Swiss Institute of Particle Physics

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Flavour Physics

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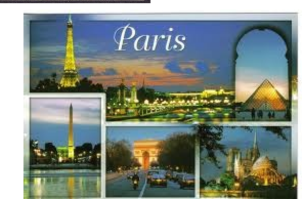
Your Lecturer

- **born in Bremen, Germany**
- **studied physics in Bonn**
- **PhD work at CERN**
  - on a small experiment you will never have heard of

- **1st PostDoc at Saclay**
  - working on the construction of the NA48 detector
  - observation of direct CP violation in neutral kaon decays



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  - indirect search for "New Physics" (= physics beyond the Standard Model) via precision measurements of CP violation and rare heavy quark decays

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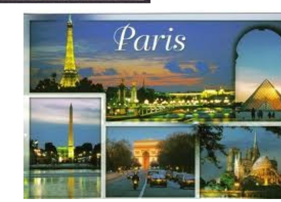

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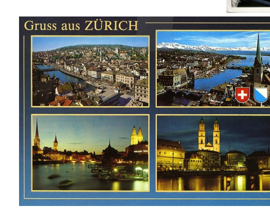

Outline

- **Part I: Introduction**
  - what is (quark) flavour physics and why is it so exciting?
  - how we got here: brief history of flavour physics in the 20th century

- **Part II: Particle-Antiparticle Mixing**
  - a short summary of the formalism (don't worry, I'm an experimentalist …)
  - introduce experimental facilities and techniques

- **Part III: Precision tests of the Standard Model**
  - CP violating observables: sin 2β, CKM angle γ, $B^0_s\overline{B}^0_s$ mixing phase ϕ_s
  - rare decays: search for $B^0_{(s)} \to \mu^+ \mu^-$, angular observables in $B^0 \to K^{*0} \mu^+ \mu^-$

[selected topics, no attempt at giving a comprehensive overview of the field !]

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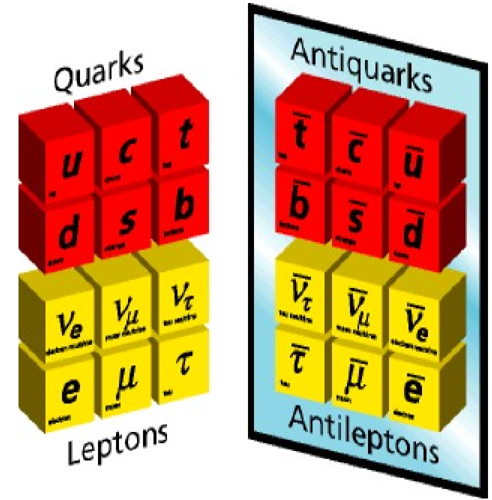
Flavour Physics

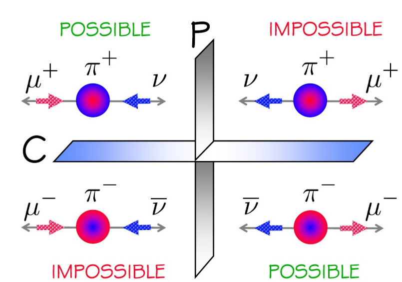
- **study properties of the three fermion families and their interactions**
  - masses, lifetimes, …
  - couplings, amplitudes, phases, …



- **it's all about the weak interaction**
  - flavour conserved in strong and electromagnetic interactions
- **three distinct sectors** (theoretical questions and experimental approaches)
  - **quarks:** measure mixing parameters, test Standard Model predictions
  - **charged leptons:** test lepton number conservation
  - **neutrinos:** measure oscillation parameters, masses, Dirac ↔ Majorana ?

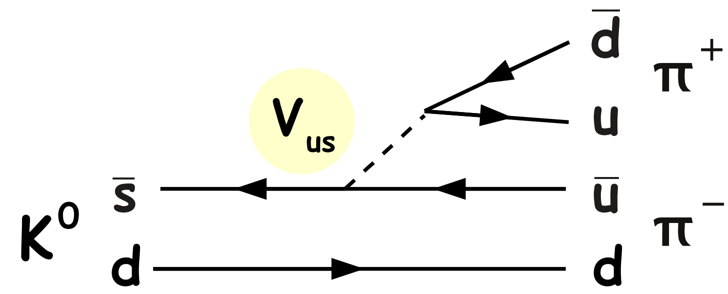
this course

- **guiding principle: symmetries and their violation**
  - Parity (P), Charge Conjugation (C), Time reversal (T), combined CP symmetry, all violated in weak interactions



CKM Matrix

Observe mixing between quark families in charged-current interactions



- e.g. kaons and B mesons would otherwise be stable particles
- described by quark mixing matrix V_{ij} (Cabibbo-Kobayashi-Maskawa = CKM) in the charged current Lagrangian

$$-L_{CC} = \frac{g}{\sqrt{2}} \bar{u}_i \gamma^\mu \left(1-\gamma_5\right) \boxed{V_{ij}} d_j W_\mu^+ + h.c.$$

$$V_{ij} = V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

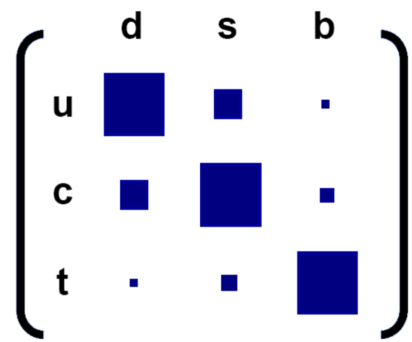
- studying the parameters of the CKM matrix is one of the main goals of quark flavour physics
- 3 quark families: 4 free parameters = 3 rotation angles + complex phase
- this complex phase is the only source of CP violation in the Standard Model

Wolfenstein Parametrization

Values of the CKM matrix elements not predicted by theory

- measured magnitudes show clear hierarchy [PDG 2012]

$$V_{CKM} = \begin{pmatrix} 0.97425 \pm 0.00022 & 0.2252 \pm 0.0009 & 0.00389 \pm 0.00044 \\ 0.2230 \pm 0.0011 & 1.023 \pm 0.036 & 0.0406 \pm 0.0013 \\ 0.0084 \pm 0.0006 & 0.0387 \pm 0.0021 & 0.88 \pm 0.07 \end{pmatrix}$$



- is there some deeper meaning hidden in this?

This hierarchy reflected in Wolfenstein parametrisation

- expand all CKM elements in terms of $\lambda = \sin\theta_C \approx 0.23$
- approximate to order λ^3
- assign the complex phase to the smallest elements, V_{td} and V_{ub}

L.Wolfenstein, [PRL 51 (1983) 1945]

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\cdot\lambda^3 \boxed{(\rho - i\eta)} \\ -\lambda & 1-\lambda^2/2 & A\cdot\lambda^2 \\ A\cdot\lambda^3 \boxed{(1-\rho-i\eta)} & -A\cdot\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Unitarity Triangles

Unitarity of CKM matrix → 6 orthogonality relations

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0 \quad (\lambda, \lambda, \lambda^5)$$

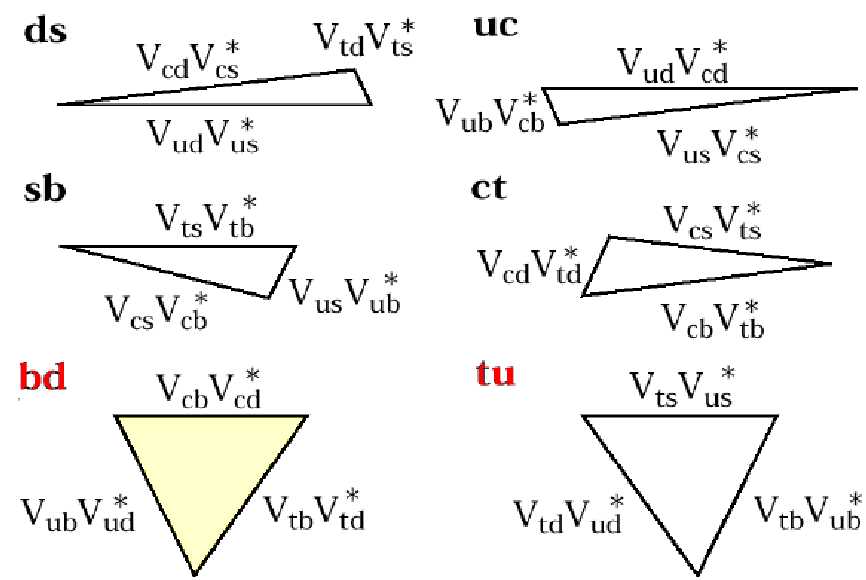
$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0 \quad (\lambda^3, \lambda^3, \lambda^3)$$

$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0 \quad (\lambda^4, \lambda^2, \lambda^2)$$

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \quad (\lambda, \lambda, \lambda^5)$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (\lambda^3, \lambda^3, \lambda^3)$$

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \quad (\lambda^4, \lambda^2, \lambda^2)$$



- **can be visualized as triangles in the complex plane**
  - all six triangles have the same surface area ∝ CP violation
  - but four of them are "squashed"

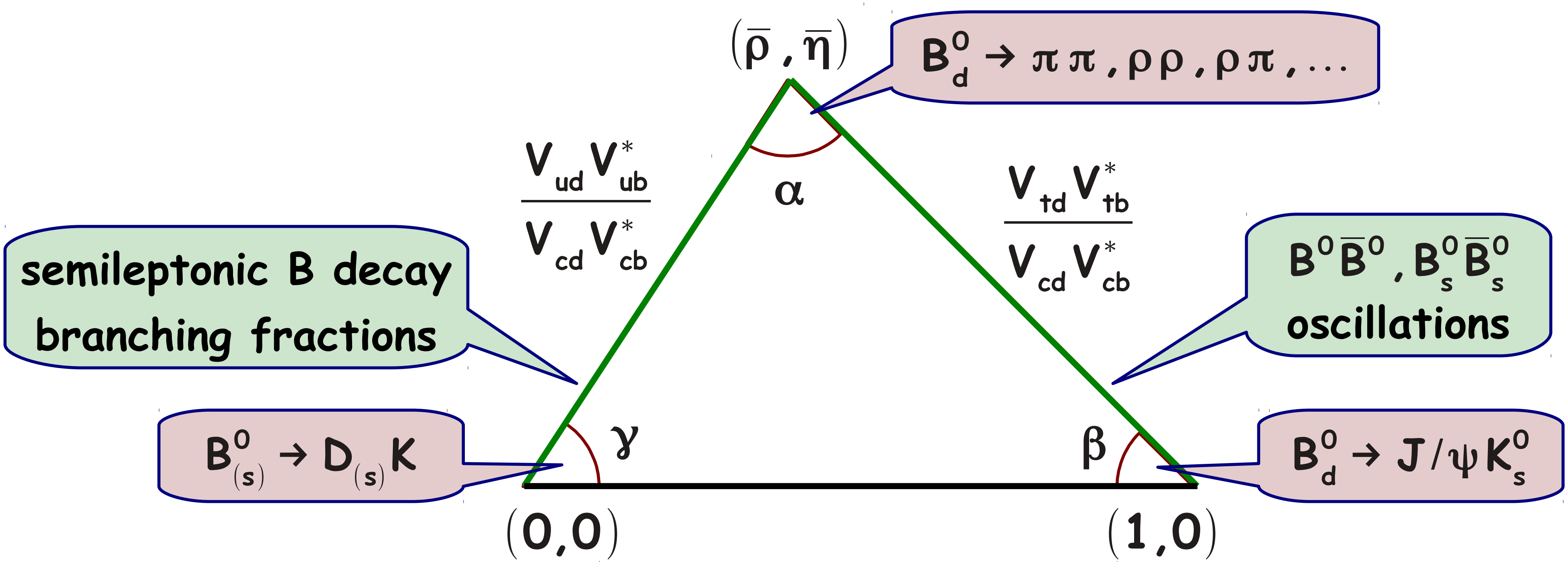
C.Jarlskog, [PRL 55 (1985) 1039]

- **the two non-squashed triangles are identical in Wolfenstein approximation**
  - differences appear at higher orders of λ → become relevant at LHCb

angles and sides of these triangles are related to measurable quantities

"The" Unitarity Triangle

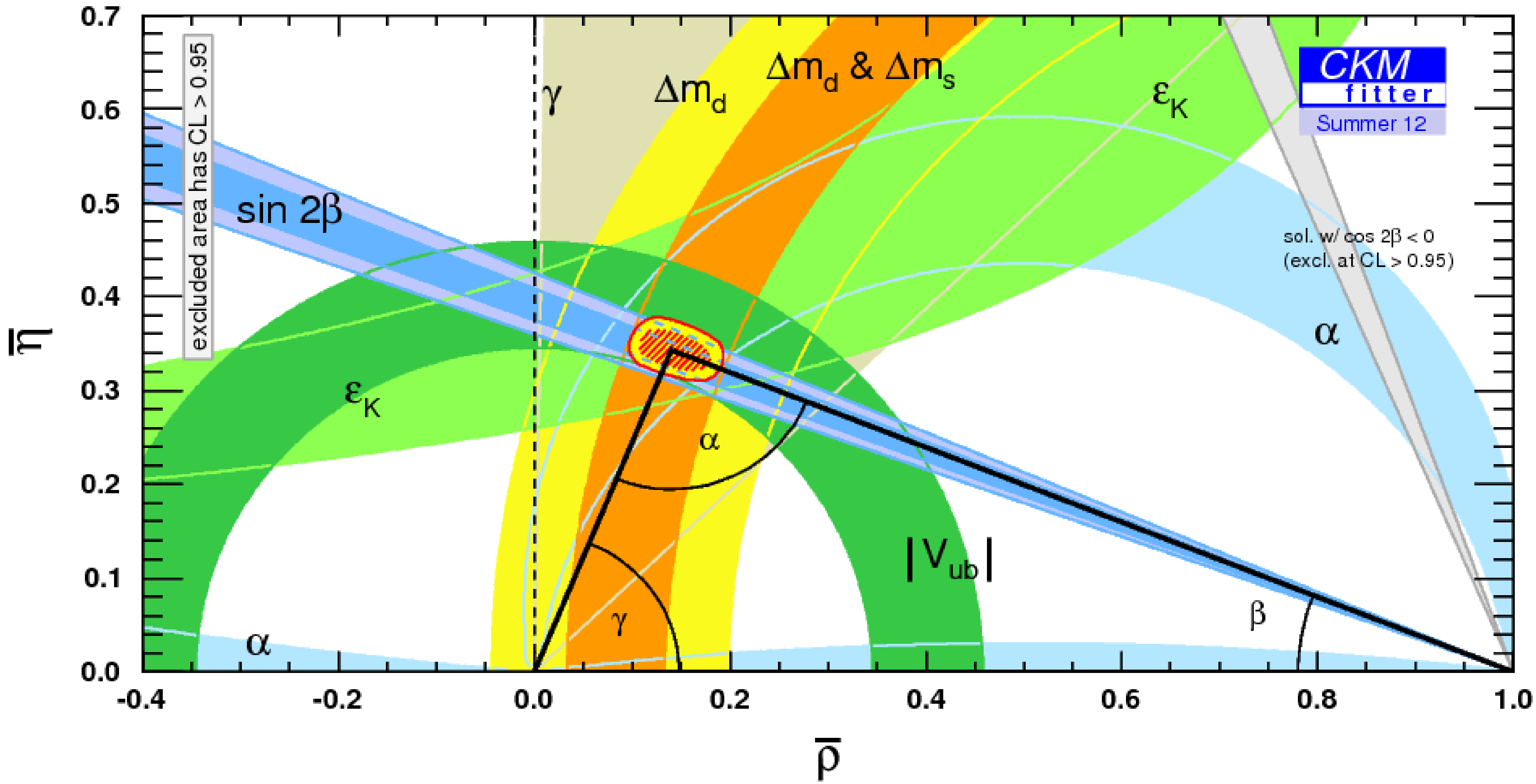
Use $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ and normalize to $V_{cd}V_{cb}^*$



- measure the lengths of the two sides: CP conserving quantities
- measure all three angles: CP violating quantities (angles = phases !)
- many observables → overconstraint determination of triangle

consistency check of Standard Model !

"The" Unitarity Triangle 2012



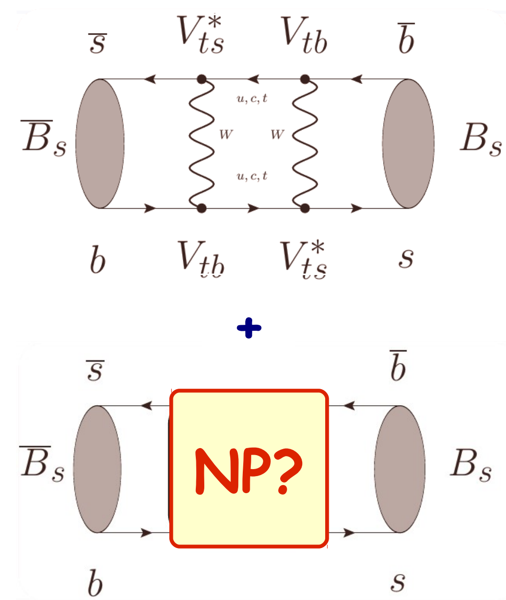
- so far a huge success story for the Standard Model
- current measurement precision permits ~20% contribution from New Physics

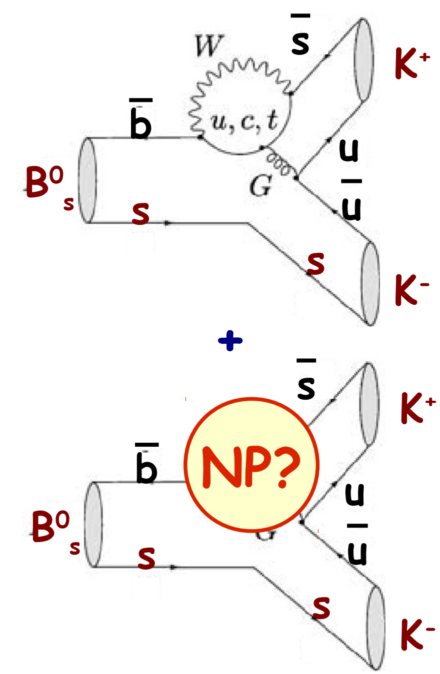
need more precise measurements: this is the goal of LHCb !

Loops !

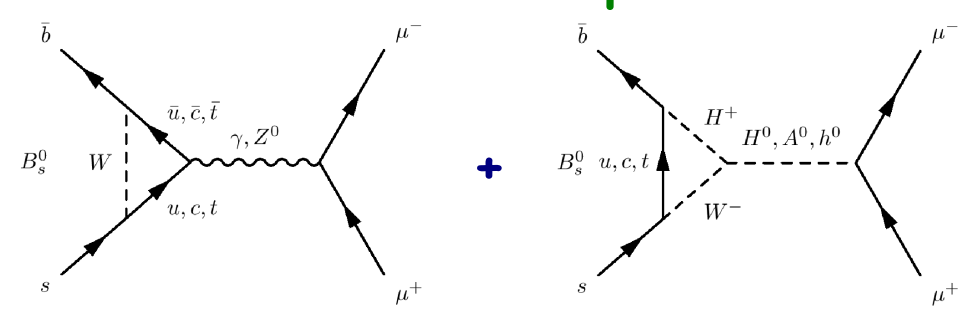
Why do we expect New Physics to show up in these observables?

- many processes involve loop diagrams:
  - box diagrams (mixing)
  - Penguin diagrams (decays)





- New Physics models usually predict new, heavy particles (e.g. SUSY)
- these particles can appear in the loops and affect magnitudes and phases
- searches are sensitive to the appearance of virtual particles in loops
  - test much higher mass scales than direct searches for new particles (limited by center-of-mass energy)
- another promising hunting ground: rare heavy quark decays



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Isospin

Observe similar behaviour of proton/neutron

- different charge but similar masses, same couplings in nuclear interactions

Heisenberg (1932): p/n form an Isospin doublet

ZfP 77 (1932) 1

- nuclear interaction invariant under global SU(2) rotation in Isospin space

$$p : (I, I_z) = (1/2, +1/2) \quad ; \quad n : (I, I_z) = (1/2, -1/2)$$

- similarly: $\pi^+/\pi^0/\pi^-$ form an Isospin triplet

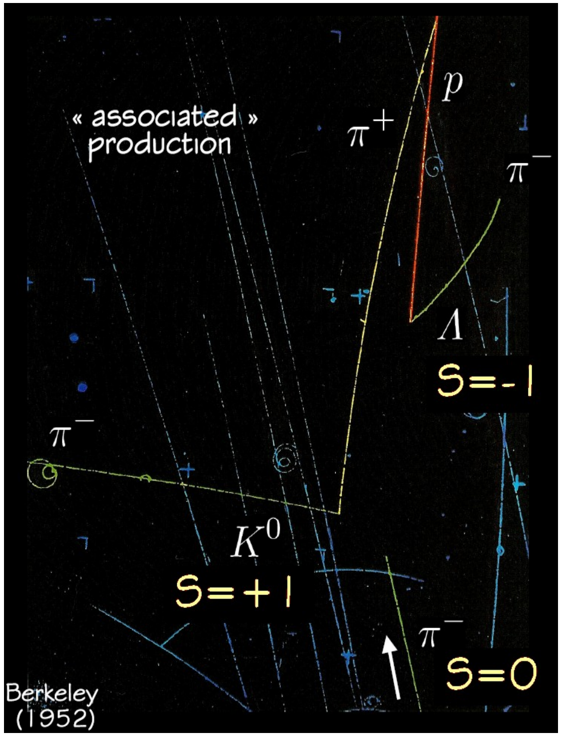
$$\pi^+ : (I, I_z) = (1, +1) \quad ; \quad \pi^0 : (I, I_z) = (1, 0) \quad ; \quad \pi^- : (I, I_z) = (1, -1)$$

In today's language: $I_z = +1/2 \rightarrow$ u quark, $I_z = -1/2 \rightarrow$ d quark

$$p = (uud) \,,\; n = (udd) \qquad \pi^+ = (u\bar{d}) \,,\; \pi^0 = 1/\sqrt{2}\,(u\bar{u} + d\bar{d}) \,,\; \pi^- = (\bar{u}d)$$

- Isospin is not an exact symmetry but rather successful as a concept
  - works so well because $m_u \sim m_d$ and m_u, $m_d \ll \Lambda_{QCD} \approx 200$ MeV

Strangeness



Observe "strangely behaved" particles

- large production cross sections
  - typical for strong interaction
- but long lifetimes of order 10^{-10}s
  - typical for weak decays
- always produced in pairs: "associated production"

Gell-Mann (1953) / Nishijima (1955): "strangeness" quantum number

PR 92 (1953) 833
PTP 13 (1955) 285

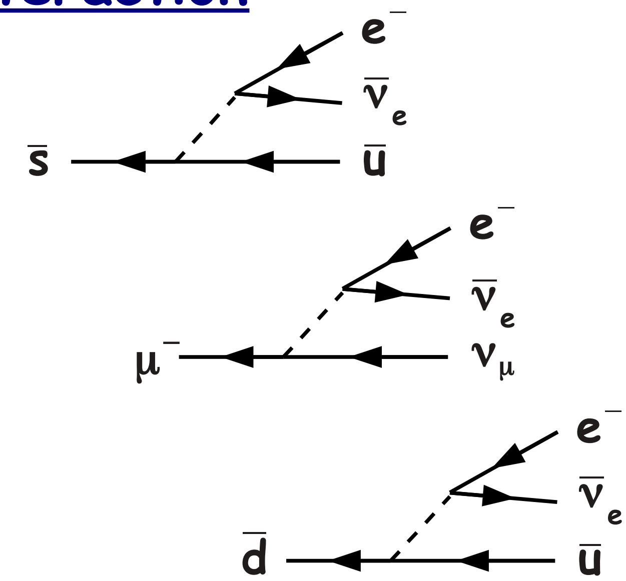
- conserved in production (strong interaction)
- not conserved in decay (weak interaction)

In today's language: strangeness → s quark

- associated production: creation of an $s\bar{s}$-pair in strong interaction

Cabibbo Angle

Observe different coupling strengths of weak interaction



- weak coupling constant should be universal if weak interactions are a fundamental force, but:
  - coupling in decays of strange particles seems about a factor 20 smaller than in muon decay
  - coupling in neutron decay about 4% smaller than in muon decay

Cabibbo (1963): weak interaction couples to a linear combination

[PRL 10 (1963) 531]

$$d' = \cos\theta_c \cdot d + \sin\theta_c \cdot s \quad \text{with} \quad \lambda = \sin\theta_c \approx 0.22$$

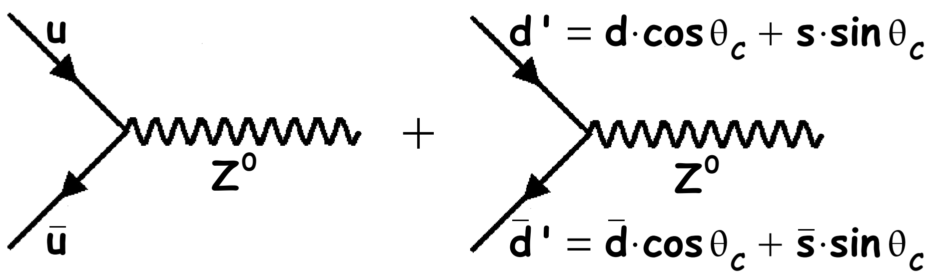
- coupling strengths in hadronic decays are then (using today's language)

$$\frac{d \to u\,W^-}{\mu^- \to \nu_\mu W^-} = \cos^2\theta_c \approx 0.96 \qquad \frac{s \to u\,W^-}{d \to u\,W^-} = \frac{\sin^2\theta_c}{\cos^2\theta_c} \approx \frac{1}{20}$$

GIM Mechanism

Observe strong suppression of Flavour-Changing Neutral Currents

- for example: BF ($K^+ \to \mu^+ \nu_\mu$) ≈ 63.5% but BF ($K^0_L \to \mu^+ \mu^-$) ≈ 7×10^{-9}
- but would expect sizeable amplitude if weak interaction couples to u and d'



$$\Rightarrow \quad u\bar{u} + d\bar{d}\cos^2\theta_c + s\bar{s}\sin^2\theta_c \; \ldots + (d\bar{s} + \bar{d}s)\cos\theta_c\sin\theta_c$$

Glashow, Ilioupolis, Maiani (1970): quark doublets

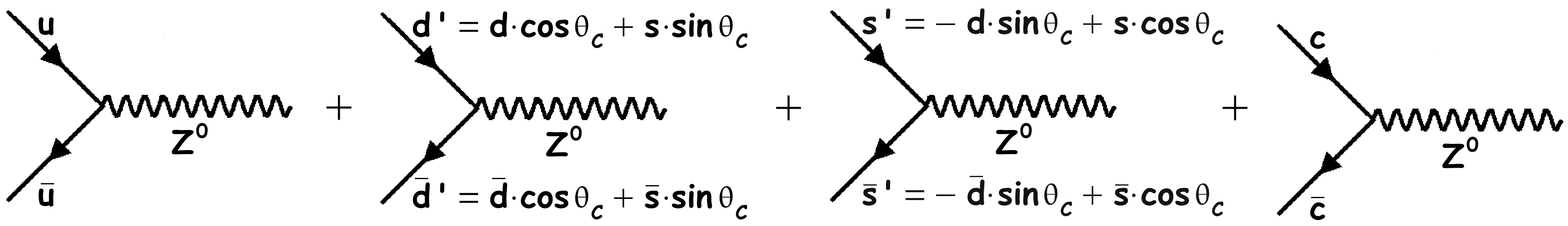
[PRD 2 (1970) 1285]

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \text{with} \quad \begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \cdot \begin{pmatrix} d \\ s \end{pmatrix}$$

- leads to cancellation of FCNC amplitudes at tree level (→ next slide)
- requires an additional, not yet observed quark (c quark discovered in 1974)

GIM Mechanism

Quark doublets → suppression of FCNC at tree level



$$u\bar{u} + c\bar{c} + (d\bar{d} + s\bar{s})\cdot\cos^2\theta_c + (d\bar{d} + s\bar{s})\cdot\sin^2\theta_c$$

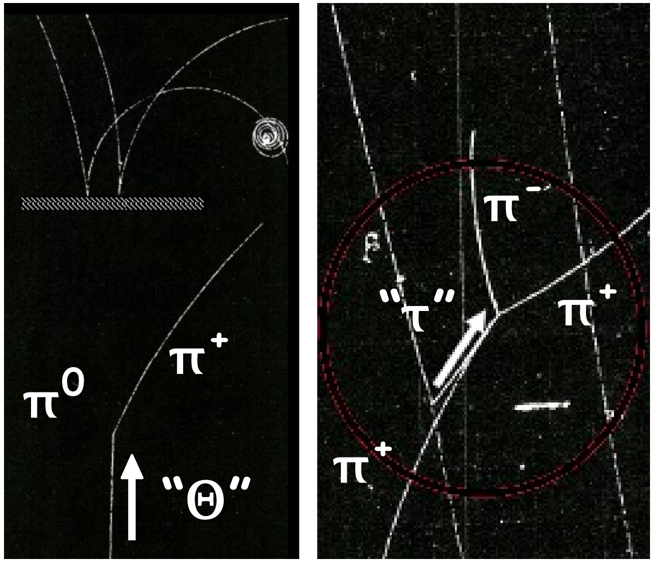
$$\ldots + (d\bar{s} + \bar{d}s)\cdot\cos\theta_c\sin\theta_c - (d\bar{s} + \bar{d}s)\cdot\sin\theta_c\cos\theta_c = u\bar{u} + c\bar{c} + d\bar{d} + s\bar{s}$$

- **cancellation only exact if all quark masses are the same**
  - valid to very good approximation, because quark masses « Z^0 mass
- **FCNC can proceed through 2nd order processes (e.g. double W-exchange)**
  - but strongly suppressed because of smallness of weak coupling constant

Parity Violation

"Θ/τ-puzzle": observe two charged, strange, spin-0 mesons

- same mass (~ 500 MeV) and same lifetime, but:
- one ("Θ") decays into $\pi^+\pi^0$ (even parity)
- the other ("τ") decays into $\pi^+\pi^+\pi^-$ (odd parity)



Yang,Lee (1956): V-A theory of weak interactions

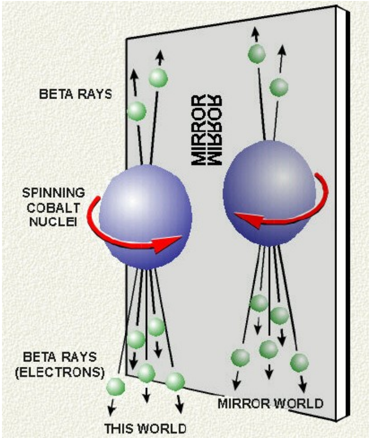
[PR 104 (1956) 254]

- parity is not conserved in weak interactions
- "Θ" and "τ" are in fact the same particle (K^+)

Wu et al. (1957): experimental proof of parity violation

[PR 105 (1957) 1413]

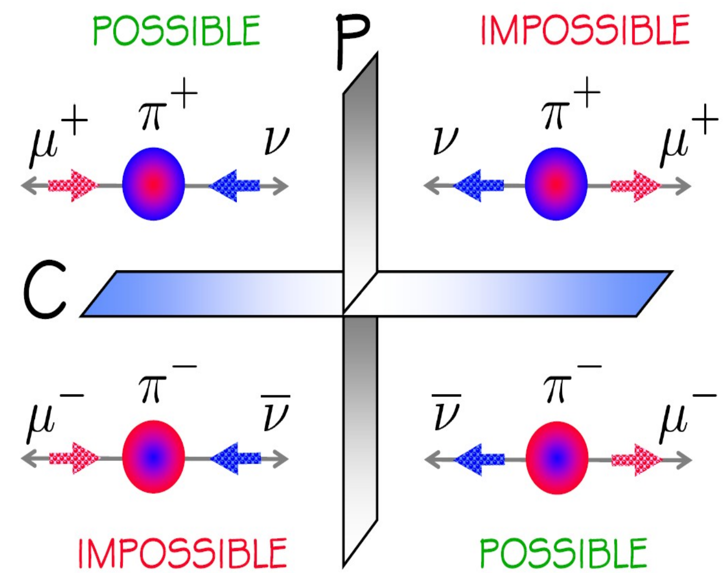
- measure angular distribution of electrons from β-decay of polarized ^{60}Co (spin=5^+) to $^{60}Ni^*$ (spin=4^+)
- must be up-down symmetric if parity is conserved
- observation: electrons are emitted predominantly opposite to ^{60}Co-spin → parity is maximally violated !



CP Symmetry

Parity violation in semi-leptonic pion decays

- **muons from $\pi^\pm$ decays are polarized:**
  - μ^- from π^--decays are left-handed
  - μ^+ from π^+-decays are right-handed
- **parity is maximally violated, as expected**
- **charge conjugation is also maximally violated**
- **but: decay rates for π^- to left-handed μ^- and for π^+ to right-handed μ^+ are the same !**



Landau, Okun (1957): relevant symmetry in weak interactions is CP

[Nucl Phys 3 (1957) 127]
[Zh Eksp Teor Fiz 32 (1957) 1587]

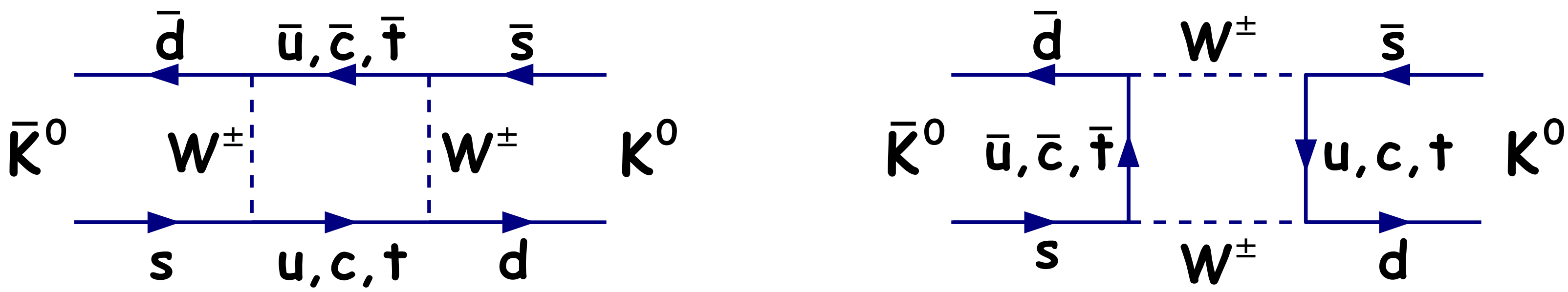
- CP = Charge conjugation × Parity
- Richard Feynman in *Symmetries in Physical Laws*, 1963:

  "it is really true that right and left symmetry is still maintained … the right-handed matter behaves the same way as the left-handed antimatter"

Two K^0 States

Short excursion: $K^0\bar{K}^0$ mixing

- **strangeness is the only quantum number that distinguishes K^0 from $\bar{K}^0$**
- **strangeness is not conserved in weak interactions: transitions $K^0 \leftrightarrow \bar{K}^0$**
  - in today's language: transitions via double W exchange ("box diagrams")



- **pure state $|K^0\rangle$ produced at time t=0 will evolve into a mixed state at t>0**

$$|\psi(t)\rangle = a(t)\cdot|K^0\rangle + b(t)\cdot|\bar{K}^0\rangle$$

- **define Eigenstates of CP operator:**

$$|K_1\rangle = \frac{1}{\sqrt{2}}\cdot\left\{|K^0\rangle + |\bar{K}^0\rangle\right\} \quad\Rightarrow\quad CP\,|K_1\rangle = +\,|K_1\rangle$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}\cdot\left\{|K^0\rangle - |\bar{K}^0\rangle\right\} \quad\Rightarrow\quad CP\,|K_2\rangle = -\,|K_2\rangle$$

Two K^0 States

Gell-Mann, Pais (1955): two K^0 states with different lifetimes

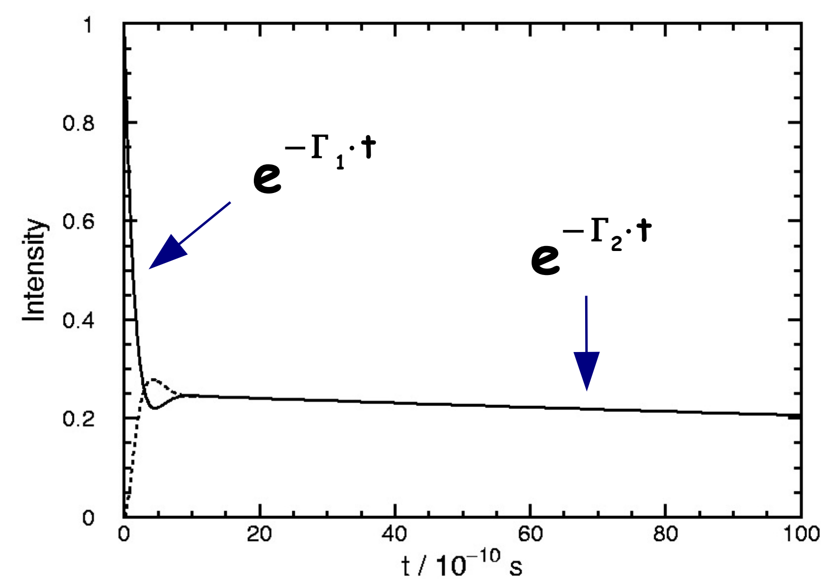
[PR 97 (1955) 1387]

- if CP conserved in weak interactions, then
  - K_1 and K_2 are also eigenstates of weak interaction
  - K_1 can decay into 2 pions
  - K_2 cannot decay into 2 pions

$$J_K = J_\pi = 0 \;\Rightarrow\; L_{\pi\pi} = 0$$
$$\Rightarrow\; CP_{\pi\pi} = -1^{L_{\pi\pi}} = +1$$

- all possible decay channels for K_2 suppressed:
  - decays to 3 pions by phase space
  - semi-leptonic decays by parity violation
- K_2 must have much longer lifetime than K_1
  - measured lifetimes:

$$\tau(K_2) \approx 500 \times \tau(K_1)$$

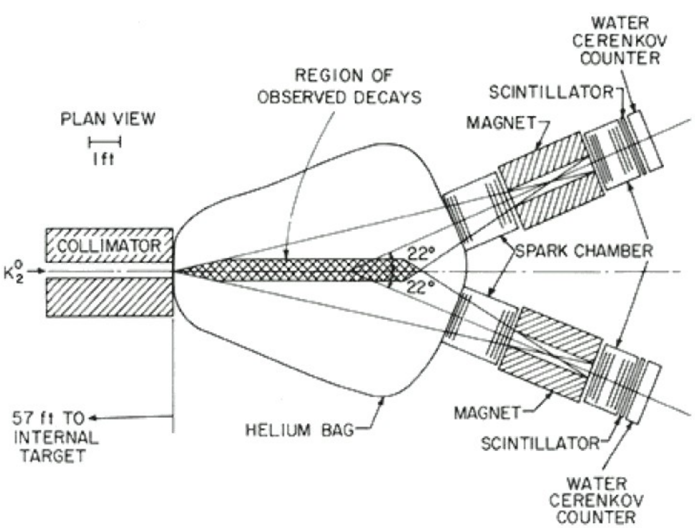


CP Violation

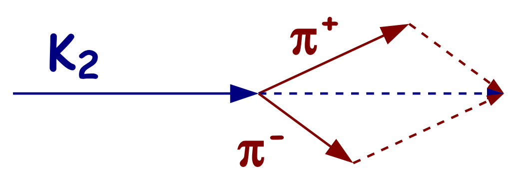
Christenson, Cronin, Fitch, Turlay (1964): observation of $K_2 \to \pi^+\pi^-$

[PRL 13 (1964) 138]

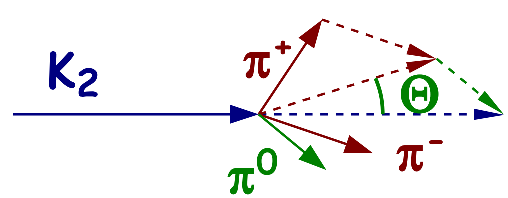
- **shoot protons into fixed target, produce K^0 and $\bar{K}^0$**
  - let them propagate in a vacuum tube
  - K_1 component decays away → obtain pure K_2 beam
- **search for $\pi^+\pi^-$ decays in this K_2 beam**
  - energy conservation: invariant mass of $\pi^+\pi^-$ pair
  - momentum conservation: momentum balance

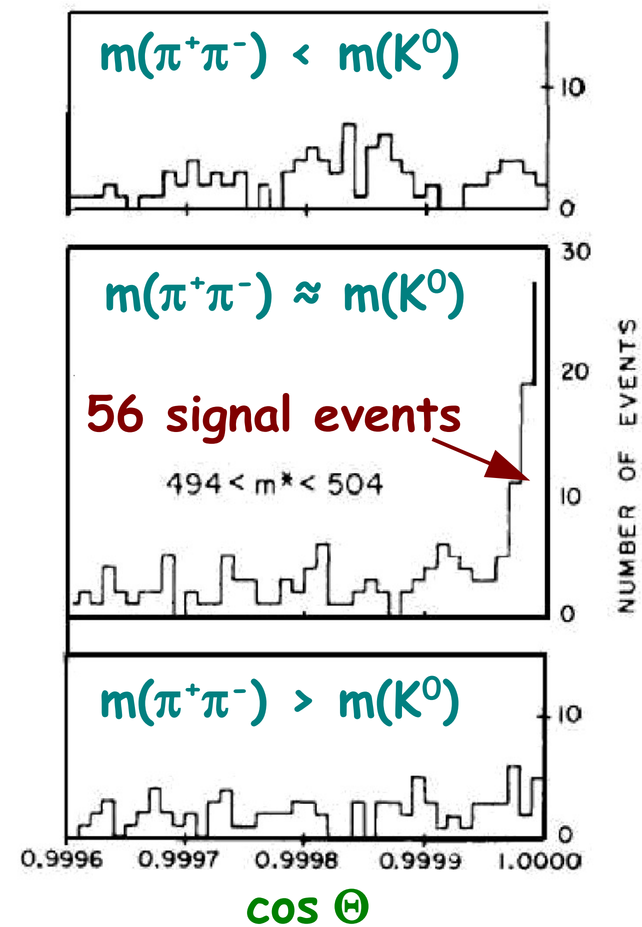


2-body decays:



3-body decays:





- **observe excess of 56 events in signal region ⇒**

BR $(K_2 \to \pi^+\pi^-) \approx 2 \times 10^{-3}$

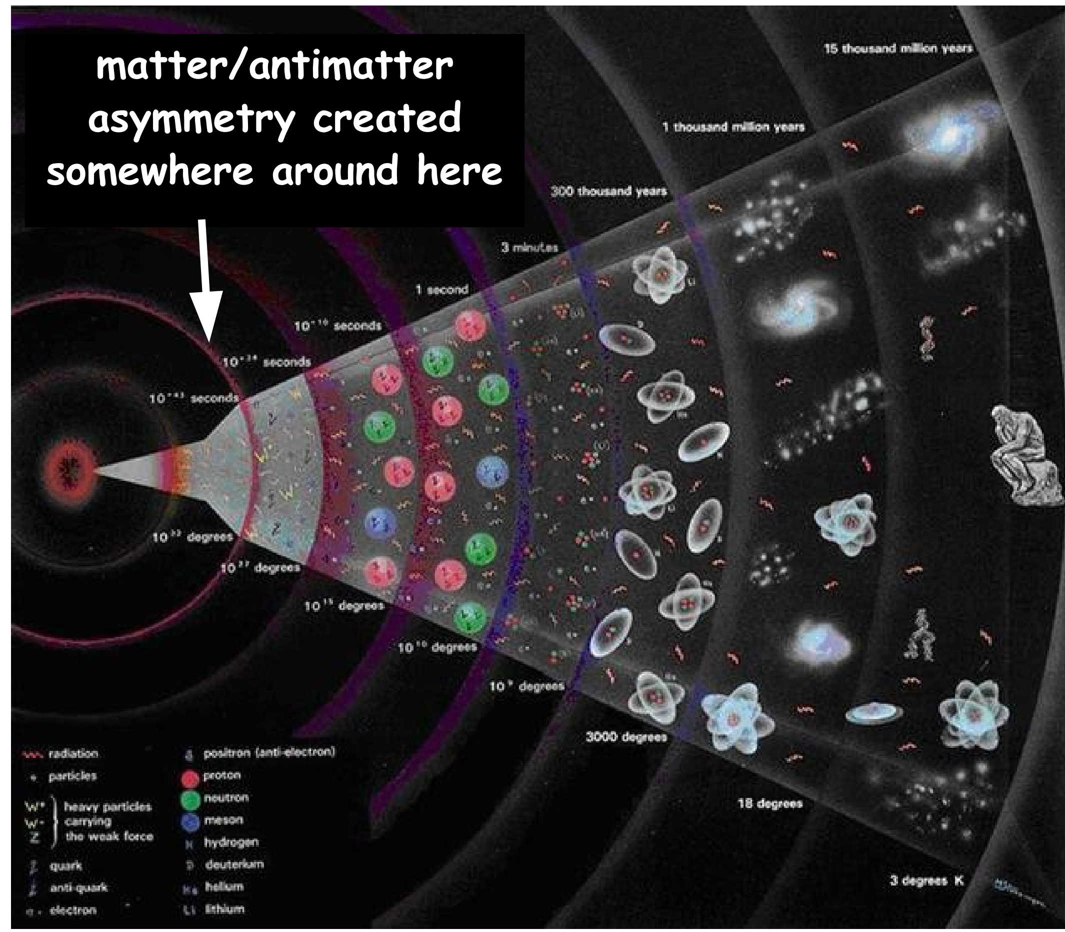
Swiss Institute of Particle Physics

Sakharov Conditions

Sakharov (1967): CP violation required to create a matter/antimatter asymmetry in the Universe

