# Experimental High Energy and Nuclear Physics

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# What topics are included in "Experimental HEP"?

- Survey of large experiments worldwide
- Measurement of cross sections, ratios, luminosity, etc.
- Classes of particle measurements:
  - Momentum vectors for charged hadrons (tracking)
  - Neutral particles (calorimetry)
  - Muons
  - Neutrinos ← Will stop somewhere around here, today
  - Jets (tracking and/or calorimetry)
- Interpretation and treatment of data with statistical fluctuations
- Simulation of experimental data
- Particle identification methods and technologies
- Specialized analysis techniques
- Trigger and data acquisition systems
- Magnet systems
- Accelerator types and technologies

Too much for 90 minutes (two semesters would be enough) so mention all + focus in a few areas
See ICFA school, and various other schools, for more

# Survey of large experiments worldwide

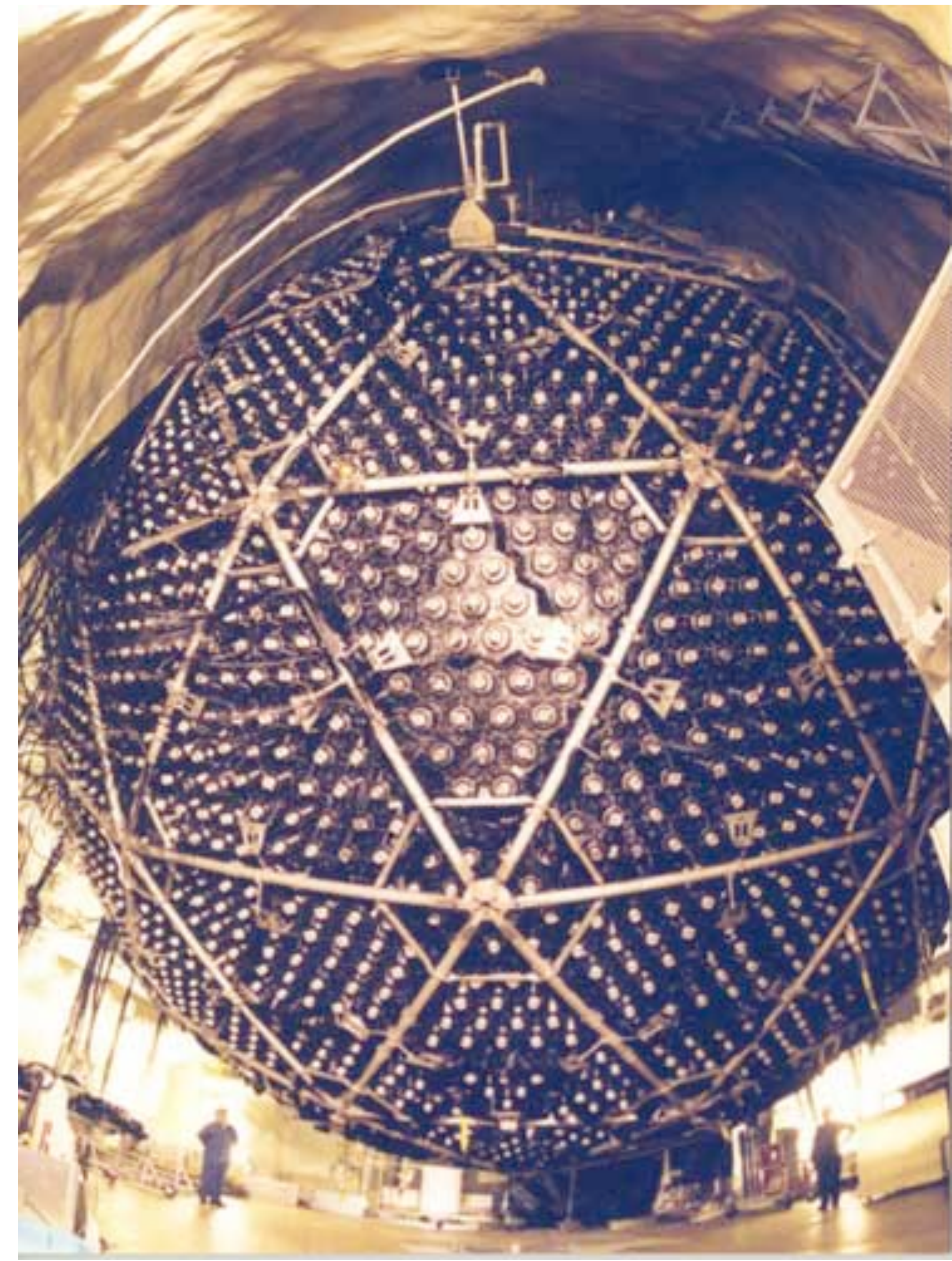
# Survey of large experiments worldwide

- http://pdg.lbl.gov/ is an enormously useful resource and is the starting point for this topic. Explore it.
- HEP/particle physics vs. nuclear physics
- Accelerator-based laboratories:
    - CERN (Geneva, Switzerland)
    - Fermi National Accelerator Laboratory ("Fermilab")
    - Brookhaven National Laboratory; RHIC
    - Jefferson Lab ("JLab")
    - Stanford Linear Accelerator Center ("SLAC")
    - DESY (Hamburg, Germany)
    - KEK (Tsukuba, Japan)
    - JINR (Dubna, Russia)
    - more: http://www-elsa.physik.uni-bonn.de/accelerator_list.html
    - http://en.wikipedia.org/wiki/List_of_accelerators_in_particle_physics

# Survey of large experiments worldwide

Non-accelerator based experiments

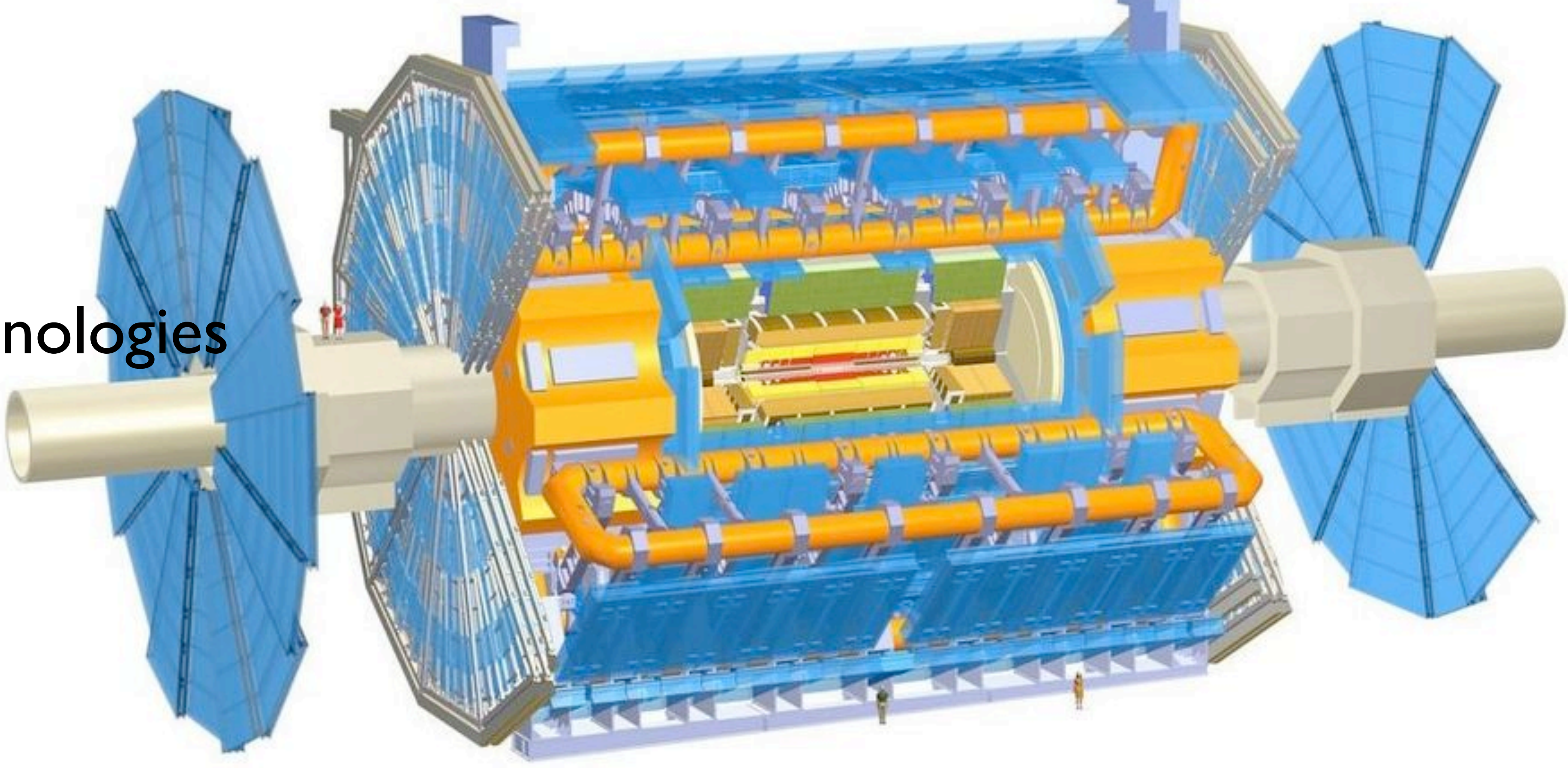
- http://en.wikipedia.org/wiki/List_of_neutrino_experiments
  - e.g., Super-K, SNO+, IceCube...
- Others (see map)

# Accelerator types and operations

- 'Collider' vs. 'fixed target'
- beam types
  - primary beams vs. secondary (tertiary)
  - charged particles - electrons/positrons, protons, ions
  - neutral particles - photons, neutrons, neutrinos
    - see SNS and how it works
    - FNAL main injector:
      - 120 GeV protons on cooled graphite
      - $\rightarrow \pi$, K. Decay in flight:
      - $\rightarrow \nu, \mu$. Large mass of iron:
      - $\rightarrow \nu$

# General characteristics of detector systems



- Combine many technologies
- Granularity
- Resolution
- Separated functions
- Ordering important
  - ATLAS example: 1) collision in vacuum, 2) low-mass tracking in magnetic field, 3) electromagnetic calorimetry, 4) hadronic calorimetry, 5) muon spectrometer with magnetic analysis
- Trigger, data acquisition system, data storage, data processing system

# General characteristics of analysis methods.

- Computer-intensive processing
  - First processing on farm or Grid (ATLAS: > 10 PB/yr)
  - Subsequent processing: attempt to reduce dataset size while retaining needed variables (→ hundreds of TB)
  - Final dataset: reside locally (10‘s TB) or remain on Grid
- Object oriented programming (e.g., Python and $C^{++}$)
- **Shared, validated, documented, archived code**
- “Events” “containers” “hits” “tracks” “particle candidates”
- Kinematic combinations of particle information
- Logical requirements (“cuts”) or probabilistic assignments
- Subtraction of “backgrounds”
- Corrections of data, e.g.: inefficiencies, resolution effects

# Measurement of cross sections; luminosity

# Measurement of cross sections, ratios, luminosity, etc.

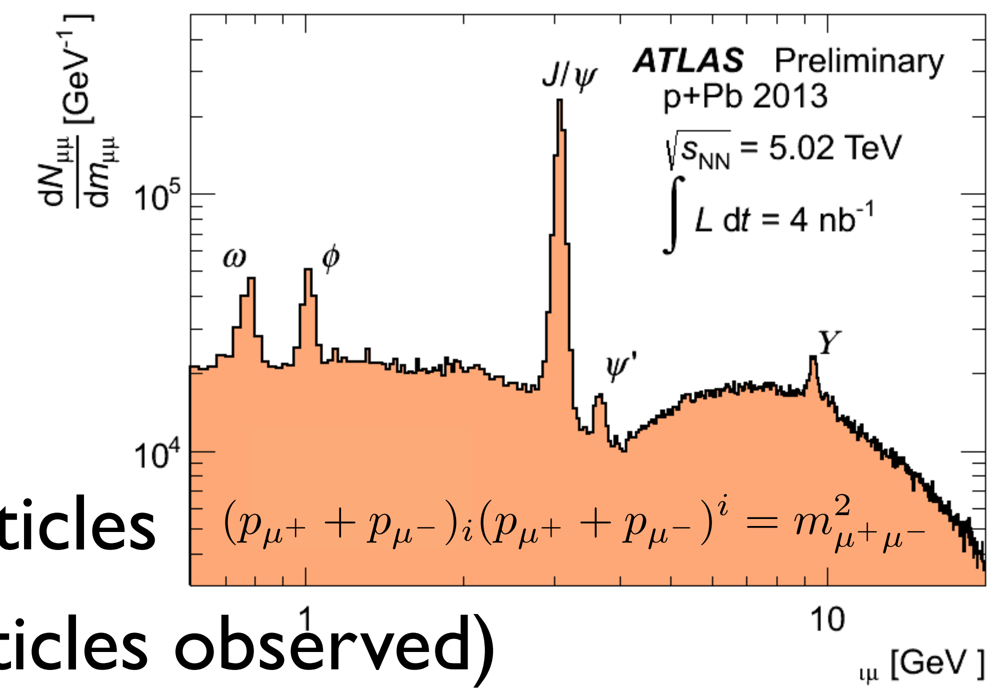
- "Cross section" ~ probability for a process to happen
  - e.g., at CM energy of 8 TeV, p+p $\rightarrow$ 3 jets
- Relationship between cross section, luminosity, rate:

$$\sigma \cdot \mathcal{L} = \mathcal{R}$$

- Units of cross section are *area*. Common unit is a "barn". One barn equals $10^{-24}$ $cm^2$. Unit of rate is $s^{-1}$. Luminosity is often given in $cm^{-2}s^{-1}$. (possible interactions per area, per second)
- This equation can be used to *measure* luminosity if the cross section is known for some particular process. Ratios of cross sections are independent of luminosity, if measured simultaneously. This can result in higher precision. The relation is differentiable:

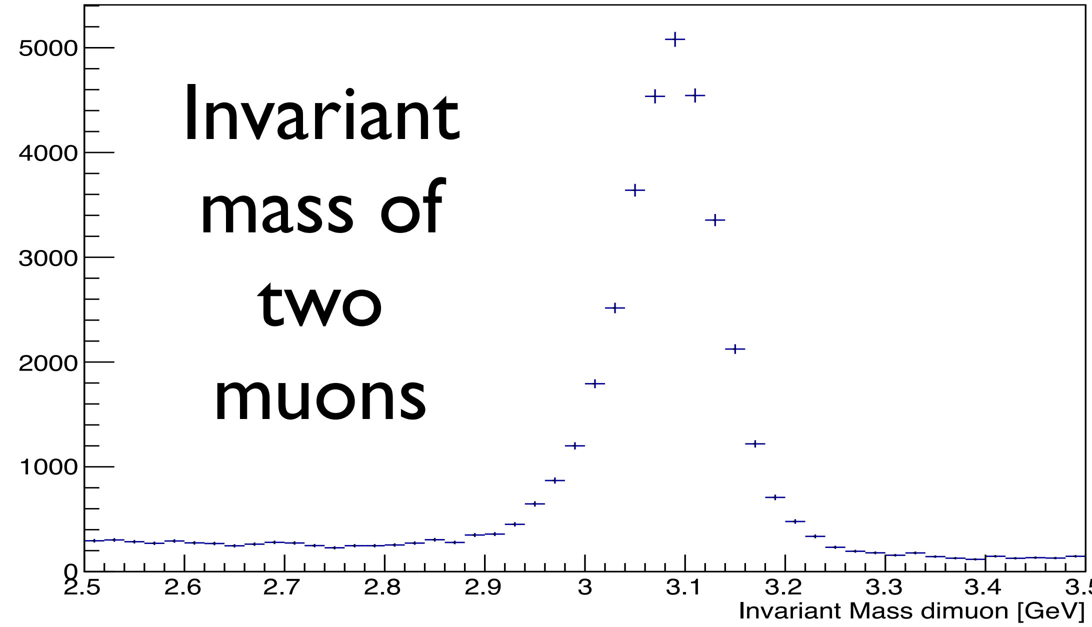
$$\frac{d\sigma(x)}{dx} \cdot \mathcal{L} = \frac{d\mathcal{R}(x)}{dx}$$

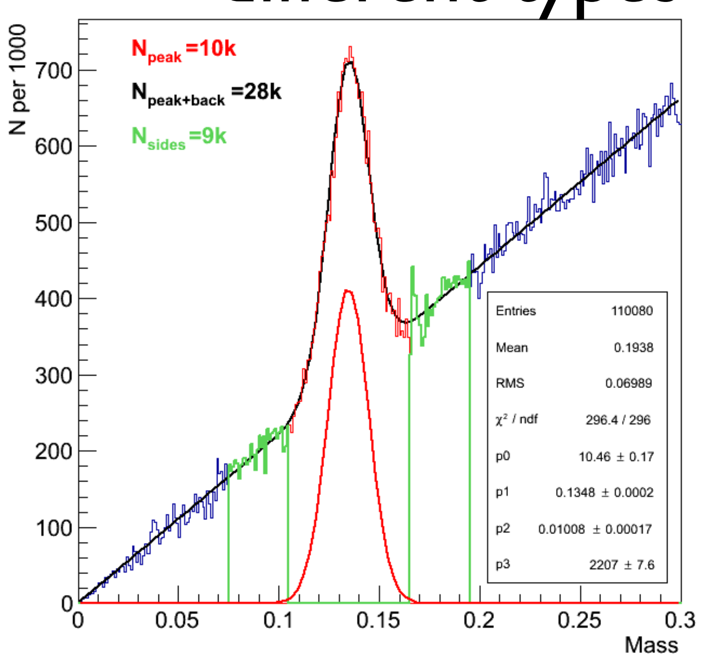
# Techniques for data analysis

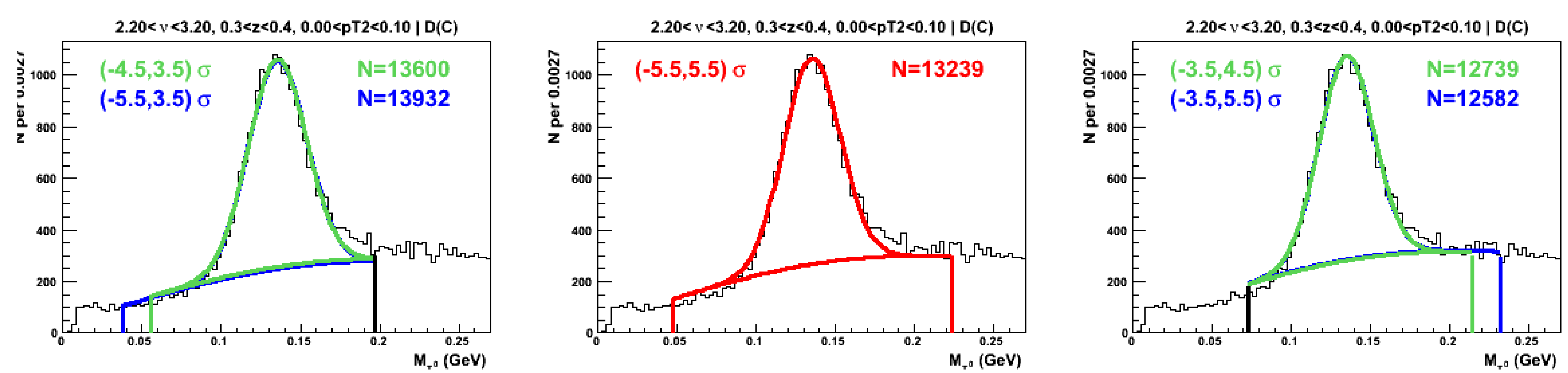



Common examples

- Form kinematic invariant from the observed particles
  - e.g., invariant mass (results in peak if all particles observed)
    - missing mass (low energies)
- Select events of interest
  - by hard cuts
  - by assigning probabilities
- Estimate and remove backgrounds
  - different types of background: random, combinatorial, "physics"



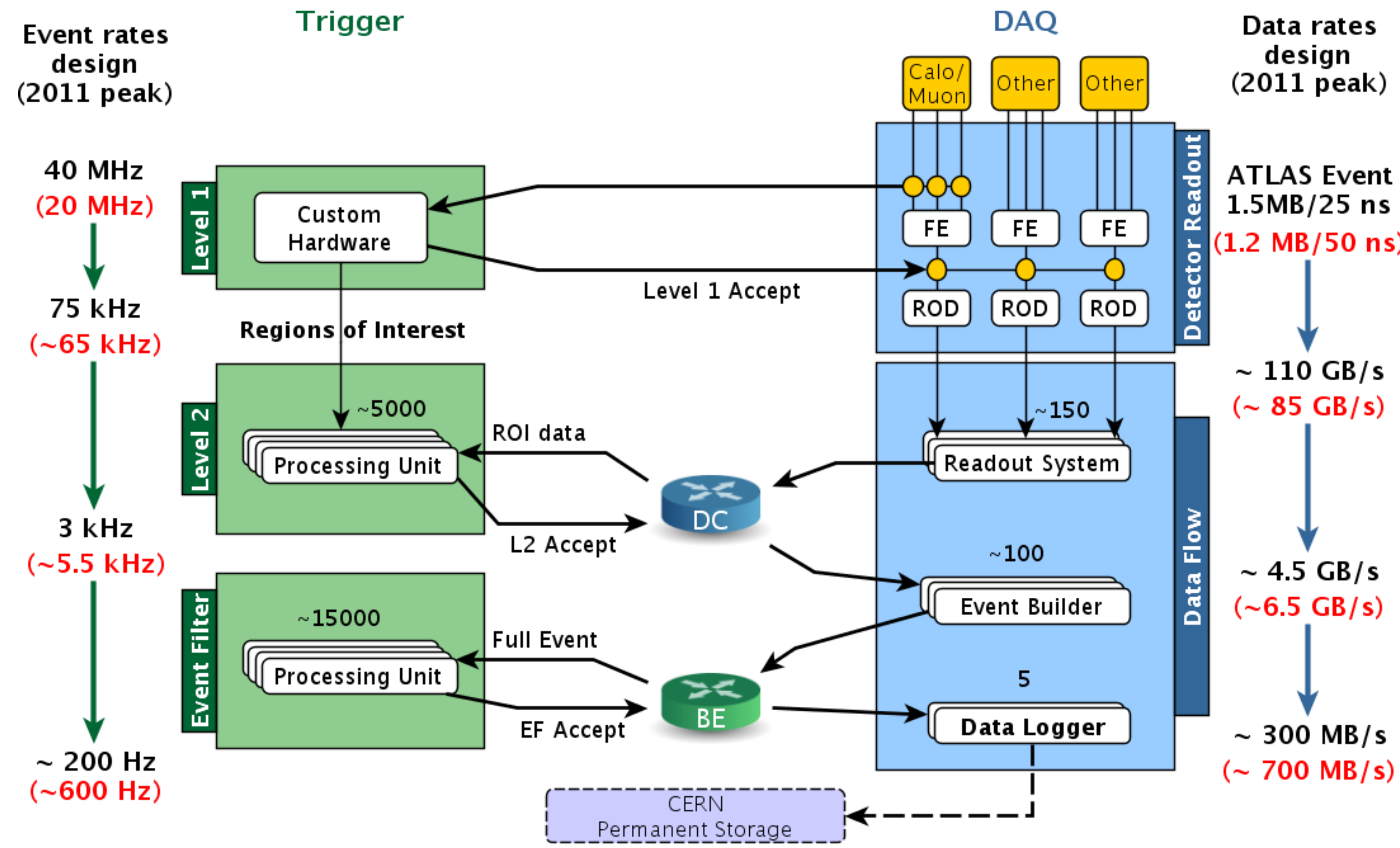

Invariant mass of two photons

# Computing and Data Flow

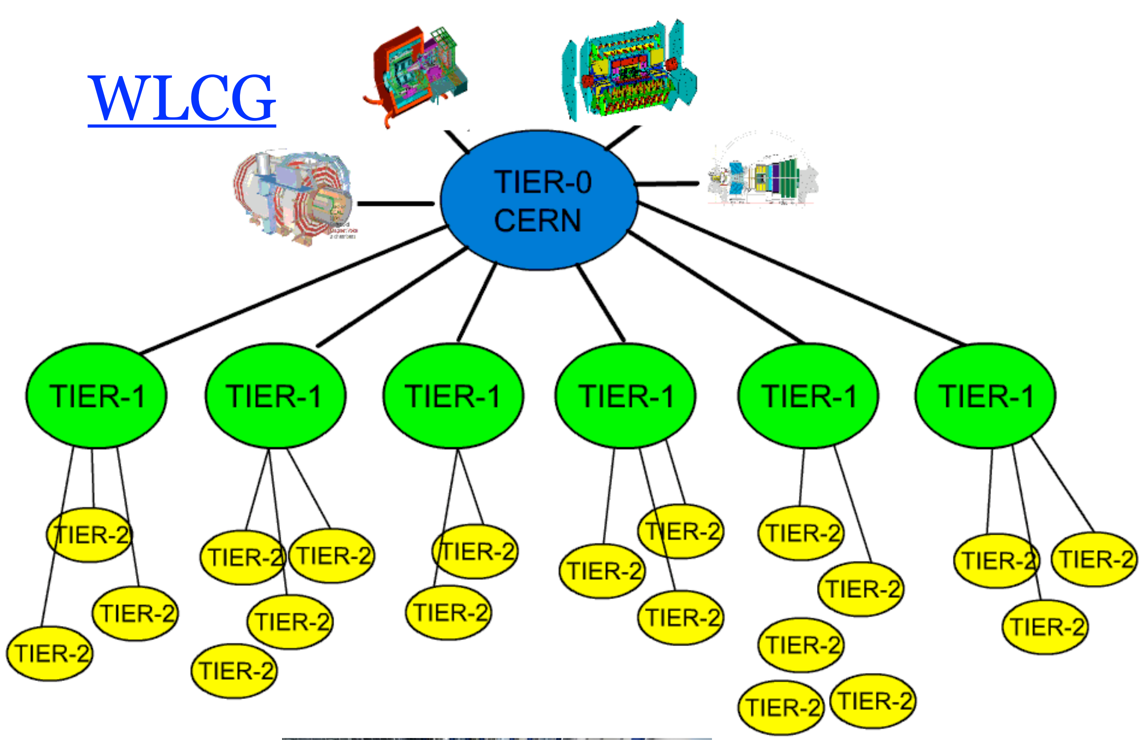
On L1 accept, data are sent from the front end electronics to detector-specific modules (ROD), which build event fragments and push them via ~1600 optical links to dedicated memories. The latter are in charge of storing the data during L2 and EB latencies and are hosted on PCI boards mounted on ~150 PCs (ROS).

The backbone of the TDAQ system is composed of two Gigabit Ethernet networks: the data collection (DC) and the back end (BE). The DC network allows the L2 and EB systems to collect the data from the ROSes, while the BE network is used to move built events from the EB to the EF and accepted events from EF to the data logger system.

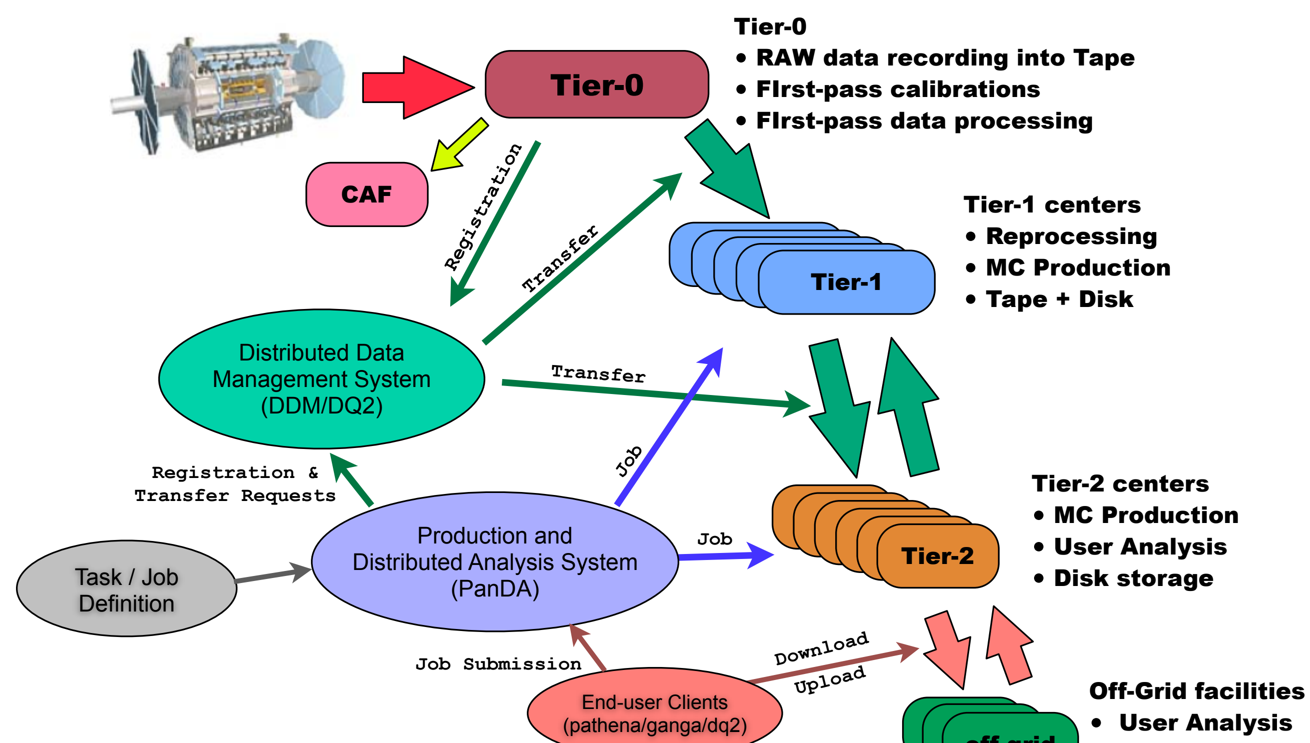
(adapted from A. Negri [paper for ICHEP 2012](paper for ICHEP 2012))




[WLCG](WLCG)




[The Tier 0 farm](The Tier 0 farm)

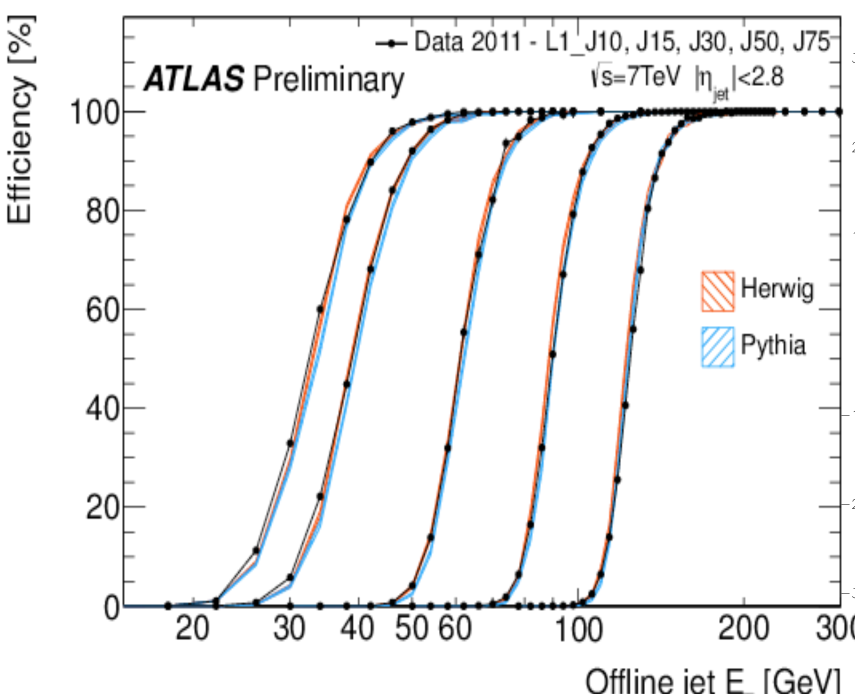



Adapted from I. Ueda's [2012 ICHEP talk](2012 ICHEP talk)

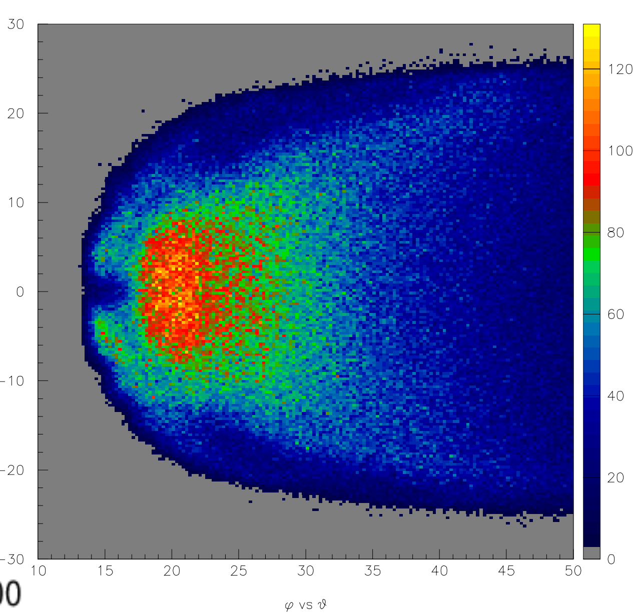
# Data Corrections

There are many reasons that data need to be "corrected." The reasons depend on the detector, the beam type, and other factors. Examples:

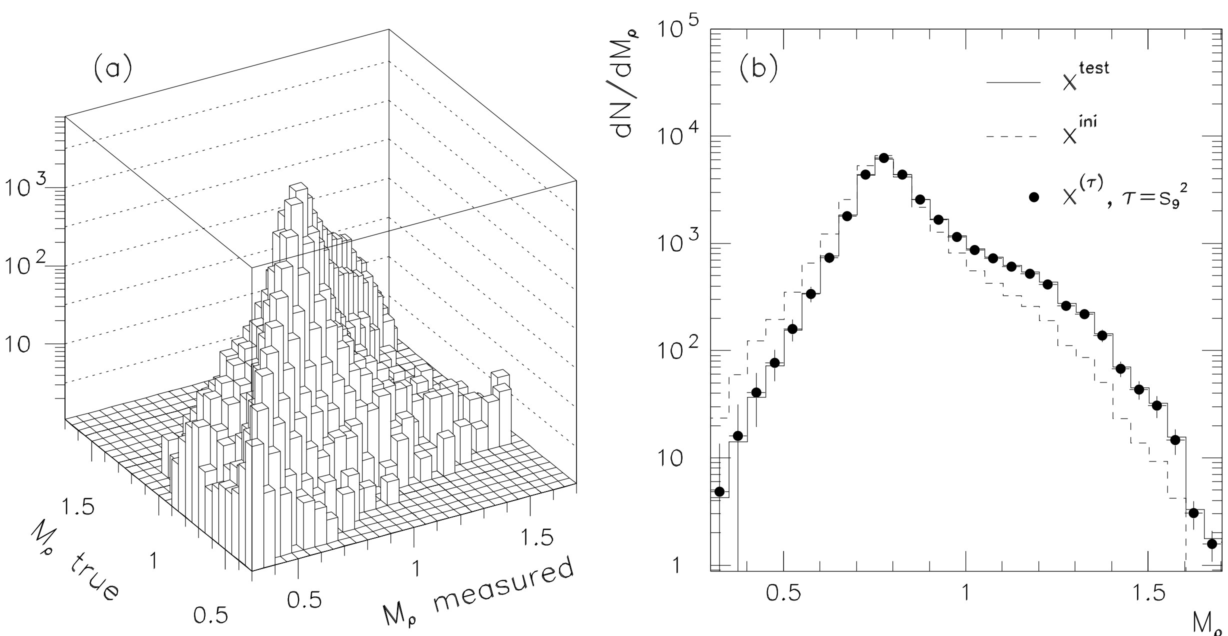
- Efficiency - detection, trigger, reconstruction, deadtime, etc.
- Acceptance - multi-variable, can be correlated for multiple particles, also takes into account losses and distortions due to many processes
- Kinematic - distortions, energy loss, etc.
- Radiation (lepton beams, particularly electron/positron beams)
- Resolution [unfolding](), such as with the [SVD method]()




Example of ATLAS [trigger efficiency]()



CLAS [electron acceptance]() for fixed momentum: laboratory angles. Grey areas have zero acceptance.




