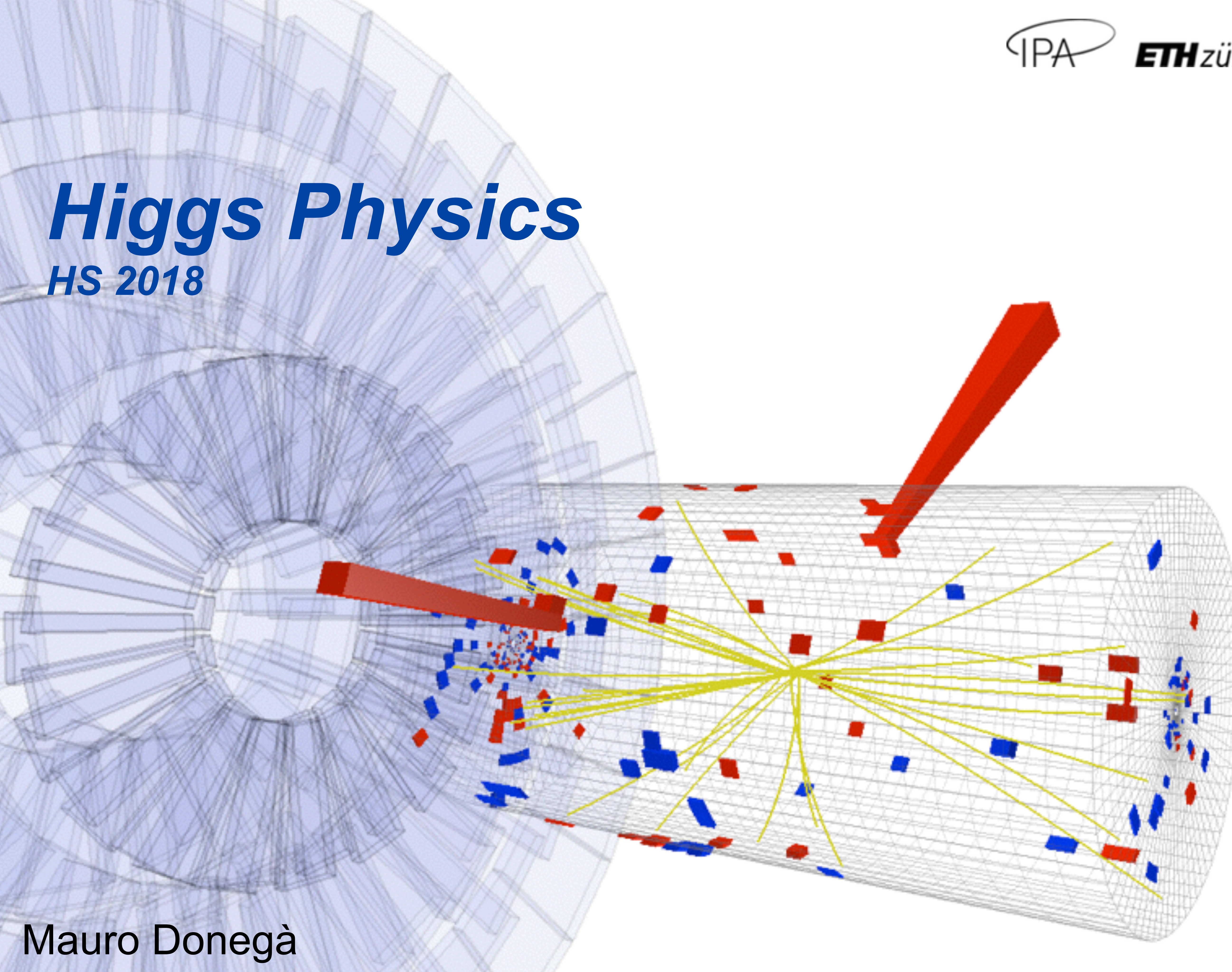
IPA ETH zürich

Higgs Physics

HS 2018



Mauro Donegà

Practicalities

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Moodle will store slides, exercises, papers and references
https://moodle-app2.let.ethz.ch/course/view.php?id=4849

Detailed bibliography will be given at each class

Outline

Lectures

- 1
  - Introduction
  - Accelerators
  - Detectors
  - EW constraints
- 2
  - Search at LEP1 / LEP 2
  - Statistics: likelihood and hypothesis testing
- 3
  - Searches at TeVatron
    - Channels overview
    - Neural Networks
    - Results
- 4
  - Boosted Decision Trees
  - Statistics at the LHC
- 5
  - LHC
    - Dissect one analysis $H \rightarrow \gamma\gamma$
    - Channels overview
- 6
  - Higgs properties

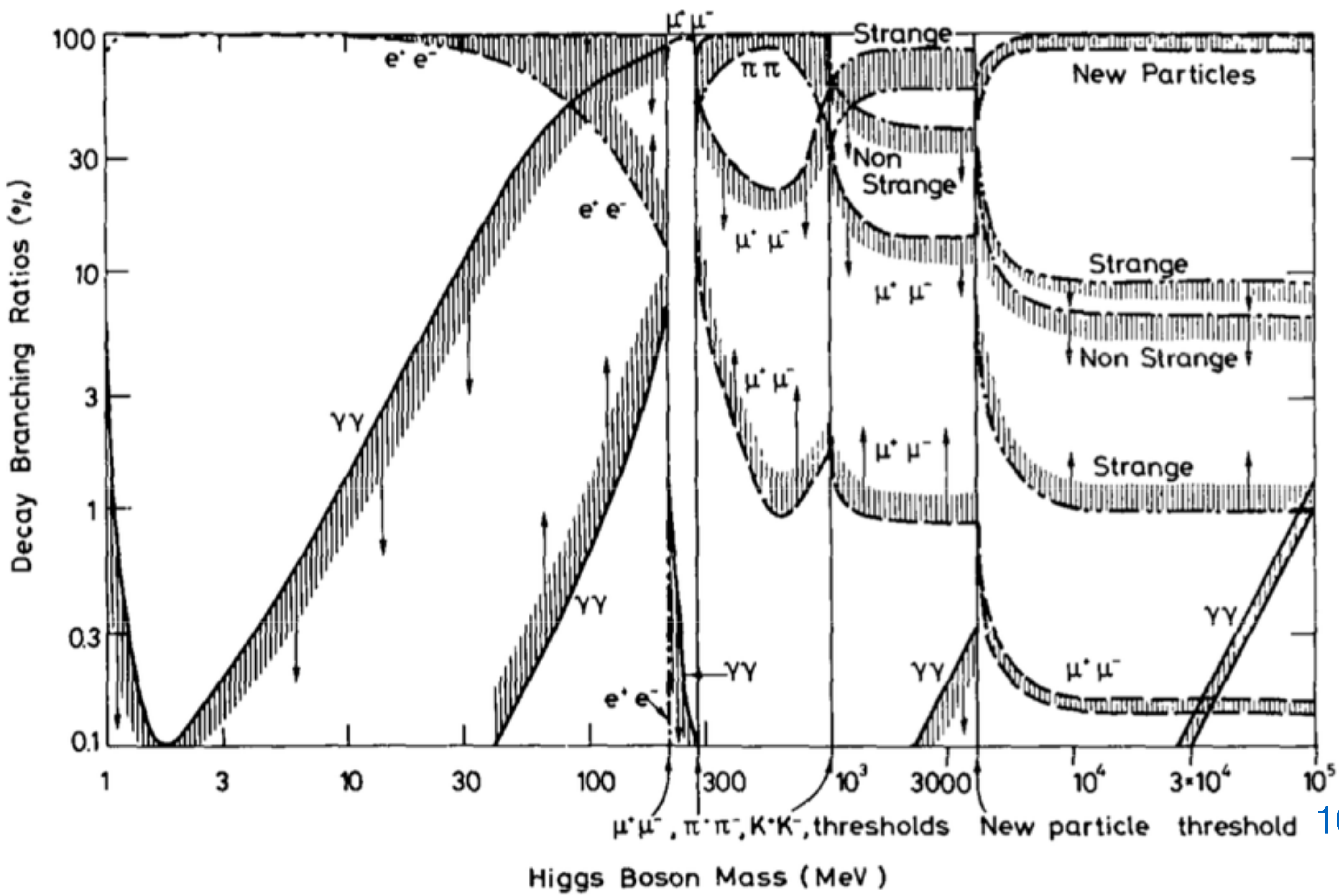
Exercises

- W mass
- CLs
- Hbb TeVatron
- SciKit MVA
- Toy CVCF

Early days

Early days

Ellis, Gaillard, Nanopoulos, 1975



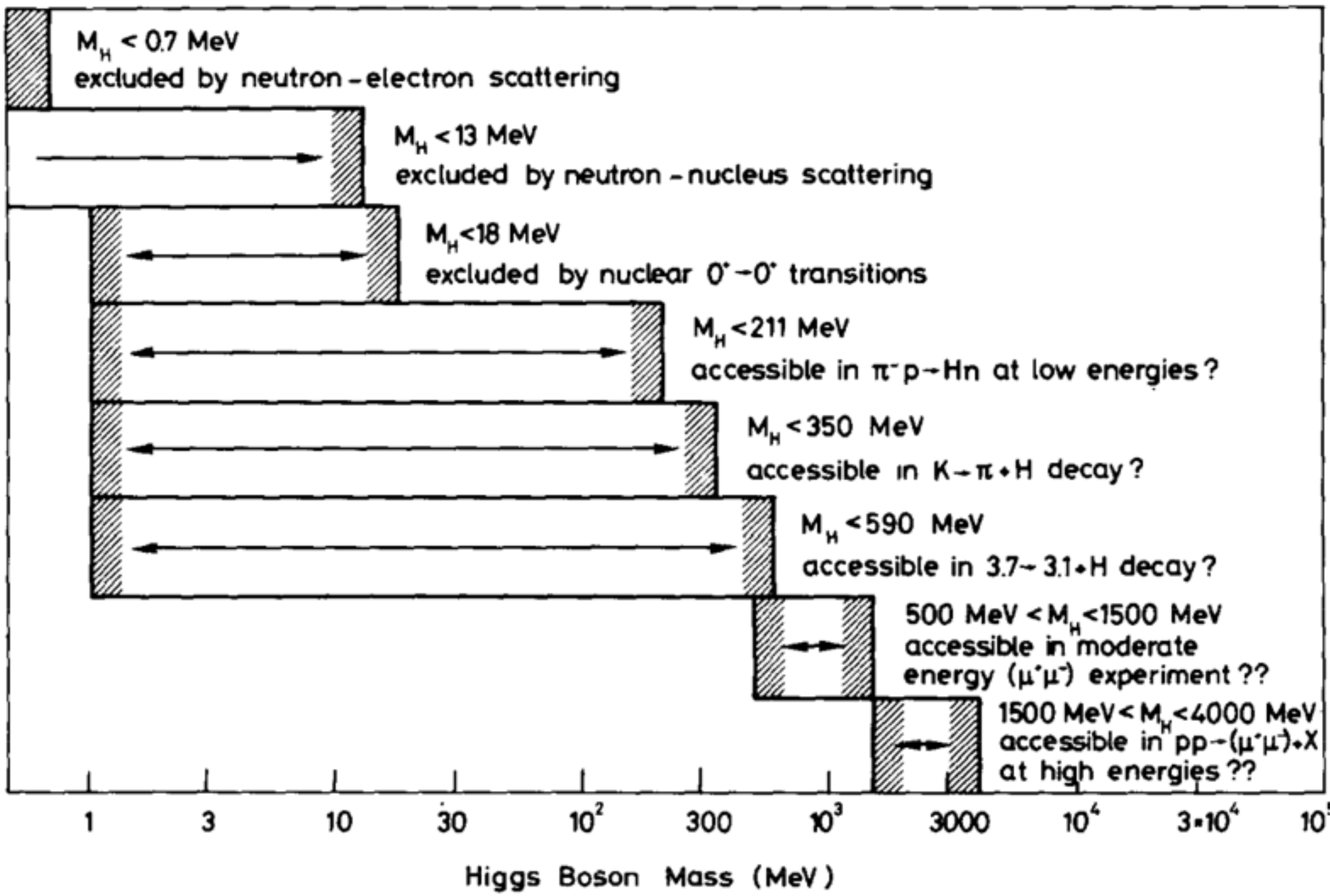
100 GeV

"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

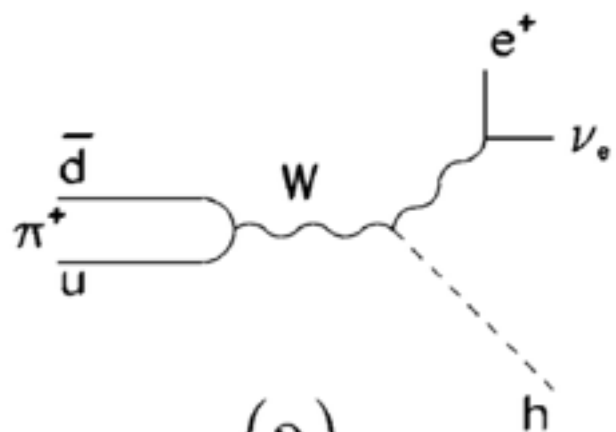
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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.

Higgs below 5 GeV

SINDRUM @ PSI

h→ee

$m_h \notin [10, 110]$ MeV

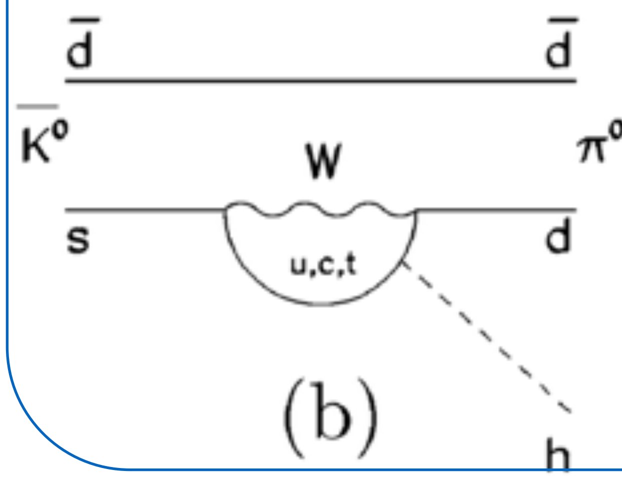


(a)

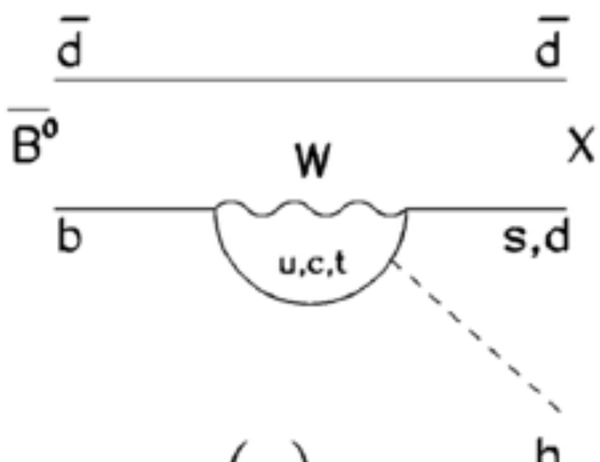
CERN-Edinburgh-Mainz-Orsay-Pisa-Siegen

h→ee $m_h < 50$ MeV

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



(b)

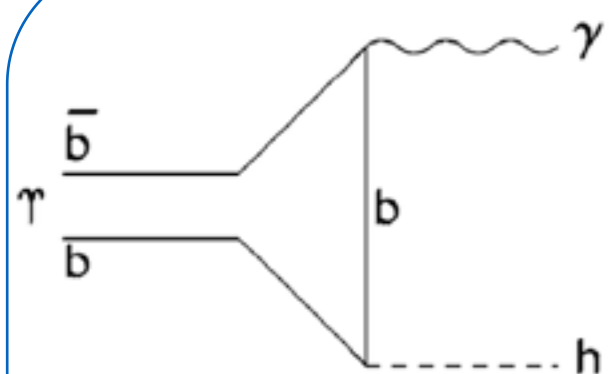


(c)

CLEO

h→ee

$m_h \notin [0.2, 3.6]$ GeV



(d)

CUSB

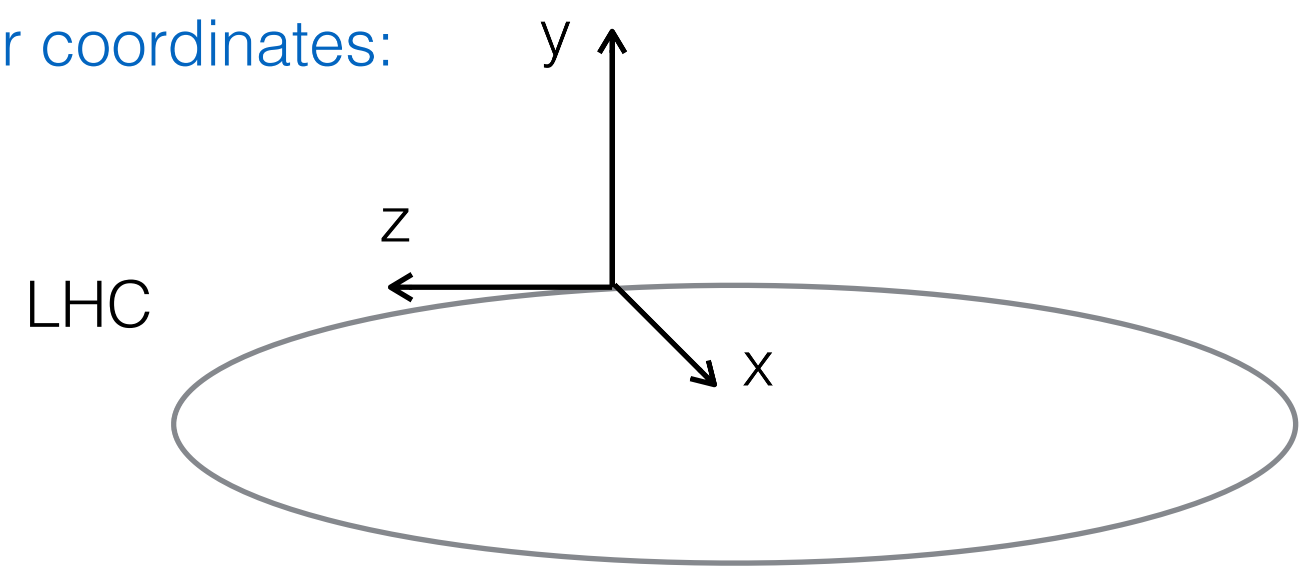
h→ee

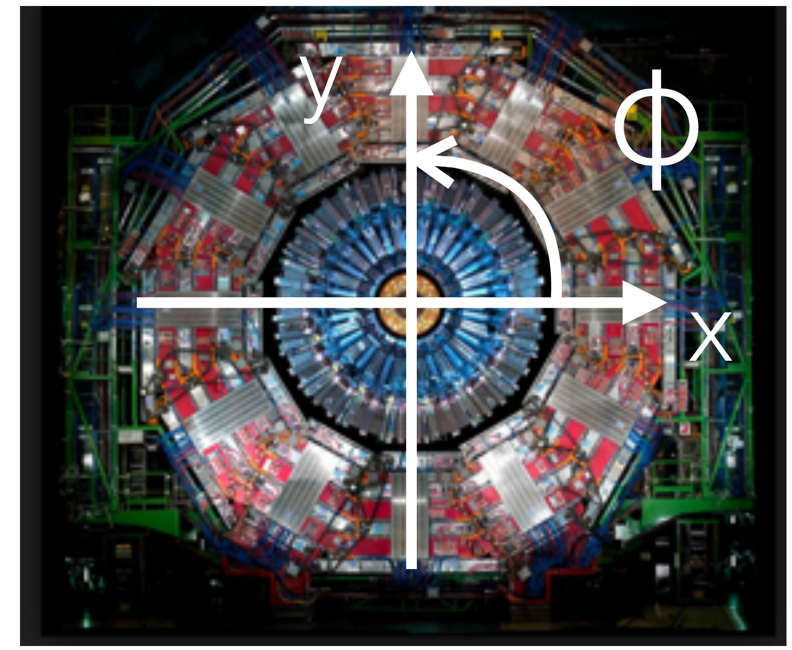
$m_h \notin [0.2, 5.0]$ GeV

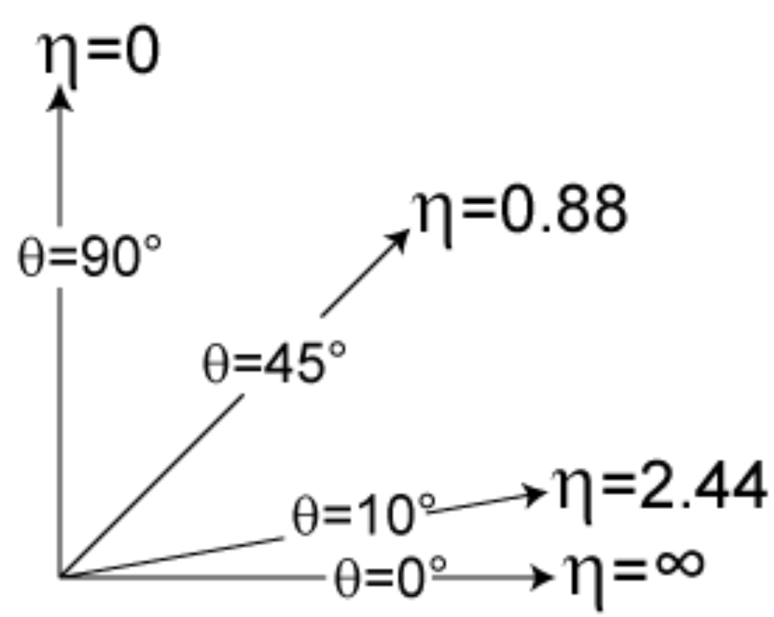
Accelerators and Detectors: basic concepts

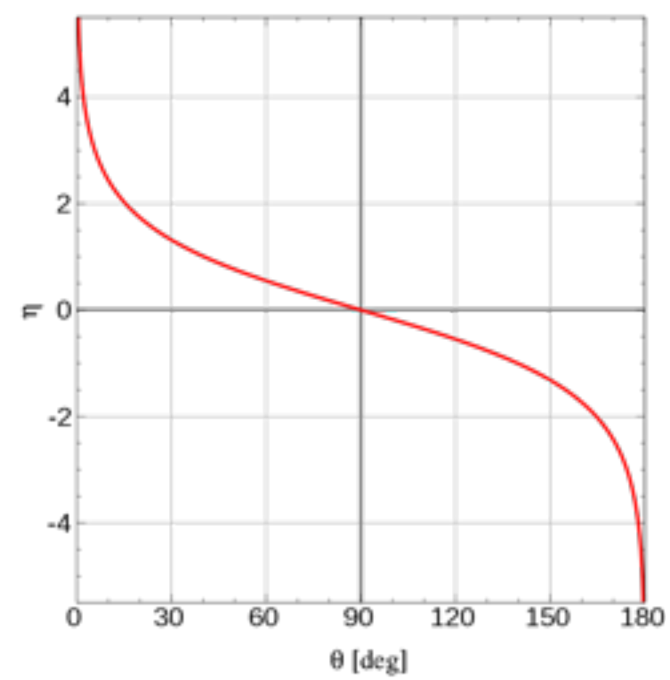
Review of basic concepts

Detector coordinates:









Pseudo-rapidity

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$$\theta = 2\arctan\left(e^{-\eta}\right)$$

Review of basic concepts

Decay: A—> B C

(integrated over all the possible kinematic configurations)

Partial width $\Gamma_{B\,C}$ = decay rate of A to B C (slang “in the B C channel”)

The sum of all the partial decay rates is the total width of A.

The total width is the inverse of the lifetime: $\Gamma = 1 / \tau$.