[JETP Lett 5 (1967) 24]

- **Sakharov's three conditions:**
  - Baryon-number violation
  - C violation and CP violation
  - thermal non-equilibrium



- **but: baryon asymmetry observed in the universe is**

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

- **CKM-induced CP violation gives**

$$\eta \approx 10^{-18}$$

- **need additional sources of CP violation**

CKM Mechanism

Kobayashi, Maskawa (1972): CP violation if three quark doublets

[PTP 49 (1973) 652]

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix} \quad \text{with} \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- 9 complex numbers = 18 parameters
  - 9 unitarity constraints ($V^\dagger V = VV^\dagger = 1$)
  - 5 arbitrary ("unphysical") phases

  = 4 free parameters: 3 rotation angles + 1 complex phase

$$\left.\begin{array}{l} u_i \to e^{i\phi_i} u_i \\ d_j \to e^{i\phi_j} d_j \end{array}\right\} \Leftrightarrow V_{ij} \to e^{i(\phi_j - \phi_i)} V_{ij}$$

- CP violation due to interference if diagrams with different weak phase contribute to the same process
- "prediction" of third quark family before even charm quark was discovered

Various other models proposed at the time to explain CP violation

- most prominent: new "superweak" force that acts only in kaon mixing

Charm Quark

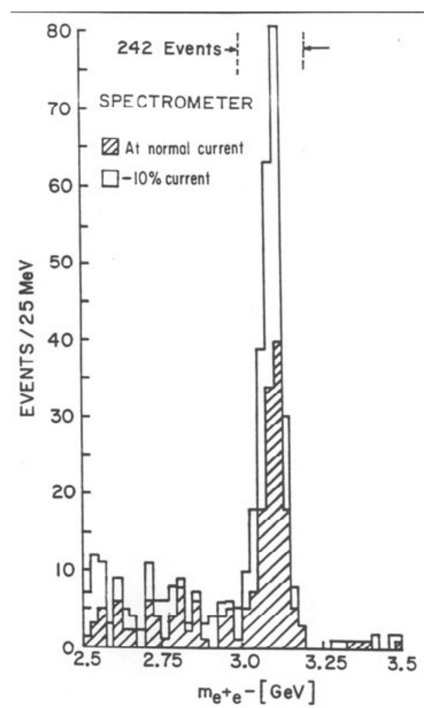
"November revolution" (1974)

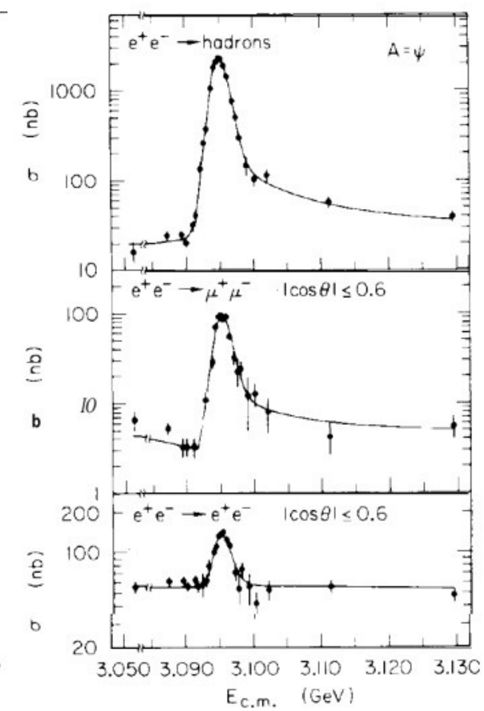
[PRL 33 (1974) 1404]
[PRL 33 (1974) 1406]

- observation of a narrow resonance at a mass of 3.1 GeV, simultaneously
  - in $p + Be \rightarrow e^+ e^- + X$ at BNL (Ting et al.) → "J"
  - in $e^+ e^- \rightarrow e^+ e^-$, $\mu^+ \mu^-$, hadrons at SLAC (Richter et al.) → "ψ"
  - } J/ψ
  - in both cases, measured width dominated by the detector resolution
- narrow width → long lifetime
  → cannot be an excited u,d,s state
- interpretation: bound $c\bar{c}$ state

m(c) ~ 1.5 GeV

- soon confirmed by observation of other $c\bar{c}$ states and of open charm (D mesons)



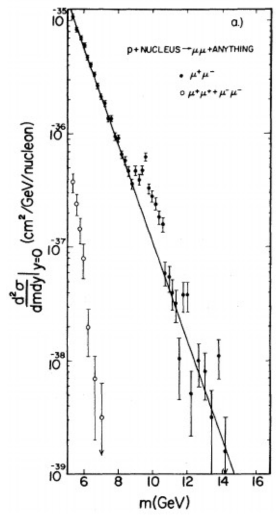


Bottom and Top Quarks

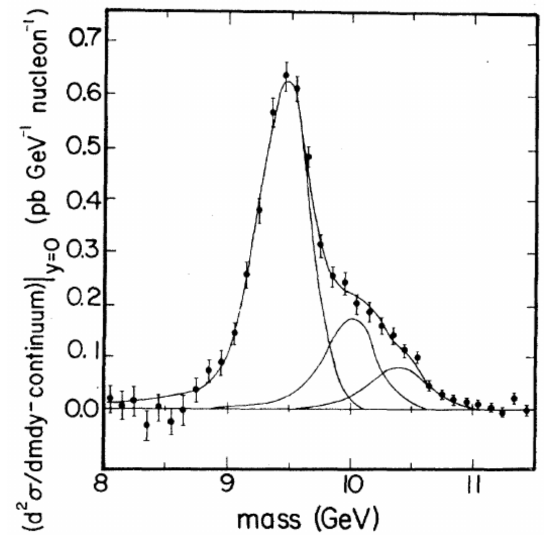
Lederman et al. (1977): search for $b\bar{b}$ resonances in $p + Cu \rightarrow \mu^+ \mu^- + X$

- observe excess of $\mu^+\mu^-$ pairs around an invariant mass of 9.4-10.4 GeV
- resolved into three resonances, interpreted as bound $b\bar{b}$ states

m(b) ~ 4.5 GeV



[PRL 39 (1977) 252]



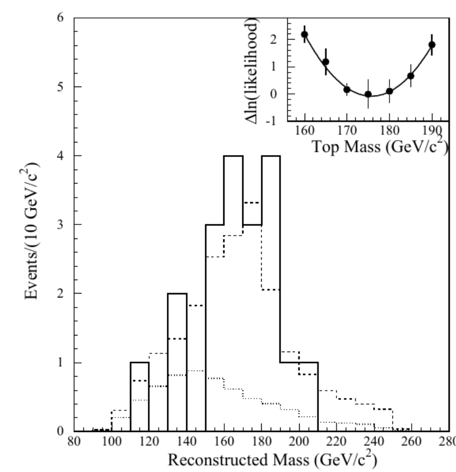
[PRL 42 (1979) 486]

CDF/D0 (1995): first observation of top quark

[PRL 74 (1995) 2626]
[PRL 74 (1995) 2632]

- existence of top quark taken for granted after discovery of b quark
- mass around 170 GeV predicted from fits to electroweak precision measurements at LEP and SLC
- production in 1.8 TeV $p\bar{p}$ collisions at Tevatron
- detection in $t \rightarrow W\,b$ decays

m(t) ~ 176 GeV



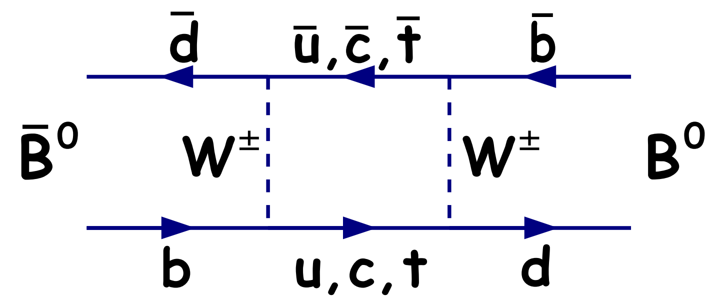
$B^0\bar{B}^0$ Mixing

Argus experiment at DESY (1987)

[PLB192 (1987) 245]

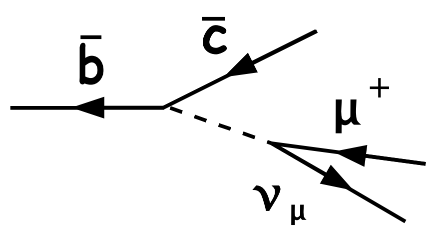
- e^+e^- collider operating at $\Upsilon(4s)$ resonance
- produce $B^0\bar{B}^0$ pairs through

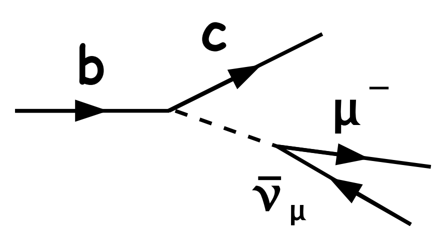
$$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0\bar{B}^0$$

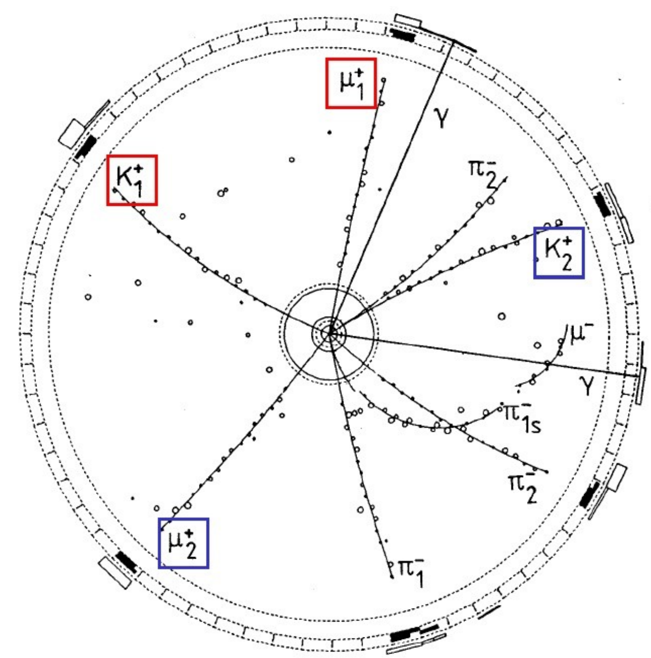


- $B^0\bar{B}^0$ mixing through box diagrams
- can be observed in semi-leptonic decays

$$B^0 \rightarrow D^{*-}\mu^+\nu_\mu \qquad \bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu$$





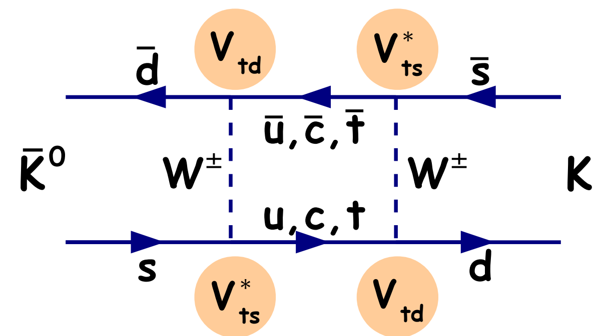


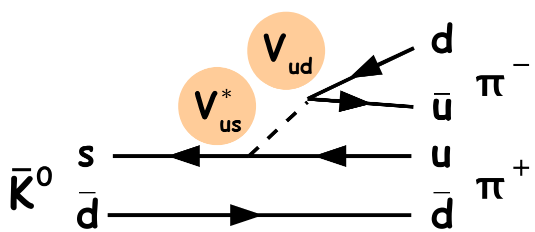
- observe "like-sign event" with two μ^- or two μ^+
  $\rightarrow$ B^0 or $\bar{B}^0$ must have mixed
- strong mixing observed $\rightarrow$ predict large top quark mass

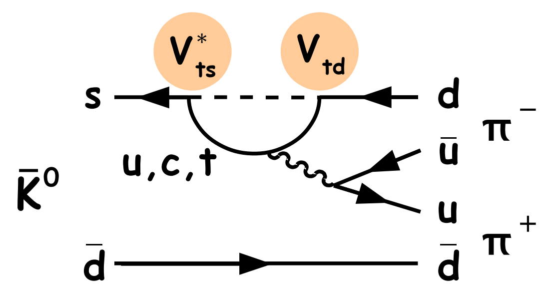
Direct CP Violation

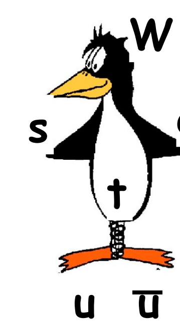
CKM: CP violation from interference of diagrams with different phase

- interference of box diagrams with different internal quarks: "indirect" CP violation in K mixing
- interference of tree and penguin decay diagrams with different phases: "direct" CP violation in decay









- can be tested by comparing CP violation in $\pi^+\pi^-$ and $\pi^0\pi^0$ decays: different decay diagrams → expect CP violation to be slightly different

$$\eta_{+-} = \frac{\Gamma\left(K_L \to \pi^+\pi^-\right)}{\Gamma\left(K_S \to \pi^+\pi^-\right)} = \varepsilon + \varepsilon' \quad ; \quad \eta_{00} = \frac{\Gamma\left(K_L \to \pi^0\pi^0\right)}{\Gamma\left(K_S \to \pi^0\pi^0\right)} = \varepsilon - 2\varepsilon'$$

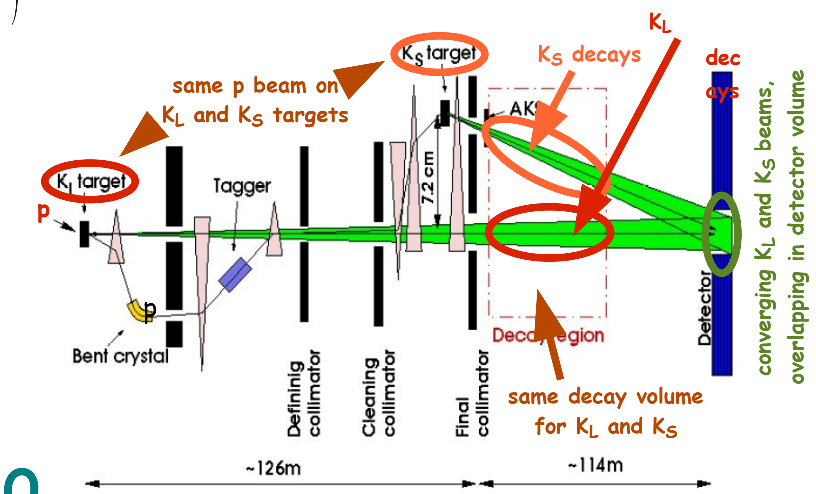
- in Standard Model expect $\varepsilon'/\varepsilon \approx 10^{-3}$
- if CP violation only in K mixing (superweak interaction): $\eta_{+-} = \eta_{00}$, $\varepsilon' = 0$

Direct CP Violation

Experimental approach: measure the “double ratio”

$$R = \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 = \frac{\Gamma\left(K_L \to \pi^0\pi^0\right) / \Gamma\left(K_S \to \pi^0\pi^0\right)}{\Gamma\left(K_L \to \pi^+\pi^-\right) / \Gamma\left(K_S \to \pi^+\pi^-\right)} \approx 1 - 6 \cdot \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

- challenge: control systematics to $O(10^{-4})$
- many systematic effects cancel to first order if all four decay rates are measured simultaneously (same beam, same detector)



NA48 simultaneous K_L and K_S beams

NA48/KTeV (2001): observation of $\varepsilon'/\varepsilon \neq 0$

- end of a decades long competition CERN ↔ FNAL

NA48@CERN: $\mathrm{Re}\left(\varepsilon'/\varepsilon\right) = \left(14.7 \pm 2.2\right) \times 10^{-4}$ [PLB 544 (2002) 97]

KTeV@FNAL: $\mathrm{Re}\left(\varepsilon'/\varepsilon\right) = \left(19.2 \pm 2.1\right) \times 10^{-4}$ [PRD 83 (2011) 092001]

- vindication of CKM model of CP violation
- but large hadronic uncertainties, do not learn much about CKM parameters

CP Violation in The $B^0\bar{B}^0$ System

Many advantages over $K^0\bar{K}^0$ system

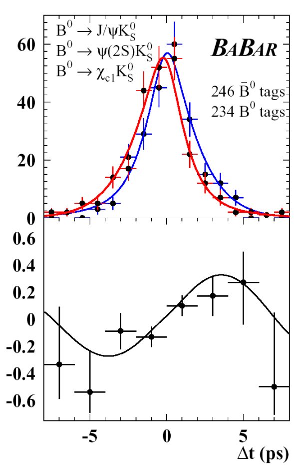
- many decay channels and observables, large CP asymmetries, theoretically "clean" predictions, …

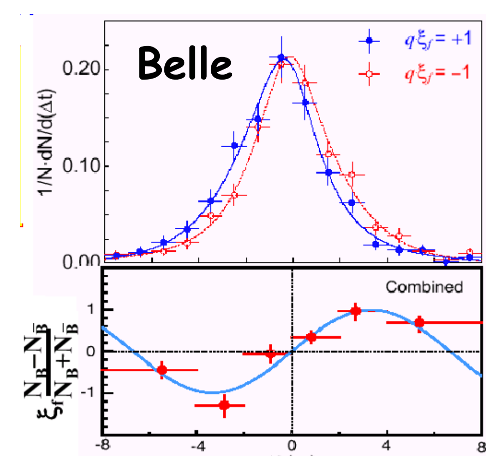
But experimental challenges

- B mesons heavy → small production cross section
- many decay channels → small branching ratios
- short lifetime and fast oscillation frequency

} need high-luminosity accelerators and very precise detectors

- dedicated "B factories" constructed especially for CP measurement: BaBar at PEP-II, Belle at KEKB
- 2001: both observe CP asymmetry in "golden decay channel" $B^0 \rightarrow J/\psi\, K^0_S$
  - measured values in good agreement with CKM prediction





2001 ++

Many more and much more precise results

- BaBar/Belle, CDF/D0 at Tevatron, now LHCb
- results so far in very good agreement with CKM predictions (2-3σ deviations came and went)

} remainder of this lecture

- Babar and Belle stopped data taking, Belle collected ~ 1 ab^{-1}
- Tevatron stopped in autumn 2011 → CDF/D0 collected ~ 9 fb^{-1}
- LHCb collected ~1 fb^{-1} at 7 TeV in 2011 and ~2 fb^{-1} at 8 TeV in 2012
  - $b\bar{b}$ production cross section ~ 5 x Tevatron, ~ 500'000 x Babar/Belle
  - many analyses ongoing, already ~ 80 papers published
- LHC shutdown in 2013/2014, resume at ≥ 13 TeV in 2015
  - another factor two in $b\bar{b}$ production cross section
- "Belle II" under construction; goal: collect ~ 50 x Belle luminosity by 2022

Outline

- **Part I: Introduction**
  - what is (quark) flavour physics and why is it so exciting?
  - how we got here: brief history of flavour physics in the 20th century
- **Part II: Particle-Antiparticle Mixing**
  - a short summary of the formalism (don't worry, I'm an experimentalist …)
  - introduce experimental facilities and techniques
- **Part III: Precision tests of the Standard Model**
  - CP violating observables: sin 2β, CKM angle γ, $B^0_s\overline{B}^0_s$ mixing phase ϕ_s
  - rare decays: search for $B^0_{(s)} \rightarrow \mu^+ \mu^-$, angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

$P^0\bar{P}^0$ Mixing

Applies for all neutral meson systems ($K^0\bar{K}^0$, $D^0\bar{D}^0$, $B^0\bar{B}^0$, $B^0_s\bar{B}^0_s$)

- different phenomenologies due to different mass and lifetime differences
- flavour mixing through box diagrams → coupled system

$$|\psi(t)\rangle = a(t)\,|P^0\rangle + b(t)\,|\bar{P}^0\rangle$$

- time evolution described by two-component Schrödinger equation

$$-i\frac{\partial}{\partial t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = H \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

- with an effective Hamiltonian H
  - H is not Hermitian since it does not include decay products
- decompose H into Hermitian parts:

$$M \equiv \frac{1}{2}\left(H + H^\dagger\right) \quad ; \quad \frac{1}{2}\Gamma \equiv \frac{1}{2i}\left(H - H^\dagger\right)$$

$$H = M - \frac{i}{2}\Gamma = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

$P^0\bar{P}^0$ Mixing (ii)

- **assume CPT is conserved: particle/antiparticle have same mass/lifetime**

$$\left.\begin{array}{l} M \equiv M_{11} = M_{22} \\ \Gamma \equiv \Gamma_{11} = \Gamma_{22} \end{array}\right\} \quad \Rightarrow \quad H = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}$$

- **Eigenvalues**

$$\omega_{H,L} = M - \frac{i}{2}\Gamma \pm \sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)} \equiv m_{H,L} - \frac{i}{2}\Gamma_{H,L}$$

- **Eigenstates** (labeled by their mass, H for "heavy", L for "light")

$$\left|P_{H,L}\right\rangle = p\left|P^0\right\rangle \mp q\left|\bar{P}^0\right\rangle \quad \text{with} \quad \frac{q}{p} = -\sqrt{\frac{H_{21}}{H_{12}}} = -\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

- **these are states with well-defined mass and decay width**

$$\left|P_H(t)\right\rangle = \left(p \cdot \left|P^0\right\rangle - q \cdot \left|\bar{P}^0\right\rangle\right) \cdot e^{-im_H t} \cdot e^{-\Gamma_H t/2}$$

$$\left|P_L(t)\right\rangle = \left(p \cdot \left|P^0\right\rangle + q \cdot \left|\bar{P}^0\right\rangle\right) \cdot e^{-im_L t} \cdot e^{-\Gamma_L t/2}$$

$P^0\bar{P}^0$ Mixing (iii)

- time evolution of initially pure flavour states

$$\left|P^0_{(t=0)}(t)\right\rangle = g_+(t)\cdot\left|P^0\right\rangle + \frac{q}{p}\cdot g_-(t)\cdot\left|\bar{P}^0\right\rangle$$

$$\left|\bar{P}^0_{(t=0)}(t)\right\rangle = g_+(t)\cdot\left|\bar{P}^0\right\rangle + \frac{p}{q}\cdot g_-(t)\cdot\left|P^0\right\rangle$$

with:

$$g_\pm(t) = \frac{1}{2}\left(e^{-\omega_L t} \pm e^{-\omega_H t}\right)$$

$$= \frac{1}{2}\, e^{-iMt}\, e^{-\Gamma t/2}\left(e^{+i\Delta m t/2} e^{+\Delta\Gamma t/4} \pm e^{-i\Delta m t/2} e^{-\Delta\Gamma t/4}\right)$$

$$\Delta m \equiv m_H - m_L > 0$$

$$\Delta\Gamma \equiv \Gamma_H - \Gamma_L$$

- mixing probabilities as a function of time t:

$$\text{Prob}_{(P^0\to P^0)}(t) = \text{Prob}_{(\bar{P}^0\to\bar{P}^0)}(t) = \left|g_+(t)\right|^2 = \frac{1}{2}\, e^{-\Gamma\cdot t}\left\{\cosh\left(\frac{\Delta\Gamma}{2}\cdot t\right) + \cos\left(\Delta m\cdot t\right)\right\}$$

$$\text{Prob}_{(P^0\to\bar{P}^0)}(t) = \left|\frac{q}{p}\right|^2\cdot\left|g_-(t)\right|^2 = \frac{1}{2}\cdot\left|\frac{q}{p}\right|^2\cdot e^{-\Gamma\cdot t}\cdot\left\{\cosh\left(\frac{\Delta\Gamma}{2}\cdot t\right) - \cos\left(\Delta m\cdot t\right)\right\}$$

$$\text{Prob}_{(\bar{P}^0\to P^0)}(t) = \left|\frac{p}{q}\right|^2\cdot\left|g_-(t)\right|^2 = \frac{1}{2}\cdot\left|\frac{p}{q}\right|^2\cdot e^{-\Gamma\cdot t}\cdot\left\{\cosh\left(\frac{\Delta\Gamma}{2}\cdot t\right) - \cos\left(\Delta m\cdot t\right)\right\}$$

$P^0\bar{P}^0$ Mixing (iv)

- observable time-dependent asymmetries

$$a_{mix}(t) \equiv \frac{N(P^0\to P^0) - N(P^0\to \bar{P}^0)}{N(P^0\to P^0) + N(P^0\to \bar{P}^0)} = \frac{\cos(\Delta m\cdot t) + \delta\cdot\cosh(\Delta\Gamma\cdot t/2)}{\cosh(\Delta\Gamma\cdot t/2) + \delta\cdot\cos(\Delta m\cdot t)}$$

$$\bar{a}_{mix}(t) \equiv \frac{N(\bar{P}^0\to \bar{P}^0) - N(\bar{P}^0\to P^0)}{N(\bar{P}^0\to \bar{P}^0) + N(\bar{P}^0\to P^0)} = \frac{\cos(\Delta m\cdot t) - \delta\cdot\cosh(\Delta\Gamma\cdot t/2)}{\cosh(\Delta\Gamma\cdot t/2) - \delta\cdot\cos(\Delta m\cdot t)}$$

with

$$\delta \equiv \frac{1-|q/p|^2}{1+|q/p|^2}$$

$\delta \neq 0 \;\Leftrightarrow\;$ CP violation in mixing

- assume for now that CP is conserved in mixing, i.e. $\delta = 0$

$$a_{mix}(t) = \bar{a}_{mix}(t) = \frac{\cos(\Delta m\cdot t)}{\cosh(\Delta\Gamma\cdot t/2)} = \frac{\cos(x\cdot\Gamma\cdot t)}{\cosh(y\cdot\Gamma\cdot t)}$$

with $\begin{cases} x = \Delta m/\Gamma \\ y = \Delta\Gamma/2\Gamma \end{cases}$

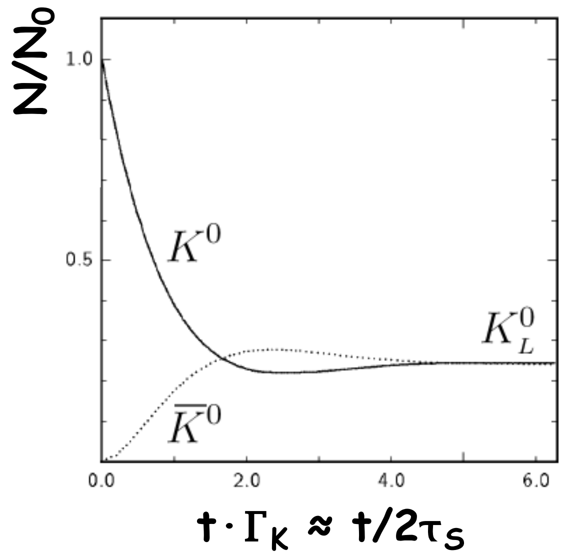
- oscillation frequency x: mass difference
- damping parameter y: lifetime difference

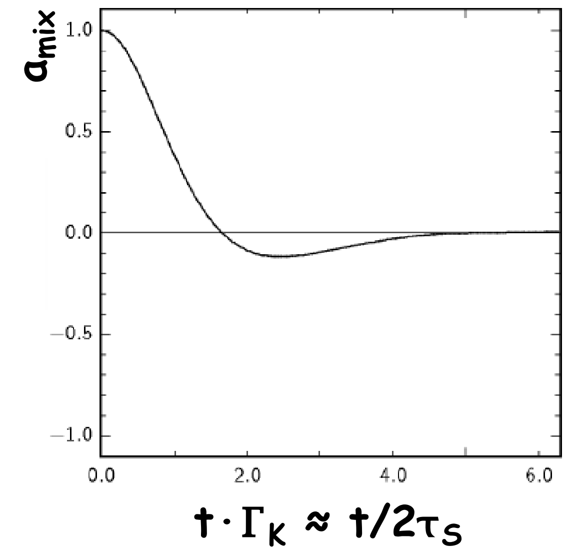
} between the two weak Eigenstates

Mixing: $K^0\bar{K}^0$ and $D^0\bar{D}^0$

$K^0\bar{K}^0$

- $x_K \approx 0.95$
- $y_K \approx -0.996$ ($\tau_L \gg \tau_S$)
- strong damping, only K_L left after about one oscillation

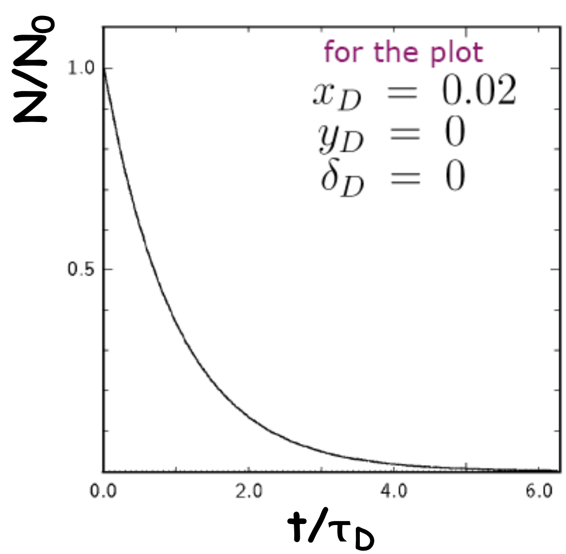


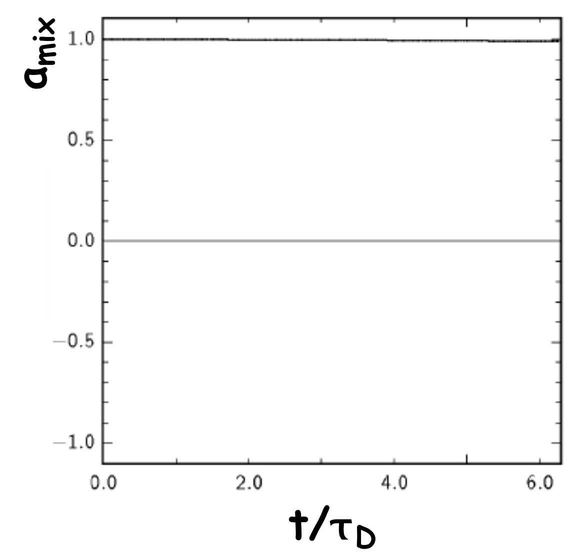


$D^0\bar{D}^0$

- $x_D \approx 0.008$
- $y_D \approx 0.007$
- mixing very small, e.g. time-integrated probability

$$\chi_D = \frac{x_D^2 + y_D^2}{2\,(1 + x_D^2)} \approx 3\times10^{-5}$$





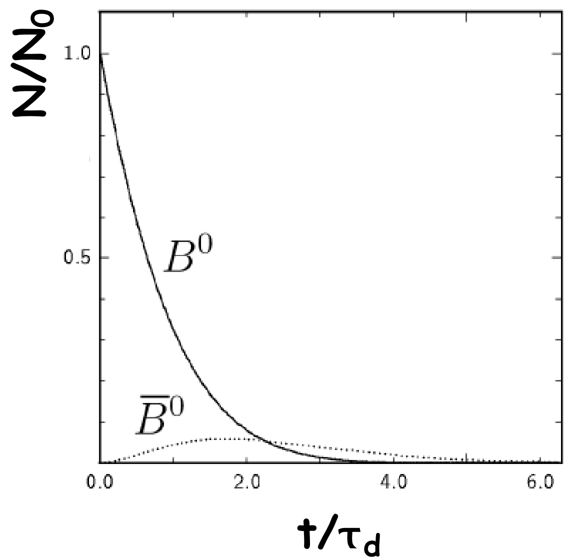
- 2007: first evidence @ B factories; 2012: first observation @ LHCb

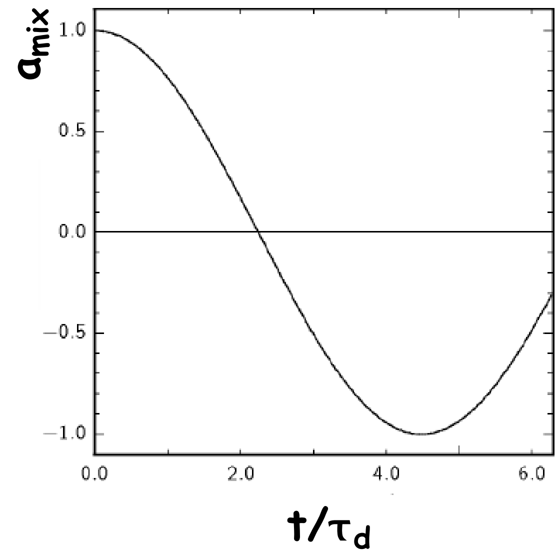
Mixing: $B^0\bar{B}^0$ and $B^0_s\bar{B}^0_s$

$B^0\bar{B}^0$

- $x_d \approx 0.7$
- $y_d \approx 0$
- significant mixing:

$$\chi_d = \frac{x_d^2}{2\,(1 + x_d^2)} \approx 18\,\%$$

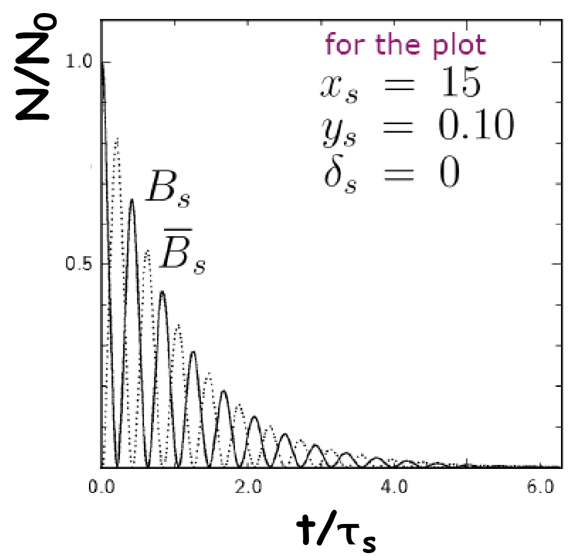


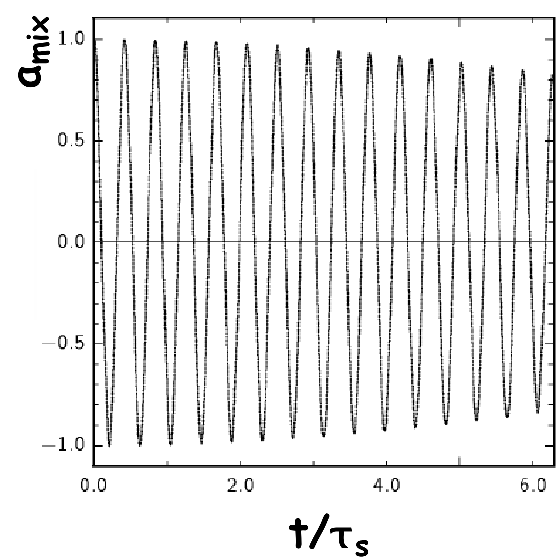


$B^0_s\bar{B}^0_s$

- $x_s \approx 26$
- $y_s \approx 0.07$
- very fast oscillation, complete mixing:

$$\chi_s = \frac{x_s^2 + y_s^2}{2\,(1 + x_s^2)} \approx 50\,\%$$



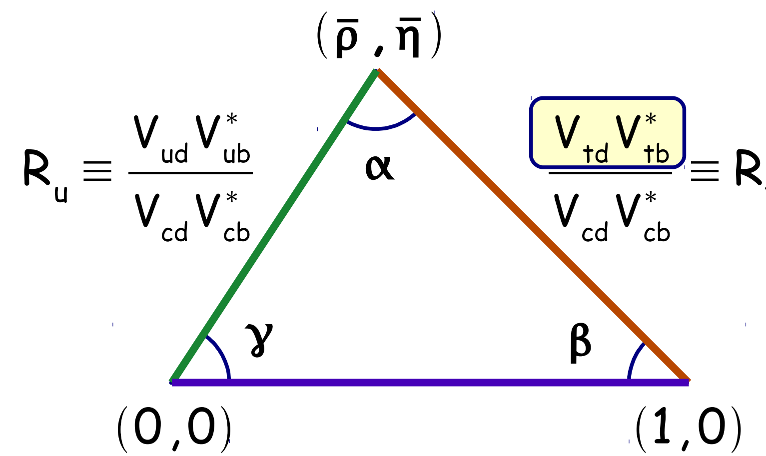


$B^0\bar{B}^0$ Oscillations

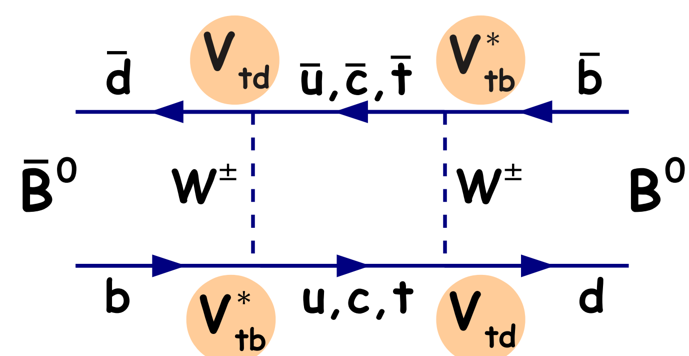
$B^0\bar{B}^0$ oscillation frequency → length of R_t side of the Unitarity Triangle

- $B^0\bar{B}^0$ transitions due to the off-diagonal elements of the effective Hamiltonian

$$H_{12} = M_{12} - (i/2)\,\Gamma_{12}$$



- M_{12}: dispersive part of the amplitude, transitions via off-shell intermediate states
  - dominated by t-box: $M_{12} \propto (V_{td}V_{tb}^*)^2$
- Γ_{12}: "absorptive part of the amplitude, transitions via on-shell intermediate states
  - dominated by c-box: $\Gamma_{12} \ll M_{12}$

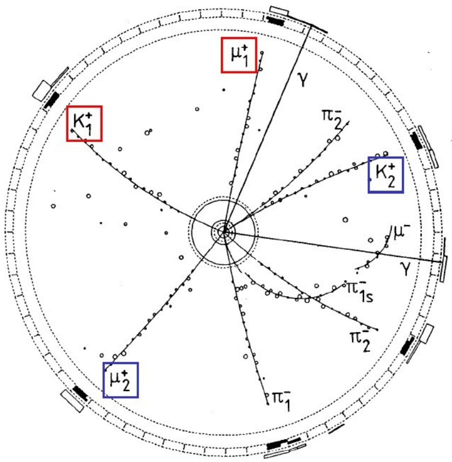


$$\Rightarrow \quad \Delta m = 2\left|M_{12}\right| \propto \left|V_{td}\right|^2 \cdot \left|V_{tb}\right|^2$$

$B^0\overline{B}^0$ Oscillations

First observation of time-integrated asymmetry by Argus (1987)

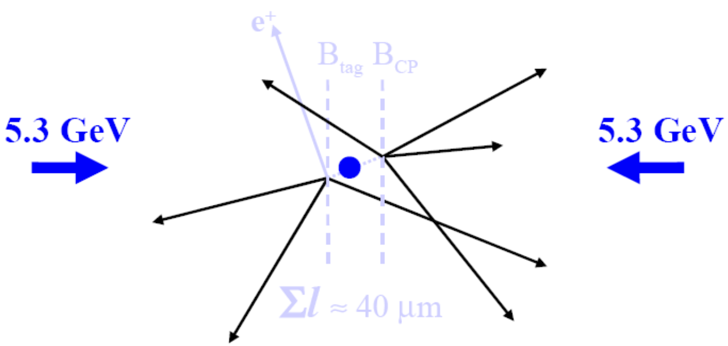
$$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0\overline{B}^0$$



- look at semi-leptonic decays, count fraction of like-sign dimuon events → gives integrated mixing probability

But: impossible to observe oscillation pattern at Argus

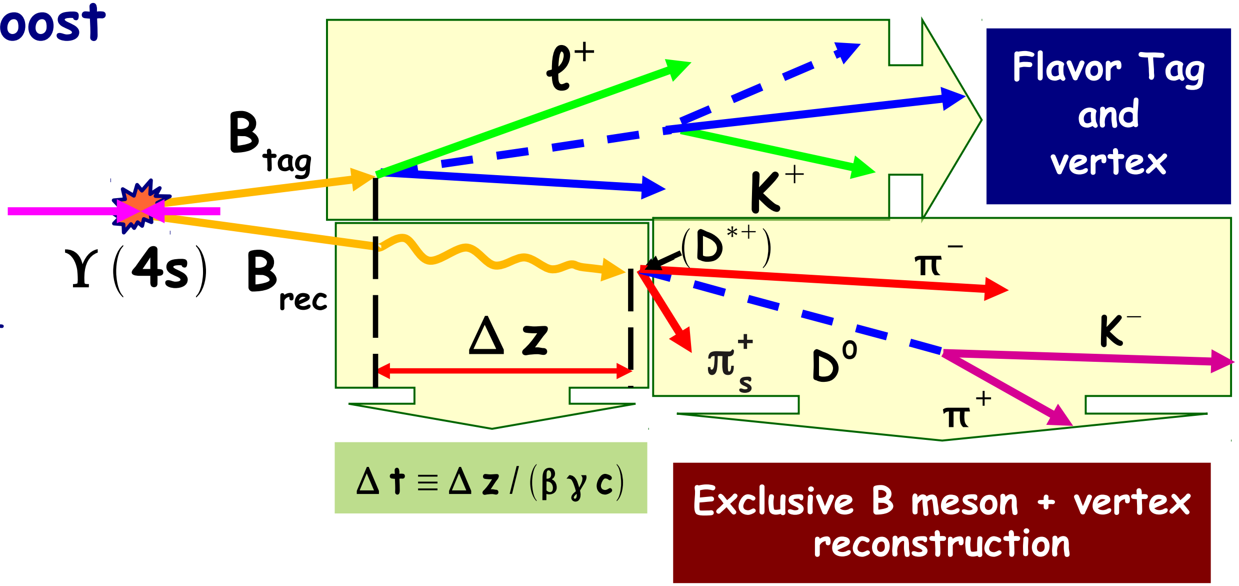
- symmetric beam energies → lab frame = $\Upsilon(4s)$ rest frame
  - $m_{\Upsilon(4s)}$ = 10.58 GeV → p_B = 340 MeV → $\beta\gamma$ = 0.064
  - mean B decay length $c\tau_B \cdot \beta\gamma$ ~ 30 μm, too small to resolve
- $B^0\overline{B}^0$ produced in coherent quantum state, oscillate in phase until one decays
  - need to measure difference of decay times to observe oscillation pattern
  - but $B^0\overline{B}^0$ produced back-to-back, cannot reconstruct position of production vertex



B Factories

High-luminosity e^+e^- colliders with asymmetric beam energies

- produce $\Upsilon(4s)$ with Lorentz boost
- Babar: 9 GeV e^- + 3.1 GeV
  - $\beta\gamma = 0.56$, $\langle\Delta z\rangle = 260\ \mu m$
- Belle: 8 GeV e^- + 3.5 GeV e^+
  - $\beta\gamma = 0.425$, $\langle\Delta z\rangle = 200\ \mu m$



