Calorimetry and Particle Identification

Brigitte Vachon
McGill University

Overview

- Calorimetry
  - Physics of showers development
  - Electromagnetic Calorimeter
  - Energy Resolution
  - Hadronic Calorimeter
  - Calorimeter Gallery
- Particle Identification
  - Tracker
  - Charged particle ID
  - Calorimeter ID
  - Putting it all together!

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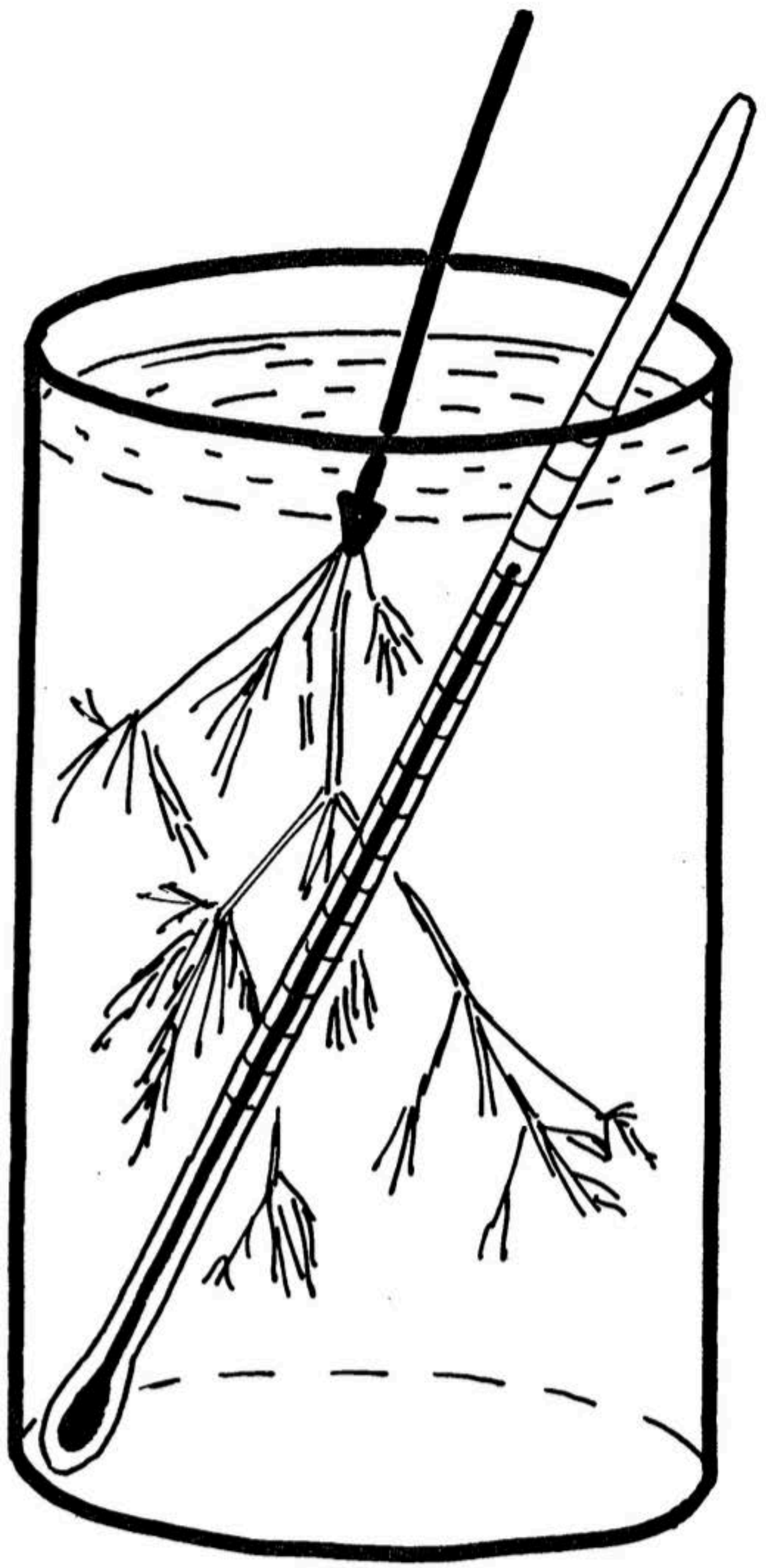
Foreword

I would like to personally acknowledge and thank **Kate Pachal** and **Max Swiatlowski** for their past contributions to this topic.

They jointly developed materials and presented at previous GRIDS conferences, and today's presentation builds on their work. My slide deck is heavily inspired by their contributions - Thank you

What is a calorimeter ?

- Device that measures amount of energy output.
- In subatomic physics, calorimeters are used to measure the energy of particles (both charged and neutral!).
  - **Total absorption** in a volume of matter
  - Signal amplitude **proportional (linear)** to energy deposited
  - **Destructive** measurement process
- Practical considerations
  - Size
  - Cost
  - Radiation hardness
  - Read-out fast enough for event rate
  - Required energy resolution
  - etc.

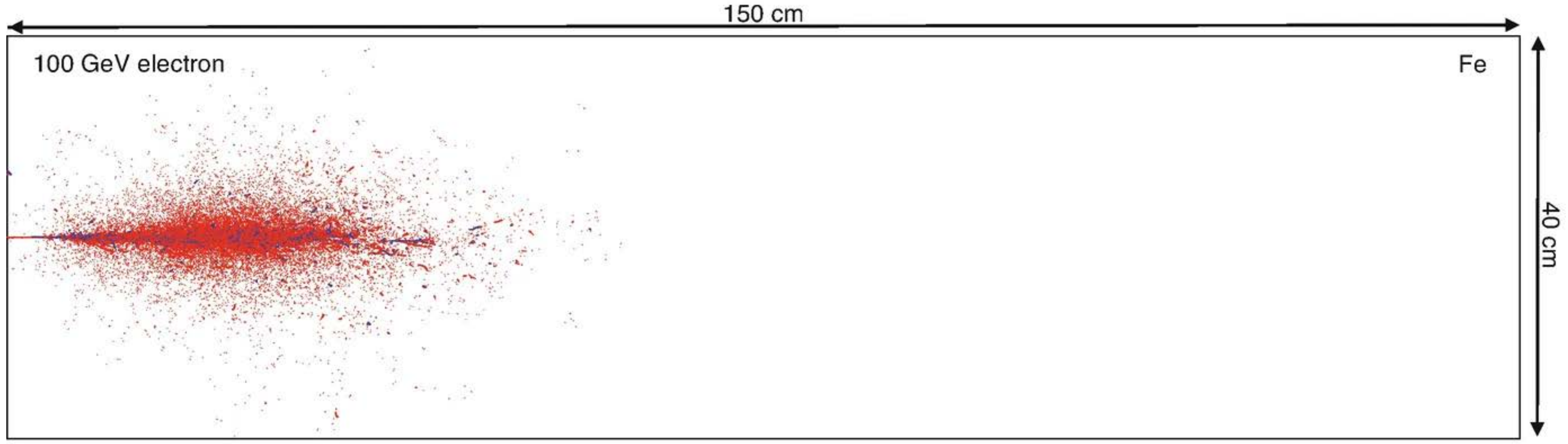


Physics of shower development

Physics of shower development

Electromagnetic Showers

- Initiated by electron, positron and photons
- Dominated by electromagnetic interactions.



Sefkow, F., Simon, F. (2021). Calorimeters. In: Fleck, I., Titov, M., Grupen, C., Buvat, I. (eds) Handbook of Particle Detection and Imaging. Springer, Cham. https://doi.org/10.1007/978-3-319-47999-6_53-1

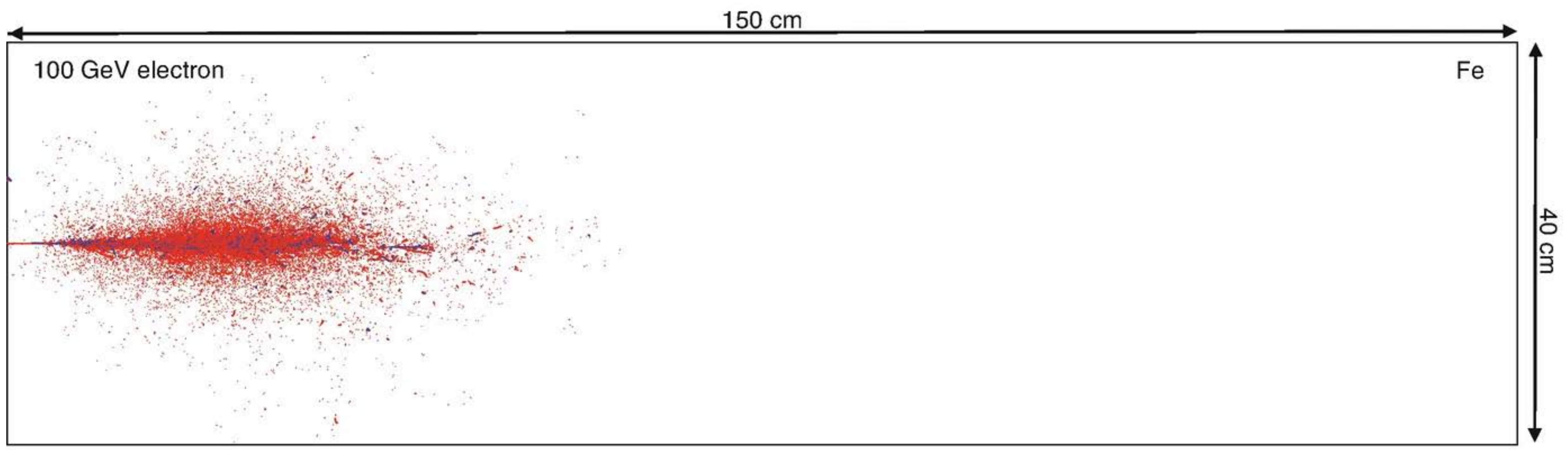
Physics of shower development

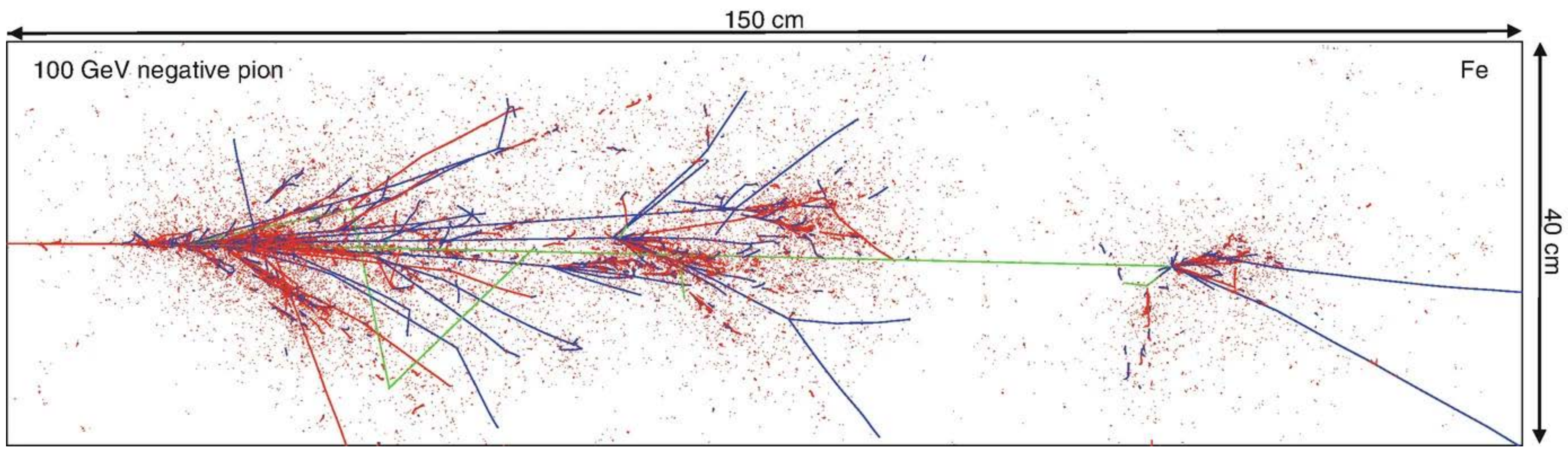
Electromagnetic Showers

- Initiated by electron, positron and photons
- Dominated by electromagnetic interactions.

Hadronic Showers

- Initiated by hadrons
- Dominated by strong interactions
  - Contains secondary electromagnetic interactions.





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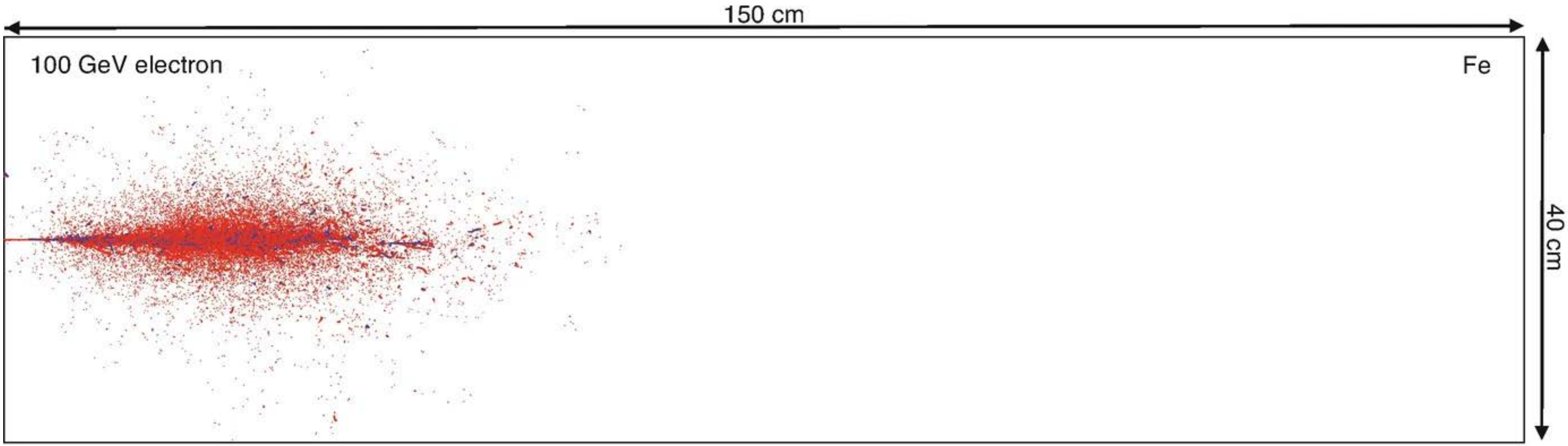
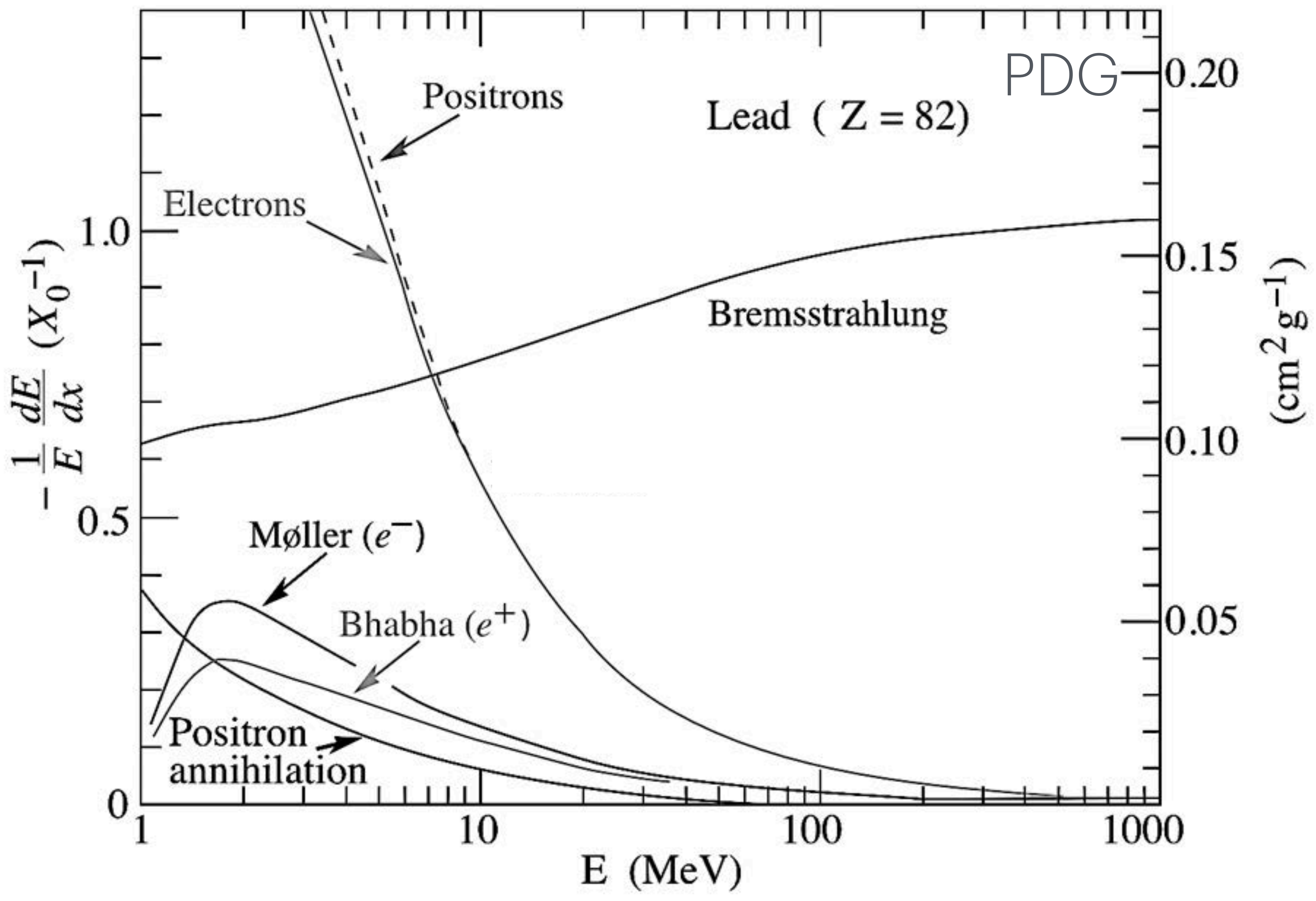
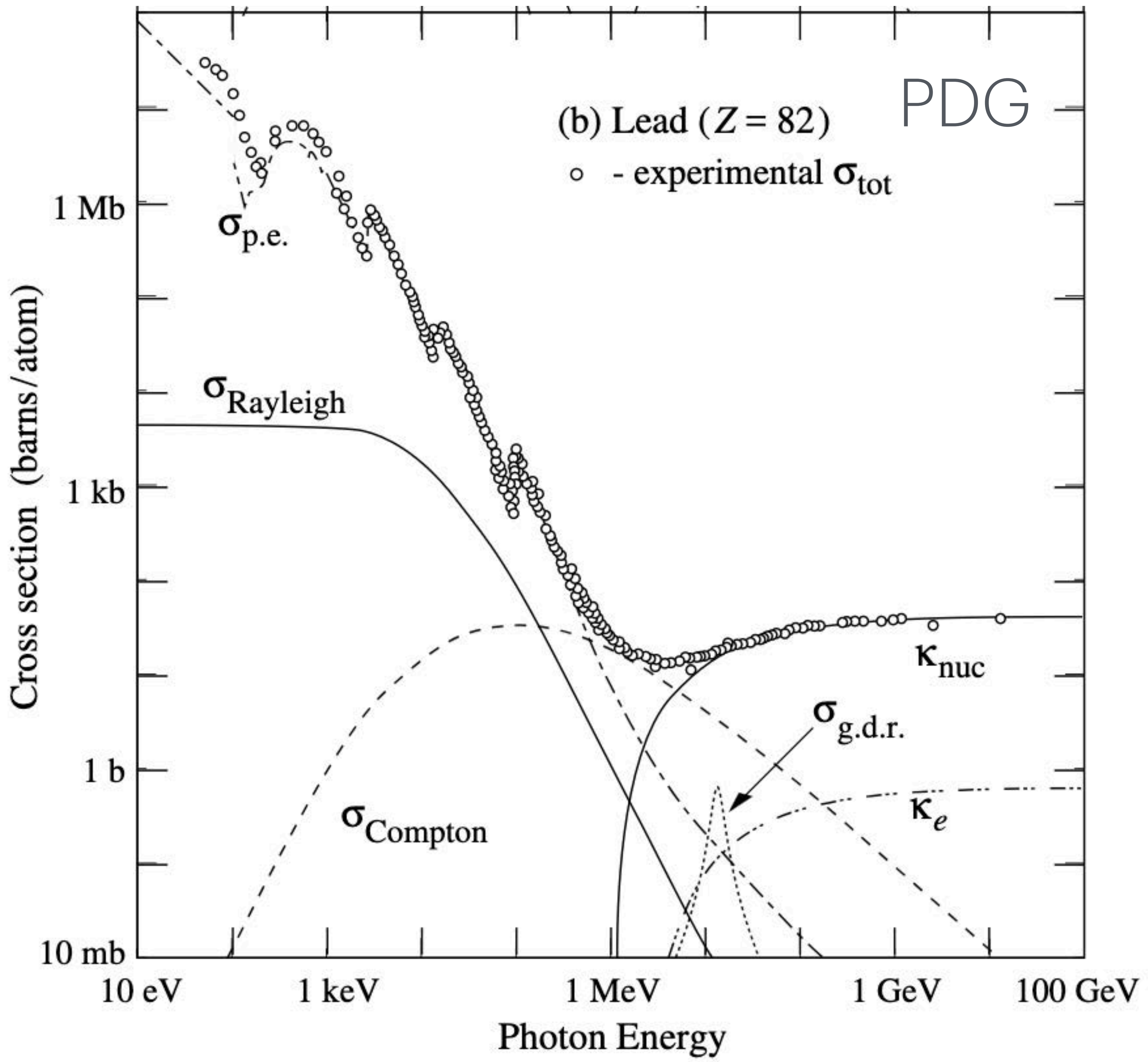
Electromagnetic Calorimetry



Electron and Photons interactions with matter





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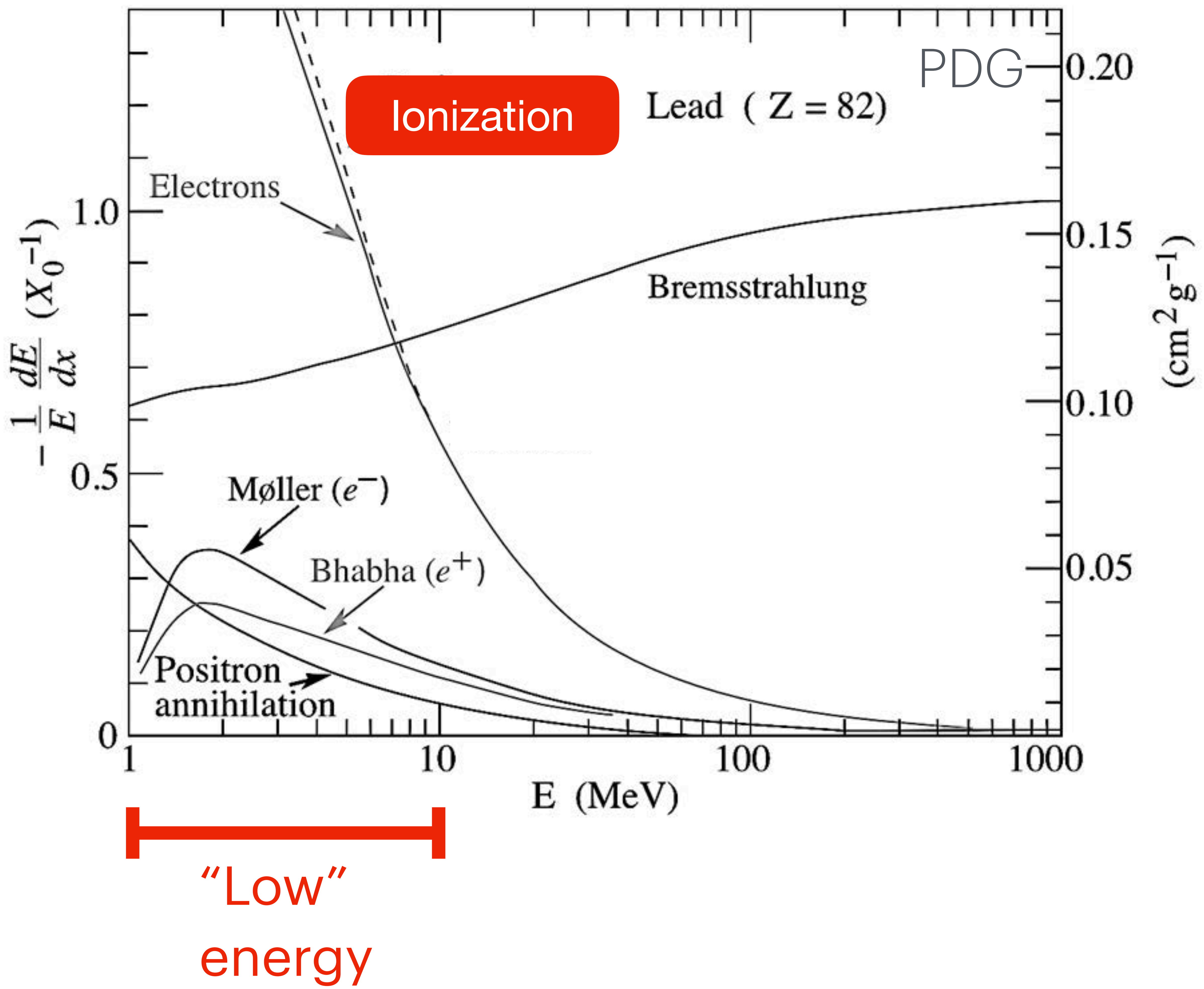

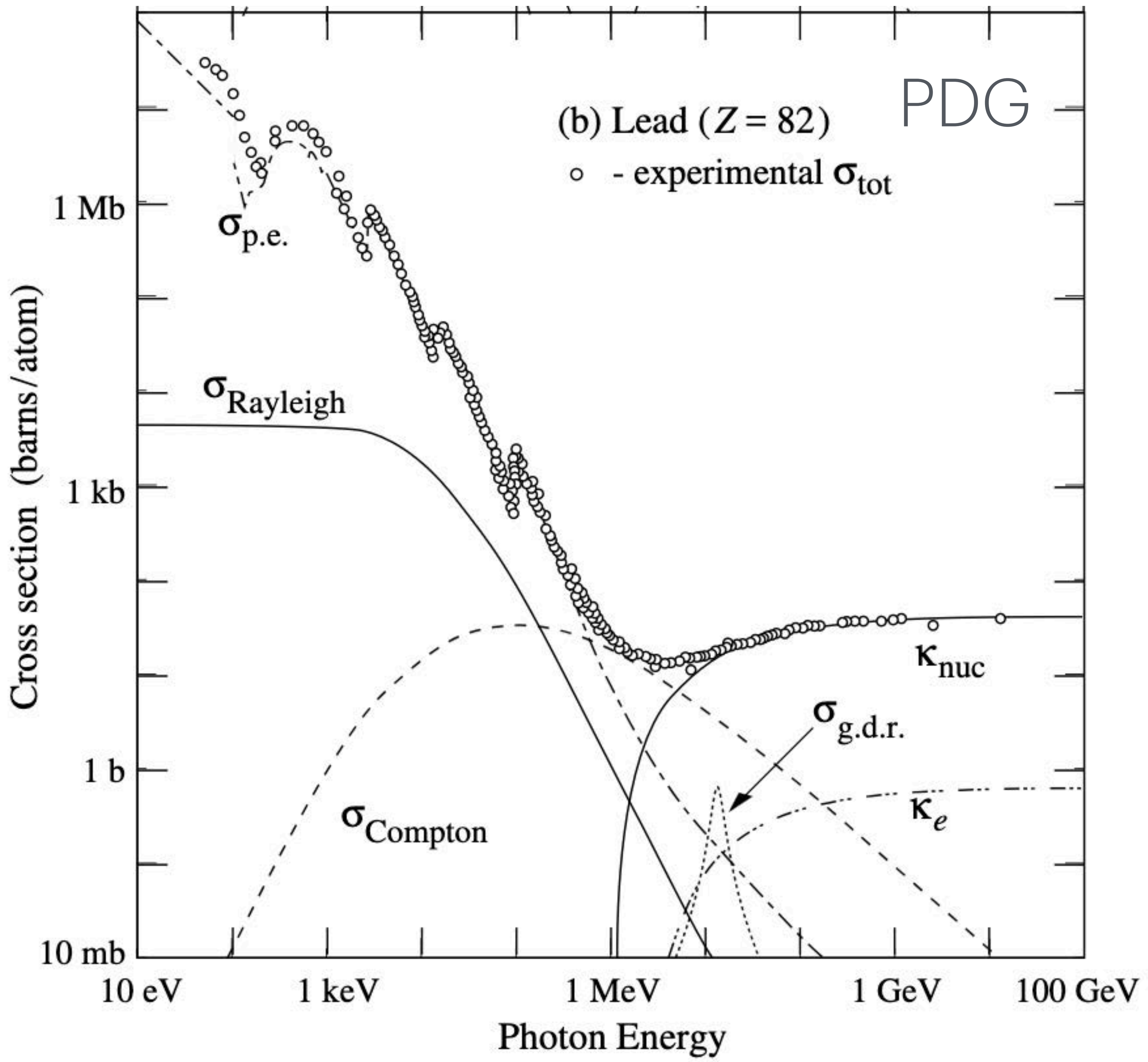

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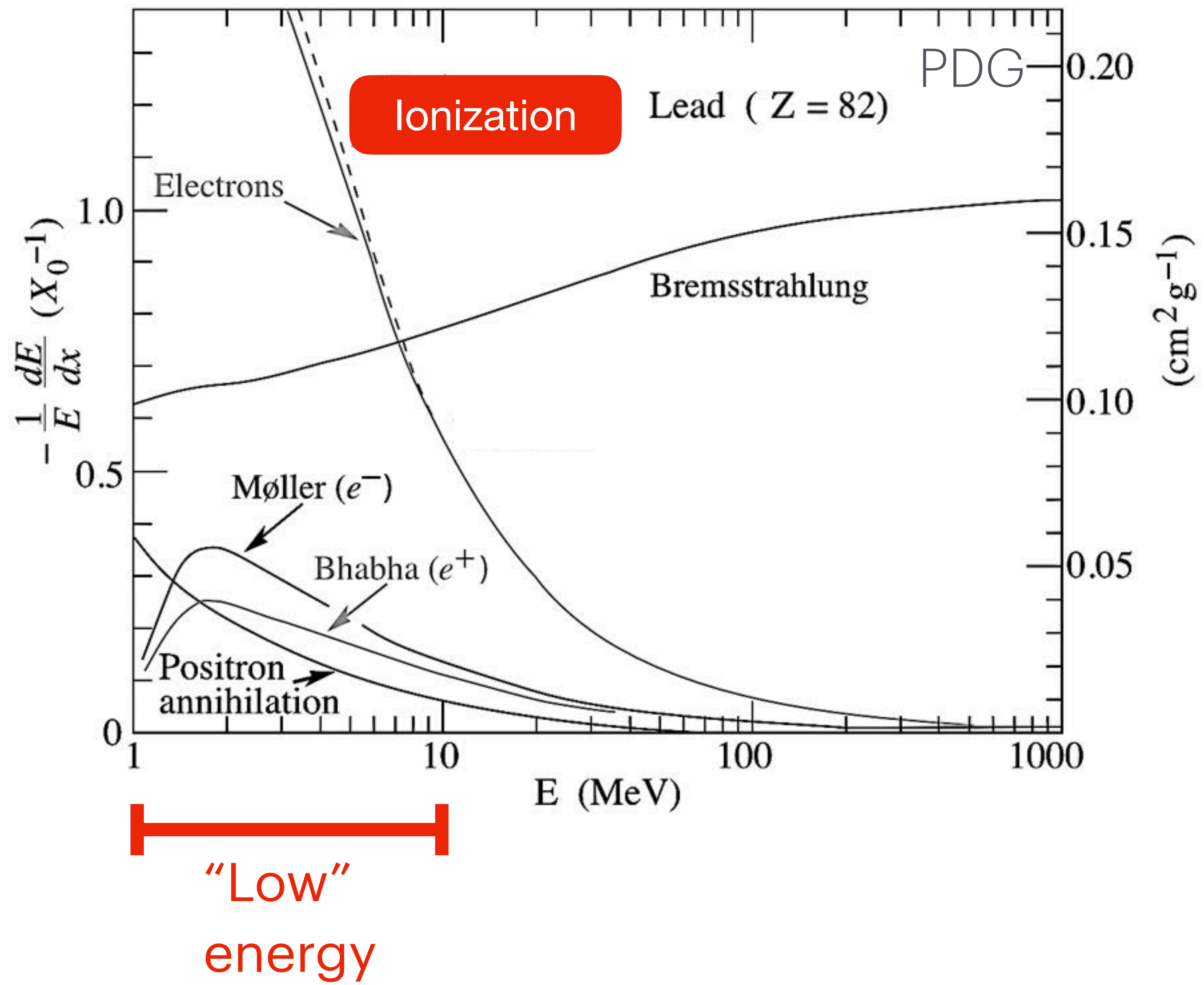

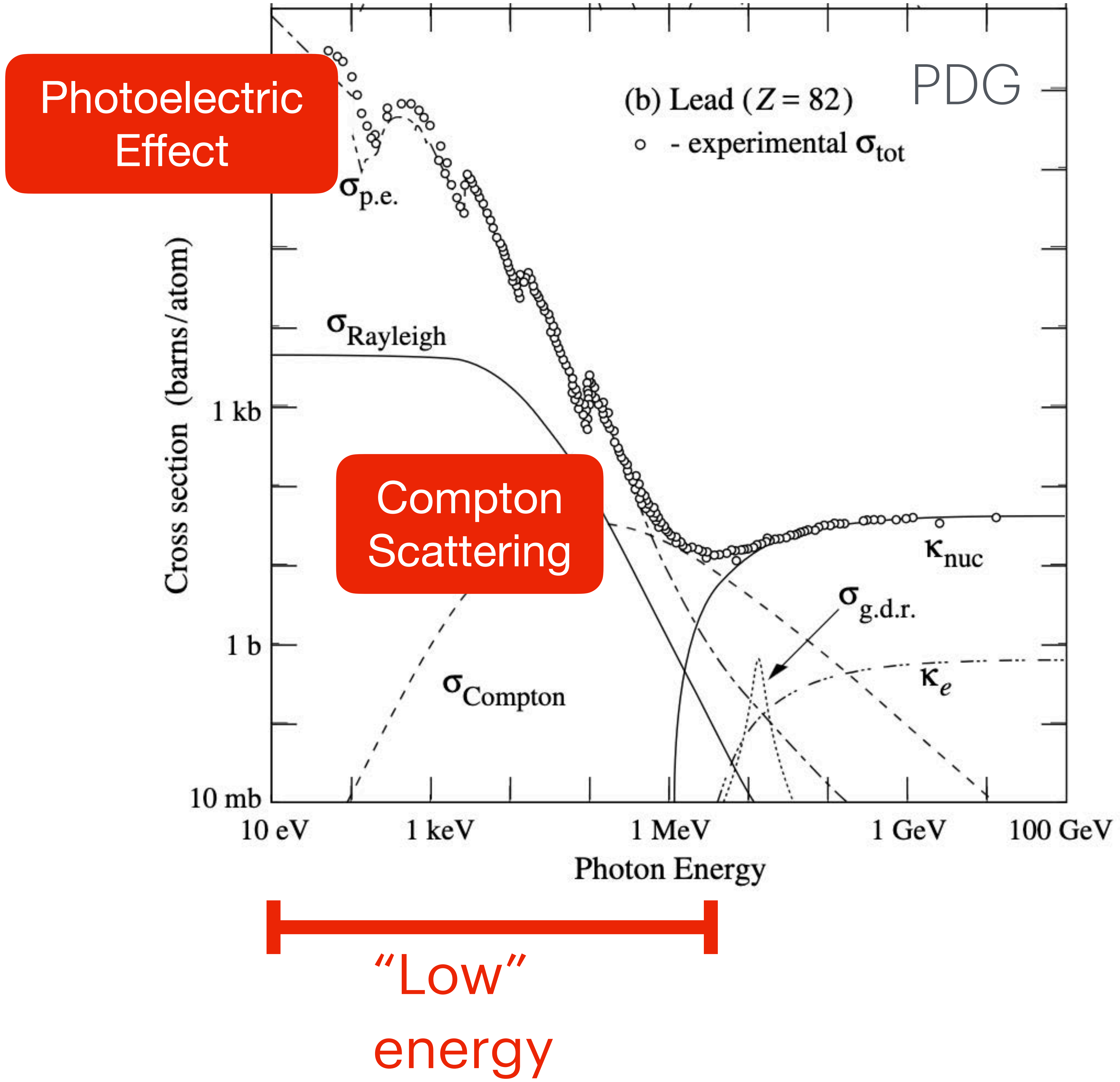

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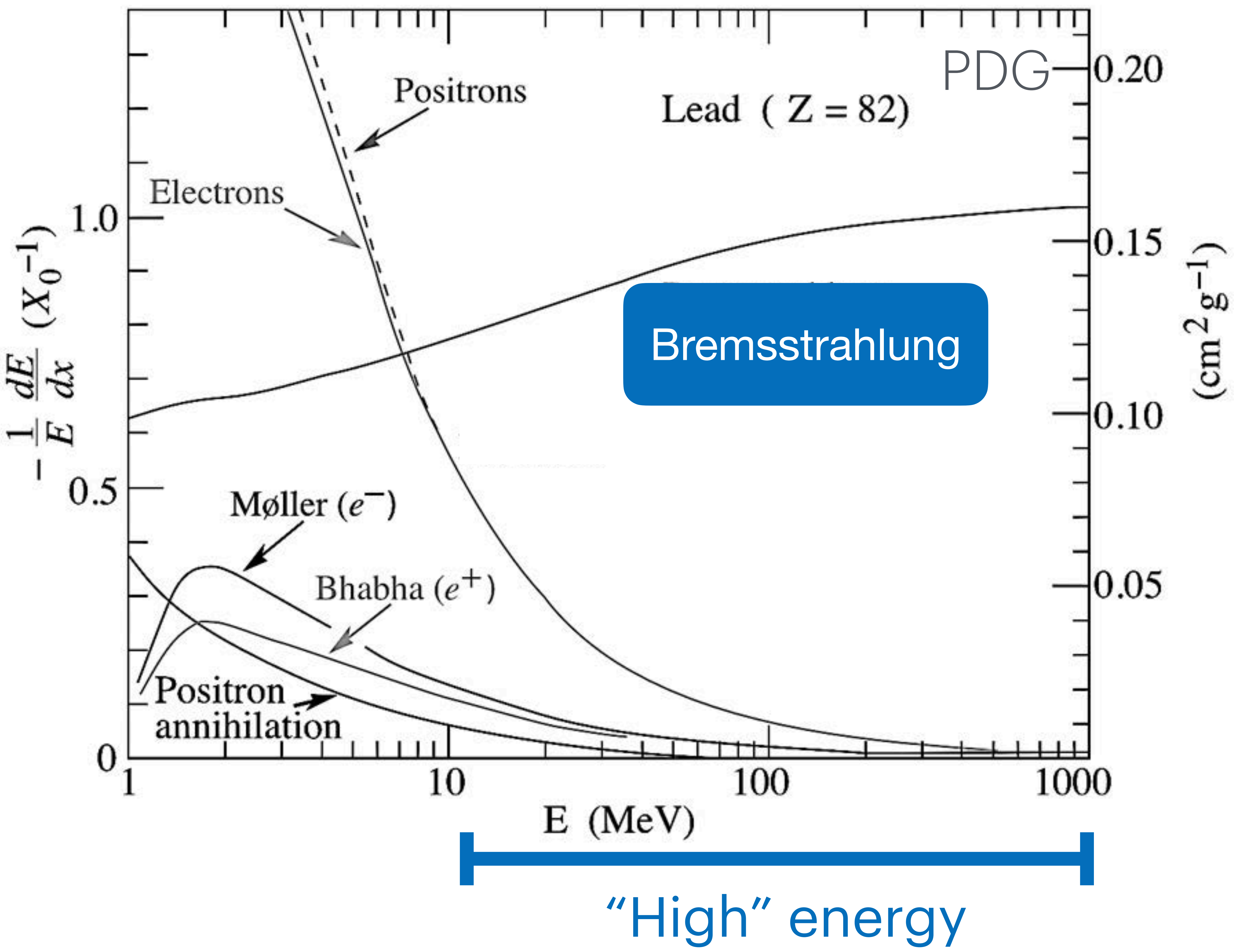

