Lecture 12, 20.02.2019

Systematic Uncertainties: The NA48 Experiment at CERN

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FROM MGA TO NUST MISIS 100 YEARS 1918-2018 OPENING A NEW CENTURY

MISIS National University of Science and Technology

SHiP Search for Hidden Particles

LHCb

University of Zurich UZH

Olaf Steinkamp

Born in Bremen (Germany)

Studied physics in Bonn (D)

PhD thesis work at CERN (GE)

1st PostDoc at CEA Saclay (F)

NA48 experiment at CERN

2nd PostDoc at NIKHEF Amsterdam (NL)

HERA-B experiment at DESY (Hamburg)

Since 2000 at University of Zurich:

LHCb experiment at CERN (new: also Mu3e at PSI)

Lectures on data analysis & experimental techniques

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CP Violation

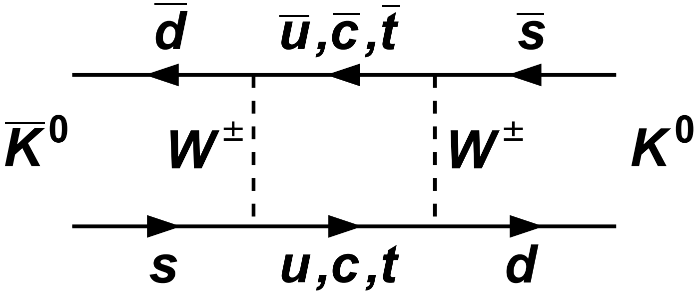
- **Charge conjugation *C*: $q \rightarrow -q$ for all charge-like quantum numbers**
- **Parity *P*: $(x,y,z) \rightarrow (-x,-y,-z)$**
- **Time reversal *T*: $t \rightarrow -t$**
- **all three conserved in strong and electromagnetic interactions**
- ***C* and *P* maximally violated in weak interactions**
  - predicted in 1950 (Nobel 1957)
  - first observed in 1953 in decays of polarized ^{60}Co nuclei

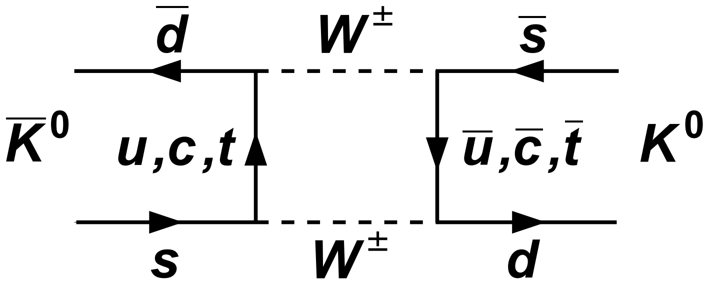
$$\begin{tikzcd}
\nu_L \arrow[r, "P"] \arrow[d, "C"'] \arrow[dr, "CP"] & \cancel{\nu_R} \arrow[d] \\
\cancel{\bar{\nu}_L} \arrow[r] & \bar{\nu}_R
\end{tikzcd}$$

- ***violation of combined symmetry CP in weak interactions***
  - discovered 1964 in K^0 decays (Nobel 1980)
  - explained by a single complex phase in 3×3 CKM matrix (Nobel 2008)

Neutral Kaon System

Transitions $K^0 \leftrightarrow \bar{K}^0$ through exchange of two *W* bosons ("box diagrams")





- **K^0 (or $\bar{K}^0$) produced at time $t = 0$ will evolve into a mixed state at time $t > 0$**

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

Can define mixed states that are Eigenstates of the *CP* operator

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

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

- **these are also Eigenstates of the weak interaction, if *CP* is conserved**

Neutral Kaon System

Look at decay of Kaons into two pions

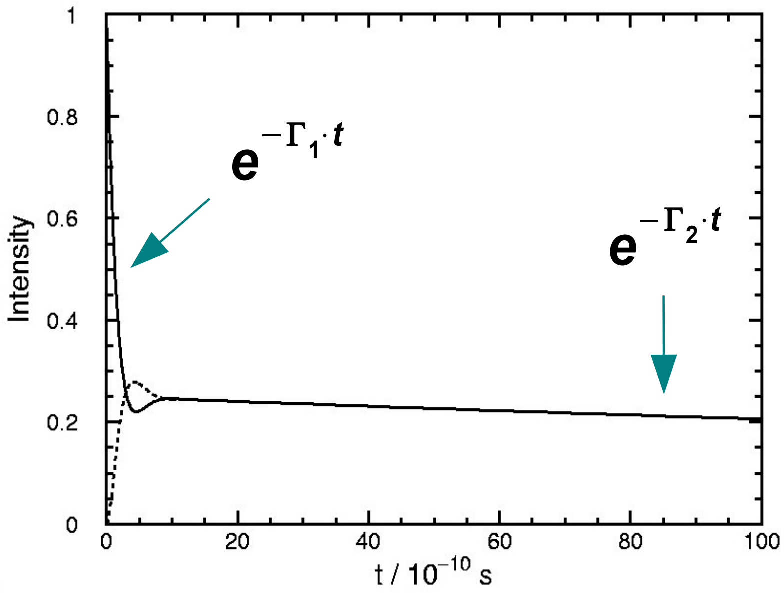
- **Kaons and pions are spin-0 mesons**
- **conservation of angular momentum in the decay**

⇒ $L_{\pi\pi} = 0$

- **$CP\,(\pi\pi) = -1^{L}$ ⇒ 2π final state is *CP* even**

If *CP* is conserved in weak interactions

- **K_2 (*CP* odd) cannot decay into 2π**
- **other decay channels for K_2 also suppressed**
  - $K_2 \rightarrow 3\pi$ by phase space
  - $K_2 \rightarrow \pi^{\pm}\ell^{\mp}\nu_{\ell}$ by parity violation
- **K_2 has much longer lifetime than K_1**
  - this has been observed:
  - measure $\tau(K_2) \approx 500 \times \tau(K_1)$

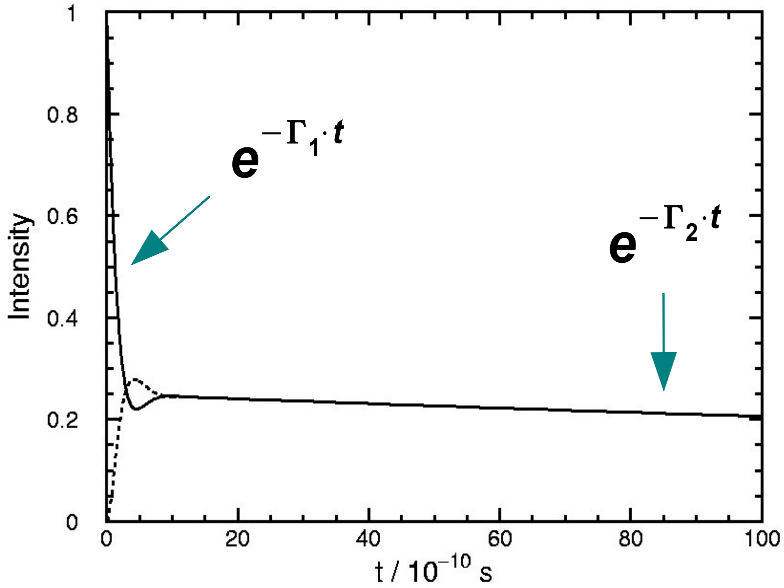


Neutral Kaon System

$K^0/\bar{K}^0$ propagating in vacuum

- K_1 component decays ⇒ pure K_2 state
- e.g. after 20 × K_1-lifetime:
  - K_1 intensity down to 2 x 10^{-9}
  - K_2 intensity still at 96%

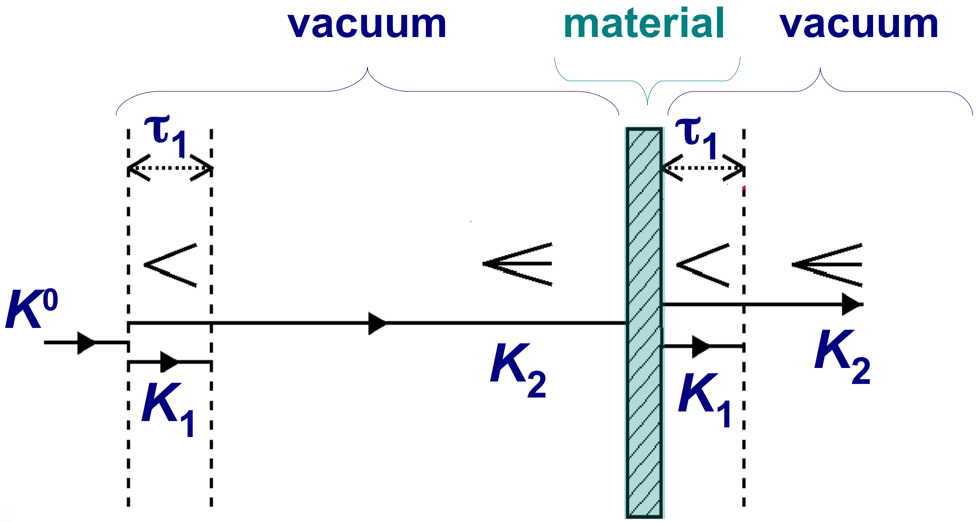
} of initial intensity



If K_2 beam traverses material

$$|K_2\rangle \equiv \frac{1}{\sqrt{2}} \cdot \left\{ |K^0\rangle - |\bar{K}^0\rangle \right\}$$

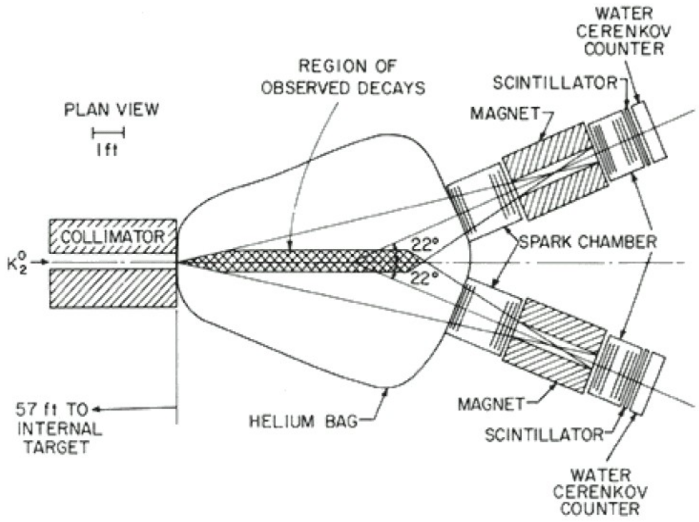
- K^0 ($d\bar{s}$) and $\bar{K}^0$ ($\bar{d}s$) have different strong interaction cross sections
- $\bar{K}^0/K^0$ mixture changes
- regeneration of a K_1 component



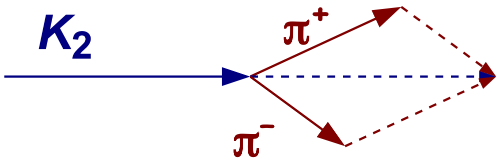
Discovery of *CP* Violation

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

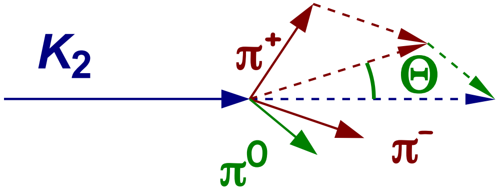
- **search for $\pi^+\pi^-$ decays in a pure K_2 beam**
- **to identify $\pi^+\pi^-$ decays use**
  - energy conservation: invariant mass of $\pi^+\pi^-$ pair
  - momentum conservation: momentum balance

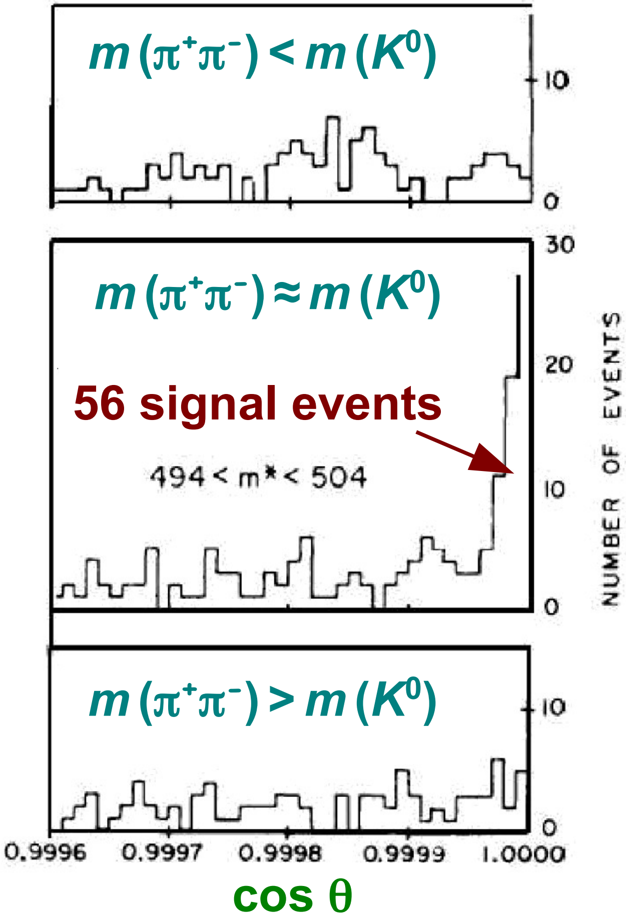


2-body decays:



3-body decays:



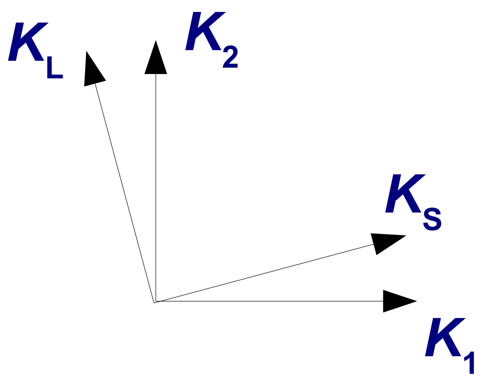


Discovery of *CP* Violation

Interpretation: Kaon mass eigenstates are not identical to *CP* eigenstates

- long lived mass Eigenstate (K_L) has small admixture from *CP*-even state K_1

$$\underbrace{\begin{aligned} |K_L\rangle &\equiv \frac{1}{1+|\varepsilon|^2}\cdot\left\{|K_2\rangle - \varepsilon\cdot|K_1\rangle\right\} \\ |K_S\rangle &\equiv \frac{1}{1+|\varepsilon|^2}\cdot\left\{|K_1\rangle + \varepsilon\cdot|K_2\rangle\right\} \end{aligned}}_{\varepsilon\text{: complex parameter}}$$



- measure |ε| through decay width ratios of *CP* forbidden and allowed decays

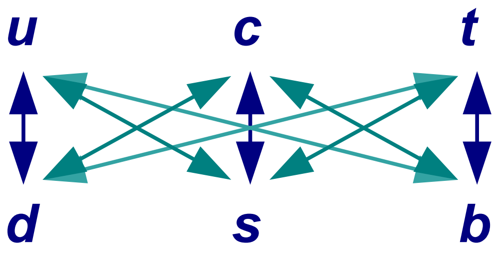
$$\eta_{+-} \equiv \frac{\Gamma\left(K_L\to\pi^+\pi^-\right)}{\Gamma\left(K_S\to\pi^+\pi^-\right)} = \left(2.286 \pm 0.017\right)\cdot 10^{-3} \approx |\varepsilon|$$

$$\eta_{00} \equiv \frac{\Gamma\left(K_L\to\pi^0\pi^0\right)}{\Gamma\left(K_S\to\pi^0\pi^0\right)} = \left(2.274 \pm 0.017\right)\cdot 10^{-3} \approx |\varepsilon|$$

CP Violation in the Standard Model

3 quark generations: 3x3 quark mixing matrix (Kobayashi-Maskawa,1973)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- **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

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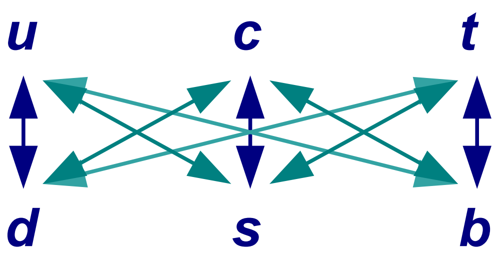

- **9 complex numbers = 18 parameters**

– 9 unitarity constraints ($V^\dagger V = VV^\dagger = 1$)

– 5 arbitrary (“unphysical”) phases

$$\left.\begin{aligned} u_i &\rightarrow e^{i\varphi_i} u_i \\ d_j &\rightarrow e^{i\varphi_j} d_j \end{aligned}\right\} \Leftrightarrow V_{ij} \rightarrow e^{i(\varphi_j - \varphi_i)} V_{ij}$$

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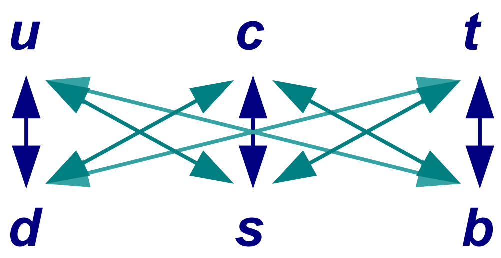

