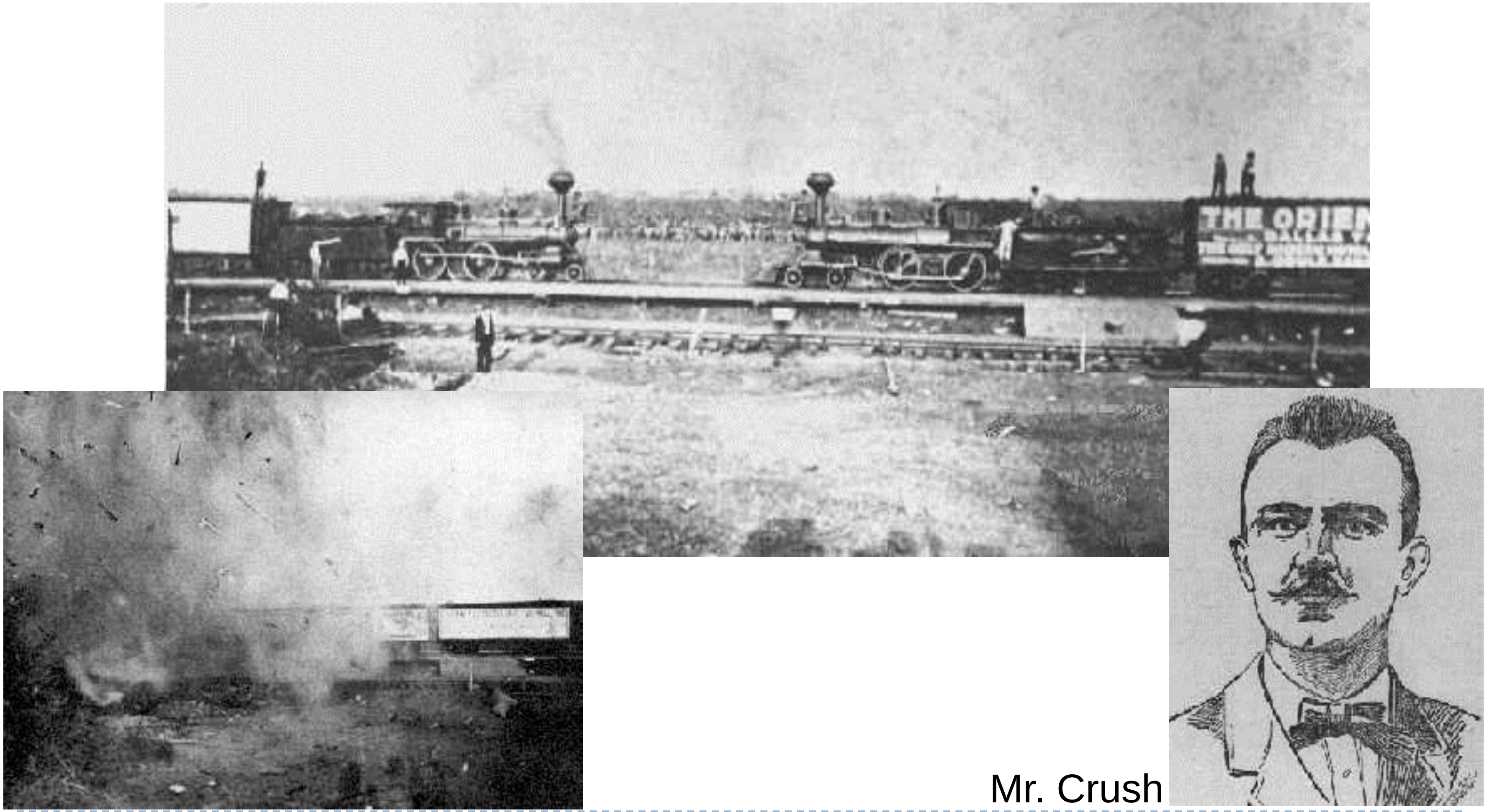
LABORATORIUM FÜR HOCHENERGIEPHYSIK
LHEP
UNIVERSITÄT BERN

Detector Physics

M. Weber

Crash at Crush, TX (1896)

First attempt to produce Higgs ?

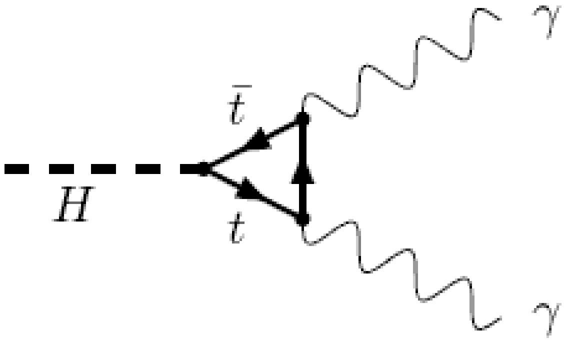


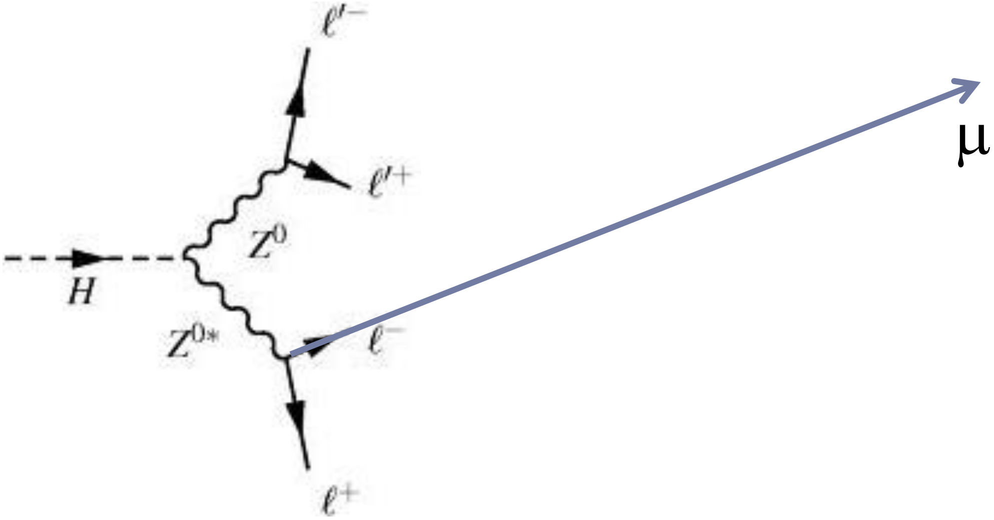
Mr. Crush

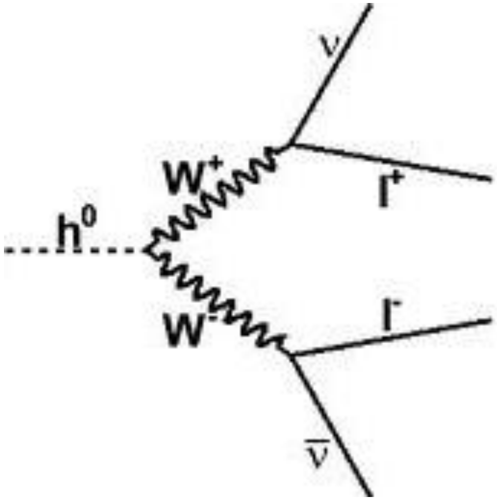
Overview

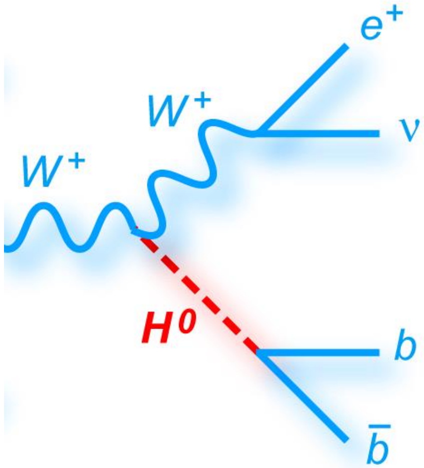
- How do we "measure" particles ?
- What we measure (tracks, momentum, energy)
- How well we do it

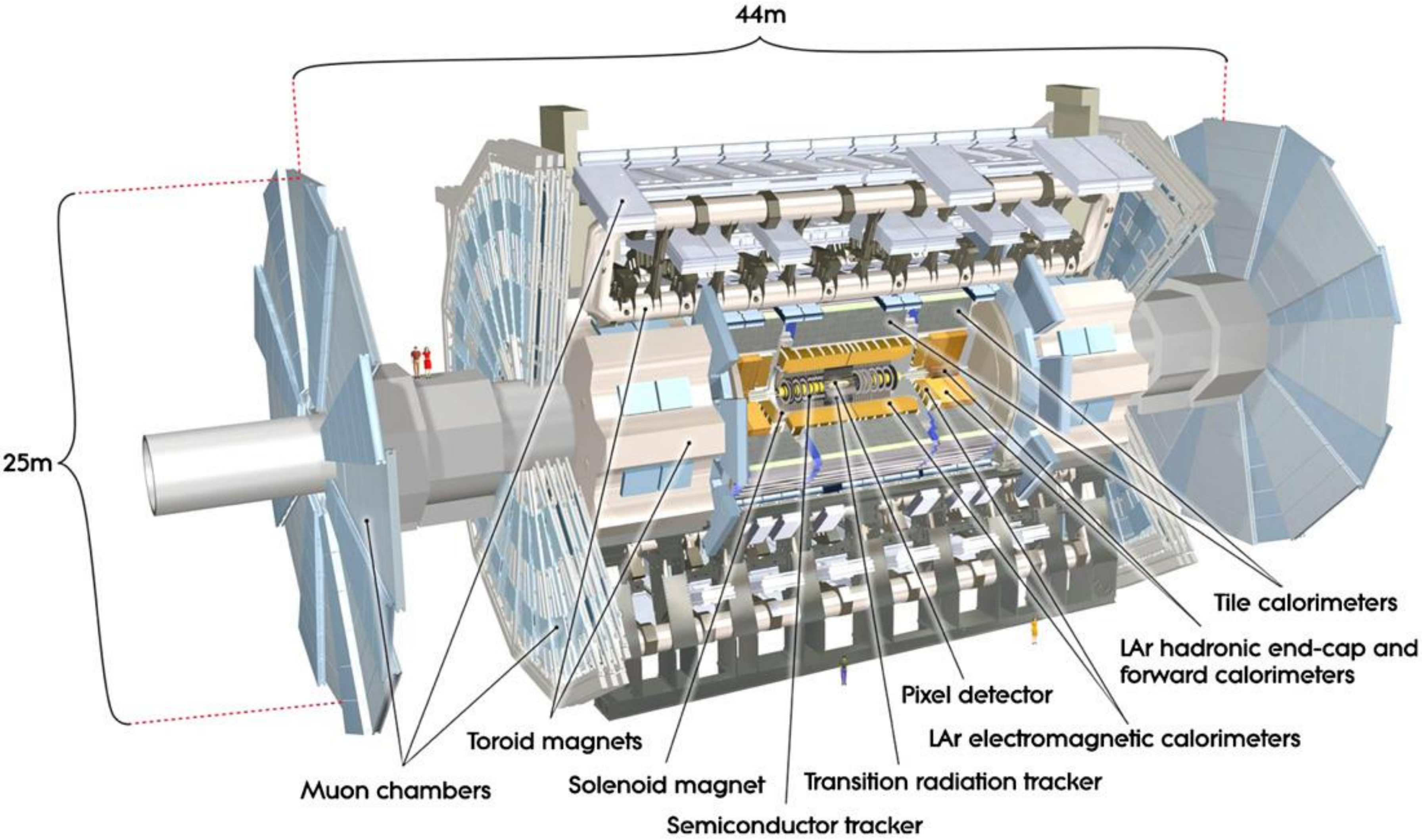
One lesson…
I chose to stay general and give an overview... The basics…


γ
$\bar{t}$
H
t
γ


ℓ'^-
μ
ℓ'^+
Z^0
H
Z^{0*}
ℓ^-
ℓ^+


ν
W^+
l^+
h^0
W^-
l^-
$\bar{\nu}$


e^+
W^+
ν
W^+
H^0
b
$\bar{b}$


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

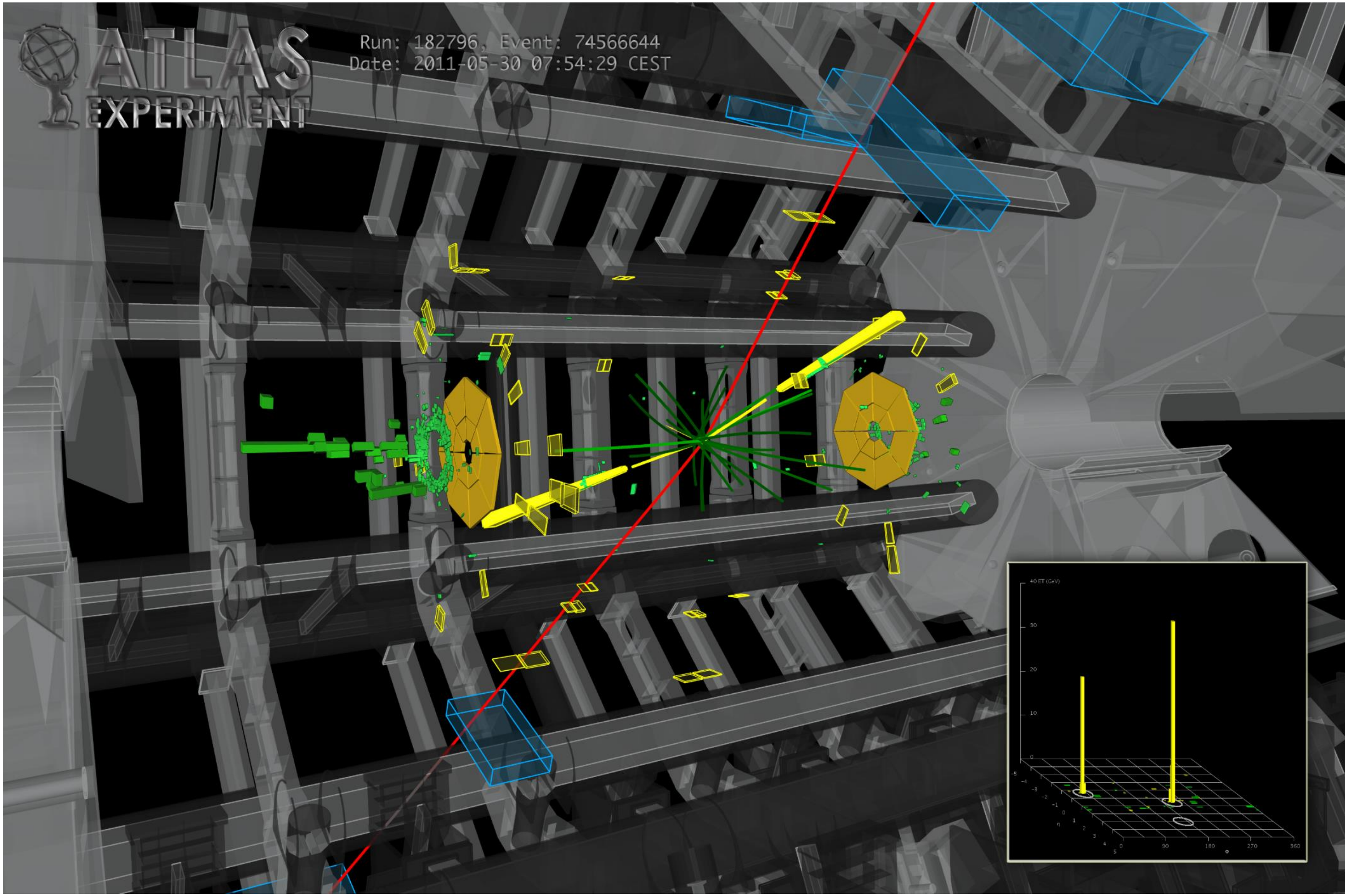
Tracks

© Kim A. Cabrera

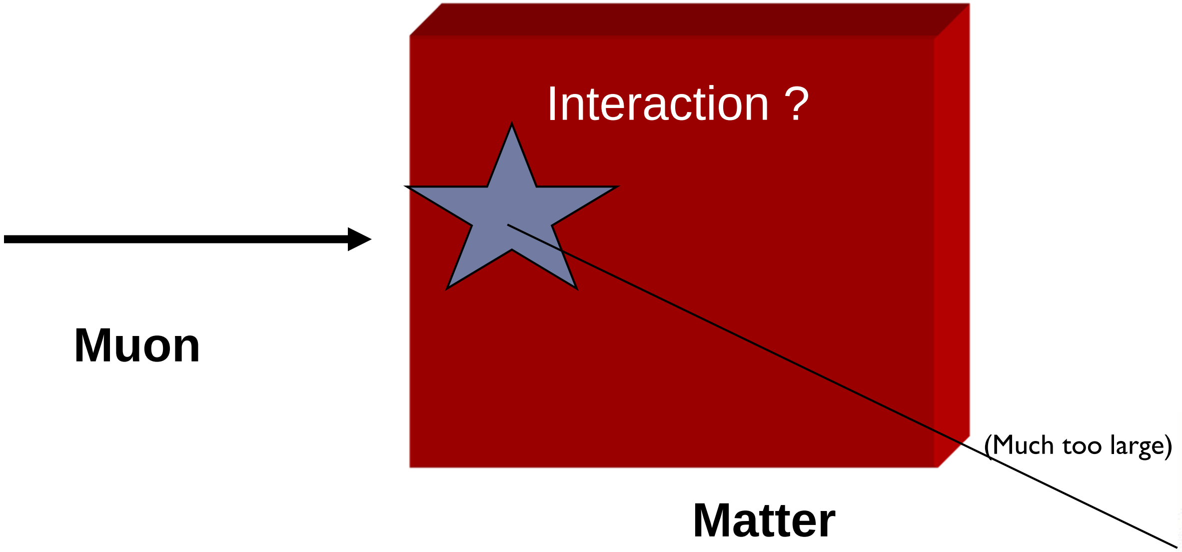
© Mark Seaver

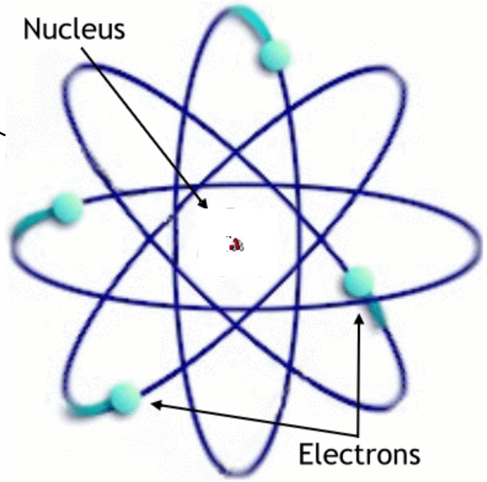
Which one is the deer mouse and which one the gray fox ?

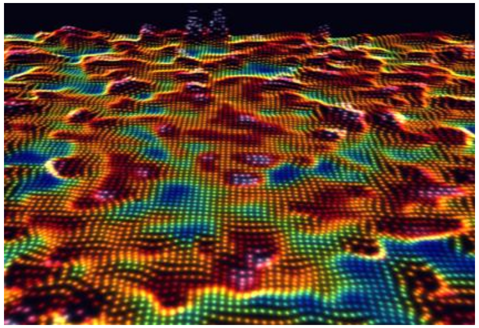
Can we learn more ?
- Weight ?
- Speed ?
- Running ?
- Animal tired ?
- Being hunted ?
- Does it have a tail ?
- …


ATLAS EXPERIMENT
Run: 182796, Event: 74566644
Date: 2011-05-30 07:54:29 CEST
ET (GeV)
η
φ

Charged Particles



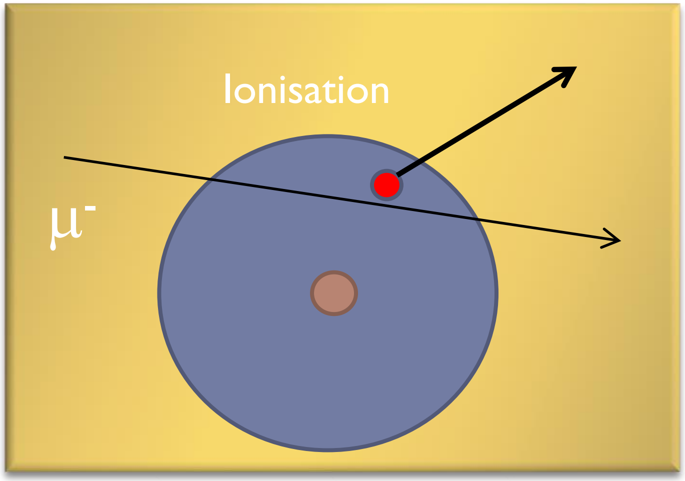


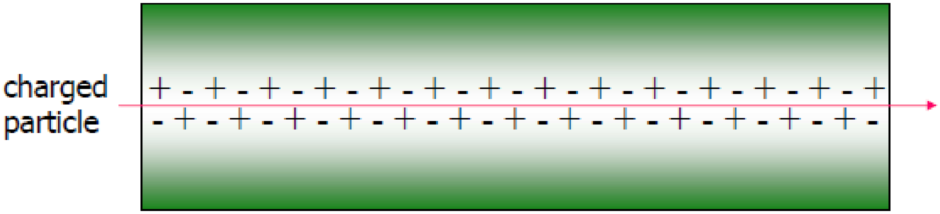

Kitta MacPherson-Princeton

Energy loss by interaction with atomic electrons

- Very soft collision: atom is excited (electron to higher shell)
- More energy transfer: atom is **ionised** (electron kicked out)
- Negligible deflection since $m_{muon} >> m_{electron}$
- Small energy loss per collision (eV), but many electrons in the way: in total a large effect

