LHC detectors

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Course on Physics at the LHC

LIP, 7th-9th March 2022

Outline

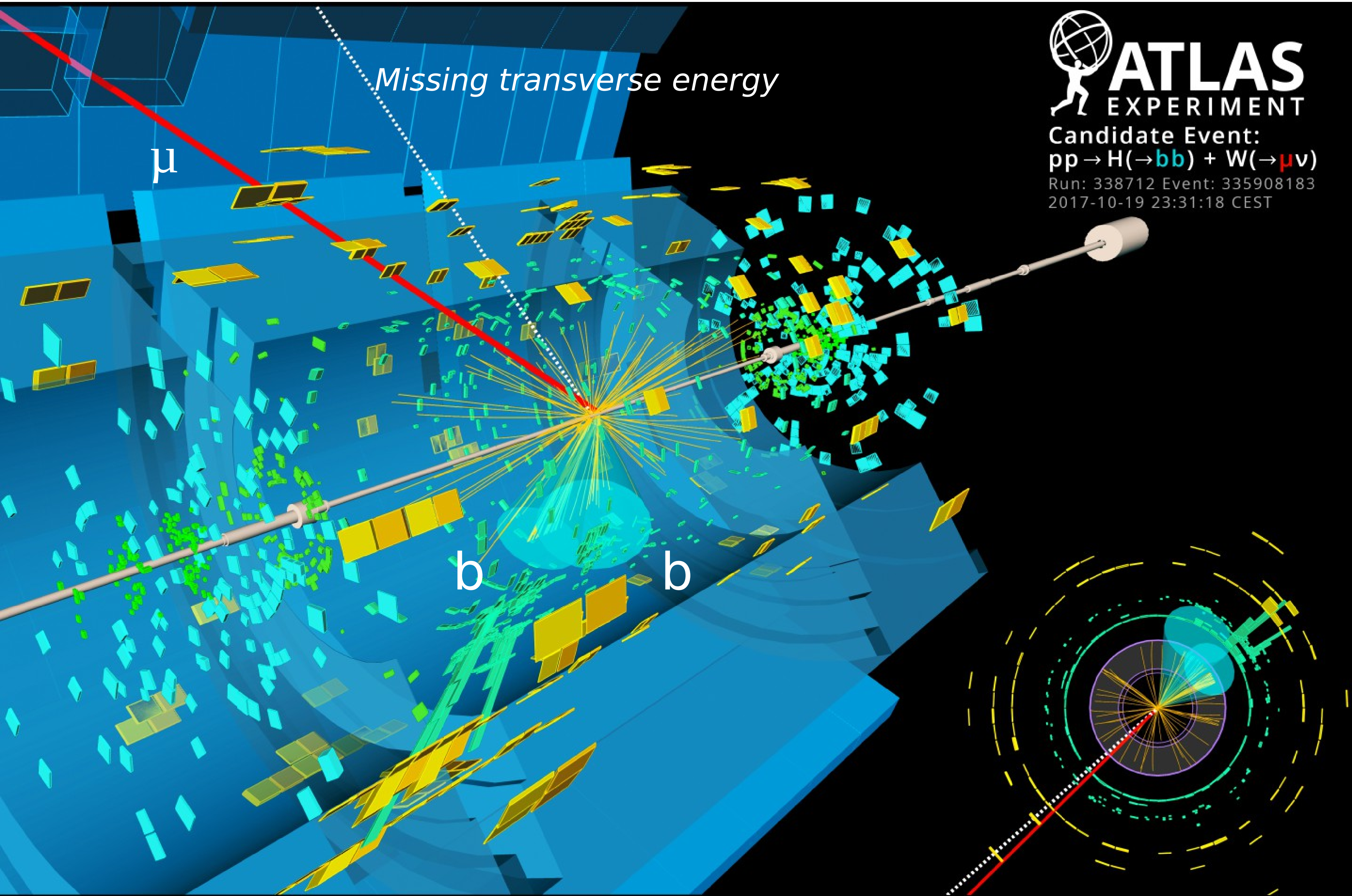
- From collision remnants to physics
- Connecting the dots: tracking
- Si-based detectors
- Calorimetry for pedestrians
- Getting data on tape: trigger systems

1st part

2nd part

From
collision remnants
to
physics

At the LHC the hunt for new physics has exciting signatures

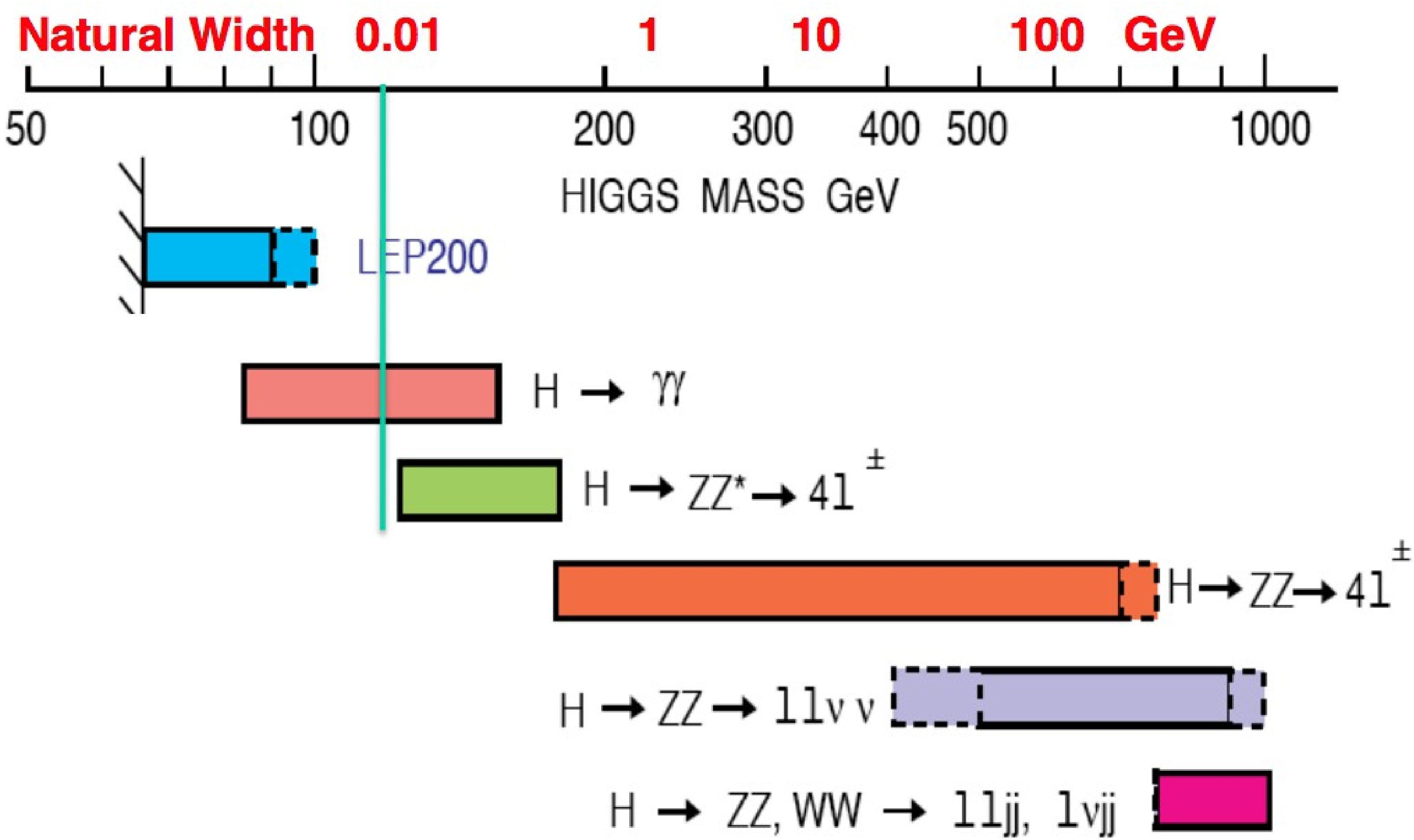


Discovery drove the LHC detectors concept

Before the Higgs discovery different signatures were expected depending on m_H

4π-hermetic general purpose detectors were needed

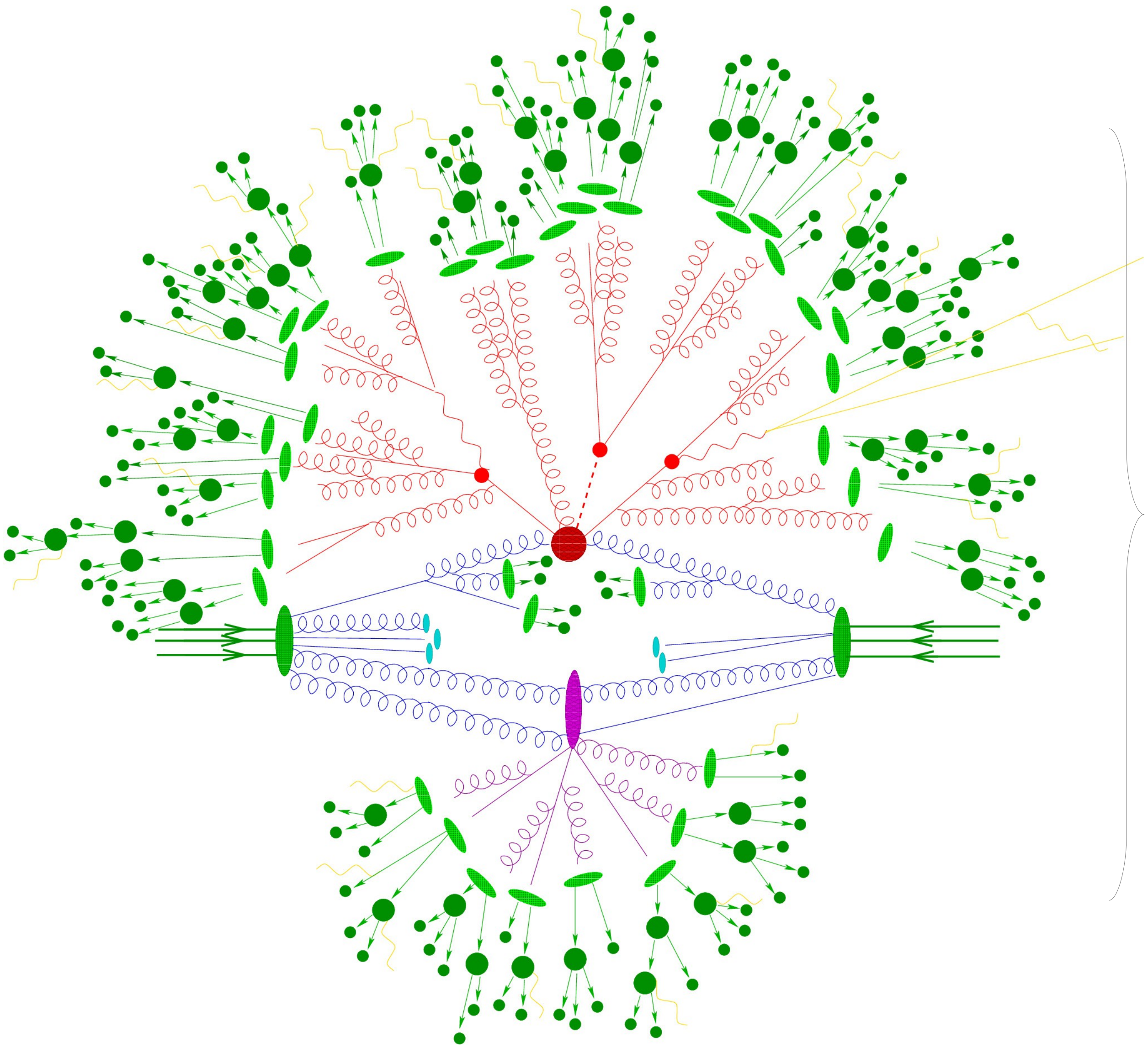
- covering: leptons, photons, jets, missing energy ...



Proton-remnants underlie the hard processes

A hadron collider scans a large energy range but yields an underlying event

Single proton collisions produce high multiplicity events



Hard process

+

Initial/Final state radiation (ISR/FSR)

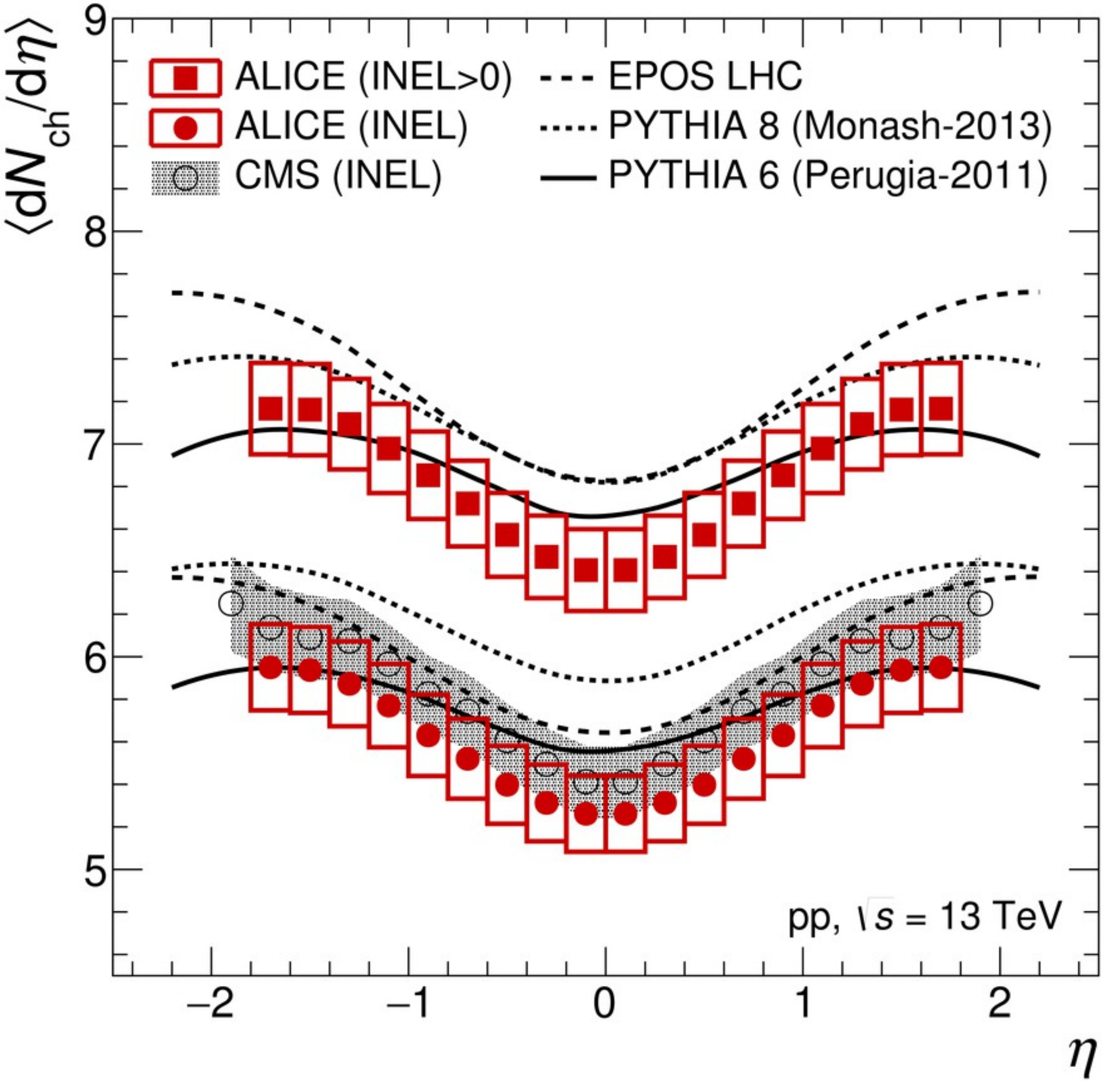
Multiple particle interactions (MPI)

Beam remnants

Proton-remnants underlie the hard processes

A hadron collider scans a large energy range but yields an underlying event

Single proton collisions produce high multiplicity events (approx. uniform in η)



*Average **15-20 charged particle**s per inelastic collision*

Proton-remnants underlie the hard processes

A hadron collider scans a large energy range but yields an underlying event

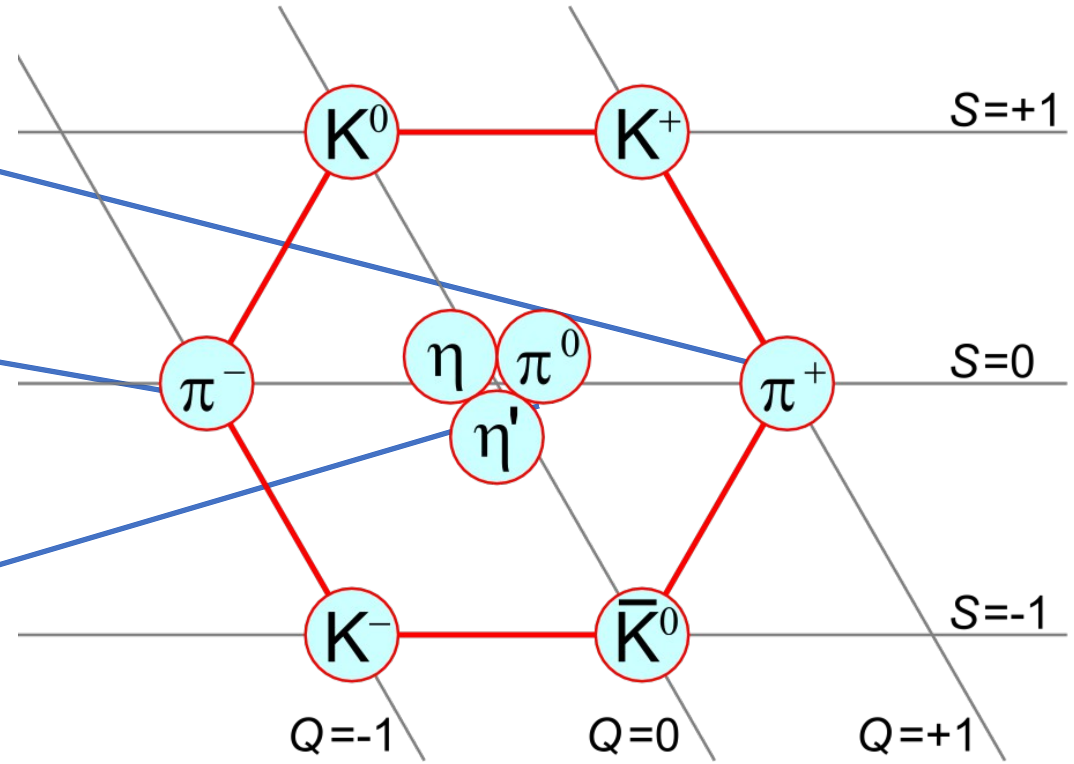
Single proton collisions produce high multiplicity events (approx. uniform in η)

Most particles are pions with $$N(\pi^0) \approx \frac{1}{2} N(\pi^\pm)$$

$$\pi^+ = |u\bar{d}>$$

$$\pi^- = |\bar{u}d>$$

$$\pi^0 = \frac{1}{\sqrt{2}}\left(|u\bar{u}> - |d\bar{d}>\right)$$



strong interactions preserve isospin

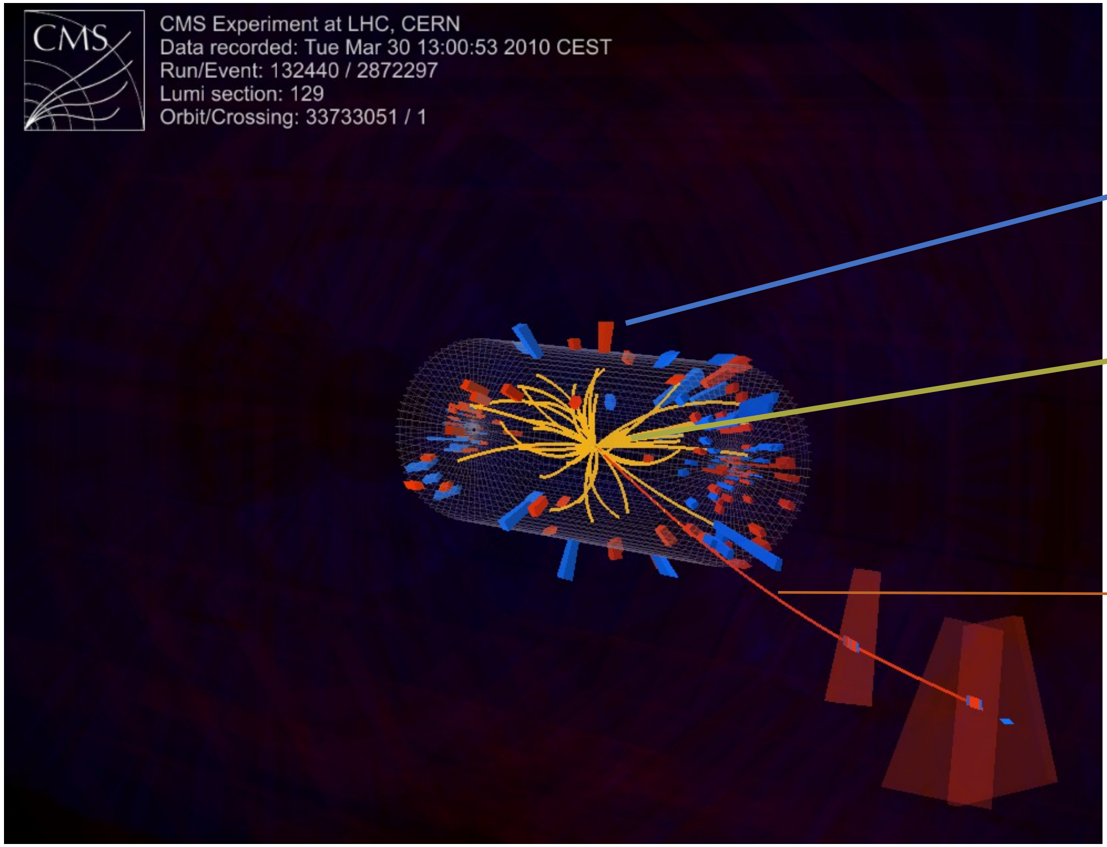
Proton-remnants underlie the hard processes

A hadron collider scans a large energy range but yields an underlying event

Single proton collisions produce high multiplicity events (approx. uniform in η)

Most particles are pions with $$N(\pi^0) \approx \frac{1}{2} N(\pi^\pm)$$

As BR($\pi^0 \rightarrow \gamma\gamma$)=99% we expect approx. the same number of photons and $\pi^\pm$



calorimetric energy deposits

charged particle tracks

minimum bias

a muon

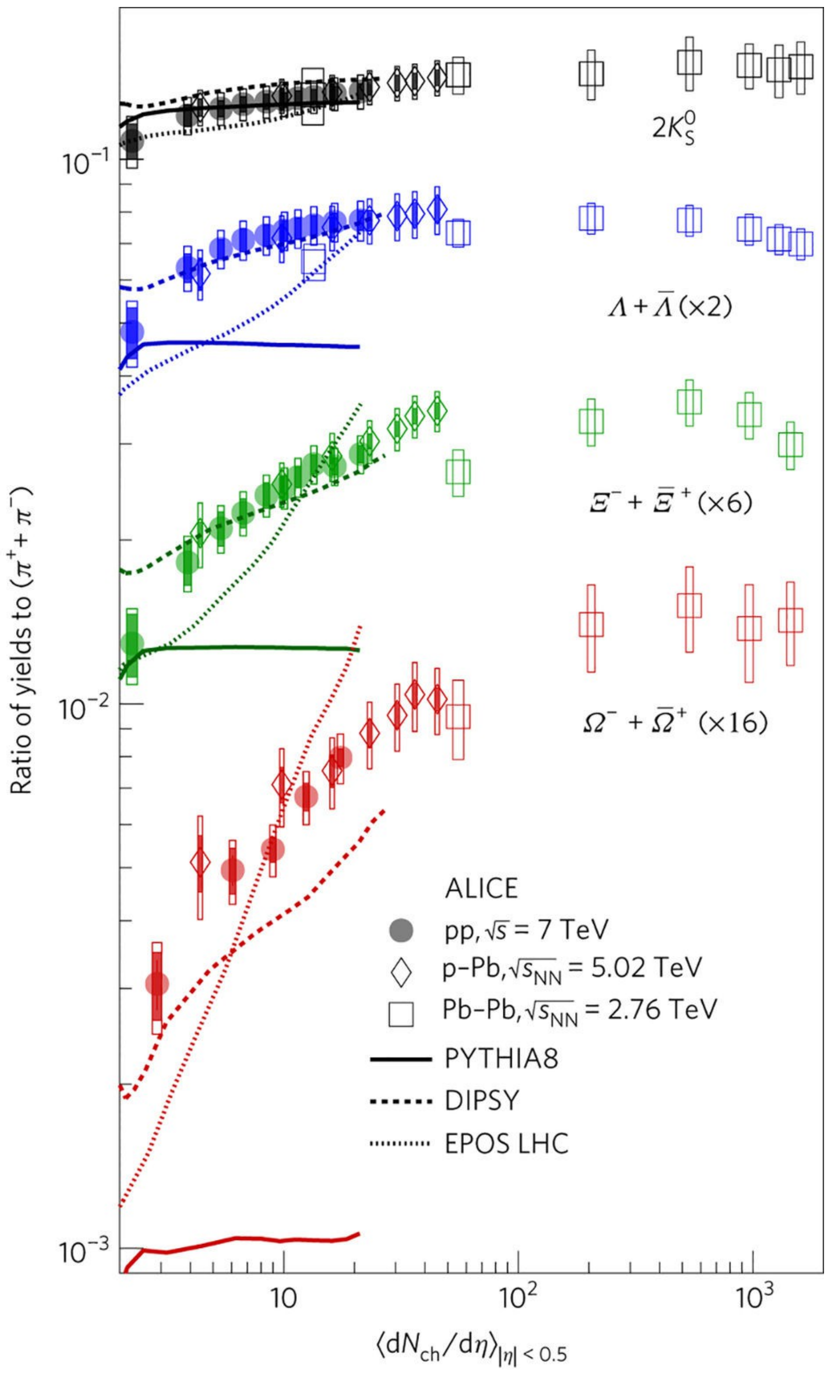
trigger for physics

Beyond pions and photons

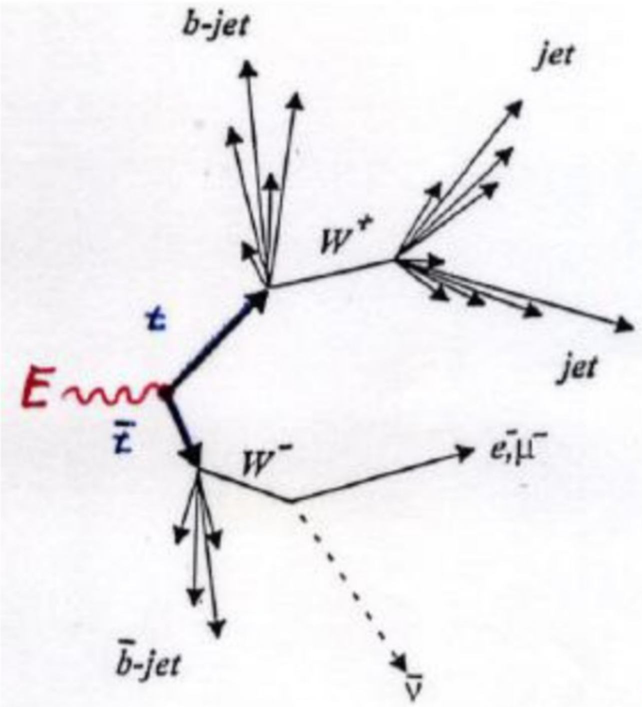
Production of other particles suppressed by

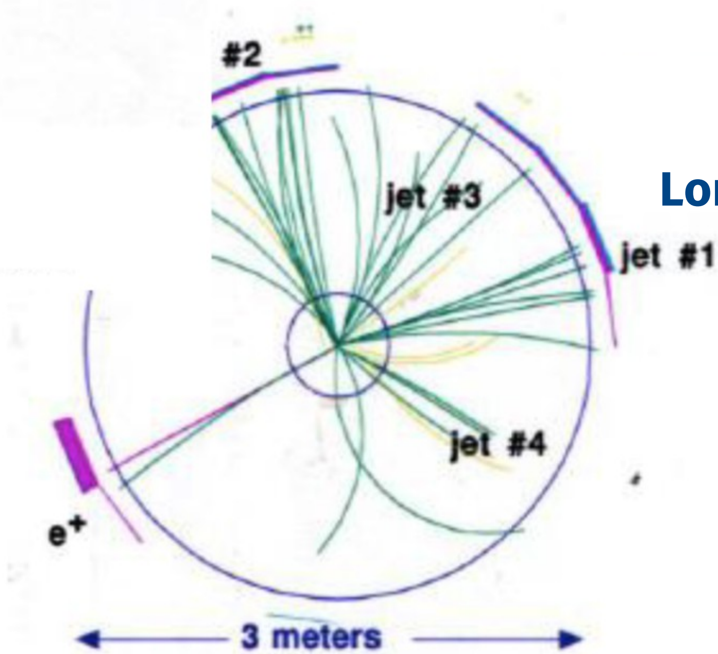
- content of the proton (PDFs)
- mass (m_s~$19m_d$)

