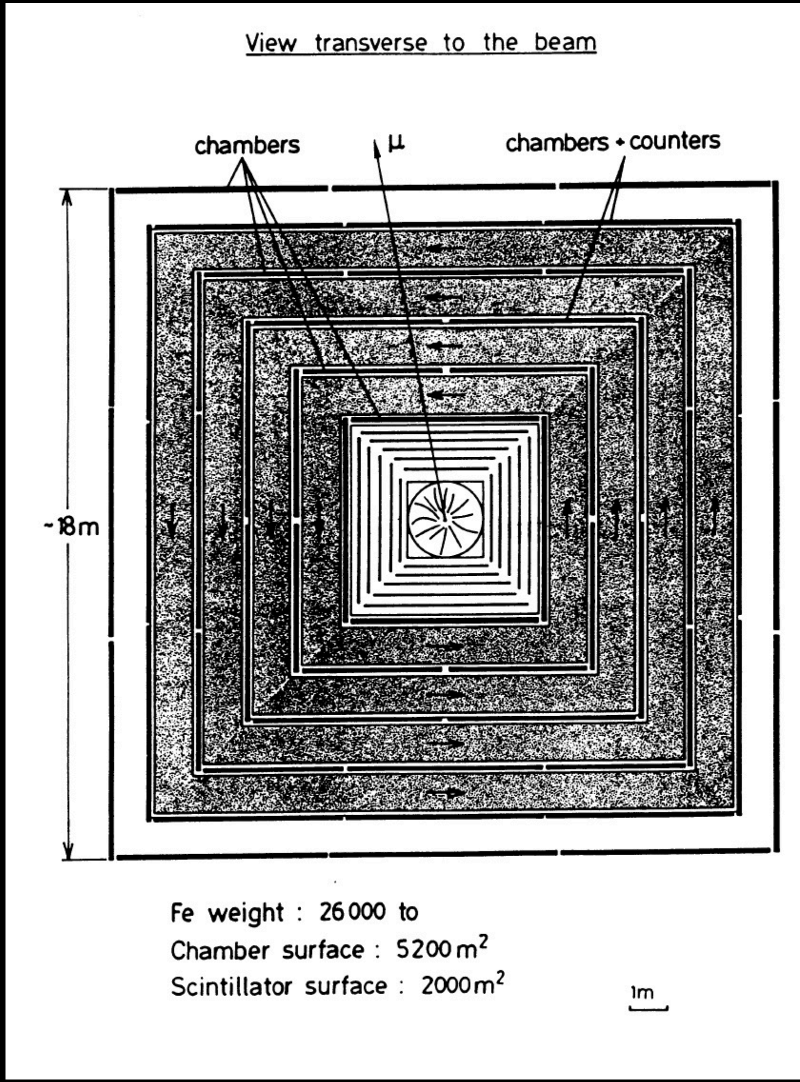
Detector Technologies

Daniela Bortoletto

Road path to the instrumentation lectures

- Why instrumentation is important ?
- Introduction on how we detect particles
- The LHC detectors
  - Demonstrating that a luminosity of 10^{34} s^{-1} cm^{-2} could be usable was not easy and required a large RD effort that took decades
- New technologies for the LHC upgrades and FCC



First ideas for LHC detectors in 1984 Lausanne ECFA meeting

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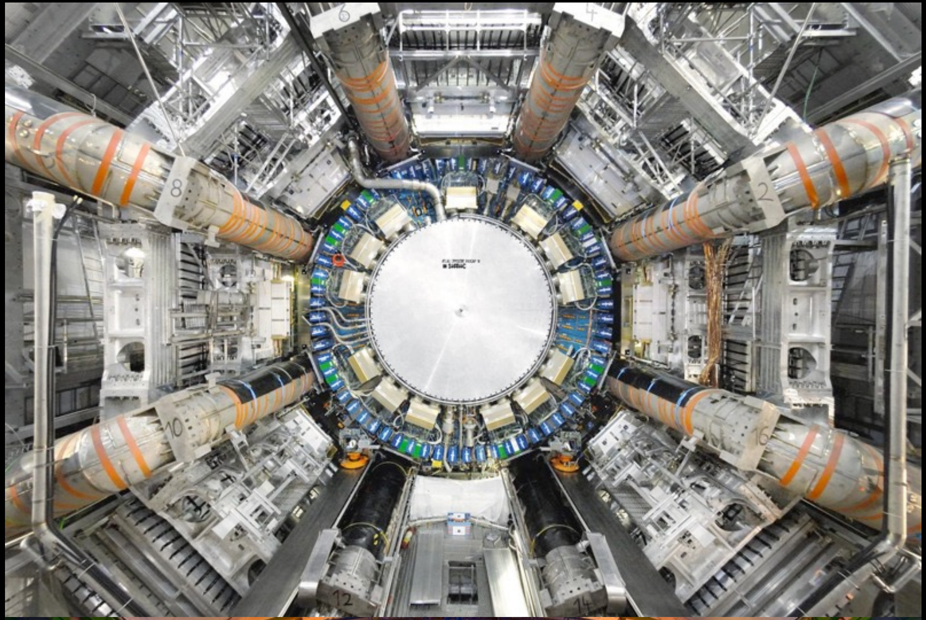
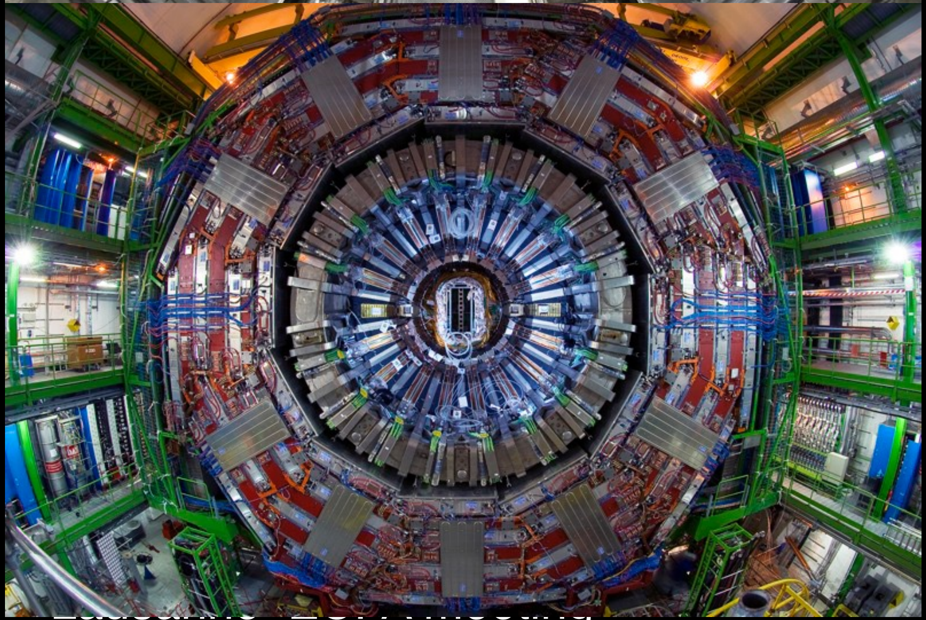
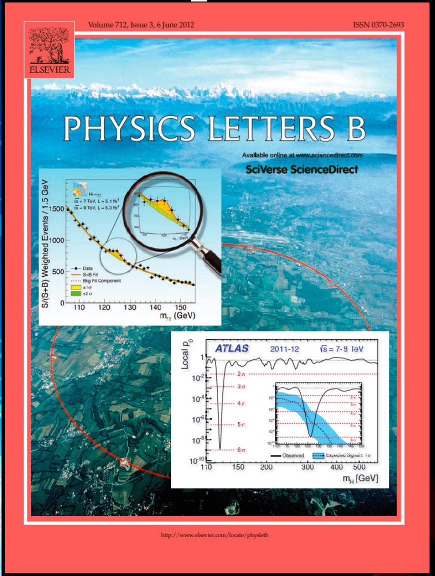




Large Hadron Collider (LHC)

A 27km discovery machine colliding pp at 13 TeV

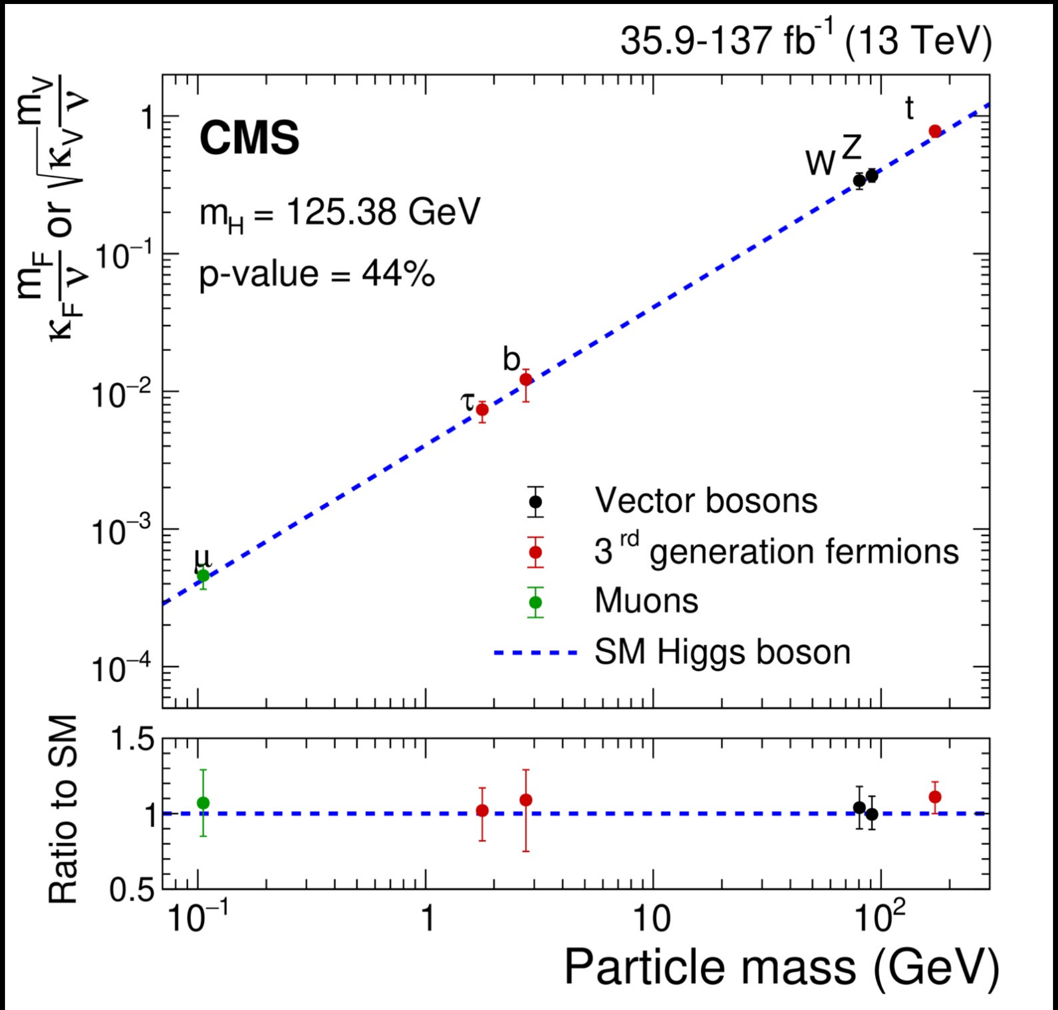
Unprecedented discoveries: Higgs



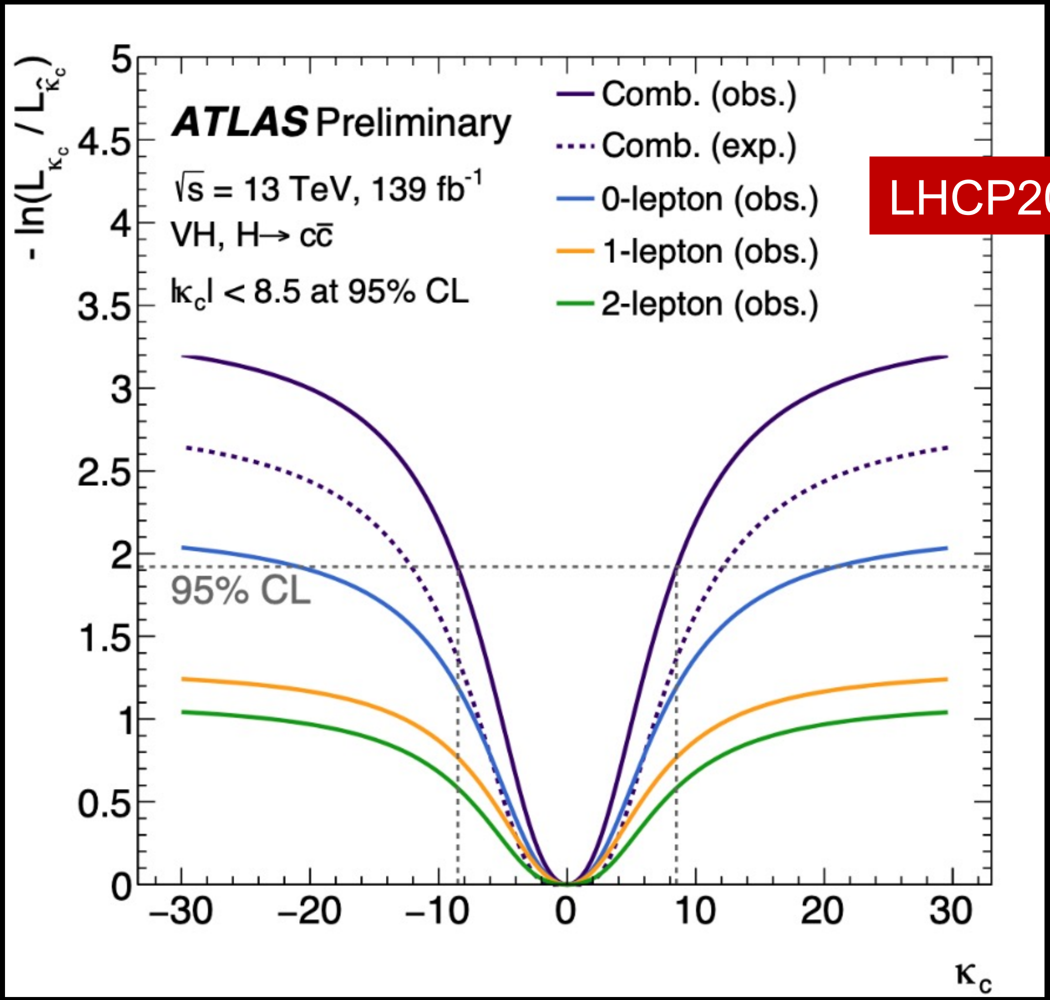
To François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider "

Unprecedented discoveries: Higgs

Probing the predictions of SM



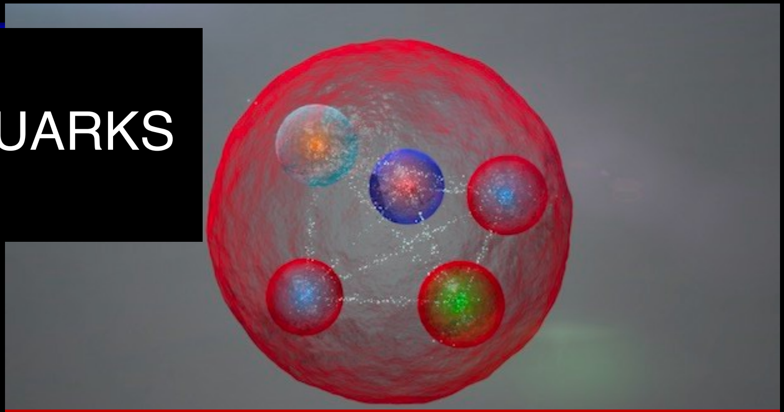
Yukawa coupling modifier $|\kappa_c|<8.5$ at 95% CL



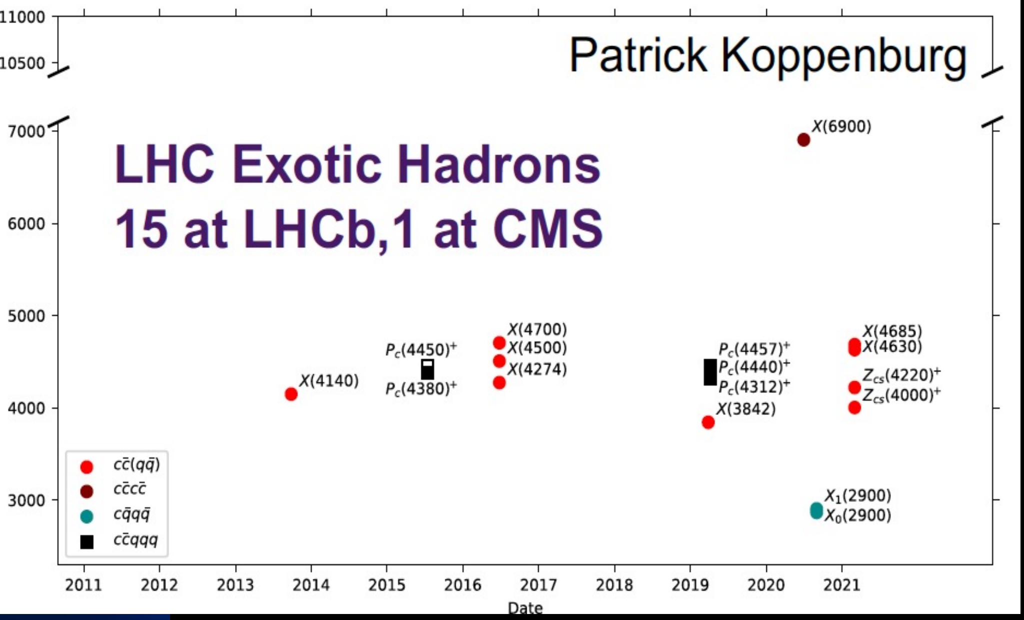
LHCP2021

But also others

LHCb: PENTAQUARKS 2015



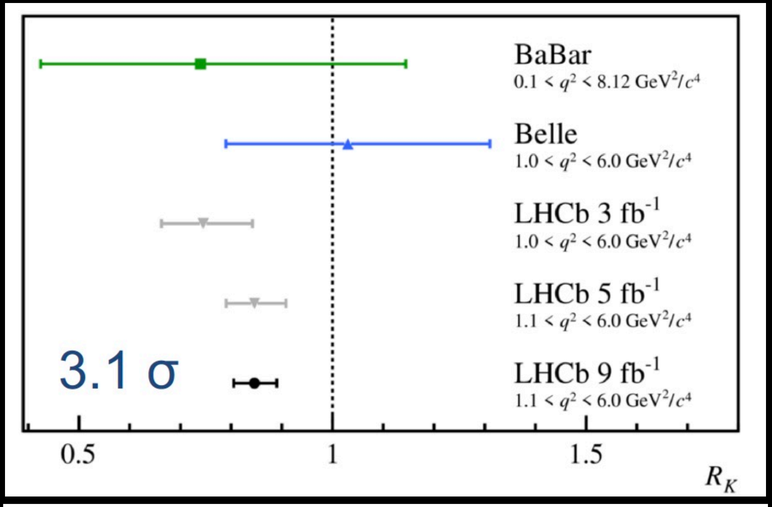
Spherical: five tightly bound quarks contained in symmetric volume?

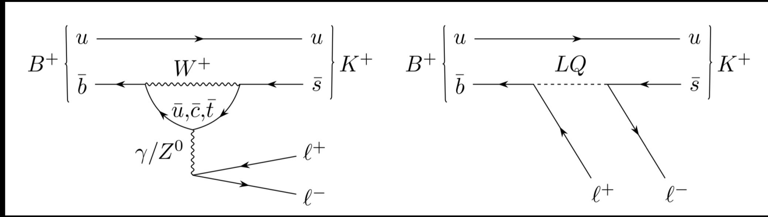


LHCb: R_K
Perhaps showing some cracks in the SM

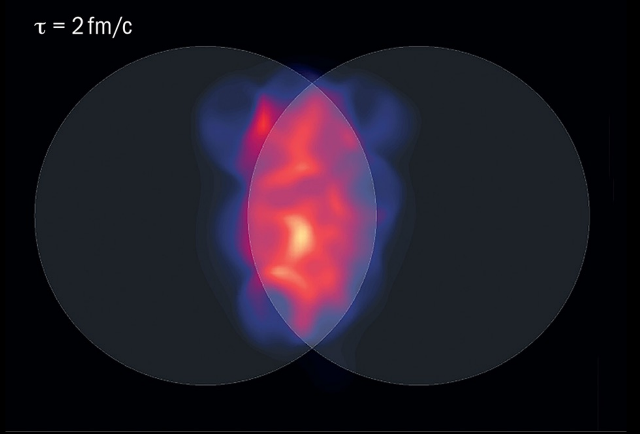
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

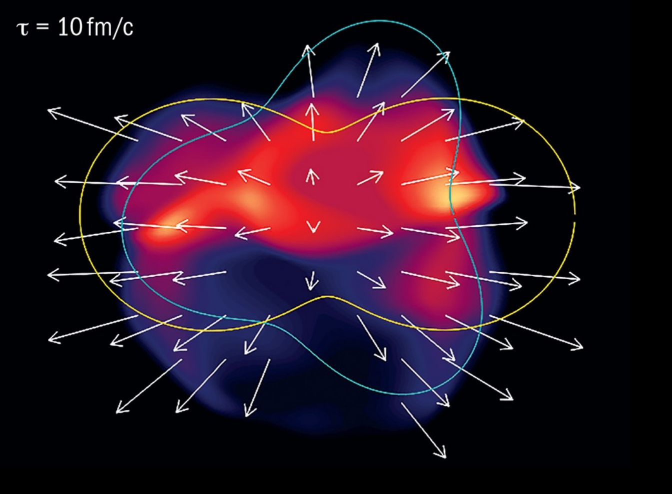
$$R_K = 0.846 \,{}^{+0.044}_{-0.041}$$





ALICE: QGP





Elliptical flow

UNIVERSITY OF OXFORD

A PRIMER ON DETECTORS IN HIGH LUMINOSITY ENVIRONMENT

Or why you can't do physics at 10^{33}

R. Huson, L. M. Lederman and R. Schwitters
Fermi National Accelerator Laboratory*
Batavia, Illinois 60510

tracking efficiency; there is in fact a fair likelihood that these high multiplicities will render any of the tracking devices, as we now understand them, inoperable. PWC's have operated at ambient

confused by the integration, but it is also clear that a large enough number of random accumulations of 10 or 20 minimum bias events can generate fake physics.

1982 SNOWMASS

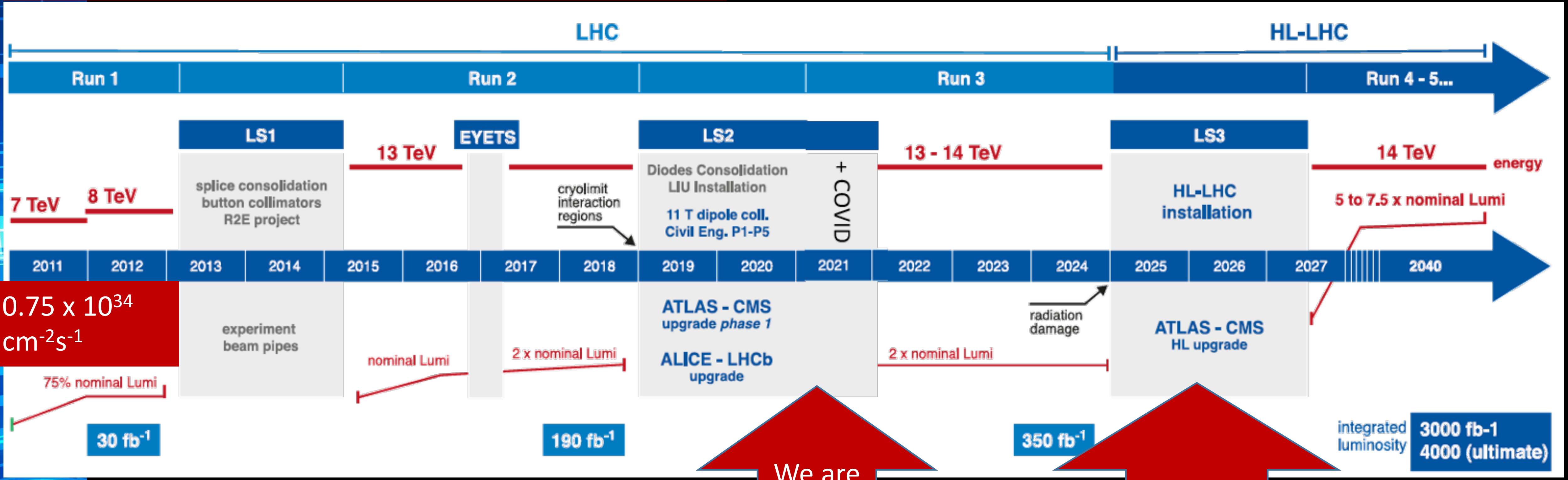
program of which 10 years have already been spent. Nevertheless, (and this is the principal motivation of this paper), work must continue on decreasing the integrating time of tracking detectors, preferably without breaking the bank by infinite readout channels. Calorimetry is fundamentally ugly; a cure here would be to improve resolution, decrease integrating time and find a cheap substitute for steel.

LHC and High-Luminosity LHC

LHC Nominal Instantaneous Luminosity 1×10^{34} $cm^{-2}s^{-1}$

2×10^{34} $cm^{-2}s^{-1}$

$5\text{-}7.5 \times 10^{34}$ $cm^{-2}s^{-1}$



0.75×10^{34} $cm^{-2}s^{-1}$

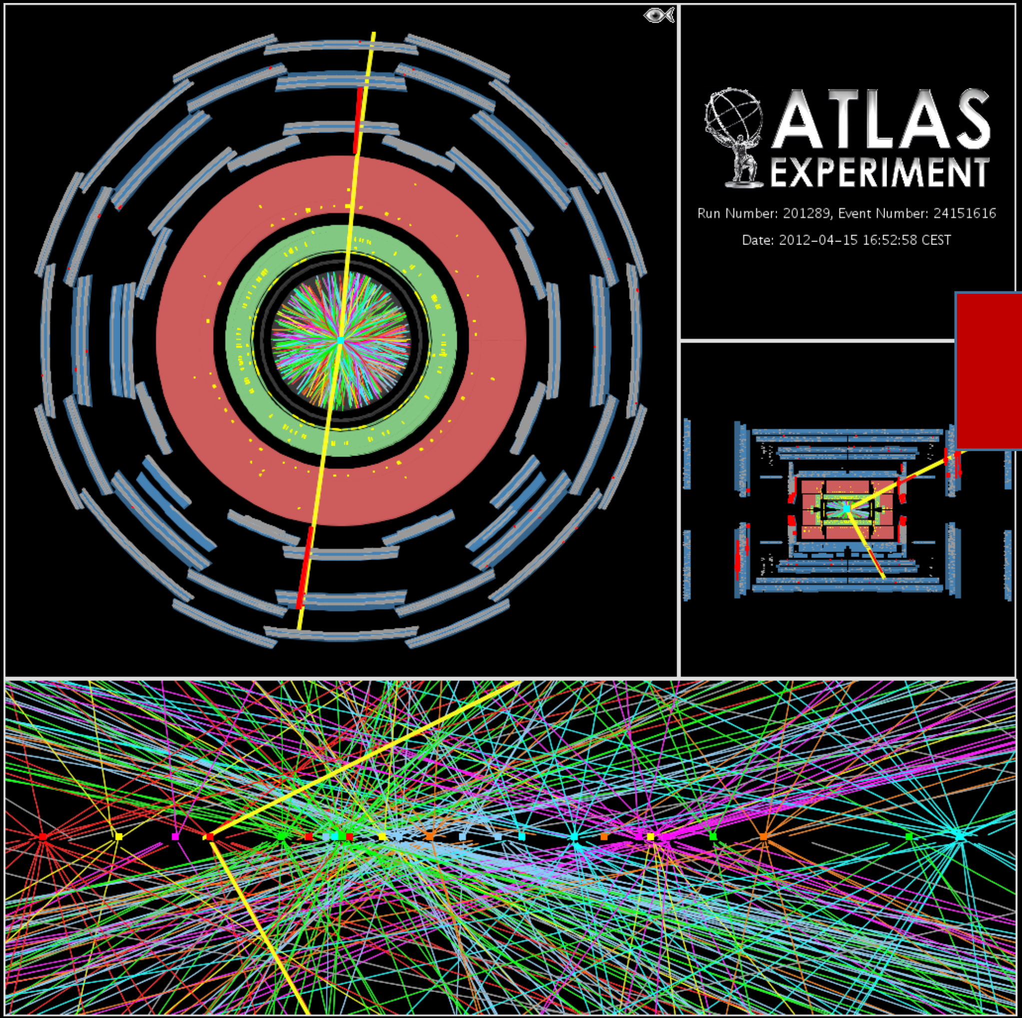
We are here

Upgrades

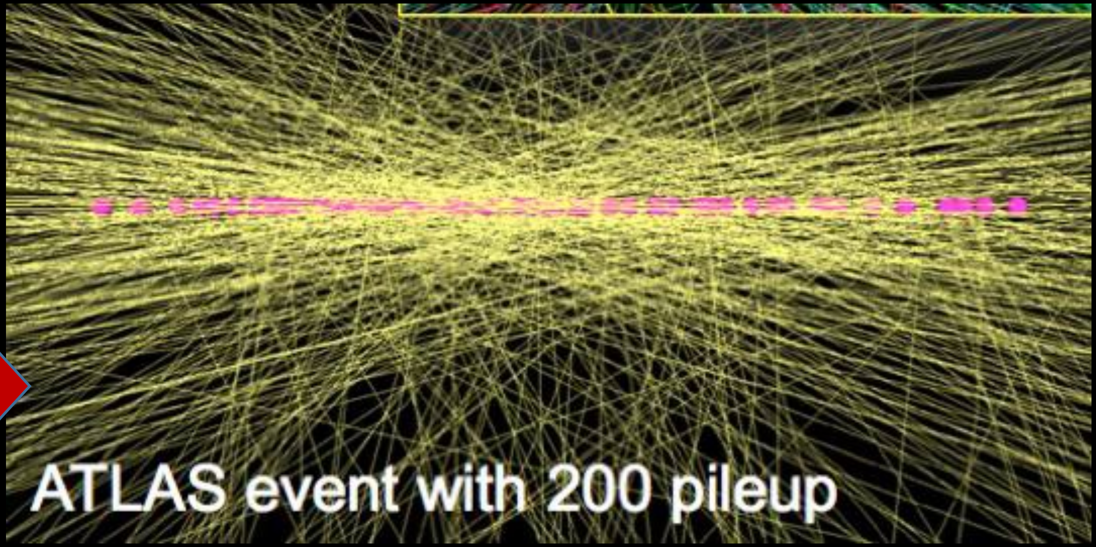
- 190 fb^{-1} only about 5% of the entire programme
- LHC + HL-LHC is the largest pp dataset for the next few decades

The incredible challenge of HL-LHC

Run 2 LHC pileup $<\mu> = 37$

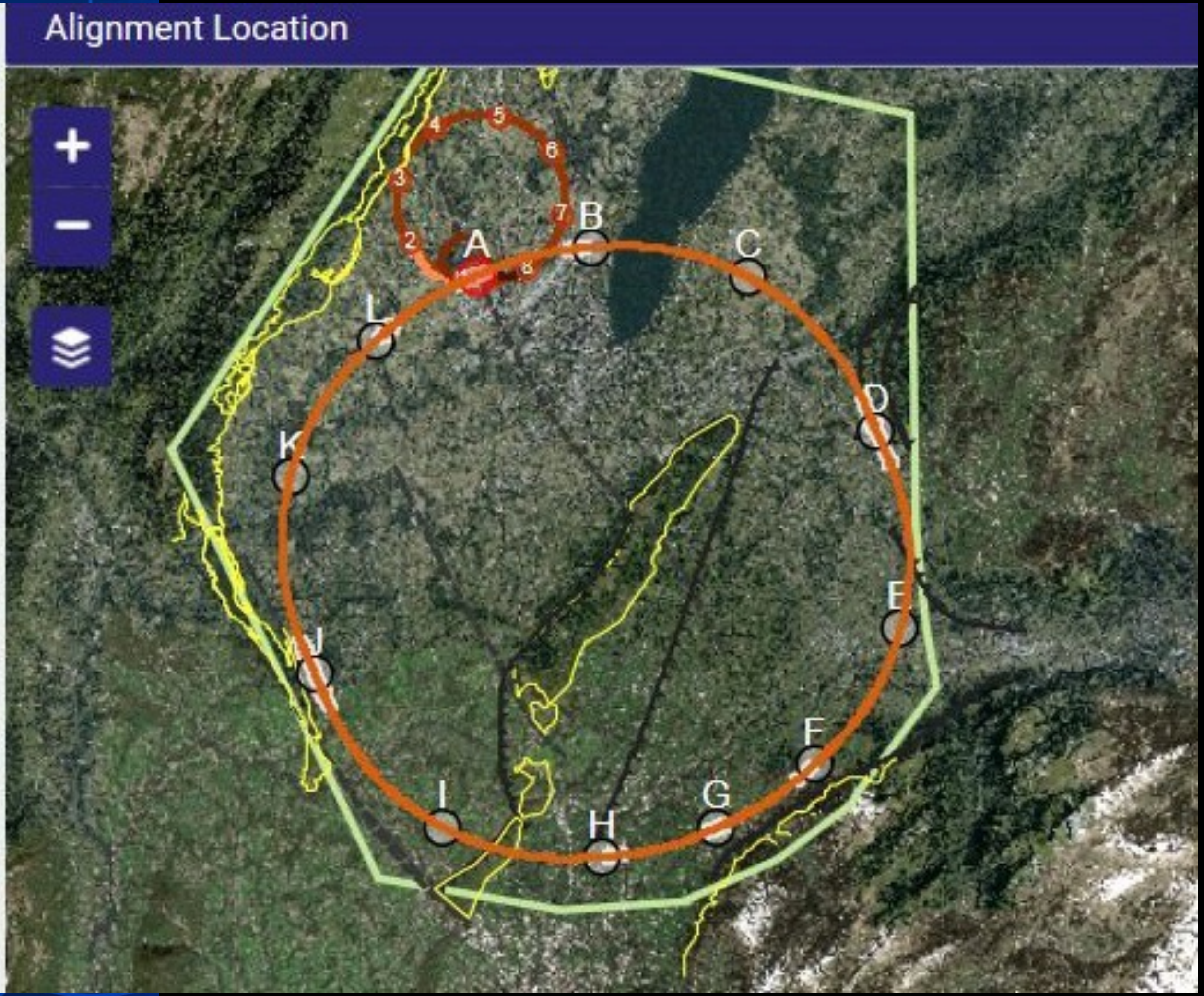


HL-LHC pileup $<\mu> = 200$



- Radiation levels up to:
  - fluence of 2×10^{16} 1 MeV n_{eq}/cm^2
  - Total Ionizing Dose (TID) ~ 1 Grad

The FCC Project



100 Km Tunnel (CHF 5B)

- e^+e^- collider (FCC-ee) at the intensity frontier (CHF 5B, 2040-2050)
  - High luminosity
  - $\sqrt{s}$ = 90-400 GeV
- Ultimate goal: 100TeV pp collider (FCC-hh) at the energy frontier (CHF 15B, 2050-2075)
  - Requires R&D for 16T magnets
  - Defines the infrastructure

Increased Performance Hadron Colliders

LHC	HL-LHC	FCC-hh
Peak Luminosity	Peak Luminosity	Peak Luminosity
1-2 x 10^{34} $cm^{-2}s^{-1}$	5-7 x 10^{34} $cm^{-2}s^{-1}$	5-30 x 10^{34} $cm^{-2}s^{-1}$
Integrated Luminosity	Integrated Luminosity	Integrated Luminosity
300-400 fb^{-1}	3000-4000 fb^{-1}	30 ab^{-1}

x10

x10

INSTRUMENTATION

"New directions in science are launched by new tools much more often than by new concepts.

