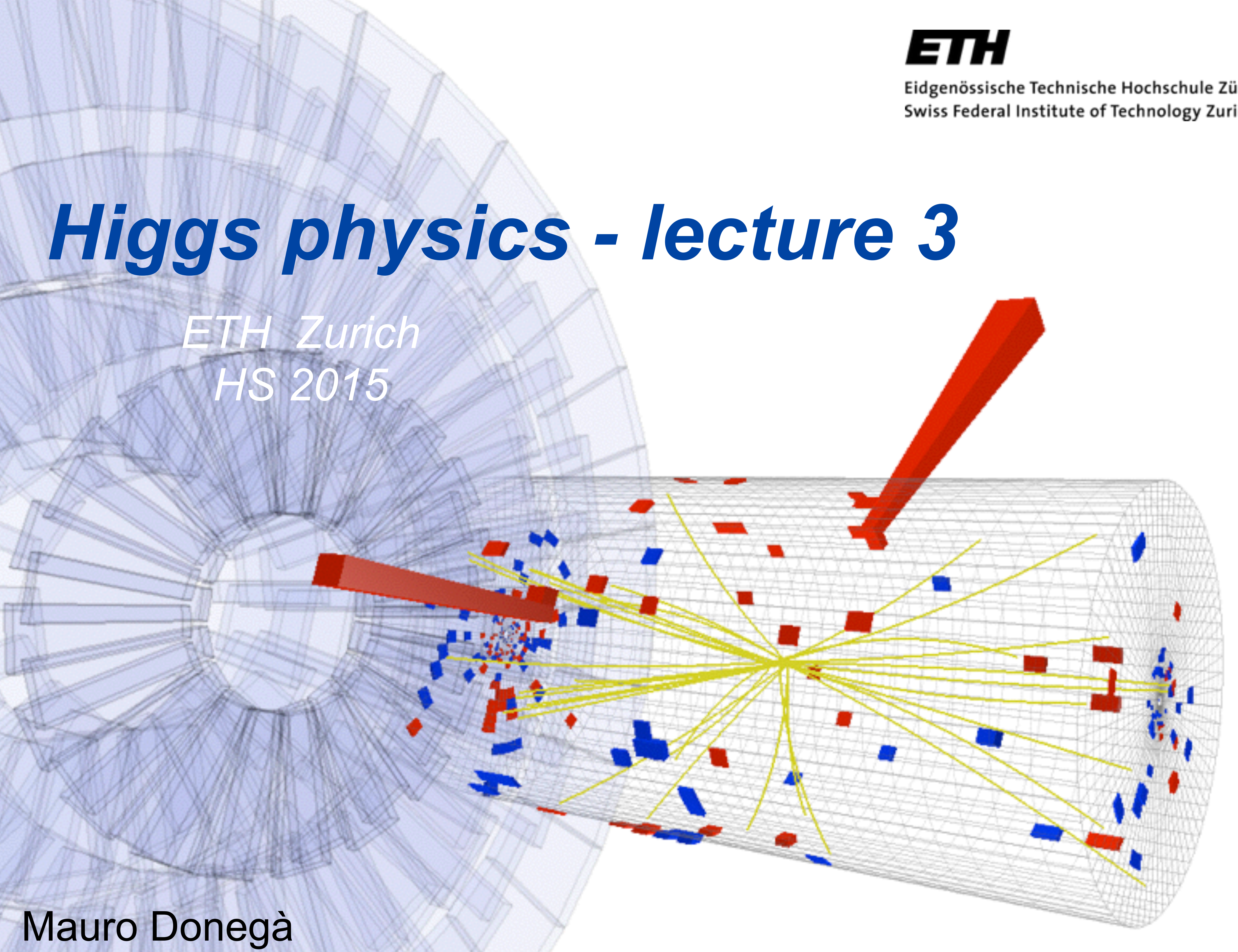
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Higgs physics - lecture 3

ETH Zurich
HS 2015



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Practicalities

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Moodle will store slides, exercises, papers and references

Detailed bibliography will be given at each class

Outline

▶ 1
- Introduction
- Accelerators
- Detectors
- EW constraints

▶ 2
- Statistics: likelihood and hypothesis testing
- Electroweak global fits
- LEP 2

▶ 3
- TeVatron
  - Multivariate Analysis Techniques
  - Results

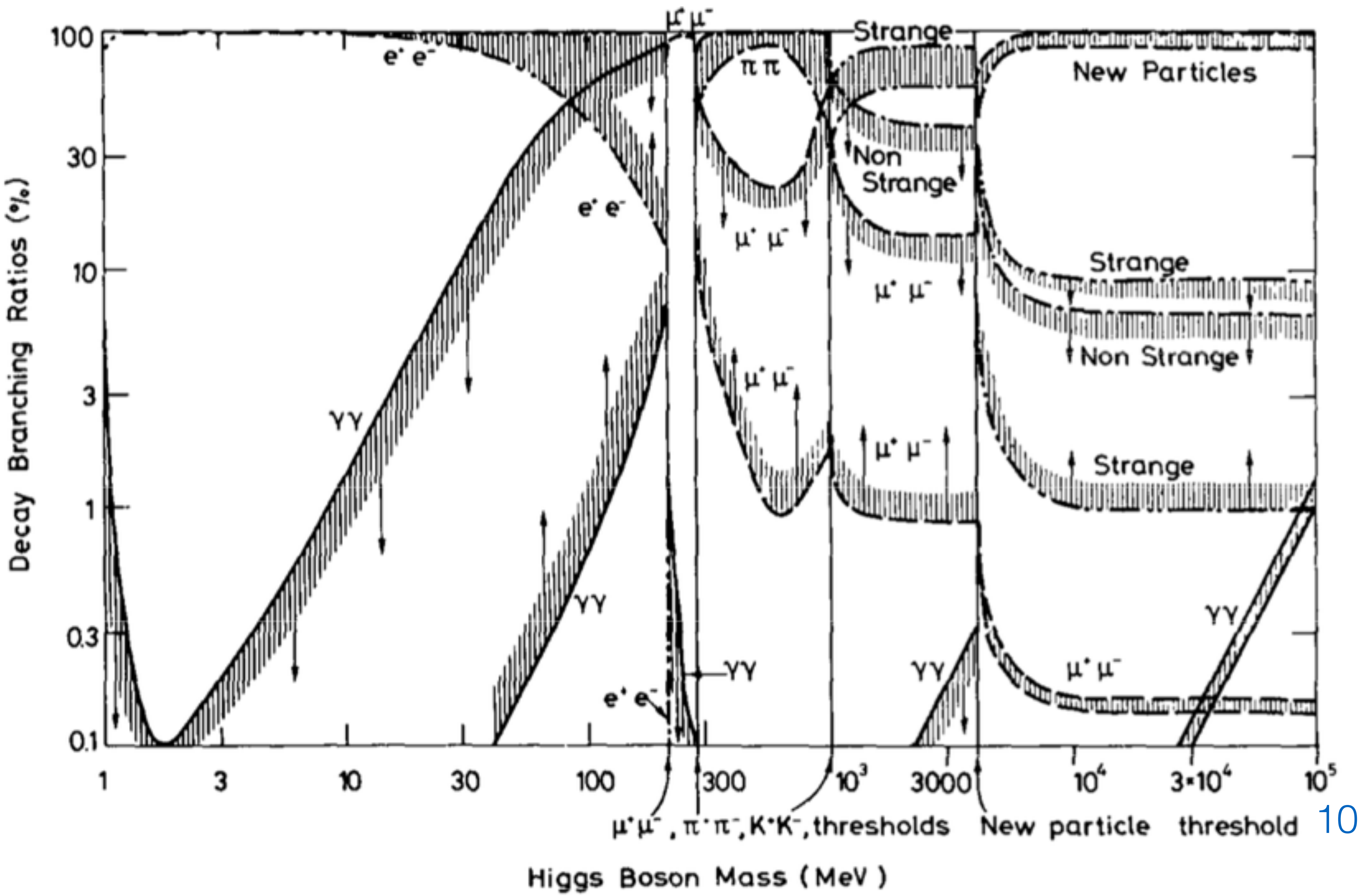
▶ 4
- LHC
  - channels overview

▶ 5
  - dissect one analysis
  - Higgs combination

▶ 6
- Extras
  - differential distributions
  - off shell
  - Beyond Standard Model
  - pseudo-observables / EFT

Early days

Ellis, Gaillard, Nanopoulos,1975

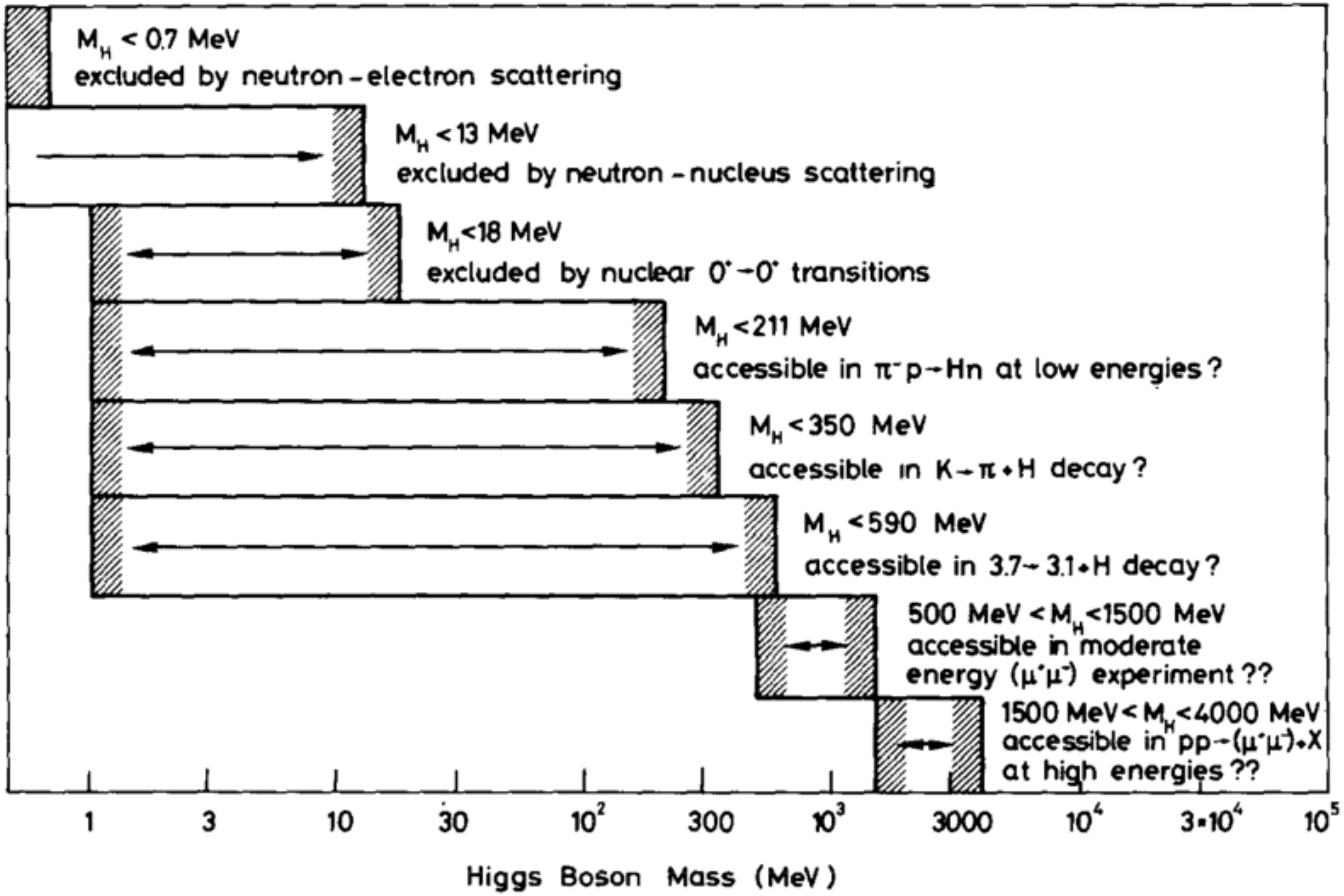


100 GeV

“at the time of writing the discovery of the charm has not been confirmed”
…let alone beauty (’77), gluon (’79) and top (’95)

Early days

Ellis, Gaillard, Nanopoulos,1975



Early days

Ellis, Gaillard, Nanopoulos,1975

Many people now believe that weak and electromagnetic interactions may be described by a unified, renormalizable, spontaneously broken gauge theory [I]. This view has not been discouraged by the advent of neutral currents, or the existence of the new narrow resonances [2].

Standard Model

Gargamelle @ CERN

J/ψ resonance Richter/Ting

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Review of basic concepts

Cross section

definition → flux $\sigma = \frac{1}{nIA}\frac{dW}{dz}$

$\sigma_{tot} = \sum_i \sigma_i$ $[\sigma] = \text{barn} = 10^{-28}\,m^2$

$pb = 10^{-12}\,b$

$fb = 10^{-15}\,b$ $ab = 10^{-18}\,b$

Luminosity

colliding (gaussian) beams

$$\mathcal{L} = \frac{f \cdot n_1 \cdot n_2}{4\pi\sigma_x\sigma_y} \left(= \frac{f \cdot n_1 \cdot n_2}{4(\beta^* \cdot \epsilon)} \right)$$

LHC

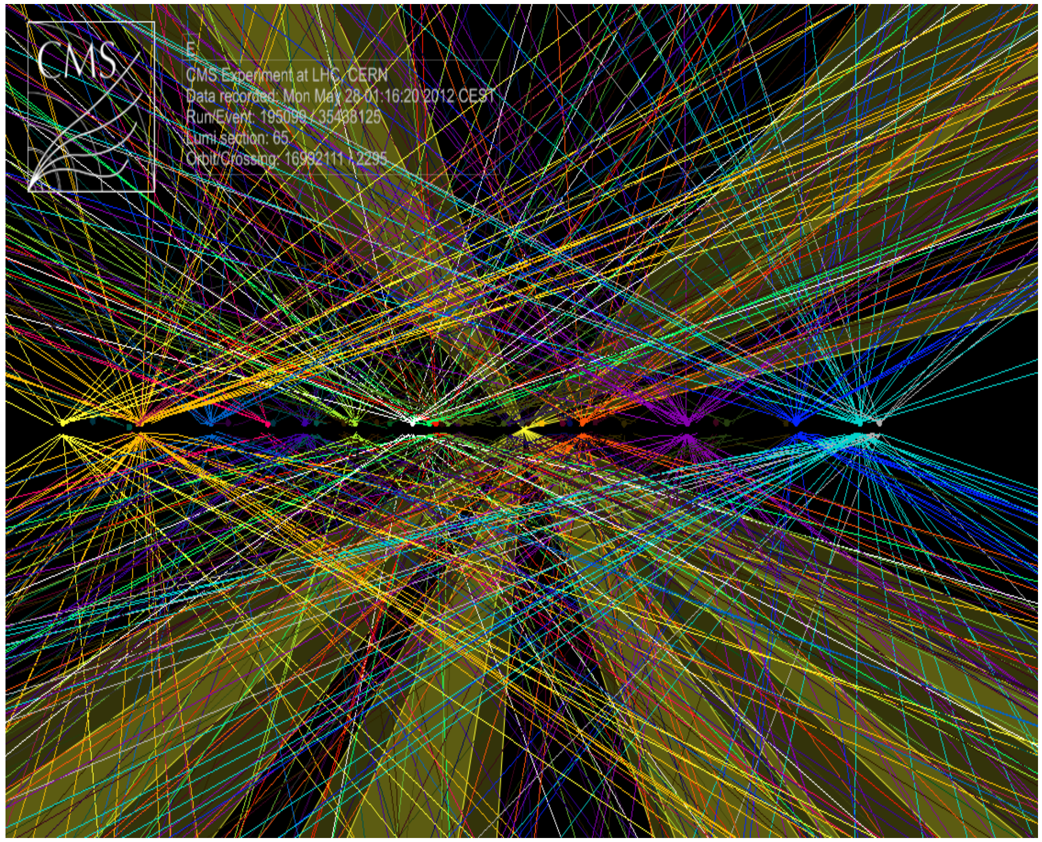
$n \sim 10^{11}$ × 2808 bunches

$\sigma \sim 20\ \mu m$

$f \sim 11\ kHz$ (27km)

