Calorimetry and Tracking - Day 1

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Designing Particle Physics Experiments

- Suppose someone gave you a pile of money to build a particle physics experiment
- How would you go about it?
- What questions would you ask?
- What would motivate your choices?

Designing Particle Physics Experiments

Physics measurements?

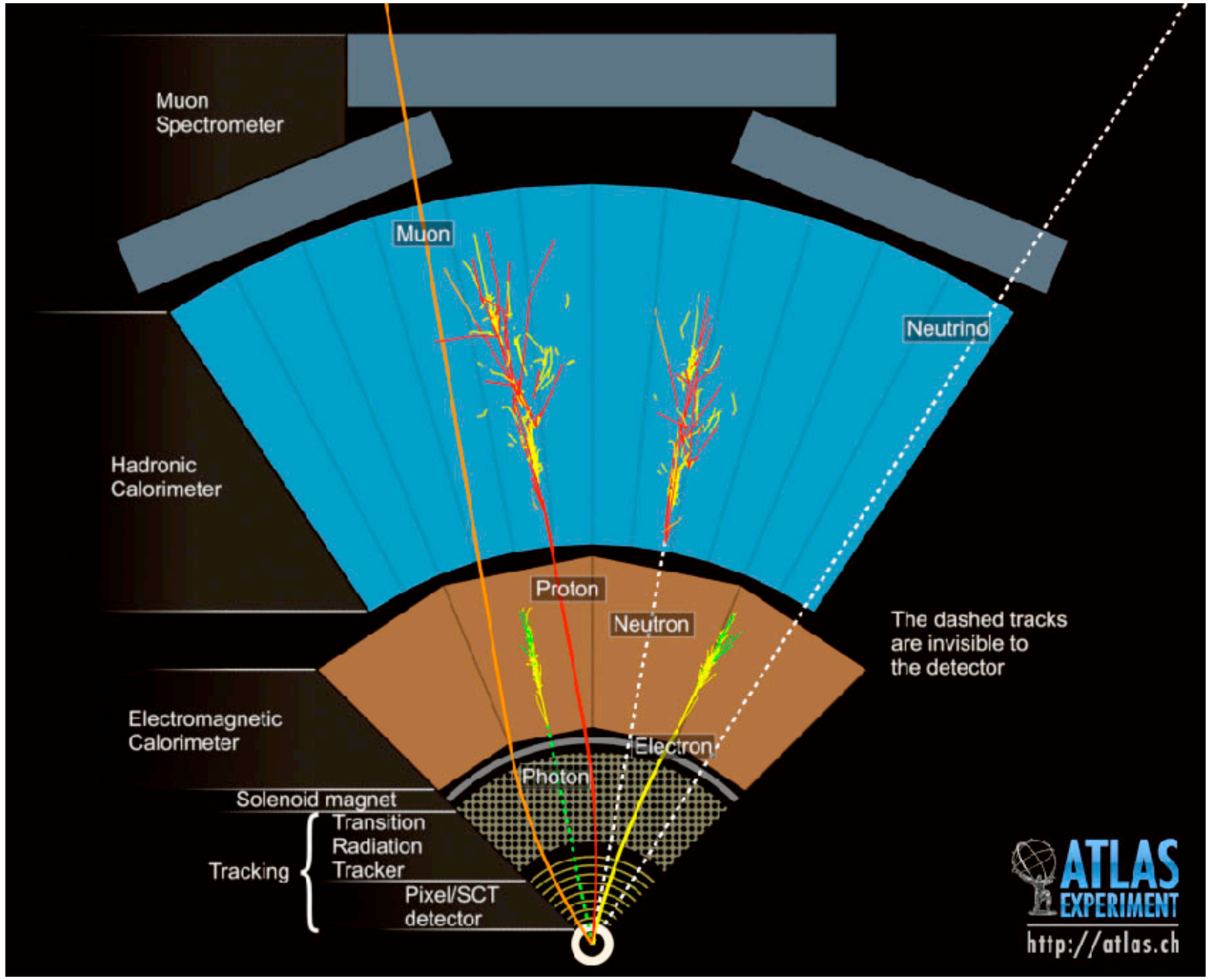
Mechanical constraints?

Accelerator conditions?

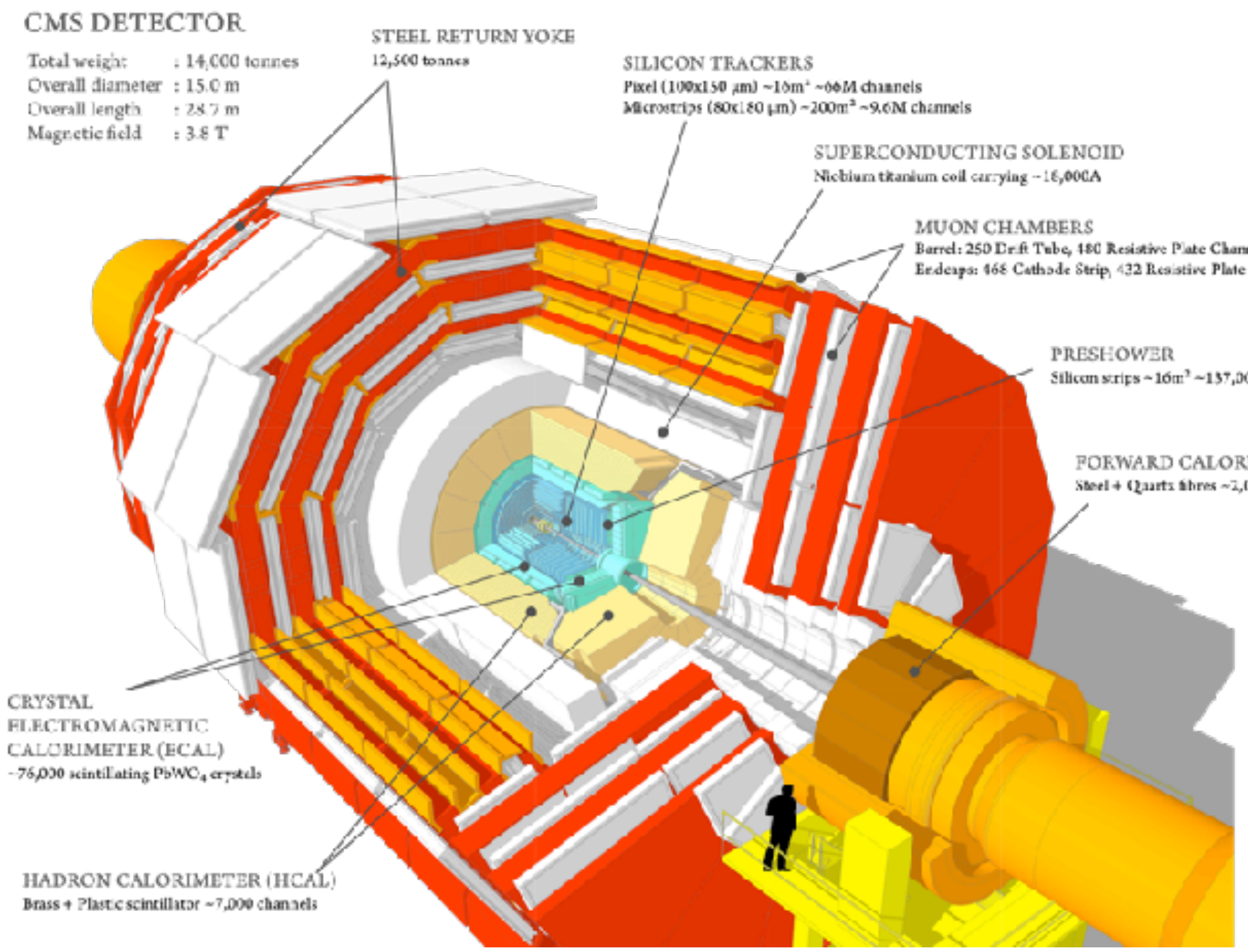
Cost and schedule?

Modern Particle Physics Experiments

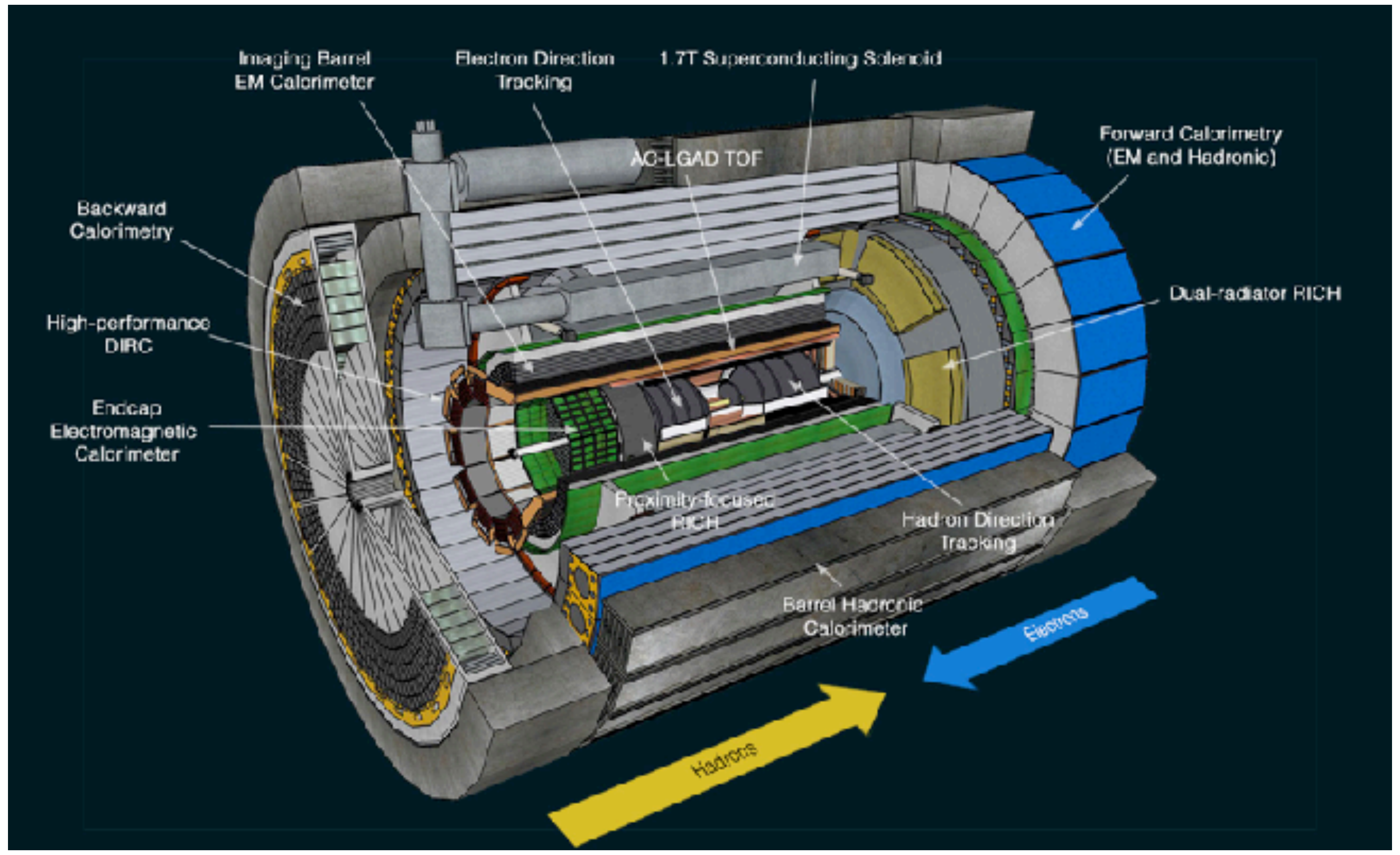
- Things we might want to know
  - Particle type
  - 4 momentum and position of origin
  - Charge
  - Time of flight
- An integrated system of detectors is required to achieve this - each technology has strengths and weaknesses
- NHEP experiments are designed around common features as they have common reconstruction goals



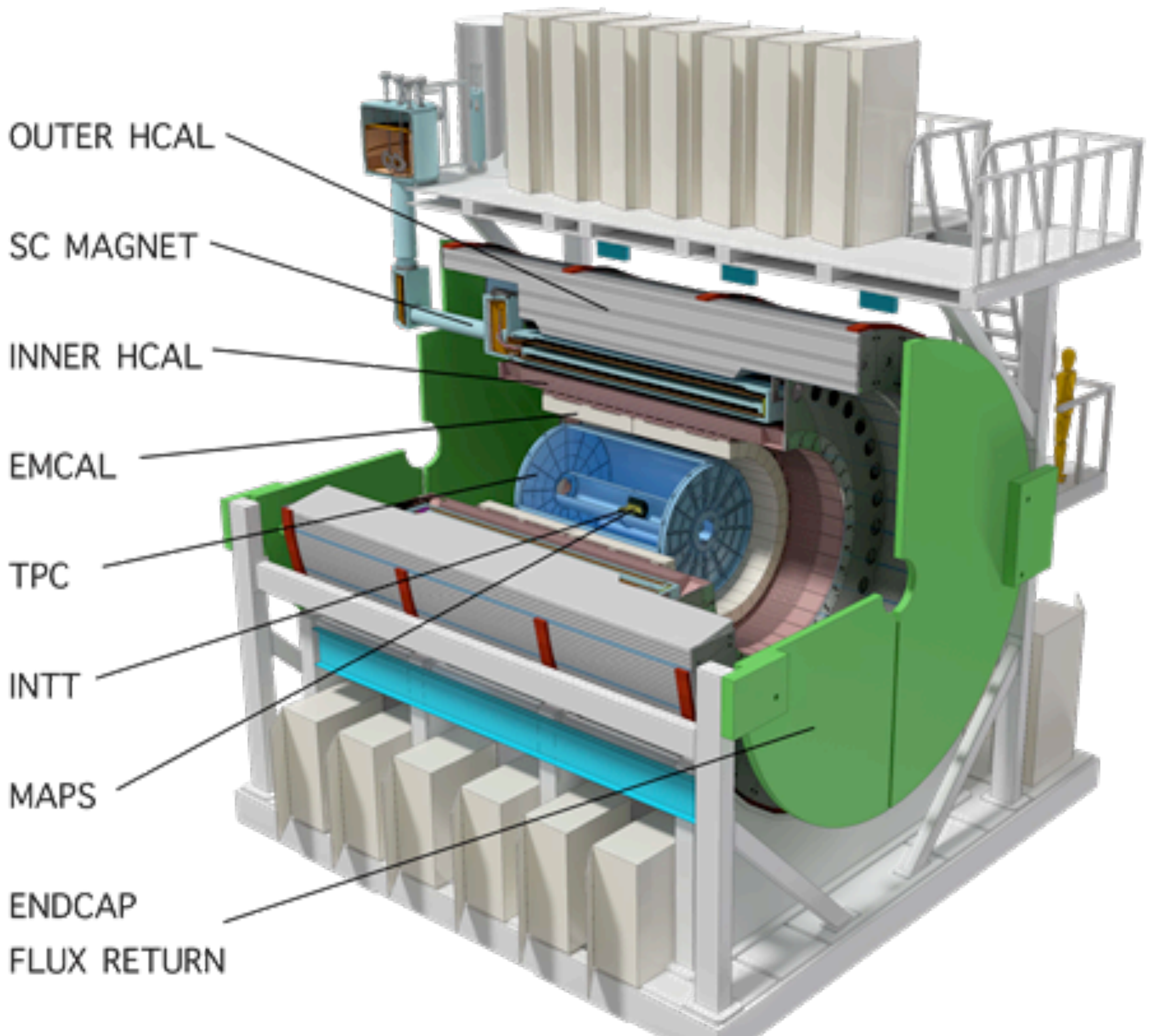
Examples



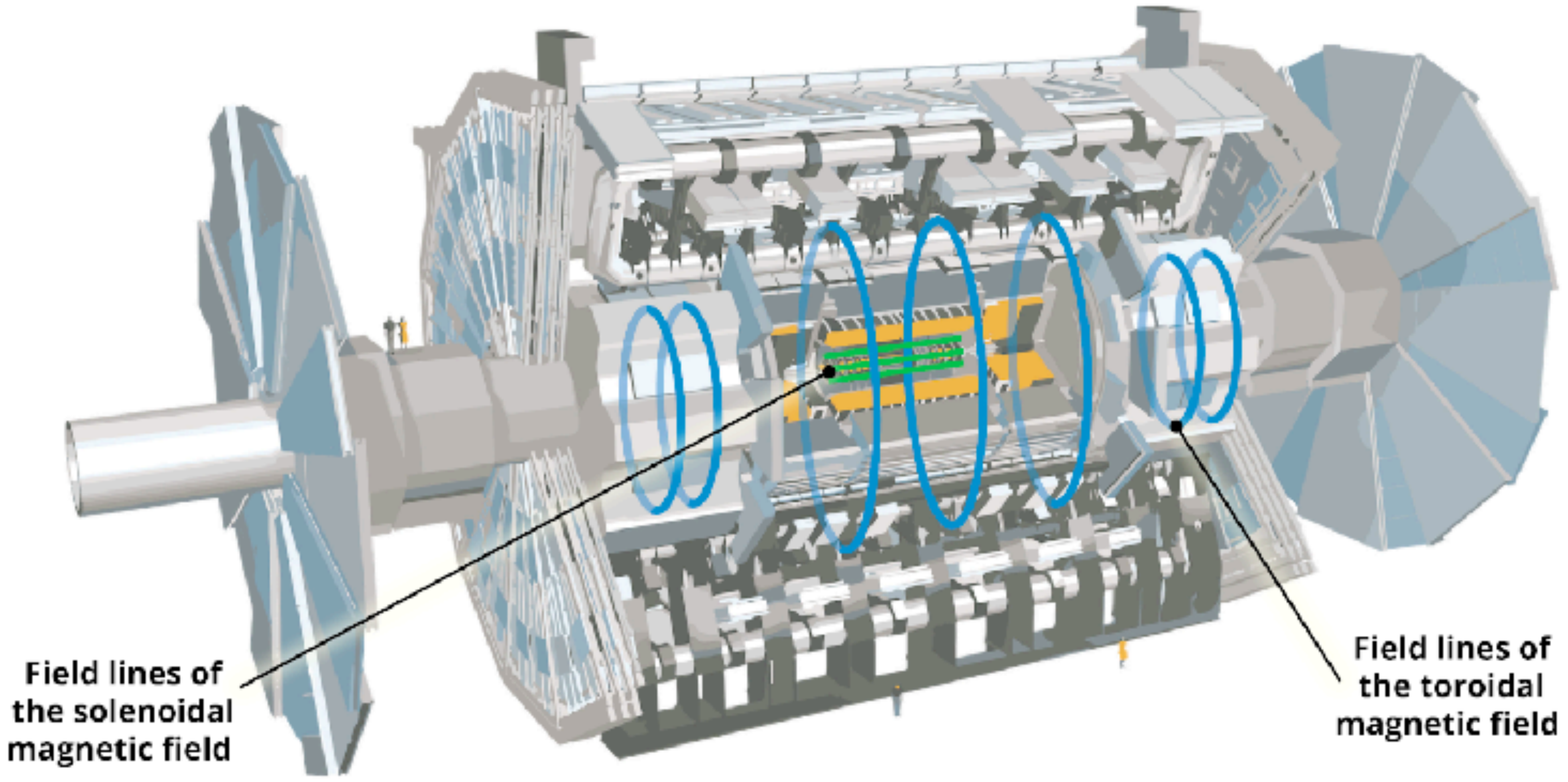
CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels



Imaging Barrel EM Calorimeter
Electron Direction Tracking
1.7T Superconducting Solenoid
AC-LGAD TOF
Forward Calorimetry (EM and Hadronic)
Backward Calorimetry
High-performance DIRC
Dual-radiator RICH
Endcap Electromagnetic Calorimeter
Proximity-focused RICH
Hadron Direction Tracking
Barrel Hadronic Calorimeter
Electrons
Hadrons



OUTER HCAL
SC MAGNET
INNER HCAL
EMCAL
TPC
INTT
MAPS
ENDCAP
FLUX RETURN



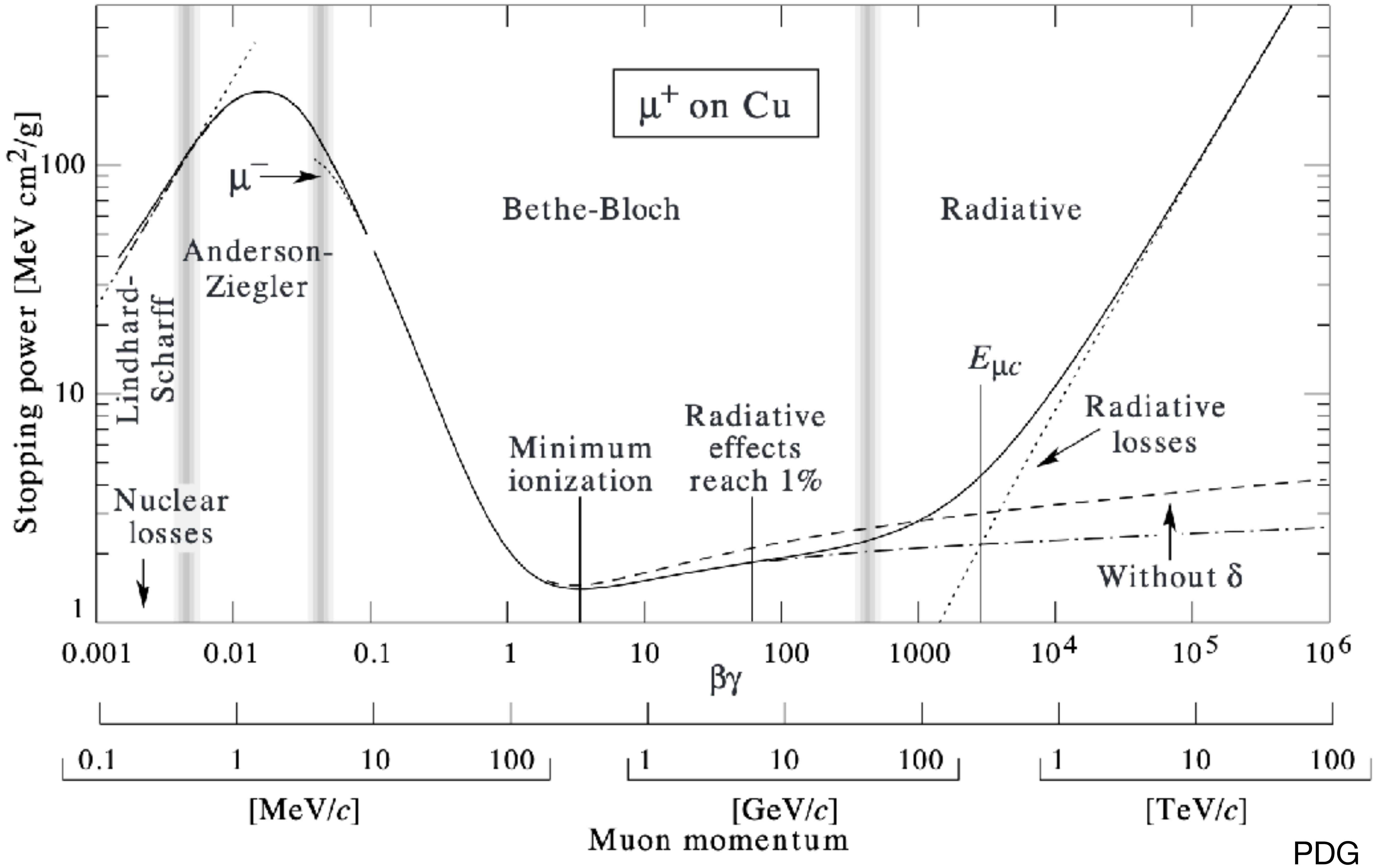
Field lines of the solenoidal magnetic field
Field lines of the toroidal magnetic field

