"Detector Physics: from particle interactions to tracking concepts "

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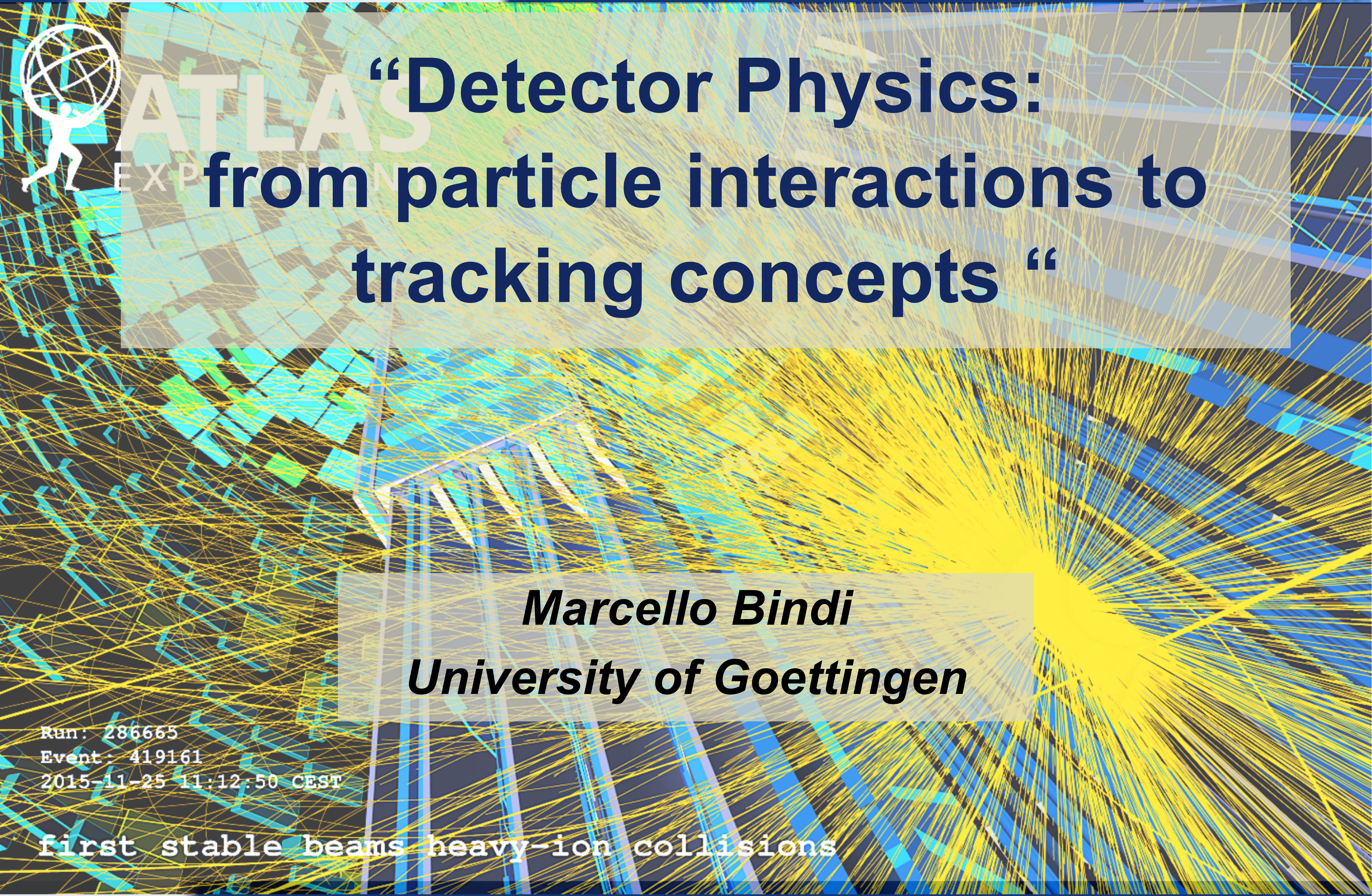


Outline of the Detector lecture

- 1st part (this talk)
  - Particle detection concepts: detection vs identification
  - Interaction radiation/matter: charge vs neutral particles
  - Ionization detectors: electronic detector
  - Excitation and scintillation: light detector
  - Tracking: from track reconstruction to vertex finding
- 2nd part (next talk)
  - Calorimeters: Electromagnetic and hadronic showers
  - Overall detector system concepts
  - Near future developments

Questions to answer today

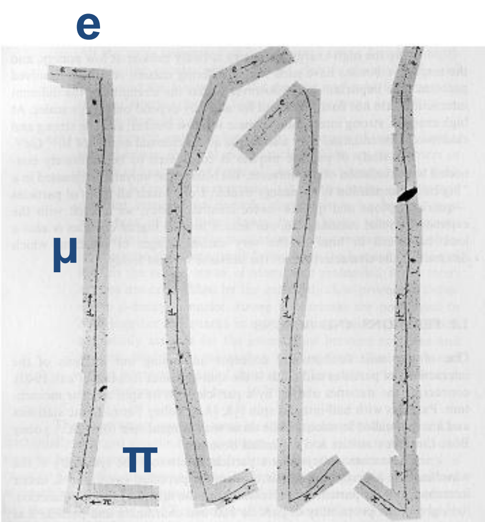
- Introduction to basic concepts of particle interaction
  - **how the various particles interact with matter?**
  - **which type of detectors are best to use for?**
- Introduction to main concepts of tracking detectors
  - **how to extract tracks/vertices from single hits?**
  - **how to design a tracking detectors?**
  - **how does a tracker nowadays look like?**

ATLAS example

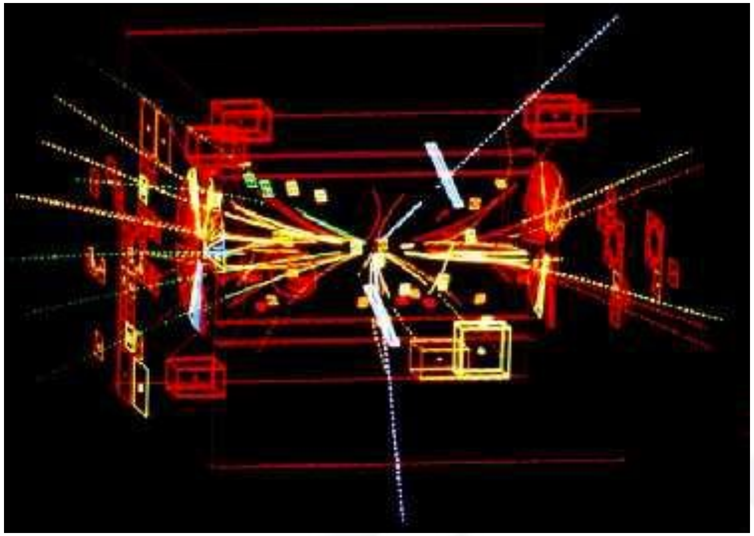
A few detection principles

- **Detection** (counting) vs **identification** (mass/charge measurement) of particles
- Different type of interactions for **charged** and **neutral** particles
- Different “scale” processes for **electromagnetic** and **strong** interactions

➔ *Evolution from pure “Image” reconstruction to “Electronics image” deduction.*



Pion discovery (1947) via nuclear emulsion

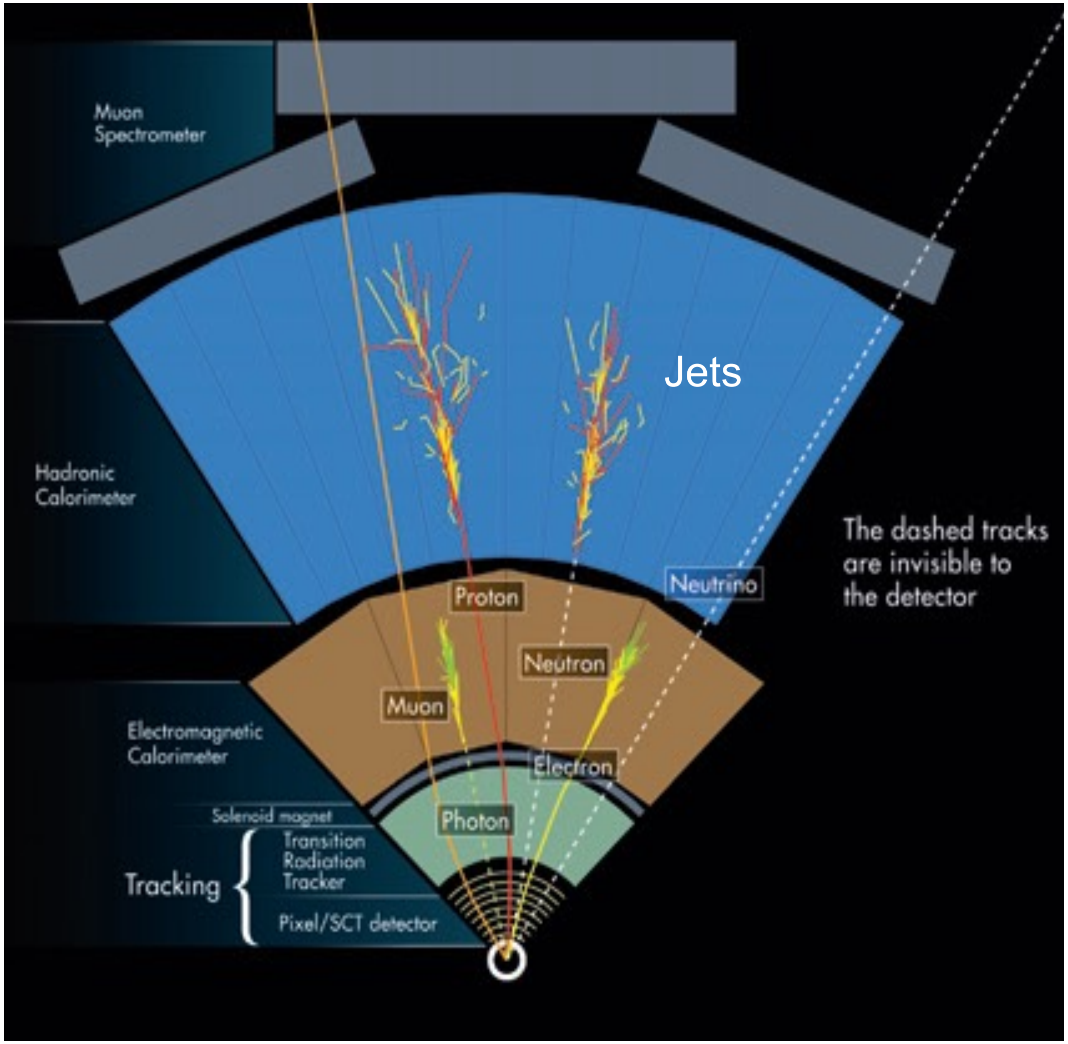


Z_0 boson discovery at UA1 CERN (1983)

- Detection/Identification based on different type of interaction of the incoming particles (originated from the collisions) with matter:
  - Charged particles (Ionization, Bremsstrahlung, Cherenkov)
  - γ-radiation (Photo-electric/Compton effect, pair production)
  - Neutrons (Strong interactions)
  - Neutrinos (Weak interactions)

Particle detection at LHC

- The detector sees only "stable" particles ($c\tau > 500\ \mu m$)
  ➔ 8 most frequently produced **$e^\pm$, $\mu^\pm$, γ, $\pi^\pm$, $K^\pm$, K^0, $p^\pm$, n**



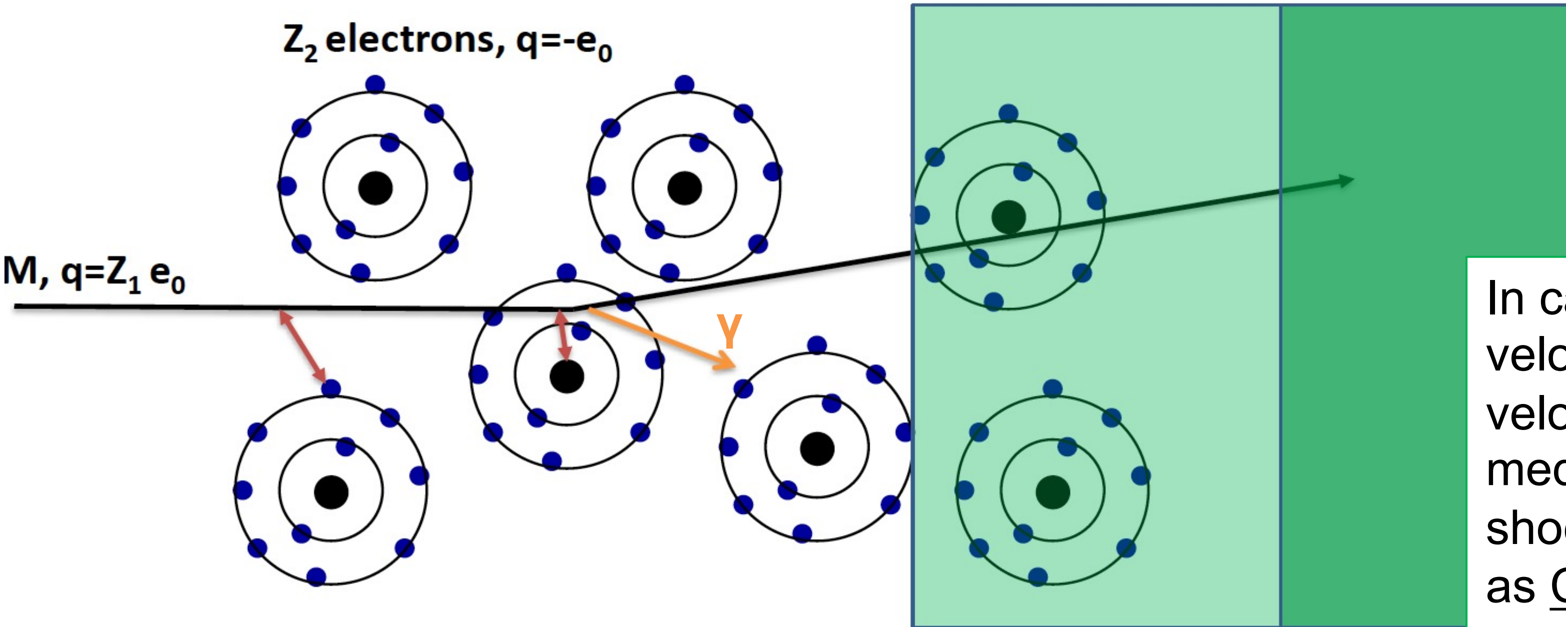
- To detect a particle, it has to interact/***deposit energy***:
  - could be a **part** (trackers) or the **full** (calorimeters) energy!
- Ultimately, **the signals** comes from the ***charged particle interactions:***
  - Neutral particles (photons, neutrons) must transfer their energy to charged particles to be measured (calorimeters)

Electromagnetic Interactions Particles/Matter

Three type of electromagnetic interactions:

1. **Excitation/Ionization (of the atoms of the traversed material)**
2. Emission of Cherenkov light
3. Emission of Transition Radiation

How the energy loss became a fundamental quantity instead of a prime issue!



In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation.

Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected causing multiple scattering in the material. During this scattering a Bremsstrahlung photon can be emitted.

When the particle crosses the boundary between two media, there is a probability (~1%) to produced an X ray photon, called Transition radiation.

Energy loss for heavy charge particles

- For heavy charged particles like proton, k, π, μ, .. where $\mathbf{m_{incident} \gg m_e}$
  - dE/dx can be described by Coulomb interaction and simple kinematics

  Classic Bohr's stopping power ➔ Quantum mechanic "Bethe-Bloch"

What's the average energy lost ***–<dE> [MeV]*** *in a material thickness* ***dx [cm]?***

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

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

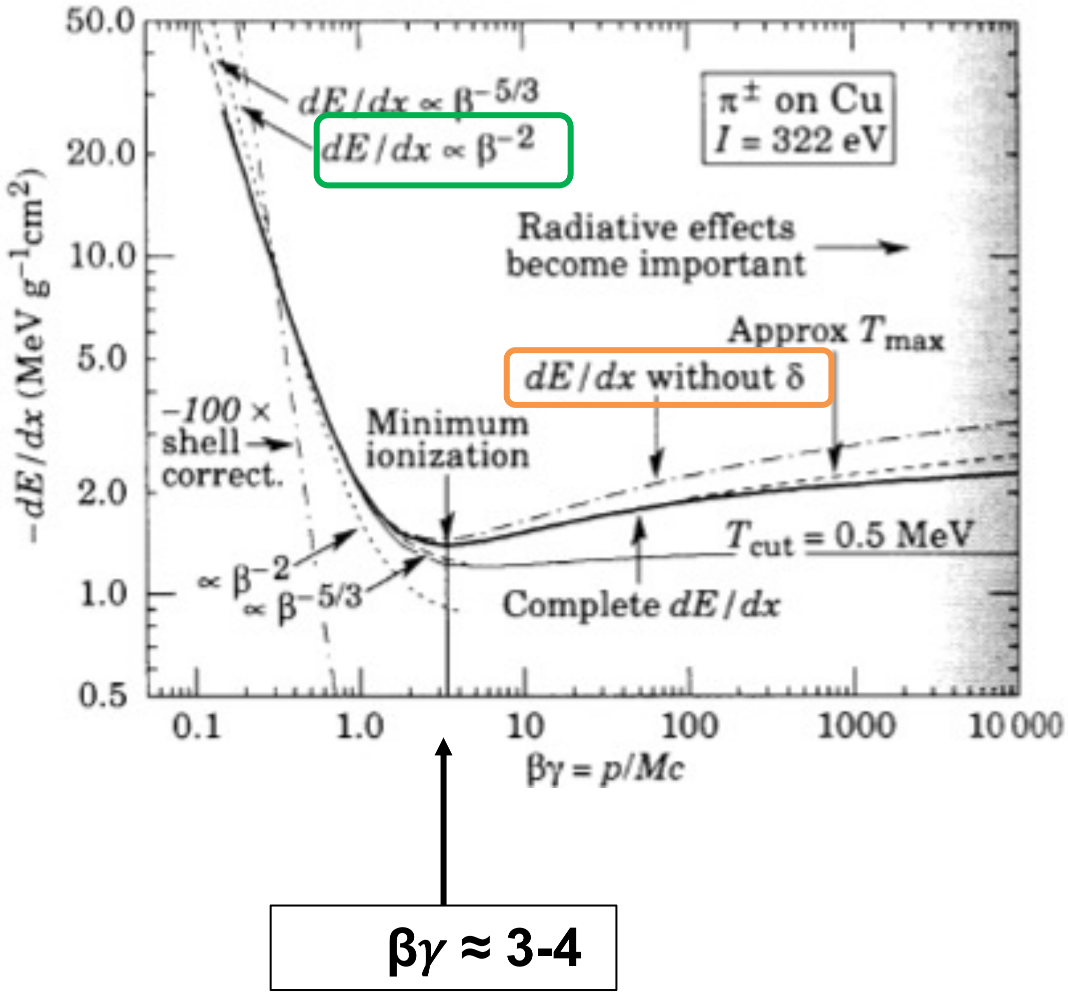
Fundamental constants
- r_e=classical radius of electron
- m_e=mass of electron
- N_a=Avogadro's number
- c =speed of light

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

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

Energy loss for heavy charge particles/2

- For heavy charged particles like proton, k, π, μ, .. where $\mathbf{m_{incident} \gg m_e}$



Three distinctive regions:

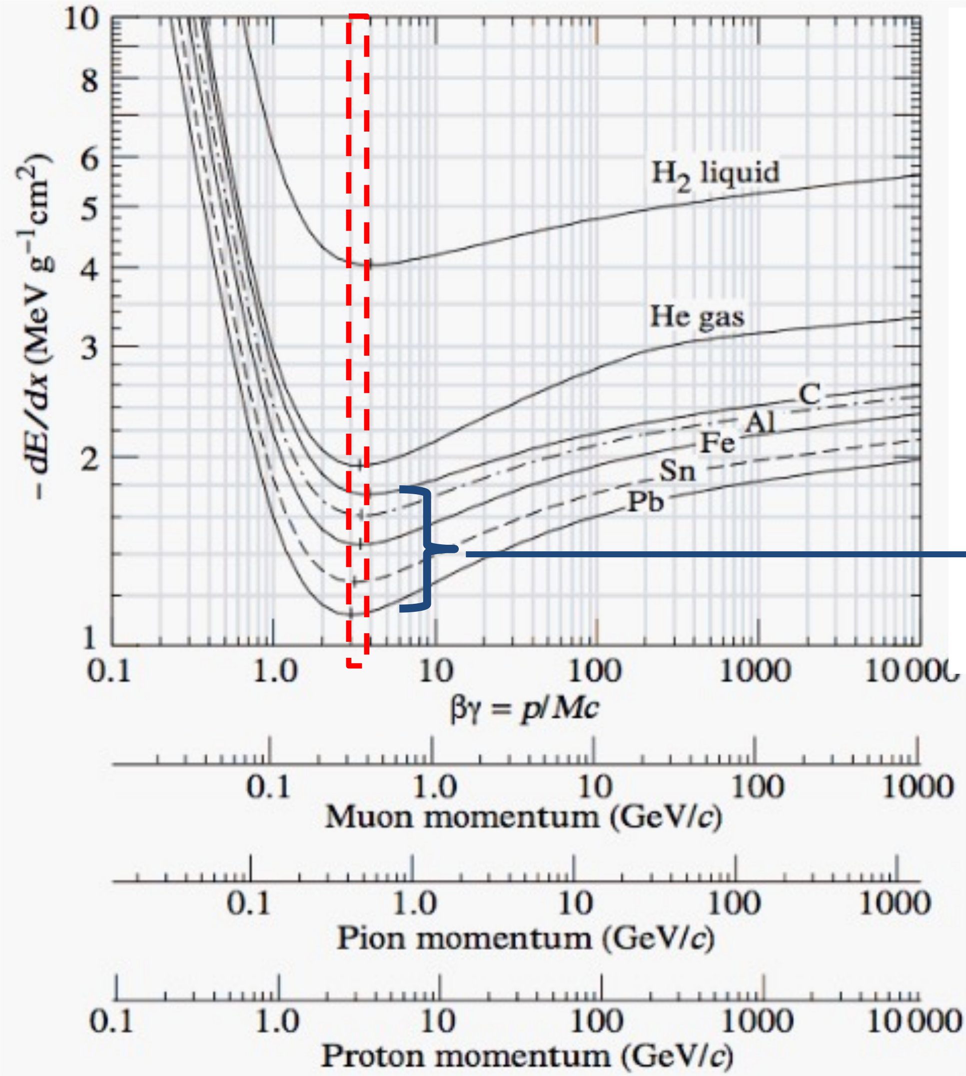
1. Steeply falling (kinematic factor) as $\mathbf{1/\beta^2}$ down to $\boldsymbol{\beta\gamma \approx 3\text{-}4}$
   - **Minimum Ionization Particle (MIP)**
2. Relativistic (modest) rise $\mathbf{\ln(\beta^2\gamma^2)}$
   - highly relativistic particles very similar in dE/dx
3. Density effect and saturation ($-\delta/2$)

Units: MeV g^{-1} cm^2 or MeV/(g • cm^{-2})
➔ **<dE/dx>$_{min}$ ~ 1- 2 MeV g^{-1} cm^2**

Density of copper: ρ=9.94 g/cm^3
➔ MIP looses ~ 13 MeV/cm in copper

Energy loss dependence on material

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



What is the dependency of the <dE/dx> on the traversed material?

- For **Z/A ≈ 0.5** (majority of materials), at the **minimum of the ionization (βγ ≈3)**

<dE/dx> $_{MIP}$ ≈ 1.4 MeV g^{-1} cm^2

Example:
M.I.P. traversing **Iron**
- thickness = 100 cm;
- ρ= 7.87 g/cm3

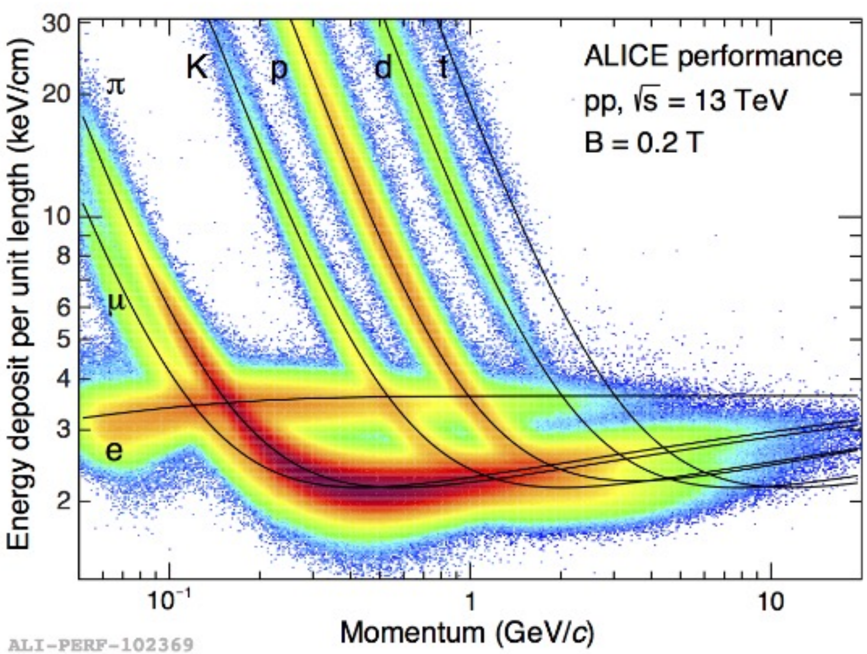
dE ≈ 1.4*100*7.87 = 1102 MeV = 1.1 GeV

➔ 1 GeV muons can travers 1 m of iron!