Resolution unfolding for rho meson reconstruction from [Hoecker and Kartvelishvili]()

# Classes of particle measurements: momentum vectors for charged hadrons (tracking)

Preface: we are performing experiments to learn about physics through detecting particles.

Ideal:

1. Measure all particles in each event - none missed
2. Perfect measurement quality - no inefficiency, resolution
3. Identify all particle types that are measured
4. Determine momentum vector and vertex for each particle

Reality: (1) acceptance limitations; (2) inefficiencies/resolution/distortion of measured properties; (3) can identify some particles within some momentum ranges; (4) can determine momentum vector ***p*** and vertex origin ***r*** for charged particles.

Also, some neutral particles decay into charged particles, so ***p*** and ***r*** can often be determined for them.

# Tracking

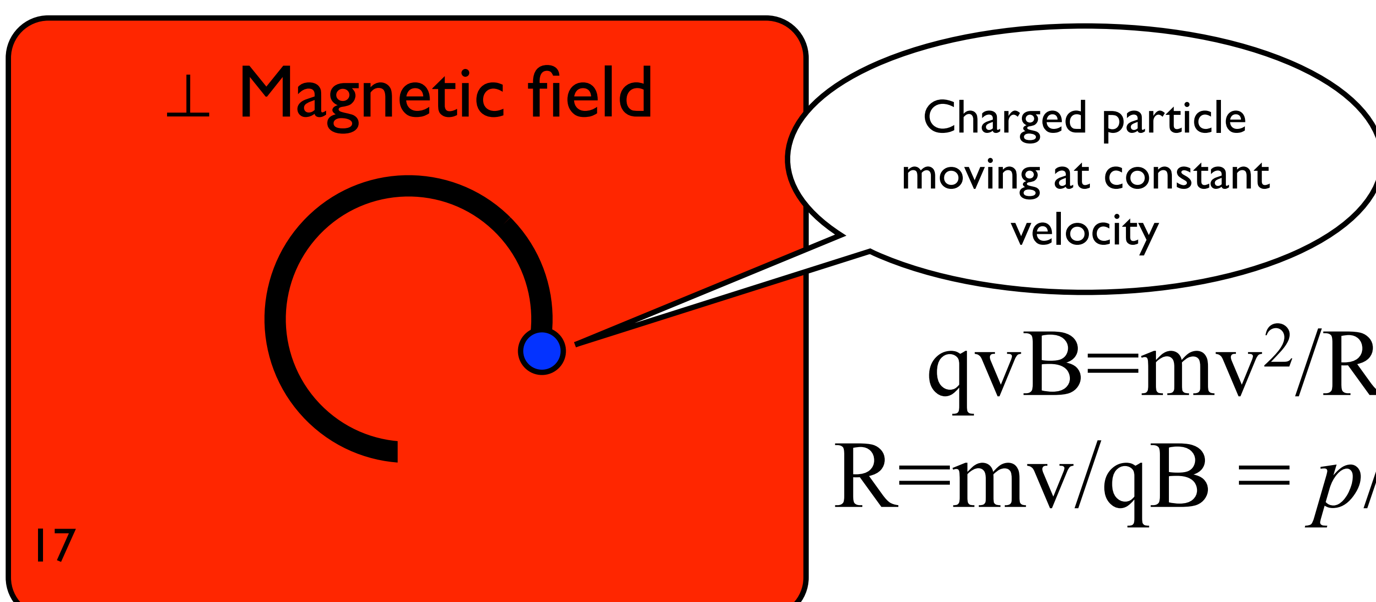
- With "tracking" of charged particles we sample the particle trajectories as they pass through a magnetic field
  - measure how much they bend → momentum
  - measure their directions → vertex, matching
- *Sample* particle trajectories in various ways:
  - solid state detectors
    - silicon-based detectors
    - scintillators (fibers/strips)
  - gas-based detectors (MWPC {Nobel prize 1992 - Georges Charpak} drift chambers, MPGDs, etc)
  - Other position-sensitive detectors

## 4. Determine momentum vector and vertex for each particle

(4) can determine momentum vector ***p*** and vertex origin ***r*** for <u>charged particles</u>

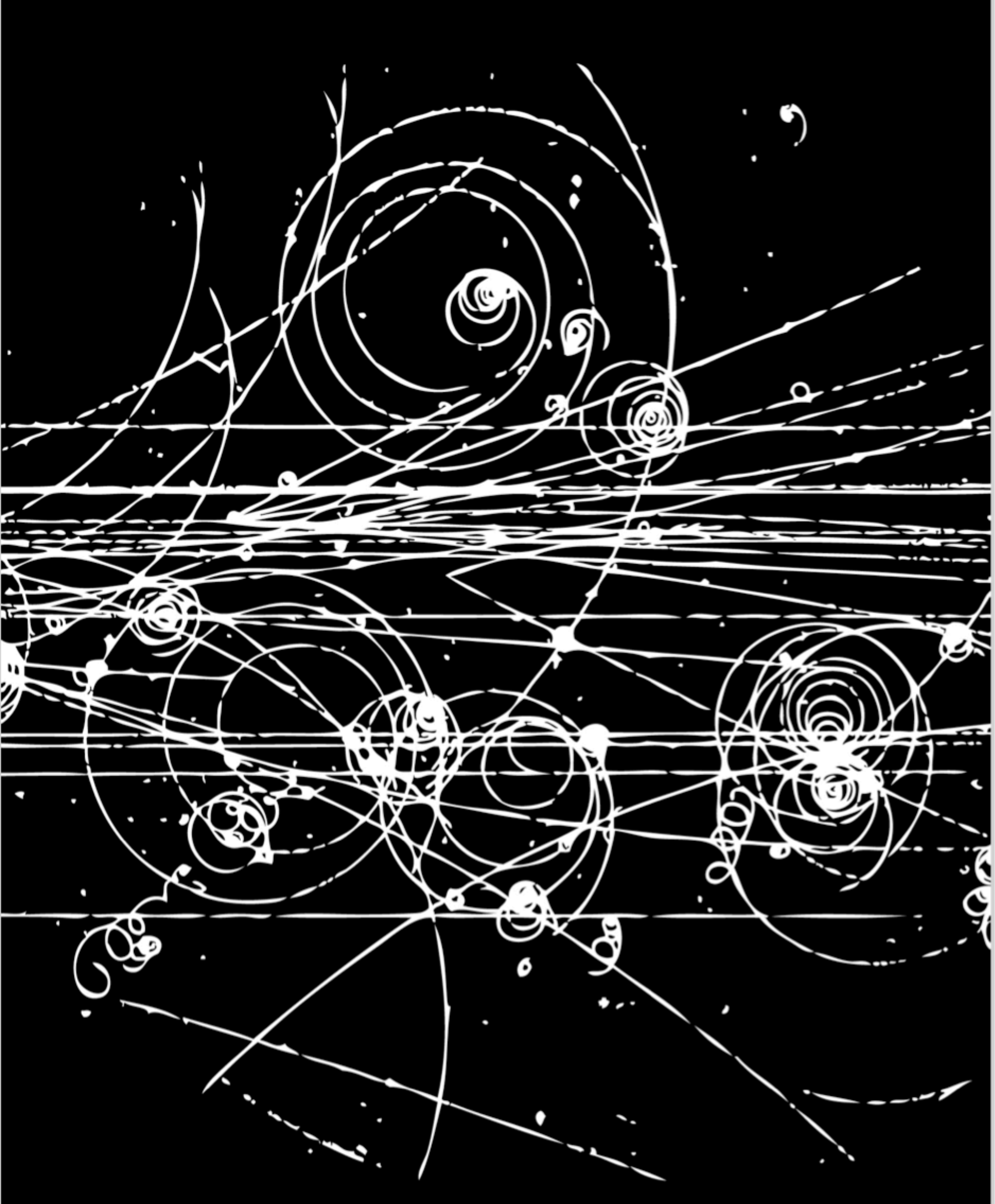
Determination of ***p*** and ***r*** for charged particles is usually the foundational function for all accelerator-based experiments

Recall: charged particle with constant velocity in a constant magnetic field perpendicular to the velocity moves in circular path:




$$qvB=mv^2/R,$$
$$R=mv/qB = p/qB$$

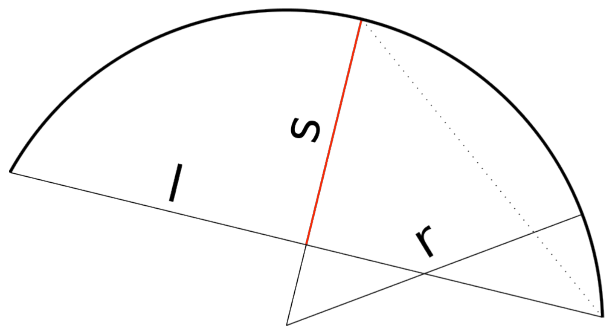
This is the principle we use in measuring momentum - measure the trajectory in a known magnetic field, calculate ***p***



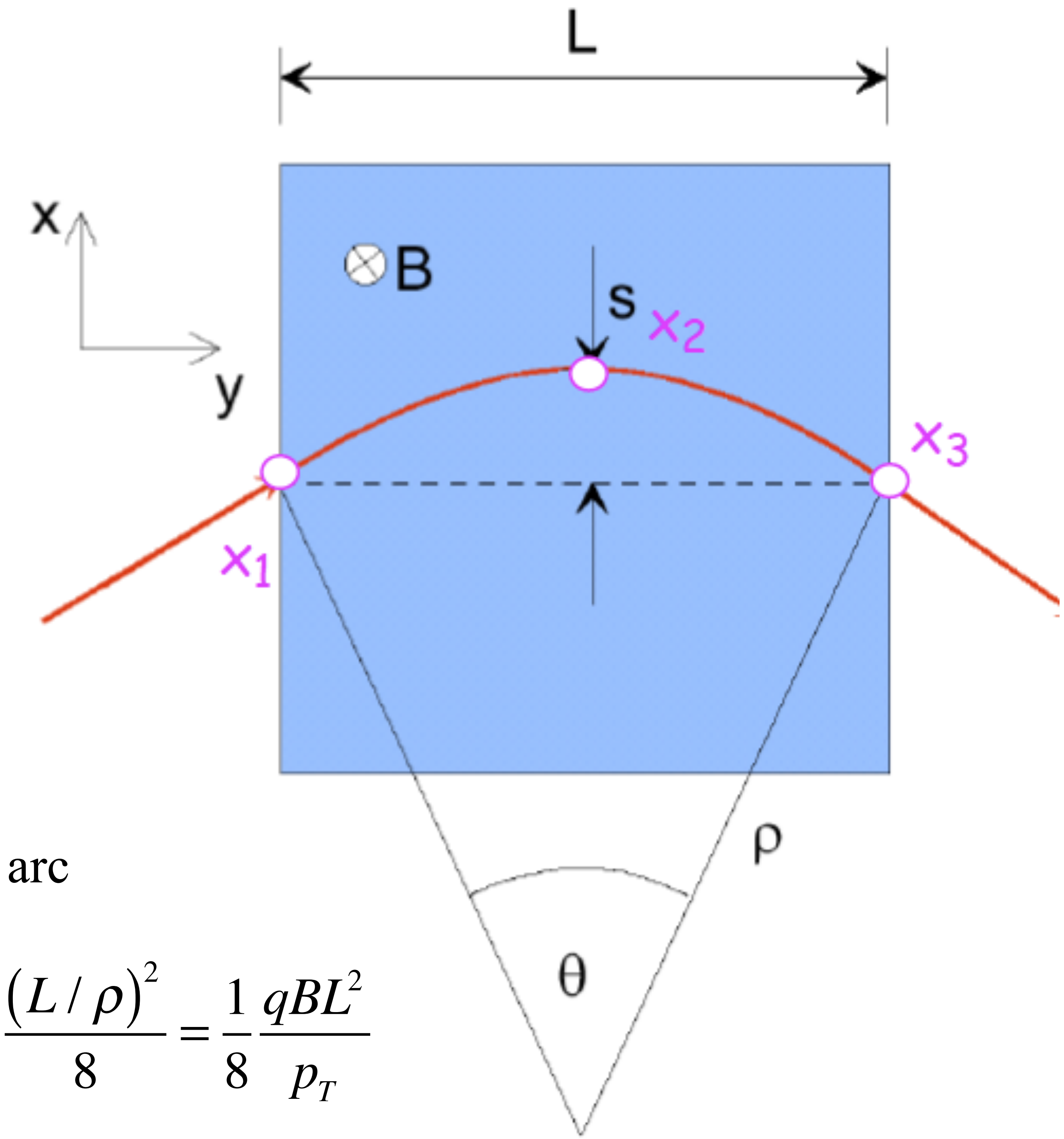
# Bubble Chamber

Invented 1952,
Nobel prize 1960,
used through 1970's

# Momentum measurement method (pedagogical)




"Sagitta" **s** (red line)




$\rho = \dfrac{p_T}{qB}$ Radius of circular arc

Sagitta is: $s = \rho\left(1 - \cos\dfrac{\theta}{2}\right) \approx \rho\dfrac{\theta^2}{8} \approx \rho\dfrac{(L/\rho)^2}{8} = \dfrac{1}{8}\dfrac{qBL^2}{p_T}$

$p_T = \dfrac{1}{8}\dfrac{qBL^2}{s}$ Momentum transverse to the direction of the magnetic field, $p_T$

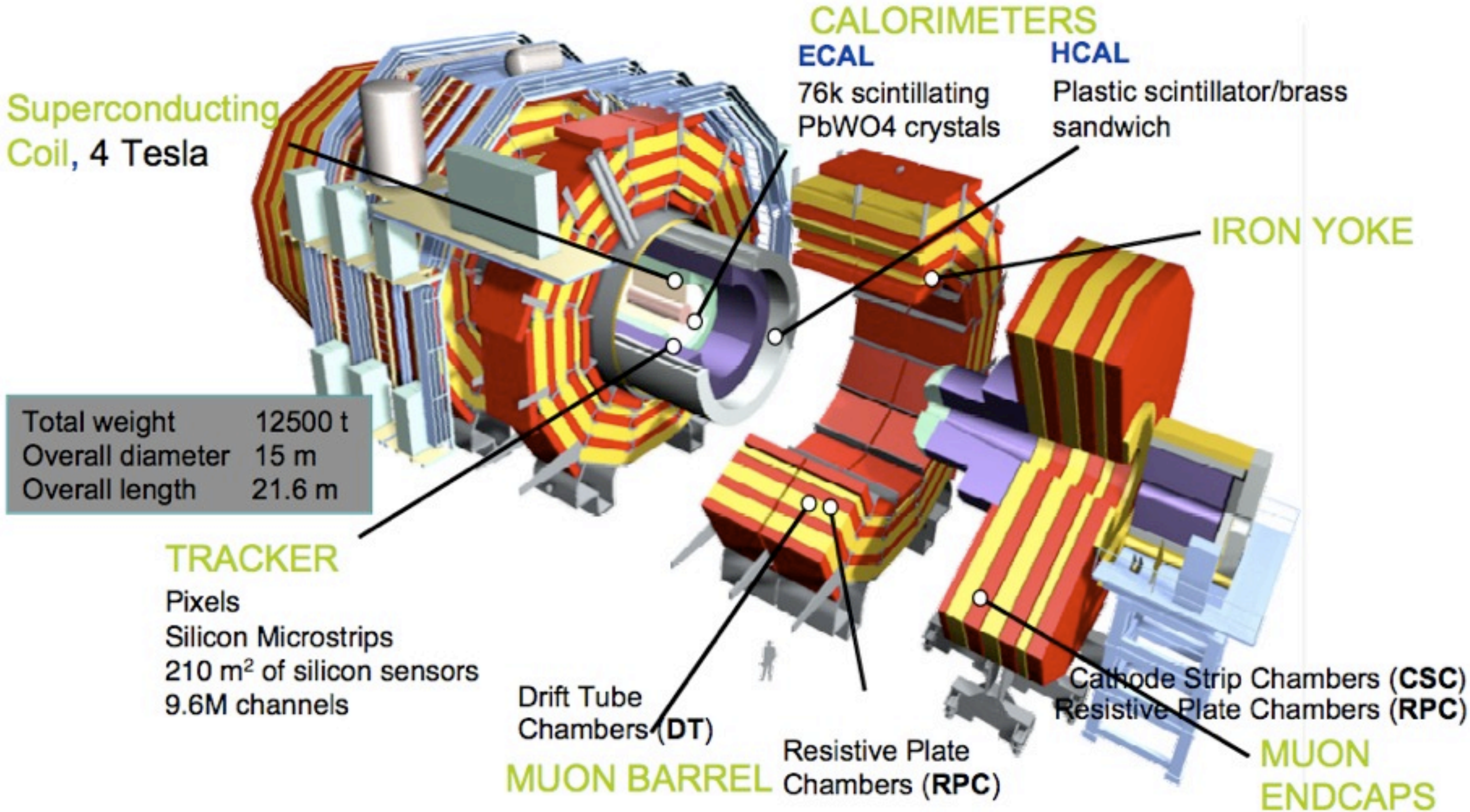
If we measure the trajectory well enough to determine the sagitta for known magnetic field, we measure $p_T$

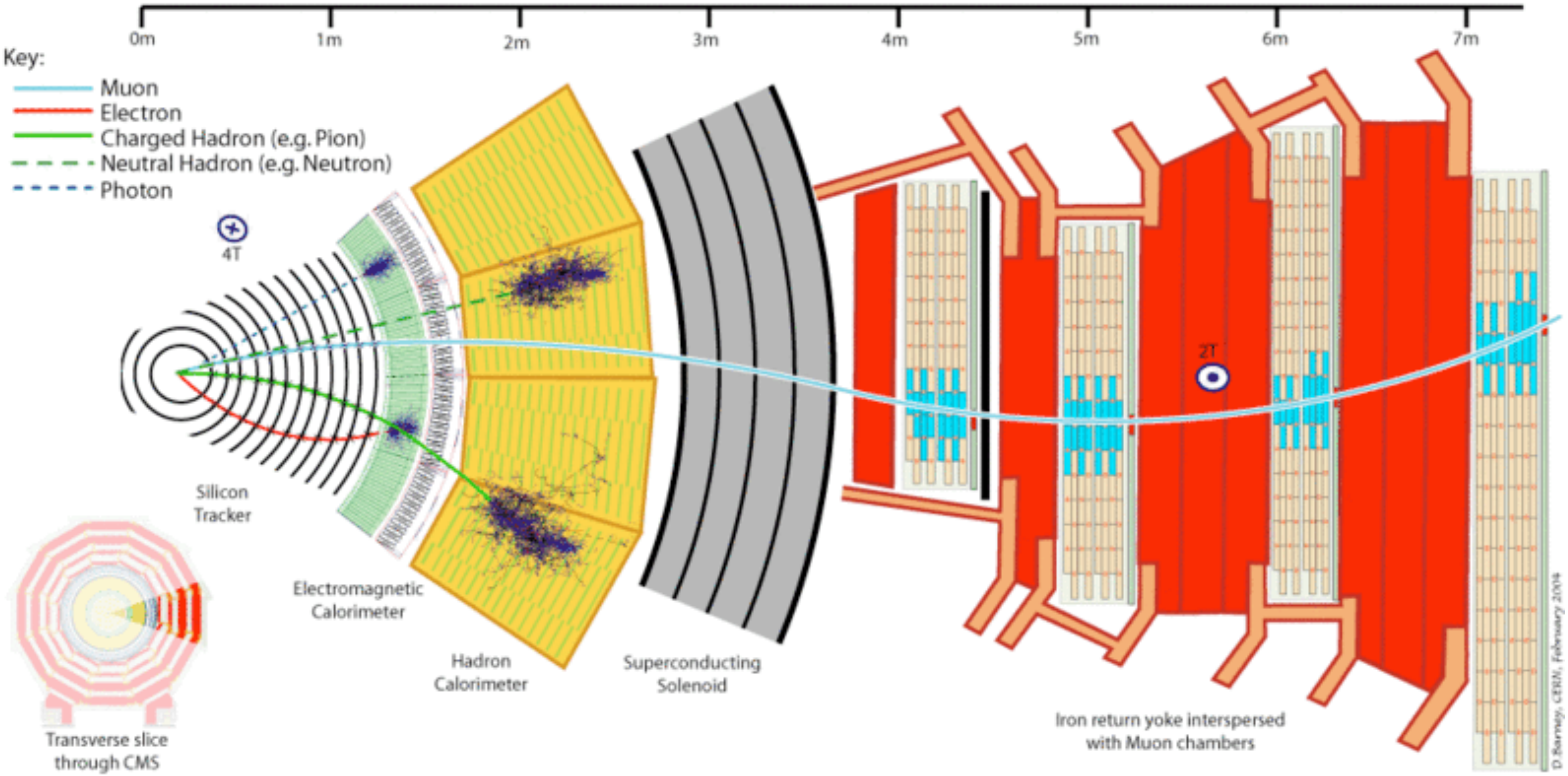
“If we measure the trajectory well enough to determine the sagitta for known magnetic field, we measure $p_T$”

- “Well enough” → precision of position determination:
    - granularity of position readout (e.g., semiconductor pixels detectors)
    - position resolution (e.g., gas-based detectors; calibrations, gas system control)
    - high degree of control in fabrication quality
    - high precision alignment (potentially including, e.g., thermal control and continuous alignment monitoring)
- “known magnetic field” → superconducting magnets
    - precise knowledge of coil placement, under load
    - extensive specialized subfield

The determination of charged particle trajectories in a magnetic field is called “tracking.” Systems that do this are called “tracking systems.” Some tracking systems follow:

# The CMS Experiment

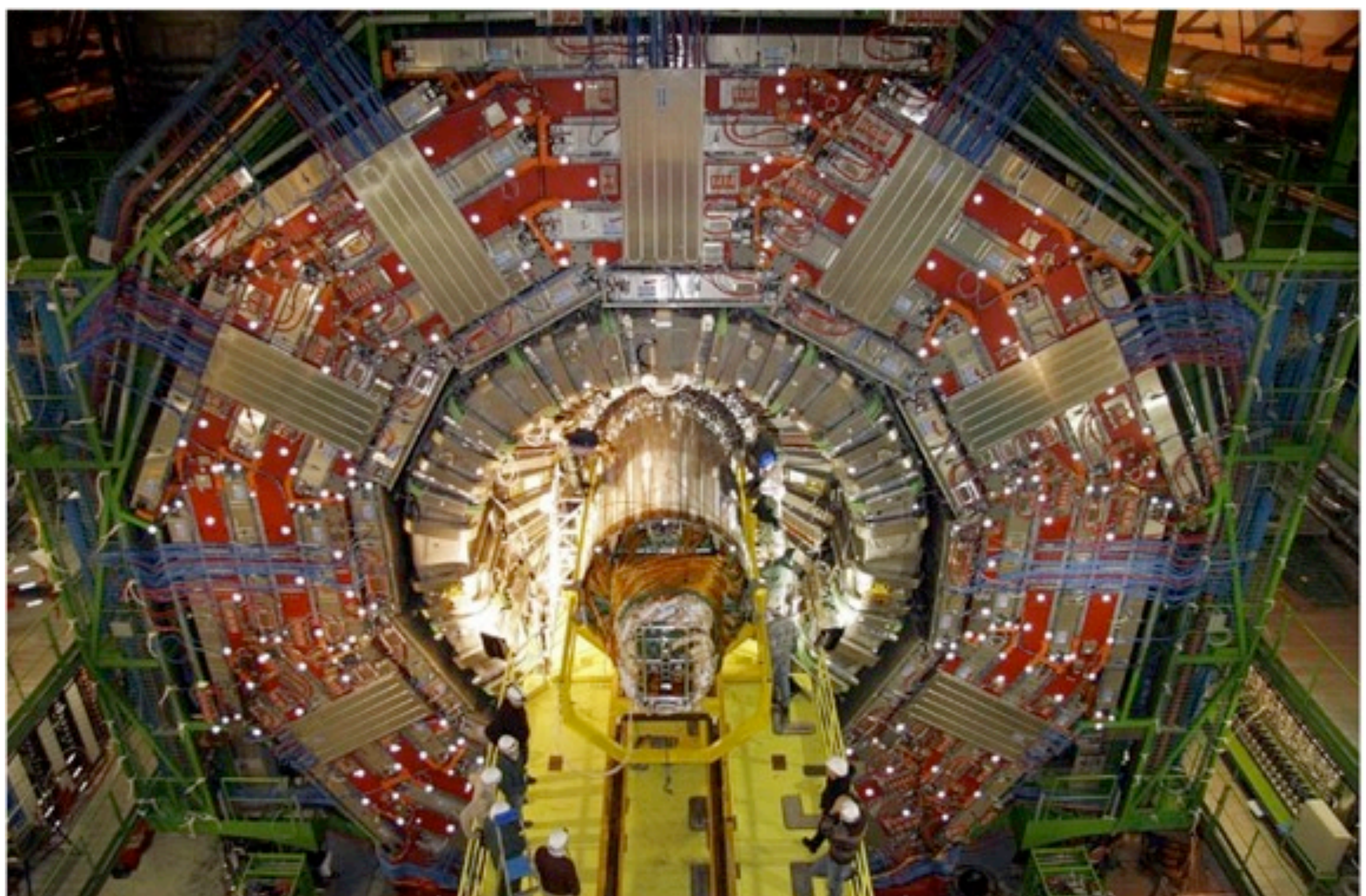


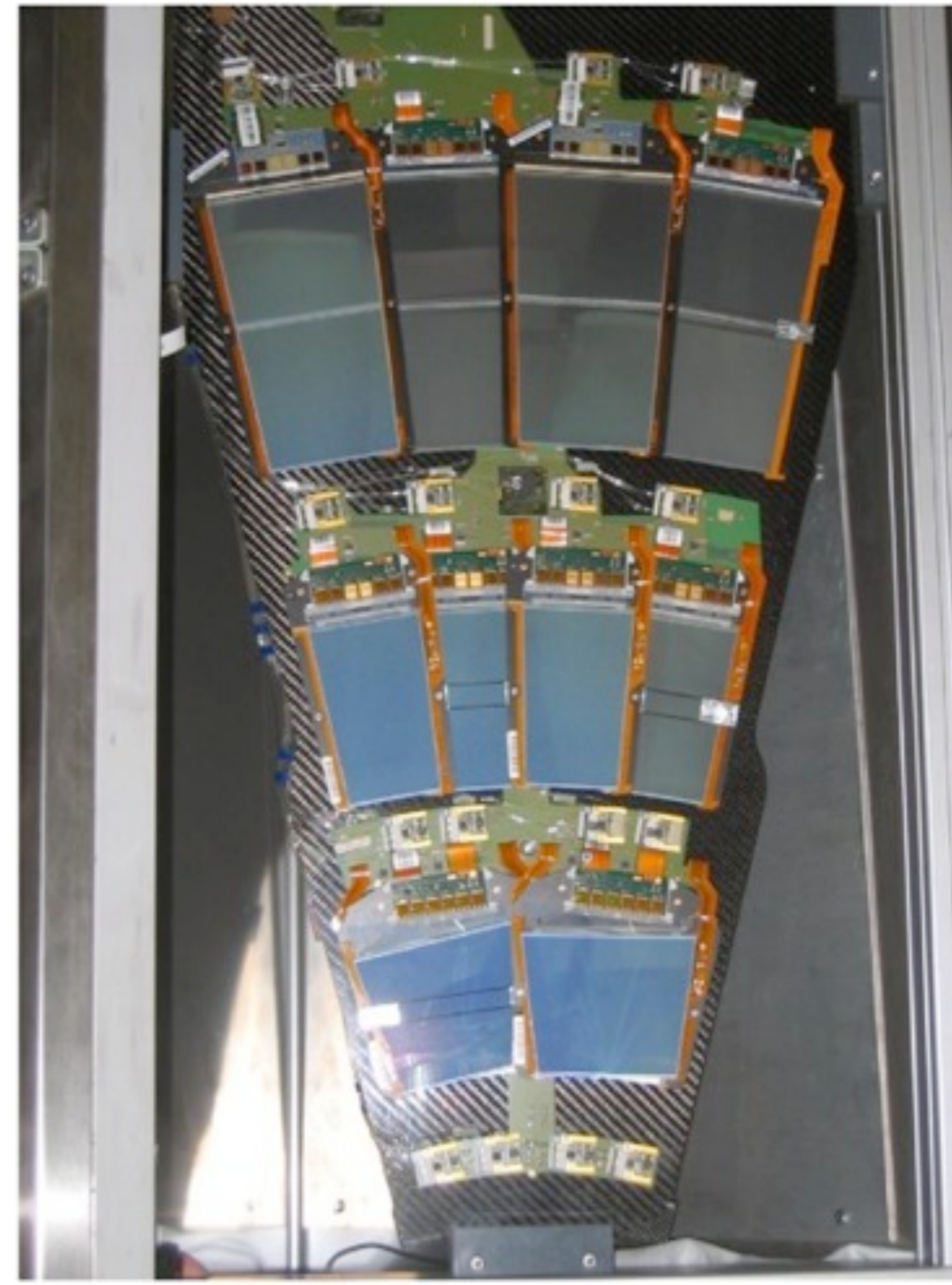


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

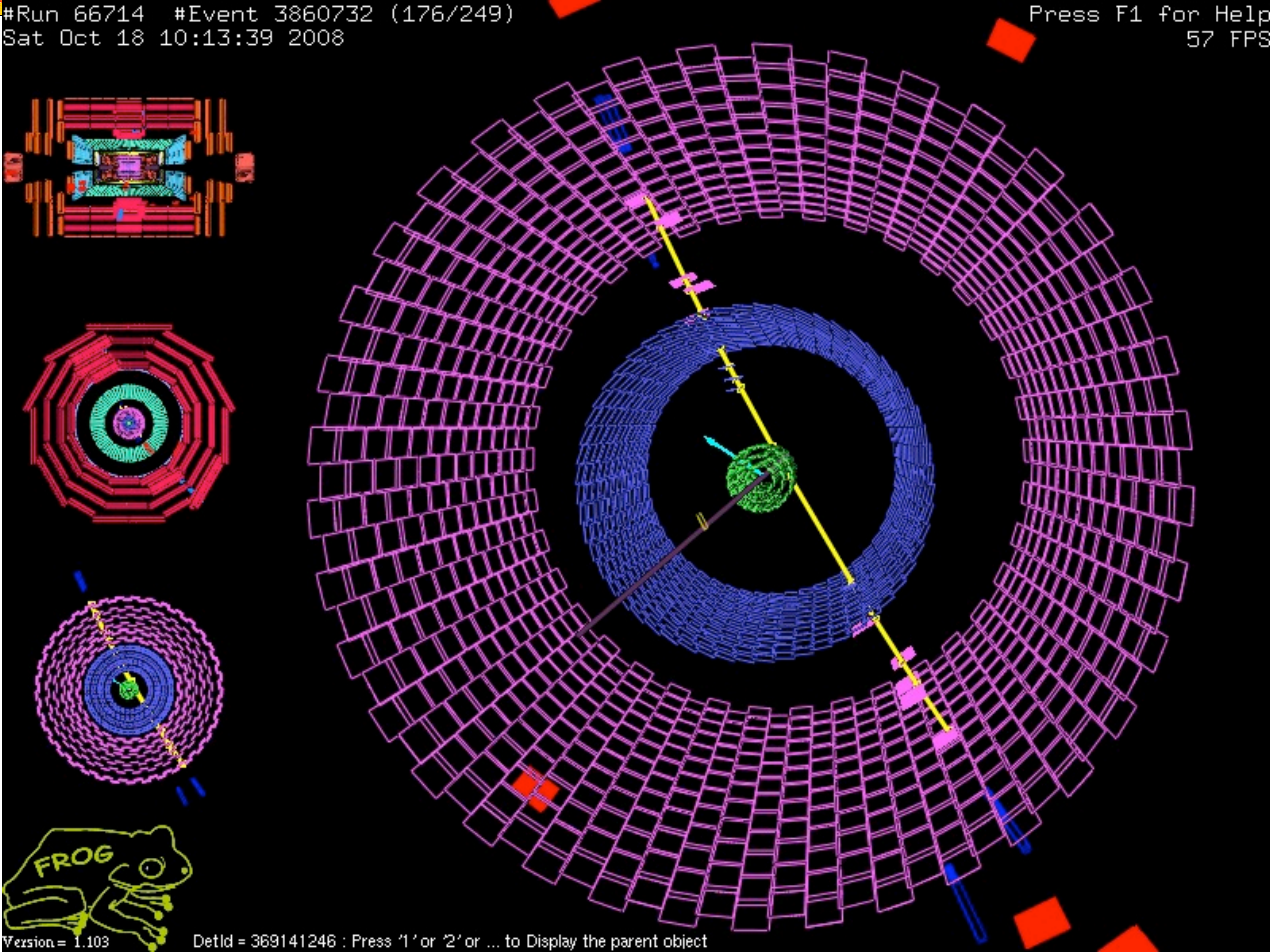
# CMS Silicon Tracker

Silicon Microstrips: 214 $m^2$ of silicon strip sensors, 11.4 million strips, diameter: 2.4 m