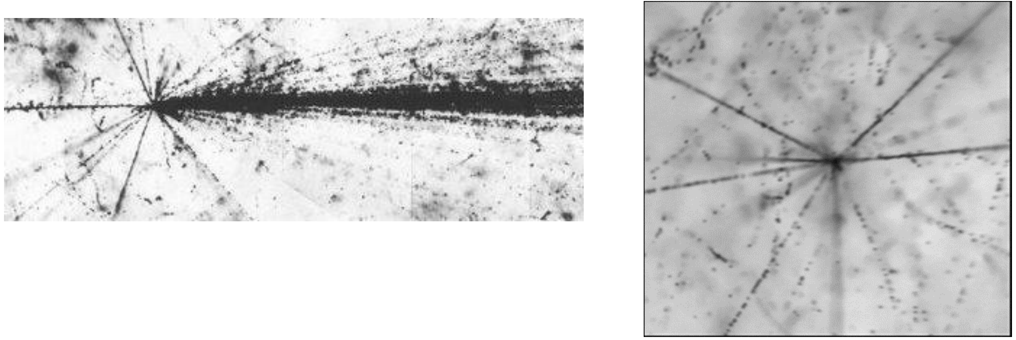
Charged particles



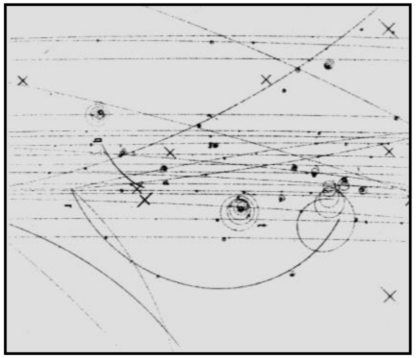


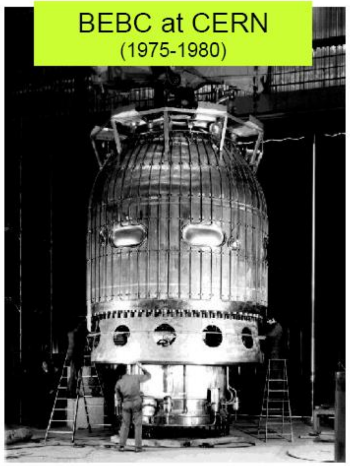
- Wilson Chamber

- Photographic emulsion



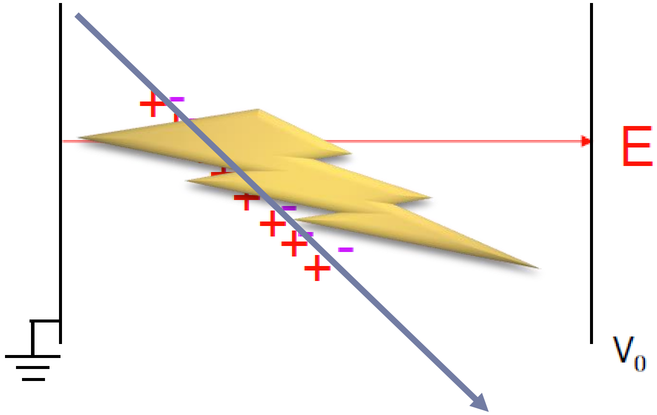
- Bubble chamber

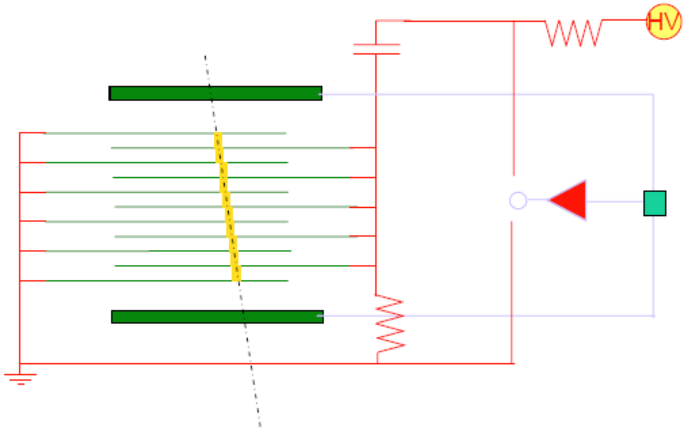




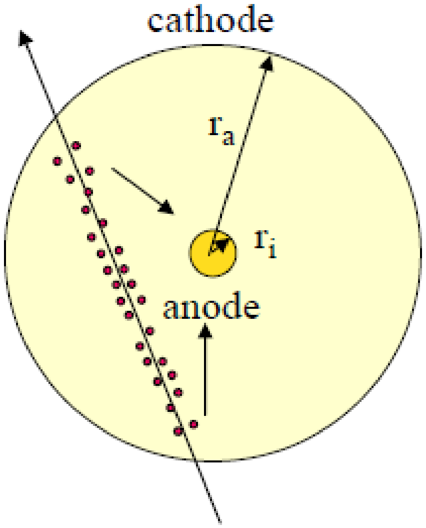
BEBC at CERN
(1975-1980)

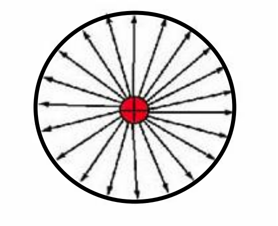
Ionization detector

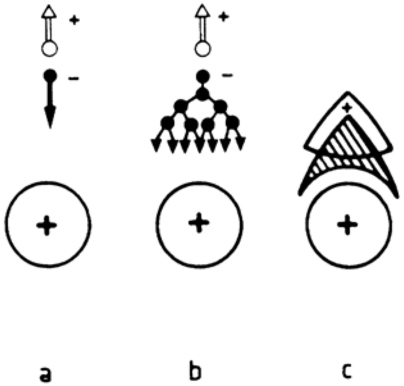


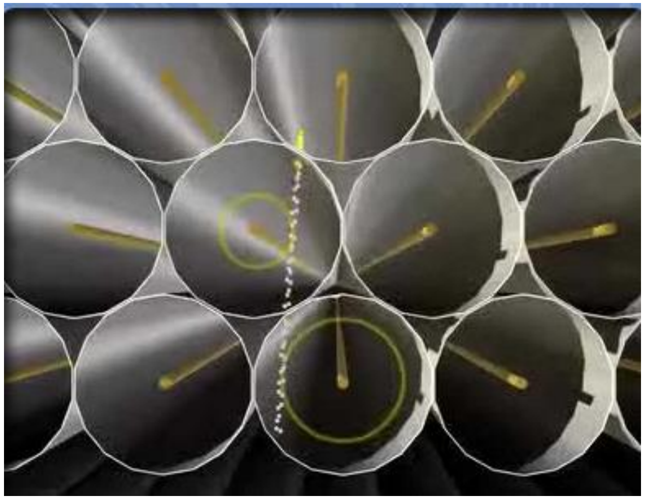


Drift tubes





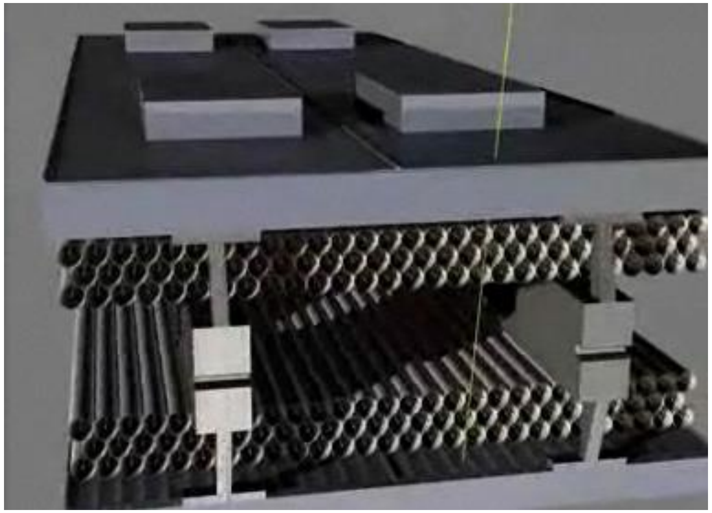


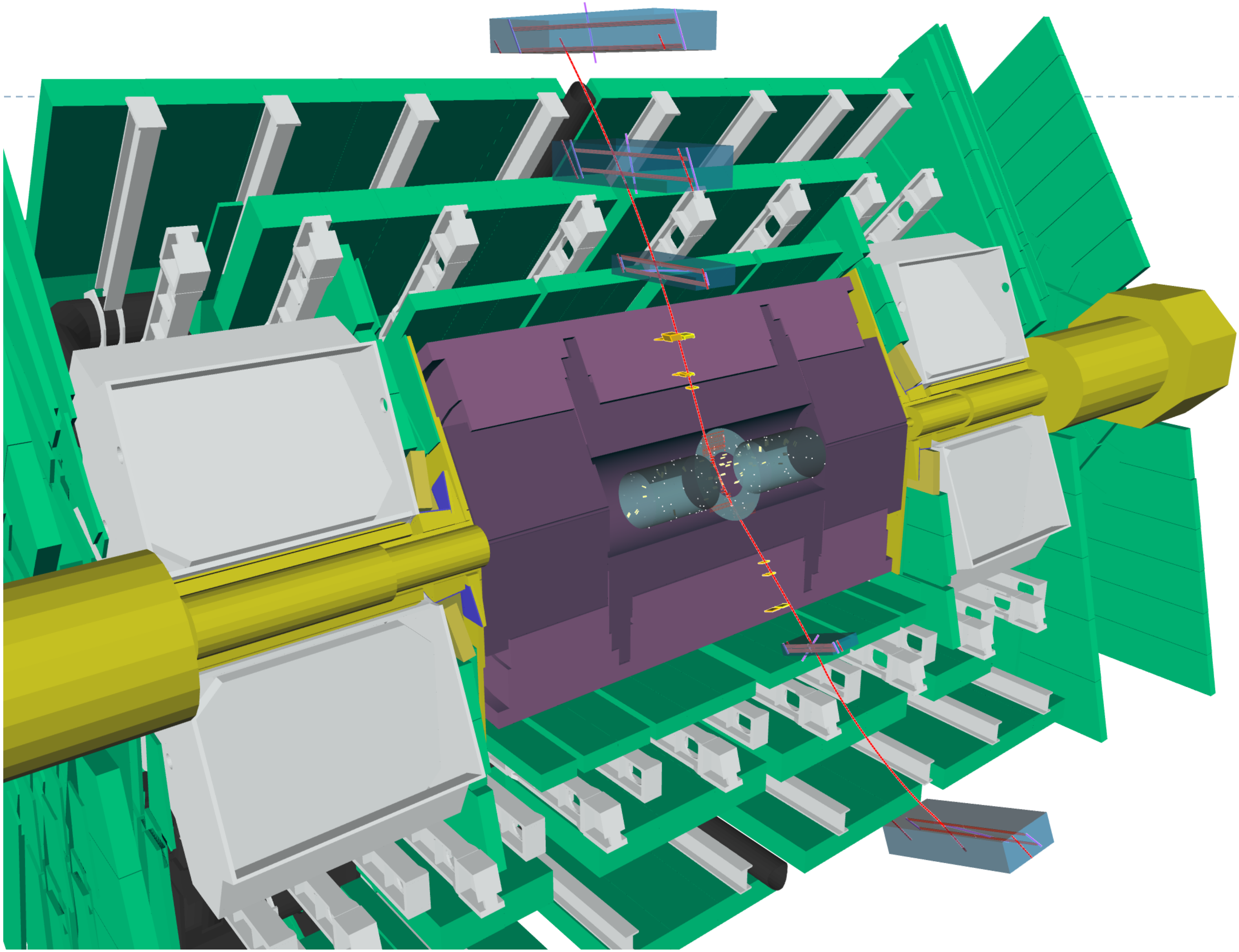


$$V(r)=V_0\frac{\ln r/r_a}{\ln r_i/r_a}$$

$$\vec{E}(r)=-\frac{V_0}{\ln r_a/r_i}\frac{1}{r}$$

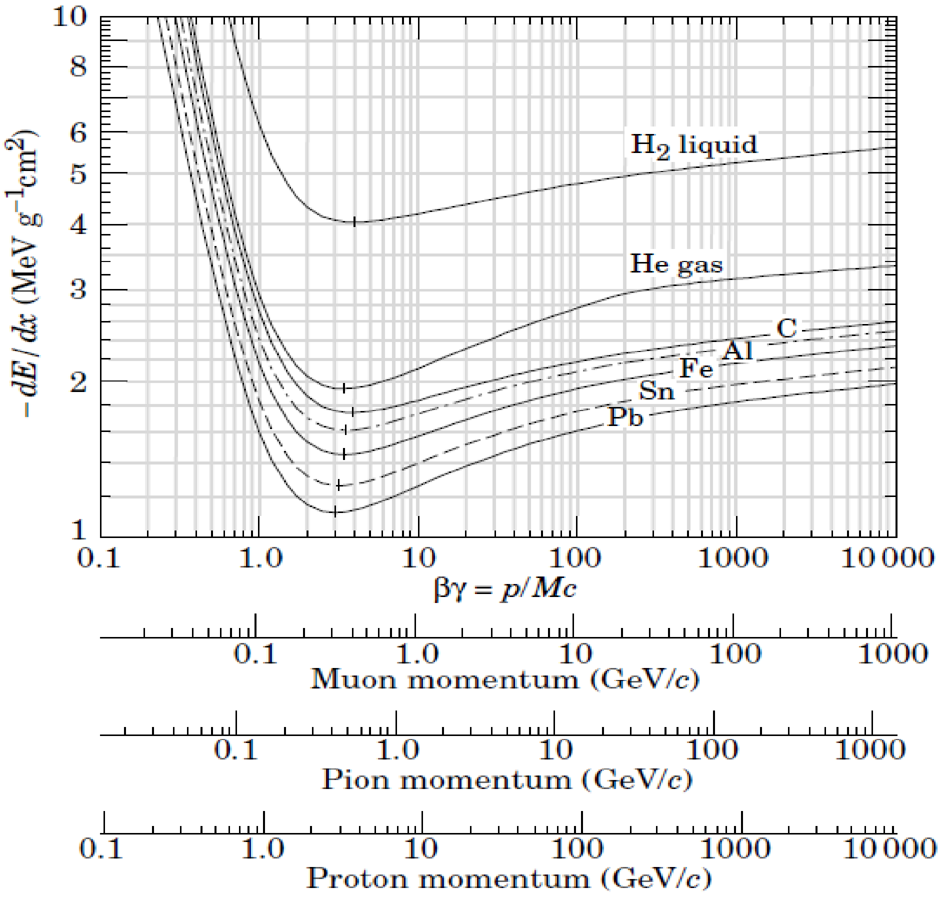
NOTE: Drift speed (mobility) of electrons is much larger than the one of ions





Ionization energy loss (Bethe Bloch)

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



$K = 4\pi N_A r_e^2 m_e c^2$

Z: Atomic number of absorber

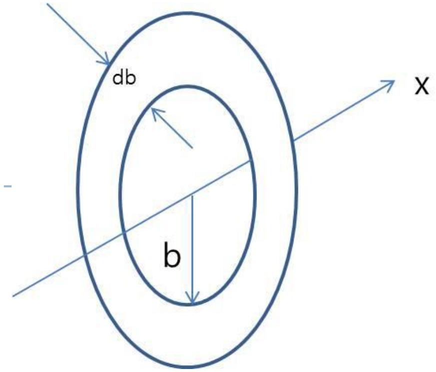
A: Atomic mass of absorber

I: Mean excitation energy

δ: density effect correction

- *dE*/*dx* in MeVg^{-1}cm^2
- *dE*/*dx* depends on β
- MINIMUM: M.I.P.
- *Z*/*A* similar for most elements
- $I \approx I_0 Z$, with $I_0 \approx 10$ eV

Bethe Bloch

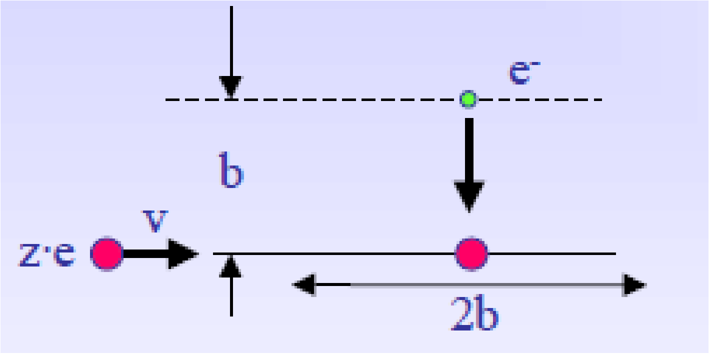


$$\int \Delta E \cdot \sigma(b) \cdot db$$

here

Next slide

Energy transfer (loss):



$$F_C = \frac{ze^2}{b^2} \;;\; \Delta t = \frac{2b}{v} \;;\; \Delta p_e = F_C \Delta t$$

$$\Delta E = \frac{(\Delta p_e)^2}{2m_e} = \frac{2z^2e^4}{b^2v^2m_e} = \frac{2r_e^2 m_e c^2 z^2}{b^2}\cdot\frac{1}{\beta^2}$$

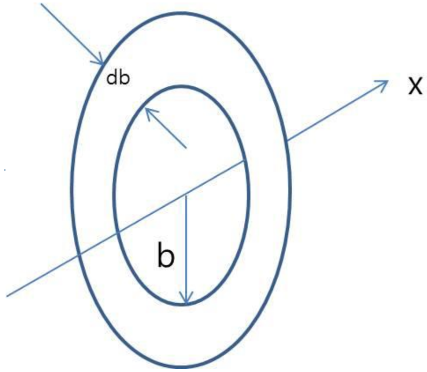
with $r_e = \frac{e^2}{m_e c^2}$

$$-\left\langle \frac{dE}{dx} \right\rangle = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{1}{\beta^2} \frac{Z}{A} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

- **To take home: Depends on time → $1/b^2$**

Bethe Bloch

$$\int \Delta E \cdot \sigma(b) \cdot db$$



$$\Delta E = \frac{2r_e^{\,2} m_e c^2 z^2}{b^2} \cdot \frac{1}{\beta^2}$$

"Interaction density":

$$N_e = \frac{N_A}{A} 2\pi b \cdot Z \cdot db$$

$[g^{-1}cm^2]$

$$\rightarrow \int_0^\infty \frac{db}{b} \rightarrow \int_{b_{\max}}^{b_{\min}} \frac{db}{b}$$

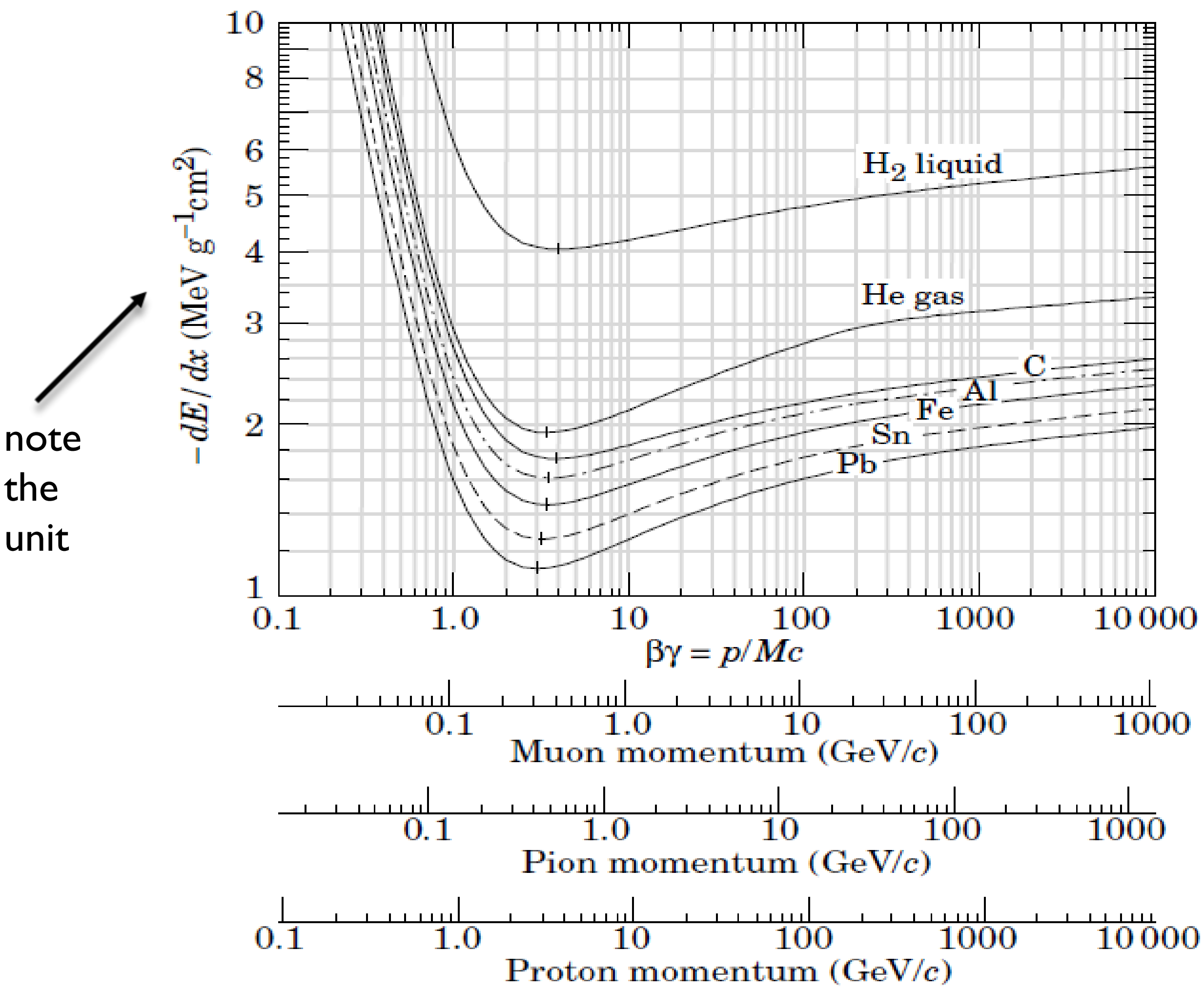
$$b_{\max} = \frac{\beta\gamma hc}{I}$$

$$b_{\min} = h/2p = \frac{h}{2\beta\gamma mc}$$

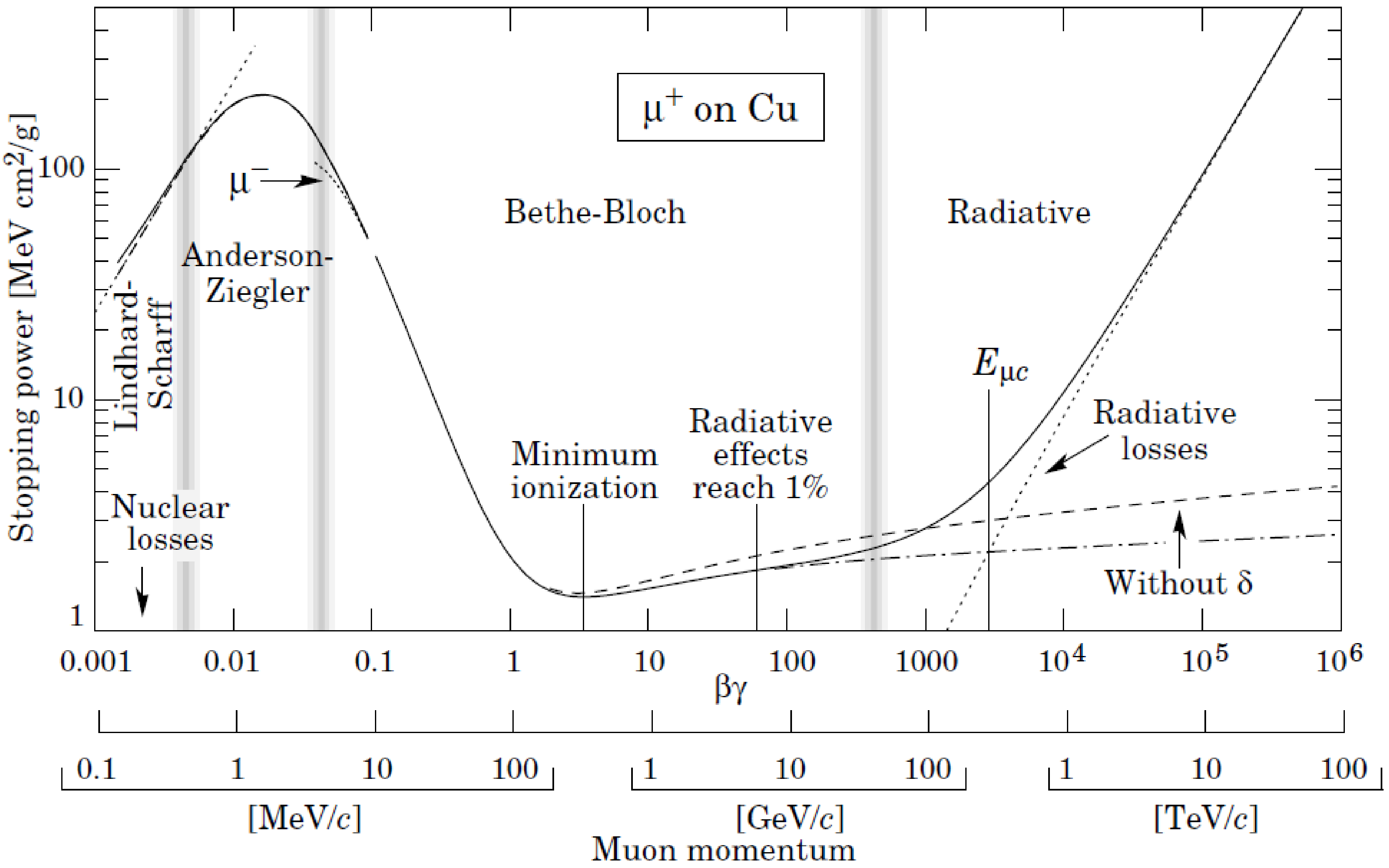
$$-\left\langle \frac{dE}{dx} \right\rangle = 4\pi N_A r_e^{\,2} m_e c^2 z^2 \frac{1}{\beta^2} \frac{Z}{A} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Energy loss by ionization

