Calorimetry at the EIC

Ross Corliss

Stony Brook University

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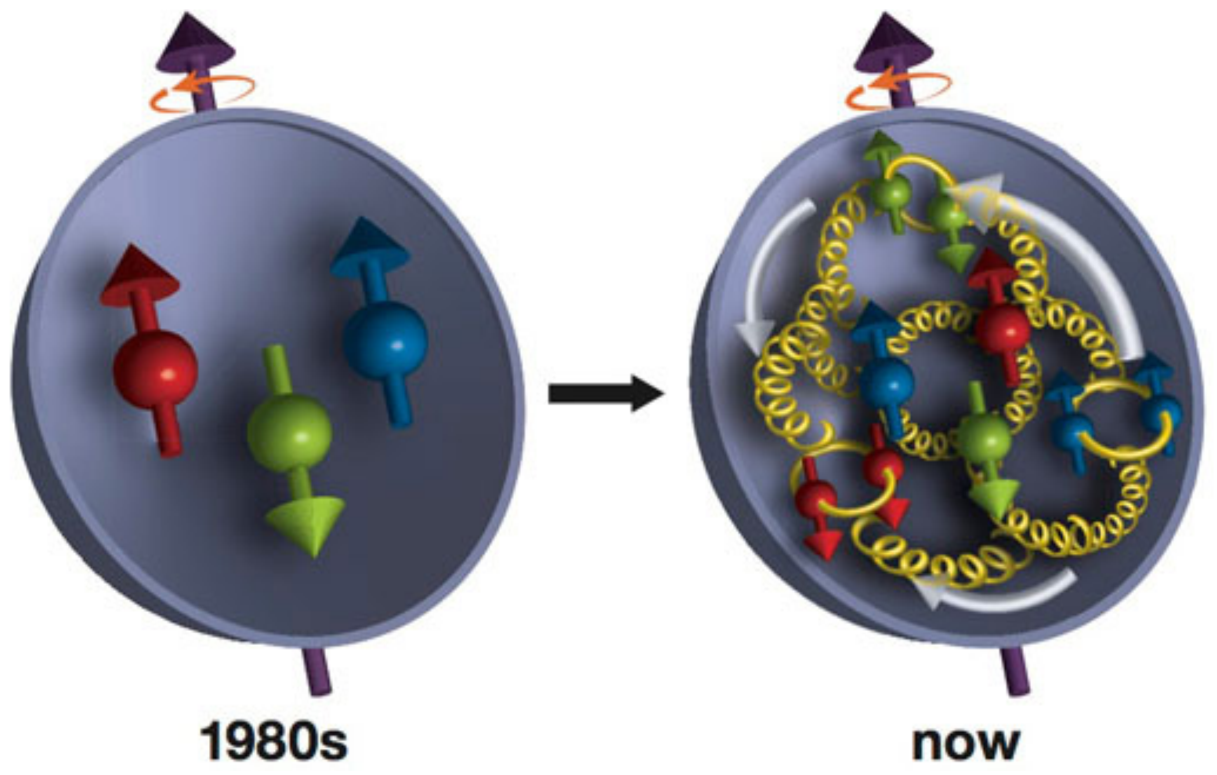
Center for Frontiers in Nuclear Science

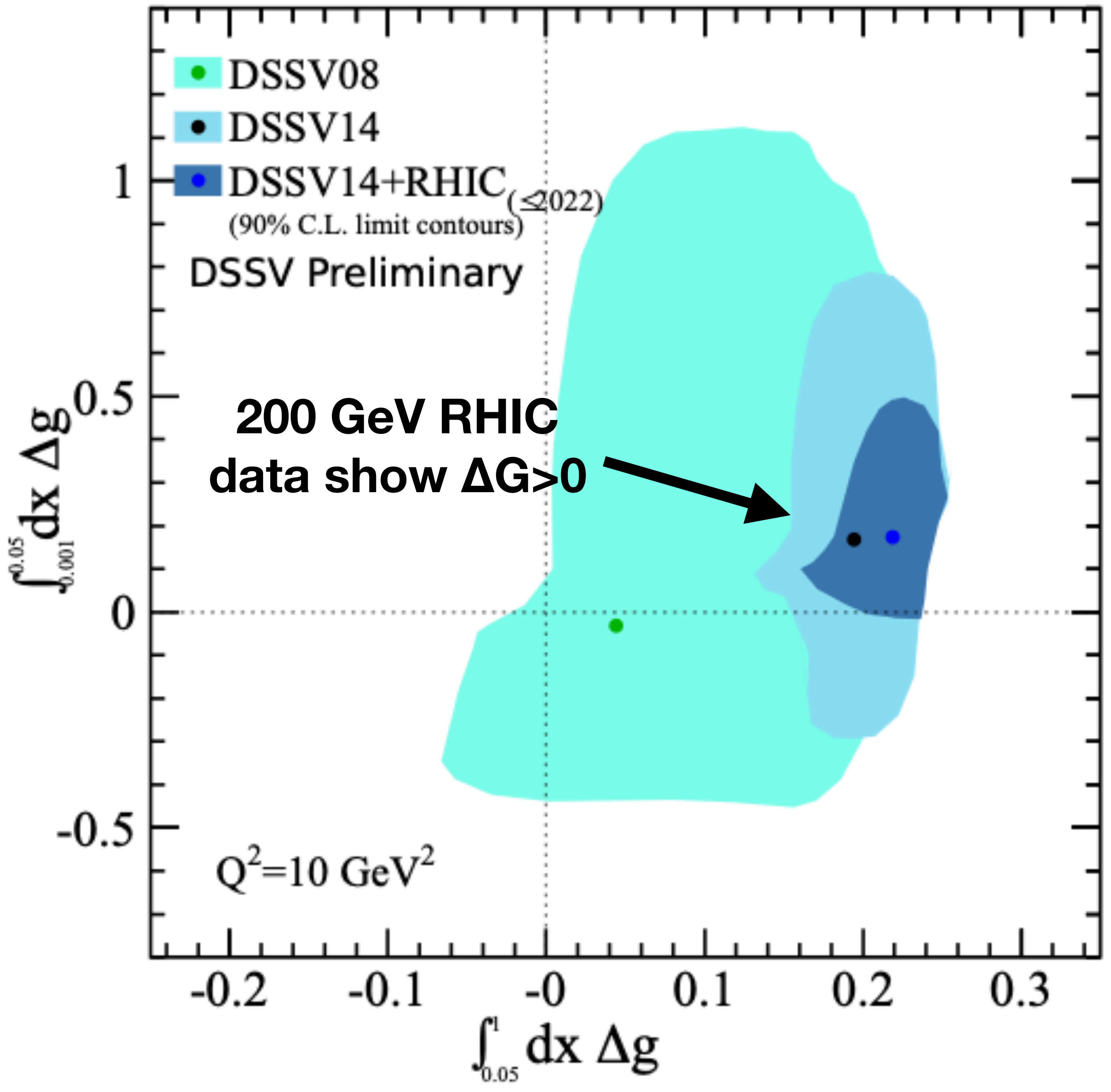
Understanding Proton Spin

- Valence quarks do not carry all the spin. More complex dynamics are at hand:

$$\frac{1}{2} = \underset{\text{quarks}}{\frac{1}{2}\sum_q \Delta Q} + \underset{\text{gluons}}{\Delta G} + \underset{\text{orbital motion}}{L_q + L_g}$$

- **Longitudinal** -- how do partons polarize wrt the proton?
- **Transverse** -- how are proton spin and parton transverse momentum / spin correlated?





200 GeV RHIC data show ΔG>0

arxiv:2302.00605

Motivation: 3D Tomography

- Polarized DIS: Structure functions dSig, dG
  - onward to low x <~0.01 (global fits die out at that point). EIC can continue down to x<1e-4, better accessing gluons
  - prove whether gluons are a major source of gluon spin
- SIDIS: flavor-separated du, dubar, etc
  - Transverse Momentum Dependent pdfs
- Exclusive: Generalized Parton Distributions (coord. space), aiming for Lg, Lq.

- For the neutron as well as the proton
- And explore parity-violating BSM

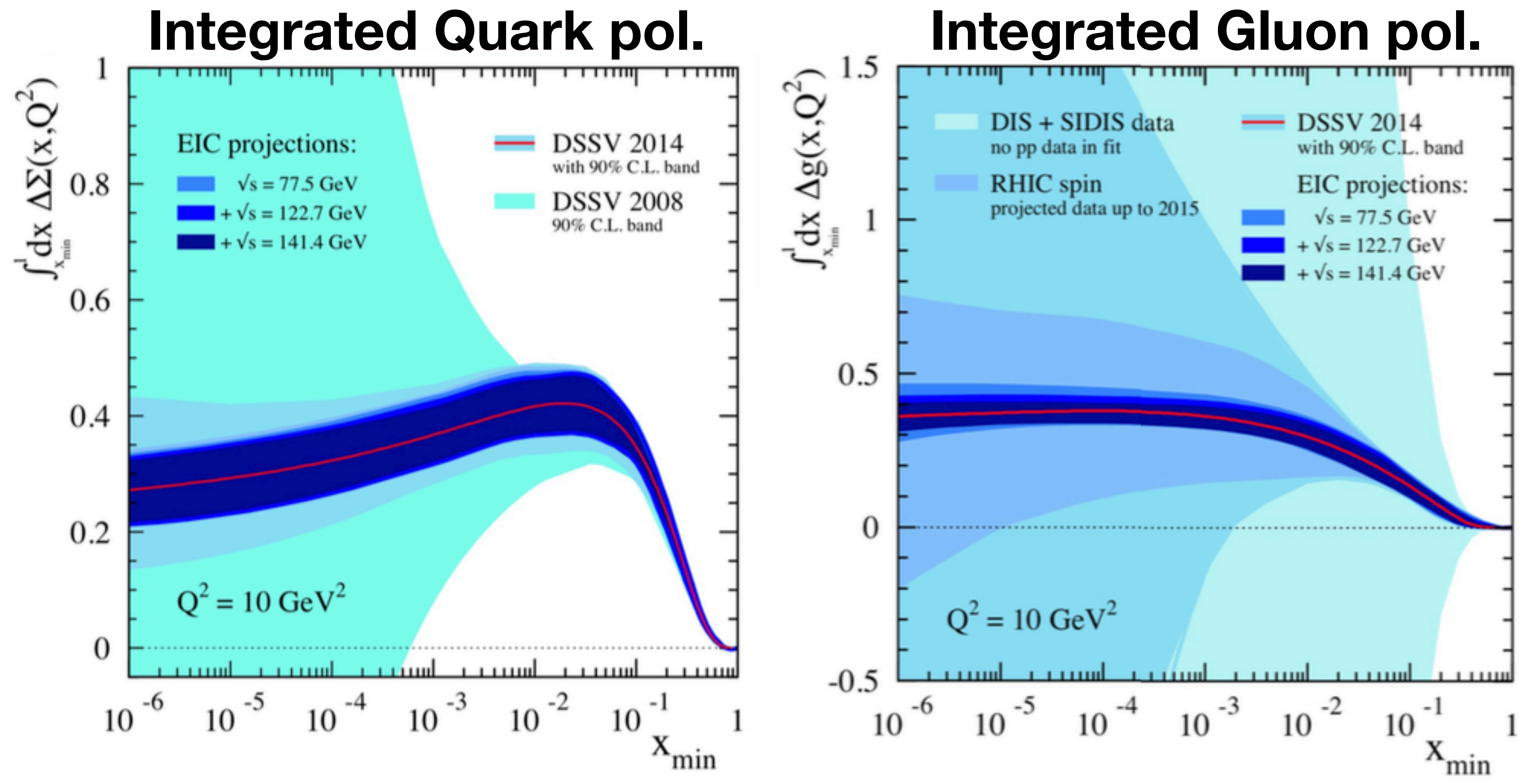


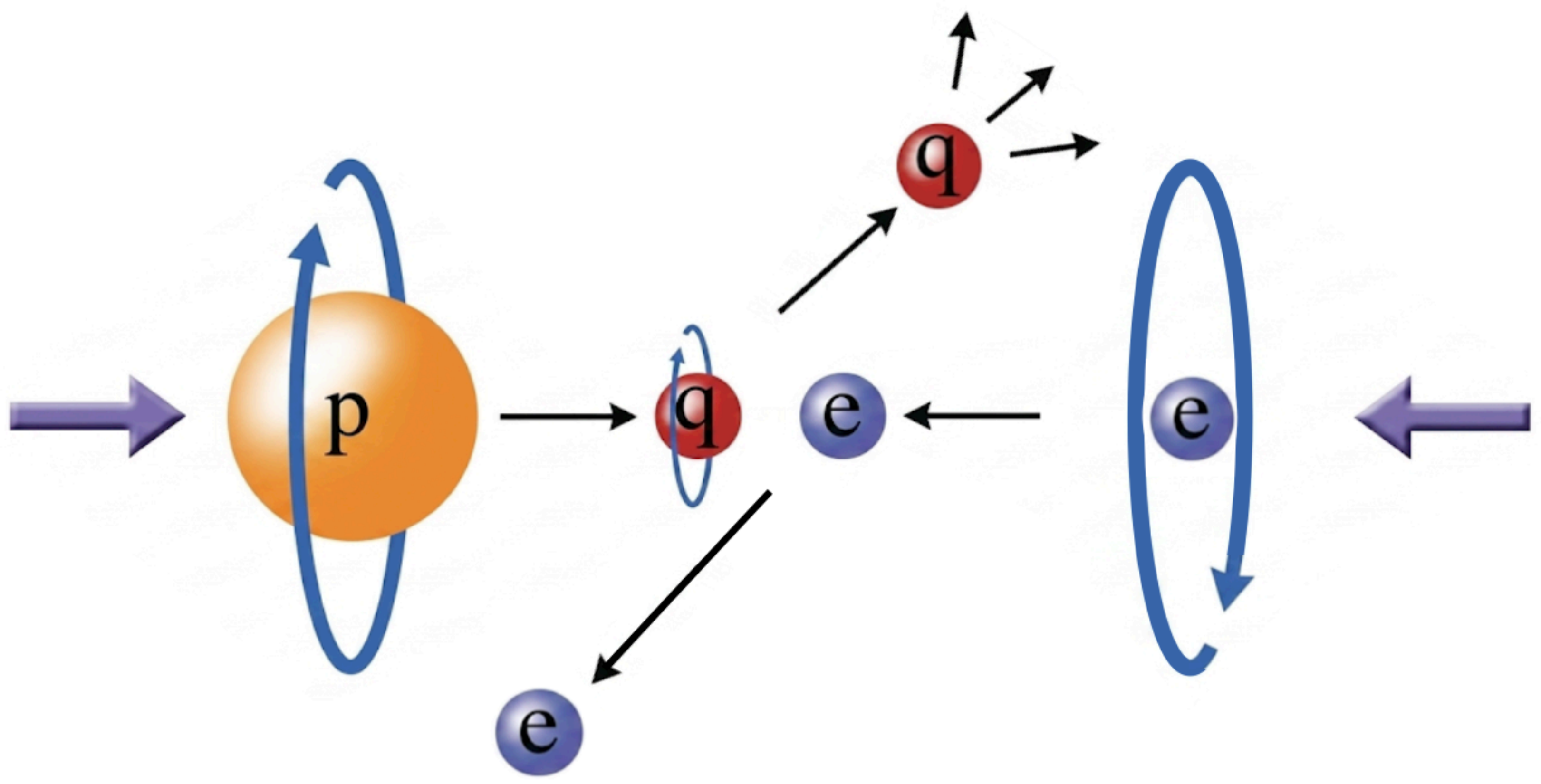
Figure 6: Comparison of polarized PDFs at $Q = 10$ GeV obtained from the `pDIS+SIDIS base` fit and from fits including projected EIC SIDIS pseudodata for the two beam-energy configurations $E_e \times E_p = 5 \times 41$ GeV^2 and 18×275 GeV^2, using the default hadron-energy cut $z > z_{\rm min} = 0.2$.

Longitudinal Asymmetries

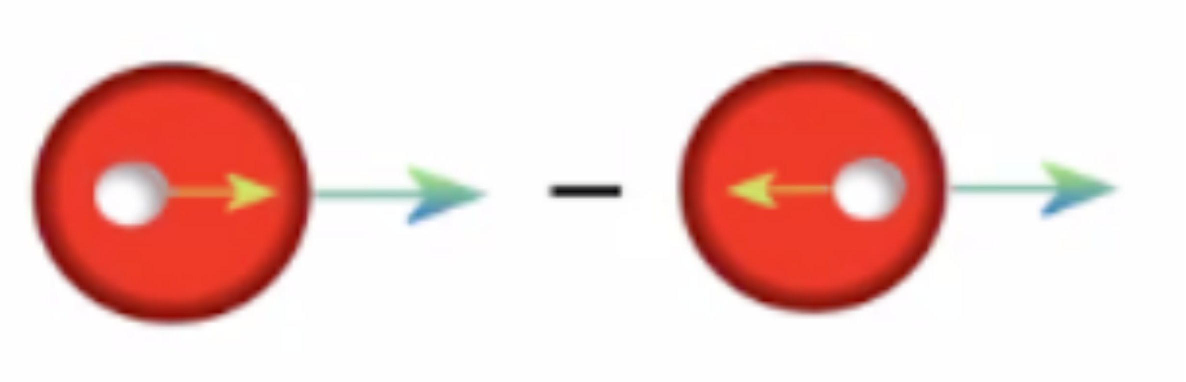
$$A_{LL} = \frac{\sigma^{-\uparrow} - \sigma^{+\uparrow}}{\sigma^{-\uparrow} + \sigma^{+\uparrow}} = \frac{\Delta\sigma}{\sigma_0}$$

$$\Delta\sigma = \sum_a \Delta f_{a/p} \otimes \Delta\sigma_{ea}$$

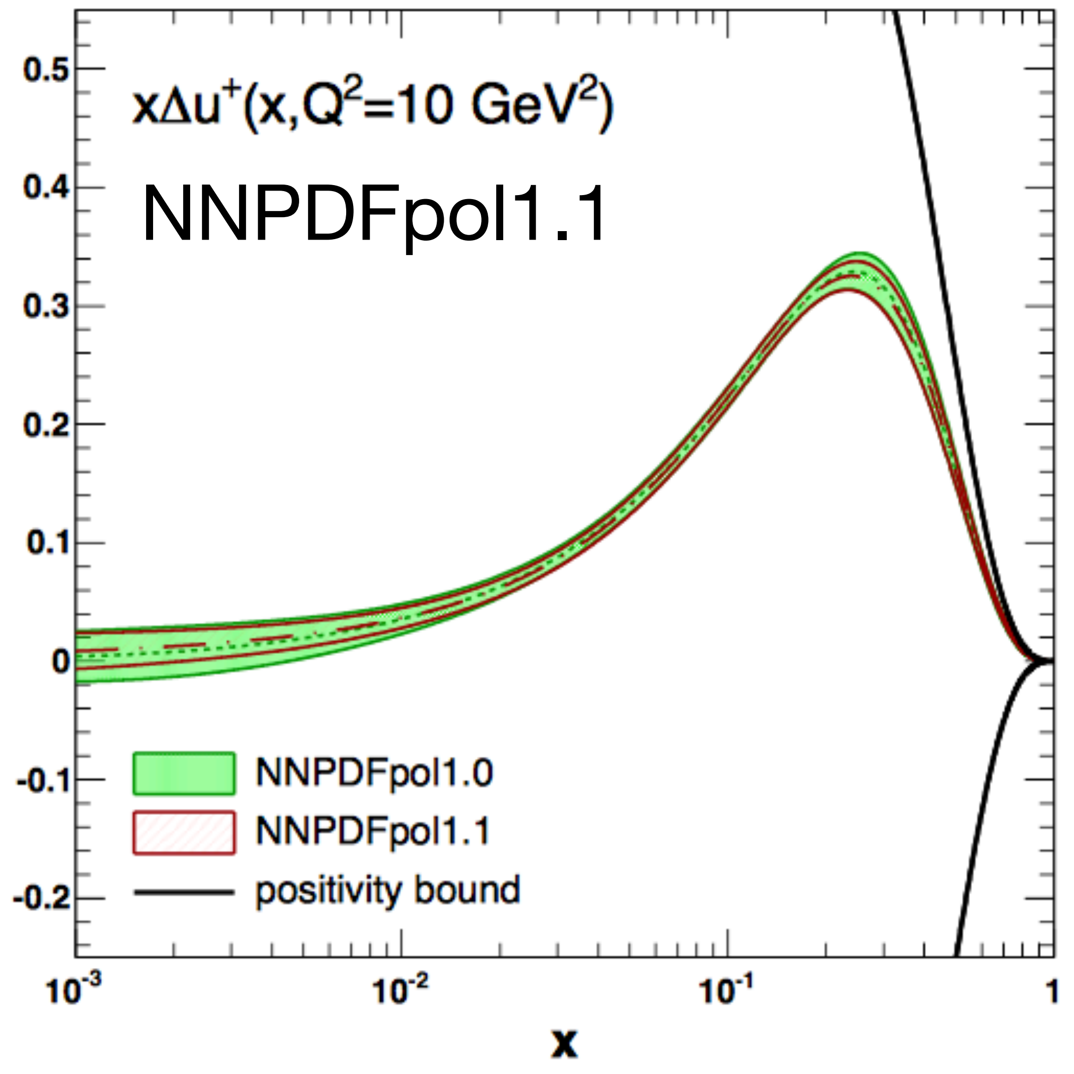
$$\Delta\sigma = \left[e_u^2 \Delta u(x) + e_d^2 \Delta d(x) + e_s^2 \Delta s(x) + \ldots\right] \otimes \Delta\sigma_{\mathrm{ea}}$$



$$\Delta q(x) =$$



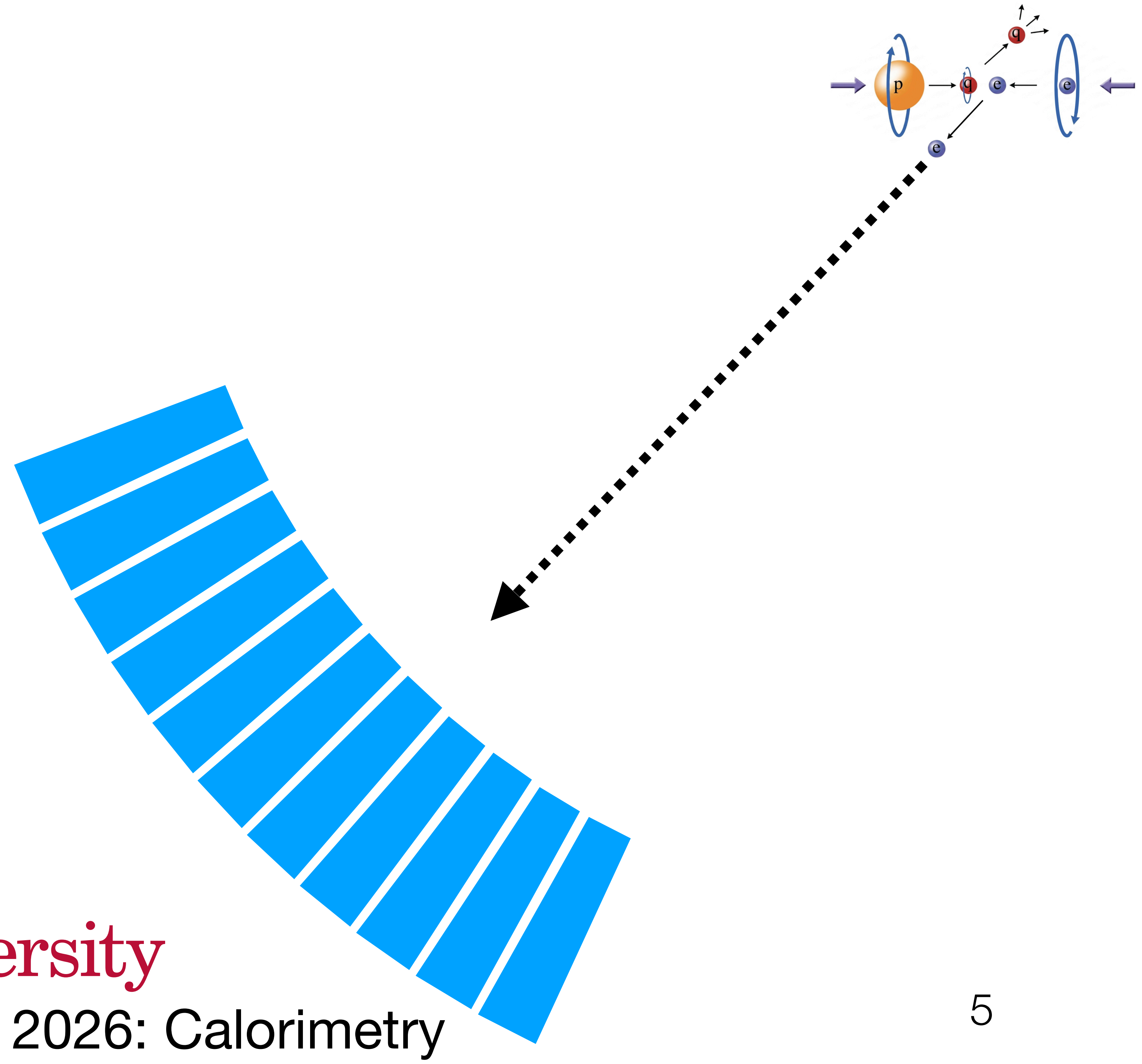
- Partonic asymmetries can be large
- In (SI)DIS we can discriminate, but we need to identify the electron momentum vector (and other final state vectors)
- Combine different detectors (EMCal, HCal, tracking) to measure particle properties and identify them



arxiv:1406.5539 : Nucl.Phys.B 887, 276 (2014)

Now What?

- To reconstruct DIS, all we need is the opening angle **θ** and the e$^-$ energy **E'** (and we can ask the accelerator folks to tell us what **E** and **s** are)
- We need a ***Calorimeter*** to measure the energy. (We also need to know the angle)



$$Q^2 = 4EE'\sin^2\left(\frac{\theta}{2}\right)$$

$$y = 1 - \frac{E'}{E}\cos^2\left(\frac{\theta}{2}\right)$$

$$x = \frac{Q^2}{sy}$$

Caution: Dramatic oversimplification

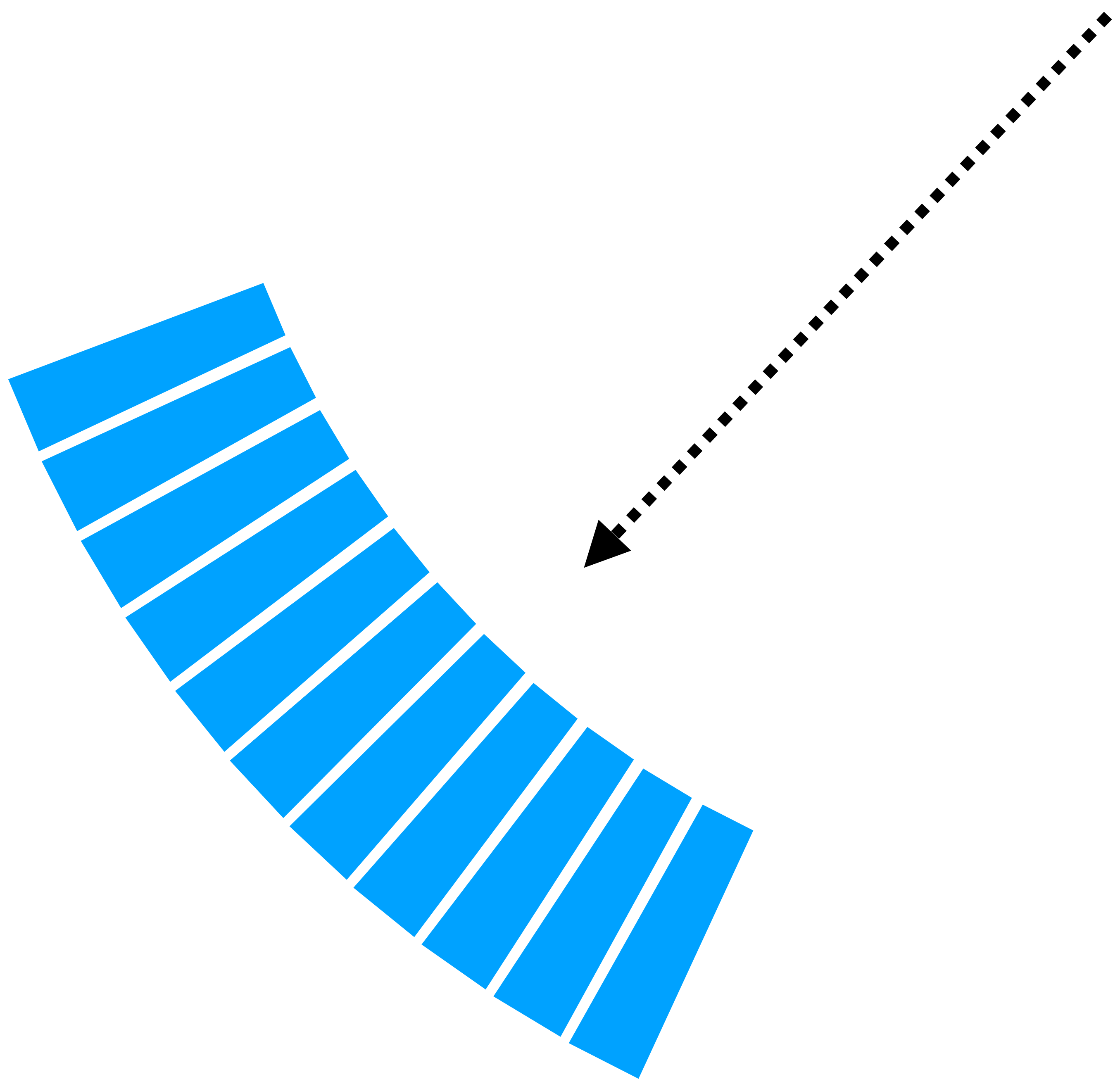
"Calorimeter"

- A calorimeter is a device to measure the heat generated in a process
- Lavoisier and Laplace: Measure how much ice melts and you have a measure of the heat (energy) transferred to the ice.