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  - **– 9 unitarity constraints ($V^\dagger V = VV^\dagger = 1$)**
  - **– 5 arbitrary (“unphysical”) phases**
  - **= 4 free parameters: 3 rotation angles + 1 complex phase**

source of *CP* violation

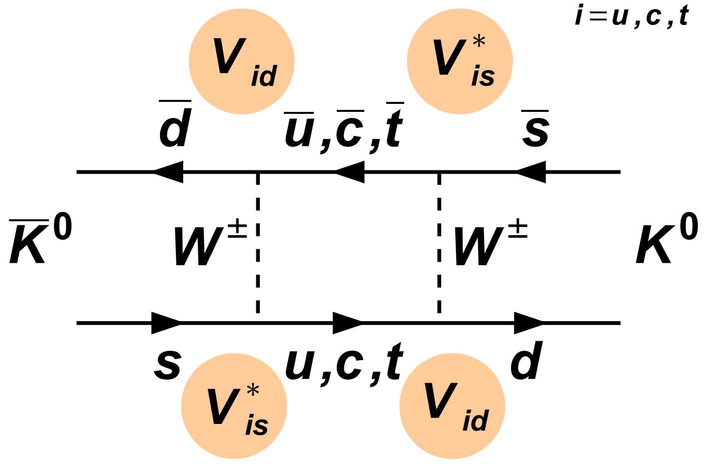
Wolfenstein parametrisation

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

Indirect and Direct *CP* Violation

Explains “indirect” *CP* violation in Kaon mixing

- **interference of box diagrams with different quarks (**= different weak phases**) in the loop**



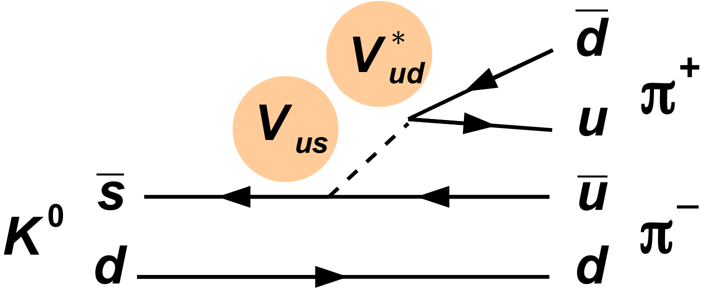
Predicts “direct” CP violation in Kaon decays

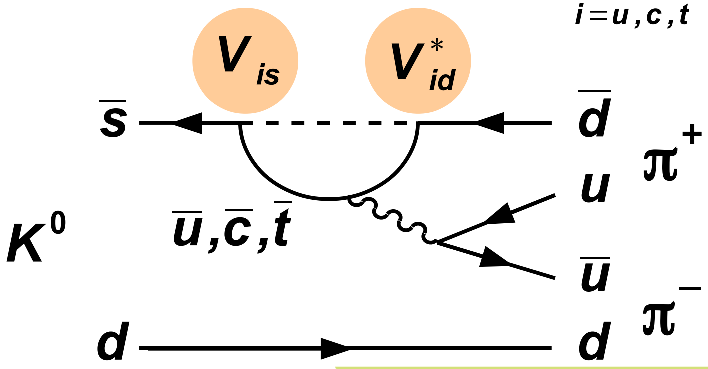
- **due to interference of “Tree” and “Penguin” diagrams with different weak phases**
- **can be measured by comparing**

$$\eta_{+-} = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'$$

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

- **ε' ≡ 0 if *CP* violation only in mixing**
- **expect $\varepsilon'/\varepsilon \approx 10^{-3}$ in Standard Model**





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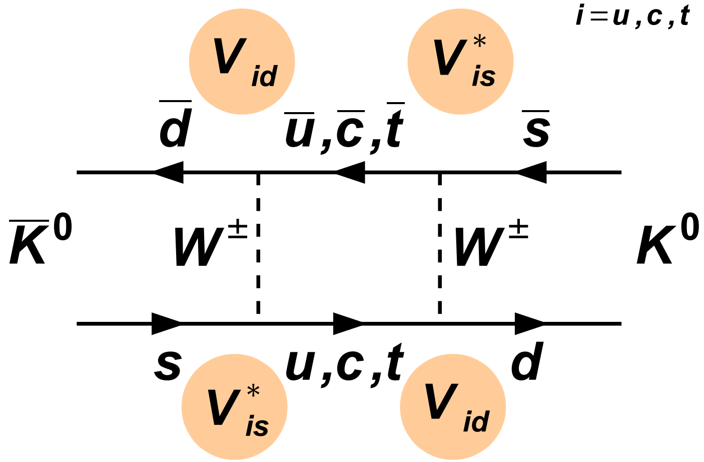

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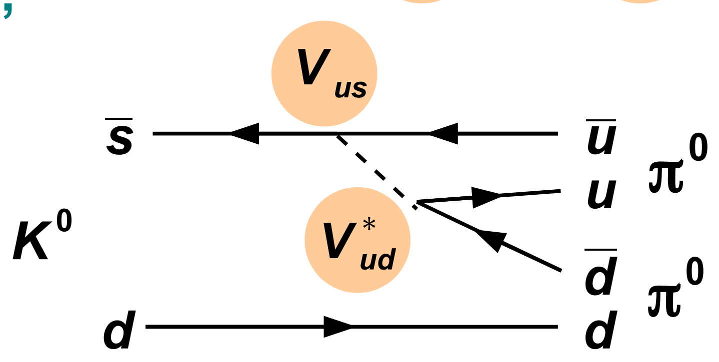

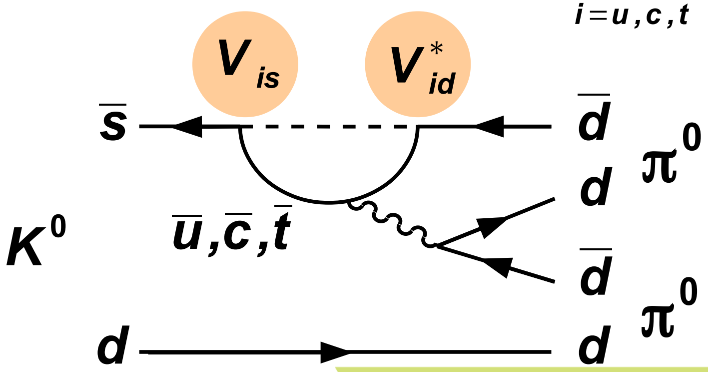

- **$\varepsilon' \equiv 0$ if *CP* violation only in mixing**
- **expect $\varepsilon'/\varepsilon \approx 10^{-3}$ in Standard Model**

Search for Direct *CP* Violation

Measure Re (ε'/ε) through "double ratio" of decay widths

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

Experiment: count number of events

$$R_{\mathrm{exp}} = \frac{N\left(K_L\to\pi^0\pi^0\right)/N\left(K_S\to\pi^0\pi^0\right)}{N\left(K_L\to\pi^+\pi^-\right)/N\left(K_S\to\pi^+\pi^-\right)}$$

with $N = \int_t \Phi(\mathrm{t})\cdot\Gamma\cdot A(t)\,dt$

$\Phi(t)$: particle flux (accelerator) ; $A(t)$: efficiency (detector)

- **double ratio: many systematic uncertainties cancel to first order, if the four event rates are measured at the same time in the same experiment**

$$R = \int_t \frac{\left\{\cancel{\Phi_{K_L}(t)}\cdot\Gamma\left(K_L\to\pi^0\pi^0\right)\cdot A_{\pi^0\pi^0}(t)\right\}/\left\{\cancel{\Phi_{K_S}(t)}\cdot\Gamma\left(K_S\to\pi^0\pi^0\right)\cdot A_{\pi^0\pi^0}(t)\right\}}{\left\{\cancel{\Phi_{K_L}(t)}\cdot\Gamma\left(K_L\to\pi^+\pi^-\right)\cdot A_{\pi^+\pi^-}(t)\right\}/\left\{\cancel{\Phi_{K_S}(t)}\cdot\Gamma\left(K_S\to\pi^+\pi^-\right)\cdot A_{\pi^+\pi^-}(t)\right\}}\,dt$$

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Experiment: count

$$R_{\mathrm{exp}} = \quad N \qquad \left.t\right) \cdot \Gamma \cdot A\left(t\right) dt$$

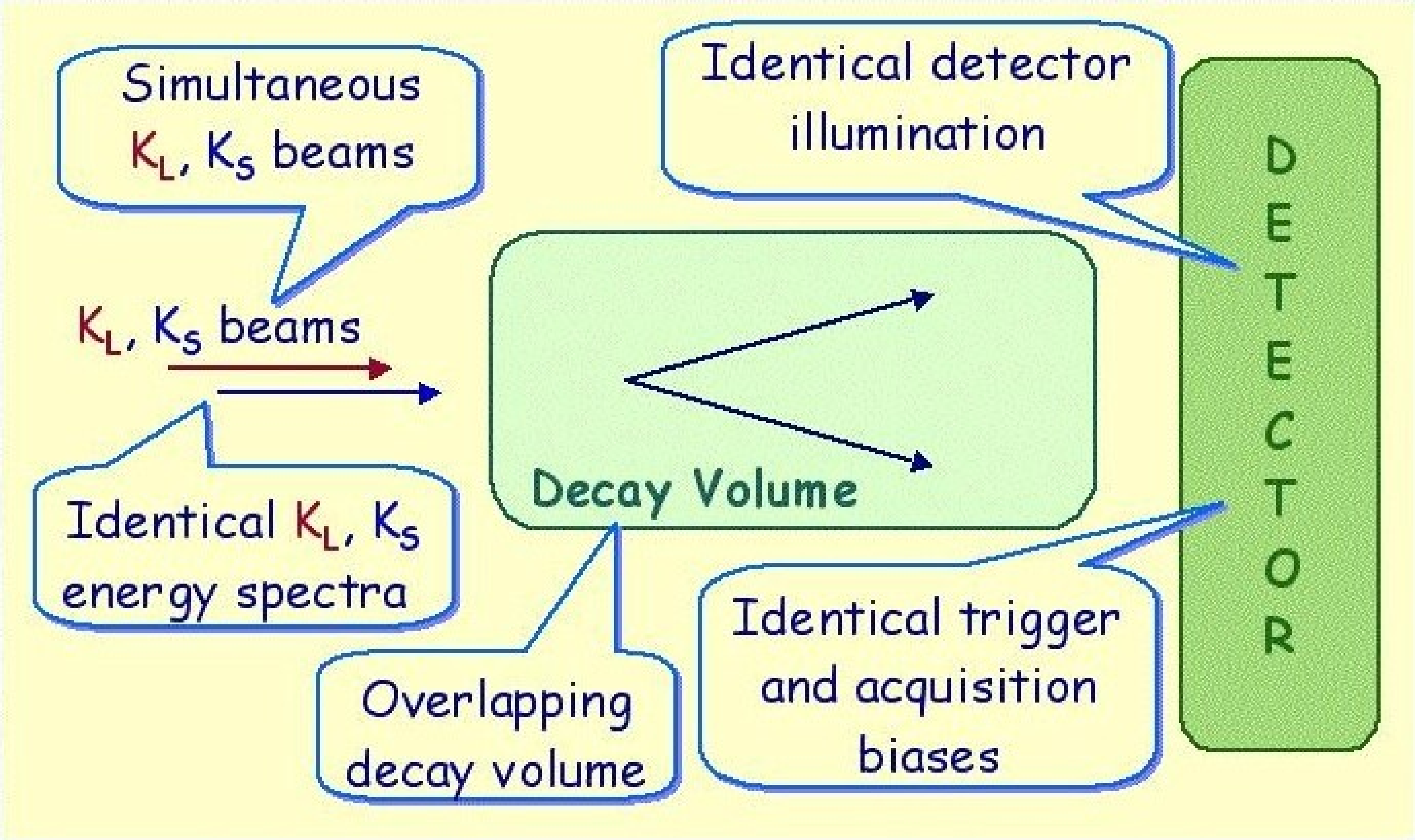
$\Phi\left(t\right.$ (detector)

Relative measurements are often more precise than absolute measurements

- double ra es cance to first order, if the four event ra ed at the same time in the same experiment

$$R = \int_t \frac{\left\{\cancel{\Phi_{K_L}\left(t\right)} \cdot \Gamma\left(K_L \to \pi^0\pi^0\right) \cdot \cancel{A_{\pi^0\pi^0}\left(t\right)}\right\} / \left\{\cancel{\Phi_{K_S}\left(t\right)} \cdot \Gamma\left(K_S \to \pi^0\pi^0\right) \cdot \cancel{A_{\pi^0\pi^0}\left(t\right)}\right\}}{\left\{\cancel{\Phi_{K_L}\left(t\right)} \cdot \Gamma\left(K_L \to \pi^+\pi^-\right) \cdot \cancel{A_{\pi^+\pi^-}\left(t\right)}\right\} / \left\{\cancel{\Phi_{K_S}\left(t\right)} \cdot \Gamma\left(K_S \to \pi^+\pi^-\right) \cdot \cancel{A_{\pi^+\pi^-}\left(t\right)}\right\}} dt$$

Ideal Experiment



Simultaneous K_L, K_S beams

K_L, K_S beams

Identical K_L, K_S energy spectra

Overlapping decay volume

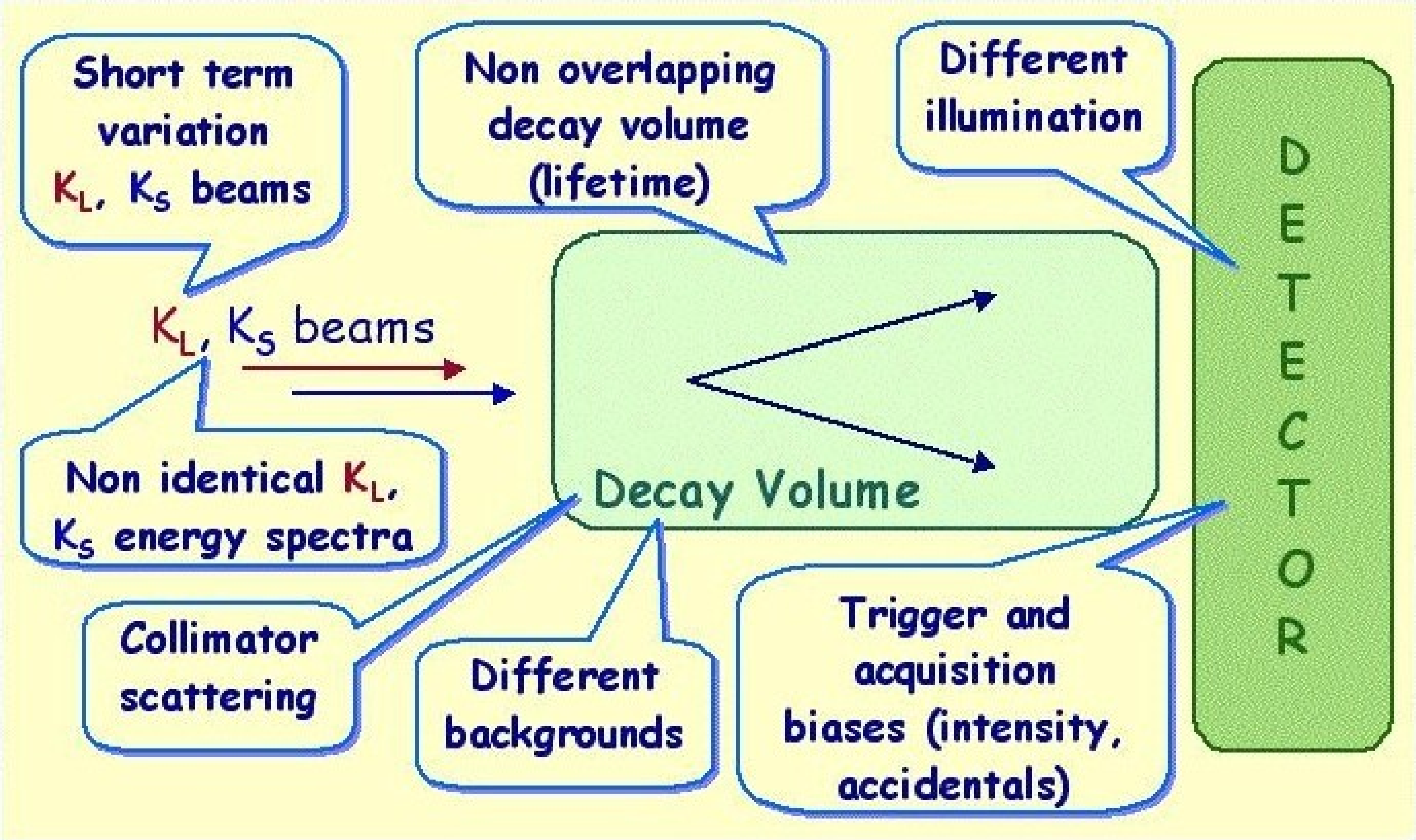
Decay Volume

Identical detector illumination

Identical trigger and acquisition biases

DETECTOR

Real Experiment



Backgrounds

K_L: large backgrounds from *CP*-conserving 3-body decays

- $K_L \to \pi^\pm e^\mp \nu$ (39%)
- $K_L \to \pi^\pm \mu^\mp \nu$ (27%)
- $K_L \to \pi^+ \pi^- \pi^0$ (13%)
- $K_L \to \pi^0 \pi^0 \pi^0$ (21%)
- $K_L \to \pi^+ \pi^-$ (0.206%)
- $K_L \to \pi^0 \pi^0$ (0.09%)