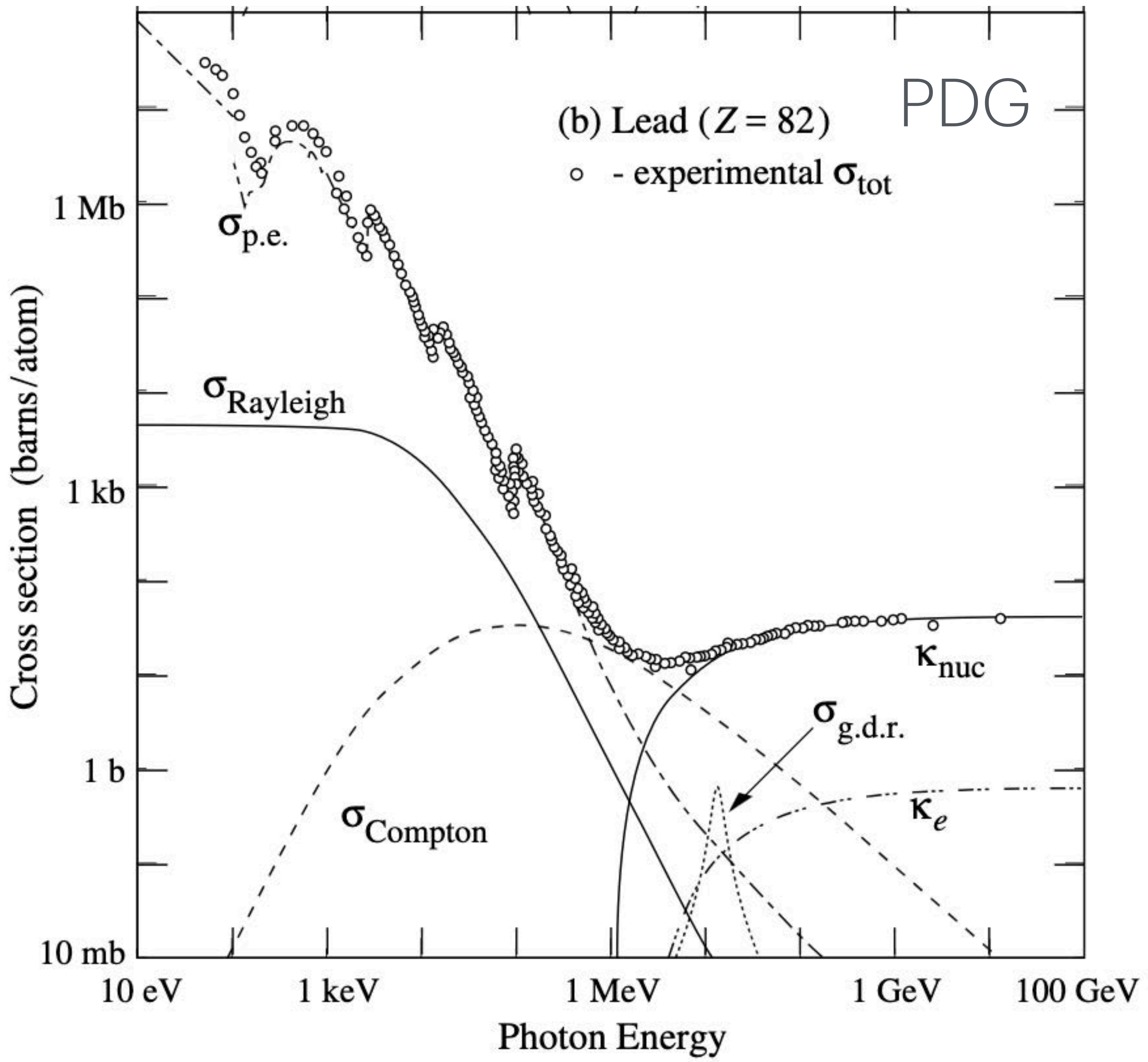

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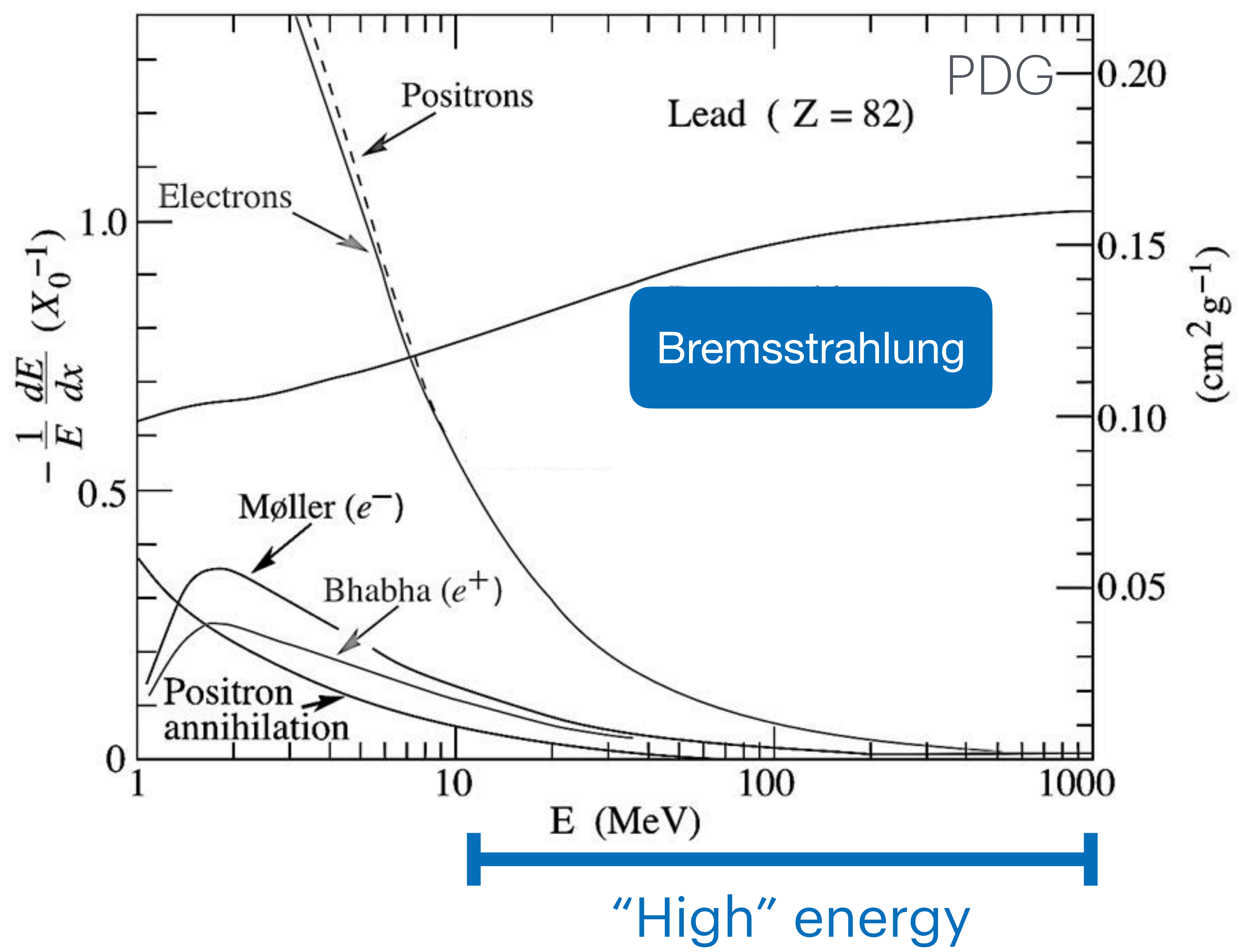

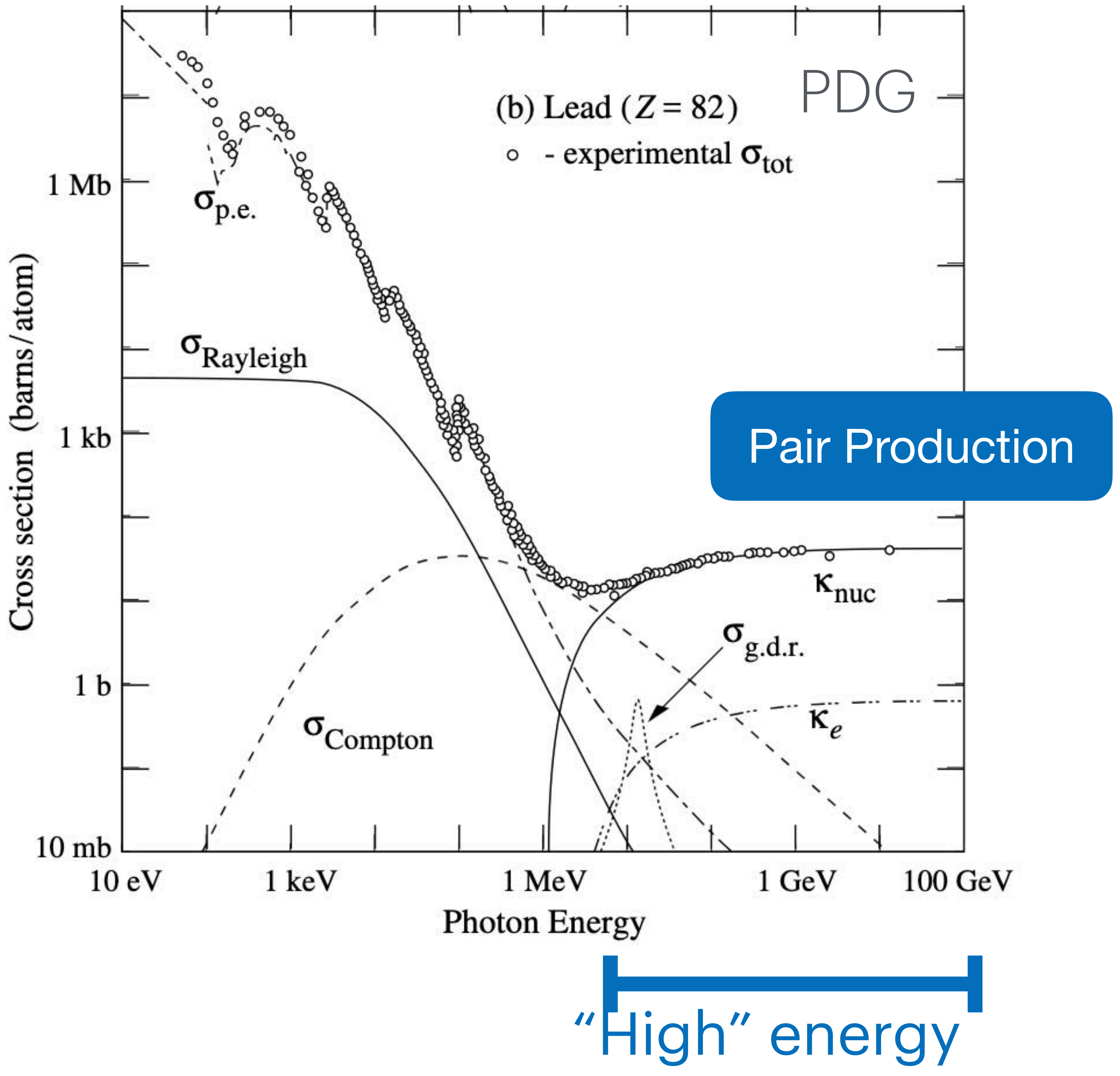

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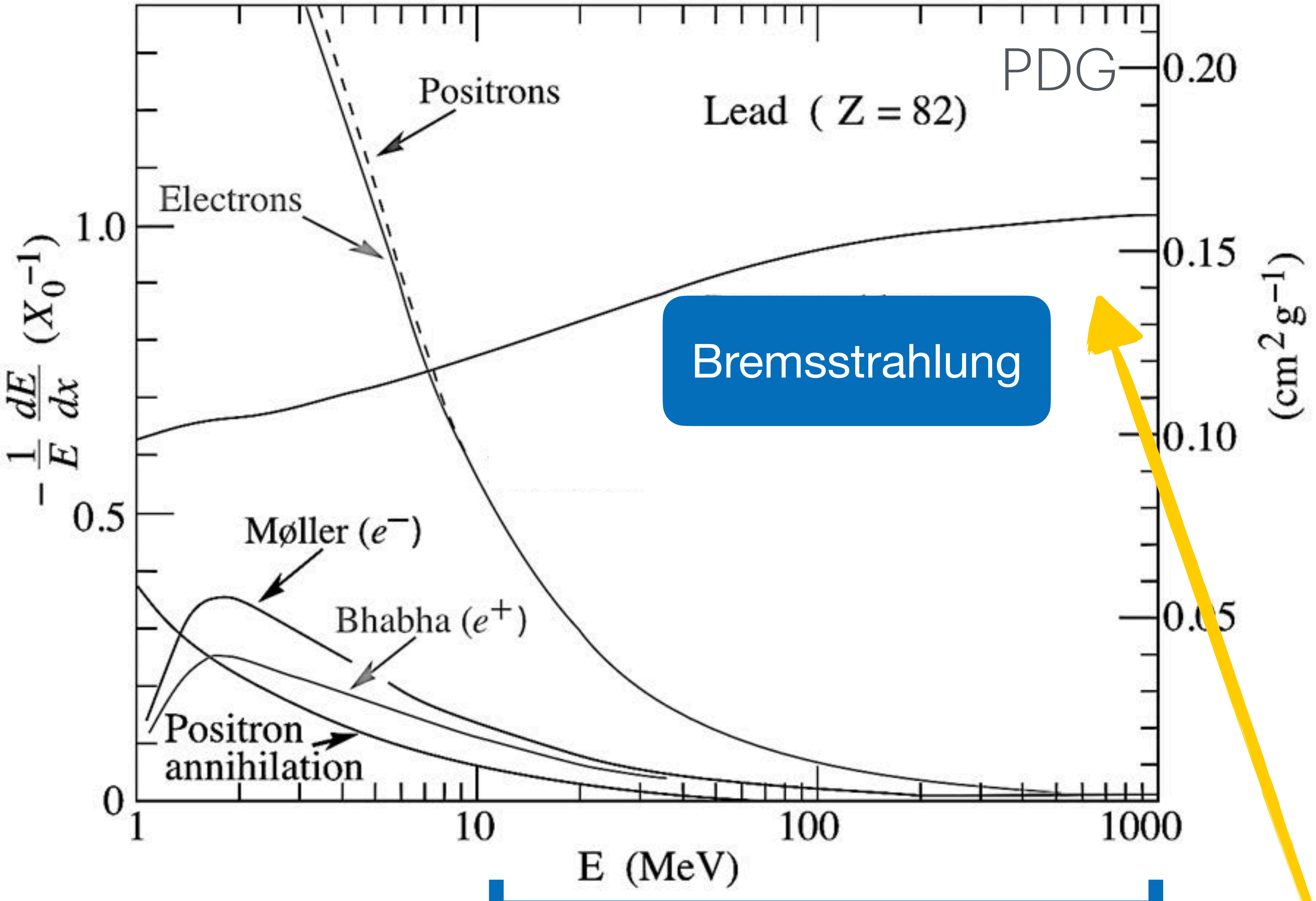
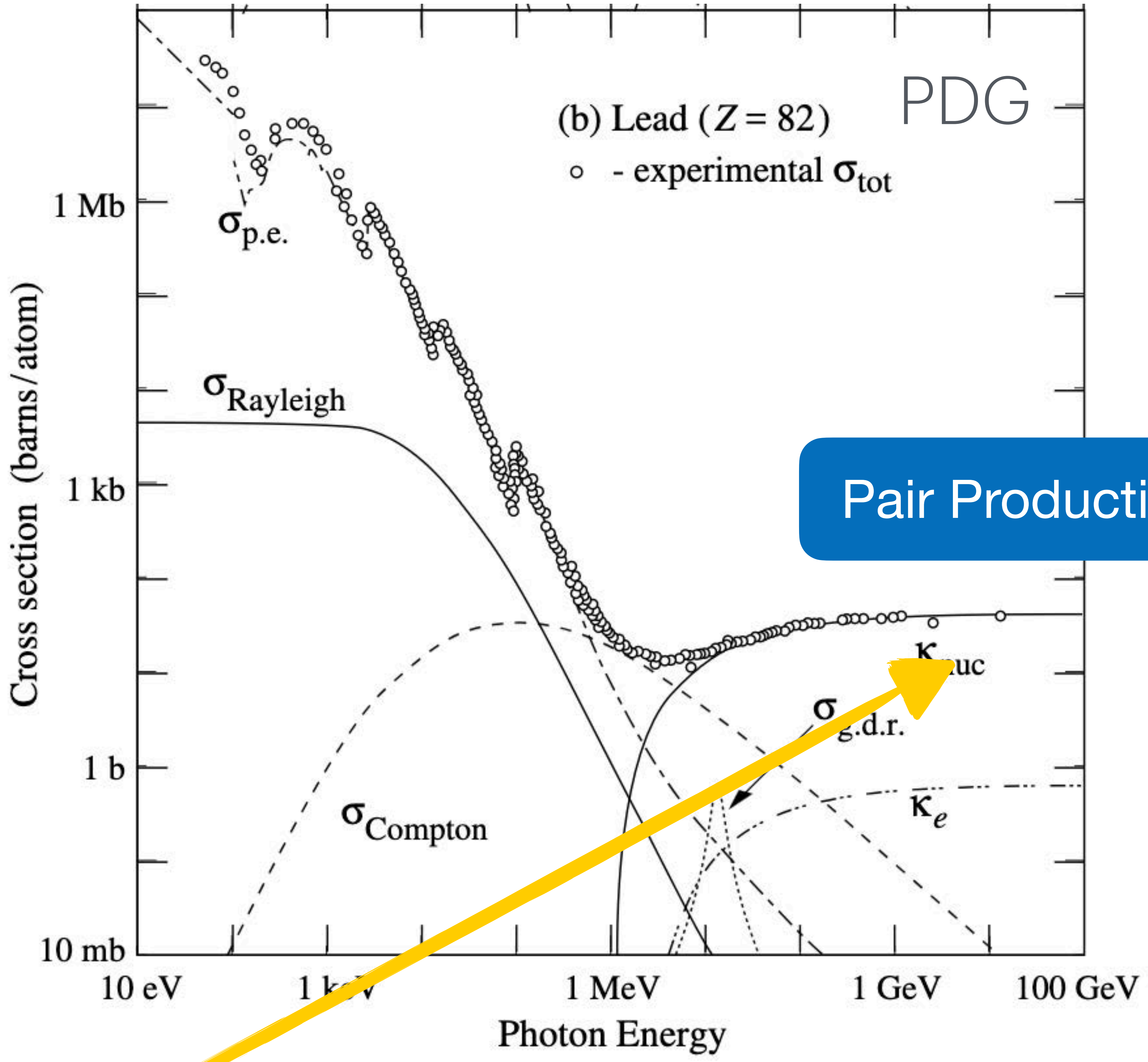


Bremsstrahlung

"High" energy

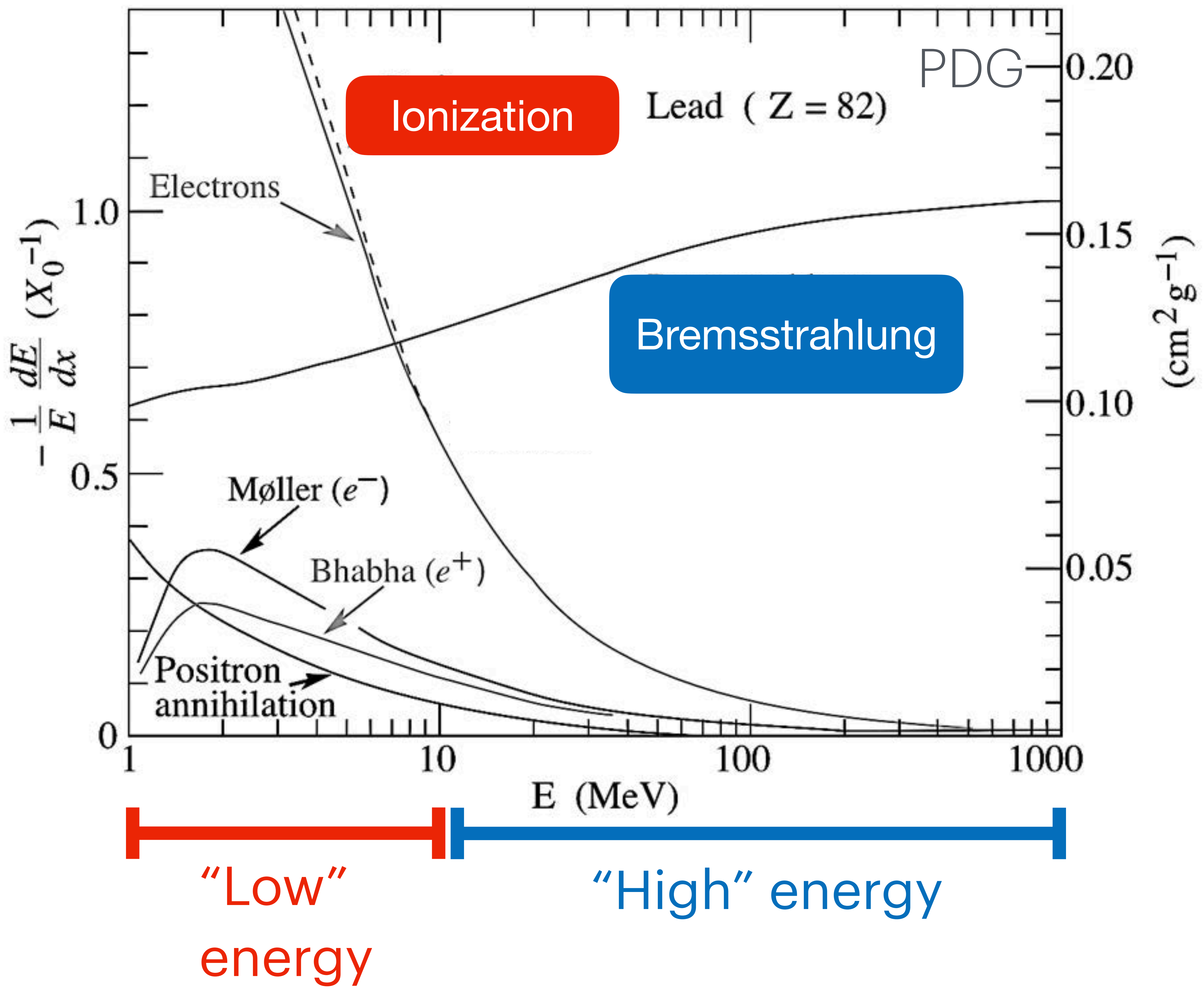


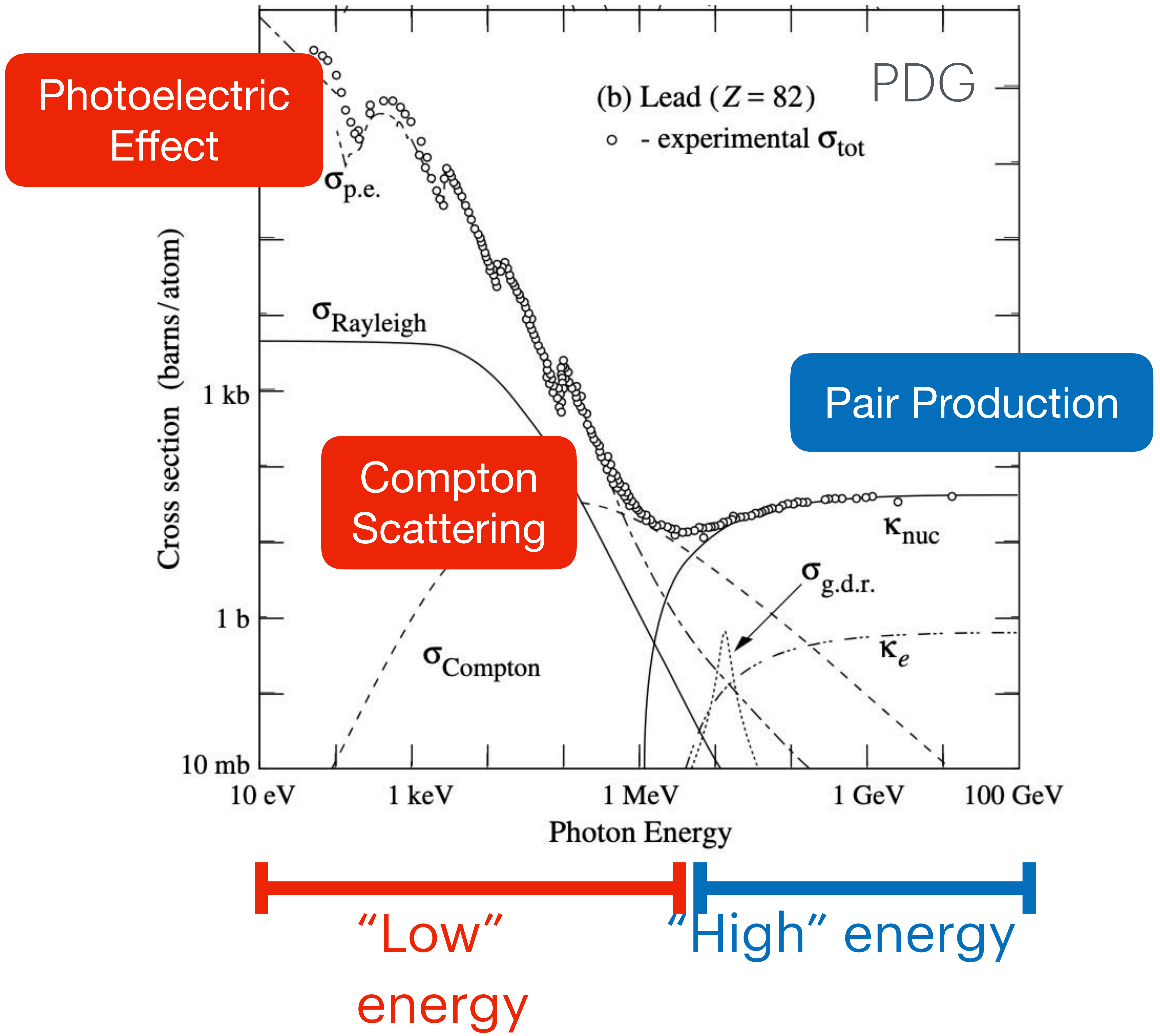
Pair Production

"High" energy

For E $\geq$ 1 GeV, mostly independent of energy

Electron and Photons interactions with matter





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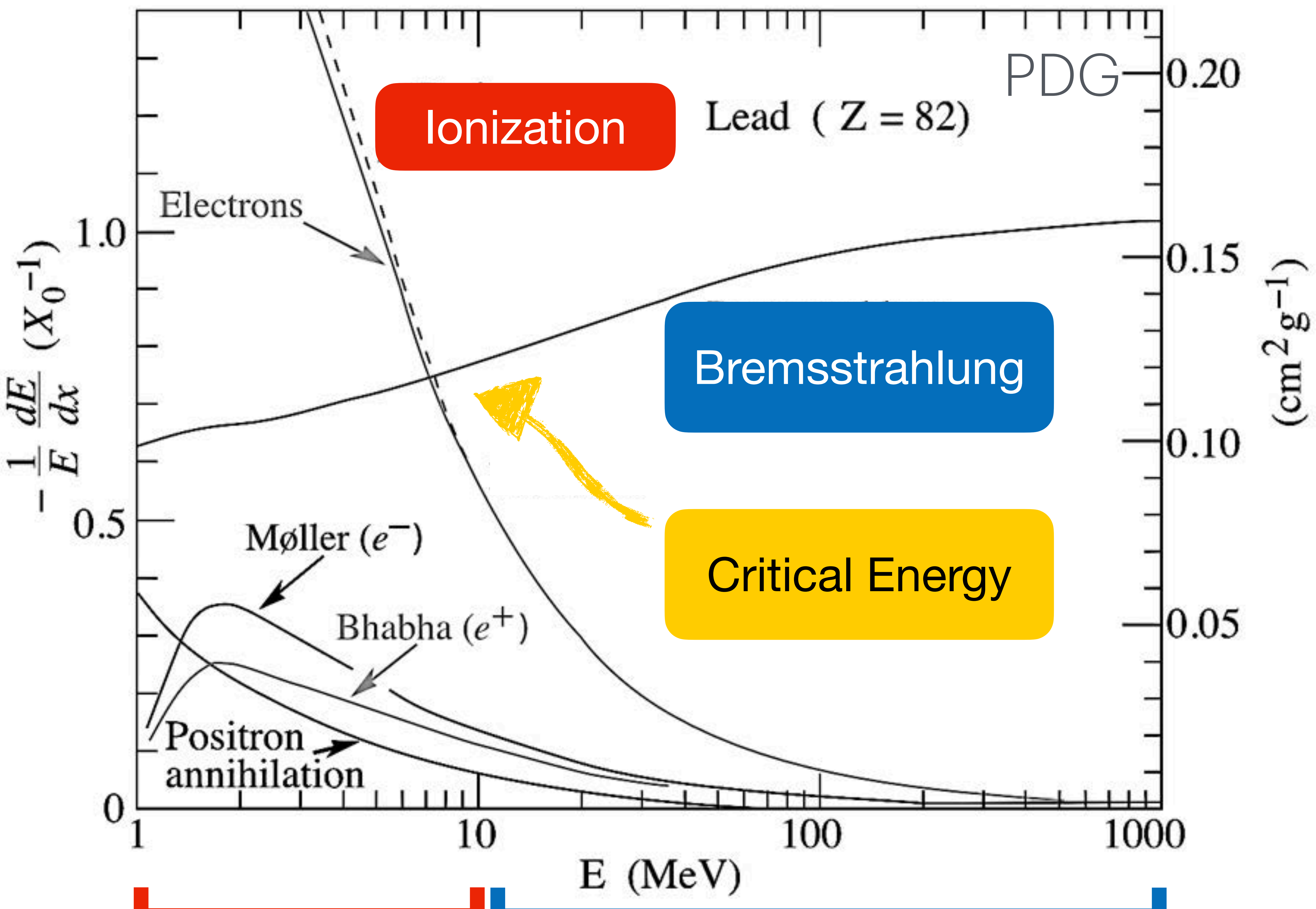
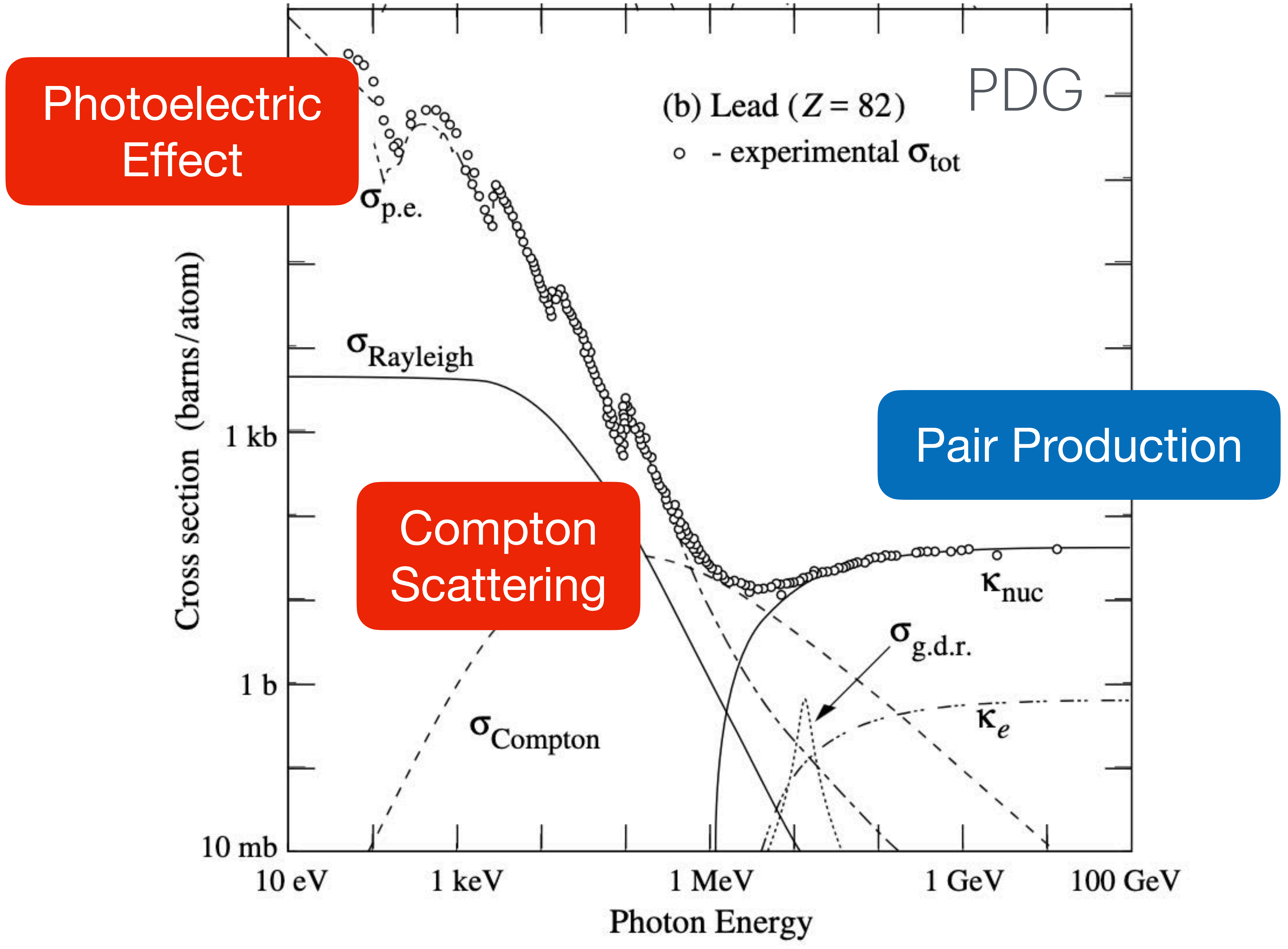


"Low" energy

"High" energy



"Low" energy

"High" energy

Electromagnetic Showers

Electron/Photons with $\geq$ 1 GeV
initiate an electromagnetic shower

Electromagnetic Showers

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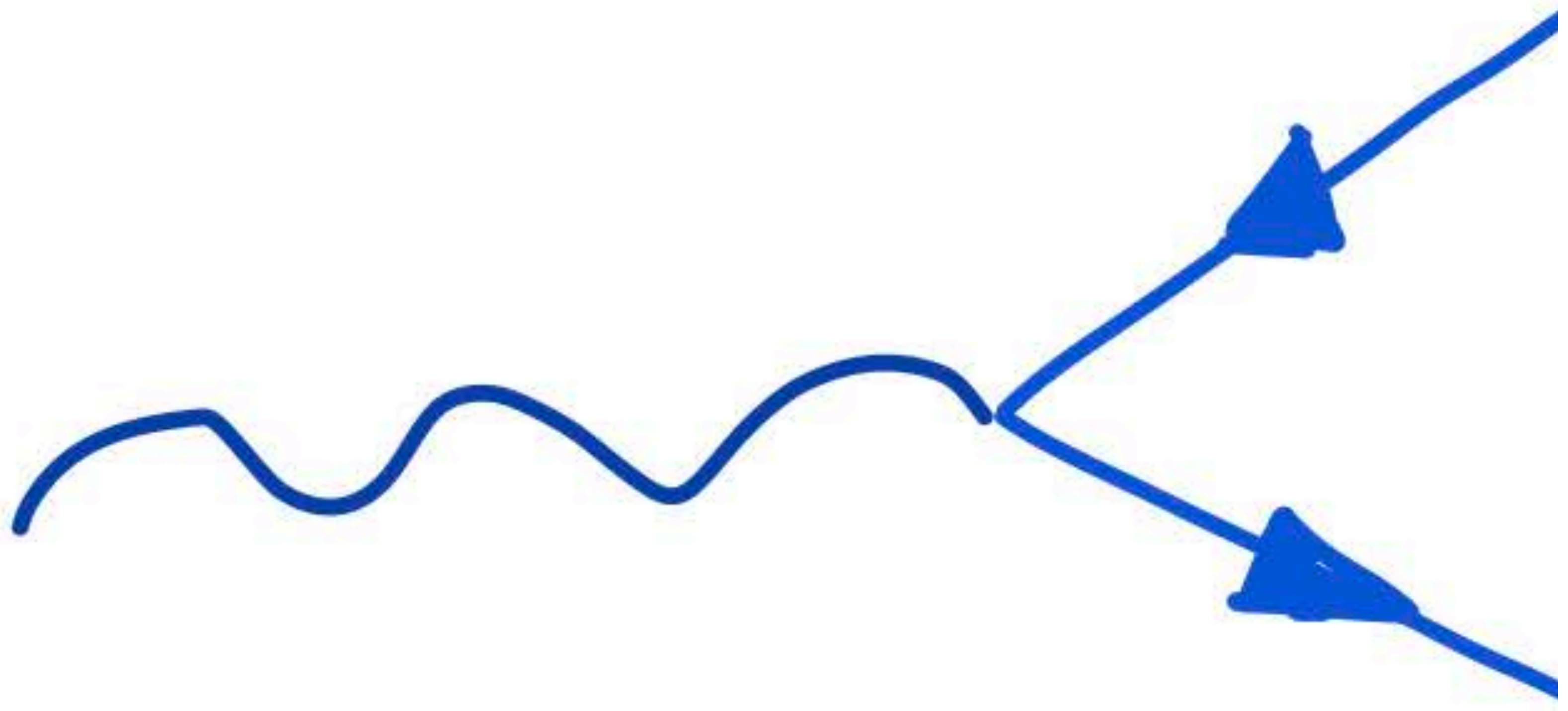

