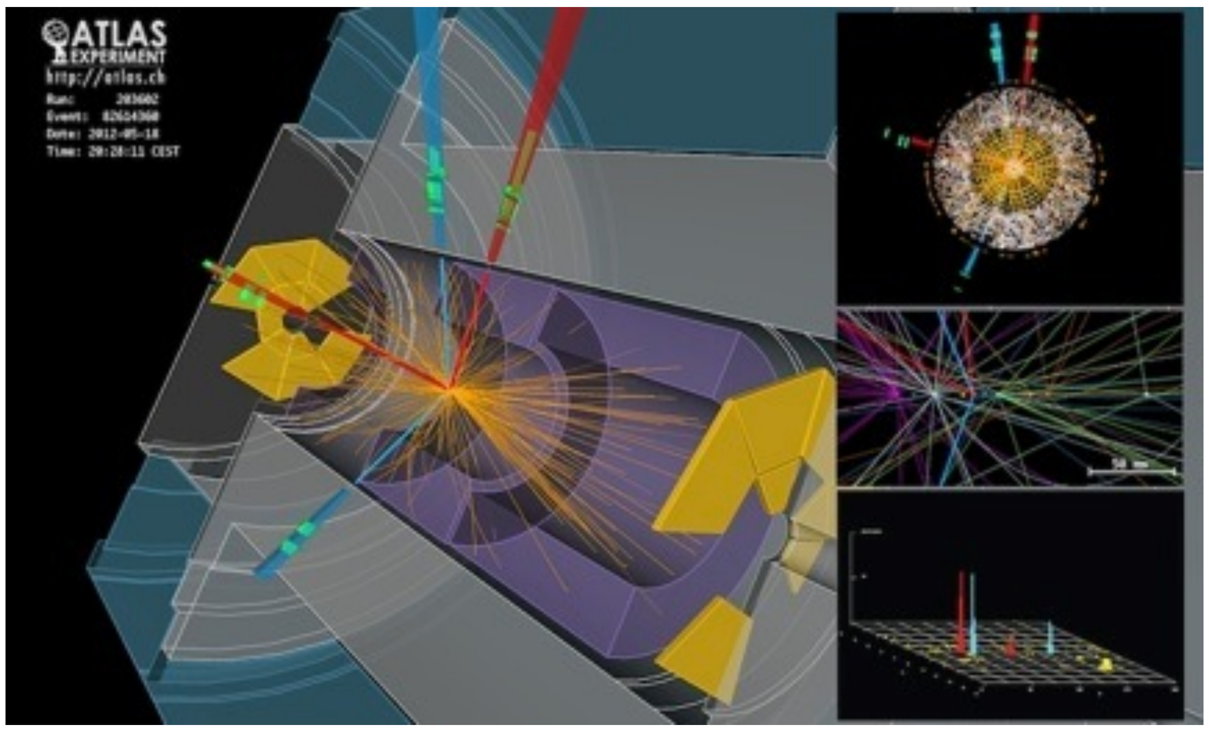
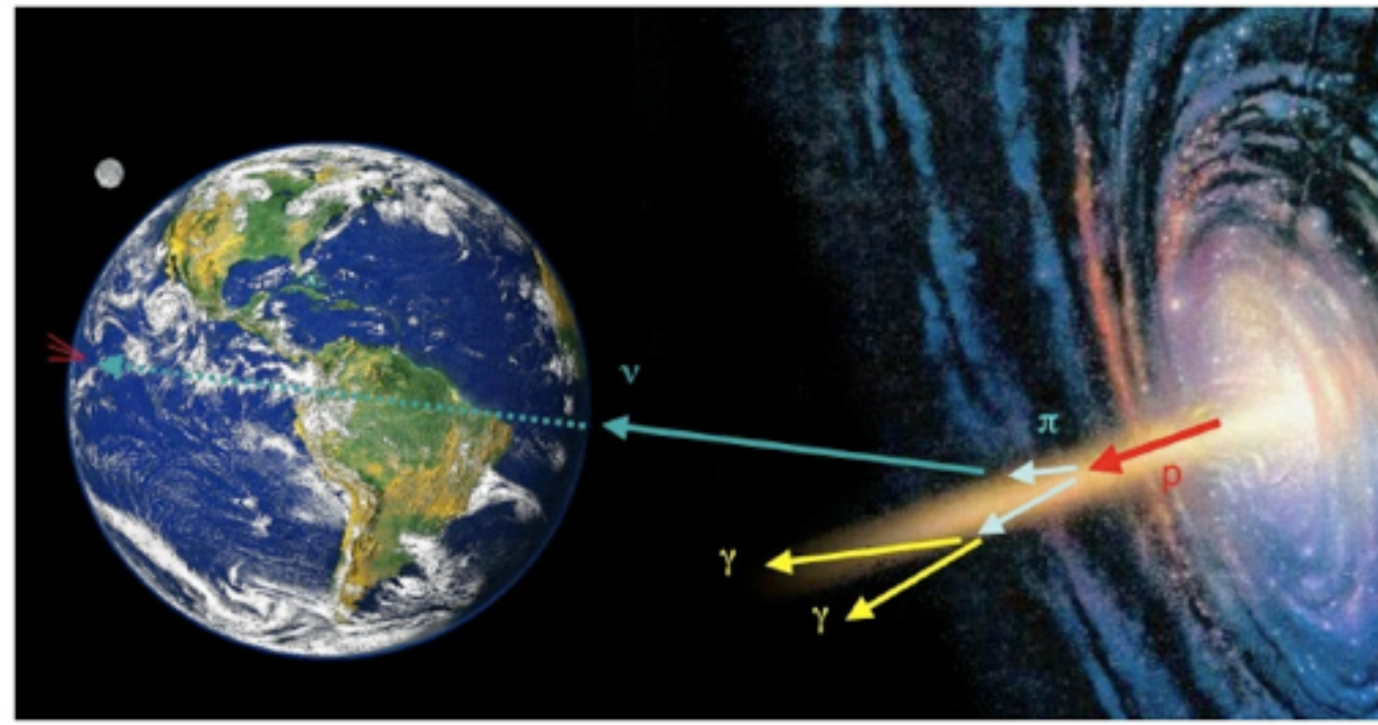
Particle Physics at Colliders and in the High Energy Universe





11. Collider Detectors II

07.01.2019

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Dr. Frank Simon
Dr. Bela Majorovits

Detectors: Overview

- Lecture Detectors I
  - Introduction, overall detector concepts
  - Detector systems at hadron colliders
  - Basics of particle detection: Interaction with matter
  - Methods for particle detection

  - And *special feature*: Novel acceleration techniques

- **Lecture Detectors II**
  - Tracking detectors: Basics
  - Semiconductor trackers
  - Calorimeters

Momentum Measurement with Trackers

Tracking: Momentum Measurement in B-Field

- Charged particles are deflected in magnetic field
  - only acts on the component transverse to the field

The radius of the trajectory gives transverse momentum:

$$\frac{p_T}{\mathrm{GeV}/c} = 0.3\,\frac{B}{\mathrm{T}}\,\frac{r}{\mathrm{m}}$$

Example:

45 GeV μ, 4 T field:

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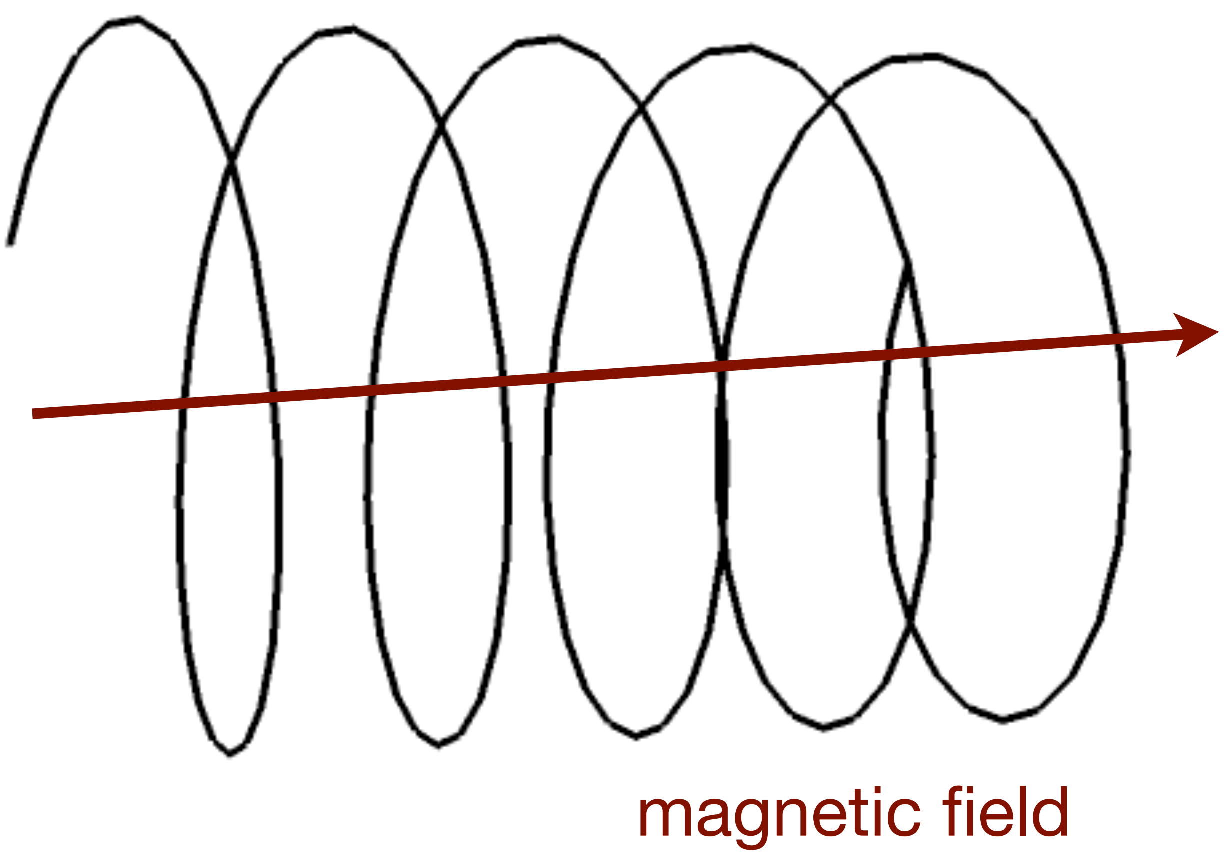

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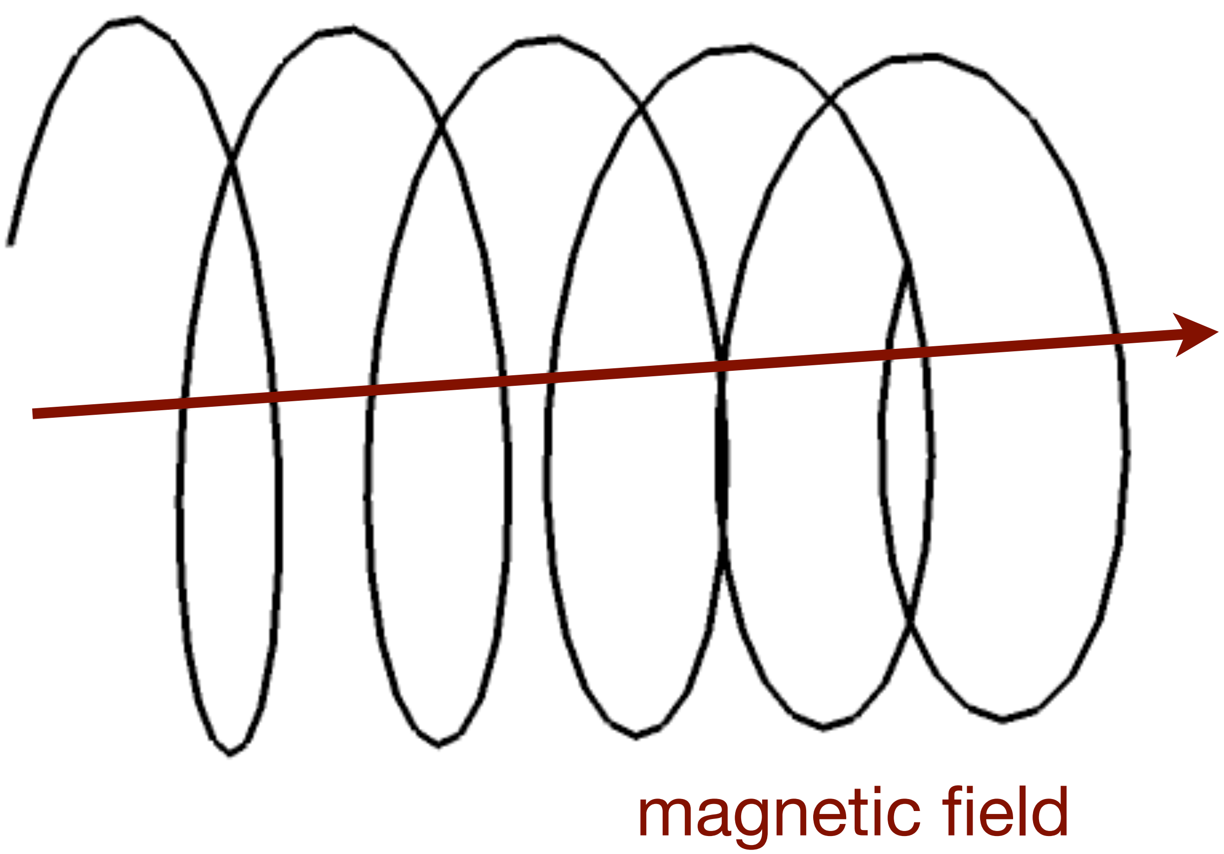
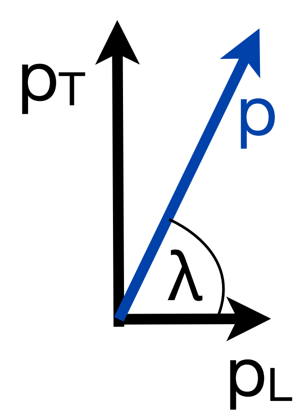
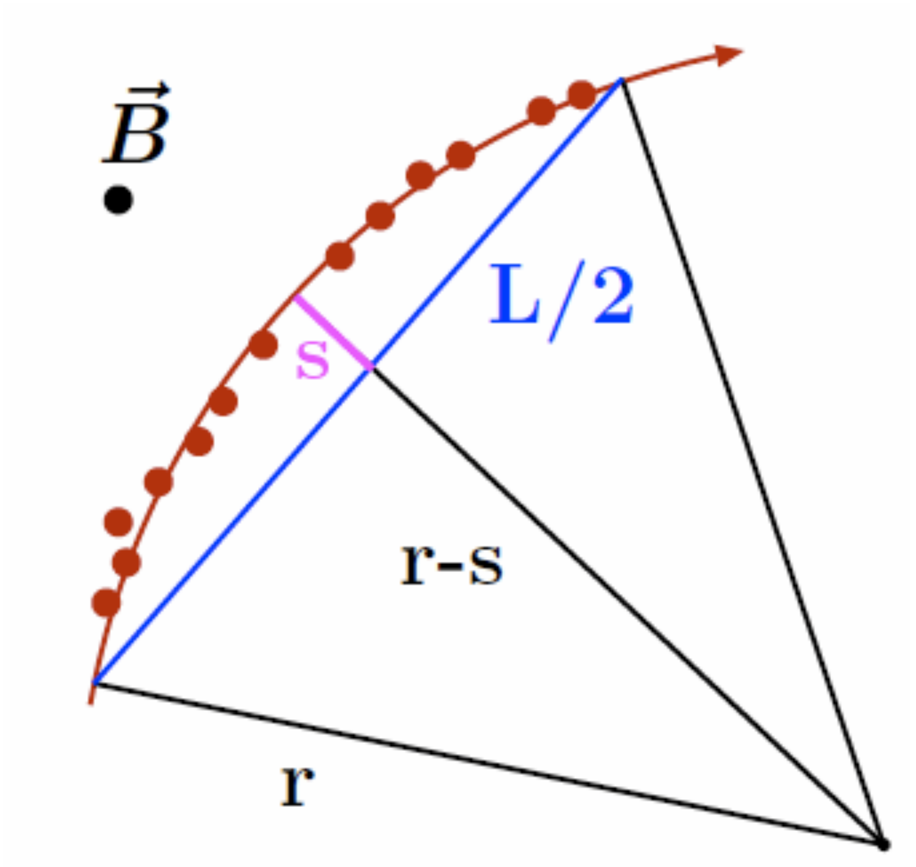


The total momentum is determined with the "dip angle" in addition to p_T:



$p = p_T / \sin\lambda$

Momentum Measurement in B-Field II



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  - Characteristic variable: **sagitta**

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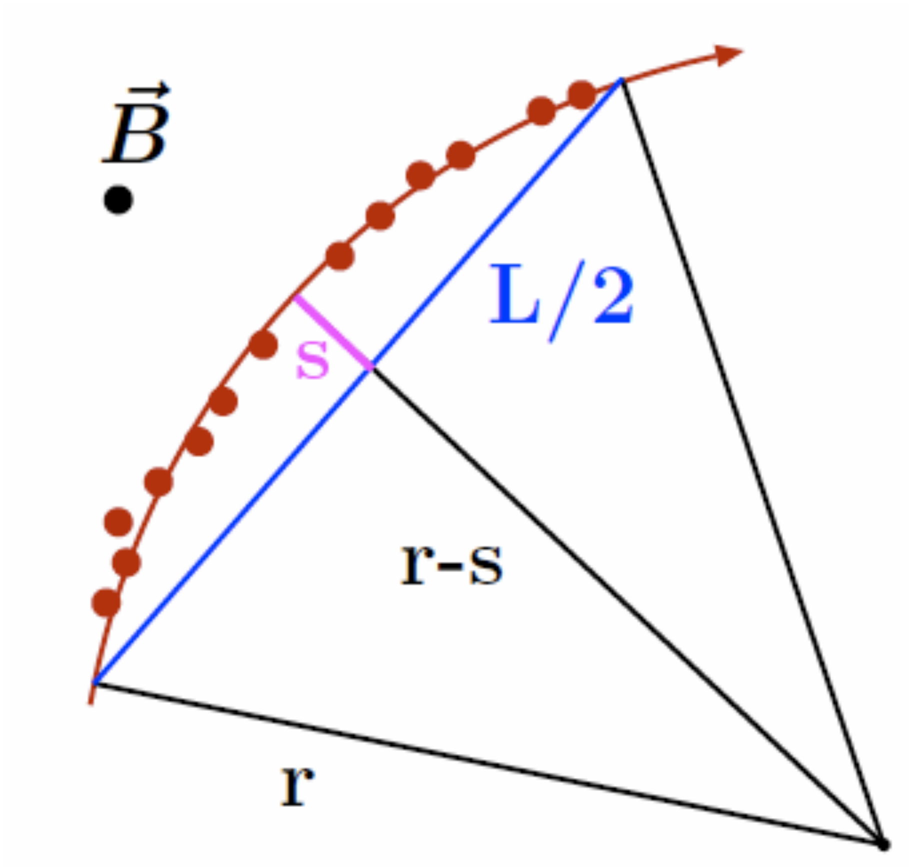

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Mathematical calculation:

$$s = r - \sqrt{r^2 - \frac{L^2}{4}}$$

$$\Rightarrow r = \frac{s}{2} + \frac{L^2}{8s} \approx \frac{L^2}{8s} \quad (s \ll L)$$

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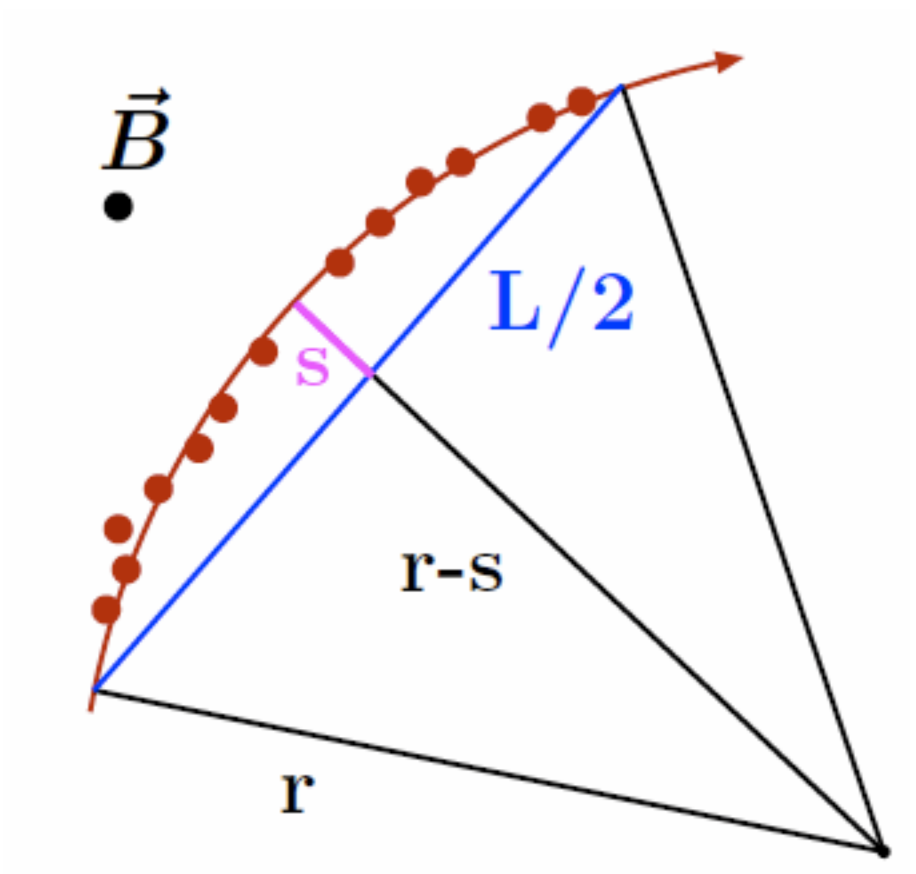

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Taking the relation of radius, momentum and B-field gives:

$$r = \frac{p_T}{0.3\,B} \Rightarrow s = \frac{0.3\,B\,L^2}{8\,p_T}$$

Momentum Measurement in B-Field III

- A minimum of 3 points are required to determine the sagitta
  - Taking into account the point-by-point measurement uncertainty:

$$\sigma^2(s) = \frac{1}{N-1}\sum_{i=1}^{N}\sigma^2(x)$$

für N = 3 there are 2 degrees of freedom

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generalization to an arbitrary number of points:

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(x)}{0.3\,B\,L^2}\sqrt{720/(N+4)}\,p_T$$

R.L. Gluckstern, NIM 24, 381 (1963)

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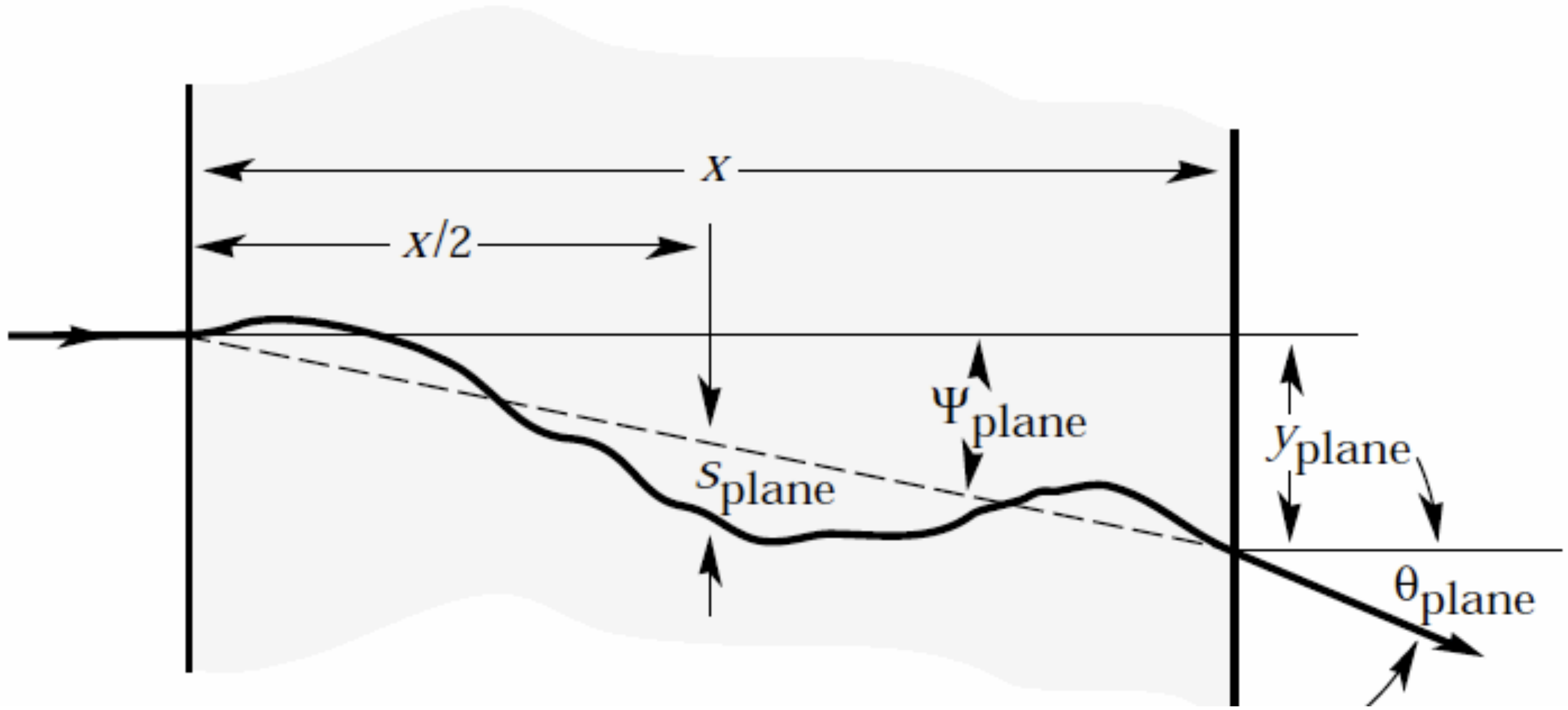
➠ The bigger B, lever arm L and the number of measurements and the better the spatial resolution, the higher is the accuracy of the momentum measurement

example (ATLAS Si-Tracker): N =7, L = 0.5, B = 2T, σ(x) = 20 μm, p_t = 5 GeV/c:
$\Delta p_t / p_t$ = 0.5 %, r = 8.3 m, s = 3.75 mm

Conflicting Effect: Multiple Scattering

- Charged particles are deflected when traversing matter: Multiple scattering via Coulomb interaction



$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}}\theta_{\text{space}}^{\text{rms}} \qquad \theta_0 = \frac{13.6\,\text{MeV}}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

- valid for relativistic particles (β = 1), the central 98% of the distribution, for layer thicknesses from 10^{-3} X_0 to 100 X_0 with an accuracy of better than 11%

Multiple Scattering vs Spatial Resolution

- Two effects influence the momentum resolution $\sigma(p_T)/p_T$ of tracking systems:
  - Momentum resolution of the tracker: $\sigma(p_T) \propto p_T$

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The measurement of low-momentum particles is limited by multiple scattering!
At higher momenta the intrinsic resolution of the detector dominates.

Multiple Scattering vs Spatial Resolution

- An optimisation question:
  - Intrinsic resolution:

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(x)}{0.3\,B\,L^2}\sqrt{720/(N+4)}\,p_T$$

~ 1/√N

number of layers in the detector

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multiple scattering spread:
~ 1/p, ~ √x , x ~ N !

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- Multiple scattering and intrinsic resolution are competing effects: More tracking layers improve the intrinsic resolution, but at the same time lead to more scattering -> Optimisation depends on “target” momentum!