note
the
unit



x density = -dE/dx

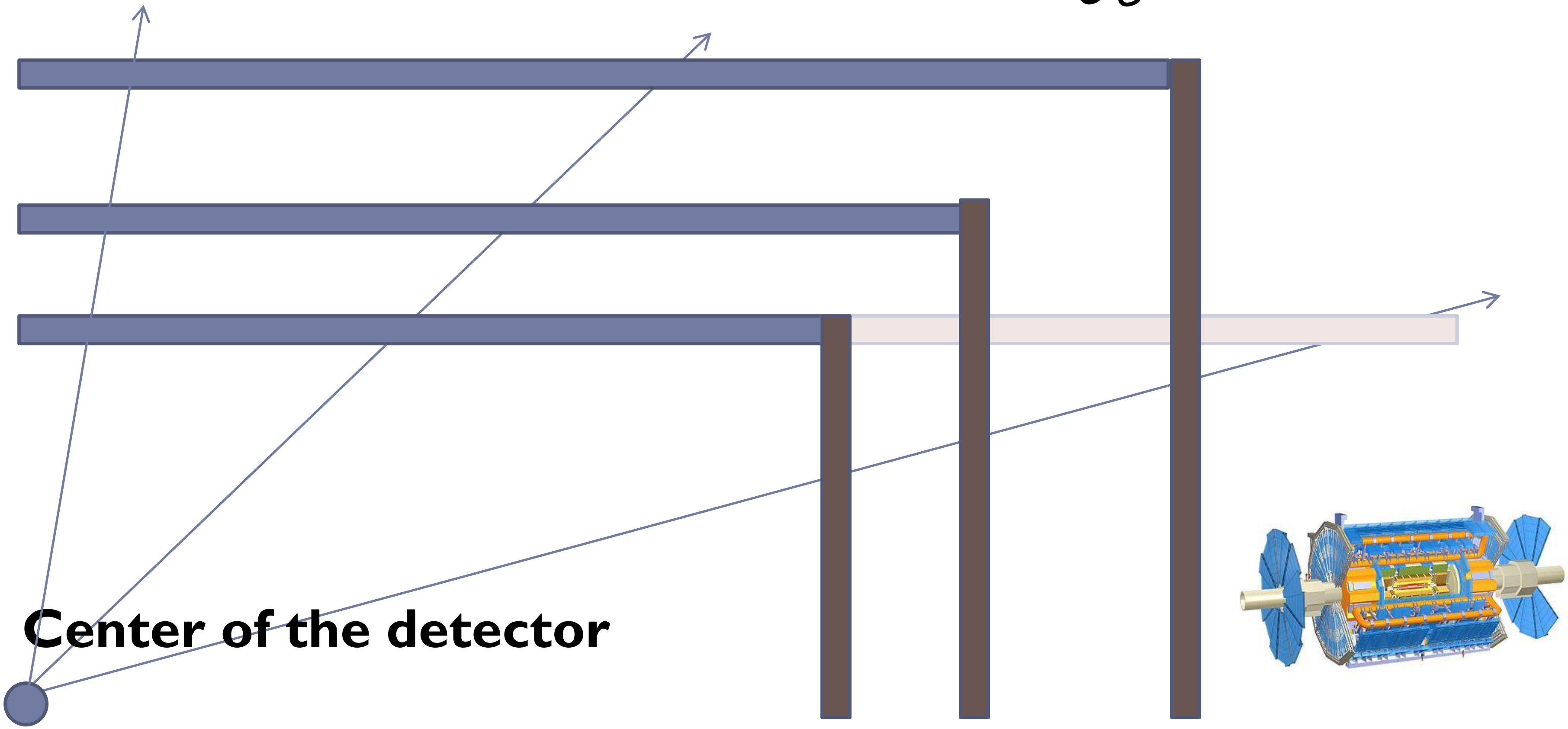


J. Beringer *et al.*(PDG), PR D86, 010001 (2012)

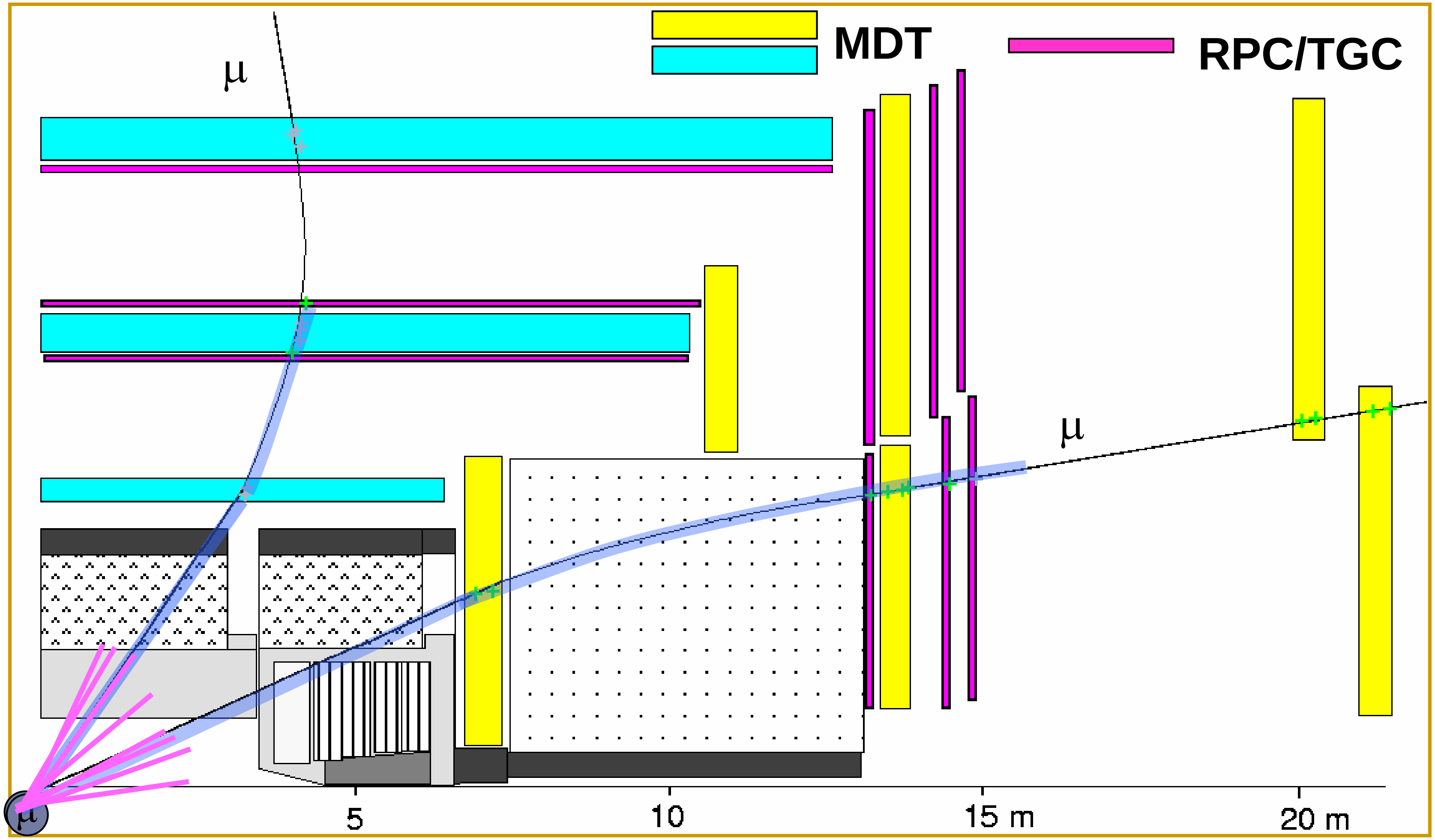
We can track muons

- Optimal detector geometry ?

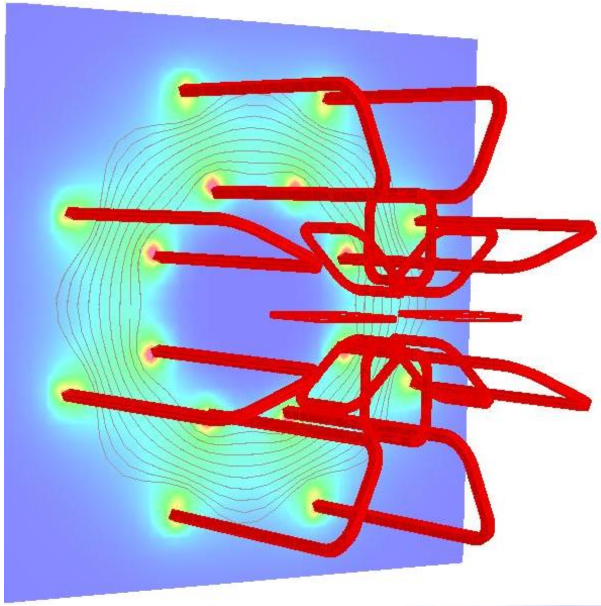
What about measuring properties of the tracked particle ??
e.g. momentum ??

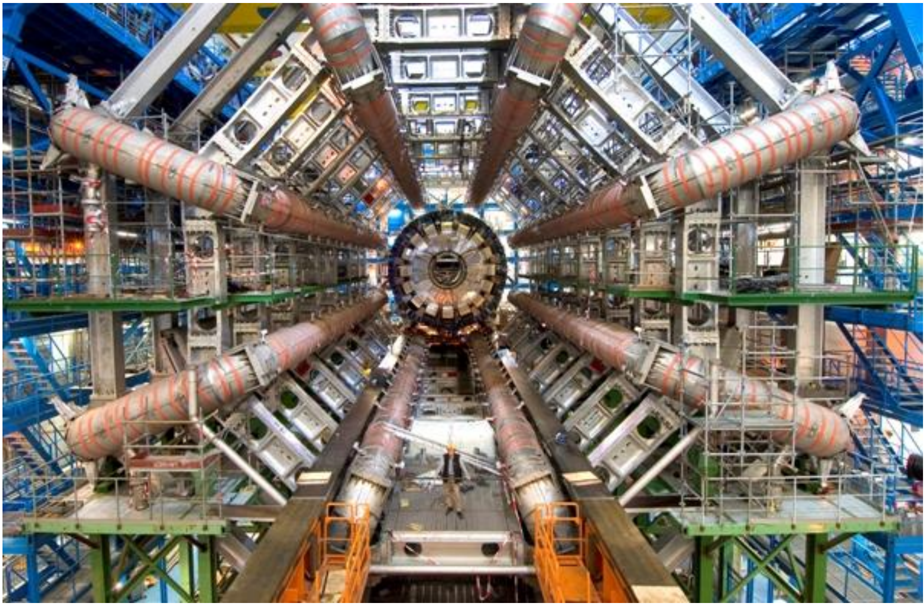


Magnets / bending (Measure momentum)



Toroid

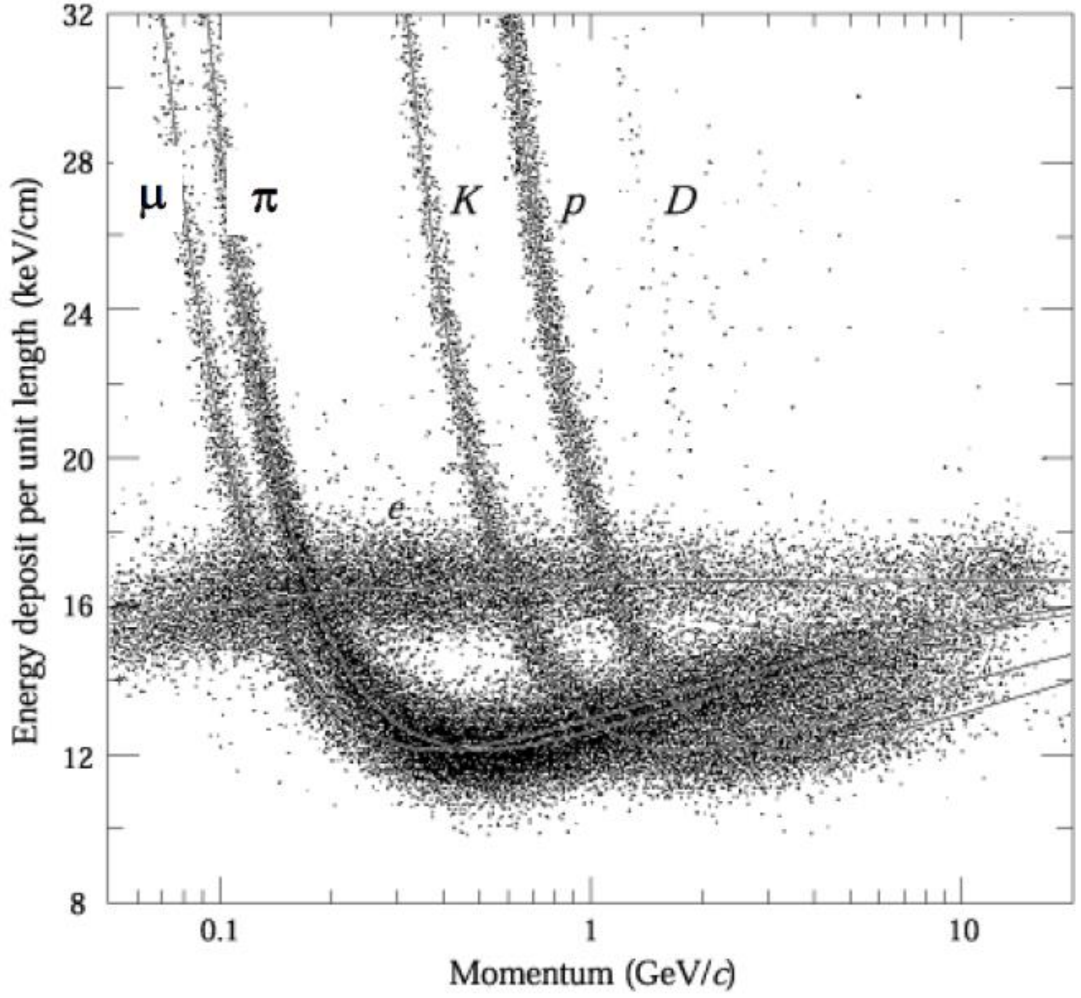


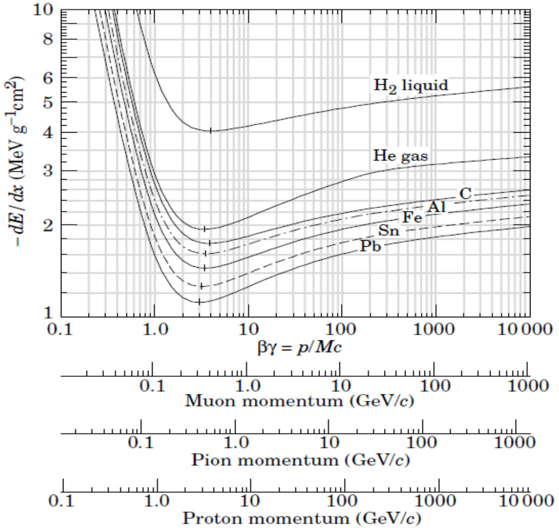


$$qvB = \frac{p}{R} v$$

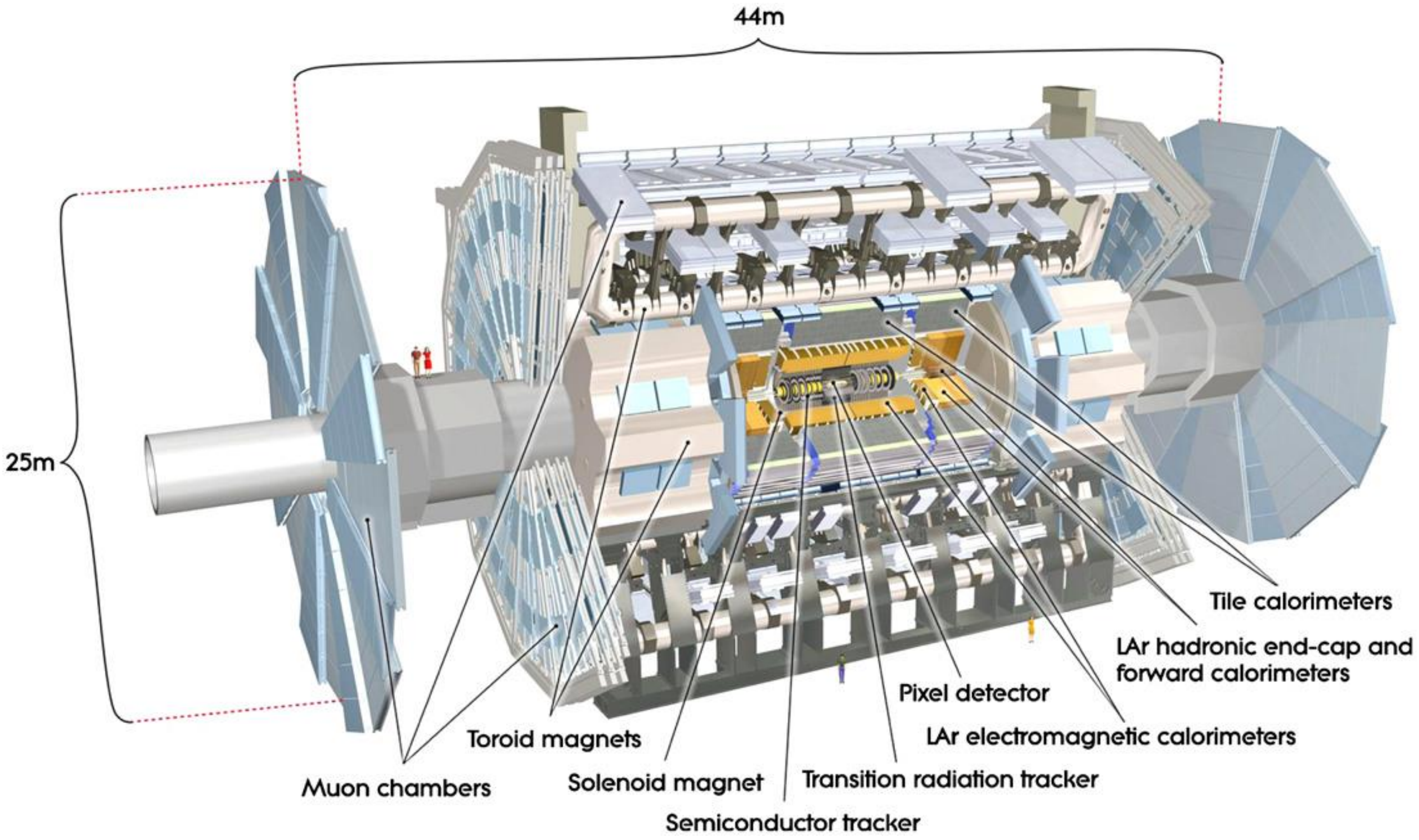
$$B[\mathsf{T}]\cdot R[\mathsf{m}] = 3.3356\cdot p\left[\mathsf{GeV}/\mathsf{c}\right]$$

Particle ID and tracking

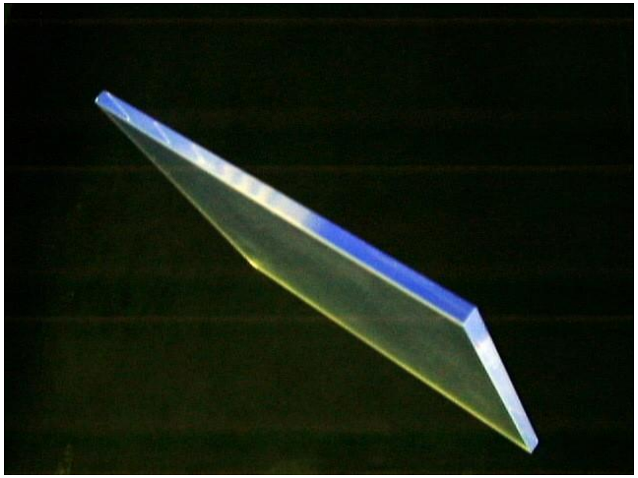


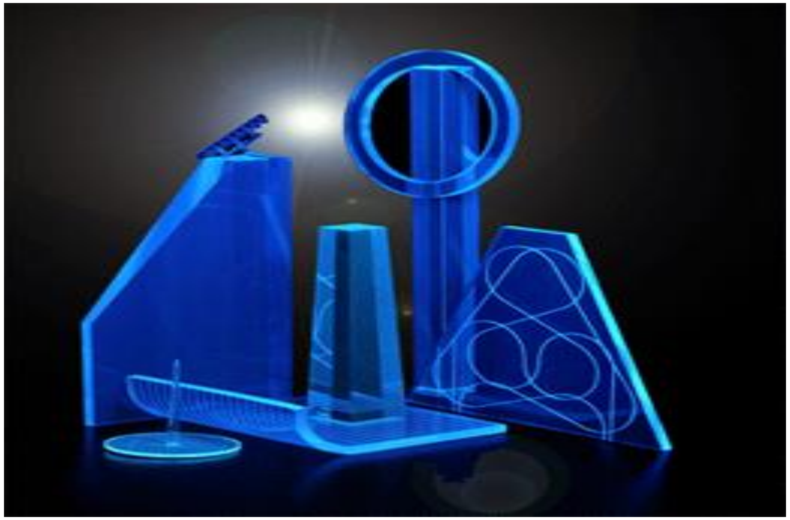


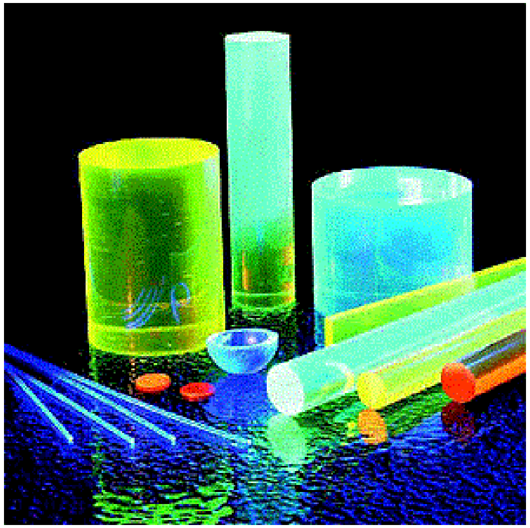
Are we done ??...