Examples - Commonalities

- As much coverage as possible (close to 4π) to measure all particles from interaction
- Wide variety of technologies (tracking, calorimetery, particle identification…) providing precise resolution of
  - Momentum
  - Energy
  - Position of closest approach (particle origin/trajectory)
- Collect and analyze data at high rates provided by accelerator facilities

Measuring Particles

- All measurement techniques are based on the same general principle
- “Amplify and read out a signal that is measured from the particle’s interaction with some matter”
- Therefore: important to understand how particles interact with matter



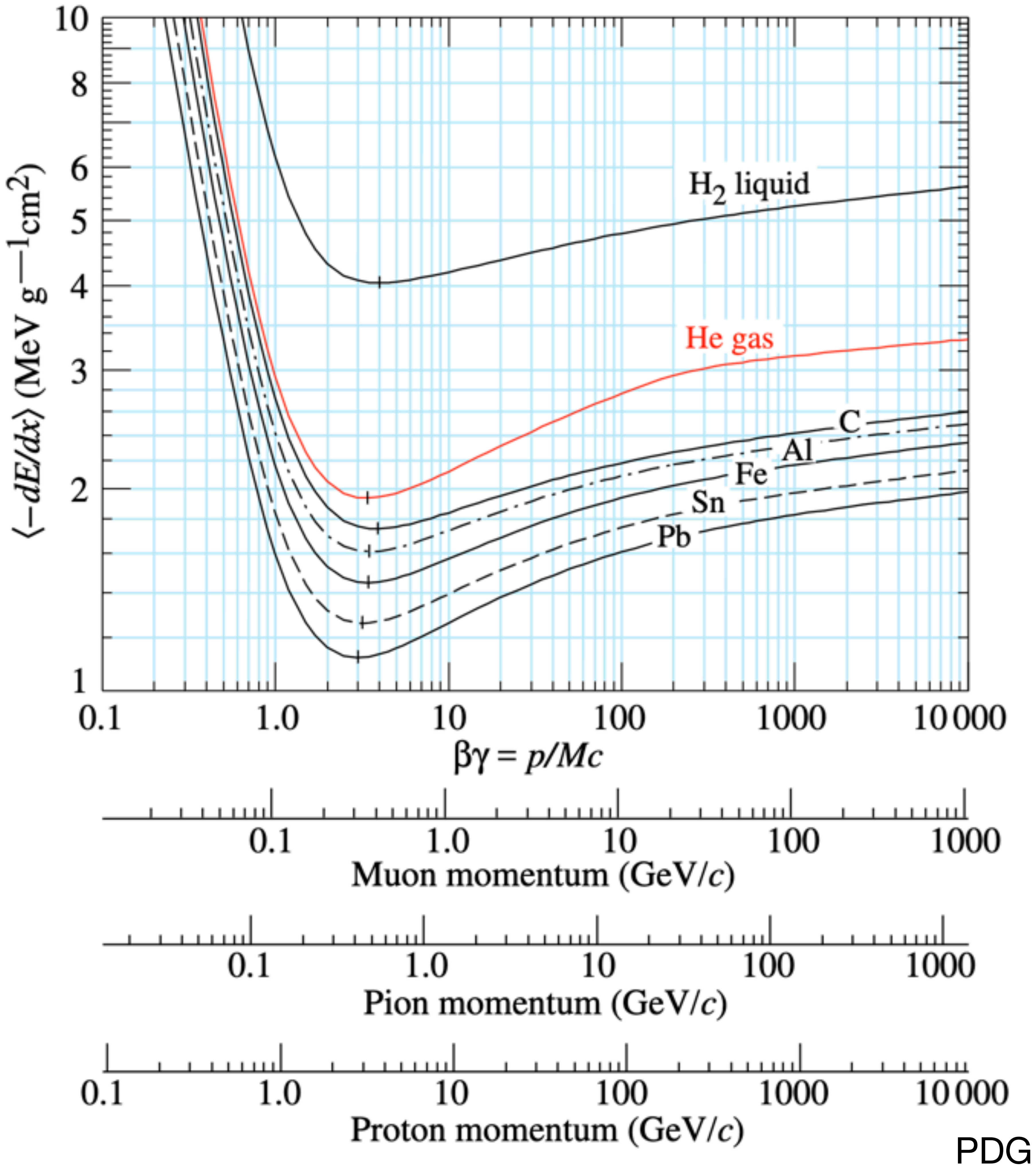
PDG

Bethe Bloch

- Energy loss of a “heavy” charged particle - Hans Bethe (1930)
- For a particle with some charge and velocity

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

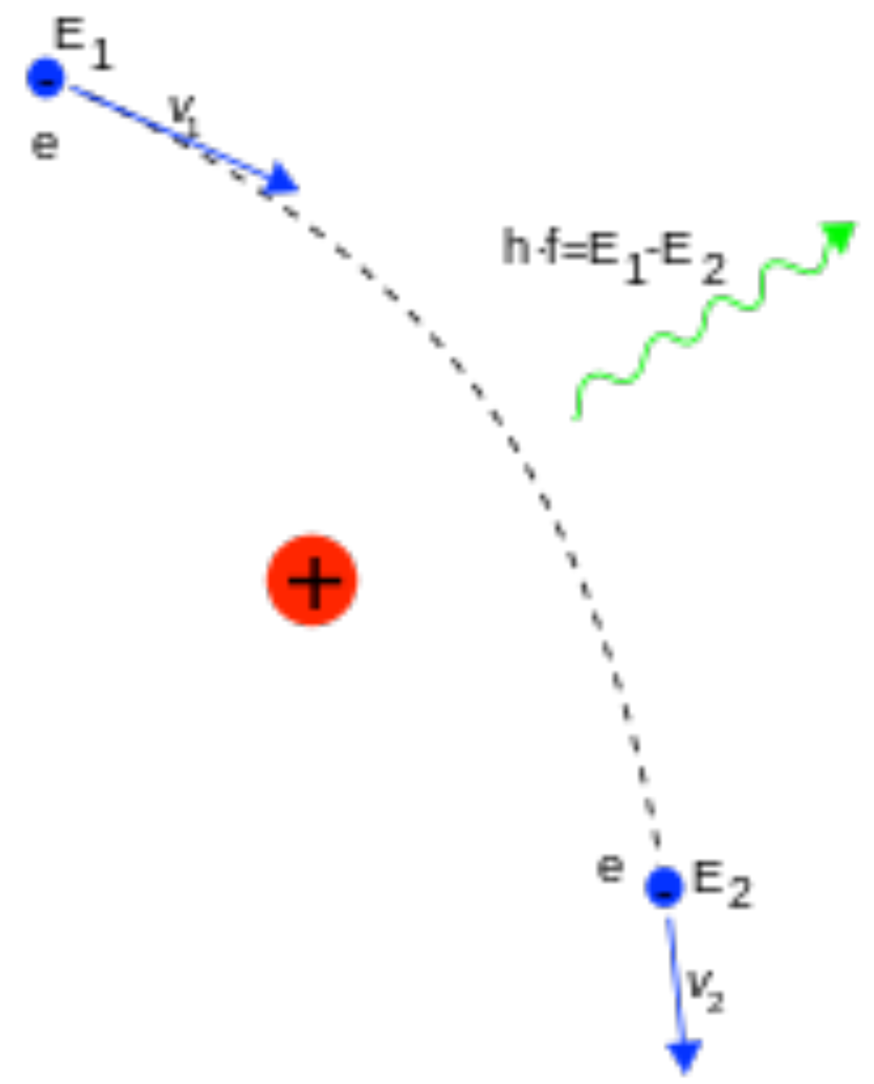
- Valid for 0.1<βɣ<1000 within a few percent. Outside of this, other effects become important (e.g. radiative)



PDG

Electron/Positron Energy Loss

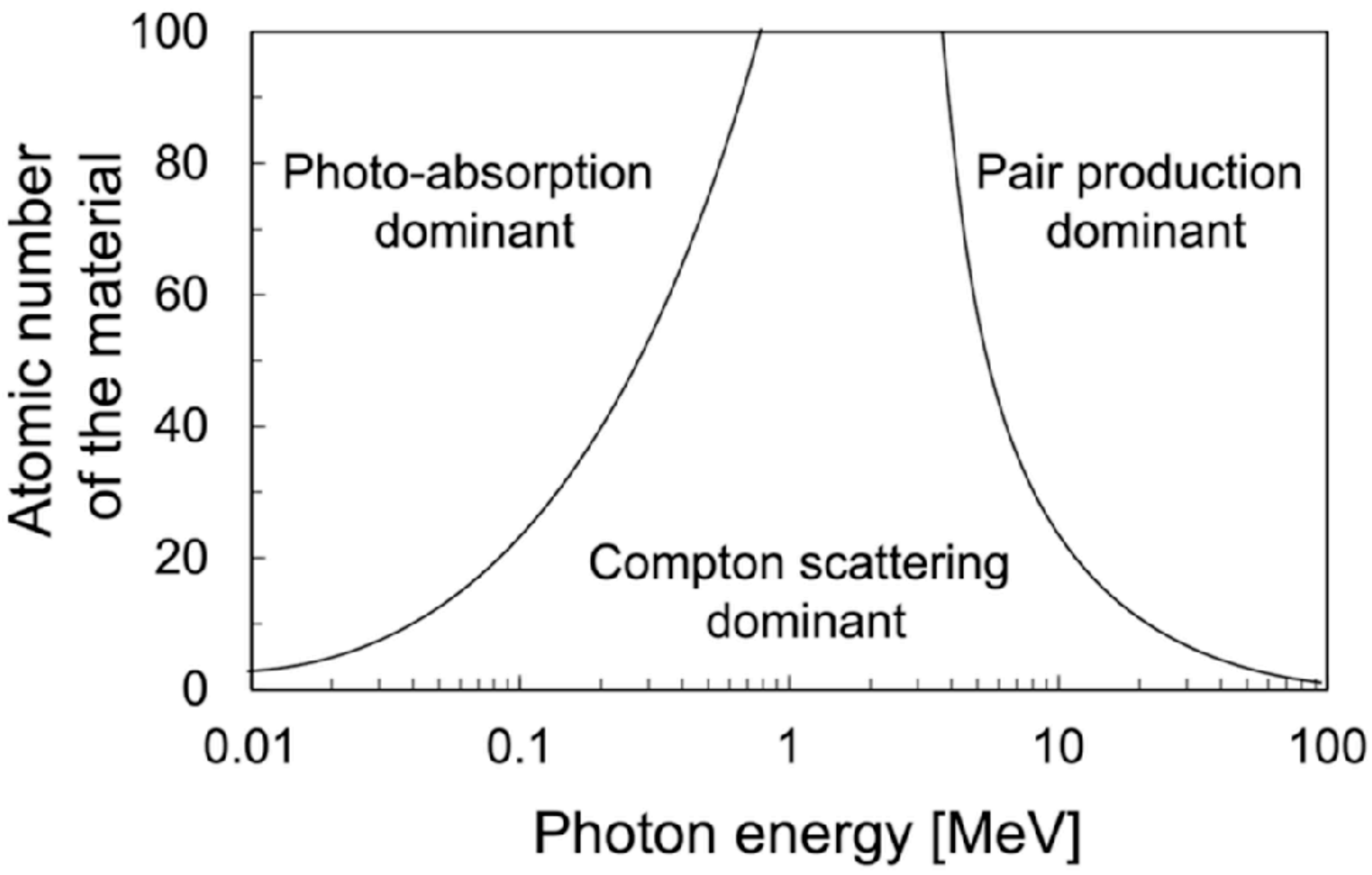
- Electrons are light - lose energy faster and scatter at larger angles
    - For a constant force, acceleration is larger
- Also lose energy via bremsstrahlung - accelerated charge!
- What term dominates depends on incident energy



$$\frac{\left(\frac{dE}{dx}\right)_{brem}}{\left(\frac{dE}{dx}\right)_{coll}} \sim \frac{(T + m_e c^2)Z}{m_e c^2}$$

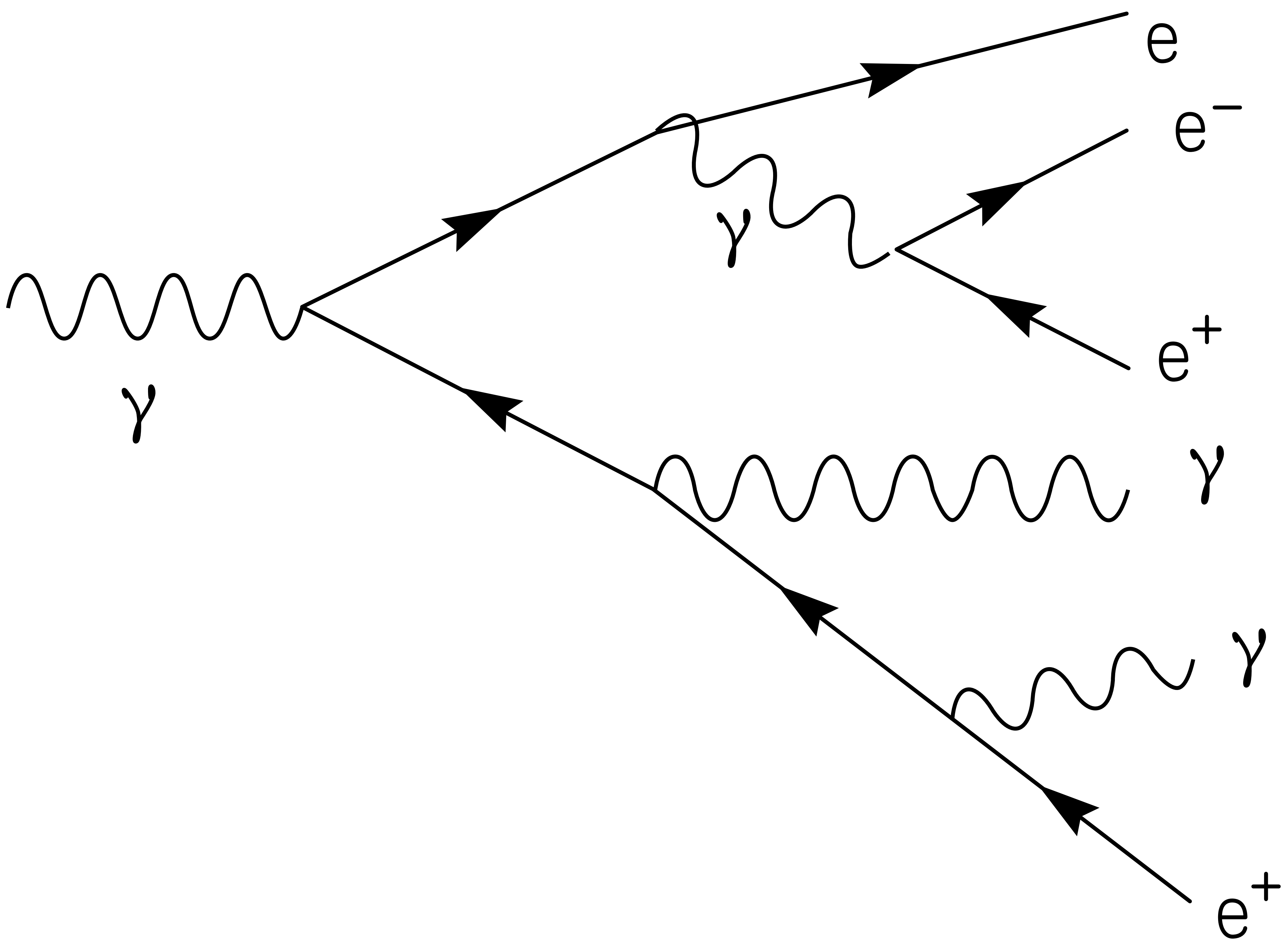
Photon Interactions

- Photons can also interact via
  - Photoelectric effect - absorption of a photon
  - Compton scattering - scattering of a photon
  - Pair production - e^+e^- generation
- With three types of processes, an interacting photon or electron rapidly leads to a cascade of electromagnetic particles
  - Leads to concept of radiation length



Radiation Length

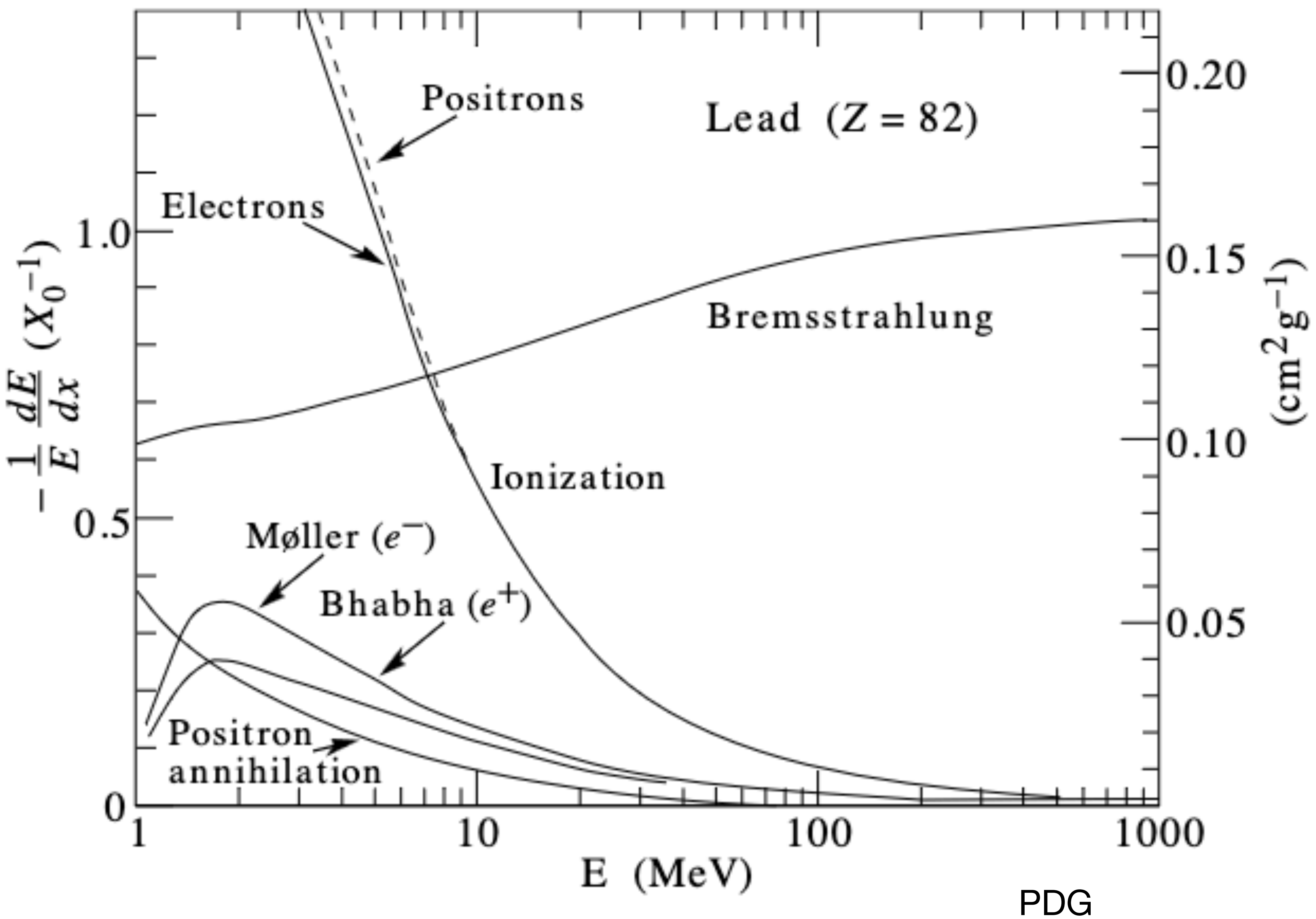
- For energies ≳ 10 MeV, electrons primarily lose energy by bremsstrahlung
  - Photons convert to electron-positron pairs - cascade/shower of electromagnetic particles
- The average distance a high energy electron loses all but 1/e of its energy is the radiation length (X_0) of a material



$$X_0 \sim \frac{A}{Z(Z+1)ln\frac{287}{\sqrt{Z}}}$$

Calorimeters

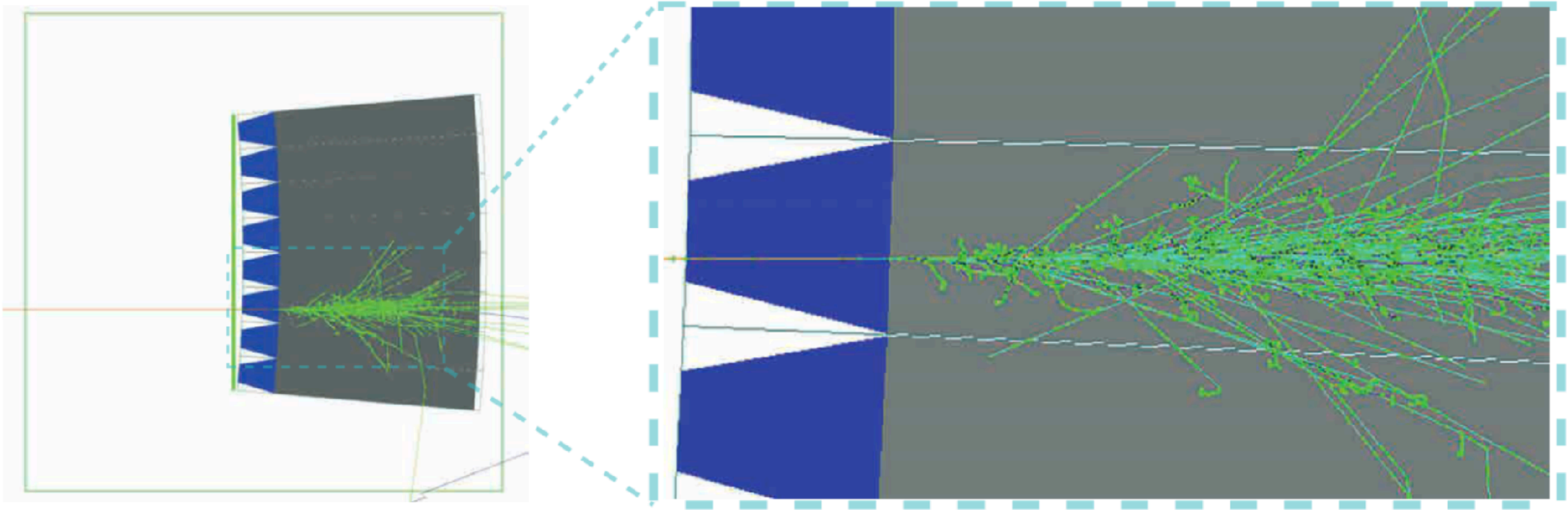
- Calorimeters use material interactions to stop high energy particles
    - Typically built of high density materials
- Cascade of electromagnetic particles is collected and readout to determine energy of incident particle
- Electromagnetic calorimeter - photons/e±
- Hadronic calorimeter - hadrons