backgrounds for $\pi^+ \pi^-$ reconstruction

- neutrino leaves no trace in the detector
- π^0 could be missed

background for $\pi^0 \pi^0$ reconstruction

- one π^0 could be missed
- photon clusters from two π^0's could merge

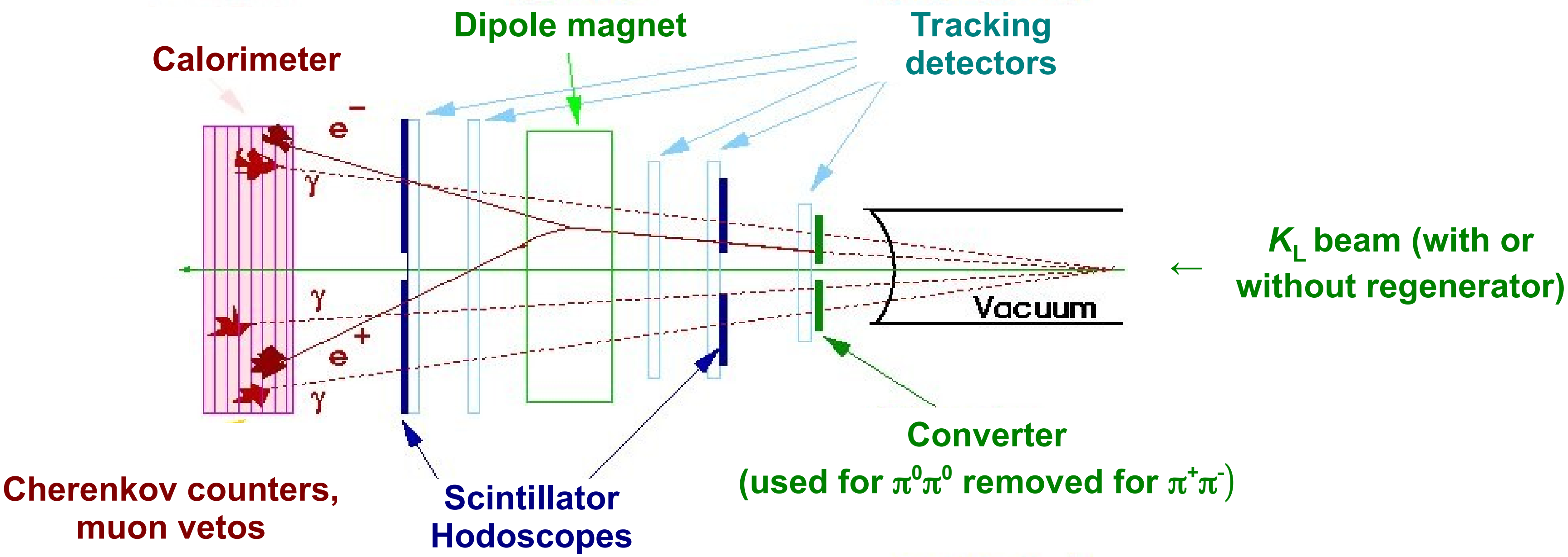
- **apply selection cuts on event topology, kinematics, particle identification to suppress these backgrounds**

K_S: backgrounds completely negligible

- **but apply the same selection cuts as for K_L to minimize systematics**

Princeton Experiment (1972)

First measurement of double ratio in one experiment

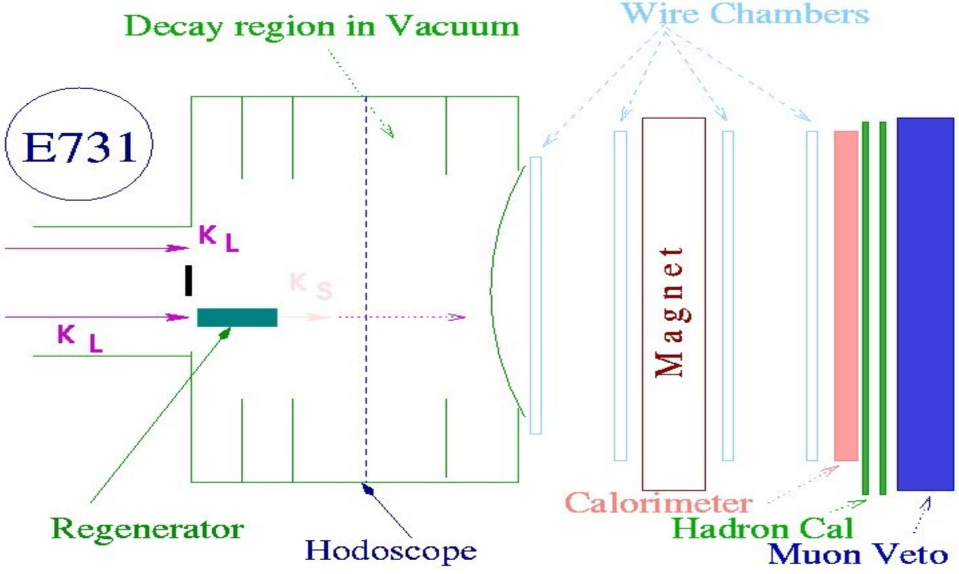


- but: four decay modes measured in four consecutive data taking periods
  (charged vs. neutral detector) × (with vs. without K_S regenerator)
- dominating systematics: beam flux monitored to 3% precision
- statistics: 124 ± 11 $K_L \rightarrow \pi^0 \pi^0$ events collected
- collaboration: 5 physicists

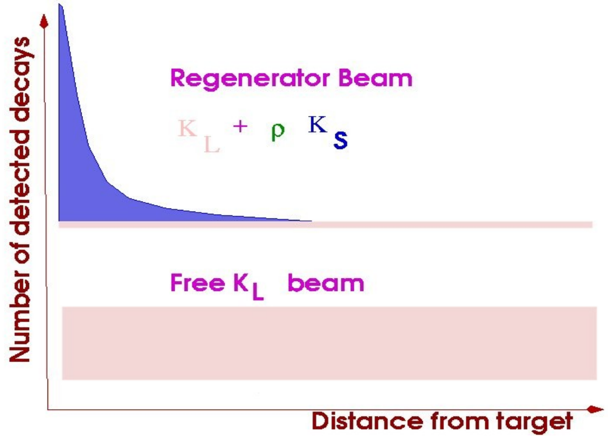
Re (ε'/ε) = -0.008 ± 0.020

E731 at Fermilab (1985-87)

Two parallel K_L beams, one of them with a K_S regenerator



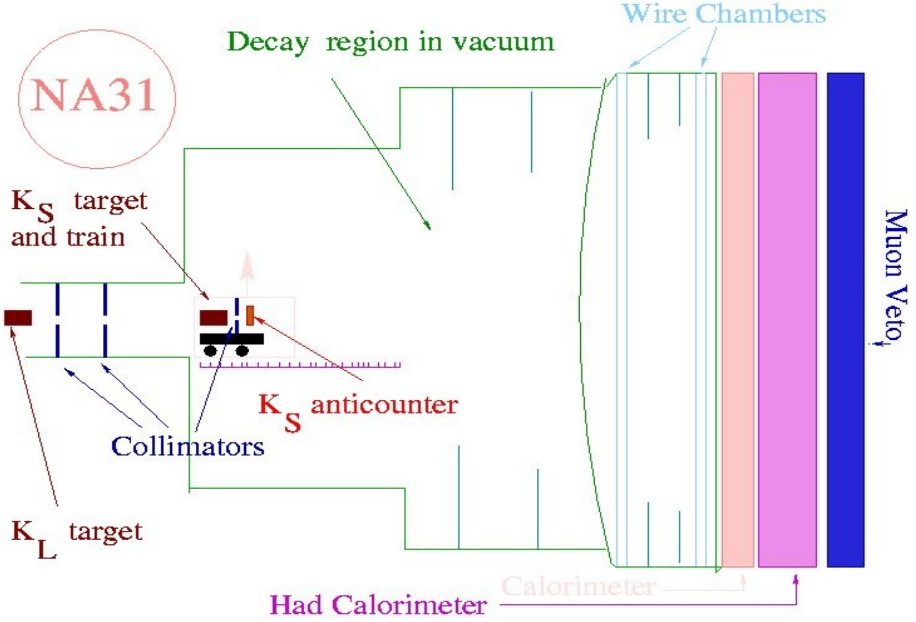
- **wire chambers + dipole magnet for reconstruction of $\pi^+\pi^-$ decays**
- **electromagnetic calorimeter for reconstruction of $\pi^0\pi^0$ decays**
- **photon and muon vetos for background rejection**
- **K_L and K_S modes collected at the same time**
- **but very different decay vertex distributions for K_L and K_S due to the different lifetimes**
  - different illumination of detector
  - acceptance correction by Monte Carlo simulation

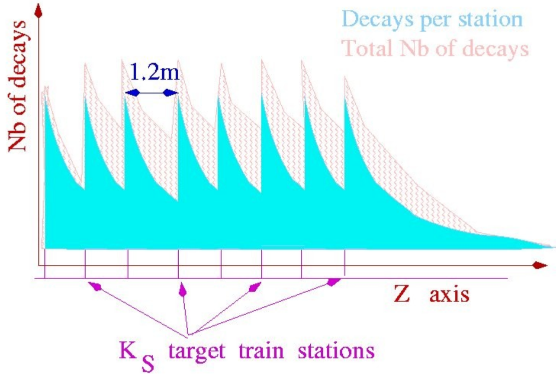


NA31 at CERN (1986-89)

Separate K_L and K_S production targets in the same proton beam

- **wire chambers and hadron calorimeter for reconstruction of $\pi^+\pi^-$ decays** (no momentum measurement !)
- **electromagnetic calorimeter for reconstruction of $\pi^0\pi^0$ decays**
- **photon and muon vetos**
- **moveable K_s target to emulate flat decay vertex distribution by taking data at different target positions**
  - much smaller acceptance corrections
  - but K_L and K_S modes not collected at the same time





Final Results (1993)

E731

- about 410 k reconstructed $K_L \to \pi^0 \pi^0$ events

Re (ε'/ε) = (7.4 ± 5.2 ± 2.9) × 10^{-4}

- total uncertainty 6.0 × 10^{-4}
- result compatible with zero

NA31

- about 428 k reconstructed $K_L \to \pi^0 \pi^0$ events

Re (ε'/ε) = (23.0 ± 4.1 ± 5.1) × 10^{-4}

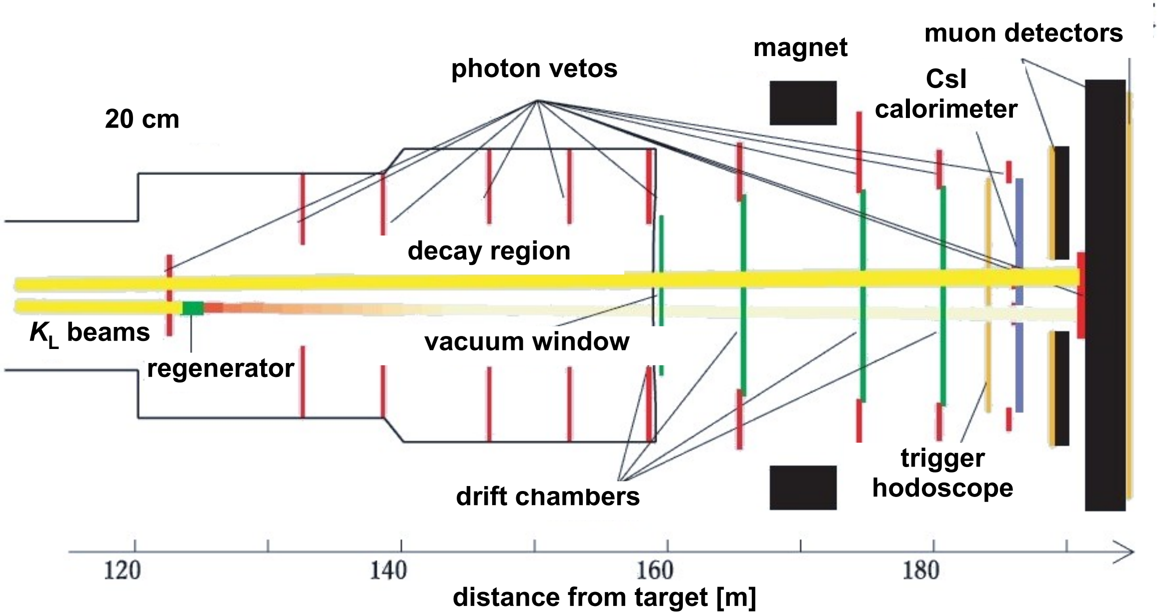
- total uncertainty 6.5 × 10^{-4}
- 3.3 σ deviation from zero

⇒ New round of experiments
“3rd generation”
goal: measure Re (ε'/ε) to precision of 1–2 x 10^{-4}

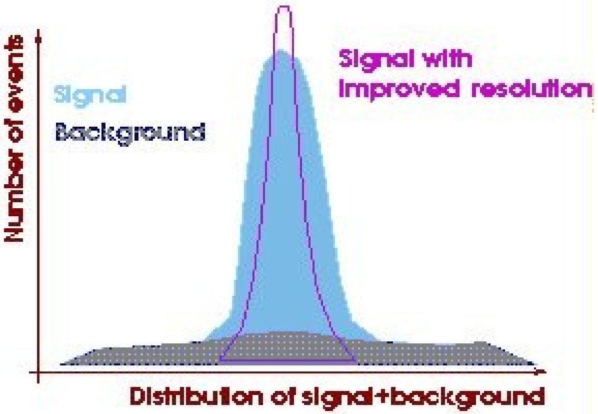
KTeV at Fermilab (1996-99)

Setup similar to E731, but significant improvements in details

- **more intense beams to collect more statistics**
- ***K*$_S$ regenerator switched between the two beams once every minute**
- **more precise detectors for better background rejection**
    - in particular, CsI calorimeter with excellent energy resolution

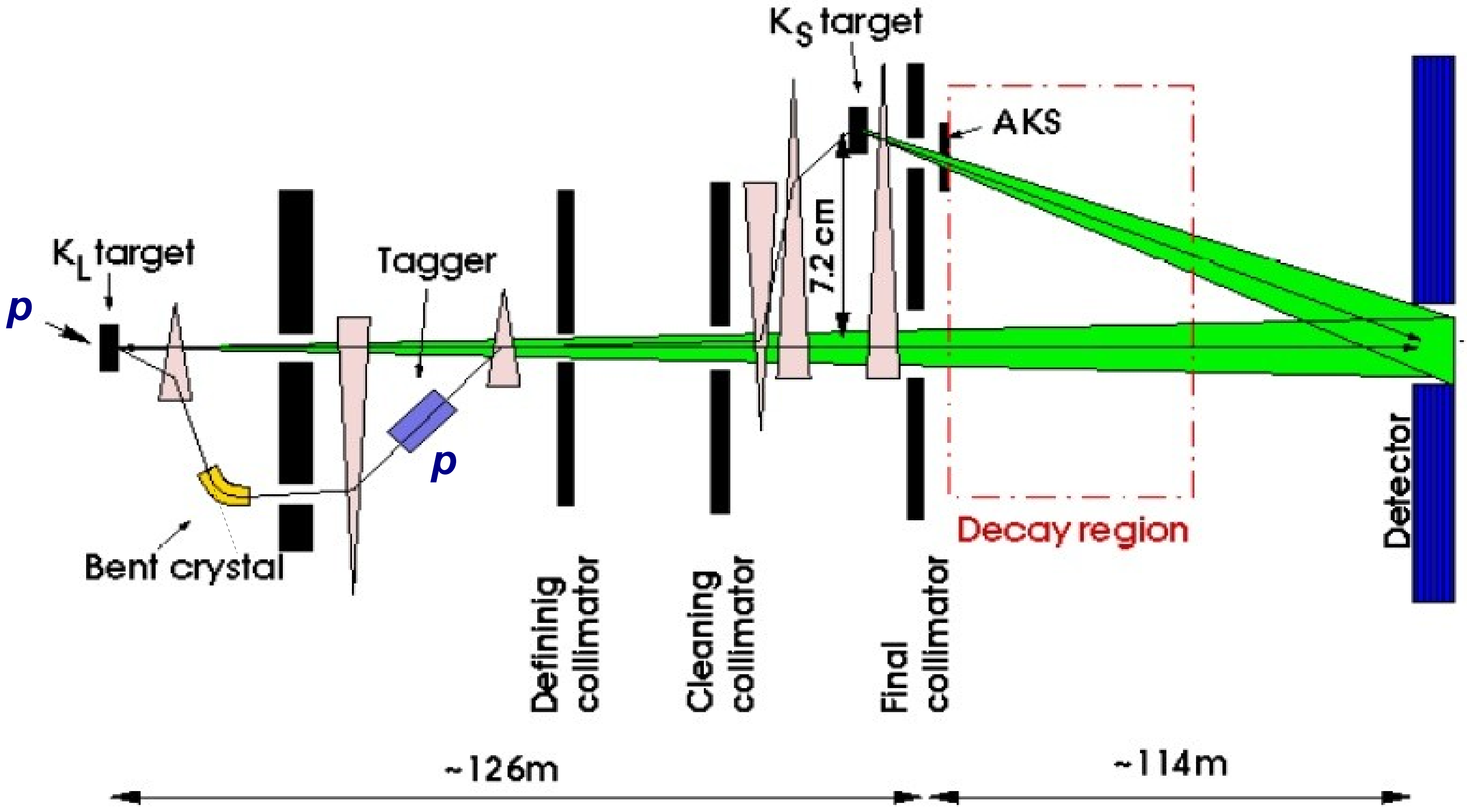


Better resolution → narrower signal window
→ less background in signal window
→ smaller uncertainty from background subtraction