Particles with strangeness end up accounting for O(10%) of the multiplicities



What can we detect?





maximum information needed to reconstruct the hard process

Final states

- in rare cases we can reconstruct decays producing secondary vertices

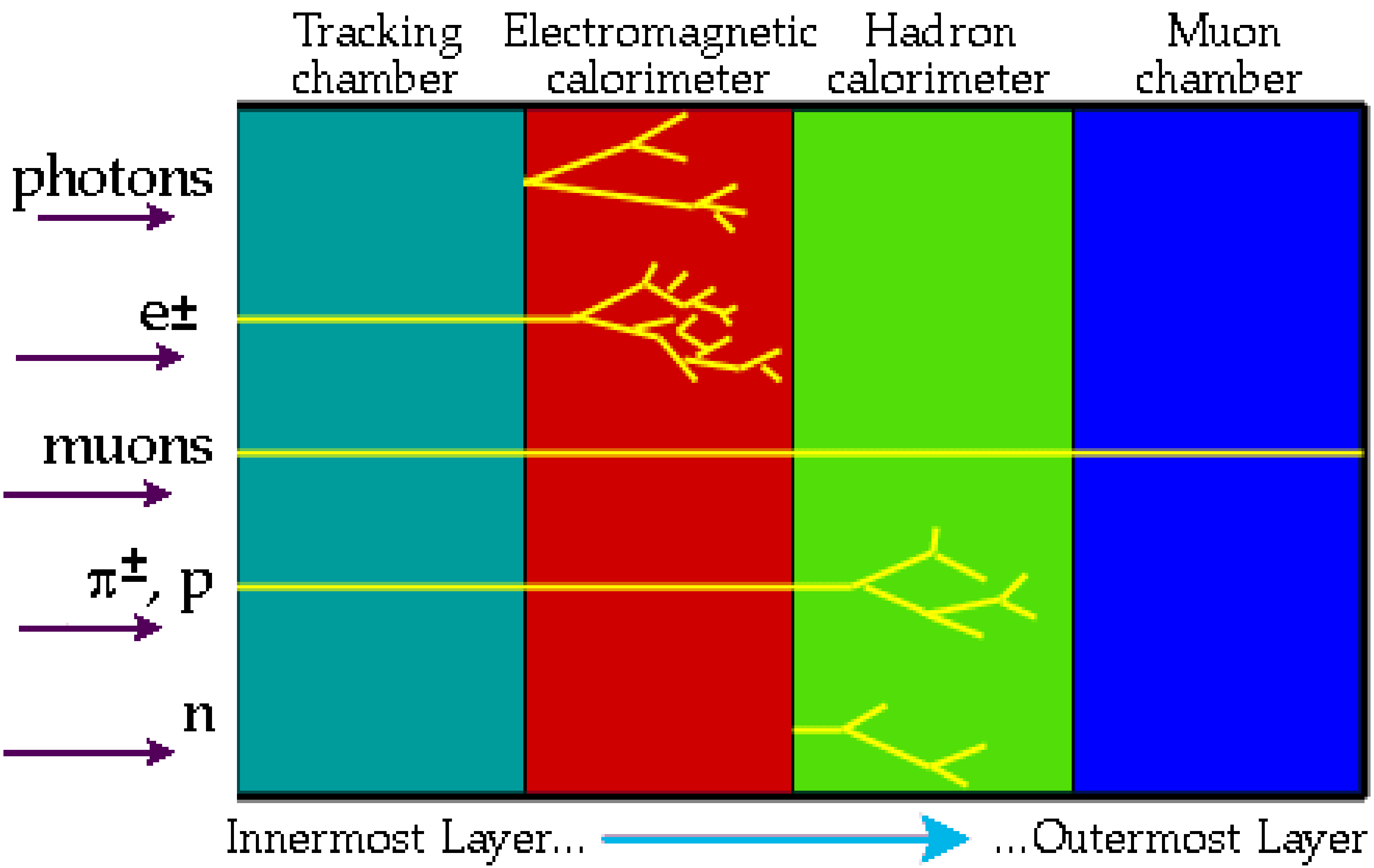
Must interact within detector volume

- electromagnetic or strong interactions
- electrons, muons, photons
- neutral or charged hadrons

Long-lived weakly interacting particles

- indirectly detected
- missing transverse energy
- good resolution when balancing energy

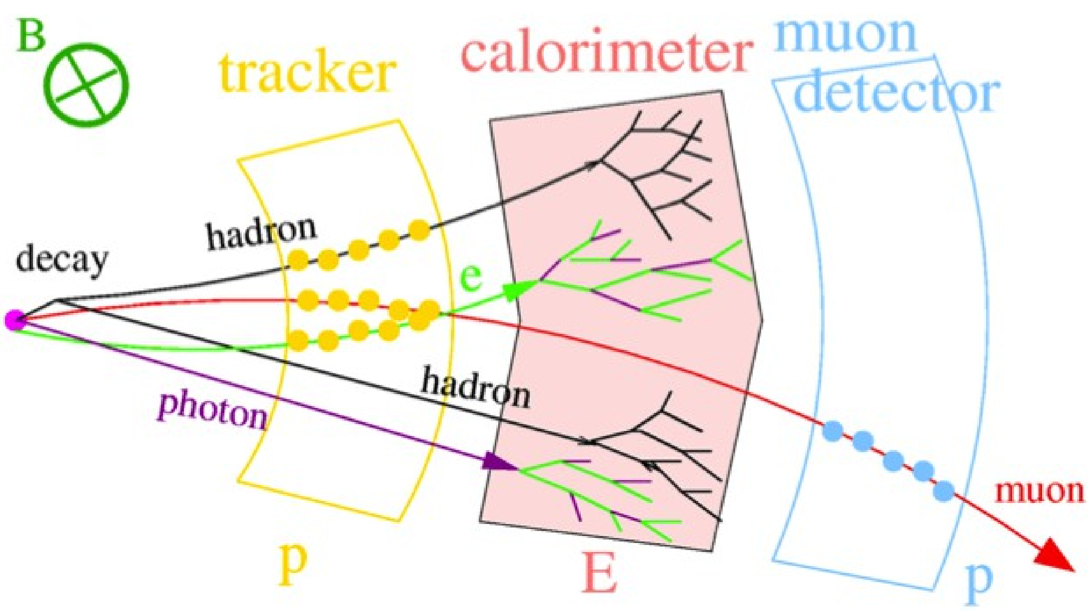
Particles and their interactions



Detectors register the passage of particle through matter – how ?

Absorbers (force interactions) + sensitive materials (convert charge/light to voltage)

Main concepts behind general purpose detectors



Magnetic field "$F_c = qvB$"

- separate by charge
- measure p by curvature

Calorimetry

- measure E from deposits
- electromagnetic and hadronic

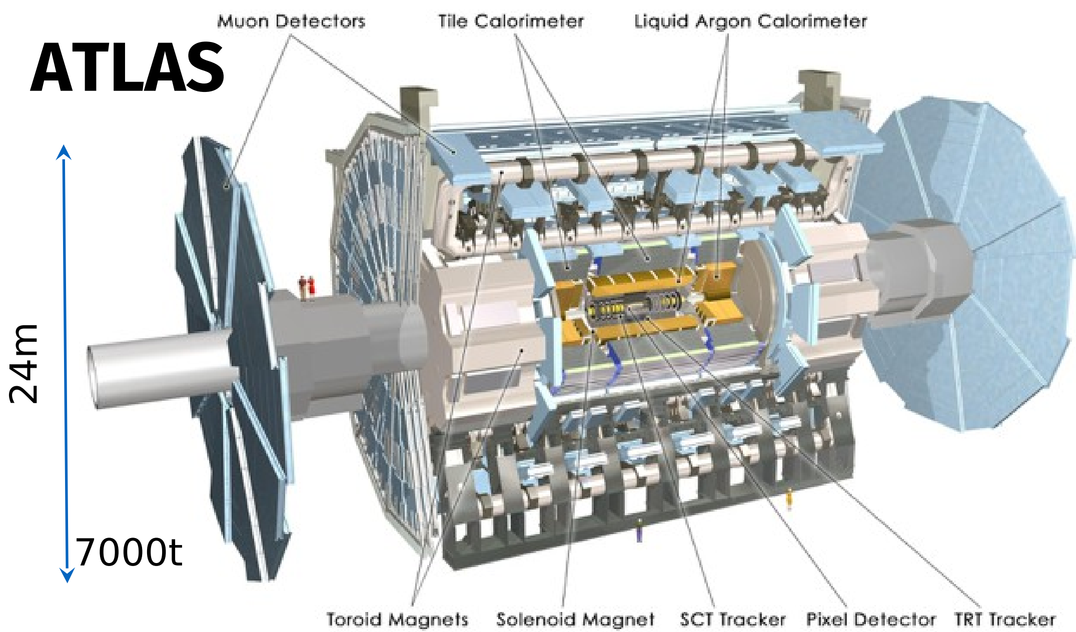
Inner tracking

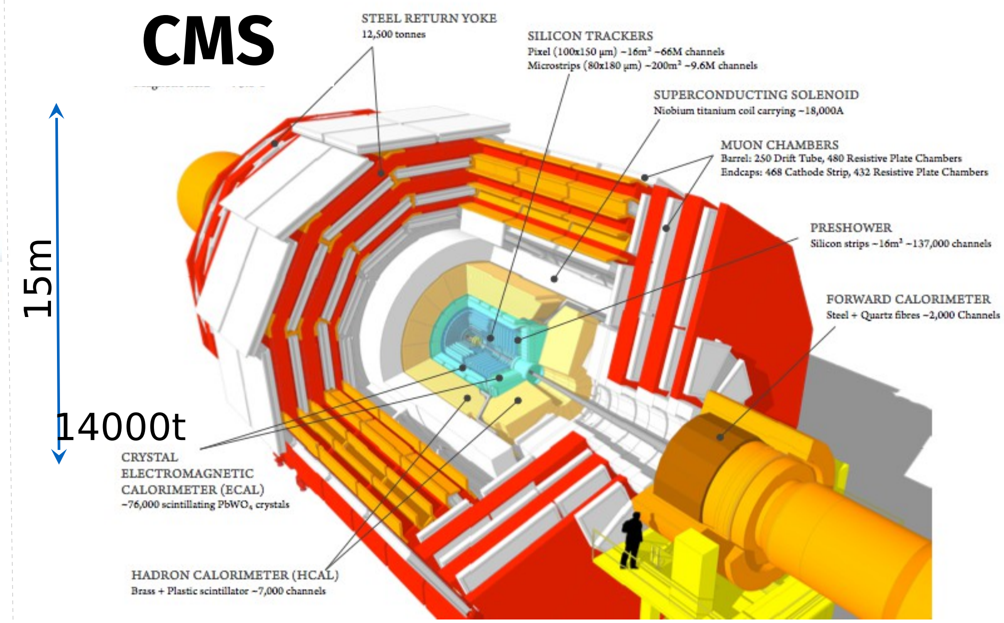
- minimal interference with event
- points to measure curved tracks
- particle identification

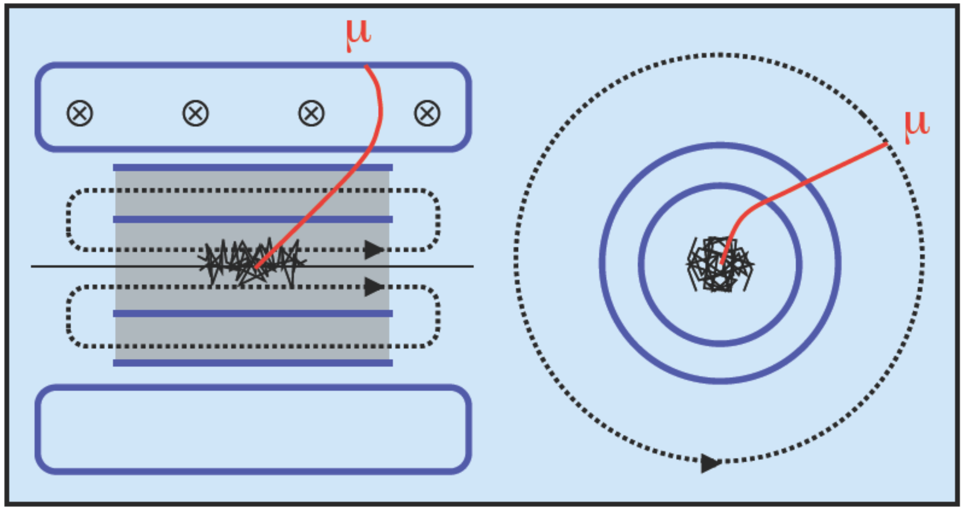
Outer tracking

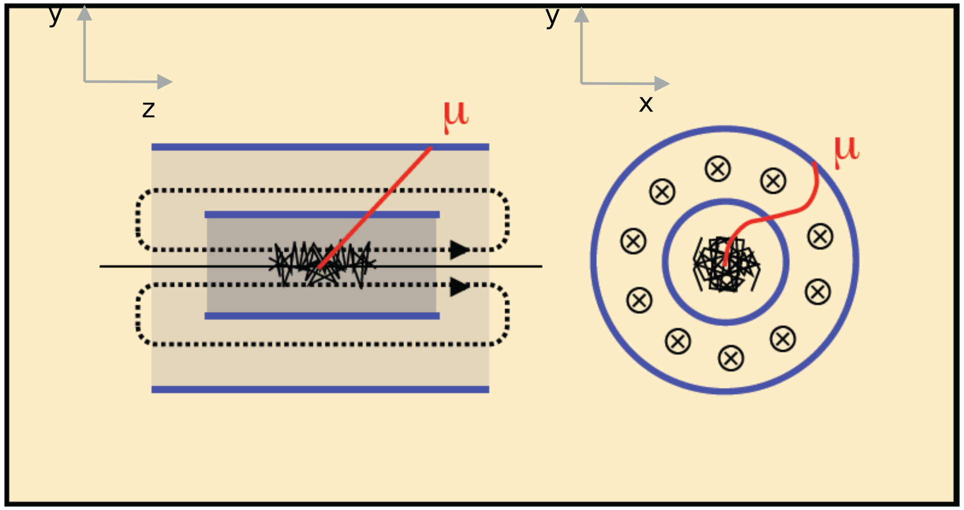
- muons (weakly interacting)

The two general purpose detectors





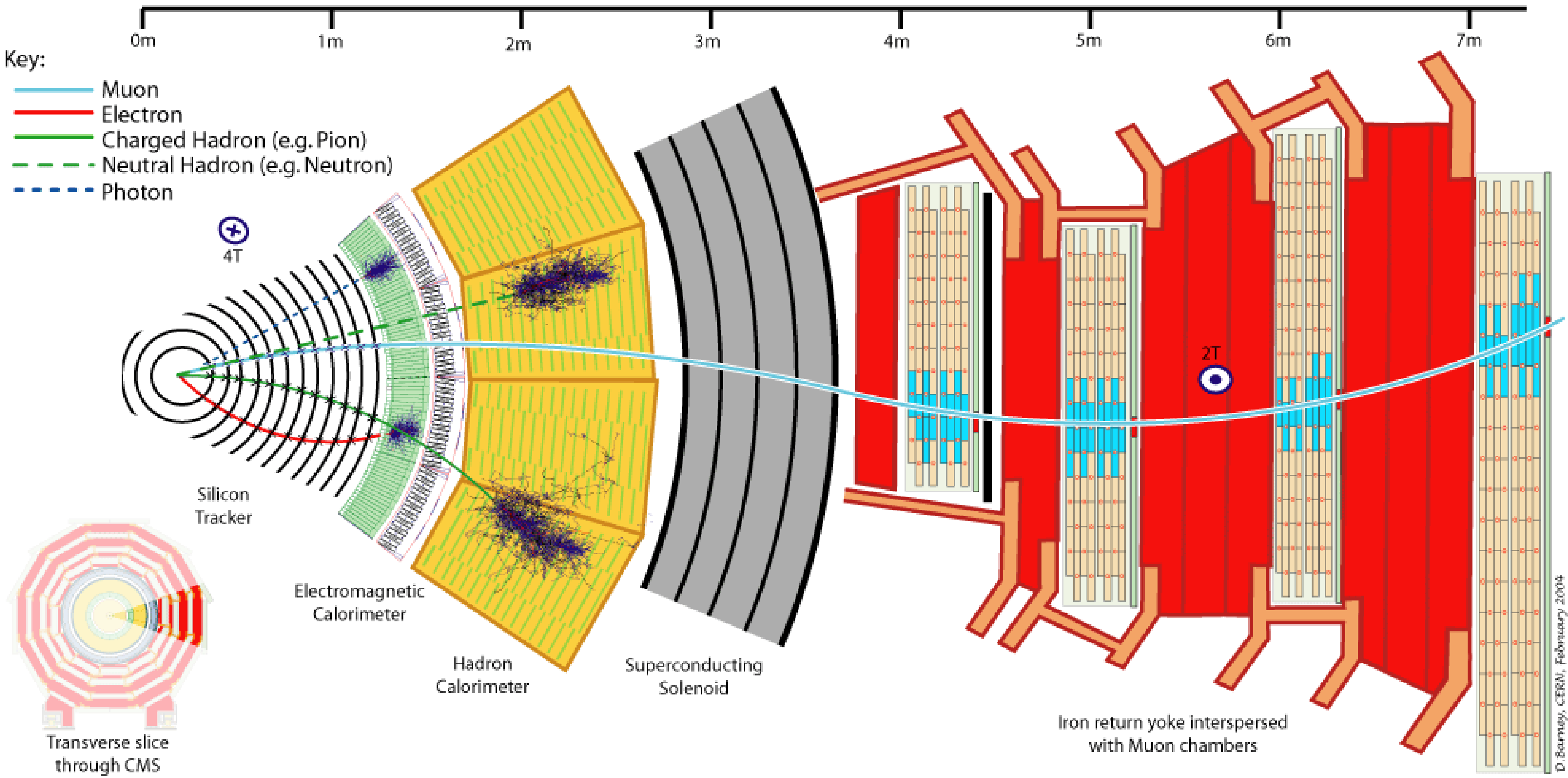




- Standalone measurement of p(μ)
- Resolution is flat in η and independent of pileup

- Two complementary p(μ) measurements
- Tracks point to primary vertex

Particles and their interactions



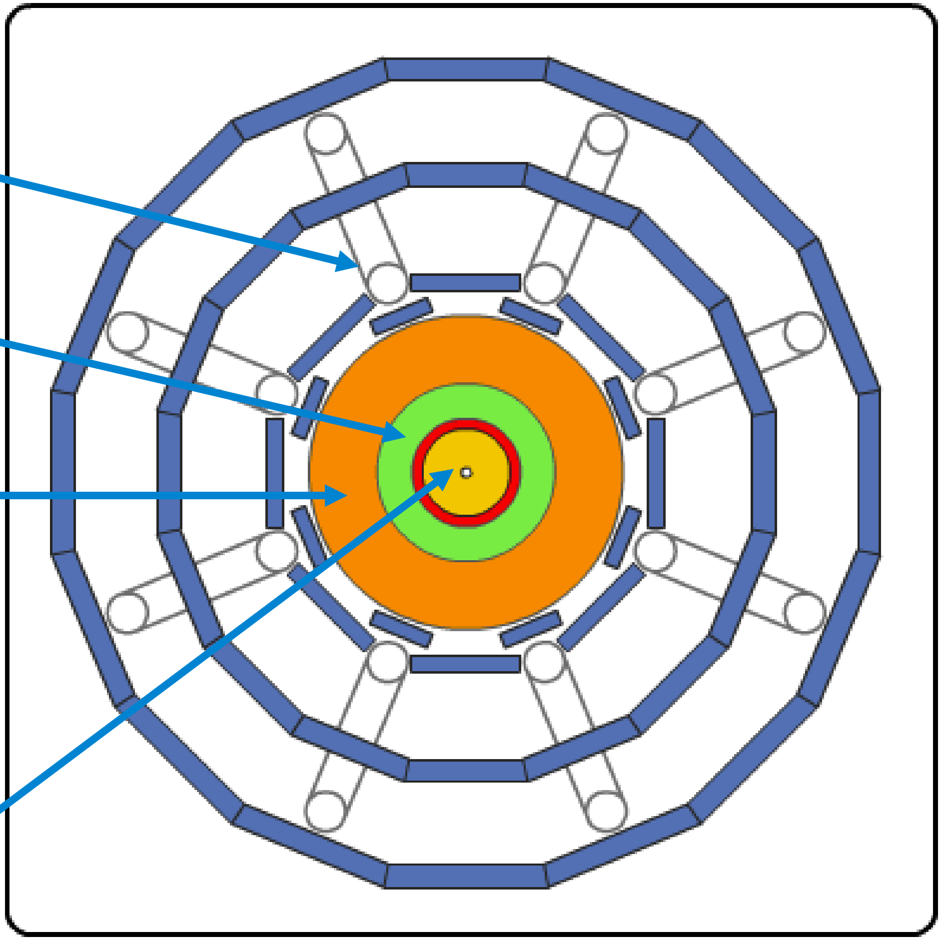
Material distribution in general purpose detectors

B field source

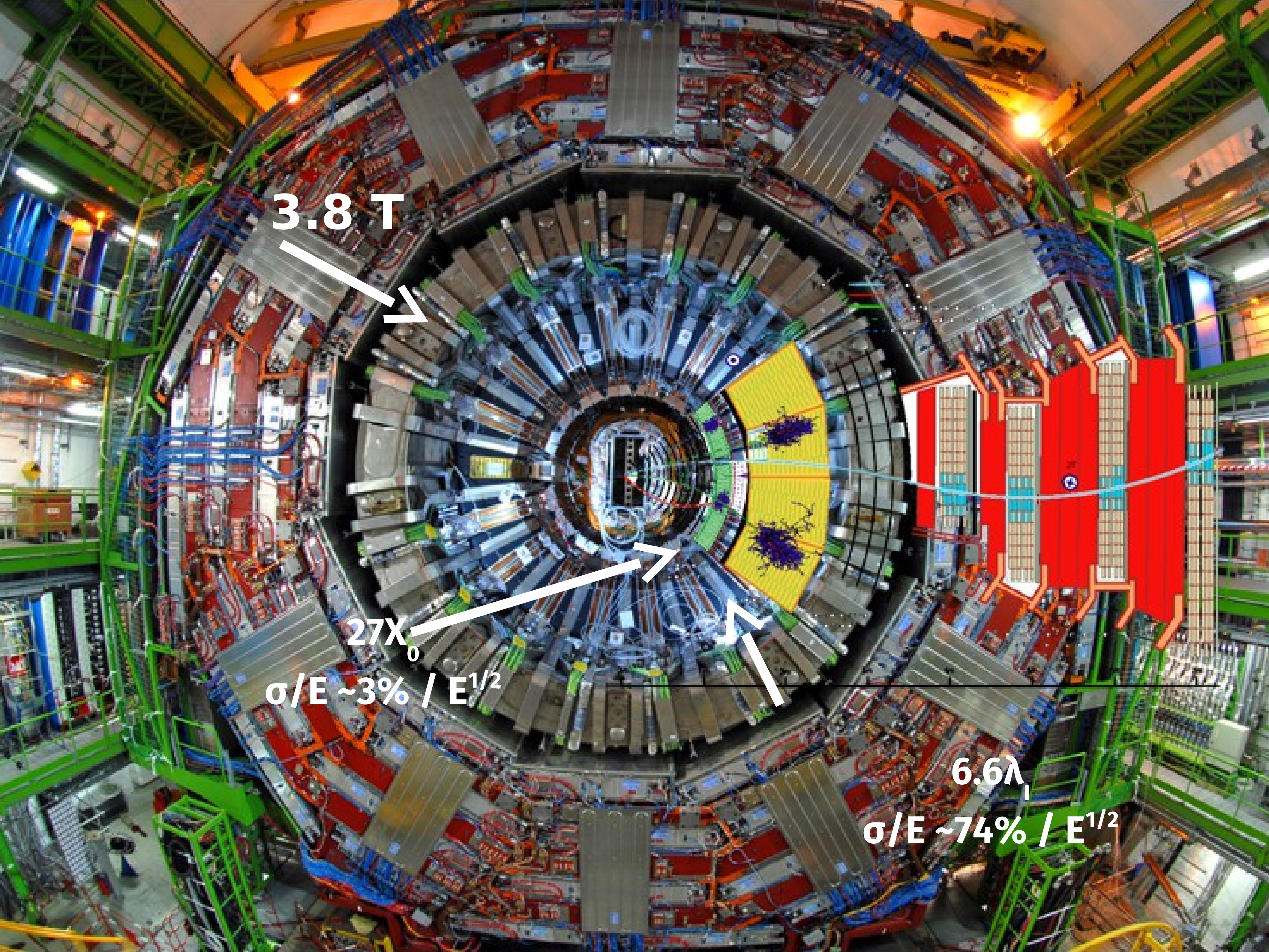
High-Z materials

Dense materials (e.g. Iron, Copper, Brass, Stainless Steel, Uranium)

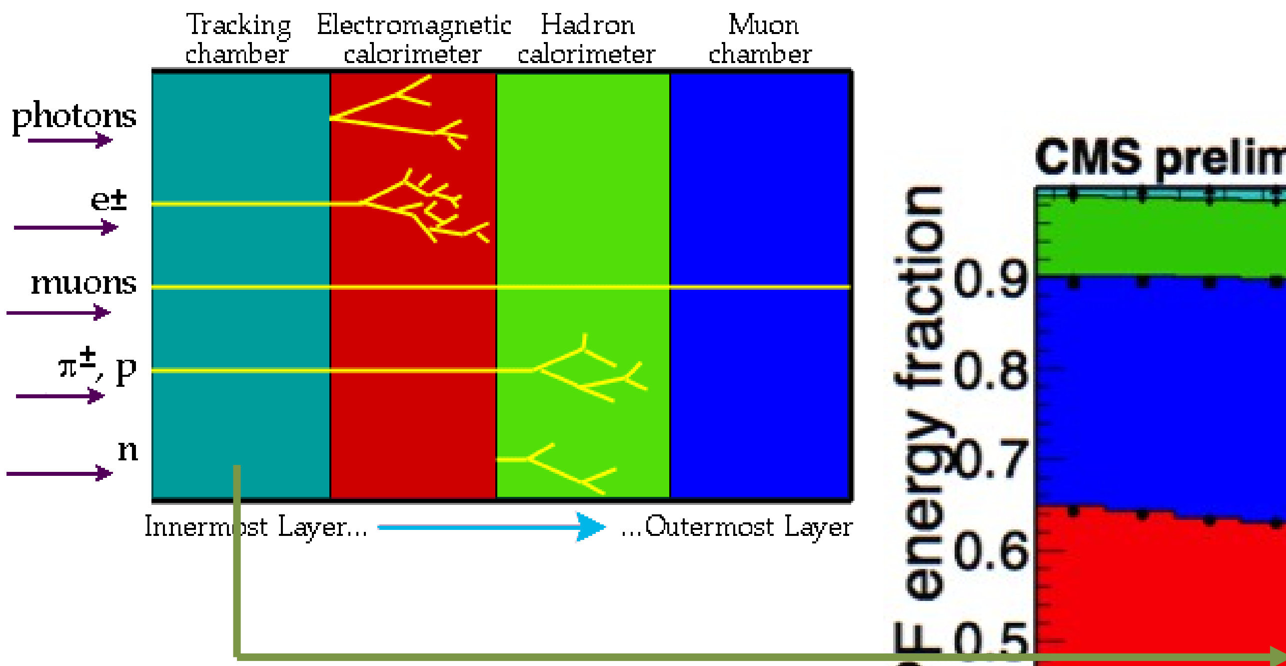
Lightweight materials (Si, gaseous)



