Detector Physics

Outline:

- Introduction
- Physics of particle interaction with matter
- Basic concepts of detector construction
- Tracking
- Energy measurement
- Particle identification
- Case studies

Wolfgang Kühn, Universität Giessen

Credits: A lot of material stolen from:

Hans-Christian Schultz-Coulon (Univ. Heidelberg), Erika Garutti (Univ. Hamburg), Johanna Stachel (Univ. Heidelberg), CERN/DESY, summer school lectures, Particle Data Group

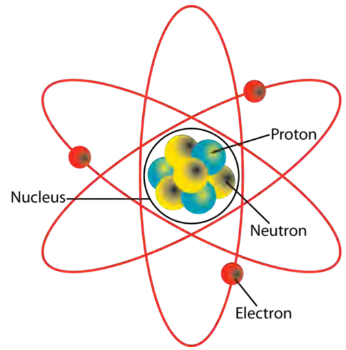
A perfect detector would be able to ....

- detect **charged particles**
  - charged leptons, charged hadrons, …
- detect **neutral particles**
  - Photons, neutral hadrons, neutrinos
- perform **particle identification**
- **precisely measure the energy and/or the momentum** of each particle
  - allow to construct **4-vectors** for all particles produced in an interaction
  - do so even at very **high interaction rates** (> 20 MHz ?)

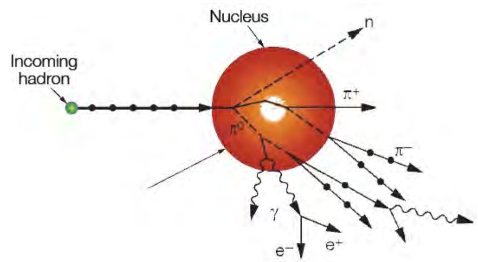
Detectors are made out of matter ...

Interaction of particles with matter

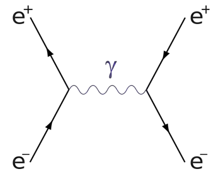
- Matter : Atoms = Electrons + Nuclei
- Interactions depend on particle type
- Energy loss strongly dependent on energy



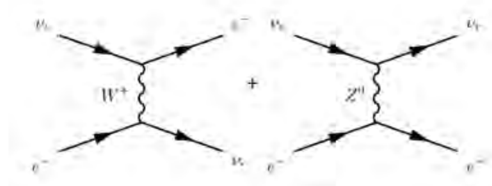
Strong interaction of hadrons with nuclei

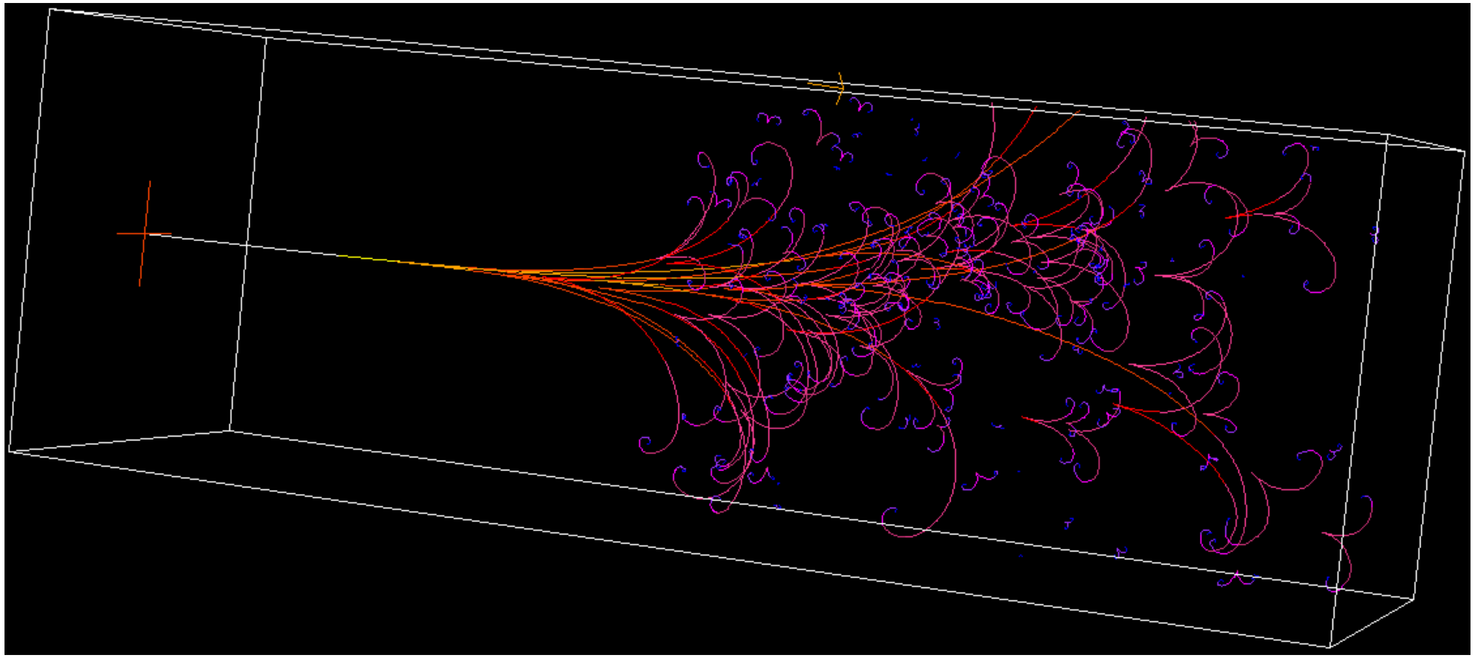


Electromagnetic interaction of charged particles and photons with electrons and nuclei



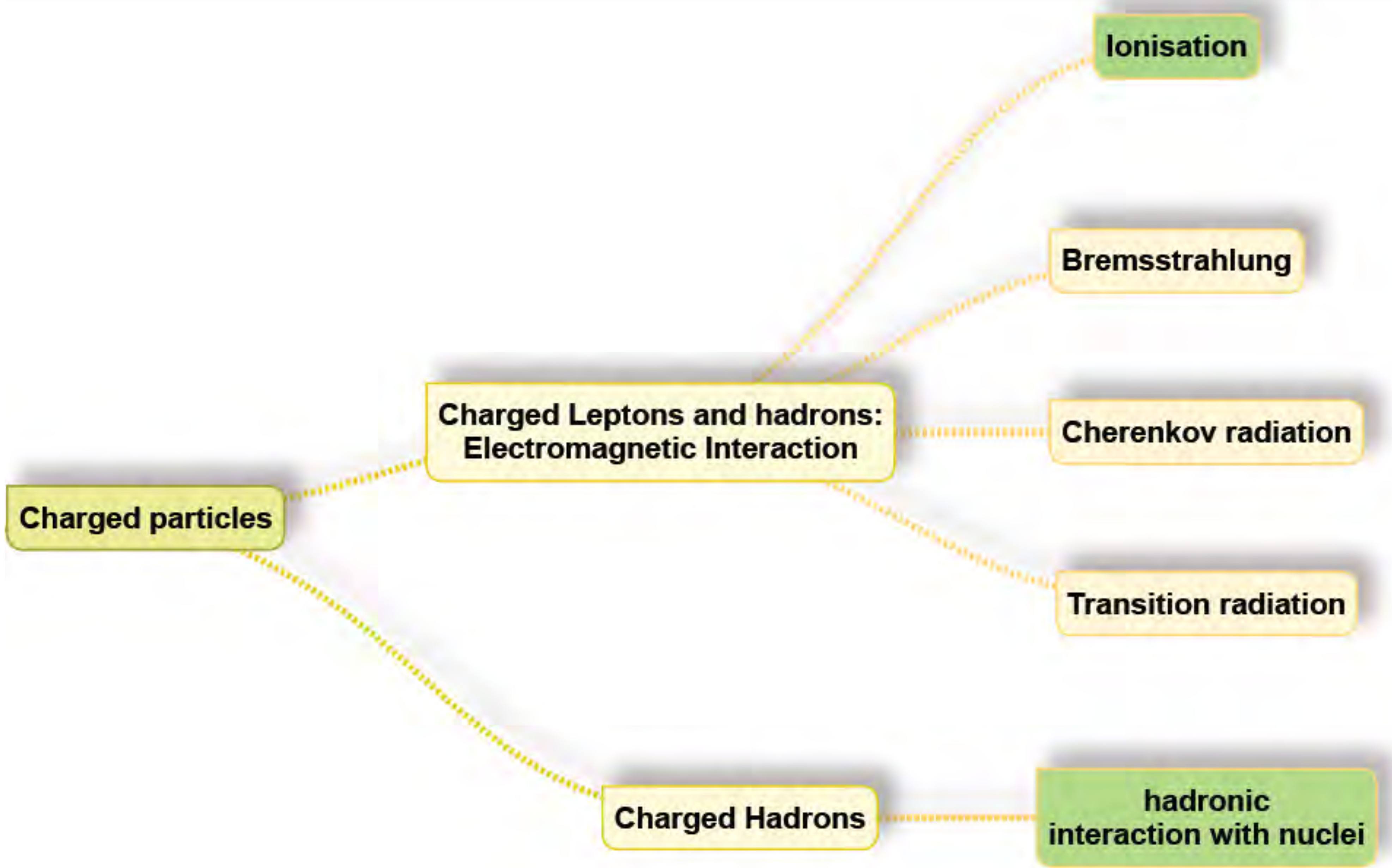
Weak interaction of neutrinos with electrons and nuclei





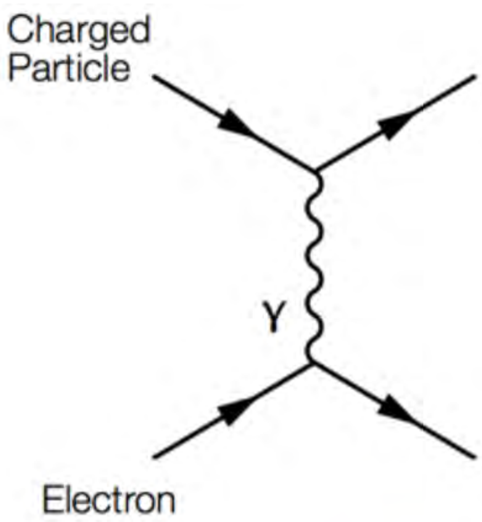
Physics of particle interaction with matter

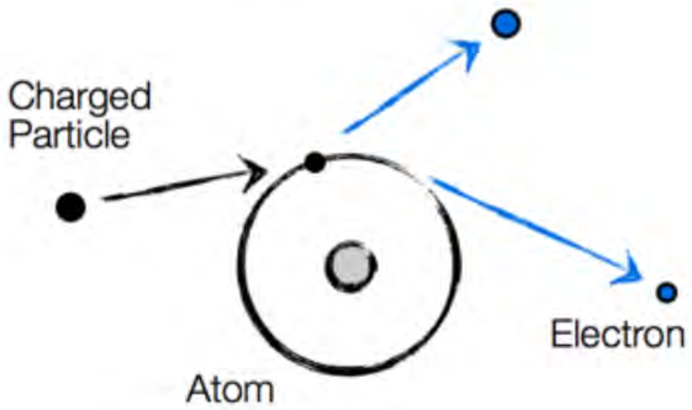
Mechanisms for energy loss: charged particles



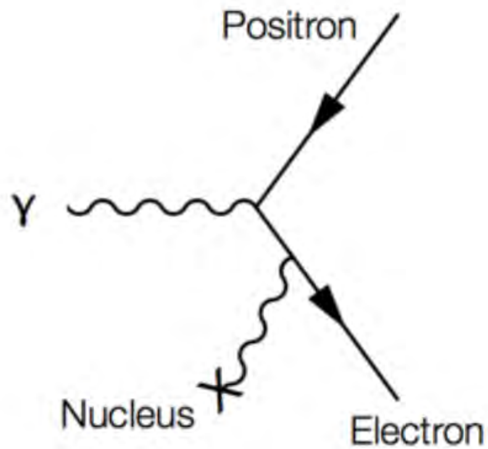
Electromagnetic Interaction

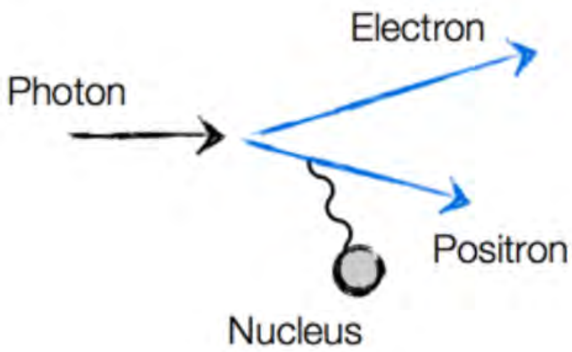
Ionisation



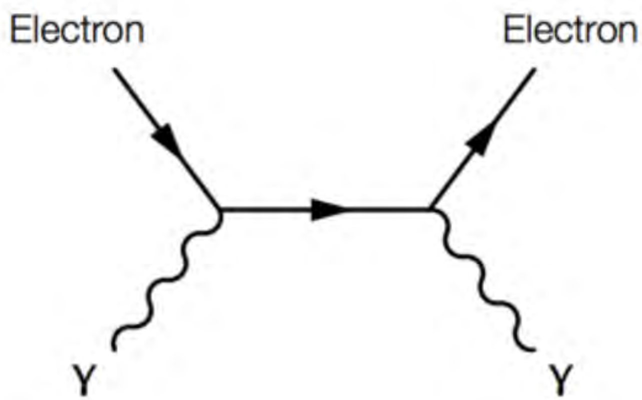


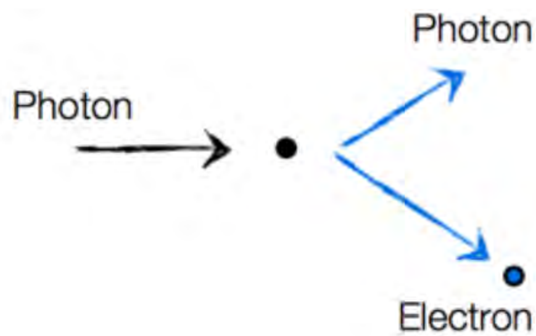
Pair Production



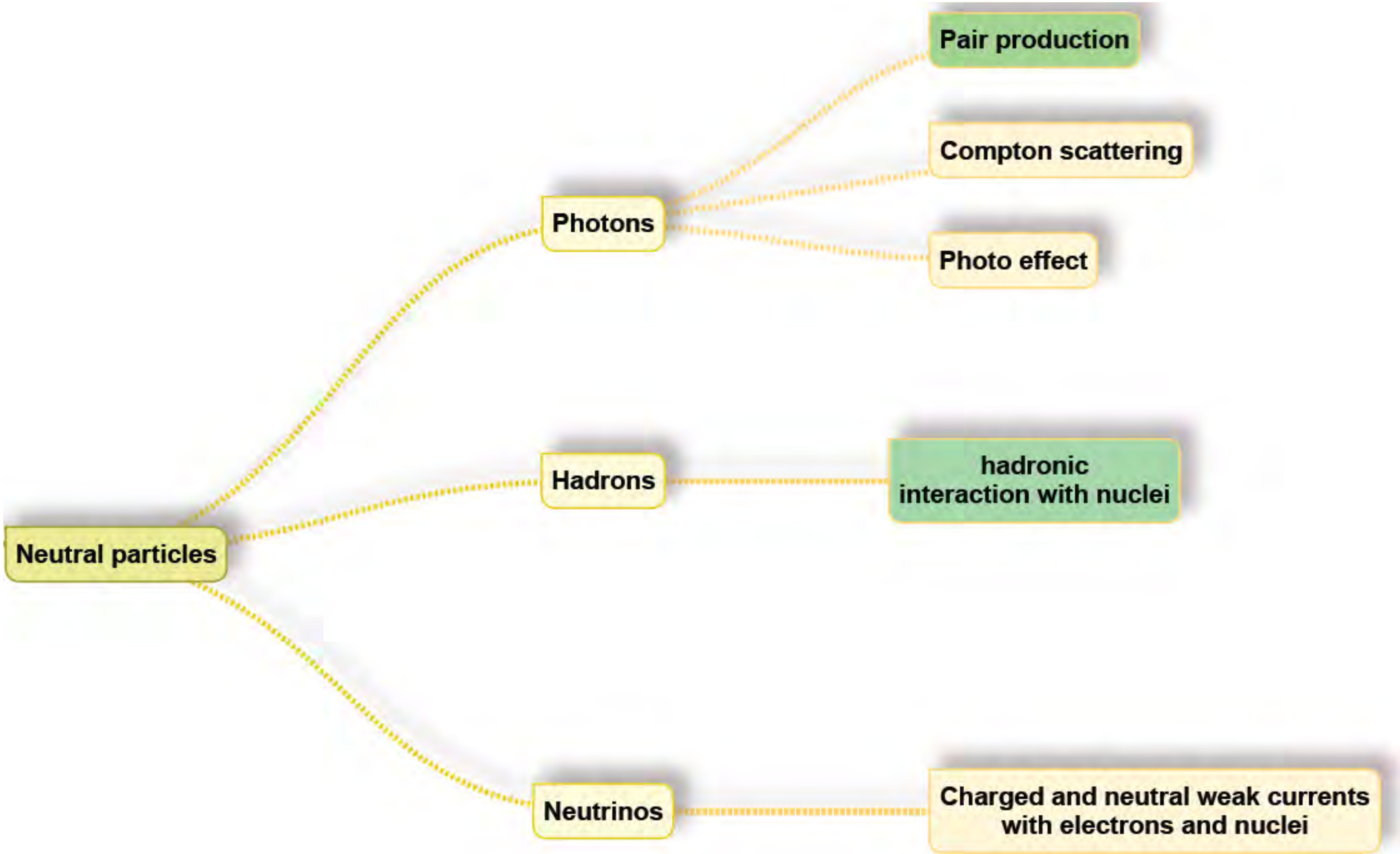


Compton Scattering





Mechanisms for energy loss: neutral particles

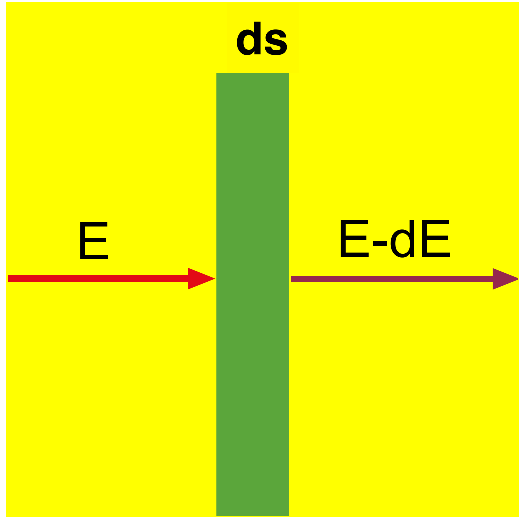


Remarks

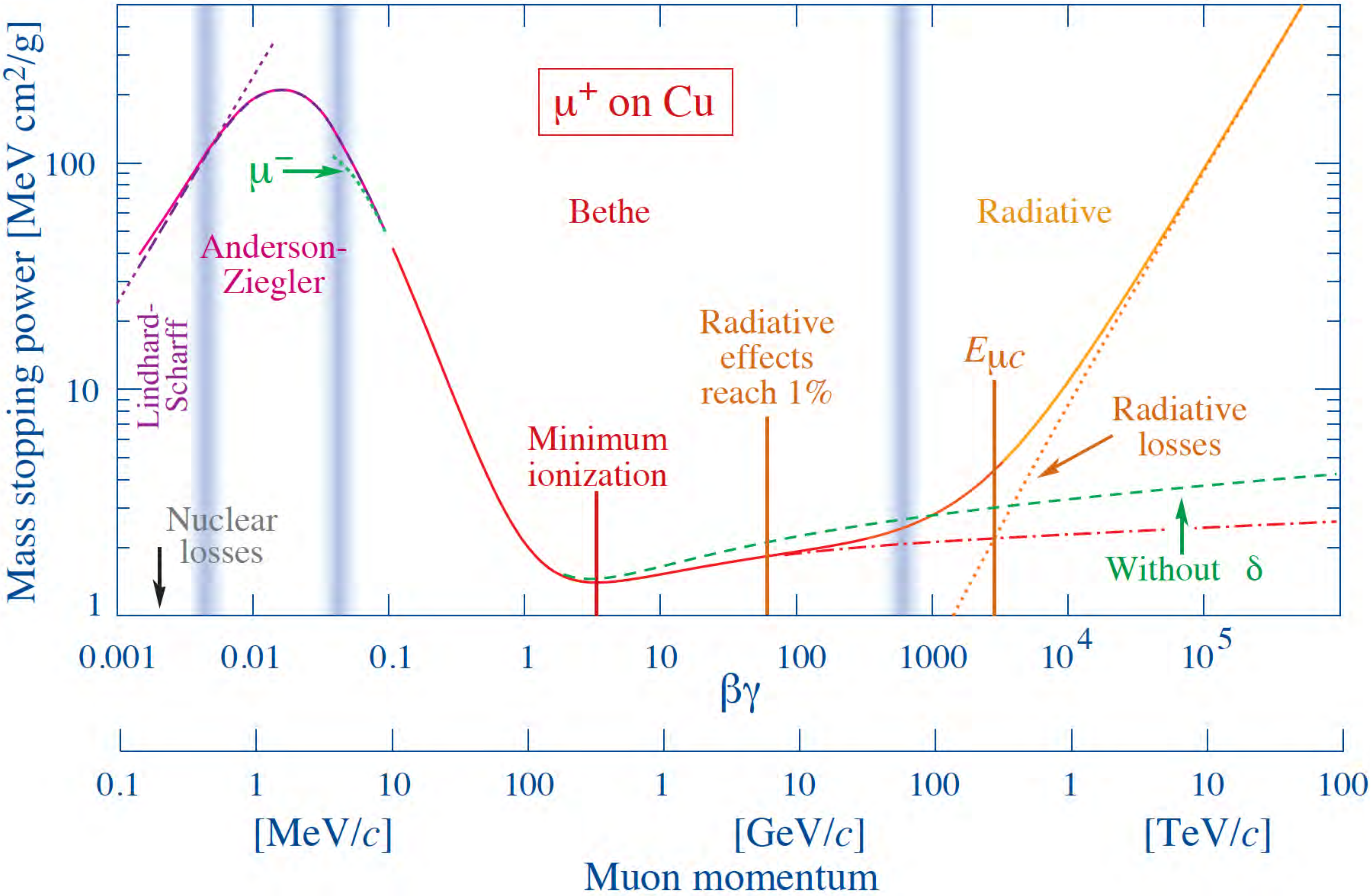
- All effects mentioned on the previous two slides are **strongly dependent on the type and momentum** of the incident particle
- **Only a few mechanisms lead to significant energy loss** at typical energies relevant in particle physics (marked in green on the previous two slides)
  - Ionisation, pair production, interactions with the absorber material's nuclei
- In spite of this, the other effects are important, because they allow us to construct detectors for **particle identification**
  - Example: Cherenkov detectors

Electronic energy loss of heavy charged particles

- Consider a muon traversing some absorber material with a given thickness and density
- After passing the absorber, the muon has lost some energy dE.
  - Note: the energy loss is the result of a very large number of interactions with the atoms of the absorber
    - At this point, we consider only the average energy loss for a large number of mono-energetic muons
- The energy loss dE/dx is called "**stopping power**"
- x = density・thickness is measured in g/cm^2
  - To calculate the thickness "ds", you have to divide x by the density of the absorber material
- dE/dx has the units MeV cm^2/g



Stopping Power (dE/dx) for Muons



Bethe-Bloch Formula: Energy Loss by Ionisation

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

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307$ MeV g^{-1} cm^2

$$W_{\max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

Maximum energy loss in a single collision:

$\delta(\beta\gamma)$ density effect correction to ionization energy loss

describes the mean rate of energy loss in the region
$0.1 <\sim \beta\gamma <\sim 1000$
for intermediate-Z materials with an accuracy of a few percent.

z	:	Charge of incident particle
M	:	Mass of incident particle
Z	:	Charge number of medium
A	:	Atomic mass of medium
I	:	Mean excitation energy of medium

Three regions for dE/dx from Bethe-Bloch-Formula:

1. **<u>Low energies / momenta:</u>**

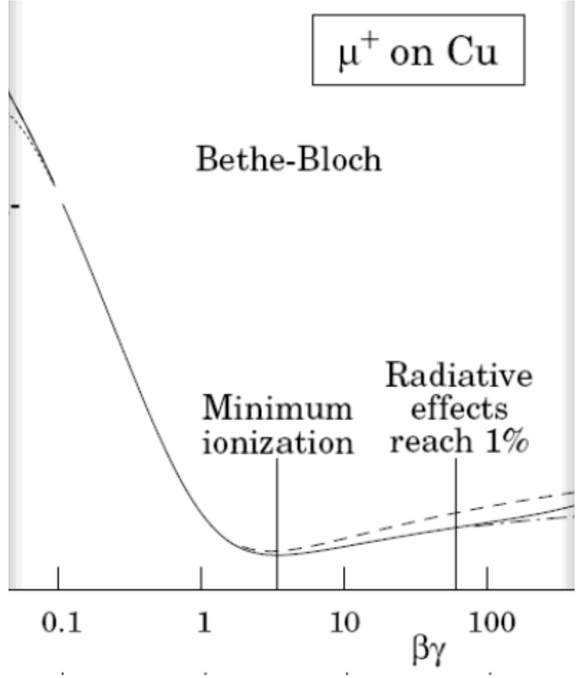
   - dE/dx decreases like $1/\beta^2$ up to a minimum value which is reached around $\beta\gamma$ =3-3.5

     - Particles in this kinematic range are called "**minimum ionizing particles**" (MIPS)

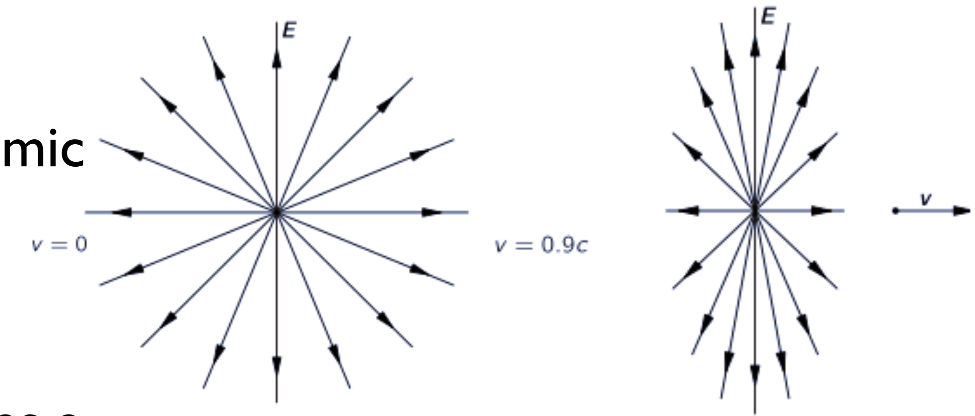
     - dE/dx is only weakly dependent on the absorber material and is typically about 1-2 MeV $g^{-1} cm^2$ (4 MeV $g^{-1} cm^2$ for H_2)

2. **<u>For larger values of $\beta\gamma$</u>** there is a logarithmic rise of dE/dx with increasing energy ("**relativistic rise**")

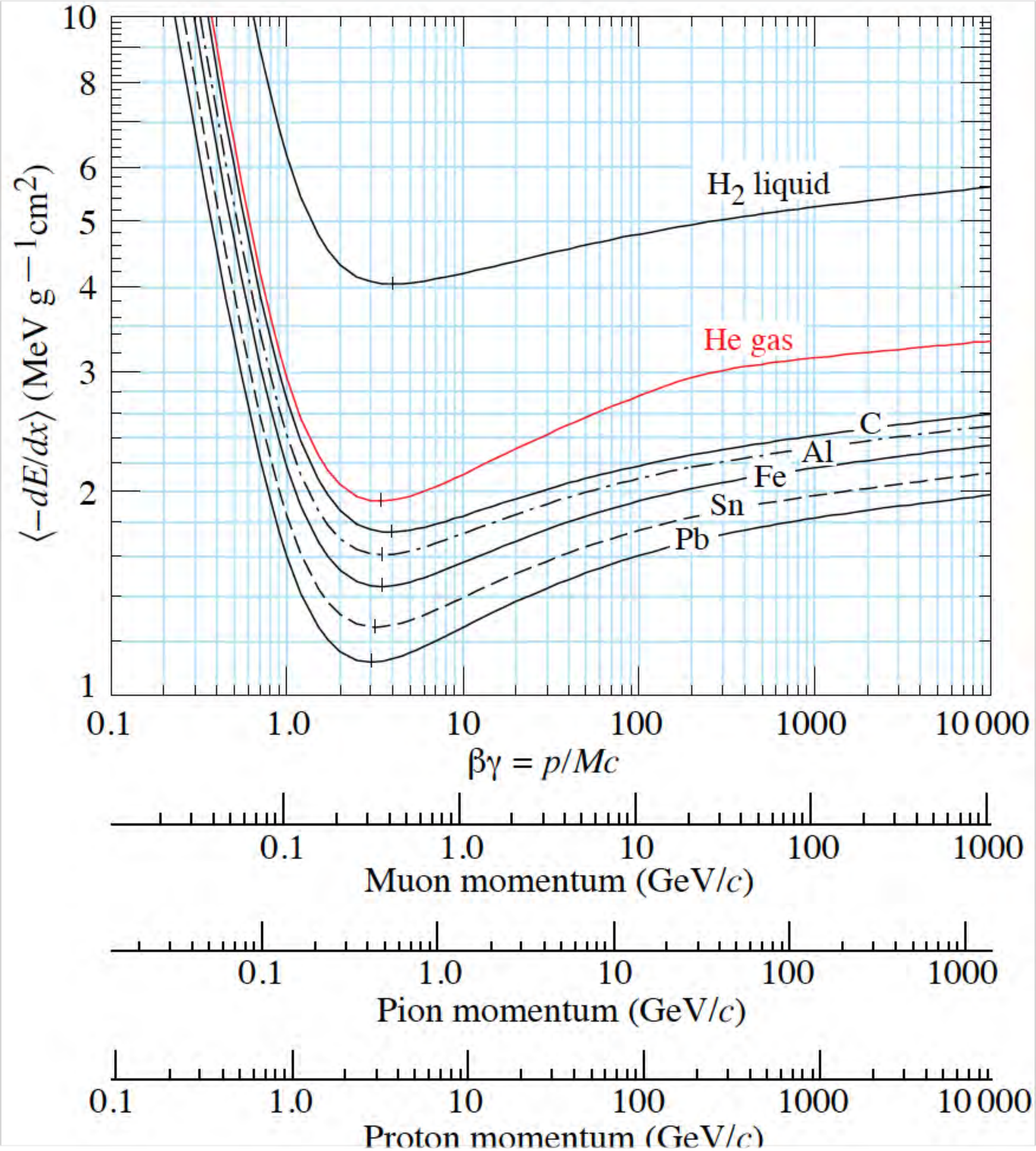
3. **<u>At higher energies</u>**, the energy loss reaches a plateau

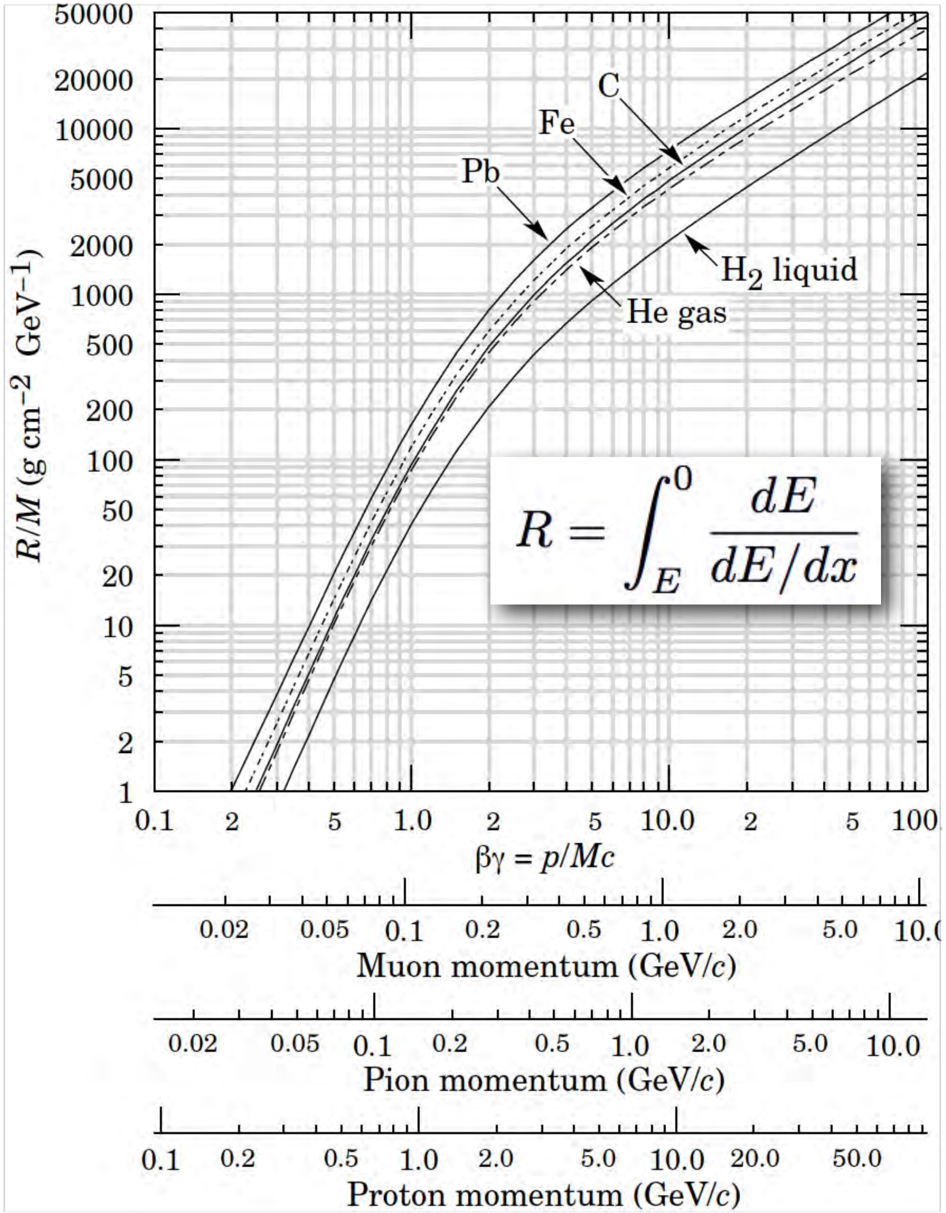


MIP looses ~ 13 MeV/cm
[density of copper: 8.94 g/cm³]



Energy loss and range of charged particles (Bethe-Bloch)