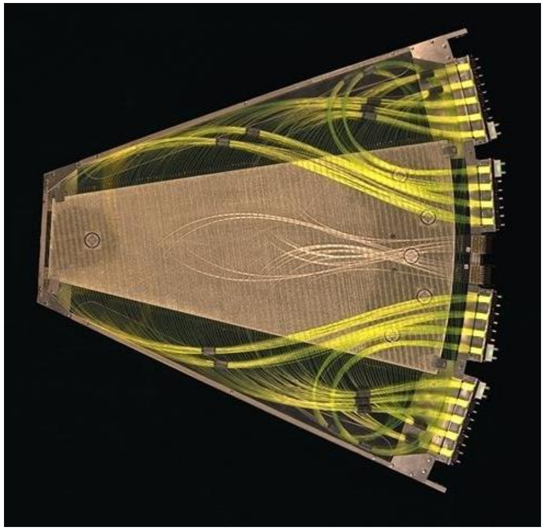

44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Solenoid magnet
Transition radiation tracker
Muon chambers
Semiconductor tracker

Szintillation detectors (fast, dE/dx)



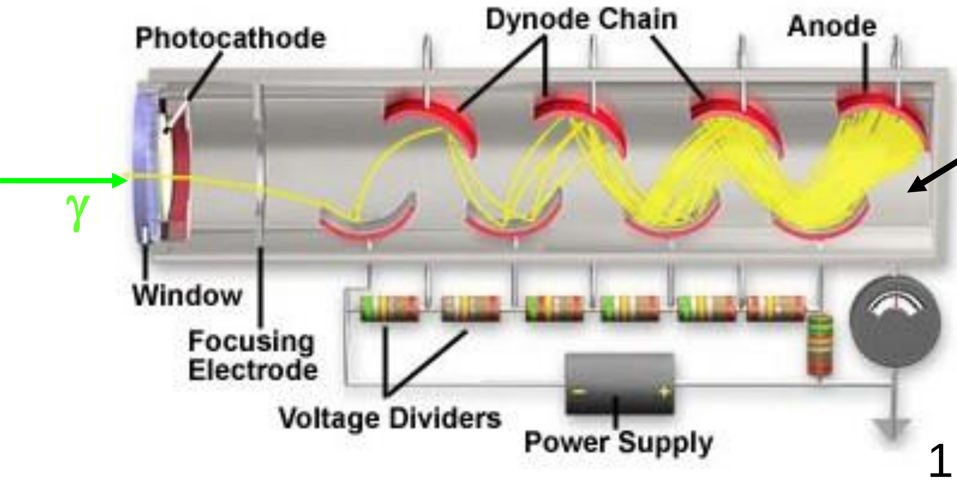




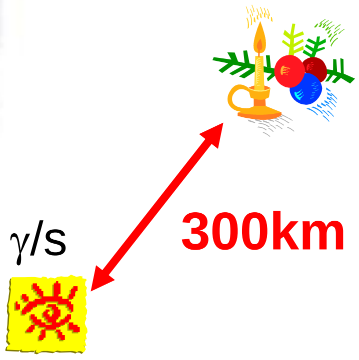


The light needs to be collected and measured

Photomultiplier



Vacuum

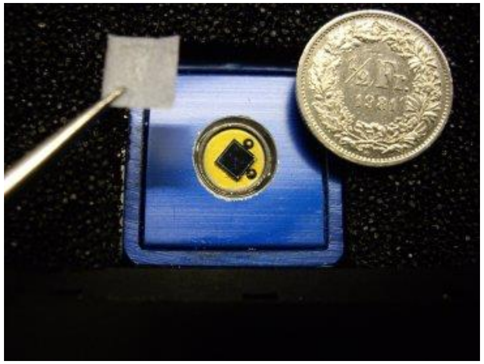


Charge proportional to light

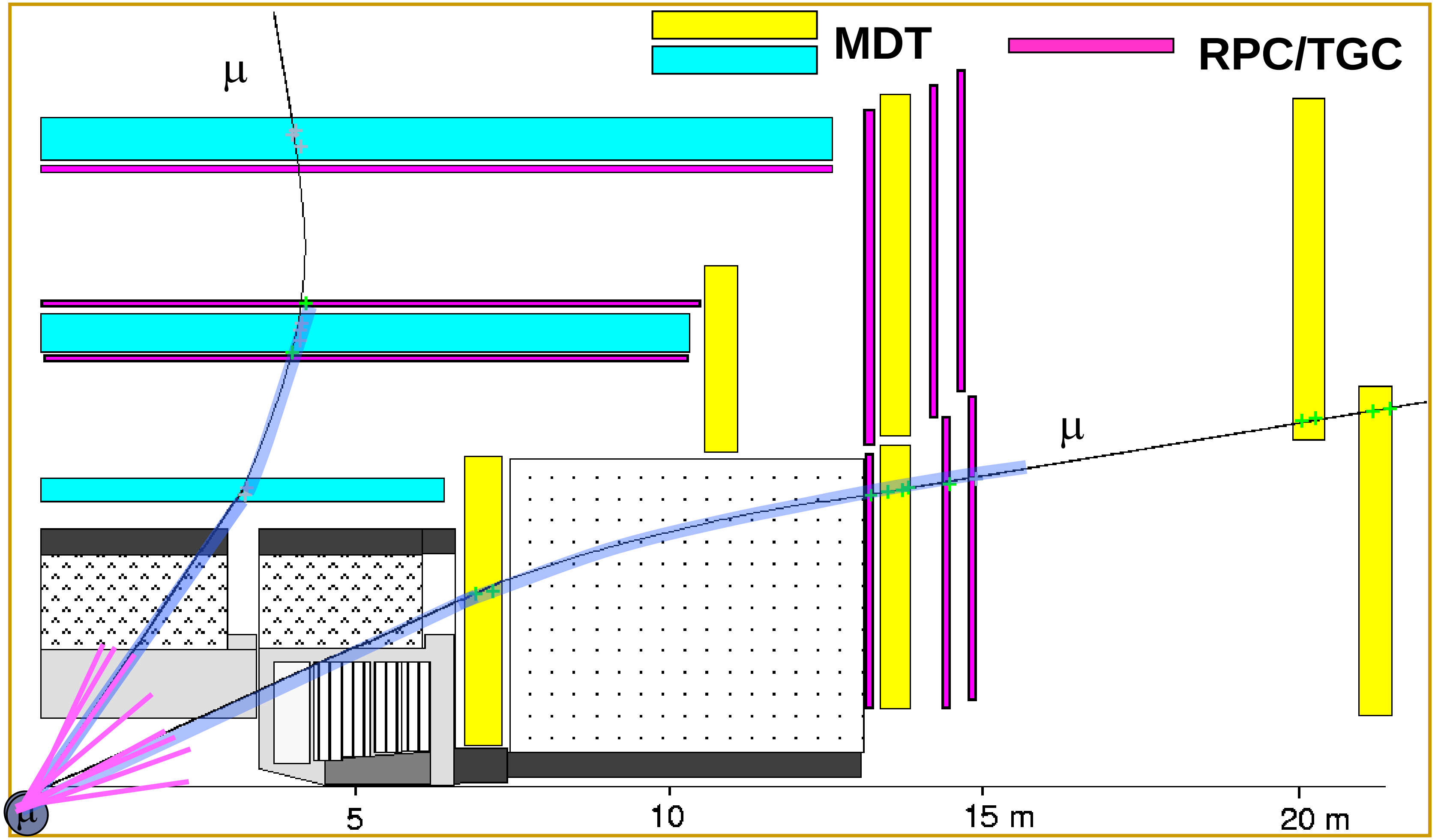
~10^6 Electrons per incident photon

Excellent timing information ! << 1 ns achievable !

Being replaced by silicon based detectors

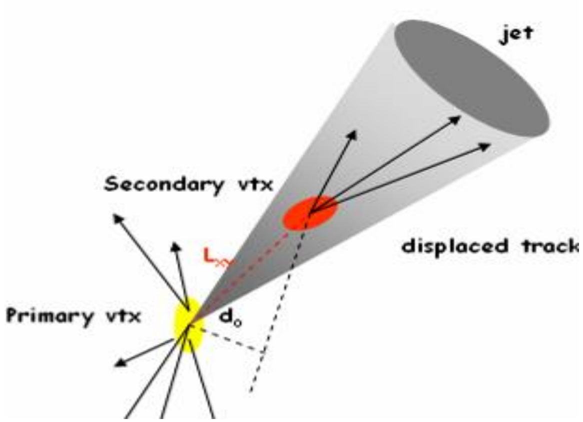


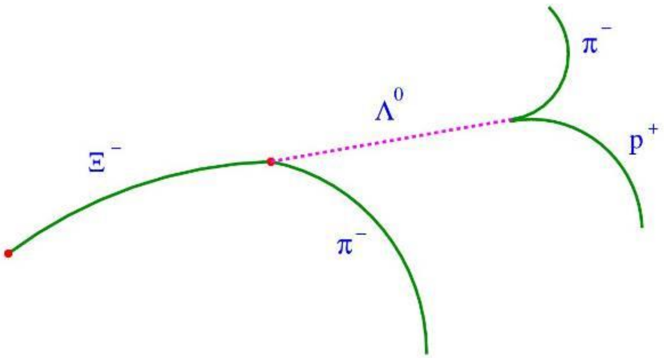
Going closer to the interaction point

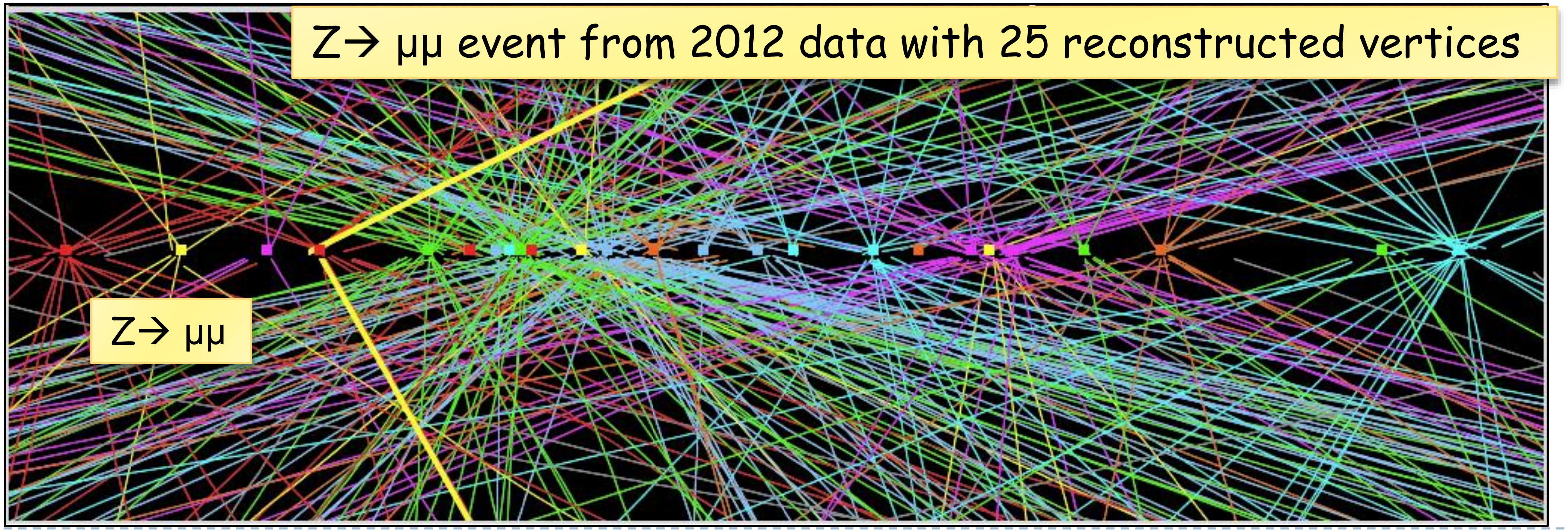


Why ?

- There is more than muons… there is much more to look at…





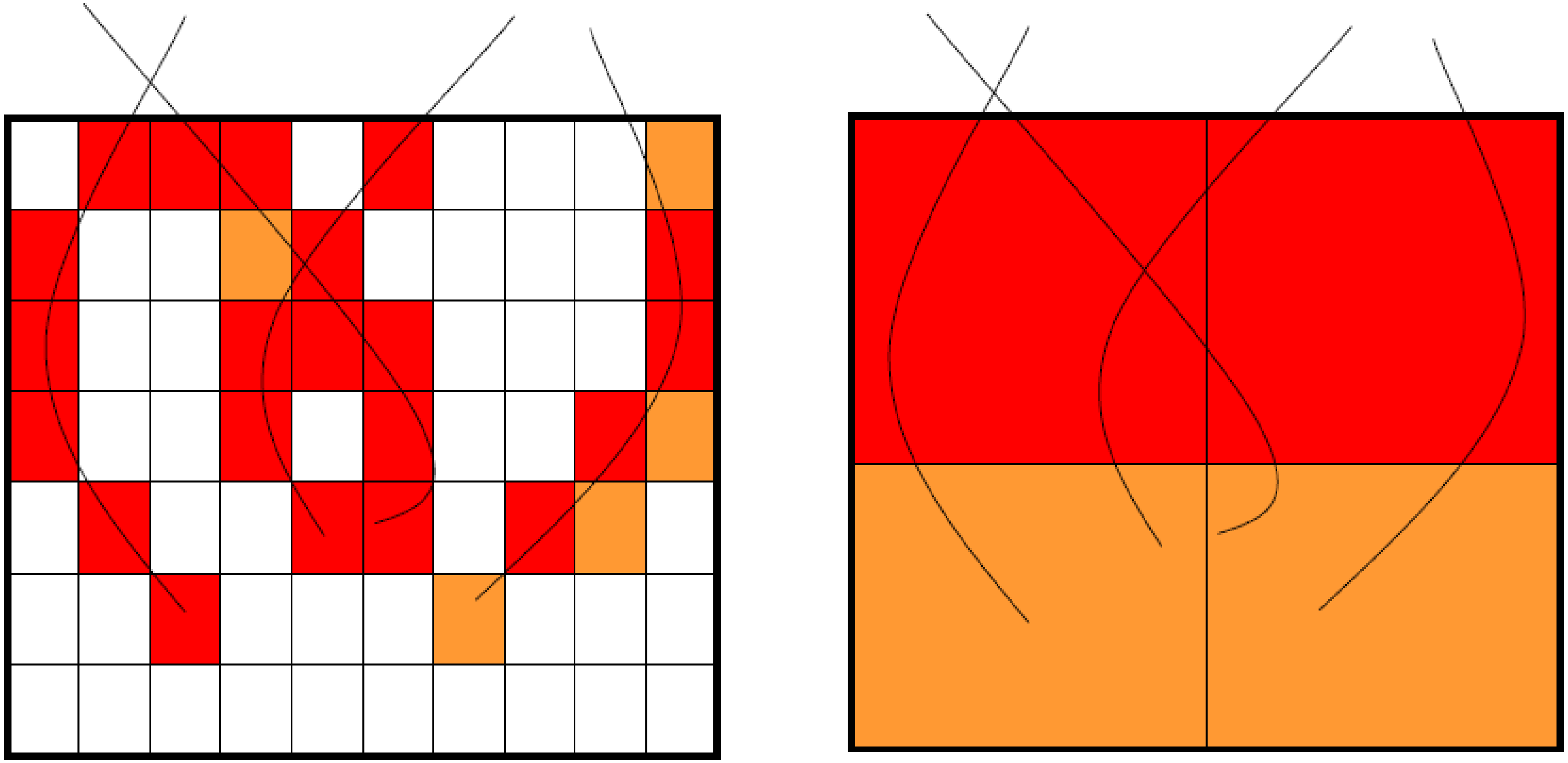


Z→ μμ event from 2012 data with 25 reconstructed vertices

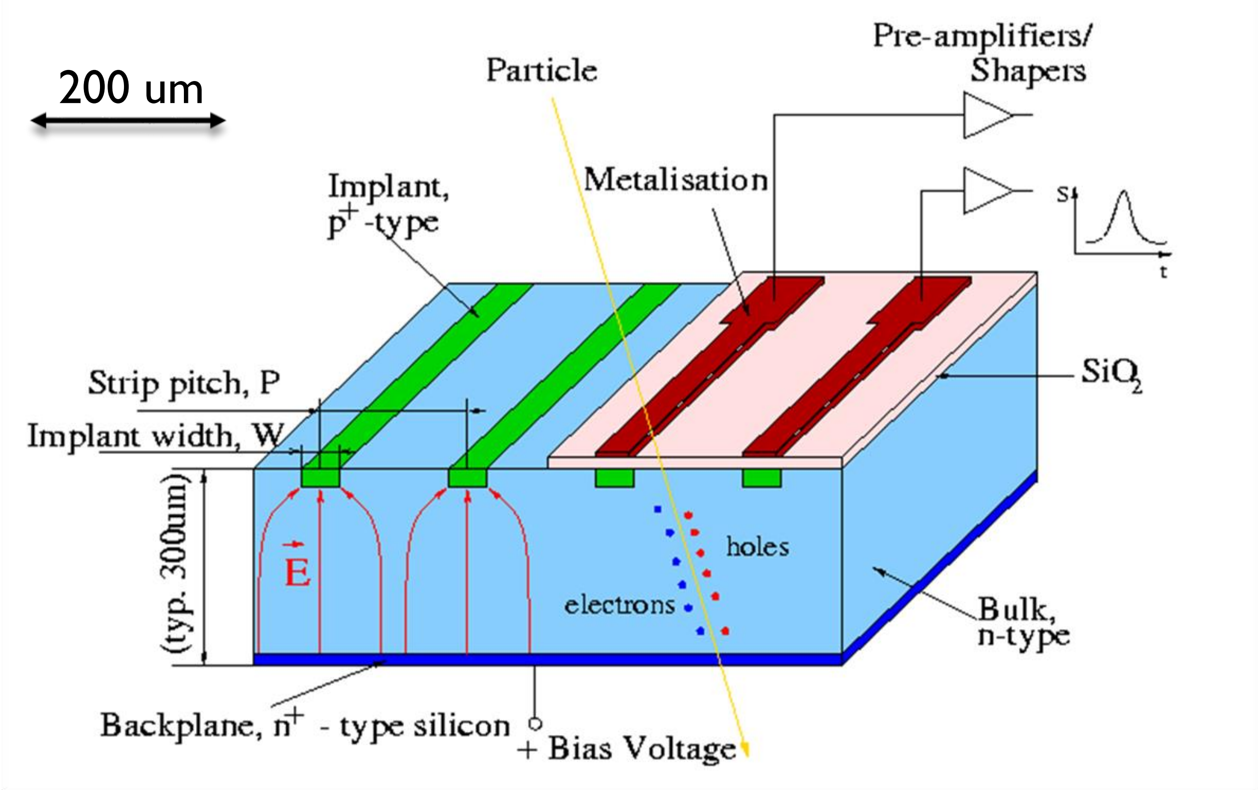
Z→ μμ

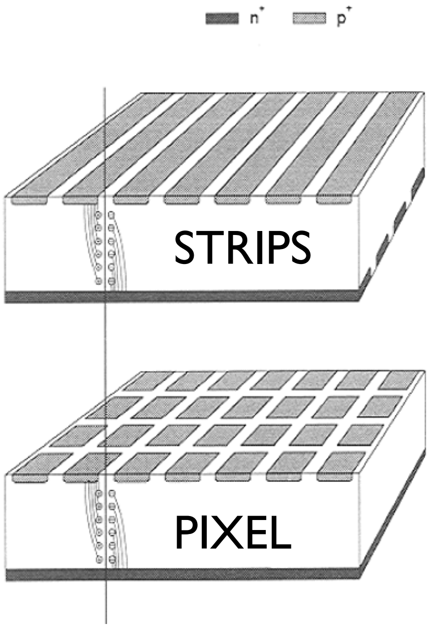
Resolution

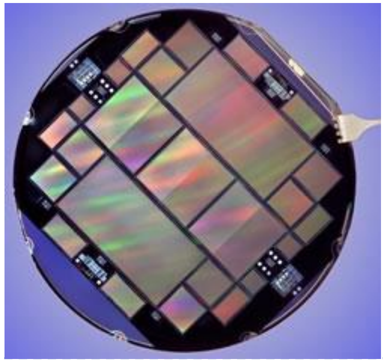
- Tracking close to the interaction point: need resolution !