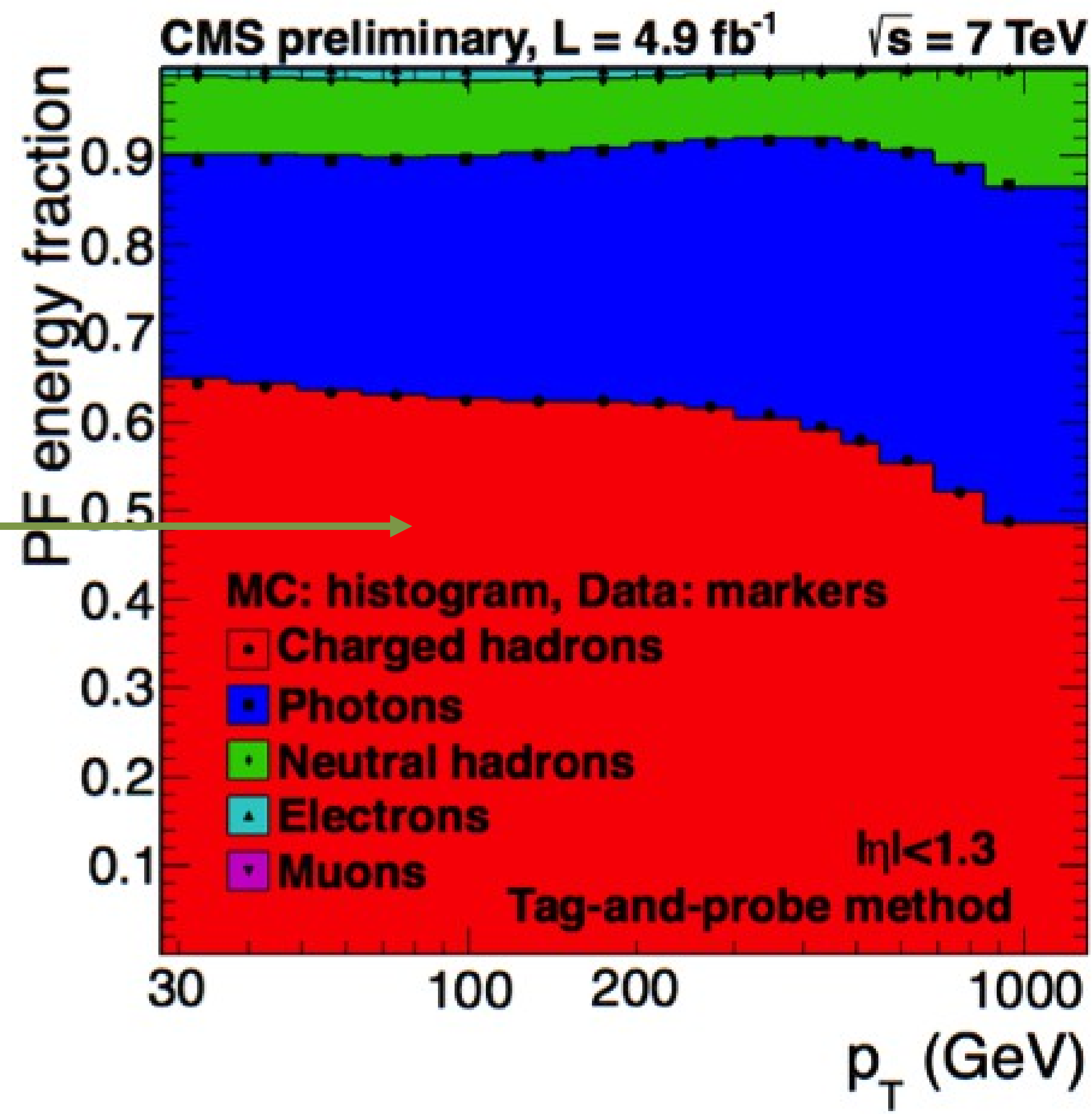
it's a challenge to fit it all within volume
trade-off between best energy resolution and particle identification


3.8 T
$27X_0$
$\sigma/E \sim 3\% / E^{1/2}$
$6.6\lambda_I$
$\sigma/E \sim 74\% / E^{1/2}$

Particle flow



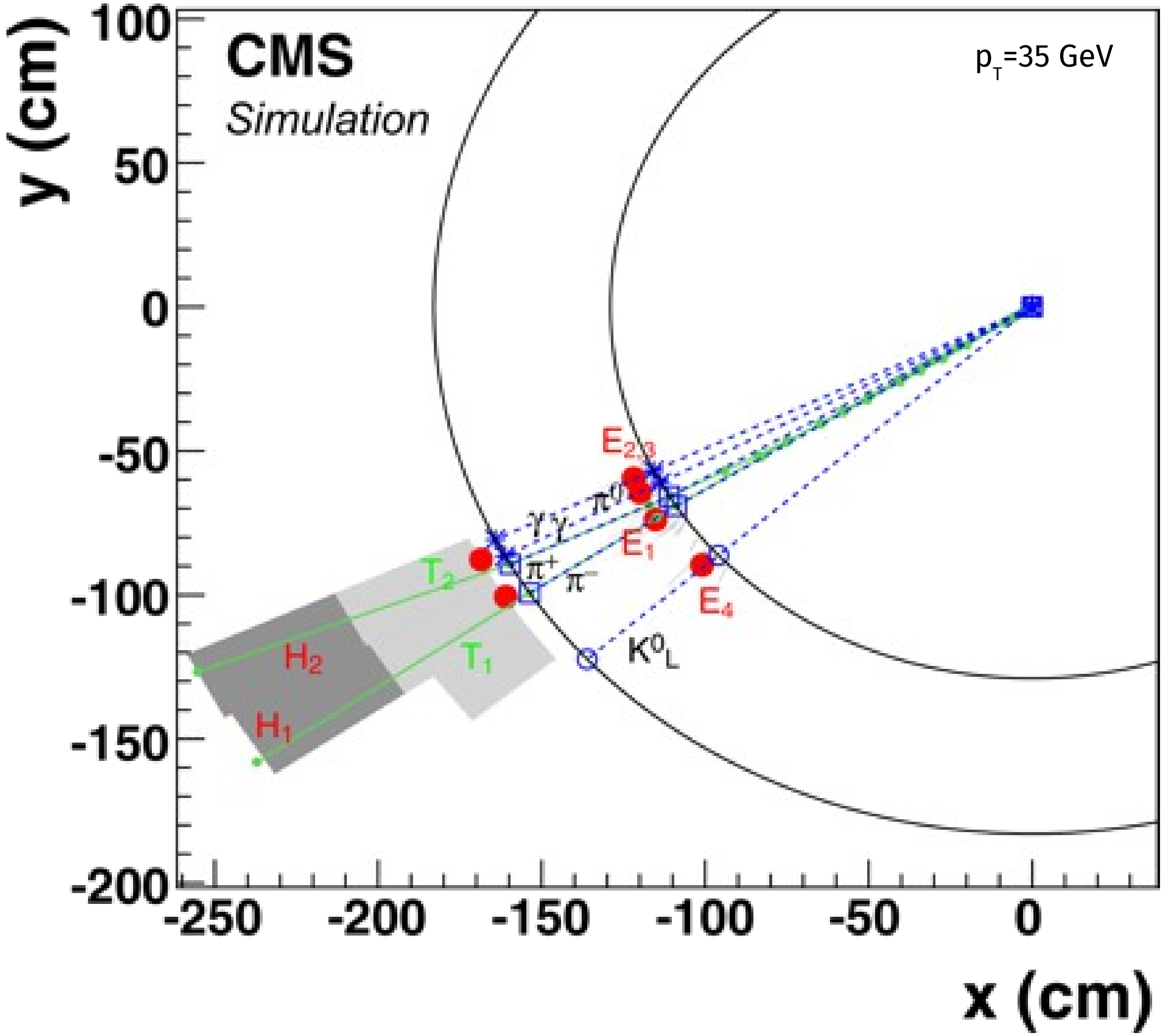
>60% of the energy of a jet may be reconstructed at the level of the tracker



Example: a jet of 5 particles

Reconstruction starts in the tracker

- Start from well reconstructed tracks, use remaining hits for others
- but that accounts only for 2/3 particles in this jet

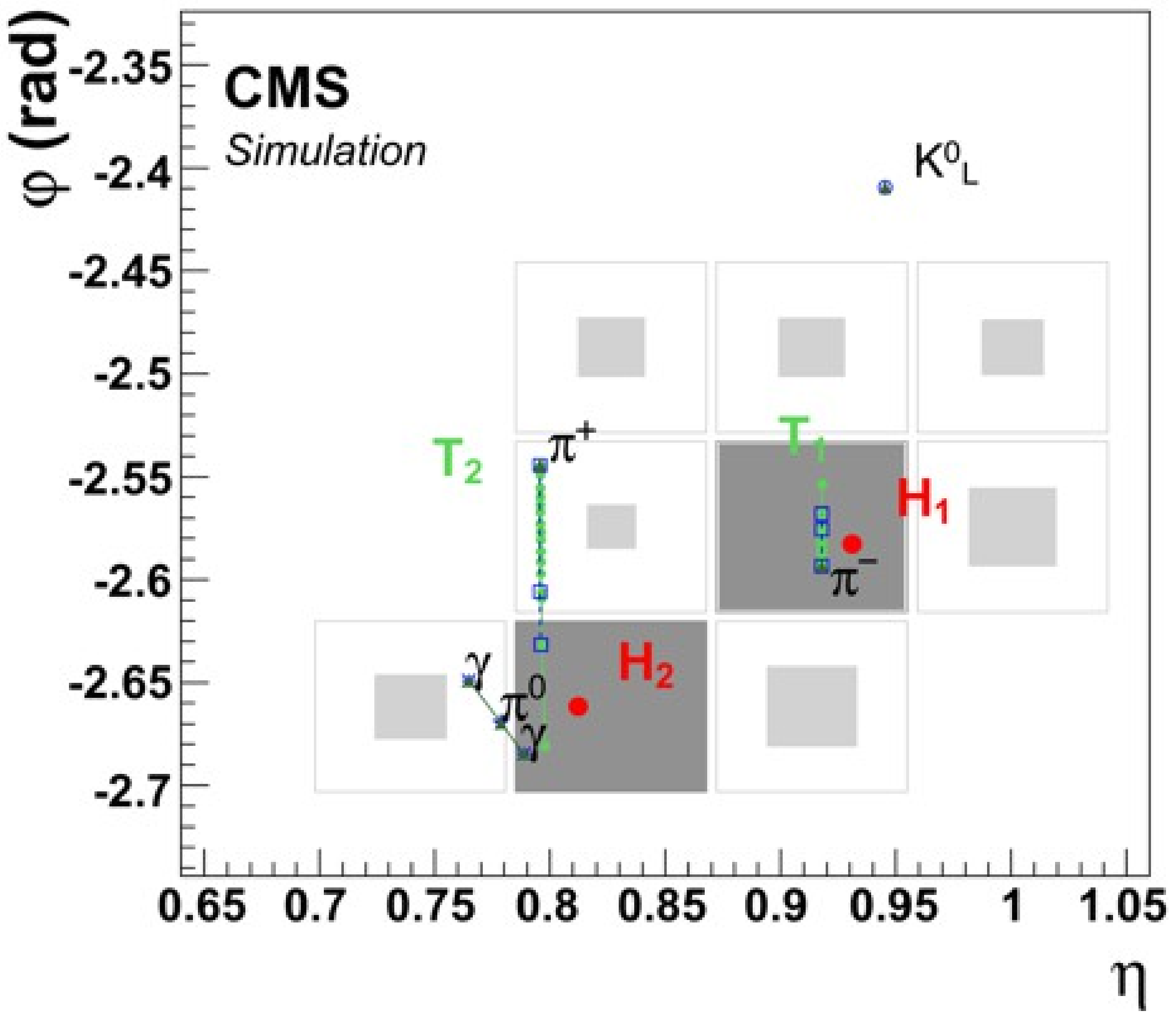


Example: a jet of 5 particles

Coarse granularity in the calorimeters (here hadronic)

Find local energy maxima and connect to neighbors

Determine energy sharing iteratively balancing with tracks

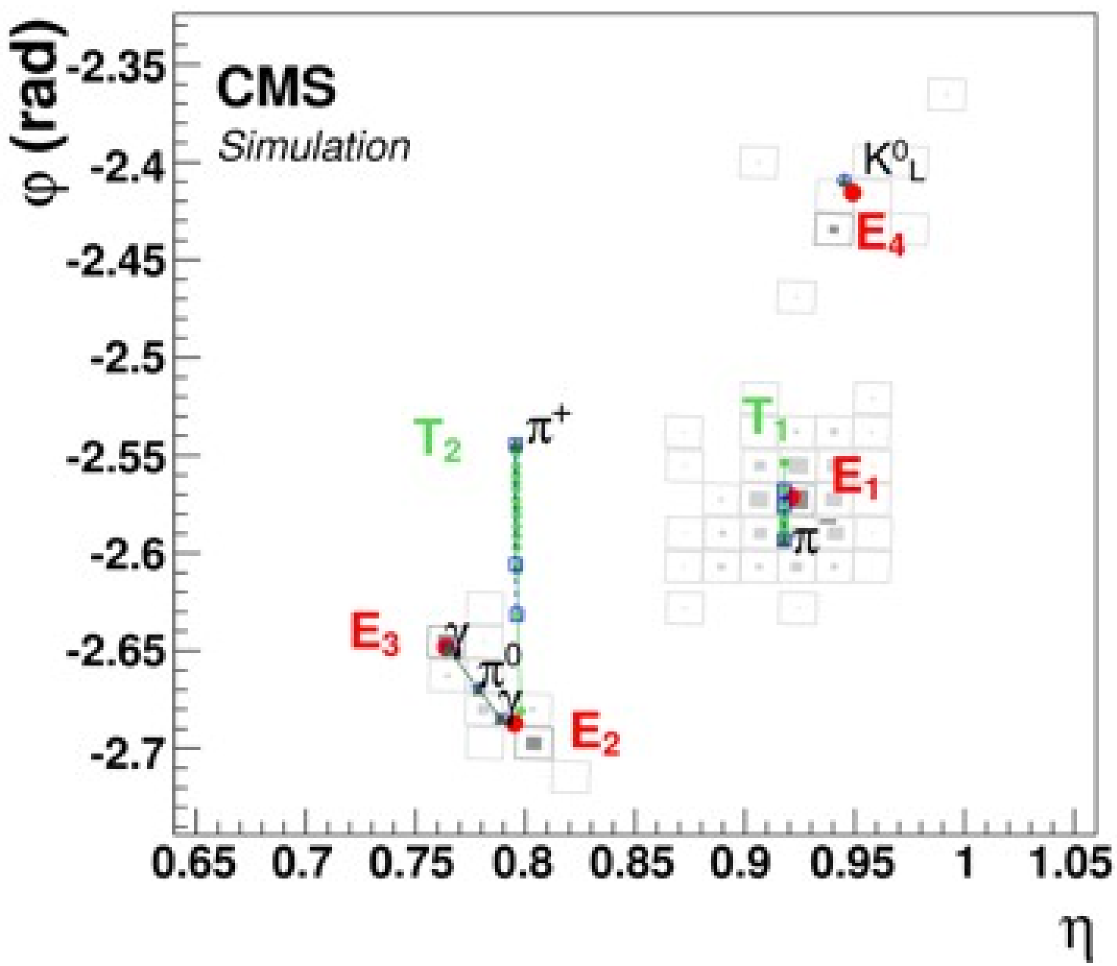


Example: a jet of 5 particles

The electromagnetic calorimeter makes finer measurements ($\Delta\phi$,$\Delta\eta$~0.02)

Use to refine entry point in calorimeter, link to tracks and balance energy

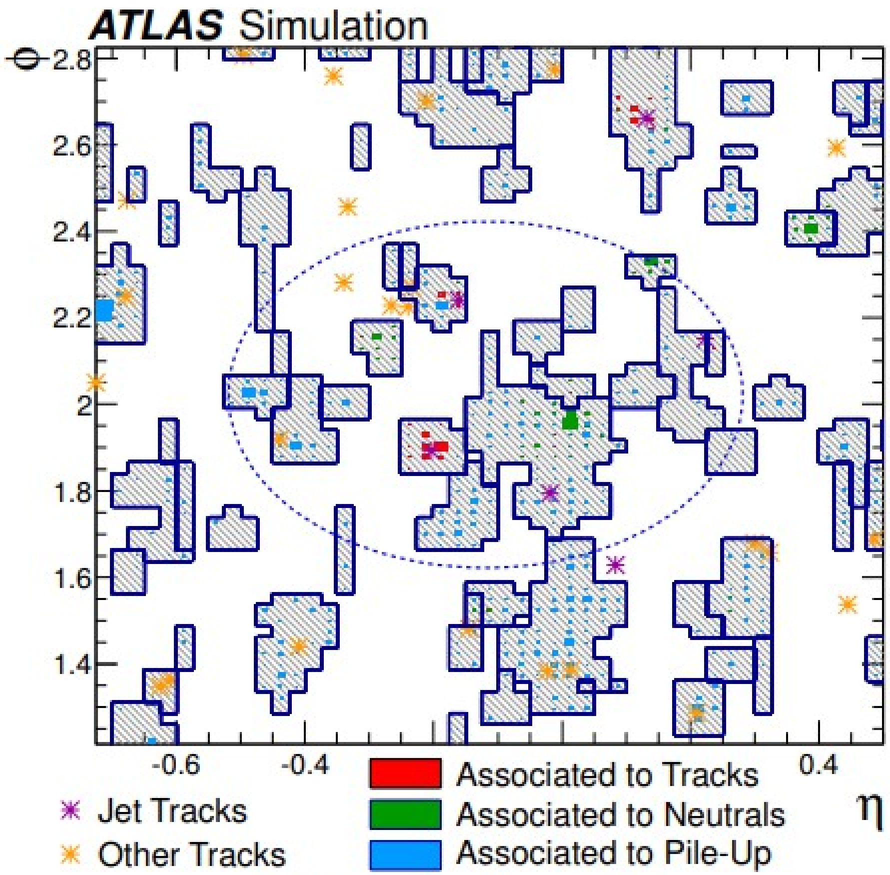
If energy can't be tracks ⇨ create photons and neutral hadron candidates



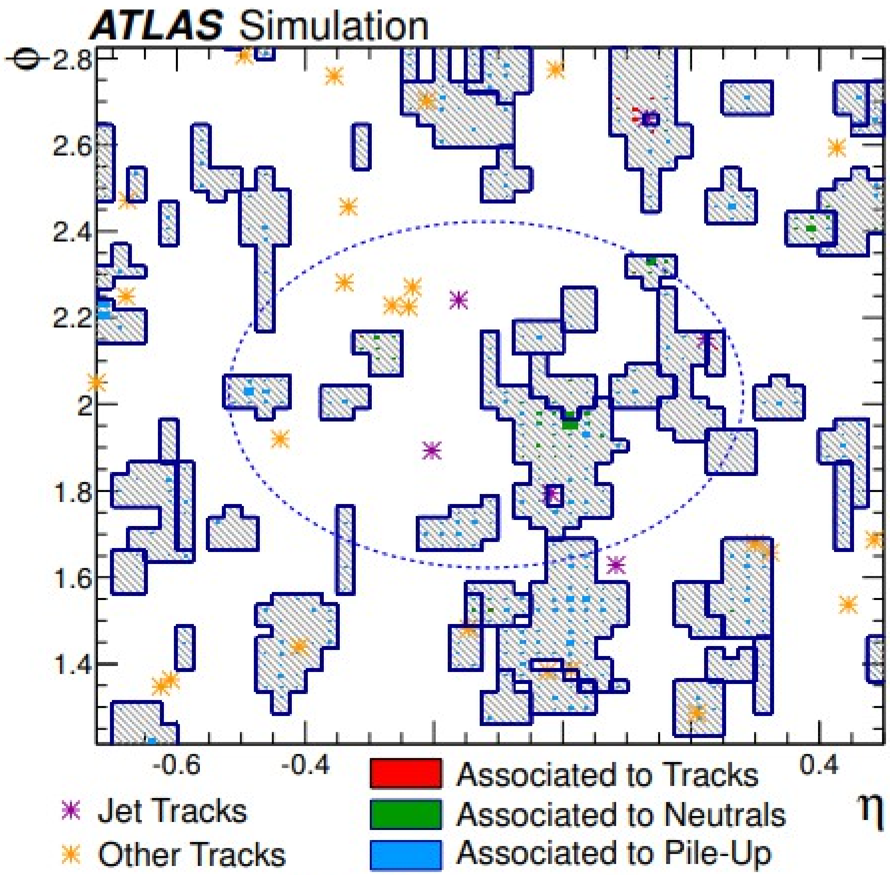
Example with pileup

Noise, pileup complicates the procedure and particle flow may benefits from cleaning

- Using tracks associated only to the primary vertex
- Removing calorimetric energy deposits/clusters compatible with noise/pileup

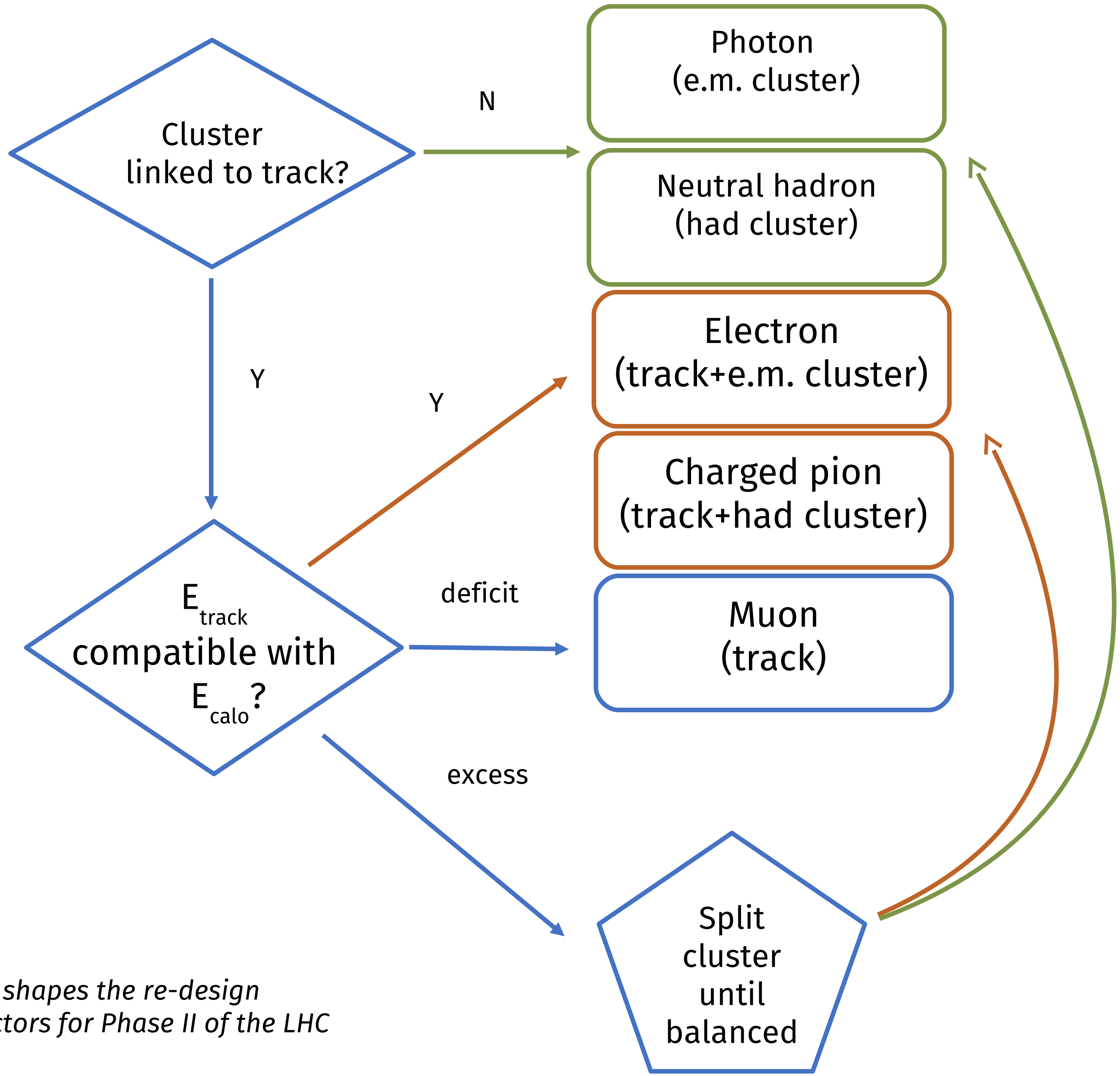


(c) Before subtraction, $\mu = 40$.



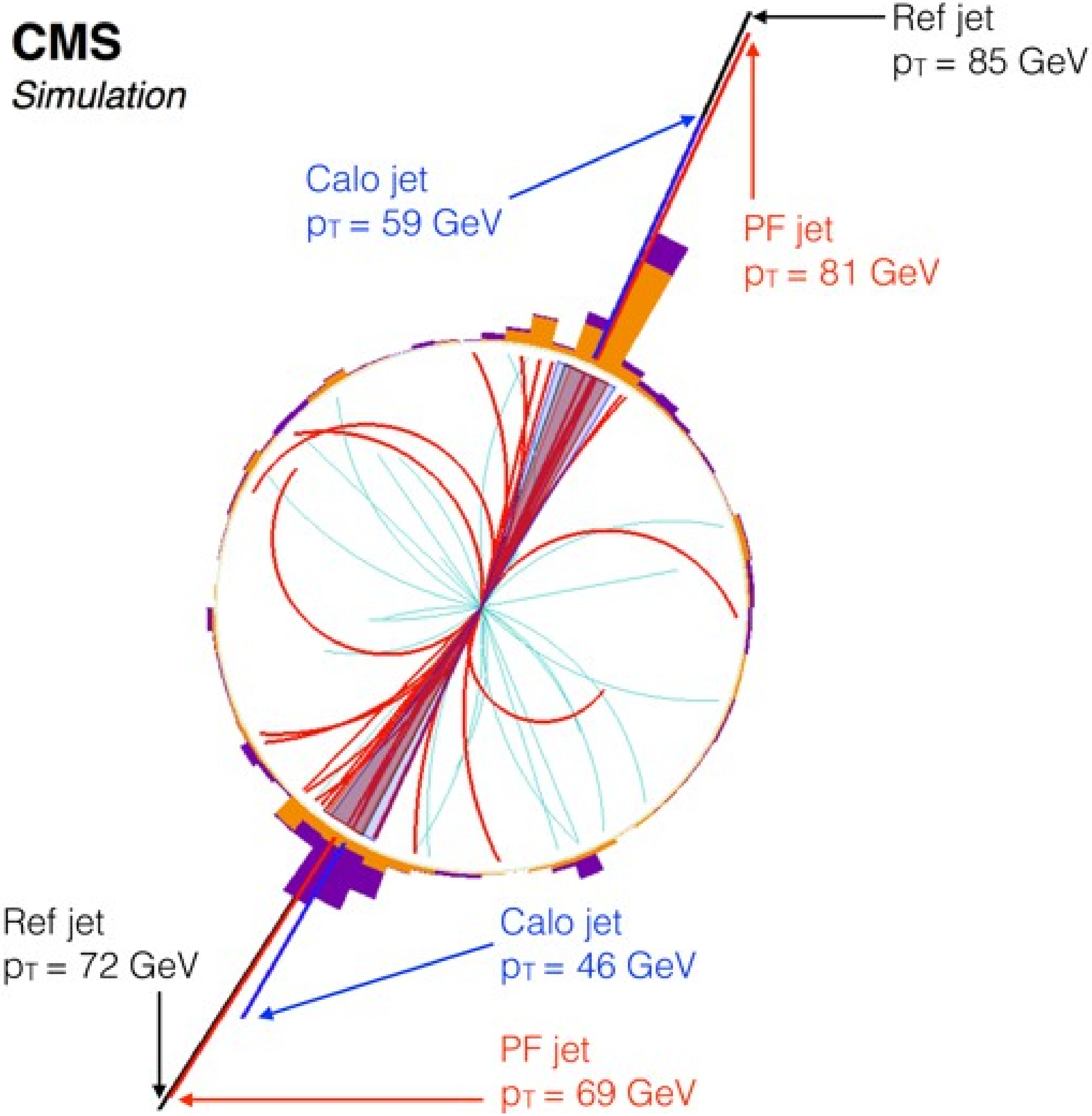
(d) After subtraction, $\mu = 40$.