Branching ratio of A —> B C is $\Gamma_{B\,C} / \Gamma$

Review of basic concepts

Cross section

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

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

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

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

$n \sim 10^{11} \quad \times 2808$ bunches

$\sigma \sim 20\ \mu m$

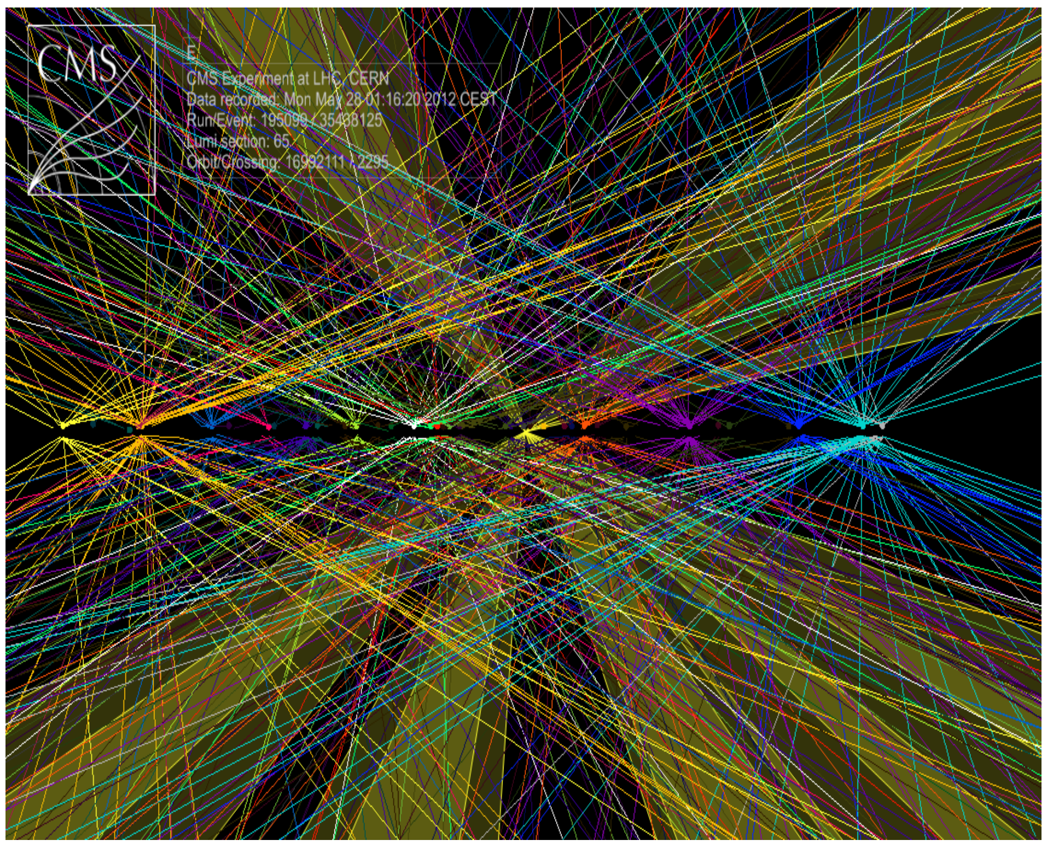
$f \sim 11\ kHz \quad (27 km)$

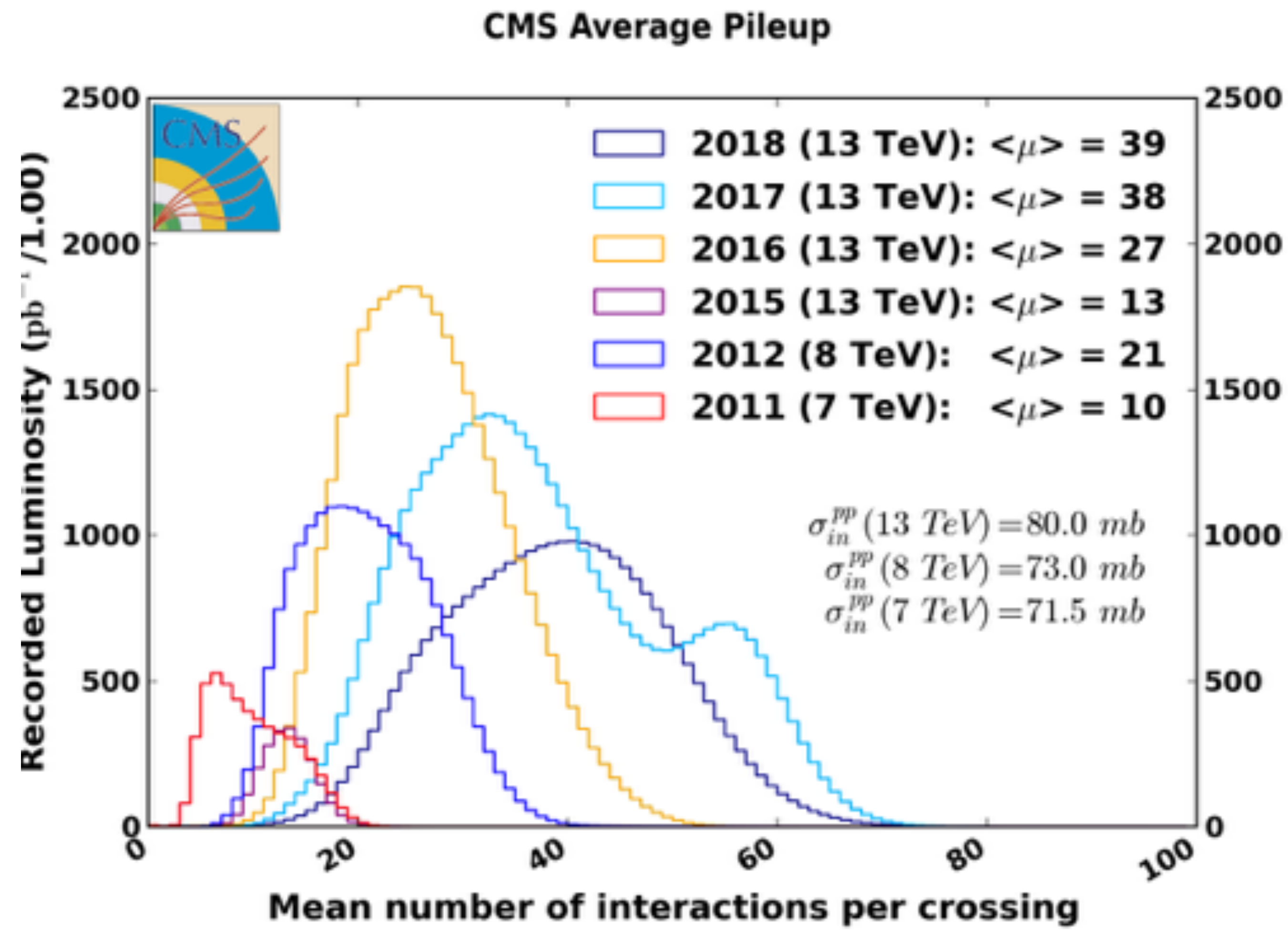
$\mathcal{L} \sim 10^{34} / cm^2 s$ $\qquad$ $L = \int \mathcal{L}\, dt$

instantaneous $\qquad$ integrated

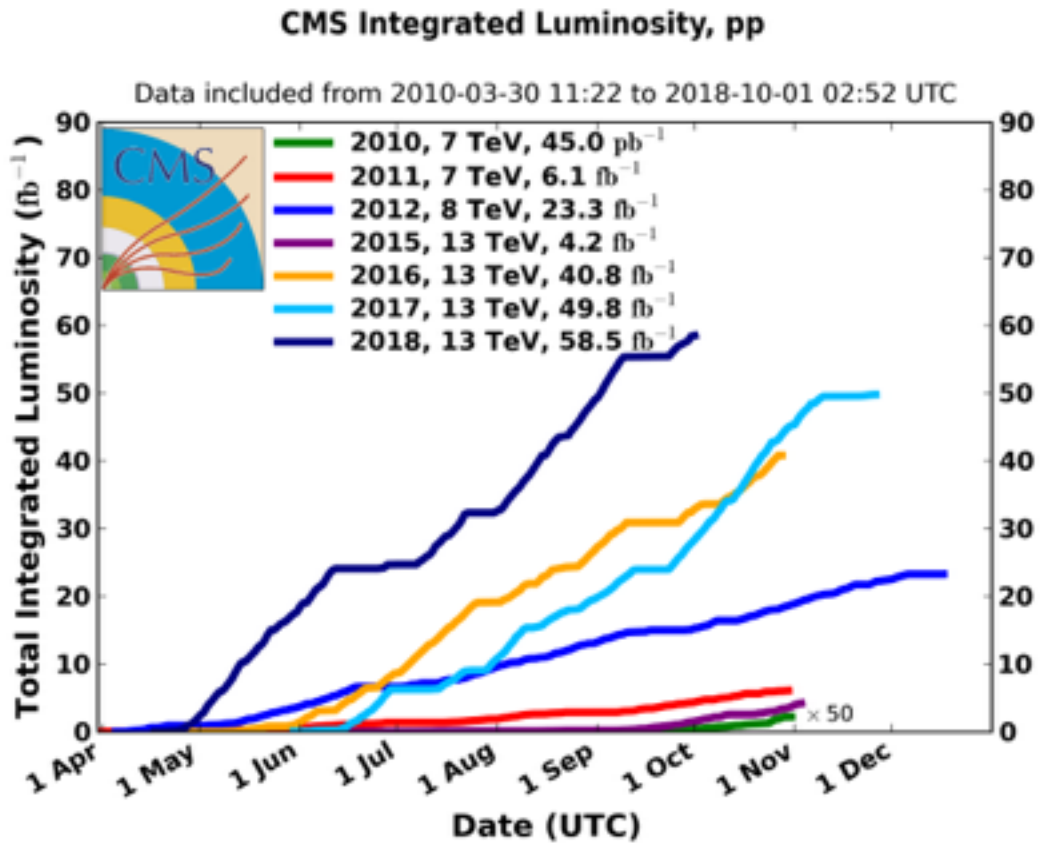
LHC luminosity - Pileup

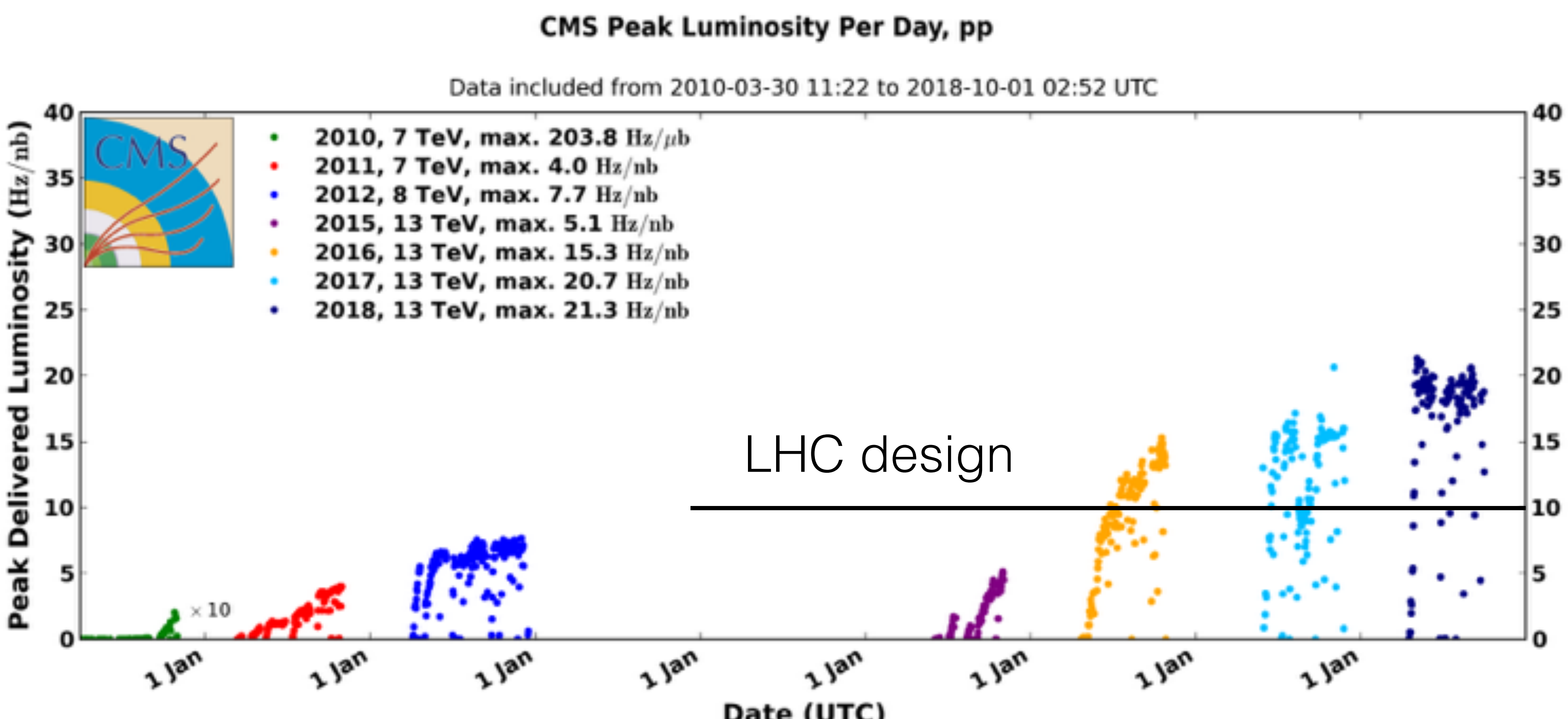
(intime) Pile up





LHC luminosity @ CMS





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?

Colliders

Lepton Colliders | Hadron Colliders

e^+e^- SLC polarized

LEP

$\mu^+\mu^-$ μ- collider

S$p\bar{p}$S

TeVatron

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. $m = \sqrt{s} \sim \sqrt{2 E_p m_p}$ $m = 125$ $E_p \sim 30$ TeV

C.B. $m = \sqrt{s} \sim \frac{E}{2}$ $m = 91$ GeV
$E_{e^+} = E_{e^-} \simeq 45$ GeV

Colliders

Lepton → point like (fixed E) precise knowledge of the CM energy

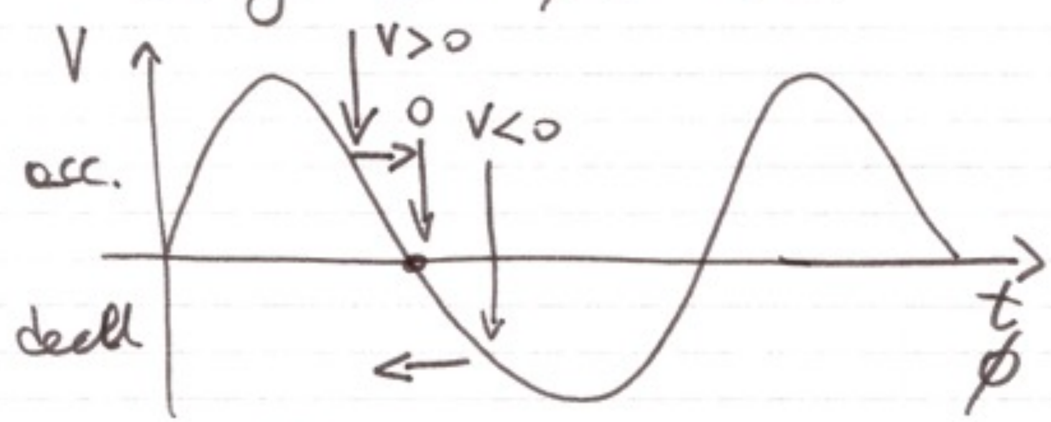
Hadrons → (protons) composite (pdf) we will see the details of $p\bar{p}$ / pp collisions with LHC/TeVatron

Linear / Circular single shot / no brem

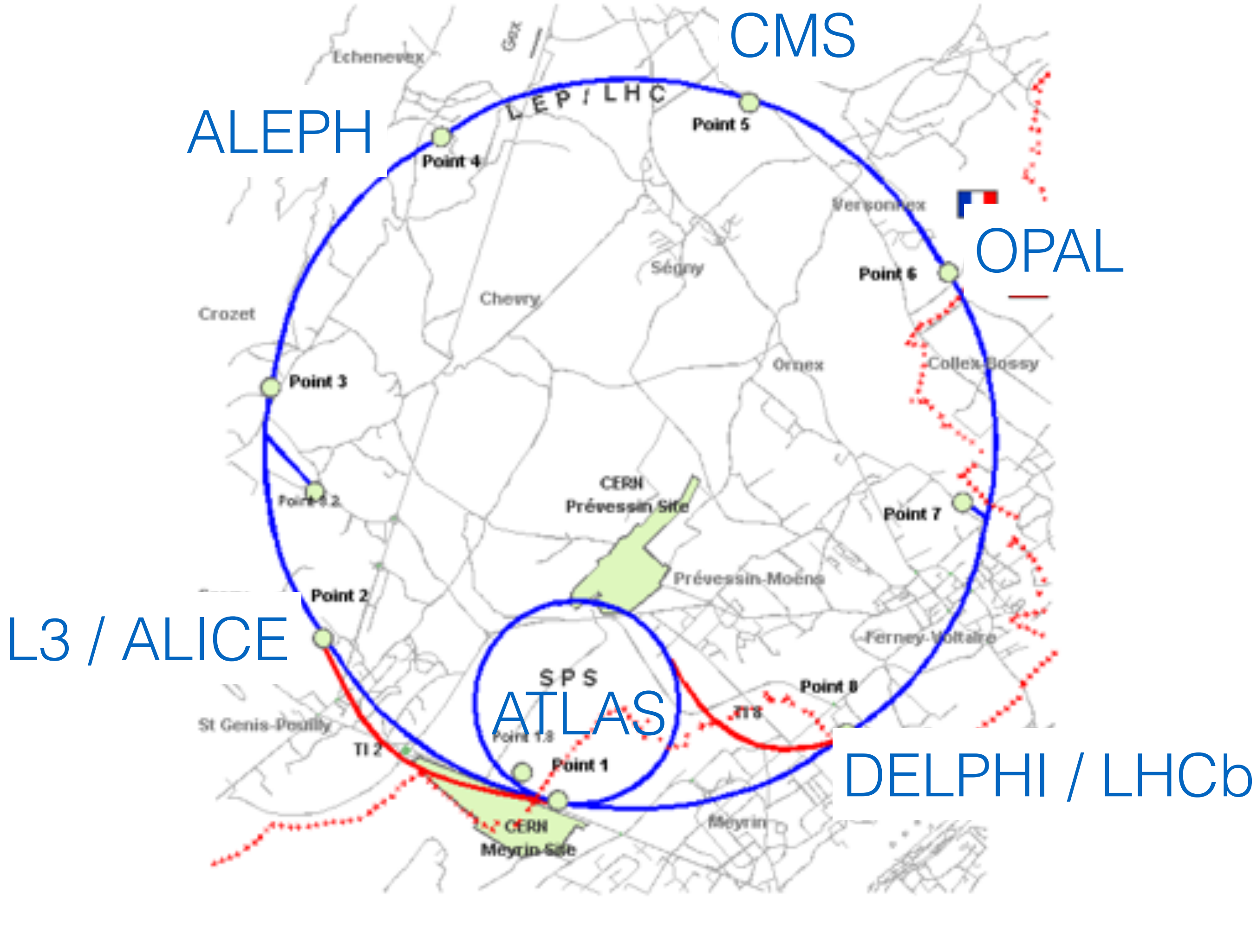
RF cavities

(CLIC / plasma wakefield)

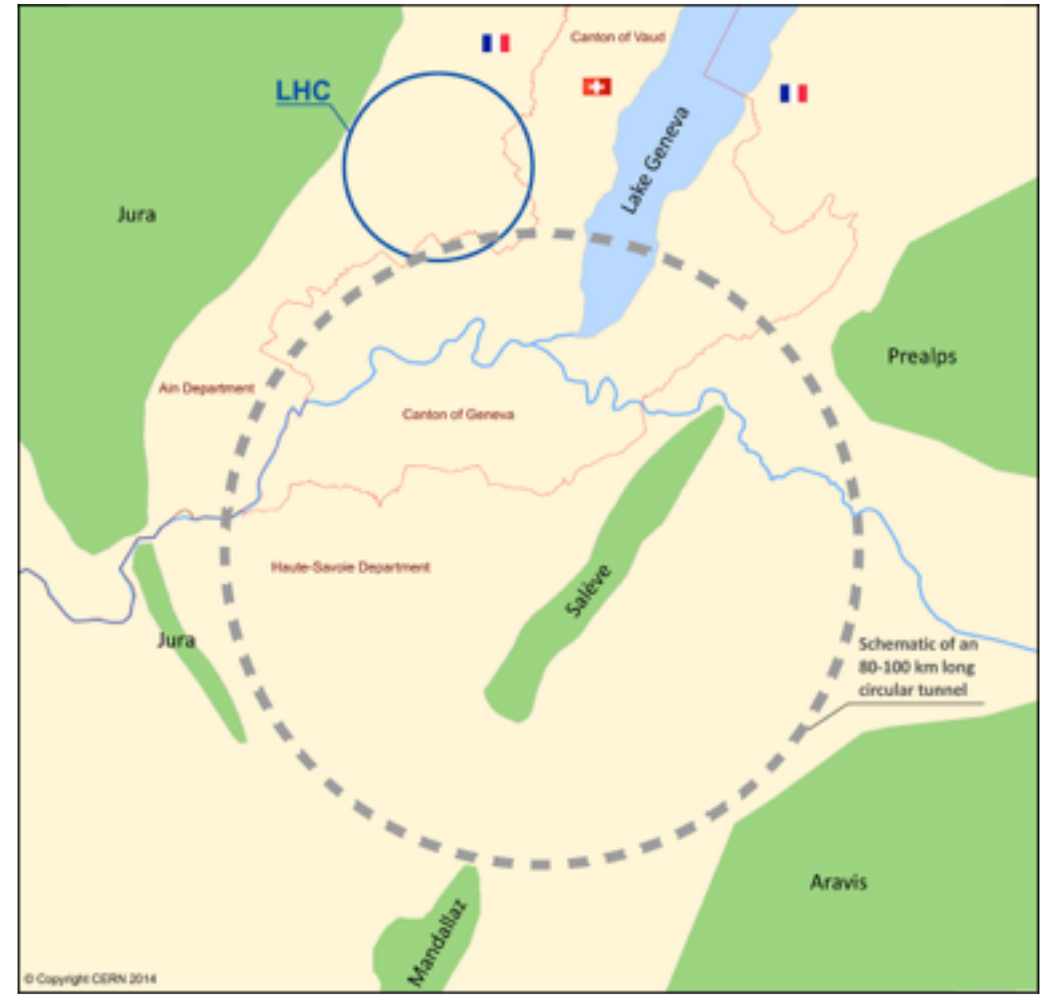
$\mathcal{O}$(MV/m)

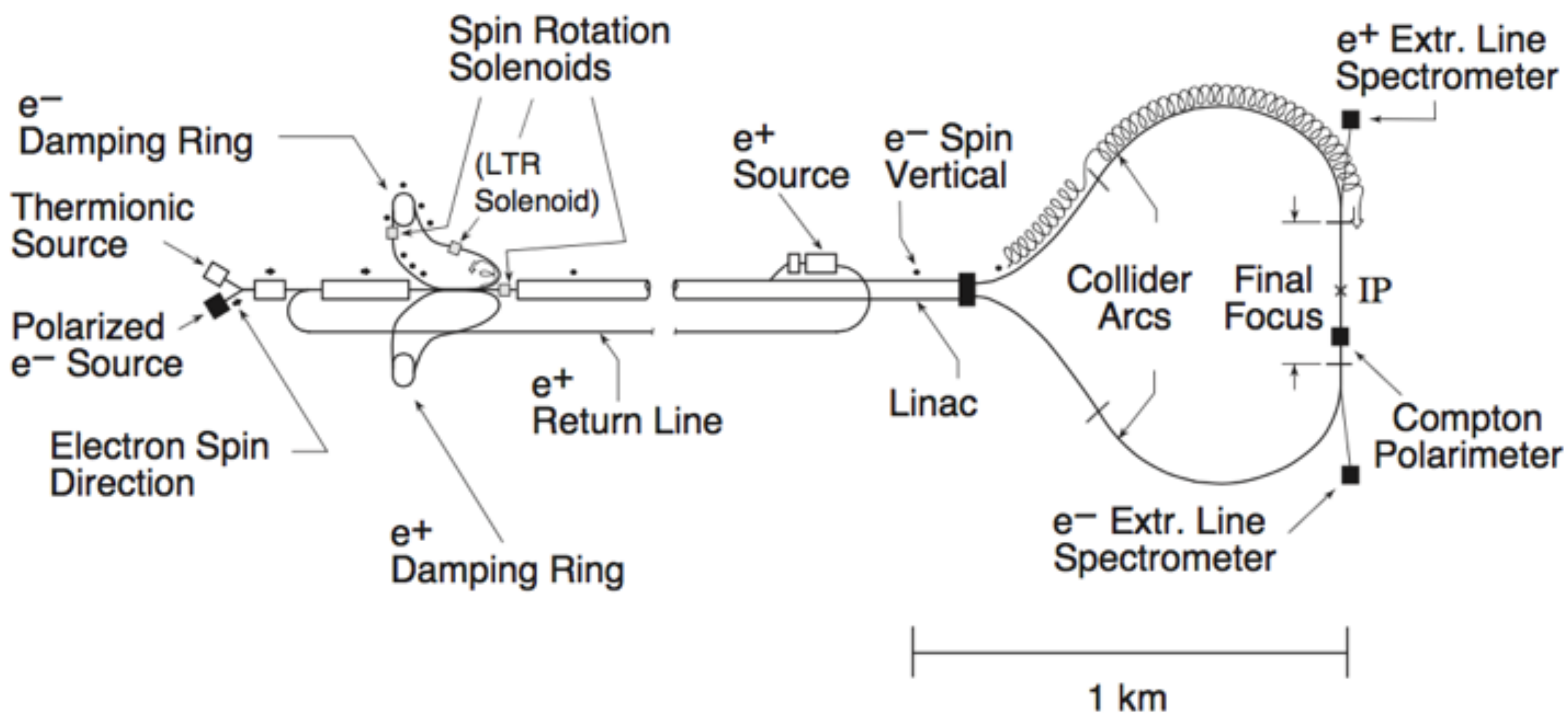


Bunch



Map of CERN sites and LHC access points





Magnetic fields for detectors

The arrangement of the magnetic fields is what defines the fundamental design of the full detector