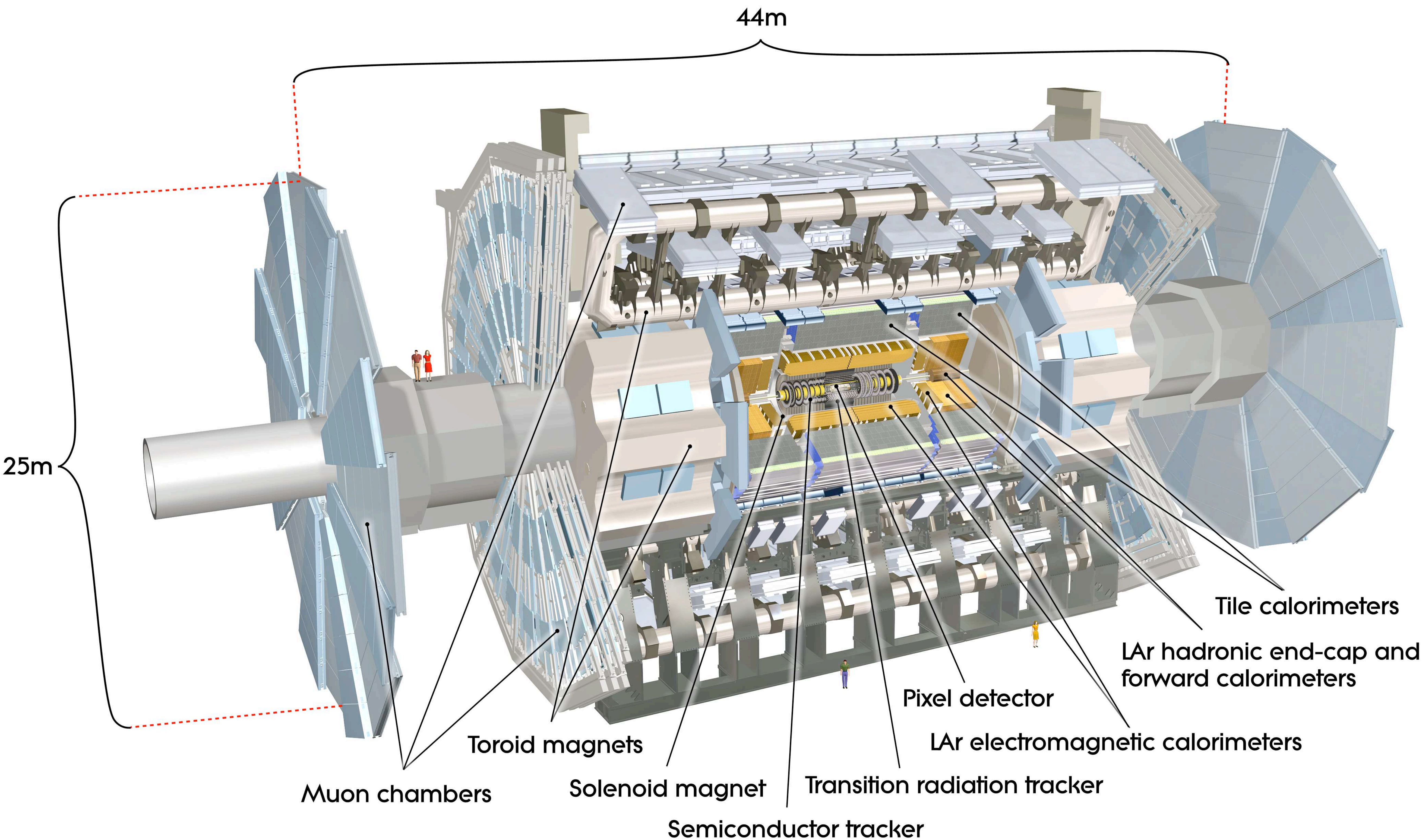




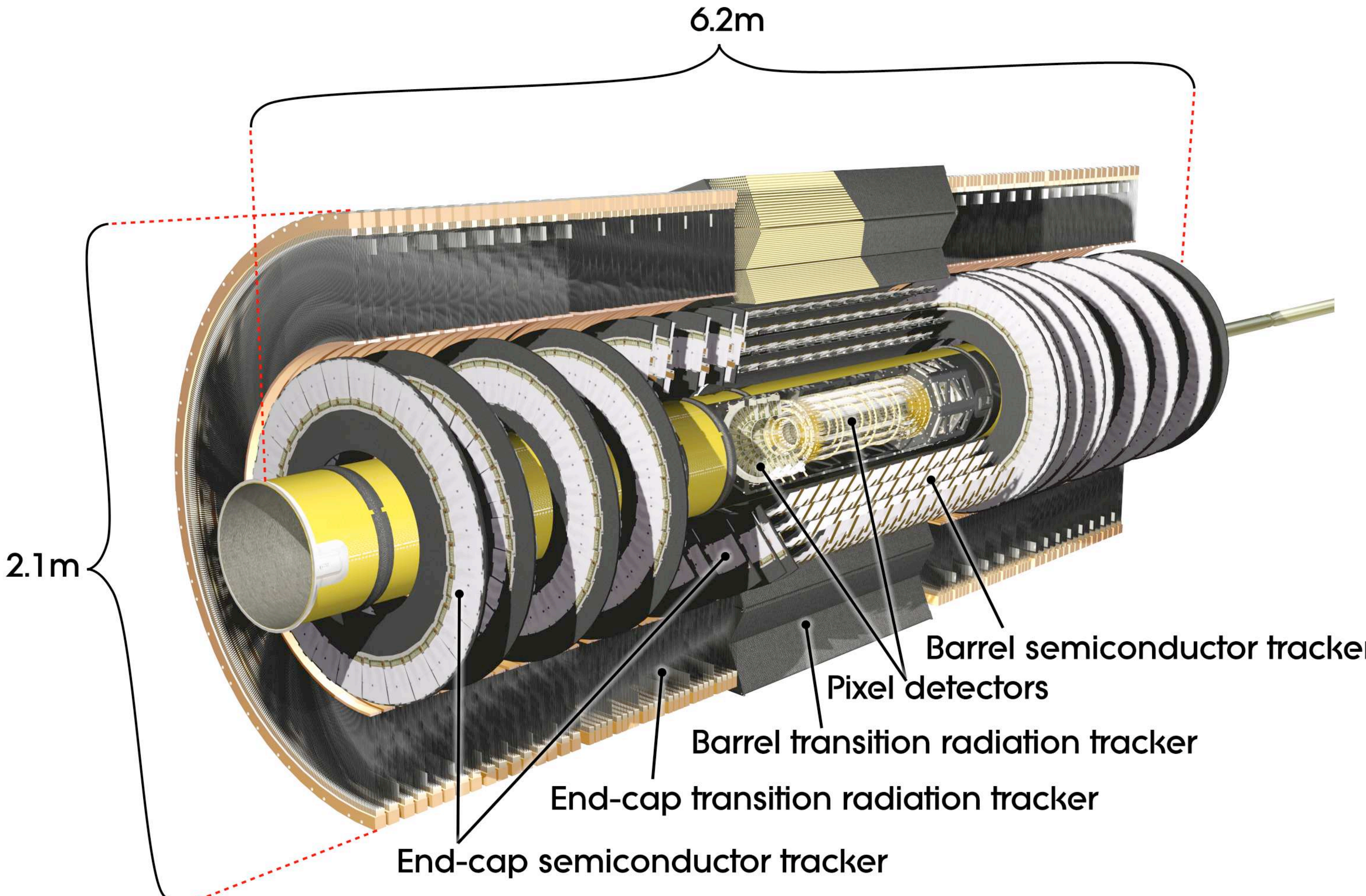
Silicon pixel tracker:
Inner 3 layers: silicon pixels ( $1m^2$), 66 million pixels ($100 \times 150\ \mu m^2$). Precision: $\sigma(r\varphi) \sim \sigma(z) \sim 15\ \mu m$


#Run 66714 #Event 3860732 (176/249)
Sat Oct 18 10:13:39 2008
Press F1 for Help
57 FPS
FROG
Version = 1.103
DetId = 369141246 : Press '1' or '2' or ... to Display the parent object

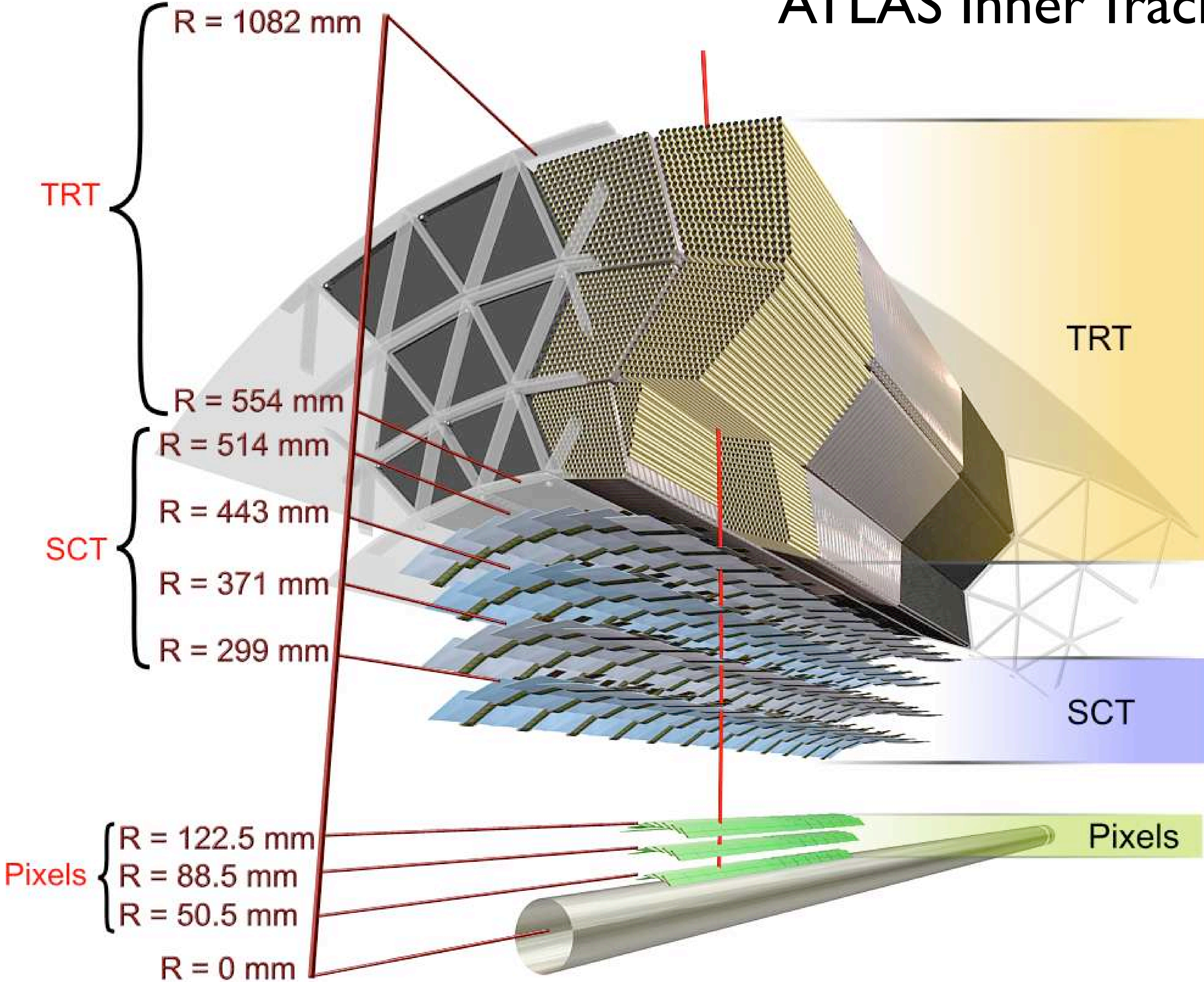
# ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

# ATLAS Inner Tracker - barrel



# ATLAS Inner Tracker



# ATLAS Inner Tracker

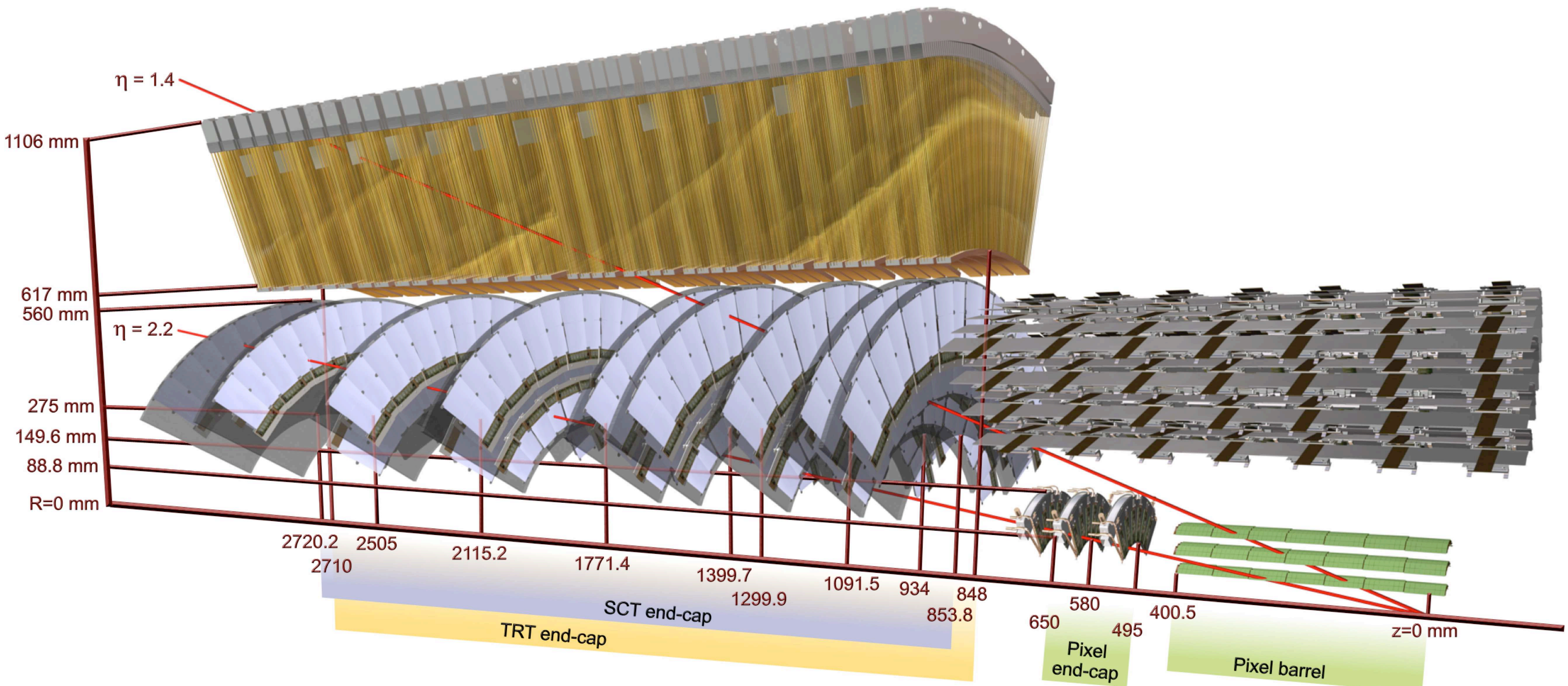
**Pixel Detector**
3 pixel layers
Pixel size in R-φ × z: 50 × 400 μm2
Barrel accuracies are 10 μm (R-φ), 115 μm (z)
Disk accuracies are 10 μm (R-φ), 115 μm (R)
80.4 million readout channels!

**Silicon Strip Tracker SCT**
Barrel
8 strip layers (4 space points) per track
stereo strips (40 mrad) parallel to z
6.4 cm long daisy chained sensors (80 μm pitch) accuracies 17 μm (R-φ), 580 μm (z)

Endcap
set of radial strips
set of stereo strips (40 mrad)
mean pitch about 80 μm
accuracies 17 μm (R-φ), 580 μm (z)

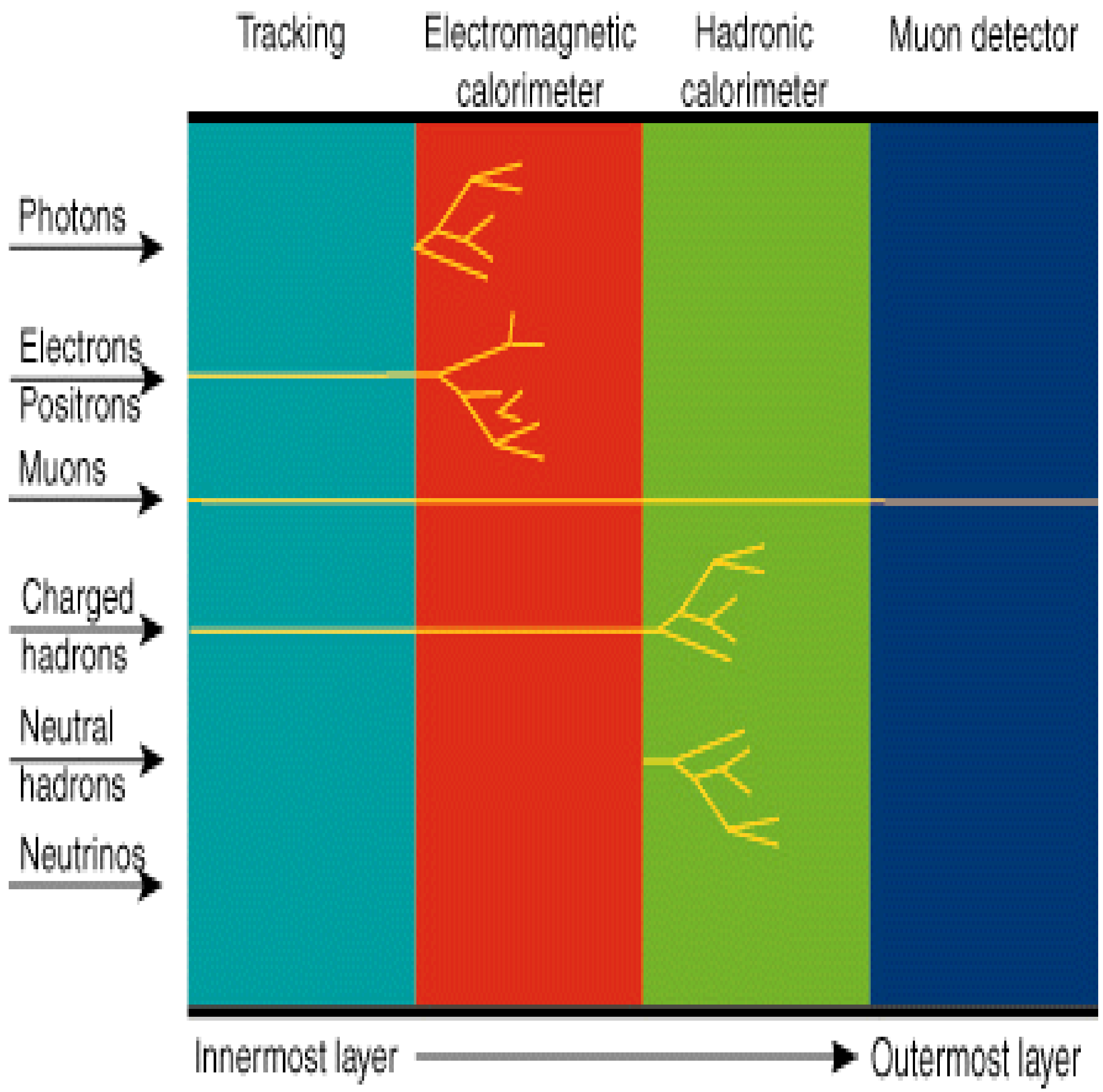
**Transition Radiation Tracker TRT**
351 000 readout channels
36 hits per track
4 mm diameter straw tubes
144 cm long straws, divided in 2 halves
accuracy 130 μm per straw endcap 37 cm long radial straws

# ATLAS Inner Tracker, endcap



# How do {tracking} detectors work?

(how do particles interact with matter??)



# Energy loss of particles passing through matter

- The energy deposited by a particle in the detector elements must be large enough so that a reliable signal can be formed from it

- This can place minimum limits on the detector thickness: more thickness → more energy deposited → bigger signal

- Relativistic Formula: Bethe (1932), others added more corrections later
- Gives "stopping power" (energy loss = *dE/dx*) for charged particles passing through material:

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

where

$A$, $Z$: atomic mass and atomic number of absorber

$z$: charge of incident particle

$\beta, \gamma$ : relativistic velocity, relativistic factor of incident particle

$\delta(\beta\gamma)$: density correction due to relativistic compression of absorber

$I$: ionization potential

$T_{max}$: maximum energy loss in a single collision;

$dE/dx$ has units of MeV $cm^2/g$

$x$ is $\rho\, s$, where $\rho$ is the material density, $s$ is the pathlength

# Ionization Loss: minimum ionization

- Position of minimum is a function of $\beta\gamma = p/Mc$
- occurs around $p/Mc$ = 3-3.5

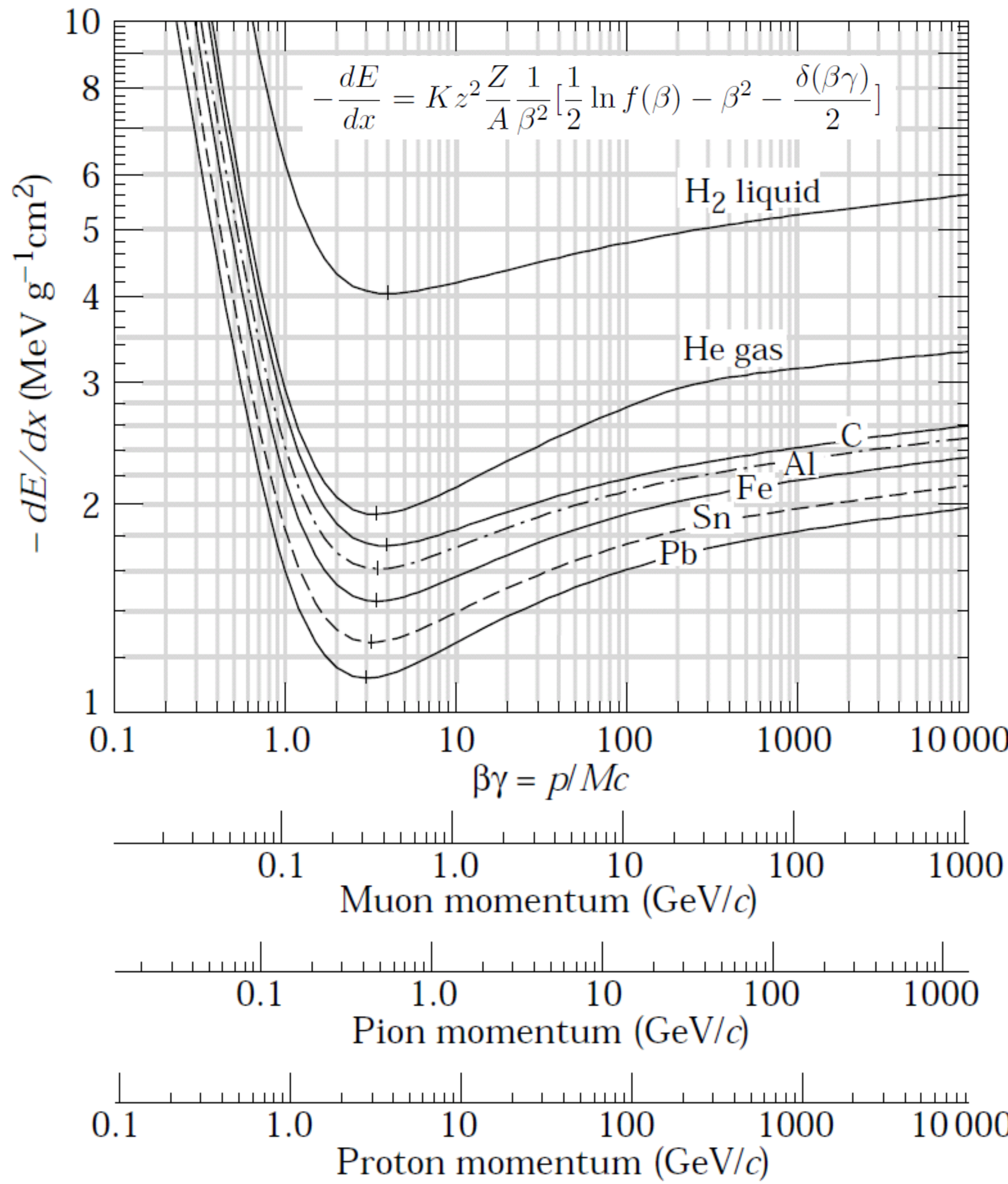
  ~ independent of material
- Characteristic shape of $1/\beta^2$ fall-off followed by relativistic rise
- Approximate value (e.g., for plastics and common low-Z materials):

  $dE/dx \sim 2$ MeV/cm $\times\rho$ (g/cm$^3$)
- Typical values:
  - liquids/solids:

    ~ few MeV/cm
  - gases:

    ~ few keV/cm

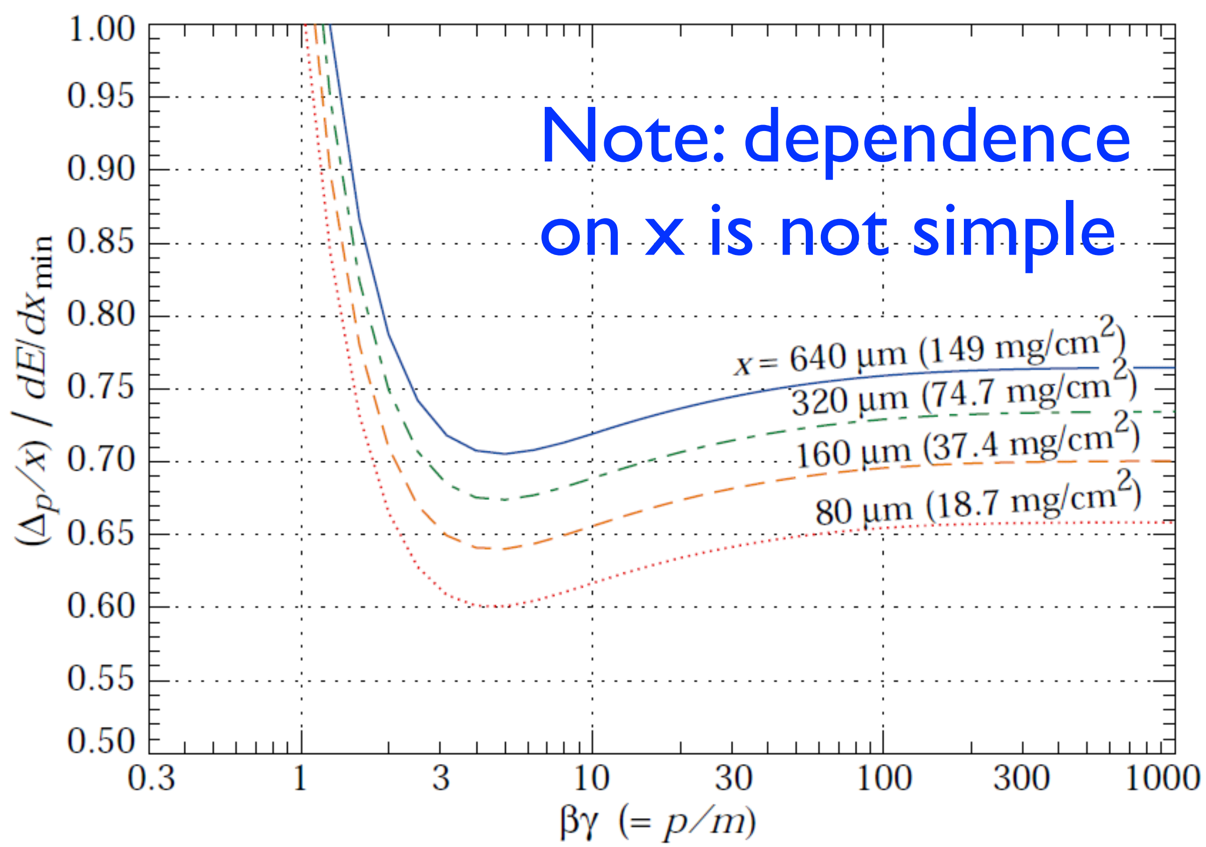
  $\Rightarrow$ valid over wide range of most common momenta in accelerator-based experiments



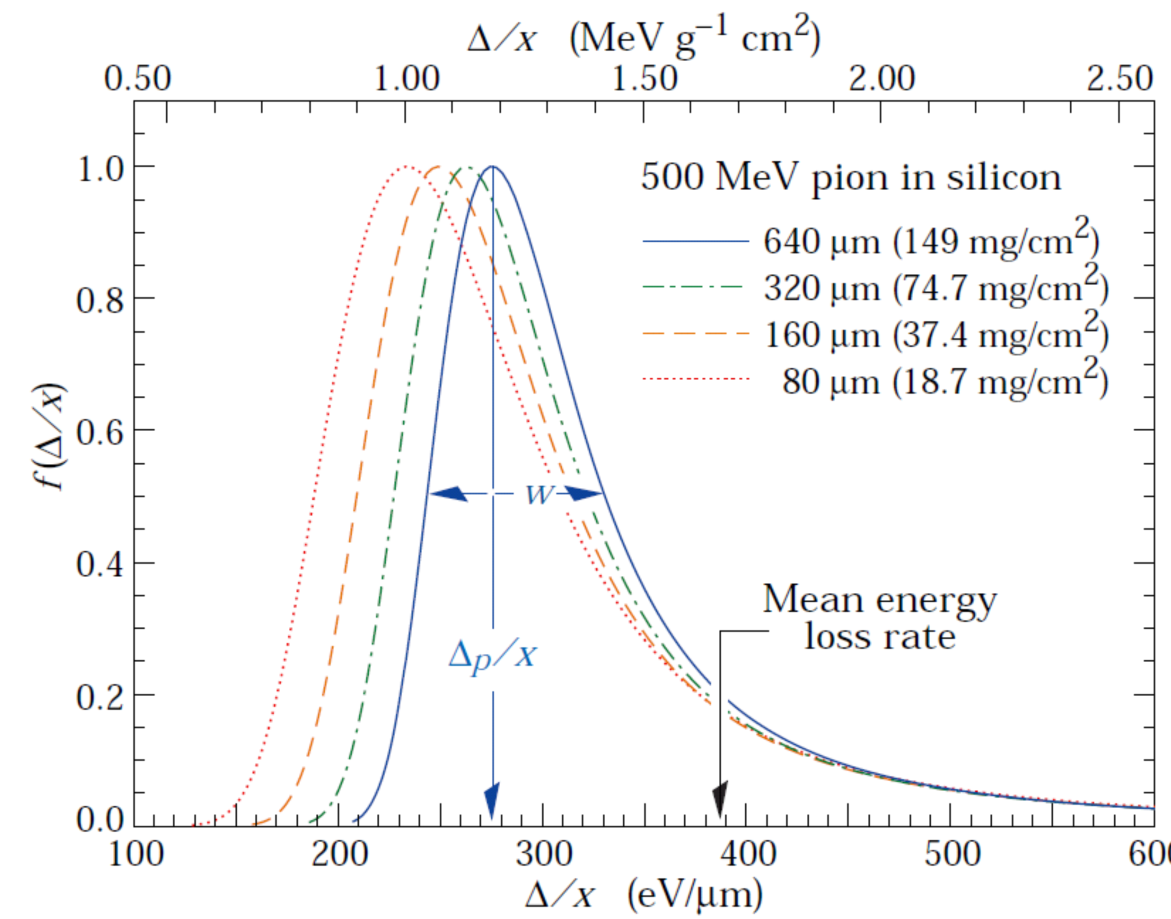
# Most Probable Energy Loss

$$\Delta_p = \xi\left[\ln\frac{2mc^2\beta^2\gamma^2}{I} + \ln\frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma)\right]$$

where $\xi = (K/2)\,\langle Z/A\rangle\,(x/\beta^2)$ MeV for a detector of thickness $x$.