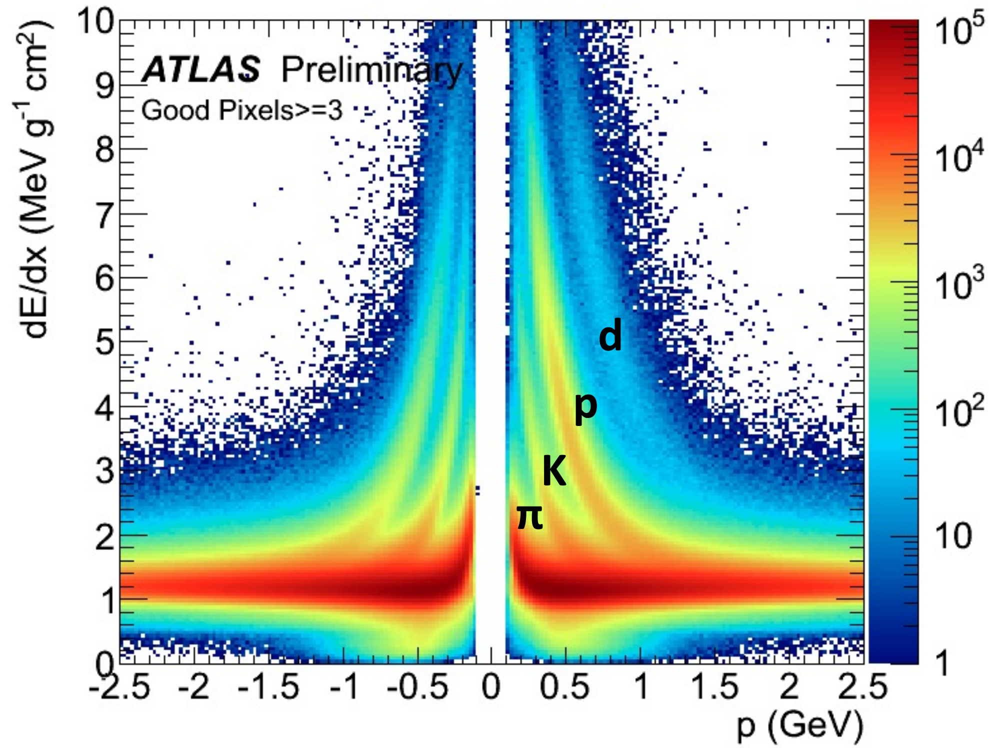
dE/dx for particle identification

- <*dE/dx*>: identical for particles with the same charge (***z***) vs ***βγ* = *p/mc***,
  ..different vs momentum ***p***

ALICE Experiment at CERN



ATLAS Experiment at CERN



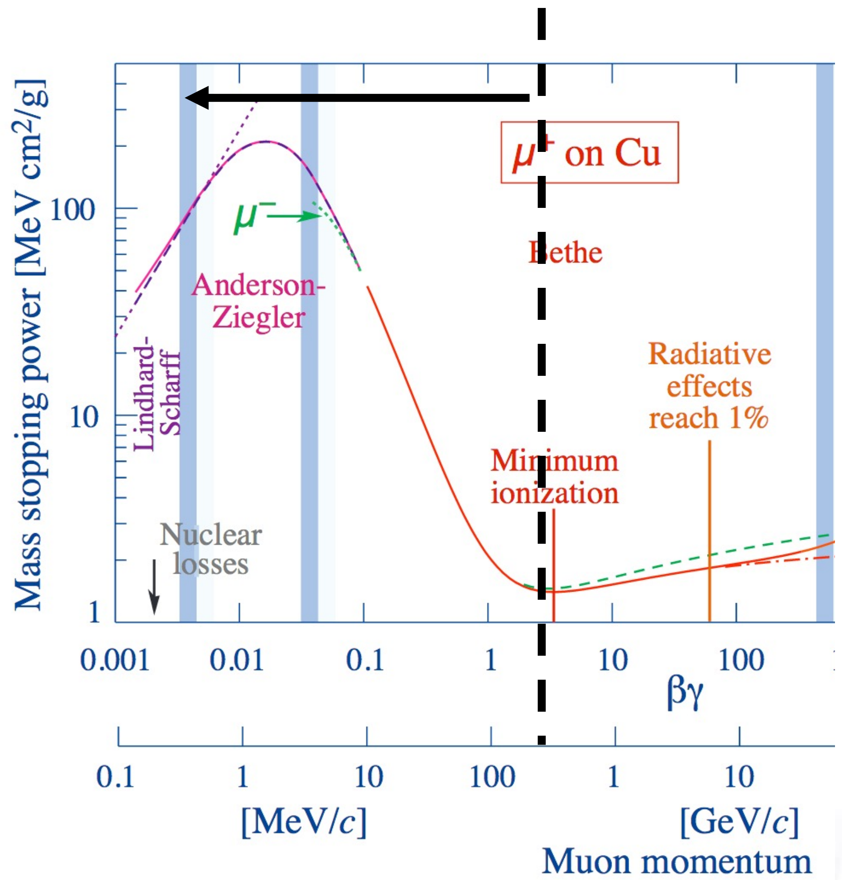
- The energy loss vs ***p*,** depends on the particle mass ***m***
- By measuring ***p*** (deflection in magnetic field) and ***dE/dx***
  ➔ mass of the particle, i.e. particle ID (in certain energy regions)

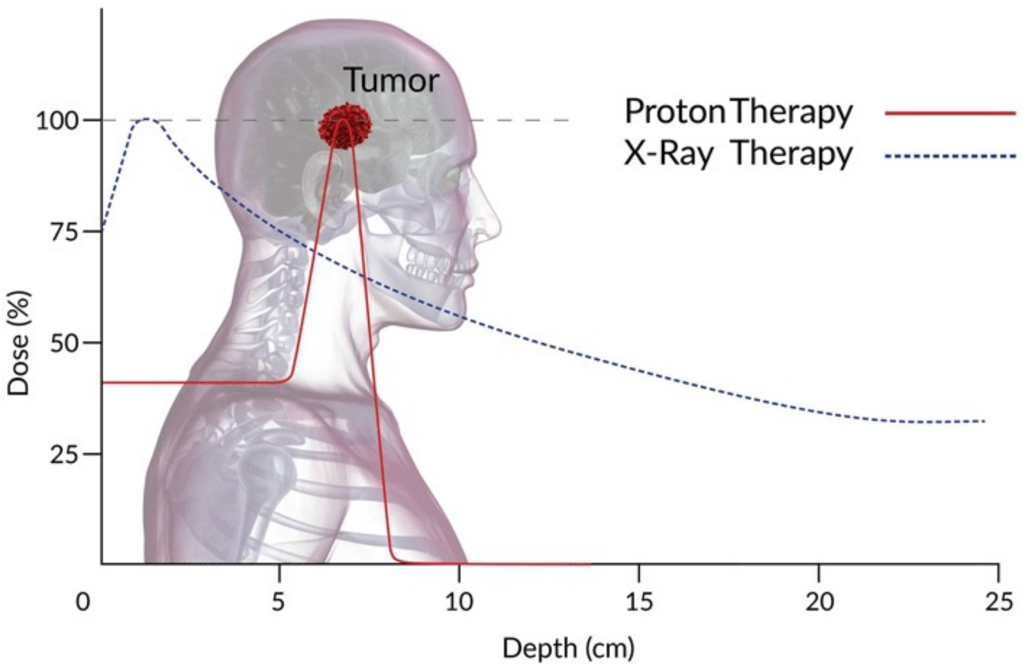
Energy loss at small momentum / Range

- For $\beta\gamma > 3$ the energy loss is ~constant
- Energy loss increases $\mathbf{1/\beta^2}$ for $\beta\gamma < 3$
  - ➔ Particles deposit most of their energy at the end of their track

Bragg peak

Important effect for cancer therapy!





Range of particles (*R*)

Particle enters the matter and looses energy until it comes to rest

$$R(T) = \int_0^T \left[-\frac{dE}{dx} \right]^{-1} dE$$

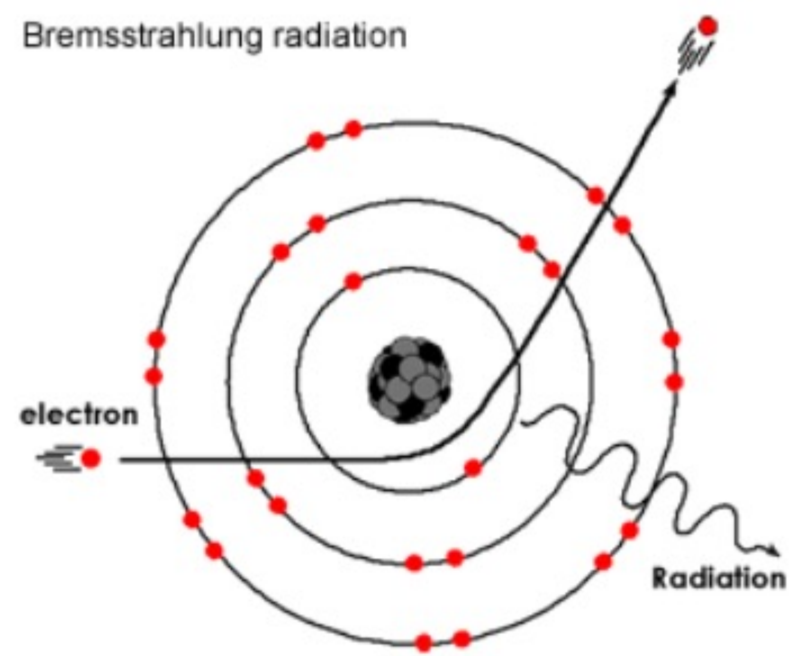
Energy loss for electrons: Bremsstrahlung

- For electrons, Bethe-Bloch formula needs corrections since:
  - Incident and target electron have same mass, QM indistinguishable

$$-\left\langle \frac{dE}{dx} \right\rangle_{Ionization} \propto \ln(E)$$

- Additional effect becoming predominant for E > 10-30 MeV

Bremsstrahlung: photon emission by the electron accelerated in the Coulomb field of nucleus.



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

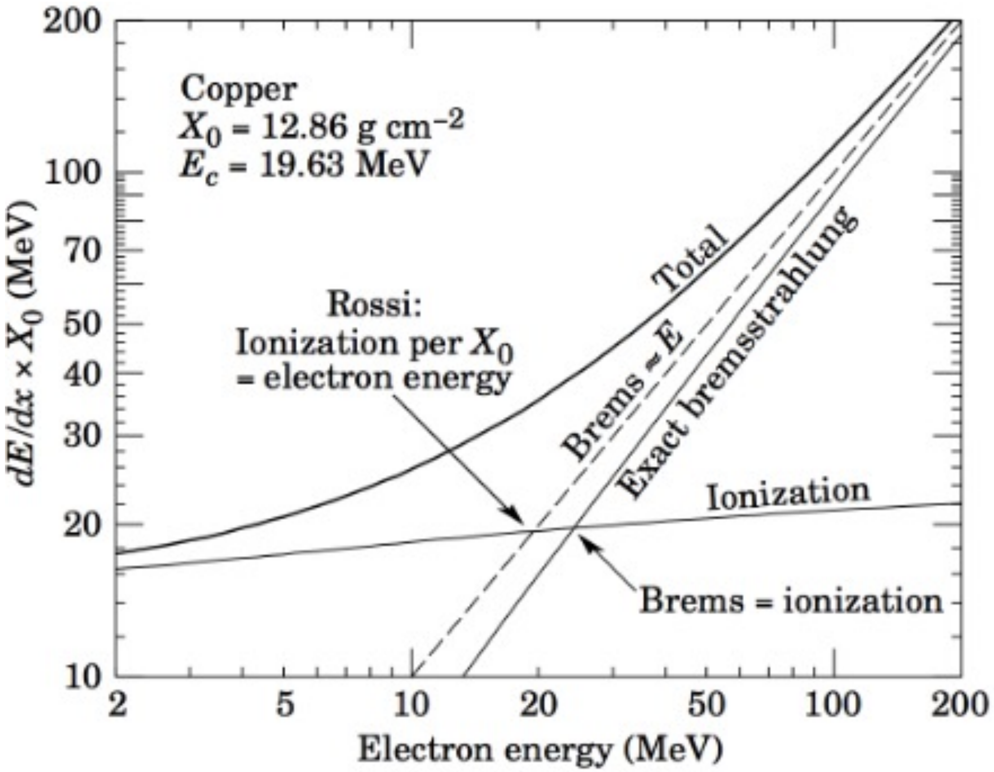
- Energy loss proportional to $1/m^2$
  ➔ **main relevance for electrons (or ultra-relativistic muons)**

Total energy loss for electrons

- Specifically for the electron, we introduce a new quantity, $\boldsymbol{X_0}$

$$X_0 = \frac{A}{4\alpha N_A\, Z^2 r_e^2\, \ln \frac{183}{Z^{\frac{1}{3}}}} \rightarrow -\left\langle \frac{dE}{dx} \right\rangle_{Brems} = \frac{E}{X_0} \rightarrow E(x) = E_0 \exp\left(-\frac{x}{X_0}\right)$$

Material specific [**g • cm^{-2}**]



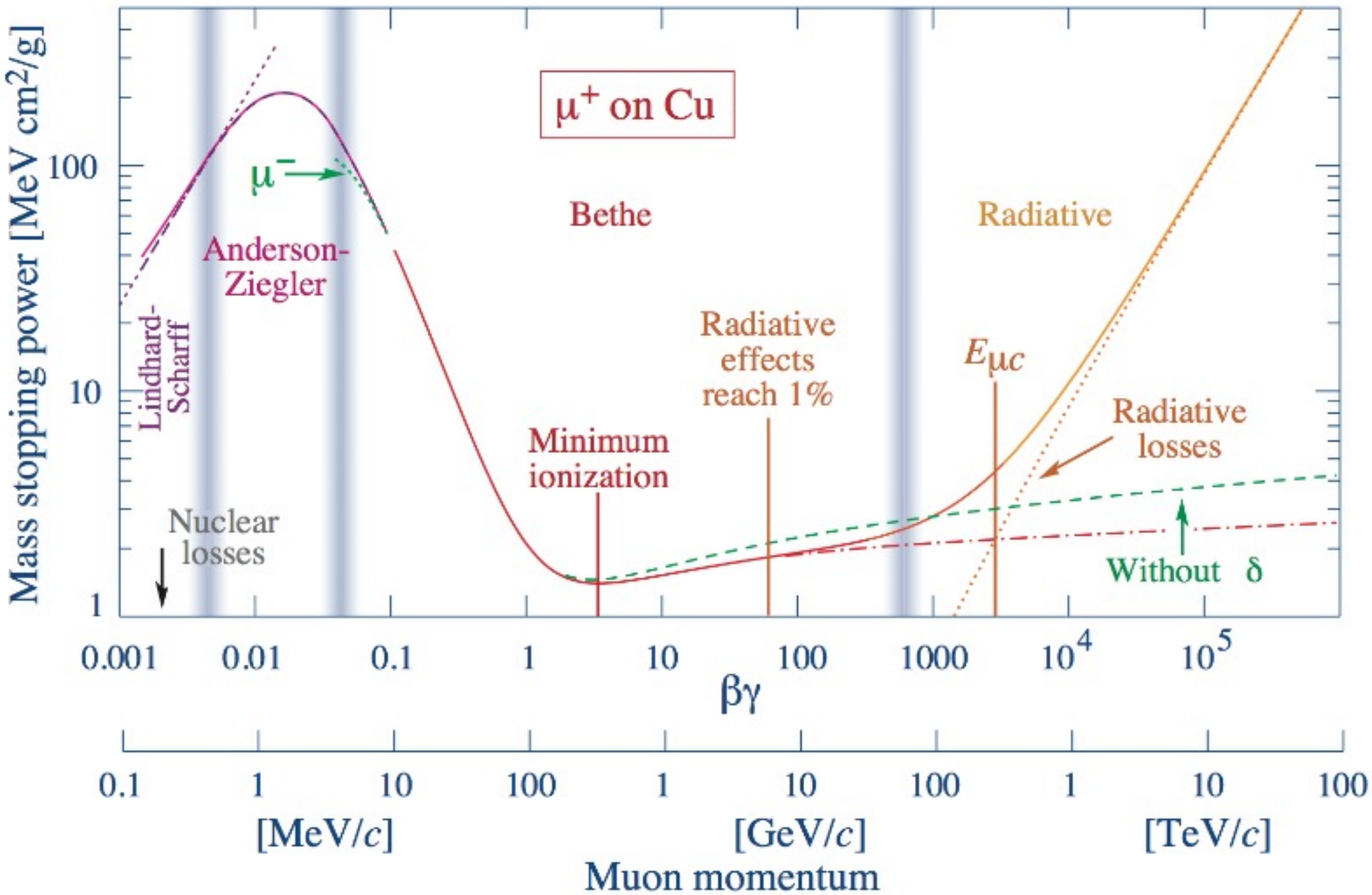
X_0 = radiation length
"distance" after which the initial energy E_0 is reduced by a factor *1/e*

$$-\left\langle \frac{dE}{dx} \right\rangle_{Total} = -\left\langle \frac{dE}{dx} \right\rangle_{Ionization} \oplus -\left\langle \frac{dE}{dx} \right\rangle_{Brems}$$

E_c = critical energy

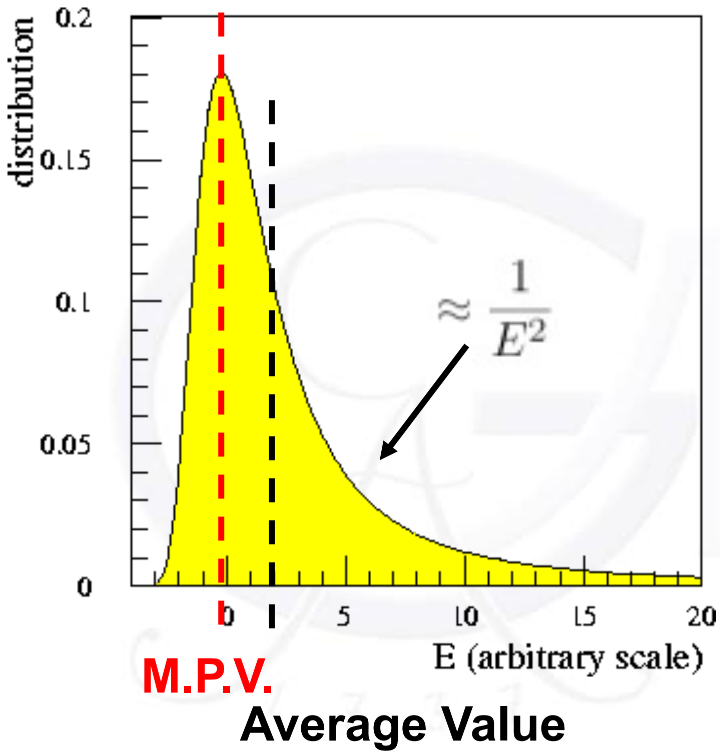
$$-\left\langle \frac{dE}{dx} \right\rangle_{Ionization} = -\left\langle \frac{dE}{dx} \right\rangle_{Brems}$$

Summary for energy loss



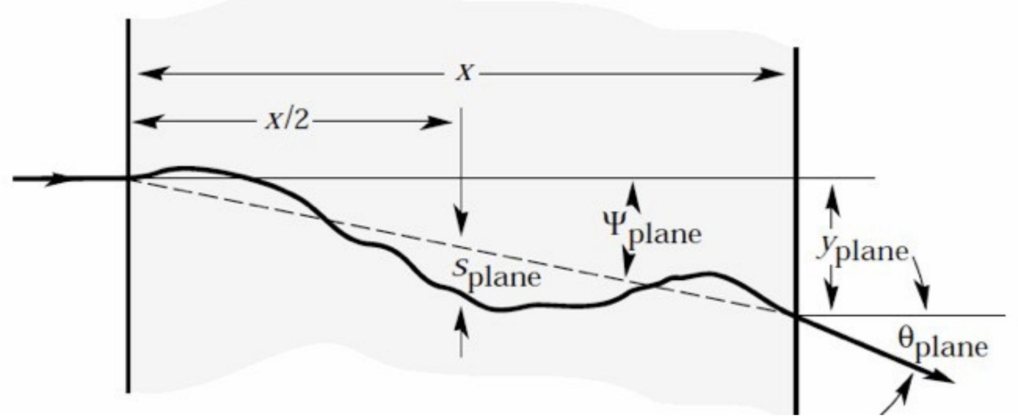
Fluctuation of energy loss

- Bethe-Bloch formula describes **mean** energy loss <dE/dx>
- Single energy loss is a statistical process, fluctuating event by event
  - for very thin absorbers, Landau distribution gives a good description
    - Asymmetric tail due to large single-collision energy transfers between a massive highly relativistic particle and a single electron → **δ-electron**
    - Average value ≠ Most probable value (MPV)
  - correction needed for thicker material
    - Vlavilov, Bichsel models.



Multiple Scattering

- Incident particle can scatter in the Coulomb field of the atomic nucleus
  - already described for the Bremsstrahlung case
  - deflection will be more significant because of the factor **Z**!



For many collisions (>20):
statistical treatment
"Molière theory"

- Probability that a particle is defected by an angle after travelling a distance **x** in the material: Gaussian distribution approximation with **σ**:

$$\sqrt{\langle\theta^2(x)\rangle} = \theta_{rms}^{plane} = \frac{13.6\ \mathrm{MeV}}{\beta pc} z \sqrt{\frac{x}{X_0}}\left(1 + 0.038 \ln \frac{x}{X_0}\right)$$

- Material constant X_0: radiation length
- $\propto \sqrt{x}$ → use thin detectors
- $\propto 1/\sqrt{X_0}$ → use light detectors
- $\propto 1/\beta p$ → serious problem at low momenta

Cherenkov Radiation

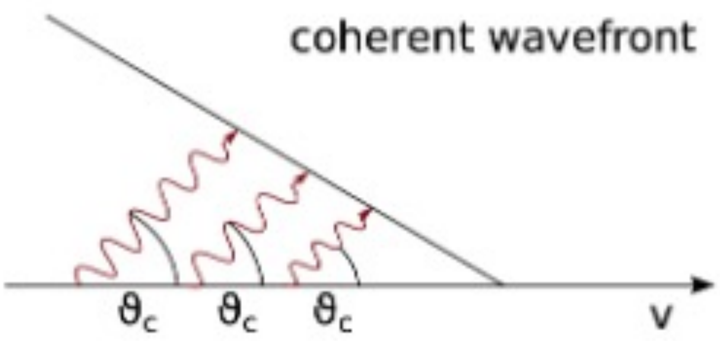
Three type of electromagnetic interactions:

1. Excitation/Ionization (of the atoms of the traversed material ✔
2. **Emission of Cherenkov light**
3. Emission of Transition Radiation

- Ionization is one way of energy loss, photons emission is also possible
  - Velocity of the particle: *v*
  - Velocity of light in a medium of refractive index *n*: *c/n*
- If particle travels with ($v > c/n$) or ($\beta > 1/n$) ..EM shockwave creation

➔ **real photons emitted!**

$$\cos\theta_c = \frac{\omega}{k \cdot v} = \frac{1}{n\beta}$$



Energy loss by Cherenkov radiation **very small w.r.t. ionization** (< 1%)

Interesting application to **measure *β*** *of the particle!* ➔ *RICH detectors.*

Transition Radiation

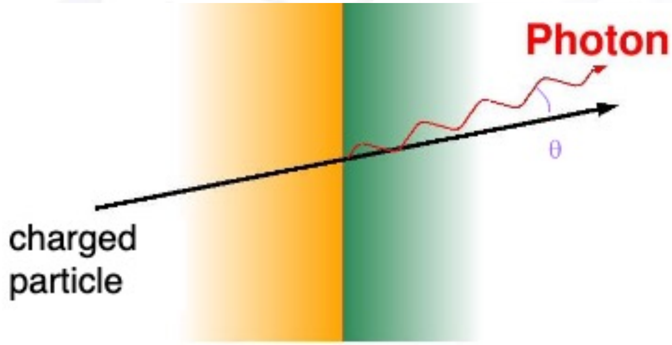
Three type of electromagnetic interactions:
1. Excitation/Ionization (of the atoms of the traversed material ✔
2. Emission of Cherenkov light ✔
3. **Emission of Transition Radiation**

- Relativistic particle (large γ) crosses the boundary between two media with different dielectric constants (ε_1, ε_2)
  ➔ probability ~1% to produced an X-ray photon

- The number of photons are small so many transitions are needed
  ➔ use a stack of radiation layers interleaved by active detector parts.

- **Intensity I ~ γ = E/m**
  - Used for identification of particle of momenta 1-100 GeV
  - The photons are emitted at a small angle ($\theta \sim 1/\gamma$)

- **Emitted energy ~ (ε_1-ε_2)**
  - HEP: gases (ε_1) and light plastics (ε_2),
    ➔ photon energies ~10-30 keV
  - Choice of material with big difference but photon should not be absorbed!