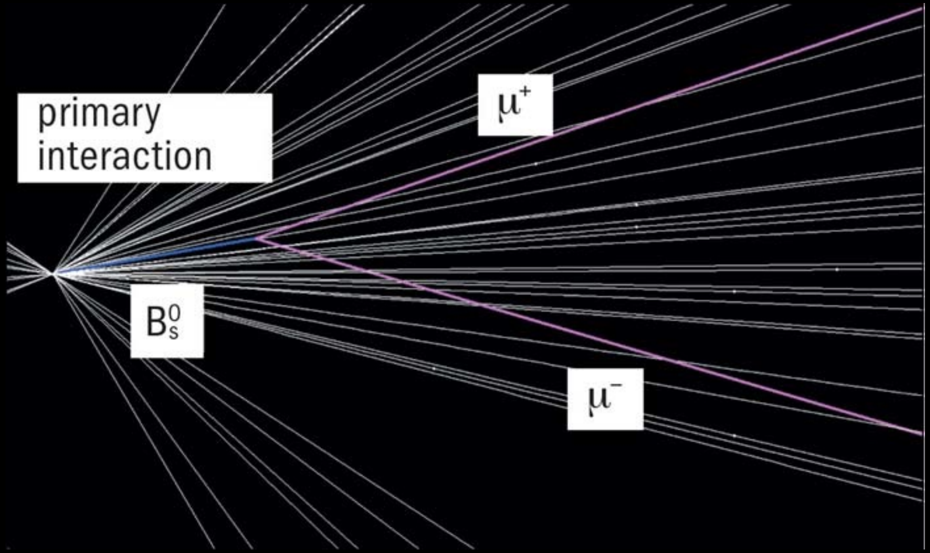
The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson

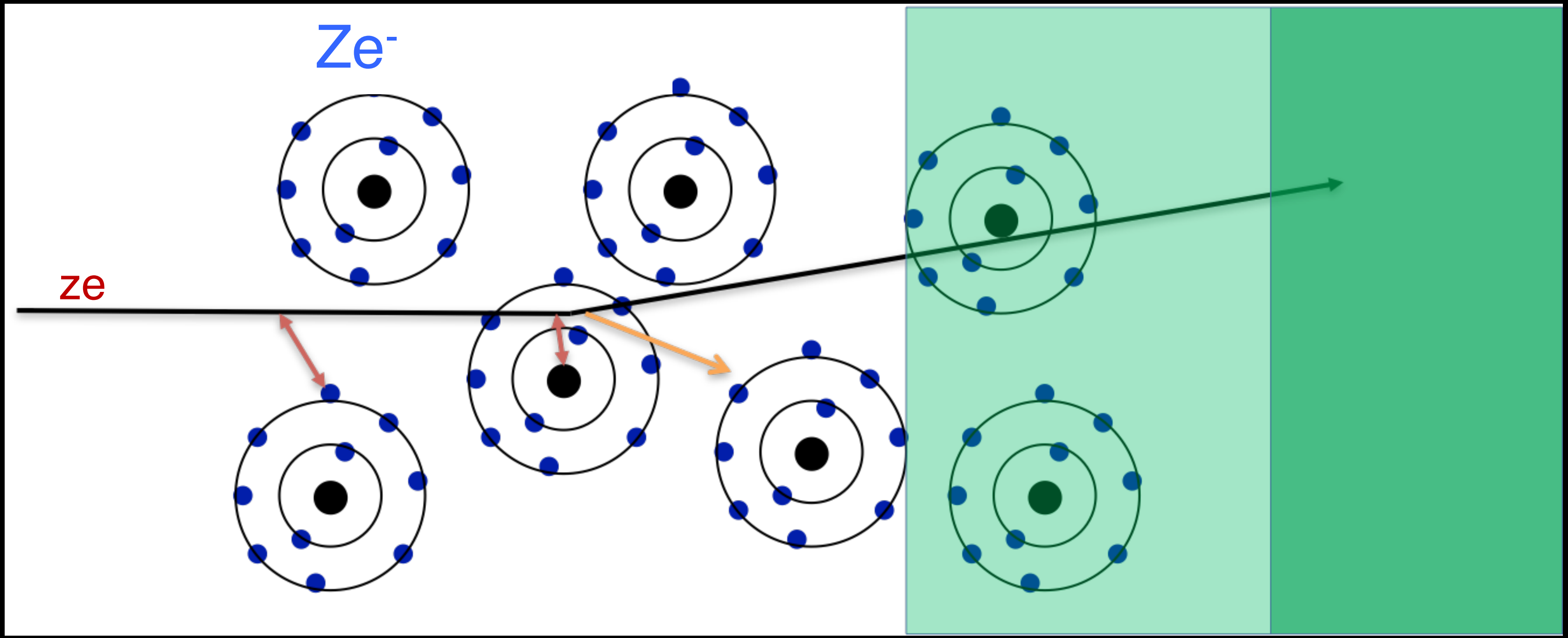
Detecting Elementary Particles

- The goal of LHC detectors was to measure well: e, μ, τ, γ, W, Z, jets, missing E_T, b tagging
- For W and Z, the information would be reconstructed through their decay to: $Z \rightarrow e^+e^-, \mu^+\mu^-$, qq….and W→ $e\nu, \mu\nu$,qq'…..
- B-tagging: reconstructing vertices of charged particles (e, μ, $p, \pi^{\pm}$, $K^{\pm}$) with a precision of $\approx 10\ \mu m$



- Every effect of particles or radiation can be used as a working principle for a particle detector.

EM interaction of charged particles with matter



Interaction with the atomic electrons

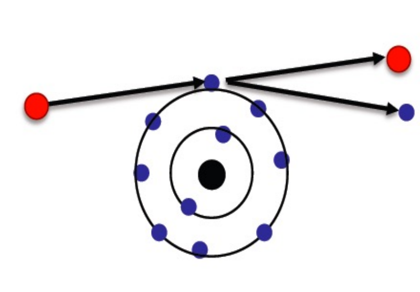
Incoming particles lose energy and atoms are excited or ionized.

Interaction with the atomic nucleus.

Particles are deflected and a Bremsstrahlung photon can be emitted.

If the particle's velocity is > the velocity of light in the medium → Cherenkov Radiation.

When a particle crosses the boundary between two media, there is a probability ≈1% to produce an X ray photon Transition radiation.



Energy loss by ionization

- The Bethe-Bloch equation for energy loss

Valid for heavy charged particles ($m_{incident} >> m_e$), e.g. proton, k, π, μ

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

$2\pi N_a r_e^2 m_e c^2$ = 0.1535 MeV cm²/g

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2} \ln\left(a\beta^2\gamma^2 \right)$$

Fundamental constants

r_e = classical radius of electron
m_e = mass of electron
N_a = Avogadro's number
c = speed of light

Absorber medium

I = mean ionization potential
Z = atomic number of absorber
A = atomic weight of absorber
ρ = density of absorber
δ = density correction
C = shell correction

Incident particle

z = charge of incident particle
β = v/c of incident particle
$\gamma = (1-\beta^2)^{-1/2}$
W_{max} = max. energy transfer in one collision

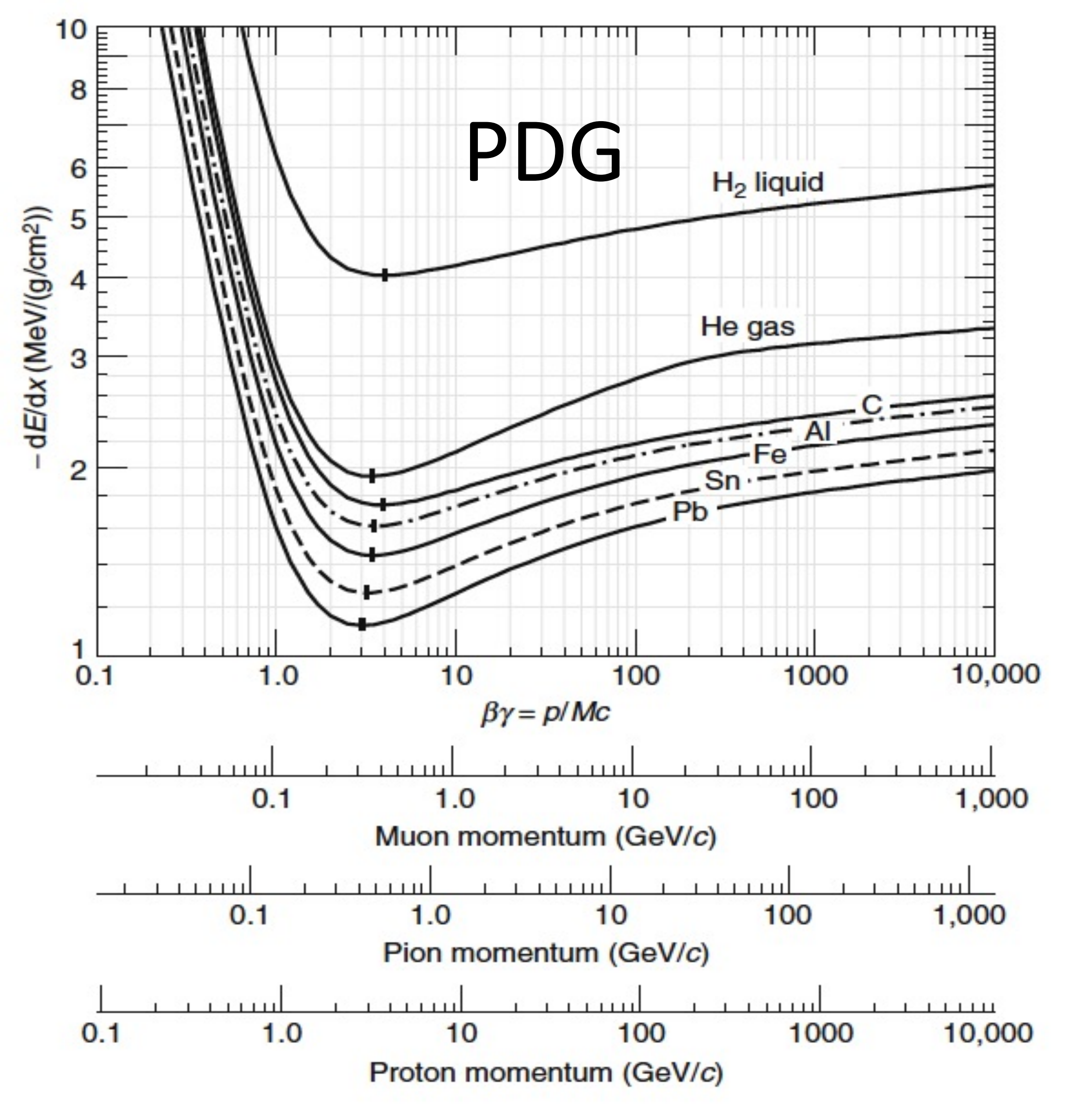
$$r_e = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{m_e c^2}$$

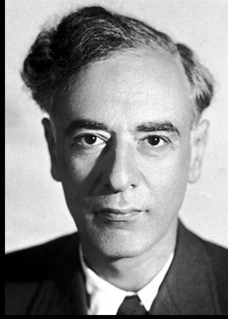
The Bethe-Bloch Formula

- Common features:
  - fast growth, as $\mathbf{1}/\beta^2$, at low energy
  - wide minimum in the range $3 \leq \beta\gamma \leq 4$,
  - slow increase at high $\beta\gamma$.

- A particle with d**E/**d**x** near the minimum is a minimum-ionizing particle or mip.

- The mip's ionization losses for all materials except hydrogen are in the range 1-2 MeV/(g/cm^2)
  - increasing from large to low Z of the absorber.

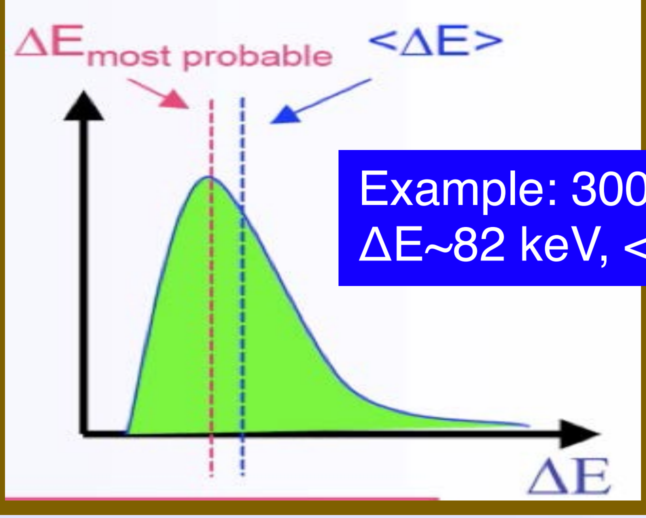




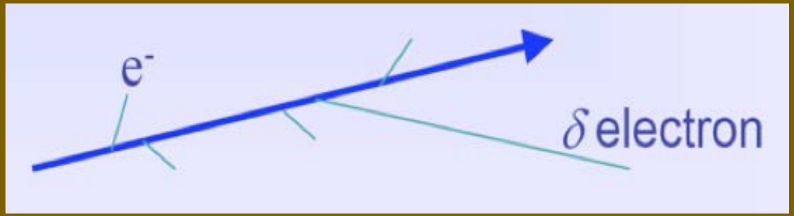
dE/dx Fluctuations

- A real detector cannot measure <dE/dx>
  - It measures the energy ΔE deposited in layers of finite thickness Δx
  - Repeated measurements are needed

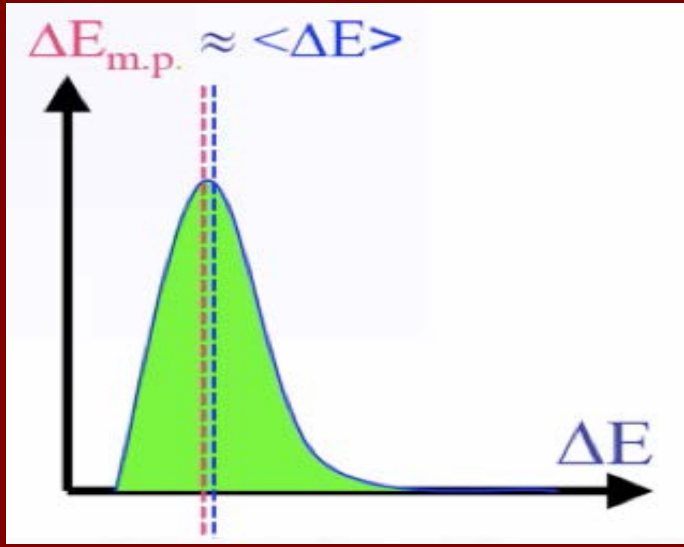
- Thin layers or low density materials: dE/dx has large fluctuations towards high losses (Landau-Vavilov, Bichsel)

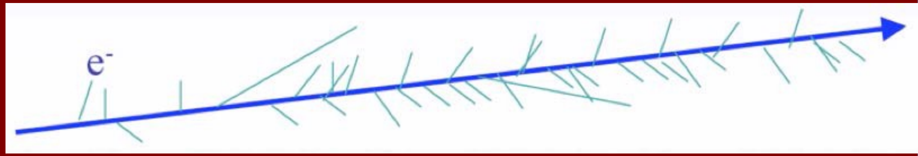


Example: 300 µm thick Silicon
ΔE~82 keV, <ΔE> ~115 keV



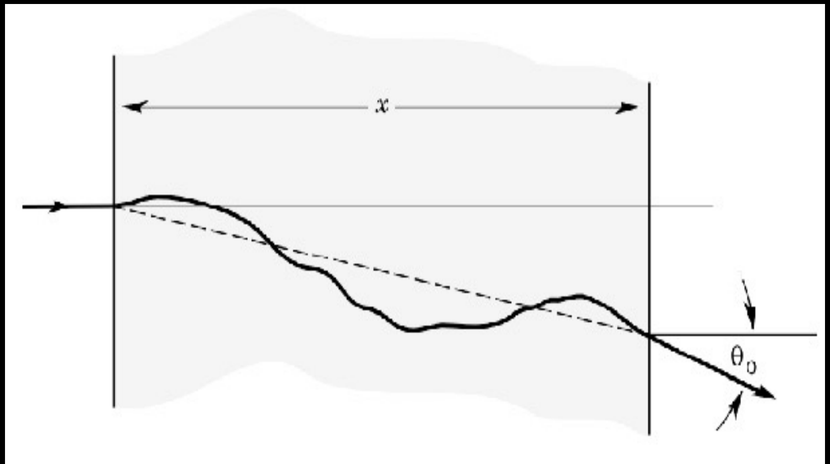
- Thick layers and high density materials: the dE/dx is a more Gaussian-like (many collisions





PDG

Multiple scattering



- A particle passing through material undergoes also multiple deflections due to Coulomb scattering with the nuclei
- The scattering angle as a function of the thickness x is

$$\theta_{\rm rms}^{\rm proj} = \sqrt{\langle \theta^2 \rangle} = \frac{13.6\ \text{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln(x/X_0)\right]$$

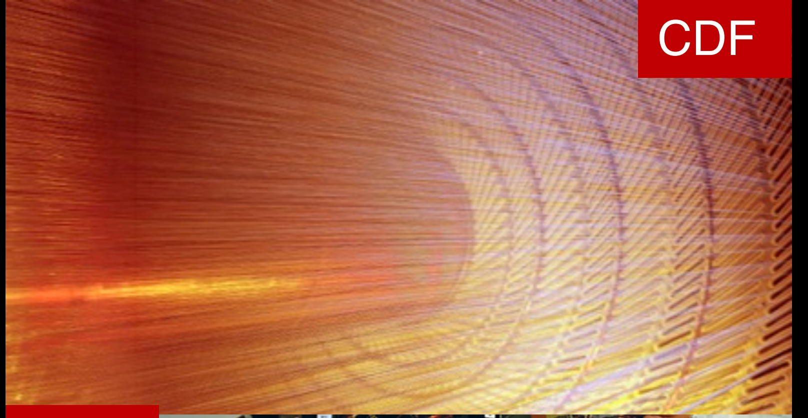
$$X_0 \cong \frac{716.4\ g \cdot cm^{-2}\ A}{Z(Z+1) ln\left(287/\sqrt{Z}\right)}$$

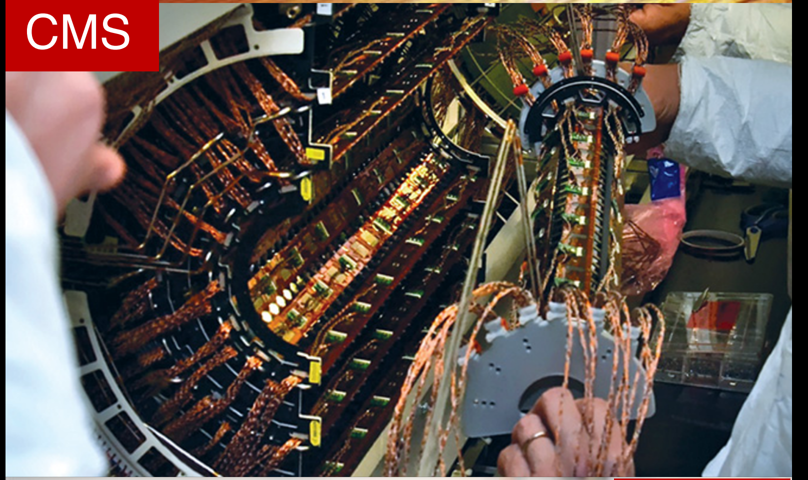
- Where:
  - p (in MeV/c) is the momentum, βc the velocity
  - z the charge of the scattered particle
  - x/X_0 is the thickness of the medium in units of radiation radiation length (X_0).

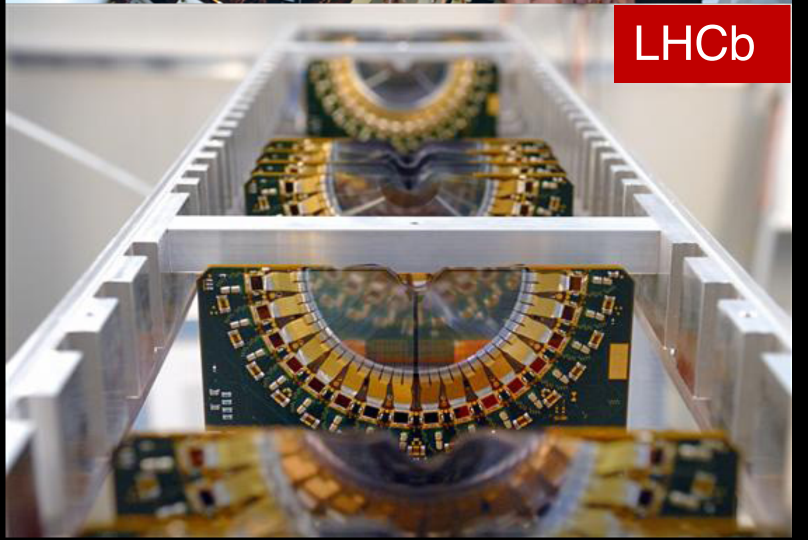
- Small deflections:
  - Large Radiation length X_0 – i.e. low Z and low density material (Be, C …)
  - Small x i.e. very thin detector elements
- Multiple scattering limiting tracking performance at low p

Tracking detectors

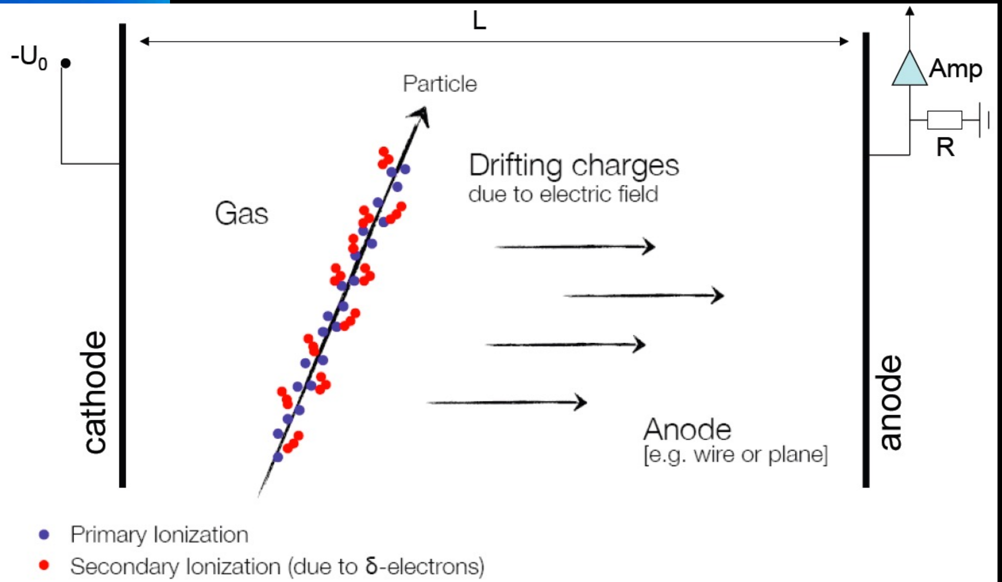
- High granularity detectors close to the interaction region measuring the trajectory using "hits" due to charged particles ionizing a material (gas, silicon)
  - charged particles' momenta determined from their curvature in a B field (R[m]=p[GeV/c]/(0.3B[T]))
  - Extrapolation to origin allows the reconstruction of Primary Vertex of the "hard scattering", while secondary vertices identify tau-leptons, b and c-hadrons by lifetime tagging ($d = \beta\gamma c\tau$)



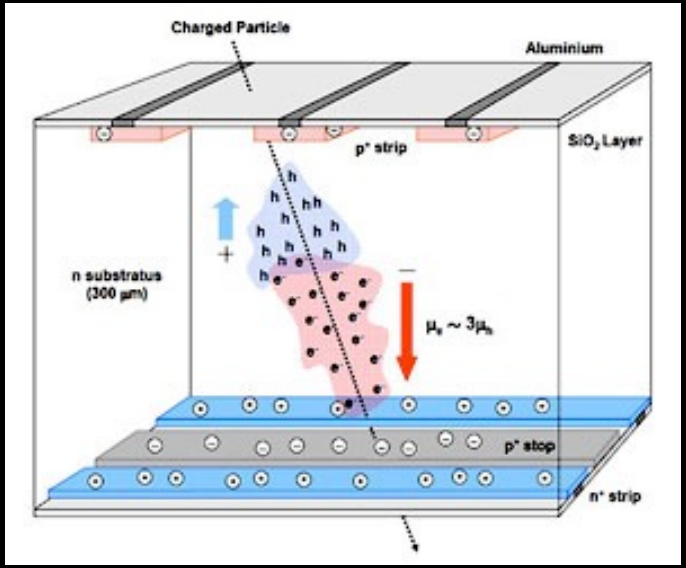




Gas Detectors

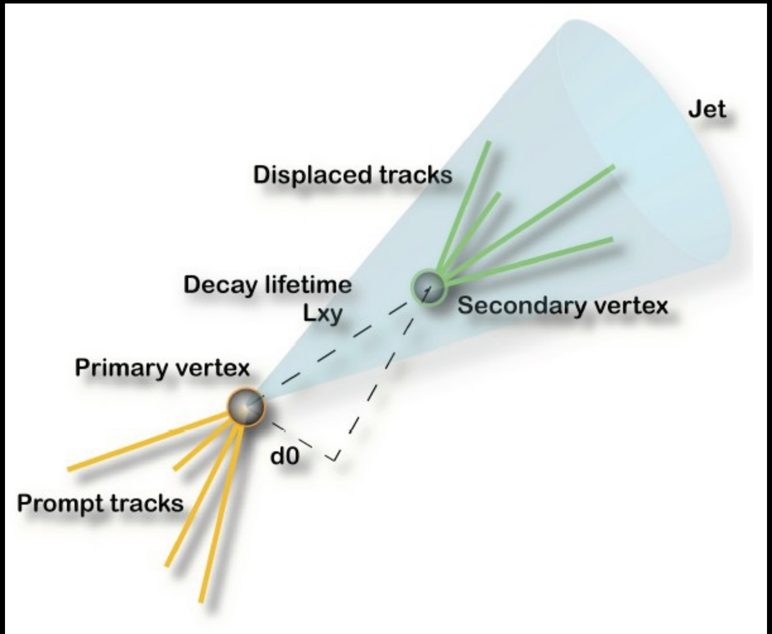


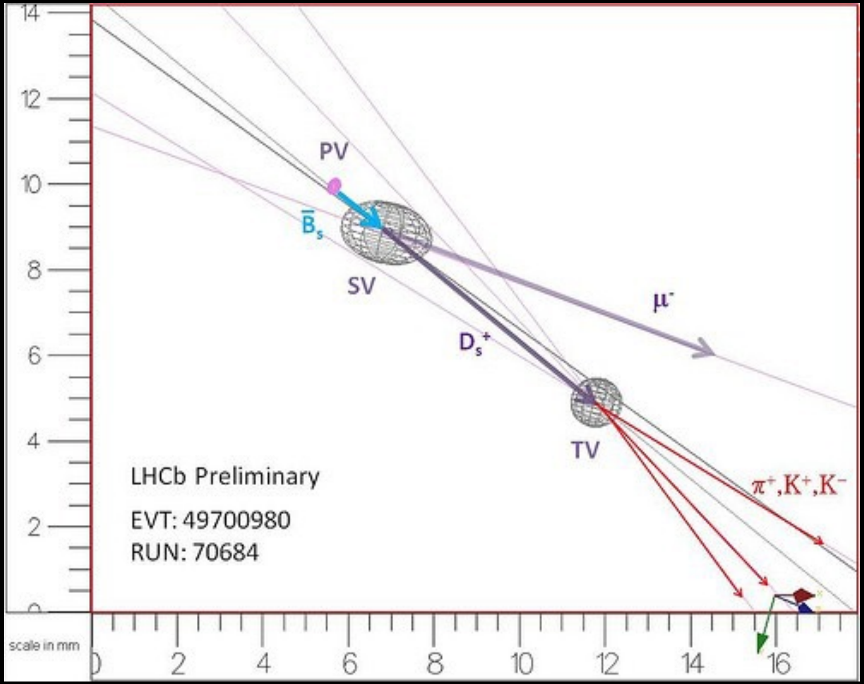
Silicon Detectors



Impact Parameter

- Distance between primary vertex and prolongation is called impact parameter (d).
- If d is large the probability is high that the track comes from a secondary vertex
- Distance can be used for tagging b-jets and c-jets ($\beta\gamma c\tau$)



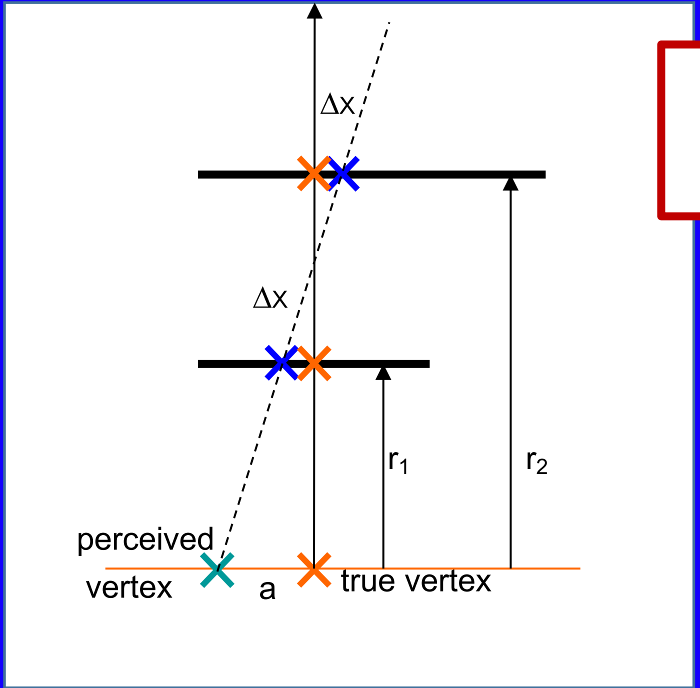


Impact Parameter resolution

- Vertex projection from two points: simplified telescope equation

Pointing resolution = (a $\oplus$ b) µm

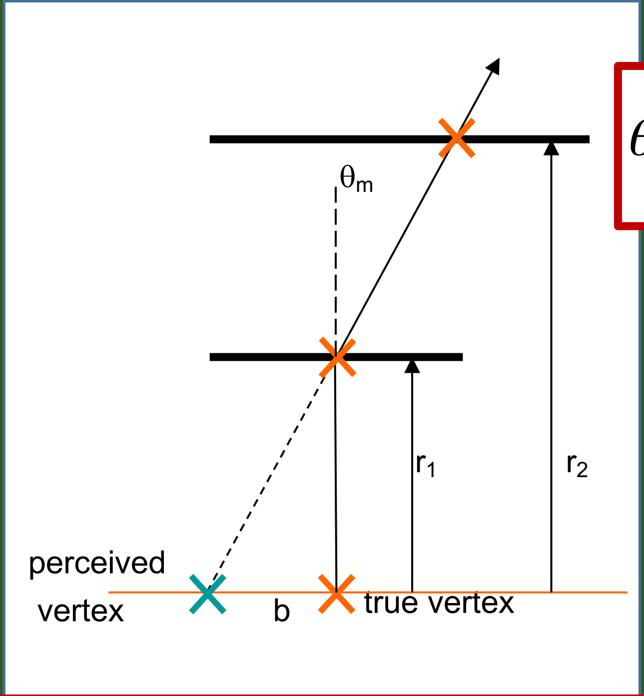
a= depends on detector position resolution



$$a = \Delta x \cdot \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$

Minimize Δx: e.g. 50 μm pixel and r_2 very large compared to r_1 (first layer as close as possible to IP) → a=Δx=50/√12 = 15 μm

b= depends on multiple scattering

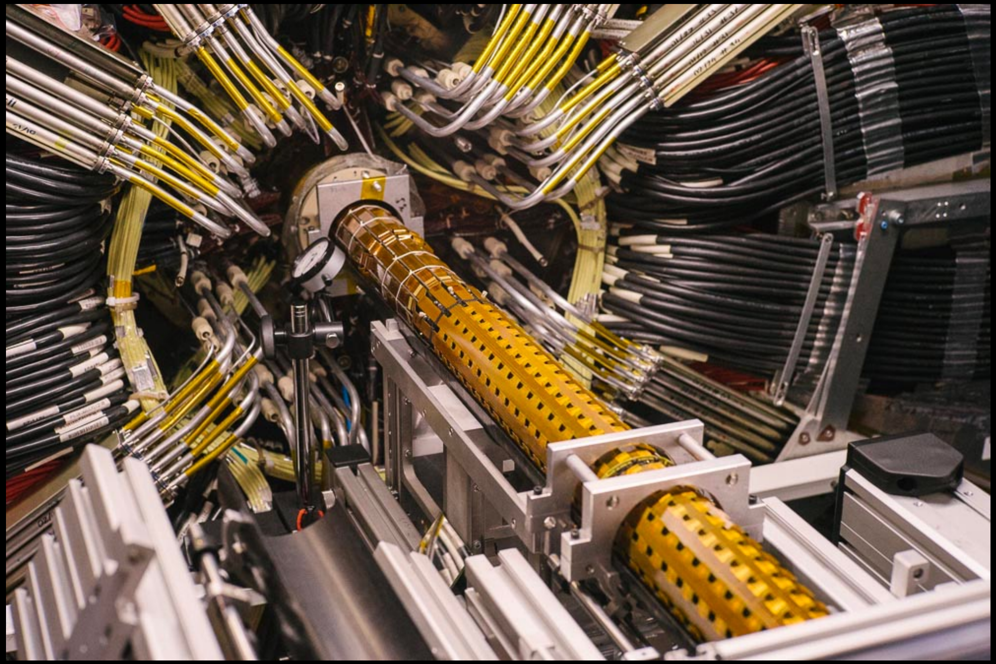


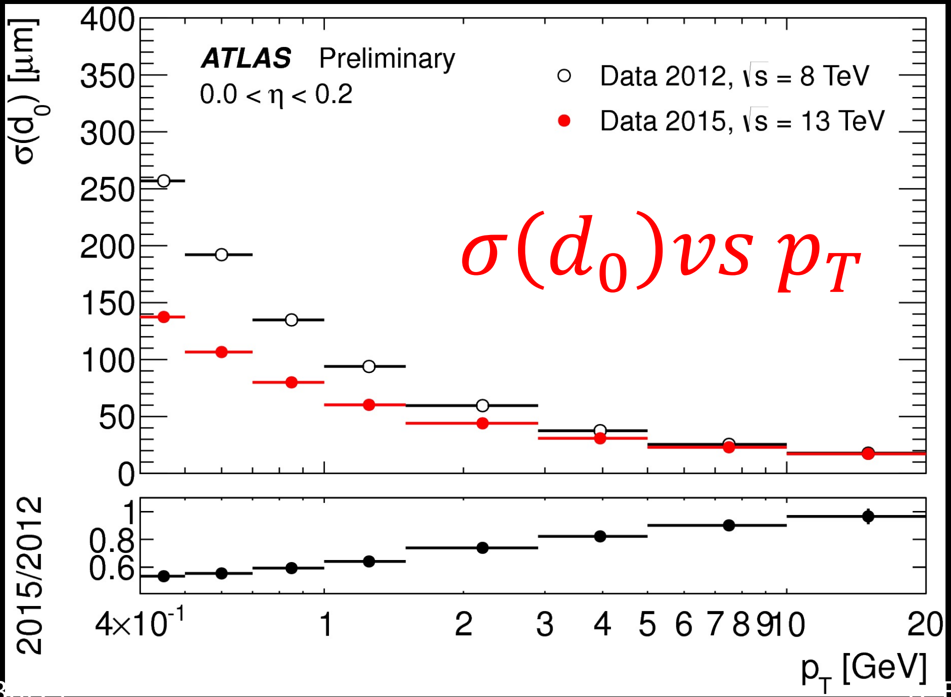
$$\theta_m = \frac{13.6 Mev}{\beta \cdot c \cdot p} \cdot \sqrt{x / X_0}$$

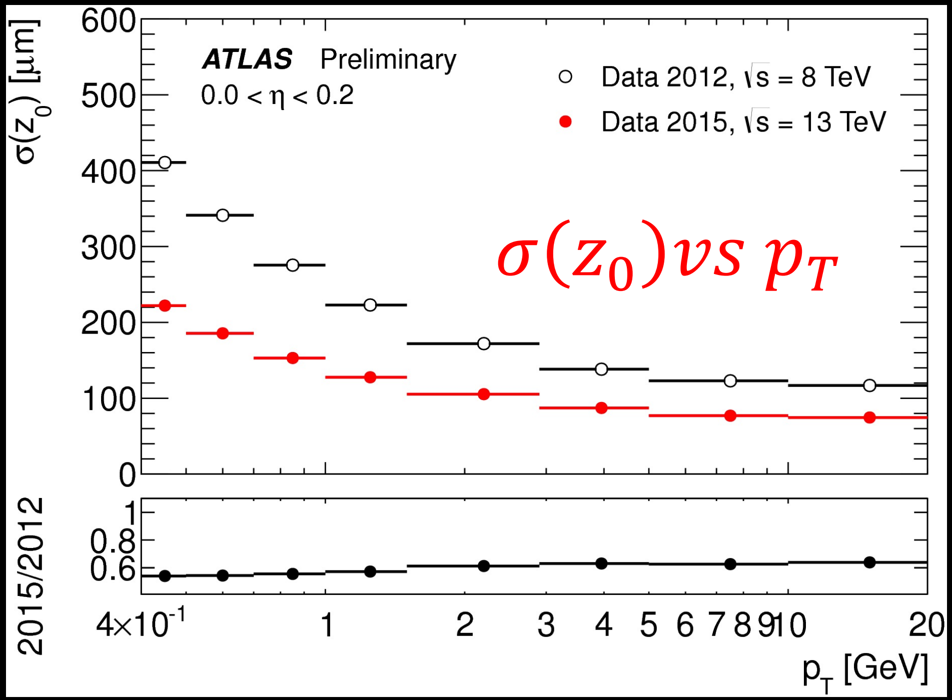
First layer with minimal amount of material: e.g. x/X_0 = 0.0114, r_1= 39mm → b= 57 μm for p=1GeV/c

Impact Parameter resolution

- Improvement by inserting IBL in the ATLAS Pixel system just before the start of Run 2 in 2015
- IBL: radius of 3.3 cm, smaller pixels 50 µm× 250 µm (instead of 50 µm×400 µm) and lower mass

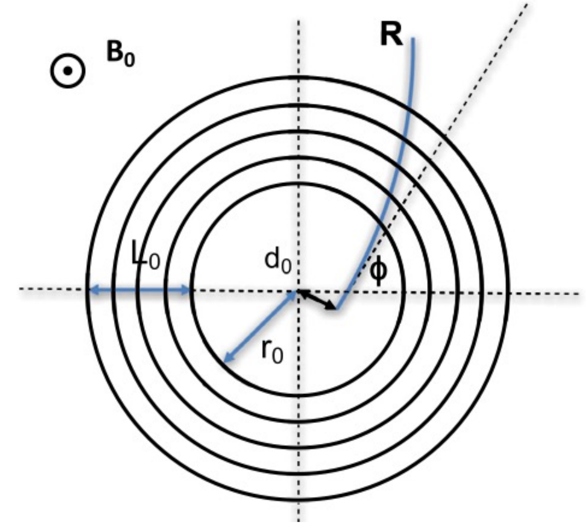




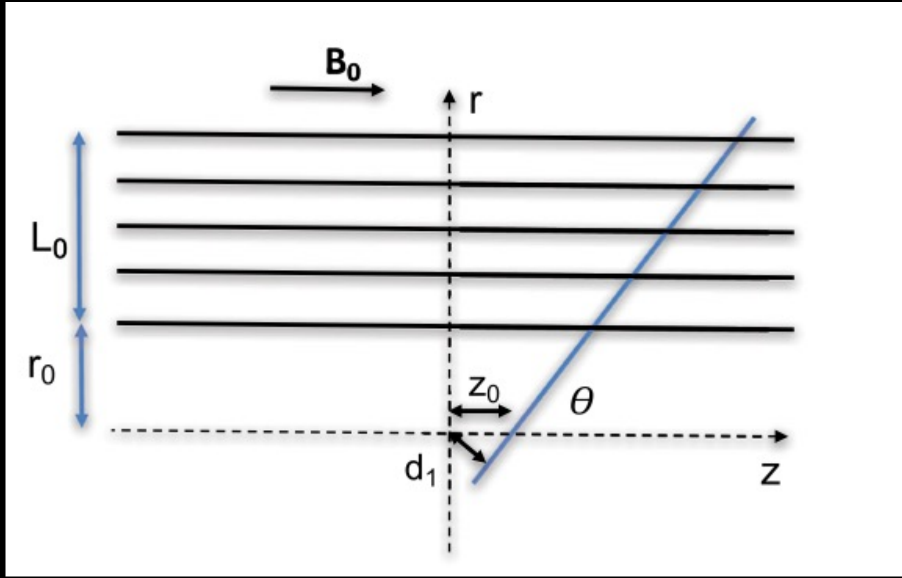


Momentum resolution

- Analytic expressions for momentum, track angle and impact parameter resolution have been calculated for equidistant layers