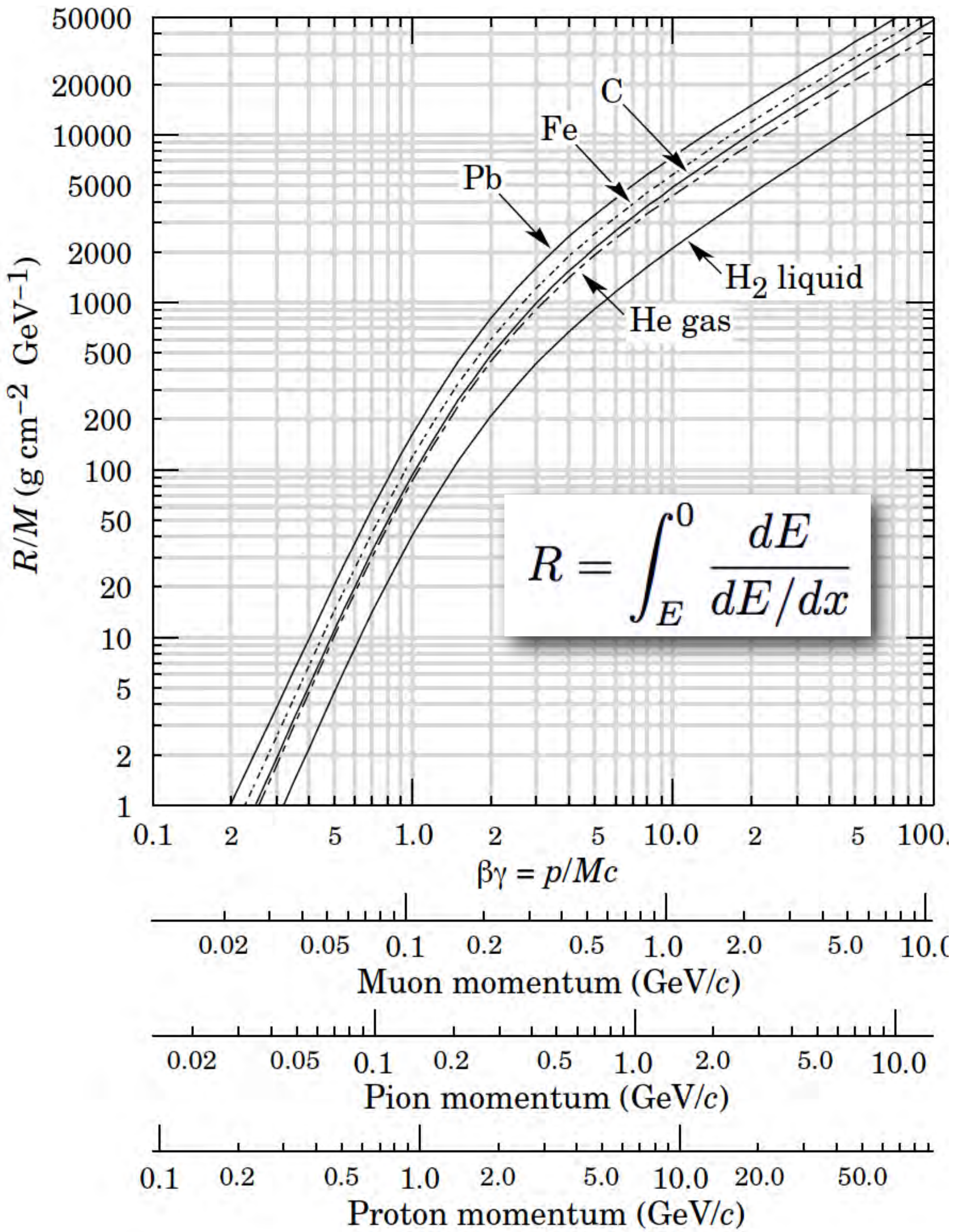
Example for range calculation

- Consider proton with momentum of 1 GeV on a Pb target ($\rho \approx 11.3\ g/cm^3$)

- From the figure, we read:

  $R/M \approx 200\ g\ cm^{-2}\ GeV^{-1}$

  $\Rightarrow R = 200/11.3\ cm \approx 18\ cm$



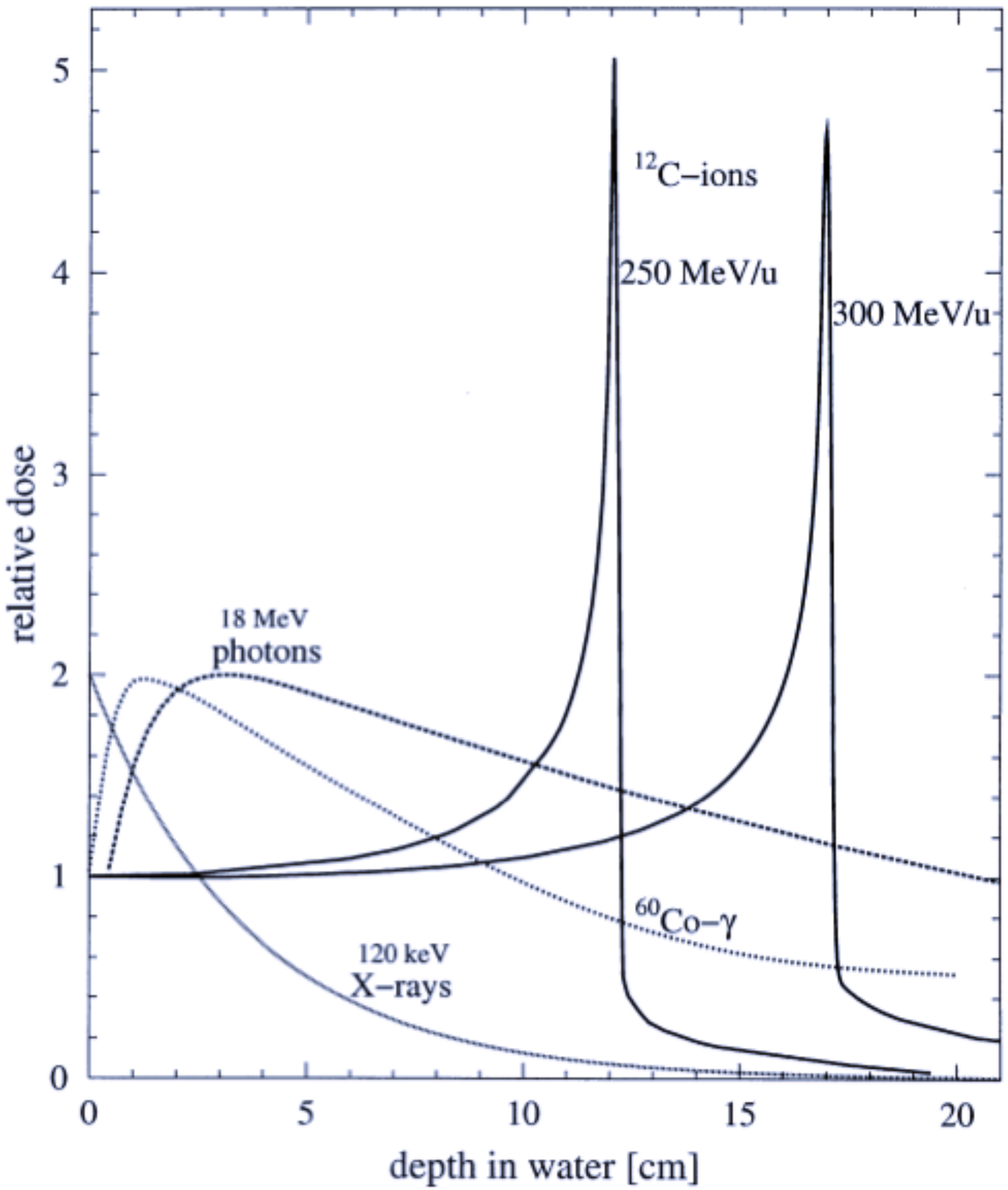
Note:

Figure is only valid for particles which lose energy only by ionization and atomic excitation

- Low energy hadrons
- Muons up to a few 100 GeV

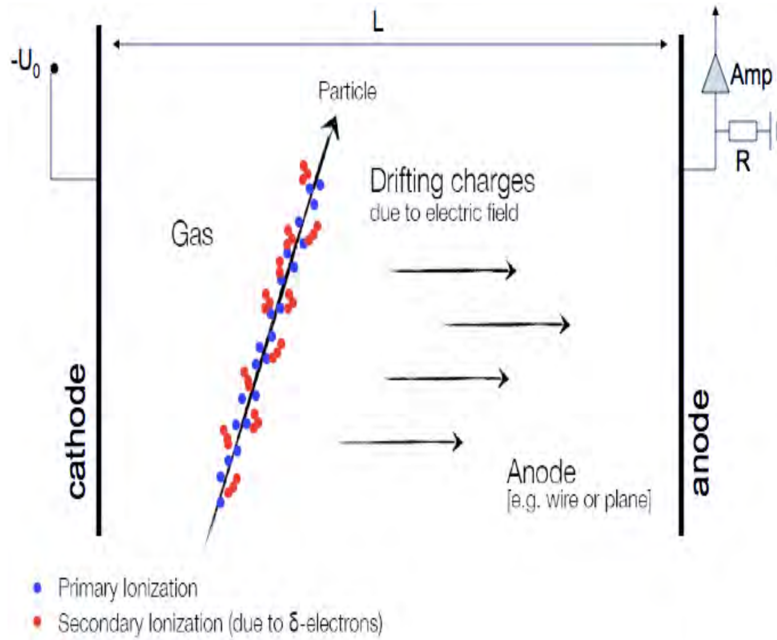
Bragg Peak

- Depth distribution of energy loss for charged particles not uniform
- **Most of the energy is deposited near the end of the range**
  - Bragg Peak
- Application: tumor therapy with protons and heavy ions; HIT
- Adjust beam energy to place Bragg peak inside tumor

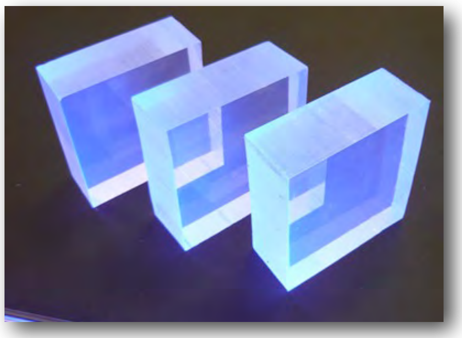


How can we measure energy deposition ?

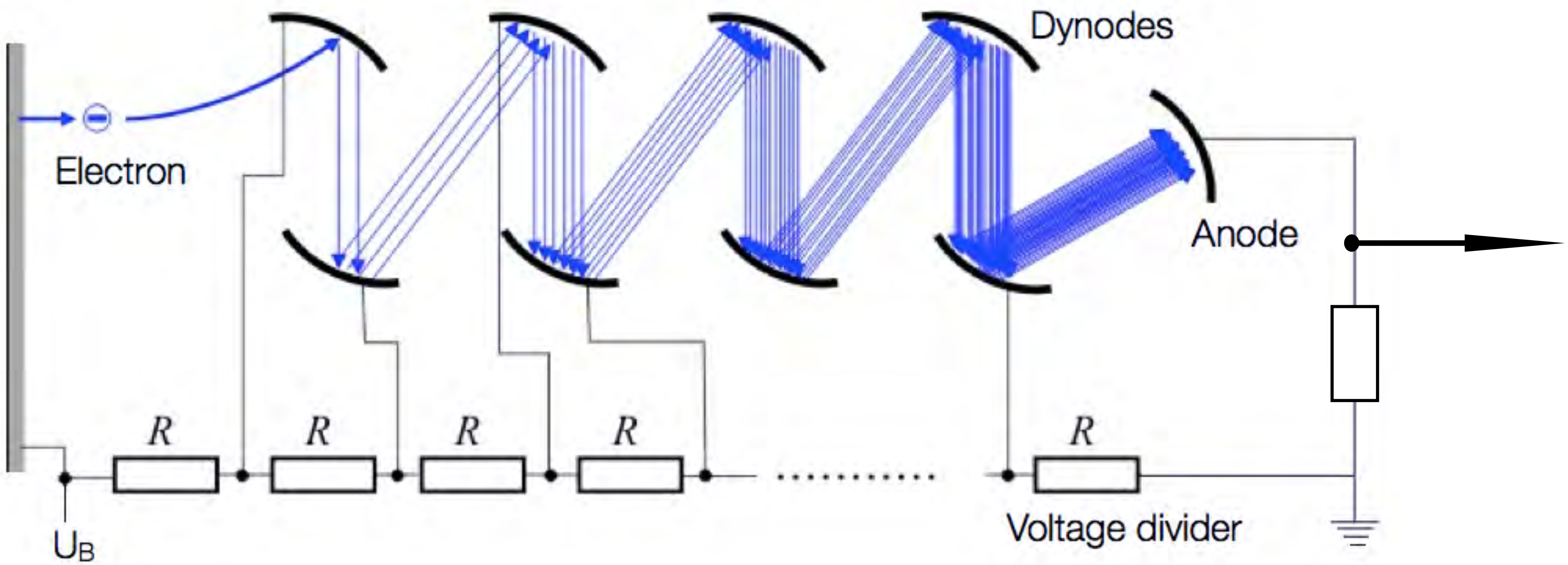
- **Detect ionization** by measuring electric currents in an electric field
  - in gaseous detectors
  - in cryogenic detectors working with liquid nobel gases
  - in semiconductor detectors



- **Detect scintillation light** from atomic excitations
  - Inorganic scintillators
  - Organic scintillators



Photomultiplier: Detection of visible light

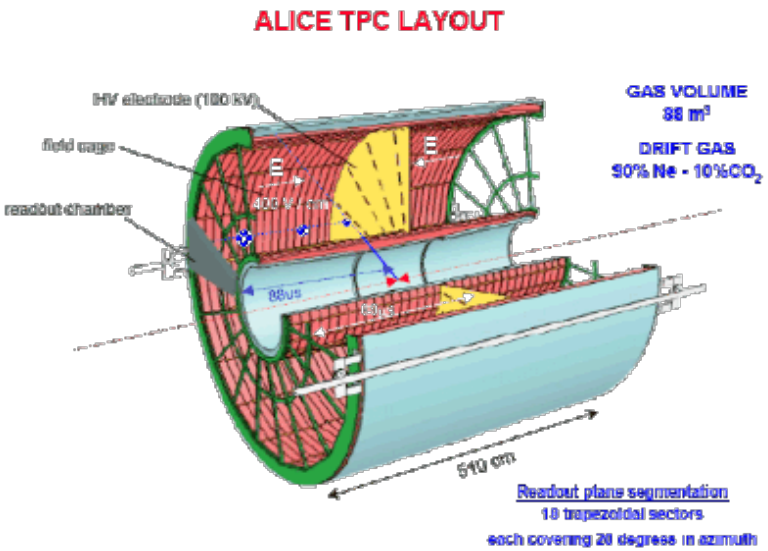


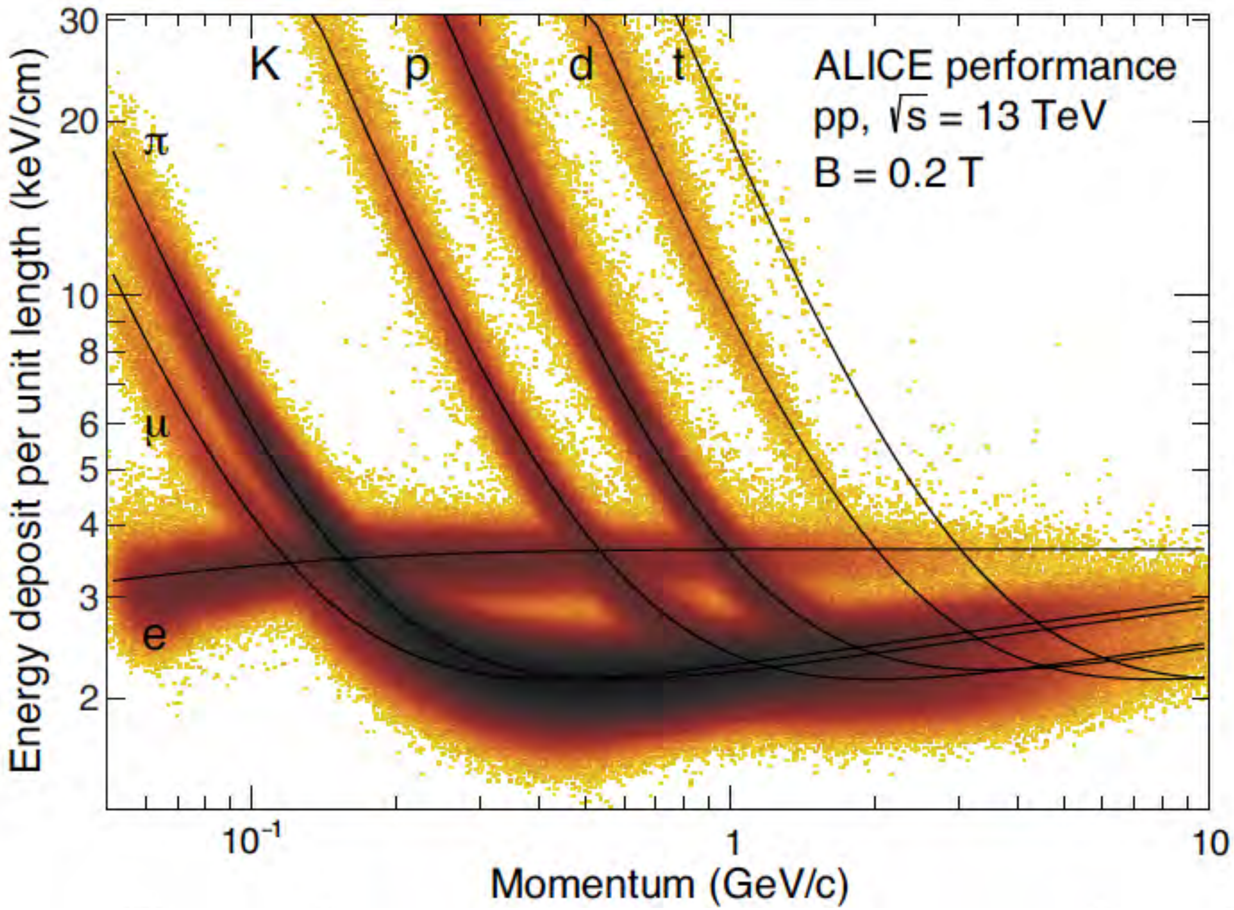
- Scintillation photon absorbed by photo-cathode and photo-electron released: "**Quantum Efficiency**" typically 10-30 %
- Photo-electron is accelerated towards first dynode and produces secondary electrons which are further amplified in the dynode chain
- Typical gain: 10^6 - 10^8; we obtain an electrical signal which is proportional to the number of photons hitting the photo-cathode
- Photo-multipliers have problems working in magnetic fields

Application example: Particle identification with the Alice TPC

$$\beta\gamma = \frac{p}{E}\frac{E}{m} = \frac{p}{m}$$

- Energy loss depends on $\beta\gamma$
- Particle identification by measuring energy loss vs. momentum



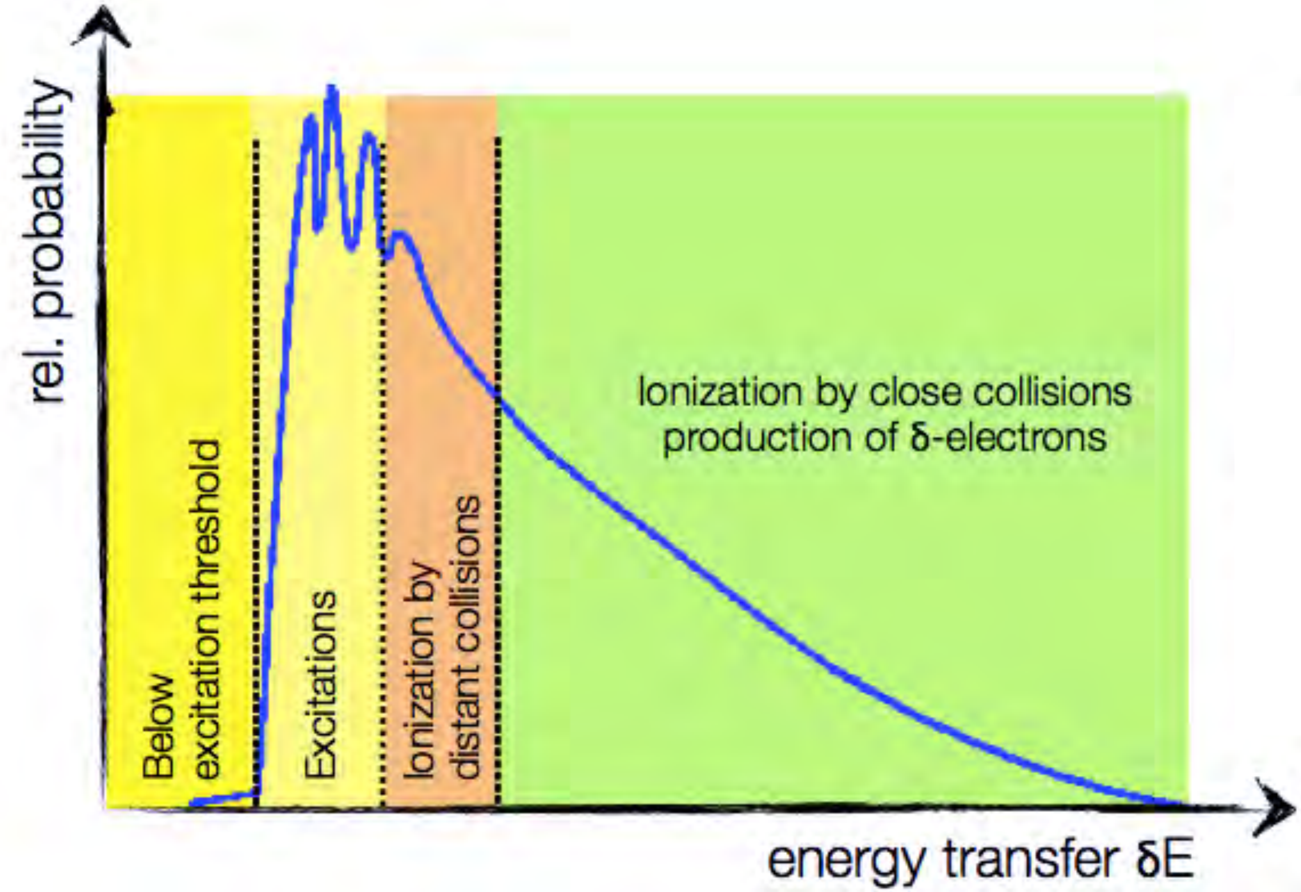


ALICE Collab., ALICE-PUBLIC-2015-004 (2015).

Fluctuations of the energy loss: Energy Straggling

- The Bethe-Bloch formula describes the **mean energy loss,** resulting from a sum of N small energy transfers δE_n during the passage of the particle through the absorber:

$$\Delta E = \sum_{n=1}^{N} \delta E_n$$

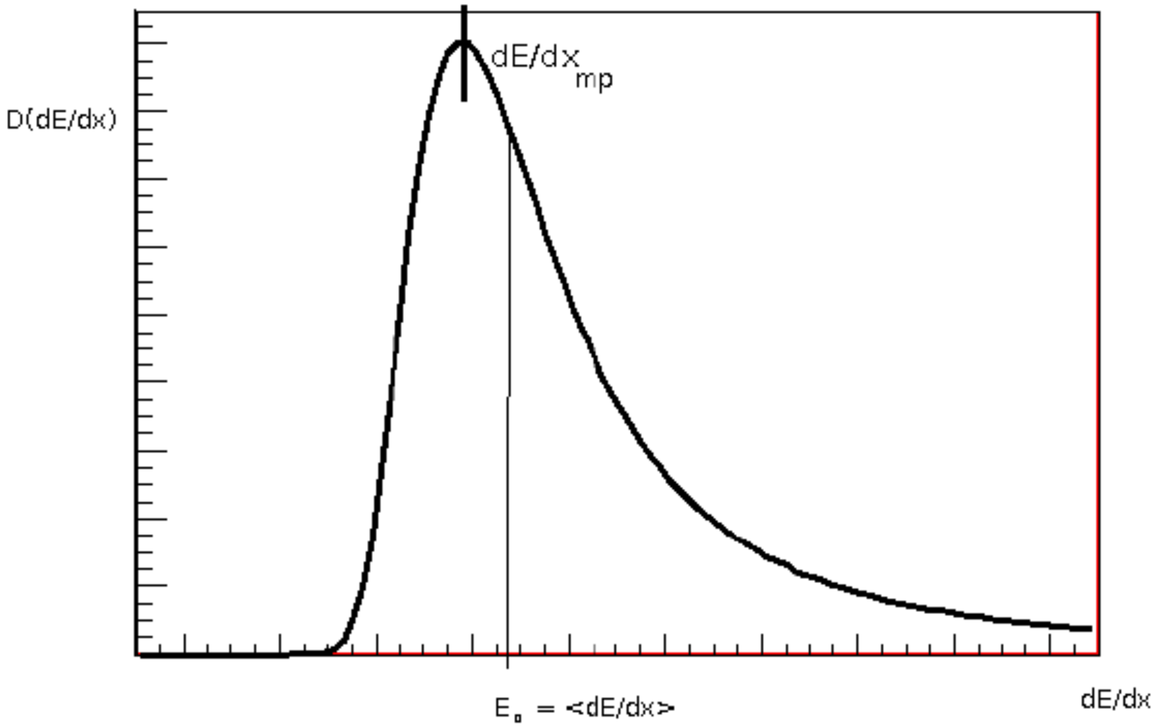


Landau distribution

$$D\left(\frac{dE}{dx}\right) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\underbrace{\frac{\frac{dE}{dx} - \frac{dE}{dx}_{mp}}{\xi}}_{\lambda} + e^{-\lambda}\right)\right)$$

ξ is a material constant

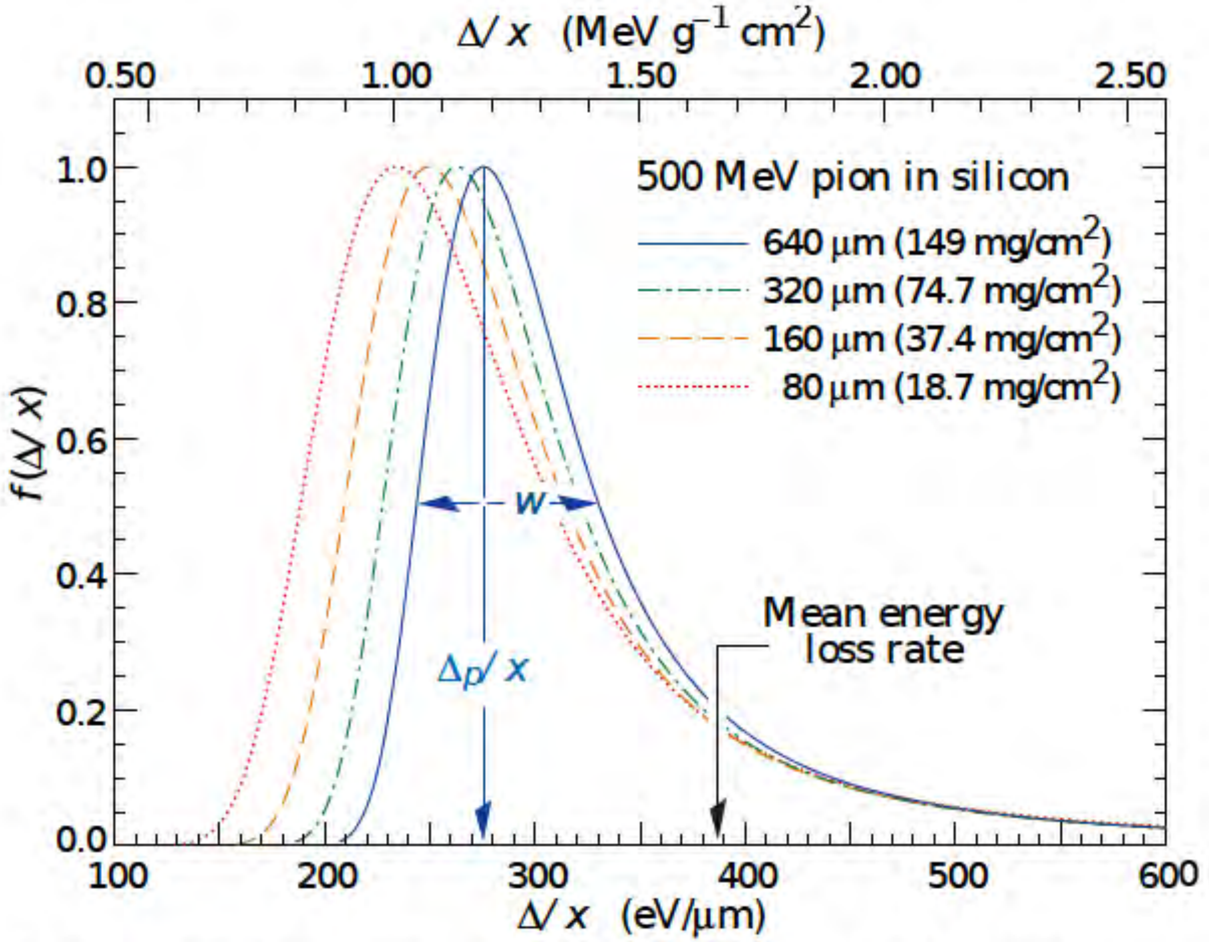
- Describes distribution of energy loss around mean value
- Most probable value smaller than mean value
- Tail towards higher energy losses due to δ electrons
- Not accurate for very thin absorbers



Example: Straggling of pions in silicon

Energy loss distribution normalized to thickness x
with increasing thickness:

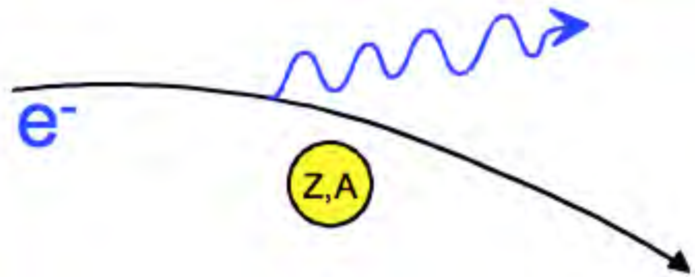
- most probable $\mathrm{d}E/\mathrm{d}x$ shifts to large values
- relative width shrinks
- asymmetry of distribution decreases

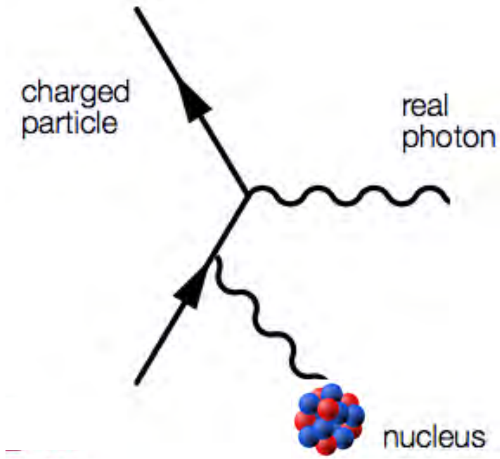


Straggling functions in silicon for 500 MeV pions, normalized to unity at the most probable value Δ_p/x. The width w is the full width at half maximum.

Energy loss for electrons

- From the Alice plot, electrons seem to behave differently
- Two reasons:
  - Bethe-Bloch formula only valid for heavy particles with $m \gg m_e$
  - Radiative energy losses are much more important than for heavy particles

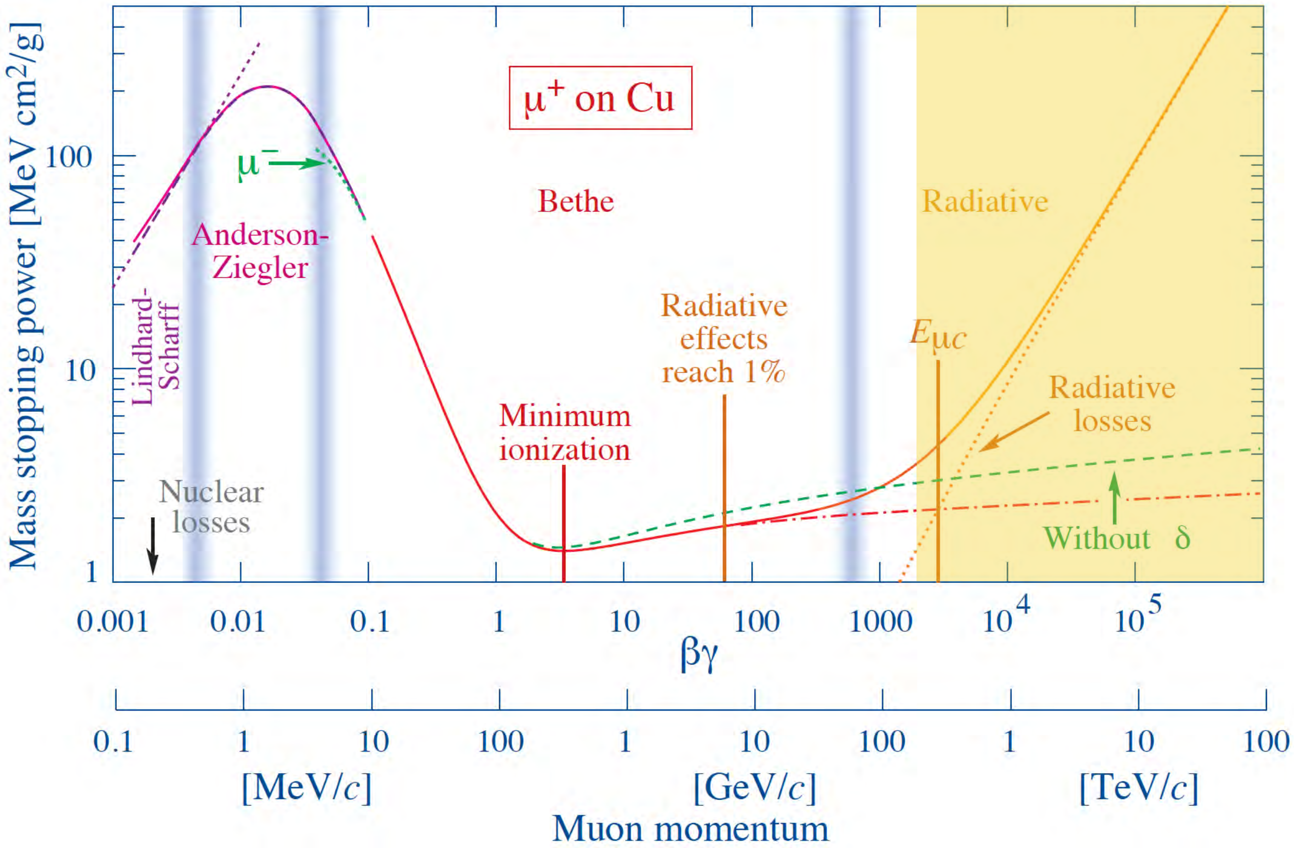




Energy loss via Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A \frac{z^2 Z^2}{A}\left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{\frac{1}{3}}} \propto \frac{E}{m^2}$$

- **Proportional to m^{-2}**
- Ratio of energy loss for electrons and muons at the same energy is $(m_\mu/m_e)^2 \approx 4 \cdot 10^4$



Critical Energy

- The critical energy E_c for a particle is defined as:

$$\left.\frac{dE}{dx}(E_c)\right|_{\text{Brems}} = \left.\frac{dE}{dx}(E_c)\right|_{\text{Ion}}$$

- Total energy loss:

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

- For electrons approximately:

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

$$E_c^{\text{Sol/Liq}} = \frac{610\text{ MeV}}{Z+1.24}$$

- Example for copper (Z=29): $E_c \approx 610/30 \approx 20$ MeV
  - An electron of 20 MeV traversing a thin copper foil loses equal amounts of energy by ionization and by Bremsstrahlung

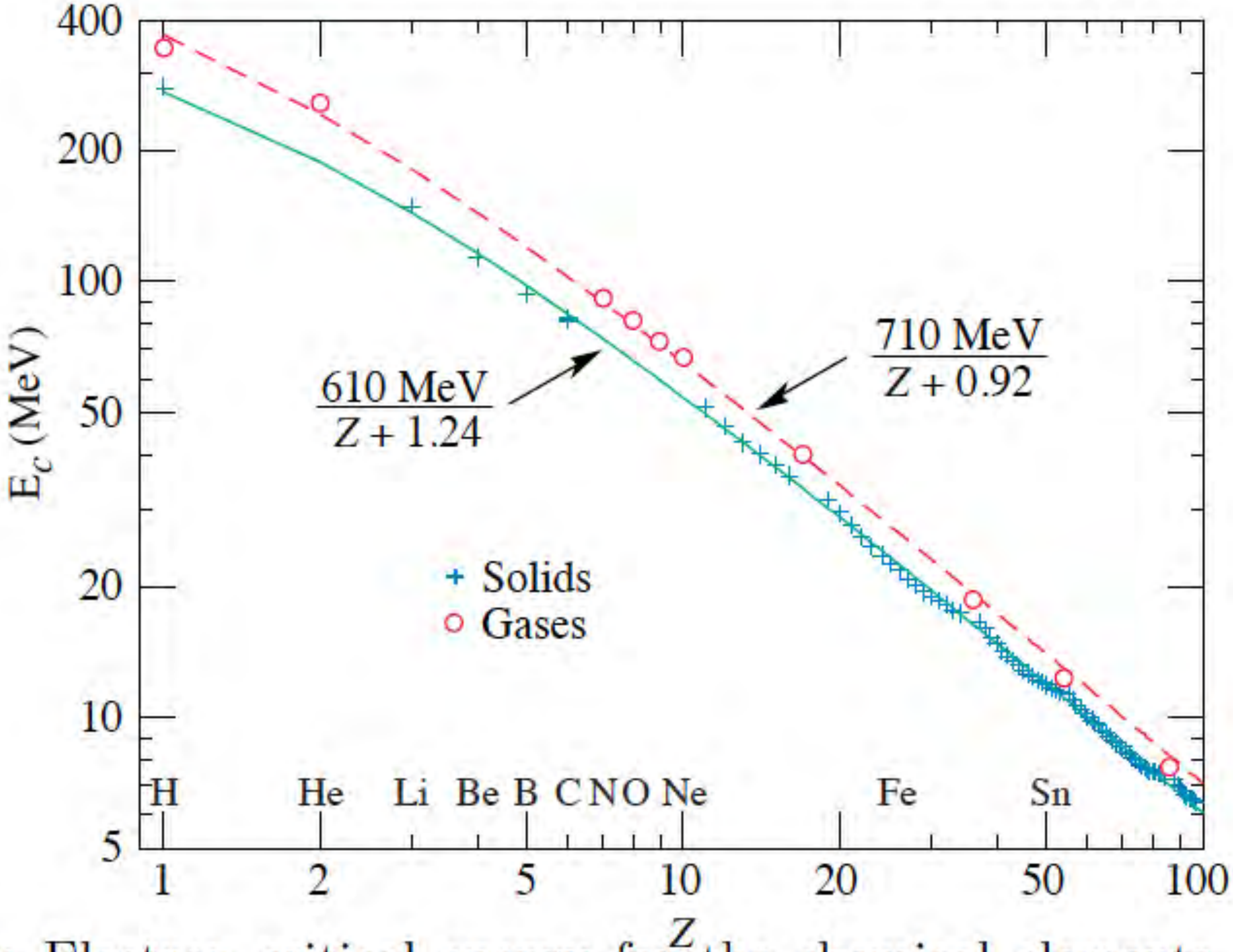


Figure 32.14: Electron critical energy for the chemical elements, using Rossi's definition [2]. The fits shown are for solids and liquids (solid line) and gases (dashed line). The rms deviation is 2.2% for the solids and 4.0% for the gases.

