GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

ATLAS EXPERIMENT

# Detector Physics (II part): particle identification, photon detector silicon detectors tracking concepts “


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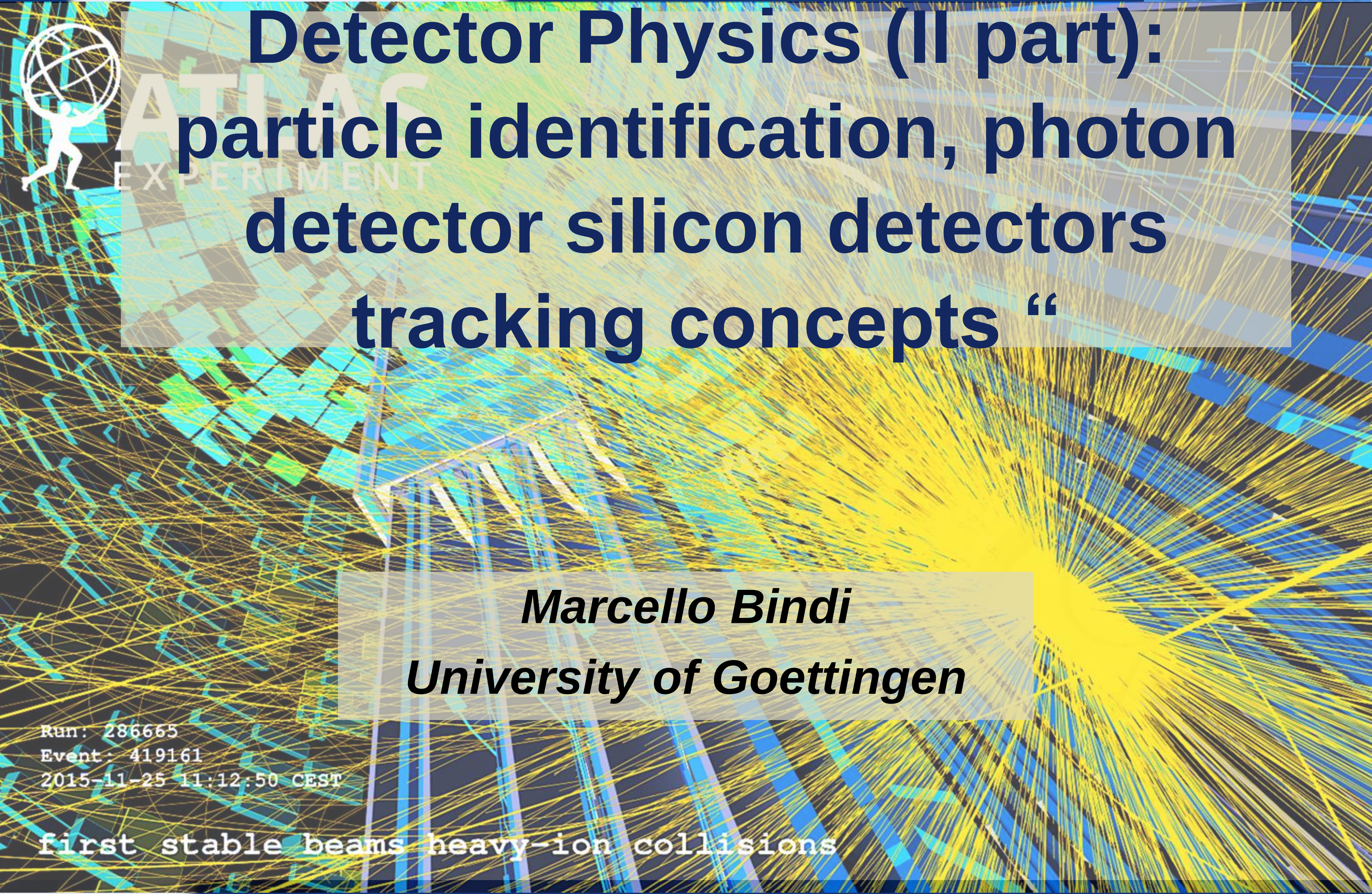


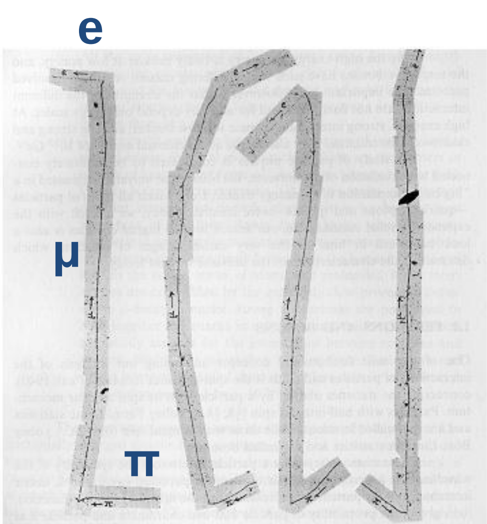
# Outline of the Detector lecture

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

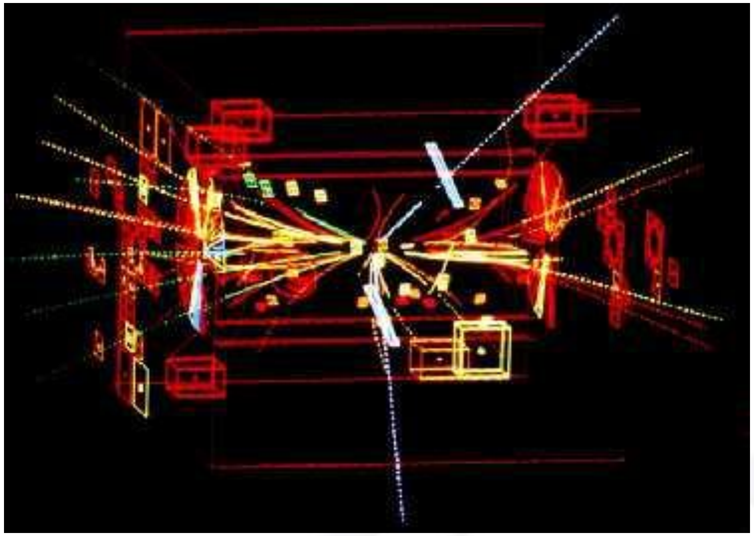
# A few detection principles

- **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**

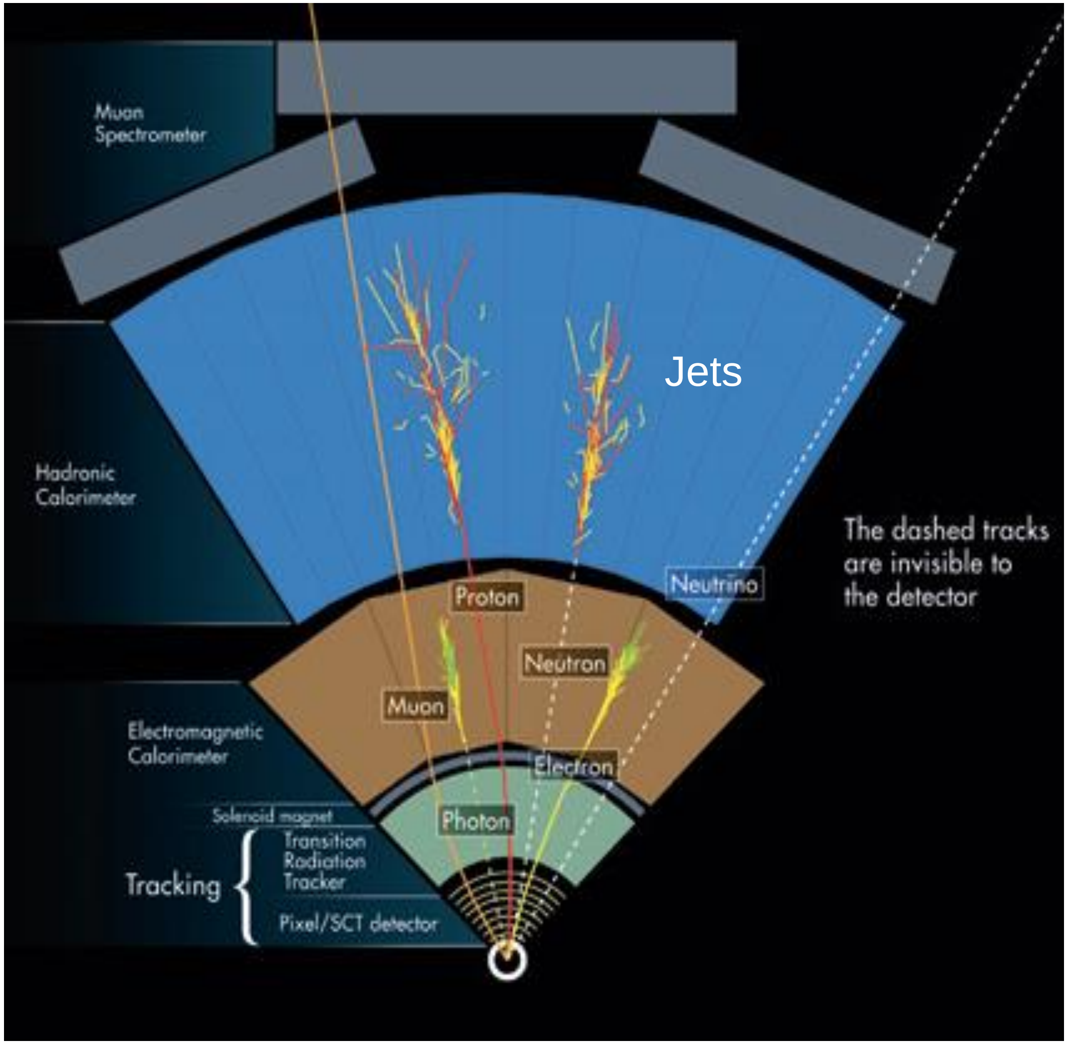


**$Z_0$ boson discovery at UA1 CERN (1983)**

- 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 (cτ > 500 μm)
  ➔ 8 most frequently produced **$e^{\pm}$, $\mu^{\pm}$, γ, $\pi^{\pm}$, $K^{\pm}$, $K^0$, $p^{\pm}$, n**

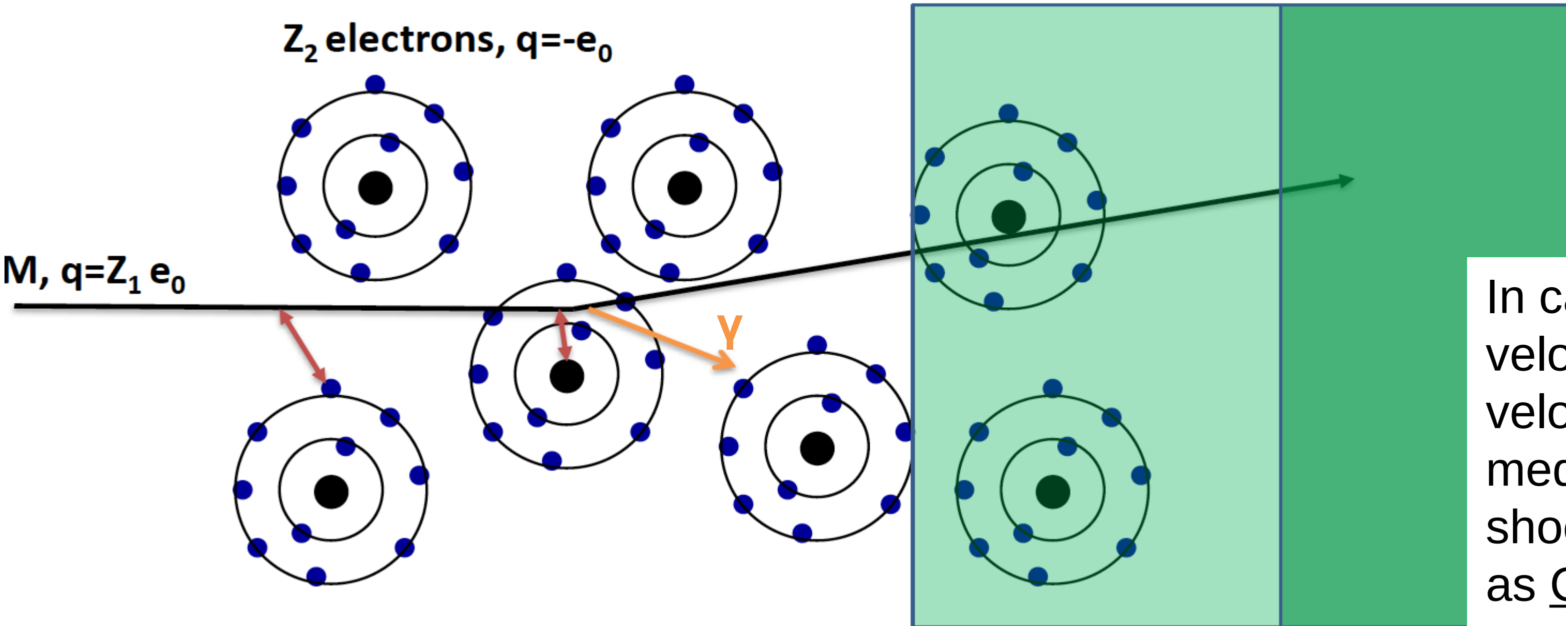



- To detect a particle, it has to interact/***deposit energy***:
  - could be a **part** (trackers) or the **full** (calorimeters) energy!
- Ultimately, **the signals** comes from the ***charged particle interactions:***
  - Neutral particles (photons, neutrons) must transfer their energy to charged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

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.

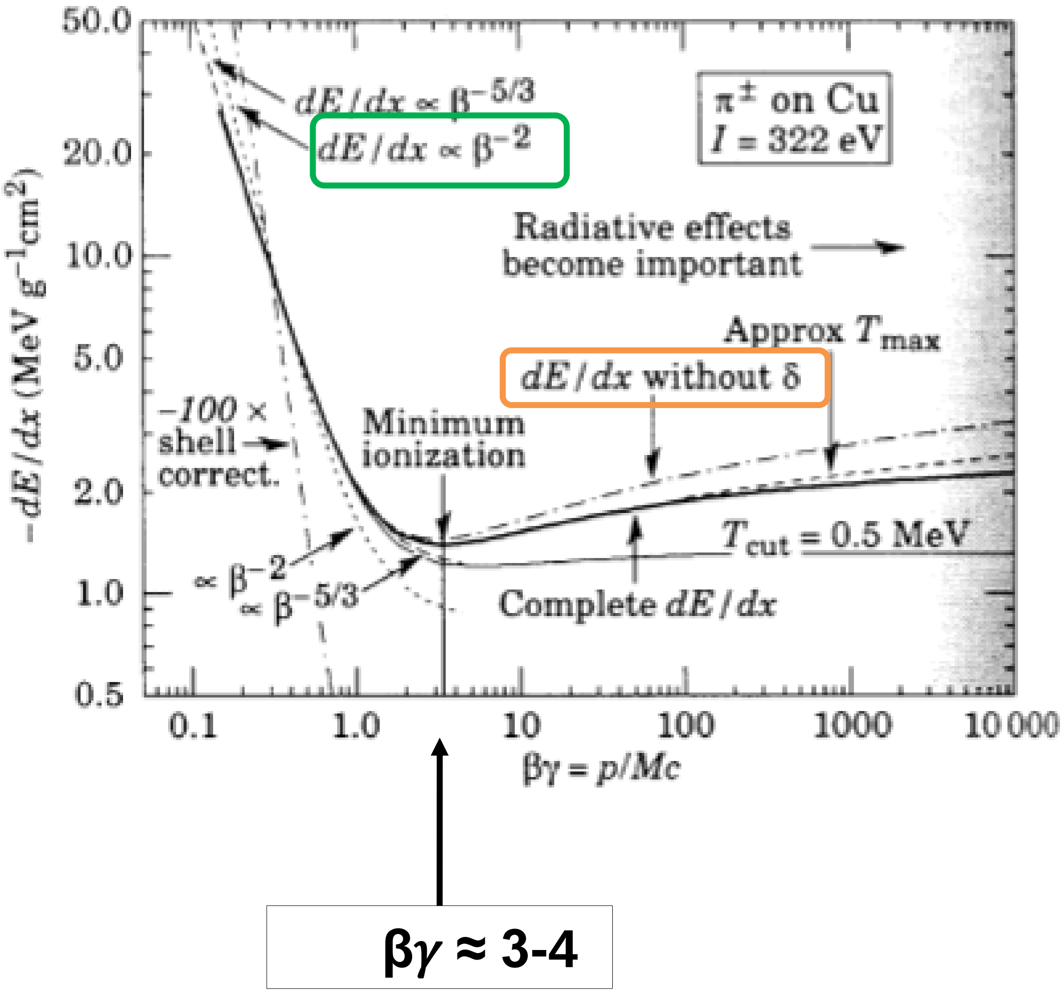
**Interaction with the atomic electrons.** The incoming particle loses energy and the atoms are excited or ionized.

**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/2

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




Three distinctive regions:

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

Units: MeV g$^{-1}$ cm$^2$ or MeV/(g • cm$^{-2}$)

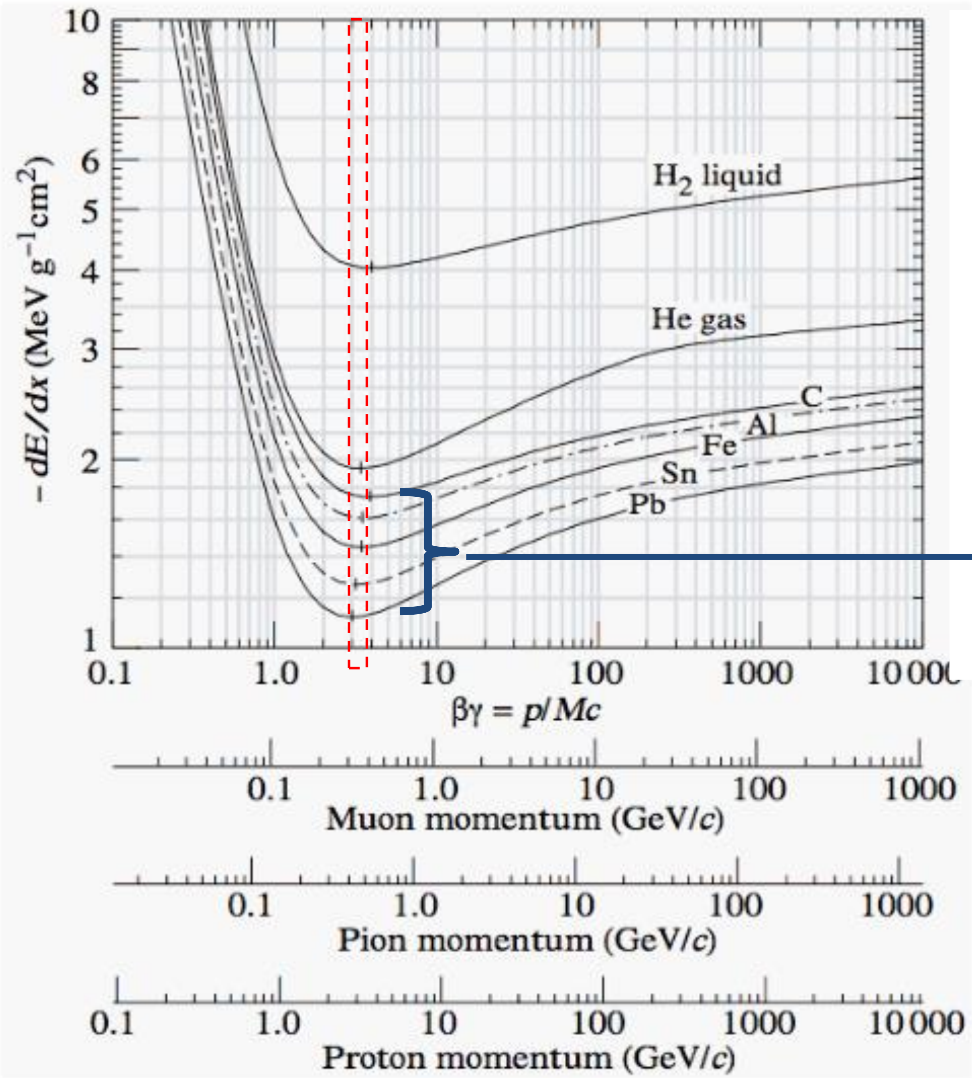
➔ **$\langle dE/dx \rangle_{min}$ ~ 1- 2 MeV g$^{-1}$ cm$^2$**

Density of copper: $\rho$=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 ($\beta\gamma$ ≈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

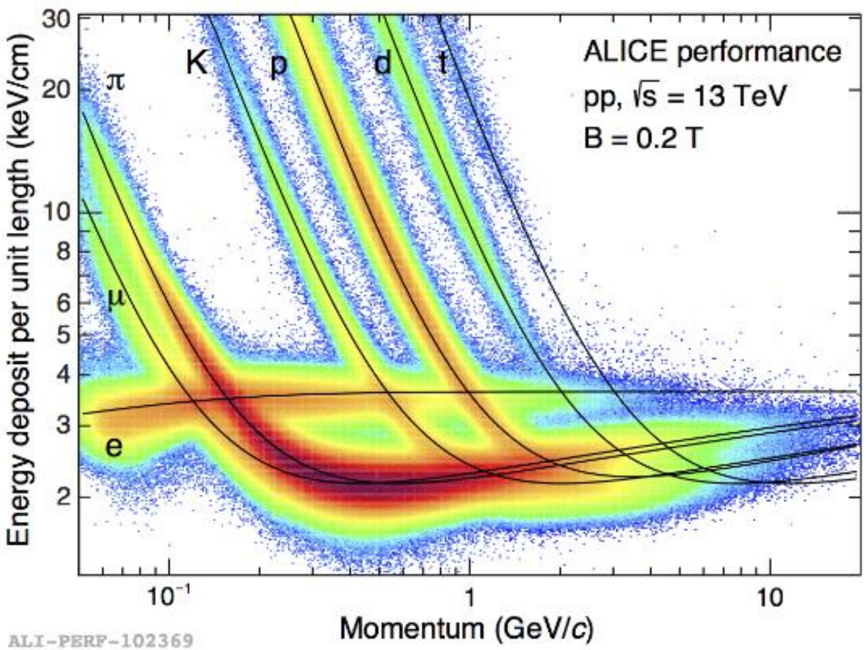
dE ≈ 1.4*100*7.87 = 1102 MeV = 1.1 GeV

➔ 1 GeV muons can travers 1 m of iron!