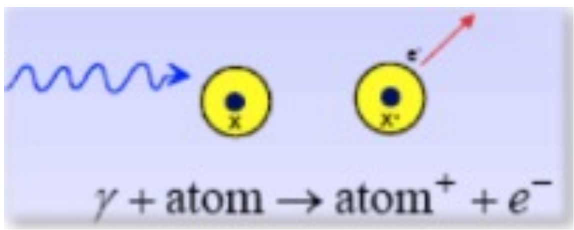
Interaction of photons with matter

Interaction of photons with matter/1

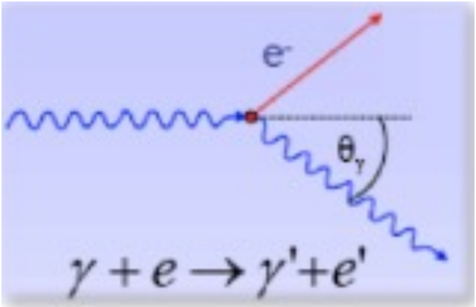
- Photon removed from an beam after one single interaction because of **total absorption** or **scattering**

$E\gamma$

1) Photoelectric Effect

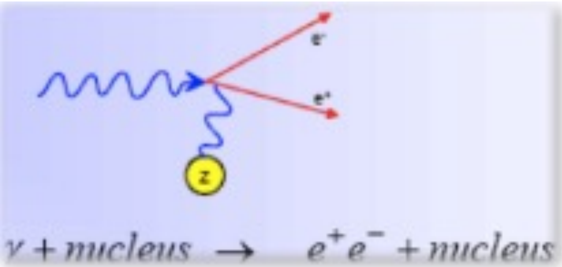


2) Compton Scattering

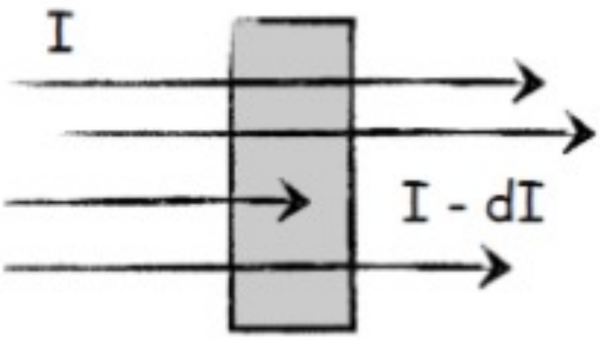


$E\gamma$

3) Pair Production



$E\gamma$



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

Mean free path

$$\lambda = 1/\mu$$

Interaction of photons with matter/2

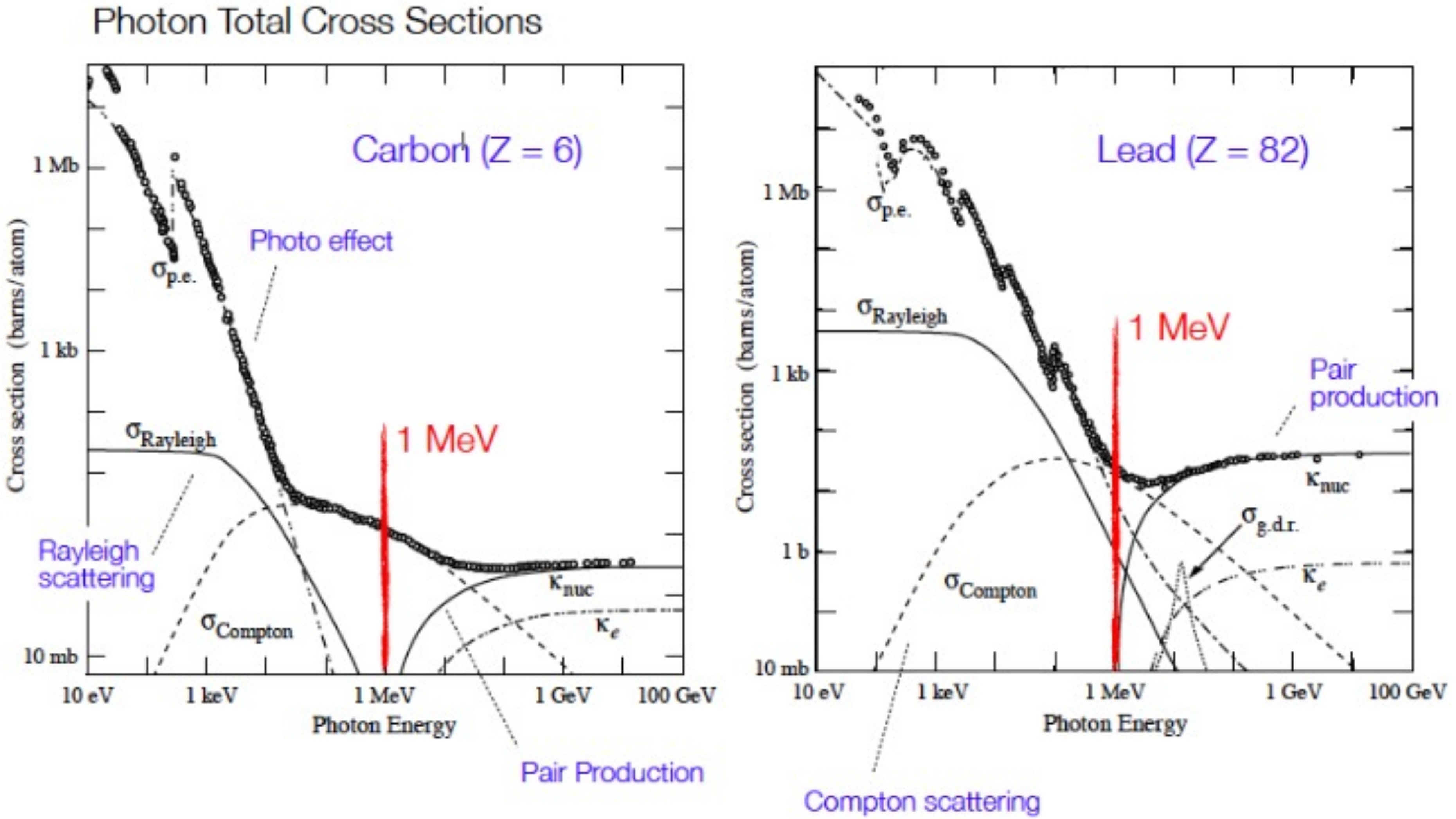
- Photoelectric effect: $E_\gamma \lesssim m_e c^2$
  - photo electron is release with $\mathbf{E_e = E_\gamma - I_b}$ with $\mathbf{I_b}$= electro-nucleus binding energy
  - I_b depends strongly on Z ➔ the cross section ∝ $\mathbf{Z^5}$
- Compton scattering: $E_\gamma >> I_b$
  - Quasi-free electron ➔ scattering of photon off an electron
- Pair production: for $E_\gamma > 2\, m_e c^2$
  - interaction in the Coulomb field of atomic nucleus allows $\gamma \rightarrow e^+ + e^-$
  - similar process to Bremsstrahlung
  - σ_{pair} raises above threshold, saturates at large E_γ (nuclear charge screening)

$$\sigma_{\text{pair}} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9}\ln\frac{183}{Z^{1/3}} - \frac{1}{54}\right)$$

$$X_0 = \frac{A}{4\alpha N_A\, Z^2 r_e^2\, \ln\frac{183}{Z^{\frac{1}{3}}}}$$

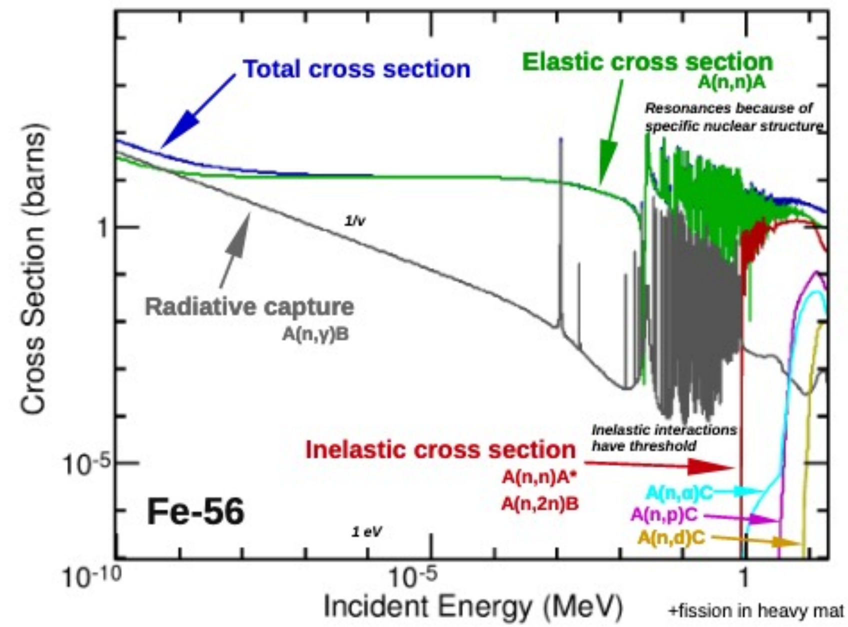
$$\sigma_{pair} = \frac{7}{9}\frac{N_A}{A}\cdot\frac{1}{X_0} \rightarrow \lambda_{pair} = (9/7)\bullet X_0$$

Interaction of photons with matter/3



Hadronic Interactions

- None of the above applies to neutrons
  - can measure them indirectly:
  - ➔ knocking off nuclei, measure charged object
  - scattering with same mass partner (proton)
  - ➔ use organic material (significant H content)



- p, n, π, K at high energies
  - additional processes possible (inelastic collisions)

    with creation of further hadrons that undergo further inelastic collisions..
  - Nuclear interactions → new γ, n, p (+nuclear fragments)
  - Avg. had. interaction length for inelastic absorption $\boldsymbol{\lambda_A \gg X_0}$

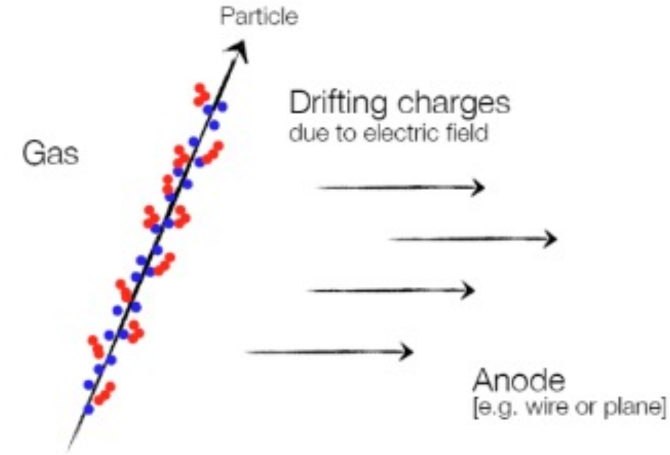
$$N(x) = N_0 \exp\left(-\frac{x}{\lambda_A}\right)$$

➔ *See next talk about Calorimetry for more details*

Ionization detectors

Ionisation detectors concept

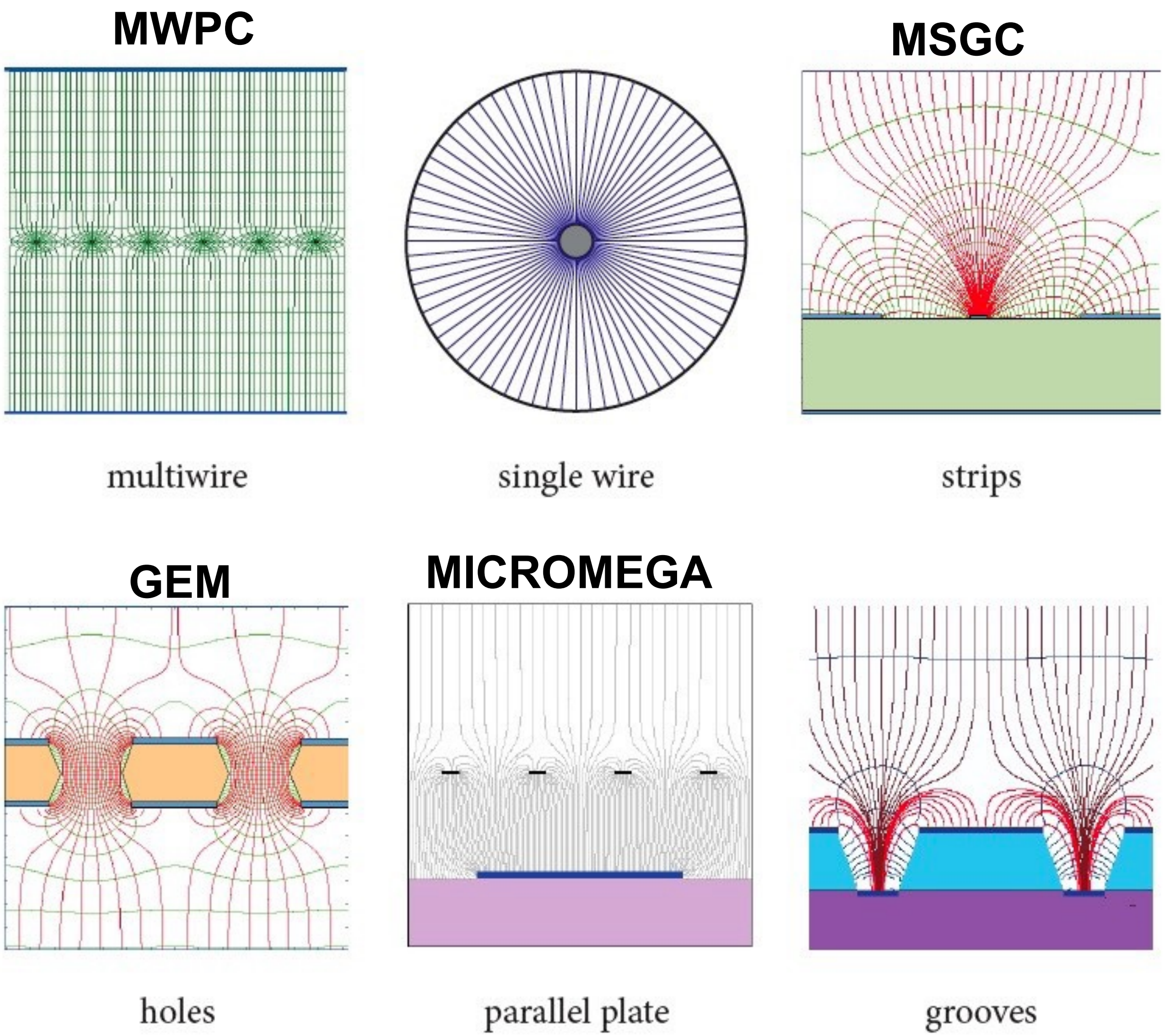
- Charged particles leave a trail of ions/excited atoms along their path: **Electron-Ion** pairs in gases and liquids, **electron-hole** pairs in solids.
- Deposited energy $\mathbf{E_{dep}}$ causes ionisation (average energy **I** needed)
  ➔ releasing a total $n = E_{dep} / I$ charge carriers
- Apply electric field to extract and read charge pulse (charge drifting + induction)
- Typical media used:
  - Gas: e-ion pairs, I ~ few 10 eV
  - Semiconductor: e-hole pairs, I ~ few eV



- Bethe-Bloch signal **dE/dx ∝ density (ρ)**
  - Gas:
    too little charge released ($q=80\ e^-/cm$) to have a good signal
    → **internal amplification** needed (e.g., wire chamber)
  - Semiconductors:
    charge detectable, but competing with intrinsic charge carriers

Gaseous detectors: Field Configuration

For high electric fields (100 kV/cm), the electrons gain energy in excess of the ionization energy → secondary ionization → **electron avalanche**!

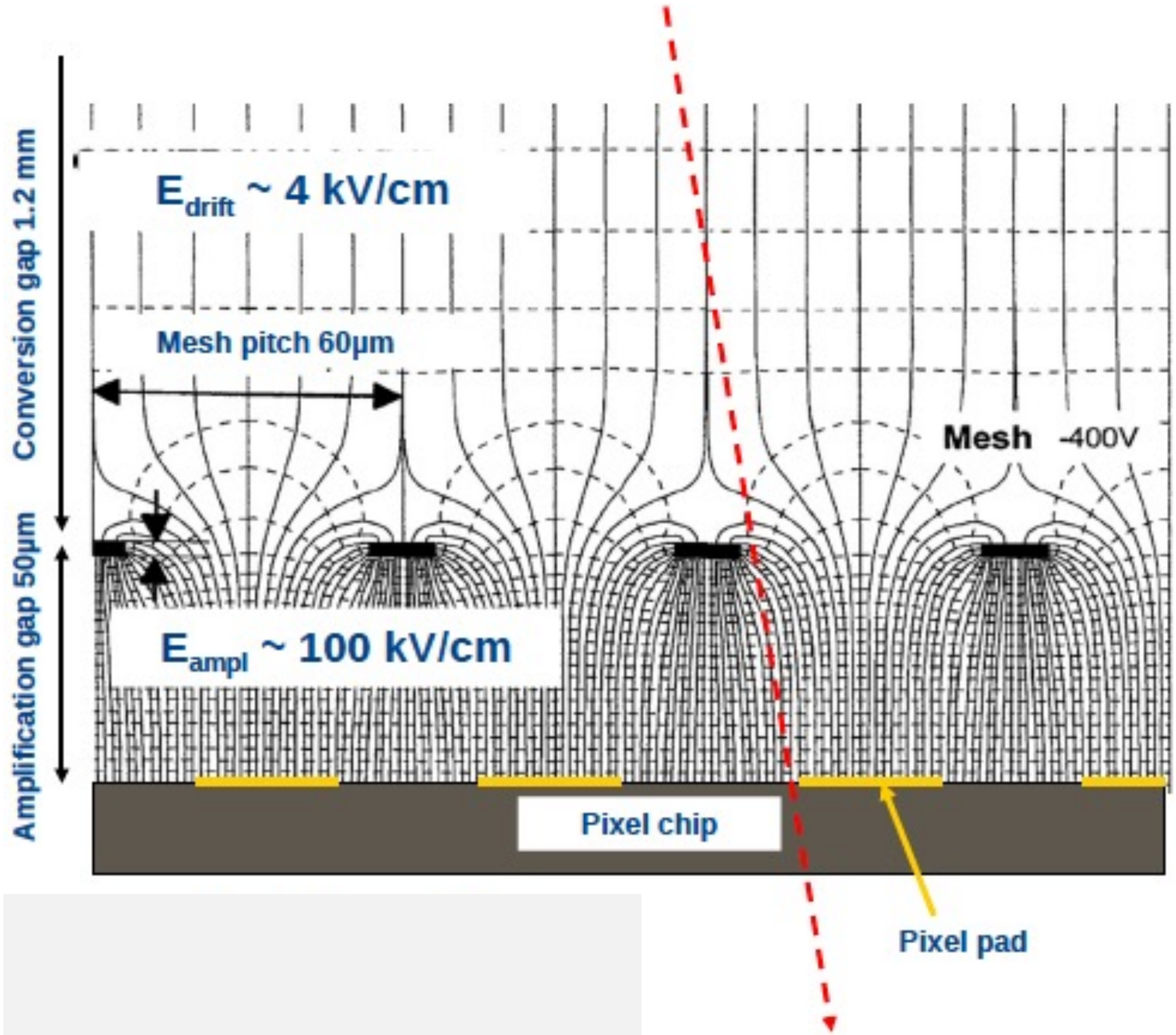


- To achieve high electric field, small or very close electrodes needed
  - Small read-out segments (wires)
  - Specific perforated foils

Gaseous detectors: Amplification

Gas amplification factor:

- **Ionization mode**:
  no amplification (gain=1).
- **Proportional mode:**
  multiplication, signal proportional to original ionization
  → measurement of dE/dx
  (gain ~ 10^4-10^5).
- **Saturated mode**:
  strong photo-emission, high gain, simple electronics.
- **Geiger mode**:
  massive photo emission
  → eventually limits the gas gain due to continuous discharge.

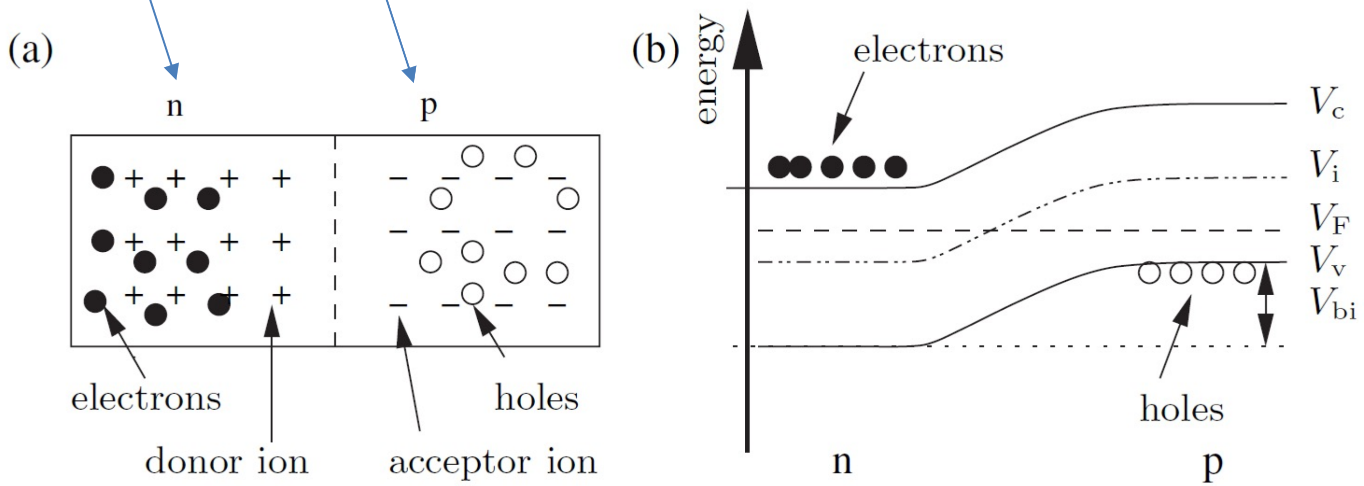


Example:

- Perforated foil supported by pillars
- Pixel electrodes beneath
  → amplification and read-out separated.

Semiconductor : *pn*-junction

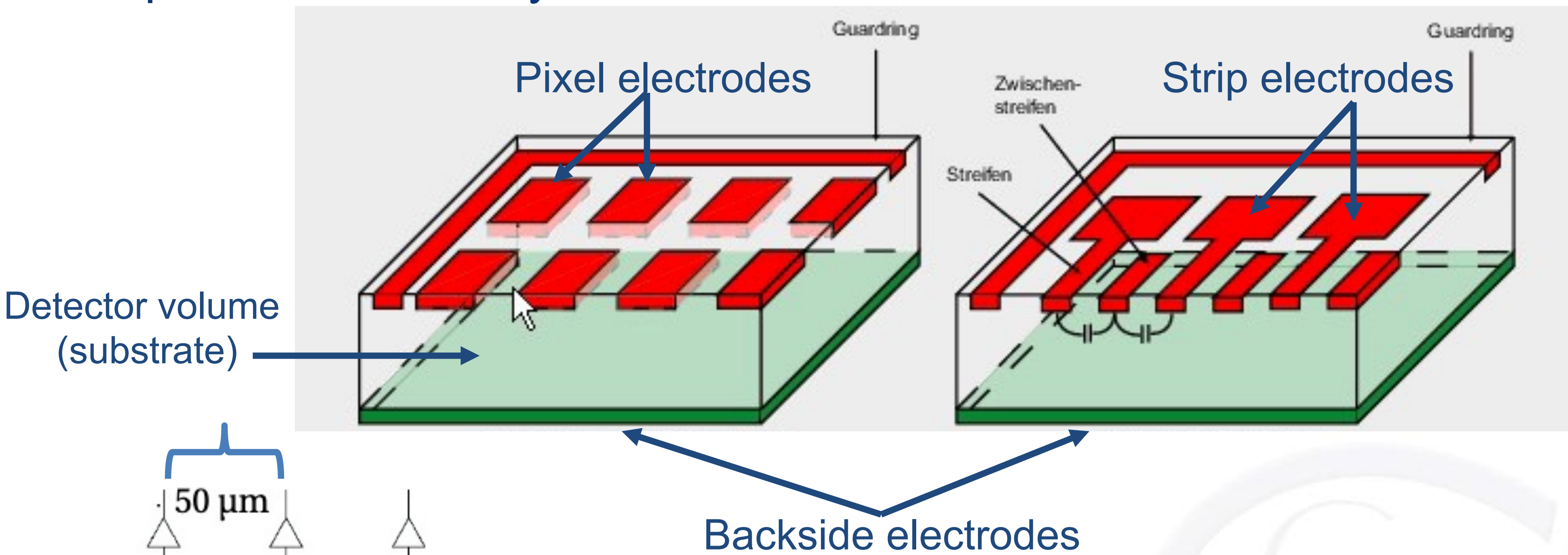
- Ionization as in gas detectors
  → Semiconductors = solid materials with crystalline structure (Si, Ge)
  → electron-hole pairs (instead of electron-ion)
- Usage of special materials "Extrinsic or doped semiconductors":
  → Majority of charge carriers provided by impurity atoms at lattice sites of the crystal
  → n-type (p-type) materials with excess of e^- (holes)

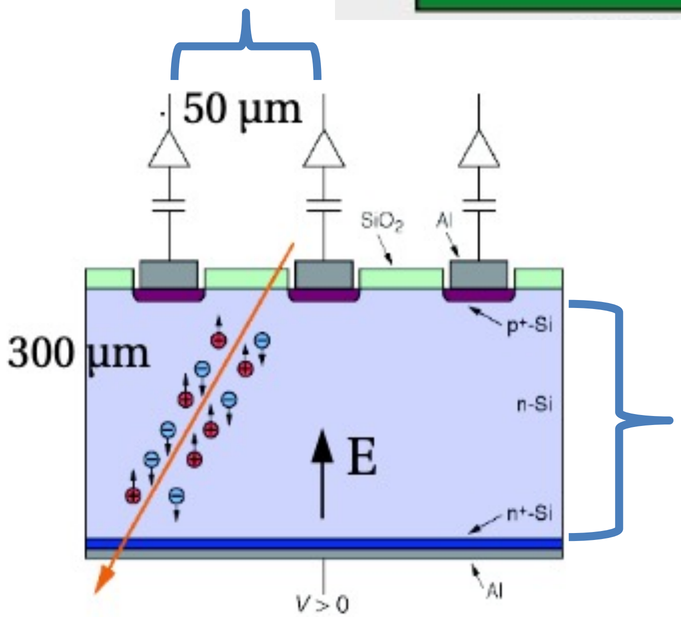


- *pn*-junction under reverse bias (High Voltage applied to electrodes):
  - Extract electrons or holes present from doping (depletion region)
  - Provides electric field needed for charge drifting

Segmented Semiconductors

- Segmenting *pn*-junctions into pads, strips and pixels
  → position sensitivity