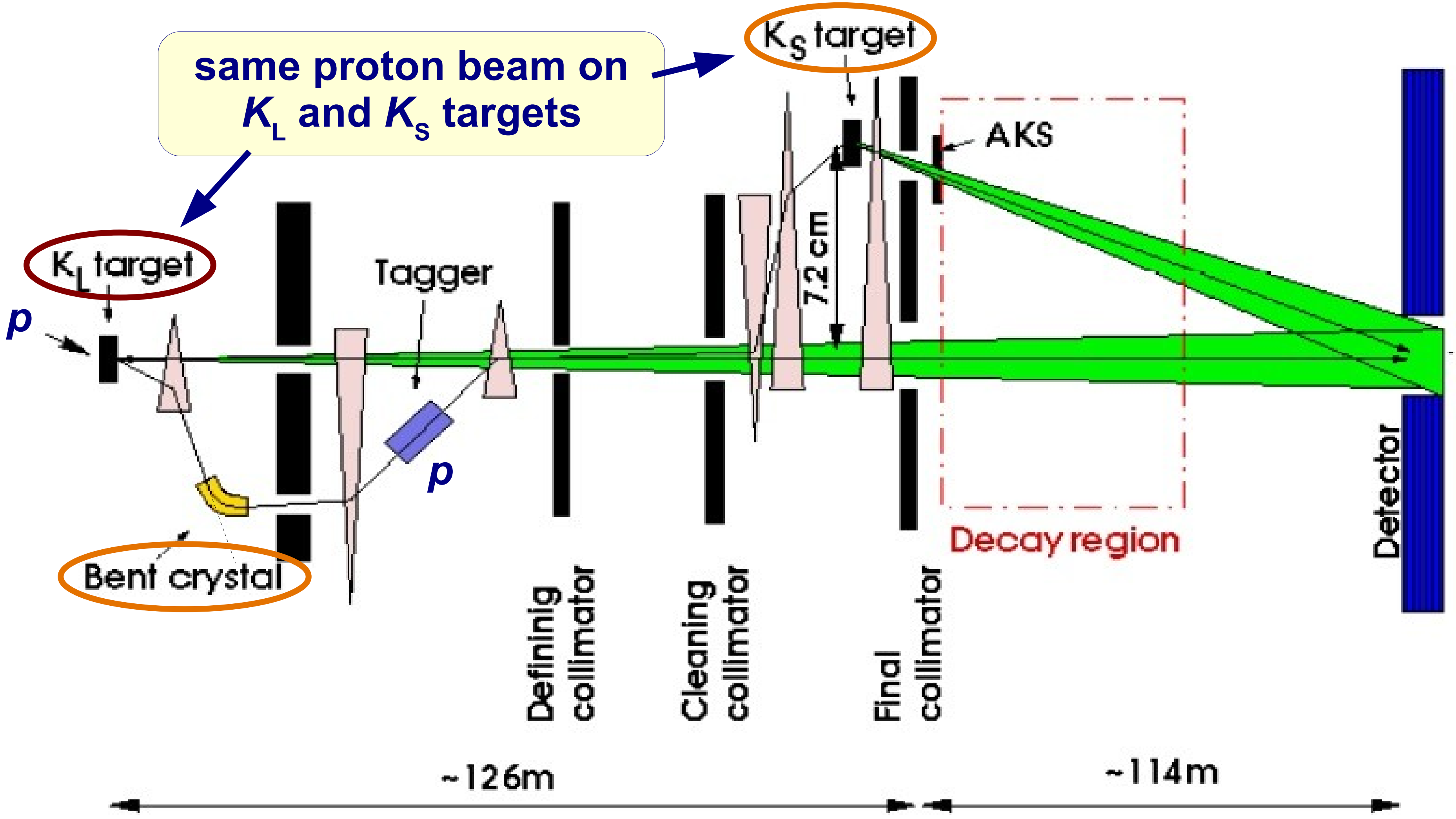
NA48 at CERN (1997-2001)

Simultaneous measurement of K_L and K_S



NA48 at CERN (1997-2001)

Simultaneous measurement of K_L and K_S

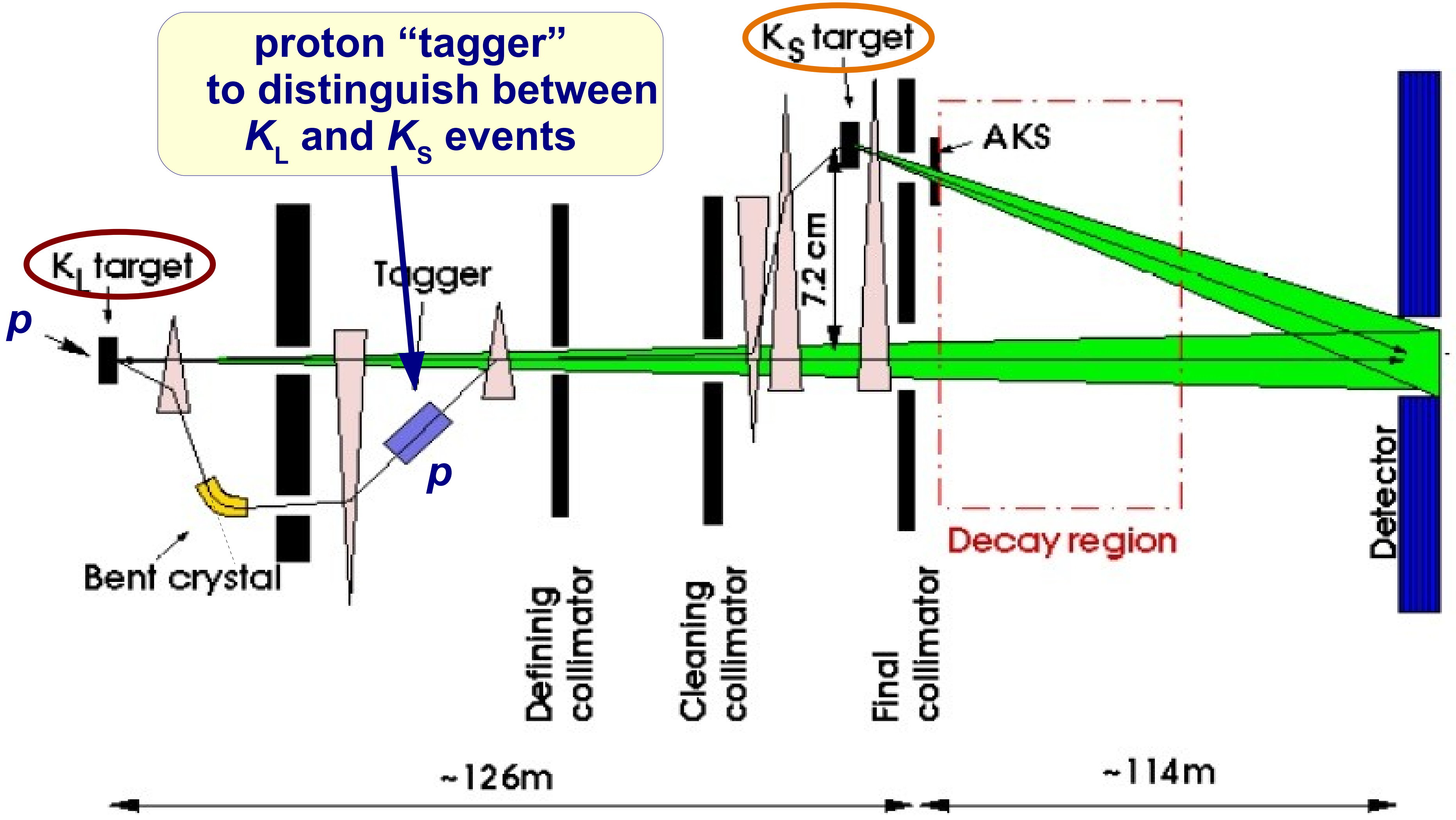


same proton beam on K_L and K_S targets

NA48 at CERN (1997-2001)

Simultaneous measurement of K_L and K_S

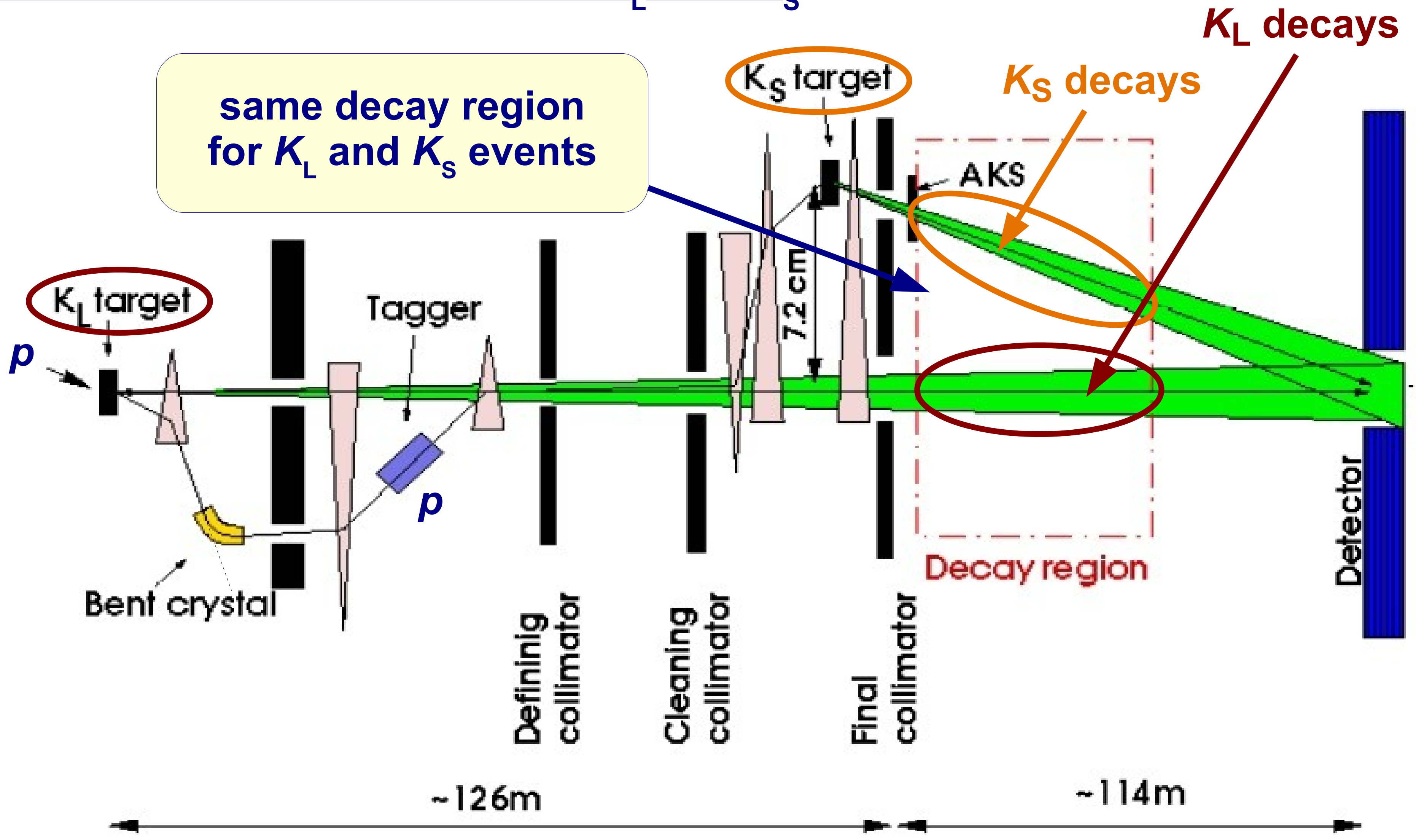
proton “tagger” to distinguish between K_L and K_S events



NA48 at CERN (1997-2001)

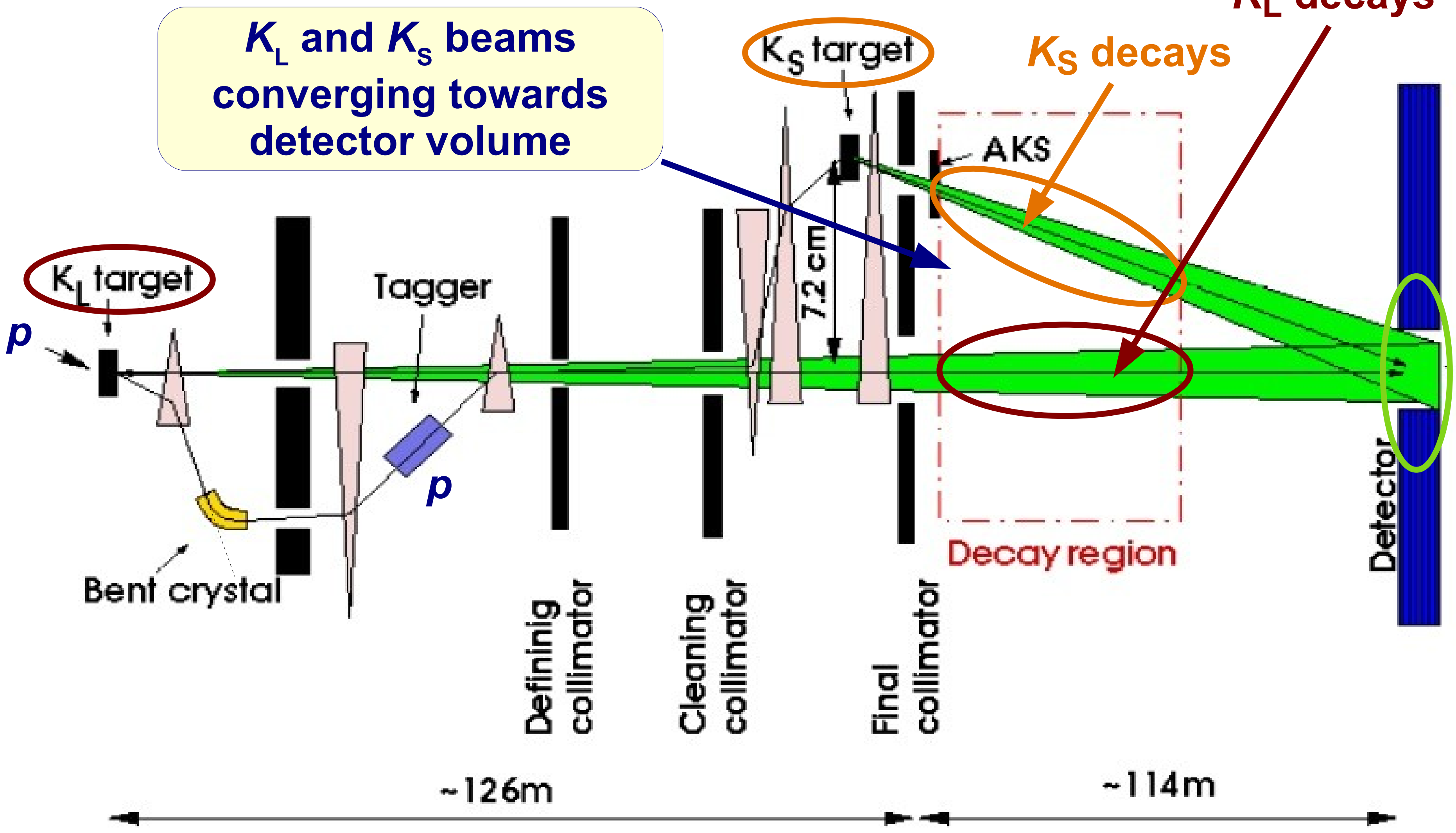
Simultaneous measurement of K_L and K_S

same decay region for K_L and K_S events



NA48 at CERN (1997-2001)