PDG

Calorimeters

- Example - 8 GeV electron simulation on SciFi (scintillating fiber) tungsten electromagnetic calorimeter



Calorimeters - Resolution

- Reminder - radiation length only dependent on material
- Typically for ~99% containment of a shower, need ~20 X0
- In a perfect calorimeter, the resolution depends on the number of particles produced in the shower
- Reality is never perfect…

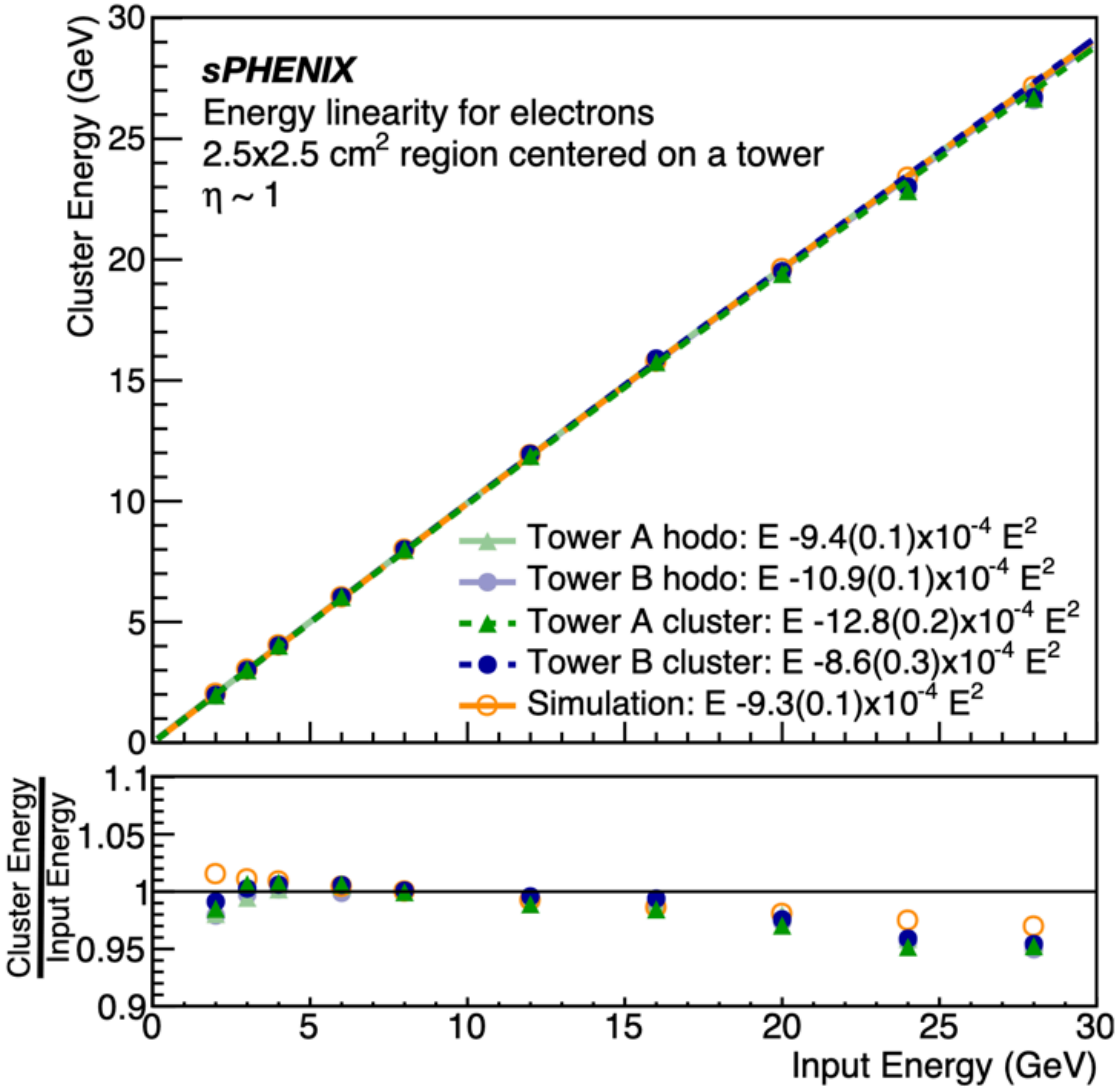
Constant term - inhomogeneities, energy leakage…

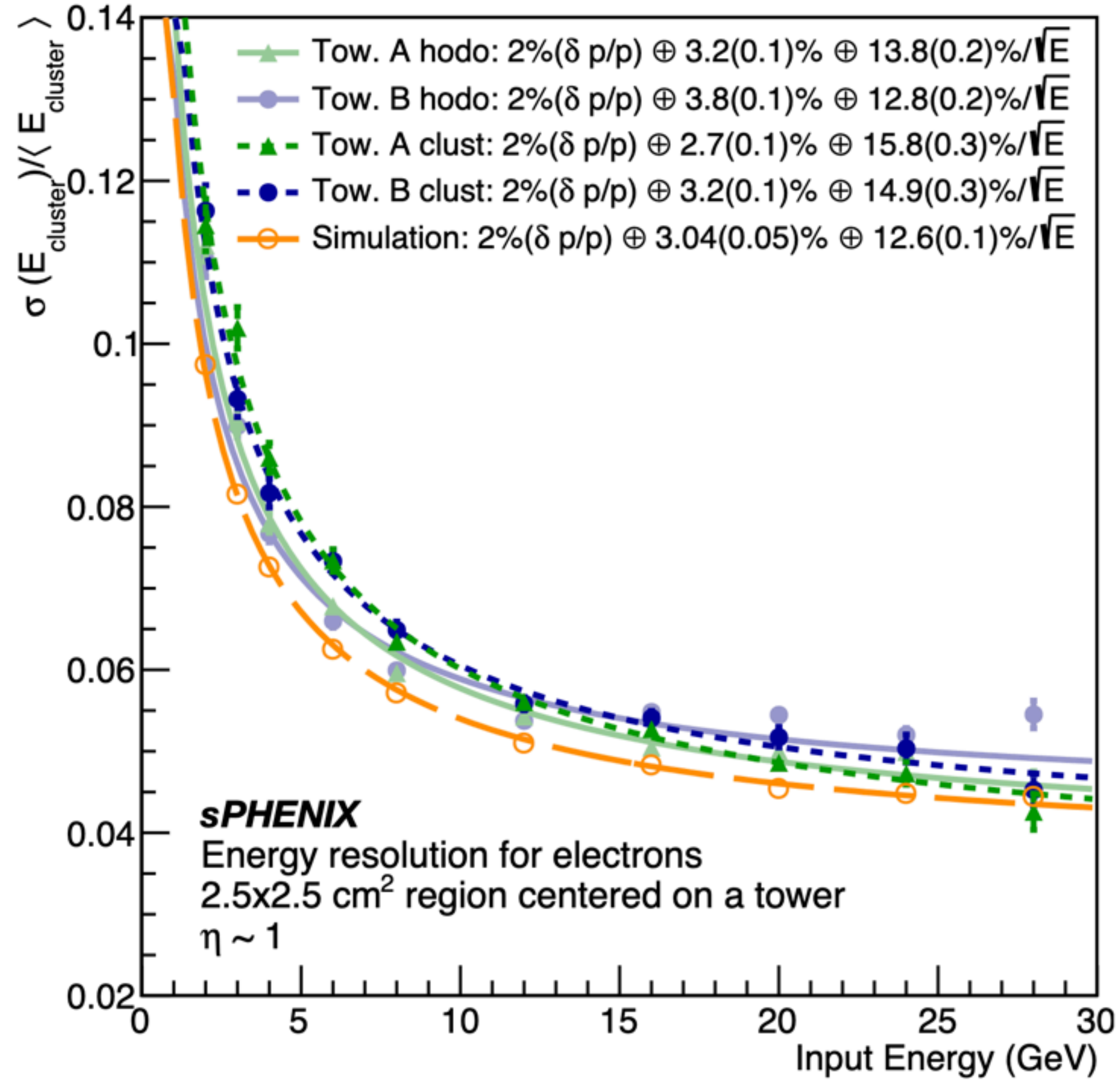
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Stochastic term - intrinsic shower fluctuations

Noise term - readout electronic noise

Calorimeters - Resolution





Quadratic sum of terms - 2% beam uncertainty + constant + stochastic

particles

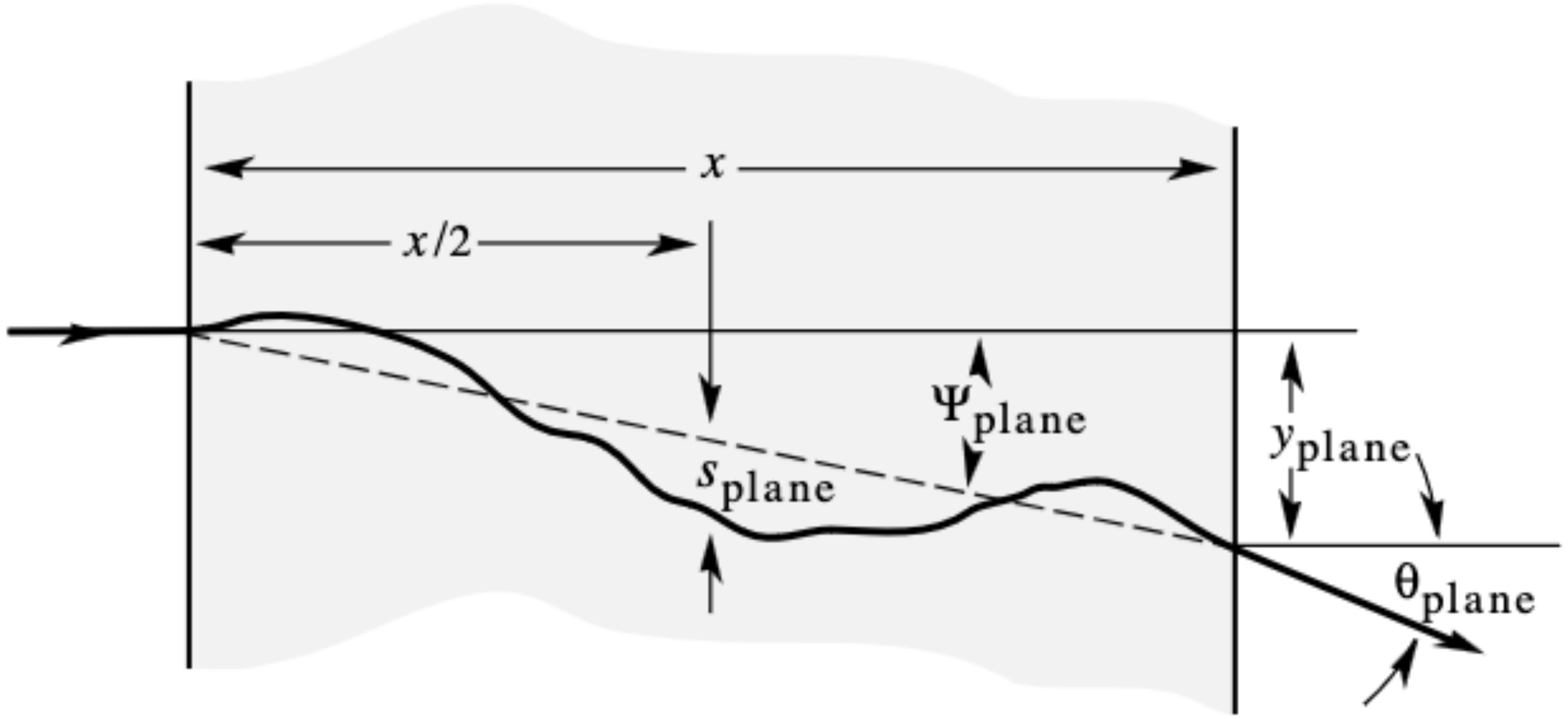
mogeneities,

Noise term - readout electronic noise

Stochastic term intrinsic shower fluctuations

Multiple Scattering

- Particles can also undergo Rutherford scattering (scattering from atomic nuclei)
    - Deflects direction through many small-angle scatters
    - Approximately Gaussian with width θ_0
- Smaller thickness of material —> fewer scatters —> better measurement of particle trajectory



PDG

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

Thickness of material in radiation lengths

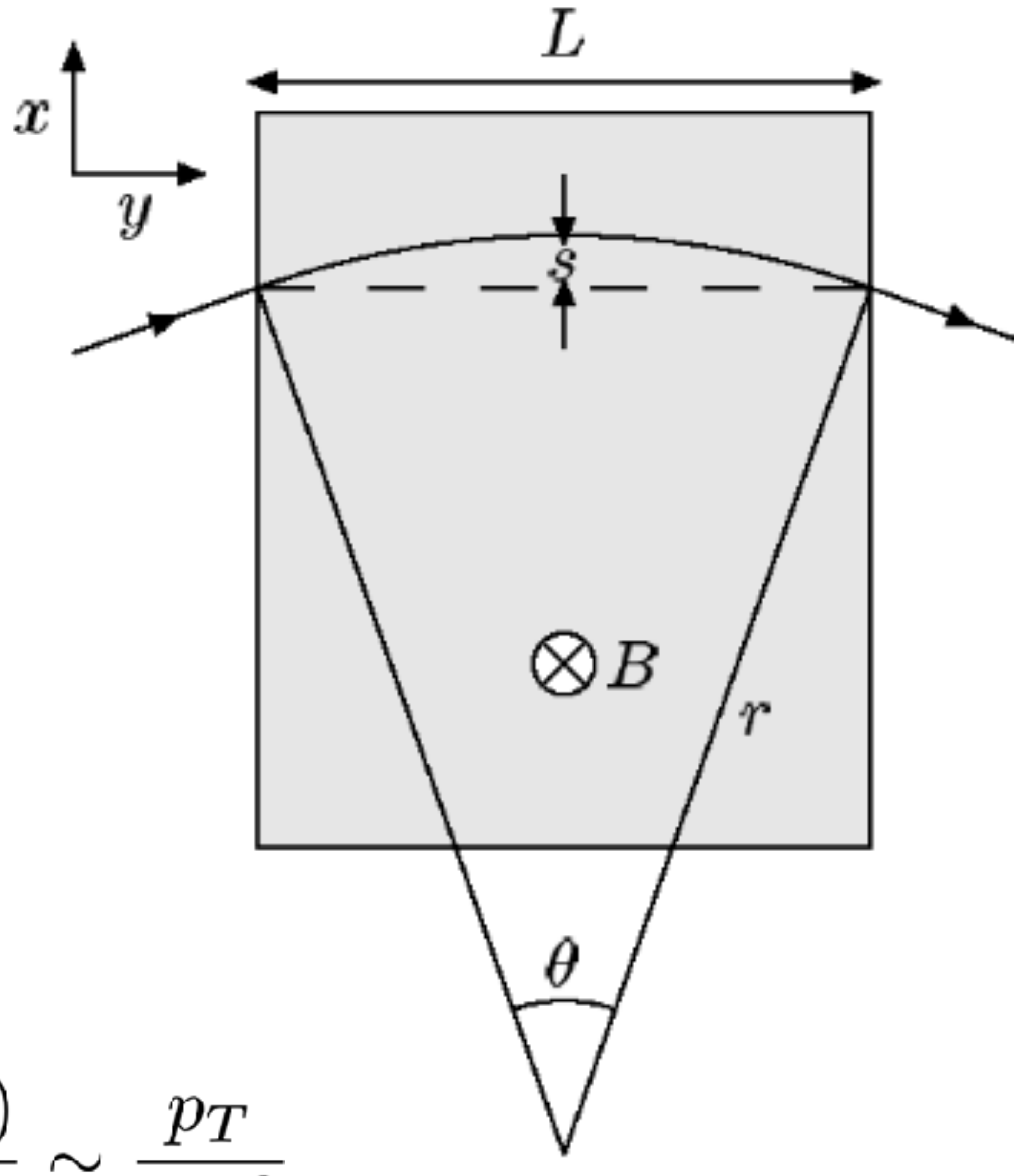
Tracking

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

$$p_T[GeV/c] = 0.3B[T] \times R[m]$$

- Charged particles bend in a magnetic field
- Measurement of sagitta (radius of curvature) provides the momentum
- For precise measurements, need:
    - Large B field
    - Long lever arm
    - Many measurements along trajectory - but multiple scattering scales with the amount of material traversed!

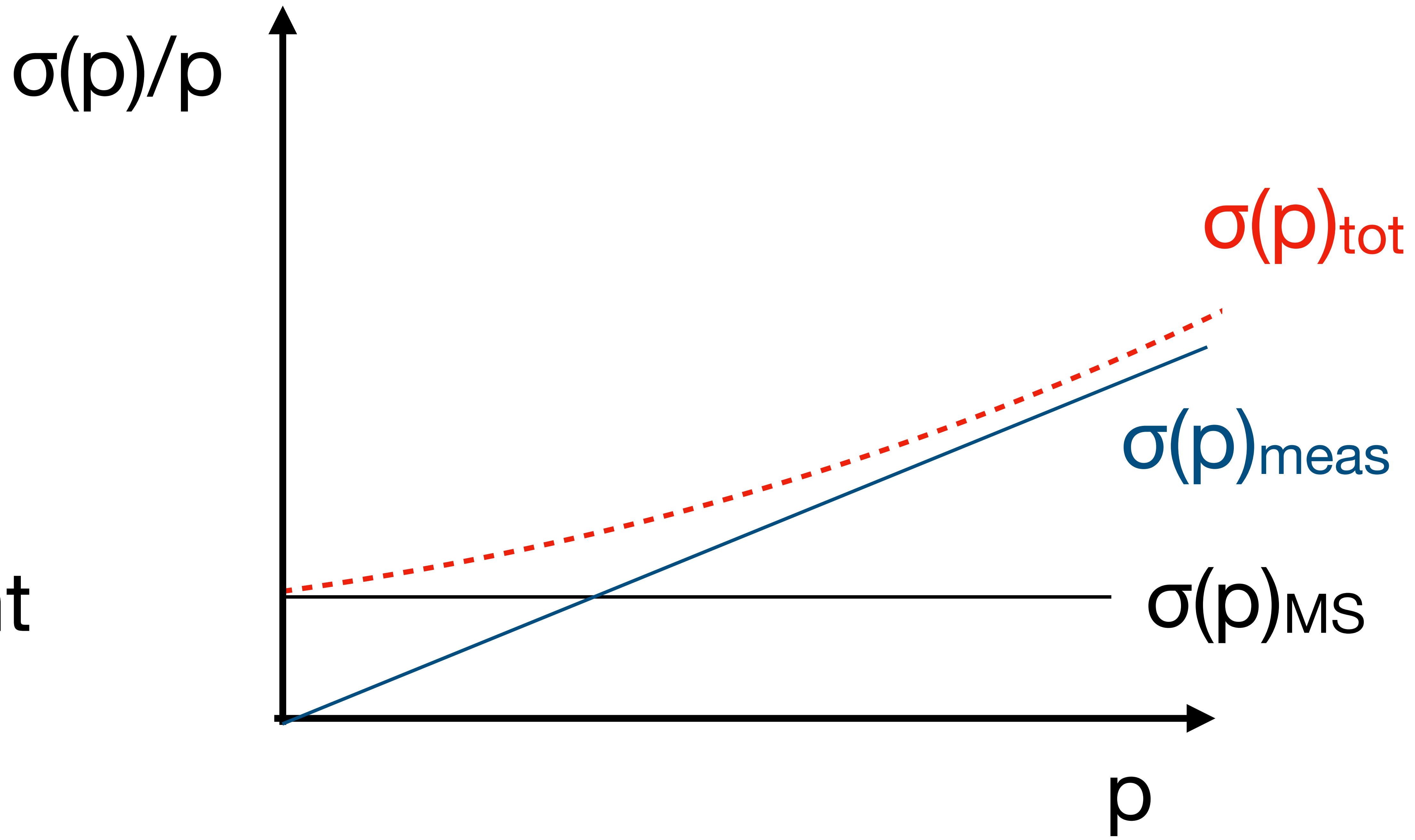
$$\frac{\sigma(p_T)}{p_T} \sim \frac{p_T}{BL^2}$$



NIM 24, 381 (1963)

Tracking Momentum Resolution

- Momentum resolution has
  - Constant term from multiple scattering
  - Linear term dependent on measurement uncertainties
- Need to optimize path length and number of measurements on trajectory while minimizing the total material traversed!