R[m]=p[GeV/c]/(0.3B[T])



- solenoid spectrometer with a constant B-field
- $N + 1$ equal and equidistant detector planes.
- d_i the thickness of a single detector plane in X_0 units
- $d_{tot} = (N + 1)\, d_i$

$$\frac{\Delta p_T}{p_T}\Big|_{res.} = \frac{\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{720 N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{12\, \sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} = \frac{N}{\sqrt{(N+1)(N-1)}}\,\frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0} \times \sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}\left(1 + 0.038\ln\frac{d}{X_0\,\sin\theta}\right) \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

Drasal & Riegler: https://doi.org/10.1016/j.nima.2018.08.078

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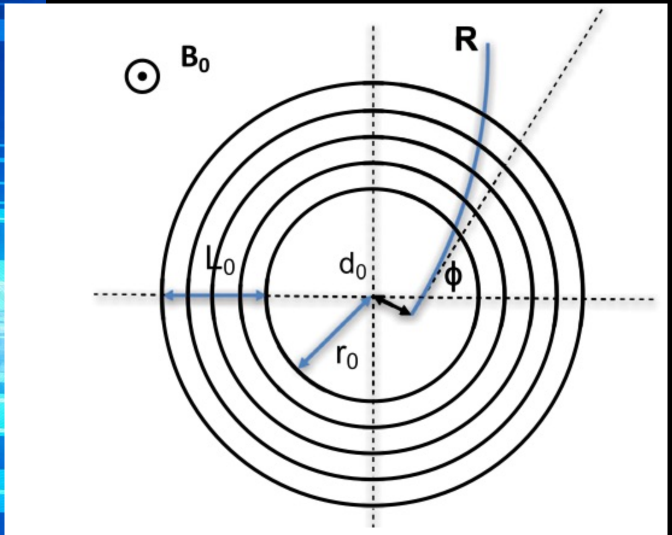
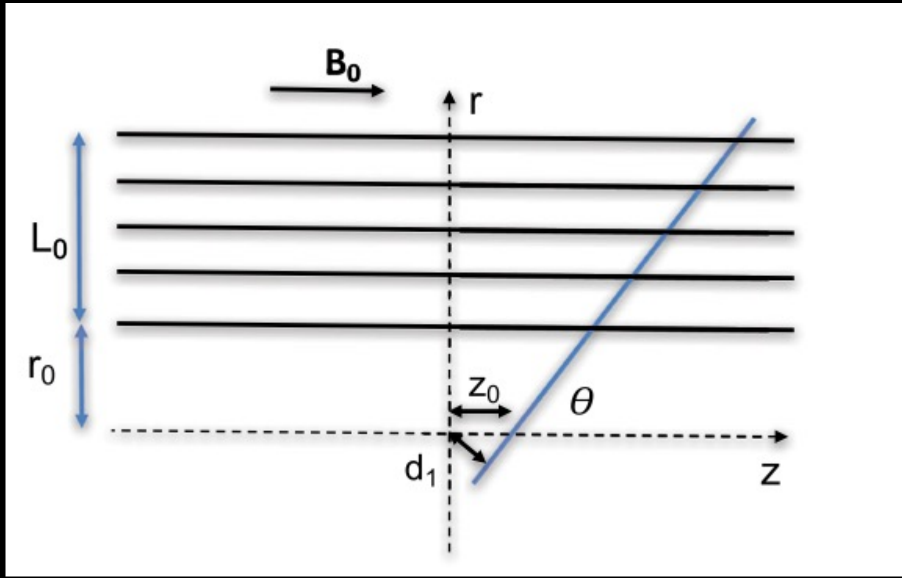


R[m]=p[GeV/c]/(0.3B[T])



- solenoid spectrometer with a constant B-field
- $N+1$ equal and equidistant detector planes.
- d_i the thickness of a single detector plane in X_0 units
- $d_{tot} = (N+1)\ d_i$

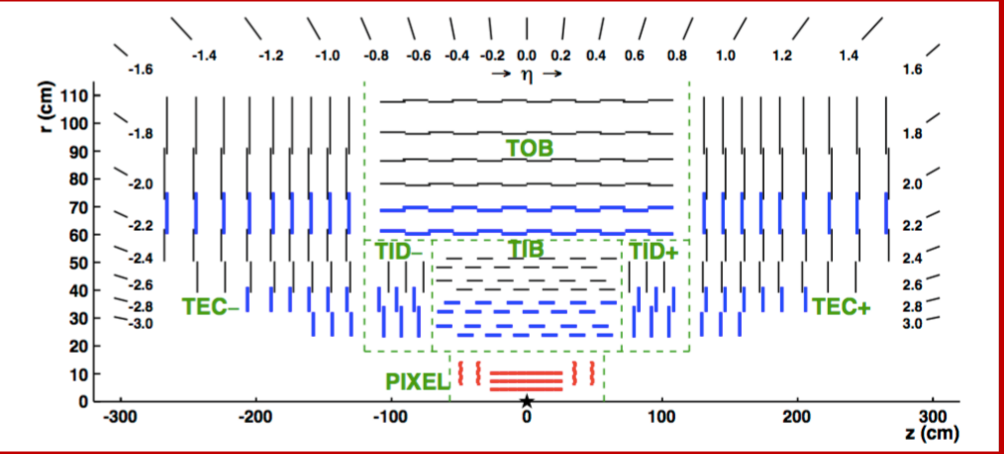
- Good transverse momentum resolution requires: small $\sigma_{r\phi}$, strong B field, large L_0 (as L_0^2) , many measurement layers N (as $\sqrt{N}$), thin measurement layers (d_i), long X_0, low Z materials
- Momentum resolution gets worse at large p_T

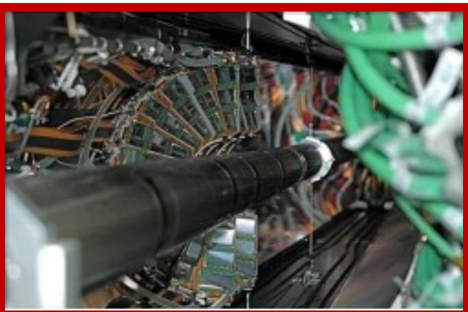
Drasal & Riegler: https://doi.org/10.1016/j.nima.2018.08.078

Atlas and CMS tracking

CMS

All silicon system in 3.8 T solenoid field



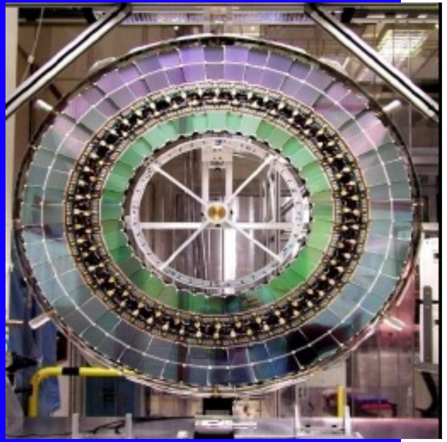


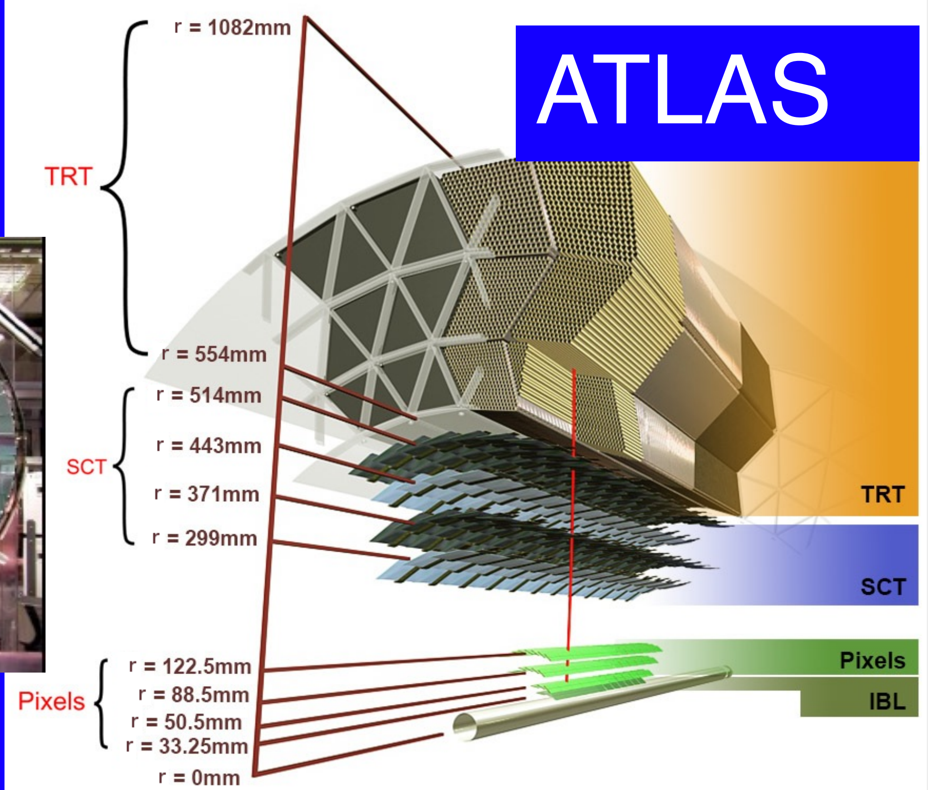
Strips: 198m² with 9.3 M channels
Inner: 4 barrel layers, 3 end-cap disks
Outer: 6 barrel layers, 9 wheels

Pixels: 66M pixels each 150 x 100 μ m² pixels
3 barrel layers, 2 endcap disks/side (Upgraded in phase 1 to 4 barrel layers + 3 endcaps/side)

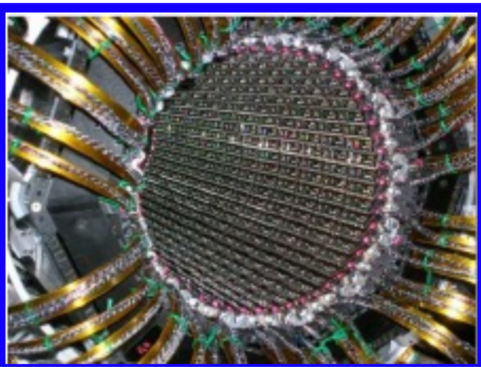
ATLAS

Silicon pixel and strip + transition radiation tracker (TRT) in 2 T field





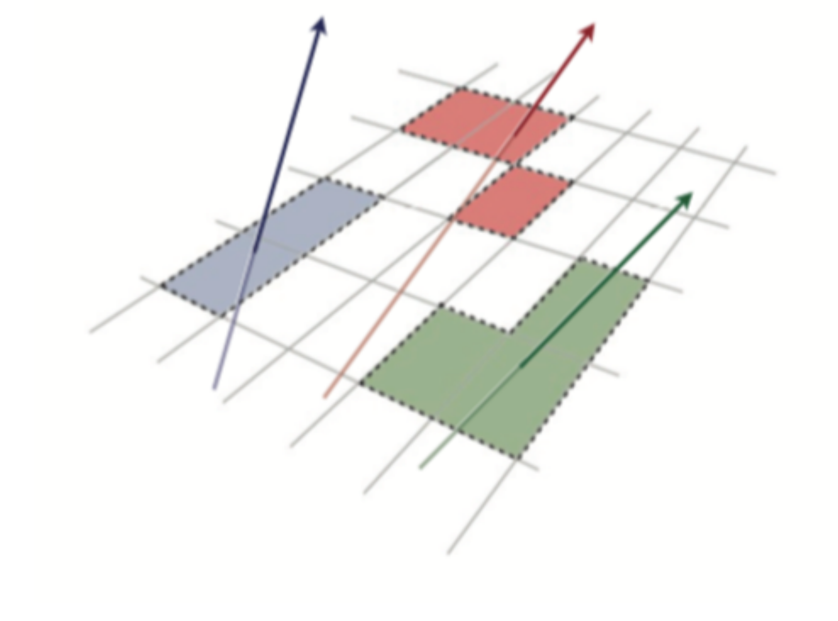
Strips: 61m² with 6.2 M channels
4 barrel layers + 9 disks per endcap
30cm < R < 52cm



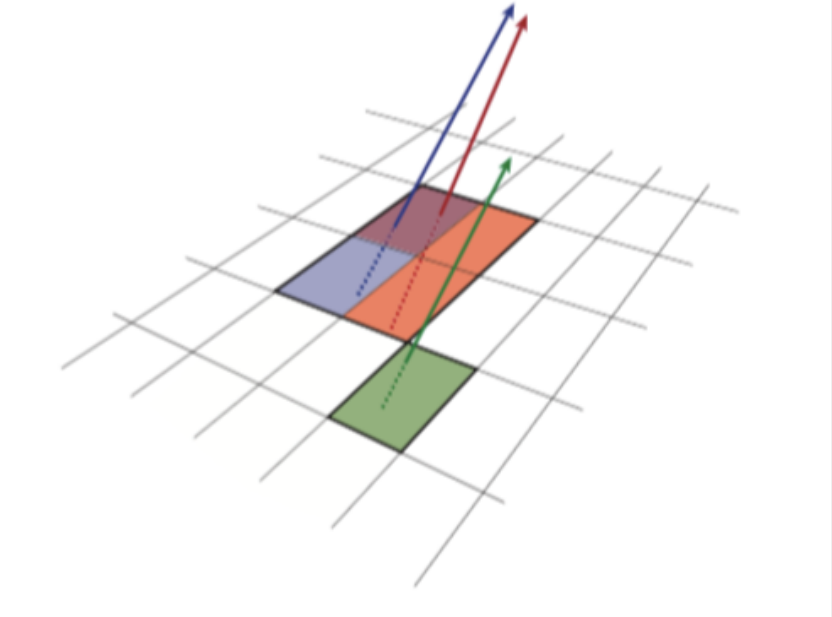
Pixels: 80M pixels each 50 x 400 μ m²
3 Barrel layers
3 endcap disks/side
IBL: 50 x 250 μm²

From particle to hits

- Charged particle will create O(24000) electron-hole pairs
- Charge > threshold is considered a hit
- If charge is collected in multiple adjacent pixel/strips, the hits are grouped together into a cluster
  - Challenge: this can lead to merged clusters in dense environments
- Detector granularity critical to maintain low occupancy
- Hit reconstruction efficiency (in working modules) is > 99% typically
- As a rule of thumb the position resolution is pitch/sqrt(12)



(a) Single-particle pixel clusters

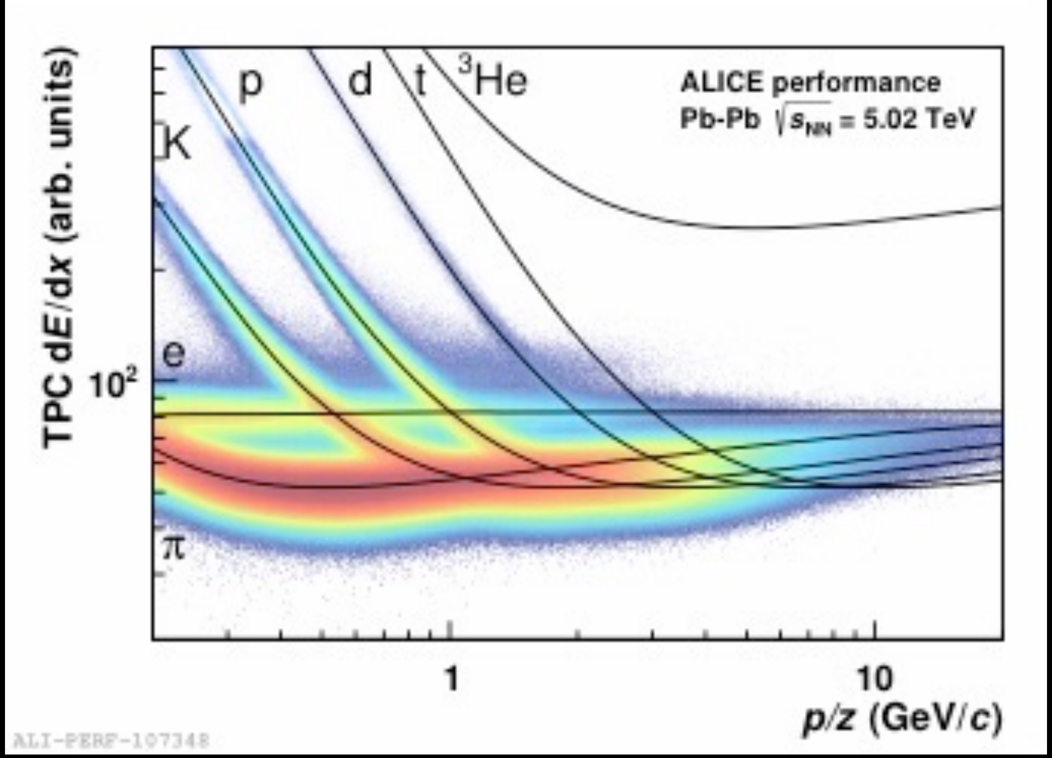


(b) Merged pixel cluster

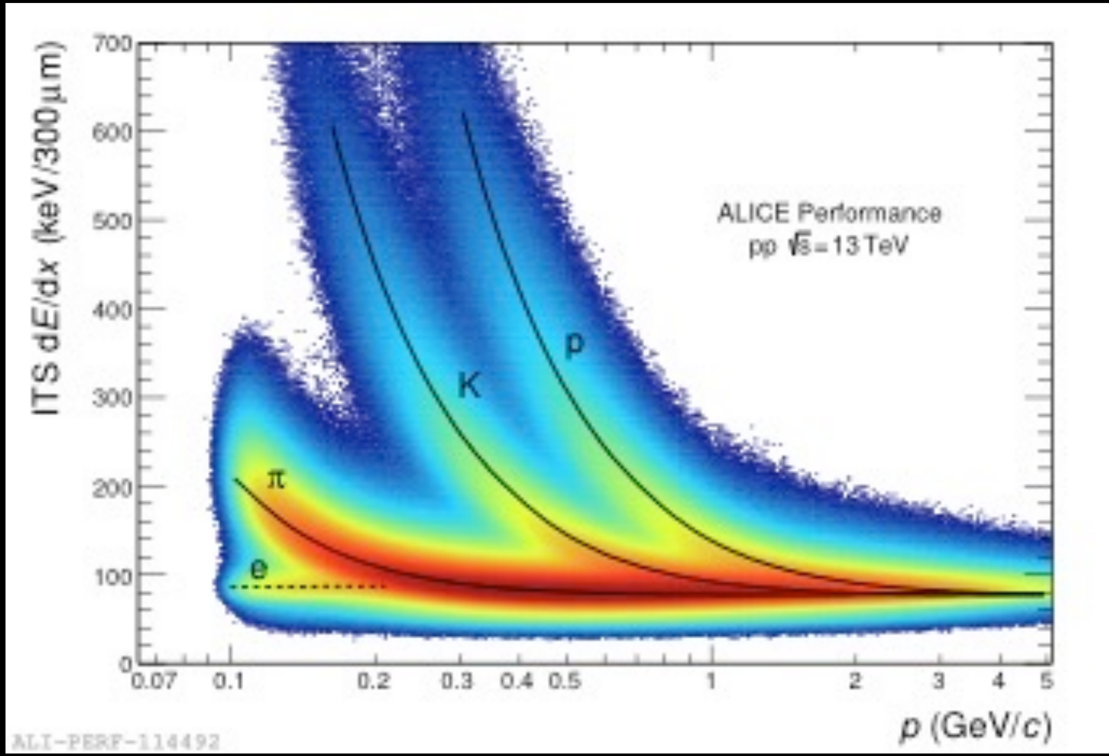
dE/dx and particle ID

- dE/dx is a function of βγ =P/Mc and can be used to separate different particles once p is known
- μ/π separation impossible, but π/K/p generally achievable

ALICE TPC – Gas detectors



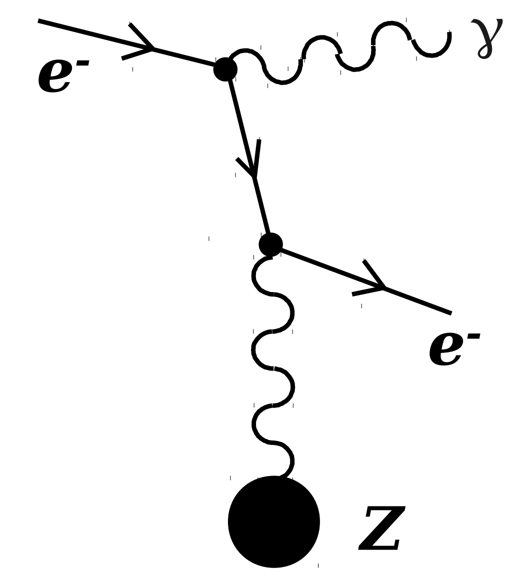
ALICE TPC – silicon ITS



Electron energy loss

- Electrons loose energy in their interaction with matter mainly through:
  - Ionization – modified Bethe-Bloch formula for identical particles
  - Bremsstrahlung - energy loss proportional to $1/m^2$
    - Dominant for electrons with $E_e > 10$ MeV (and for h.e. muons) leading to exponential attenuation of the electron energy

$$\left(\frac{dE}{dx}\right)_{Brem} = -\frac{E}{X_0} \qquad E(x) = E(0)\exp\left(-\frac{x}{X_0}\right)$$



- <dE/dx>$_{brem}$ increases linearly with the initial energy E
- After passing a layer of material of thickness $\mathbf{X_0}$ the electron has 1/e of its initial energy.

$$X_0 \cong \frac{716.4\ g\ \cdot cm^{-2}\ A}{Z(Z+1)ln\left(287/\sqrt{Z}\right)}$$

X_0=radiation length g/cm^2

Must multiply by density to get a length!

- To contain an electron need small X_0 high Z materials
- The Moliere radius is the transverse size of the electron shower:

$$R_M \cong \frac{21.2\ MeV}{E_c} X_0$$

Total Energy loss and Critical energy

Critical energy

$$\frac{dE}{dx}(E_c)\bigg|_{brems} = \frac{dE}{dx}(E_c)\bigg|_{ion}$$

$$\left(\frac{dE}{dx}\right)_{\text{Tot}} = \left(\frac{dE}{dx}\right)_{\text{Ion}} + \left(\frac{dE}{dx}\right)_{\text{Brems}}$$

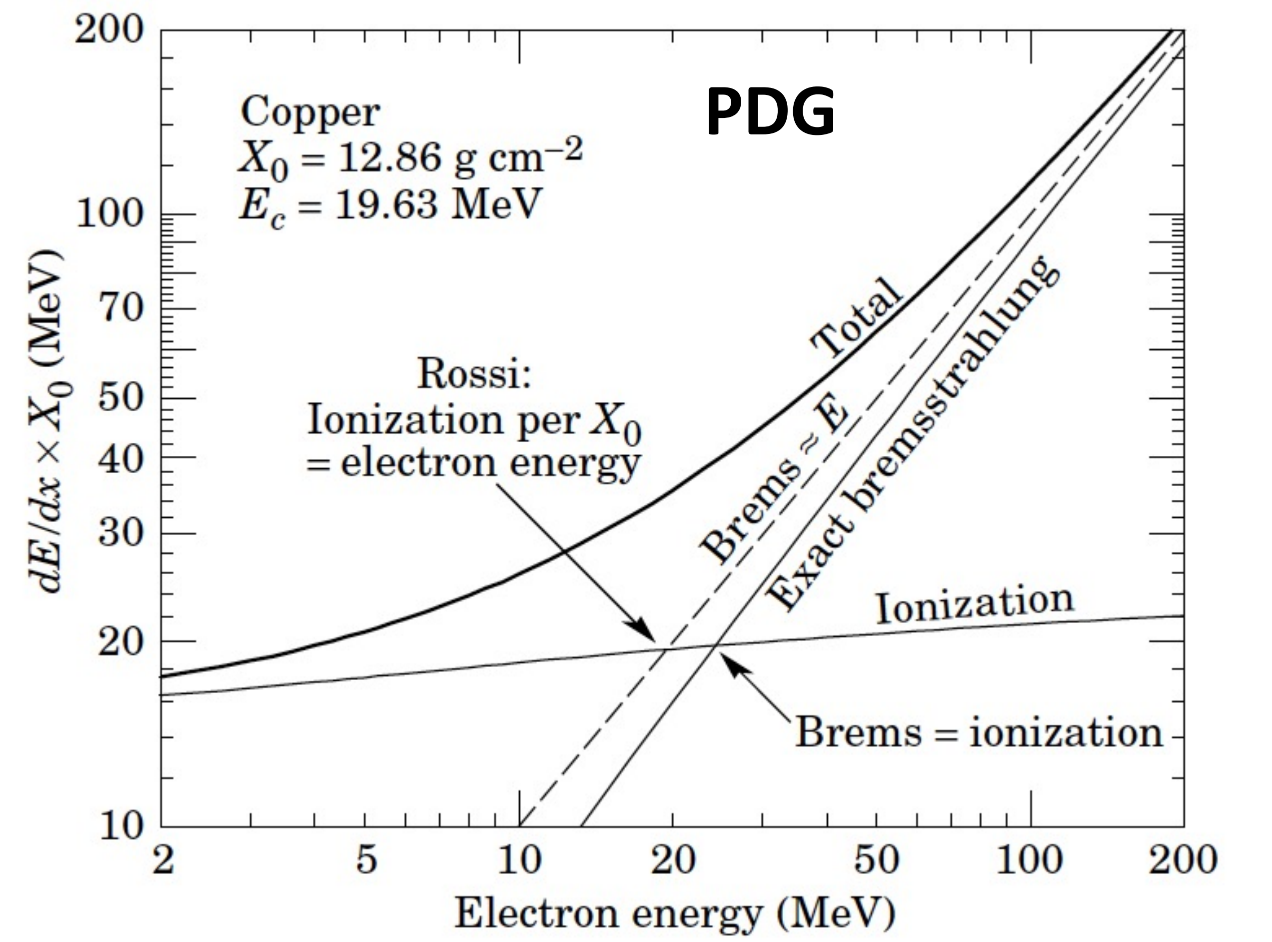
For solid and liquids

$$E_c = \frac{610\text{ MeV}}{Z+1.24}$$

For gasses

$$E_c = \frac{710\text{ MeV}}{Z+0.92}$$

Example Copper:
$E_c \approx 610/30$ MeV ≈ 20 MeV

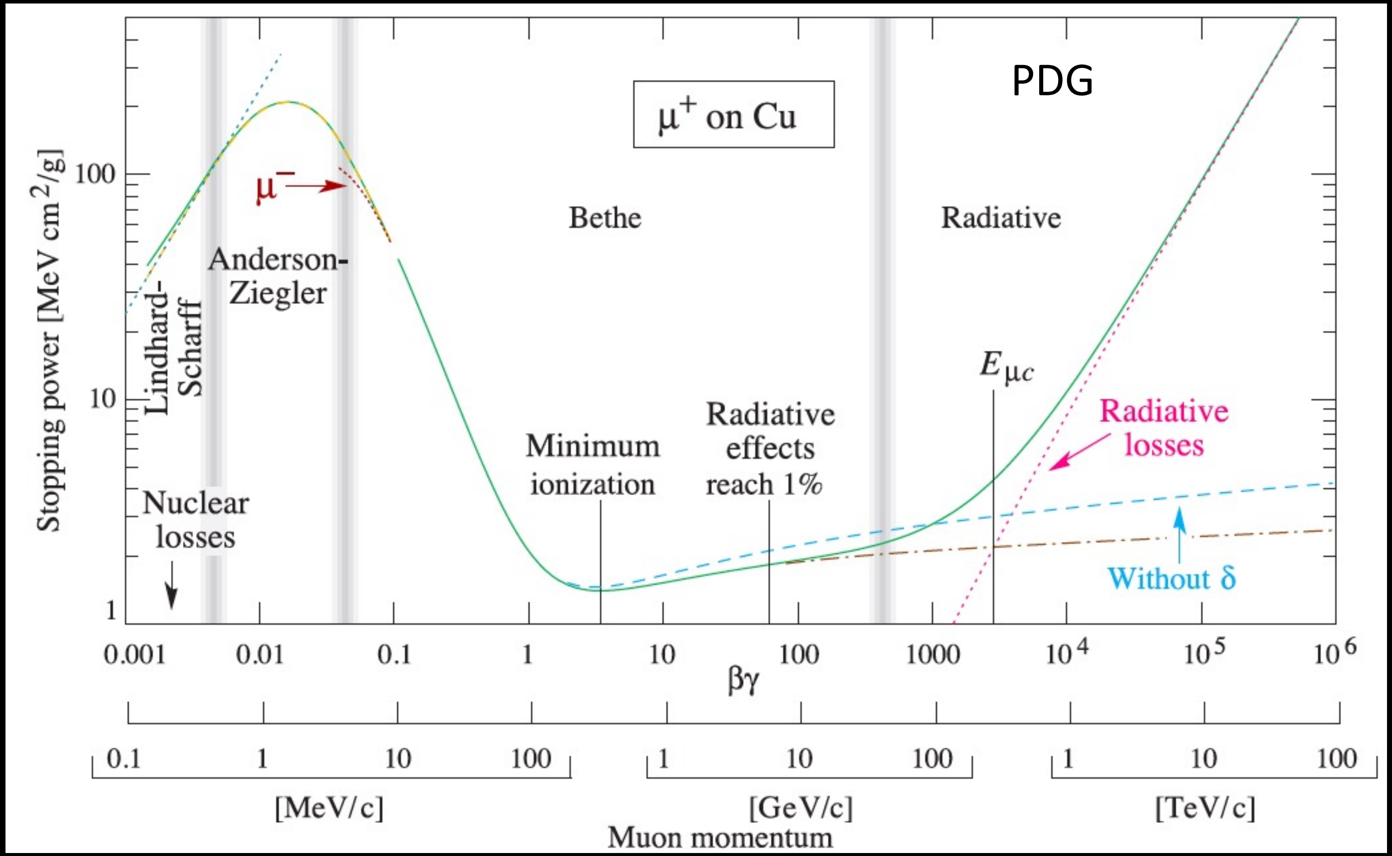


Muon Energy loss

The bremsstrahlung cross section is proportional to $1/m^2$

$$-\left\langle \frac{dE}{dx} \right\rangle_{brem} \propto \frac{E}{m^2}$$

Since $(m_\mu/m_e)^2 \approx 44100$ E_c for muons > 100s GeV.



- Critical energy for muons is 450 GeV in copper
- At high energies (E 1 TeV) bremsstrahlung contributes about 40% to average muon energy loss.
- Muons with energies > ~10 GeV can penetrate thick layers of matter
- This is the key signature for muon identification

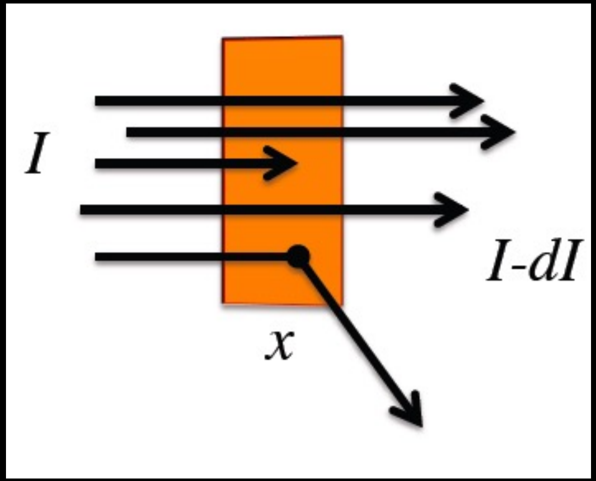
Interaction of photons with matter

- A photon can disappear or its energy can change dramatically at every interaction

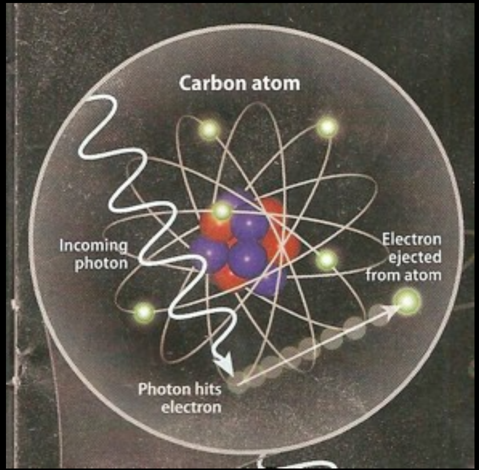
$$I(x) = I_0 e^{-\mu x} \qquad \mu = \frac{N_A}{A}\sum_{i=1}^{3}\sigma_i$$

$$\lambda = \frac{1}{\mu}$$

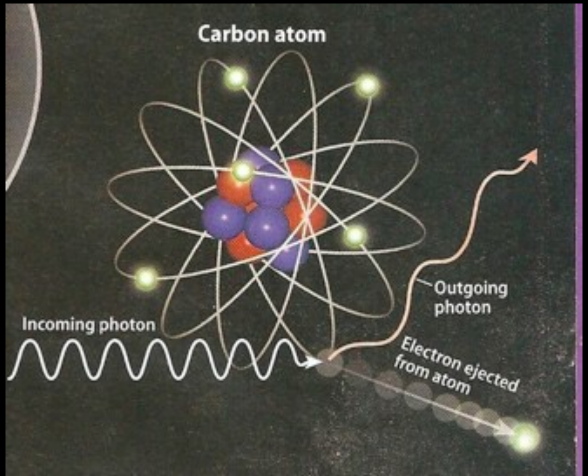
μ=total attenuation coefficient
σ_i=cross section for each process



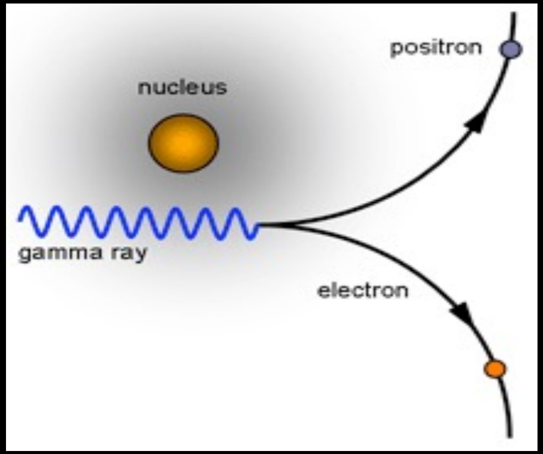
Photoelectric Effect



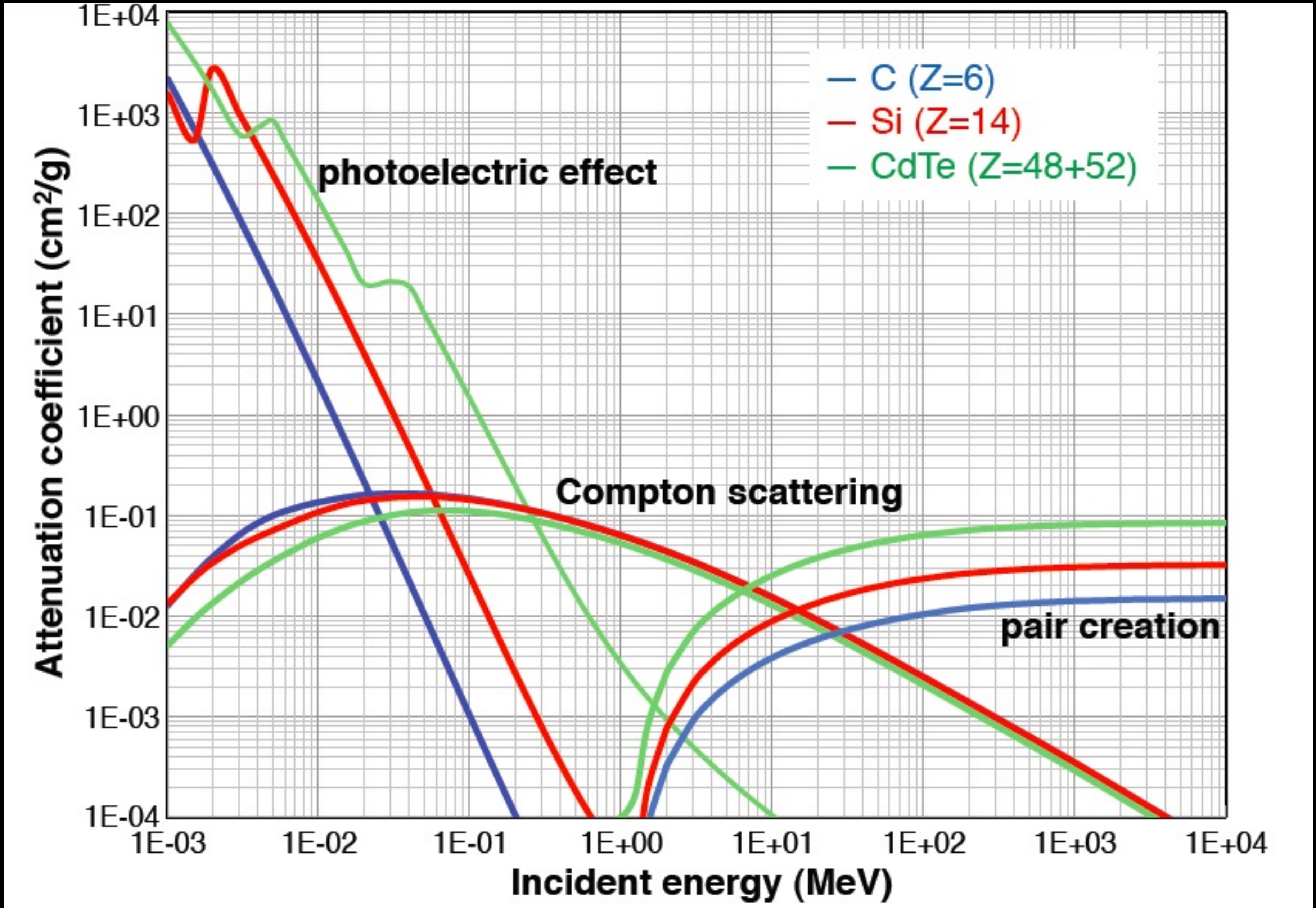
Compton Scattering



Pair production



Interaction of photons with matter



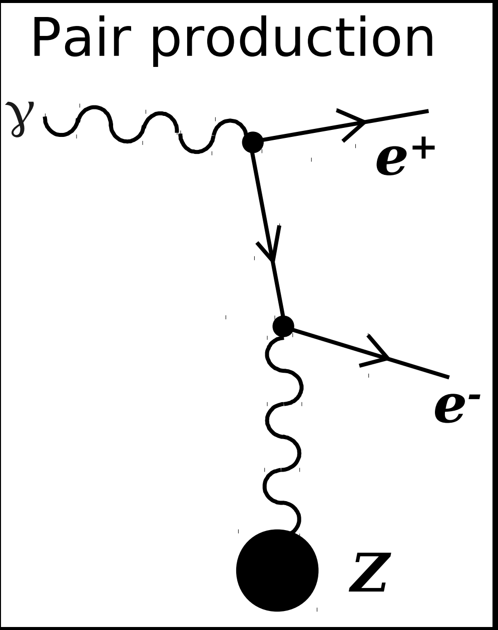
Pair production

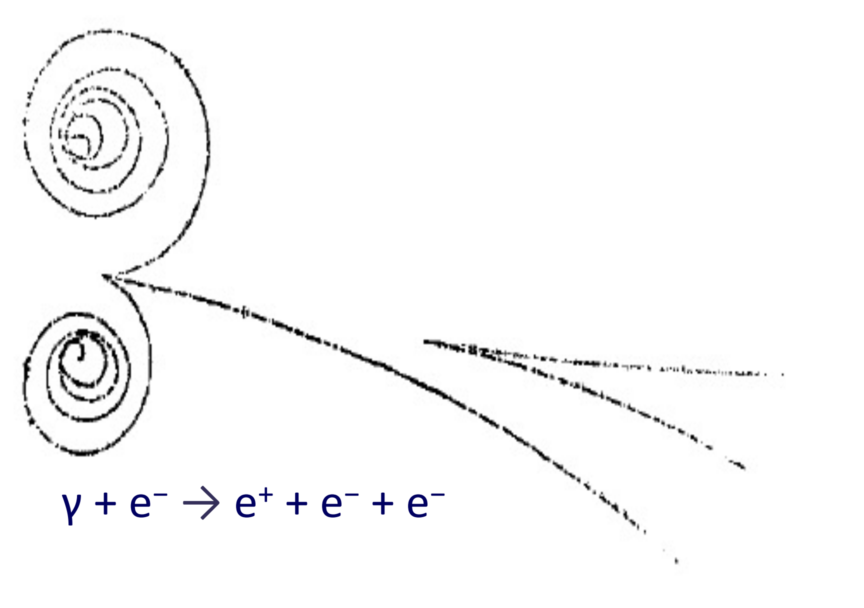
- Photons with E>100 MeV loose most of their energy in e^+e^- pair production
  - The threshold in the field of nuclei is $T=2m_ec^2$ =1.022 MeV
- The pair production cross section is:

$$\sigma_{pair} \sim \frac{7}{9}\frac{A}{N_A}\frac{1}{X_0}$$

Where A is the mass number of the target and N_A Avogadro Number

- The radiation length X_0 is also 7⁄9 of the mean free path for pair production by a high-energy photon