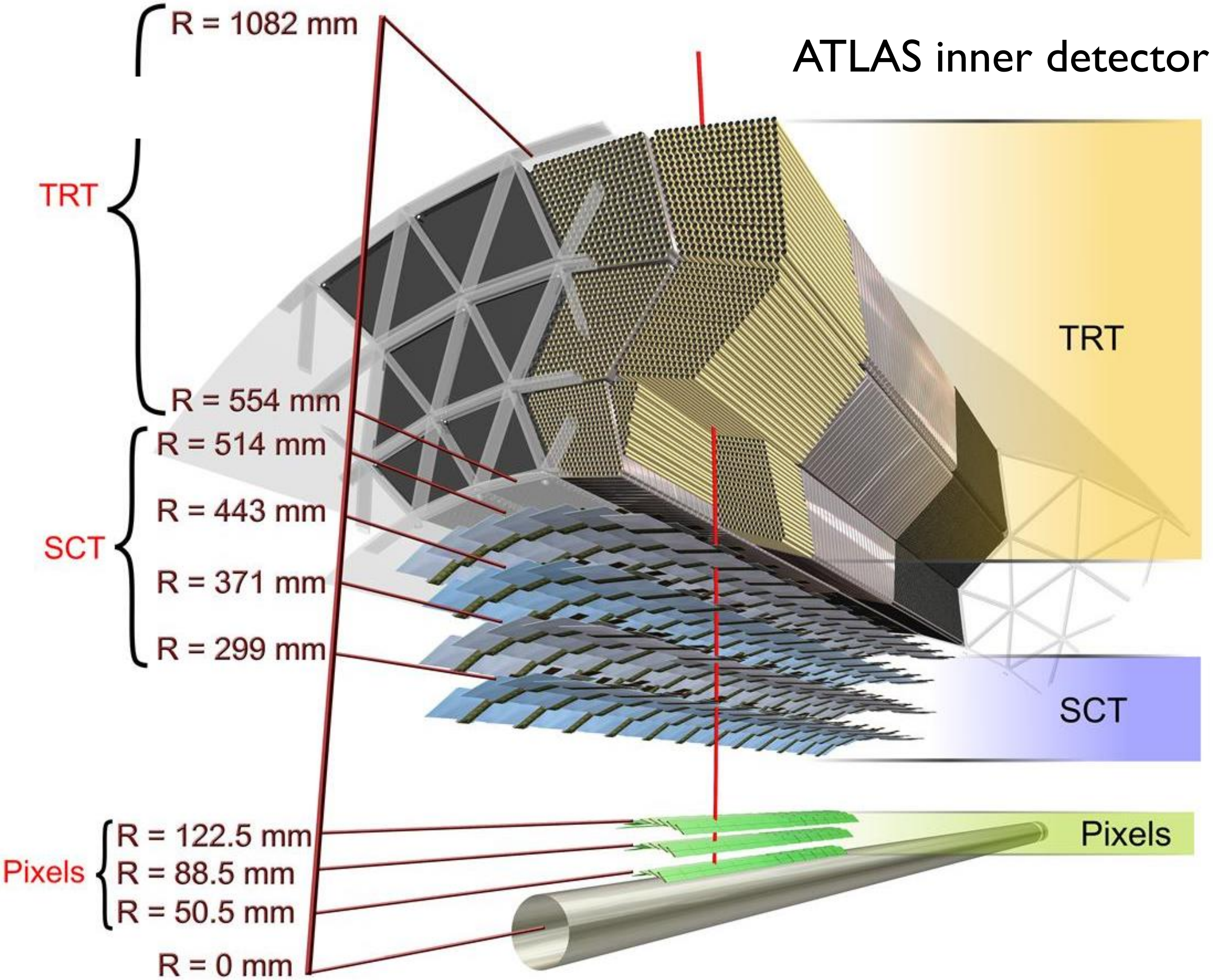
Silicon detectors



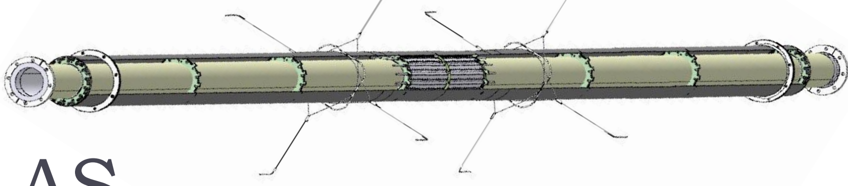


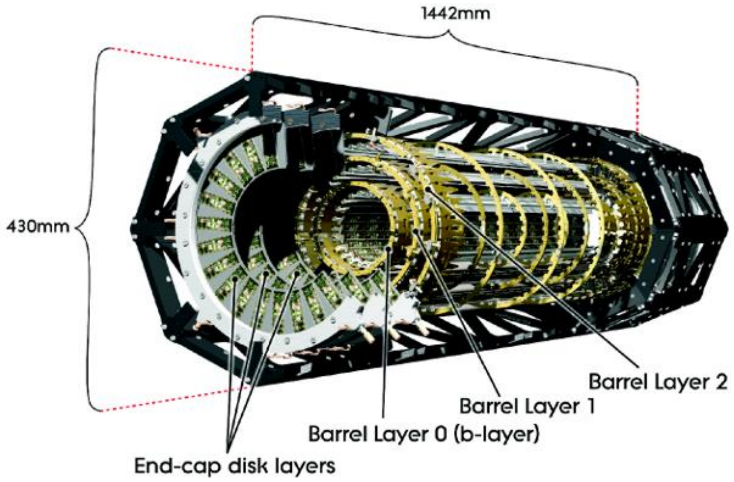


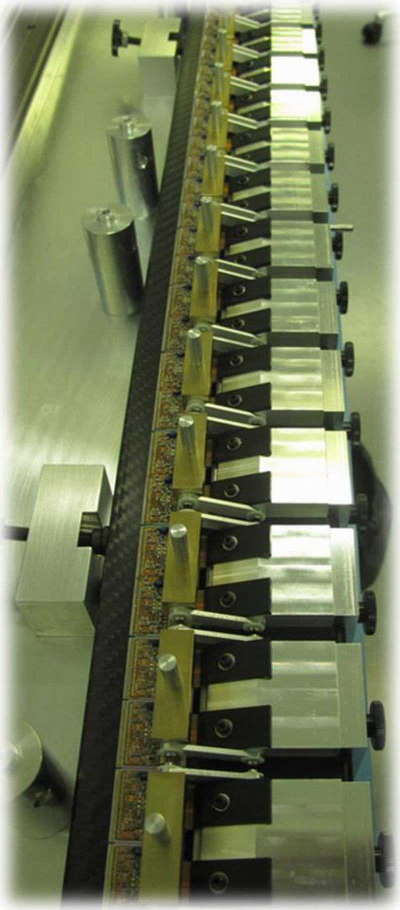
ATLAS inner detector

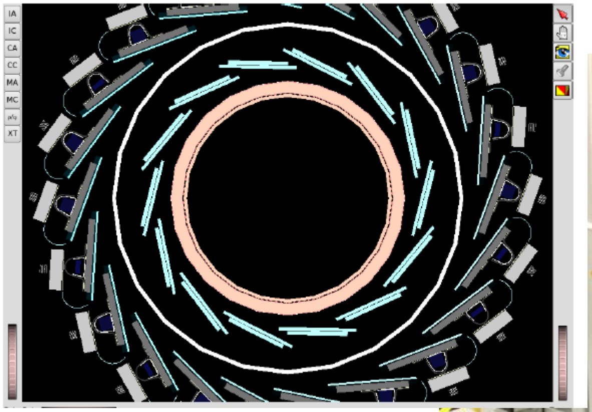


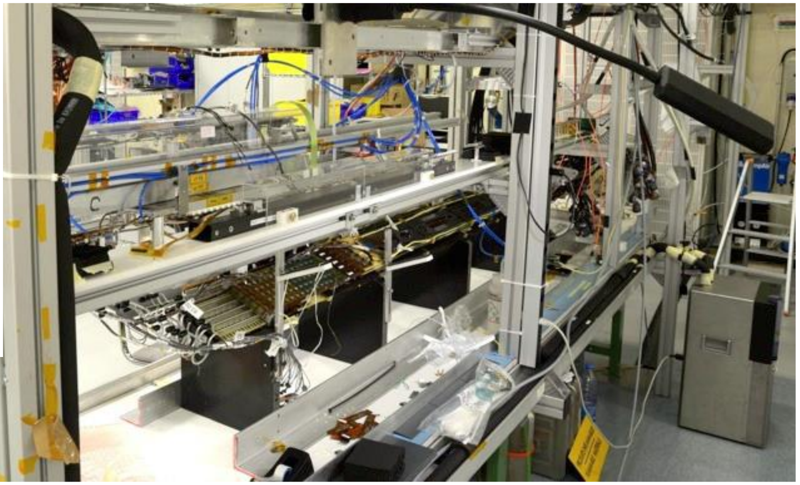
IBL
New layer of Pixels in ATLAS



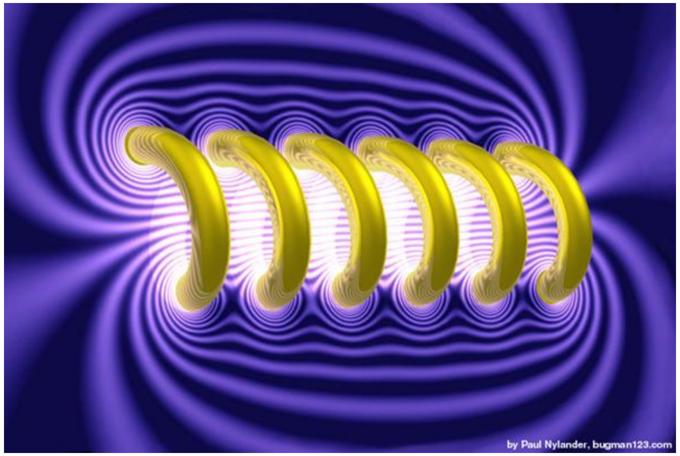


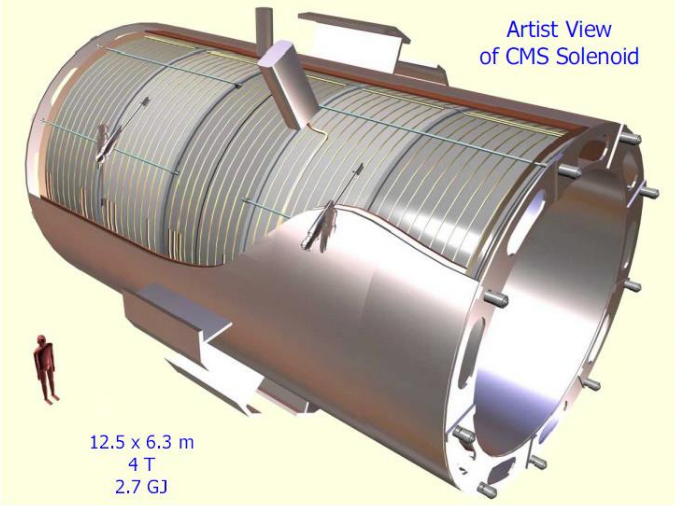


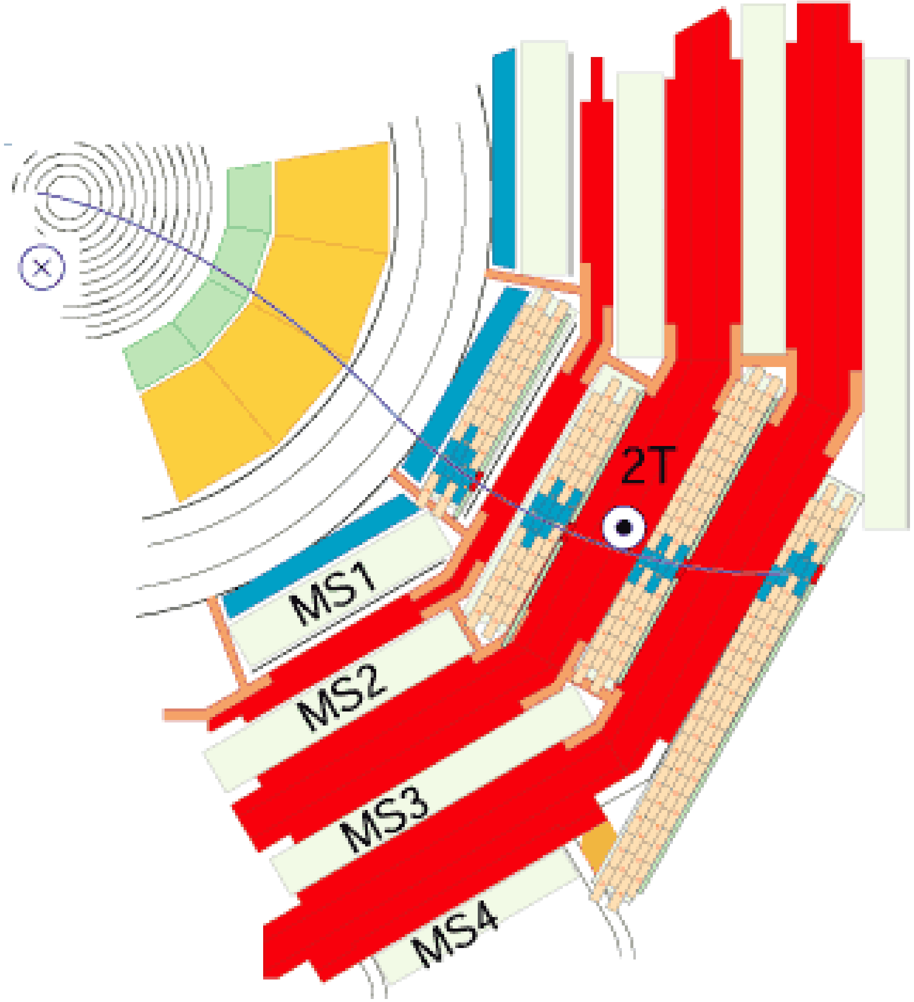




Solenoid magnets



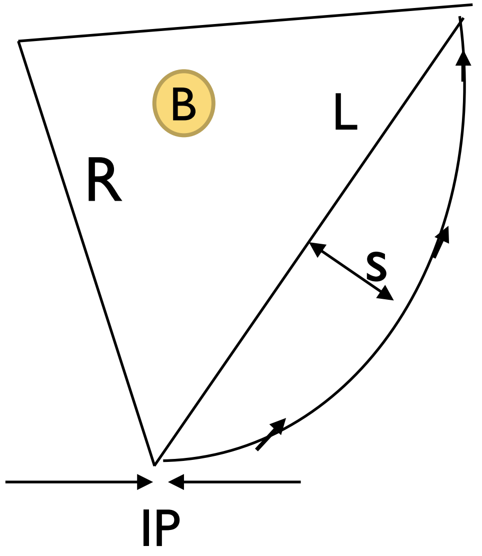




$$qvB = \frac{p}{R} v$$

$$B[\mathsf{T}] \cdot R[\mathsf{m}] = 3.3356 \cdot p \left[\mathsf{GeV}/\mathsf{c}\right]$$

Momentum Resolution



$$s \cong L^2/8R$$

$$B\,R = p\,/\,q \qquad q=1$$

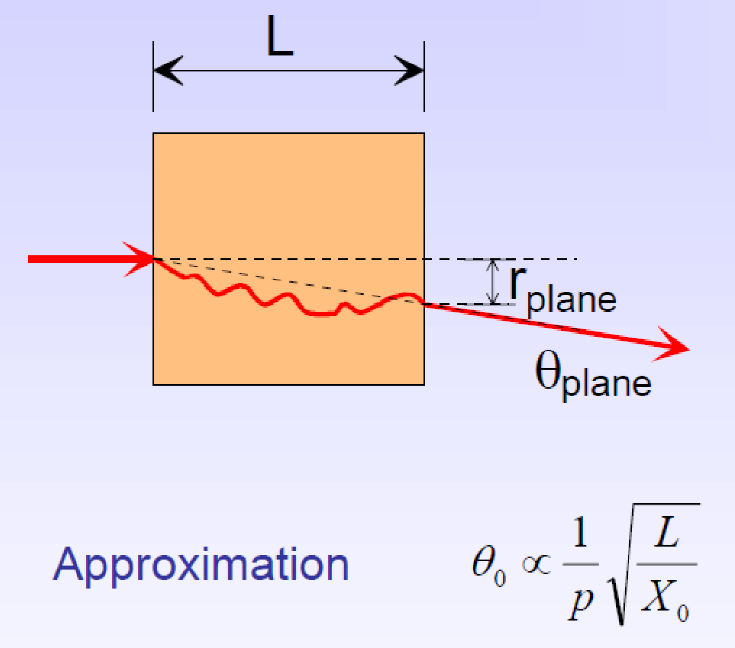
$$\frac{\Delta p}{p} \approx 0.25 \frac{\Delta s[\mu\mathrm{m}]}{(L[\mathrm{cm}])^2 B[\mathrm{T}]} p[\mathrm{GeV}]$$

$$\frac{\Delta p}{p} \cong 0.25 \frac{50\mu\mathrm{m}}{\left(40\mathrm{cm}\right)^2 2\mathrm{T}} 10\mathrm{GeV} \cong 4\%$$

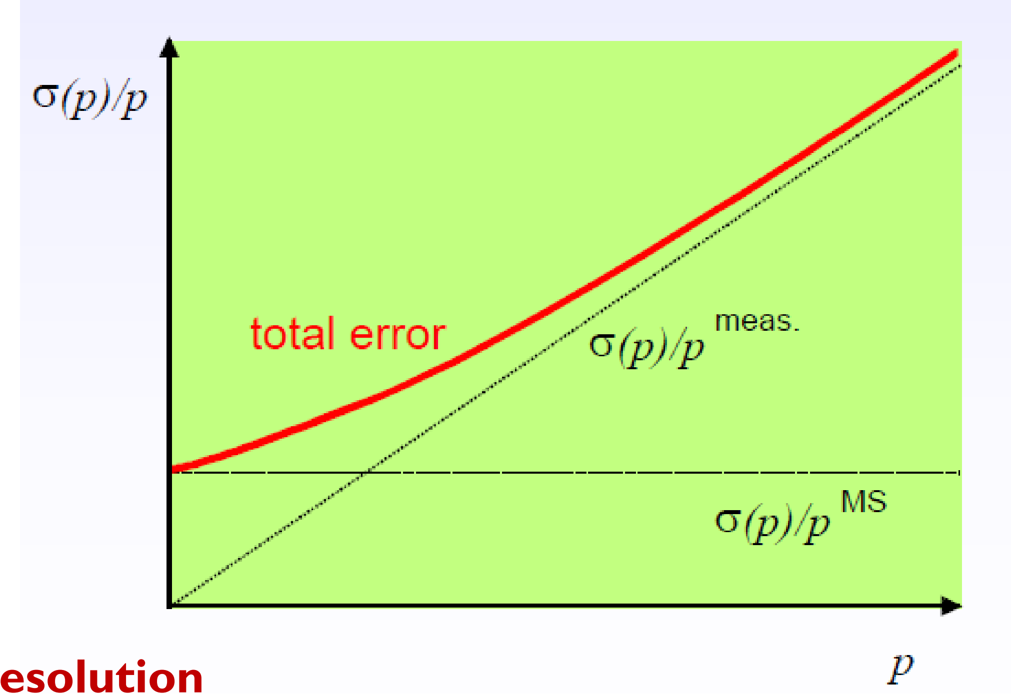
- **Momentum resolution is proportional to the momentum**
- Momentum resolution gets better:
  - with the square of the lever arm L
  - linearly with the magnetic field B
- 100% error is the momentum measurement limit (also limiting the charge sign determination)

→ for an ideal undisturbed particle path… no interactions….

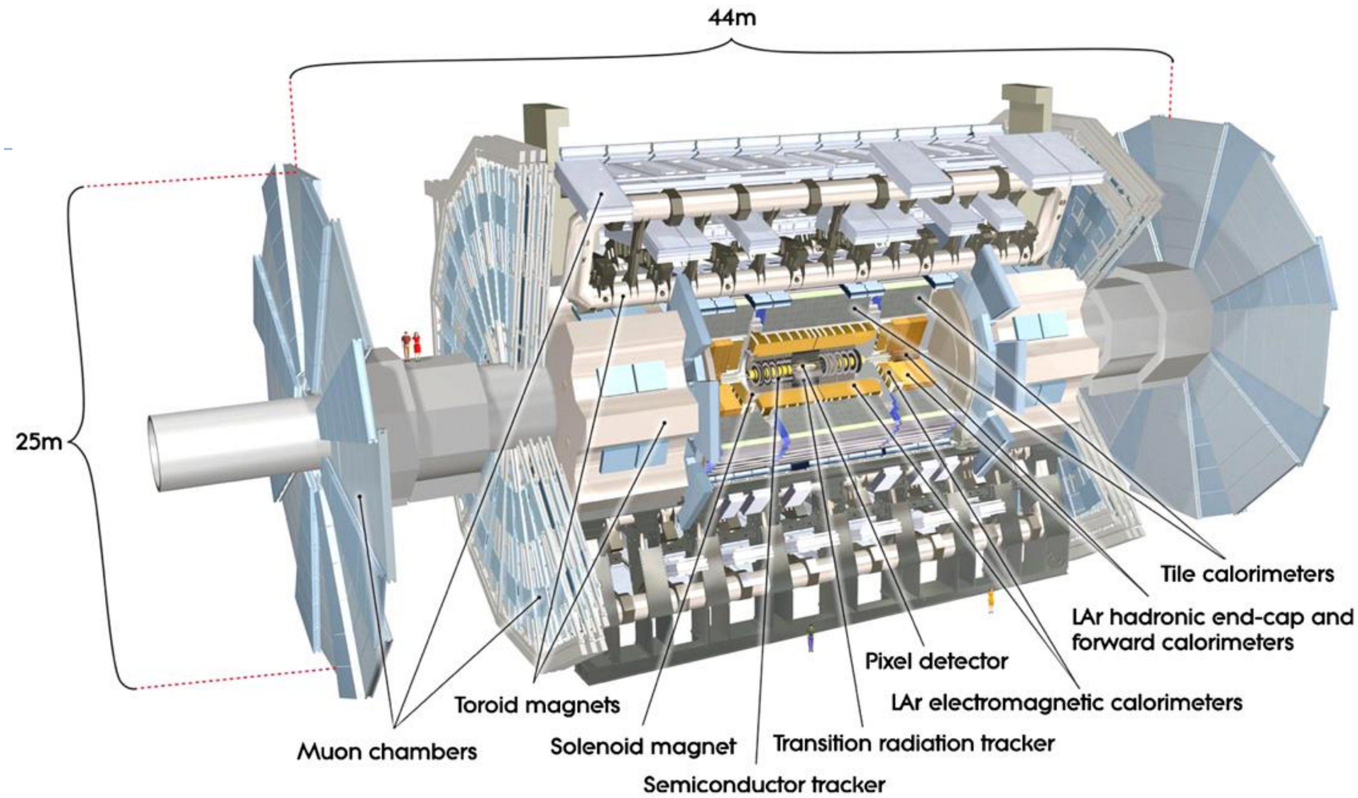
Multiple scattering



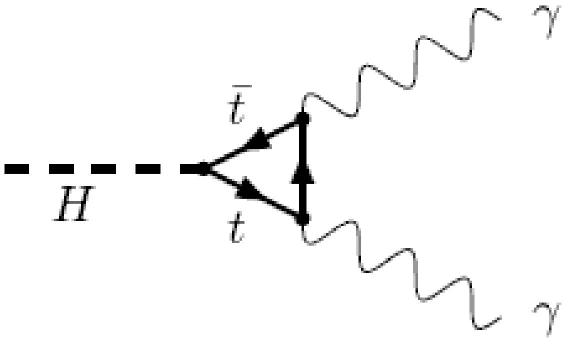
Approximation $\theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$