Simultaneous measurement of K_L and K_S



K_L and K_S beams converging towards detector volume

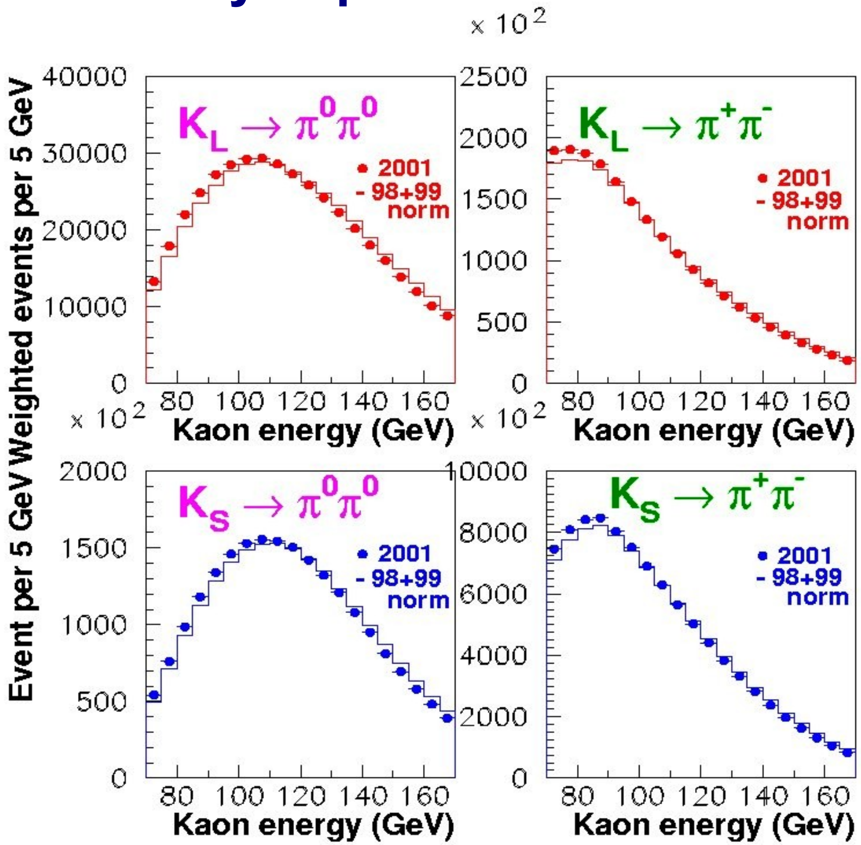
K_S decays

K_L decays

K_L and K_S Beams

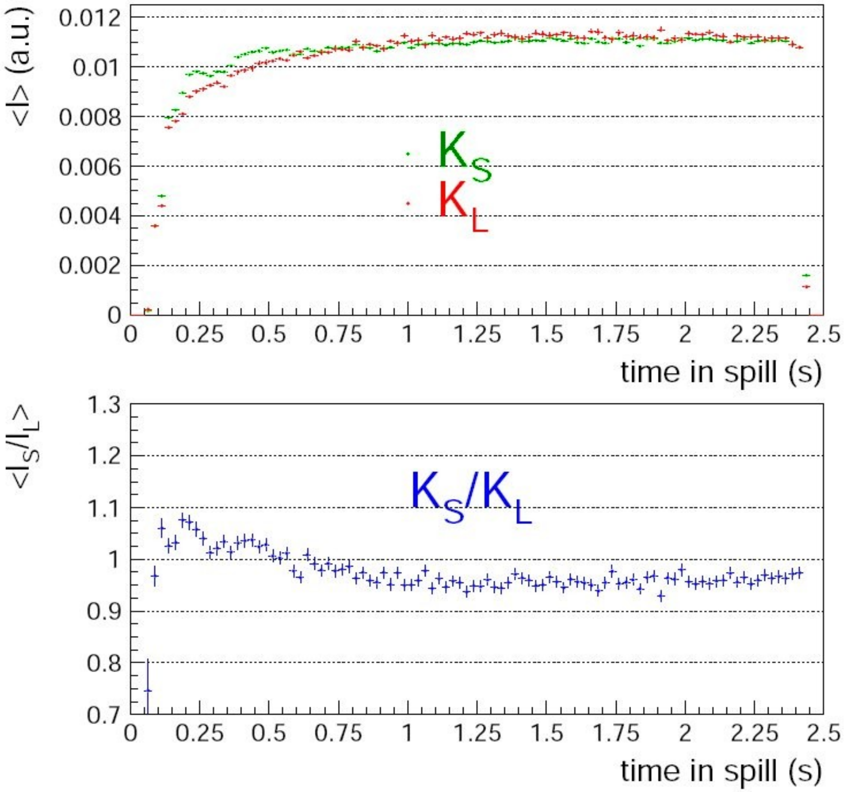
Similar momentum spectra

- important because detector acceptance and reconstruction efficiency depend on momenta



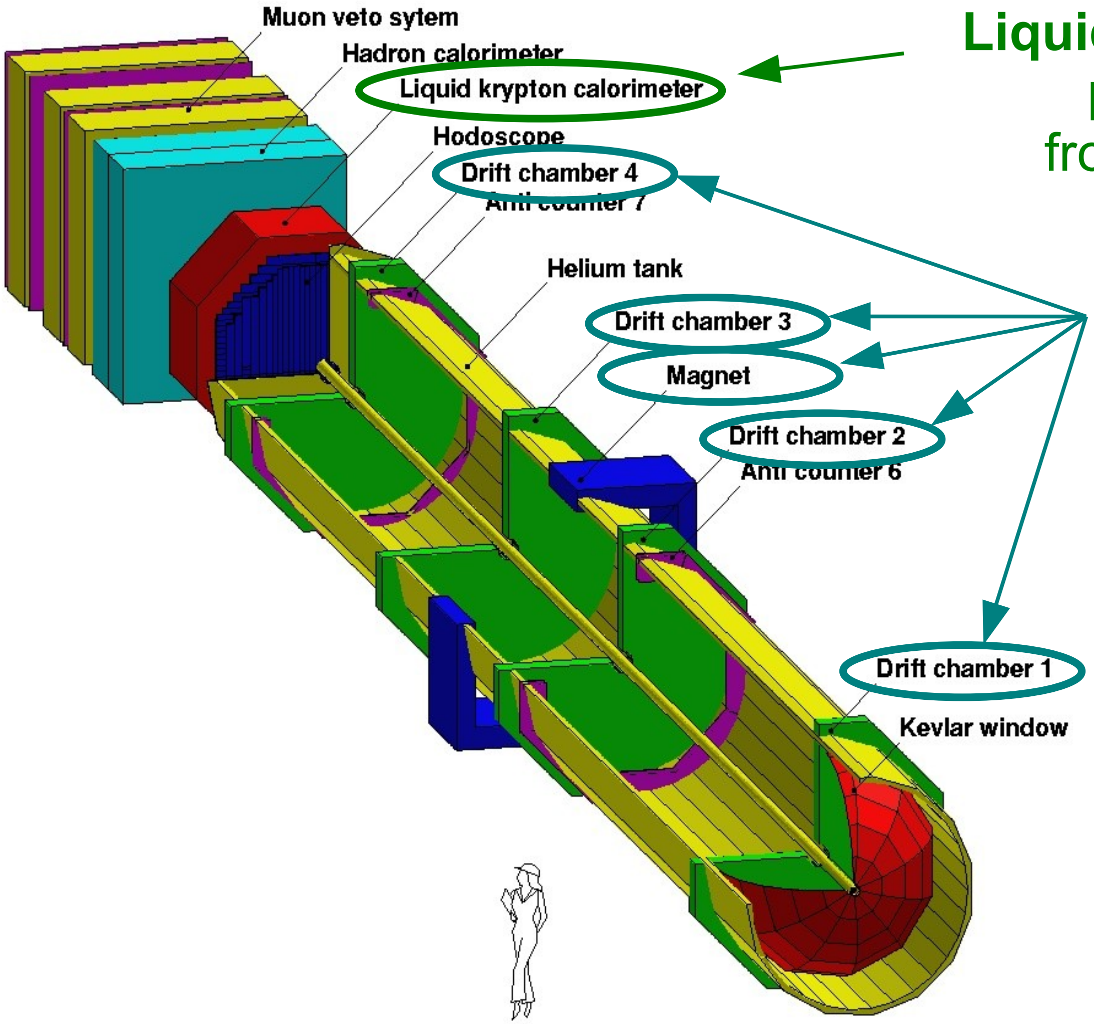
Intensities equal to a few %

- important because overlapping events in the detector can cause efficiency losses



Detector

Simultaneous measurement of $\pi^+\pi^-$ and $\pi^0\pi^0$



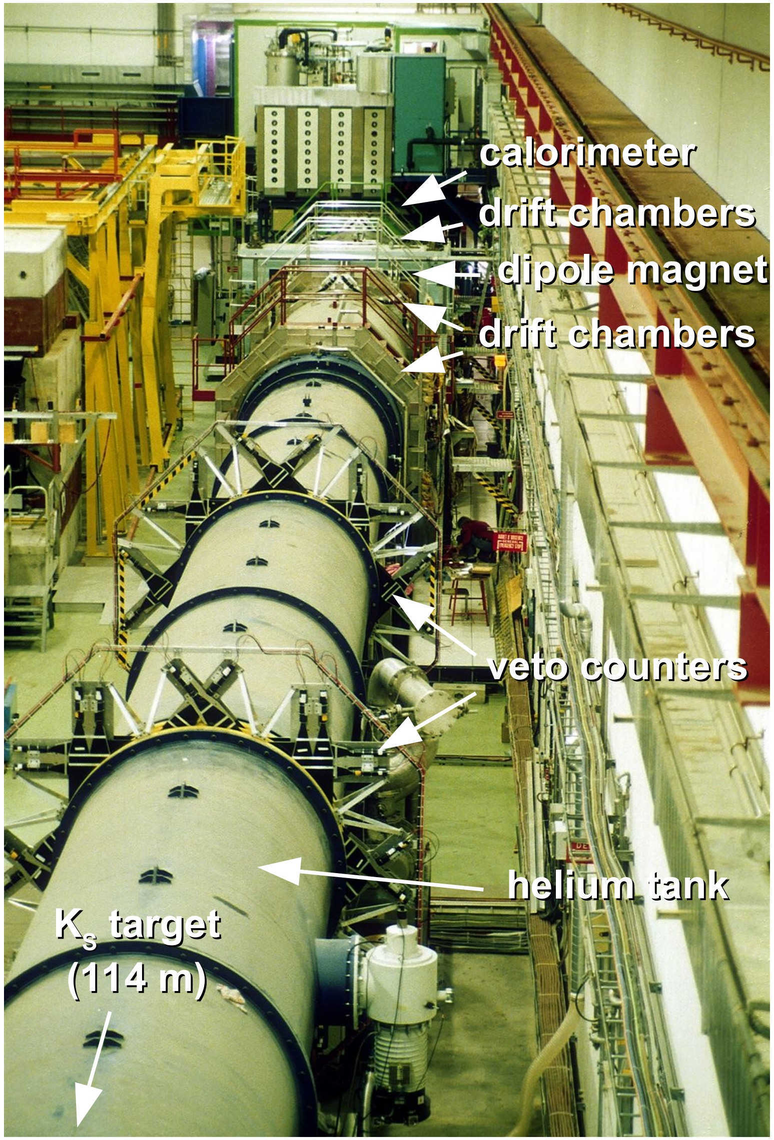
Liquid-Kr electromagnetic calorimeter:
position and energy of photons
from $K \to \pi^0(\to\gamma\gamma)\,\pi^0(\to\gamma\gamma)$ decays

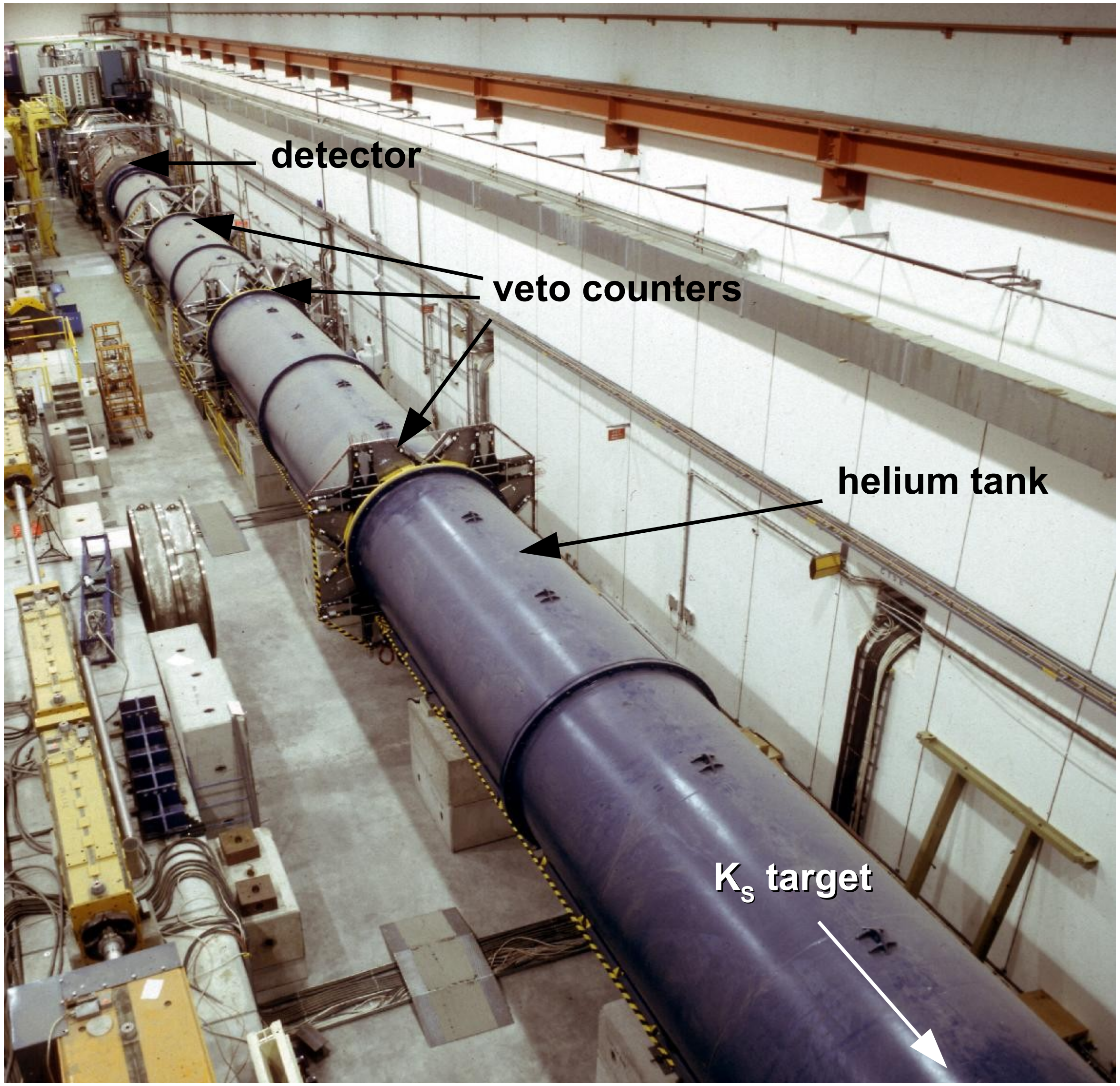
Drift chambers + dipole magnet:
direction and momentum of
charged pions from $K \to \pi^+\pi^-$

Kinematic reconstruction of Kaon momentum and Kaon decay vertex

Veto counters to suppress background decays

Detector

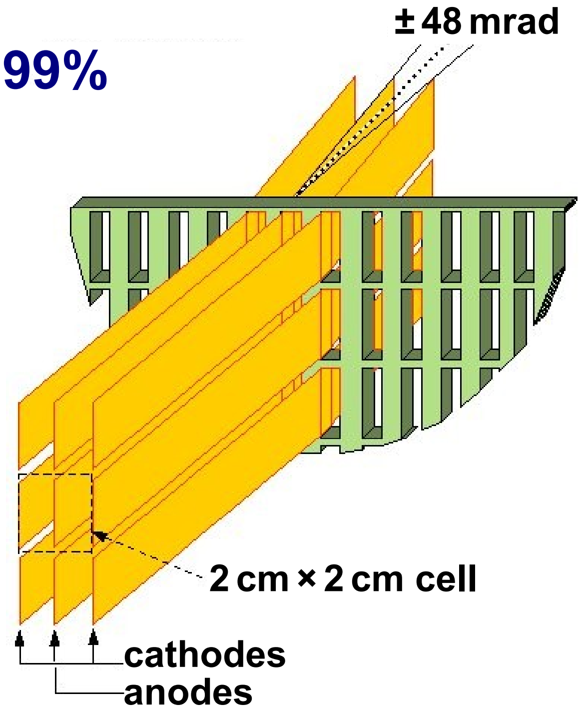

calorimeter
drift chambers
dipole magnet
drift chambers
veto counters
helium tank
K_s target
(114 m)

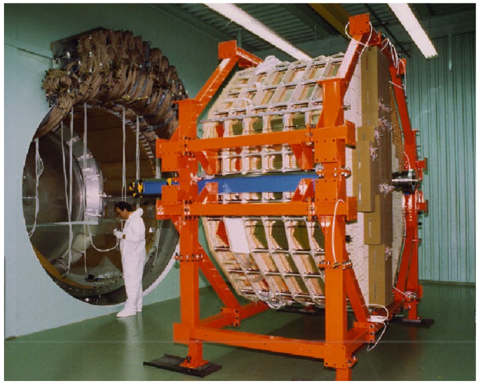

detector
veto counters
helium tank
K_s target

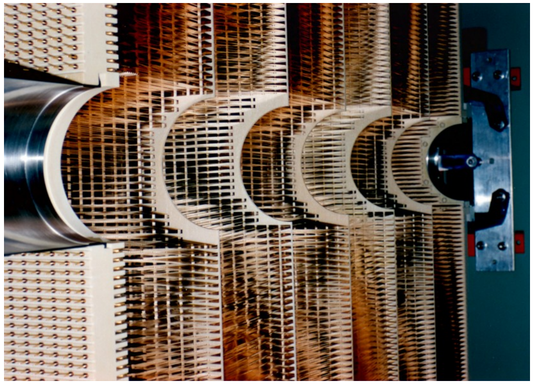
Electromagnetic Calorimeter

10 m^3 of liquid Krypton (at $T = 120$ K**) as converter and detection medium**

- **27 X_0 thick ⇒ electromagnetic showers contained to > 99%**
- **13'500 readout cells, defined by Cu-Be ribbons**
  - 3000 V between electrodes to collect charges generated by ionization in the LKr
  - “accordeon structure” to improve homogeneity of response
- **excellent energy resolution**
  - almost as good as CsI in KTeV
- **excellent time resolution**
  - better than 250 ps
  - will see later why this is important