Plate XI: The Calorimeter of Lavoisier and La Place, 1801 (wikipedia)

"Calorimeter"

- A calorimeter is a device to measure the heat generated in a process
- Lavoisier and Laplace: Measure how much ice melts and you have a measure of the heat (energy) transferred to the ice.
- In principle: Make our calorimeter out of ice, and we could collect the water melted by our electron as it comes to rest in it: $E' \propto V_{H_2O}$

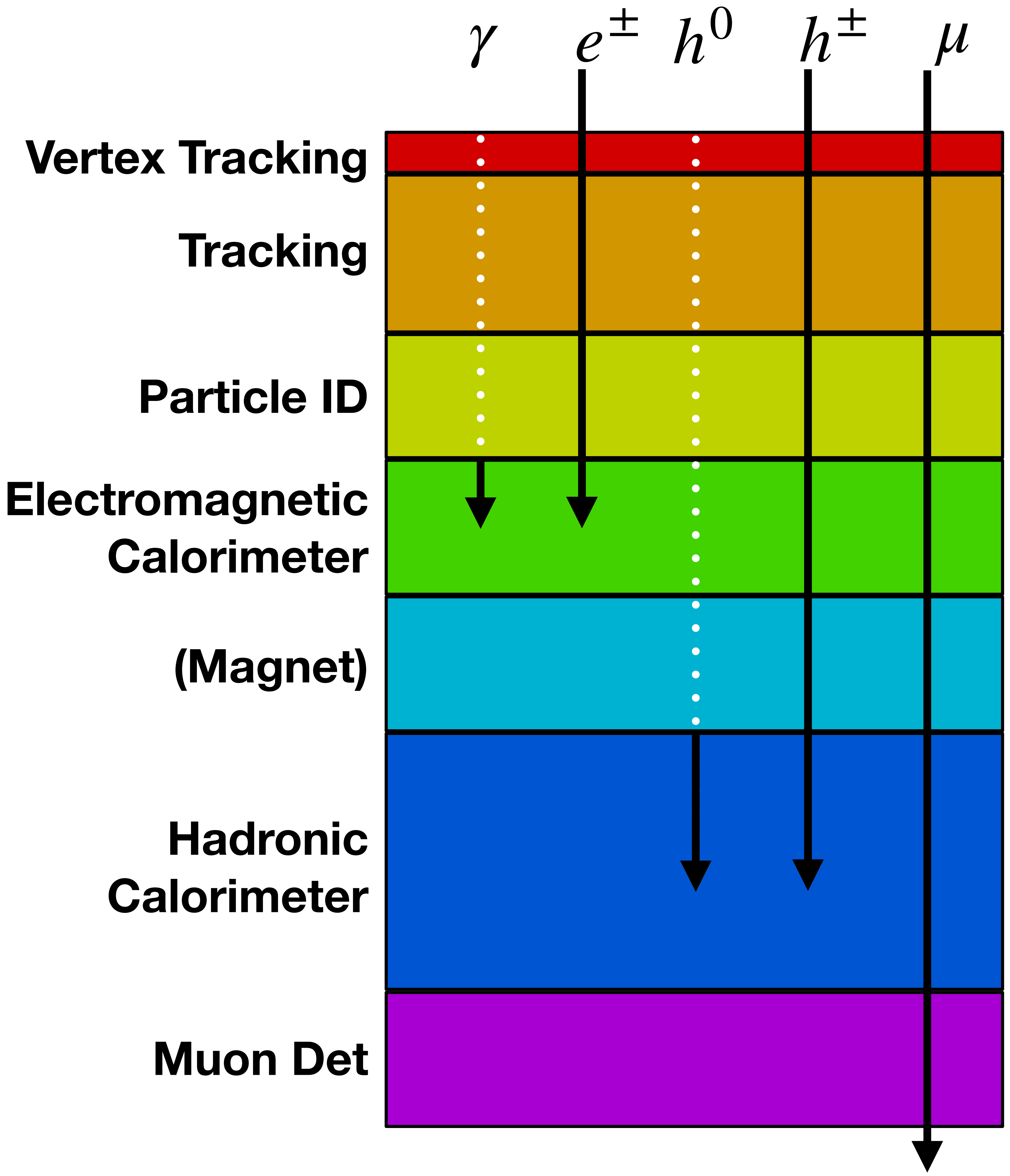


Modern Calorimetry

- A calorimeter is a device to measure the *Energy* of a *particle*.
- Generally we choose to do this destructively:
  - Absorb all of the particle's energy in our detector: EM interactions
  - Convert that energy to an electronic signal: Light (and eventually voltage)

All-Purpose Detector Stack

- Tasks: ~ $(E, \vec{p})$, $(t, \vec{x})$, and ID of all the stuff
- Vertex+Tracking: Measure the origin, trajectory, and momentum of charged particles*
- PID: measure the velocity dependent signal of charged particles that pass through.
- Calorimeters: measure the rough position and energy *deposited* by all particles
  - EM Calorimeters: Charged **and neutral** particles that interact through EM
  - Hadronic Calorimeters: Measure the the rough position and energy *deposited* by charged **and neutral** particles that interact through nuclear or EM
- Muon: Measure the the position/trajectory and energy deposited by charged particles that make it this far



*... by measuring the rough energy deposited by all charged particles

Outline

- Intro (✅)
- Electromagnetic Calorimetry
  - Physics of Showers
  - Calorimeter Design
  - Performance
- Hadronic Calorimetry
- Future Calorimeters: ePIC and Beyond

Physics of Showers: Photons

- Above ~100 MeV, pair and triple production dominate, ~ flat vs E
- The mean free path for a photon is:

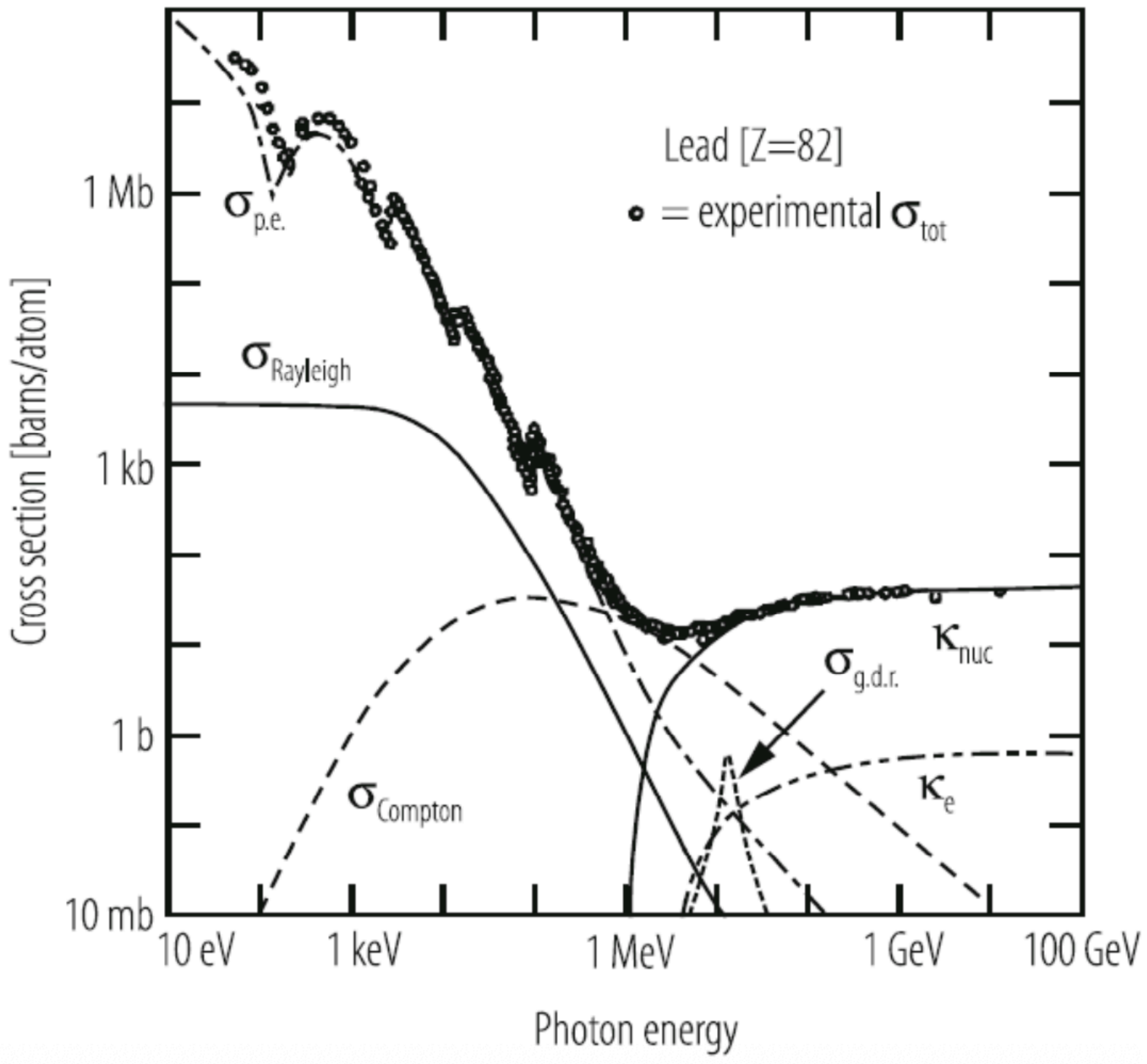
$$\lambda = \frac{9}{7} X_0$$

$$X_0 = \frac{(716.4 \text{ g cm}^2) \cdot A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- Why not "921.1 g cm²"? Stay tuned.

Process	Scaling
Photoelectric Effect $\gamma e^-_{(b)} \rightarrow e^-$	**Z⁴ to Z⁵**
Rayleigh Scattering $\gamma A \rightarrow \gamma' A^*$	**Z²**
Compton Scattering $\gamma e^-_{(b)} \rightarrow \gamma' e^-$	**Z**
Giant Dipole Resonance $\gamma N \rightarrow N^*$	**Z**
Pair Production $\gamma N \rightarrow N e^+ e^-$	**Z²**
Triplet Production $\gamma e^- \rightarrow e^- e^+ e^-$	**Z**

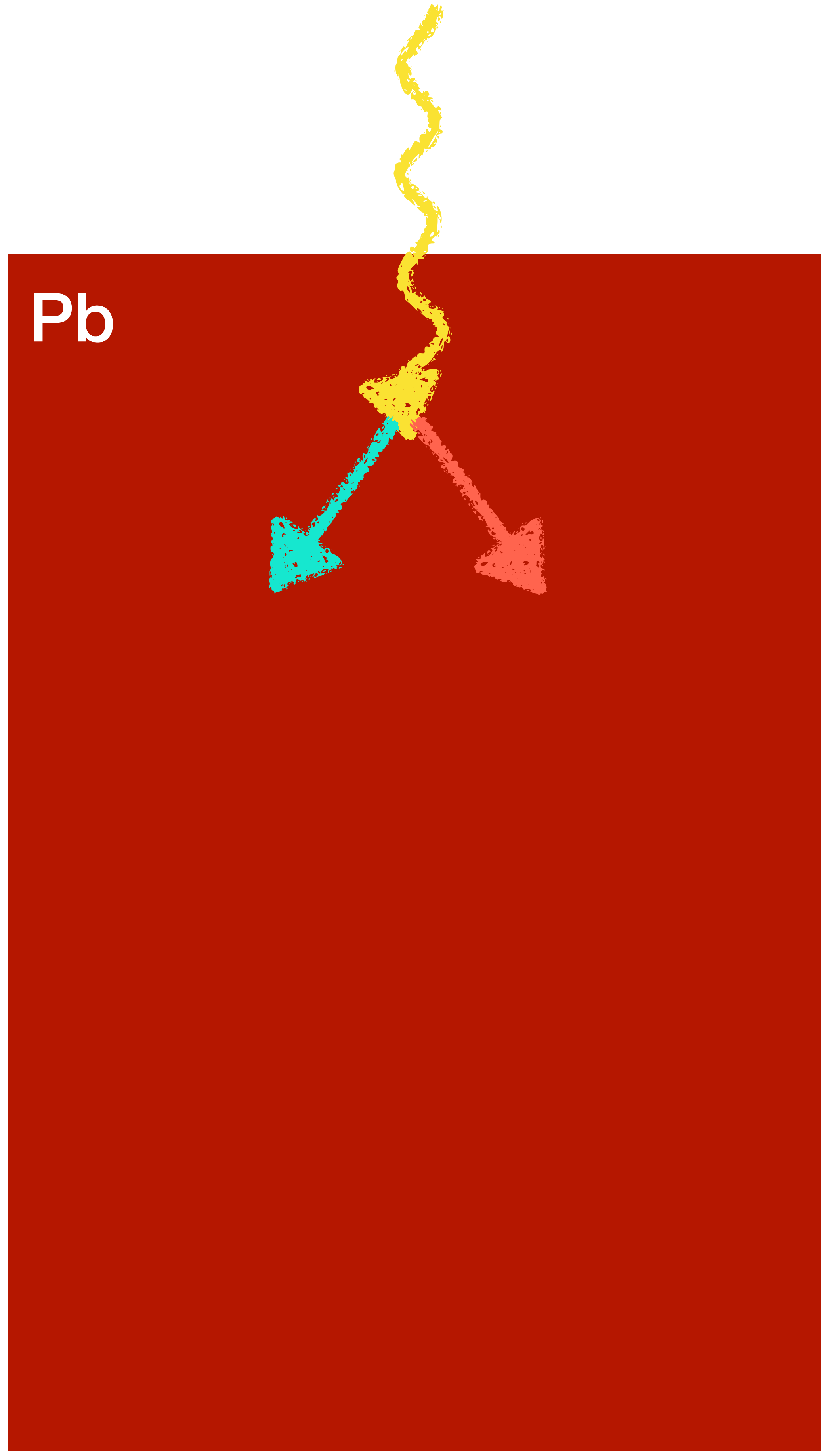
Photon cross sections in Lead



$$\kappa_{\text{nuc}} \approx \alpha r_e^2 Z^2 \left[\frac{28}{9} \ln\left(\frac{183}{Z^{1/3}}\right) - \frac{2}{27}\right] \quad \kappa_{\text{e}} \approx \alpha r_e^2 Z \left[\frac{28}{9} \ln\left(\frac{1429}{Z^{2/3}}\right) - \frac{2}{27}\right]$$

Physics of Showers: Photons

- A high energy photon $E_\gamma > 1\mathrm{GeV}$ hits our Pb block. What happens?
- The photon is neutral so it loses no energy until (on average) 0.72cm into the material.
- Once there, it probably pair produces: $\gamma N \rightarrow N e^+ e^-$
- So it's gone, and we have two electrons, each with $E_e \approx 0.5 E_\gamma$



Physics of Showers: Electrons

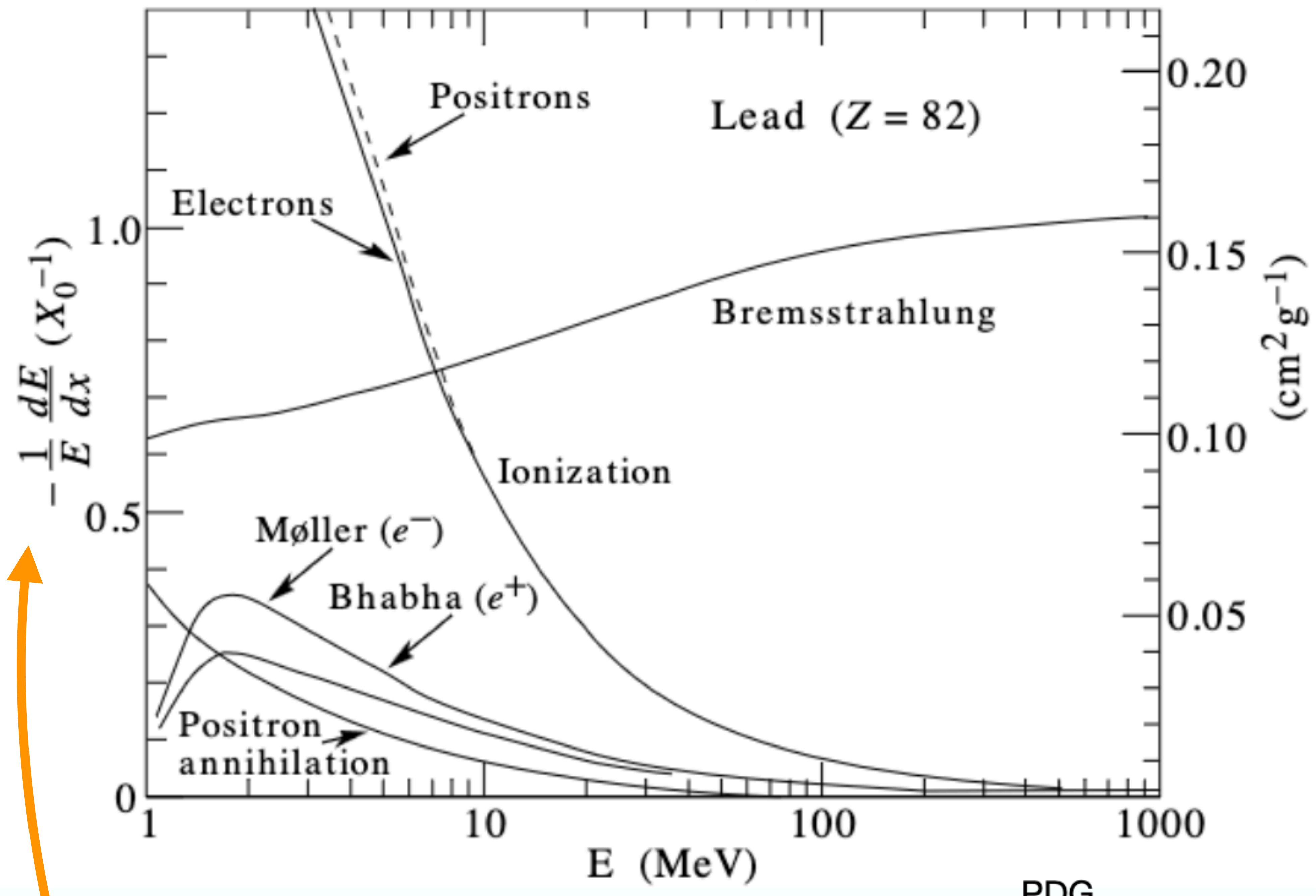
- Above ~100 MeV, Bremsstrahlung dominates, ~flat vs E
- At high energy, an e± loses (on average) 1/e of its energy in one **Radiation Length**:

$$X_0 = \frac{(716.4\ \mathrm{g\ cm^2}) \cdot A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- The Bremsstrahlung spectrum has $dW/dE_\gamma \approx \mathrm{const.}$, so the energy loss is generally dominated by ~ one, highest energy photon.

Process	Scaling
Bremsstrahlung $e^\pm \to \gamma e^\pm$	**Z²**
Ionization (Total) $e^\pm e^-_{(b)} \to e^\pm e^-$	**Z**
Bhabha $e^+ e^-_{(b)} \to e^+ e^-$	**Z**
Møller $e^- e^-_{(b)} \to e^- e^-$	**Z**
Positron Annihilation $e^+ e^-_{(b)} \to \gamma\gamma$	**Z**

Electron/positron energy loss in Lead

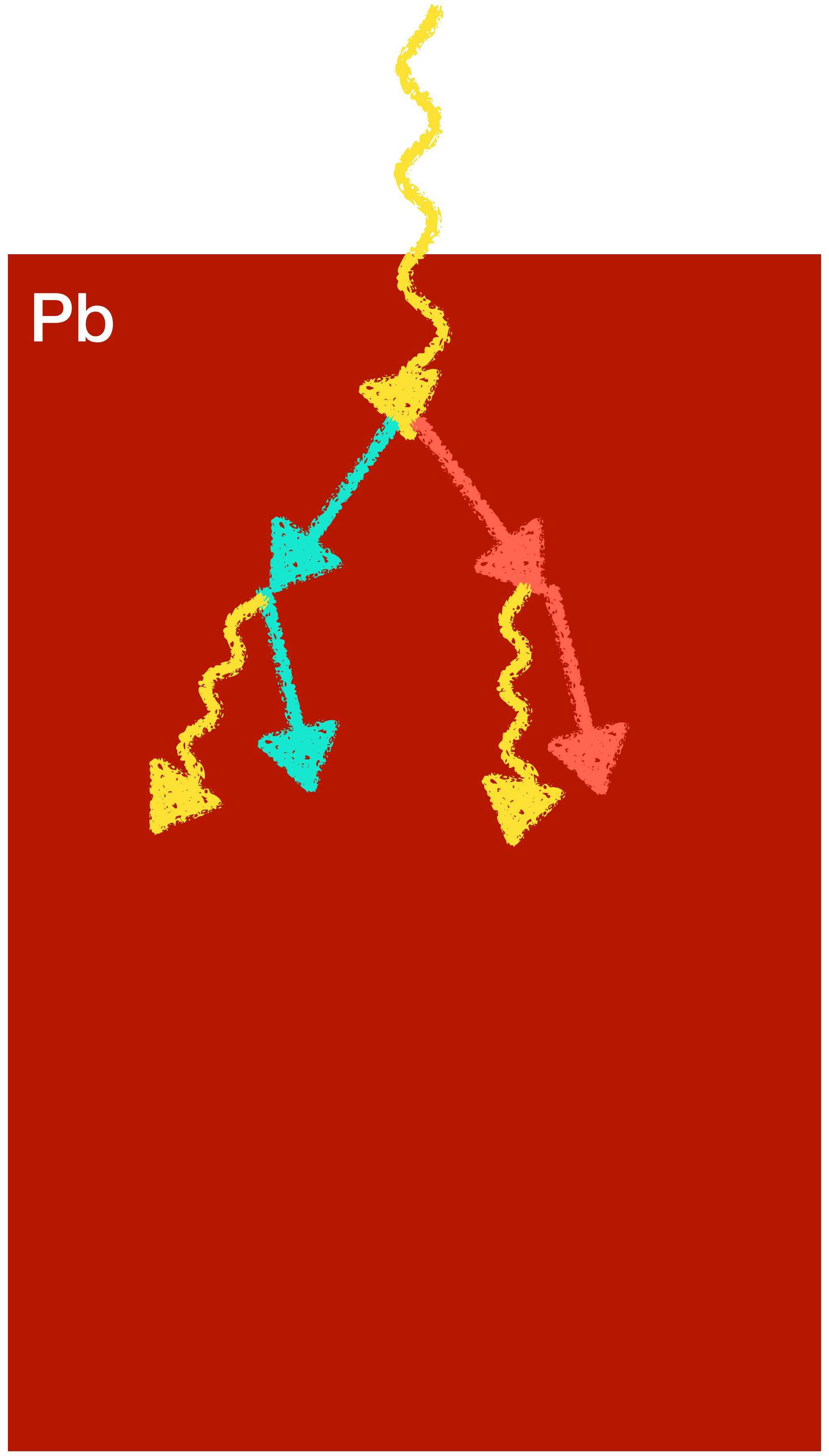


PDG

Fractional energy loss per radiation length

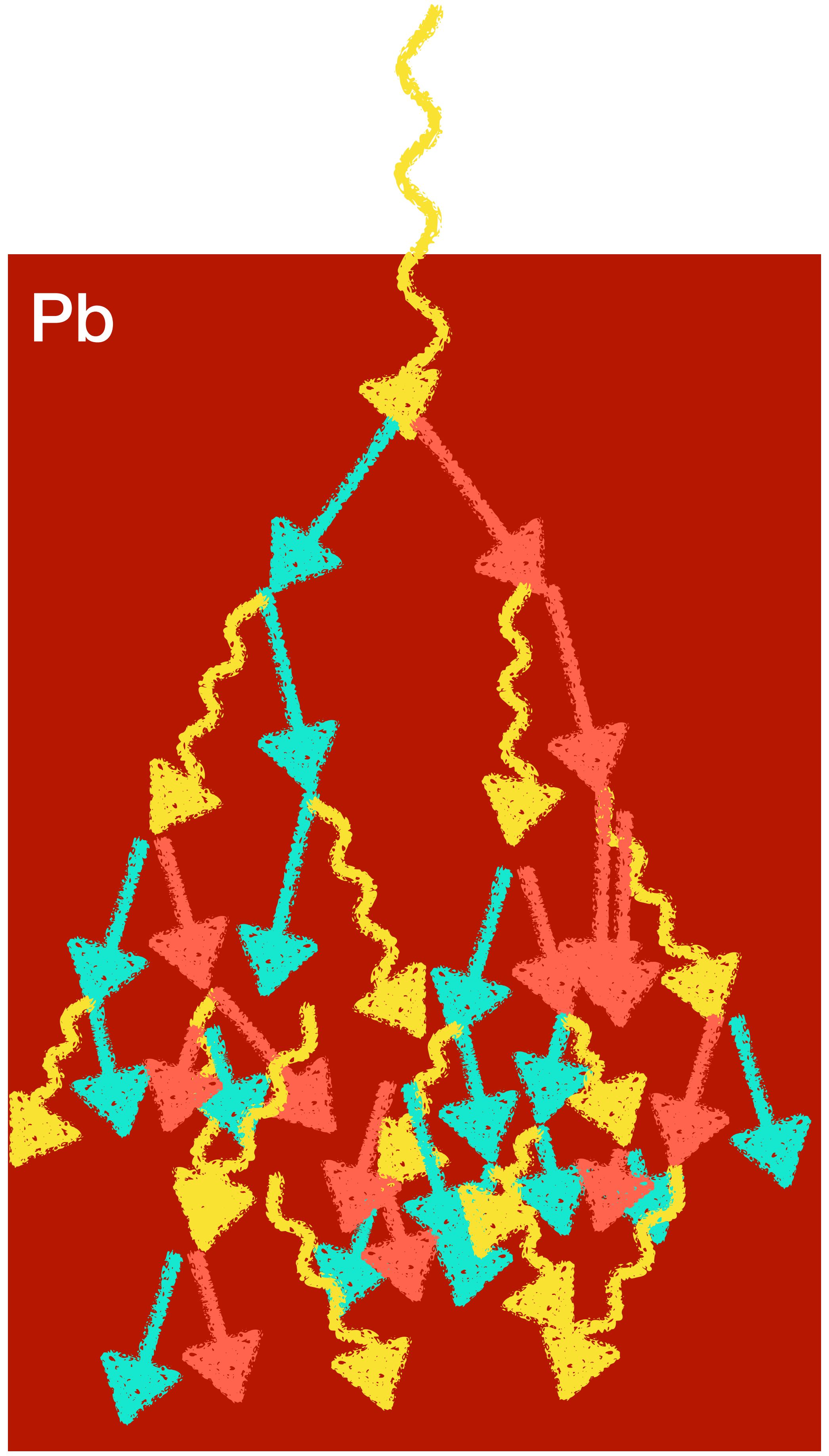
Physics of Showers: Electrons

- A high energy photon $E_\gamma > 1\mathrm{GeV}$ hits our Pb block and converted into e^+e^- What happens next?
- Each of these particles has ~500MeV, so they are dominated by Bremstrahlung,
- Over a distance X_0 they each emit ~1 photon with ~36% of their energy



Physics of Showers

- Then What?



Physics of Showers

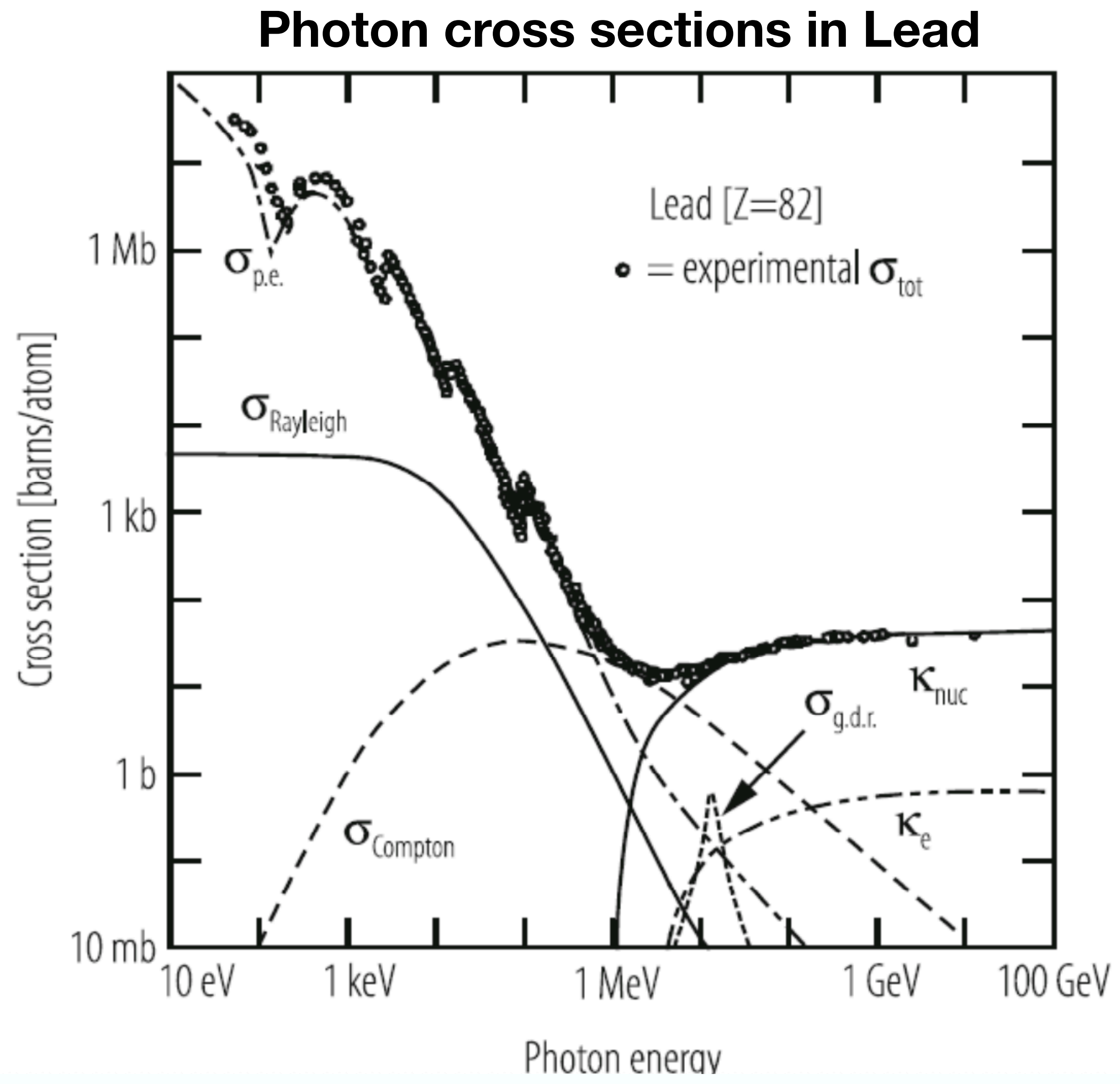
- Eventually the energy per particle drops below the threshold to (on average) feed this cycle:

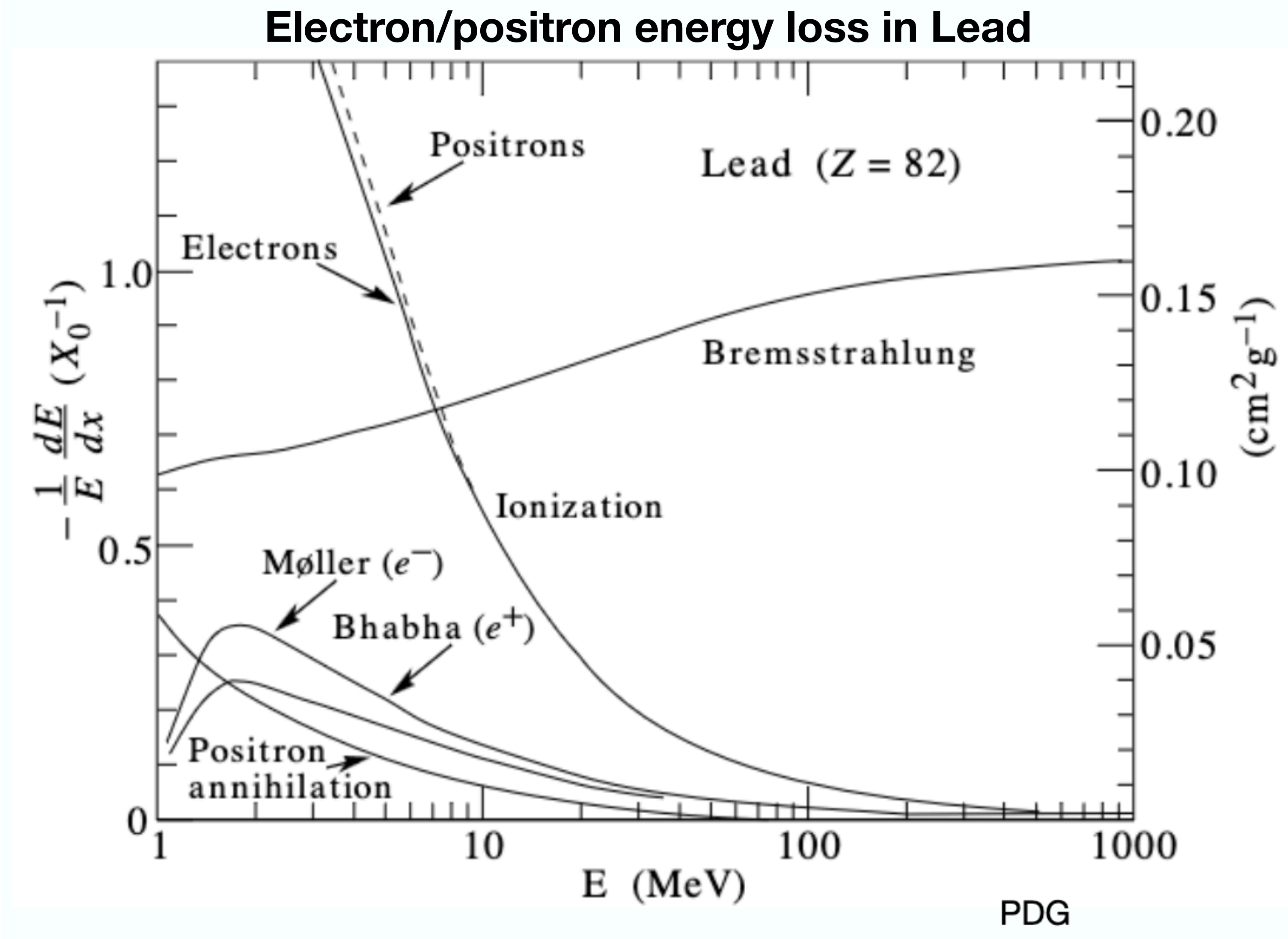
$$\left(\frac{dE}{dx}\right)_{\text{Brems}} = \left(\frac{dE}{dx}\right)_{\text{Ion}}$$

- This defines the Critical Energy:

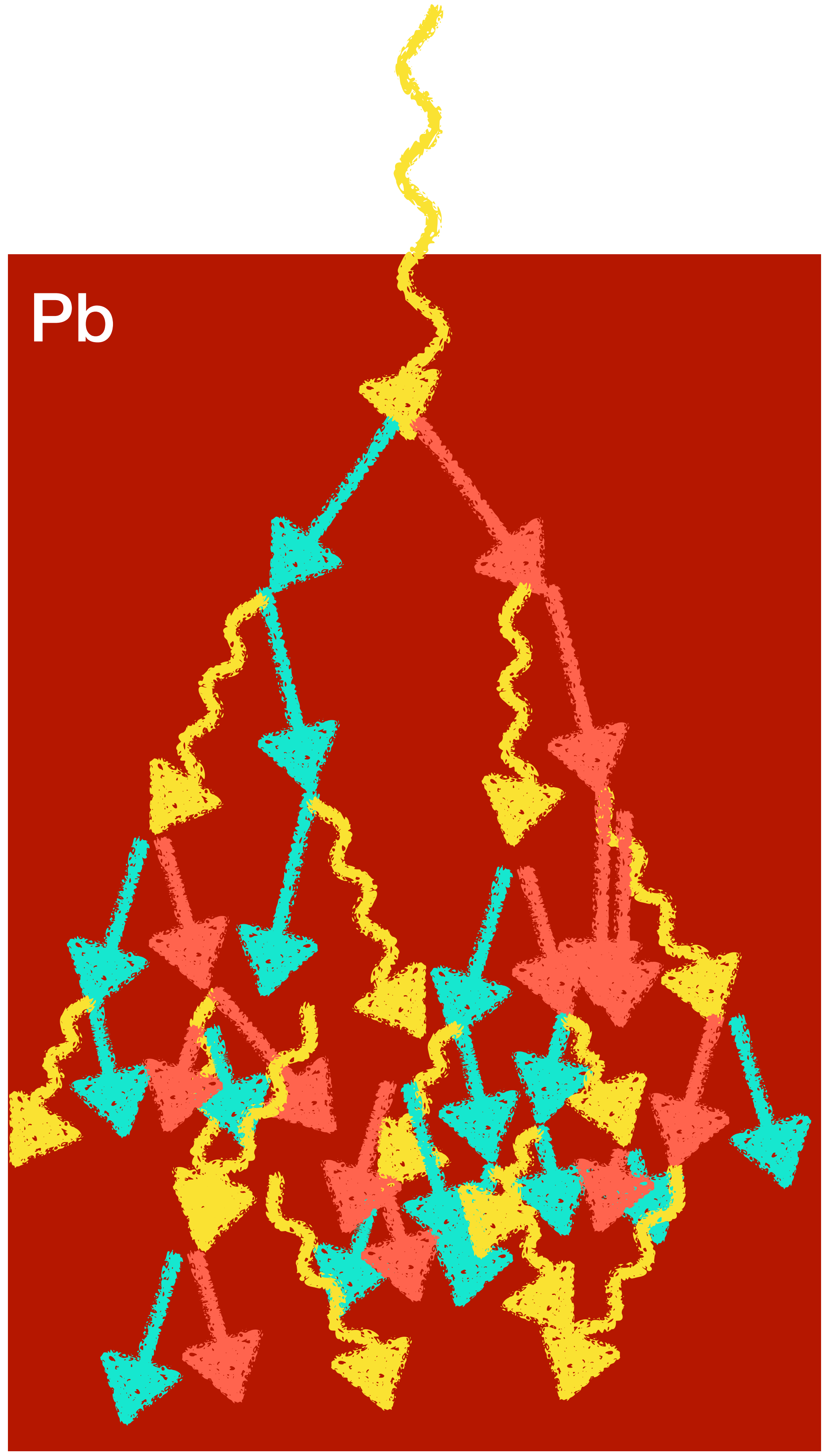
$$E_c \approx \frac{610\ \text{MeV}}{Z + 1.24}$$

- The shower continues to deposit energy until everything is at rest or absorbed


Photon cross sections in Lead


Electron/positron energy loss in Lead

PDG

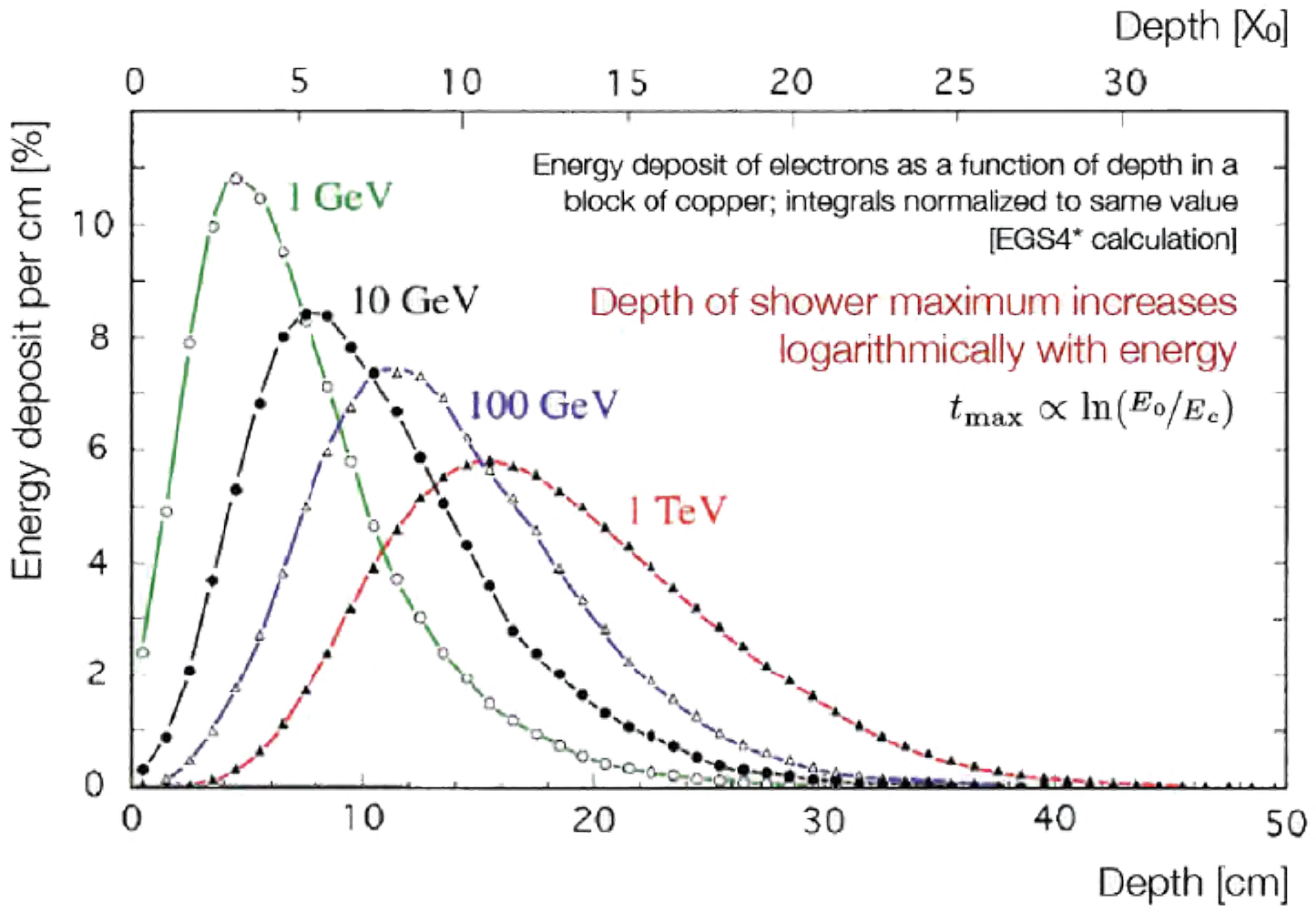


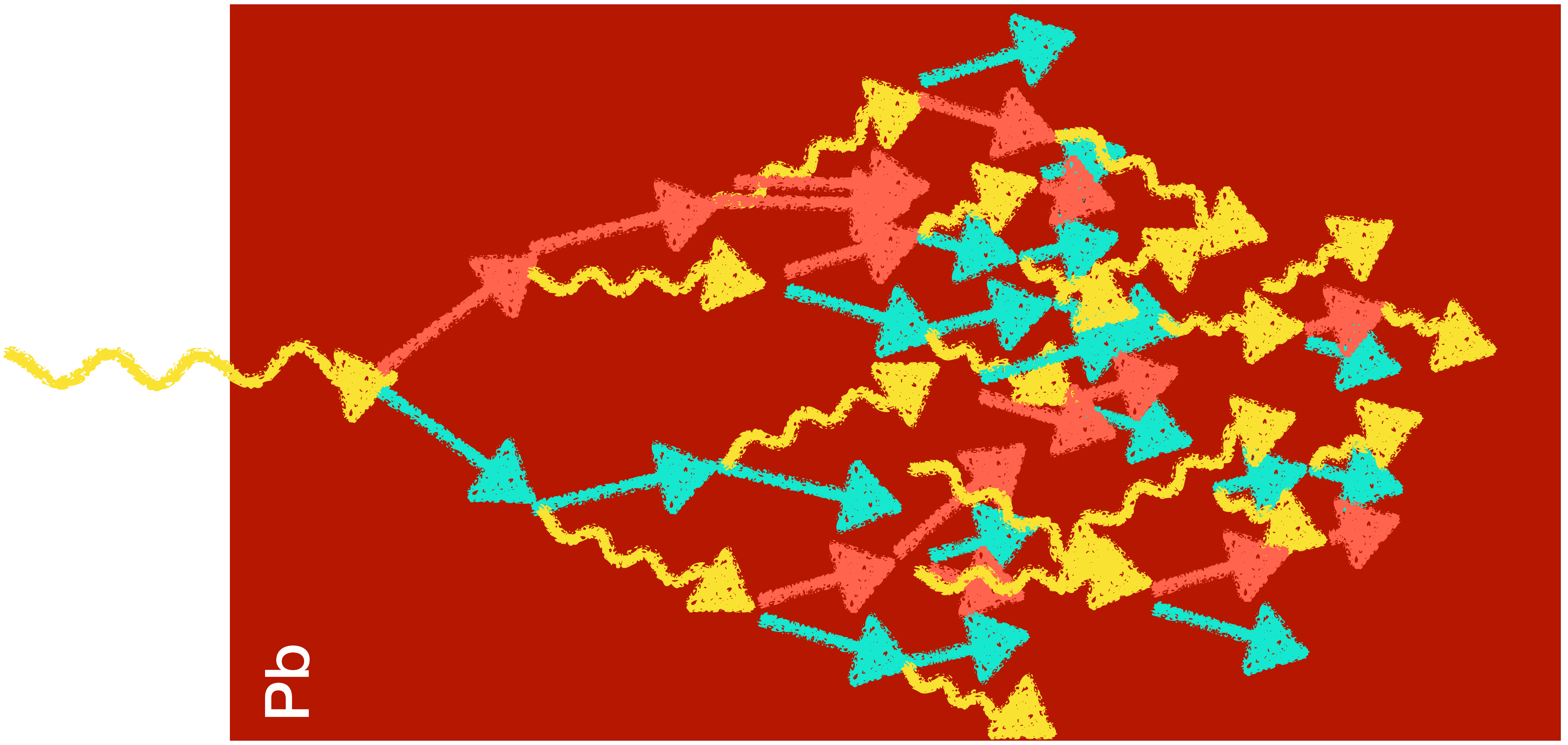
Physics of Showers

- The Shower Max, where dE/dx is highest, moves with $\ln(E_0/E_c)$
- This defines the Critical Energy:

$$E_c \approx \frac{610\ \mathrm{MeV}}{Z + 1.24}$$

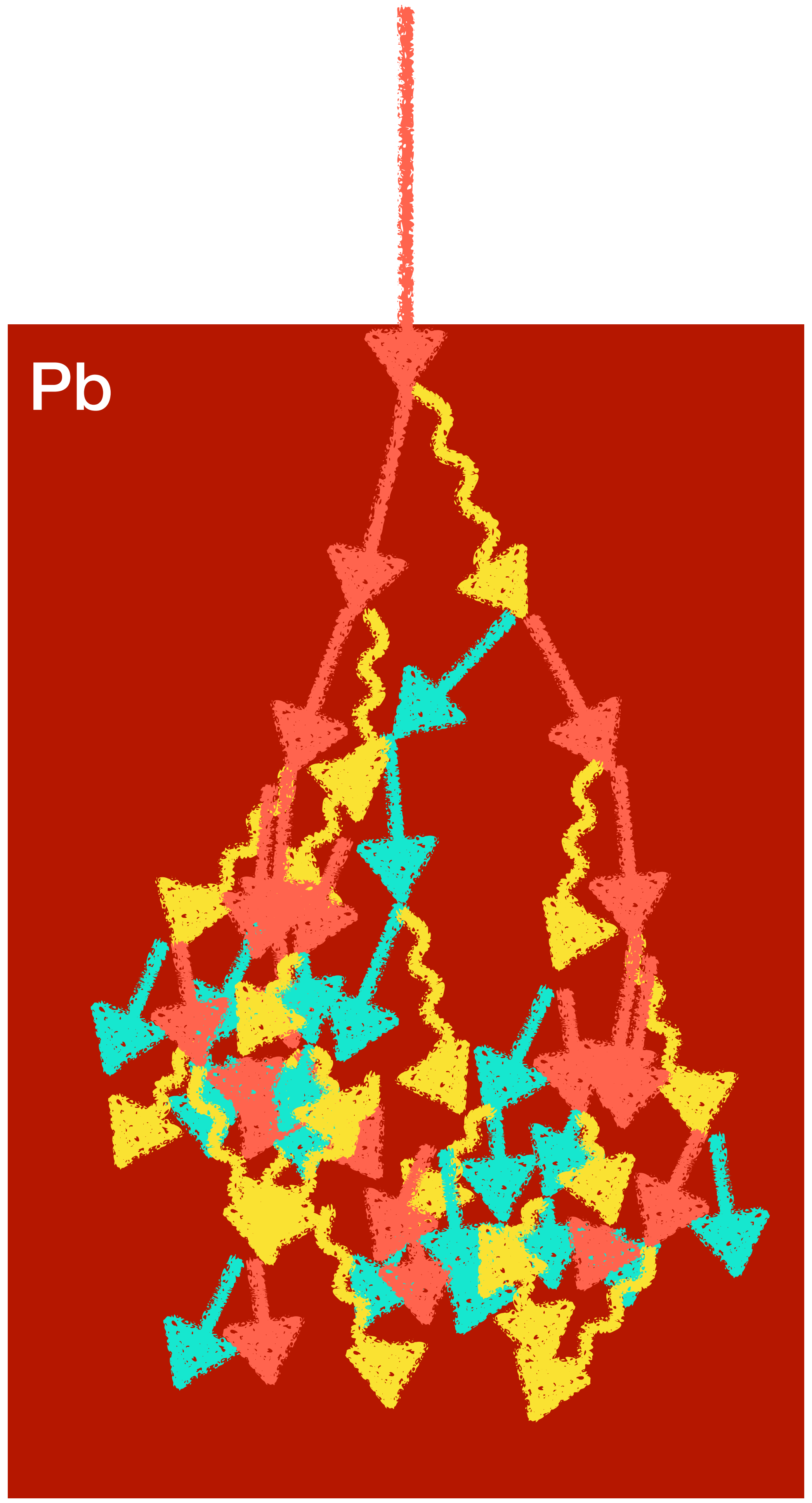
- The shower continues to deposit energy until everything is at rest or absorbed



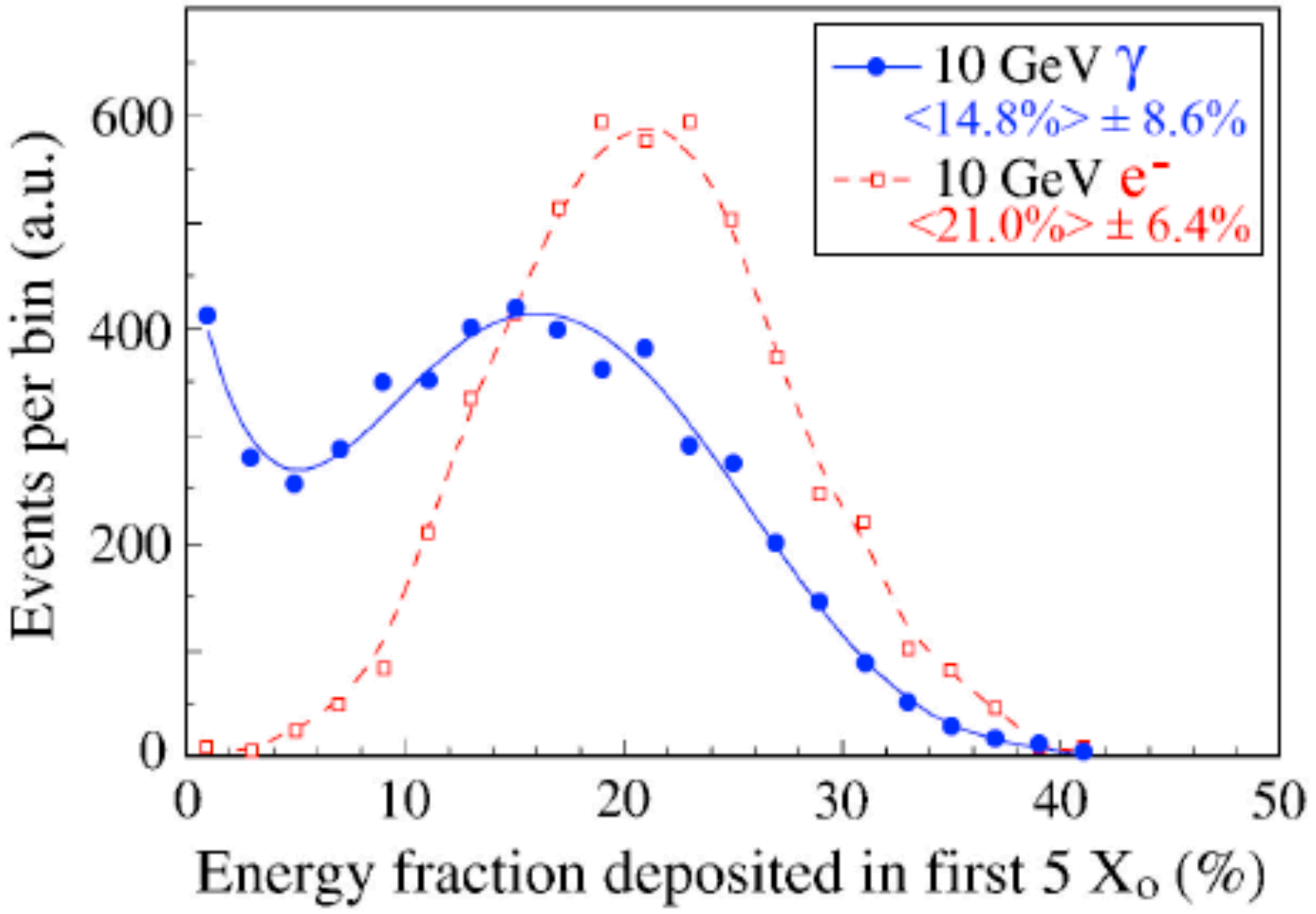


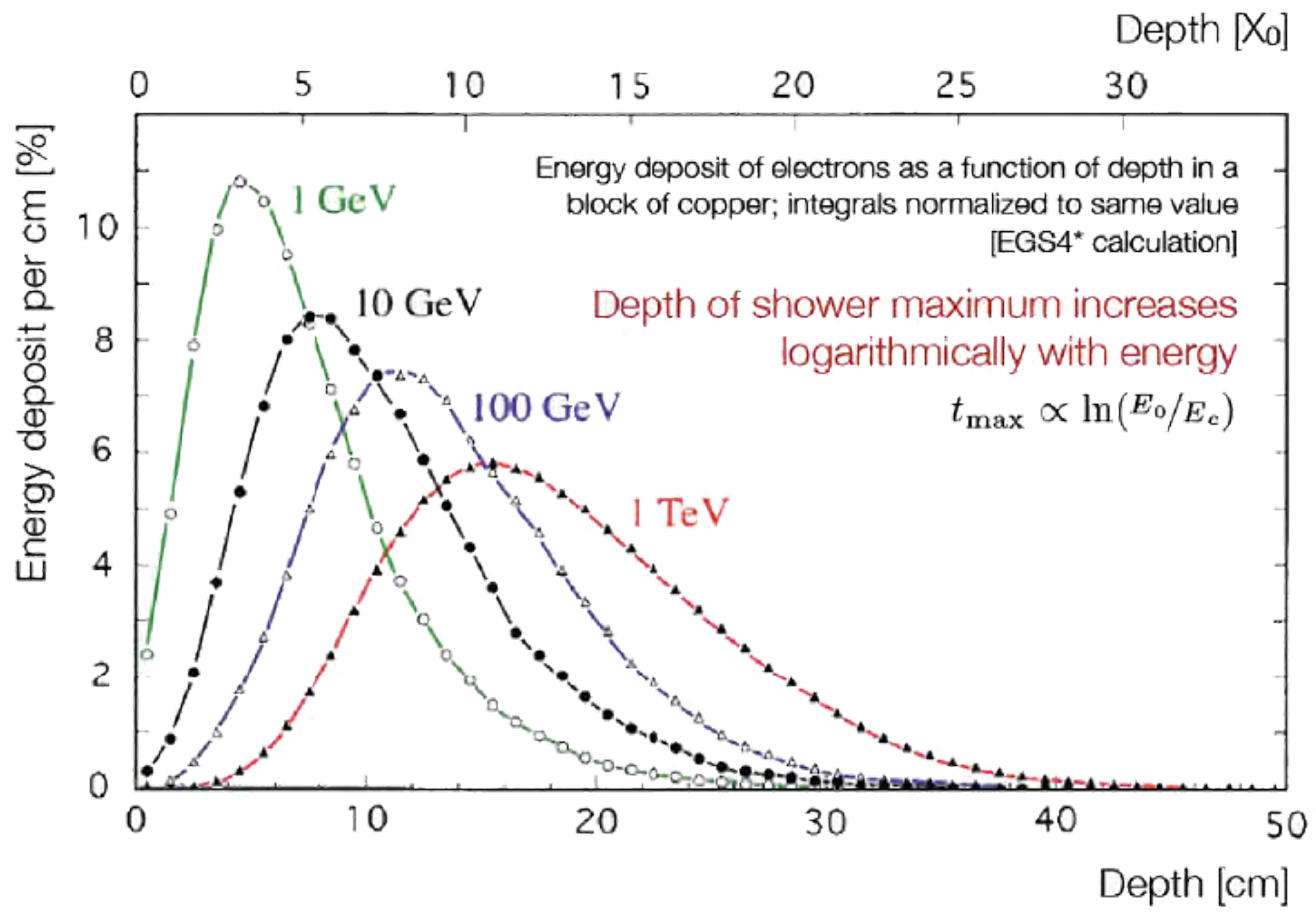
Physics of Showers

- A high energy positron $E_{e^+} > 1\mathrm{GeV}$ hits our Pb block. What happens?
- The positron is charged, so it starts losing energy immediately. Somewhere within the first X_0~0.5cm it emits a noteworthy photon.
- and the process continues from there.