Spatial Resolution of Tracking Detectors

- Depends on detector geometry and charge collection:
  - distance between strips
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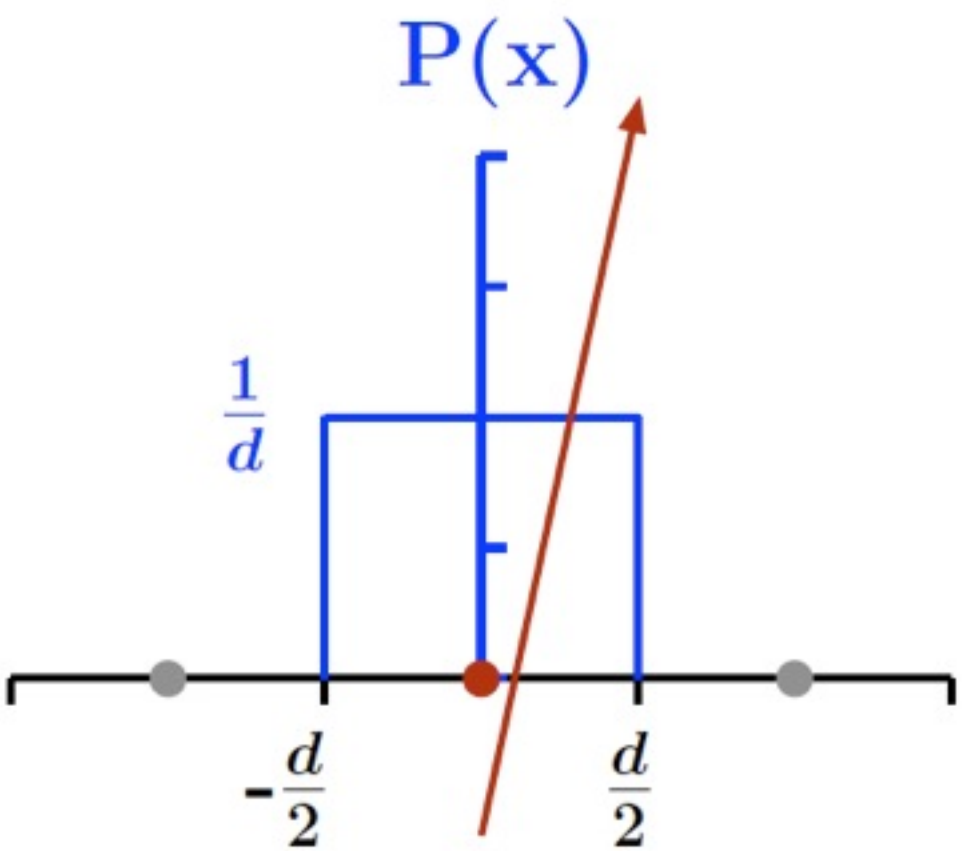

- Particle impact generates a signal in the hit strip
  - The response does not depend on impact point, no point on the strip is "special"
  - ▸ Equal probability distribution for particle position:

$$P(x) = \frac{1}{d} \quad \Rightarrow \int_{-d/2}^{d/2} P(x)\,dx = 1$$

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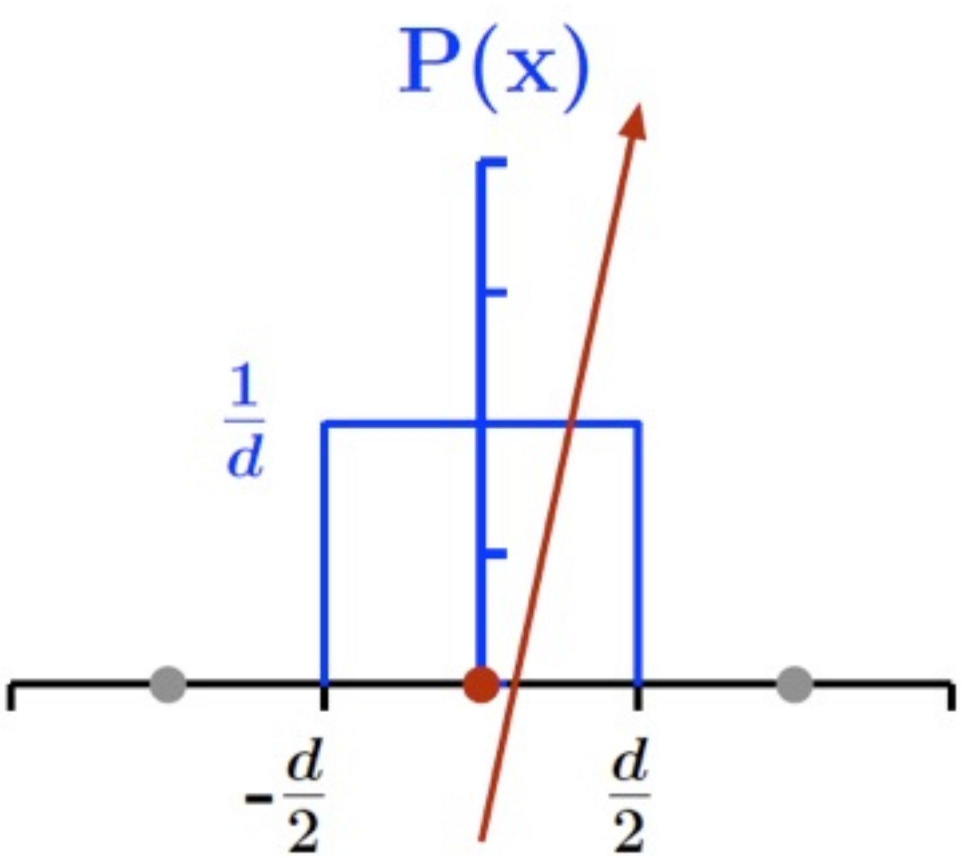

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The reconstructed impact position is always the strip center:

$$\langle x \rangle = \int_{-d/2}^{d/2} x\, P(x)\, dx = 0$$

Spatial Resolution of Tracking Detectors II

- The spatial resolution orthogonal to the strip direction is thus:

$$\sigma_x^2 = \left\langle (x - \langle x \rangle)^2 \right\rangle = \int_{-d/2}^{d/2} x^2 \, P(x) \, dx = \frac{d^2}{12}$$

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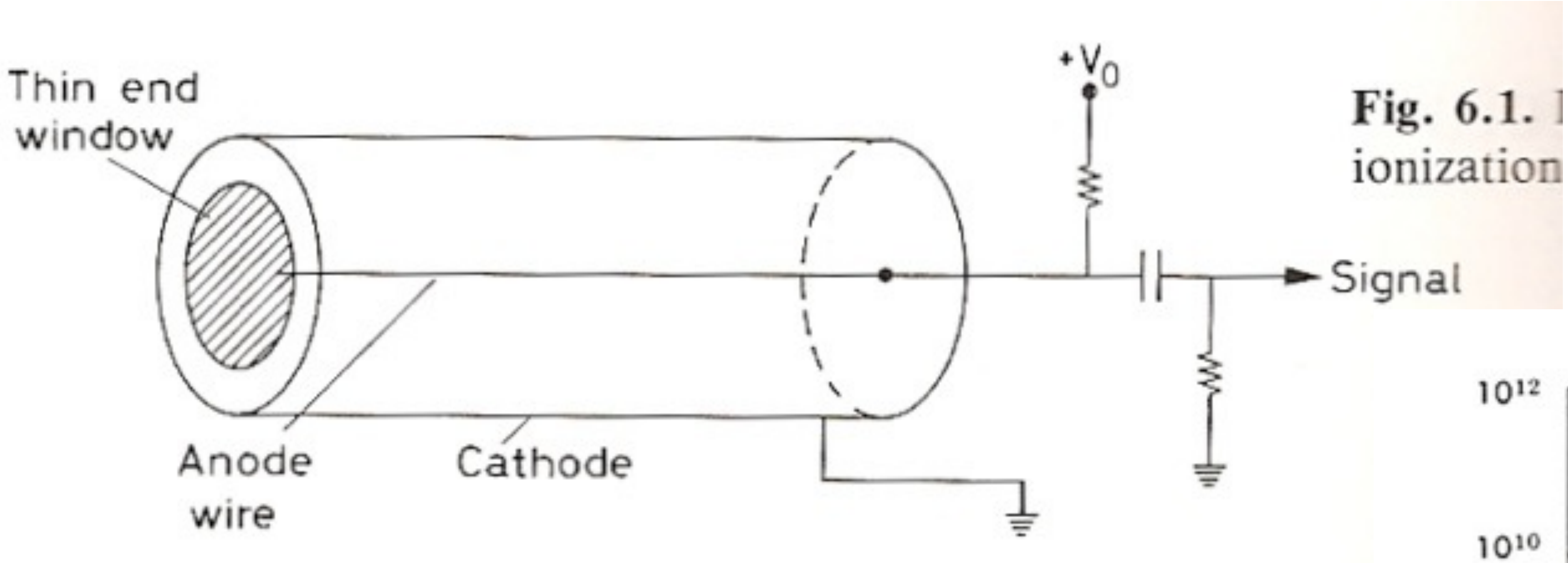
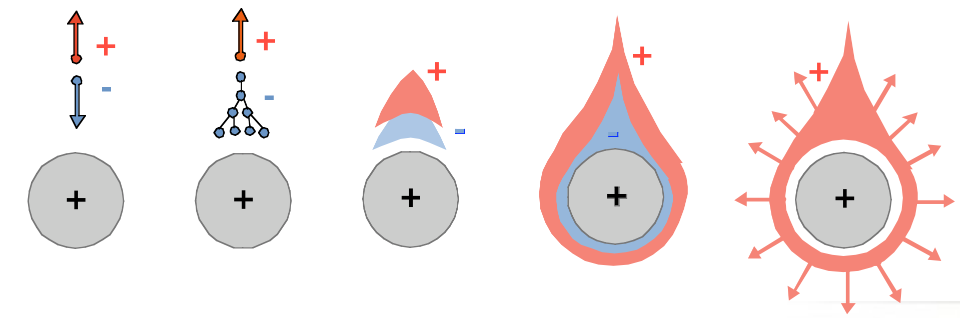
- For silicon detectors with a strip pitch of 80 μm (ATLAS) the minimum resolution is ~ 23 μm
- If the charge is collected by more than one strip, and if the charge sharing depends on the position of the particle impact the resolution can be substantially improved by calculating the center of gravity of the total signal

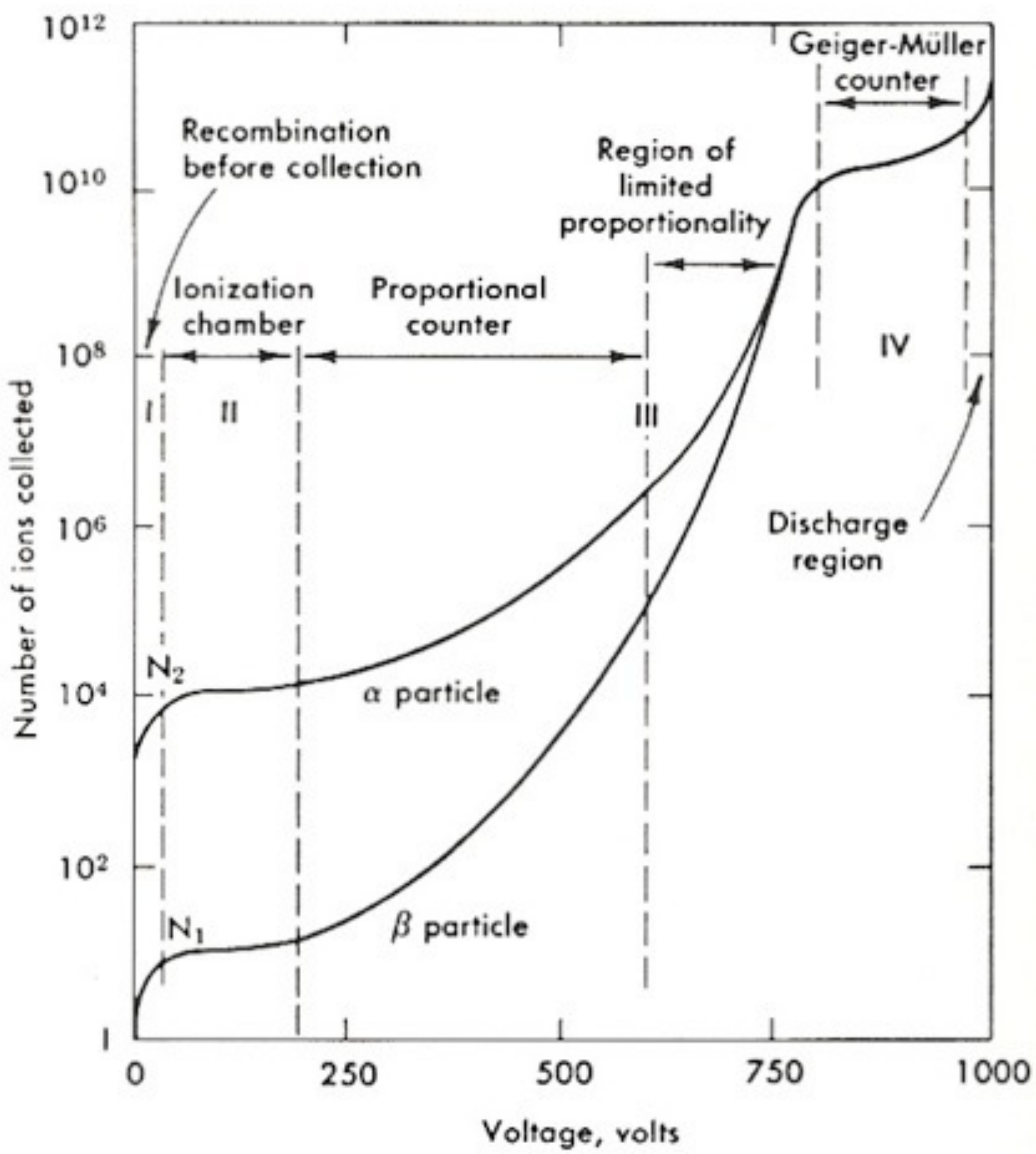
Tracker Technologies: Gas Detectors

Reminder: The Classic Ionization Chamber



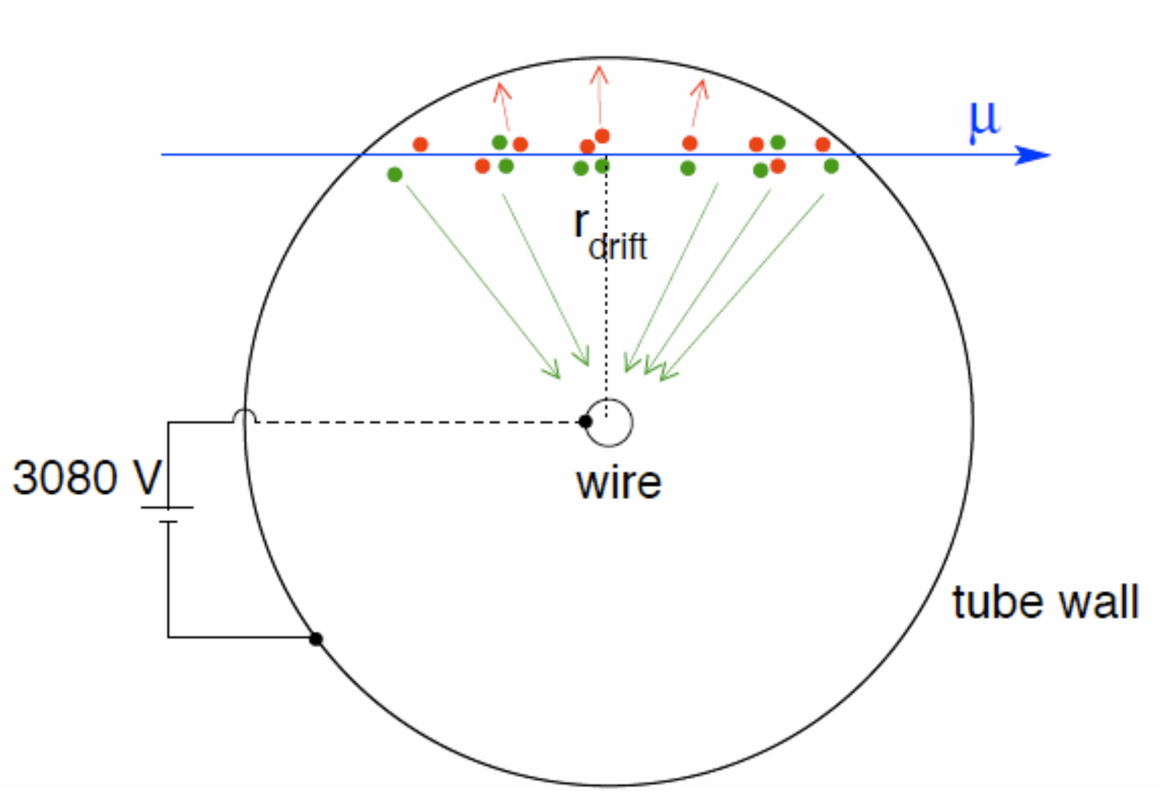


- Particles create electron-ion pairs in gas volume
- Electrons are accelerated in strong electric field, resulting in avalanche multiplication
- Depending on the applied voltage, the signal is proportional to the original energy deposition or goes into saturation



A Common Technique: Drift Tubes

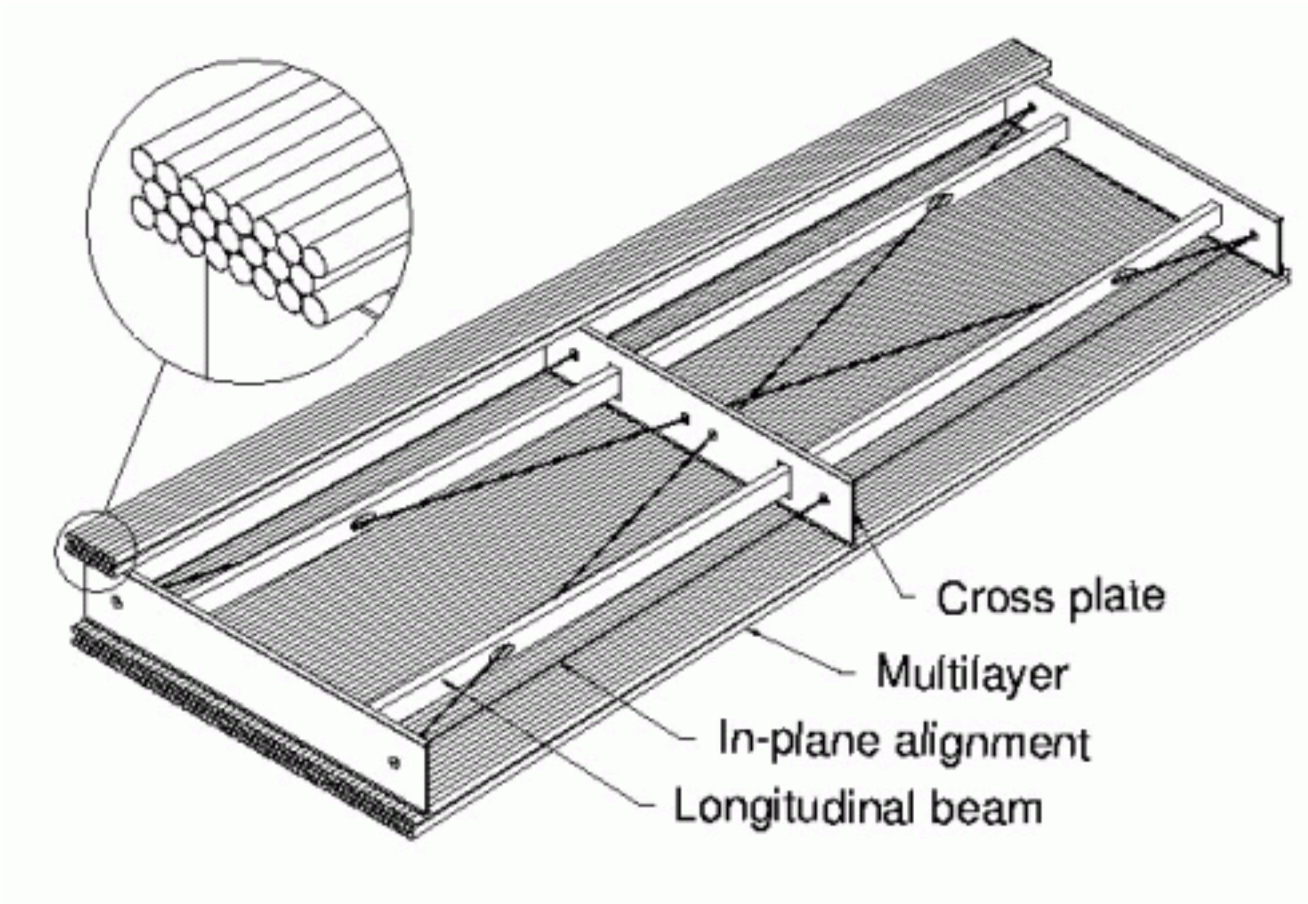
- For example: ATLAS muon system



Measurement of the drift time: gives smallest distance to wire

➯ Left/right ambiguity: Several staggered layers are required

➯ Typical spatial resolution ~100 μm



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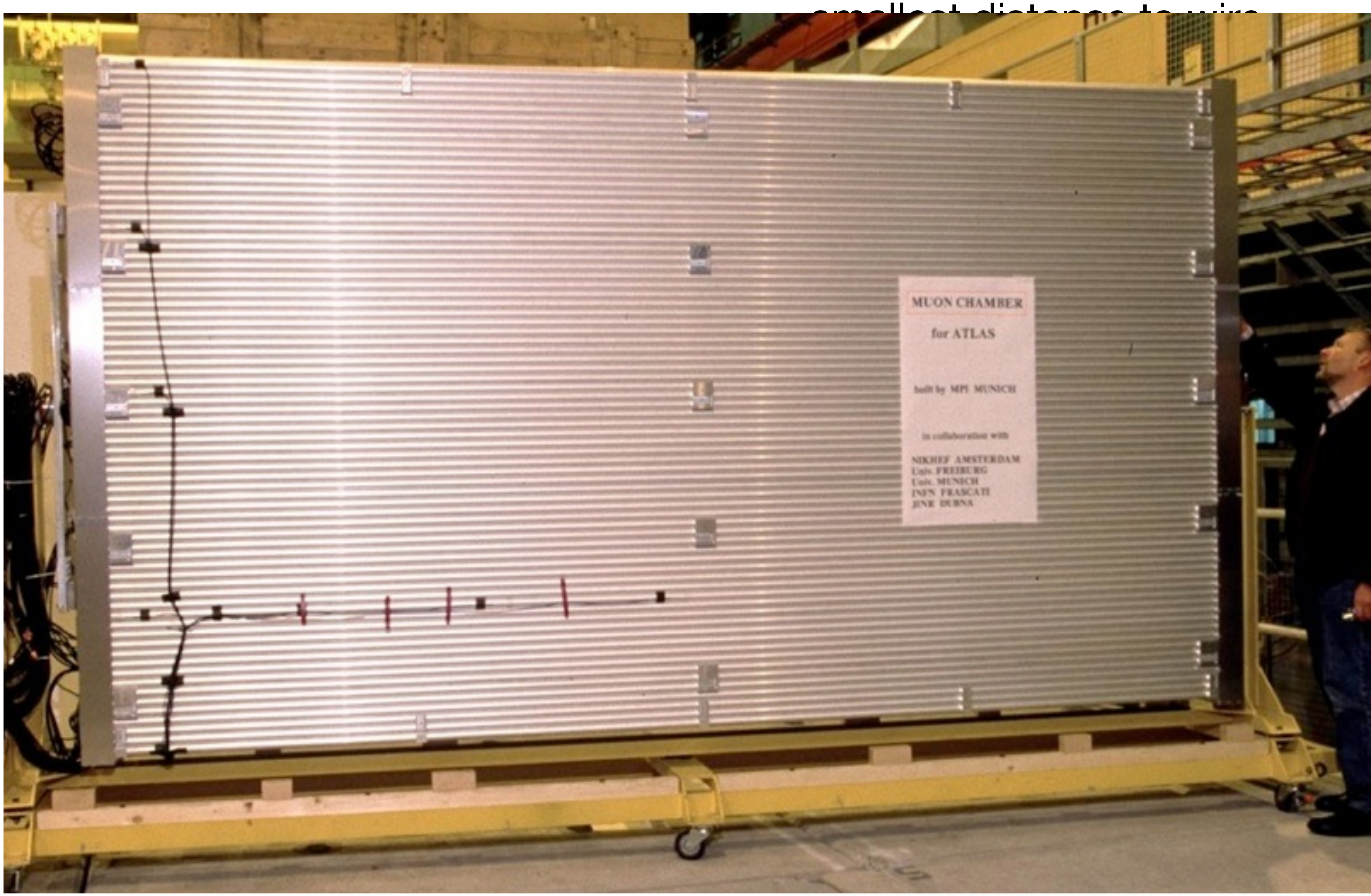


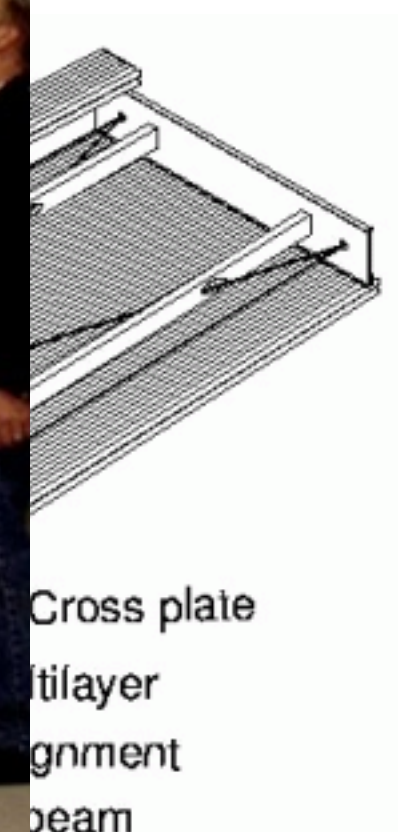
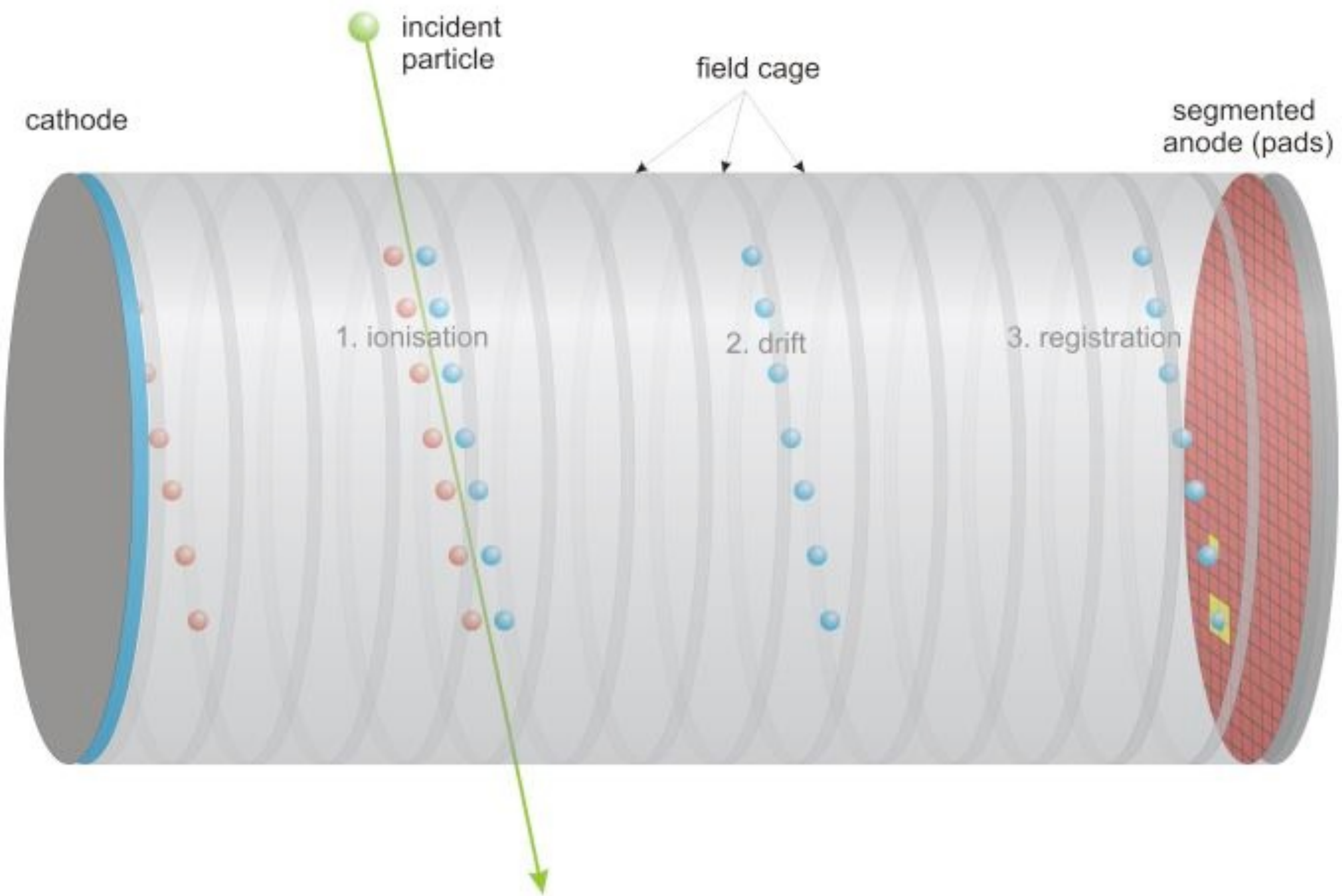


Foto: CERN

TPC: 3D Track Reconstruction

- The drift chamber idea - pushed further: Combination of 2D spatial information and time into real 3D point reconstruction



readout at the anode typically with MWPCs, newer technologies increasingly common

TPCs in Real Life: STAR

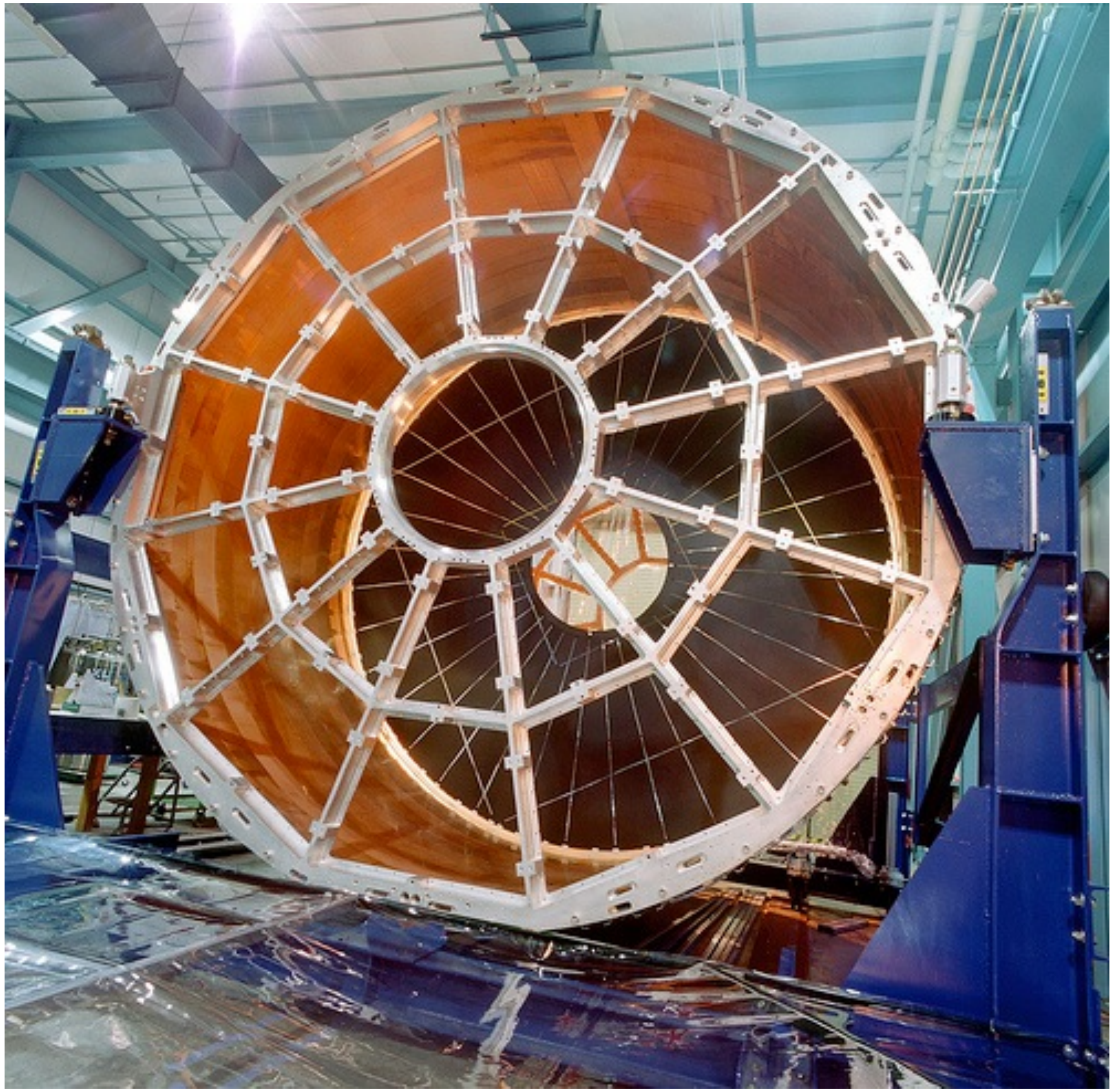
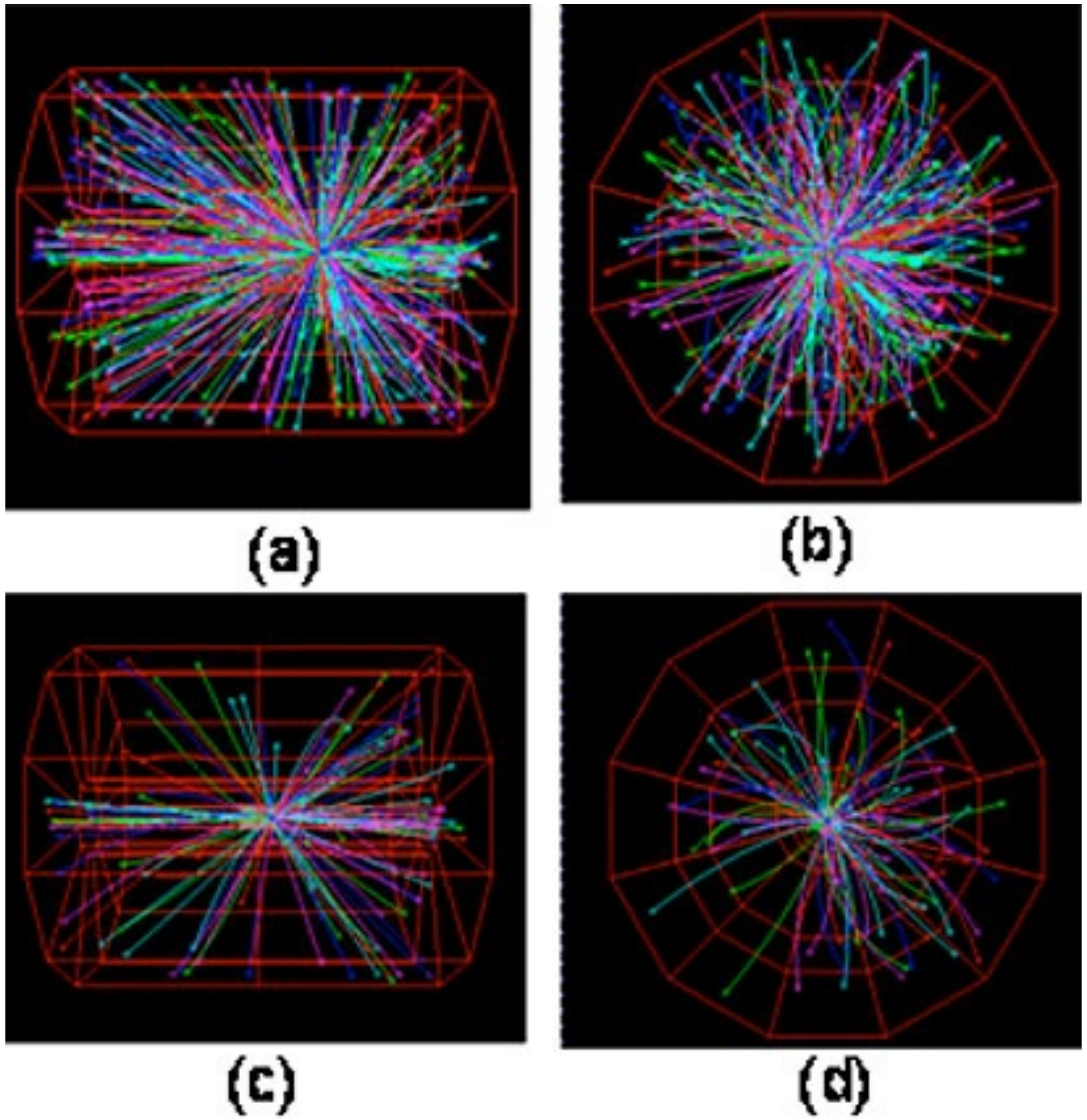