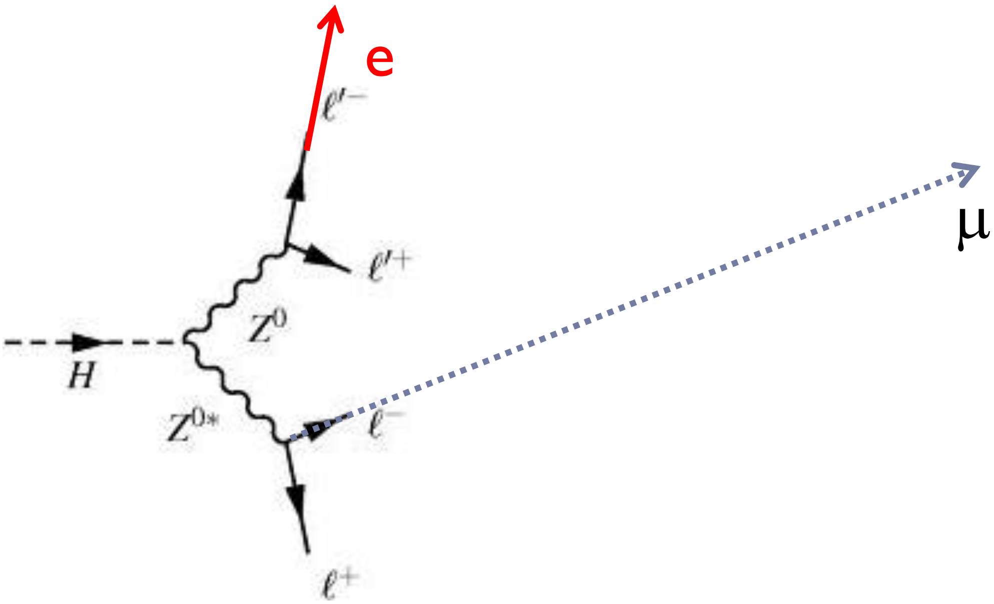


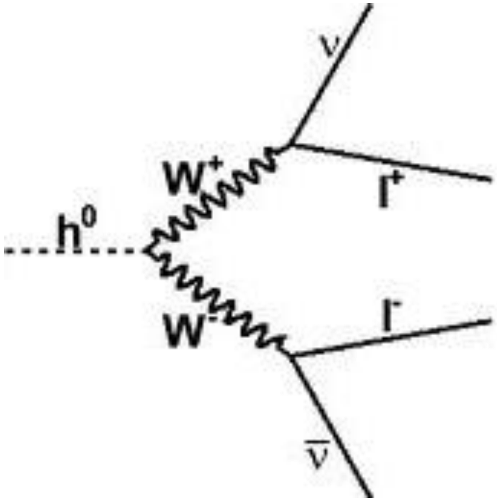
Higher momentum -> worse resolution

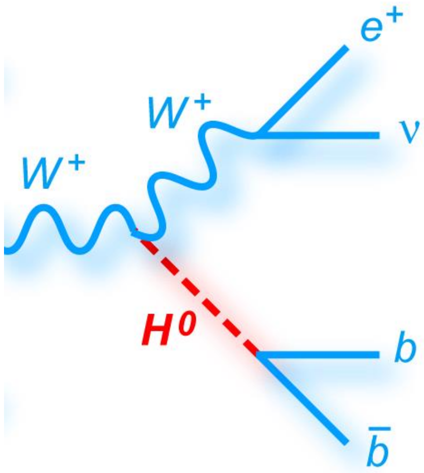


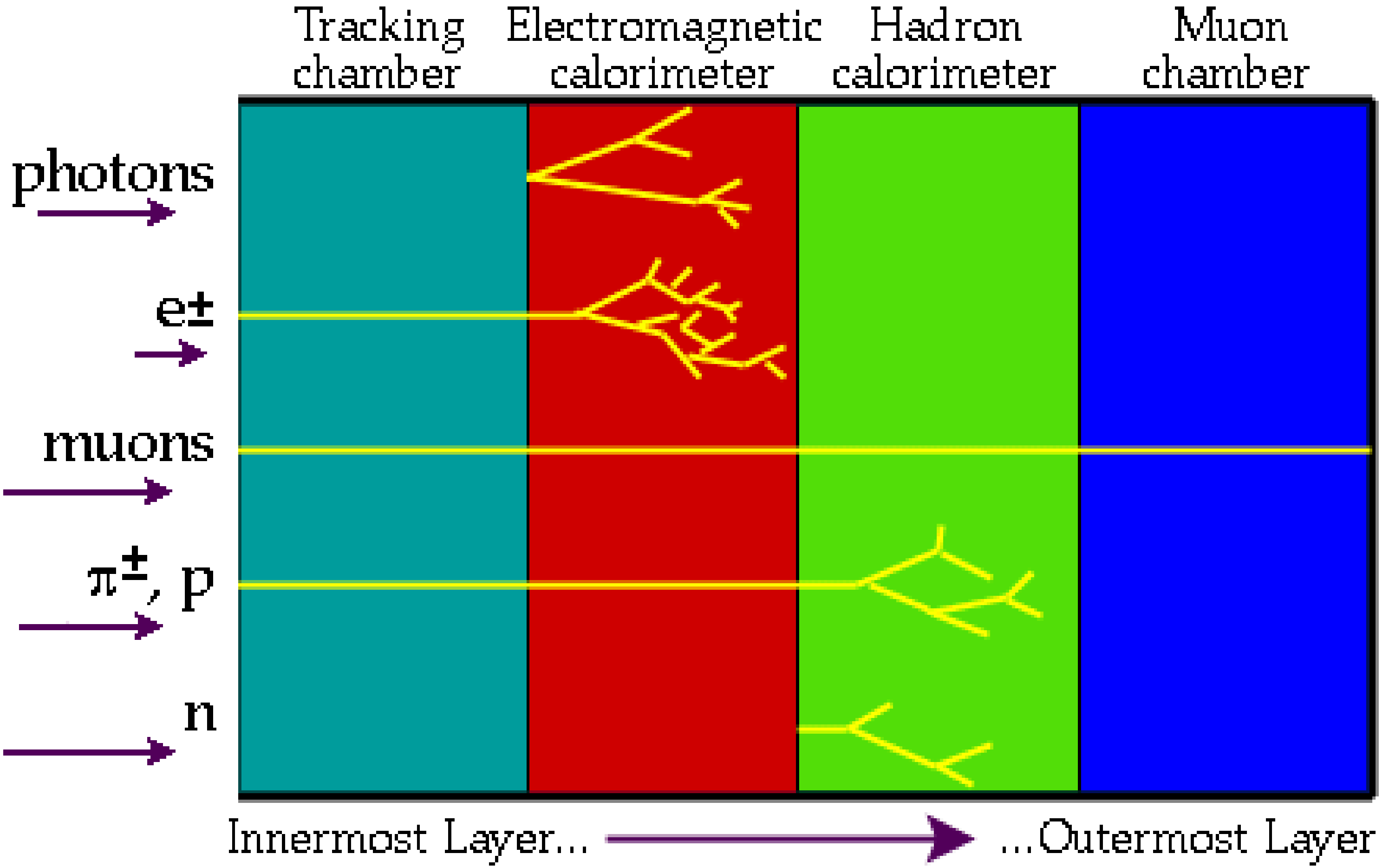
- We can now:
  - Track muons
  - Identify particles by dE/dx
  - Track charged particles close to the interaction point
  - measure momentum and charge


$\bar{t}$
γ
H
t
γ

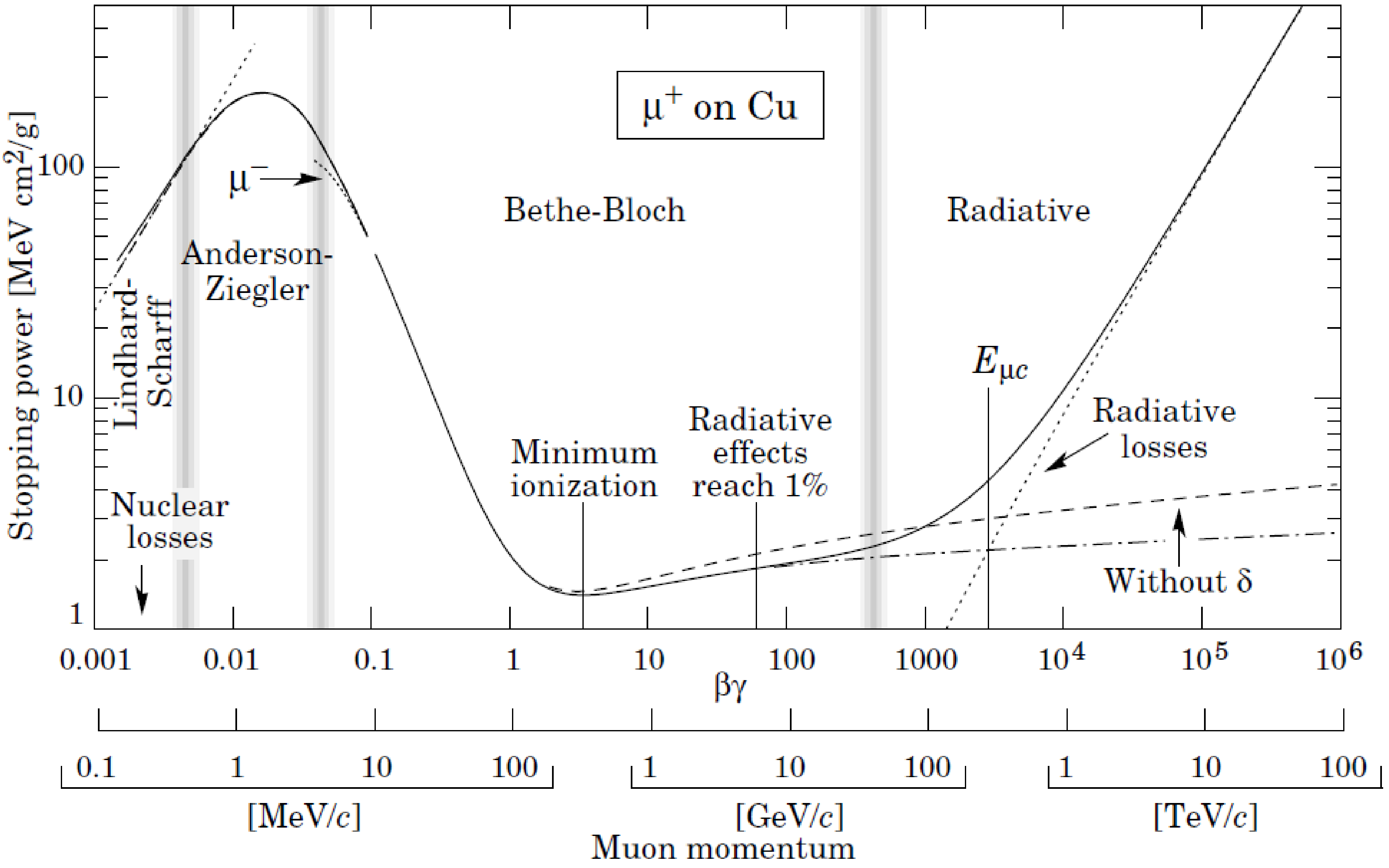

e
ℓ'^-
μ
ℓ'^+
Z^0
H
Z^{0*}
ℓ^-
ℓ^+


ν
W^+
l^+
h^0
l^-
W^-
$\bar{\nu}$


e^+
W^+
ν
W^+
H^0
b
$\bar{b}$


Tracking chamber
Electromagnetic calorimeter
Hadron calorimeter
Muon chamber
photons
e±
muons
π±, p
n
Innermost Layer...
...Outermost Layer

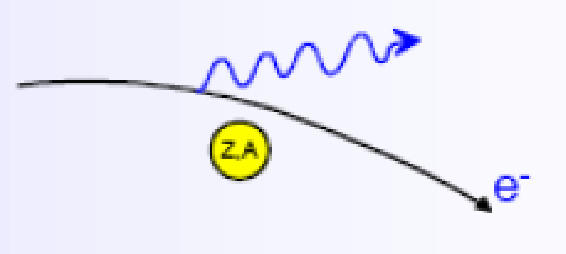
J. Beringer *et al.*(PDG), PR D86, 010001 (2012)



Electron mass is much smaller → higher βγ → radiative losses !

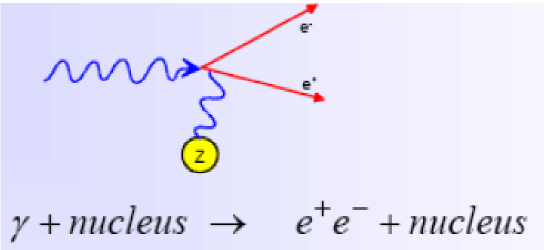
Bremsstrahlung / Pair production

- Energy loss due to emission of photons in the electromagnetic field of the nucleus (and of the atomic electrons).

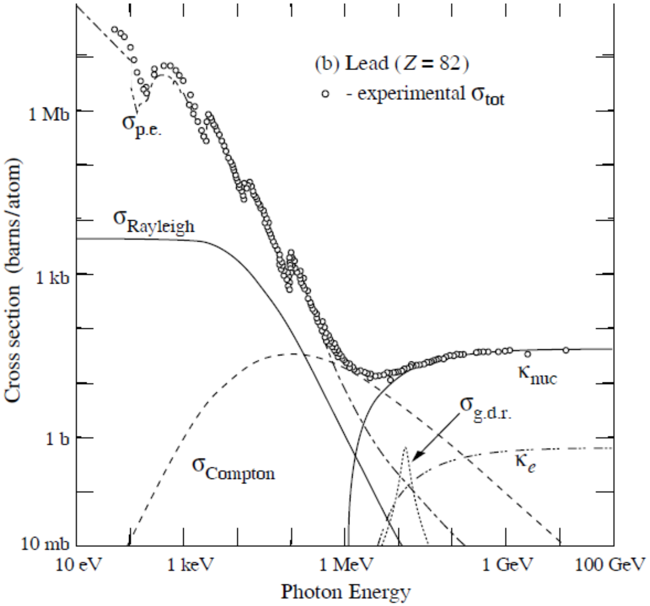


$$\sigma \propto E / m_{\text{particle}}^2$$

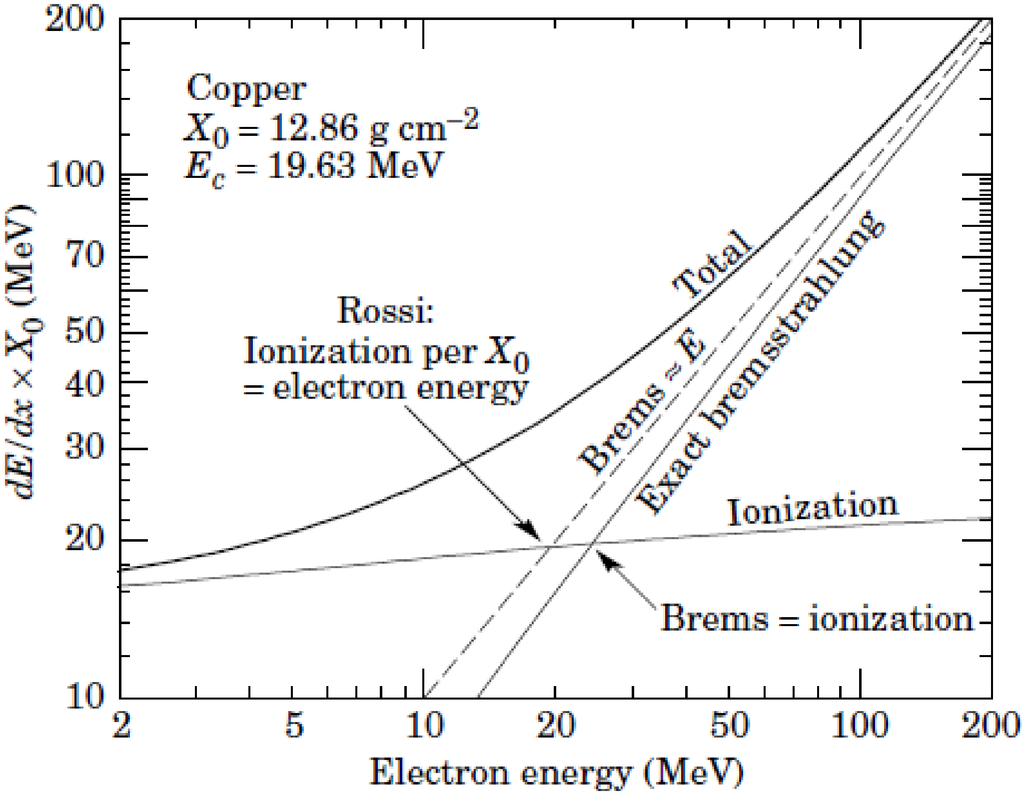
- Pair Production

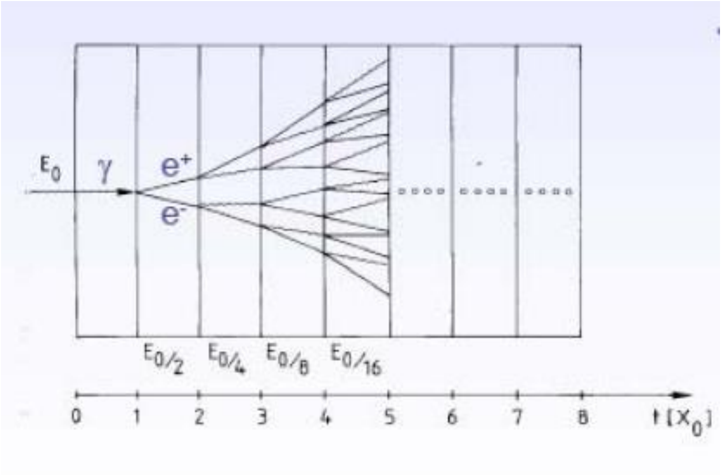


$$\gamma + nucleus \rightarrow e^+e^- + nucleus$$



Radiation Length

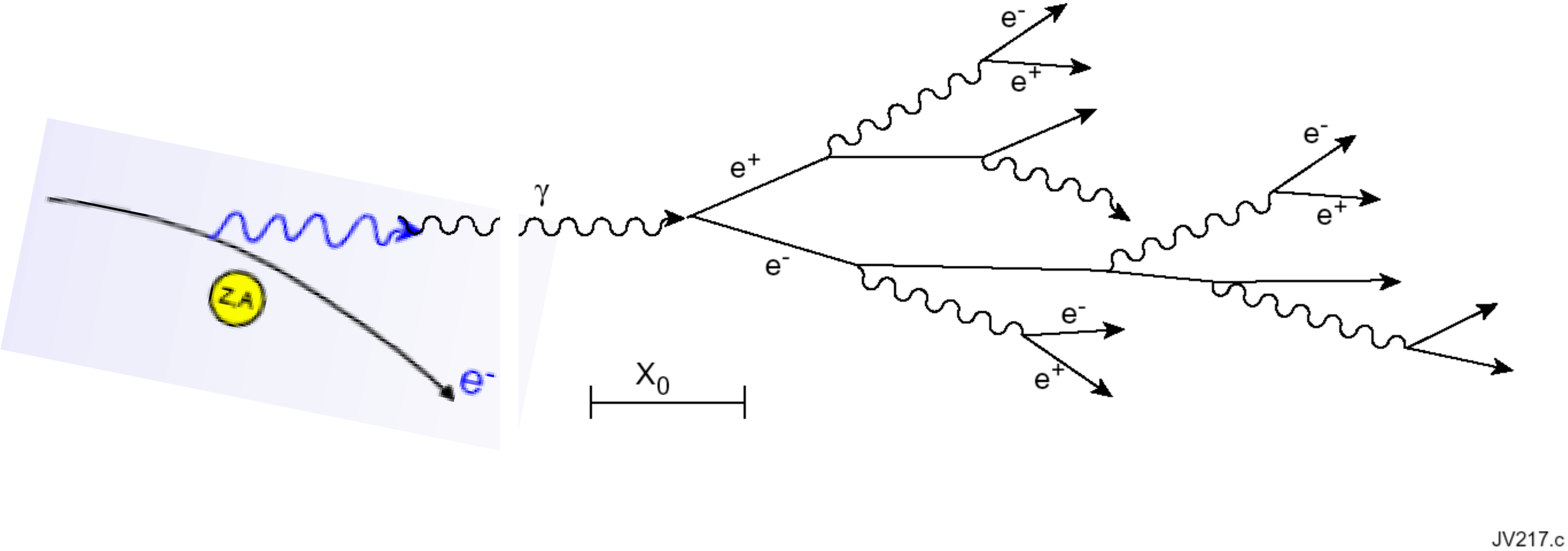




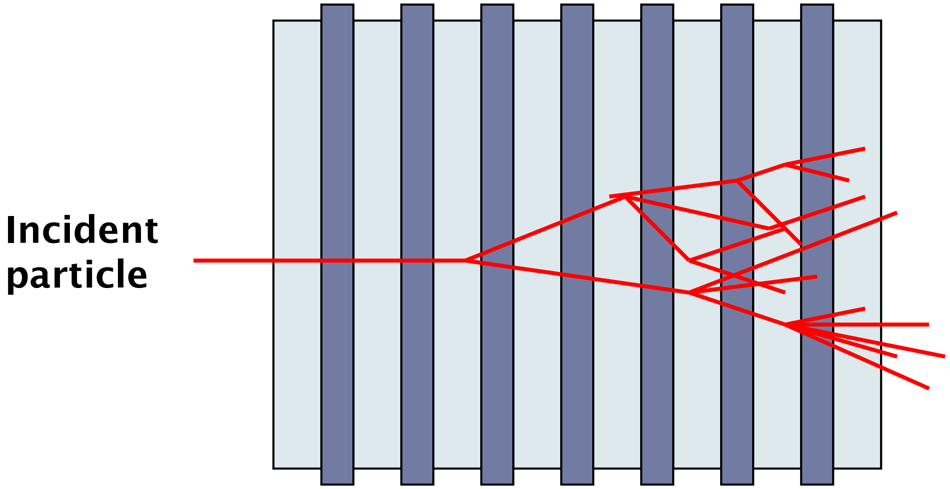
E.g. Lead: X_0=6.3 mm

$20X_0$ =12.6 cm

Bremsstrahlung and Pair production



Sampling Calorimeters



▢ **Absorber**

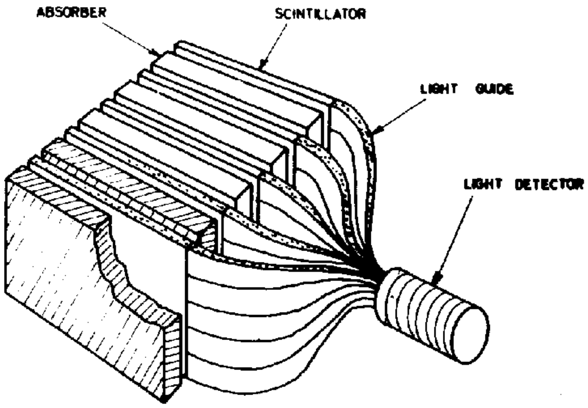
Lead, Tungsten, Uranium

▨ **Detector**

MWPC, scintillator, silicon pads, noble liquid

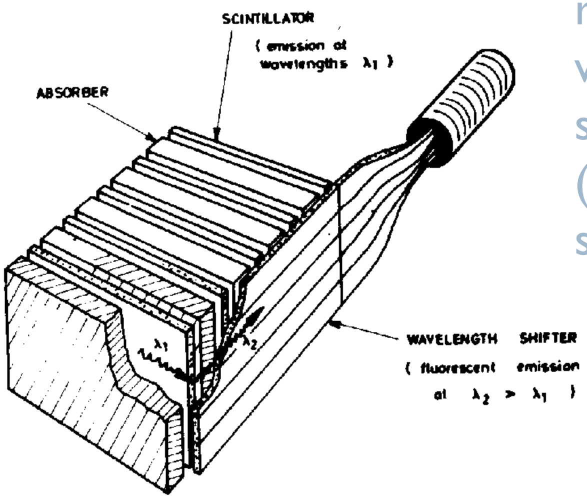
- Absorber (passive) and detector (active) layers
- Fluctuations in visible energy: "sampling fluctuations" due to variation of the nnumber of charged particles in the detector

Scintillator readout



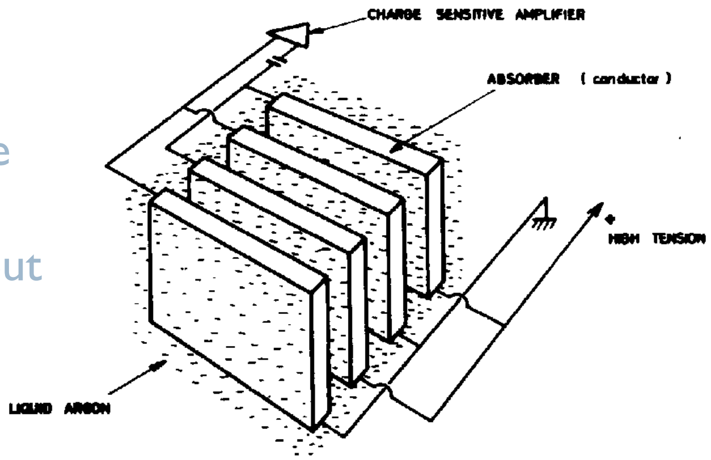
a)

Scintillator readout with wavelength shifter bars (or wavelength shifting fibers)