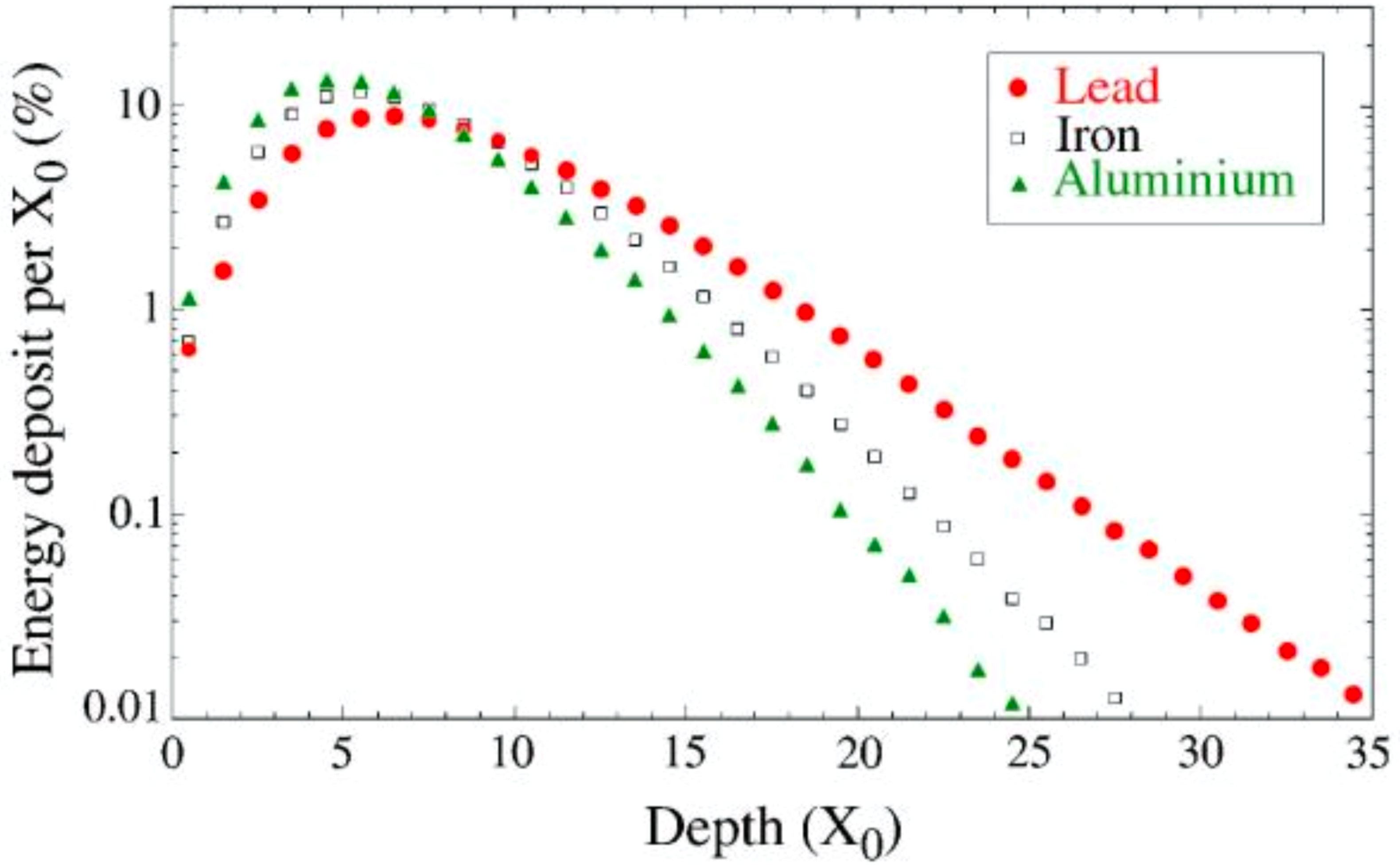
Longitudinal Shower Shape




Energy deposit of electrons as a function of depth in a block of copper; integrals normalized to same value [EGS4* calculation]

Depth of shower maximum increases logarithmically with energy

$t_{\max} \propto \ln(E_0/E_c)$



- The shower start is delayed for photons compared to charged particles.

$$C_e = -1.0 \quad C_\gamma = -0.5$$

- For the bulk, growth is a power law increase in energetic secondaries and an exponential loss of due to absorption:

$$\frac{dE}{dt} = E_0 t^{\alpha} e^{-\beta t} \qquad t_{\max} = \frac{\alpha - 1}{\beta} = \ln\left(\frac{E_0}{E_c}\right) + C_{e\gamma}$$

- The shower tails don't exactly follow X0 scaling

$\alpha_{2\text{GeV}} \approx 2.0 \quad \beta_{2\text{GeV}} \approx 0.5$

Longo, 1975

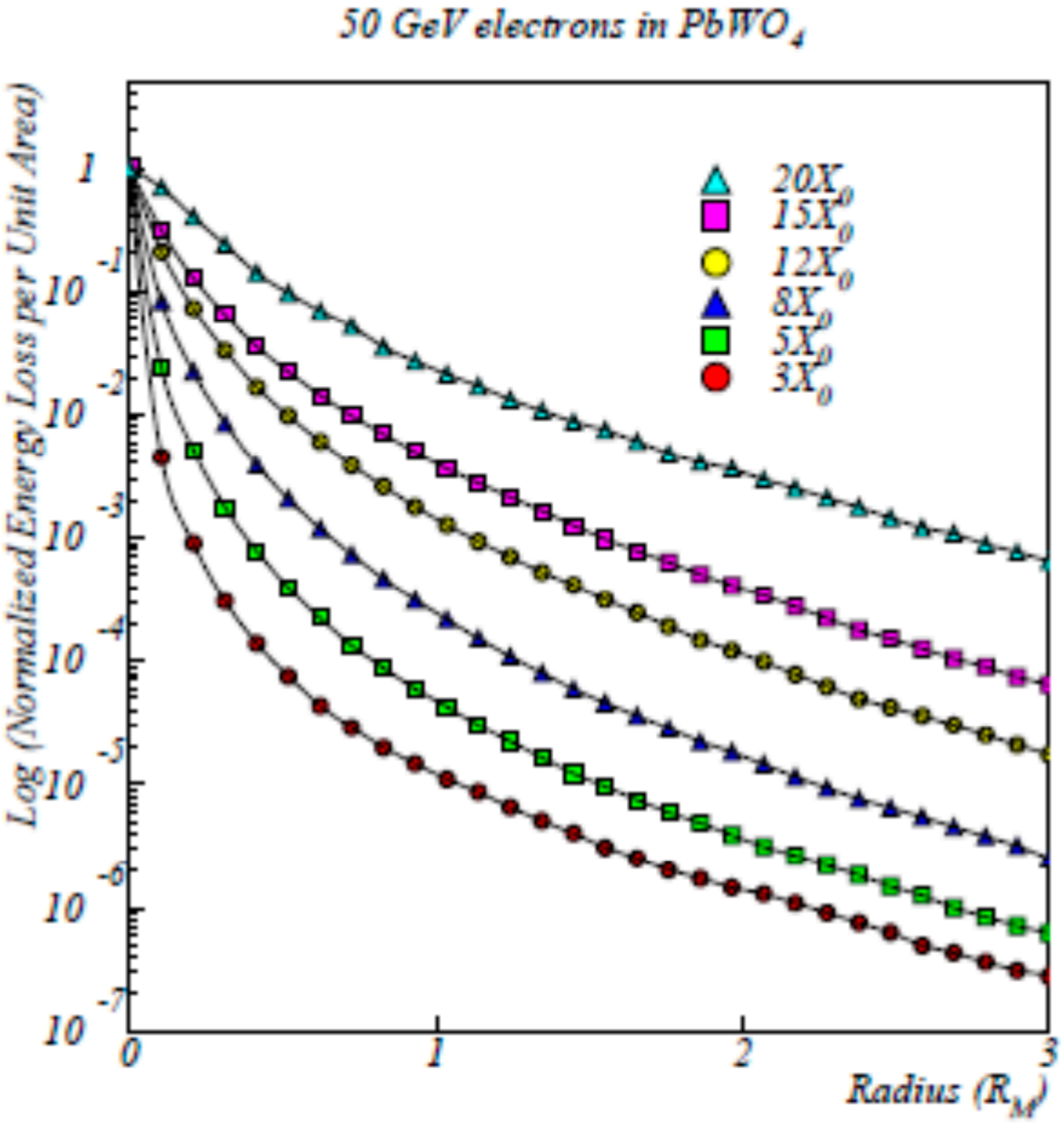
Transverse Shower Shape

- Low-energy e± scattering causes shower to spread out as it develops:

$$\langle\theta\rangle = \frac{21.2\ \mathrm{MeV}}{E_e}\sqrt{\frac{x}{X_0}}$$ [β = 1, c = 1, z = 1]

- Also spreads due to
  - Bremsstrahlung $\langle\theta\rangle > 0$
  - Photon propagation
- 90% of EM energy is within the **Molière Radius**:

$$R_M = \frac{E_s}{E_c}X_0 \approx \frac{21.2\ \mathrm{MeV}}{E_c}X_0$$



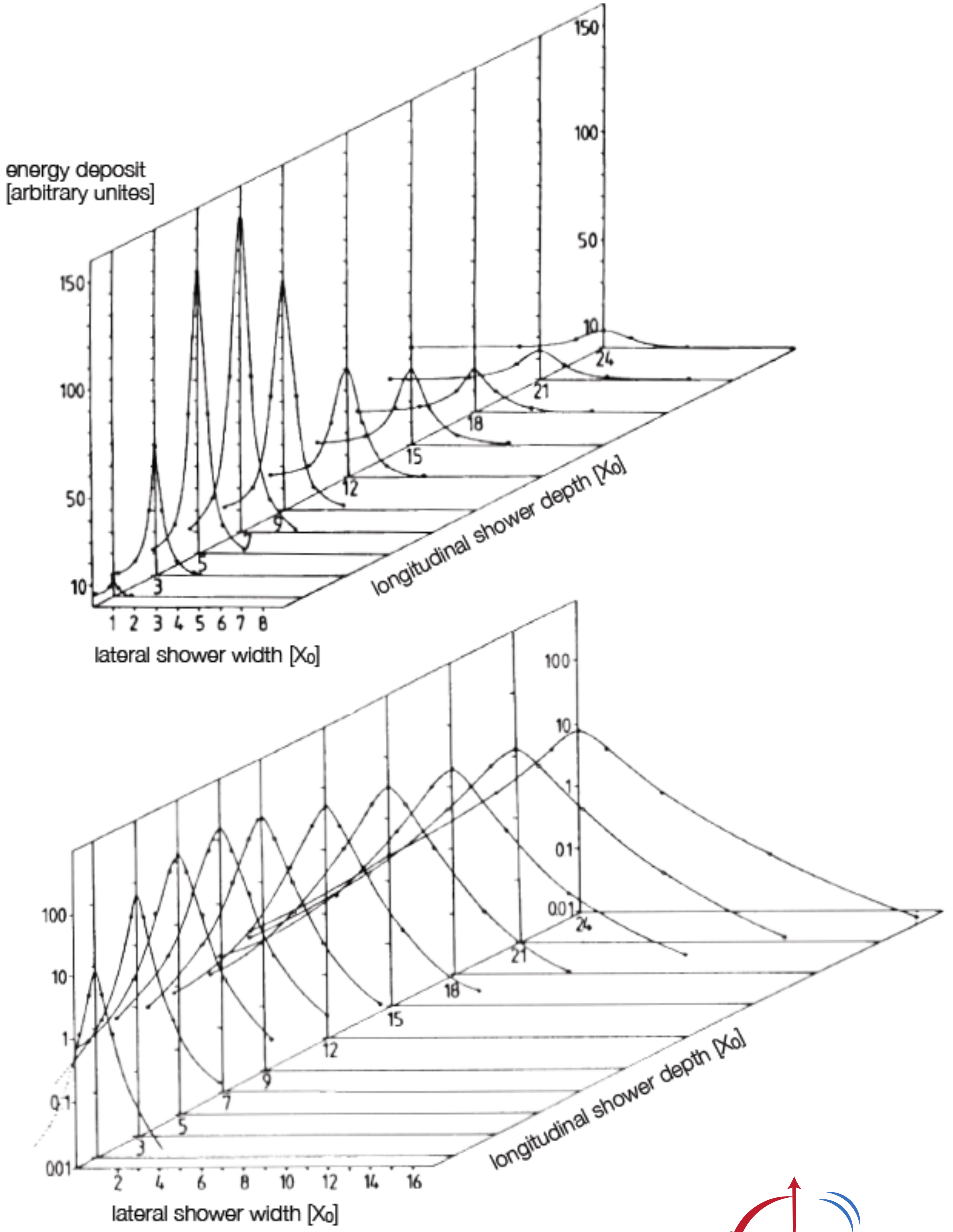
Analytic from multiple Coulomb scattering: $E_s = m_e c^2\sqrt{\frac{4\pi}{\alpha}} \approx 21.2\ \mathrm{MeV}$

Shower Shape Quick Math

- Radiation length: $X_0 = (180 \text{ g cm}^2) \cdot \dfrac{A}{Z^2}$
- Critical energy: $E_c = \dfrac{550 \text{ MeV}}{Z}$
  Rossi definition (rough)
- Shower max: $t_{\max} = \ln(E_0/E_c) + (1 \text{ or } 0.5)$
- Dimensions:
  - $L(95\%) = (t_{\max} + 0.08Z + 9.6) \cdot X_0$
  - $R(90\%) = R_M = \dfrac{E_s}{E_c} X_0 \approx \dfrac{20 \text{ MeV}}{E_c} X_0$
  - $R(95\%) = 2R_M$

Linear Scale

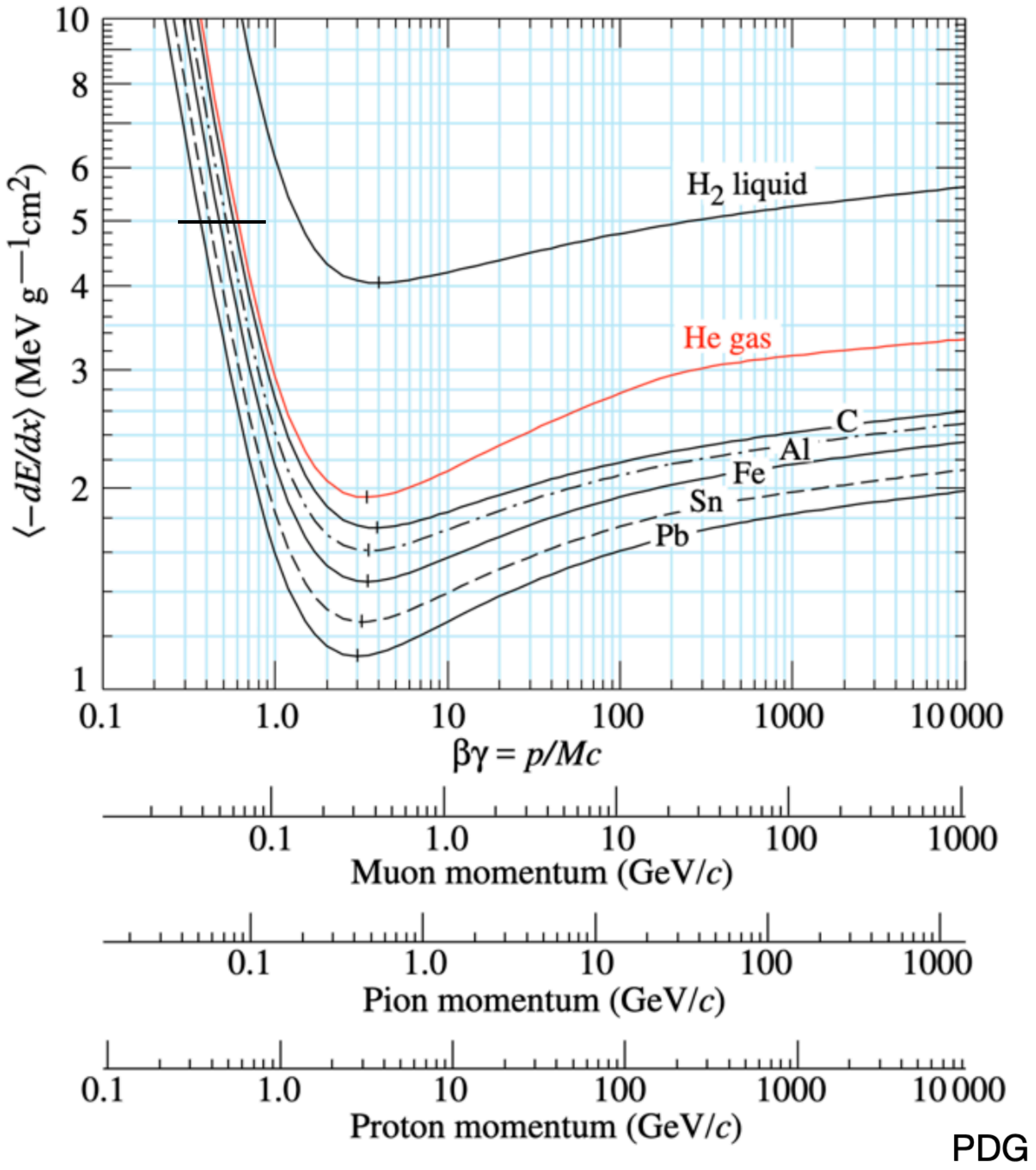
Log Scale



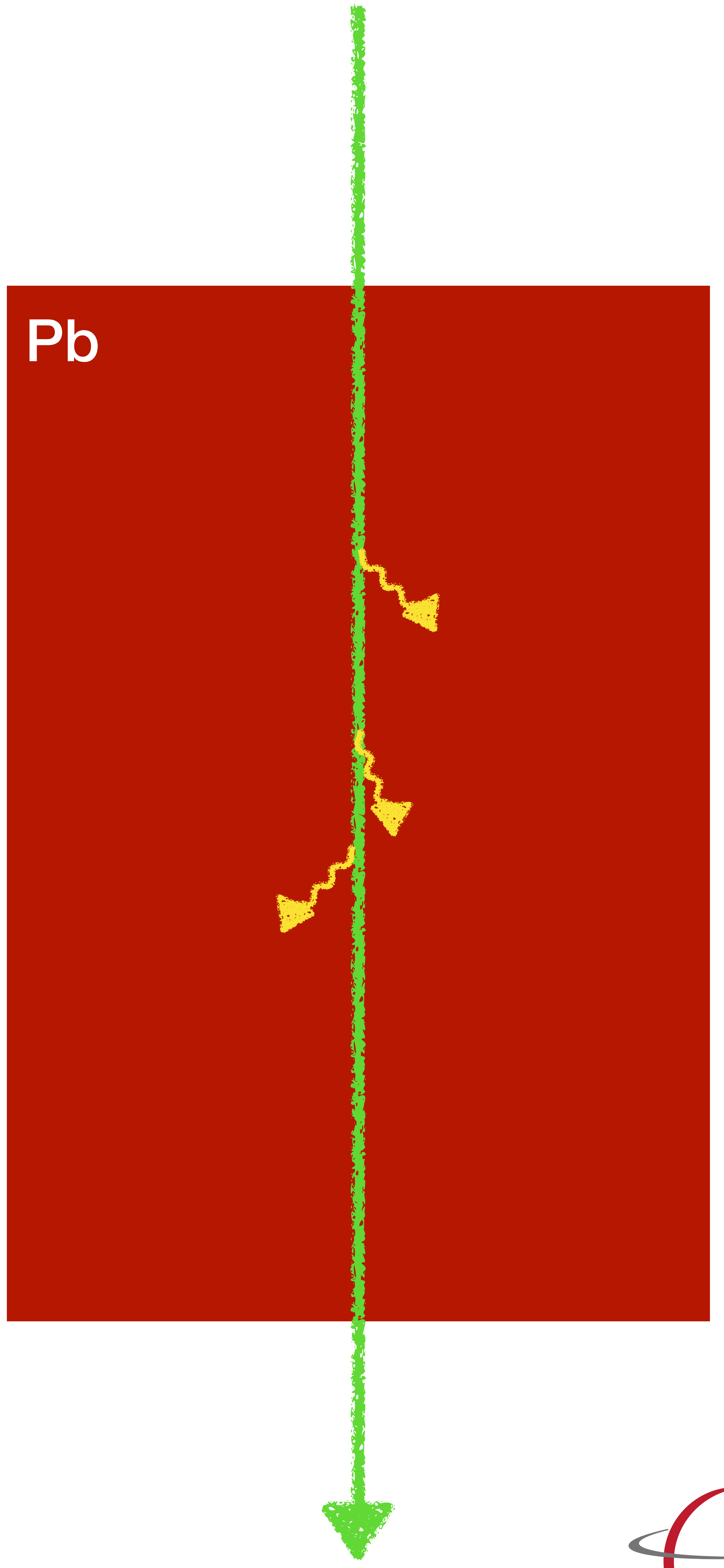
Berger & Seltzer formula is more accurate: $E_c = \dfrac{610 \text{ MeV}}{Z + 1.24}$

Physics of Showers

- A high energy muon $E_\mu > 1\mathrm{GeV}$ hits our Pb block. What happens?
- Basically nothing: The muon (and all heavy particles) act as ~ Minimum-Ionizing Particles. We see a small number of photons.

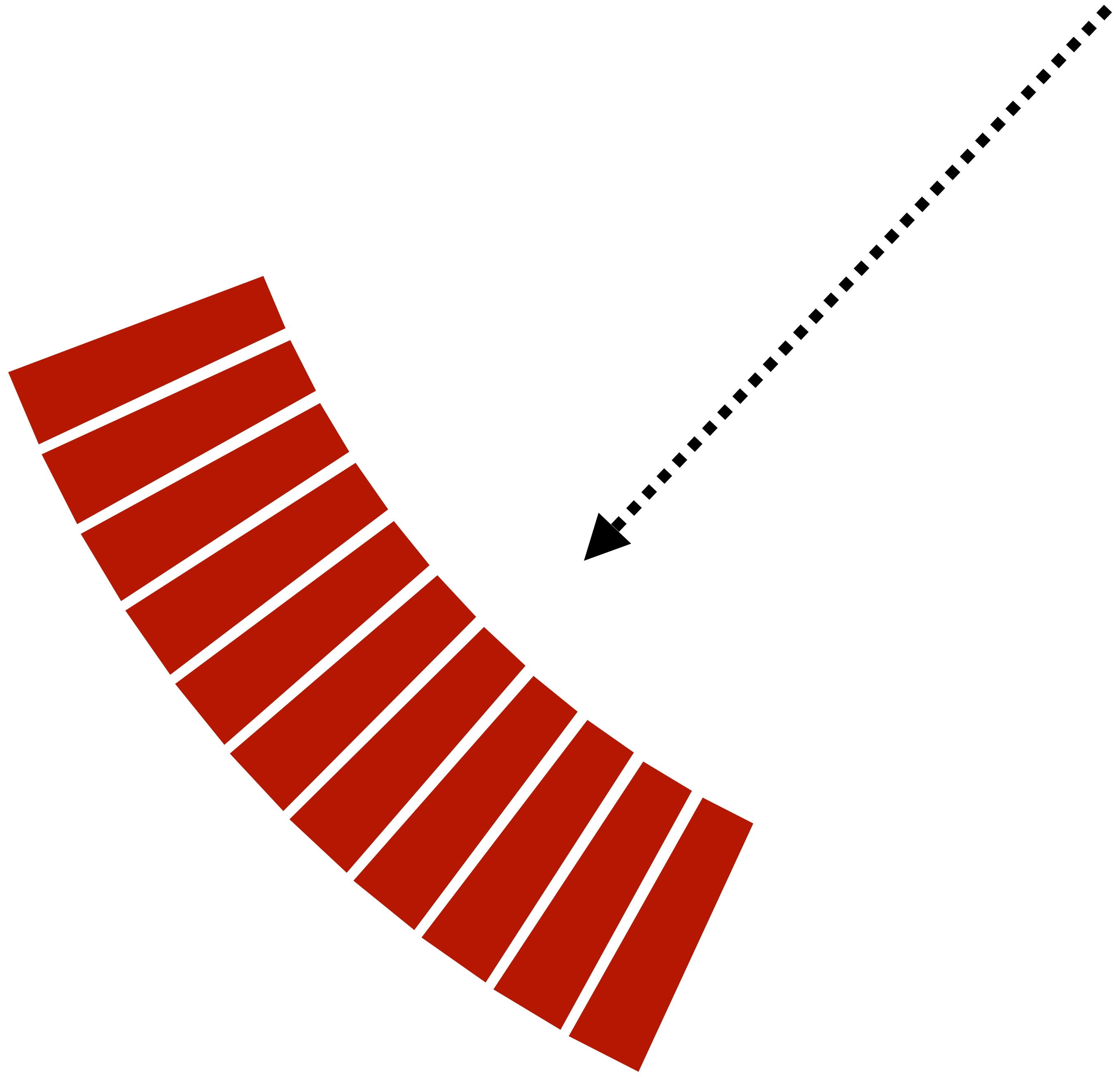


PDG



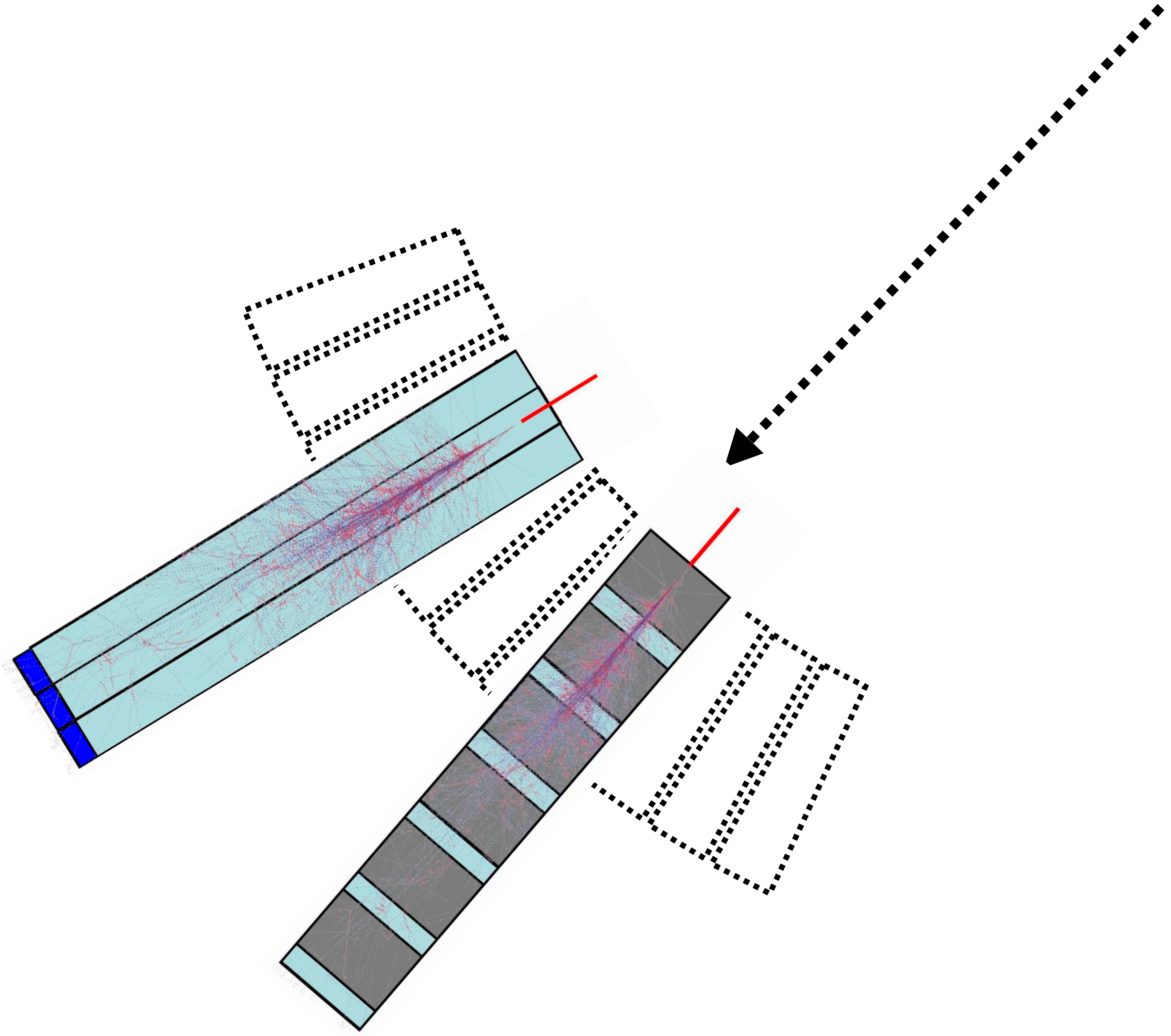
Reading out our Calorimeter

- In principle: Make our calorimeter out of ice, and we could collect the water melted by our electron as it comes to rest in it: $E' \propto V_{H_2O}$
- Okay, so is it made out of lead?
- How do we get a signal proportional to the energy?



Reading out our Calorimeter

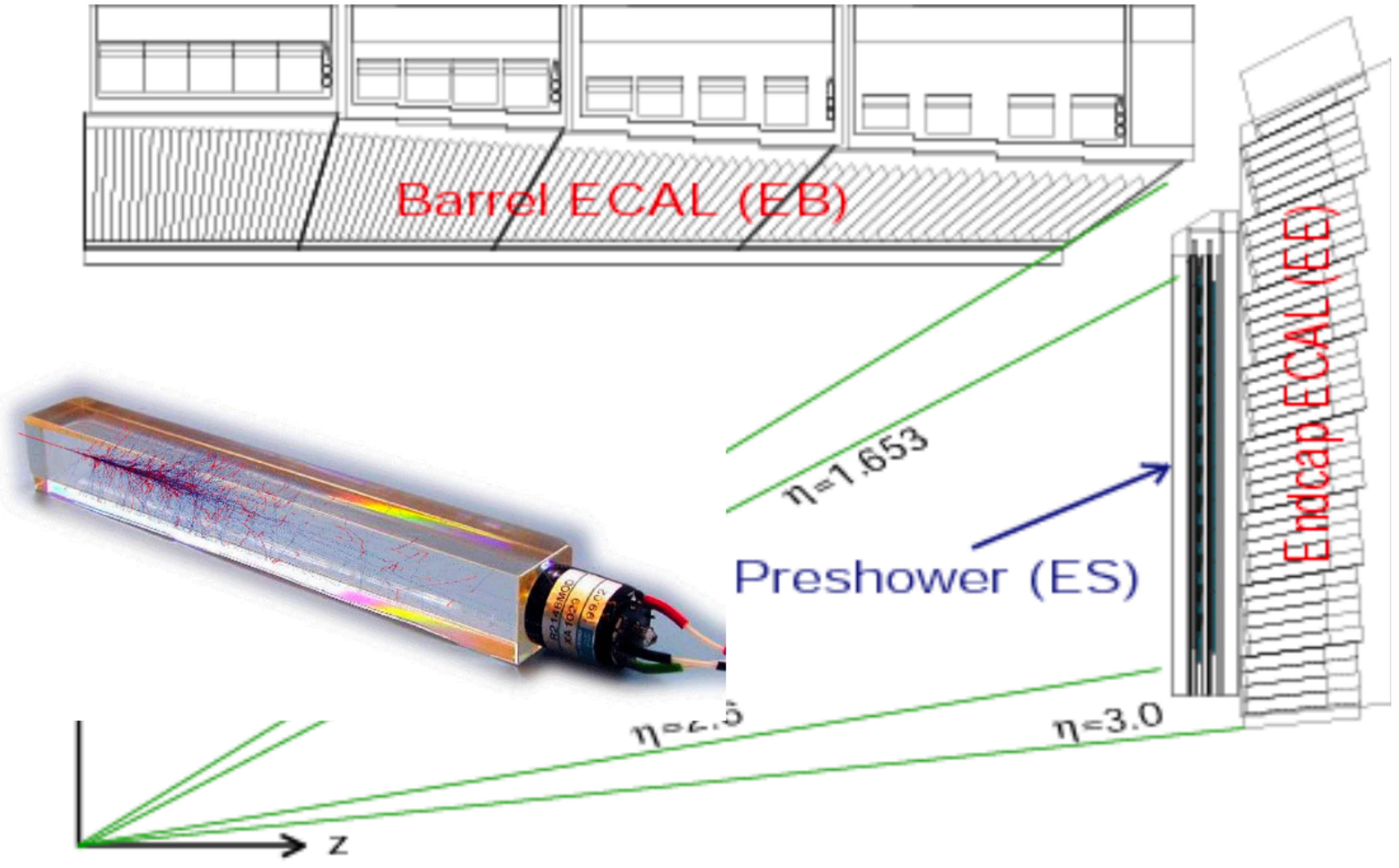
- Recall: The Bremsstrahlung spectrum has $dW/dE_\gamma \approx \text{const}$.
  - Then: We have some high-E photons.
  - Now: We have a HUGE number of low-E photons.
- Usually: Design our calorimeter to be transparent to that light, and get it to a photon detector.
- **Homogeneous calorimeter**: A single medium serves as both absorber and detector. Examples: liquified Xe or Kr, dense crystal scintillators (BGO, PbWO4…), lead-loaded glass.
- **Sampling calorimeters**: Layers of passive absorber (such as Pb, or Cu) alternate with active detector layers such as Si, scintillator or liquid argon



Adapted from Barak Shmookler's CFNS 2025 Summer School slides

Homogeneous Calorimeters

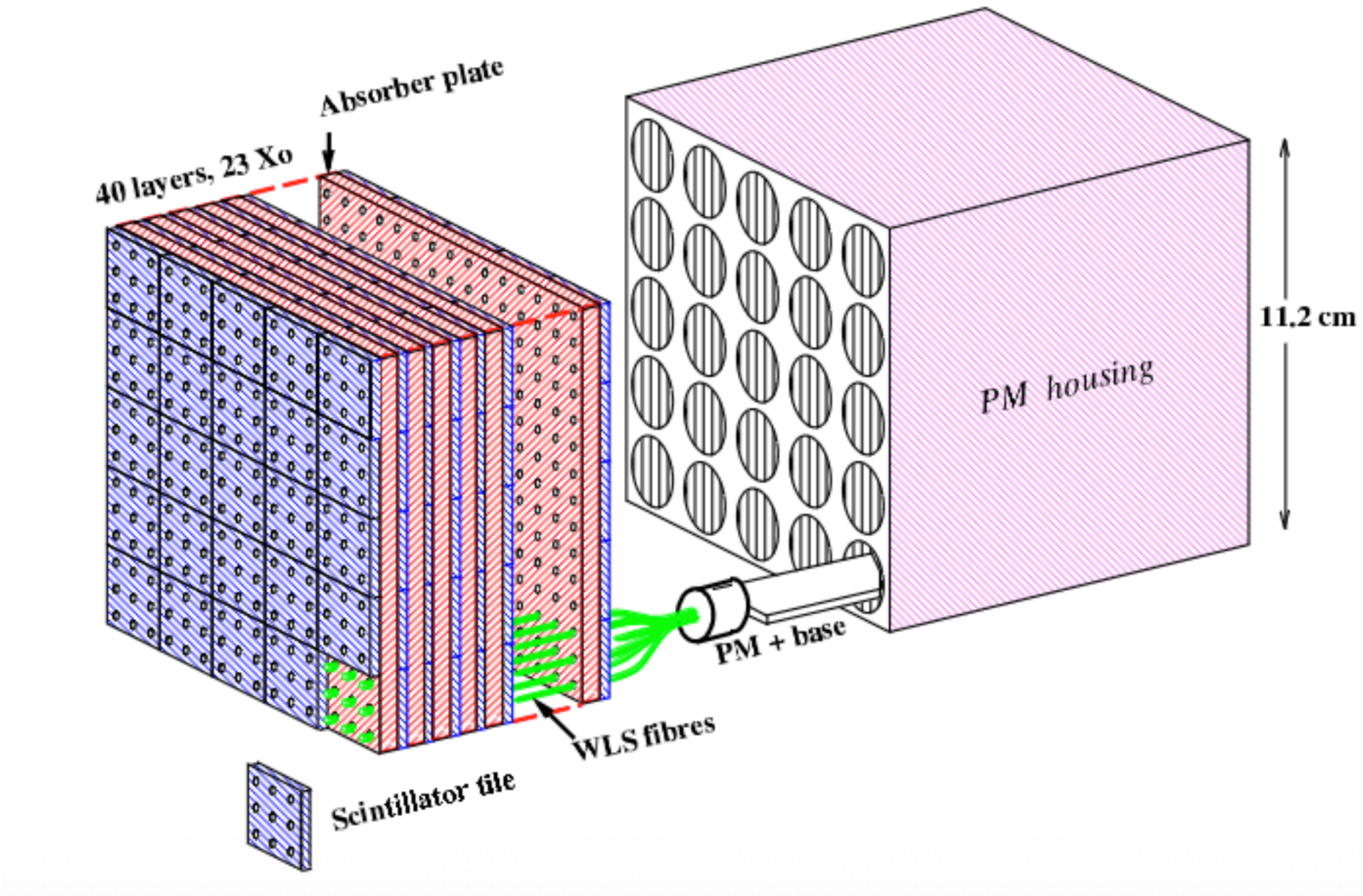
- The energy absorbed and the active medium are the same thing
  - *Example:* CMS uses $PbWO_4$ scintillating crystals (high density, high Z: $X_0 \approx 0.89\ \mathrm{cm}$). Optimized for $H \to \gamma\gamma$
  - Sensitive to entire shower. No energy deposited in dead regions
  - good linearity: measured E scales with incident particle E
- Practical Concerns
  - Expensive. Limited segmentation
- Other examples: Germanium (Ge) or other semiconductor crystals from MeV gamma spectroscopy. *(but these are a bad idea)*