$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = \left(\frac{\sigma_{p_T}}{p_T}\right)^2 + \left(\frac{\sigma_\theta}{\sin\theta}\right)^2$$

Multiple scattering term

Tracking Momentum Resolution

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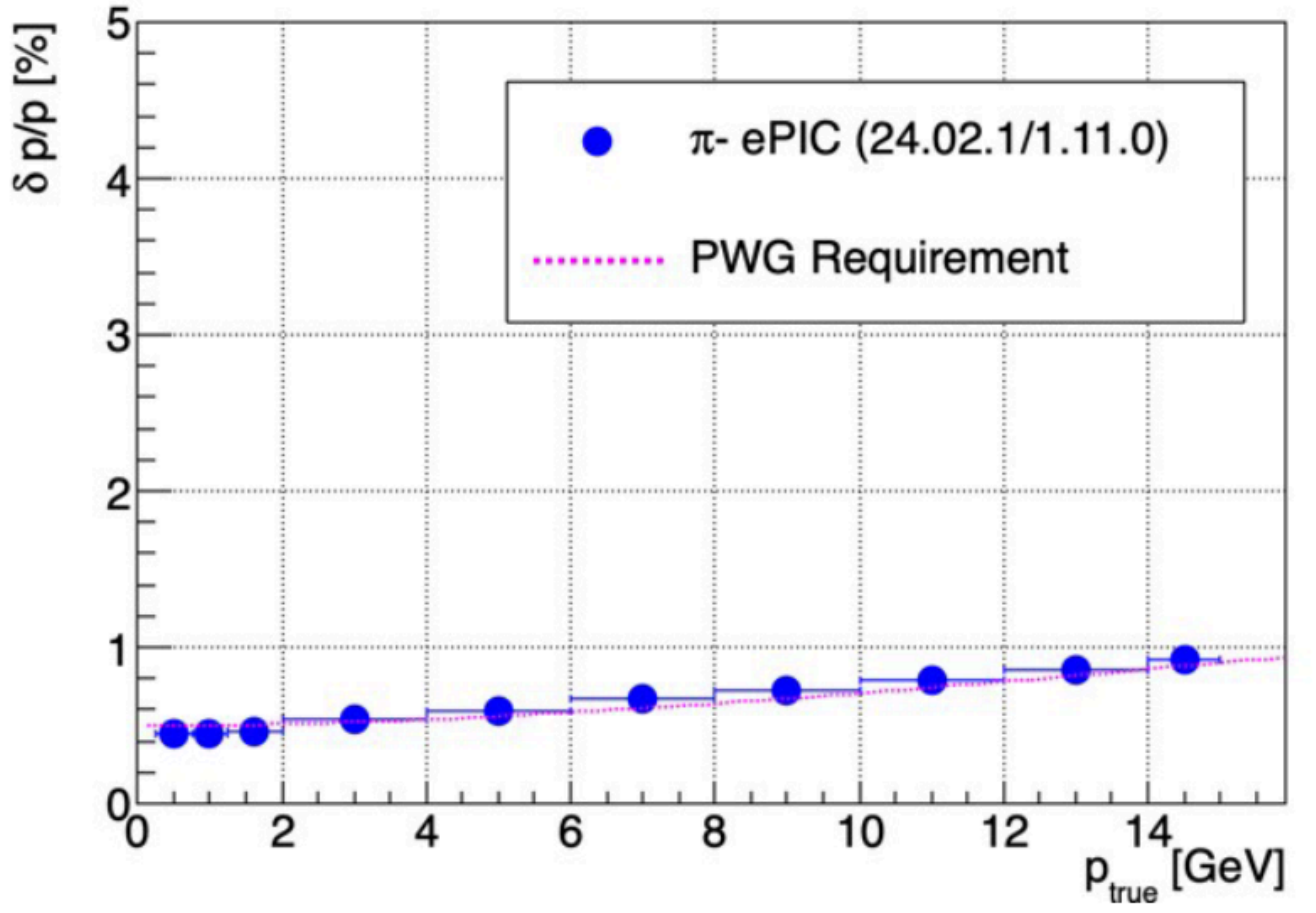


$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\frac{\sigma_{p_T}}{p_T}\right)^2 + \left(\frac{\sigma_\theta}{\sin\theta}\right)^2$$

Multiple scattering term

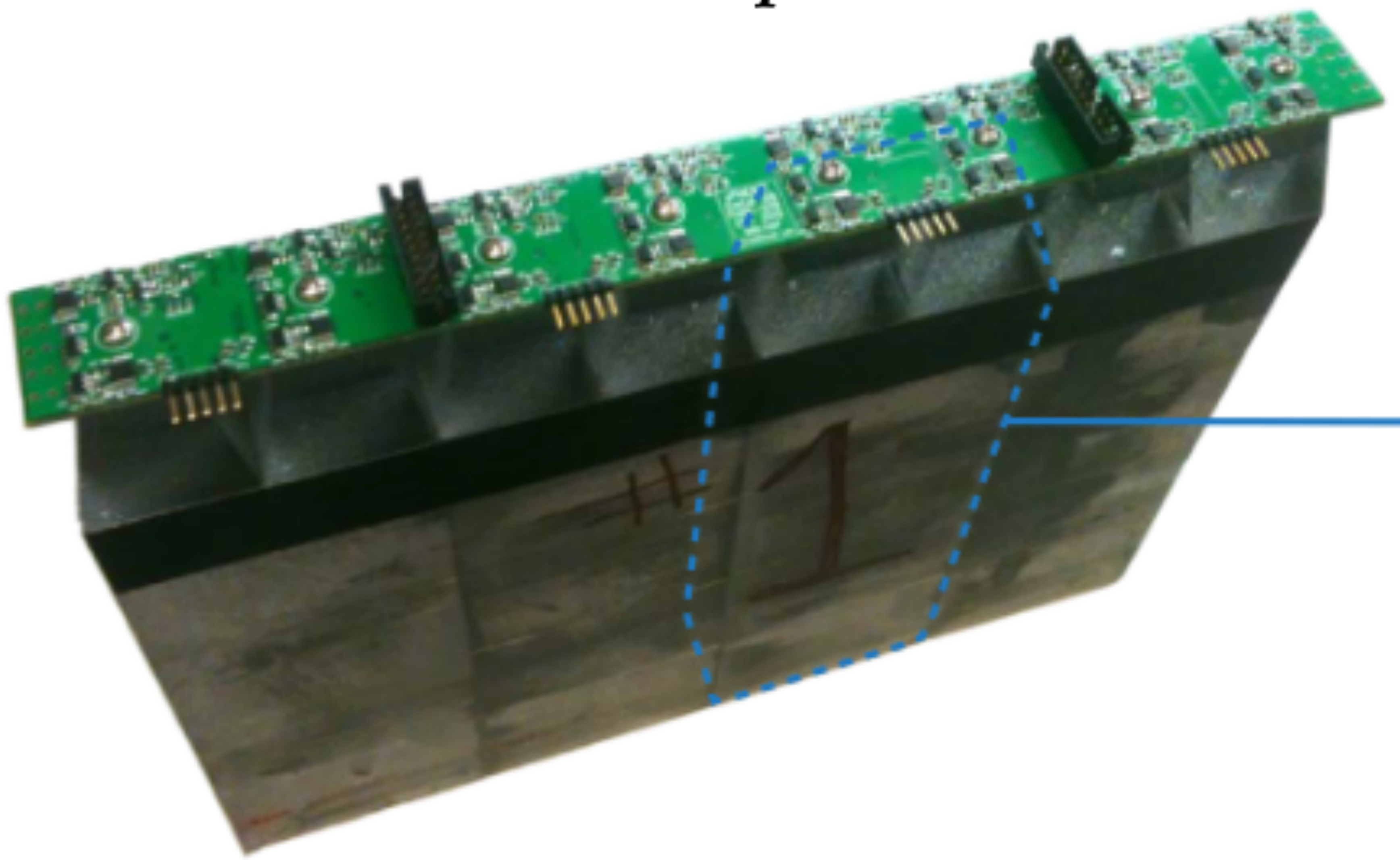
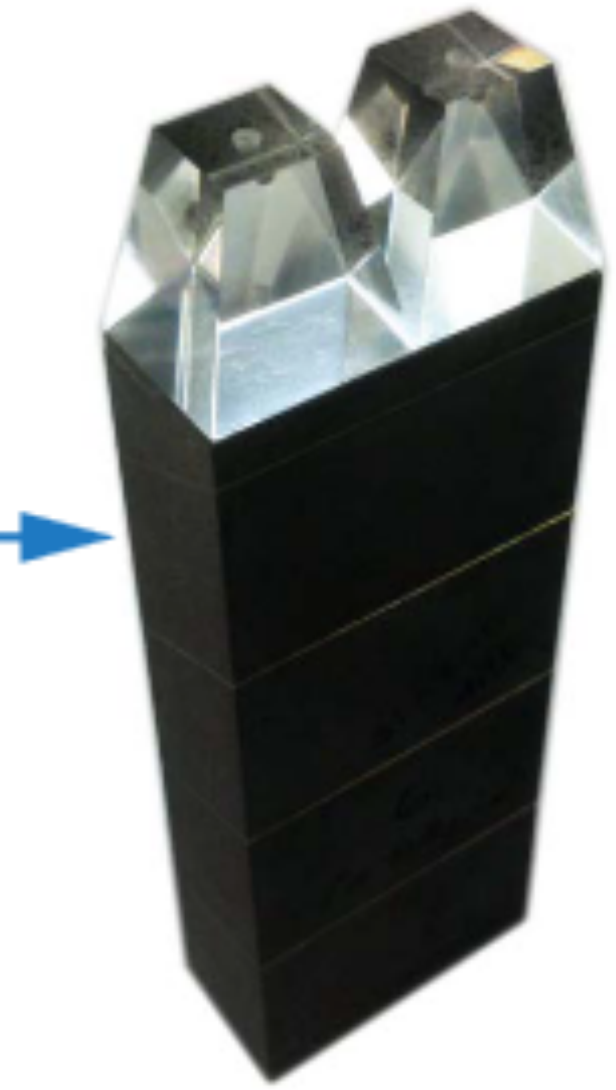
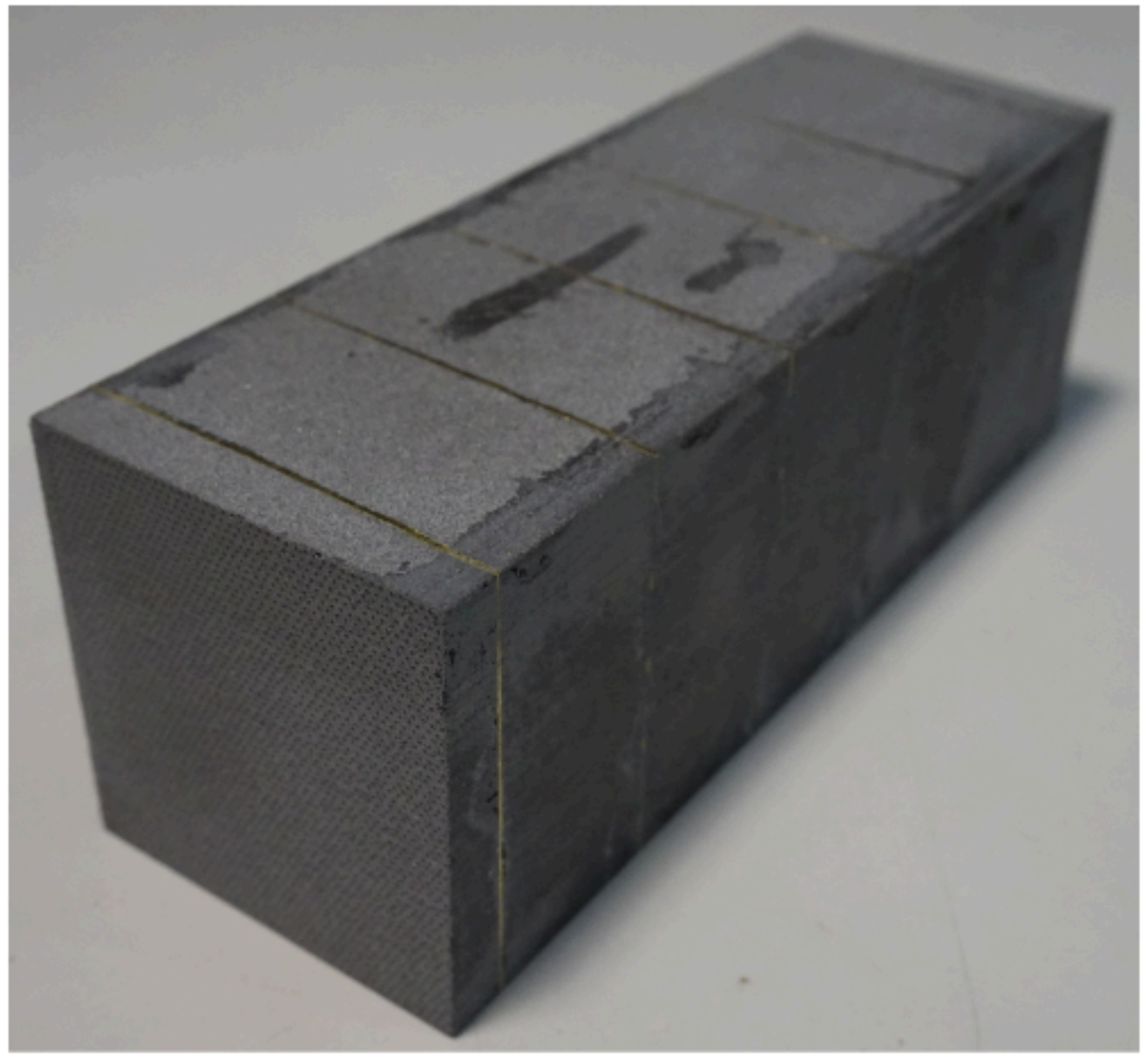
Particle Detection

- Now we know the processes by which radiation and matter interact - how do we use it to detect radiation?
- What did we want to measure?
  - 4 momentum - energy and momentum
  - Charge
- We need two things:
  - Detectors that interact very little with the particle, but enough to measure a signal (tracking)
  - Detectors that can stop a particle and measure the deposited energy (calorimetry)

EMCalorimeters (Sampling)

- Different materials do the sampling (provides signal) and absorbing (dense material to degrade particle energy)
- Example - sPHENIX barrel EMCal, tungsten and scintillating fiber (spaghetti)

$$E_{meas} = \frac{E_{samp}}{f_{samp}} \qquad f_{samp} = \frac{E_{mip}(active)}{E_{mip}(active) + E_{mip}(absorber)}$$

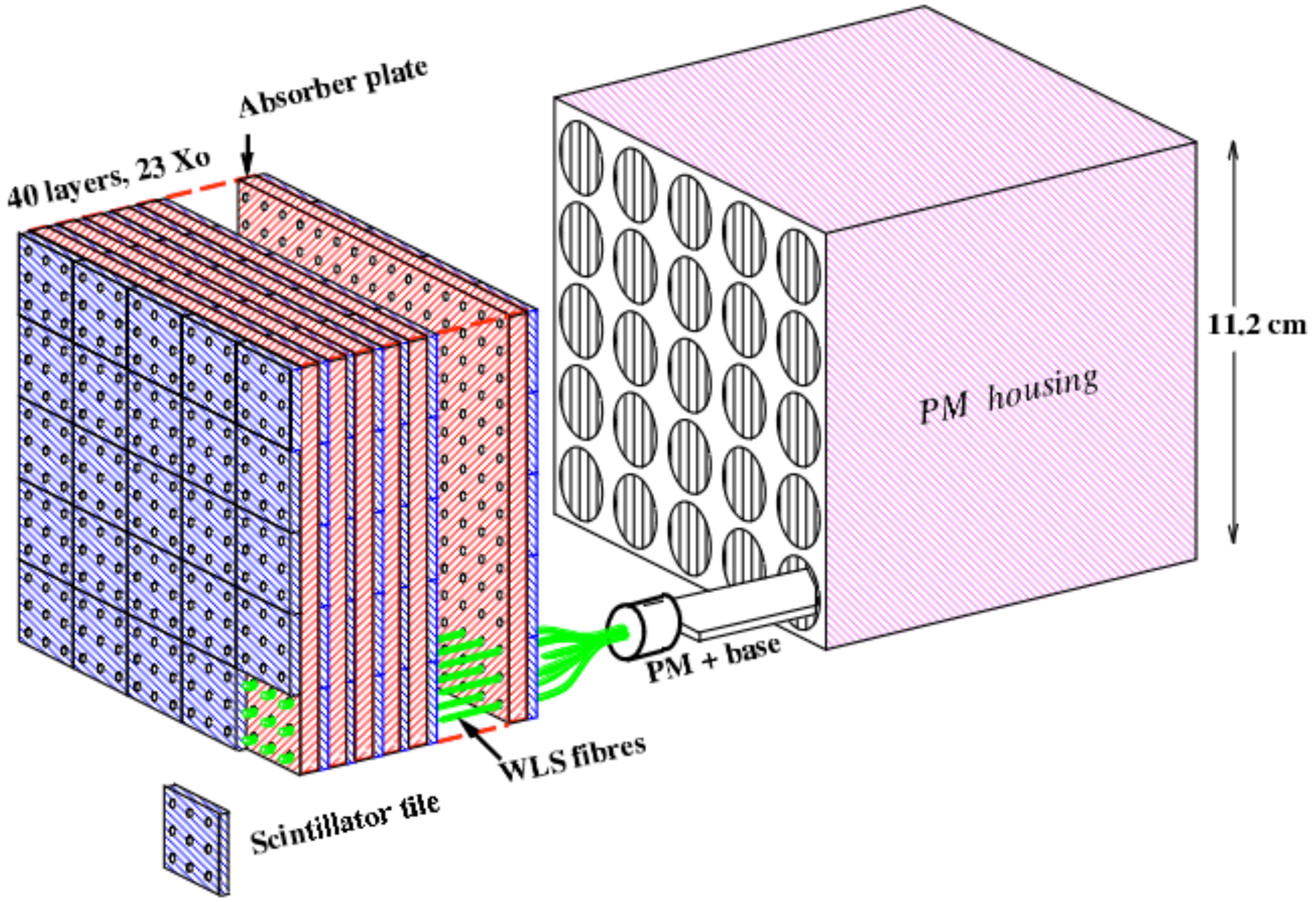




EMCalorimeters (Sampling)

- Sandwich or Shashlik sampling calorimeters also common
- Some absorber (e.g. lead/tungsten/copper…) interleaved with plates of scintillator (e.g. plastic/crystal)

ATLAS liquid Argon calorimeter

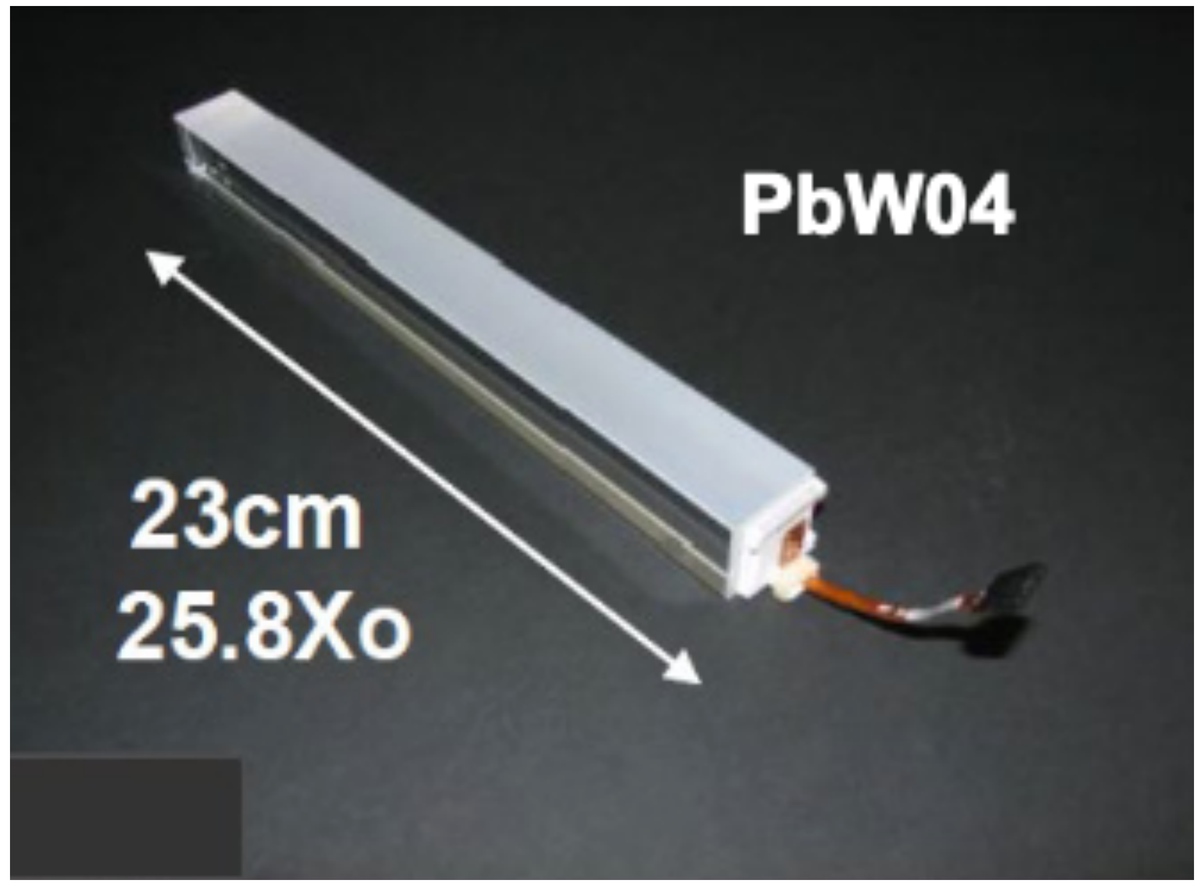
HERA-B shashlik ECal



EMCalorimeters (Homogenous)