$\mathcal{L} \sim 10^{34} / cm^2 s$ $L = \int \mathcal{L}\, dt$

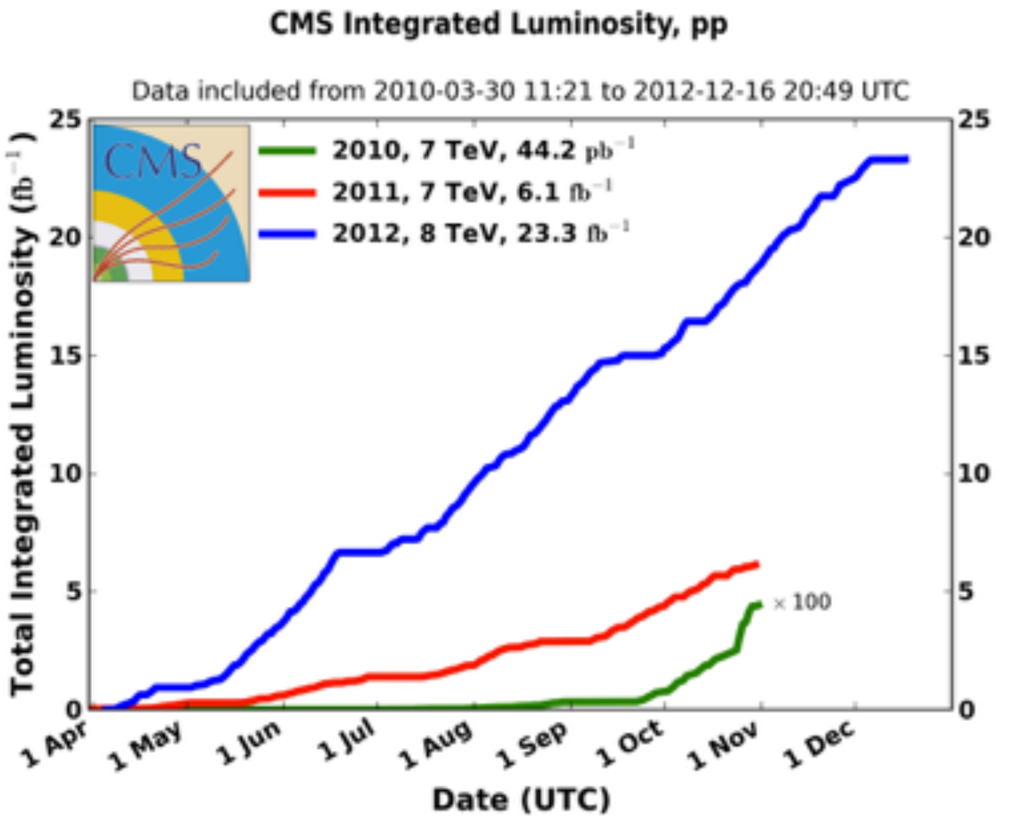
instantaneous   integrated

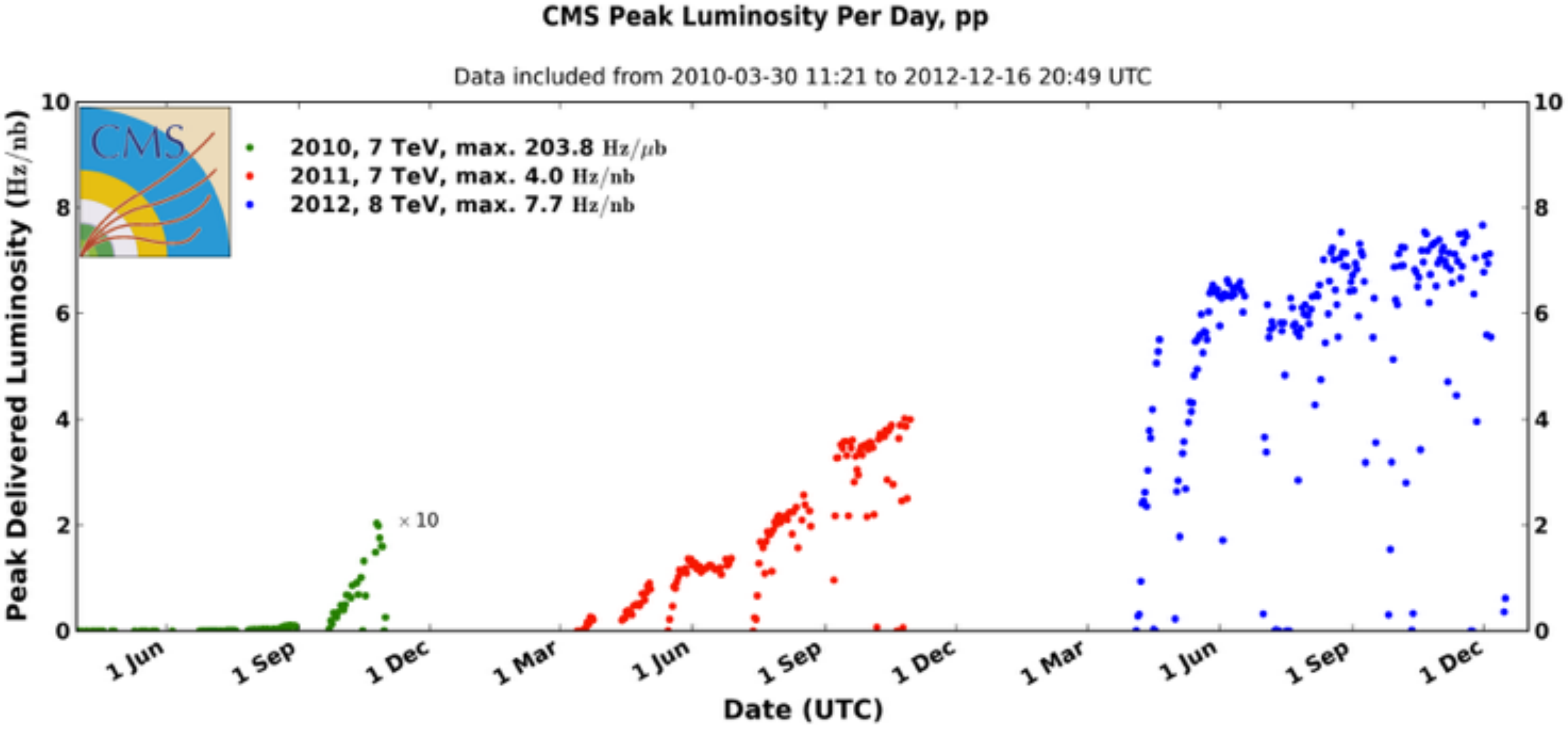


LHC luminosity Run 1

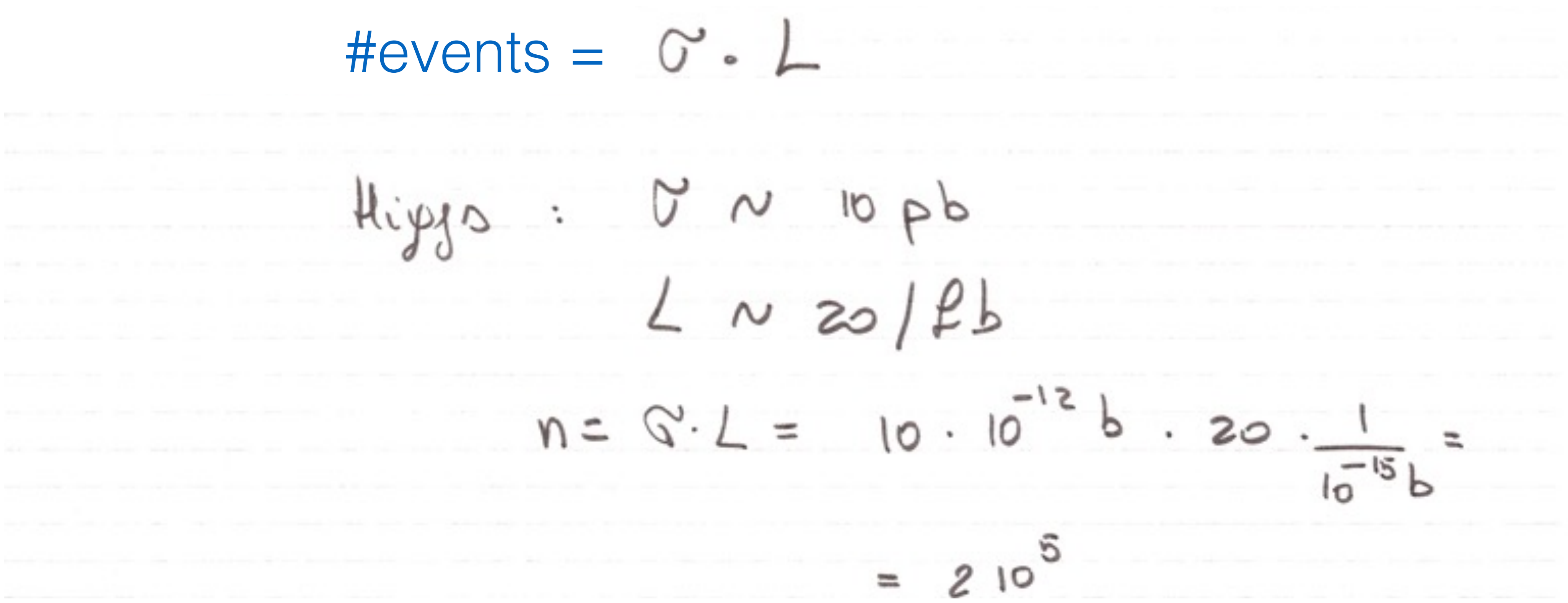
~30 fb^{-1} delivered to experiments

7 TeV: ~44 pb^{-1} in 2010,
~6 fb^{-1} in 2011
8 TeV: ~23 fb^{-1} in 2012





Review of basic concepts



#events = $\sigma \cdot L$

Higgs : $\sigma \sim 10\ pb$

$L \sim 20/fb$

$$n = \sigma \cdot L = 10 \cdot 10^{-12}\, b \cdot 20 \cdot \frac{1}{10^{-15}\, b} =$$

$$= 2\ 10^{5}$$

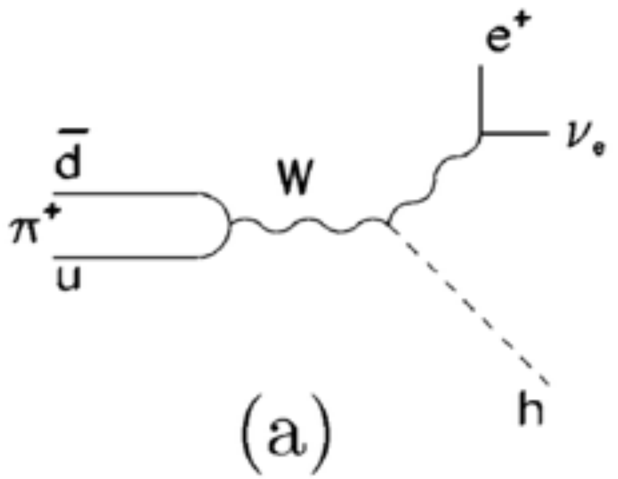
How many you expect in H->ZZ ?
How many do you see in the CMS invariant mass plot?

Higgs below 5 GeV

SINDRUM @ PSI

h→ee

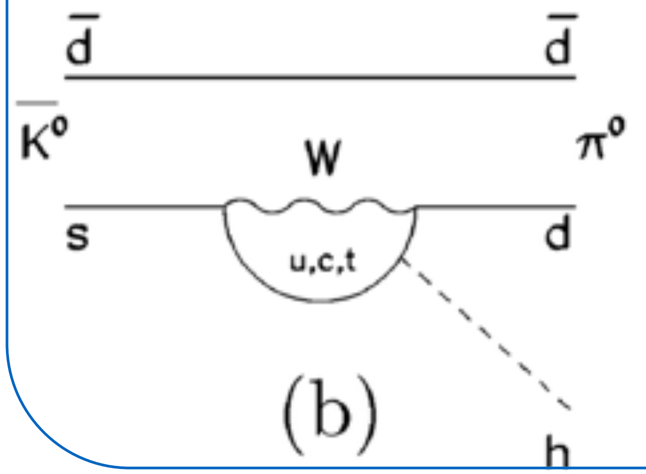
$m_h \notin [10, 110]$ MeV

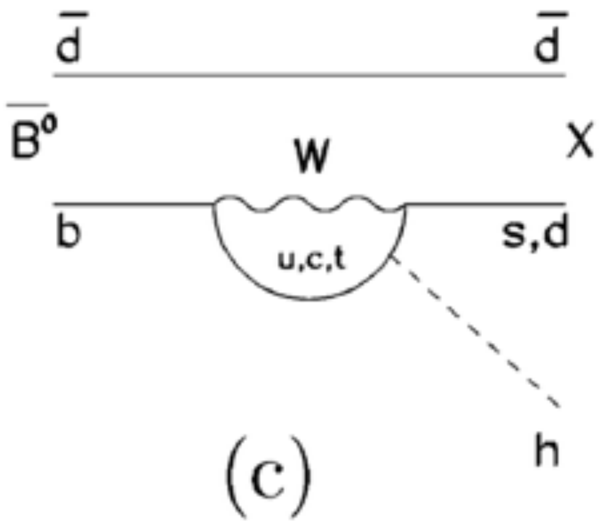


CERN-Edinburgh-Mainz-Orsay-Pisa-Siegen

h→ee m_h<50 MeV

$$BR(K_L^0 \to \pi^0 H) \times BR(H \to e^+e^-) < 210^{-8}$$

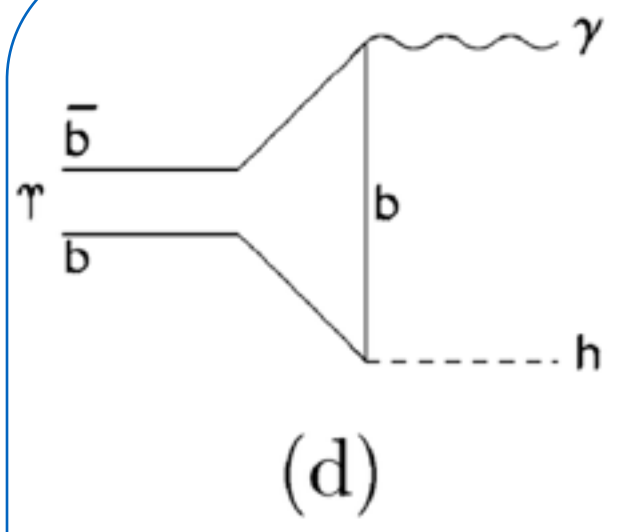




CLEO

h→ee

$m_h \notin [0.2, 3.6]$ GeV



CUSB

h→ee

$m_h \notin [0.2, 5.0]$ GeV

Colliders

Lepton Colliders			Hadron Colliders
e^+e^-	SLC	polarized	$Sp\bar{p}S$
	LEP		TeVatron
$\mu^+\mu^-$	μ-collider		LHC

What are the pro/con of a muon collider ?

Collider vs. fixed target

$$s = (p_1^\mu + p_2^\mu)^2 = m^2$$

F.T. $m = \sqrt{s} \sim \sqrt{2 E_p m_p}$ $\quad m = 125 \quad E_p \sim 30\,\text{TeV}$

C.B. $m = \sqrt{s} \sim \frac{E}{2}$ $\quad m = 91\,\text{GeV}$

$E_{e^+} = E_{e^-} \simeq 45\,\text{GeV}$

Colliders

Lepton → point like (fixed E)

precise knowledge of the CM energy

Hadrons → (protons) composite (pdf)

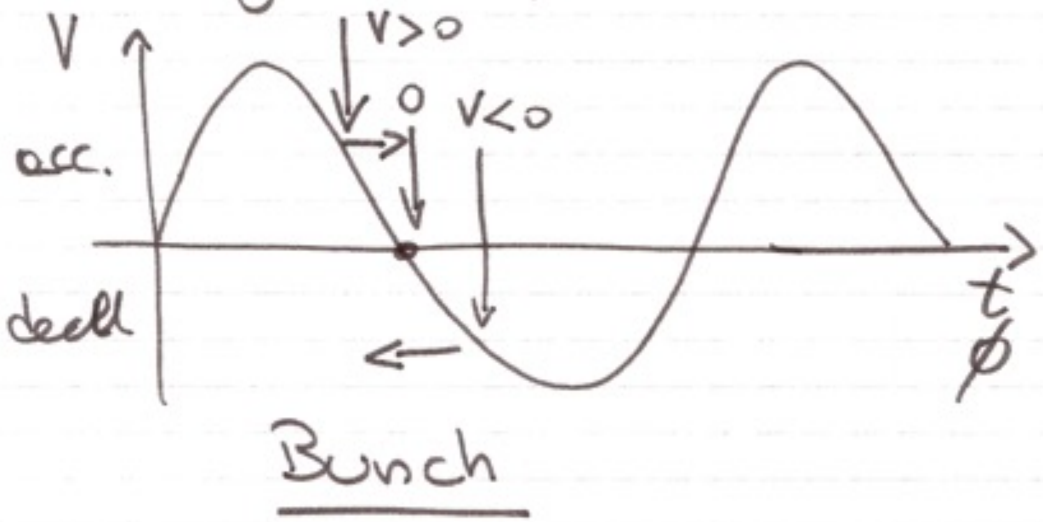
we will see the details of $p\bar{p}$ / pp collisions with LHC/TeVatron