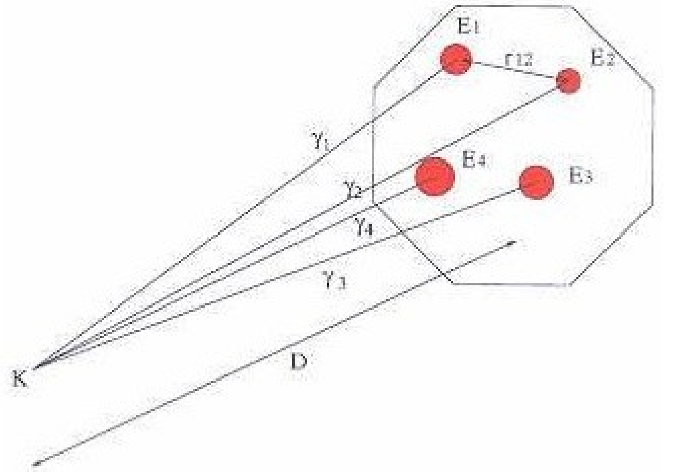






$K \rightarrow \pi^0 \pi^0$ Reconstruction

Select events with four γ-clusters in the calorimeter



- **measure cluster positions (x_i,y_i) and energies (E_i)**
- **assume that the 4 γ come from a Kaon decay**
  - i.e. assume invariant mass is equal to Kaon mass
- **calculate decay vertex position along beam axis**

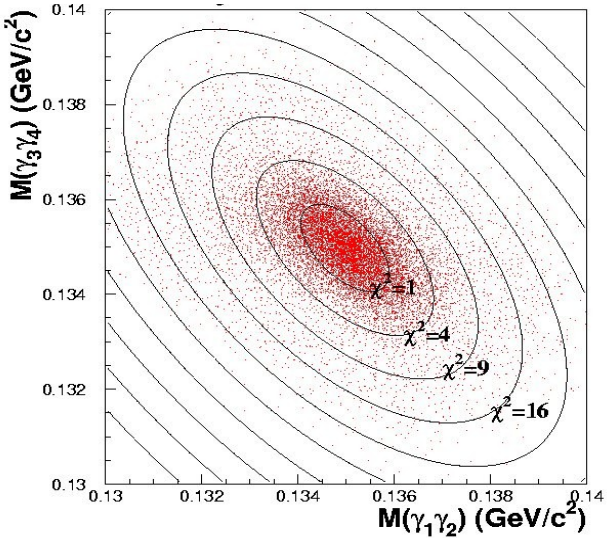
$$D = \frac{\sqrt{\sum_{ij} E_i E_j r_{ij}^2}}{m_K}$$

- **calculate 2γ invariant mass for all pairs of clusters**

$$M_{ij} \equiv M(\gamma_i \gamma_j) = \frac{\sqrt{E_i E_j r_{ij}^2}}{D}$$

- **calculate combined compatibility with the π^0 mass, select best combination, cut to reject background**

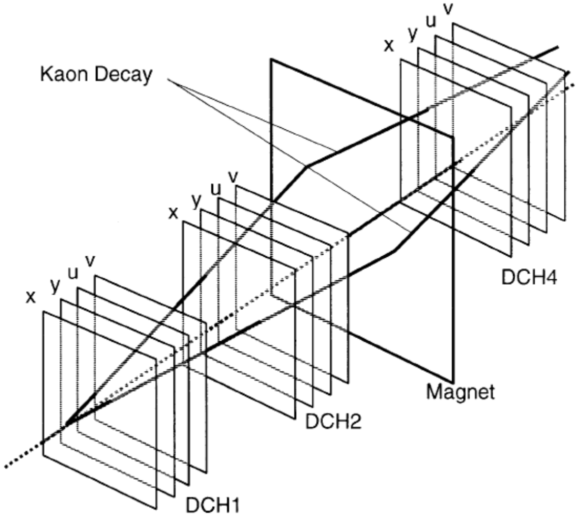
$$\chi^2 \equiv \left(\frac{M_{12} + M_{34} - 2 m_{\pi^0}}{\sigma_{M_{12}+M_{34}}} \right)^2 + \left(\frac{M_{12} - M_{34}}{\sigma_{M_{12}-M_{34}}} \right)^2$$

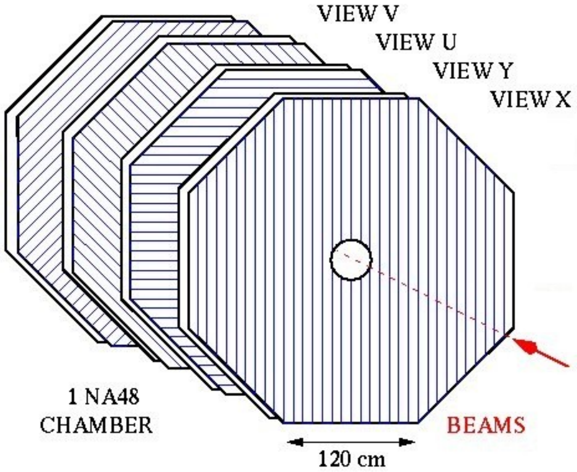


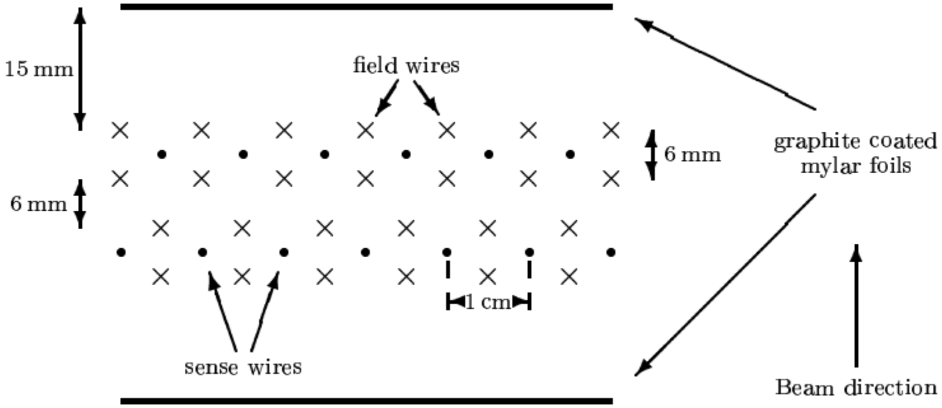
Dipole Spectrometer

Typical setup of a fixed-target experiment

- **four planar drift chambers**
  - two before and two after a 0.83 Tm dipole magnet
- **each chamber four detection layers**
  - wires vertical, horizontal, + 45°, – 45°
  - each detection layer: two staggered wire planes



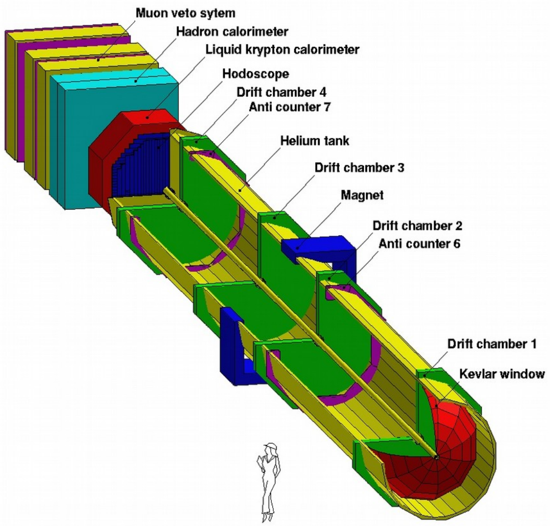




Dipole Spectrometer

Drift chambers embedded in a 23 m long, 2.8 m Ø Helium tank

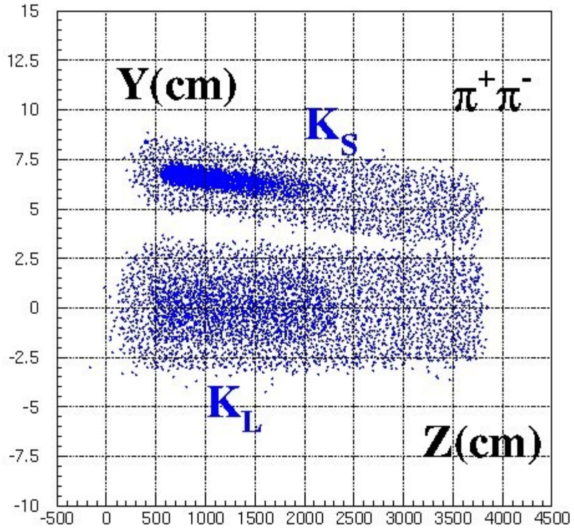
- **to minimize multiple scattering of the $\pi^{\pm}$**
  - multiple scattering deteriorates momentum resolution
- **inside this tank: vacuum beam pipe for the kaon beam**
  - wall as thin as possible to minimize multiple scattering
  - initially aluminum, then replaced by carbon fibre
  - suddenly imploded after 2 years of operation
- **drift chambers destroyed, had to be rebuilt**

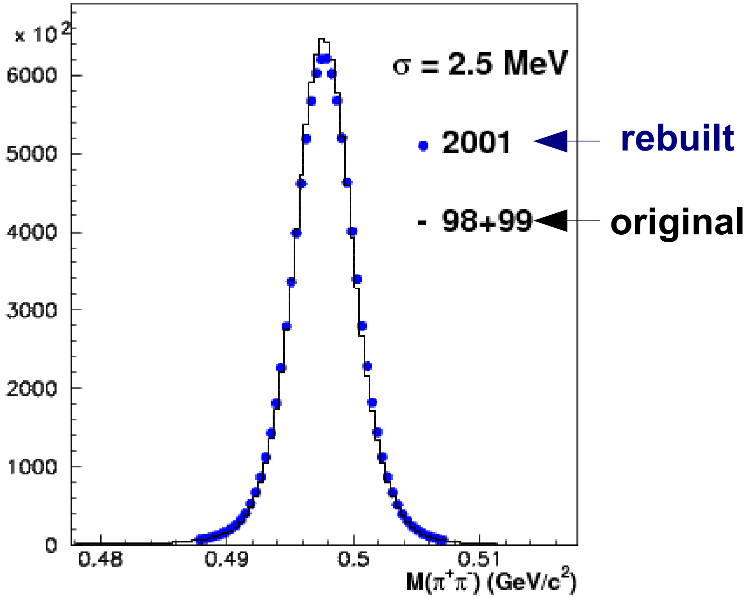


$K \rightarrow \pi^+ \pi^-$ Reconstruction

Select events with two reconstructed tracks

- **reconstruct position of Kaon decay vertex from track segments upstream of dipole magnet**
  - transverse vertex resolution ~ 2 mm
  - sufficient to separate K_L and K_S vertices
    → but used only in cross checks (see later slide)
- **reconstruct momenta from bending in magnet**
- **assume $\pi^\pm$ mass for both tracks, calculate invariant mass and Kaon momentum**
- **cut on kinematic variables to reject background**





Trigger

Requirements

- fast response, good background rejection
- efficiency > 99%
- no deadtime
- well understood response to “accidentals”

} to minimize systematics between $\pi^0\pi^0$ and $\pi^+\pi^-$

Implementation

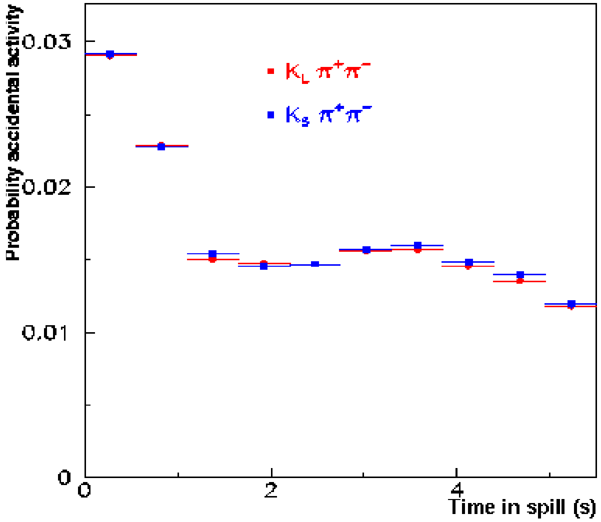
- custom-made electronics boards
- fully pipelined to avoid dead time
  - novel at the time
- design specs for $\pi^+\pi^-$ implementation made slightly too optimistic assumptions on hit multiplicities in wire chambers
  - FPGAs were very expensive at the time

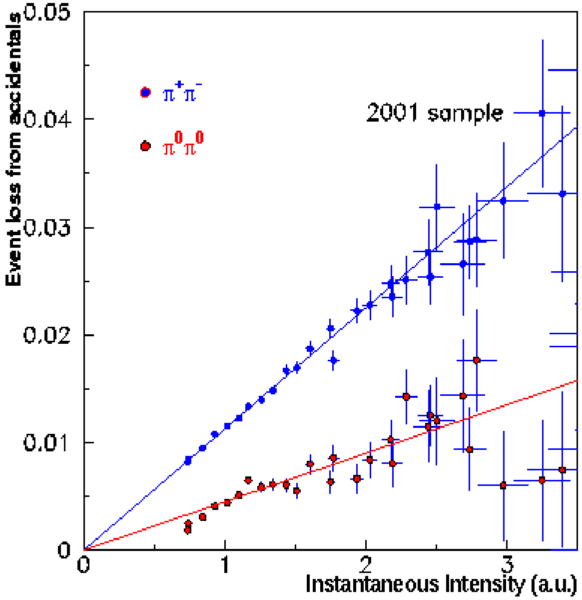
} ≈ 1.3 % inefficiency ≈ 0.3 % deadtime → source of systematic uncertainty

“Accidental Activity”

Inefficiencies due to accidental coincidences

- **cause systematic effect if losses are different for $\pi^+\pi^-$ vs $\pi^0\pi^0$ or for K_L vs K_S**
- **difference between K_L and K_S is small by design**
  - simultaneous beams ⇒ K_L and K_S decays always see the same beam intensity
- **difference between $\pi^+\pi^-$ and $\pi^0\pi^0$ is mainly due to different trigger dead times**
  - dead-time conditions are continuously recorded during data taking
  - same dead-time conditions are then applied to all event types by “throwing away” events during the offline reconstruction
  - small loss of statistics but large gain in systematics

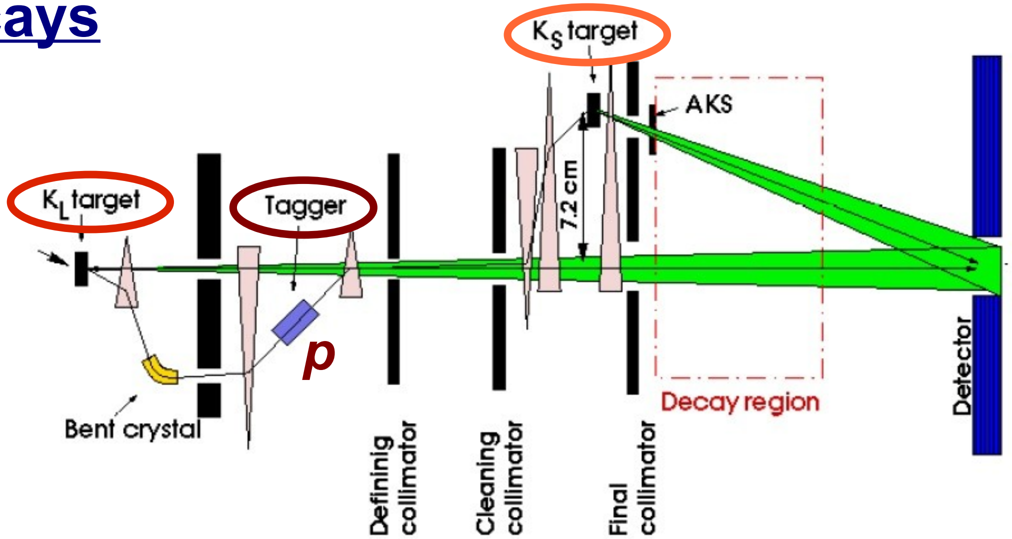


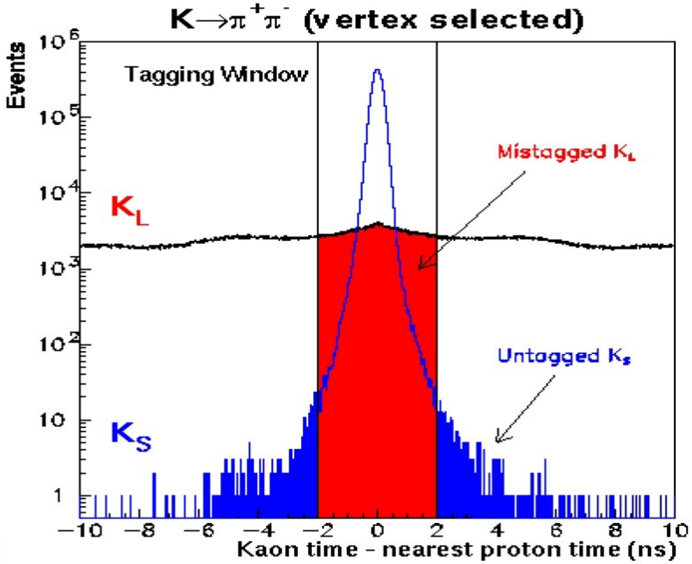


K_L / K_S Tagging

To distinguish K_L decays from K_S decays

- **measure time difference between**
  - **the event measured in detector**
    - $\pi^0\pi^0$: electromagnetic calorimeter
    - $\pi^+\pi^-$: scintillator hodoscope
  - **a proton on its way to the K_S target**
    - tagging counter in proton beam
- **time coincidence ⇒ “K_S event”**
- **no time coincidence ⇒ “K_L event”**
- **need excellent timing resolutions** (200 ps) **to keep mis-tag rates small**
  - for $\pi^+\pi^-$: cross check by comparing with the reconstructed vertex positions