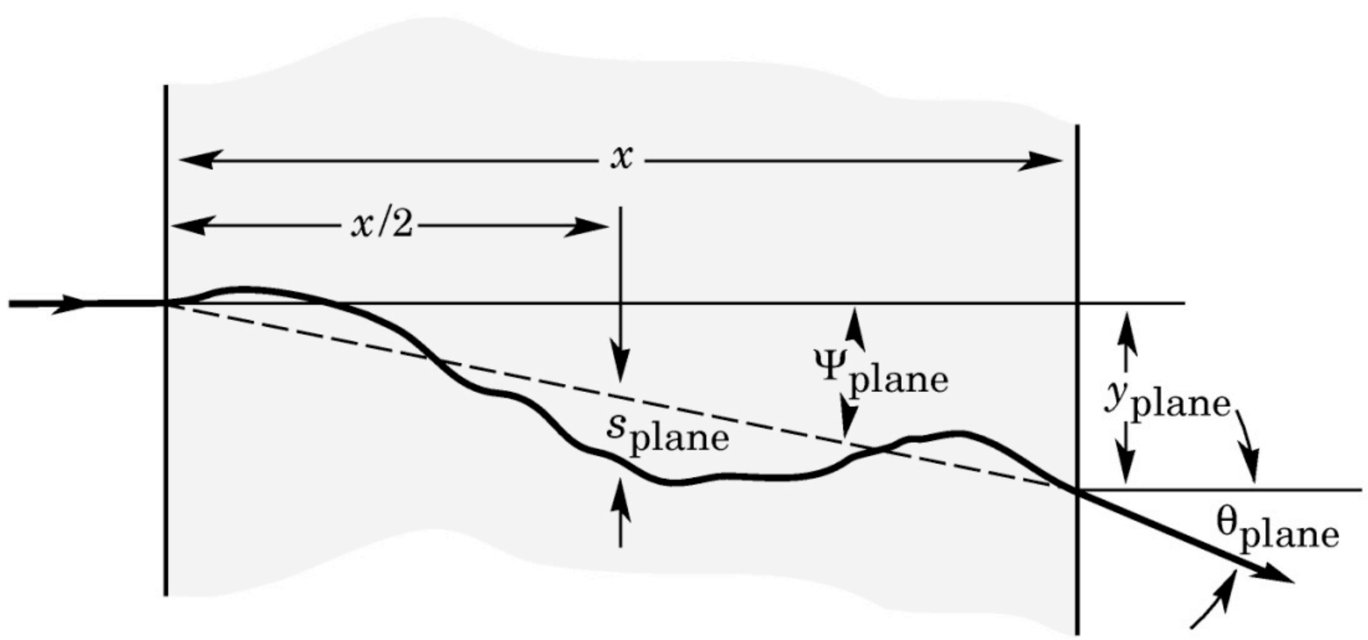

$\Delta_p/x$ compared to minimum $dE/dx$




Distribution of $\Delta_p/x$

# Multiple Scattering

- Often called Multiple Coulomb Scattering: momentum transfer between particle and medium diverts particles from straight path
  - usually electromagnetic; hadronic interactions contribute, too
  - scattering angles well-described by Molière theory:




$$\psi_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}\,\theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}\,\theta_0\,,$$

$$y_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}\,x\,\theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}\,x\,\theta_0\,,$$

$$s_{\text{plane}}^{\text{rms}} = \frac{1}{4\sqrt{3}}\,x\,\theta_{\text{plane}}^{\text{rms}} = \frac{1}{4\sqrt{3}}\,x\,\theta_0$$

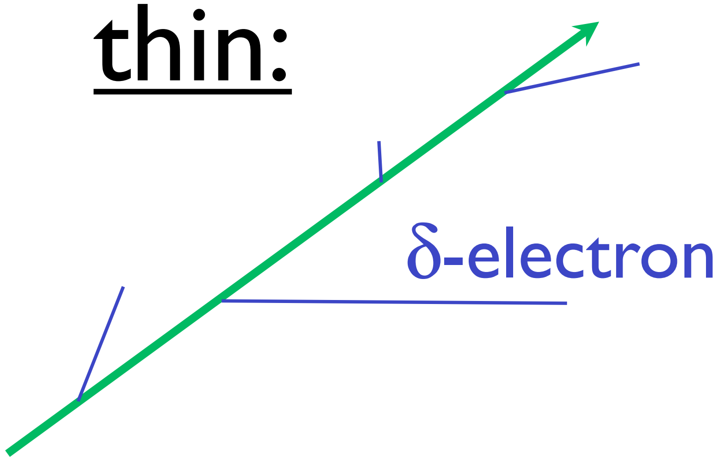
$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}}\,\theta_{\text{space}}^{\text{rms}}$$

Here $\theta_0$ is a (mostly) gaussian distribution defined as with a width of $\theta_0 = \frac{13.6\text{ MeV}}{\beta c p}\, z\,\sqrt{x/X_0}\Big[1 + 0.038\ln(x/X_0)\Big]$

This process can be limit on tracking accuracy

# Energy Loss Fluctuations

**thin:**

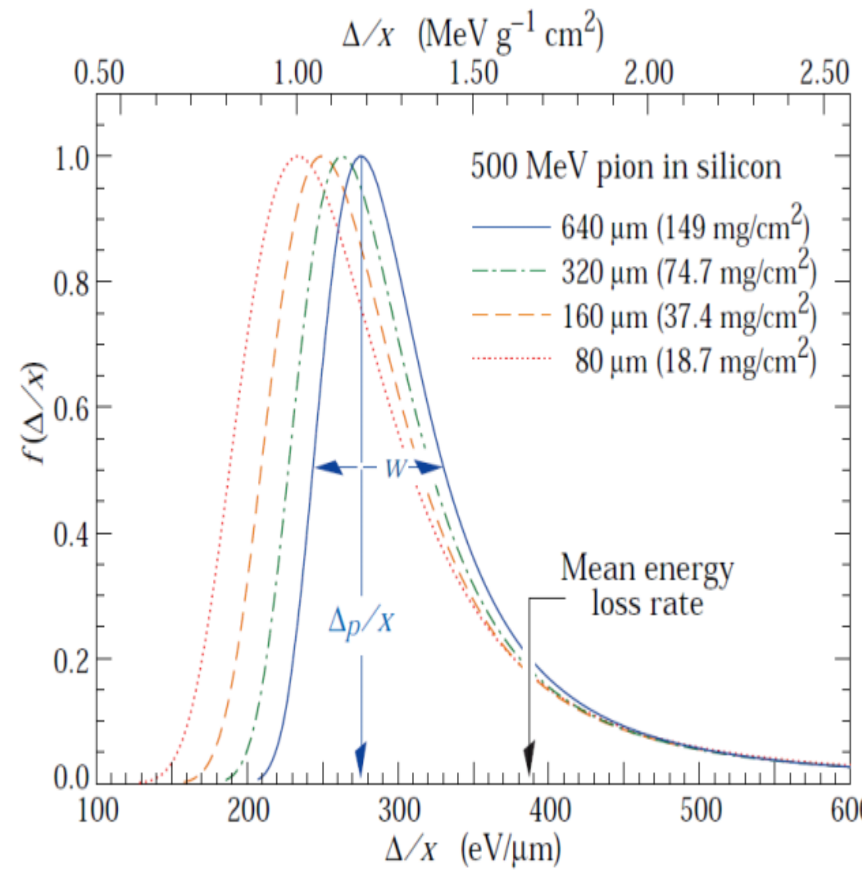



- Few collisions
- some with large energy transfer
- large fluctuations in energy loss

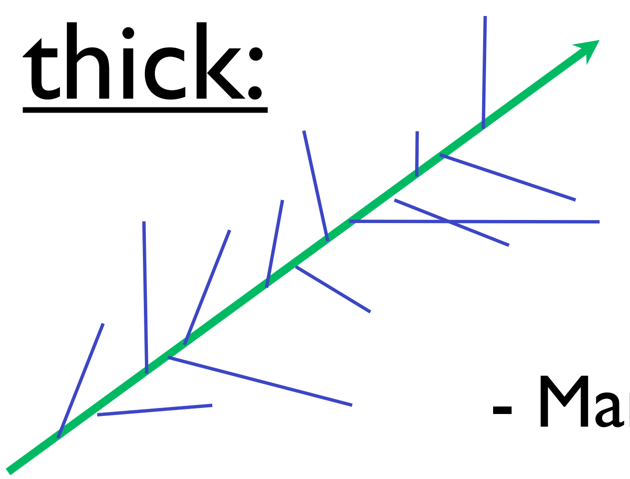
$\Rightarrow$ Landau distribution

- e.g.: 300um thick Si sensor:

$\Delta E_{mp}$ = 82 keV, <$\Delta$E> ~ 115 keV



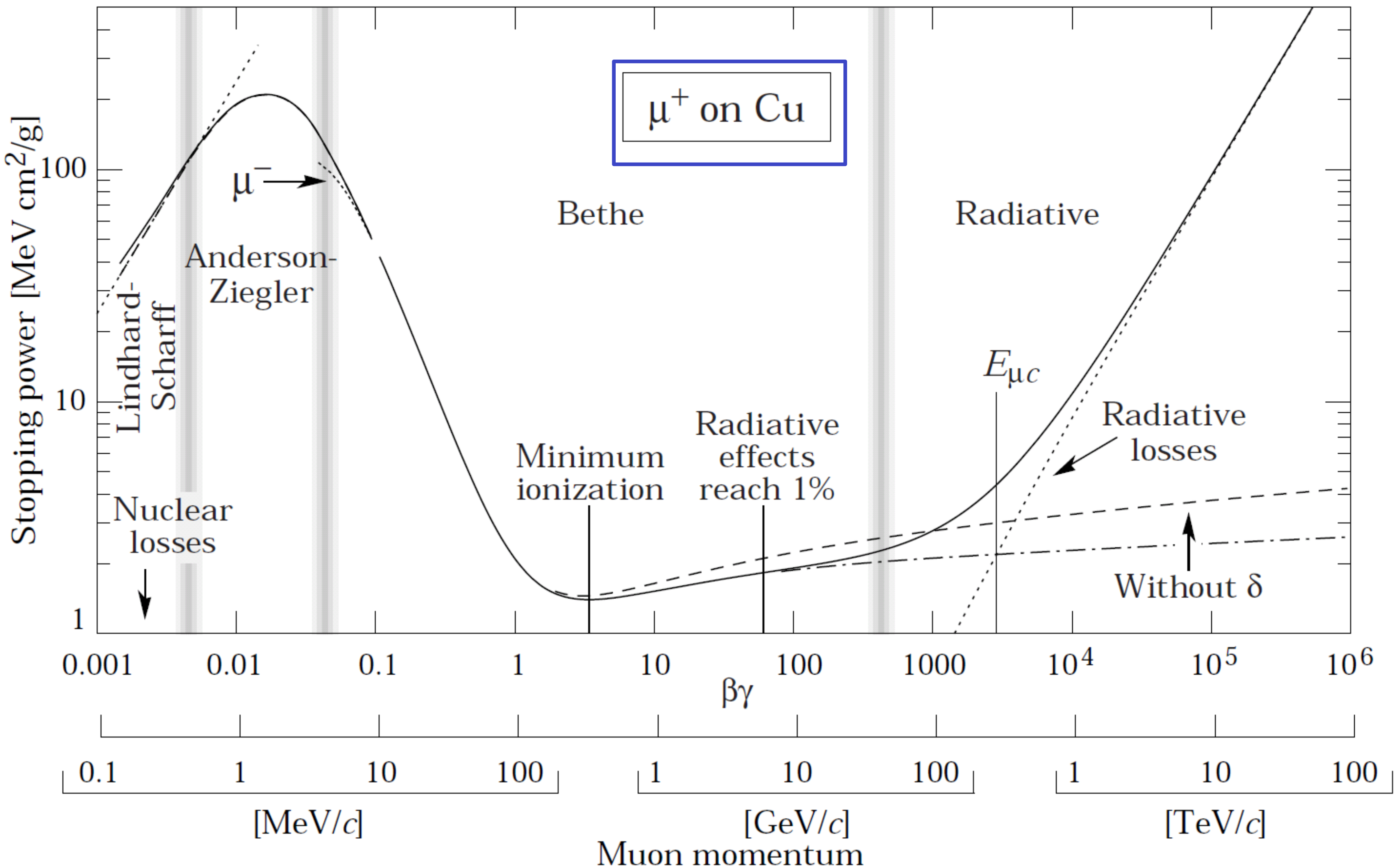

**thick:**



- Many collisions
- wide spectrum of energies
- distribution tends toward gaussian
- $\Delta E_{mp} \approx$ <$\Delta$E>

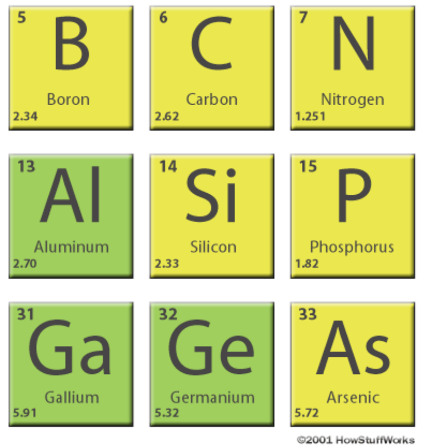
- Energy loss in material can be significant (c.f. ATLAS or CMS trackers): radius of curvature *increases* along path as $p$ falls
- Fluctuations in Energy Loss in thin/thick samples of material:

# Ionization Loss: full spectrum

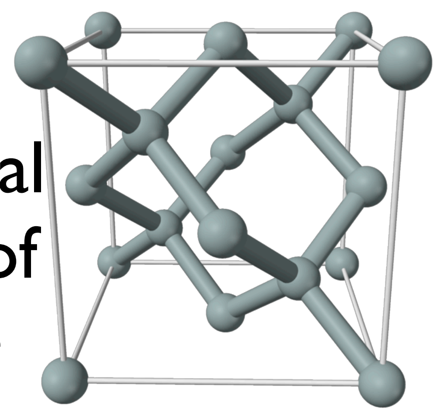


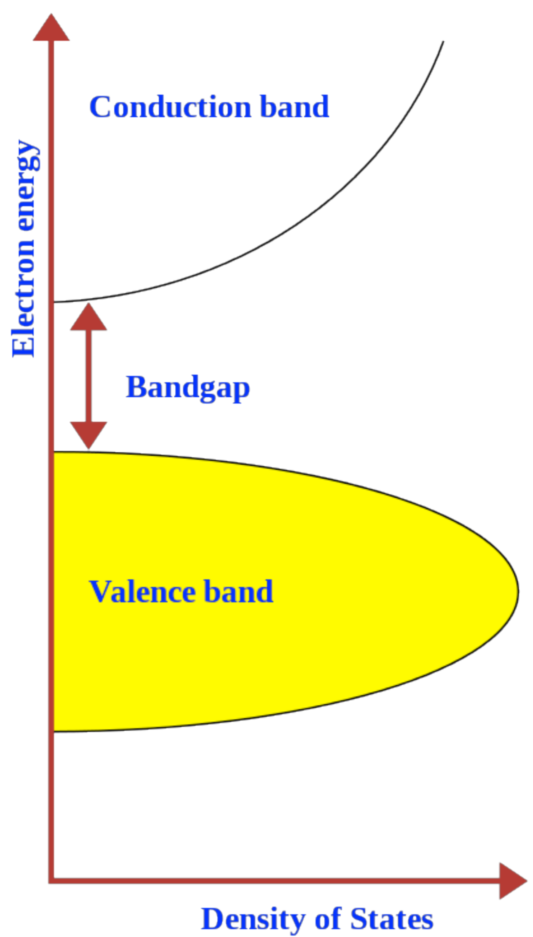
{back to tracking}

# Reminder: semiconductor properties

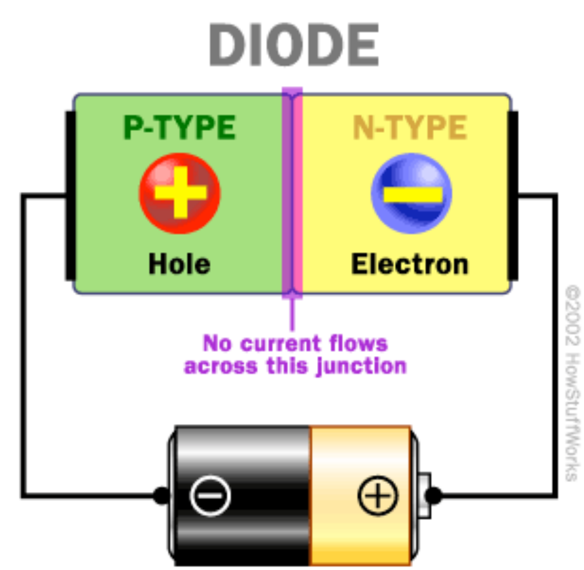



Diamond cubic crystal structure of Si and Ge

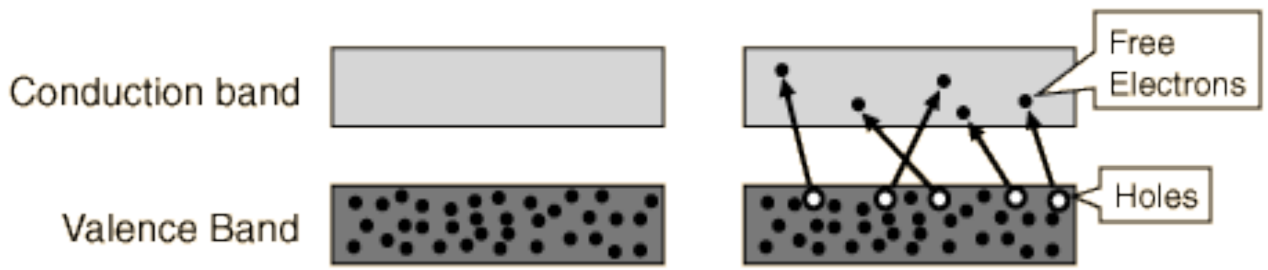





- Pure silicon: 4 valence electrons. Forms crystal, good *insulator* because four electrons in covalent bonds.
- Dope with small amount of P or As, which have 5 valence electrons. Get N-type semiconductor.
- Dope with small amount of B or Ga, which have 3 valence electrons. Get P-type semiconductor.
- P-N junction: get diode. Current flows one direction but not the other.
- Depletion zone: junction has a zone with few charge carriers, due to diffusion and to reverse-bias.
- Band gap: range of energy-levels between the top of the valance band and the bottom of the conduction band of a semiconductor.



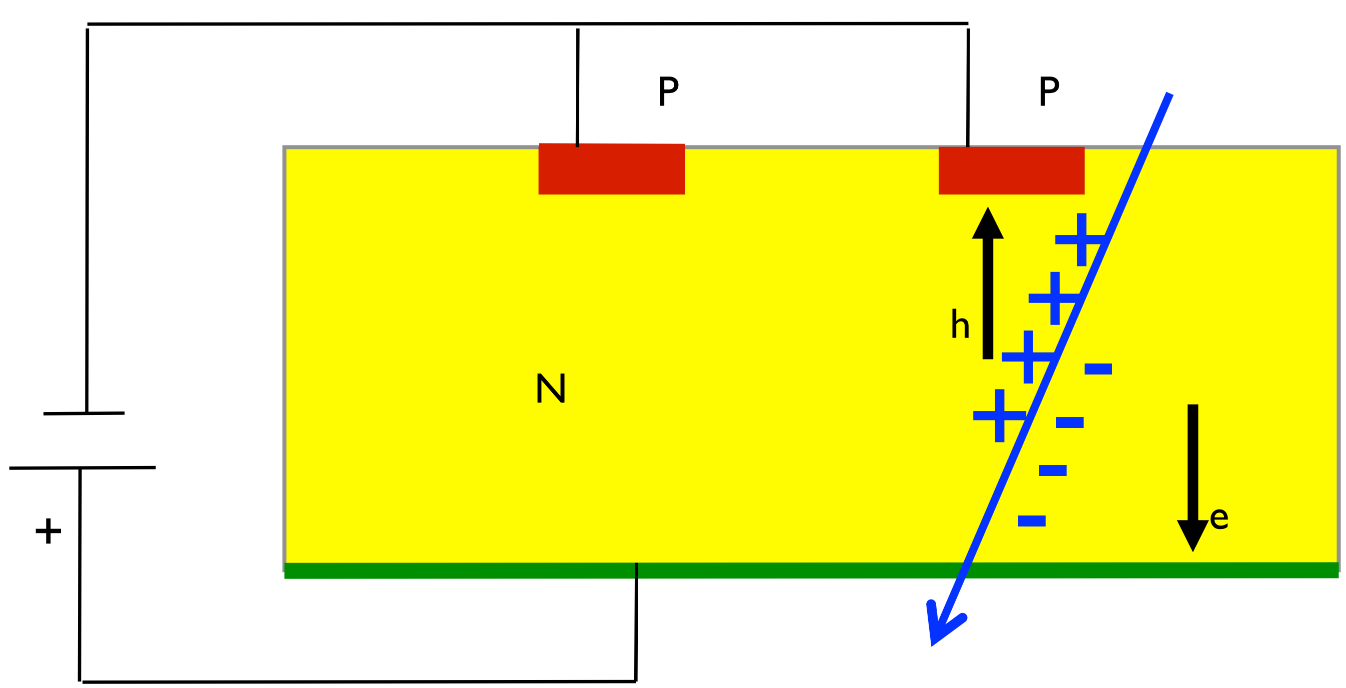
# Solid state detectors (pixels) - basic operational principle



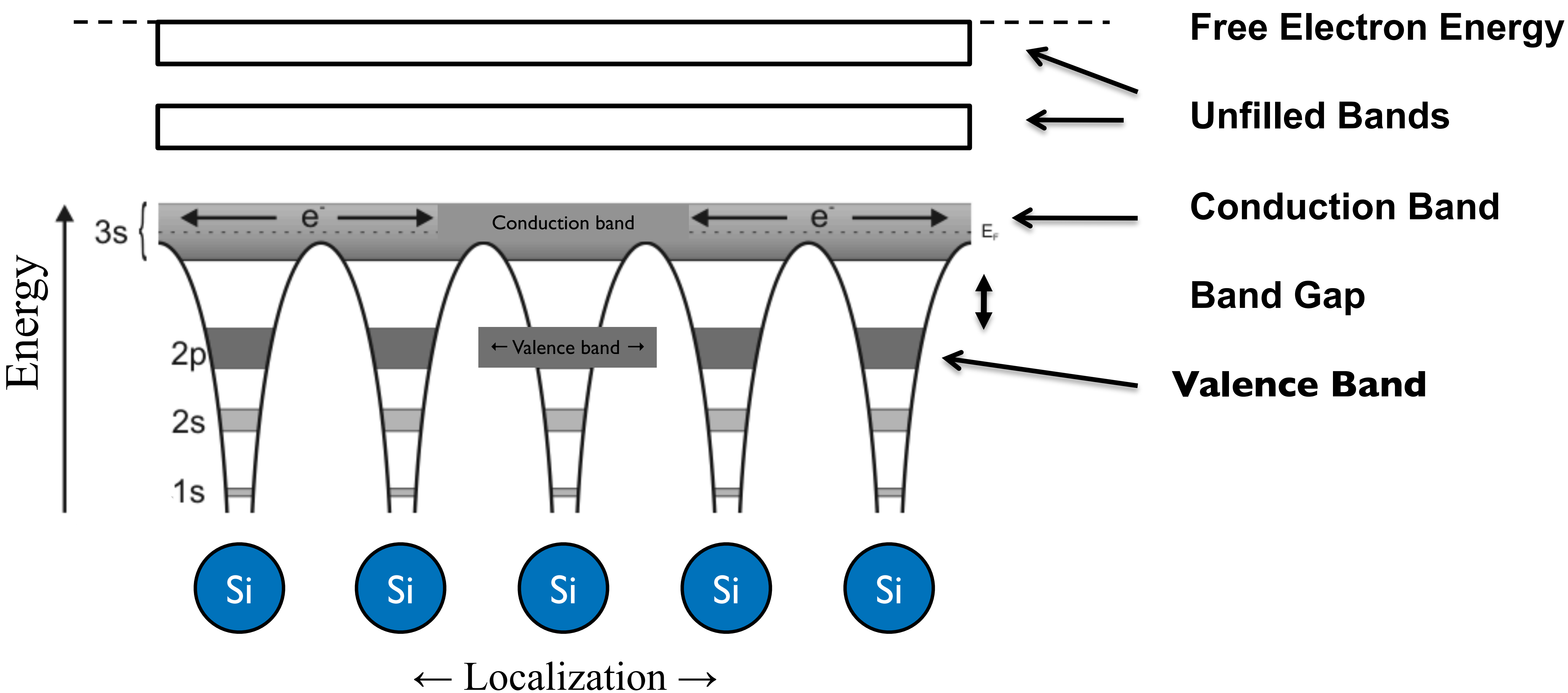

electrons excited (thermally or otherwise) into conduction band become mobile

Use reverse biased, fully depleted semiconductor

- crystalline silicon band gap is 1.1 eV
  - yields 80 electron-hole pairs/μm for minimum-ionizing track
    - ( 1 e-h pair per 3.6 eV of deposited energy )
  - 99.9% of ejected electrons have less than 1μm path length
    - fine-granularity devices can easily be made



# Solid State Detectors




## Conductor, Insulator, Semiconductor

**In case the conduction band is filled the crystal is a conductor.**

**In case the conduction band is empty and 'far away' from the valence band, the crystal is an insulator.**

**In case the conduction band is empty but the distance to the valence band is small, the crystal is a semiconductor.**

Adapted from W. Riegler

# More Details on Semiconductor Detectors

- As mentioned, we use *doped* semiconductors for tracking detectors.
- The fundamental reason for this is to get a larger signal size so as to achieve a good signal-to-noise (S/N) ratio. "Noise" is primarily thermal noise from the semiconductor itself.
- The signal size is larger because the charge carrier concentration is higher. In a non-doped (intrinsic) semi-conductor the density of electrons and holes is equal and it depends on temperature: $n_e = n_h = n_i(T)$.
- For low doping levels, if the density of electrons and holes is $n_e$ and $n_h$,

$$n_e \cdot n_h = n_i^2$$

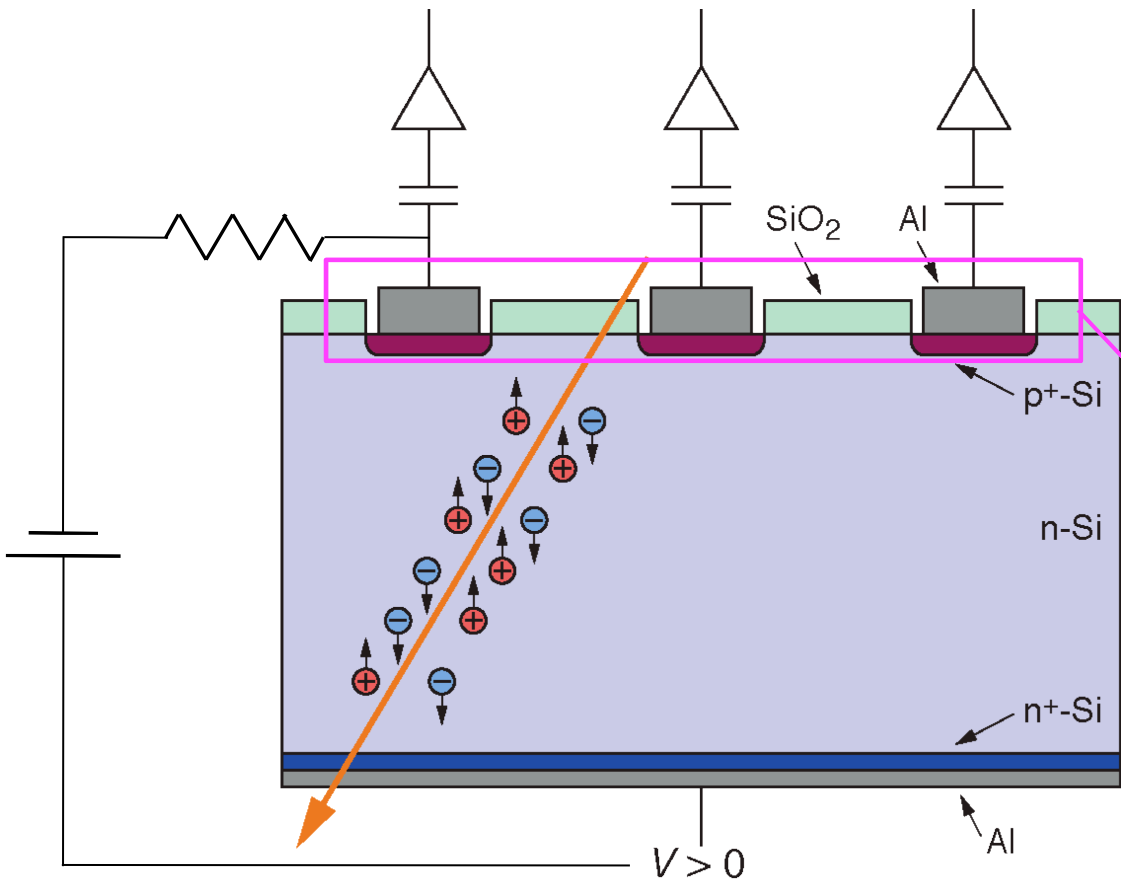
and the temperature dependence of the charge carrier concentrations is:

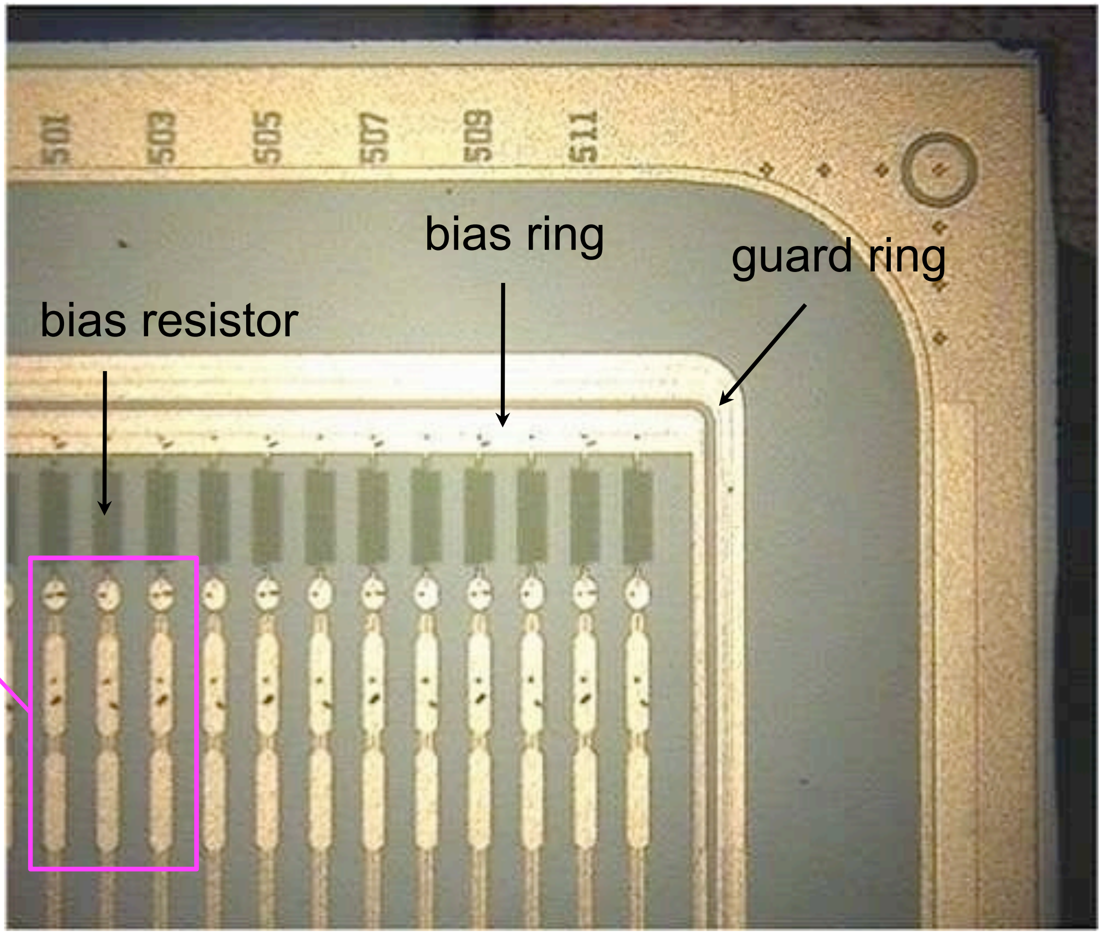
$$n_e = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot e^{\frac{(E_F - E_C)}{kT}} \qquad n_h = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \cdot e^{\frac{(E_V - E_F)}{kT}}$$

where $E_C$ is the minimum energy of the conduction band, $E_V$ is the maximum energy of the valence band, and $E_F$ is the Fermi level. The $m^*$ are the effective masses of the electrons and holes.

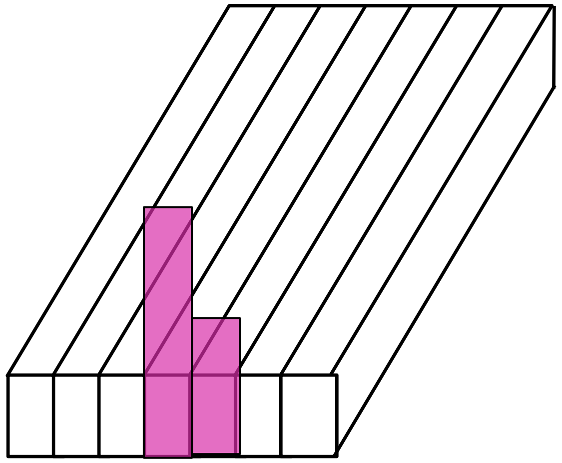
# SSTDs: Silicon Microstrips

- The easiest thing to do is put down sensor lines, read out at end




- Charge sharing improves position resolution:



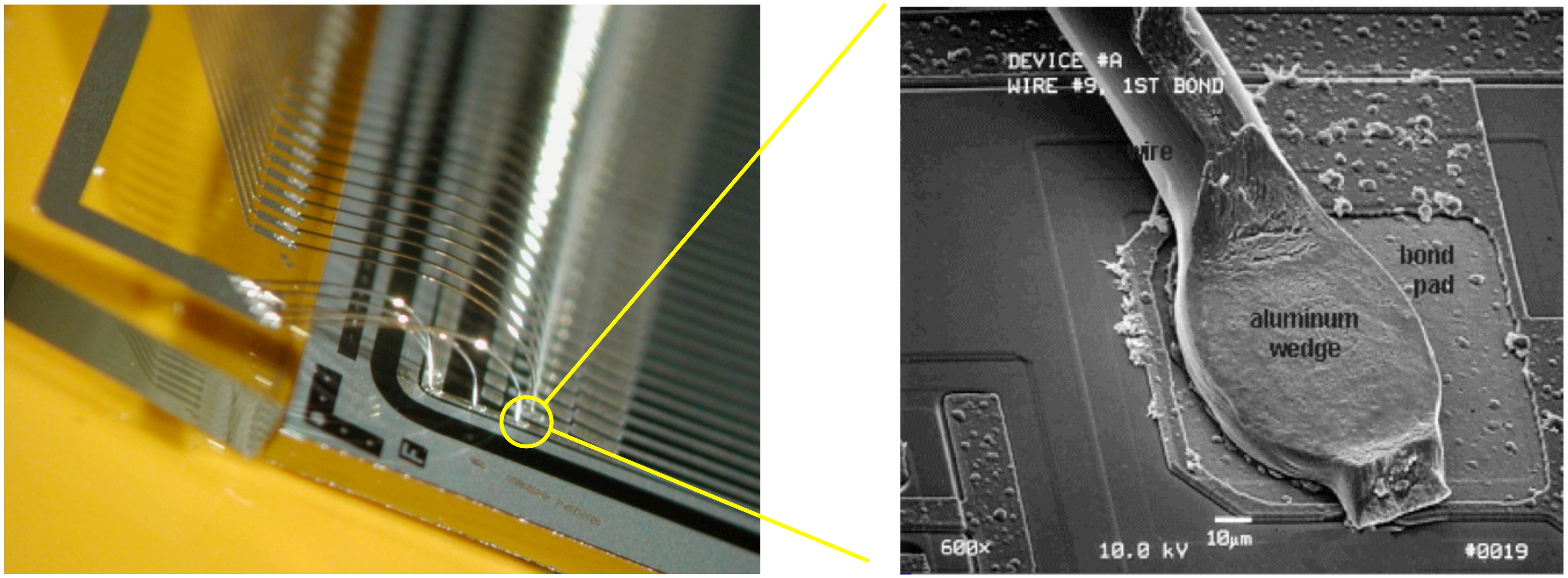
$$\bar{x} = \frac{\sum x_i q_i}{\sum q_i}$$

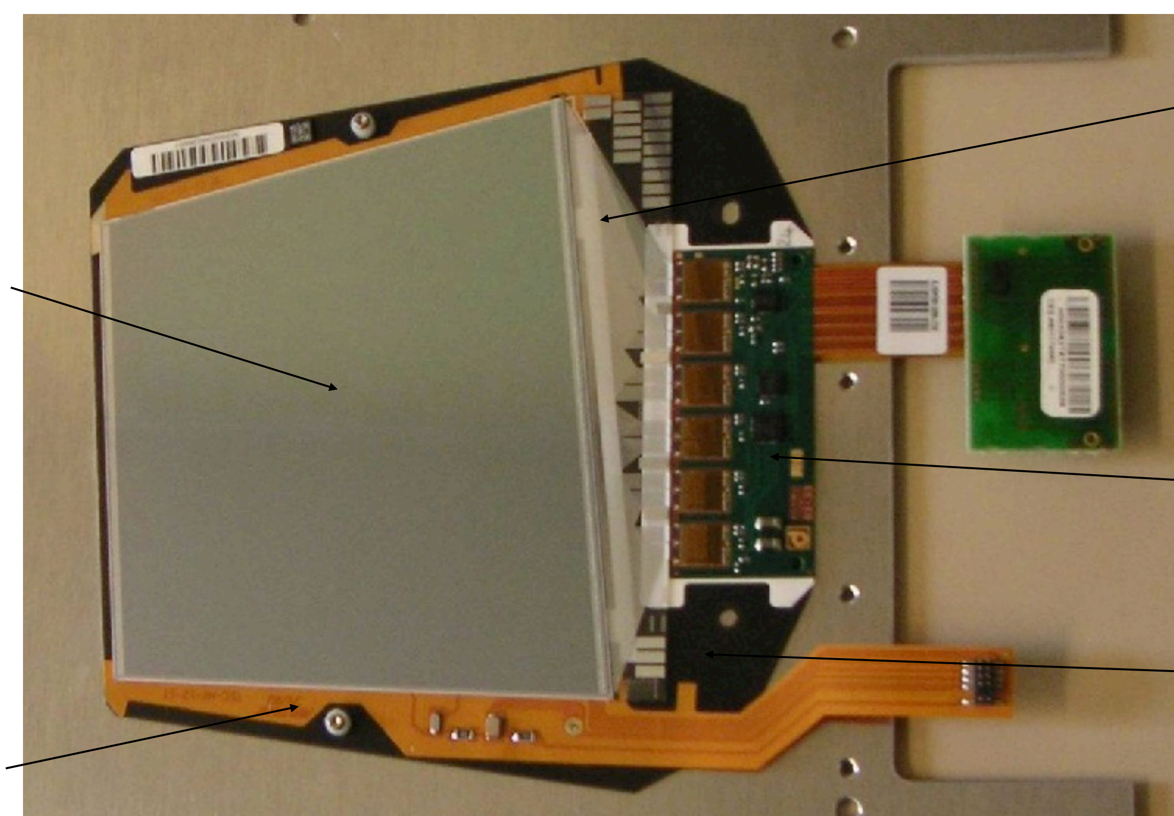
- Typical pitch width: 50μm – 200μm
  - one strip: width/$\sqrt{12}$
  - two strips: width/4
  - more than two: width/2

*Adapted from Mike Hildreth*

# SSTDs: Silicon Microstrips

- Exquisitely complicated micro-mechanical construction

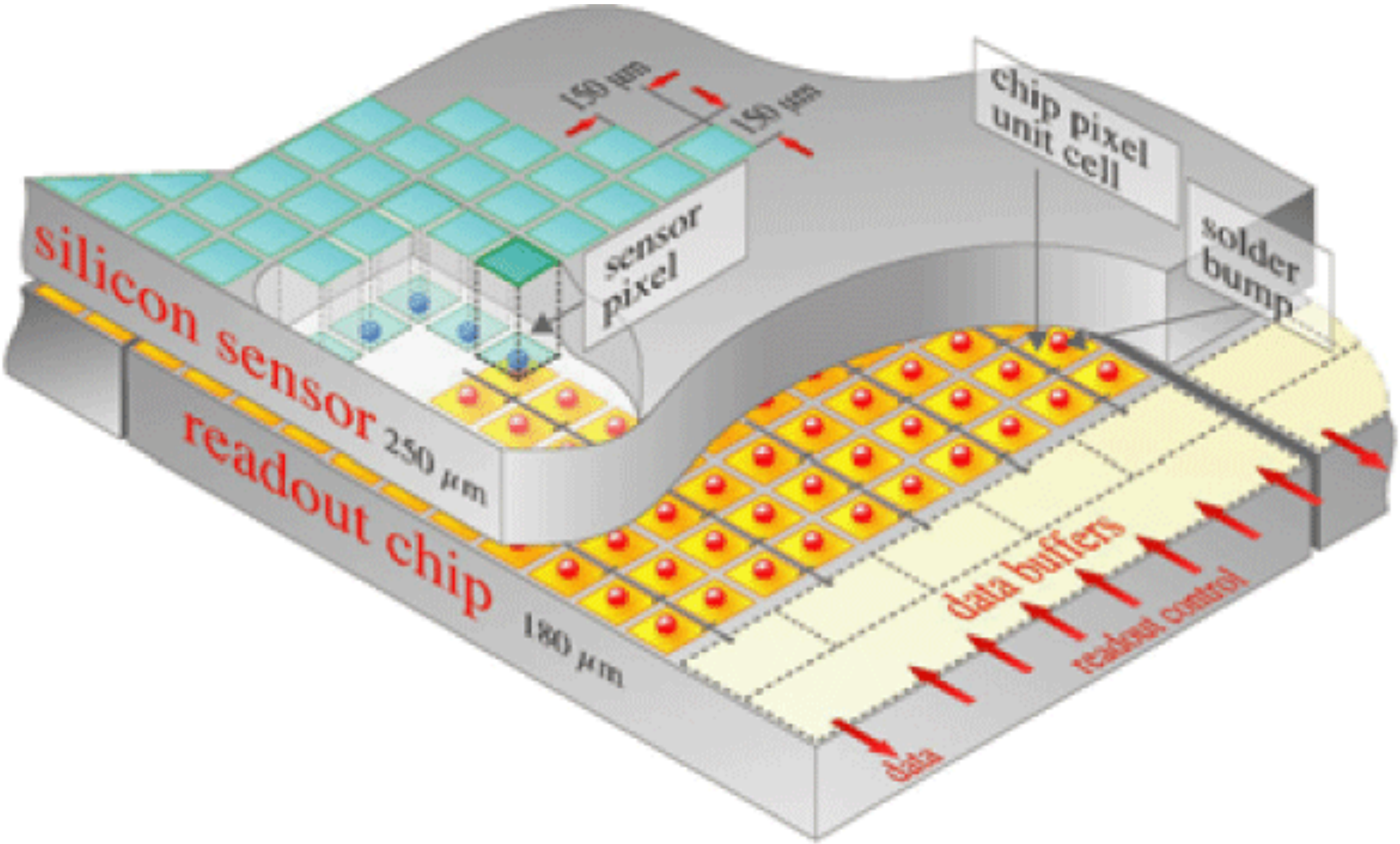





*Adapted from Mike Hildreth*

# Pixel detectors - True 2-dimensional readout




Uses bump bonding to connect pixels to electronics

# Classes of particle measurements:
# *Neutral particles* (calorimetry)

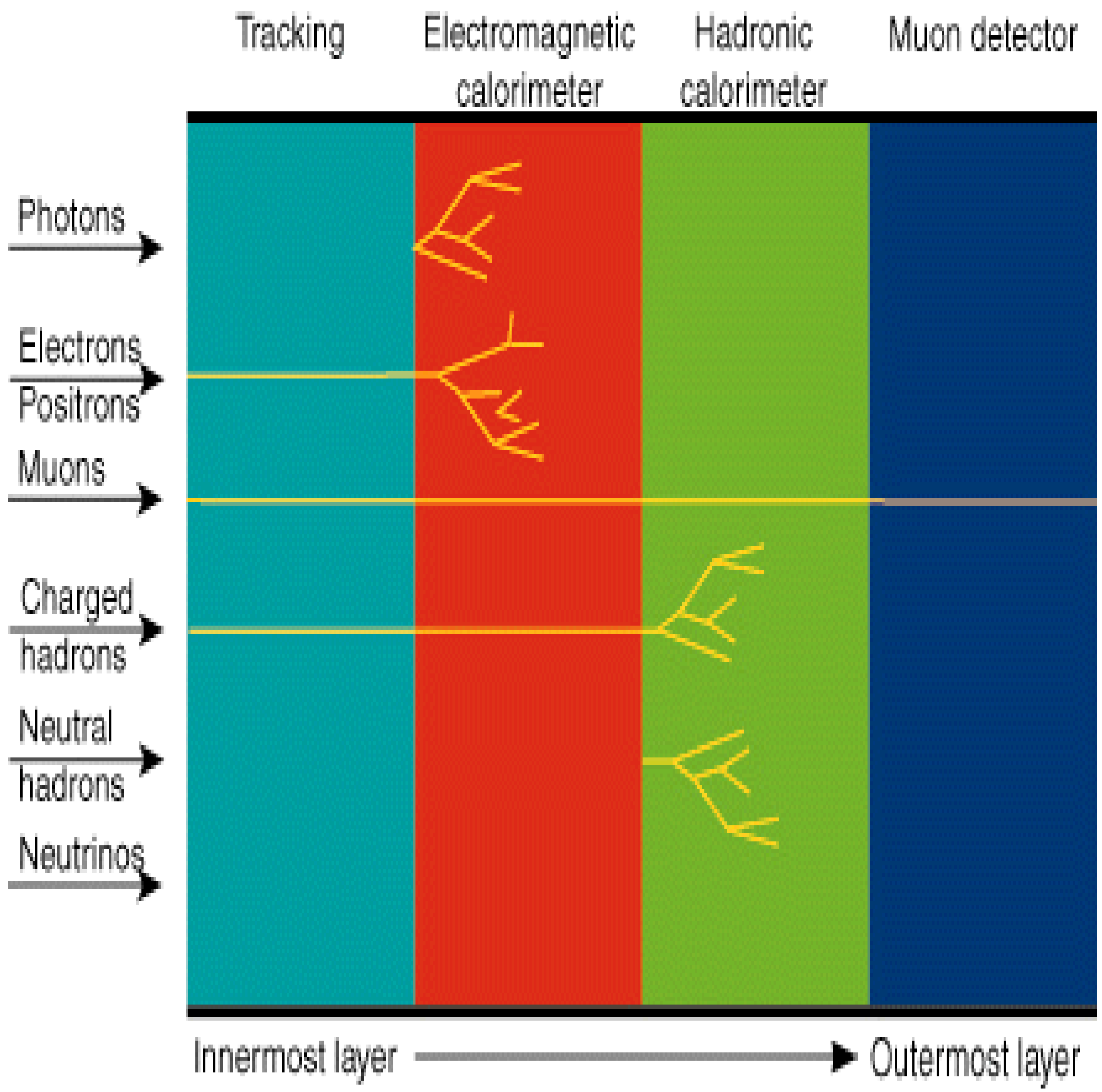
# Calorimeters

- Calorimeters in high energy physics are often divided into *electromagnetic* {shower} calorimeters or *hadronic* calorimeters
  - electromagnetic calorimeters: higher energy $e^-$, $e^+$, $\gamma$ ($\pi^{0,}$,$\eta$, ....)
  - hadronic calorimeters: higher energy hadrons (p, n, $\pi^+$, $\pi^-$ $K^+$ $K^-$, ...)

- Calorimeters measure *energy*. Either:
  - total particle energy (e.g., crystal calorimeters) or, more commonly,
  - sample a *fraction* of the particle energy and infer the total particle energy ("sampling calorimeters").

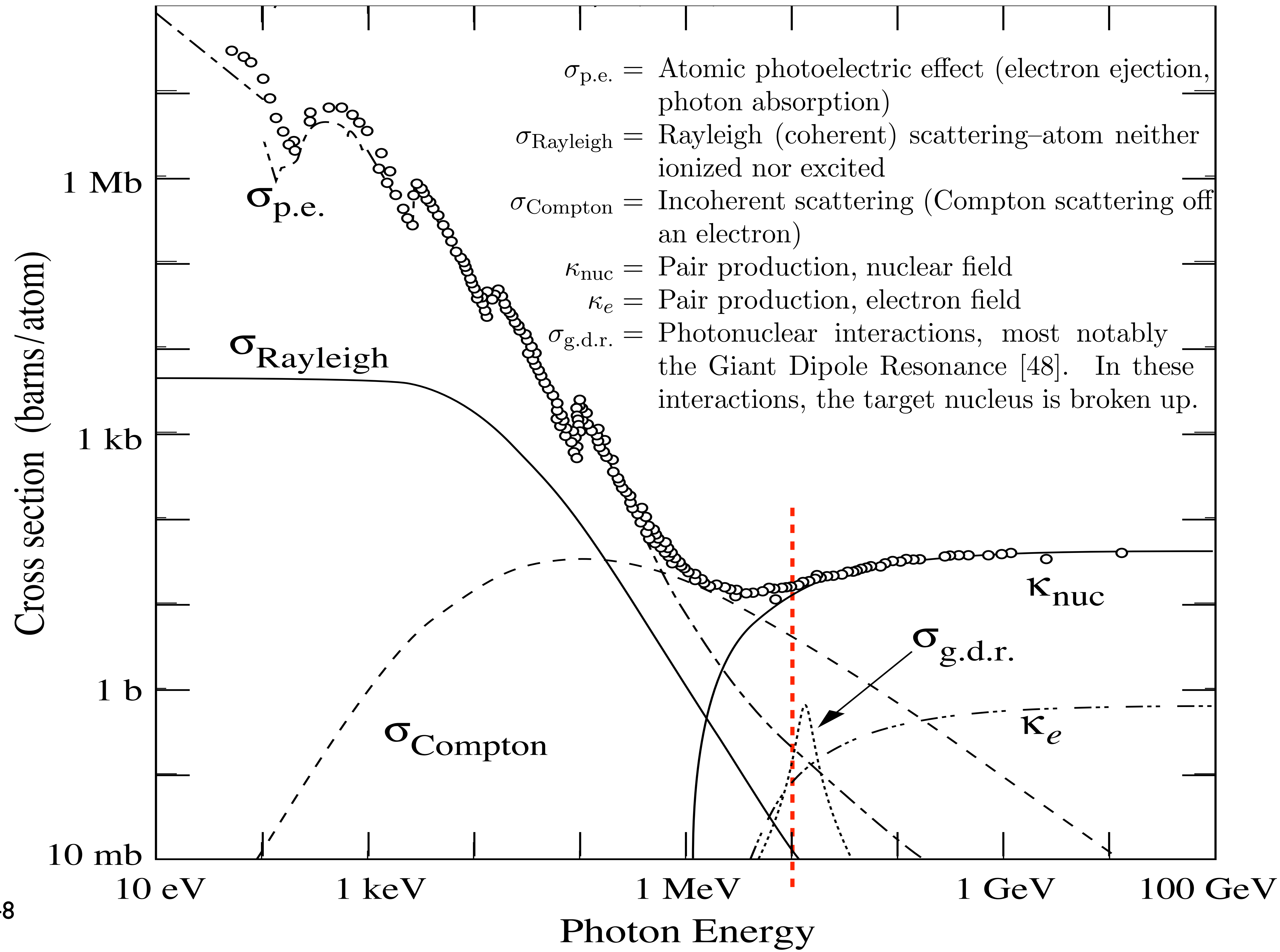
# How do {calorimeter} detectors work?

## (how do particles interact with matter??)



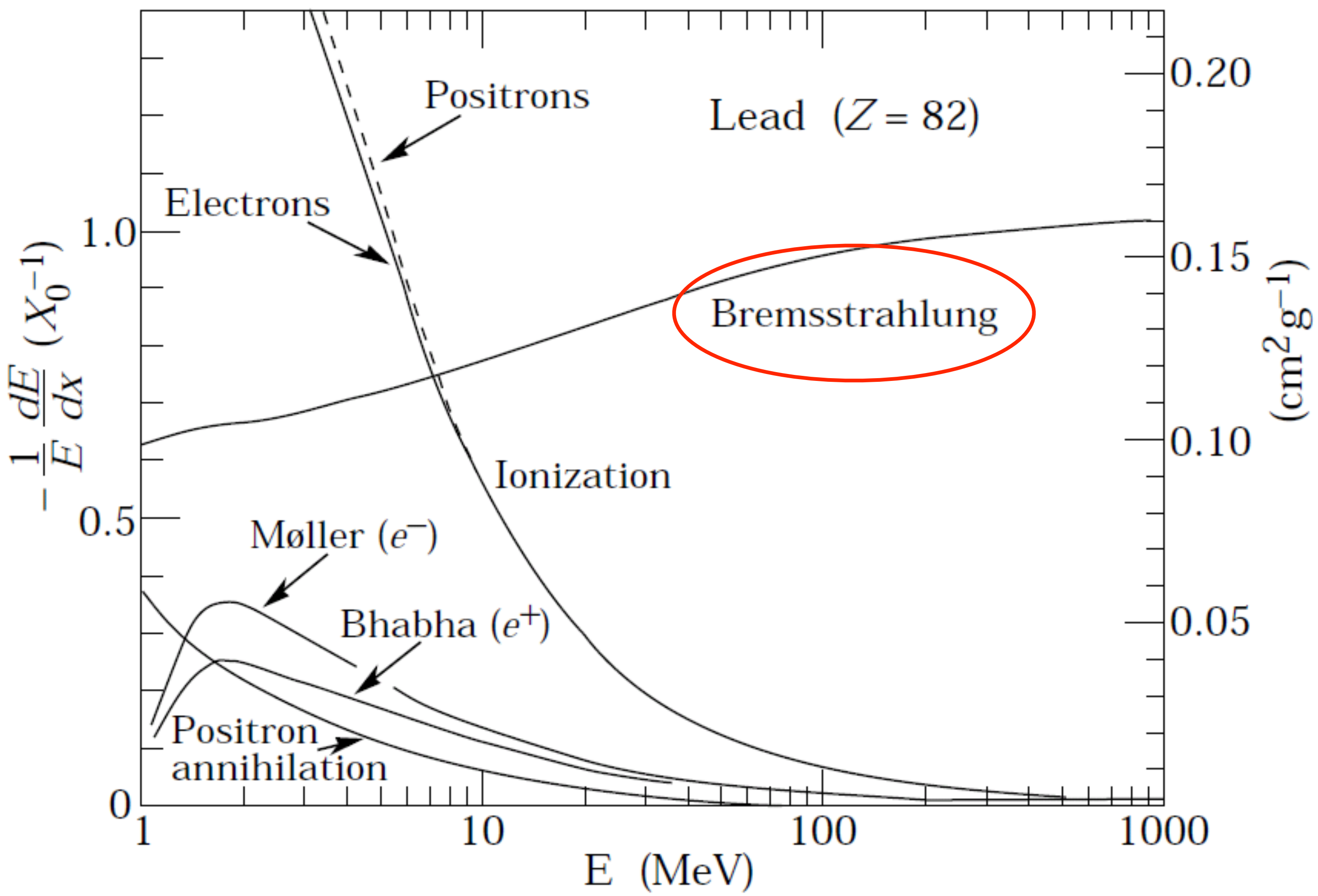

Start with *electromagnetic shower calorimeters:* alternating between bremsstrahlung and pair production

# Electromagnetic processes of the photon on Pb (Z=82)



# Bremsstrahlung

- Large discrete energy loss
- Acceleration due to interaction with Coulomb field of nuclei
- Dominant energy loss mechanism for electrons and positrons:




$$\frac{d\sigma}{dk} = \frac{A}{X_0 N_A k}\left(\tfrac{4}{3} - \tfrac{4}{3}y + y^2\right) \propto Z^2\alpha^3$$

where

$k$ = photon energy

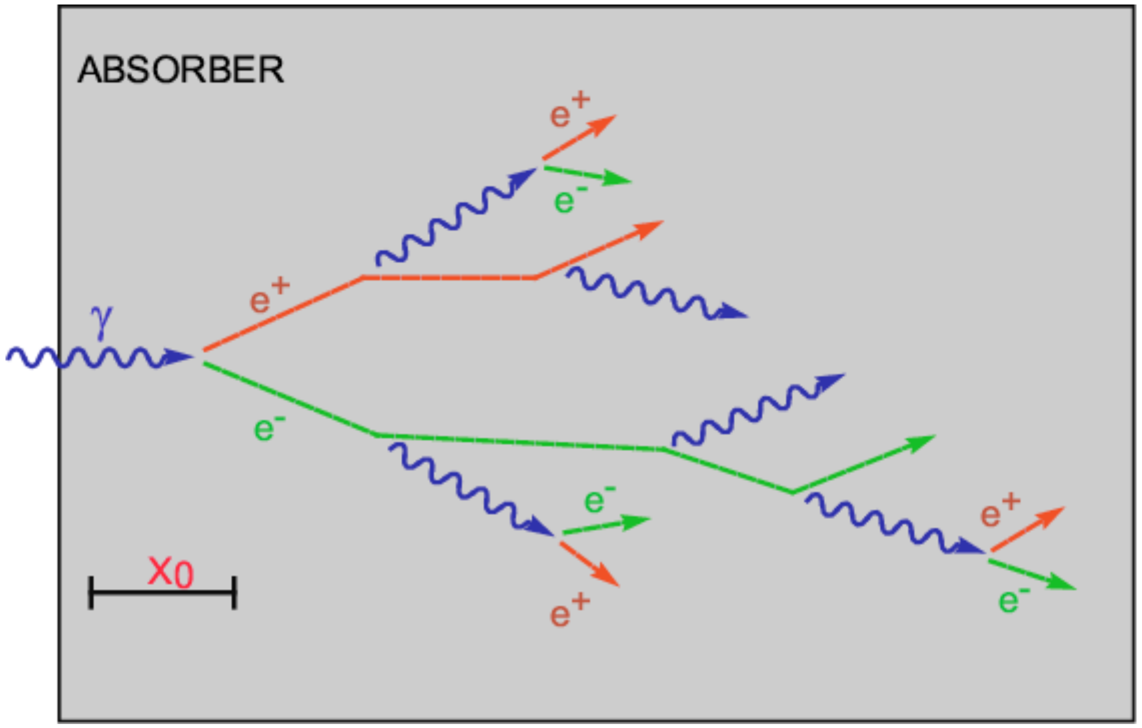
$y = k/E$

$E$ = lepton energy

Overall probability of photon emission $\propto m^{-4}$; can become important for high energy $\mu$

Electron/positron bremsstrahlung in tracking systems undesirable, dictates low-mass and low-Z components

# Electromagnetic showers




$X_0$ (radiation length)

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ ln\frac{287}{\sqrt{Z}}} \quad g \cdot cm^{-2}$$