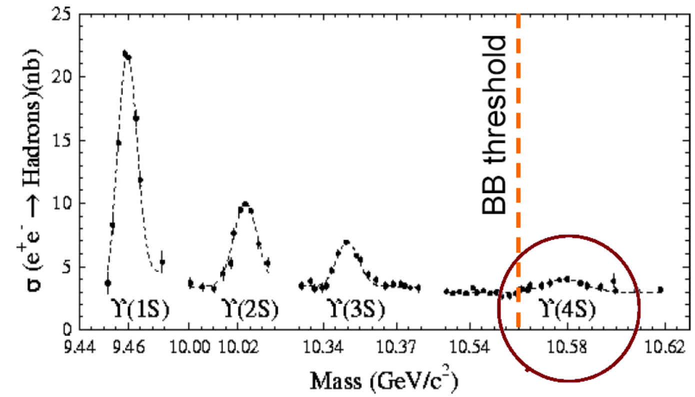
Reconstruction strategy:

- reconstruct B_{rec} fully → B_{rec} decay vertex, momentum and flavour at decay
- assign remaining final-state particles to B_{tag} decay (no full reconstruction)
  - reconstruct B_{tag} decay vertex → fixes t=0 for oscillation measurement
  - infer flavour of B_{tag} at its decay → fixes flavour of B_{rec} at t=0
- B_{rec} oscillated (not oscillated) if opposite (same) flavour at t=0 and decay
- calculate oscillation time from B_{rec} momentum and Δz of decay vertices

B factories

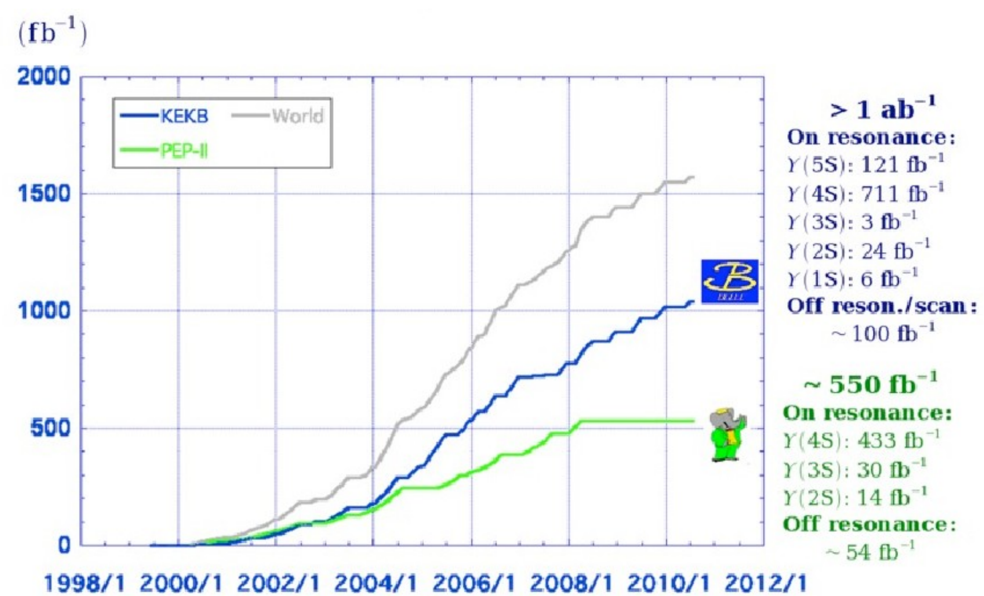
Υ(4s) resonance: bound $b\bar{b}$ state just above $B\bar{B}$ threshold

- decays ~ 50% to B^+B^- and ~ 50% to $B^0\bar{B}^0$
- $\sigma_{b\bar{b}} \approx 1$ nb → with 1 fb^{-1} produce 10^6 $B\bar{B}$ pairs
- $\sigma_{b\bar{b}} / \sigma_{tot} \approx 0.25$ → large fraction of B events
- "clean" events → only tracks from B decays



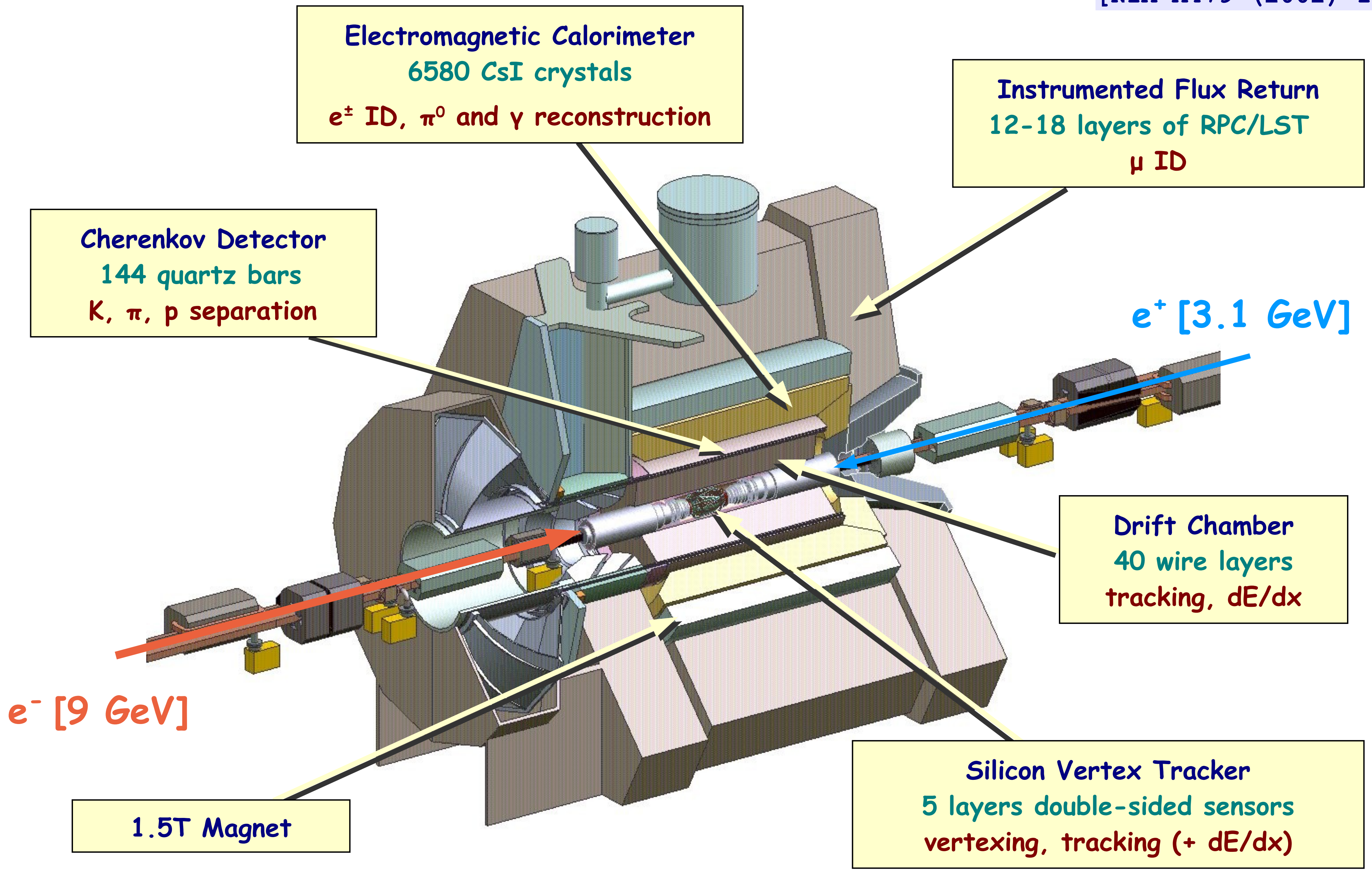
Need highest possible luminosity to beat small production cross section

- PEP-II ring at SLAC, California
  - peak luminosity 12×10^{33} $cm^{-2}s^{-1}$
  - integrated luminosity: 553 fb^{-1}
- KEK-B ring at KEK, Japan
  - peak luminosity 21×10^{33} $cm^{-2}s^{-1}$
  - integrated luminosity: 1040 fb^{-1}



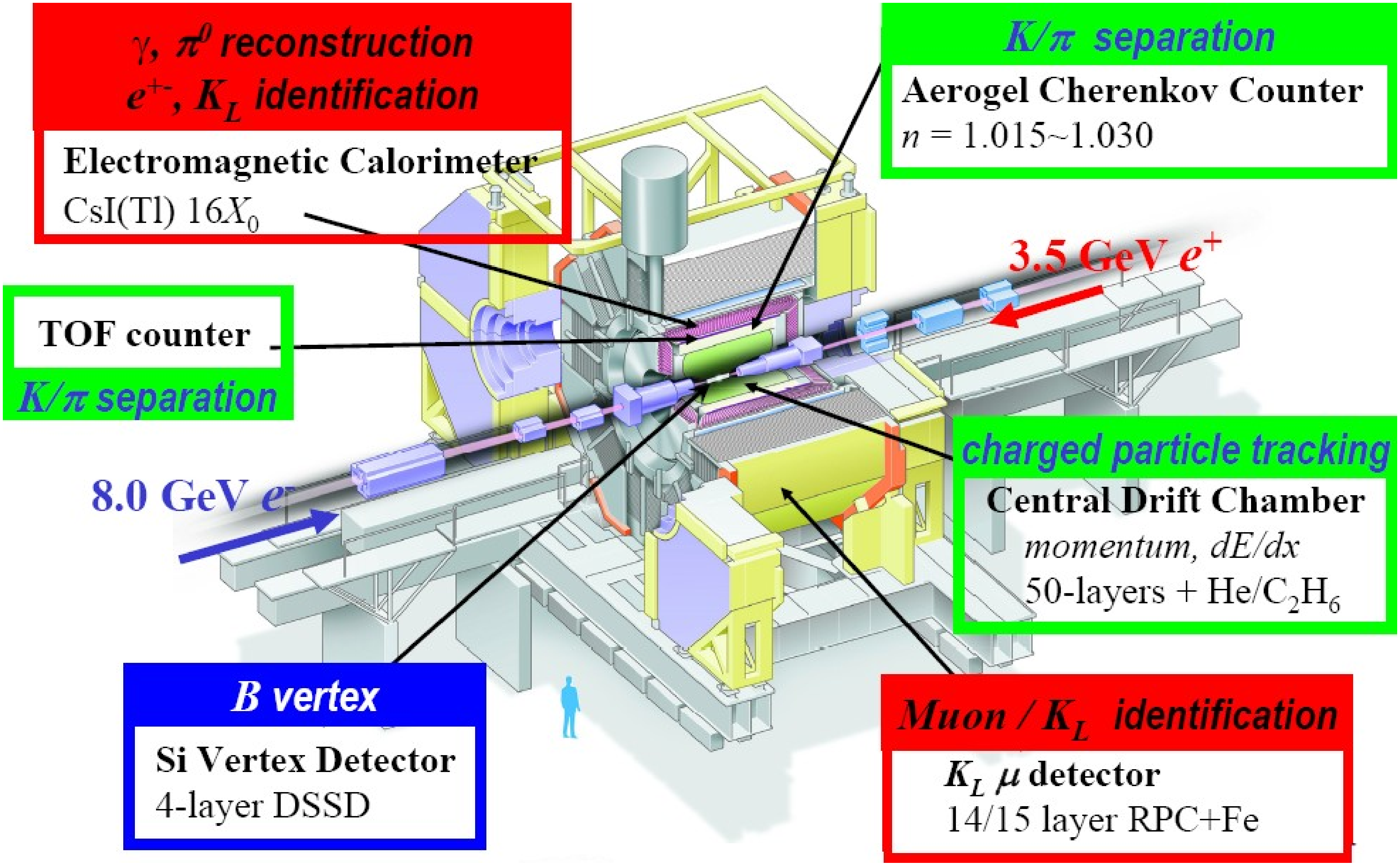
Babar

[NIM A479 (2002) 1]



Belle

[NIM A479 (2002) 117]



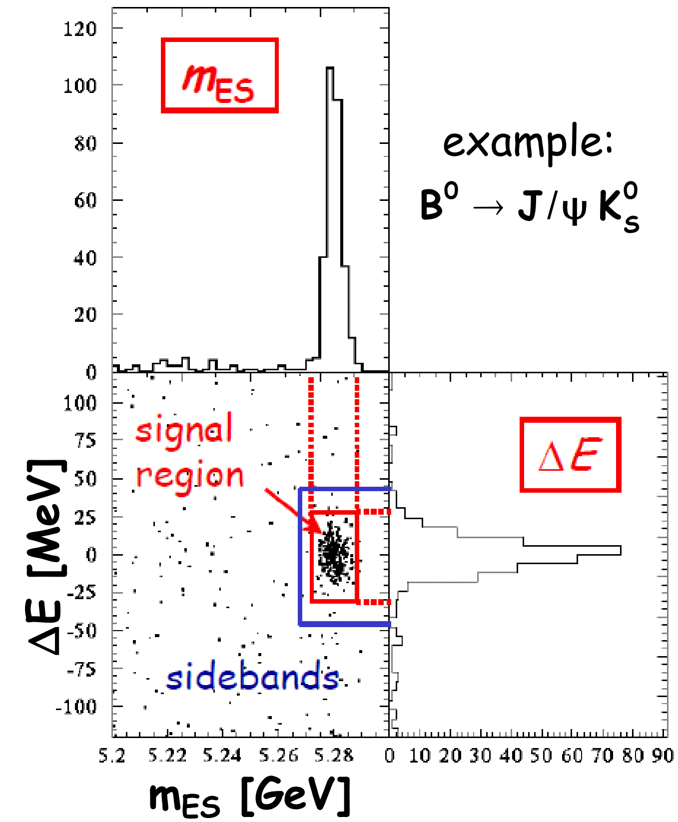
Event Selection

Kinematic variables: exploit precisely known beam energy

- energy conservation in center-of-mass frame

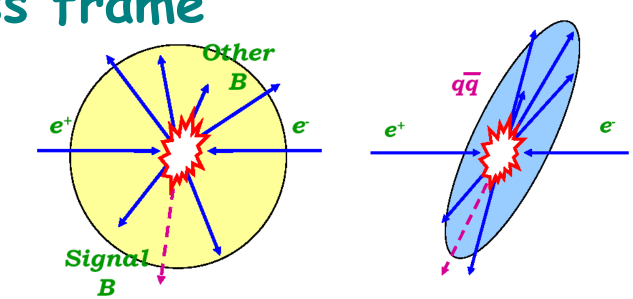
$$E_B^* = \frac{\sqrt{s}}{2} = E_{beam}^* \quad \begin{cases} \Delta E \equiv E_B^* - E_{beam}^* = 0 \\ m_{ES} \equiv \sqrt{(E_{beam}^*)^2 - (\vec{p}_B^*)^2} \end{cases}$$

- m_{ES}: "energy-substituted" invariant mass
  - E^*_{beam}: beam energy, known to ~ 2.5 MeV
  - E^*_B: energy of B meson, only known to ~ 10–40 MeV from detector resolution



Event shape:

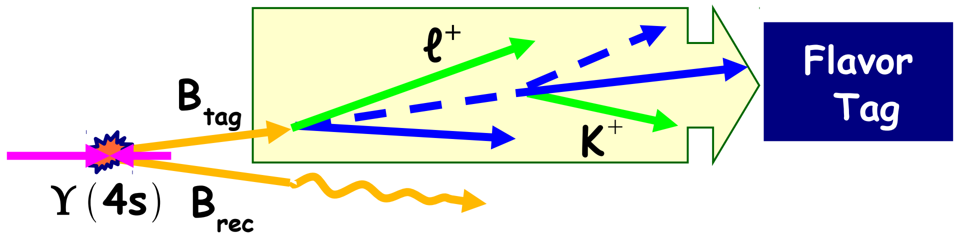
- B mesons produced almost at rest in center-of-mass frame
  → decay products isotropically distributed
- light quarks produced with high momenta
  → boost along flight direction → jet-like topology



Flavour Tagging

Infer flavour of B_{rec} at t=0 from decay properties of B_{tag}

- **lepton tag ($b \to c\, \ell^-\, \bar{\nu}$)**
  - small wrong-tag fraction < 5%
  - contamination of wrong-sign leptons from $b \to c \to s$ cascade decays small
  - clean identification of $e^\pm$, $\mu^\pm$
  - low efficiency: BF only 11% each
- **kaon tag ($b \to c \to s$)**
  - high efficiency: 66% of B^0 decay to K^+
  - but significant wrong-tag fraction:
  - 13% of B^0 have a K^- in the decay chain
  - contamination from mis-identified π^+
- **inclusive tags (e.g. decay vertex charge)**
  - typically use neural-net techniques
  - high efficiency, high wrong-tag fraction



efficiency ε:
fraction of reconstructed events for which flavour tag is obtained

wrong-tag fraction ω:
fraction of tagged events for which tagging decision is wrong

figure of merit:
effective tagging power

$$\varepsilon \cdot D^2 = \varepsilon \cdot (1 - 2\omega)^2$$

total tagging power at B factories, combining all algorithms

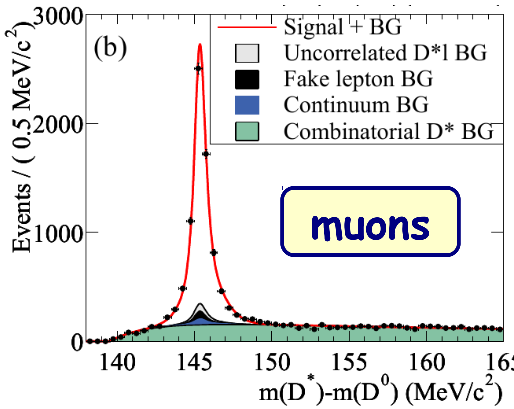
$$\varepsilon \cdot D^2 \approx 30\%$$

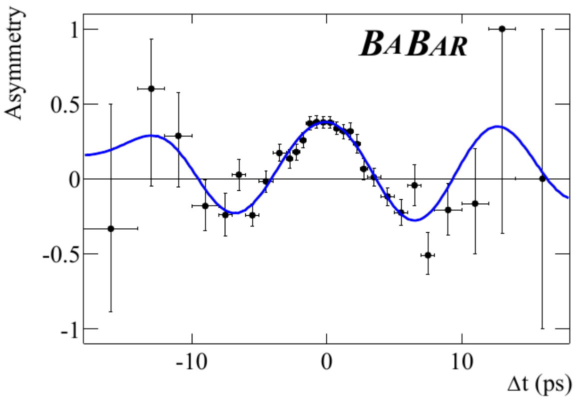
B_{rec} Reconstruction

Semi-leptonic decays:

- $B^0 \to D^{*-} \ell^+ \nu_\ell$ with $D^{*-} \to \bar{D}^0 \pi^-$
- reasonable branching fraction
- clean event sample
  - soft pion from $D^{*-} \to \bar{D}^0 \pi^-$
- but neutrino not reconstructed
- B flavour from lepton charge

[PRD 67 (2003) 072002]

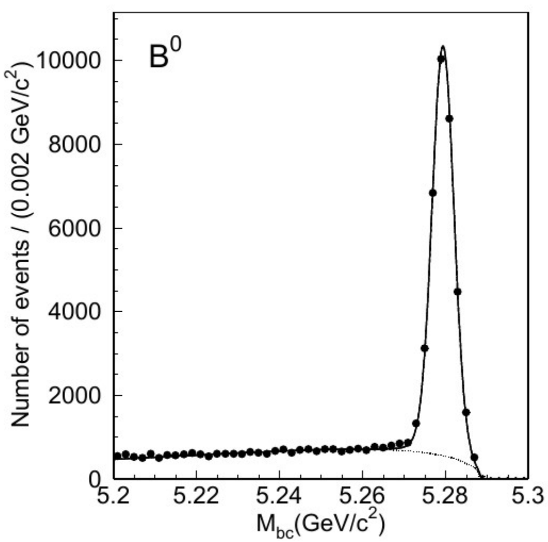


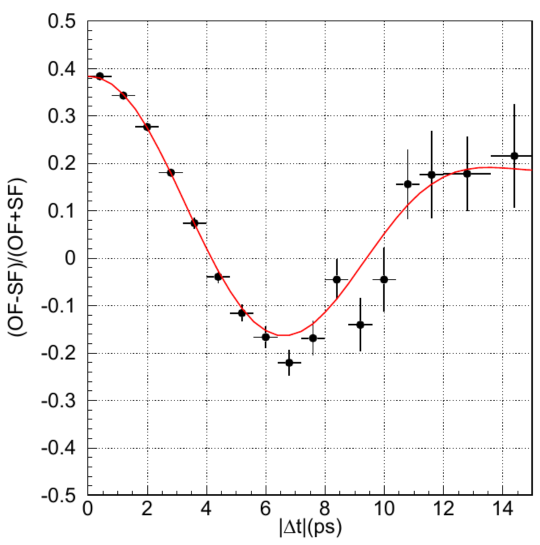


Hadronic decays:

- $B^0 \to D^{*-} \pi^+$ with $D^{*-} \to \bar{D}^0 \pi^-$
- $B^0 \to J/\psi\, K^{*0}$ with $K^{*0} \to K^+ \pi^-$
- clean event samples
- all particles reconstructed
- but small branching fractions

[PRD 71 (2005) 072003]

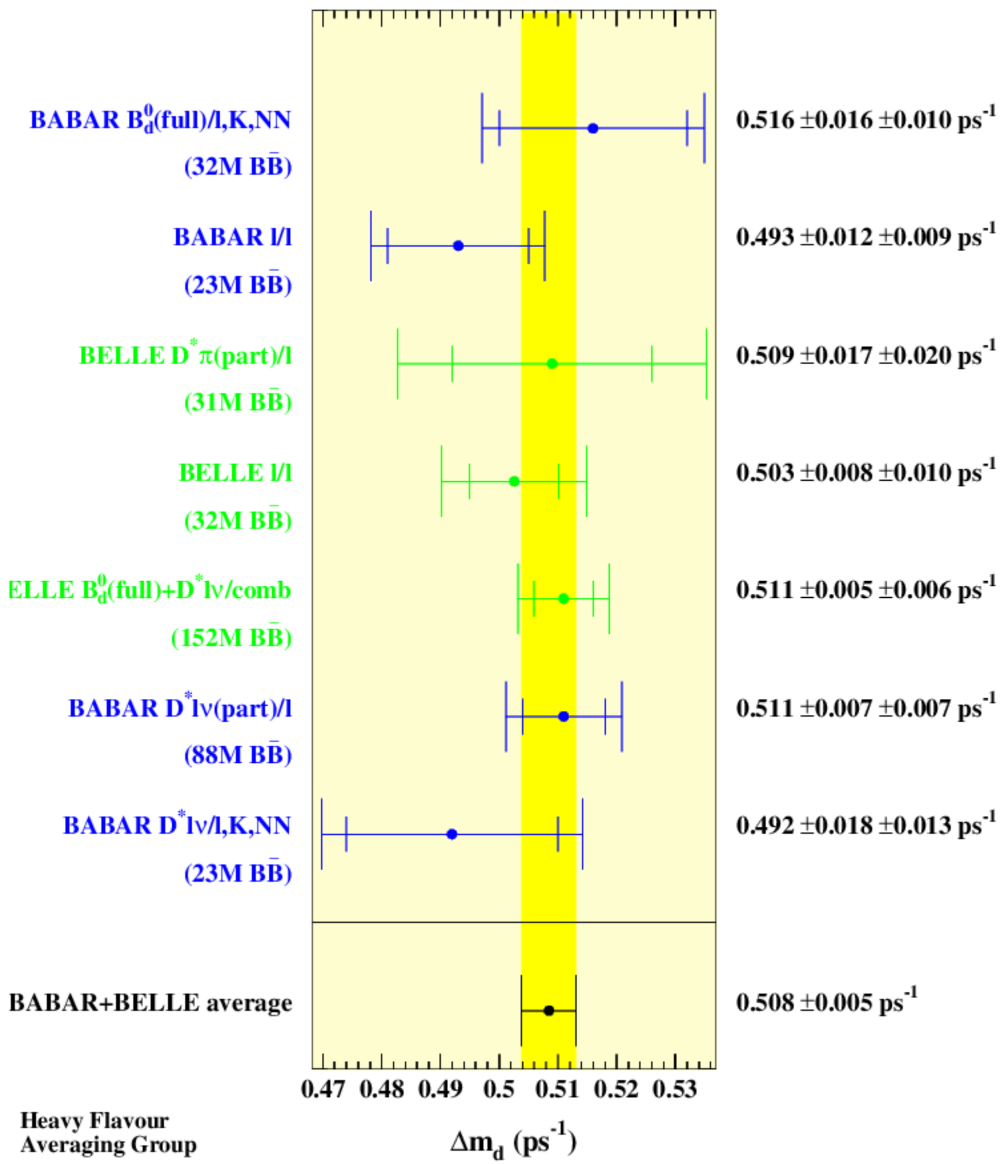


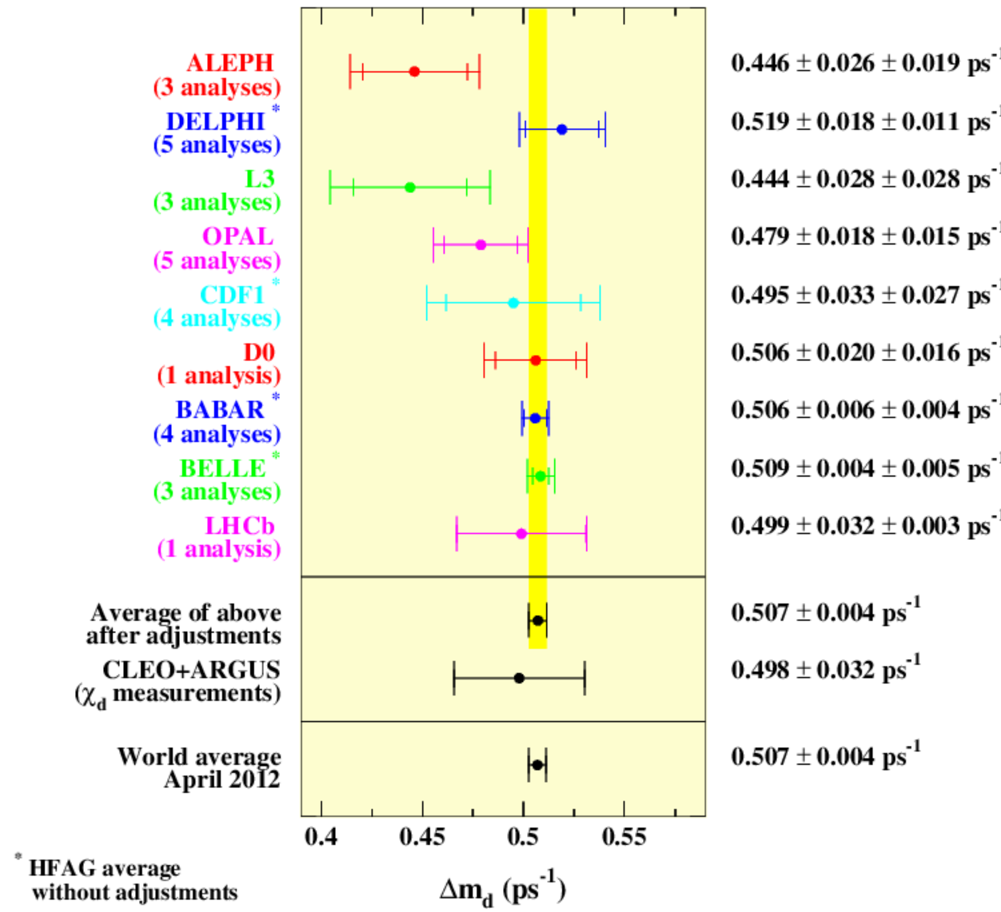


- B flavour from charge of fast pion ($D^{*-} \pi^+$) or Kaon ($J/\psi\ K^{*0}$)

Swiss Institute of Particle Physics

Results Δm_d





Heavy Flavour Averaging Group
[http://www.slac.stanford.edu/xorg/hfag/]

Swiss Institute of Particle Physics

Theory Uncertainties

Uncertainty on $|V_{tb}|^2 \cdot |V_{td}|^2$ dominated by non-perturbative QCD factors

$$\Delta m_d = \frac{G_F}{6\pi^2} \cdot m_W^2 \cdot \eta_b \cdot S_0\left(\frac{m_t^2}{m_W^2}\right) \cdot m_{B_d} \cdot f_{B_d}^2 \cdot \hat{B}_{B_d} \cdot |V_{tb}|^2 |V_{td}|^2$$

- G_F: Fermi constant
- m_W^2: W-boson mass
- η_b: perturbative QCD
- $S_0\left(\frac{m_t^2}{m_W^2}\right)$: "Inami-Lim function" for box diagram
- m_{B_d}: B_d mass
- $f_{B_d}^2$: decay constant
- $\hat{B}_{B_d}$: "bag parameter"

- best determination of $f_{B_d}^2$ and $\hat{B}_{B_d}$ from lattice QCD → uncertainty ~ 10 %

Theory uncertainties partially cancel in the ratio $\Delta m_d / \Delta m_s$

- uncertainty from lattice QCD ~ 3%
- still measure R_t side of unitarity triangle, since $|V_{tb}|^2 \cdot |V_{ts}|^2$ hardly depends on ρ and η
- measure Δm_s from $B^0_s \overline{B}^0_s$ oscillation frequency
- B^0_s not produced at the $\Upsilon(4s)$ → hadron colliders

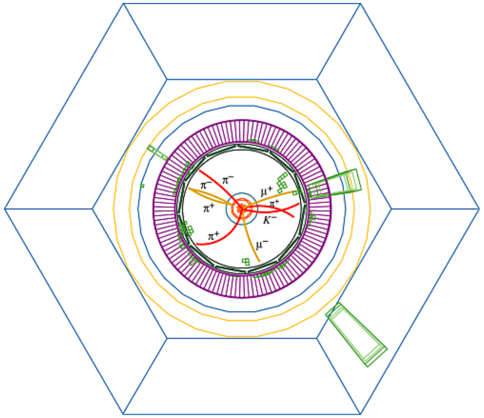
$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \cdot \frac{f_{B_d}^2 \hat{B}_{B_d}}{f_{B_s}^2 \hat{B}_{B_s}} \cdot \frac{|V_{tb}|^2 |V_{td}|^2}{|V_{tb}|^2 |V_{ts}|^2}$$

$b\bar{b}$ Production at Hadron Colliders

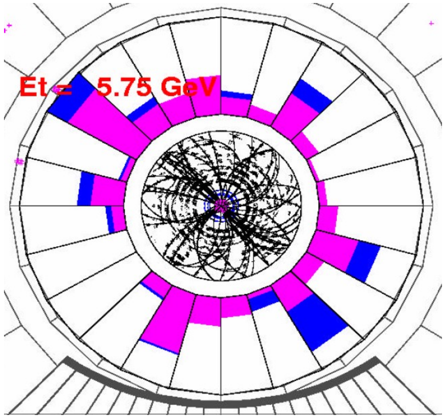
Advantages and disadvantages with respect to $e^+e^- \rightarrow \Upsilon(4s)$ B factories

- all species of b hadrons produced:
  $B^\pm$, B^0, B^0_s, B^+_c, Λ_b
- $\sigma_{b\bar{b}}$ much higher than at B factories
- $\sigma_{b\bar{b}}/\sigma_{tot}$ much smaller than at B factories
- large number of additional particles from underlying hadronic interaction
- selective and efficient trigger vital
- exploit features of B decays:
  - B mesons heavy → decay products have large transverse momentum p_T
  - B mesons live long → decay products have large impact parameters with respect to primary vertex

Facility	$\sqrt{s}$	$\sigma_{b\bar{b}}$ [nb]	$\sigma_{b\bar{b}}/\sigma_{tot}$
e^+e^- @ $\Upsilon(4s)$	10.58 GeV	1	0.25
HERA-B pA	42 GeV	~ 30	10^{-6}
Tevatron $p\bar{p}$	1.96 TeV	5×10^3	10^{-3}
LHC pp	7 TeV	3×10^5	10^{-2}
LHC pp	14 TeV	6×10^5	10^{-2}



$B^0 \rightarrow J/\psi K^0_S$ event in BaBar

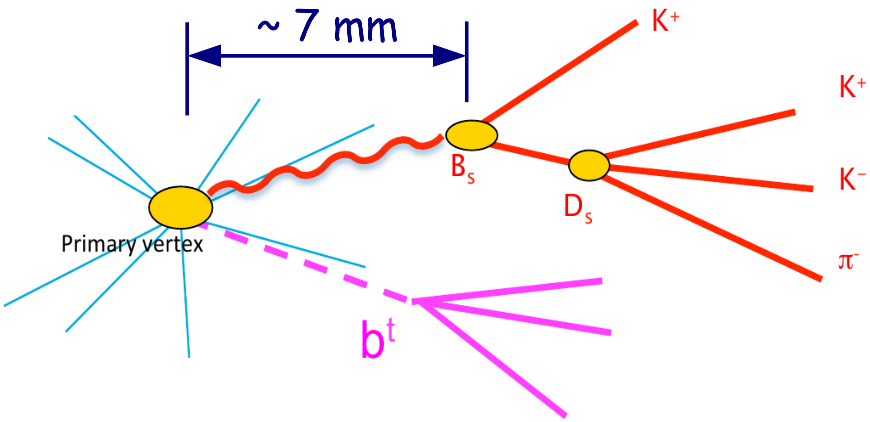


$J/\psi \rightarrow \mu^+\mu^-$ event in CDF

$b\bar{b}$ Production at Hadron Colliders

$b\bar{b}$ pair is not created in a coherent quantum state

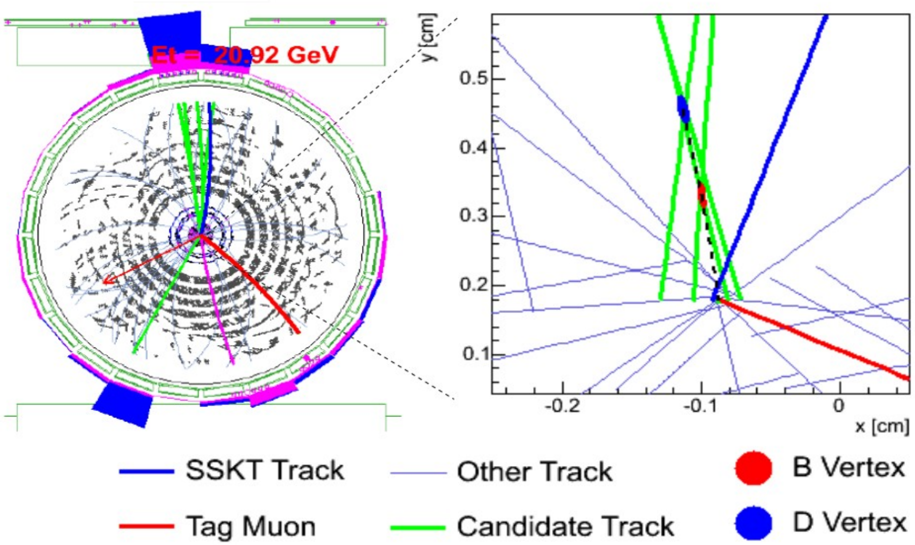
- reference for oscillation measurement: primary vertex, B flavour at production
- primary vertex reconstruction: excellent precision due to large number of charged tracks from underlying event



Flavour tagging: more challenging due to the many extra tracks

- "opposite side tagging" a la B factories (lepton, kaon, vertex charge)
- in addition "same side tagging": charge of a kaon from b fragmentation chain or from B^{**} decays
  - select kaon close to B in phase space
- combined tagging power

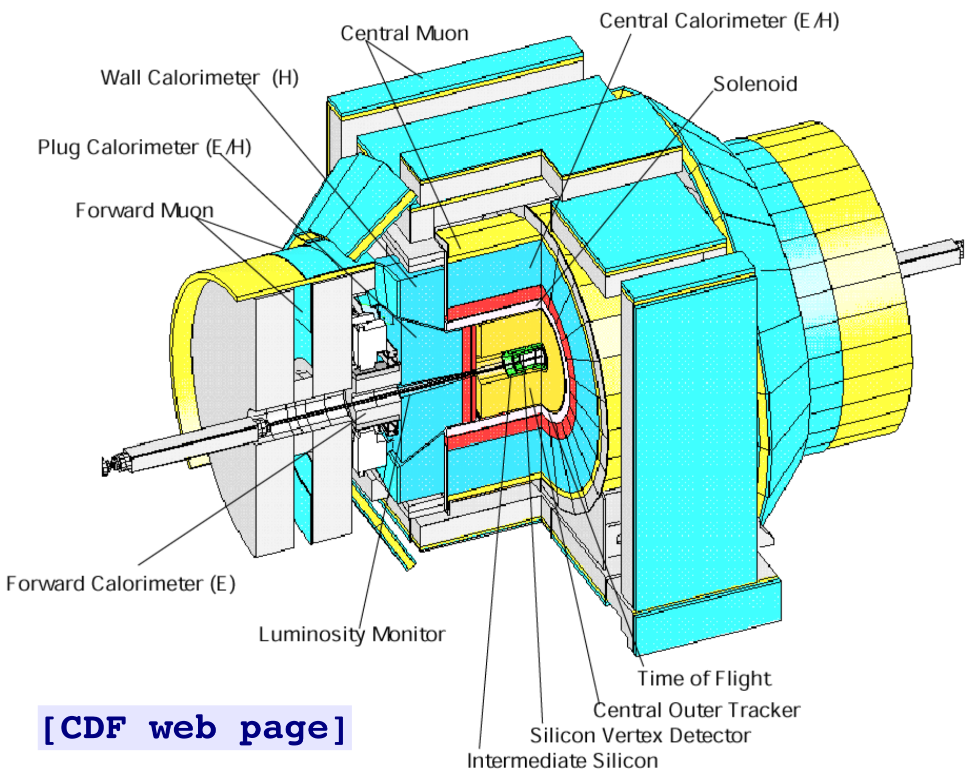
$$\varepsilon \cdot D^2 = \text{few } \%$$



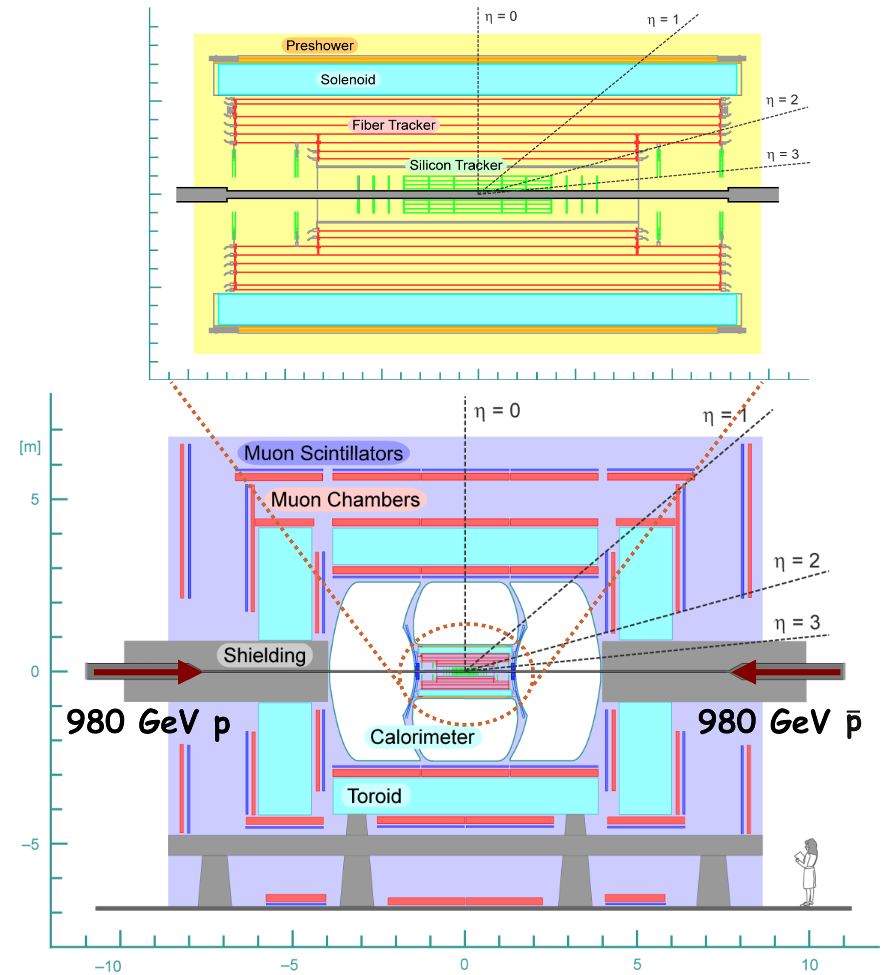
Tevatron: CDF and D0

Typical general-purpose detectors

- **main focus: high-energy frontier, top-quark physics and Higgs searches**
- **but also significant B-physics programme**
  - e.g. first observation of $B^0_s \overline{B}^0_s$ oscillation
  - main limitations: trigger, π/K separation



[CDF web page]



D0, [NIM A565 (2006) 463]

LHCb

Dedicated experiment for heavy flavour physics at the LHC

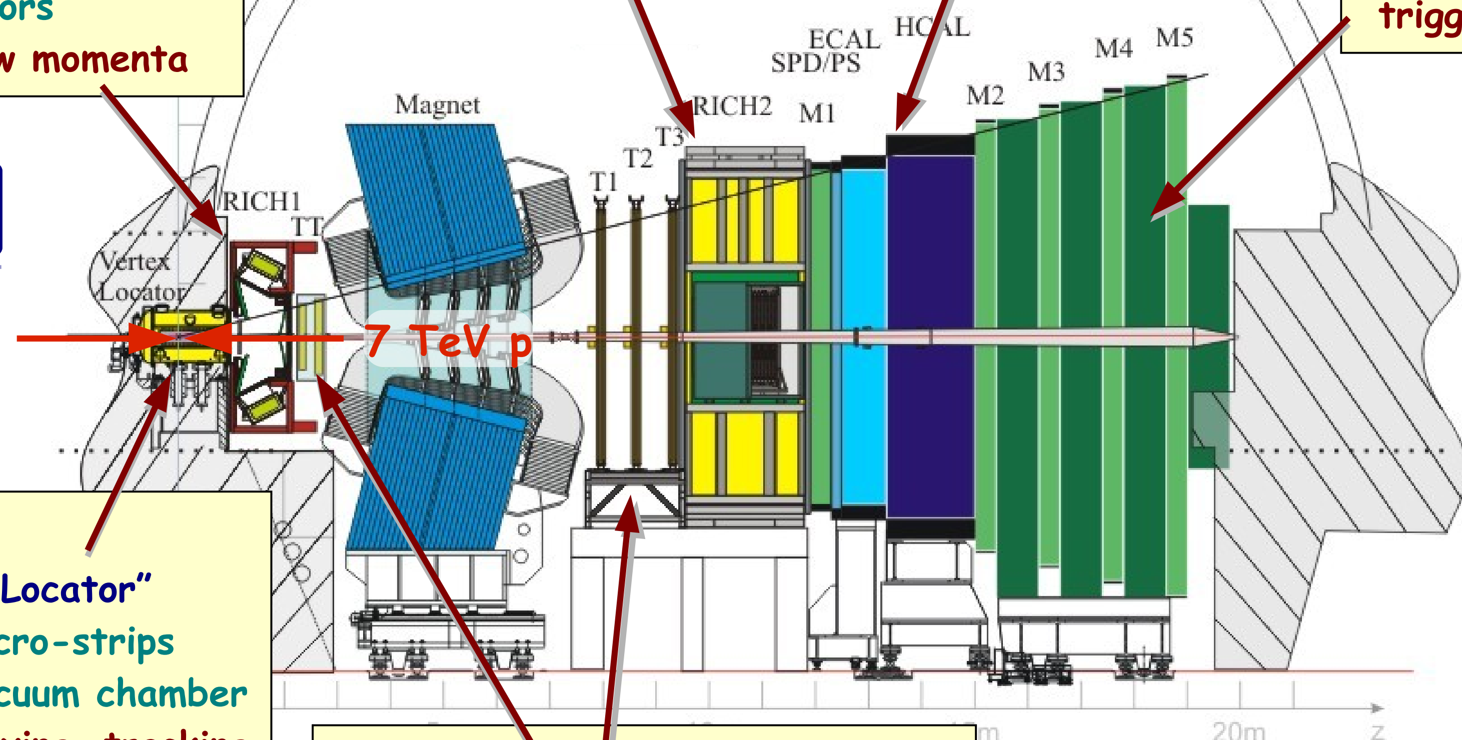
RICH1
Aerogel and C4F10 radiators
K/π-ID at low momenta