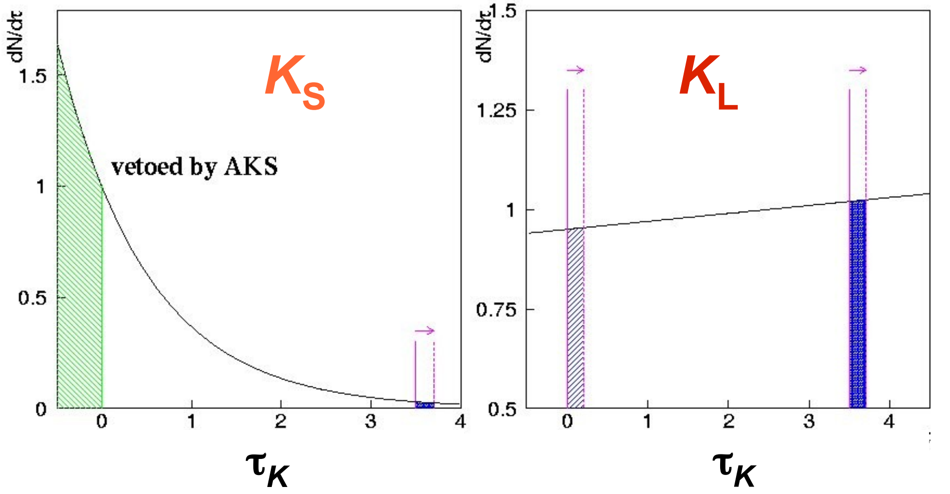
Decay Volumes

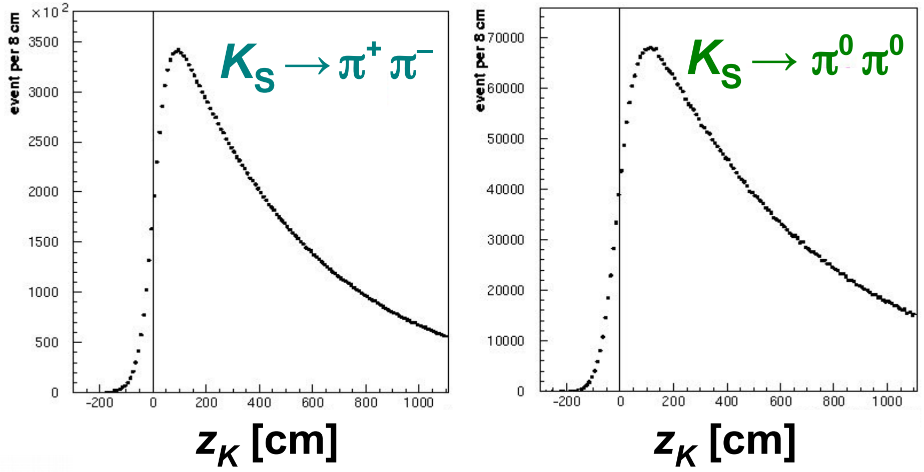
Define region along K_L and K_S beams from which decays are accepted

- **most critical: definition of upstream limit of K_S decay region**
  - dedicated veto counter (“AKS”)
- **definition of all other limits: use reconstructed kaon proper life time**

$$\tau = z_K / \left(\beta_K \gamma_K c \right)$$

- **possible systematic bias on τ_K due to**
  - lateral dimensions of drift chambers
  - lateral dimensions of calorimeter
  - absolute energy scale of calorimeter
- **cross check by comparing reconstructed *z* position with known position of AKS**

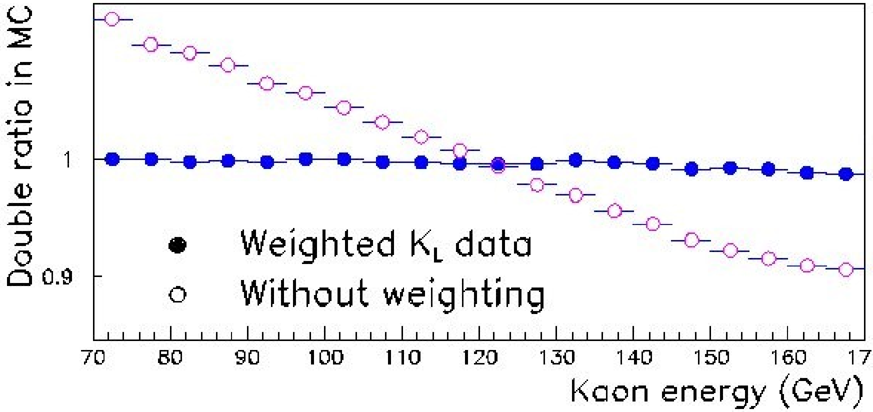




Lifetime Weighting

Still need to correct for the very different lifetimes of K_L and K_S

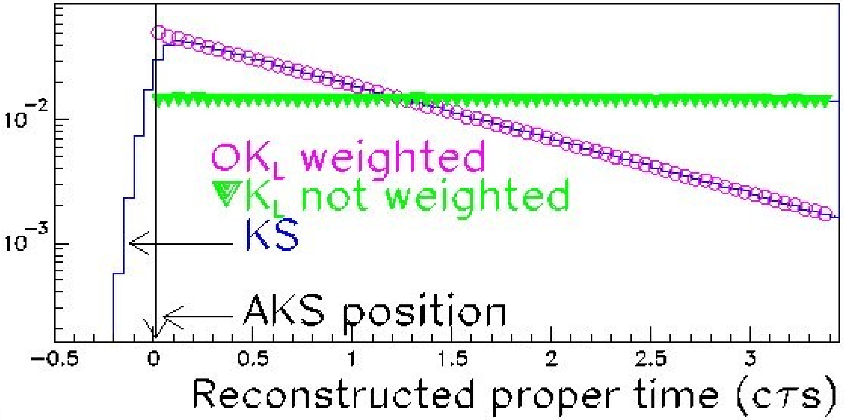
- **leads to very different decay vertex distributions along the fiducial region:**
  - different detector acceptance
  - different illumination of detectors
- **simulation: causes 10% systematic effect on the measured value of double ratio**



- **trick: in analysis, weight each K_L event**

$$w = \exp\left\{-\frac{z_V}{\beta_K\gamma_K c}\cdot\left(\frac{1}{\tau_S}-\frac{1}{\tau_L}\right)\right\}$$

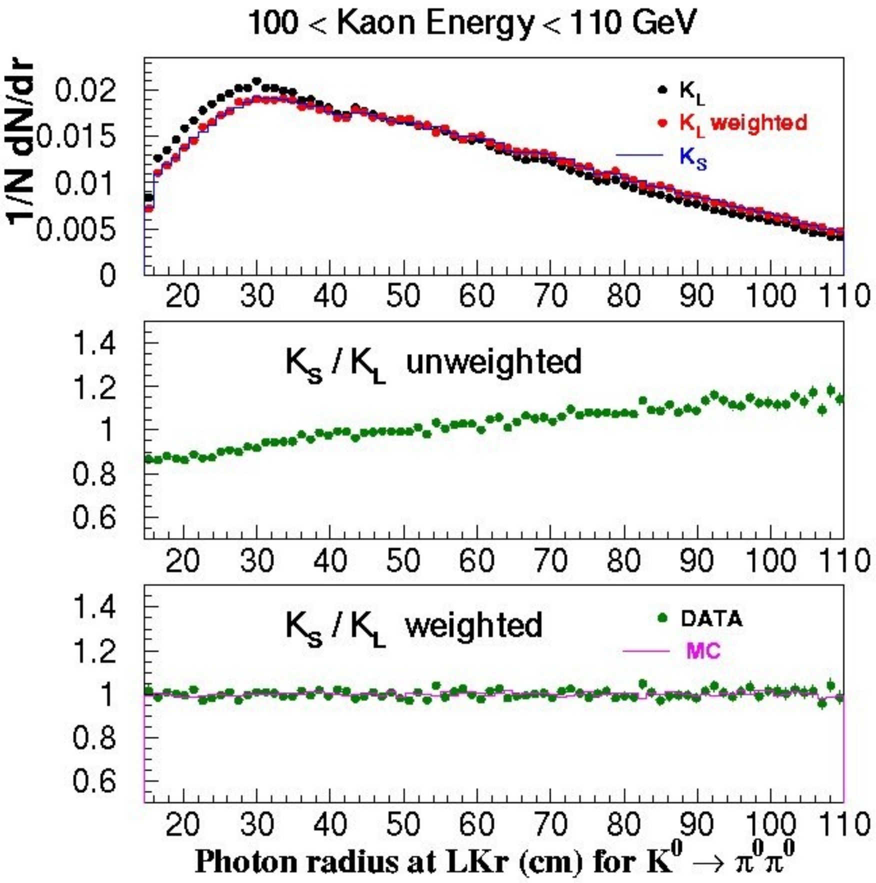
  - results in similar "effective" decay time distribution for K_L as for K_S
- **increase statistical uncertainty by ≈ 35% but large gain in systematic uncertainty**



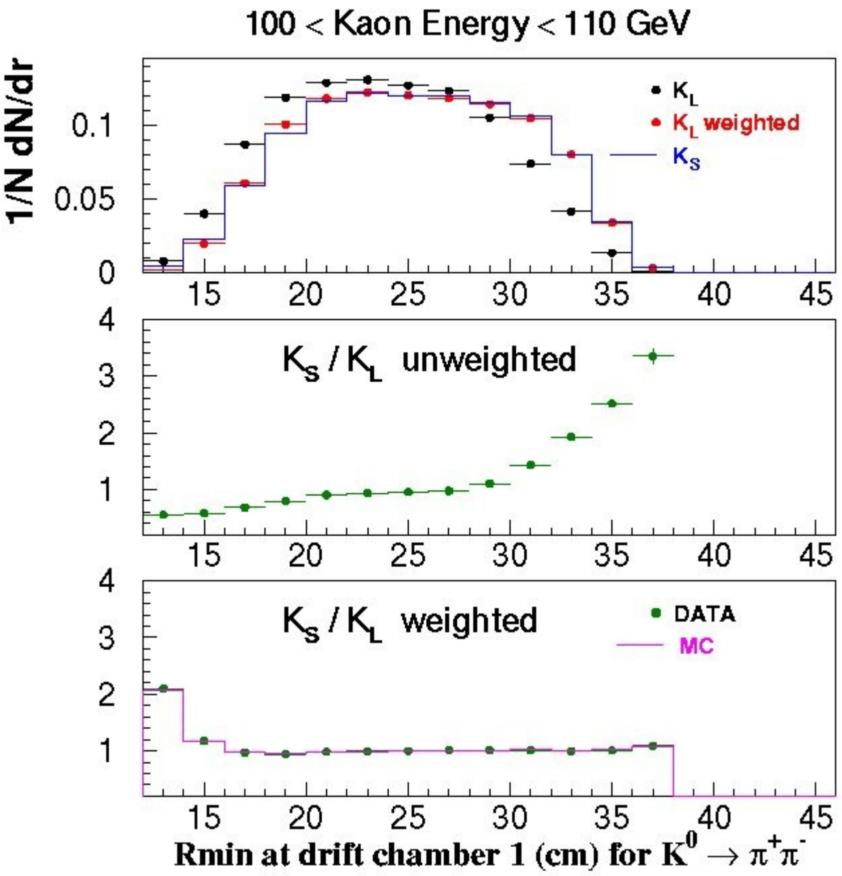
Lifetime Weighting

Illustration: effect on “effective” detector illumination

- $\pi^0\pi^0$: radial cluster positions in electromagnetic calorimeter



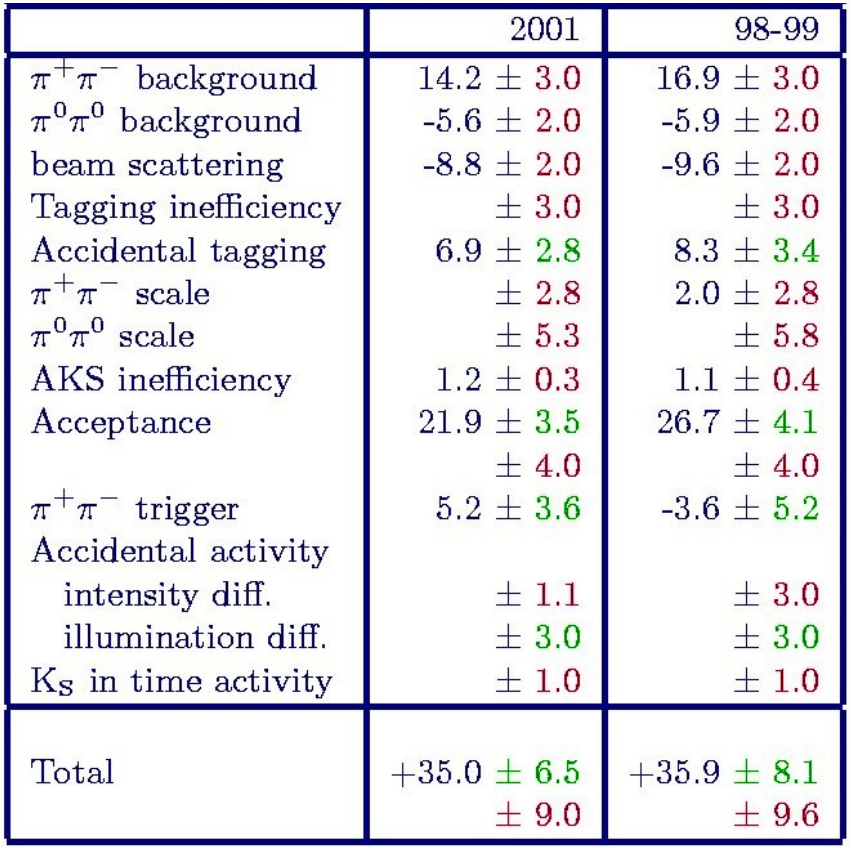
- $\pi^+\pi^-$: radial position of innermost hits in 1st drift chamber



Corrections and Systematics

Summary of all corrections applied to the raw value of the double ratio:

- **all in units of 10^{-4}**
  - statistical uncertainties in green
  - systematic uncertainties in red
- **sum of all corrections is smaller than the deviation of the double ratio from unity**



	2001	98-99
$\pi^+\pi^-$ background	14.2 ± 3.0	16.9 ± 3.0
$\pi^0\pi^0$ background	-5.6 ± 2.0	-5.9 ± 2.0
beam scattering	-8.8 ± 2.0	-9.6 ± 2.0
Tagging inefficiency	± 3.0	± 3.0
Accidental tagging	6.9 ± 2.8	8.3 ± 3.4
$\pi^+\pi^-$ scale	± 2.8	2.0 ± 2.8
$\pi^0\pi^0$ scale	± 5.3	± 5.8
AKS inefficiency	1.2 ± 0.3	1.1 ± 0.4
Acceptance	21.9 ± 3.5 ± 4.0	26.7 ± 4.1 ± 4.0
$\pi^+\pi^-$ trigger	5.2 ± 3.6	-3.6 ± 5.2
Accidental activity		
intensity diff.	± 1.1	± 3.0
illumination diff.	± 3.0	± 3.0
K_S in time activity	± 1.0	± 1.0
Total	+35.0 ± 6.5 ± 9.0	+35.9 ± 8.1 ± 9.6

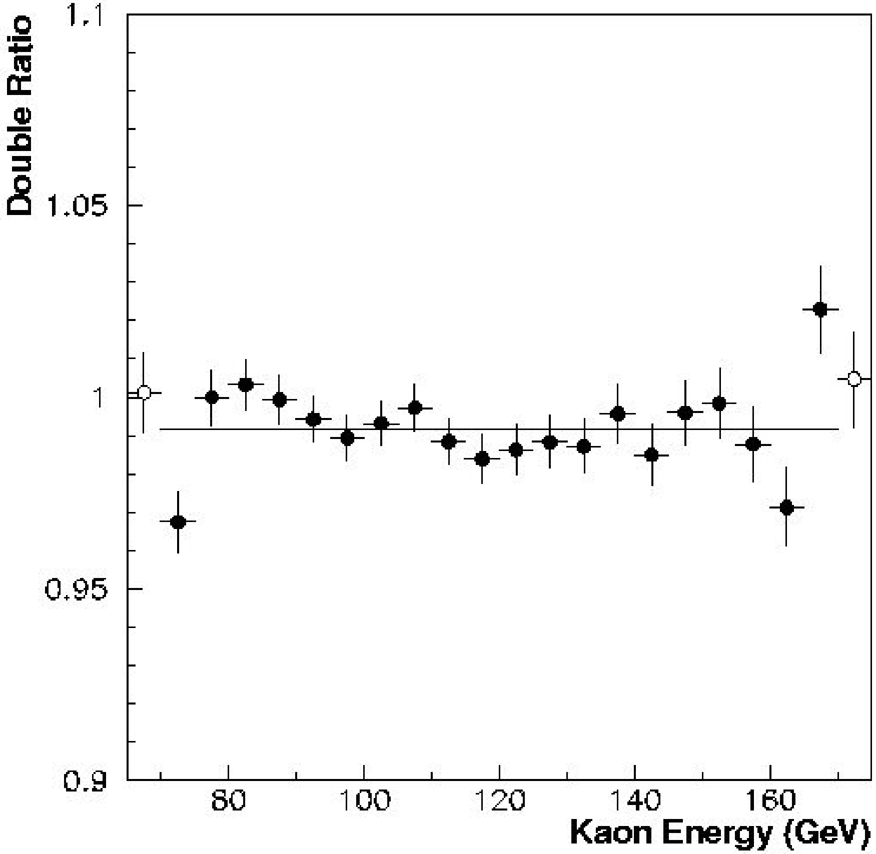
Final result:

$$R = \underbrace{1 - (1.169 \pm 0.147)\%}_{\text{result before corrections}} + \underbrace{(0.350 \pm 0.111)\%}_{\text{corrections}}$$