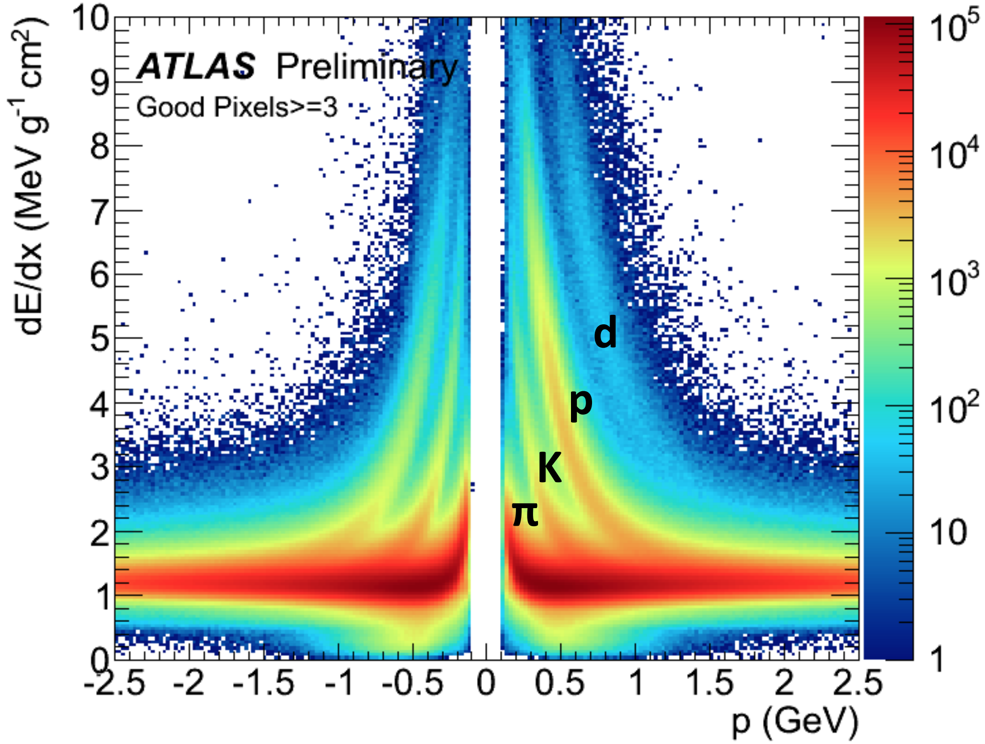
# dE/dx for particle identification

- *<dE/dx>*: identical for particles with the same charge (***z***) vs $\boldsymbol{\beta\gamma} = \boldsymbol{p/mc}$, 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)

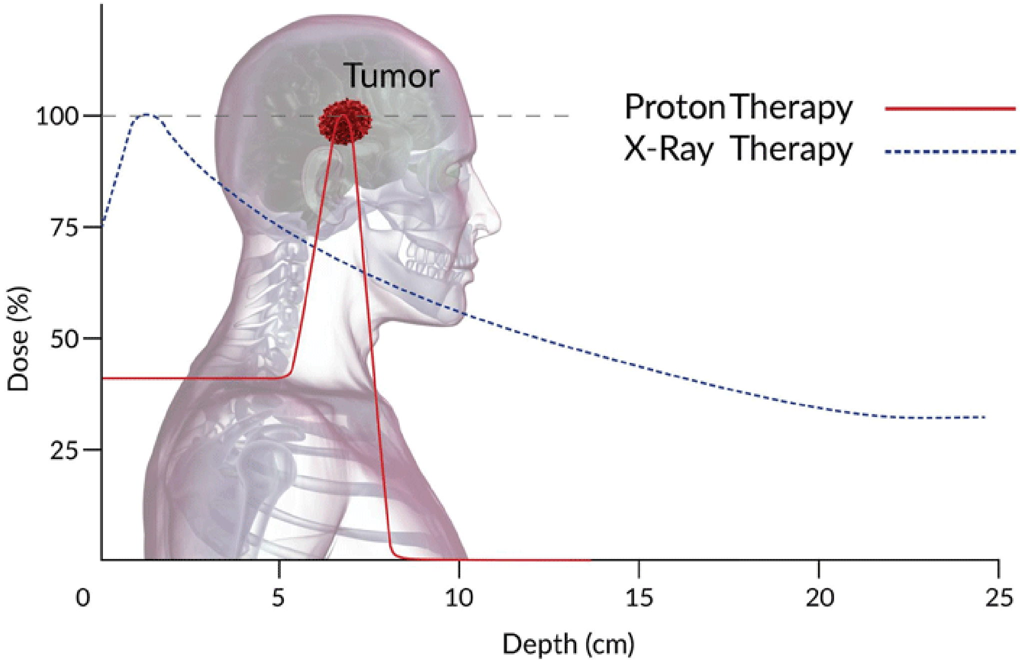
# Energy loss at small momentum / Range

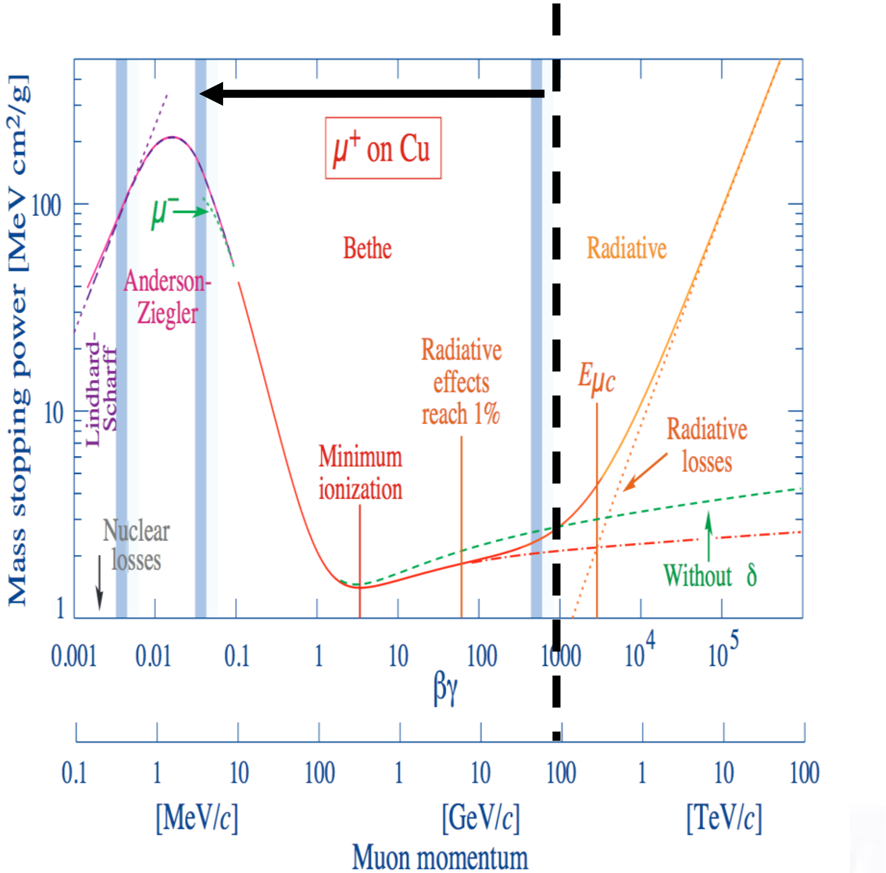
- For $\beta\gamma > 3$ the energy loss is ~constant
- Energy loss increases $\mathbf{1/\beta^2}$ for $\beta\gamma < 3$

➔ 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

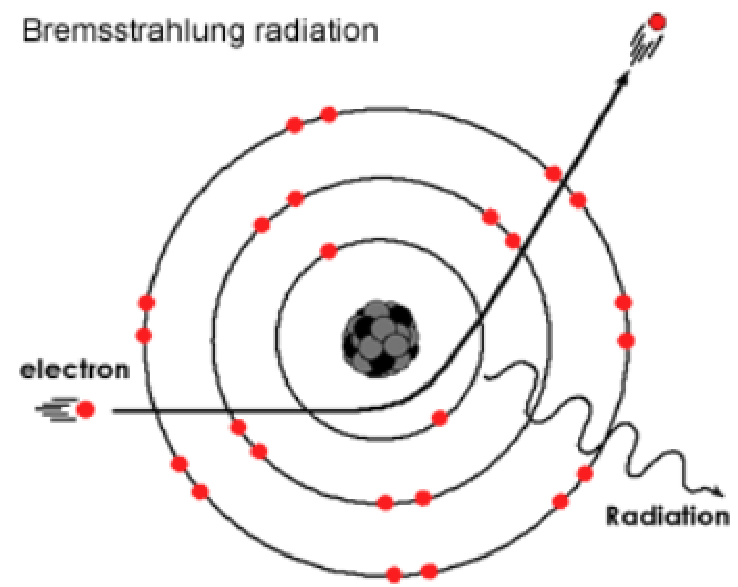
- For electrons, Bethe-Bloch formula needs corrections since:
  - Incident and target electron have same mass, QM indistinguishable

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

- 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)**

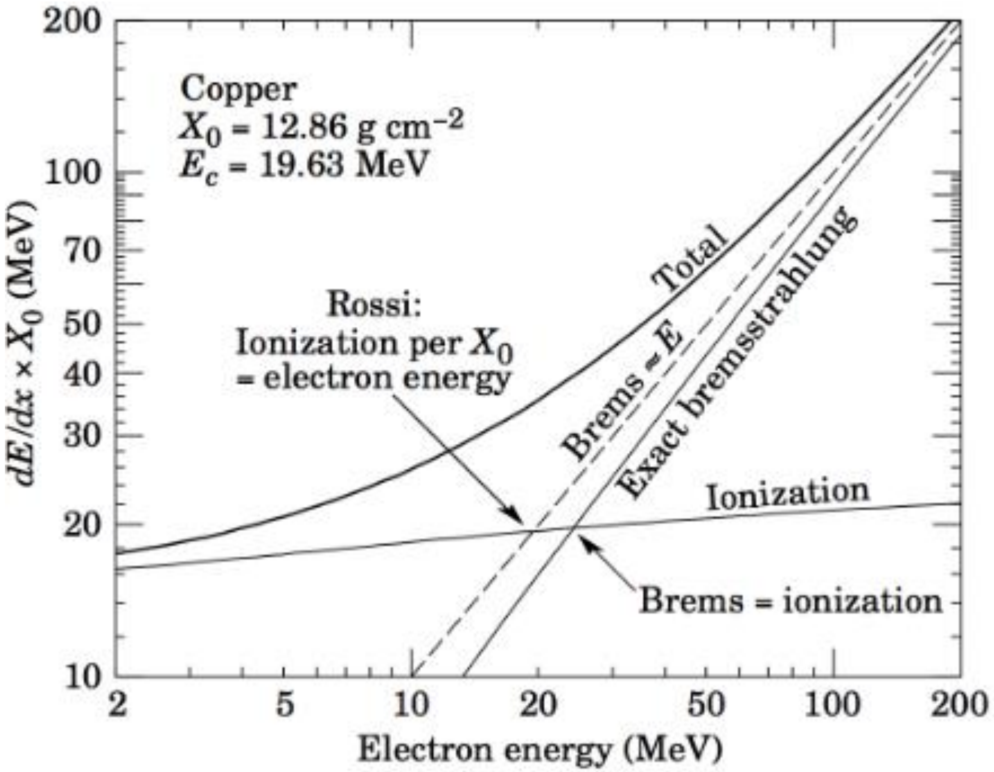
# Total energy loss for electrons

- Specifically for the electron, we introduce a new quantity, $X_0$

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

Material specific [**g • cm**$^{-2}$]

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

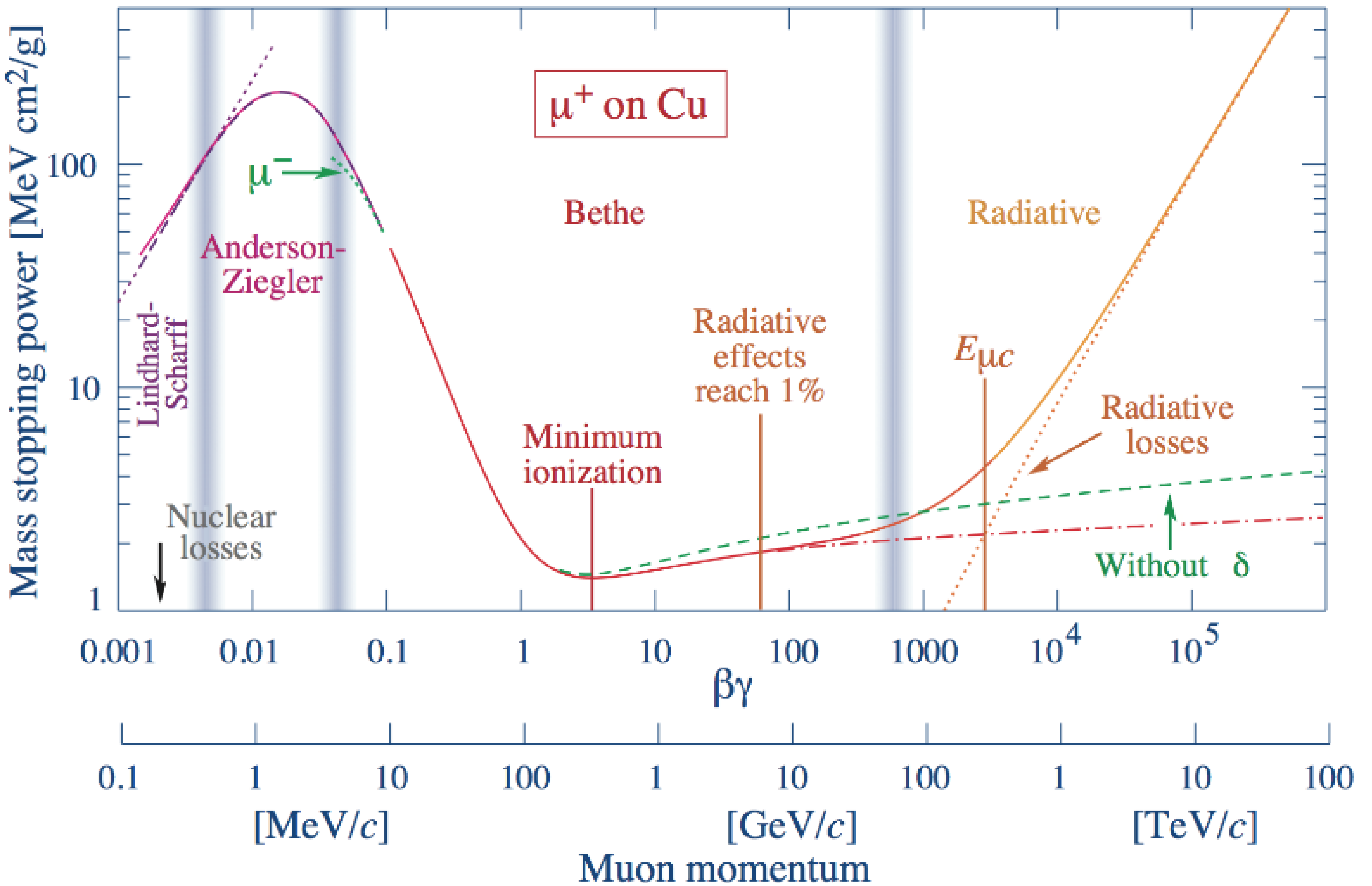



$$-\left\langle \frac{dE}{dx} \right\rangle_{Total} = -\left\langle \frac{dE}{dx} \right\rangle_{Ionization} \oplus -\left\langle \frac{dE}{dx} \right\rangle_{Brems}$$

**$E_c$ = critical energy**

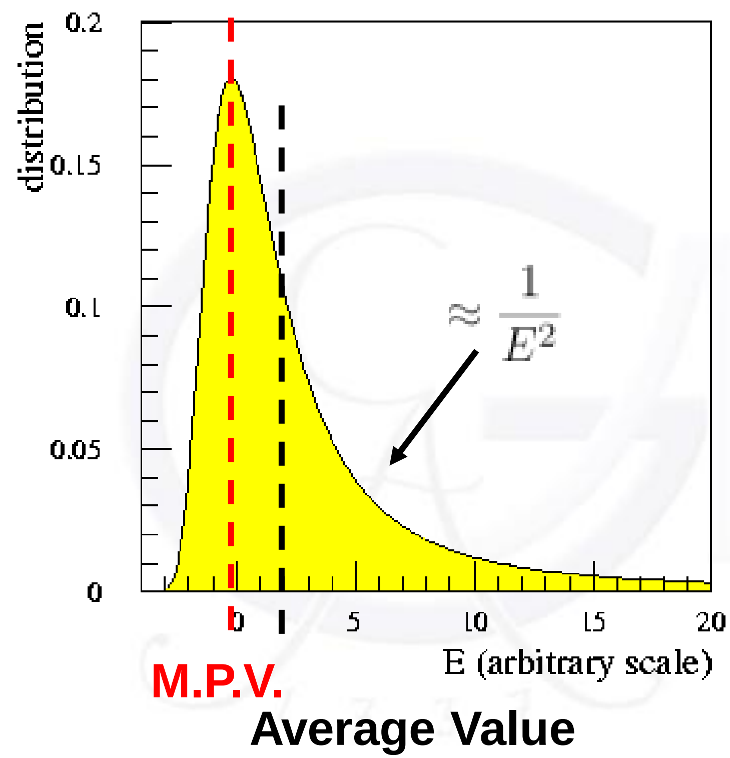
$$-\left\langle \frac{dE}{dx} \right\rangle_{Ionization} = -\left\langle \frac{dE}{dx} \right\rangle_{Brems}$$

# Summary for energy loss



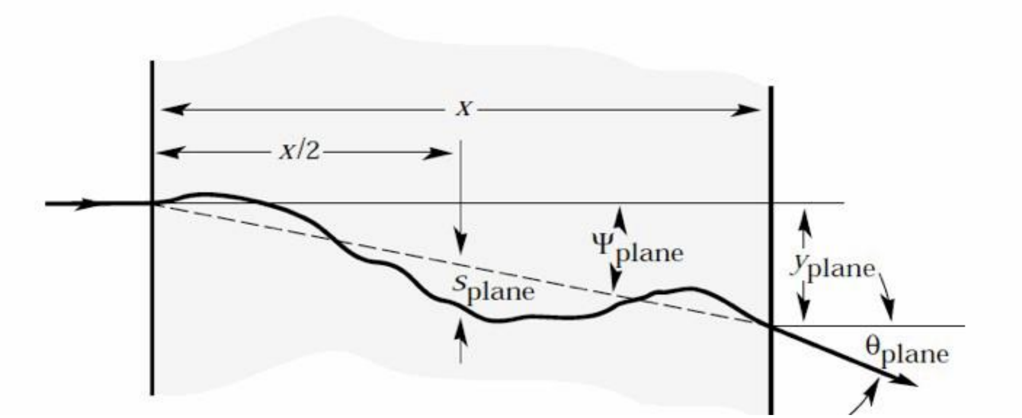
# Fluctuation of energy loss

- 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**:

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

- 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

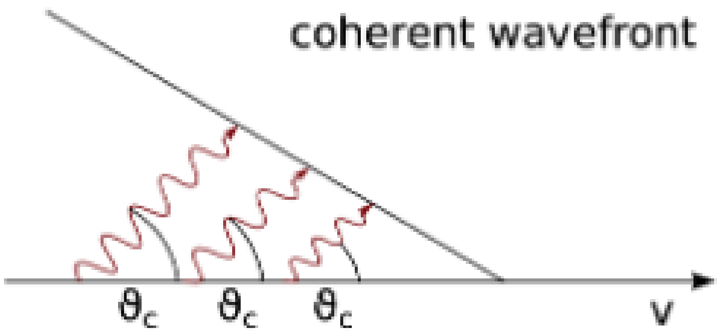
Three type of electromagnetic interactions:

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!**

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



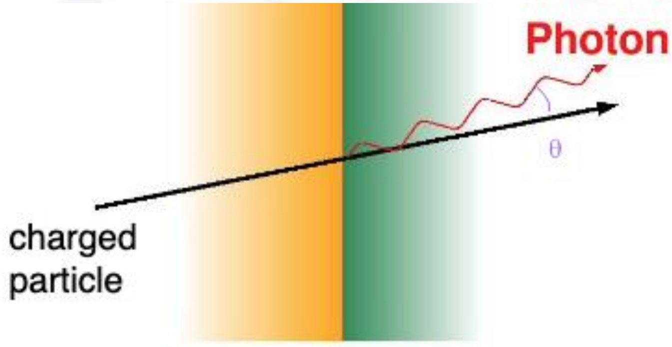

Energy loss by Cherenkov radiation **very small w.r.t. ionization** (< 1%)

Interesting application to **measure $\boldsymbol{\beta}$** *of the particle!* ➔ *RICH detectors.*

# Transition Radiation

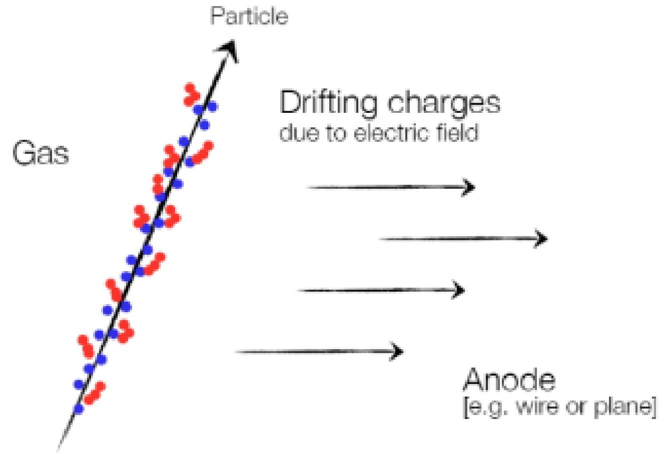
Three type of electromagnetic interactions:
1. Excitation/Ionization (of the atoms of the traversed material) ✔
2. Emission of Cherenkov light ✔
3. **Emission of Transition Radiation**

- Relativistic particle (large $\gamma$) crosses the boundary between two media with different dielectric constants ($\varepsilon_1$, $\varepsilon_2$)
  ➔ 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 ~ $\gamma$ = 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 ~ ($\varepsilon_1$-$\varepsilon_2$)**
  - HEP: gases ($\varepsilon_1$) and light plastics ($\varepsilon_2$),
    ➔ photon energies ~10-30 keV
  - Choice of material with big difference but photon should not be absorbed!