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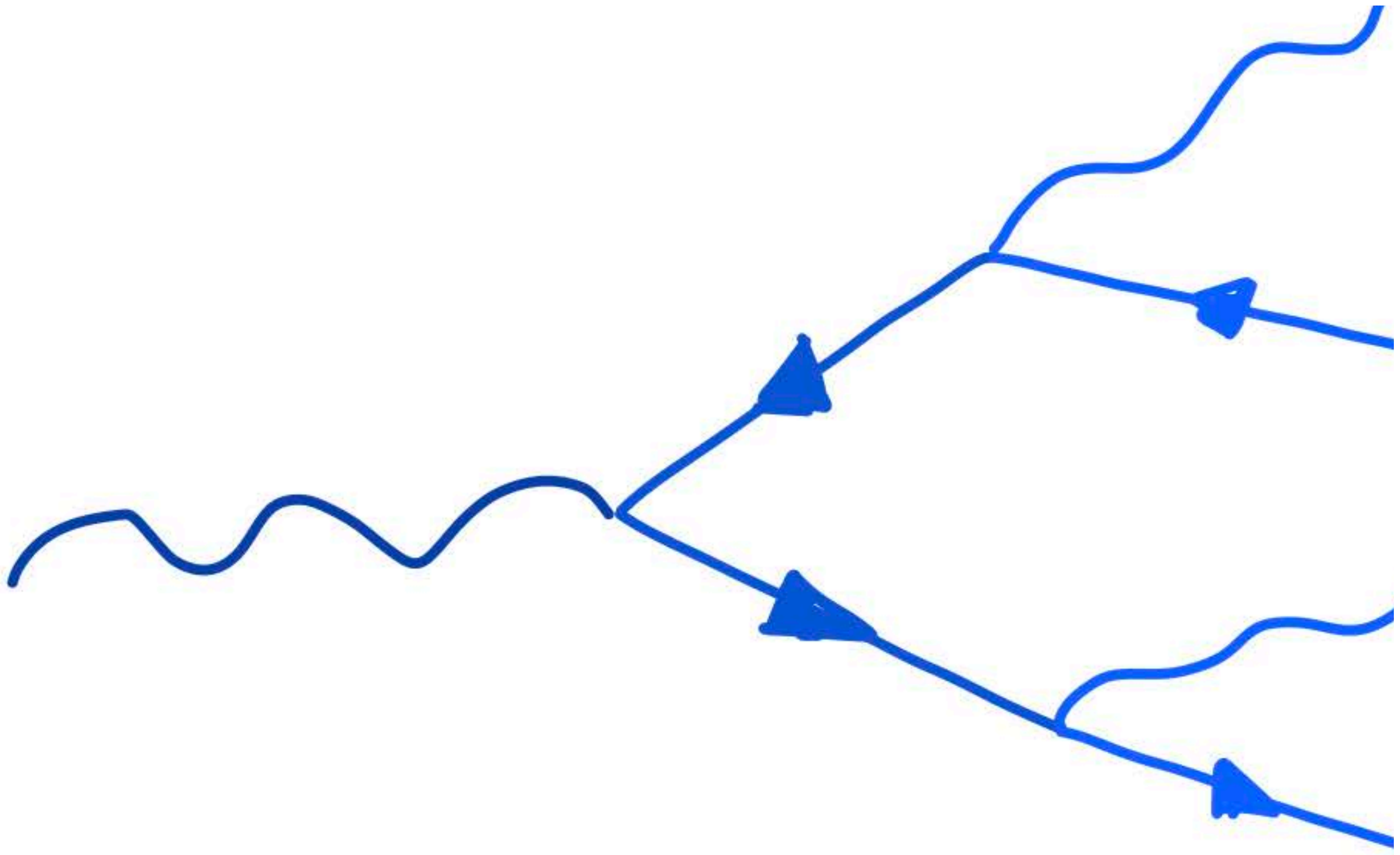

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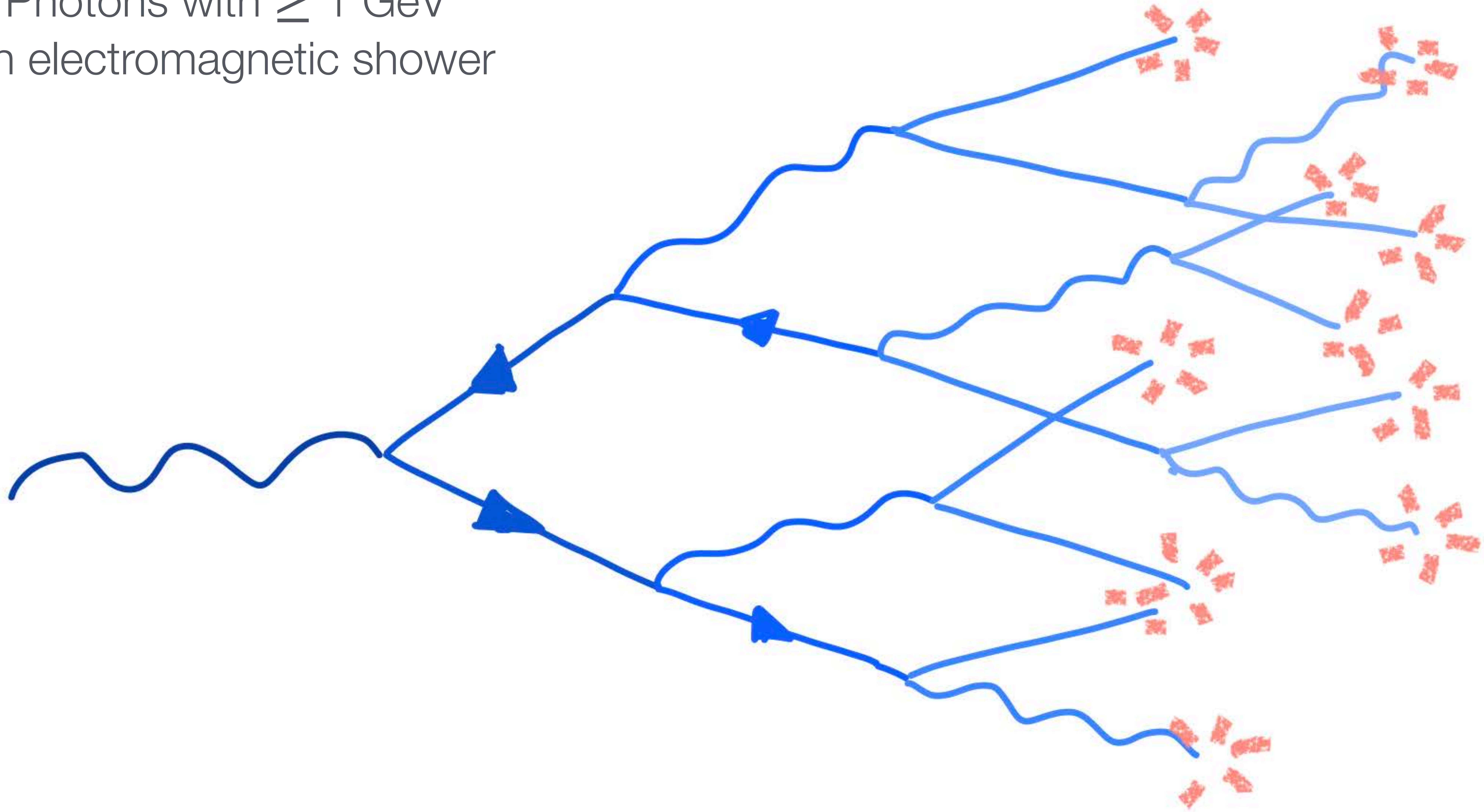
Courtesy of Kate Pachal

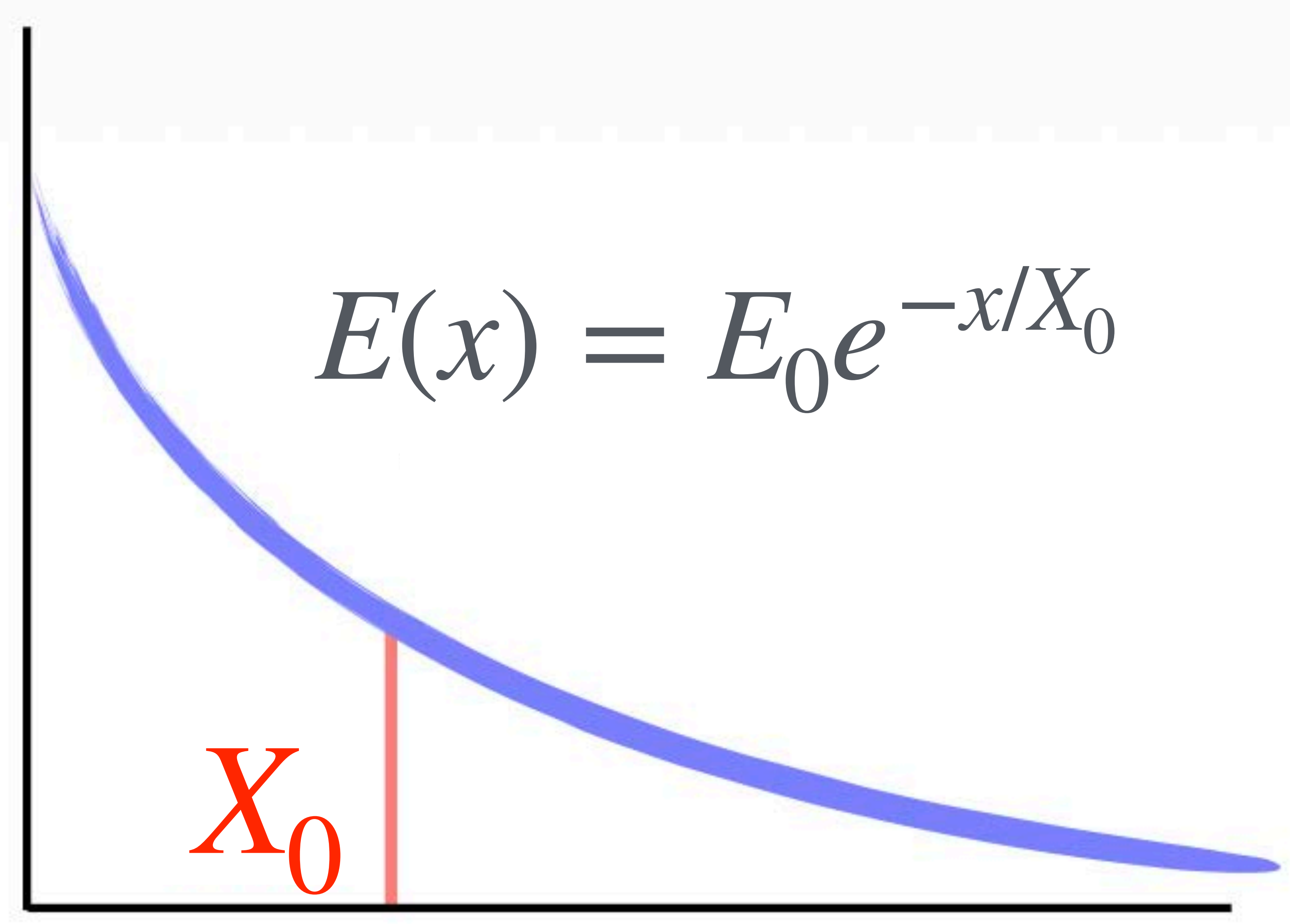


EM Shower : Longitudinal development

- Longitudinal shower development governed by high-energy part of the cascade

- Shower development can be described in terms of “**radiation length**"

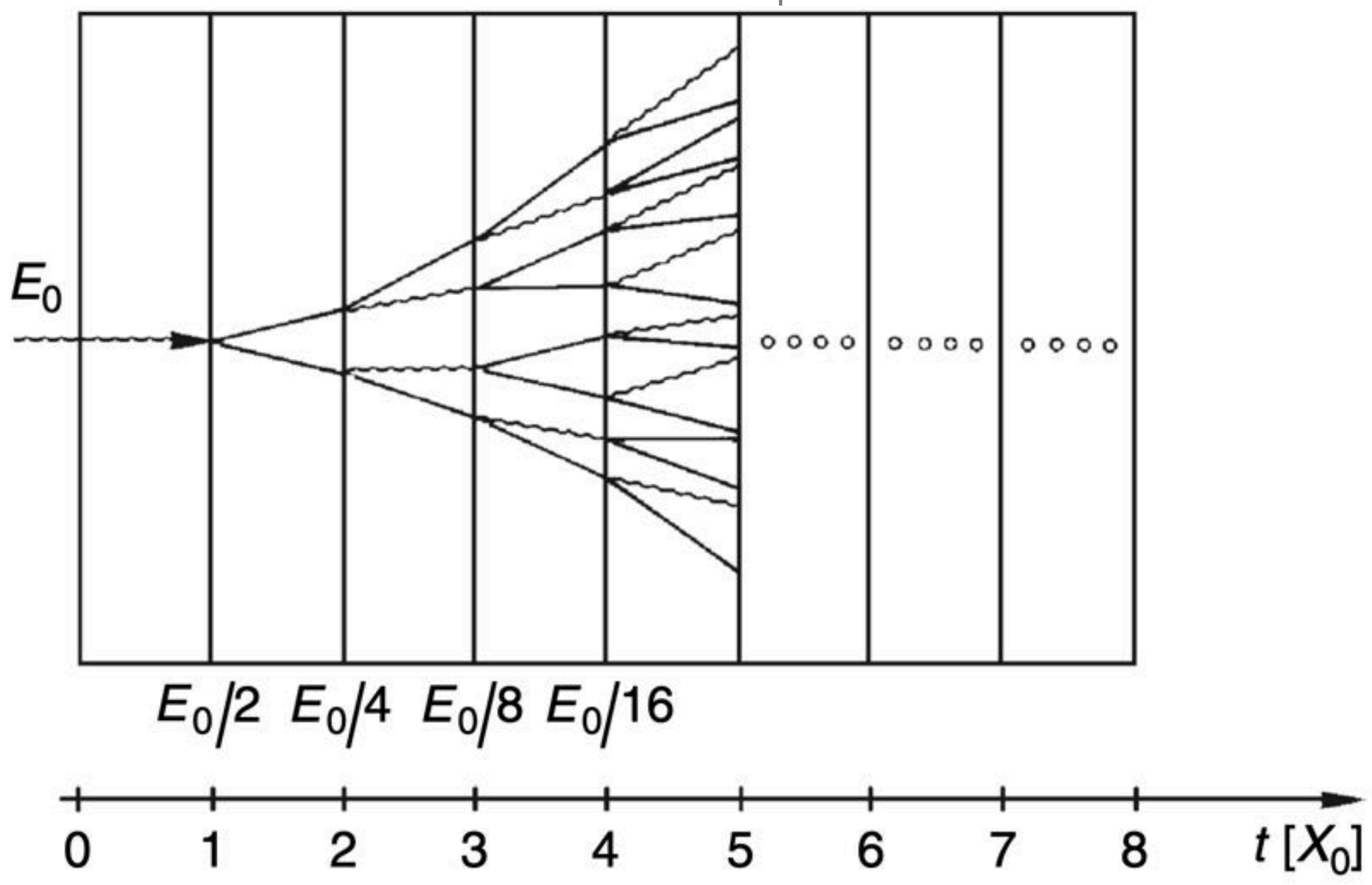
- Radiation length (X_0) : Average distance over which a high-energy electron loses all but $1/e$ (~37%) of its energy due to bremsstrahlung
  - Units: g/cm^2
  - $X_0 \propto A/Z^2$



EM Shower : Longitudinal development

- Simple shower model:
  - Interaction every ~ X_0
  - Energy shared equally at each interaction
  - Showering process continues until E_c

Grupen & Schwartz



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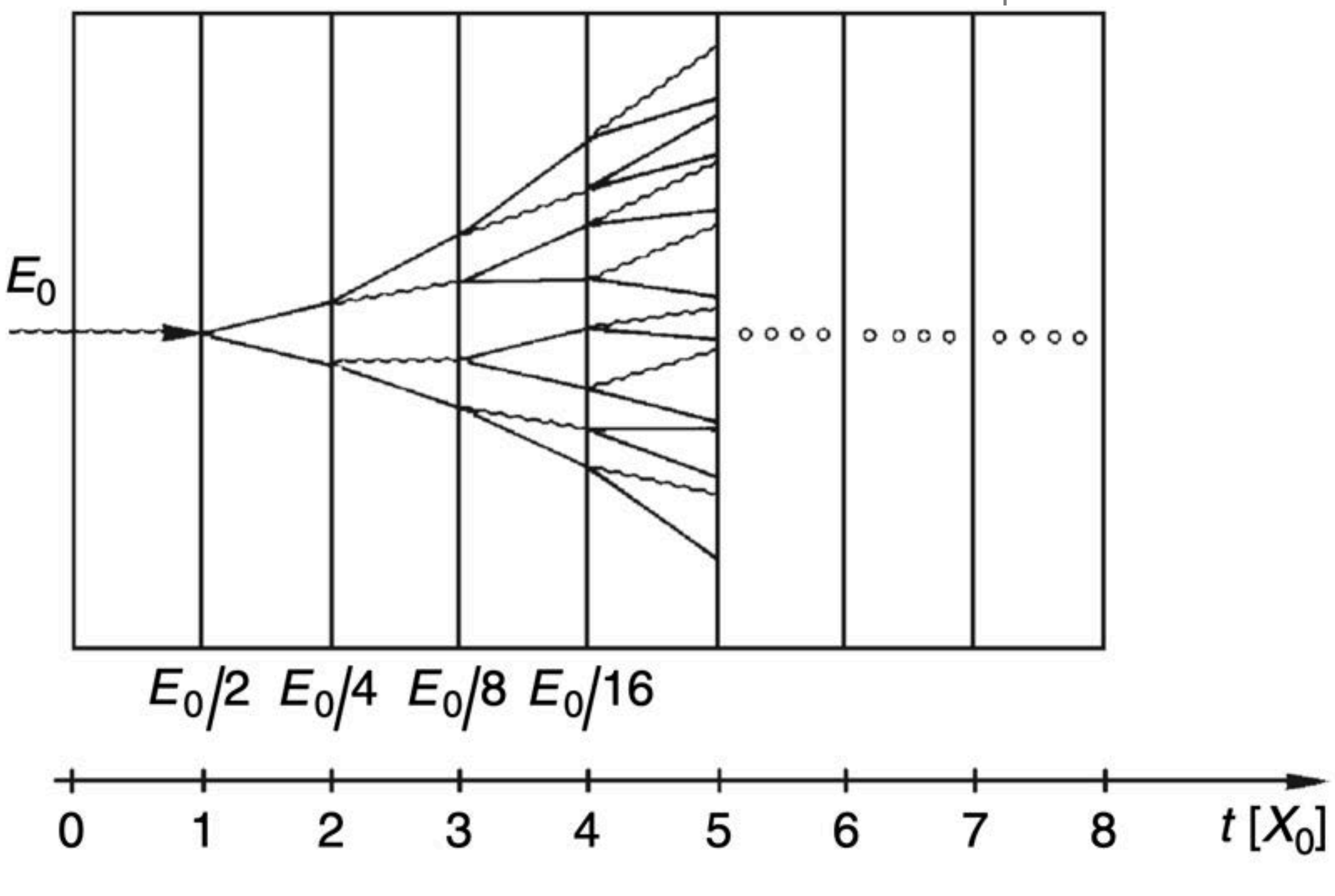

- Depth at which shower maximum occurs :

$$t_{max} = \log_2\left(E_0/E_c\right)$$

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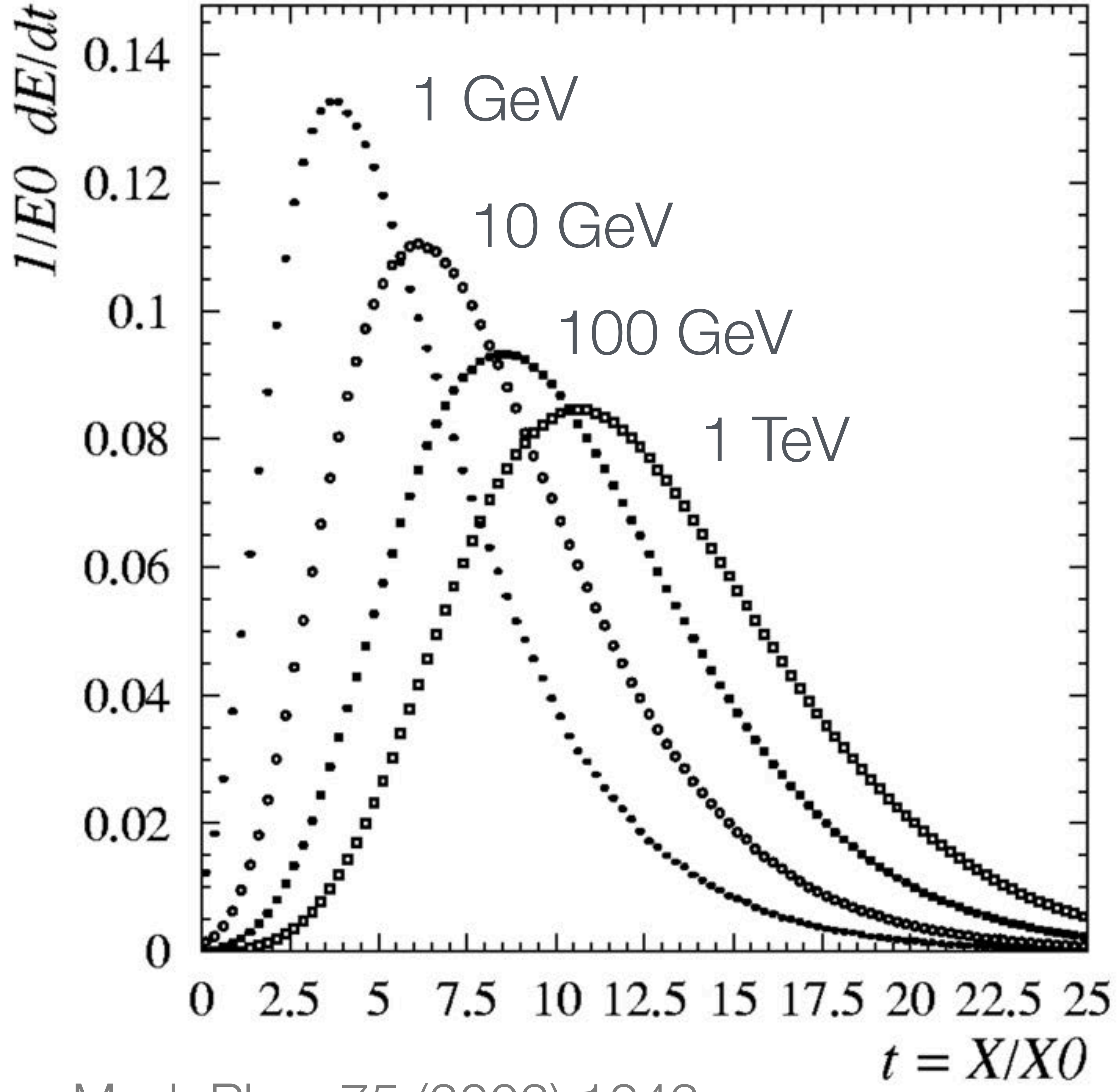

Rev. Mod. Phys 75 (2003) 1243

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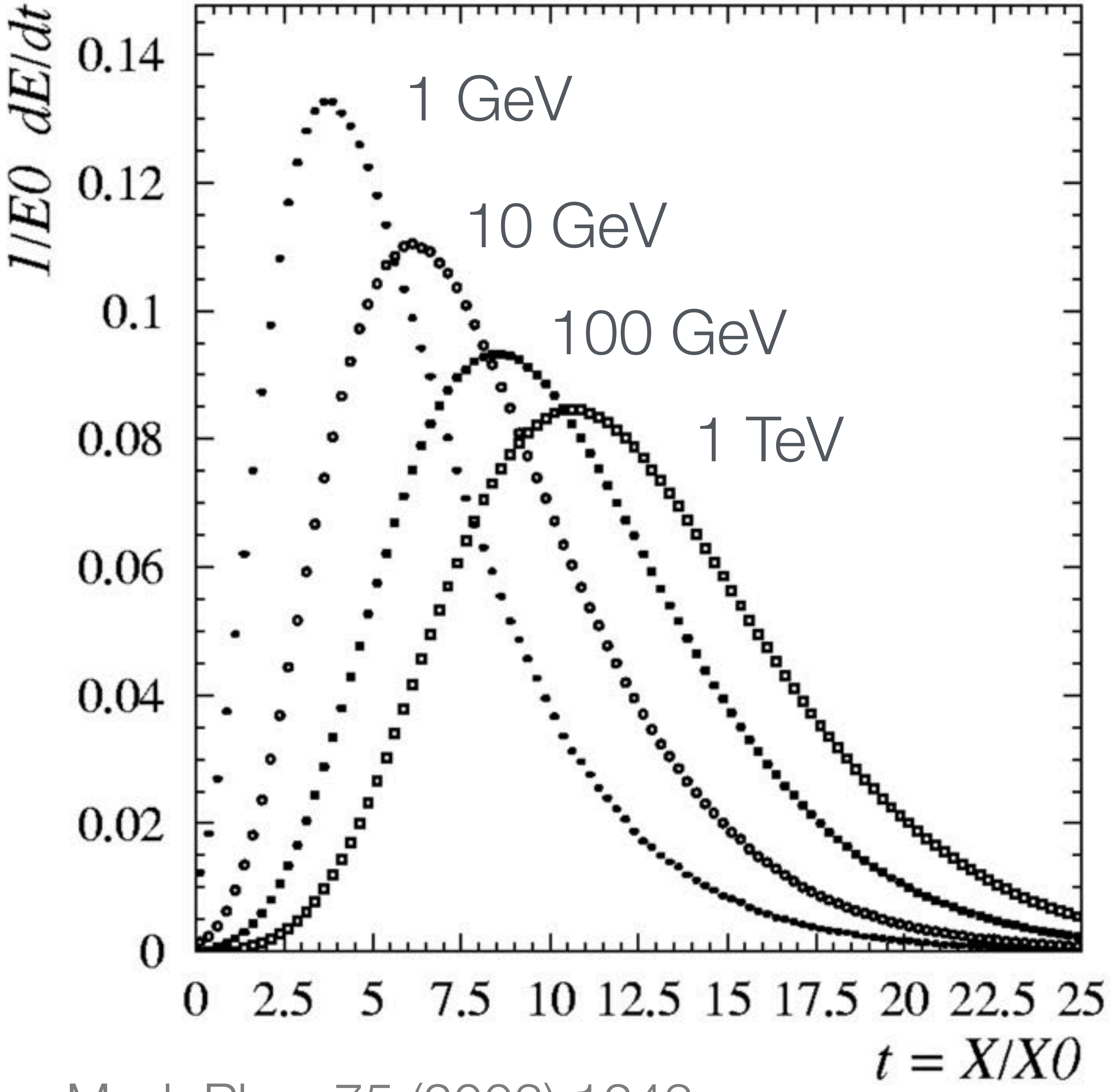

Depth for 95% of shower energy

$$t_{95\%} \simeq t_{max} + 0.08Z + 9.6$$

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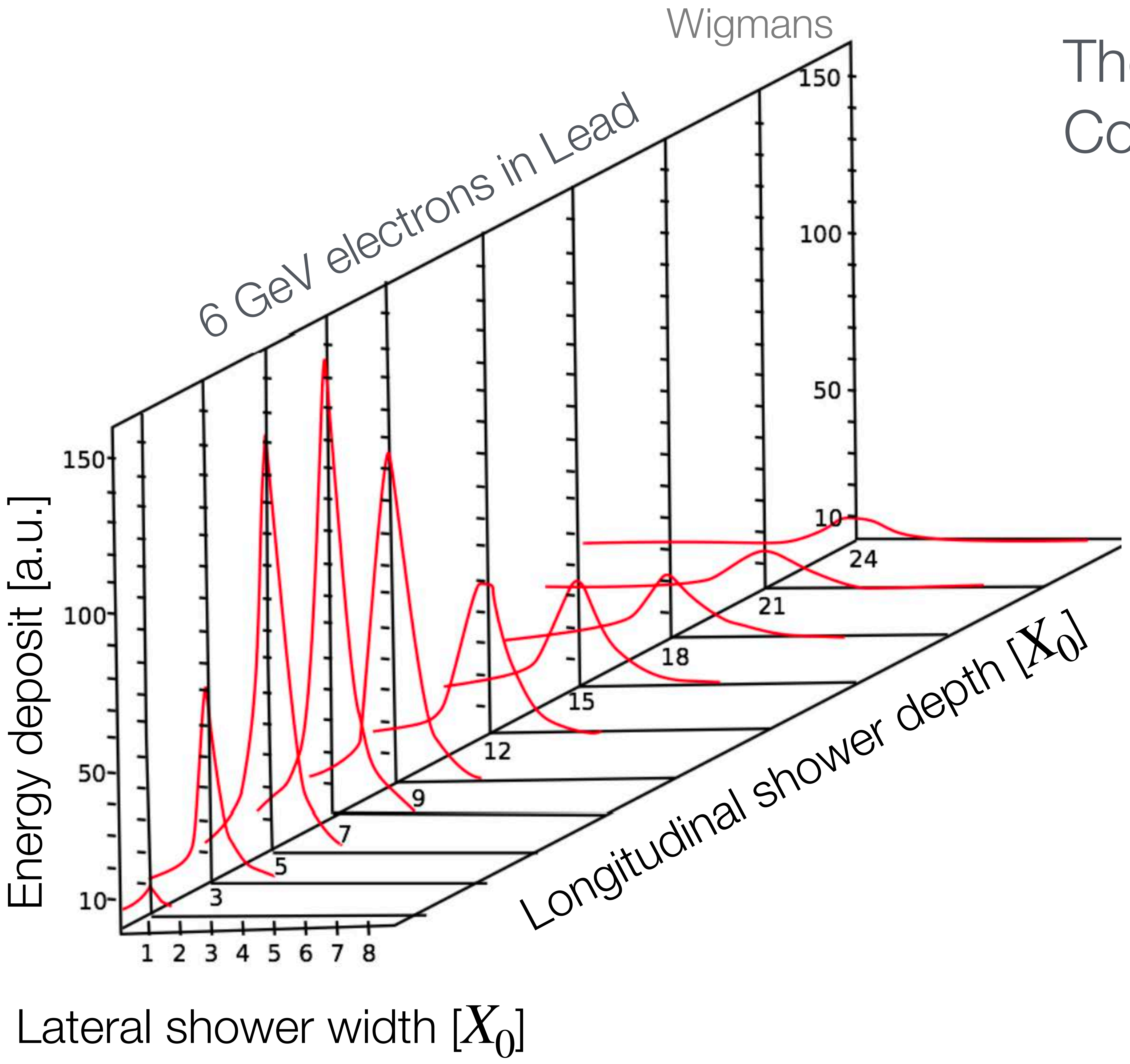
Electromagnetic Showers : Transverse development

The transverse size mainly due to multiple Coulomb scattering of electrons/positrons



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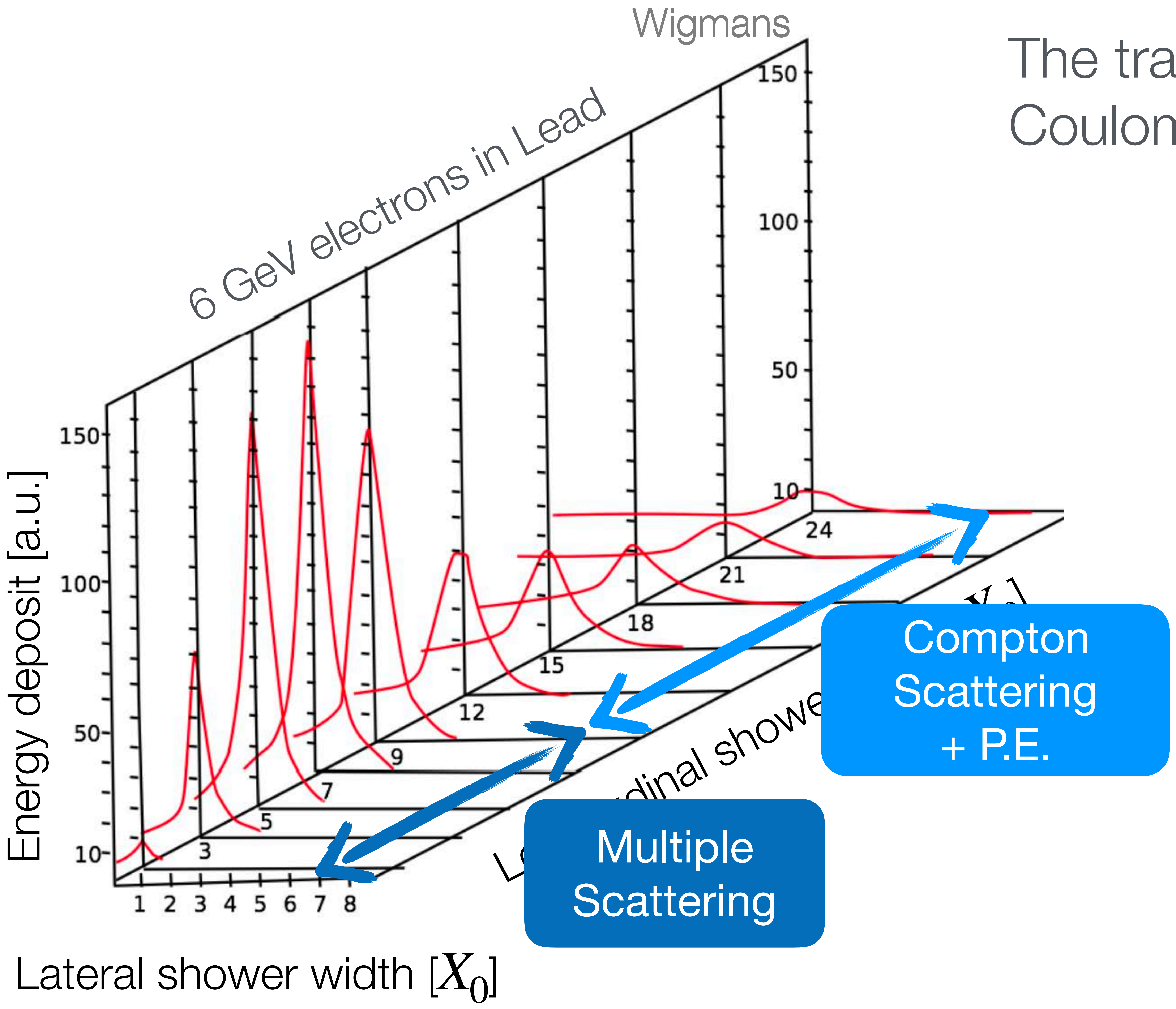

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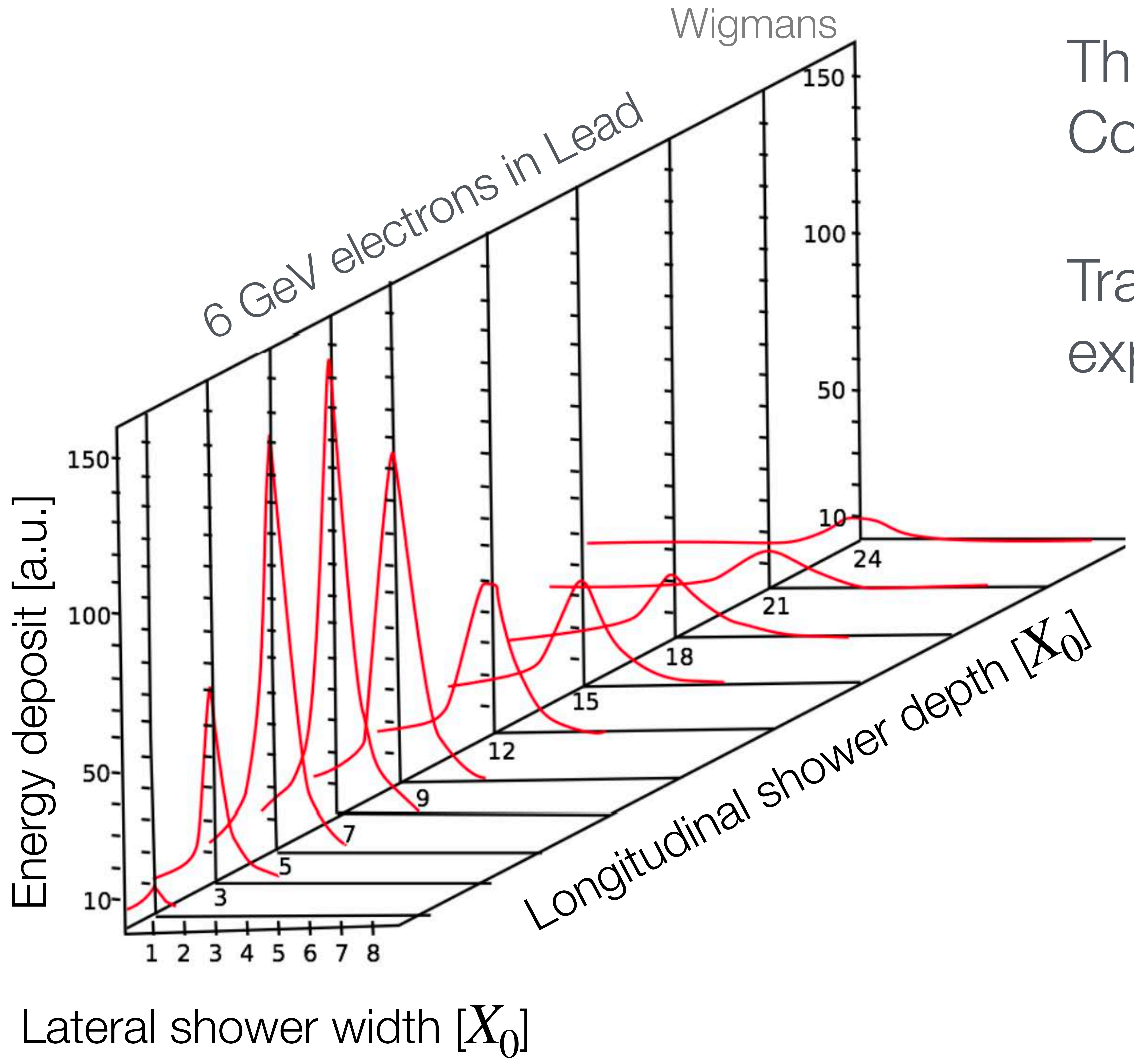