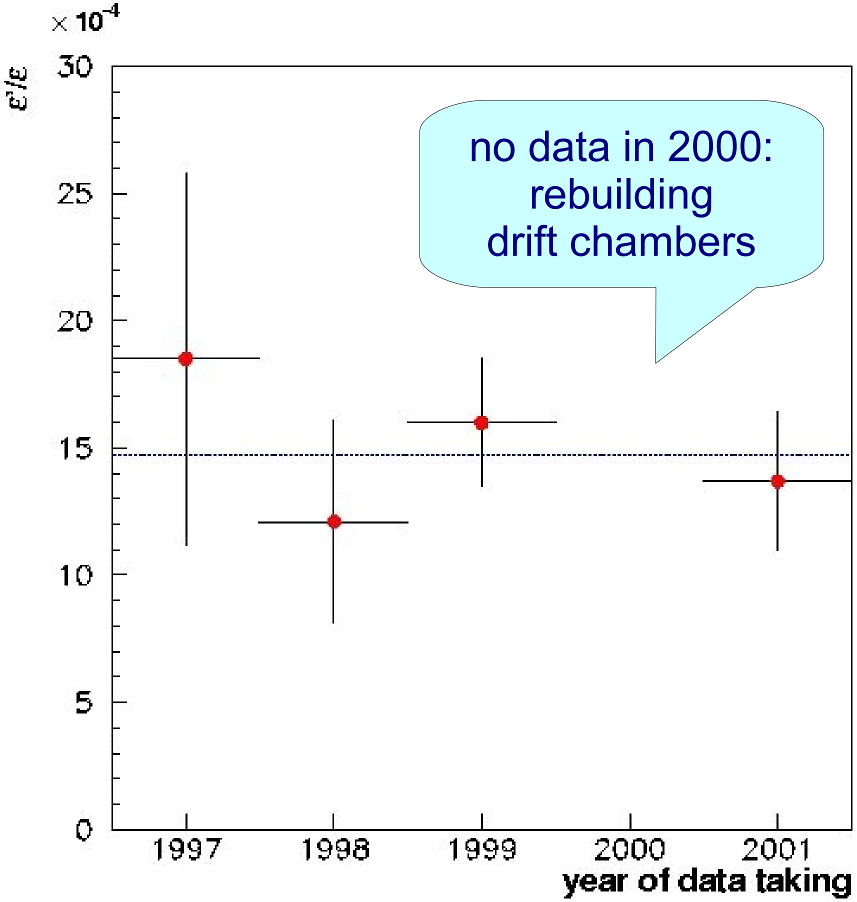
Cross Checks

Study stability of result against various parameters, e.g.

- calculate the double ratio in bins of the reconstructed kaon energy



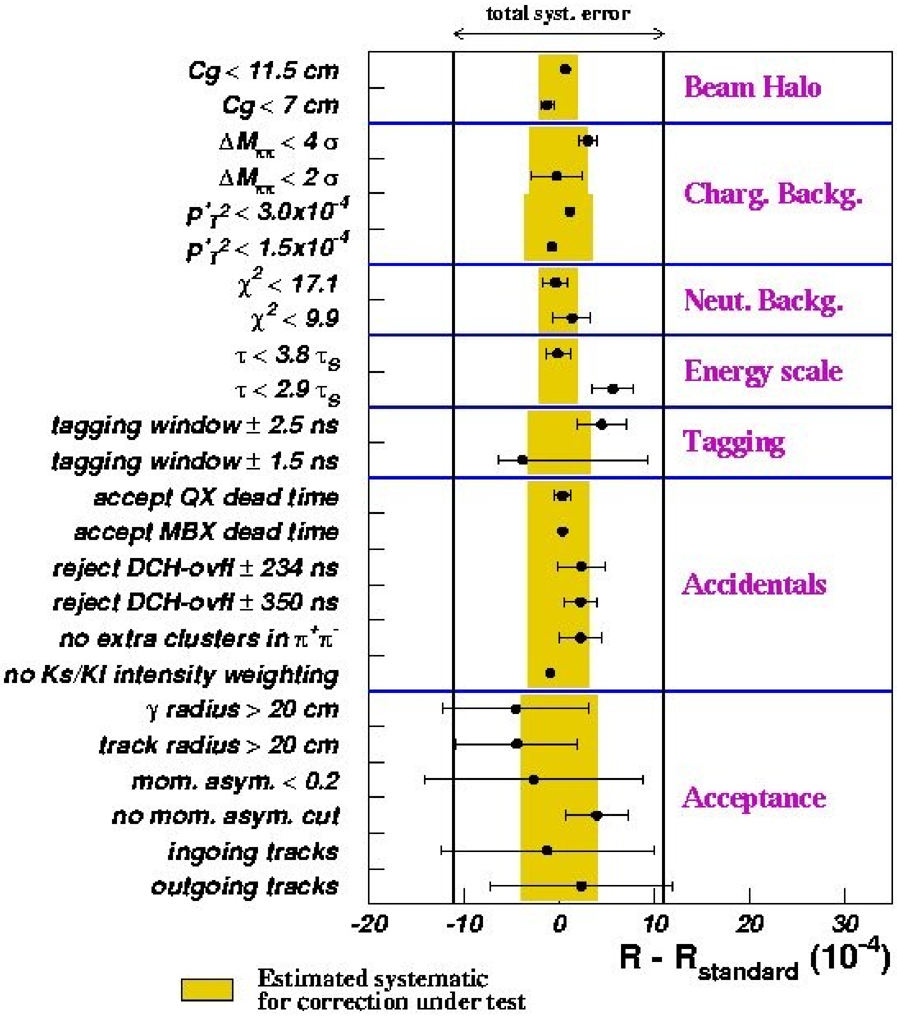
- calculate Re (ε'/ε) separately for different run periods



no data in 2000: rebuilding drift chambers

Cross Checks

Recalculate double ratio for different values of the selection cuts



Final Results

- **NA48 (**data taking 1997-2001, final result announced in 2002**)**

Re (ε'/ε) = (14.7 ± 2.2) × 10^{-4}

- **KTeV (**data taking 1996-1999, final result announced in 2009**)**

Re (ε'/ε) = (19.2 ± 2.1) × 10^{-4}

- **ε'/ε ≠ 0 was an important milestone**
  - ruled out alternative models of *CP* violation (e.g. new “Superweak” interaction)
- **unfortunately large theoretical uncertainties on Standard Model prediction**
  - do not learn much about the Standard Model parameters, ρ and η

Final Results

- **NA48 (**data taking 1997-2001, final result announced in 2002**)**

$$\mathrm{Re}\,(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4}$$

- **KTeV (**data taking 1996-1999, final result announced in 2009**)**

Re (ε'/ε) = (19.2

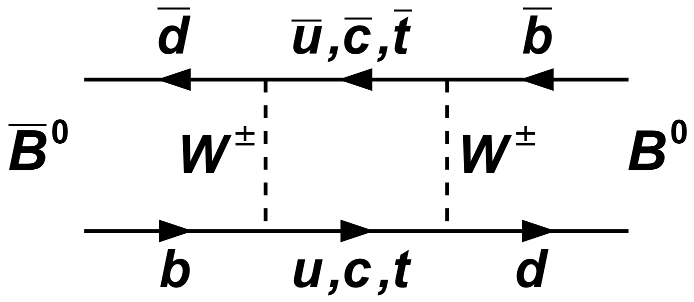
This might actually be changing due to improved precision in lattice-QCD calculations

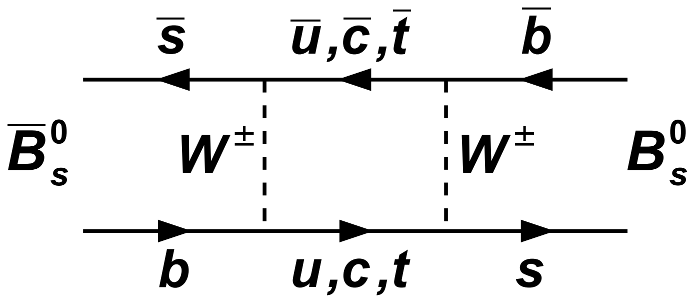
- **ε'/ε ≠ 0 was an important milestone**
  - ruled out alternative models of *CP* violation (e.g. new “Superweak” interaction)
- **unfortunately large theoretical uncertainties on Standard Model prediction**
  - do not learn much about the Standard Model parameters, ρ and η

Other Neutral Meson Systems

$B^0\,\overline{B}{}^0$ and $B_s^0\,\overline{B}{}_s^0$ systems

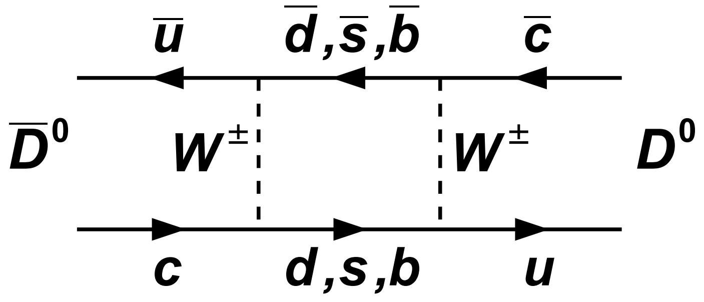
- **significant mixing and *CP* violation predicted and observed**
  - one of the main research topics in LHCb
- **many decay channels, many observables, precise theory predictions**
- **allows precision tests of the Standard Model**



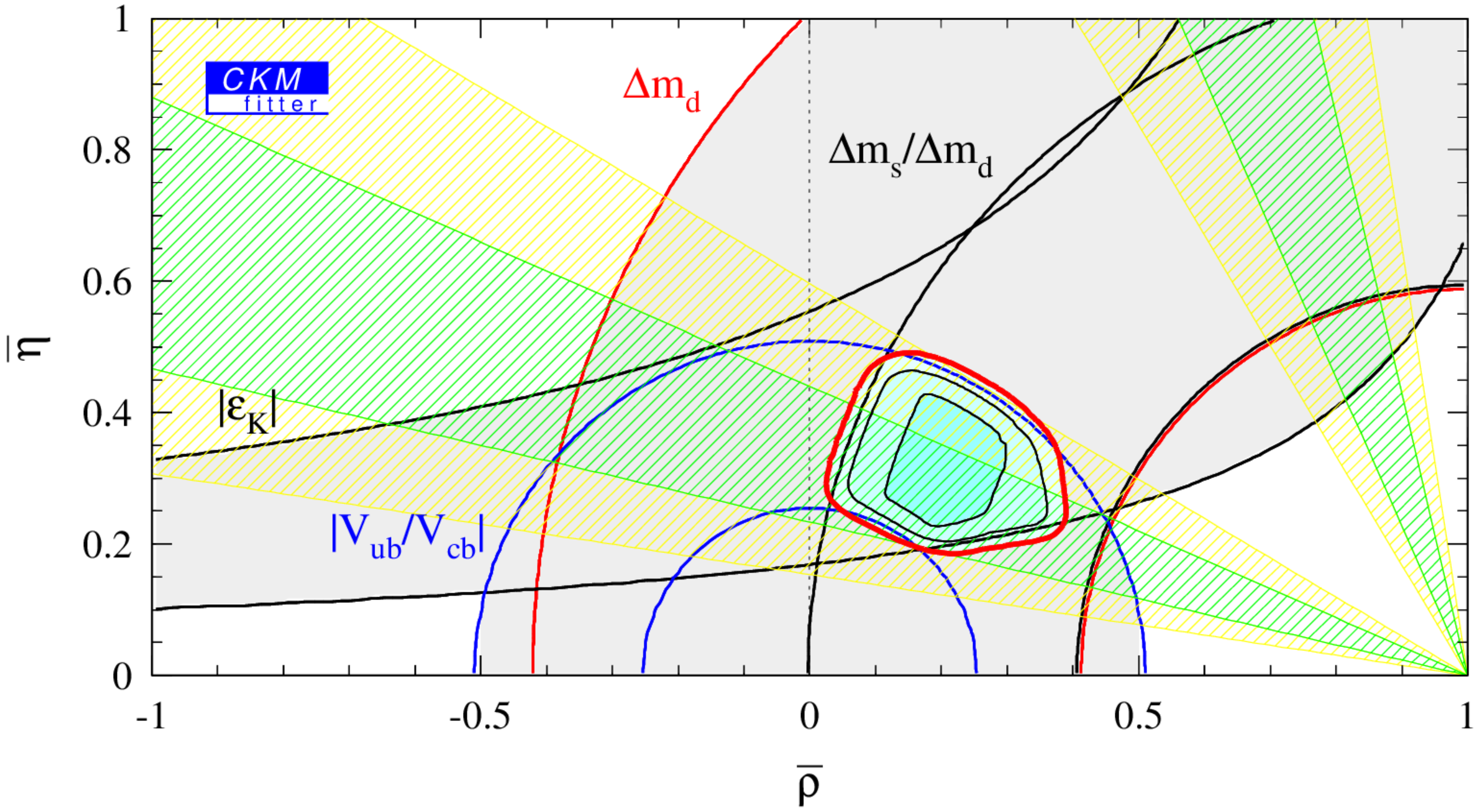


$D^0\,\overline{D}{}^0$ system

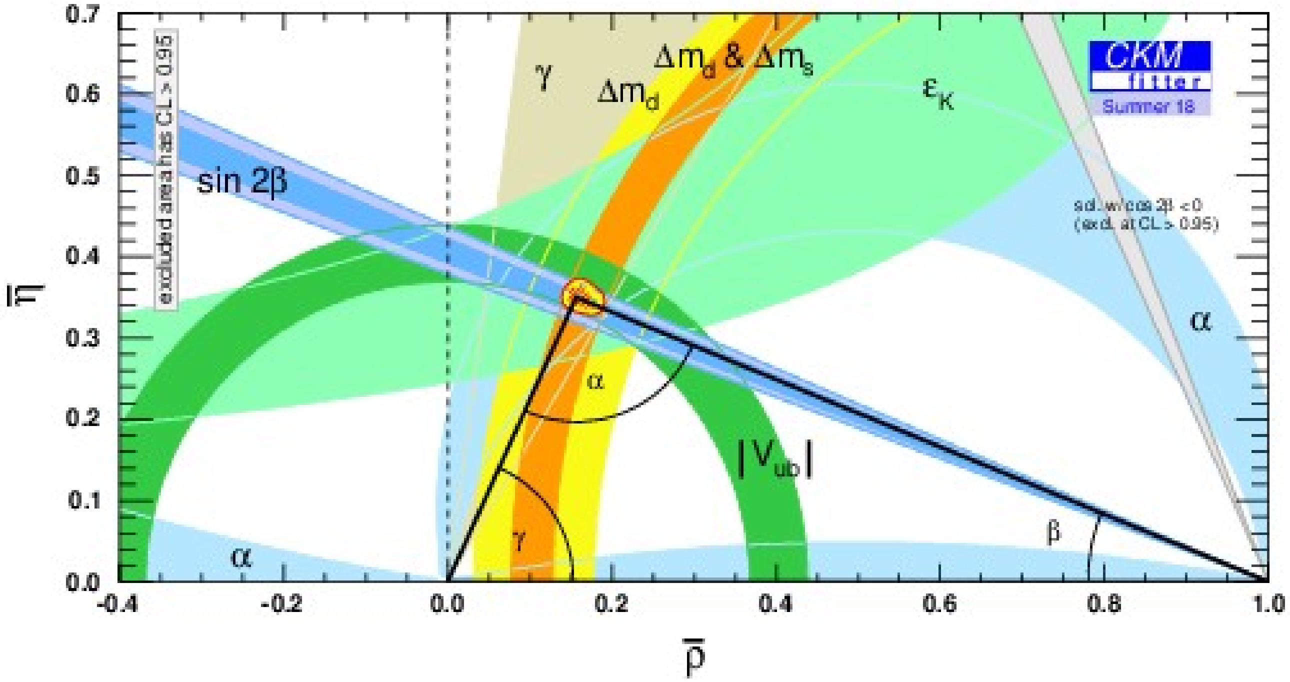
- **mixing and *CP* violation predicted to be very small**
  - also studied in LHCb
- **mixing has been observed**
- ***CP* violation has not yet been observed**



Unitarity Triangle



Unitarity Triangle



The slides of this lecture are available at

http://www.physik.uzh.ch/~olafs/pdf/190220_MISIS.pdf