Particle flow algorithm is a reconstruction paradigm



it also shapes the re-design of the detectors for Phase II of the LHC

Particle flow algorithm is a reconstruction paradigm

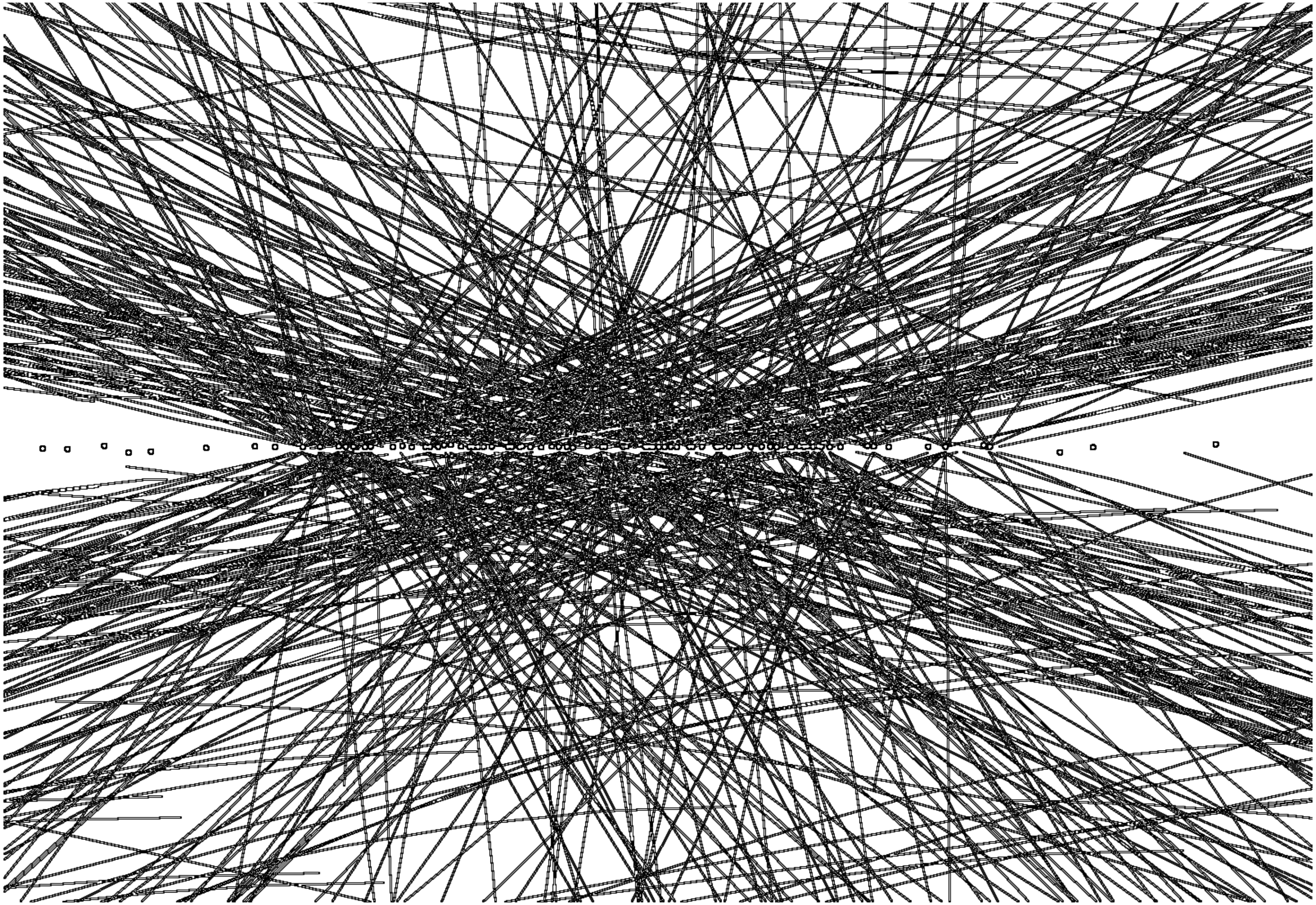


Connecting the dots: tracking

Why?

- Identify the vertex from the hard interaction

  ...but also secondary vertices from long lived particles



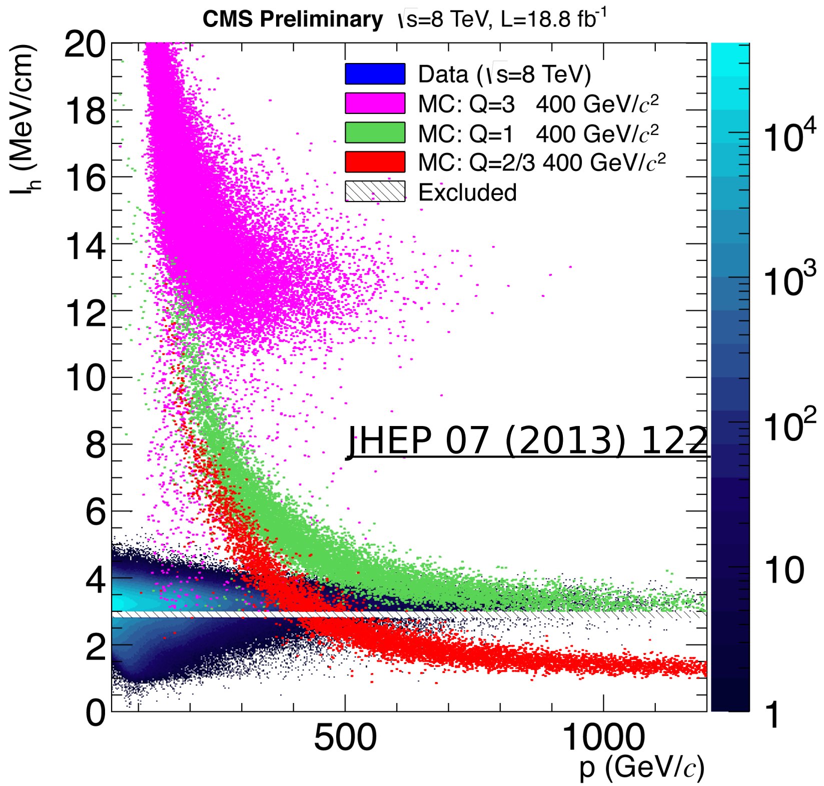
Why?

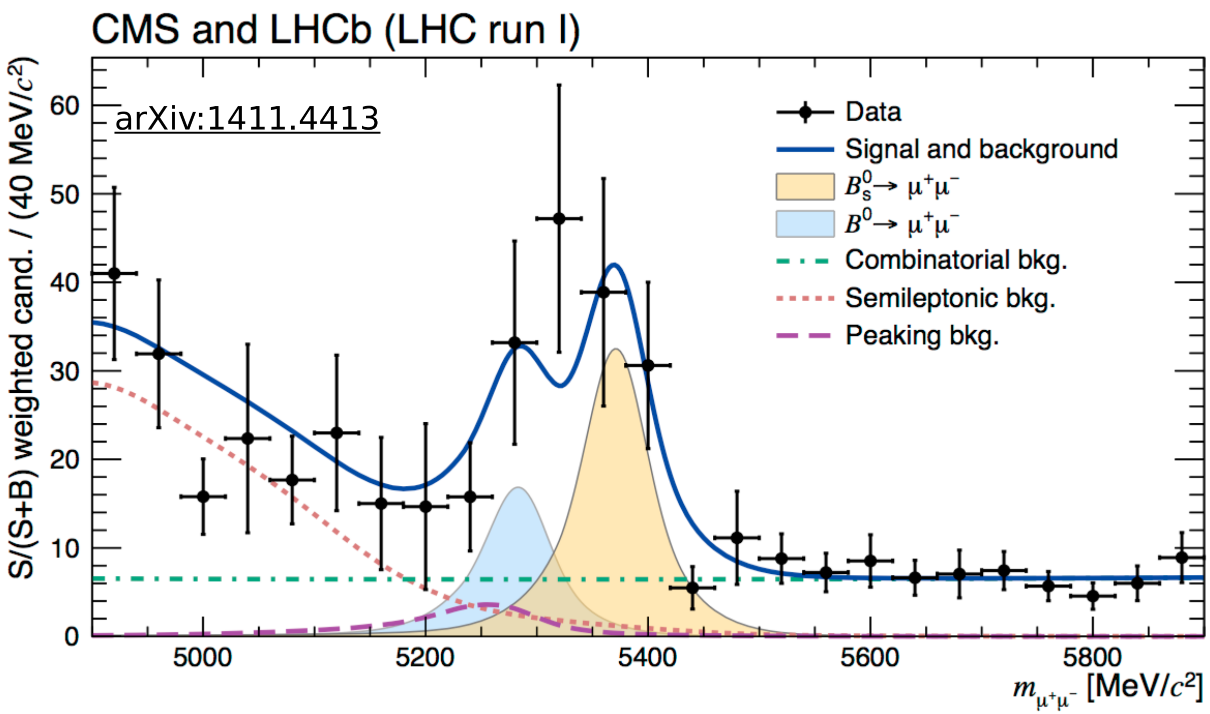
- Identify the vertex from the hard interaction

  ...but also secondary vertices from long lived particles

- Measure particle trajectories

  momentum (p), energy loss (dE/dx), link to coarser calorimeters and muon chambers

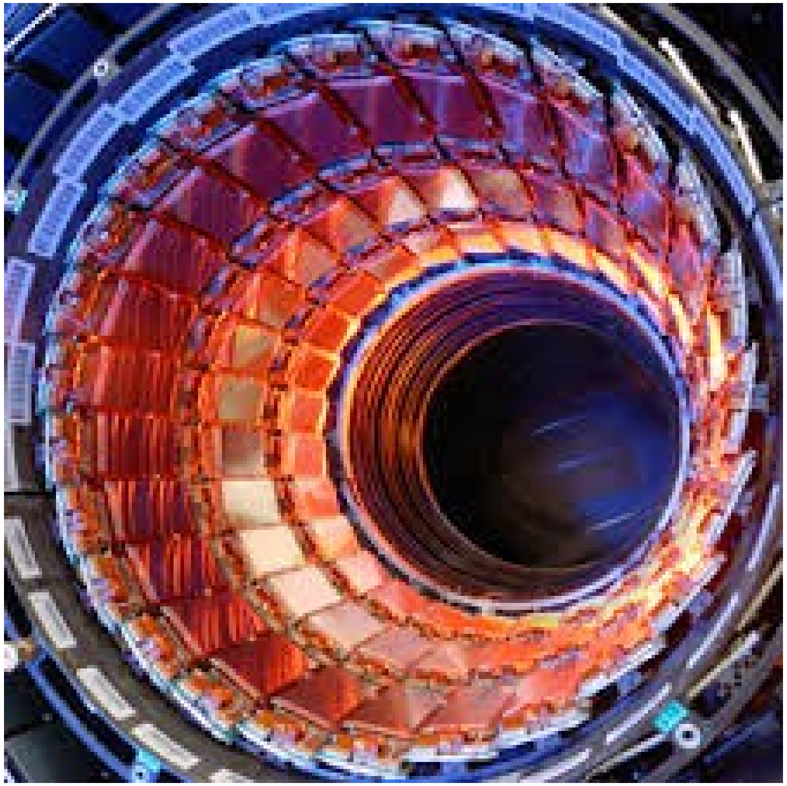


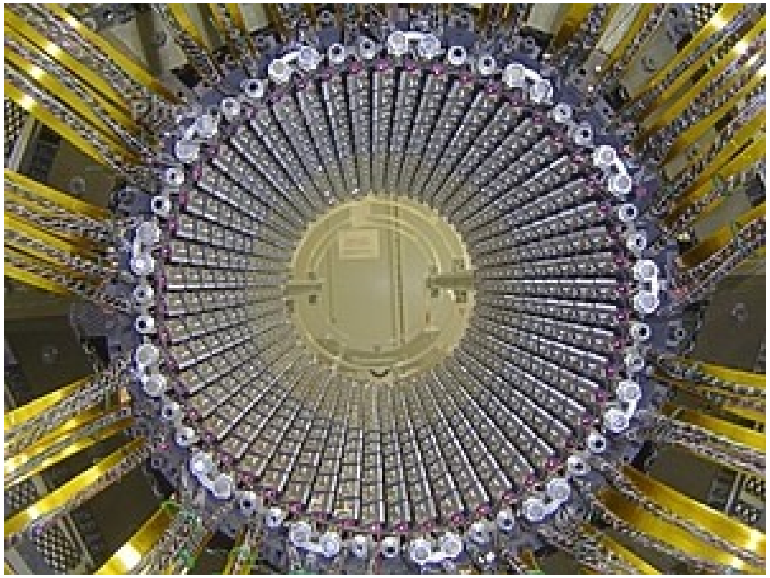


With what?

Solid state detectors

- Ge, Si, Diamond,...
- pixels and strips

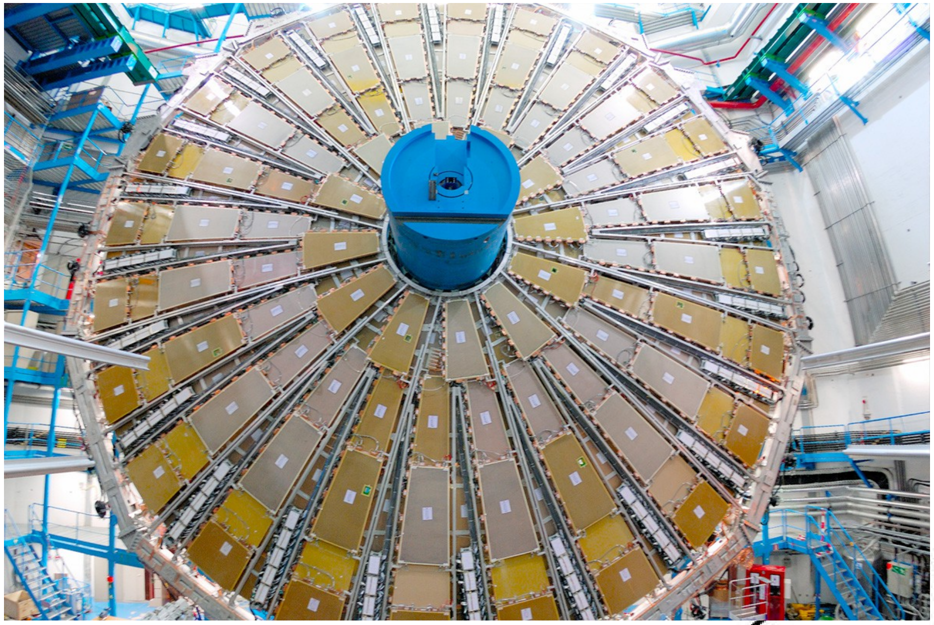


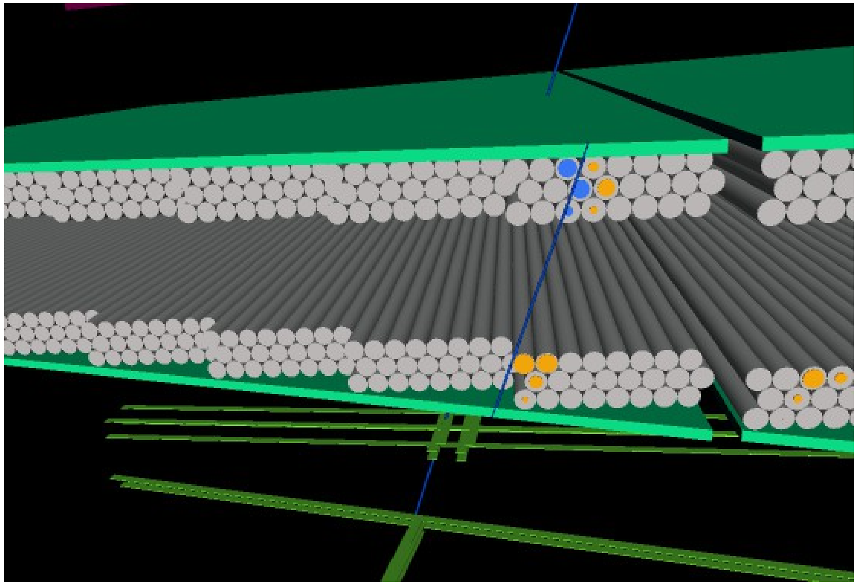


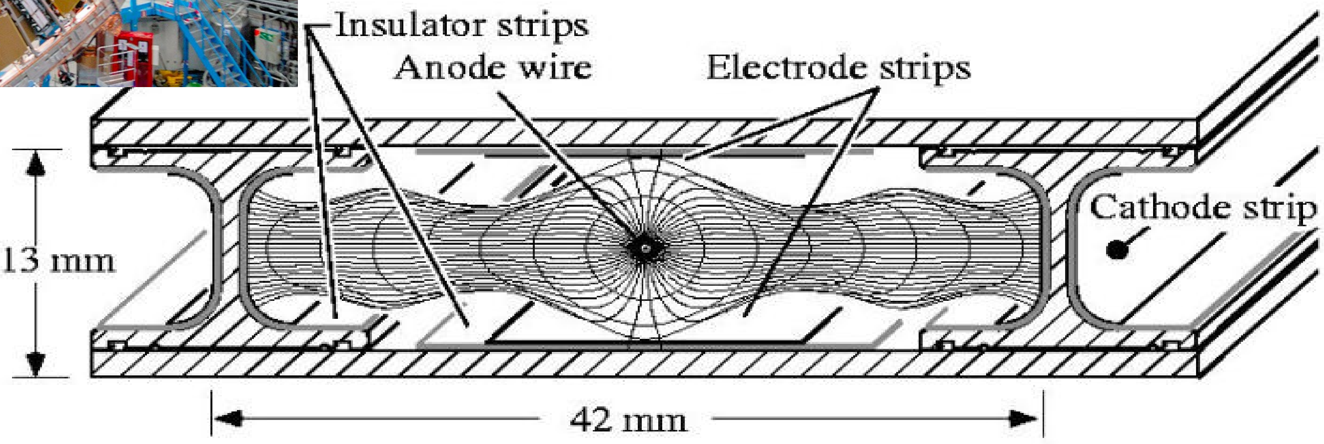
With what?

Gaseous detectors

- drift tubes, resistive plate chambers, cathode strip chambers, gas electron multipliers, ...
- usually for outer tracking



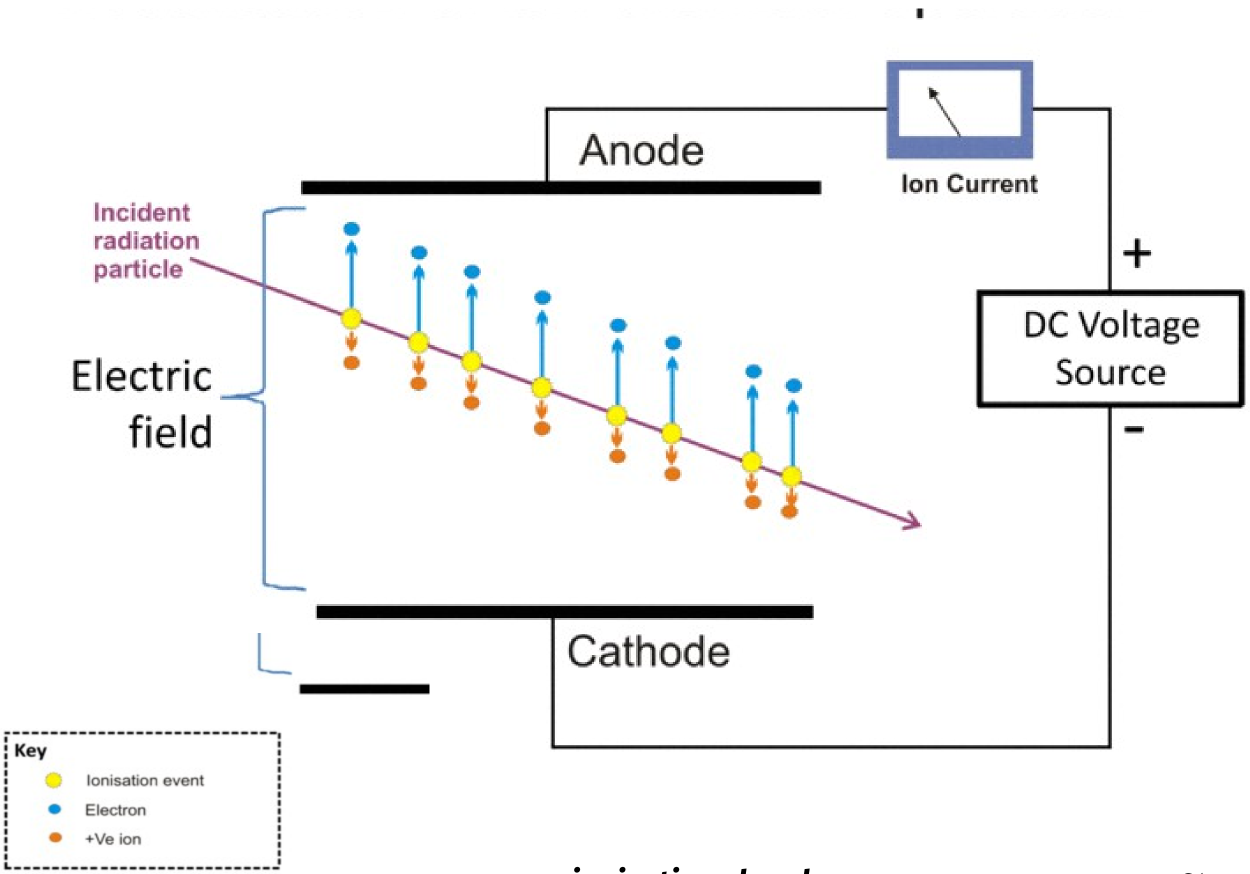




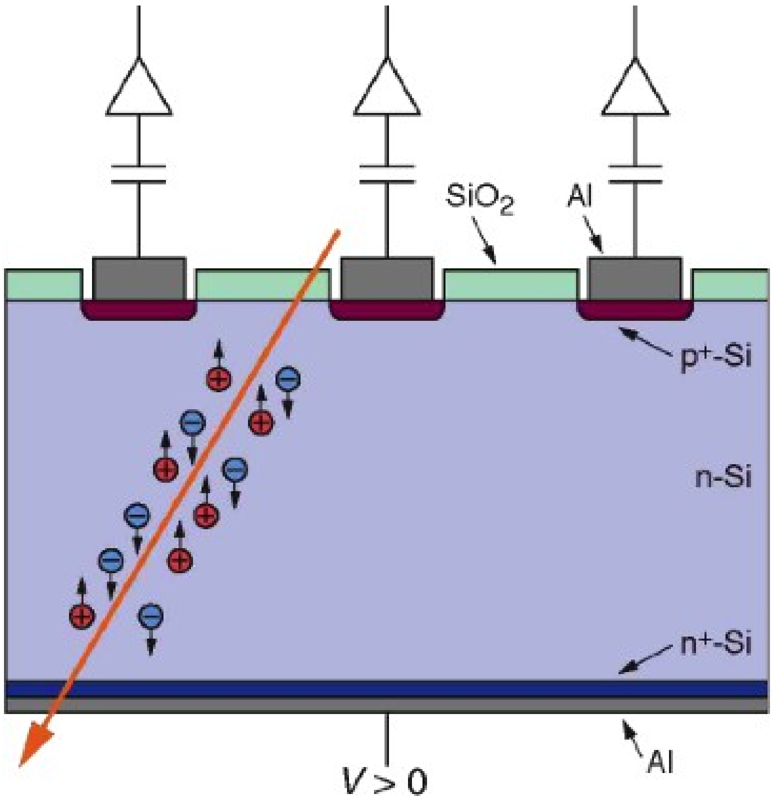
How?

While transversing a medium a charged particle leaves an ionization trace

- create depletion zone in between electrodes: gaseous, liquid or solid-state (semi-conductor)
- ionization charges drift towards electrodes
- amplify electric charge signal and deduce position from signals collected in individual strips



ionization chamber ≈



Si strip detector

Gaseous versus solid state

In solid state detectors ionization energy converts in e-h pairs

- 10 times smaller with respect to gaseous-based ionization
- charge is increased → improved E resolution

	Gas		Solid state	
Density (g/cm^3)	Low	$C_2H_2F_4$	High	Si
Atomic number (Z)	Low	(~95% for CMS RPC)	Moderate	
Ionization energy (ε_I)	Moderate	30eV	Low	3.6eV
Signal speed	Moderate	10ns-10μs	Fast	<20ns

$$n = \frac{E_{loss}}{E_{eh}} \rightarrow \frac{\sigma_E}{E} \propto \frac{1}{\sqrt{n}} \propto \sqrt{\frac{E_{eh}}{E_{loss}}}$$

Gaseous versus solid state

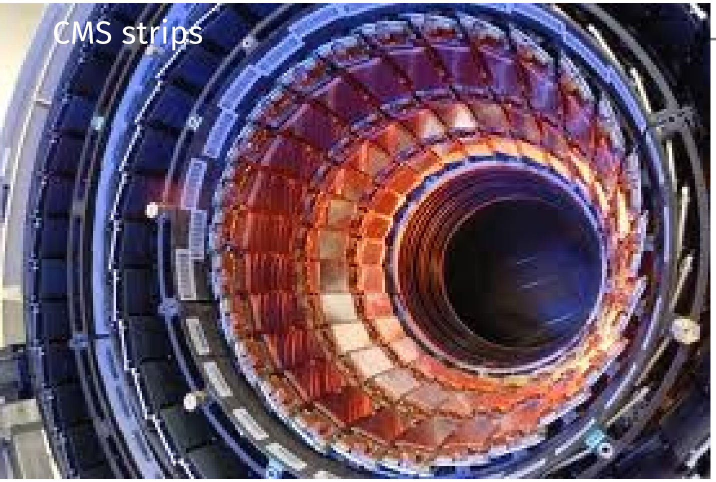
Higher density materials are used in solid state detectors

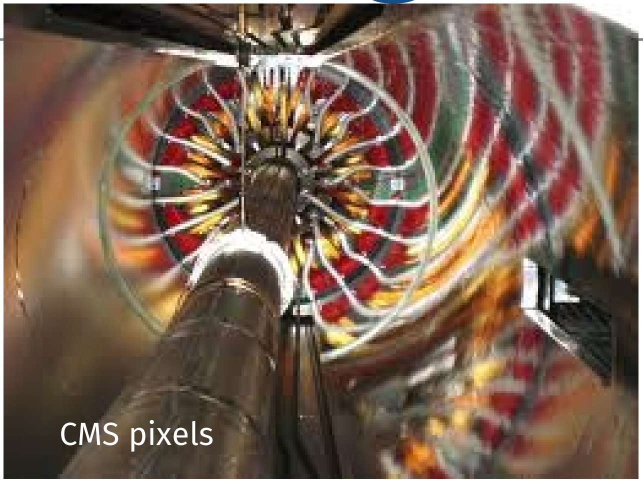
- charge collected is proportional to the thickness
- most probable value for Silicon

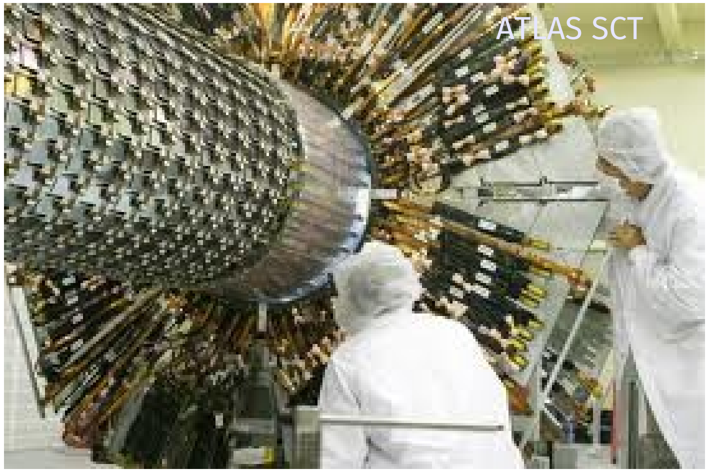
$$\frac{\Delta_p}{x} \sim 0.74 \cdot 3.876 \text{ MeV/cm} \rightarrow N_{eh} \sim \frac{23 \cdot 10^3}{300 \ \mu m}$$

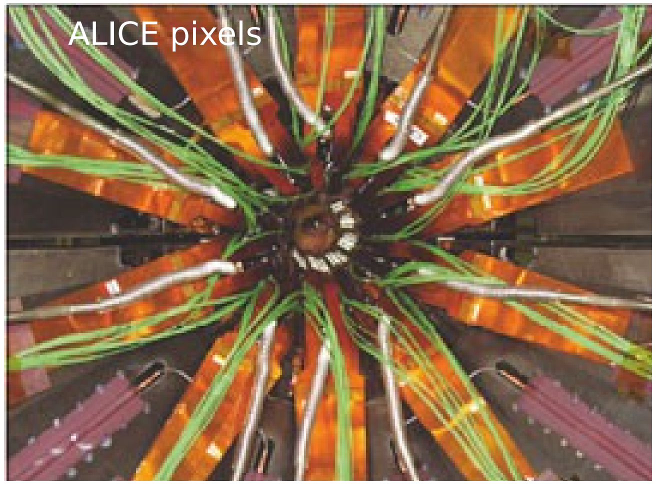
- excellent spatial resolution: short range for secondary electrons