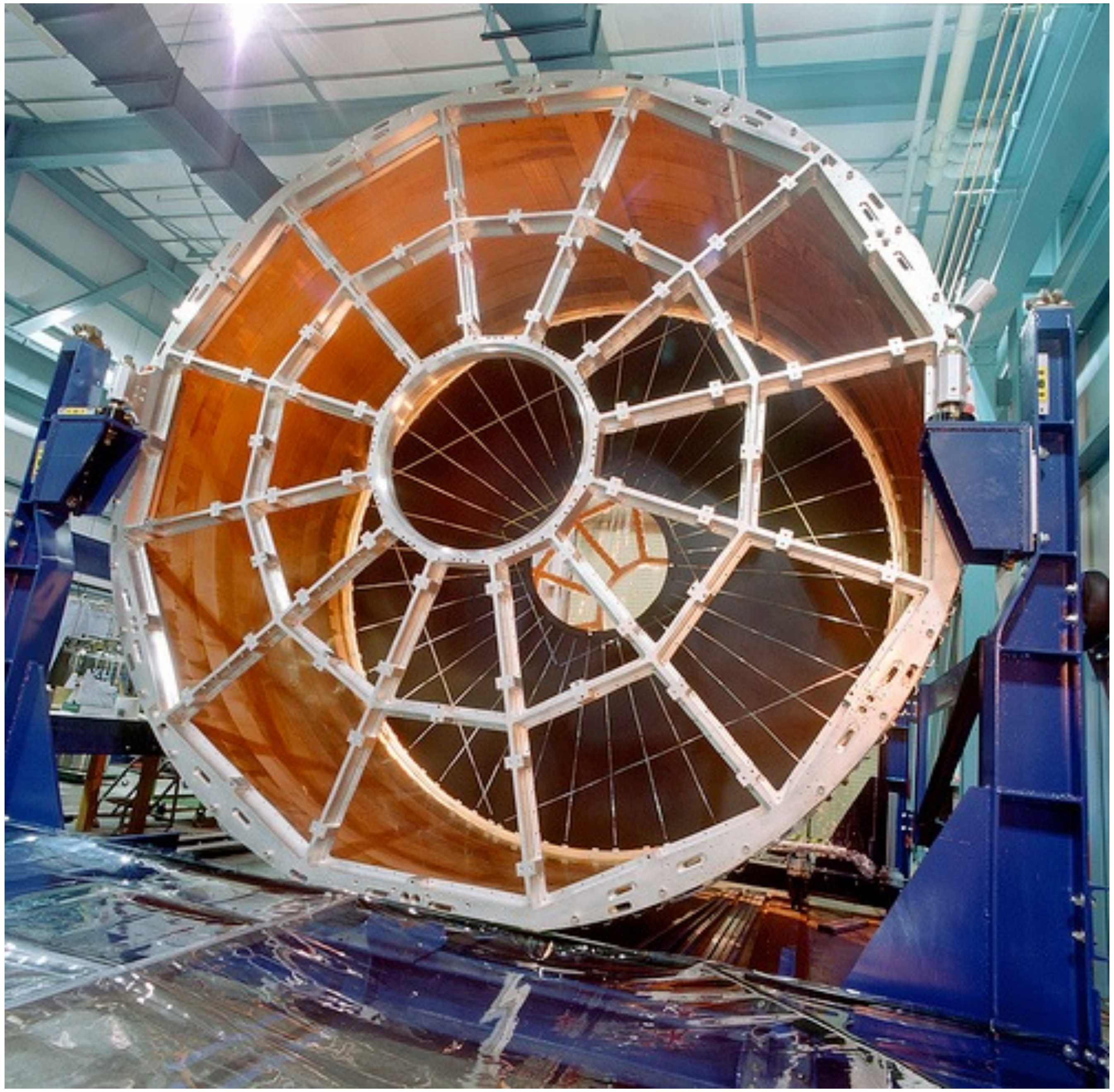
Foto: LBL



Events with low track multiplicity
Au+Au collisions at 9.2 GeV/nucleon

- 4 m diameter, 4.2 m long

TPCs in Real Life: STAR



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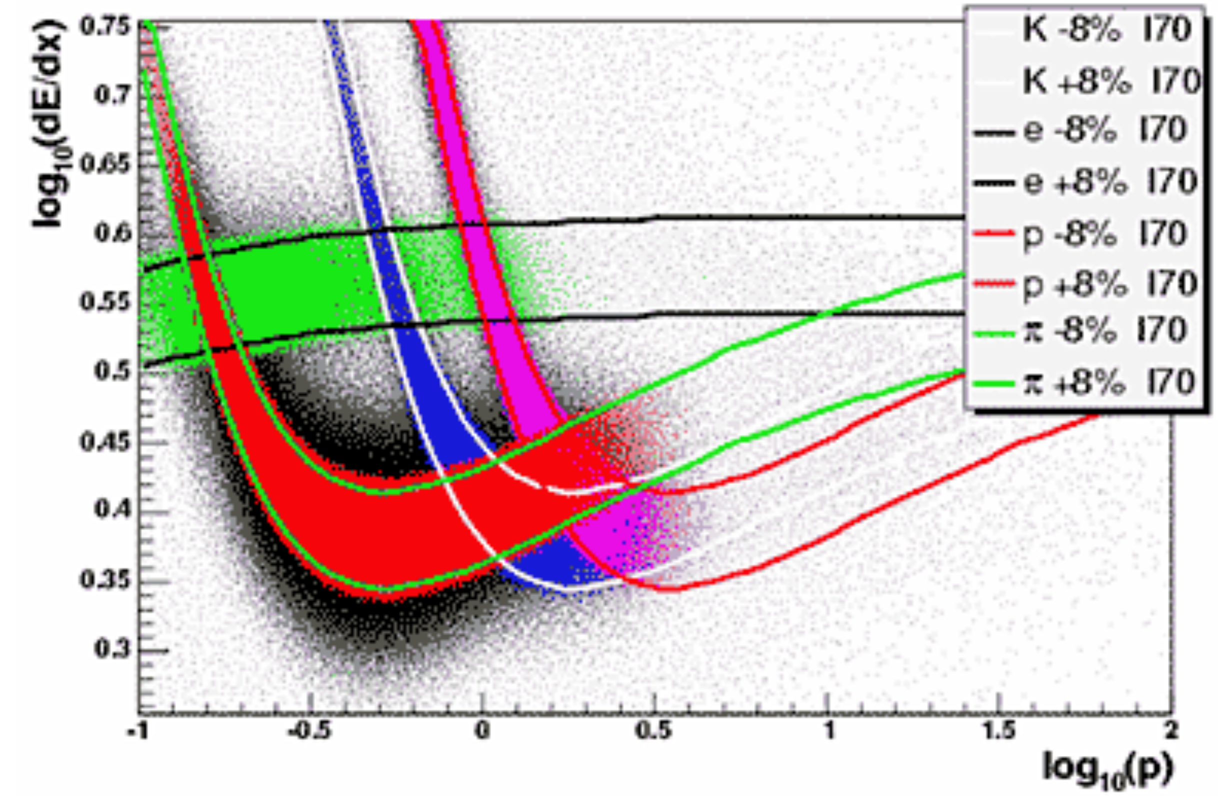
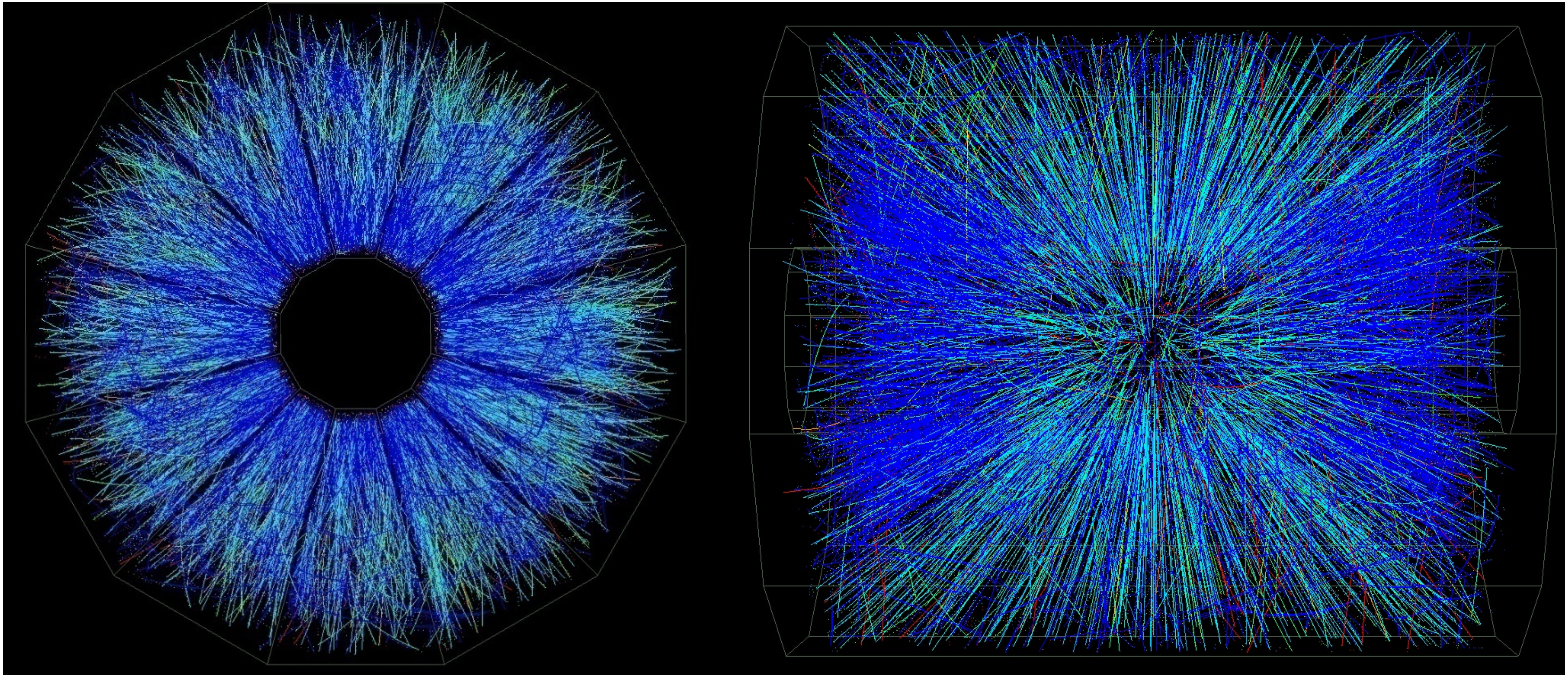


Particle identivication vie specific energy loss dE/dx

(pion ID also works at high energy!)

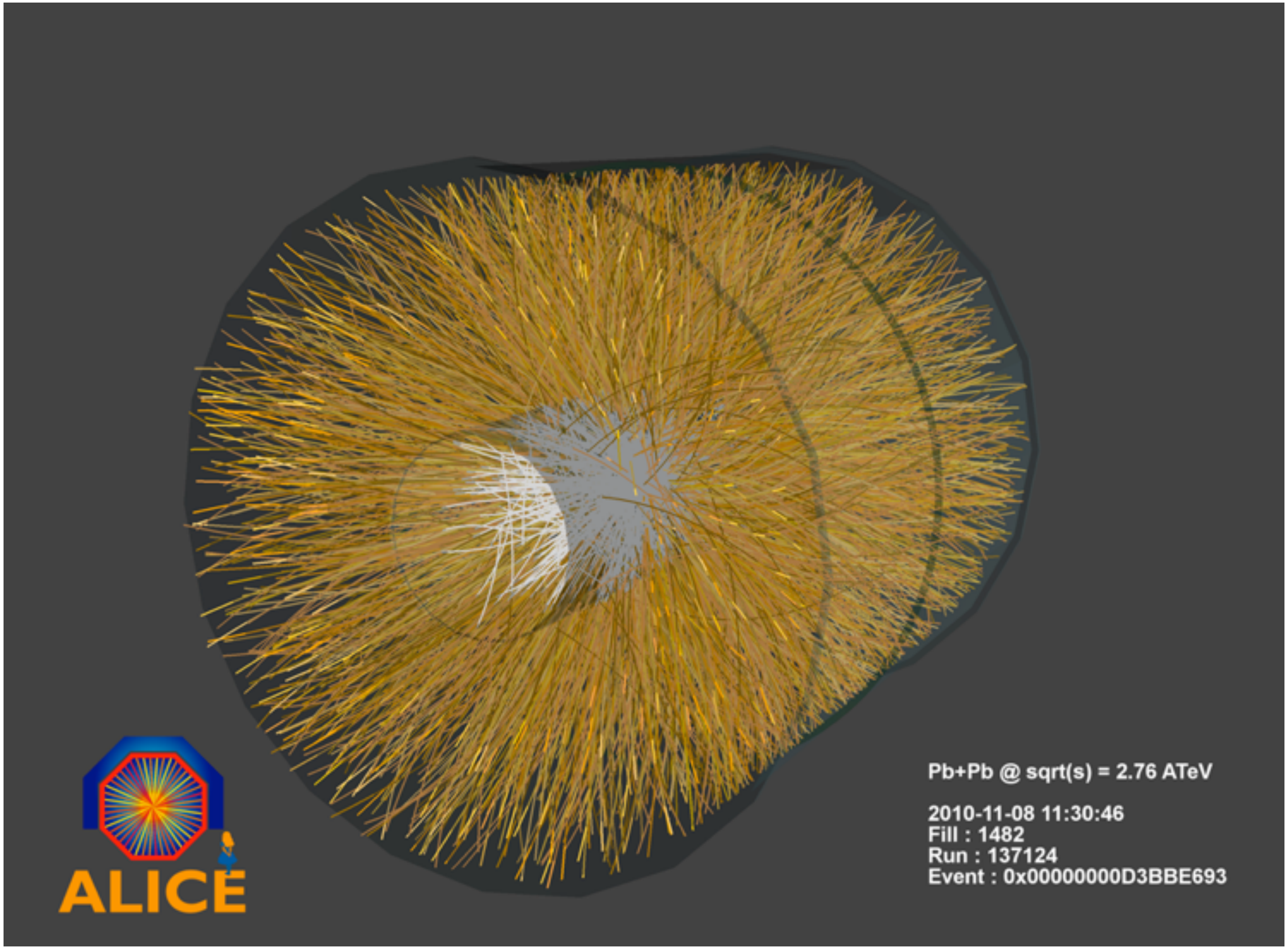
STAR TPC: Central Au+Au Collisions at 200 GeV



- TPCs can reconstruct complex events with many particles - several 1000 tracks
  - The limitation: Long readout times due to the drift time of electrons: ~ 40 μs

The biggest TPC: ALICE

- 4.9 m diameter, 5 m length

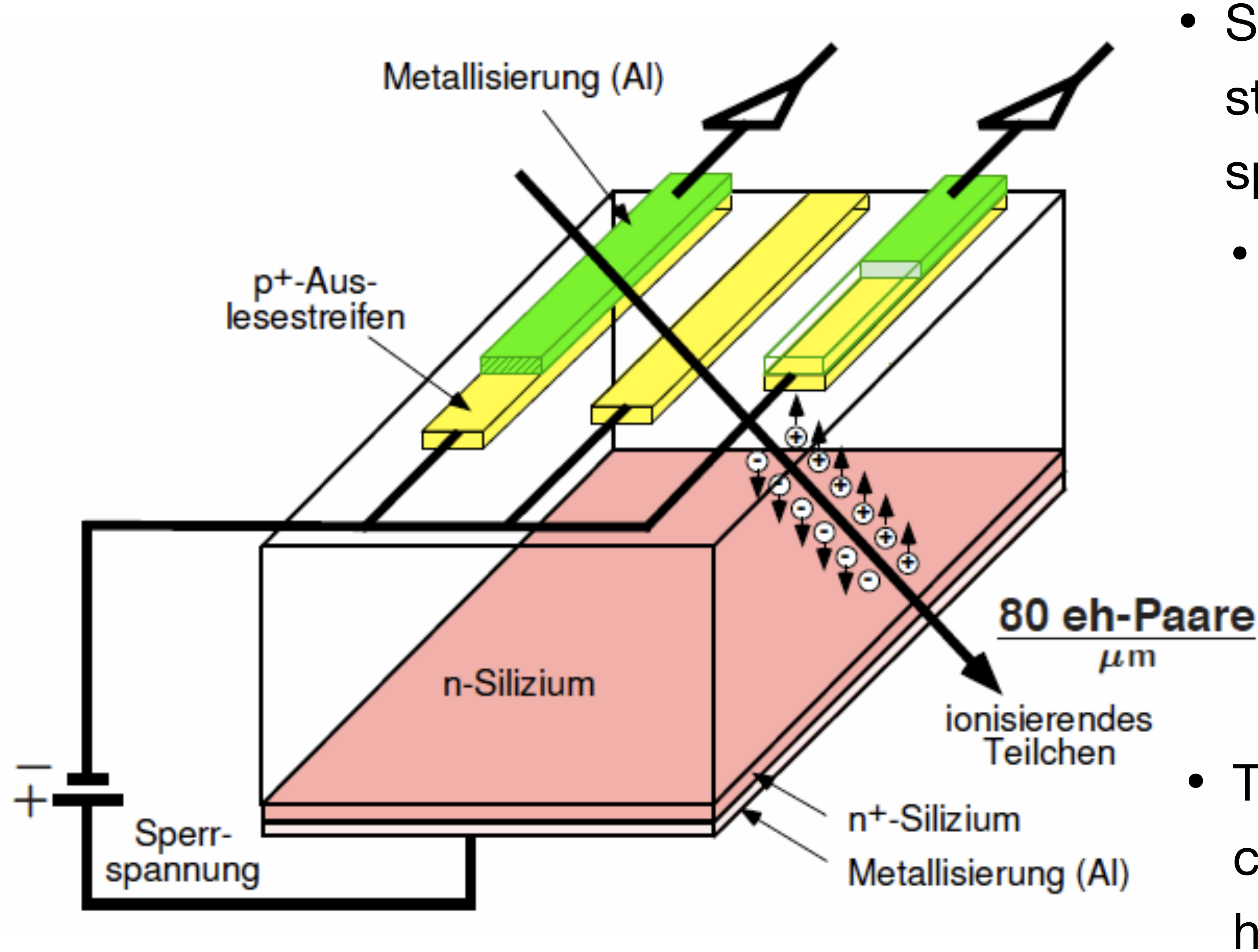


Pb-Pb collisions at 2.76 TeV/nucleon - many thousand tracks per event!

Image: CERN

Tracker Technology: Semiconductor Detectors

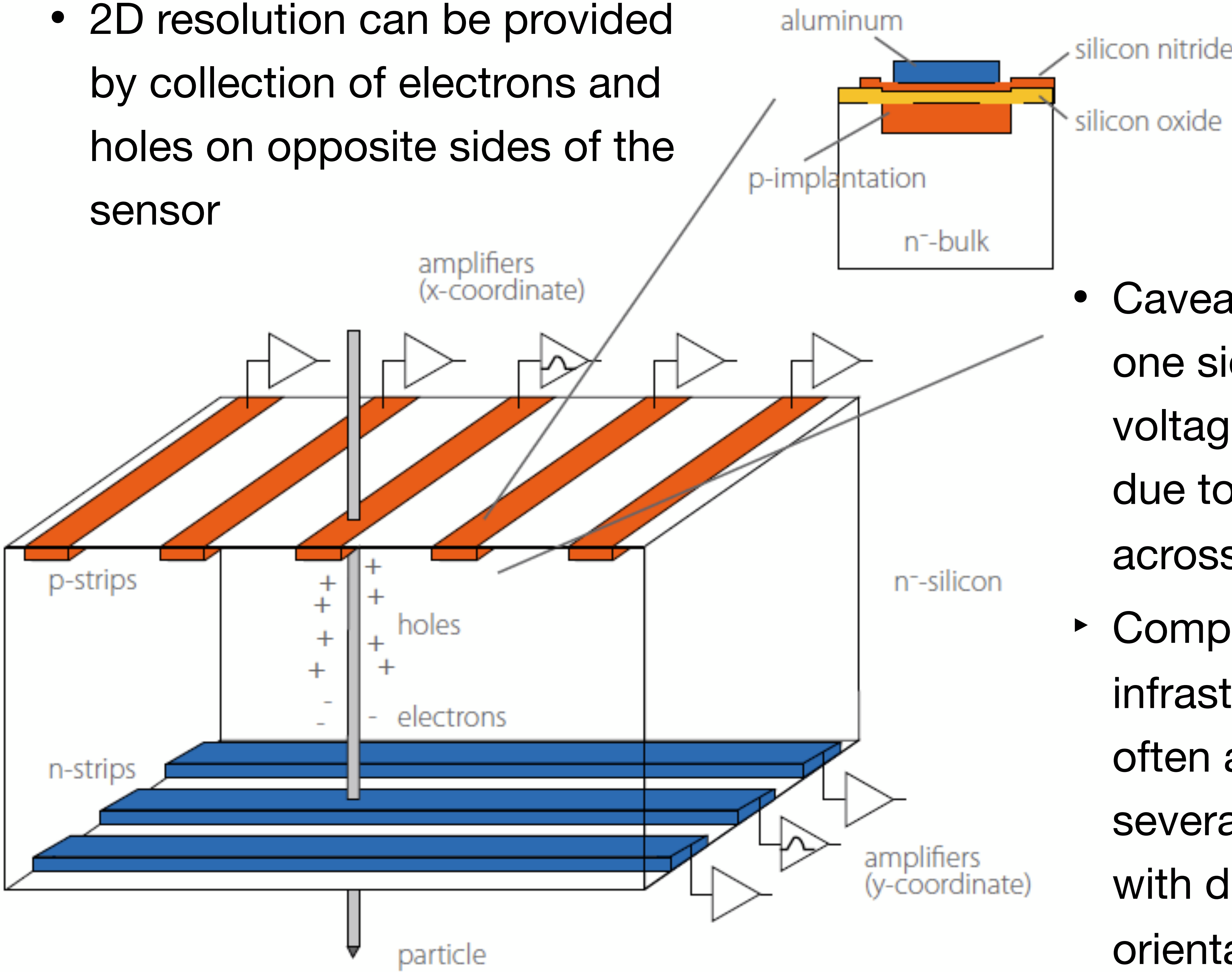
Spatial Resolution: Strip Detectors



- Silicon allows very fine structures - ideal for high spatial resoluton
  - typical strip-to-strip distance ~ 50 µm
- The price to pay: Very high channel counts - Requires highly integrated electronics

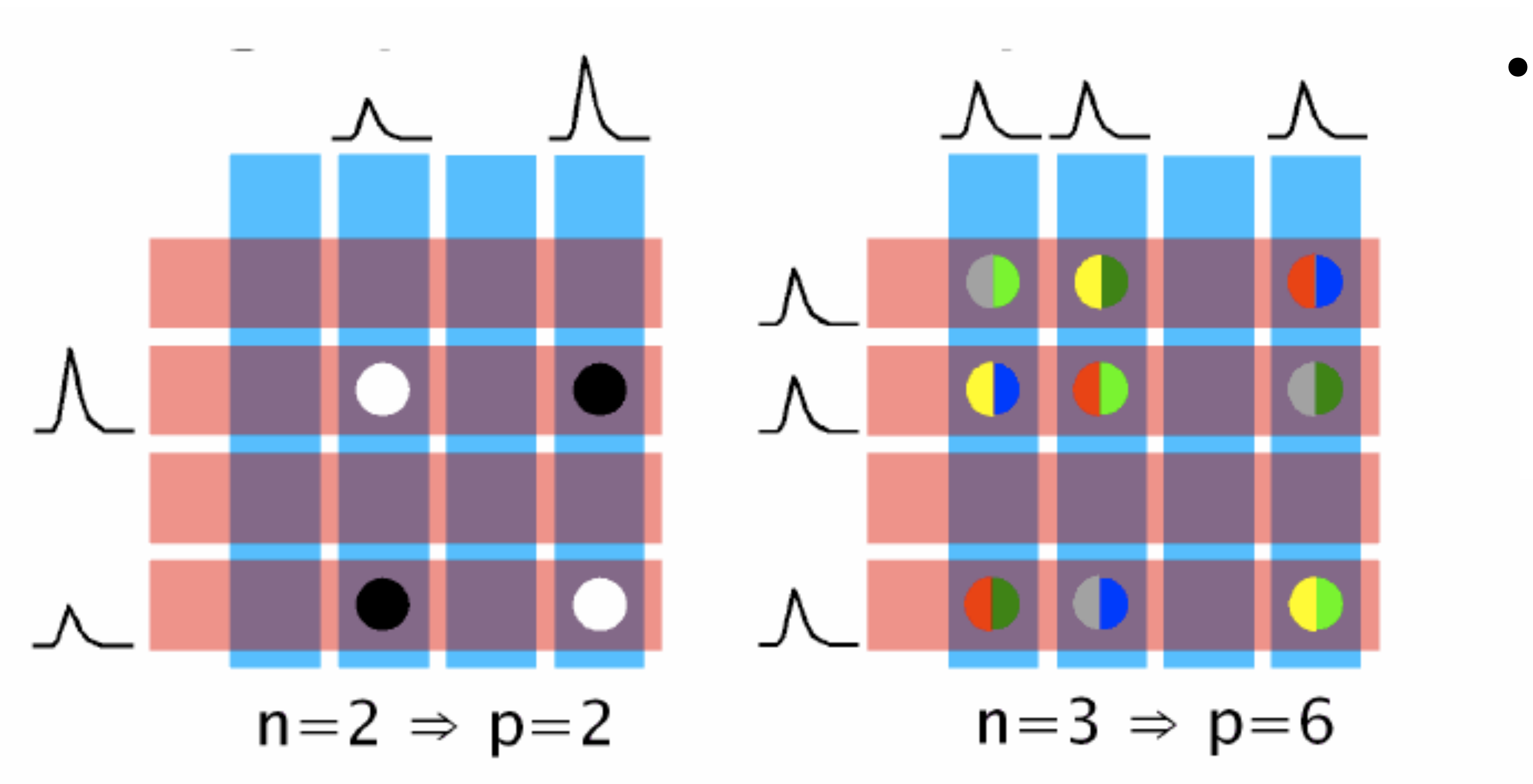
2D - Resolution with Silicon

- 2D resolution can be provided by collection of electrons and holes on opposite sides of the sensor



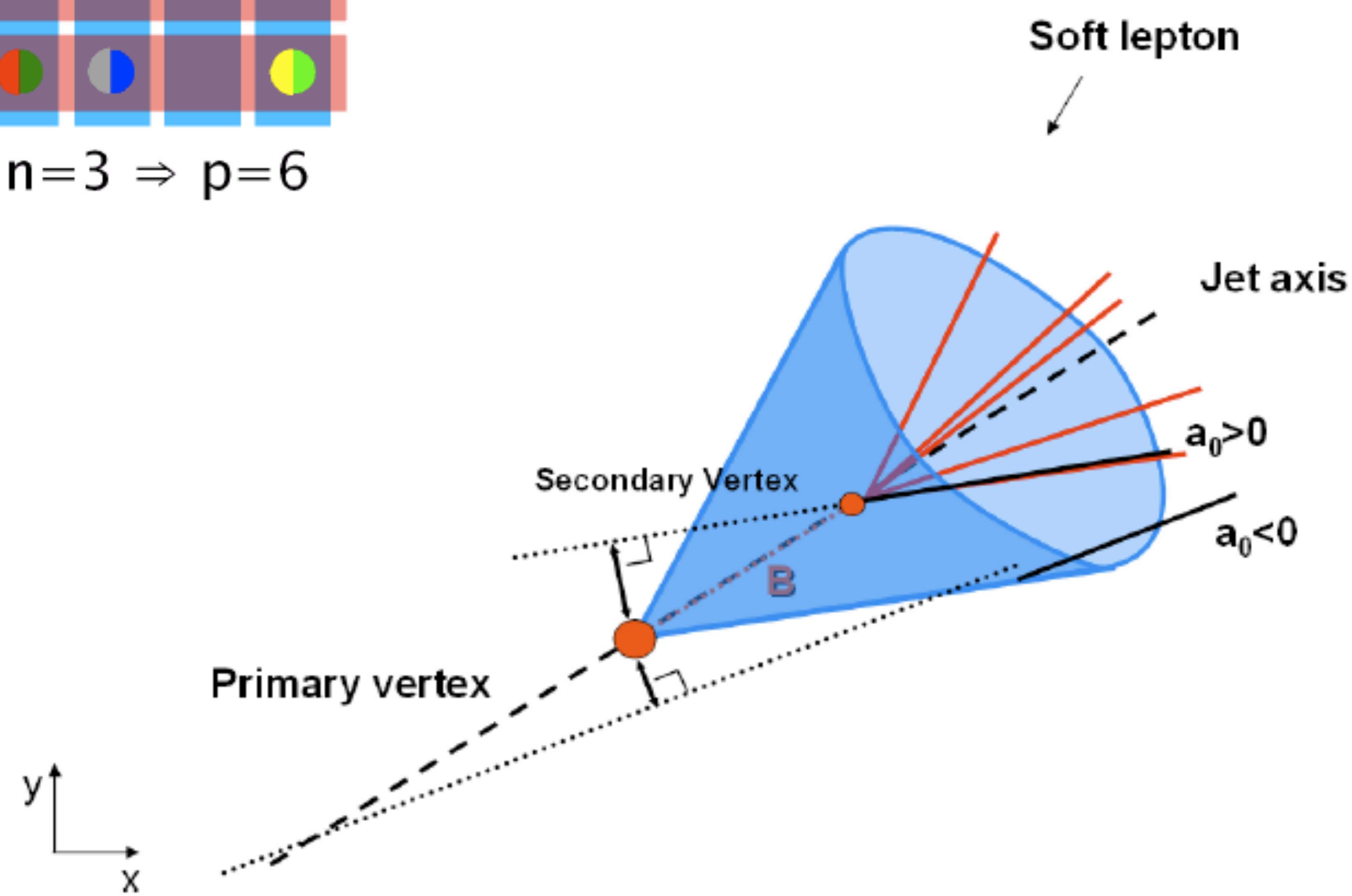
- Caveat: The electronics on one side has to be on high voltage instead of ground, due to the bias voltage across the sensor
  - Complicates the detector infrastructure considerably, often avoided by using several single-sided layers with different strip orientation