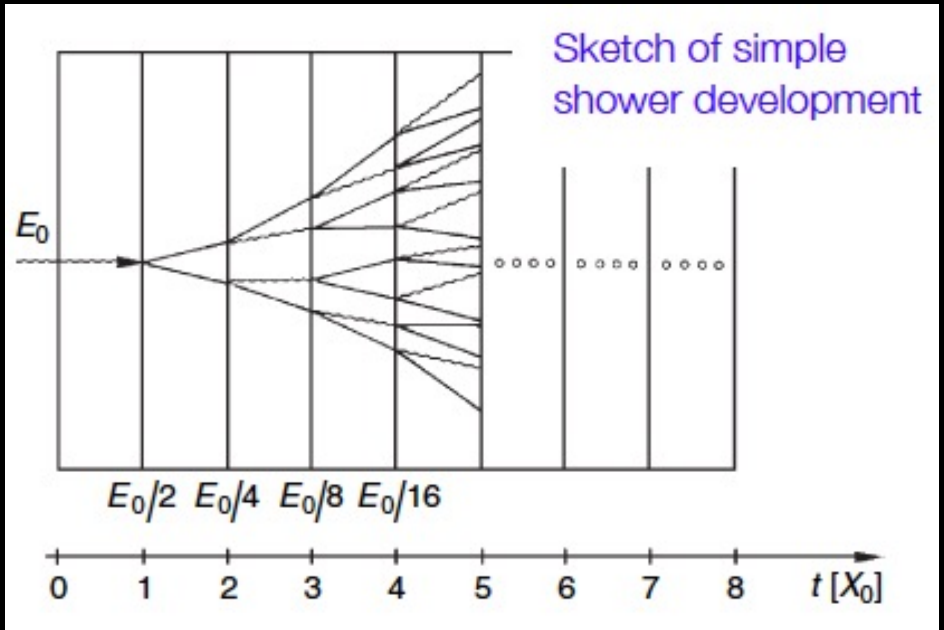


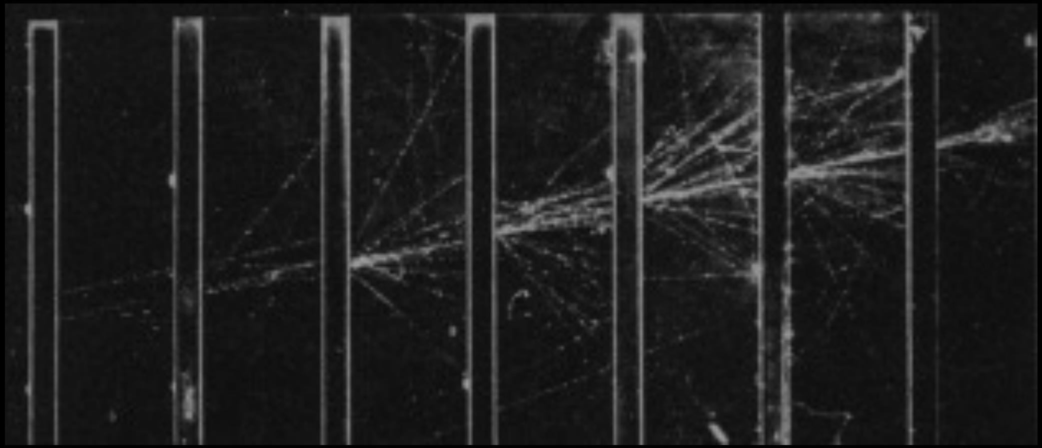
γ + e⁻ → e⁺ + e⁻ + e⁻

EM showers and X_0

- Simplified model [Heitler]: shower development governed by X_0
  - e^- loses [1 - 1/e] = 63% of energy in 1 X_0 (Brems.)
  - A γ will convert into a e^+e^- (pair prod.) with a probability P = 1 - exp(-7/9)=0.54
- Assume e≈2 and that for $E > E_c$ no energy loss by ionization/excitation
- Simple shower model:
  - $N(t)=2^t$ particles after $t = x/X_0$ each with energy $E(t)=E_0/2^t$
  - Stops if E (t) < $\mathbf{E_c=E_0 2^{tmax}}$
  - Location of shower maximum at

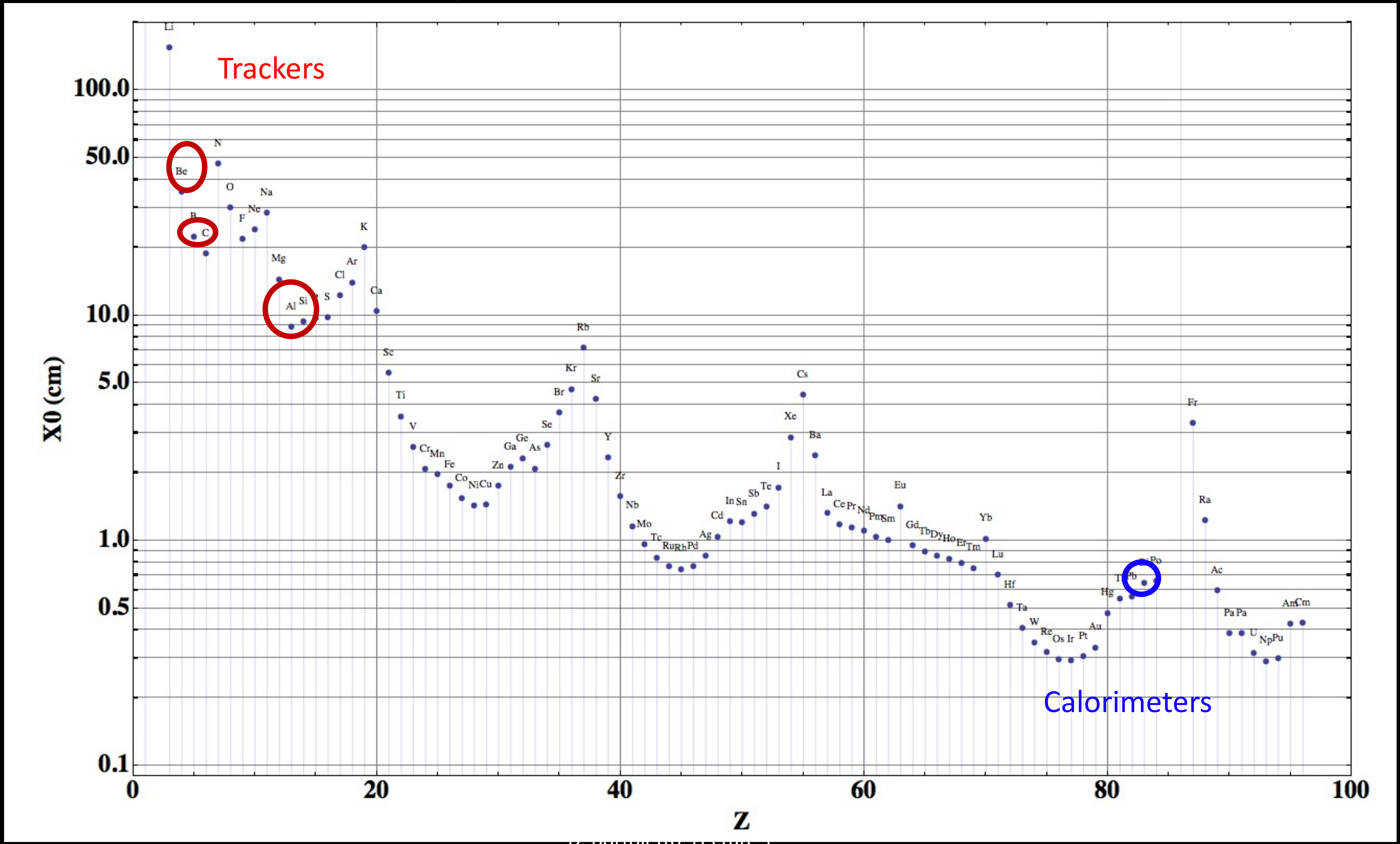
$$t_{max}=\frac{\ln(E_0/E_C)}{\ln 2} \propto \ln\left(\frac{E_0}{E_C}\right)$$



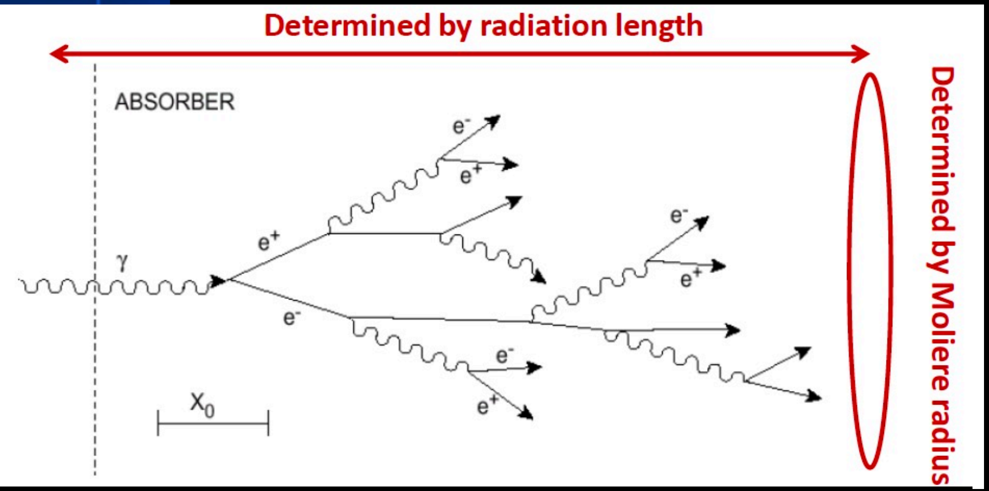


$$N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_C}$$

Radiation length of different elements

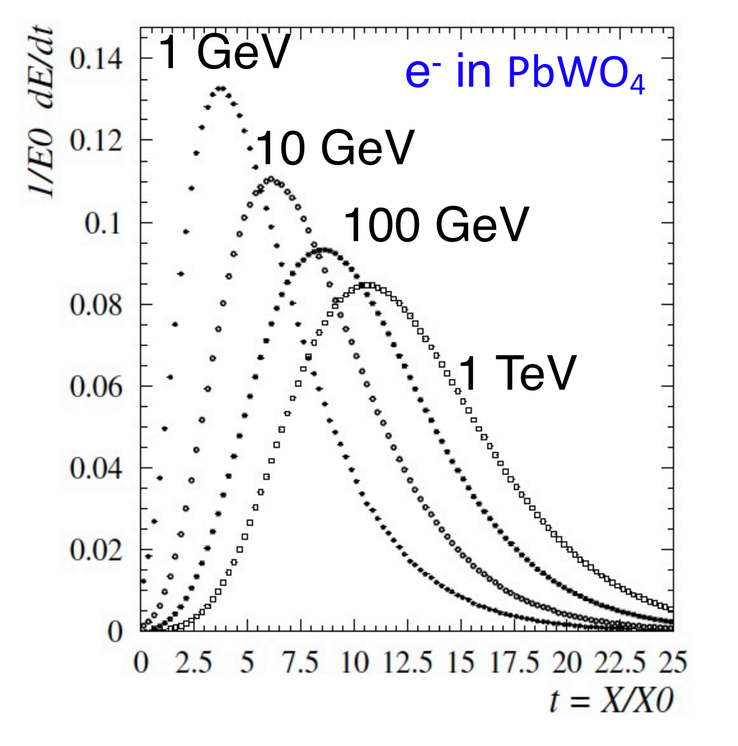


EM Shower development

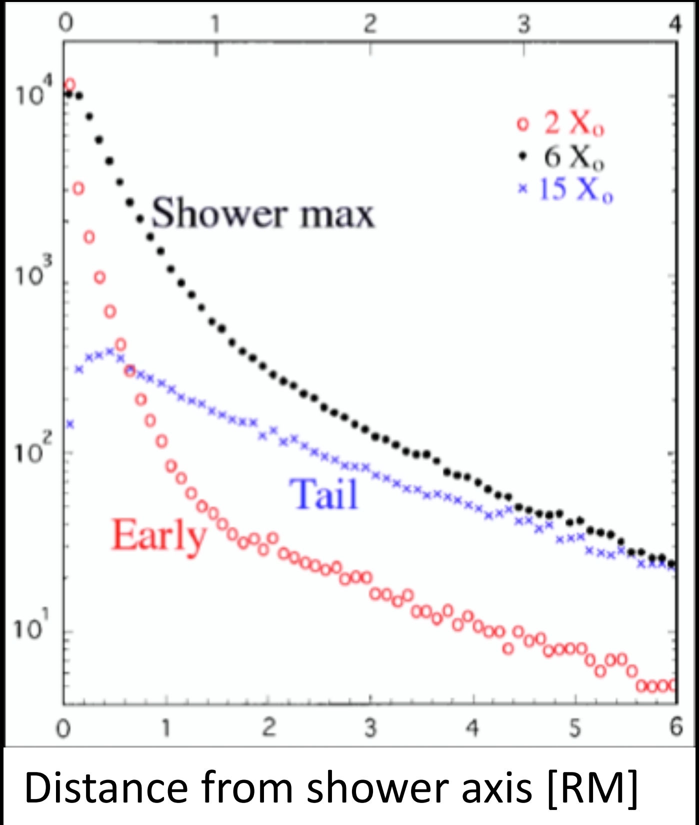


- Size of calorimeter driven by X_0
- Cell size related to R_M and chosen such that 70-80% of energy of a particle is deposited in the cell
- Granularity: size of detector elements in transverse and longitudinal direction. Determines the ability to resolve two showers induced by nearby particles

Longitudinal development



Transverse development for 10 GeV electron showers in Cu



95% of energy within:

$L(95\%) = t_{max} + 0.08\,Z + 9.6\,X_0$

90% of energy: R_M

Beyond shower max broadening due to low energy γ

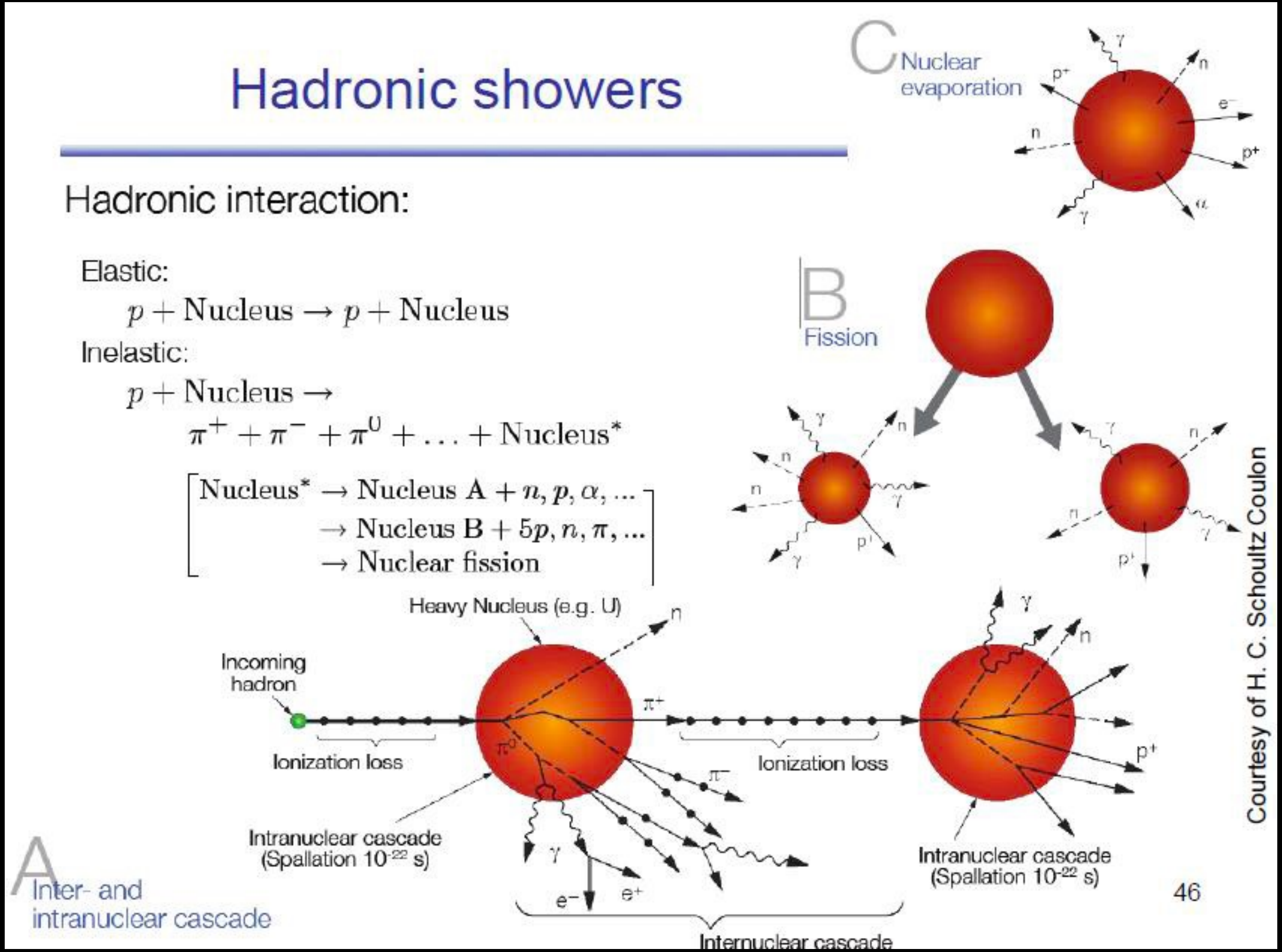
$X_0 = \frac{180A}{Z^2}\,(g\,cm^{-2})$ and $t_{max} = \ln\frac{E}{E_c} - 1$

(for e induced showers)

$$R_M = \frac{21\,MeV}{E_c}X_0$$

Hadron interactions with matter

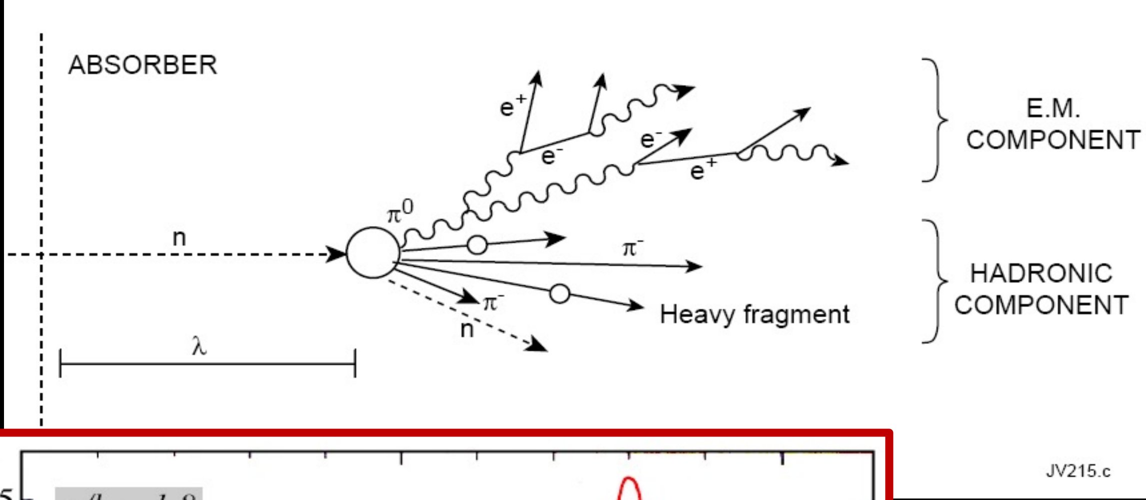
- Many processes involved:
  - –Ionization,
  - –hadron production (fragmentation, …
  - –Charge exchange $\pi^{+/-}$n→ π^0p/pbar
  - –nuclear de-excitation,
  - –nuclear breakup,
  - –spallation neutrons,
  - –muon and pion decay+
  - –……

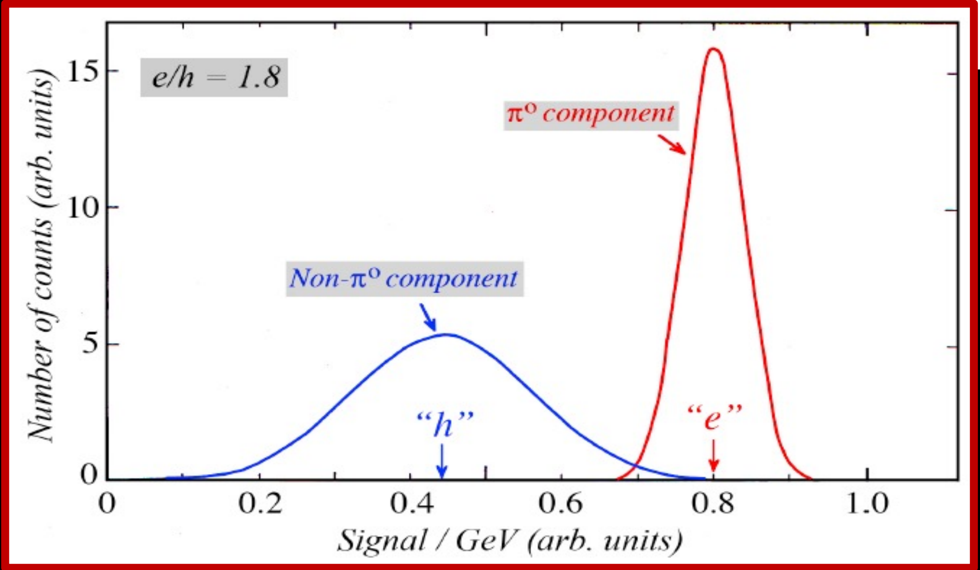


Hadronic Showers

- **Electromagnetic component:**
  - Electrons, photons (from excitation, radiation, decay of hadrons, photo-effect, …)
  - Neutral pions (eg,$\pi^0 \to \gamma\gamma, \eta \to \gamma\gamma$)

- **Hadronic component:**
  - Charged hadrons $\pi^{\pm}$, $K^{\pm}$,…:ionization, excitation, nuclei interaction (spallation p/n production, evaporation n, spallation products)
  - Neutrons: Elastic collisions, thermalization + capture (=>γ's)
  - Break-up of nuclei





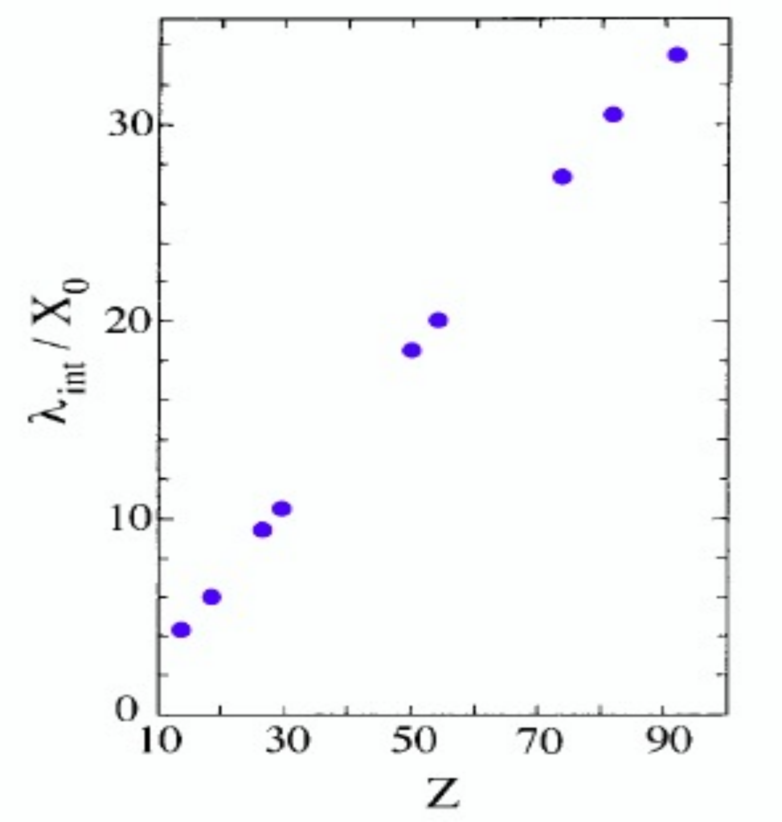
Part of the energy is lost in breaking nuclei (nuclear binding energy)

- Large **non-Gaussian** fluctuations of each component (EM vs non-EM)
- Large, **non-Gaussian** fluctuations in "invisible" energy losses

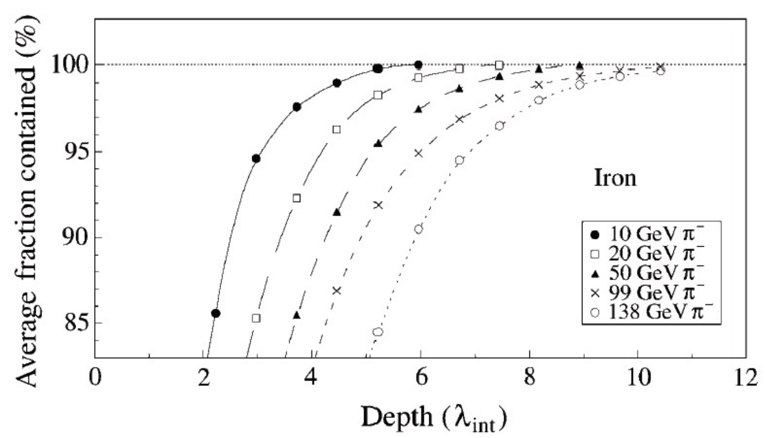
Nuclear Interaction Length

- Hadronic showers are governed by the interaction length λ_{int}: the mean free path between inelastic interaction

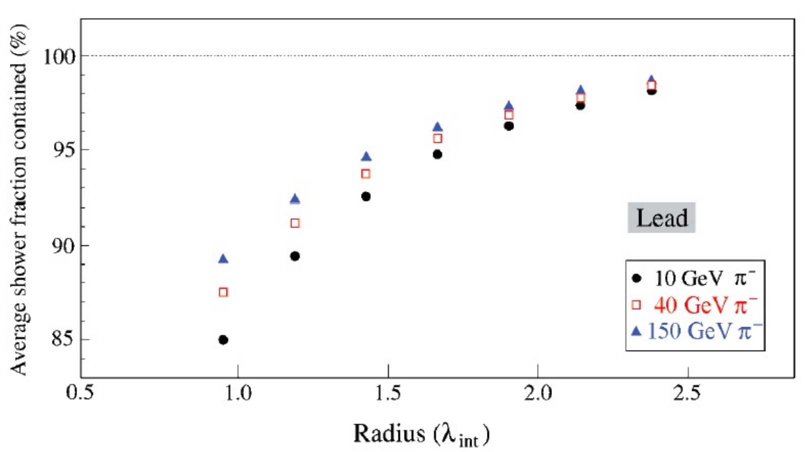
$$\lambda_{int} \approx \frac{35\ cm}{\rho} A^{1/3}$$



- Longitudinal: Need about **~10** λ_{int} to contain most of the hadronic showers



- Transverse : Need about **~1.5** λ_{int} to contain most of the hadronic showers



Nuclear Interaction length

- To contain an hadronic, you need small λ_{int}
- λ_{int} (Fe)=17 cm

	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

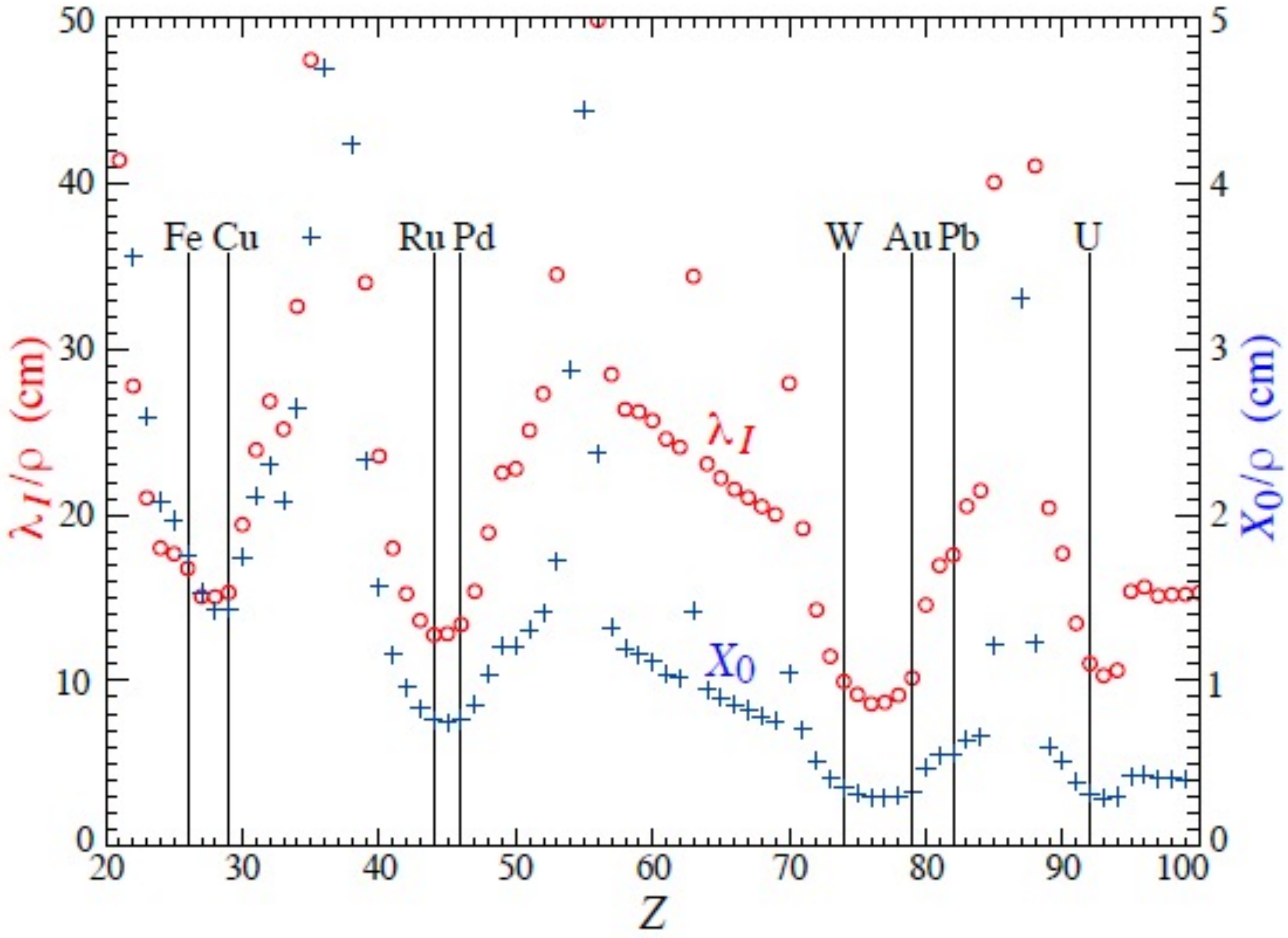
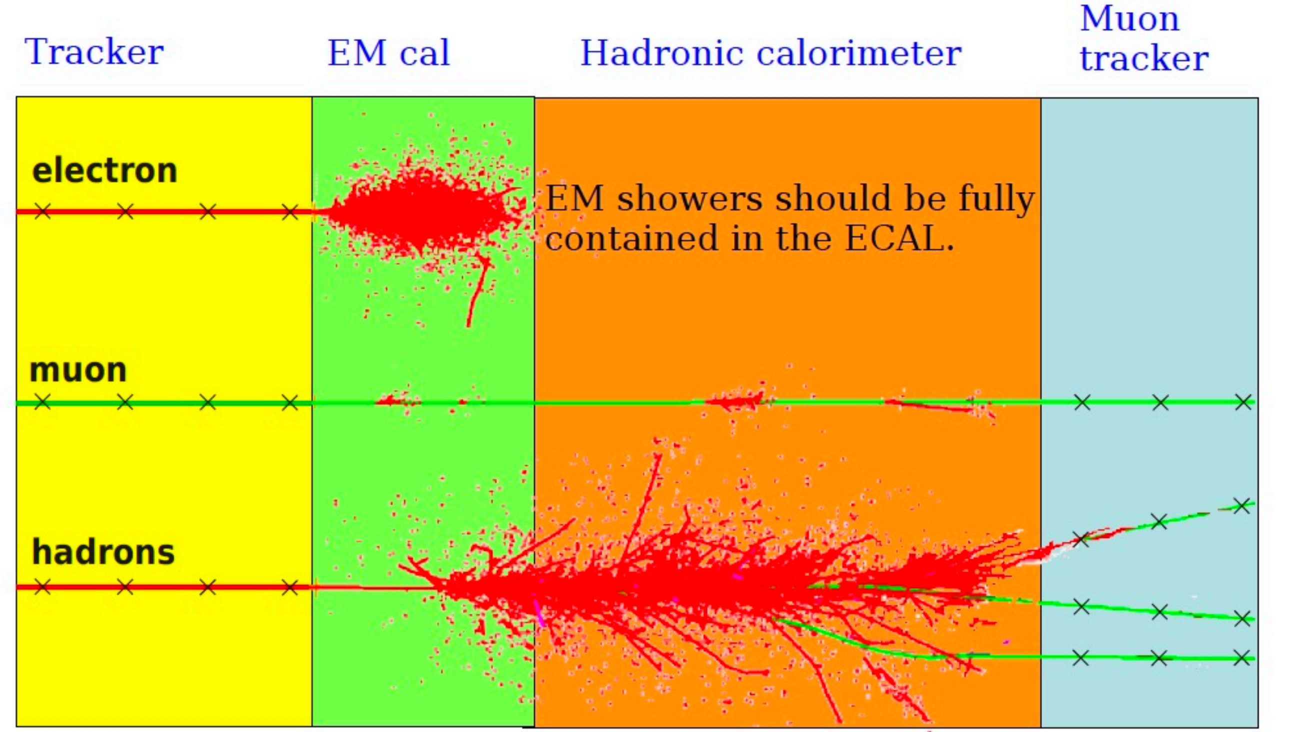


Figure 34.21: Nuclear interaction length λ_I/ρ (circles) and radiation length X_0/ρ (+'s) in cm for the chemical elements with $Z > 20$ and $\lambda_I < 50$ cm.

Calorimetry

- Calorimetry refers to the detection of particles through total absorption in a block of matter
  - The measurement process is destructive for almost all particle
  - The exception are muons (and neutrinos) → identify muons easily since they penetrate a substantial amount of matter
- Calorimeters are essential to measure neutral particles



Hadronic showers may already start in the ECAL and extend into the HCAL.