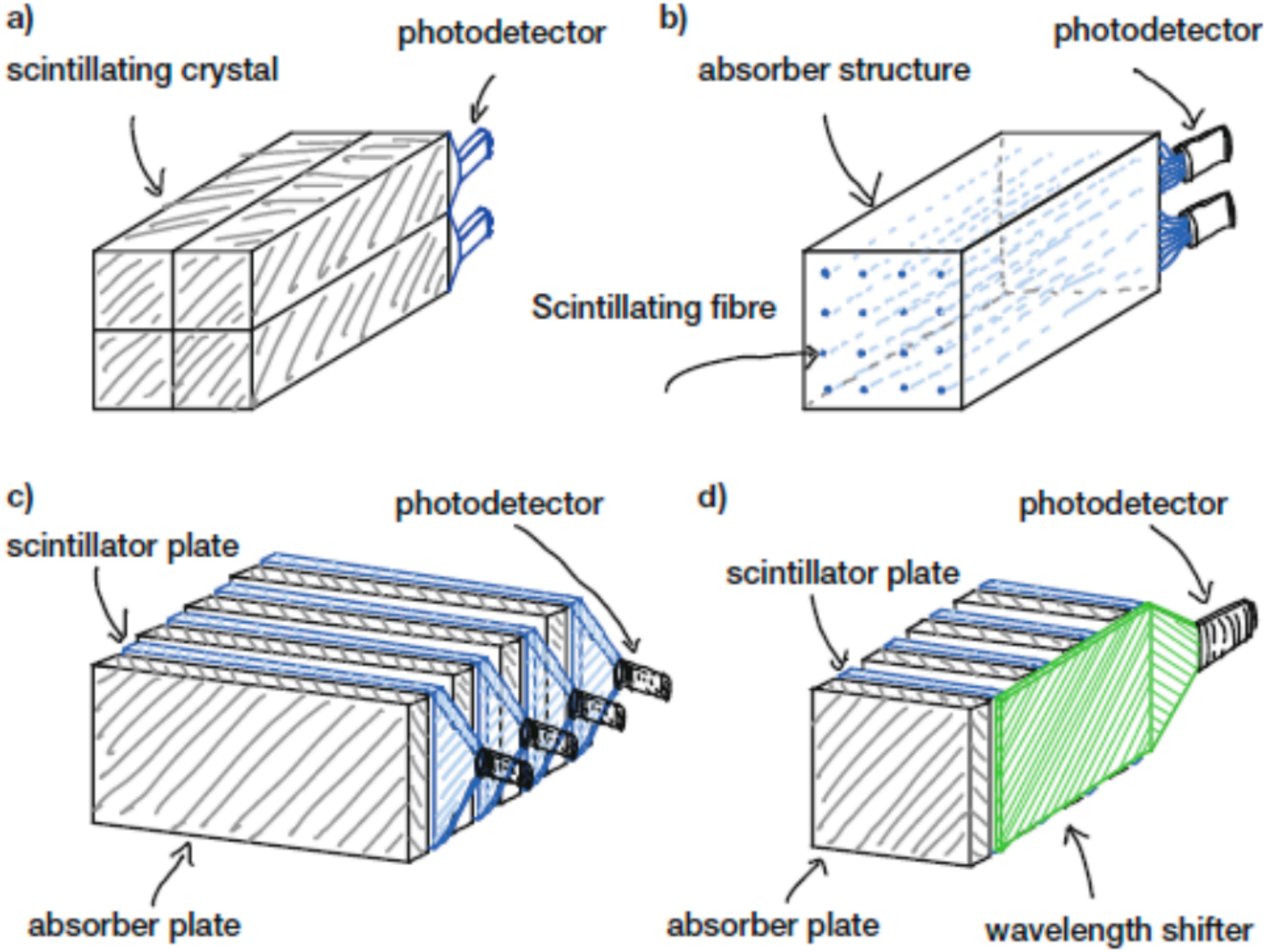
Sampling Calorimeter

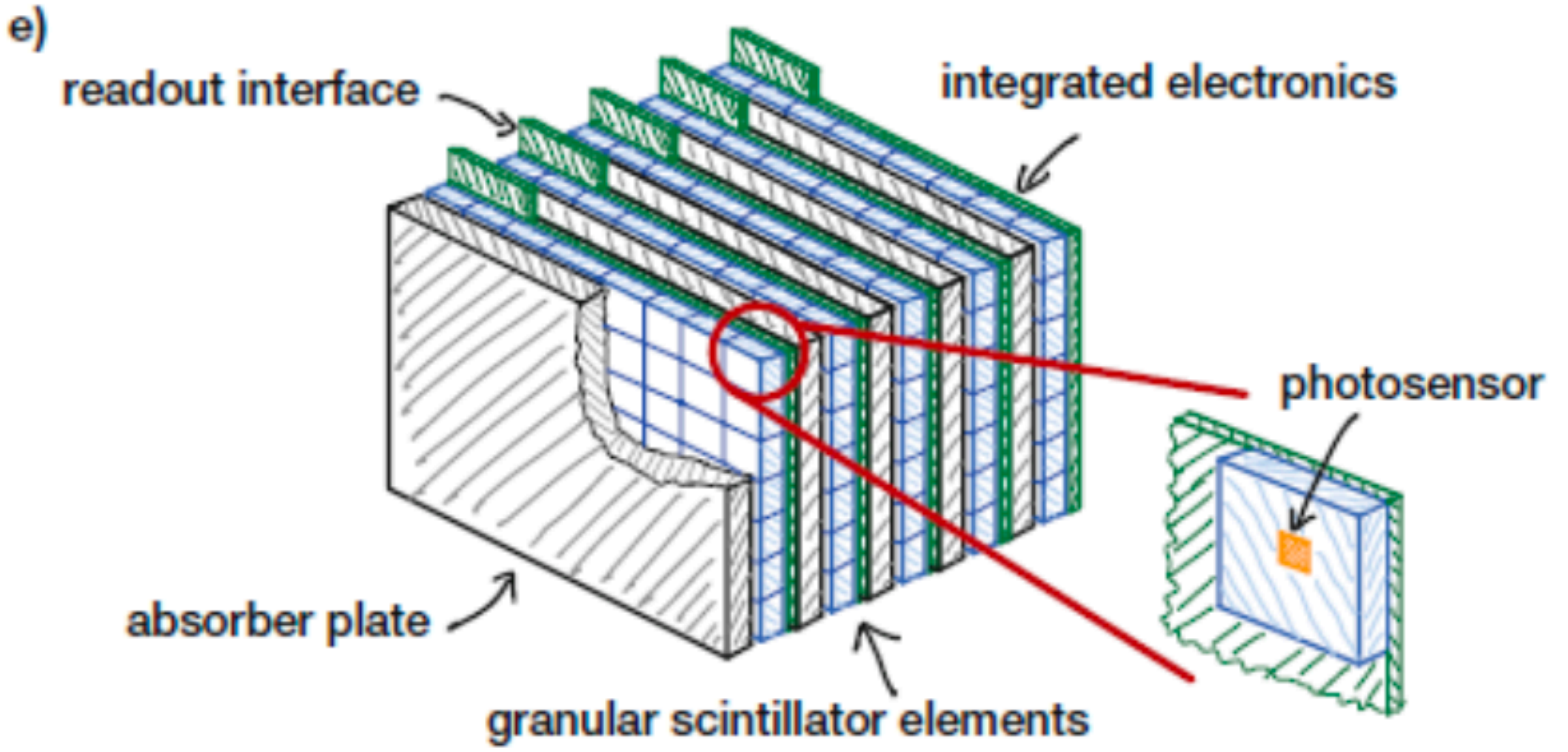
- The absorber and active material are interleaved, usually in layers (Shashlik) or embedded fibers (SPACAL).
    - Absorber: Lead, W, etc (Small X0, dominates shower development)
    - Actice: scintillating plastic (X0 ~10x larger, but produces photons for readout)
    - Sensitive to shower only in active regions: need to correct for sampling fraction.
    - worse linearity: fraction of E sampled might change wrt where shower max occurs. Landau tails from narrow sampling region
- Practical Concerns
    - Cheaper. More segmentation options (long. and trans.)
- Other Examples: ATLAS EMCal, sPHENIX Cals, etc.

HERA-B shashlik ECal



Reading out a Calorimeter



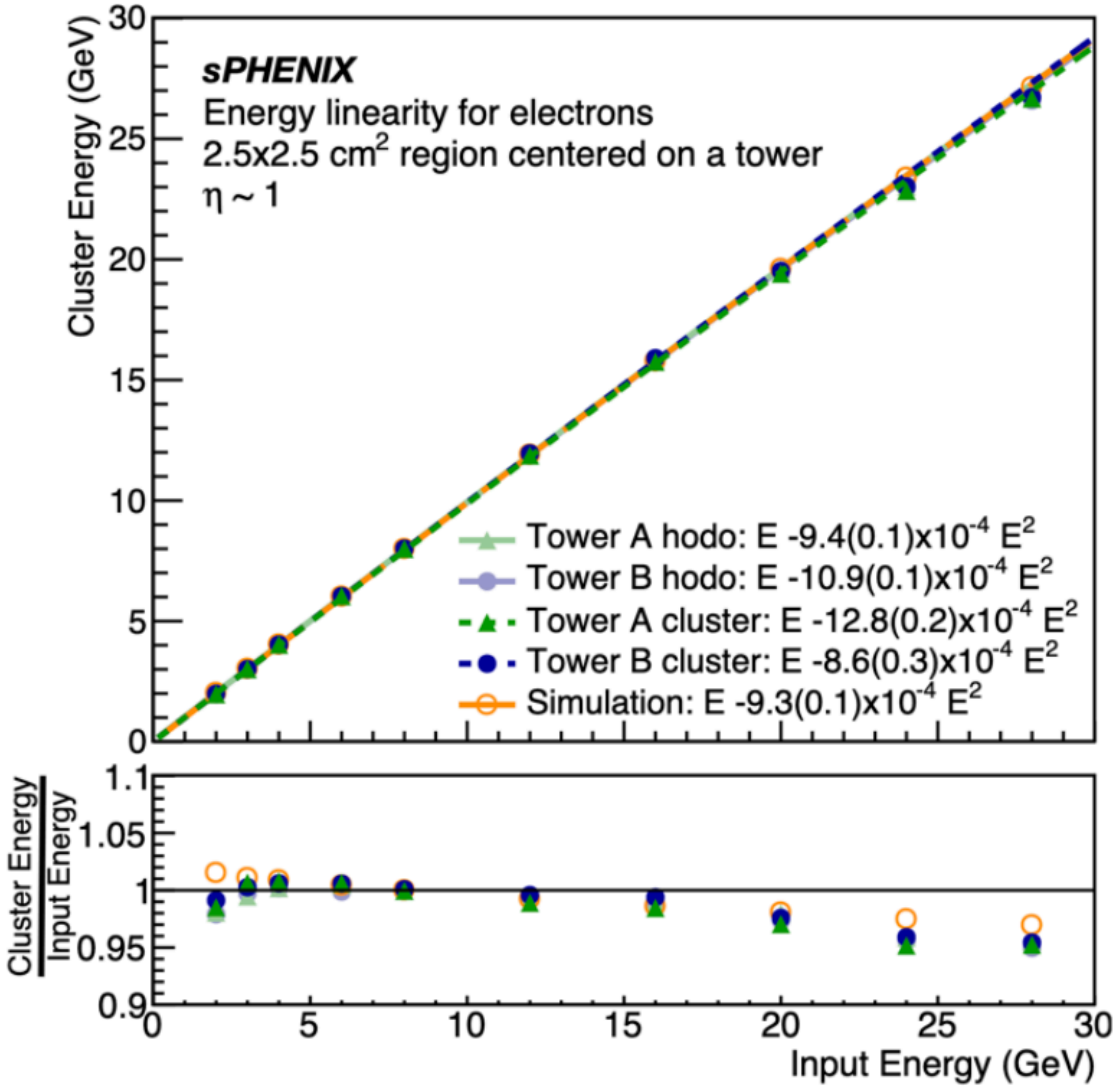


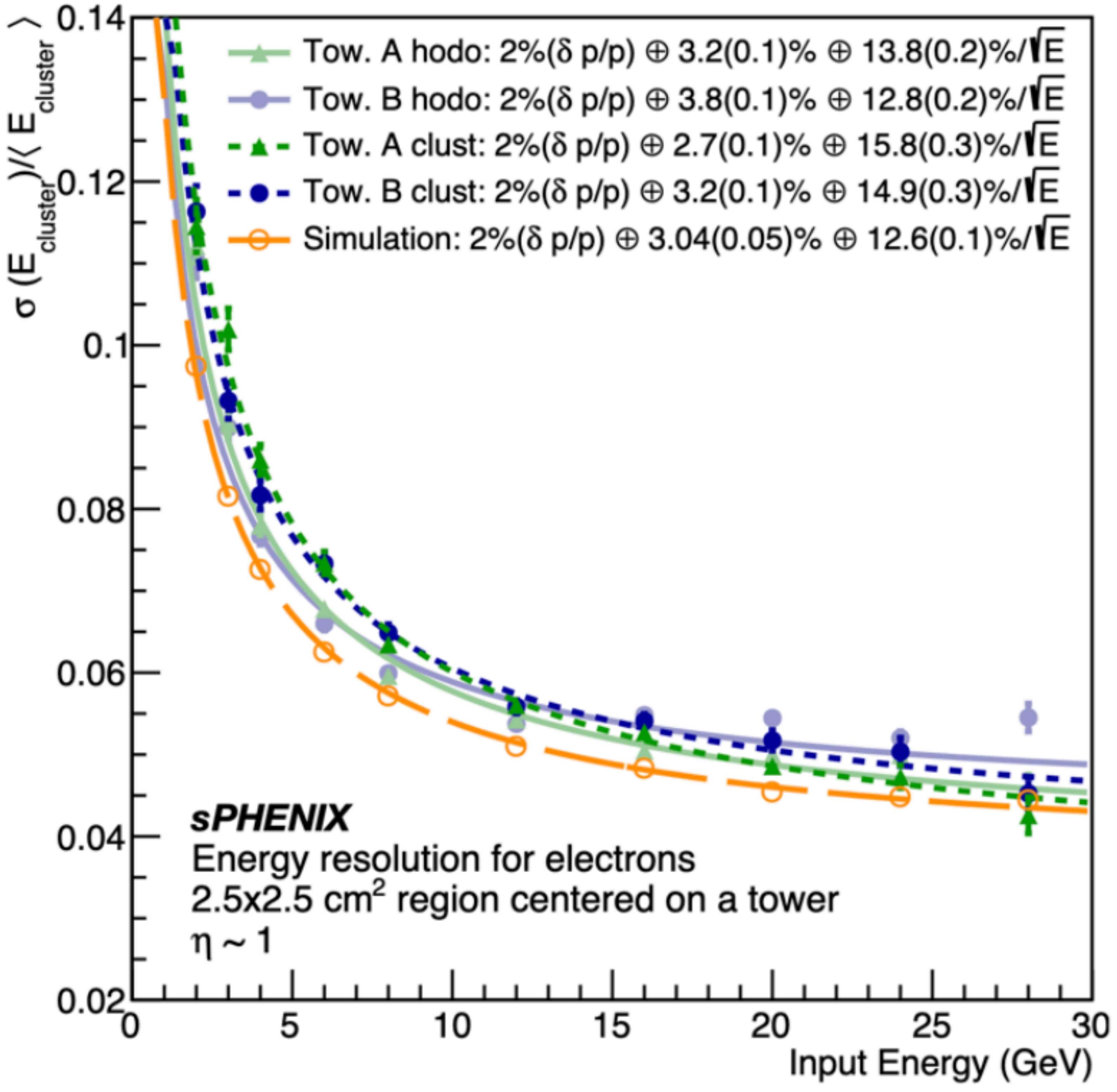
- Remember: Signals have to come out one way or another.
- The more channels we have, the more dead area we have to leave

Calorimeter Resolution

$$\frac{\sigma(E)}{E} = \sqrt{\frac{a^2}{E} + b^2 + \frac{c^2}{E^2}} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

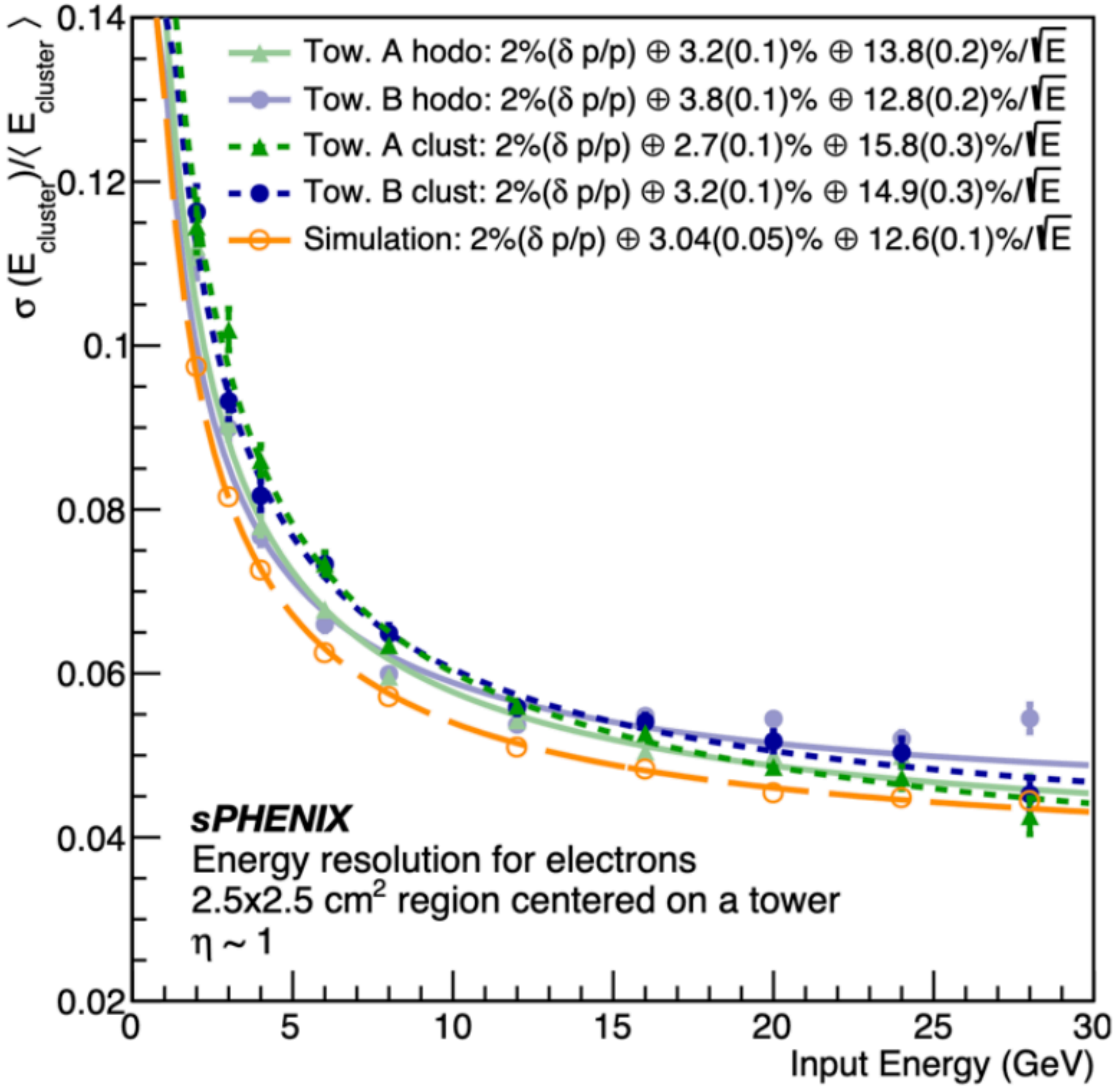
- Different effects have different energy dependence:
- a: Stochastic (intrinsic fluctuations): shower shape, sampling, quantum efficiency at readout, ...
- b: deterministic non-uniformities: dimensional variations, nonlinear readout effects, energy leakage (punch-through), ...
- c: noise: readout electronics, RF pickup, pile-up fluctuations



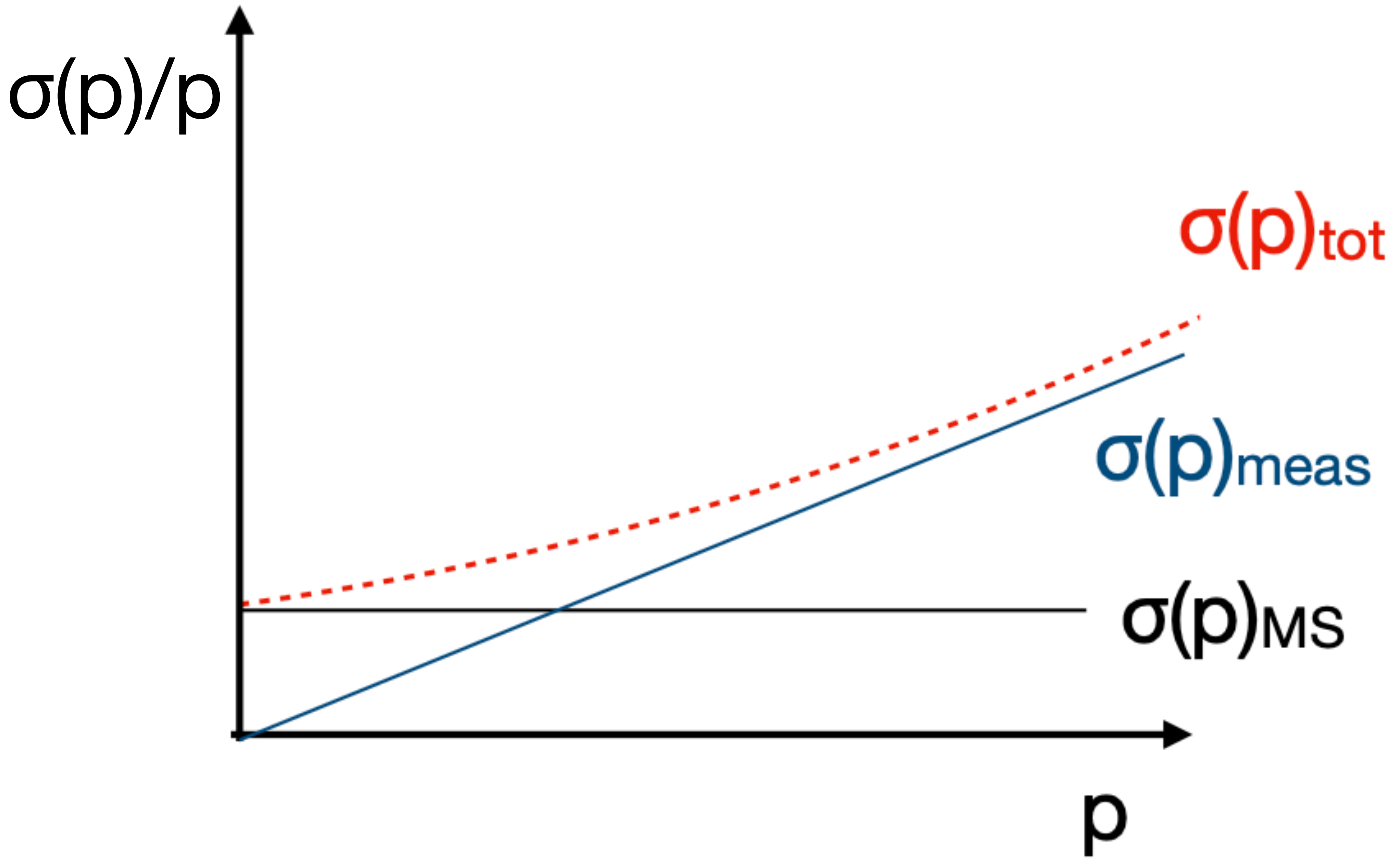


(Tracking Resolution)

EM Calorimeter Resolution vs E

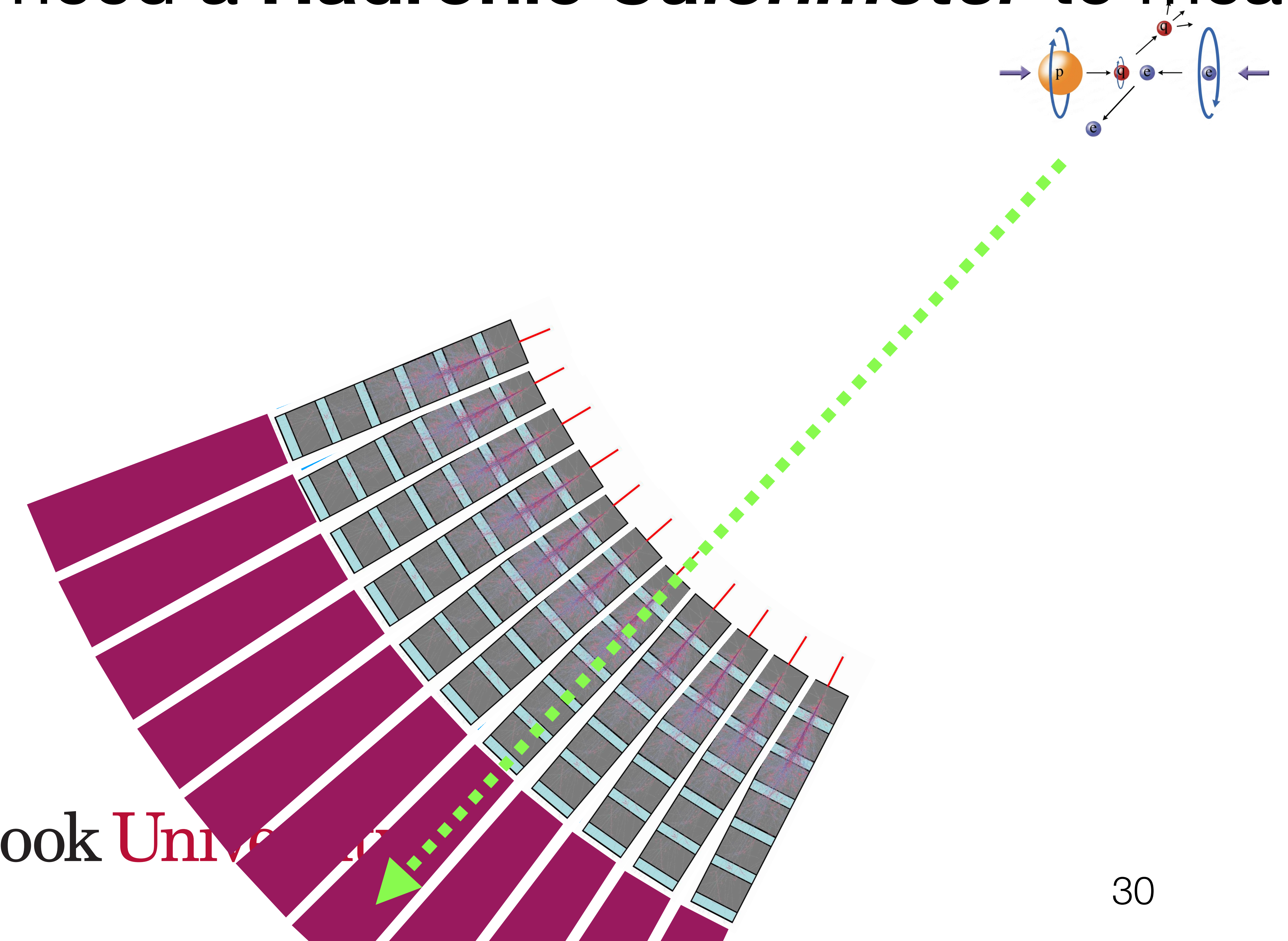


Tracking Resolution vs p



Now What?: Hadronic Version

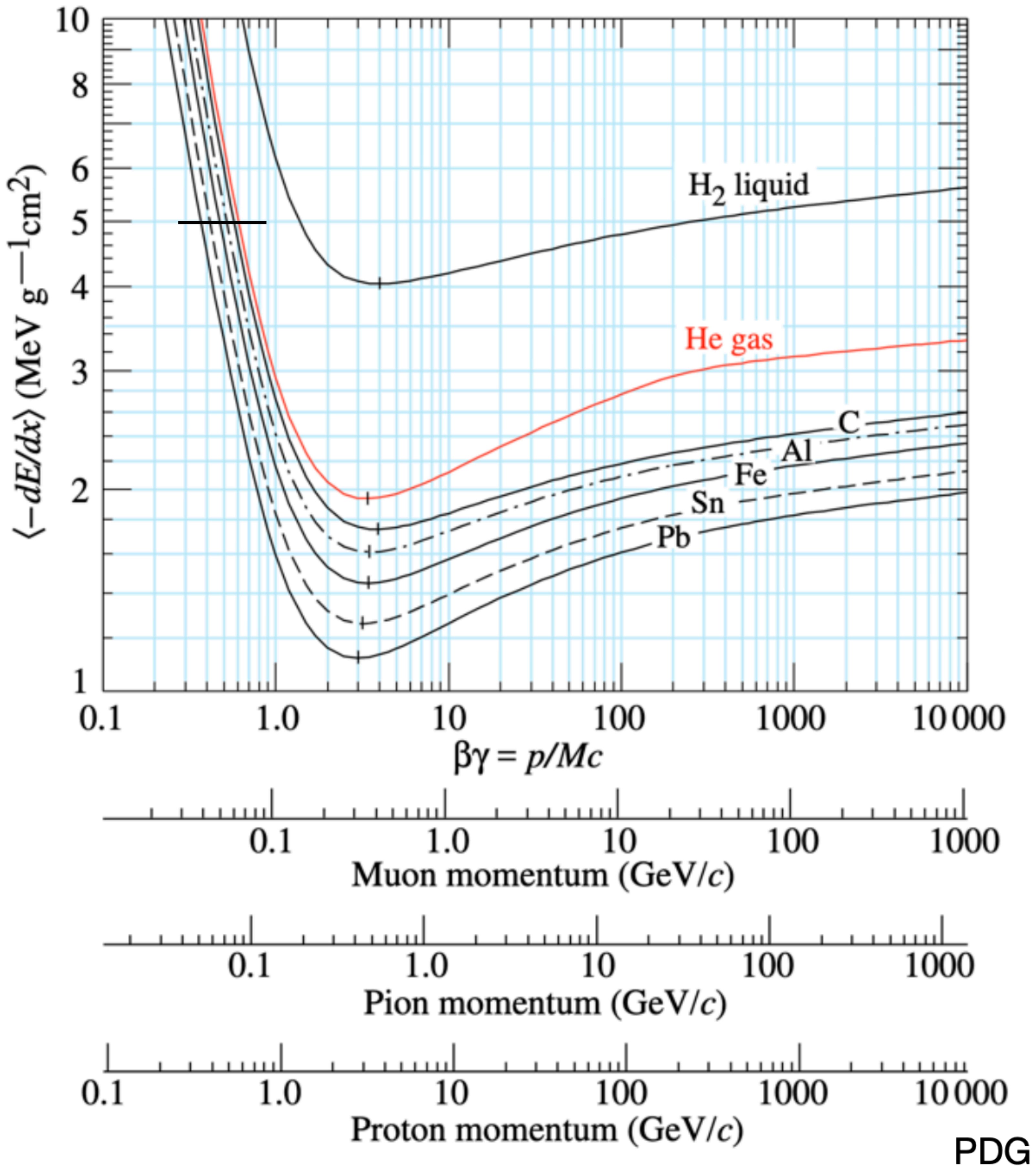
- To reconstruct SIDIS, we need the opening angle **θ** , the e^- energy **E'** , and also need to reconstruct something about the hadronic final state
- But hadrons don't deposit much E in an EM Calorimter!
- We need a **Hadronic *Calorimeter*** to measure their energy.