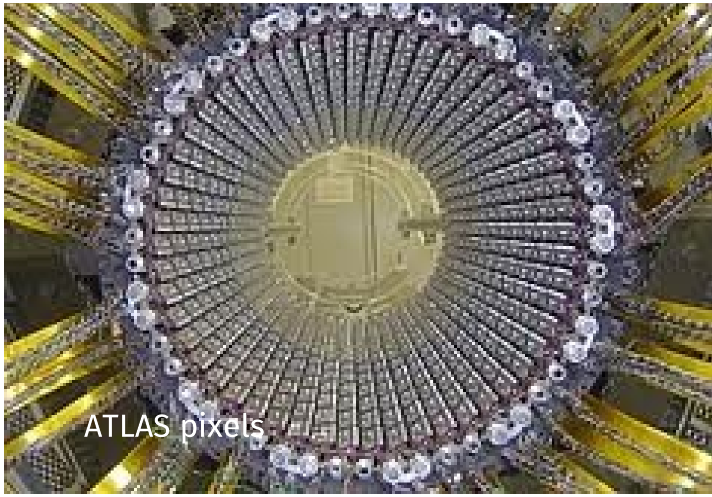
Inner tracking at the LHC

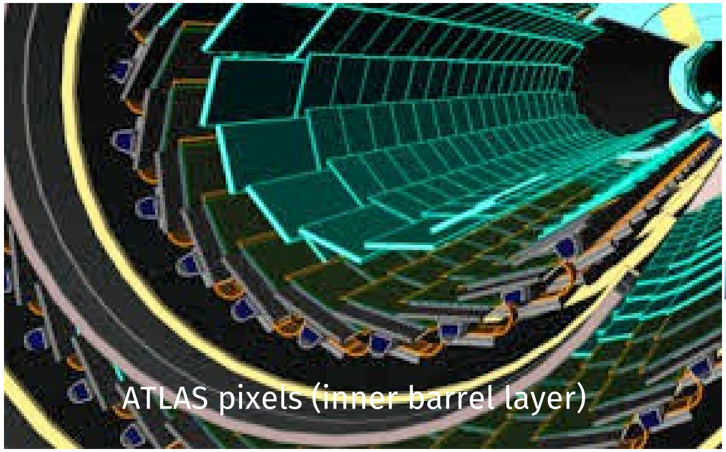


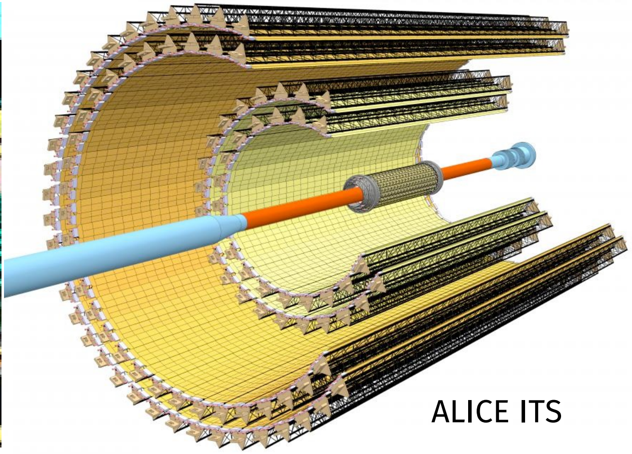




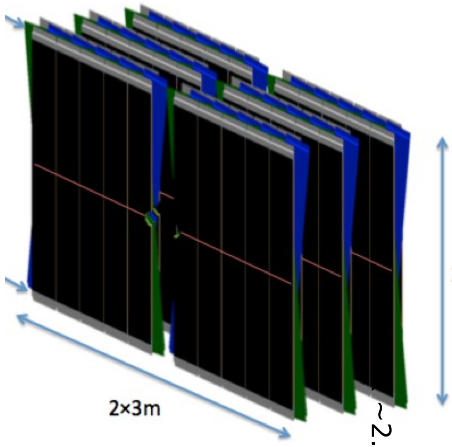




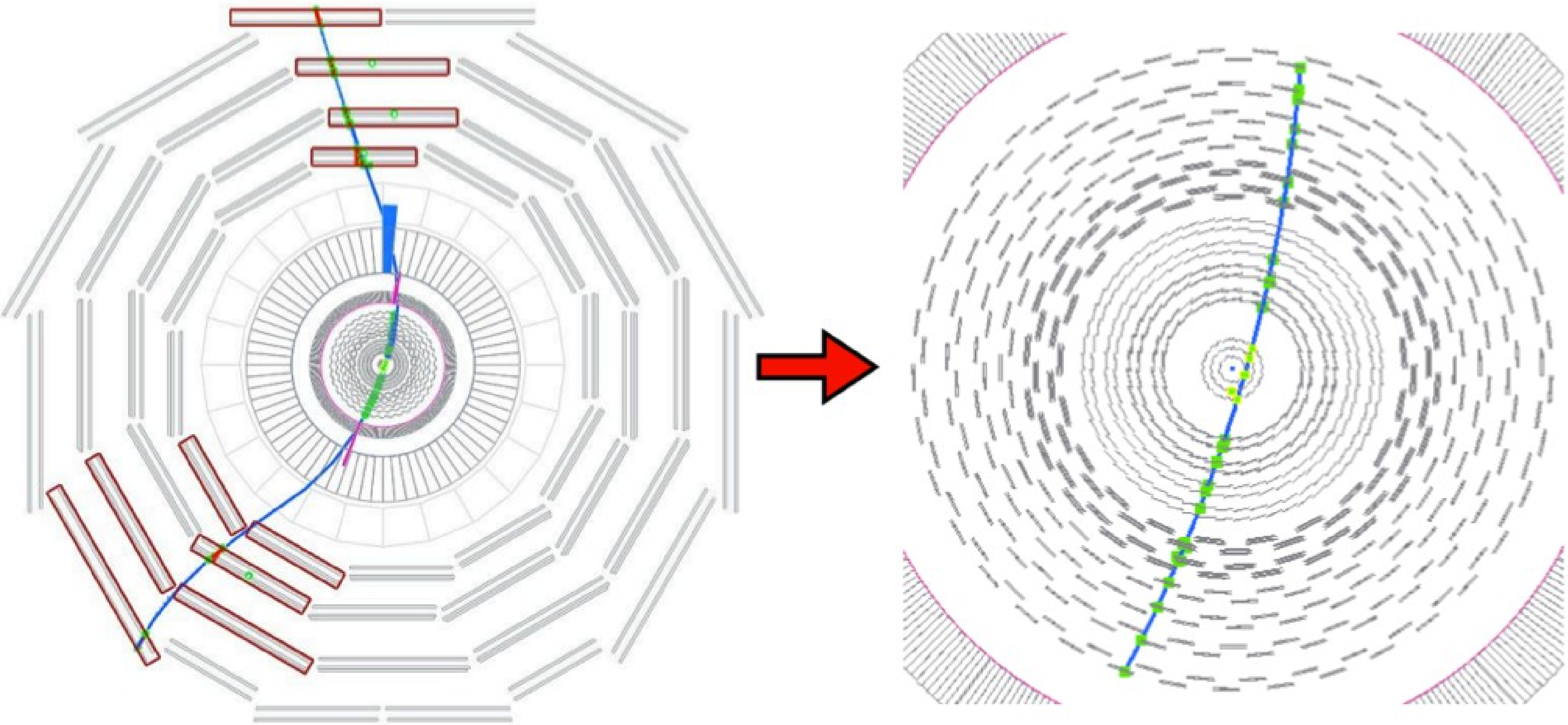




LHCb SciFi



Outer ⟷ inner tracking

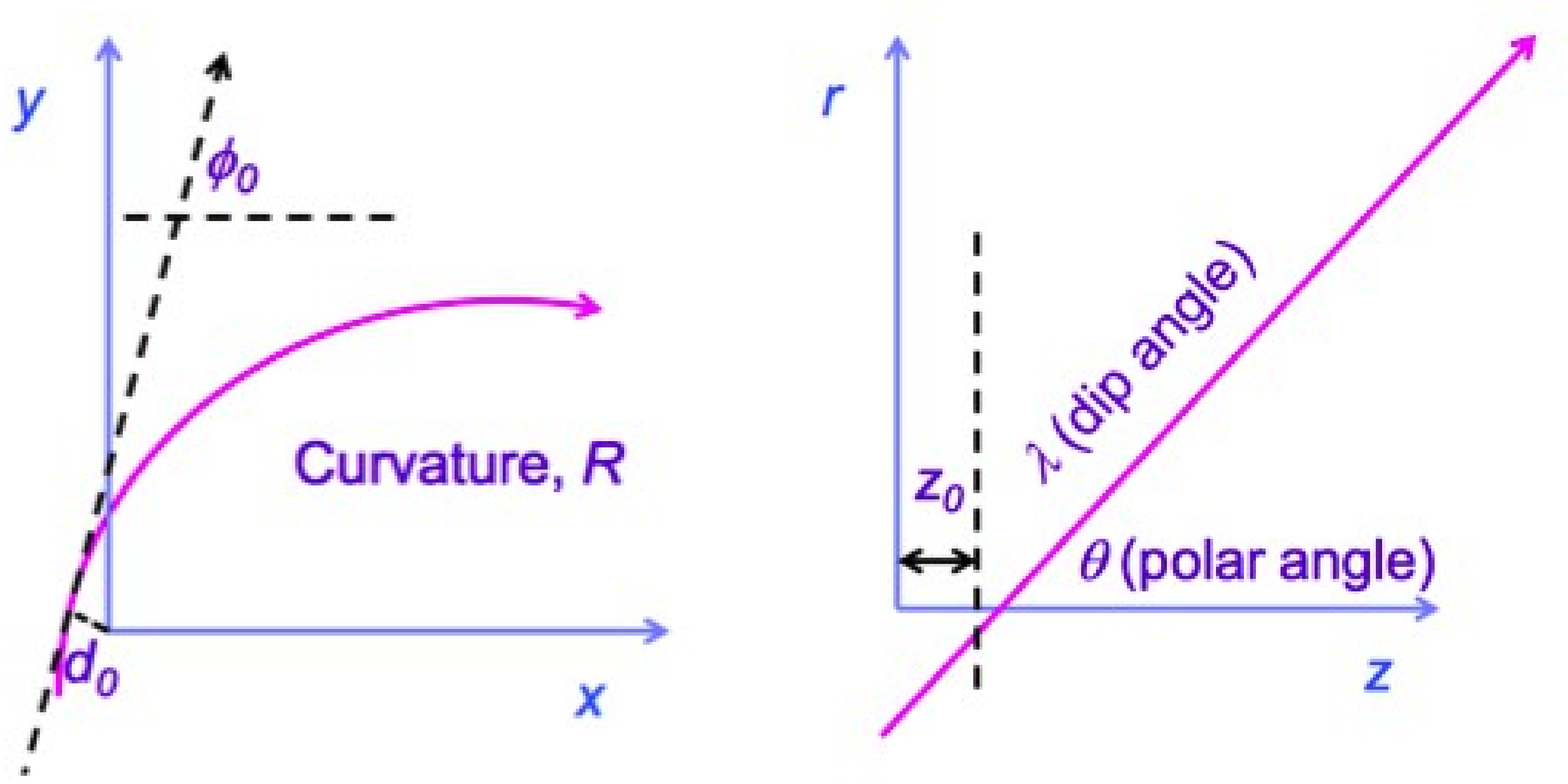


Coordinates for tracking

The LHC experiments use a uniform B field along the beam line (z-axis)

- trajectory of charged particles is an helix – radius R
- use transverse (xy) and longitudinal (rz) projections
- pseudo-rapidity: $\eta = -\ln \tan\frac{\theta}{2}$ transverse momentum: $p_{\mathrm{T}} = p\sin\theta = p/\cosh\eta$

Impact parameter is defined from distance of closest approach to primary vertex



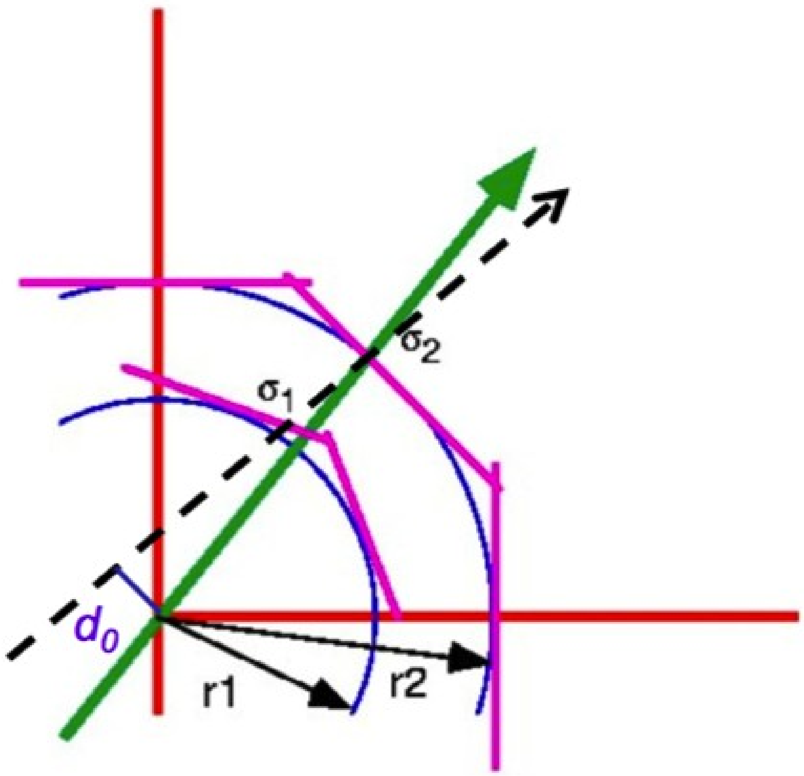
Impact parameter reconstruction

Depends on radii+space point precisions

For two layers we expect

$$\sigma_{d0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$$

- Improve with small r_1, large r_2
- Improves with better σ_i



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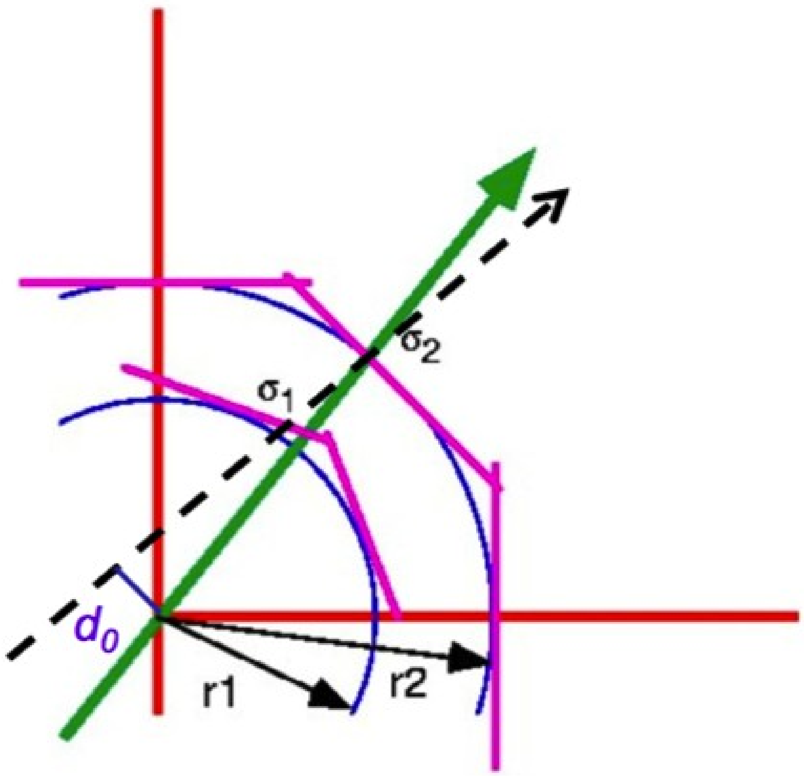

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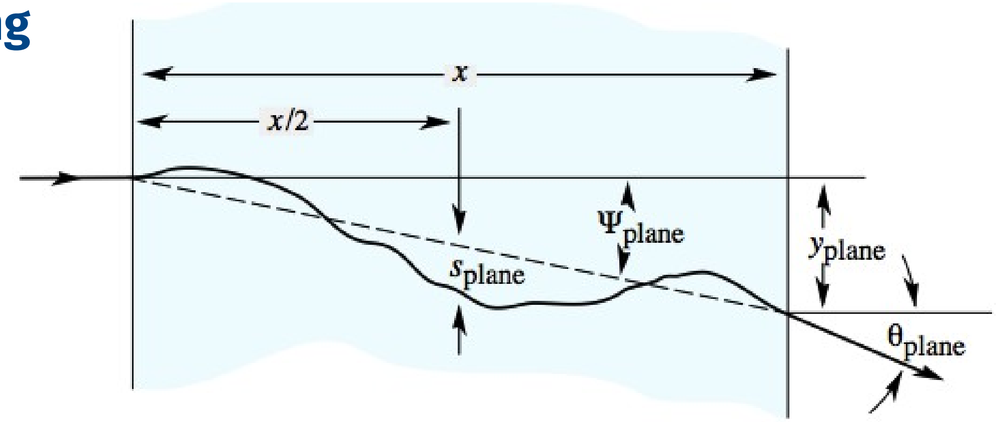
Precision is degraded by multiple scattering

- Gaussian approximation is valid
- Width given by

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

$$\sigma_{d0} \sim \theta_0$$

- extra degradation term for d_0



Resolution for the impact parameter

For a track with θ≠90⁰ we can write r → r/sinθ

By substitution in the formulas of the previous slide we have:

$$\sigma_{d_0} \sim \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \oplus \frac{r}{p\sin^{3/2}\theta} \rightarrow a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

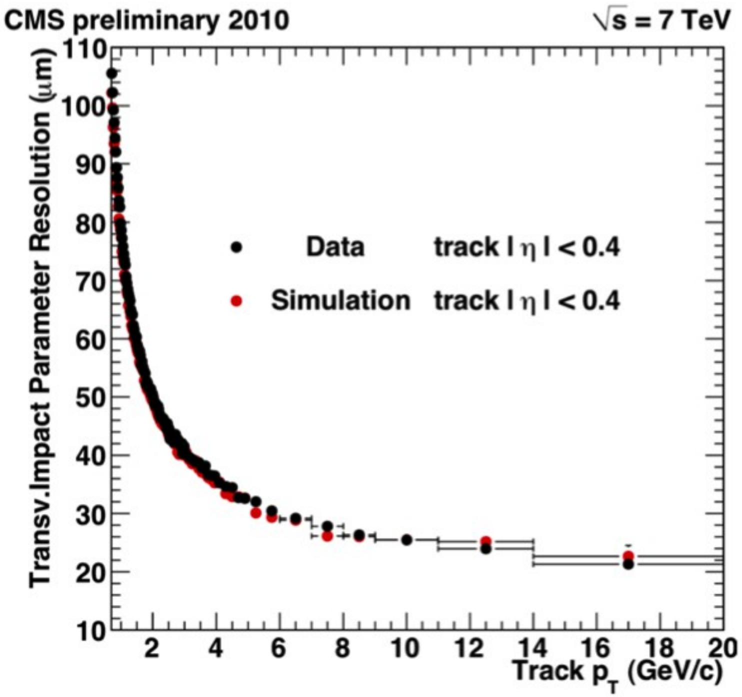
geometry-dependent   Material- and p_T-dependent

Typical resolution:

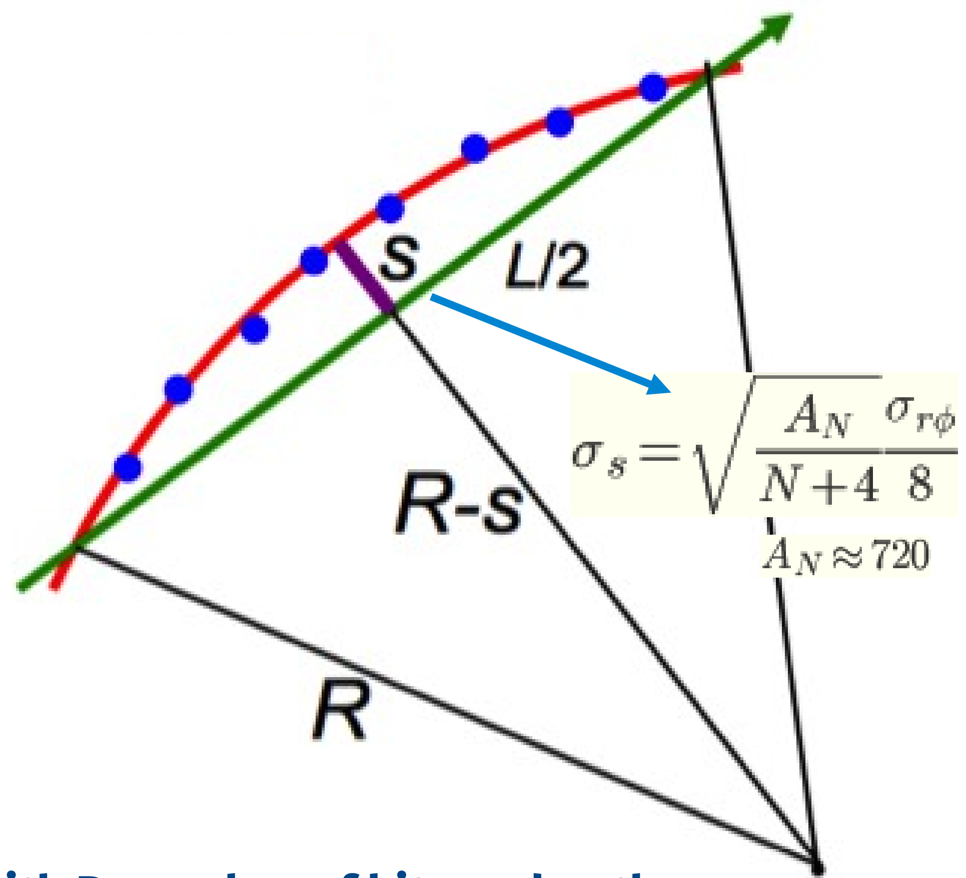
- 100 μm @ 1 GeV   20 μm @ 20 GeV

Typical lifetimes (rest frame)

- B ~ 500μm D_0 ~120μm τ ~ 87 μm



Momentum measurement



Circular motion under uniform B-field

$$p_T[\text{GeV}] = 0.3 \times q \times B[\text{T}] \times R[\text{m}]$$

Typically measure the sagitta

- deviation to straight line relates to R by

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

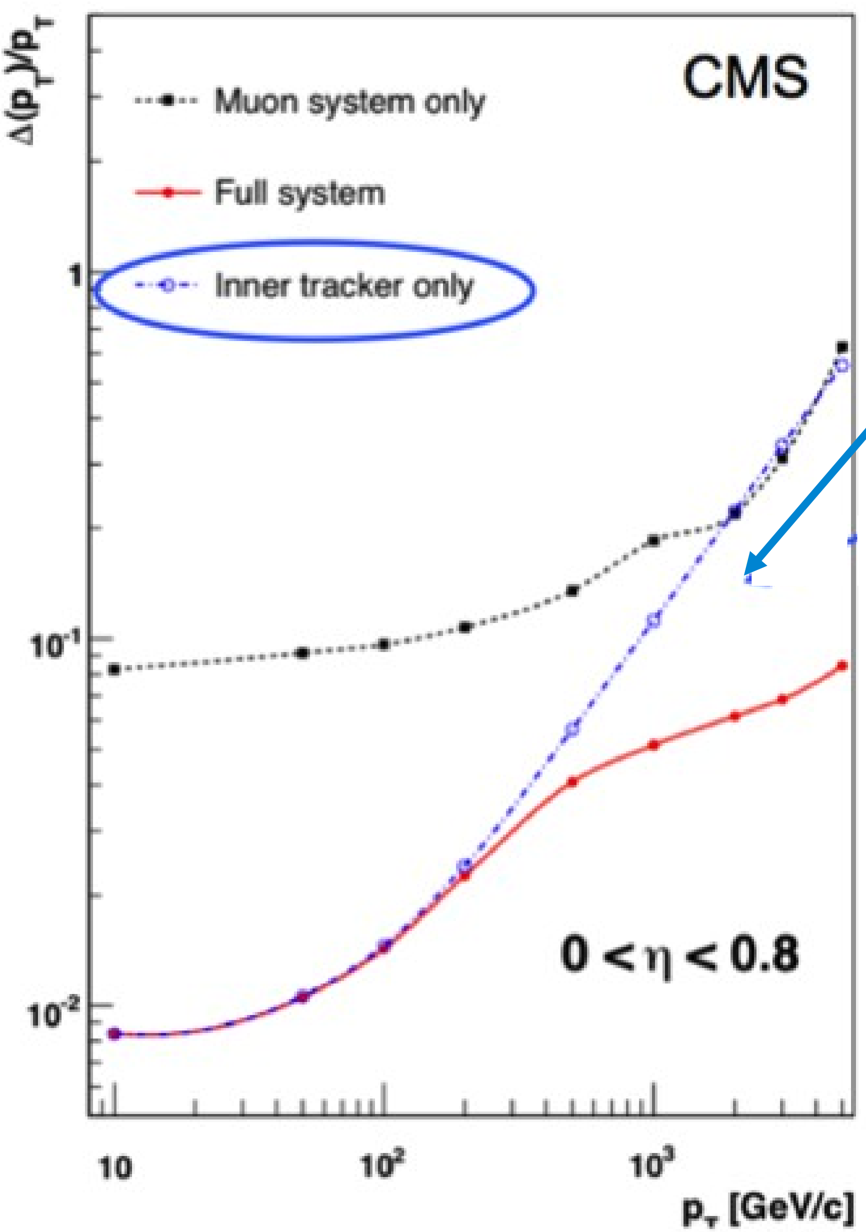
Uncertainty in p_T measurement improves with B, number of hits and path

$$\frac{\sigma_{p_T}}{p_T} = \frac{8 p_T}{0.3 B L^2} \sigma_s$$

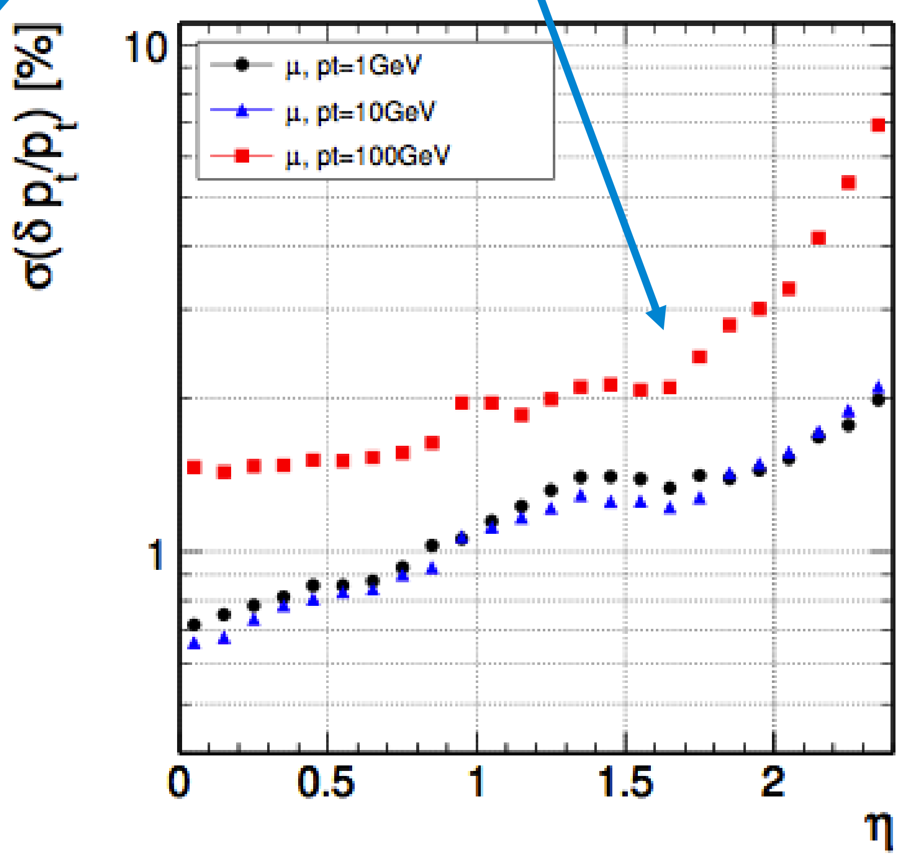
Multiple scattering introduces, again extra degradation

$$\frac{\sigma_{p_T}}{p_T} \sim a p_T \oplus \frac{b}{\sin^{1/2}\theta}$$

Momentum resolution



$$\frac{\sigma_{p_T}}{p_T} \sim a p_T \oplus \frac{b}{\sin^{1/2}\theta}$$



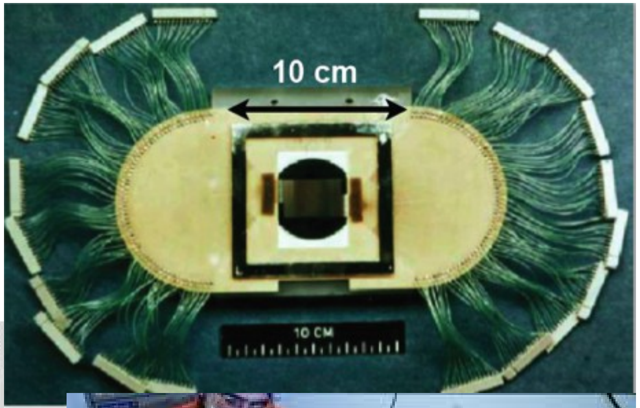
Si-based detectors

Usage of Si-based trackers for HEP

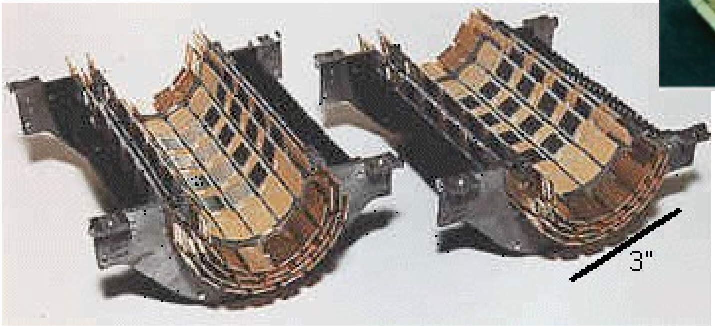
Kemmer, 1979 transferred Si-technology for electrons to detector - NIM 169(1980)499