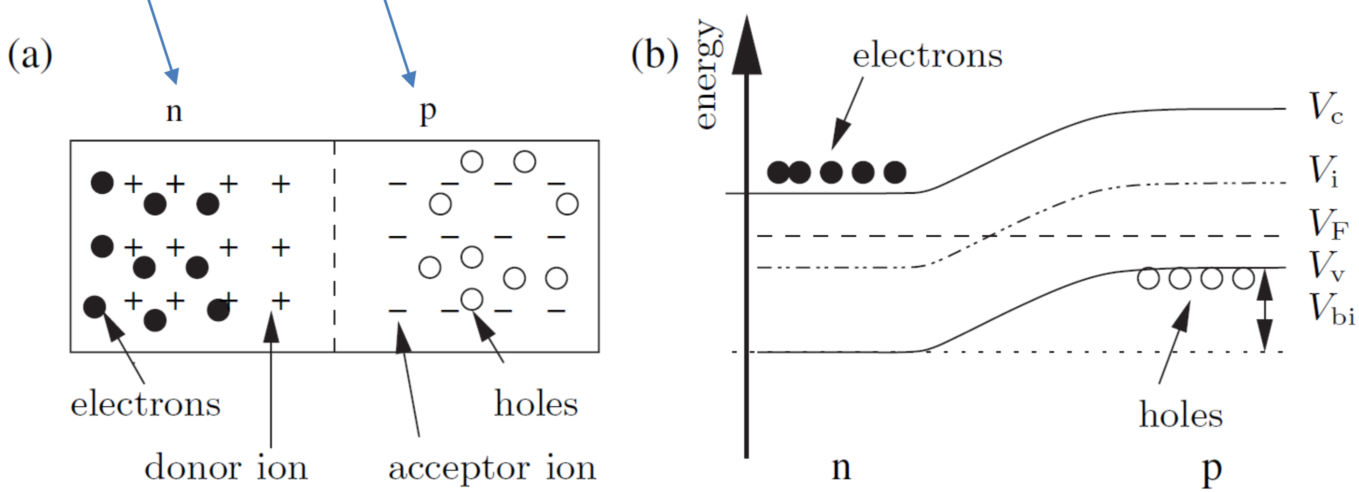
# Ionisation detectors concept

- 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



# Semiconductor : *pn*-junction

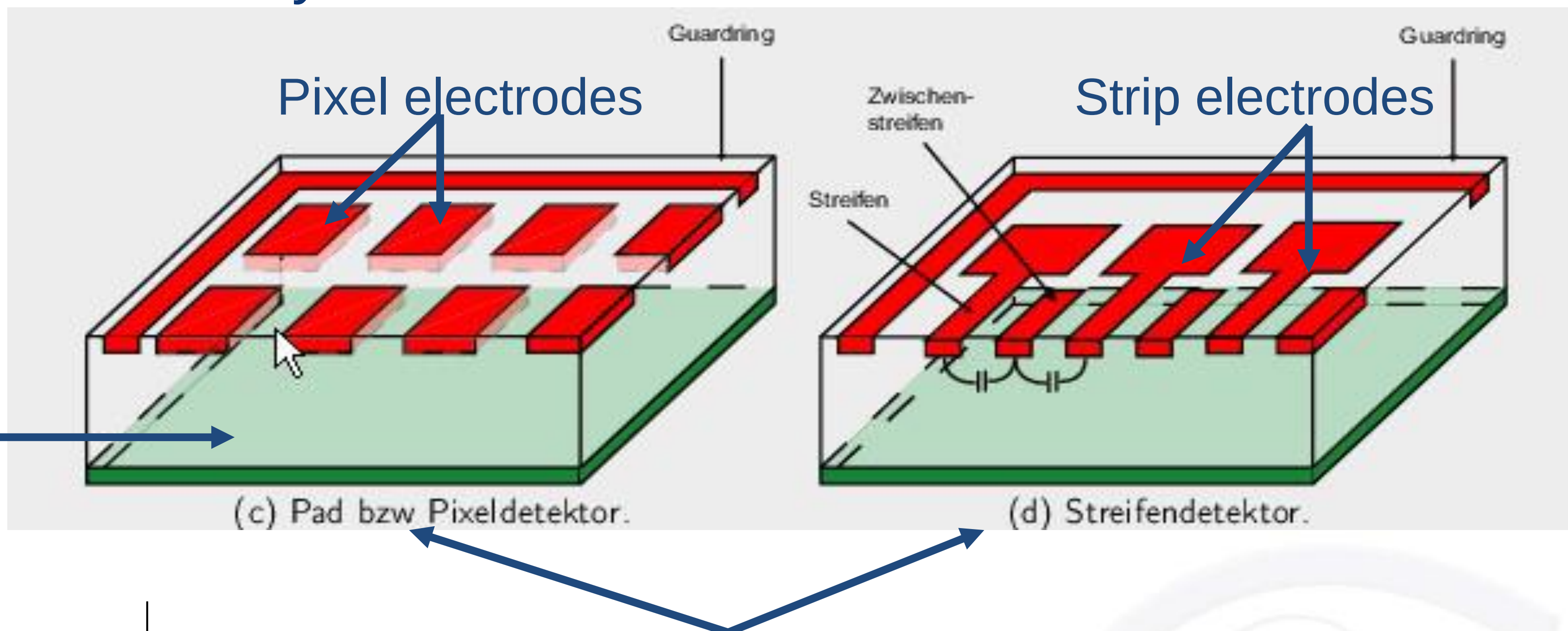
- Ionization as in gas detectors
  → Semiconductors = solid materials with crystalline structure (Si, Ge)
  → electron-hole pairs (instead of electron-ion)
- Usage of special materials "Extrinsic or doped semiconductors":
  → Majority of charge carriers provided by impurity atoms at lattice sites of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

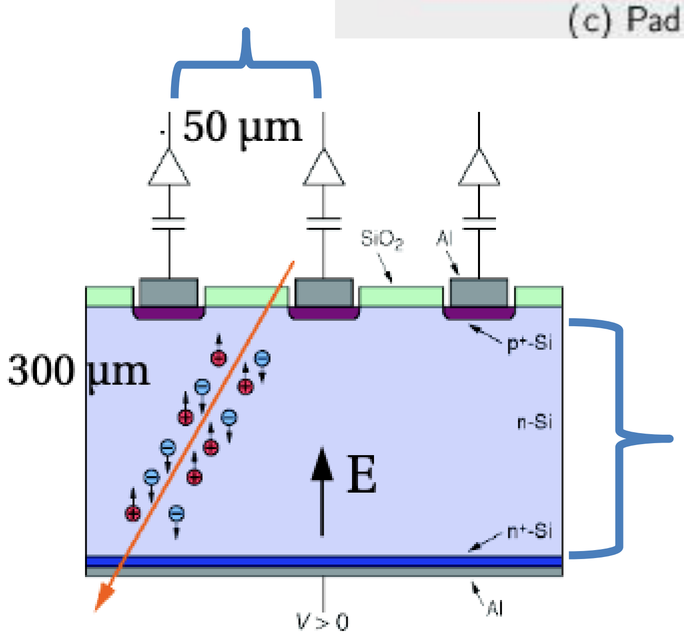



- *pn*-junction under reverse bias (High Voltage applied to electrodes):
  - Extract electrons or holes present from doping (depletion region)
  - Provides electric field needed for charge drifting

# Segmented Semiconductors

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




Typical sizes:

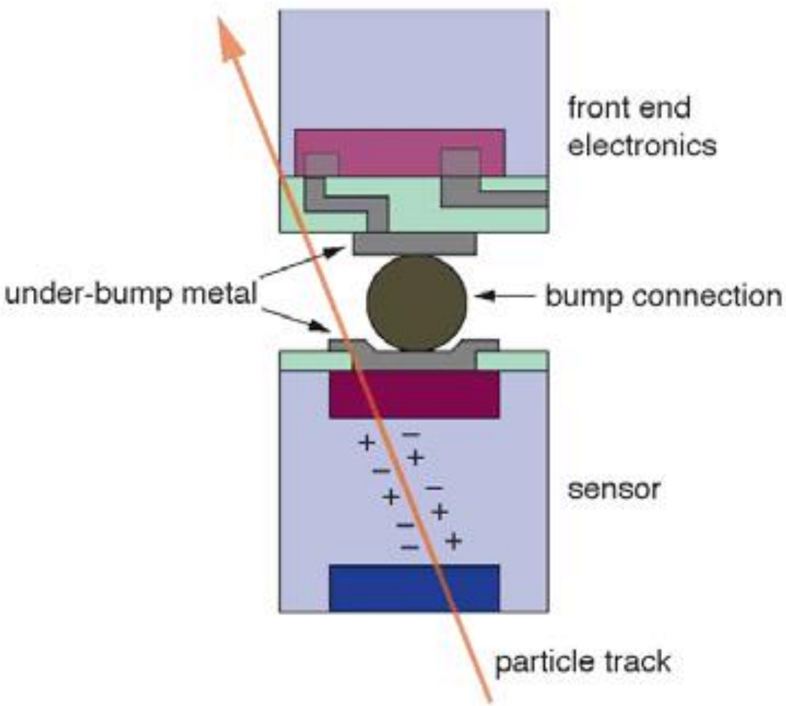
- Strip or Pixel pitch ≈ 50/250/500 µm
- Detector Thickness ≈ 200-300 µm
  - Enough to create a good signal

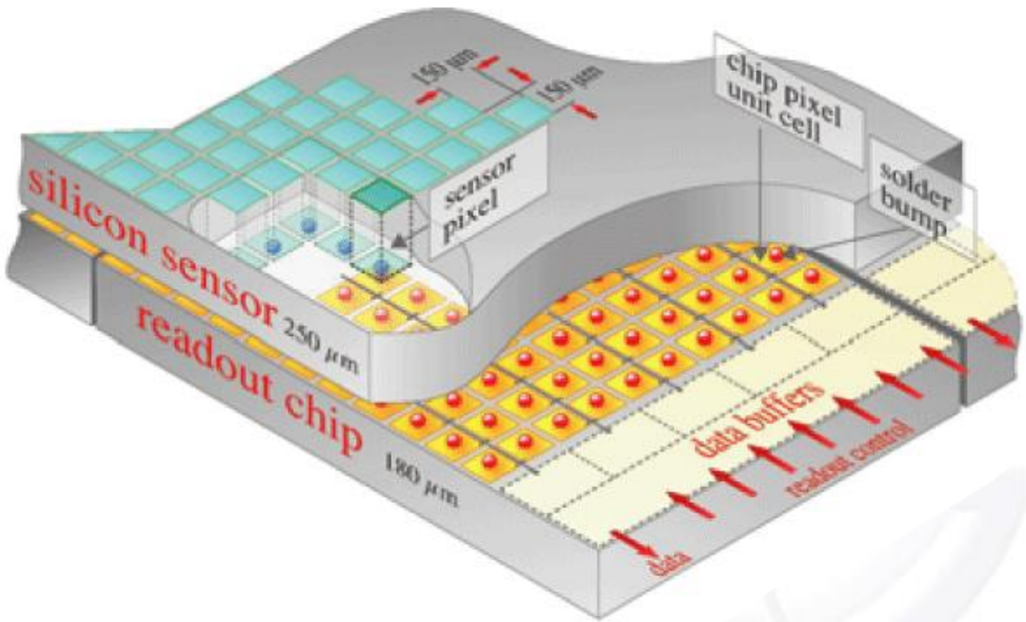
# Pixel Detector Read-out

Hybrid technology:

1:1 connection sensor segments to the read-out cell

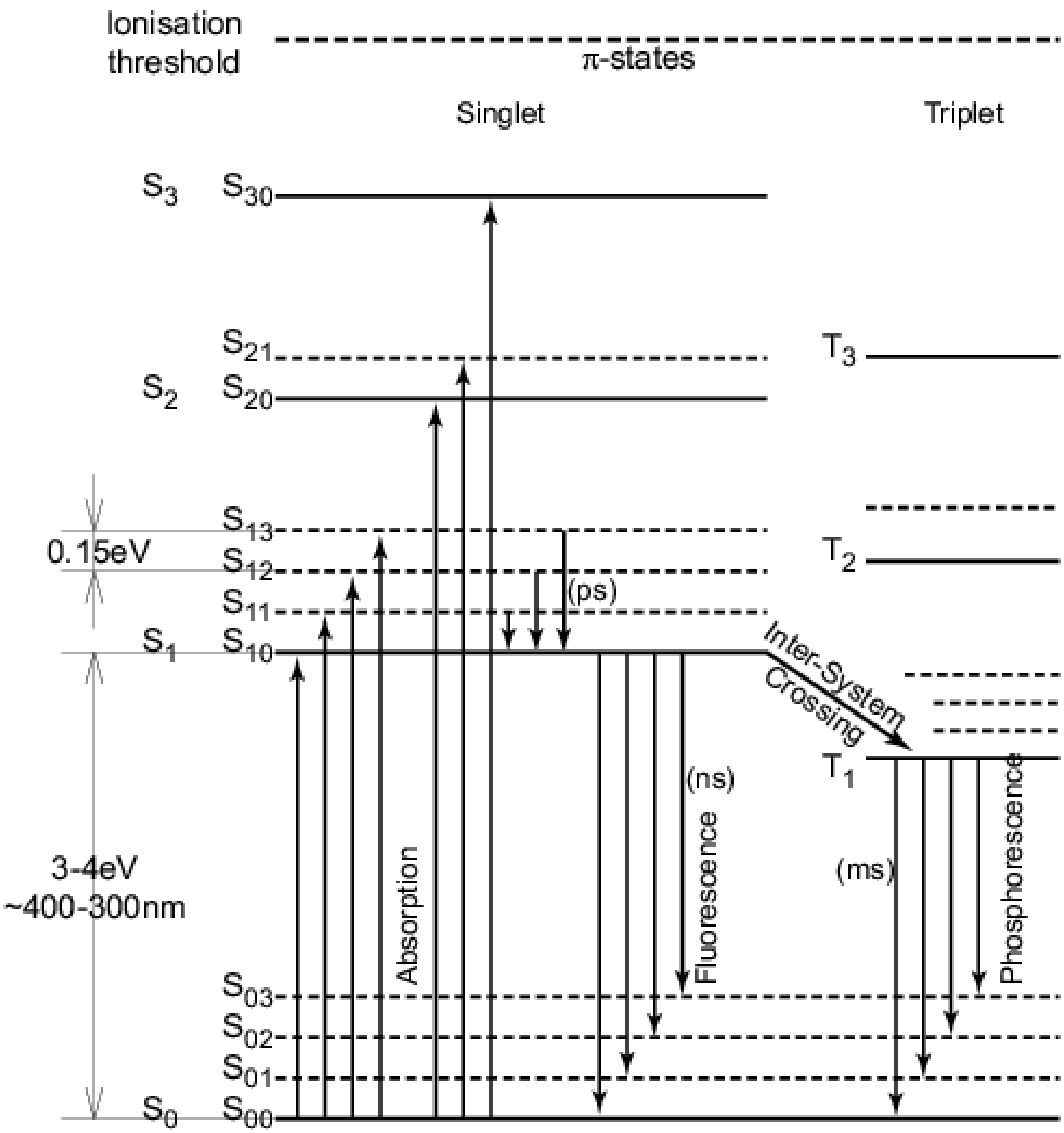
➔ bump bonding technique



# Light-based Detectors: Scintillation & Čerenkov Radiation

# Scintillation

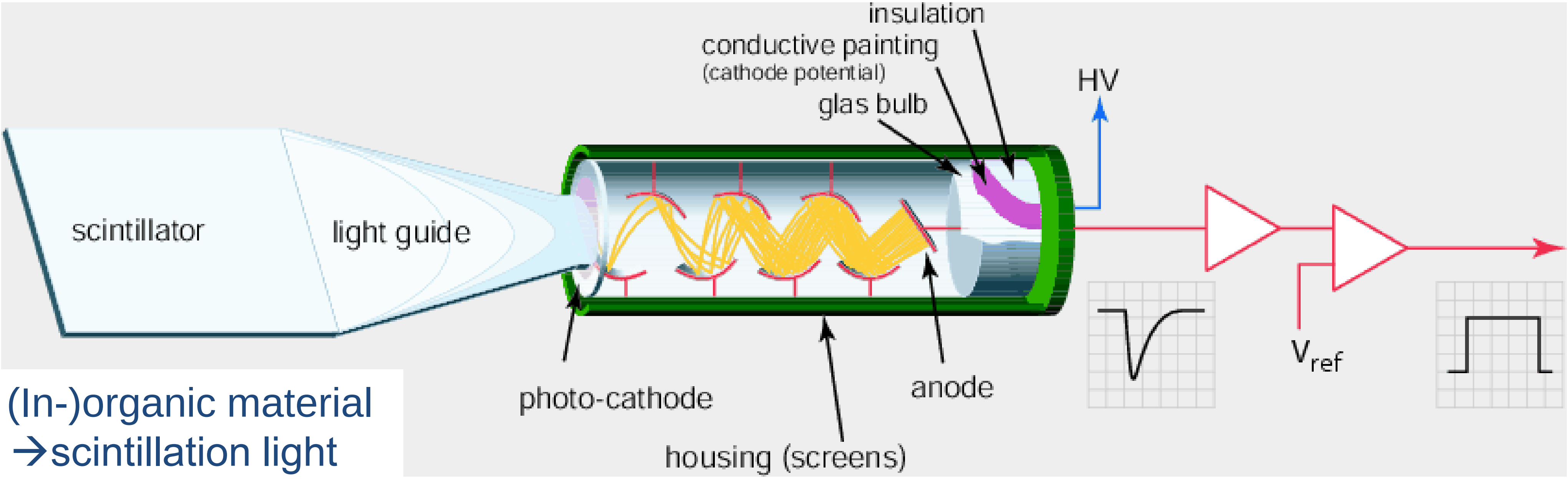



Excitation from:

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

Resulting in de-excitation
➔ scintillation light

# Light Readout: PMT and APD

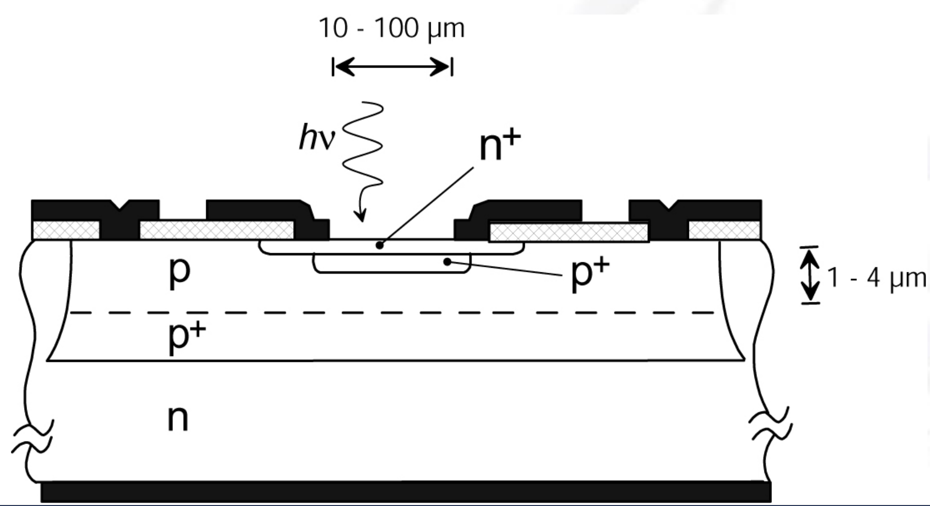



(In-)organic material
→scintillation light

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

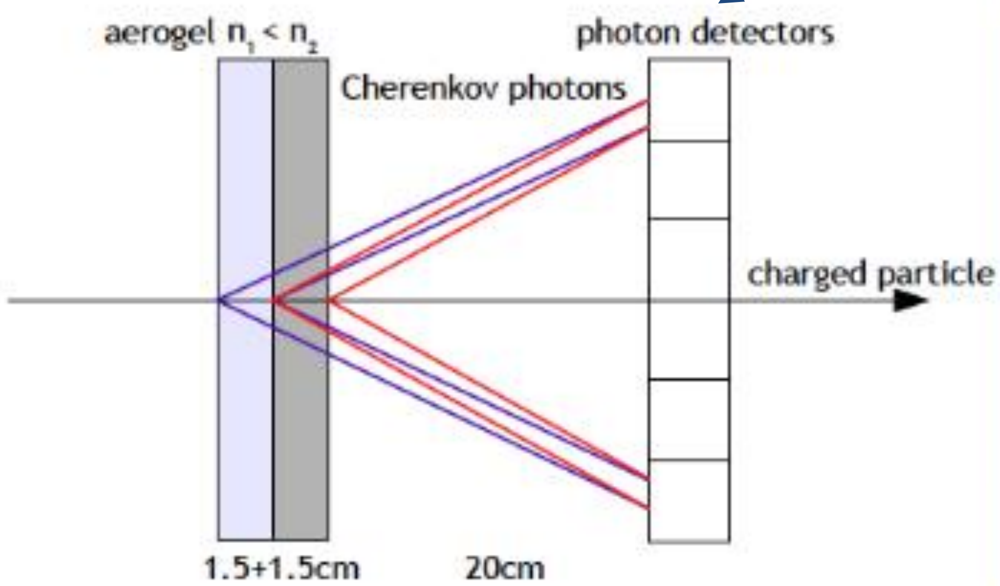


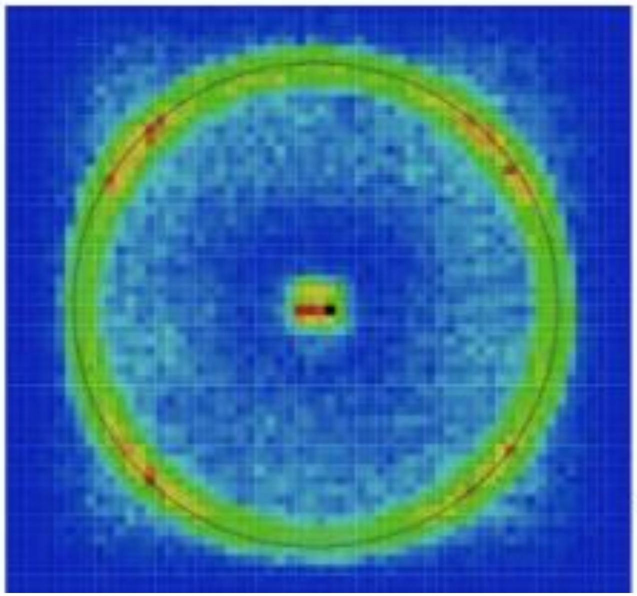
# Cherenkov radiation: RICH detectors

- 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



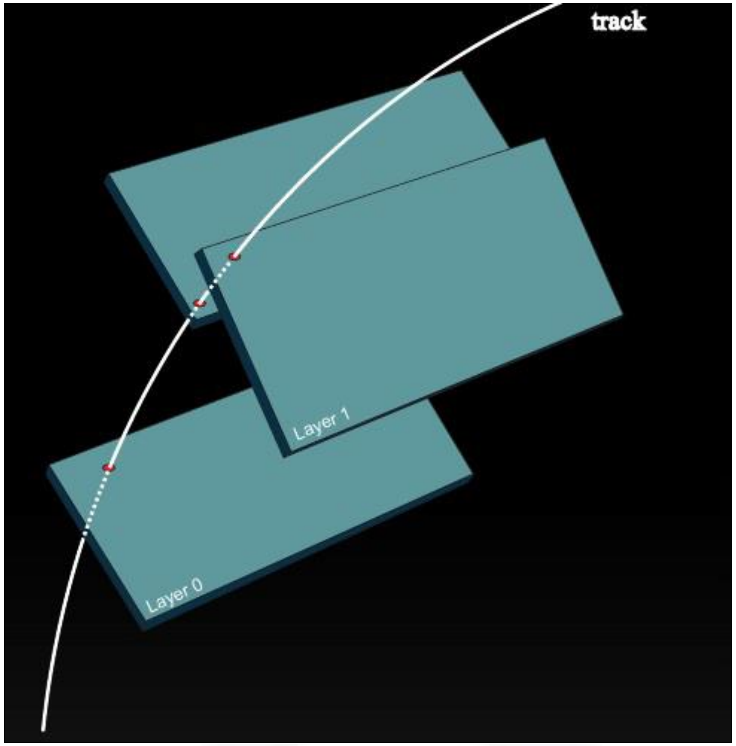



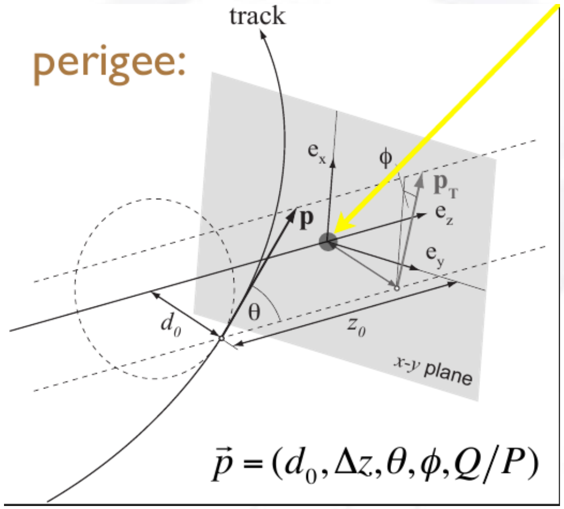
# Tracking detectors

# What to expect from trackers?

## Measure trajectory of **charged** particles

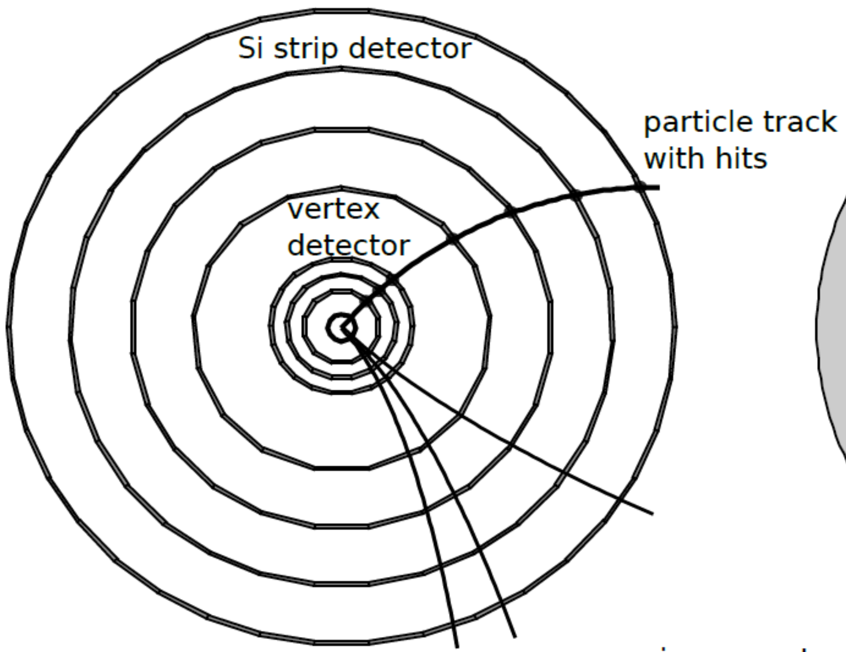
- Measure several points along the track and fit curves to the points **(helicoidal trajectories with magnetic field**)
- Use the track curvature in magnetic field to determine the particle **momentum** and **charge**
- Extrapolate tracks to the point of origin
- Determine positions of **primary vertices**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



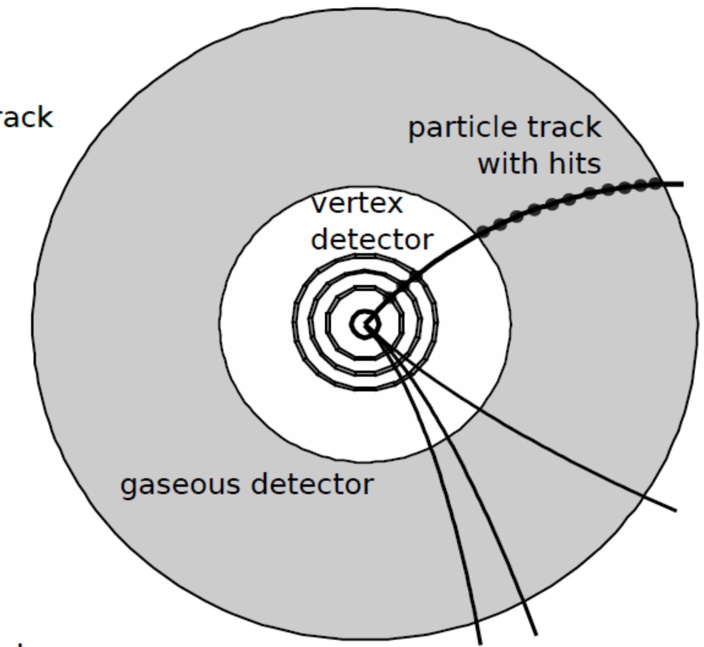



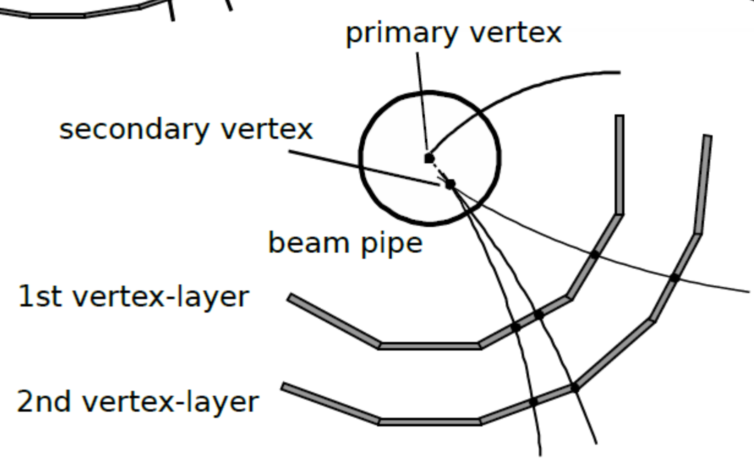
# Tracking Concepts

## Full silicon tracker
(CMS)




## Gaseous + Silicon tracker
(ATLAS)

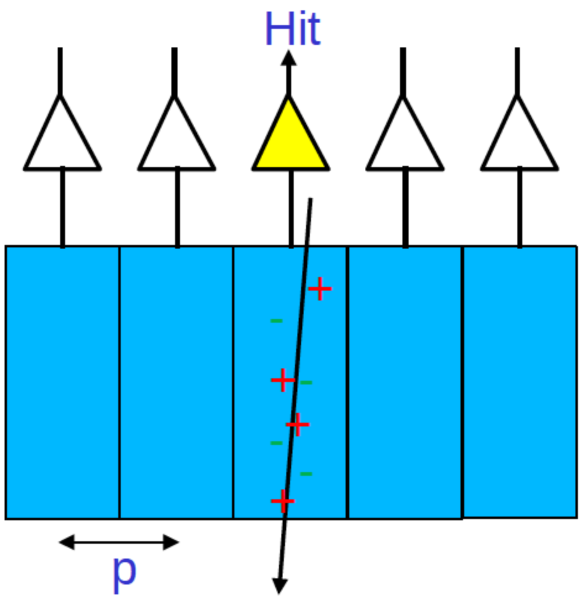


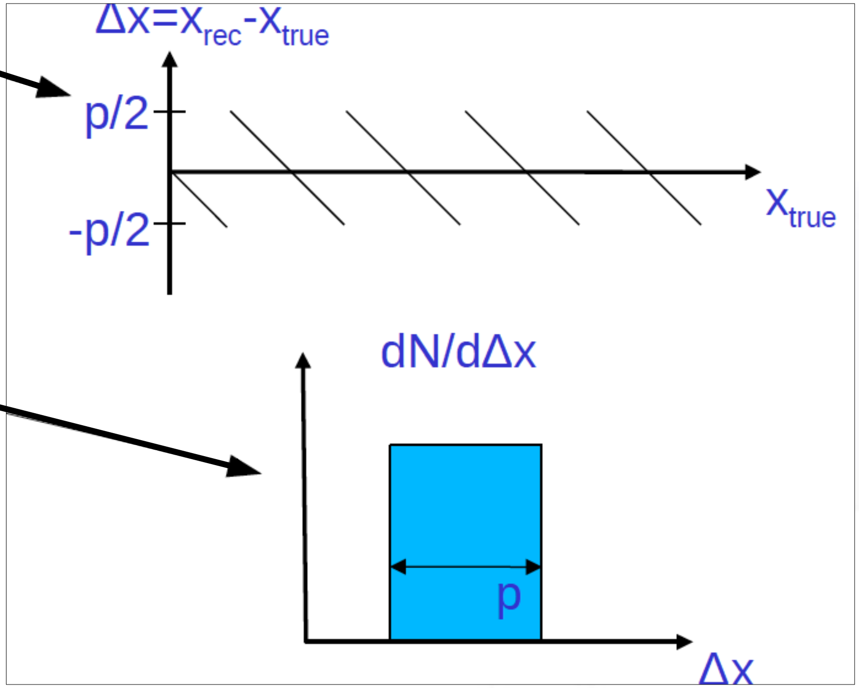



# Single Point Resolution (1)

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)

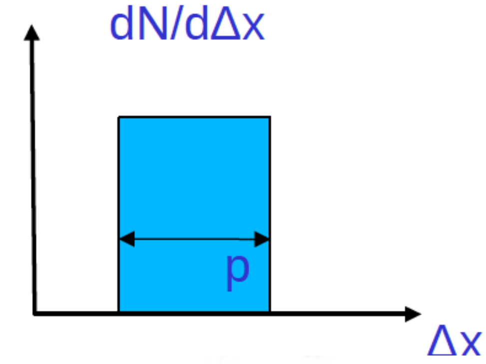
- Reconstruction error
  → std. deviation defined by probability distribution

- 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 **$\sigma_X$ ~ 14 µm** for a pixel/strip pitch **p = 50 µm**

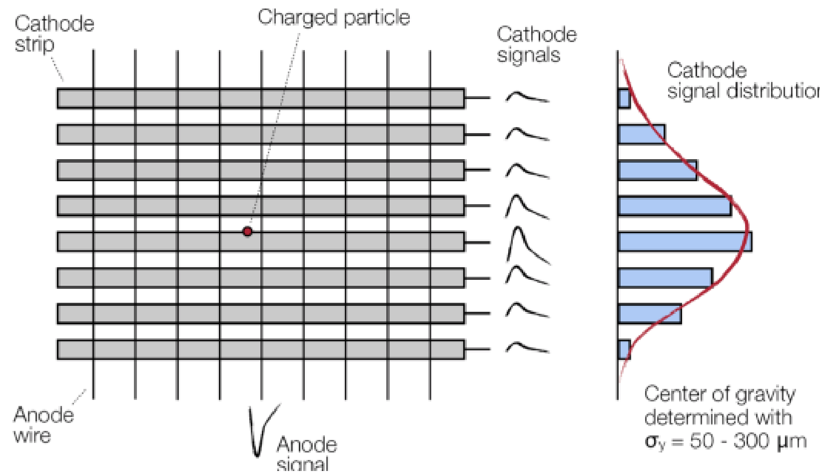
- Worst possible resolution with pure binary readout
  - Value improves if several segments are recorded per each track:
    → weighting with pulse height information



# Pulse Height Weighting

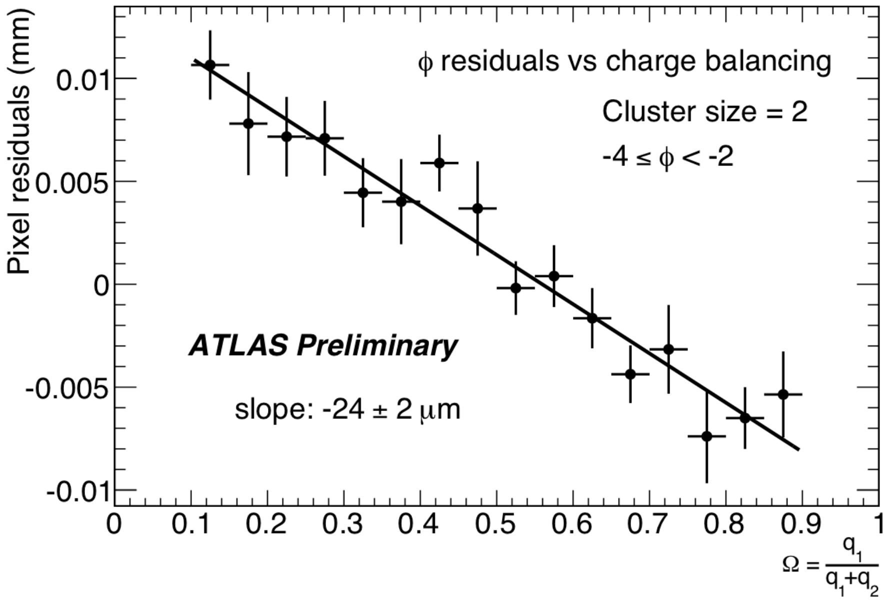
- Simplest method :
  linear interpolation, using the charge deposited in the edge pixels of the cluster:

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




- 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

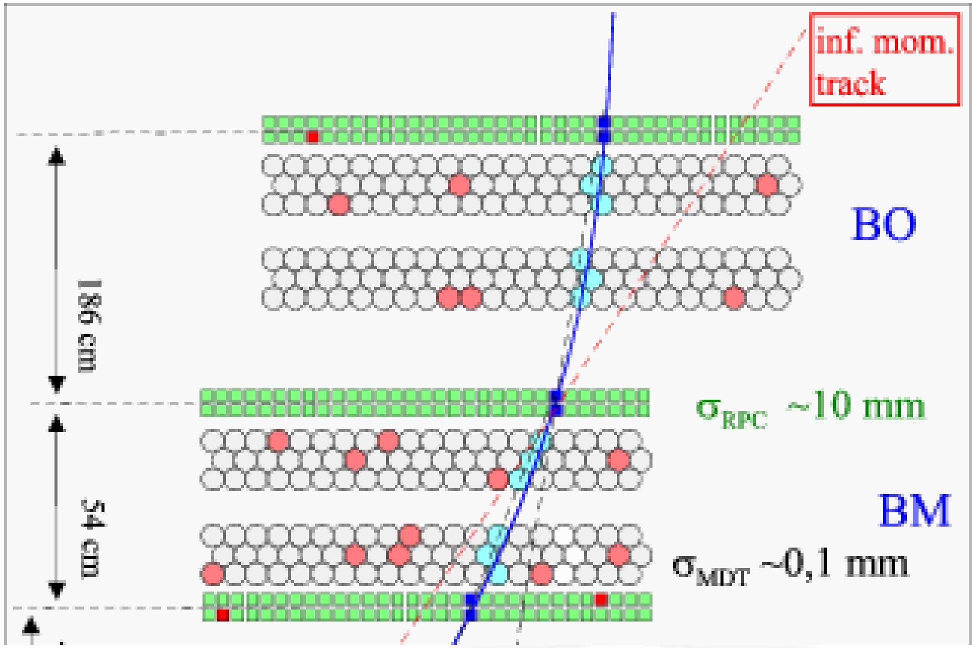
Resolution can be < p/√12 if using drift time:

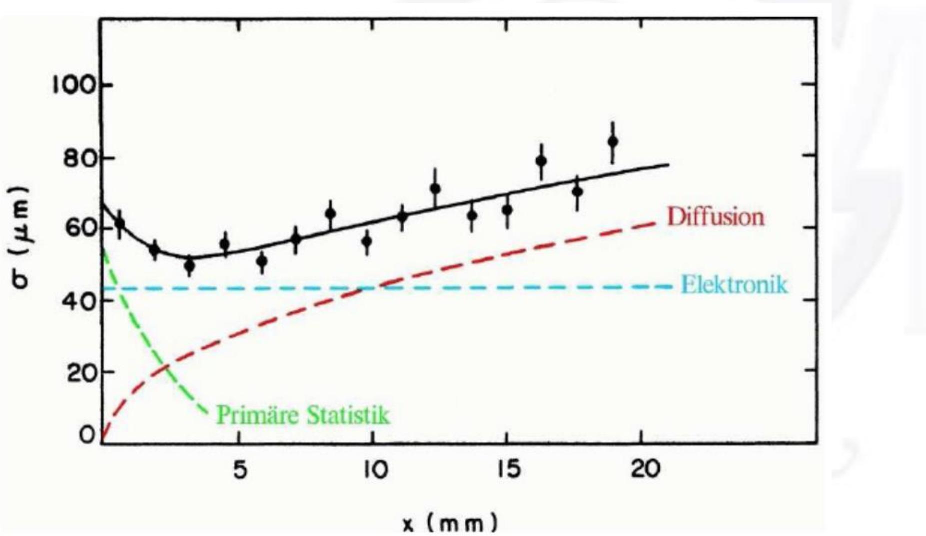
- Precise measurement of arrival time of charge signal
- Known electric field
  → drift velocity $v = \mu E$ is known
  → determine distance of ionisation location from electrode
- Precision driven by Electronics (timing resolution) and smearing due to **Diffusion**

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

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

ATLAS MDT



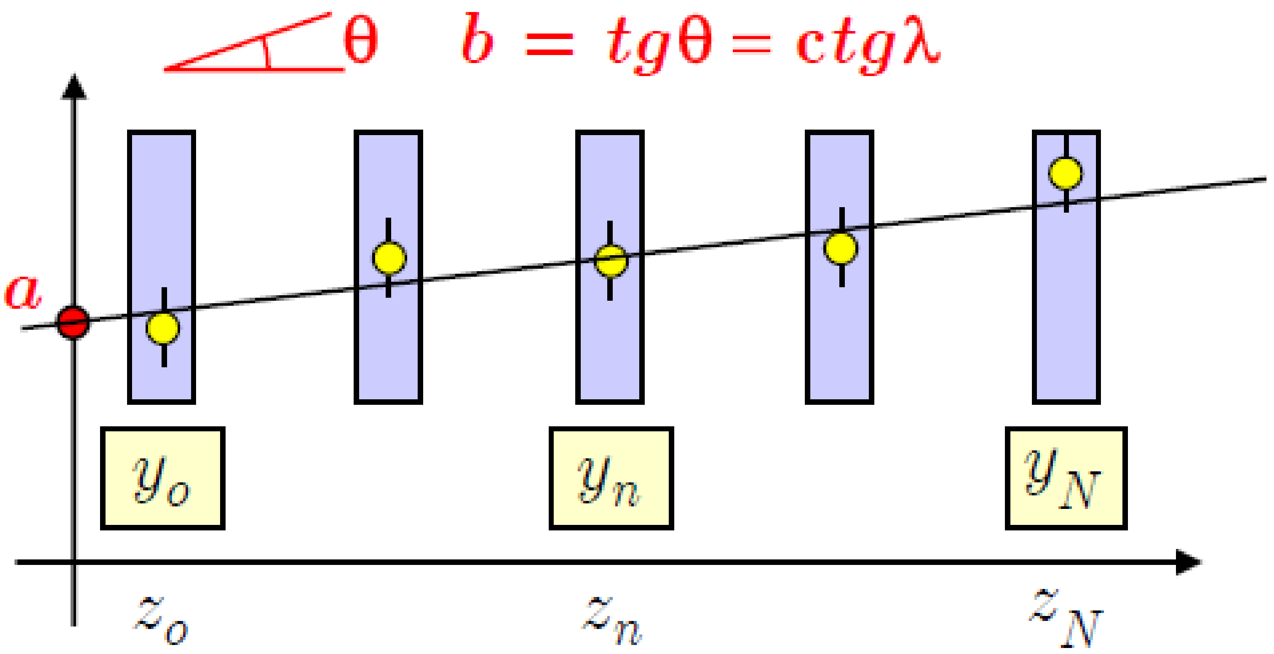
# From Hits to a Track

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

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

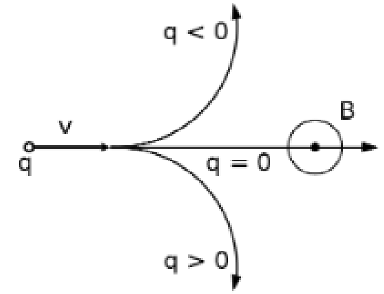
- Errors on a, b from covariance matrix

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

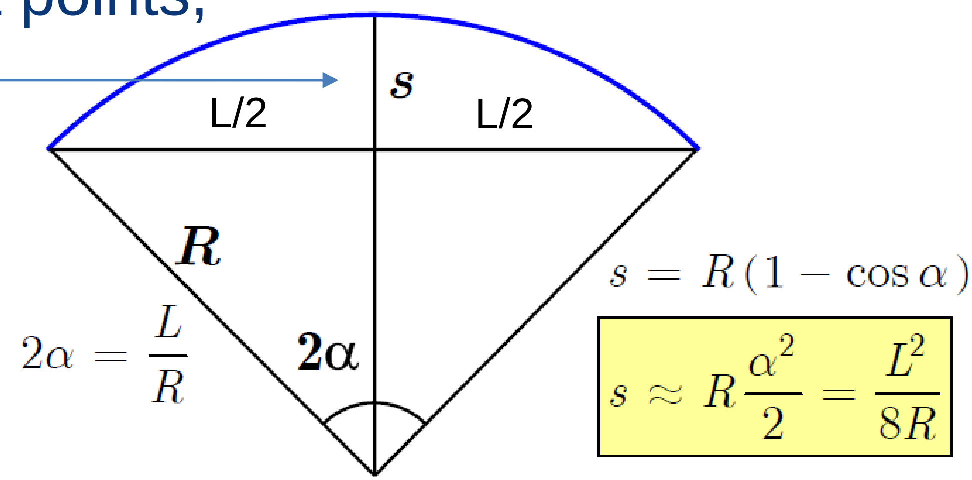


# Momentum determination/resolution

- 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***



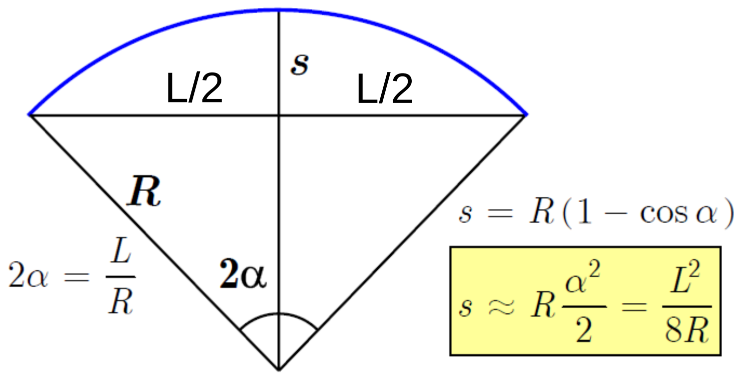

What about the $p_T$ resolution?