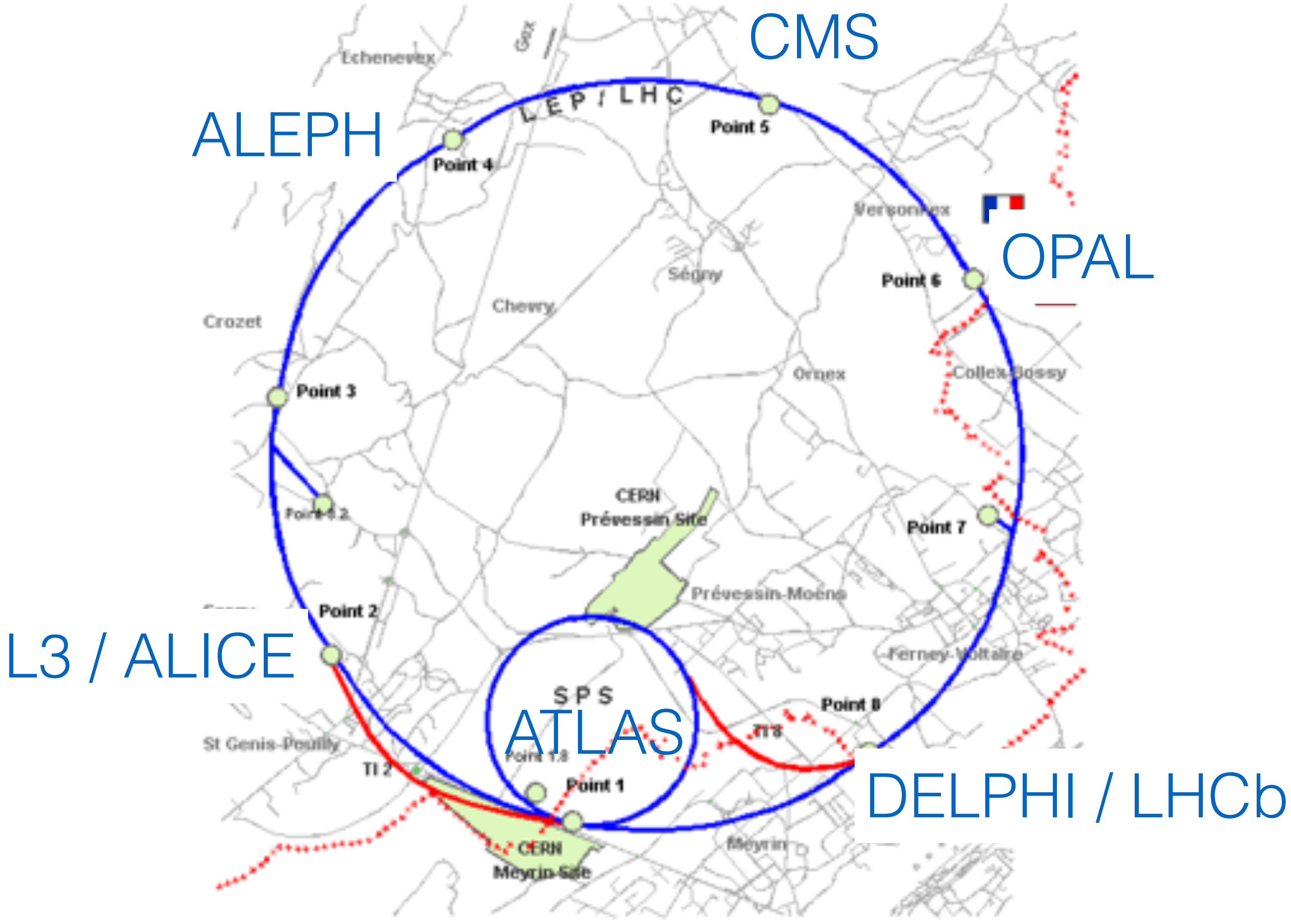
Linear/Circular

single shot /no brem

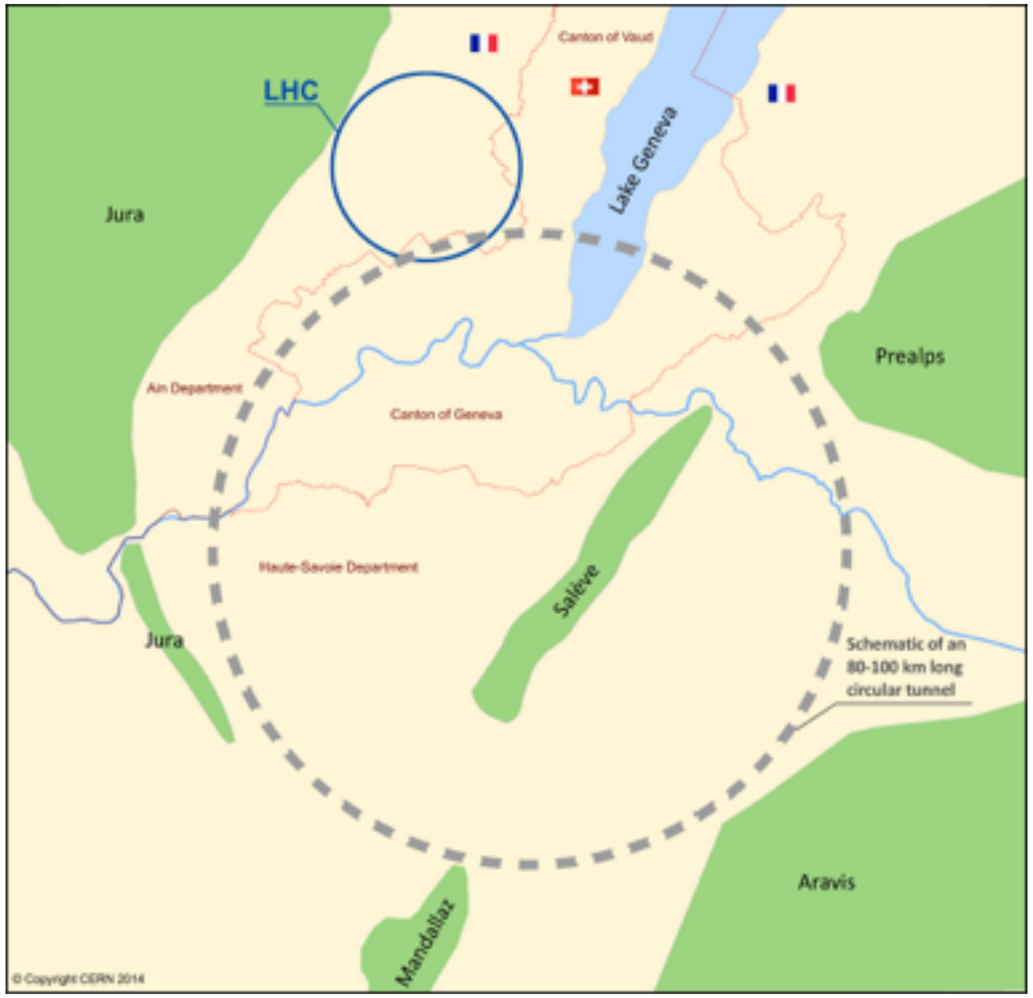
RF cavities
(clic / plasma wakefield)

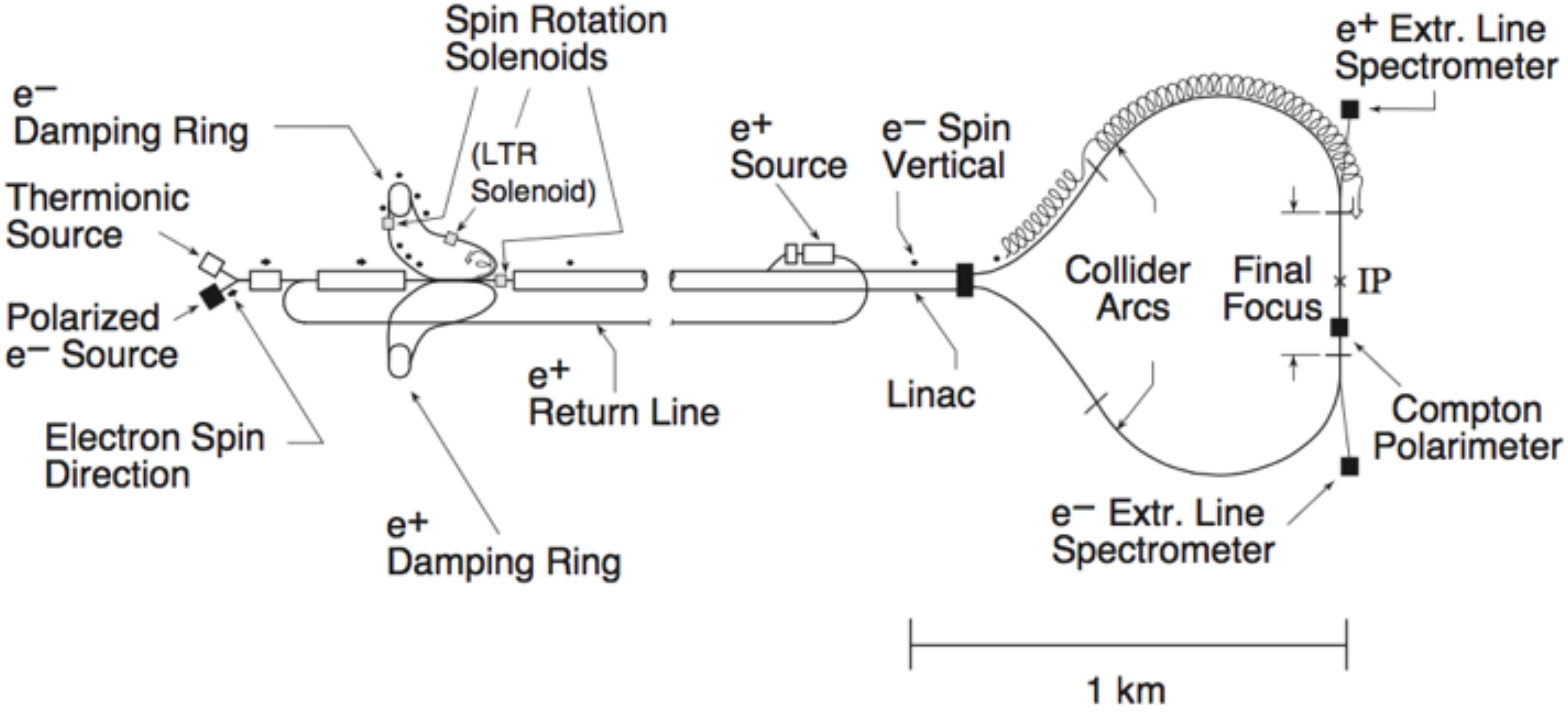
$\mathcal{O}$(MV/m)



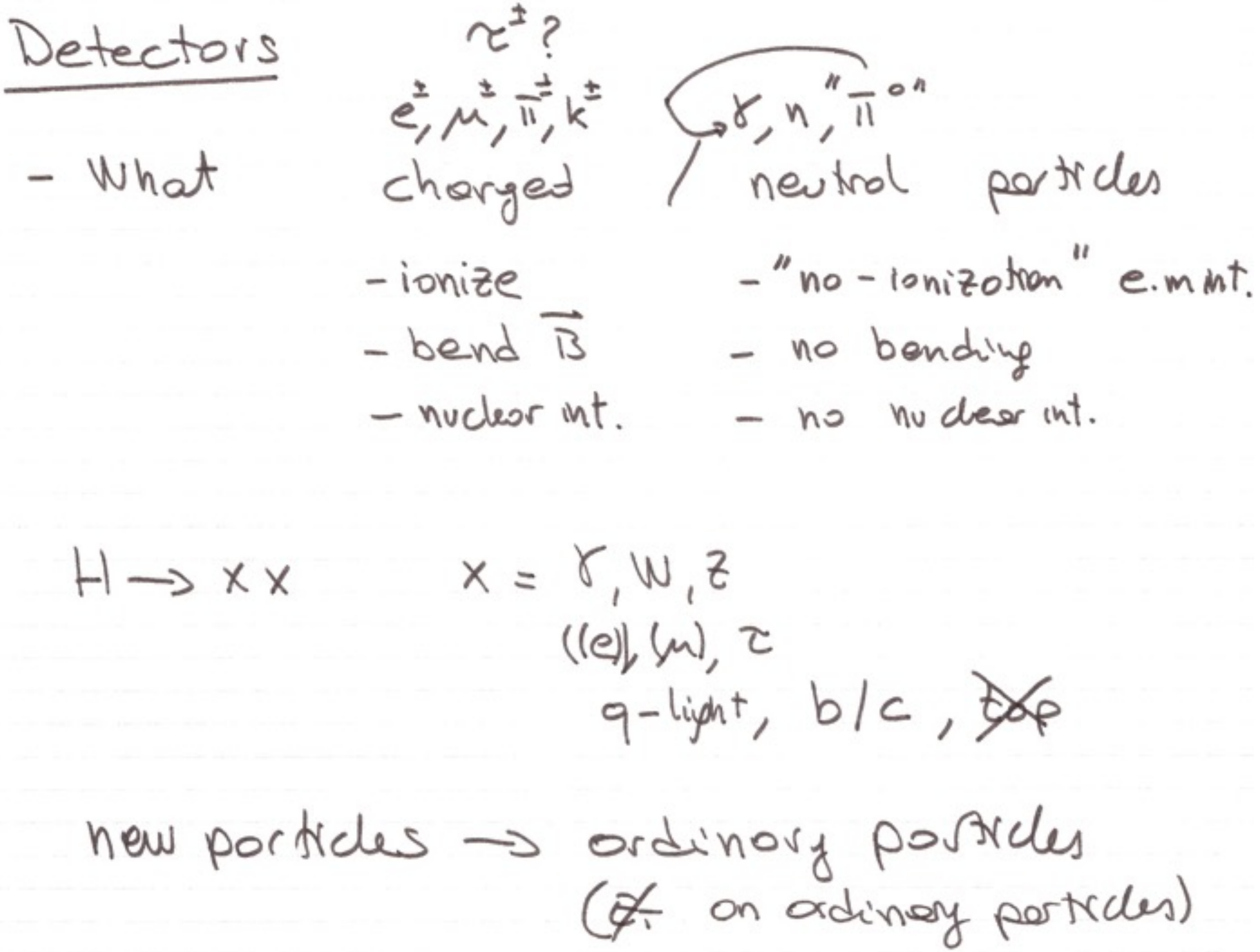


Map of CERN sites and LHC access points





Detectors



Detectors

- What

$\tau^{\pm}$? $e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}$ charged	γ, n, "π^0" neutral particles
- ionize	- "no-ionization" e.m. int.
- bend $\vec{B}$	- no bending
- nuclear int.	- no nuclear int.

$H \to XX$ $\quad X = \gamma, W, Z$

((e)), (μ), τ

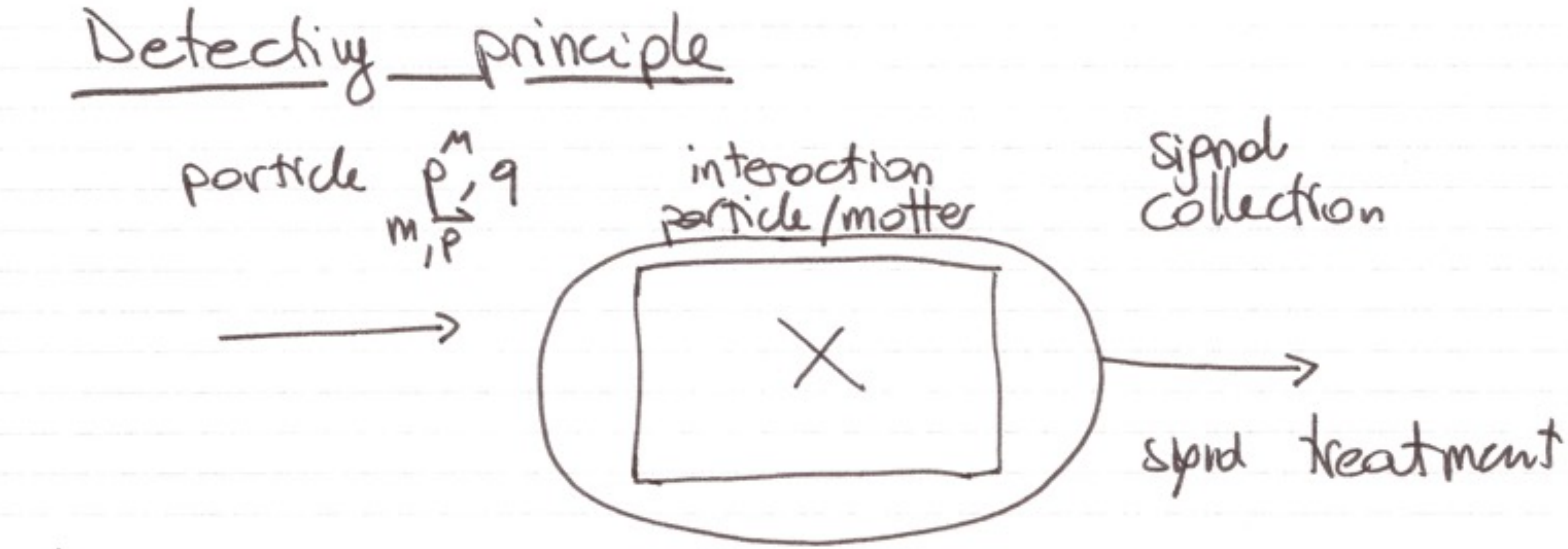
q-light, b/c, ~~top~~

new particles → ordinary particles

($\not{E}_T$ on ordinary particles)

What can create missing transverse energy ?

Detectors



$\vec{B}$ $p = 0.3 \cdot B \cdot R$ $[B] = T$ $[R] = m$ $[p] = GeV$

What is a LOOPER for ATLAS (B=2T) and CMS (B=4T) ?

Passage of particles through matter

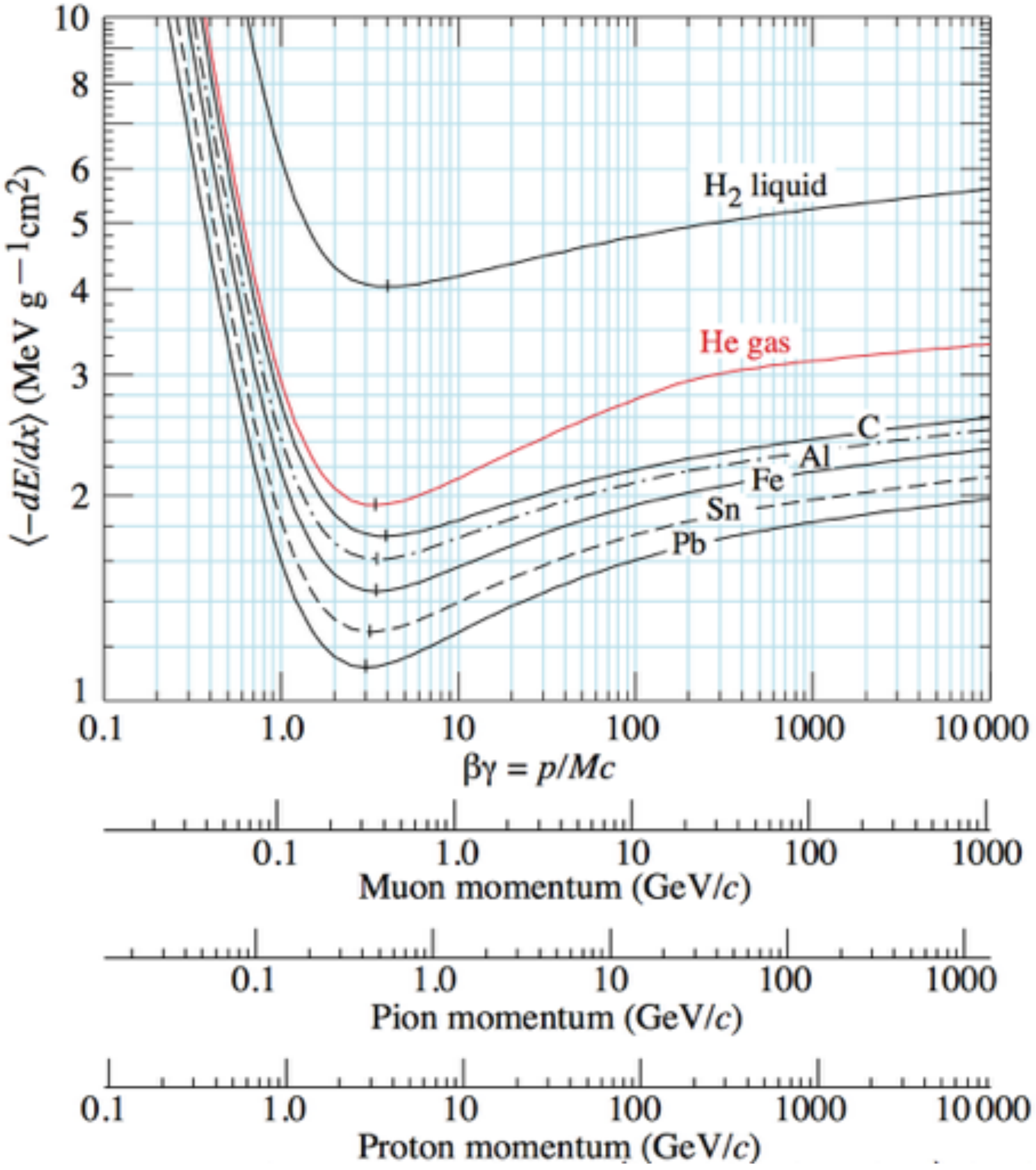
Momentum range for Higgs physics

$[\mathcal{O}(1\,GeV) - \mathcal{O}(1\,TeV)]$

Ionization energy loss

- "electronic" energy loss by heavy particles
  - heavy $> m_e$ $\mu, \pi, p, \dots$
  - stopping power – Bethe-Bloch
  - (density effects, δ-rays, Landau-fluctuation, multiple scattering...) μ-brems few 100 GeV

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



How do you get from the Bethe-Bloch to the Bragg peak ?