NA11/32 spectrometer at CERN →

- 6 planes Si-Strip, <2k channels
- Resolution ~4.5μm



SLD vertex detector at SLAC →



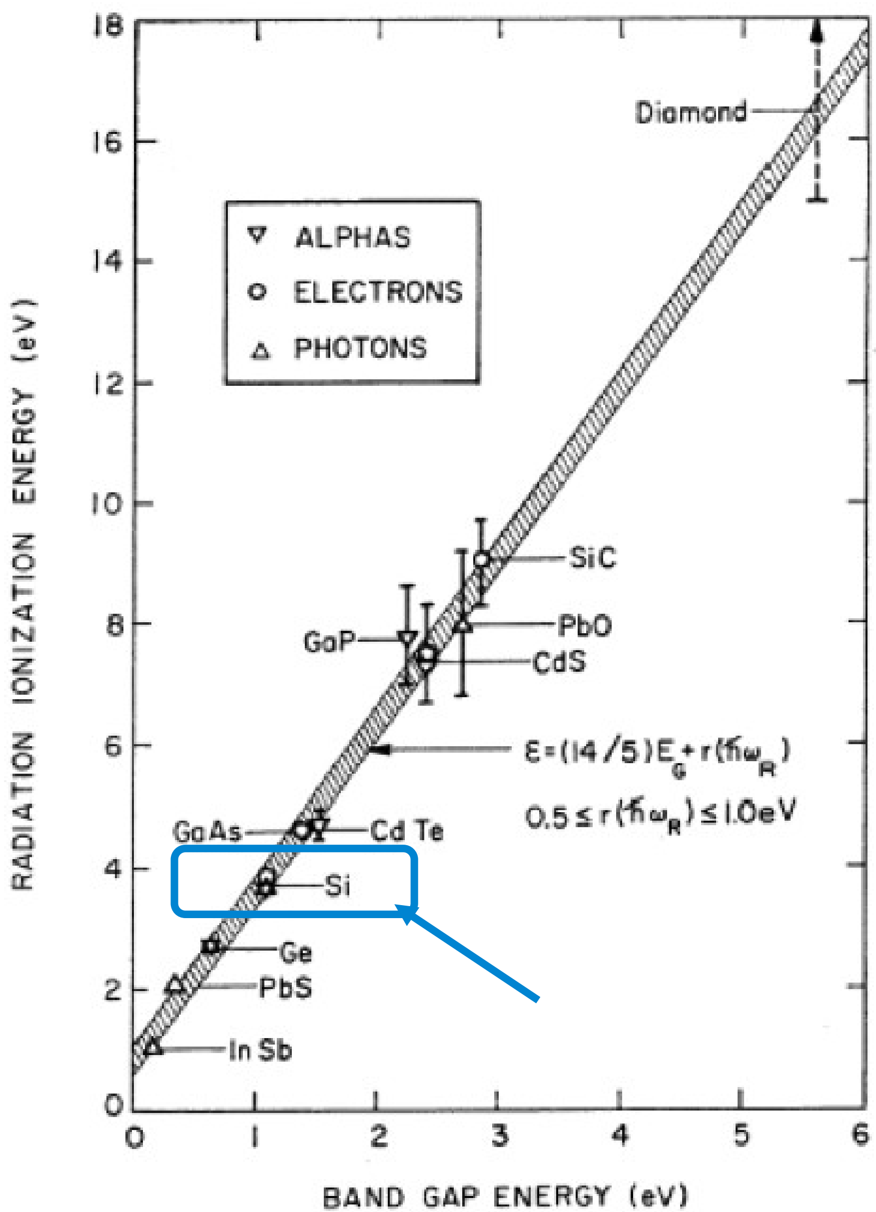
- 120-307 M pixels: 0.4%X_0
- Resolution <4μm, d_0~11-9μm

ALEPH detector at LEP →

- Enable precise measurements for B-physics (lifetime, b-tagging)

Experiment	Detectors	Channels (10^3)	Si area [m^2]
Aleph (LEP)	144	95	0.49
CDF II (TEV)	720	405	1.9
D0 II (TEV)	768	793	4.7
AMS II	2300	196	6.5
ATLAS (LHC)	4088	6300	61
CMS (LHC)	15148	10000	200

Si properties



Widely used in high energy physics and industry

Low ionization energy

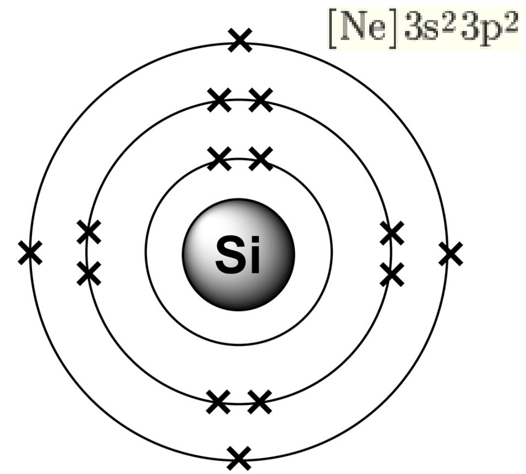
- Band gap is 1.12 eV
- Takes 3.6 eV to ionize atom
  → remaining yields phonon excitations
- Long free mean path
  → good charge collection efficiency
- High mobility
  → fast charge collection
- Low Z
  → reduced multiple scattering

Good electrical properties (SiO_2)

Good mechanical properties

- Easily patterned to small dimensions
- Can be operated at room temperature
- Crystalline
  → resilient against radiation

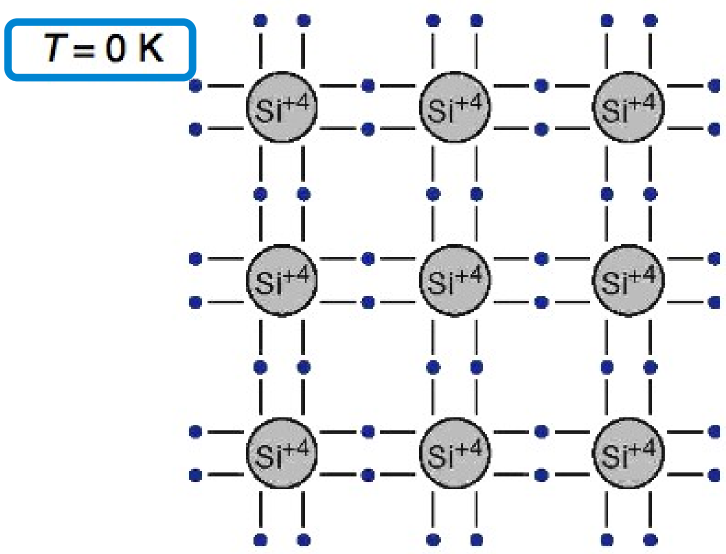
Bond model of semi-conductors

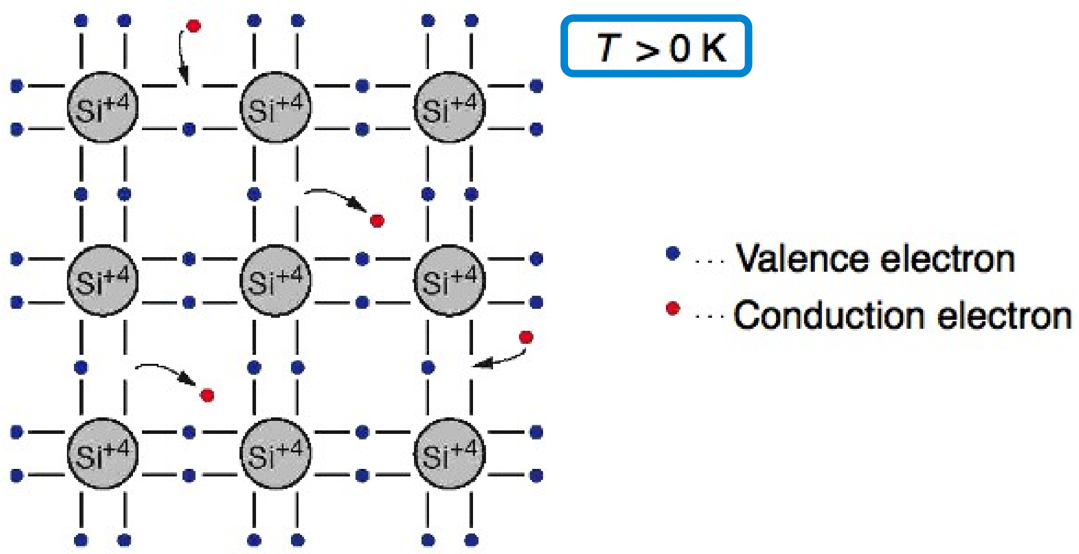


Covalent bonds formed after sharing electrons in the outermost s

Thermal vibrations

- break bonds and yield electron conduction (free e-)
- remaining open bonds attract free e- → holes change position → hole conduction

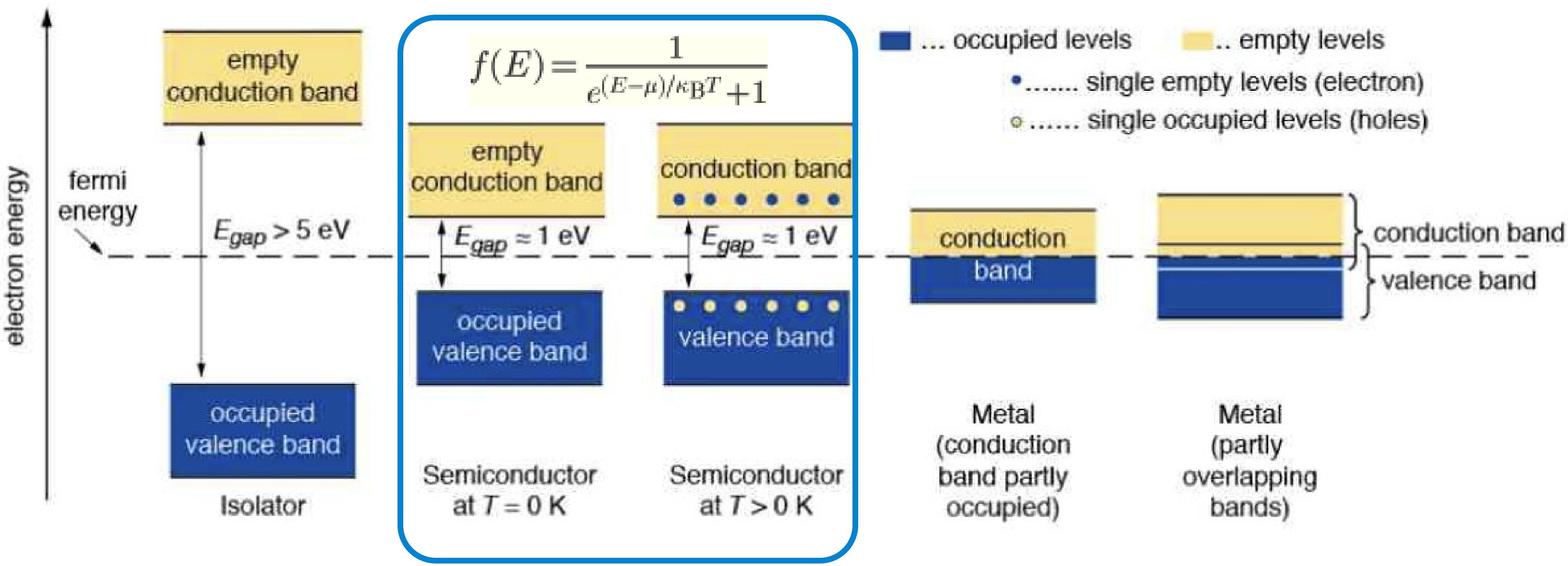




Energy bands in semi-conductors

In solids, the quantized energy levels merge

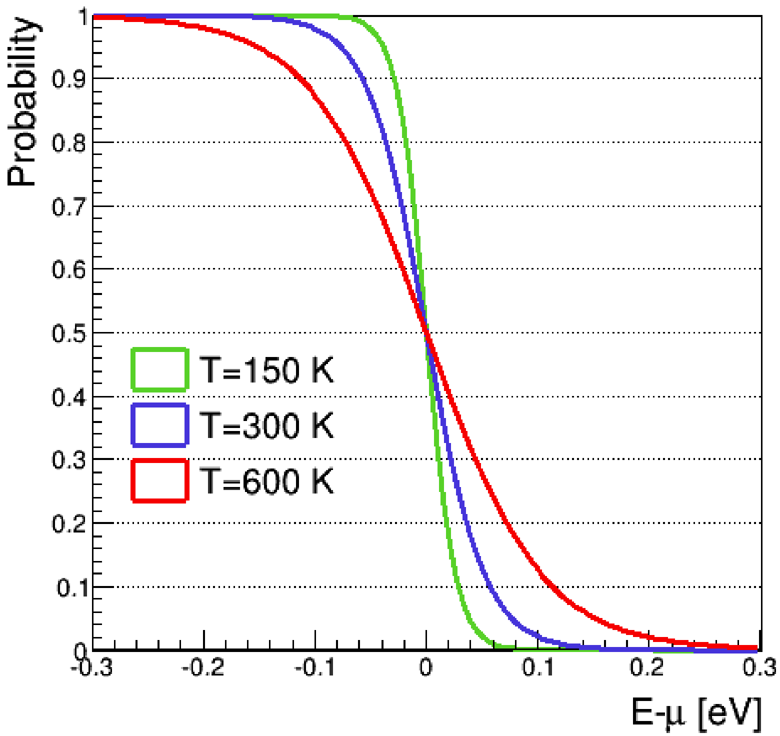
- Metals: conduction and valence band overlap
- Insulators and semi-conductors: conduction and valence band separated by energy (band) gap
- If μ (band gap) sufficiently low : electrons fill conduction band according to Fermi-Dirac statistics



Intrinsic noise: intrinsic carrier concentration

Energy state occupation probability follows Fermi statistics distribution

$$f(E) = \frac{1}{e^{(E-\mu)/\kappa_B T} + 1}$$



Typical behaviour @ room temperature

- excited electrons move to conduction band
- electrons recombine with holes

Excitation and recombination in thermal equilibrium

Intrinsic carrier concentration given by

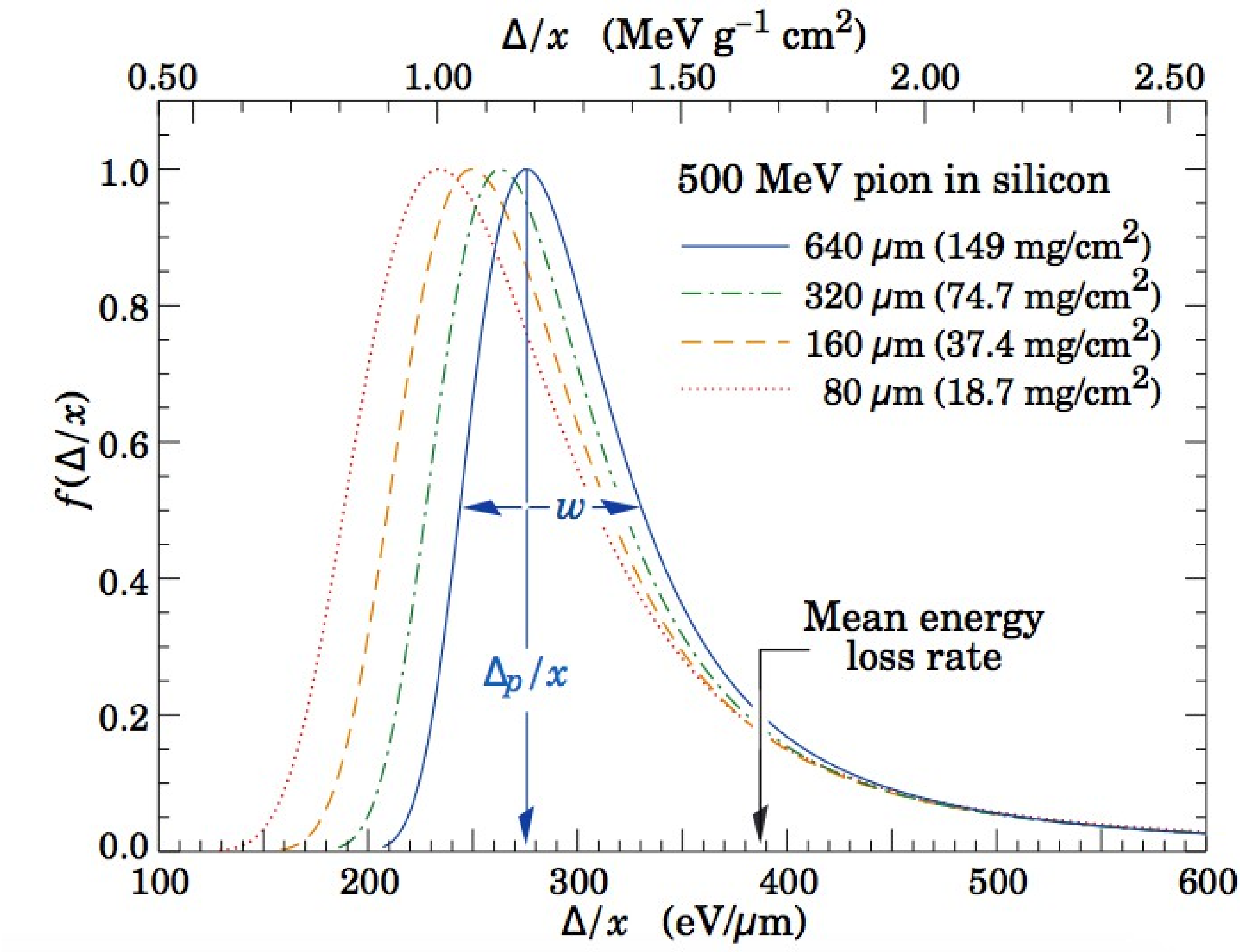
$$n_e = n_h = n_i = A \cdot T^{3/2} \cdot e^{-E_g/k_B T}$$

with $A=3.1\times10^{16}\ K^{-3/2}cm^{-3}$ *and* $E_g/2k_B = 7\times10^3 K$

$n_i \sim 1.45\times10^{10}\ cm^{-3}$

⇒1/10^{12} Si atoms is ionized

What about signal? energy loss in the Si

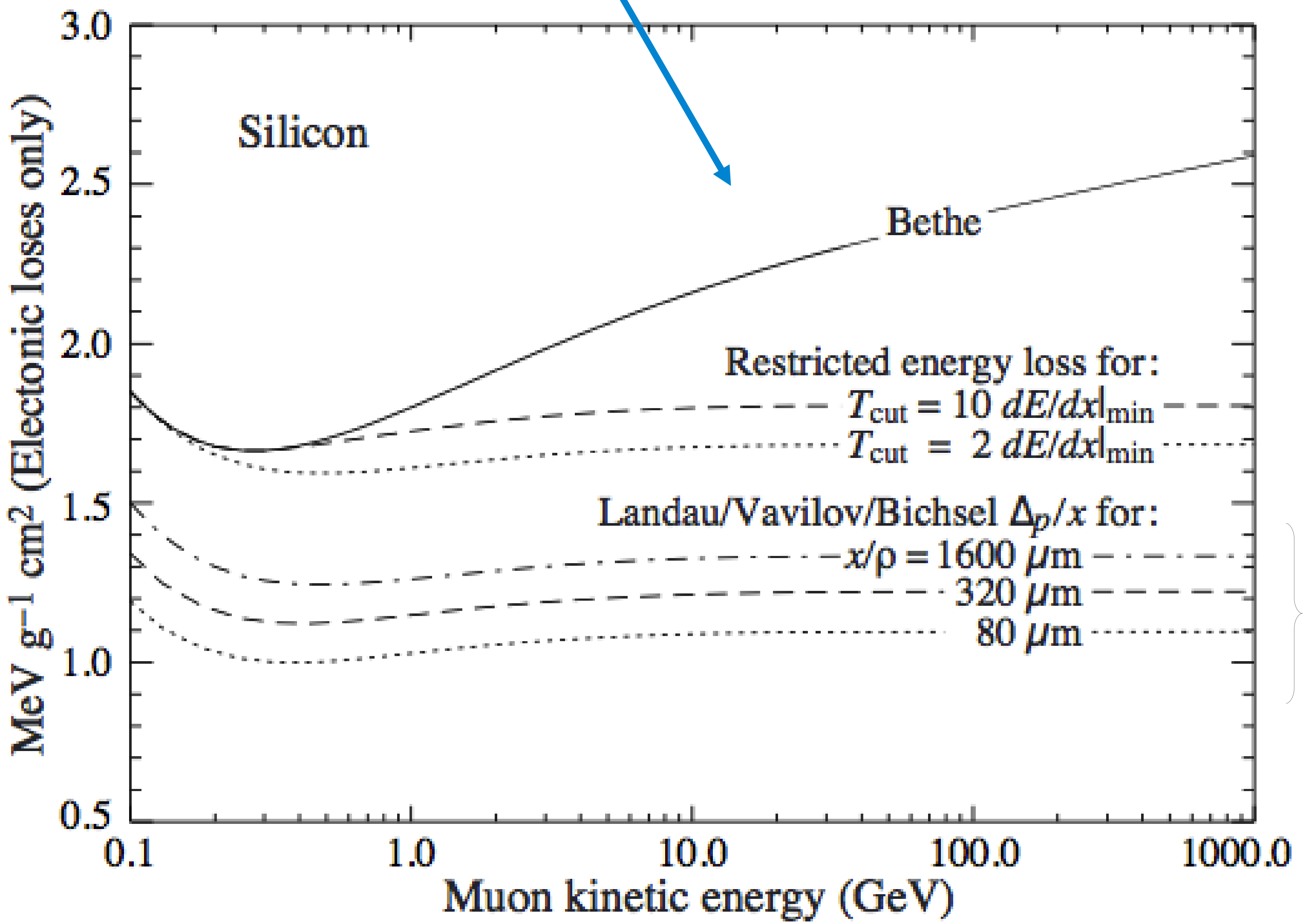


Most probable value of the Landau distribution for energy loss defines the minimum ionizing particle

MIP as function of the energy: Bethe-Bloch curve

Example: Si detector with thickness d=300µm

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



Slight dependency on Si sensor thickness, approx. constant at large $\beta\gamma$

Intrinsic S/N in a Si detector

For a 300µm thickness sensor

- Minimum ionizing particle (MIP) creates:

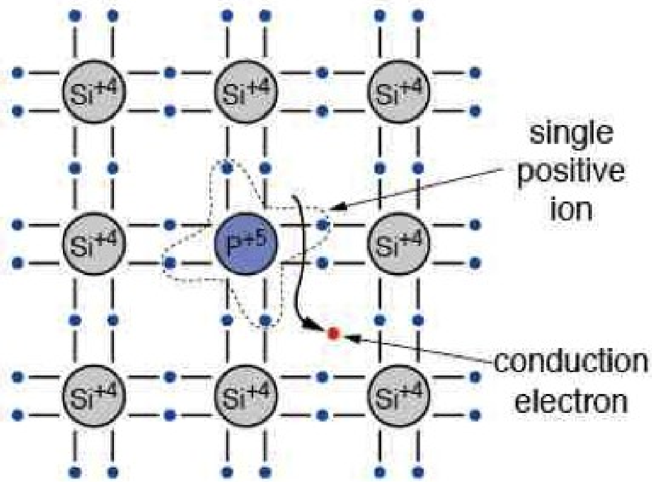
$$\frac{1}{E_{\mathrm{eh}}}\frac{dE}{dx}\cdot d=\frac{3.87\cdot 10^{6}\mathrm{eV}\,/\,\mathrm{cm}}{3.63\mathrm{eV}}\cdot 0.03\mathrm{cm}=3.2\cdot 10^{4}\mathrm{eh\ pairs}$$

- Intrinsic charge carriers (recall slide 43):

$$n_i\cdot d=1.45\cdot 10^{10}cm^{-3}\cdot 0.03cm=4.35\cdot 10^{8}\mathrm{eh\ pairs}$$

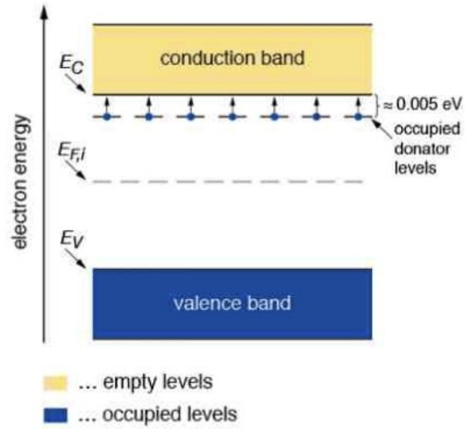
Number of thermally-created e-h pairs exceeds mip signal by factor 10^4!