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

*Error calculation by Gluckstern: approximate curved track by parabolic fit*

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

# 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 $\sigma_\alpha$

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

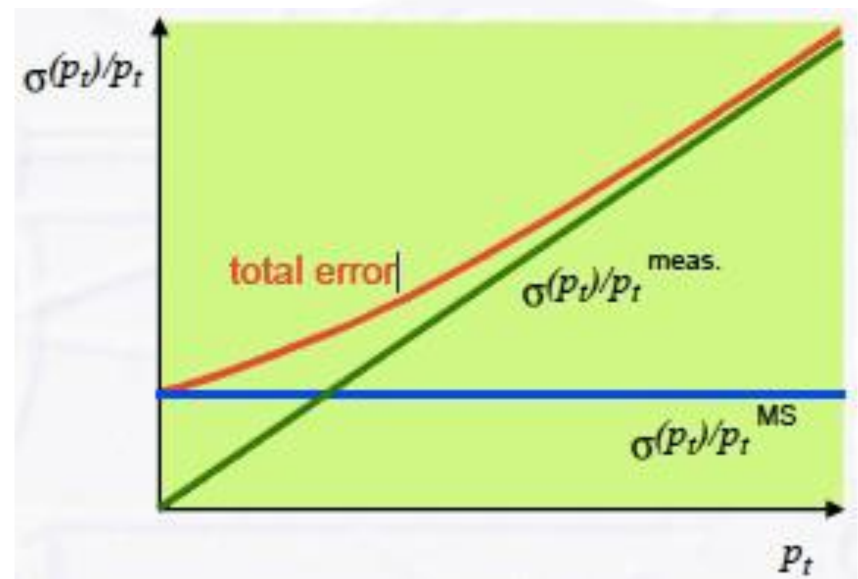
$$\sqrt{\langle\theta^2(x)\rangle} = \theta_{\text{rms}}^{\text{plane}} = \frac{13.6\ \text{MeV}}{\beta pc} z \sqrt{\frac{x}{X_0}}\left(1 + 0.038 \ln\frac{x}{X_0}\right)$$

- 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

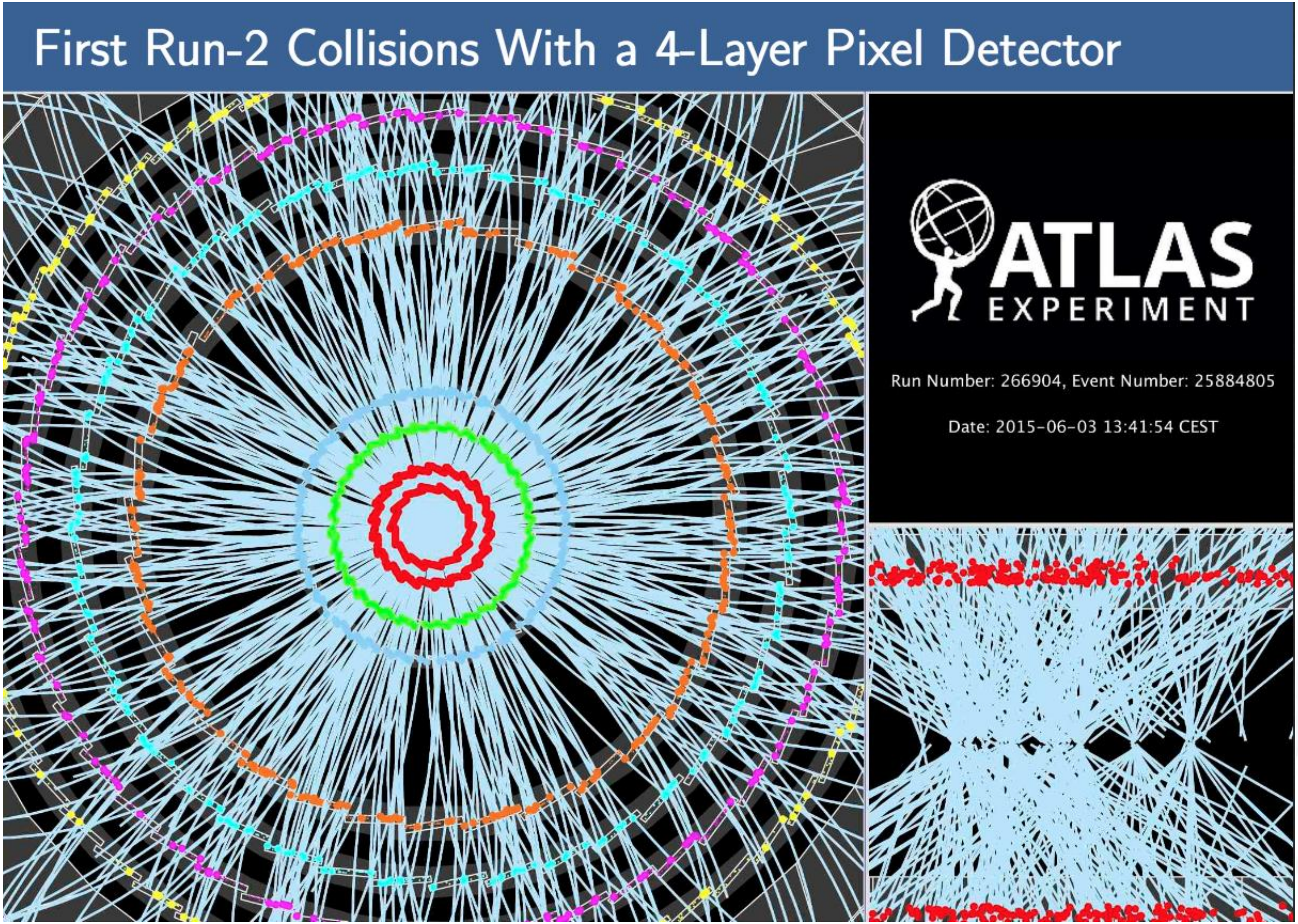
Added in quadrature to intrinsic resolution:

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

→ Intrinsic resolution dominates at high $p_T$

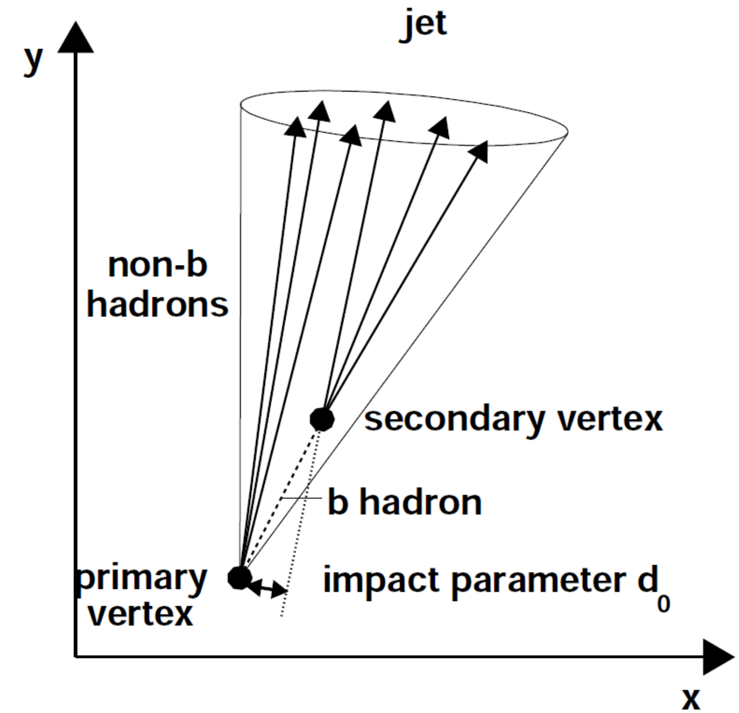


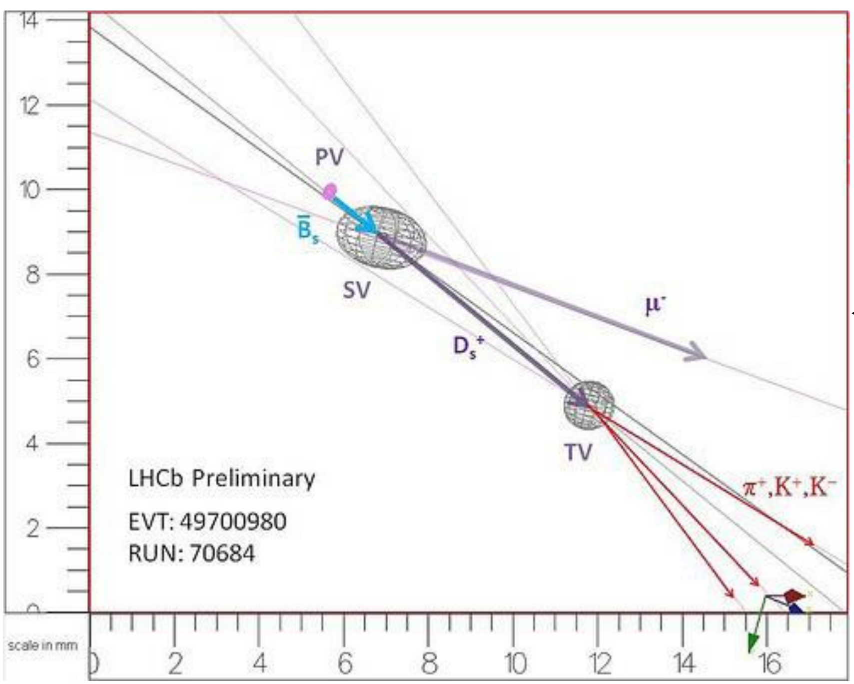
# Vertex reconstruction



# Lifetime Tagging

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



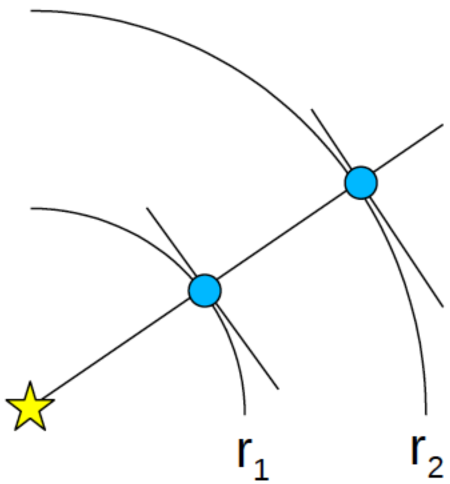




Example of a fully reconstructed event from LHCb with primary, secondary and tertiary vertex

# 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

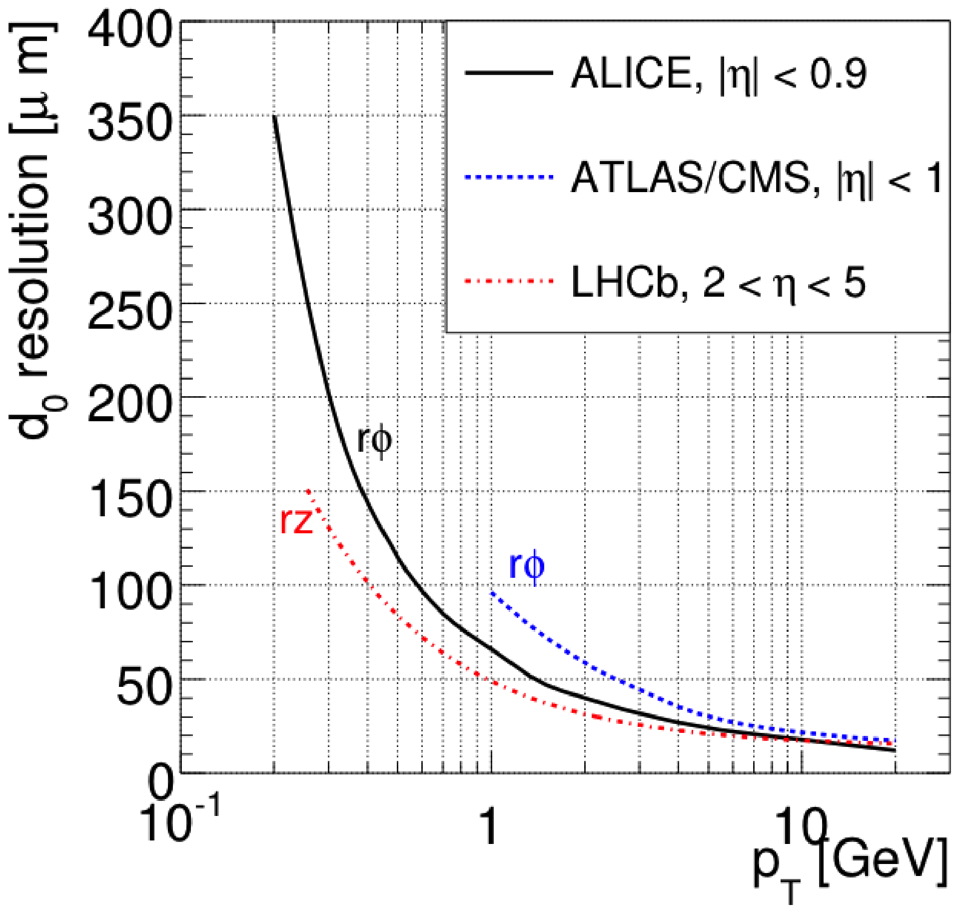
- Additional contribution due to multiple scattering to be added

$$\sigma_i \rightarrow \sigma_{|i} \oplus \Delta r \, \sigma_\theta$$

with $\sigma_\theta$ as for momentum

- Resulting in

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



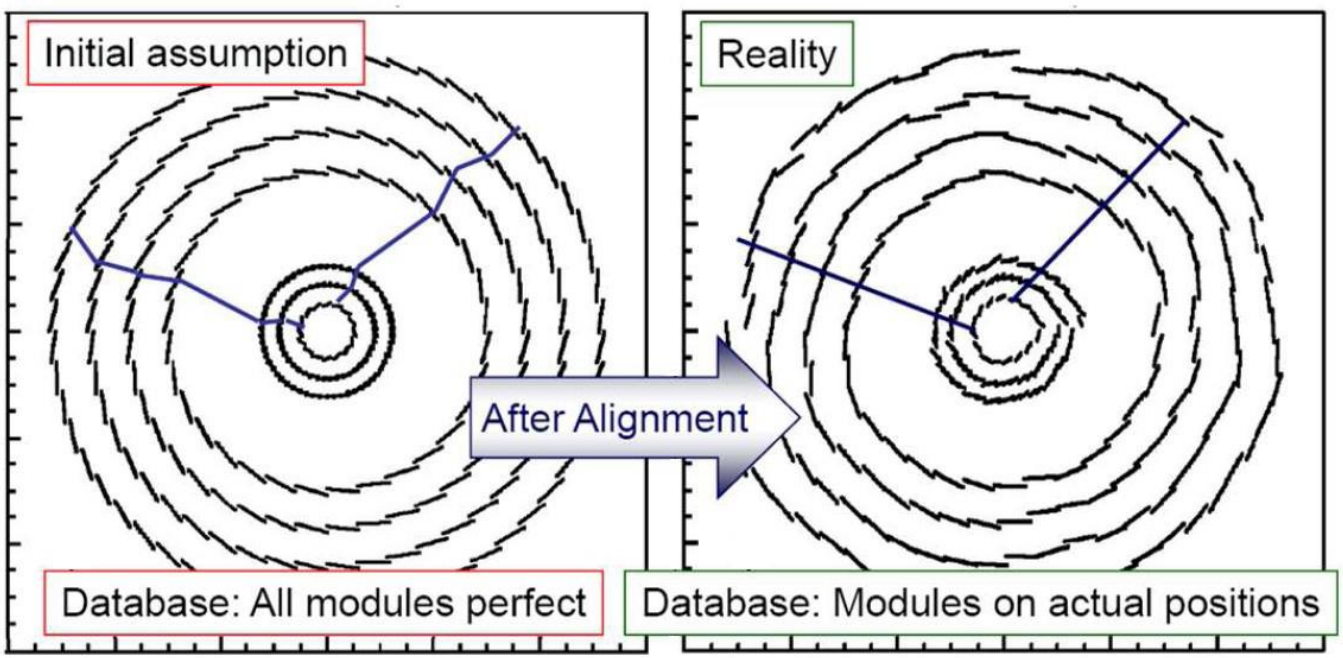

$$\sqrt{\langle \theta^2(x) \rangle} = \theta_{\text{rms}}^{\text{plane}} = \frac{13.6\text{ MeV}}{\beta p c} z \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln \frac{x}{X_0}\right)$$

- 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

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

$$\frac{\sigma_{pT}}{p_T} = \frac{p_T\sigma_{pt}}{0.3BL^2}\sqrt{\frac{720}{N+4}} \oplus \frac{27.2\,\text{MeV}}{0.3B\sqrt{L}X_0}$$

Tracker design:

- Vertex resolution: outer radius ***($r_2$)*** as large as possible, inner radius ***($r_1$)*** as small as possible with best point resolution **.**
- 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 (**$X_0$)**

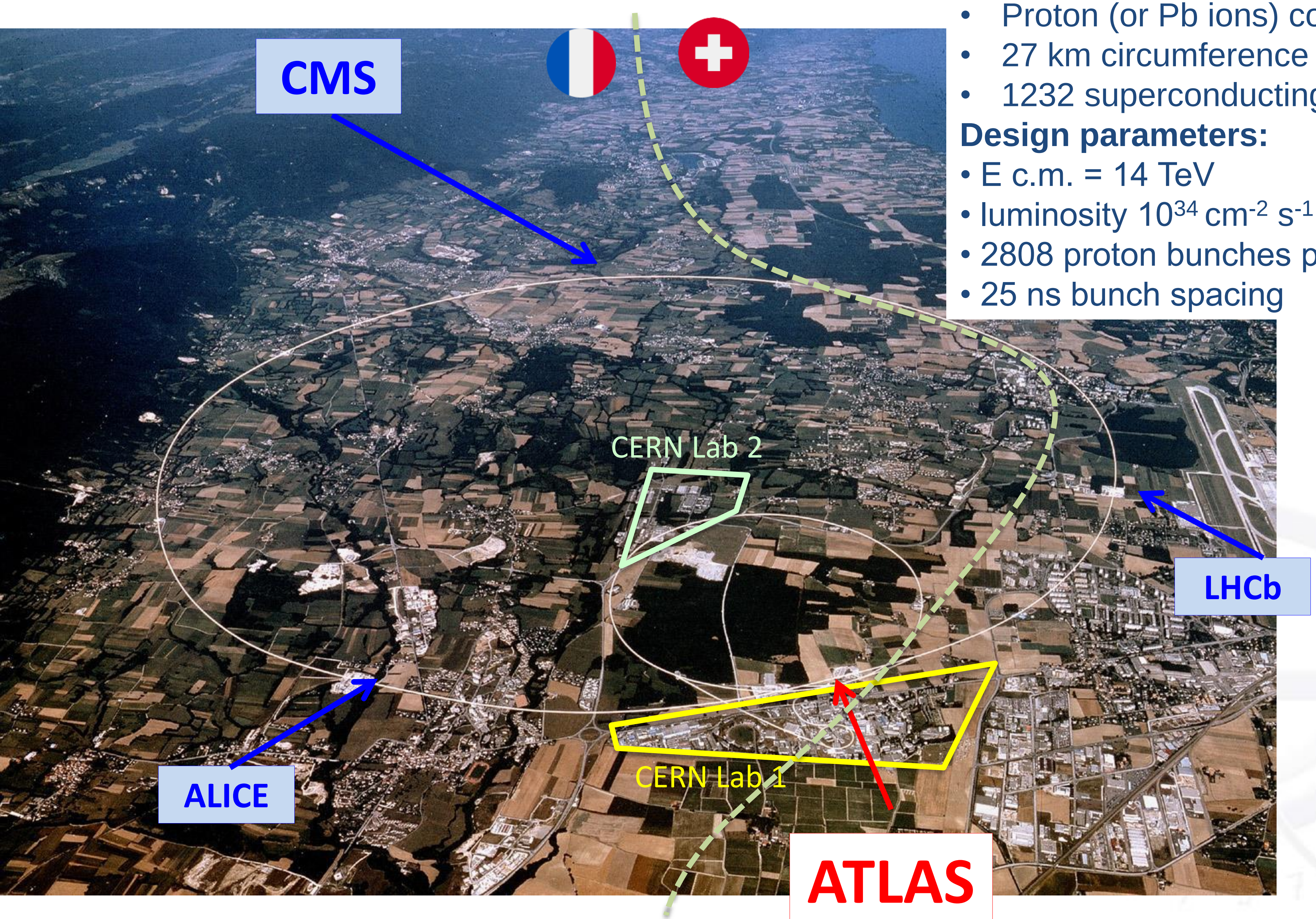
- **Reducing Inner radius**:
  Beam pipe presence, track density and radiation damage increase.
- **Increasing Outer radius**:
  Overall detector size increase ➔ Cost increase.