The Limits of Strip Detectors

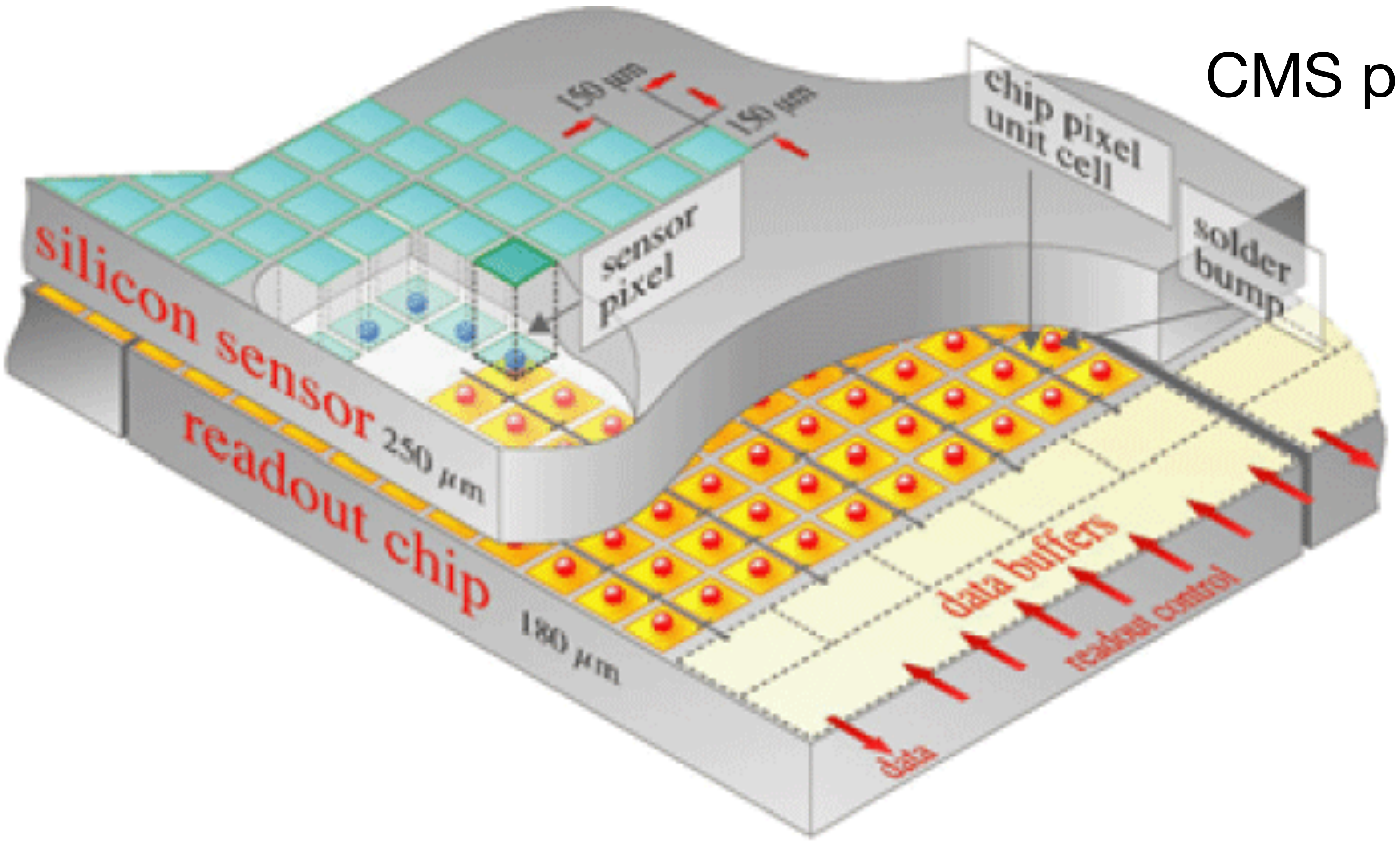


- For high particle densities there are ambiguities when going from 1D hits to 2D points: Track reconstruction collapses at some point

- Also: Spatial resolution typically only good in one coordinate (orthogonal to strip) - Insufficient to reconstruct secondary vertices



Pixel Detectors - The Principle



CMS pixel scheme

“Hybrid Pixels”

- CMS Pixels: ~65 M channels 150 x 150 µm
- ATLAS Pixels: ~80 M channels 50 x 400 µm (long in z or r)

- Pixel-detectors allow tracking in environments with high particle density without ambiguities
- Good spatial resolution in two coordinates with a single layer (depending on pixel size and charge sharing between pixels)
- Very high channel count -> Challenging readout, in particular if it needs to be fast

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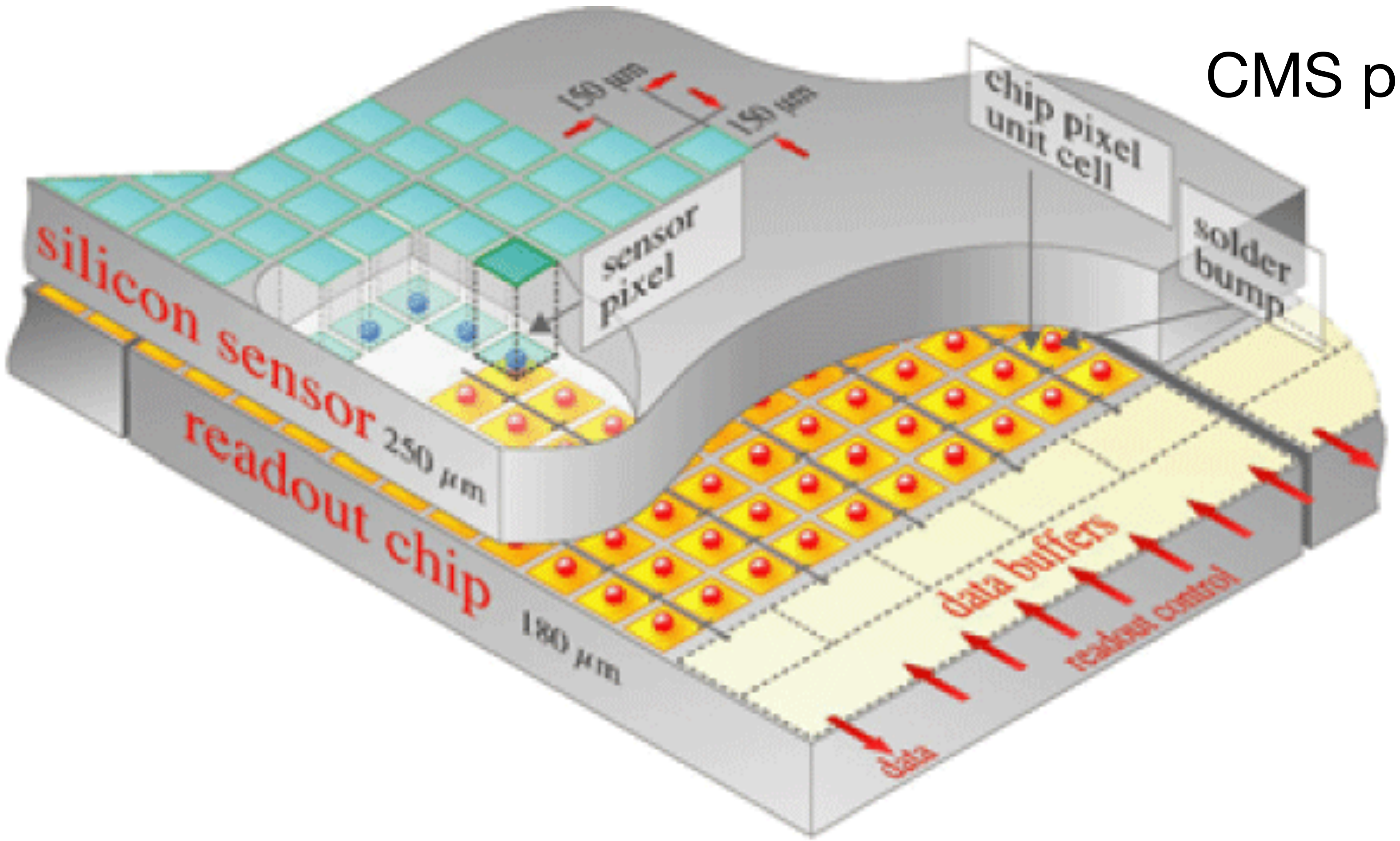

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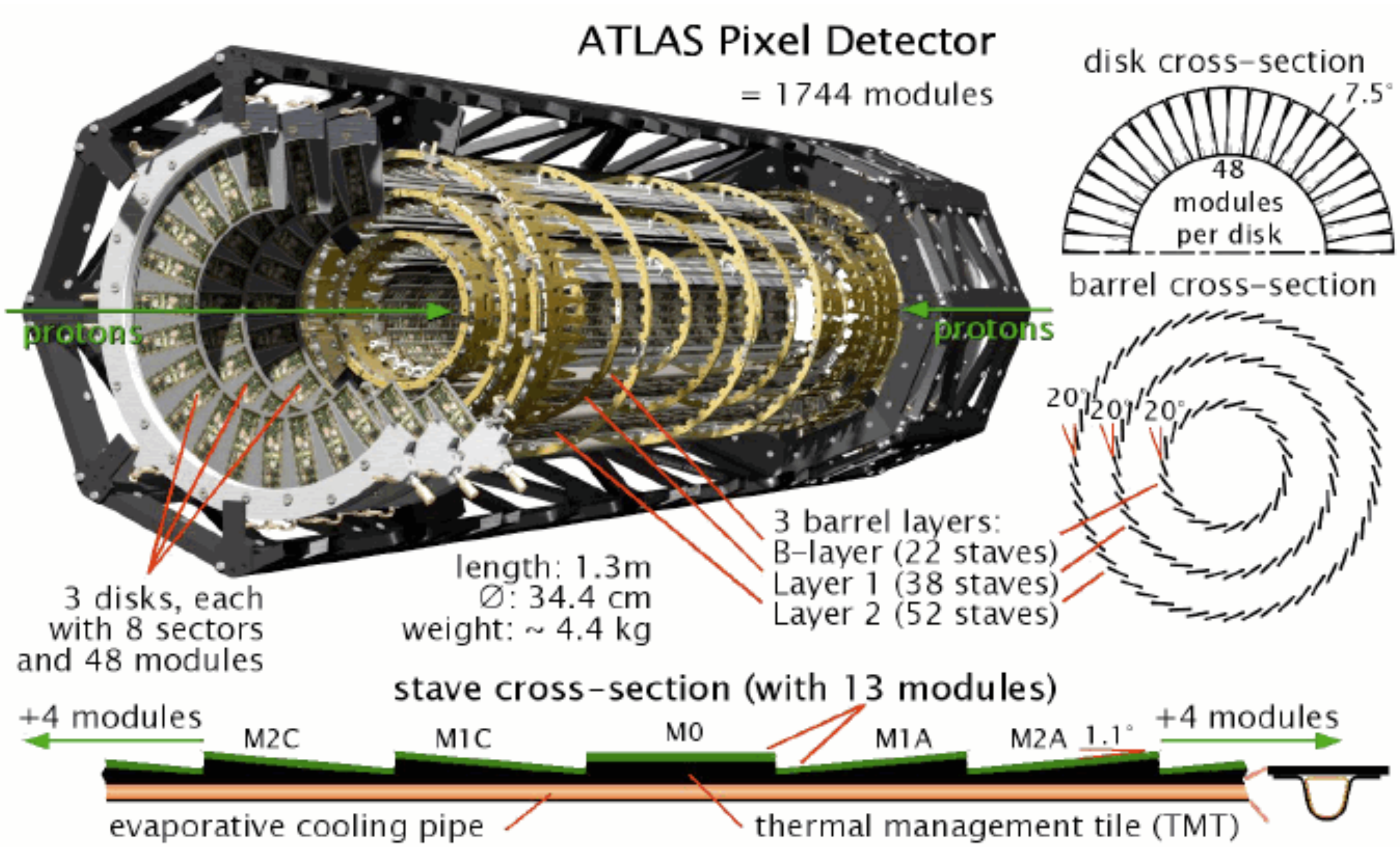
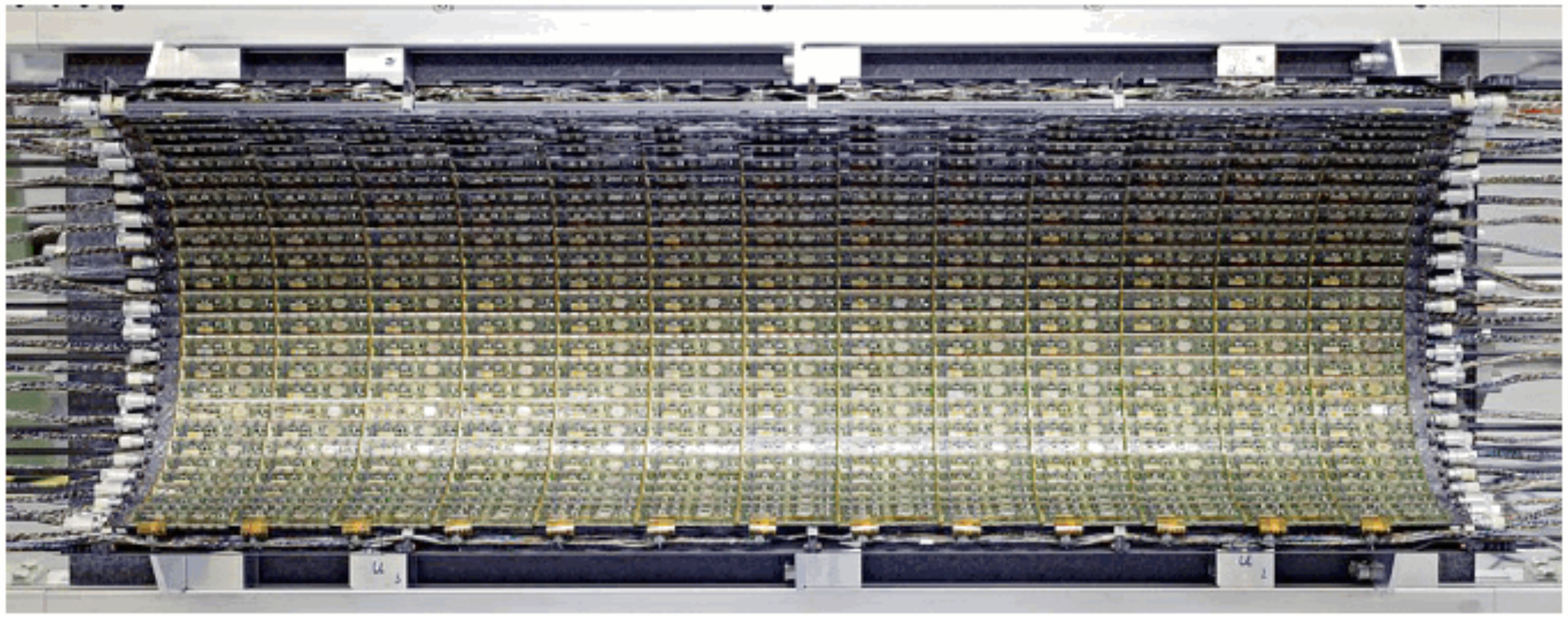
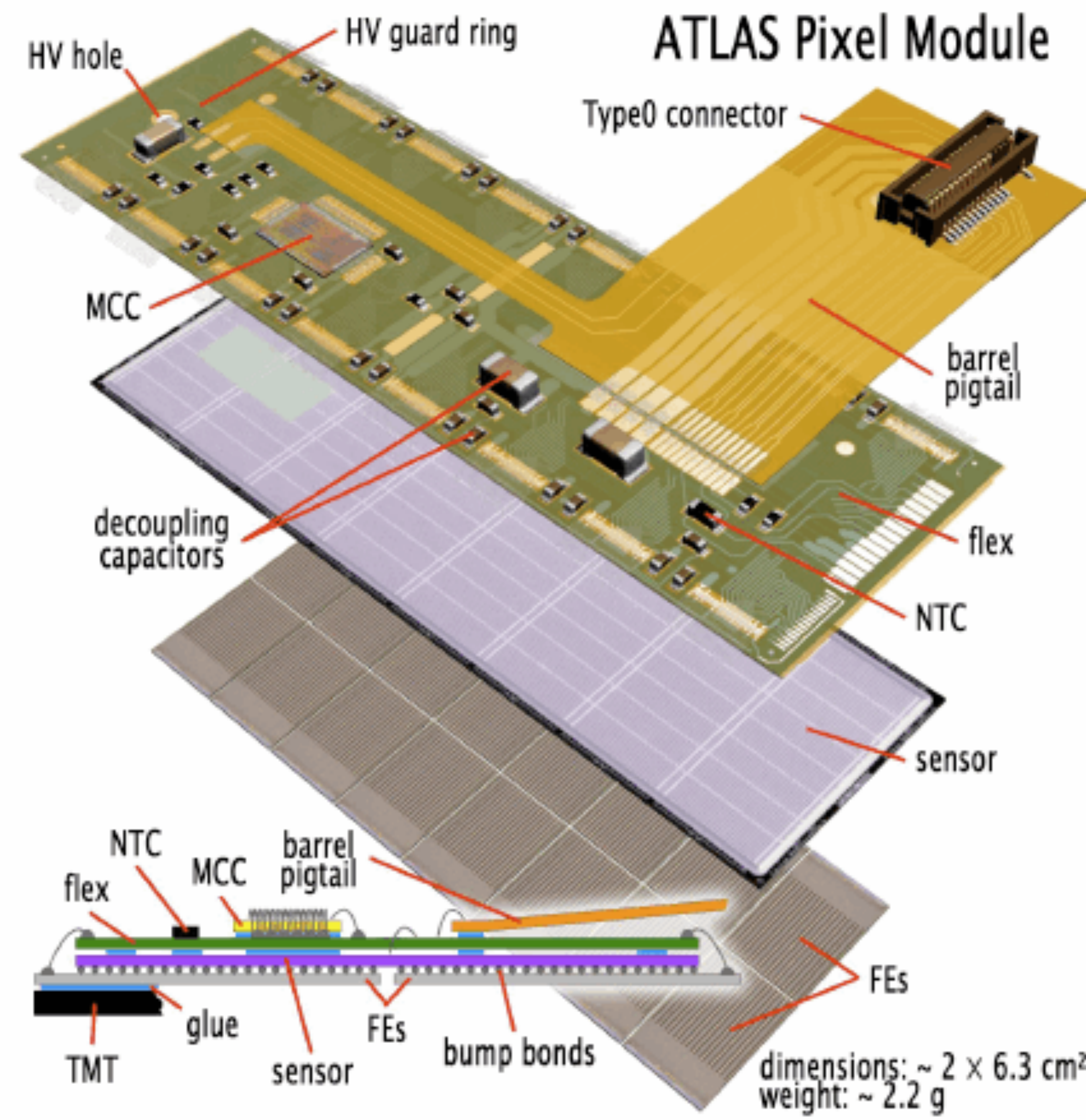
... relatively high material budgets with fast readout: separate electronics layer!

ATLAS Pixels: A Closer Look

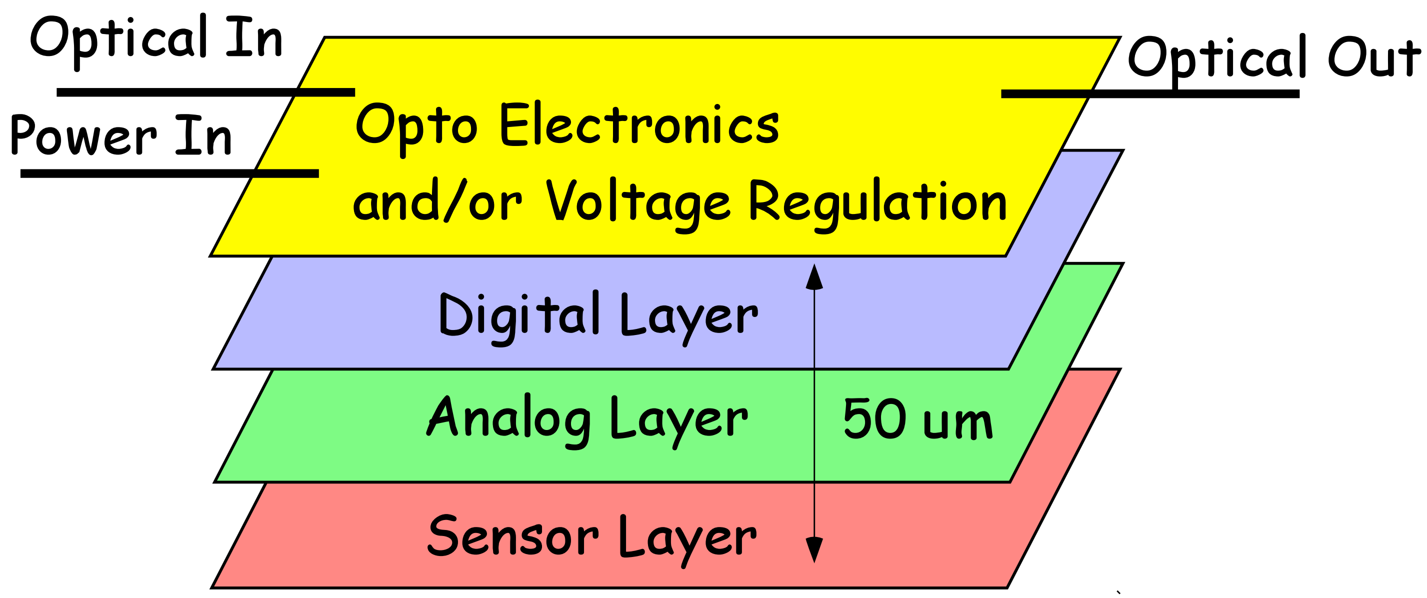






Technologies for the Future: 3D Silicon

- The dream: All on a single chip
  - sensitive detector
  - analog pulse shaping
  - digitization
  - communication and control



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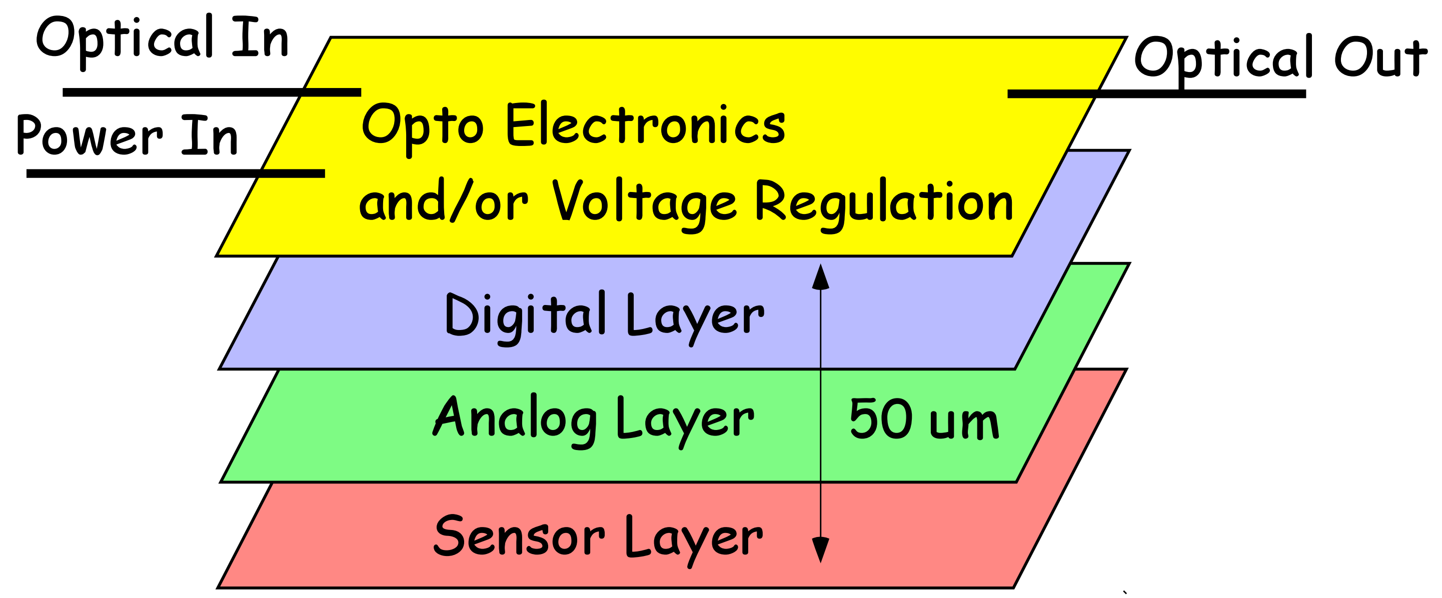
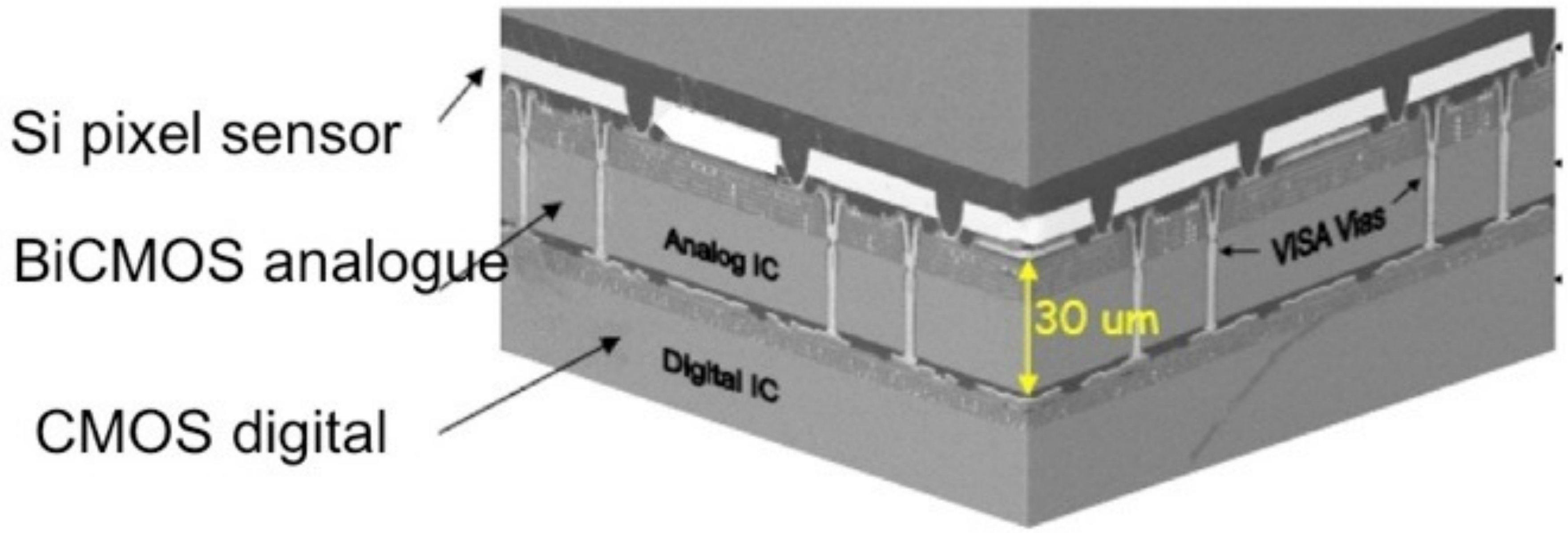


- Use of several thin Si layers which can be based on different processing technologies
- Important: The electrical connection between the different layers



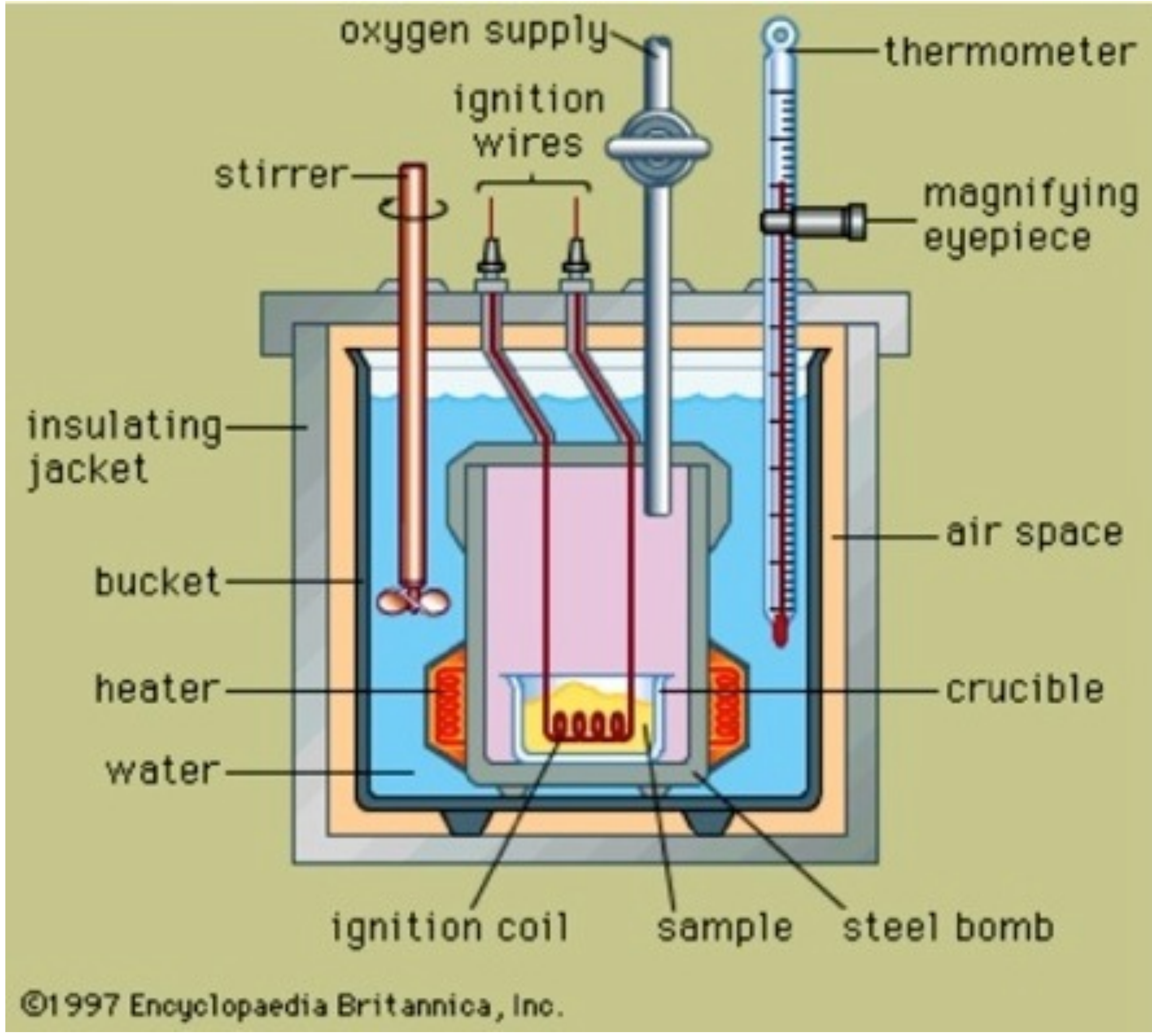
At the moment different technologies are being developed and tested...