Radiation Length

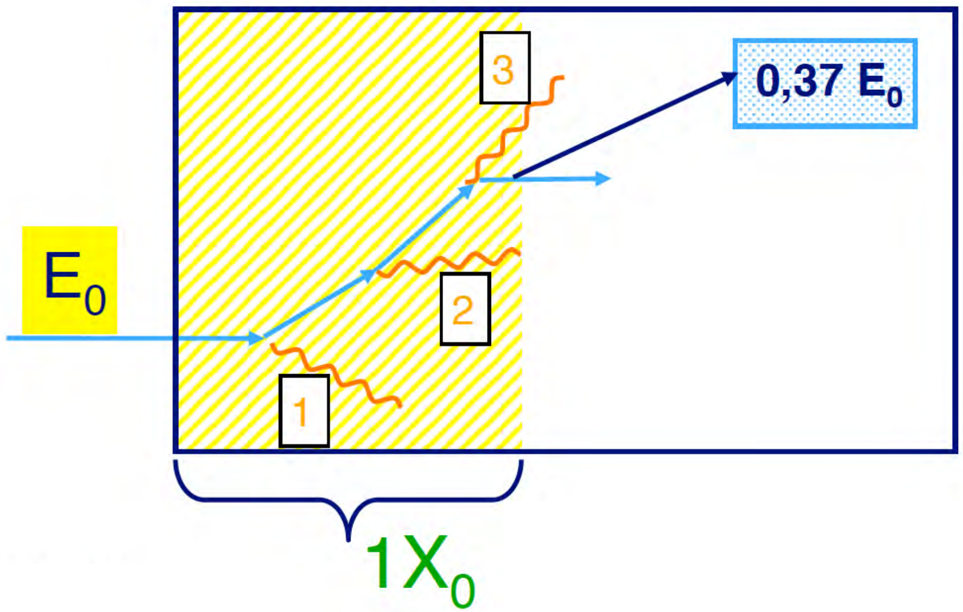
- Energy loss via Bremsstrahlung for electrons:

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E \ln \frac{183}{Z^{\frac{1}{3}}}$$

$$\frac{dE}{dx} = \frac{E}{X_0} \qquad \text{with} \quad X_0 = \frac{A}{4\alpha N_A\, Z^2 r_e^2 \,\ln \frac{183}{Z^{\frac{1}{3}}}}$$

$$E = E_0 e^{-x/X_0}$$

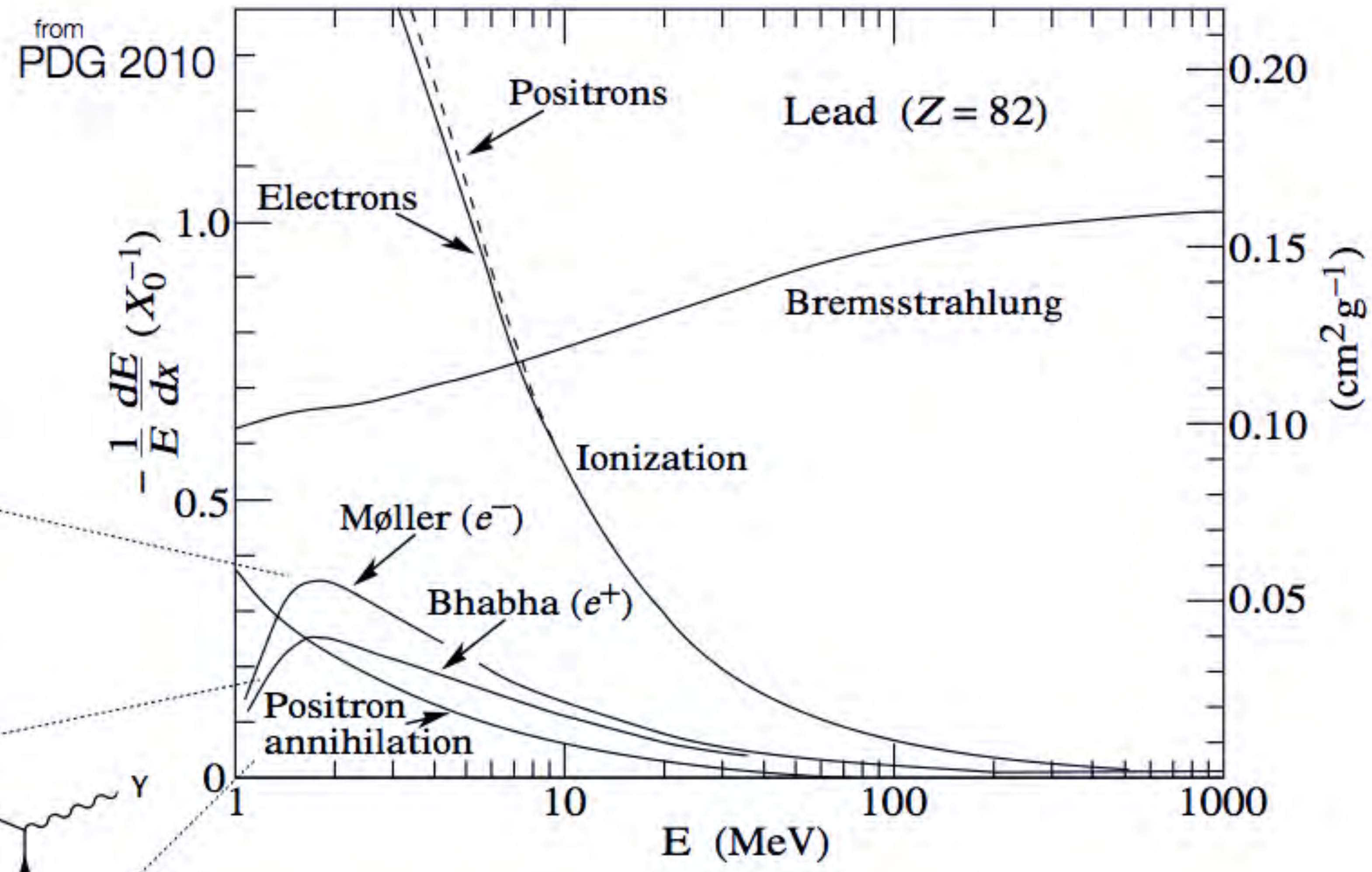
- X_0 is called "**radiation length**"
- After passing one X_0, the energy of the electron **is reduced by a factor of 1/e**

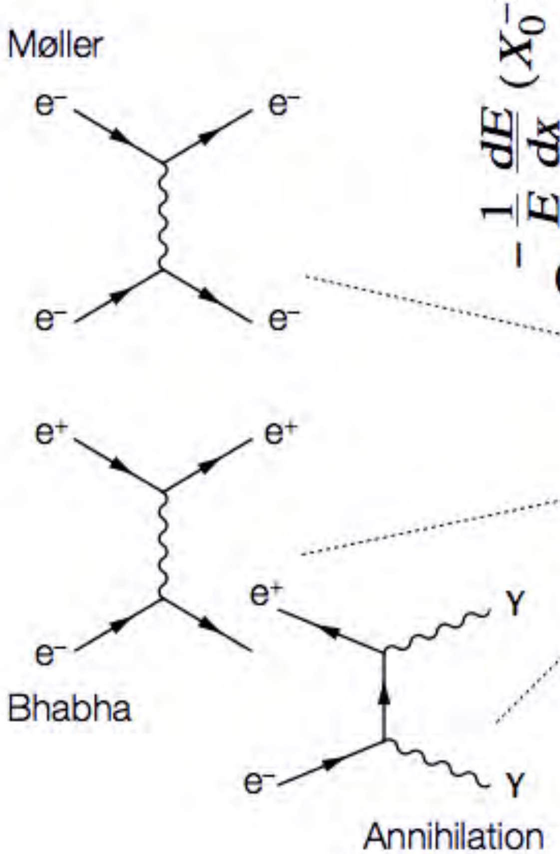


Radiation length and critical energy

Material	Z	X_0 (cm)	E_c (MeV)
H_2 Gas	1	700000	350
He	2	530000	250
Li	3	156	180
C	6	18.8	90
Fe	26	1.76	20.7
Cu	29	1.43	18.8
W	74	0.35	8.0
Pb	82	0.56	7.4
Air	7.3	30000	84
SiO_2	11.2	12	57
Water	7.5	36	83

Energy loss for electrons and positrons

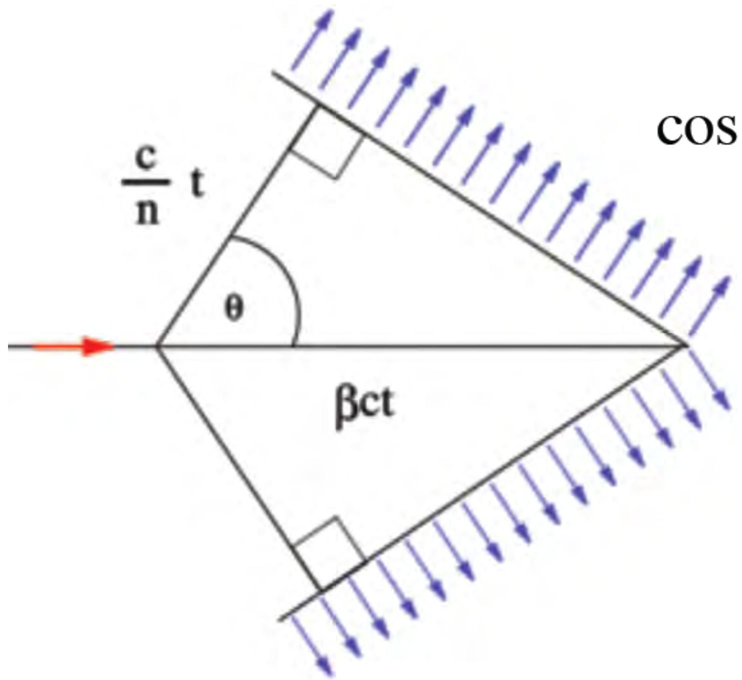




Fractional energy loss per radiation length in lead as a function of electron or positron energy

Cherenkov Radiation

- A charged particle radiates photons when traversing a medium, if its velocity is larger than the local phase velocity v_g of light in the material
- Index of refraction: $n=c/v_g$
- The light is emitted in a cone with a characteristic opening angle, the Cherenkov angle θ, which depends on the velocity of the particle and the index of refraction:



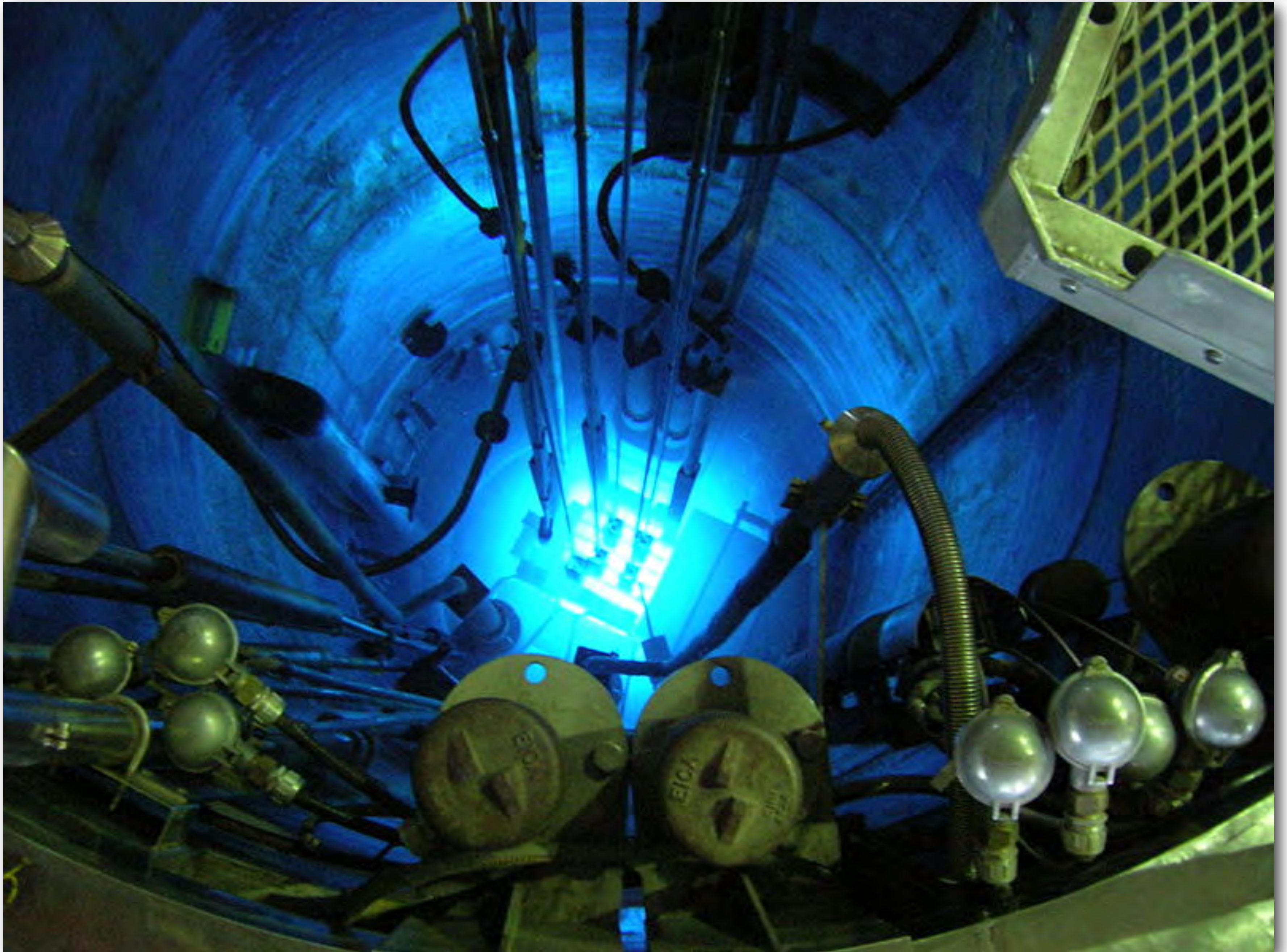
$$\cos\theta_c = \frac{1}{n\beta}$$

Cherenkov threshold:

$$v_{th} \geq \frac{c}{n} \Rightarrow \beta_{th} \geq \frac{1}{n}$$

- **Idea: we can use the Cherenkov effect to distinguish particles with different velocity. If we know the momentum of the particle, we can determine its mass**

Cherenkov light from a nuclear reactor



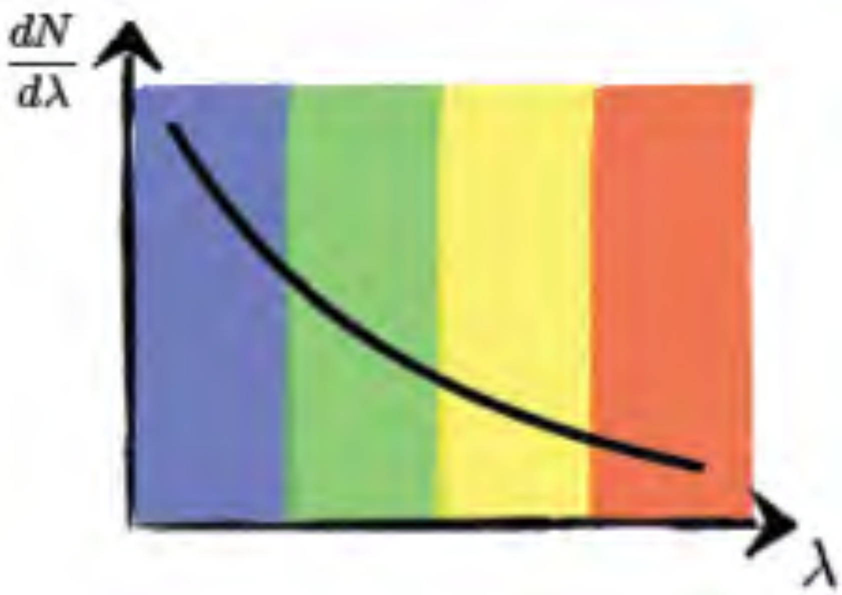
Emission spectrum

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_C$$

Integrate over sensitivity range:
[for typical Photomultiplier]

$$\frac{dN}{dx} = \int_{350\text{ nm}}^{550\text{ nm}} d\lambda \frac{d^2N}{d\lambda dx}$$

$$= 475\, z^2 \sin^2\theta_C \text{ photons/c}$$



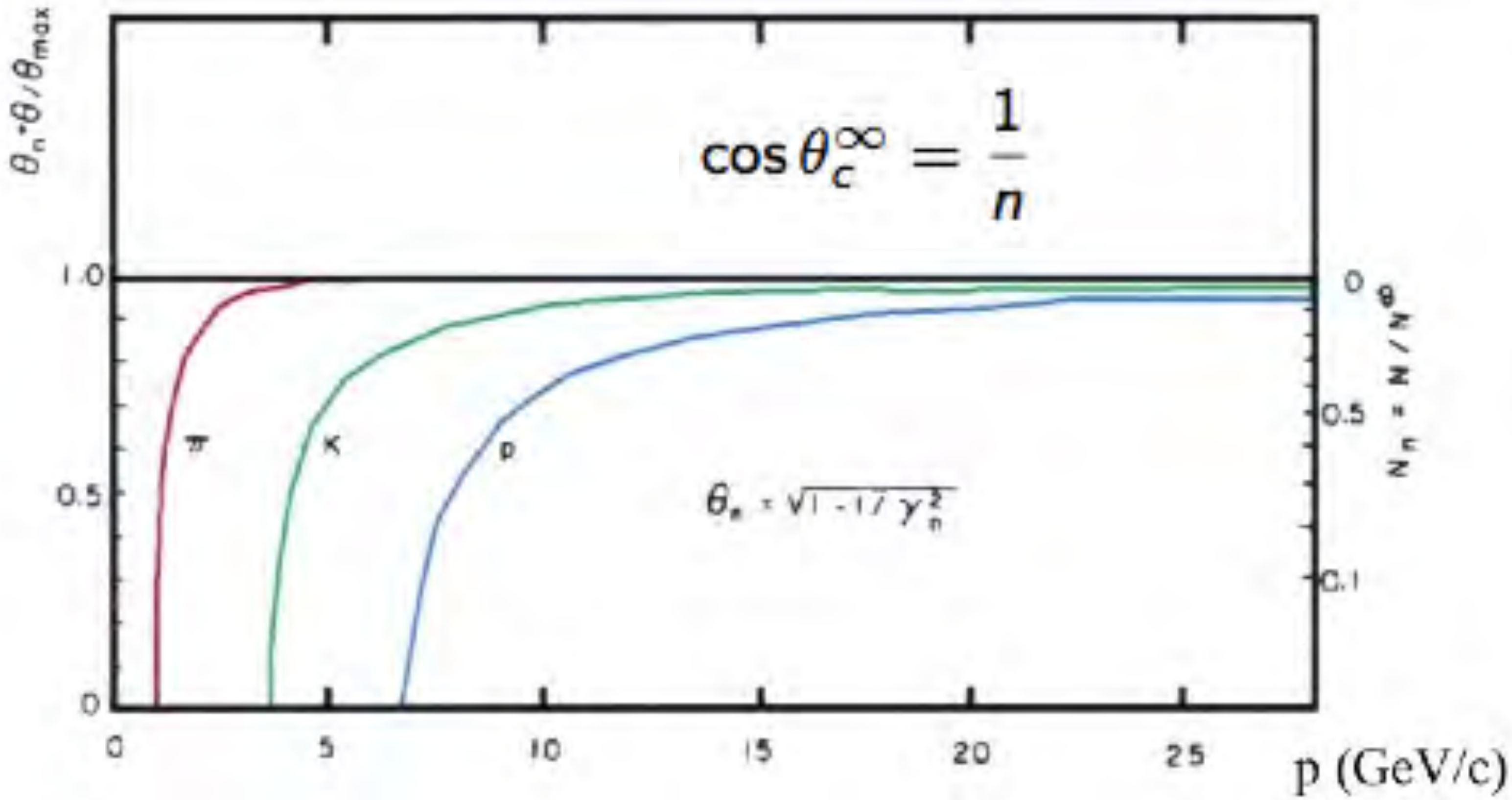
- Most of the light is emitted in the blue / ultraviolett region
- Needs to be considered when thinking about detecting Cherenkov photons
  - Glas (photomultiplier window) absorbs UV light !

Examples for Cherenkov Radiator Materials

Medium	n	β_{thr}	θ_{max} [β=1]	N_{ph} [eV^{-1} cm^{-1}]
Air	1.000283	0.9997	1.36	0.208
Isobutane	1.00127	0.9987	2.89	0.941
Water	1.33	0.752	41.2	160.8
Quartz	1.46	0.685	46.7	196.4

- Gases have a very high β_{thr}, due to their low density
  - Suitable for electron identification
  - Drawback: small number of Cherenkov photons, need large radiator path

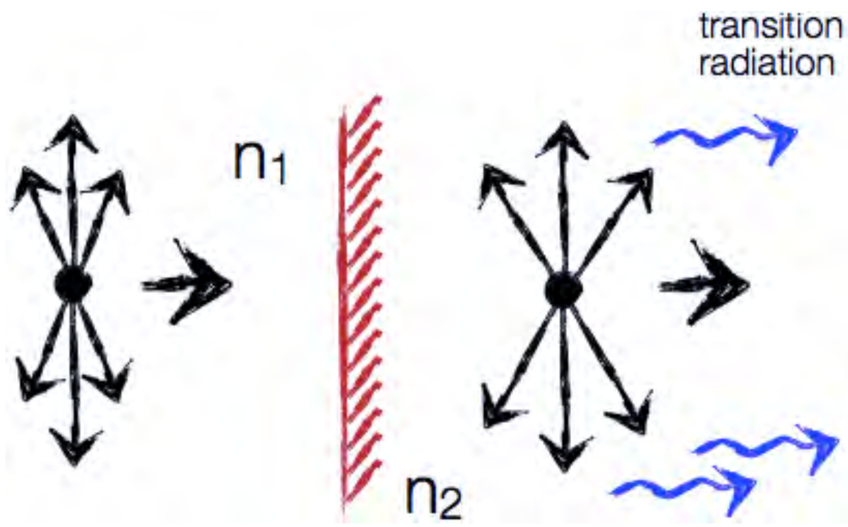
Momentum dependence of Cherenkov angle



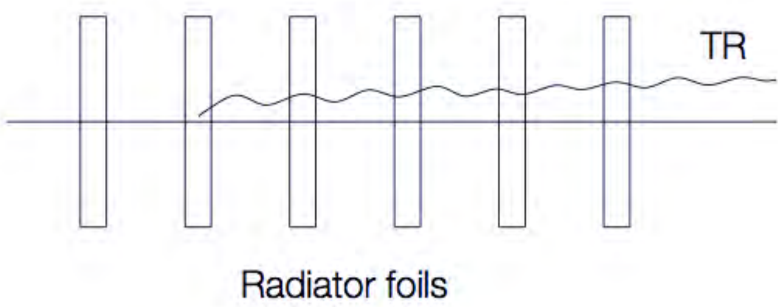
- Particles of different mass have different Cherenkov thresholds and reach the asymptotic region at different momenta
- If we know the momentum, we can identify the particle type
  - Threshold Cherenkov detectors
  - Ring imaging Cherenkov detectors
    - Need to select material with suitable index of refraction for the desired momentum region

Transition radiation

- Transition radiation occurs when ultra relativistic particles pass the boundary between two media with different indices of refraction
  - Reason: re-arrangement of E-field
  - Radiated power:



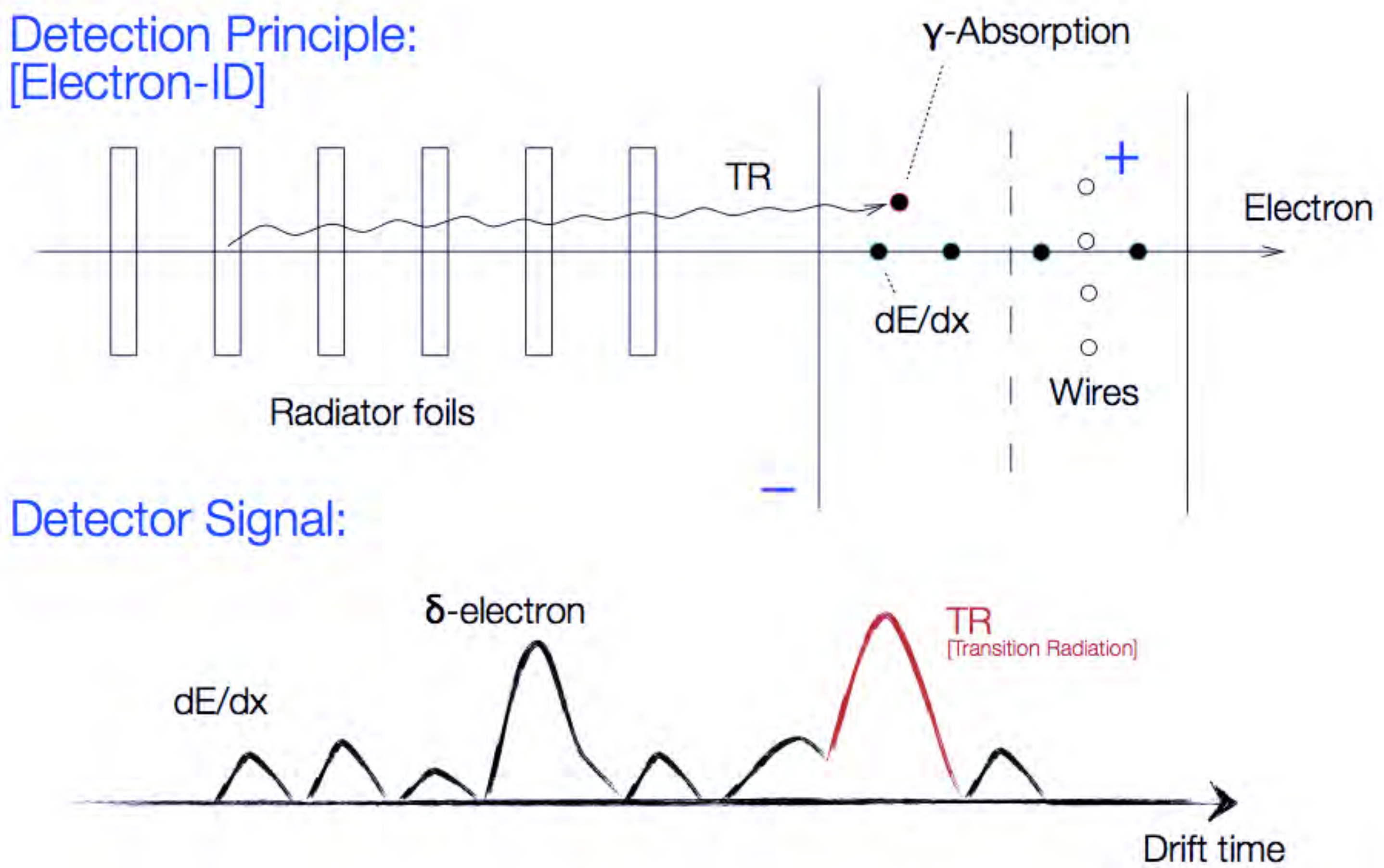
$$\frac{dP}{d(\hbar\omega)} \propto \alpha \cdot \frac{E}{mc^2}$$



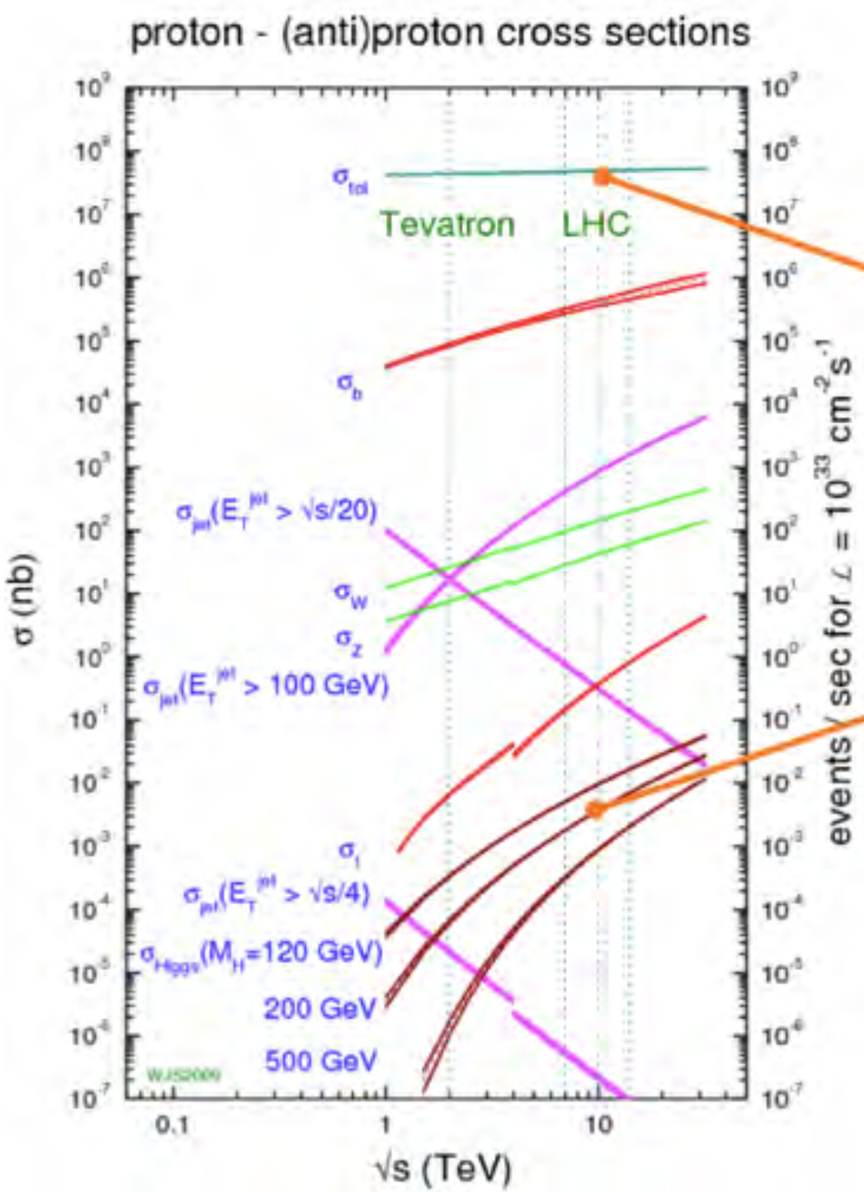
- “white” spectrum (no ω dependence)
- proportional to E/m = γ
- proportional to α
  - times the number of radiator foils

Application: Electron identification

- Hardon/electron discrimination via transition radiation
  - For fixed momentum, electrons have much larger E/m than hadrons
  - We need to detect X-rays via compton scattering or photo effect
  - This happens near the entrance of the detector, because the X-rays are quickly absorbed
  - Measuring the drift time, we can discriminate the X-rays from ionization due to the passing electron



Importance of particle identification



40 millions beam crossing/s
1 billion collisions/s

10^8 events/s

$\sim 10^{10}$

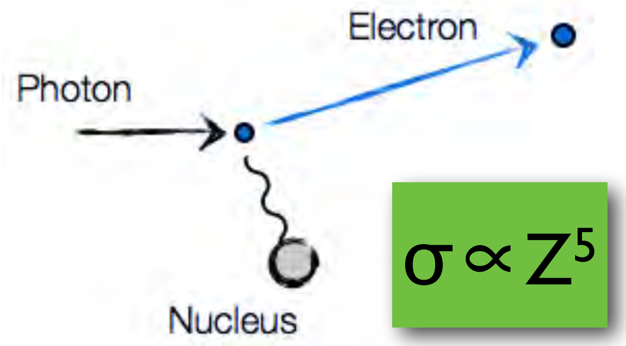
10^{-2} events/s ~
10 events/min

[m_H ~ 120 GeV]

0.2% H → γγ
1.5% H → ZZ

Interaction of photons

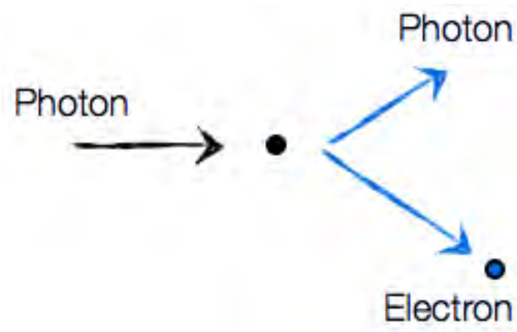
- **Photo effect**
  - The photon is absorbed by by an atom and an electron is emitted
  - The energy of the electron has a fixed value : $\mathbf{E_e=h\nu - I_b}$ (binding energy of the electron)



$$E_e = h\nu - I_b$$

$$\sigma \propto Z^5$$

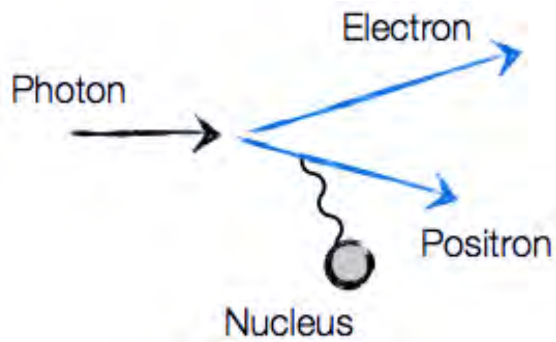
- **Compton effect**
  - Elastic scattering of photons on electrons, with scattering angle θ between ingoing and outgoing photon



$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)}$$

$$T_e = \frac{\frac{E_\gamma^2}{m_e c^2}(1 - \cos\theta)}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)}$$

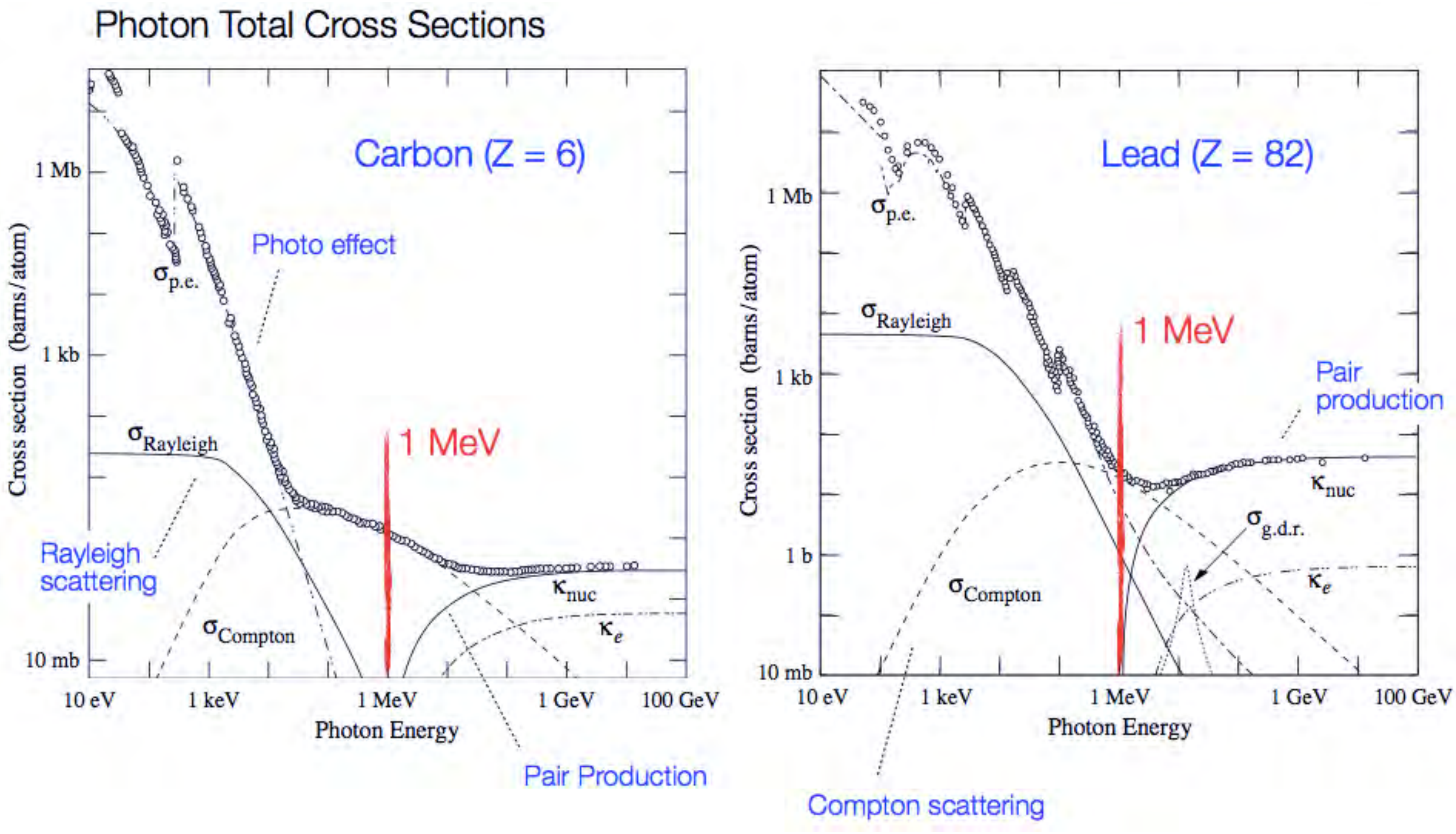
- **Pair production**
  - The photon converts in the field of nucleus into an electron-positron pair



Threshold:

$$E_\gamma \geq 2m_e c^2(1+m_e/m_n)$$

Energy dependence: pair production dominates for high energy photons

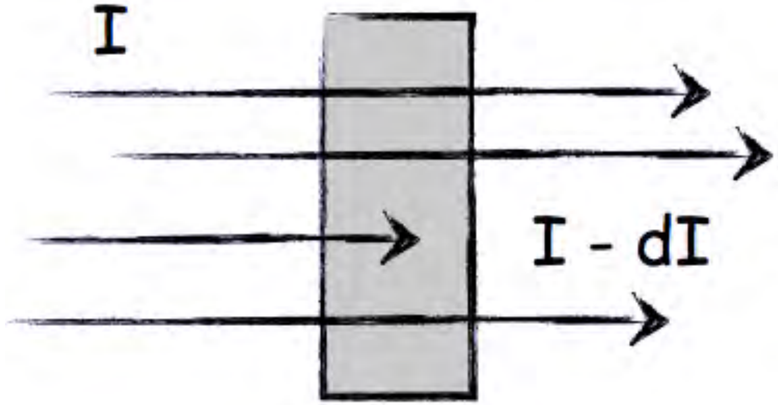


Absorption of photons

- Consider beam of mono energetic photons with intensity I hitting an absorber.