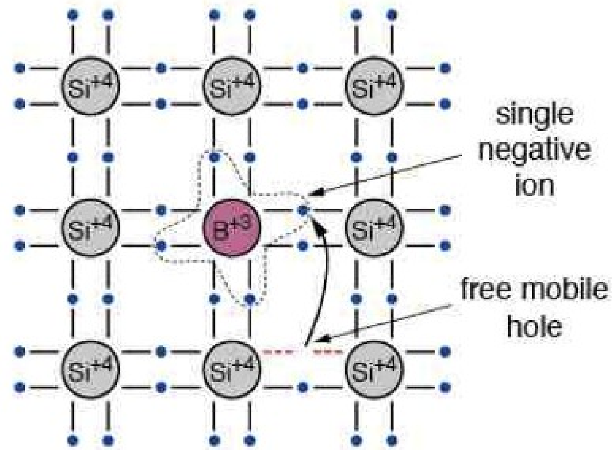
How to improve S/N: first dope Si



n-type

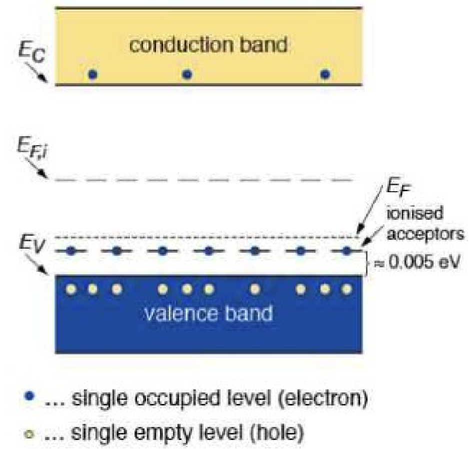
- Group 5 atom: P, As, Sb
- Loosely bound valence electron
- Tends to leave a positive ion in grid





p-type

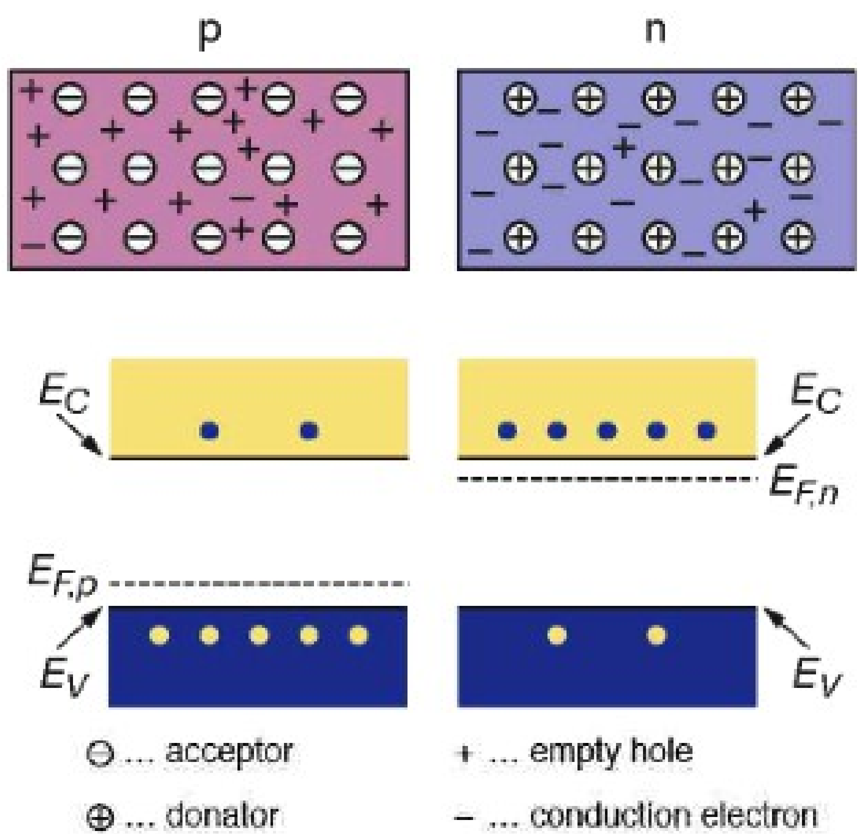
- Group 3 atom: B, Al, Ga, In
- open valence bounds attracts electrons
- Tends to leave negative ion in the grid

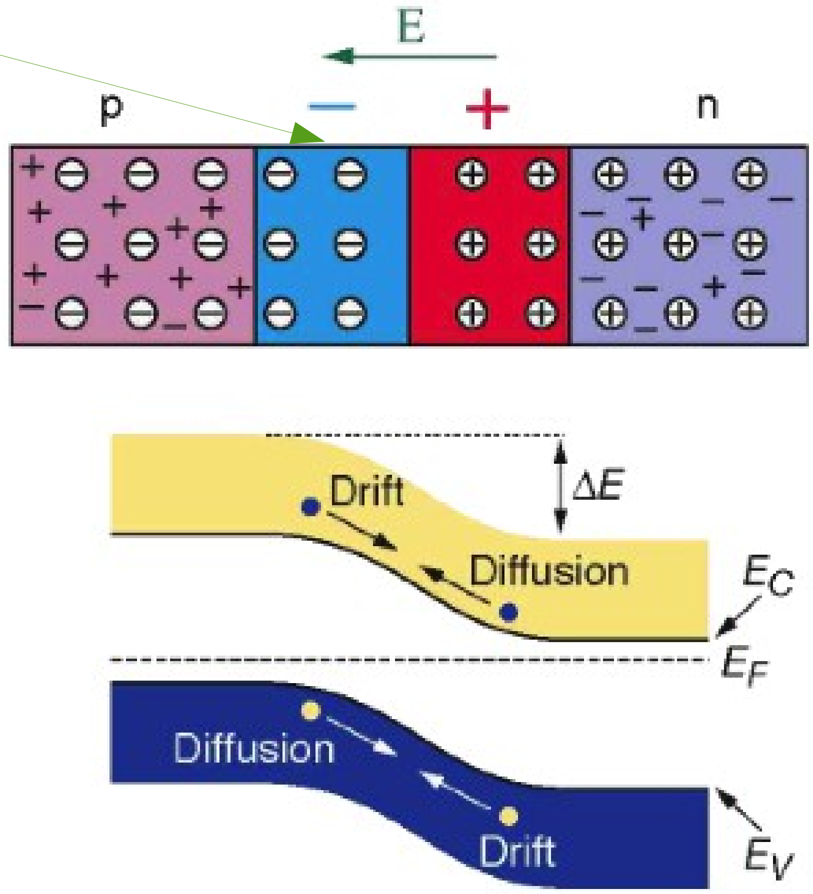


How to improve S/N: second make a junction of doped Si

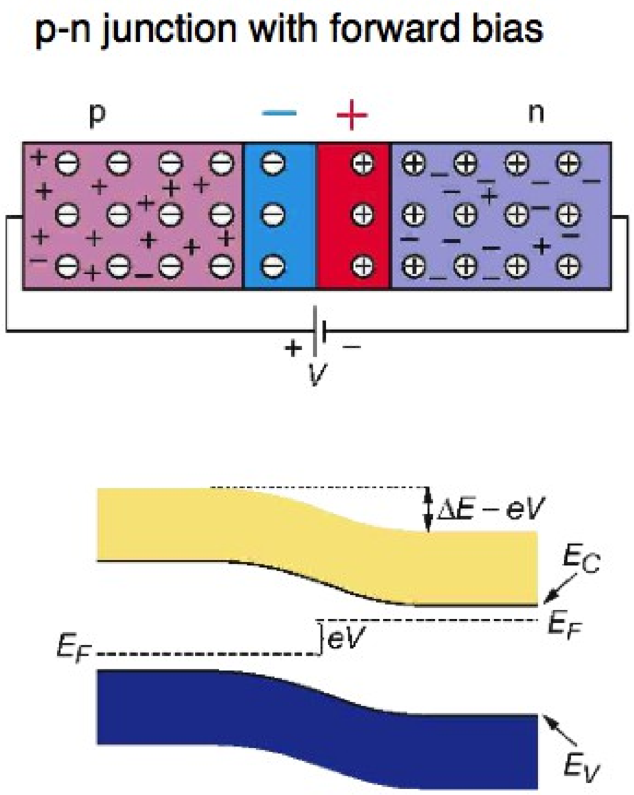
Difference in Fermi levels at the interface of n-type or p-type

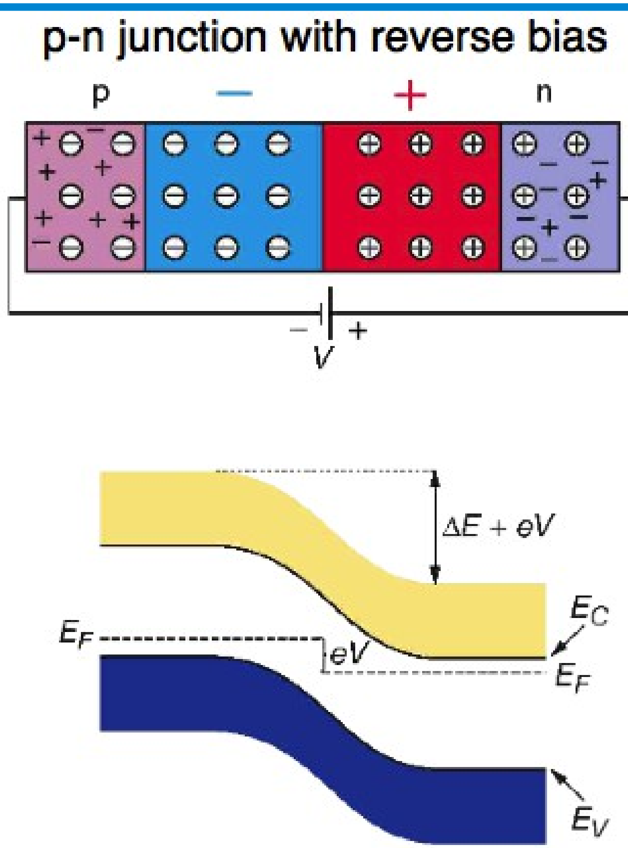
- diffusion of excess of charge carriers until thermal equilibrium (or equal Fermi level)
- **remaining ions create a depletion zone**: electric field prevents further the diffusion





How to improve S/N: finally bias the junction





Forward-biased junction

- Anode to p, cathode to n
- Depletion zone becomes narrower
- Smaller potential barrier facilitates diffusion
- Current across the junction tends to increase

Reverse-biased junction

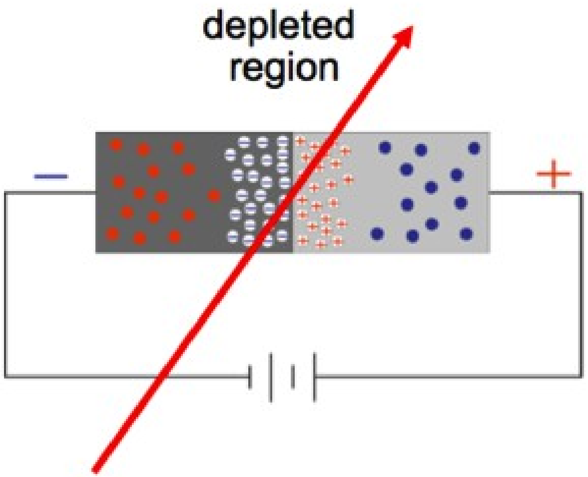
- Anode to n, cathode to p
- e,h pulled out of the depletion zone
- Potential barrier is suppressed
- Only leakage current across junction

Depletion zone: width and capacitance

Characterize depletion zone from Poisson equation with charge conservation: $\nabla^2\phi = -\frac{\rho_f}{\varepsilon}$

Typically: $N_a = 10^{15}$ cm^{-3} (p region) >> $N_d = 10^{12}$cm^{-3} (n bulk)

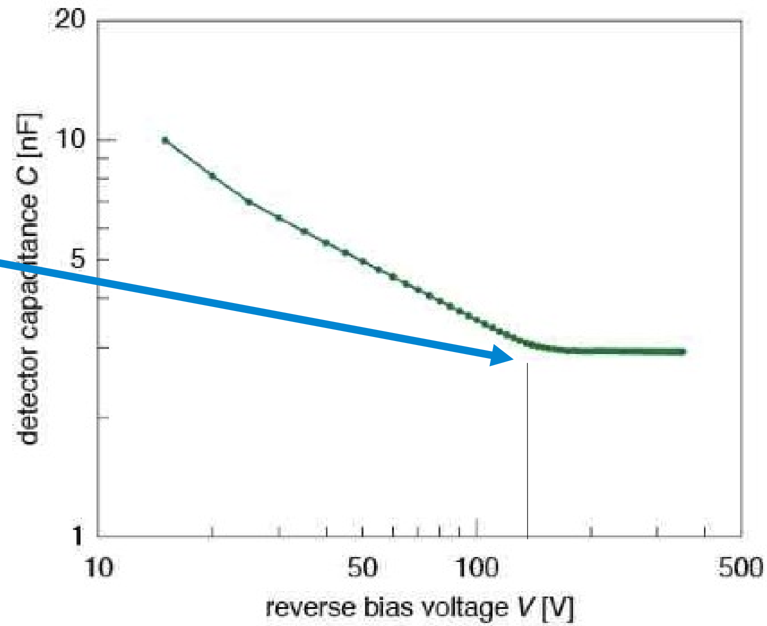
Width of depletion zone (n bulk): $W \approx \sqrt{\frac{2\varepsilon V_{\text{bias}}}{q} \cdot \frac{1}{N_d}}$



Reverse bias voltage (V)	W_p (µm)	W_n (µm)
0	0.02	23
100	0.4	363

Device behaves as parallel-plate capacitor

$$C = \frac{q}{V} = \frac{\varepsilon A}{d} = A\sqrt{\frac{\varepsilon q N_d}{2V_{\text{bias}}}}$$



- Depletion voltage saturates the capacitance
- Typical curve obtained for CMS strip detector

Depletion zone: leakage current

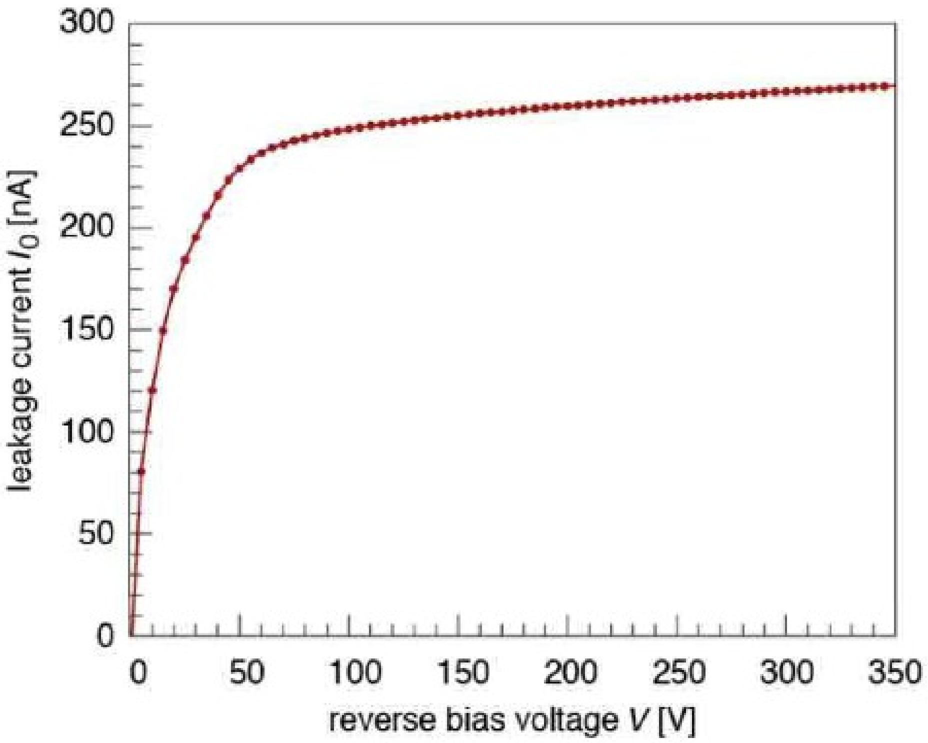
- Thermal excitation generates eh pairs
- Reverse bias applied separates pairs
- eh pairs do not recombine and drift

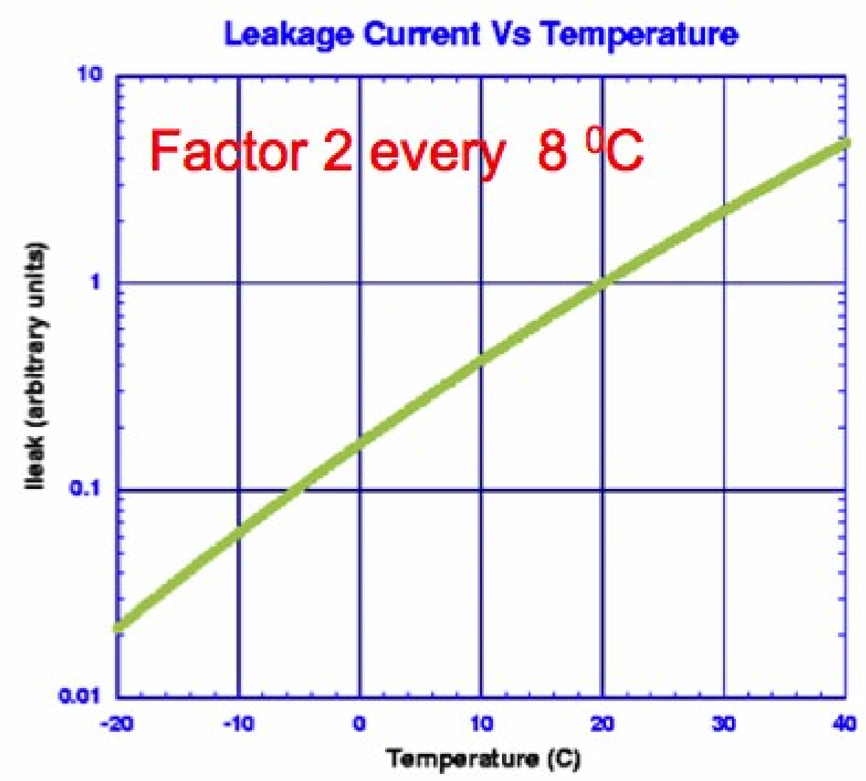
  ⇒ leakage current

- Depends on purity, defects and temperature

$$j_{\text{gen}} \propto T^{3/2} e^{\frac{1}{\kappa_B T}}$$

⇒ usually require detector cooling for stable operation (-30°-10°C)

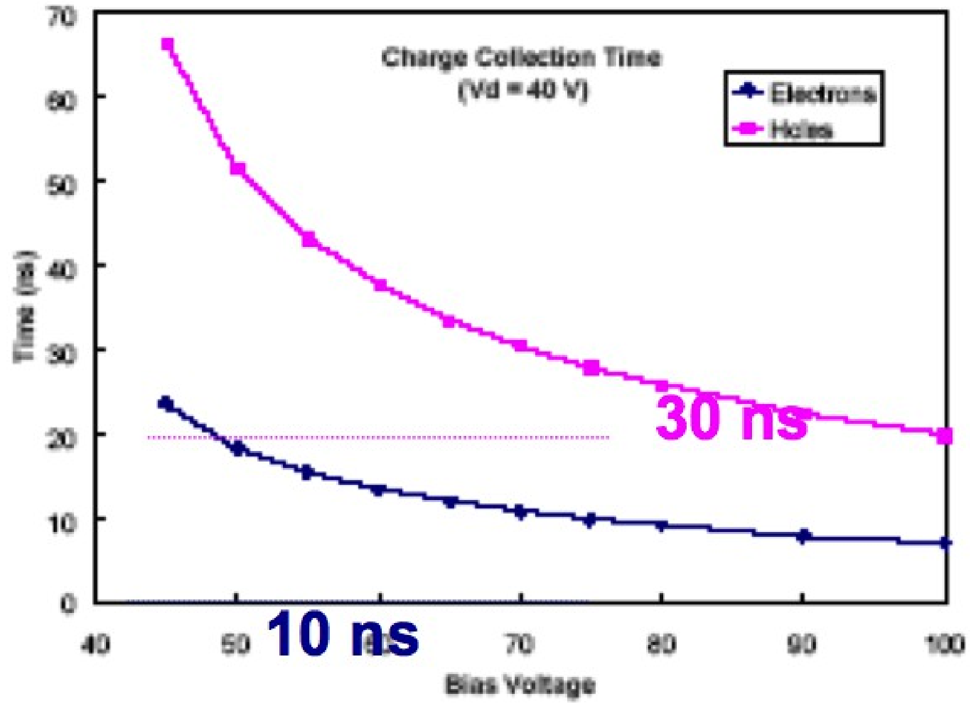


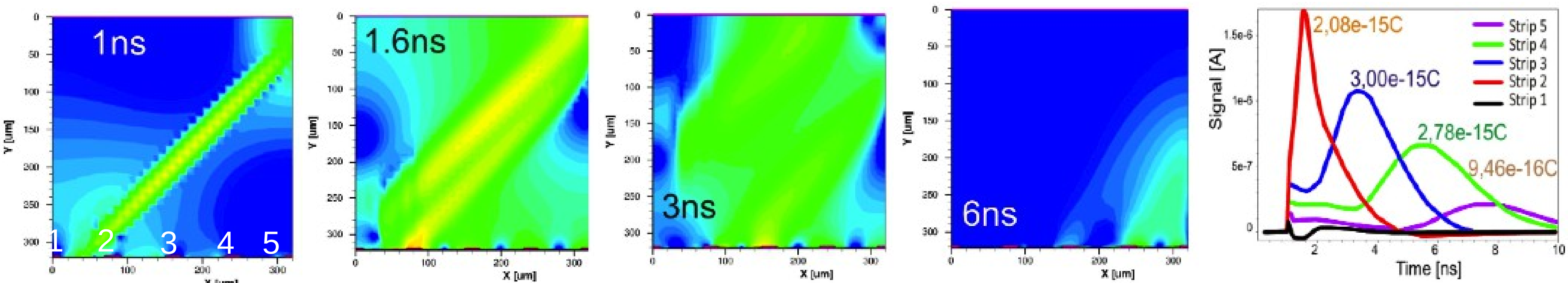


Charge collection from signal deposits

eh pairs move under the electric field

- larger biases smaller collection times
- typically smaller than LHC bunch crossing





Simulation by Thomas Eichhorn (KIT)

charge collection simulation for a 45^0 incident particle

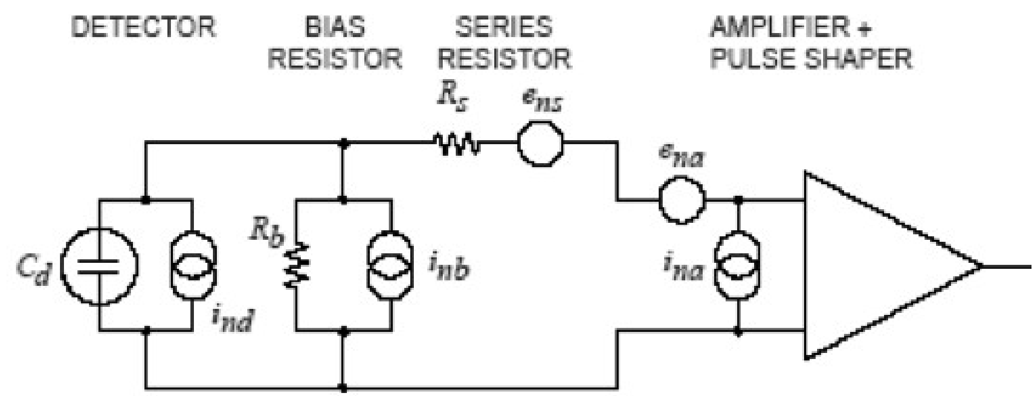
Factors impacting performance: S/N

Signal depends on the thickness of the depletion zone and on dE/dx of the particle

Noise suffers contributions from:

$$\mathrm{ENC} = \sqrt{\mathrm{ENC}_C^2 + \mathrm{ENC}_I^2 + \mathrm{ENC}^2\mathrm{R}_{\|} + \mathrm{ENC}_{\mathrm{R}_{\mathrm{series}}}^2}$$

capacitance — leakage current — parallel resistor — series resistor

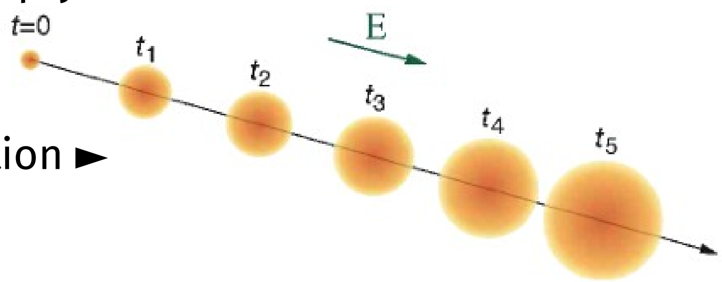


$$\mathrm{ENC_{peak}} = (36.6 \pm 1.9)\, e^-/\mathrm{cm} \cdot L + (405 \pm 27)\, e^-$$
$$\mathrm{ENC_{dec}} = (49.9 \pm 3.2)\, e^-/\mathrm{cm} \cdot L + (590 \pm 47)\, e^-$$

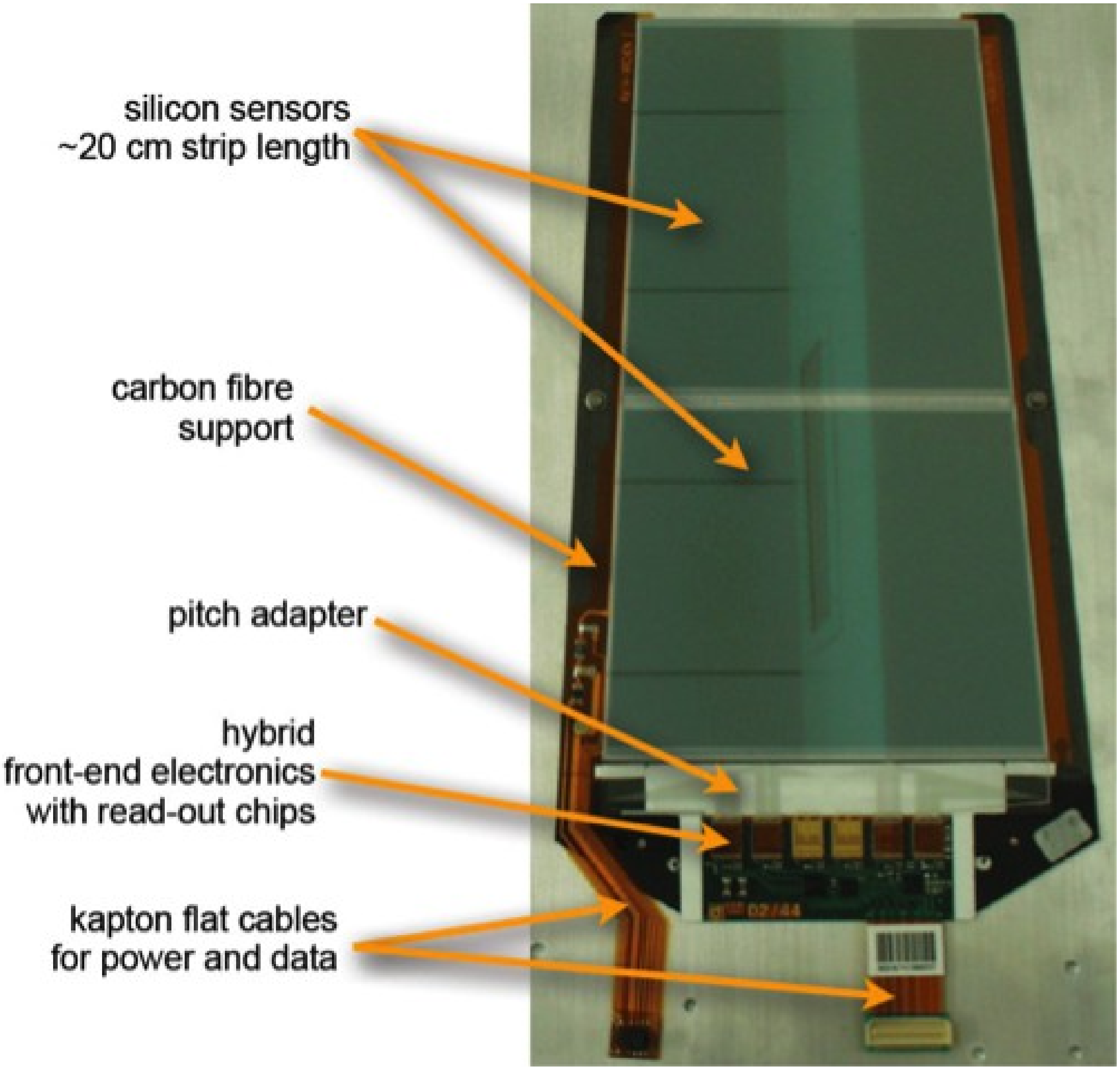
CMS strips

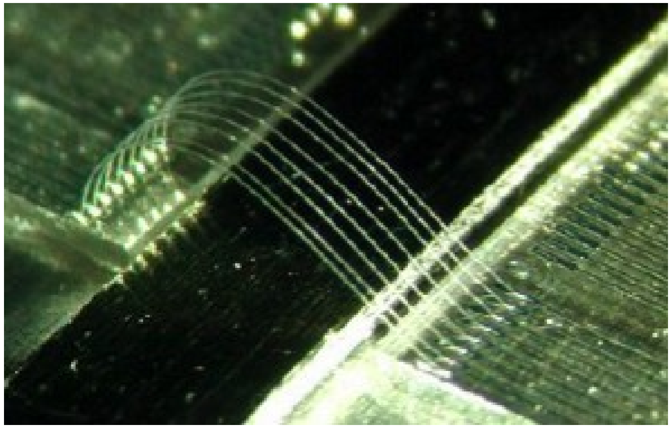
Optimizing S/N

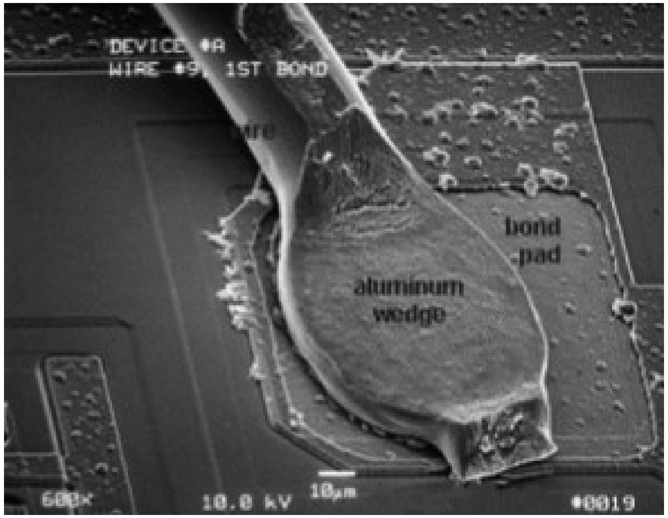
- N_{ADC}>thr, given high granularity most channels are empty
- decrease noise terms (see above)
- minimize diffusion of charge cloud after thermal motion ►
- (typically ~8µm for 300µm drift)
- radiation damage severely affects S/N (next slide)



CMS module (strips)