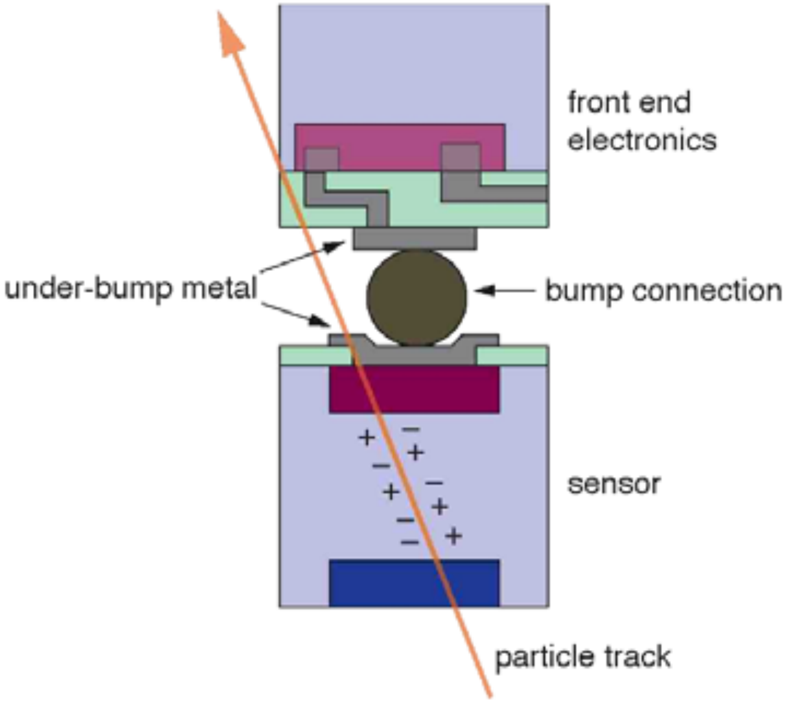


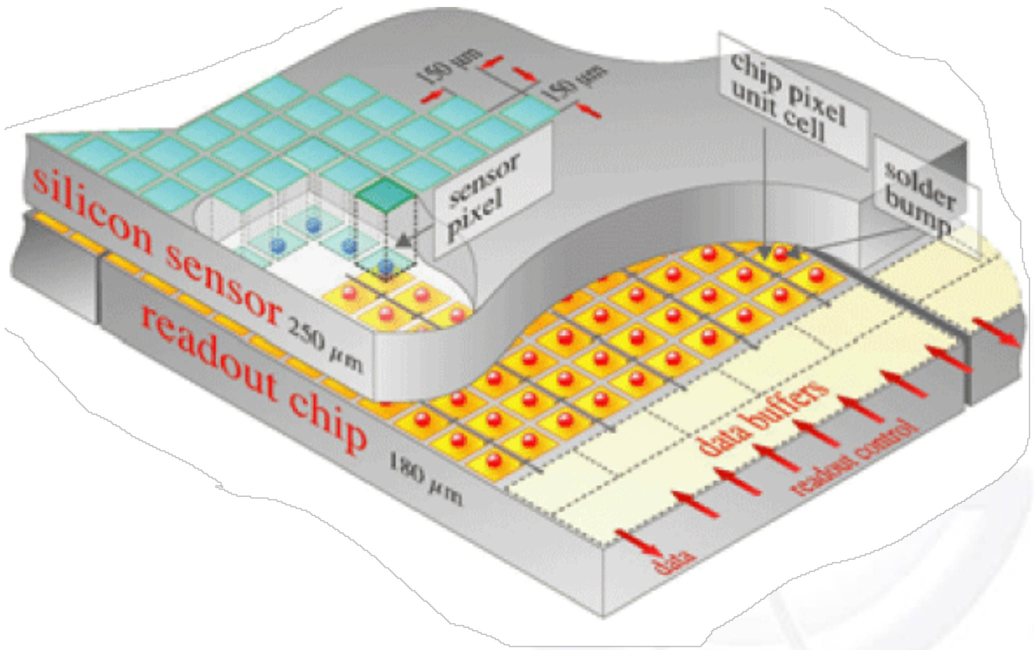
Typical sizes:

- Strip or Pixel pitch ≈ 50/250/500 µm
- Detector Thickness ≈ 200-300 µm
  - Enough to create a good signal

Pixel Detector Read-out

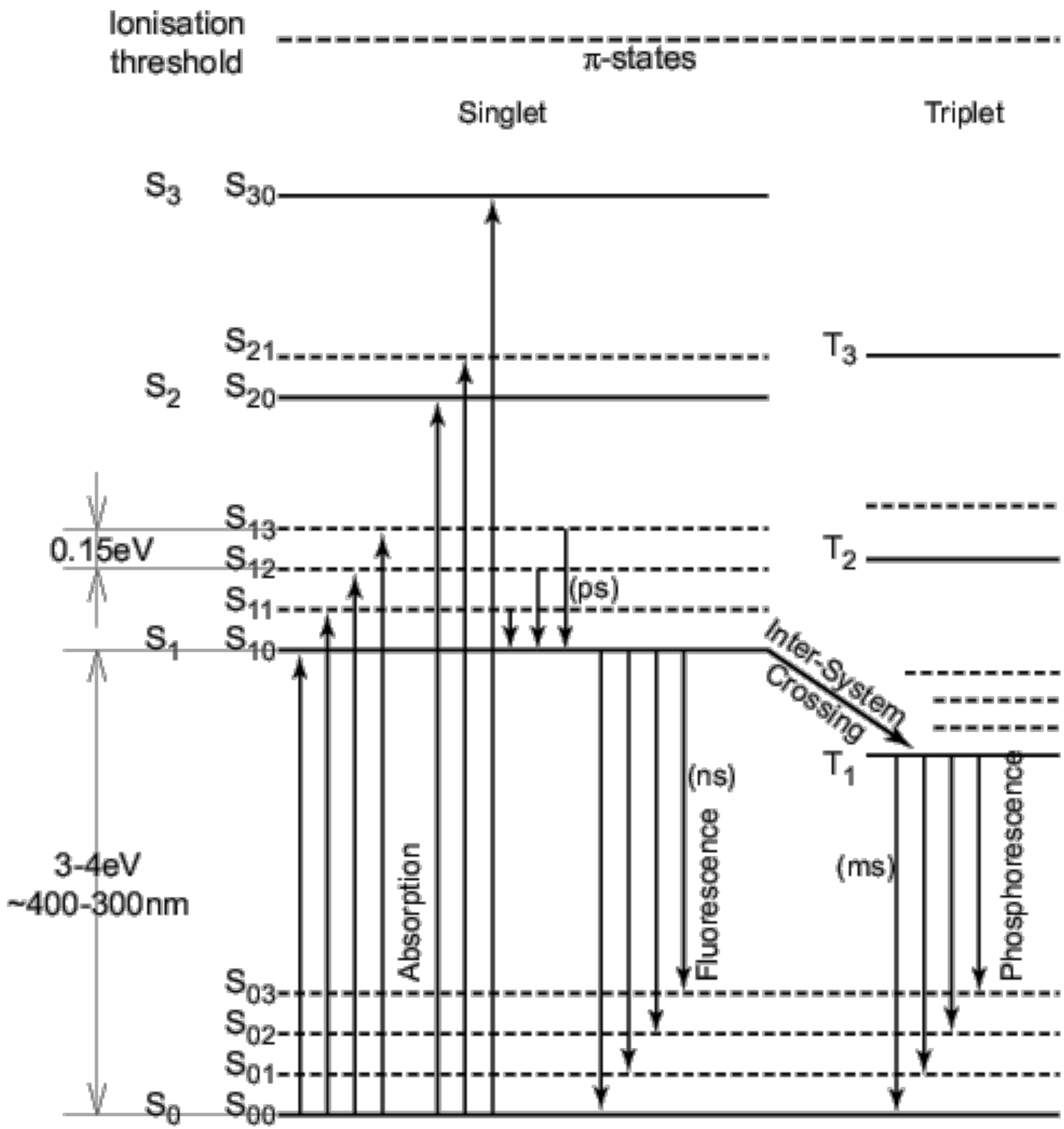
Hybrid technology:
1:1 connection sensor segments to the read-out cell
➔ bump bonding technique





Light-based Detectors: Scintillation & Čerenkov Radiation

Scintillation

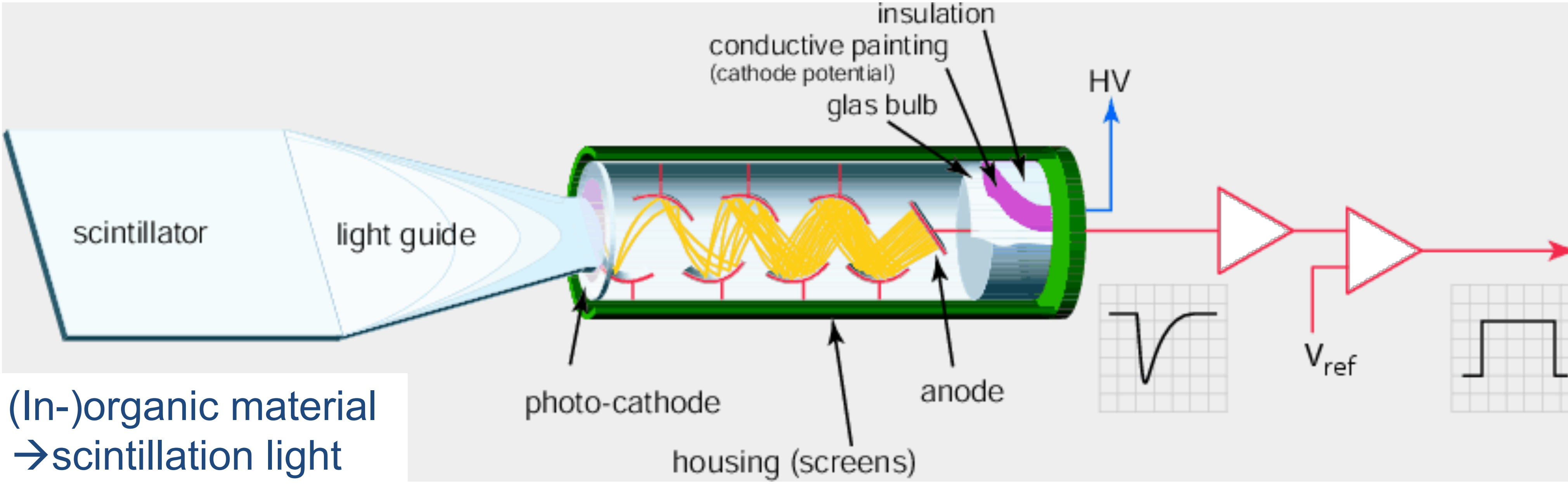


Excitation from:

- Bethe-Bloch (charged particles)
- Photo-electrons ($\rightarrow$ detection of γ)
- Neutrons knocking off protons

Resulting in de-excitation
➔ scintillation light

Light Readout: PMT and APD

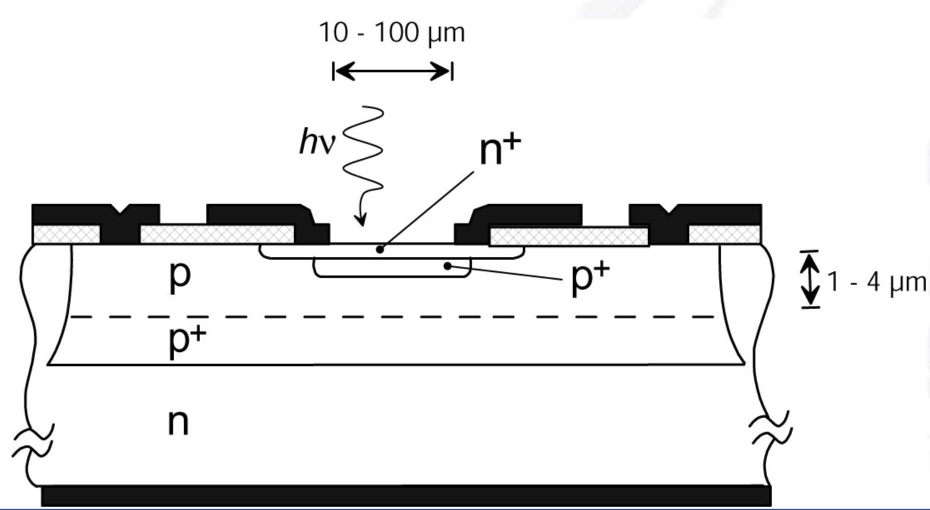


(In-)organic material
→scintillation light

Light guide
→connecting scintillator to PMT

Photo multiplier tube (PMT)
→signal amplification before read out

Alternative to PMT:
Silicon *pn*-junction with amplification (Avalanche Photo Diode, APD

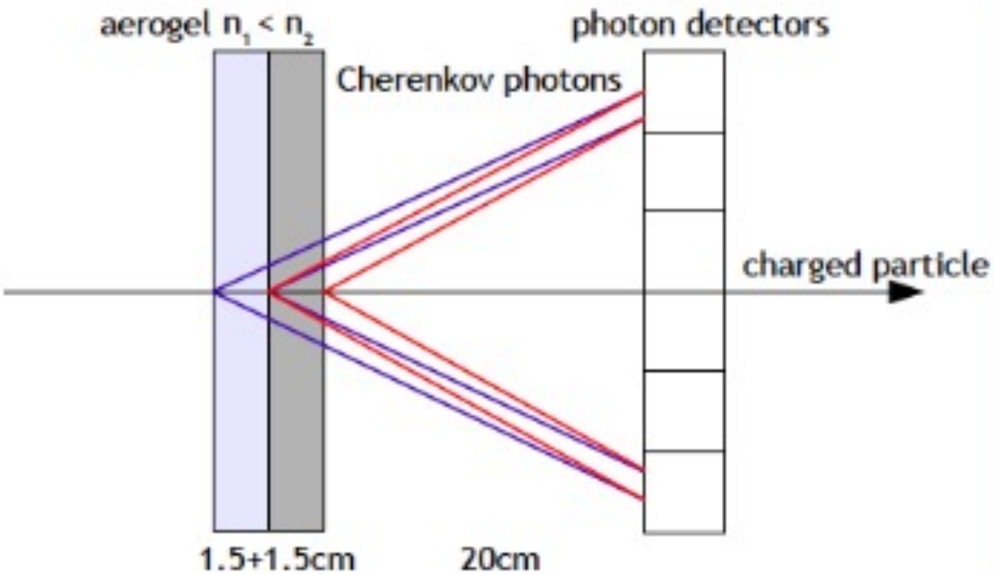


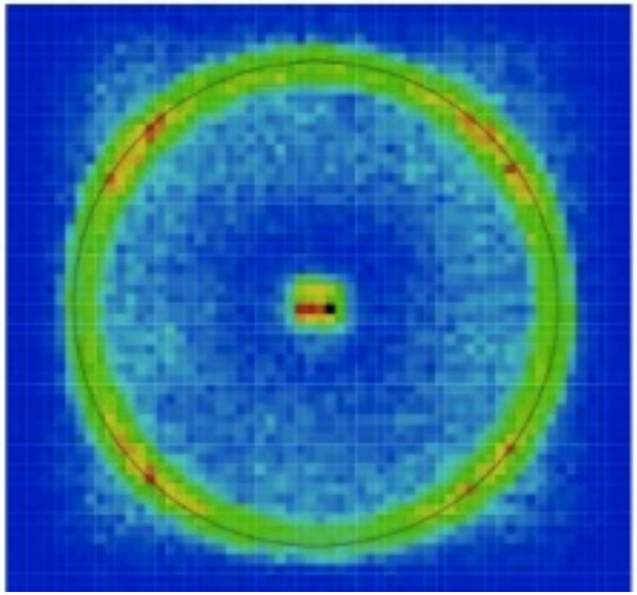
Cherenkov radiation: RICH detectors

- In a Cherenkov detector, the produced photons are measured.
- Principle: project Cherenkov cone into a ring, we measure its radius
  ➔ emission angle $\boldsymbol{\theta_c}$
  ➔ β of the particle

$$\cos\theta_c = \frac{\omega}{k \cdot v} = \frac{1}{n\beta}$$

- If particle momentum ***p*** provided by other detectors ➔ particle ID!
- Components: radiator (+ mirror) + photon detector



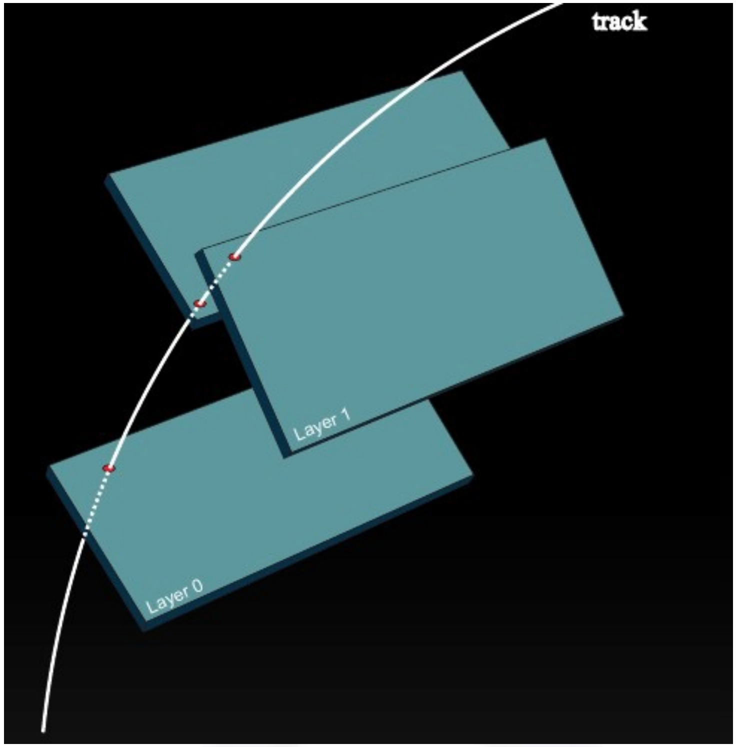


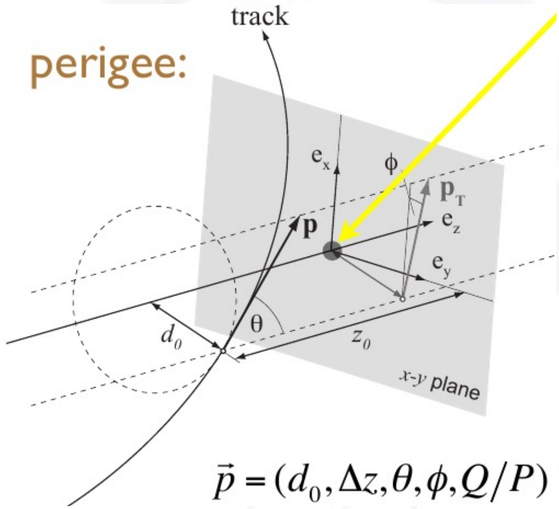
Tracking detectors

What to expect from trackers?

Measure trajectory of **charged** particles

- Measure several points along the track and fit curves to the points **(helicoidal trajectories with magnetic field**)
- Use the track curvature in magnetic field to determine the particle **momentum** and **charge**
- Extrapolate tracks to the point of origin
- Determine positions of **primary vertices** and identify collision vertex
- Find **secondary vertices** from decay of long-lived particles (**lifetime tagging**)

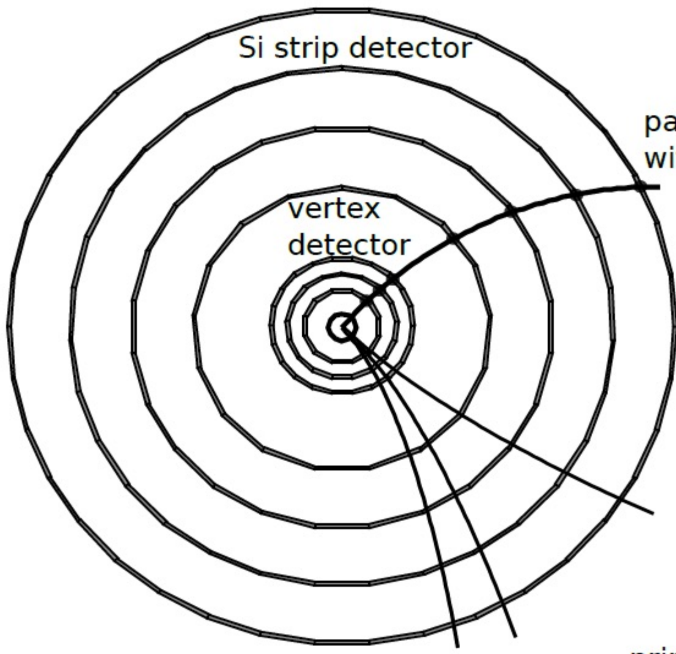




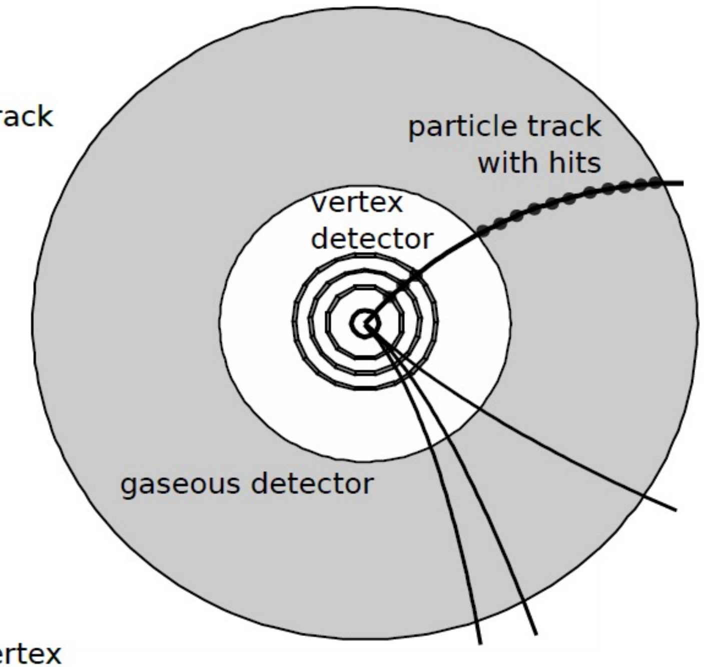
$$\vec{p} = (d_0, \Delta z, \theta, \phi, Q/P)$$

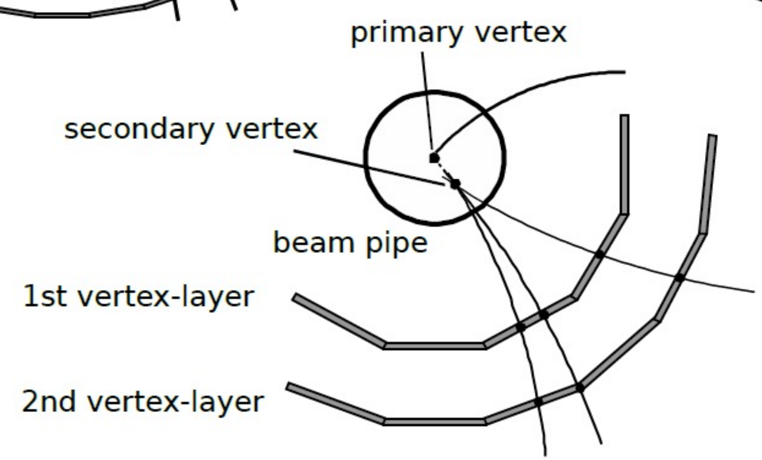
Tracking Concepts

Full silicon tracker
(CMS)



Gaseous + Silicon tracker
(ATLAS)

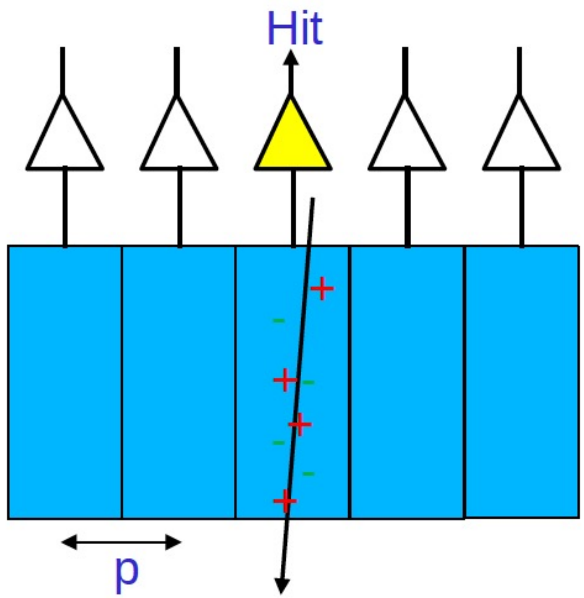


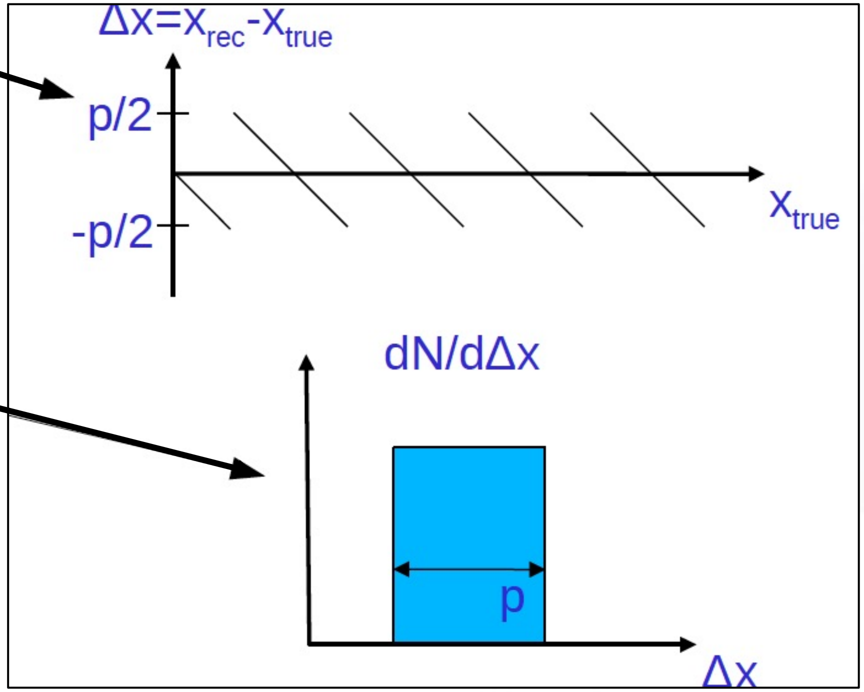


Single Point Resolution (1)