- Homogenous calorimeters: whole volume filled by high-density material (BGO, Lead glass, noble gases …)
  - Exclusively used for EM part
  - Best resolution
  - Expensive

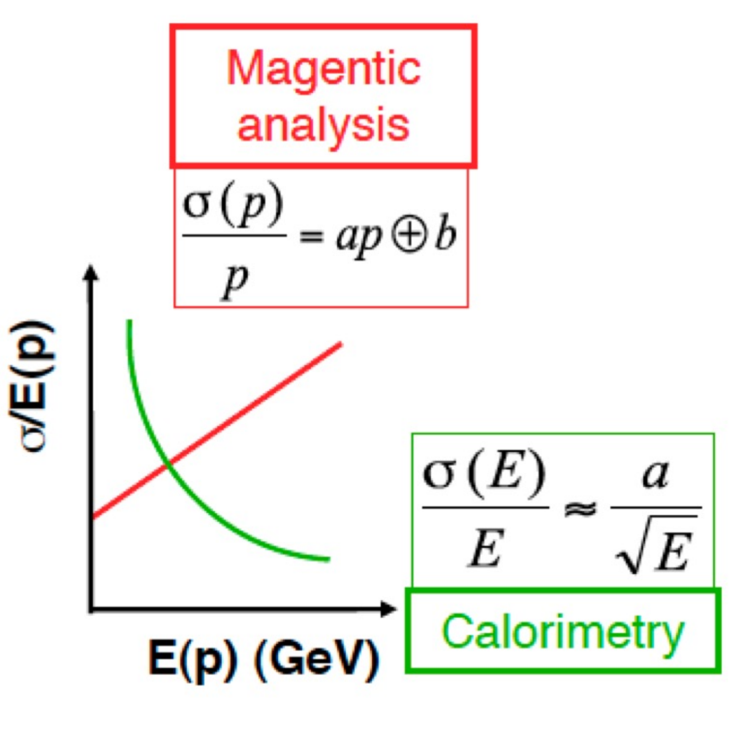
- Sampling calorimeters: alternating layers of "absorbers" and active materials
  - Absorbers: Iron, Cupper, Lead….
  - Active: Plastic scintillators, silicon detectors, gas detectors…

Energy resolution

- Calorimeters are the ideal instrument to measure the full energy of particles, particularly at high momentum

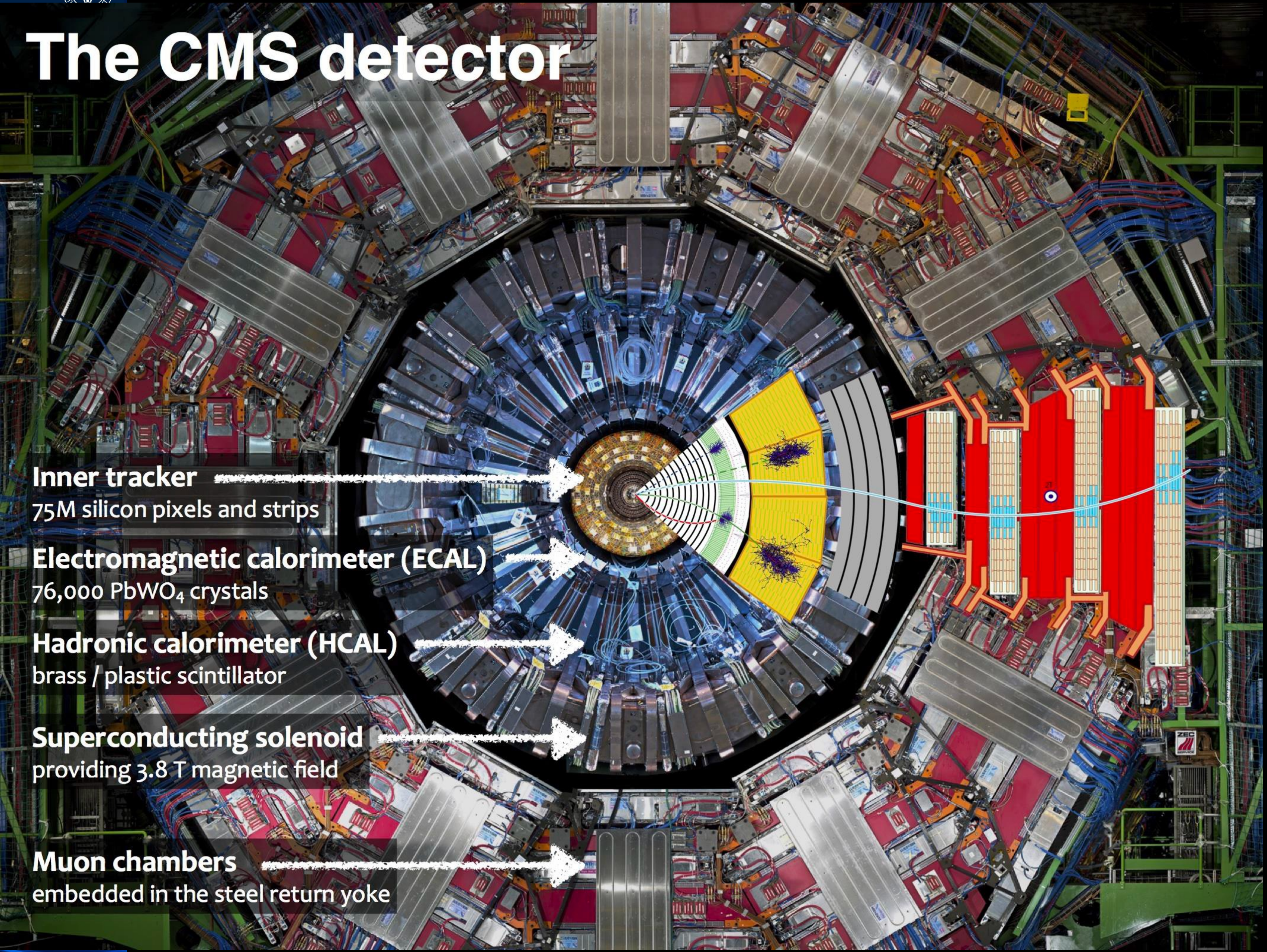
$$E \propto N \qquad \sigma_E \approx \sqrt{N} \approx \sqrt{E}$$

$$\sigma_E = a\sqrt{E} \oplus bE \oplus c \qquad \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$



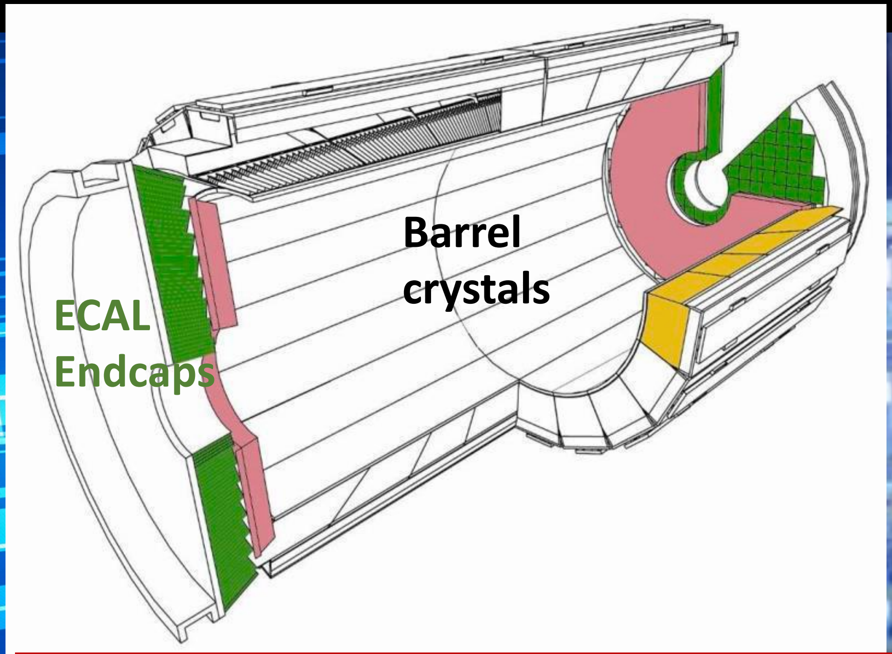
- a: stochastic term
  - intrinsic statistical shower fluctuations
  - sampling fluctuations
  - signal quantum fluctuations (e.g. photo-electron statistics)
- c: noise term
  - readout electronic noise
  - Radio-activity, pile-up fluctuations
- b: constant term
  - inhomogeneities (hardware or calibration)
  - imperfections in calorimeter construction (dimensional variations, etc.)
  - non-linearity of readout electronics
  - fluctuations in longitudinal energy containment (leakage can also be ~ E-1/4)
  - fluctuations in energy lost in dead material before or within the calorimeter

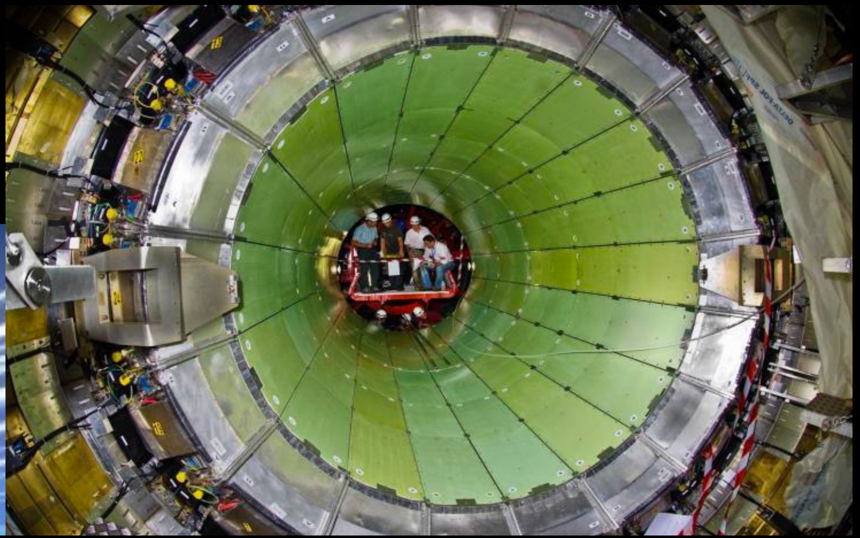
The CMS detector



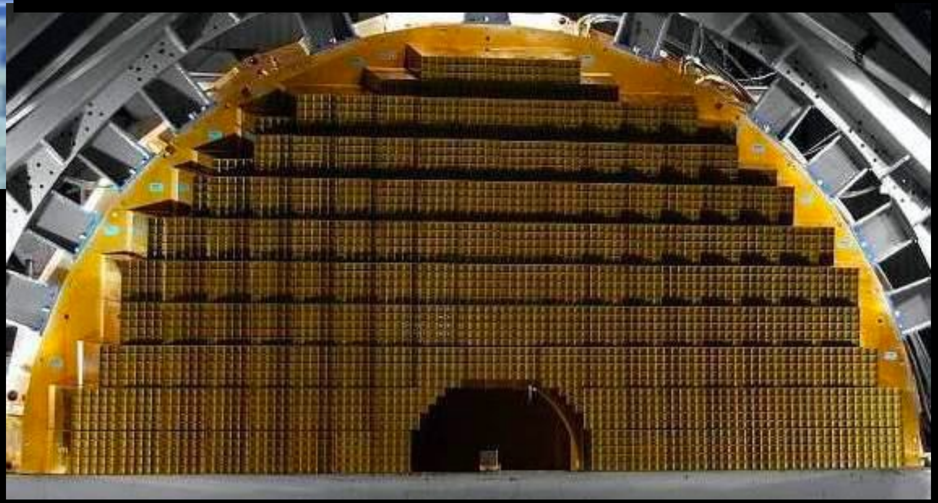
CMS ECAL

Homogeneous Ecal, $PbWO_4$ crystals 23 (22) cm long in Barrel (endcap)





- Barrel ($|\eta|<1.48$), ~ 67 t
- 61200 crystals in 36 super-modules

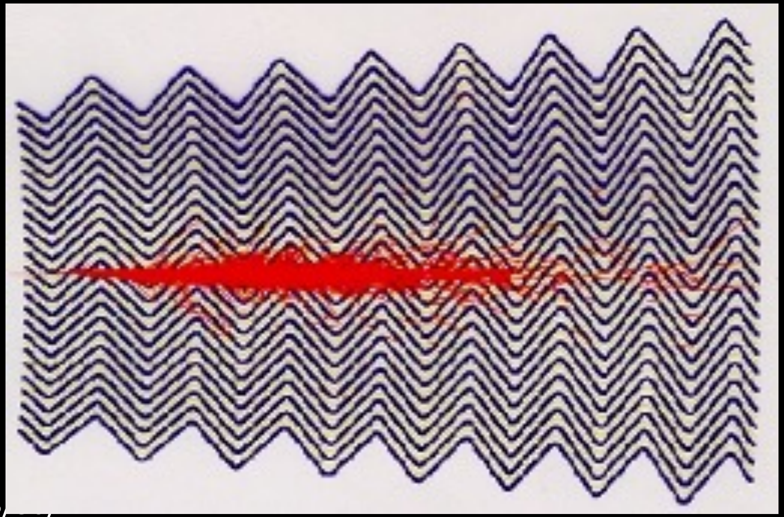


- Excellent energy resolution
  - $X_0 = 0.89\ cm \Rightarrow$ compact calorimeter
  - $R_M = 22\ cm \Rightarrow$ compact shower development
- Fast light emission
- Radiation hard (10^5 Gy)
- But low light yield ($150\ \gamma/\mathrm{MeV}$) and response depends on Temperature and dose

- Endcap I ($1.48 < |\eta|<3$), ~ 23 t
- 14648 crystals over 4 Dees (2 per endcap)

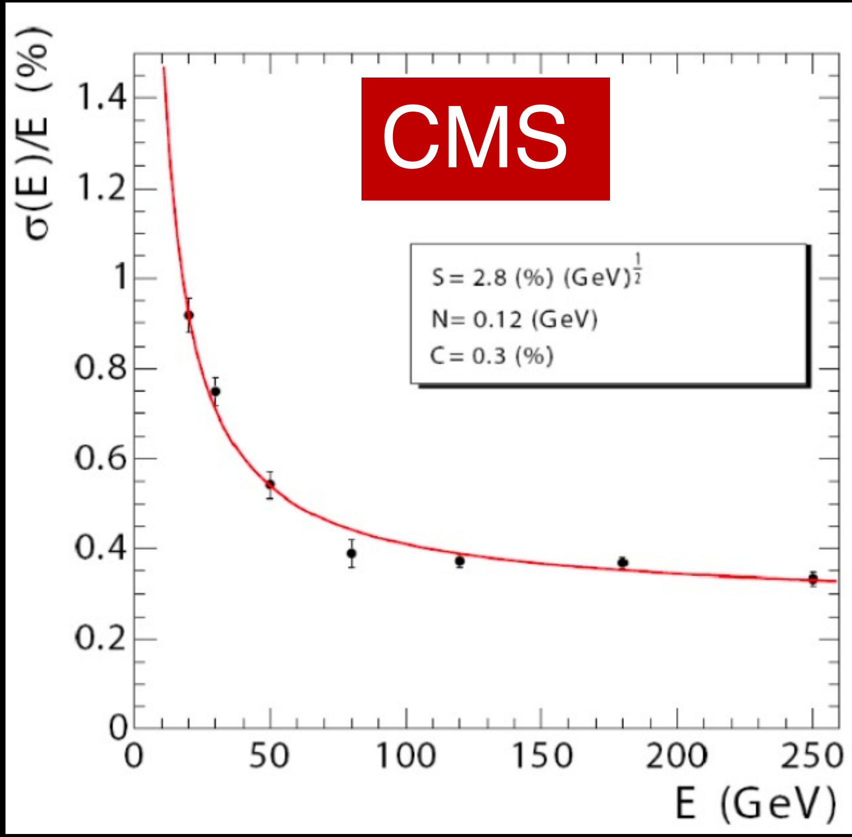
ATLAS ECAL

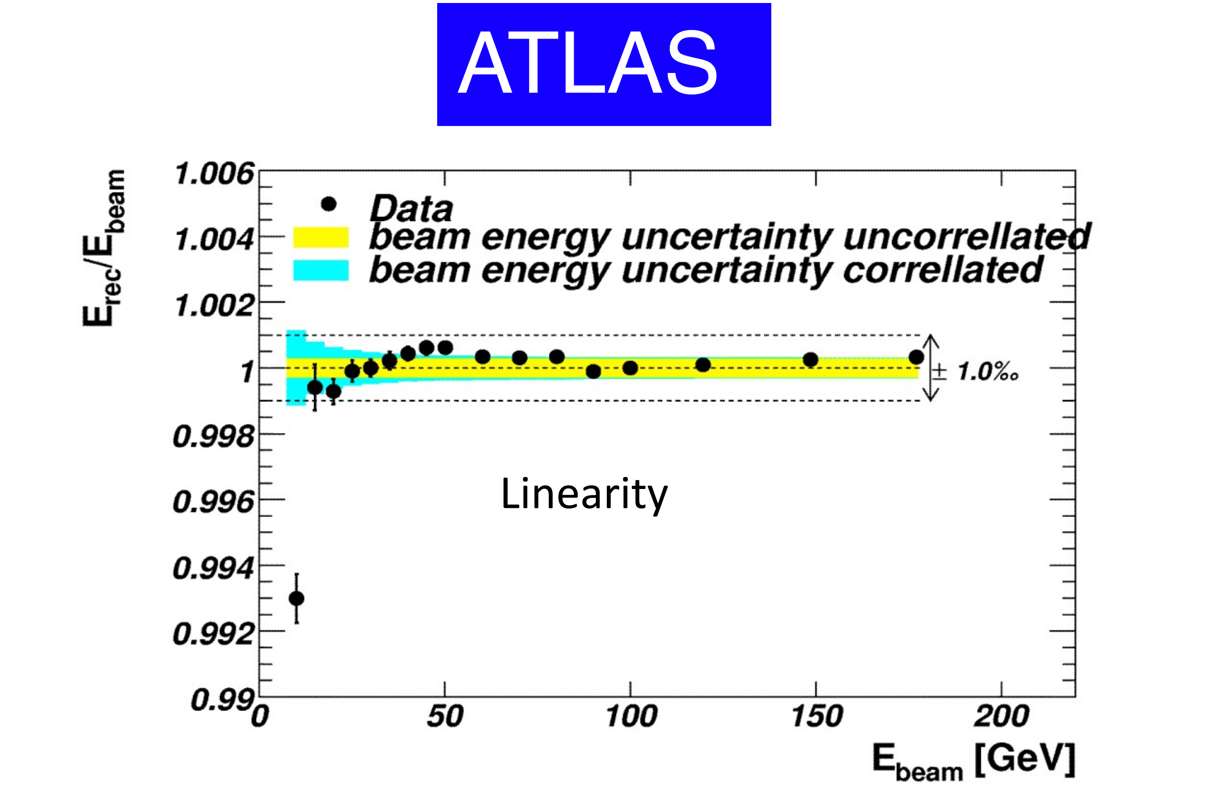
- Sampling Pb/LAr calorimeter with "accordion" geometry
- Longitudinal depth ~ 25 X_0, 47 cm (vs 22 cm for CMS)
- 3 layers up to $|\eta|=2.5$
- 2 layers $2.5<|\eta|<2.$
- Usage of Liquid Argon
  - Radiation Hard
  - High number of electron-ion pair produced by ionization (1 GeV deposit → $5x10^6$ e-)
  - Stable vs time but needs cryostat (90K)



CMS and ATLAS calorimeter performance

- Standalone performance in test beams



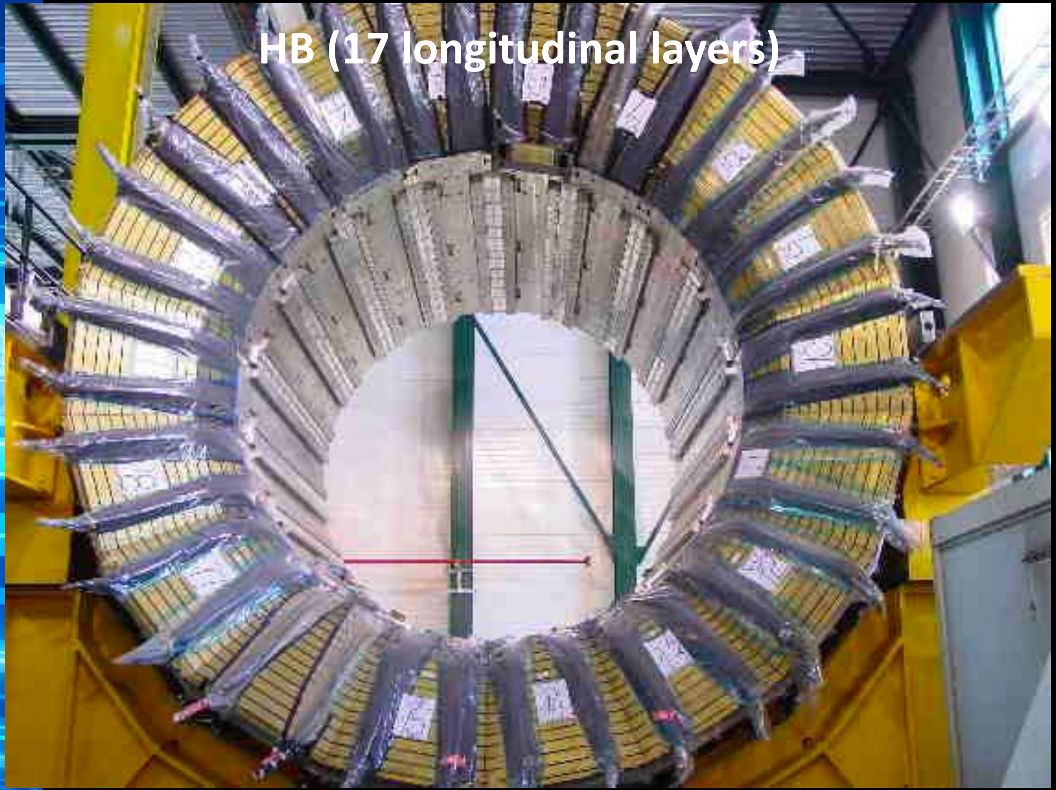


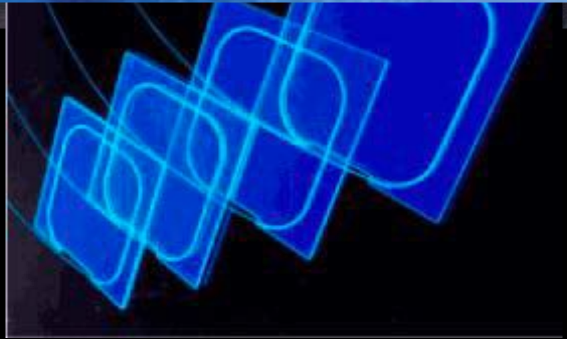
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

$$\frac{\sigma}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.3}{E} \oplus 0.7\%$$

CMS HCAL

- HB/HE: Sampling Brass/plastic scintillator calorimeter

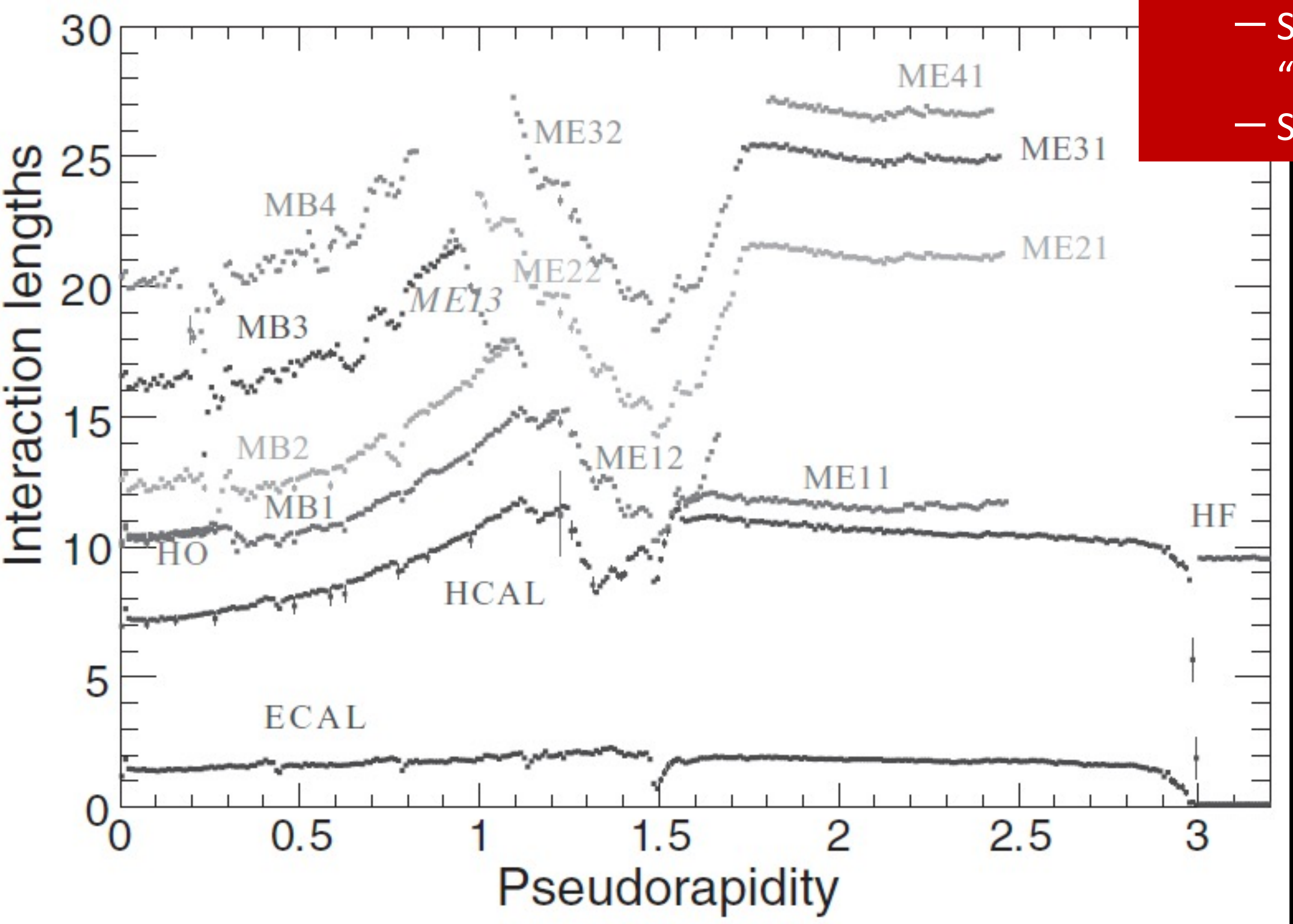


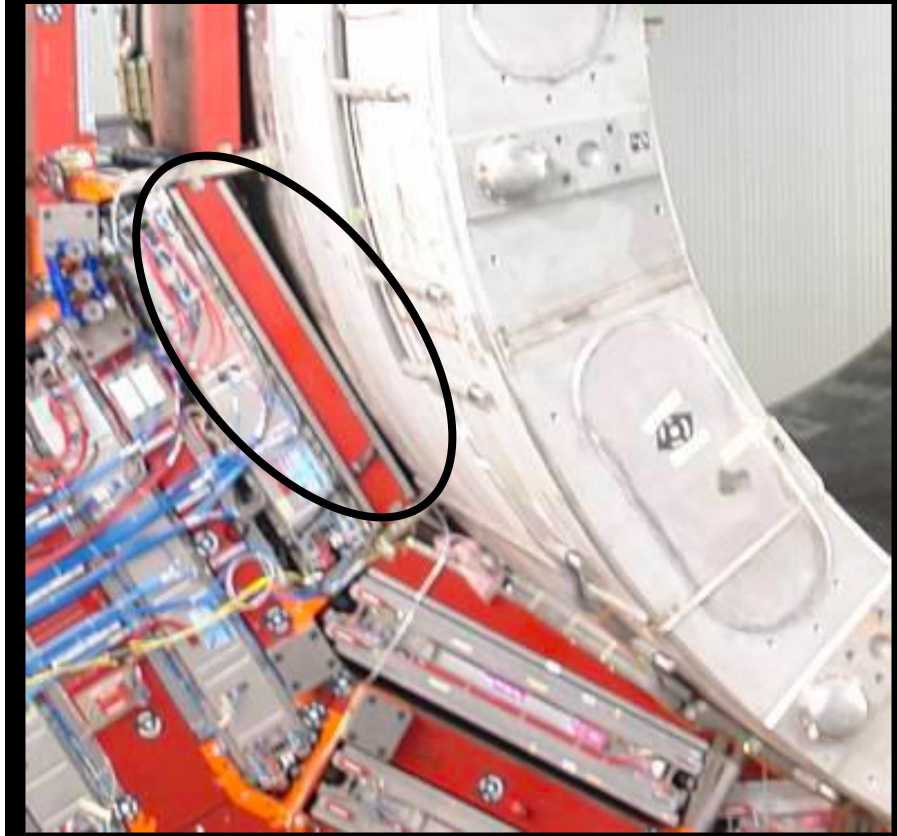


Segmentation: $\Delta\eta$x $\Delta\phi$ =0.087x0.087 (larger at high η)
8x20° "wedges" with alternate brass plates (5-8 cm) and "tiles" embedded with Wave Length Shifter (WLS).
Light from scintillator: blue-violet → WLS: absorb light then fluorescence in green → Green light read by Hybrid Photo Diode (HPD)

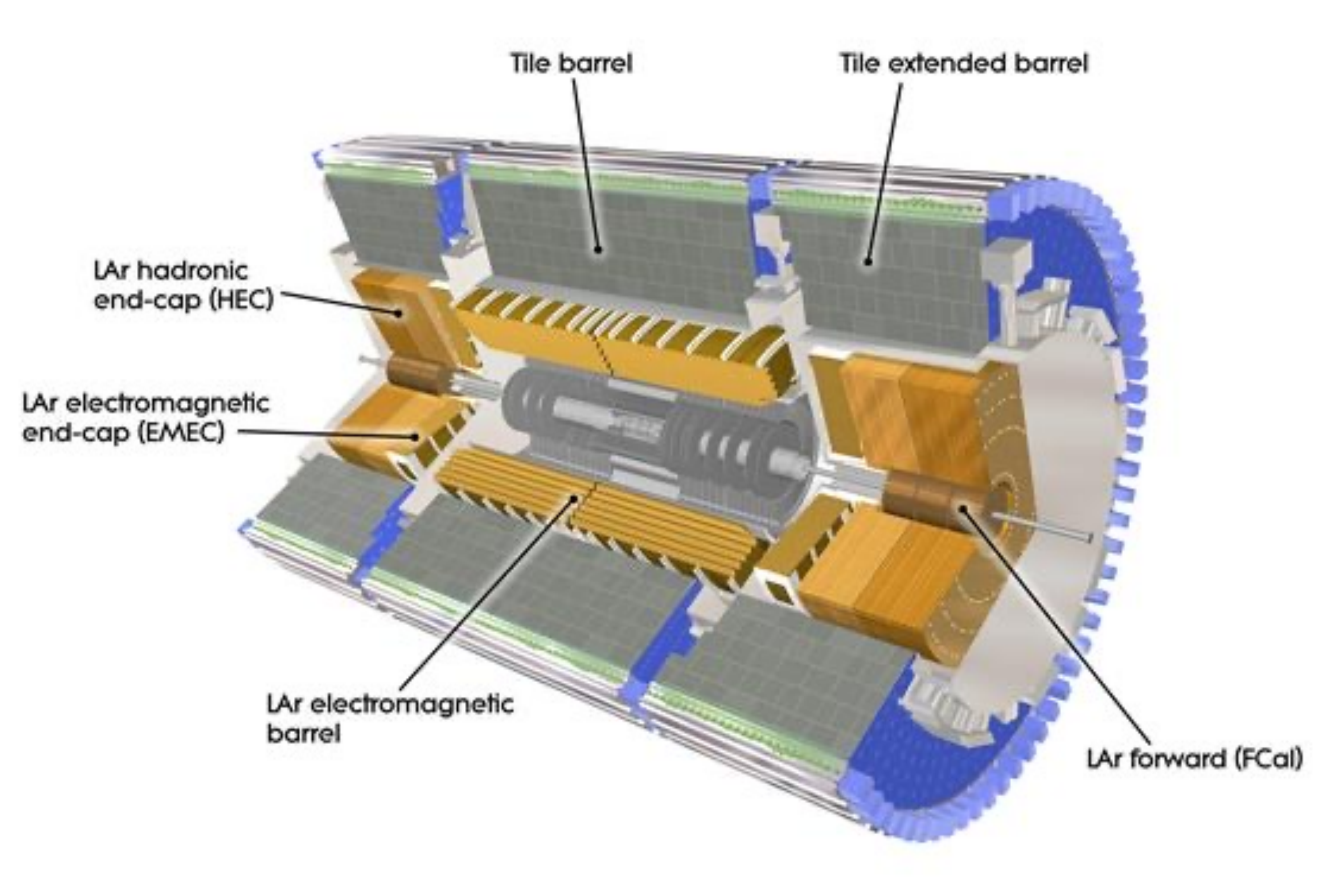
CMS HCAL

- At $|\eta|=0$, λ_{int} from HB =5.8 (7.2 with ECAL) → Large leakage…
- CMS adds HCAL Outer (HO):
  - Scintillator + WLS outside coil acting as "tail catcher"
  - Standalone resolution 100%/sqrt(E)





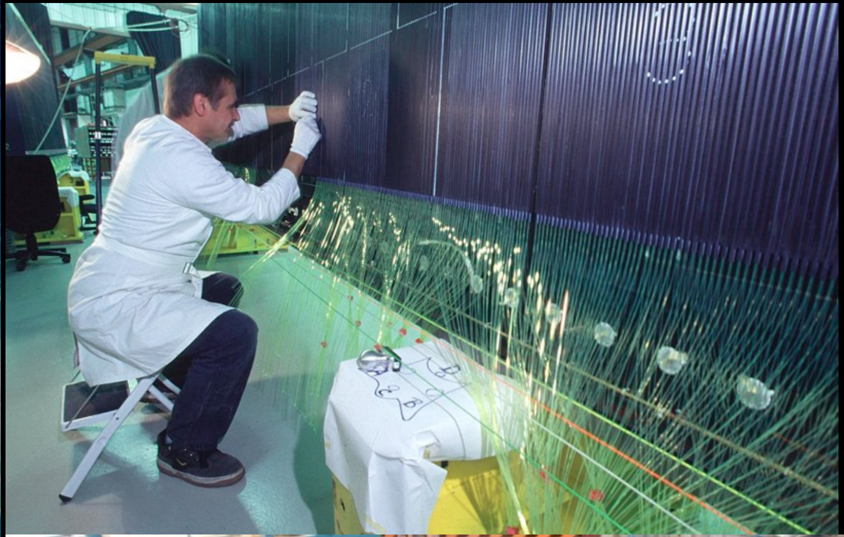
ATLAS HCAL

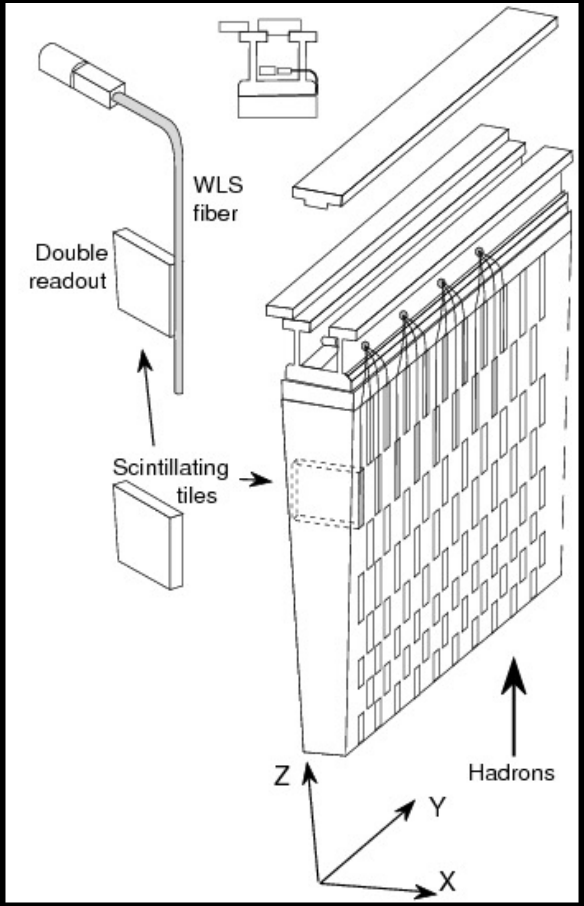


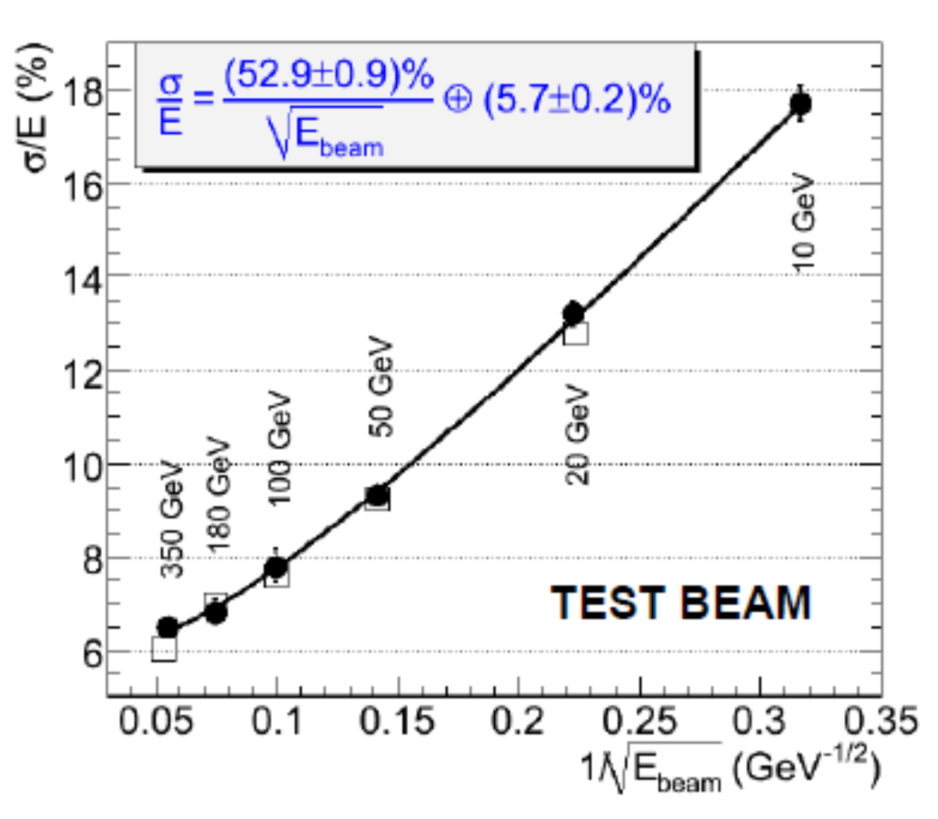
- Different technologies depending on the dose
- Total thickness about 8-10 λ_{int}
- $|\eta|< 1.7$ - Tile calorimeter Iron and scintillator
- $1.7<|\eta|< 3.2$ LAr/Cu
- $3.2<|\eta|< 4.9$ Forward calorimeter LAr/Cu or W

ATLAS Tile calorimeter

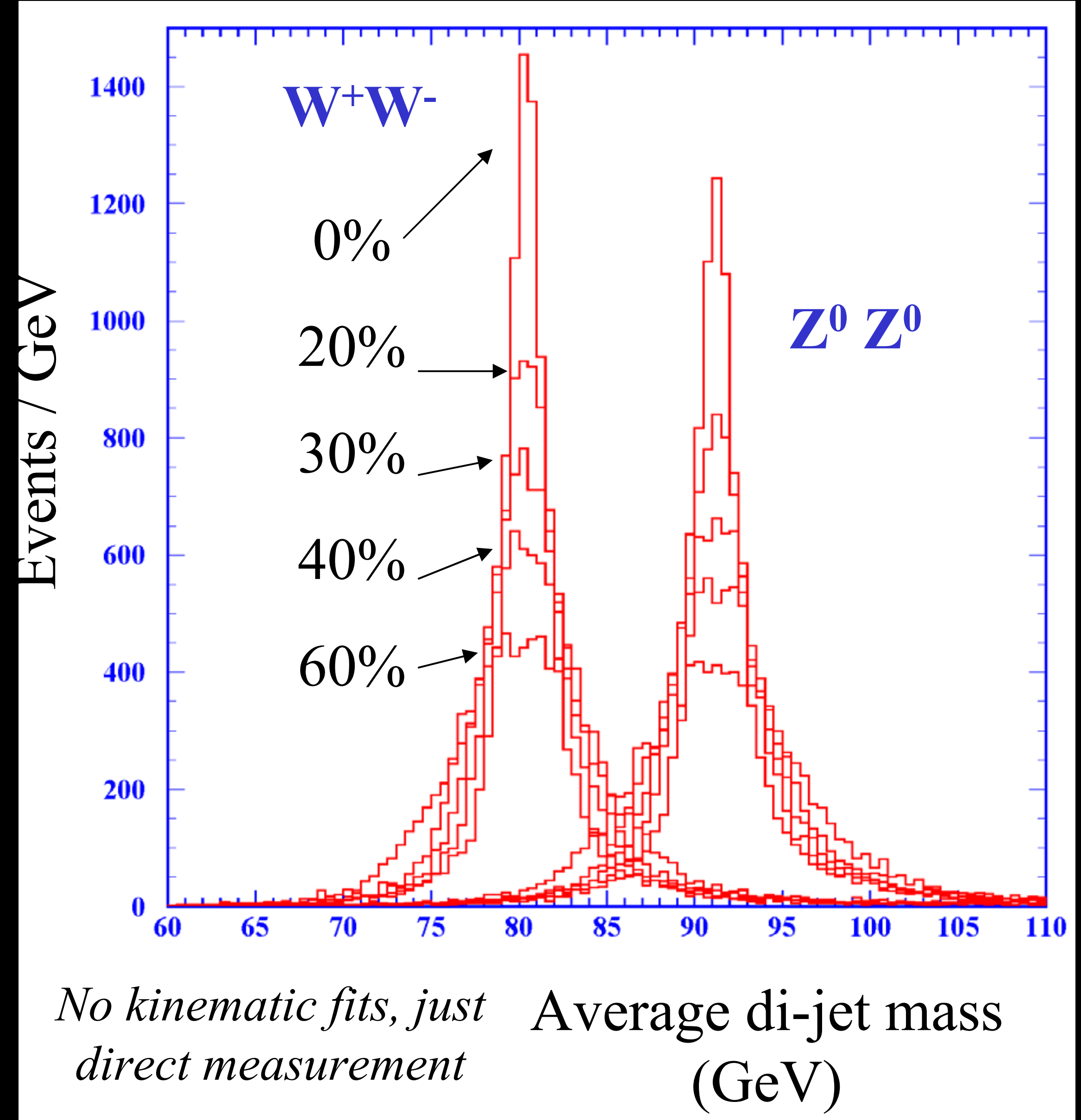
- steel/scintillator, scintillating fibers, readout by photomultiplier







Impact of calorimeter resolution



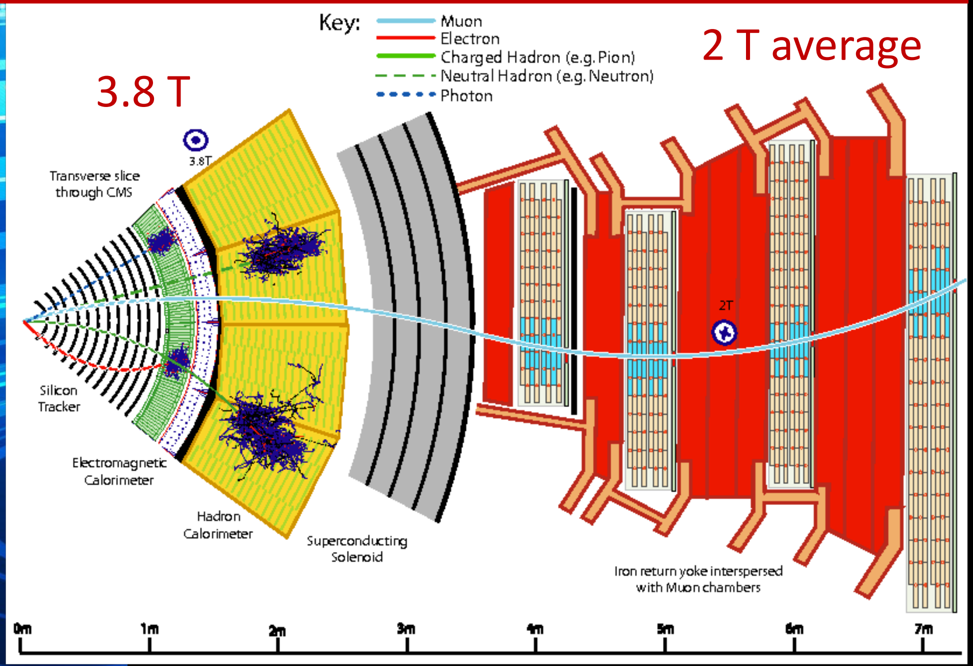
No kinematic fits, just direct measurement

- Comparing $e^+e^- \to WW$ and $e^+e^- \to ZZ$ at $\sqrt{s}$=300 GeV (hadronic decays only, assume WW:ZZ = 1:1 for illustration)
- *Reality = 7:1 !*
- 30%$\sqrt{E_{jet}}$ is a good target. Physics may demand even more !