Calorimetry: Energy Measurement

The Concept

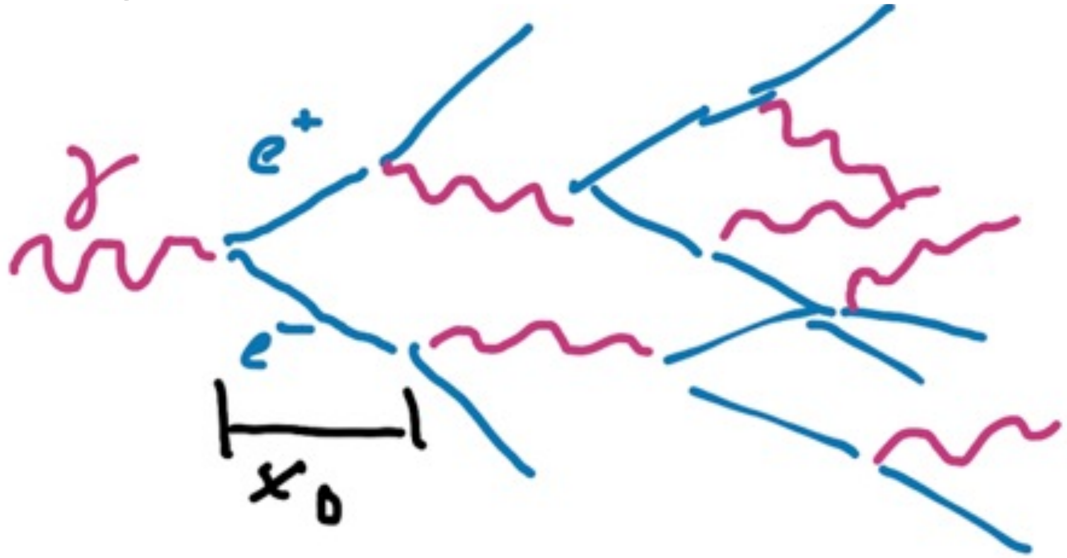
- Originally from chemistry: Measurement of the released heat by a chemical reaction: Here increase of temperature of a well-known amount of water

- For elementary particles: Measurement of the energy of a particle by total absorption
  - 1 cal = 10^7 TeV: Very small energies, no temperature increase!
    - Somewhat more sophisticated strategy for energy measurement needed

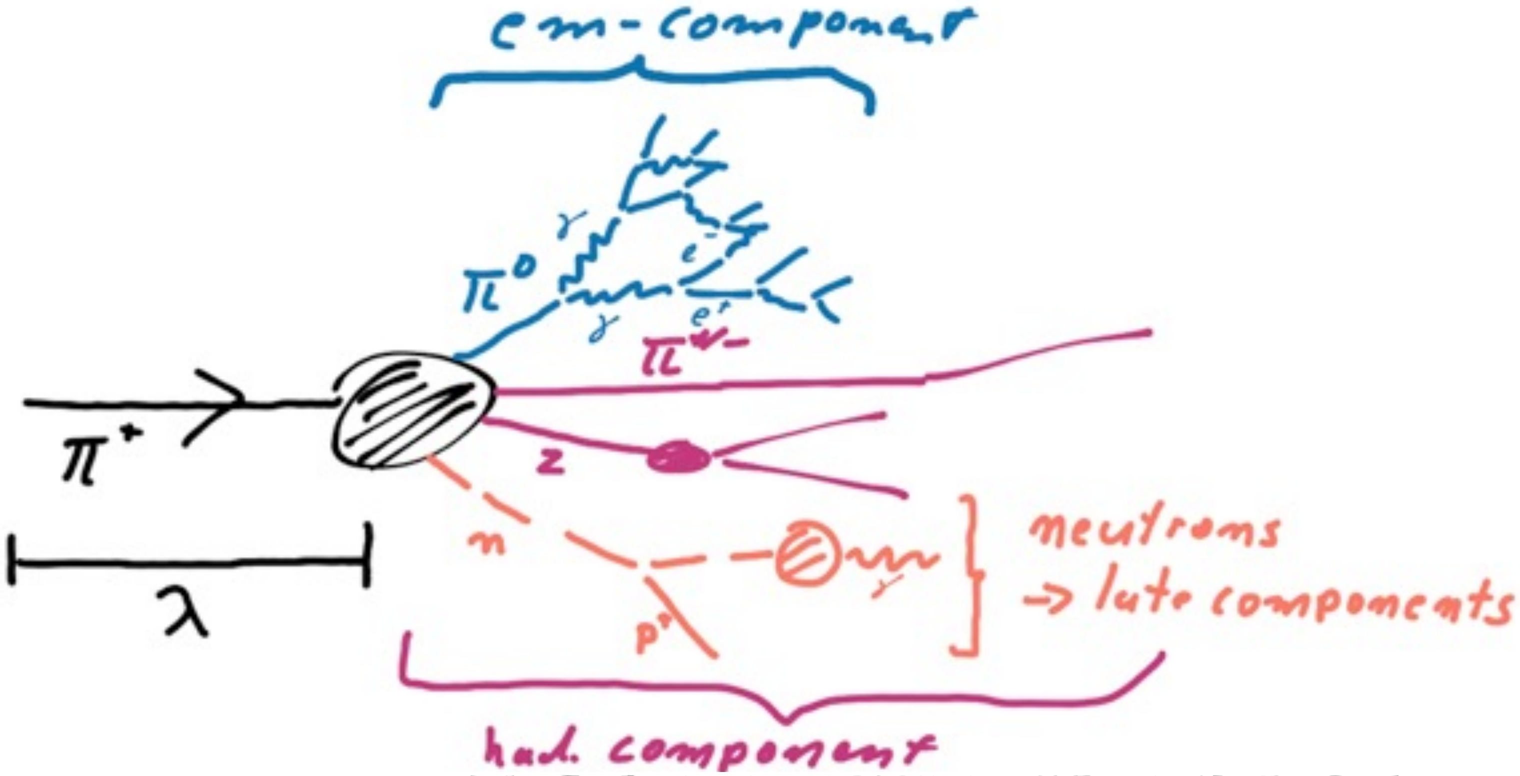


Particle Showers

- Measurement of highly energetic particles: Showers
  - Electromagnetic: Successive pair creation / Bremsstrahlung

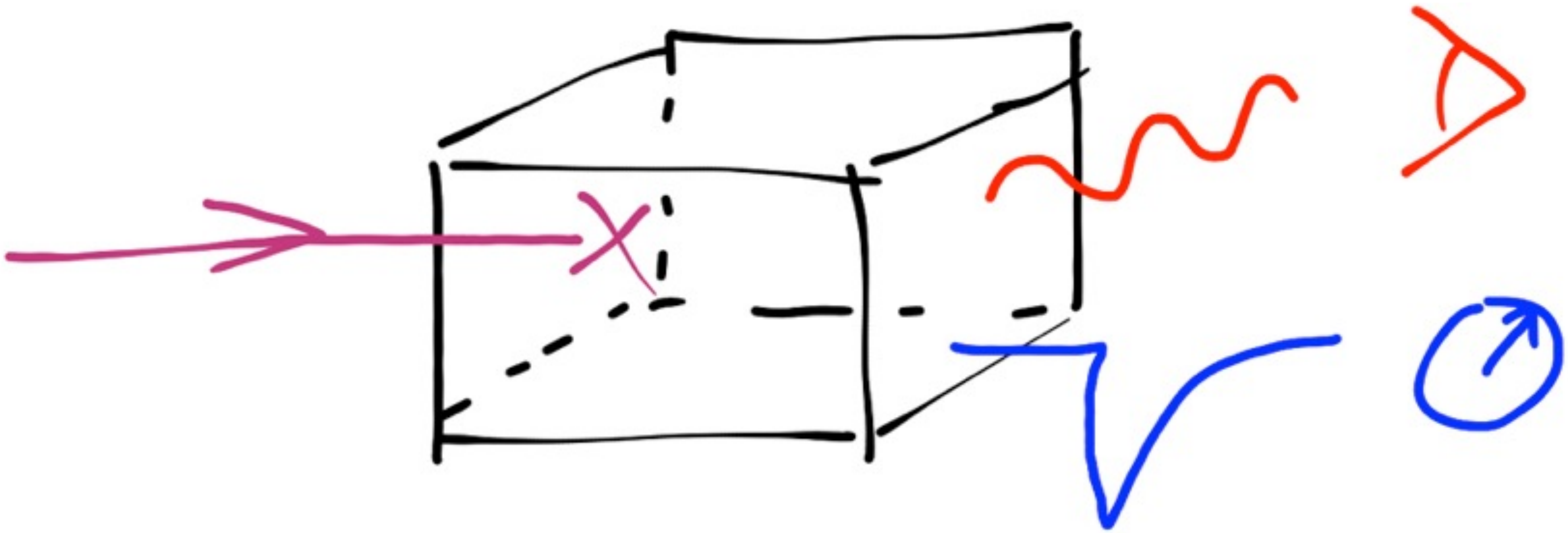


  - Hadronic: Hadronic cascade with hadronic and em content



Measuring Energy with a Calorimeter

- Convert the energy of the incident particle to a detector response
- Choose something that is easily detectable also for “small” energies
  - Electric charge
  - Photons (in or close to visible range)



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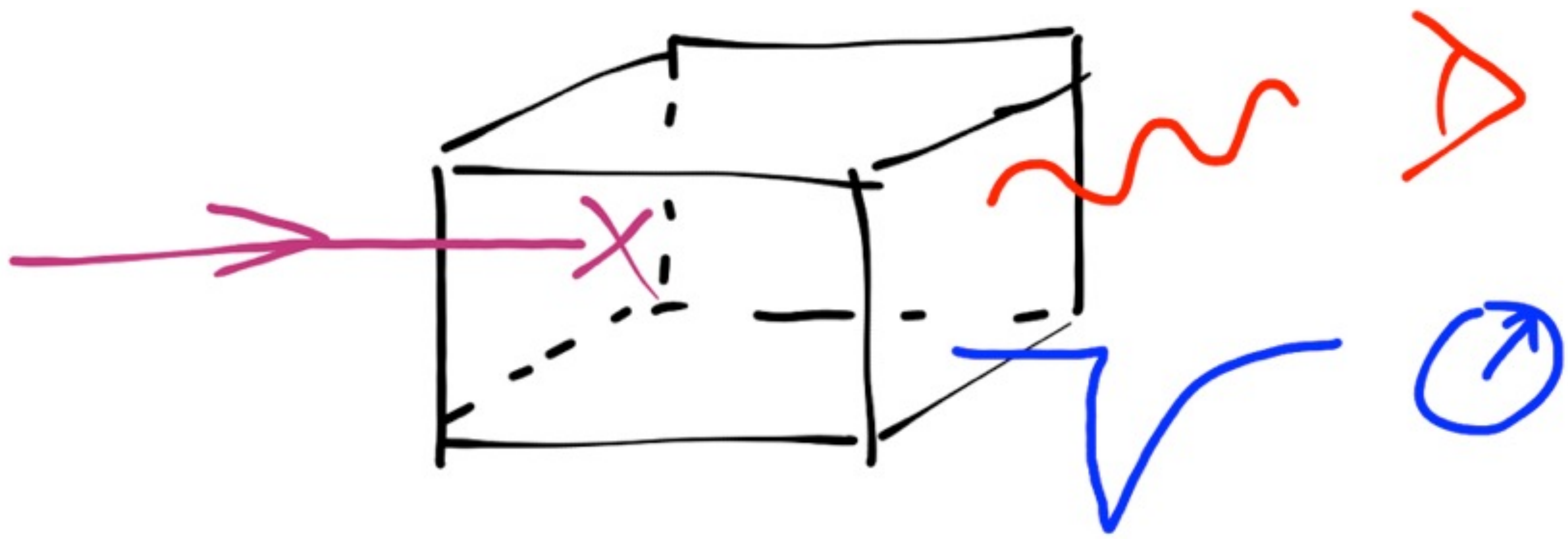


N.B.: Also other channels are used - thermal for example in cryogenic DM-search experiments, acoustic measurements, ... Not covered here!

Measuring Energy with a Calorimeter

- Calorimetric processes are stochastic:
  - Counting of photons / created charge carriers
  - Number of secondary particles in showers induced by high-energy particles

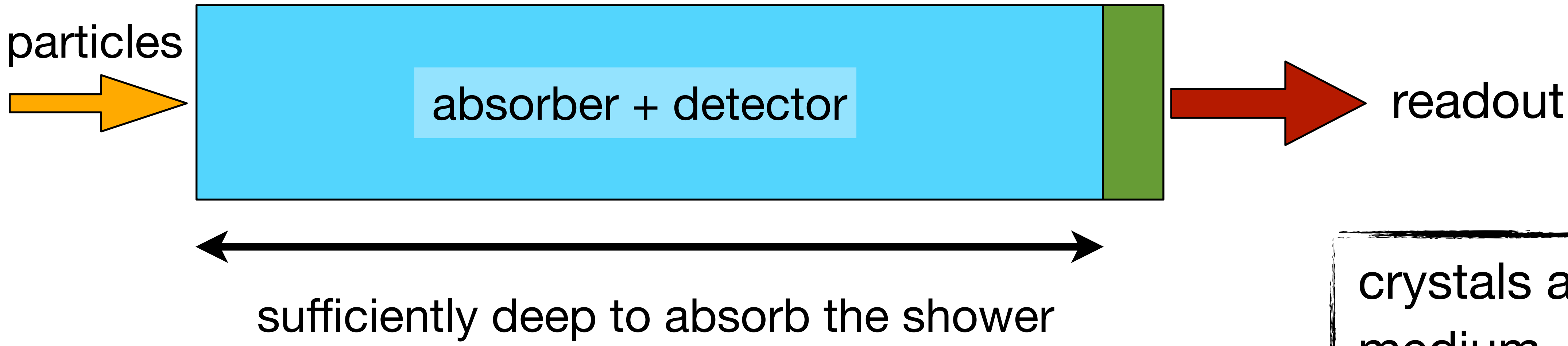
Energy resolution often well-described by $$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Three components:
  - *a*: The **stochastic** term: The counting aspect of the measurement: Simple statistical error: scales with the square root of the number of particles
    ➩ Resolution term scales with $1/\sqrt{E}$
  - *b*: The **noise** term: Constant, energy-independent noise contribution to the signal -
    ➩ Resolution term scales with 1/E
  - *c*: The **constant** term: Contributions that scale with energy: Influence of inhomogeneities in the detector material, un-instrumented or dead regions, ...
    ➩ Resolution term is independent of energy

Calorimeter Types

- The dream: Contain the full energy of one particle, convert all energy into a measurable signal which is linear to the deposited energy
  - Reality is often different, in particular when measuring hadrons

Two types: ***homogeneous calorimeters*** and *sampling calorimeters*



crystals as active medium

- The shower develops in the sensitive medium
  - Potentially optimal energy resolution: Complete energy deposit is measured
  - Challenging readout: No passive readout structures in detector volume

Calorimeter Types

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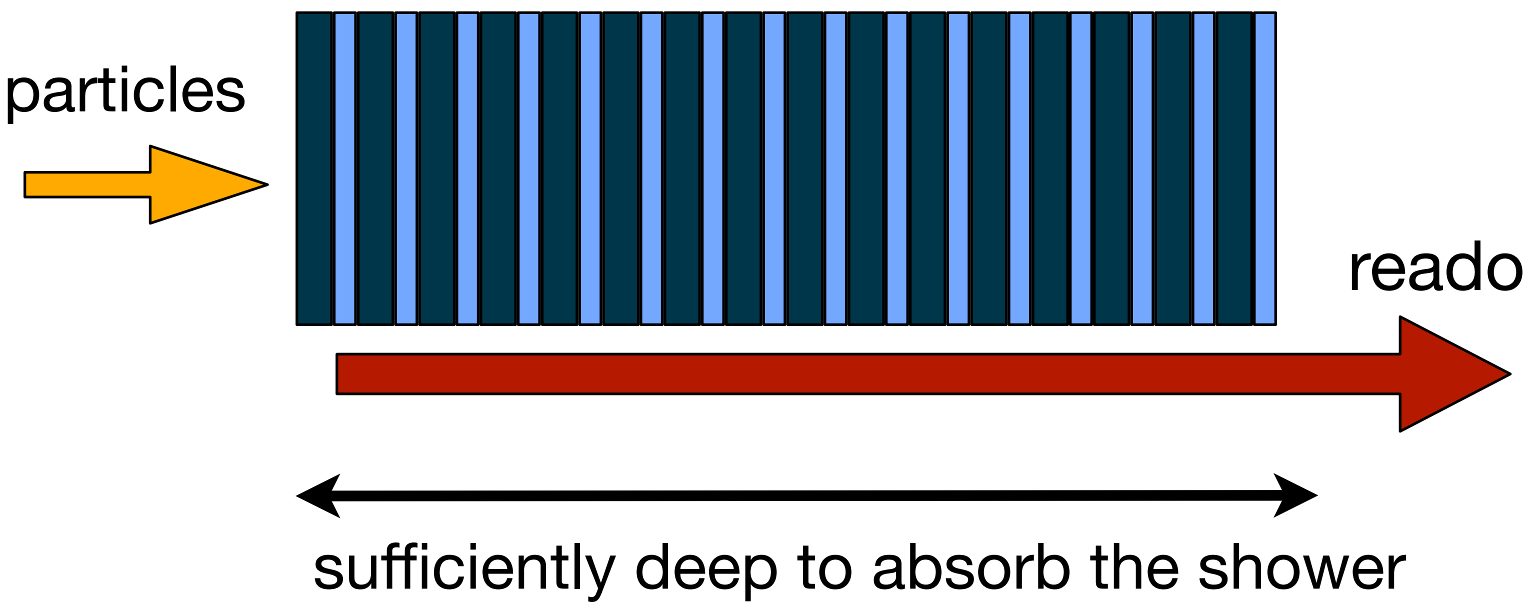
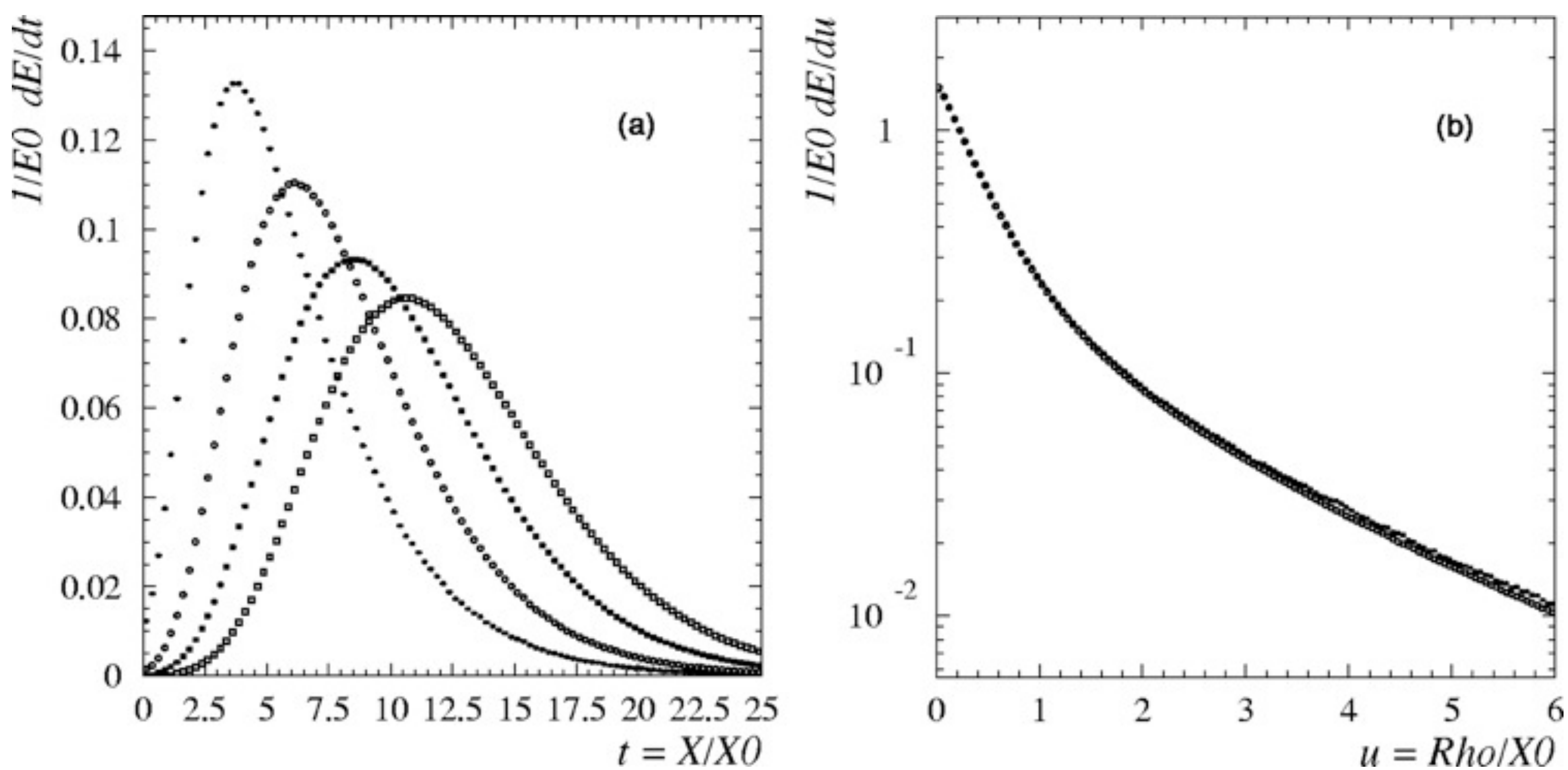


highly flexible in choice of absorbers and active medium

- The shower develops (mostly) in dense absorber medium, particles are detected in interleaved active structures
- Potentially reduced energy resolution: Only a fraction of the deposited energy is detected

Characteristic Parameters of Showers - EM

- Longitudinal development described by X_0
- Lateral shower size given by Moliere Radius ρ_M (also depends on X_0)
  90% of all energy is contained in a cylinder with a radius of 1 ρ_M around the shower axis
- Shower maximum: Depth where number of particles in the shower is maximal
  - $t_{max} \sim \ln(E_0/\varepsilon) + t_0$ in X_0, with $t_0 = -0.5$ für e^-, $+0.5$ für γ



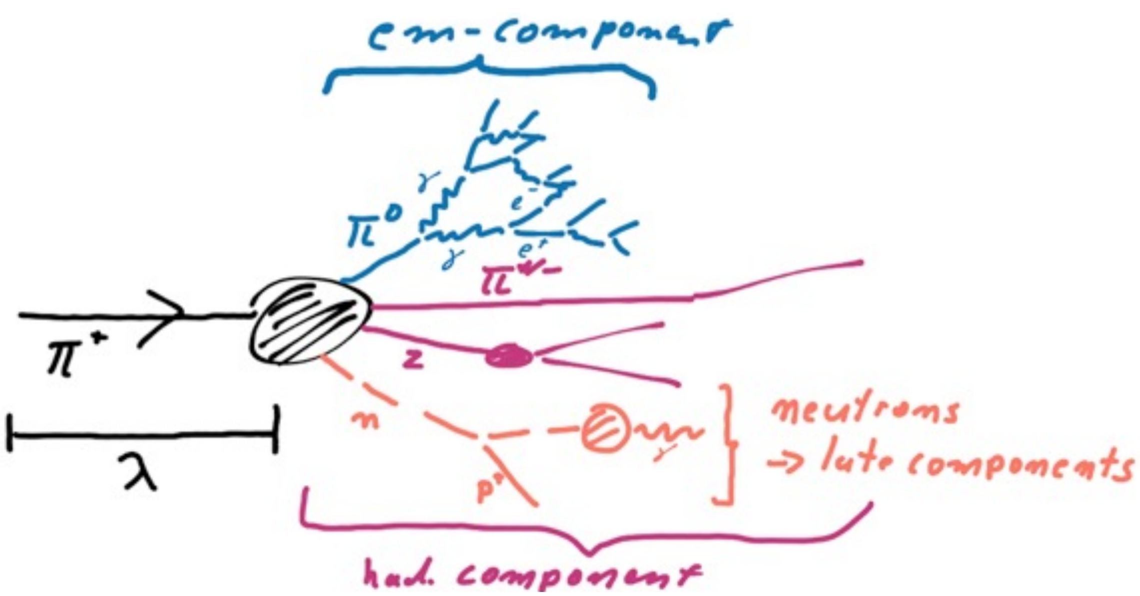
Characteristic Parameters of Showers - Hadronic

- The length scale of hadronic showers is given by the **nuclear interaction length λ_I** (mean free path between hadronic interactions)

$\lambda_I > X_0$ for all materials with $Z > 4$

	λ_I	X_0
Polystyrene	81.7 cm	43.8 cm
PbWO	20.2 cm	0.9 cm
Fe	16.7 cm	1.8 cm
W	9.9 cm	0.35 cm

Hadronic showers are complicated:

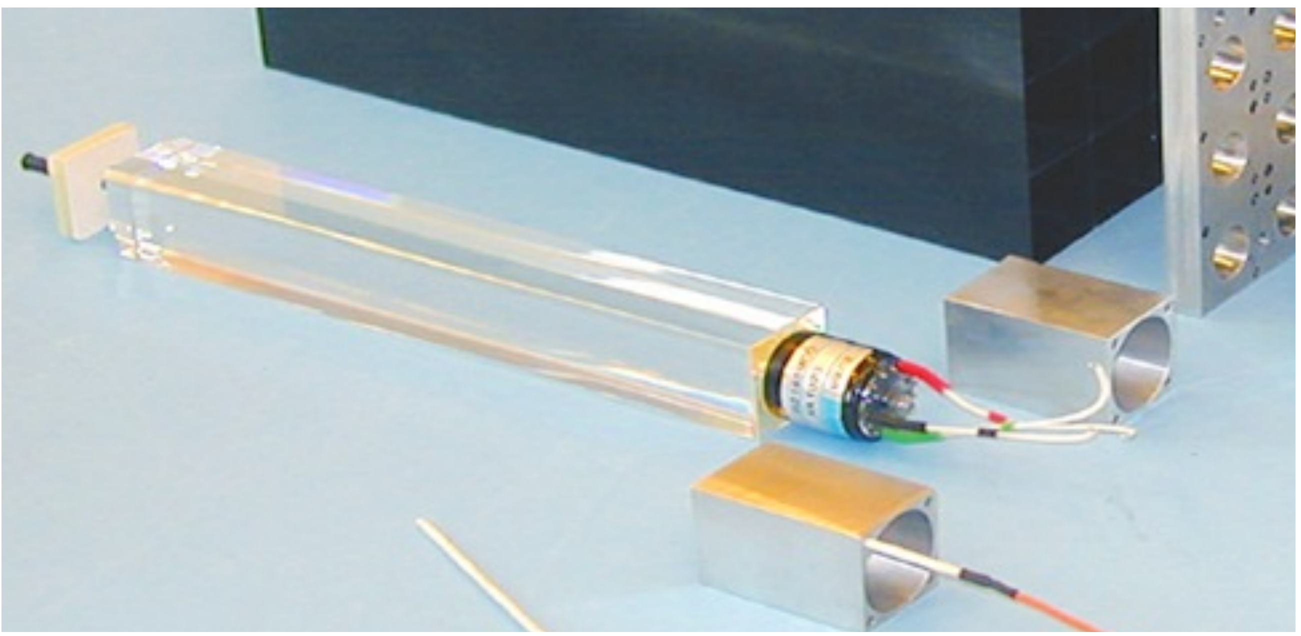


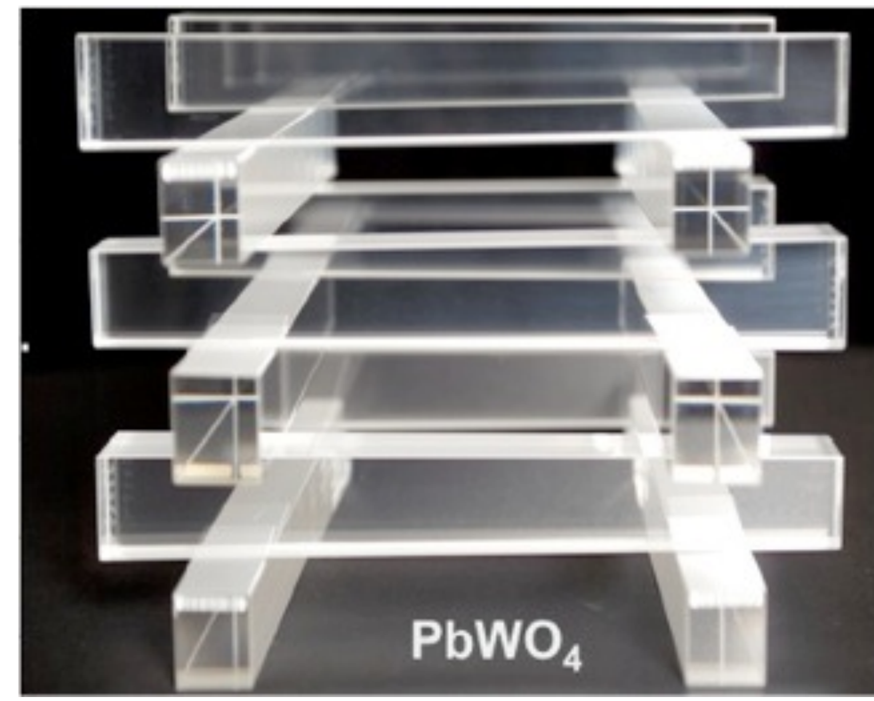
- Relativistic hadrons created in interactions with nuclei, carry a sizeable fraction of momentum of original particle [*O* GeV]
- About 1/3 of all pions created are π^0: instantaneous decay to photons, em subshower
- Neutrons created in evaporation/spallation, photons from neutron capture -> MeV (or lower)
- Energy loss due to binding energy, ...