The transverse size mainly due to multiple Coulomb scattering of electrons/positrons

Transverse dimension conveniently expressed in terms of Molière radius:

$$R_M \simeq \frac{21\ \text{MeV}}{E_c}\, X_0 \quad [g/cm^2]$$

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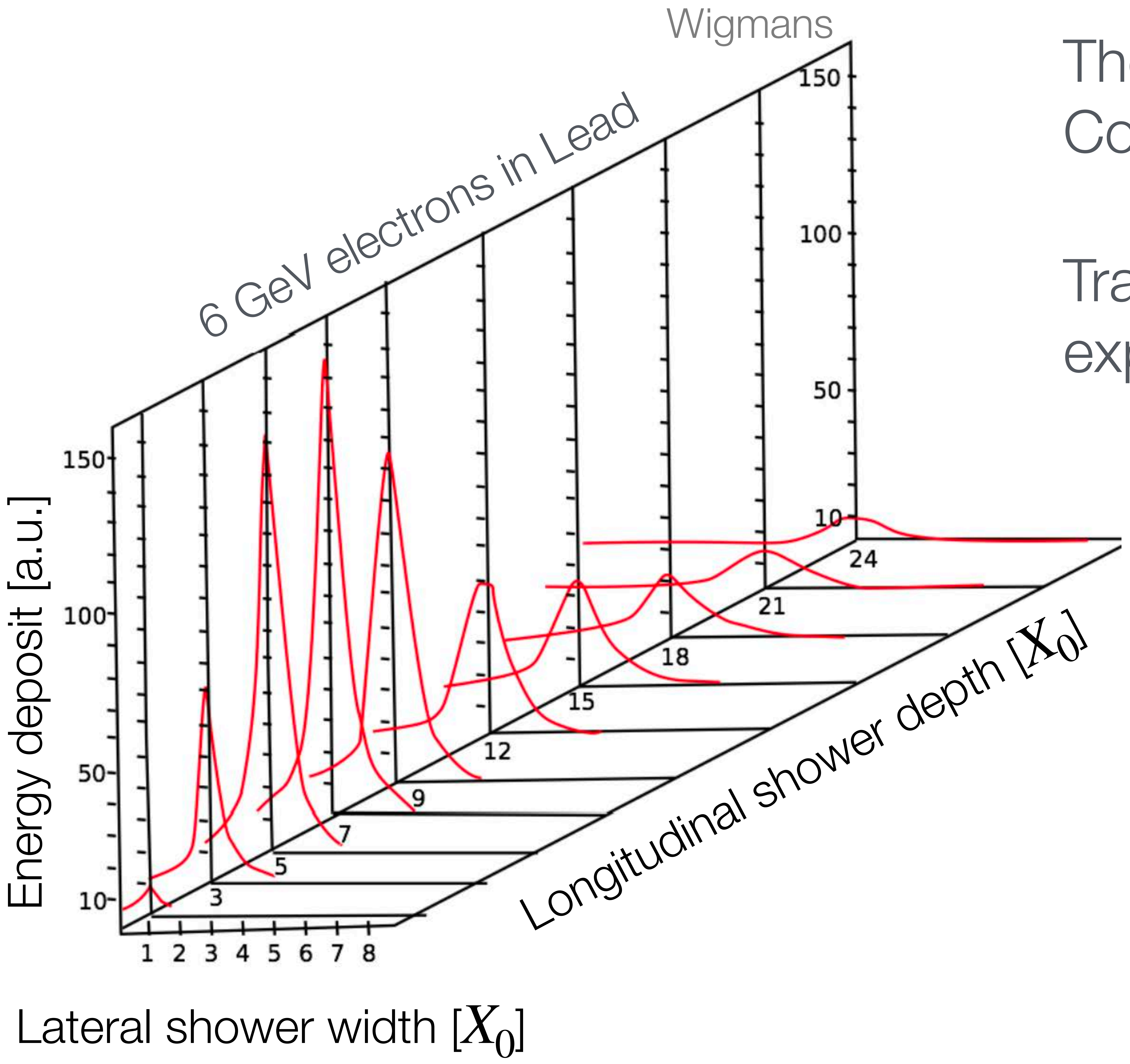

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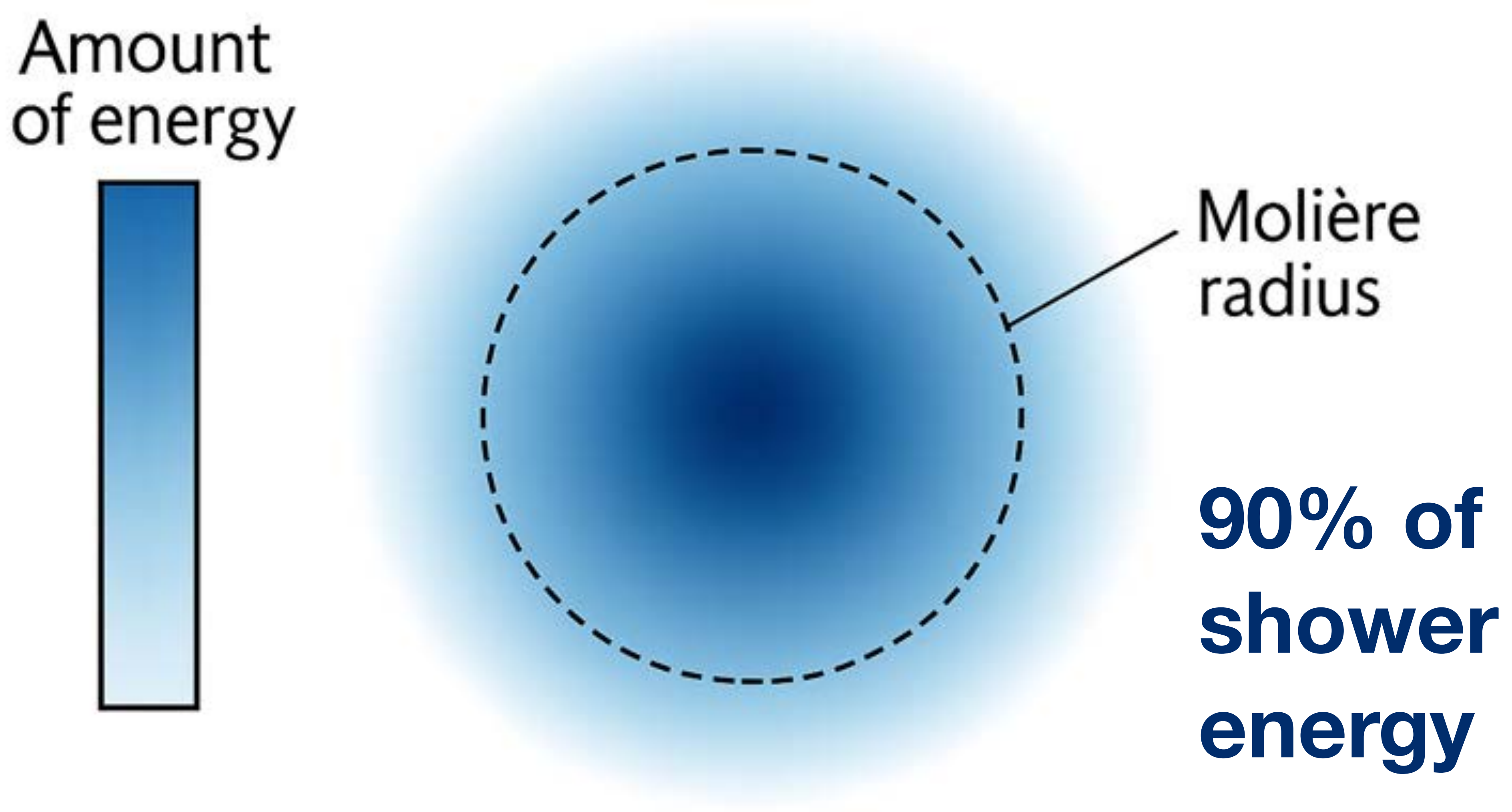

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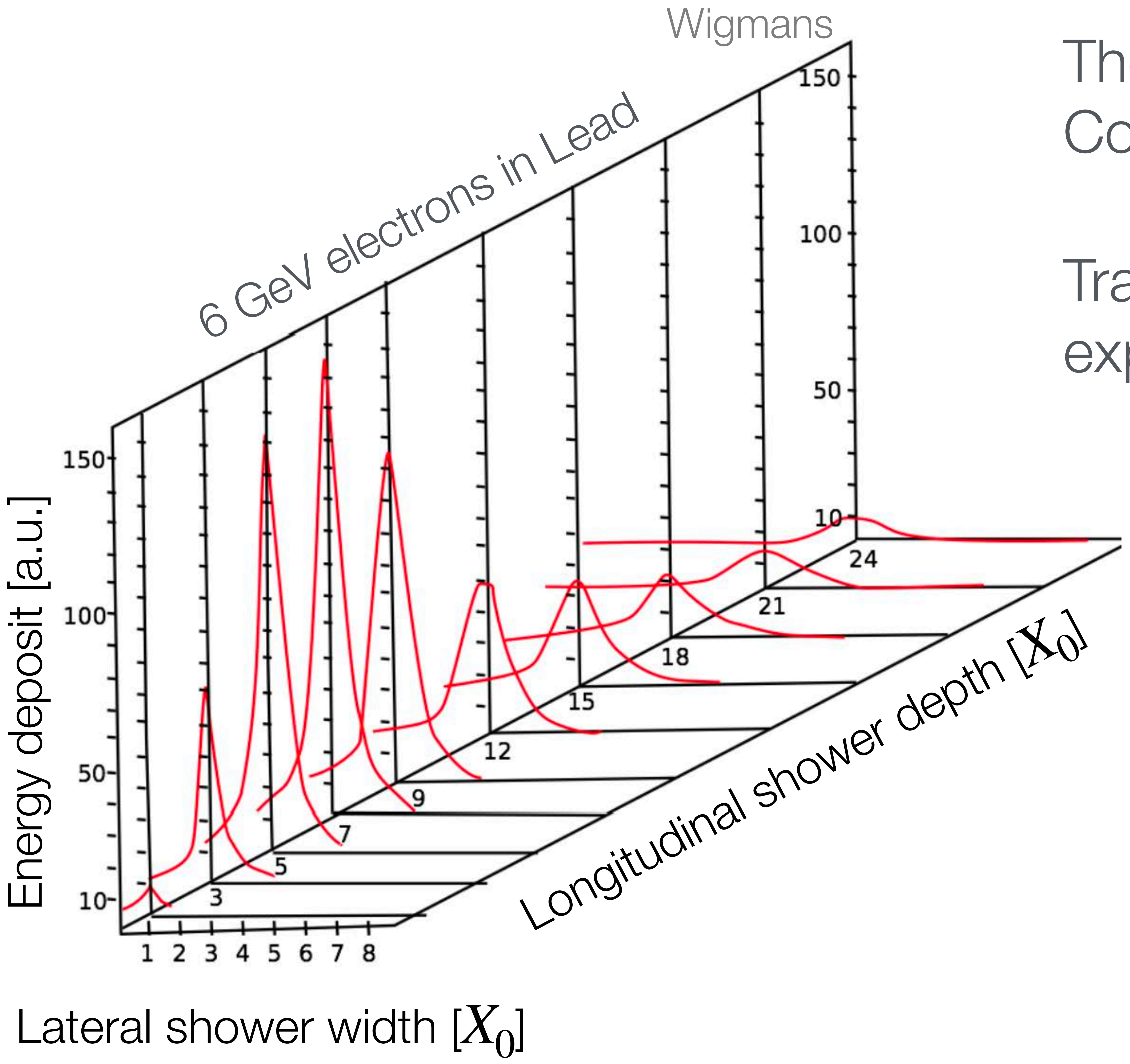

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$X_0 \rightarrow \frac{A}{Z^2}$

$E_c \rightarrow \frac{1}{Z}$

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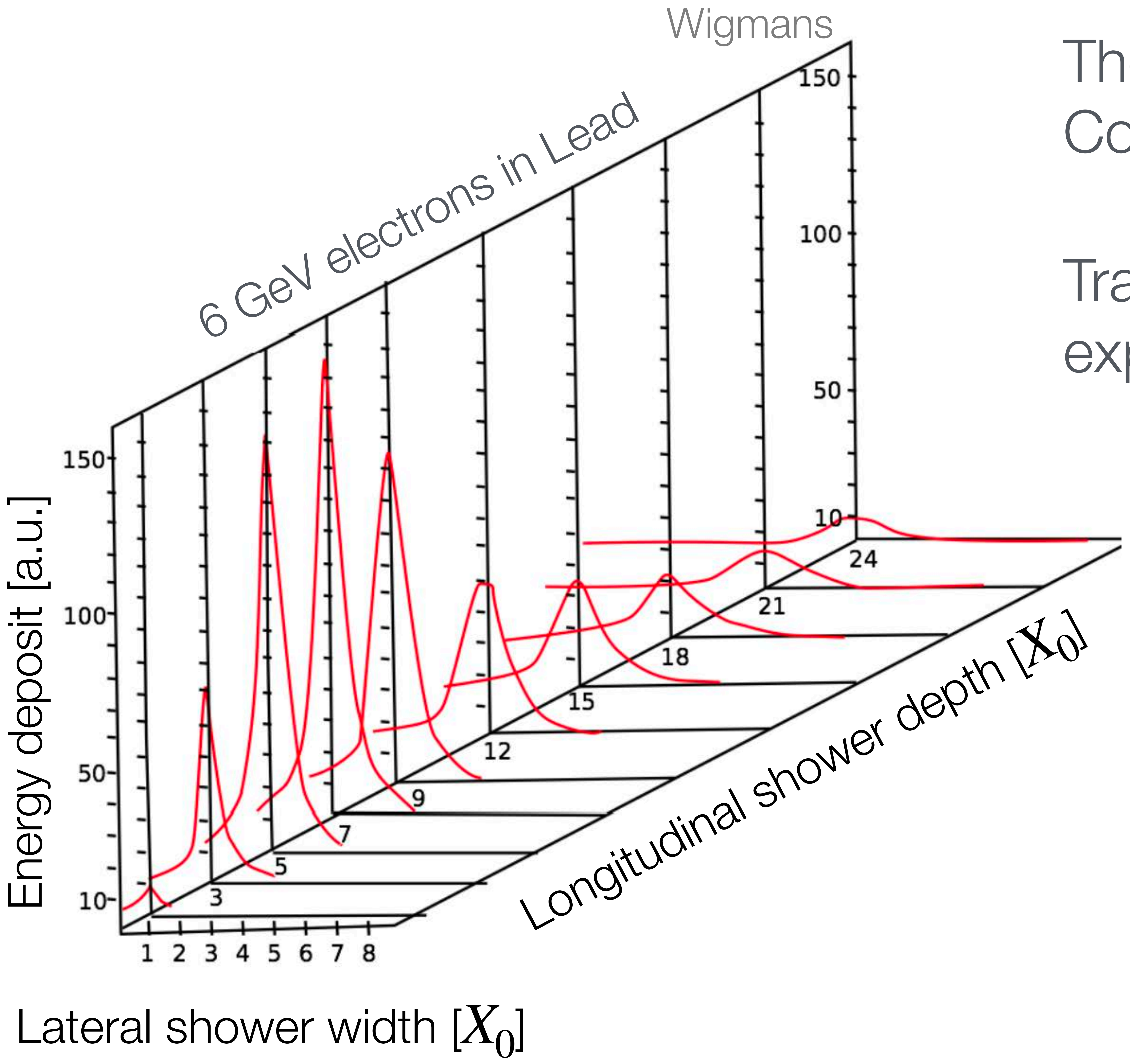

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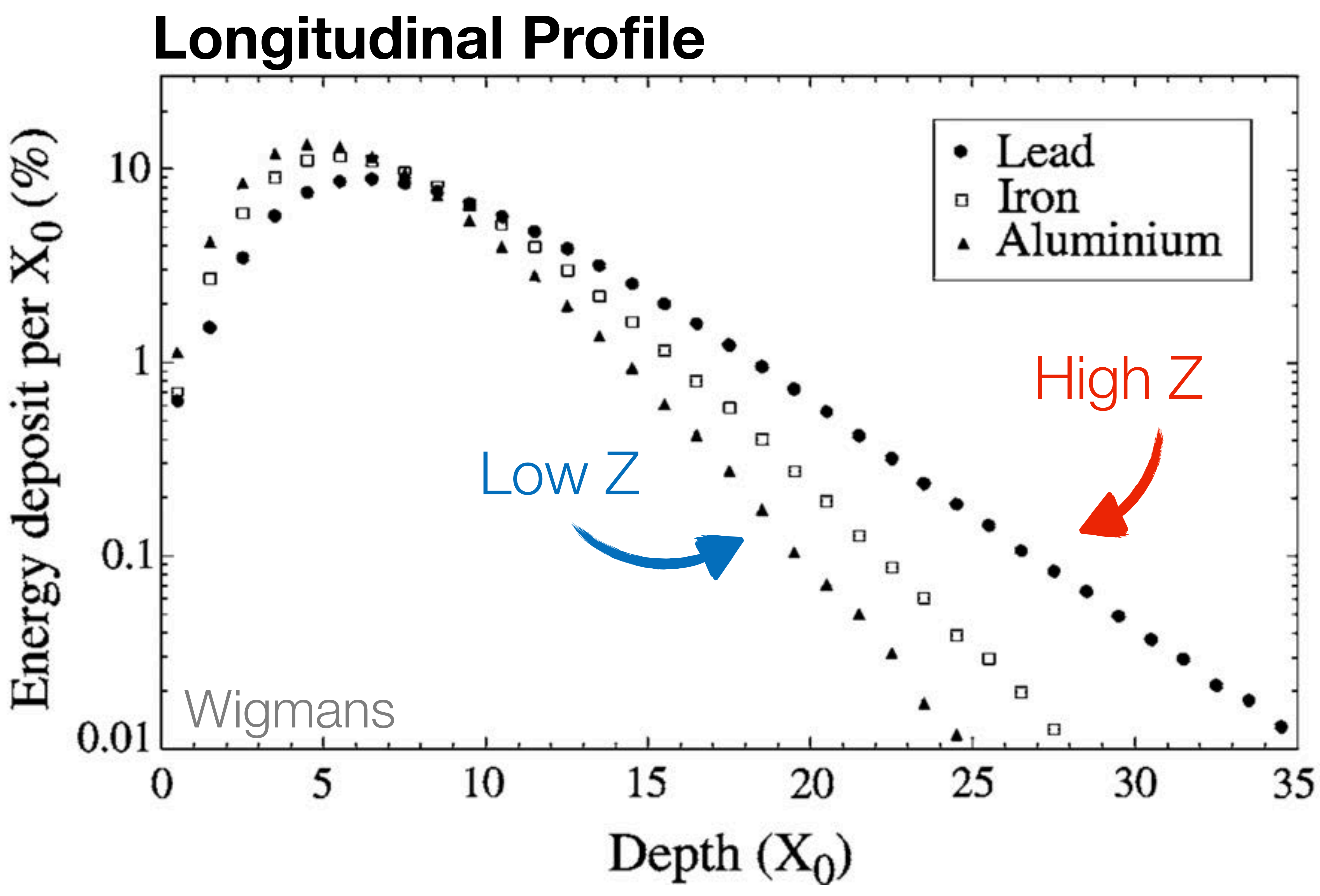
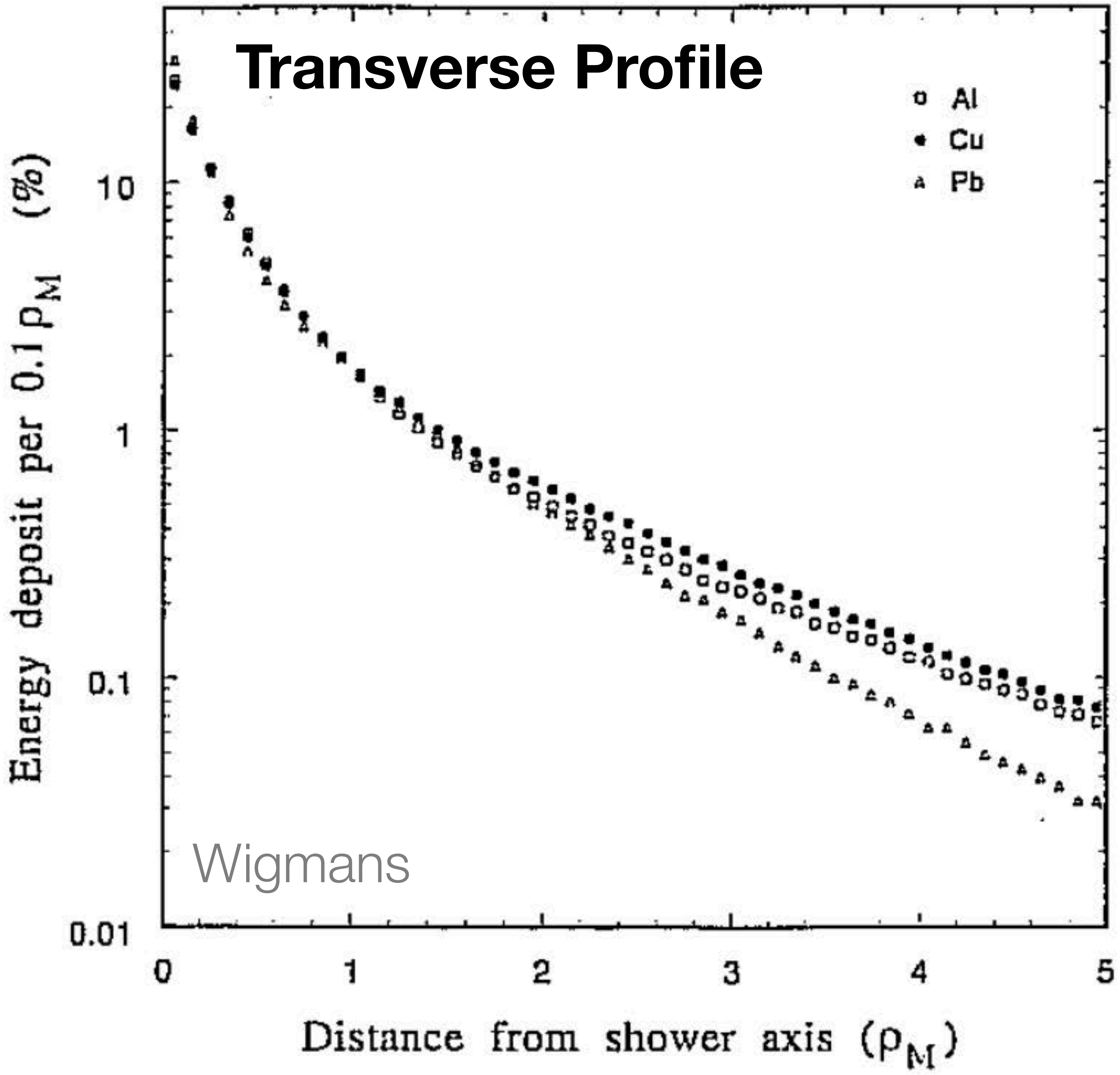
Transverse dimension conveniently expressed in terms of Molière radius:

$$R_M \sim \frac{X_0}{E_c} \sim \frac{A}{Z}$$

Electromagnetic Showers : Material dependence

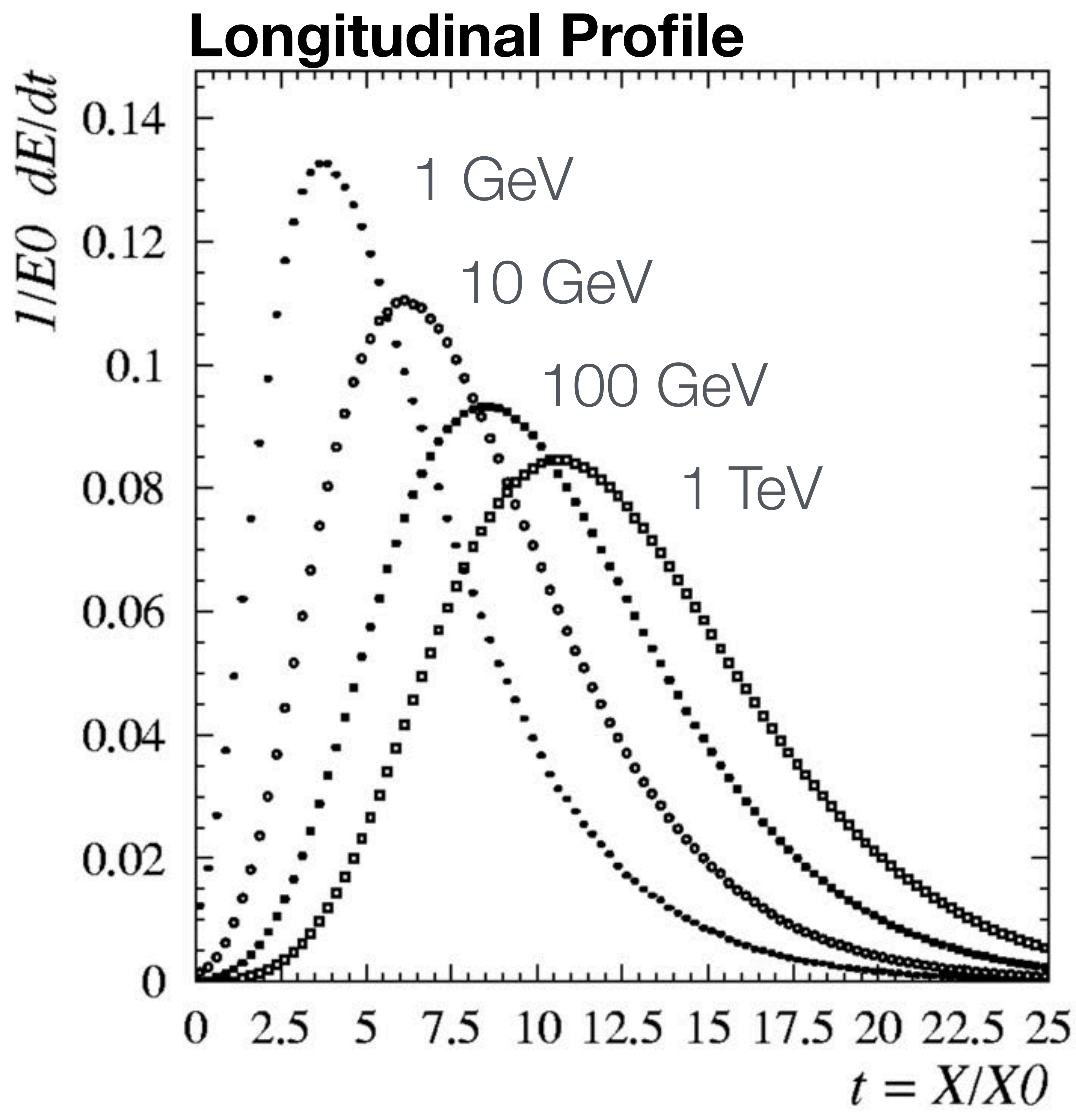
Expressed in terms of X_0 and R_M, electromagnetic shower development is approximately material independent.





Differences attributable to low-energy effects → differences in E_c for different materials

Electromagnetic Showers : Energy dependence



$$t_{95\%} \simeq t_{max} + 0.08Z + 9.6$$

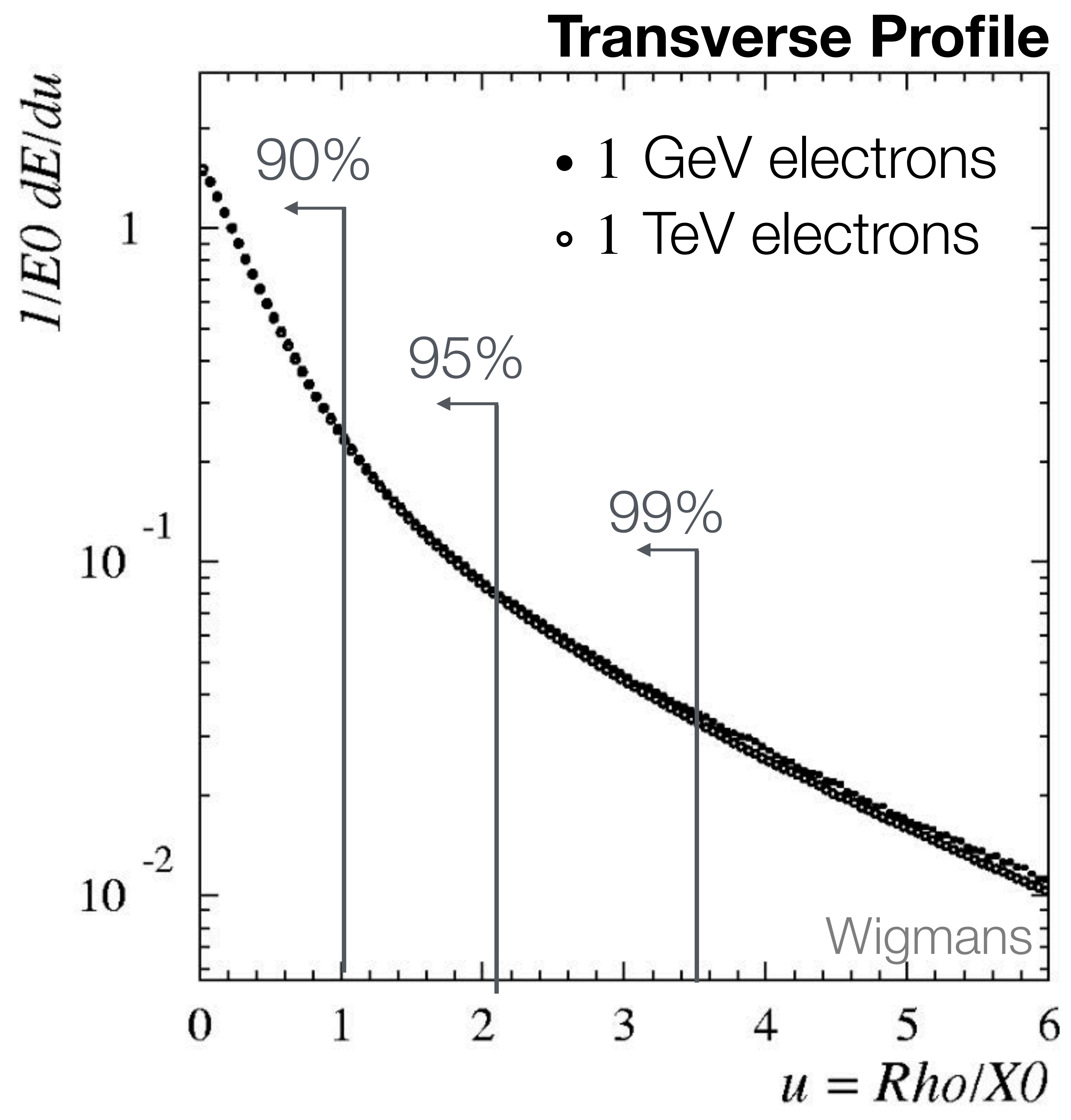
Calorimeter thickness increases logarithmically with incident particle energy

Electromagnetic Showers : Energy dependence

Transverse size roughly independent on incident particle energy.

95% of shower contained within $2R_m$

Cells of segmented calorimeter must be comparable in size to (or smaller than) one R_M to measure shower position!

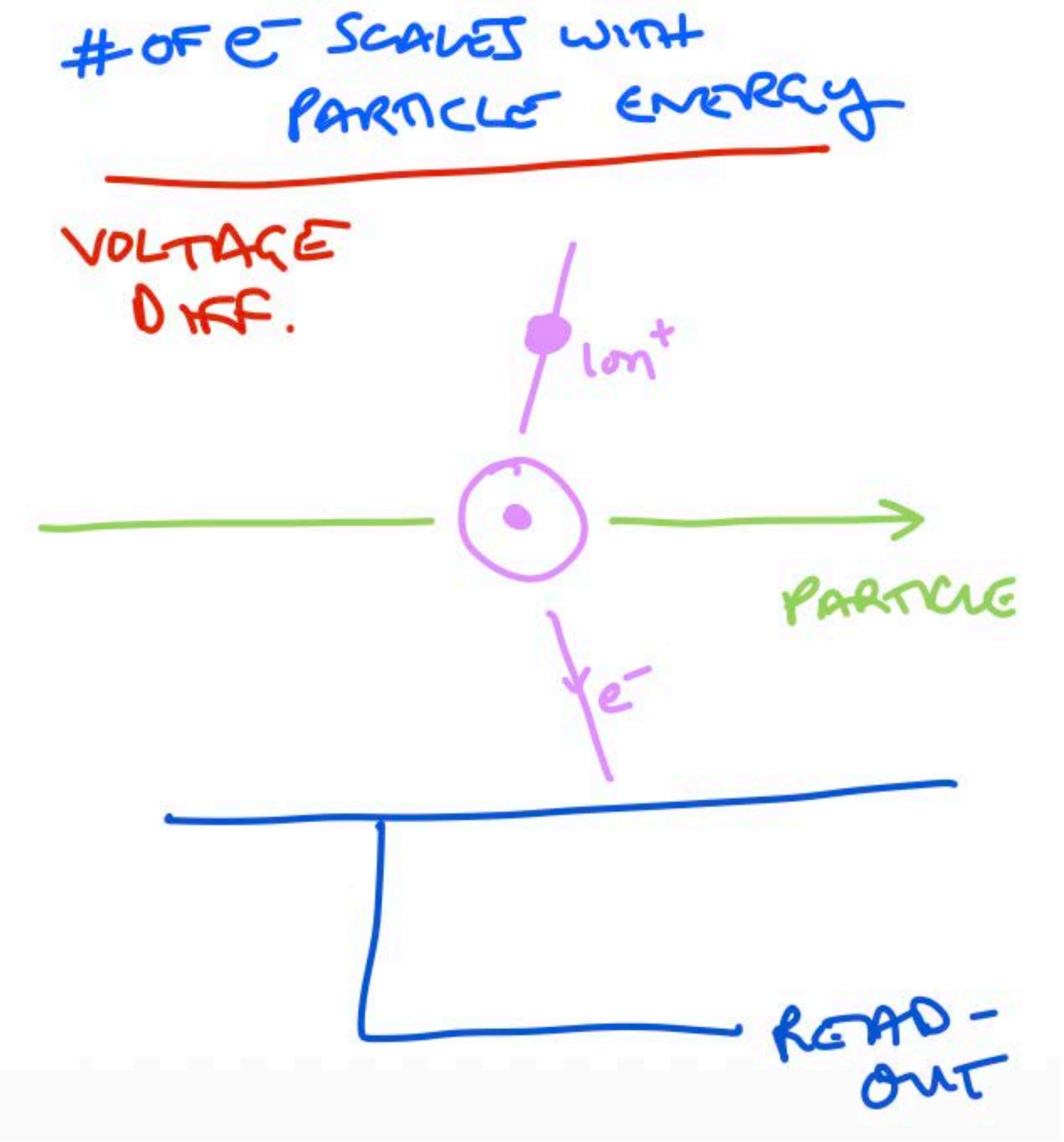


How is the shower energy made detectable?

Courtesy of Kate Pachal

How is the shower energy made detectable?