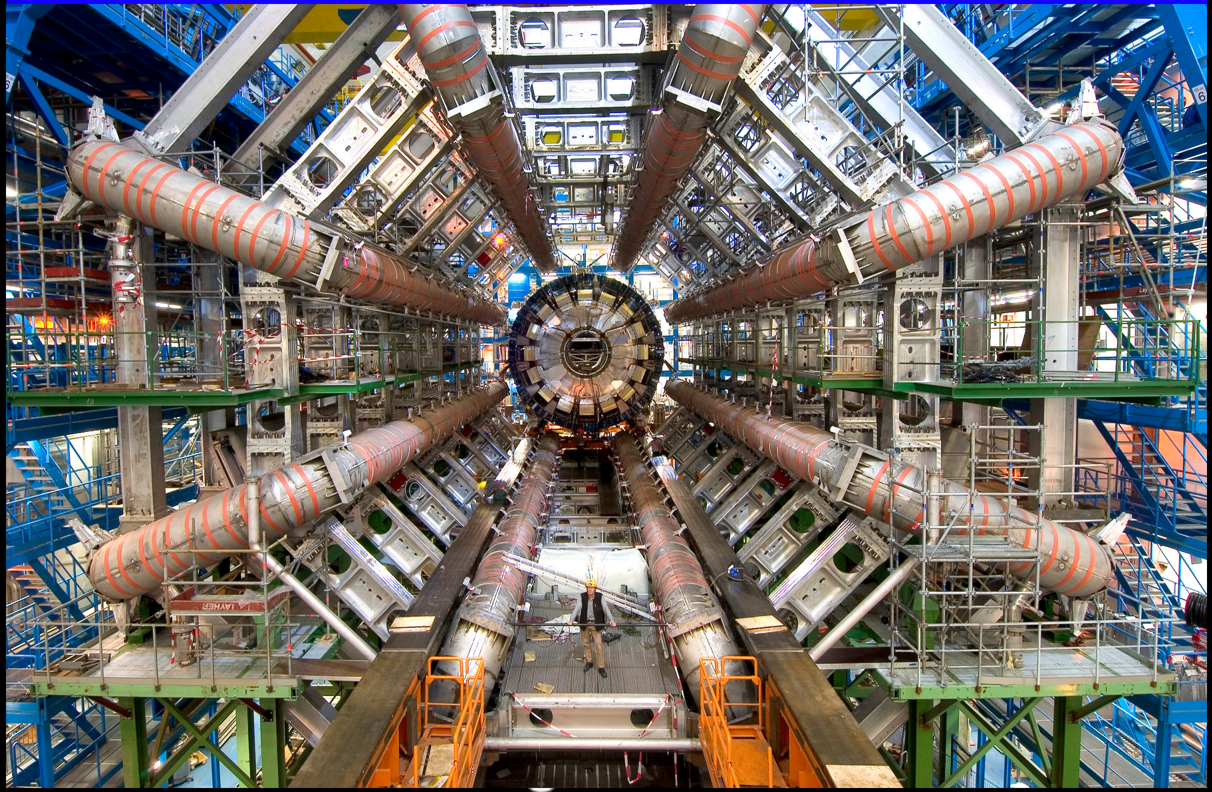
Muon Detection

- Muon identification, momentum measurement, and triggering depends on inner tracking system and muon spectrometers located after the calorimeters
- Layout depends critically on the magnet configuration adopted for the experiment.
- Both ATLAS and CMS inner trackers are in a solenoidal B field along the beam direction

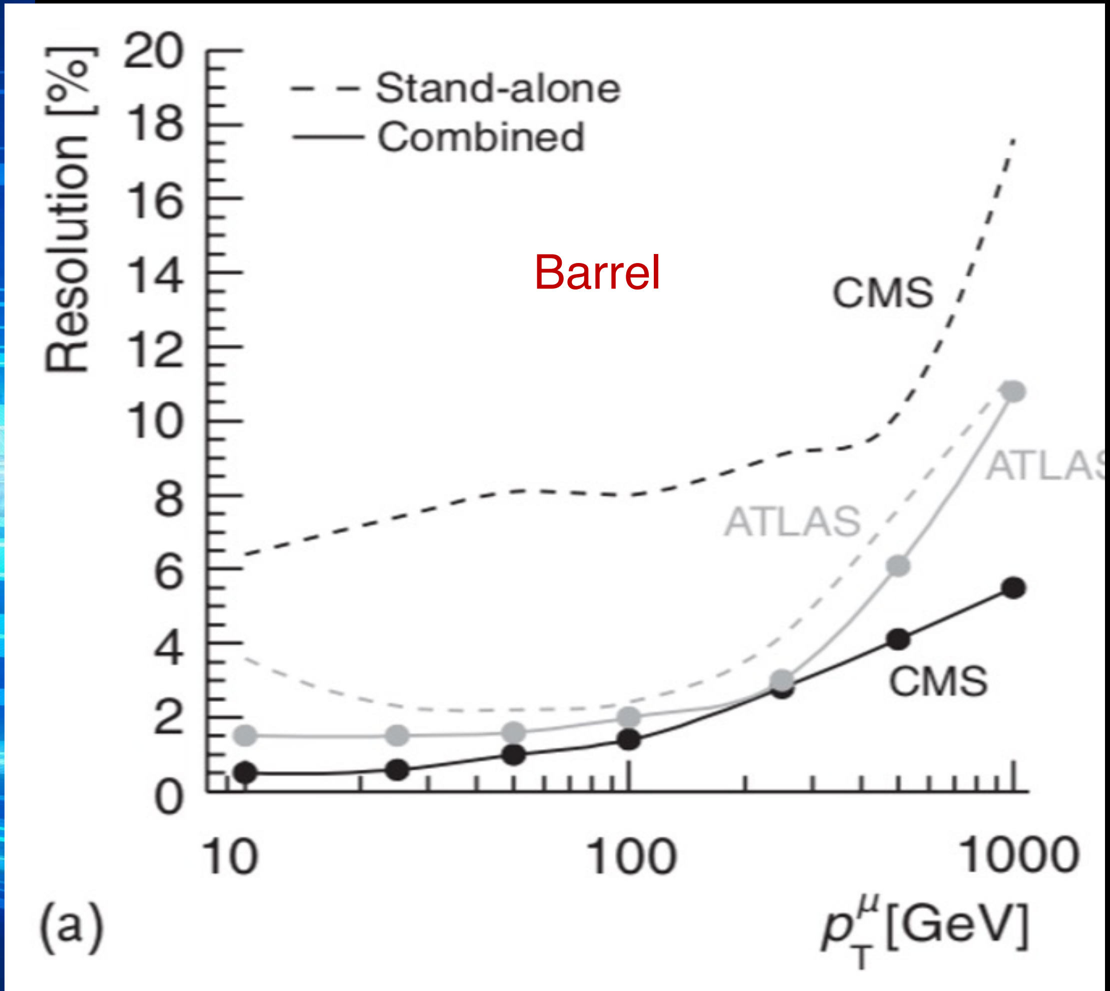
CMS Muon spectrometer
return field of solenoid for CMS

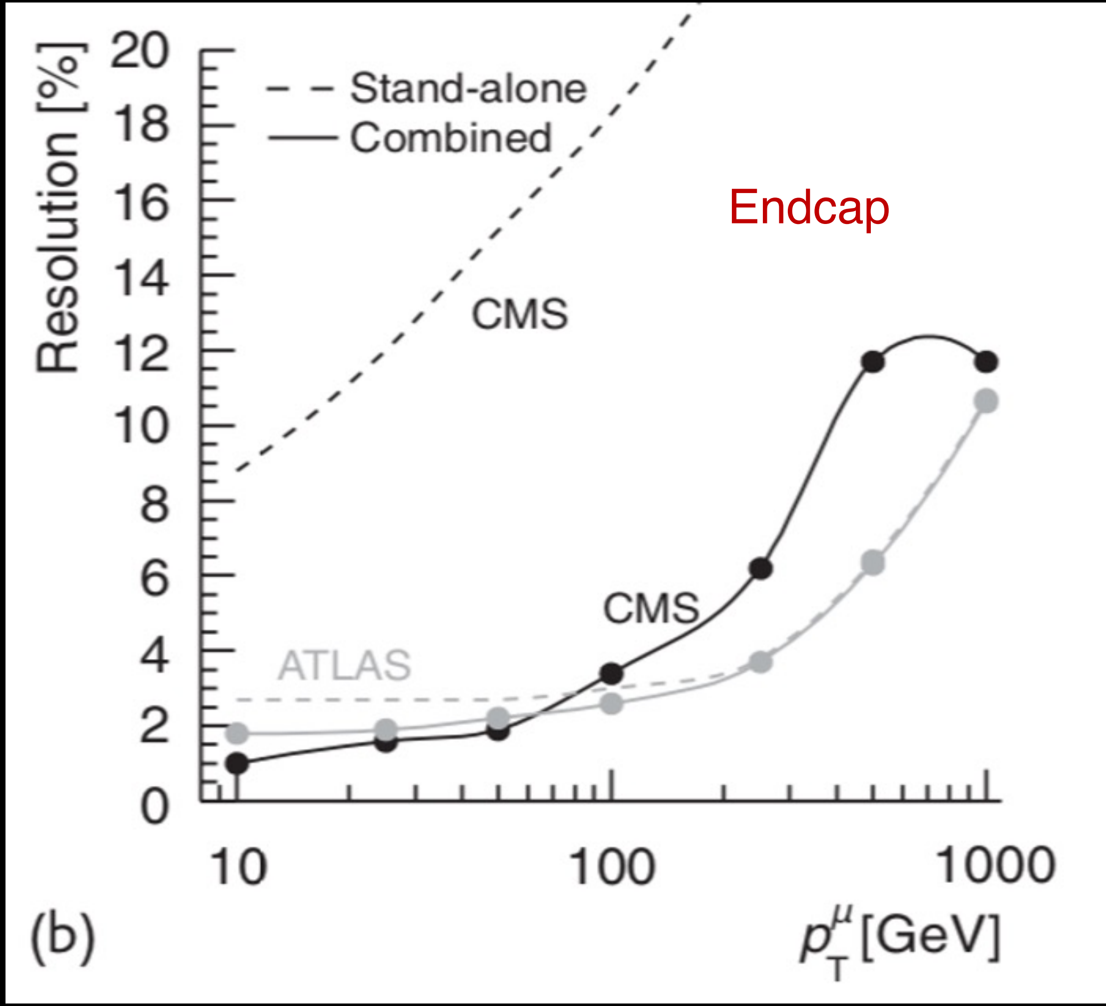


ATLAS muon spectrometer in air core Toroids (3.8 T peak) 0.8 T average in Barrel Toroid



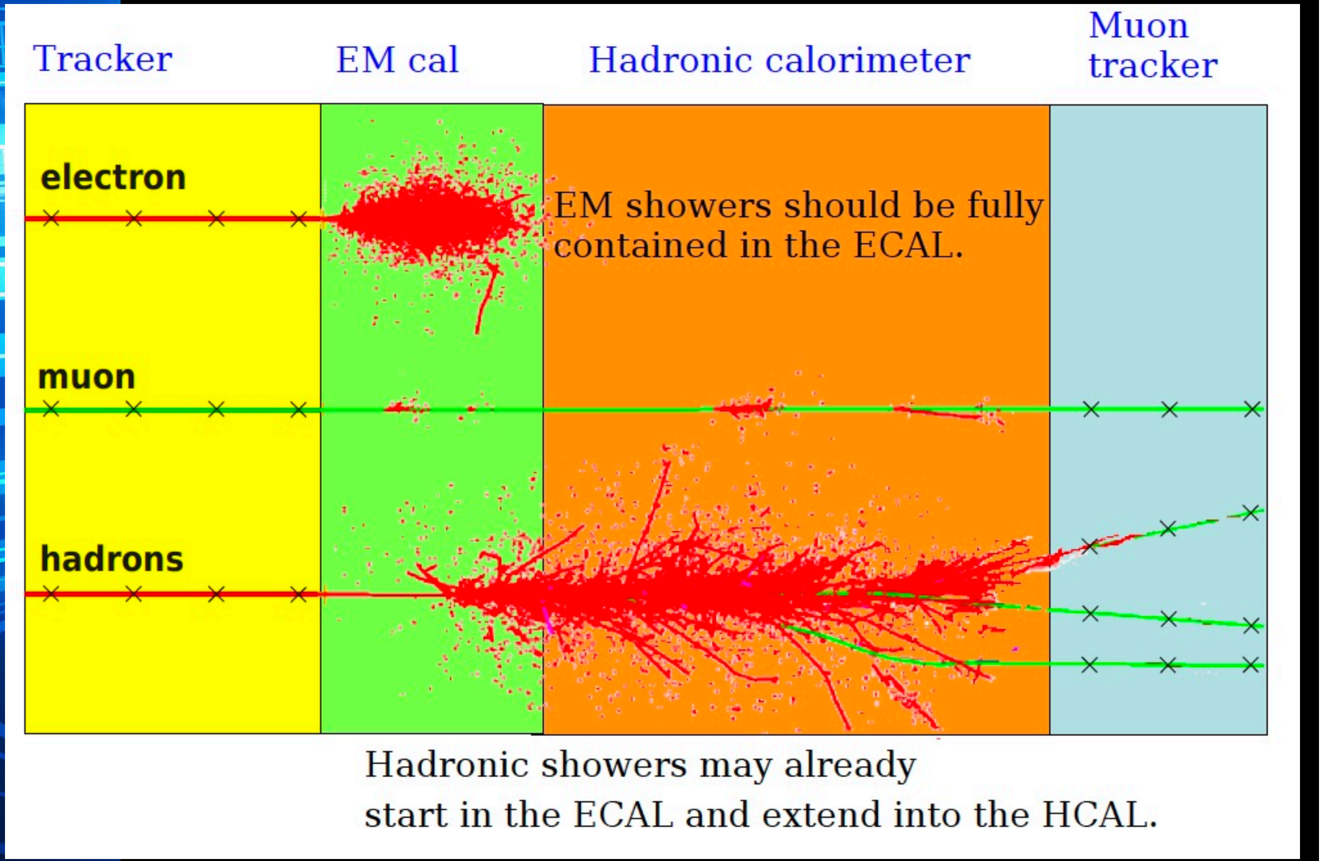
ATLAS vs CMS Muon resolution



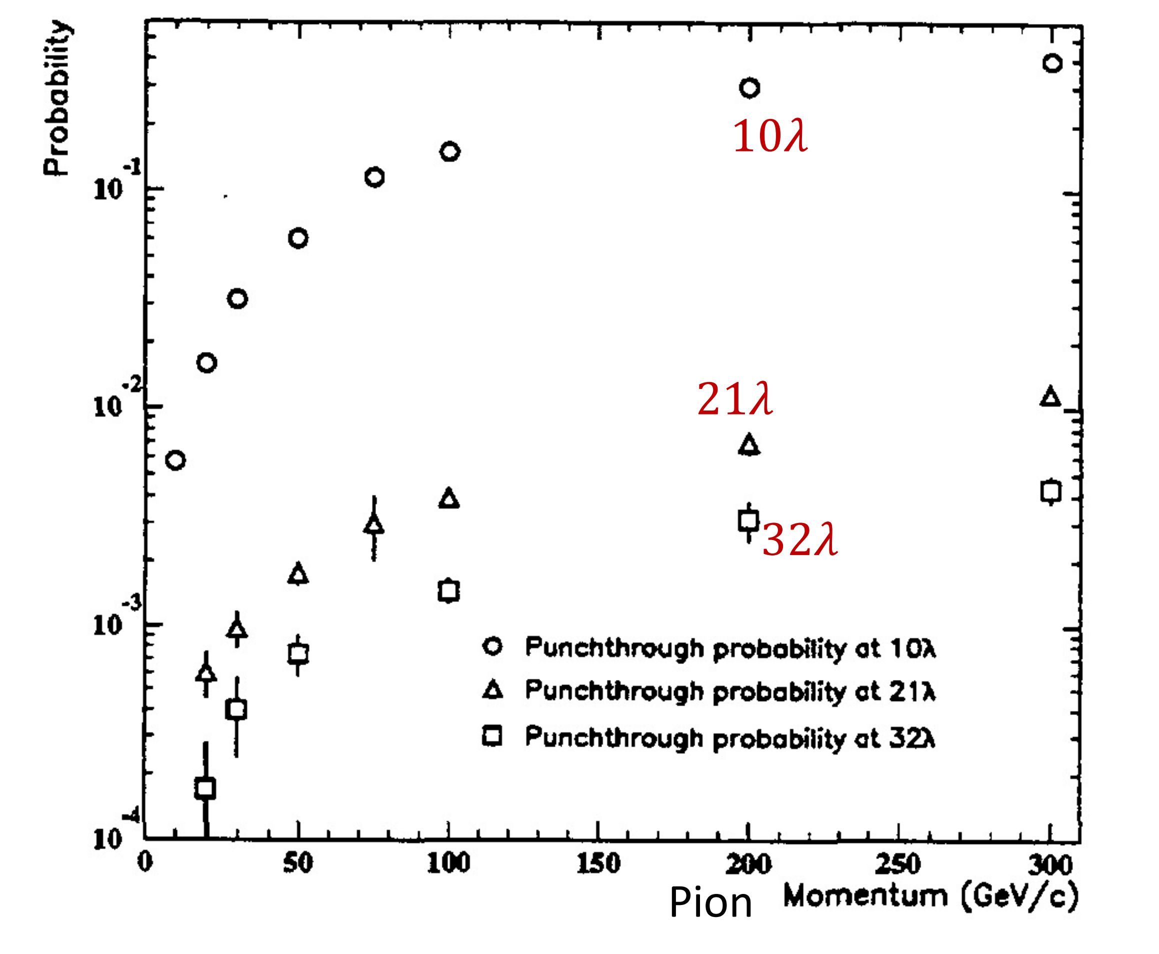


Punchthrough

- When does a pion look like a muon?
- Total punchthrough probability of hadronic showers at a given depth x is $P(x) = \frac{N_{hit}(x)}{N_{tot}}$



Pion Punchthrough probability – from RD5



The RD5 muon spectrometer

('93 setup , Top view)

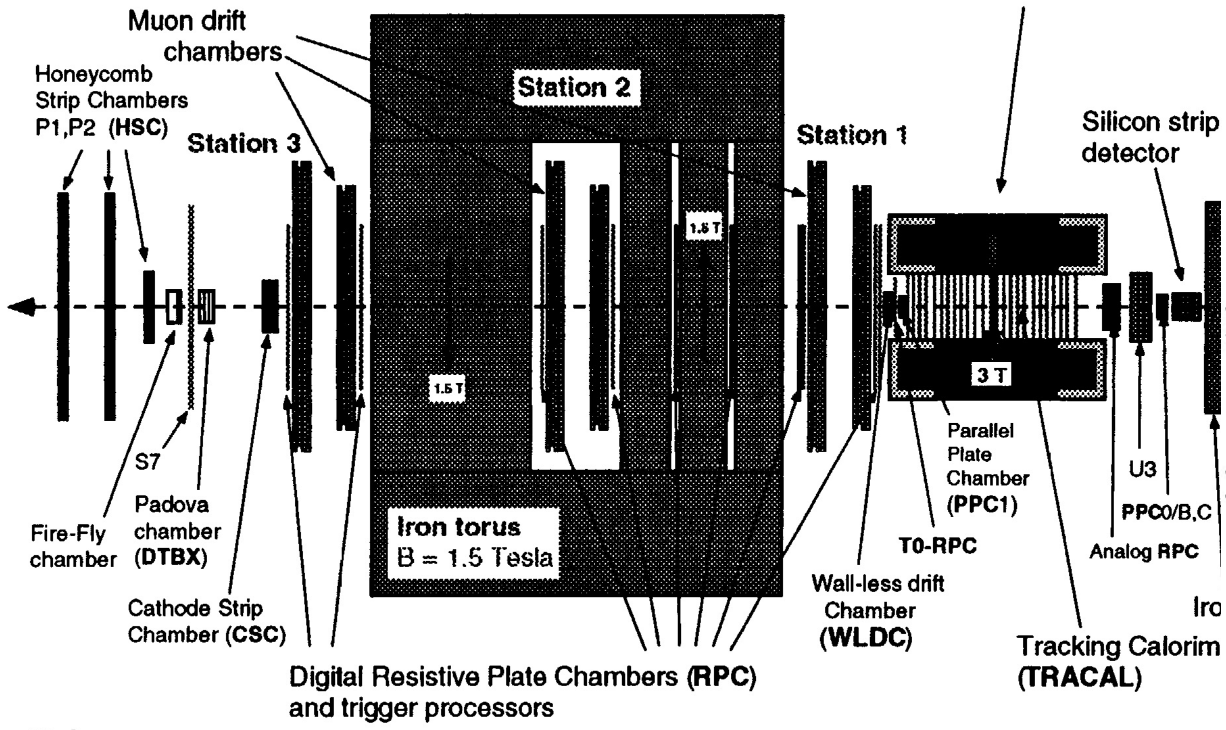


Figure 1: Schematic of the RD5 detector it its 1993 configuration.

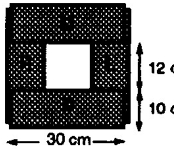
Trigger:

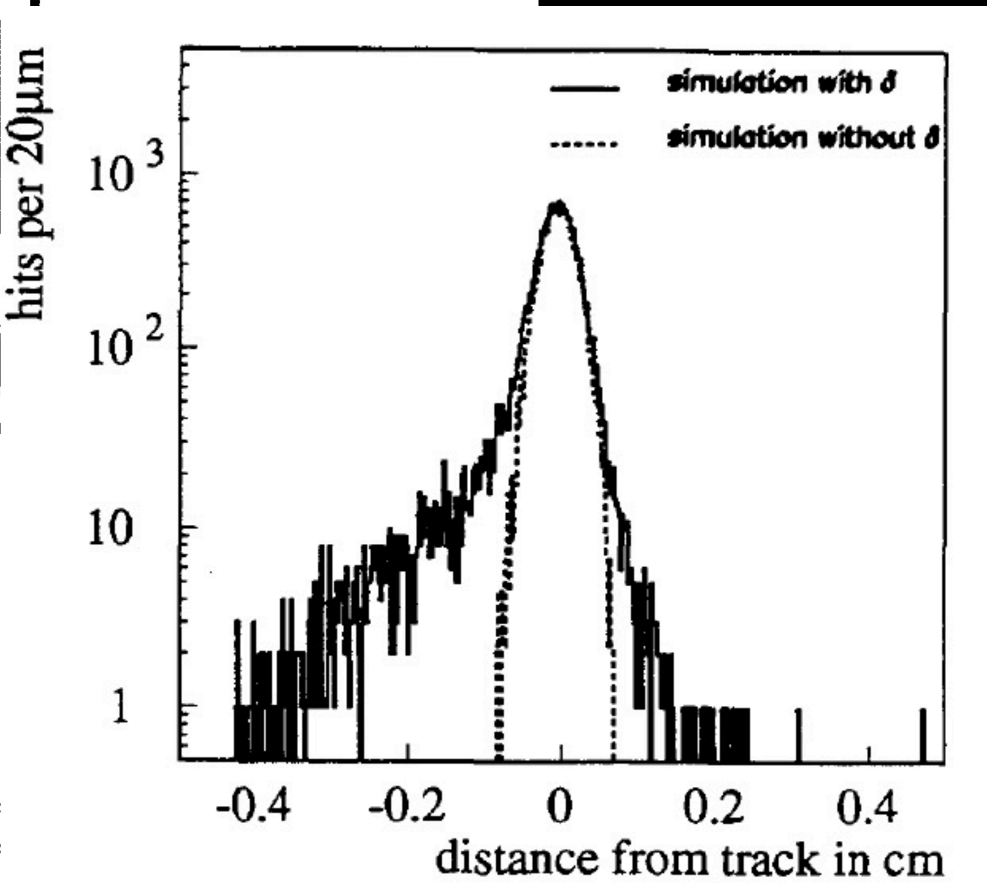
	μ	π		
		min.bias.	>10λ	>20λ
S1 x S5	●	●	●	●
VETO	●	●	●	●
S4	●	●	●	●
Station 1	●		●	●
Station 2	●			●

Scintillation counters:

S1: 10 cm x 15 cm
S4a: 4 cm x 4 cm
S4b: 2 cm x 2 cm
S5: 15 cm x 15 cm
S7: 100 cm x 250 cm

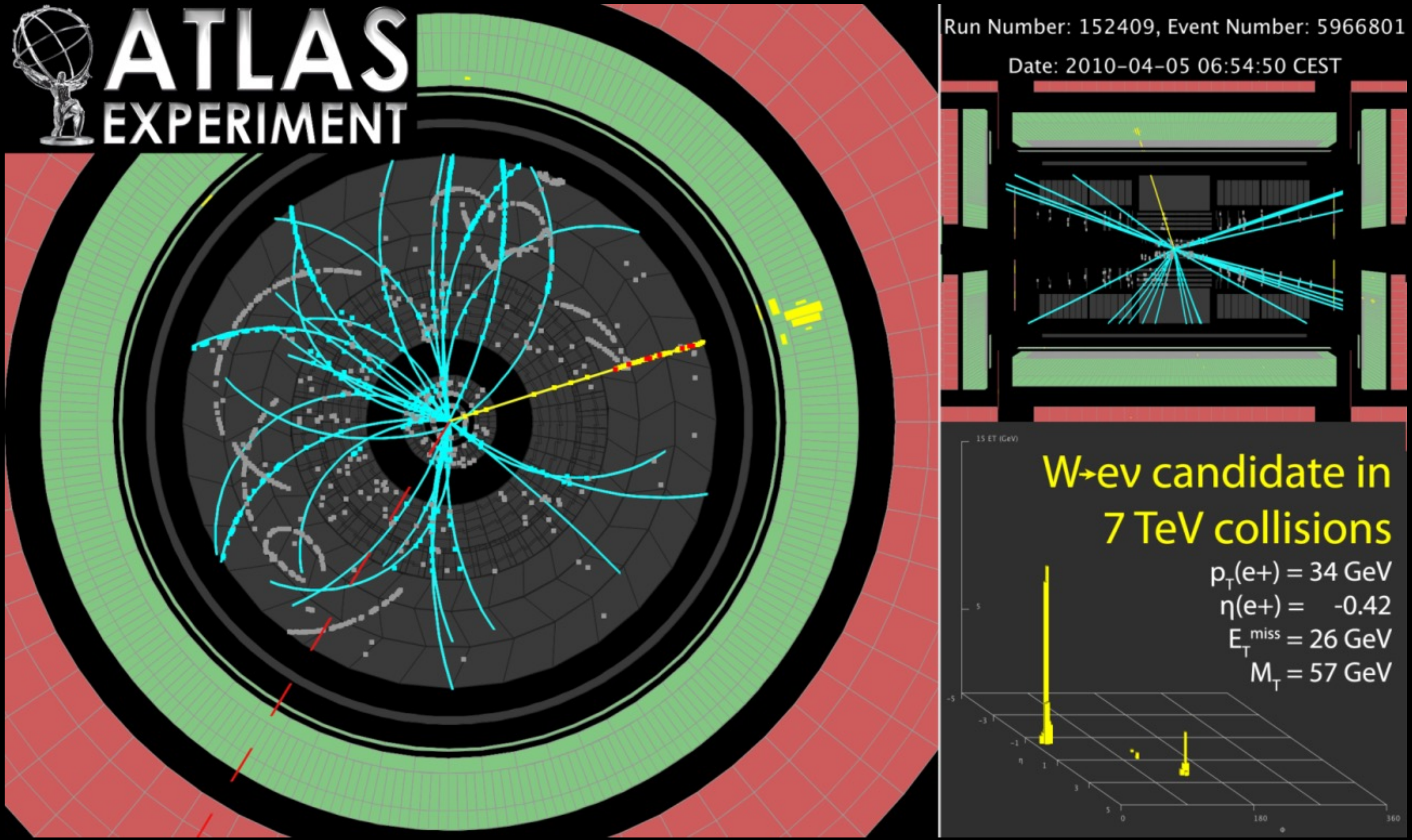
S2, S3 counters:





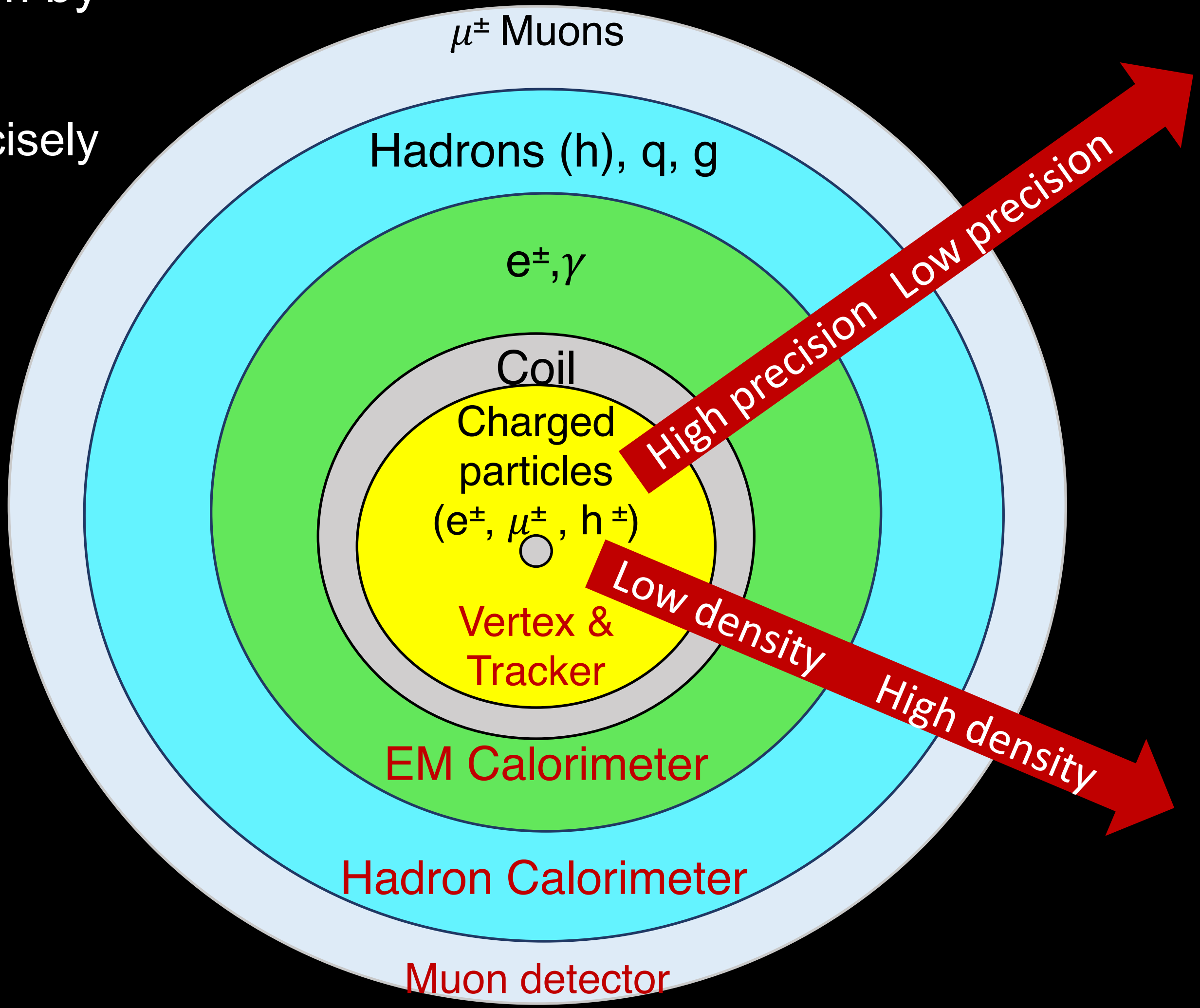
Neutrinos

- "Detected" by missing momentum – Must make sure your detector is hermetic !