RICH2
CF4 radiator
K/π -ID at high momenta

Calorimeters
scintillating fibres
trigger, $e/\gamma/\pi^0$-ID

5 muon stations
drift tubes
trigger, μ-ID

2011: 3.5+3.5 TeV
2012: 4+4 TeV



"Vertex Locator"
Silicon micro-strips
inside LHC vacuum chamber
trigger, vertexing, tracking

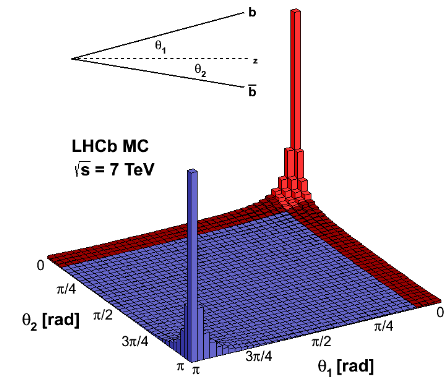
4 tracking stations
Silicon strips, straw drift tubes
tracking, momentum reconstruction

[JINST 3 (2008) S08005]

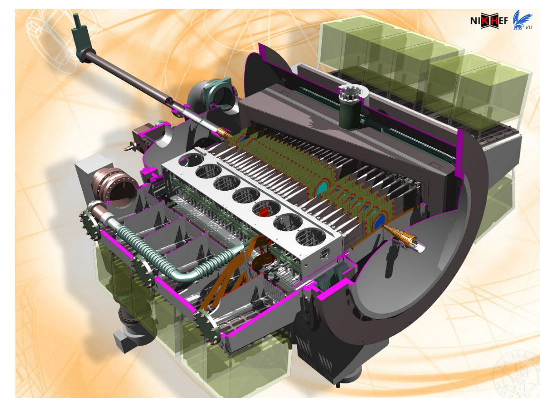
LHCb

Key features that distinguish LHCb from general purpose detectors

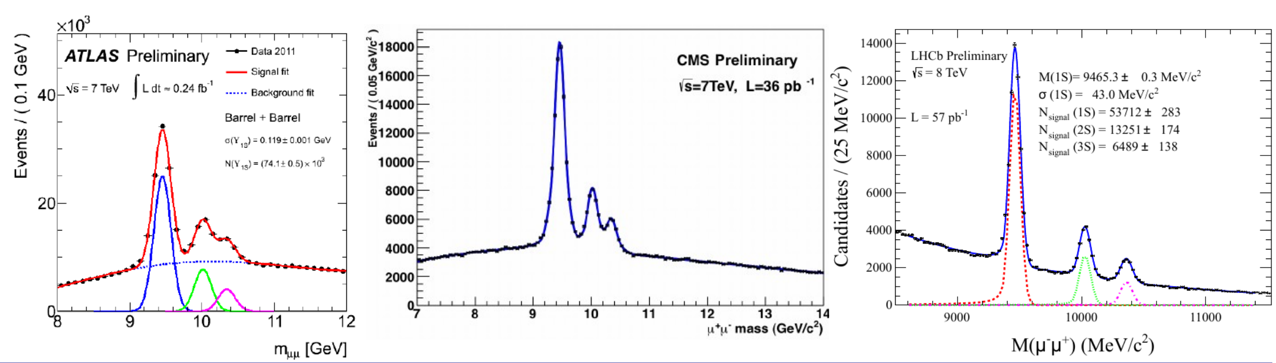
- **forward geometry**
  - large acceptance, $b\bar{b}$ production forward peaked
  - large Lorentz boost, helps with proper-time resolution
  - lower p_T trigger thresholds than at central detectors



- **vertex detector inside LHC vacuum vessel**
  - impact parameter resolution to identify tracks from B decays (→ trigger)
  - proper-time resolution, e.g. to resolve fast $B^0_s\bar{B}^0_s$ oscillations

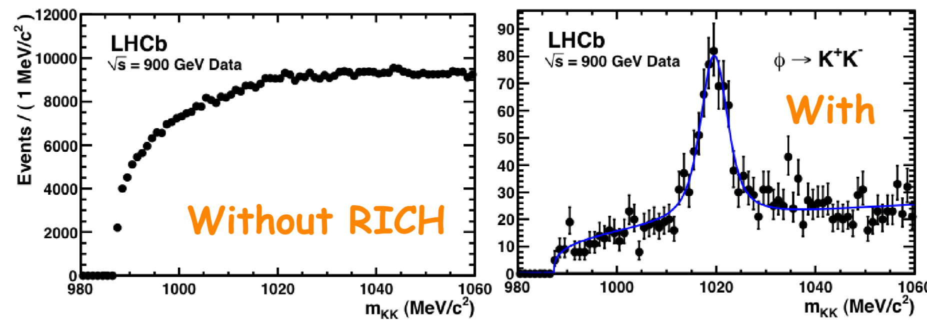


- **tracking system**
  - momentum and invariant mass resolution to fight combinatorial backgrounds

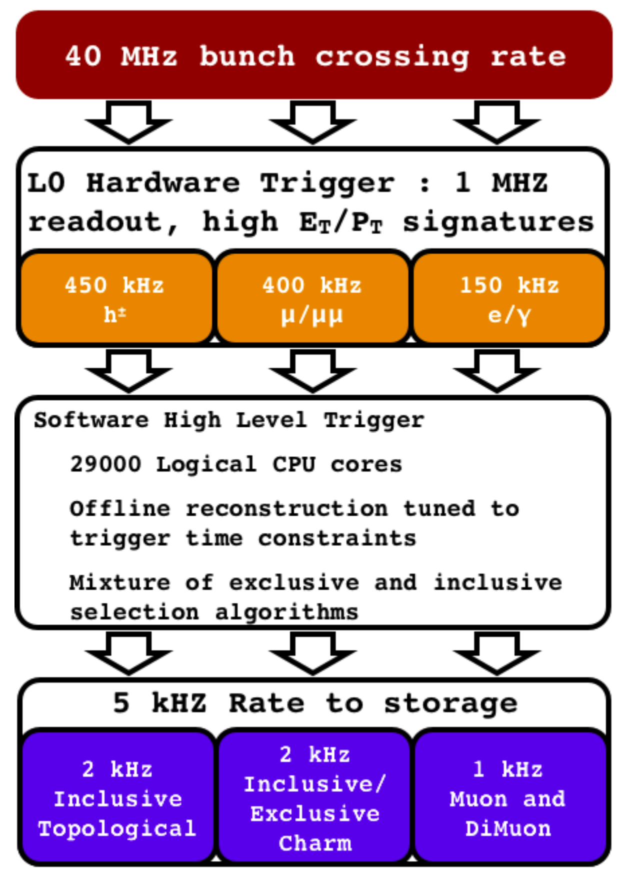


LHCb

- **two RICH detectors for**
  - efficient K/π separation from few GeV for flavour tagging up to 100 GeV, e.g. to separate $B^0 \to \pi\pi$, $B^0_{(s)} \to K\pi$, $B^0_s \to KK$



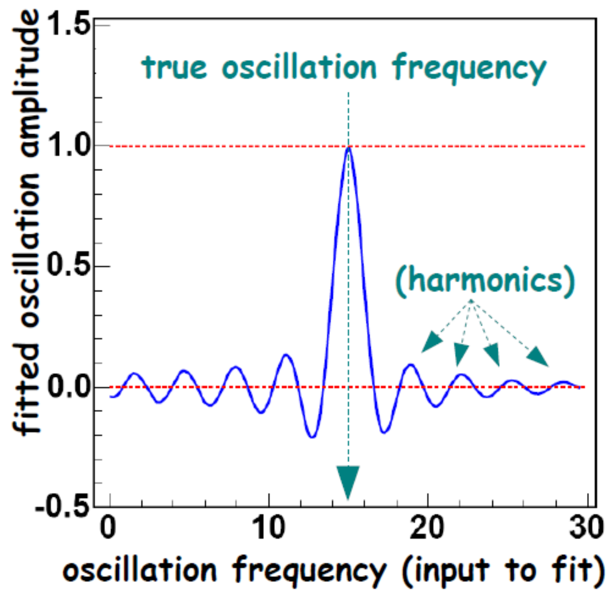
- **flexible, selective and efficient trigger, also for hadronic final states**
  - **hardware level (L0):**
    - high-pT track segments in muon system
    - high-ET clusters (e,h,γ) in calorimeters
  - **software level (HLT):**
    - multi-processor computing farm
    - access to full detector data
  - **combined efficiency:**
    - 90 % for dimuon channels (e.g. J/psi)
    - 30 % for fully hadronic final states



Back to Δm_s: Amplitude Scan

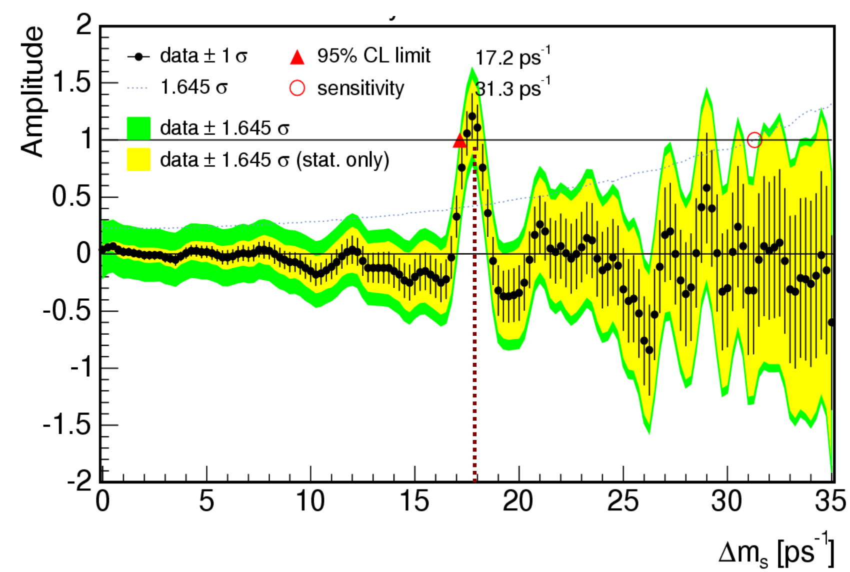
Perform frequency-domain analysis

- scan over oscillation frequency, fit amplitude *A* as a function of the assumed frequency
- normalize to the expected signal amplitude
  → *A*=1 at true mixing frequency, *A*~0 elsewhere
- useful method for combining results from different experiments when no clear signals observed
- similar method applied for Higgs searches now



CDF (2006, 1fb^{-1})

- clear signal at Δm_s = 17.75 ps^{-1}
  → statistical significance A/σ_A = 6.05
- lower limit at 95 % CL: Δm_s = 17.2 ps^{-1}
  → frequency below which $A+1.645 \cdot \sigma_A < 1$
- sensitivity: 31.3 ps^{-1}
  → value for which $1.645 \cdot \sigma_A = 1$



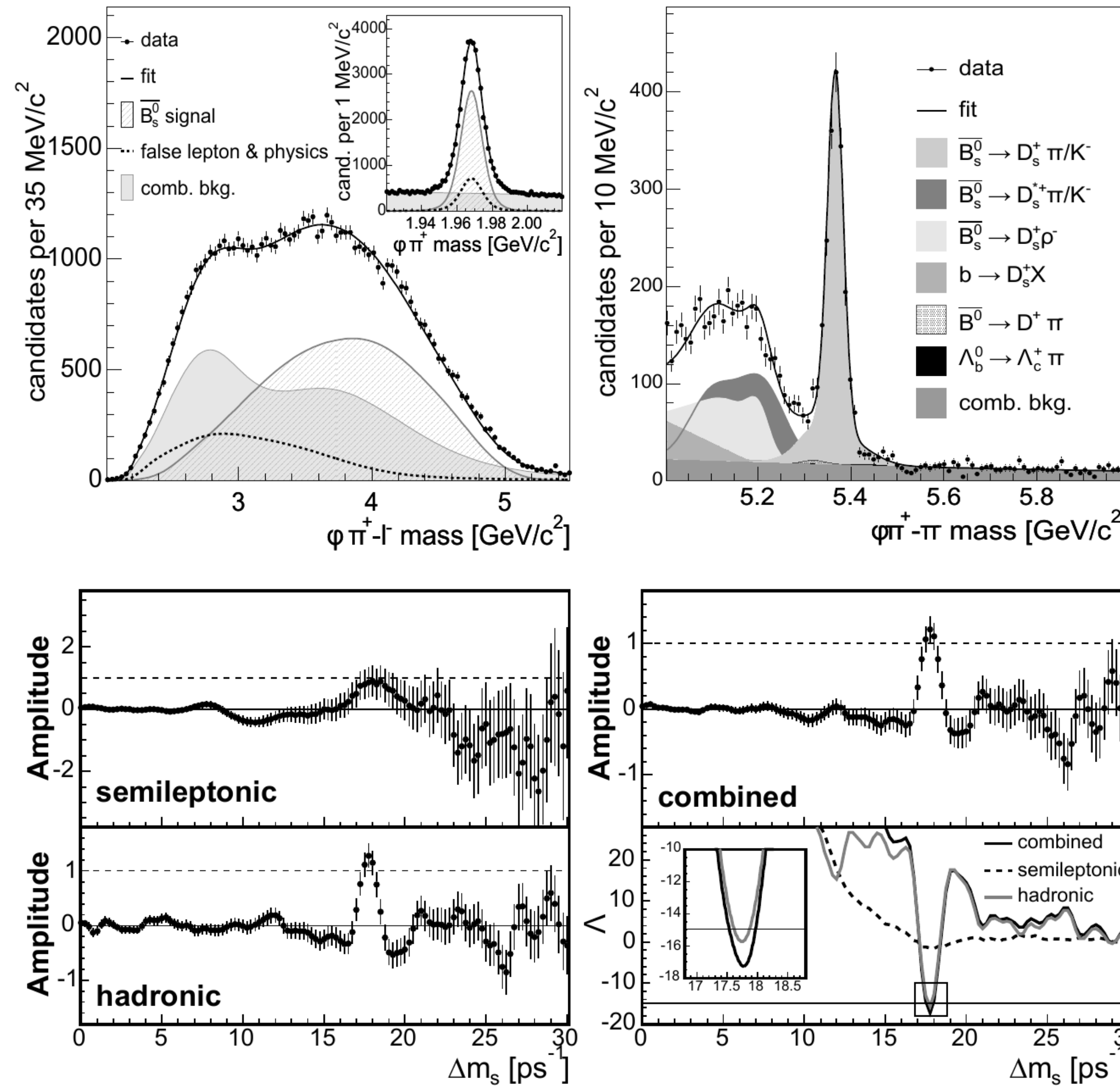
Δm_s at CDF

Semi-leptonic decays:

- $B^0_s \rightarrow D^-_s \ell^+ \nu_\ell$ with
  $D_s^- \rightarrow \phi\,\pi^-$, $K^{*0} K^-$ or $\pi^- \pi^+ \pi^-$
- B flavour from lepton charge
- reasonable branching fraction
- but neutrino not reconstructed
  - limits proper time resolution

Hadronic decays:

- $B^0_s \rightarrow D^-_s \pi^+$, $B^0_s \rightarrow D^-_s 3\pi$ with
  $D_s^- \rightarrow \phi\,\pi^-$, $K^{*0} K^-$ or $\pi^- \pi^+ \pi^-$
- B flavour from fast pion charge
- smaller branching fraction
- but all particles reconstructed



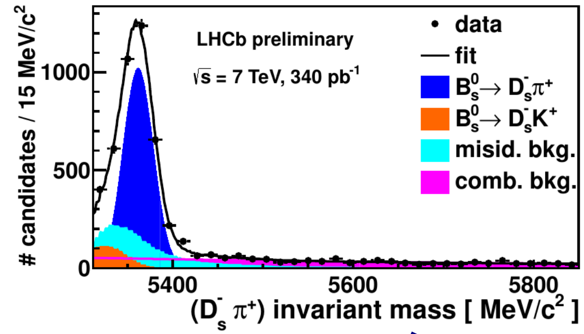
$$\Delta m_s = 17.75 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})\ \text{ps}^{-1}$$

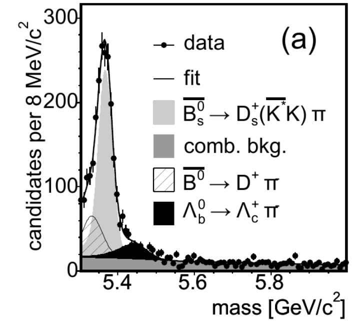
[PRL 97 (2006) 242003]

Δm_s at LHCb

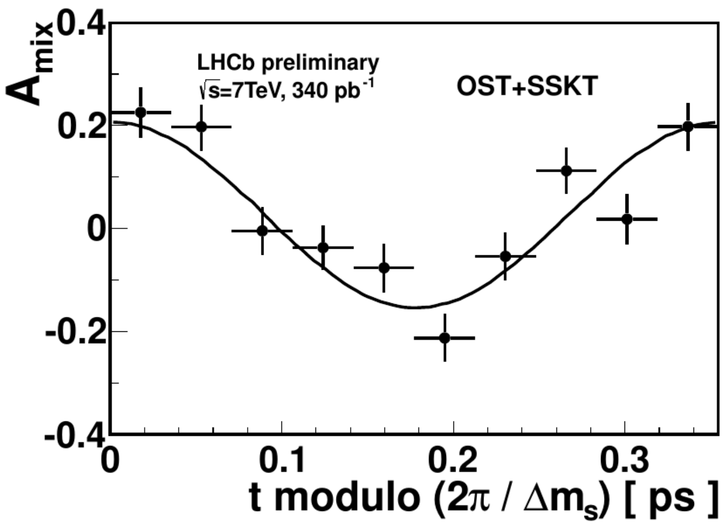
Analysis strategy inspired by CDF

- but look only at fully reconstructed hadronic decays $B^0_s \to D^-_s \pi^+$ to fully exploit excellent proper-time resolution
- employ opposite-side tagging and same-side kaon tagging algorithms





	LHCb	CDF
signal event yields $B^0_s \to D^-_s \pi^+$	9200 in 0.34 fb^{-1}	4100 in 1 fb^{-1}
proper time resolution	45 ps	87 ps
tagging power opposite side	3.2 %	1.8 %
tagging power same side	1.3 %	3.7 %



$$\Delta m_s = 17.725 \pm 0.041 \pm 0.026\ ps^{-1}$$

[LHCb-CONF-2011-050] preliminary

Outline

- **Part I: Introduction**
  - what is (quark) flavour physics and why is it so exciting?
  - how we got here: brief history of flavour physics in the 20th century

- Part II: Particle-Antiparticle Mixing
  - a short summary of the formalism (don't worry, I'm an experimentalist …)
  - introduce experimental facilities and techniques

- **Part III: Precision tests of the Standard Model**
  - **CP violating observables: sin 2β**, CKM angle γ, $B^0_s\overline{B}^0_s$ mixing phase ϕ_s
  - rare decays: search for $B^0_{(s)} \rightarrow \mu^+ \mu^-$, angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

CP Violation in Mixing

CP violated in $P^0\bar{P}^0$ mixing if $\bar{a}_{mix}(t) \neq a_{mix}(t)$

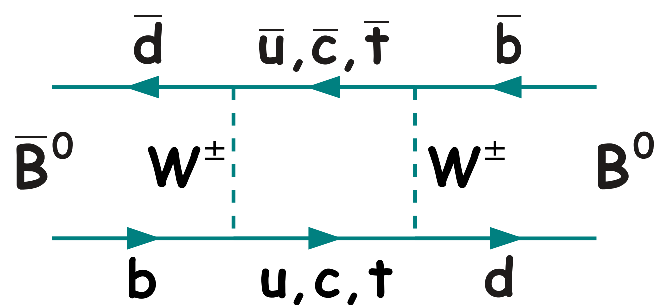
- requires relative phase arg $(q/p) \neq 0$ between M_{12} and Γ_{12}

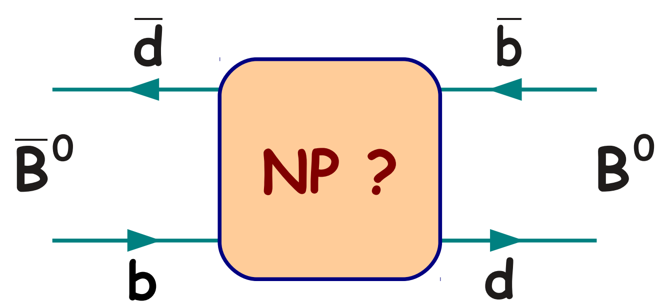
$$a_{mix}(t) = \frac{\cos(\Delta m \cdot t) + \delta \cdot \cosh(\Delta\Gamma \cdot t/2)}{\cosh(\Delta\Gamma \cdot t/2) + \delta \cdot \cos(\Delta m \cdot t)}$$

$$\bar{a}_{mix}(t) = \frac{\cos(\Delta m \cdot t) - \delta \cdot \cosh(\Delta\Gamma \cdot t/2)}{\cosh(\Delta\Gamma \cdot t/2) - \delta \cdot \cos(\Delta m \cdot t)}$$

$$\delta = \frac{1-|q/p|^2}{1+|q/p|^2} \quad ; \quad \frac{q}{p} = -\sqrt{\frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}}$$

- remember, for $B^0\bar{B}^0$ (and similar for $B^0_s\bar{B}^0_s$)
  - Γ_{12} dominated by c-box, $\Gamma_{12} \propto \left(V_{cd}V_{cb}^*\right)^2$
  - M_{12} dominated by t-box, $M_{12} \propto \left(V_{td}V_{tb}^*\right)^2$
  - different weak phases involved, but $\Gamma_{12} \ll M_{12}$
  - expect CP violation in mixing to be very small





- promising hunting ground for New Physics:

new heavy particles can enter in box, have significant effect!

CP Violation in Decay

CP violated in decay if $A(\bar{P}^0 \to \bar{f}) \neq A(P^0 \to f)$

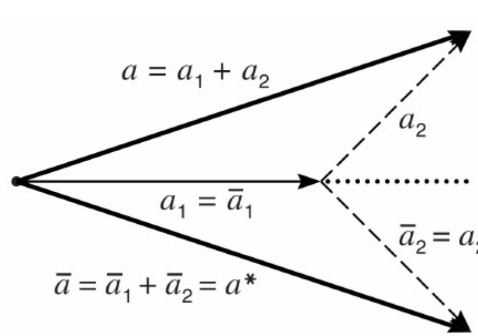
- **requires interference of (at least) two decay amplitudes with different weak phase and different strong phase leading to the same final state**

$$\left.\begin{aligned} A_f &\equiv A\left(P^0 \to f\right) = \sum_i a_i\, e^{i(\delta_i+\phi_i)} \\ \bar{A}_{\bar{f}} &\equiv A\left(\bar{P}^0 \to \bar{f}\right) = \sum_i a_i\, e^{i(\delta_i-\phi_i)} \end{aligned}\right\}$$

φ_i: weak phase, changes sign under CP

δ_i: strong phase, does not change sign under CP

$$\left|A_f\right|^2 - \left|\bar{A}_{\bar{f}}\right|^2 = -2\sum_{ij} a_i a_j \cdot \sin\left(\phi_i - \phi_j\right) \cdot \sin\left(\delta_i - \delta_j\right)$$

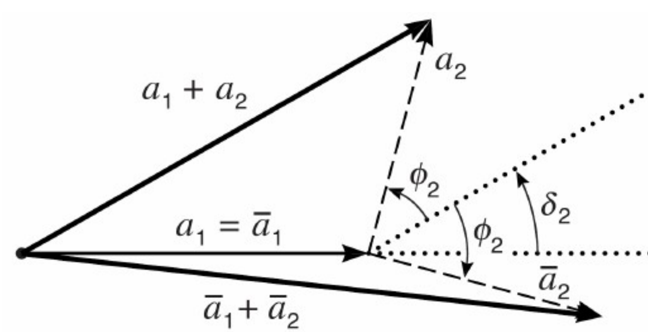


$\phi_2 \neq \phi_1$

$\delta_2 = \delta_1$

$\Rightarrow |\bar{a}| = |a|$

$(\varphi_1 = \delta_1 = 0)$



$\phi_2 \neq \phi_1$

$\delta_2 \neq \delta_1$

$\Rightarrow |\bar{a}| \neq |a|$

$(\varphi_1 = \delta_1 = 0)$

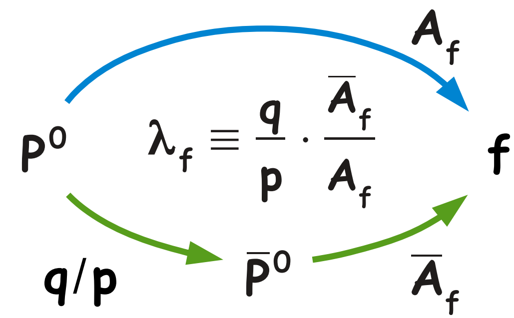
- **interference and CP violation can be large**
  - New Physics can enter through loops if Penguin diagrams involved
- **but have to battle large theoretical uncertainties due to the strong phase**

CP Violation in Interference of Mixing and Decay

For decays into a CP eigenstate f that is accessible to both P^0 and $\bar{P}^0$

- CP violated due to interference between direct decay and decay after mixing if

$$\mathrm{Im}\left(\frac{q}{p}\cdot\frac{\bar{A}_f}{A_f}\right) \neq 0$$



- measure time-dependent decay rate asymmetry:

$$a_f(t) = \frac{N(P^0_{(t=0)}\to f,\, t) - N(\bar{P}^0_{(t=0)}\to f,\, t)}{N(P^0_{(t=0)}\to f,\, t) + N(\bar{P}^0_{(t=0)}\to f,\, t)} \approx \underbrace{\frac{-C_f\cos(\Delta m\cdot t) + S_f\sin(\Delta m\cdot t)}{\cosh(\Delta\Gamma\cdot t/2) + \Omega_f\sinh(\Delta\Gamma\cdot t/2)}}$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\ ;\ S_f = \frac{2\cdot\Im(\lambda_f)}{1+|\lambda_f|^2}\ ;\ \Omega_f = 1 - S_f^2 - C_f^2$$

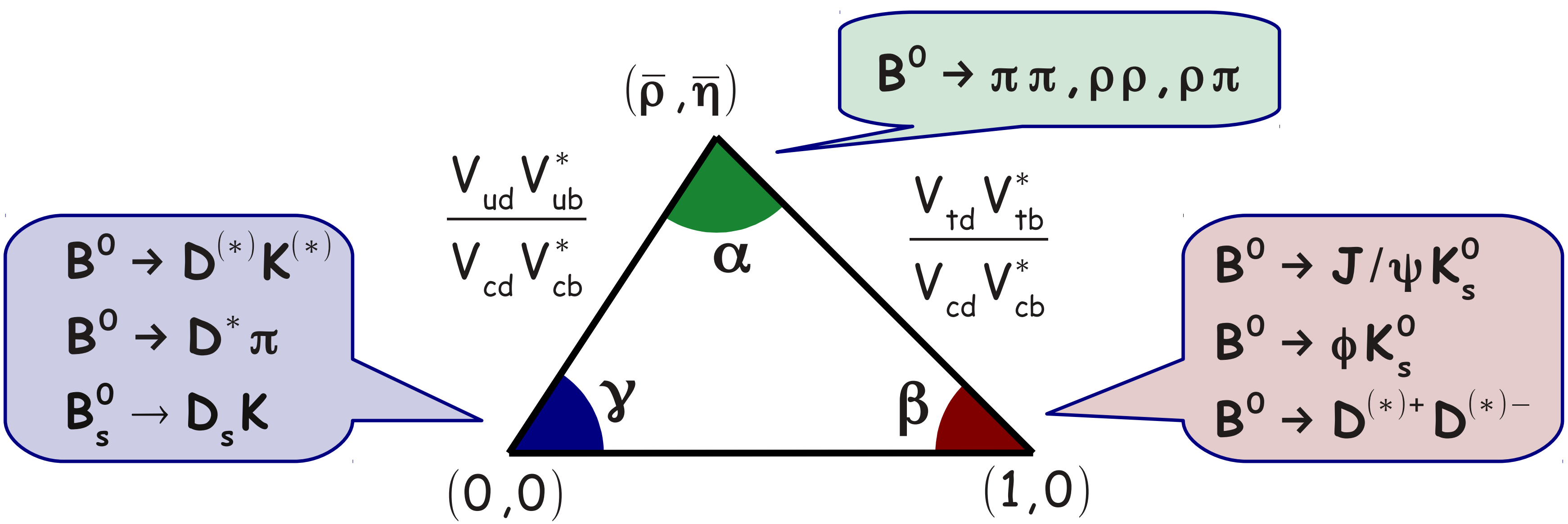
- the ideal case: asymmetries can be large and no strong phase involved
- prominent example: measurement of CKM angle sin 2β in $B^0 \to J/\psi\ K^0_s$
  - one dominating decay amplitude, negligible CP violation in mixing, ΔΓ « 1

$$\Rightarrow\quad a_f(t) = \Im(\lambda_f)\cdot\sin(\Delta m\cdot t) = \sin 2\beta\cdot\sin(\Delta m\cdot t)$$

CP Violation: Observables

CP-violating observables depend on phases of CKM elements

- can be used to measure angles of Unitarity Triangle
- β easiest, "golden channel" $B^0 \to J/\psi\, K^0_s$: measured to $\pm$ 0.5° at B factories
- γ experimentally most challenging: currently measured to about $\pm$ 15°



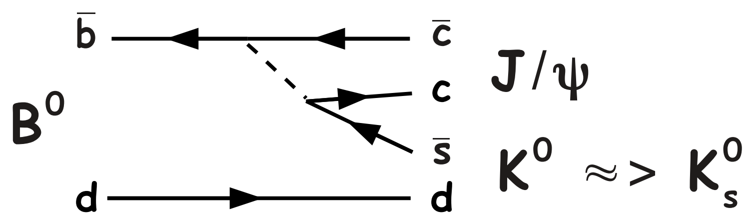
+

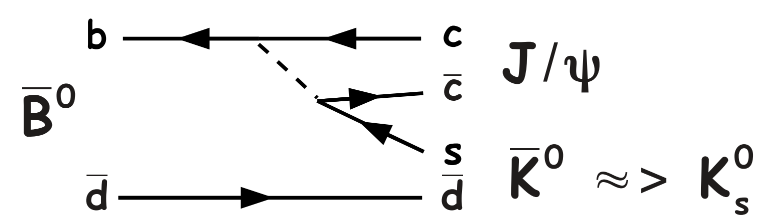
$B^0_s \to J/\psi\, \phi$ $\to$ "golden channel" to measure CP mixing phase in $B^0_s\bar{B}^0_s$ system

$\sin 2\beta$ from $B^0 \rightarrow J/\psi\, K^0_S$

CP violation due to interference between mixing and decay

- $J/\psi\, K^0_S$ is a CP-odd eigenstate, accessible to both B^0 and $\overline{B}^0$





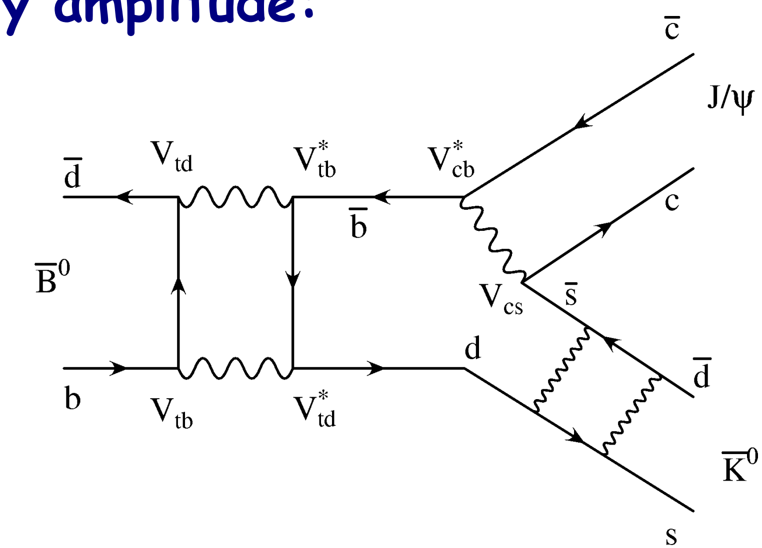
- CKM phase for the dominating tree decay amplitude:

$$\lambda_{J/\psi K_s} = \left(\frac{q}{p}\right)_{B^0} \cdot \left(\frac{\overline{A}_{J/\psi K^0}}{A_{J/\psi K^0}}\right) \cdot \left(\frac{q}{p}\right)_{K^0}$$

$$= \left(\frac{V^*_{tb} V_{td}}{V_{tb} V^*_{td}}\right) \cdot \left(\frac{V^*_{cs} V_{cb}}{V_{cs} V^*_{cb}}\right) \cdot \left(\frac{V^*_{cd} V_{cs}}{V_{cd} V^*_{cs}}\right)$$

$$= \left(\frac{V^*_{tb} V_{td}}{V^*_{cb} V_{cd}}\right) \Big/ \left(\frac{V_{tb} V^*_{td}}{V_{cb} V^*_{cd}}\right)$$

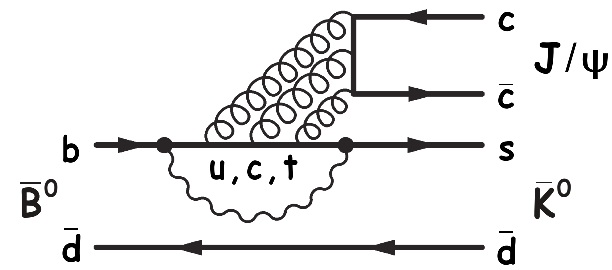
$$= 2 \cdot \arg\left(\frac{V^*_{tb} V_{td}}{V^*_{cb} V_{cd}}\right) = 2 \cdot \beta \quad \Rightarrow \quad a_{B^0 \rightarrow J/\psi K^0_s}(t) = \sin 2\beta \cdot \sin(\Delta m_d \cdot t)$$



sin 2β from $B^0 \to J/\psi\, K^0_s$: "Golden" Channel

Theory "clean": leading Penguin (P) has same weak phase as Tree (T)

$$A_{J/\psi K^0} = (T + P_c)\cdot(V^*_{cb}V_{cs}) + P_t\cdot(V^*_{tb}V_{ts}) + P_u\cdot(V^*_{ub}V_{us})$$



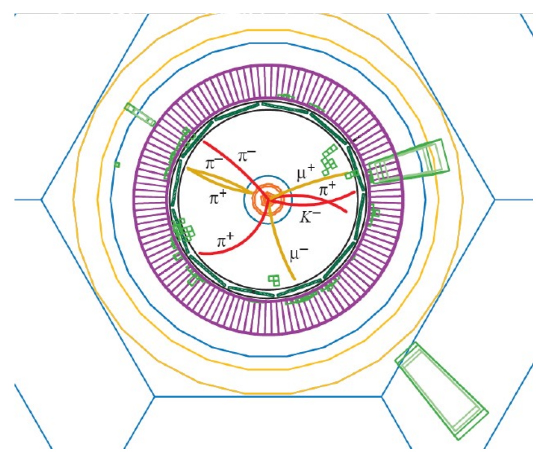
- unitarity of CKM matrix: $V^*_{tb}V_{ts} = -V^*_{cb}V_{cs} - V^*_{ub}V_{us}$

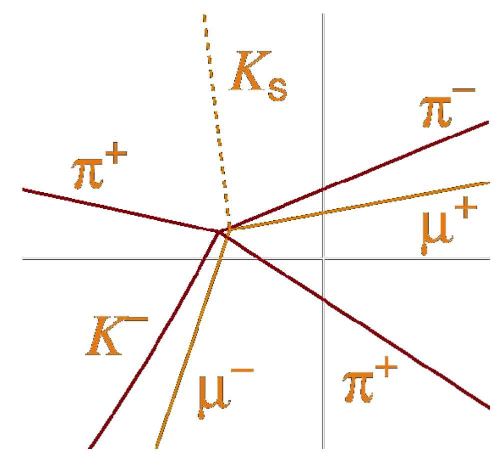
$$A_{J/\psi K^0} = \underbrace{(T + P_c - P_t)}_{\approx 0.1\cdot T}\cdot\underbrace{(V^*_{cb}V_{cs})}_{\propto \lambda^2} + \underbrace{(P_u - P_t)}_{\approx 0.1\cdot T}\cdot\underbrace{(V^*_{ub}V_{us})}_{\propto \lambda^4}$$

- contamination from $V^*_{ub}V_{us}$ smaller than 1%

Also attractive from point of view of experiment

- clear event signature
  - lepton pair from J/ψ decay
  - 2nd displaced vertex from K^0_s decay
  - J/ψ and K^0_s invariant masses
- reasonably large branching ratio



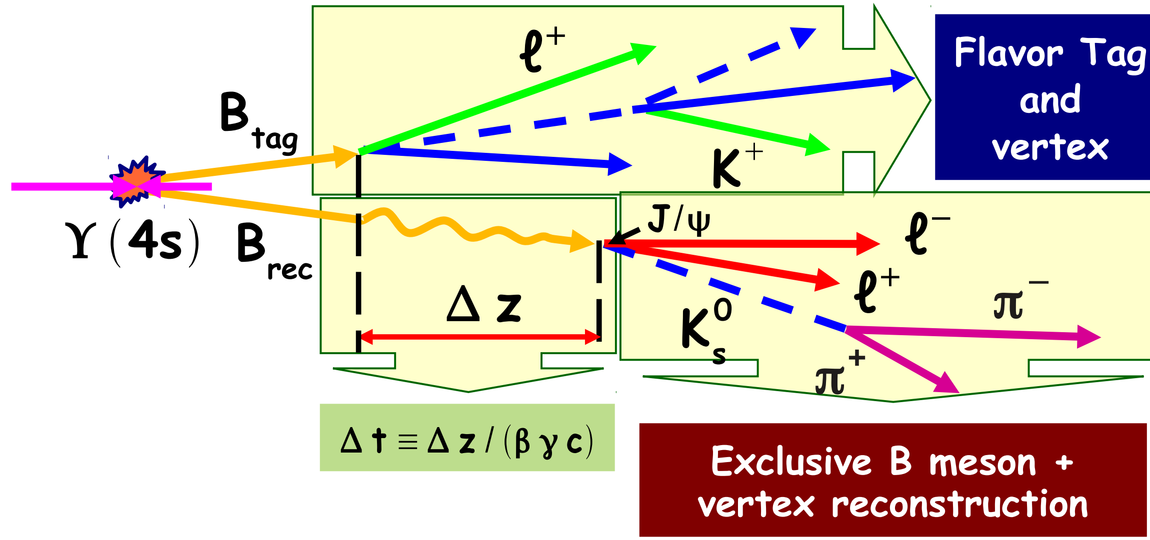


$$BF\,(B^0 \to J/\psi K^0_s) \times BF\,(J/\psi \to \ell^+\ell^-) \times BF\,(K^0_S \to \pi^+\pi^-) \approx 7\times 10^{-5}$$

$\sin 2\beta$ from $B^0 \to J/\psi K^0_s$: Measurement Principle

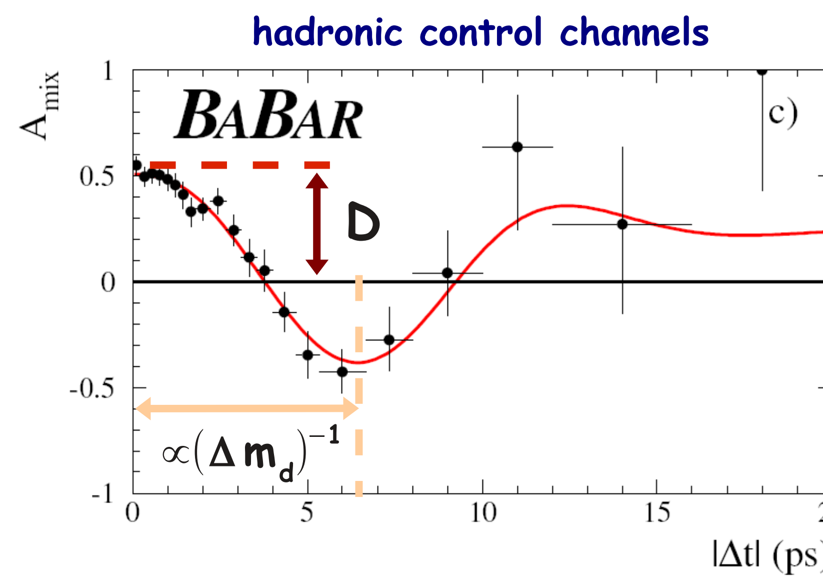
Similar approach as for mixing measurements

- fully reconstruct signal B in final state $J/\psi K_S$
- reconstruct the two B decay vertices, determine Δz and Δt
- infer flavour at "t=0" from decay products of tagging B



Extract $\sin 2\beta$ from oscillation AMPLITUDE

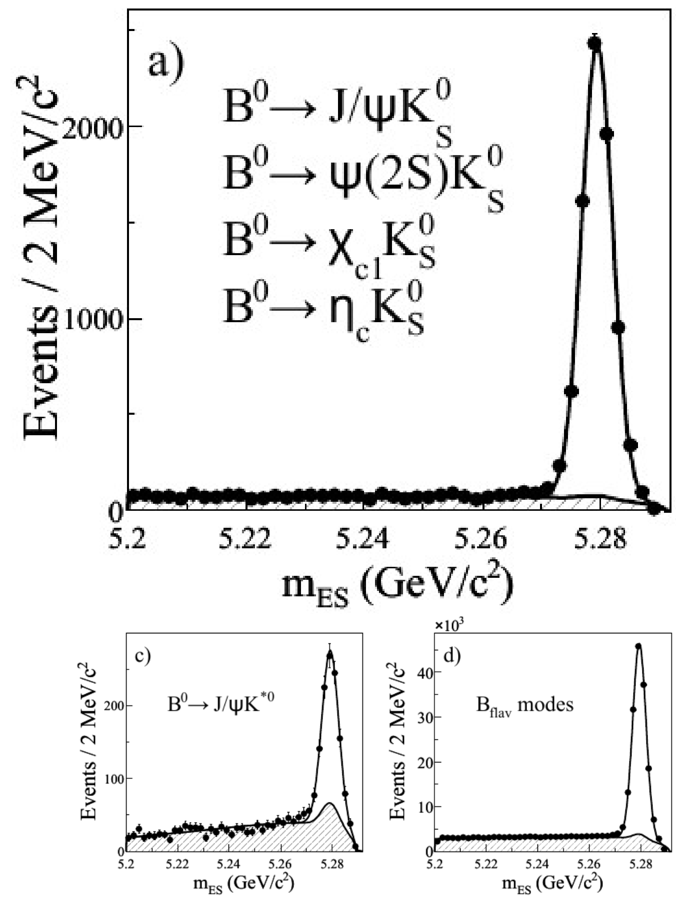
- measured asymmetry reduced by
  - tagging dilution $D = 1 - 2\cdot\omega$
  - finite decay-time resolution
- determine these effects from data using flavour-specific decay modes
  - e.g. $B^0 \to D^{(*)+}\pi^-$ and $B^0 \to J/\psi K^*(K^+\pi^-)$



sin 2β from $B^0 \to J/\psi K^0_S$: Analysis

Fit m_{ES} distributions to determine composition of the event sample

- $J/\psi K^0_S$ and other $b \to c\bar{c}s$ signal channels
  - other $c\bar{c}$ resonances: $\psi(2s)$, χ_c, η_c
  - CP odd final state: $J/\psi K^0_L$
- $B^0 \to D^{(*)+} \pi^-$, $B^0 \to J/\psi K^*$ control channels