- Homogeneous calorimeters use the same material as the absorber and sampler

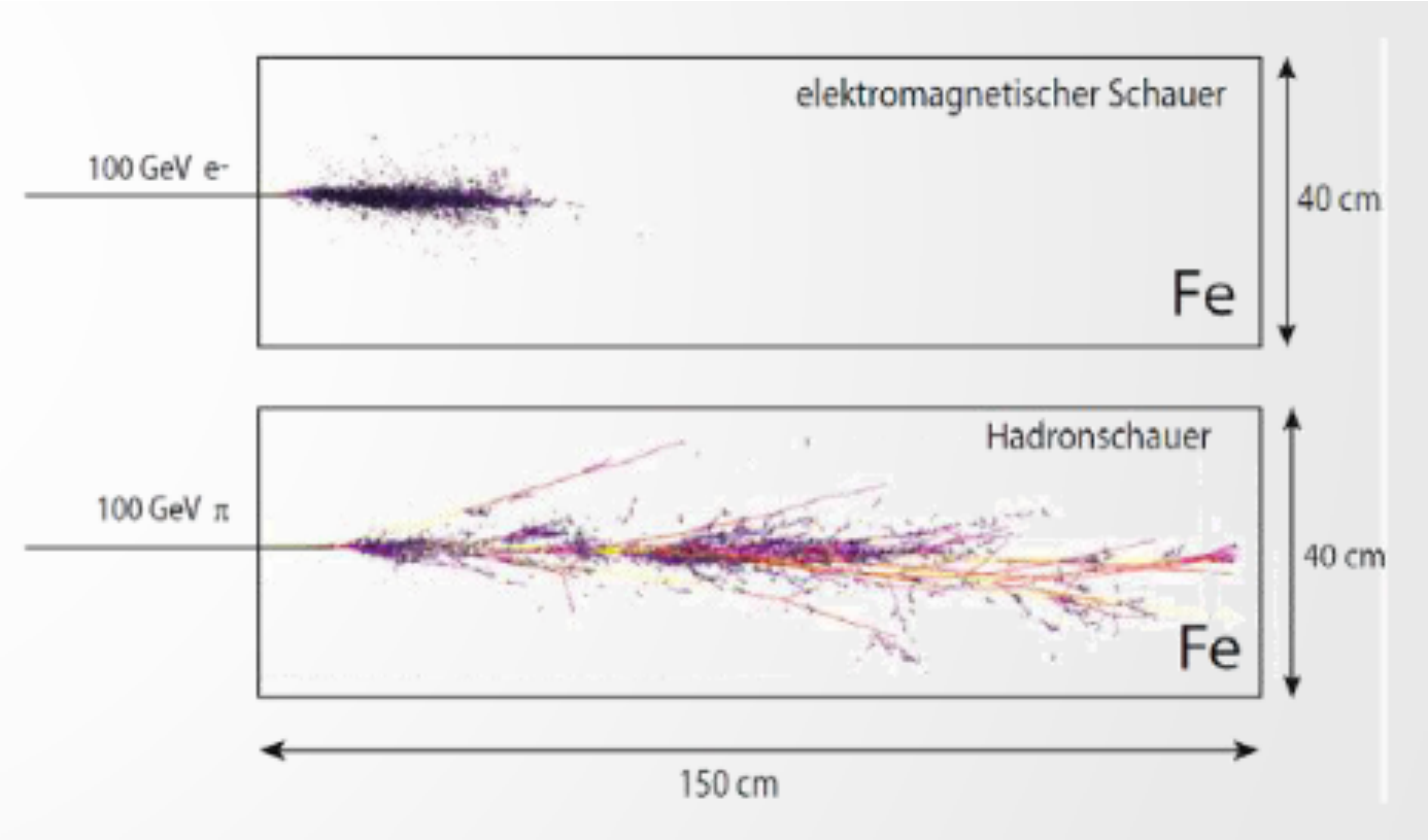
CMS Barrel Pb-Tungstate crystal

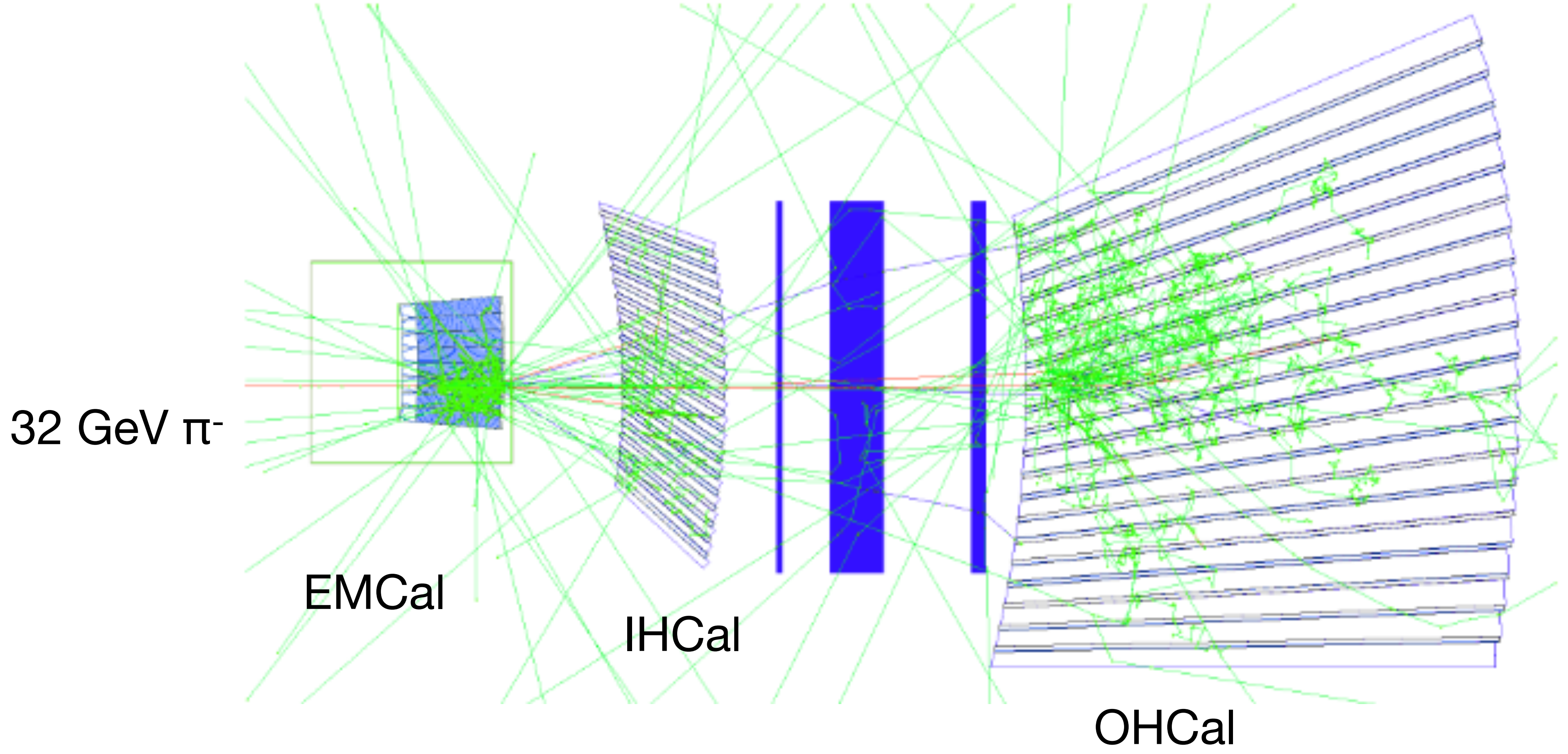


	Pros	Cons
Homogeneous	Best energy resolution	Expensive
Sampling	Cheaper, compact, more “customizable”	Fraction of the shower is captured

Hadronic Calorimeters

- Hadrons interact with nuclei and create both an electromagnetic and hadronic cascade
    - Shower development scales with nuclear absorption length - analogous to radiation length
- More complicated than electromagnetic calorimeters
- Need to be thicker to capture the shower development

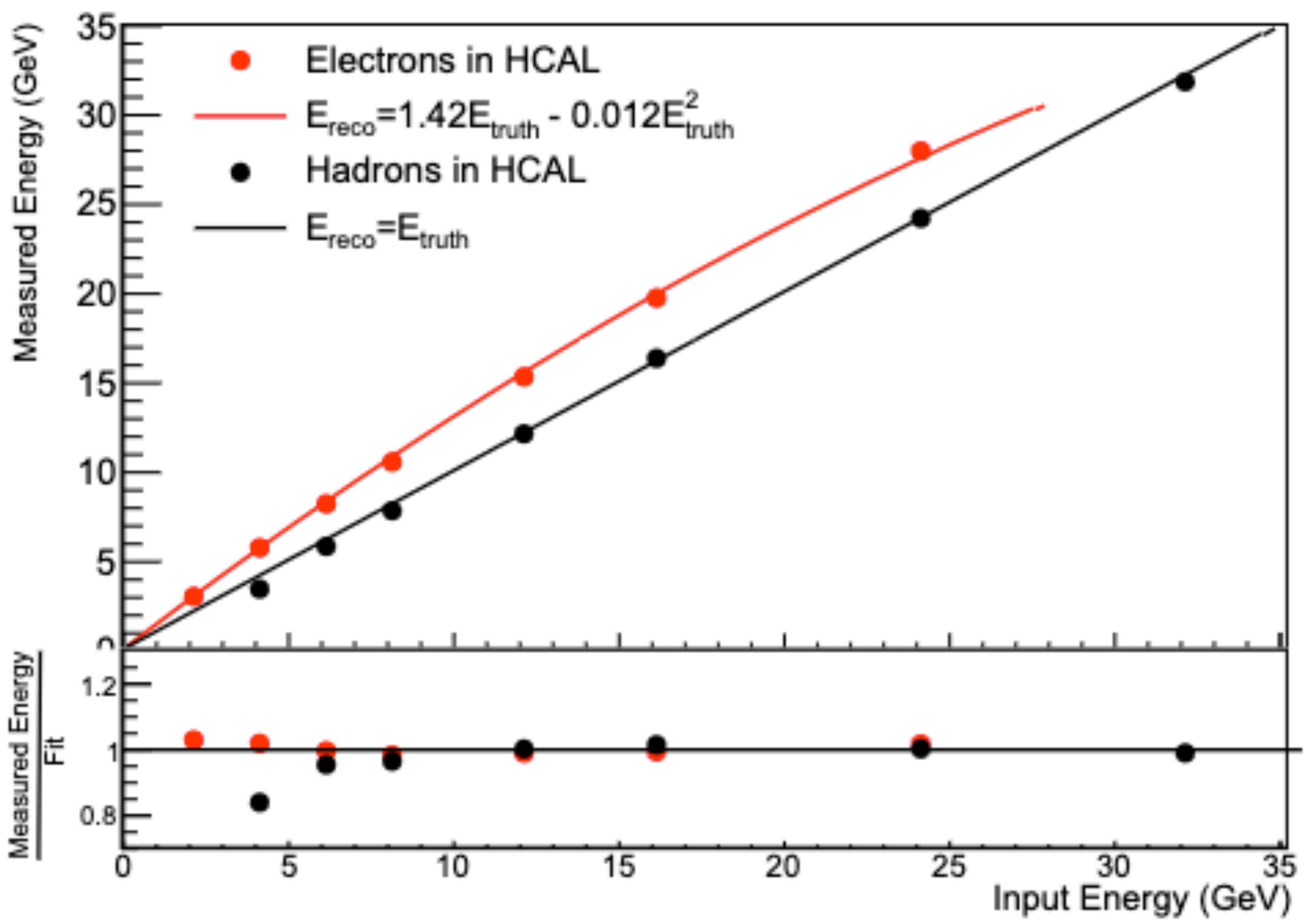


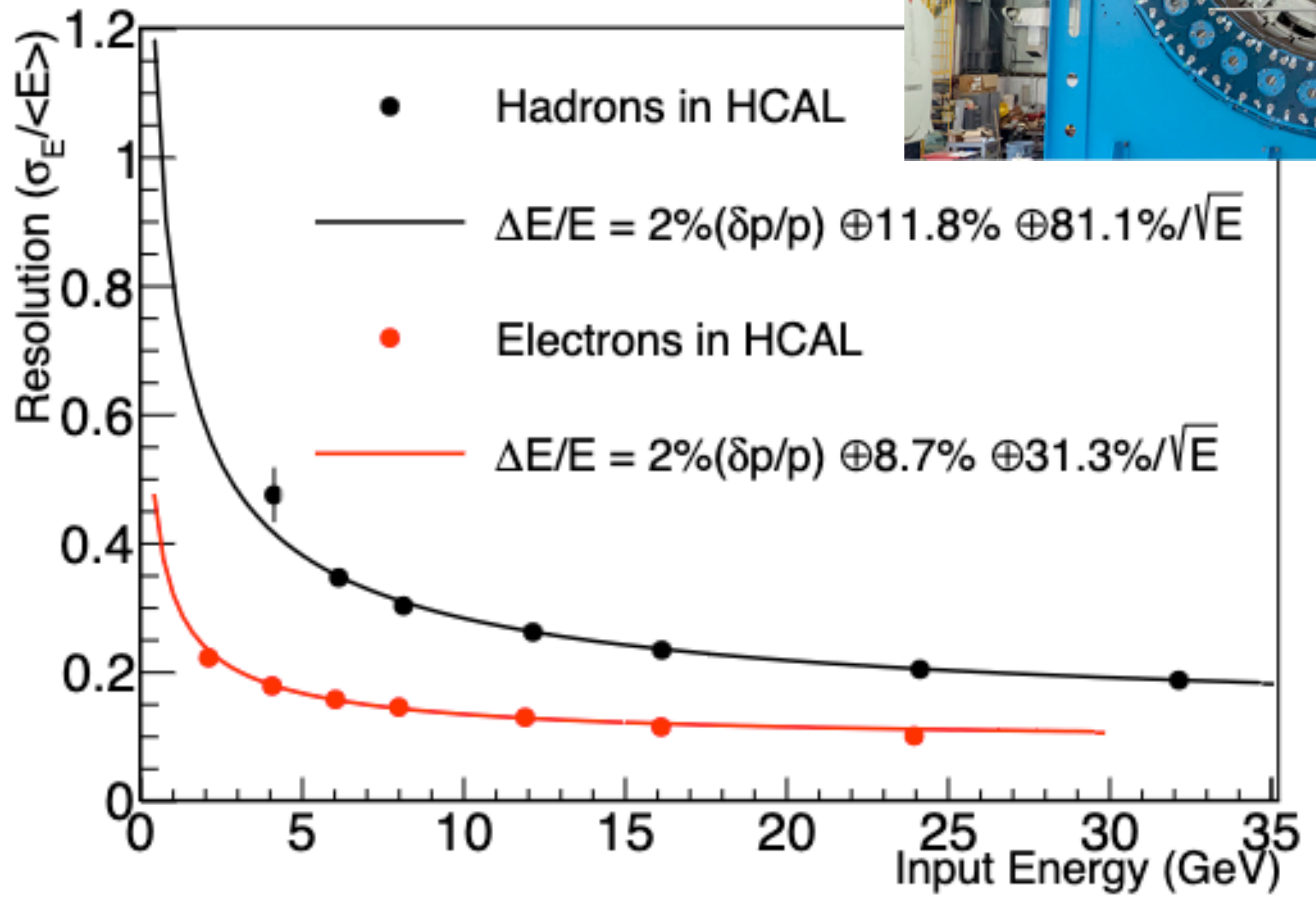


Hadronic Calorimeters

- Fluctuations of the shower development are large, limiting the energy resolution capabilities

- Typical to have ~50% (or larger) stochastic term





IEEE TNS 65 (2018) 12, 2901

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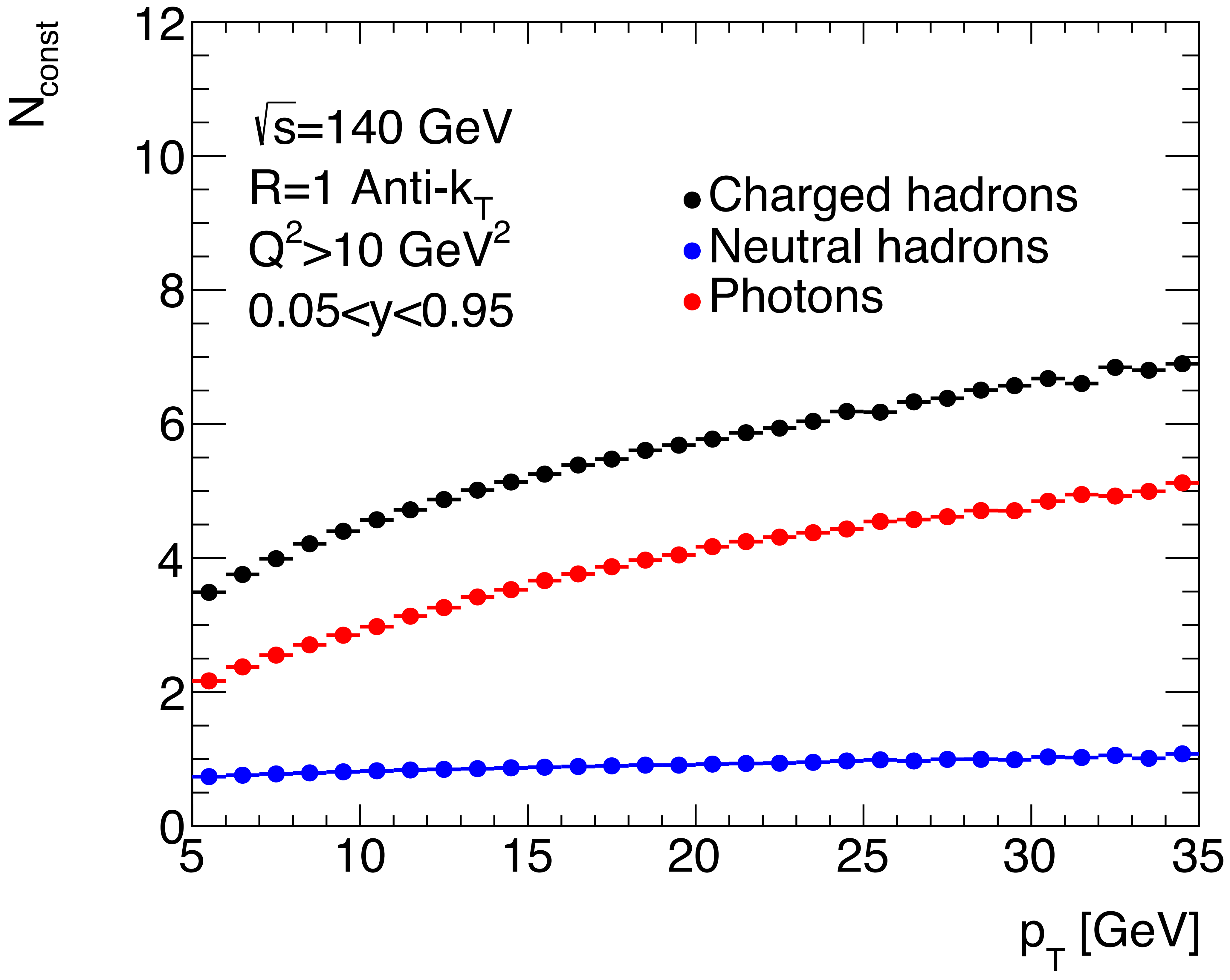
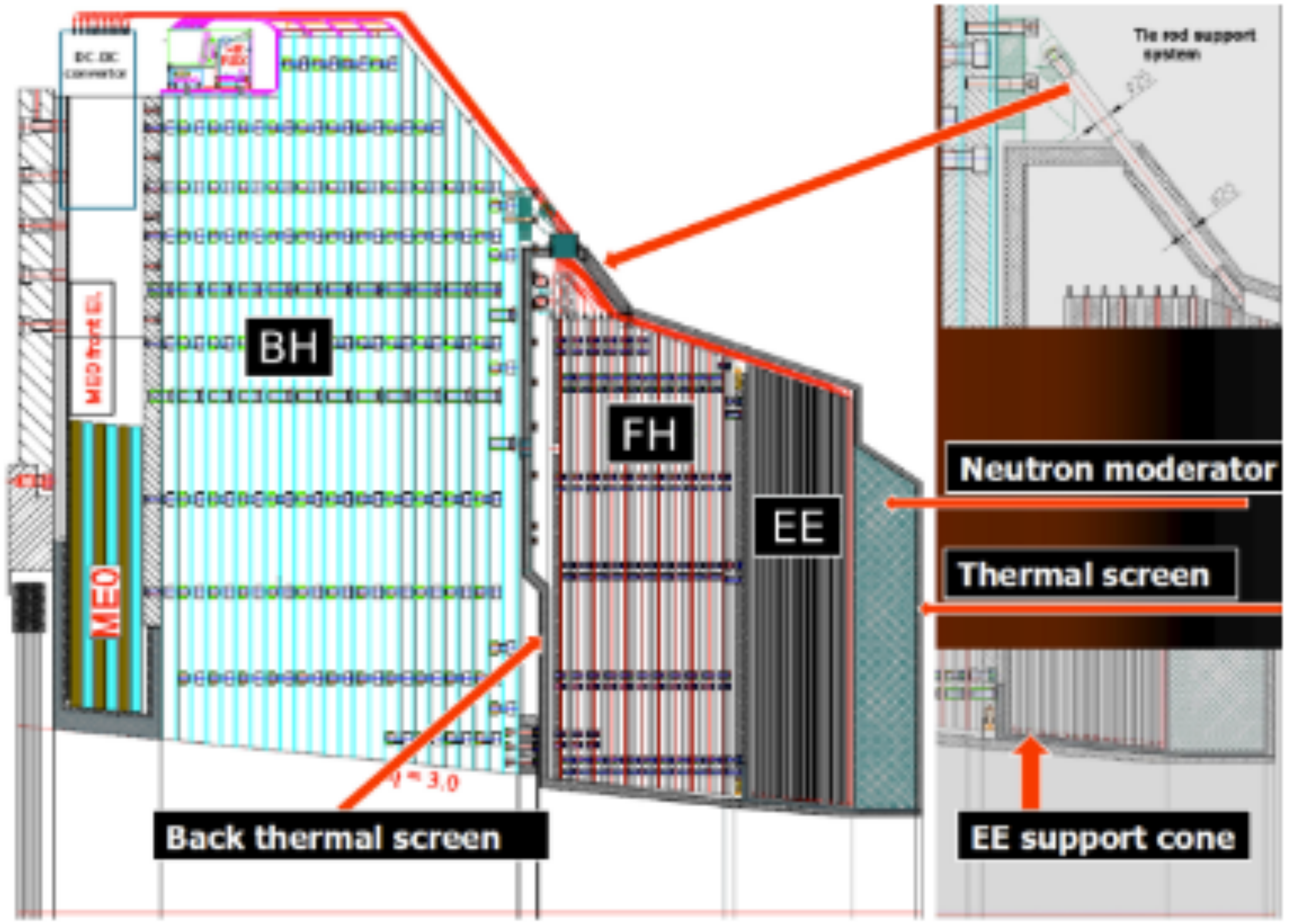


  - Nonzero contribution in EIC collisions! Large fraction of jet is from neutral particles

  - Capturing the entire jet requires EMCal+HCal

Next Gen Calorimeters

- Next generation calorimeters combine EMCal and HCal technologies for 3D (or 4 or 5D) shower development
- Example - CMS HGHCal:
  - 28 layers tungsten/copper plates with silicon sensors for EMCal
  - 12 layers brass/copper plates with silicon sensors for HCal
- Large number of channels for precise shower development determination (e.g. 6M channels vs. sPHENIX EMCal+HCal with ~28k channels!)