Passage of particles through matter

Electrons E>1 GeV only bremsstrahlung

Electrons E>1GeV only pair production

e/γ Radiation length

- mean distance over which an electron loses all but 1/e of its energy by bremsstrahlung
- 7/9 of the mean free path for pair production by a γ

$\sigma_{TOT} \simeq (\sigma_{compton}) + \sigma_{p.p.}$

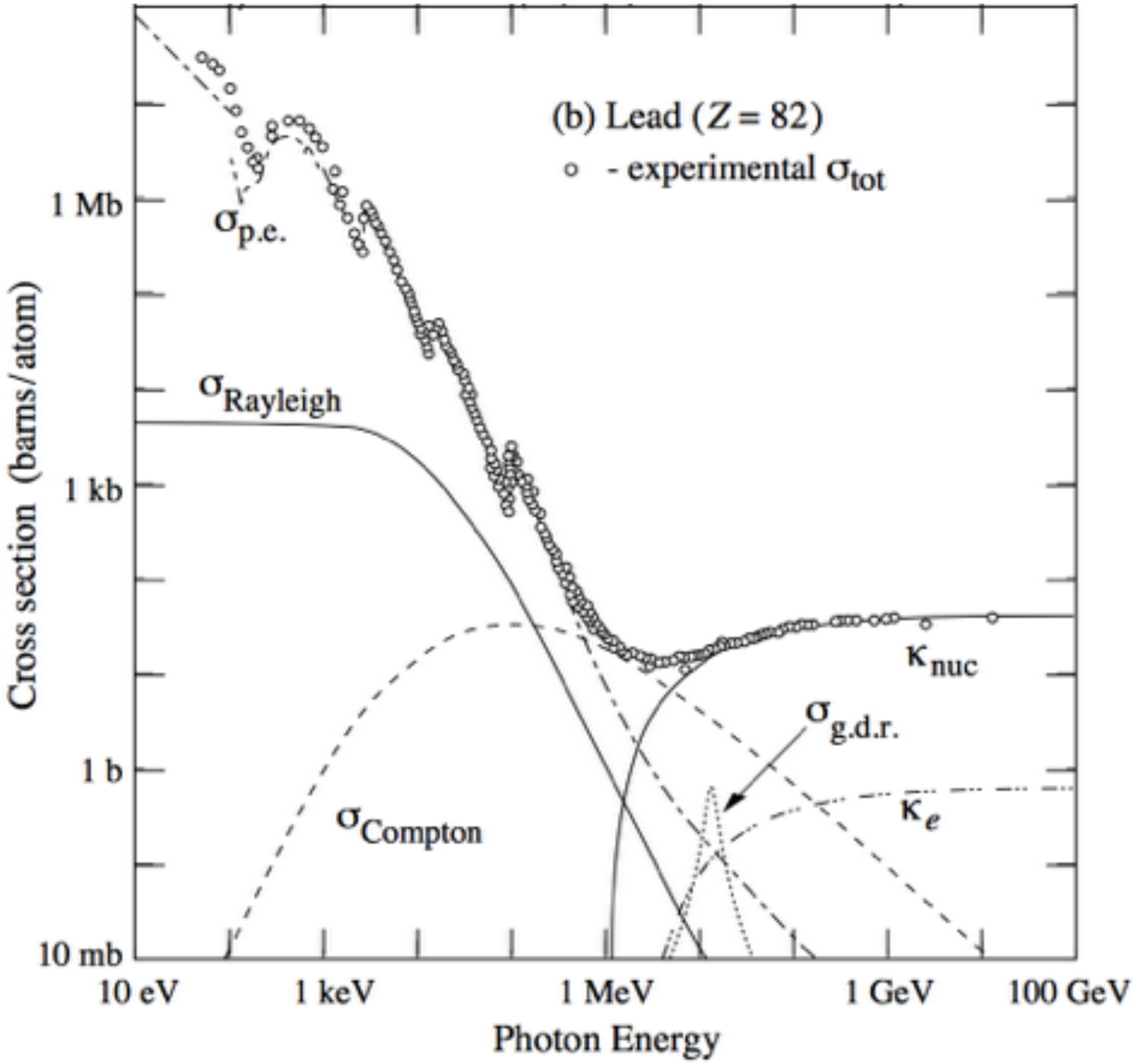
e.m. cascades

critical energy $E_{brem} = E_{ioniz.}$

$(\propto E_{electr.})$ $(\propto \log E_{electr.})$

brem – pair prod : at each step lower E down to critical energy → ioniz/excitatio

Scale vars $t = \frac{x}{X_0}$ $y = \frac{E}{E_c}$



Passage of particles through matter

Electromagnetic shower development

$$\frac{dE}{dt} = E_0 \cdot b \cdot \frac{(bt)^{a-1}\, e^{-bt}}{\Gamma(a)}$$

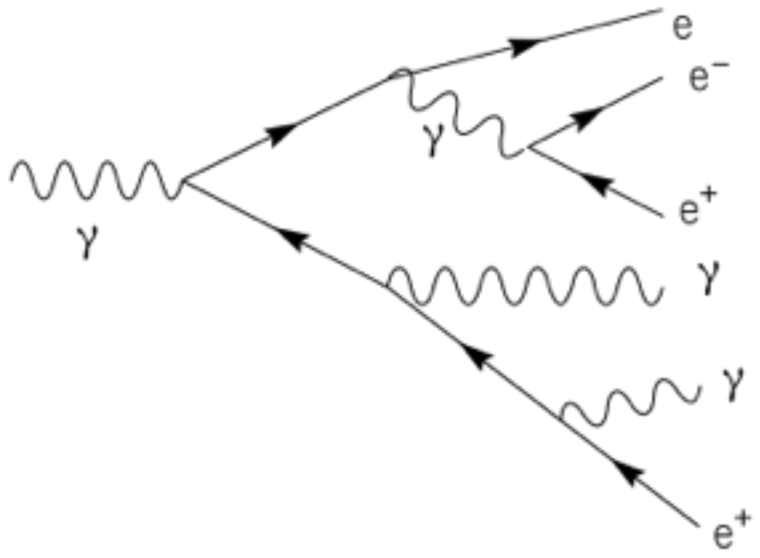
$$t_{max} = \frac{a-1}{b} = \ln y + C \qquad C \begin{cases} +0.5 & \gamma \\ -0.5 & e \end{cases}$$

shower max

shower length depends on Z and energy

Moliére Radius $R_M = X_0 \cdot \frac{E_s}{E_c}$ $E_s \approx 21\,\text{MeV}$

simulations

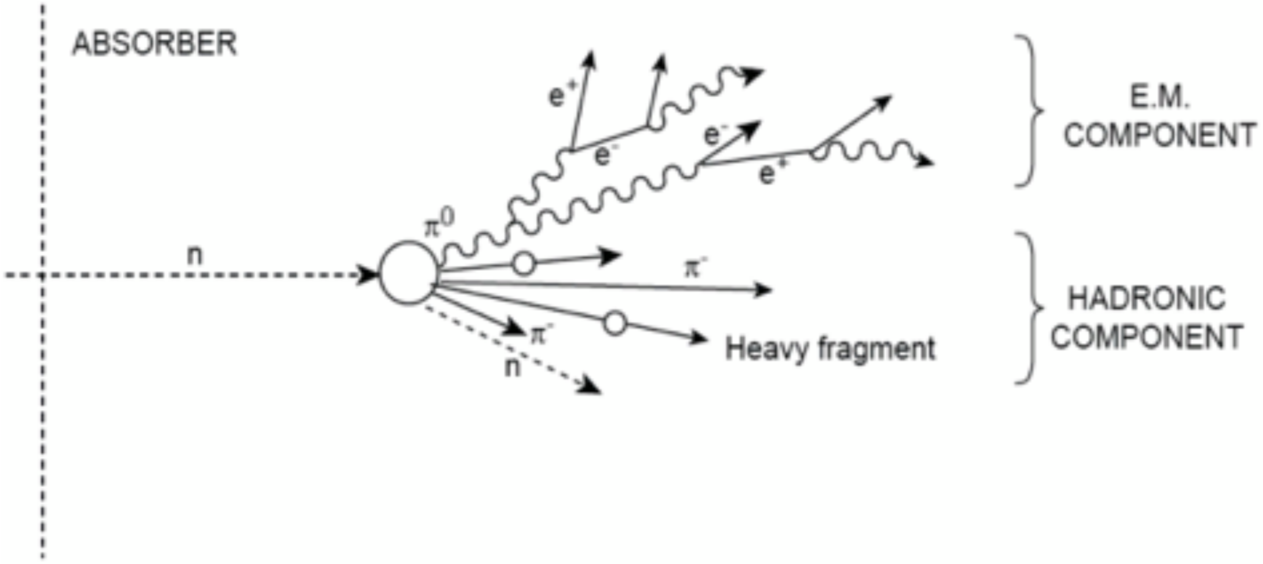


How thick a calorimeter has to be to contain 99% of the energy of a 1 GeV photon ? and for 1 TeV ?

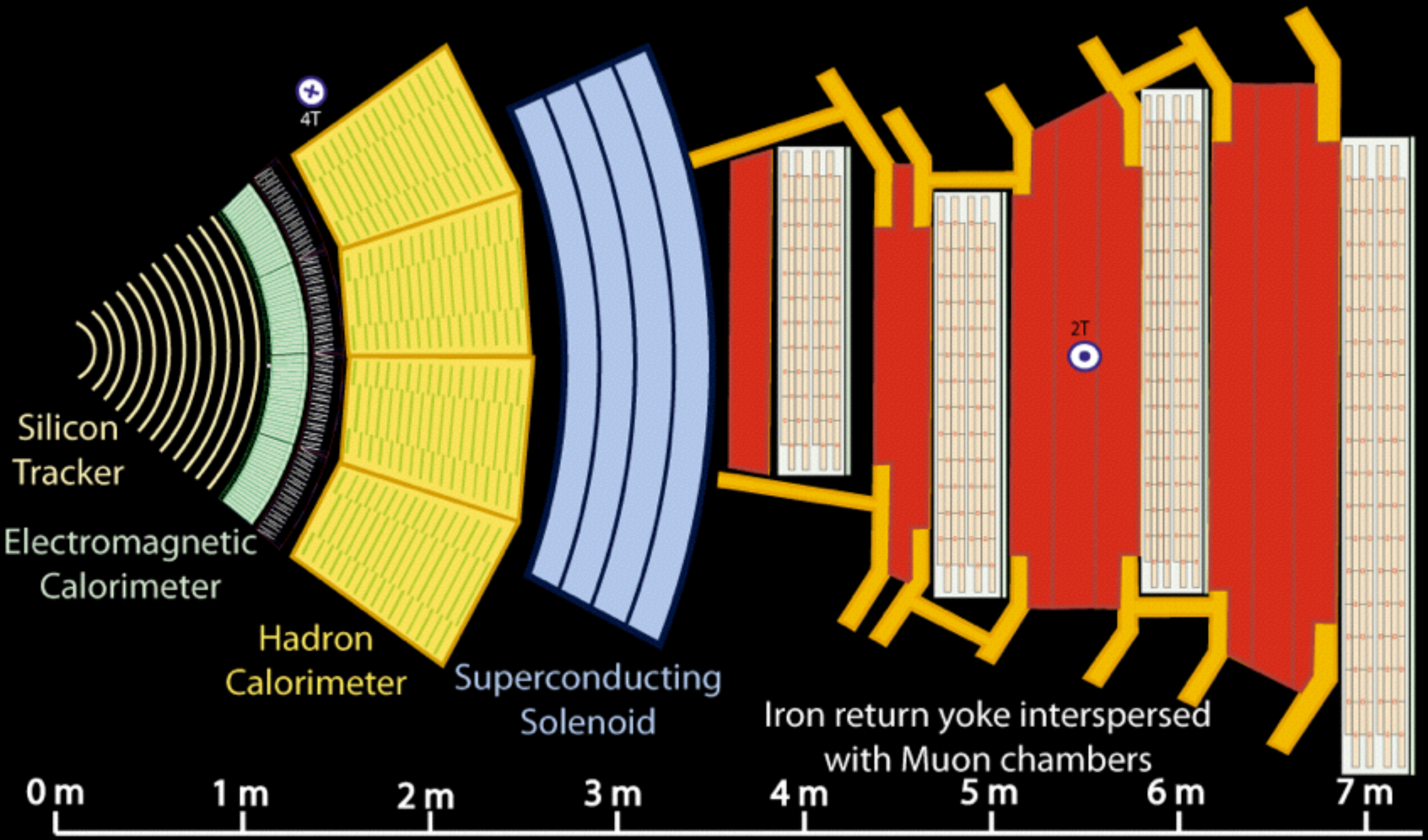
Hadronic shower:
- hadronic interactions
  (fission, cascades, spallation, …)
- more penetrating
- e.m. and hadronic components

$$N(x) = N_0 \exp(-x/\lambda_{\text{int}})$$

$$\lambda_{\text{int}} = \frac{1}{\sigma_{\text{tot}} \cdot n} = \frac{A}{\sigma_{pp}\, A^{2/3} \cdot N_A \rho} \sim A^{1/3}$$



“General” HEP collider detector



Different experiments choose different technologies

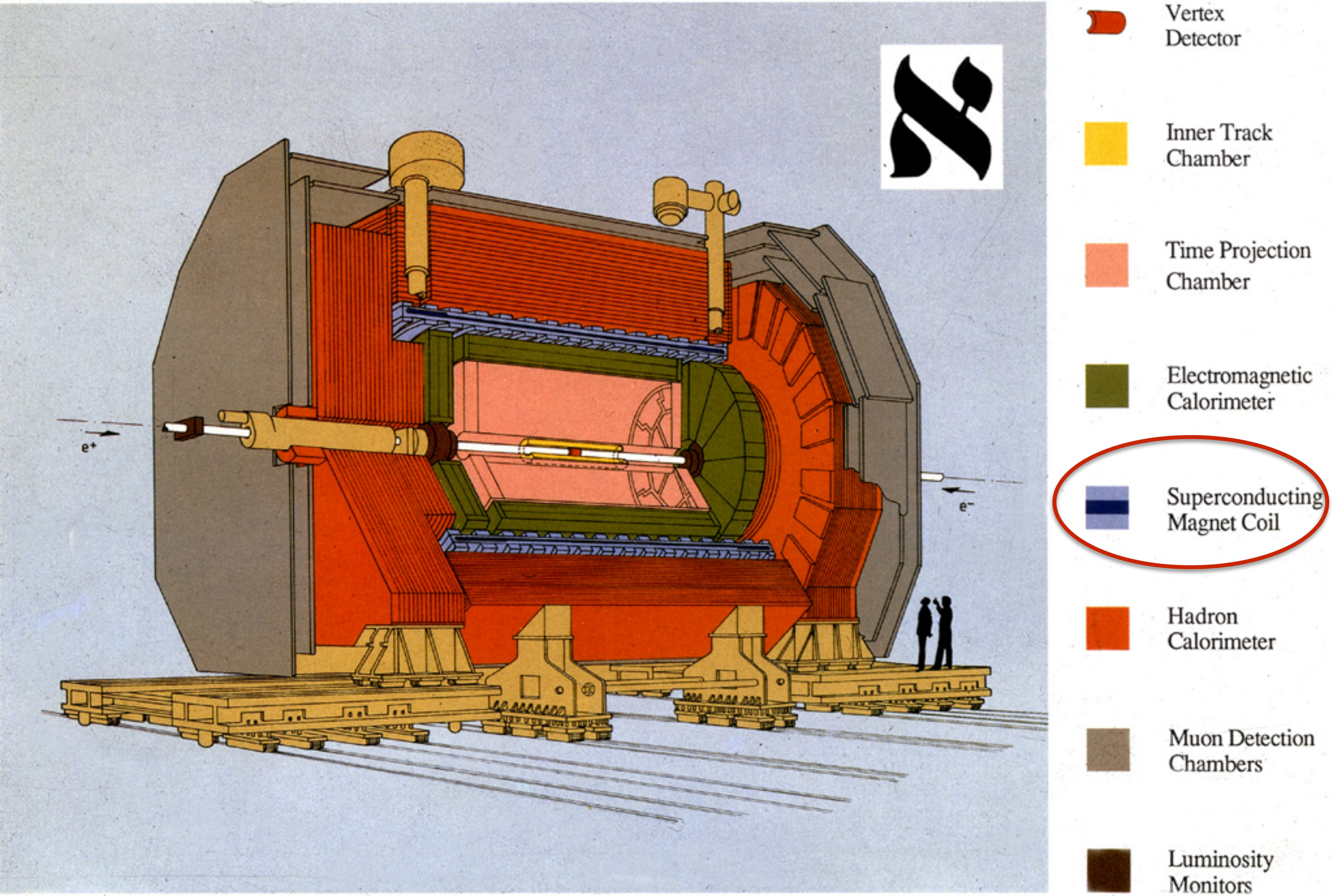
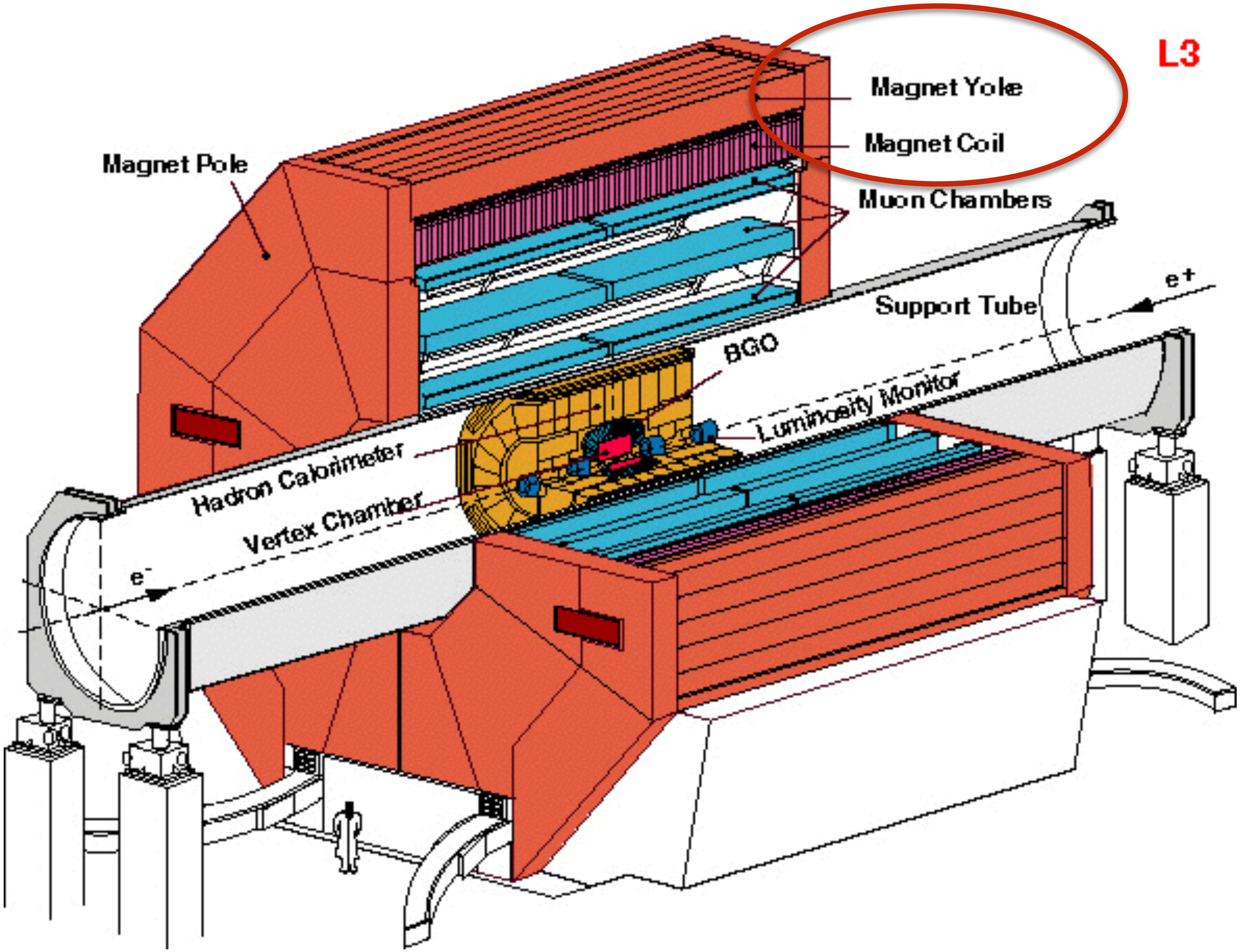
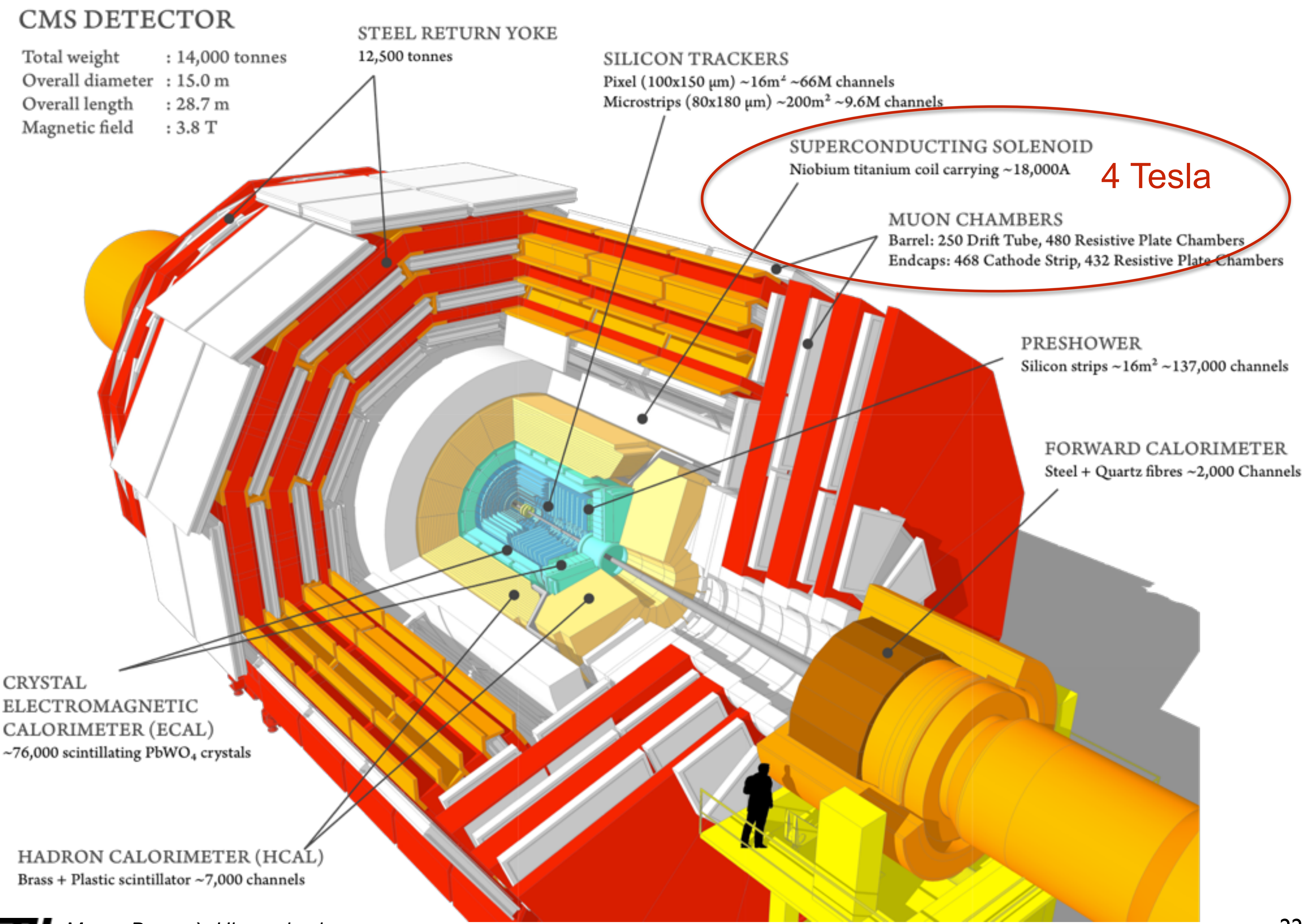