Fit Δt distributions to extract sin 2β

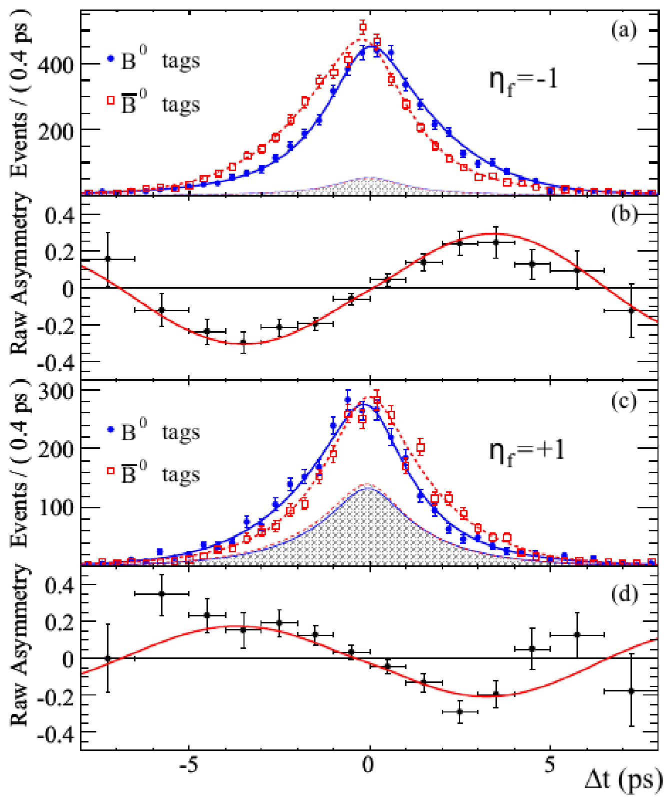
- simultaneous fit to signal and control channels
- e.g. Babar fit has 71 free parameters:
  - S_f (= sin 2β) and C_f
  - 7 to parametrize Δt resolution in signal channels
  - 12 for average mis-tag fractions ω and possible differences Δω between B^0 and $\bar{B}^0$
  - 7 for possible difference in reconstruction and tagging efficiencies for B^0 and $\bar{B}^0$
  - 43 to describe mis-tag fraction, Δt resolution, possible CP violation in backgrounds

sin 2β from $B^0 \to J/\psi\, K^0_s$: Results

Time-dependent CP asymmetry

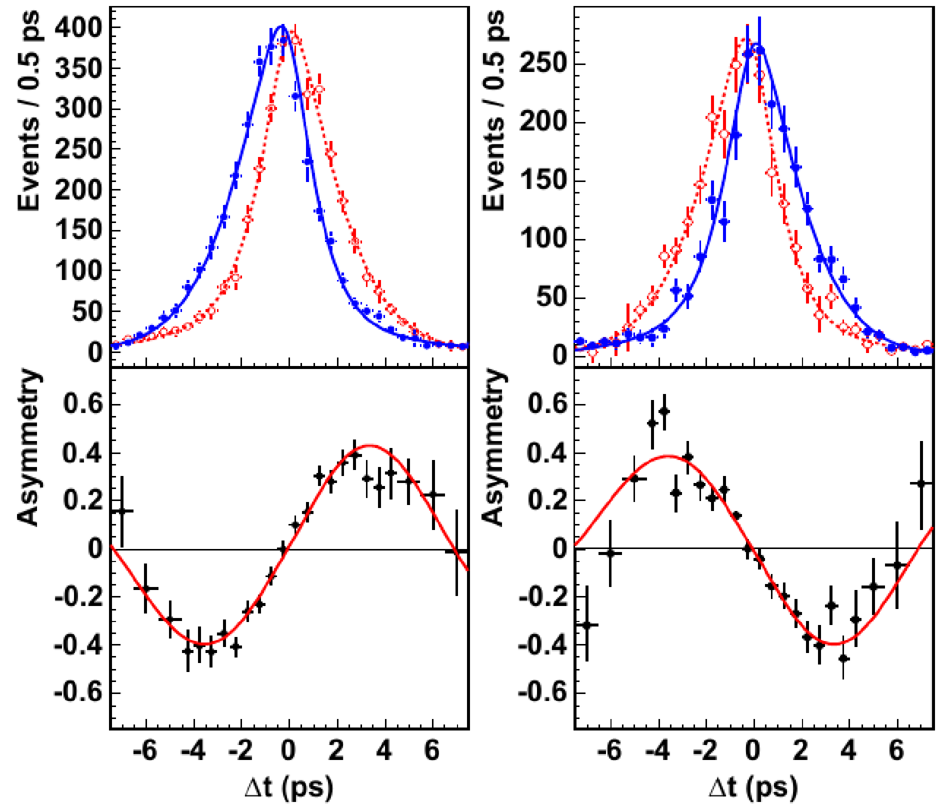
CP-even channels

CP-odd channels



CP-even channels

CP-odd channels



Babar

$$\sin 2\beta \;=\; 0.687 \pm 0.028 \pm 0.012$$

[PRD 79 (2009) 072009]

- C_f = 0.024 ± 0.020 ± 0.016

Belle

$$\sin 2\phi_1 \;=\; 0.667 \pm 0.023 \pm 0.012$$

[PRL 108 (2012) 171802]

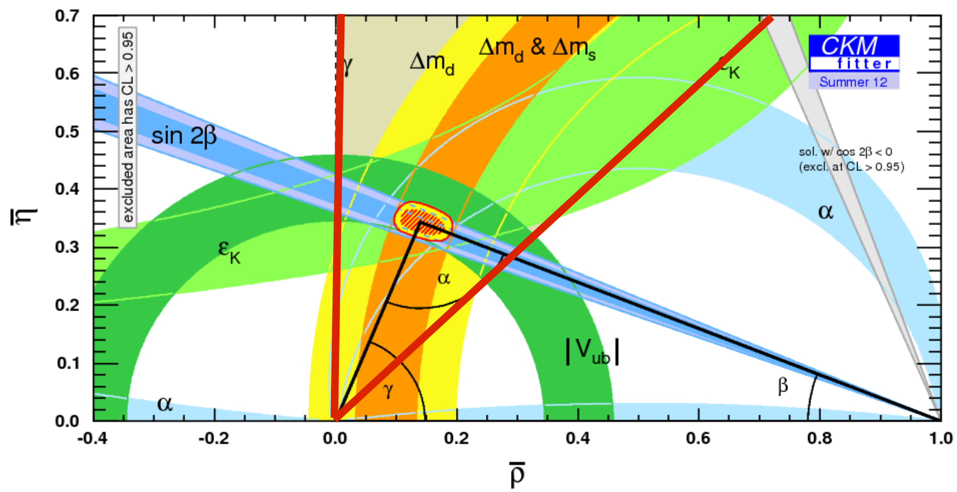
- C_f = 0.006 ± 0.019 ± 0.012

Outline

- **Part I: Introduction**
  - what is (quark) flavour physics and why is it so exciting?
  - how we got here: brief history of flavour physics in the 20th century
- Part II: Particle-Antiparticle Mixing
  - a short summary of the formalism (don't worry, I'm an experimentalist …)
  - introduce experimental facilities and techniques
- **Part III: Precision tests of the Standard Model**
  - **CP violating observables:** sin 2β, **CKM angle γ**, $B^0_s\overline{B}^0_s$ mixing phase ϕ_s
  - rare decays: search for $B^0_{(s)} \rightarrow \mu^+ \mu^-$, angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

CKM angle γ from Tree Decays

- CKM fits so far in good agreement with Standard Model
- need more precise measurements to test for subtle effects from possible New Physics



- the CKM parameter that is least well constrained by direct measurements:

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$\gamma = (66 \pm 12)^\circ$ [CKMfitter]

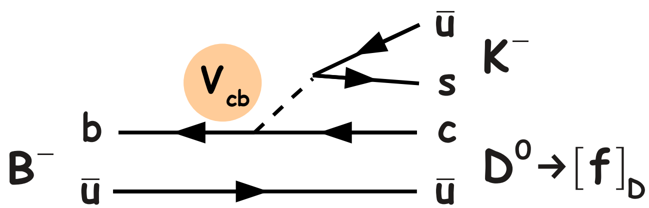
$\gamma = (72 \pm 9)^\circ$ [UTfit]

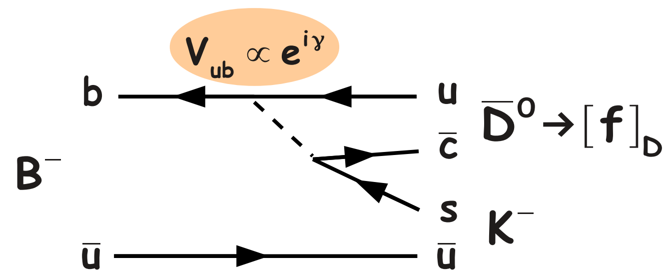
- tree-level B decays can provide a theoretically "clean" measurement of γ
  - no loops → largely unaffected by possible effects from New Physics
- but experimentally very challenging
  - decays to purely hadronic final states (→ trigger, K/π separation)
  - branching fractions are small (→ need large number of B's)

γ from Trees: $B^\pm \to D K^\pm$

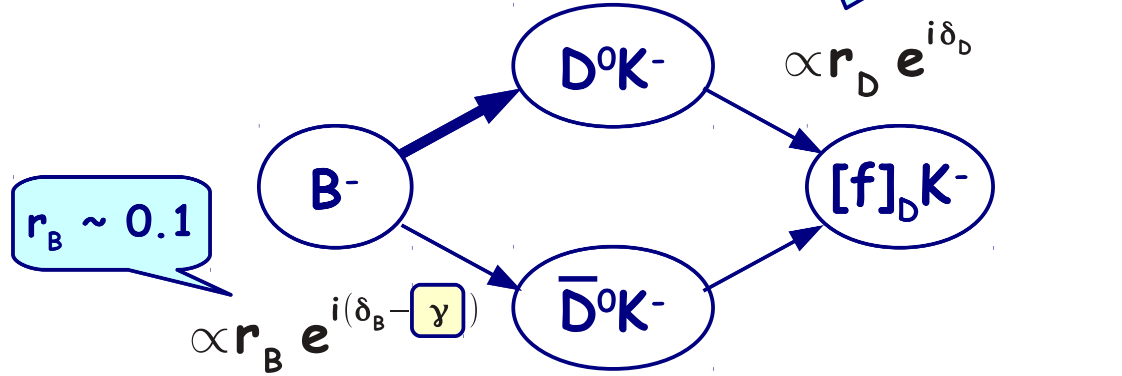
$B^\pm \to D K^\pm$ tree decays to final states $[f]_D$ accessible to D^0 and $\overline{D}^0$

- interference of $b \to c$ and $b \to u$ ($V_{ub} \propto e^{i\gamma}$) tree diagrams:





- theory uncertainties due to
  - strong phase difference δ_B
  - ratio r_B of the magnitudes of the two interfering amplitudes



- different methods proposed that in principle allow clean extraction of γ
  - named after initials of their proponents: "GLW", "ADS", "GGSZ"
  - combined analysis to extract γ and hadronic parameters r_B, δ_B, r_D, δ_D

(formalisms also hold for $B^\pm \to D^* K^\pm$ and $B^\pm \to D K^{*\pm}$)

γ from Trees: $B^\pm \to D K^\pm$

"GLW": Gronau, London, Wyler

[PLB 253 (1991) 483]
[PLB 265 (1991) 172]

- D decays to CP eigenstates $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$
- disadvantage: small value of r_B → small interference

"ADS": Atwood, Dunietz, Soni

[PRL 78 (1997) 3257]
[PRD 63 (2001) 036005]

- Cabibbo favoured $D^0 \to K^+\pi^-$ / doubly Cabibbo suppressed $D^0 \to K^-\pi^+$
- advantage: small r_D compensates small r_B → larger interference
- disadvantage: very small branching fraction for suppressed decay (~ 10^{-7})

"GGSZ": Giri, Grossman, Soffer, Zupan

[PRD 68 (2003) 054018]
[PRD 70 (2004) 072003]

- exploit interference patterns in $D^0 \to K^0_S h^+ h^-$ Dalitz plot ($h = \pi, K$)
- powerful method, dominates precision on γ from B factories
- complication: rich resonance structure, δ_D varies across Dalitz plot

γ from Trees: GLW modes

Measure decay rates to CP eigenstates and flavour-specific states

- CP eigenstates $D^0_{CP+} \to \pi^+\pi^-,\ K^+K^-$, $D^0_{CP-} \to K^0_S\pi^0,\ K^0_S\omega,\ K^0_S\phi$
- flavour-specific final states: $D^0 \to K^+\pi^-$, $\overline{D}^0 \to K^-\pi^+$
- $|D^0_{CP+}\rangle = \frac{1}{2}\,(\,|D^0\rangle + |\overline{D}^0\rangle\,) \to$ two triangles in complex plane

$$\sqrt{2}\cdot A(B^+ \to D^0_{CP+}K^+) = A(B^+ \to D^0K^+) + A(B^+ \to \overline{D}^0K^+)$$

$$\sqrt{2}\cdot A(B^- \to D^0_{CP+}K^-) = A(B^- \to \overline{D}^0K^-) + A(B^- \to D^0K^-)$$

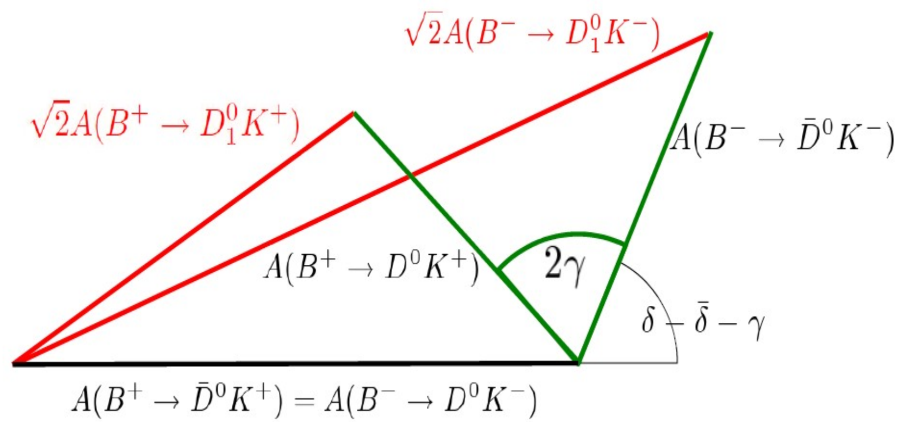
similar for $|D^0_{CP-}\rangle$

- one common side ($b \to c$ real)

$$A(B^+ \to \overline{D}^0K^+) = A(B^- \to D^0K^-)$$

- extract γ from angle between $b \to u$ sides

$$A(B^+ \to D^0K^+) = e^{2i\gamma}\cdot A(B^- \to \overline{D}^0K^-)$$



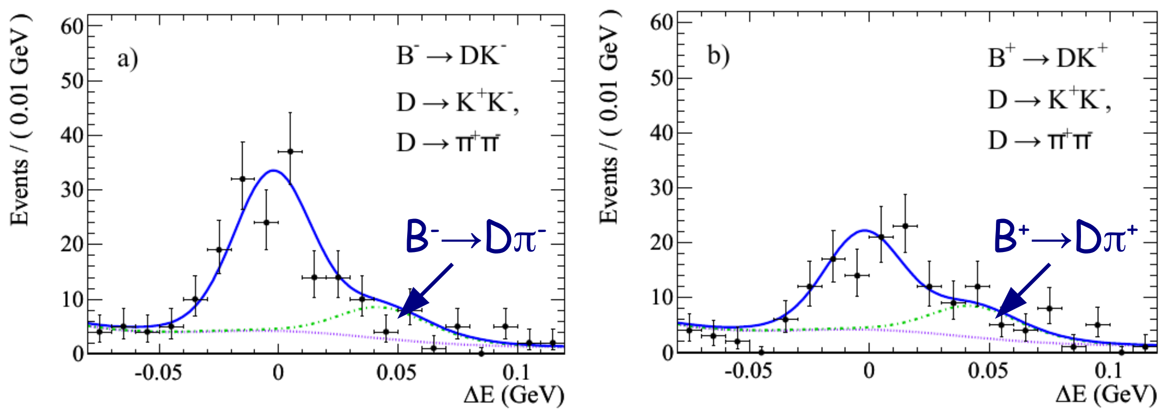
- r_B small $\to$ triangles very squashed $\to$ sensitivity to γ limited

GLW modes at B Factories

Decay rate ratios and asymmetries (→ cancellation of systematics)

$$R_{CP+} = \frac{\Gamma(B^- \to [h^+h^-]_D K^-) + \Gamma(B^+ \to [h^+h^-]_D K^+)}{1/2 \cdot \left[\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)\right]} = 1 + r_B^2 + 2 \cdot r_B \cdot \cos\delta_B \cdot \cos\gamma$$

$$A_{CP+} = \frac{\Gamma(B^- \to [h^+h^-]_D K^-) - \Gamma(B^+ \to [h^+h^-]_D K^+)}{\Gamma(B^- \to [h^+h^-]_D K^-) + \Gamma(B^+ \to [h^+h^-]_D K^+)} = + \frac{2 \cdot r_B \cdot \cos\delta_B \cdot \cos\gamma}{R_{CP+}}$$

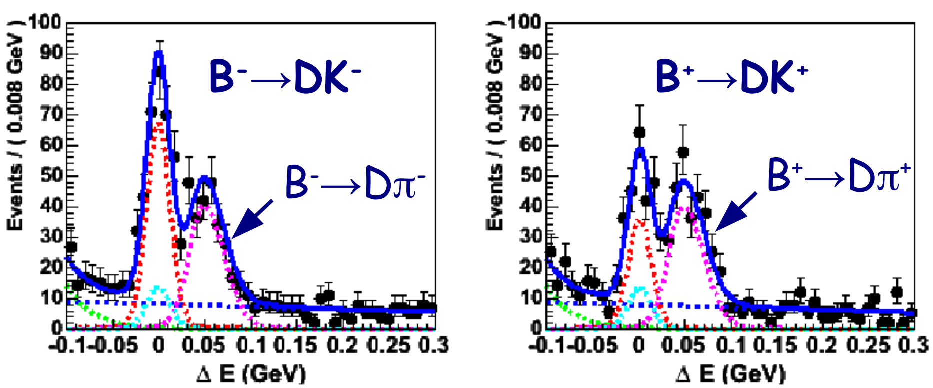


Babar

467×10^6 $\Upsilon(4s) \to B\bar{B}$ decays

$$A_{CP+} = (25 \pm 6 \pm 2)\,\%$$

[PRD 82 (2010) 072004]



Belle

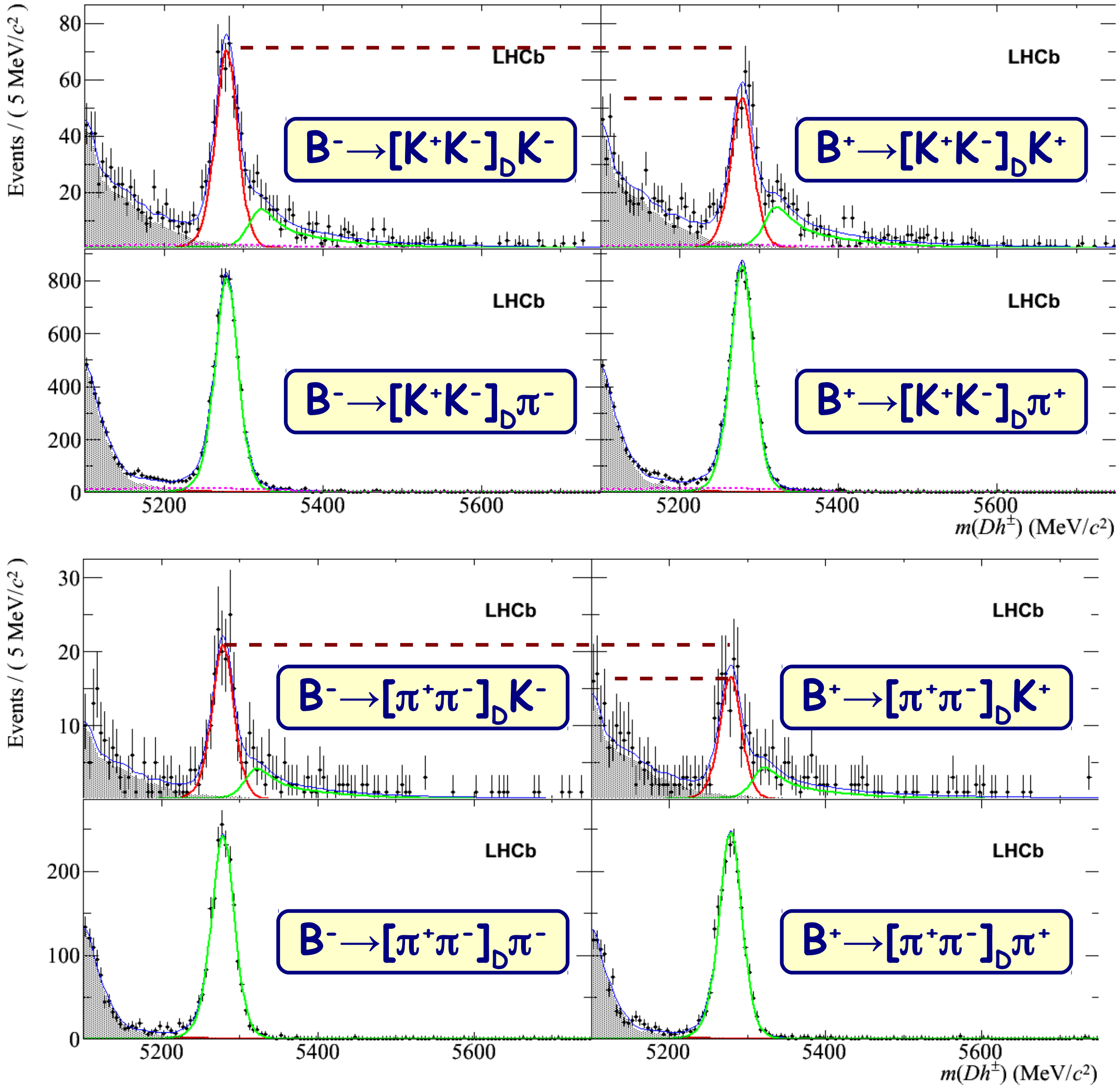
772×10^6 $\Upsilon(4s) \to B\bar{B}$ decays

$$A_{CP+} = (29 \pm 6 \pm 2)\,\%$$

[arXiv:1112.1984]

GLW modes at LHCb

Analysis of 1.0 fb^{-1} (2011 data set)



$$A_{CP+} = (14.5 \pm 3.2 \pm 1.0)\ \%$$

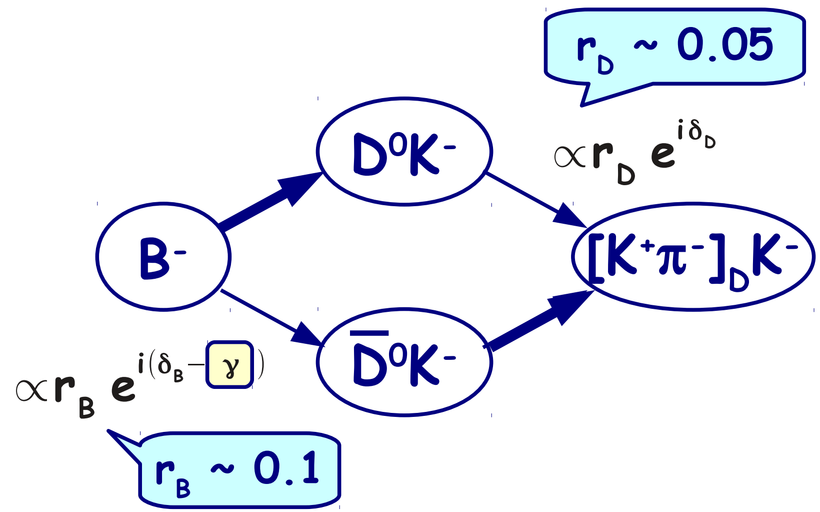
[PLB 713 (2012) 351]

- note suppression of $B^\pm \to D\pi^\pm$ contamination in the $B^\pm \to DK^\pm$ samples !

γ from Trees: ADS modes

$\overline{D}^0$ decay Cabibbo-allowed / D^0 decay doubly Cabibbo-suppressed

- interfering amplitudes of similar magnitude, larger CP violation
- price to pay: very low branching fraction for the doubly Cabibbo-suppressed mode



$$r_D = \frac{|A(D^0 \to K^+\pi^-)|}{|A(\overline{D}^0 \to K^+\pi^-)|} \approx \frac{|V^*_{cd}V_{us}|}{|V^*_{ud}V_{cs}|} = \lambda^2 \approx 0.05$$

- again, measure ratios and asymmetries to cancel systematics

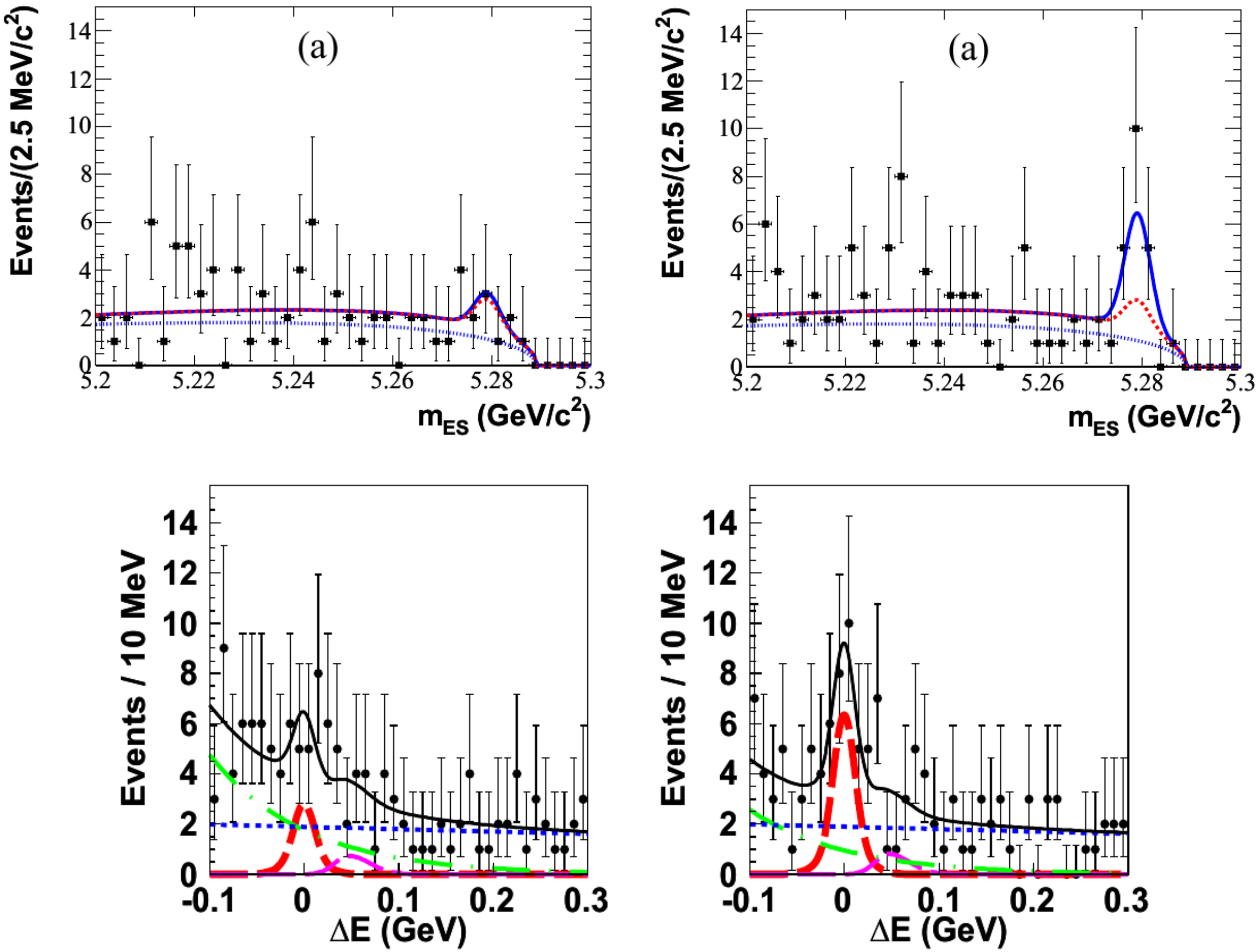
$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2 \cdot r_B r_D \cdot \cos(\delta_B + \delta_D) \cdot \cos\gamma$$

$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = \frac{2 \cdot r_B r_D \cdot \sin(\delta_B + \delta_D) \cdot \sin\gamma}{R_{ADS}}$$

ADS modes at B Factories

Limited statistics in the doubly Cabibbo suppressed decay mode

$B^- \to [\pi^- K^+]_D K^-$ $B^+ \to [\pi^+ K^-]_D K^+$



Babar

$467 \times 10^6\ \Upsilon(4s) \to B\bar{B}$ decays

$$A_{ADS}(DK) = \left(-86 \pm 47\,^{+12}_{-16}\right)\%$$

[arXiv:1006.4241]

Belle

$772 \times 10^6\ \Upsilon(4s) \to B\bar{B}$ decays

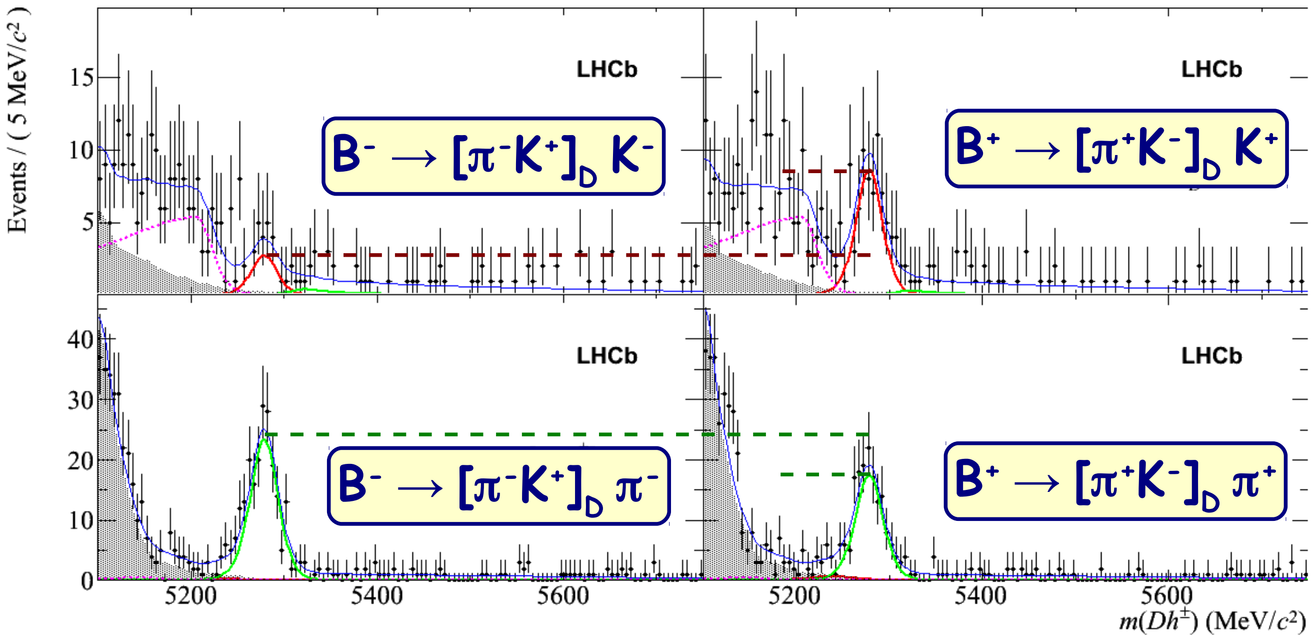
$$A_{ADS}(DK) = \left(-39\,^{+26}_{-28}\,^{+4}_{-3}\right)\%$$

[PRL 106 (2011) 231803]

ADS modes at LHCb

Analysis of 1 fb^{-1} (2011 data set)

- **first observation of the doubly Cabibbo suppressed mode (10 σ significance)**
- **evidence for asymmetry in $B^{\pm} \to DK^{\pm}$ (4 σ significance)**

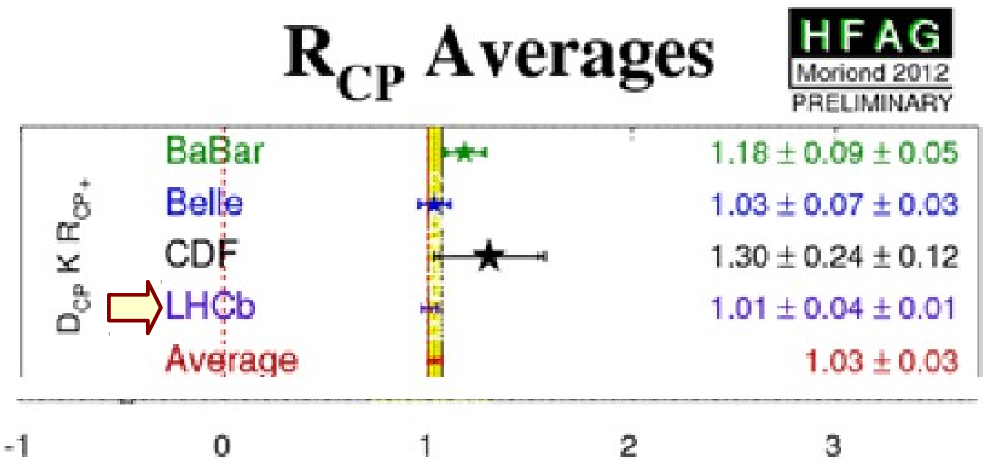


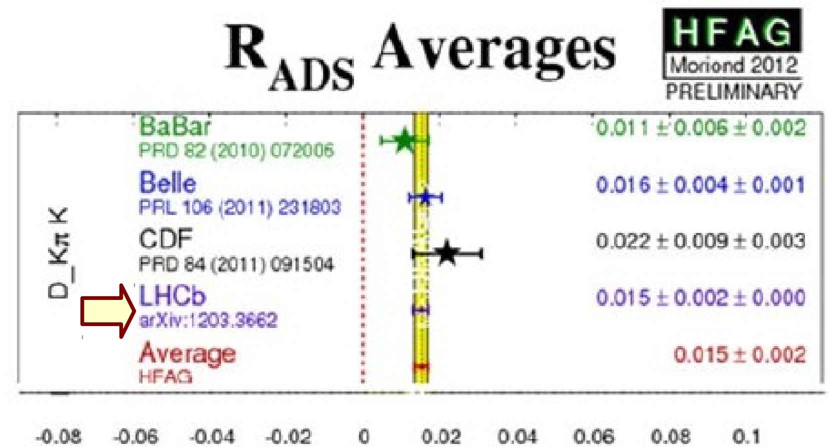
$$A_{ADS}(DK) = (-52 \pm 15 \pm 2)\ \%$$

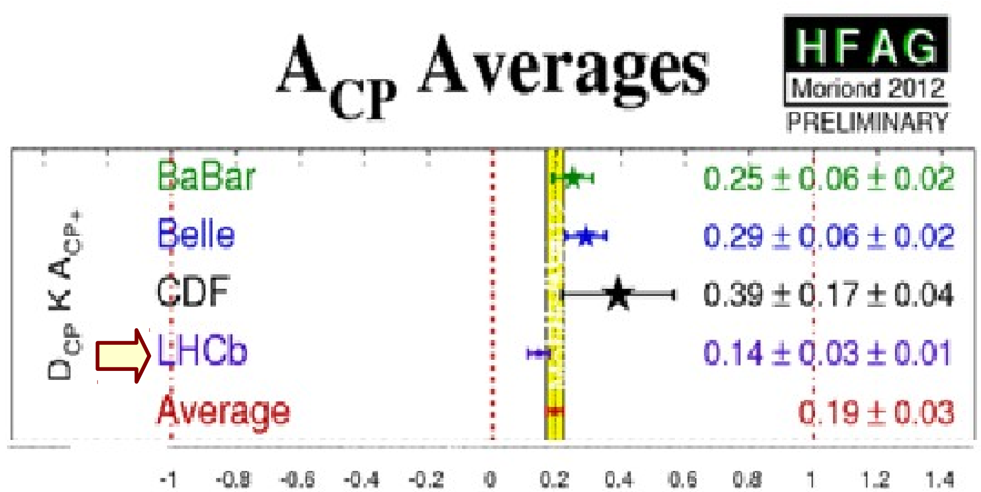
PLB 712 (2012) 203]

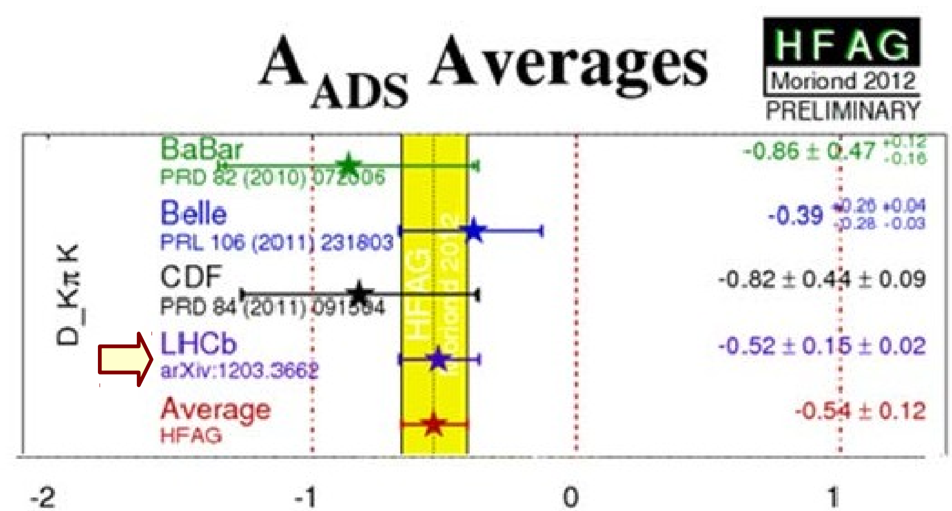
- **hint of a positive asymmetry in $B^{\pm} \to D\pi^{\pm}$ (2.4 σ significance)**

GLW / ADS: LHCb Impact









γ from Trees: GGSZ

Exploit interference patterns in $D \to K^0_s h^+ h^-$ Dalitz plots ($h = \pi, K$)

- Dalitz plot: $D \to K^0_s h^+ h^-$ decay amplitude f_D as a function of

$$m_+^2 \equiv m^2(K_S^0 h^+) \quad ; \quad m_-^2 \equiv m^2(K_S^0 h^-)$$

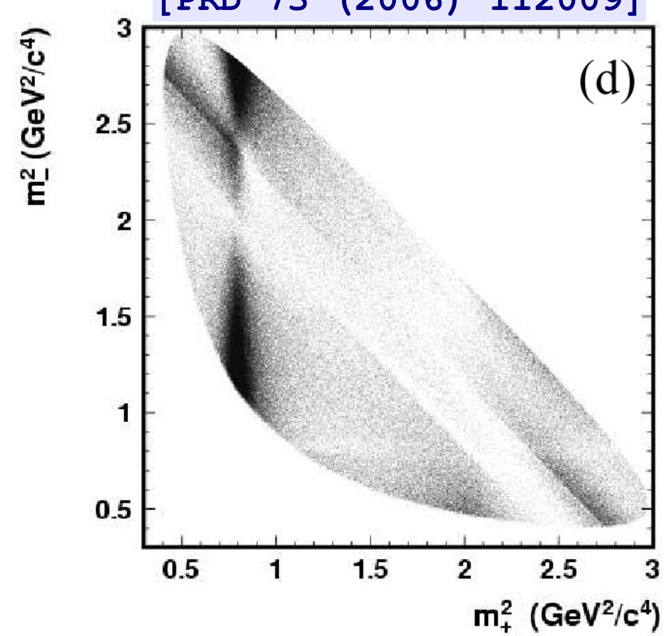
- intermediate resonances → structure above flat phase-space distribution
- assuming no CP violation in D decays (expected to be very small)

$$f_{\overline{D}^0}(m_+^2, m_-^2) = f_{D^0}(m_-^2, m_+^2)$$

- measure $f_D(m_-^2, m_+^2)$ using large samples of flavour-tagged $D \to K^0_s h^+ h^-$ decays
  - B factories: $D^{*\pm} \to D\pi^\pm$
    - use pion charge to tag D flavour
  - CLEO-c: $e^+e^- \to \psi(3770) \to D^0 \overline{D}^0$
    - use flavour-specific decay of accompanying D to tag D flavour

Belle

[PRD 73 (2006) 112009]



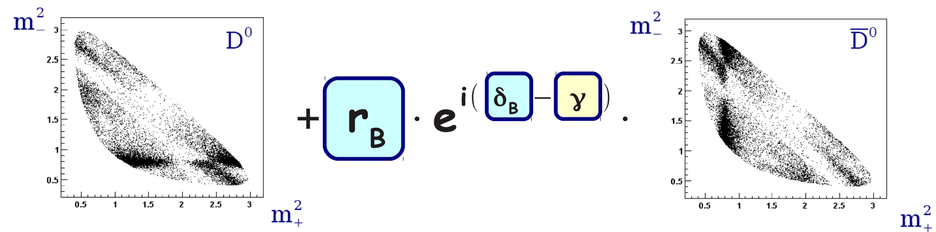
- observe rich resonance structure → large interference possible

γ from Trees: GGSZ

Extract r_B, δ_B, γ from difference in B^- and B^+ interference patterns

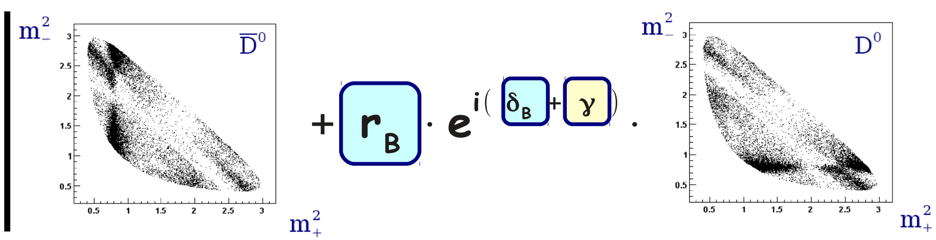
- $B^- \to [K^0_S\, h^+ h^-]_D\, K^-$:

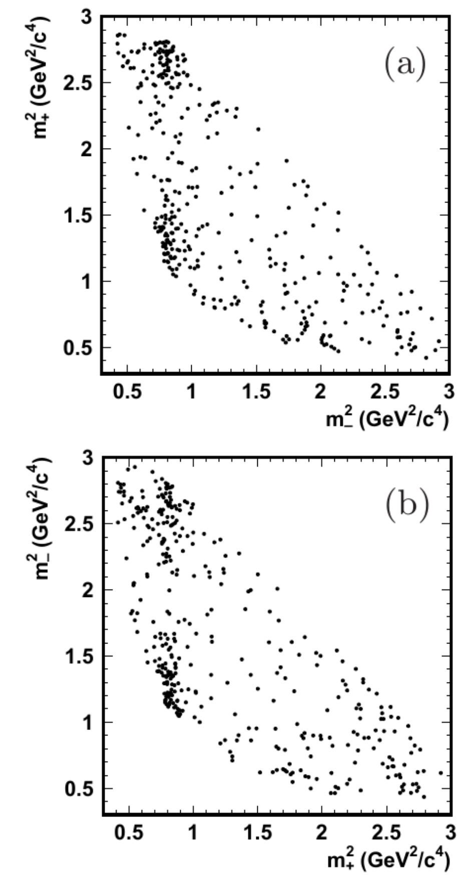
$$\Gamma_{B^-}(m_+^2, m_-^2) \propto \Big| \ [D^0 \text{ Dalitz plot}] + r_B \cdot e^{i(\delta_B - \gamma)} \cdot [\overline{D}^0 \text{ Dalitz plot}] \ \Big|^2 \Rightarrow$$



- $B^+ \to [K^0_S\, h^+ h^-]_D\, K^+$ $\;(\, f_{D^0} \leftrightarrow f_{\overline{D}^0}\,,\ -\gamma \leftrightarrow +\gamma\,)$

$$\Gamma_{B^+}(m_+^2, m_-^2) \propto \Big| \ [\overline{D}^0 \text{ Dalitz plot}] + r_B \cdot e^{i(\delta_B + \gamma)} \cdot [D^0 \text{ Dalitz plot}] \ \Big|^2 \Rightarrow$$





Belle, [PRD 81 (2010) 112002]

- difference:

$$\Delta\Gamma(m_-^2, m_+^2) \propto \left|f_D(m_-^2, m_+^2)\right|^2 + r_B^2 \cdot \left|f_D(m_+^2, m_-^2)\right|^2$$
$$+\ 2\, r_B \cdot \mathrm{Re}\left\{ f_D(m_-^2, m_+^2) \cdot f_D^*(m_+^2, m_-^2) \cdot e^{-i(\delta_B - \gamma)} \right\}$$