- A **single interaction** (photo-effect, Compton scattering or pair production) will remove the photon from the beam
  - After Compton scattering, there is still a photon left, but with different energy

- In contrast to the interaction of charged particles, there is a non-zero probability, that even a very thick absorber cannot stop all the incident photons



$$dI = -\mu \, I \, dx$$

[μ: absorption coefficient]

→ Beer-Lambert law:

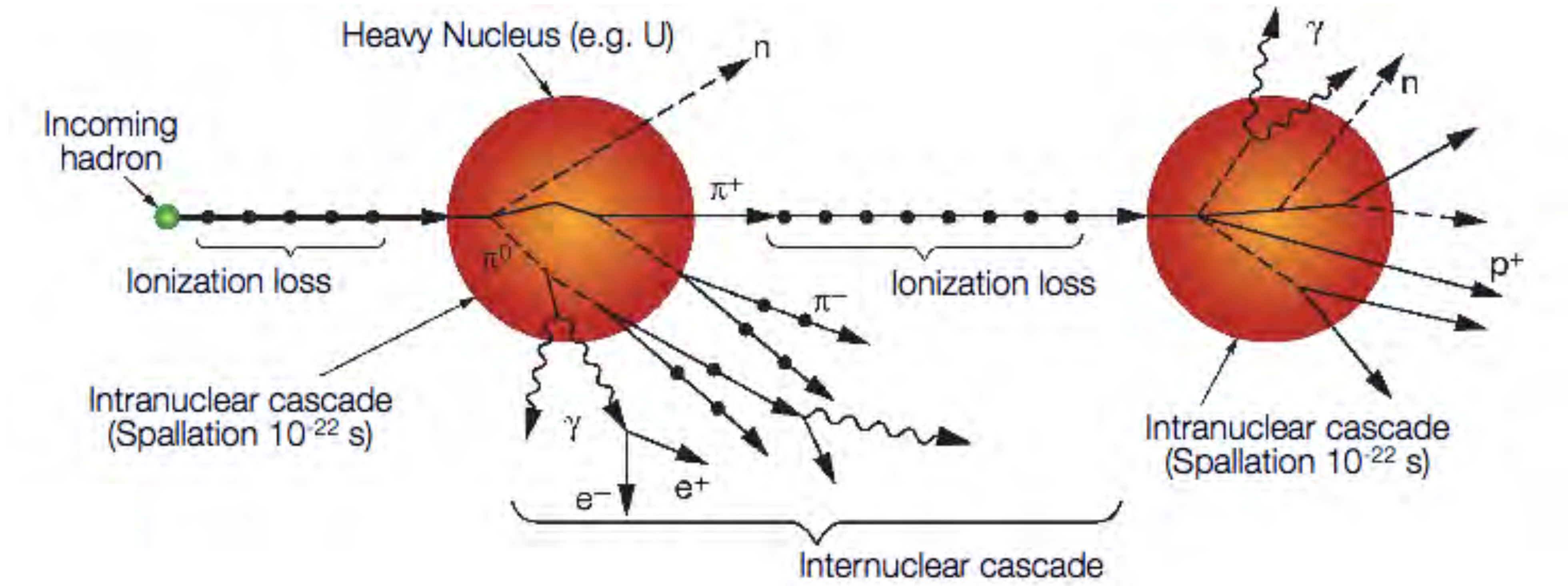
$$I(x) = I_0 e^{-\mu x}$$

with $\lambda = 1/\mu = 1/n\sigma$

[mean free path]

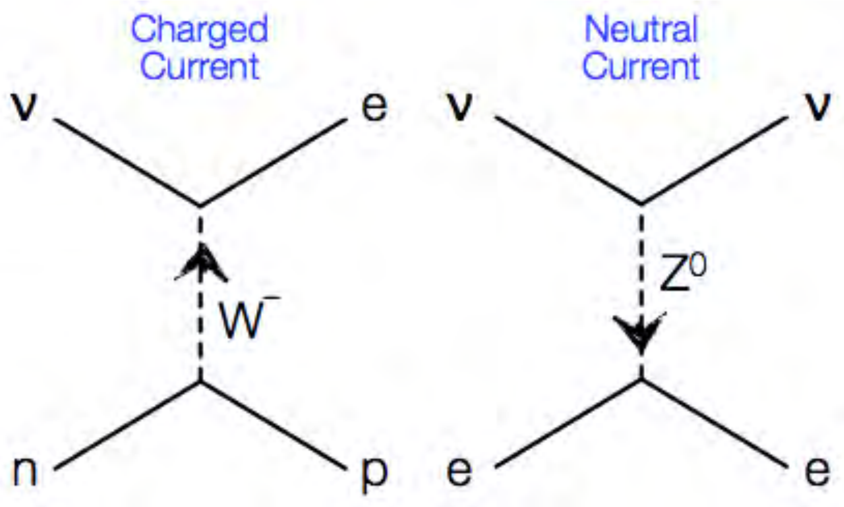
Hadronic interactions

- Dominant contribution to stopping of high energy hadrons
- Intranuclear cascade, leading to spallation
- Internuclear cascade, development of hadronic shower



Weak interaction

- Only relevant for neutrinos
- Charged and neutral currents
- Extremely small cross sections



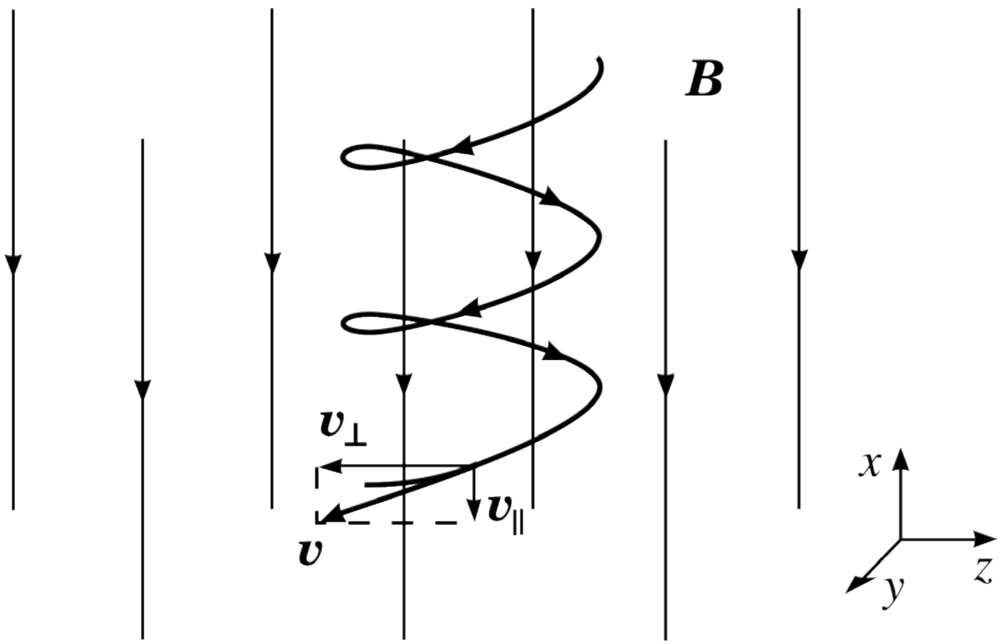
Neutrino nucleon x-Section:
[examples]

10 GeV neutrinos: $\sigma = 7 \cdot 10^{-38}$ cm^2/nucleon

Interaction probability for 10 m Fe-target: $R = \sigma \cdot N_A\,[mol^{-1}/g] \cdot d \cdot \rho = 3.2 \cdot 10^{-10}$
with $N_A = 6.023 \cdot 10^{23}\,g^{-1}$; $d = 10$ m; $\rho = 7.6\,g/cm^3$

Solar neutrinos [100 keV]: $\sigma = 7 \cdot 10^{-45}$ cm^2/nucleon

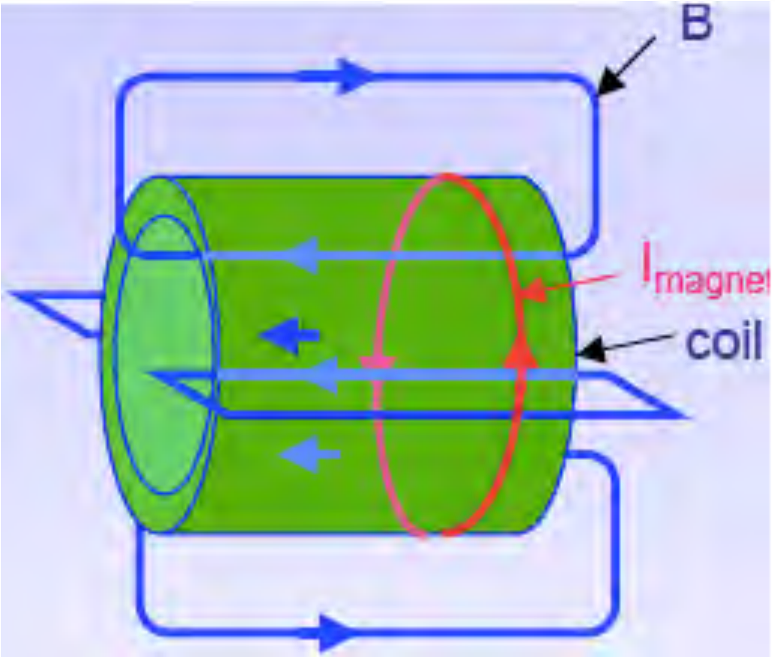
Interaction probability for earth: $R = \sigma \cdot N_A\,[mol^{-1}/g] \cdot d \cdot \rho \approx 4 \cdot 10^{-14}$
with $N_A = 6.023 \cdot 10^{23}\,g^{-1}$; $d = 12000$ km; $\rho = 5.5\,g/cm^3$

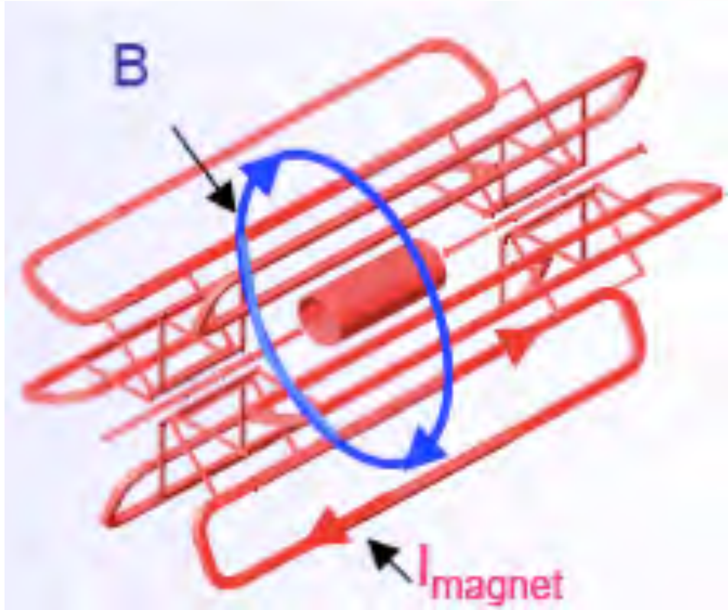


Tracking and momentum measurement

- measure track in magnetic field: determine momentum of charged particles
- identify secondary vertices: heavy flavor decays
- separation of multiple interactions in single bunch crossing

Field geometries for 4π detectors (colliders)





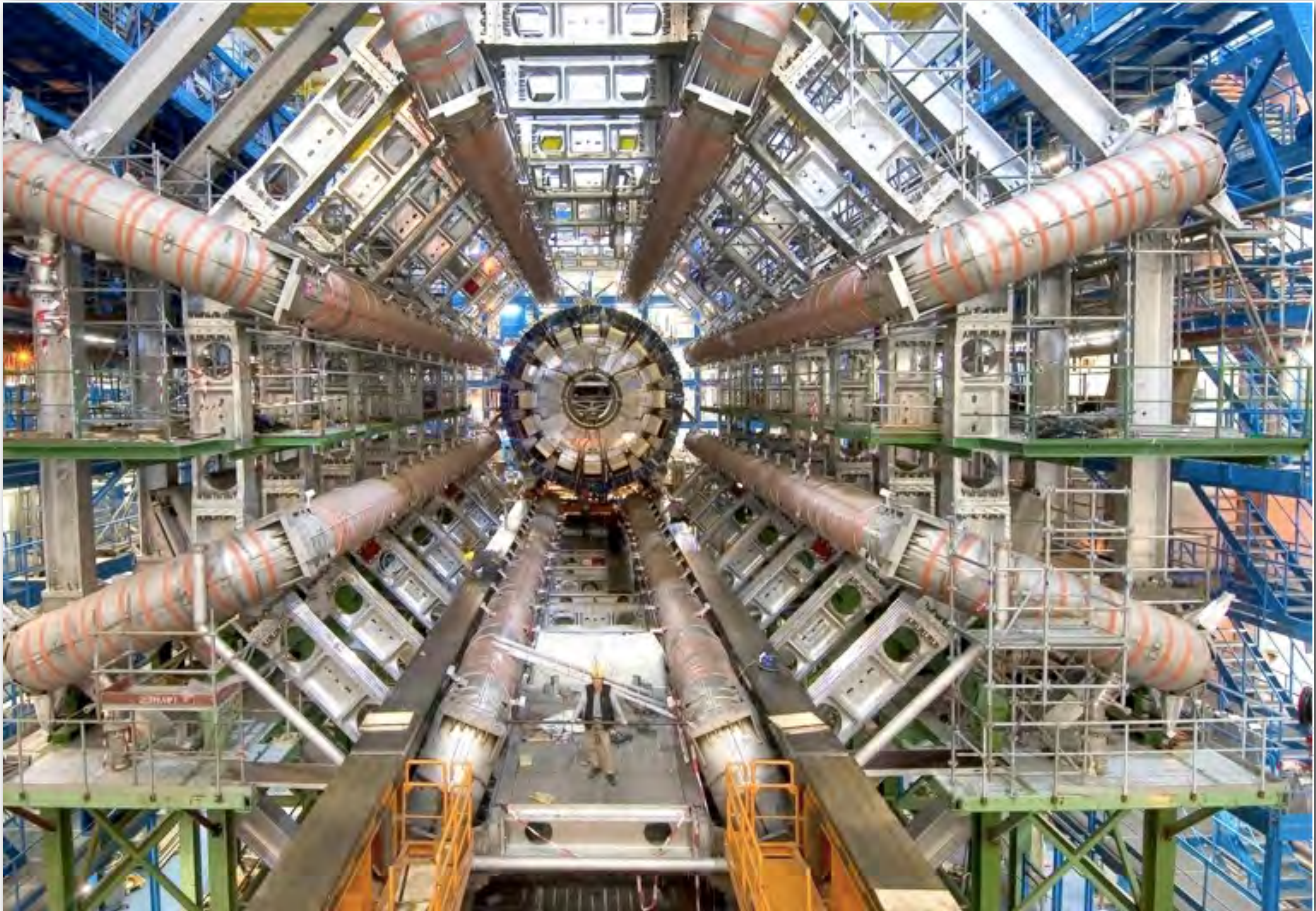
- **<u>Solenoid</u>**: field lines parallel to beam direction
- The track of a charged particle represents a helix
- Needs magnetic flux return (iron)

<u>Examples</u>:
•Delphi: SC, 1.2 T, 5.2 m, L 7.4 m
•L3: NC, 0.5 T, 11.9 m, L 11.9 m
•CMS: SC, 4 T, 5.9 m, L 12.5 m

- **<u>Toroid</u>**: field lines are circles in a plane perpendicular to beam direction
- The track of a charged particle represents a helix
- Needs magnetic flux return (iron)

<u>Example</u>:
•ATLAS: Barrel air toroid, SC, ~1 T, 9.4 m, L 24.3 m

ATLAS Toroid



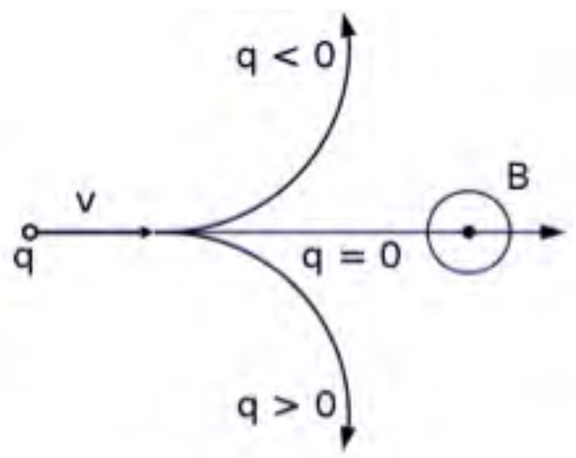
Momentum determination

- Lorentz force = centrifugal force
  - determine momentum from radius of curvature
- **Charge** from orientation of helix

$$\vec{F} = q\vec{v} \times \vec{B}$$

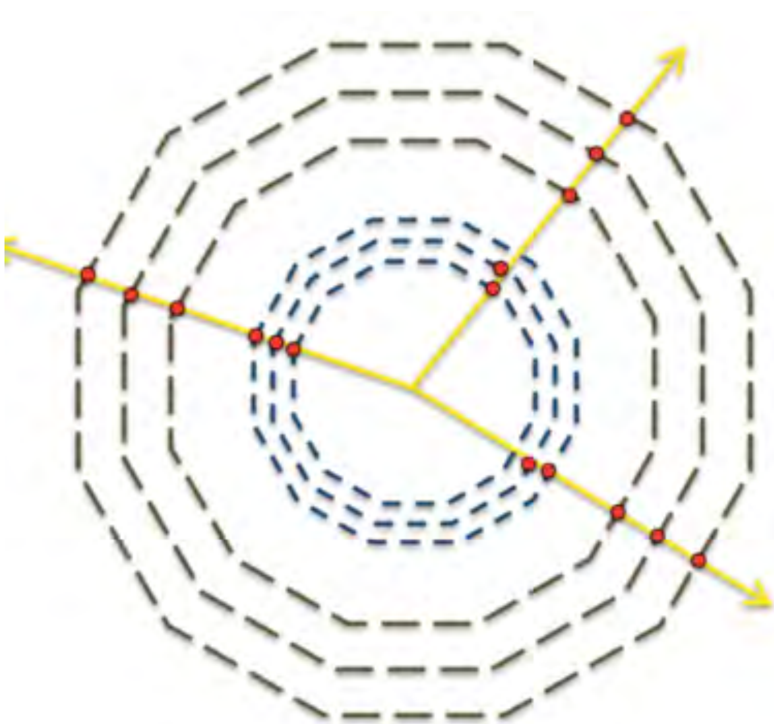
$$\frac{mv^2}{r} = qvB$$

$$p\left[\frac{GeV}{c}\right] = 0.3\ \mathrm{B[T]\ R[m]}$$

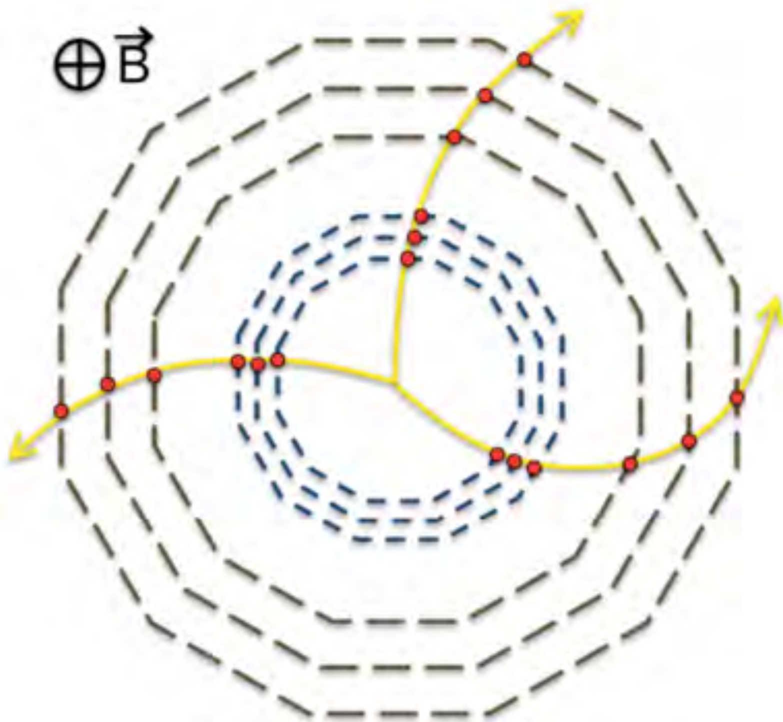


Deflection in solenoidal field geometry

No field



B-field ⊥ to projection



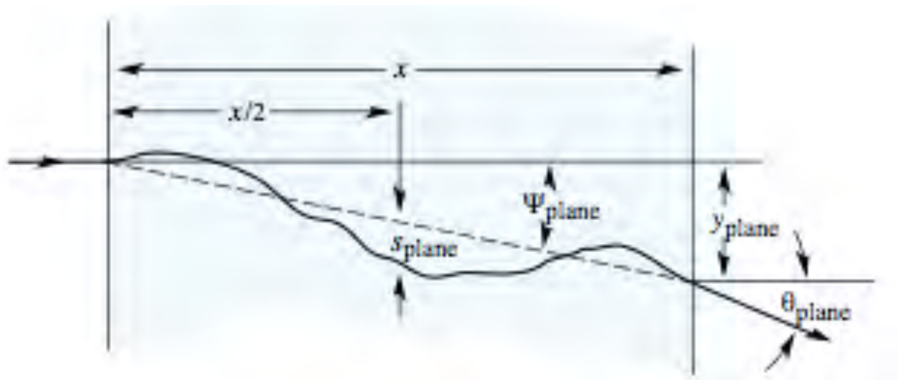
Tracking detectors

- We need to measure charged particle tracks in a magnetic field
- Requirements for a perfect tracking detector:
  - Large volume coverage
  - Position resolution in 3 dimensions
  - Excellent position resolution
  - Minimum perturbation of the particle's momentum
  - Can be operated at high rates
  - Reasonable cost

partially contradicting requirements !!

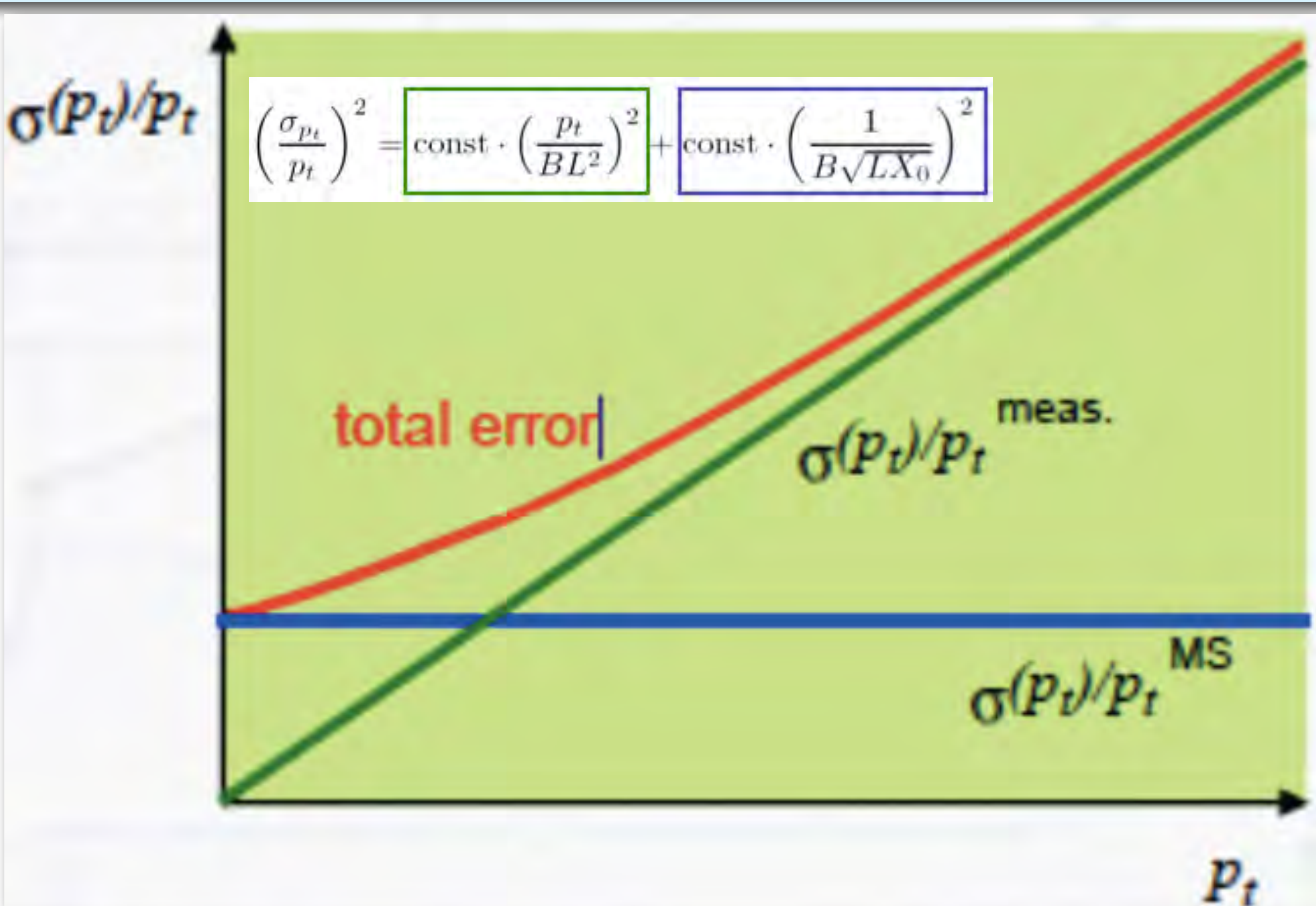
Limitations to momentum resolution

- Momentum resolution limited:
  - At high momentum by **position resolution** of the detector / **strength of magnetic field**
  - At low momentum by **multiple scattering**



$$\theta_0 = \frac{13.6\text{ MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038\ln(x/X_0)\Big]$$

Consequences for momentum resolution



Gaseous detectors

Ionization mode:

full charge collection
no multiplication; gain ≈ 1

Proportional mode:

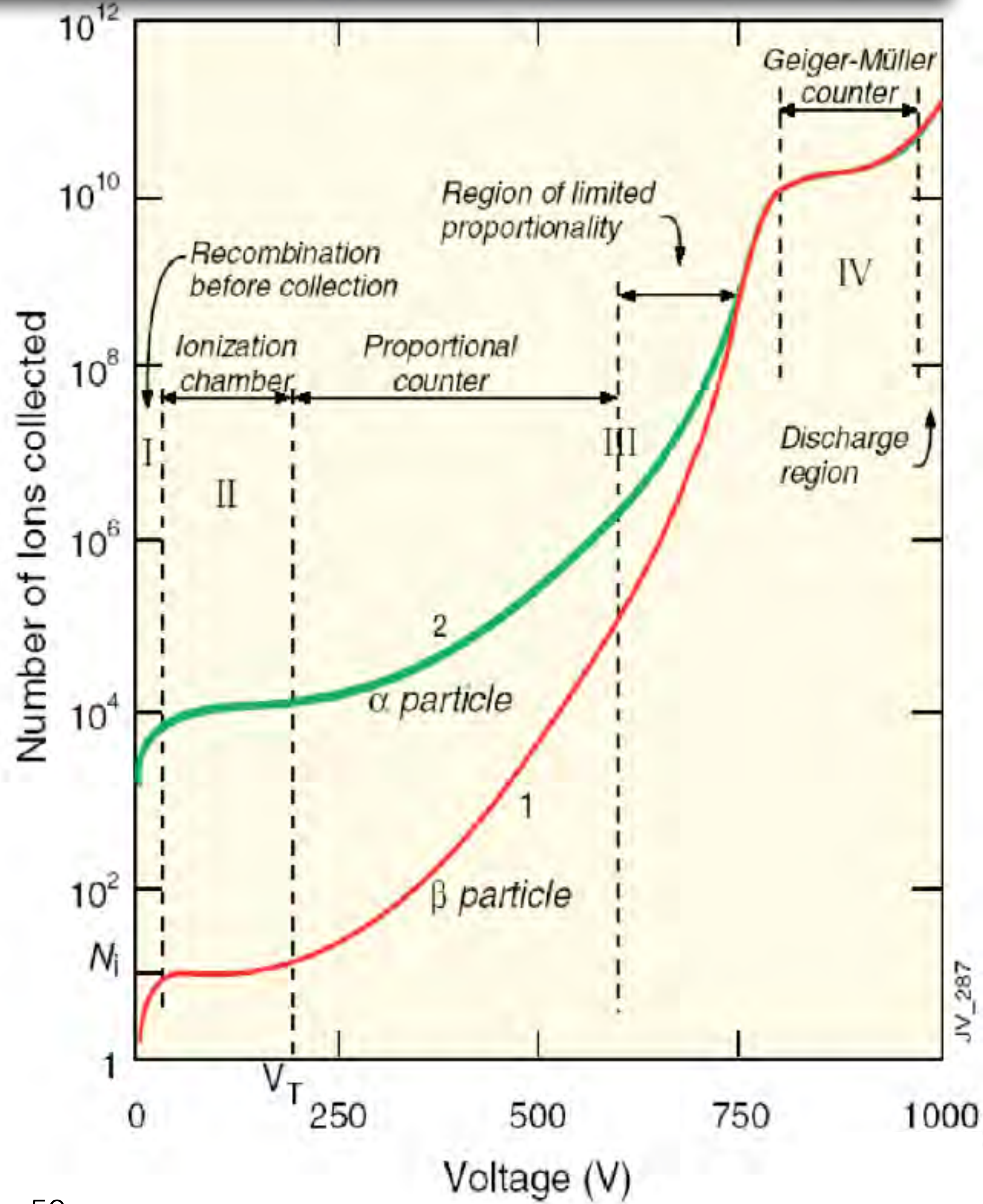
multiplication of ionization
signal proportional to ionization
measurement of dE/dx
secondary avalanches need quenching;
gain ≈ $10^4 - 10^5$

Limited proportional mode:
[saturated, streamer]

strong photoemission
requires strong quenchers or pulsed HV;
gain ≈ 10^{10}

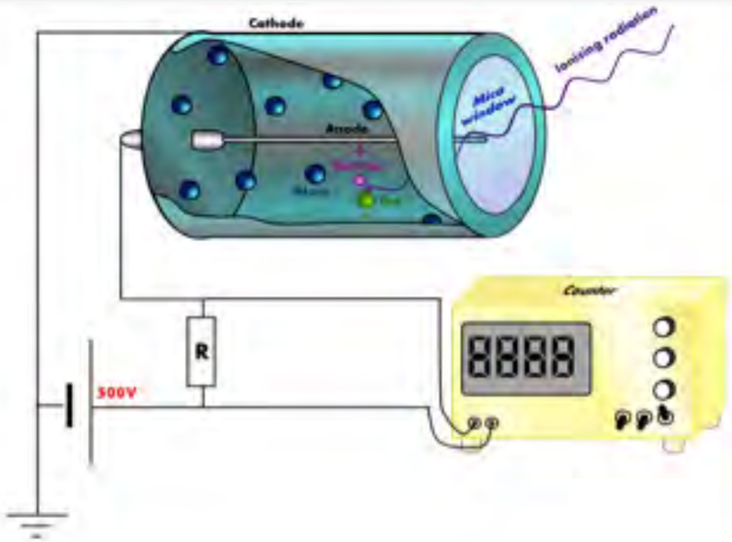
Geiger mode:

massive photoemission;
full length of the anode wire affected;
discharge stopped by HV cut