Homogeneous ECAL: Inorganic Crystals

- High purity: good transmission of scintillation light
- High density: Drives the depth of the calorimeter

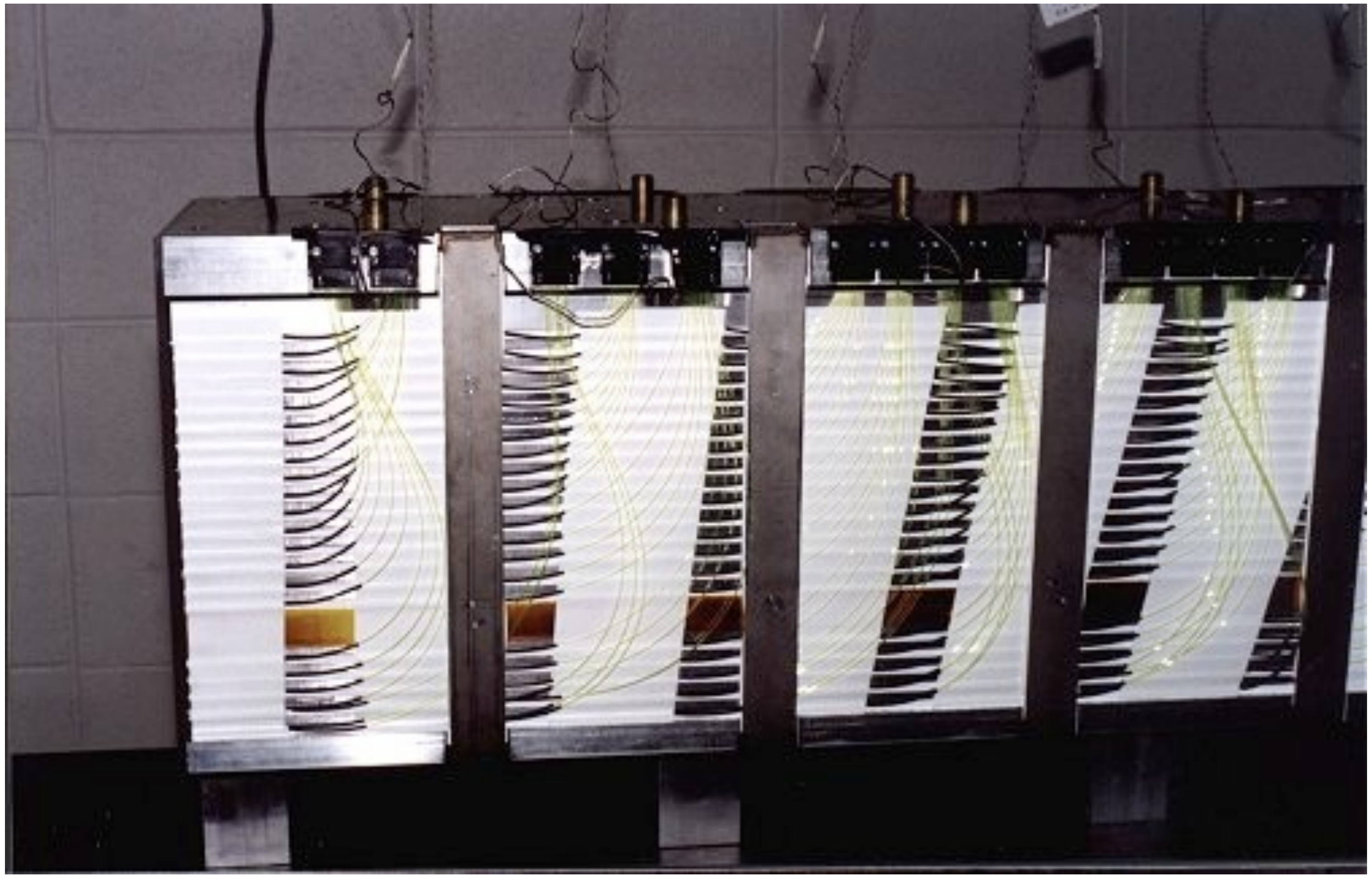
Example: CMS ECAL

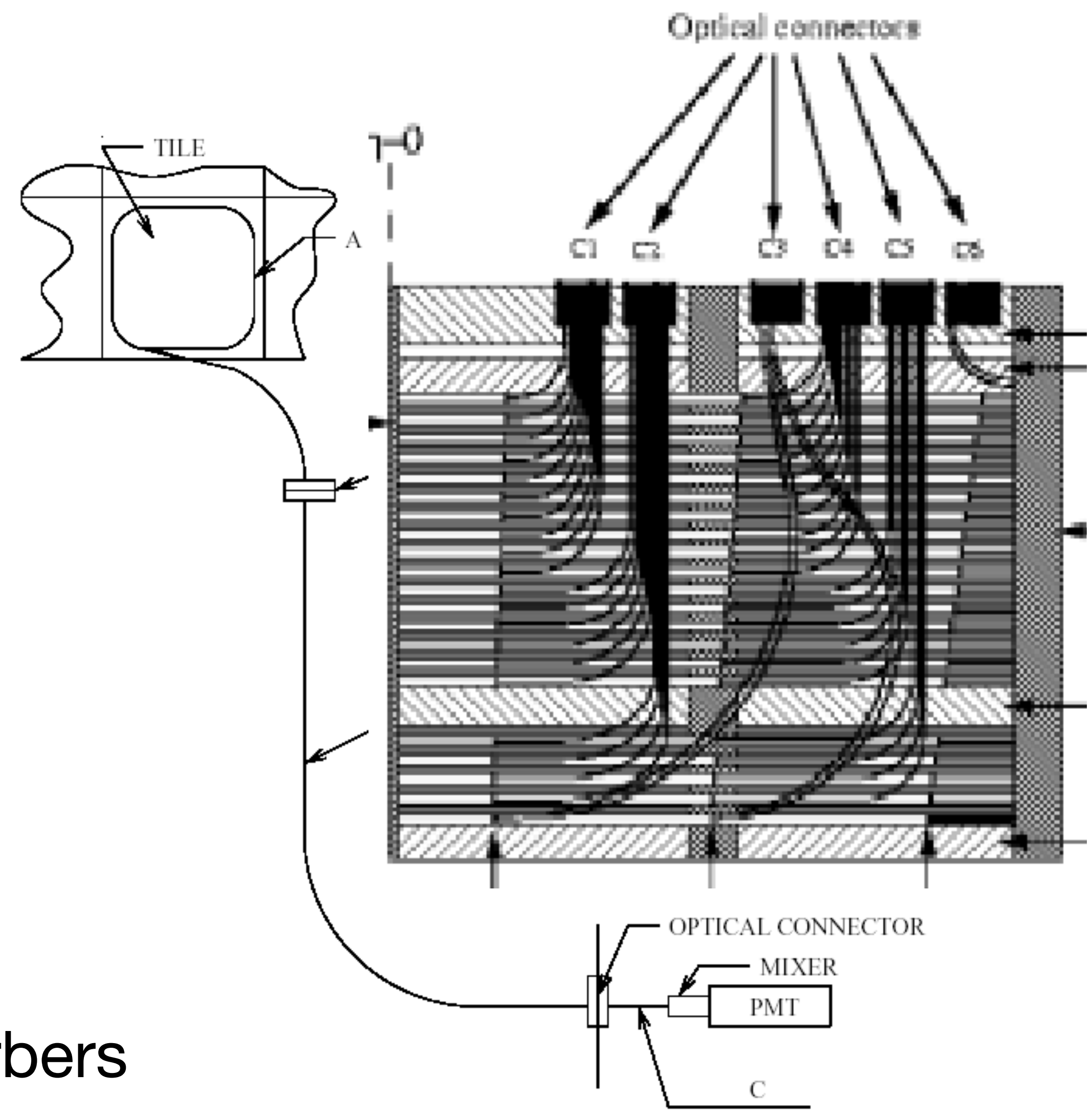




- $PbWO_4$: Fast, high-density scintillator
  - Density ~ 8.3 g/cm^3 (!)
  - ρ_M 2.2 cm, X_0 0.89 cm
  - low light yield: ~ 100 photons / MeV, temperature dependent: -2%/°C

Sampling Calorimeter: STAR ECAL

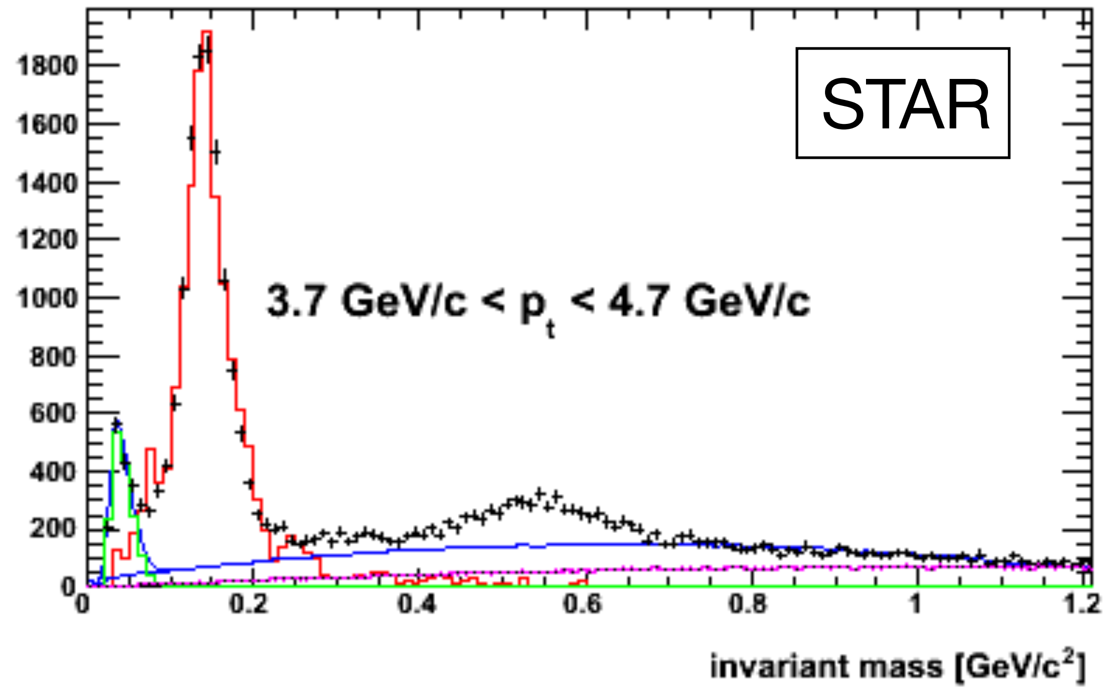


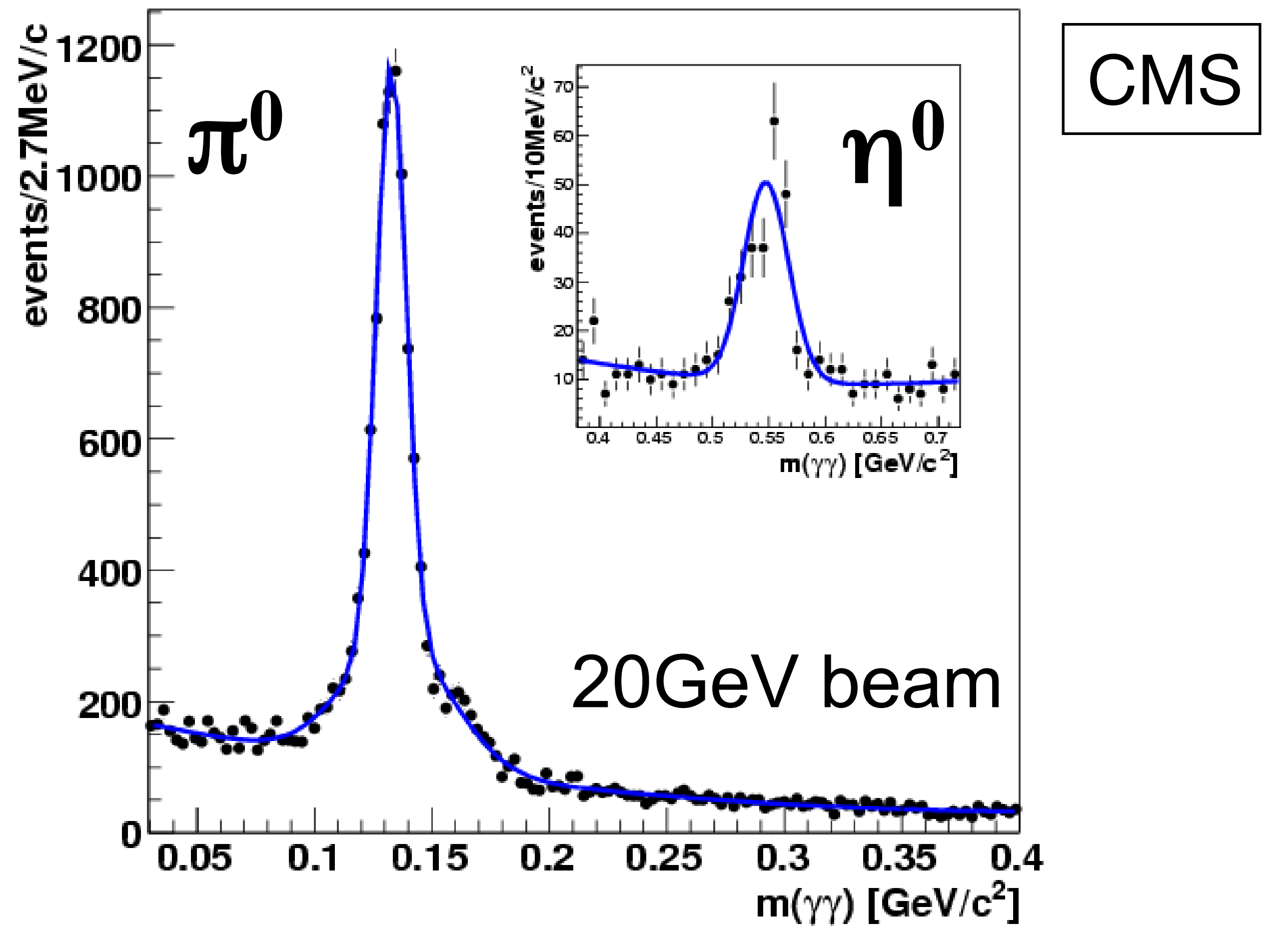


- Plastic scintillator plates between lead absorbers
- The light is collected in each plate by wavelength-shifting fibers
- The fibers guide the light outside of the magnetic field, where it is concentrated per "tower" and read out with a PMT

Homogeneous vs Sampling: Resolution!

Neutral pions

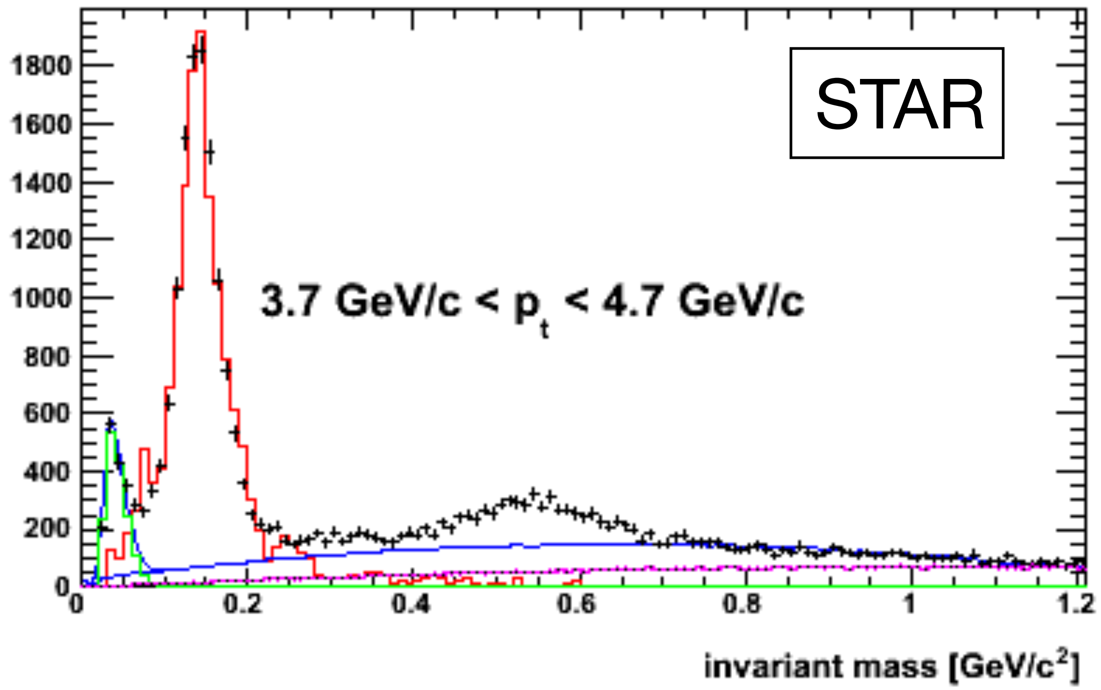


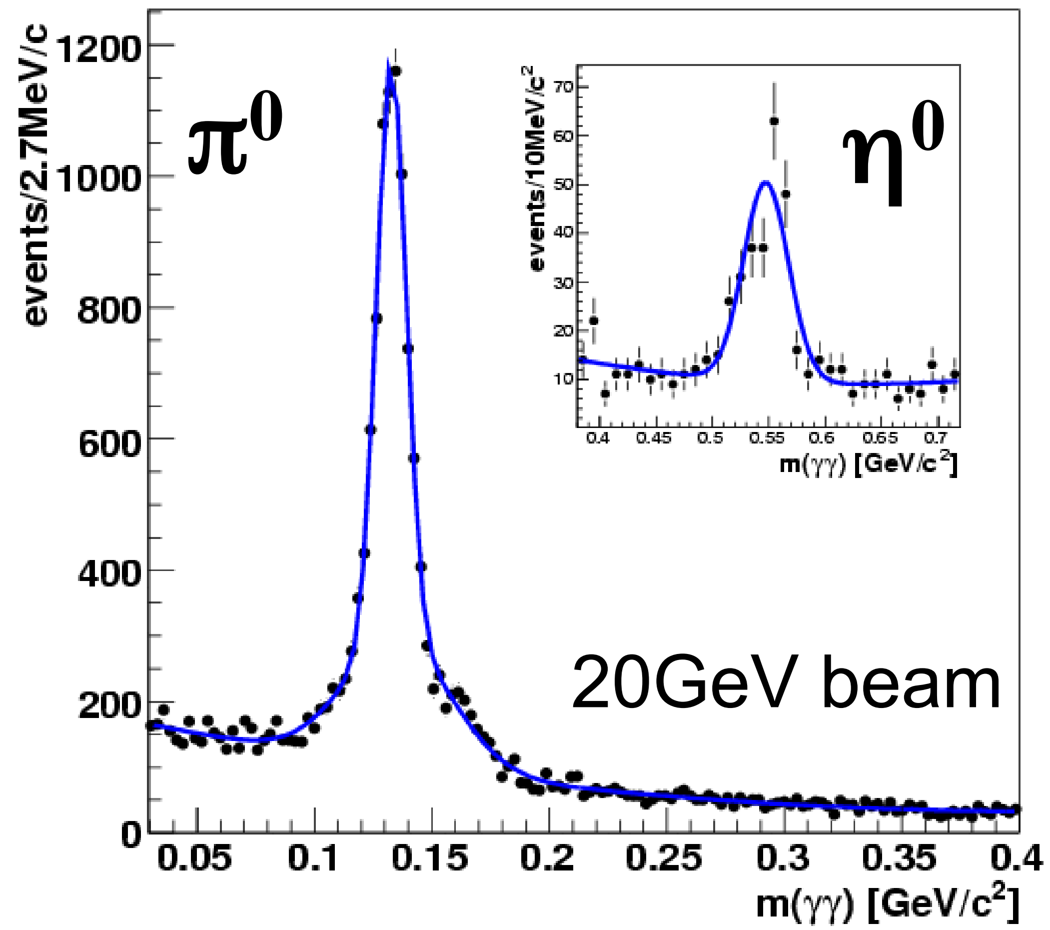


- Stochastic Term:
  - STAR: ~ 14%
  - CMS: 2.8%

Homogeneous vs Sampling: Resolution!

Neutral pions



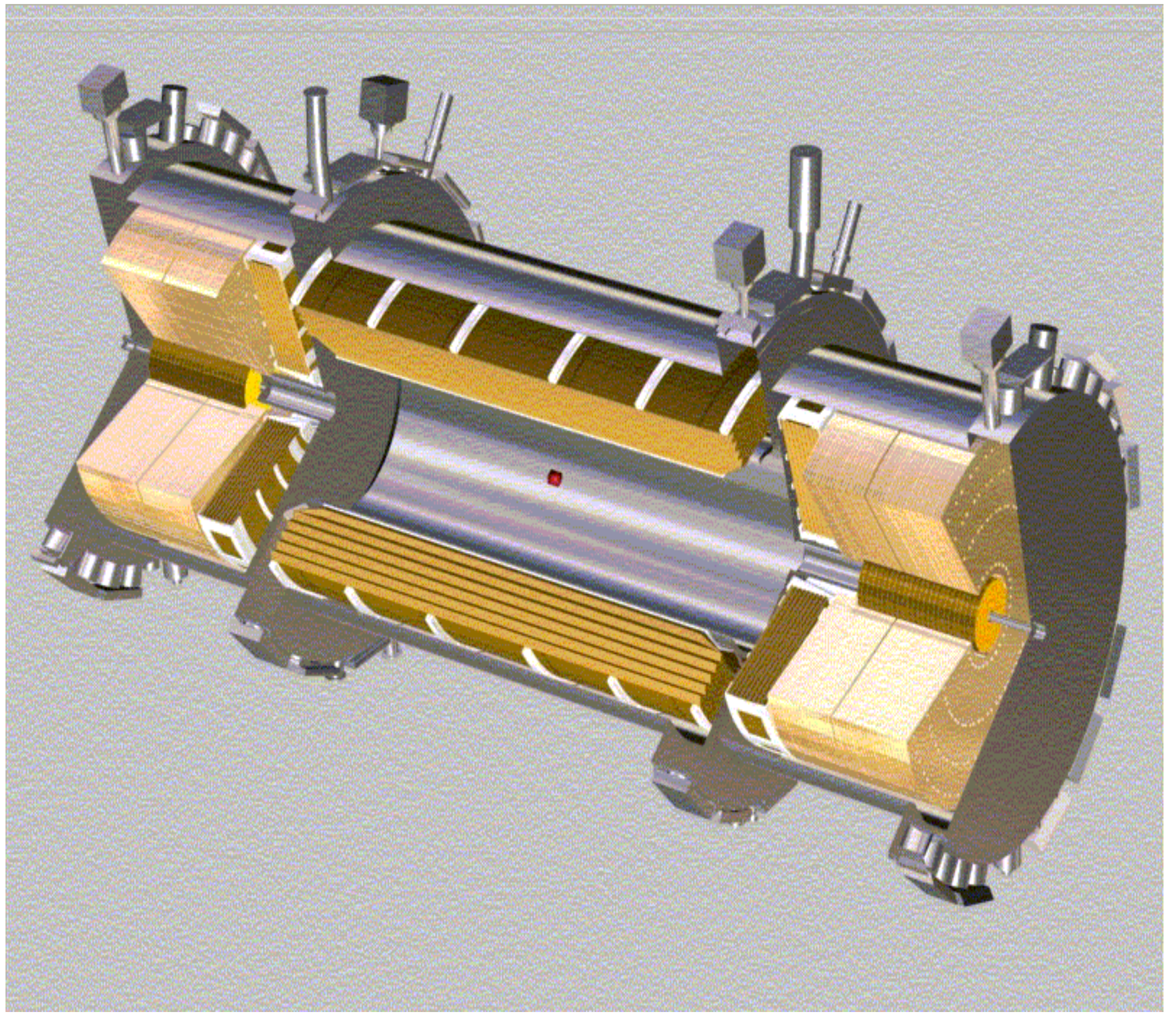


- Stochastic Term:
  - STAR: ~ 14%
  - CMS: 2.8%

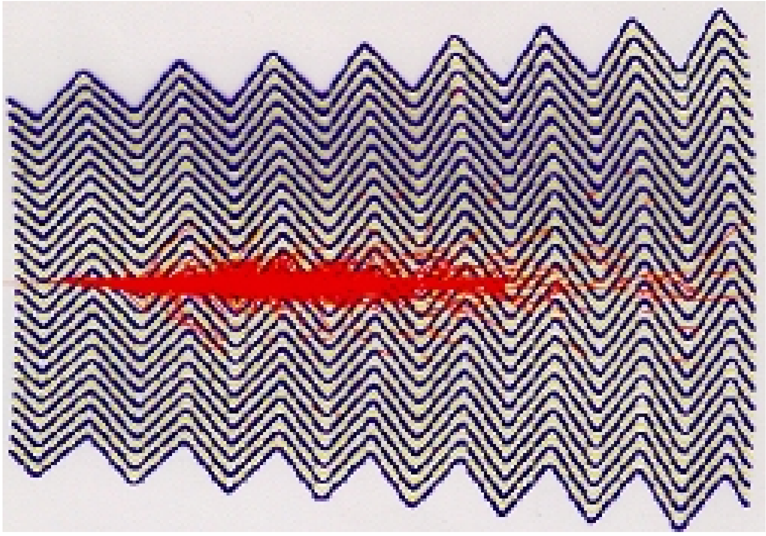
But:
Crystals are very expensive!

And: In combination with hadron calorimeters they provide often a very poor hadronic energy resolution

Alternative Technology: ATLAS Liquid Argon

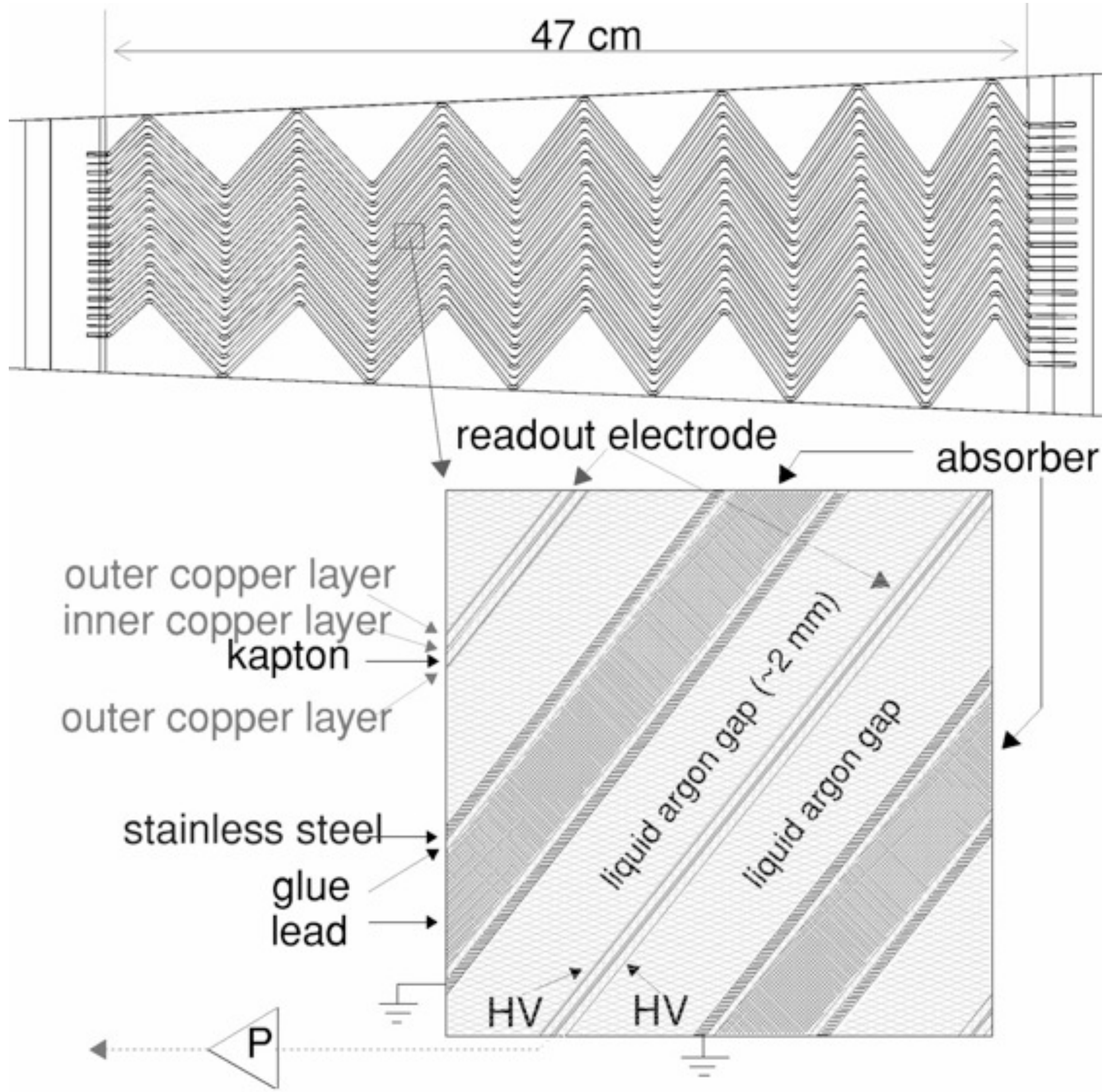


- Barrel EMC
  - (The ATLAS barrel HCAL uses steel + plastic scintillator)
- Endcap - EMC and HCAL
- ECAL: Pb-LAr, with “accordeon geometry”



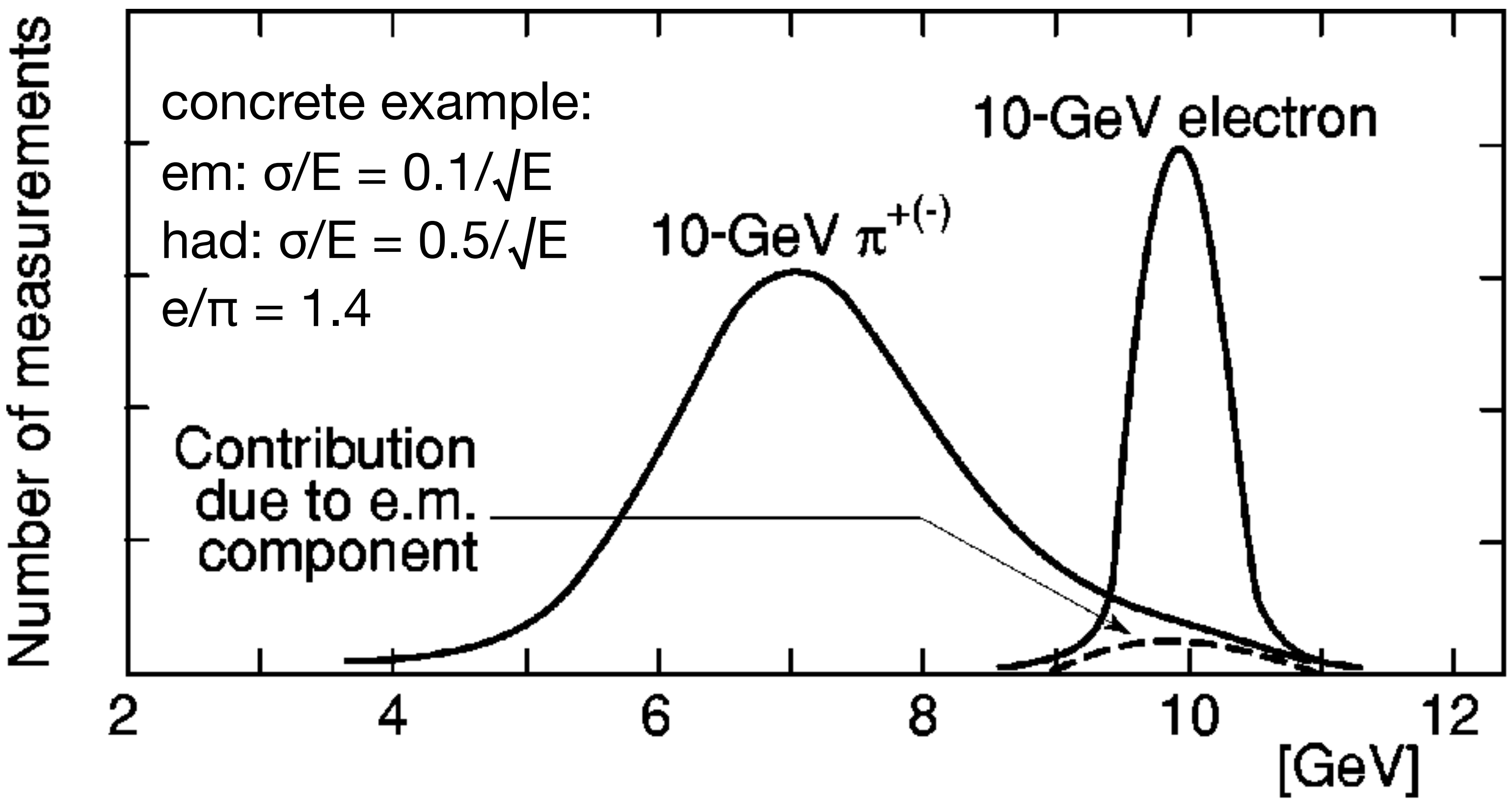
LAr Calorimeters

- LAr: Density 1.4 g/cm³, X_0 14 cm
  - relatively high sampling fraction
- Charge is produced by through-going particles
- Charge collection on electrons (no amplification!)
- high purity of cryogenic liquid required - but then (with constant filtering) the active medium is indestructible also by high radiation levels
- accordeon geometry simplifies readout, minimizes drift length and thus allows high rates