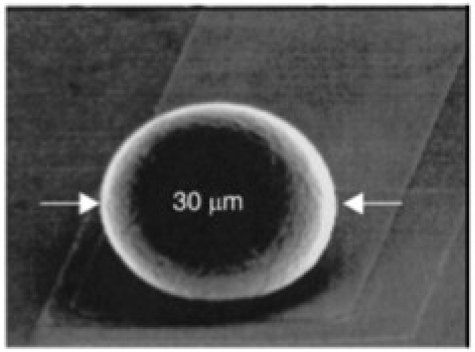


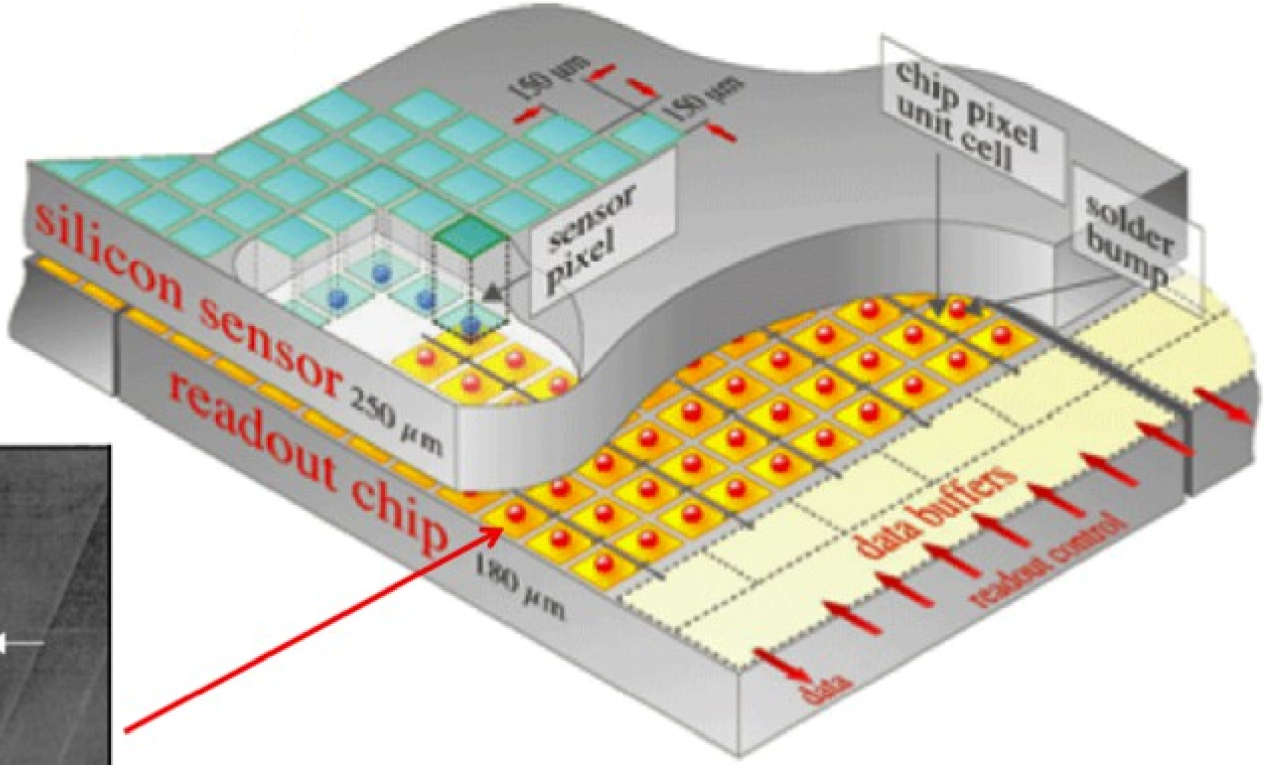
Pixel sensors

High track density better resolved with 2D position information

- back-to-back strips for 2D position information → yields “ghost” hits

Hybrid pixel detectors with sensors and bump-bonded readout chips





one sensor, 16 front-end chips and 1 master controller chip

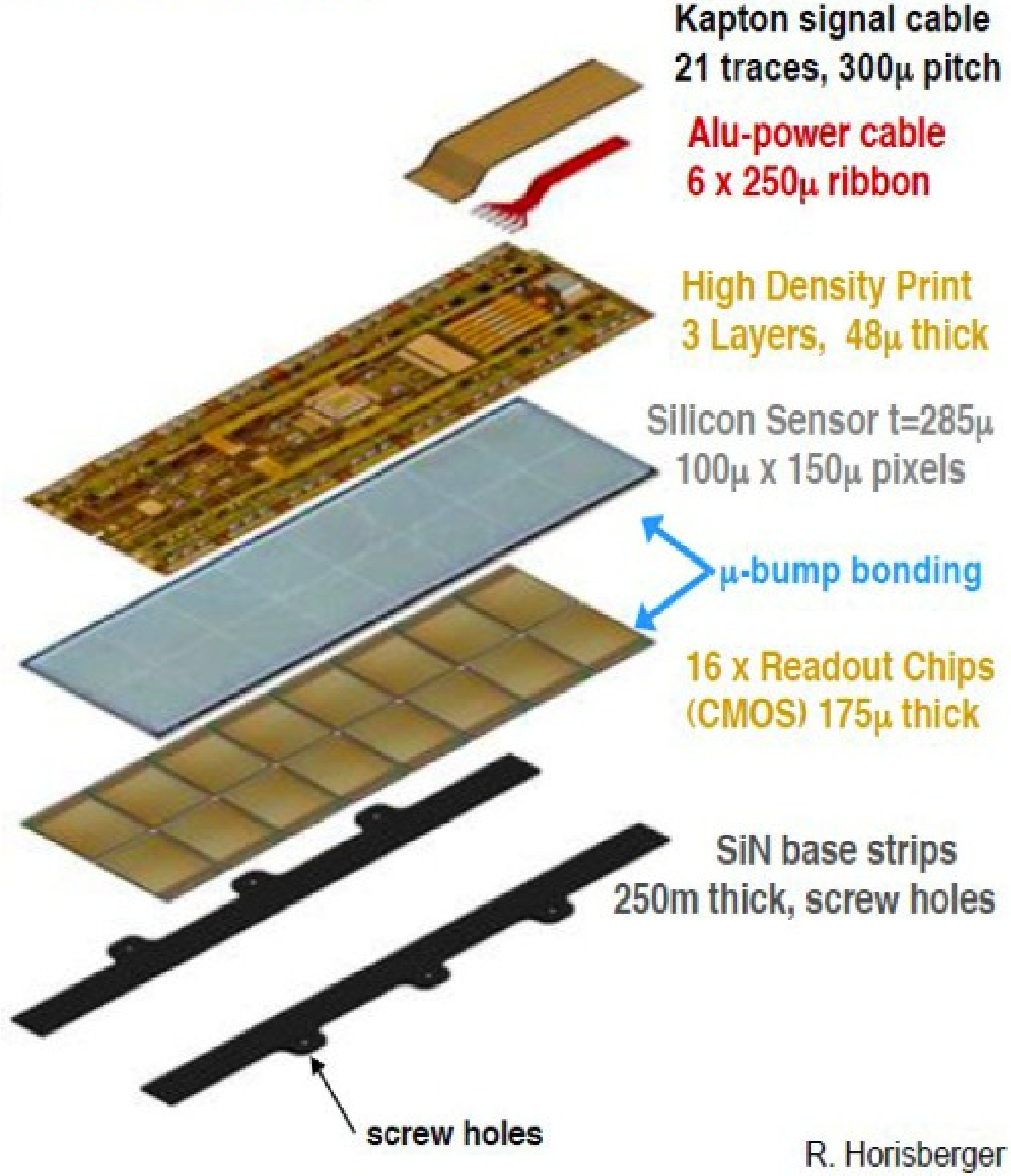
Hybrid Pixel Module for CMS

Sensor:

- Pixel Size: 150mm x 100mm
  - Resolution $\sigma_{r\text{-}\varphi}$ ~ 15µm
  - Resolution σ_z ~ 20µm
- n+-pixel on n-silicon design
  - Moderated p-spray → HV robustness

Readout Chip:

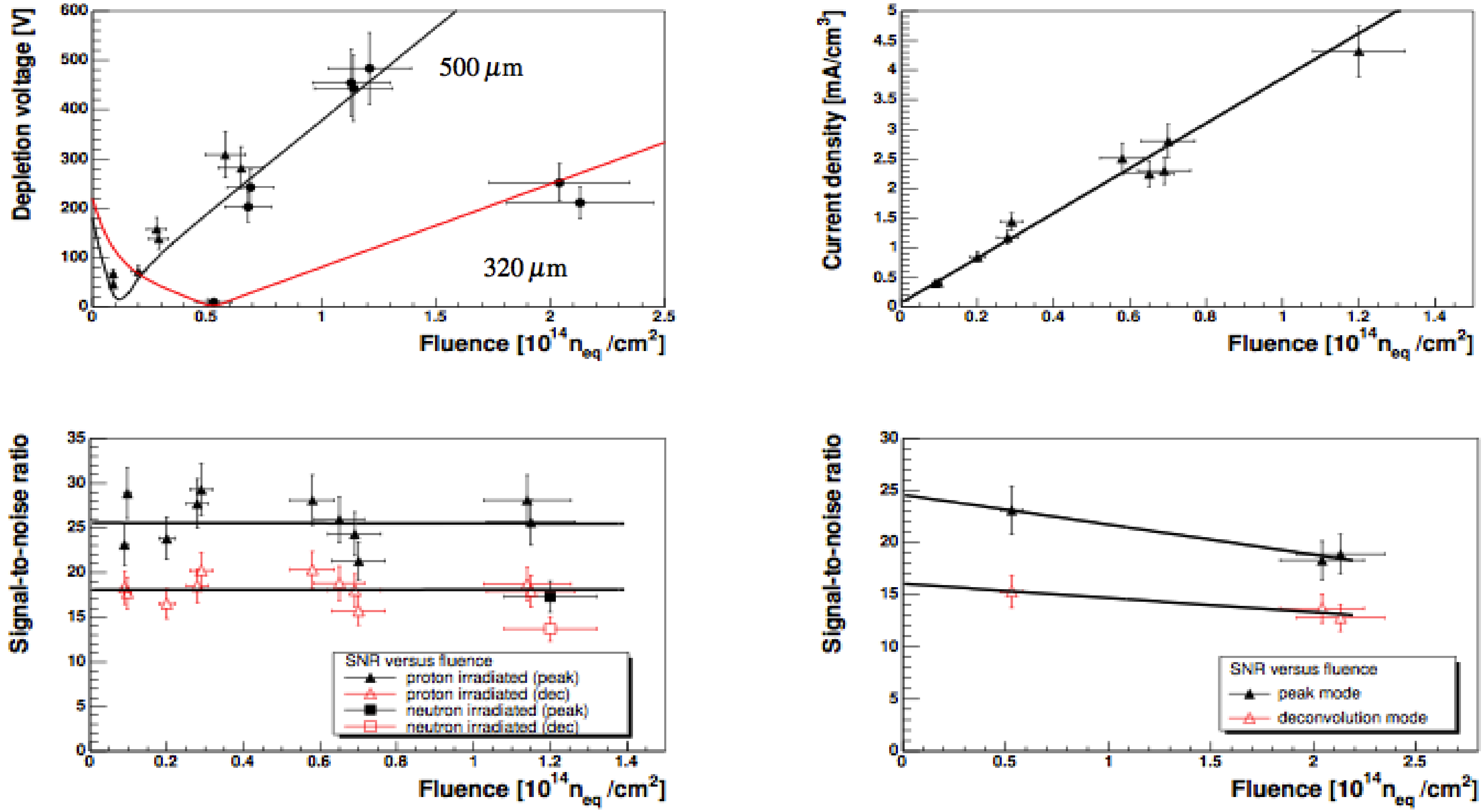
- Thinned to 175µm
- 250nm CMOS IBM Process
- 8" Wafer



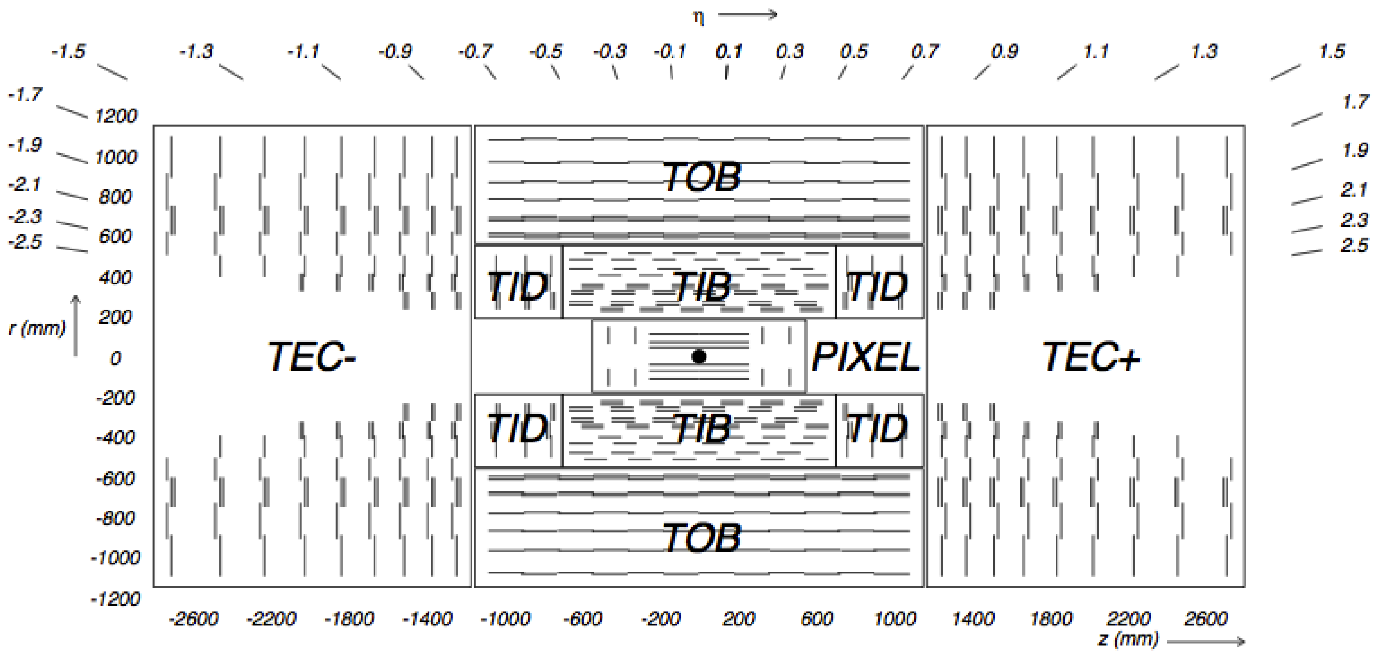
Influence of radiation

Si is not fully robust against radiation

- induced defects result in noise, inefficiency, leakage,...
- need to increase depletion voltage at higher fluences
- expected hit finding efficiency after 10 years of LHC operation: 95%



CMS tracker

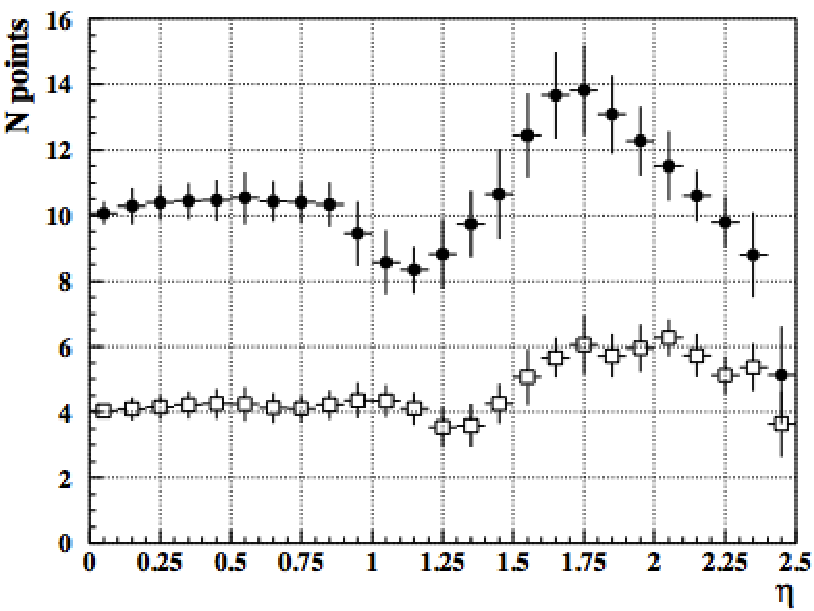


Pixel detector: ~1m² area

- 1.4k modules ⇒ 66M pixels

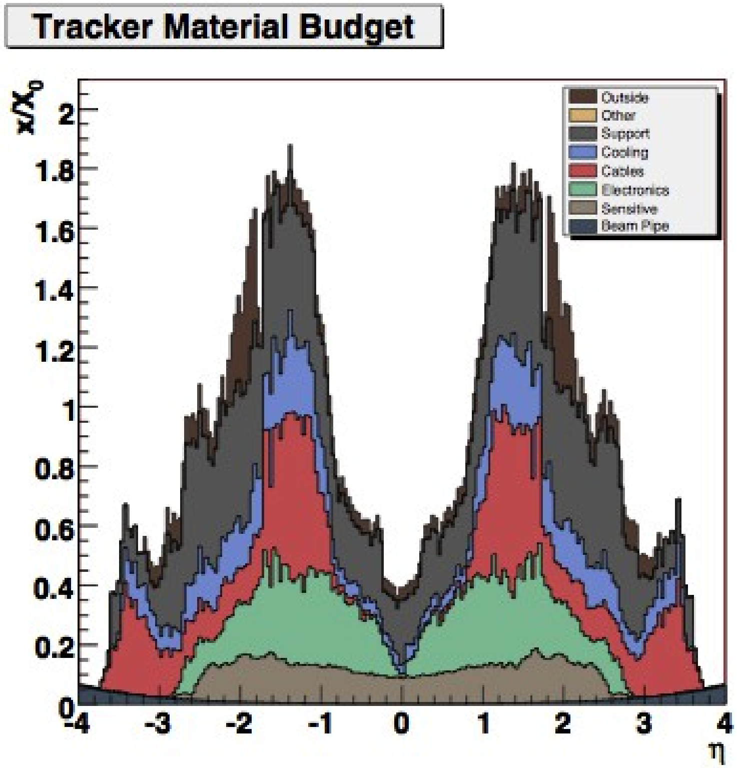
Strips: ~200m² area

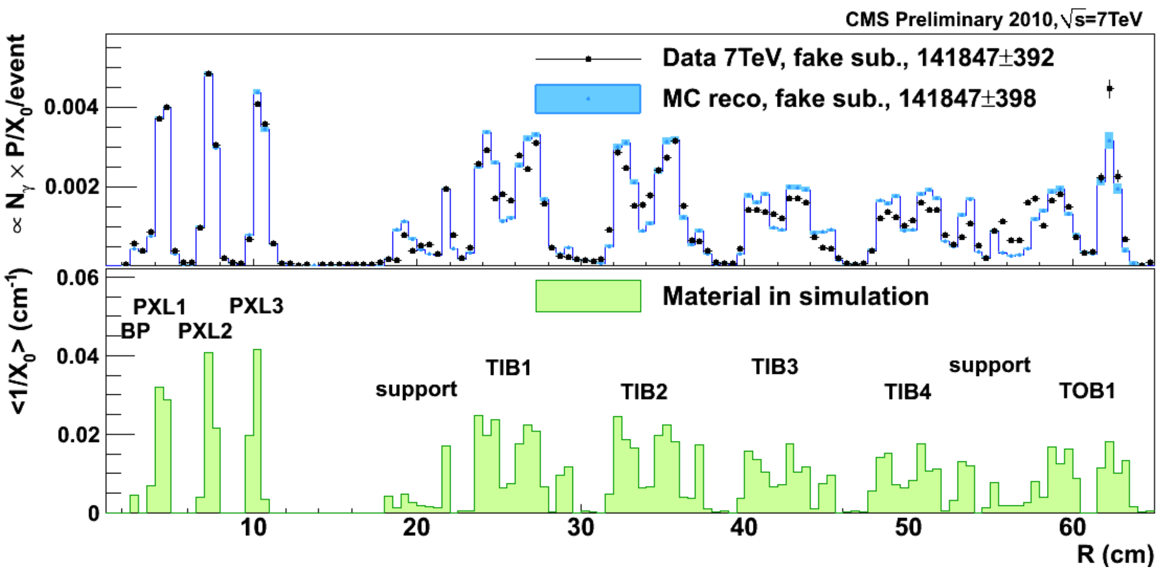
- 24k single sensors, 15k modules
- 9.6M strips = electronics channels
- 75k readout chips



CMS tracker budget

- **In some regions can attain 1.8X_0**
  - often photons will convert, electrons will radiate :(
  - use for alignment and material budget estimation :)
- **Precise knowledge is crucial, e.g. for Higgs with γ and electrons in the final state**

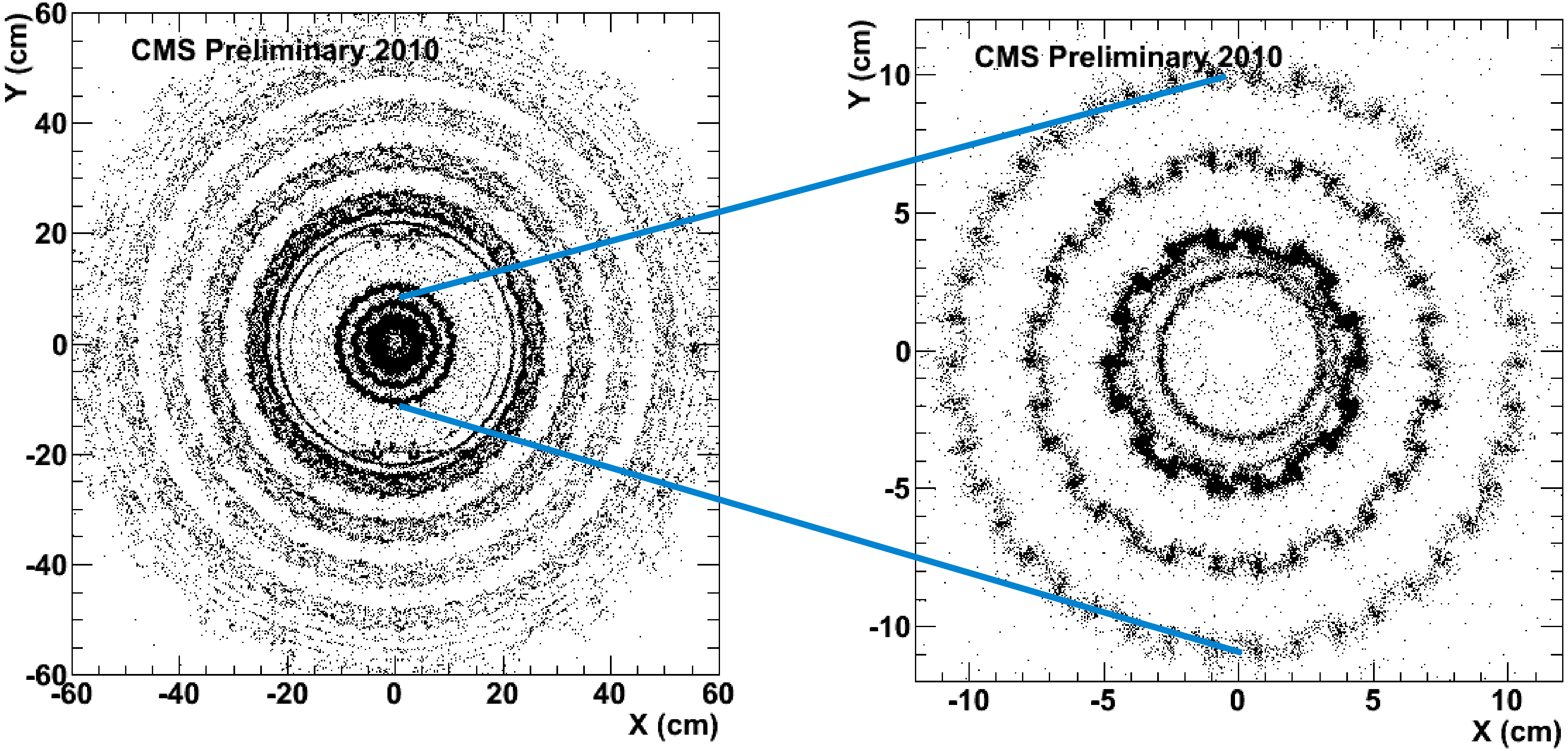


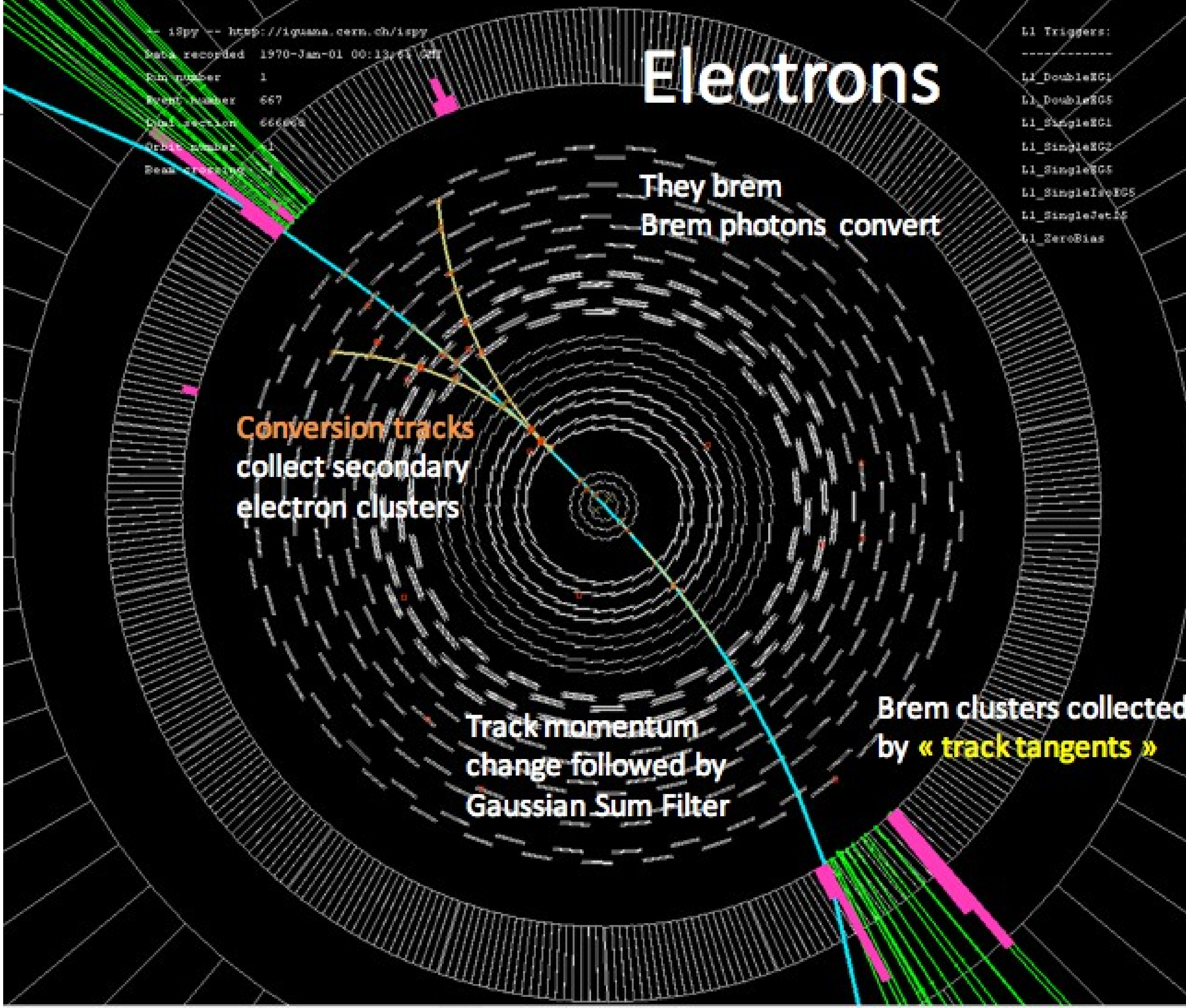


X-ray of the CMS tracker

Use photon conversions ($\gamma \to e^+e^-$)

- probability of interaction depends on the transversed material ($1-e^{-x/X_0}$)
- 54% of the H → γγ events have are expected to have at least one conversion




Electrons
They brem
Brem photons convert
Conversion tracks
collect secondary
electron clusters
Track momentum
change followed by
Gaussian Sum Filter
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by « track tangents »