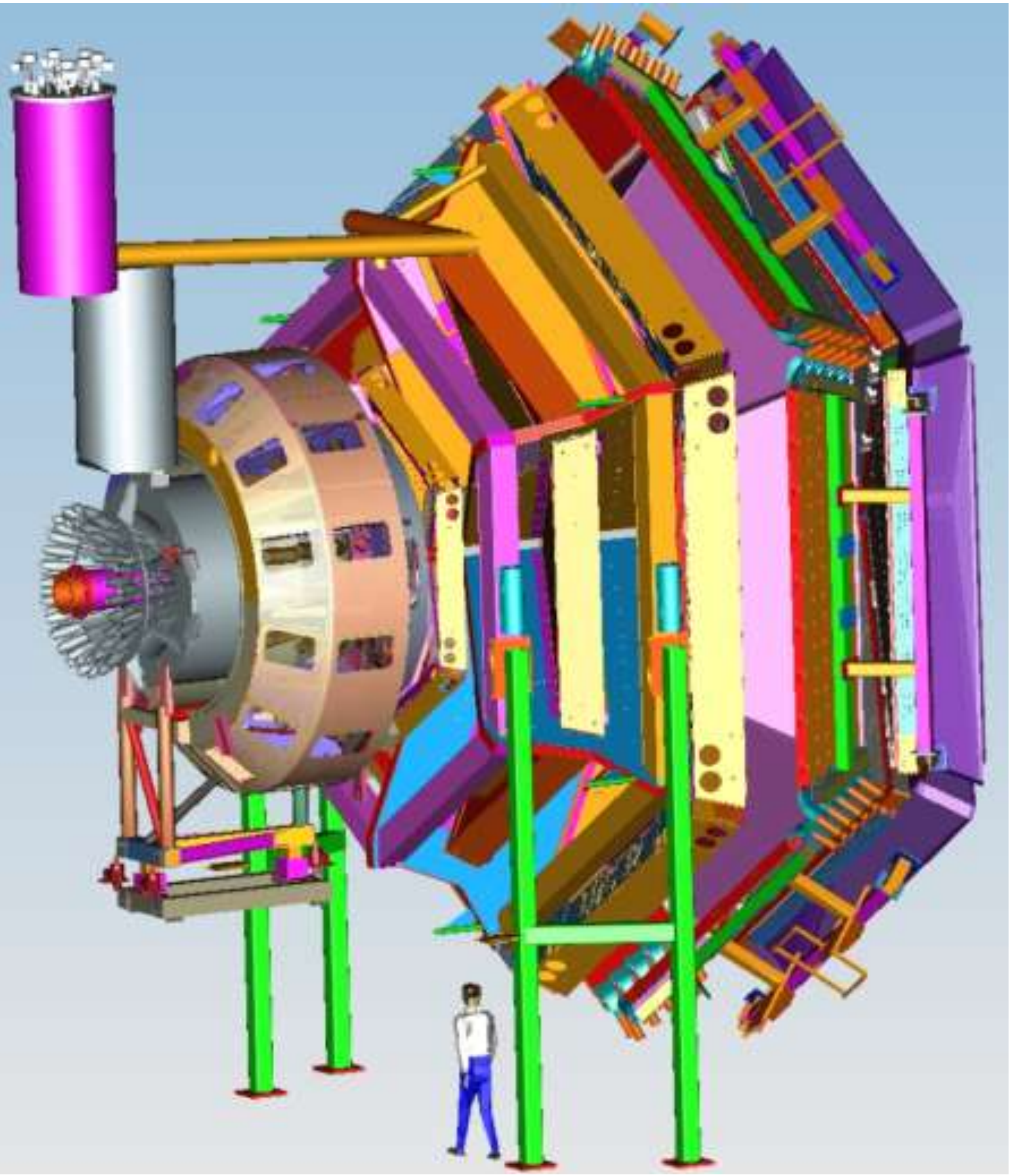
| Material | $X_0$ |
| --- | --- |
| air | 14460 cm |
| Pb (lead) | 0.56 cm |

http://pdg.lbl.gov/2010/reviews/contents_sports.html

$$X = X_0 \frac{ln(E_0/E_c)}{ln2}$$ shower depth

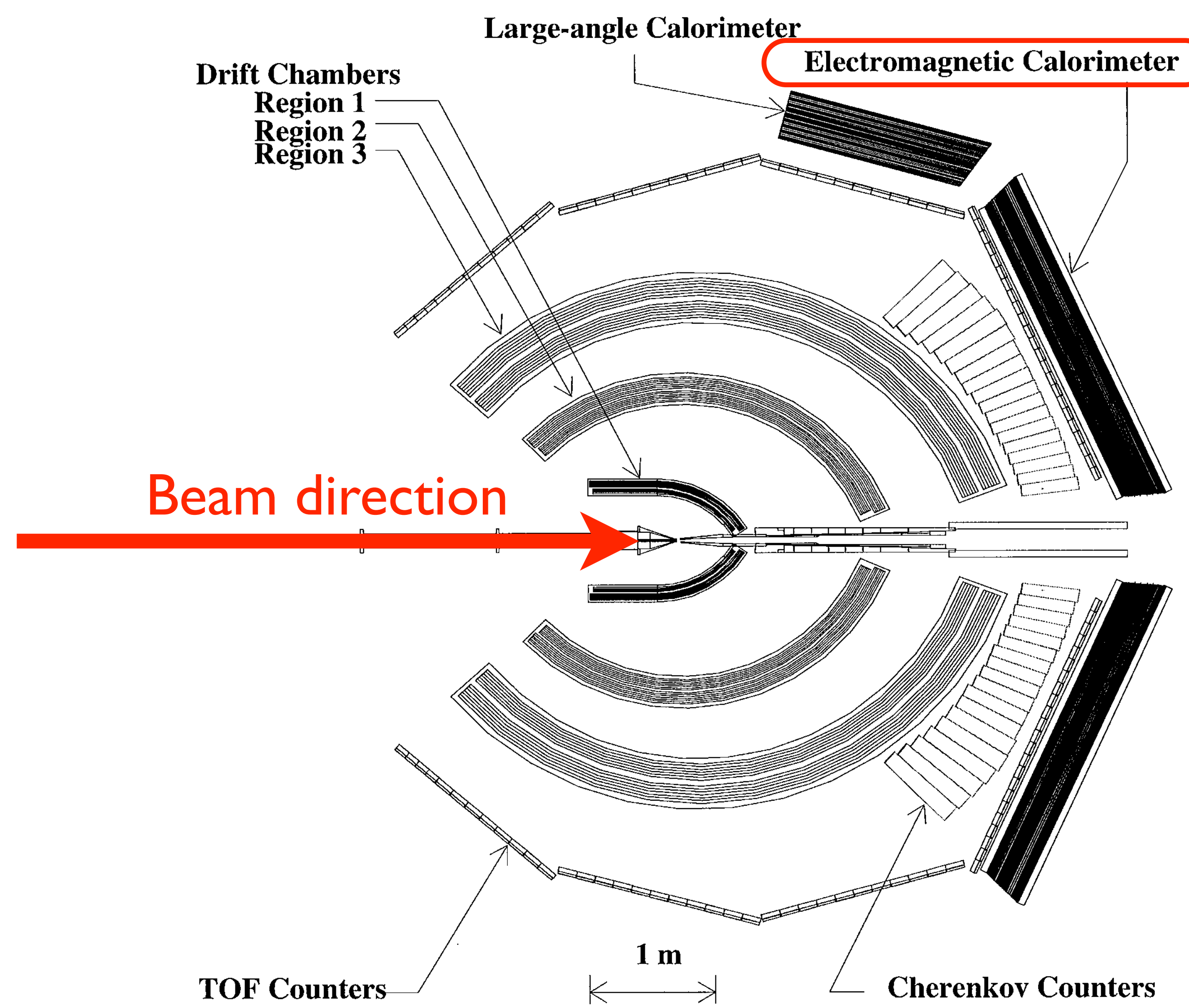
$$R_M = 0.0265 X_0 (Z + 1.2)$$ Molière radius

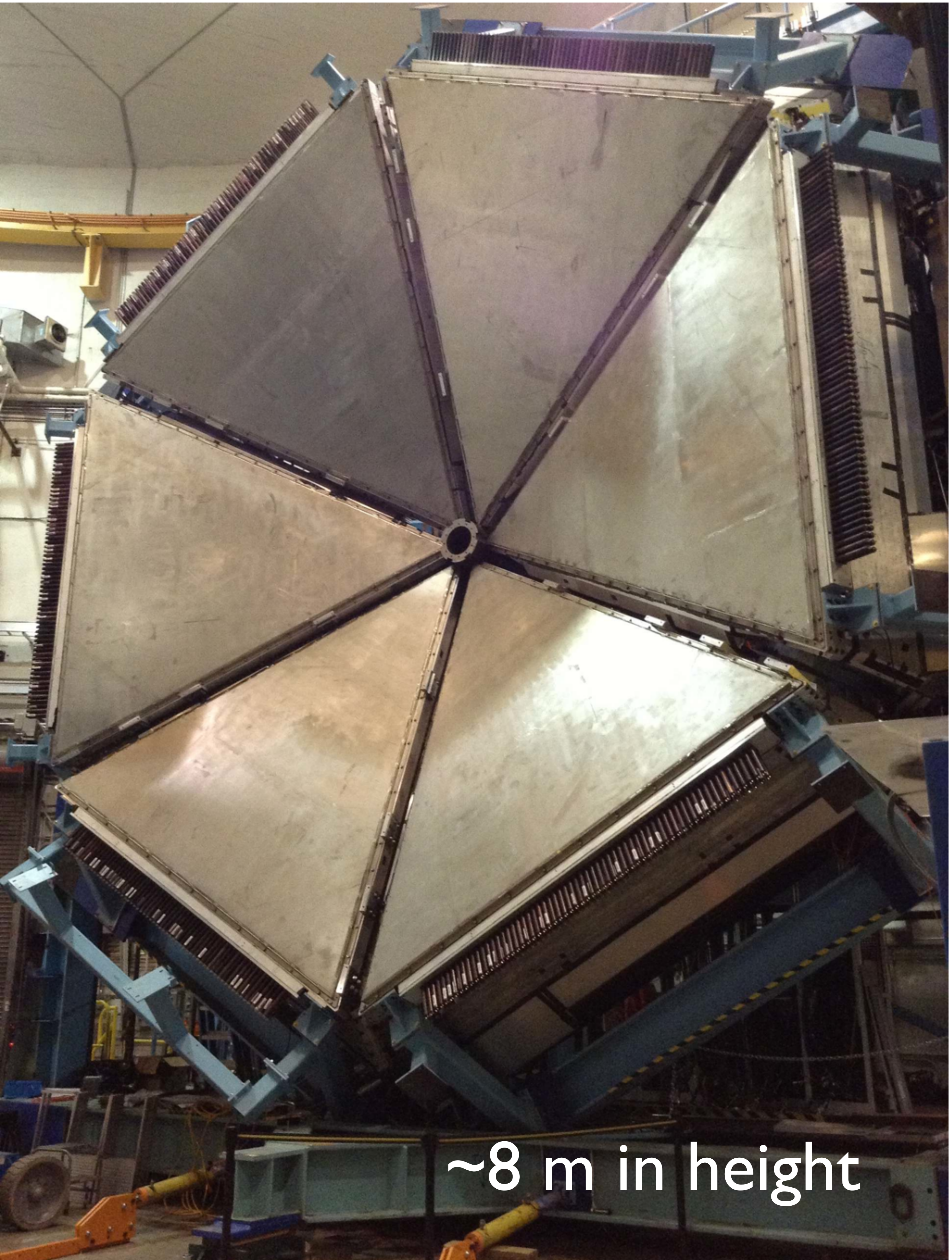
# CLAS and CLAS12 at Jefferson Lab



CLAS12 (2016-~2030)

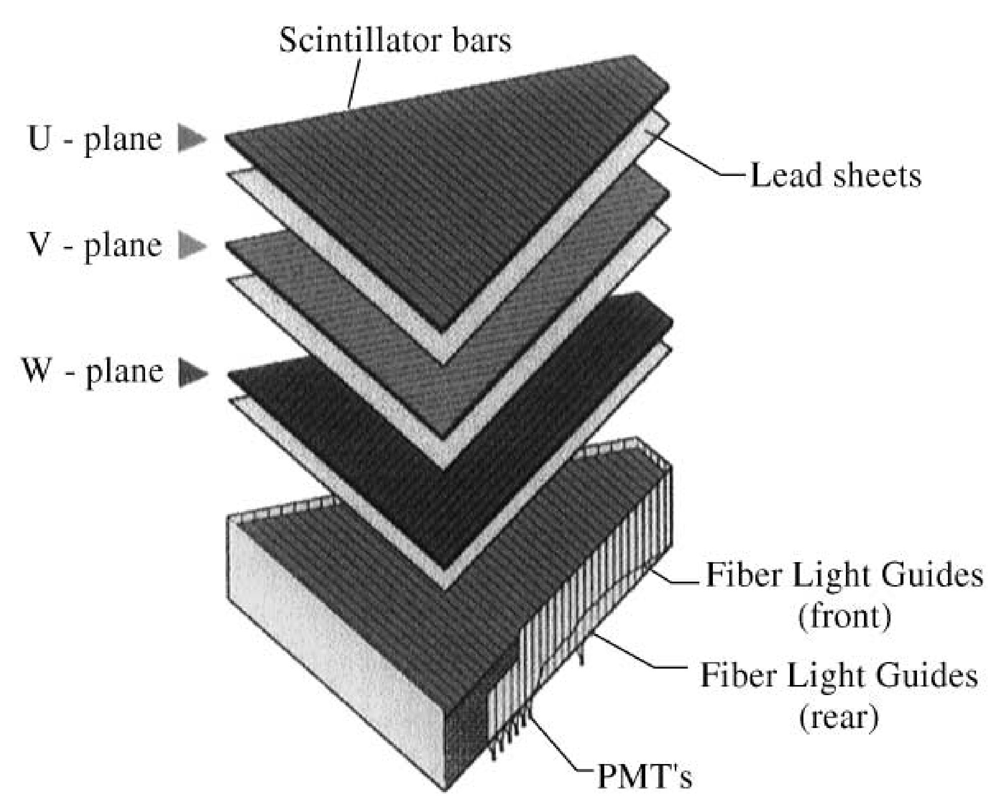
## CLAS (1997-2013)

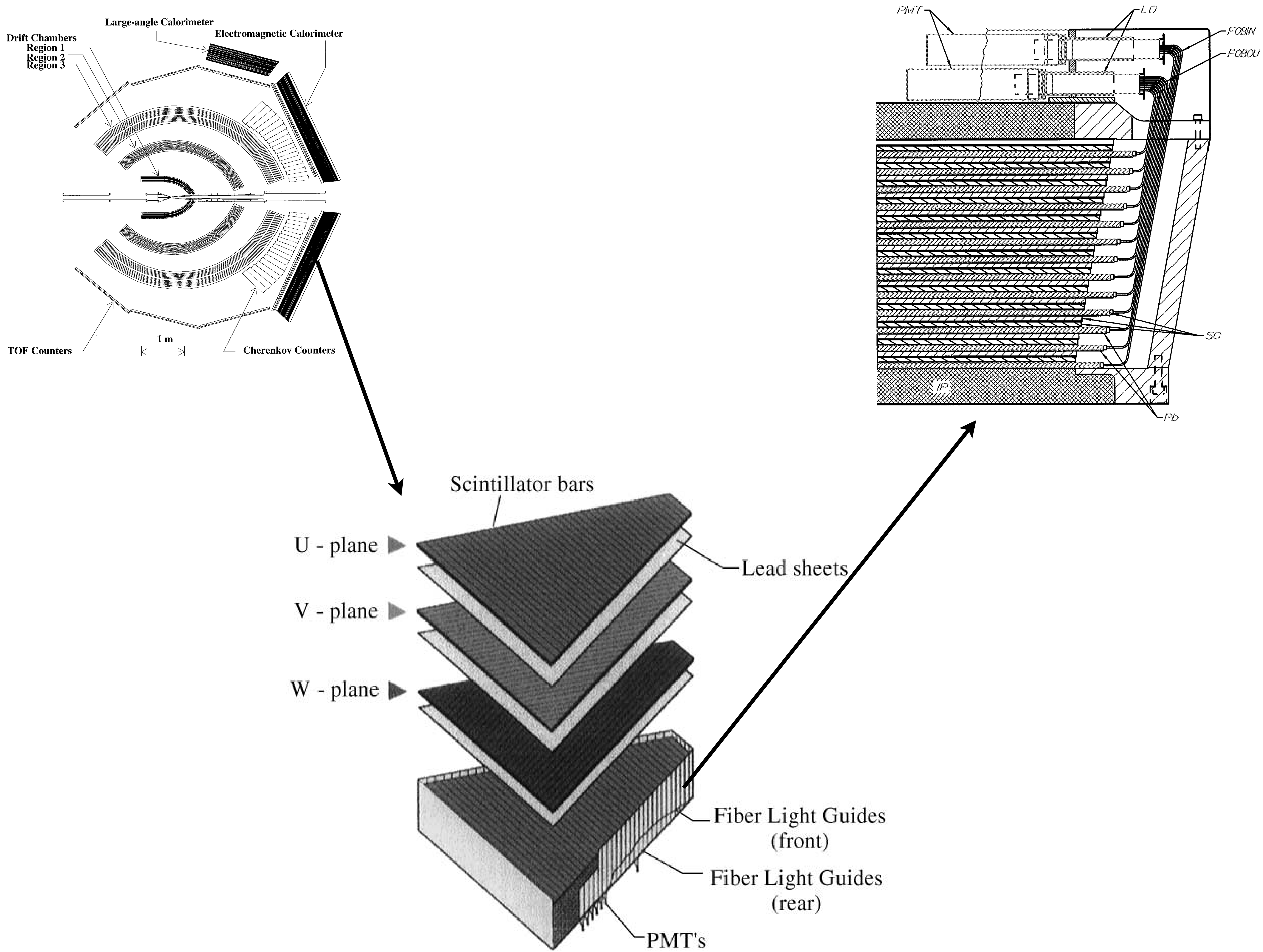





# The CLAS12 forward electromagnetic calorimeters

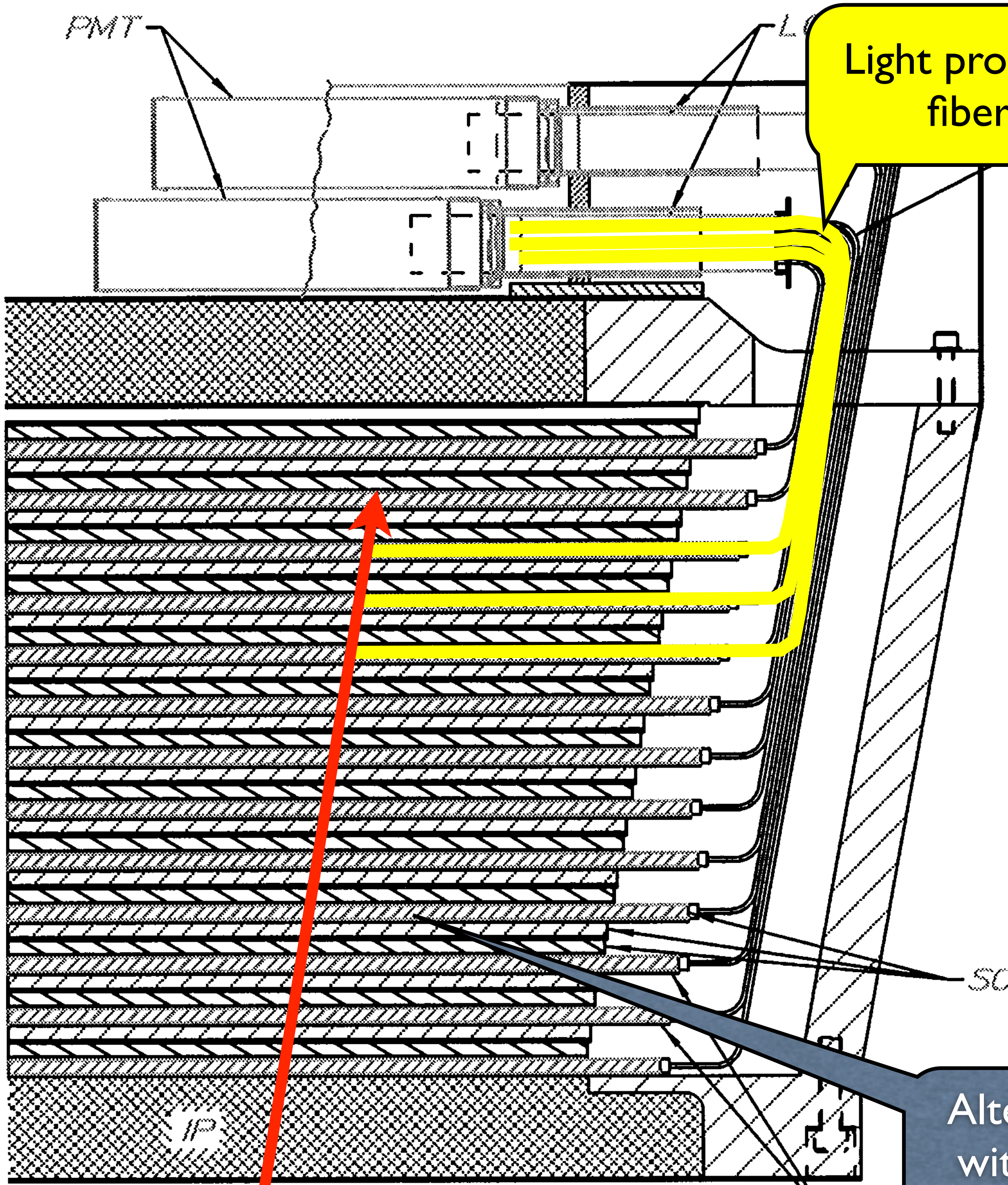
(photo December 2013)

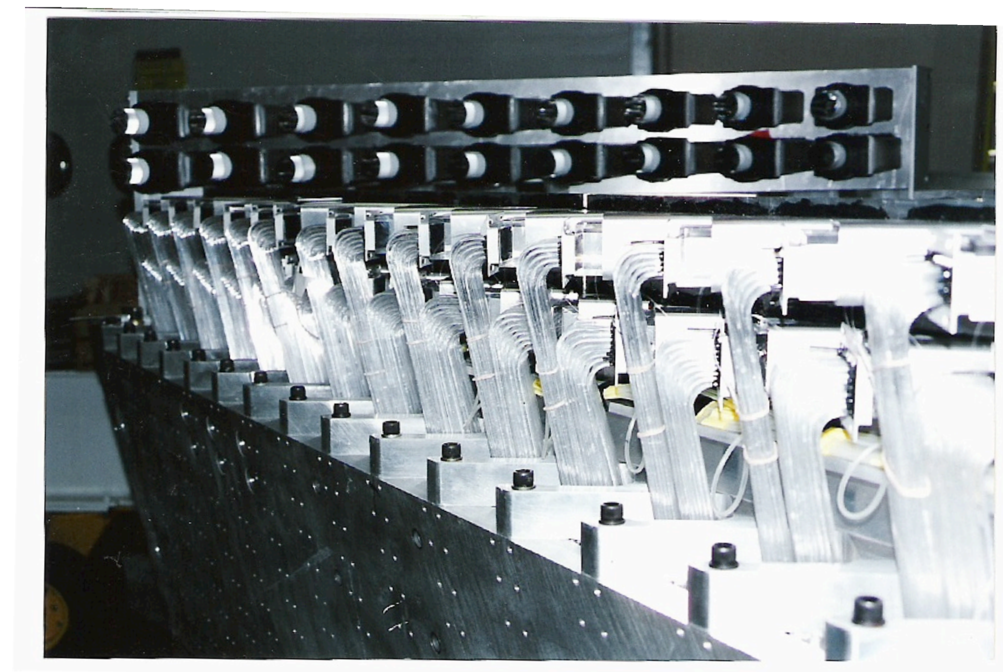



Large-angle Calorimeter
Electromagnetic Calorimeter
Drift Chambers
Region 1
Region 2
Region 3
TOF Counters
1 m
Cherenkov Counters
PMT
LG
FOBIN
FOBOU
SC
IP
Pb
Scintillator bars
U - plane
V - plane
W - plane
Lead sheets
Fiber Light Guides
(front)
Fiber Light Guides
(rear)
PMT's

# The CLAS12 forward electromagnetic calorimeters

Light produced in scintillators is transported through fiber lightguides to the PMT (light detector)

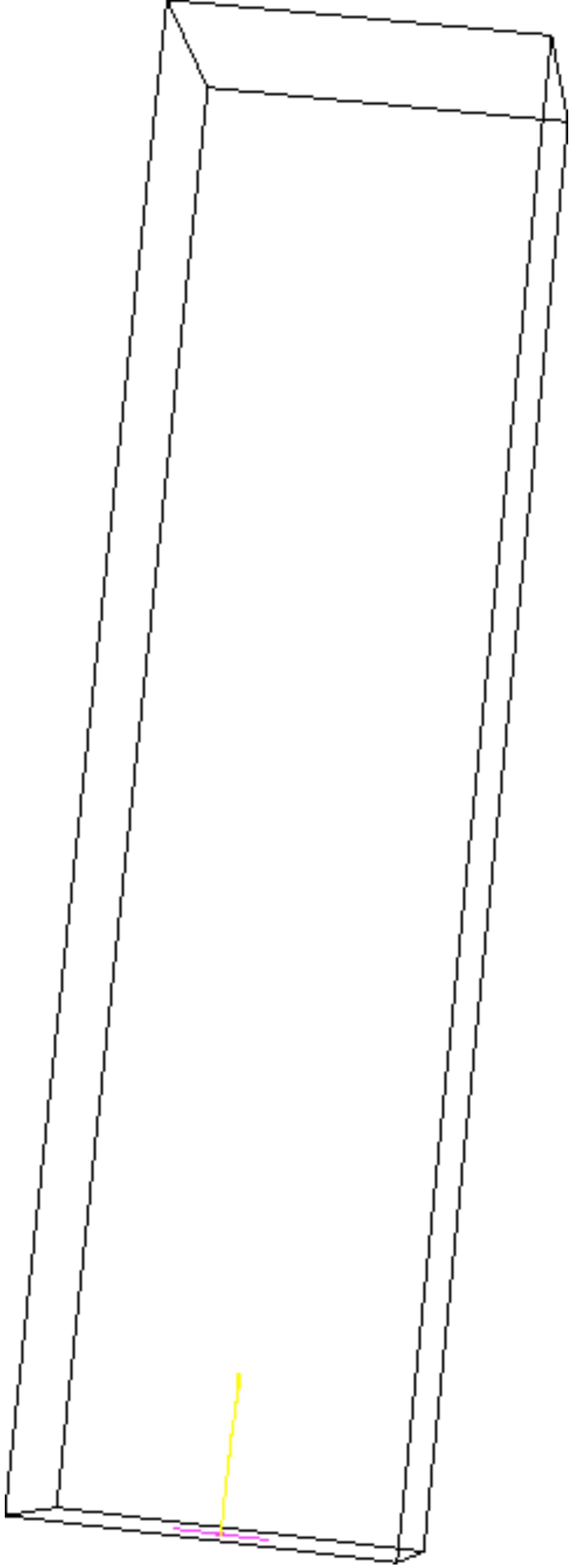


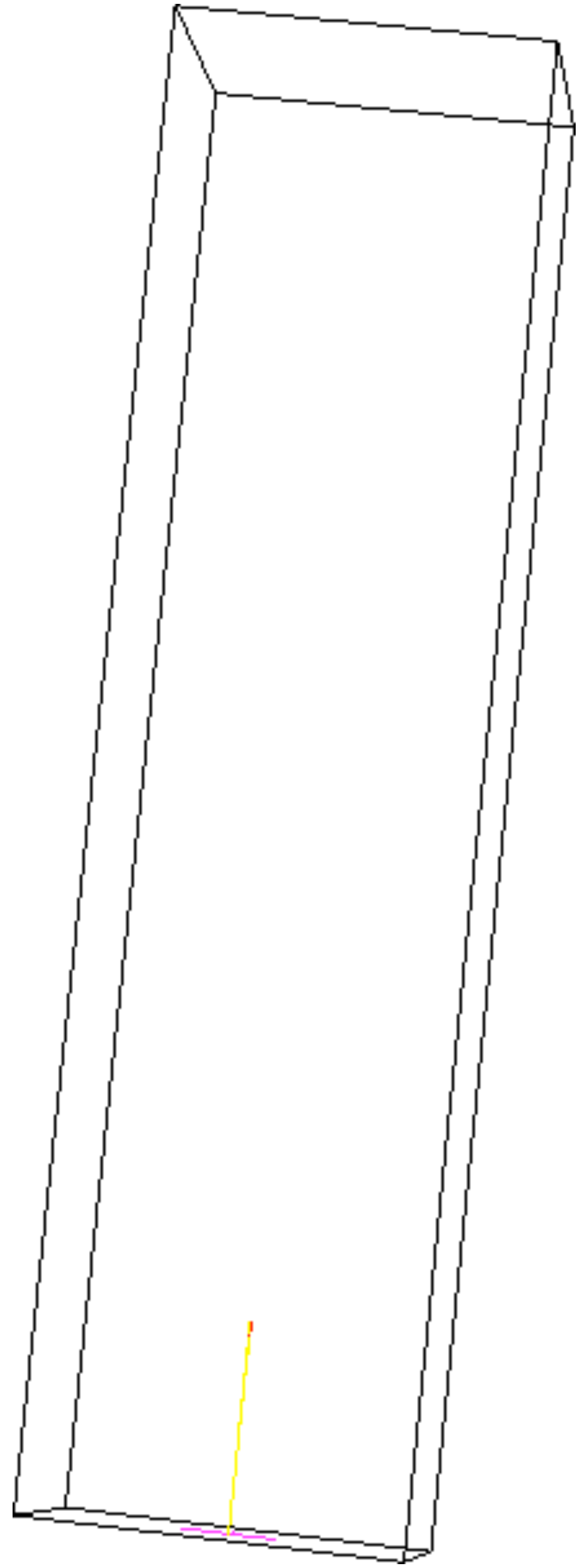
Alternating layers of Pb metal (2.3 mm thick) with plastic scintillator (10 mm thick) which creates light in proportion to energy deposited

Particle from interaction

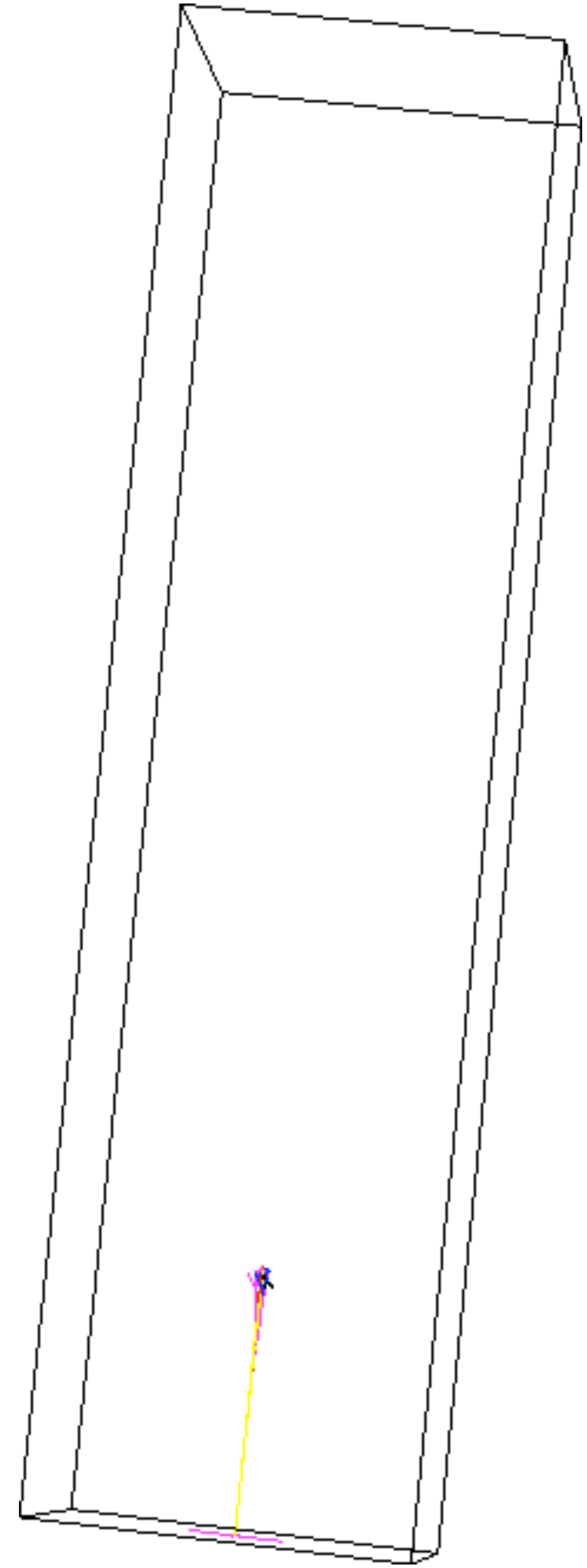
This is a typical sampling calorimeter



2 GeV electron
Lead glass

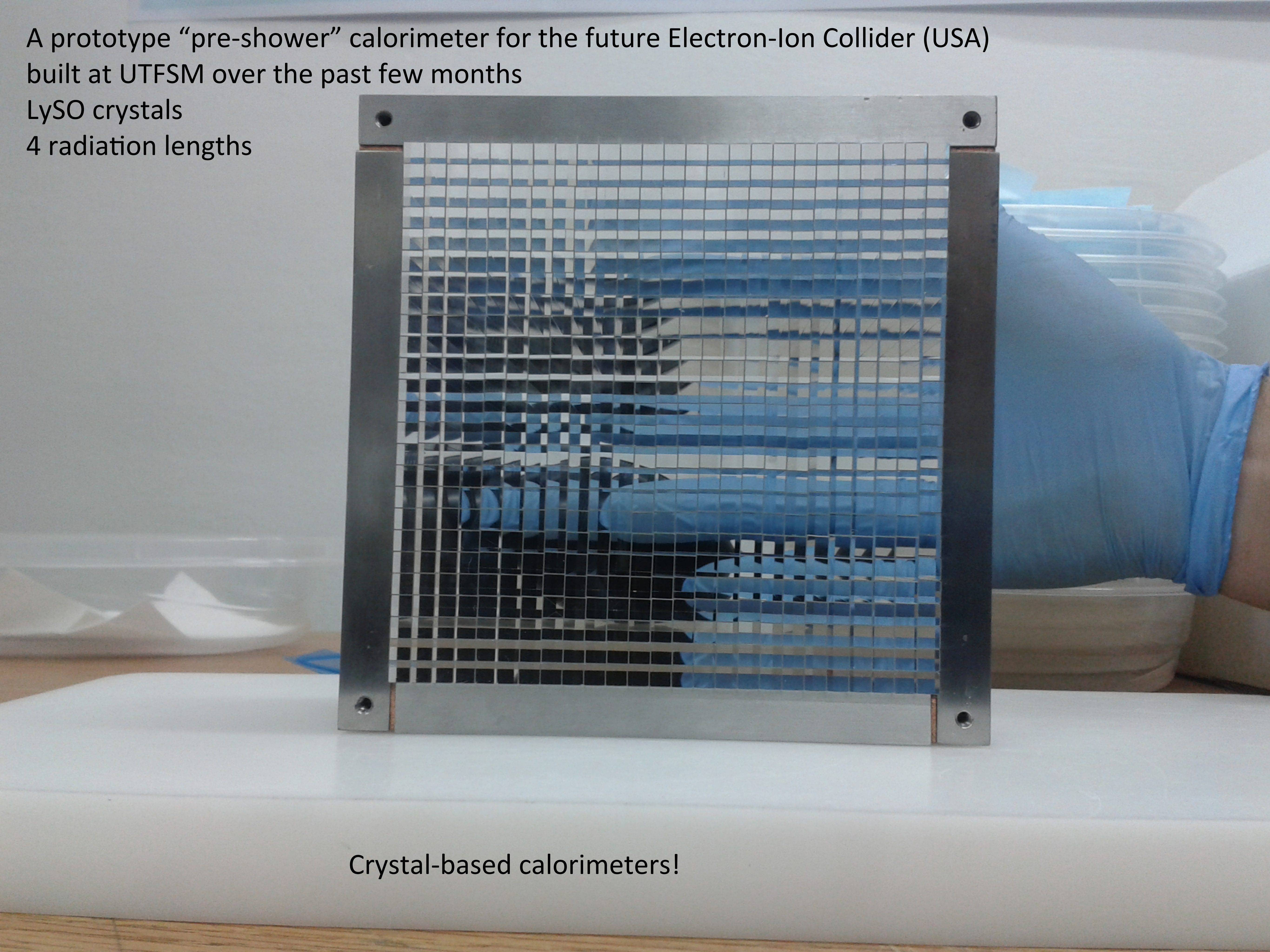


10 GeV electron
Lead glass



80 GeV electron
Lead glass

A prototype “pre-shower” calorimeter for the future Electron-Ion Collider (USA)
built at UTFSM over the past few months
LySO crystals
4 radiation lengths



Crystal-based calorimeters!