# 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

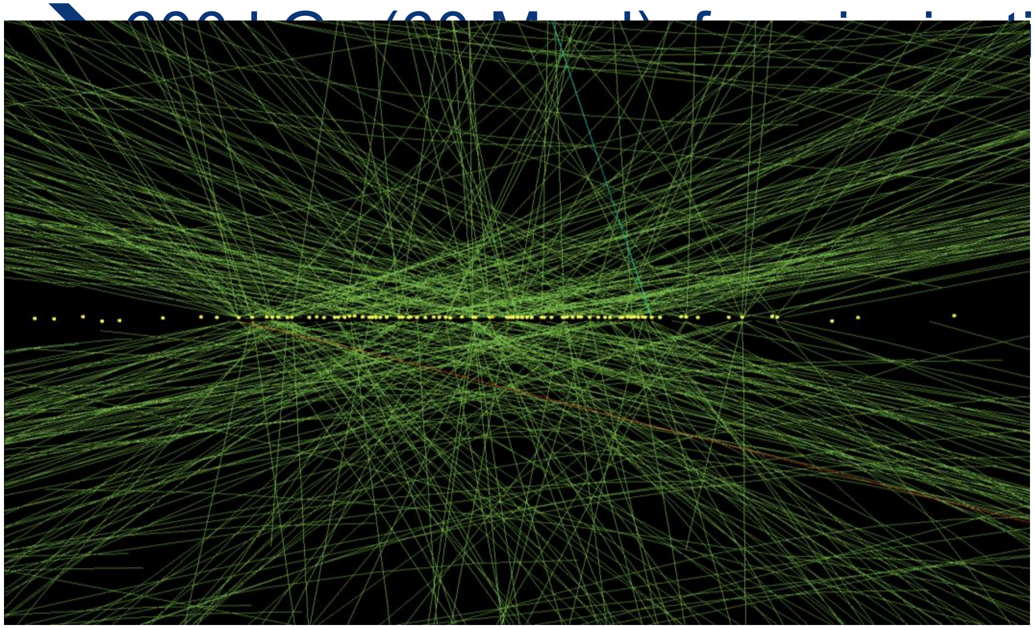


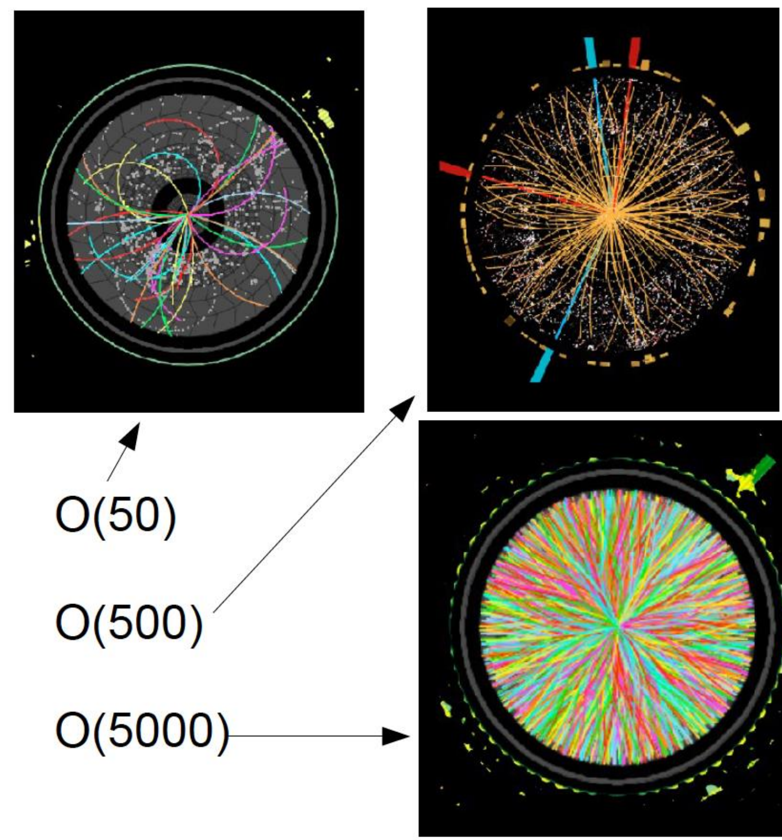
# Silicon Trackers at LHC

## 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

➔ … ion o

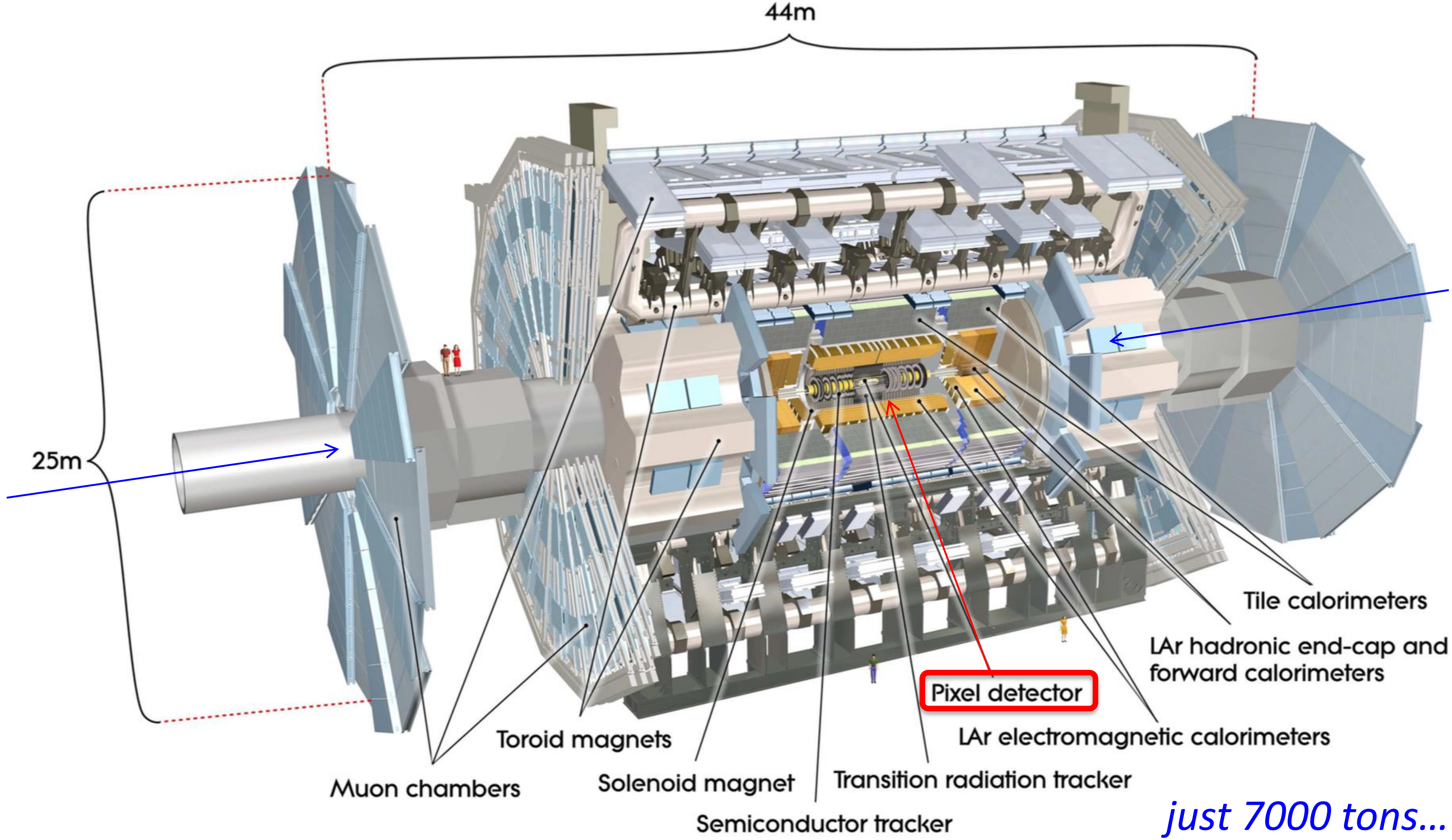




# For every taste…

# The ATLAS detector @ LHC

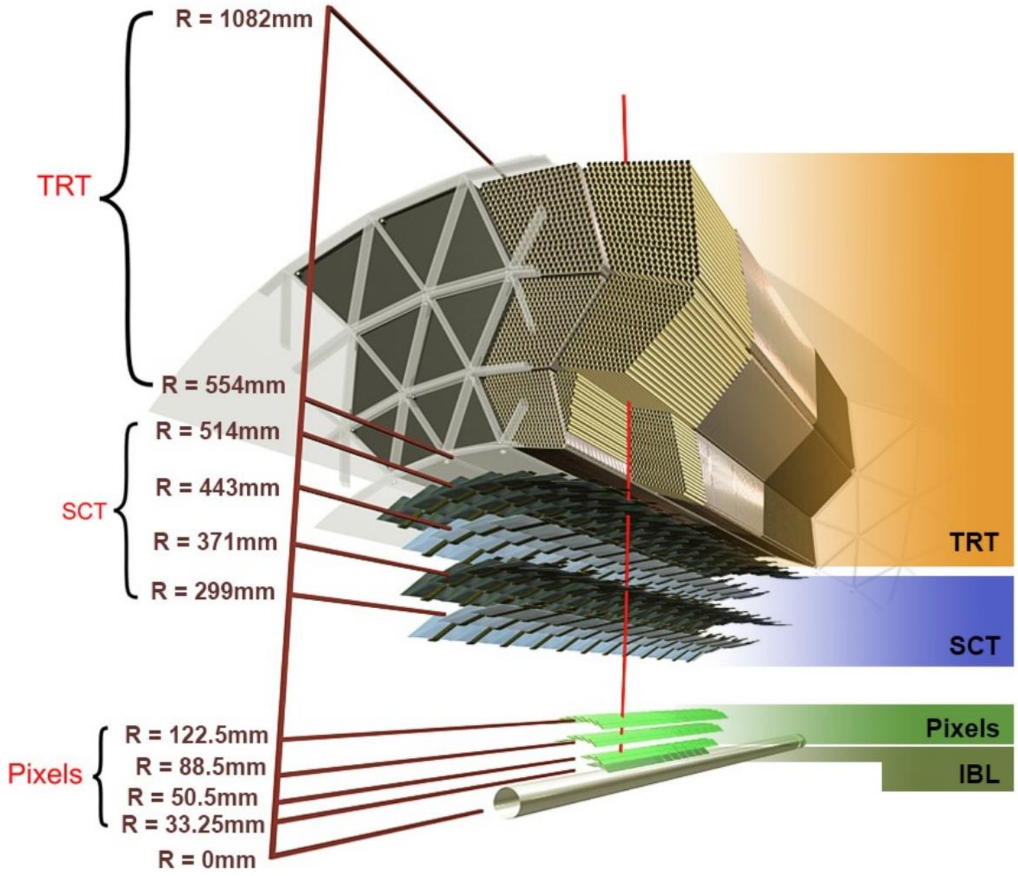
Very large, general purpose magnetic detector for the LHC




*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.

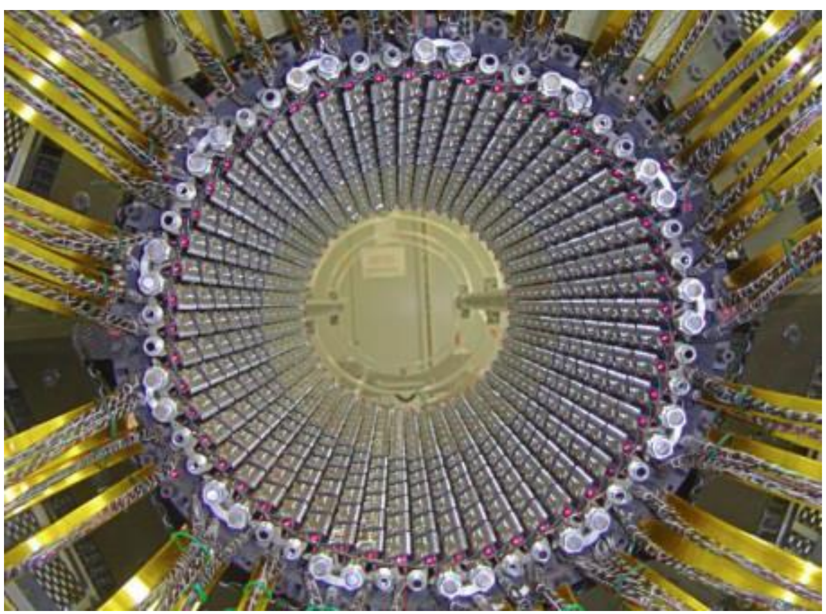
**Intermediate** is a large silicon strip tracker:
- 4 barrel layers and 9 disk layers contain 61 $m^2$ of silicon with 6.2 M channels.

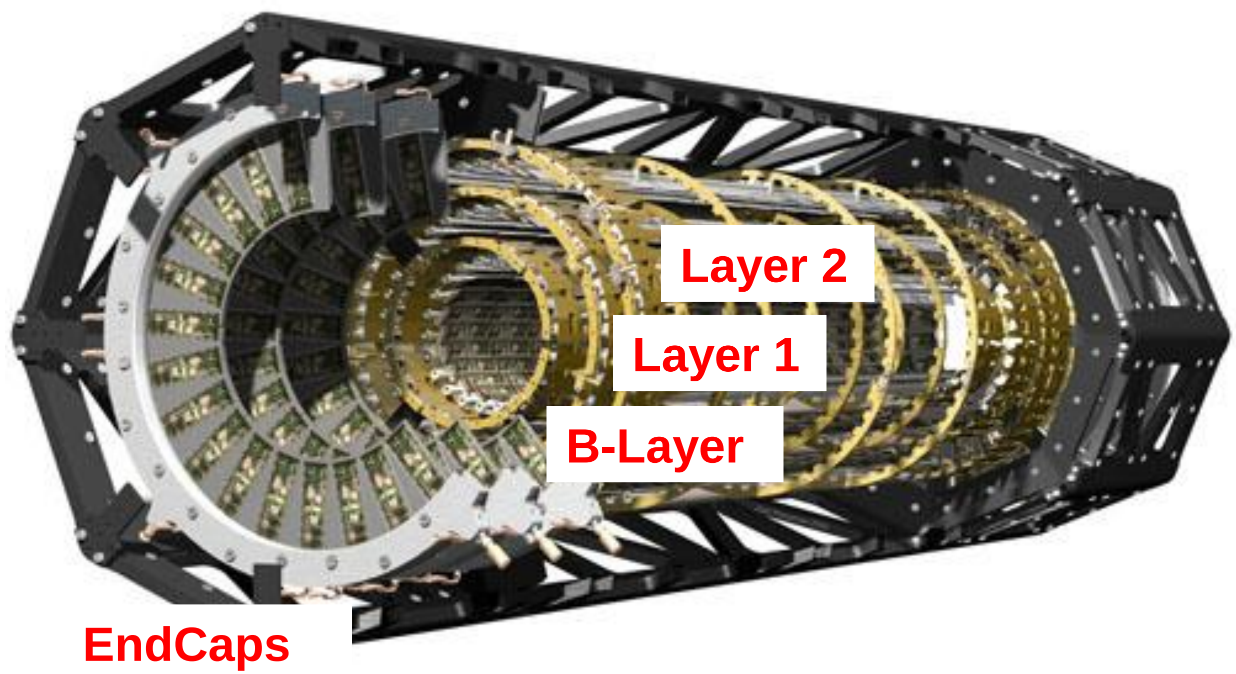
**Innermost is a silicon pixel tracker:**
- **4 barrel layers and 3 disk layers contain <u>1.92 $m^2$ of silicon</u> and <u>92 M channels.</u>**

# 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 **|η|< 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% $X_0$** .





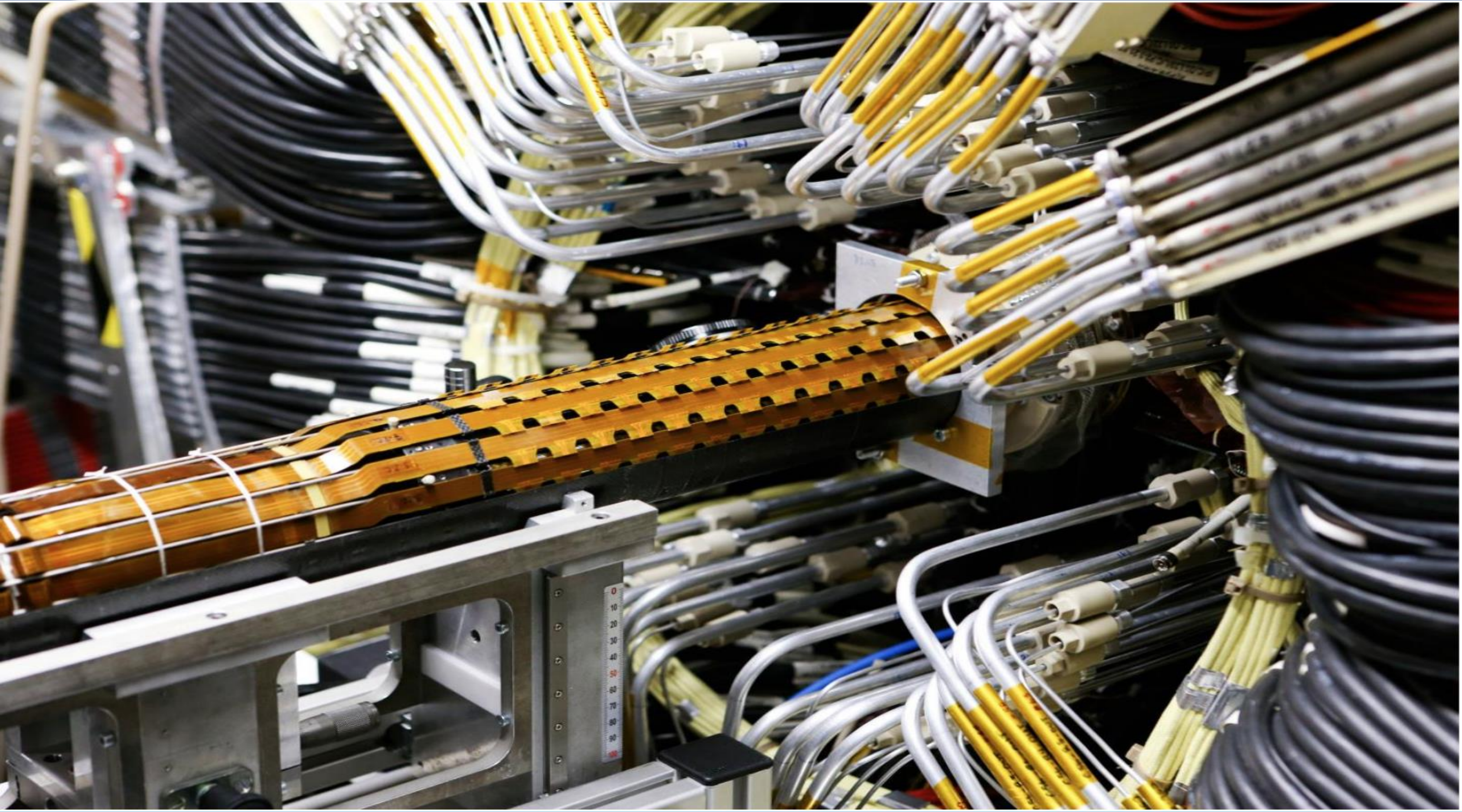
# Why we needed a 4th Layer?