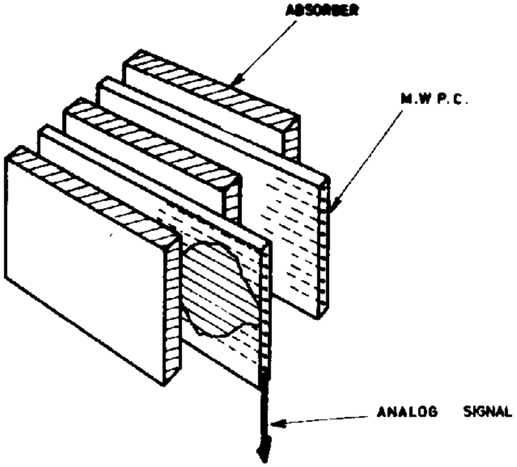
b)

Noble liquid readout



c)

Readout with gaseous detectors (MWPCs or streamer tubes)



d)

C.Joram. CERN Academic Training 1997-1998

Energy resolution

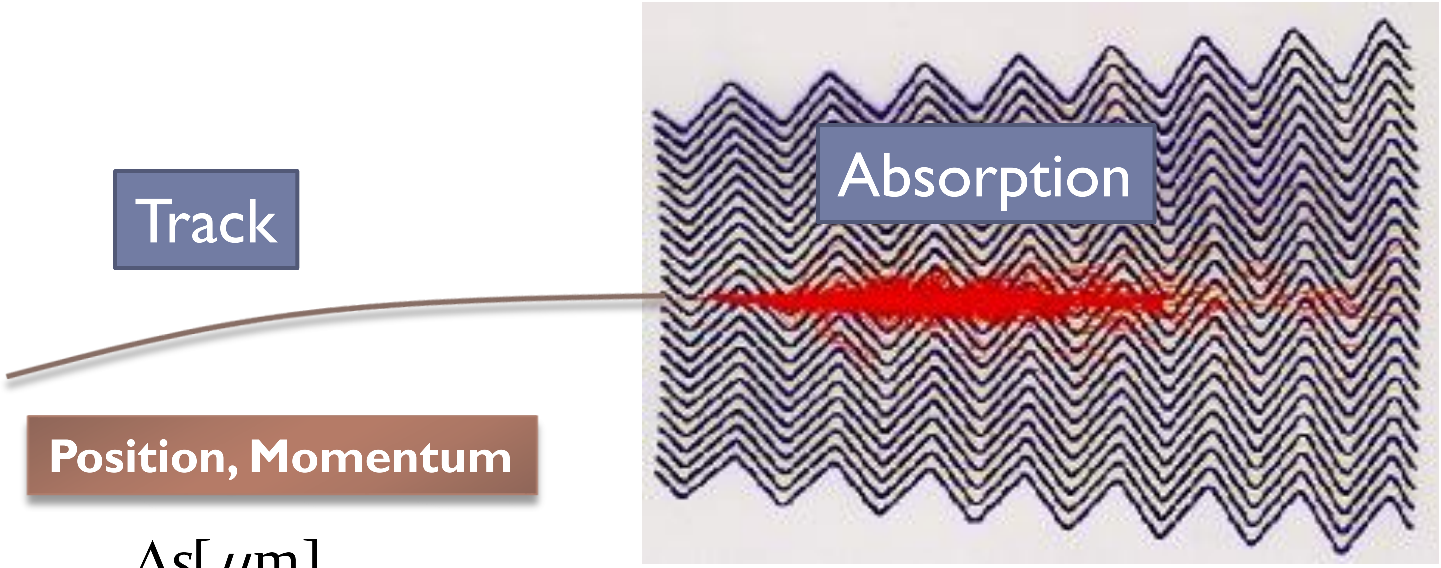
- Statistical fluctations
  - In the number of particles in the shower
  - In the number of escaping or undetected particles
- Noise
  - Electronic noise
  - Pile up
- Constant
  - Dead material
  - Calibration errors
  - Mechanical imperfections

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{\sigma_n}{E} \oplus \text{constant}$$

- **Higher energy -> better resolution**

Position, momentum, energy

$$\frac{\sigma(\mathrm{E})}{\mathrm{E}} = \frac{\mathrm{a}}{\sqrt{\mathrm{E}}} \oplus \frac{\sigma_{\mathrm{n}}}{\mathrm{E}} \oplus \mathrm{constant}$$



Track

Absorption

Position, Momentum

Energy

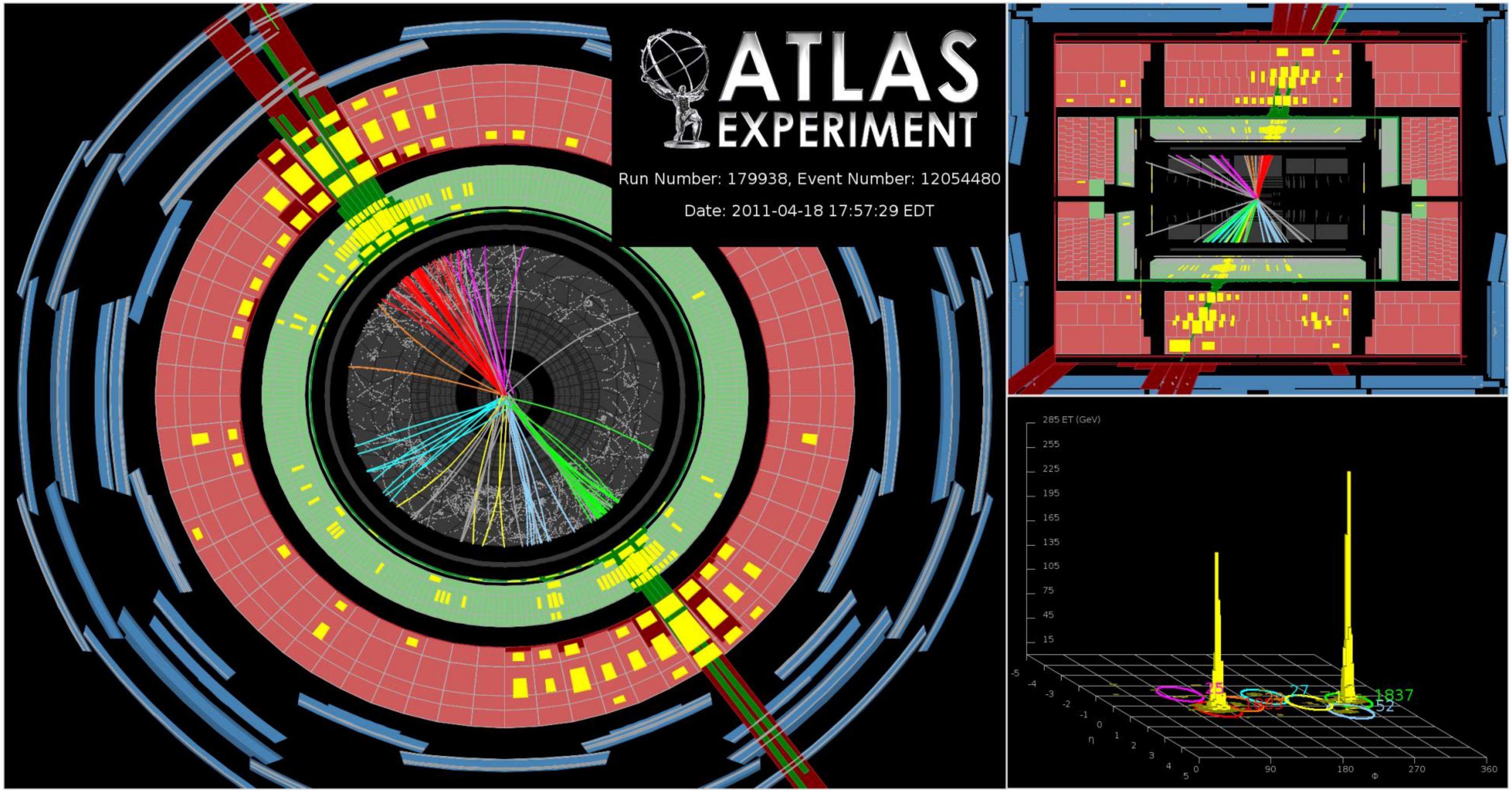
$$\frac{\Delta p}{p} \approx 0.25 \frac{\Delta s[\mu\mathrm{m}]}{(L[\mathrm{cm}])^2 B[\mathrm{T}]} p[\mathrm{GeV}]$$

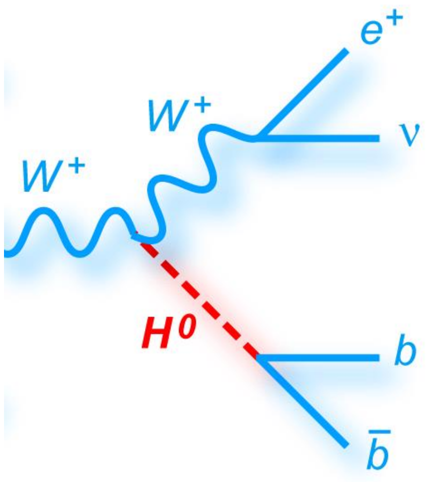
$$\propto p$$

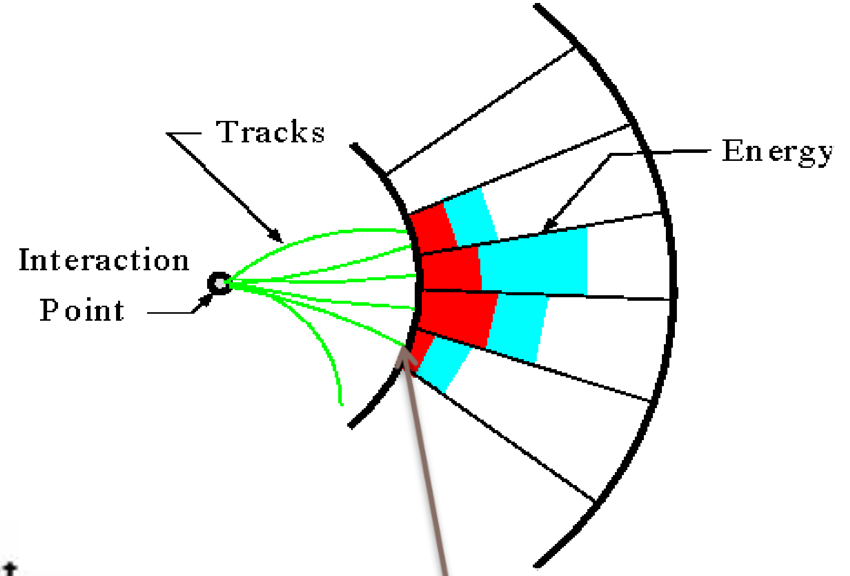
$$\propto \frac{1}{\sqrt{E}}$$

And… the most common objects ?

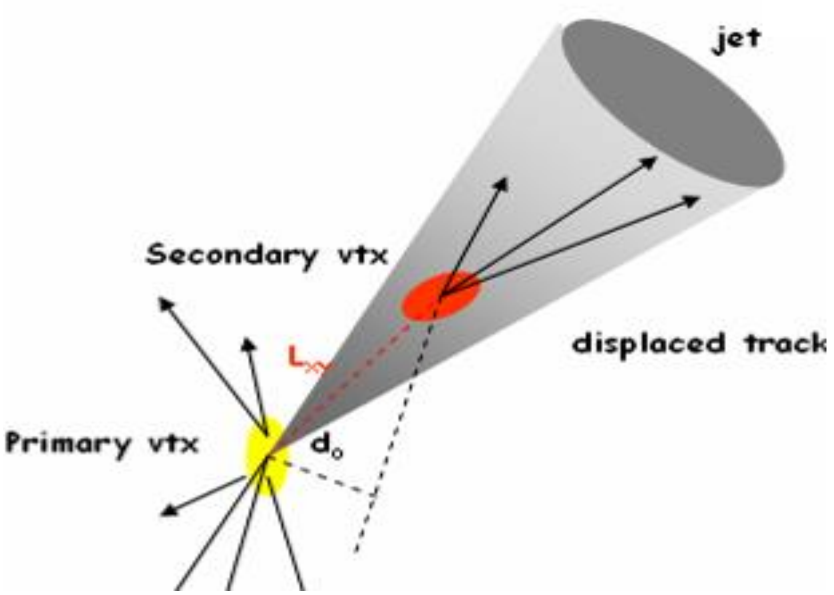
- Jets



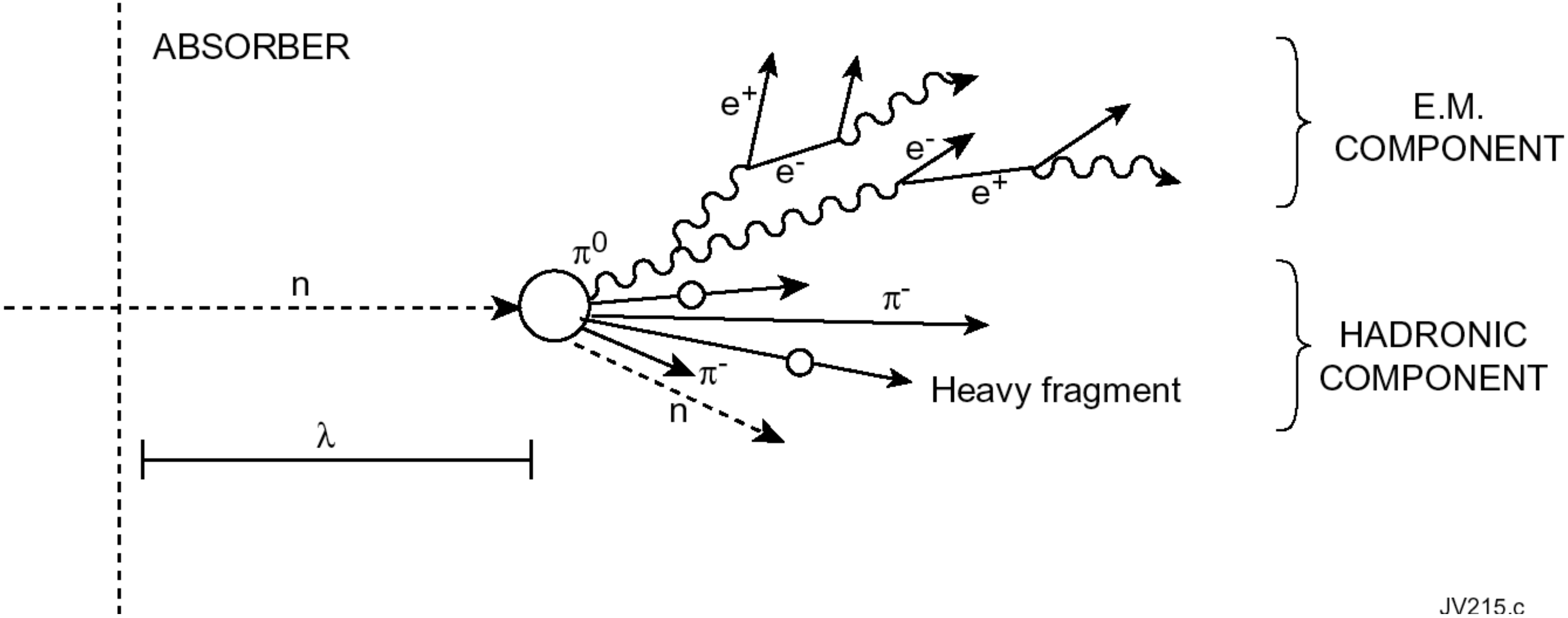




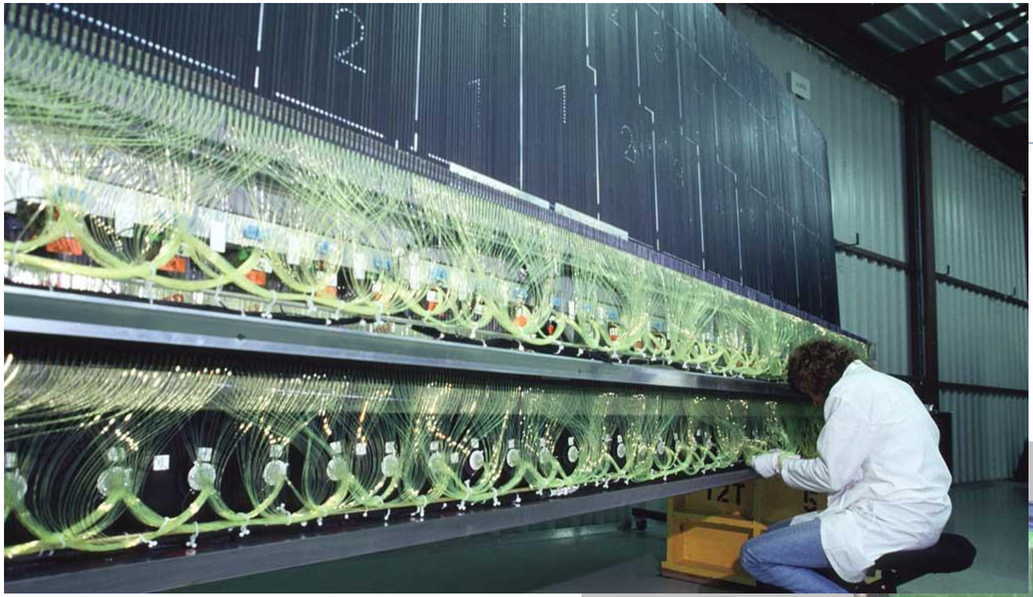
What happens here ?

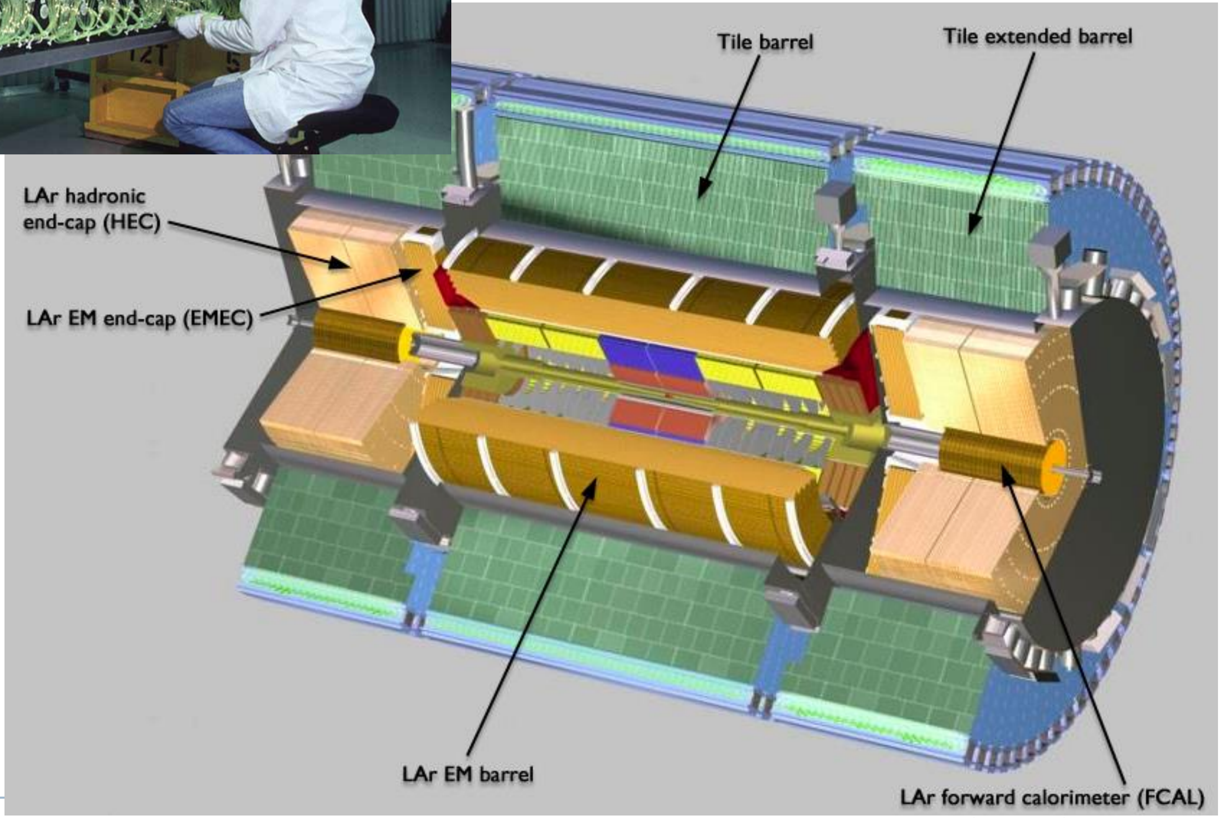


Hadron interactions

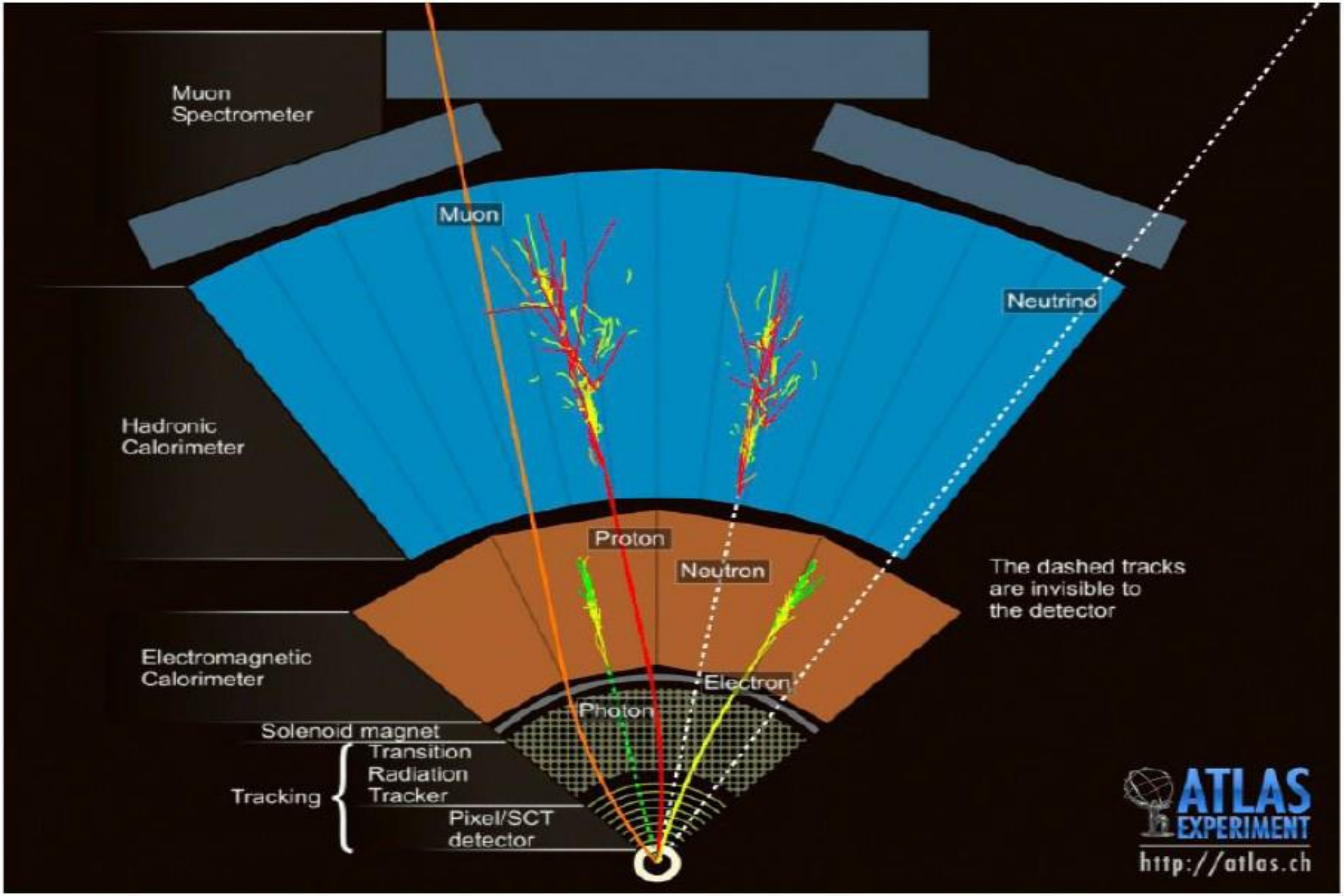


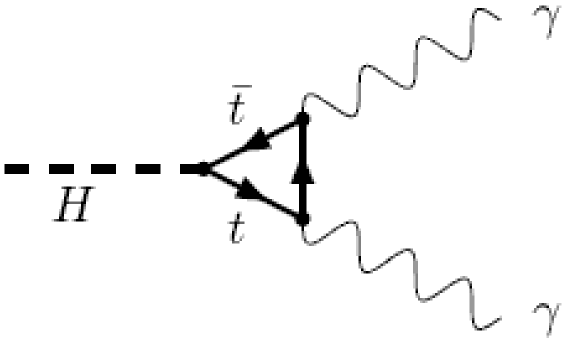
- Interaction length λ is much larger than the radiation length X_0
- Due to strong interaction, the shower is much wider