Ionisation



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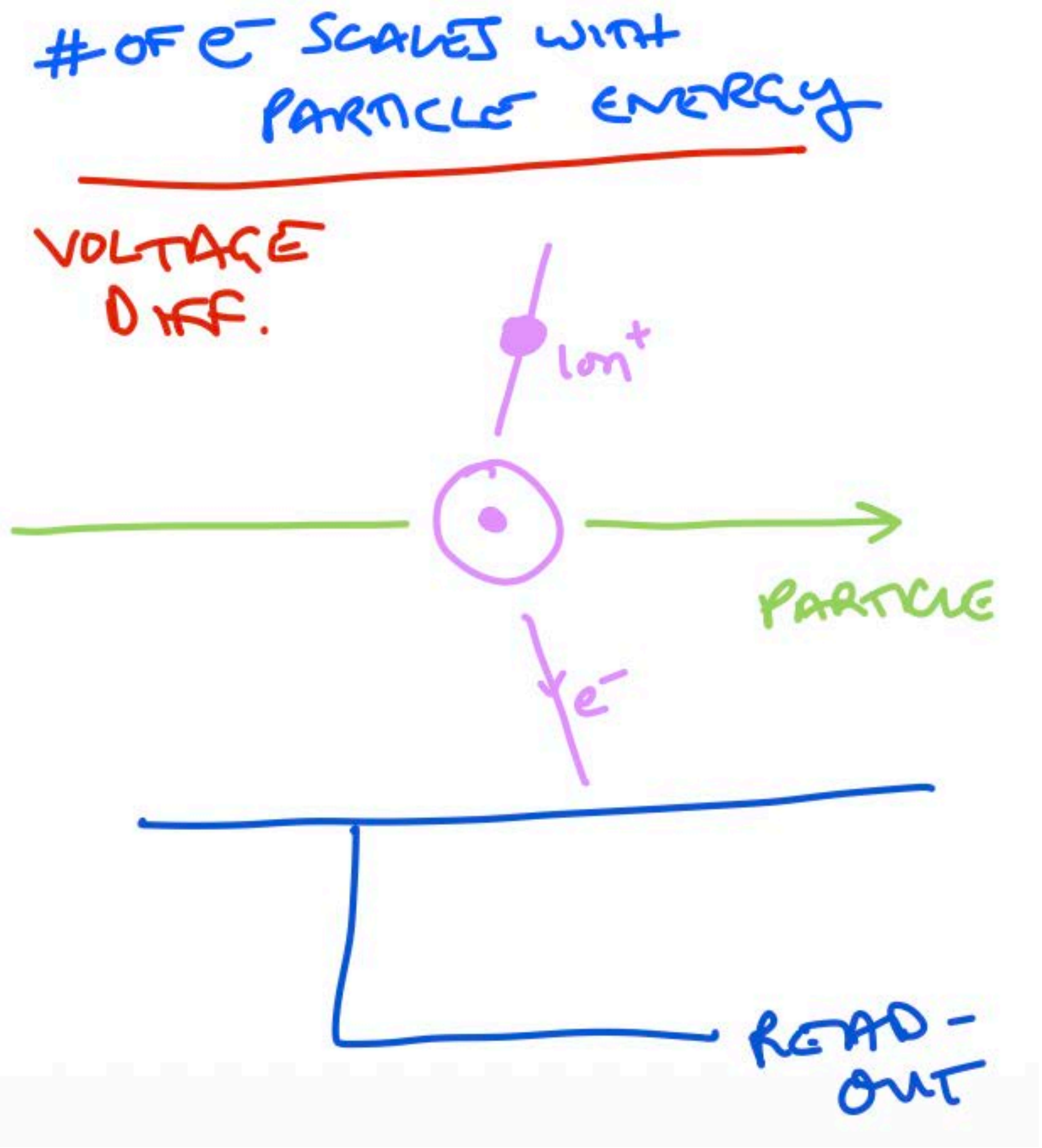
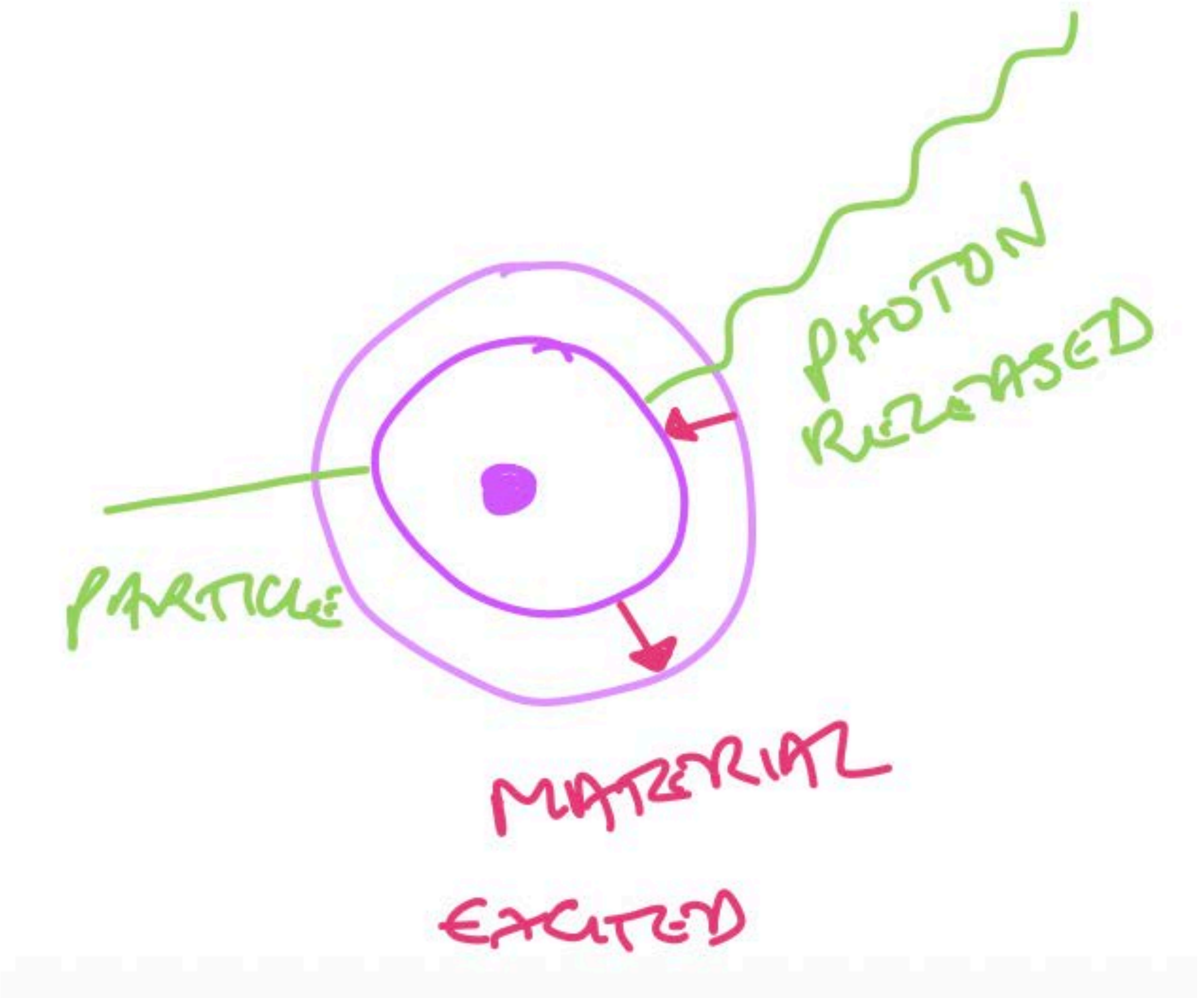


Scintillation



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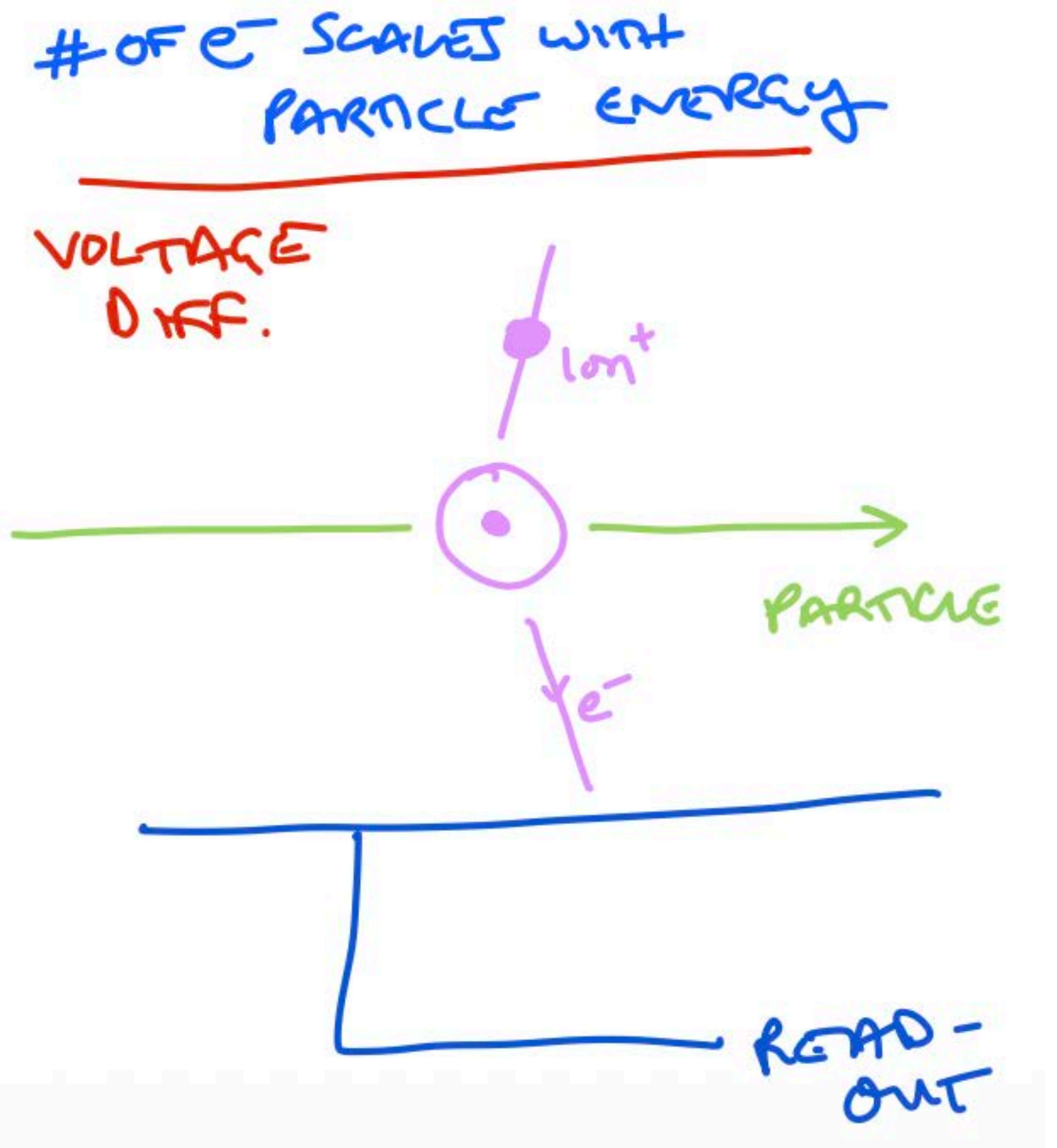

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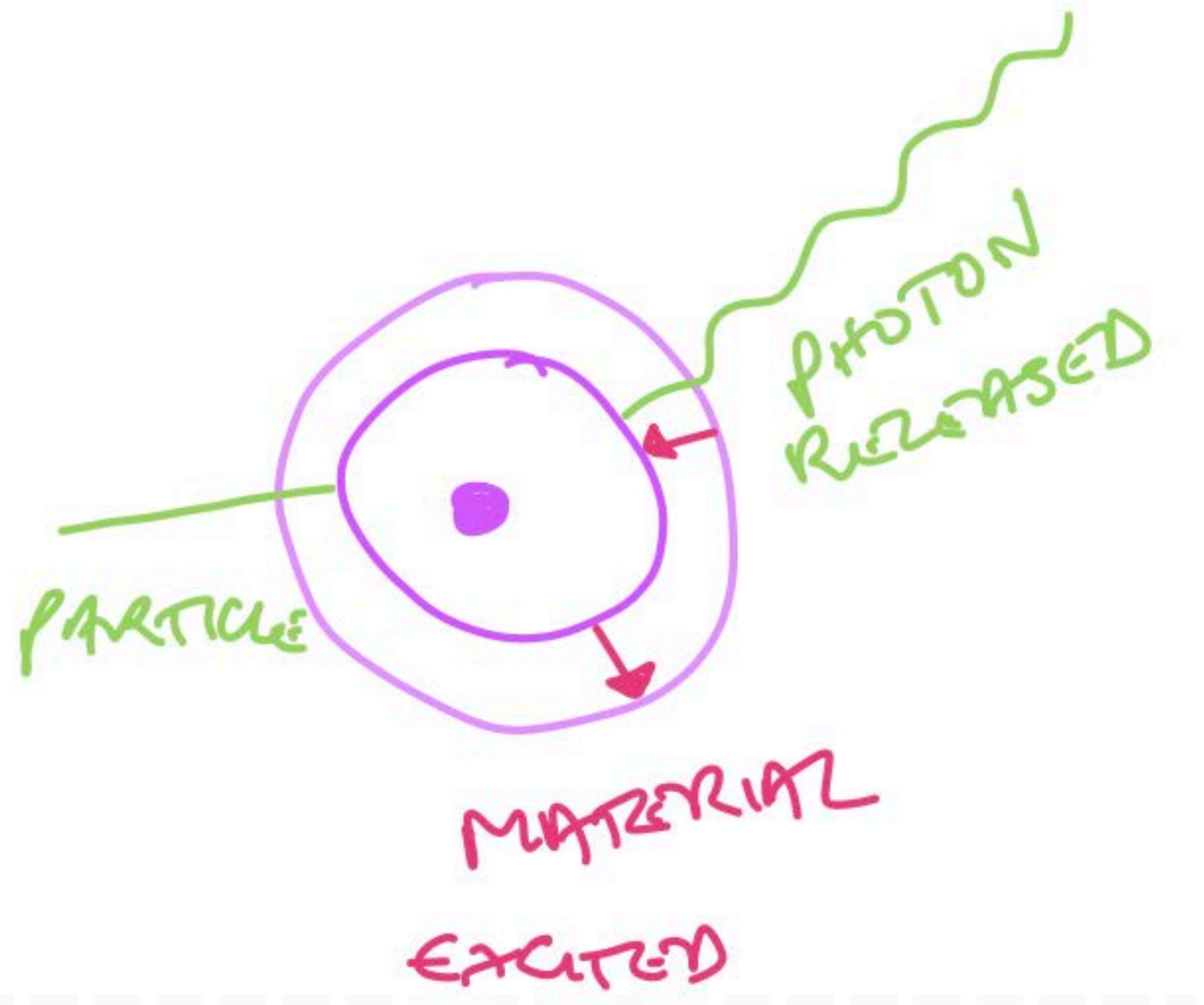
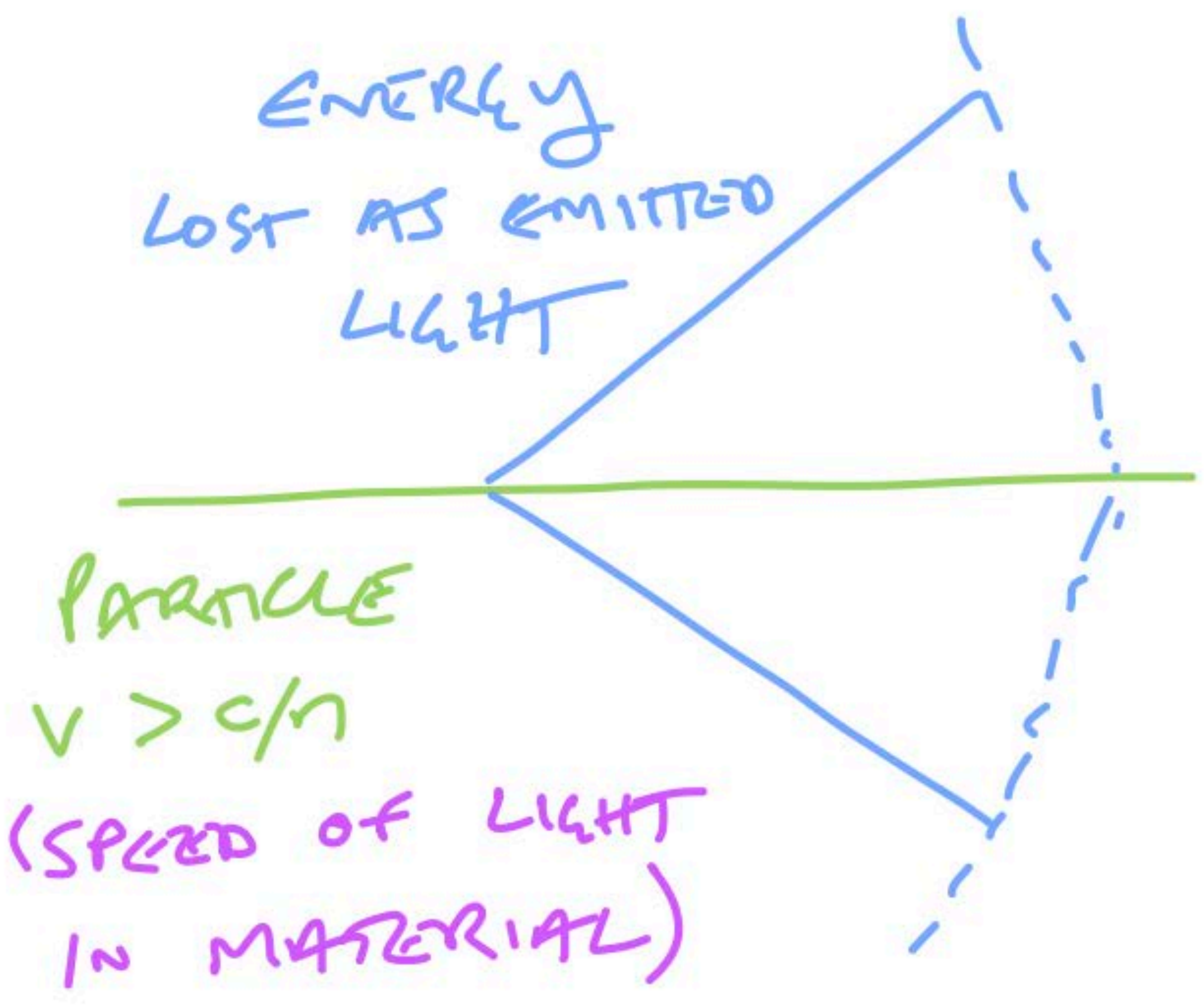


Cherenkov radiation



Courtesy of Kate Pachal

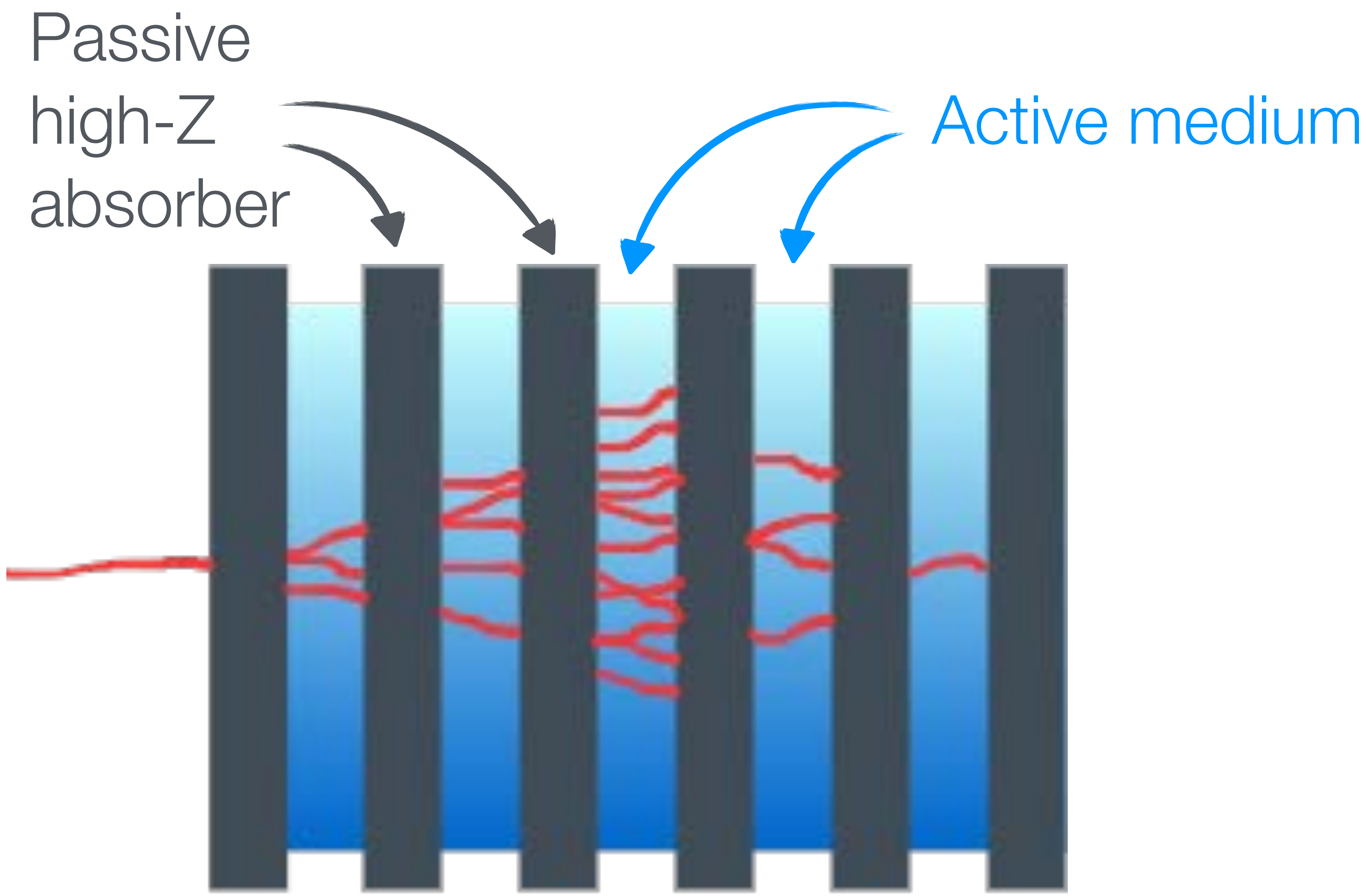
Calorimeter types

Homogeneous

Entire volume made of single material that act both as absorber and active medium

- ✗ Large volume (although some dense material now allow for some compact volume)
- ✗ Expensive
- ✓ Excellent energy resolution

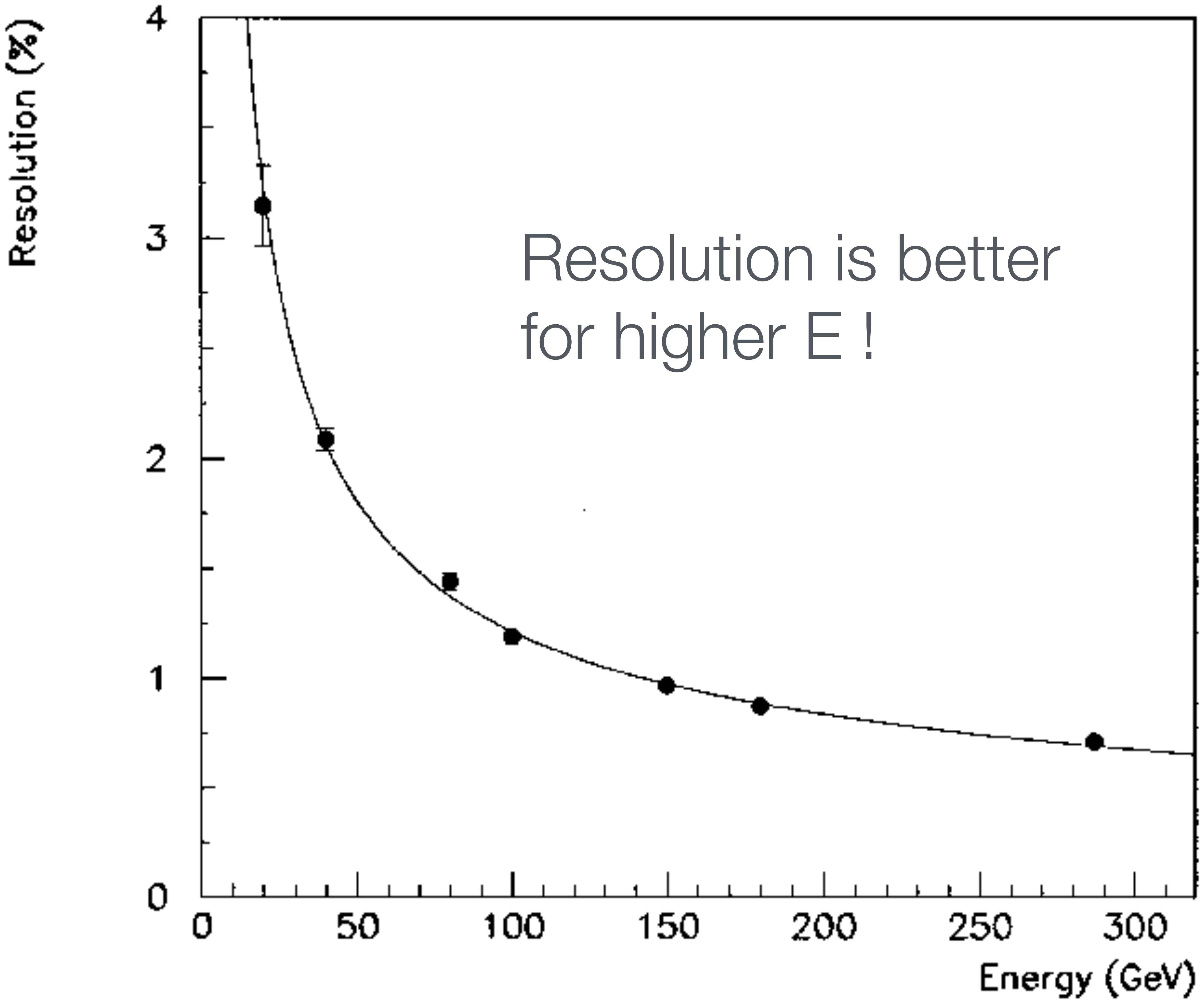
Sampling



- ✓ Compact
- ✓ Cheaper
- ✗ Worse energy resolution

Energy Resolution

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

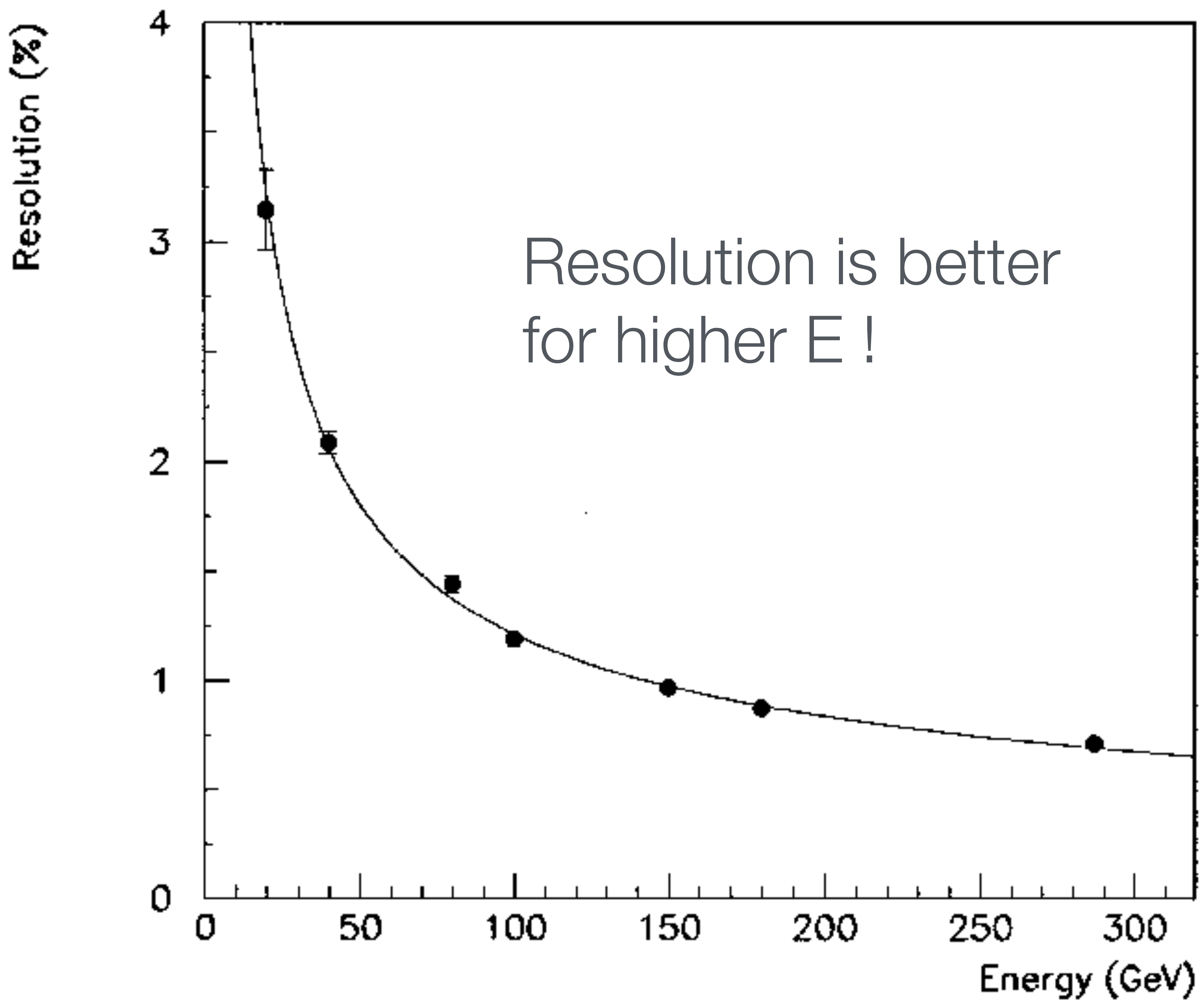


Resolution is better for higher E !

Energy Resolution

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Showering fluctuations and $1/\sqrt{N}$ statistics



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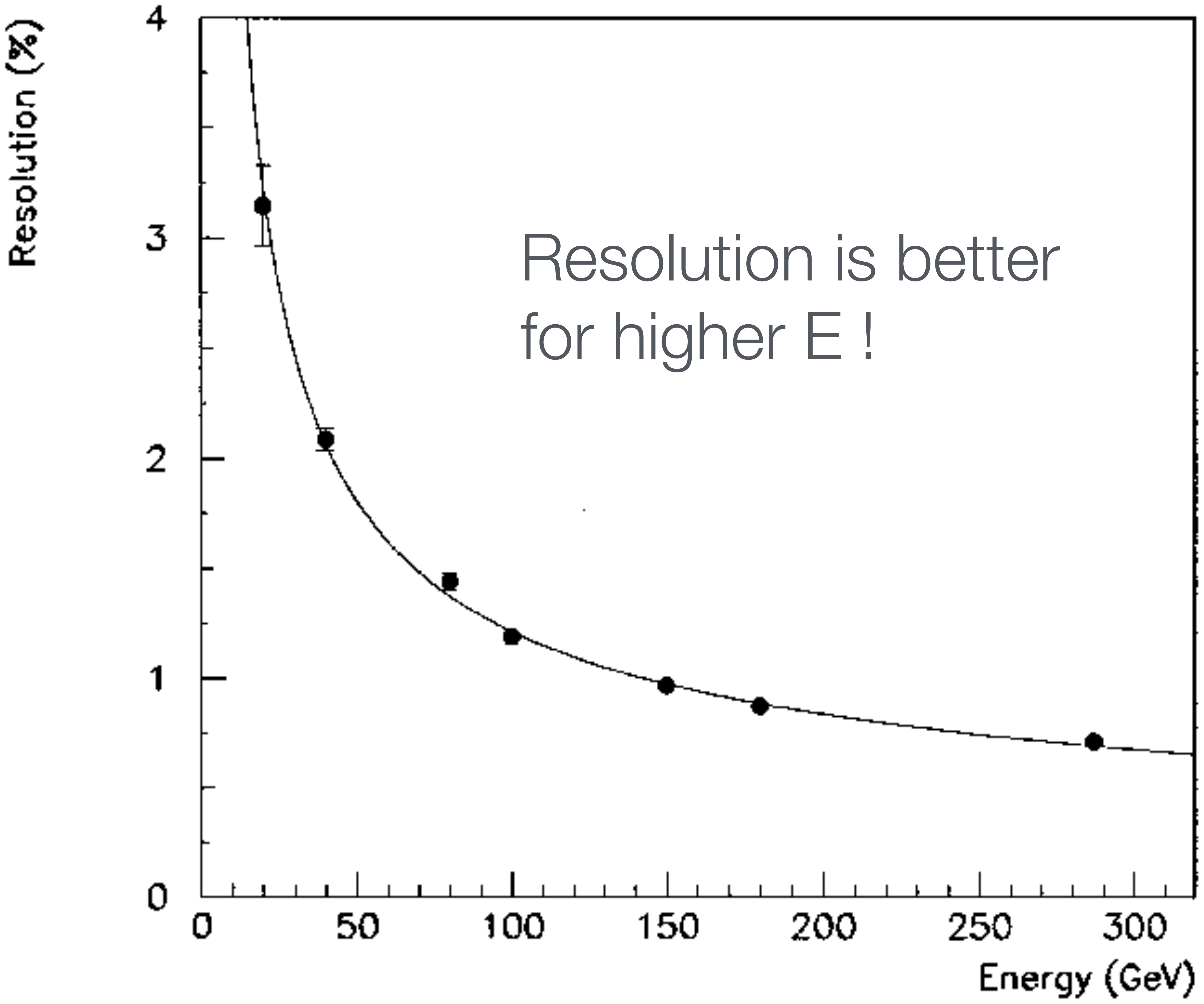

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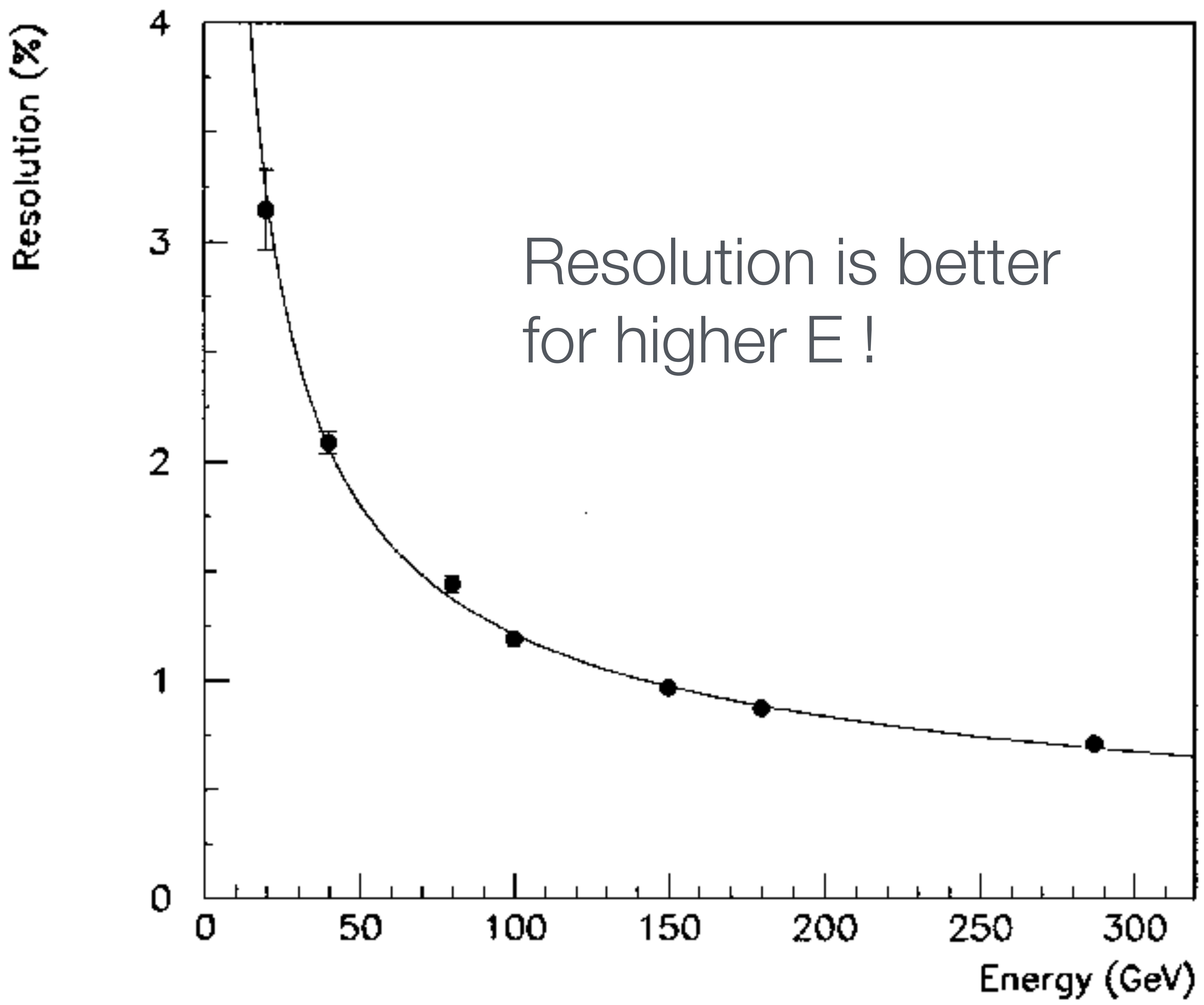
Shower leakage



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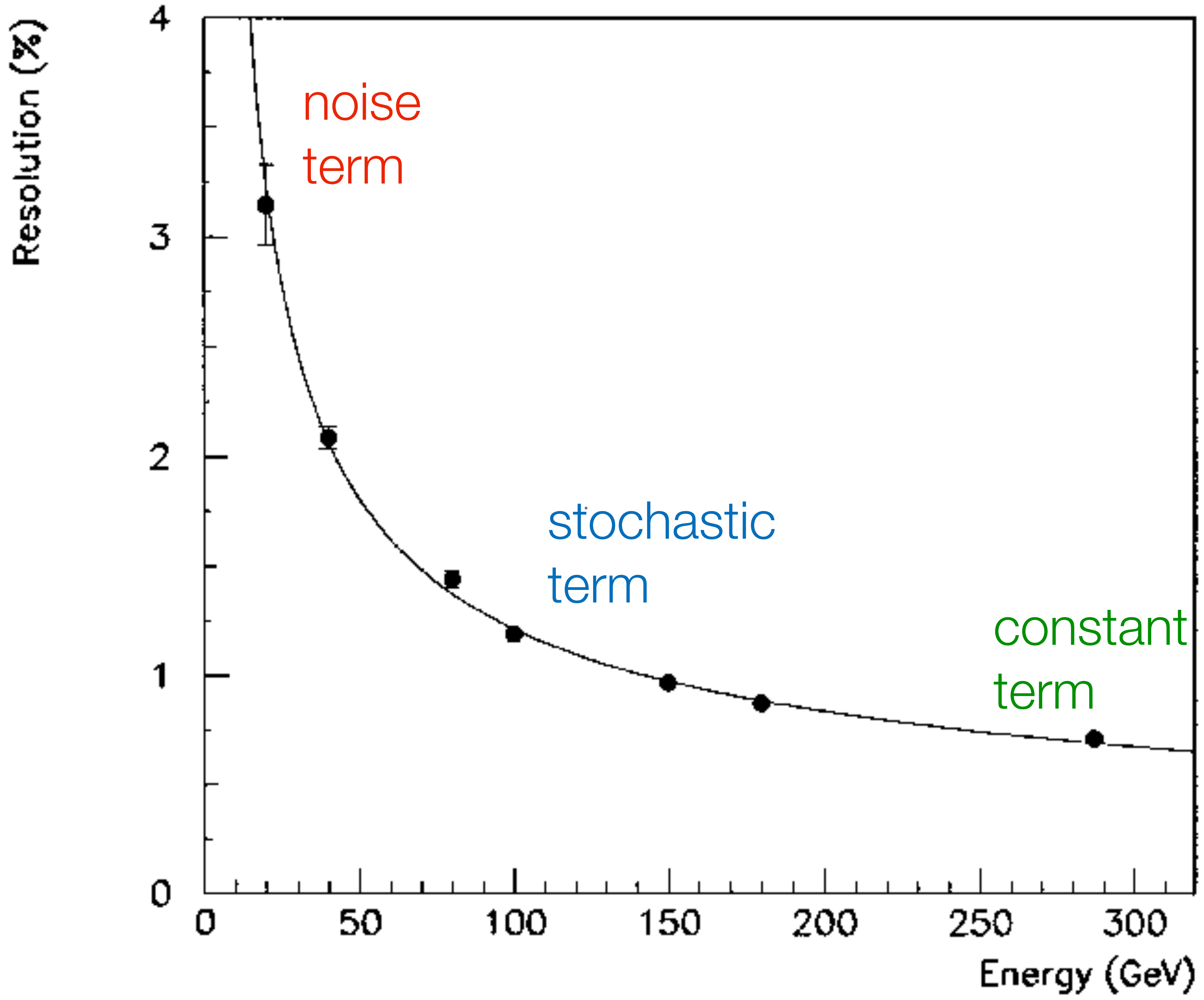