Caution: Dramatic oversimplification

Physics of Hadronic Showers

- Like a photon, a hadron deposits ~no energy until it interacts.
- Photon: EM interaction
- Hadron: Nuclear interaction



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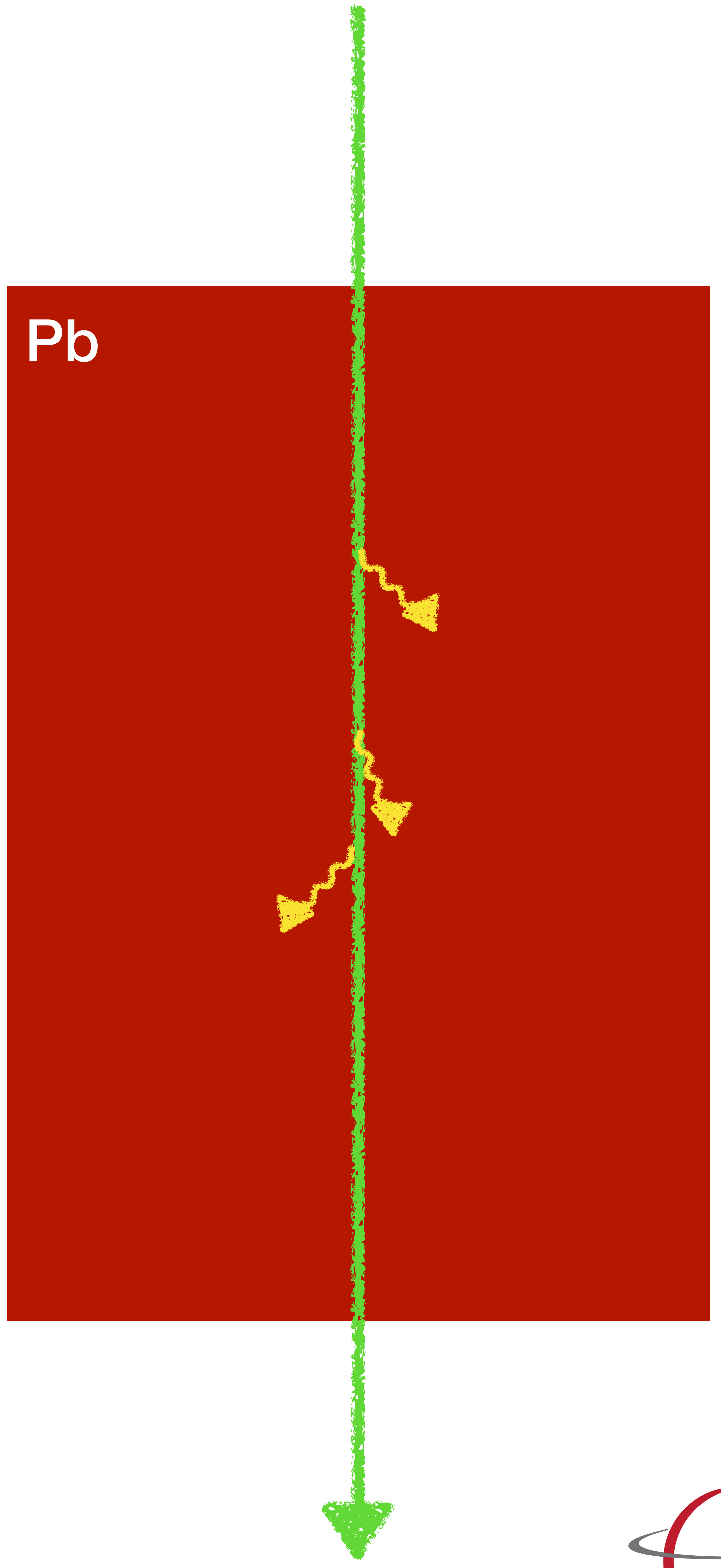


Hadronic Interactions

Hadronic interaction:

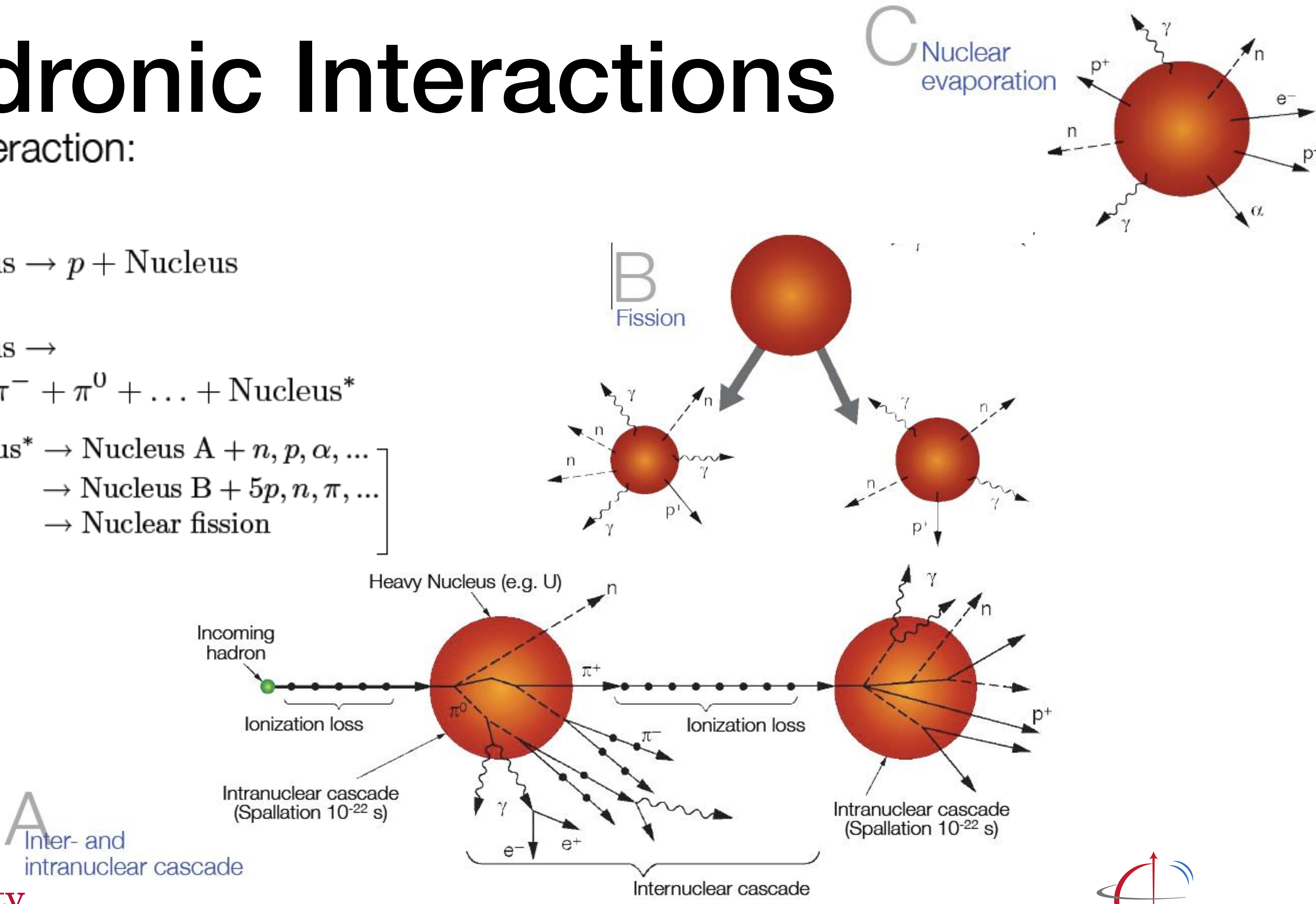
Elastic:

$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

Inelastic:

$$p + \text{Nucleus} \rightarrow$$
$$\pi^+ + \pi^- + \pi^0 + \ldots + \text{Nucleus}^*$$

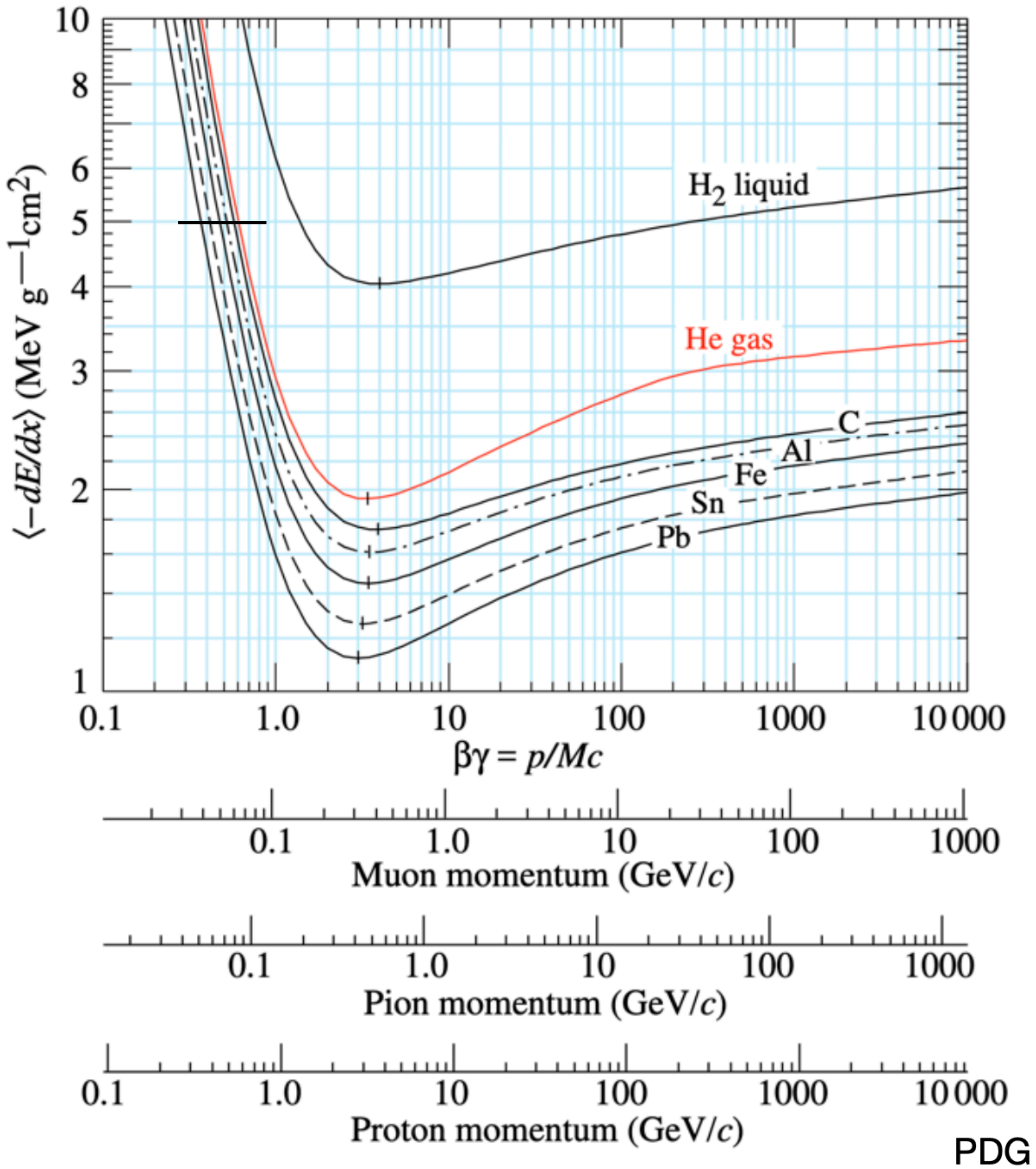
$$\left[\begin{array}{ll} \text{Nucleus}^* & \rightarrow \text{Nucleus A} + n, p, \alpha, \ldots \\ & \rightarrow \text{Nucleus B} + 5p, n, \pi, \ldots \\ & \rightarrow \text{Nuclear fission} \end{array}\right]$$



Adapted from Barak Shmookler's CFNS 2025 Summer School slides

Physics of Hadronic Showers

- Nuclear interaction length $\lambda_{\text{int}} \approx 35\ \text{g cm}^2 \cdot A^{1/3}$
- After each spallation event, some fraction will convert into EM particles (notably π⁰)



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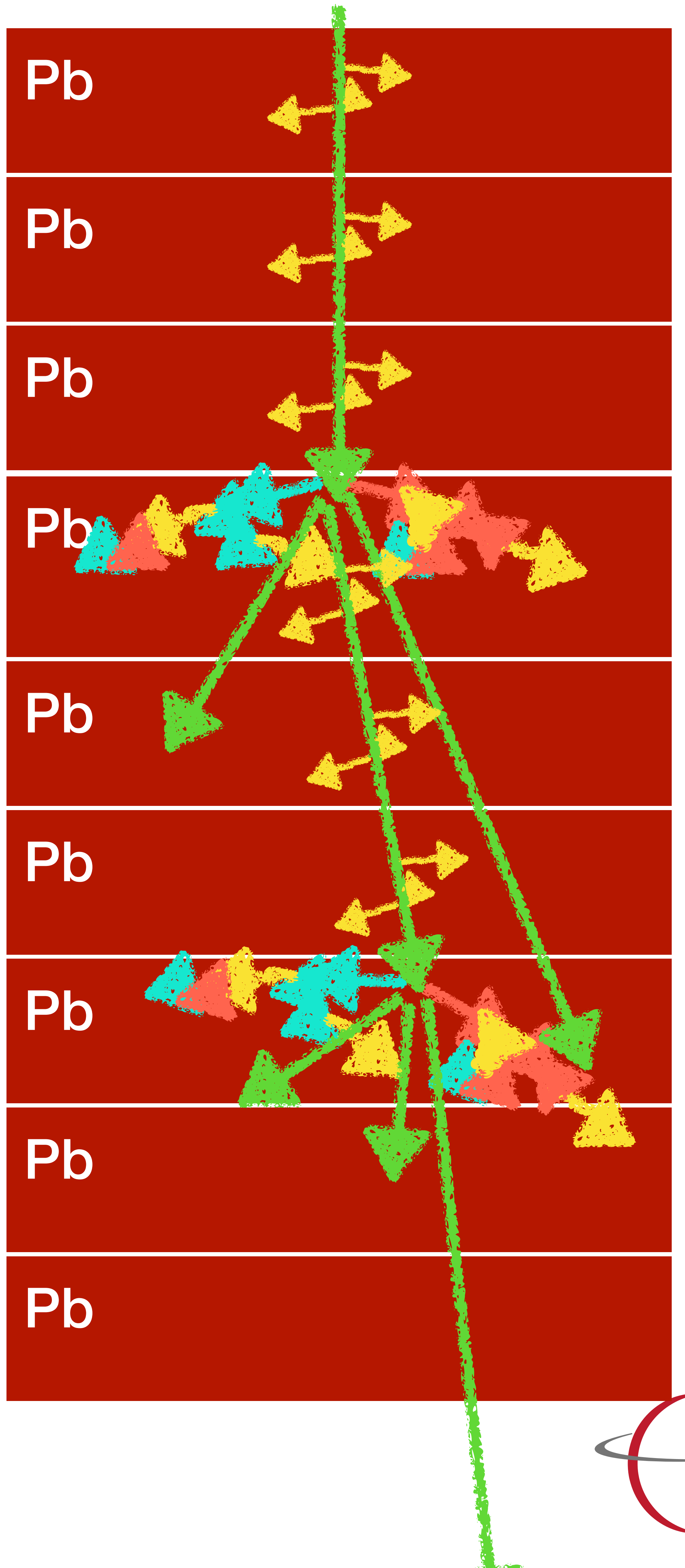

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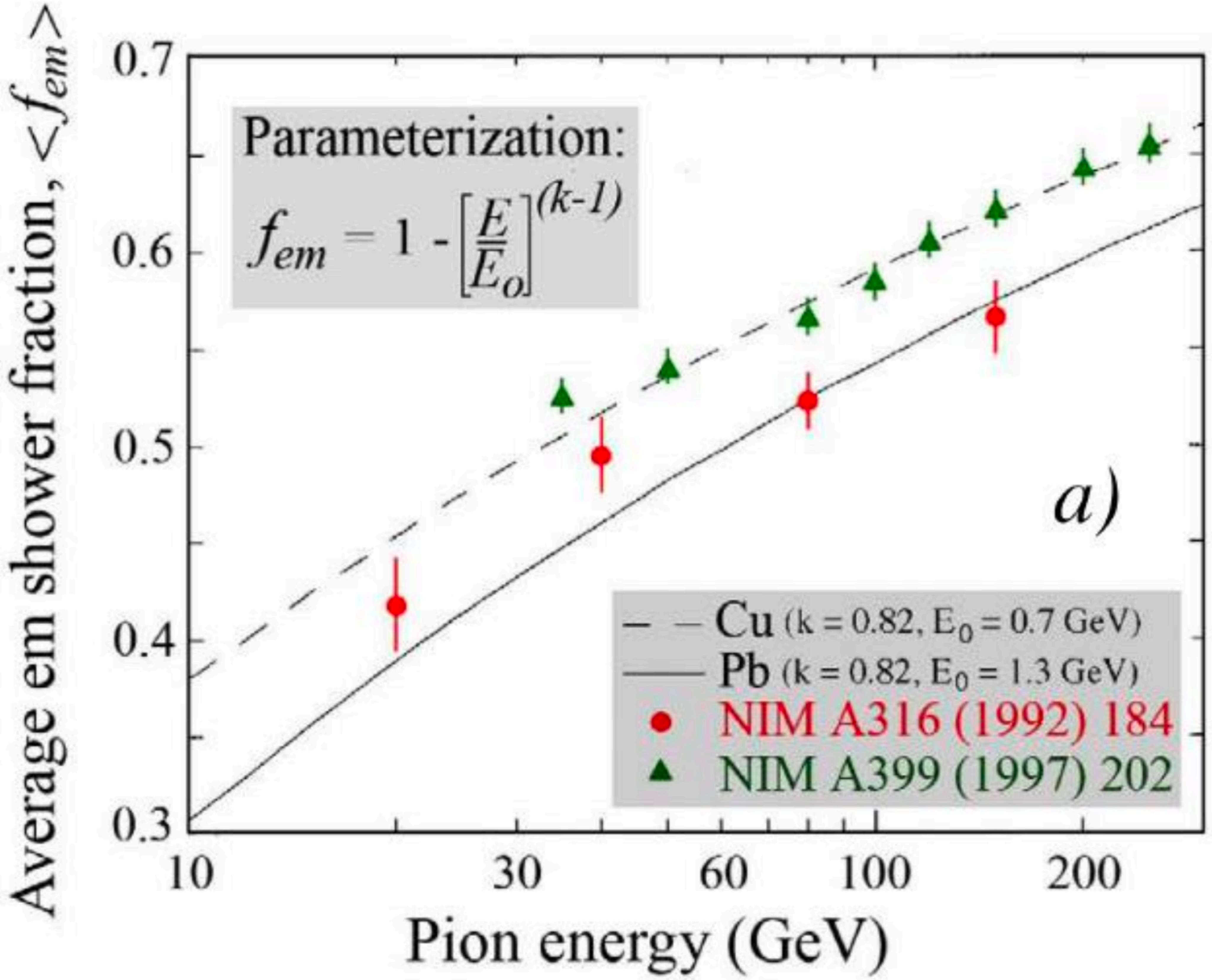
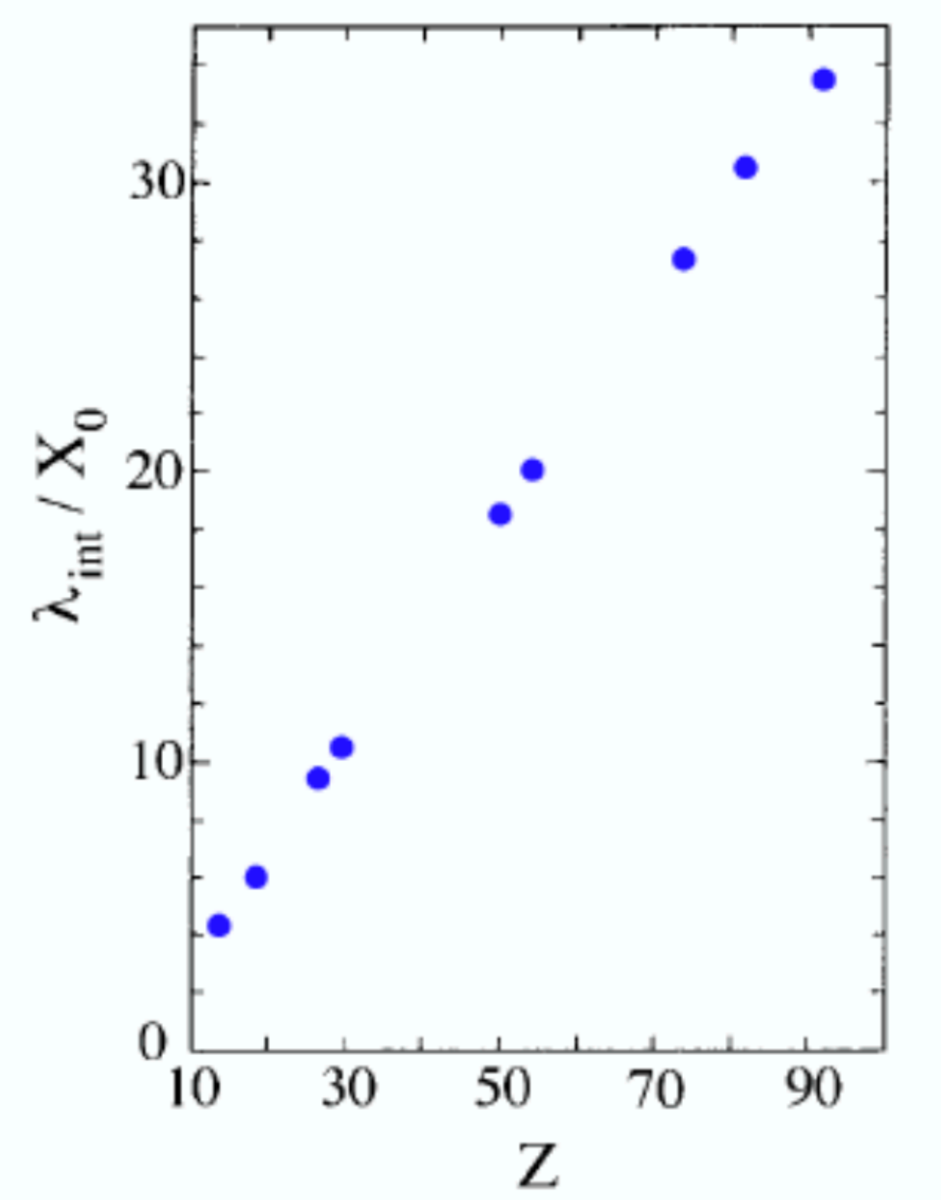
Electromagnetic Component

- Particle multiplicity scales with energy and particle type:
  - $\pi^{\pm}$: 1/3 of shower particles are π^0 (from charge-exchange). If this happens early, EM shower will dominate E loss
  - *p*: fewer neutral π^0 produced due to baryon number conservation
- **Invisible energy:**
  - nuclear binding energy
  - neutrons from evaporation
  - nuclear recoils below the scintillation sensitivity

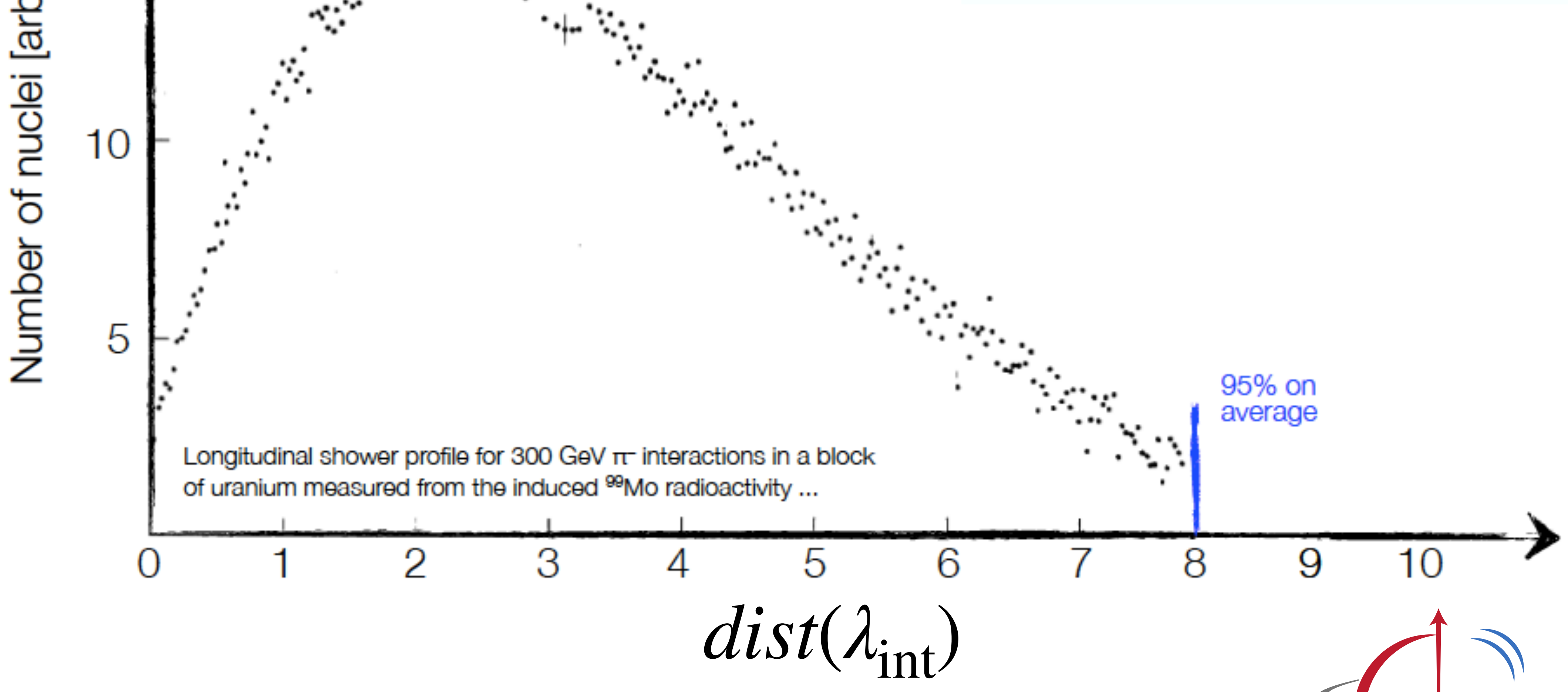


Hadronic Shower Shape

- Structure analogous to EM Shower (but bigger and more variation):
  - Interaction length: $\lambda_{\text{int}} = (35\ \text{g cm}^{-2}) \cdot A^{1/3}$
  - Shower max: $t_{\max} \approx 0.2 \cdot \ln(E_0/\text{GeV}) + 0.7$
  - Containment:
    - longitudinal: (6-9 lengths) $L(95\%) = (t_{\max} + 2.5(E/\text{GeV})^{0.3}) \cdot \lambda_{\text{int}}$
    - radius: $R(95\%) = \lambda_{\text{int}}$



300GeV Pion in U block



95% on average

Longitudinal shower profile for 300 GeV π^- interactions in a block of uranium measured from the induced ^{99}Mo radioactivity ...