Resolution of Hadronic Calorimeters

- The general considerations for calorimeters apply also here
  - stochastic, constant and noise term
- but: Typically the detector responds differently to pure hadronic sub-showers and electromagnetic components (due to different length scale of interactions and “invisible” losses in hadronic reactions): $e/\pi > 1$
- Fluctuations of electromagnetic fraction deteriorate resolution and result in non-linearities: deviations from expected $1/\sqrt{E}$ behaviour



Signal (in energy units) obtained for a 10 GeV energy deposit

C. Fabjan, F. Gianotti, Rev. Mod. Phys. 75, 1243 (2003)

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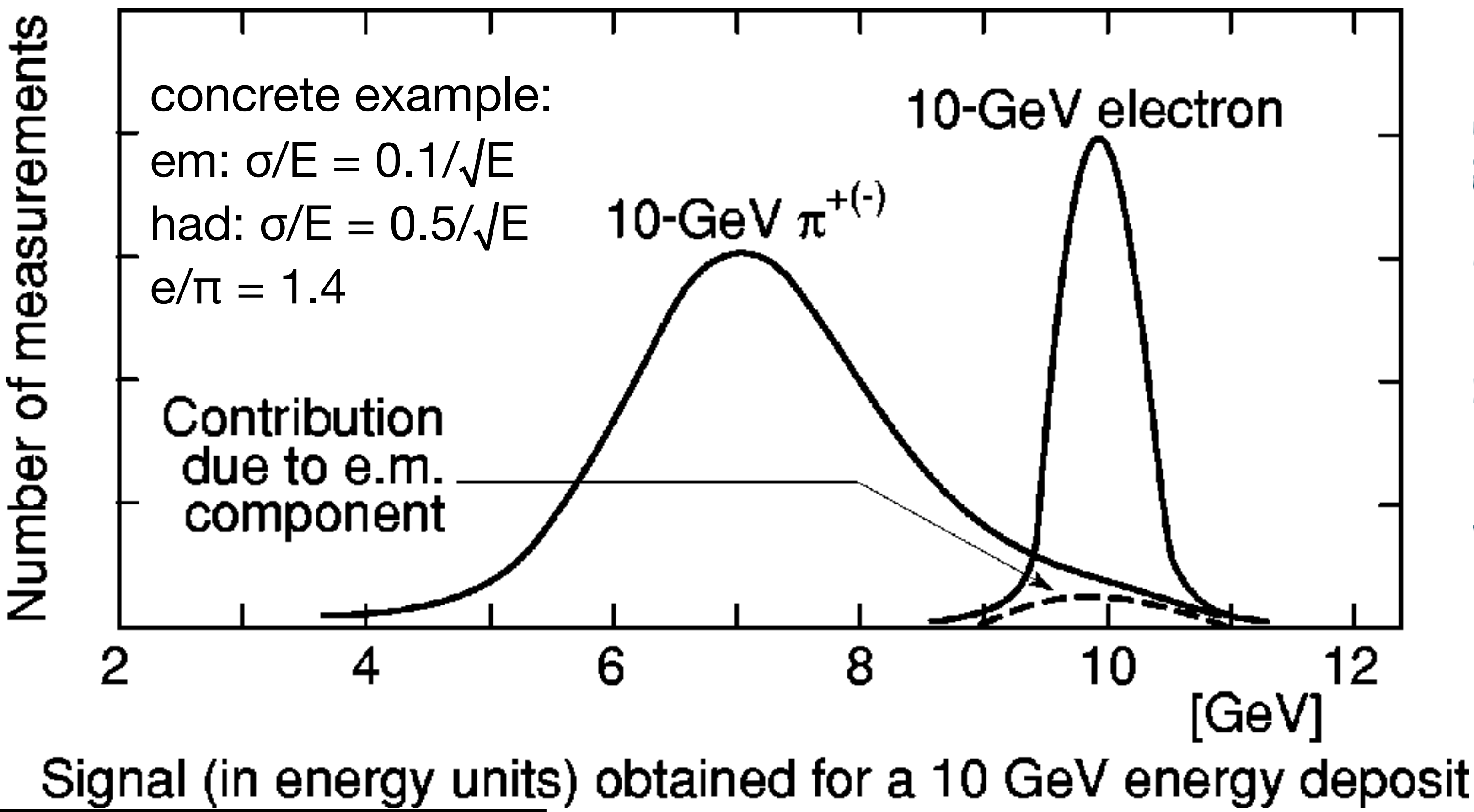
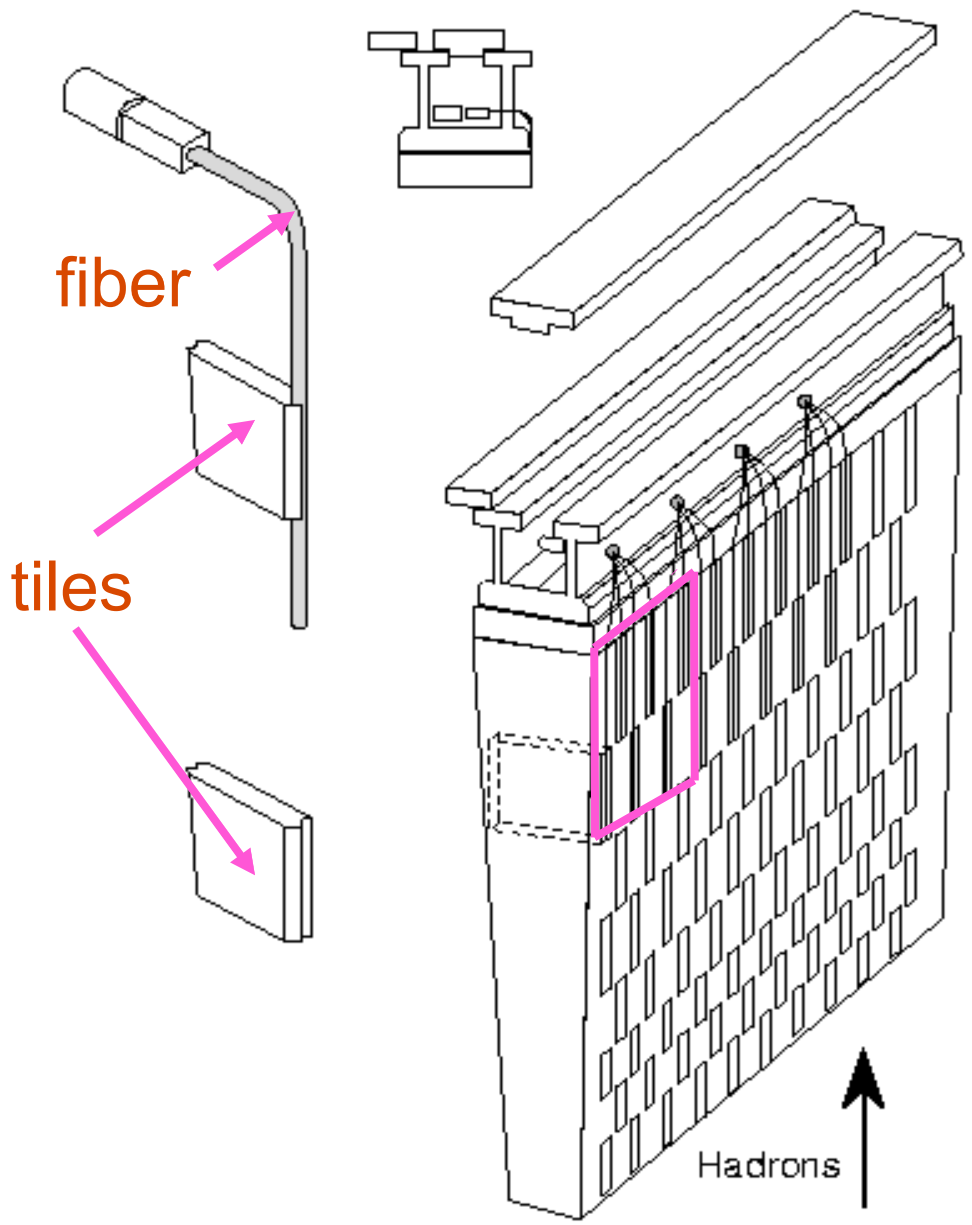


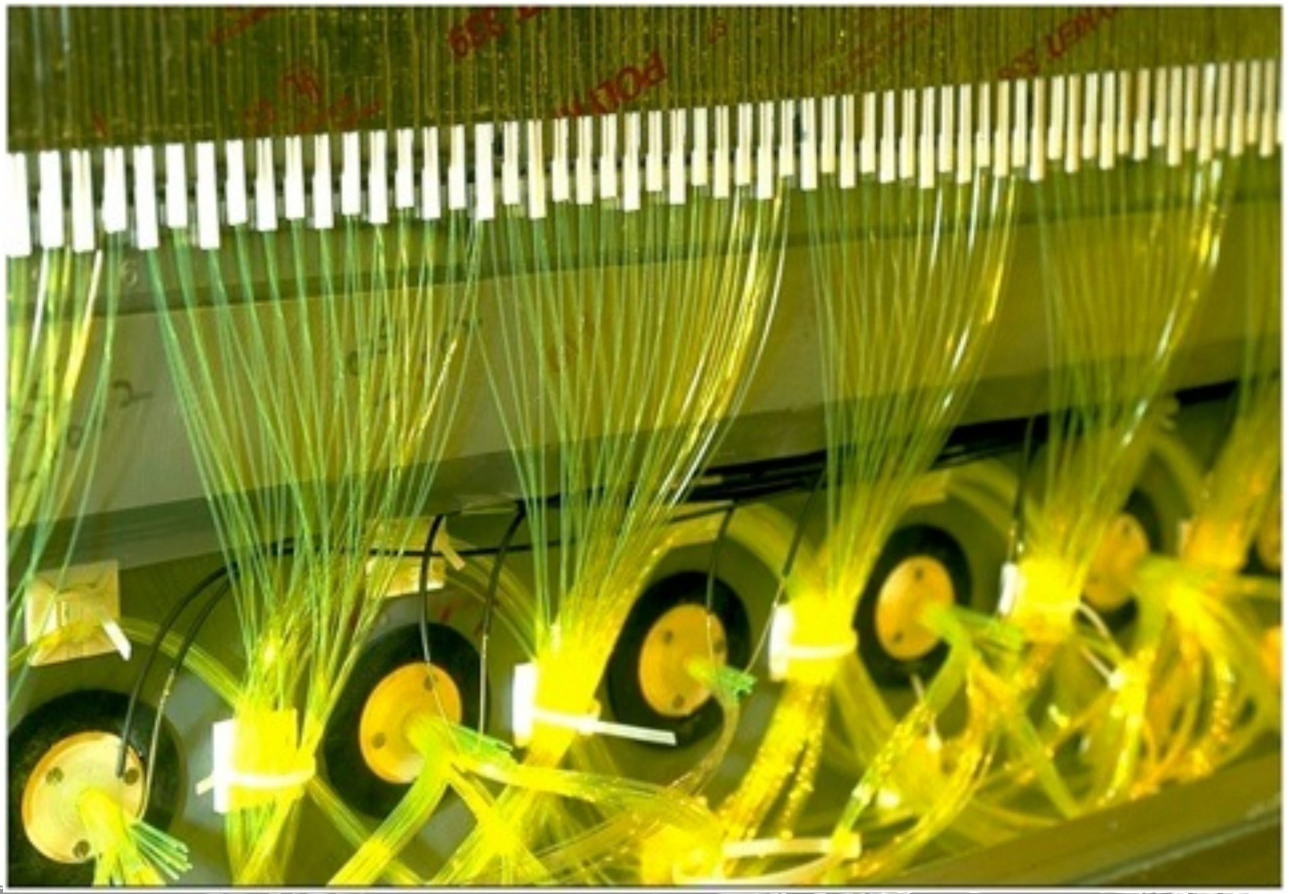
C. Fabjan, F. Gianotti, Rev. Mod. Phys. 75, 1243 (2003)

can be fixed with “compensating calorimeters” $e/\pi = 1$ - But requires very specific geometries, for best results the use of Uranium absorbers and provides rather poor electromagnetic performance

ATLAS Barrel HCAL

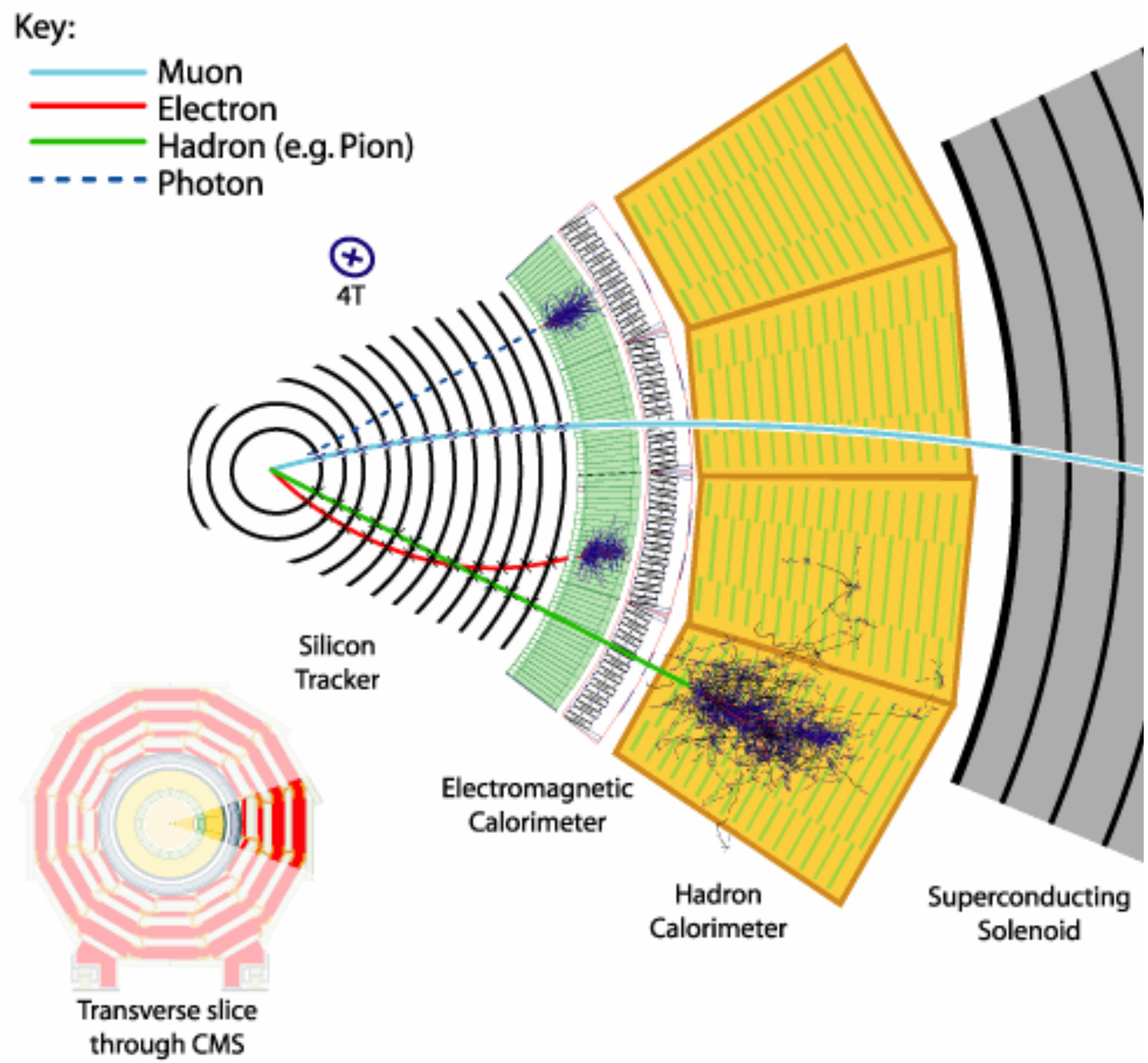


- Stainless steel / scintillator
- Scintillator cells parallel to particle incidence - works since most particles are low energy and travel at larger angles
- Readout with two fibers per tile
- 3 longitudinal segments, fibers are bundled for each segment and read out with a PMT outside magnet

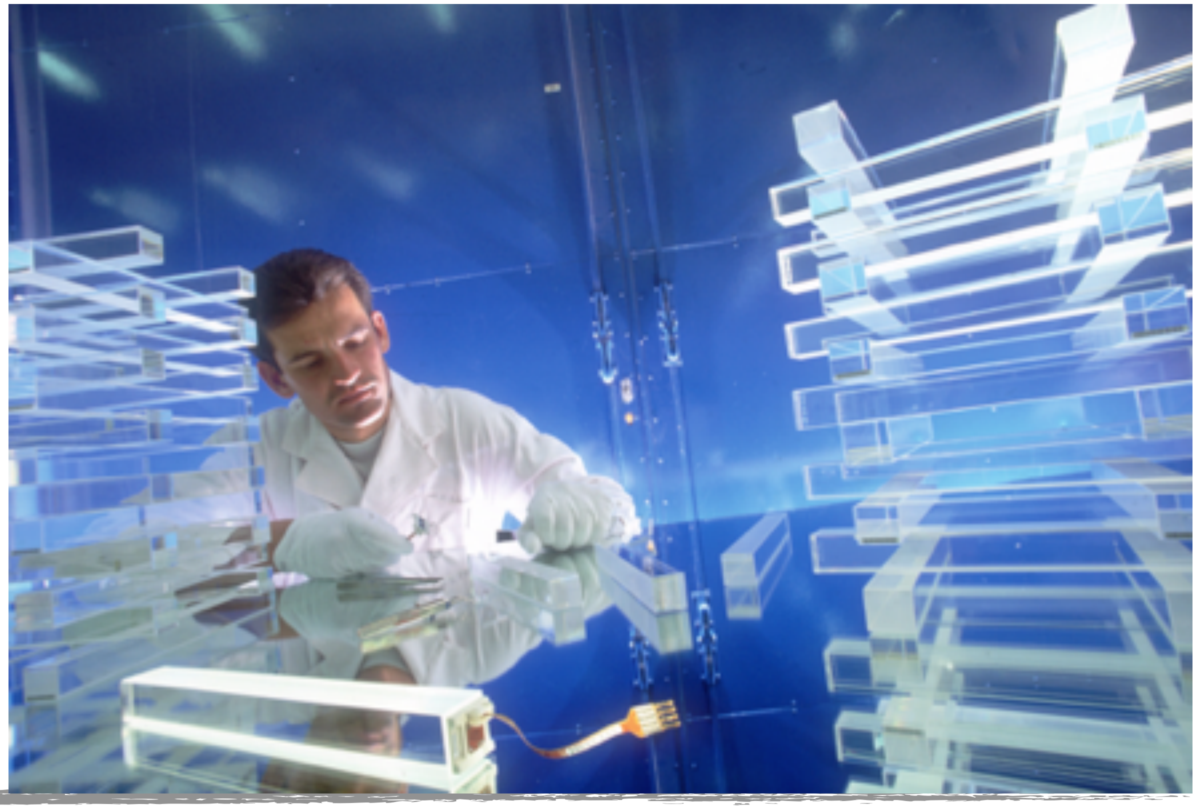


Global Performance for Hadrons - CMS

- A LHC Phase I System: CMS

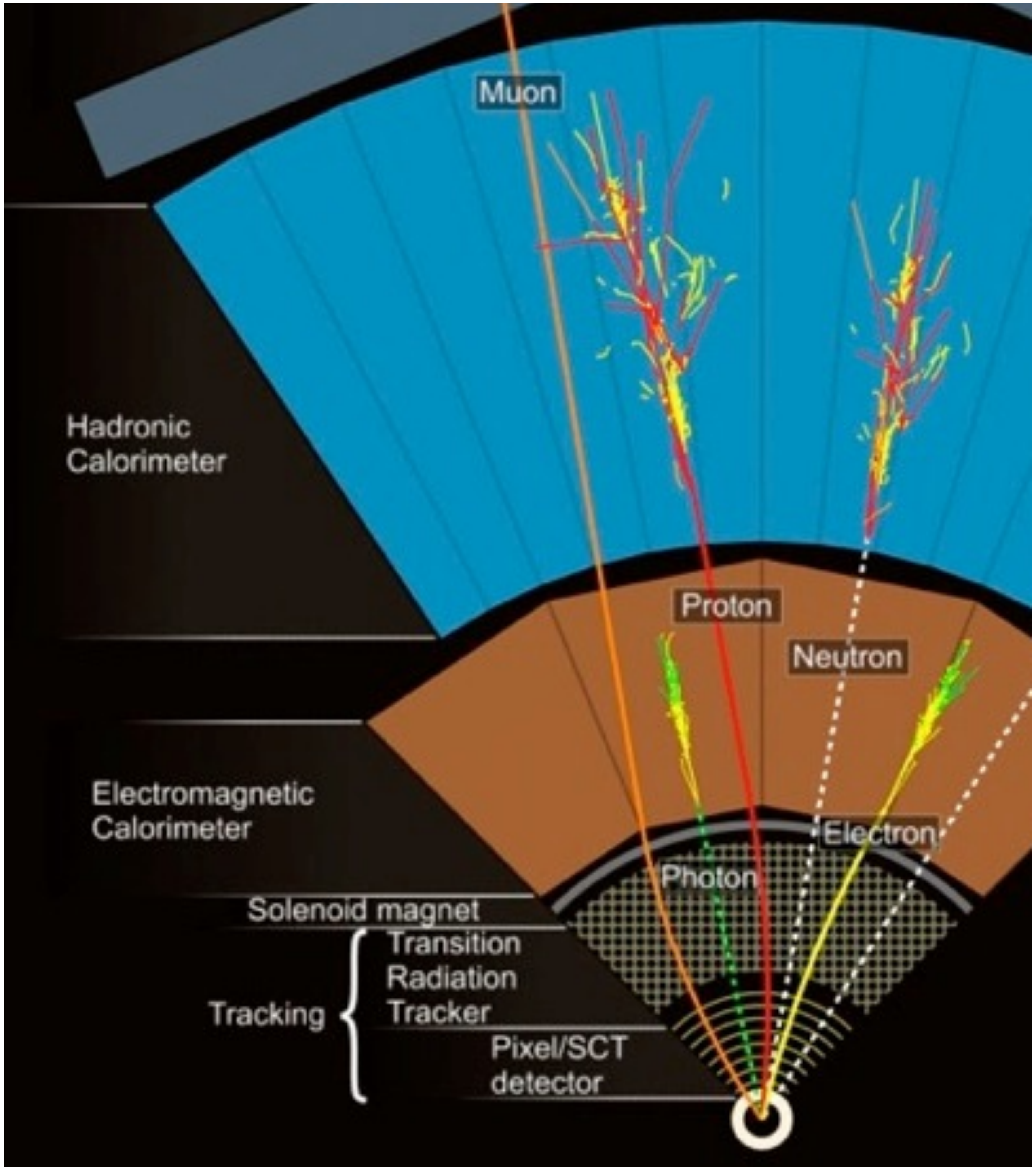


- A fantastic ECAL - $PbWO_4$ crystals with APD readout
- EM energy resolution ~ 2.8%/√E
- The price to pay: Single hadron stochastic term ~93%



Global Performance for Hadrons - ATLAS

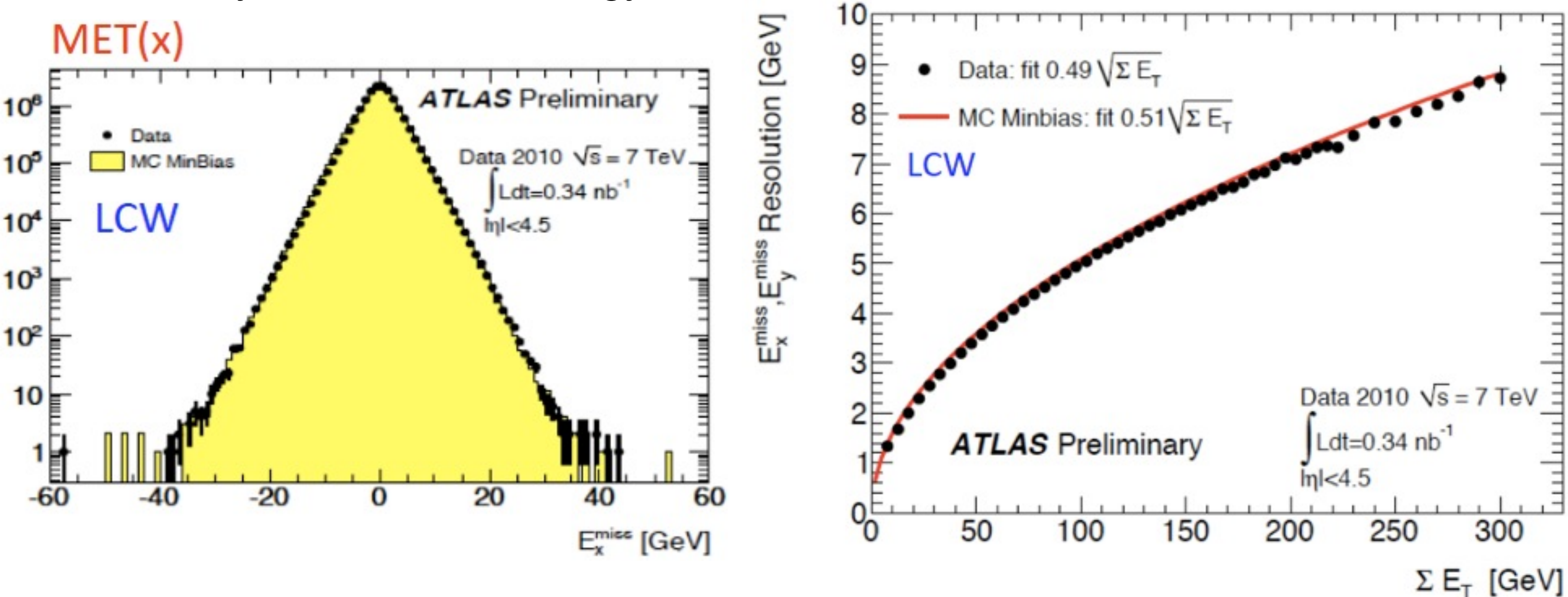
- A LHC Phase I system: ATLAS



- LAr ECAL, Scintillator HCAL in Barrel both longitudinally segmented
  - EM resolution ~9%/√E
  - Single hadron stochastic term ~42% (with software “compensation” making use of segmentation)

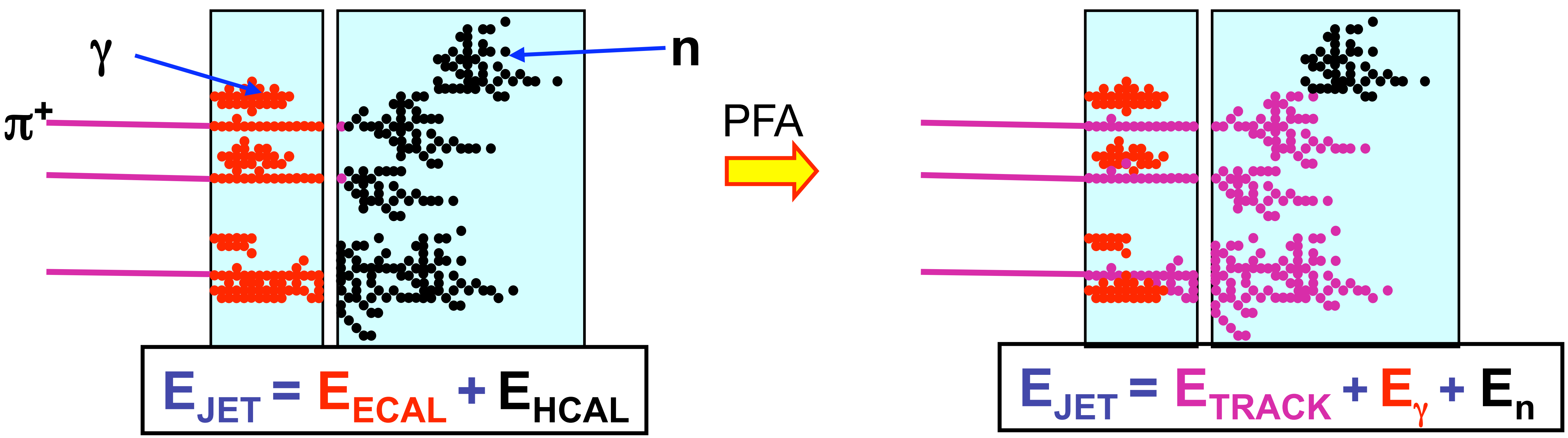
Important Measurement: Missing Energy

- Is used to reconstruct "invisible" particles
  - Neutrinos, for example in the decay of W bosons
  - New particles, for example possible dark matter particles
- An indispensable tool to search for New Physics
- Calorimeter measure the energy of all particles (except muons) - The most crucial system for total energy measurements



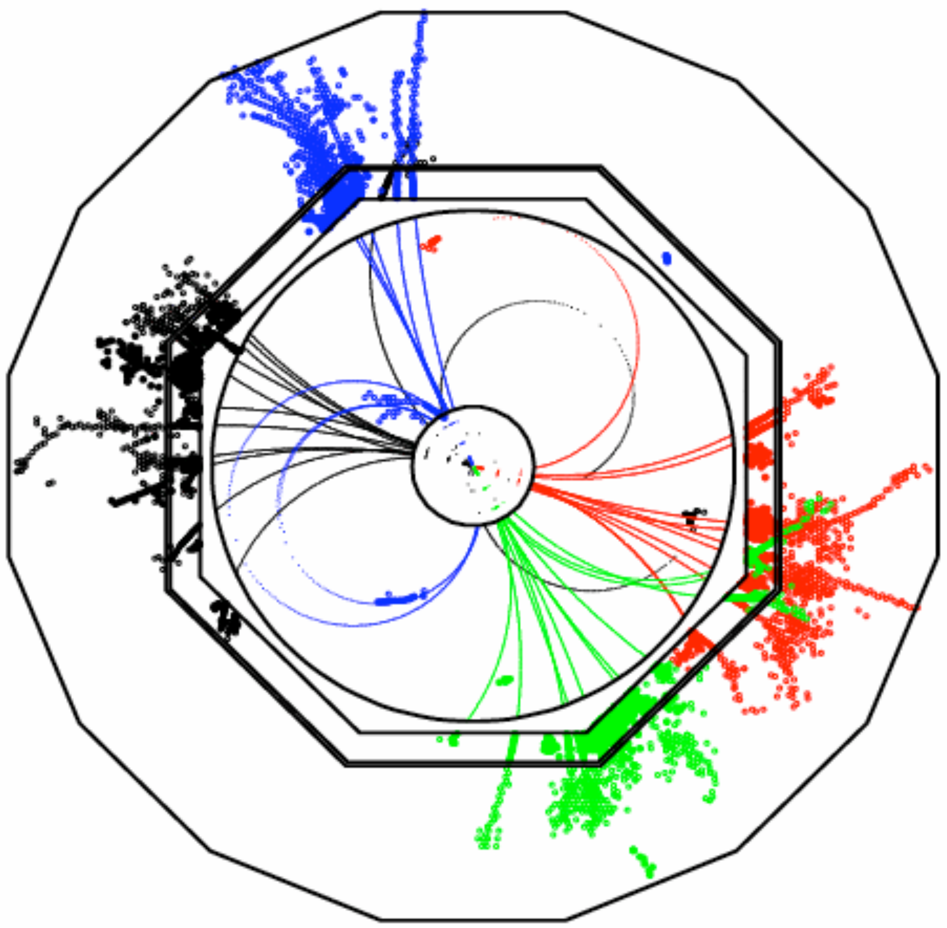
Particle Flow - Jets from Individual Particles

- Improve jet energy reconstruction by measuring each particle in the jet with best possible precision
  - Measure all charged particles in the tracker (remember, 60% charged hadrons!)
    - Significantly reduce the impact of hadron calorimeter performance: Only for neutral hadrons
    - Measure only 10% of the jet energy with the HCAL, the “weakest” detector: significant improvement in resolution



Imaging Calorimeters: Making PFA Happen

- For best results: High granularity in 3D - Separation of individual particle showers
  - Granularity more important than energy resolution!
  - Lateral granularity below Moliere radius in ECAL & HCAL
  - In particular in the ECAL: Small Moliere radius to provide good two-shower separation - Tungsten absorbers
    - Highest possible density: Silicon active elements - Thin scintillators also a possibility
  - And: Sophisticated software!