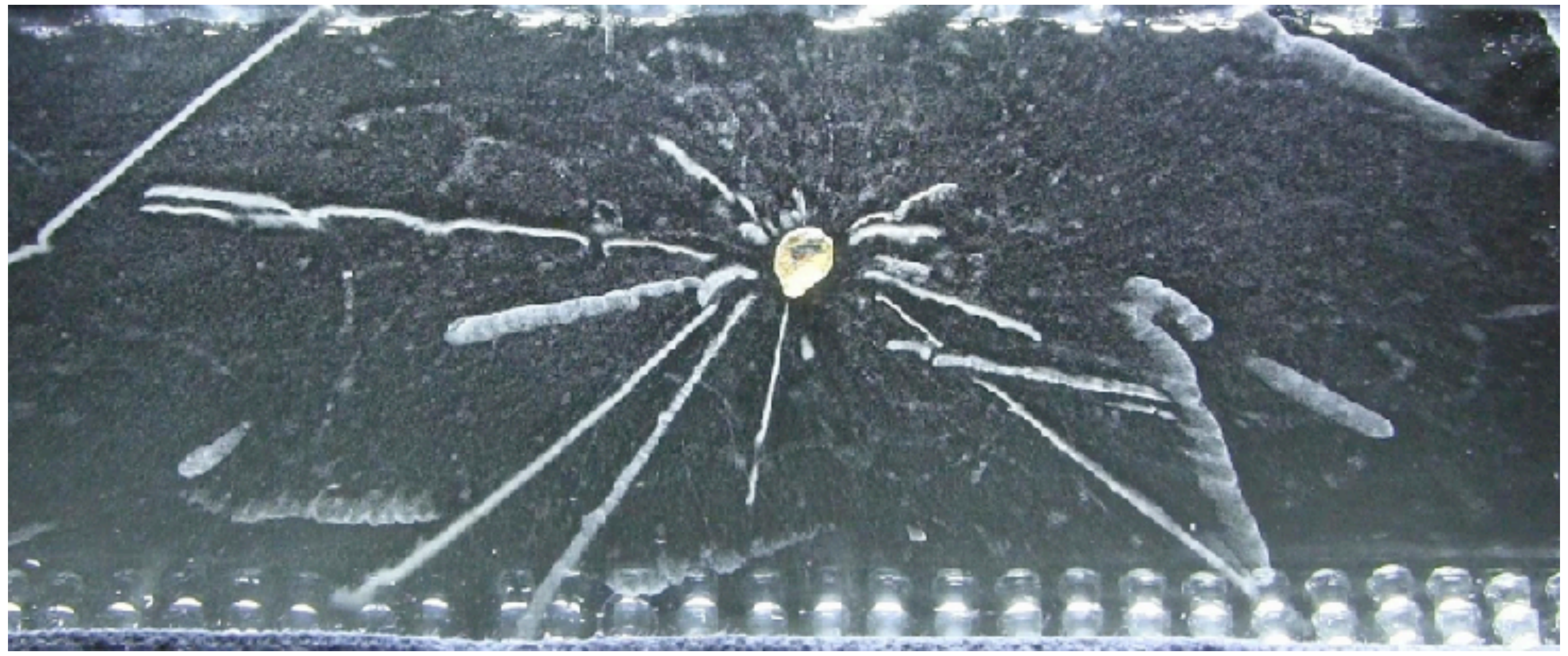
Tracking Detectors

- Tracking detectors all operate under the same principle - particle liberates some charge that is readout to determine its position

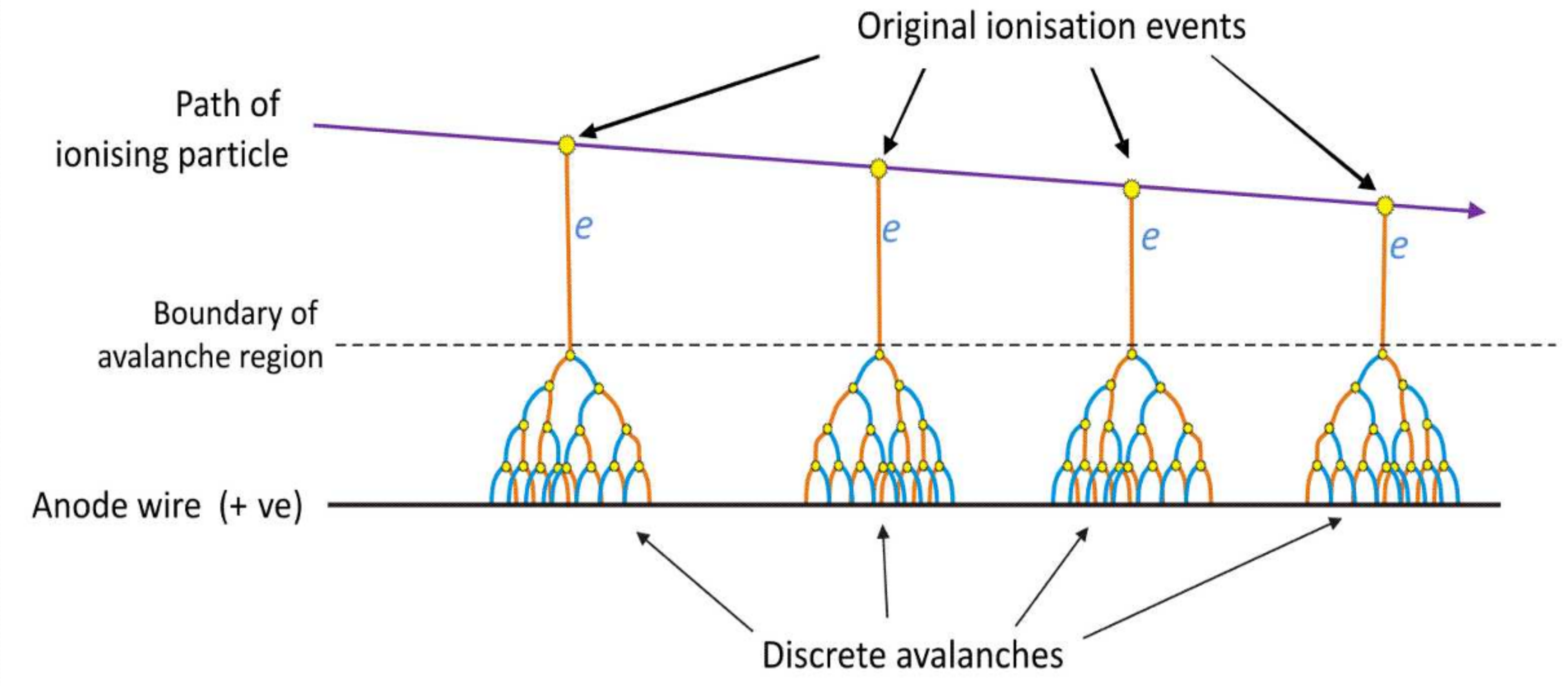
- Reminder - need to limit material interactions as much as possible!

- Tracking detector - kind of like a cloud chamber!

  - Spoiler - much more complicated than a cloud chamber



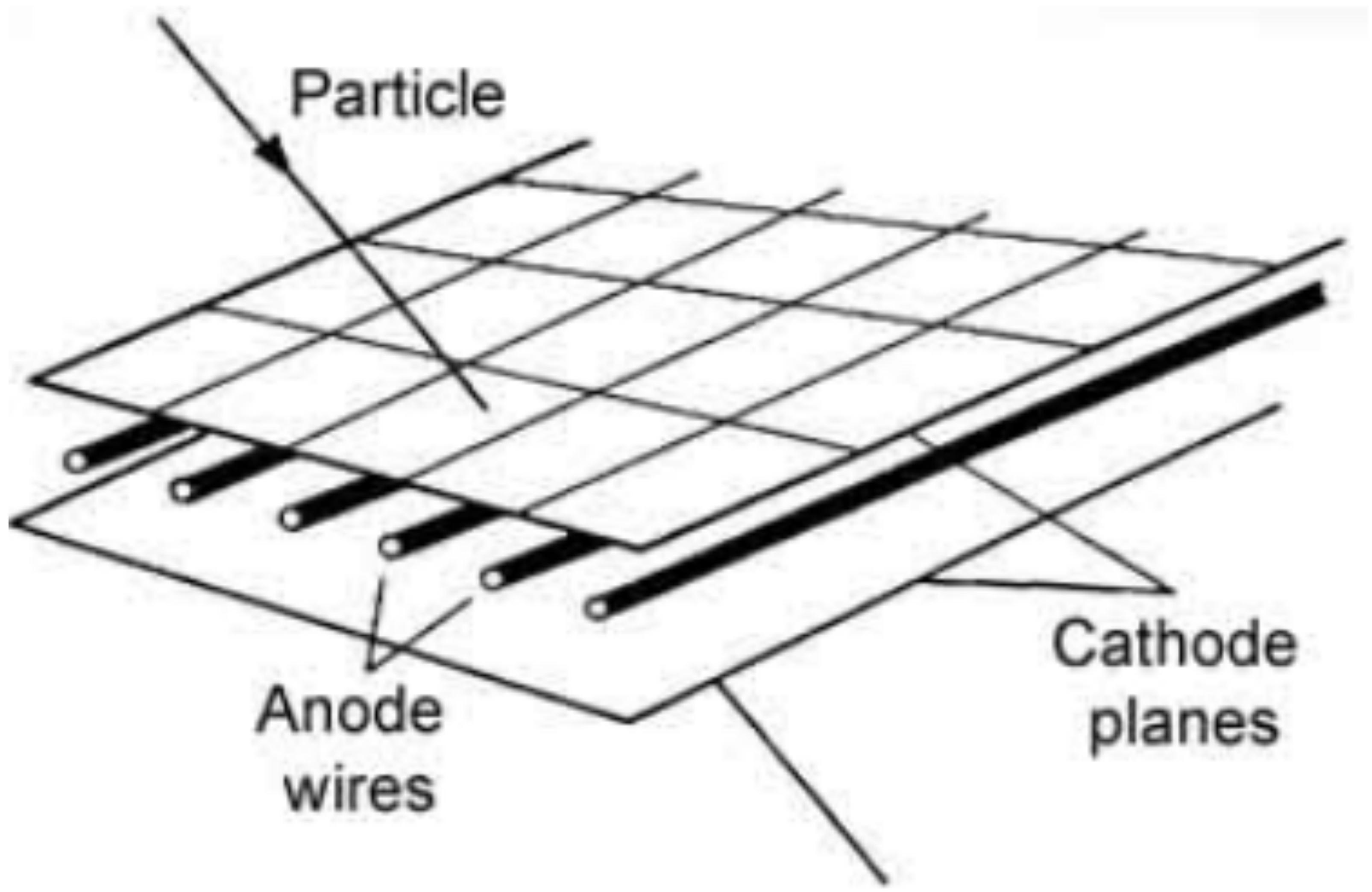
Ionization and Avalanche



- Basic principle of tracking detectors:
  - Particle liberates electrons from some material
  - Electrons avalanche and are collected to read out
  - Position is determined from this information

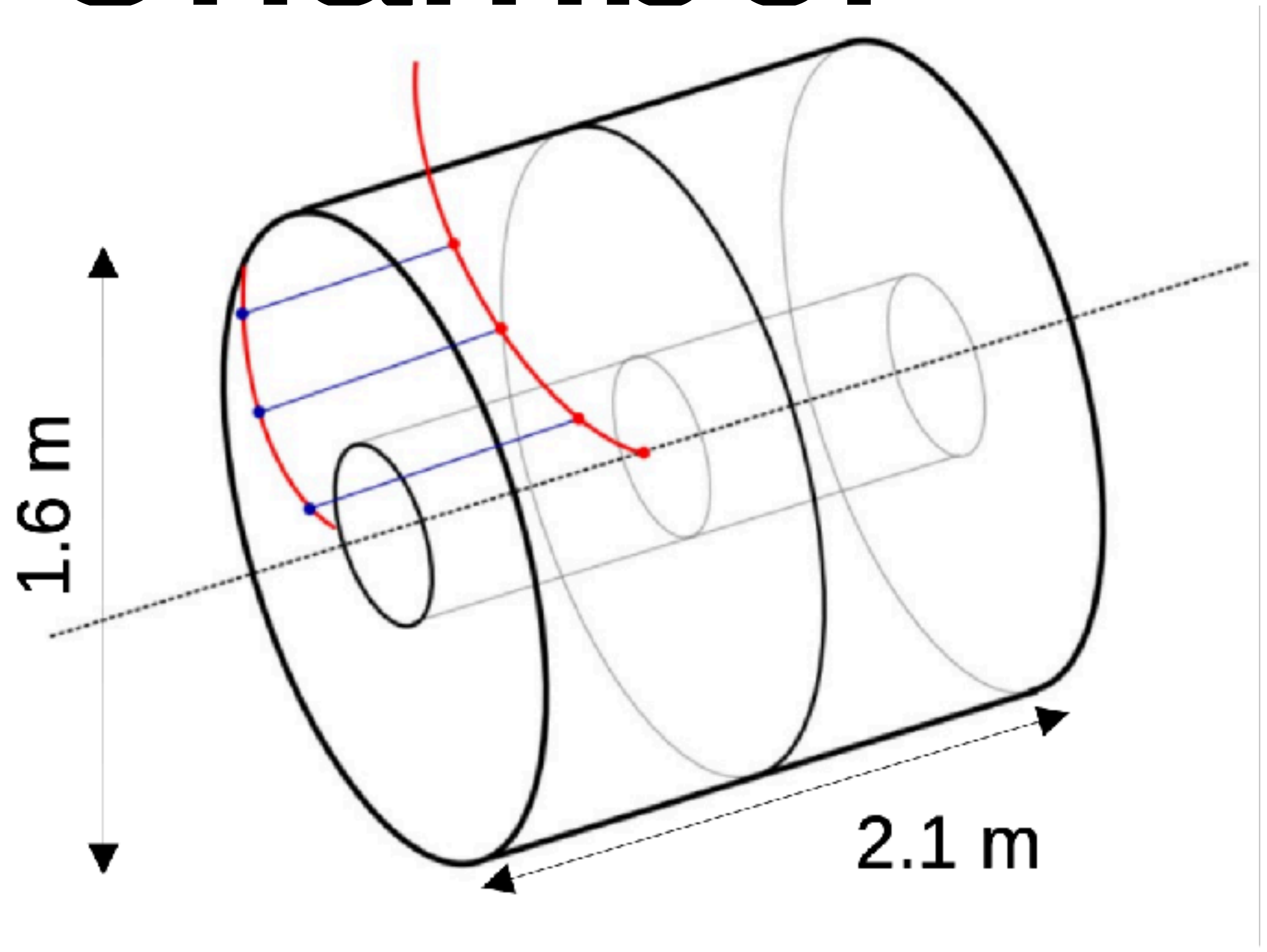
Drift/Wire Chambers

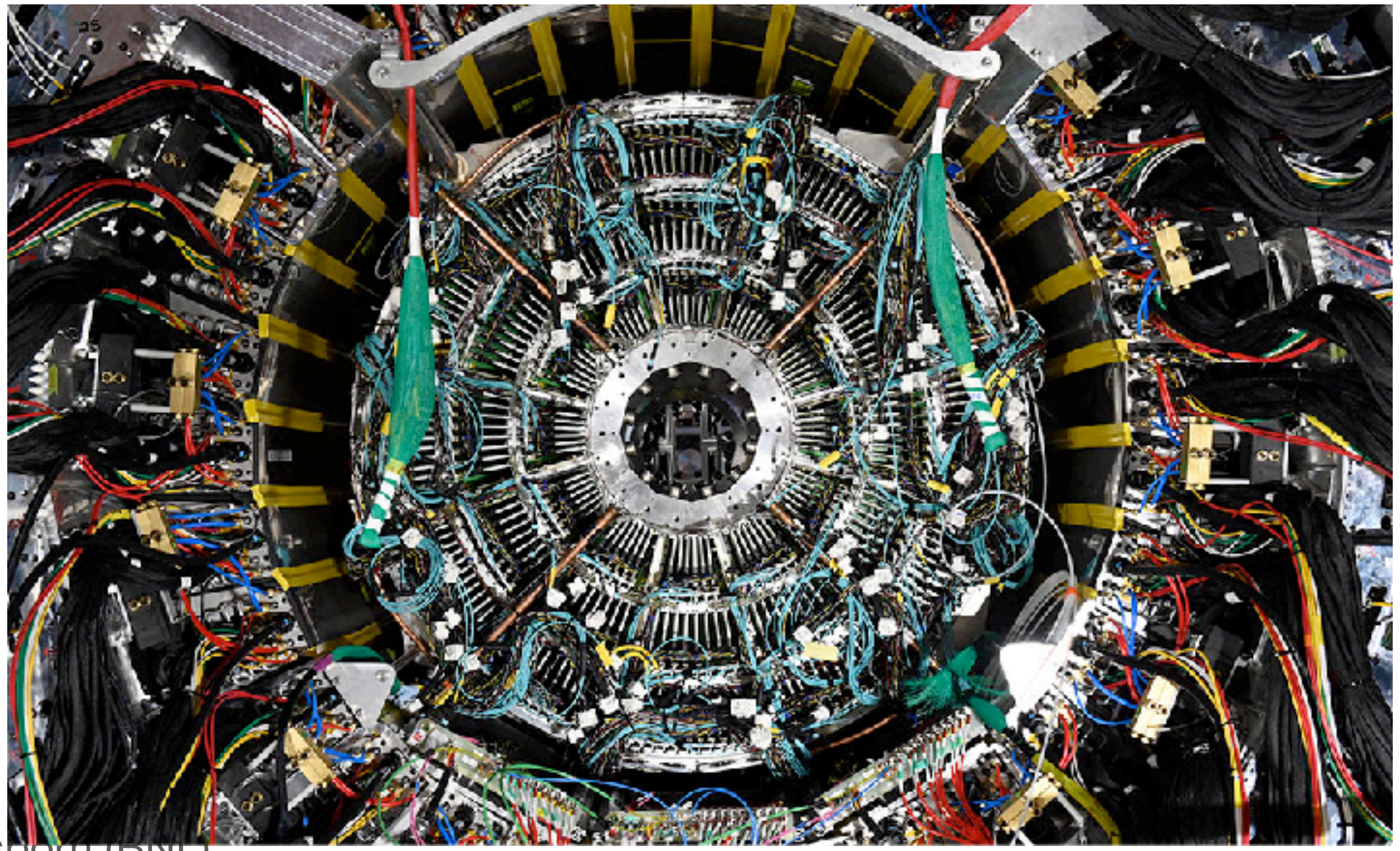
- This is the basic principle behind the wire chamber
- Particle traverses gas, liberates electrons, these drift to a wire which is read out
- Position and drift timing information provides O(100) micron hit information



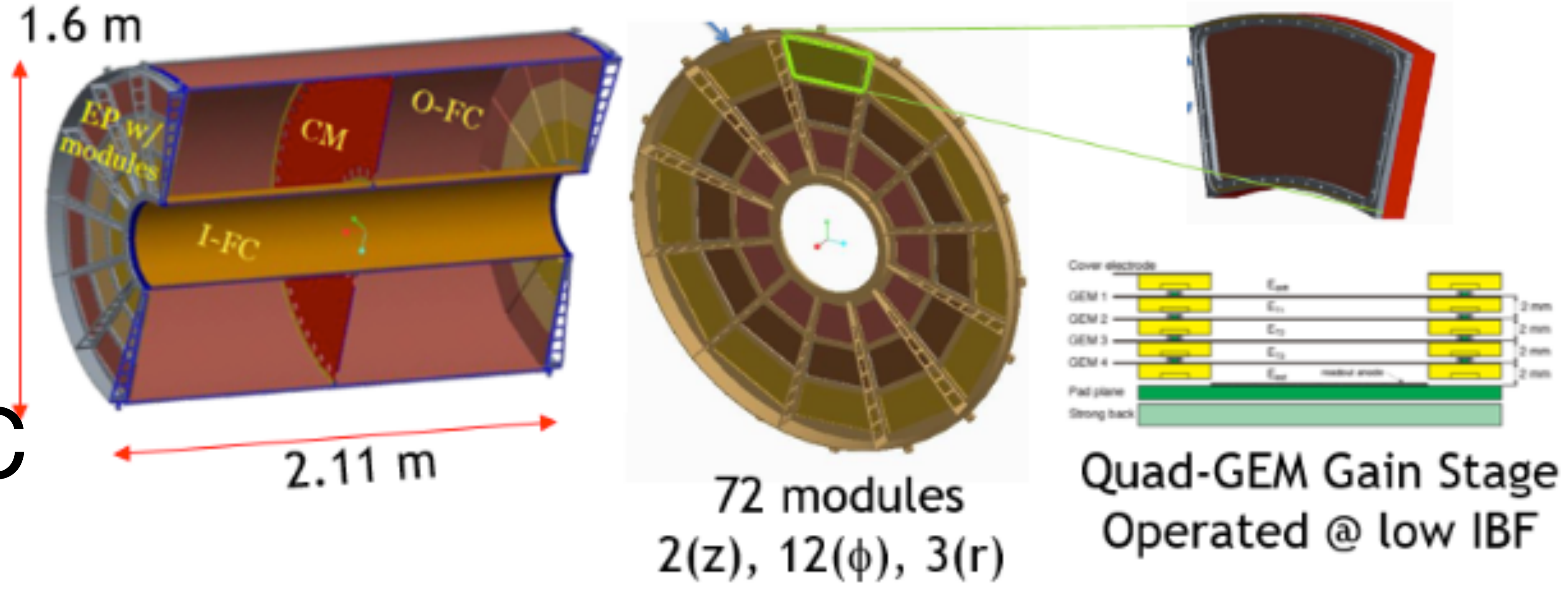
Time Projection Chamber

- Particle traverses a gas and liberates electrons, which drift to a readout plane
- Drift time gives z position
- Long drift compared to wire chambers