Fig. 1 - The ALEPH Detector


L3
Magnet Yoke
Magnet Coil
Magnet Pole
Muon Chambers
Support Tube
e+
BGO
Luminosity Monitor
Hadron Calorimeter
Vertex Chamber
e-



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

4 Tesla

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

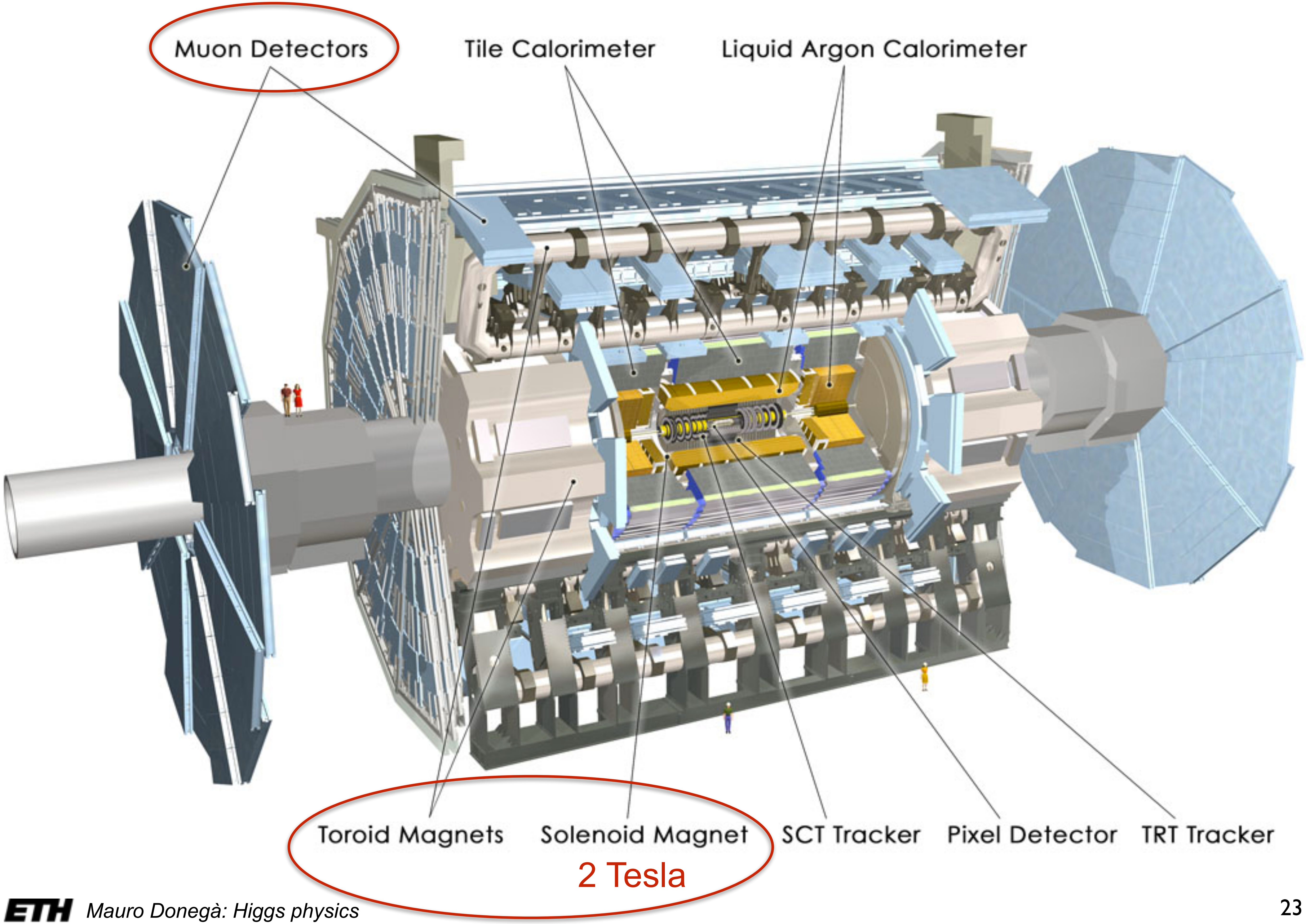
PRESHOWER
Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

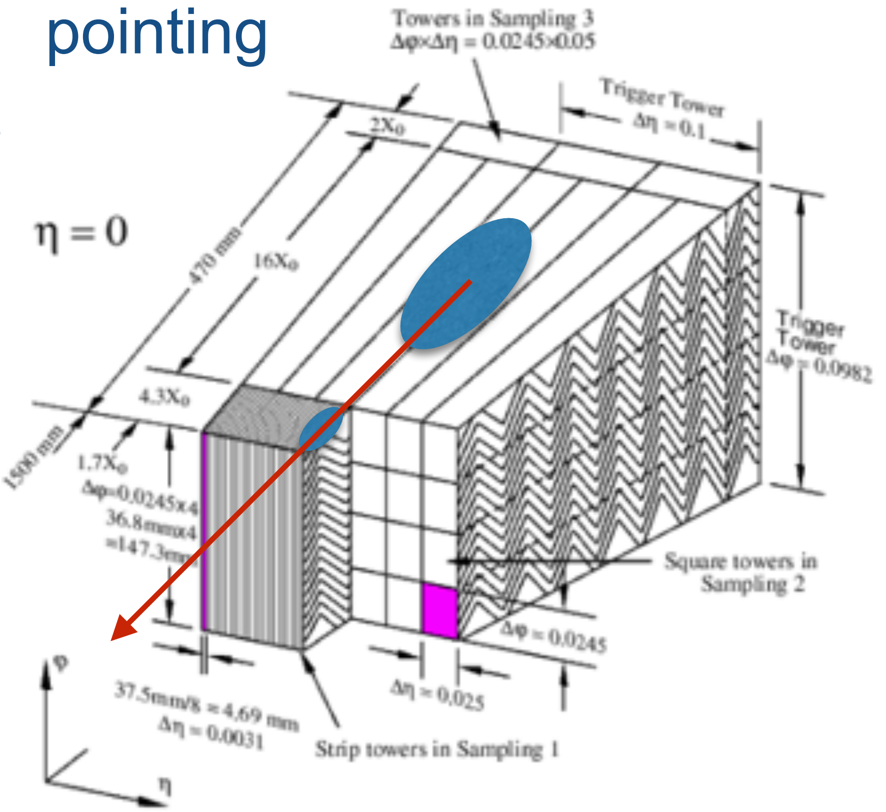
ATLAS


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
2 Tesla
SCT Tracker
Pixel Detector
TRT Tracker

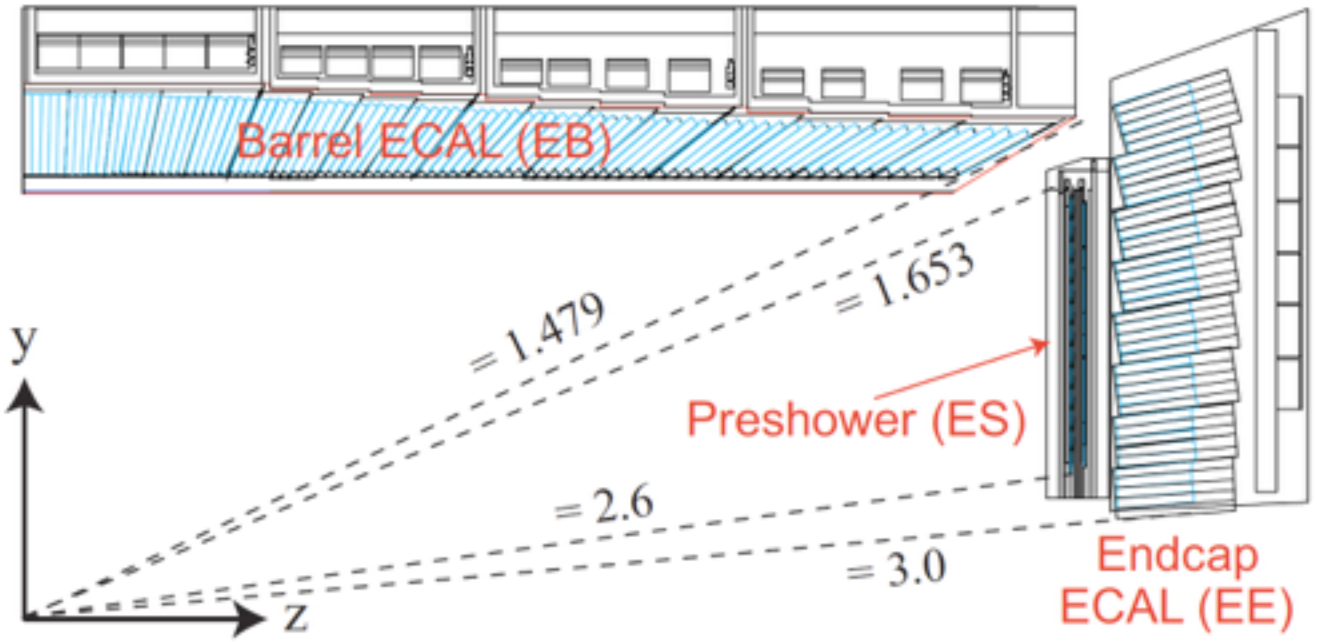
Trackers and e.m. calorimeters

ATLAS LAr accordeon
Ouside the Solenoid/Cryostat

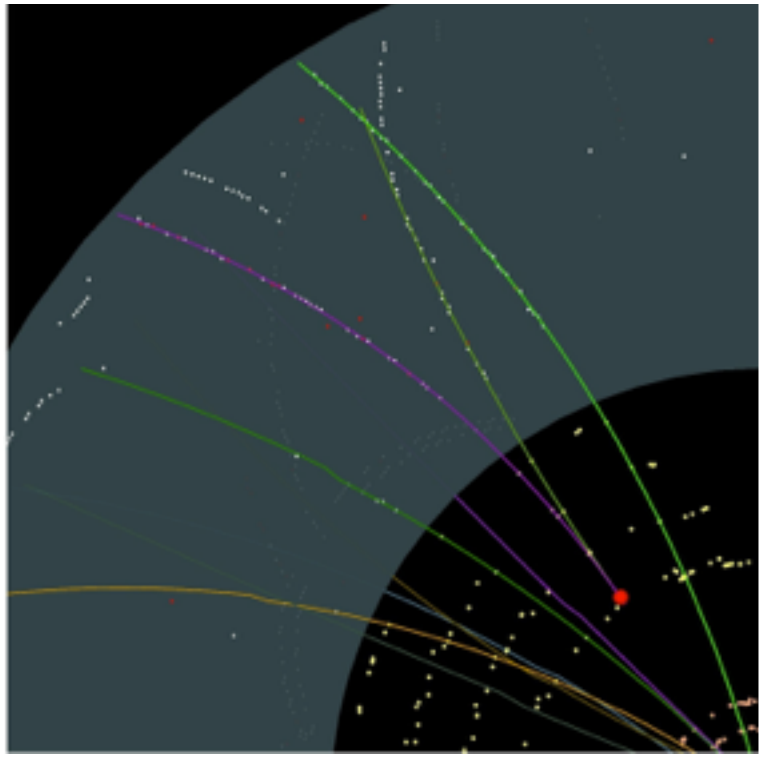
pointing



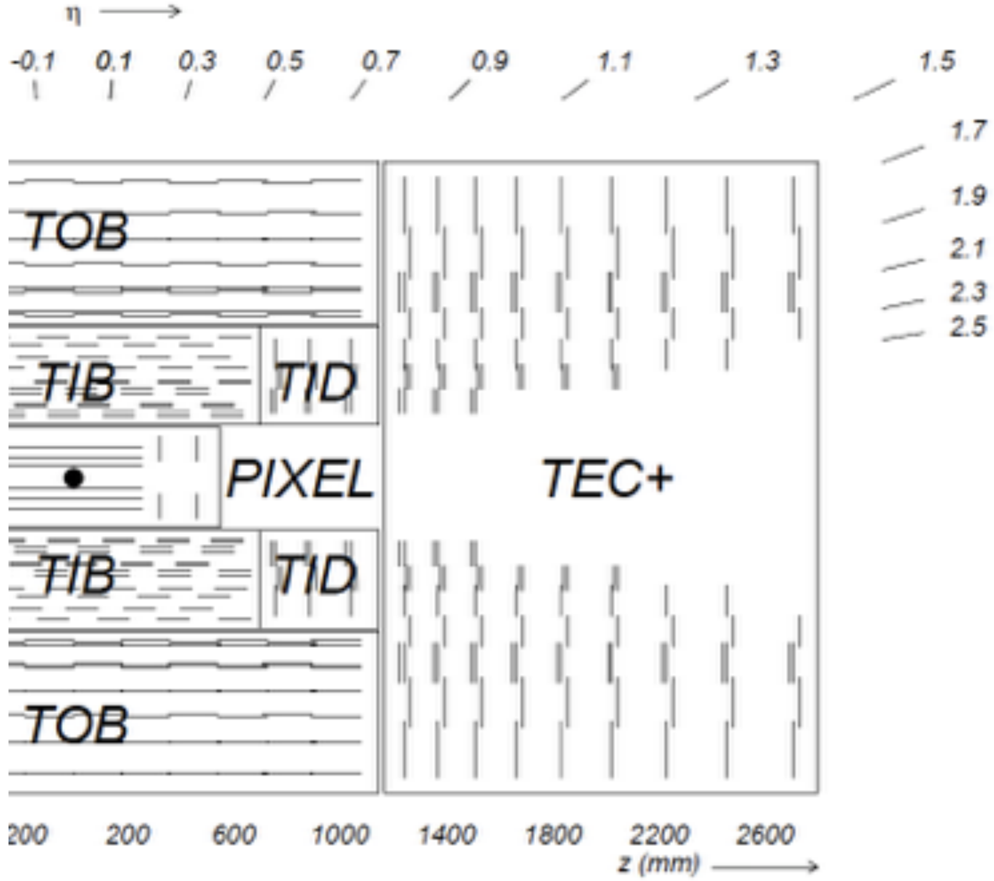
CMS crystals $PbWO_4$
Inside the Solenoid