- ***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:

    → big impact on many physics analyses.
- ***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

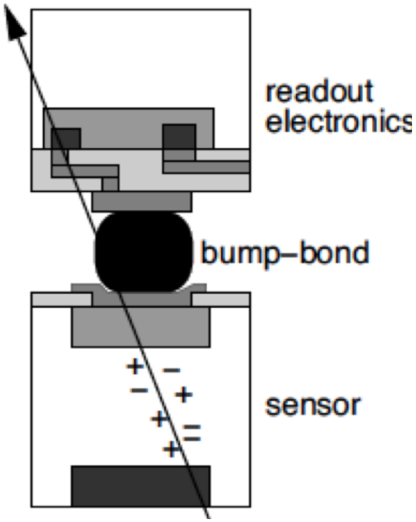


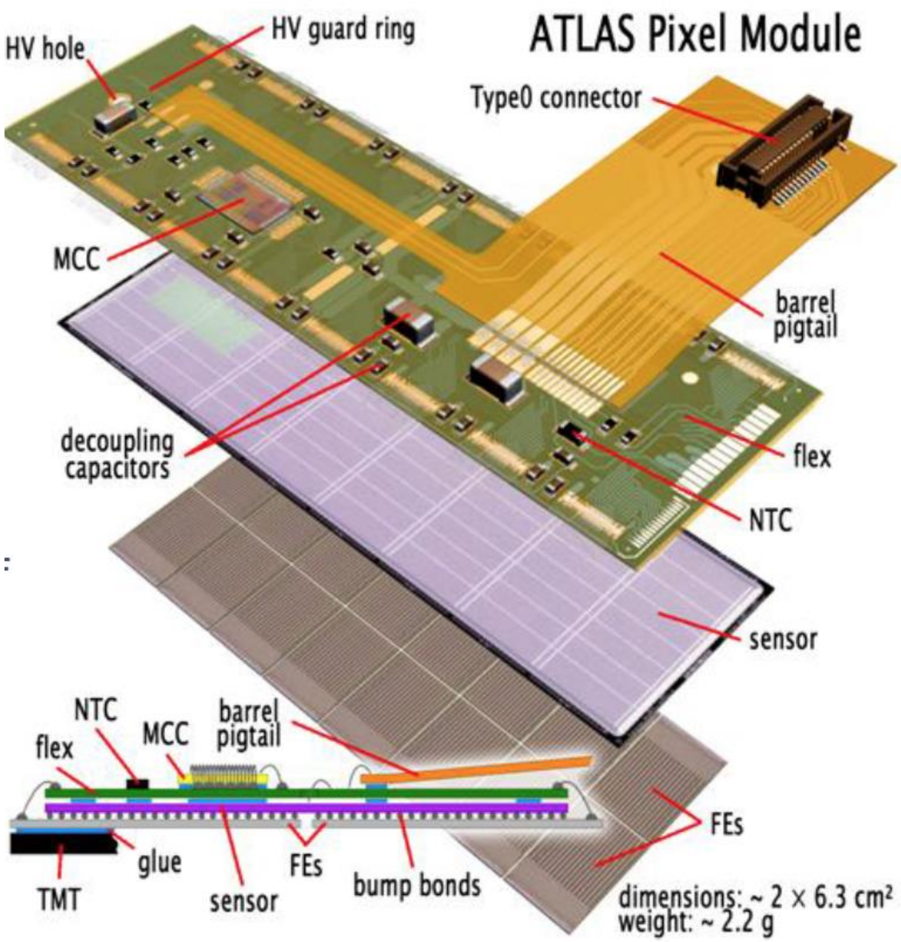
**Insertable B-Layer (IBL)** was added at the beginning of **RUN 2 (2014)**

# The building block: Pixel module

## Read-out:

- 16 Front-ends chips bump-bonded to sensor




## Sensor:

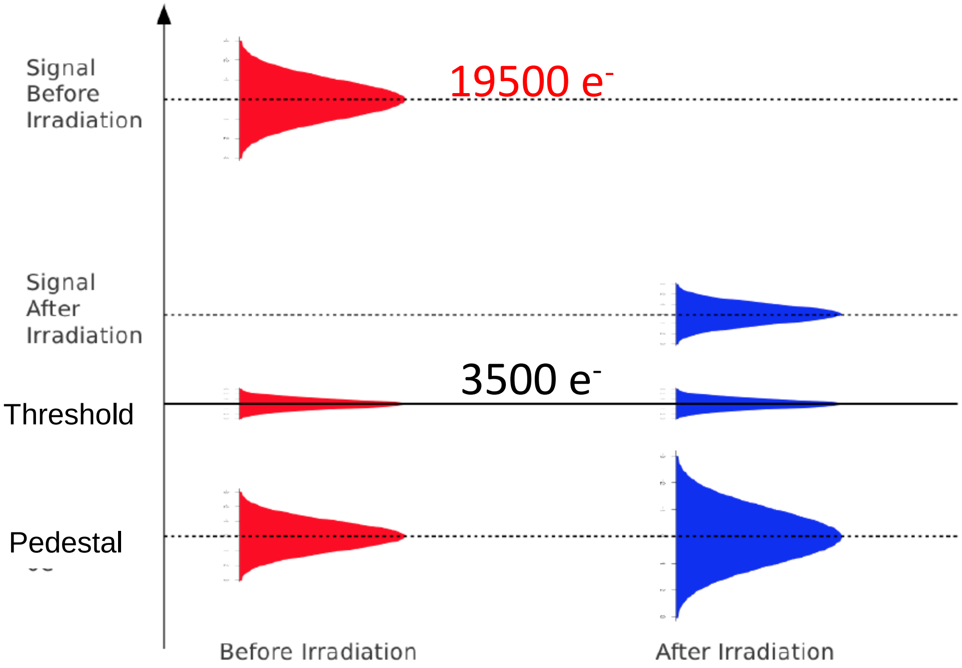
250 μm thick n-in-n Si planar sensor:
50 x 400 typical μm pixel size
Bias voltage: 150 -600 V

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

# Pixel performance after ~10 years

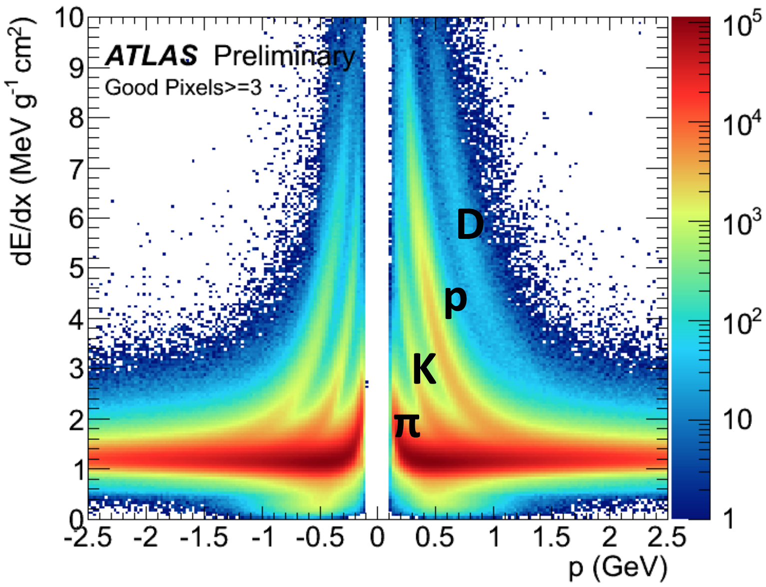
Signal of a high energy particle
**MIP ~ 19500 e$^-$ in 250 μm silicon**

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




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

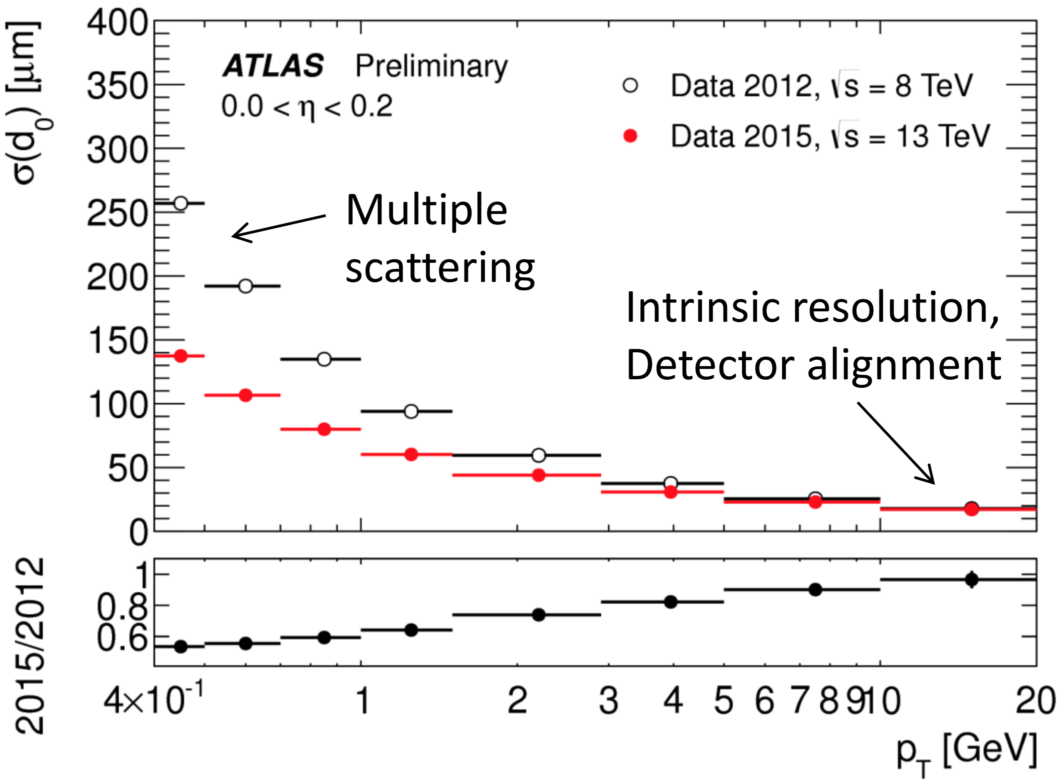
- 99.8% data taking efficiency
- ~ 96% of detector operational
- ~10 μm x 100 μm resolution
- 12% dE/dx resolution

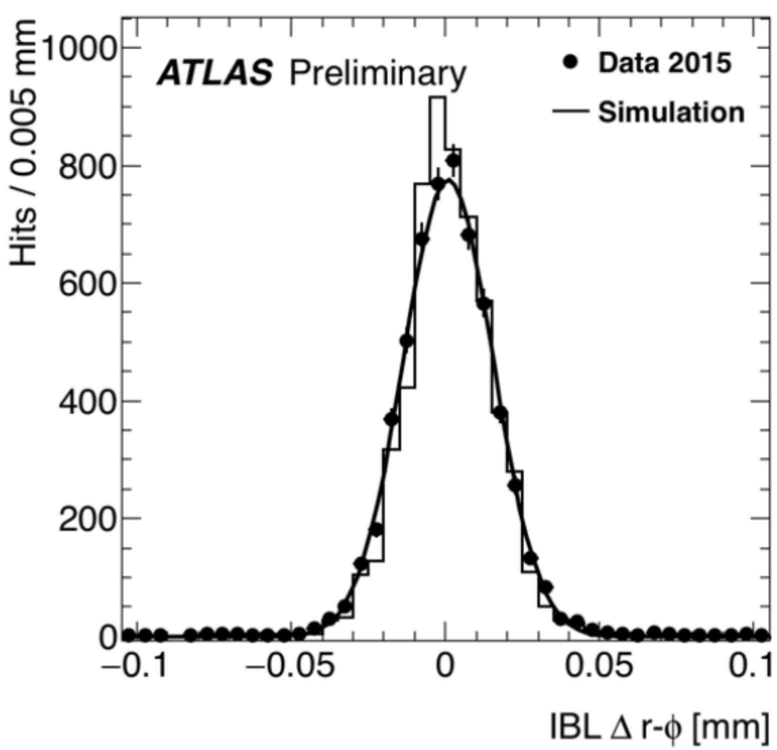


# Pixel (IBL) performance in Run 2

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

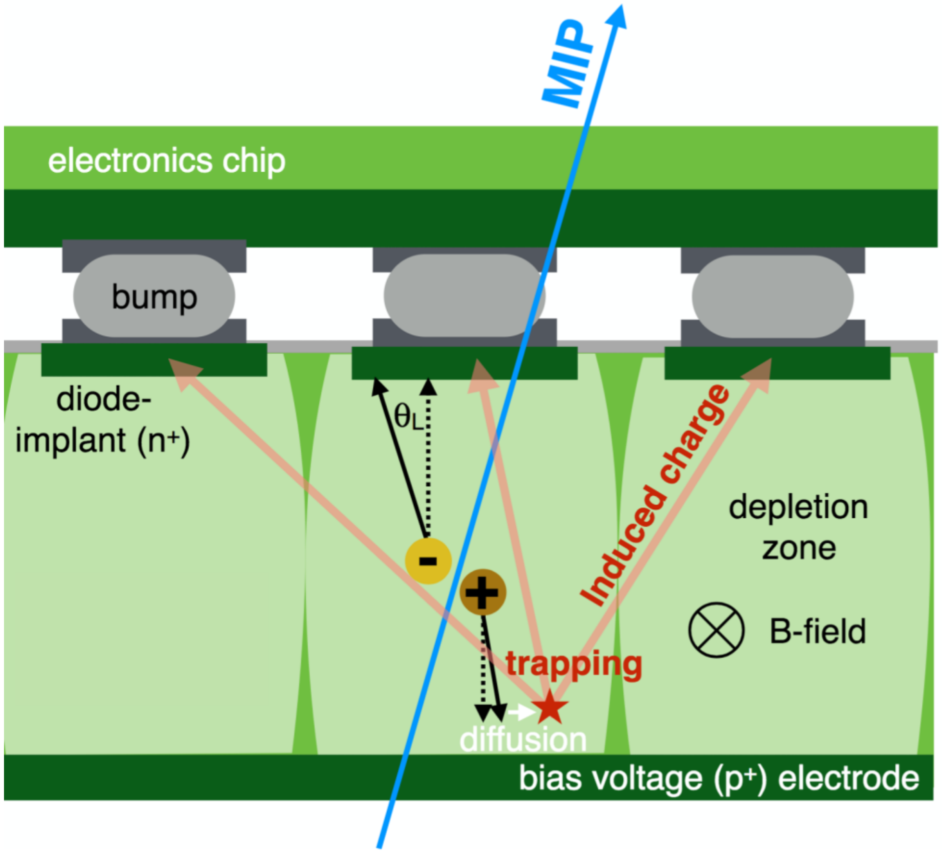
Inner radius reduction



# 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)

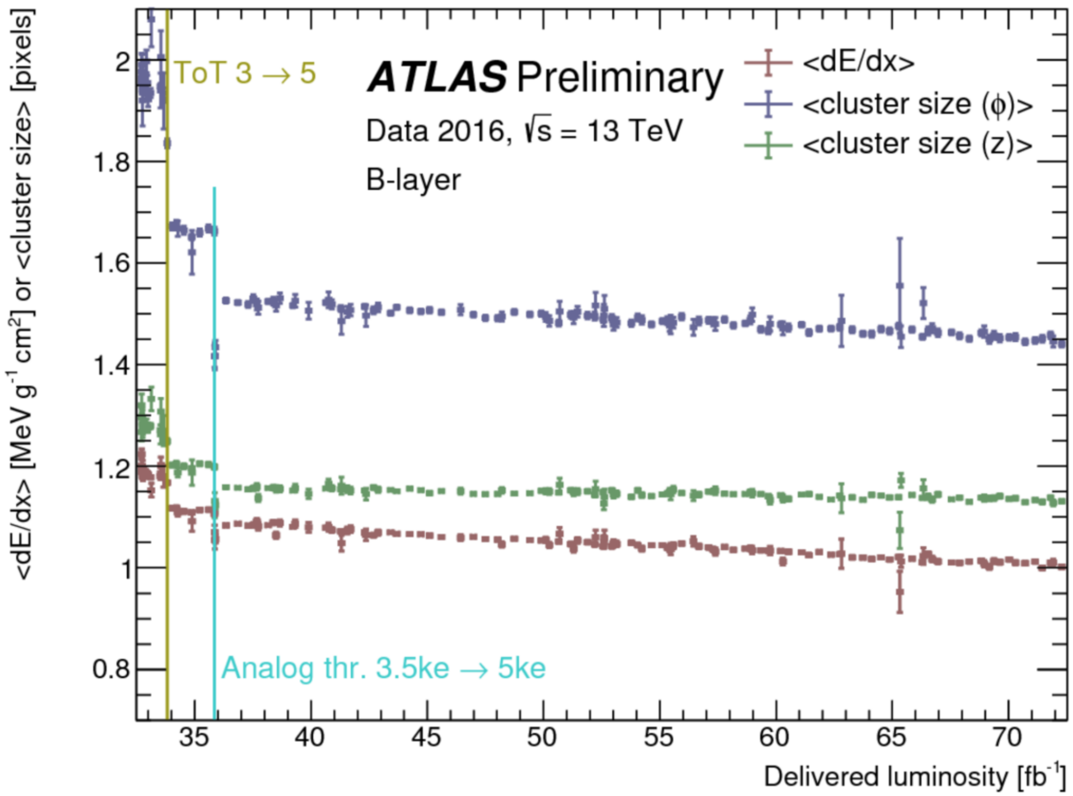
# Effect of radiation on dE/dx

- 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

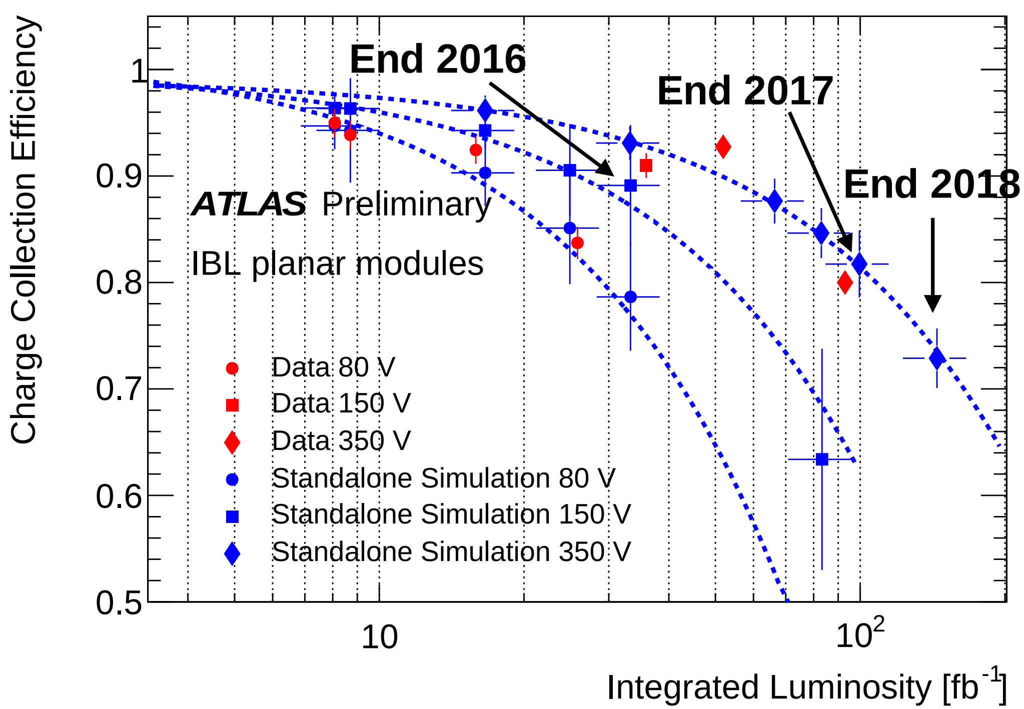


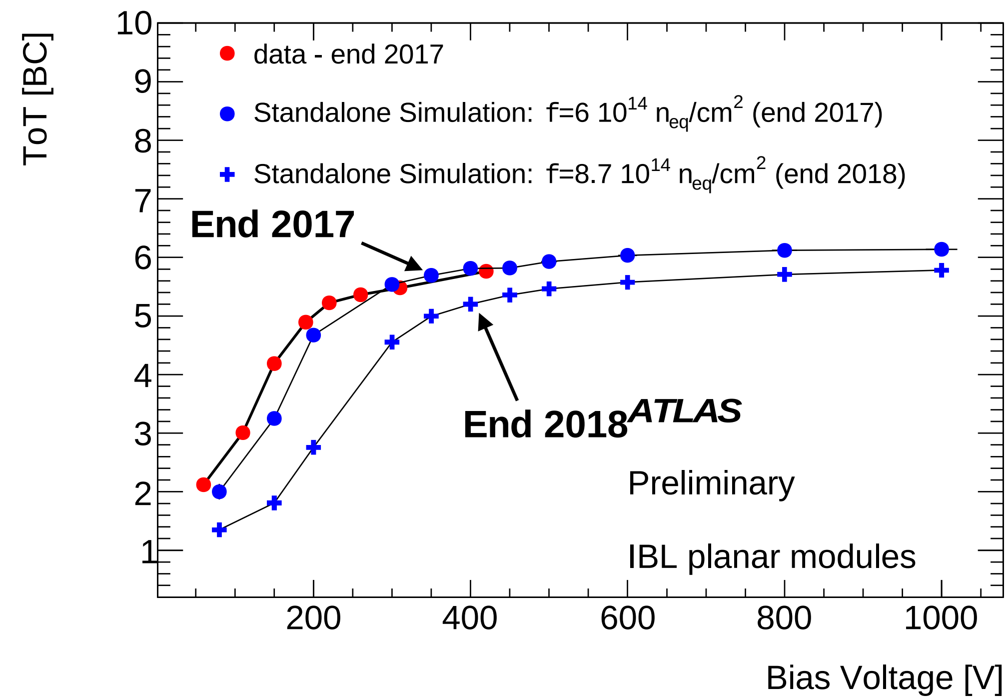
# Fighting the radiation damage

- **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:

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

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

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

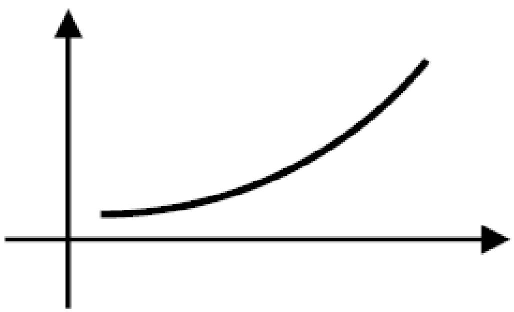
Particle Identification via measurement of

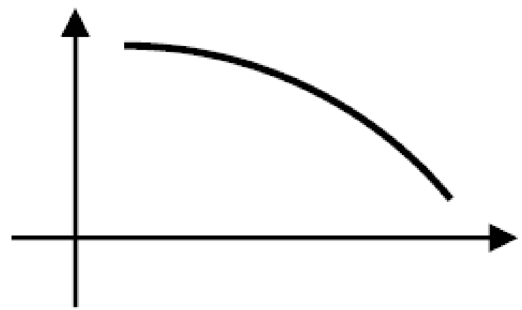
e.g. $(E, \vec{p}, Q)$ or $(\vec{p}, \beta, Q)$
$(\vec{p}, m, Q)$ ...