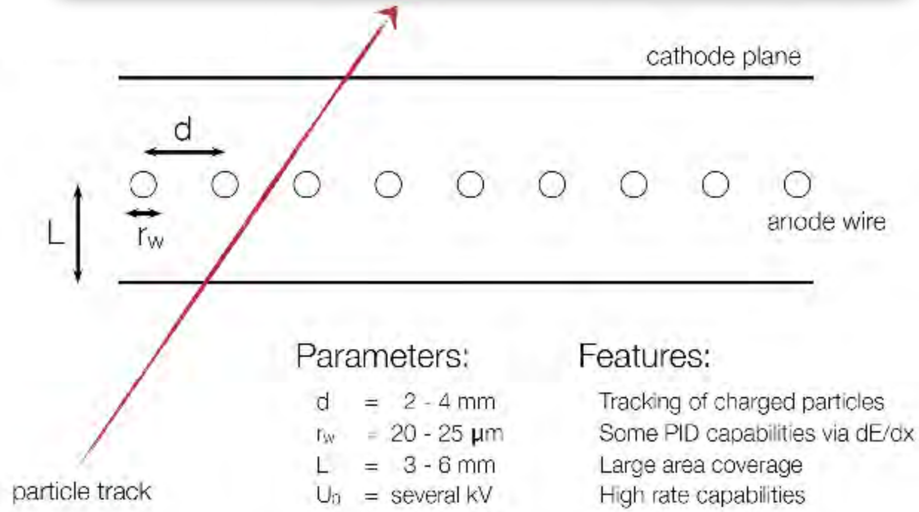


Multi-Wire-Proportional Counters (MWPC)

Simple Proportional Counter
Gas Amplification near Anode



Multi-Wire Proportional Counter
Position resolution in 1 dimension



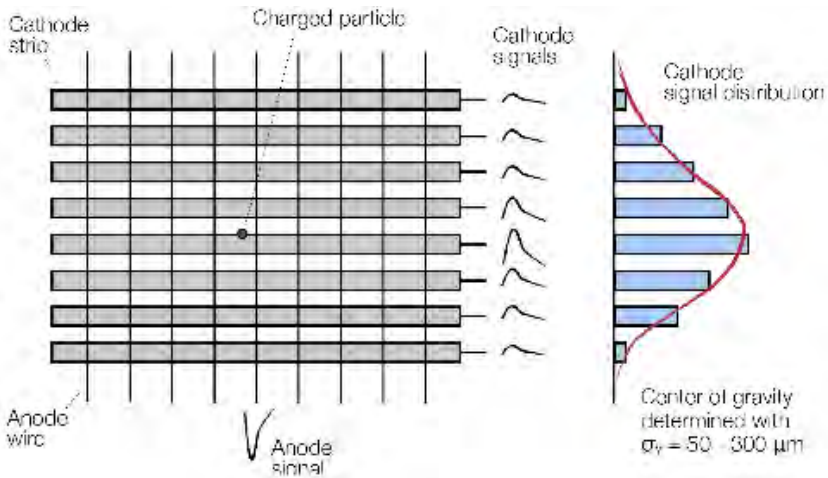
Parameters:

- d = 2 - 4 mm
- r_w = 20 - 25 µm
- L = 3 - 6 mm
- U_0 = several kV
- Total area: $O(m^2)$

Features:

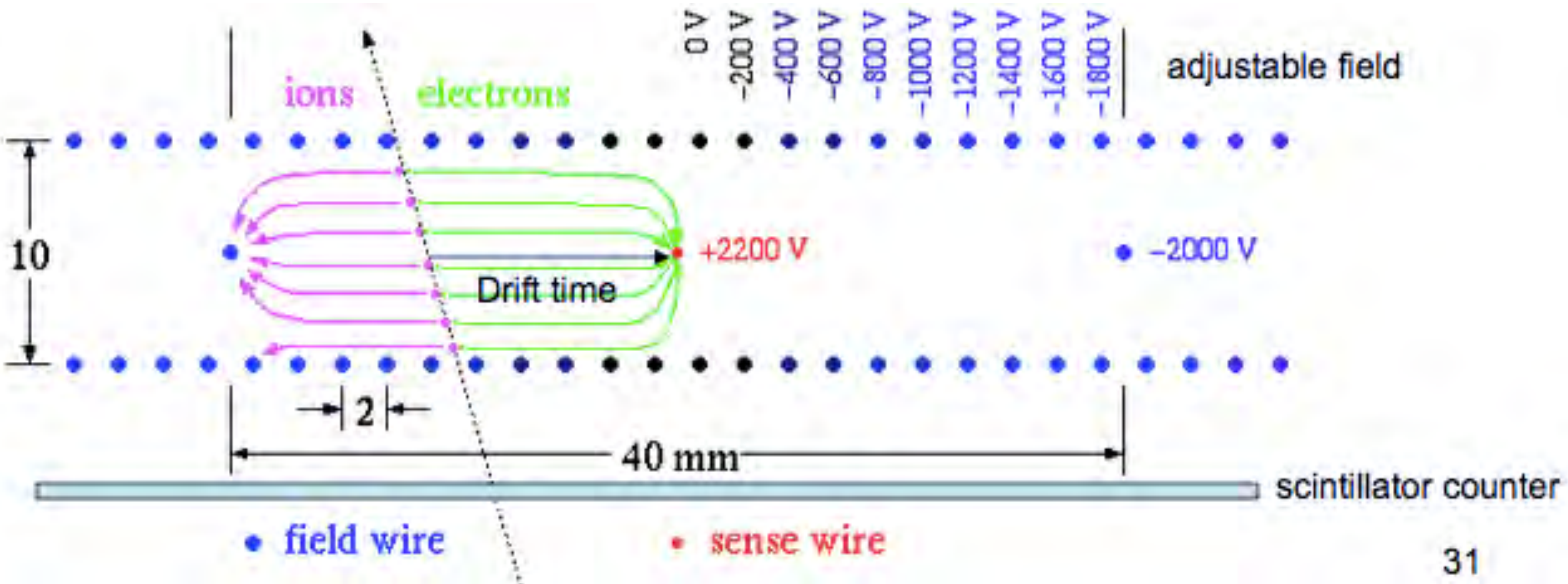
- Tracking of charged particles
- Some PID capabilities via dE/dx
- Large area coverage
- High rate capabilities

Multi-Wire Proportional Counter
Position resolution in 2 dimensions
with segmented cathode readout



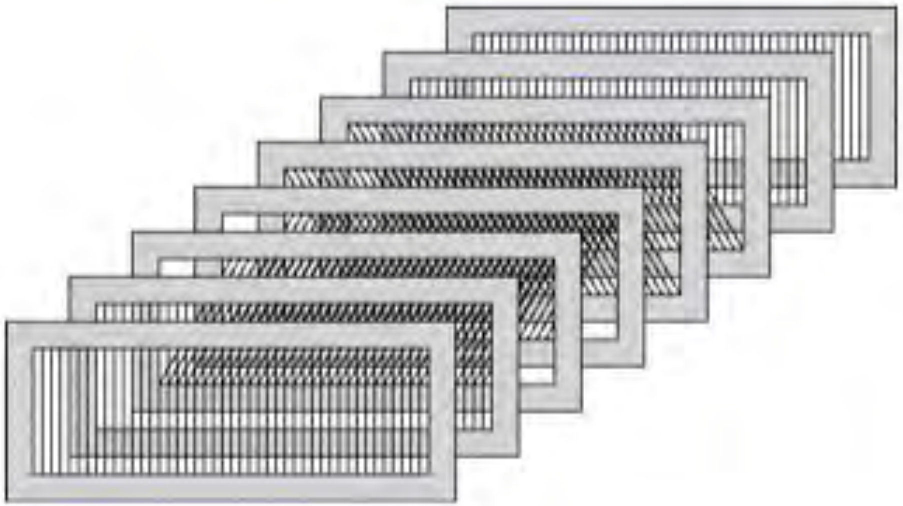
Drift chamber

- Problem with MWPC: need many wires in close distance to obtain good position resolution
  - Expensive, due to large number of readout channels, each with amplifier, signal shaper and ADC
- Idea: measure drift time with respect to external start signal in addition to wire position
- Need additional field wires to avoid region with low electric field/long drift times
- Need additional Time-to-Digital converter (TDC) to measure the drive times

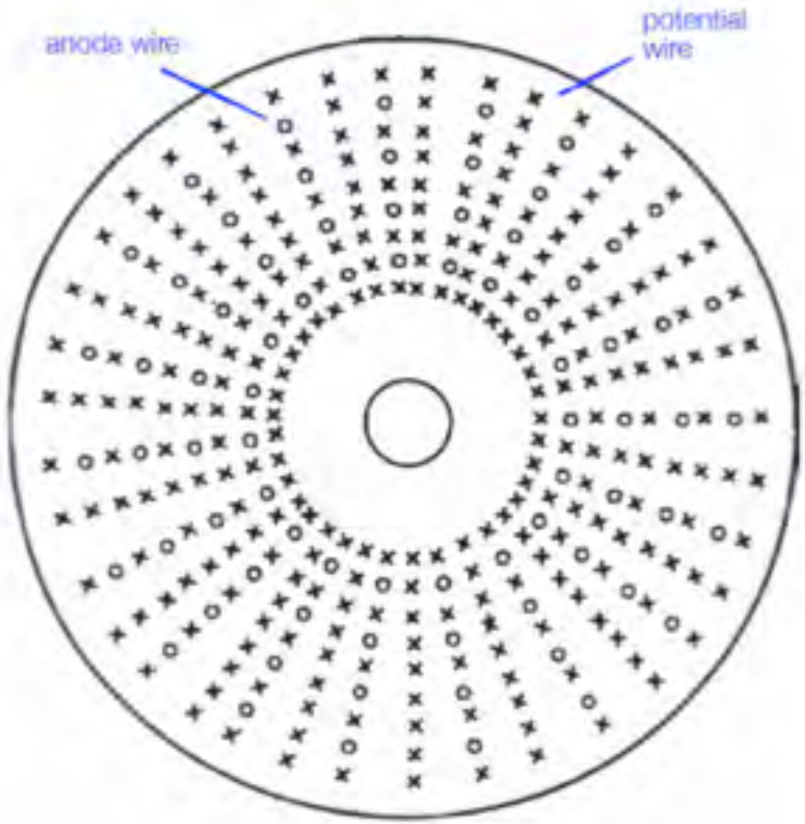


Planar and Cylindrical Drift Chambers

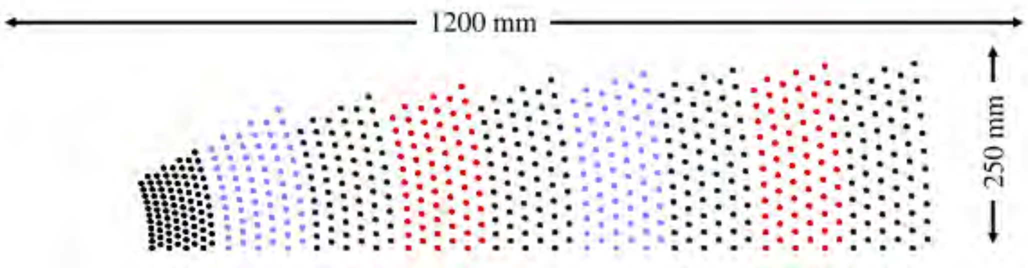
Tracking at fixed target experiments:
Multi-layer MWPC or drift chamber



Tracking at collider experiments:
cylindrical drift chamber



Example: Belle II Central Drift Chamber



	Belle II CDC
Number of layers	56
Total sense wires	14336
Gas	He:C_2H_6
Sense wire	W (ø30 µm)
Field wire	Al (ø120 µm)

- If all wires were parallel to beam axis, there would be no information on scattering angle
- Introduce "Stereo Layers"

Time Projection Chamber (TPC)

Electronic 'bubble chamber'
Full 3D reconstruction ...

xy : from wires and pads of MWPC ...
z : from drift time measurement

Momentum measurement ...

space point measurement
plus B field ...

Energy measurement ...

via dE/dx ...

TPC setup:

(mostly) cylindrical detector

central HV cathode
MWPCs at end-caps of cylinder

B || to E ➛ Lorentz angle = 0

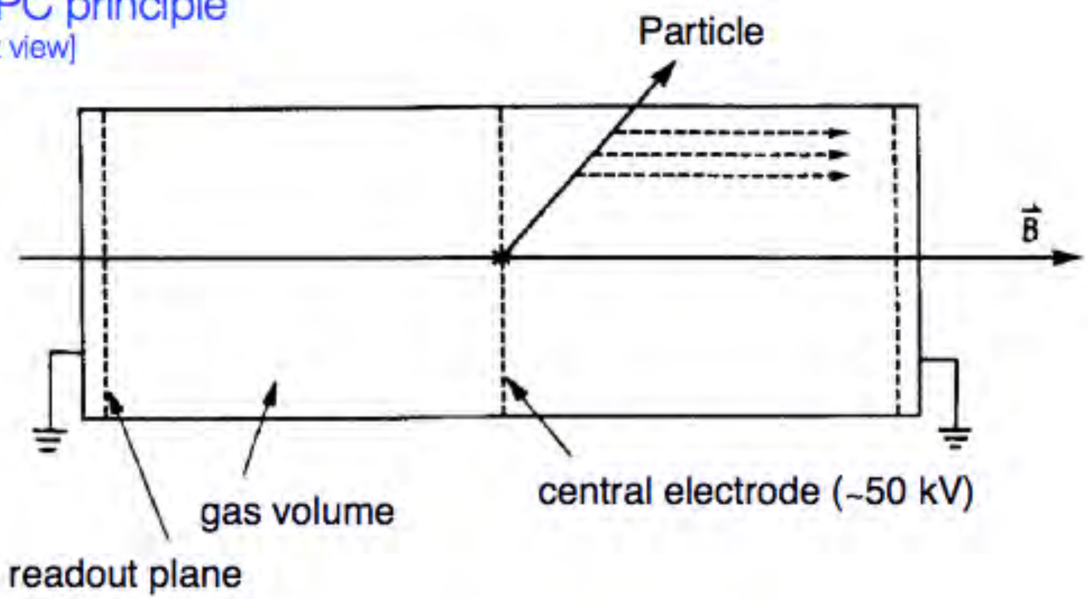
Charge transport :

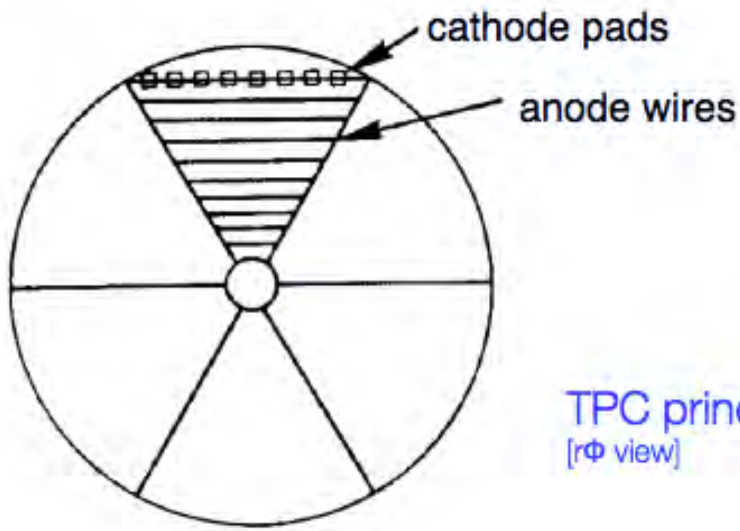
Electrons drift to end-caps

Drift distance several meters

Continuous sampling of induced
charges in MWPC

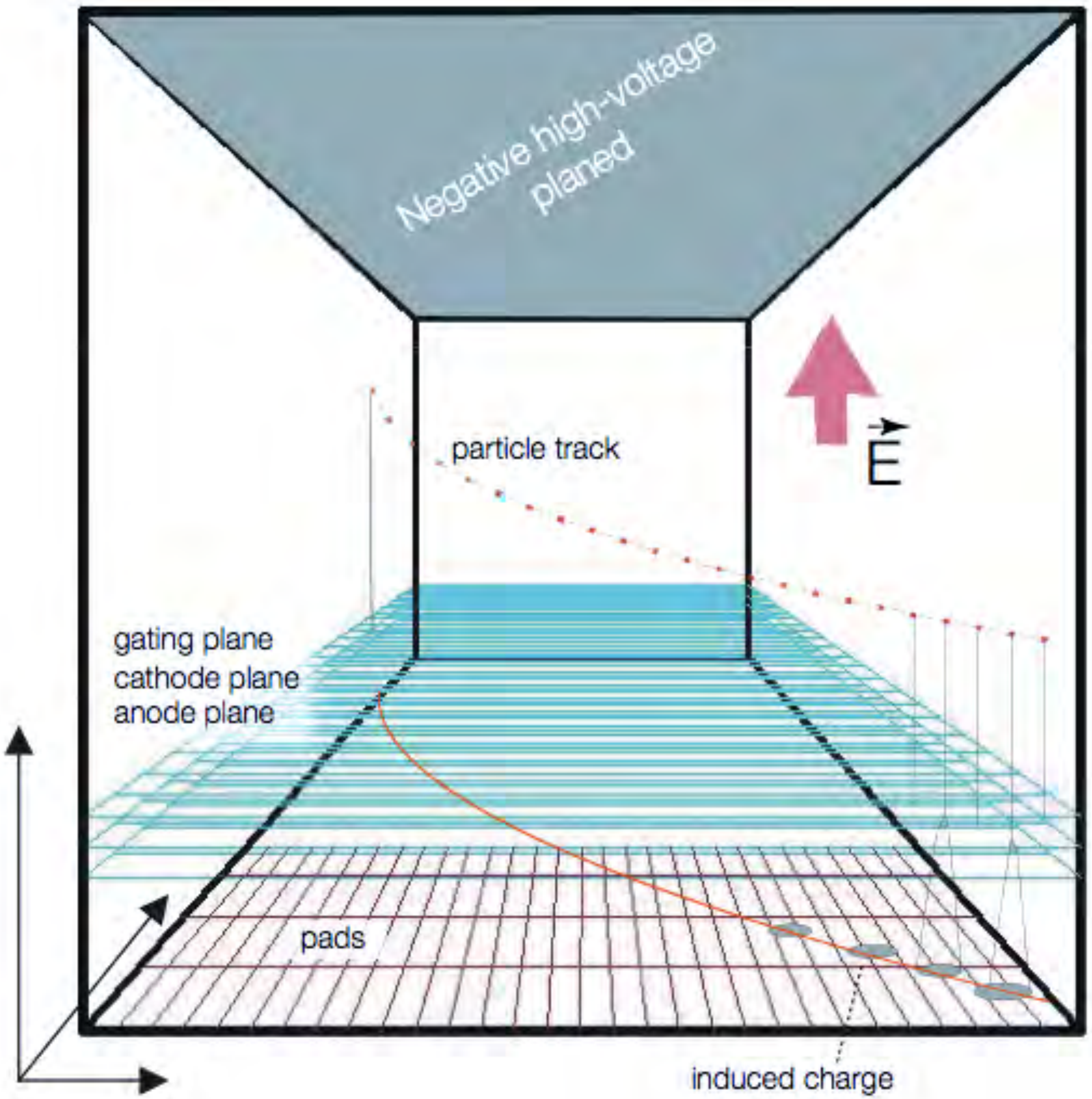
TPC principle
[rz view]





TPC principle
[rΦ view]

TPC



Advantages:

Complete track within one detector yields good momentum resolution

Relative few, short wires (MWPC only)

Good particle ID via dE/dx

Drift parallel to B suppresses transverse diffusion by factors 10 to 100

Challenges:

Long drift time; limited rate capability [attachment, diffusion ...]

Large volume [precision]

Large voltages [discharges]

Large data volume ...

Extreme load at high luminosity; gating grid opened for triggered events only ...

Typical resolution:

z: mm; x: 150 - 300 µm; y: mm
dE/dx: 5 - 10%

ALICE has the largest TPC

ALICE TPC:

Length: 5 meter
Radius: 2.5 meter
Gas volume: 88 m^3

Total drift time: 92 µs
High voltage: 100 kV

End-cap detectors: 32 m^2
Readout pads: 557568

159 samples radially
1000 samples in time

Gas: $Ne/CO_2/N_2$ (90-10-5)
Low diffusion (cold gas)

Gain: > 10^4

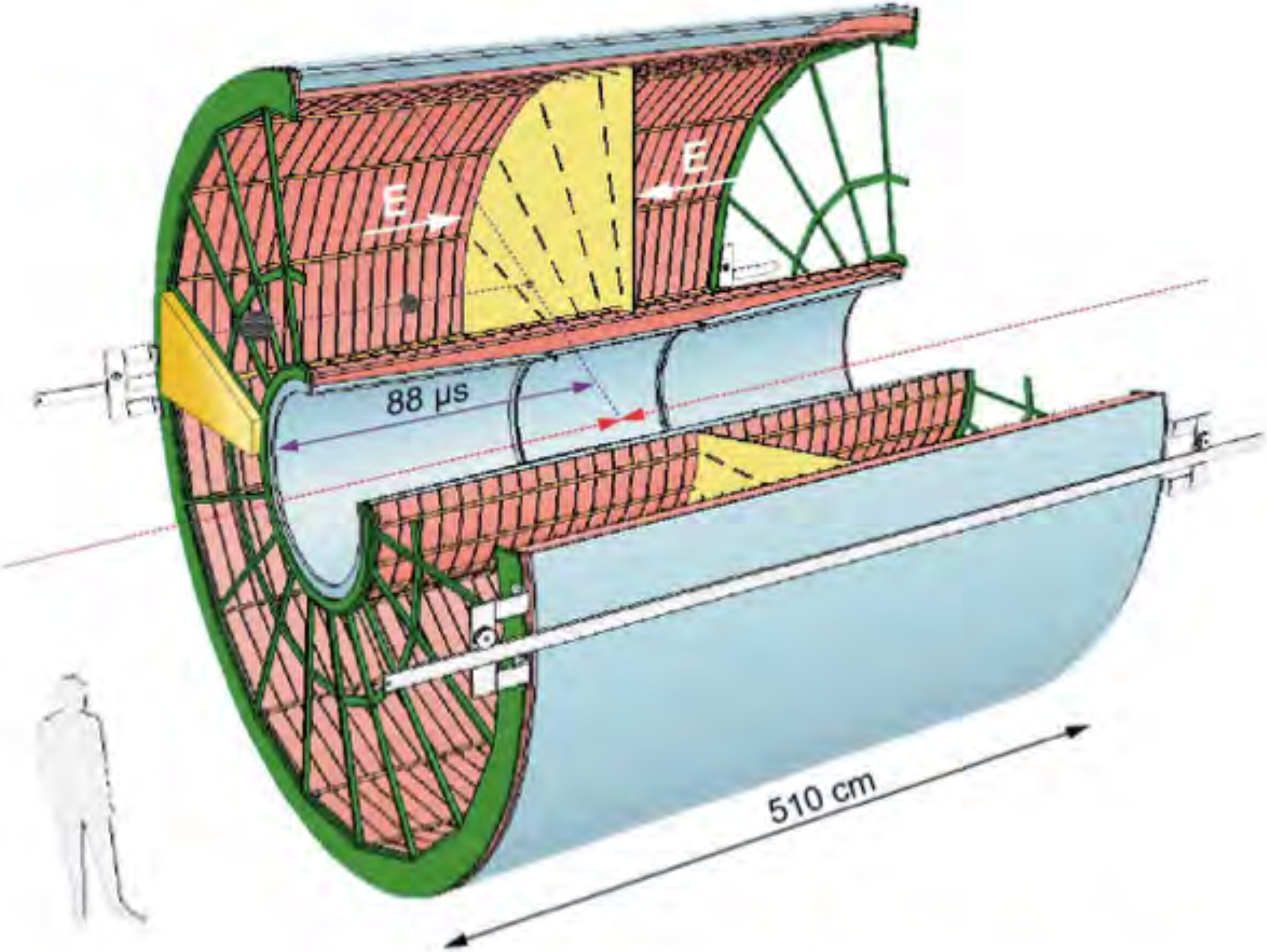
Diffusion: σ_t = 250 µm
Resolution: $\sigma \approx$ 0.2 mm

σ_p/p ~ 1% p; ε ~ 97%
$\sigma_{dE/dx}/(dE/dx)$ ~ 6%

Magnetic field: 0.5 T

Pad size: 5x7.5 mm^2 (inner)
6x15 mm^2 (outer)

Temperature control: 0.1 K
[also resistors ...]



Material: Cylinder build from composite material of airline industry (X_0= ~ 3%)

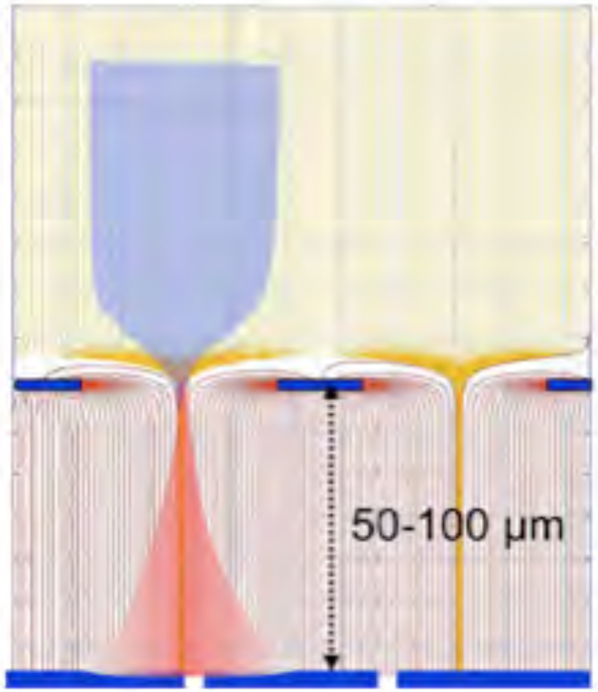
New Technologies Micro-Pattern Gas Detectors

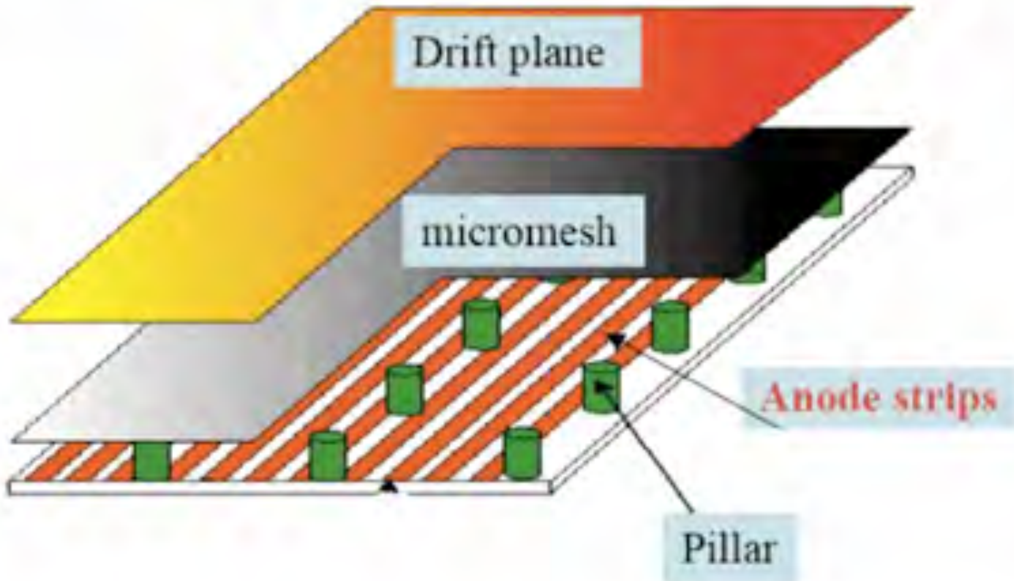
- Largely improved spacial resolution and higher particle rates:

Micro-Pattern Gas Detectors

- a number of developments were started, some with a lot of problems
- two technologies are currently the most successful: GEMs and MicroMegas
- MicroMegas: Avalanche amplification in a small gap

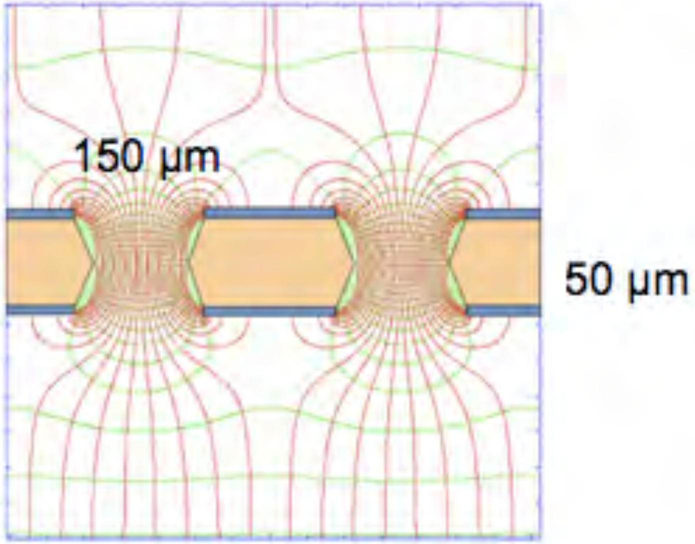
Y. Giomataris et al, NIM A376, 29(1996)

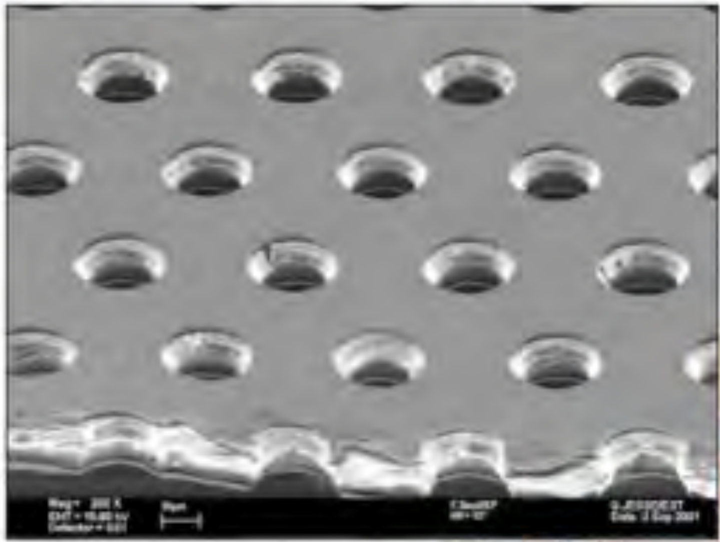




Gas Electron Multiplier (GEM)

- GEM: Gas Electron Multiplier: Gas amplification in small holes in a special foil





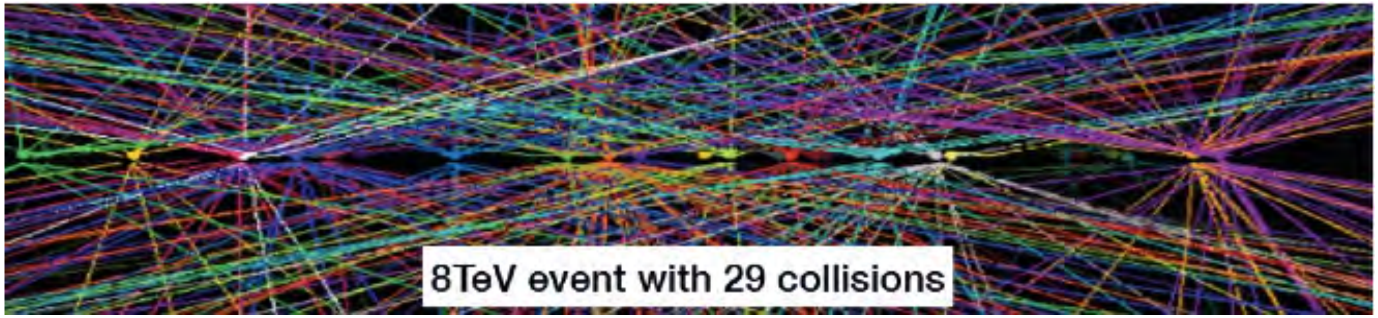
Charge collection on two separate levels: 2D structure possible: separation of amplification and read out

Both technologies, MicroMegas and GEMs are used in experiments. Typical spacial resolution: ~70 um

F. Sauli, NIM A386, 531(1997)

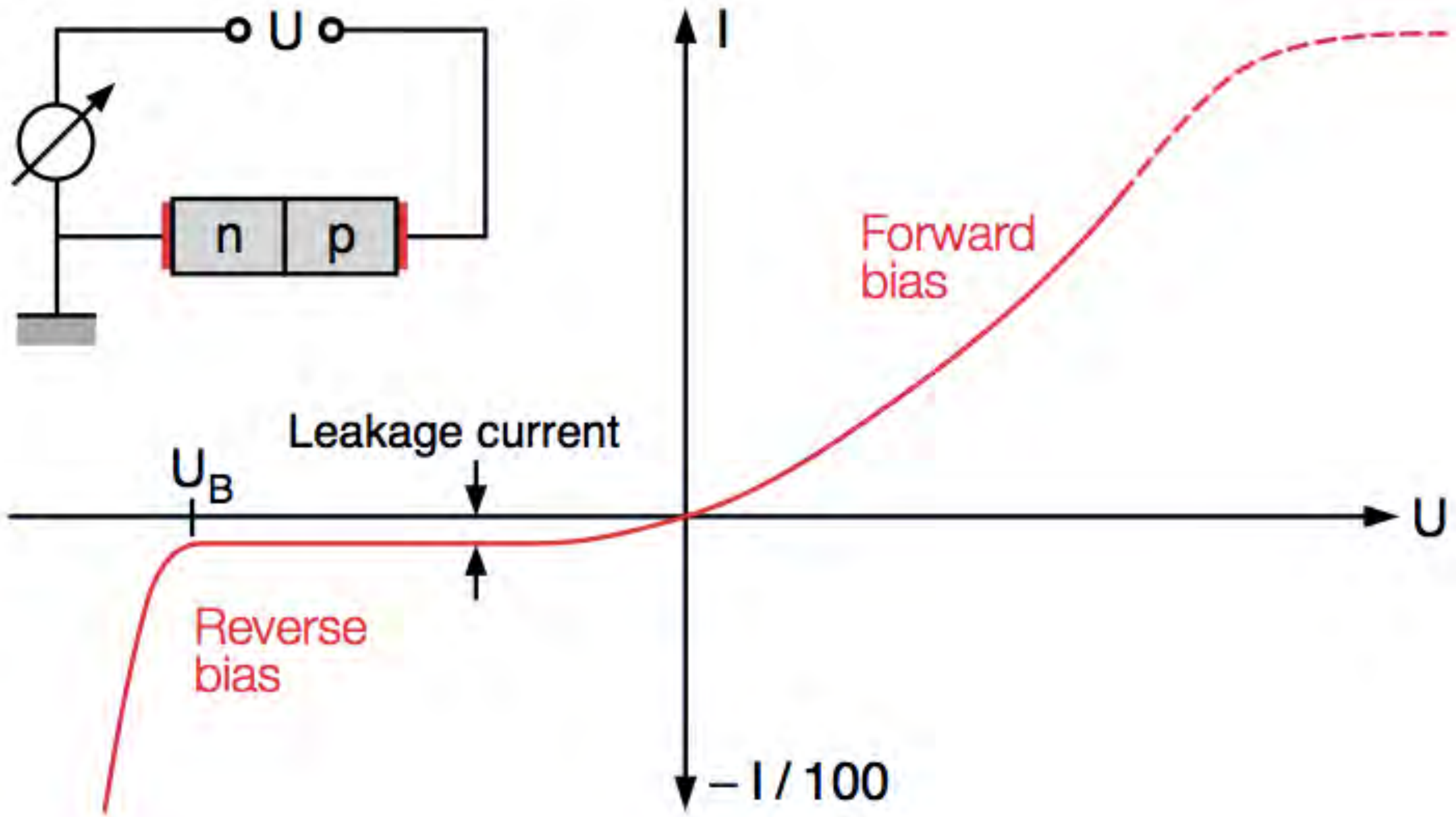
Solid-State Detectors (mostly Silicon based)

- Motivation:
  - Precision tracking close to the interaction point with minimum perturbation of the particles
- Identify individual interactions in bunch crossing



- Identify heavy flavor decays from secondary vertices

Detector principle: diode with reverse bias



Position-sensitive detectors

Principle:

Segmentation
into strips, pads, pixels ...