TRT e/hadron separation



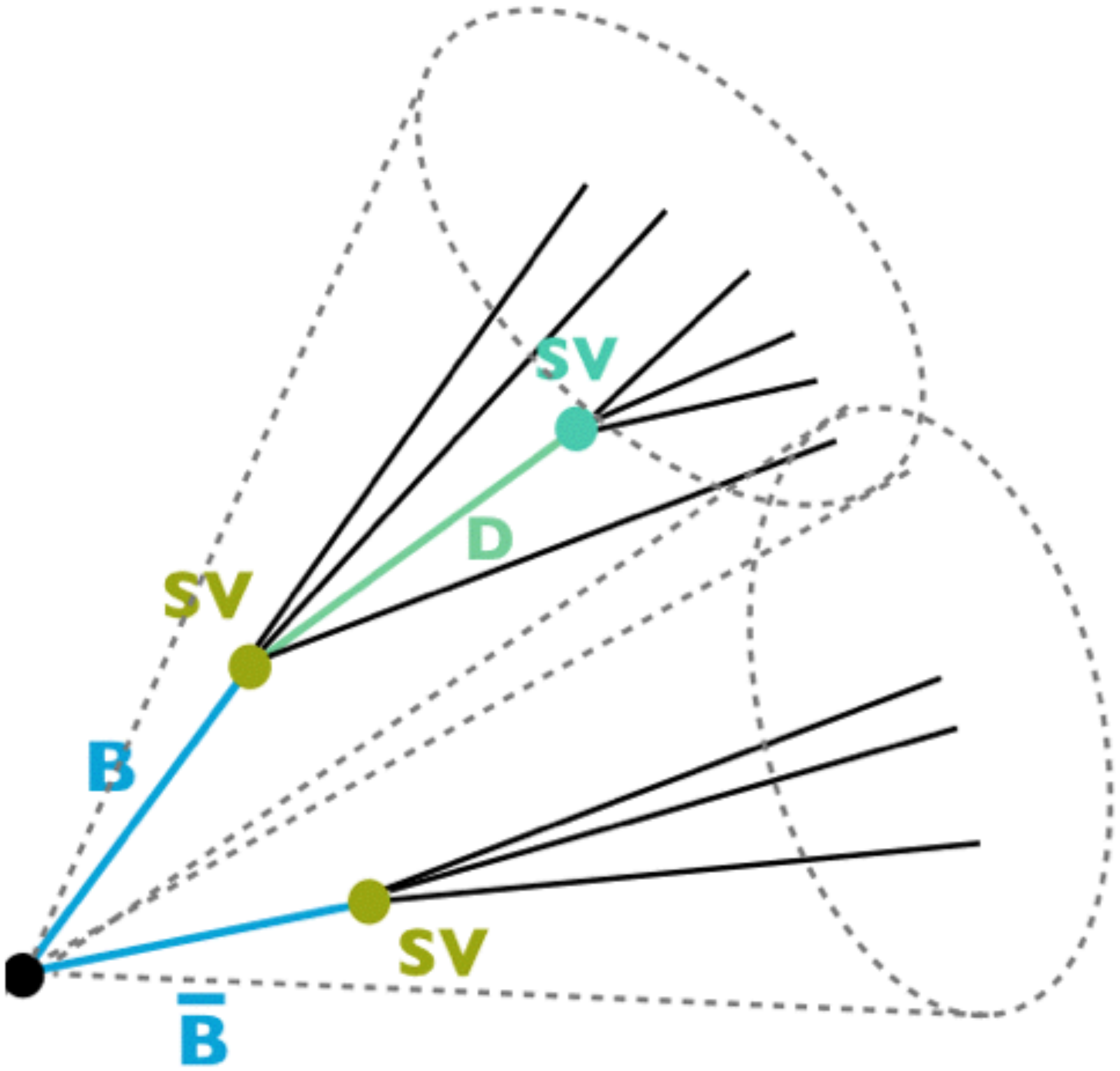
All Silicon



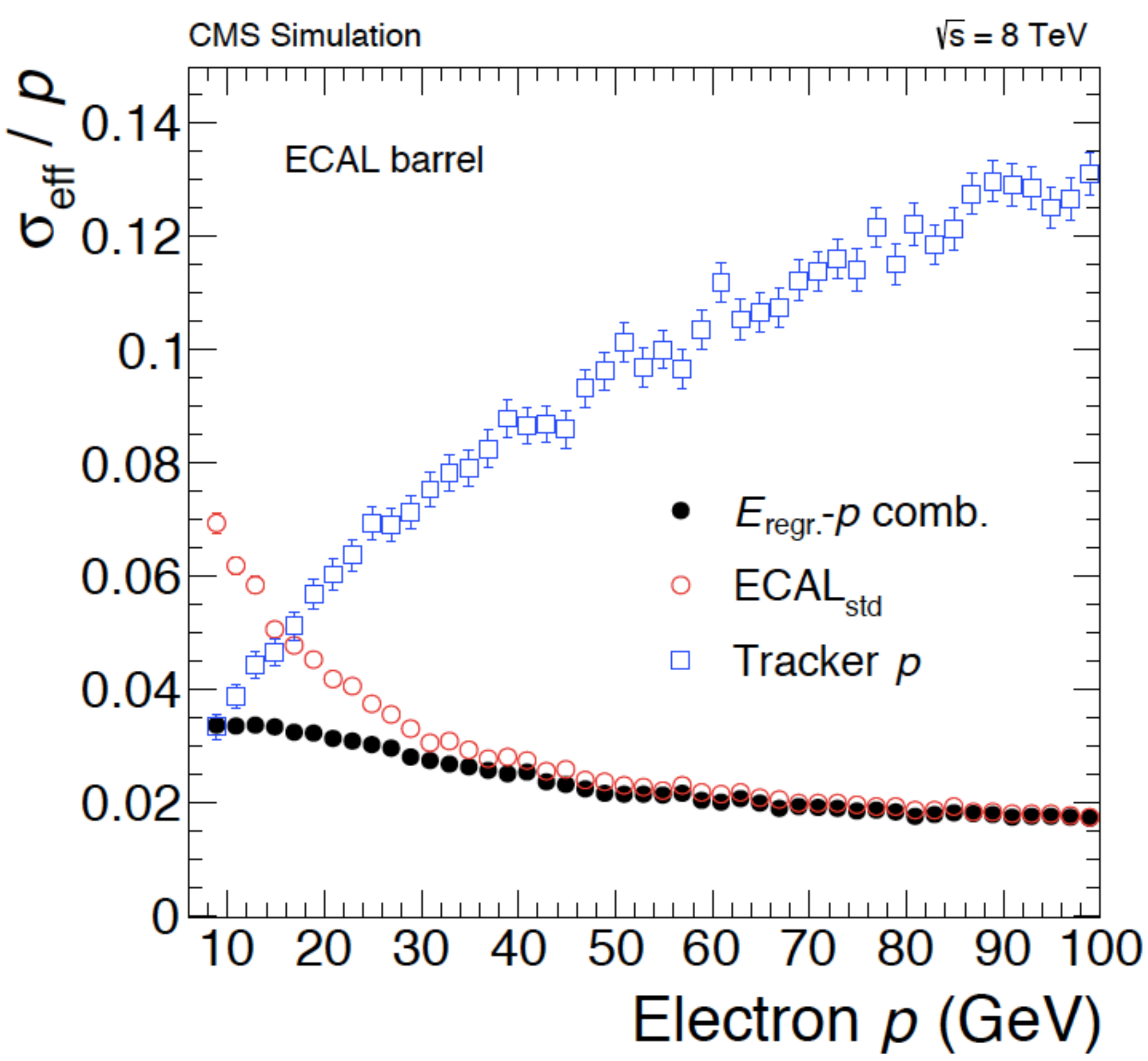
What is the Transition Radiation ? What is Cherenkov radiation ? What are they used for ?

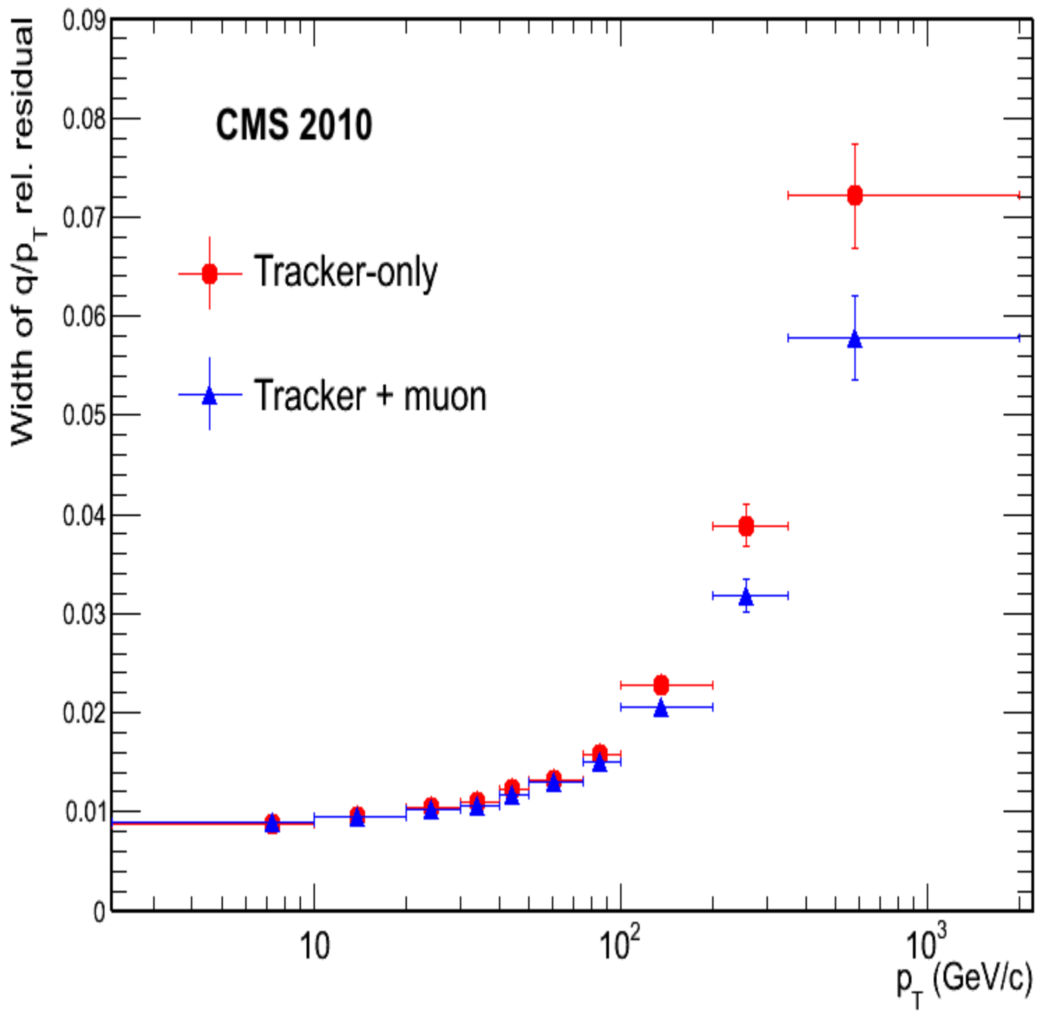
Secondary vertices

heavy flavours and tau decays can be distinguished from jets by looking for secondary vertices (SV)



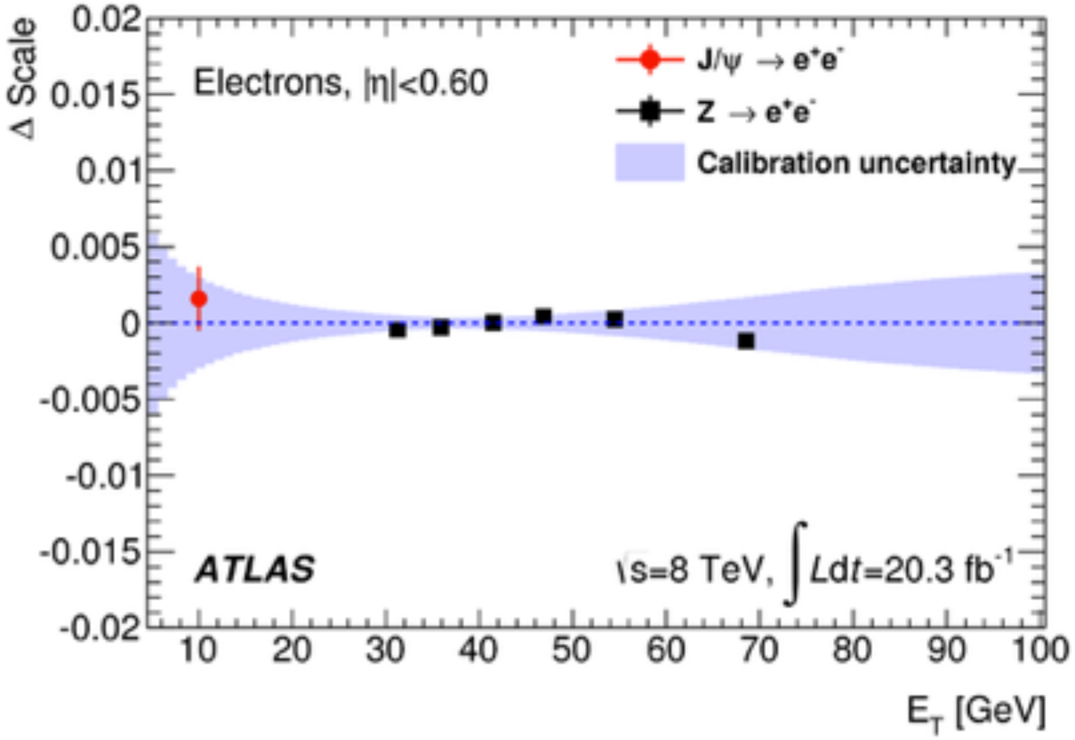
electrons: tracker / calorimeter
muons: tracker / mu-spectrometer

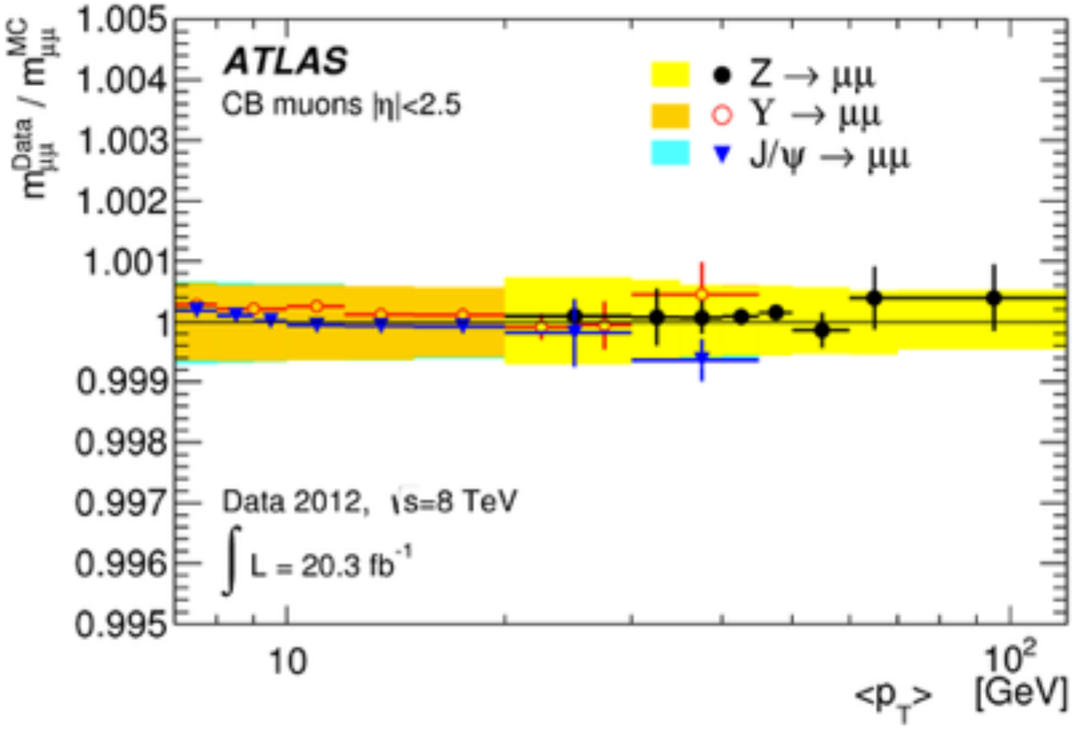




electron

muons





Electroweak fits

Two ways to discover new physics:

"direct" observation or observing deviations from theory

Infer the presence of new particles (fields) through quantum corrections on observables

Quantum corrections = loops (high oders)

Observables	Loop corrections
masses coupling constants Branching ratios production cross sections	vertices propagators

Examples:

Take an observable whose high order corrections depend on m_{top}, m_{Higgs}

⇒ can infer those masses even before observing the particles !

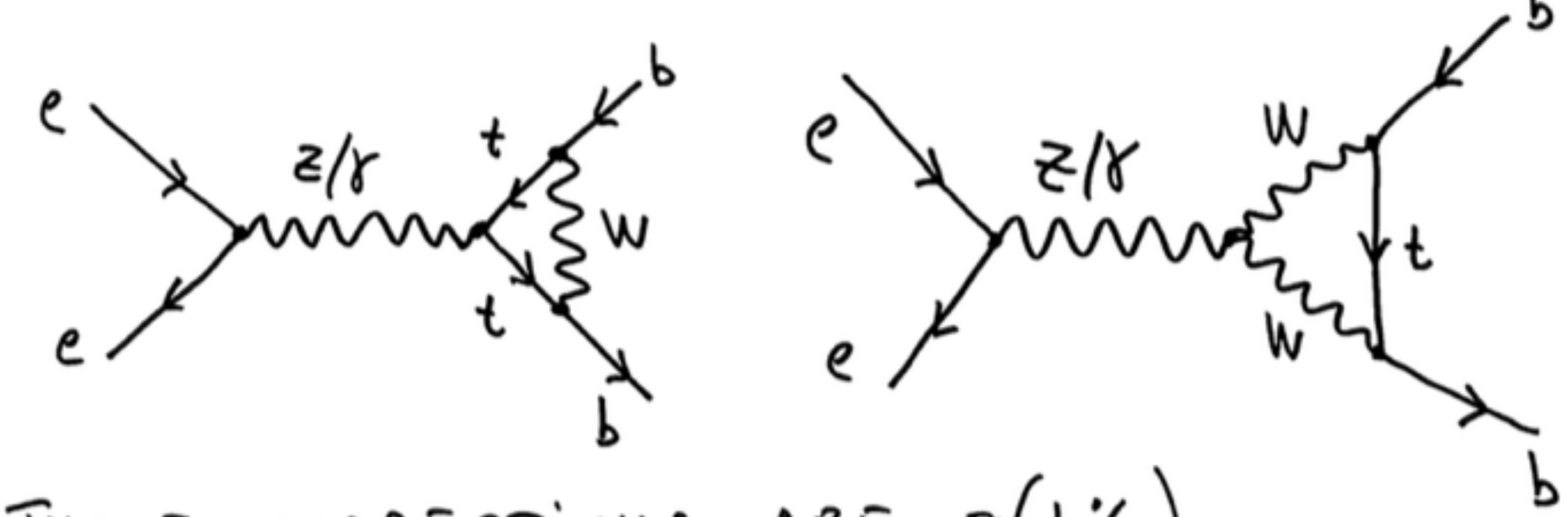
Flipping the argument, combined fits of of several observables are very stringent test of the theory/model producing the corrections

(we will go into more details about (pseudo-)observables when fitting the Higgs properties)

Example

HIGH ORDER CORRECTIONS AFFECTING

THE $Z \to b\bar{b}$



THESE CORRECTIONS ARE $\mathcal{O}(1\%)$

⇒ TO OBTAIN INDIRECT CONSTRAINTS

WE NEED <u>BOTH</u>

HIGH PRECISION PREDICTIONS

HIGH PRECISION MEASUREMENTS

5 input

5 input parameters from the Standard Model:

$$\alpha(m_Z) \quad \alpha_s(m_Z) \quad m_Z \quad m_{top} \quad m_H$$

In practice all the other parameters are either ~constant at the Z-pole or can be derived from these

Collect a (large) number of observables that depend on these inputs and fit them simultaneously to check if there is a (unique) set of values that can accommodate all measurements.