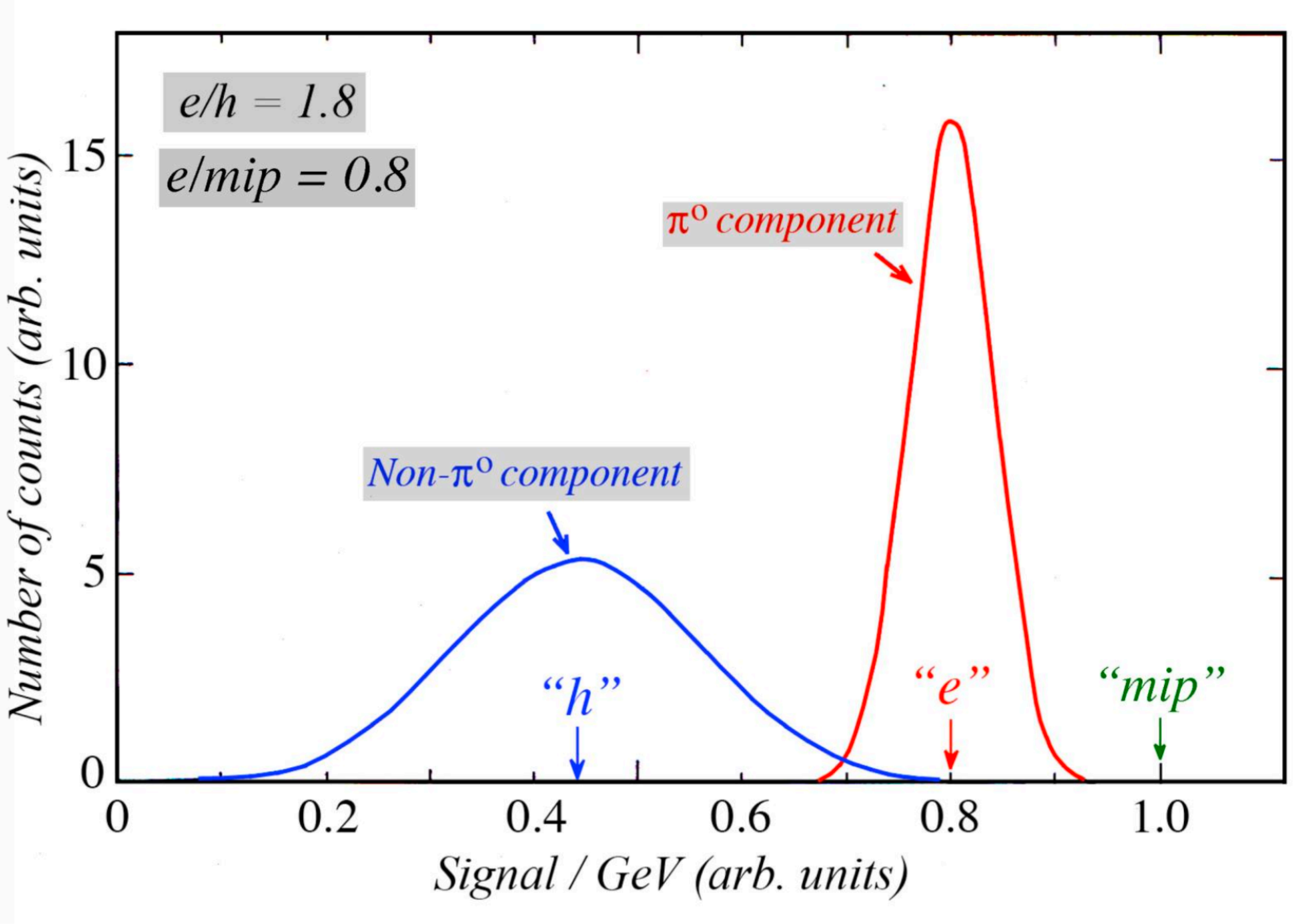
HCal Response

- for π-initiated shower

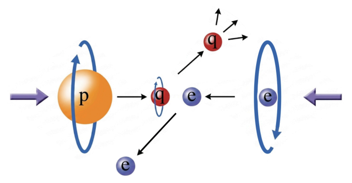
  $$R_\pi(E) = R_e(f_{EM}E) + R_h((1-f_{EM})E)$$

  or: $\pi = f_{EM}e + (1-f_{EM})h$
- So the response to an e vs a π is:

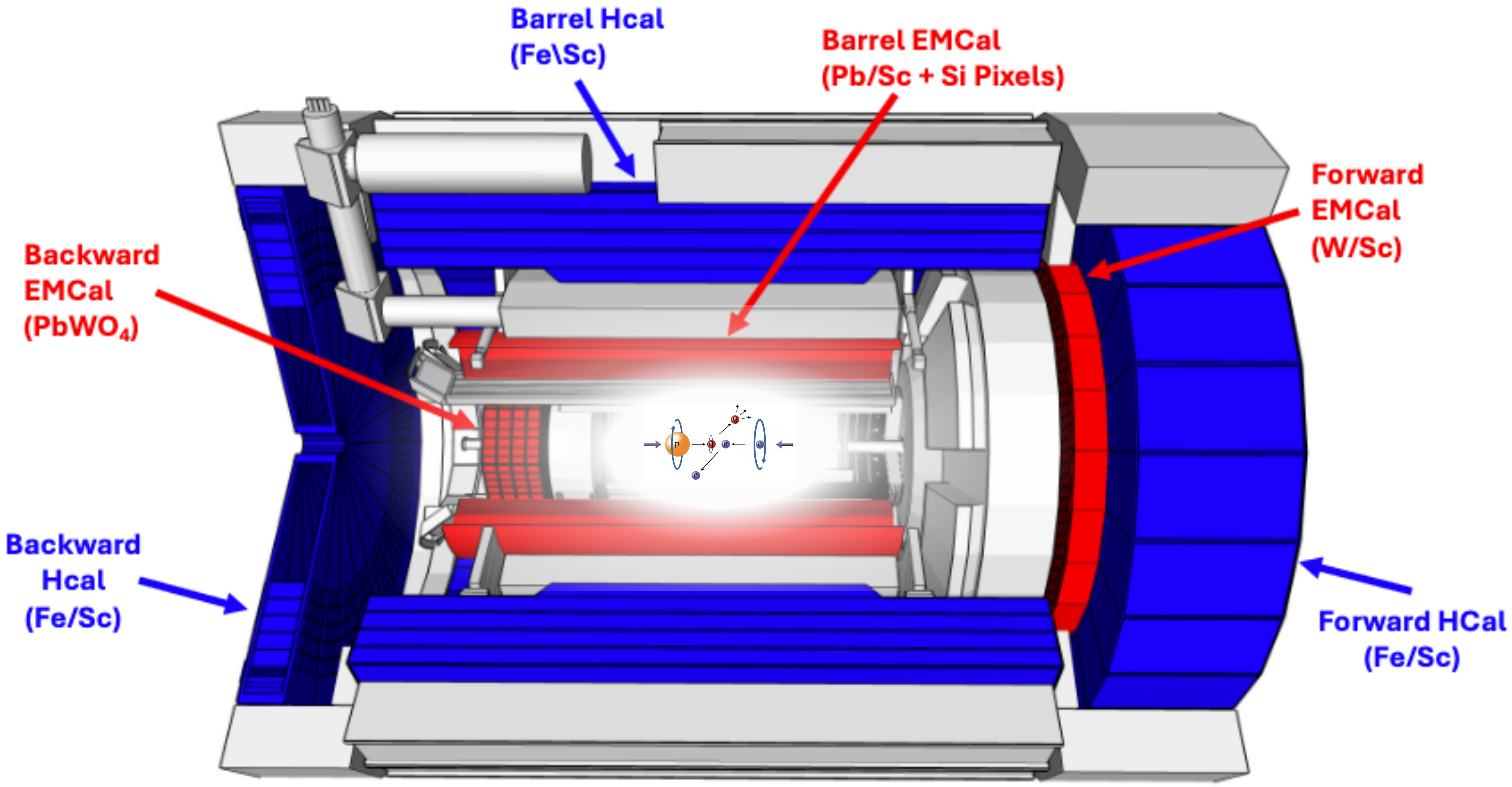
  $$\frac{e}{\pi} = \frac{e}{f_{EM}e + (1-f_{EM})h} = \frac{e}{h}\frac{1}{1+f_{EM}\left(e/h-1\right)}$$
- e/h is ~ constant, but f changes with E: intrinsic hadronic response is nonlinear (unless we *compensate*
- Large fluctuations: ~50% stochastic term is typical.



Now What?



Calorimeters at ePIC



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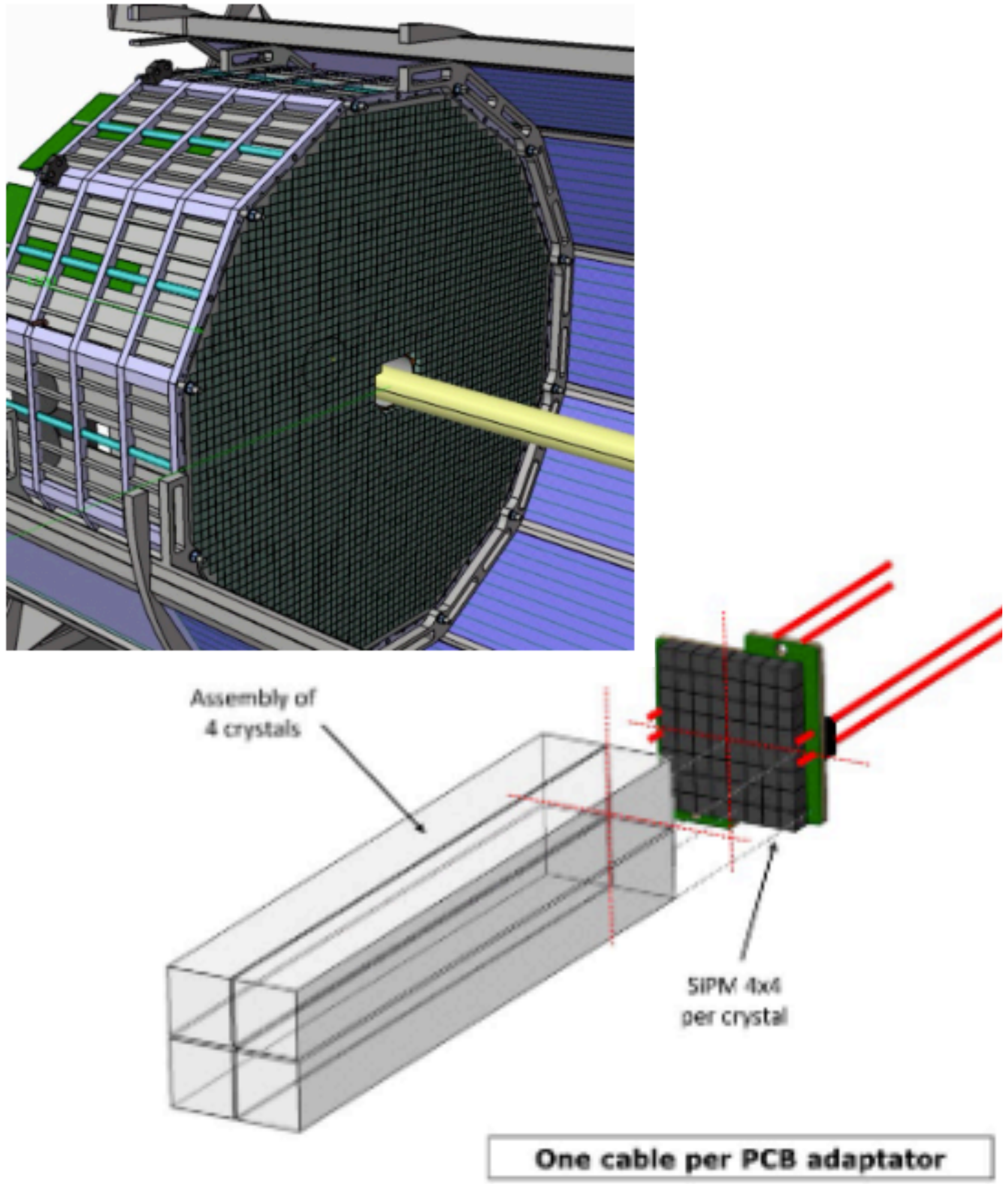
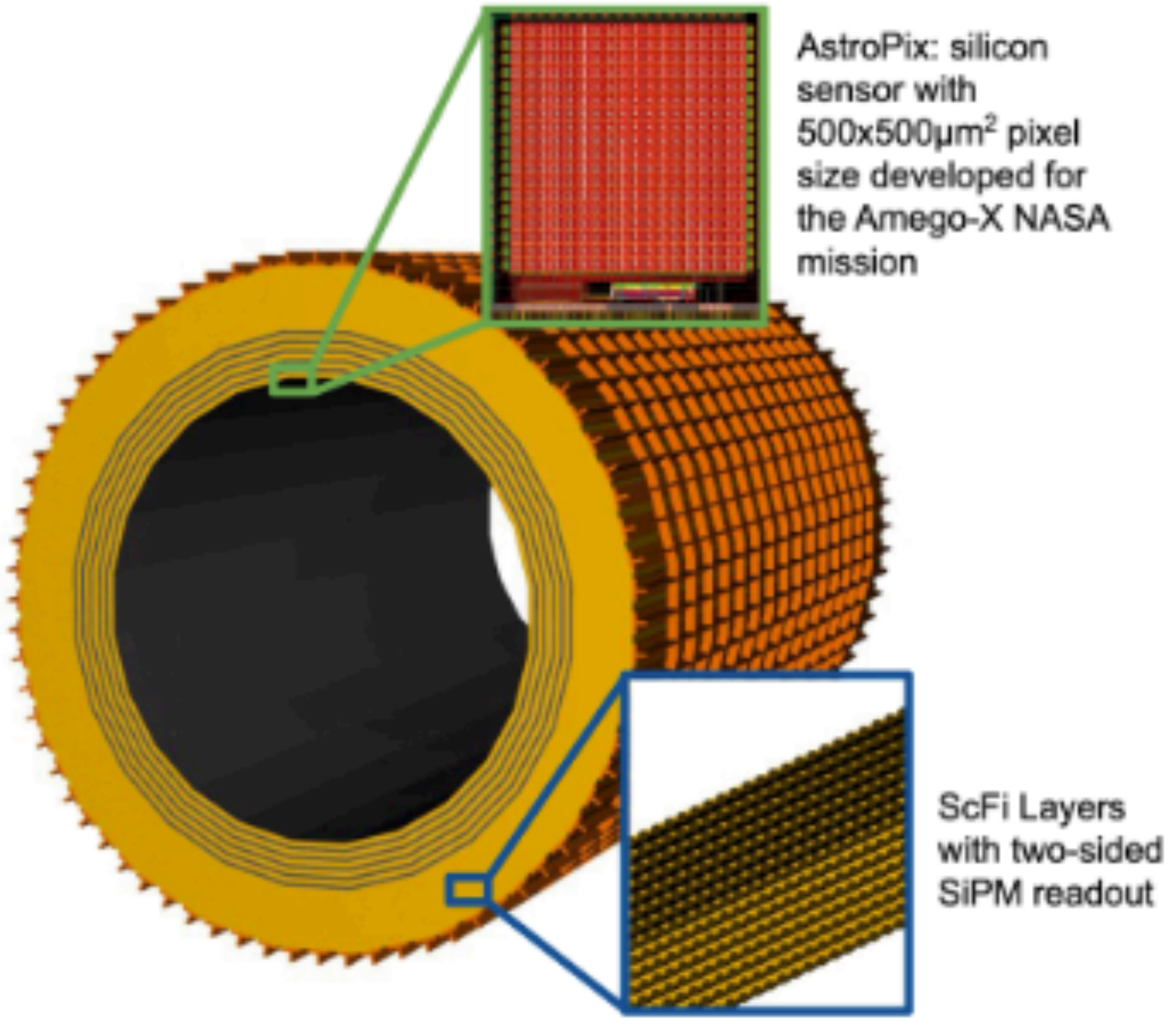
Backward EMCal

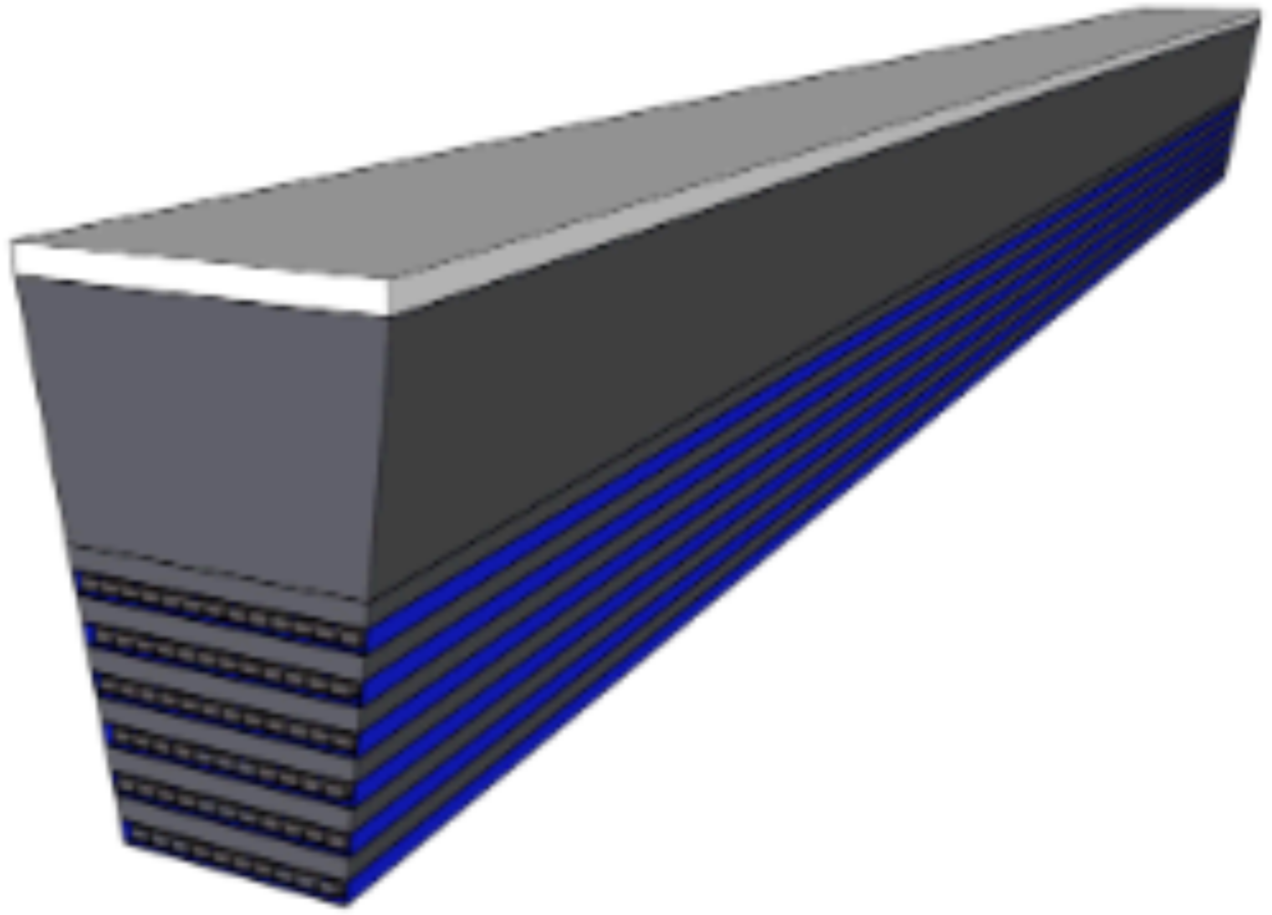
- **Task:** Precision measurement of low-Q^2 electron backward angles
  - e-pi misidentification rate of 10^{-4} or better.
- **Design**: $2 \times 2 \times 20 \, cm^3$ array of $PbWO_4$ crystals, ~22 X_0 at normal incidence.
- $-3.5 < \eta < -1.2$
- **Readout**: streaming SiPM
- **Resolution:** $\approx \frac{2\,\%}{\sqrt{E}} \oplus 3\,\%$



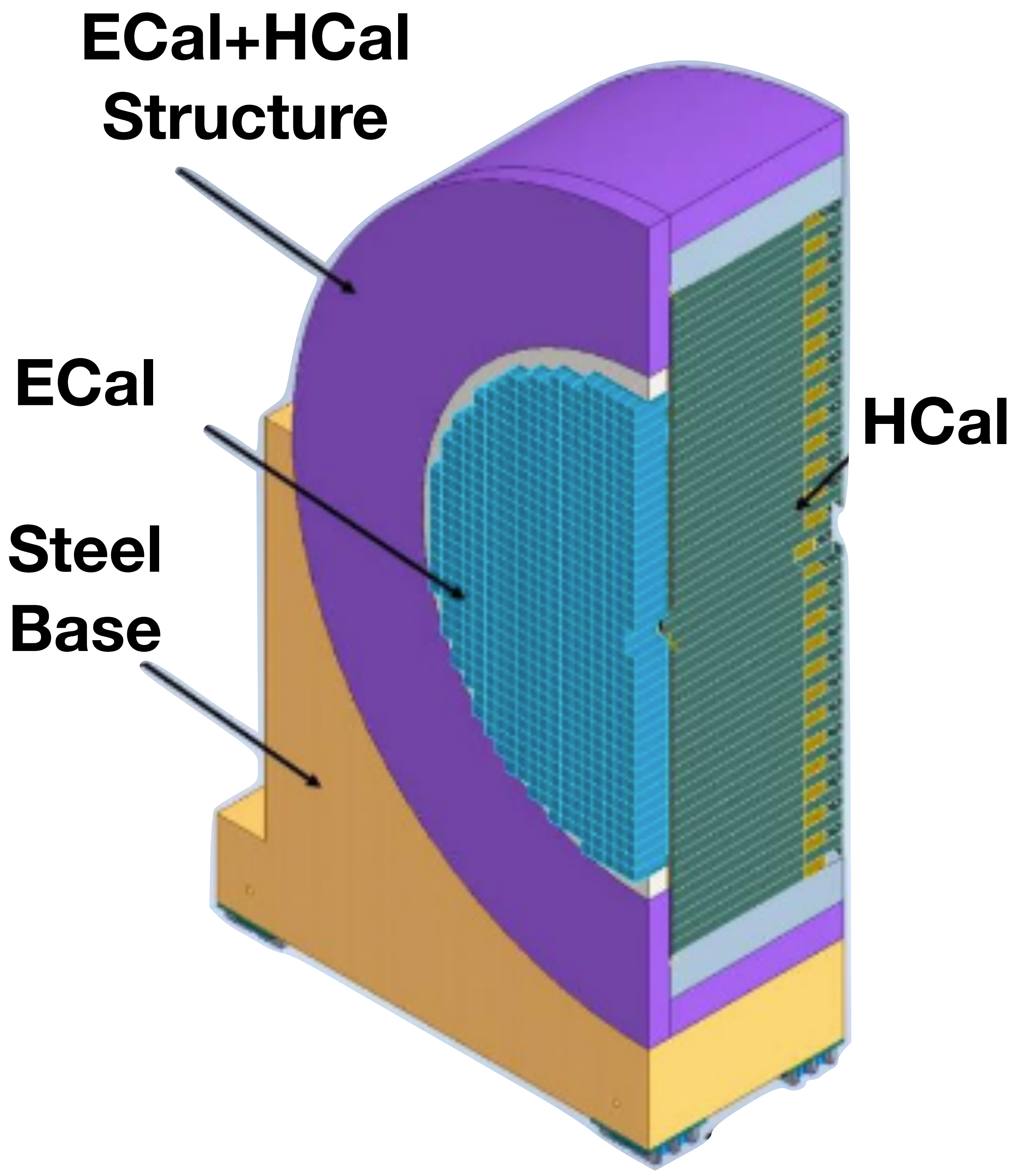
Barrel EMCal

- **Task:** Precision measurement of low-Q^2 electron backward angles
    - distinguish γ and $\pi^0 \rightarrow \gamma\gamma$ for DVCS program.
- **Design**: Pb/SciFi side-sampling matrix, $17X_0$ at $\eta = 0$.
    - double-ended uses timing to resolve position.
    - Interleaved with 4-6 layers of AstroPix Silicon MAPS sensors 500x500um^2 to image the start of the EM shower
- $-1.7 < \eta < 1.3$
- **Readout**: double-ended SiPM
- **Resolution**: $\approx \frac{5\,\%}{\sqrt{E}} \oplus 1\,\%$

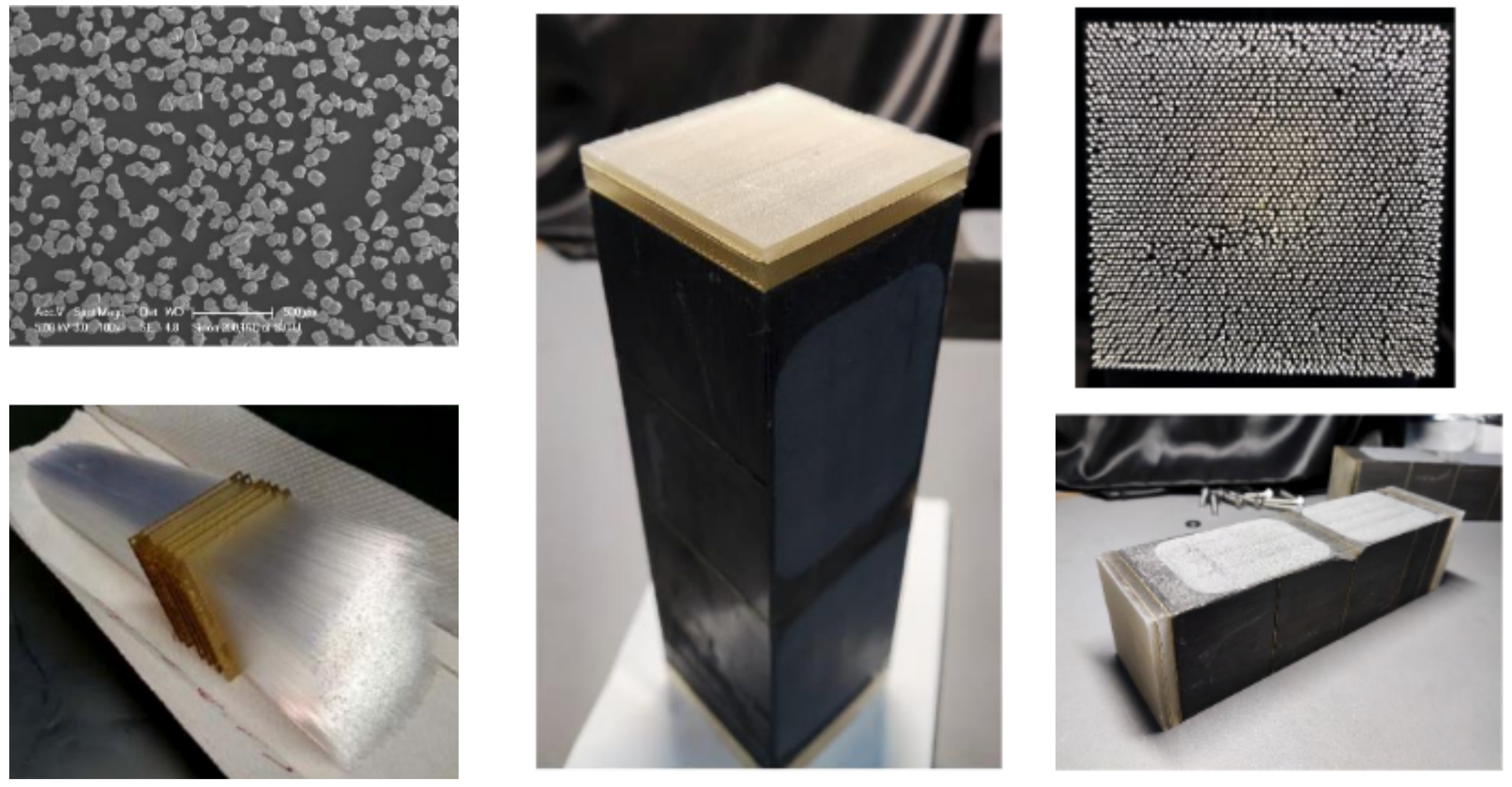




Forward EMCal

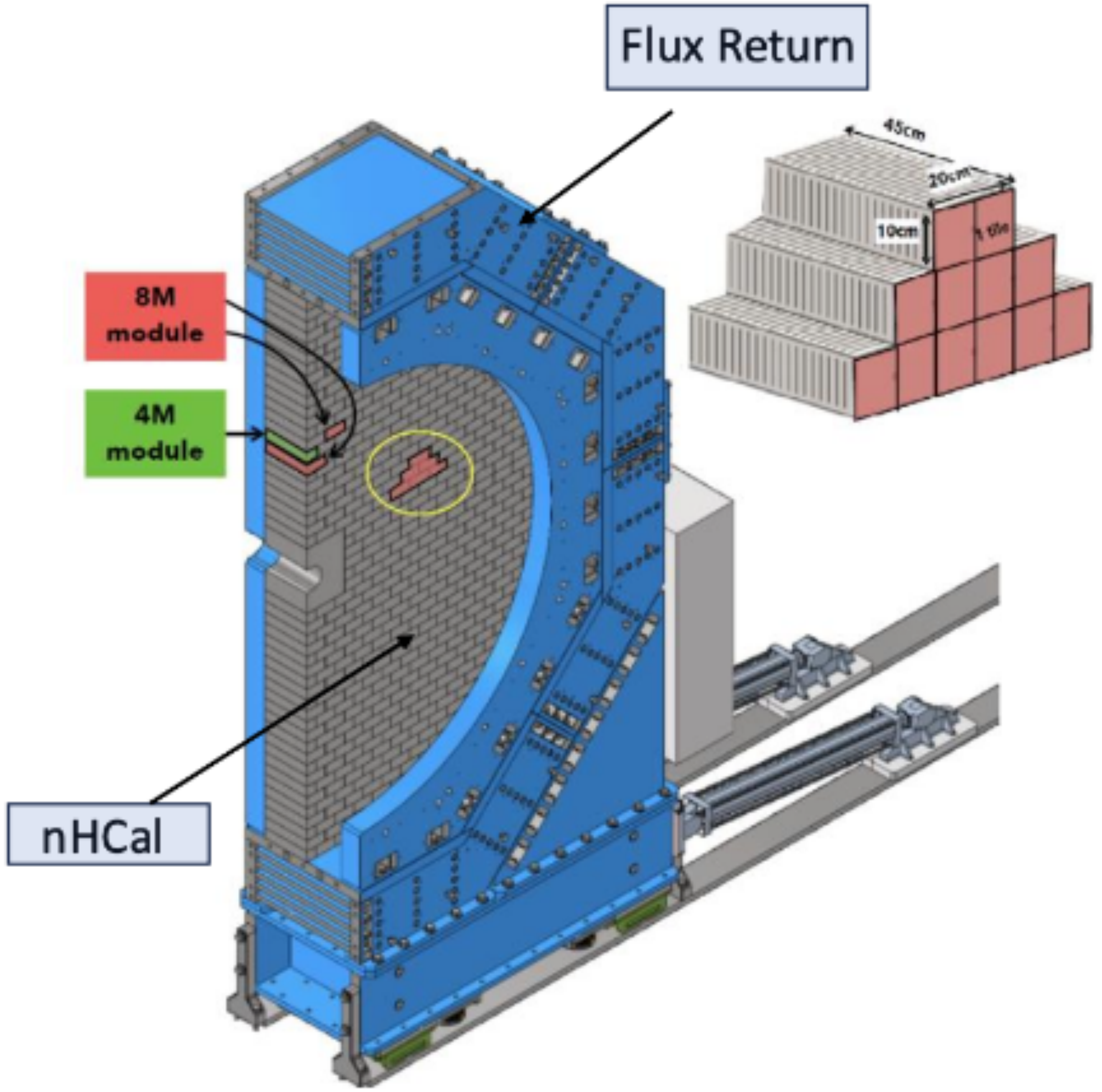


- **Task:** Measure high-E forward photons and neutral pions up to ~40GeV
  - overcome high particle density in hardon-going direction
- **Design**: 5x5x16cm^3 array of tungsten powder+epoxy with embedded SciFi (like sPHENIX, ~25 X_0 at normal incidence.
- $1.3 < \eta < 3.5$
- **Readout:** streaming SiPM via light guides
- **Resolution**: $\approx \frac{10\,\%}{\sqrt{E}} \oplus 3\,\%$