Typical parameters:

Thickness: 150 - 500 μm
Strip separation (pitch): 20 - 150 μm
Resolution: 5 - 40 μm (pitch/√12)

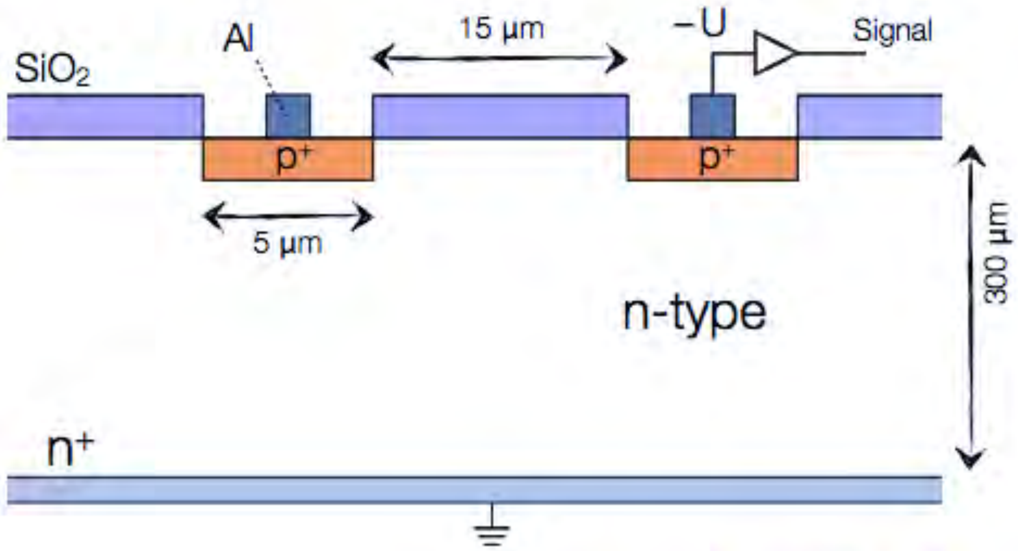
Charge collection: 20 ns
Charge integration: 120 ns

Operation voltage: 160 V

Output signal:

Total charge: Q_{out} ~ 4 fC

Average energy loss of MIP: 300 eV/μm; Si: 3.6 eV/pair.
Thus 80 electron-hole pairs per μm;
300 μm thickness → 25000 pairs/MIP



Schematics of
Silicon Strip Detector

[from 1983]

High resistive n-type silicon
onto which p^+ diode strips with
aluminum contacts are implanted

Pixel Detectors

Pixel detectors:

Like micro-strips, but 2-dim. segmentation ...

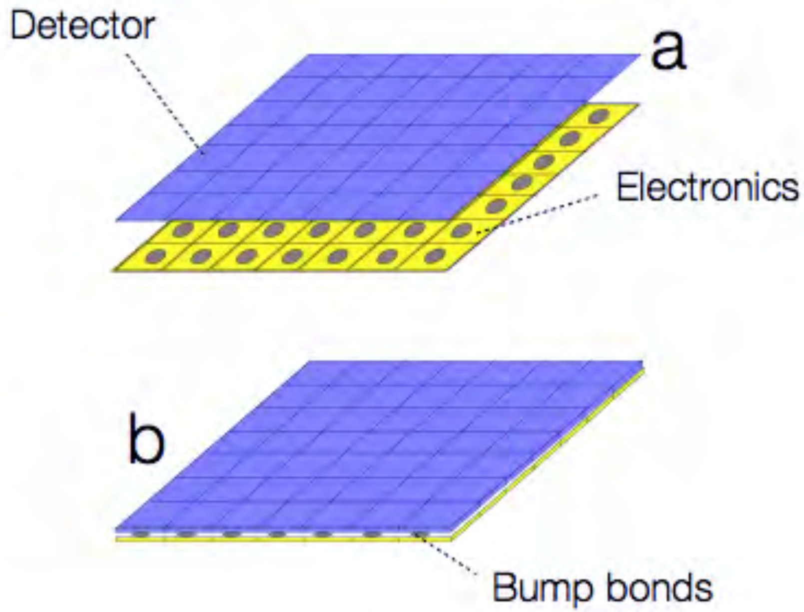
Advantage:

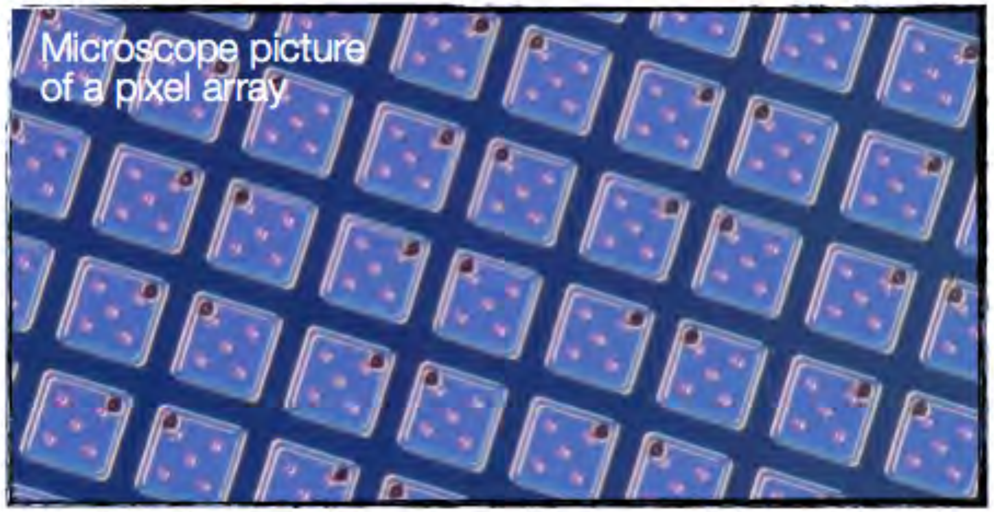
As for micro-strips 2-dim. information,
but higher occupancy allowed;

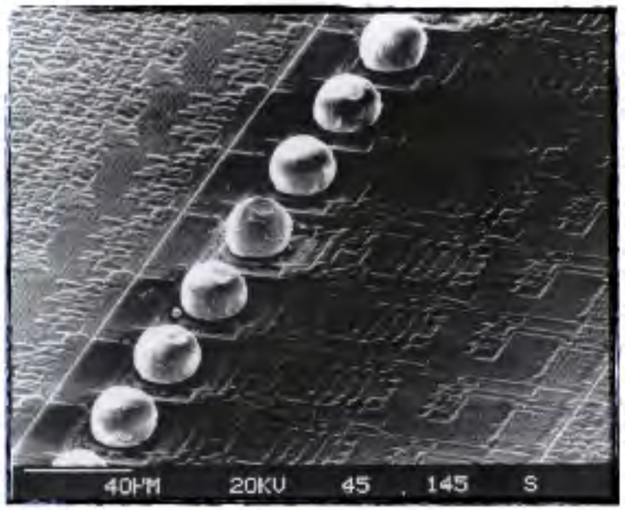
Lower noise due to lower capacitance ...

Disadvantage:

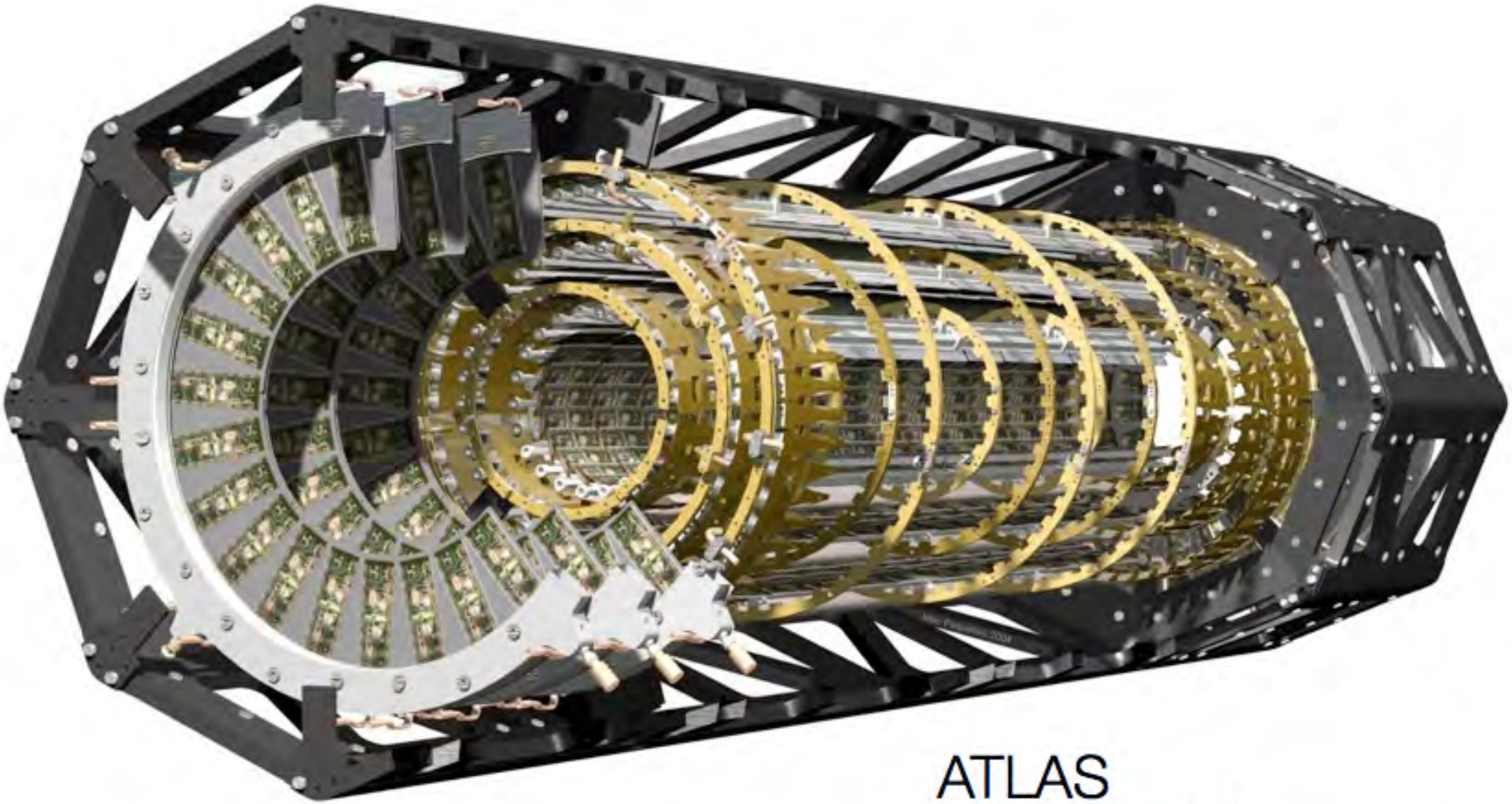
Huge number of readout channels;
Complicated technology ("bump bonding")
Requires sophisticated readout architecture ...







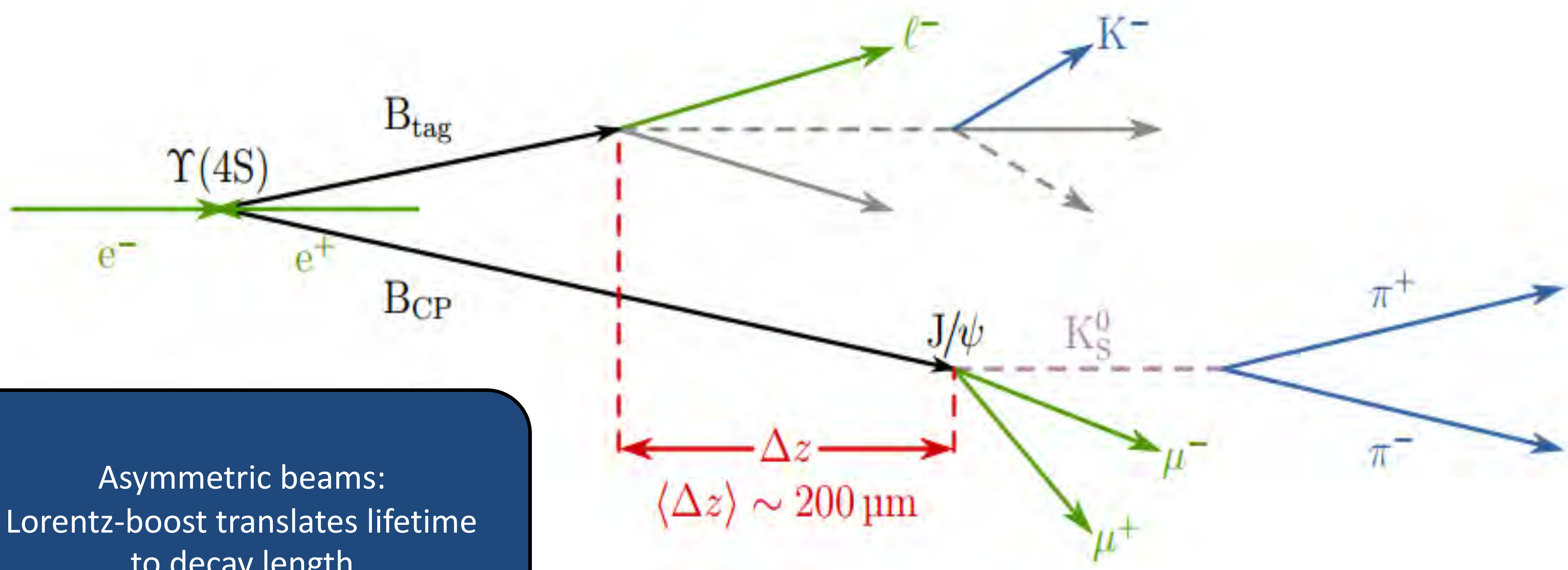
SEM Photograph
of solder bumps



ATLAS
Pixel Detector
[nominal resolution: Rϕ ~ 12 μm]

Example: Belle II experiment

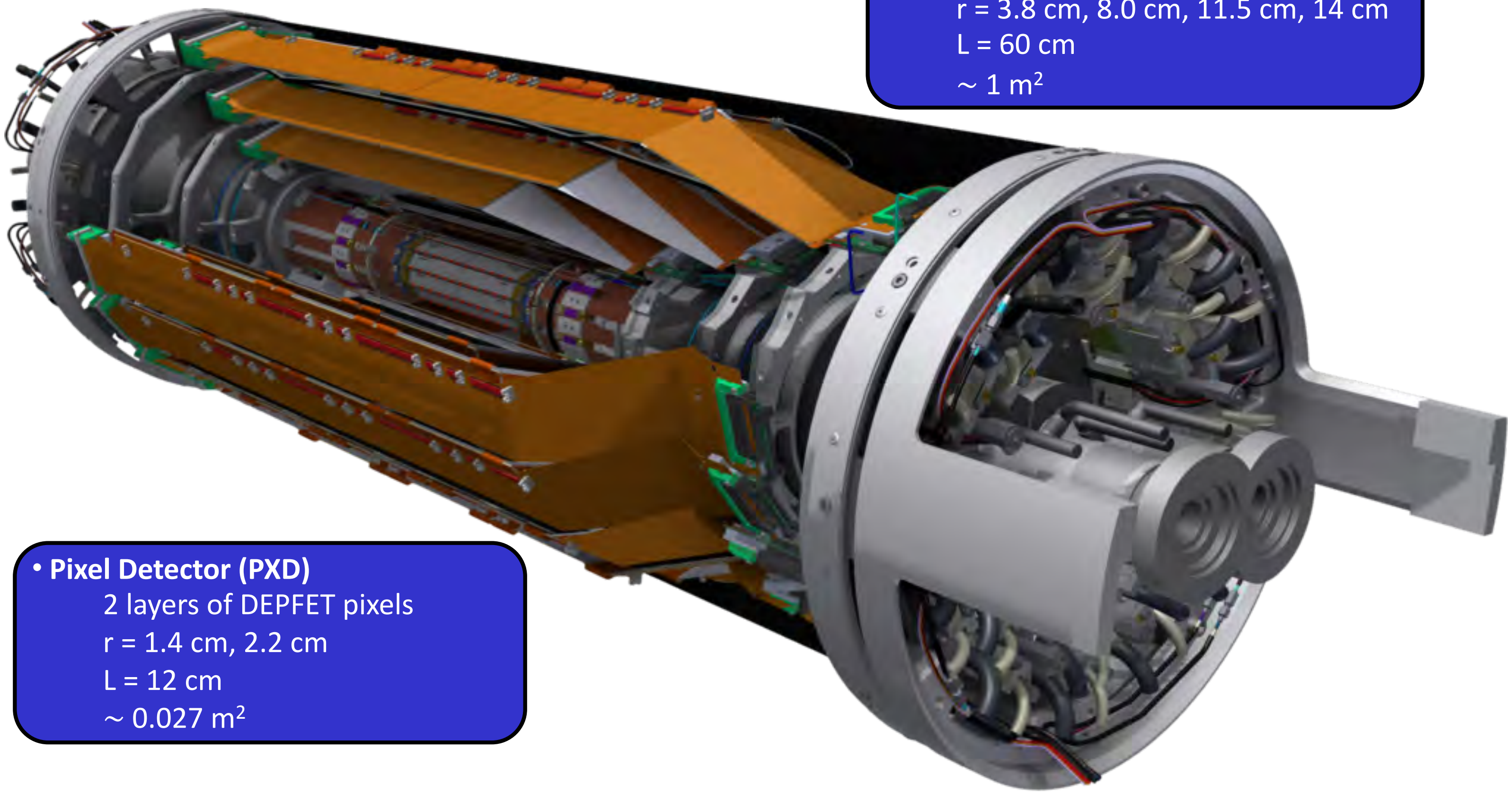
$e^+e^- \to \Upsilon(4s) \to B^0\bar{B}^0$ E_{cm} = 10.58 GeV



Asymmetric beams:
Lorentz-boost translates lifetime
to decay length

Precise vertexing essential to measure CP violation

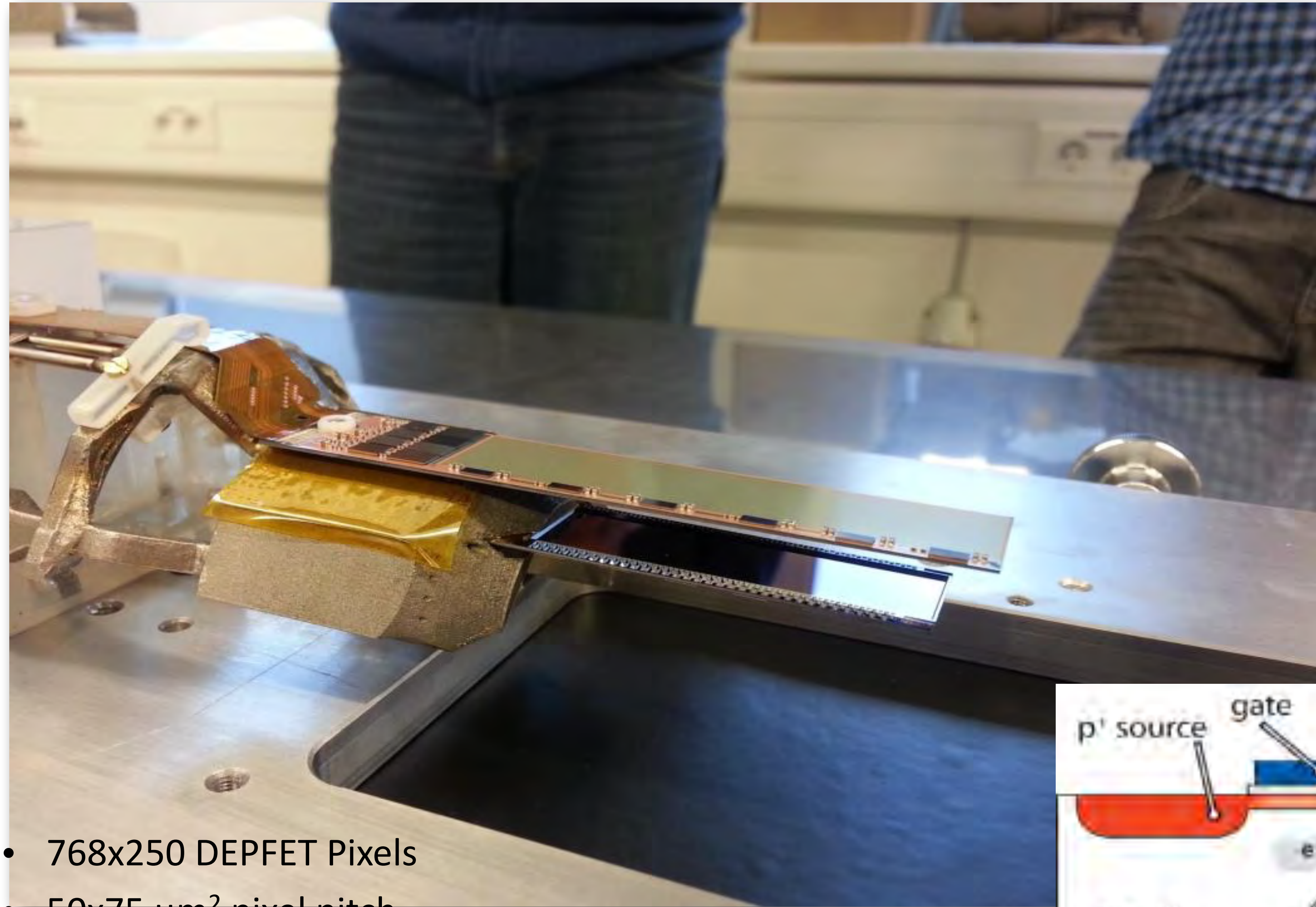
Silicon Vertex Dector

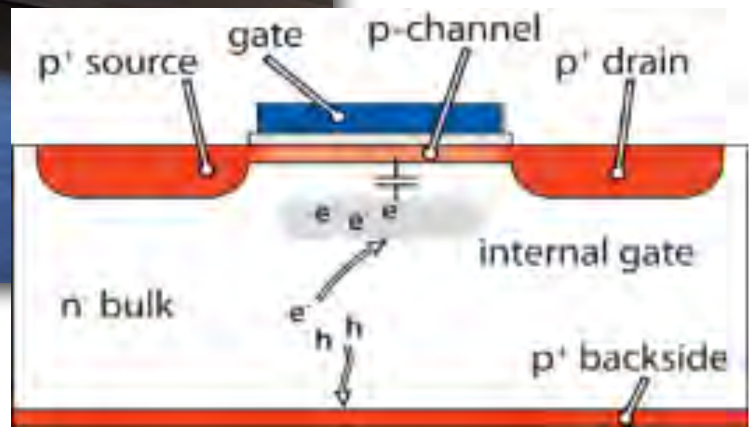


- **Silicon Vertex Detector (SVD)**
  4 layers of DSSD
  r = 3.8 cm, 8.0 cm, 11.5 cm, 14 cm
  L = 60 cm
  $\sim 1\ m^2$

- **Pixel Detector (PXD)**
  2 layers of DEPFET pixels
  r = 1.4 cm, 2.2 cm
  L = 12 cm
  $\sim 0.027\ m^2$

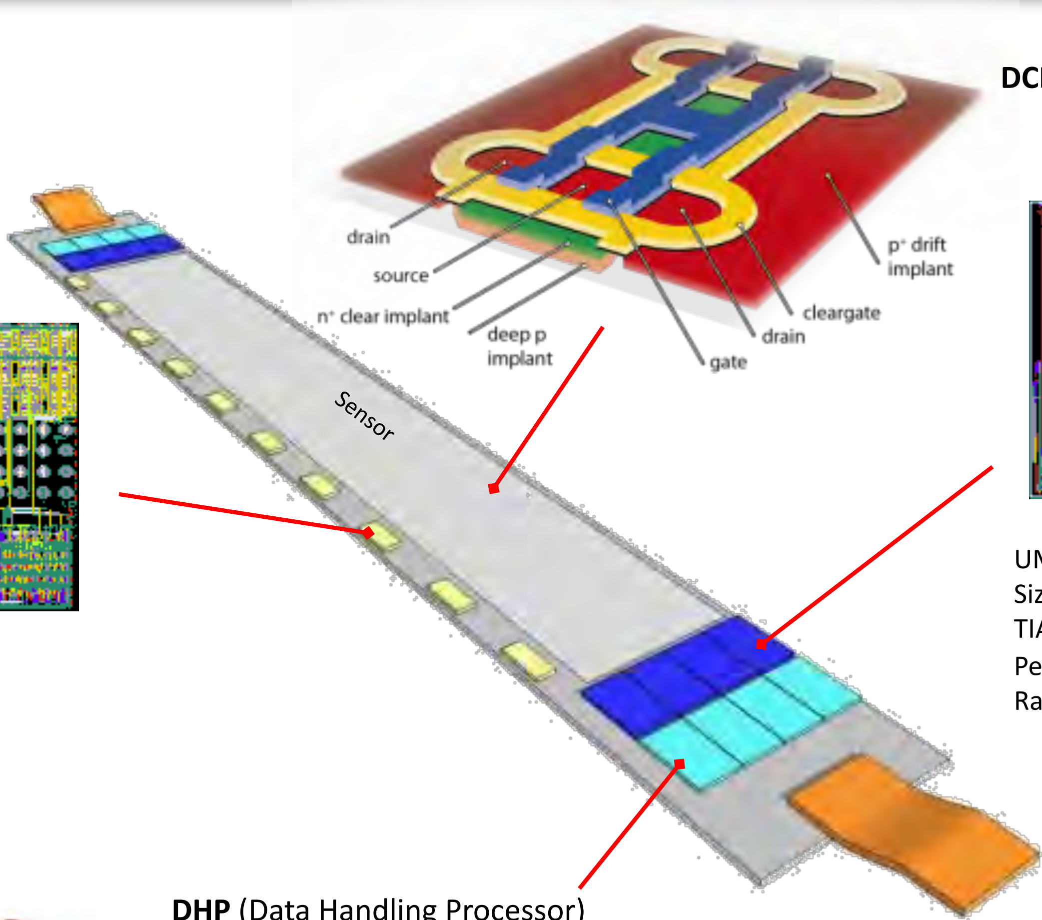
DEPFET Pixel Sensor



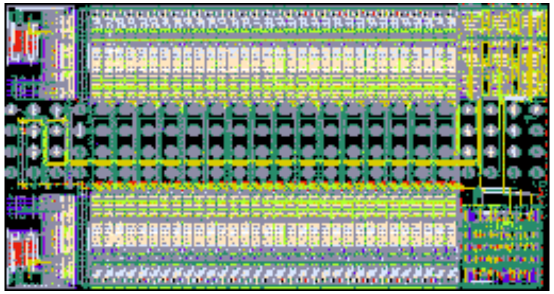


- 768x250 DEPFET Pixels
- 50x75 μm^2 pixel pitch
- 75 µm thickness

Requires dedicated ASIC development

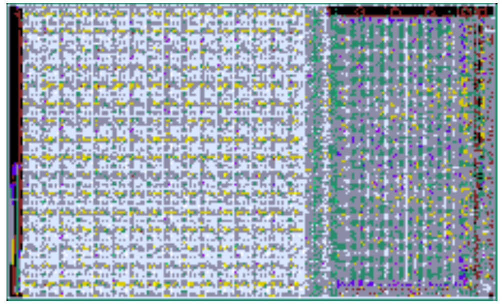


SwitcherB
Row control



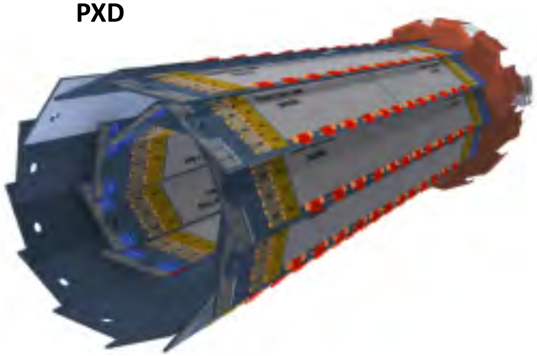
AMS/IBM HVCMOS 180 nm
Size 3.6 × 1.5 mm^2
Gate and Clear signal
Fast HV ramp for Clear
Rad. Hard proved (36 Mrad)

DCDB (Drain Current Digitizer)
Analog frontend

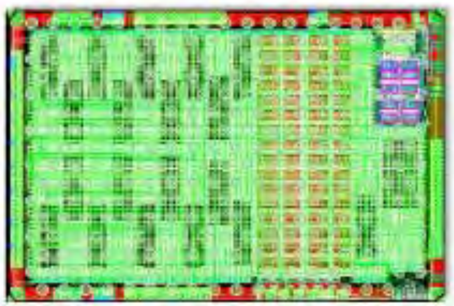


UMC 180 nm
Size 5.0 × 3.2 mm^2
TIA and ADC
Pedestal compensation
Rad. Hard proved (20 Mrad)

PXD



DHP (Data Handling Processor)
First data compression



TSMC 65 nm
Size 4.0 × 3.2 mm^2
Stores raw data and pedestals
Common mode and pedestal correction
Data reduction (zero suppression)
Timing signal generation
Rad. Hard proved (100 Mrad)

Calorimetry / Energy Measurement

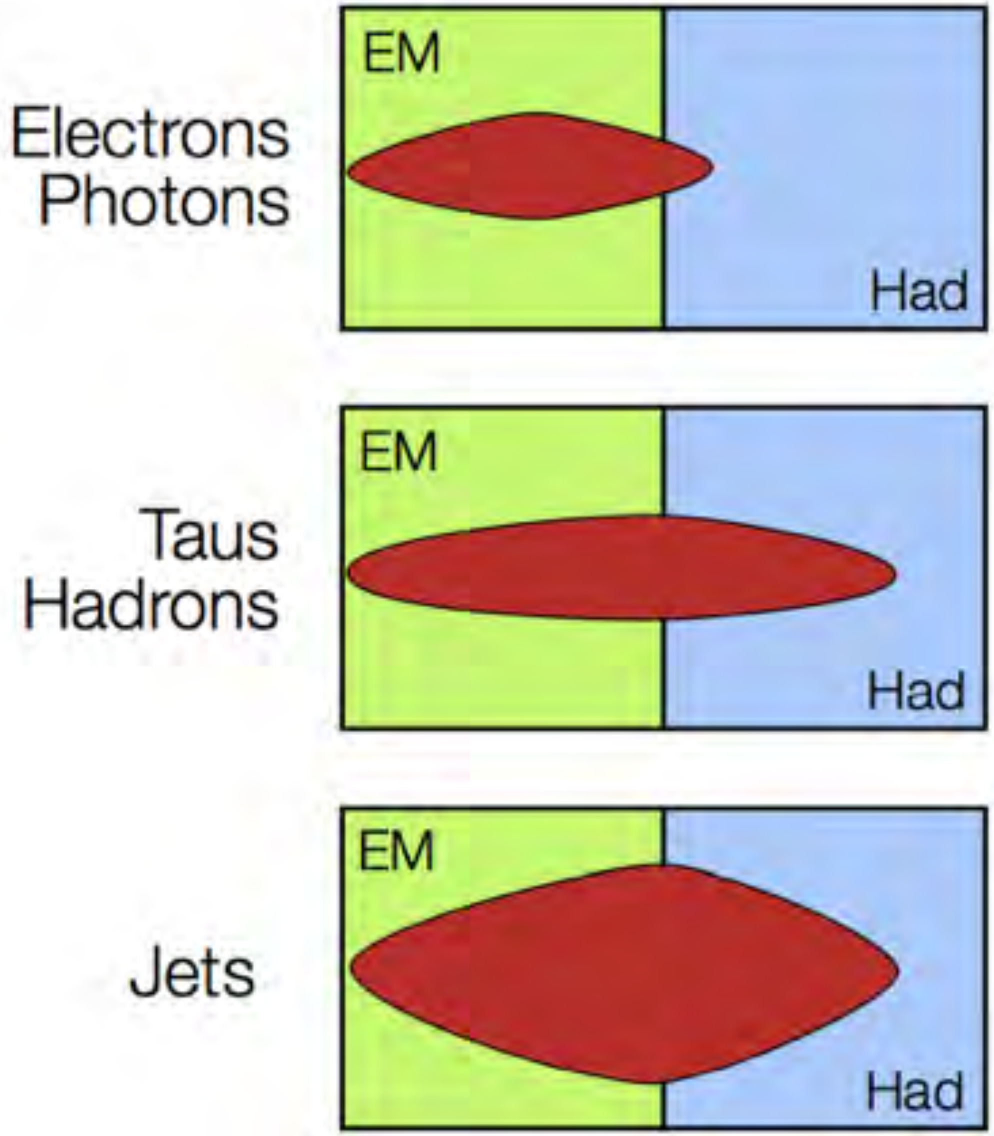
Principle

CALORIMETERS ARE DESTRUCTIVE

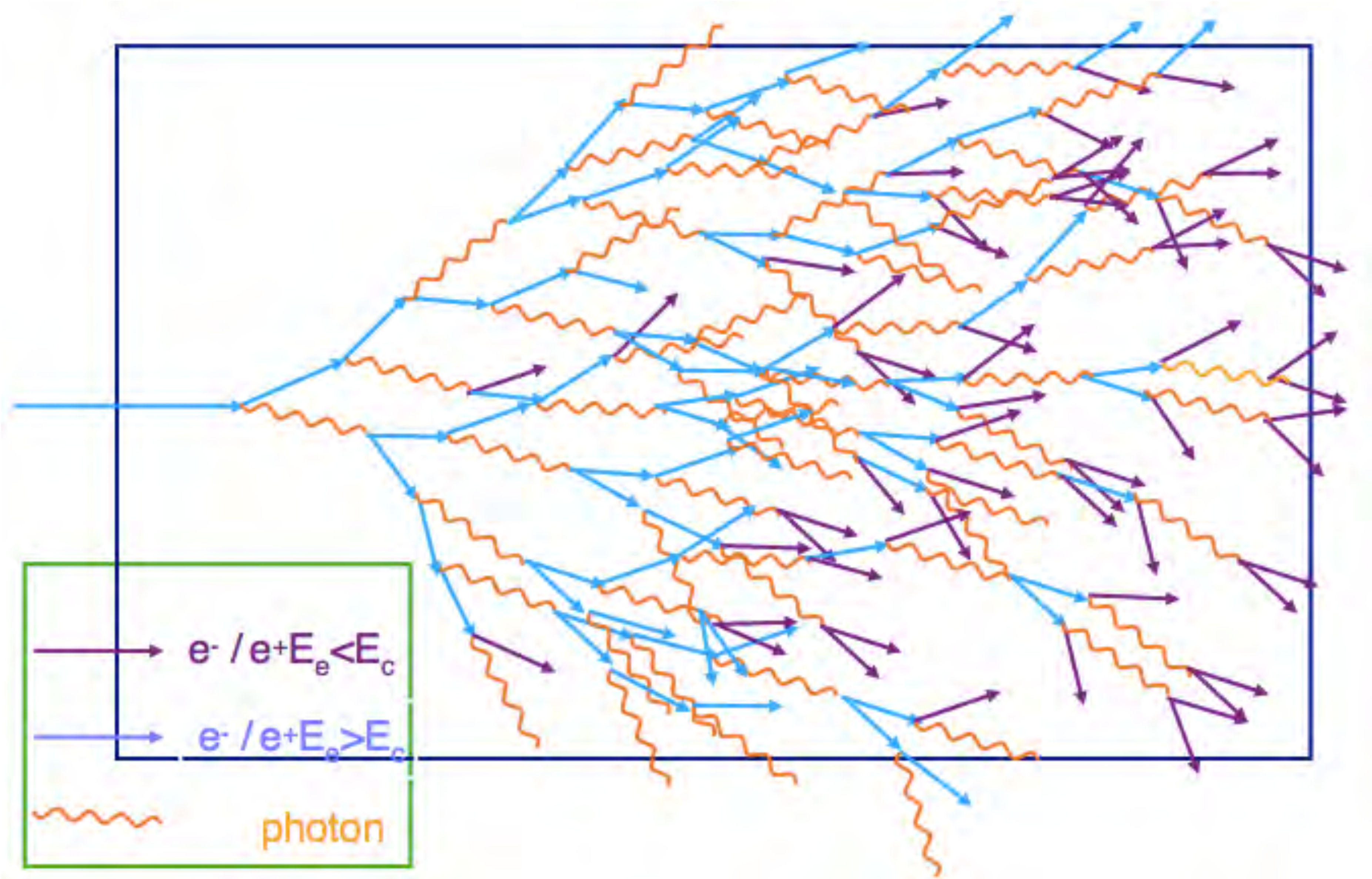
PARTICLES DO NOT COME OUT of THE CALORIMETER