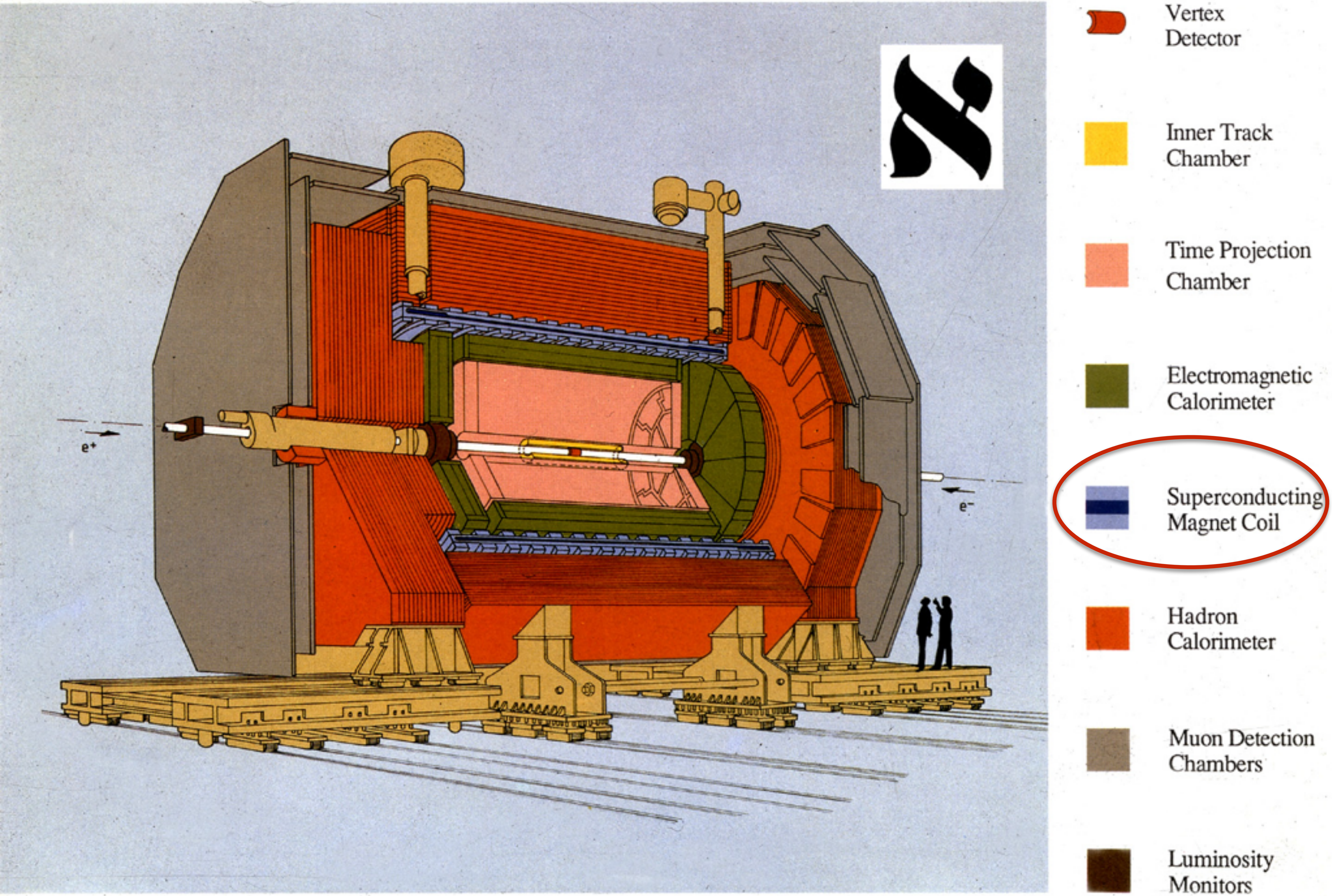
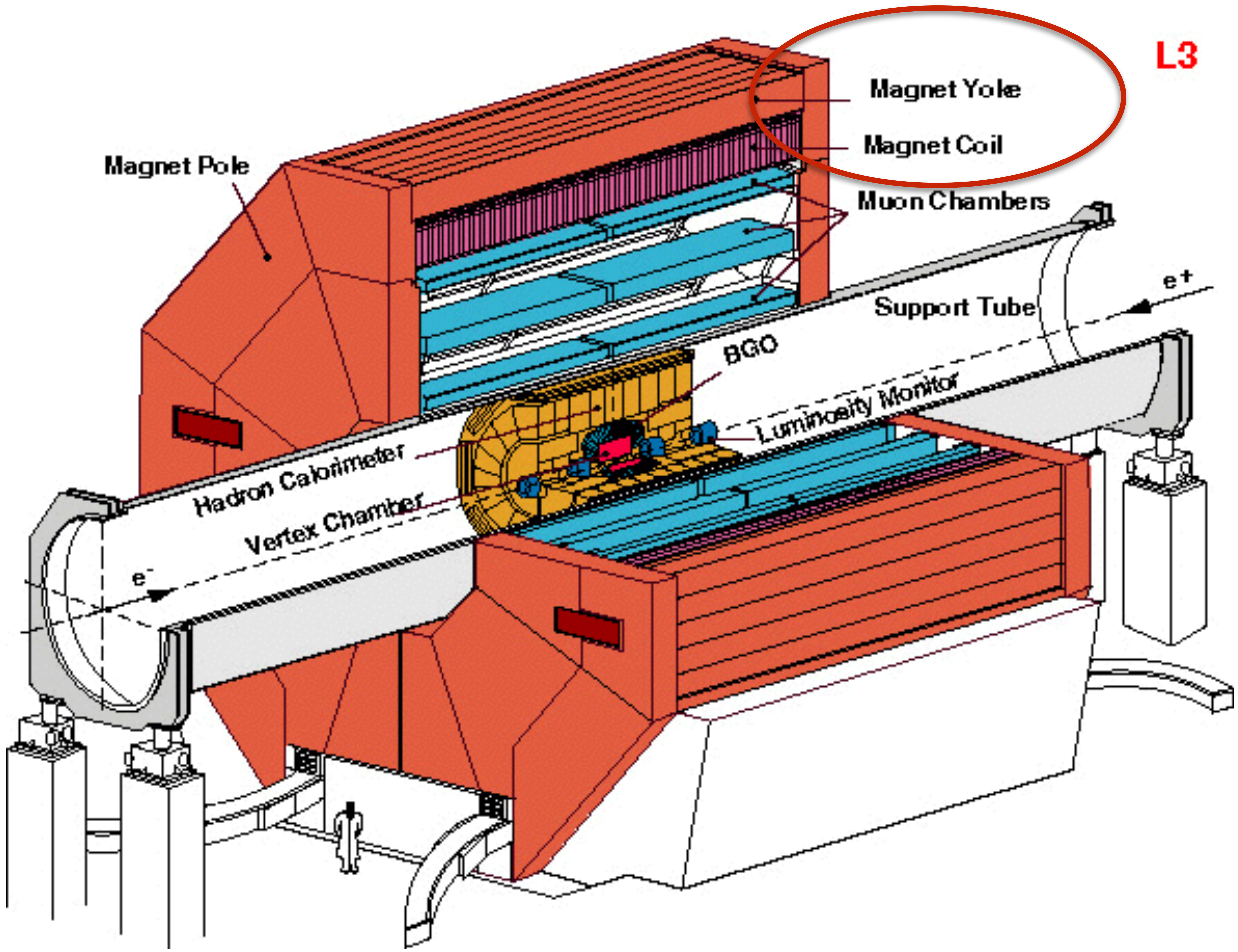
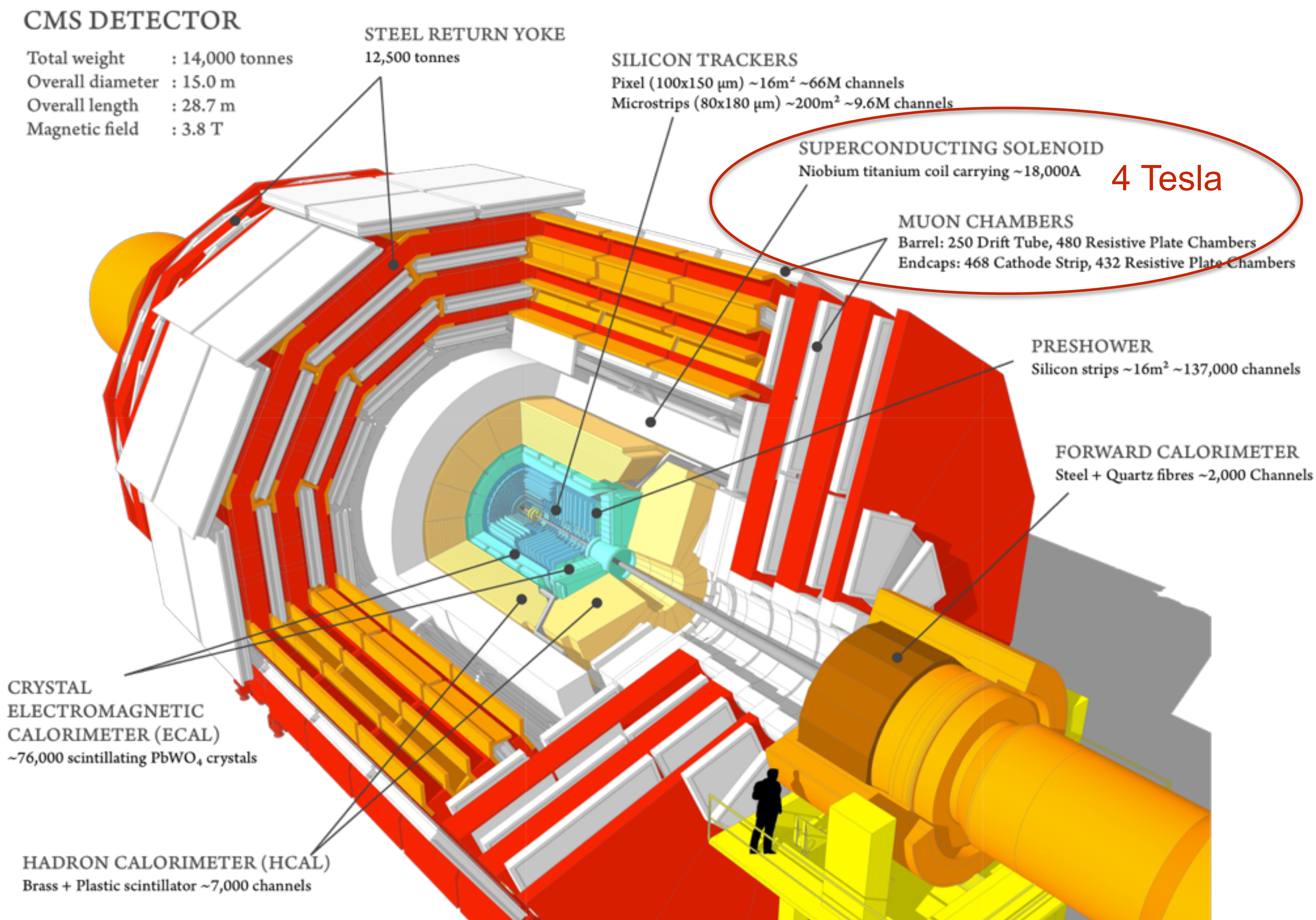
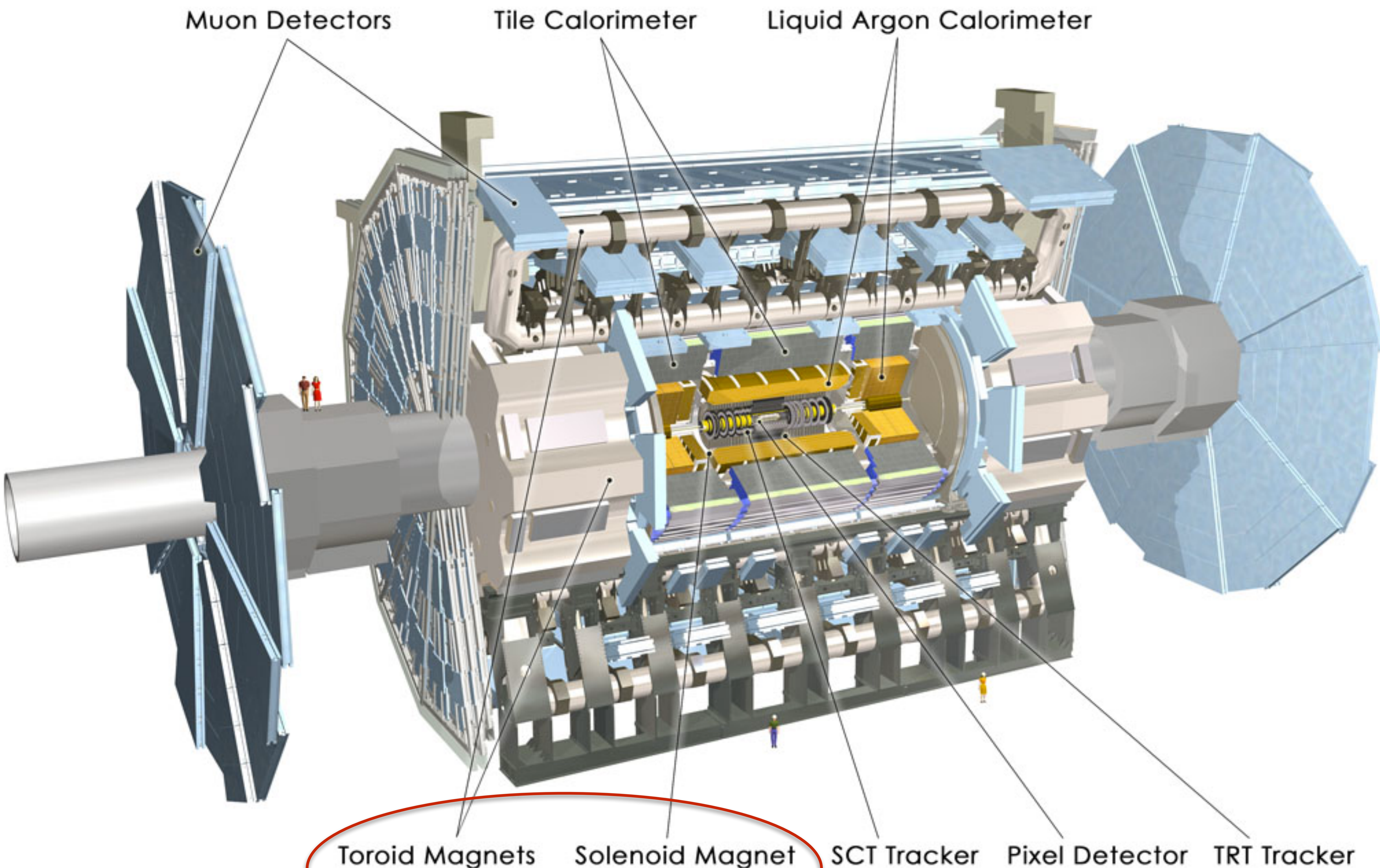


Fig. 1 - The ALEPH Detector


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

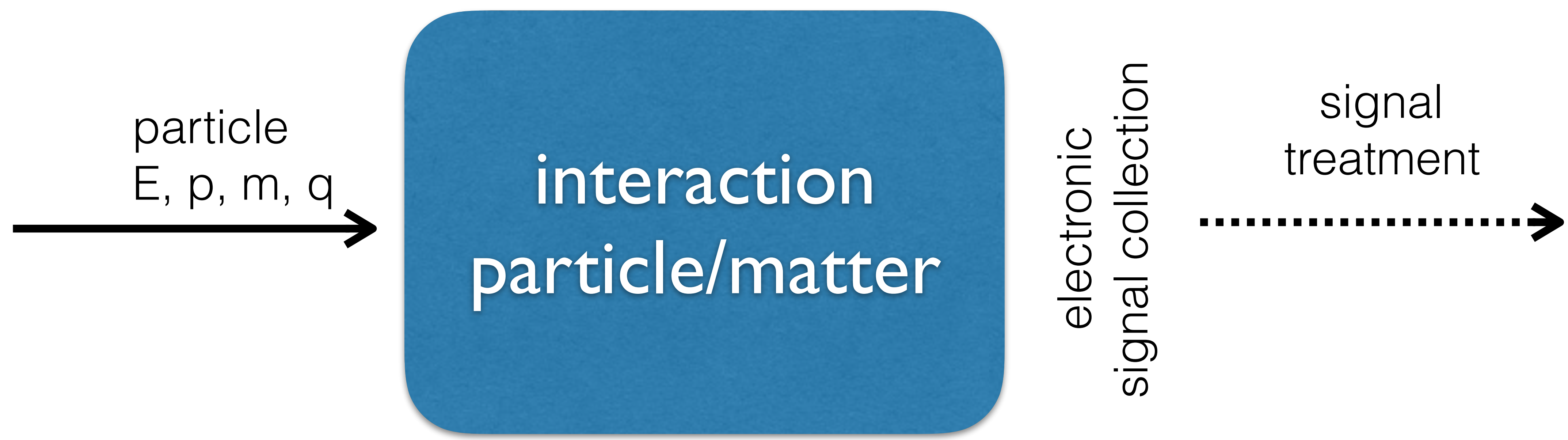

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m^2 ~66M channels
Microstrips (80x180 μm) ~200m^2 ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~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 ~16m^2 ~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



2 Tesla

“Detection principle”



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

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

Detectors

Detectors

$\tau^\pm$?

	charged	/ neutral particles
	$e^\pm, \mu^\pm, \pi^\pm, k^\pm$	$\gamma, n, "\pi^0"$
- What	charged	/ neutral particles
	- ionize	- "no - ionization" e.m int.
	- bend $\vec{B}$	- no bending
	- nuclear int.	- no nuclear int.

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

((e)), (μ), τ

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

new particles $\to$ ordinary particles

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

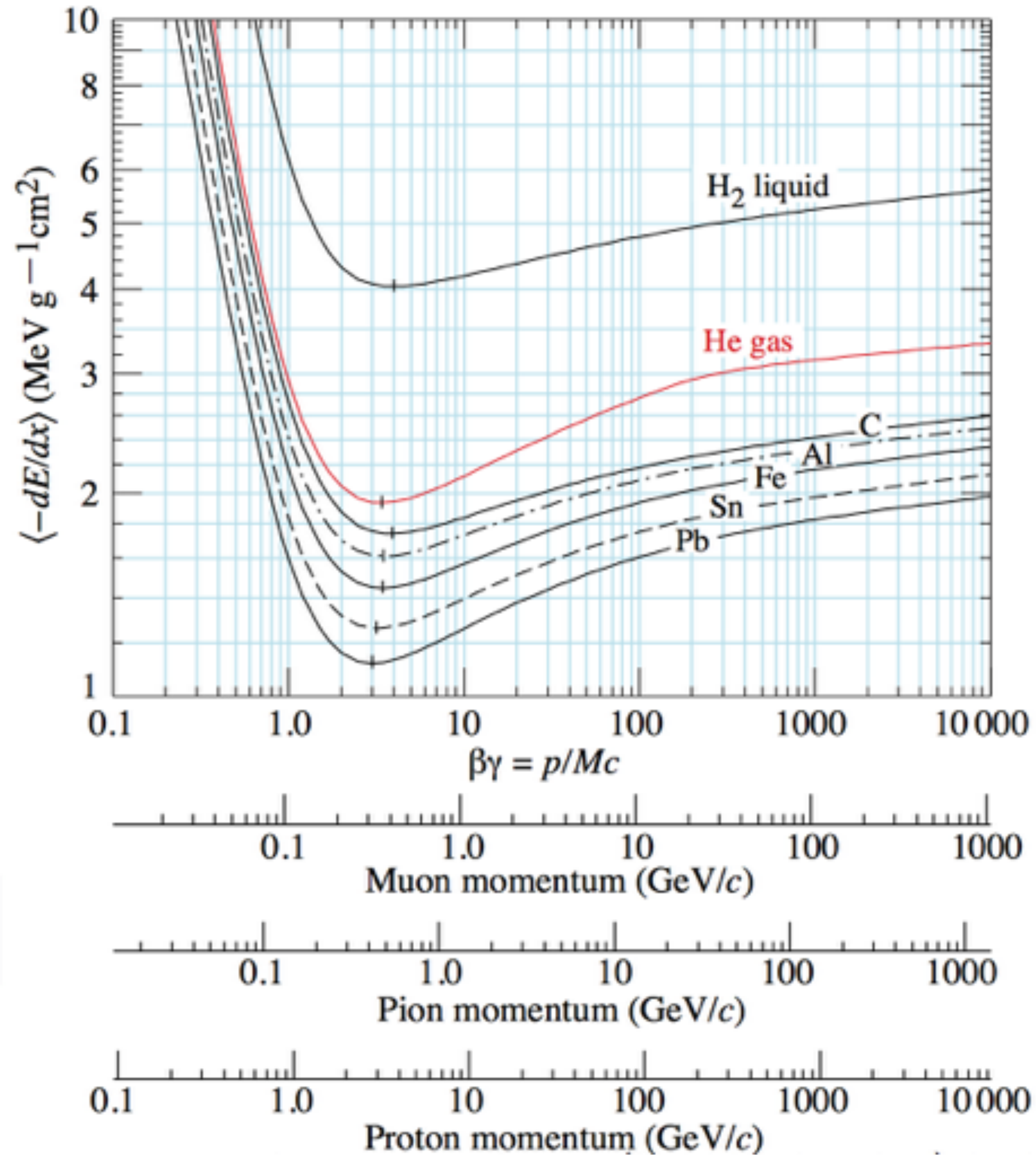
What can create missing transverse energy ?

Passage of particles through matter

Momentum range of particles to be detected for Higgs physics:
[O(1 GeV) - O(hundreds GeV)]

Ionization energy loss
(for "heavy" particles i.e not electrons)

- electronic energy loss by heavy particles
  heavy $> m_e$ $\mu, \pi, p, \ldots$
  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

e/γ <u>Radiation length</u>

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

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

e.m. cascades

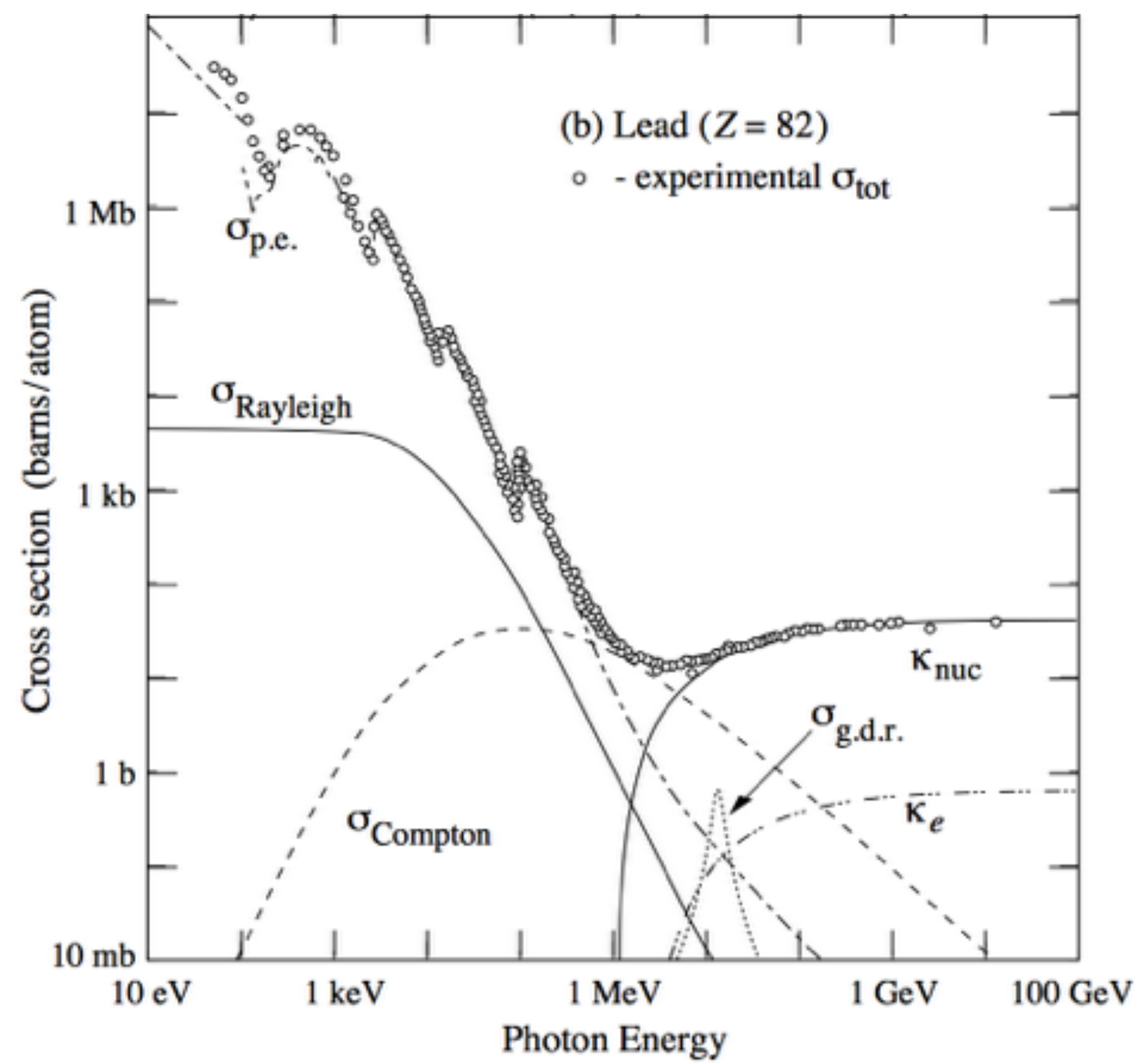
<u>critical energy</u> $E_{brem} = E_{ioniz.}$
$(\propto E_{electr.})$ $(\propto \log E_{electr.})$

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

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

Electrons E>1 GeV only bremsstrahlung

Electrons E>1GeV only pair production



Passage of particles through matter

Electromagnetic shower development

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

$$t_{max} = \frac{a-1}{b} = \ln y + C$$

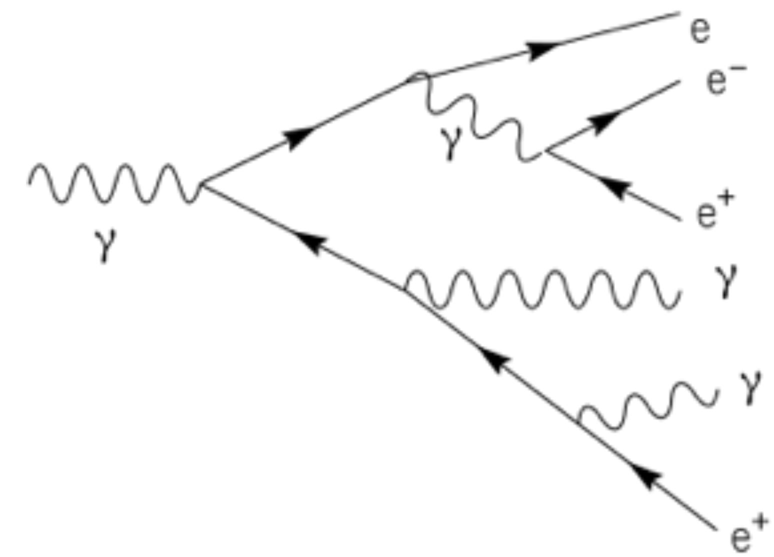
shower max

C: $+0.5$ γ, -0.5 e

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

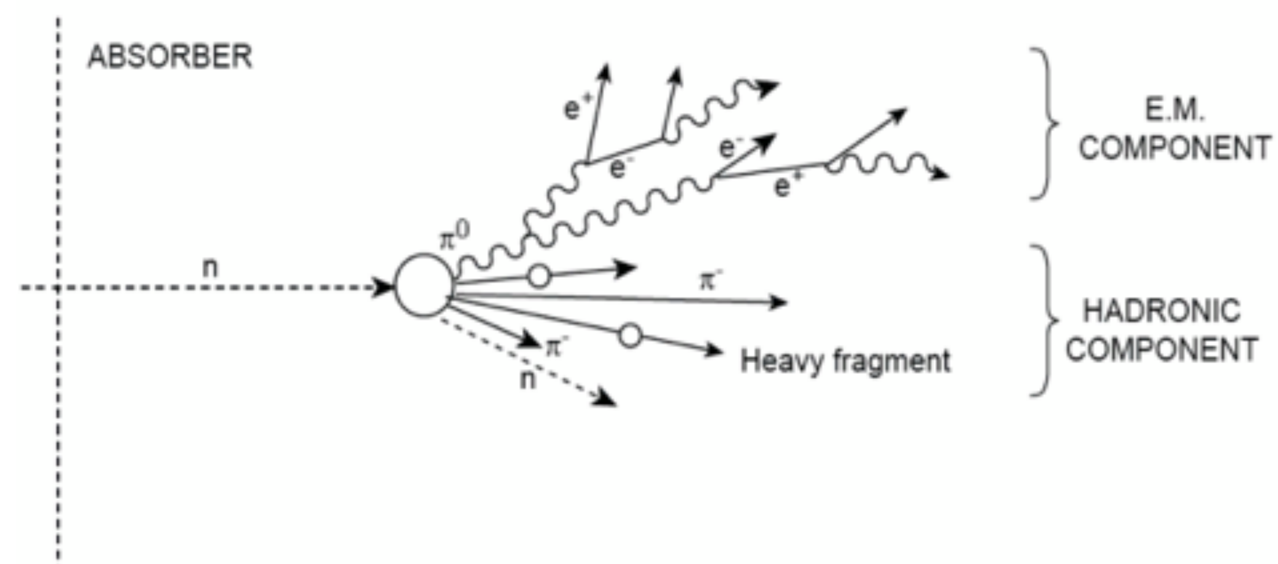


How thick a calorimeter has to be to contain 99% of the energy of a 1 GeV photon ? and for 1 TeV ?