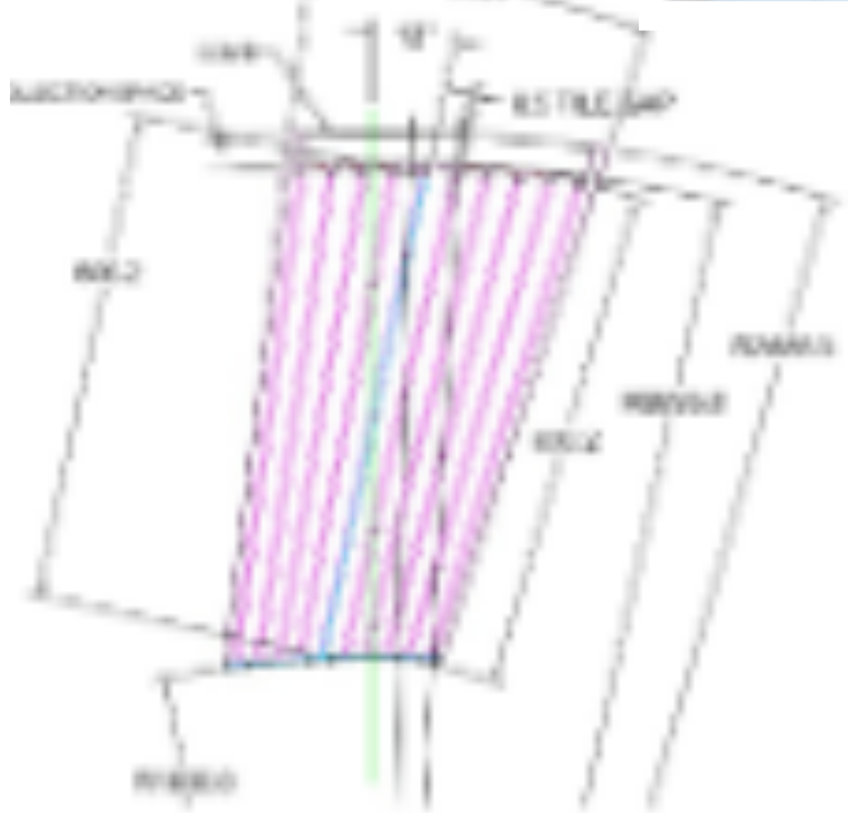
Backward "nHCal"

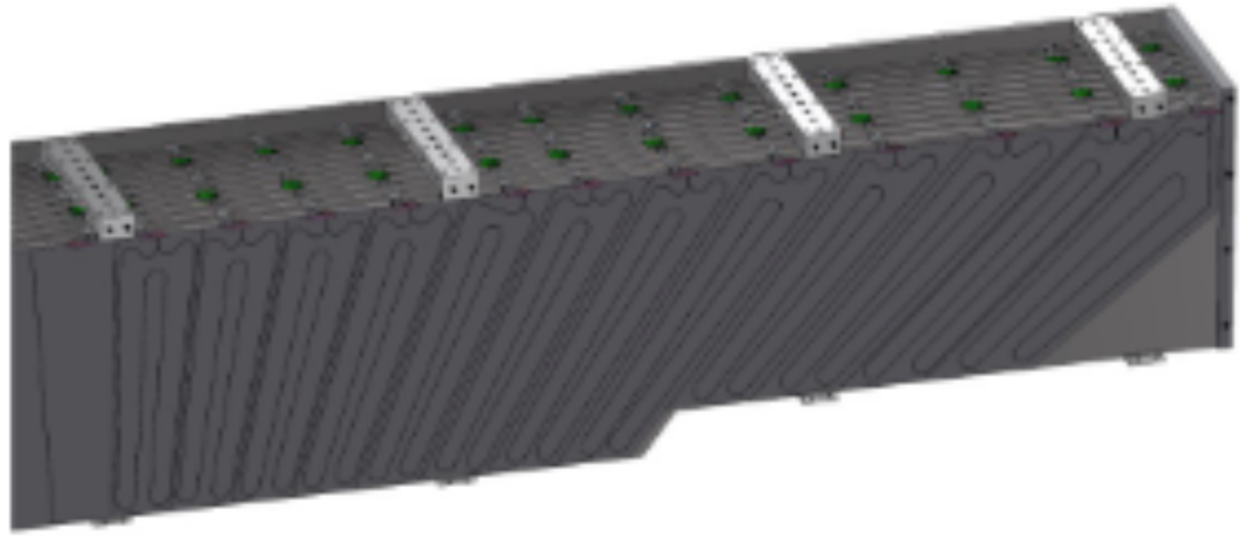
- **Task:**Tail-catching / Muon ID
  - discriminate e from low-x hadronic showers
- **Design**: 10x(40+4)mm steel-scintillator sandwich layers, ~2.4 λ_I at normal incidence.
- $-4.1 < \eta < -1.2$
- **Readout**: streaming SiPM-on-tile
- **Resolution**: TBD. mostly using as a veto.



Barrel HCal

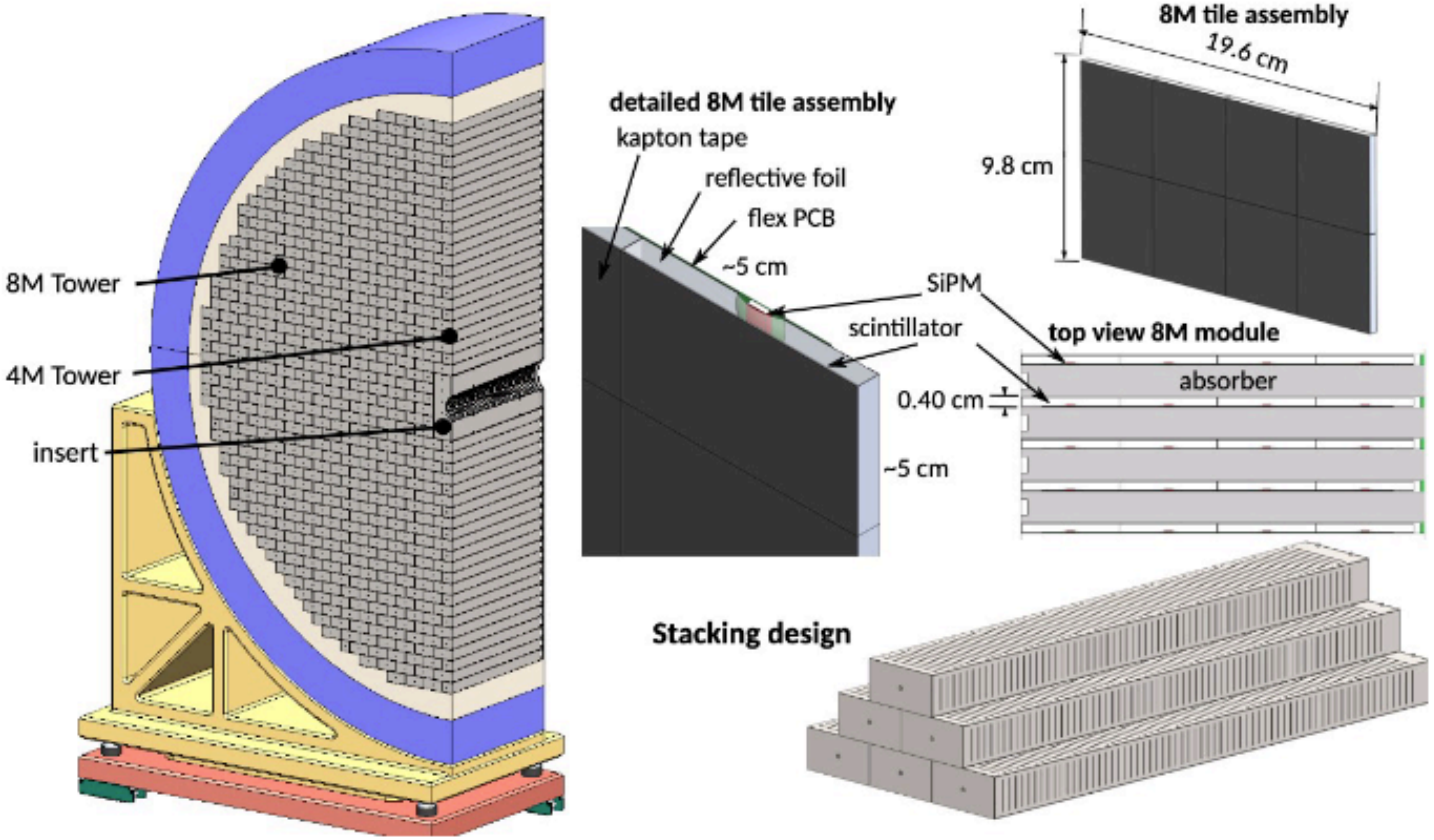
- **Task:**Jet reco, missing E_T.
  - discriminate e from low-x hadronic showers
- **Design**: 10x(40+4)mm steel/sci tes), ~4 λ_I. Tilted geom forces showers to strike multiple elements
  - reusing sPHENIX HCal
- $-1.1 < \eta < 1.1$
- **Readout**: WSL route to streaming siPM at outer radius
- **Resolution**: $\approx \frac{75\,\%}{\sqrt{E}} \oplus 15\,\%$





Forward HCal

- **Task:**Detailed 3D profile of forward hadron jets up to 150GeV
    - discriminate e from low-x hadronic showers
- **Design**: 5x5cm^2 tiles with 7 longitudinal segments. steel/scintillator sandwich, >6 λ_I at normal incidence.
- $1.2 < \eta < 3.5$
- **Readout**: streaming SiPM readout onboard each tile (custom chip)
- **Resolution:** $\approx \frac{50\,\%}{\sqrt{E}} \oplus 10\,\%$



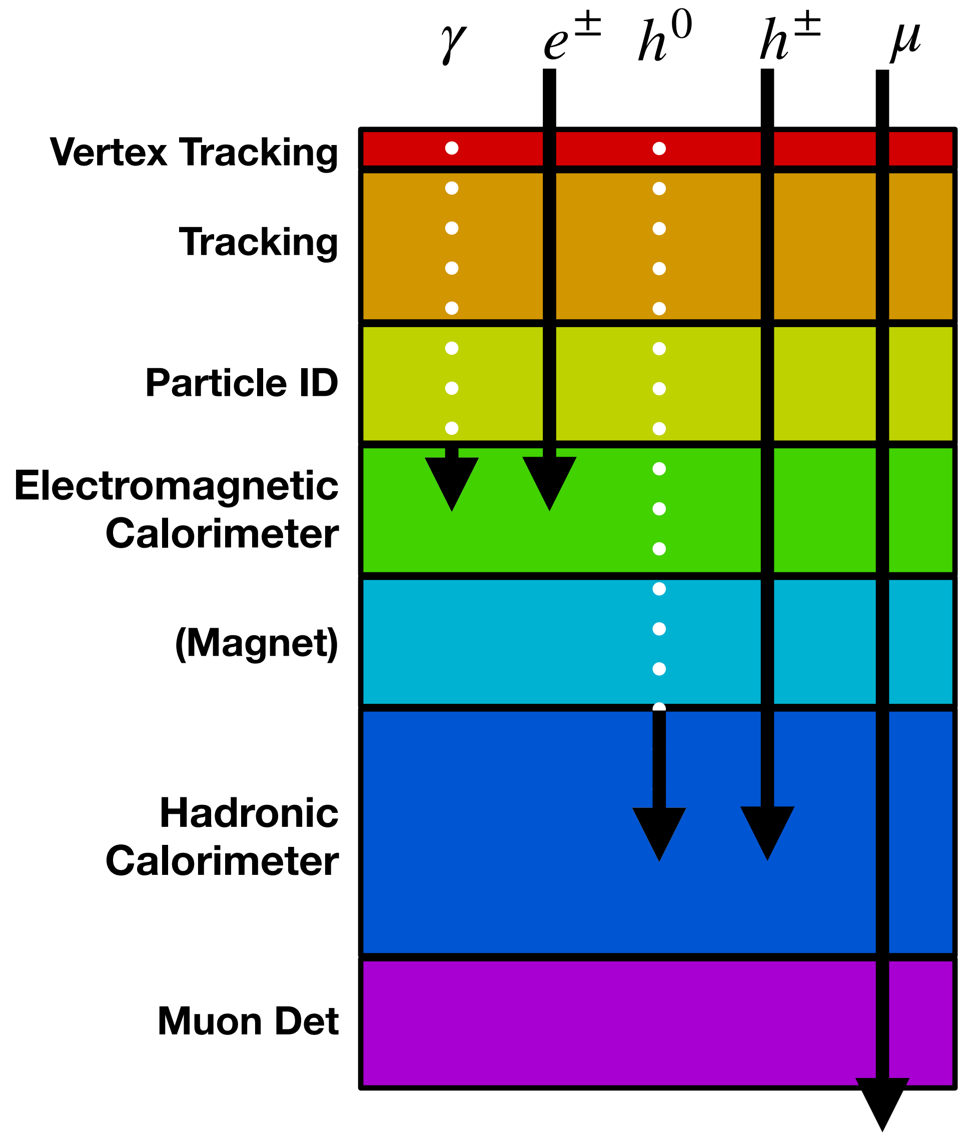
Future Directions

- **Particle Flow**
  - **Track-Cluster Matching**: (hypothetical) Cal granular enough to match tracks to tracker. Jets can now do careful bookkeeping (instead of double-counting energy in the tracker and cal)
  - **Separation**: Resolves particles within collimated jets, revealing extra HCal energy as neutral hadron halo.
  - **Scale**: Improves the stochastic resolution term by using track curvature per-track rather than energy deposition.
- **Dual Readout:** Add Cherenkov detectors in HCal to monitor EM/H fluctuations per-shower (per-event adjustment of e/h ratio to 1.0)
- **Ultra-Fast timing**: With fast enough (10-30 ps) readout, Cals can measure shower evolution and ToF-like PID 5D Imaging

Calorimetry

- Shower development in common:
  - random, but in both EM and H gives hints about parent particle
  - power-law growth and exponential die-off
- Hadronic Showers: High variation. Energy can be invisible
- Collect and digitize ~visible light as particles lose energy:
- Sampling vs Homogenous depends on your constraints
- Calorimeters: destructive E measurement, but can see neutral particles
- Essential part of modern general-purpose experiment

	EM	**Hadronic**
Growth Mechanism	Bremsstrahlung & Pair Production	Spallation
Longitudinal Scale	Radiation Length (X_0)	Interaction Length (λ_I) is 10-20x larger
Transverse Profile	Narrow core (Moliere Radius R_M)	Wide halo + EM Core
Response	Linear	Non-linear (invisible hadronic energy)



ePIC Cal Design Requirements

- **Fully Streaming DAQ**: All readout must stream to the DAQ and handle the 500 kHz collision reatre
- **Compact**: Barrel ECal must fit inside the solenoid (total radial thickness <40cm)
- **Radiation Load**: Everything must be rad-hard
  - Central, Backward: $\sim 5 \cdot 10^{9}$ $\text{neq/cm}^2\text{/year}$
  - Forward: $\sim 2 \cdot 10^{11}$ $\text{neq/cm}^2\text{/year}$ (due to nuclear fragments and beam-gas backgrounds) (~10 years in LEO per year.

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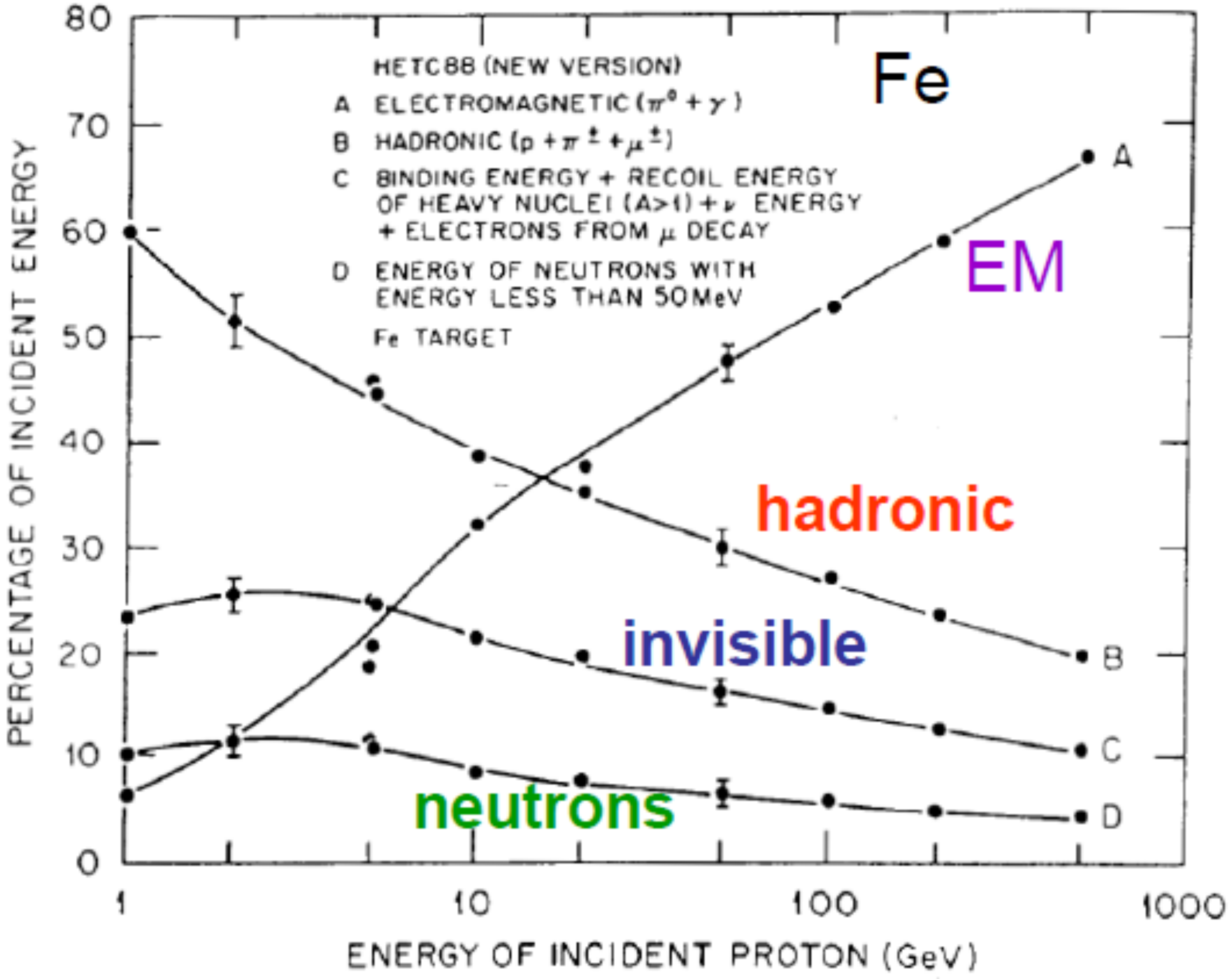
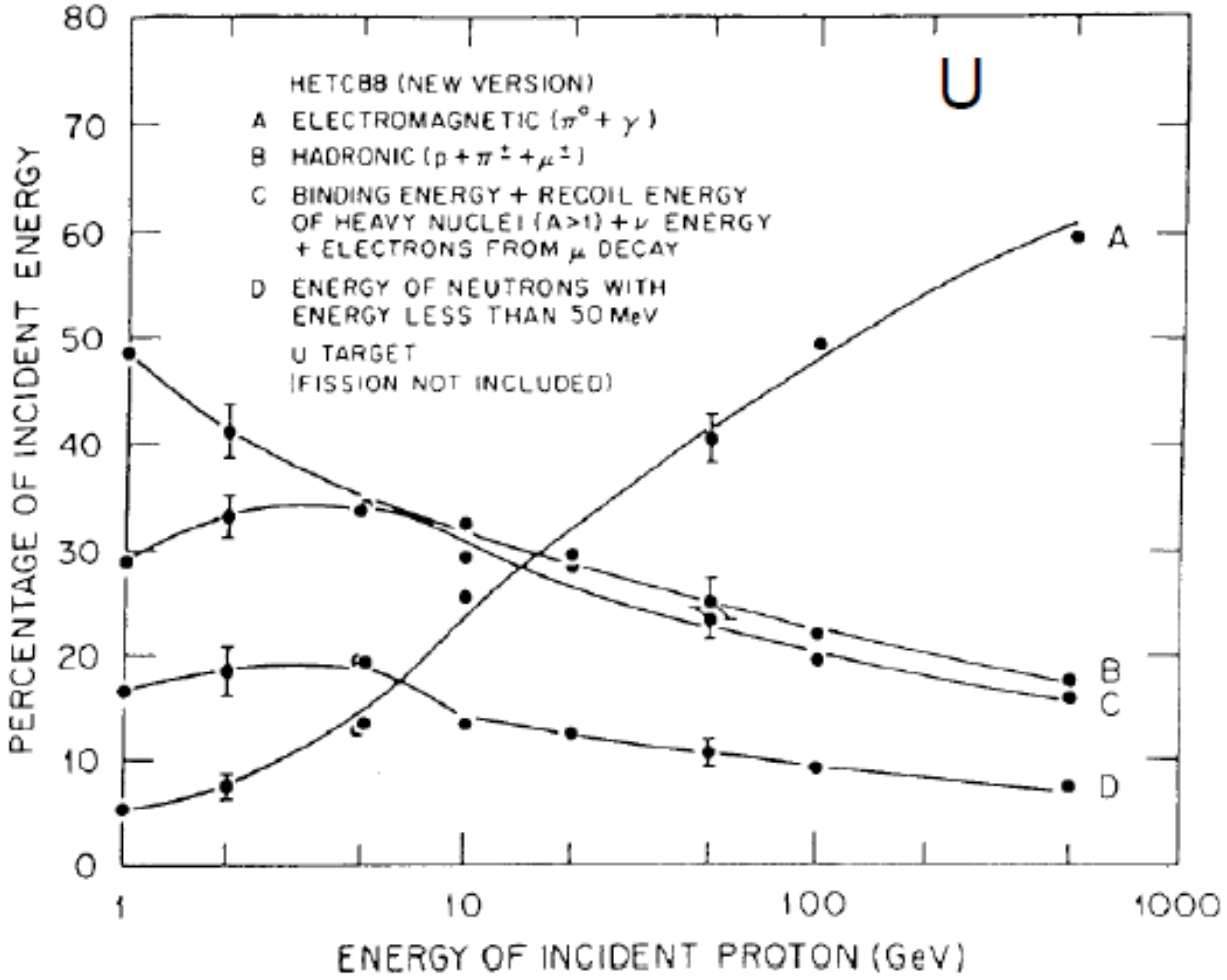
Energy Fractions

*On the plots, the fractions are shown as total energy fractions, rather than as fractions of non-em response

$$\pi = \boxed{f_{EM}}e + (1 - f_{EM})h$$

$$h = \boxed{f_{rel}} \cdot rel + \boxed{f_p} \cdot p + \boxed{f_n} \cdot n + \boxed{f_{inv}} \cdot inv$$

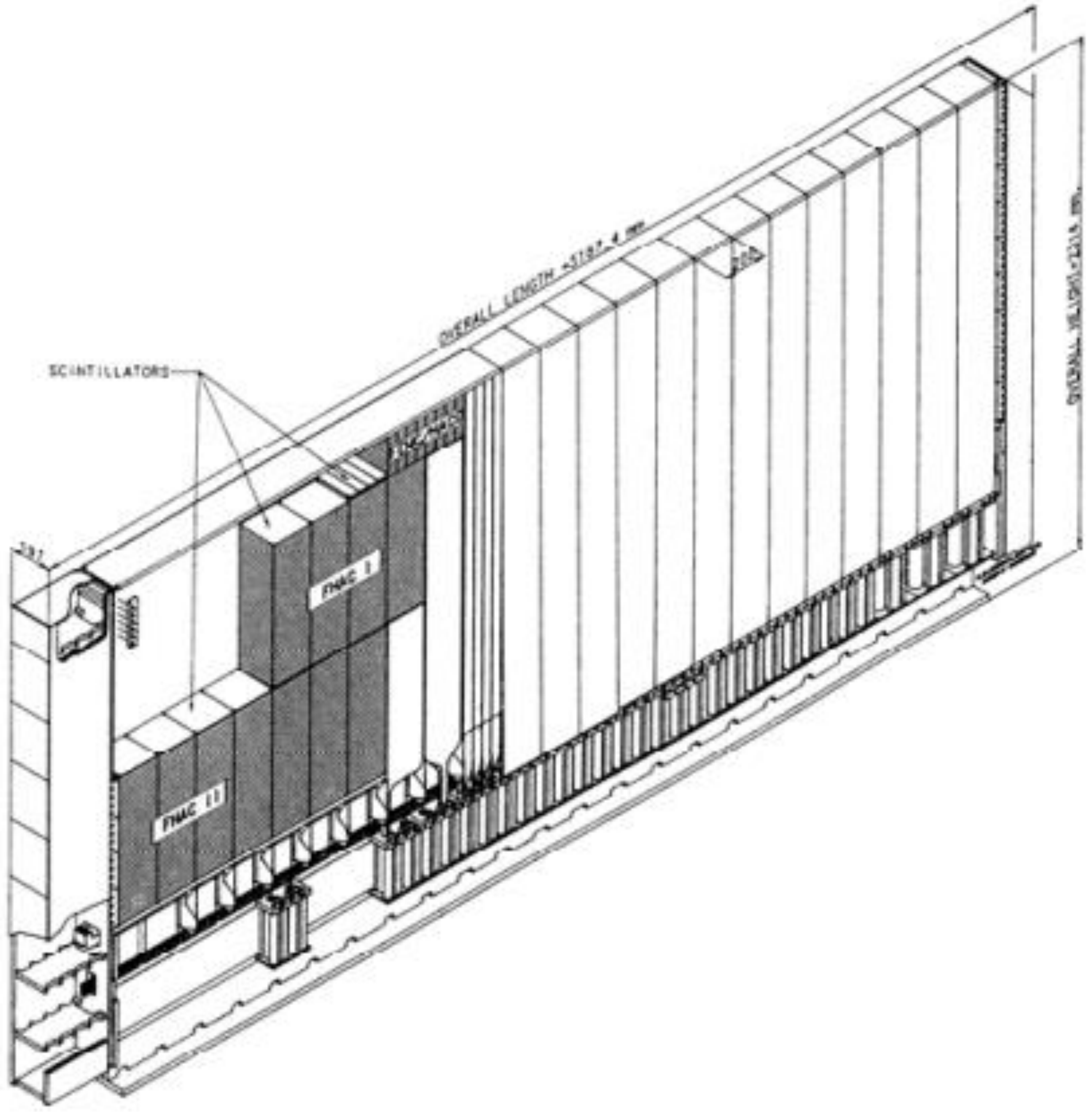




Compensated HCal

- Add hydrogenous active material to maximize np scattering
- Intentionally degrade the EM response for high-Z absorbing materials.
  - The best performance for EM particles is incompatible with e/h = 1
- Intentionally degrade the timing resolution so that neutrons decay/capture

ZEUS compensating calorimeter



View of a module of the ZEUS U-scintillator calorimeter. Wavelength-shifter readout is used to read cells of 5*20 cm^2 cross-section in the electromagnetic compartment and of 20*20 cm^2 in the two subsequent hadronic compartments

First compensating calorimeter used depleted Uranium as the absorber material:

- The ZEUS HCal had an energy resolution better than 35% / $\sqrt{E\ [GeV]}$. This is better than modern HCals at the LHC, for example.
- Initial idea was that the fission energy released in the absorption process would compensate for the invisible energy losses.
- ZEUS did achieve compensation – but fission had nothing to do with it. Uranium was neither necessary nor sufficient.
- The important things were the hydrogenous active material, the tuned sampling fraction (about 2%), and an integration time of over 30 ns.

- Even with the small sampling fraction (degraded EM/sampling resolution) and large integration time, the ZEUS HCal has the world record in hadronic energy resolution.
- The main driver for poor HCal is the *Invisible energy* produced in hadronic showers, which leads to non-compensation.

Various Calorimeters

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\% / E^{1/4}$	1983
$\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO)	$22X_0$	$2\% / \sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\% / \sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16-18X_0$	$2.3\% / E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5\text{ GeV}$	1998
PbWO_4 (PWO) (CMS)	$25X_0$	$3\% / \sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\% / \sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\% / \sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20-30X_0$	$18\% / \sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\% / \sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\% / \sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\% / \sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\% / \sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20-30X_0$	$12\% / \sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U ($\text{D}\emptyset$)	$20.5X_0$	$16\% / \sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\% / \sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Calorimeter spec sheet

Region	Angular Coverage (η)	Depth Requirement	Target Energy Resolution (EσE)	Primary Physics Driver
Backward / Electron Endcap	$-3.5 < \eta < -1.2$	$\ge 22 X_0$	$\approx \frac{2\%}{\sqrt{E}} \oplus (1\text{--}3)\%$	Precision electron reconstruction to anchor Q^2 and x kinematics.
Central Barrel (BIC)	$-1.7 < \eta < 1.3$	$\ge 17 X_0$	$\le \frac{10\%}{\sqrt{E}} \oplus 1\%$	Photon angular resolution ($<0.1^\circ$) to separate $\pi^0 \to \gamma\gamma$ in Deeply Virtual Compton Scattering (DVCS).
Forward / Hadron Endcap	$1.3 < \eta < 3.5$	$\ge 25 X_0$	$\approx \frac{10\text{--}12\%}{\sqrt{E}} \oplus	Measures high-energy forward photons and tags the electromagnetic cores of forward jets.

Region	Angular Coverage (η)	Depth Requirement	Target Energy Resolution (EσE)	Primary Physics Driver
Backward / Electron Endcap	$-4.1 < \eta < -1.2$	$\sim 2.4 \lambda_I$	--	Primarily acts as a "tail catcher" for any leak-through hadronic energy.
Central Barrel (BHCal)	$-1.1 < \eta < 1.1$	$\sim 4 \lambda_I$	$\approx \frac{75\%}{\sqrt{E}} \oplus 15\%$	Jet reconstruction and mid-rapidity missing transverse energy measurements.
Forward / Hadron Endcap (LFHCal)	$1.2 < \eta < 3.5$	$\ge 6 \lambda_I$	$\approx \frac{50\%}{\sqrt{E}} \oplus 10\%$	**Critical** Must cleanly contain showers up to ~150GeV