ELECTRONS, PHOTONS, HADRONS ARE ABSORBED by the CALORIMETERS

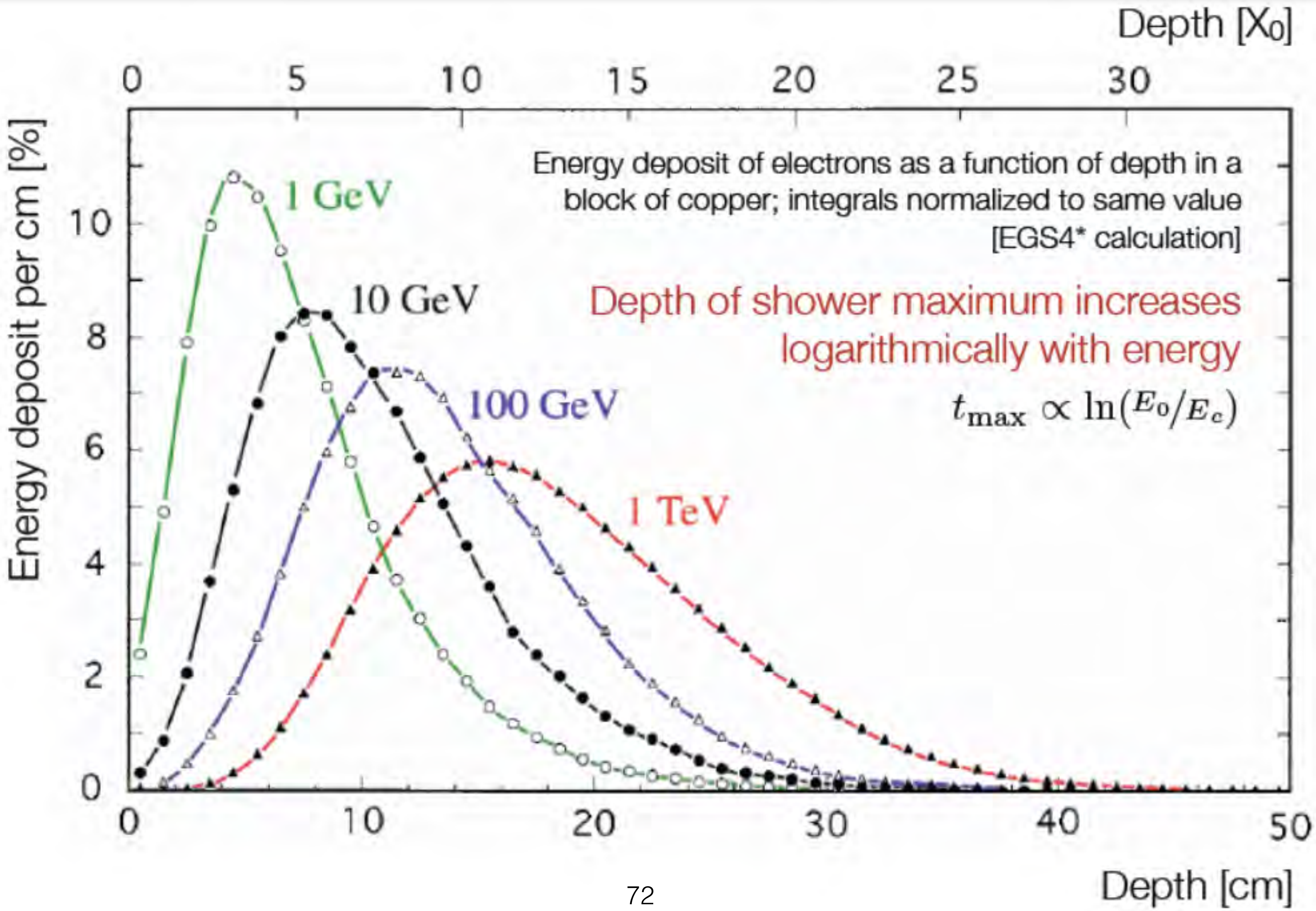
ONLY MUONS and NEUTRINOS ESCAPE



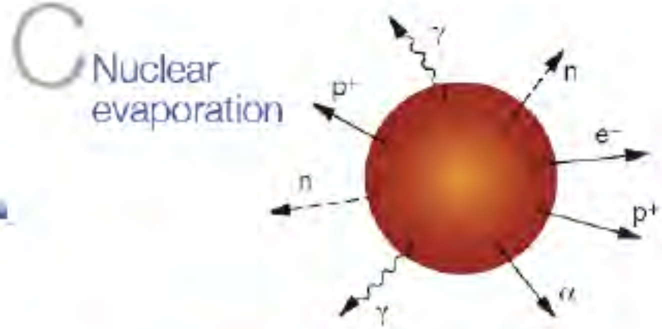
Electromagnetic Shower



Longitudinal development of electromagnetic shower in copper



Hadronic showers



Hadronic interaction:

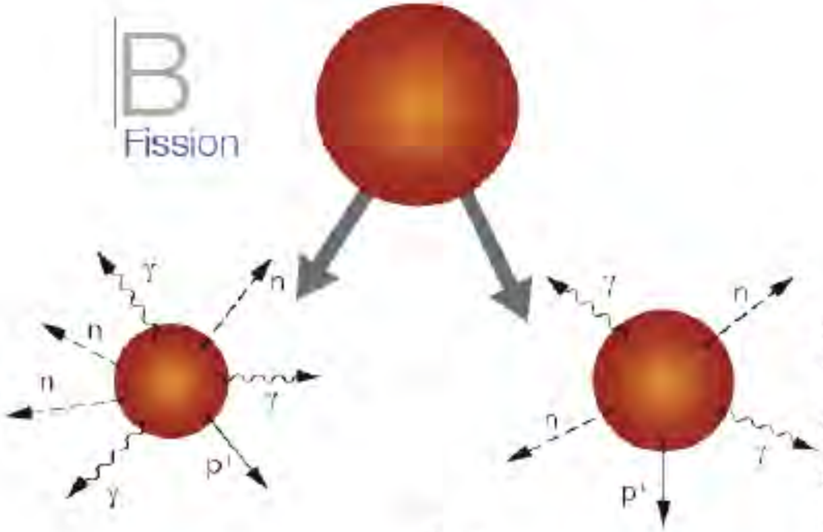
Elastic:

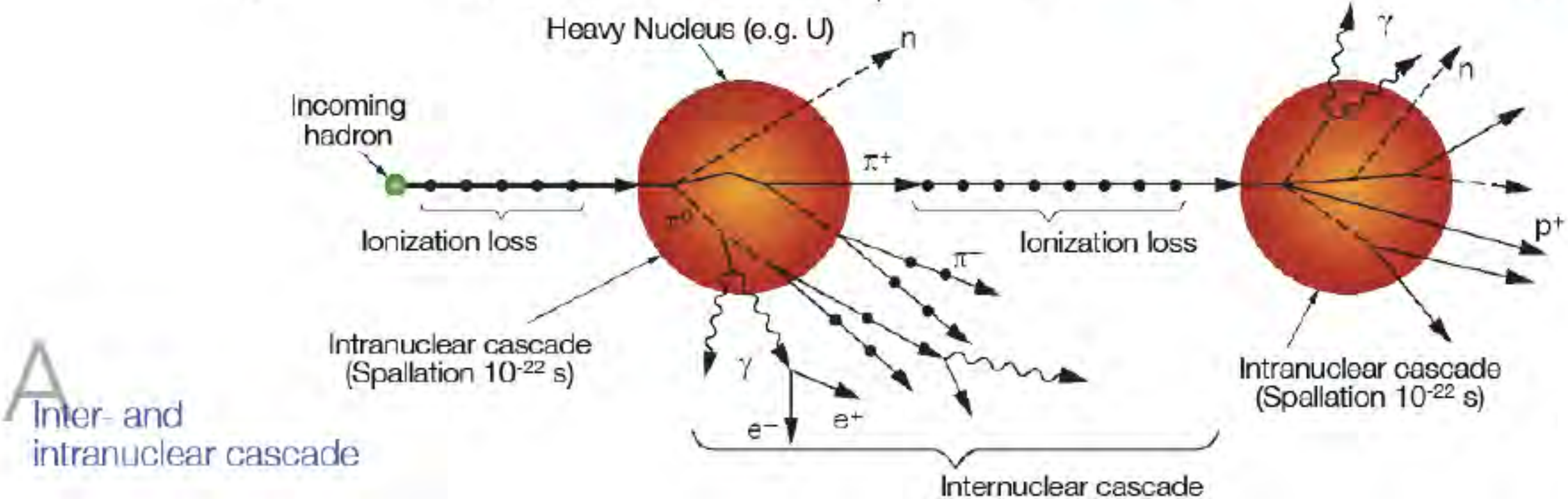
$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

Inelastic:

$$p + \text{Nucleus} \rightarrow$$
$$\pi^+ + \pi^- + \pi^0 + \ldots + \text{Nucleus}^*$$

$$\left[\begin{array}{l} \text{Nucleus}^* \rightarrow \text{Nucleus A} + n, p, \alpha, \ldots \\ \qquad\quad\;\; \rightarrow \text{Nucleus B} + 5p, n, \pi, \ldots \\ \qquad\quad\;\; \rightarrow \text{Nuclear fission} \end{array} \right]$$





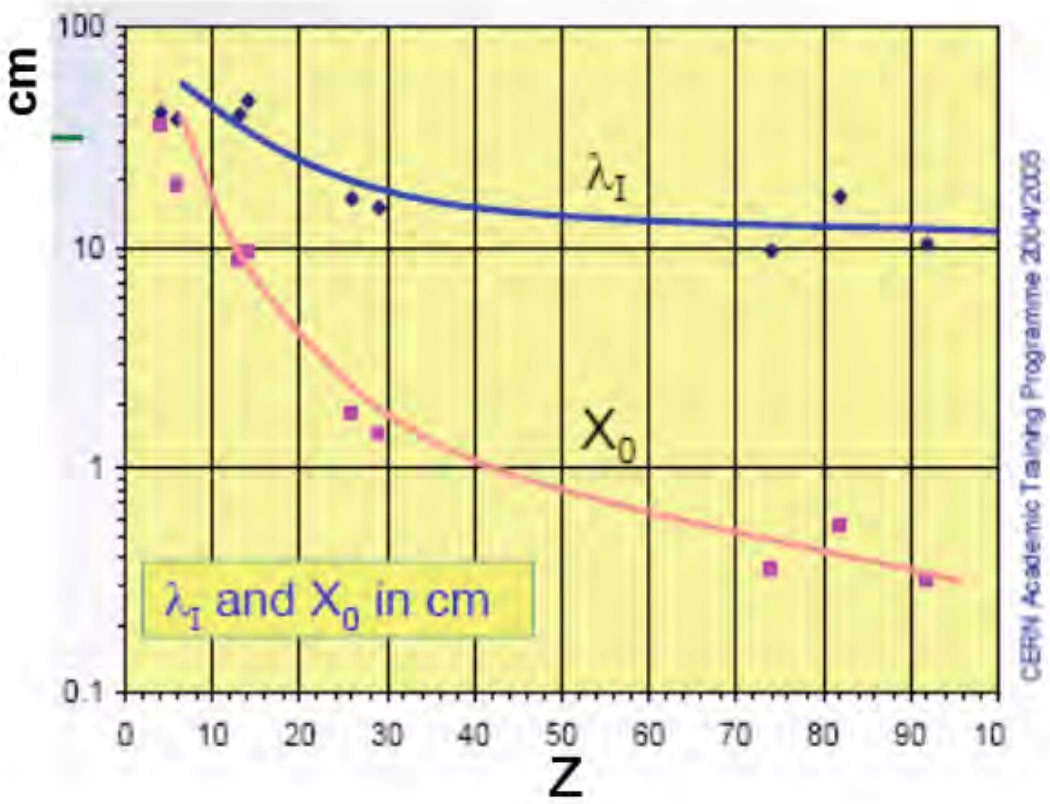
Courtesy of H. C. Schoultz Coulon

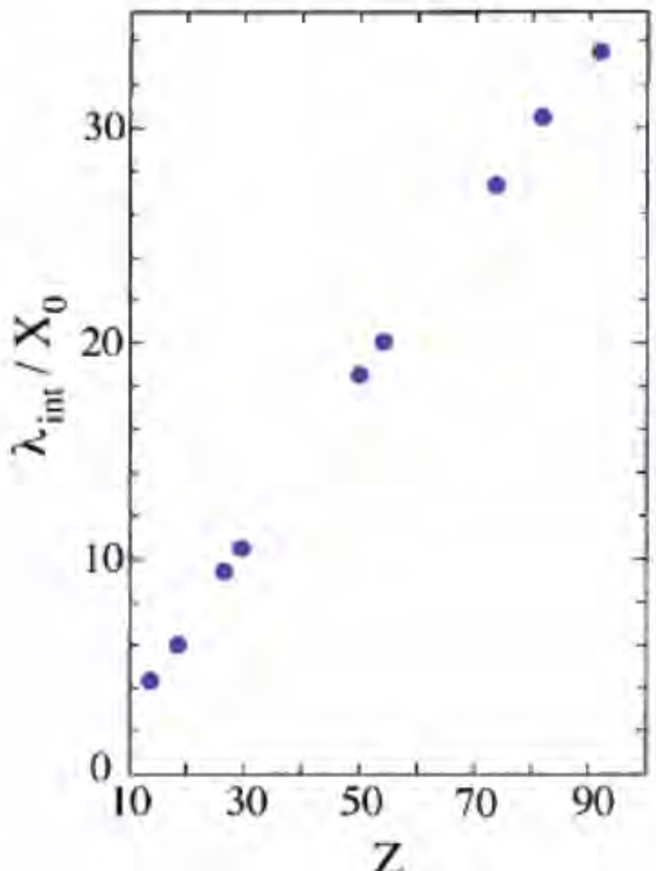
Comparison: Electromagnetic vs. Hadronic Showers

λ_{int}: mean free path between nuclear collisions

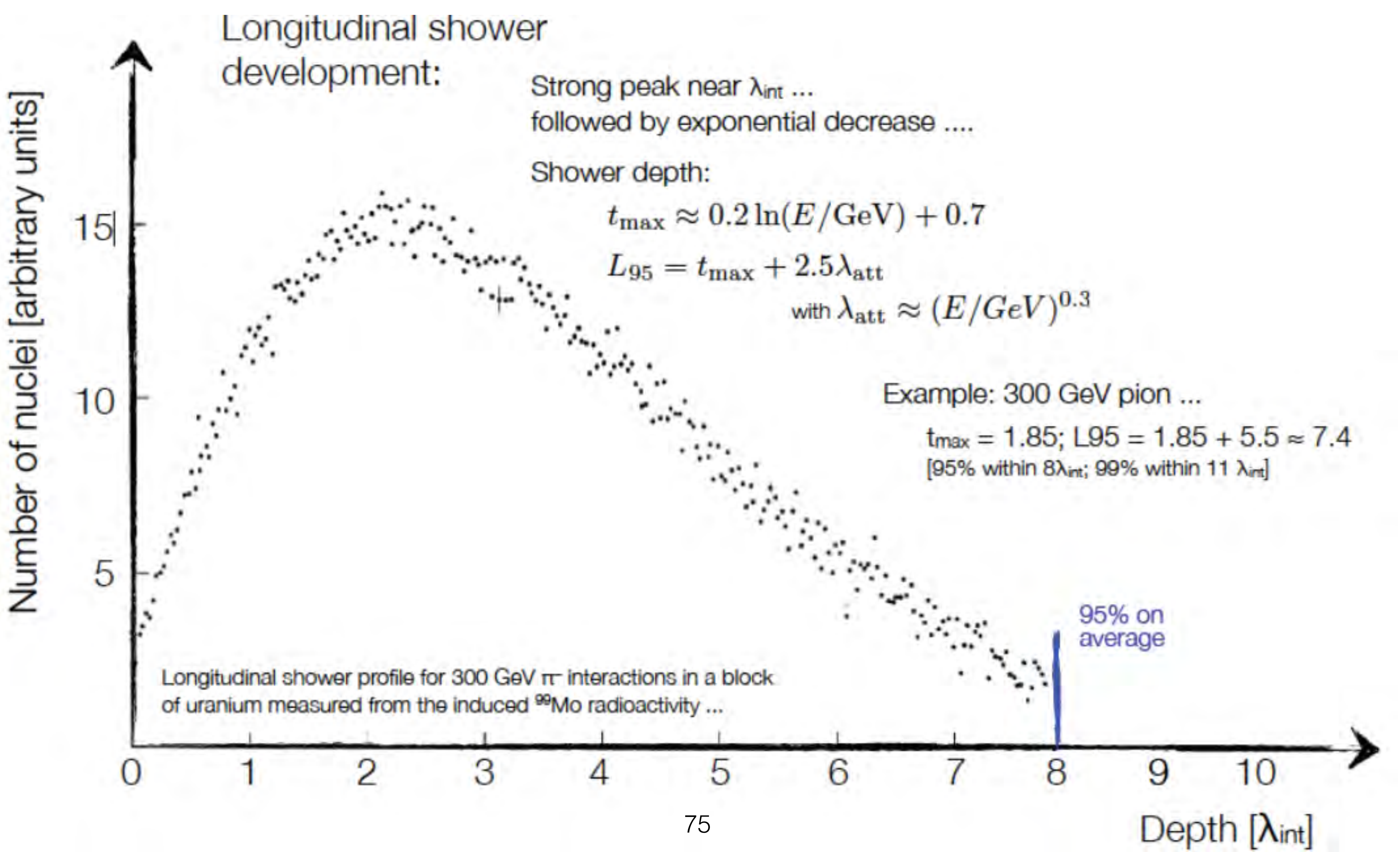
λ_{int} (g cm^{-2}) $\propto A^{1/3}$

Hadron showers are much longer than EM ones – how much, depends on Z





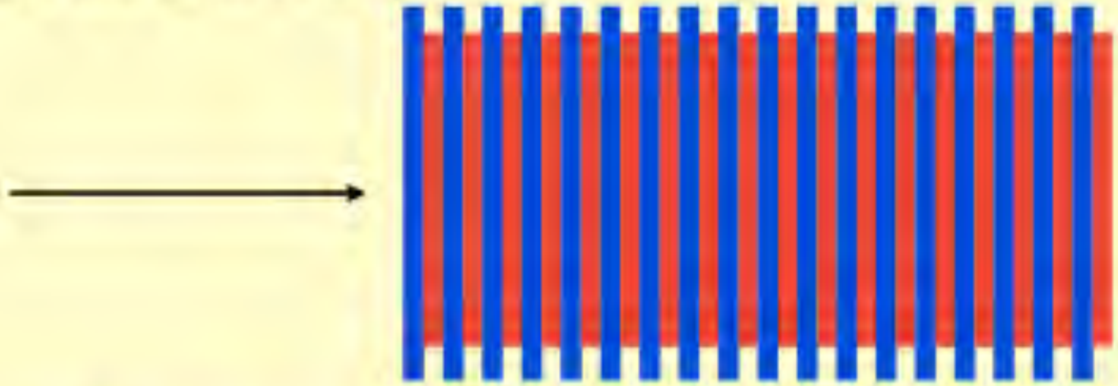
Hadronic Showers: Longitudinal development



Two types of calorimeters

Sampling calorimeters:

Layers of passive absorber (such as Pb, or Cu) alternate with active detector layers such as Si, scintillator or liquid argon



Homogeneous calorimeters:

A single medium serves as both absorber and detector, eg: liquified Xe or Kr, dense crystal scintillators (BGO, $PbWO_4$ ....), lead loaded glass.

Inorganic Scintillators

Scintillator material	Density [g/cm³]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [μs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
$Bi_4Ge_3O_{12}$	7.1	2.15	480	0.30	$2.8 \cdot 10^3$
CsF	4.1	1.48	390	0.003	$2 \cdot 10^3$
LSO	7.4	1.82	420	0.04	$1.4 \cdot 10^4$
$PbWO_4$	8.3	1.82	420	0.006	$2 \cdot 10^2$
LHe	0.1	1.02	390	0.01/1.6	$2 \cdot 10^2$
LAr	1.4	1.29*	150	0.005/0.86	$4 \cdot 10^4$
LXe	3.1	1.60*	150	0.003/0.02	$4 \cdot 10^4$

* at 170 nm

Organic Scintillators

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

Comparison

Inorganic scintillators

high light yield

[typical; $\varepsilon_{sc} \approx 0.13$]

high density

[e.g. $PBWO_4$: 8.3 g/cm^3]

good energy resolution

complicated crystal growth

large temperature dependence

expensive

Organic scintillators

easily shaped

small temperature dependence

pulse shape discrimination possible

cheap

lower light yield

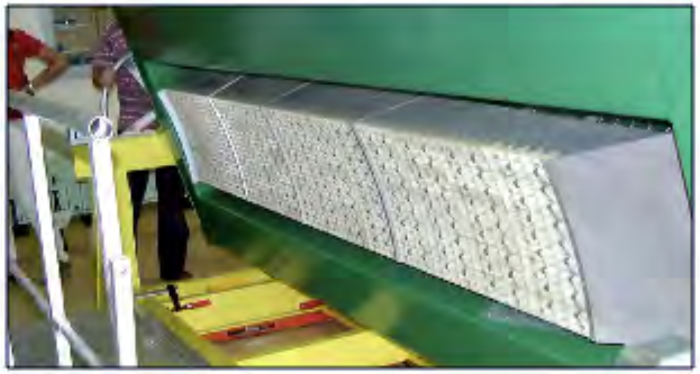
[typical; $\varepsilon_{sc} \approx 0.03$]

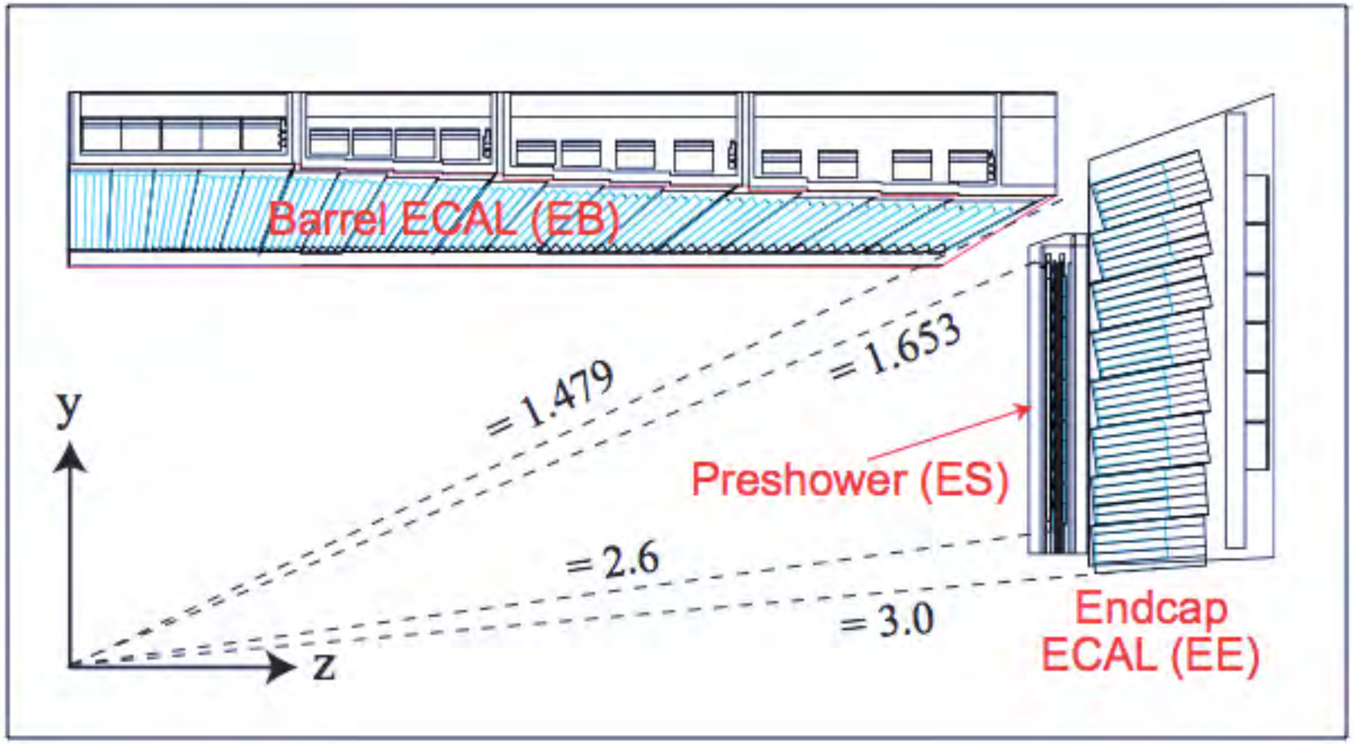
radiation damage

Example: Electromagnetic calorimeter of CMS

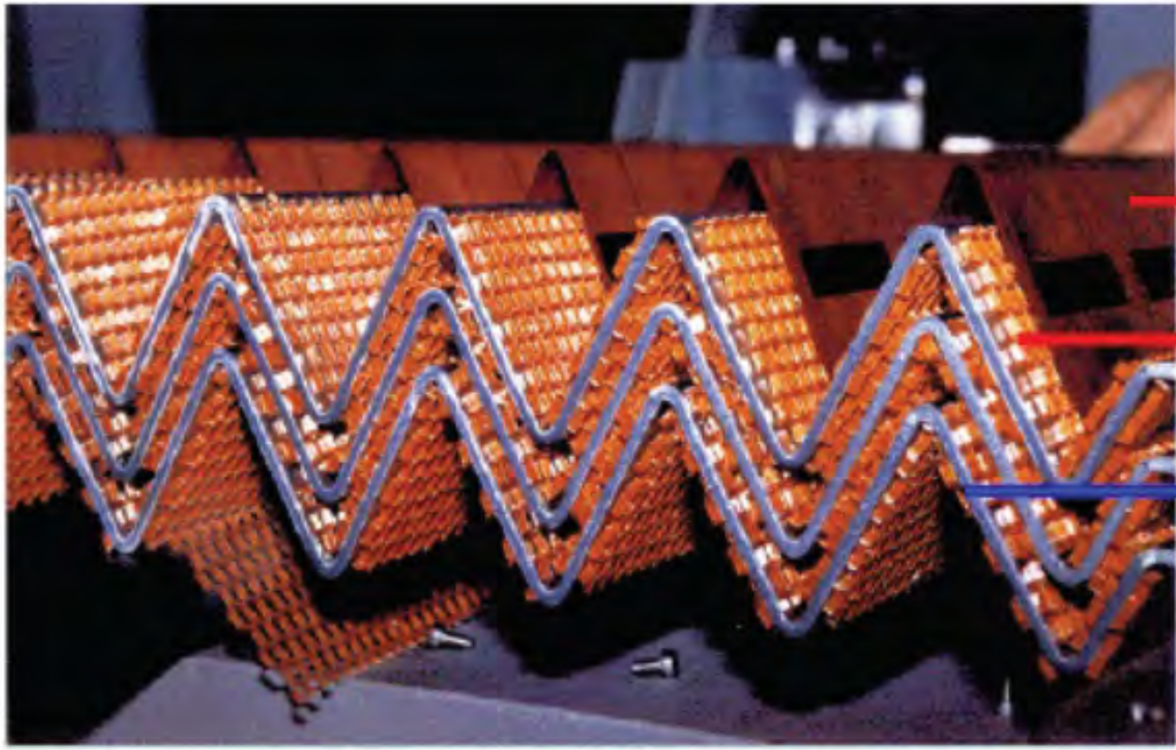
Scintillator : $PBW0_4$ [Lead Tungsten]
Photosensor : APDs [Avalanche Photodiodes]

Number of crystals: ~ 70000
Light output: 4.5 photons/MeV





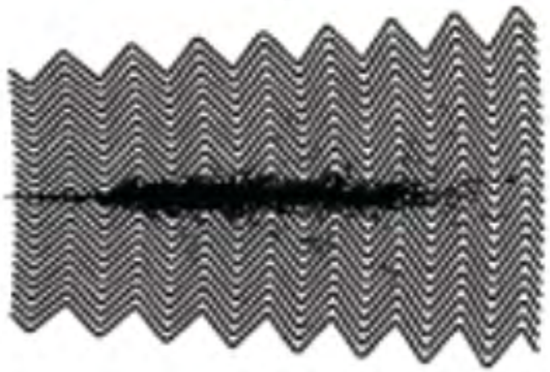
ATLAS LAr Calorimeter

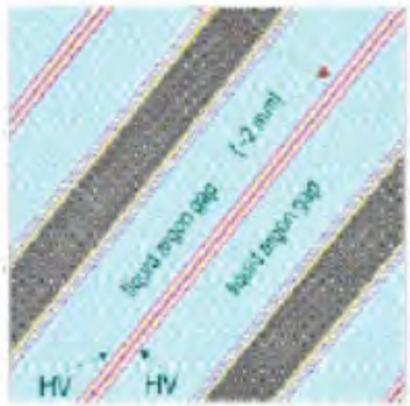


Cu electrodes at +HV

Spacers define LAr gap
2×2 mm

2 mm Pb absorber
clad in stainless steel.





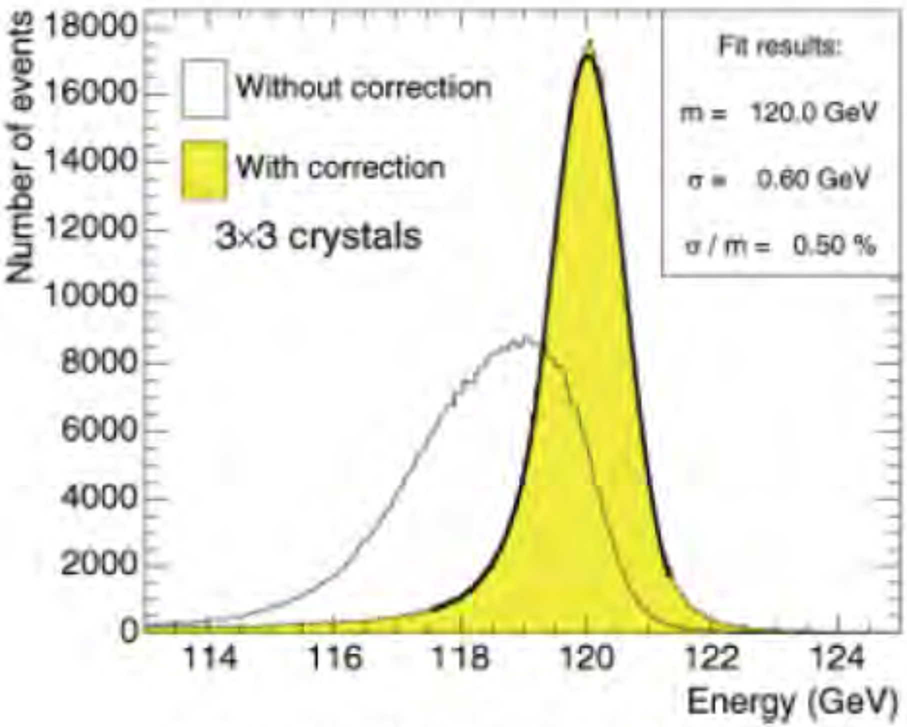
Energy resolution: 3 contributions

a: stochastic term
- intrinsic statistical shower fluctuations
- sampling fluctuations
- signal quantum fluctuations (e.g. photo-electron statistics)

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

c: noise term
- readout electronic noise
- Radio-activity, pile-up fluctuations

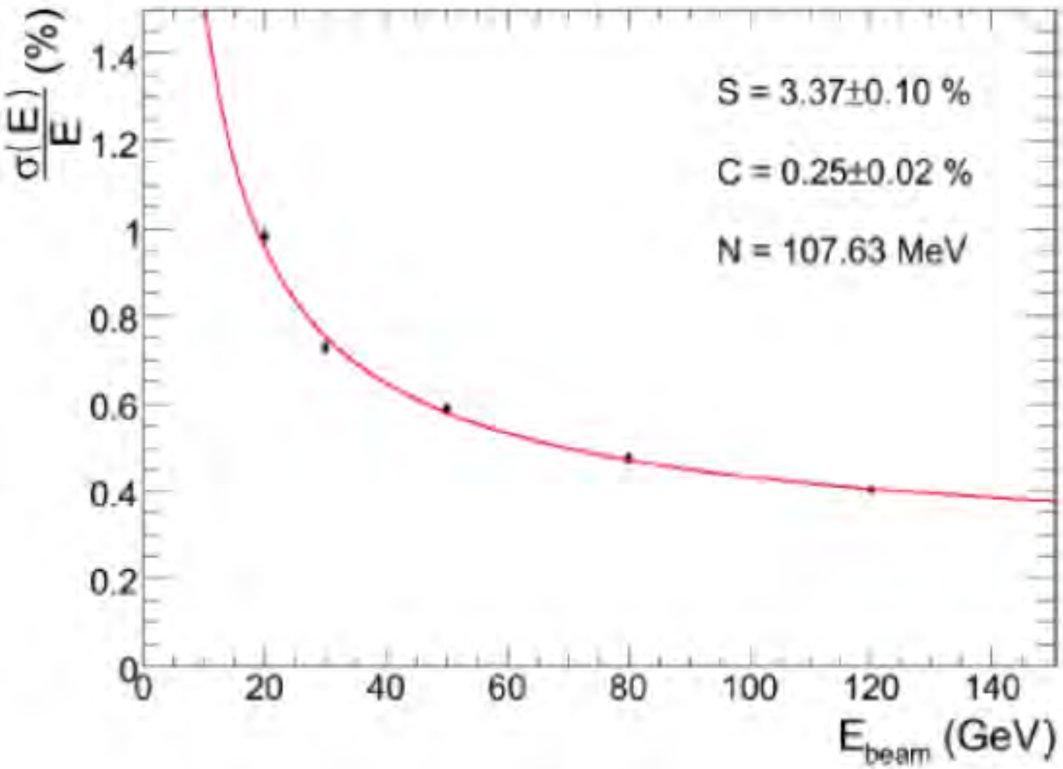
CMS ECAL Energy Resolution



Correction for radial loss

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{3.37\%}{\sqrt{E}}\right)^2 + \left(\frac{0.107}{E}\right)^2 + (0.25\%)^2$$

stoch. noise const.



The sampling term is 3 times smaller than ATLAS; other terms are similar

Particle Identification

If the momentum of a particle is known ...