Build a X^2 fit from all the observables:

$O_1(\alpha, \alpha_s, m_Z, m_{top}, m_H \; ; \vec{x_1})$
$O_2(\alpha, \alpha_s, m_Z, m_{top}, m_H \; ; \vec{x_2})$
$O_3(\alpha, \alpha_s, m_Z, m_{top}, m_H \; ; \vec{x_3})$
…
$O_N(\alpha, \alpha_s, m_Z, m_{top}, m_H \; ; \vec{x_N})$

$$X^2 = \left(\frac{\text{observed - measured}}{\text{uncertainty}}\right)^2$$

$$\frac{\partial X^2}{\partial \vec{p}} = 0$$

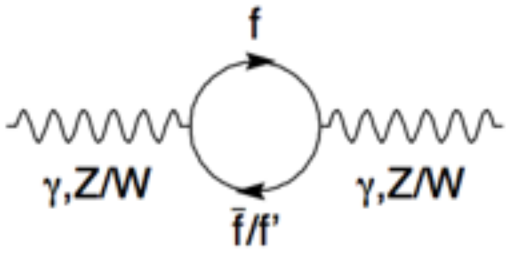
$$\vec{p} = (\alpha, \alpha_s, m_Z, m_{top}, m_H)$$

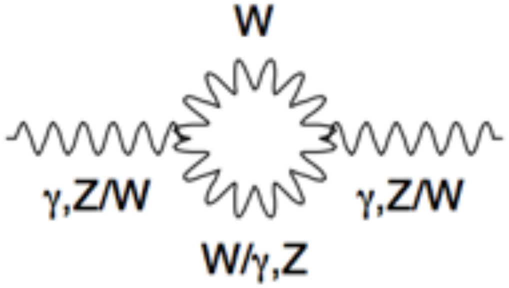
m_{top} m_H

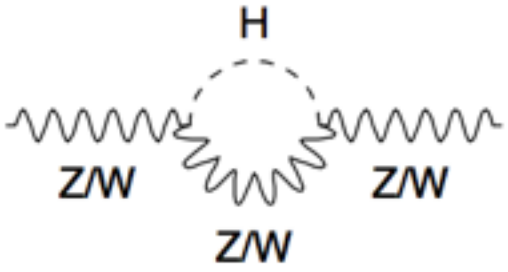
AT TREE LEVEL (Th. Lecture 1)

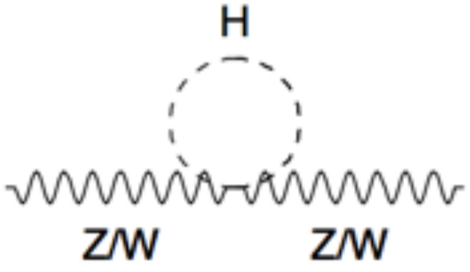
$$\rho := \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

(consequence of using only
1 doublet in SM)









AT ONE LOOP

$$m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - 4\frac{\pi\alpha}{\sqrt{2}G_F m_Z^2}\frac{1}{1-\Delta r}}\right)$$

WITH $\Delta r = \Delta\alpha + \Delta r_W$

m_{top} m_H

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-4\,\frac{\pi\alpha}{\sqrt{2}\,G_F\,m_Z^2}\;\frac{1}{1-\Delta r}}\right)$$

WITH $\Delta r = \Delta\alpha + \Delta r_W$

$\underline{\underline{\Delta\alpha}}$ from RUNNING OF THE E.M. COUPLING

→ FERMIONS IN LOOPS

$$\Delta\alpha(s) = \boxed{\Delta\alpha_{lept} + \Delta\alpha_{top}} + \boxed{\Delta\alpha_{had}}$$

from theory

from experiment
(low energy non-perturbative)

$$\Delta r_W(m_t, m_H) \simeq \frac{\alpha}{\pi\sin^2\theta_W}\left(-\frac{3}{16}\,\frac{\cos^2\theta_W}{\sin^2\theta_W}\cdot\frac{m_t^2}{m_W^2}+\frac{11}{24}\log\left(\frac{m_H}{m_Z}\right)\right)$$

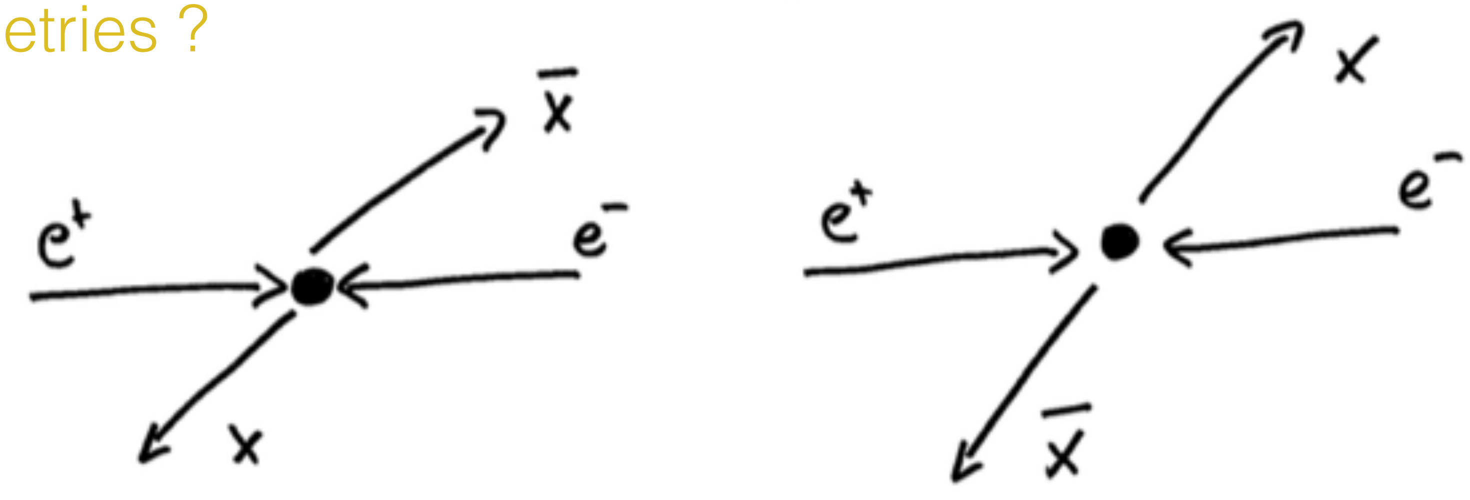
Observables

LEP 1

- Z^0 BOSON m_Z , Γ_Z
- $\sigma^0(e^+e^- \longrightarrow q\bar{q})$
- RATIO OF FERMIONIC WIDTHS TO THE HADRONIC WIDTH $R^0_f = \dfrac{\Gamma_f}{\Gamma_{q\bar{q}}}$ $f = b, c,$ leptons
- FWD - BWD ASYMMETRY OF Z^0 DECAYS

$$A^{0,x}_{FB} = \frac{\sigma^x_F - \sigma^x_B}{\sigma^x_F + \sigma^x_B} \qquad x = b, c, \text{leptons}$$

Does it make sense to talk about up/down asymmetries ?



FORWARD BACKWARD

Observables

LEP 1

- POLARIZATIONS

$$A_x = \frac{g_{Lx}^2 - g_{Rx}^2}{g_{Lx}^2 + g_{Rx}^2} \qquad x = b, c, \text{leptons}$$

ASYMMETRY IN THE COUPLINGS TO LEFT-HANDED / RIGHT-HANDED FERMIONS

SLAC SLC/SLD POLARIZED BEAMS

LEP USE τ FOR LEPTONS

How do you measure the polarization of a tau ?

- EFFECTIVE EW-MIXING ANGLE

$$\sin^2\theta_{eff}^{lep}$$

LEP 2 / TeVatron

- W BOSON m_W, Γ_W

How do you measure the W mass ?

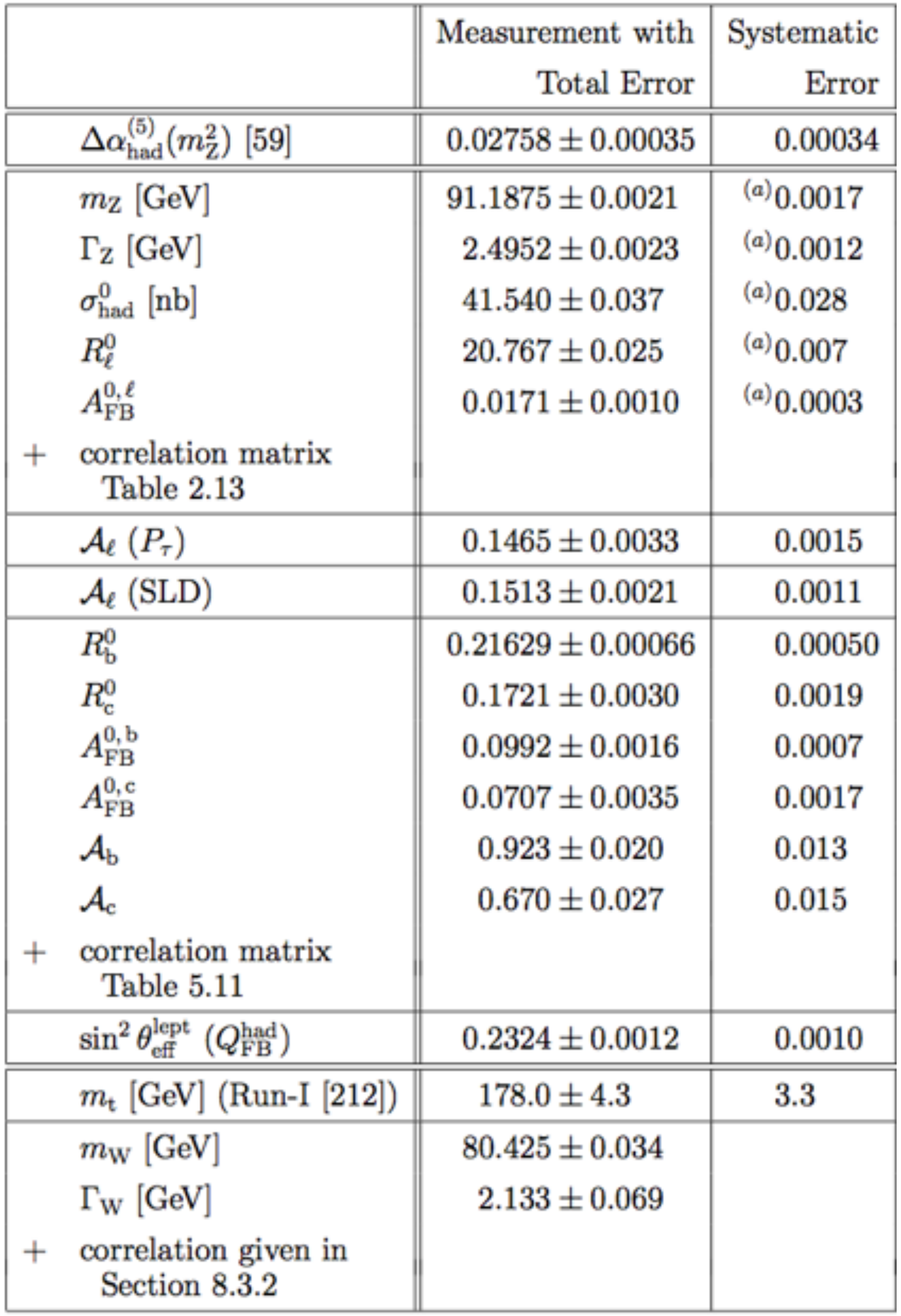
- top mass m_{top}

Observables

Low Energy cross checks

- PARITY VIOLATION IN Cs
- $\sin^2\theta$ IN MØLLER SCATTERING E-158
- $\frac{\text{NEUTRAL CURRENT}}{\text{CHARGED CURRENT}}$ AT NuTeV

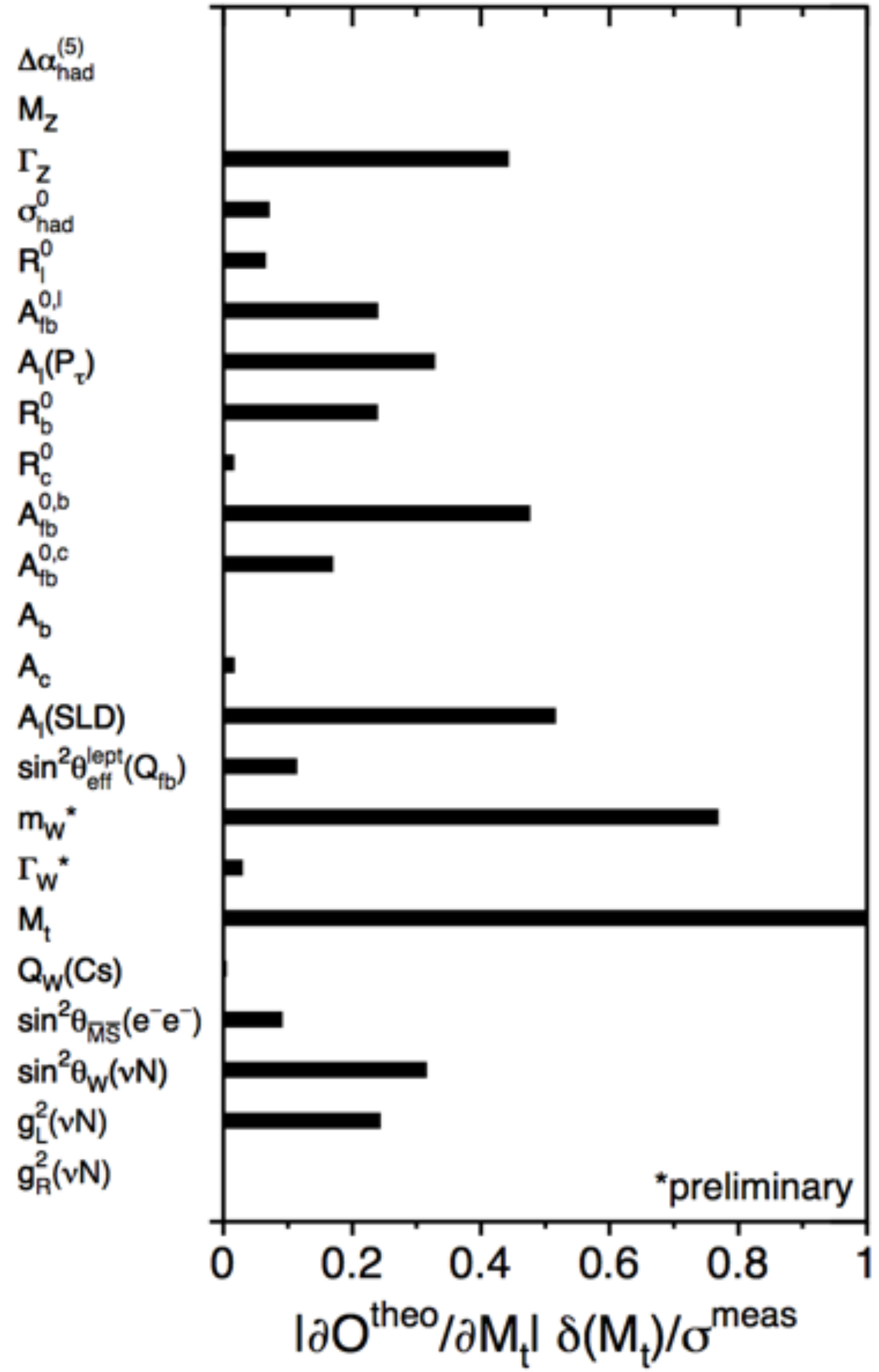
Input summary



	Measurement with Total Error	Systematic Error
$\Delta\alpha^{(5)}_{\mathrm{had}}(m^2_{\mathrm{Z}})$ [59]	0.02758 ± 0.00035	0.00034
m_{Z} [GeV]	91.1875 ± 0.0021	$^{(a)}0.0017$
Γ_{Z} [GeV]	2.4952 ± 0.0023	$^{(a)}0.0012$
σ^0_{had} [nb]	41.540 ± 0.037	$^{(a)}0.028$
R^0_ℓ	20.767 ± 0.025	$^{(a)}0.007$
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	$^{(a)}0.0003$
+ correlation matrix Table 2.13		
$\mathcal{A}_\ell$ (P_τ)	0.1465 ± 0.0033	0.0015
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.0011
R^0_{b}	0.21629 ± 0.00066	0.00050
R^0_{c}	0.1721 ± 0.0030	0.0019
$A^{0,\mathrm{b}}_{\mathrm{FB}}$	0.0992 ± 0.0016	0.0007
$A^{0,\mathrm{c}}_{\mathrm{FB}}$	0.0707 ± 0.0035	0.0017
$\mathcal{A}_{\mathrm{b}}$	0.923 ± 0.020	0.013
$\mathcal{A}_{\mathrm{c}}$	0.670 ± 0.027	0.015
+ correlation matrix Table 5.11		
$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ ($Q^{\mathrm{had}}_{\mathrm{FB}}$)	0.2324 ± 0.0012	0.0010
m_{t} [GeV] (Run-I [212])	178.0 ± 4.3	3.3
m_{W} [GeV]	80.425 ± 0.034	
Γ_{W} [GeV]	2.133 ± 0.069	
+ correlation given in Section 8.3.2		

Dependence

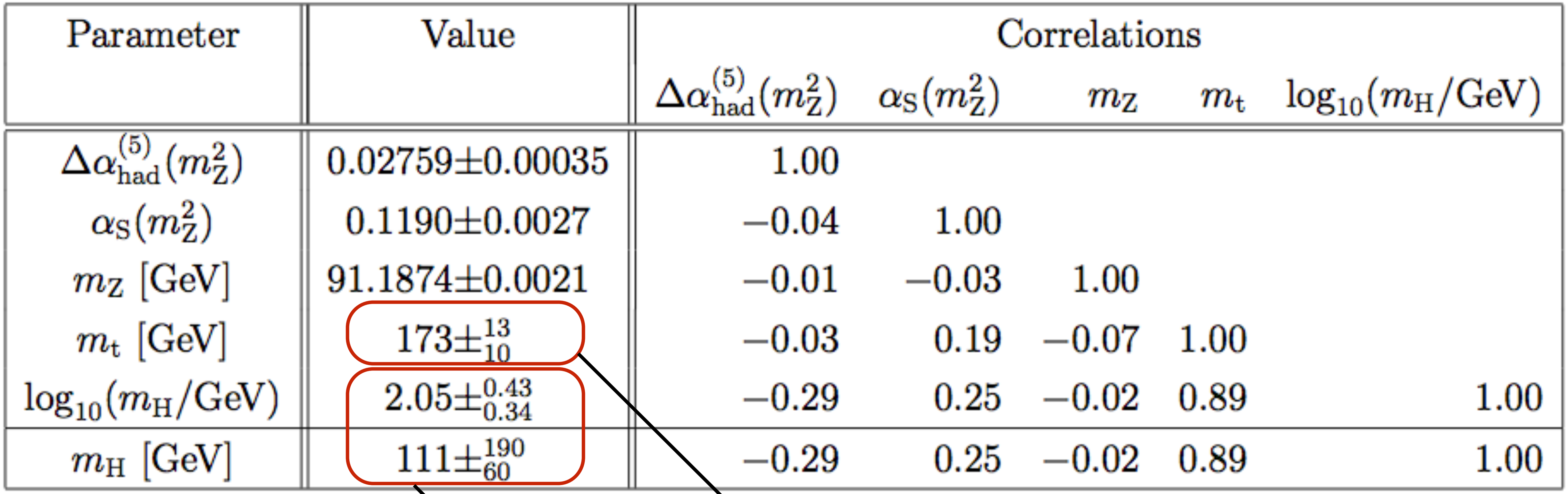
The stronger the dependence on the observable on a parameter the more precise its determination



The most amazing results ever !