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

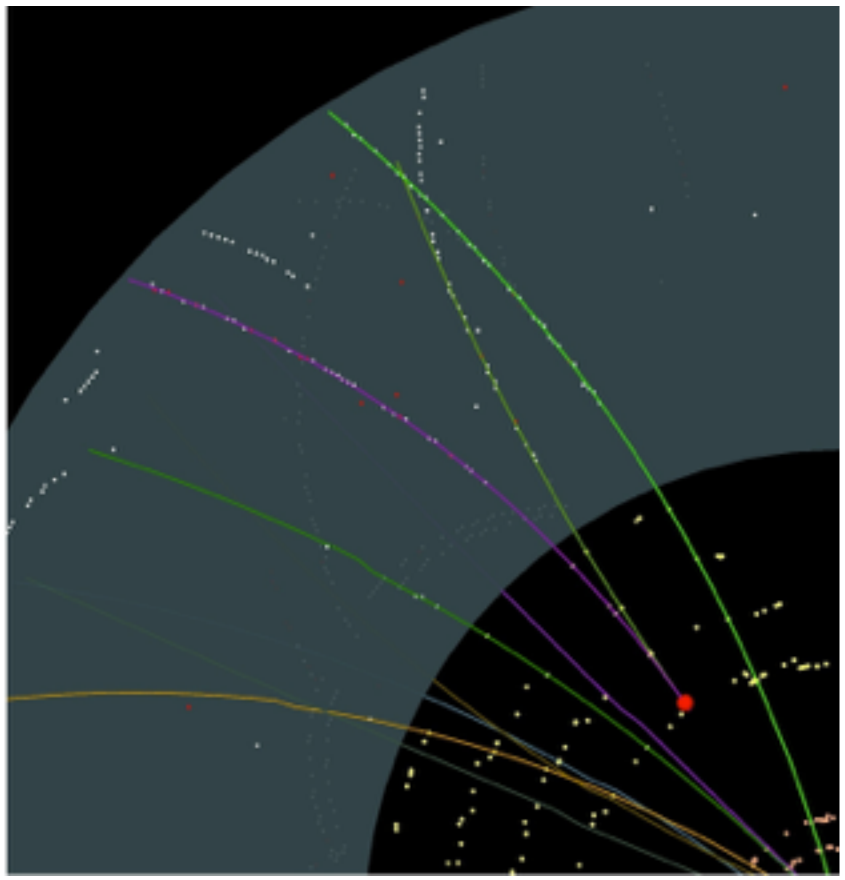
$$N(x) = N_0 \exp(-x/\lambda_{\text{int}})$$

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

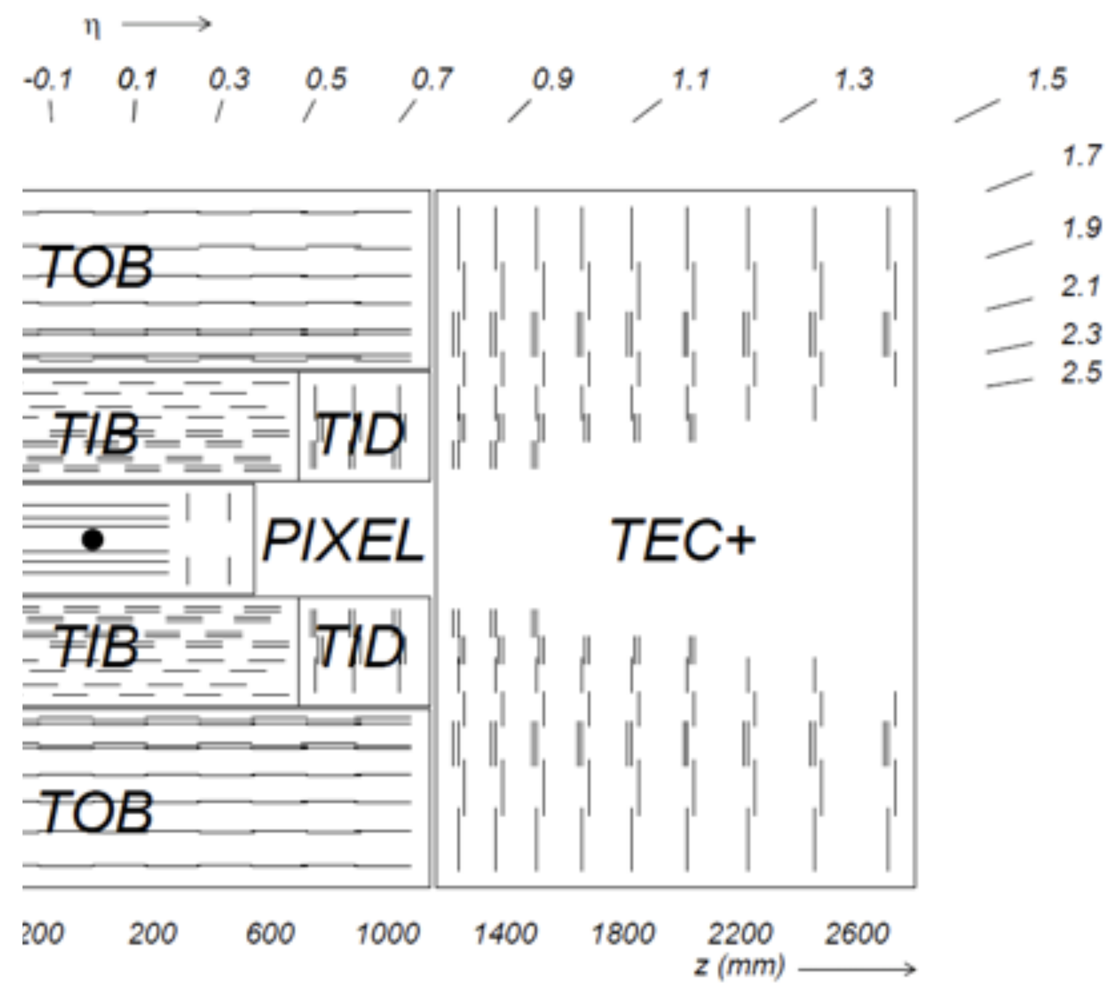


Trackers and e.m. calorimeters

TRT e/hadron separation



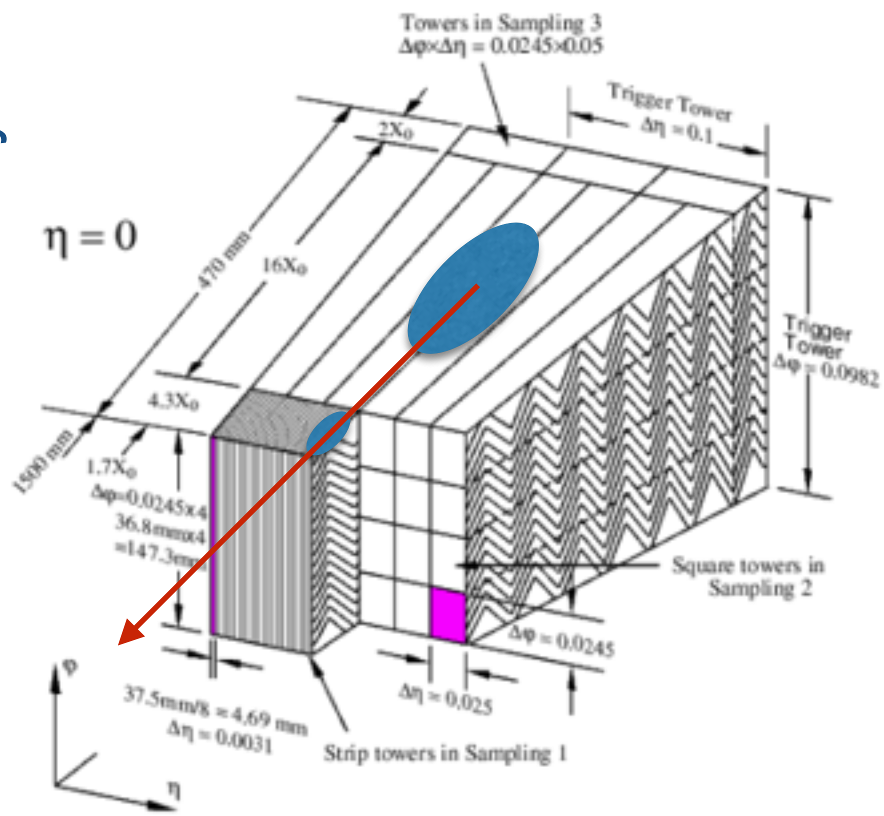
All Silicon



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

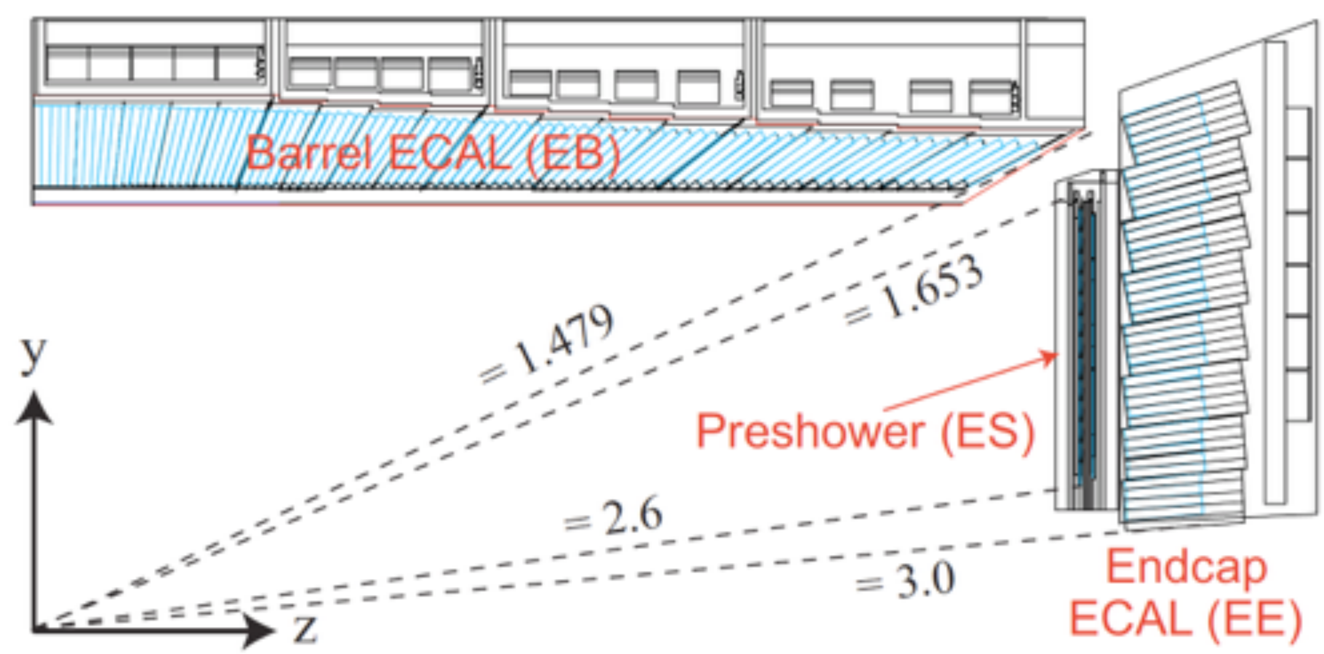
Trackers and e.m. calorimeters

ATLAS LAr accordeon
Ouside the Solenoid/Cryostat

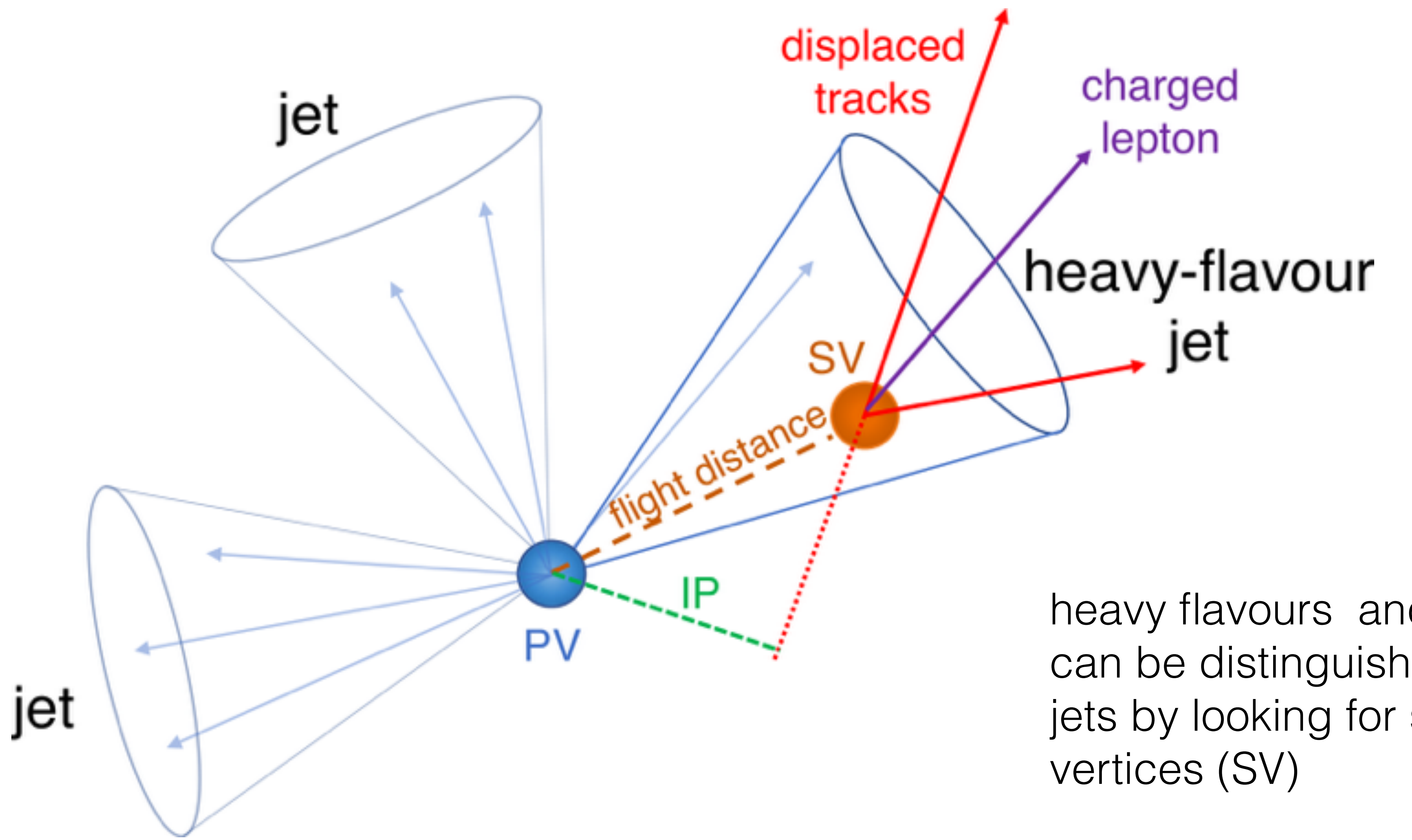


pointing

CMS crystals $PbWO_4$
Inside the Solenoid

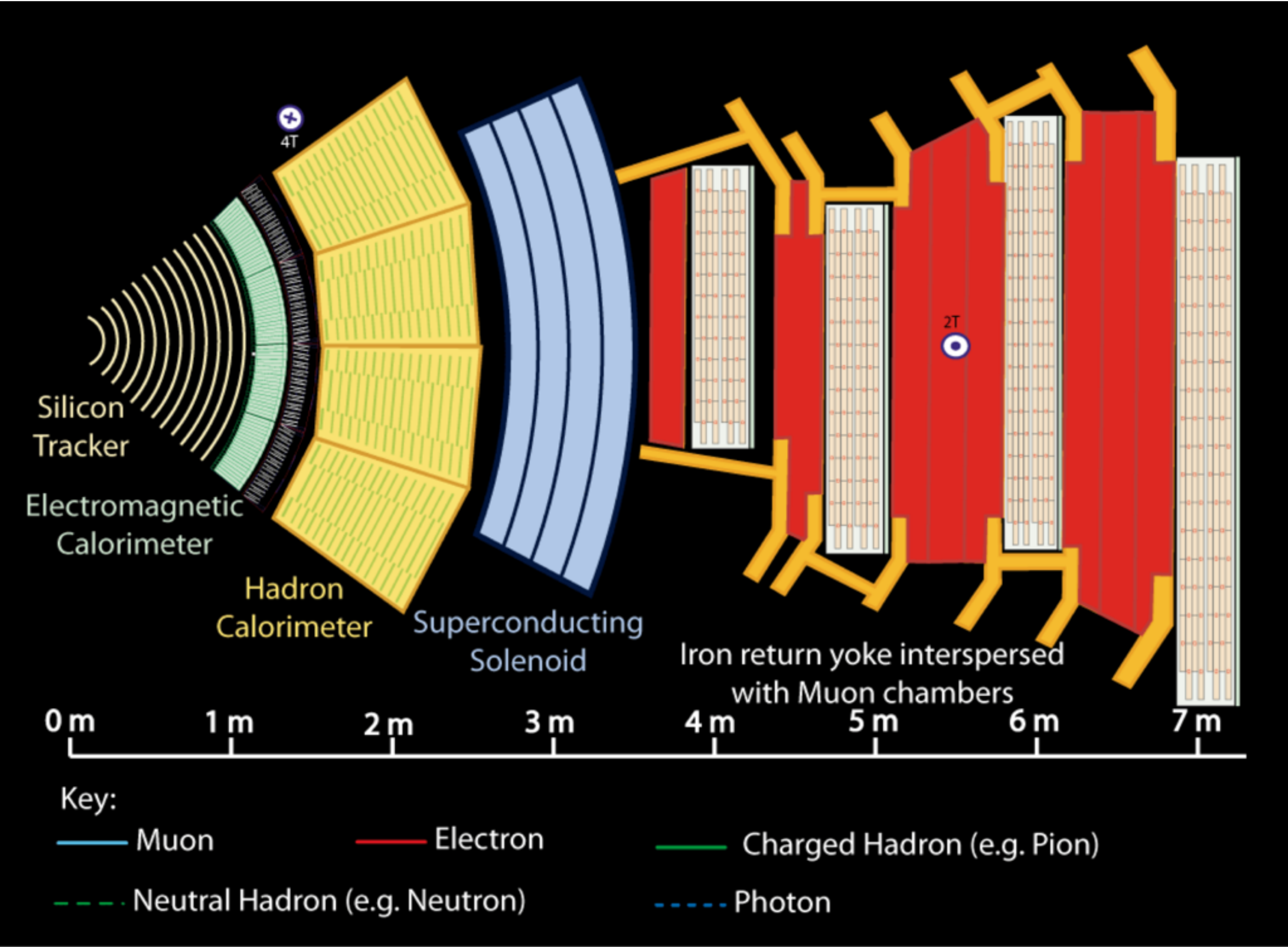


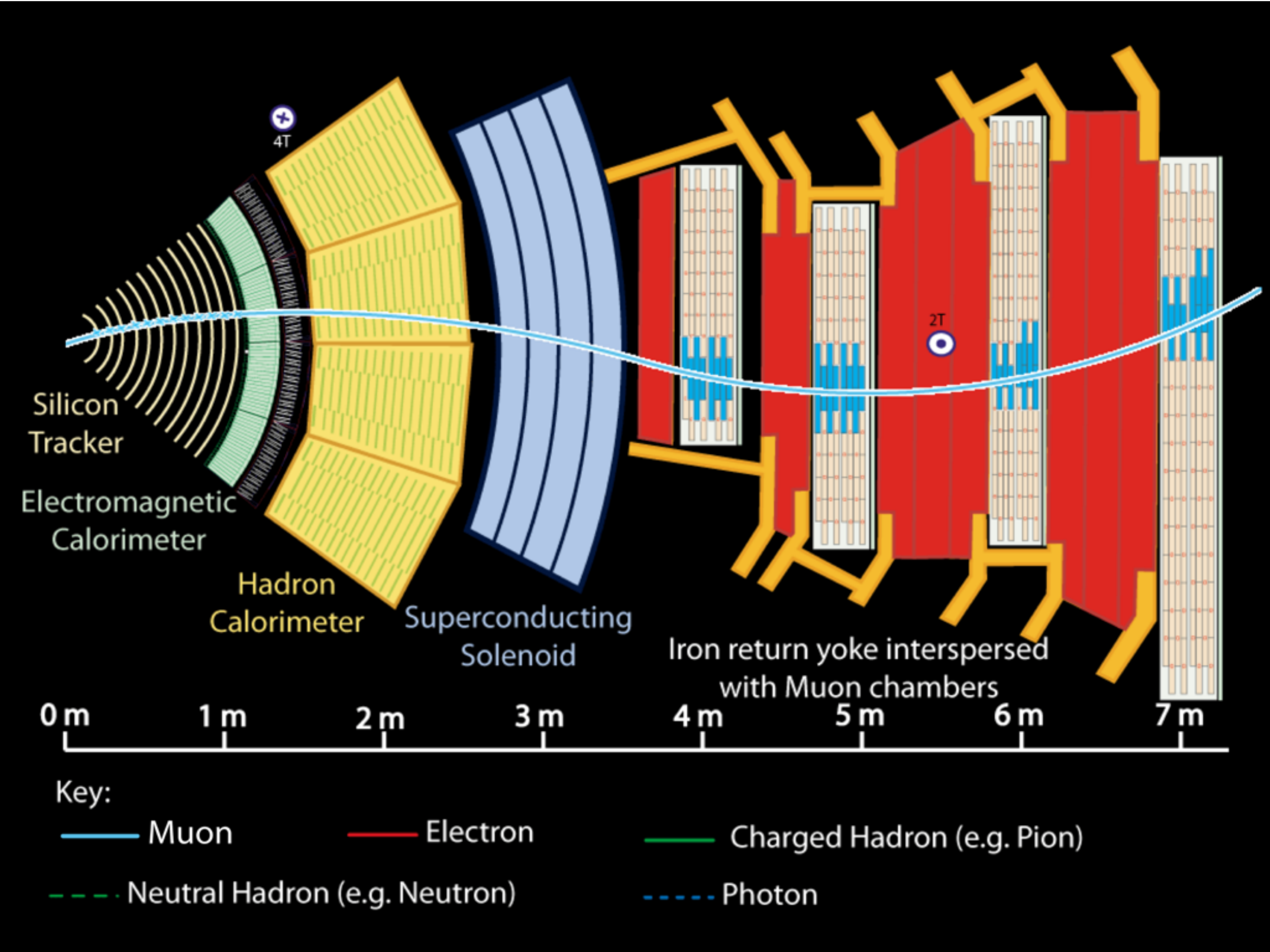
Secondary vertices



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

Several variables are fed into a multivariate discriminator to distinguish light flavours jets from b/c-jets (BDT or NN)