Simple case:
only single hit segment (binary readout)

- Segment width → ***p***
- Default hit position: centre of segment
- Reconstruction error ("residual") varies with true hit position.
- Flat hit probability: residual distribution is a box diagram





Single Point Resolution (2)

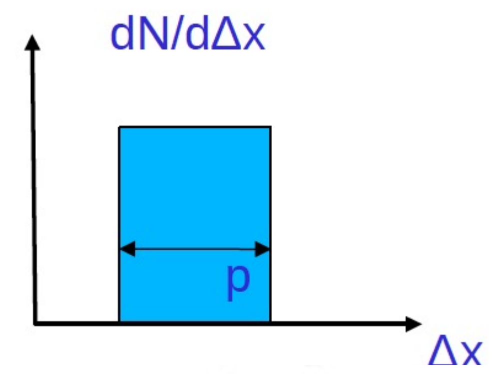
- Reconstruction error
  → std. deviation defined by probability distribution

- Normalised box distribution centred around 0 with width ***p***:

$$\sigma_x = \sqrt{\frac{1}{p}\int_{-p/2}^{p/2} x^2\,dx} = \frac{p}{\sqrt{12}}$$

➔ single point resolution **σ_X ~ 14 µm** for a pixel/strip pitch **p = 50 µm**

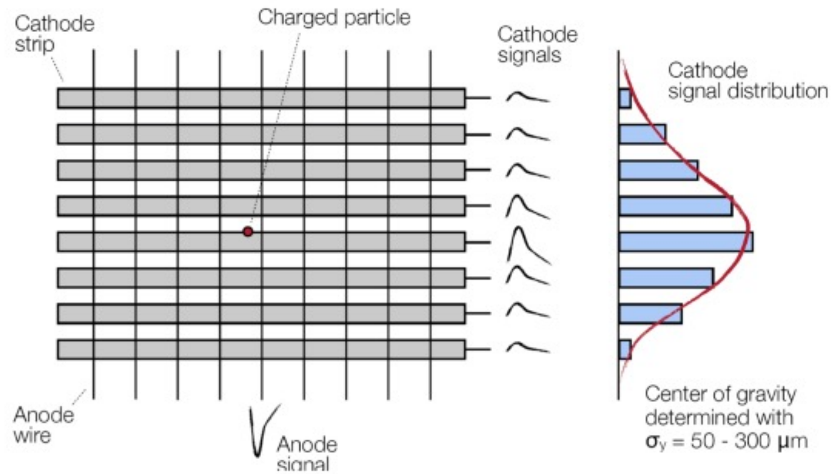
- Worst possible resolution with pure binary readout
  - Value improves if several segments are recorded per each track:
    ➔ weighting with pulse height information



Pulse Height Weighting

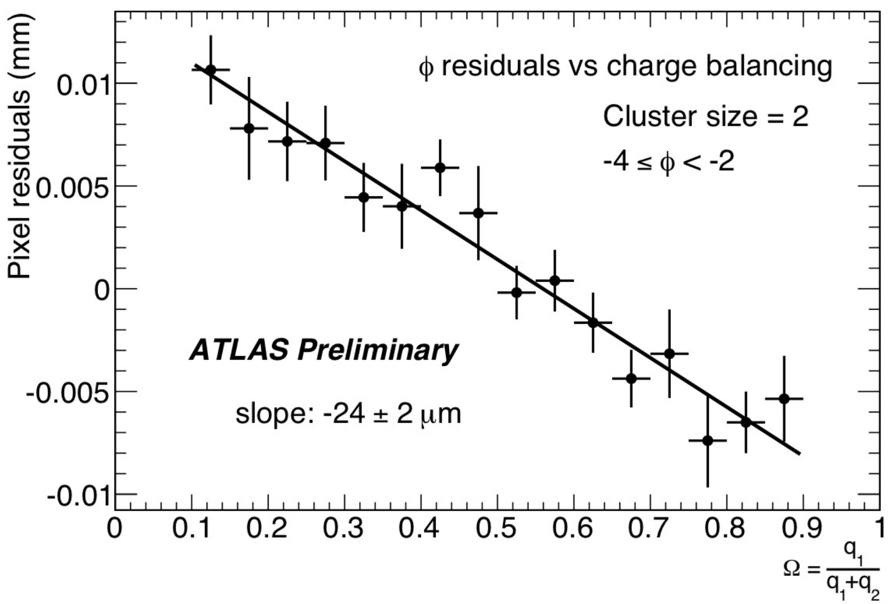
- Simplest method :
  linear interpolation, using the charge deposited in the edge pixels of the cluster:

$$\Omega = \frac{q_{last}}{q_{first} + q_{last}}$$



- Hit position: reconstructed from geometrical centre of the cluster and Ω:

$$x = x_{centre} + \Delta_x \left(\Omega_x - \frac{1}{2} \right)$$



- Δx calibrated from data
  (plotting residual vs. charge sharing)

Drift detectors

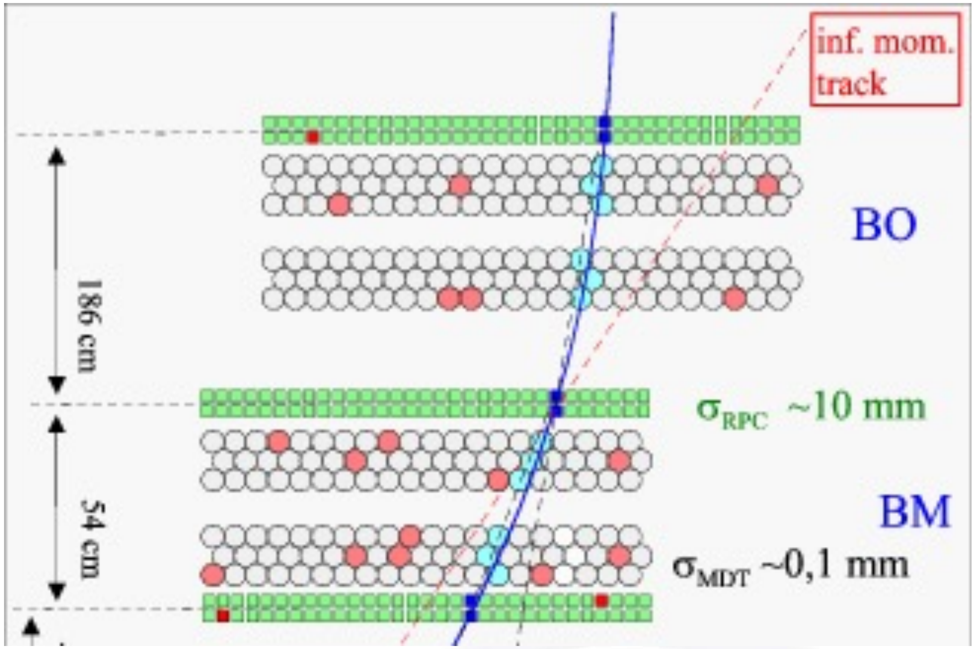
Resolution can be < p/√12 if using drift time:

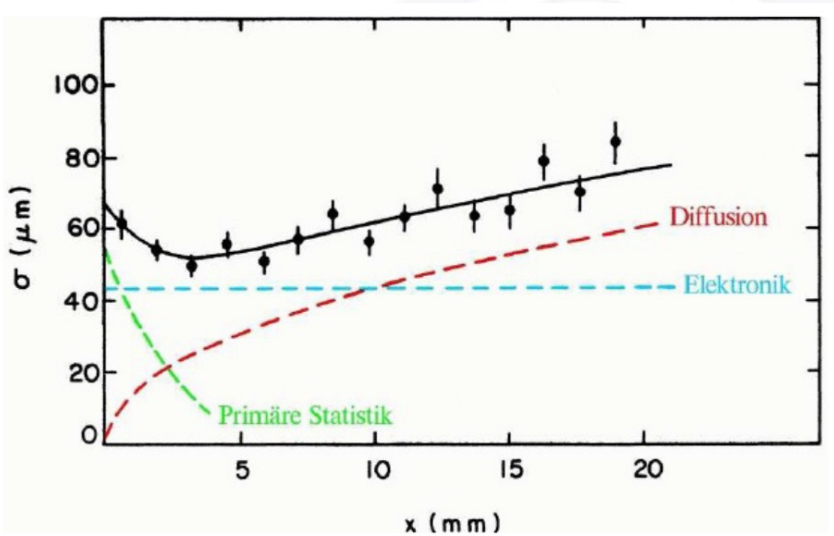
- Precise measurement of arrival time of charge signal
- Known electric field
  → drift velocity $v = \mu E$ is known
  → determine distance of ionisation location from electrode
- Precision driven by Electronics (timing resolution) and smearing due to **Diffusion**

$$D = \frac{1}{3} v \lambda = \frac{2}{3\sqrt{\pi}} \frac{1}{\sigma_0 P} \sqrt{\frac{(kT)^3}{m}}$$

- Diffusion depends on the gas pressure **P** and temperature **T**

ATLAS MDT





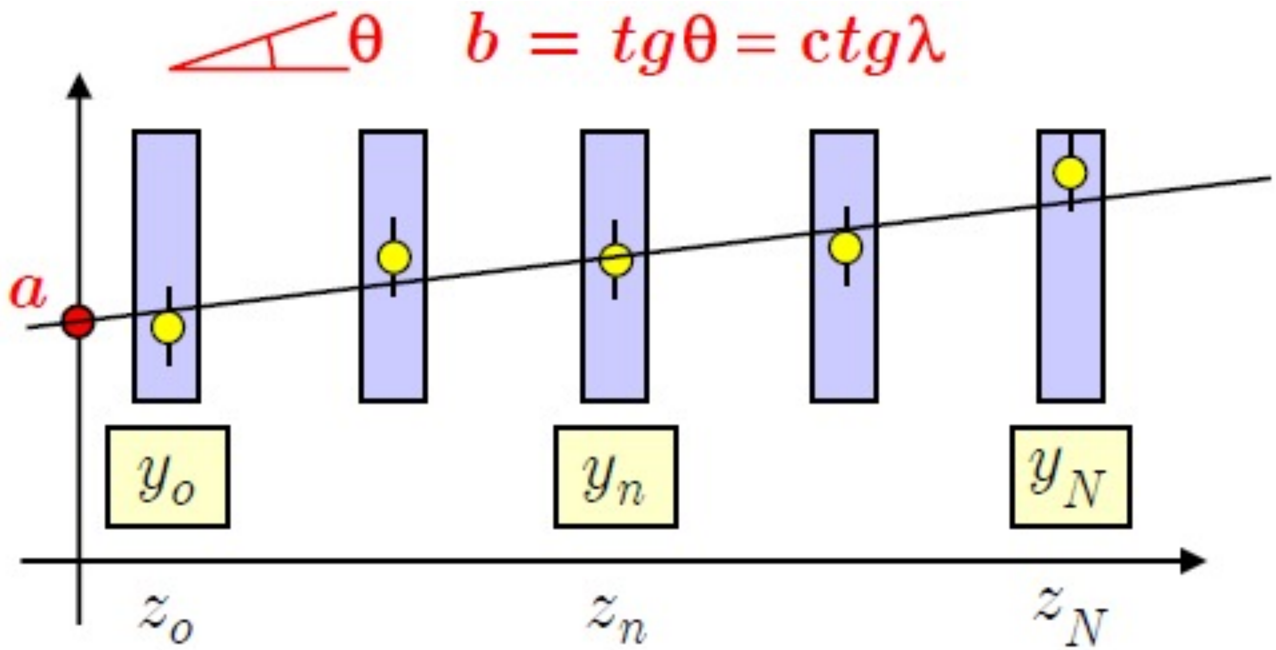
From Hits to a Track

- Simple example: straight line fit (a real track is more complex)
- Measured positions y_i with single point resolution as before χ^2 minimisation with $y_n = a + b\,x_n$:

$$\chi^2 = \sum_{n=0}^{N} \frac{(y_n - a - b\,x_n)^2}{\sigma_n^2}$$

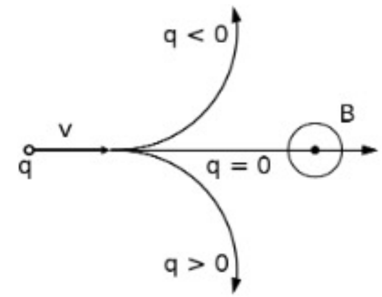
- Errors on a, b from covariance matrix

- Similar approach for real tracks allows error calculation on track parameters

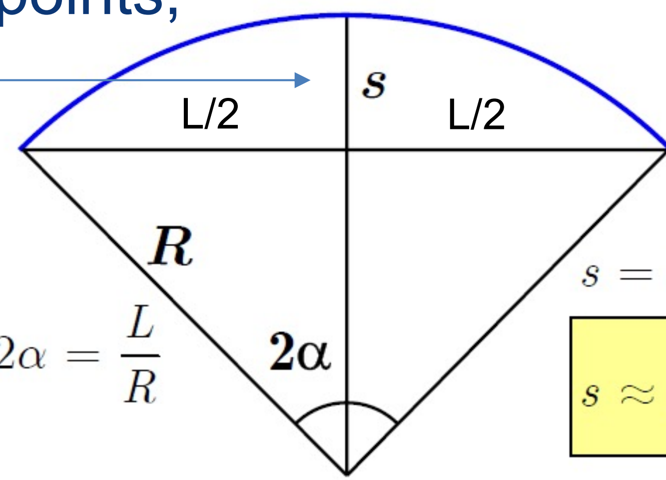


Momentum determination/resolution

- Momentum determination of charged particles can be performed by measuring the track bending in a magnetic field
  ➔ $p_T = 0.3 \cdot B \cdot R$
  component transverse to magnetic field lines



- Determine curvature from fit to N hit points, characterize by the sagitta ***s***



$$2\alpha = \frac{L}{R}$$

$$s = R(1 - \cos\alpha)$$

$$s \approx R\frac{\alpha^2}{2} = \frac{L^2}{8R}$$

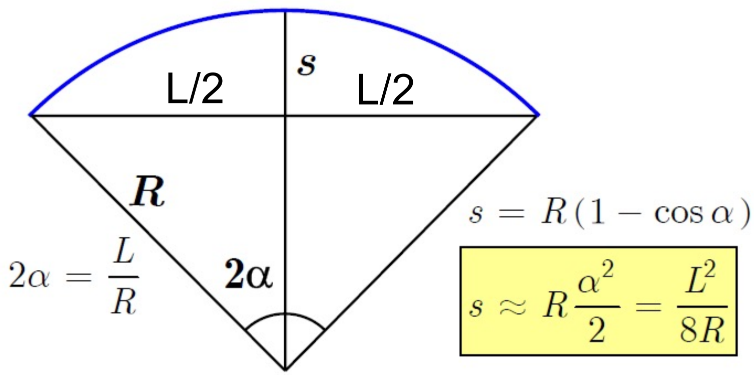
What about the p_T resolution?

- For large and equidistant N with equal errors σ_{point} on spatial hit position:

$$\frac{\sigma_{p_T}}{p_T} = \frac{p_T \sigma_{\mathrm{point}}}{0.3\, B\, L^2}\sqrt{\frac{720}{N+4}}$$

Error calculation by Gluckstern: approximate curved track by parabolic fit

Momentum Resolution/Multiple Scattering



- $p_T = 0.3 \cdot B \cdot R$
  $= 0.3 \cdot B \cdot L/(2\alpha)$
- $\sigma_\theta \propto 1/p_T$ from MS translates via error propagation into σ_α

$$\sigma_{pT}^{MS} = \frac{0.3\,BL}{2\,\alpha^2}\sigma_\alpha \rightarrow \frac{\sigma_{pT}^{MS}}{p_T} = \frac{27.2\,\mathrm{MeV}}{0.3\,B\sqrt{L\,X_0}}$$

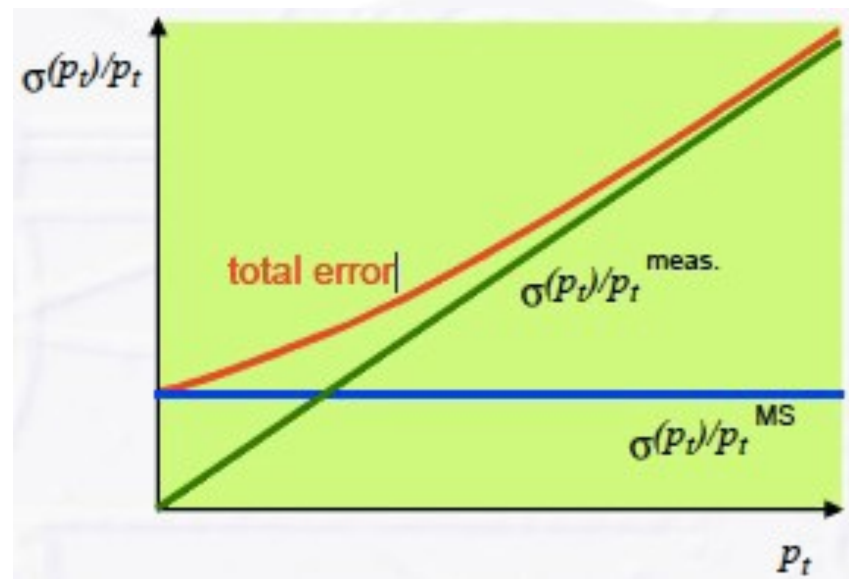
$$\sqrt{\langle\theta^2(x)\rangle} = \theta_{rms}^{plane} = \frac{13.6\ \mathrm{MeV}}{\beta pc} z \sqrt{\frac{x}{X_0}}\left(1 + 0.038 \ln\frac{x}{X_0}\right)$$

- Material constant X_0: radiation length
- $\propto \sqrt{x}$ → use thin detectors
- $\propto 1/\sqrt{X_0}$ → use light detectors
- $\propto 1/\beta p$ → serious problem at low momenta

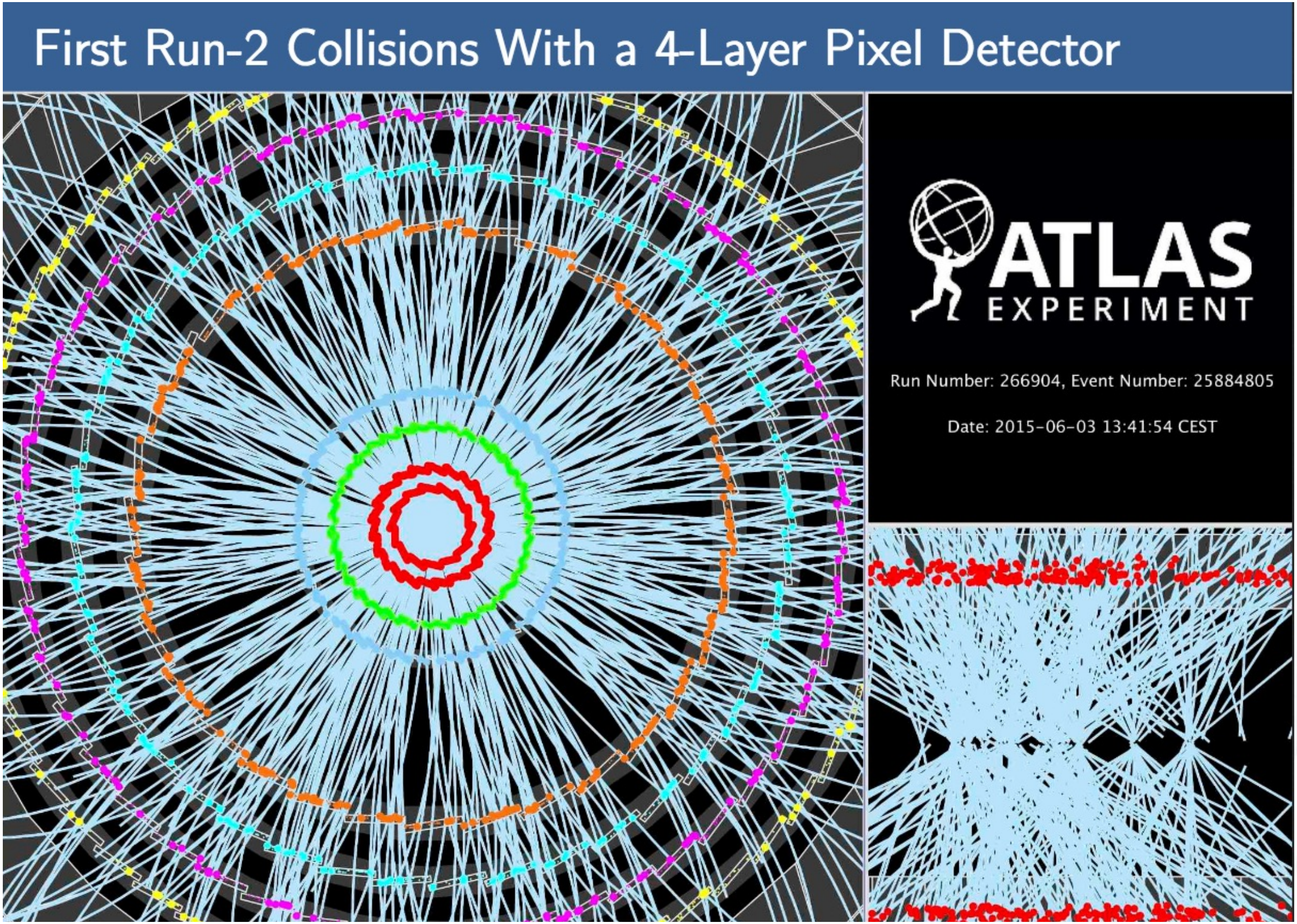
Added in quadrature to intrinsic resolution:

→ Multiple Scattering dominates at low p_T
(constant term, independent of p_T)

→ Intrinsic resolution dominates at high p_T

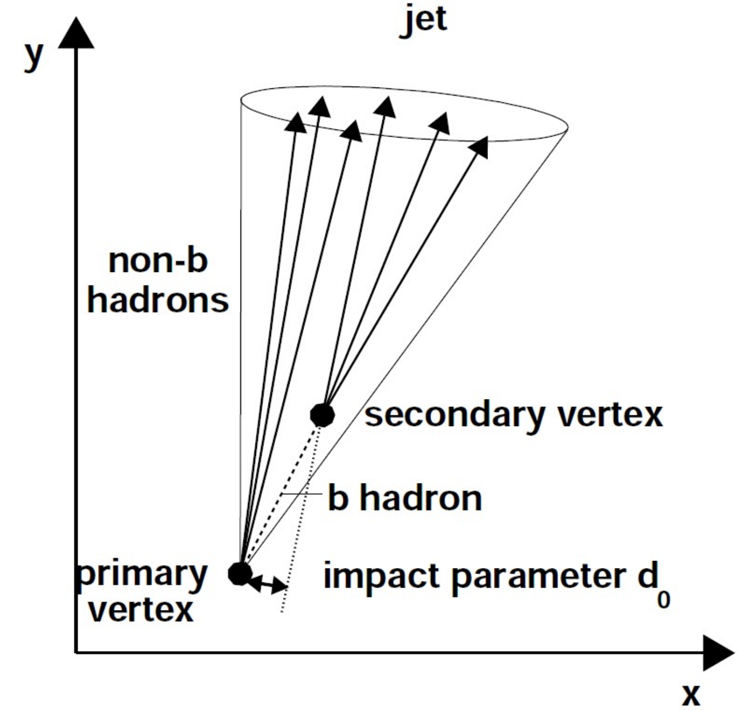


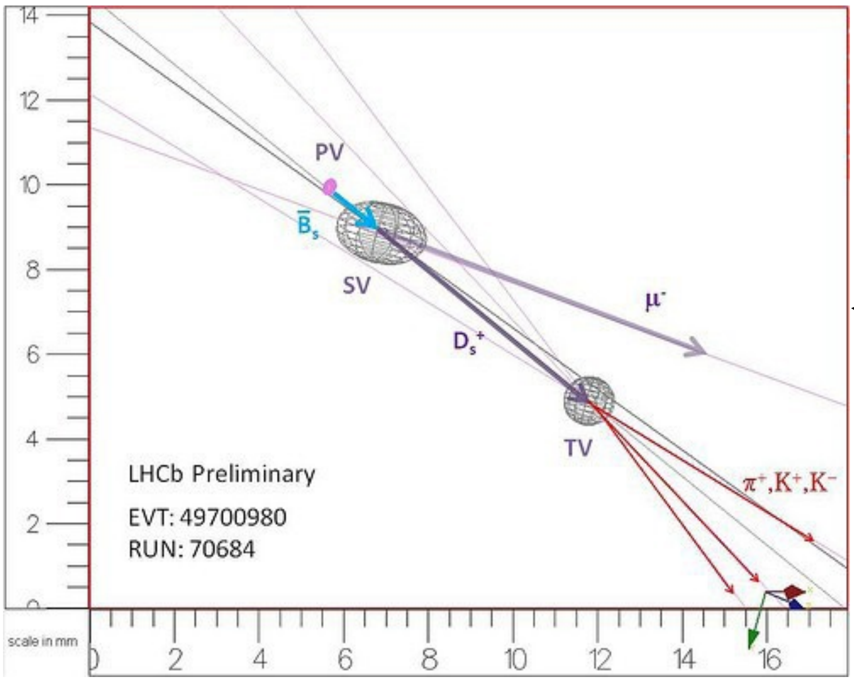
Vertex reconstruction



Lifetime Tagging

- Tracks from secondary vertex have significant impact parameter $\mathbf{d_0}$ with respect to primary vertex.