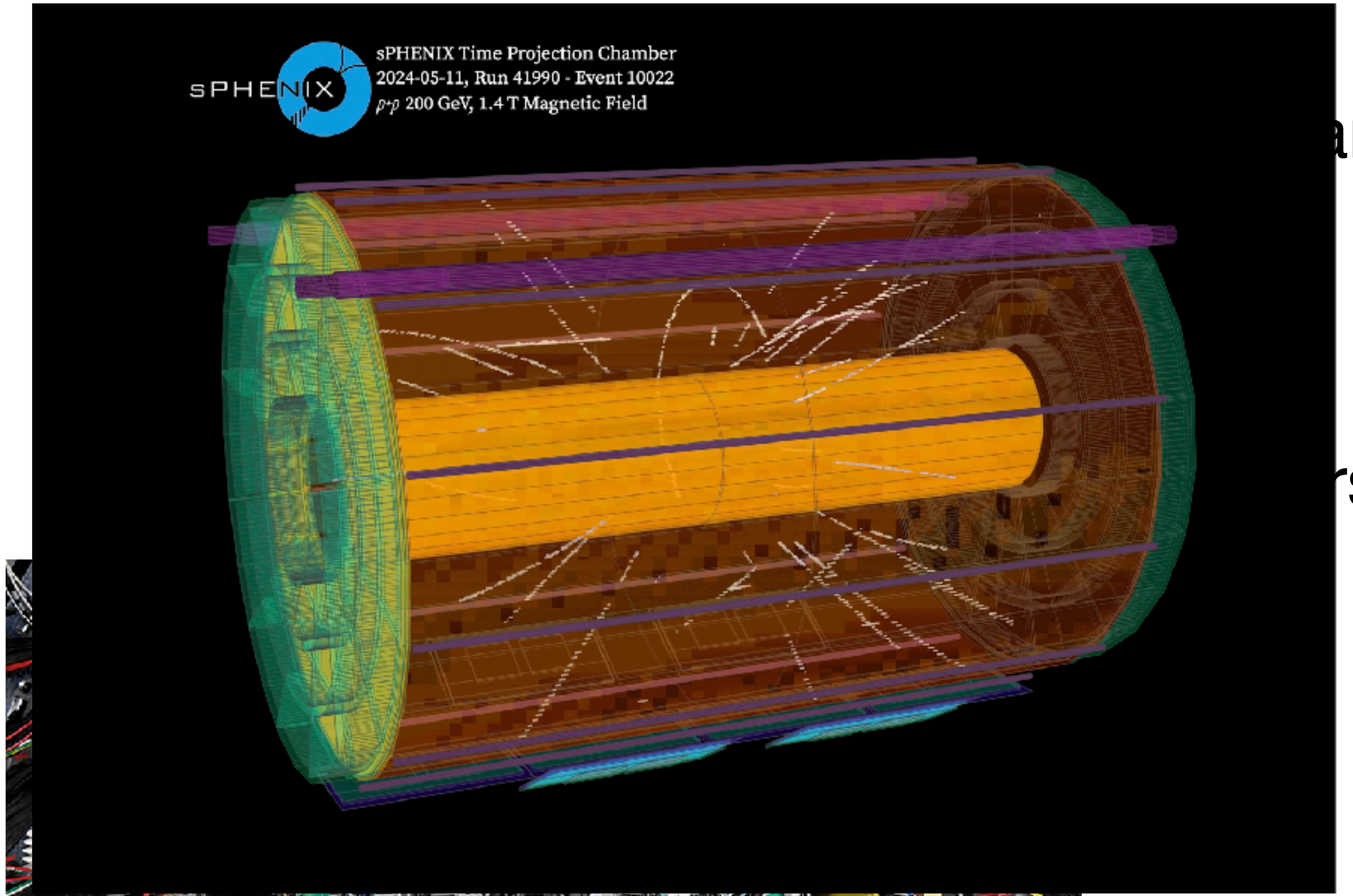


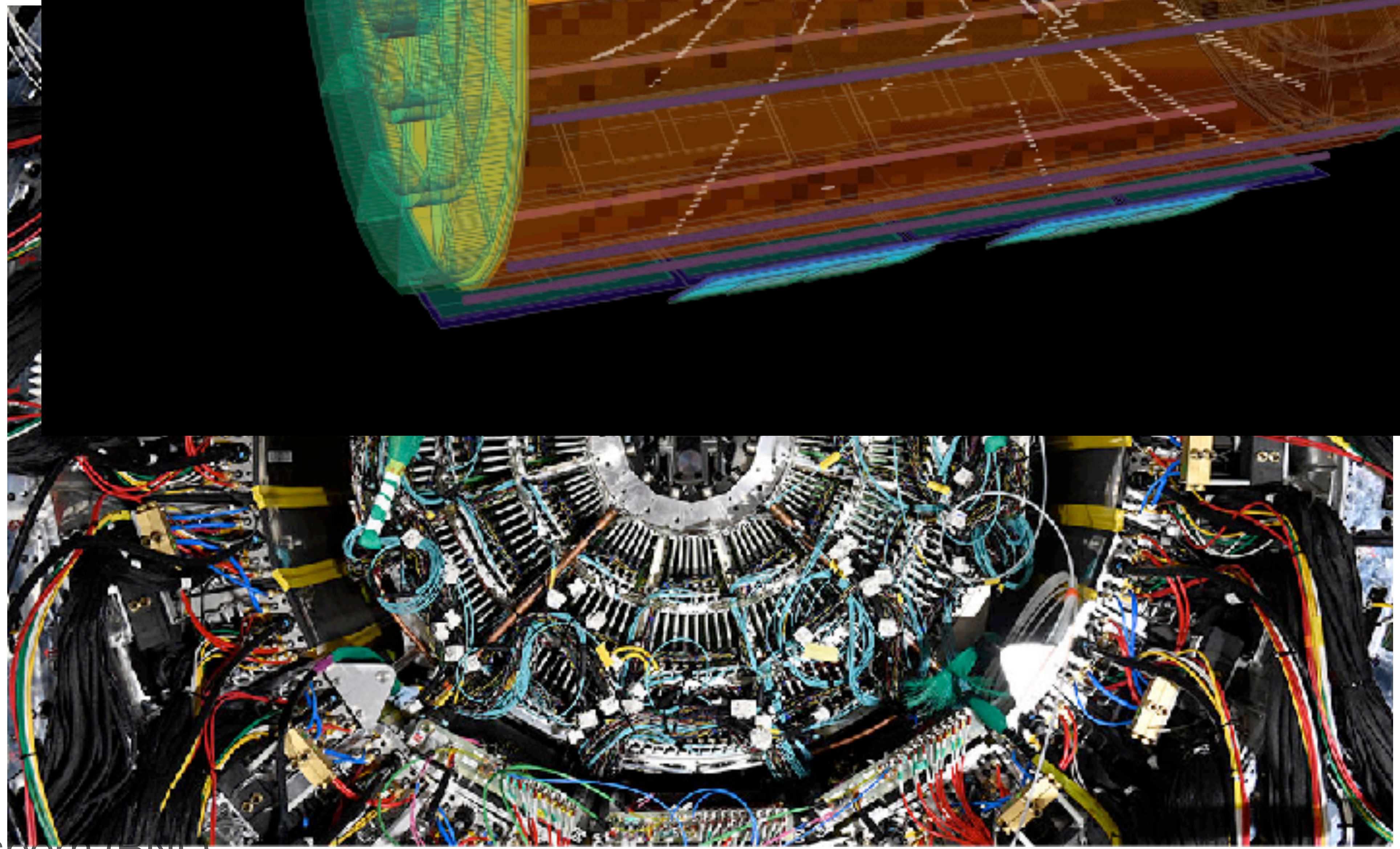


sPHENIX TPC



Time Projection Chamber





ar

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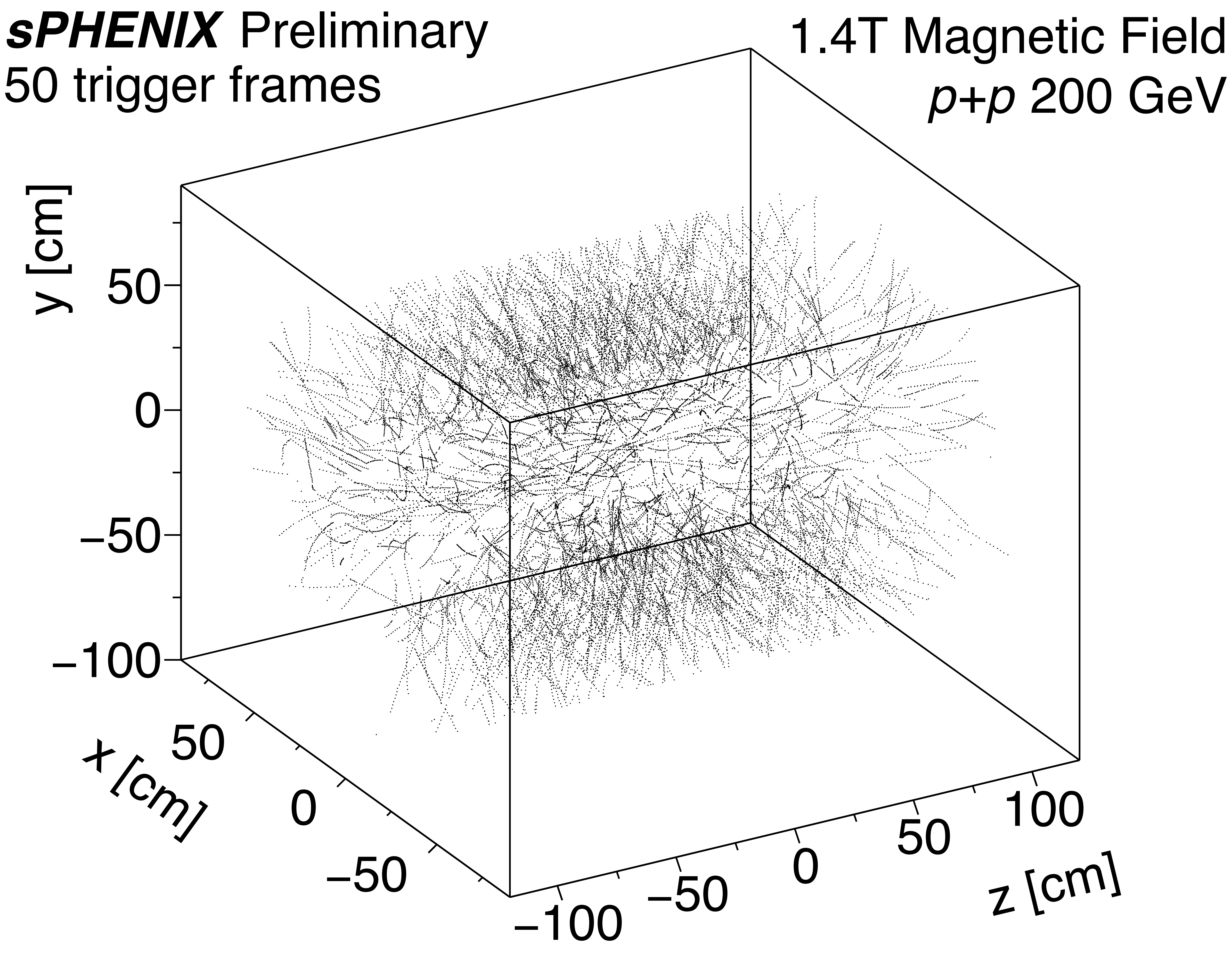
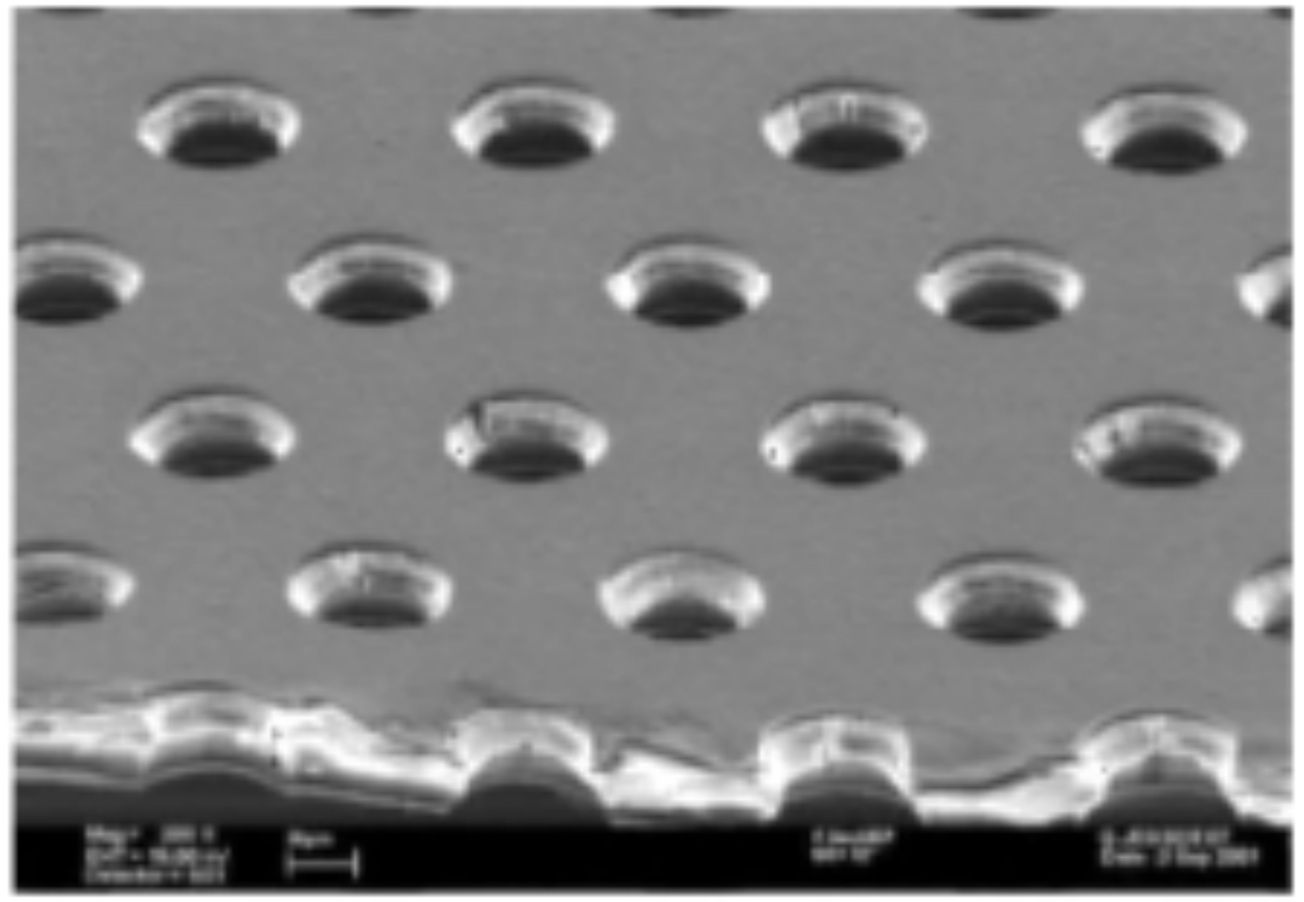
sPHENI

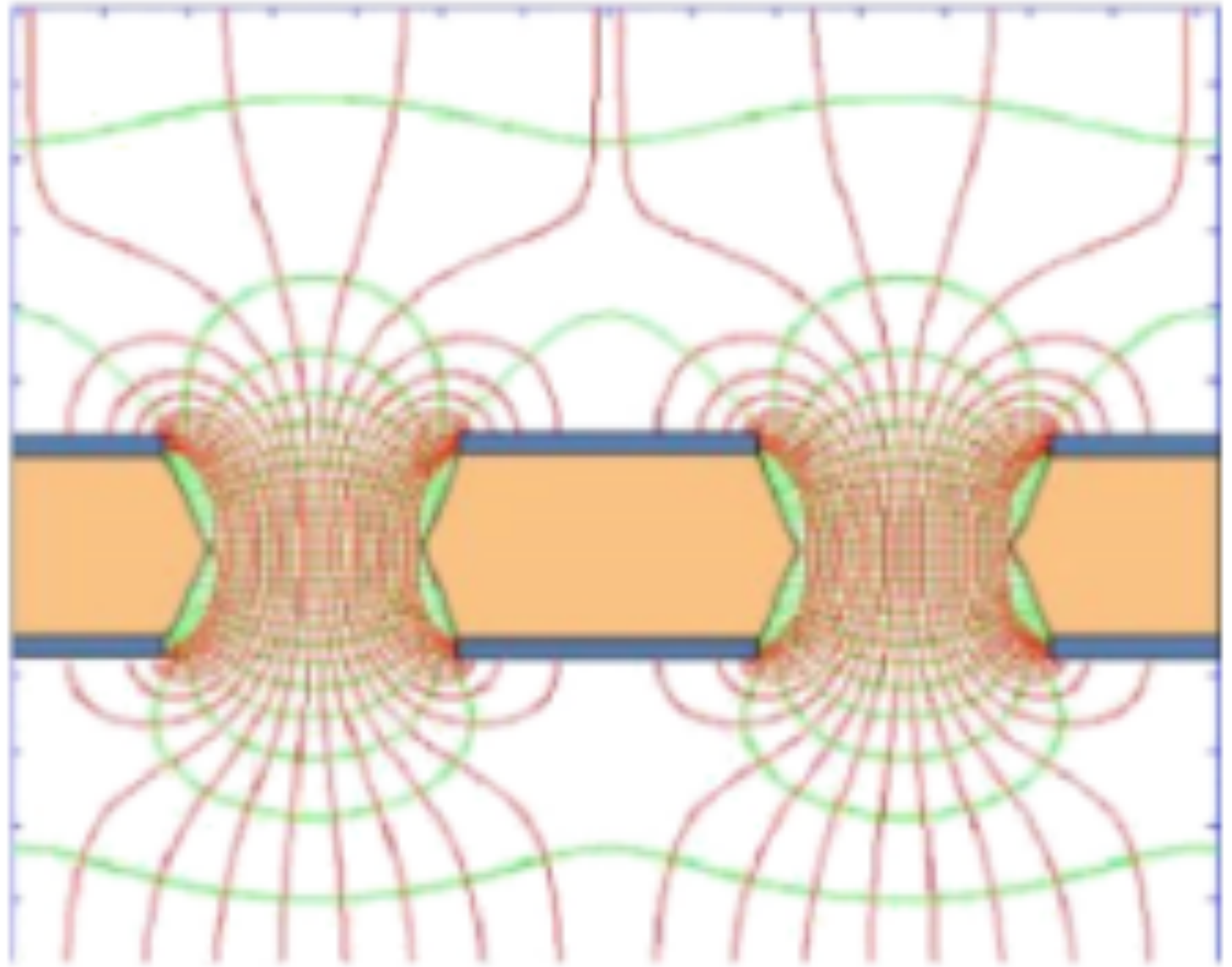


Z(z), 12(ϕ), 3(r)

GEMs

- Gas Electron Multipliers (GEMs) use thin holes in regular patterns to amplify signal
- Typically layers of GEMs provide high gain readout
- When put under voltage, holes create large large fields that amplify signals
- Can be mass produced, used at COMPASS, STAR, sPHENIX…

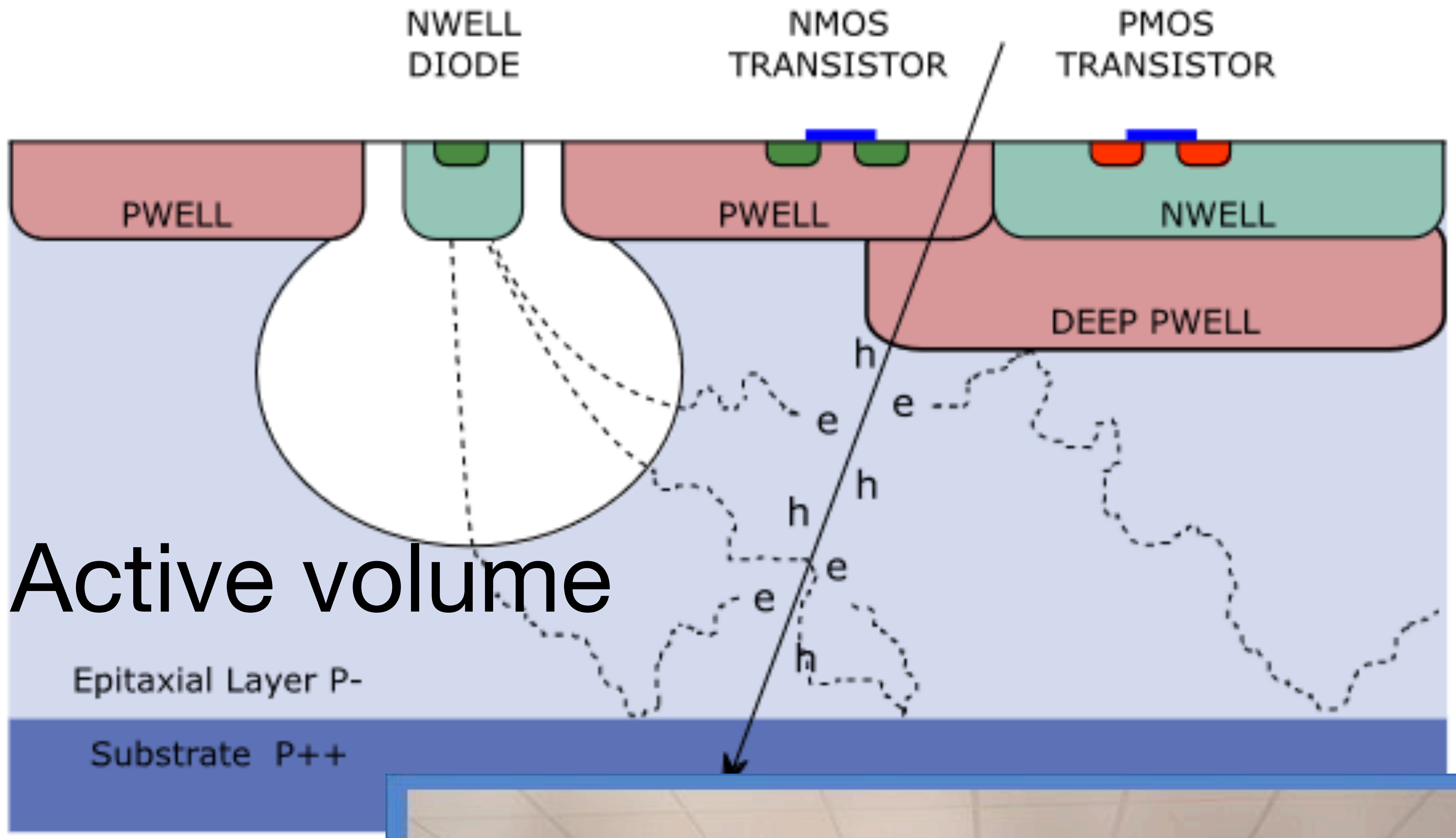


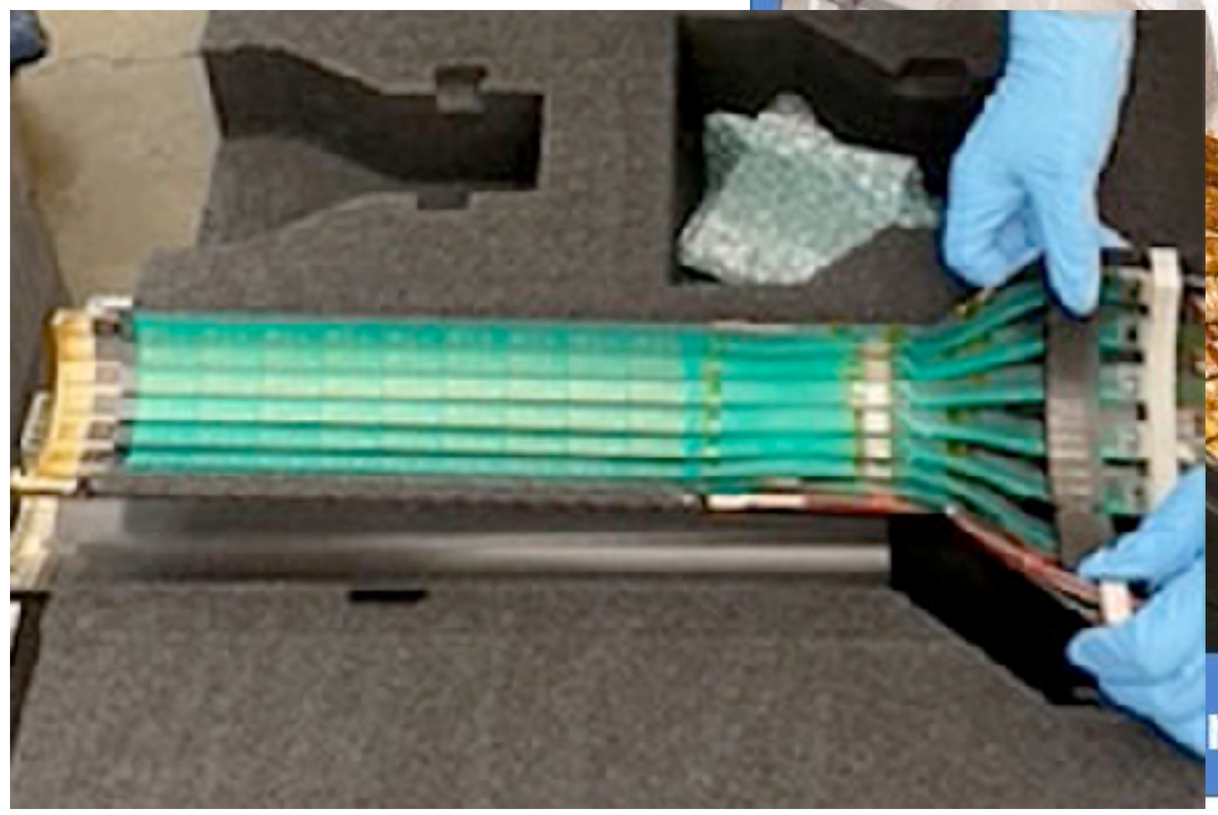


Silicon Detectors

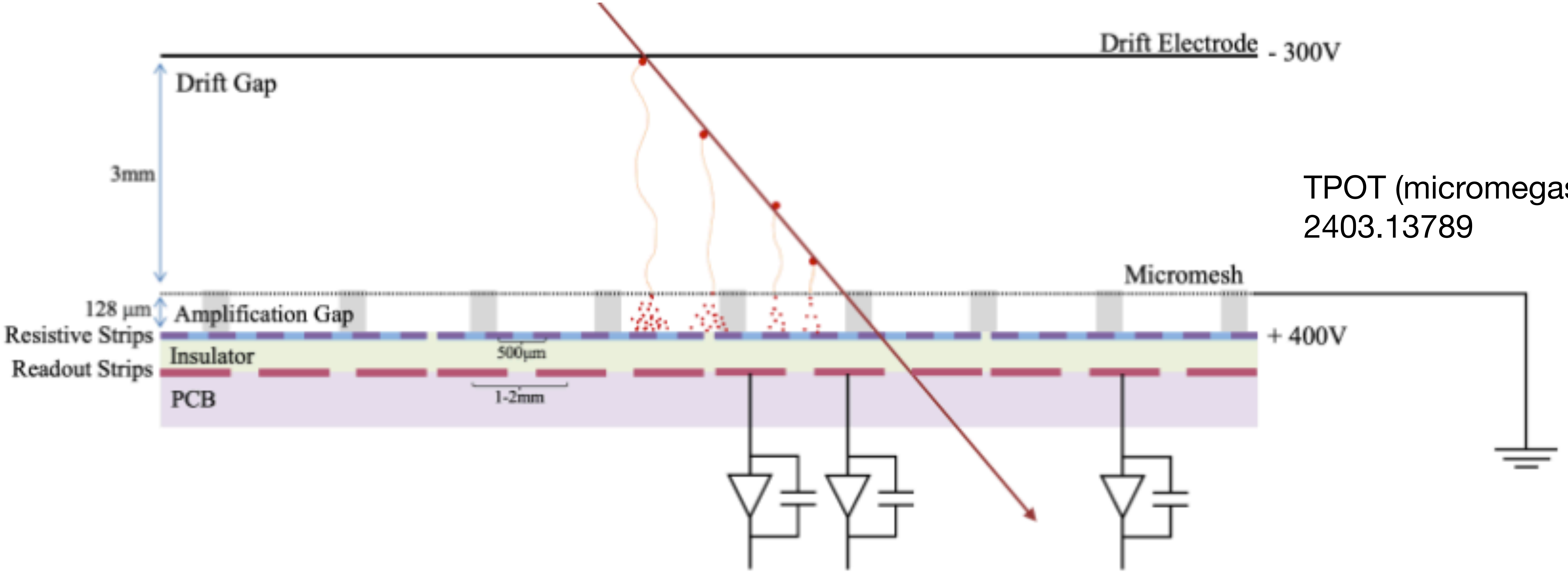
- Sensor and readout electronics integrated onto a single chip
- Extremely high precision O(microns) - pixel or strip
- Monolithic Active Pixel (MAPS) devices are thin - ~0.1%X/X_0 per layer
- Examples - MVTX at sPHENIX, ITS at ALICE
- Large channel count - expensive!