4T
2T
Silicon
Tracker
Electromagnetic
Calorimeter
Hadron
Calorimeter
Superconducting
Solenoid
Iron return yoke interspersed
with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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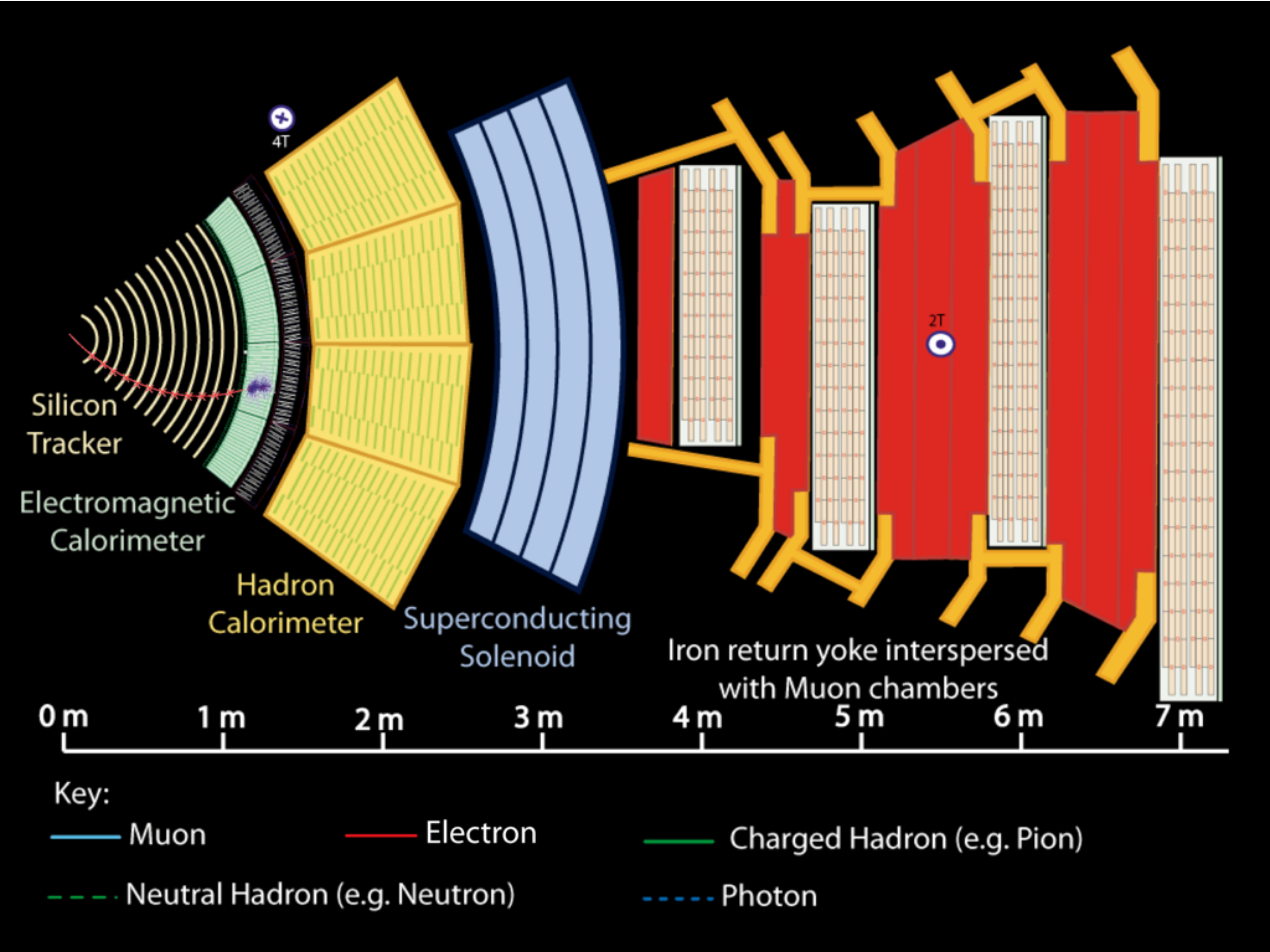
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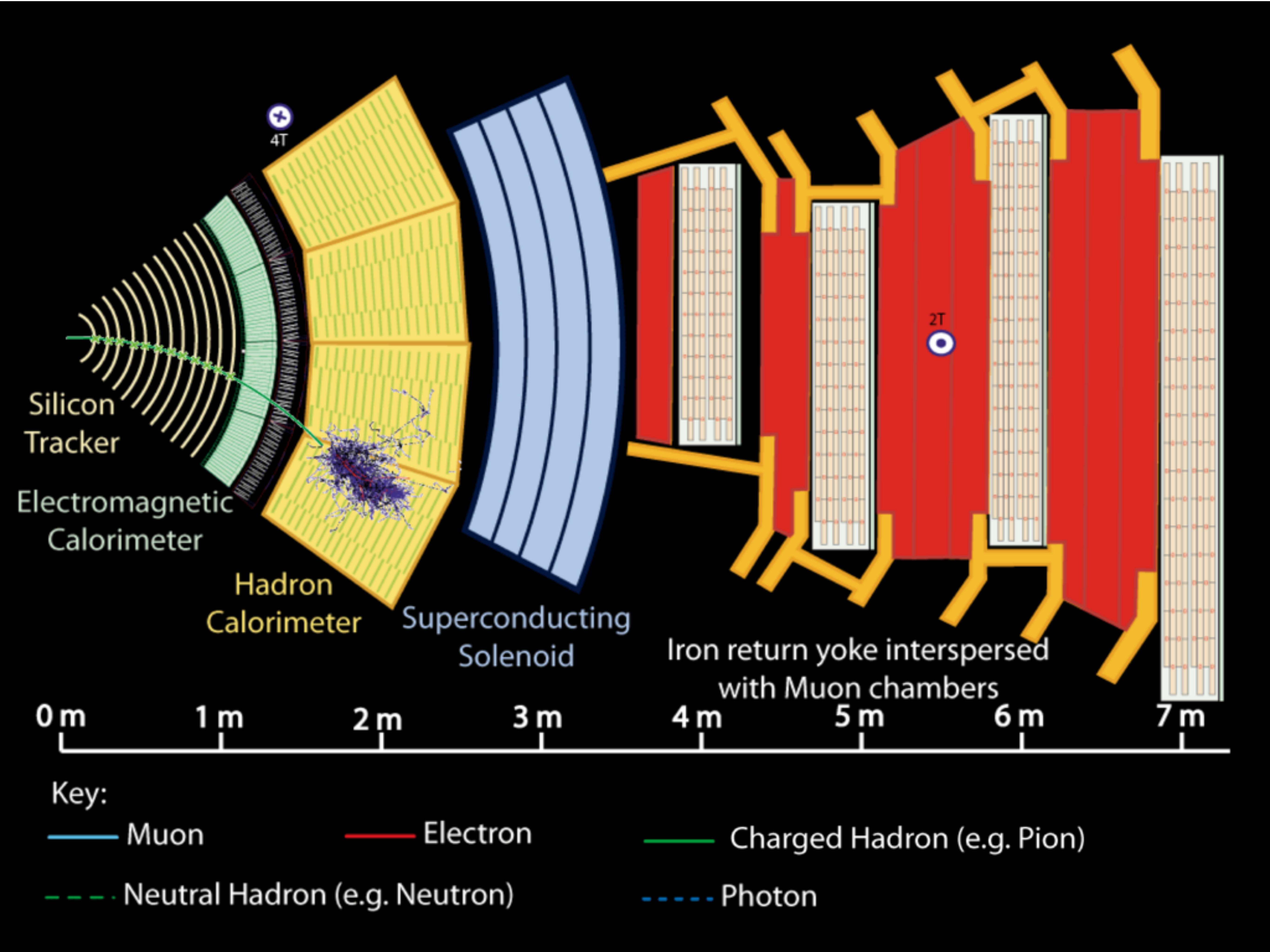

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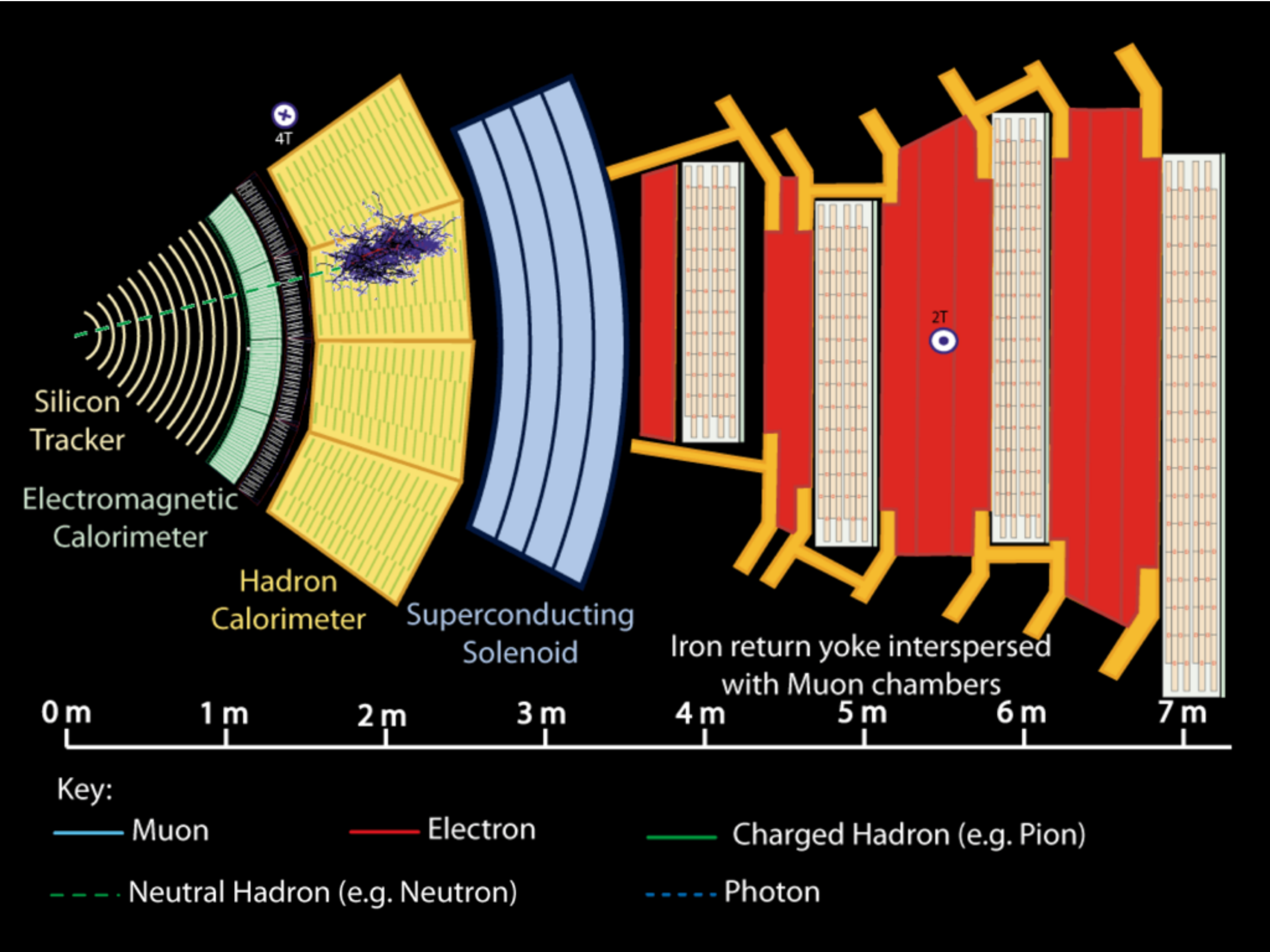
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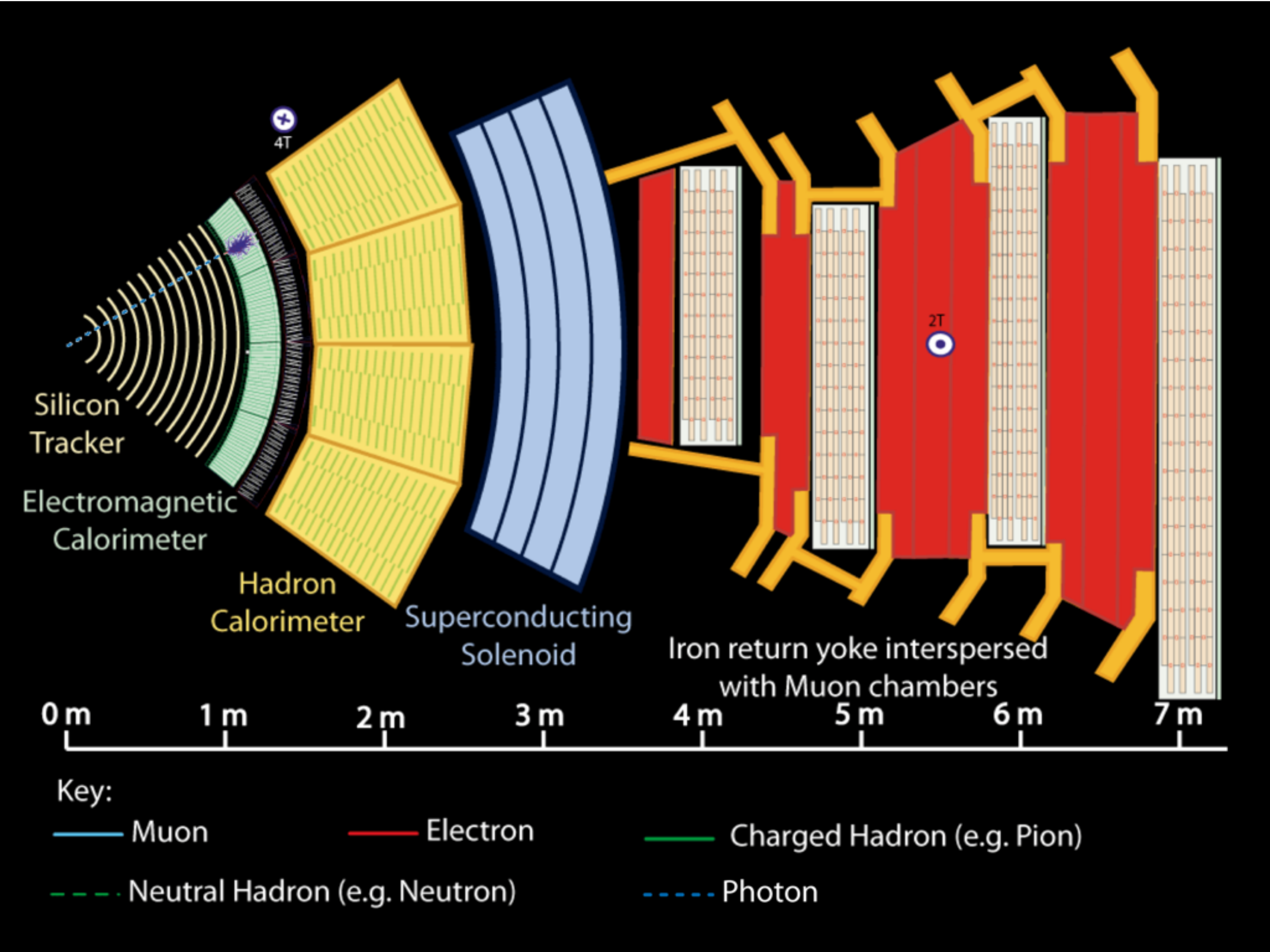

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3 m
4 m
5 m
6 m
7 m
Key:
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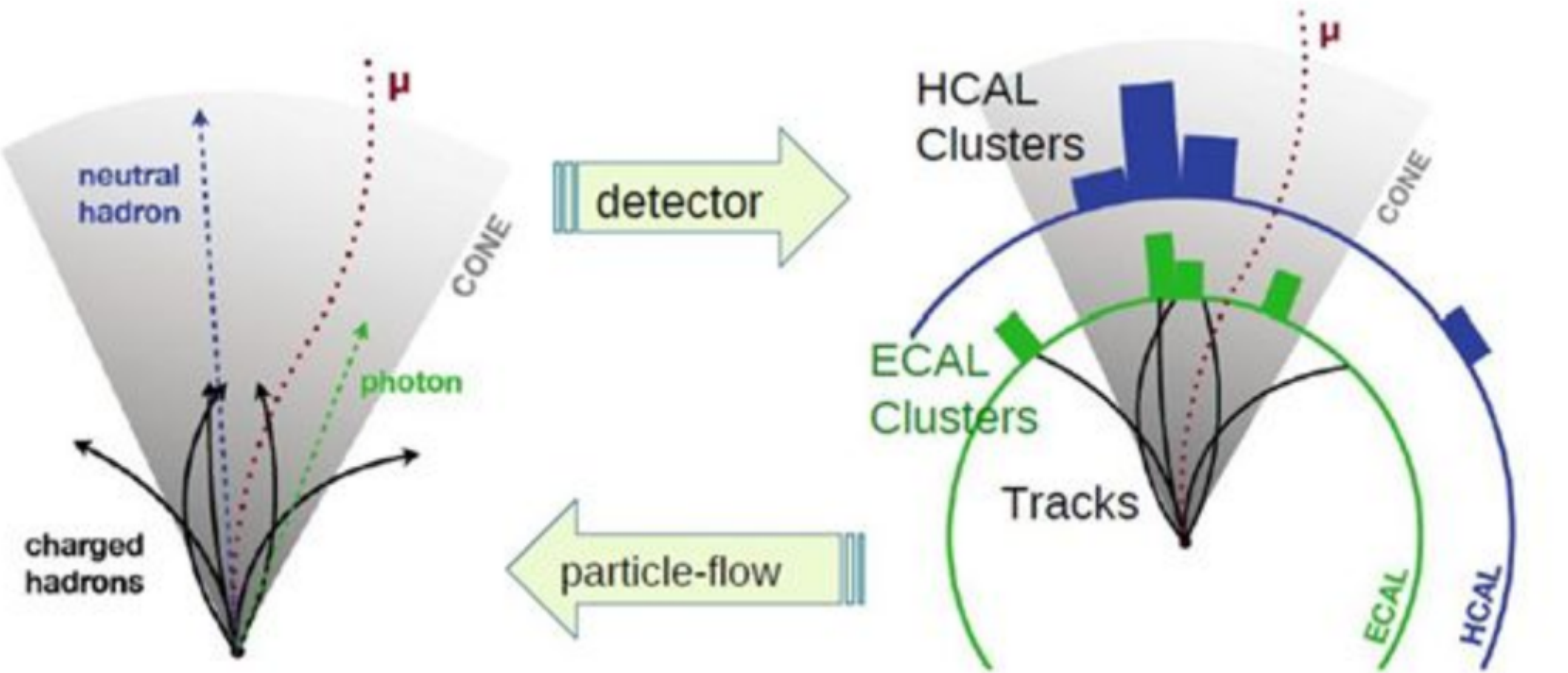
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

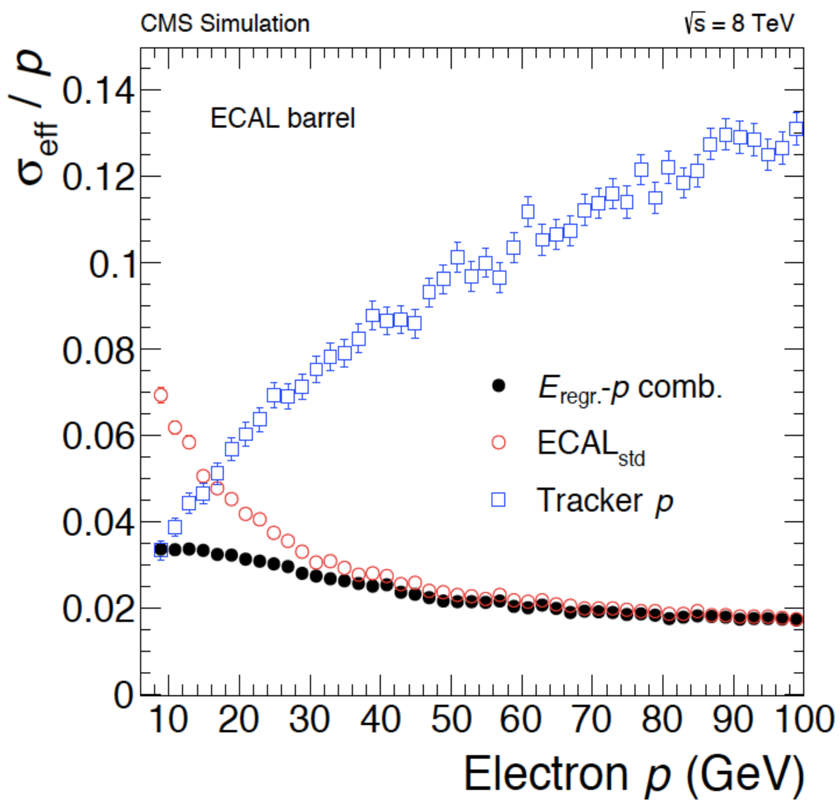
Particle flow

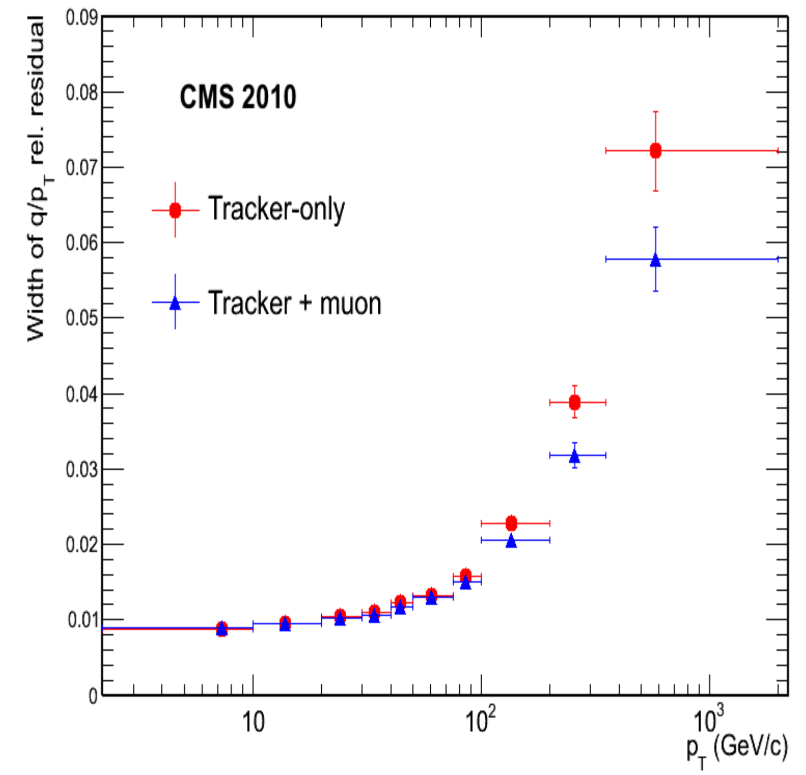
Optimal combination of the information from all subdetectors
—> returns an “interpretation of the event” in terms of all reconstructed particles



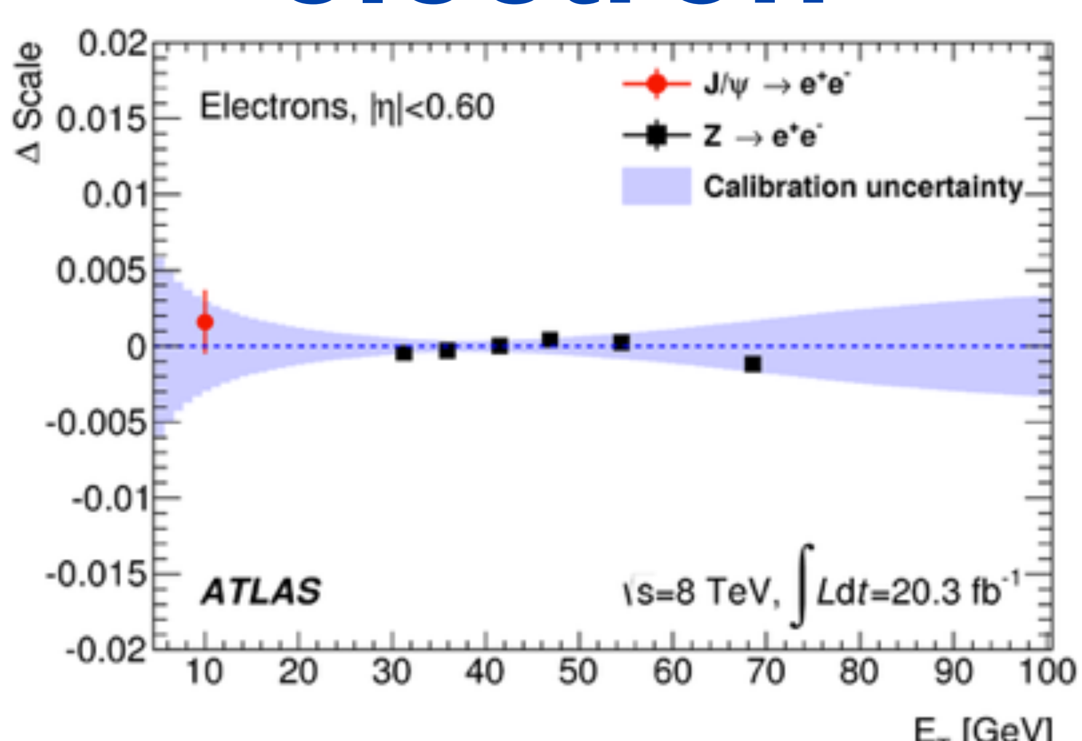
electrons: tracker / calorimeter
muons: tracker / mu-spectrometer