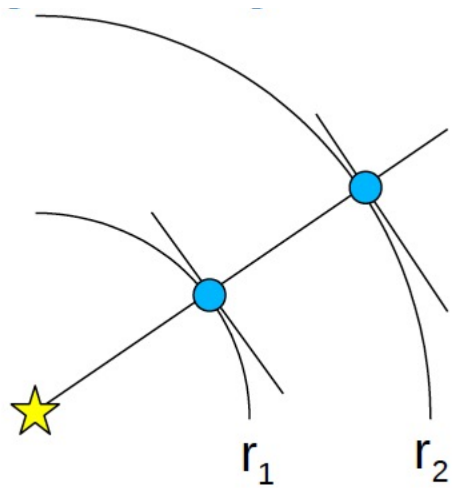


Example of a fully reconstructed event from LHCb with primary, secondary and tertiary vertex

Vertex Resolution

- Very simple case:
  Two tracking layers at radii r_1 and r_2, extrapolation to $r = 0$
  - if uncertainty in layer 1 only:

$$\sigma_{d_0} = \frac{r_2 \sigma_1}{r_2 - r_1}$$



Similarly for layer 2 only:

$$\sigma_{d_0} = \frac{r_1 \sigma_2}{r_2 - r_1}$$

- Adding the two uncertainties in quadrature:

$$\sigma_{d_0}^2 = \frac{r_2^2 \sigma_1^2 + r_1^2 \sigma_2^2}{(r_2 - r_1)^2}$$

Vertex: Multiple Scattering

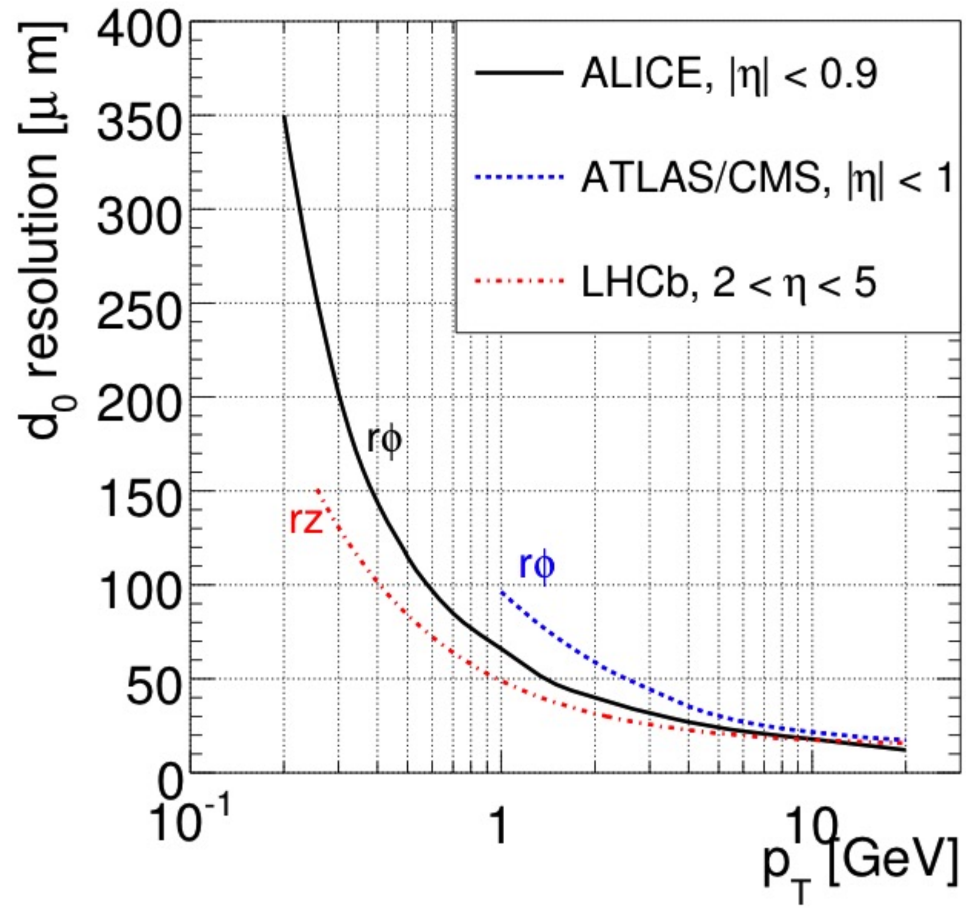
- Additional contribution due to multiple scattering to be added

$$\sigma_i \rightarrow \sigma_i \oplus \Delta r\, \sigma_\theta$$

with σ_θ as for momentum

- Resulting in

$$\sigma_{d_0} = \frac{\sqrt{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}}{r_2 - r_1} \oplus \frac{\text{const.}}{p}\sqrt{\frac{x}{X_0}}$$



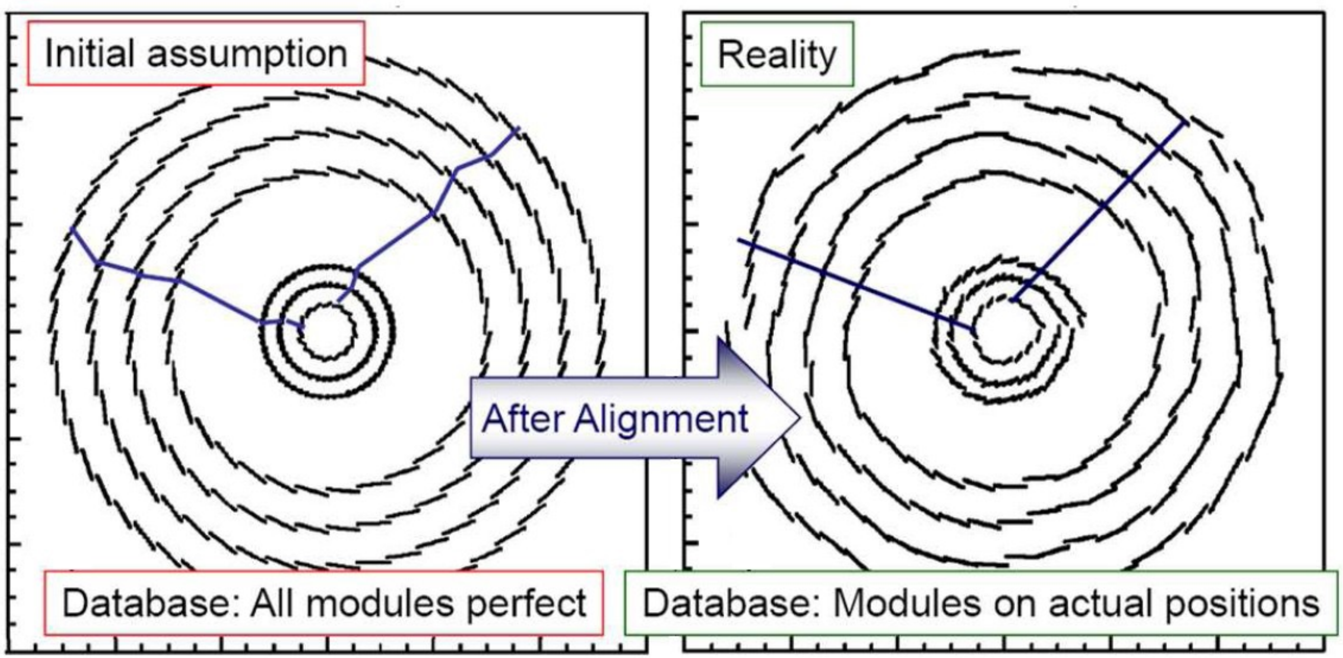
$$\sqrt{\langle\theta^2(x)\rangle} = \theta_{\text{rms}}^{\text{plane}} = \frac{13.6\ \text{MeV}}{\beta p c} z \sqrt{\frac{x}{X_0}}\left(1 + 0.038 \ln \frac{x}{X_0}\right)$$

- Material constant X_0: radiation length
- $\propto \sqrt{x}$ → use thin detectors
- $\propto 1/\sqrt{X_0}$ → use light detectors
- $\propto 1/\beta p$ → serious problem at low momenta

Detector Alignment

Track fit assumes a known position of detector elements

- However systematic shifts due to distortion in mechanical structures (twist, sagging, bending, …)
- Impact on momentum and vertex reconstruction
- Correct for "broken" tracks → alignment



Tracker Design

$$\sigma_{d_0} = \frac{\sqrt{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}}{r_2 - r_1} \oplus \frac{\text{const.}}{p}\sqrt{\frac{x}{X_0}}$$

$$\frac{\sigma_{pT}}{p_T} = \frac{p_T\sigma_{pt}}{0.3BL^2}\sqrt{\frac{720}{N+4}} \oplus \frac{27.2\,\text{MeV}}{0.3B\sqrt{LX_0}}$$

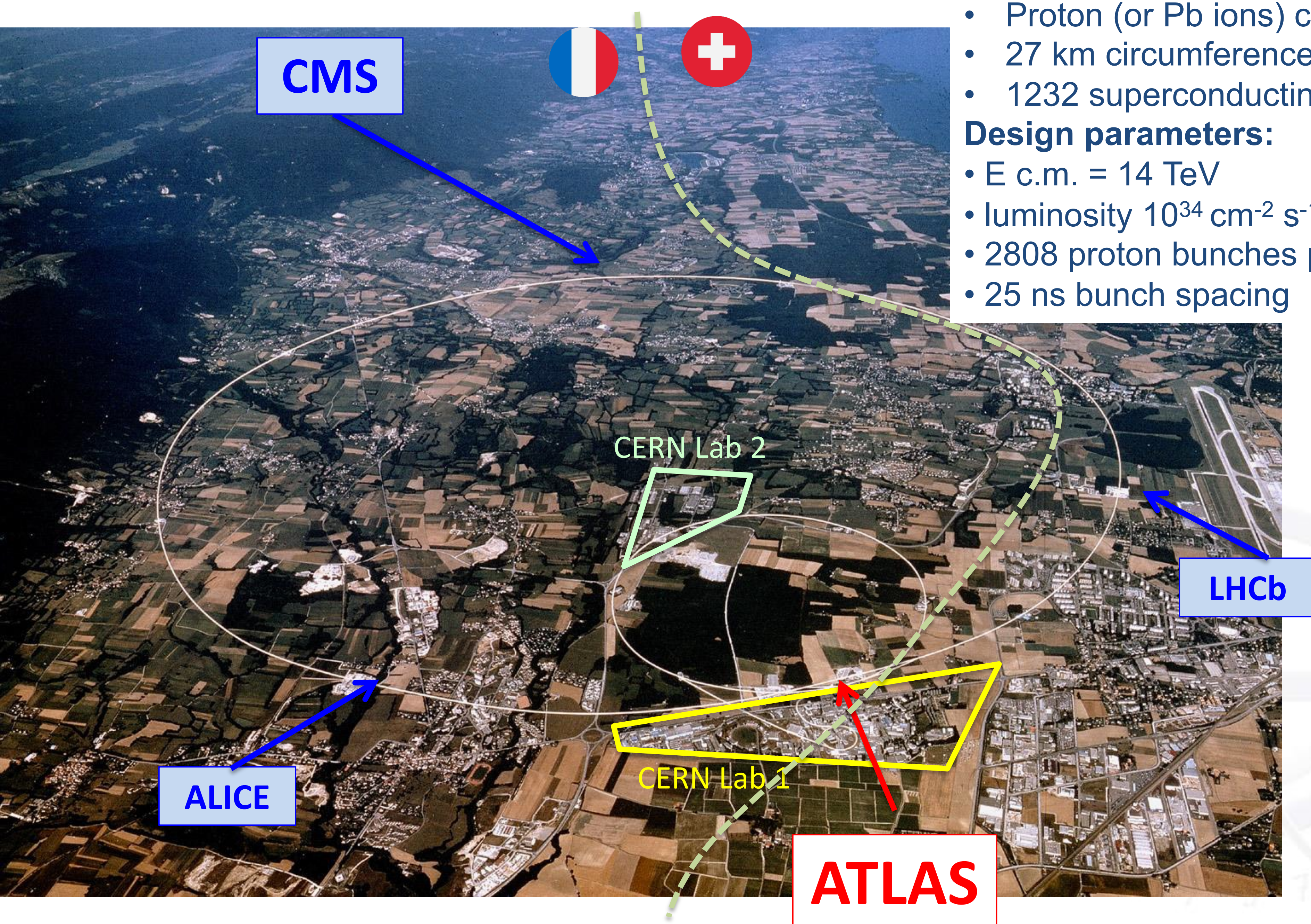
Tracker design:

- Vertex resolution: outer radius ***(r_2)*** as large as possible, inner radius (***r_1***) as small as possible with best point resolution ***σ_1*.**
- Momentum resolution: many points ***(N)*** and long lever arm (***L*),** magnetic field ***(B)*** as strong as possible.

➔ For both concepts we need as little material as possible (**X_0**)

- **Reducing Inner radius**:
  Beam pipe presence, track density, radiation damage.
- **Increasing Outer radius**:
  Overall size increase ➔ Cost increase.

CERN and the LHC



- Proton (or Pb ions) collider
- 27 km circumference
- 1232 superconducting dipoles

Design parameters:

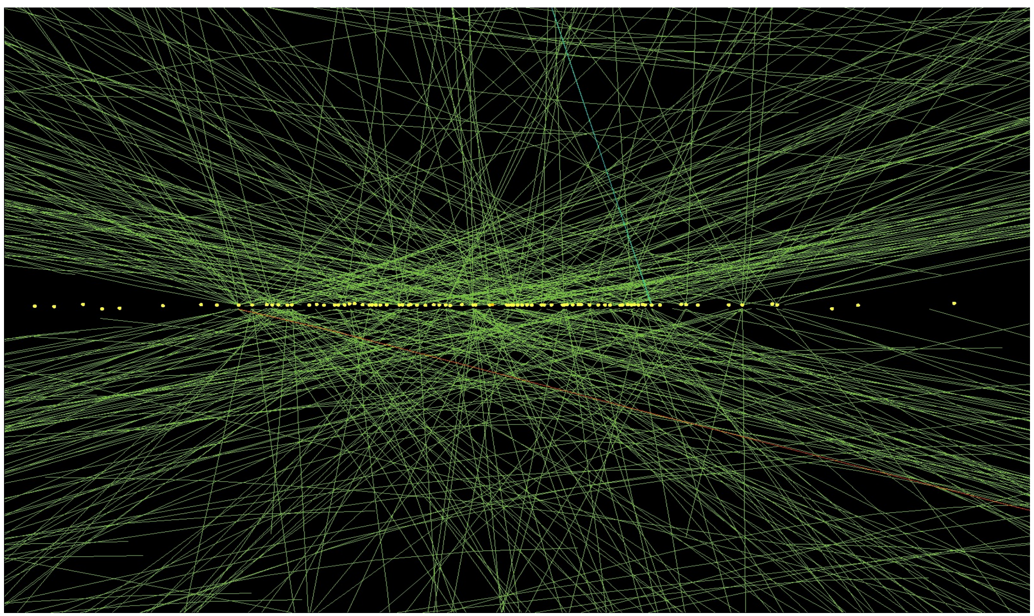
- E c.m. = 14 TeV
- luminosity 10^{34} cm^{-2} s^{-1}
- 2808 proton bunches per beam
- 25 ns bunch spacing

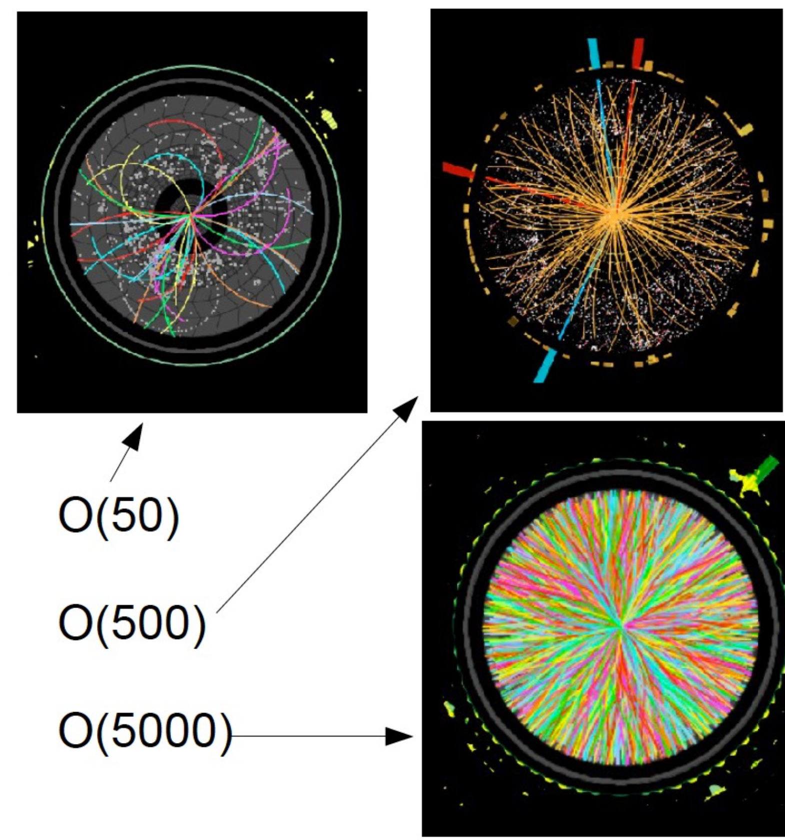
Silicon Trackers at LHC

Fast, good resolution, low dead time, radiation hard.

- ~1000 tracks every 25 ns ➔ 10^{11} tracks per second !
- High radiation dose 10^{15} n_{eq}/ cm^2 in 10 Yrs @LHC

➔ 600 kGy (60 Mrad) from ionization of MIPs in 250 μm bulk silicon

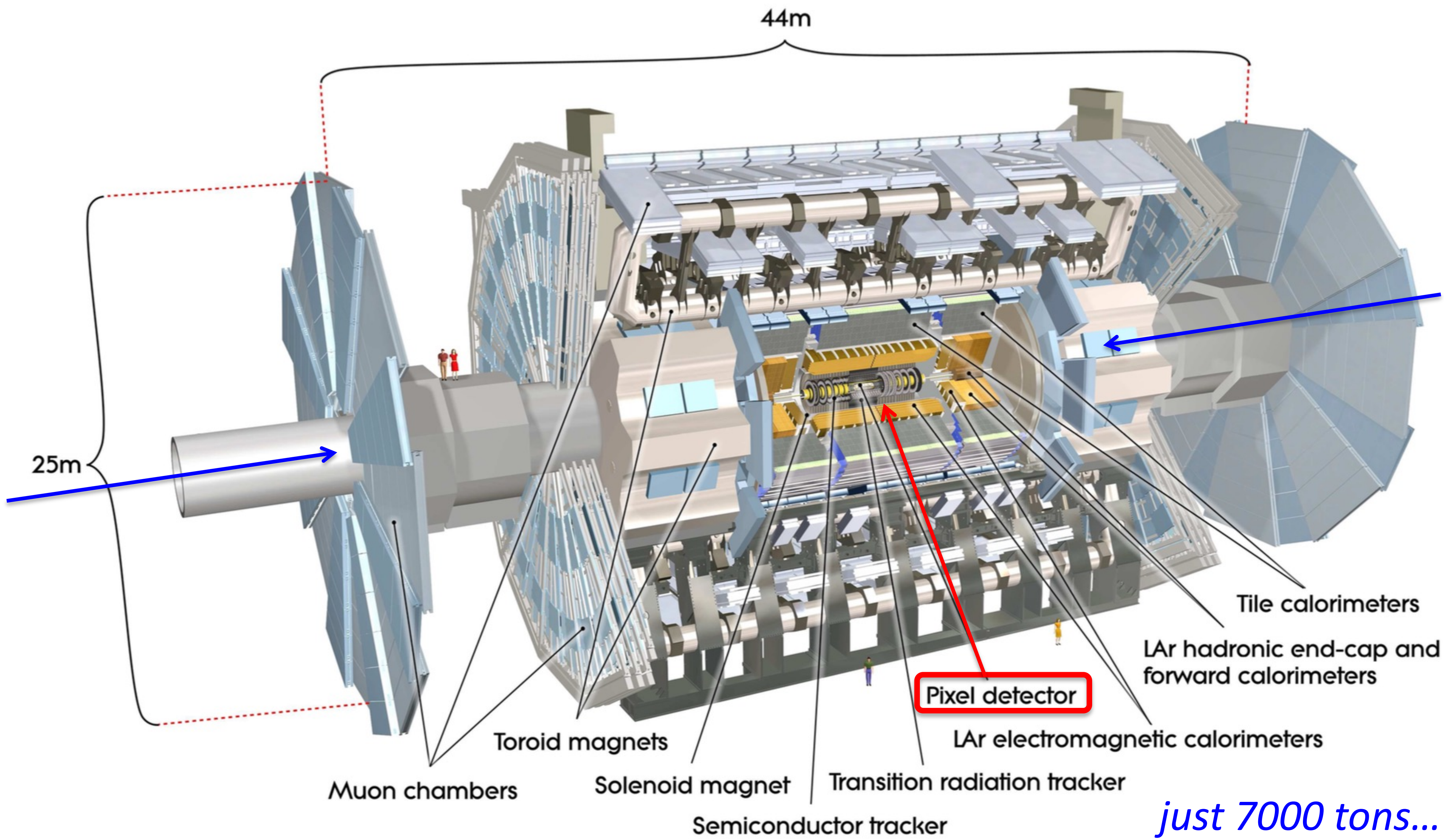




For every taste…

The ATLAS detector @ LHC

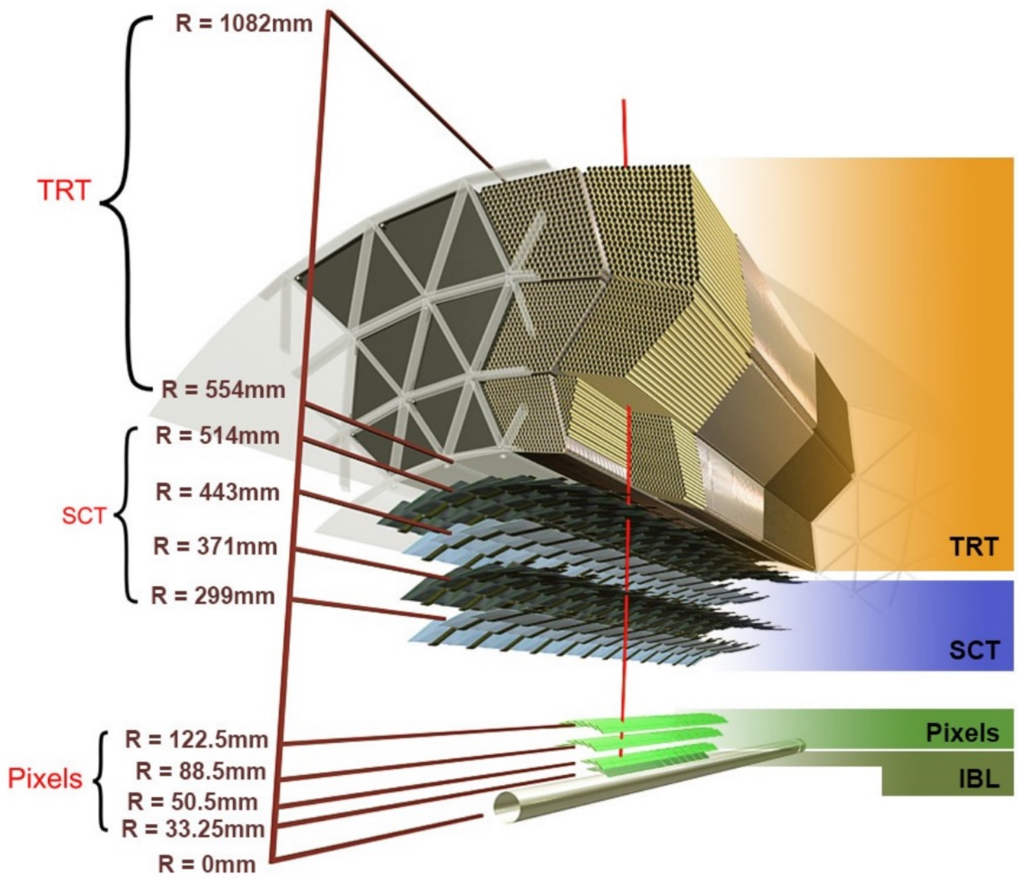
Very large, general purpose magnetic detector for the LHC



just 7000 tons…

The ATLAS Tracker

- Tracking volume is about **7m long** and has a radius of **1.2 m.**
- Sitting inside a superconducting **solenoid field of 2T.**



Outermost uses gas-filled 4mm straws:

- contains 420K electronics channels
- transition radiation detector gives particle ID.

Intermediate is a large silicon strip tracker:

- 4 barrel layers and 9 disk layers contain 61 m^2 of silicon with 6.2 M channels.