# Crystal Materials, 1

- Cerium-doped Silicate Yttrium Lutetium Crystal (Ce:LYSO)
- Lutetium Oxyorthosilicate (LSO)
- Naturally occurring lutetium (Lu) is composed of 1 stable isotope $^{175}$Lu (97.41% natural abundance) and one long-lived radioisotope, $^{176}$Lu with a half-life of $3.78 \times 10^{10}$ years (2.59% natural abundance).

| nuclide symbol | Z(p) | N(n) | isotopic mass (u) | half-life[n 1] | decay mode(s)[1][n 2] | daughter isotope(s)[n 3] | nuclear spin | representative isotopic composition (mole fraction) |
|---|---|---|---|---|---|---|---|---|
| | excitation energy | | | | | | | |
| $^{175}$Lu | 71 | 104 | 174.9407718(23) | Observationally Stable[n 4] | | | 7/2+ | 0.9741(2) |
| $^{175m1}$Lu | 1392.2(6) keV | | | 984(30) μs | | | (19/2+) | |
| $^{175m2}$Lu | 353.48(13) keV | | | 1.49(7) μs | | | 5/2- | |
| $^{176}$Lu[n 5][n 6] | 71 | 105 | 175.9426863(23) | **$38.5(7)\times10^{9}$ a** | $\beta^-$ | **$^{176}$Hf** | 7- | 0.0259(2) |
| $^{176m}$Lu | 122.855(6) keV | | | 3.664(19) h | $\beta^-$ (99.9%) | **$^{176}$Hf** | 1- | |
| | | | | | EC (.095%) | **$^{176}$Yb** | | |

# Crystal Materials, 2

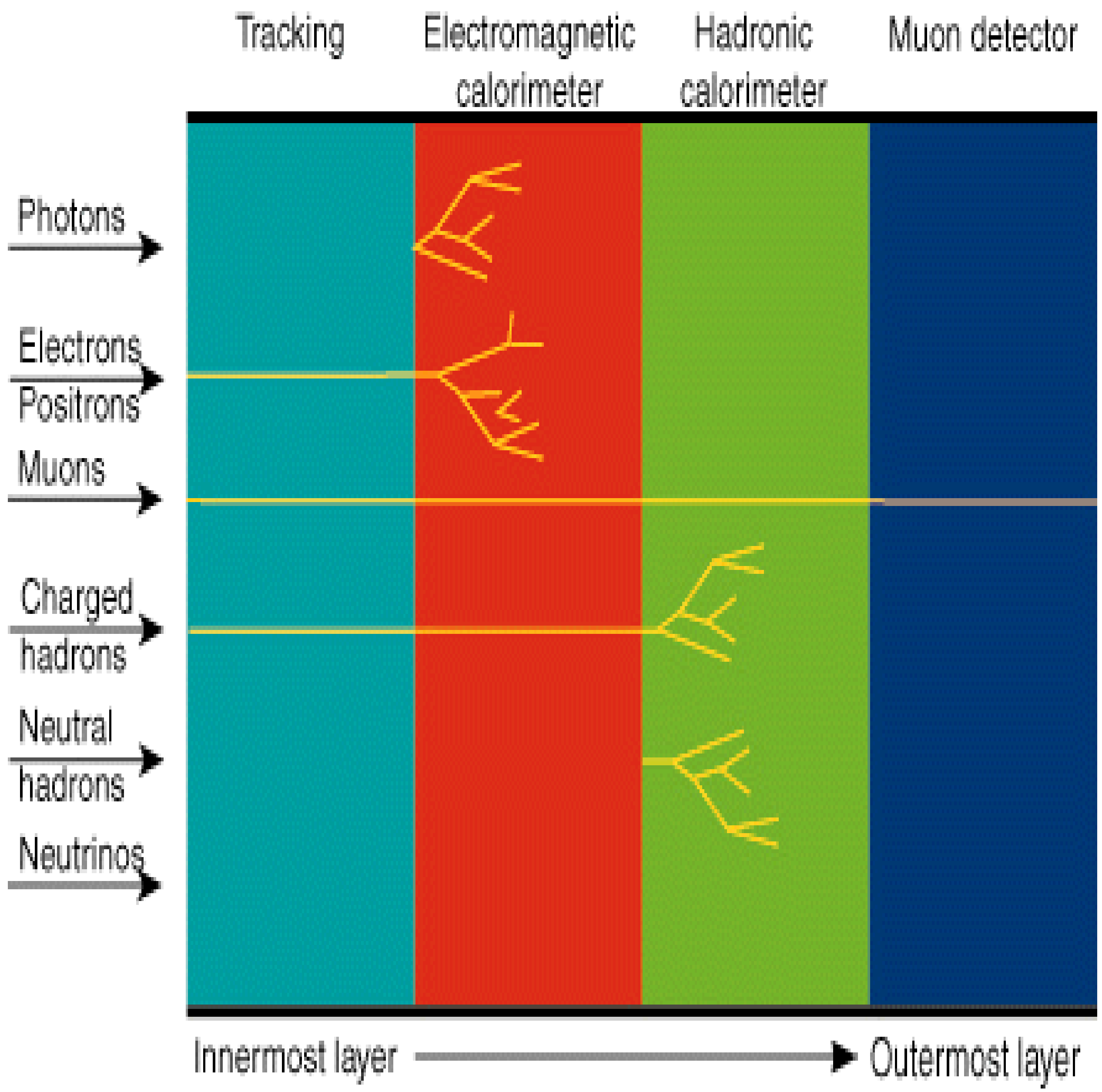
- LSO/LYSO is a bright (200 times PWO), fast (40 ns) and radiation hard crystal scintillator. The light output loss of 20 to 28 cm long crystals is at a level of 10% after 1 Mrad $\gamma$–ray irradiation, much better than all other crystal scintillators. (See talk presented at Calor2012, Santa Fe, by Ren-Yuan Zhu, Caltech)

# Crystals for HEP Calorimeters

| Crystal | NaI(Tl) | CsI(Tl) | CsI(Na) | CsI | $BaF_2$ | $CeF_3$ | BGO | PWO(Y) | LSO(Ce) |
|---|---|---|---|---|---|---|---|---|---|
| Density ($g/cm^3$) | 3.67 | 4.51 | 4.51 | 4.51 | 4.89 | 6.16 | 7.13 | 8.3 | 7.40 |
| Melting Point (°C) | 651 | 621 | 621 | 621 | 1280 | 1460 | 1050 | 1123 | 2050 |
| Radiation Length (cm) | 2.59 | 1.86 | 1.86 | 1.86 | 2.03 | 1.70 | 1.12 | 0.89 | 1.14 |
| Molière Radius (cm) | 4.13 | 3.57 | 3.57 | 3.57 | 3.10 | 2.41 | 2.23 | 2.00 | 2.07 |
| Interaction Length (cm) | 42.9 | 39.3 | 39.3 | 39.3 | 30.7 | 23.2 | 22.8 | 20.7 | 20.9 |
| Refractive Index [a] | 1.85 | 1.79 | 1.95 | 1.95 | 1.50 | 1.62 | 2.15 | 2.20 | 1.82 |
| Hygroscopicity | Yes | Slight | Slight | Sligh<br>t | No | No | No | No | No |
| Luminescence [b] (nm)<br>(at peak) | 410 | 550 | 420 | 420<br>310 | 300<br>220 | 340<br>300 | 480 | 425<br>420 | 402 |
| Decay Time [b] (ns) | 245 | 1220 | 690 | 30<br>6 | 650<br>0.9 | 30 | 300 | 30<br>10 | 40 |
| Light Yield [b,c] (%) | 100 | 165 | 88 | 3.6<br>1.1 | 36<br>4.1 | 7.3 | 21 | 0.3<br>0.1 | 85 |
| d(LY)/dT [b] (%/ °C) | -0.2 | 0.4 | 0.4 | -1.4 | -1.9<br>0.1 | 0 | -0.9 | -2.5 | -0.2 |
| Experiment | Crystal<br>Ball | BaBar<br>BELLE<br>BES III | - | KTeV | (L*)<br>(GEM)<br>TAPS | - | L3<br>BELLE | CMS<br>ALICE<br>PANDA | Mu2e<br>SuperB<br>CMS? |

a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

# How do {calorimeter} detectors work?
## (how do particles interact with matter??)




Next: *hadronic shower calorimeters:* many types of high-energy hadronic interactions contribute to creating a shower of hadrons

# Hadronic processes

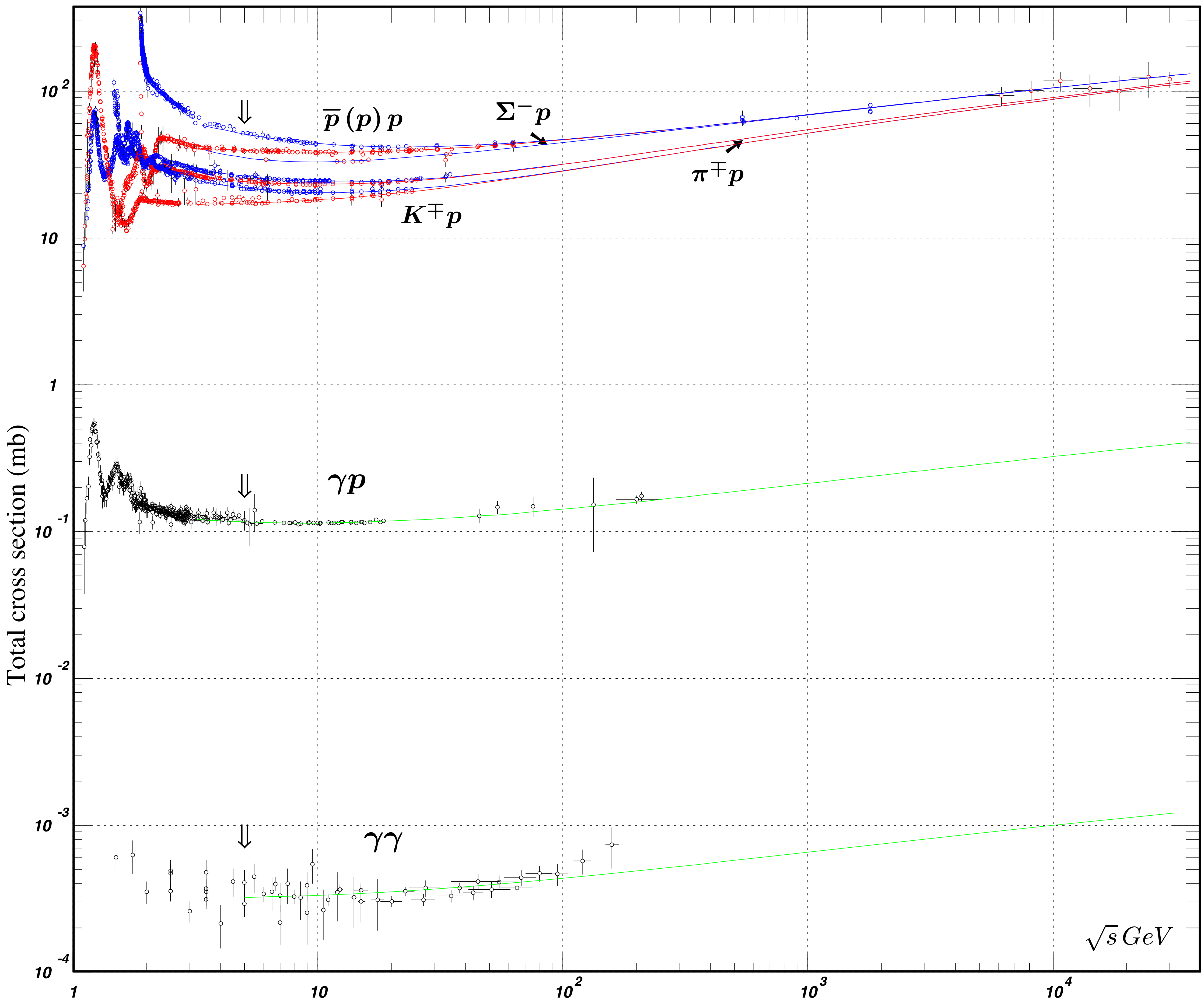
Hadronic processes at rest

- $\pi^-$ absorption
- $K^-$ absorption
- Neutron capture
- Anti-proton/anti-neutron annihilation
- $\mu^-$ capture

Processes with moving hadrons

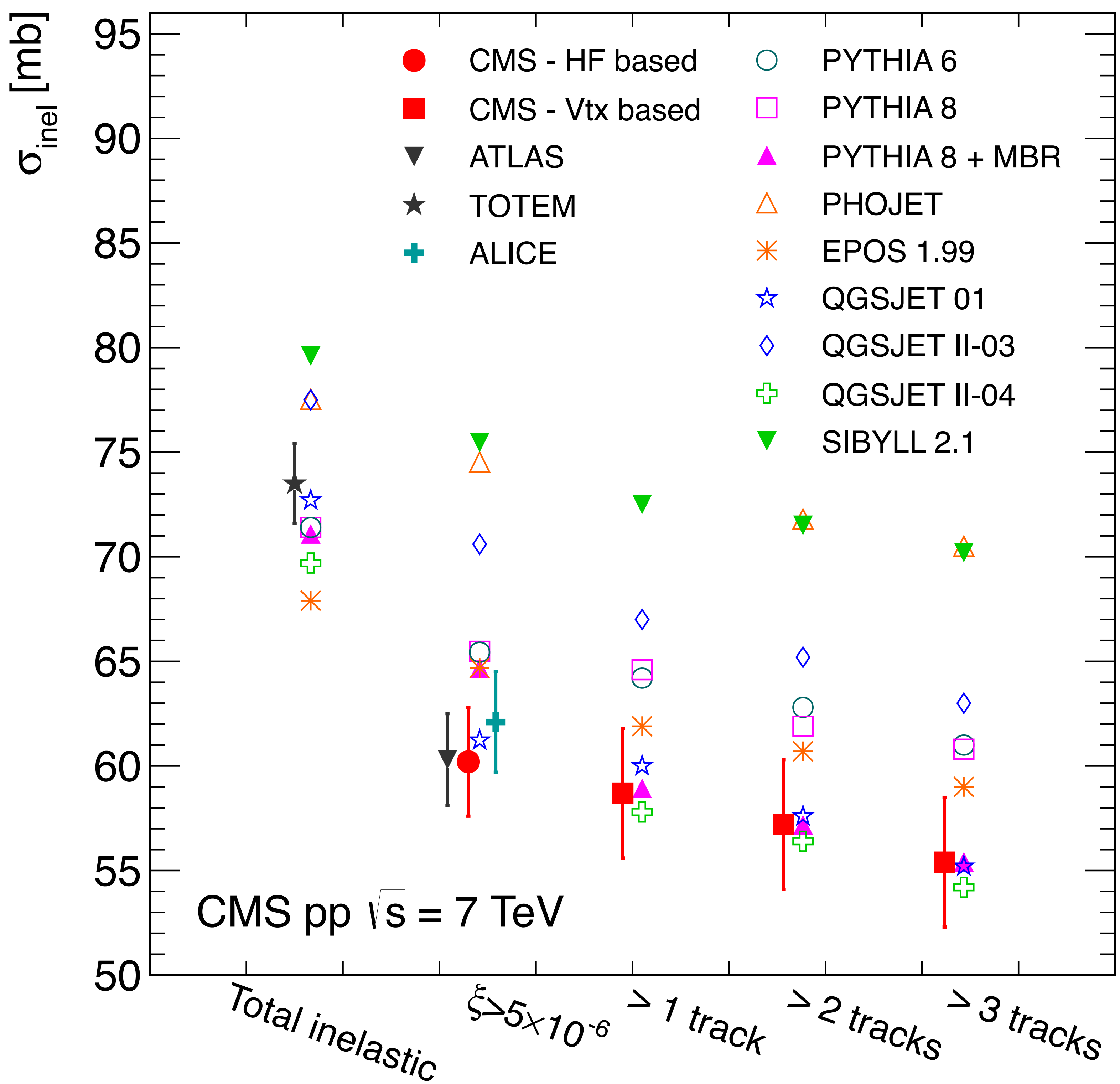
- Elastic scattering
- Inelastic scattering
- Nuclear fission
- Neutron and antineutron capture

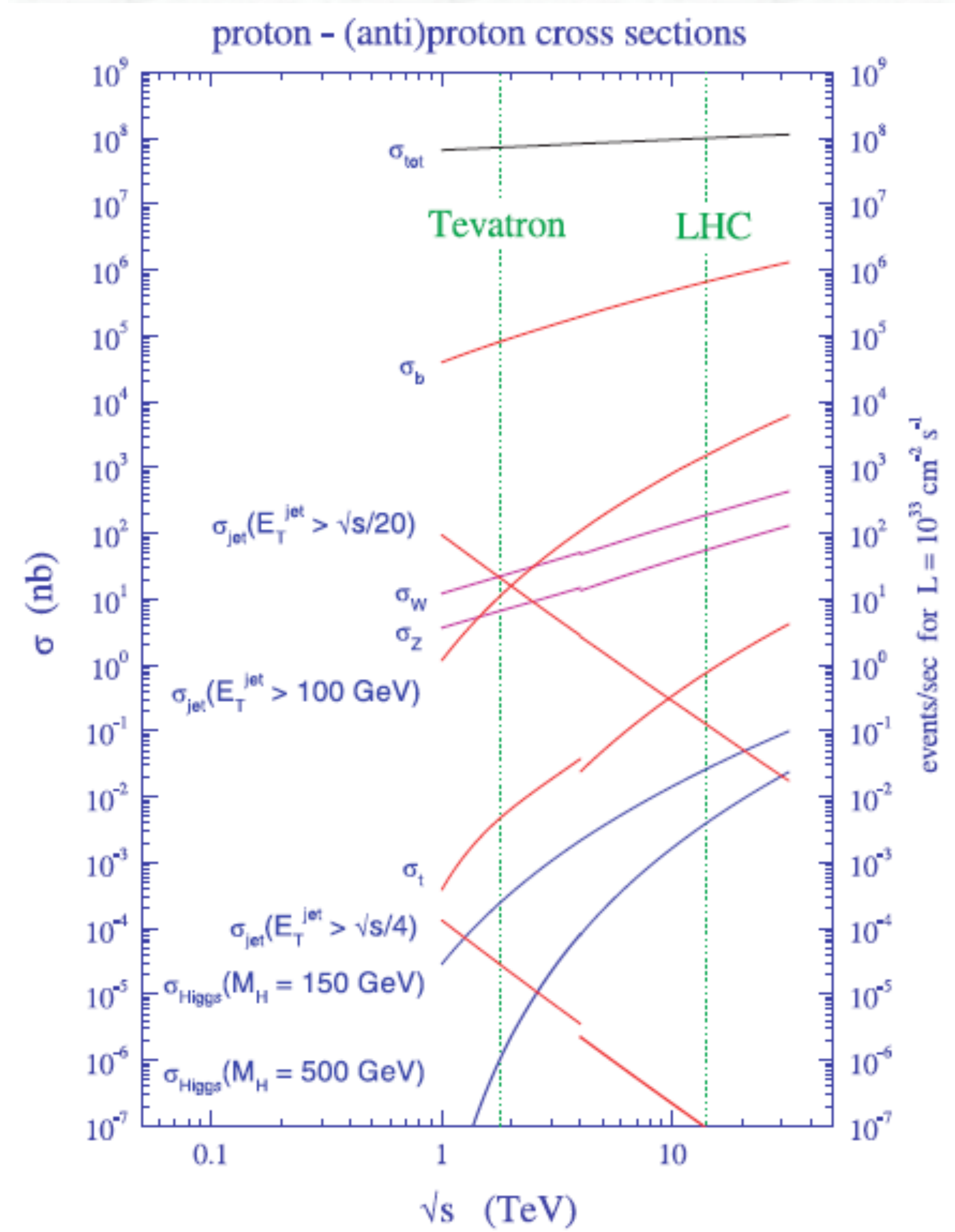
and many more.....



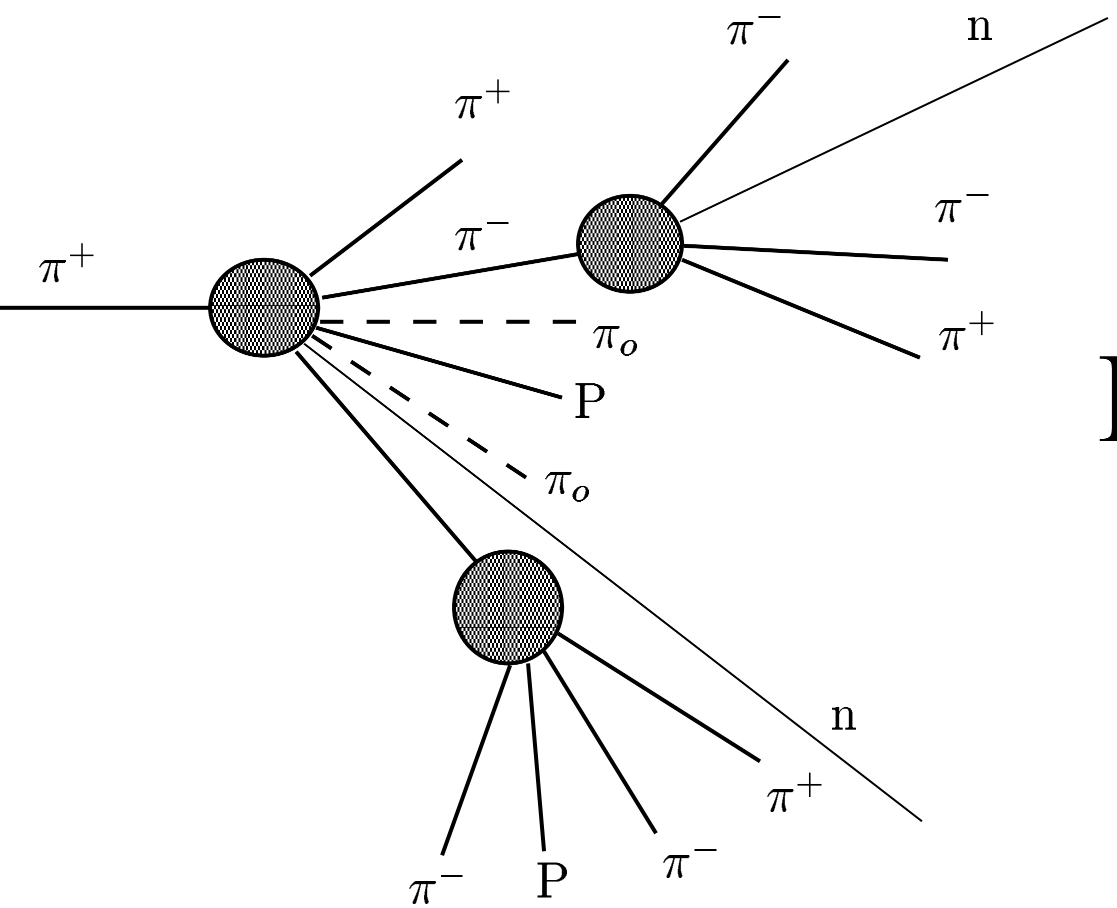
Total cross section (mb)
$10^2$
10
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
1
10
$10^2$
$10^3$
$10^4$
$\overline{p}\,(p)\,p$
$\Sigma^- p$
$\pi^\mp p$
$K^\mp p$
$\gamma p$
$\gamma\gamma$
$\sqrt{s}\,GeV$

# Inelastic cross section, proton-proton collisions

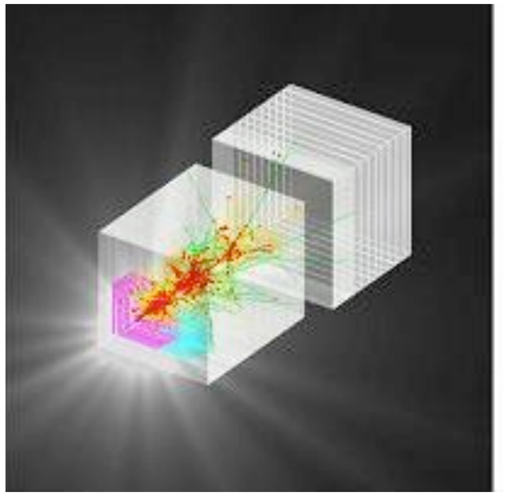


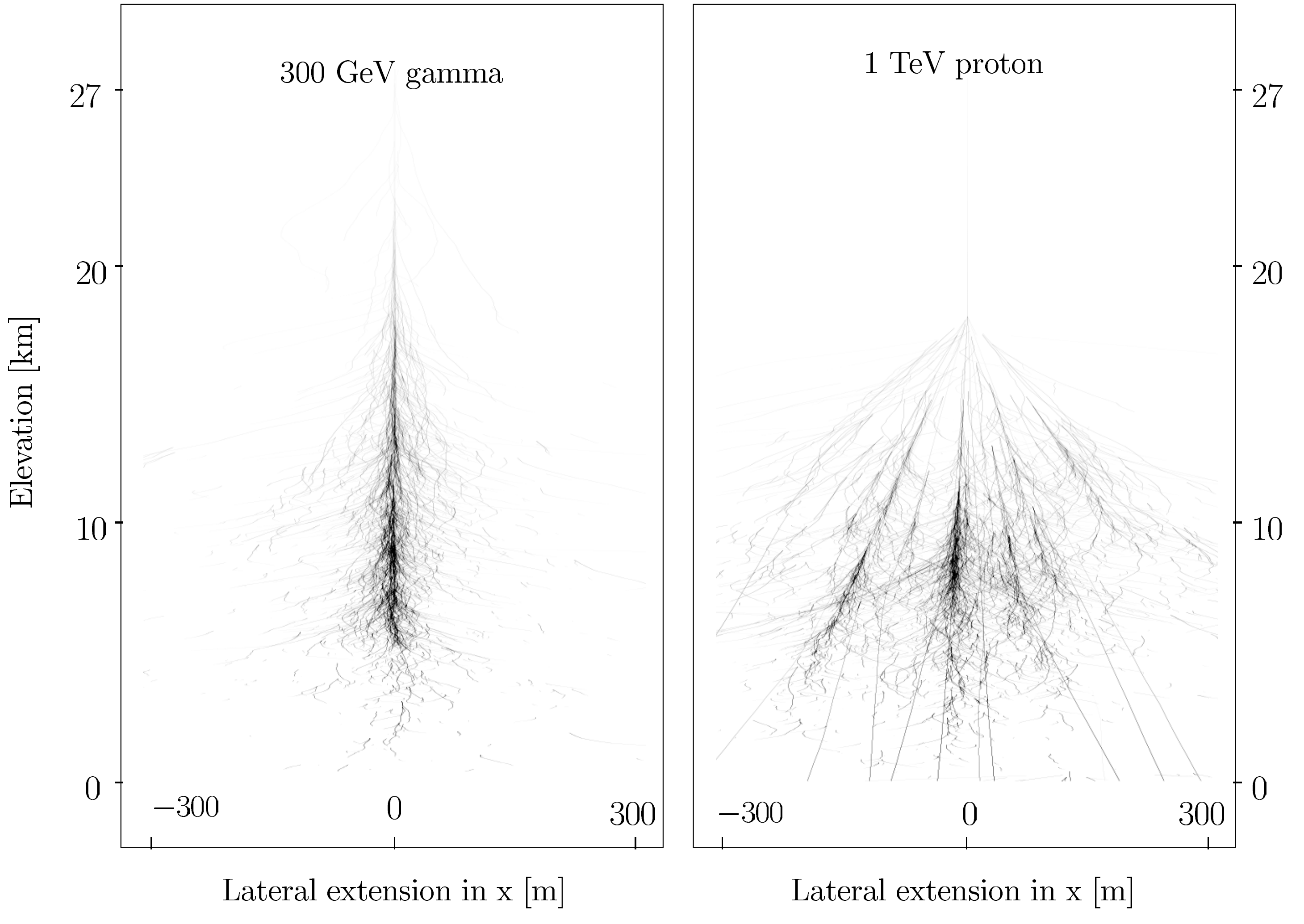

Cross sections for important hard scattering Standard Model processes at the Tevatron and the LHC colliders