NB calorimeter resolution improves with energy, while the tracker worsens

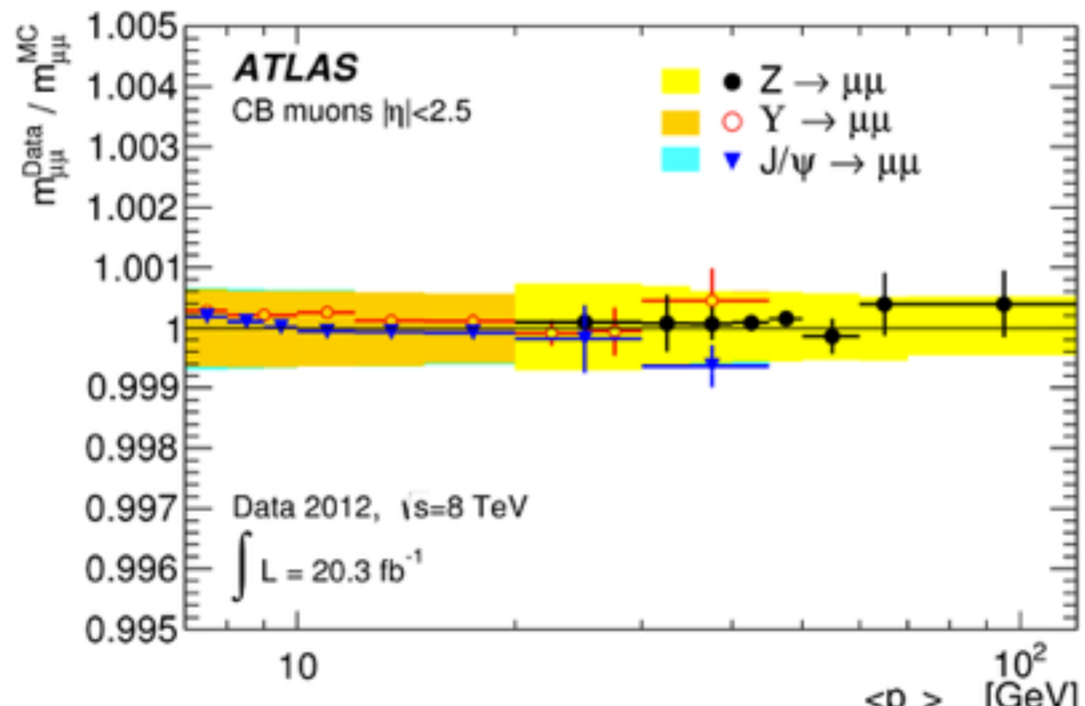




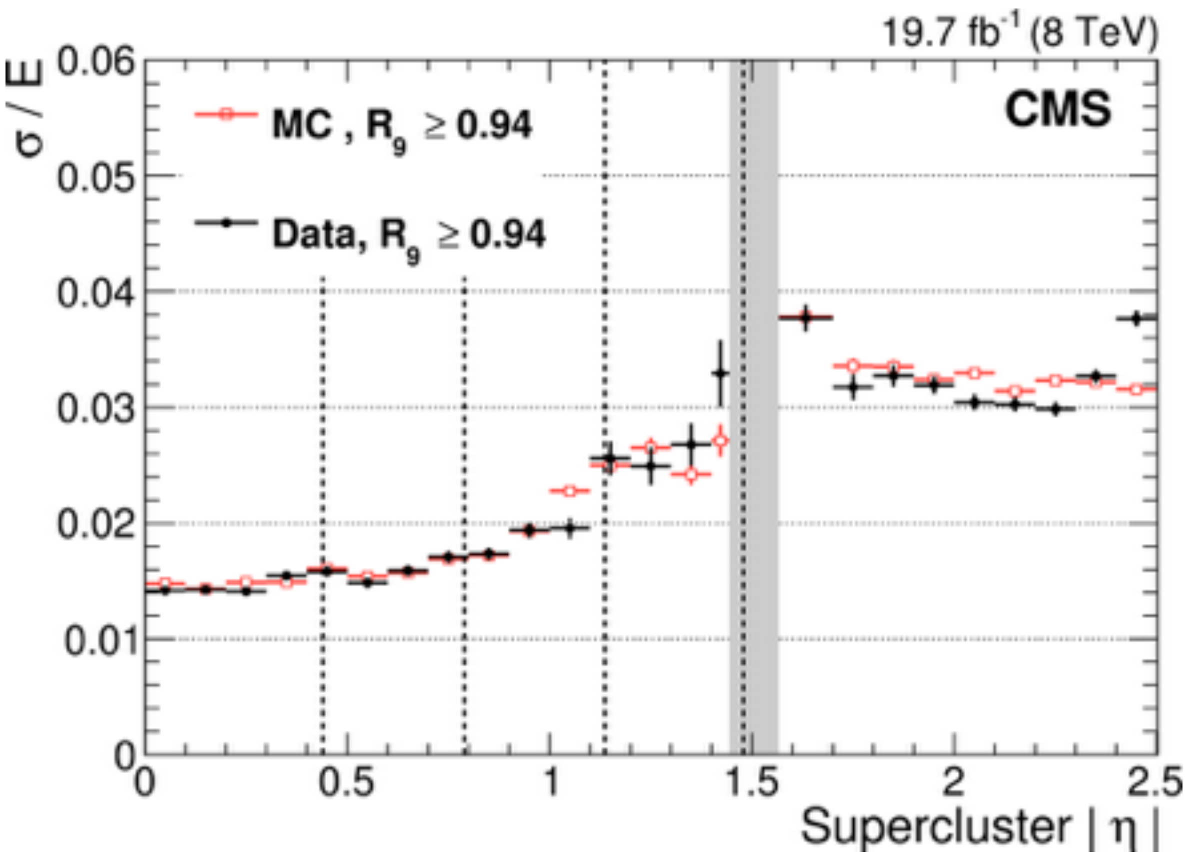
electron

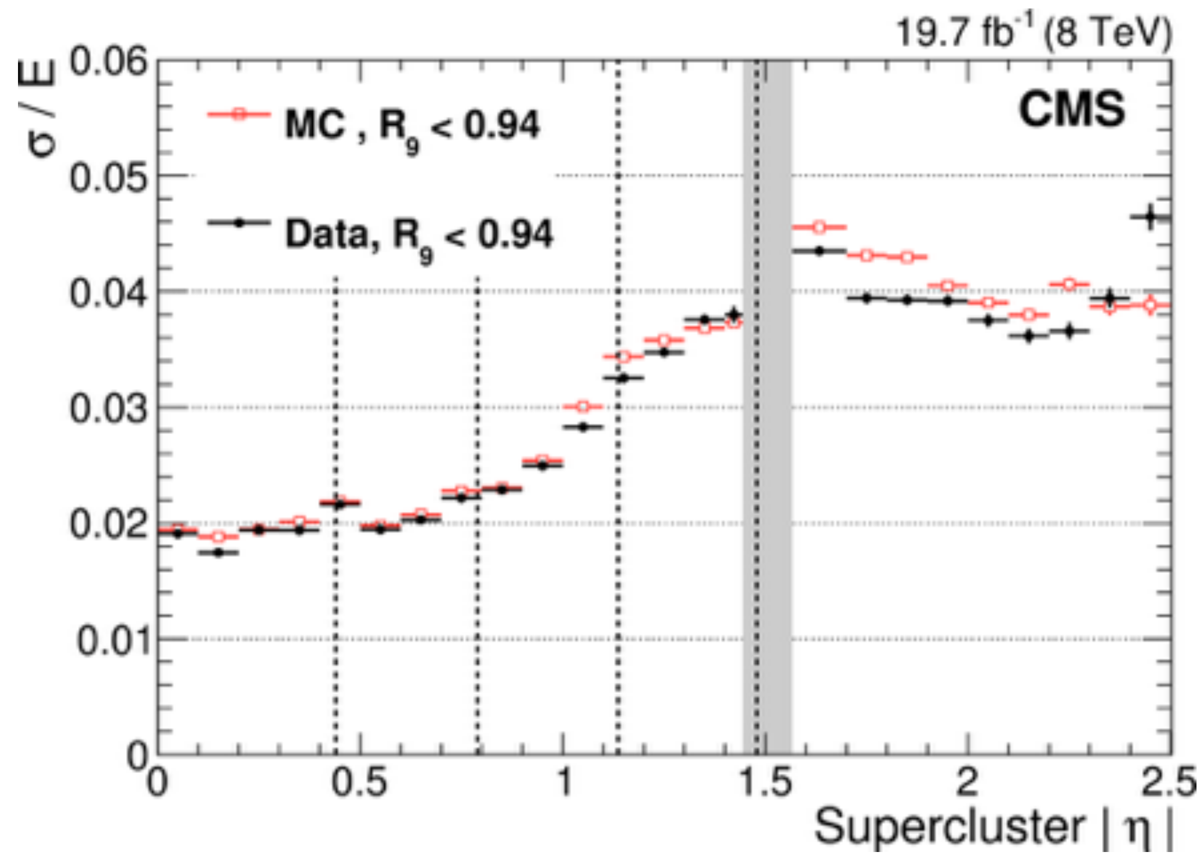


muons



Photon energy resolution

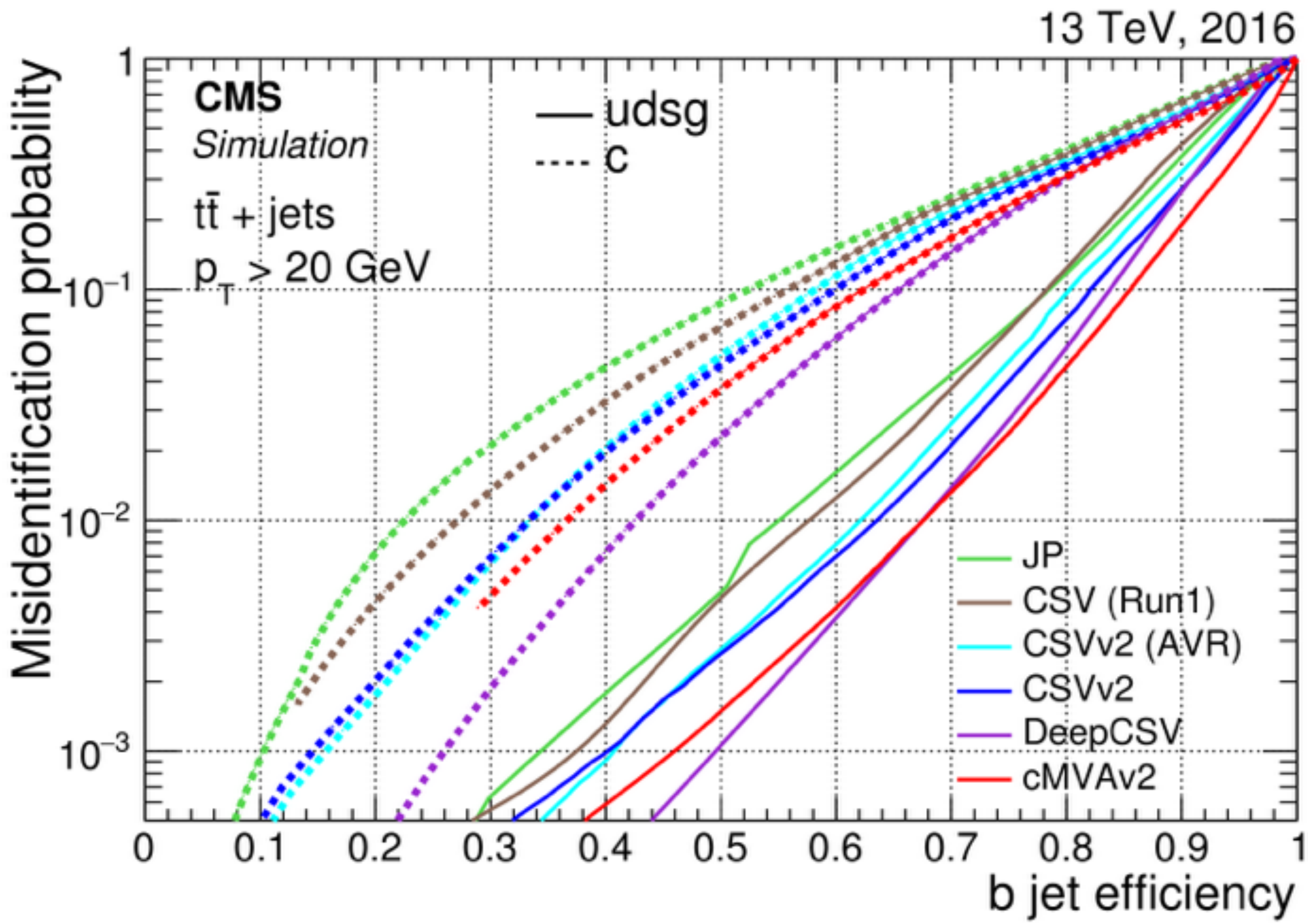




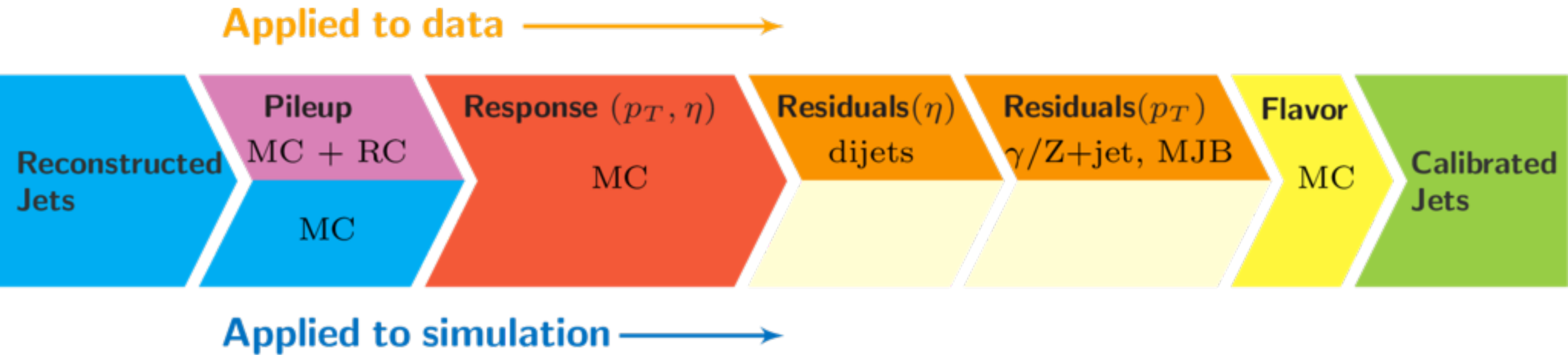
R9 = ratio of the energy in a 3x3 crystal matrix around the supercluster maximum
and the total energy of the supercluster

Loosely speaking high(low) R9 are unconverted(converted) photons

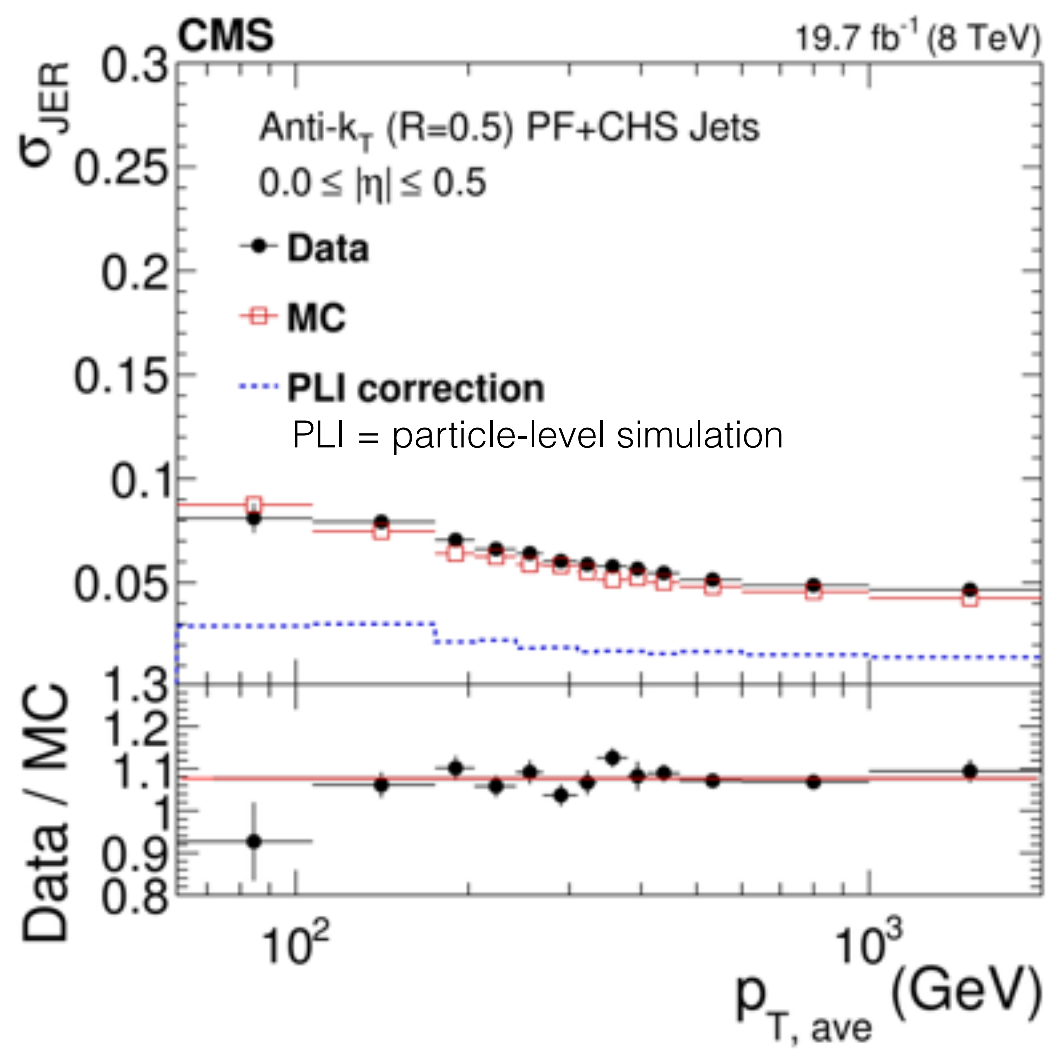
b-tagging performance



jets



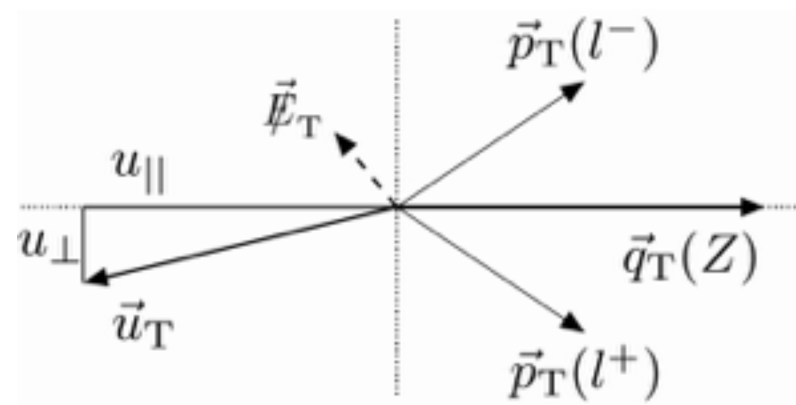
The jet energy resolution is measured in data and simulated events and is studied as a function of pileup, jet size, and jet flavor. Typical jet energy resolutions at the central rapidities are 15-20% at 30 GeV, about 10% at 100 GeV, and 5% at 1 TeV.

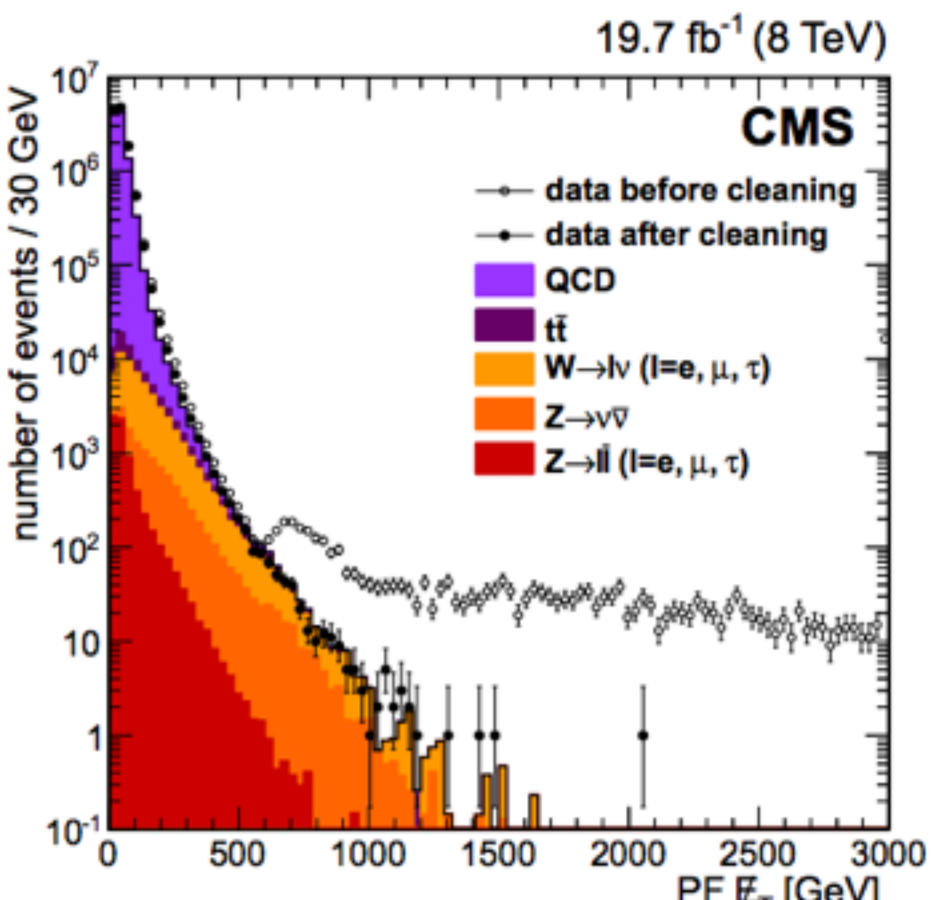


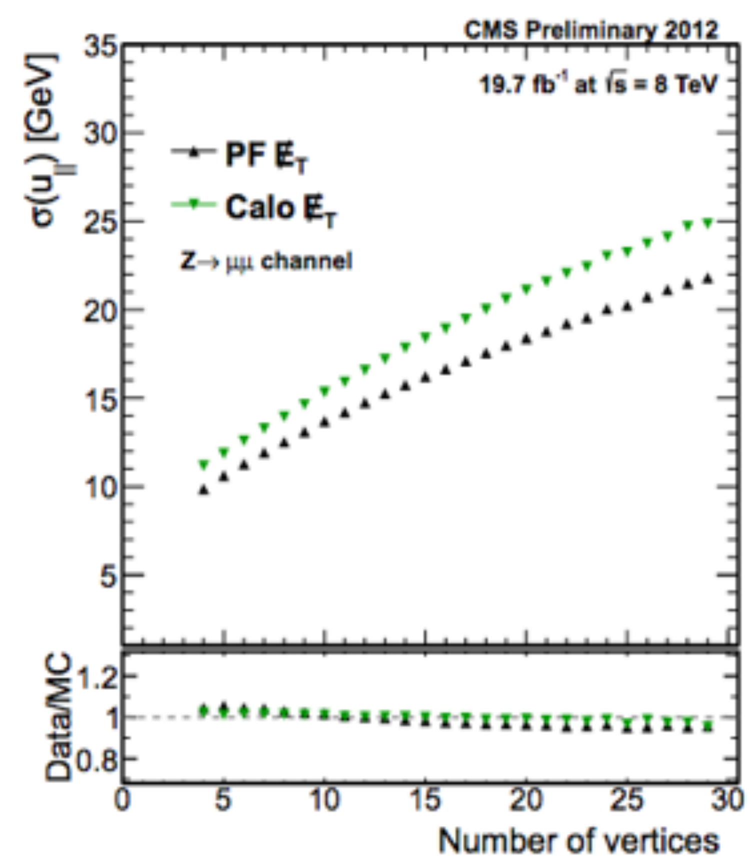
Missing transverse momentum

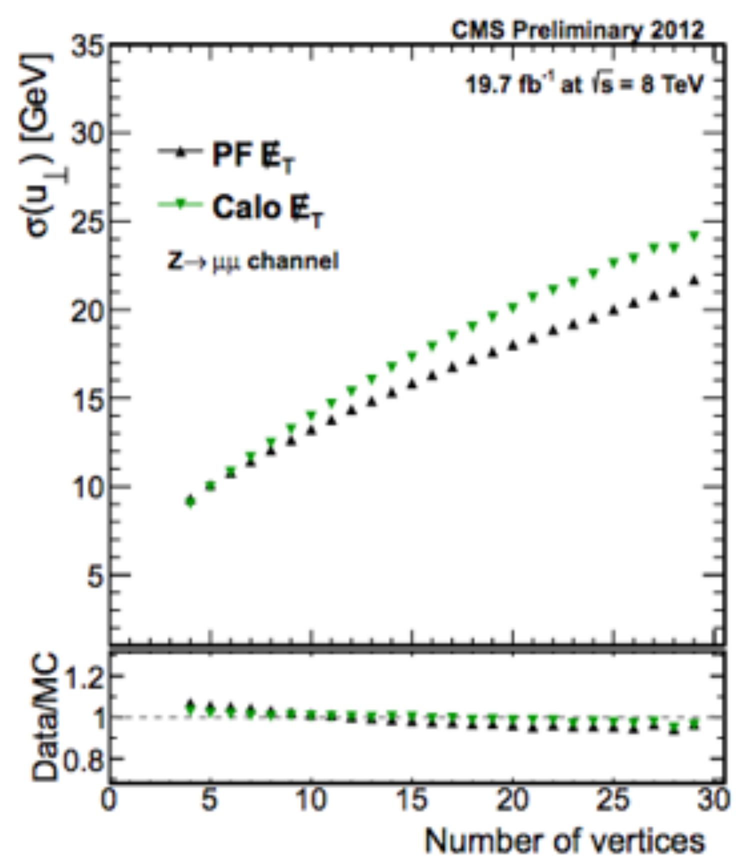
Momentum imbalance in the plane perpendicular to the beam direction $\vec{\not{E}}_{\mathrm{T}}$

The scale and resolution for missing transverse energy, are measured using events with an identified Z boson or isolated photon









Electroweak fits

Electroweak precision fit

Why high precision study of EWC (electroweak corrections) ?