Take the high precision Z-pole measurements and fit simultaneously all 5 inputs:

X^2/ndof = 16/ 10 (probability 9.9%)



Parameter	Value	Correlations				
		$\Delta\alpha^{(5)}_{\mathrm{had}}(m^2_{\mathrm{Z}})$	$\alpha_{\mathrm{S}}(m^2_{\mathrm{Z}})$	m_{Z}	m_{t}	$\log_{10}(m_{\mathrm{H}}/\mathrm{GeV})$
$\Delta\alpha^{(5)}_{\mathrm{had}}(m^2_{\mathrm{Z}})$	0.02759 ± 0.00035	1.00				
$\alpha_{\mathrm{S}}(m^2_{\mathrm{Z}})$	0.1190 ± 0.0027	−0.04	1.00			
m_{Z} [GeV]	91.1874 ± 0.0021	−0.01	−0.03	1.00		
m_{t} [GeV]	$173\pm^{13}_{10}$	−0.03	0.19	−0.07	1.00	
$\log_{10}(m_{\mathrm{H}}/\mathrm{GeV})$	$2.05\pm^{0.43}_{0.34}$	−0.29	0.25	−0.02	0.89	1.00
m_{H} [GeV]	$111\pm^{190}_{60}$	−0.29	0.25	−0.02	0.89	1.00

PDG $m = 173.21 \pm 0.51 \pm 0.71$ GeV

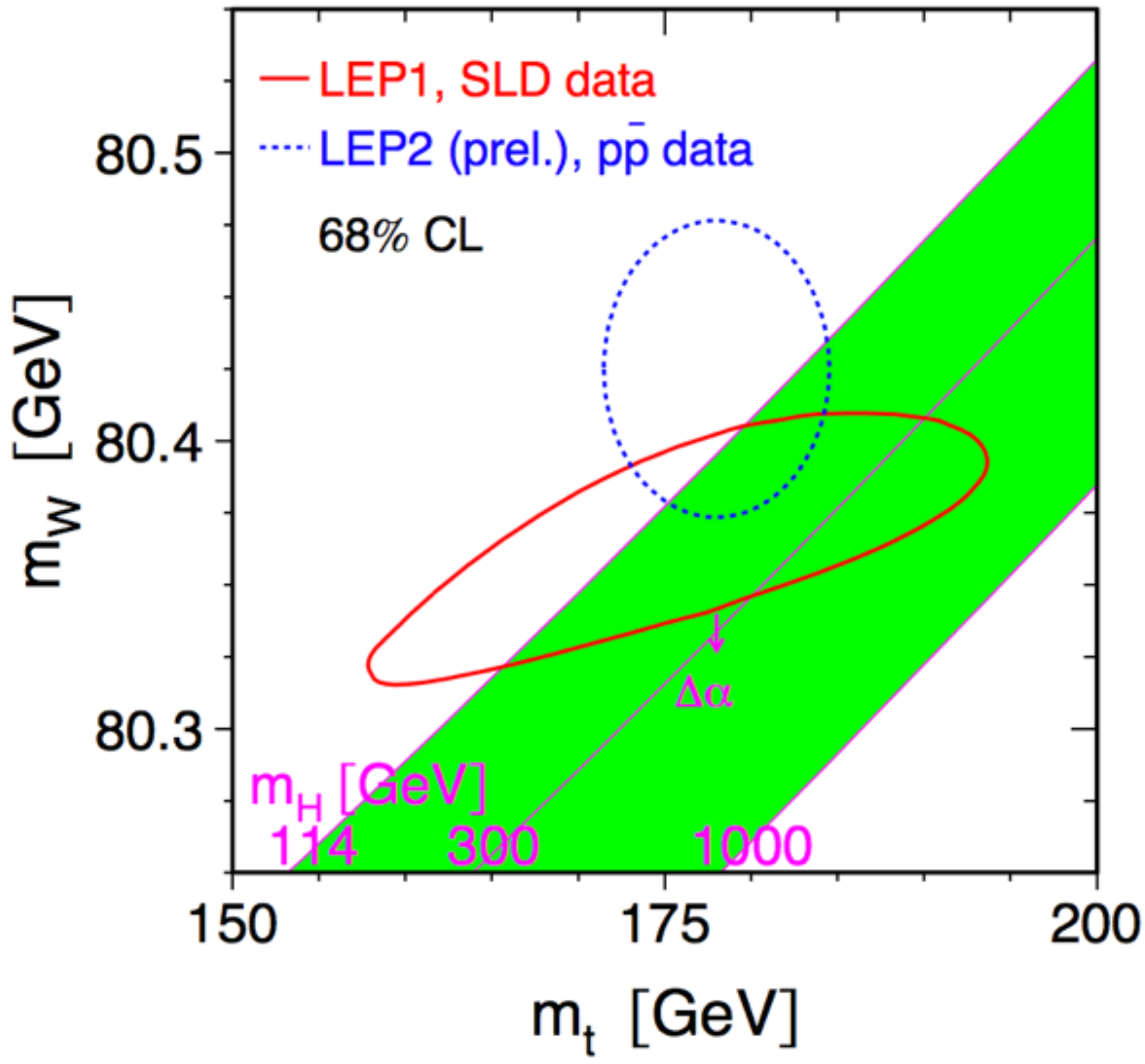
Today we discovered both:

$m_{\mathrm{H}} = 125.09 \pm 0.21(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})$ GeV

From these values we can extract all other SM parameters:

$m_{\mathrm{W}} = 80.363 \pm 0.032$ GeV PDG Mass $m = 80.385 \pm 0.015$ GeV

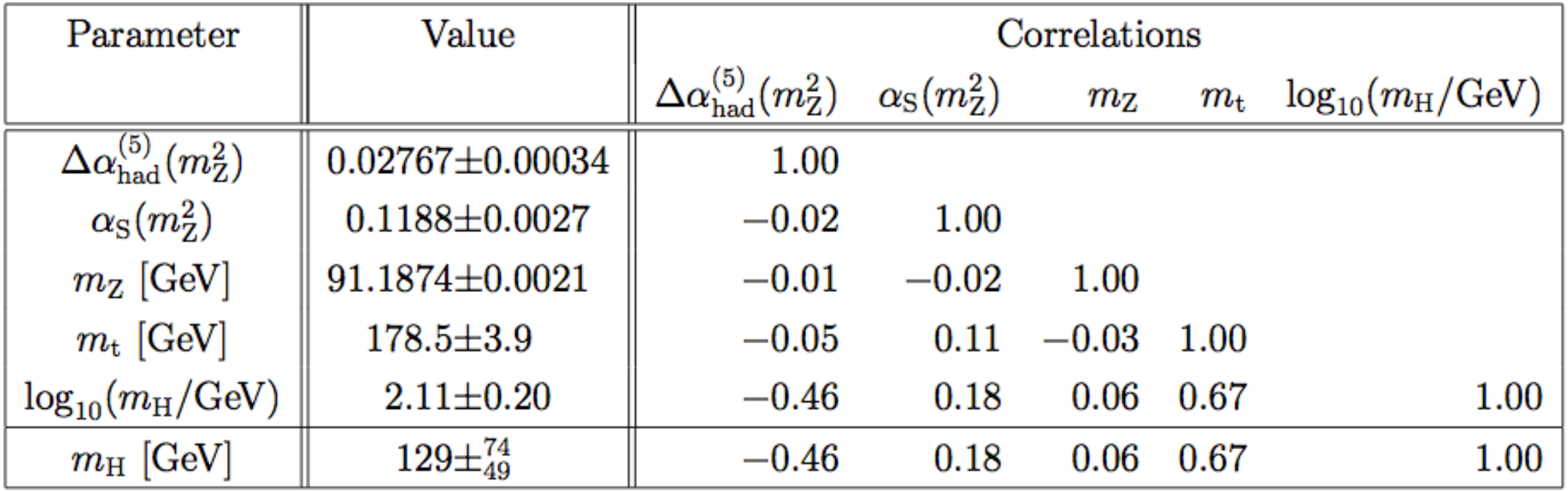
m_W vs. m_{top}


LEP1, SLD data
LEP2 (prel.), p$\bar{p}$ data
68% CL
80.5
80.4
80.3
m_W [GeV]
$\Delta\alpha$
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]

m_H

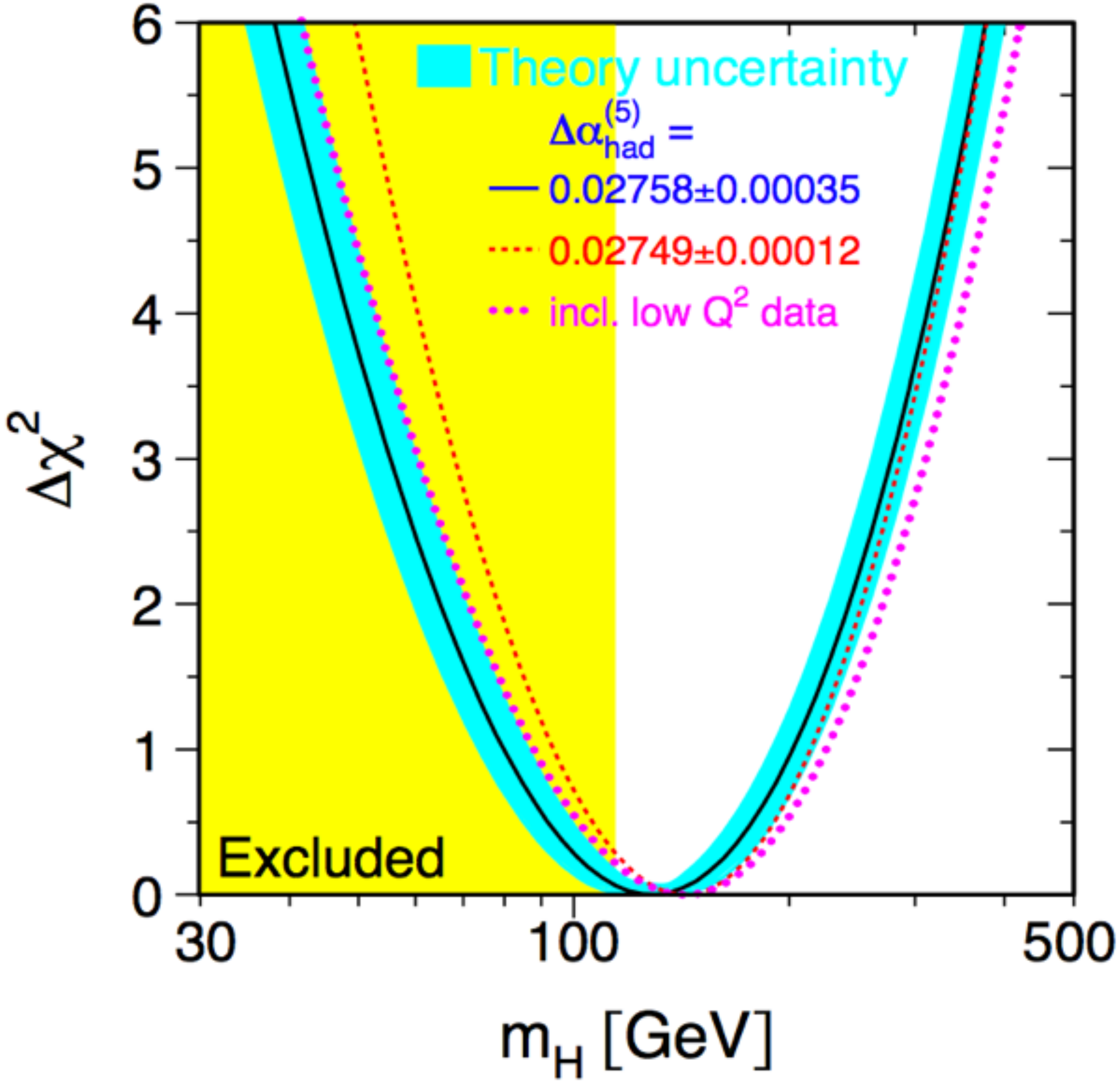
Use the same inputs as before and add m_t, m_W, Γ_W from LEP2/TeVatron results

X^2/ndof = 18.3/ 13 (probability 15%)

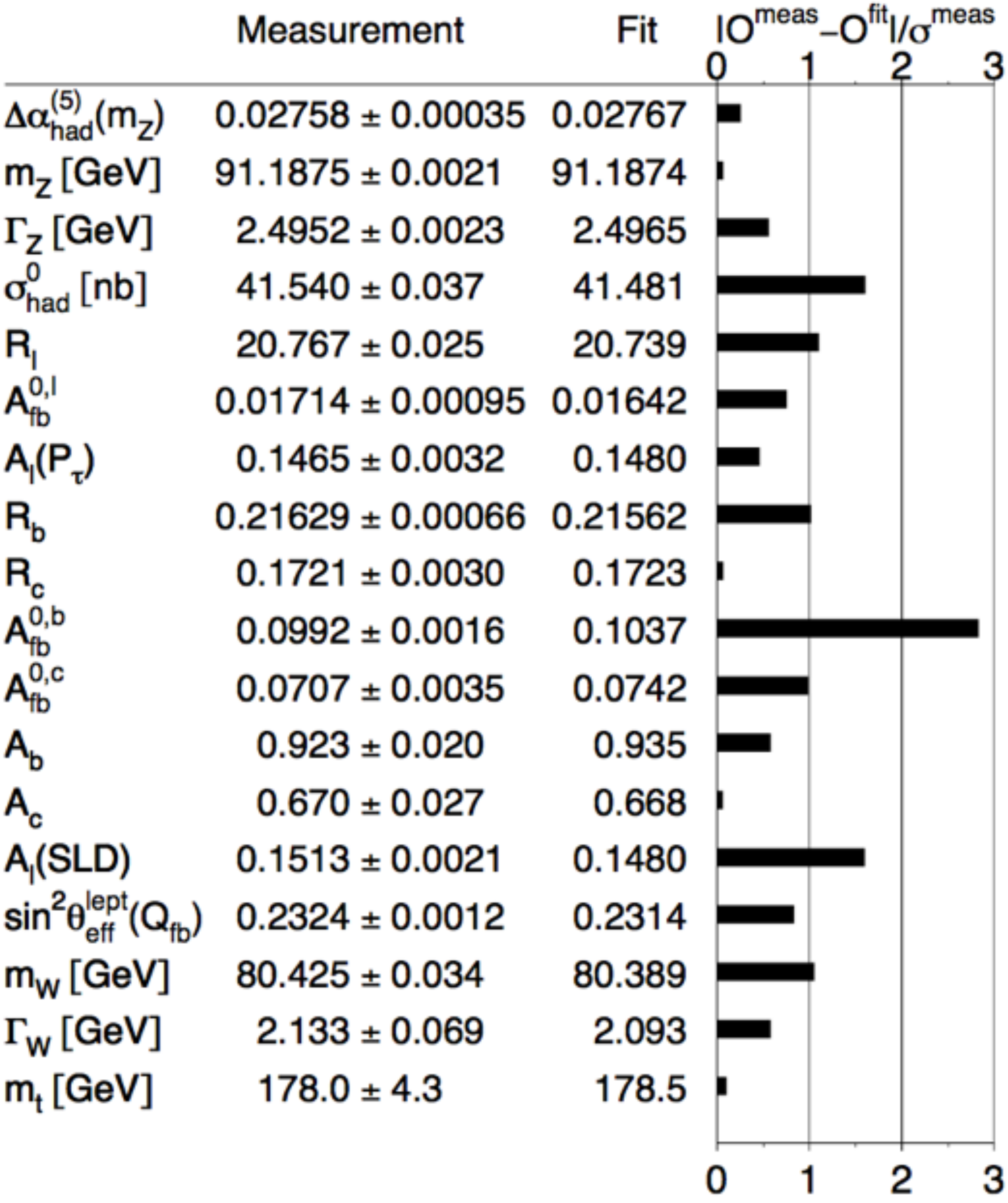


Parameter	Value	Correlations				
		$\Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2)$	$\alpha_S(m_Z^2)$	m_Z	m_t	$\log_{10}(m_H/\mathrm{GeV})$
$\Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2)$	0.02767 ± 0.00034	1.00				
$\alpha_S(m_Z^2)$	0.1188 ± 0.0027	−0.02	1.00			
m_Z [GeV]	91.1874 ± 0.0021	−0.01	−0.02	1.00		
m_t [GeV]	178.5 ± 3.9	−0.05	0.11	−0.03	1.00	
$\log_{10}(m_H/\mathrm{GeV})$	2.11 ± 0.20	−0.46	0.18	0.06	0.67	1.00
m_H [GeV]	$129\pm^{74}_{49}$	−0.46	0.18	0.06	0.67	1.00

m_H


Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
$\Delta\chi^2$
0
1
2
3
4
5
6
30
100
500
m_H [GeV]

Measured vs. expected



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5

Bibliography

PDG reviews of particle interactions with matter and detectors:

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-passage-particles-matter.pdf

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-accel-phys-colliders.pdf

All CMS publications (including performance)
http://cms-results.web.cern.ch/cms-results/public-results/publications/

Precision Electroweak Measurements on the Z Resonance
(our discussion is in chapter 8)

http://arxiv.org/abs/hep-ex/0509008