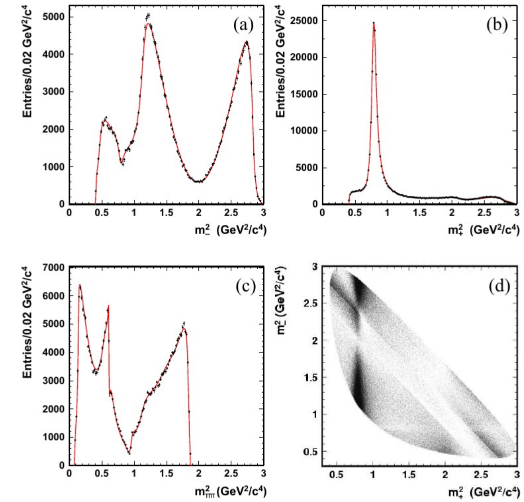
γ from Trees: GGSZ

Fit for r_B, δ_B, γ: model-dependent approach

Belle, [PRD 73 (2006) 112009]

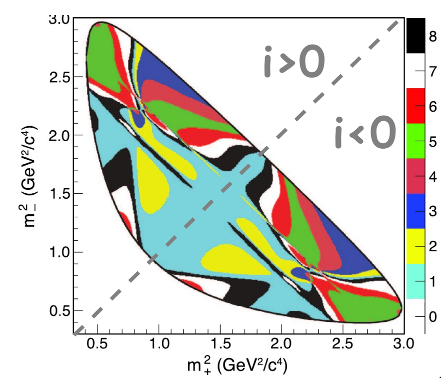
- model $f_D(m_+^2, m_-^2)$ by a coherent sum of two-body resonances and a non-resonant amplitude
  - e.g. Belle: 18 + 1 amplitudes
- model uncertainty starts to limit precision on γ

Intermediate state	Amplitude	Phase (°)	Fit fraction
$K_S^0\sigma_1$	1.43 ± 0.07	212 ± 3	9.8%
$K_S^0\rho^0$	1.0 (fixed)	0 (fixed)	21.6%
$K_S^0\omega$	0.0314 ± 0.0008	110.8 ± 1.6	0.4%
$K_S^0 f_0(980)$	0.365 ± 0.006	201.9 ± 1.9	4.9%
$K_S^0\sigma_2$	0.23 ± 0.02	237 ± 11	0.6%
$K_S^0 f_2(1270)$	1.32 ± 0.04	348 ± 2	1.5%
$K_S^0 f_0(1370)$	1.44 ± 0.10	82 ± 6	1.1%
$K_S^0\rho^0(1450)$	0.66 ± 0.07	9 ± 8	0.4%
$K^*(892)^+\pi^-$	1.644 ± 0.010	132.1 ± 0.5	61.2%
$K^*(892)^-\pi^+$	0.144 ± 0.004	320.3 ± 1.5	0.55%
$K^*(1410)^+\pi^-$	0.61 ± 0.06	113 ± 4	0.05%
$K^*(1410)^-\pi^+$	0.45 ± 0.04	254 ± 5	0.14%
$K_0^*(1430)^+\pi^-$	2.15 ± 0.04	353.6 ± 1.2	7.4%
$K_0^*(1430)^-\pi^+$	0.47 ± 0.04	88 ± 4	0.43%
$K_2^*(1430)^+\pi^-$	0.88 ± 0.03	318.7 ± 1.9	2.2%
$K_2^*(1430)^-\pi^+$	0.25 ± 0.02	265 ± 6	0.09%
$K^*(1680)^+\pi^-$	1.39 ± 0.27	103 ± 12	0.36%
$K^*(1680)^-\pi^+$	1.2 ± 0.2	118 ± 11	0.11%
non-resonant	3.0 ± 0.3	164 ± 5	9.7%



Fit for r_B, δ_B, γ: model-independent approach

- use CLEO-c measurements of δ_D, divide Dalitz plot in regions i of ~ constant phase difference $\Delta\delta = \delta_{\overline{D}^0} - \delta_{D^0}$
- determine B^+ and B^- event yields in each region i:



CLEO-c [PRD 82 (2010) 112006]

$$N_i(B^\pm) = K_{\mp i} + (x_\pm^2 + y_\pm^2) \cdot K_{\pm i} + 2\sqrt{K_{+i} K_{-i}} \cdot \{ x_\pm < \cos(\Delta\delta_D) >_i \mp y_\pm < \sin(\Delta\delta_D) >_i \}$$

$$x_\pm = \boxed{r_B} \cdot \cos(\boxed{\delta_B} \pm \boxed{\gamma}) \quad ; \quad y_\pm = \boxed{r_B} \cdot \sin(\boxed{\delta_B} \pm \boxed{\gamma})$$

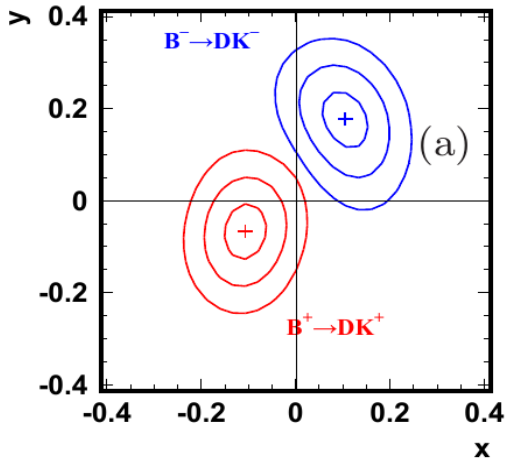
K_i: numbers of $D \to K^0_s h^+ h^-$ events from $D^{*\pm} \to D\pi^\pm$

GGSZ: Results

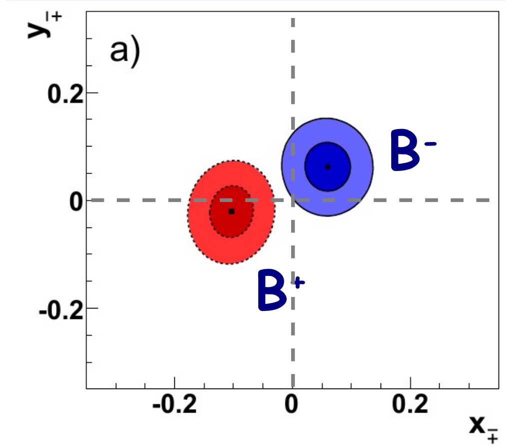
Fit in "cartesian" coordinates $x_{\pm}, y_{\pm}$ to avoid bias from $r_b > 0$

- **model-dependent approach:**
  - Belle, $657 \times 10^6\ \Upsilon(4s) \to B\bar{B}$ decays
  - Babar, $467 \times 10^6\ \Upsilon(4s) \to B\bar{B}$ decays

Belle
[PRD 81 (2010) 112002]

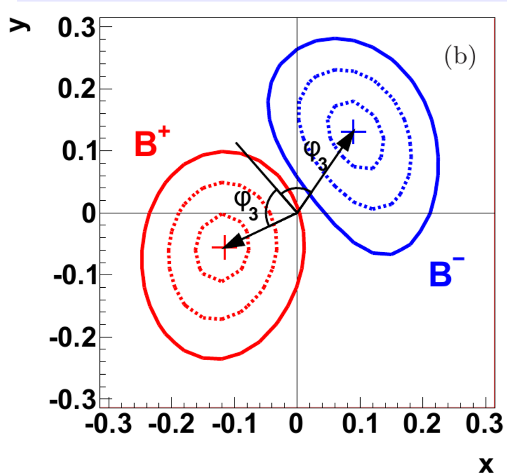


Babar
[PRL 105 (2010) 121801]

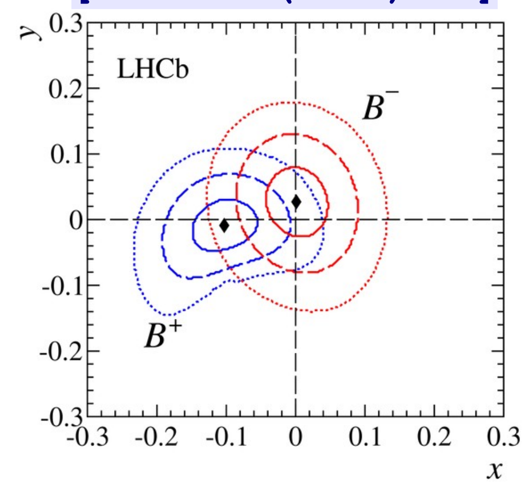


- **model-independent approach:**
  - Belle, $772 \times 10^6\ \Upsilon(4s) \to B\bar{B}$ decays
  - LHCb, 1fb^{-1} (2011 data set)

Belle
[PRD 85 (2012) 112014]



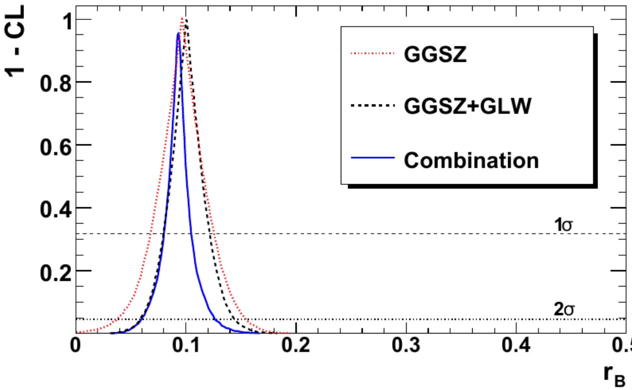
LHCb
[PLB 718 (2012) 43]

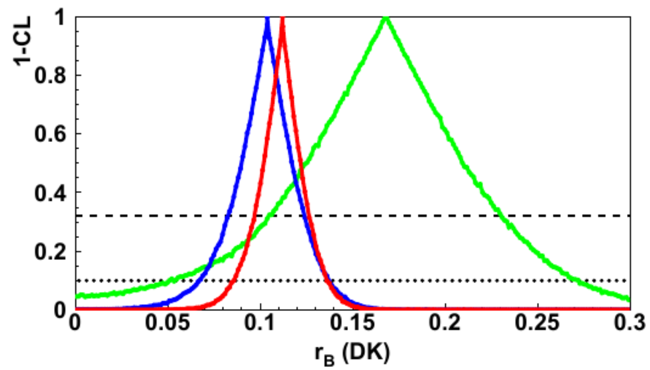


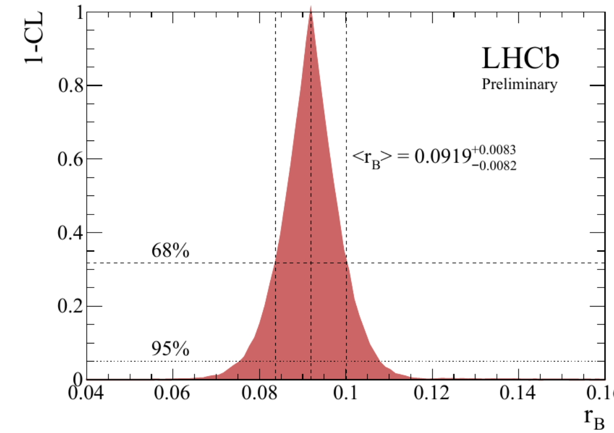
- **LHCb results already match precision from B factories**

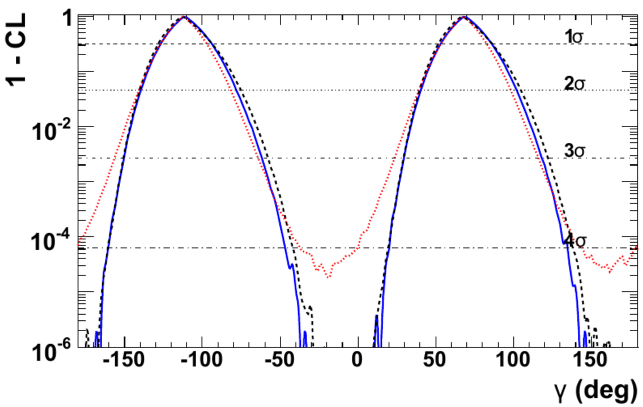
- **LHCb result indicates smaller value of $r_b \to$ sensitivity to γ reduced**

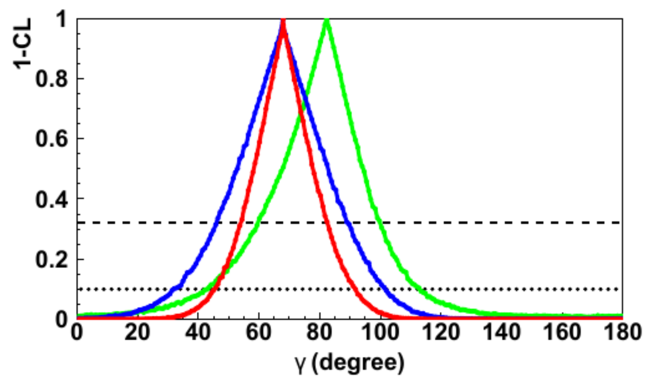
γ from Trees: Combinations

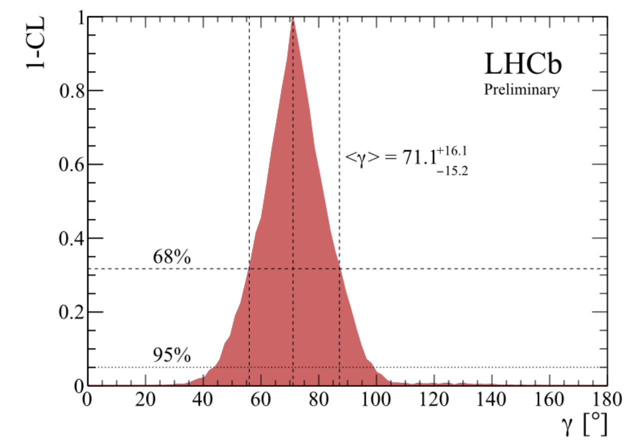












$$\langle\gamma\rangle_{\text{Babar}} = \left(69\,^{+17}_{-16}\right)^\circ$$

[arXiv:1301.1029]

$$\langle\gamma\rangle_{\text{Belle}} = \left(68\,^{+15}_{-14}\right)^\circ$$

[arXiv:1301.2033]

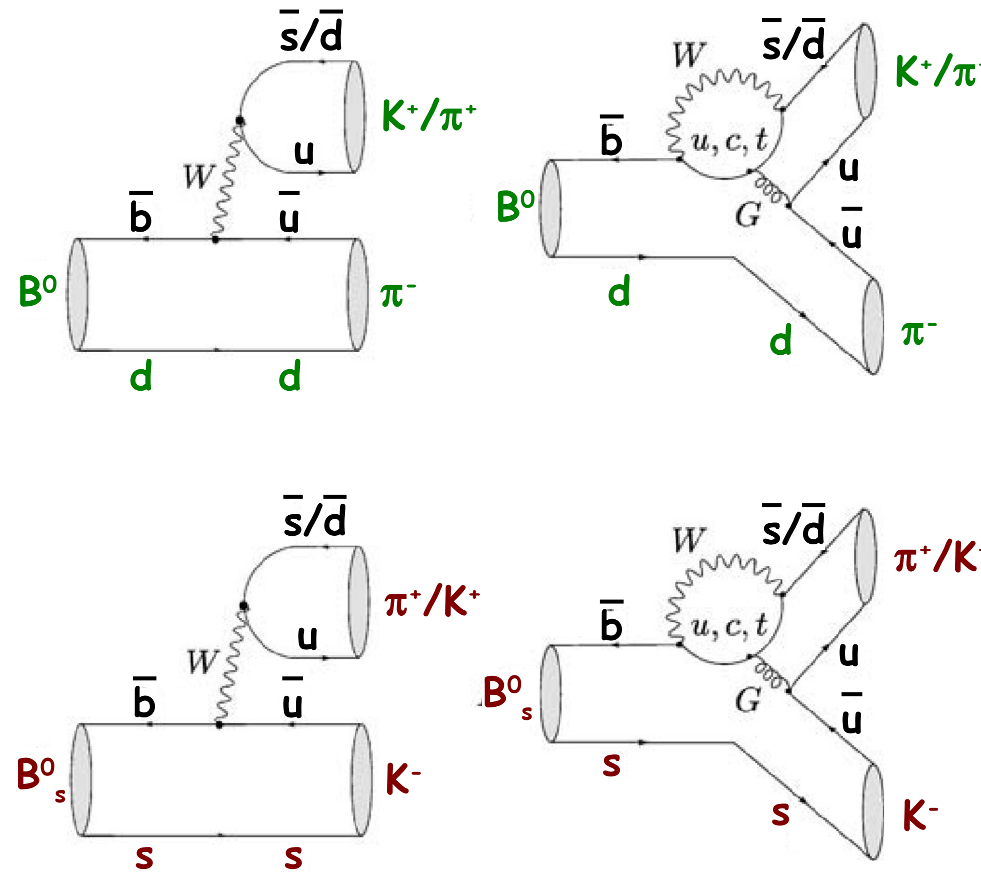
$$\langle\gamma\rangle_{\text{LHCb}} = \left(71\,^{+16.1}_{-15.2}\right)^\circ$$

[LHCb-CONF-2012-032] preliminary

γ from Loops

Direct CP violation in 2-body charmless B decays

- sensitivity to γ through interference of b→u Tree diagrams ($V_{ub} \sim e^{i\gamma}$) and b→s(d) Penguin diagrams
- sensitive to possible contribution from New Physics in Penguin loops
- comparison with from γ Trees !
- hadronic uncertainties: can be controlled using U-Spin symmetry between B^0 and B^0_s decays



R.Fleischer, [EPJ C52 (2007) 267]

- two approaches:
  - time-dependent CP asymmetry in $B^0 \to \pi^+ \pi^-$ and $B^0_s \to K^+ K^-$
  - time-integrated CP asymmetry in $B^0 \to K^+ \pi^-$ and $B^0_s \to \pi^+ K^-$

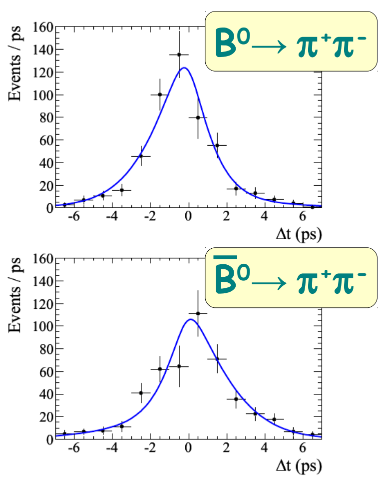
$B^0 \rightarrow \pi^+\pi^-$: B factories

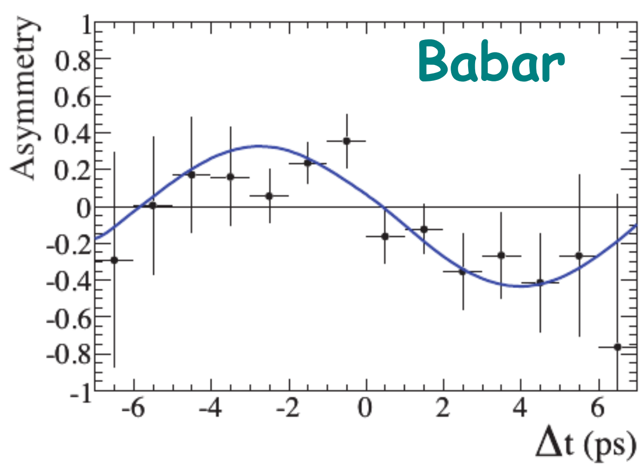
Measure time-dependent asymmetry of decay rates

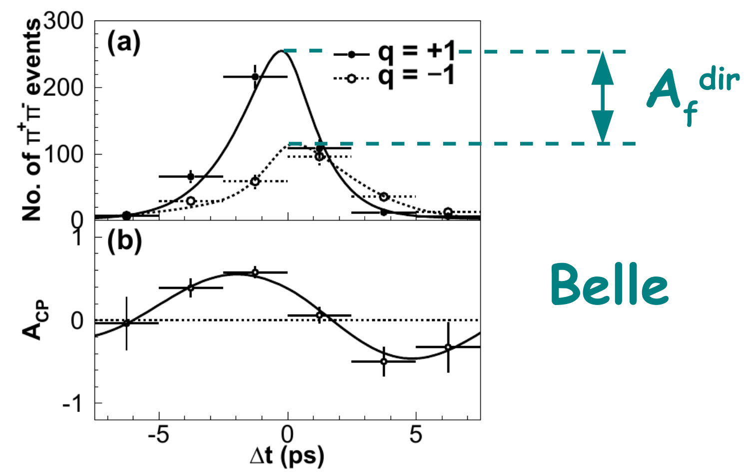
$$A_{CP}(t) = \frac{\Gamma(B^0_{(s)}(t=0)\rightarrow f) - \Gamma(\overline{B}^0_{(s)}(t=0)\rightarrow f)}{\Gamma(B^0_{(s)}(t=0)\rightarrow f) + \Gamma(\overline{B}^0_{(s)}(t=0)\rightarrow f)} = \frac{A_f^{dir}\cos(\Delta m_{(s)} t) + A_f^{mix}\sin(\Delta m_{(s)} t)}{\cosh(\frac{\Delta\Gamma_{(s)}}{2}t) - A_f^{\Delta\Gamma}\sinh(\frac{\Delta\Gamma_{(s)}}{2}t)}$$

- both mixing-induced CP violation (A_f^{mix}) and CP violation in decay (A_f^{dir})
  - for γ measurements, we are interested in A_f^{dir}
- A_f^{mix} in $B^0 \rightarrow \pi^+\pi^-$ allows to extract CKM angle sin 2α at B factories
  - exploiting Isospin relations between $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow \pi^0\pi^0$ and $B^\pm \rightarrow \pi^\pm\pi^0$
  - sorry, no time to cover this here (maybe in the discussion session?)

[arXiv:1206.3525]







[PRL 98 (2007) 211801]

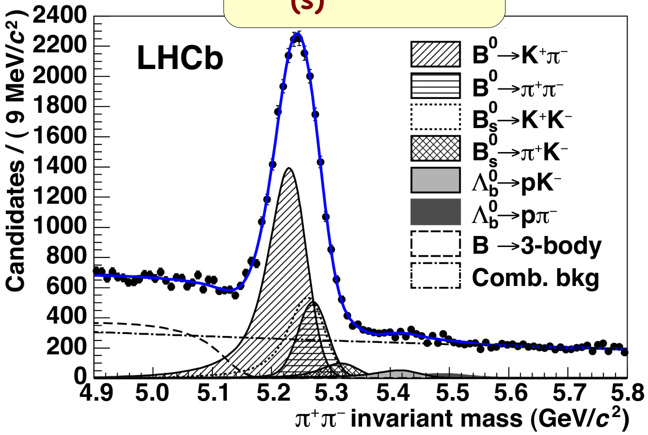
$B^0_{(s)} \to h^+ h^-$: LHCb

[LHCb-CONF-2012-007]
preliminary

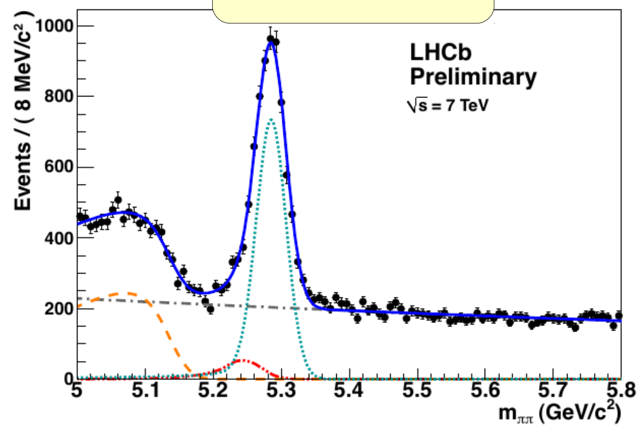
Analysis of 0.69 fb^{-1} (2/3 of 2011 data set)

- note the power and importance of π/K separation:

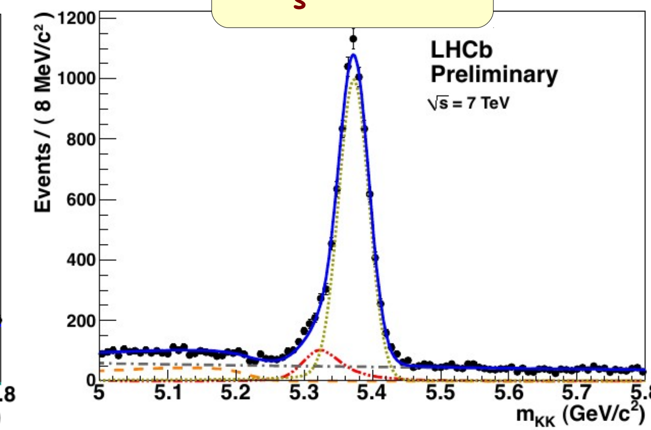
$B^0_{(s)} \to h^+h'^-$

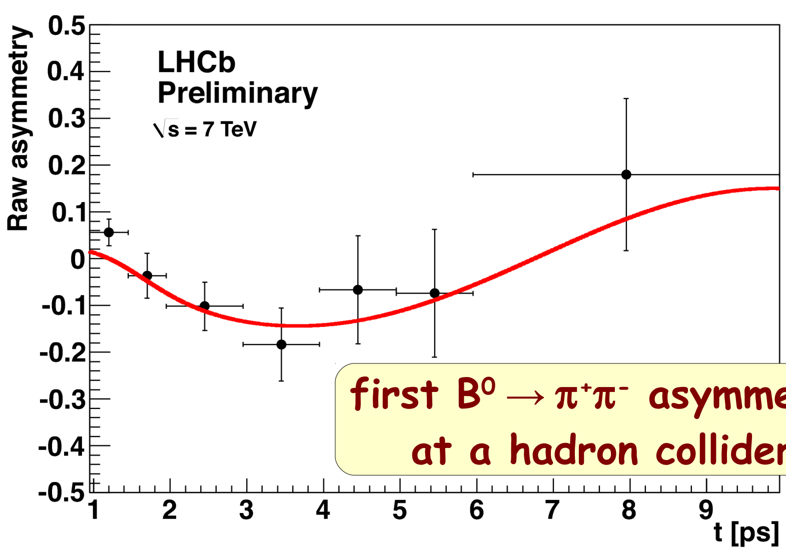


$B^0 \to \pi^+\pi^-$

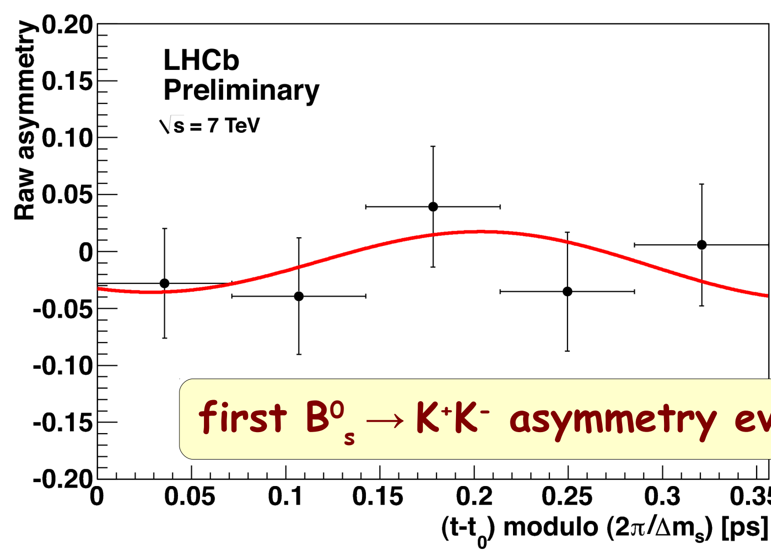


$B^0_s \to K^+K^-$





first $B^0 \to \pi^+\pi^-$ asymmetry at a hadron collider



first $B^0_s \to K^+K^-$ asymmetry ever

$B^0_{(s)} \rightarrow h^+ h^-$: Comparison

First LHCb results promising

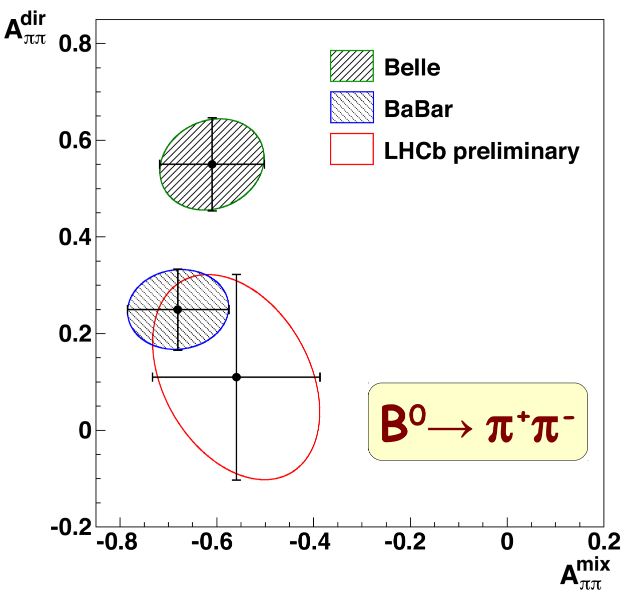
[LHCb-CONF-2012-007]
preliminary

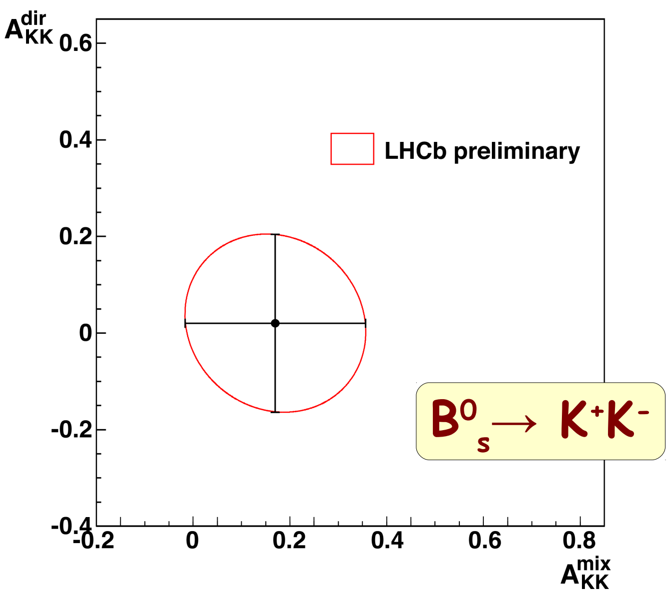
- statistical precision not yet sufficient to attempt a γ determination
  - but systematic uncertainties very small and six times more data "on tape"

$$A^{dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03$$

$$A^{dir}_{KK} = 0.02 \pm 0.18 \pm 0.04$$

- $A^{dir}_{\pi\pi}$ comparison with B factories: LHCb result favours Babar over Belle





$B^0_{(s)} \rightarrow h^+ h^-$: Comparison

Swiss Institute of Particle Physics

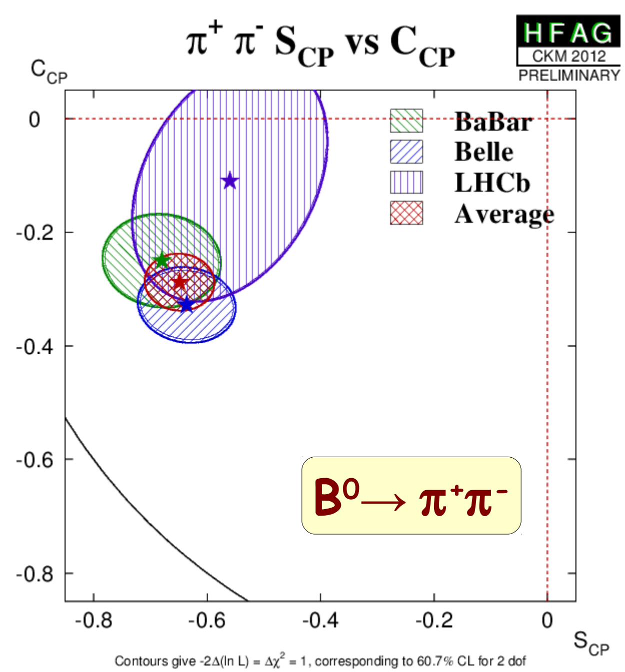
First LHCb results promising

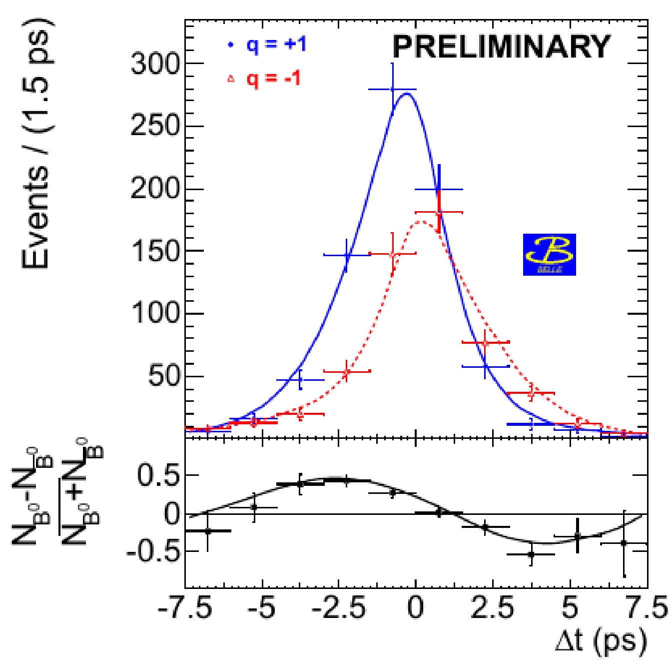
[LHCb-CONF-2012-007] preliminary

- statistical precision not yet sufficient to attempt a γ determination
  - but systematic uncertainties very small and six times more data "on tape"

$$A^{dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03$$

- $A^{dir}_{\pi\pi}$ comparison with B factories: new preliminary Belle result [CKM 2012]

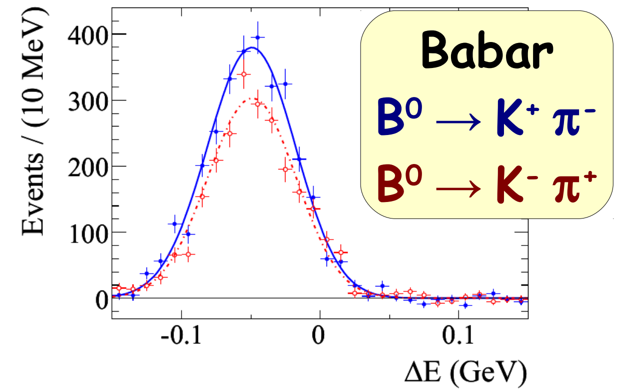




$B^0_{(s)} \to K\pi$

Time-integrated decay rate asymmetry to flavour-specific final states

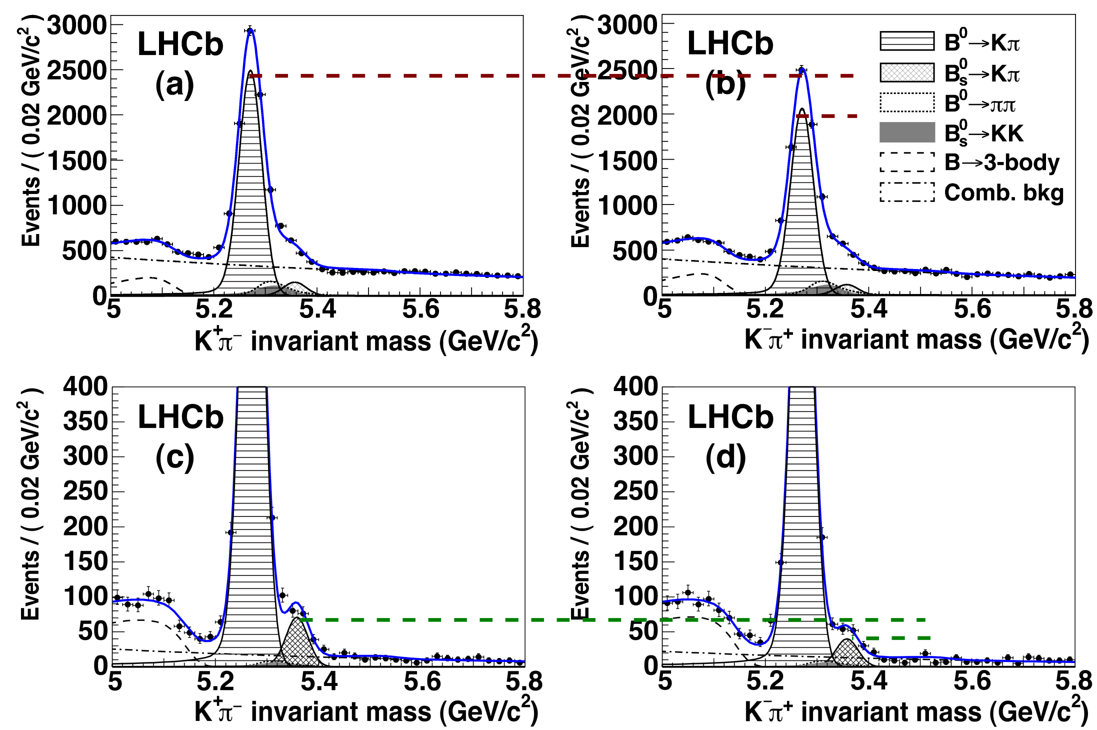
$$A_{CP} = \frac{\Gamma(B^0_{(s)} \to f) - \Gamma(\bar{B}^0_{(s)} \to \bar{f})}{\Gamma(B^0_{(s)} \to f) + \Gamma(\bar{B}^0_{(s)} \to \bar{f})}$$



- Babar analysis of full dataset [arXiv:1206.3525]

$$A_{CP} = -0.107 \pm 0.016 ^{+0.006}_{-0.004}$$

- LHCb analysis of $0.35\ \mathrm{fb}^{-1}$ (1/3 of 2011 data set) [PRL 108 (2012) 201601]



- $B^0 \to K^+\pi^-$ / $\bar{B}^0 \to K^-\pi^+$

$$A_{CP} = -0.088 \pm 0.011 \pm 0.008$$

  - first observation of CP violation at a hadron collider (6 σ)

- $B^0_s \to K^-\pi^+$ / $\bar{B}^0_s \to K^+\pi^-$

$$A_{CP} = 0.27 \pm 0.08 \pm 0.02$$

  - first evidence for CP violation in the B^0_s system (3.2 σ)

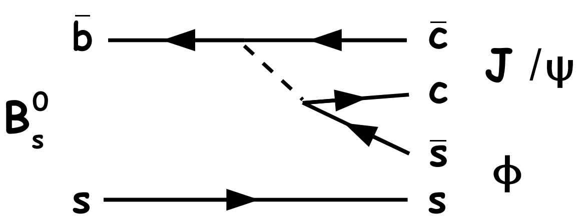
Outline

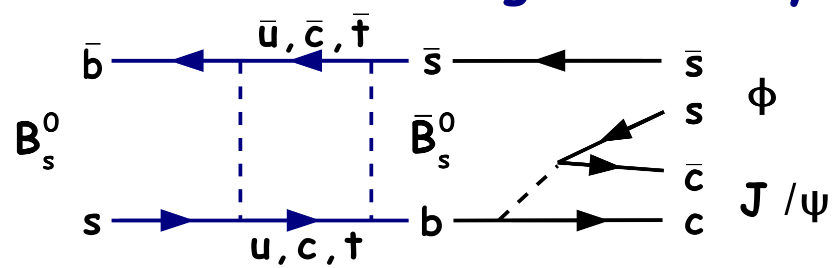
- **Part I: Introduction**
  - what is (quark) flavour physics and why is it so exciting?
  - how we got here: brief history of flavour physics in the 20^{th} century
- Part II: Particle-Antiparticle Mixing
  - a short summary of the formalism (don't worry, I'm an experimentalist …)
  - introduce experimental facilities and techniques
- **Part III: Precision tests of the Standard Model**
  - **CP violating observables:** sin 2β, CKM angle γ, **$B^0_s\bar{B}^0_s$ mixing phase ϕ_s**
  - rare decays: search for $B^0_{(s)} \to \mu^+ \mu^-$, angular observables in $B^0 \to K^{*0} \mu^+ \mu^-$

CP violation in $B^0_s \to J/\psi\,\phi$

"Golden decay" of the B^0_s system, equivalent of $B^0 \to J/\psi\, K^0_s$

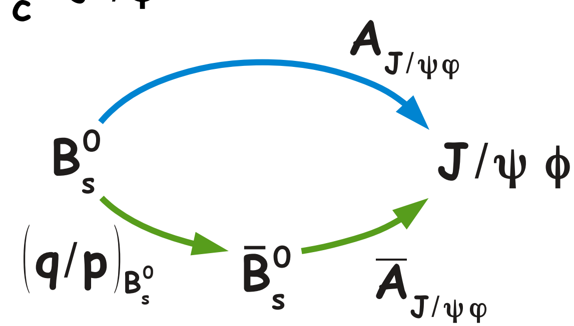
- CP violation through interference between mixing and decay





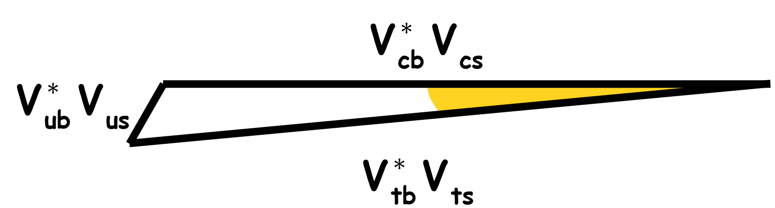
- but CP violating phase predicted to be very small

$$\lambda_{J/\psi\phi} = \left(\frac{q}{p}\right)_{B^0_s} \cdot \left(\frac{\bar{A}_{J/\psi\phi}}{A_{J/\psi\phi}}\right) = 2\left(\frac{V^*_{tb}V_{ts}}{V^*_{cb}V_{cs}}\right) = e^{-i\phi_s}$$



- ϕ_s is the small angle in one of the "squashed" unitarity triangles

$$\begin{pmatrix} V^*_{ud} & V^*_{cd} & V^*_{td} \\ V^*_{us} & V^*_{cs} & V^*_{ts} \\ V^*_{ub} & V^*_{cb} & V^*_{tb} \end{pmatrix} \times \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- Standard Model prediction:

$$\phi_s = 0.036 \pm 0.002 \text{ rad}$$

J.Charles et al., [PRD 84 (2011) 033005]

- sensitive to possible New Physics contributions in B^0_s-$\bar{B}^0_s$ mixing

CP violation in $B^0_s \to J/\psi\, \phi$

Measure time-dependent CP asymmetry

- for CP eigenstate f with eigenvalue $\eta_f = \pm 1$

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0_s(t=0) \to f) - \Gamma(B^0_s(t=0) \to f)}{\Gamma(\bar{B}^0_s(t=0) \to f) + \Gamma(B^0_s(t=0) \to f)} = \eta_f \boxed{\sin\phi_s} \sin(\Delta m_s t)$$

- determine flavour of B_s meson at $t = 0$ → mis-tag fraction $\boxed{\omega_{tag}}$
- resolve rapid B^0_s-$\bar{B}^0_s$ oscillations → finite proper time resolution $\boxed{\sigma_t}$

$$A_{CP}(t) \approx (1 - \boxed{2\,\omega_{tag}})\, e^{-\frac{1}{2}\Delta m_s^2 \boxed{\sigma_t^2}}\, \eta_f \boxed{\sin\phi_s} \sin(\Delta m_s t)$$

- final state in $B^0_s \to J/\psi\, \phi$ is a mix of CP even and odd ($L_{J/\psi\phi} = 0, 1, 2$)
  - three polarisation amplitudes, plus non-resonant $K^+ K^-$ amplitude (S-wave)
  - time-dependent angular analysis to disentangle these and determine ϕ_s
- finite lifetime difference $\Delta\Gamma_s$ between CP eigenstates in $B^0_s \bar{B}^0_s$ system
  - not well measured yet, needs to be determined simultaneously with ϕ_s