- check the consistency of the gauge / Higgs sectors of the SM: not only a good model at low energies but that as a QFT describes experimental observations up to much higher scales.
- Infer the presence of new particles (fields) through quantum corrections (loops) on observables (top, Higgs, BSM)

Two ways to discover new physics: "direct" observation or observing deviations from theoretical predictions"

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

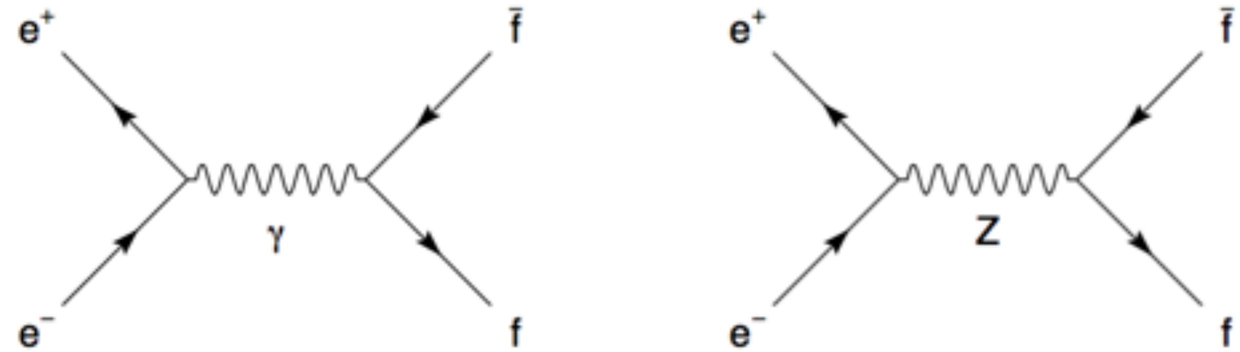
Examples:

Take an observable whose high order corrections depend on m_{top}, m_{Higgs}
⇒ can infer those masses even before observing the particles !

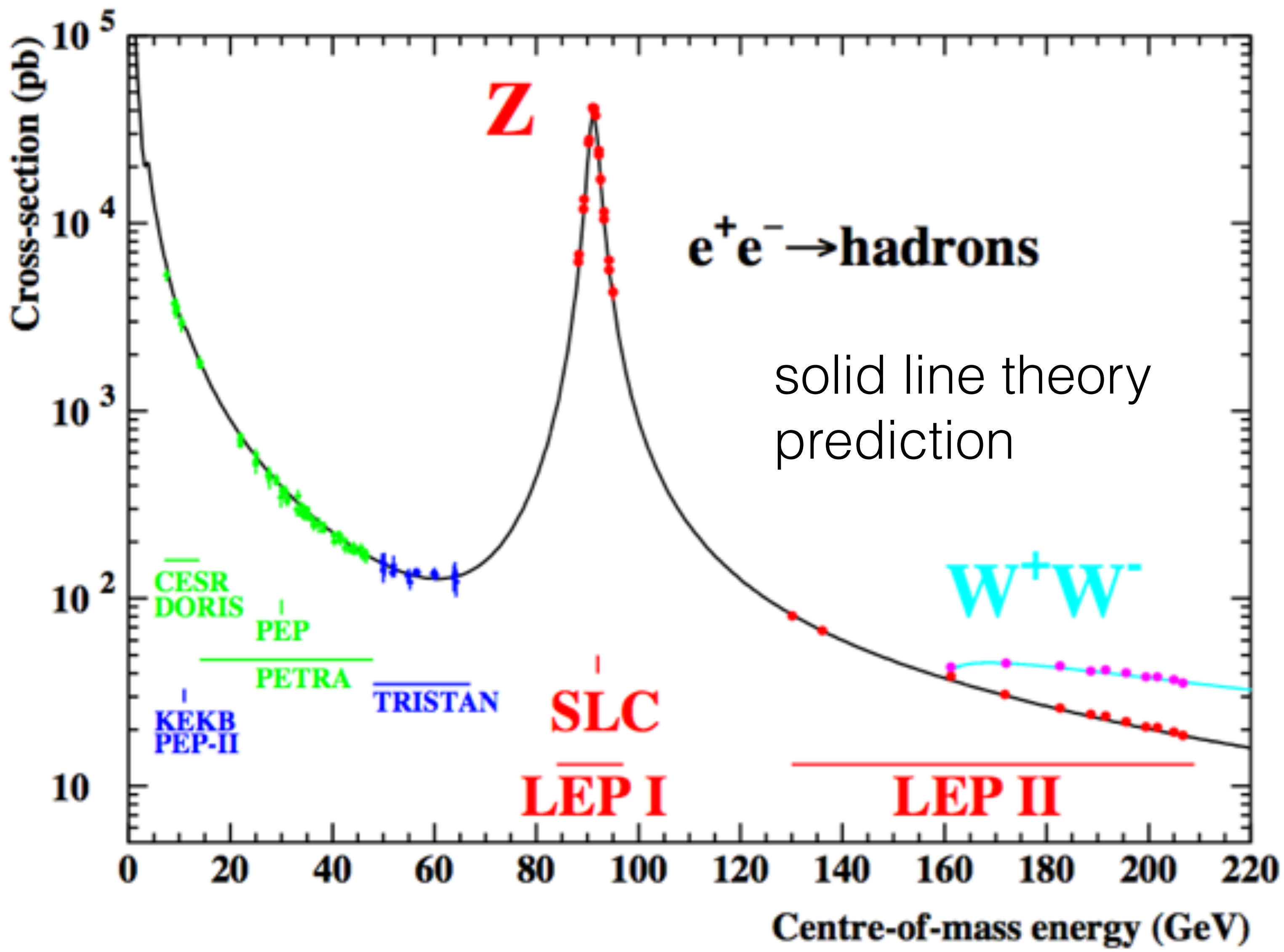
Flipping the argument, combined fits of of several observables are very stringent test of the theory/model producing the corrections

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

e^+e^- @ LEP/SLC



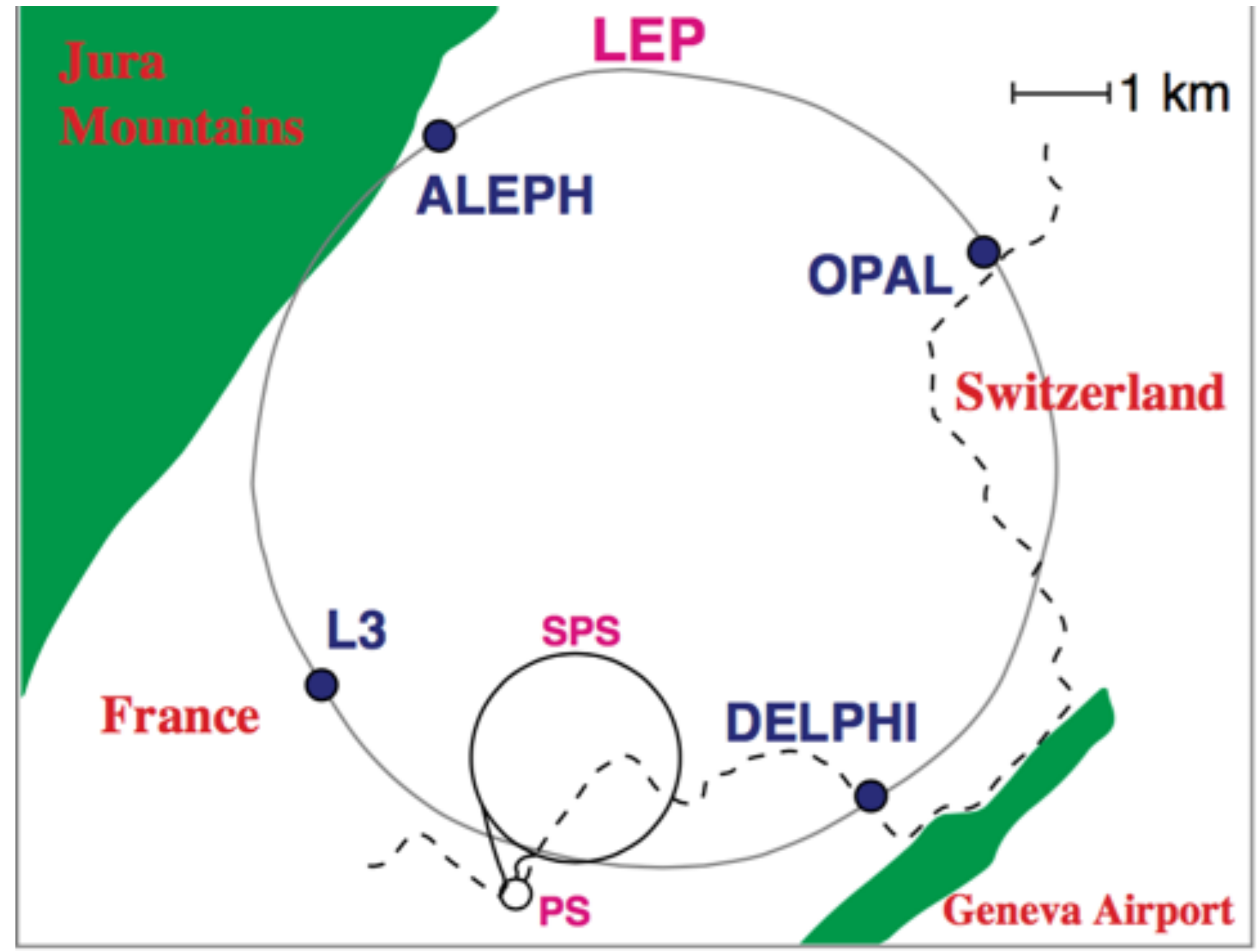
e+
f̄
γ
e−
f
e+
f̄
Z
e−
f



Cross-section (pb)
Z
e+e−→hadrons
solid line theory prediction
W+W-
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
LEP II
Centre-of-mass energy (GeV)

e^+e^- @ LEP

beam energies at ~mZ/2   (LEP 1)
beam spot 150 um x 5 um
45kHz (4 bunches —> then 8)
125 MeV loss /turn because of
bremsstrahlung
Fantastic beam energy resolution:
2 MeV (~2 10^{-5} relative unc)

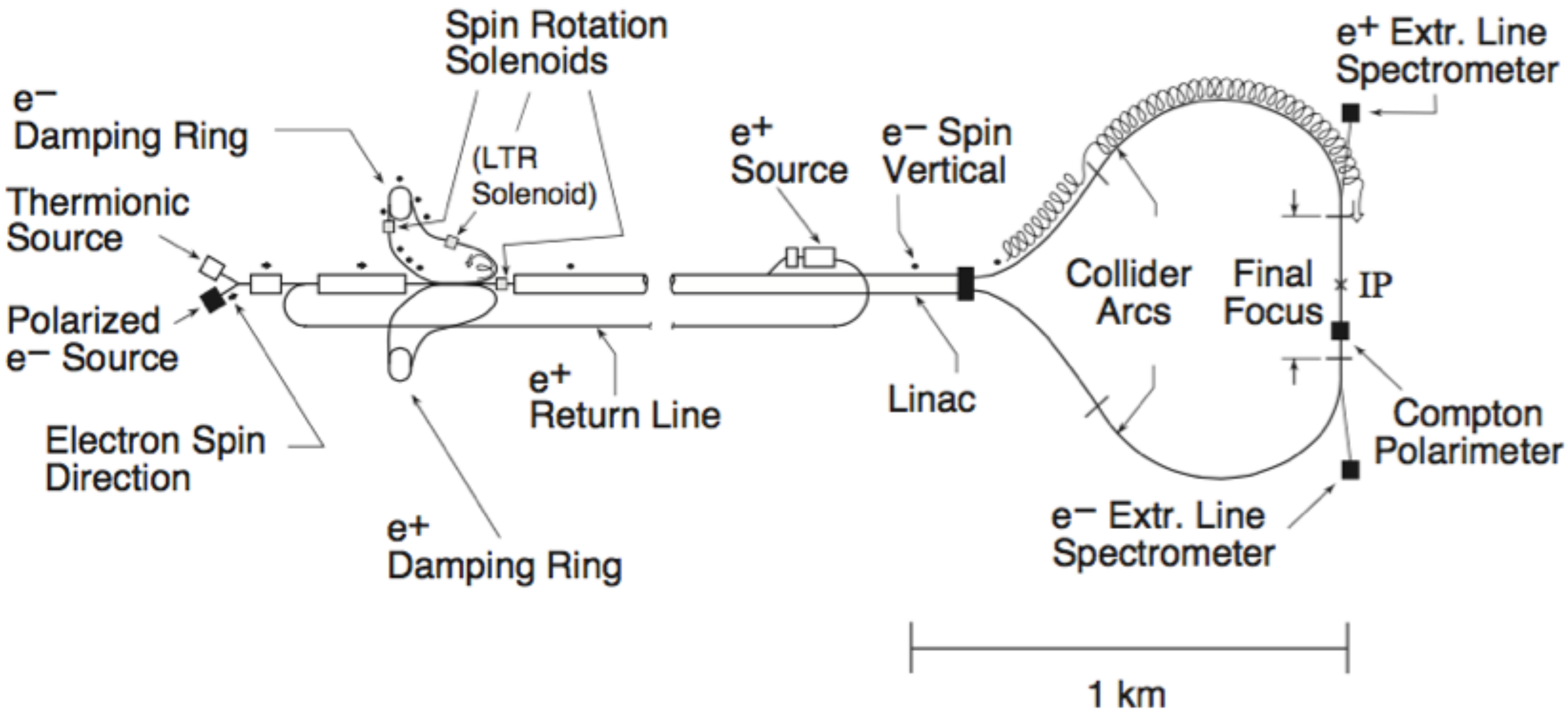


While the beam orbit length was constrained by the RF accelerating system, the focusing quadrupoles were fixed to the earth and moved with respect to the beam, changing the effective total bending magnetic field and the beam energy by 10 MeV over several hours. Sensitive to earth tides generated by the moon and sun, local geological deformations following heavy rainfall or changes in the level of Lake Geneva, electric trains

LEP: 7'000'000 Z   (1000 Z bosons/hour x 4 experiments when running at 2 10^{31} $cm^{-2}s^{-1}$)

e^+e^- @ SLC

SLC: 600’000 Z (longitudinal polarization)



Repetition rate **120 Hz**
Beam spot 1.5 um x 0.7 um (better selection of heavy quarks)
Polarized beams !

Basic measurements

Cross sections

$$\sigma = \frac{N_{\rm sel} - N_{\rm bg}}{\epsilon_{\rm sel}\mathcal{L}}$$

ε_{sel} = efficiency x acceptance

The Z couples with a mixture of vector and axial-vector couplings.

$$g_L^{\nu_e}\bar{\nu}_e\gamma_\mu(1-\gamma_5)\nu_e = g_L^{\nu_e}\bar{\nu}_{eL}\gamma_\mu\nu_{eL}$$

$$g_L^e\bar{e}\gamma_\mu(1-\gamma_5)e + g_R^e\bar{e}\gamma_\mu(1+\gamma_5)e = g_L^e\bar{e}_L\gamma_\mu e_L + g_R^e\bar{e}_R\gamma_\mu e_R$$

$$g_L^u\bar{u}\gamma_\mu(1-\gamma_5)u + g_R^u\bar{u}\gamma_\mu(1+\gamma_5)u = g_L^u\bar{u}_L\gamma_\mu u_L + g_R^u\bar{u}_R\gamma_\mu u_R$$

$$g_L^d\bar{d}\gamma_\mu(1-\gamma_5)d + g_R^u\bar{d}\gamma_\mu(1+\gamma_5)d = g_L^d\bar{d}_L\gamma_\mu d_L + g_R^u\bar{d}_R\gamma_\mu d_R.$$

This results in measurable asymmetries in the angular distributions of the final-state fermions, the dependence of Z production on the helicities of the colliding electrons and positrons, and the polarisation of the produced particles.

Basic measurements

Asymmetries

$$A_{\mathrm{FB}} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}}$$ Forward / Backward

"forward" means that the produced fermion (as opposed to anti-fermion) is in the hemi-sphere defined by the direction of the electron beam (polar scattering angle $\theta < \pi/2$).

$$A_{\mathrm{LR}} = \frac{N_{\mathrm{L}} - N_{\mathrm{R}}}{N_{\mathrm{L}} + N_{\mathrm{R}}} \frac{1}{\langle \mathcal{P}_{\mathrm{e}} \rangle}$$ @ SLC

$N_L(N_R)$ is the number of Z bosons produced for left(right)-handed electron bunches, $\langle P_e \rangle$ is the magnitude of luminosity-weighted electron polarisation

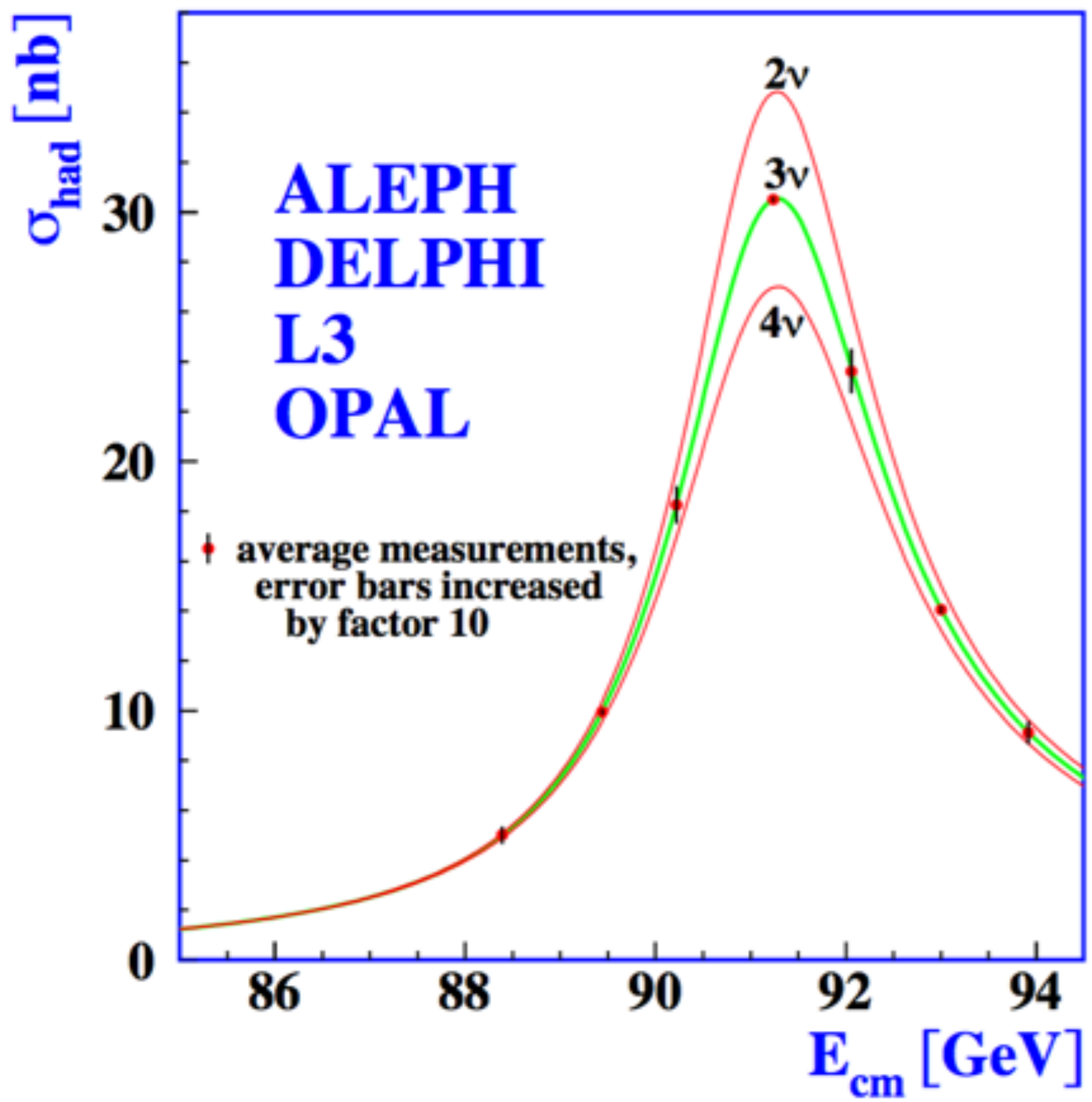
Example: number of (light) neutrino families

Determination of the number of light (i.e. kinematically accessible in Z decays) obtained by measuring the partial widths :

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + \Gamma_{inv}$$

$$\Gamma_{had} = \sum_{q \neq t} \Gamma_{q\bar{q}}$$

$$\Gamma_{inv} = N_\nu \Gamma_{\nu\bar{\nu}}$$



SM tree level relations

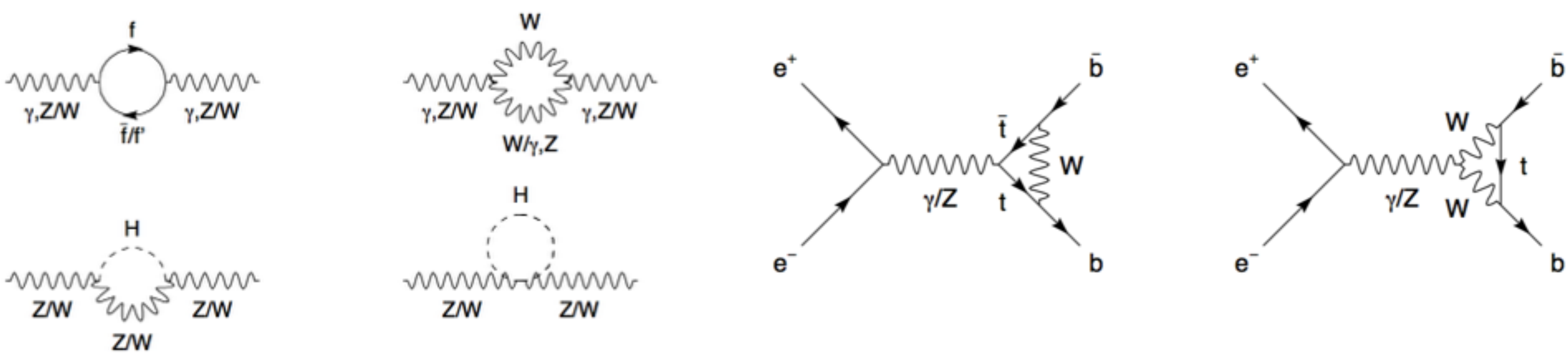
Relation between weak and e.m. couplings:

$$G_F = \frac{\pi\alpha}{\sqrt{2} m_W^2 \sin^2\theta_W^{\mathrm{tree}}}$$

Relation between neutral and charged weak couplings:
(ρ is determined by the Higgs structure of the theory:
with only one Higgs doublet $\rho = 1$)

$$\rho_0 = \frac{m_W^2}{m_Z^2 \cos^2\theta_W^{\mathrm{tree}}}.$$

Tree level relations are modified by radiative corrections to both the propagators and vertices



The effect of the corrections is O(%). If one can get both theoretical and experimental precisions to this level the effects of the loops can be tested.