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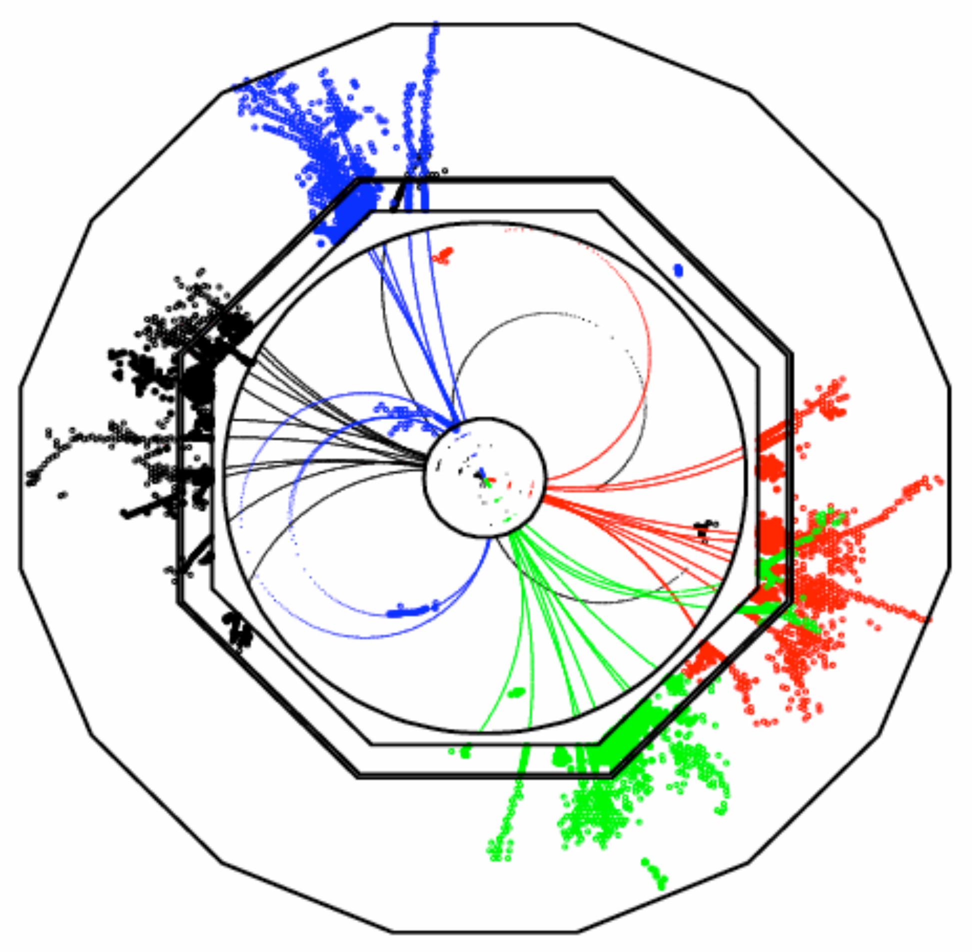
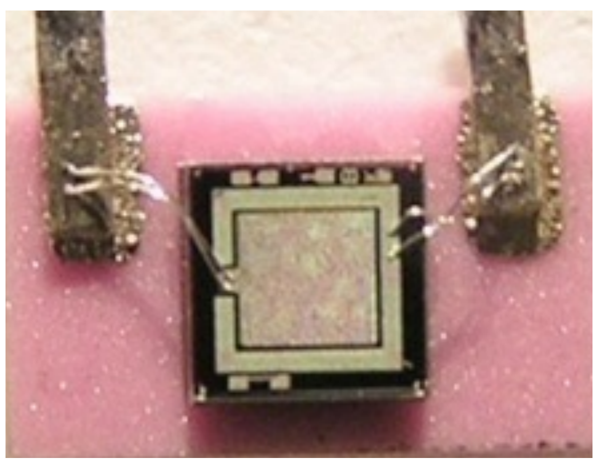


Extensively developed & studied for Linear Collider Detectors: Jet energy resolution goals (3% - 4% or better for energies from 45 GeV to 500 GeV) can be met.
Also very interesting in the LHC environment: Granularity helps to suppress background and pileup!

High Granularity with SiPMs

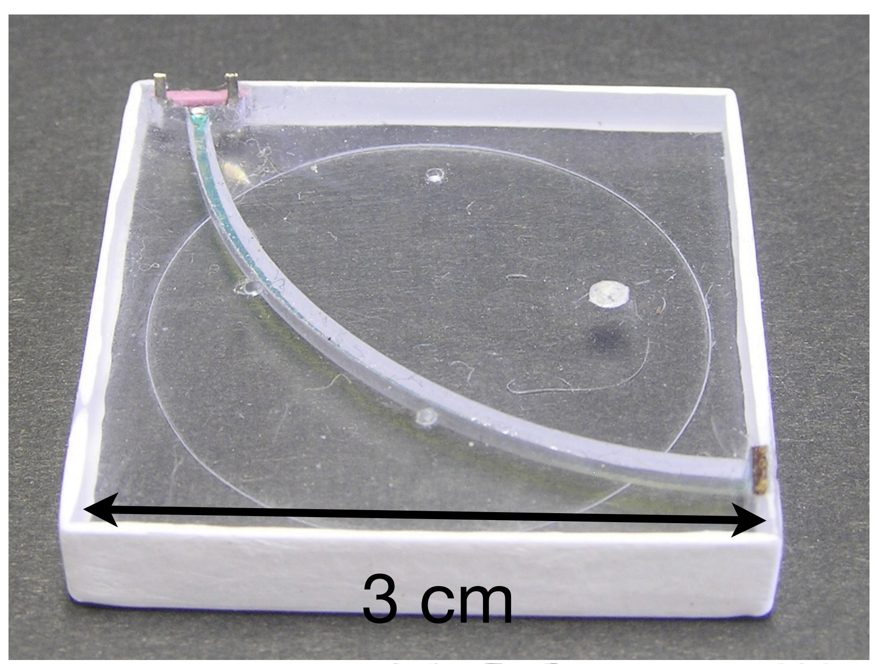
- PFA calorimeters developed by the CALICE collaboration - Various different technologies
  - ECALs with W absorber, Si & Scintillator + SiPM readout
  - HCALs with Steel and W absorber, Scintillator + SiPM & Gas detector readout

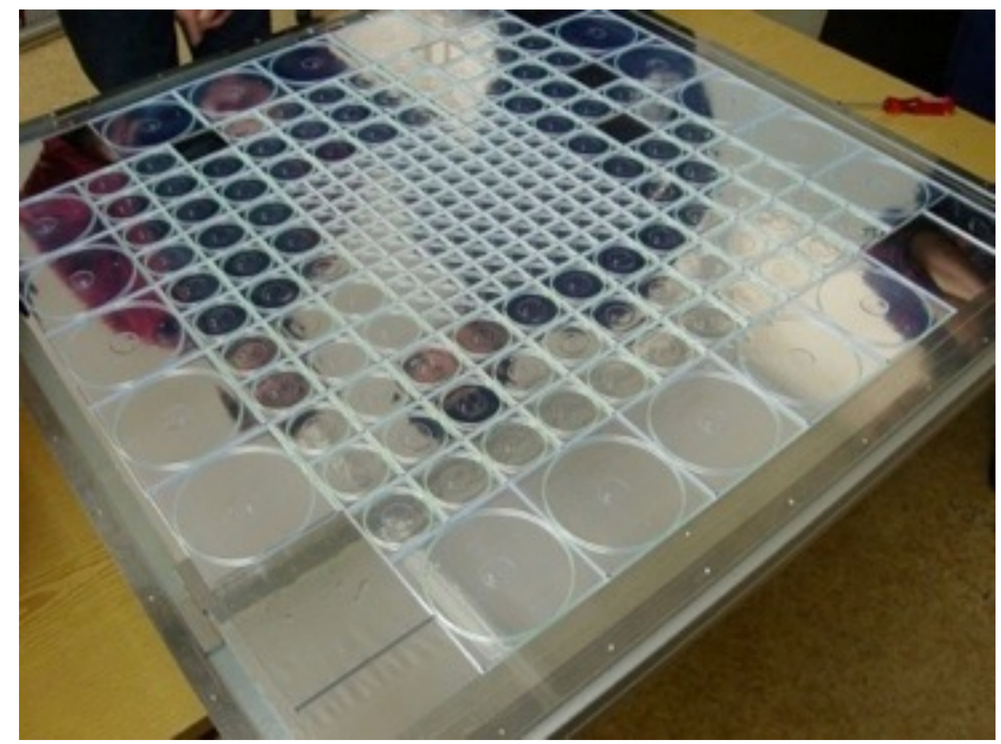
One of the technology highlights: The first large-scale use of SiPMs in the CALICE analog HCAL



SiPM: 1156 pixels, manufactured by MePhI/PULSAR

Plastic scintillator tiles with WLS fiber & SiPM





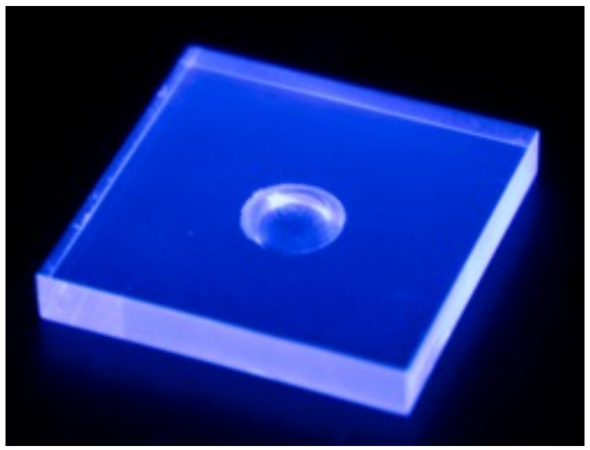
212 scintillator tiles per layer, 38 layers, each channel read out separately

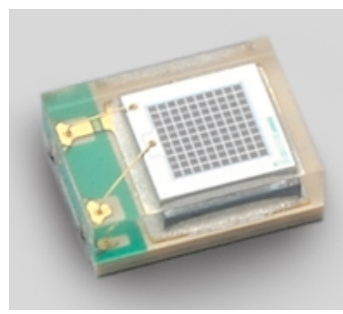
8 000 channels in total

Modern Detectors: Automatisation & Industrialisation

- At the example of the CALICE AHCAL:

  mass-produced scintillator tiles (injection molding)
  + SiPMs in SMD package





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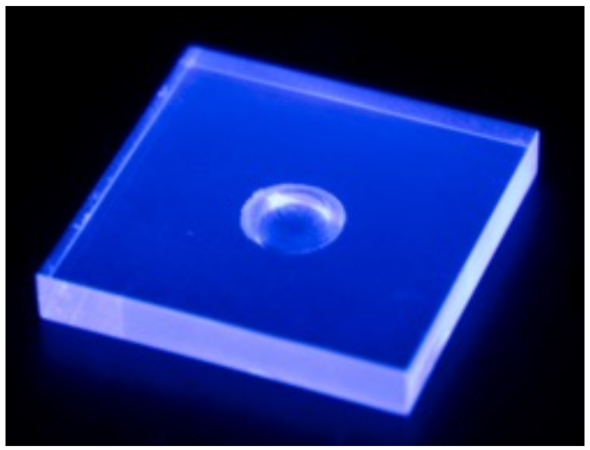

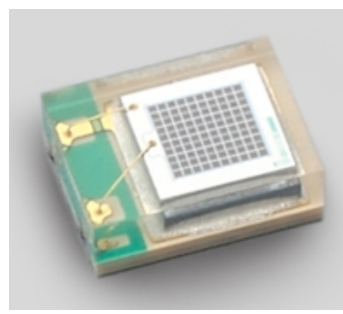

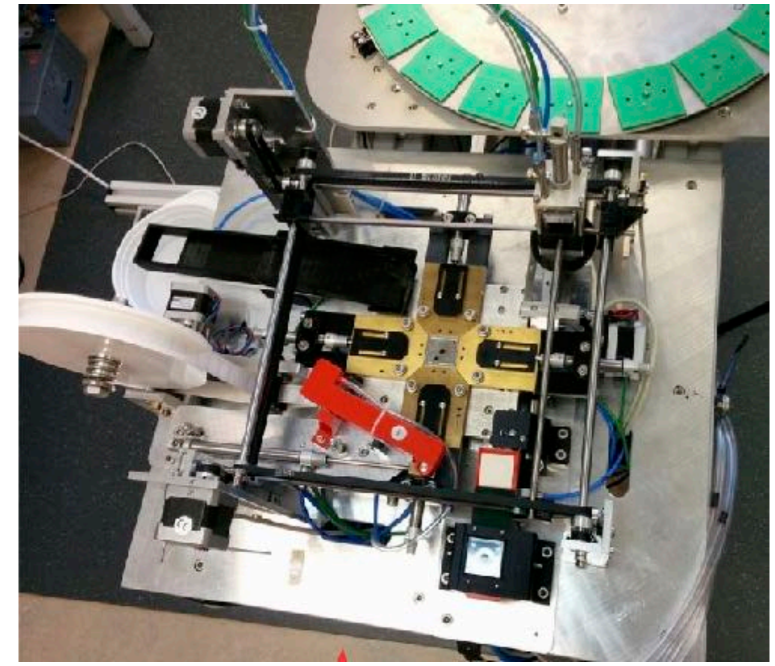

semi-automatic wrapping of
tiles in reflector foil (22k tiles)

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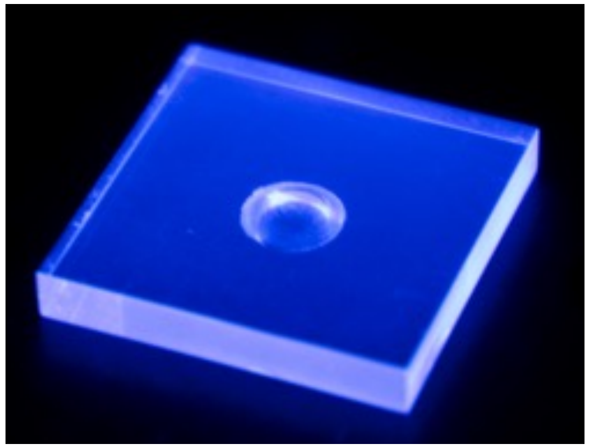
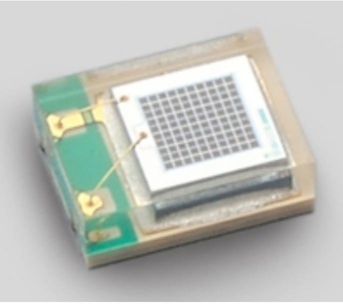
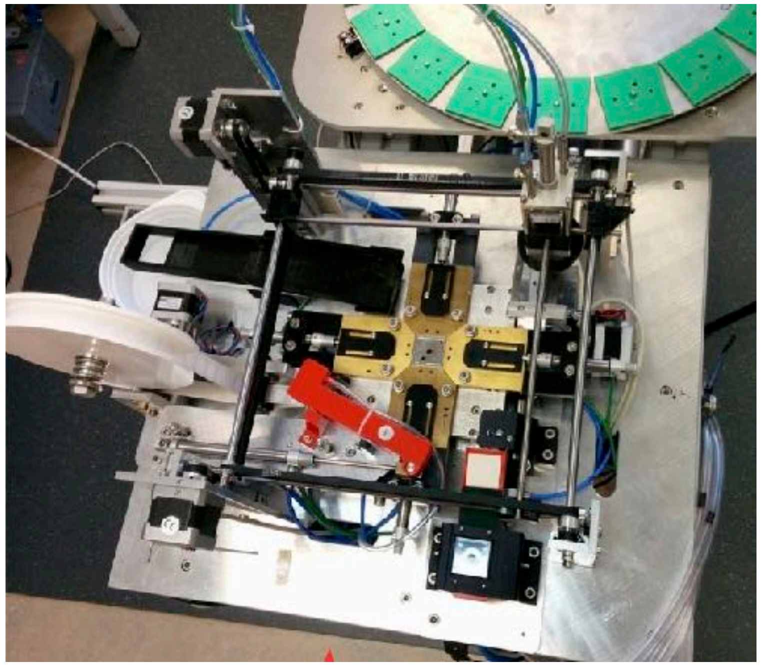






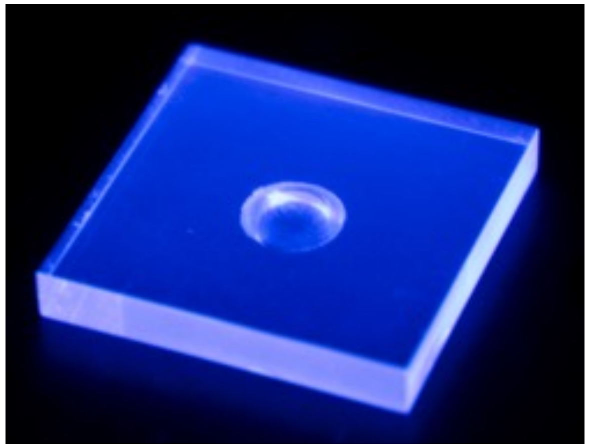
semi-automatic wrapping of tiles in reflector foil (22k tiles)

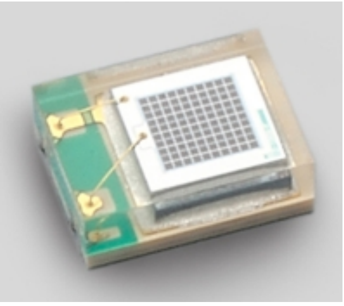
automatic mounting of scintillator tiles on electronics boards (160 boards)

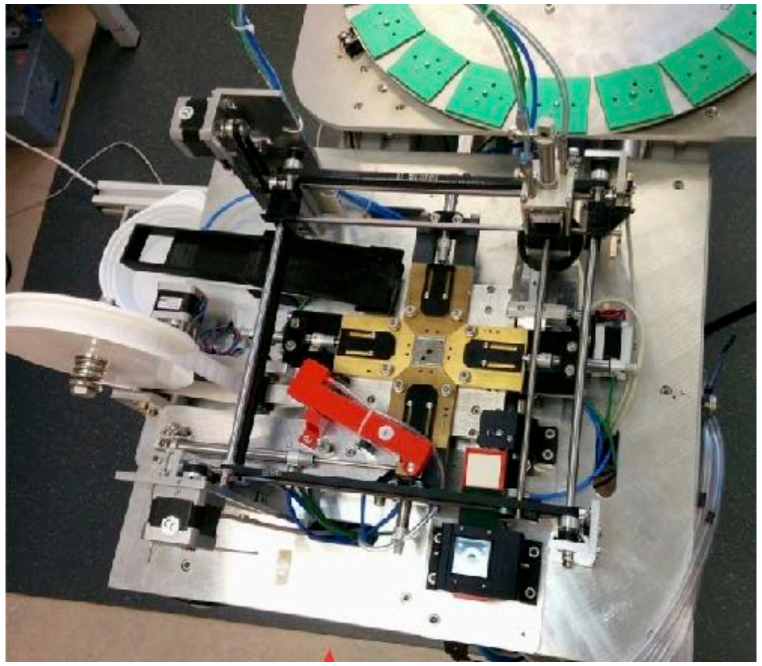
Modern Detectors: Automatisation & Industrialisation

- At the example of the CALICE AHCAL:

  mass-produced scintillator tiles (injection molding) + SiPMs in SMD package

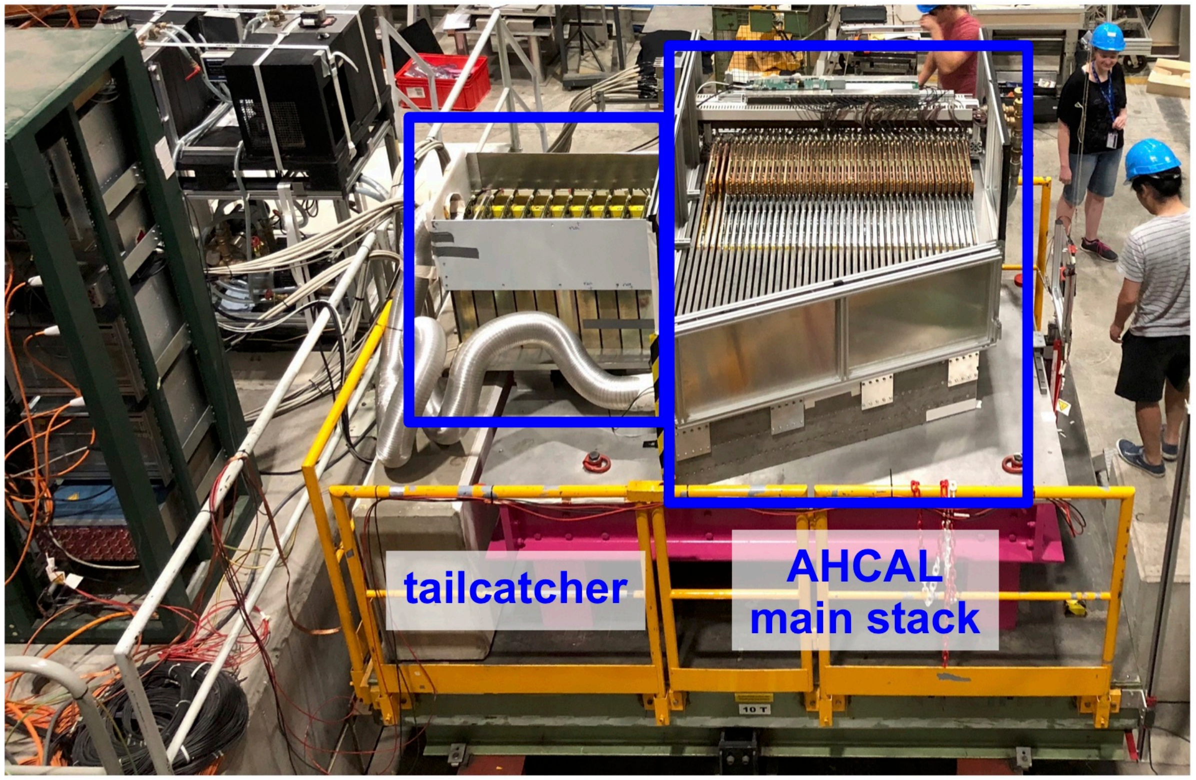






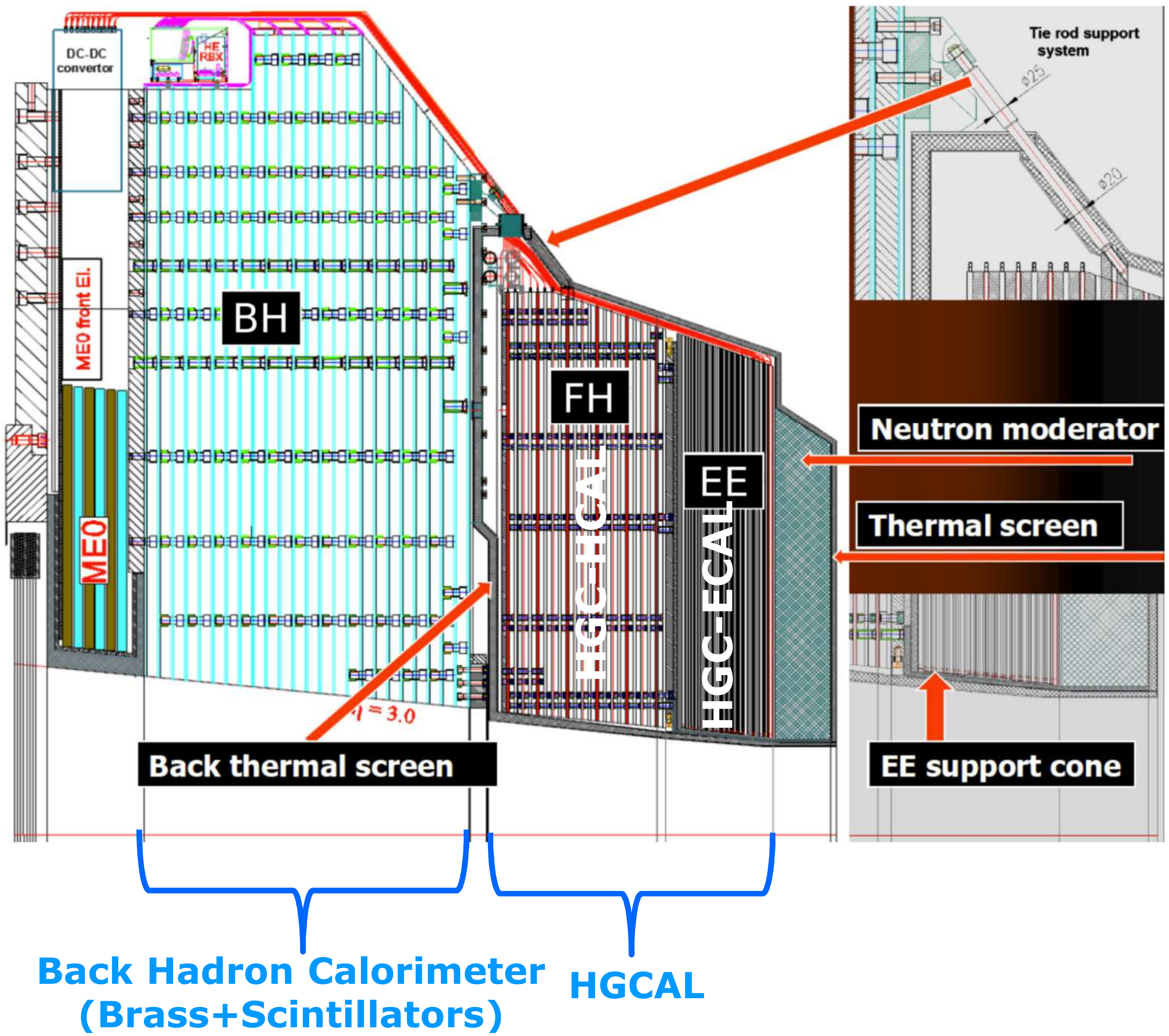
semi-automatic wrapping of tiles in reflector foil (22k tiles)

automatic mounting of scintillator tiles on electronics boards (160 boards)

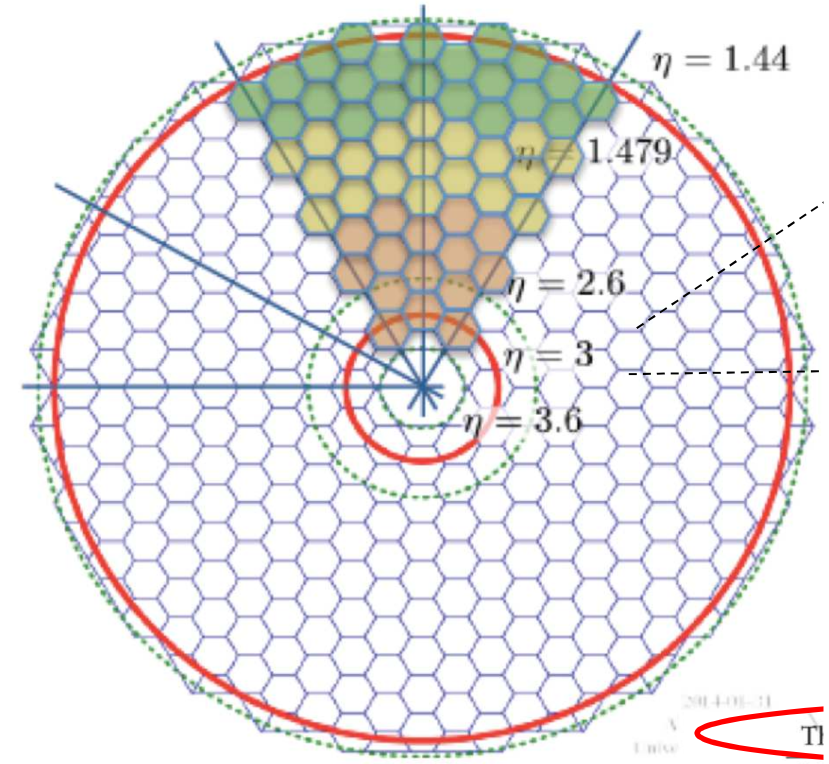


Imaging Calorimeters: Now "Main Stream"

- CMS has selected the "High Granular Calorimeter" HGCAL for the HL-LHC upgrade of its forward calorimeters - currently in development, installation 2025



HGC-ECAL:
Silicon sensors
Tungsten / Copper absorber



HGC-HCAL:
Silicon sensors
Brass absorbers

Summary

- Event reconstruction with collider detectors:
  - Tracking detectors to measure the momentum of charged particles - Via track curvature in magnetic field
    - Technology: Mostly semi-conductor or gaseous detectors
  - Calorimeters to measure the energy of (almost) all particles
    - Subdivided into
      - Electromagnetic and hadronic calorimeters
      - Homogeneous and sampling calorimeters
    - Reconstruction of invisible particles by the measurement of the total event energy (and of missing energy by applying momentum conservation)
    - Highly granular calorimeters: Exploit advances in microelectronics, enable new paradigms of event reconstruction

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Next Lecture:

Cosmic Rays I - B. Majorovits, 14.01.2018

Lecture Overview

15.10.	Introduction, Particle Physics Refresher	*F. Simon*
22.10.	Introduction to Cosmology I	*B. Majorovits*
29.10.	Introduction to Cosmology II	*B. Majorovits*
05.11.	Particle Collisions at High Energy	*F. Simon*
12.11.	The Higgs Boson	*F. Simon*
19.11.	The Early Universe: Thermal Freeze-out of Particles	*B. Majorovits*
26.11.	The Universe as a High Energy Laboratory: BBN	*B. Majorovits*
03.12.	The Universe as a High Energy Laboratory: CMB	*B. Majorovits*
10.12.	Particle Colliders	*F. Simon*
17.12.	Detectors for Particle Colliders I	*F. Simon*
	Christmas Break	
07.01.	Detectors for Particle Colliders II	*F. Simon*
14.01.	Cosmic Rays: Acceleration Mechanisms and Possible Sources	*B. Majorovits*
21.01.	Supernovae Accelerators for Charged Particles and Neutrinos	*B. Majorovits*
28.01.	Searching for New Physics at the Energy Frontier	*F. Simon*
04.02.	Baryogenesis via Leptogenesis	*B. Majorovits*