$B^0_s \to J/\psi\,\phi$: Fit

Unbinned Maximum Likelihood fit to extract physics parameters

- fit parameters:
  - ϕ_s, $\Delta\Gamma_s$
  - m_s, $\overline{\Gamma}_s$, (Δm_s)
  - $|A_0|$, $|A_\parallel|$, $|A_\perp|$, $\delta_\parallel$, $\delta_\perp$, δ_0
  - tagging parameters
  - signal fraction
  - background parameters

usually constrained to the value obtained in oscillation measurements

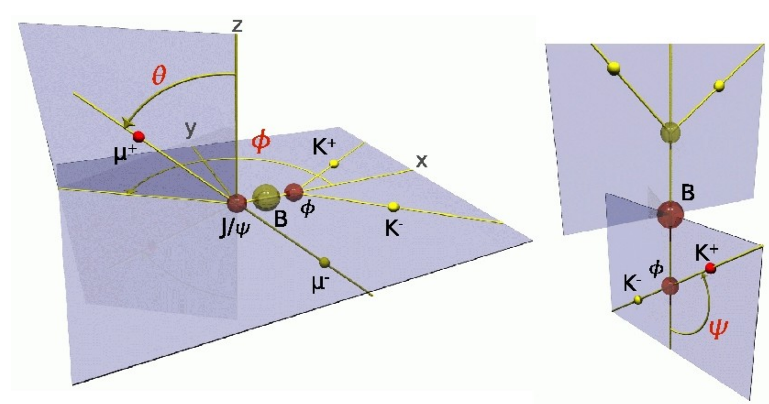
$$\frac{d^4\Gamma(B^0_s \to J/\psi\,\phi)}{dt\,d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

$$h_k(t) \;=\; N_k e^{-Gt}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right]$$

k	$f_k(\theta_\mu, \theta_K, \phi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\cos^2\phi_h\right)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\sin^2\phi_h\right)$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$\sin^2\theta_K\sin^2\theta_\mu\sin 2\phi_h$	$\lvert A_\parallel(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \cos\phi_h$	$\lvert A_0(0)A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \sin\phi_h$	$\lvert A_0(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_s(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \cos\phi_h$	$\lvert A_s(0)A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \sin\phi_h$	$\lvert A_s(0)A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K \sin^2\theta_\mu$	$\lvert A_s(0)A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

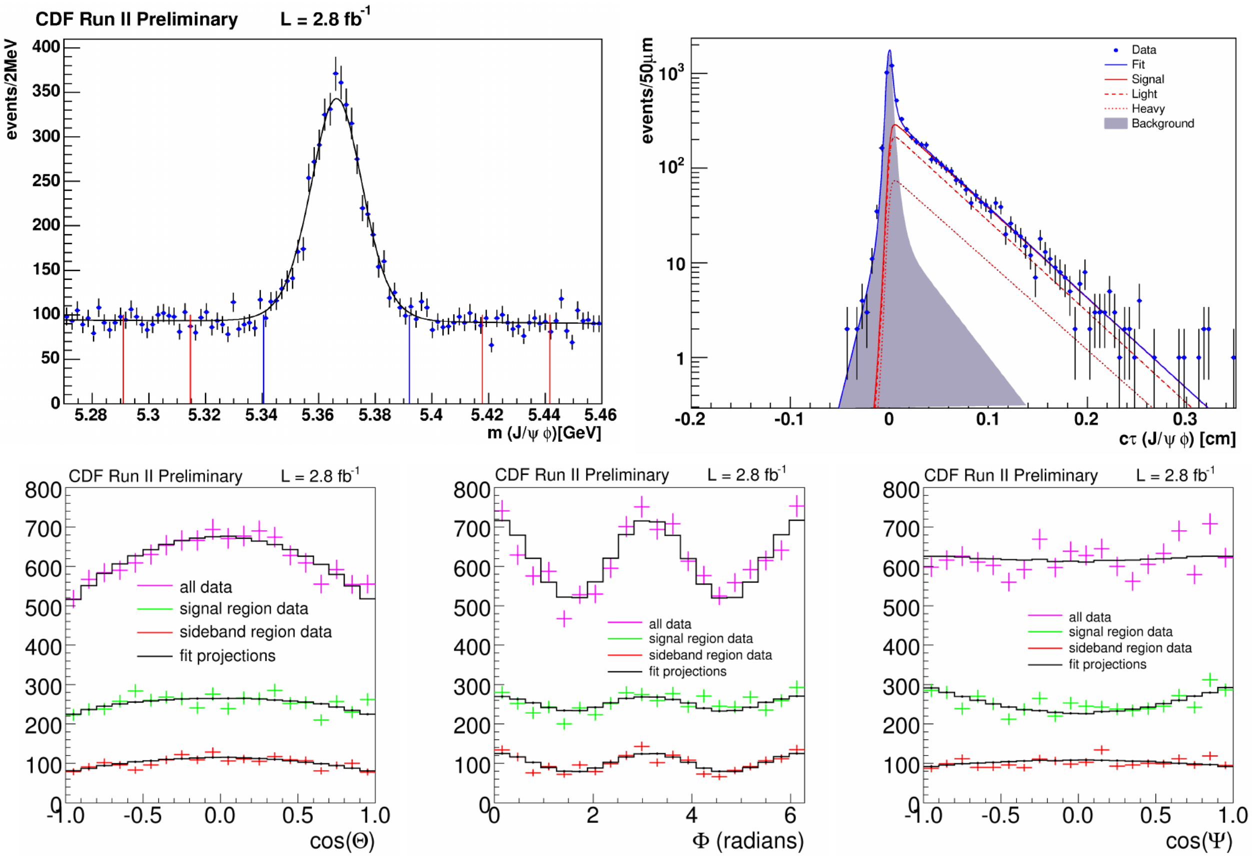
($S = \sin\phi_s$; $C = \cos\phi_s$; $D = 1 - C - S$)

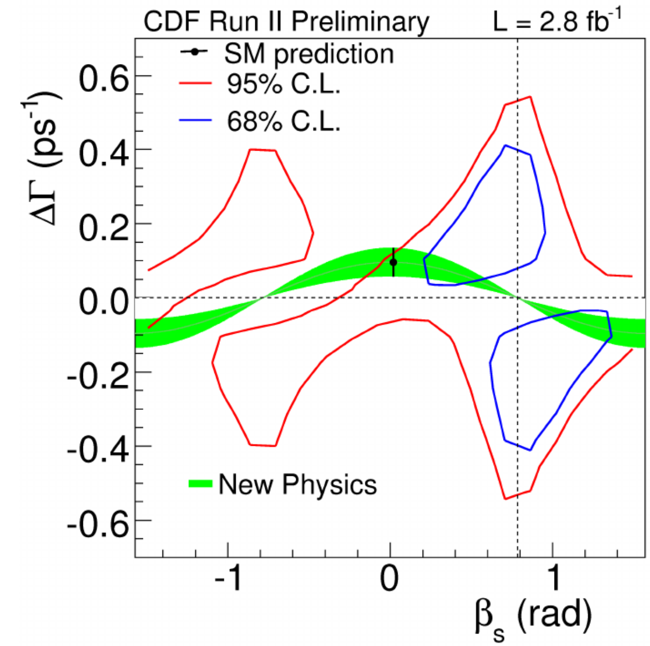
- event-by-event inputs:
  - reconstructed invariant mass & uncertainty
  - reconstructed decay time & uncertainty
  - three decay angles $\Omega = (\theta=\theta_\mu,\ \phi=\phi_h,\ \psi=\theta_K)$
  - tagging decision & estimated tagging dilution



$B^0_s \to J/\psi\,\phi$: Tevatron 2008

CDF: ~ 3'200 signal events from 2.8 fb^{-1}





1.8 σ deviation from Standard Model prediction (p-value = 7 %)

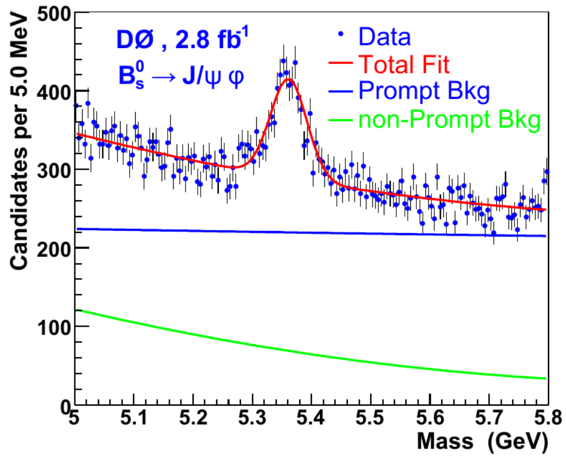
[CDF/ANAL/BOTTOM/PUBLIC 9458]

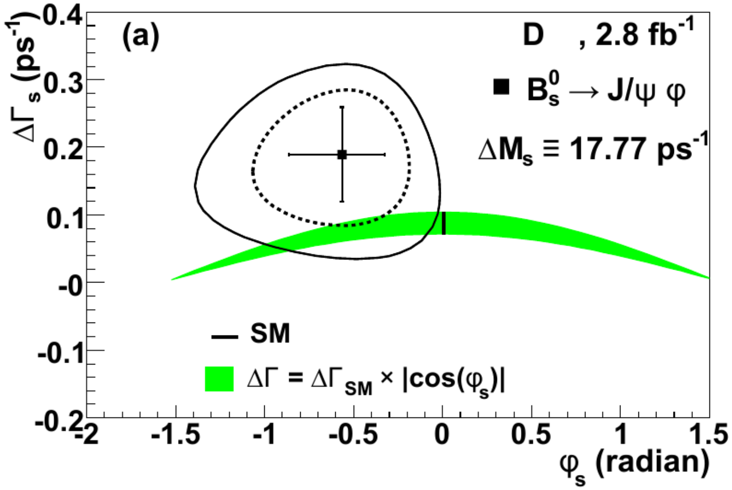
- note different convention: $\phi_s = -2\,\beta_s$
- note two-fold ambiguity: fit function invariant under transformation

$$(\phi_s,\ \Delta\Gamma_s,\ \delta_\parallel,\ \delta_\perp) \ \leftrightarrow\ (\pi-\phi_s,\ -\Delta\Gamma_s,\ 2\pi-\delta_\parallel,\ -\delta_\perp)$$

$B^0_s \to J/\psi\,\phi$: Tevatron 2008

DØ: ~ 2'000 signal events from 2.8 fb^{-1}

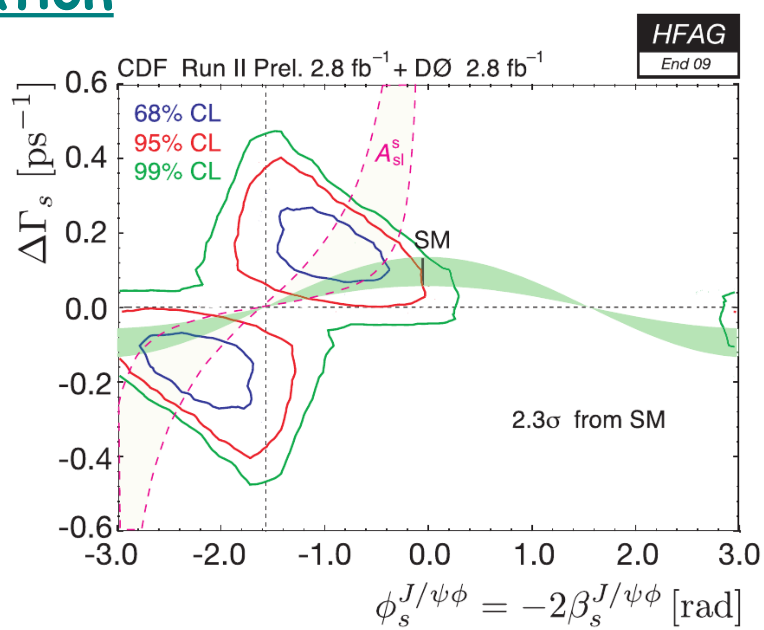




1.5 σ deviation from Standard Model prediction (p-value = 6.6 %)

[PRL 101 (2008) 241801]

CDF + D0 combination



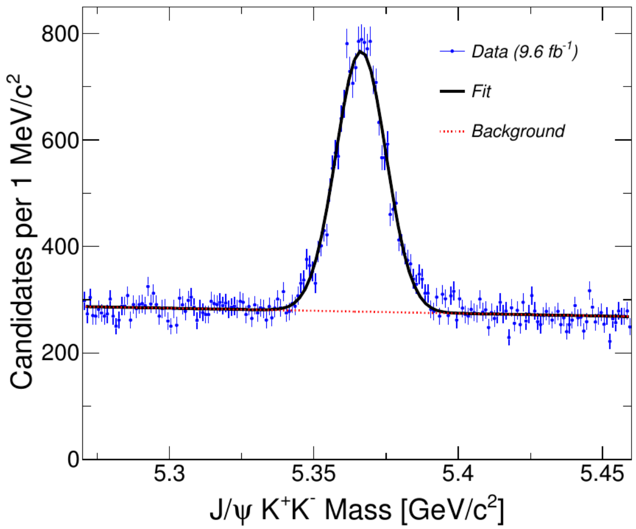
2.3 σ deviation from Standard Model prediction

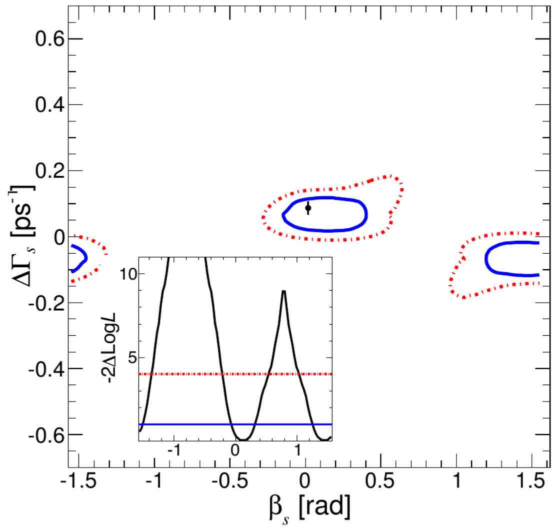
2.8 σ deviation when including D0 result for A^s_{sl}

[arXiv:1010.1589]

$B^0_s \to J/\psi\, \phi$: Tevatron 2012

CDF: ~11'000 signal events from 9.6 fb^{-1} (their full dataset)



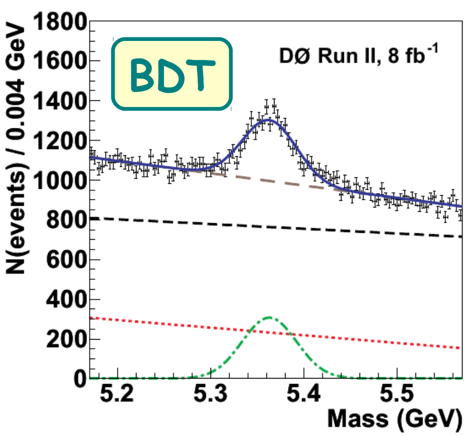


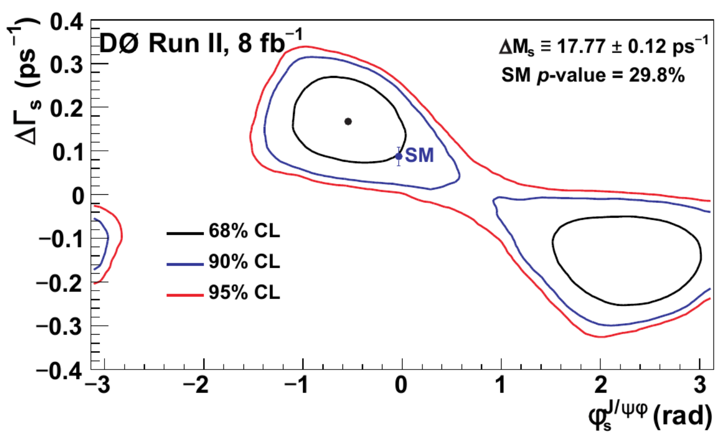
$-0.60 < \phi_s < 0.12$ @ 68% C.L.

$(\phi_s = -2\beta_s)$

[PRL 109 (2012) 171802]

DØ: ~ 5'600 signal events from 8.0 fb^{-1} (for BDT-based selection)





$\phi_s = -0.55^{+0.38}_{-0.36}$ @ 68% C.L.

[PRD 85 (2012) 032006]

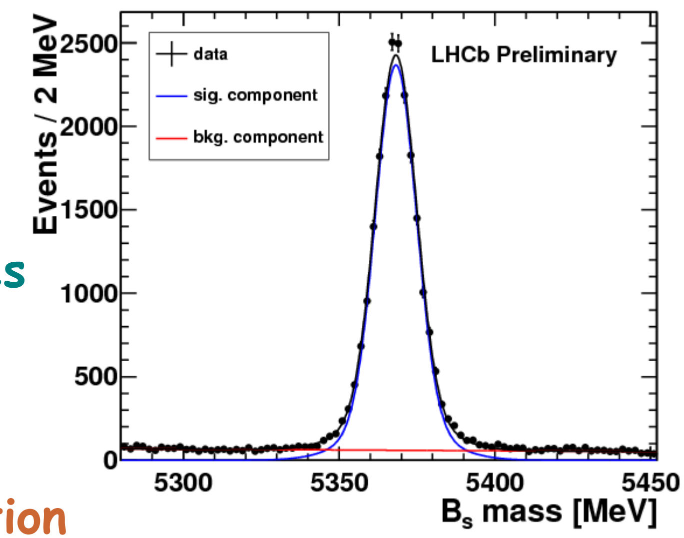
both compatible with Standard Model prediction

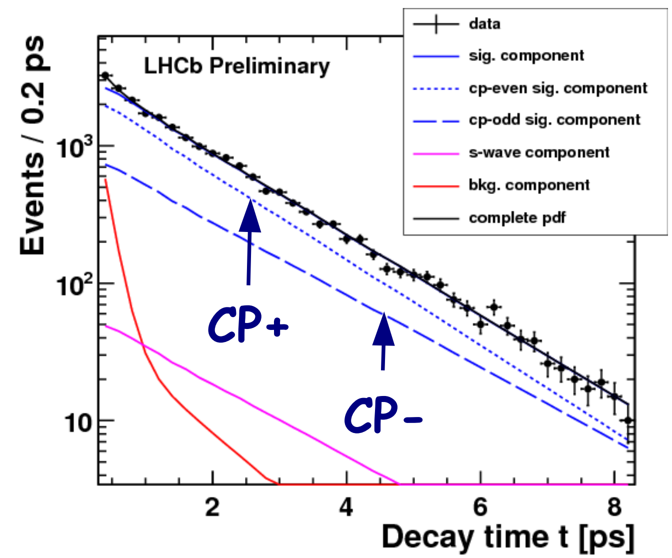
$B^0_s \to J/\psi\,\phi$: LHCb

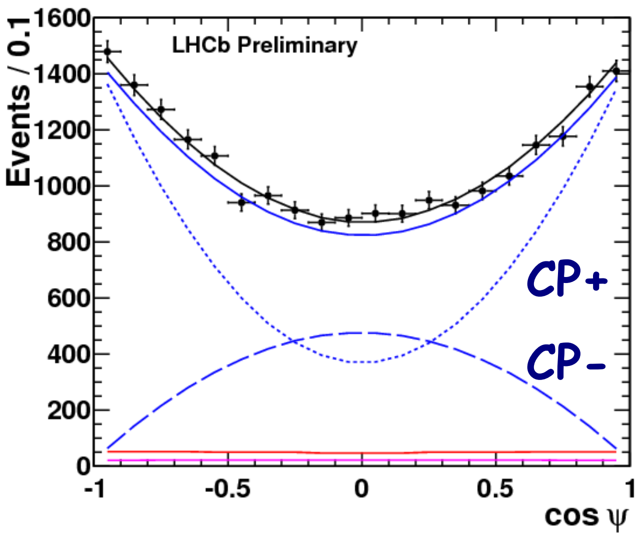
Analysis based on 1 fb^{-1} (2011 data set)

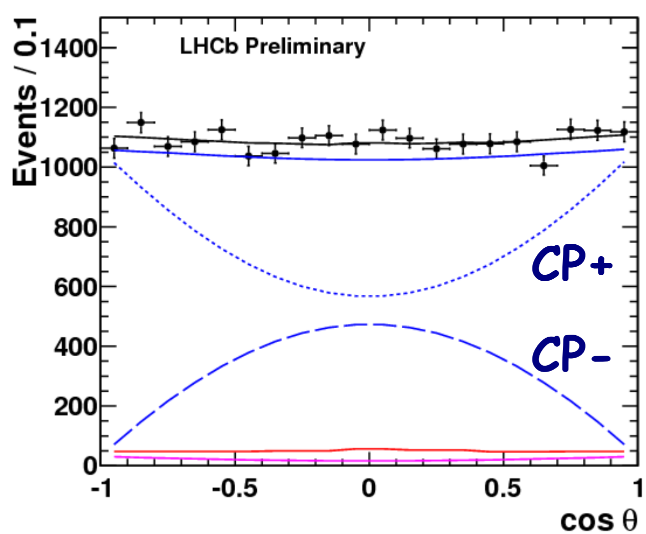
[LHCb-CONF-2012-002]
preliminary

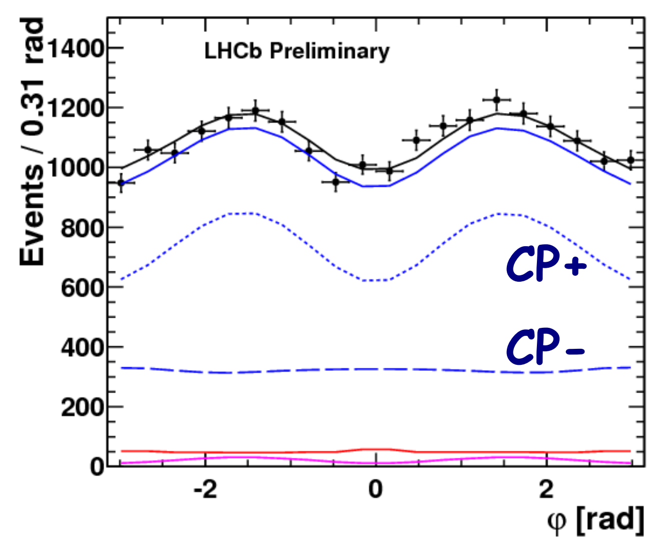
- ~ 21'000 signal events
  - 2 x CDF (!)
- only few % background
- angular fit cleanly separates CP even/odd components
- different B_H, B_L lifetimes clearly visible in fit projection







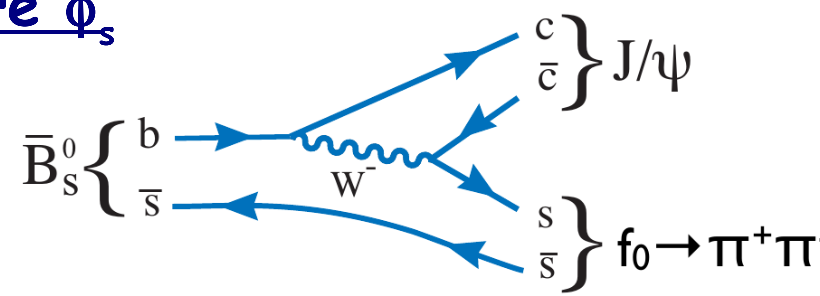




ϕ_s: LHCb

$B^0_s \to J/\psi\,\pi^+\pi^-$: another channel to measure ϕ_s

- lower branching fraction than $B^0_s \to J/\psi\,\phi$
  - 7400 candidates from 1.0 fb^{-1}
- but no angular analysis requried
  - dominated by $f_0(980) \to \pi^+\pi^-$ resonance
  - almost pure CP odd (>99.7 % @ 95% CL)



$$\phi_s = -0.019\,^{+0.173}_{-0.174}\,^{+0.004}_{-0.003}\ \text{rad}$$

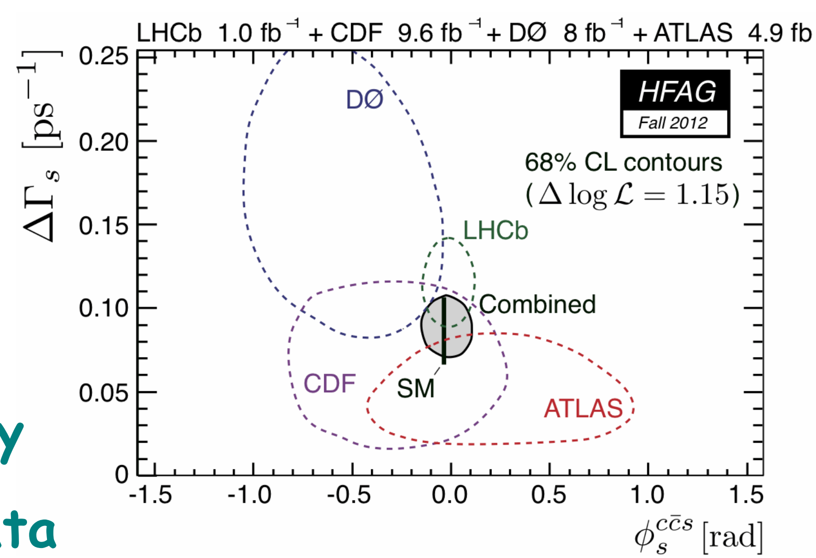
[PLB 713 (2012) 378]
[PRD 86 (2012) 052006]

Simultaneous LHCb fit of $B^0_s \to J/\psi\,\phi$ and $B^0_s \to J/\psi\,\pi^+\pi^-$

$$\phi_s = -0.002 \pm 0.083 \pm 0.027\ \text{rad}$$

[LHCb-CONF-2012-002] preliminary

- most precise measurement to date
- excellent agreement with Standard Model
- precision dominated by statistical uncertainty
- expect significant improvement with more data



LHCb: Sign of $\Delta\Gamma_s$

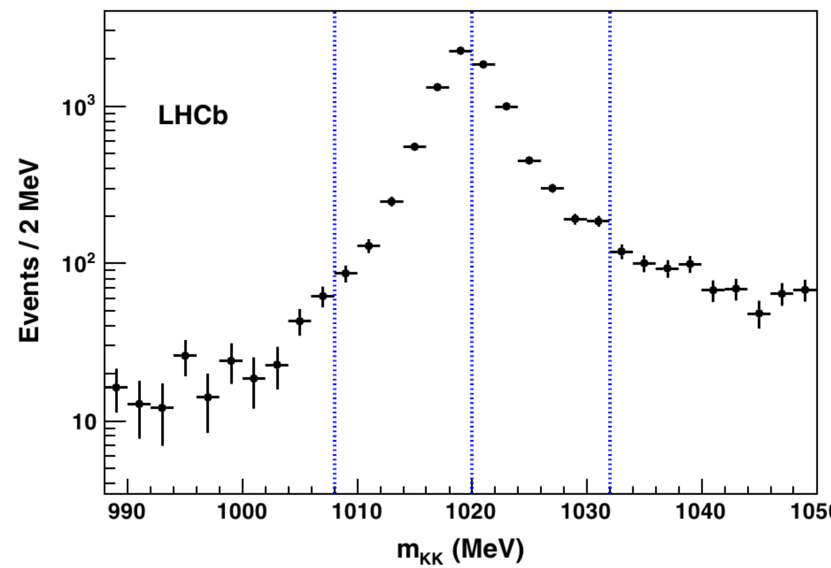
Resolve two-fold ambiguity in fit solution

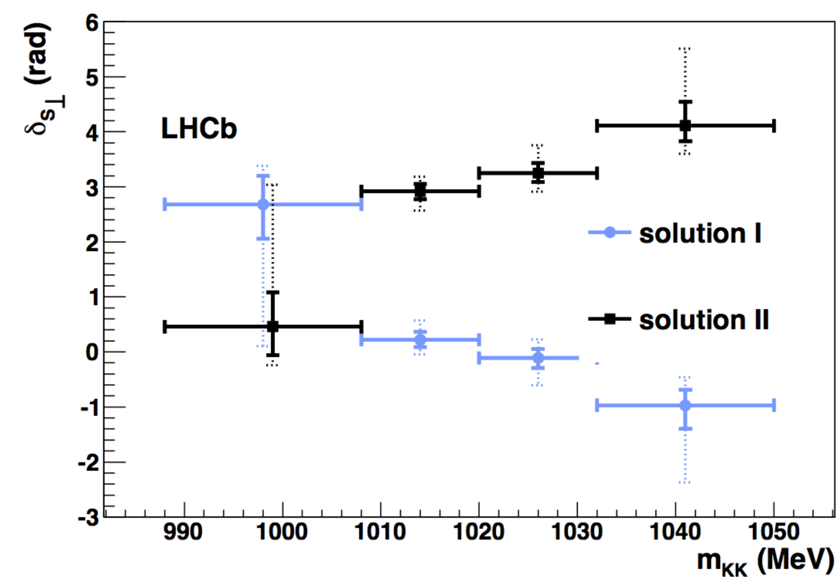
[PRL 108 (2012) 241801]

$$(\phi_s, \Delta\Gamma_s, \delta_\parallel, \delta_\perp) \leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, 2\pi-\delta_\parallel, -\delta_\perp)$$

("solution I") ("solution II")

- look at strong phase difference $\delta_{s\perp} = \delta_s - \delta_\perp$ between K^+K^- P-wave and S-wave amplitudes as a function of $m(K^+K^-)$ around the $\phi(1020)$
  - P-wave: going through $\phi(1020)$ resonance → expect rapid positive phase shift
  - S-wave: non-resonant + tail from $f_0(980)$ → expect no significant variation of phase
- LHCb analysis based on 0.37 fb^{-1}
  - determine $\delta_{s\perp}$ in four K^+K^- mass bins





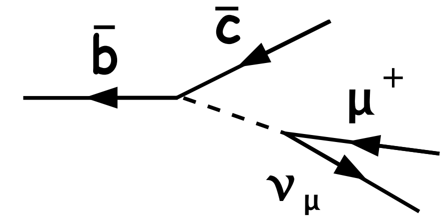
solution corresponding to $\Delta\Gamma_s > 0$ selected with 4.7 σ significance

Like-Sign Dimuon Asymmetry

Swiss Institute of Particle Physics

Compare numbers of $\mu^+\mu^+$ and $\mu^-\mu^-$ events from semileptonic B decays

- in collision produce $b\bar{b}$ pairs; $b \rightarrow \mu^- \bar{\nu}_\mu$ and $\bar{b} \rightarrow \mu^+ \nu_\mu$
  - observe $\mu^-\mu^-$ event $\rightarrow$ $B^0_{(s)}$ must have mixed
  - observe $\mu^+\mu^+$ event $\rightarrow$ $\bar{B}^0_{(s)}$ must have mixed



- observe different numbers of $\mu^-\mu^-$ and $\mu^+\mu^+$ events $\rightarrow$ CP violation in mixing

$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} - N_b^{--}} \approx 0.6 \cdot a^d_{sl} + 0.4 \cdot a^s_{sl}$$

hadronization fractions, mixing probabilities

with the semileptonic asymmetries:

$$a^d_{sl} = \frac{\Delta\Gamma_d}{\Delta m_d} \cdot \tan\phi_d \quad ; \quad a^s_{sl} = \frac{\Delta\Gamma_s}{\Delta m_s} \cdot \tan\phi_s$$

- CP violation in mixing expected to be very small
- Standard Model predictions:

$$a^d_{sl} = (-4.1 \pm 0.6) \times 10^{-4} \quad ; \quad a^s_{sl} = (-1.9 \pm 0.3) \times 10^{-5}$$

A. Lenz, [arXiv:1205.1444]

A^b_{sl}: D0

<u>Challenge: large backgrounds and $\mu^\pm$ asymmetries from other sources</u>

- largest source of background asymmetry: muons from kaons decays
  - K^+ ($u\bar{s}$) have smaller interaction cross section with matter than K^- ($\bar{u}s$)
  - K^+ have more time to decay in the detector volume → more μ^+ than μ^-
- other sources of backgrounds: pion decays, hadron punchthrough
- other sources of asymmetries: muon detection and identification efficiency

<u>D0 analysis using 9.0 fb</u>$^{-1}$ (full data sample) [PRD 84 (2011) 052007]

- basic idea: estimate and correct for background asymmetries from data using the measured charge asymmetry in large samples of inclusive muons

$$a \equiv \frac{n^+ - n^-}{n^+ - n^-}$$

$$A_{raw} = (+0.126 \pm 0.041)\ \%$$
$$a = (+0.688 \pm 0.002)\ \%$$

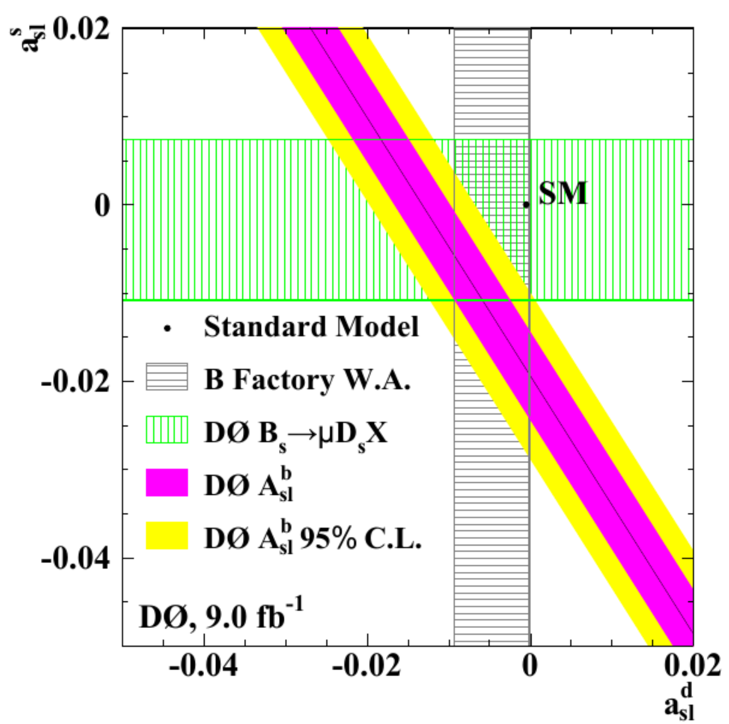
$$A^b_{sl} = (-0.787 \pm 0.172 \pm 0.093)\ \%$$

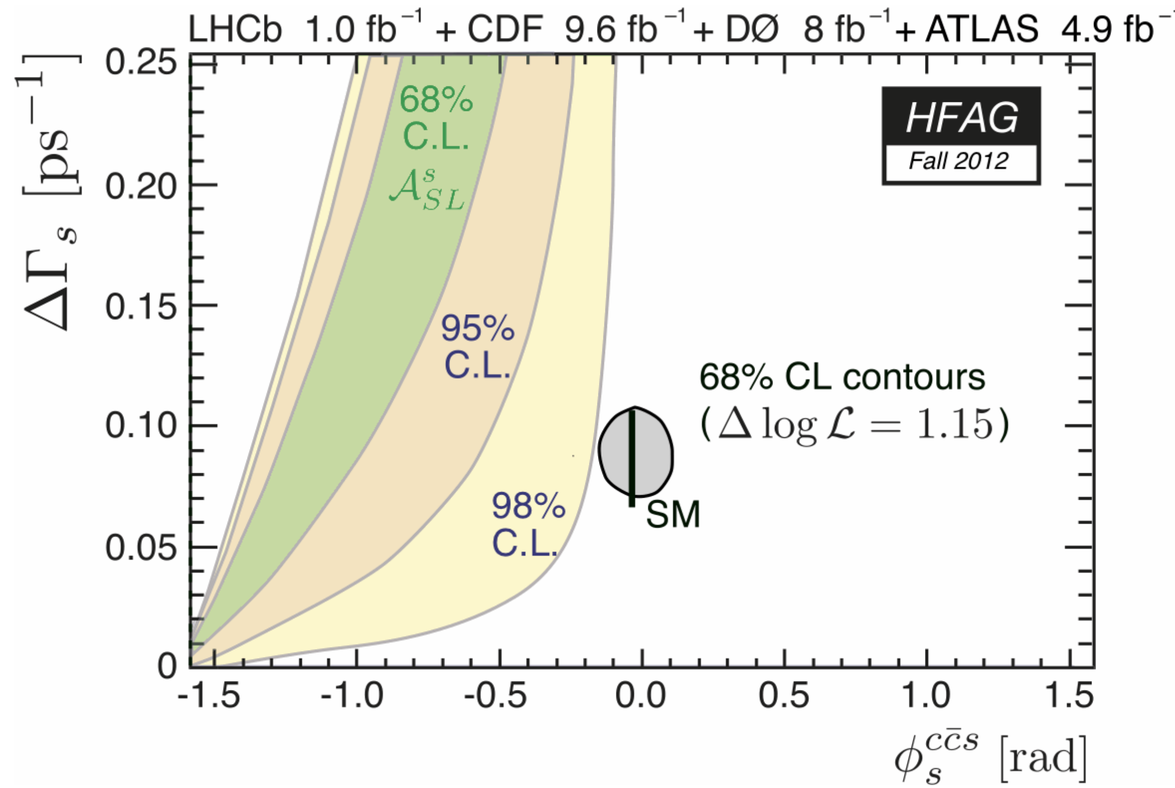
- very intricate analysis, large corrections, but also many cross checks

A^b_{ls}: D0 result

Measured asymmetry 34 times larger than Standard Model prediction

- 3.9 σ discrepancy
- tension also with value of ϕ_s measured in $B^0_s \to J/\psi\,\phi$ and $B^0_s \to J/\psi\,\pi^+\pi^-$



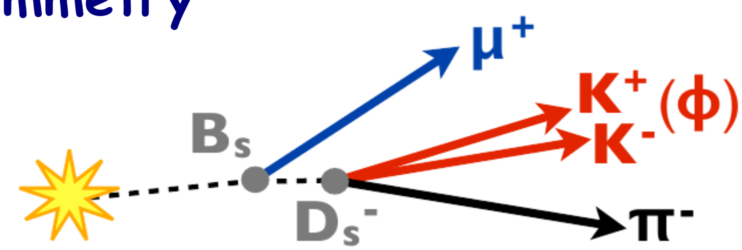


Semileptonic Asymmetry

LHC experiments cannot measure like-sign dimuon asymmetry

- large intrinsic charge asymmetry from pp collisions
- but LHCb can directly measure semileptonic asymmetry

$$a^s_{sl} = \frac{\Gamma\left(B^0_s \to D^-_s \mu^+ X\right) - \Gamma\left(\bar{B}^0_s \to D^+_s \mu^- X\right)}{\Gamma\left(B^0_s \to D^-_s \mu^+ X\right) + \Gamma\left(\bar{B}^0_s \to D^+_s \mu^- X\right)}$$



- pp collisions give rise to $B^0_s \bar{B}^0_s$ production asymmetry $a_p \sim 1\ \%$
- but: a_p strongly diluted by very rapid B^0_s-$\bar{B}^0_s$ oscillations

$$A_{raw} = \frac{N\left(D^-_s \mu^+\right) - N\left(D^+_s \mu^-\right)}{N\left(D^-_s \mu^+\right) + N\left(D^+_s \mu^-\right)} = \frac{a^s_{sl}}{2} + \left[a_p - \frac{a^s_{sl}}{2}\right] \times \underbrace{\frac{\int e^{-\Gamma_s t} \cos\left(\Delta m_s t\right) \varepsilon(t) dt}{\int e^{-\Gamma_s t} \cosh\left(\Delta \Gamma_s t/2\right) \varepsilon(t) dt}}_{= 2 \times 10^{-3} \text{ for LHCb}}$$

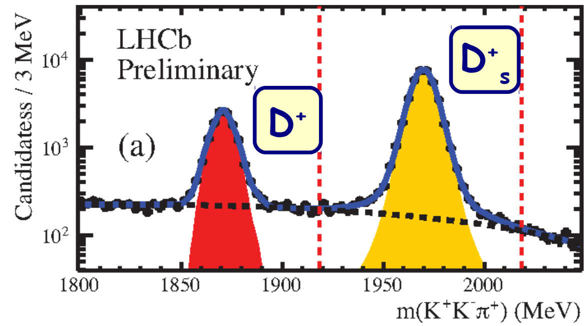
($\varepsilon(t)$ = decay time acceptance)

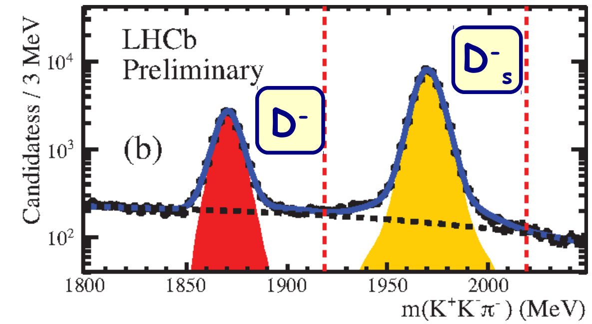
a^s_{sl}: LHCb

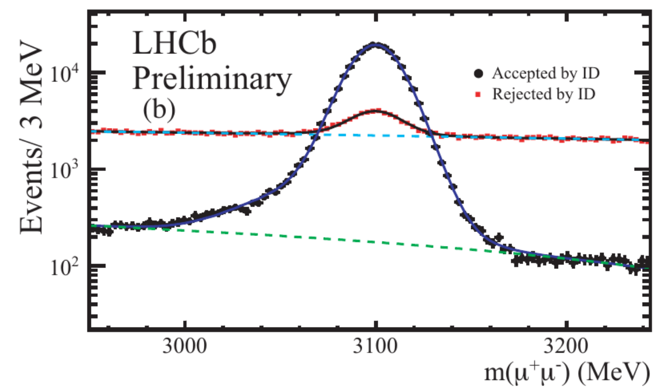
Analysis of 1.0 fb^{-1} (2011 data set)

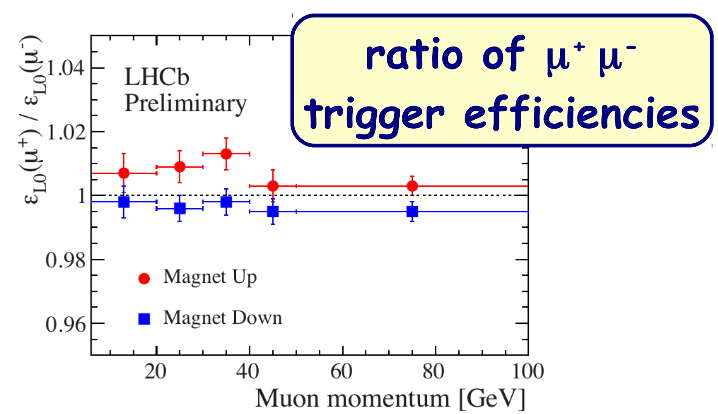
[LHCb-CONF-2012-022]
preliminary

- **clean signals, 193k events, very low backgrounds**
- **detection efficiencies determined from data using various control channels**
- **most critical: possible charge asymmetry in muon trigger and muon identification**
- **studied using large samples of $J/\psi \to \mu^+ \mu^-$**
  - kinematically reconstructed without applying muon identification criteria
  - from events selected by hadron trigger





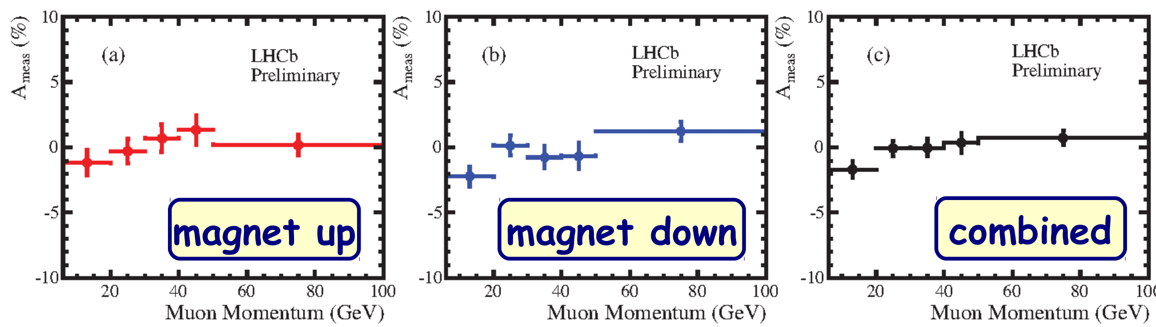




a^s_{sl}: LHCb

Valuable cross check (for many LHCb analyses)

- polarity of LHCb dipole magnet reversed every few weeks
- look at results separately for the two data samples taken with opposite magnet polarity