Fit structure

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:

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

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

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

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

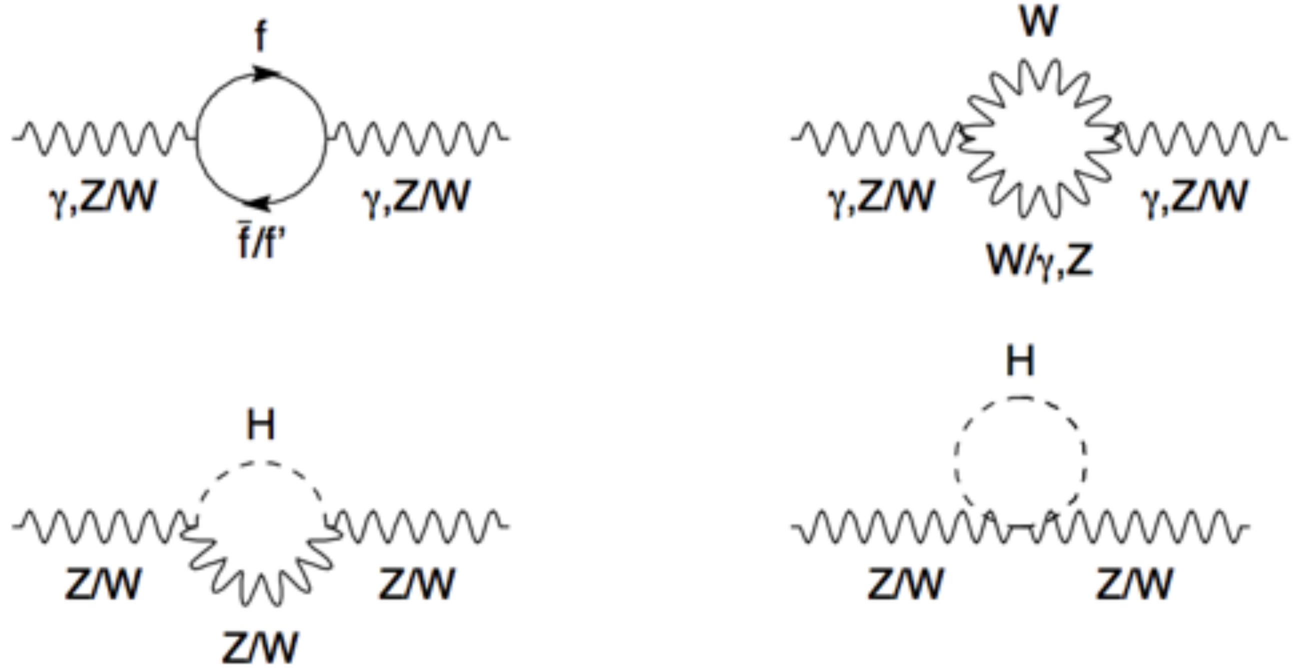
Based on the best fit values of the input parameters, predict the “SM expectation” for any observable and compare it with the measured values

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)

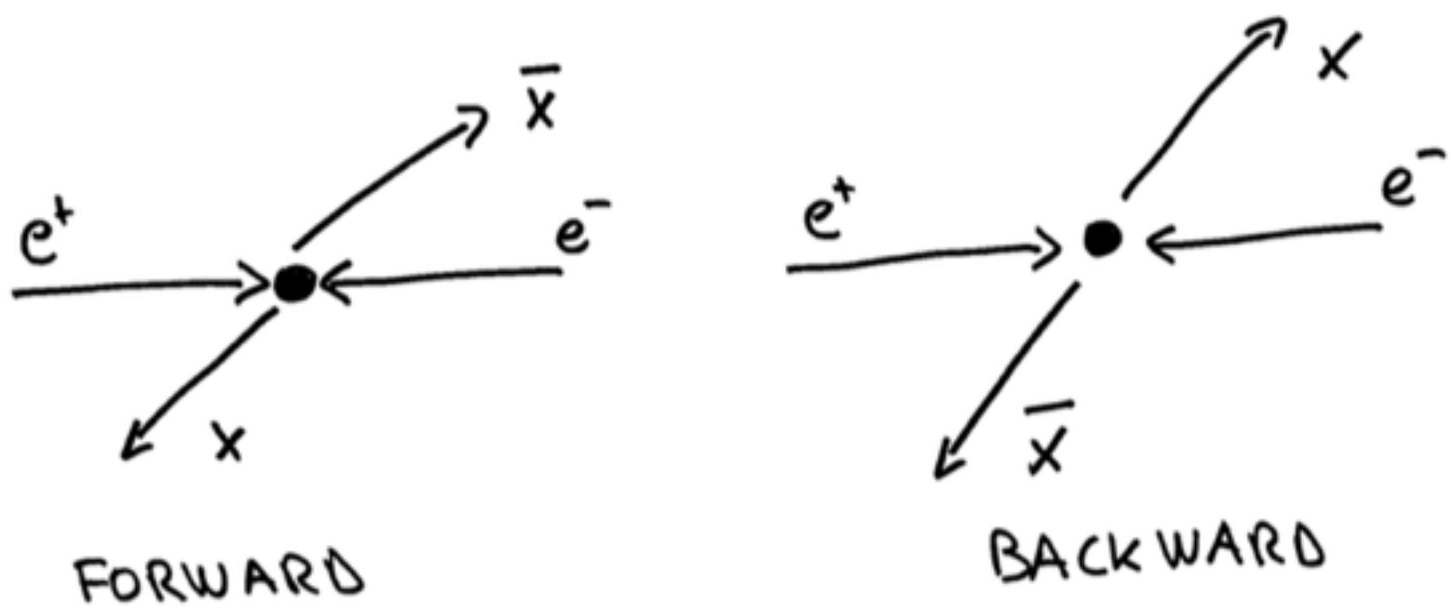
$$\Delta r_W(m_t, m_H) \simeq \frac{\alpha}{\pi \sin^2\theta_W}\left(-\frac{3}{16}\,\frac{\cos^2\theta_W}{\sin^2\theta_W}\cdot\frac{m_t^2}{m_W^2} + \frac{11}{24}\log\left(\frac{m_H}{m_Z}\right)\right)$$

Observables

LEP 1

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

$$A_{FB}^{0,x} = \frac{\sigma_F^x - \sigma_B^x}{\sigma_F^x + \sigma_B^x} \qquad x = b, c, \text{leptons}$$



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}

Measurements summary

	Measurement with Total Error	Systematic Error
$\Delta\alpha_{\mathrm{had}}^{(5)}(m_Z^2)$ [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_{had}^0 [nb]	41.540 ± 0.037	$^{(a)}$0.028
R_ℓ^0	20.767 ± 0.025	$^{(a)}$0.007
$A_{\mathrm{FB}}^{0,\ell}$	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_b^0	0.21629 ± 0.00066	0.00050
R_c^0	0.1721 ± 0.0030	0.0019
$A_{\mathrm{FB}}^{0,b}$	0.0992 ± 0.0016	0.0007
$A_{\mathrm{FB}}^{0,c}$	0.0707 ± 0.0035	0.0017
$\mathcal{A}_b$	0.923 ± 0.020	0.013
$\mathcal{A}_c$	0.670 ± 0.027	0.015
+ correlation matrix Table 5.11		
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ ($Q_{\mathrm{FB}}^{\mathrm{had}}$)	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		

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				
		$\Delta\alpha^{(5)}_{\mathrm{had}}(m^2_Z)$	$\alpha_S(m^2_Z)$	m_Z	m_t	$\log_{10}(m_H/\mathrm{GeV})$
$\Delta\alpha^{(5)}_{\mathrm{had}}(m^2_Z)$	0.02759 ± 0.00035	1.00				
$\alpha_S(m^2_Z)$	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^{+13}_{-10}	−0.03	0.19	−0.07	1.00	
$\log_{10}(m_H/\mathrm{GeV})$	$2.05^{+0.43}_{-0.34}$	−0.29	0.25	−0.02	0.89	1.00
m_H [GeV]	111^{+190}_{-60}	−0.29	0.25	−0.02	0.89	1.00

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

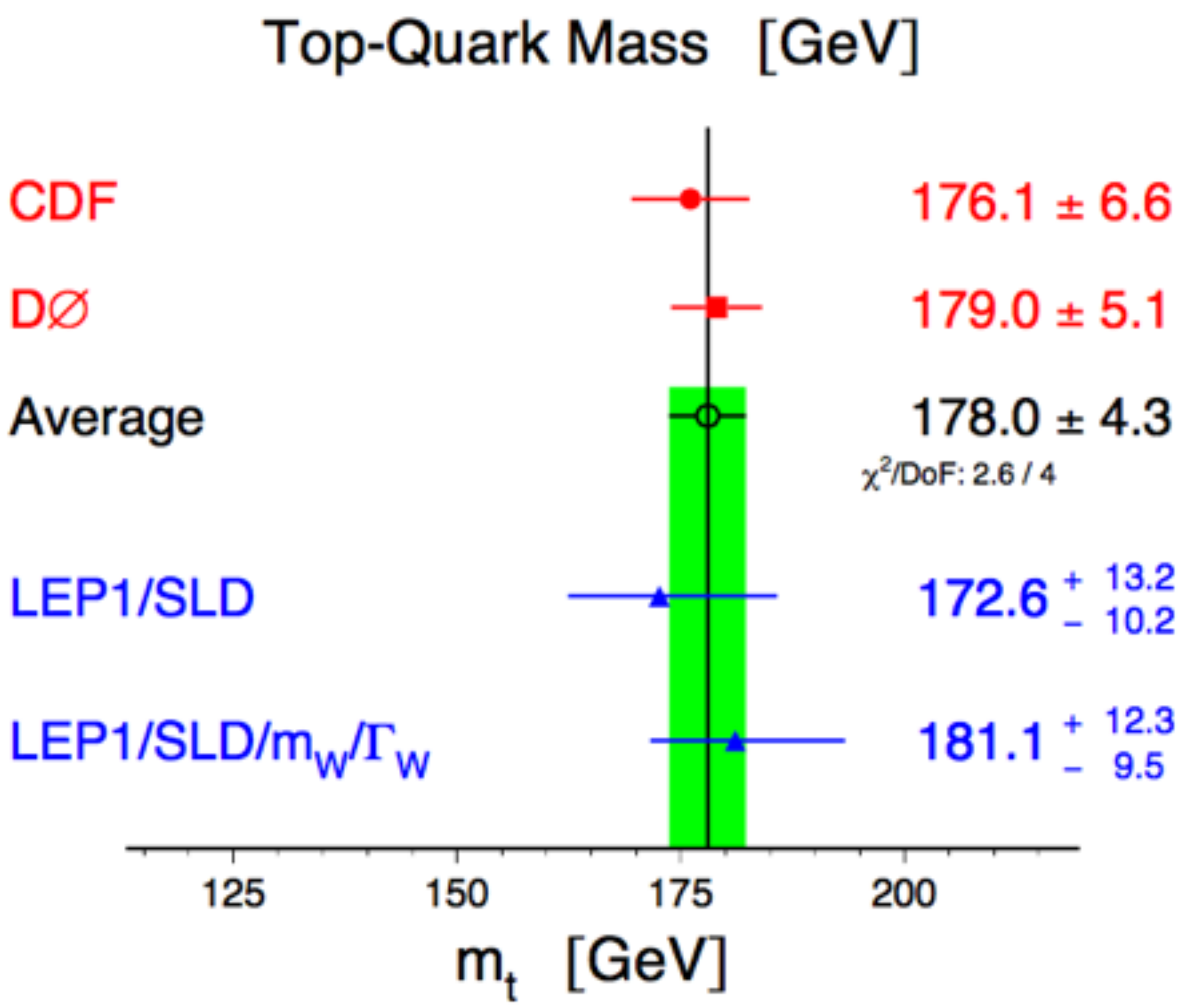
Today we discovered both:

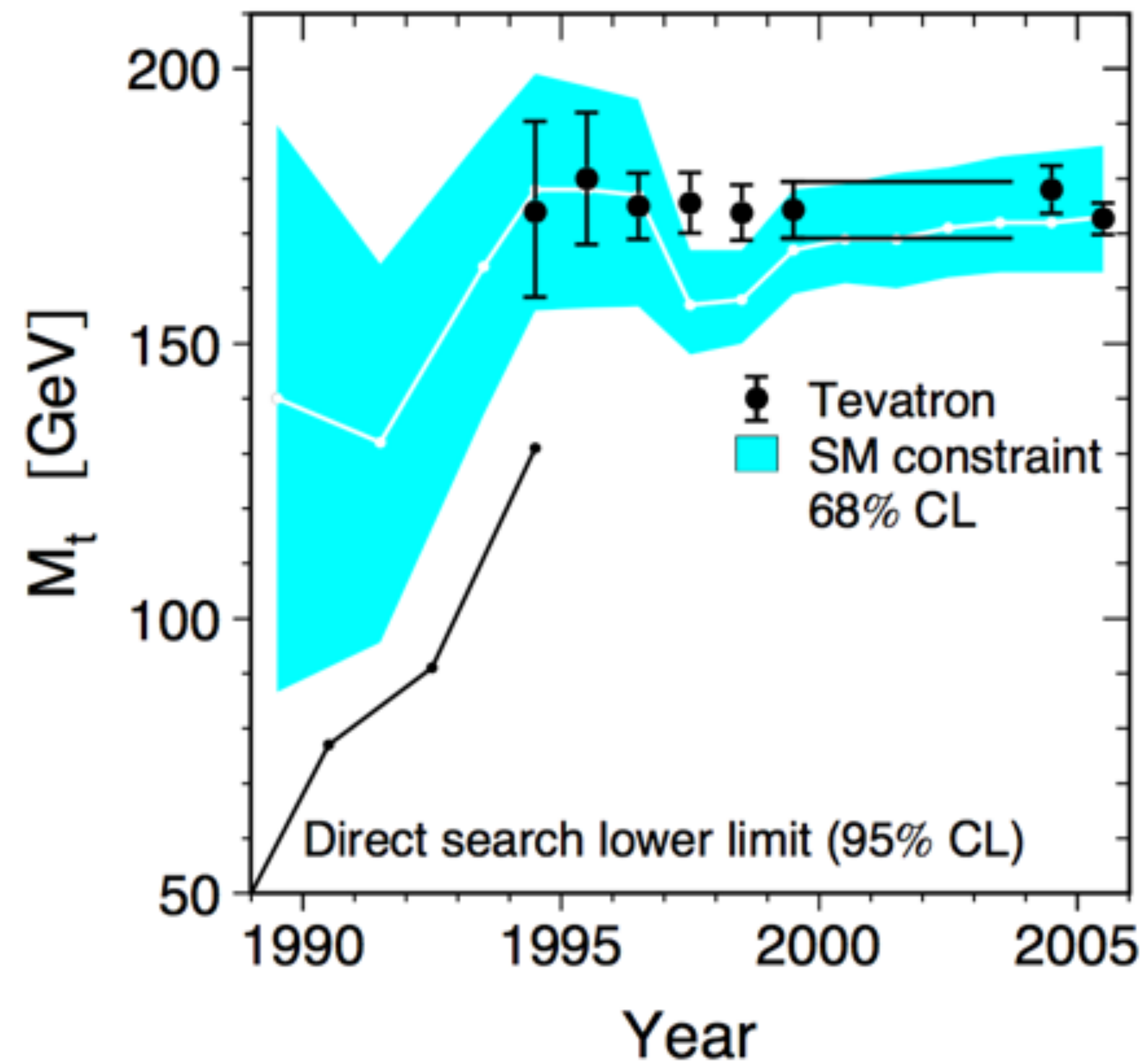
$$m_H = 125.09 \pm 0.21(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{GeV}$$

From these values we can extract all other SM parameters:

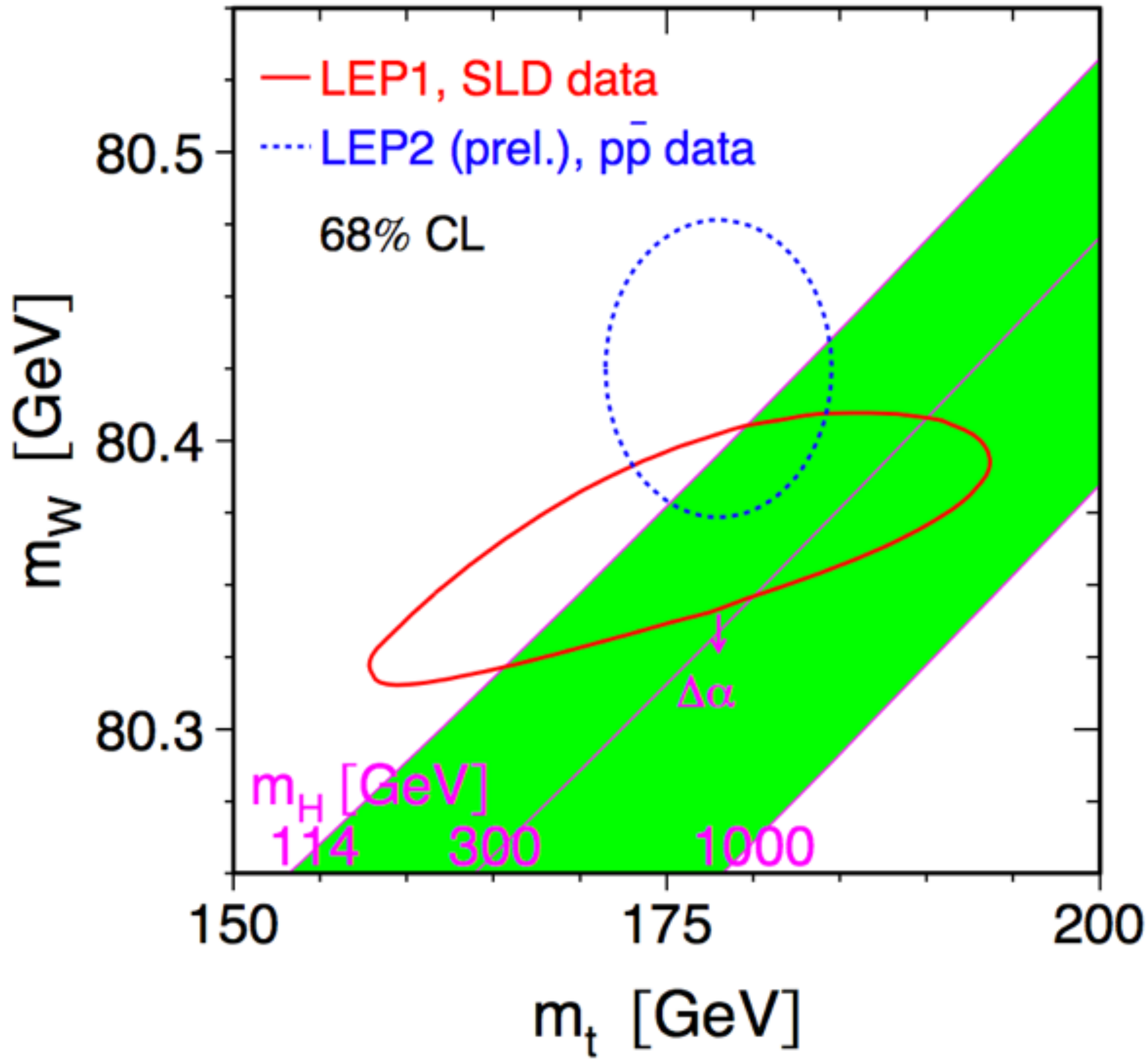
$m_W = 80.363 \pm 0.032$ GeV PDG Mass $m = 80.385 \pm 0.015$ GeV

m_{top}


Top-Quark Mass [GeV]
CDF
176.1 ± 6.6
DØ
179.0 ± 5.1
Average
178.0 ± 4.3
χ²/DoF: 2.6 / 4
LEP1/SLD
172.6 + 13.2 − 10.2
LEP1/SLD/mW/ΓW
181.1 + 12.3 − 9.5
125
150
175
200
mt [GeV]


200
150
100
50
Mt [GeV]
Tevatron
SM constraint
68% CL
Direct search lower limit (95% CL)
1990
1995
2000
2005
Year

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]

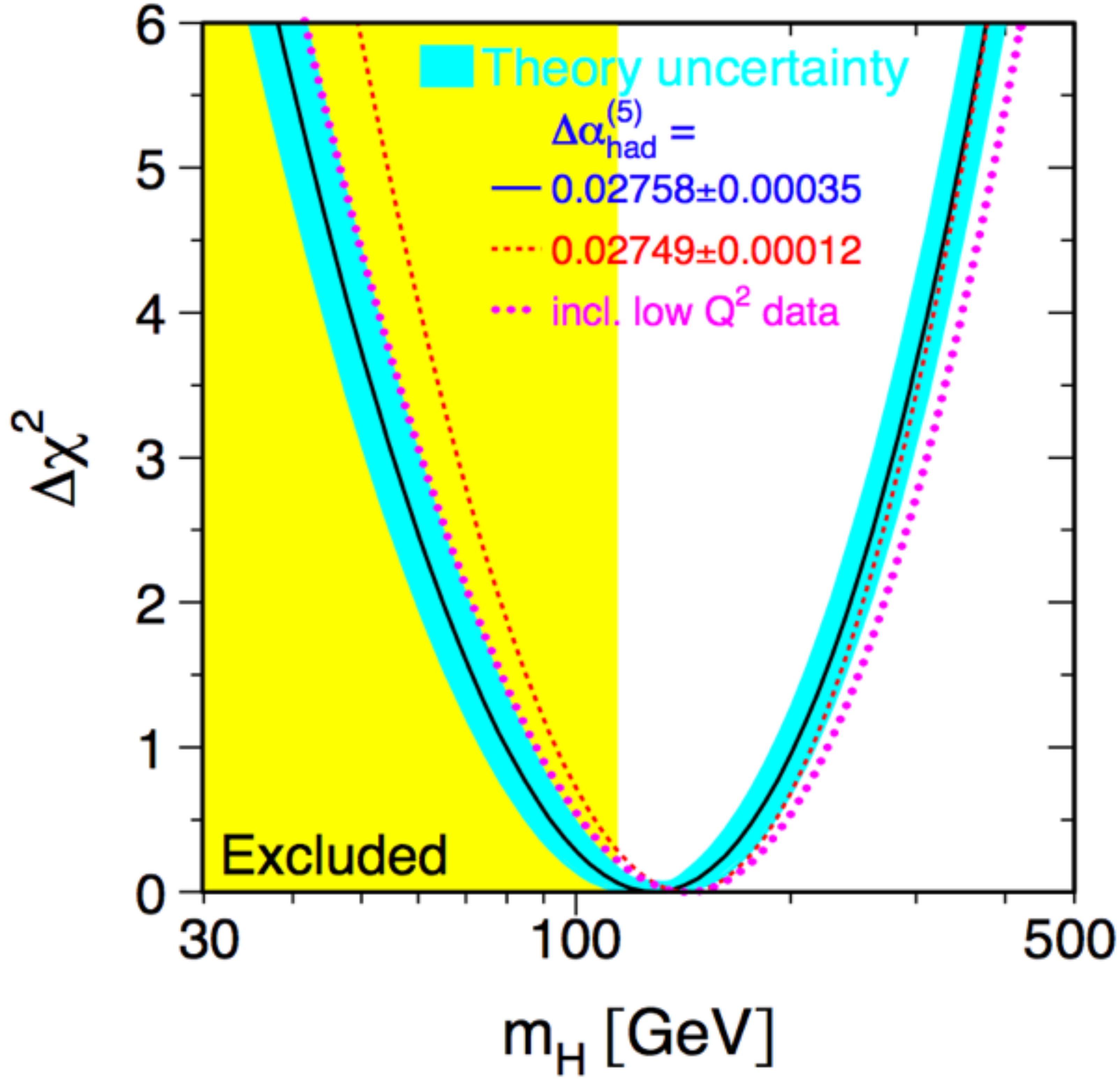
m_H @ LEP

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

χ^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^{+74}_{-49}	−0.46	0.18	0.06	0.67	1.00

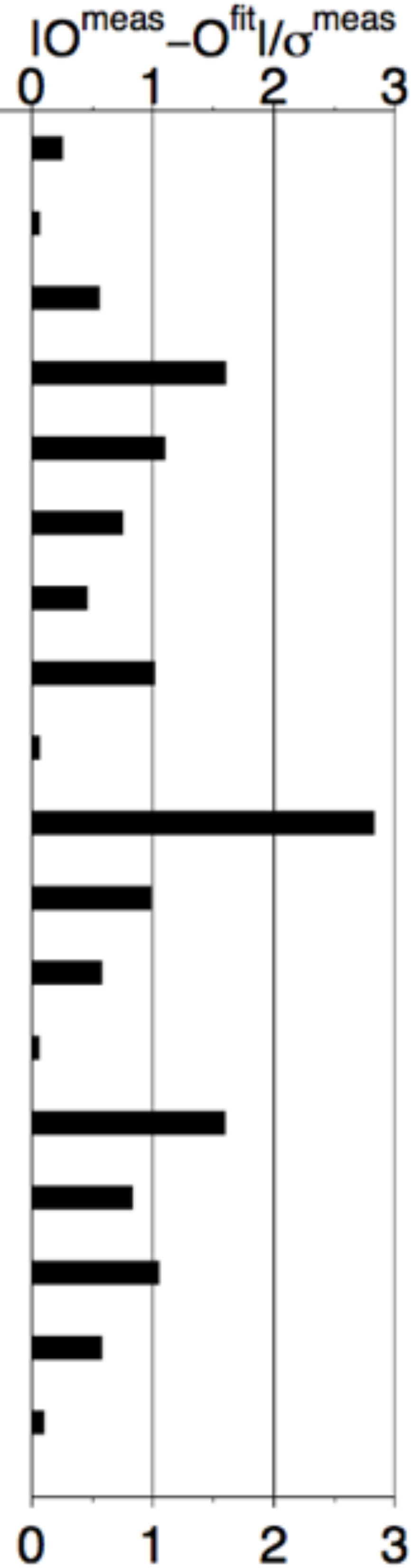
m_H @ LEP



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

Pulls

	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



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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/

CMS performance publications
https://cms-results.web.cern.ch/cms-results/public-results/publications/DET/index.html

Precision Electroweak Measurements on the Z Resonance
(our discussion is in chapter 1 and 8)

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

Fit procedure:

L. Lyons, D. Gibaut, and P. Clifford, Nucl. Instrum. Meth. A270 (1988) 110;
A. Valassi, Nucl. Instrum. Meth. A500 (2003) 391–405.