Energy Resolution

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Homogeneous calorimeters have excellent energy resolution since all deposited energy is recorded

~ 2 - 3 %

Energy Resolution

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Sampling calorimeters have additional contributions from fluctuations in amount of energy sampled

$$a \rightarrow a\sqrt{d/f_{samp}}$$

d : active layer thickness

f_{samp} : sampling fraction

Homogeneous calorimeters have excellent energy resolution since all deposited energy is recorded

~ 2 - 3 %

~ 5 - 20%

Electromagnetic Energy Resolution

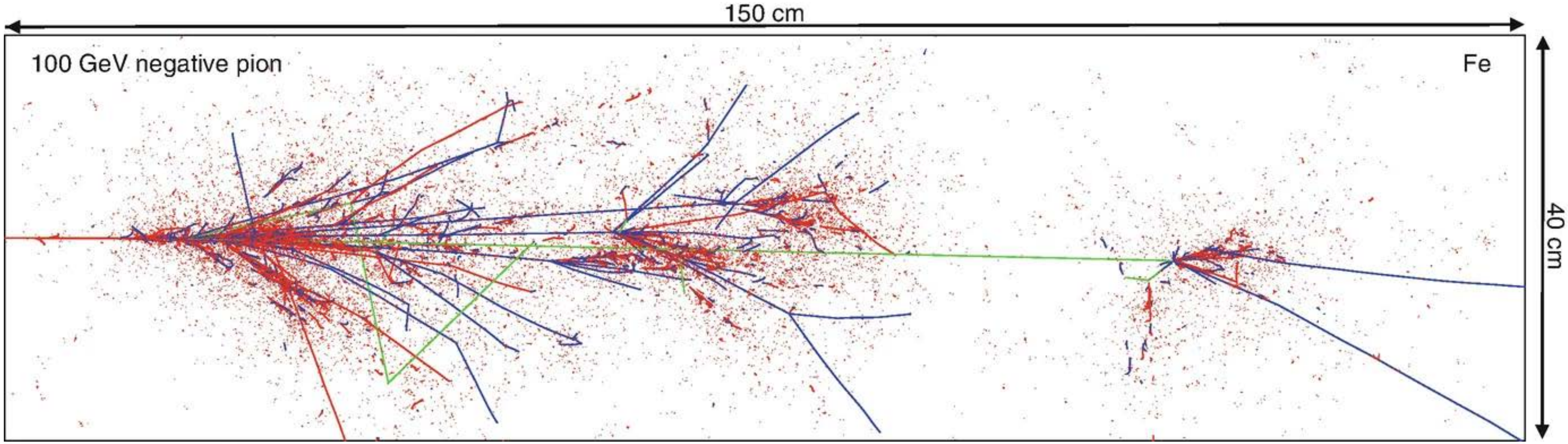
PDG

Homogeneous calorimeters

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	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 $E_\gamma > 3.5$ GeV	1998
CsI(Tl) (BES III)	$15X_0$	2.5% for $E_\gamma = 1$ GeV	2010
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
$PbWO_4$ (PWO) (ALICE)	$19X_0$	$3.6\%/\sqrt{E} \oplus 1.2\%$	2008
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
PbF_2 (g-2)	$15X_0$	$3.6\%/\sqrt{E} \oplus 1.9\%$	2019
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
SciFi/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
SciFi/W (sPHENIX)	$20X_0$	$13\%/\sqrt{E}$	2022
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 (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Sampling calorimeters

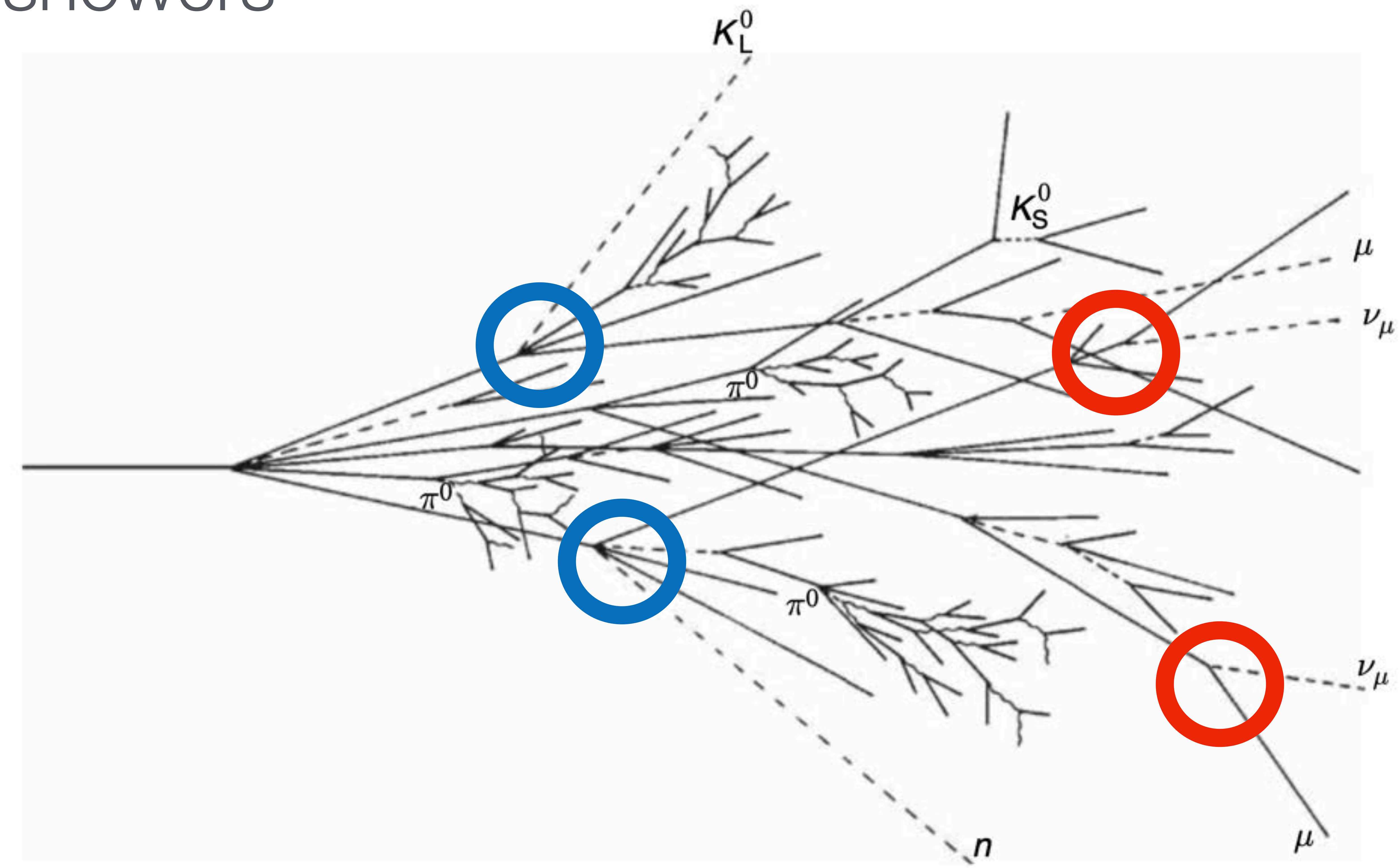
Hadronic Calorimetry



Hadronic Showers

Hadrons produced much more complex showers

Grupen & Schwartz



Nuclear spallation reactions release hadrons from target material nuclei, but binding energy won't appear in calorimeter signal

Secondary hadrons (e.g pions) can decay to (non-measured) **neutrinos**

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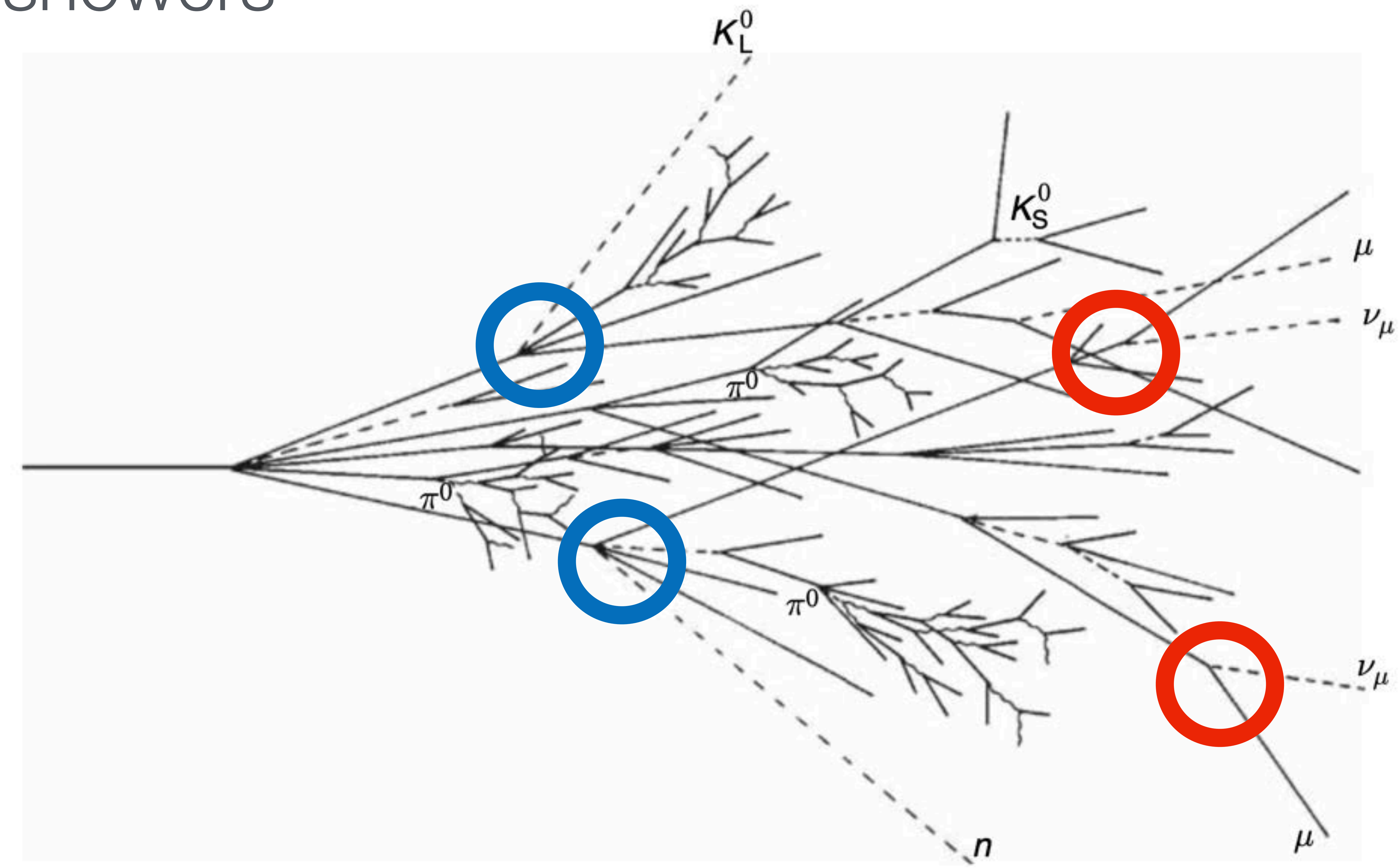

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Non-compensation

Detector unequal response to electromagnetic (e) and hadronic (h) components of a particle shower (e/h > 1)

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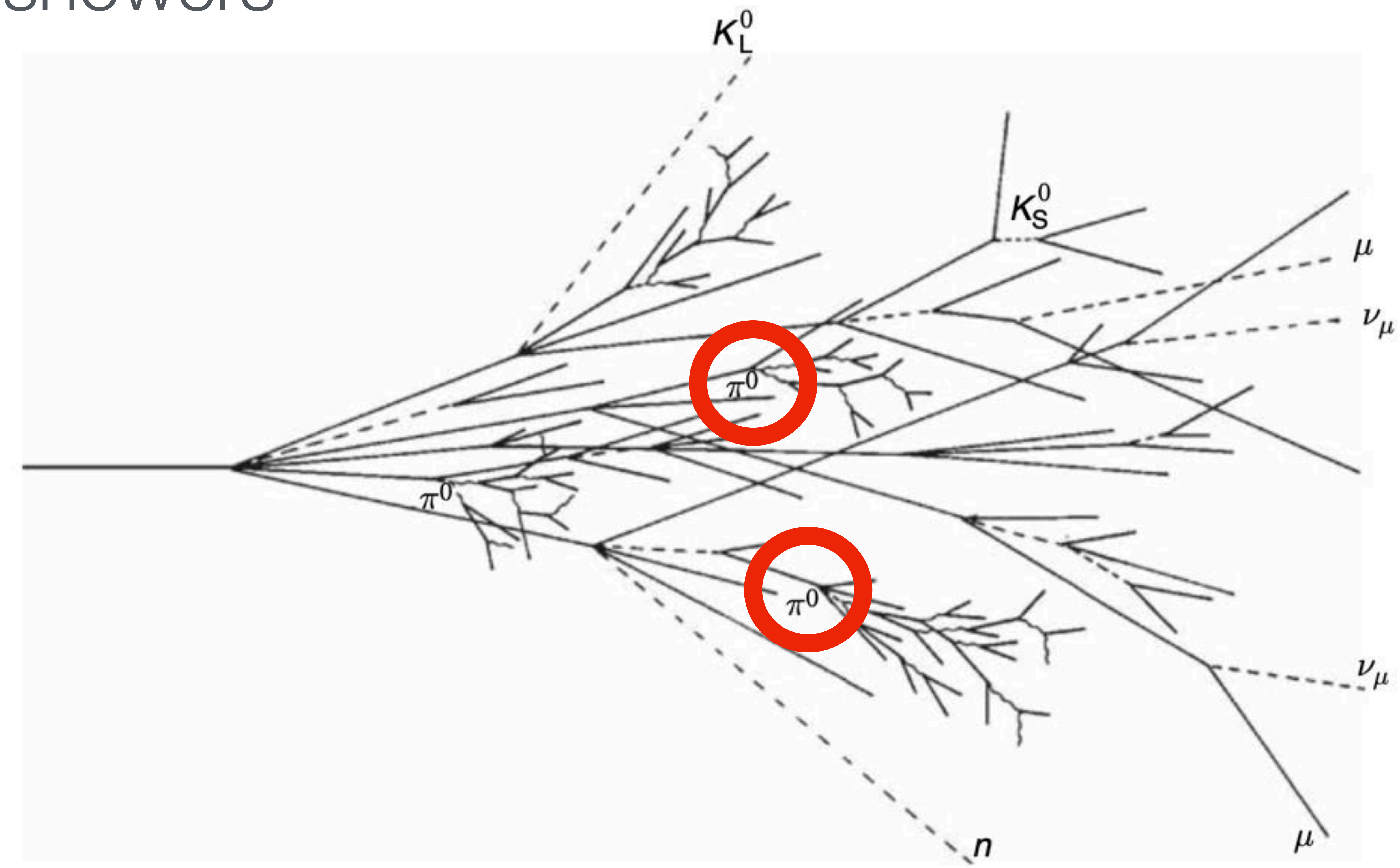

Main products of showering are pions ($\pi^{\pm}, \pi^0$)

$\pi^0 \to \gamma\gamma$ initiating electromagnetic sub-cascade (one way street!)

The more interactions take place in a shower, the more chances to create π^0

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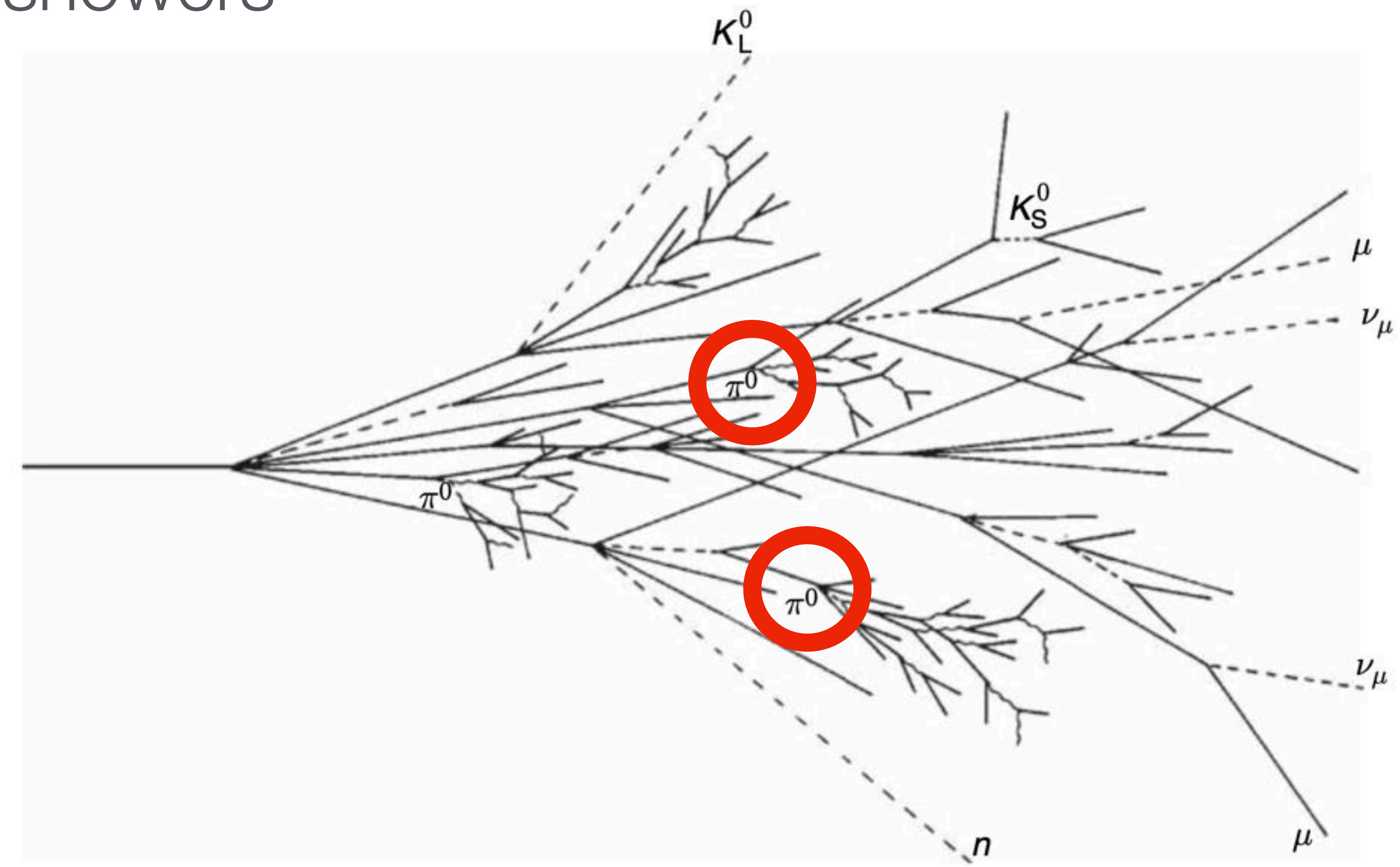
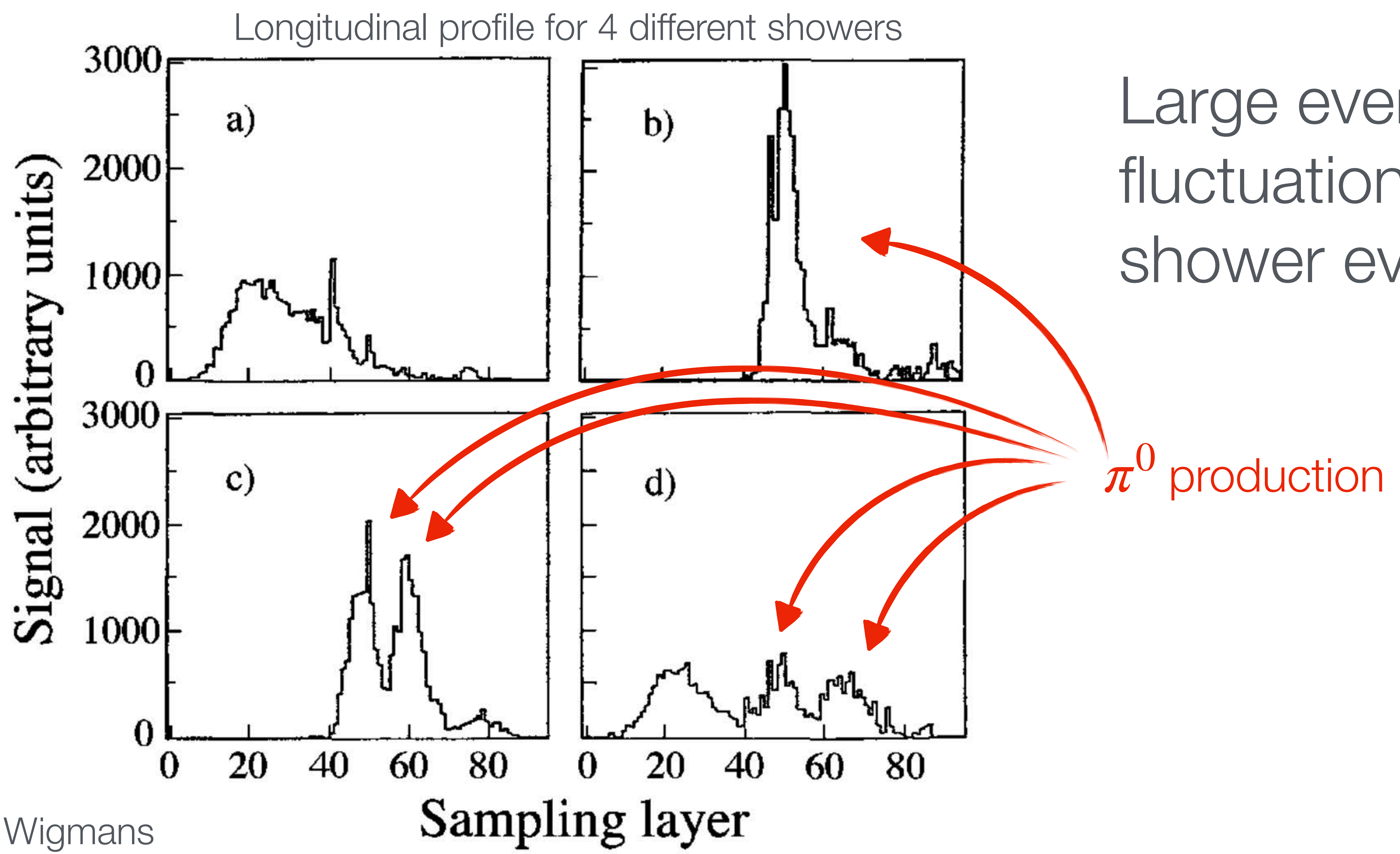


Non-linearity

Response is better for higher energy incident particle

Hadronic showers



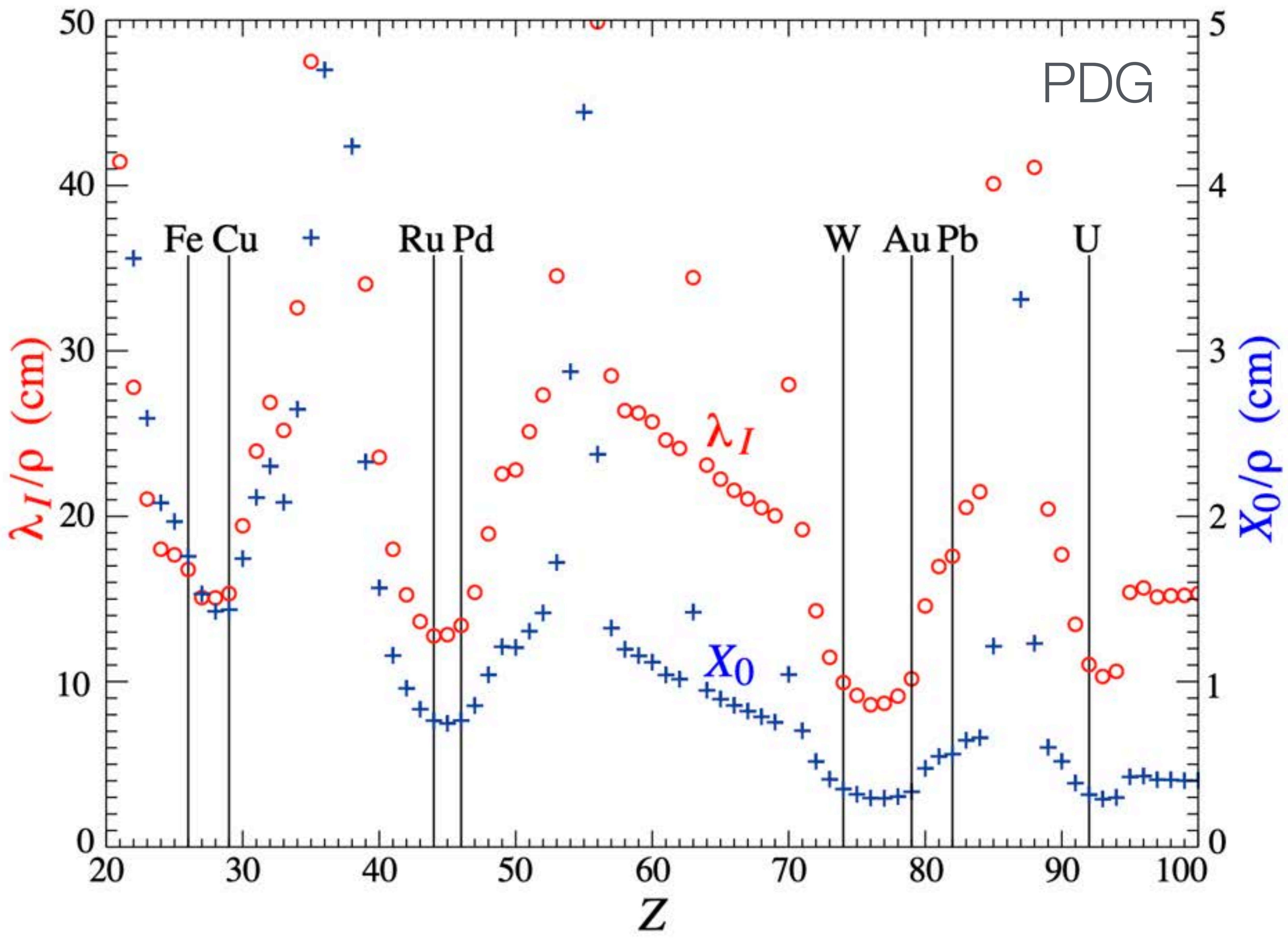
Large event-to-event fluctuations of the shower evolution

Hadronic shower profile

Interaction length (λ_{int}) : Average distance a high-energy hadron must travel before it undergoes a strong inelastic nuclear interaction

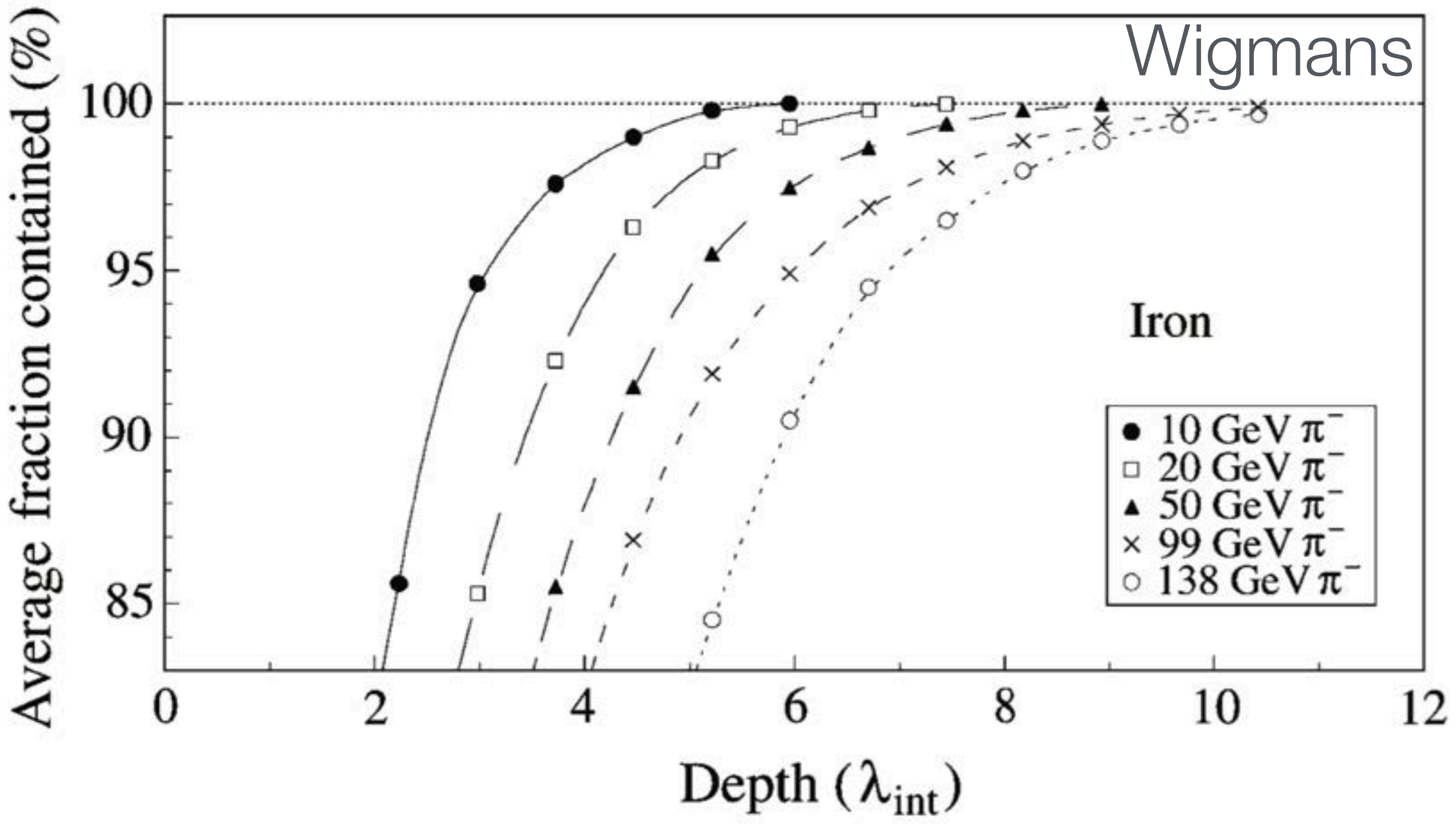
$$\lambda_{int} \sim (35\, g/cm^2) \cdot A^{1/3}$$ for high Z

→ Interaction length typically a lot longer than radiation length

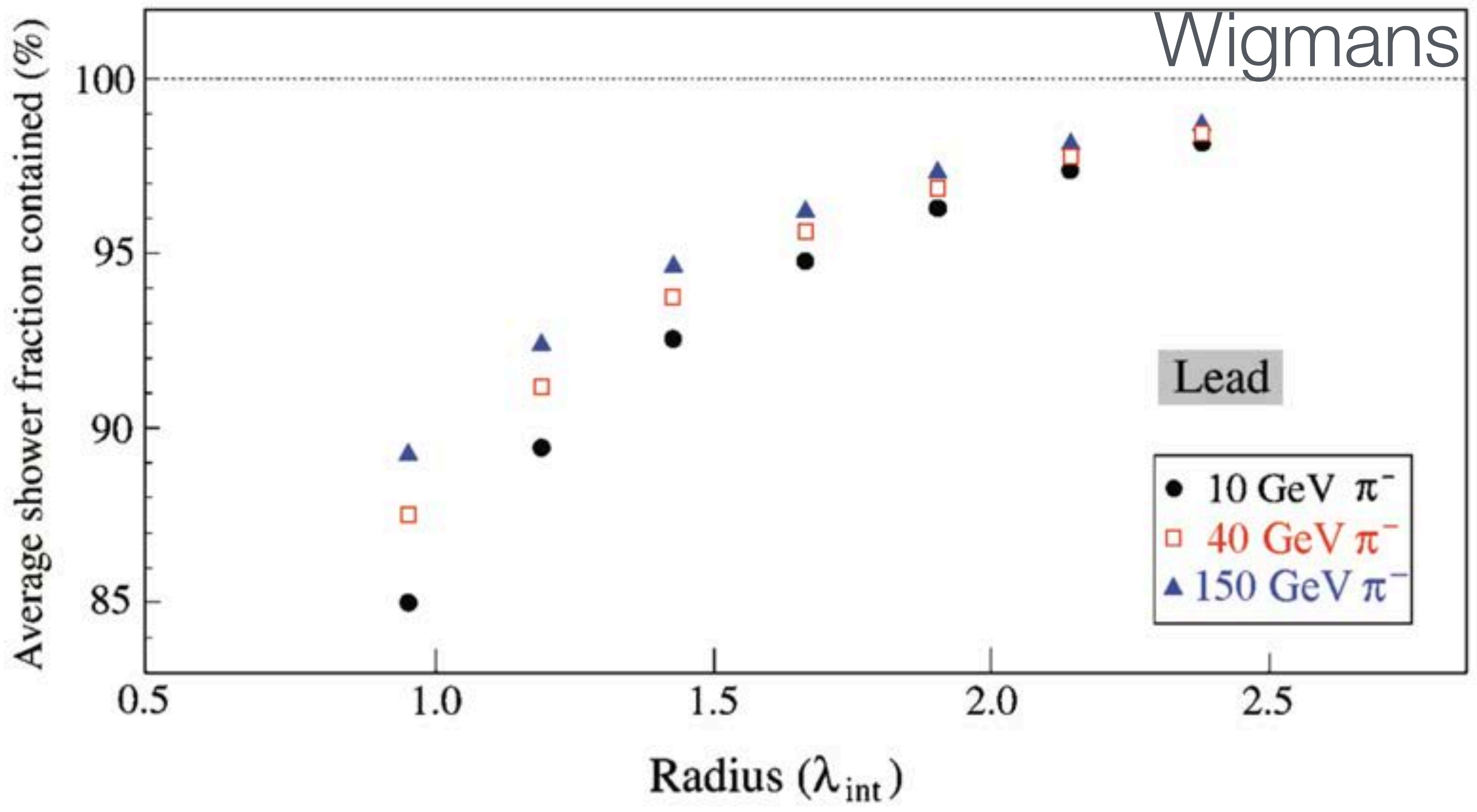


Hadronic shower profile

Hadronic shower 99% contained within ~ 9 λ_{int} longitudinally



Hadronic shower 95% contained within ~ 1 λ_{int} transversely



Hadronic calorimeter resolution

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Resolution worse for hadronic showers due to:

- Fluctuations in lost energy (neutrinos, muons, nuclear excitation energy, …)
- Fluctuations in EM fraction of showers
- Varying degrees of shower leakage

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~ 50%- 80%

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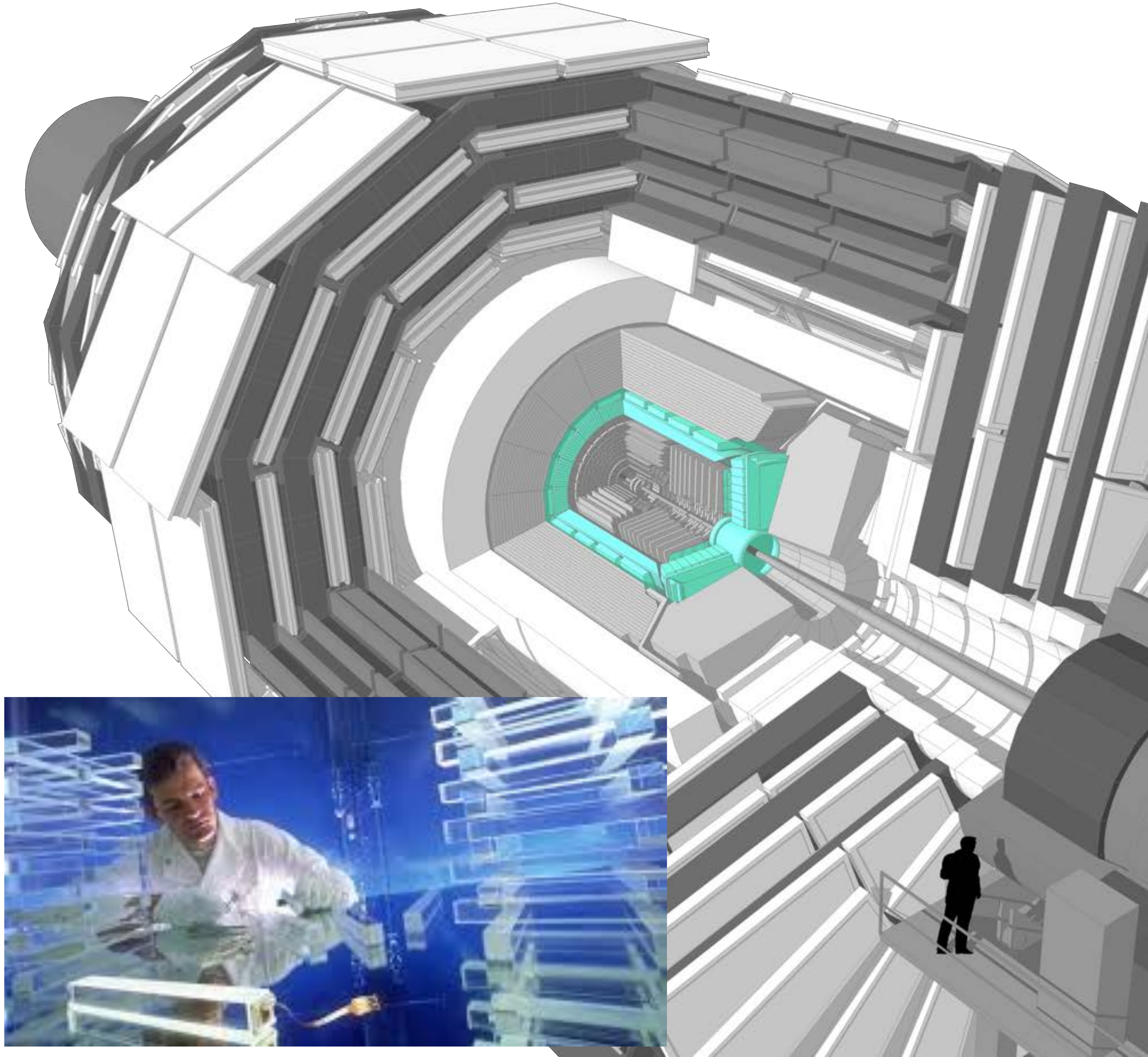
PDG