- then we need a second observable to identify the particle:

Velocity:	Time-of flight	$\tau \propto 1/\beta$
	Cherenkov angle	$\cos\theta = 1/\beta n$
	Transition radiation	$\gamma \geq 1000$
Energy loss:	Bethe-Bloch	$\frac{dE}{dx} \propto \frac{z^2}{\beta^2} \ln(a\beta\gamma)$
Total energy:	Calorimeter	$E = \gamma m_0 c^2$

Example: LHCb Ring Imaging Cherenkov Detector (RICH)

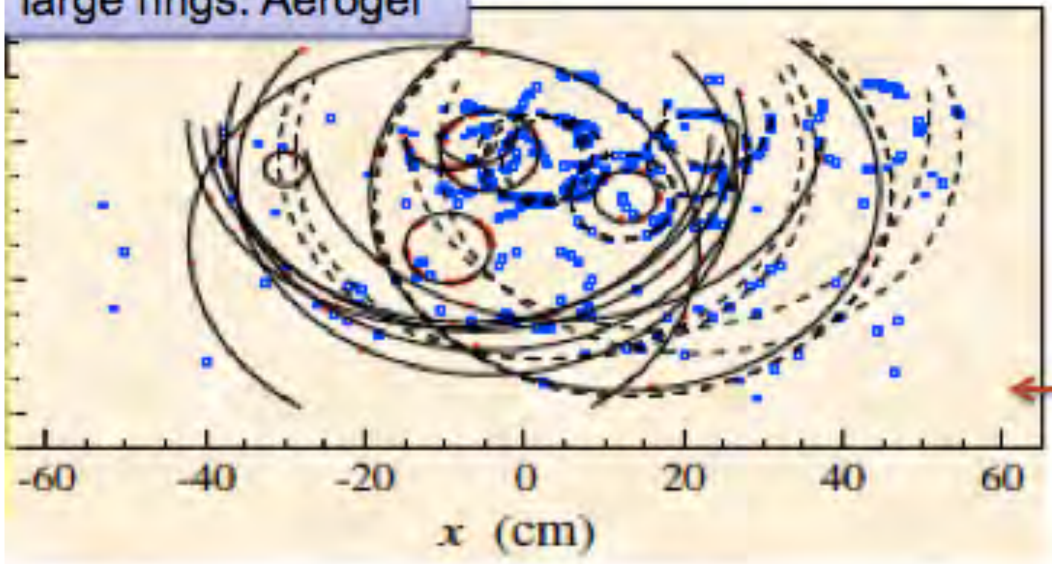
Determination of β from ring radius:

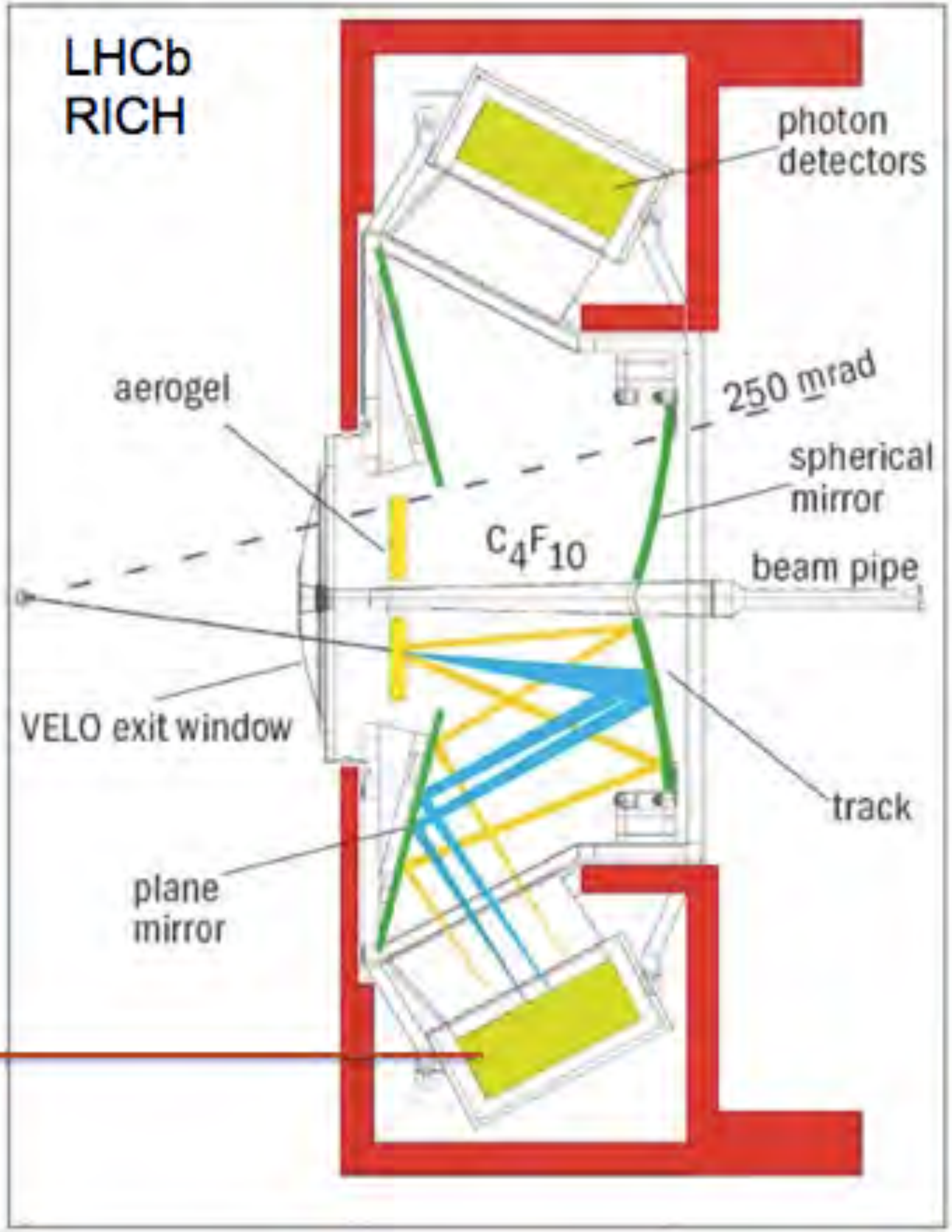
$$\beta = \frac{1}{n\cos(2r/R_s)}$$

R_s : radius of spherical mirror

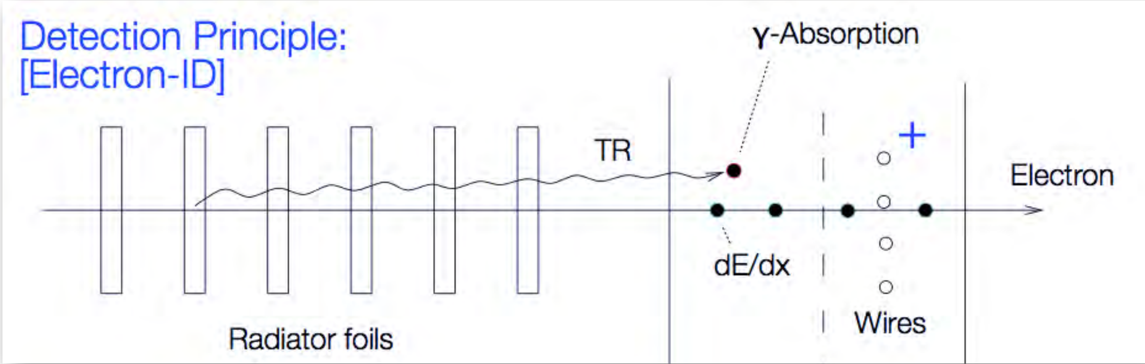
RICH (Ring Imaging Cherenkov Counter)
DIRC (Detection of Internally Reflected Cherenkov Light)
DISC (special DIRC; e.g. Panda)

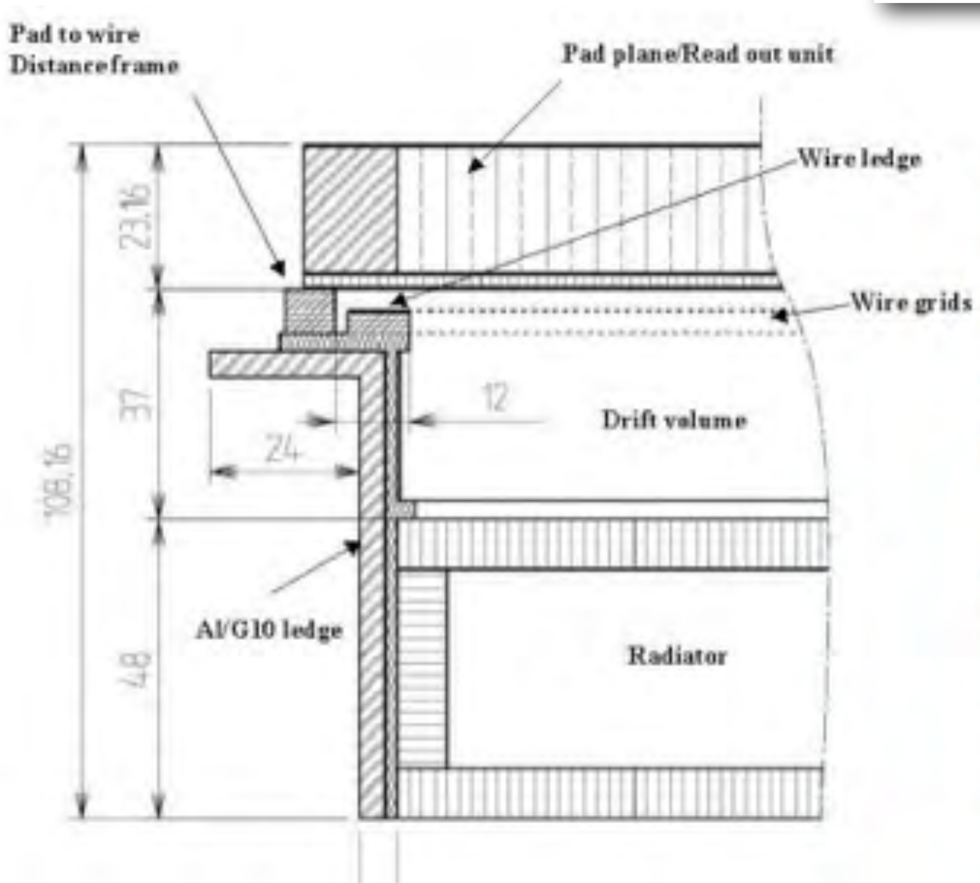
small rings: C_4F_{10}
large rings: Aerogel

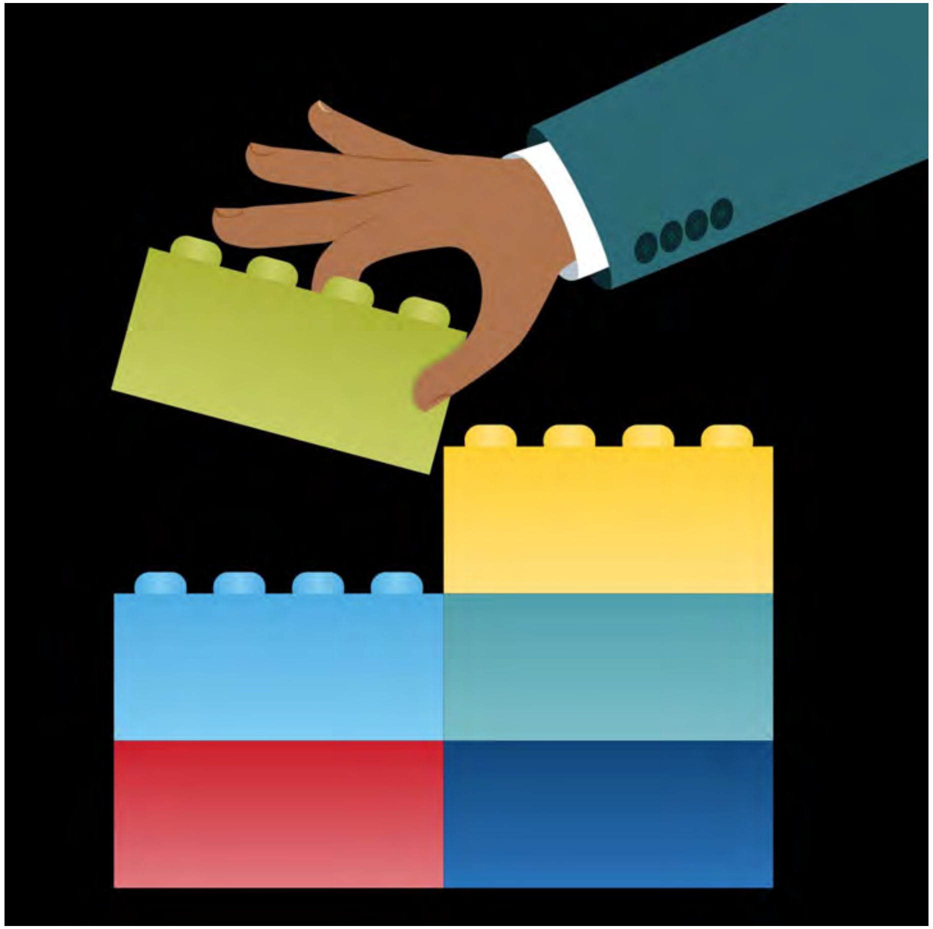




Example: Transition radiation detetor (ALICE)

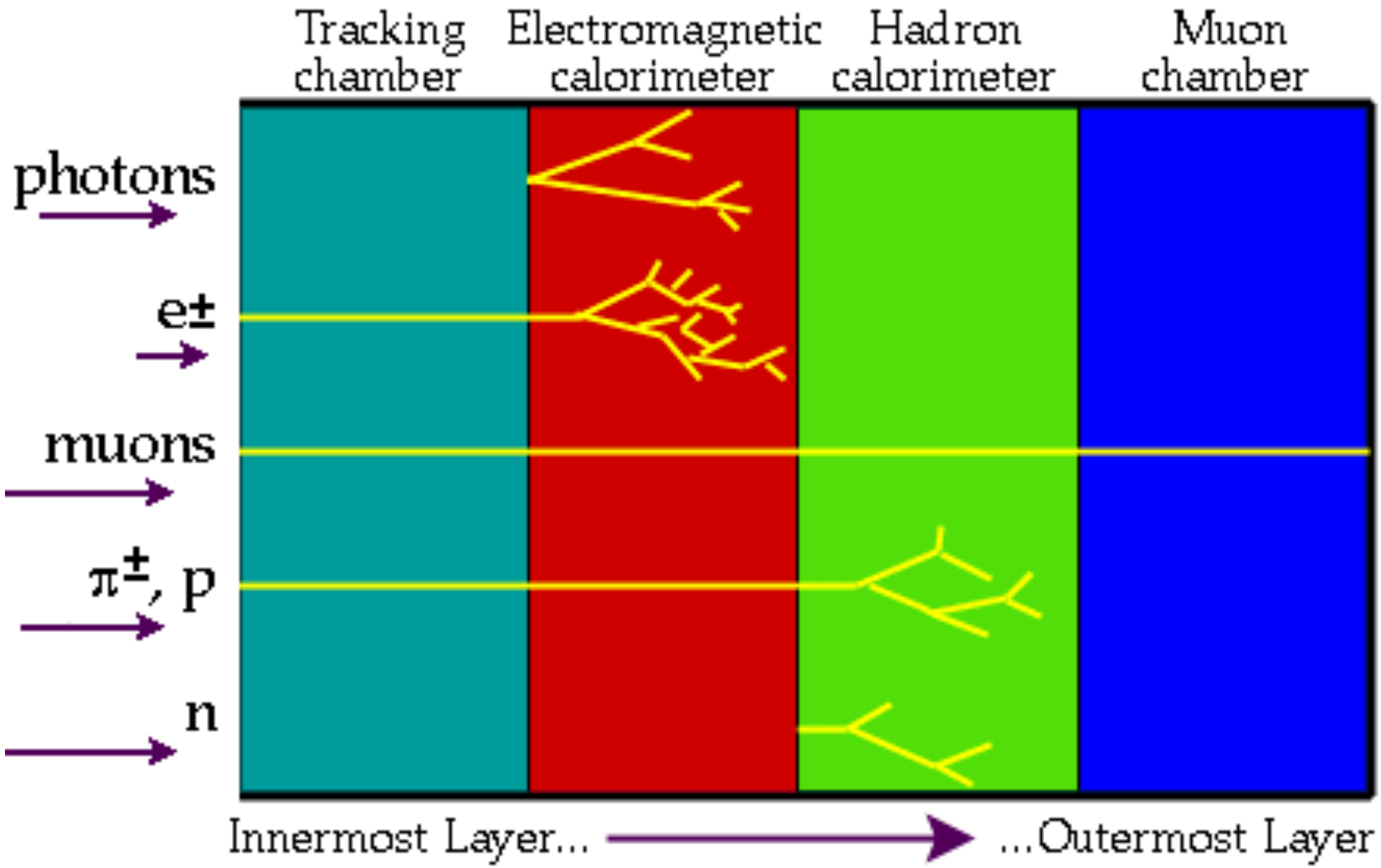




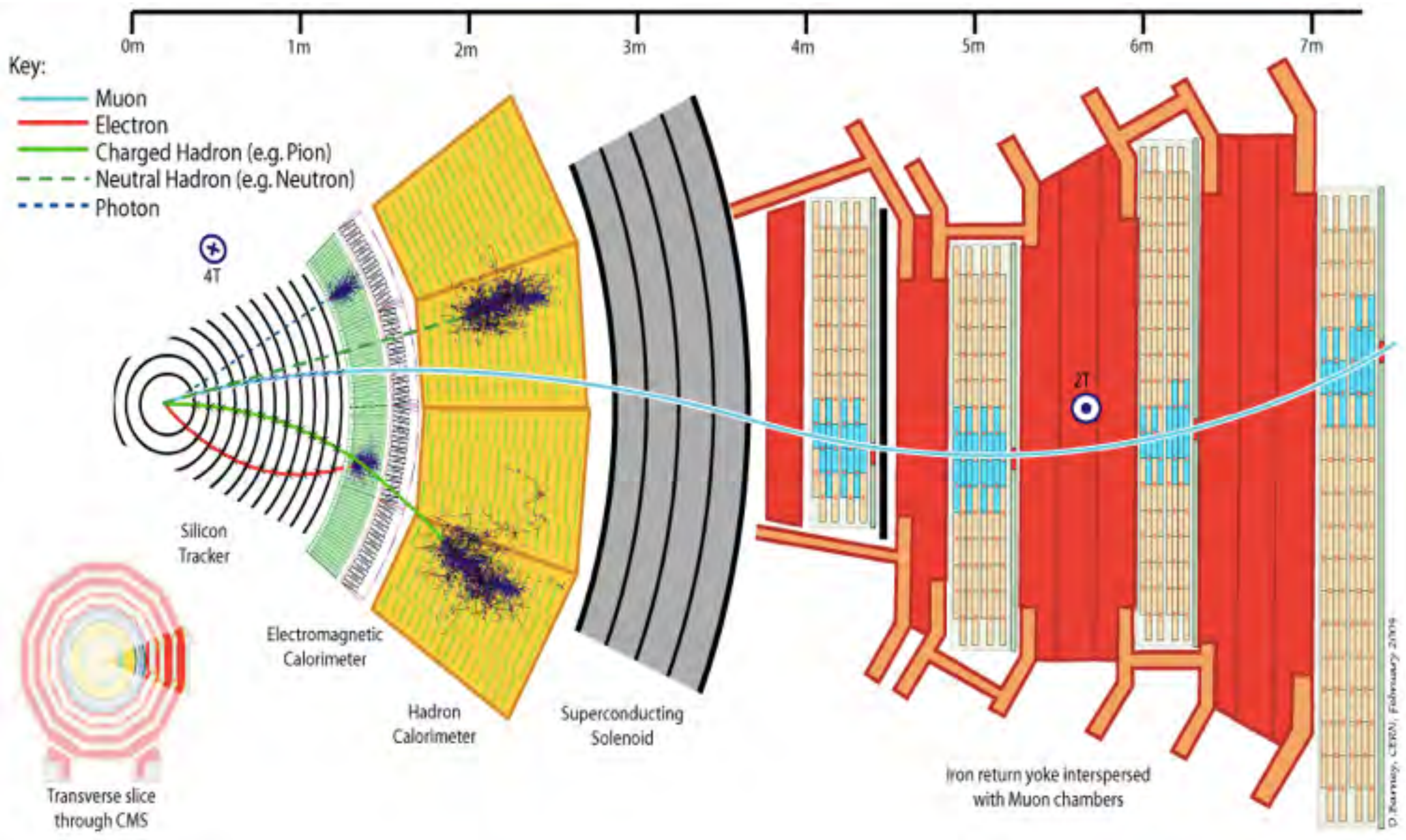


Putting everything together:

Onion Shell Principle

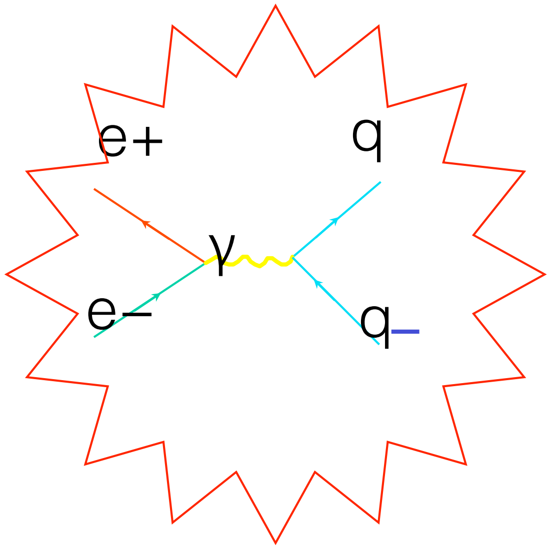


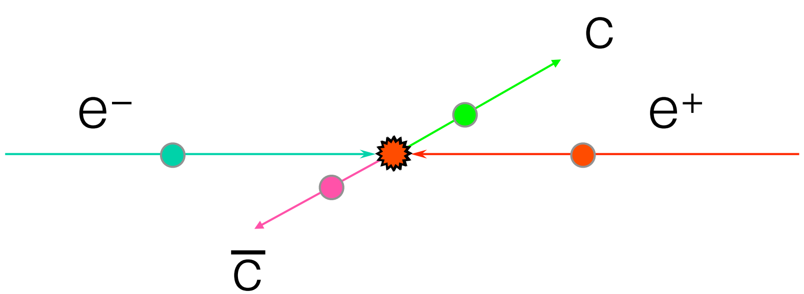
Example: CMS


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

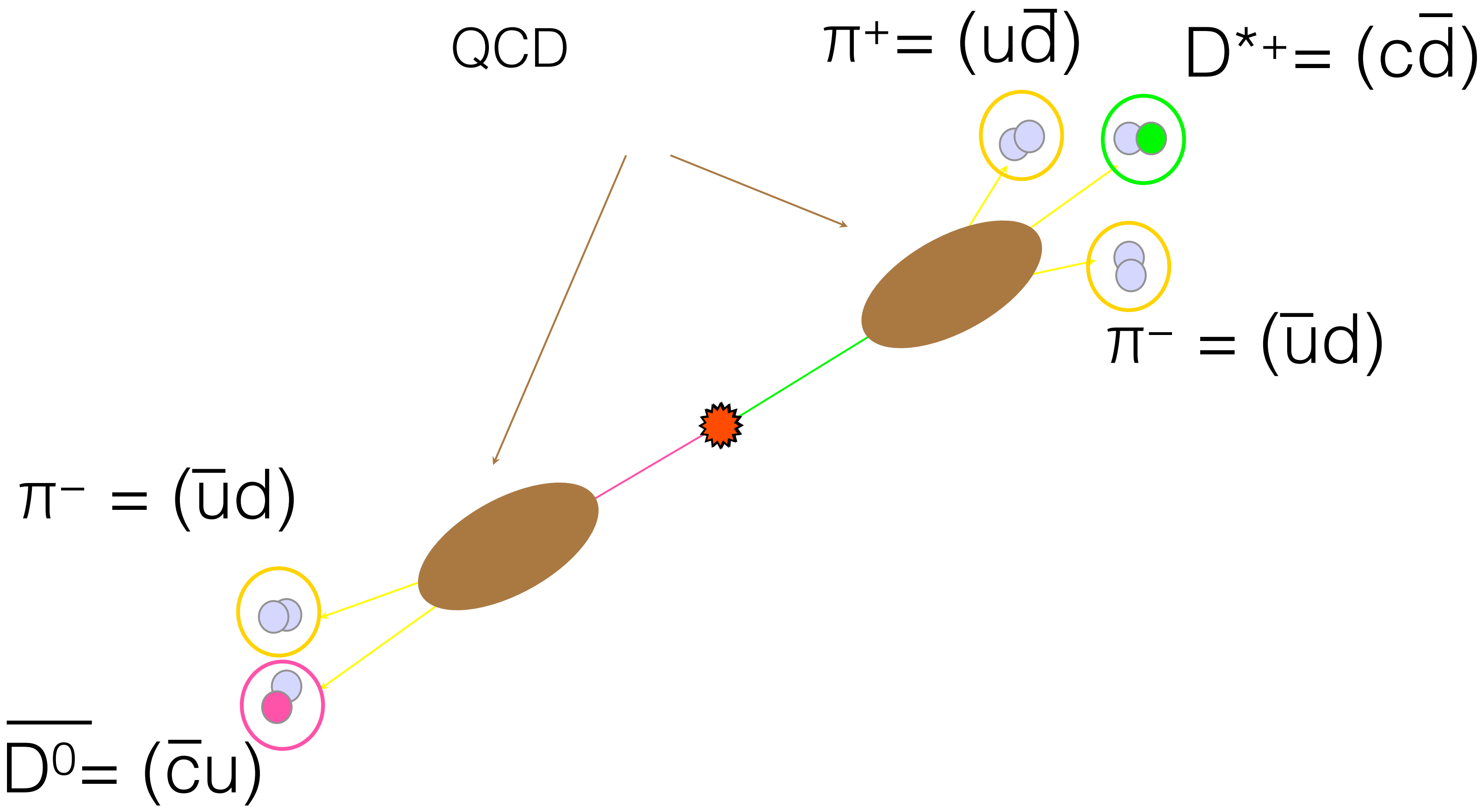
Problem: many of the particles decay before they reach the detector

- How do we detect and identify short-lived particles?
    - This depends critically on their lifetime and decay modes
- Consider as an example : Charm production in a e^+e^- collider
    - At time 0, the reaction happens:

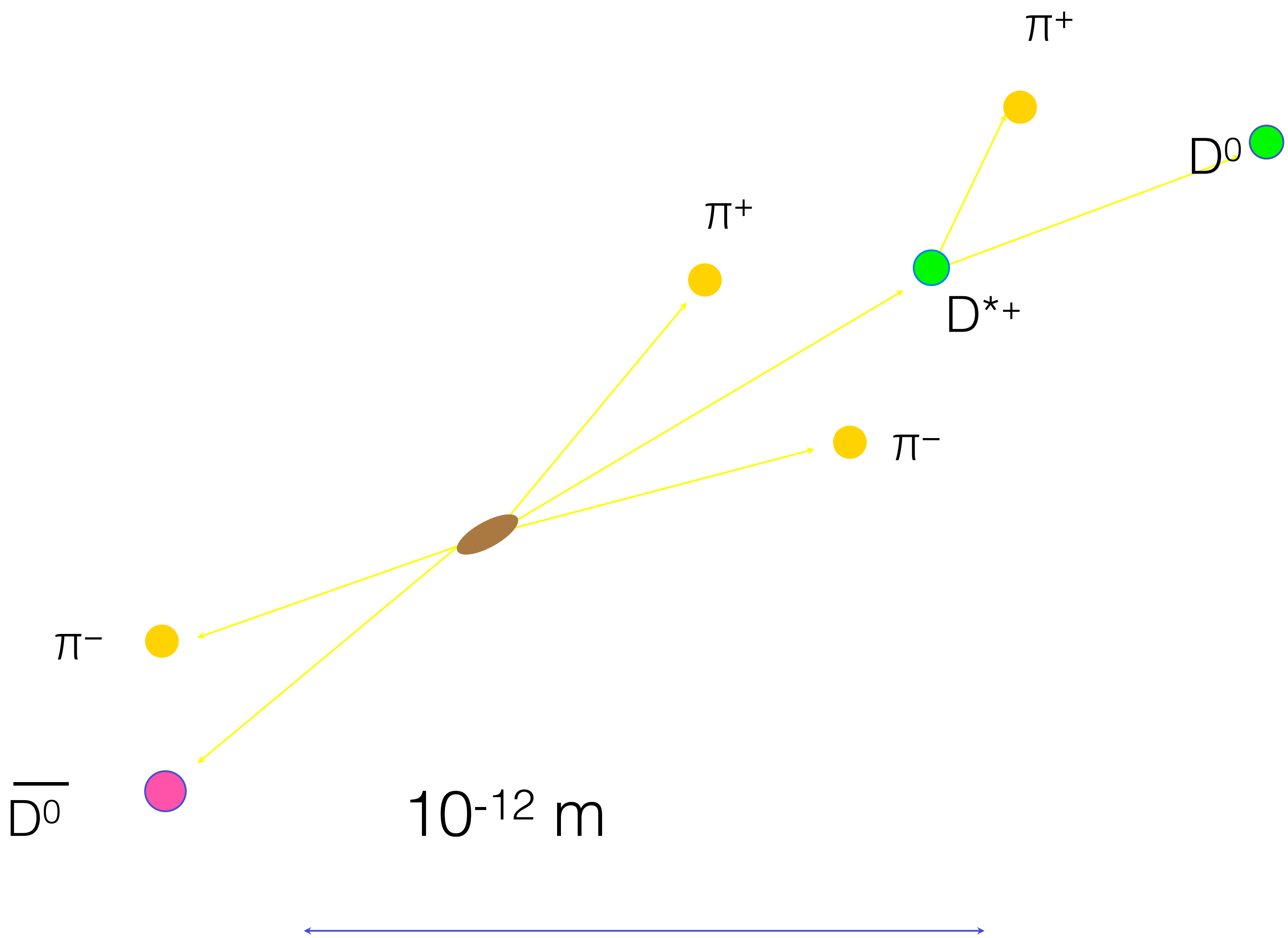




After 10^{-23} s : Hadronization

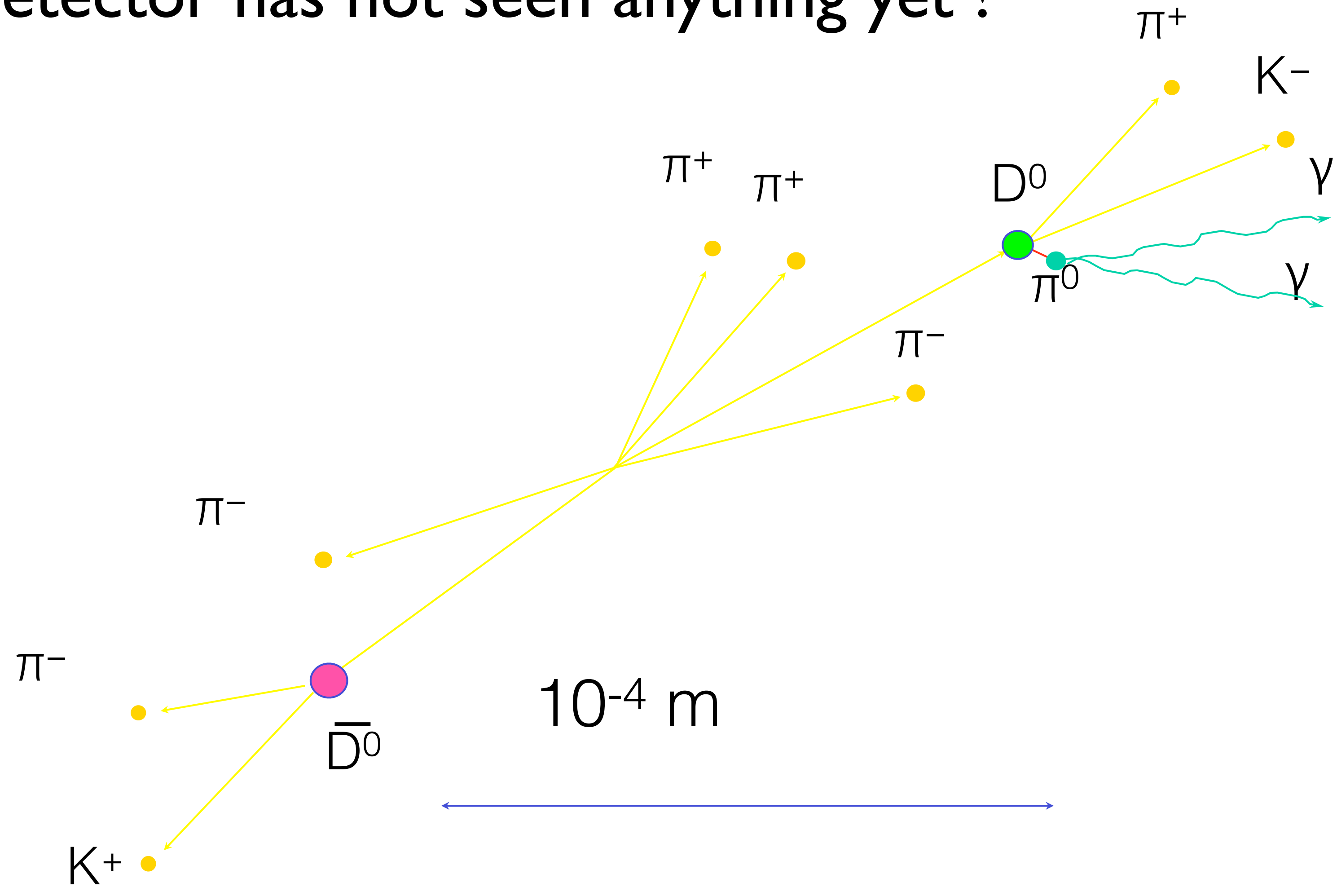


After 10^{-20} s: Hadronic Decays

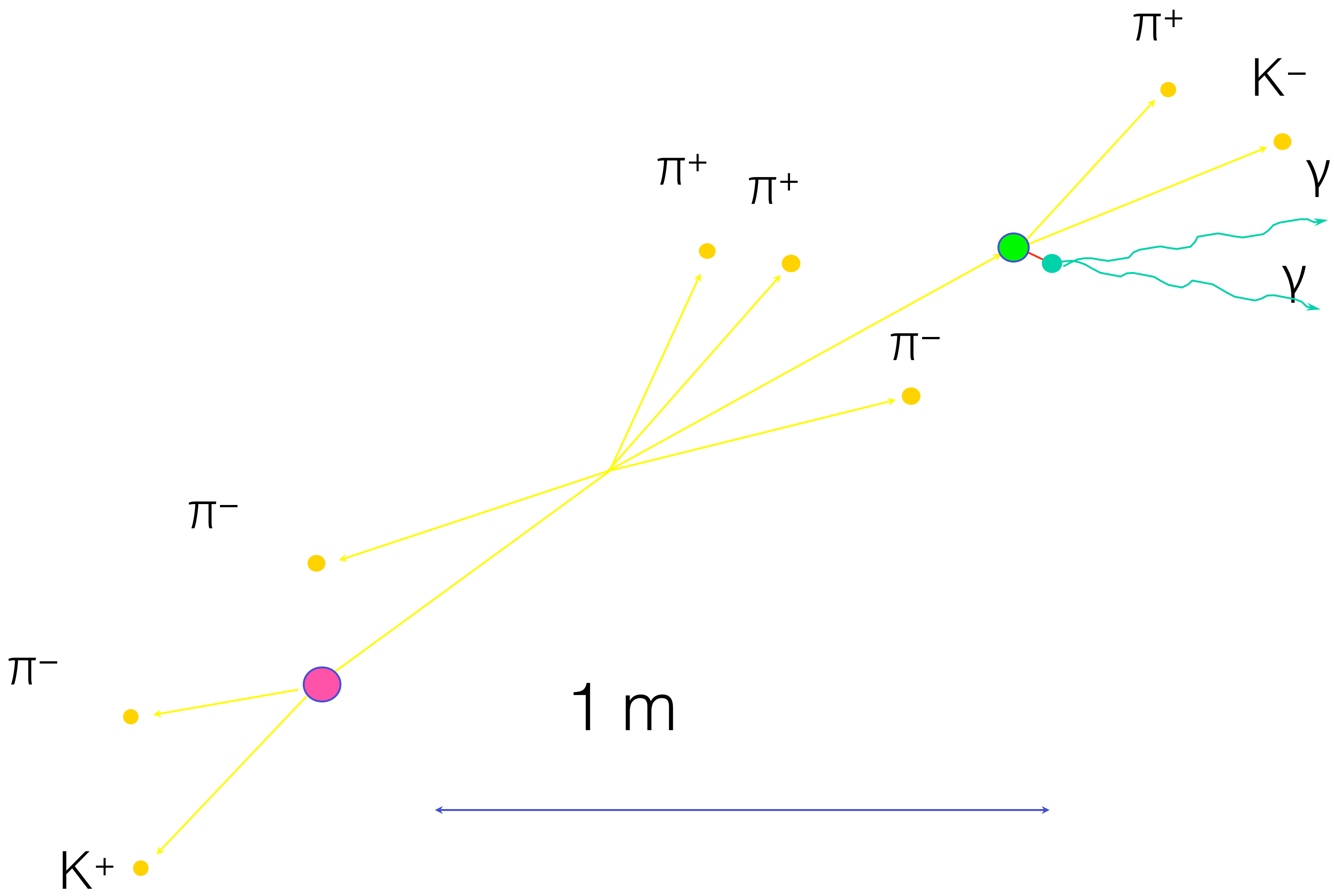


After 10^{-12} s: Weak Decays

- Our detector has not seen anything yet !



We see this (after 10^{-8} s) !



How can we reconstruct what happened ?

- We need to measure all particles, which make it into our detectors as precisely as possible
  - measure 3-momenta and angles
  - particle identification
    - particle mass
      - **construct 4-momentum vectors**
- Next step:
  - **reconstruct decaying particles** from
    - invariant mass of their decay products
      - problem : which of the detected particles belong to a parent ?
        - combinatorial background !
    - in case of a kinematically complete experiment
      - from the missing mass of all other particles
  - **identify long-lived particles from their secondary decay vertices**
    - works for week decays of particles with open strangeness, charm or beauty

Finally: modern detectors are heavy .... and big .... and expensive ...

Brandenburger Tor
in Berlin

CMS is 30% heavier than the Eiffel tower