# 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:

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

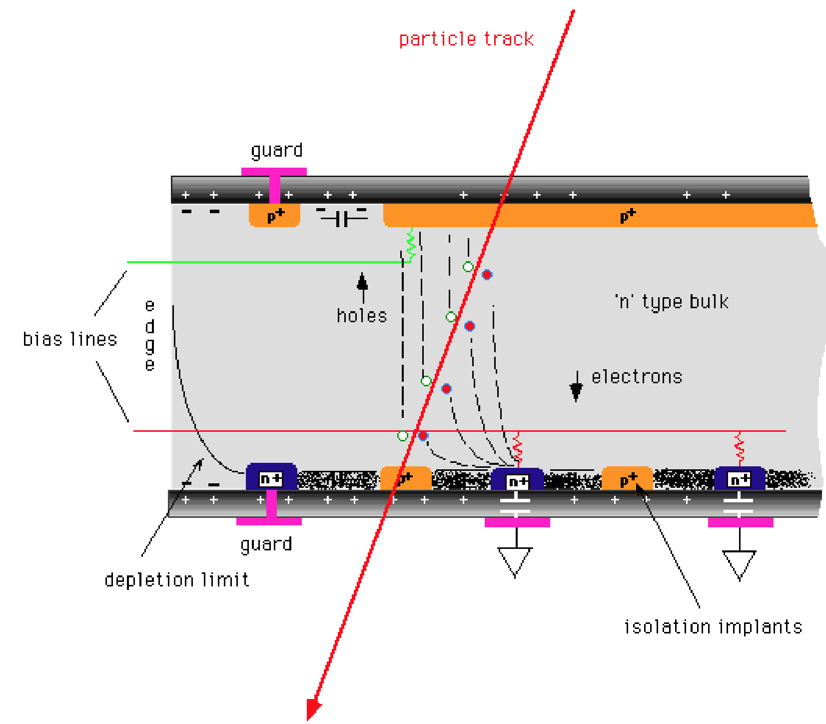
- Requiring 3σ identification → upper lim. in p:

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

# Consideration for Pixel detectors

## Requirements

- good Signal/Noise
- µm space resolution
- ~ns time resolution
- >10 MHz / mm² rate capability
- radiation hard to 50 Mrad
- radiation length per layer < 0.2% $X_0$

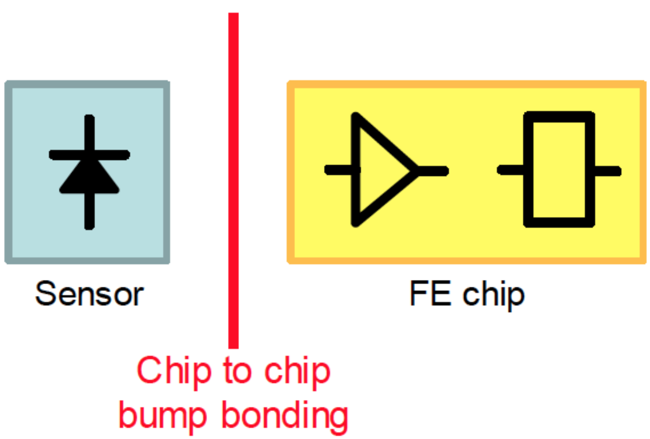



## Advantages

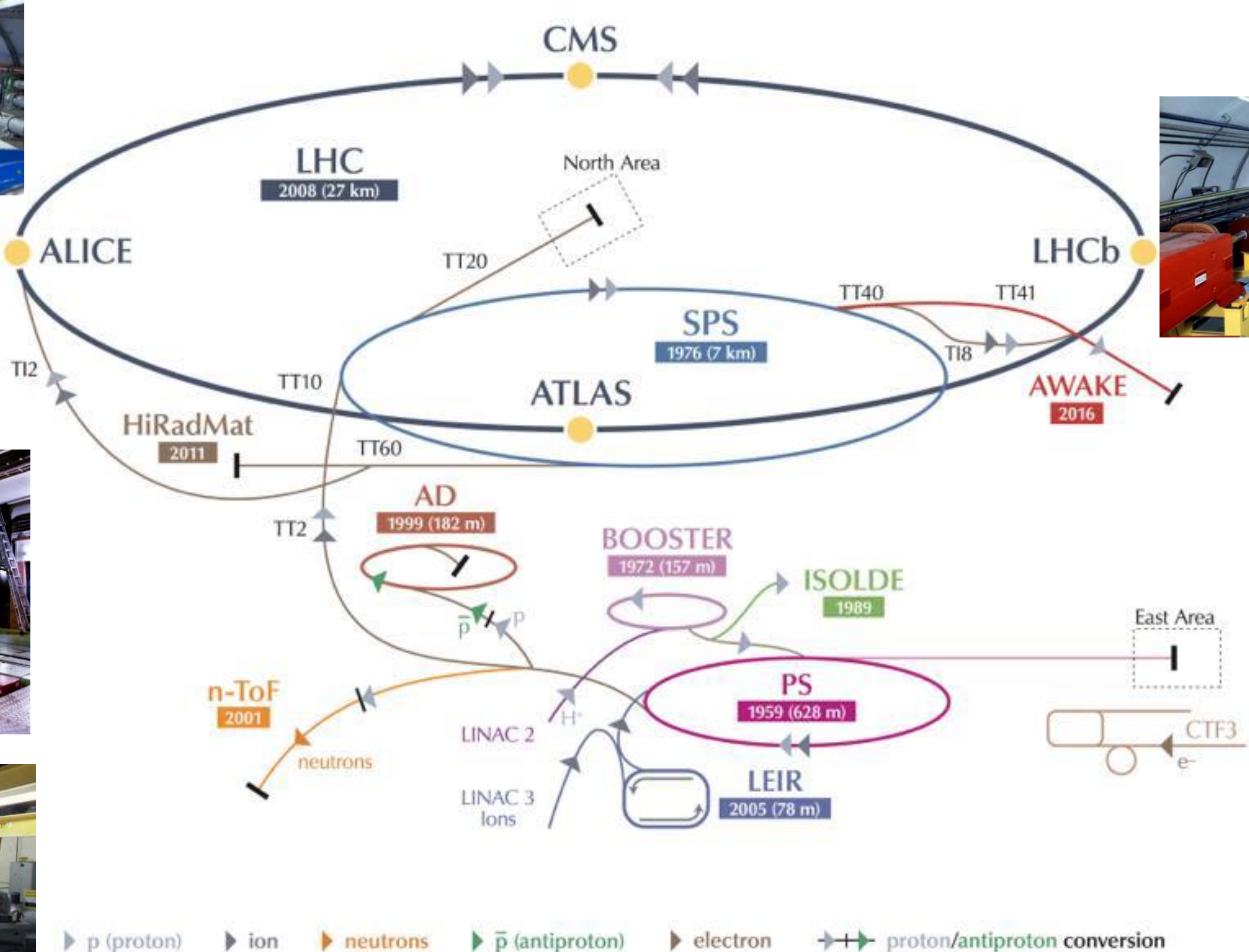
- Provides space-point information
- Small pixel area ➔ low occupancy/noise
- Small pixel volume ➔ low leakage
- n+-on n for the LHC ➔ e- faster collection time

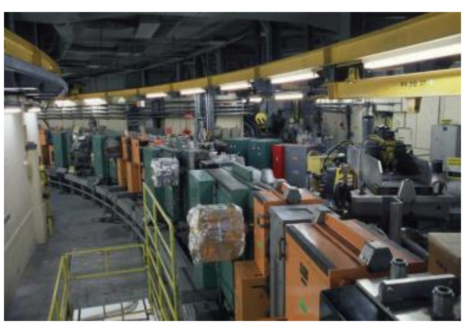
## Disadvantages:

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

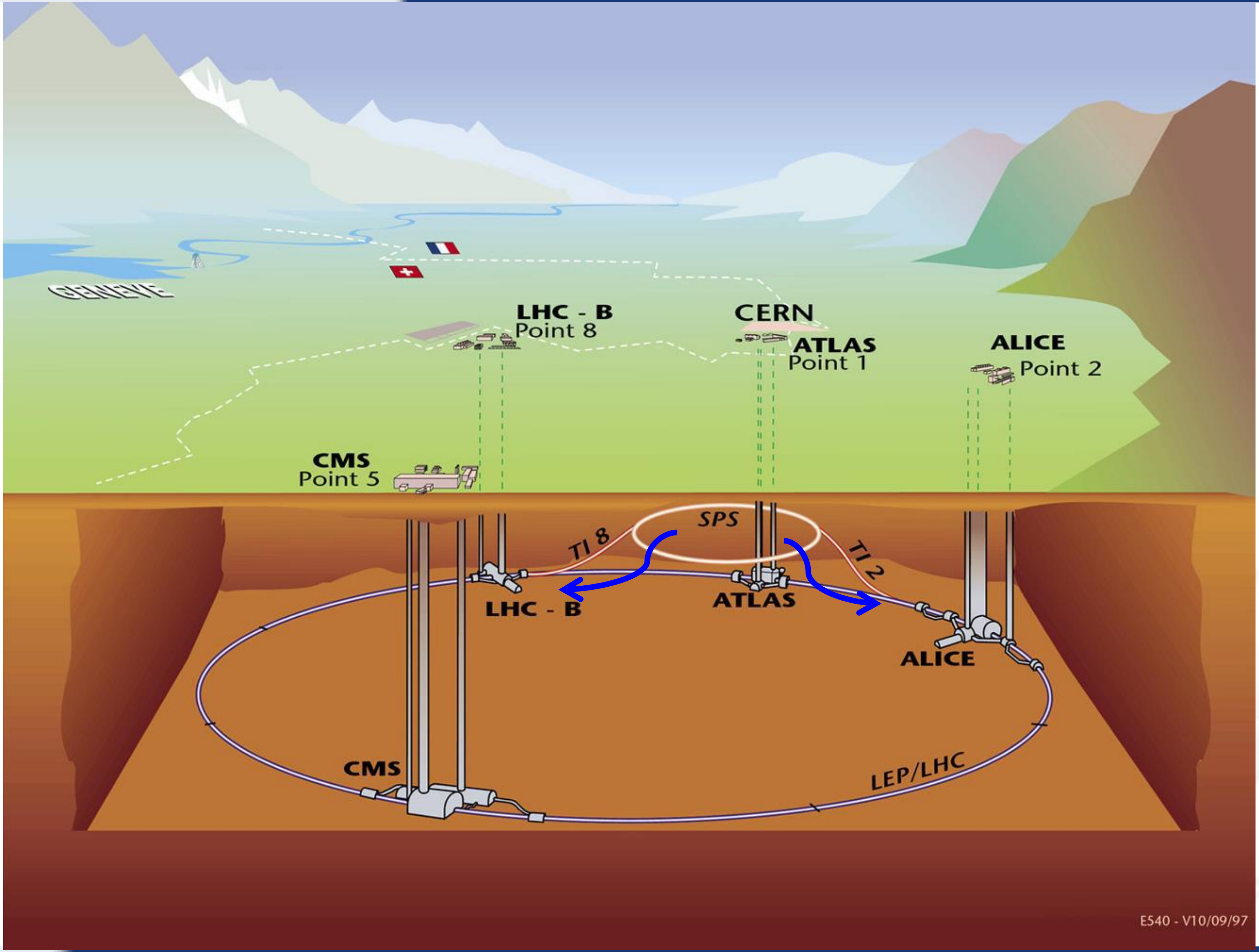


# CERN facilities.. not just LHC

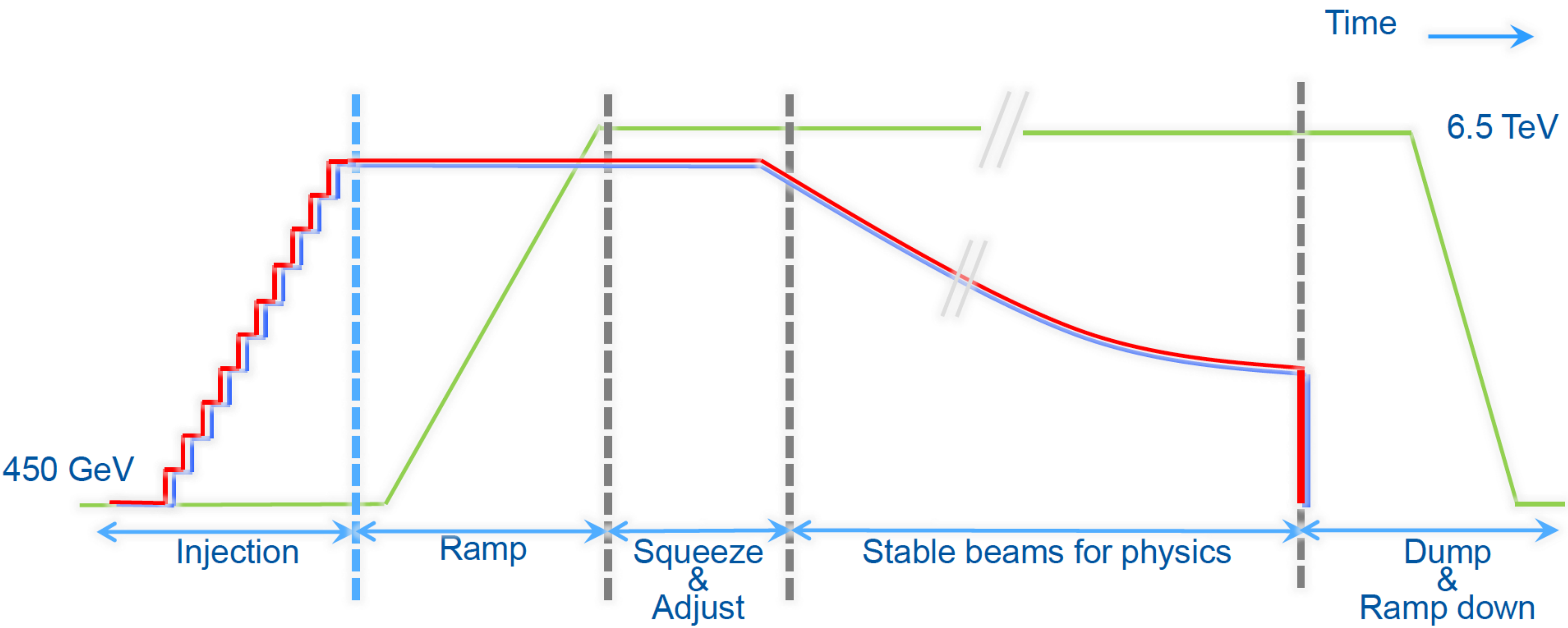


# Filling LHC on the underground



# 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**

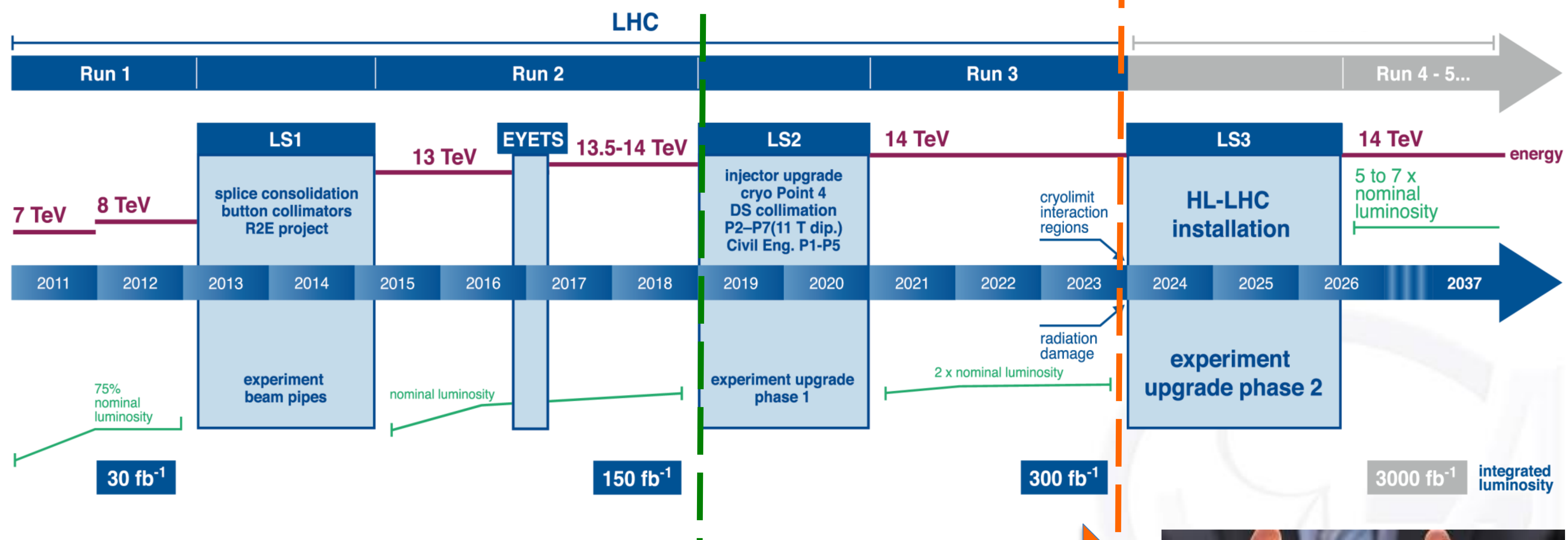
In 2012 it ran at 4 TeV per beam, 8 TeV c.o.m.

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

# LHC Timeline

**High-Luminosity territory…**

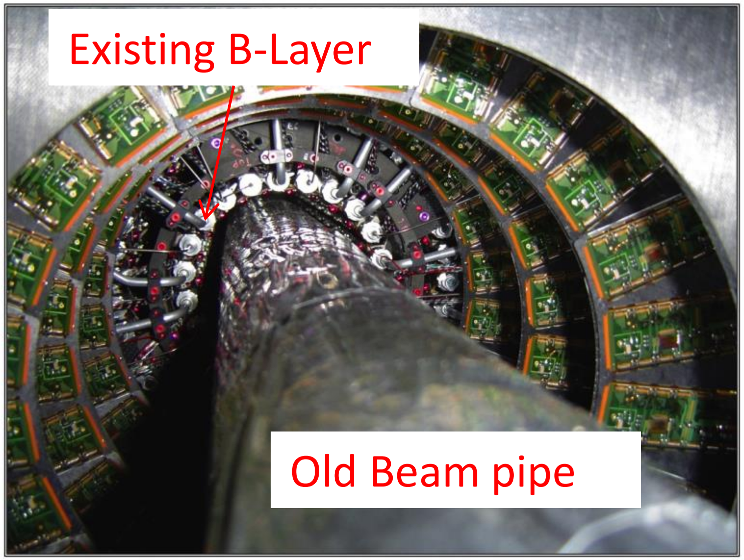
## LHC / HL-LHC Plan




# The IBL detector

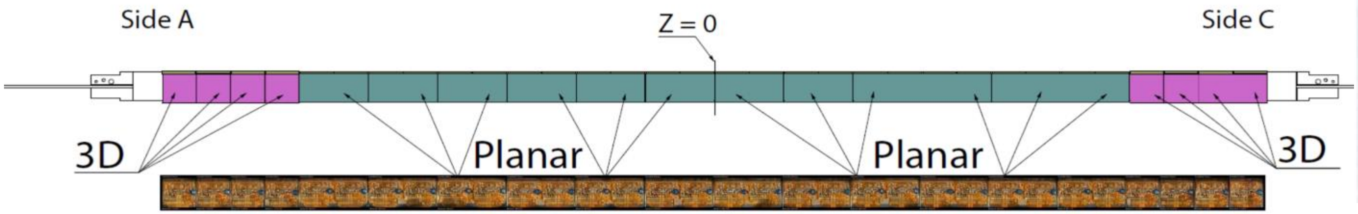
## *The IBL idea in a nutshell*

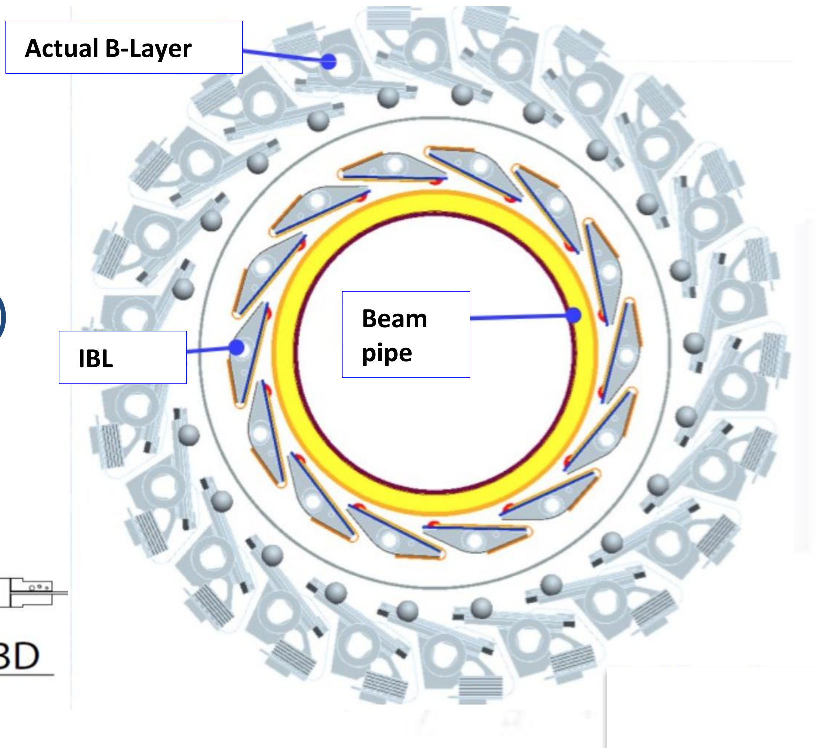
- add a single detector layer built around a new thinner Beryllium beam-pipe (radius 29 mm ➔ 25 mm).
- closer to interaction point (5.05 → 3.27 cm)
- smaller pixel size (50 × 400 → 50 × 250 μm$^2$ )
- IBL + beam pipe and structures : < 2% $X_0$




## *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!

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