Charge collection and amplification





MPGDs



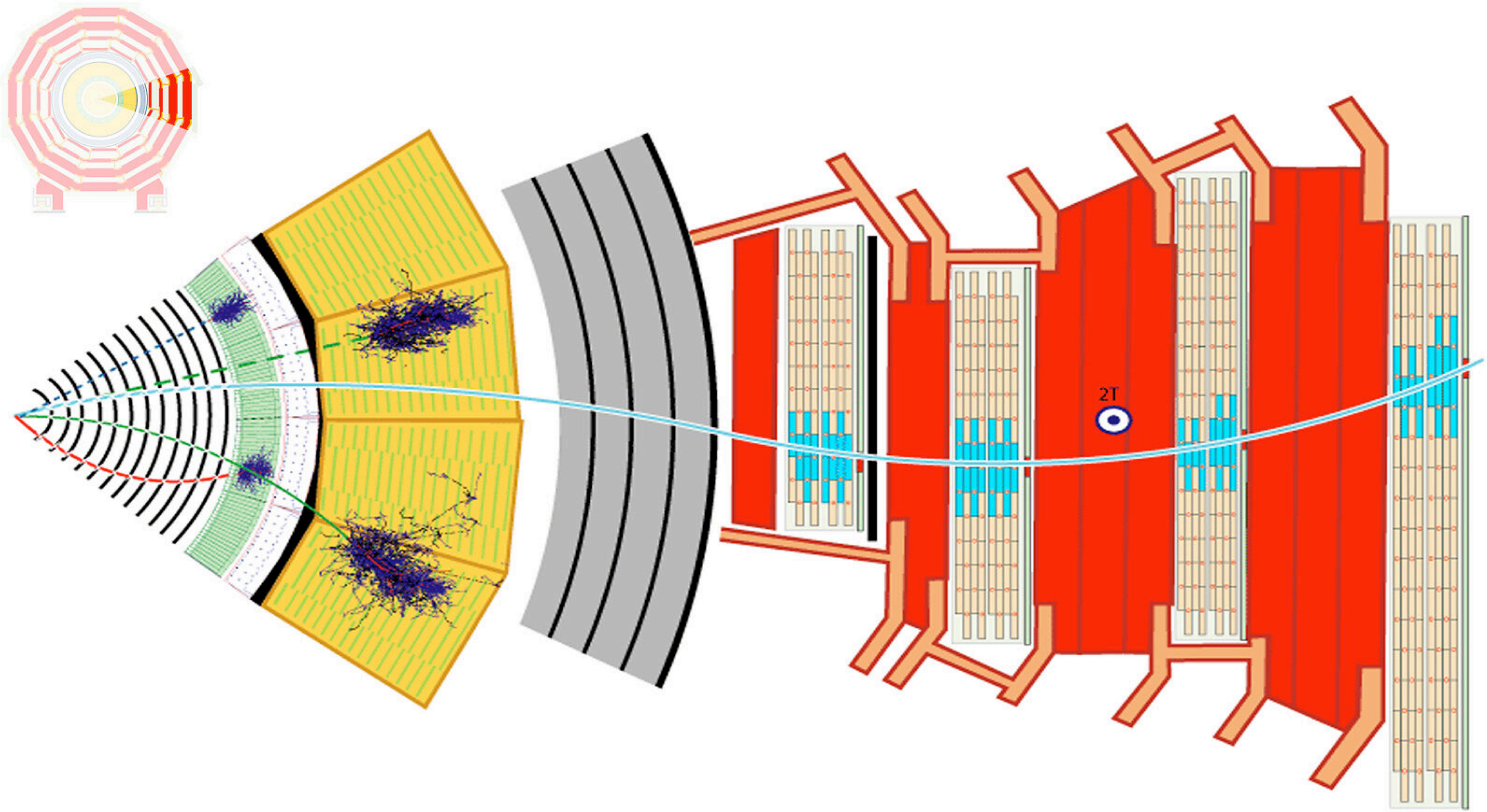
TPOT (micromegas detector)
2403.13789

- Micropattern gaseous detector (MPGD) are further evolution of wire chambers
- Provide O(100) micron spatial resolution with fast readout
- Small distances limits space charge accumulation (distorts signal)

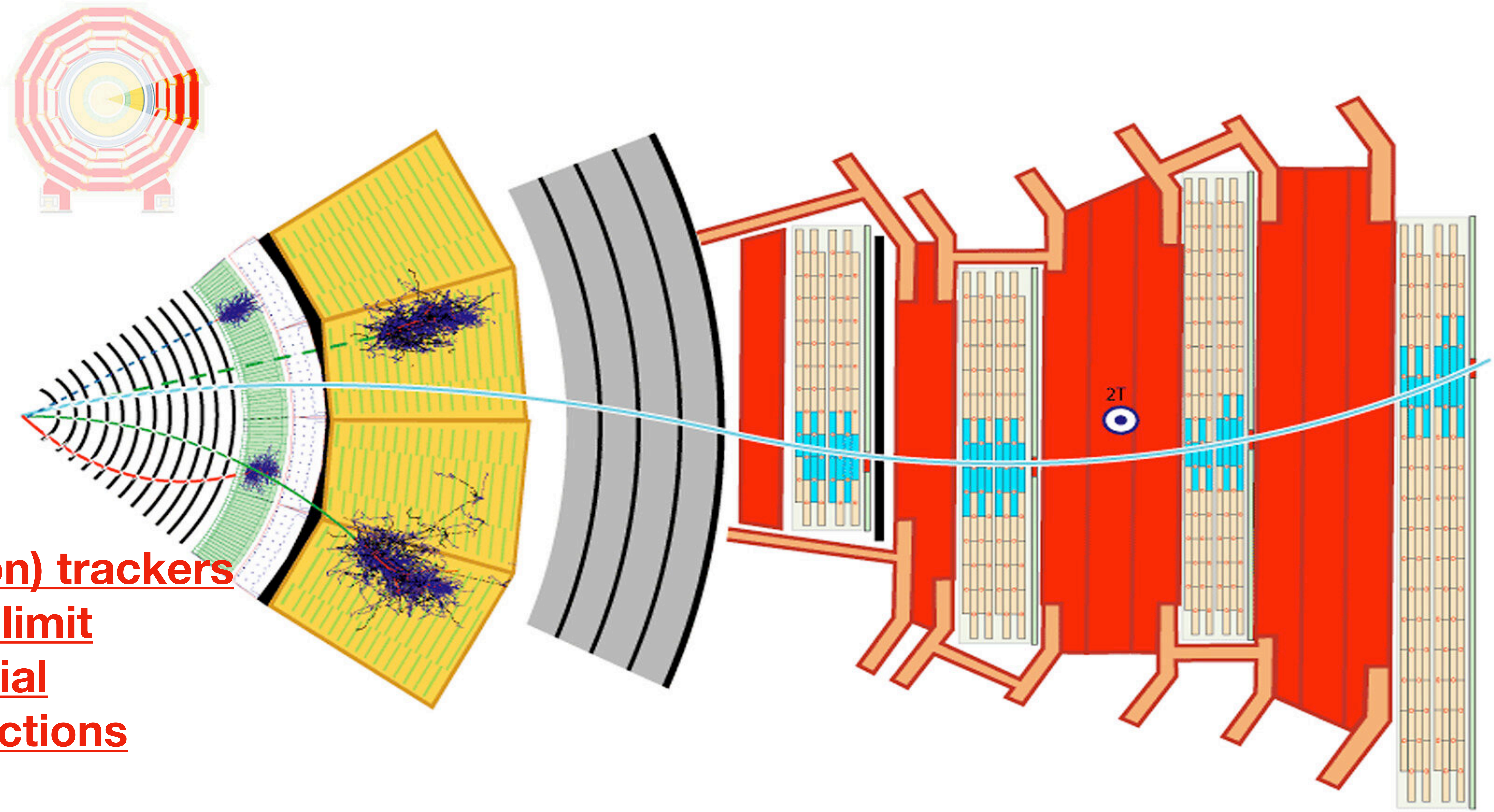
Collider Detector

- More technologies that exist…
- However, these (mostly) cover the ones that are being used or planned to be used at current/future NHEP experiments
- So let’s return to our cartoon…

Collider Detector

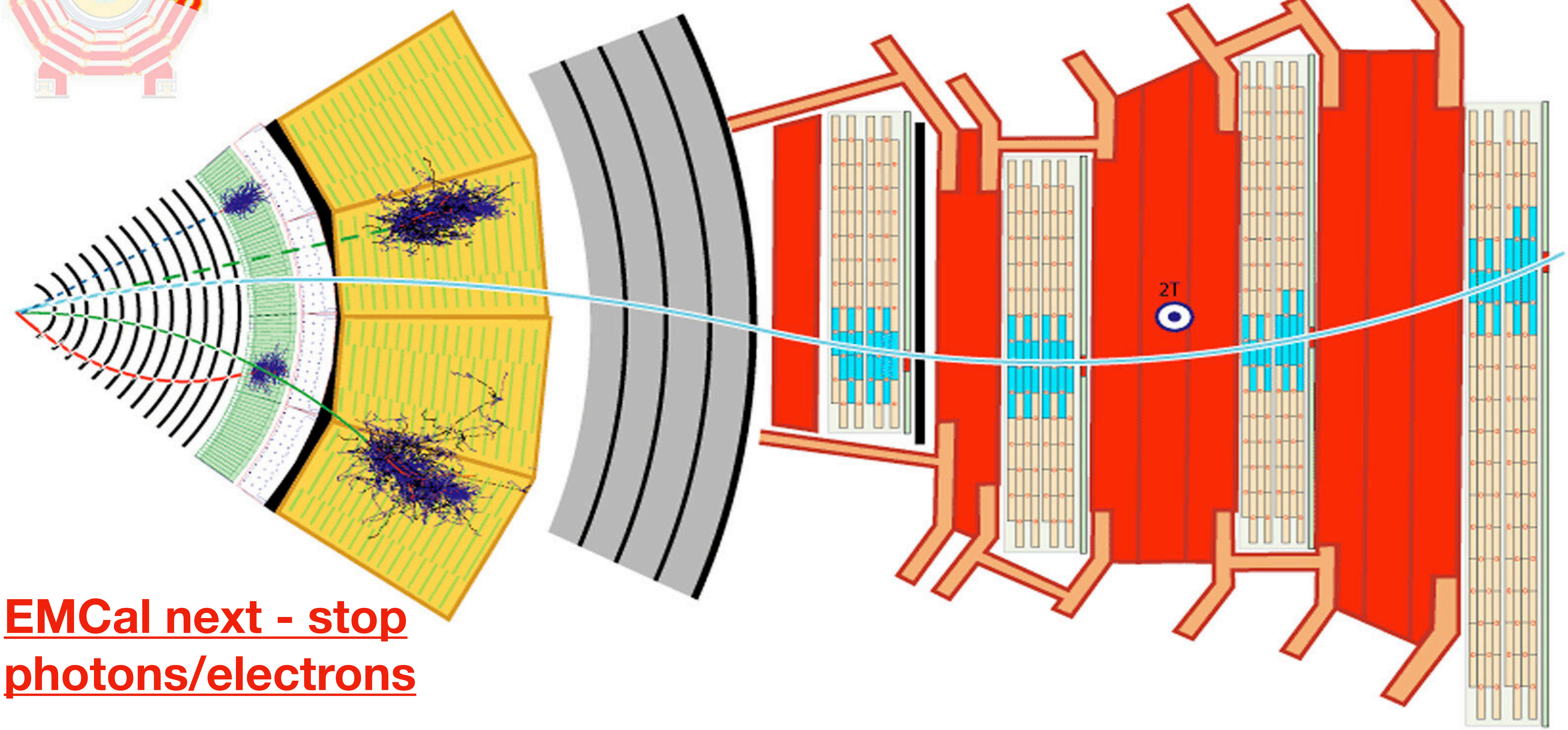


Collider Detector



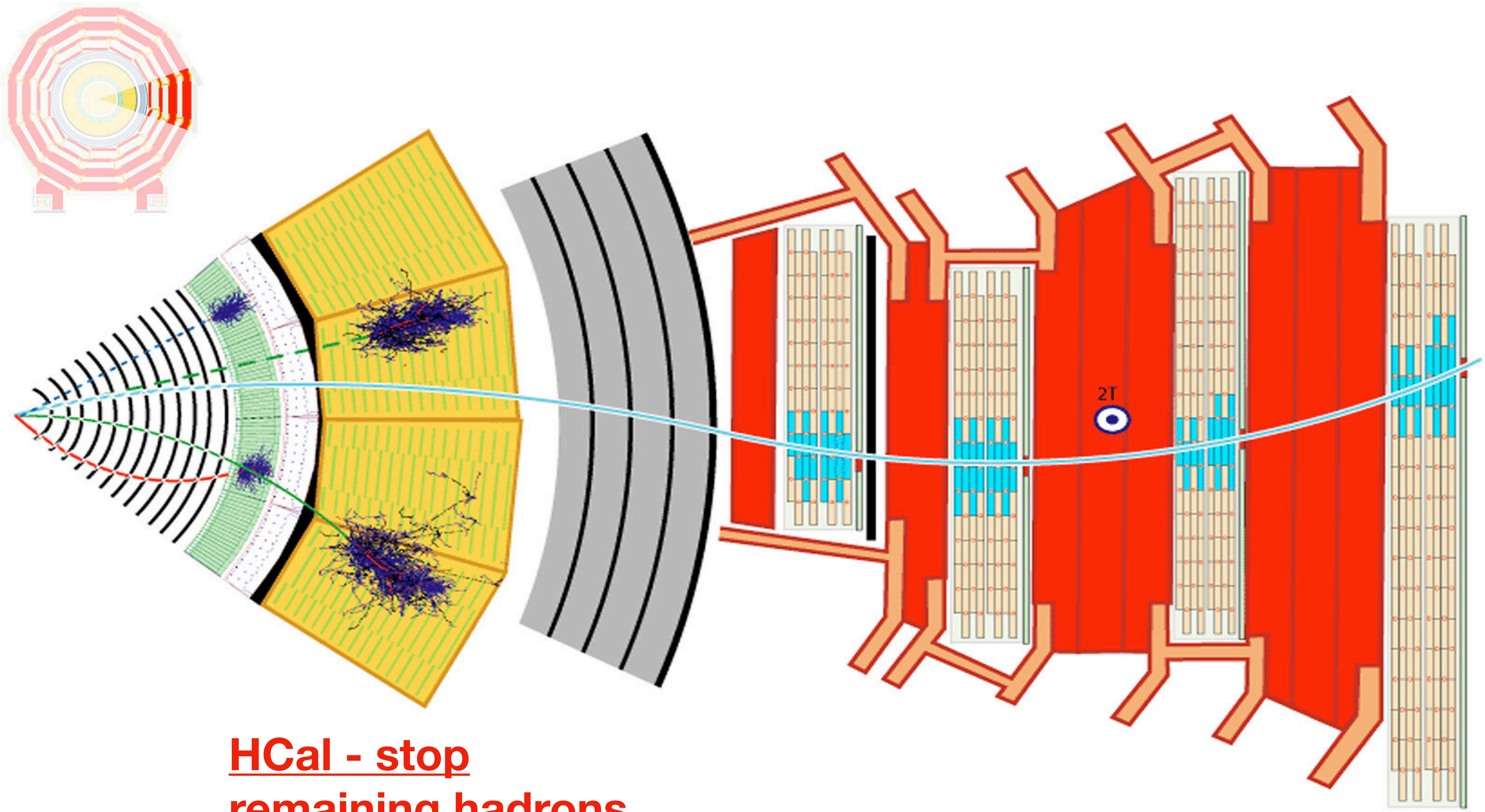
(Silicon) trackers first - limit material interactions

Collider Detector



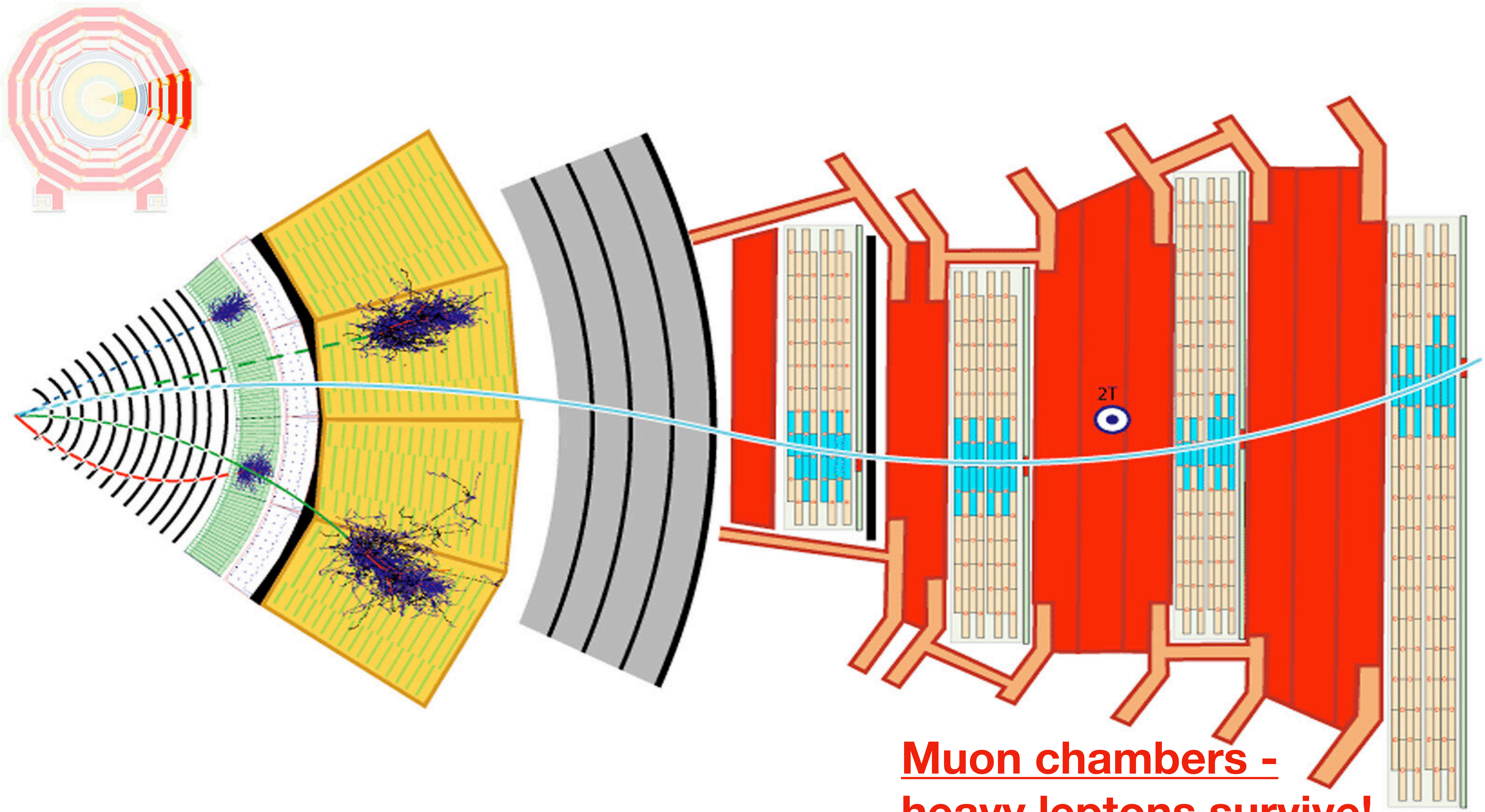
EMCal next - stop photons/electrons

Collider Detector



HCal - stop remaining hadrons

Collider Detector



Muon chambers - heavy leptons survive!

Summary

- This set of slides only scratches the surface - field is full of creative and hard working people that are excited about the next breakthrough
- So far we have discussed only some detector technologies that are used in modern NHEP experiments
- We have some detectors that measure (only!) signals of a particle. Tomorrow: How do we turn this into a physics measurement?