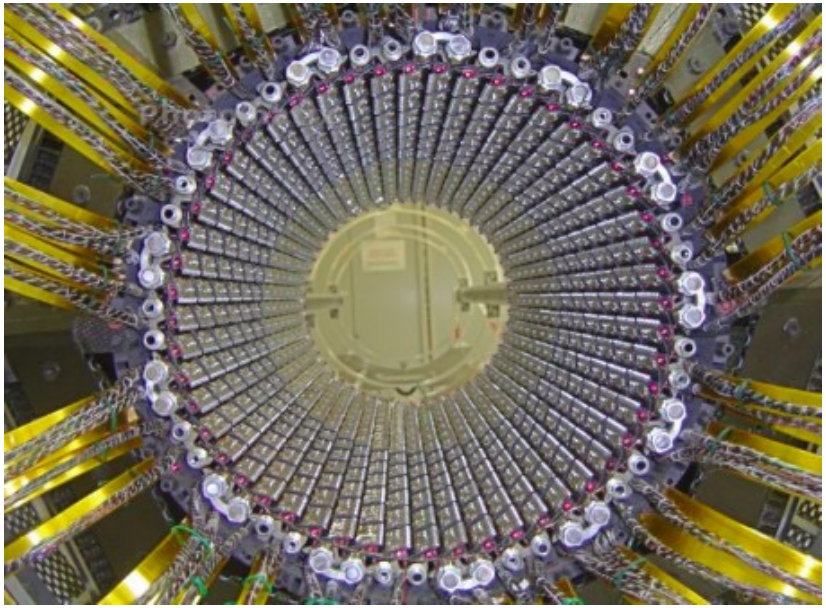
Innermost is a silicon pixel tracker:

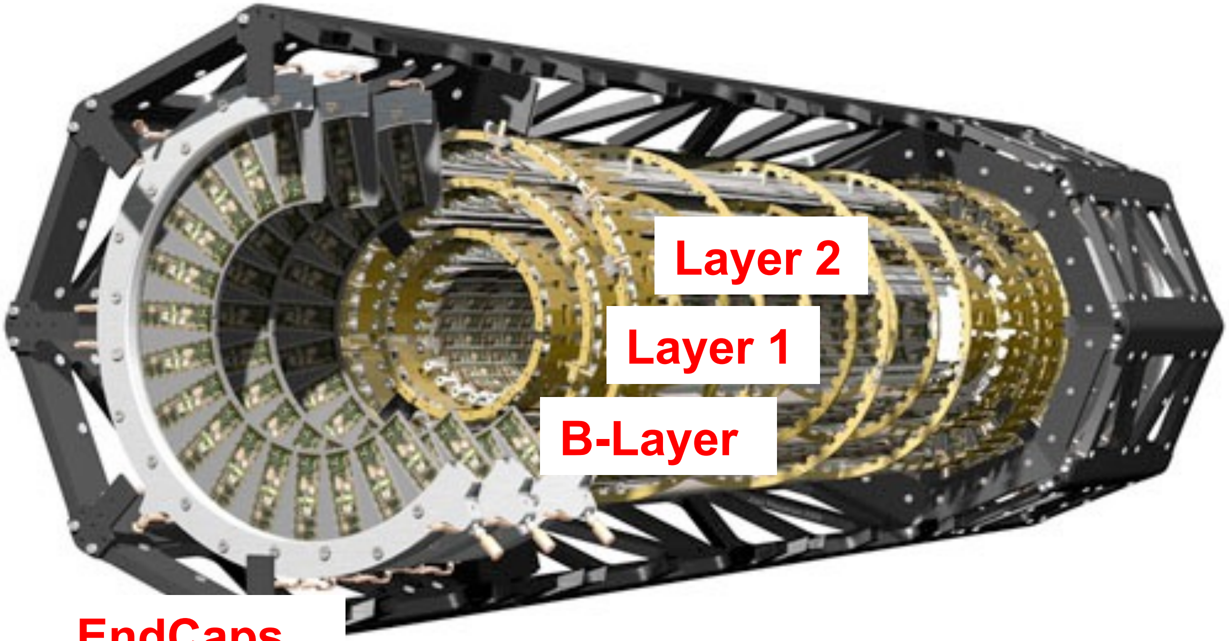
- **4 barrel layers and 3 disk layers contain 1.92 m^2 of silicon and 92 M channels.**

The ATLAS Pixel Detector

3 Layers initially (beginning of 2010)

- **3** precision measurements that determines the **impact parameter resolution** and the ability of the Inner Detector to find **short lived particles** such as B-Hadrons.
- **1744** modules arranged into **3 barrel** and **3 end-cap** layers with acceptance **$|\eta|< 2.5$** ➔ each module is **62.4 mm** long and **21.4 mm** wide.
- The modules are **overlapped** on the support structure to give **hermetic** coverage.
- The thickness of each layer (**250 µm**) is expected to be about **2.5% X_0** .





Why we needed a 4th Layer?

- ***Luminosity (particle rate) increase***
  - Front-End electronics expects inefficiency at high particle rate ($L \sim 2 \times 10^{34}\ cm^{-2}s^{-1}$).
- ***Radiation damage***
  - Sensor/electronics degradation impacts the detector efficiency.
- ***Compensate inefficiency in the Pixel***
  - The Pixel retector cannot be repaired in case of hardware failure:

    → high impact on many physics channels.
- ***Improvement of the tracking/vertexing/b-tagging***
  - Higher resolution & proximity to IP enhance pile-up separation
  - low material budget (1.5% X_0)
- ***Technology step towards the HL-LHC***

Insertable B-Layer (IBL)

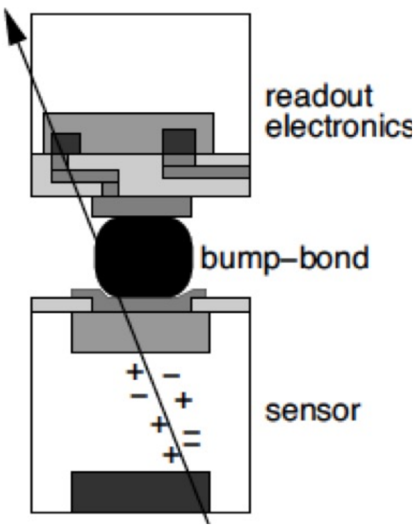
The IBL Detector

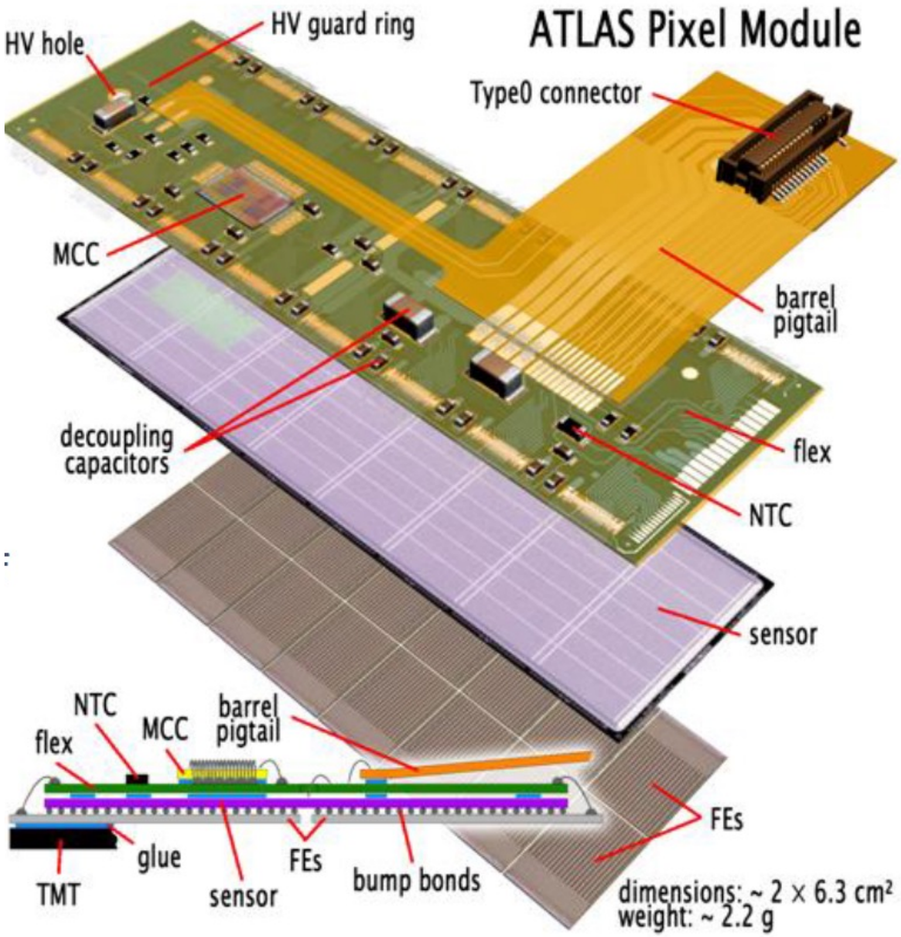
Insertable B-Layer (IBL) was added at the beginning of **RUN 2 (2014)**

The building block: Pixel module

Read-out:

- 16 Front-ends chips bump-bonded to sensor





Sensor:

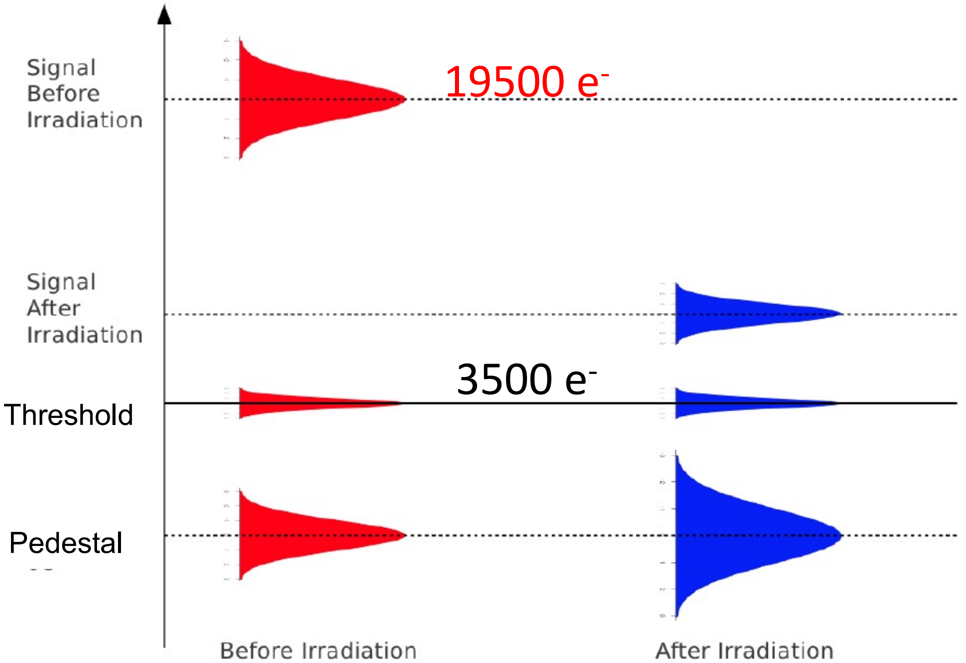
250 μm thick n-in-n Si planar sensor:
50 x 400 typical μm pixel size
Bias voltage: 150 -600 V

Resolution: ~10 μm in Rφ and ~100 μm in z

Pixel performance after ~10 years

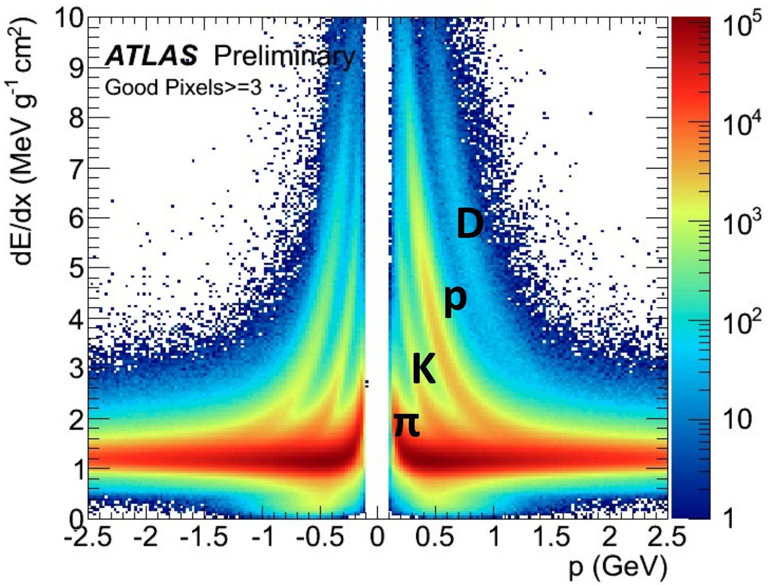
Signal of a high energy particle
MIP ~ 19500 e^- in 250 µm silicon

➔ **however, < 10000 e^- after irradiation**



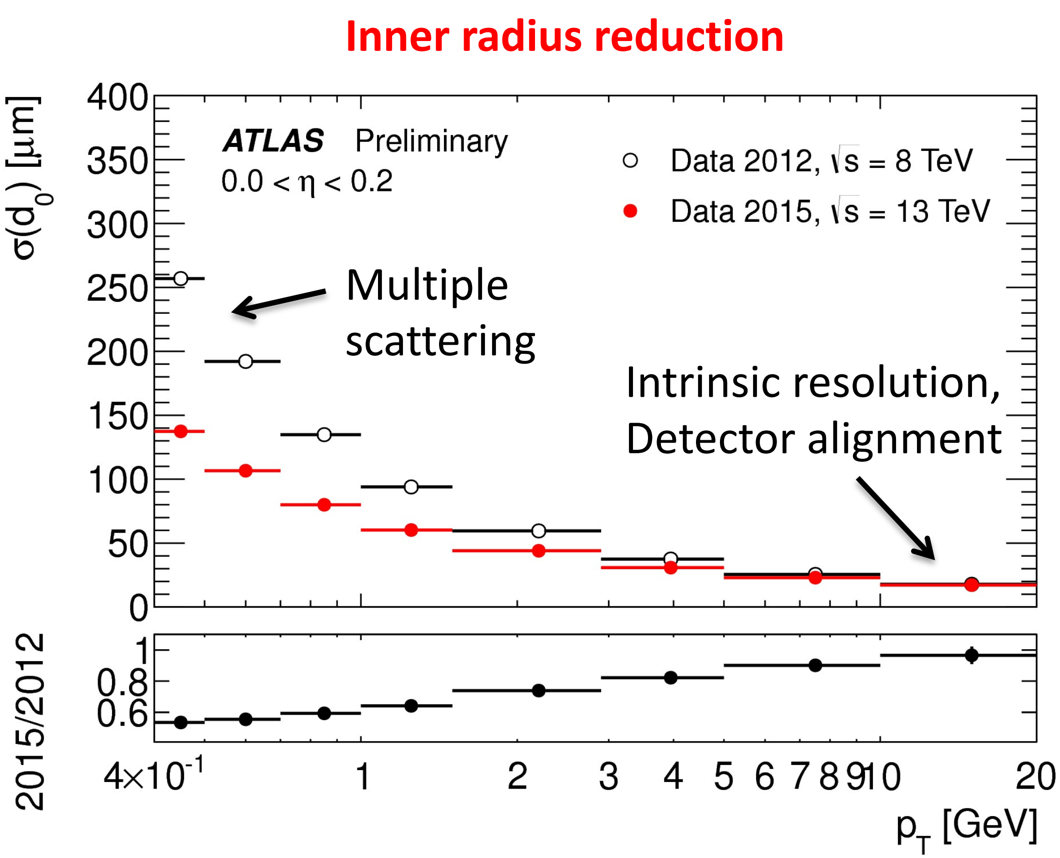
Discriminator thresholds = 3500 e^-
Noise ~200 e^-

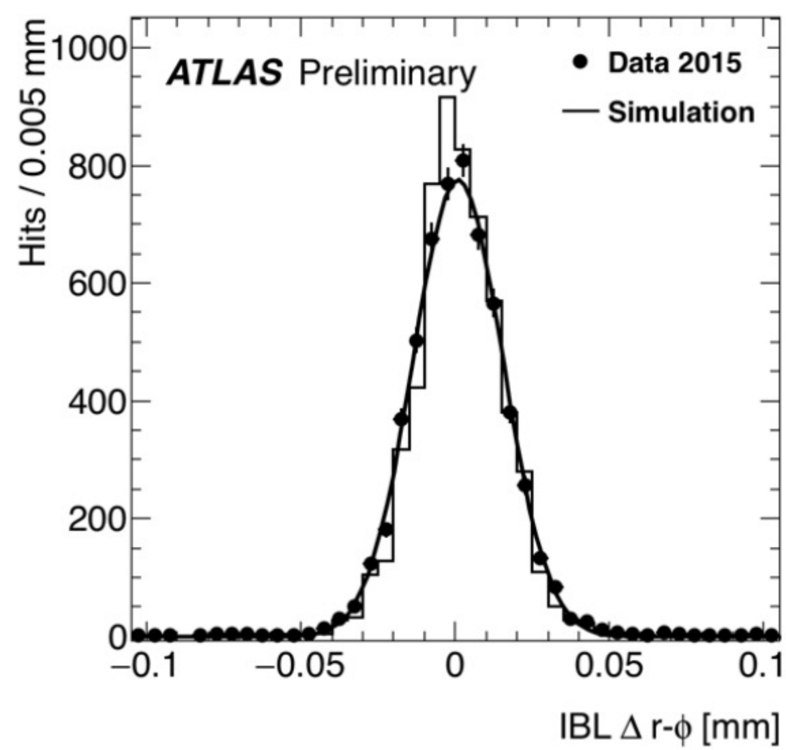
- 99.8% data taking efficiency
- ~ 96% of detector operational
- ~10 µm x 100 µm resolution
- 12% dE/dx resolution



Pixel (IBL) performance in Run 2

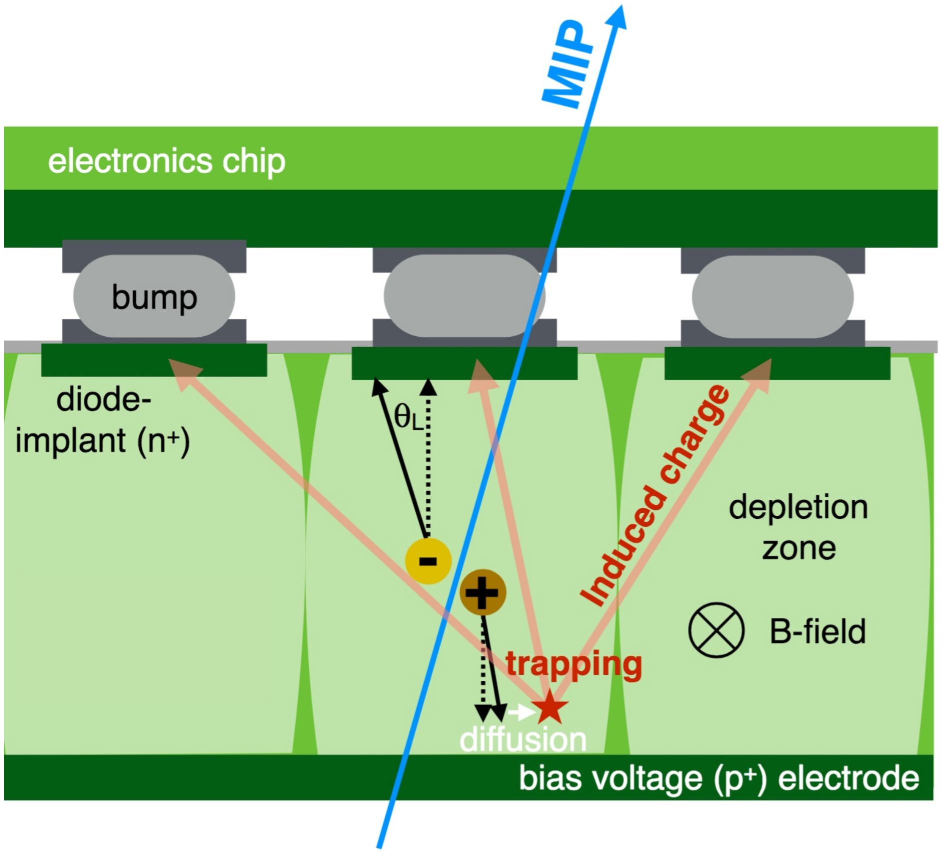
- Impact parameter resolution improvements after IBL insertion (2015 data)
- IBL spatial resolution ~ 10 µm for the transverse R-φ plane





Radiation damage in Silicon

- Charge carriers will drift toward the collecting electrode due to **electric field**, which is deformed by **radiation damage**.
- Their path will be deflected by magnetic field (Lorentz angle) and by diffusion.



Radiation damage introduces defects into the sensor bulk:

→ increases the leakage current

→ increases the "depletion voltage"

→ decreases the collected charge

→ deforms the E-field (double-peak)

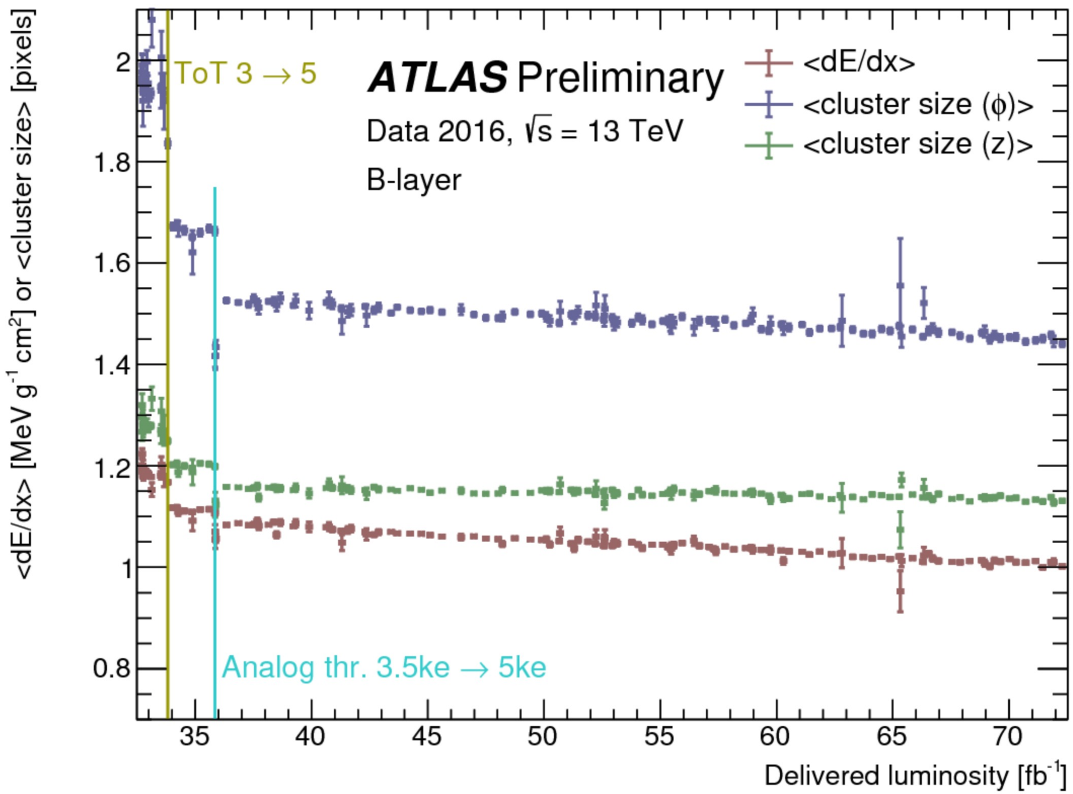
Effect of radiation on dE/dx

- Decreasing charge collection efficiency (trapping of charge carrier in the sensor bulk defects)

  ➔ measured dE/dx decreases.

- HV (or bias Voltage) can have an influence if detector not fully depleted.

- Front end electronics threshold increase show up as steps in dE/dx since hits below threshold do not get recorded anymore

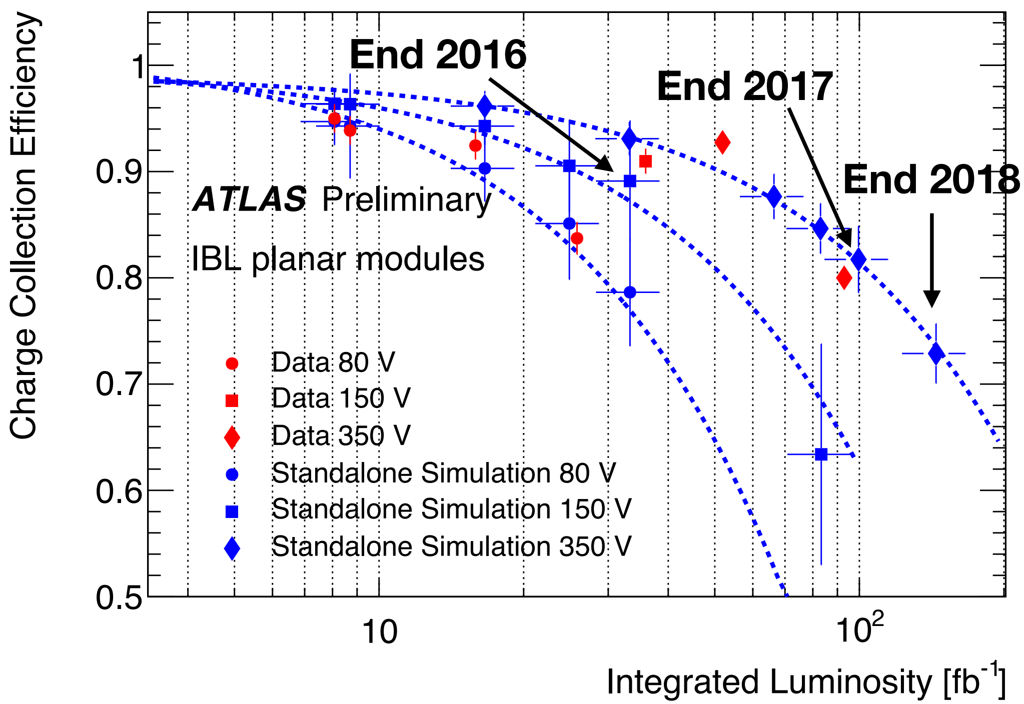


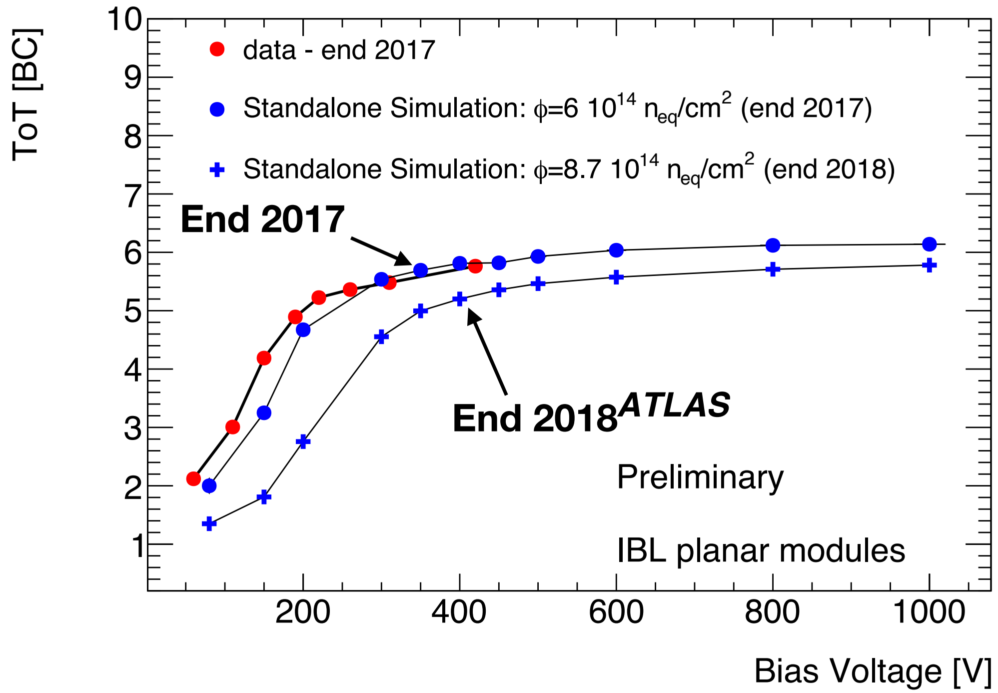
Fighting the radiation damage

- **Charge collection ratio** between **irradiated and pre-irradiation** sensor as a function of **integrated luminosity (radiation)**
  ➔ clear **decrease of the charge collected!**

- Most Probable Value of the Landau distribution of the Time Over Threshold (TOT)
  ➔ equivalent of charge!