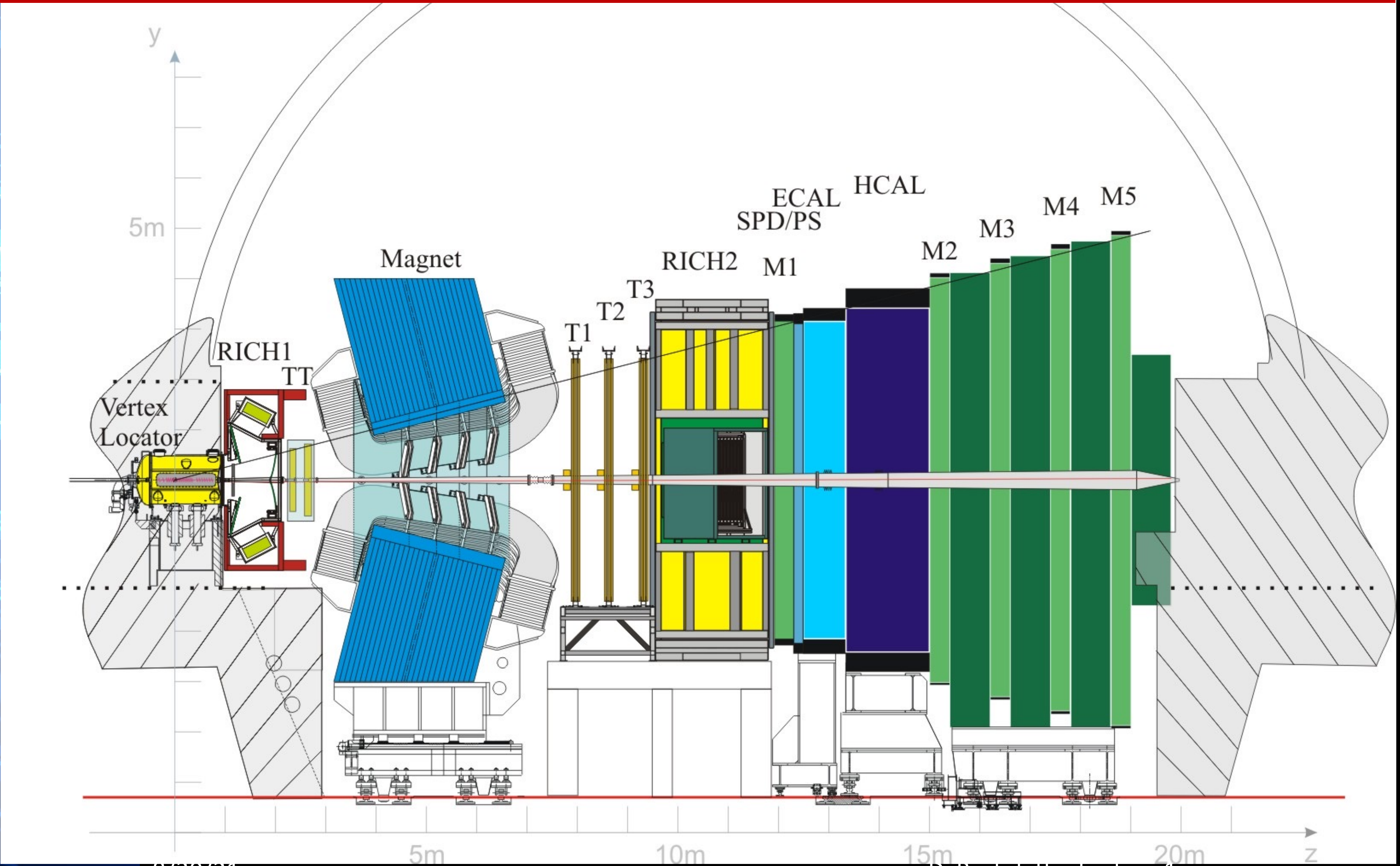
Building a collider detector

- Vertex Detectors: measure origin
- Trackers: Measure "charge" and momentum by bending the particle in a magnetic field
  - Light weight, low Z materials to measure precisely the position of the particle
- Calorimeters: detection of particles through total absorption
  - Process is destructive for almost all particles except muons and neutrinos
  - EM calorimeters: high Z materials to catch electrons and photons
  - Hadron Calorimeters: hadron interact mainly via the strong interaction, high A materials (Iron,Copper)
- Muon detectors: tracking detectors



LHCb

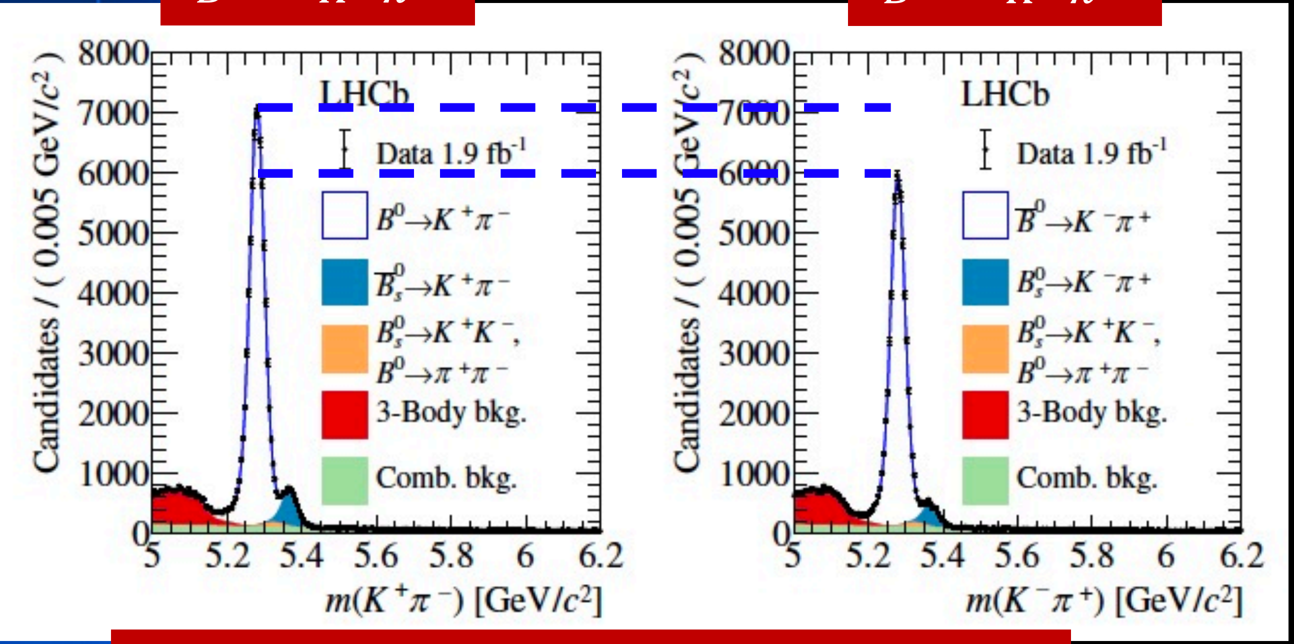
Dipole LCb integrated field 4Tm



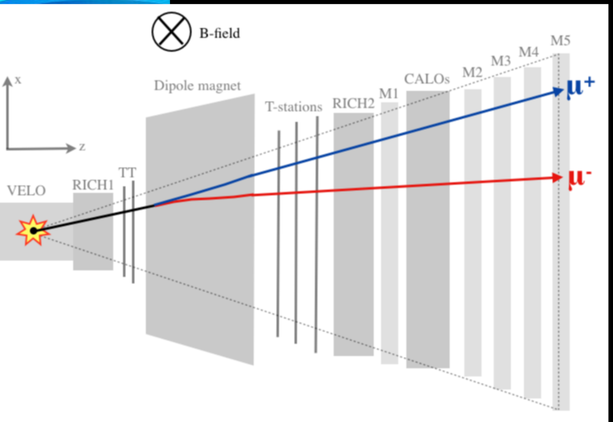
- Forward Spectrometer Configuration
  - At high energies b- and b-hadrons are produced mainly in the same forward or backward cone.
  - $<p_T(b)> \sim 80$ GeV/c $\rightarrow$ 7 mm mean decay distance $\rightarrow$ good separation between primary and decay vertices.
- Dipole magnet
  - Particle deflected in x - z plane
  - Detectors are arranged in parallel planes along z
  - Bending from difference of the slopes before and after magnet

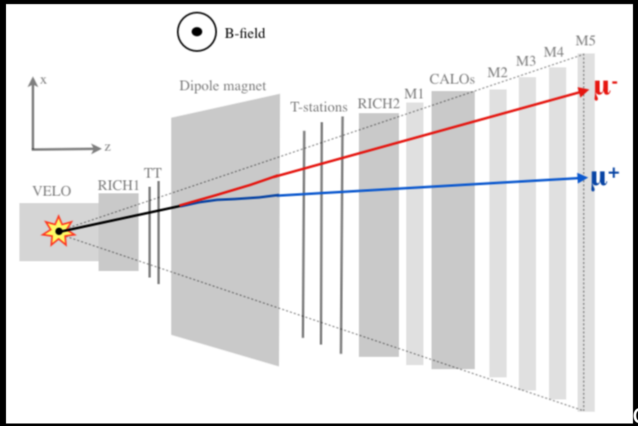
LHCb

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



$A^{CP} = (-8.2 \pm 0.03 \pm 0.03)\%$

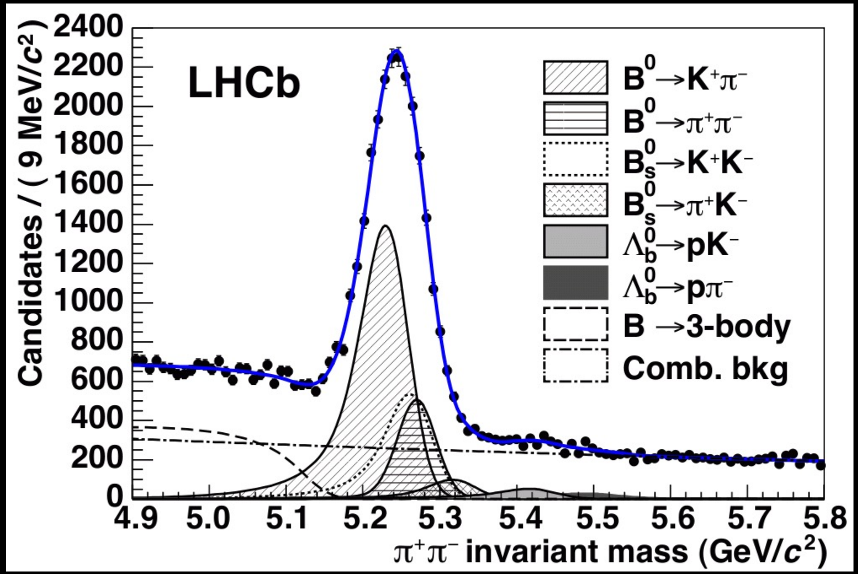




- Physics goals:
  - precision measurements of the CKM matrix to probe the validity of the SM and CP violation
  - Measurements of processes strongly suppressed in the SM which could be enhanced by NP
  - Measurements of rare decays $B_s \to \mu^+\mu^-$
  - Studies of lepton universalities
- Detector
  - Excellent vertex and proper time resolution (VELO)
  - Precise particle identification (ID): hadron π/K separation with Ring Imaging Cherenkov counters (RICH)
  - High momentum resolution for precise invariant mass reconstruction
  - A versatile trigger scheme

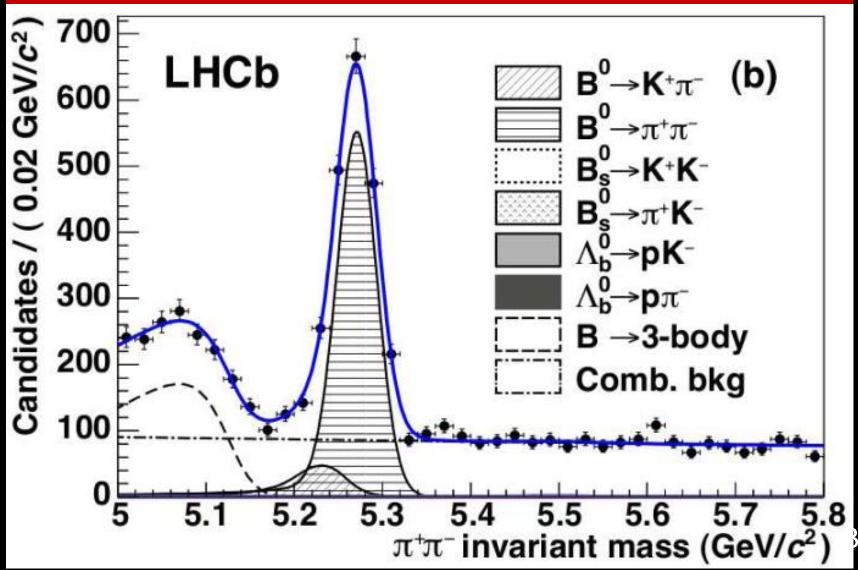
LHCb

Before RICH PID



Needed to distinguish $B^0 \to \pi^+ \pi^-$ from $B^0 \to K^+ \pi^-$

After RICH PID



- Physics goals:
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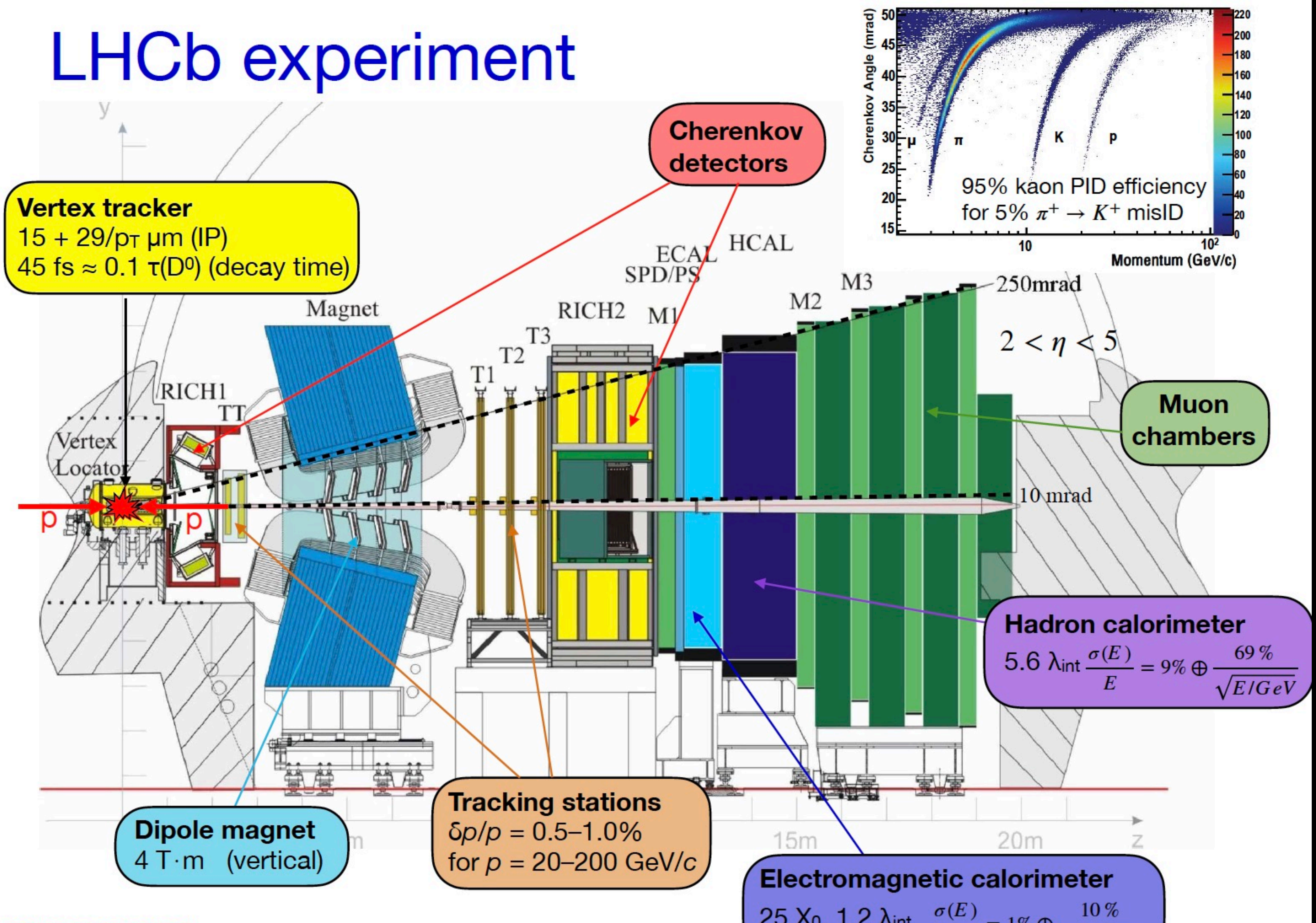
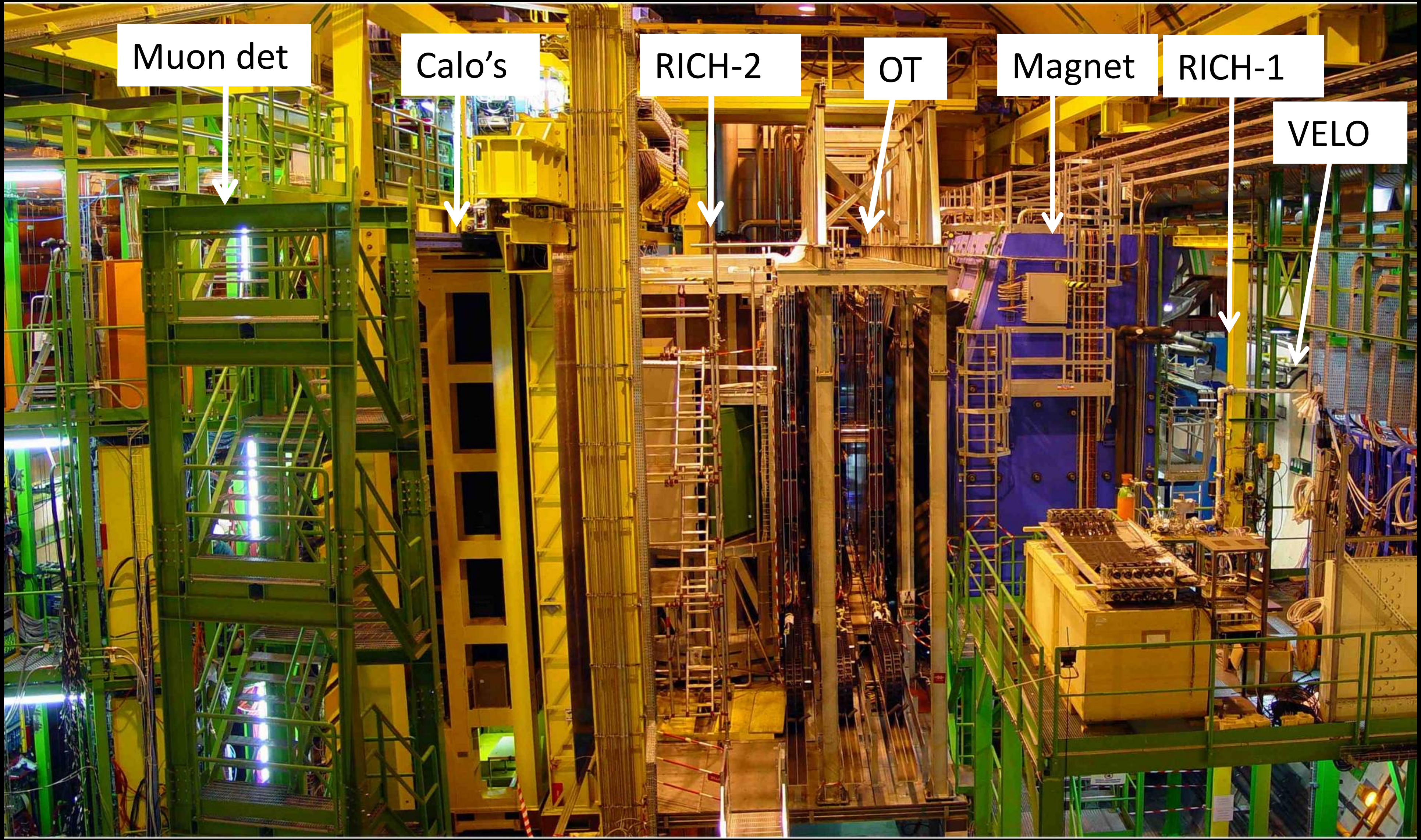
  - Excellent vertex and proper time resolution (VELO)
  - Precise particle identification (ID): hadron π/K separation with Ring Imaging Cherenkov counters (RICH)
  - High momentum resolution for precise invariant mass reconstruction
  - A versatile trigger scheme

LHCb experiment

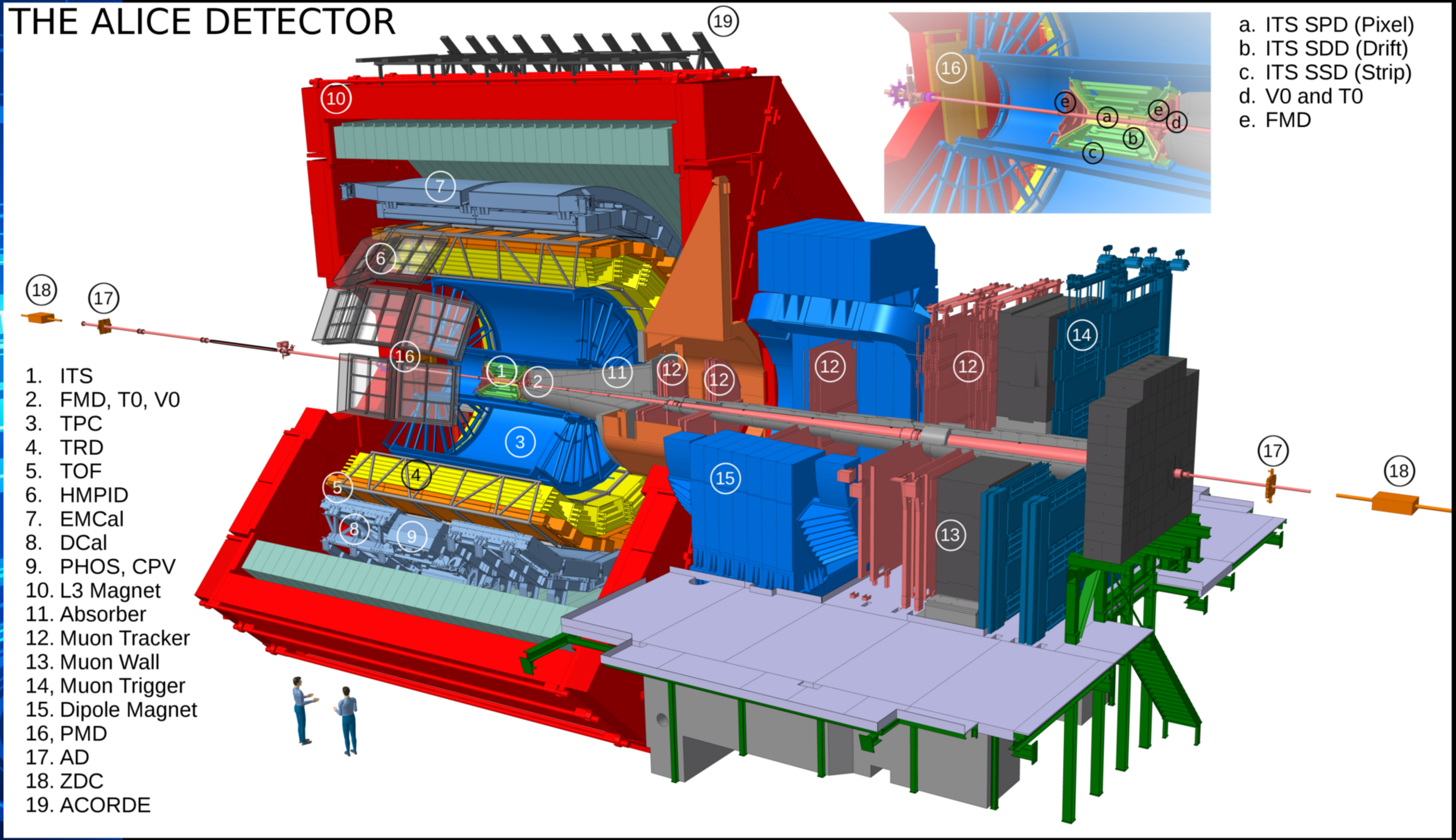


JINST 3 S08005 (2008)
Int. J. Mod. Phys. A 30 (2015) 7, 1530022

LHCb



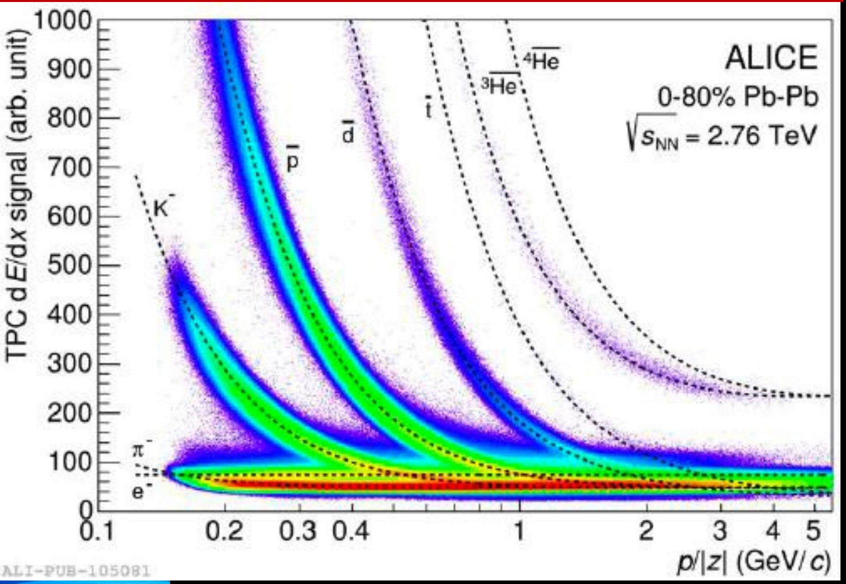
ALICE

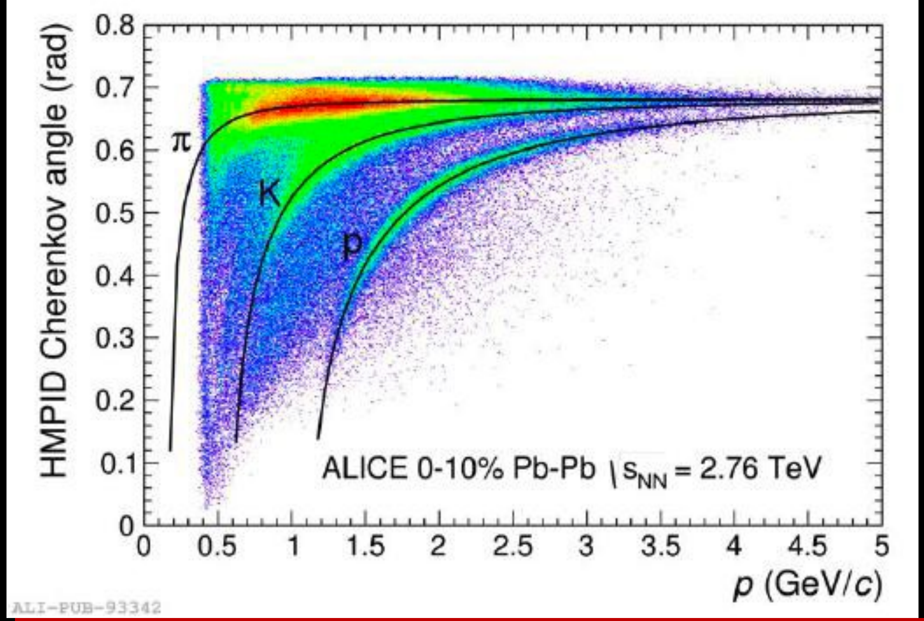


- Measurements down to very low p_T
- Particle ID in the Time Projection Chamber and Time of Flight detectors
- Excellent vertex detectors to measured heavy flavour charmed and beauty baryons
- Forward muon spectrometer studies the complete spectrum of heavy quarkonia (J/ψ and Υ resonances)

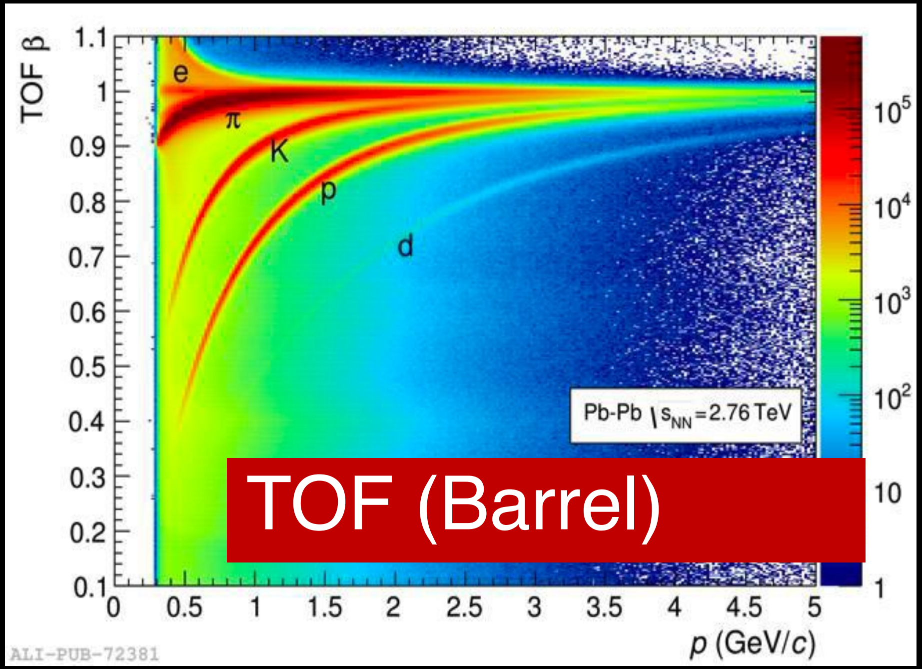
ALICE PID

TPC (+ITS) dE/dx



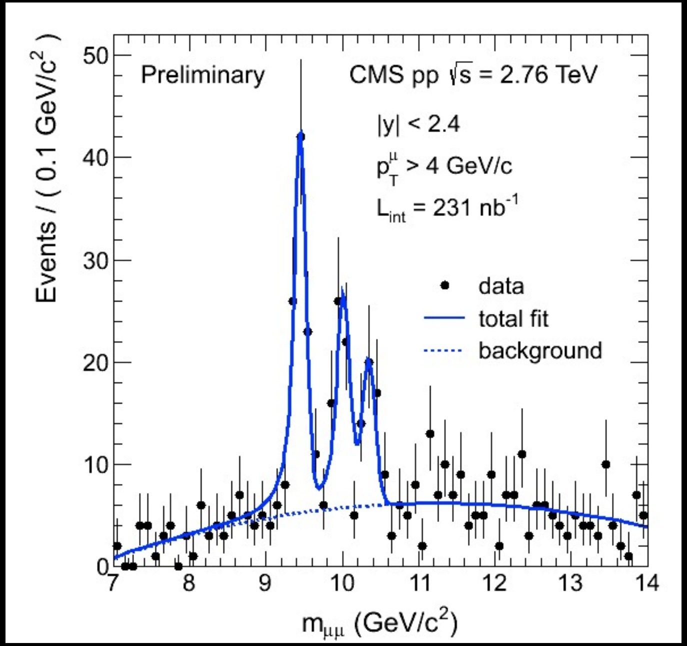


HMPID – Cherenkov radiation



TOF (Barrel)

Plus
- Transition radiation detector (TRD)
- Photon spectrometer (PHOS)
- EM calorimeter (EMCAL)
- Muon spectrometer

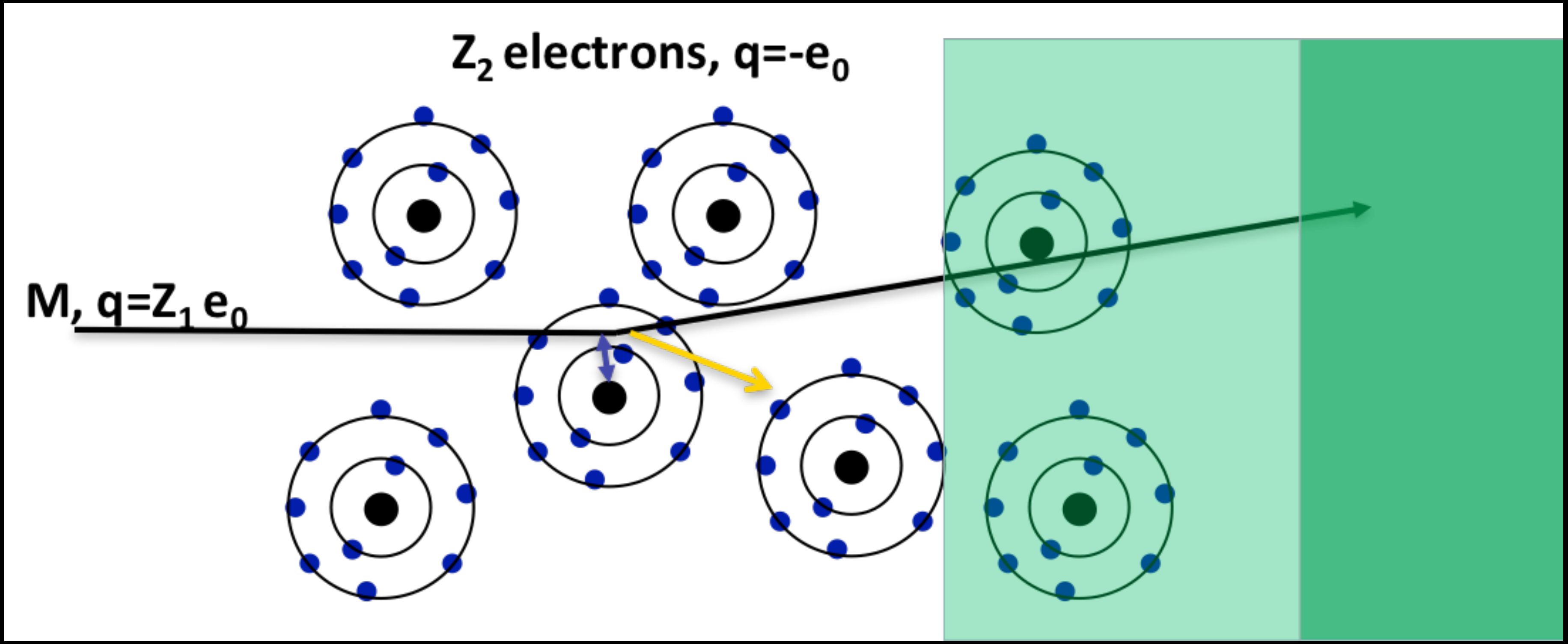


Conclusion

- Detector configuration critically depends on the physics goals
- CERN RD programme was essential to design the LHC detectors
- Similar programme must be put in place for the experiments at future colliders
- Tomorrow we will focus on silicon detectors and the new detector ideas emerging already for HL-LHC upgrade

Energy loss by photon emission

- Emission of Cherenkov light
- Emission of transition radiation



EM Shower development

Useful relations

$$X_0 = \frac{180A}{Z^2}\,(g\,cm^{-2})$$

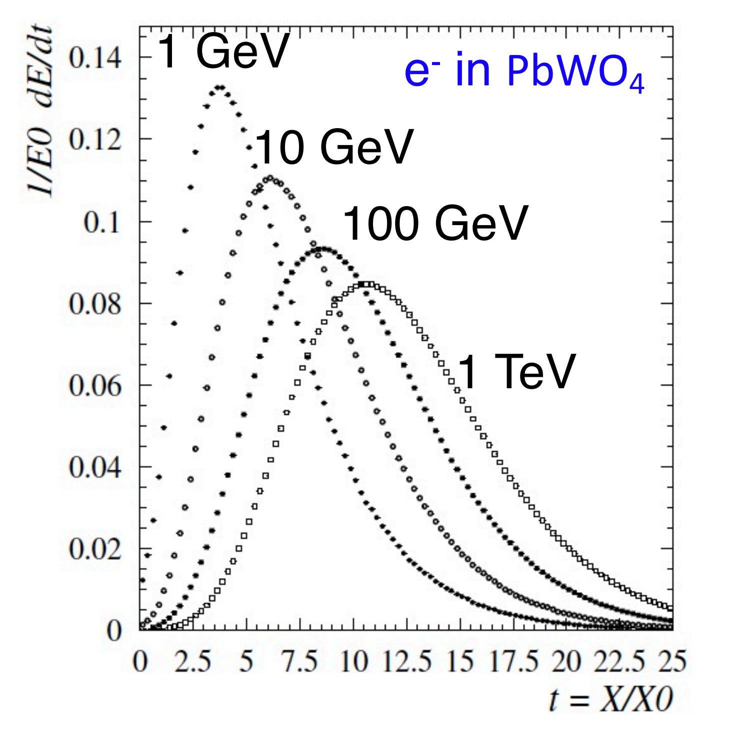
$$E_c = \frac{580}{Z}\,(\text{MeV})$$

$$R_M = \frac{21\,MeV}{E_c} X_0$$

$t_{max} = \ln \frac{E}{E_c} - 1$ e induced showers

$t_{max} = \ln \frac{E}{E_c} - 0.5$ γ induced showers

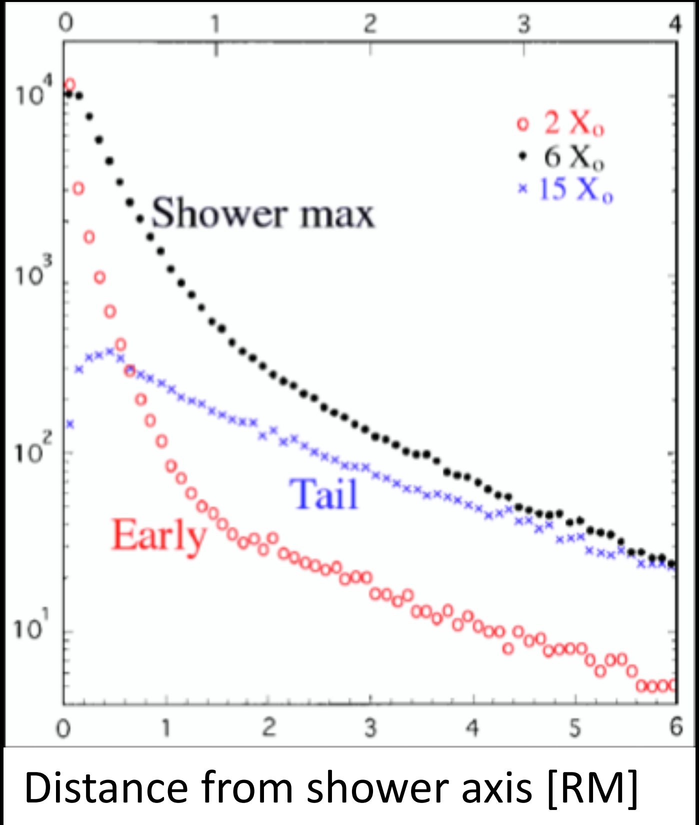
Longitudinal development



95% of energy within:

$L(95\%) = t_{max} + 0.08\,Z + 9.6\,X_0$

Transverse development for 10 GeV electron showers in Cu

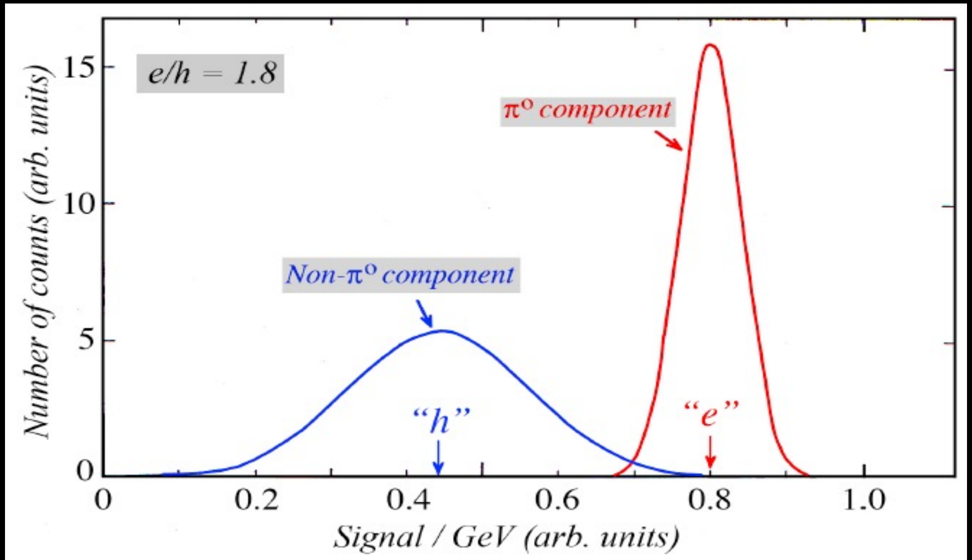


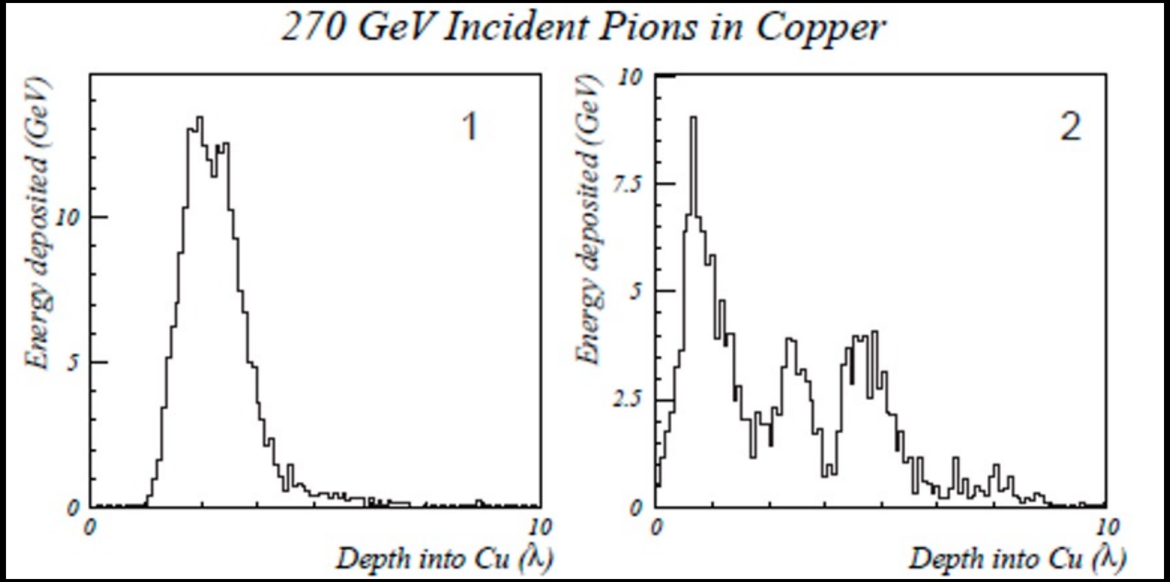
90% (95%) of energy: R_M ($2R_M$)

- Beyond shower max broadening due to low energy photons

Hadronic shower fluctuations

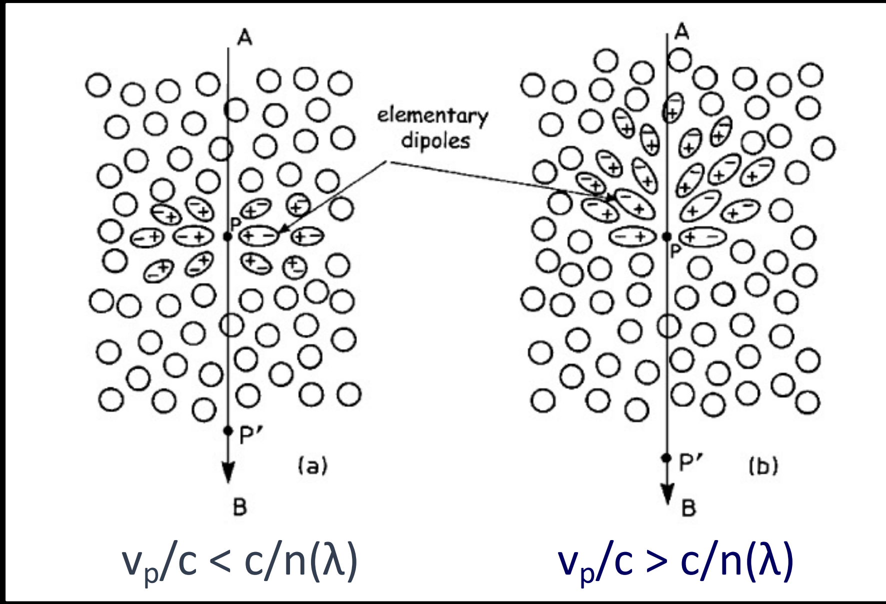
- No "characteristic" profile
- EM component (f_{em}) to the hadronic
  - on average 1/3 of mesons produced are π^0's, which yield an shower due to $\pi^0 \rightarrow \gamma\gamma$
  - hadronic decays to π^0
- Considerable event-to-event fluctuation in f_{em}
- Non linear response





Cherenkov emission

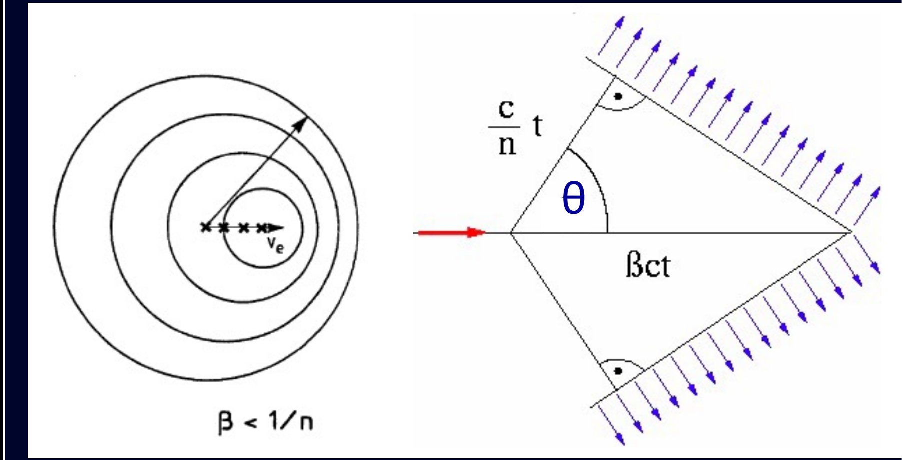
- If the velocity of a particle is such that **$\beta = v_p/c > c/n(\lambda)$** where $n(\lambda)$ is the index of refraction of the material, a pulse of light is emitted around the particle direction with an opening angle (**θ_c**)



Symmetric dipoles

coherent wavefront

Cherenkov angle



$$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$

- The threshold velocity

$$\beta_{th} = \frac{v_{th}}{c} = \frac{1}{n(\lambda)}$$

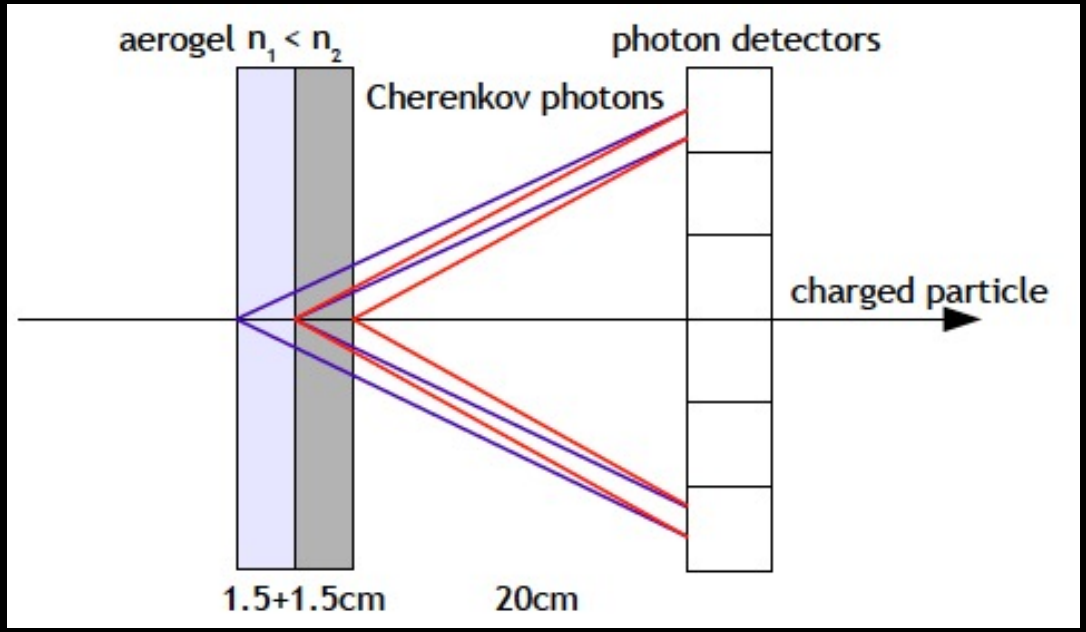
Number of produced photons:

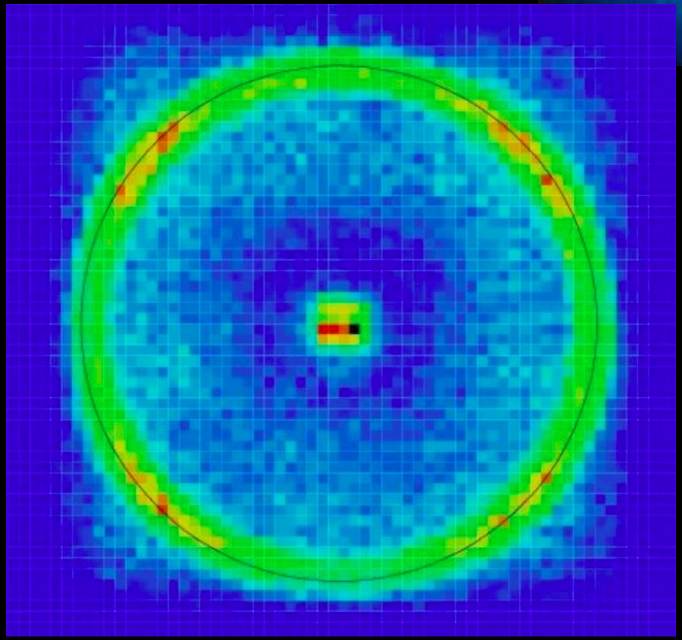
$$N_{photons} = L\frac{\alpha}{\hbar c}Z^2\int \sin^2\theta_c(E)dE$$

Cherenkov photon emission

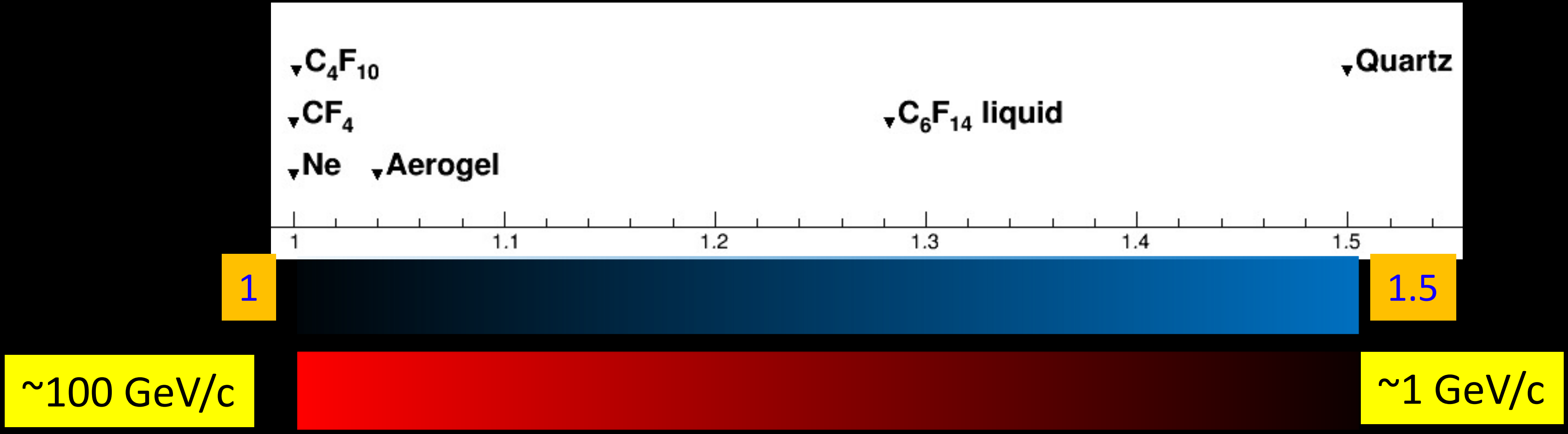
- Cherenkov emission is a weak effect and causes no significant energy loss (<1%)
- It takes place only if the track L of the particle in the radiating medium is longer than the wavelength λ of the radiated photons.
- Typically O(1-2 keV / cm) or O(100-200) visible photons /cm


Cherenkov radiation glowing in the core of a reactor





Refractive index range



Momentum

Silica Aerogel

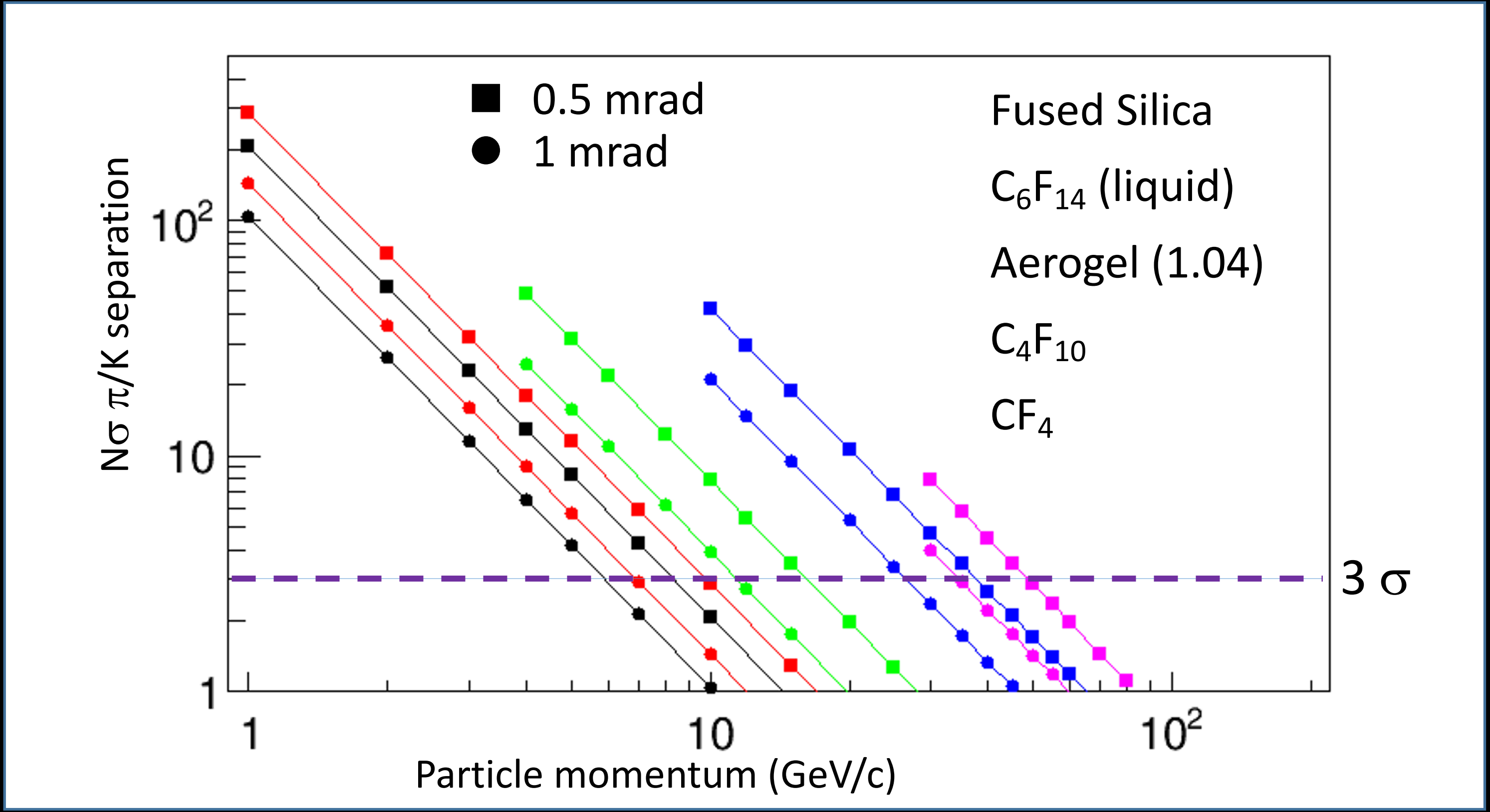
Quartz fibersl

RICH performance

$$N_\sigma \approx \frac{\left|m_1^2 - m_2^2\right|}{2P^2\sigma[\theta_c(tot)]\sqrt{n^2-1}}$$

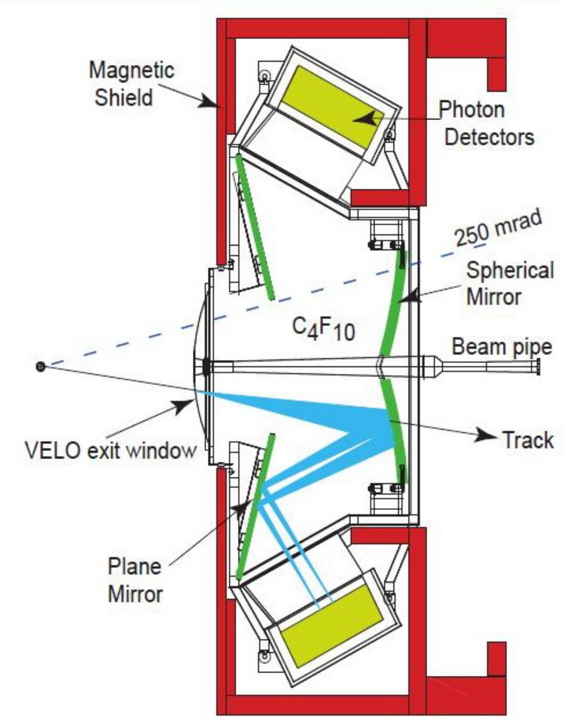
For particles well above threshold

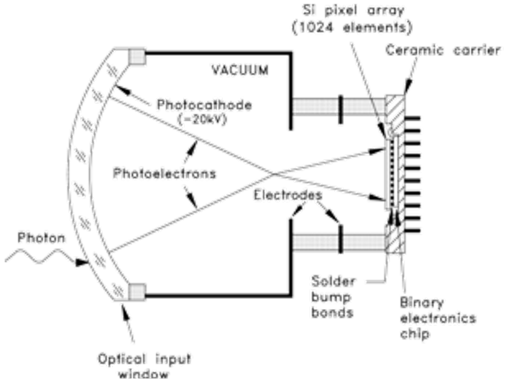
B. N. Ratcliff, NIMA 502 (2003) 211-221

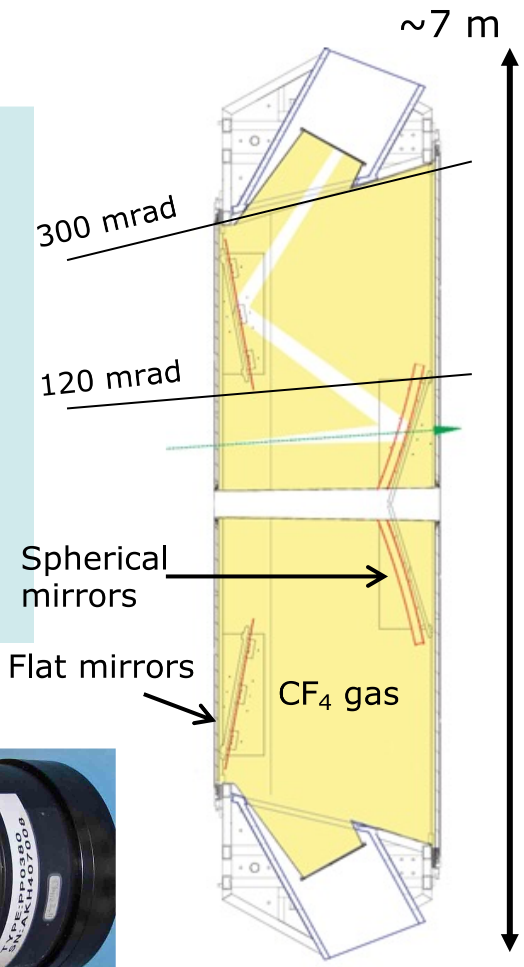


LHCb

- Two detectors with gas radiators (C_4F_{10} and CF_4)
  - Originally with a 3rd radiator (aerogel)
- “Novel” photon detectors, pixel HPDs
  - Aging, issues with vacuum
- Two mirror systems
- Complex pattern recognition
  - 100s of tracks
  - Global likelihood method

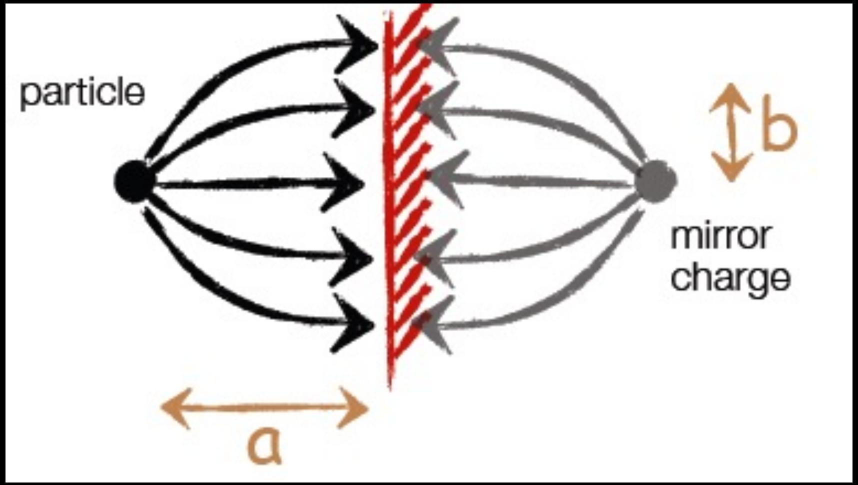


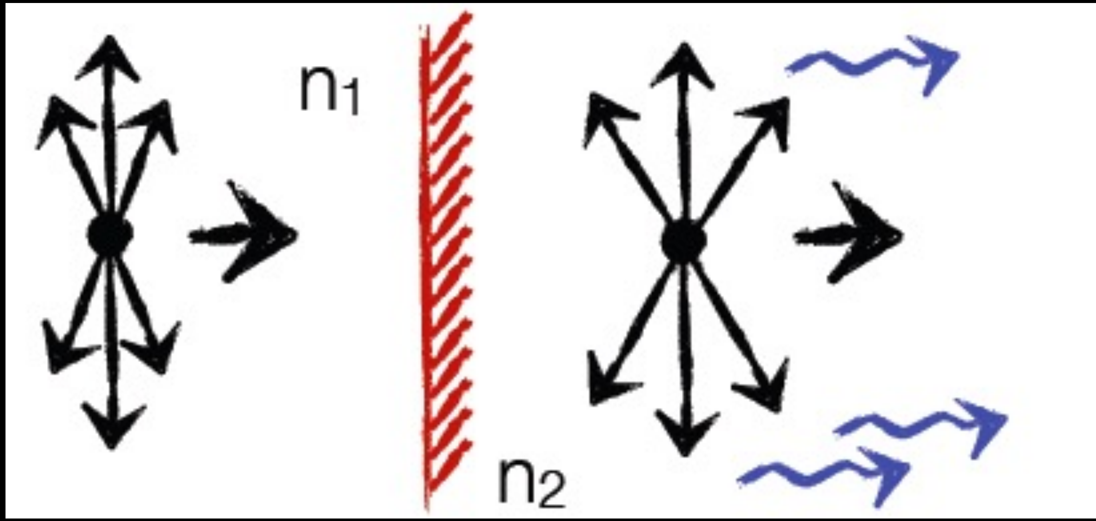




Transition radiation

- Transition radiation occurs if a relativist particle (large **γ**) passes the boundary between two media with different refraction indices ($n_1 \neq n_2$) [predicted by Ginzburg and Frank 1946; experimental confirmation 70ies]
- Effect can be explained by re-arrangement of electric field
- A charged particle approaching a boundary creates a dipole with its mirror charge

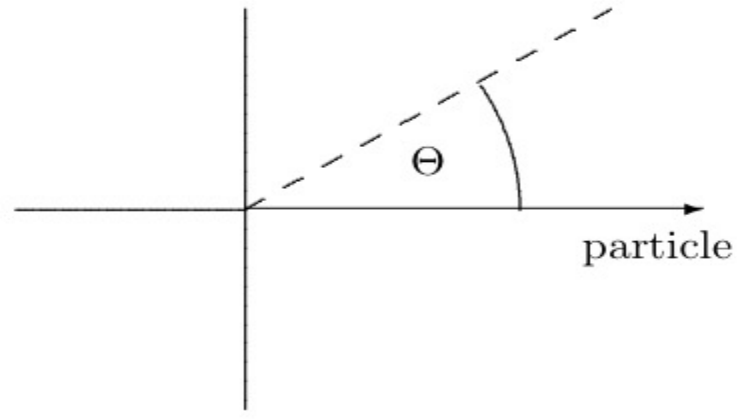




The time-dependent dipole field causes the emission of electromagnetic radiation

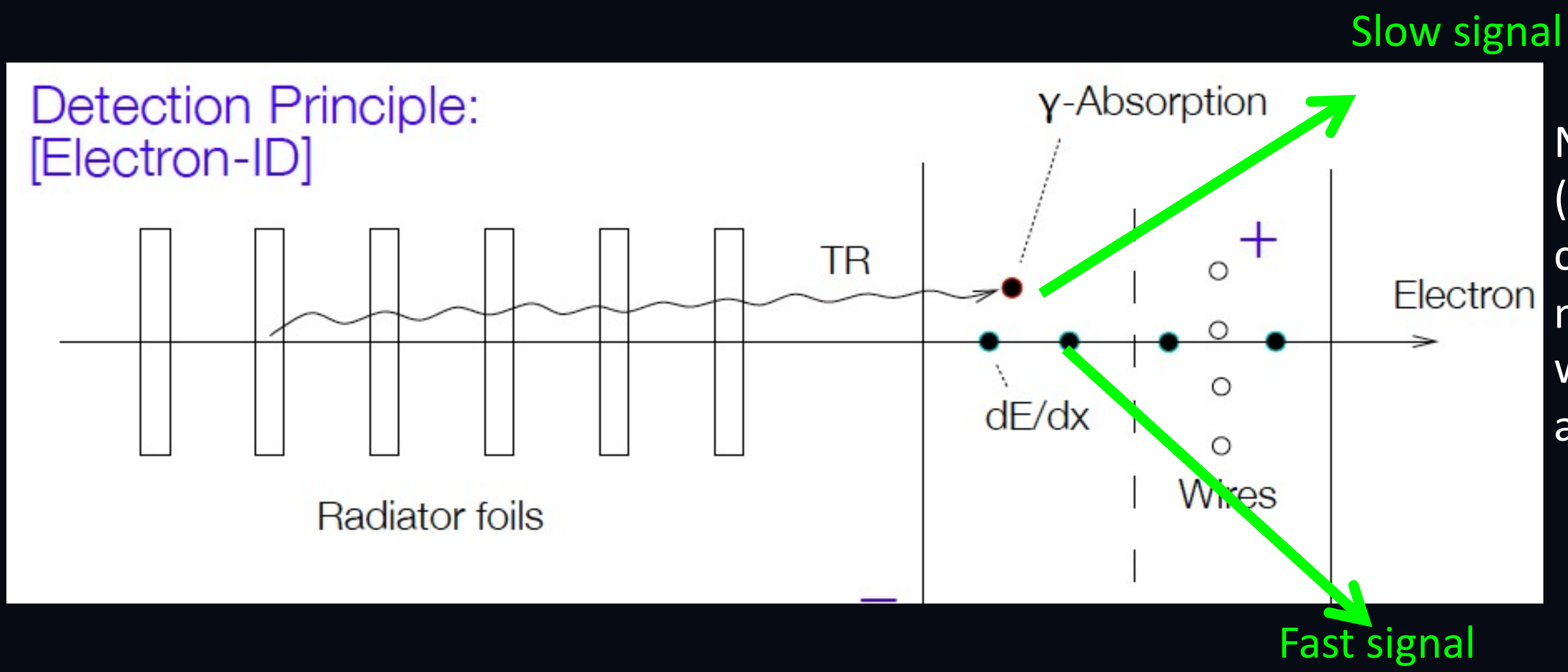
$$S = \frac{1}{3}\alpha z^2 \gamma \hbar \omega_P \quad \left(\hbar\omega_P \approx 28.8\sqrt{\frac{Z\rho}{A}}eV\right)$$

Transition Radiation



- Typical emission angle: $\theta=1/\gamma$
- Energy of radiated photons: $\sim \gamma$
- Number of radiated photons: $\alpha \mathbf{z}^2$
- Effective threshold: $\gamma > 1000$

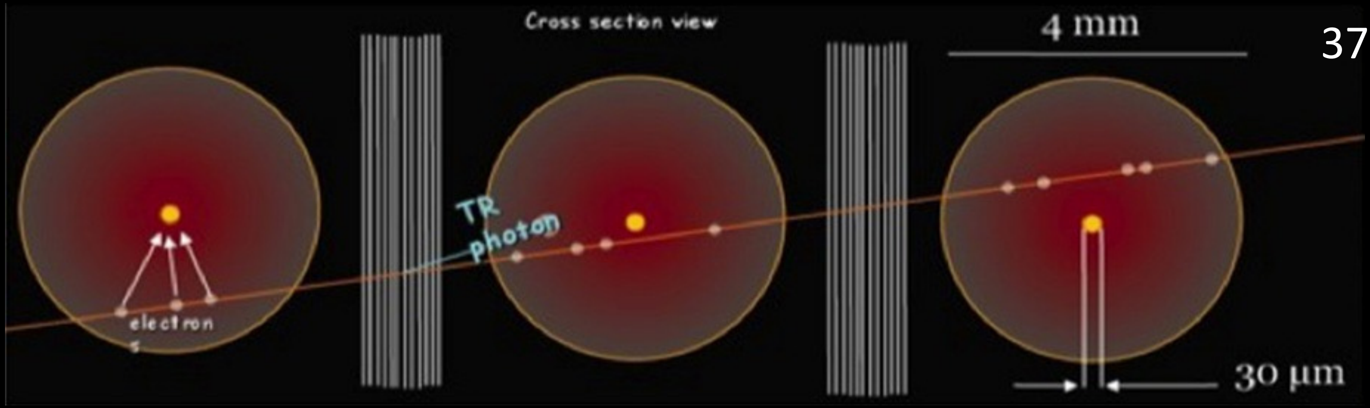
- Use stacked assemblies of low Z material with many transitions and a detector with high Z



Note: Only X-ray (E>20keV) photons can traverse the many radiators without being absorbed

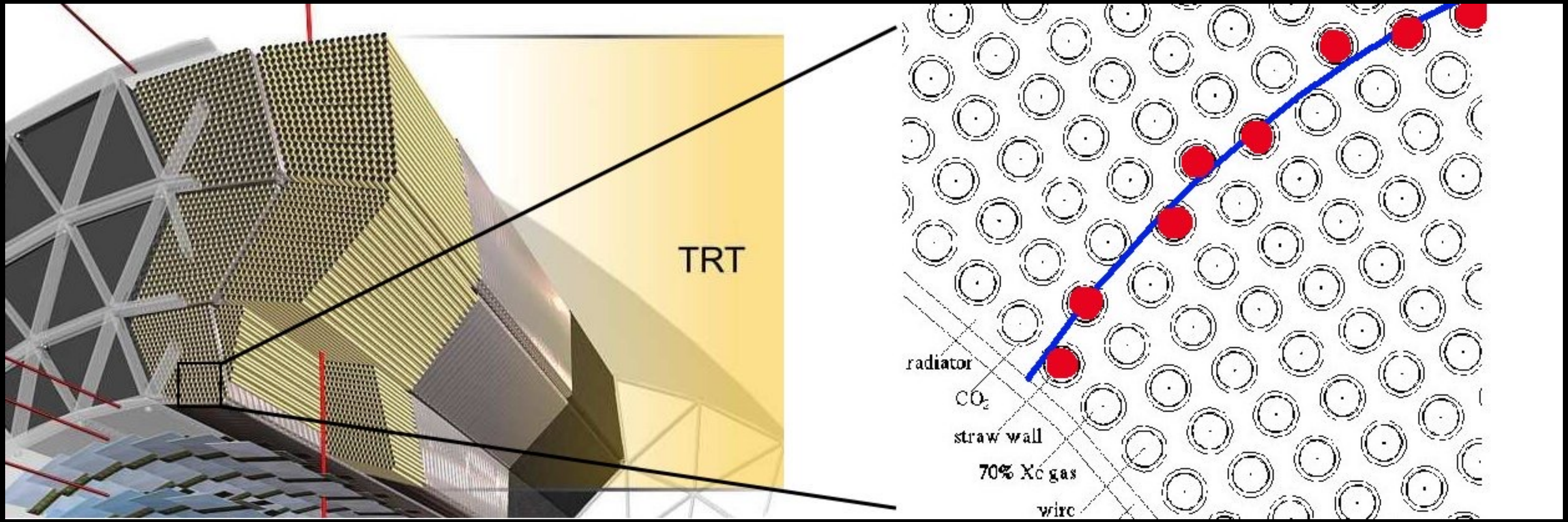
The ATLAS Transition Radiation Tracker

- The TRT main element are gas filled tubes (d=4 mm, 40-150 cm long) to measure precisely the position

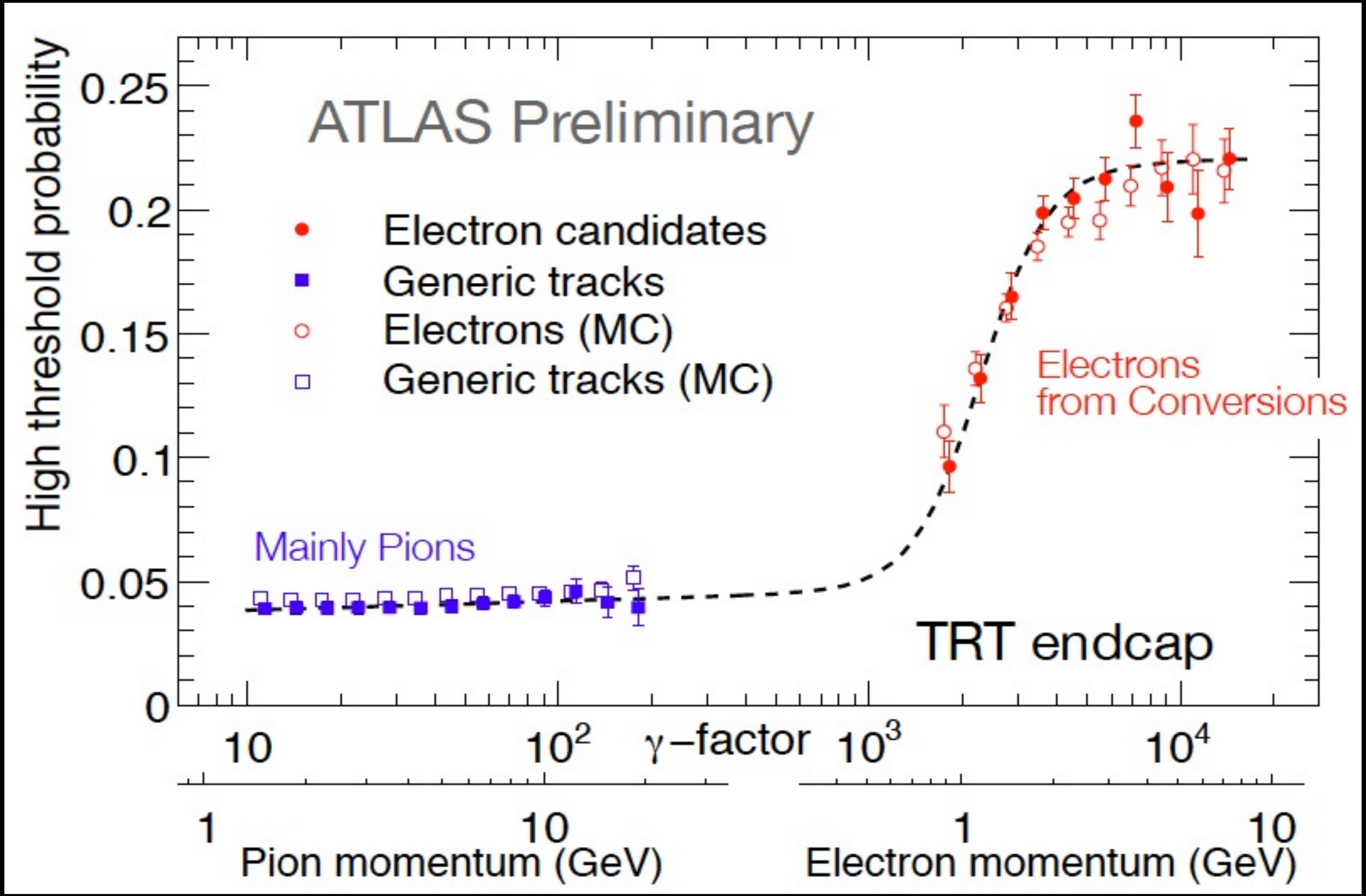


370,000 drift tubes. Eac layer of straws interleaved with polypropylene as a radiator

Polypropylene fibers fill the gap between straws to distinguish e^- from hadrons



ATLAS Transition radiation tracker



Collider Detectors Approaches