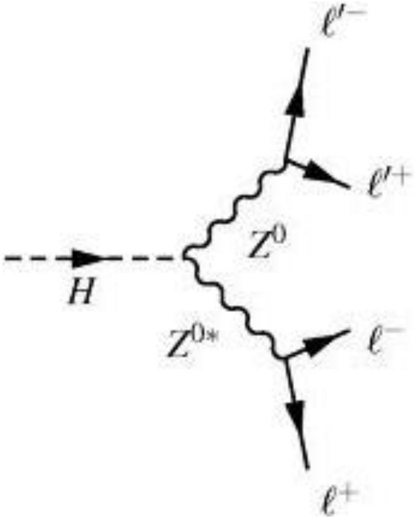


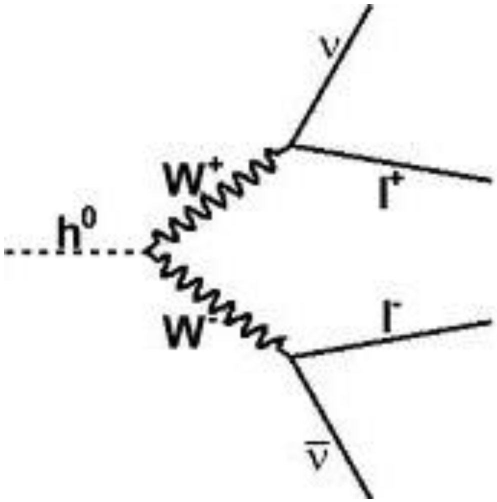


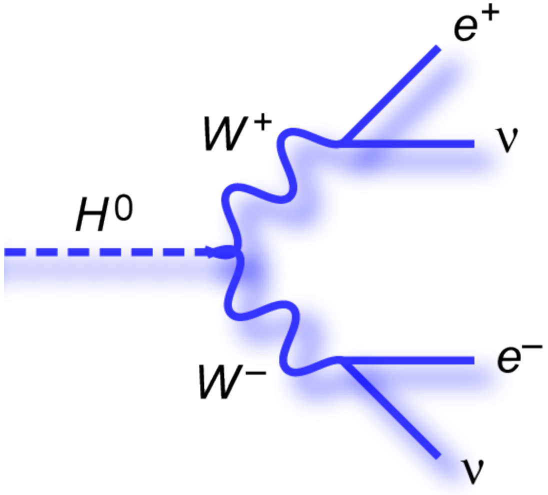
Tile barrel
Tile extended barrel
LAr hadronic end-cap (HEC)
LAr EM end-cap (EMEC)
LAr EM barrel
LAr forward calorimeter (FCAL)

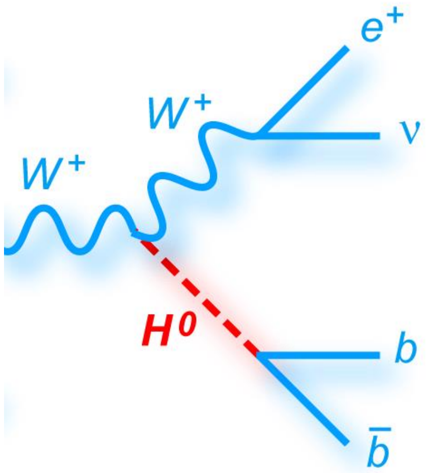

Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

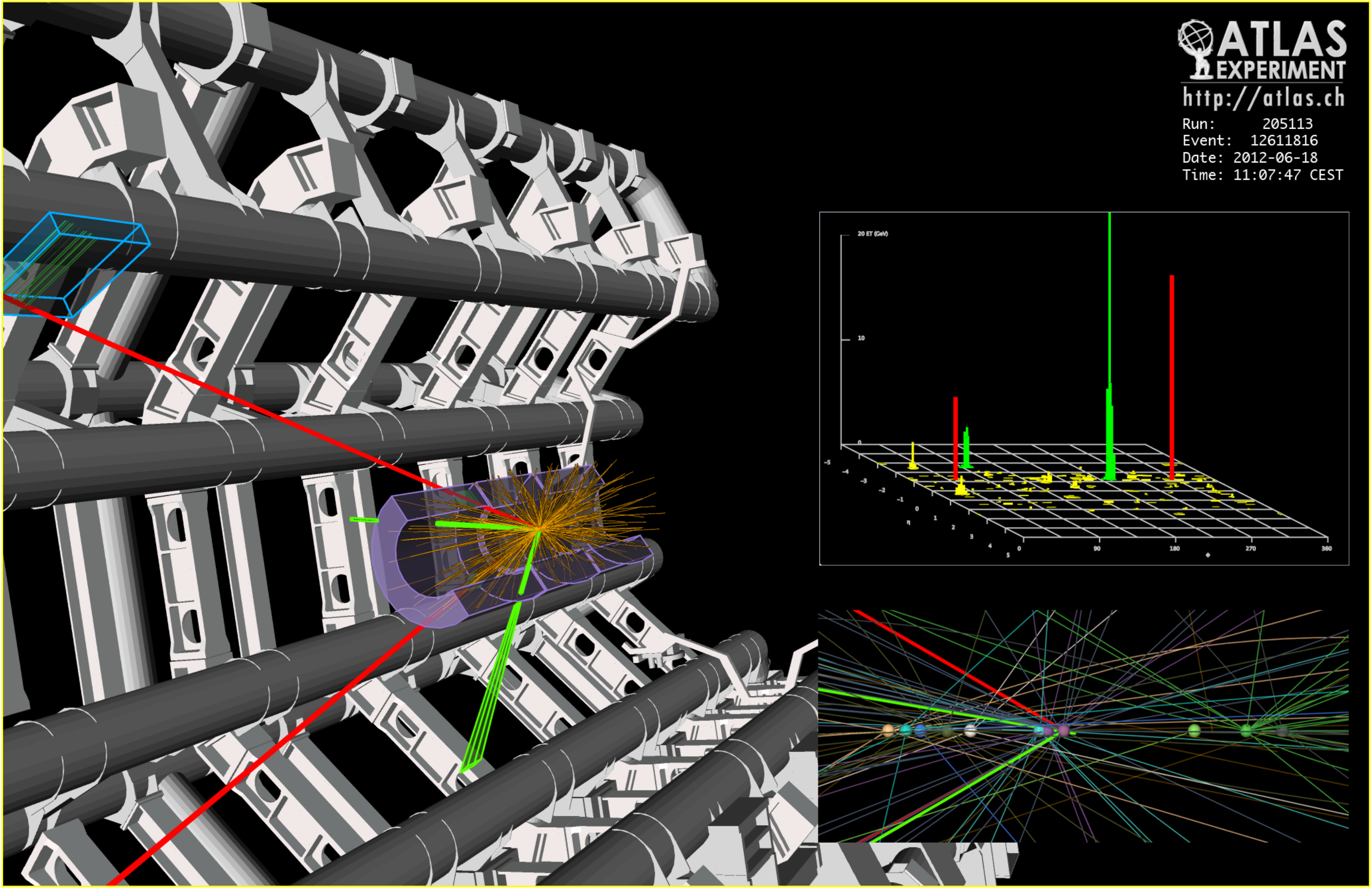

γ
$\bar{t}$
H
t
γ

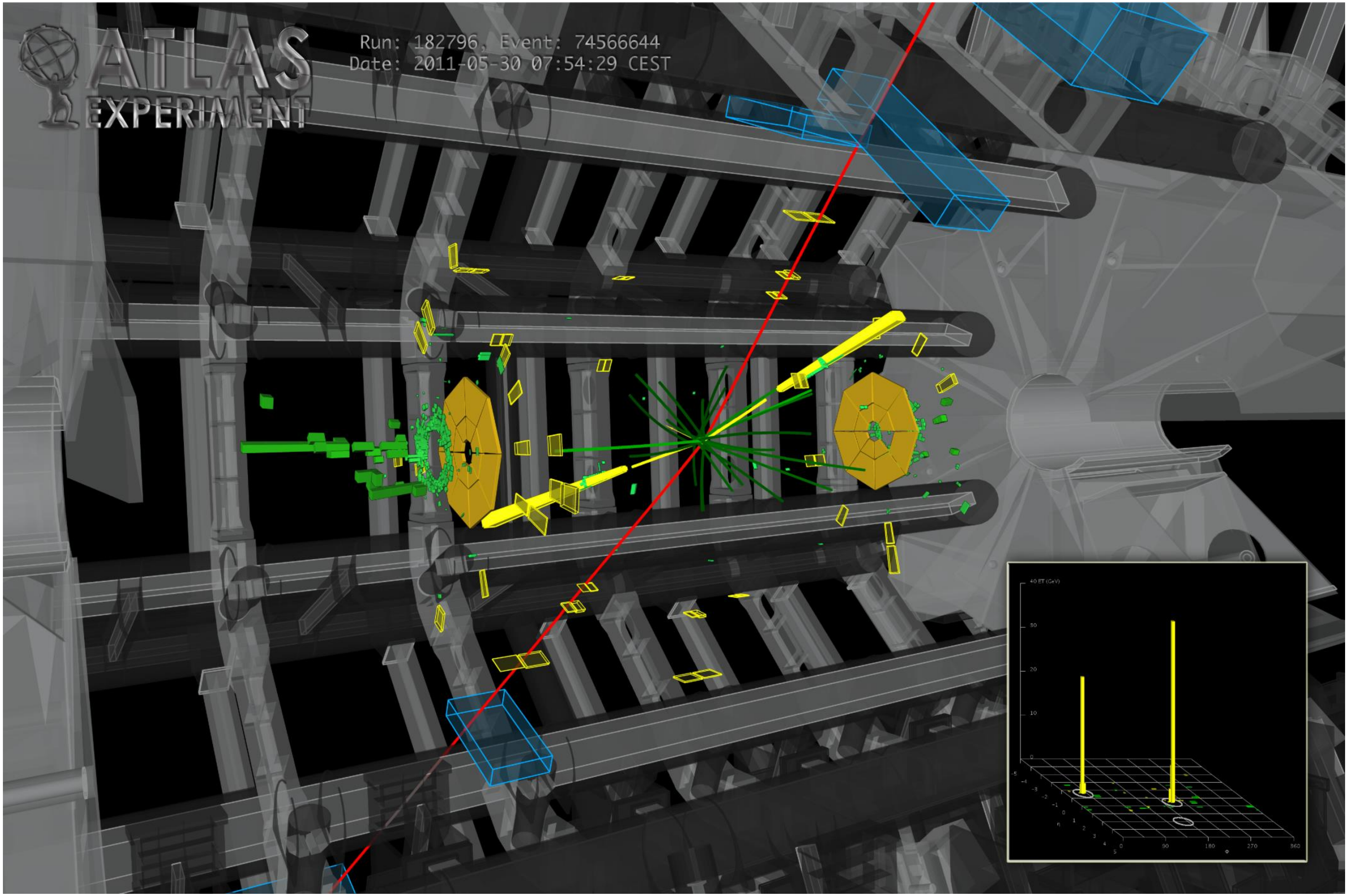

ℓ'^-
ℓ'^+
Z^0
H
Z^{0*}
ℓ^-
ℓ^+

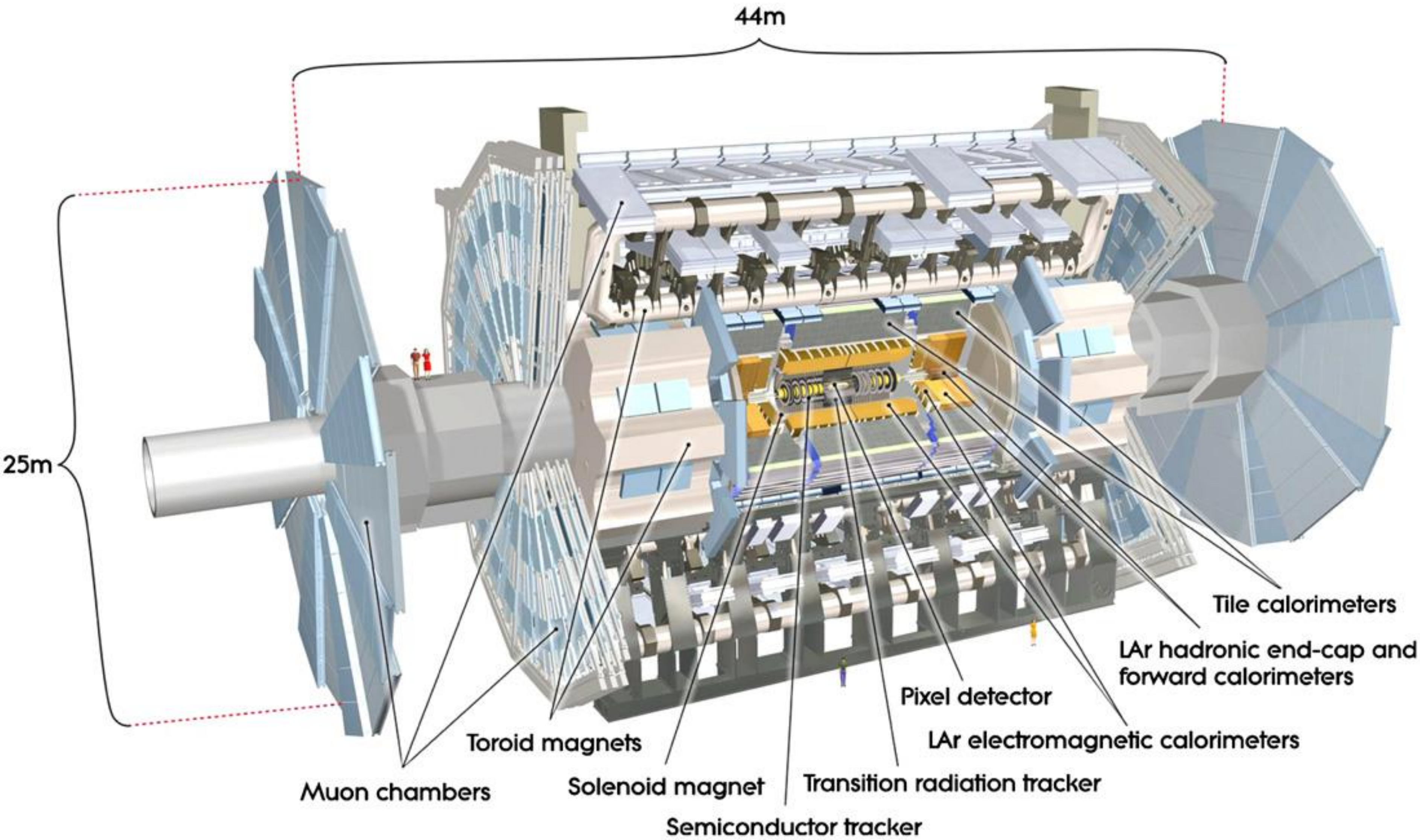

ν
W^+
l^+
h^0
W^-
l^-
$\bar{\nu}$


e^+
W^+
ν
H^0
W^-
e^-
ν

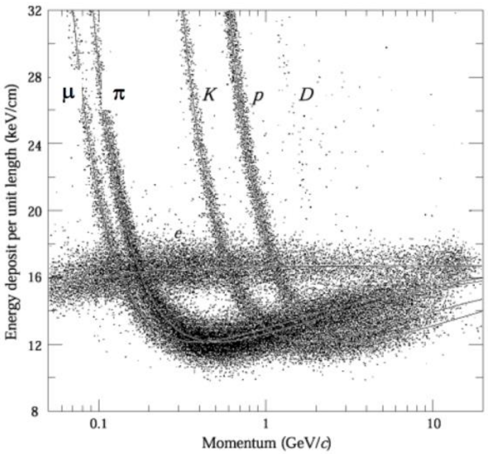

e^+
W^+
ν
W^+
H^0
b
$\bar{b}$


ATLAS EXPERIMENT
http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST
20 ET (GeV)
10
-5
-4
-3
-2
-1
0
η
1
2
3
4
5
0
90
180
270
360
φ


ATLAS EXPERIMENT
Run: 182796, Event: 74566644
Date: 2011-05-30 07:54:29 CEST
40 ET (GeV)
30
20
10
0
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
Φ


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

Summary



- Ionisation
- Magnets

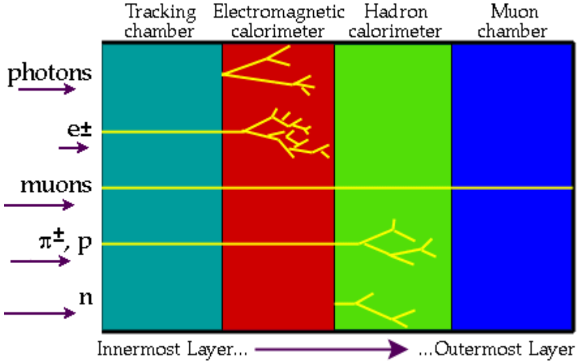
$$B[\mathrm{T}]\cdot R[\mathrm{m}] = 3.3356\cdot p\left[\mathrm{GeV}/\mathrm{c}\right]$$

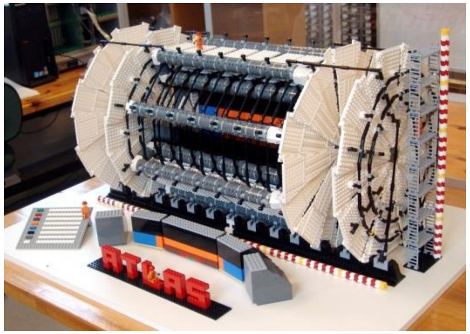
- Tracking detectors
  - Momentum resolution
  - Impact parameter resolution

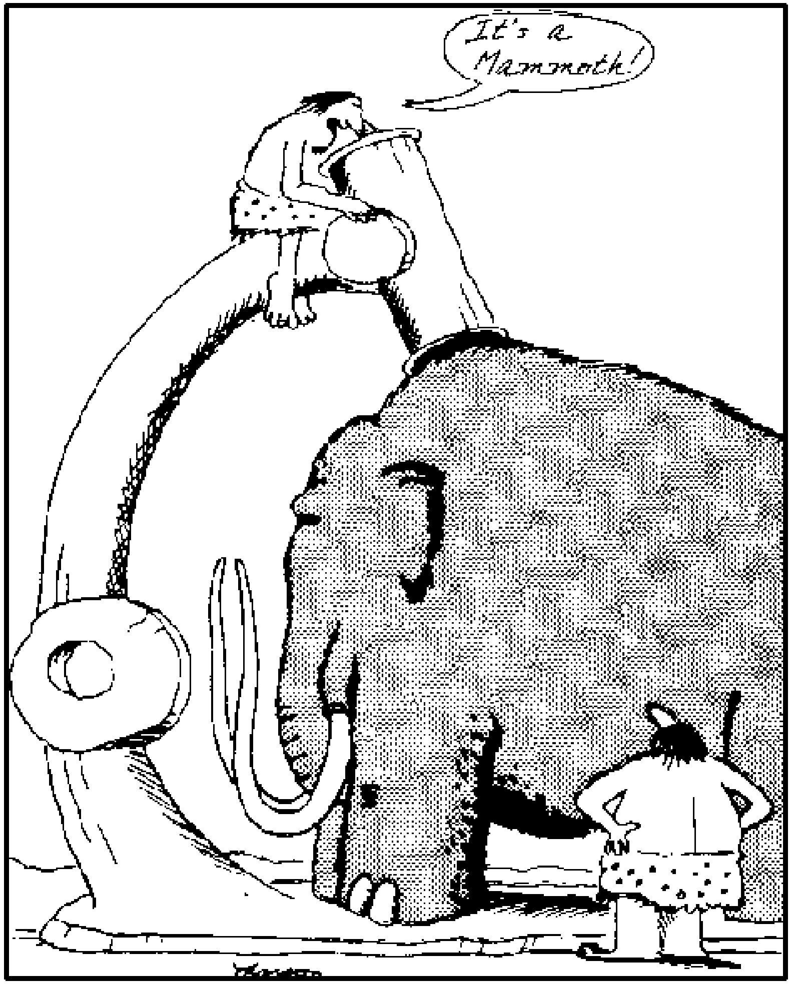
$$\frac{\Delta p}{p} \approx 0.25 \frac{\Delta s[\mu\mathrm{m}]}{(L[\mathrm{cm}])^2 B[\mathrm{T}]} p[\mathrm{GeV}]$$

$$\frac{\sigma(\mathrm{E})}{\mathrm{E}} = \frac{\mathrm{a}}{\sqrt{\mathrm{E}}} \oplus \frac{\sigma_\mathrm{n}}{\mathrm{E}} \oplus \mathrm{constant}$$

- Showers / Calorimeters
  - Energy
- Particle ID
- Collider detectors







Early Microscope

Nuclear Instruments & Methods in Physics Research

topical issue

Instrumentation and detector technologies for frontier high energy physics

Volume 666, pages 1 - 222 (21 February 2012)

Edited by:
Archana Sharma (CERN)

Technological advances in radiation detection have been pioneered and led by particle physics. The ever increasing complexity of the experiments in high energy physics has driven the need for developments in high performance silicon and gaseous tracking detectors, electromagnetic and hadron calorimetry, transition radiation detectors and novel particle identification techniques. Magnet systems have evolved with superconducting magnets being used in present and, are being designed for use in, future experiments. The alignment system, being critical for the overall detector performance, has become one of the essential design aspects of large experiments. The electronic developments go hand in hand to enable the exploitation of these detectors designed to operate in the hostile conditions of radiation, high rate and luminosity. This volume provides a panorama of the state-of-the-art in the field of radiation detection and instrumentation for large experiments at the present and future particle accelerators.