- **Bias voltage scans** to monitor the “depletion voltage” evolution





References

General particle detection books:

K. Kleinknecht: *Detectors for Particle Radiation*, Cambridge University Press
W. R. Leo: *Techniques for Nuclear and Particle Physics Experiments*, Springer
G. F. Knoll: *Radiation Detection and Measurement*, Wiley.

Semiconductor detectors books:
H. Spieler, *Semiconductor Detector Systems*, Oxford Science Publications
G. Lutz, *Semiconductor Radiation Detectors*, Springer Verlag
L. Rossi, P. Fischer, T. Rohe, N. Wermes, *Pixel Detectors*, Springer Verlag

Detector lectures:

W. Riegler, *Fundamentals of Particle Detectors and Developments in Detector Technologies for Future Experiments*, CERN.
D. Pitzl, Detector for Particle Physics, DESY.
E. Garutti, The Physics of Particle Detector, DESY.

Back-up

Miscellanea

Particles are characterized by

Mass	[Unit: eV/c^2 or eV]
Momentum	[Unit: eV/c or eV]
Energy	[Unit: eV]
Charge	[Unit: e]

[+ Spin, Lifetime ...]

$eV = 1.6 \cdot 10^{-19}$ J
c = 299 792 458 m/s
$e = 1.602176487(40) \cdot 10^{-19}$ C

Relativistic kinematics:

$$E^2 = \vec{p}^{\,2} c^2 + m^2 c^4$$

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$E = m\gamma c^2 = mc^2 + E_{\mathrm{kin}} \qquad \vec{p} = m\gamma\vec{\beta}c \qquad \vec{\beta} = \frac{\vec{p}c}{E}$$

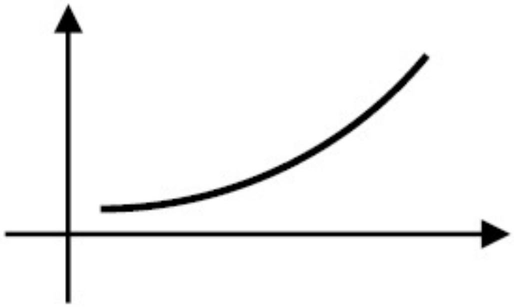
Particle Identification via measurement of

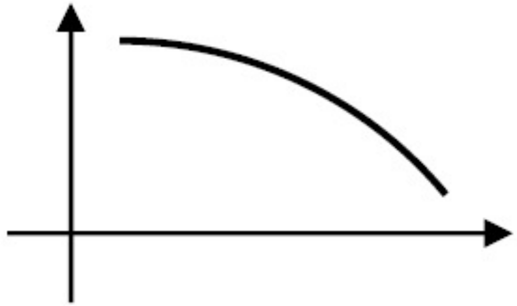
e.g. $(E, \vec{p}, Q)$ or $(\vec{p}, \beta, Q)$
$(\vec{p}, m, Q)$ ...

Charge sign

- Sign of charge is defined by the sign of 1/R=k :

$$Q = +1 \quad \frac{1}{R} > 0 \qquad\qquad Q = -1 \quad \frac{1}{R} < 0$$





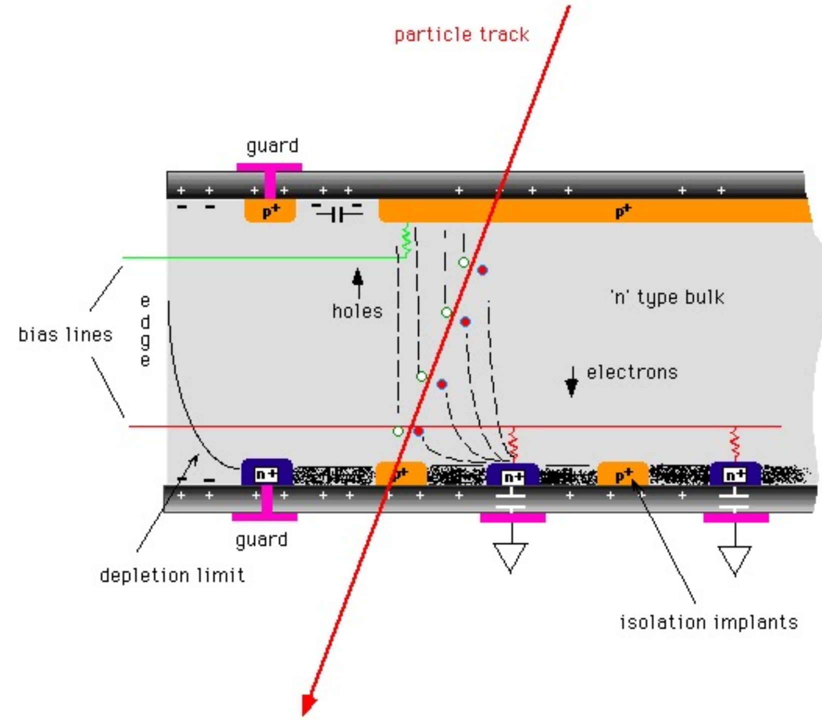
- Precision on k from Gluckstern:

$$\sigma_k = \frac{\sigma_{\text{point}}}{L^2}\sqrt{\frac{720}{N+4}}$$

- Requiring 3σ identification → upper lim. in p:

$$\frac{1}{R} > 3\sigma_k = \frac{3\sigma_{\text{point}}}{L^2}\sqrt{\frac{720}{N+4}} \Rightarrow p < \frac{0.3\,B\,L^2}{3\,\sigma_{\text{point}}}\sqrt{\frac{N+4}{720}}$$

Consideration for Pixel detectors



Requirements

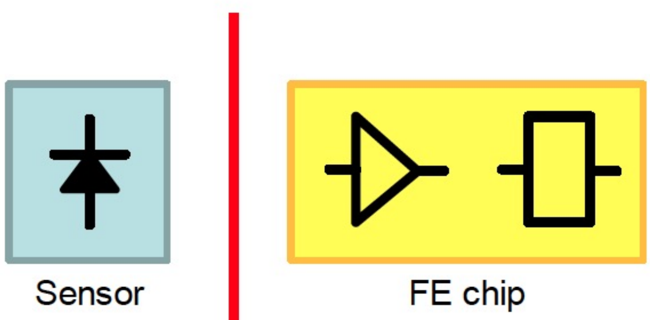
- good Signal/Noise
- μm space resolution
- ~ns time resolution
- >10 MHz / mm^2 rate capability
- radiation hard to 50 Mrad
- radiation length per layer < 0.2% X_0

Advantages

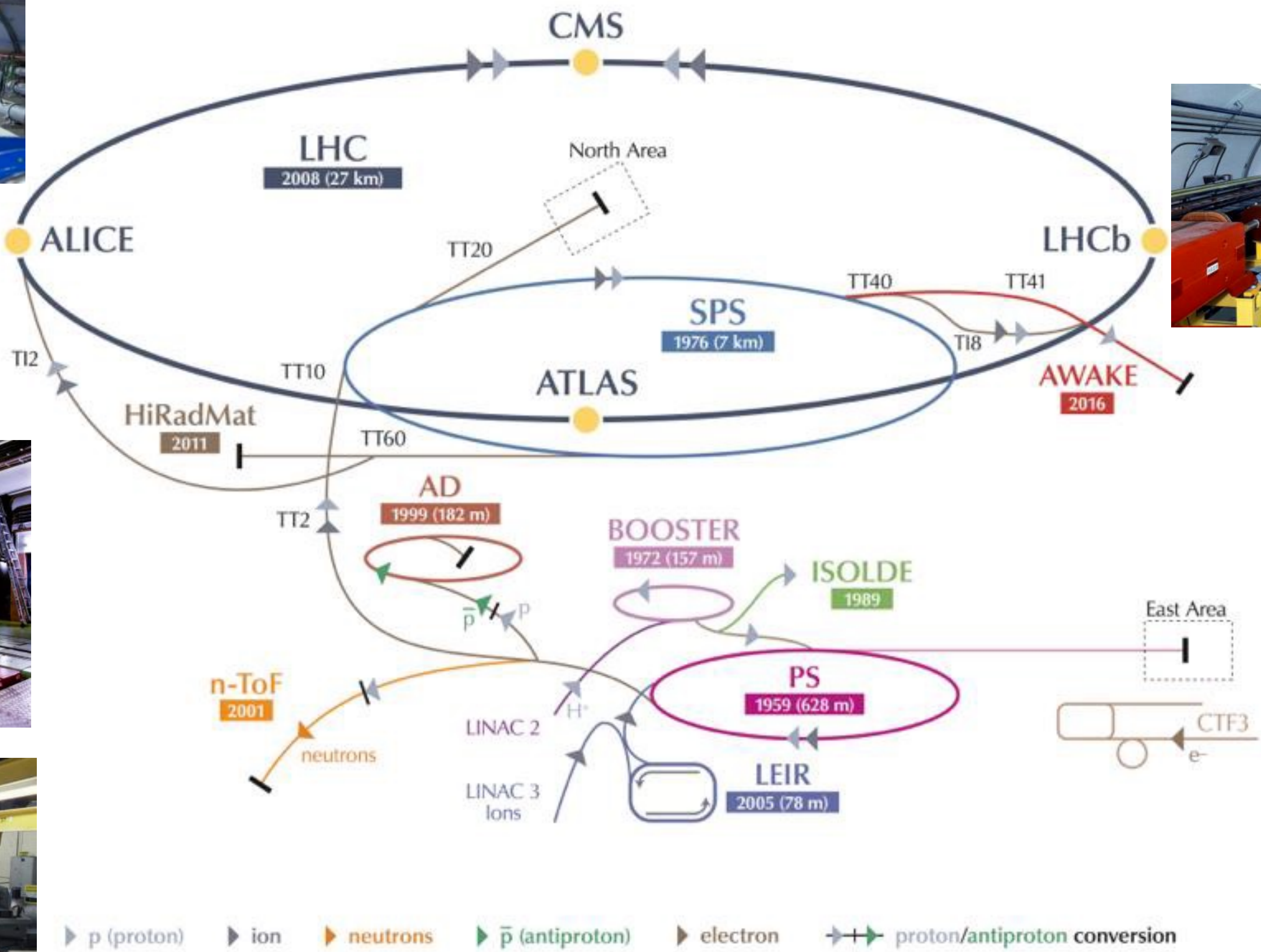
- Provides space-point information
- Small pixel area ➔ low occupancy/noise
- Small pixel volume ➔ low leakage
- n+-on n for the LHC ➔ e- faster collection time

Disadvantages:

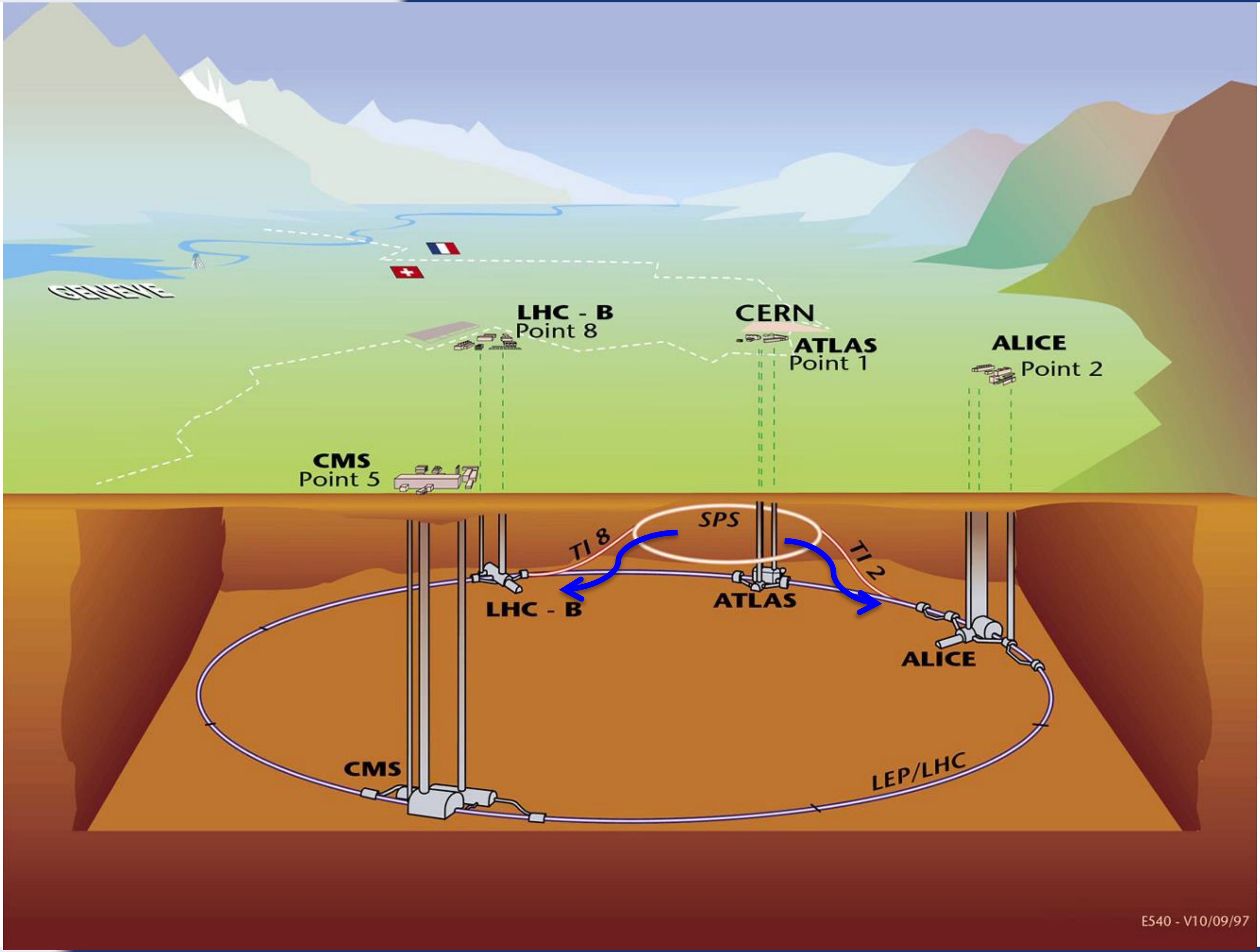
- Large number of readout channels
- Large bandwidth
- Large power consumption
- Bump bonding is costly



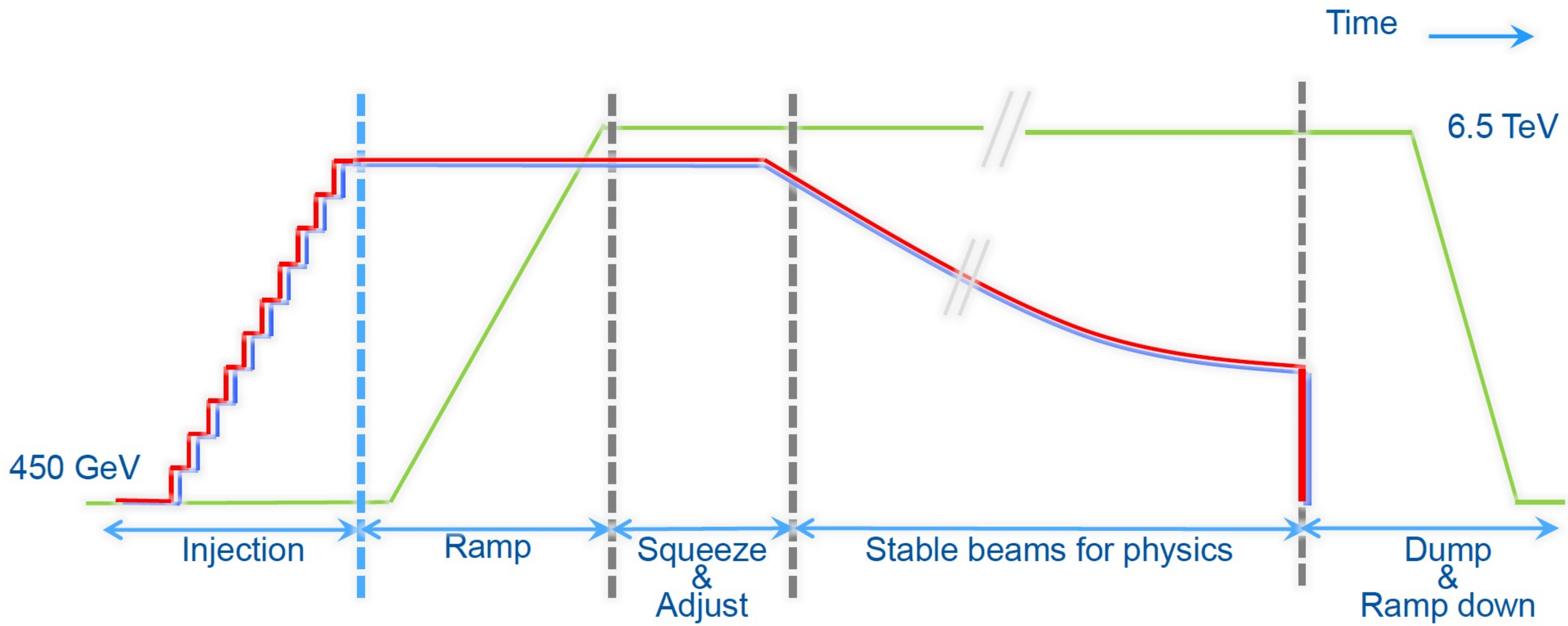
CERN facilities.. not just LHC



Filling LHC on the underground



Injection, Acceleration, Collision



- = Field in main magnets
- = Beam 1 intensity (current)
- = Beam 2 intensity (current)

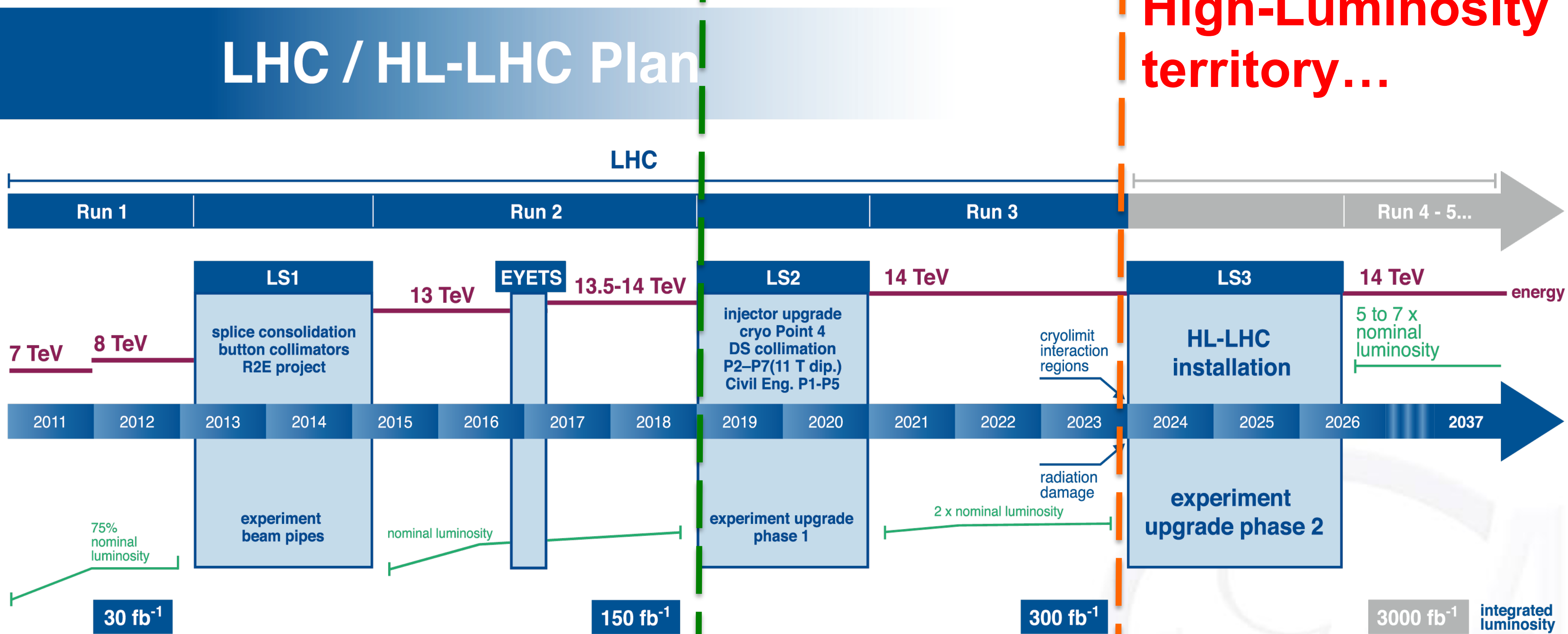
The LHC is built to collide protons at 7 TeV per beam, which is **14 TeV centre of Mass**

In 2012 it ran at 4 TeV per beam, 8 TeV c.o.m.

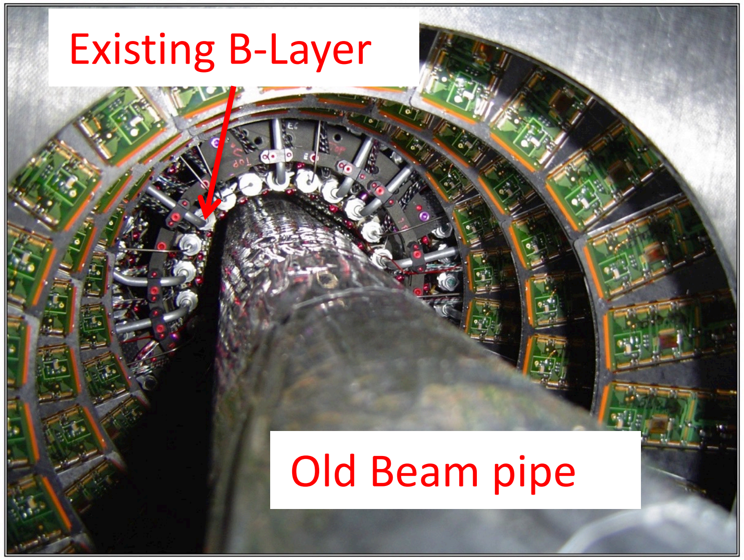
In 2015 it ran at 6.5 TeV per beam, 13 TeV c.o.m

LHC Timeline

High-Luminosity territory…



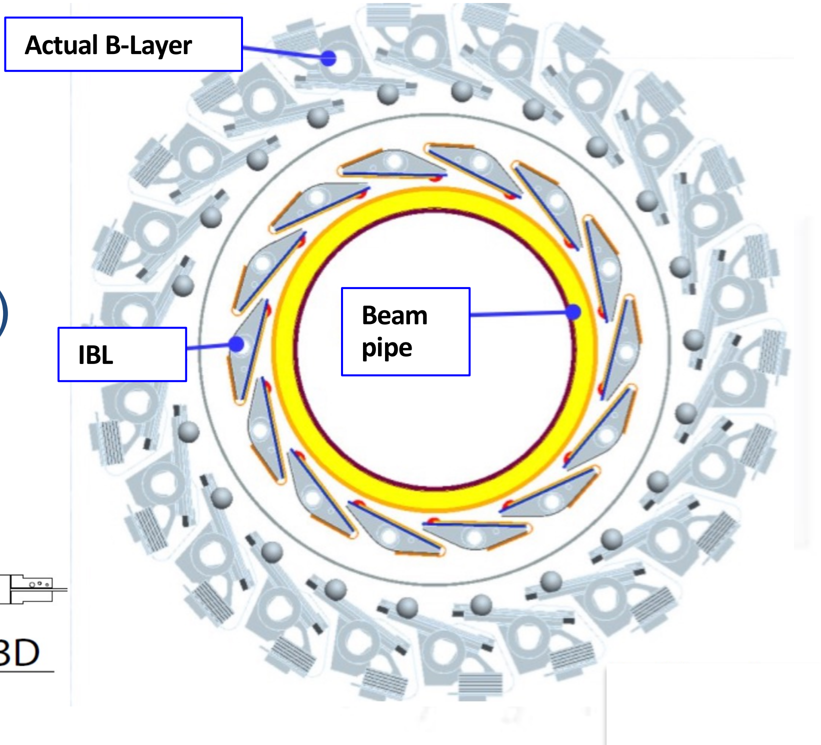
The IBL detector



The IBL idea in a nutshell

- add a single detector layer built around a new thinner Beryllium beam-pipe (radius 29 mm ➔ 25 mm).
- closer to interaction point (5.05 → 3.27 cm)
- smaller pixel size (50 × 400 → 50 × 250 μm^2)
- IBL + beam pipe and structures : < 2% X_0

The IBL layout



- 14 staves in the phi coordinate
- 32 front-end chips along the eta (z) coordinate
- mixed configuration of planar (75%) and 3D (25%) sensors technologies along the staves.
- ~12 million pixels in total!