# Hadronic showers



$\lambda_I$ = nuclear interaction length



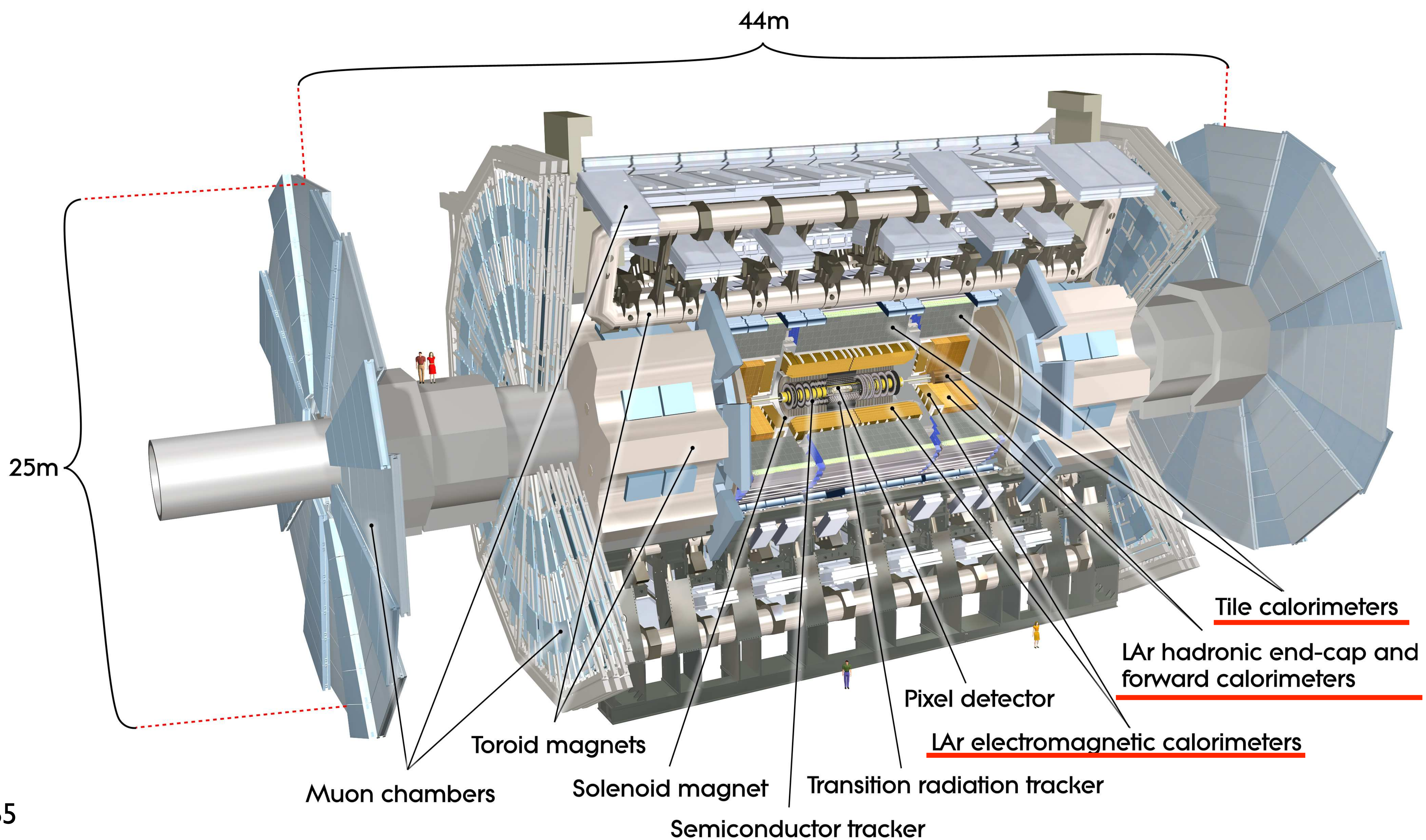

| **Material** | $\lambda_I$ |
|---|---|
| air | 74800 cm |
| Pb (lead) | 17.6 cm |

http://pdg.lbl.gov/2010/reviews/contents_sports.html

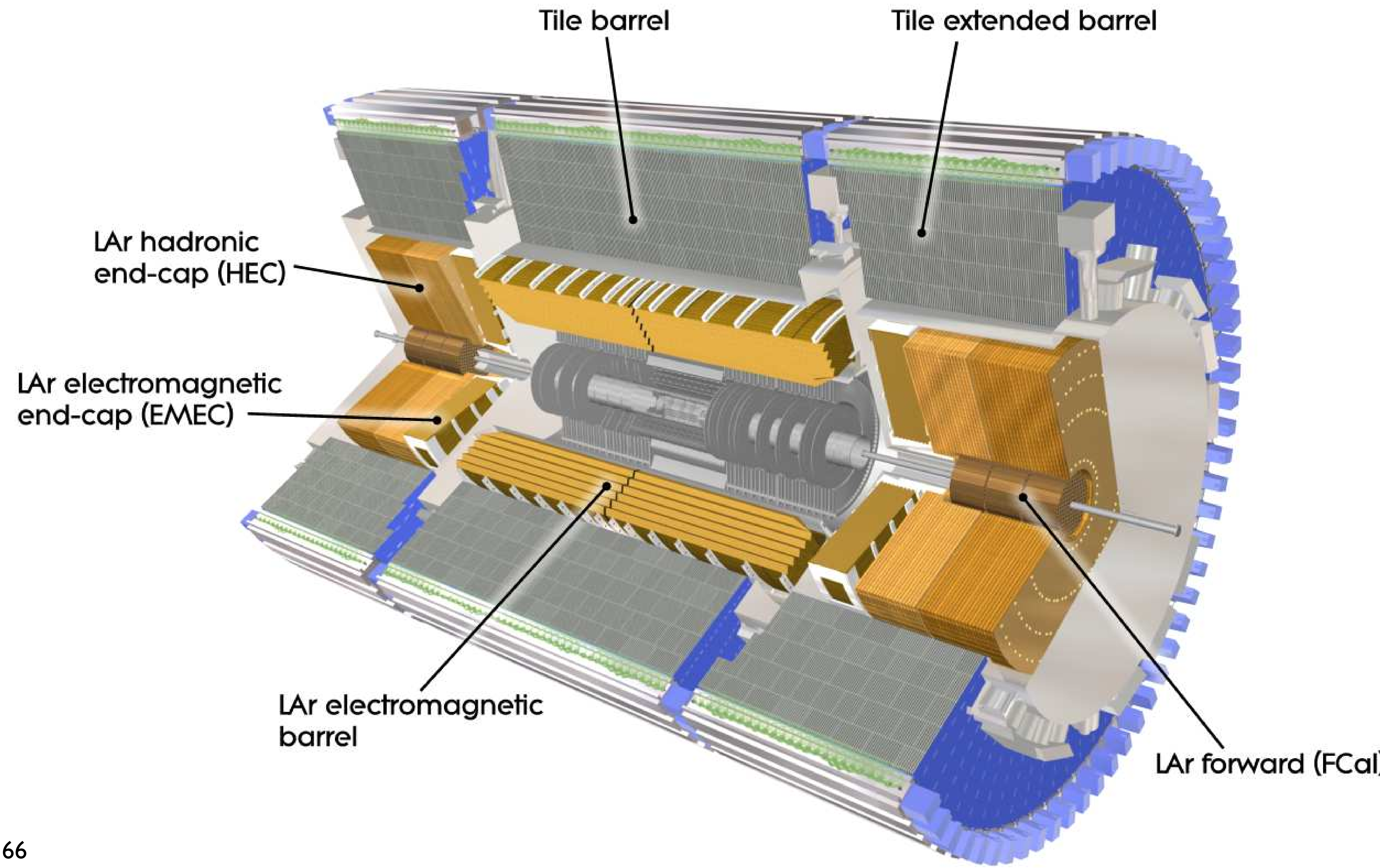
*→ Hadronic calorimeters are generally much "thicker" than electromagnetic calorimeters*

# Calorimeters in ATLAS

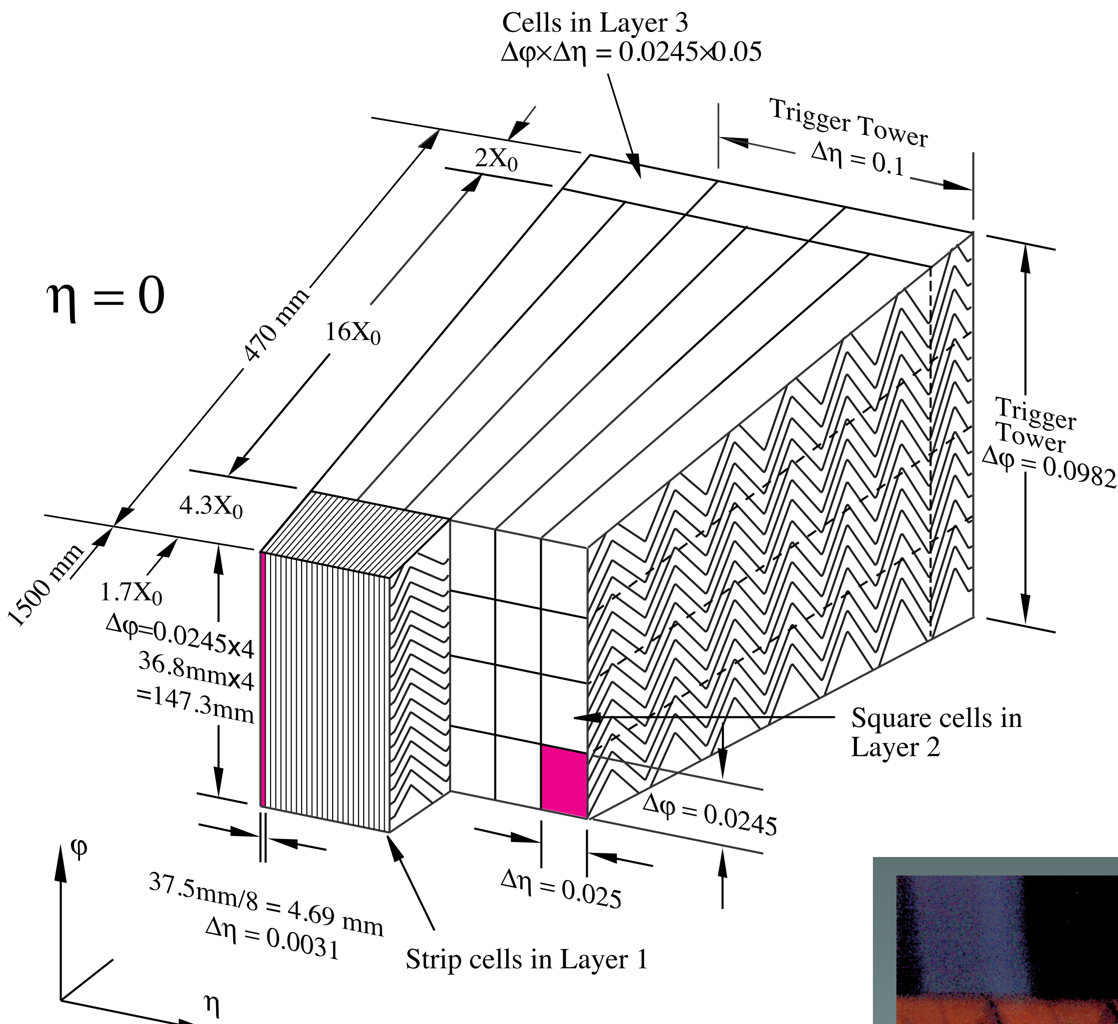
- Electromagnetic and hadronic calorimeters surround the tracking region

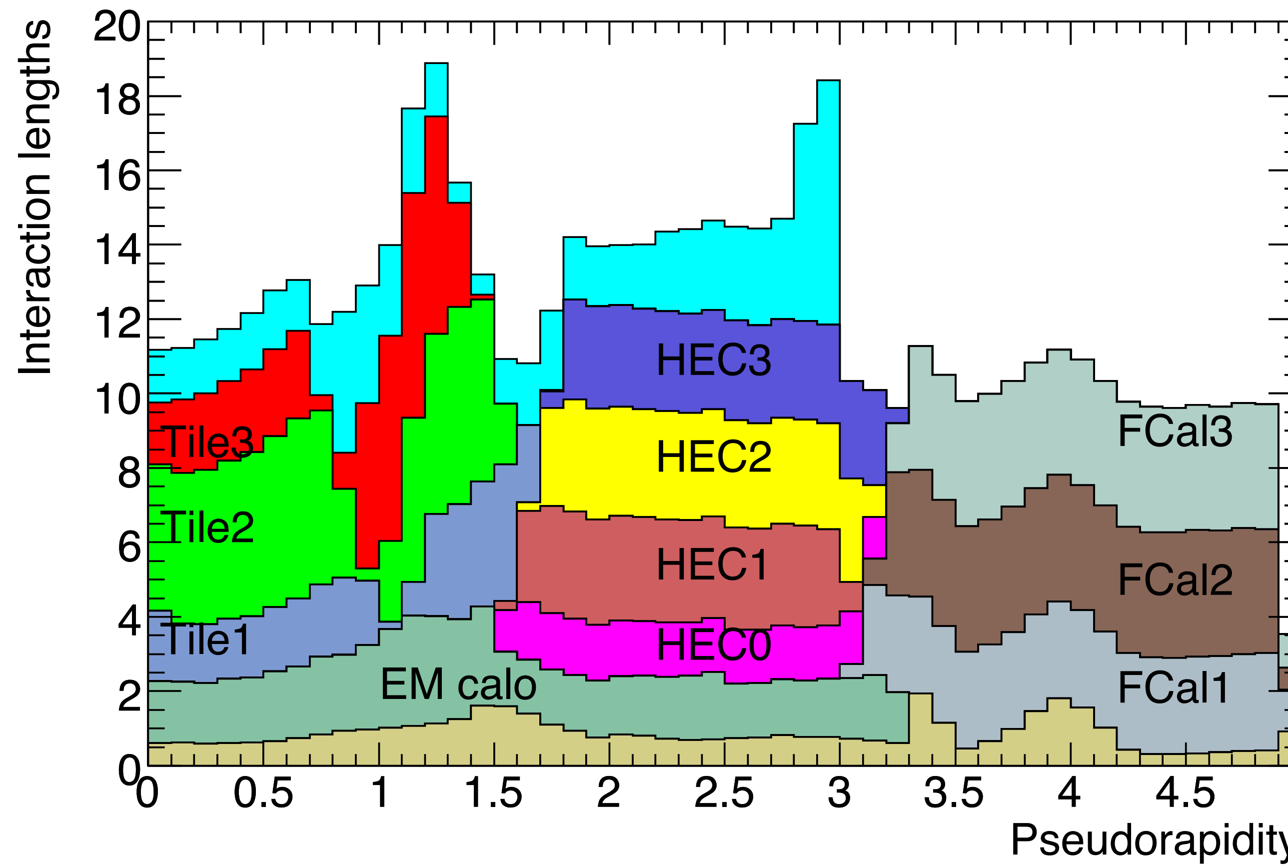


# ATLAS Calorimeter System

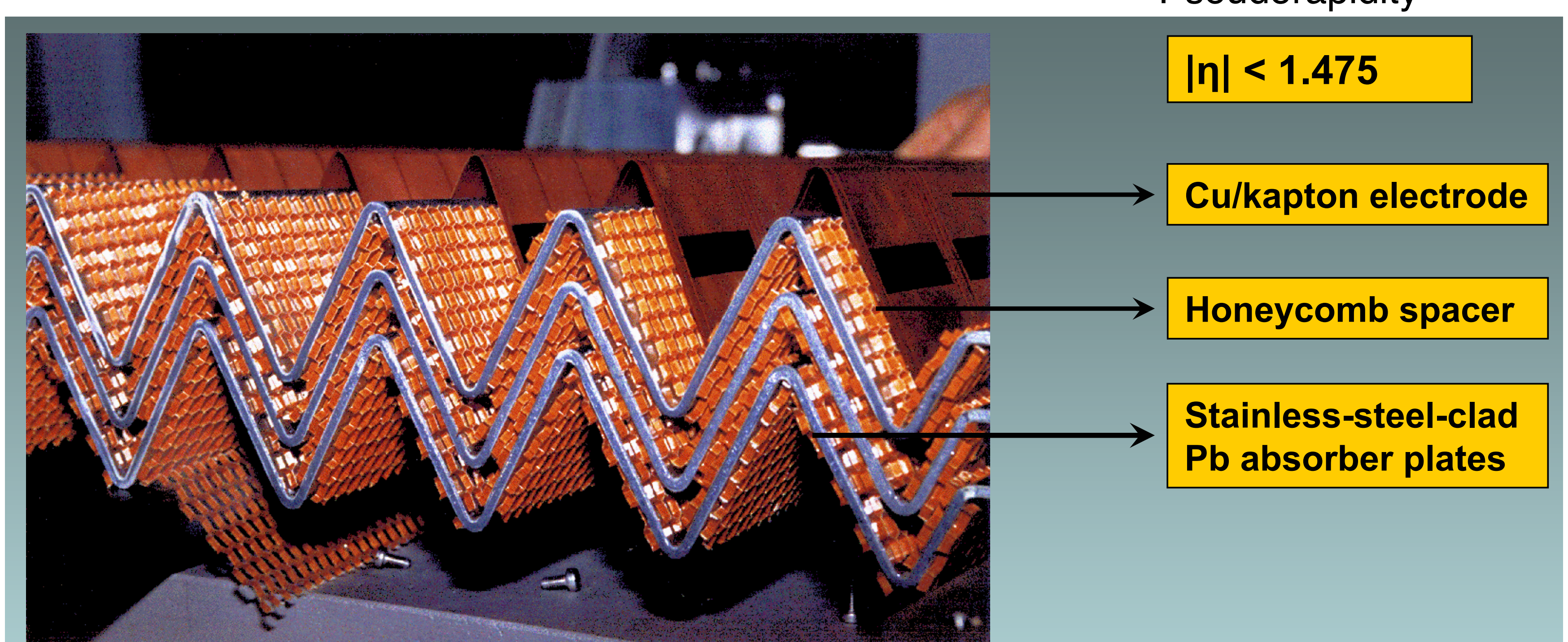


# ATLAS Calorimeters



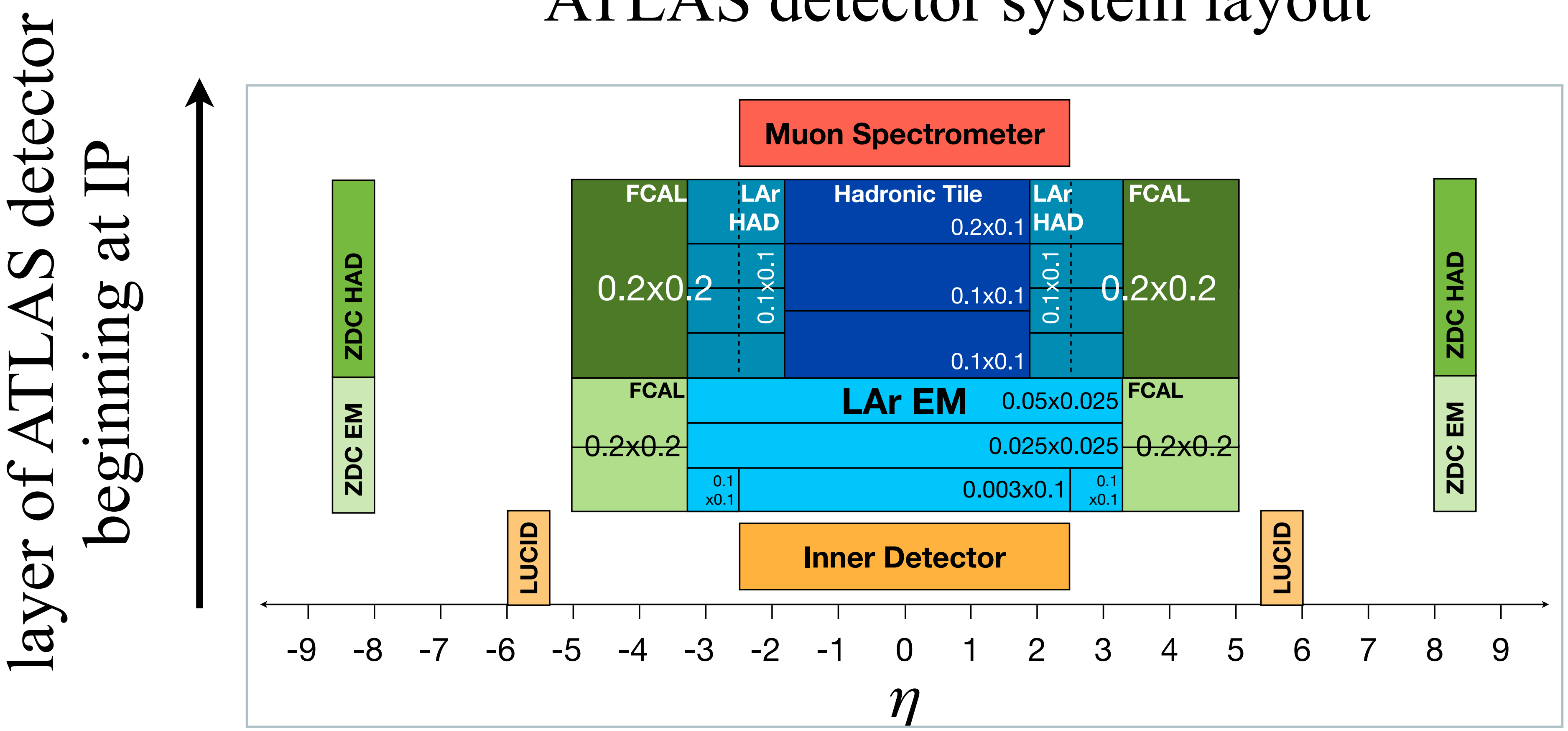




Accordian-style liquid argon calorimeter barrel section

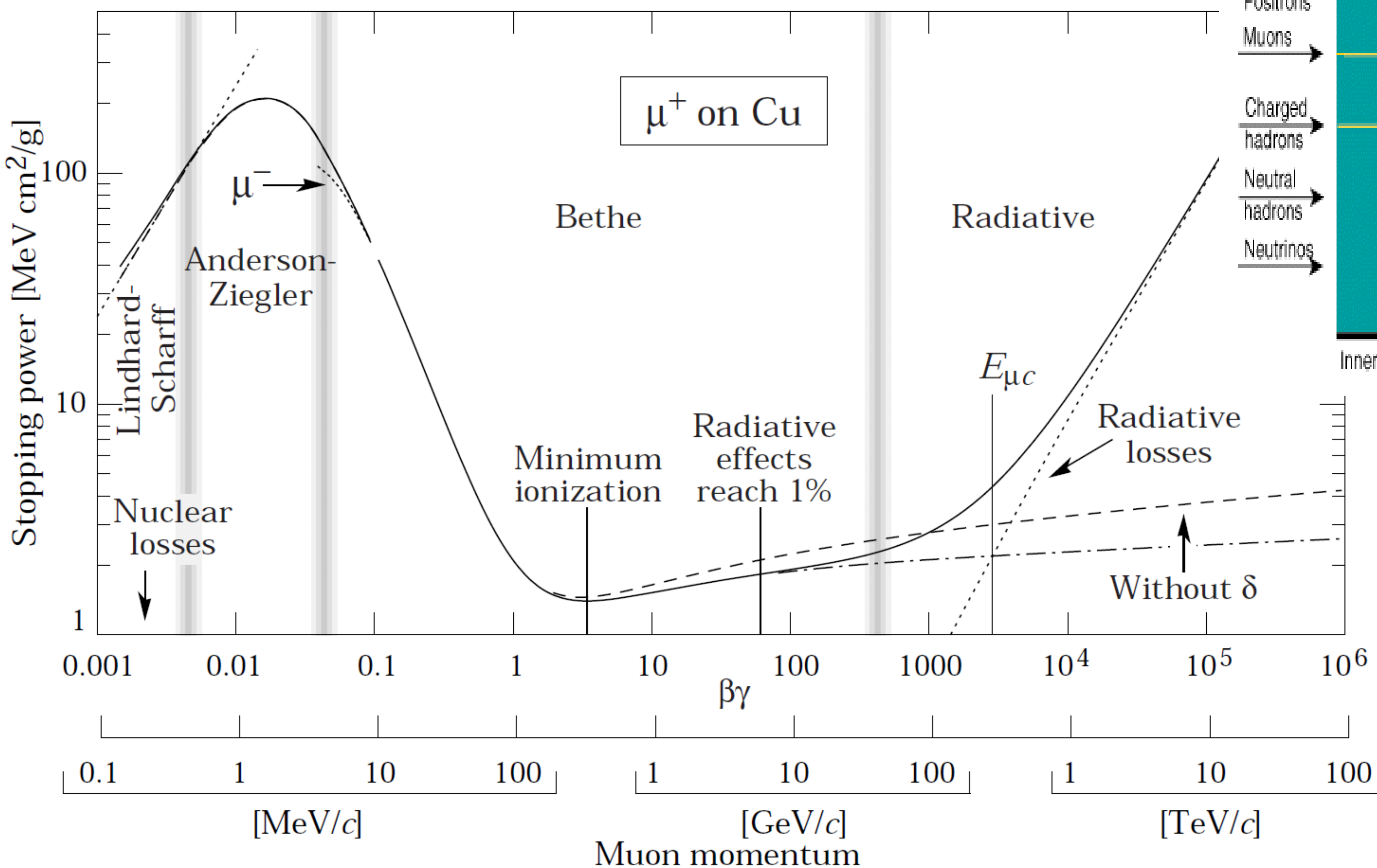


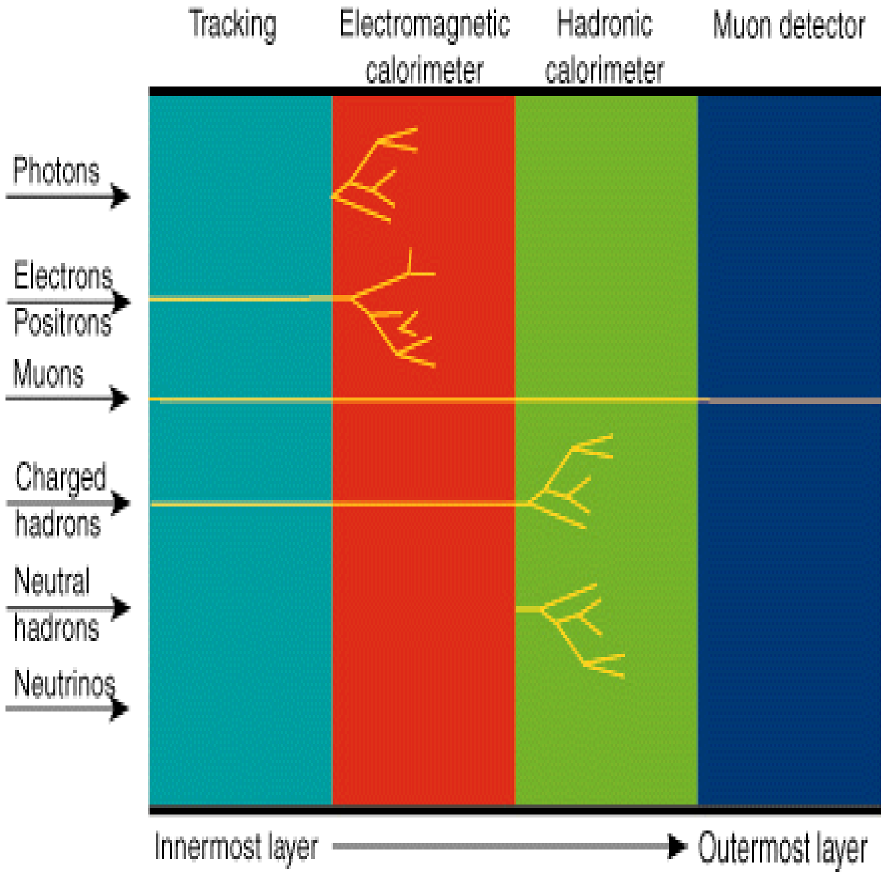
# Classes of particle measurements: *muons*

ATLAS detector system layout



# Ionization Loss: full spectrum



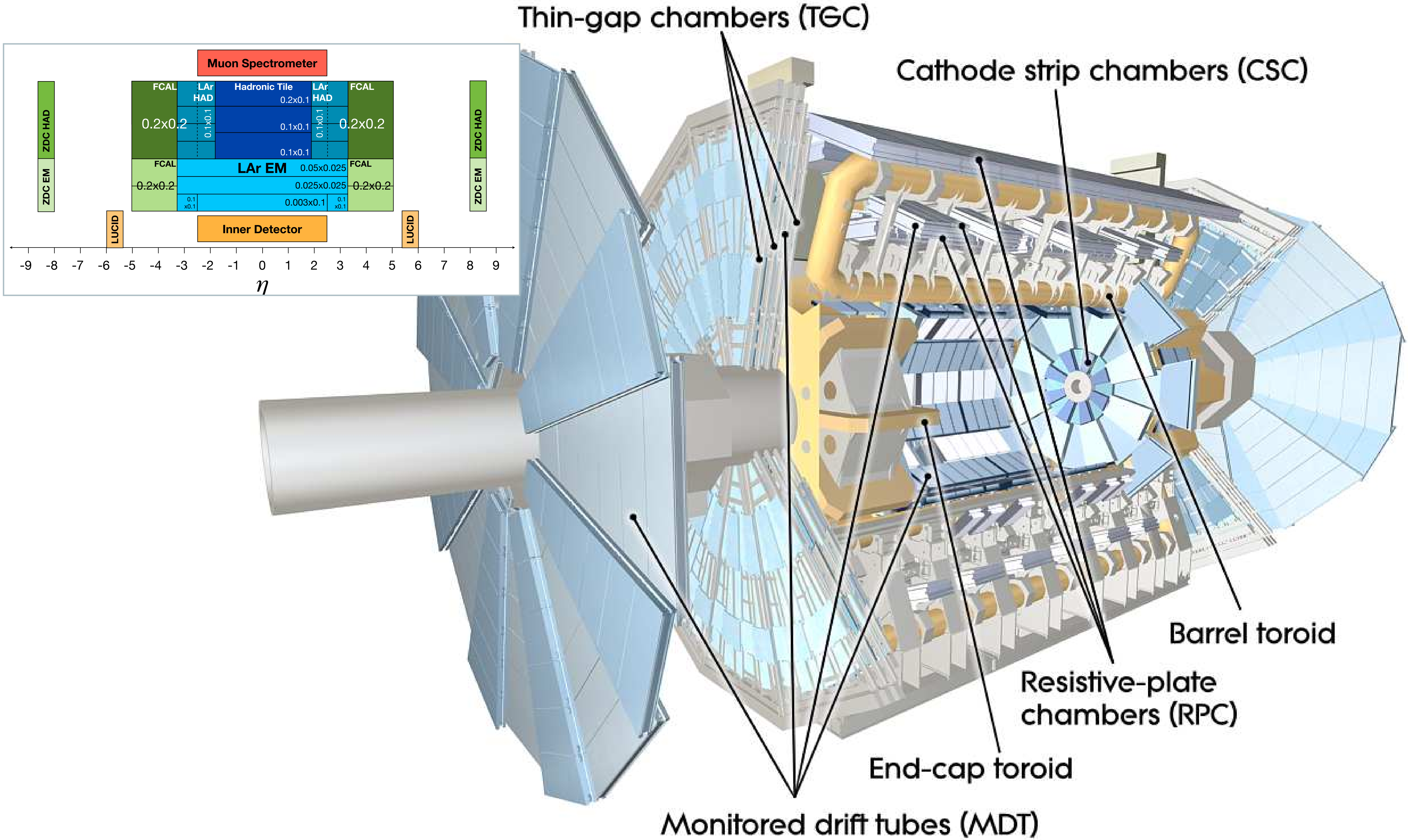




GeV muons primarily lose energy by ionization

→ *penetrate ~all materials until stopped*

TeV muons primarily radiate

# The ATLAS muon system




Muons penetrate through calorimeters; precision measurement of trajectories, requires ultra-precise dynamic alignment system. Eight toroidal coils provide field for momentum analysis.

# Classes of particle measurements:
*neutrinos*

# Neutrinos

- To directly measure neutrinos, you need a LOT of MASS (or a LOT of TIME)
  - cross sections are small
- It also helps to make the neutrinos with an accelerator....

MINERVA experiment at Fermilab