Experiment	technology (ECAL, HCAL)	Combined hadronic resolution	Reference
H1	Pb/LAr, Steel / LAr	$46\%/\sqrt{E} \oplus 2.6\% \oplus 0.73/E$	[512]
ZEUS	depleted U / plastic scintillator	$35\%/\sqrt{E}$	[513]
CDF	Pb/plastic scint., Steel/plastic scint.	$68\%/\sqrt{E} \oplus 4.1\%$	[514]
D0	depleted U / LAr	$44.6\%/\sqrt{E} \oplus 3.9\%$	[515]
ATLAS	Pb/LAr, Steel/plastic scintillator	$52\%/\sqrt{E} \oplus 3.0\% \oplus 1.6/E$	[516]
CMS	$PbWO_4$, brass/plastic scintillator	$84.7\%/\sqrt{E} \oplus 7.4\%$	[517]

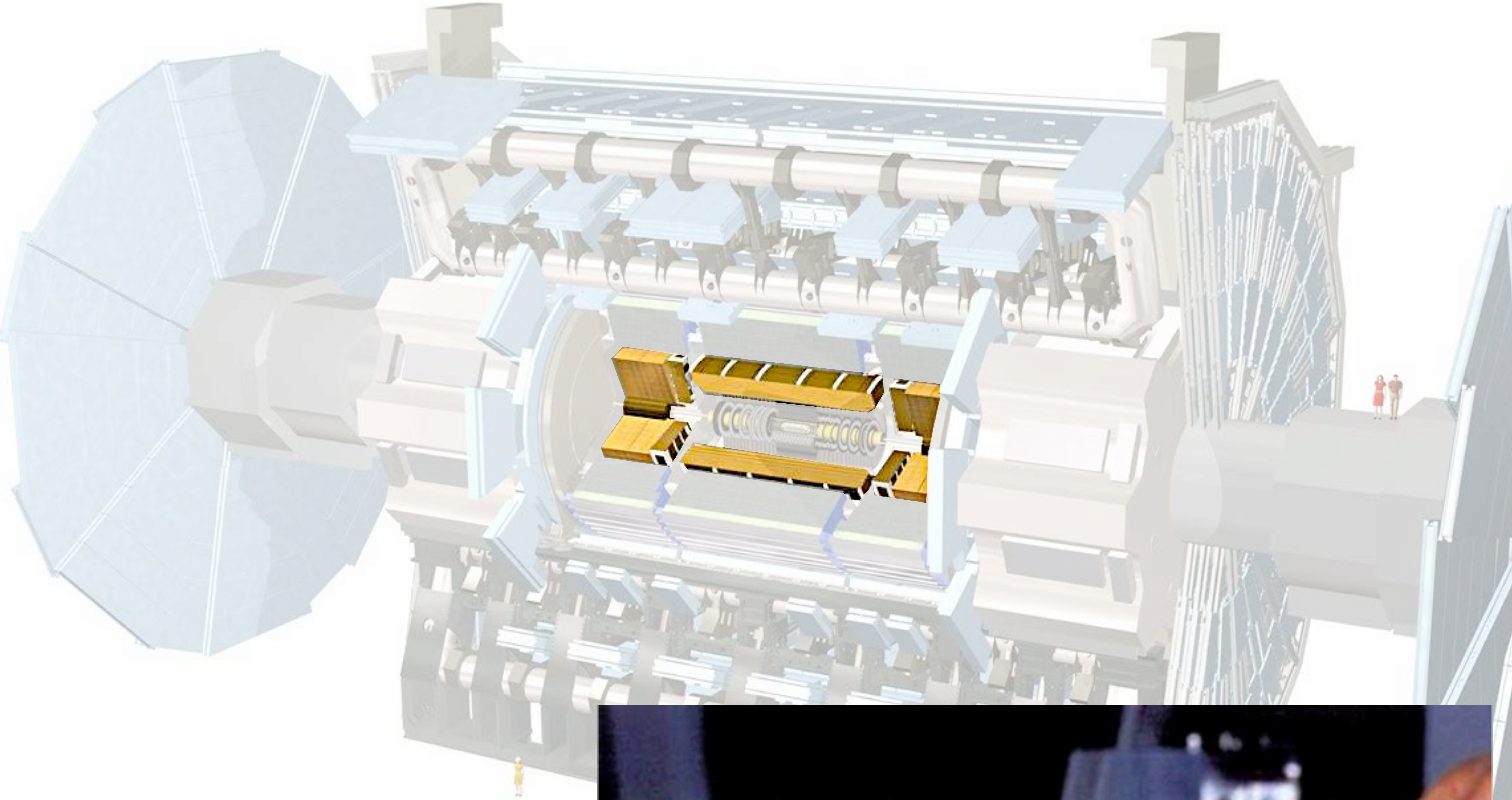
CMS Electromagnetic Calorimeter

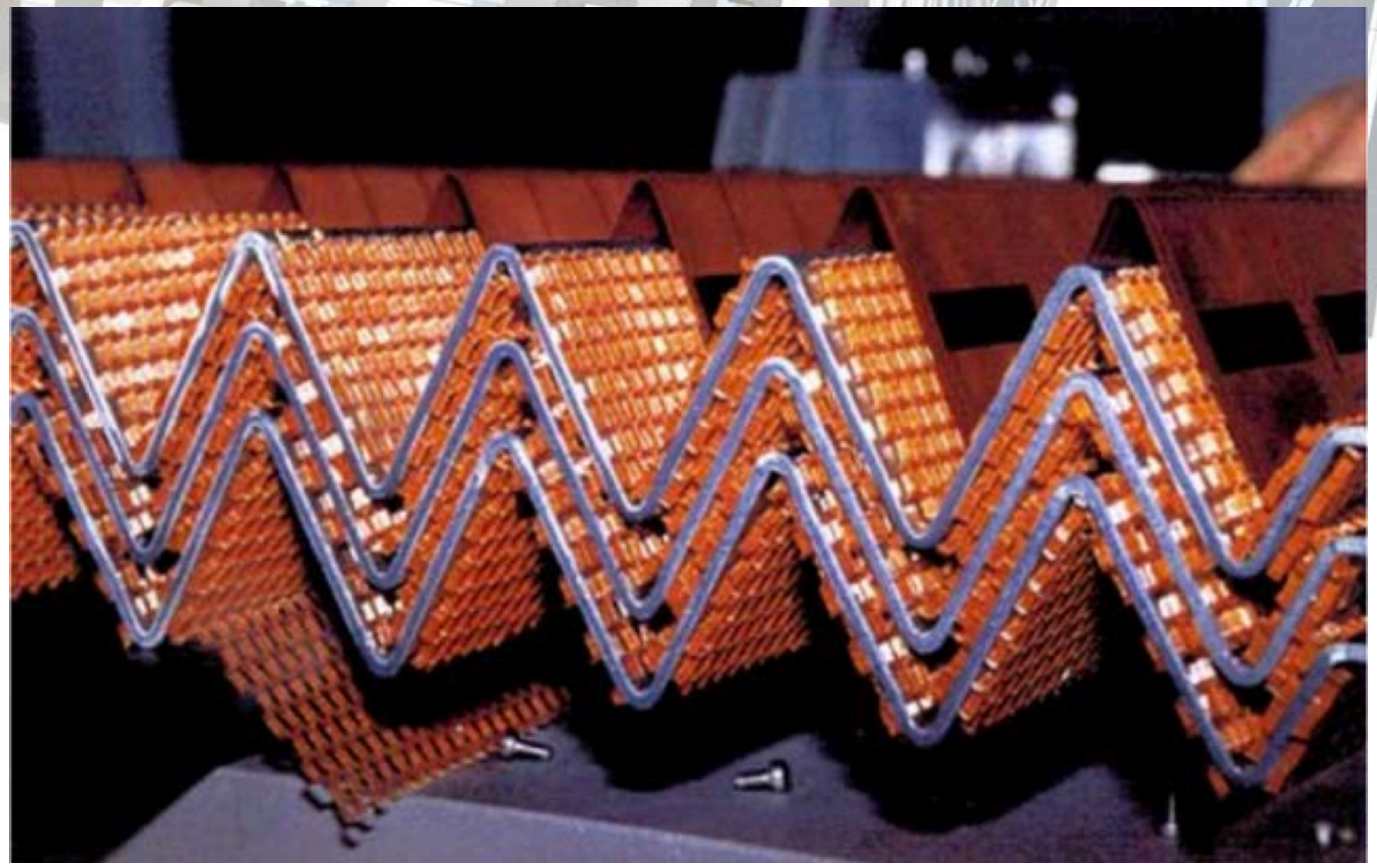
- Homogeneous calorimeter
- 76,000 scintillating crystals of lead tungstate ($PbWO_4$)
- Signal: Scintillation light
- **Pros**: Compact, fast signal, excellent energy resolution ~ 2% !
- **Cons**: Expensive, low light yield, light yield strongly temperature dependent, radiation degradation



ATLAS Electromagnetic Calorimeter

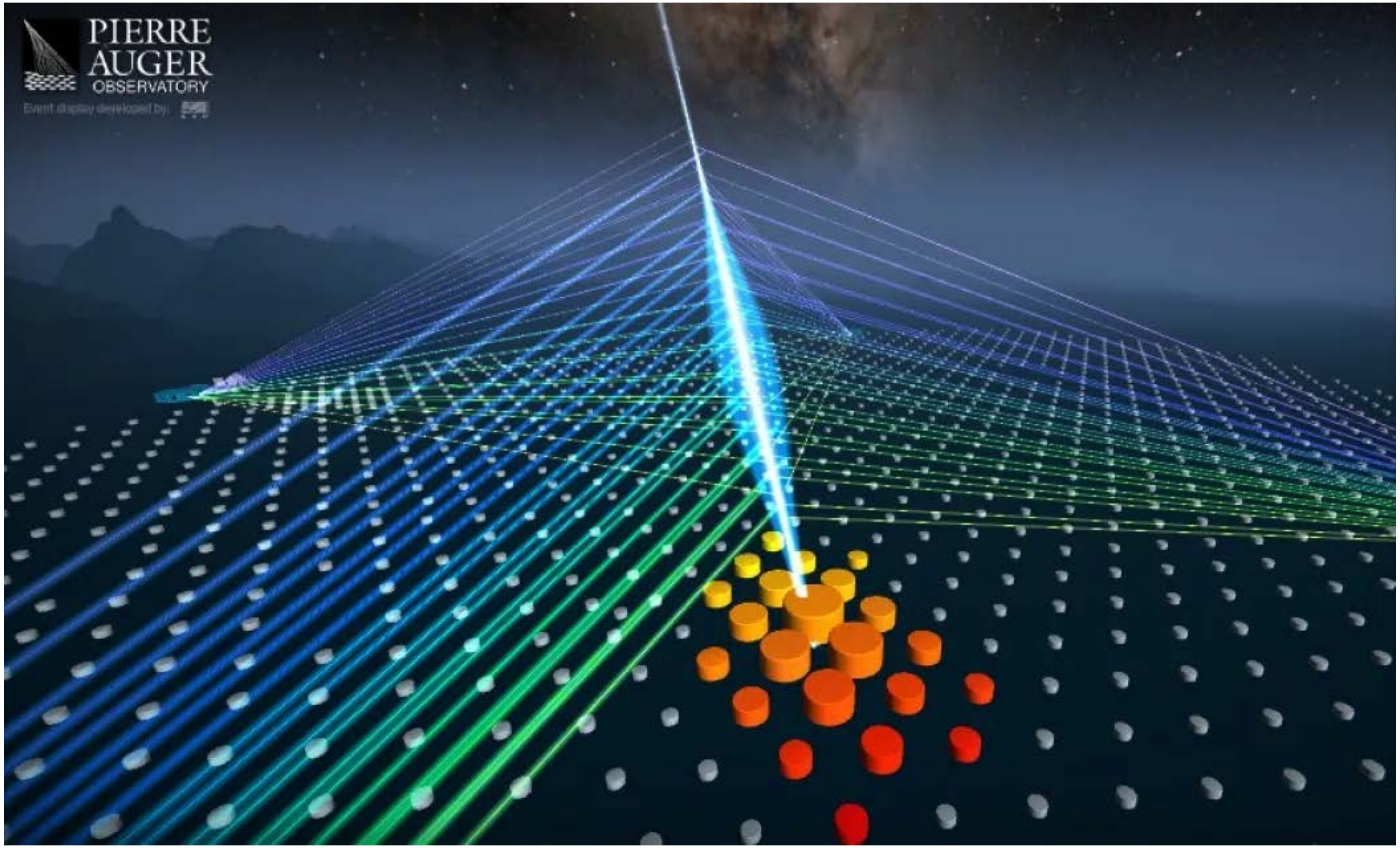
- Sampling calorimeter
- LAr + Lead with unique "accordion" geometry
- Fine segmentation laterally and in depth : 182,000 channels
- Signal : Ionisation
- **Pros**: Radiation hardness, excellent stability, good linearity and uniformity, strong PID capability.
- **Cons**: Worse energy resolution ~10%, larger size, slow signal, cryogenics infrastructure





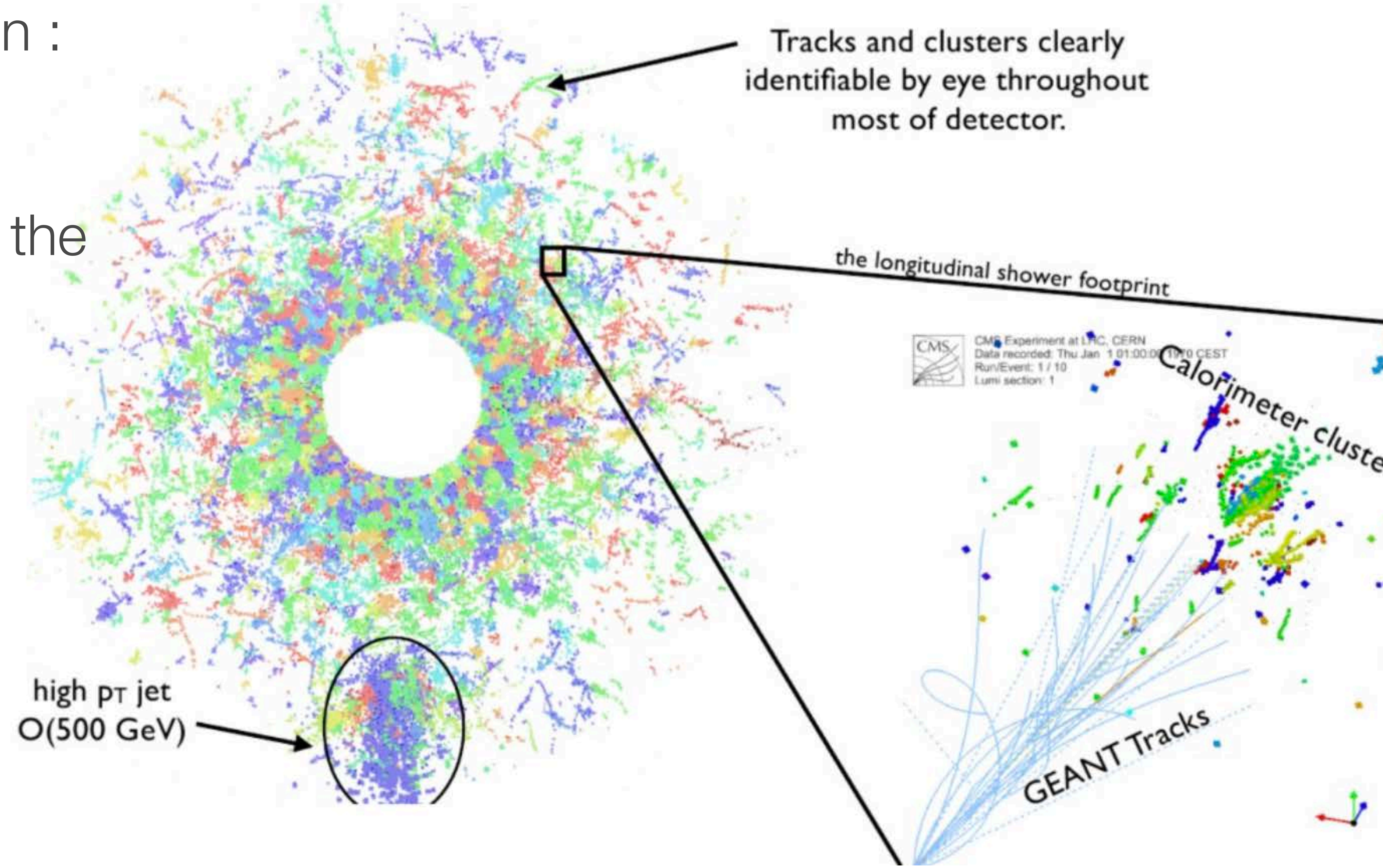
The world-largest calorimeter

- Pierre Auger Observatory
- Located in Argentina
- Ultra-high energy cosmic rays shower in Earth's atmosphere
- Signals:
  - Fluorescence
  - Cherenkov detectors



High Granularity Calorimetry

- Extremely high segmentation : Silicon readout at 0.5 cm^2
- Image individual portions of the shower evolution
- **Very large** stochastic term ~ 22% ! Why bother?



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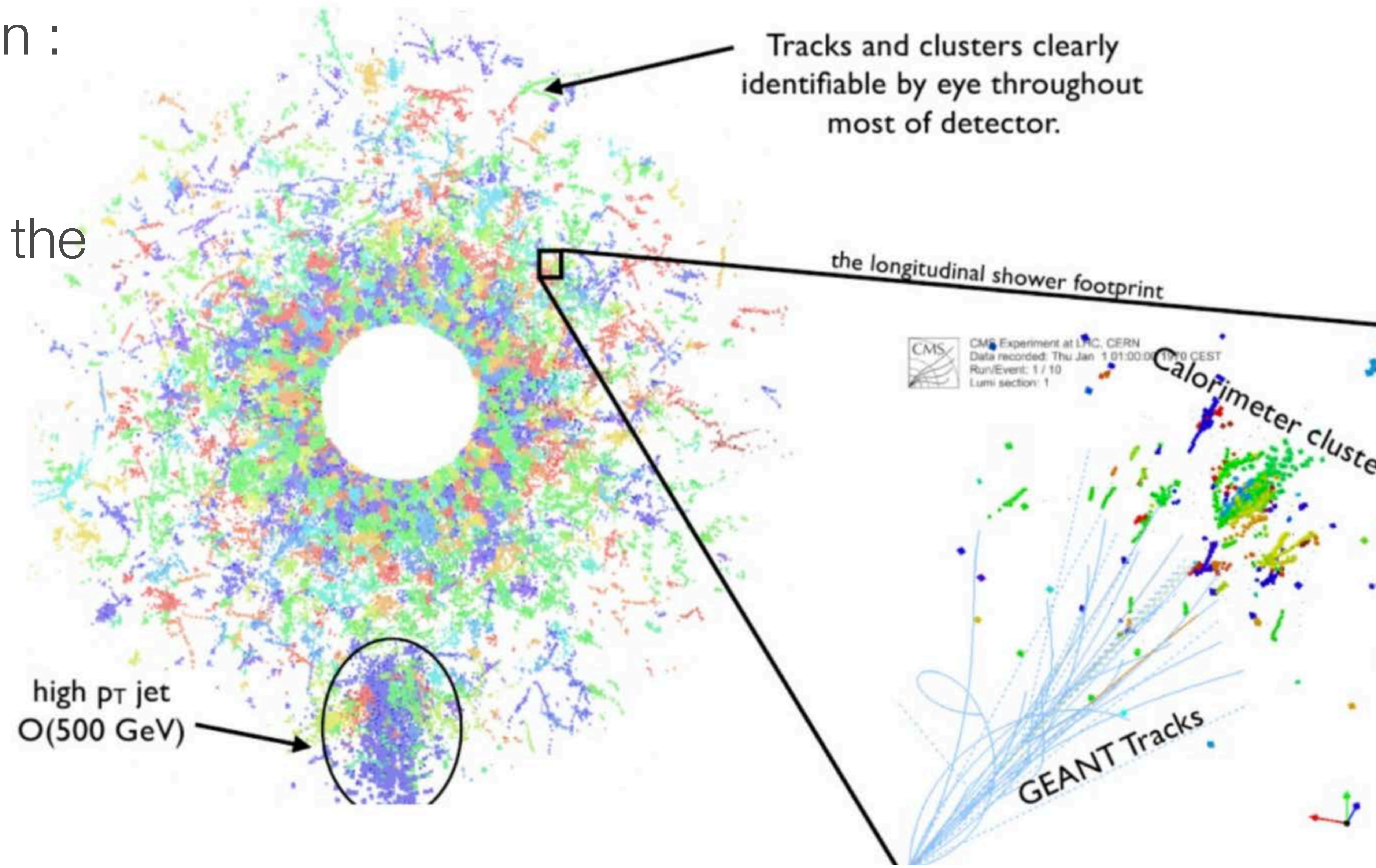
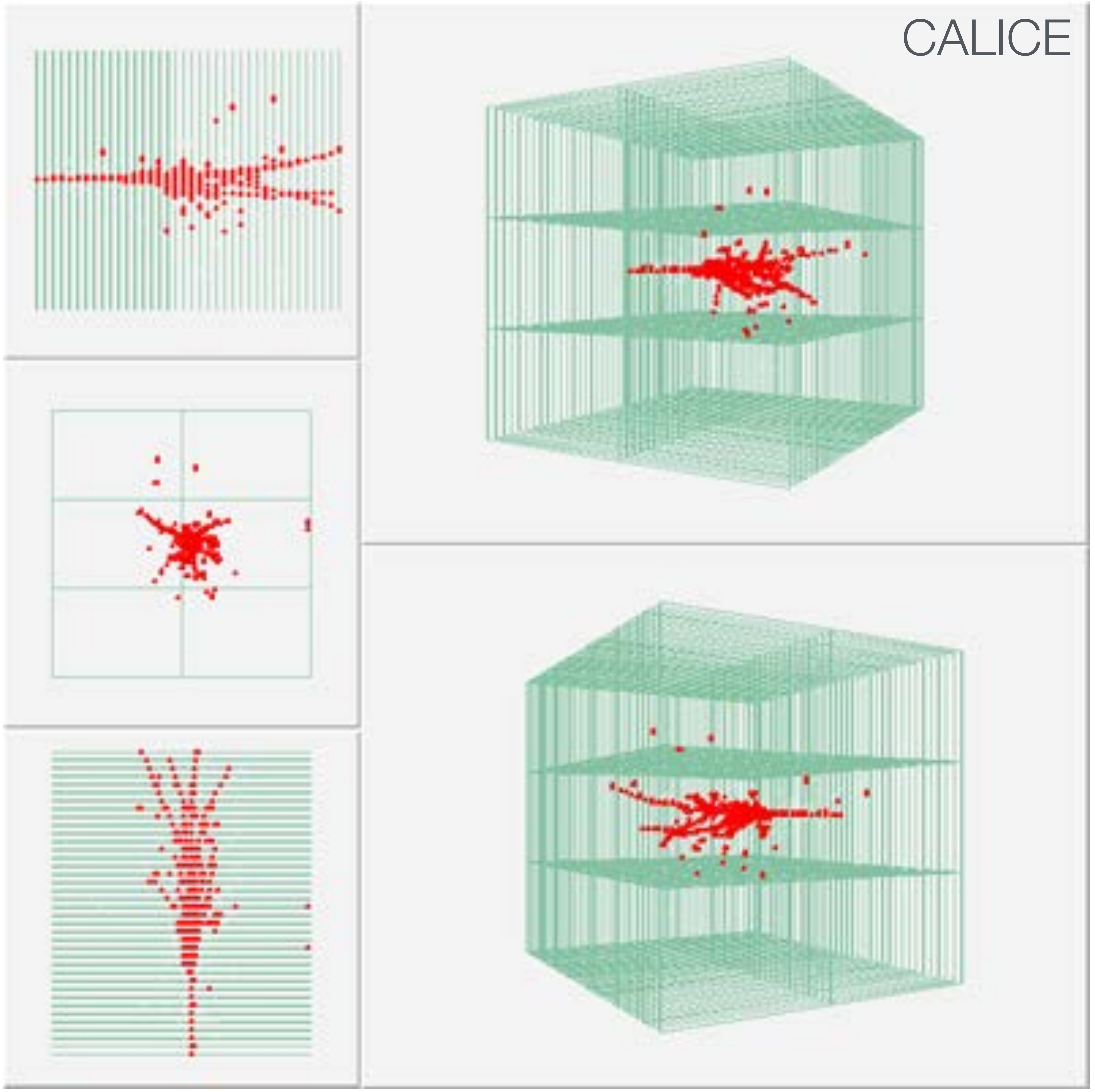
"Particle Flow"



Digital Calorimetry

- Take granularity to even more extreme
  - Energy per readout cell becomes smaller and smaller
  - Eventually just read a “hit” : Digital signal
  - Total number of cell hits $\propto$ total number of MIP interactions $\propto$ energy



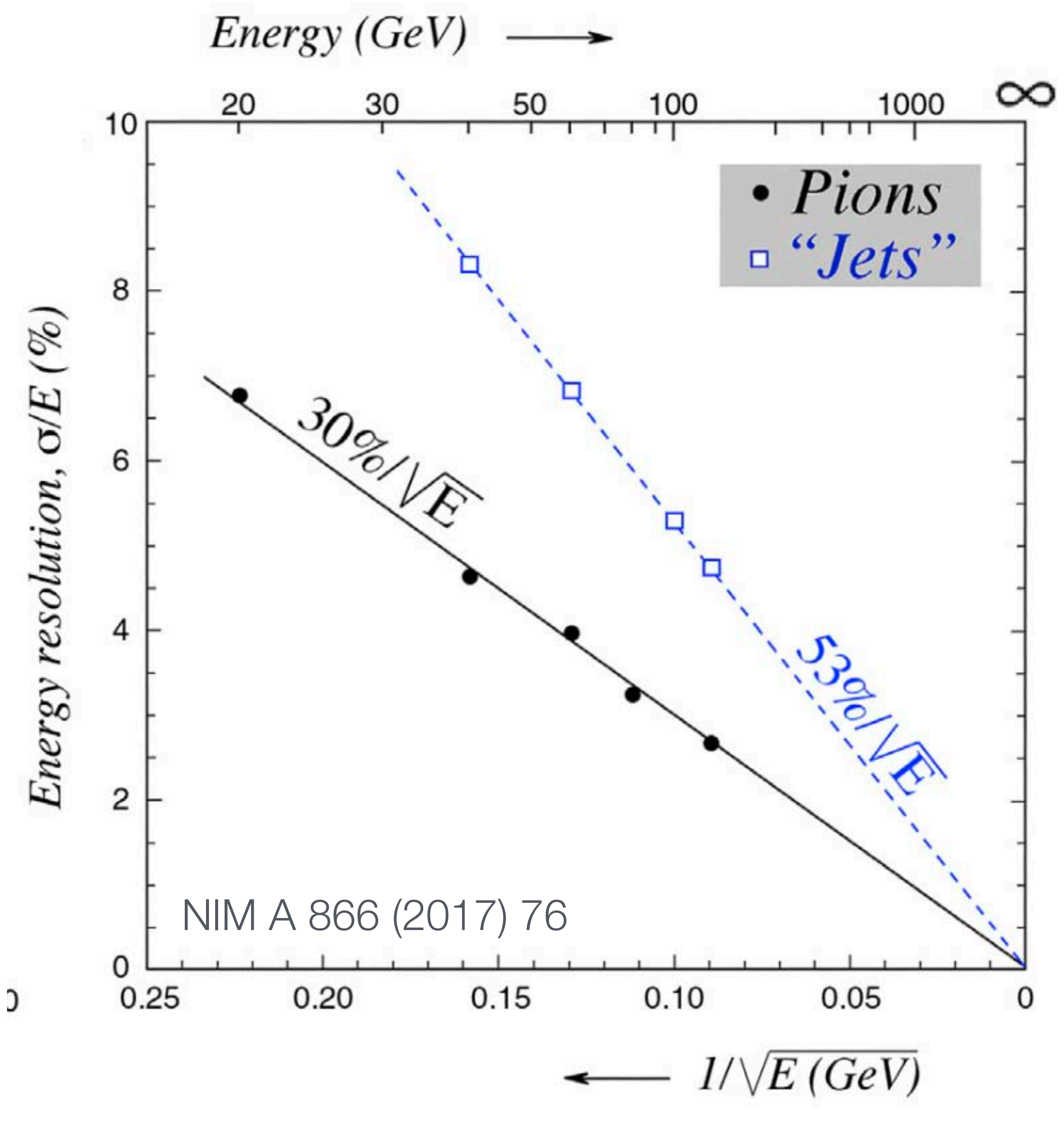
Dual Readout Calorimeter

- Hadronic calorimeter resolution degraded by non-compensation

- In many materials, you can detect more than one type of signal (e.g. scintillation + Cherenkov)

- Combine two types of signal to **compensate** to achieve $e/h \sim 1$

- Demonstrated improved energy resolution



BREAK

PARTICLE IDENTIFICATION

Particle ID : What and Why?

Critical to be able to identify particles involved in an interaction to understand the physics reactions that took place

- **Long-lived particles** : Identified by their unique properties (mass, charge, interaction types, shower shapes, etc.)
- **Short-lived particles** : Identified by their decay products
- Need to combine information from all parts of the detector to do PID!
- Different experimental programs have different PID needs

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B-physics requires ability to distinguish different hadrons: $K/\pi/\Lambda/p$ etc.

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General purpose experiment : decent at everything

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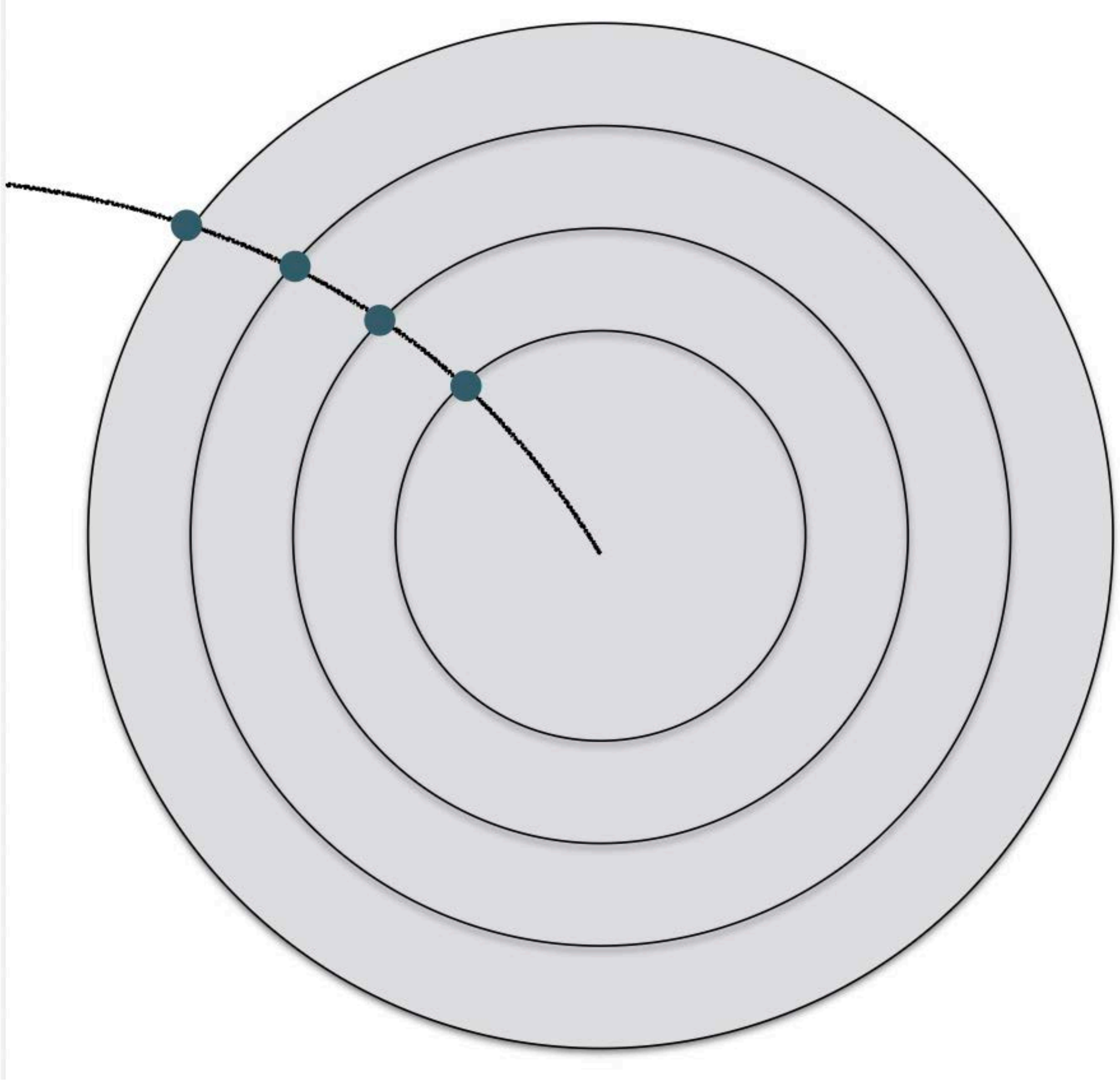
Electron-Ion collision physics requires unprecedented PID to separate hadrons (π, K, p) over a wide phase-space and low-momentum e/π separation

ePIC

A brief word about trackers

- Non-destructive measurement
  - Only sensitive to charged particles!
- Measurements
  - Trajectories of charged particles
  - Electric charge (+/-)
  - Interaction point (vertex)
  - Decay path of unstable particles
- Radius of curvature + B-field value
  → Momentum
- But you still don't know the mass of the particle to identify it!
  - Need to measure velocity to infer the mass



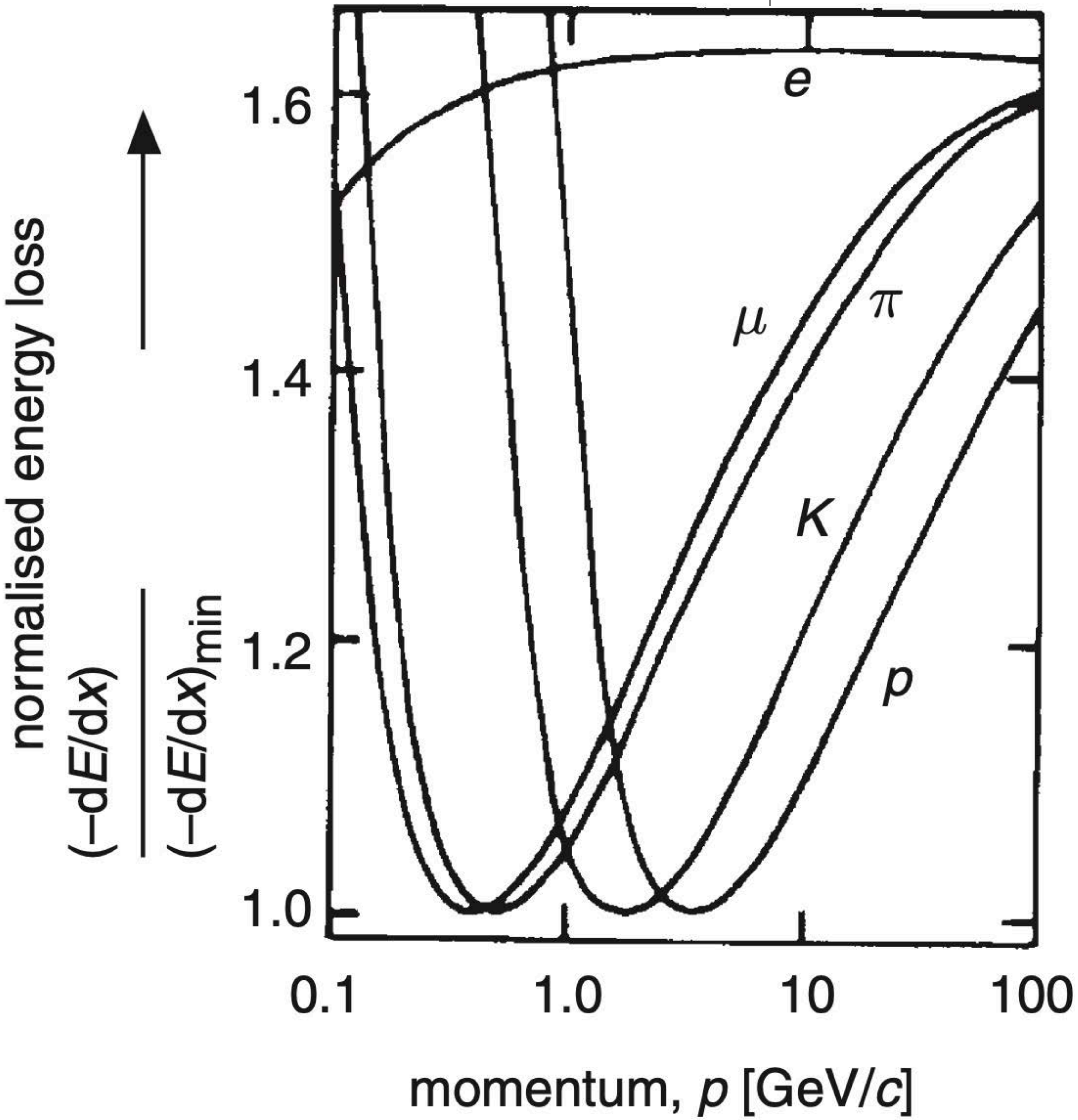
Charged particle ID : **Energy loss**

- Energy loss via ionisation dominates for heavy (non-e) charged particles

- For relativistic particles can approximate Bethe-Bloch formula

$$\frac{dE}{dx} \sim \frac{1}{\beta^2} \ln(\beta^2\gamma^2)$$

Grupen & Schwartz



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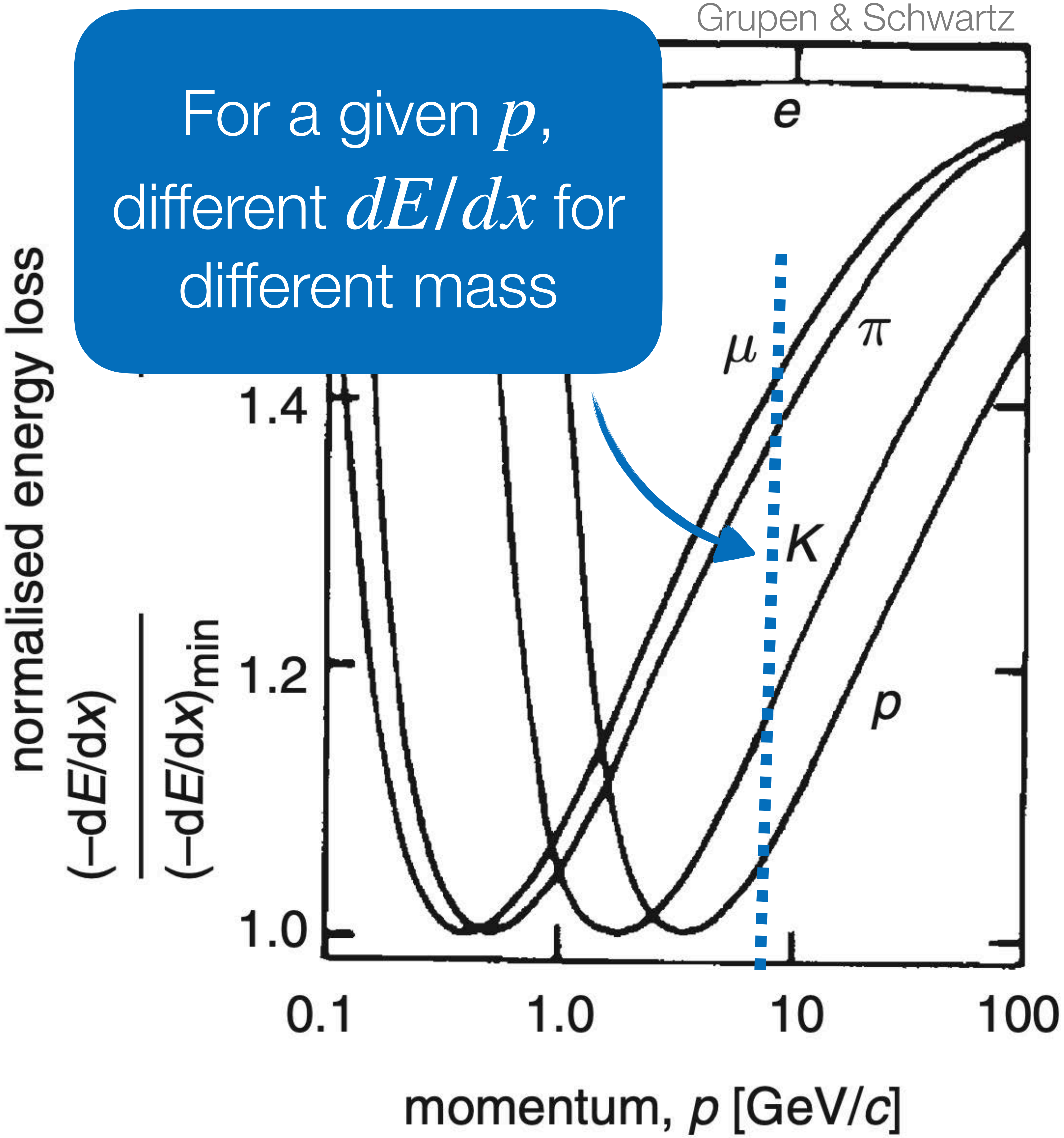