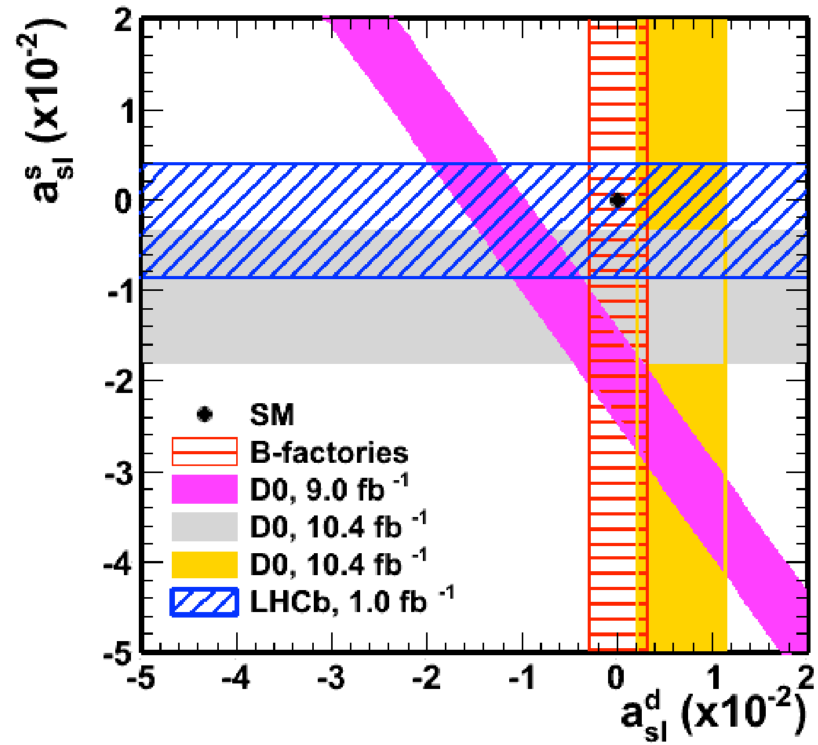


Result

$$a^s_{sl} = (-0.24 \pm 0.54 \pm 0.33)\,\%$$

[LHCb-CONF-2012-022] preliminary

- most precise measurement to date
- consistent with Standard Model
- all measurements of a^s_{sl}, a^d_{sl} compatible with each other at < 2 σ level



Outline

- **Part I: Introduction**
  - what is (quark) flavour physics and why is it so exciting?
  - how we got here: brief history of flavour physics in the 20^{th} century

- Part II: Particle-Antiparticle Mixing
  - a little bit of phenomenology (don't worry, I'm an experimentalist …)
  - introduce experimental facilities and techniques

- **Part III: Precision tests of the Standard Model**
  - CP violating observables: sin 2β, CKM angle γ, $B^0_s\overline{B}^0_s$ mixing phase ϕ_s
  - **rare decays**: search for $B^0_{(s)} \rightarrow \mu^+ \mu^-$, angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Rare Decays

b → s(d) transitions, mediated by Flavour Changing Neutral Currents

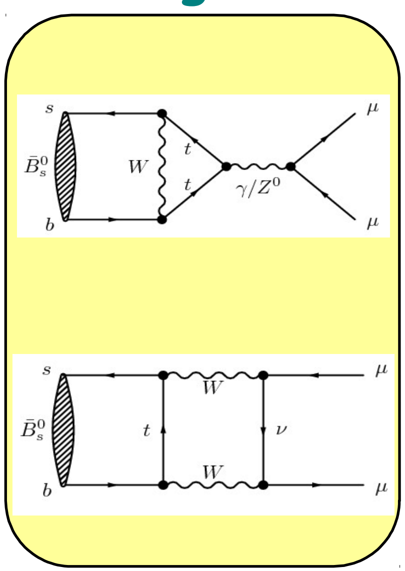
- ideal hunting ground for New Physics

can proceed only via loop processes → suppressed in the Standard Model

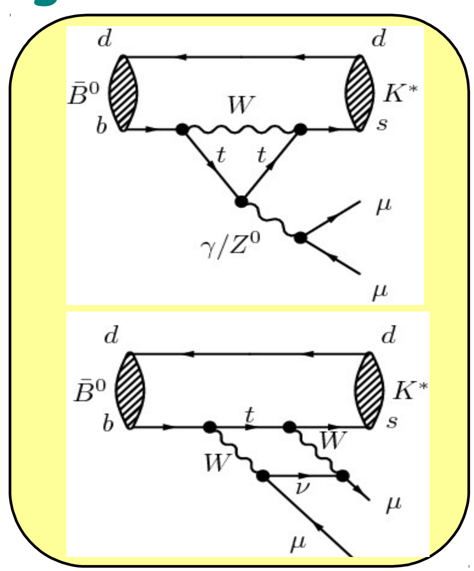
↓ new particles can enter in the loops → New Physics can appear at the same order as Standard Model

Most prominent examples

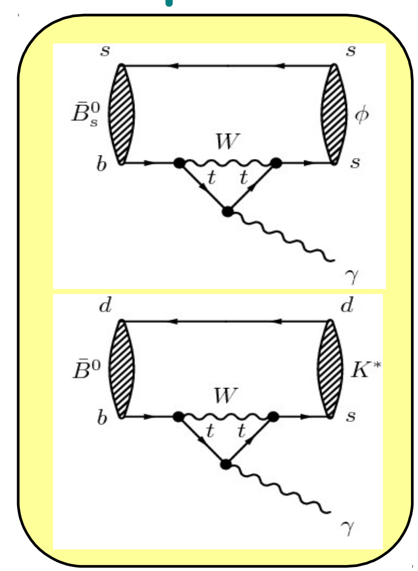
$B^0_{(s)} \to \mu^+ \mu^-$
branching fraction



$B^0 \to K^{0*} \mu^+ \mu^-$
angular distributions



$B^0 \to K^{0*} \gamma$ and $B^0_s \to \phi \gamma$
photon polarization



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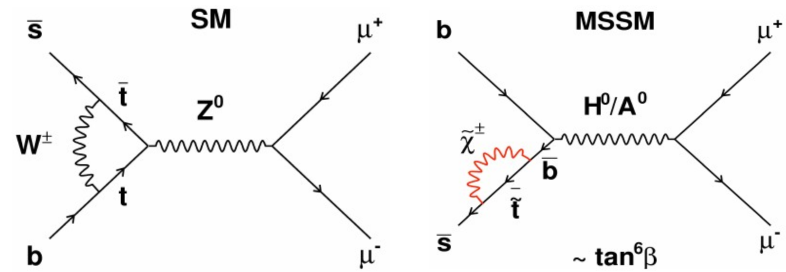
Rare Decays: $B^0_{(s)} \rightarrow \mu^+ \mu^-$

$B^0_s \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$ very rare in the Standard Model



- GIM suppression and helicity suppression
- predicted branching fractions:

$$BF\left(B^0_s \rightarrow \mu^+\mu^-\right) = \left(3.23 \pm 0.27\right) \times 10^{-9}$$

$$BF\left(B^0 \rightarrow \mu^+\mu^-\right) = \left(1.07 \pm 0.10\right) \times 10^{-10}$$

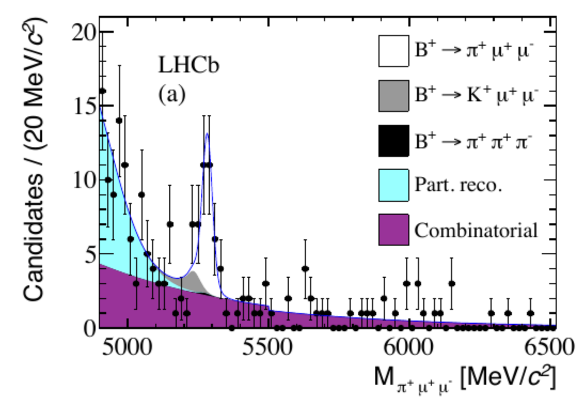
A. Buras et al., [EPJ C72 (2012) 2172]

- sensitive to contributions from scalar and pseudo-scalar sector
  - interesting probe for New Physics with extended Higgs sector
  - e.g. in MSSM, branching fraction scales approximately as $\tan^6\beta \,/\, M_A^{\,4}$

- compare: rarest B decay observed so far (> 5 σ significance)

$$BF\left(B^+ \rightarrow \pi^+ \mu^+ \mu^-\right) = \left(2.3 \pm 0.6 \pm 0.1\right) \times 10^{-8}$$

LHCb, [JHEP 1212 (2012) 125]

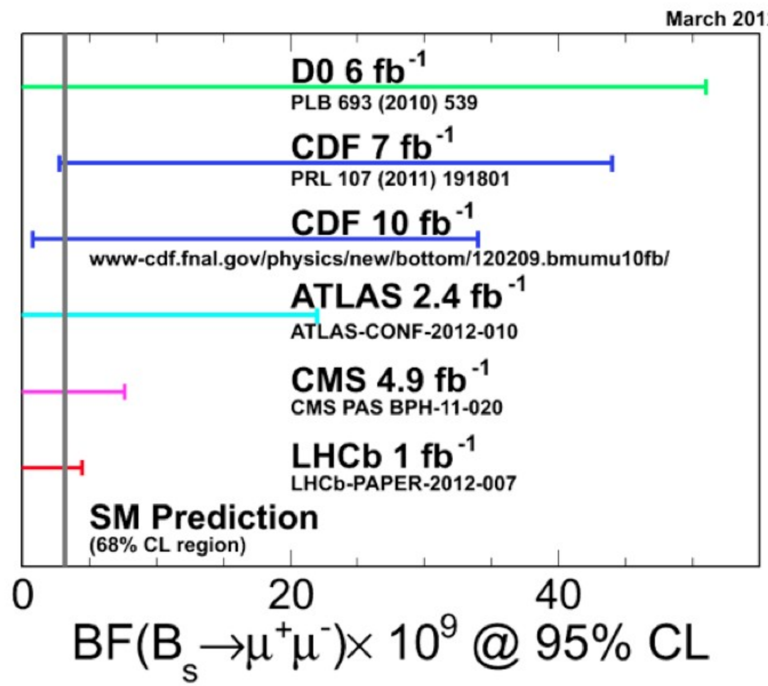


Rare Decays: $B^0_s \to \mu^+ \mu^-$

Searches at Tevatron and LHC

- key features: statistics, mass resolution

	ATLAS	CMS	LHCb
Luminosity	2.4 fb^{-1}	4.9 fb^{-1}	1.0 fb^{-1}
$p^{\mu}_{T,min}$	4 GeV	4 GeV	1.5 GeV
Mass window	± 130 MeV	± 75 MeV	± 60 MeV



- LHC combination, June 2012:

$$BF\,(B^0_s \to \mu^+\mu^-) < 4.2 \times 10^{-9} \text{ @ 95\% C.L.}$$

[LHCb-CONF-2012-017]

Subtlety when comparing with Standard Model prediction

- measure time-integrated BF but theoretical prediction evaluated for t = 0
  - the two are not equal since $\Delta\Gamma_s \neq 0$
- "corrected" Standard Model prediction:

$$BF\,(B^0_s \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$$

K. De Bruyn et al., [PRD 86 (2012) 014027]

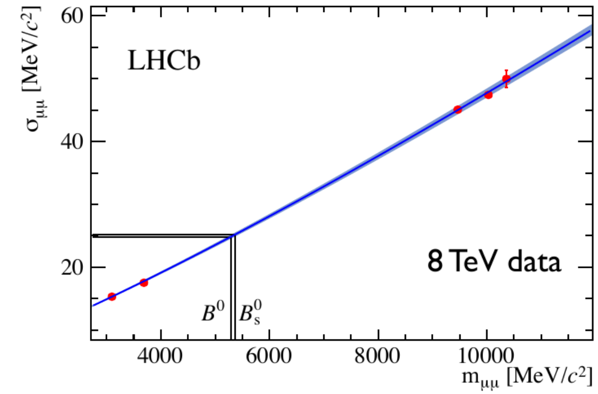
e.g. BF ($K^0 \to \pi^+ \pi^-$):
~ 100 % for t = 0
~ 50 % time-integrated

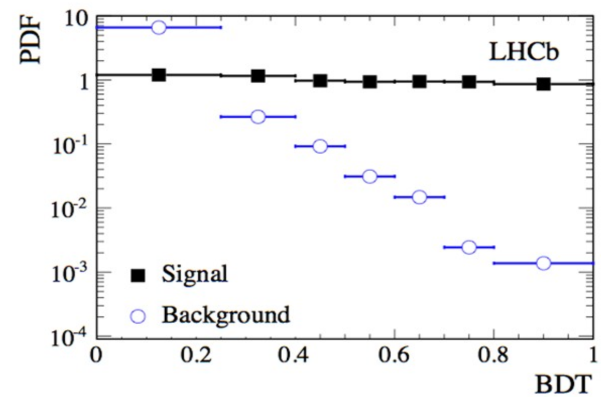
$B^0_s \rightarrow \mu^+ \mu^-$: LHCb

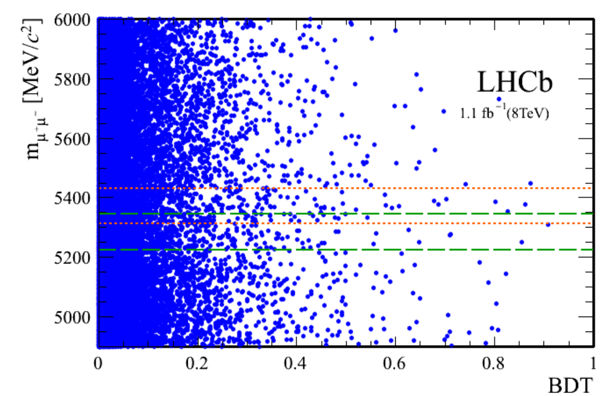
[PRL 110 (2013) 021801]

LHCb analysis of 2.1 fb^{-1} (2011 + 50% of 2012 sample)

- **signal/background discrimination based on:**
- **$\mu^+\mu^-$ invariant mass**
  - peak positions calibrated using samples of $B^0 \rightarrow \pi^+\pi^-$, $B^0_{(s)} \rightarrow K\pi$, $B^0_{(s)} \rightarrow K^+K^-$
  - resolution from interpolation between $J/\psi(ns) \rightarrow \mu^+\mu^-$ and $\Upsilon(ns) \rightarrow \mu^+\mu^-$
- **BDT classifier, combining 9 topological variables**
  - B decay vertex, impact parameters, …
  - selected to avoid correlation with mass
  - trained on simulated event samples
  - calibrated an data using of $B \rightarrow h^+h'^-$ (signal) and invariant mass side bands (background)







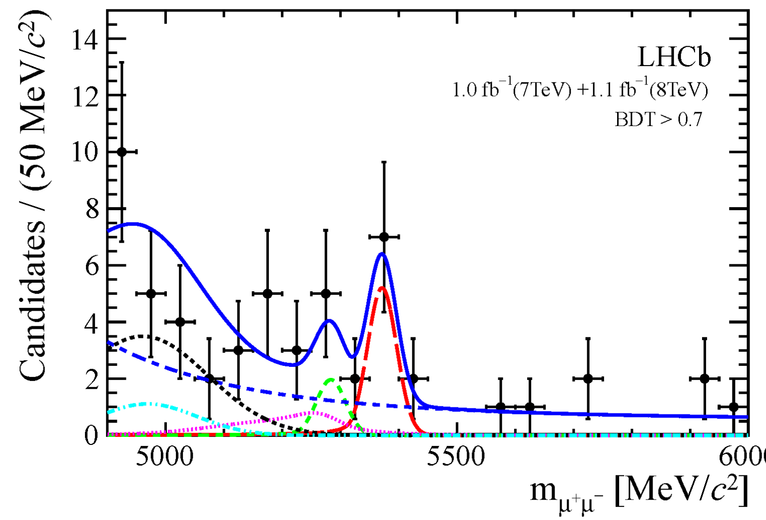
$B^0_{(s)} \to \mu^+ \mu^-$: LHCb

First evidence for $B^0_s \to \mu^+ \mu^-$

[PRL 110 (2013) 021801]

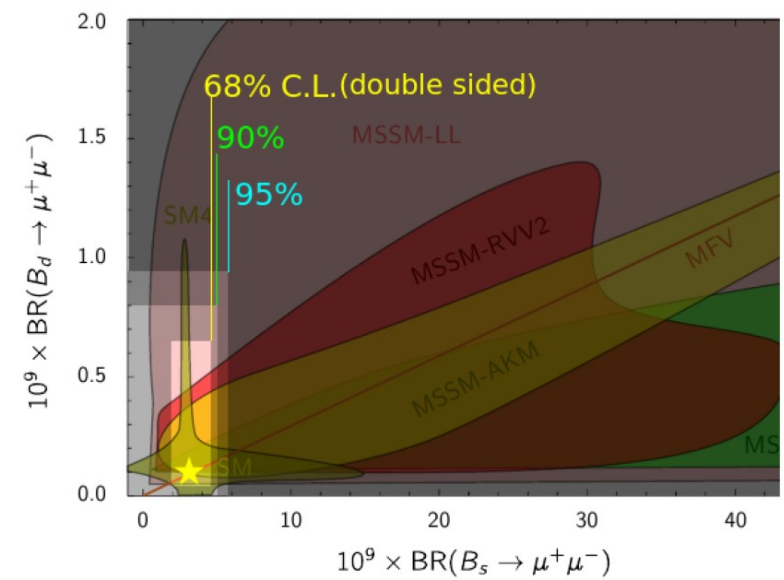
- observe 3.5 σ excess over background-only hypothesis (p-value = 5.3×10^{-4})
- branching fraction normalized to
  - $B^\pm \to J/\psi\ K^\pm$ (similar trigger but extra track)
  - $B^0 \to K^+ \pi^-$ (different trigger, same # tracks)
  - normalisation factors agree

$$\mathrm{BF}\left(B^0_s \to \mu^+\mu^-\right) = \left(3.2\,^{+1.4}_{-1.2}\,^{+0.5}_{-0.3}\right) \times 10^{-9}$$



- also improved upper limit on $B^0 \to \mu^+ \mu^-$

$$\mathrm{BF}\left(B^0 \to \mu^+\mu^-\right) < 9.4 \times 10^{-10}\ \text{@ 95\% C.L.}$$



- results compatible with Standard Model, put stringent constraints on New Physics scenarios

using M.Straub, [arXiv:1205.6094]

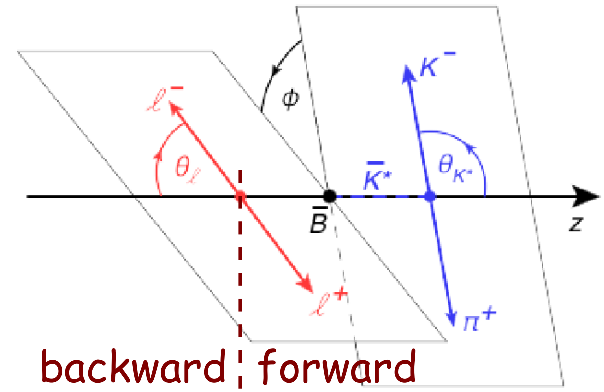
Outline

- **Part I: Introduction**
  - what is (quark) flavour physics and why is it so exciting?
  - how we got here: brief history of flavour physics in the 20^{th} century
- Part II: Particle-Antiparticle Mixing
  - a little bit of phenomenology (don't worry, I'm an experimentalist …)
  - introduce experimental facilities and techniques
- **Part III: Precision tests of the Standard Model**
  - CP violating observables: sin 2β, CKM angle γ, $B^0_s\overline{B}^0_s$ mixing phase ϕ_s
  - **rare decays:** search for $B^0_{(s)} \to \mu^+ \mu^-$, **angular observables in $B^0 \to K^{*0} \mu^+ \mu^-$**

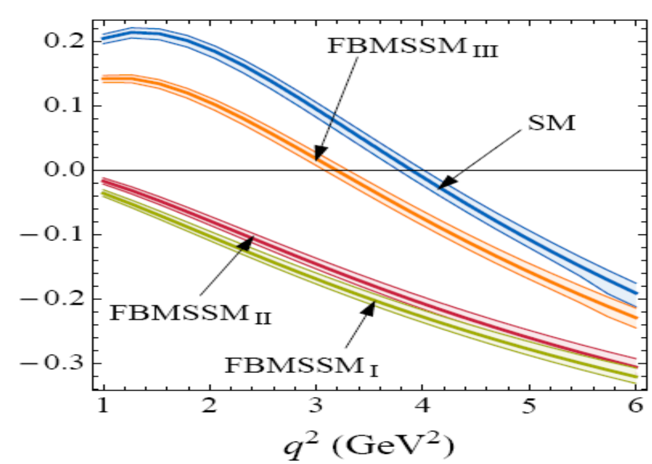
Rare Decays: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Angular distributions sensitive to contributions from New Physics

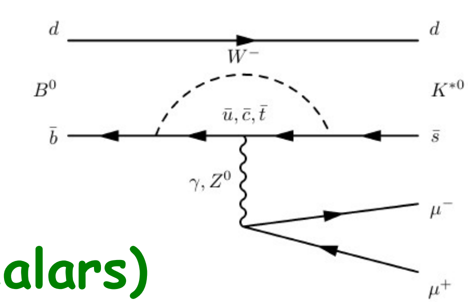
- decay can be fully described by three angles (θ_ℓ, θ_K, ϕ) and $q^2 = m^2(\mu^+\mu^-)$
- differential cross section as a function of these angles gives rise to eight independent observables for which precise predictions can be made as a function of q^2
- prominent example: A_{FB} = forward-backward asymmetry of the muon in the B^0 rest frame
  - Standard Model predicts zero-crossing of A_{FB} at a well defined point in q^2
- sensitive to New Physics contributions that affect the helicity structure of the decay (e.g. new scalars, pseudo-scalars)

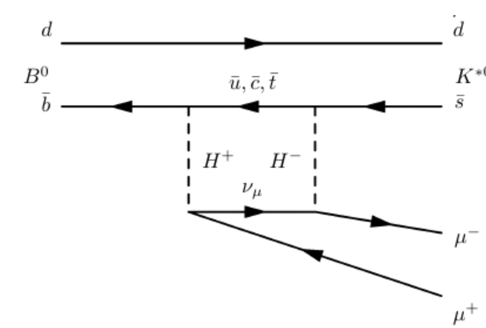


+ c.c.



W.Altmannshofer et al. [JHEP 0901 (2009) 019]





$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: A_{FB}

First measurements at B factories and CDF

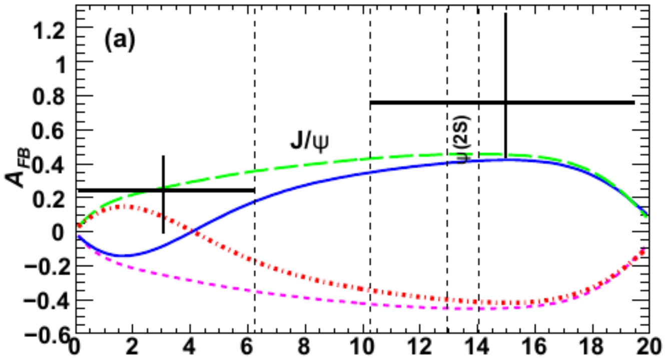
- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ is a rare decay, but not too rare: $BF = (1.05\,^{+0.16}_{-0.13}) \times 10^{-6}$ [PDG]

Babar:

384×10^6 $\Upsilon(4s) \rightarrow B\bar{B}$ decays

64 signal events

[PRD 79 (2009) 031102]

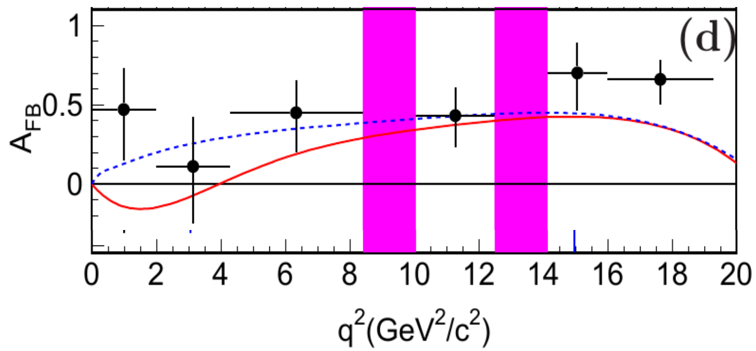


Belle:

657×10^6 $\Upsilon(4s) \rightarrow B\bar{B}$ decays

244 signal events

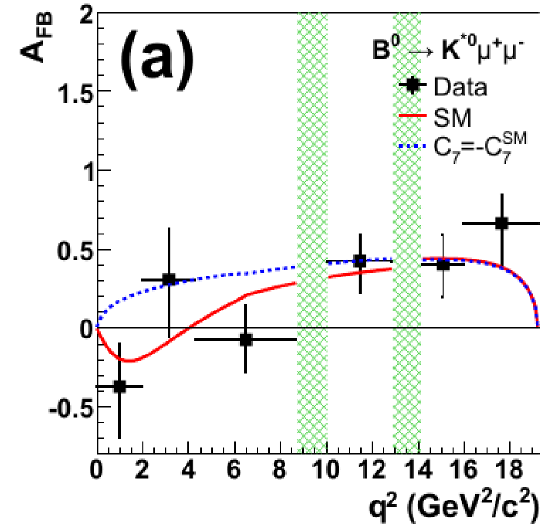
[PRL 103 (2009) 171801]



CDF: 6.8 fb^{-1}

164 signal events

[PRL 108 (2012) 081807]



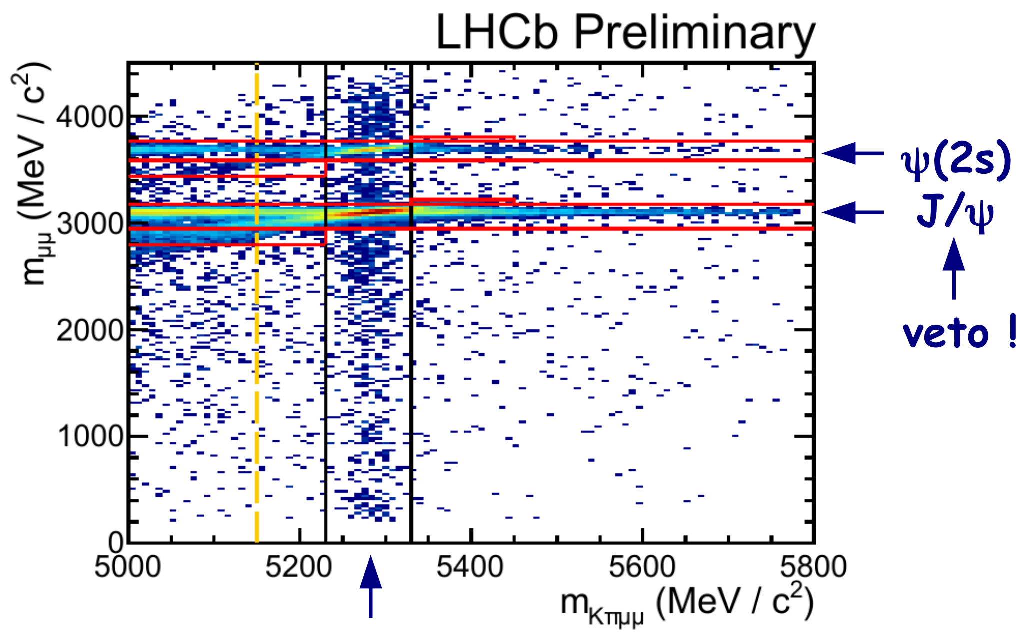
- hint for deviation from Standard Model prediction (solid lines) at low q^2?
  - Belle: A_{FB} exceeds Standard Model expectation by 2.7 σ
- but statistics limited, measurement uncertainties still large

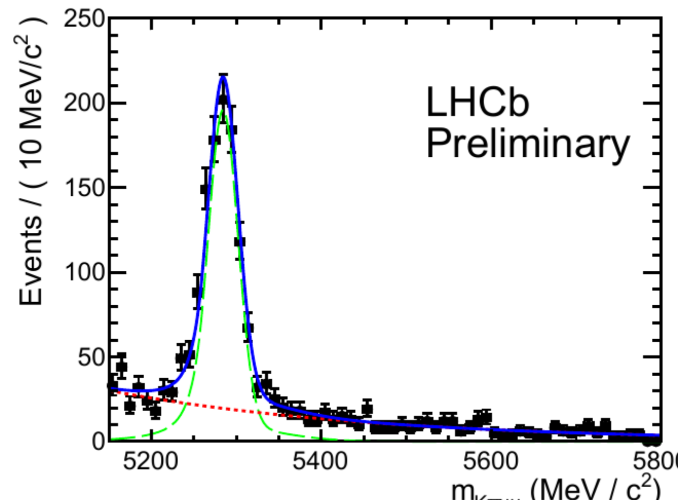
$B^0 \rightarrow K^{*0}\mu^+\mu^-$: LHCb

<u>900 signal events from 1 fb^{-1}</u> (2011 data set)

[LHCb-CONF-2012-008]
preliminary

- event selection: BDT using track quality criteria, kinematic and topological event properties,
- have to veto $\mu^+\mu^-$ mass windows around J/ψ and $\psi(2s)$ to suppress irreducible backgrounds from $B^0 \rightarrow K^{*0} J/\psi$ and $B^0 \rightarrow K^{*0}\psi(2s)$
- large sample of $B^0 \rightarrow K^{*0} J/\psi\ (\mu^+\mu^-)$ used to train BTD, also ideal control sample to study acceptance effects on the angular distributions





"every disadvantage has its advantage"
(Johan Cruijff, footballing philosopher)

$B^0 \to K^{*0}\,\mu^+\,\mu^-$: LHCb

"Folding technique"

- differential cross section as a function of (θ_ℓ, θ_K, ϕ, q^2)

$$
\begin{aligned}
\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} \propto\; & I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + \left(I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K\right)\cos 2\theta_\ell \\
& + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi \\
& + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi \\
& + \left(I_6^s \sin^2\theta_K + I_6^c \cos^2\theta_K\right)\cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi \\
& + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi
\end{aligned}
$$

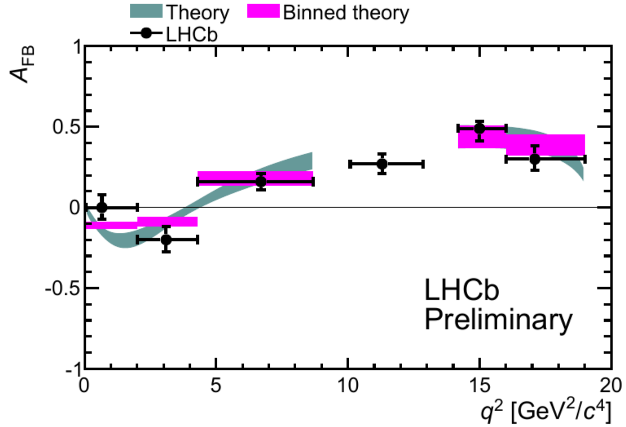
- $I_i = I_i\,(q^2)$; the observables we want to extract are combinations of these I_i
- event sample not (yet) large enough to fit all observables simultaneously
  - reduce number of fit parameters by integrating over some of the angles
  - better: apply "folding technique" exploiting symmetry of sin/cos functions
    - e.g. replacing ϕ by $\phi + \pi$ for $\phi < 0$ cancels all terms with I_4, I_5, I_7, I_8
    - four observables remain (one of them A_{FB}) → fit these simultaneously

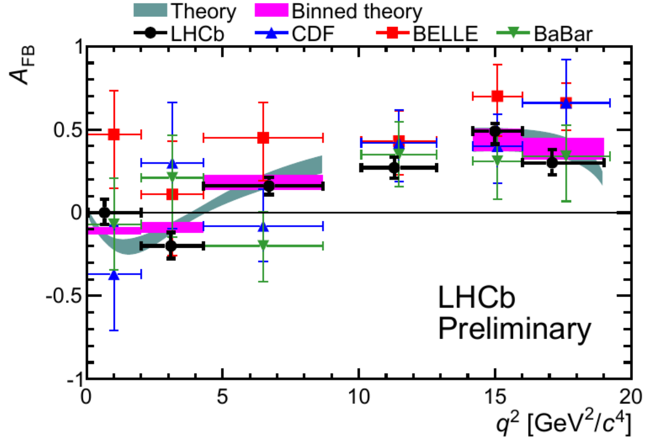
$B^0 \to K^{*0} \mu^+ \mu^-$: LHCb

LHCb: results (from 1 fb^{-1})

[LHCb-CONF-2012-008] preliminary

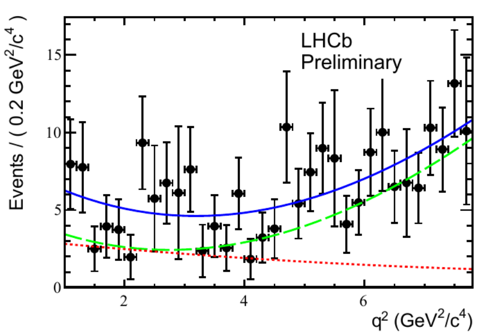
- all observables in good agreement with Standard Model prediction
- also compatible with previous experiments

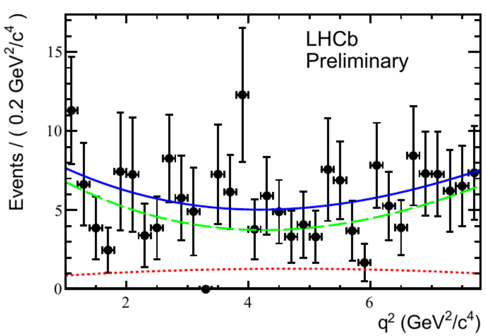


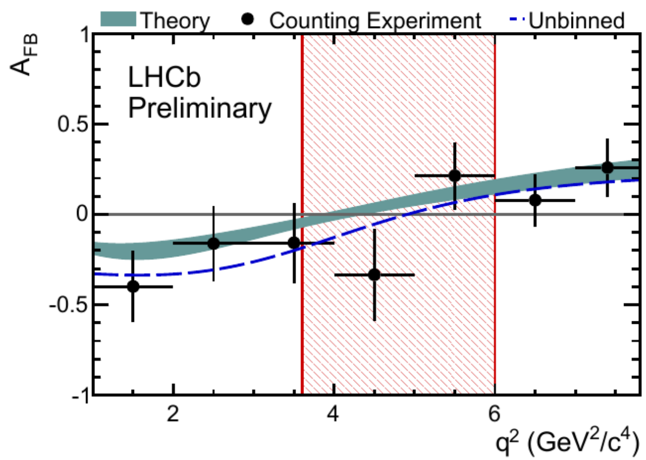


Also: first extraction of the zero crossing point of $A_{FB}(q^2)$

- separately fit event yields for forward-going and backward-going events as a function of q^2, then calculate the asymmetry
- again, result agrees with Standard Model







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Short Appendix: Outlook

- Part III: Precision tests of the Standard Model
  - CP violating observables: sin 2β, CKM angle γ, $B^0_s\overline{B}^0_s$ mixing phase ϕ_s
  - rare decays: search for $B^0_{(s)} \to \mu^+\mu^-$, angular observables in $B^0 \to K^{*0}\mu^+\mu^-$

Outlook: LHCb Upgrade

- LHC and LHCb are a spectacular success
- and so is the Standard Model

  … at least so far
- current precision of measurements still leaves lots of room for sub-dominant contributions from New Physics
- almost all LHCb results are completely dominated by statistical uncertainties
- leading systematic uncertainties will also decrease with increasing statistics

NEED MORE STATISTICS
⇒
THE LHCb UPGRADE !

2010	0.037 fb^{-1} @ 7 TeV
2011	1 fb^{-1} @ 7 TeV
2012	2 fb^{-1} @ 8 TeV
2013 2014	LHC LS1
2015 2016 2017	5 fb^{-1} @ 13 TeV
2018 2019	LHC LS2, LHCb upgrade
2020 2021 2022	5 fb^{-1} per year

LHCb Upgrade

- goal: reach measurement precision that matches theory uncertainties

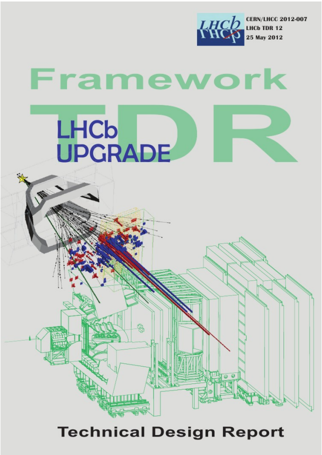
[CERN-LHCC-2012-007]

Type	Observable	Current precision	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s$ $(B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ $(B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ $(B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	γ $(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	β $(B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

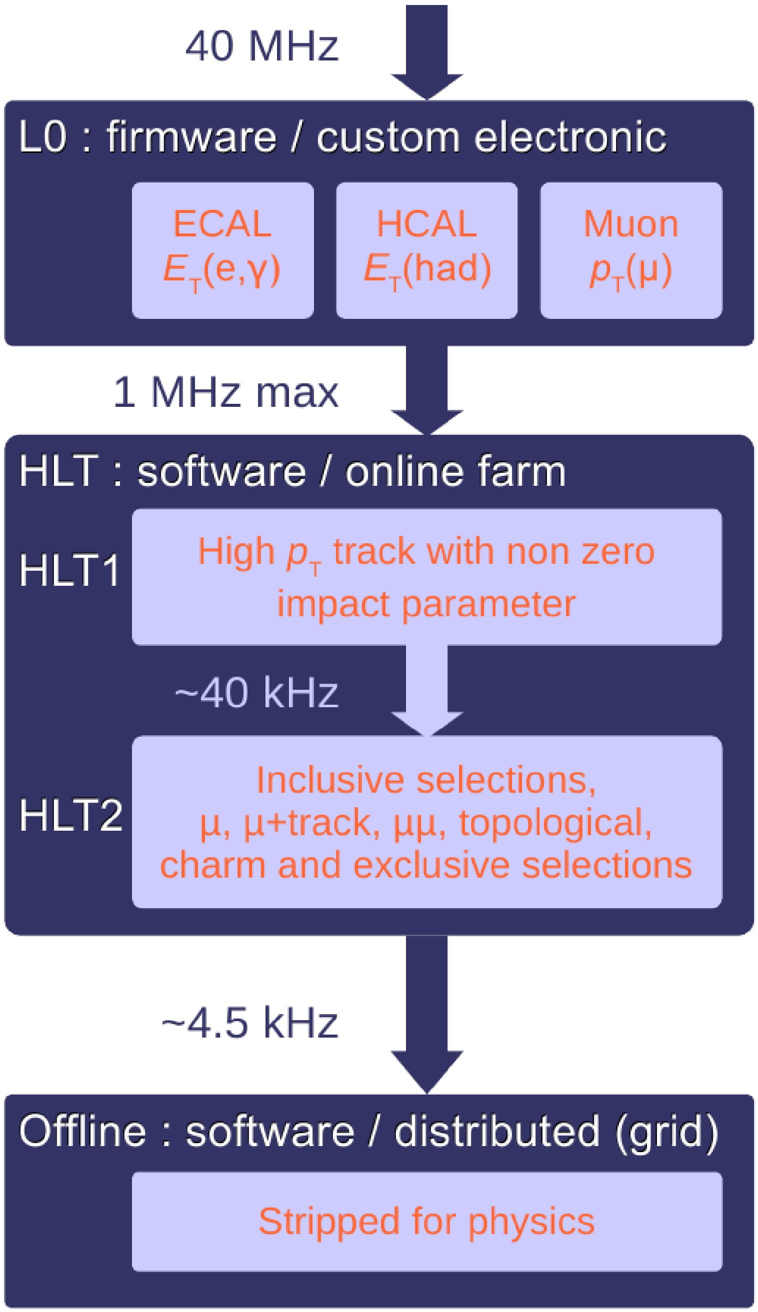
- two lines of attack
  - increase trigger efficiencies for hadronic final states
    - read out the full detector at the LHC bunch-crossing frequency
  - operate the detector at up to x 5 higher luminosity
    - new main tracker to cope with increase in particle densities

expected increase in rate (compared to 2011):
x 10 for channels involving final-state muons
x 20 for channels to fully hadronic final states

- details are described in
  - Letter of Intent [CERN-LHCC-2011-001]
  - Framework TDR [CERN-LHCC-2012-007]
- endorsed by the LHCC



Reminder: Current LHCb Trigger



Hardware level (L0):

- maximum output rate 1 MHz
- typical thresholds 2012:

  $E_T(e/\gamma) > 2.7$ GeV

  $E_T(h) > 3.6$ GeV

  $p_T(\mu) > 1.4$ GeV

Software level (HLT):

~ 30000 tasks in parallel on ~ 1500 nodes

Combined efficiency (L0+HLT):

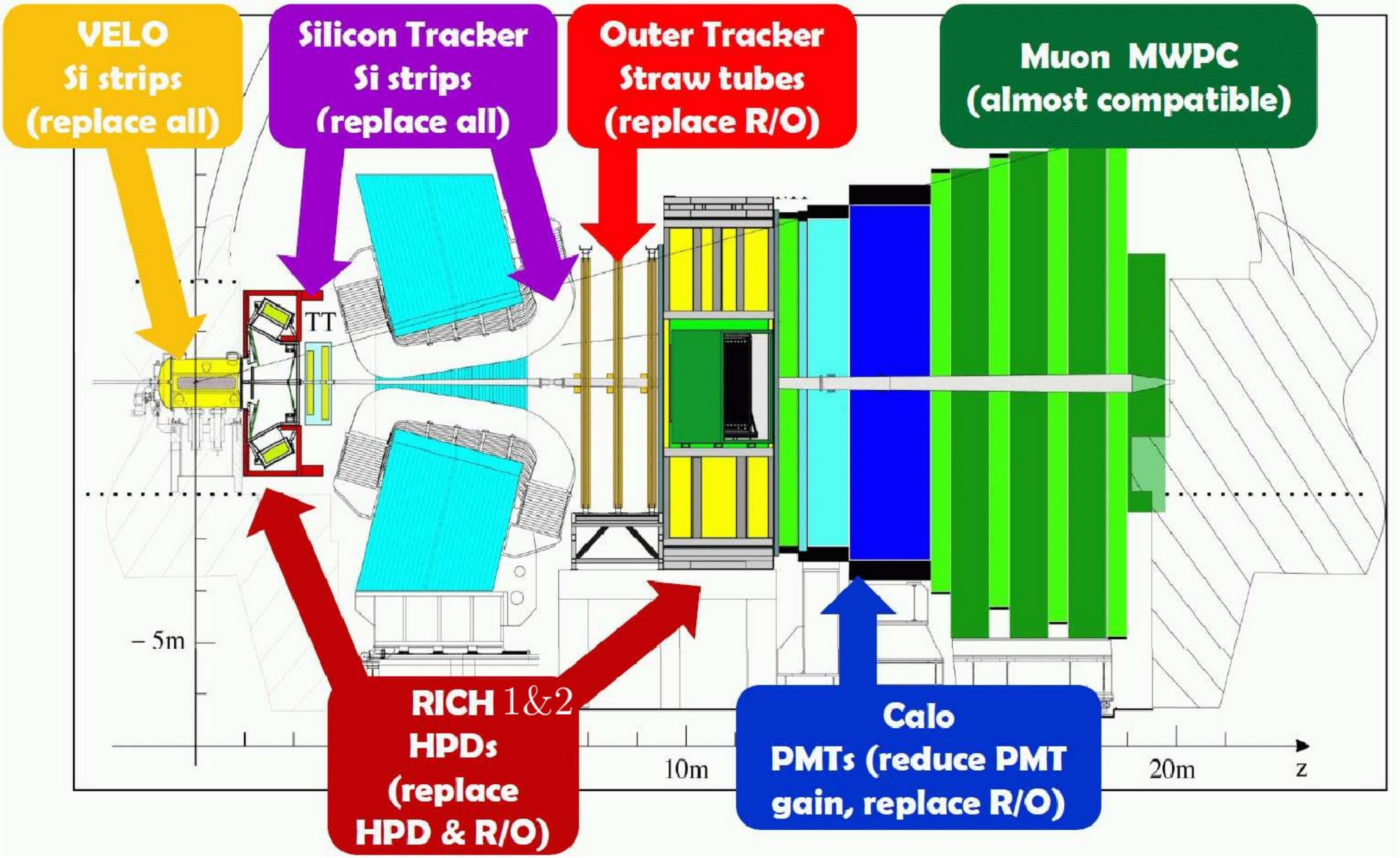
~ 90 % for di-muon channels

~ 30 % for multi-body hadronic final states

Offline processing:

~ 10^{10} events, 700 TB recorded per year

Upgrade



- **2012/2013: R&D, technology choices, preparation of sub-system TDRs**
- **2014: funding, procurements**
- **2015-2019: construction and installation**