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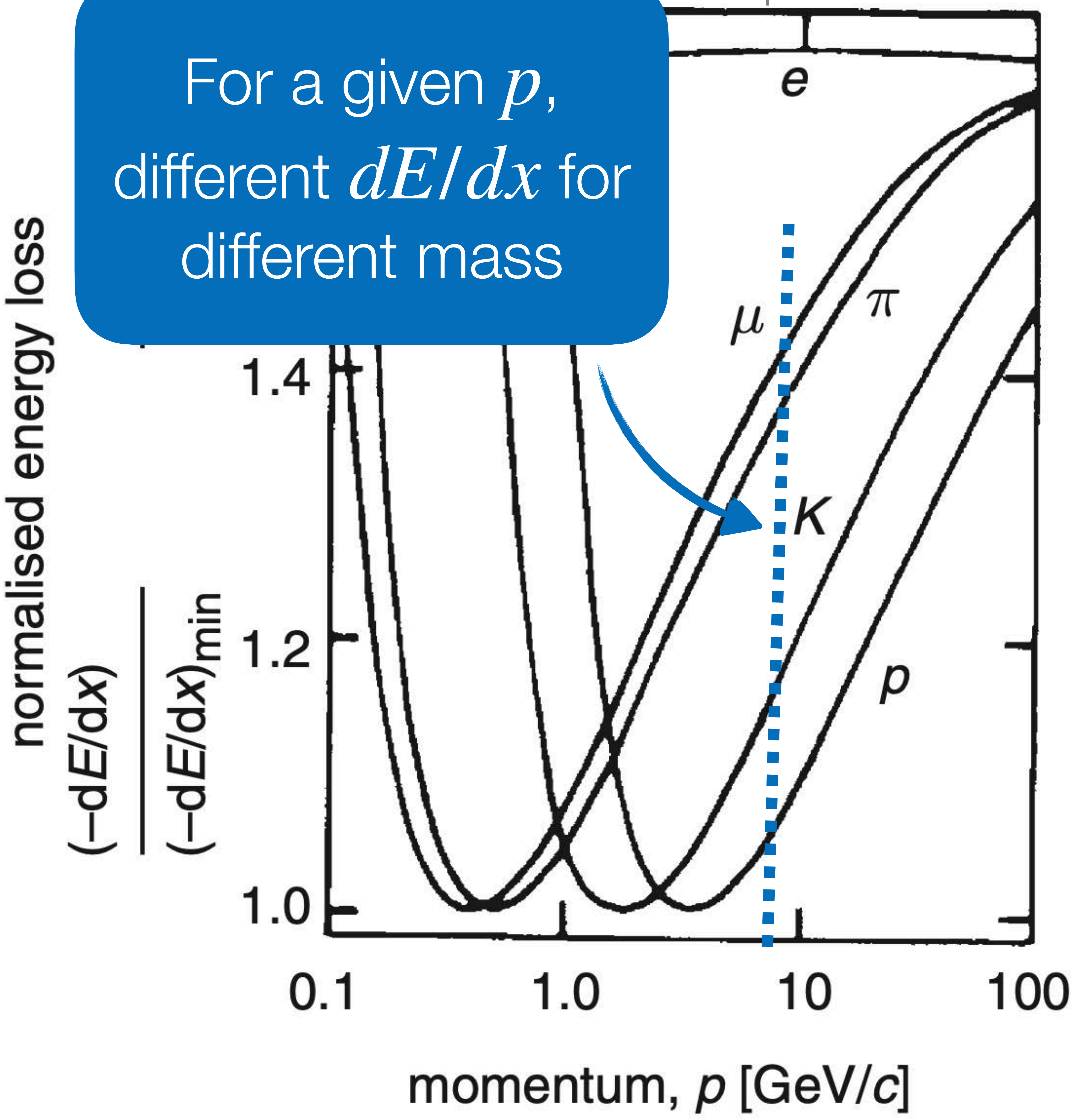
Q: Why so little discrimination between μ and π ?

Grupen & Schwartz

For a given p, different dE/dx for different mass



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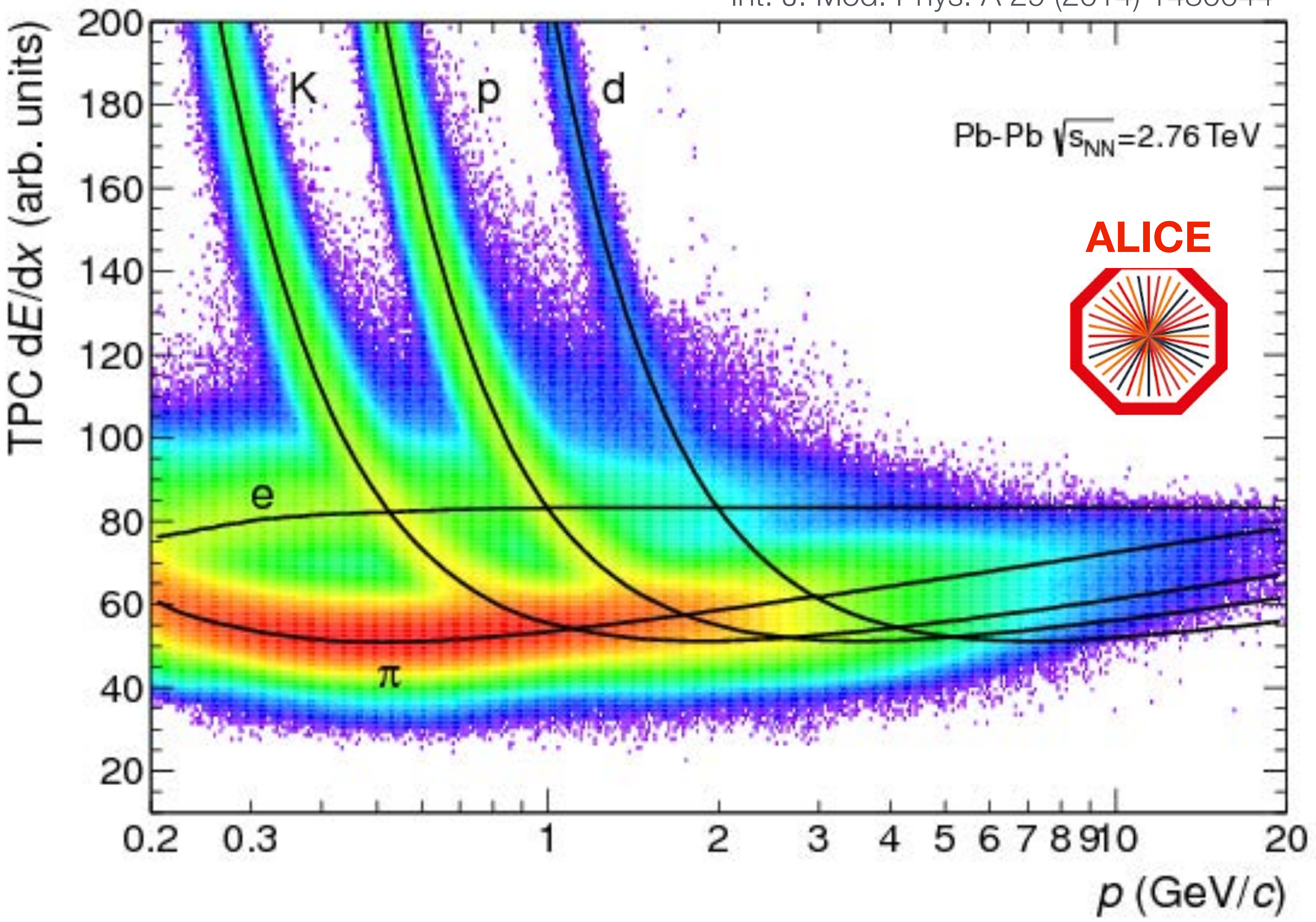
Int. J. Mod. Phys. A 29 (2014) 1430044



Energy loss measured by ALICE Time Projection Chamber

Fluctuations in dE/dx limit PID capability

Charged particle ID : **Time of flight**

- Time it takes for particles to travel a fixed distance

$$t_{TOF} = \frac{d}{c\beta} \sim 3 \text{ ns} \frac{1}{\beta}$$

- Need very fast counters!

- As $\beta \rightarrow 1$, TOF measurements no longer provide any mass discrimination

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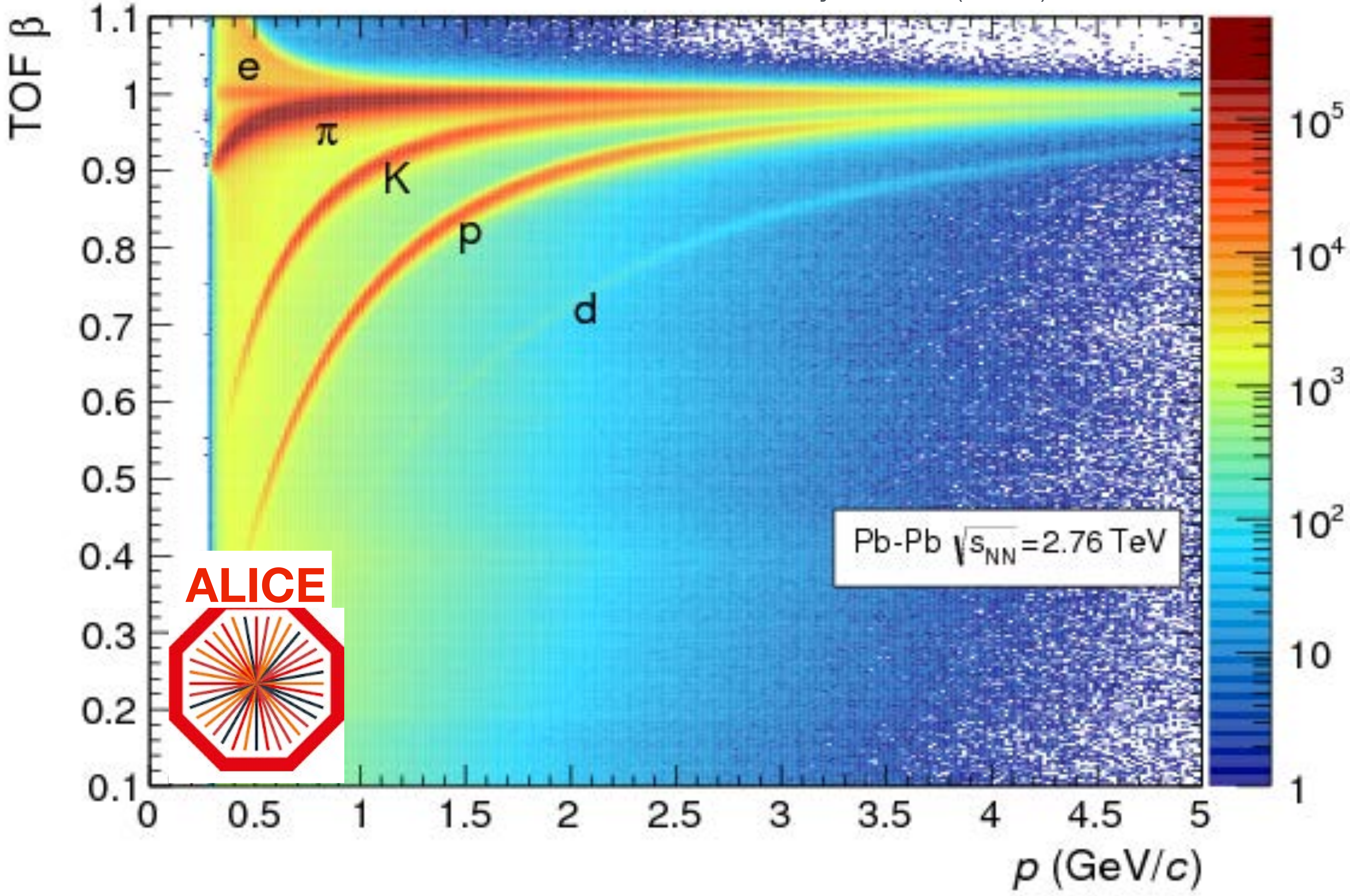

Charged particle ID : **Cherenkov radiation**

- Measure of the angle at which Cherenkov radiation is produced allows determination of the velocity of the particle.

$$\theta_c = \frac{1}{n\beta}$$

- Challenge:
  - Detection of Cherenkov photons with high efficiency over large surface
  - Precise measurement of photon position

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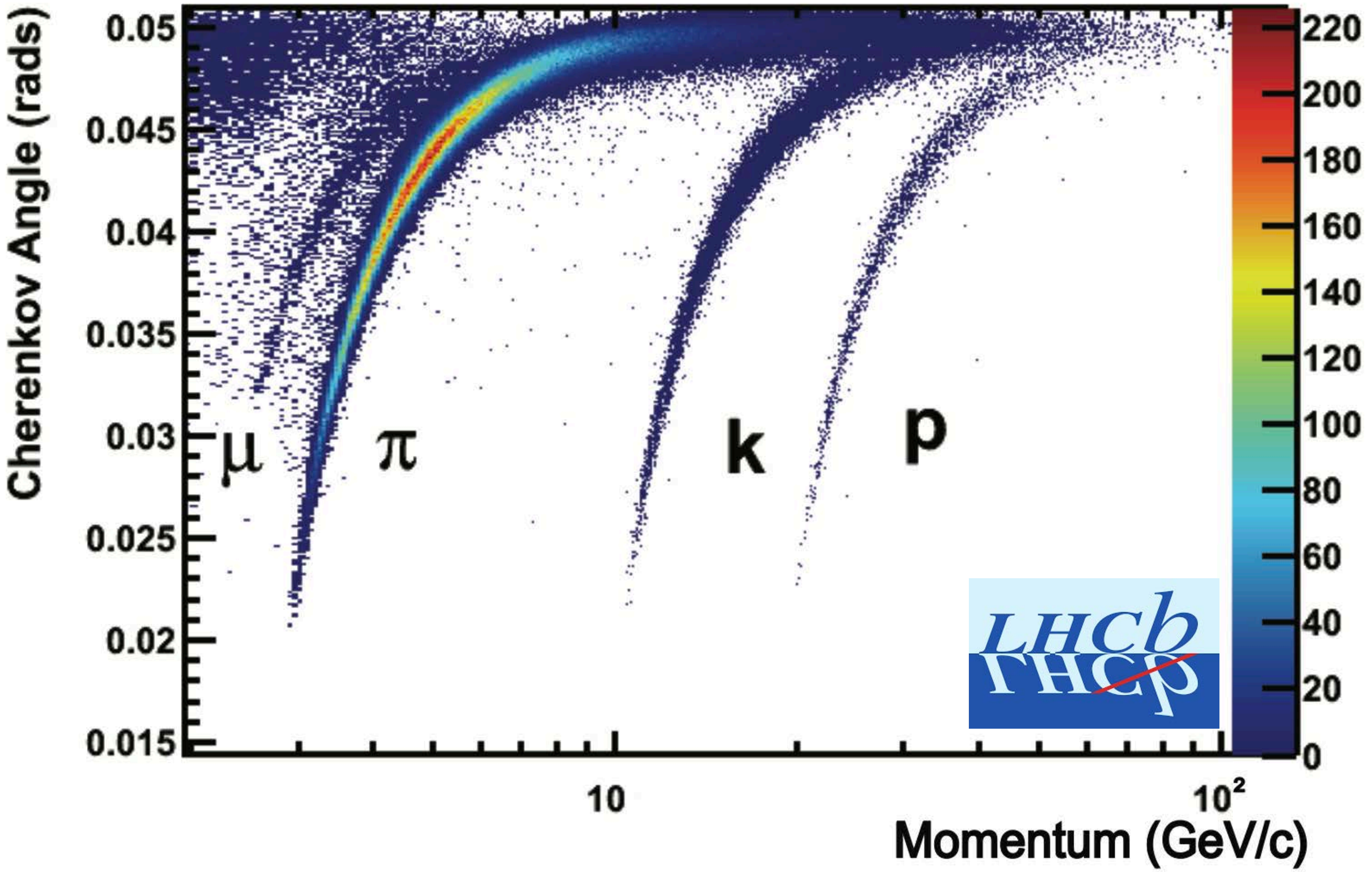
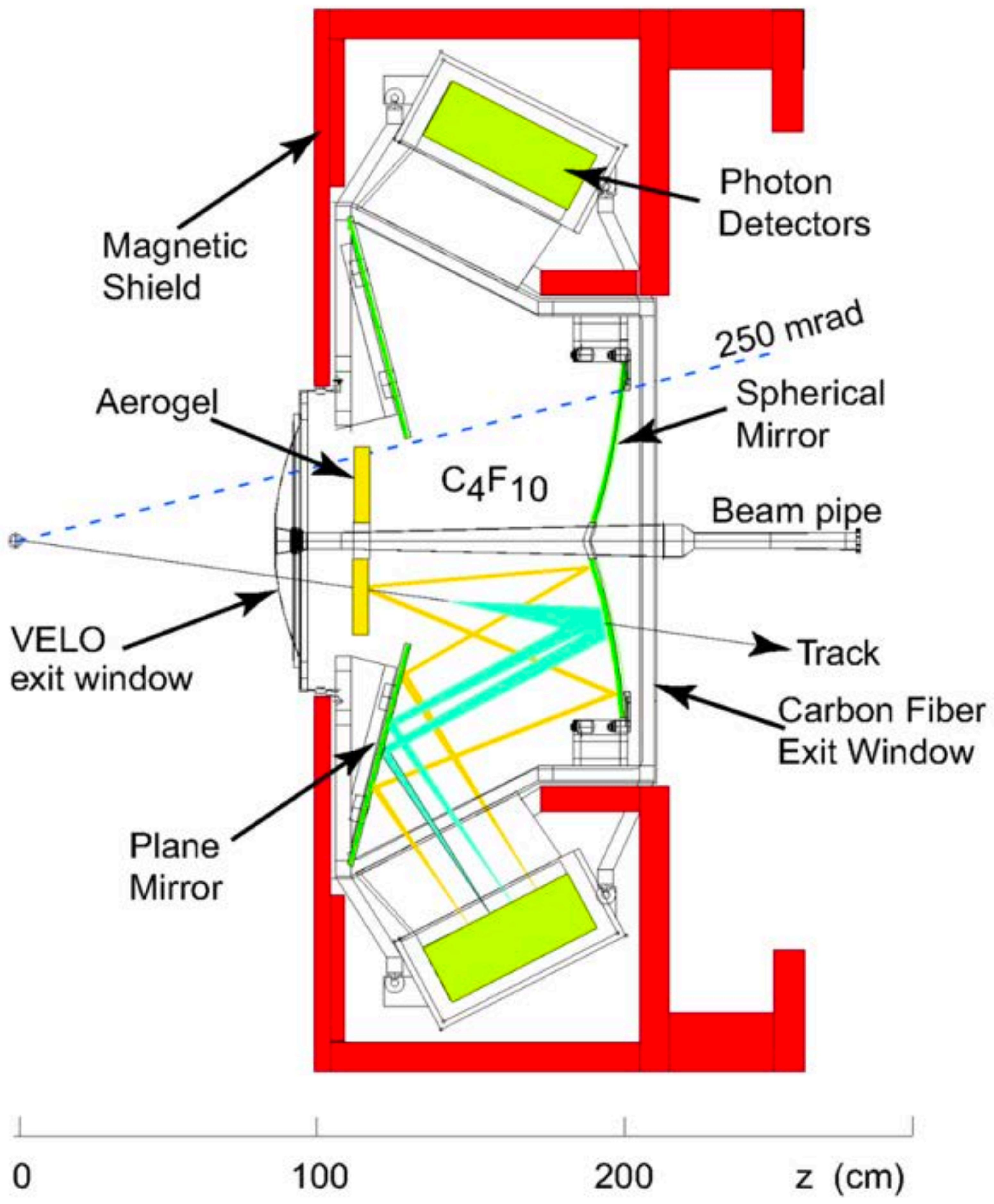
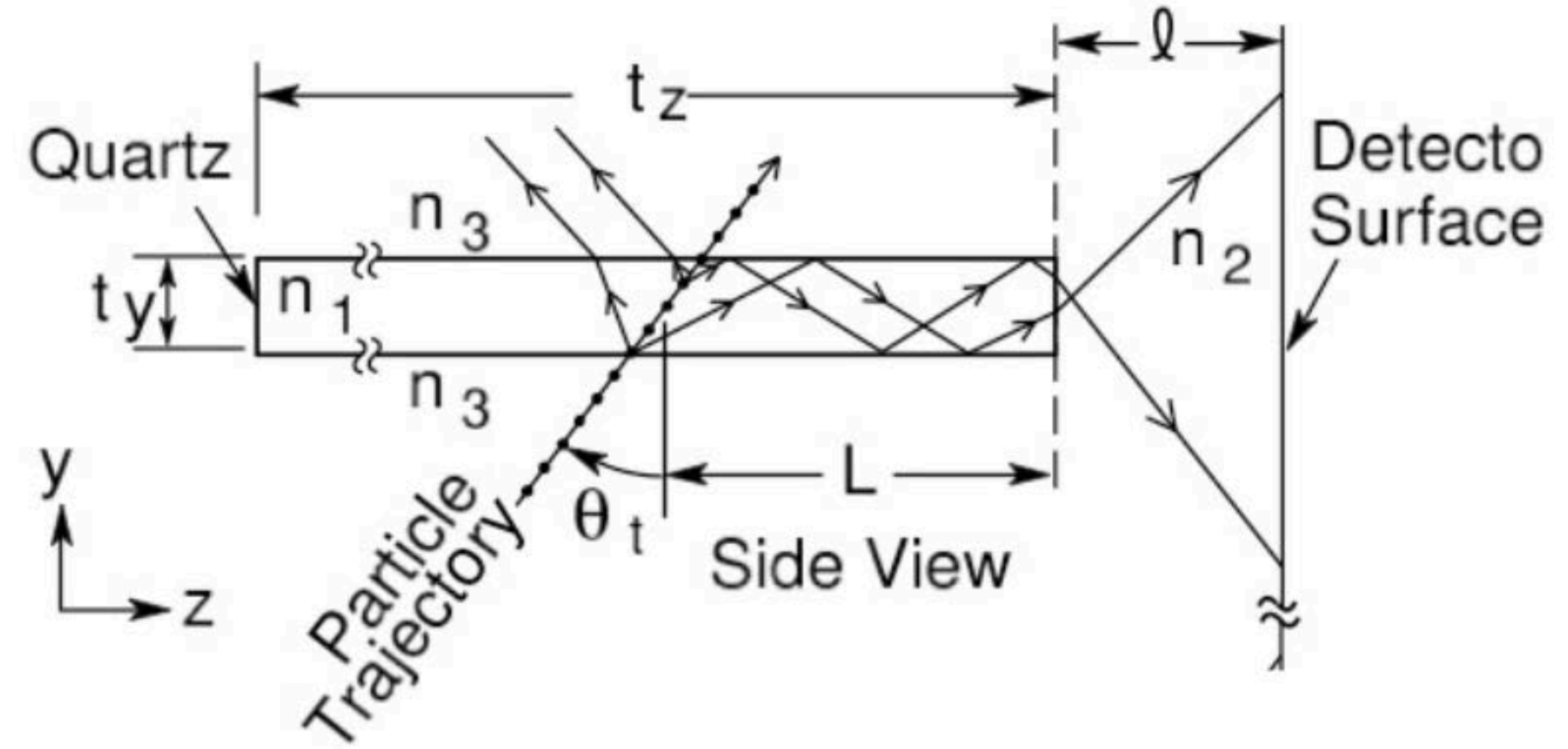


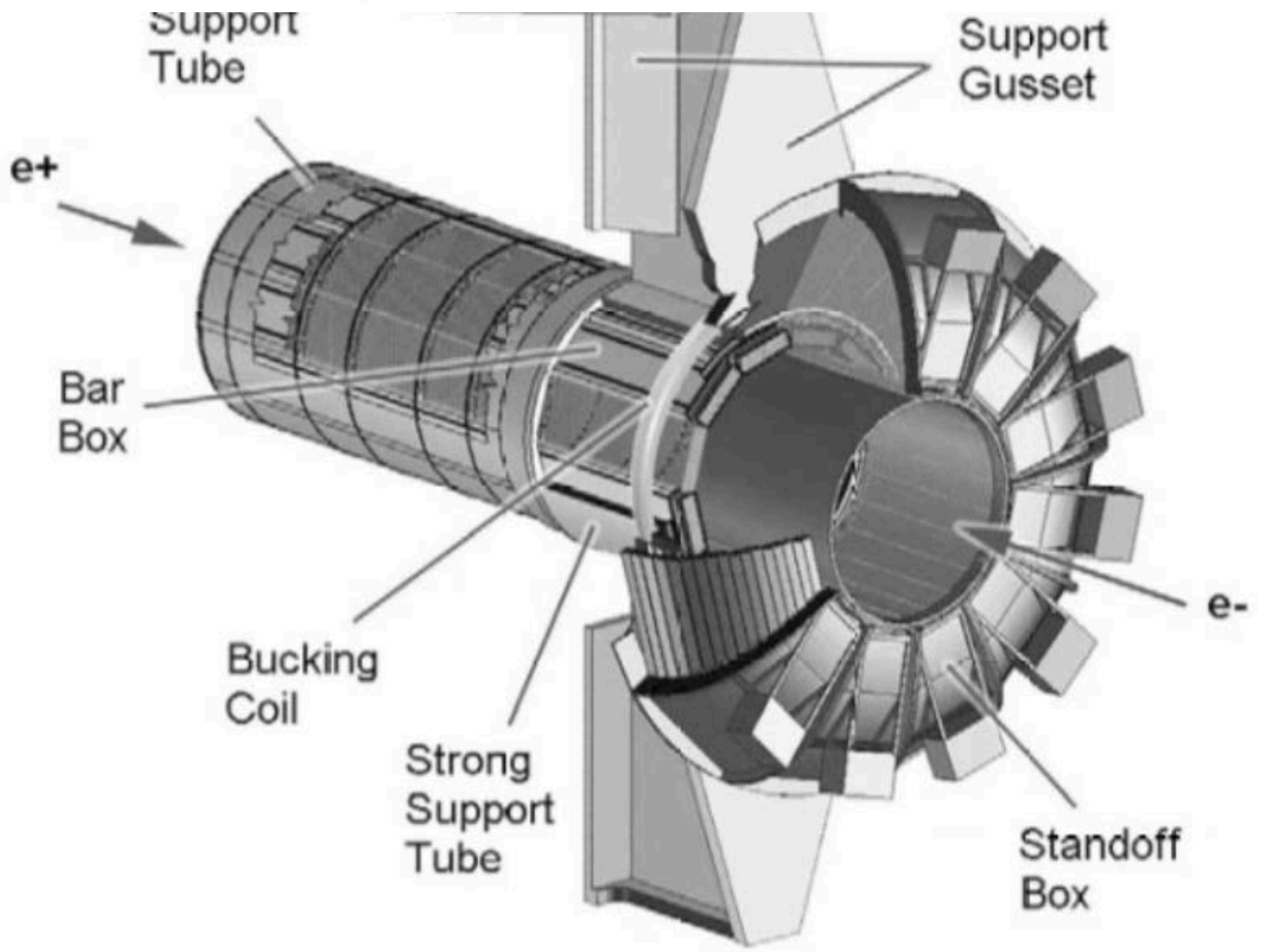
Charged particle ID : **Cherenkov radiation**

LHCb RICH
Ring Imaging Cherenkov



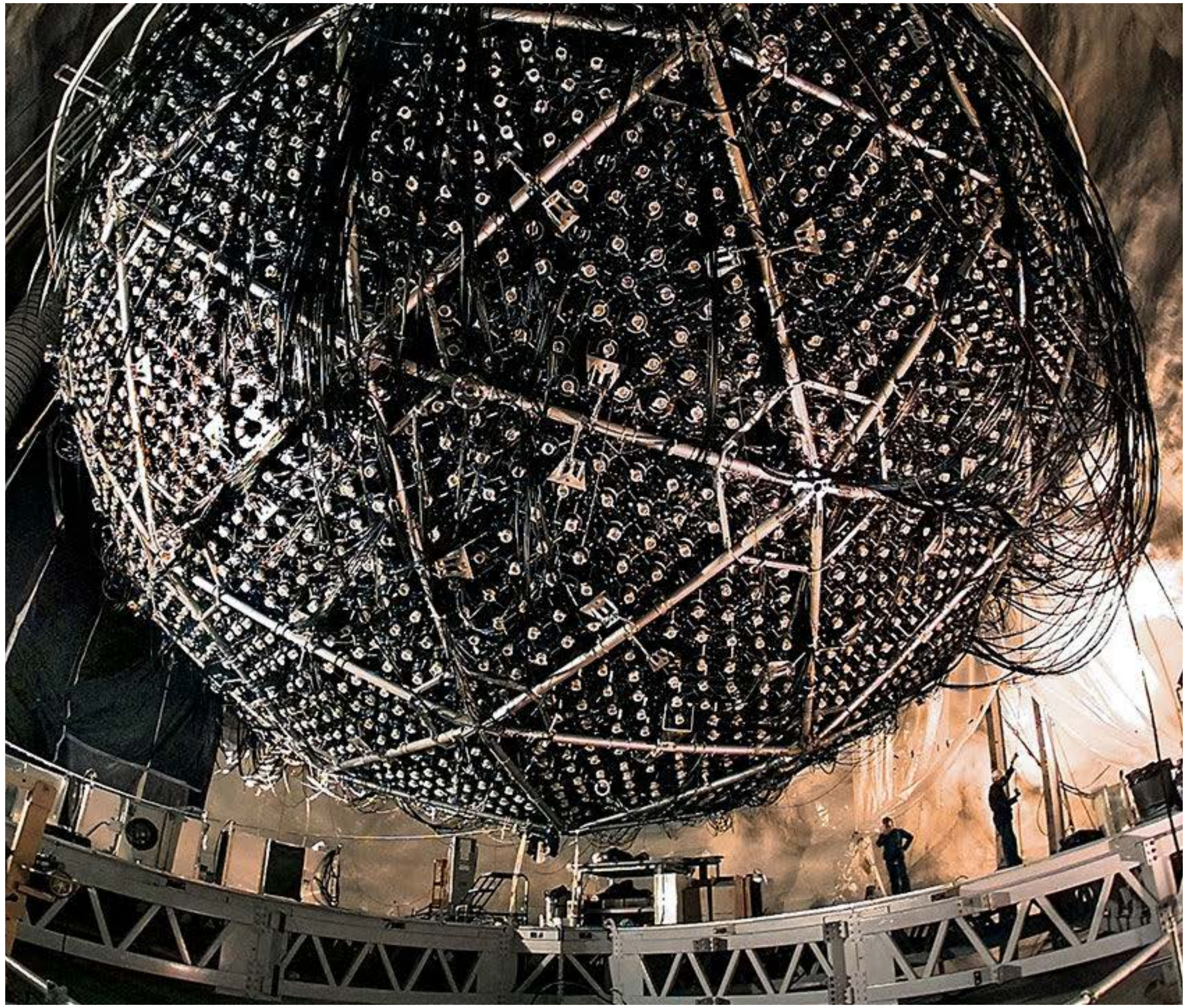
Babar DIRC
Detector of Internally Reflected Cherenkov

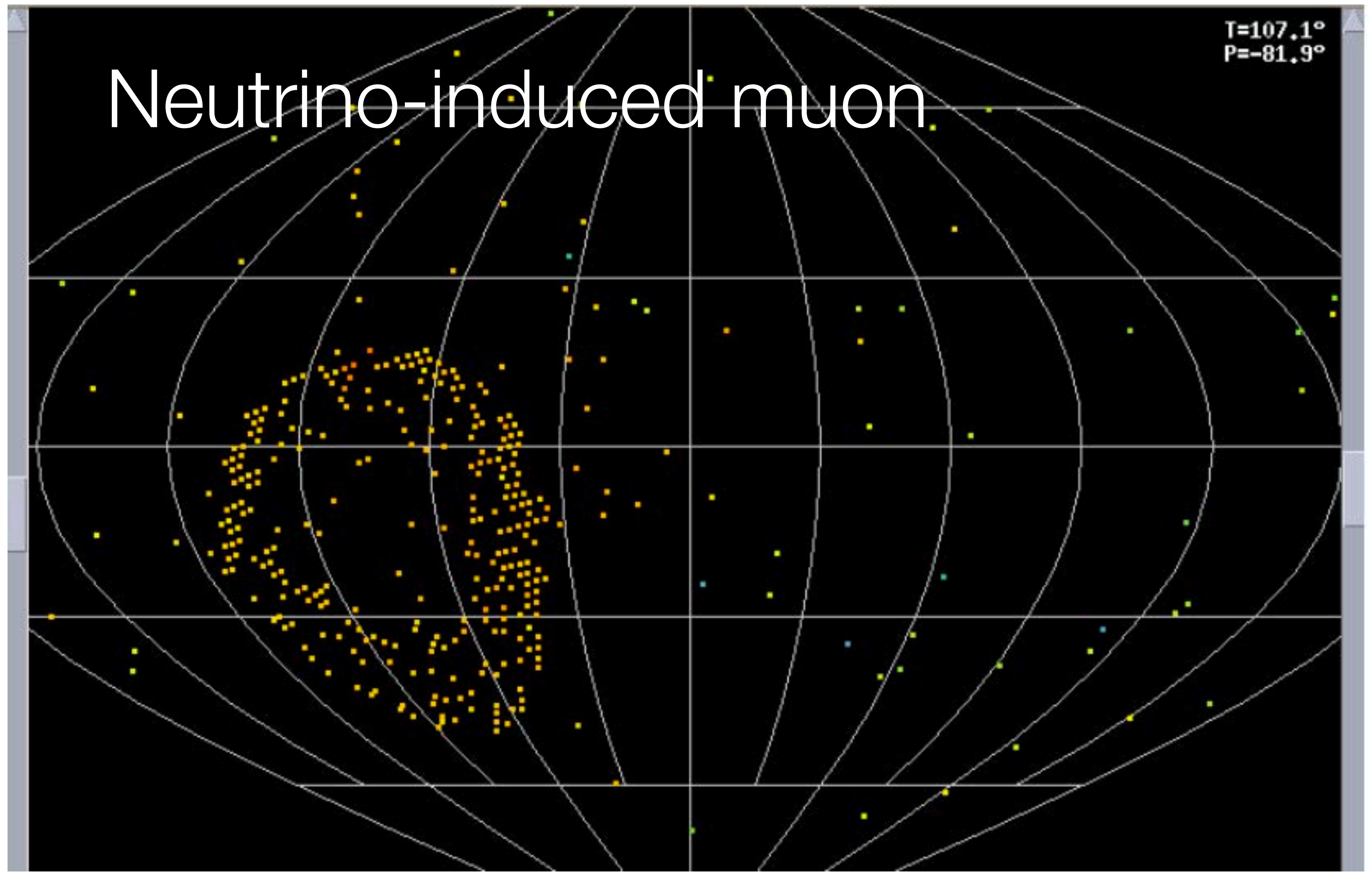


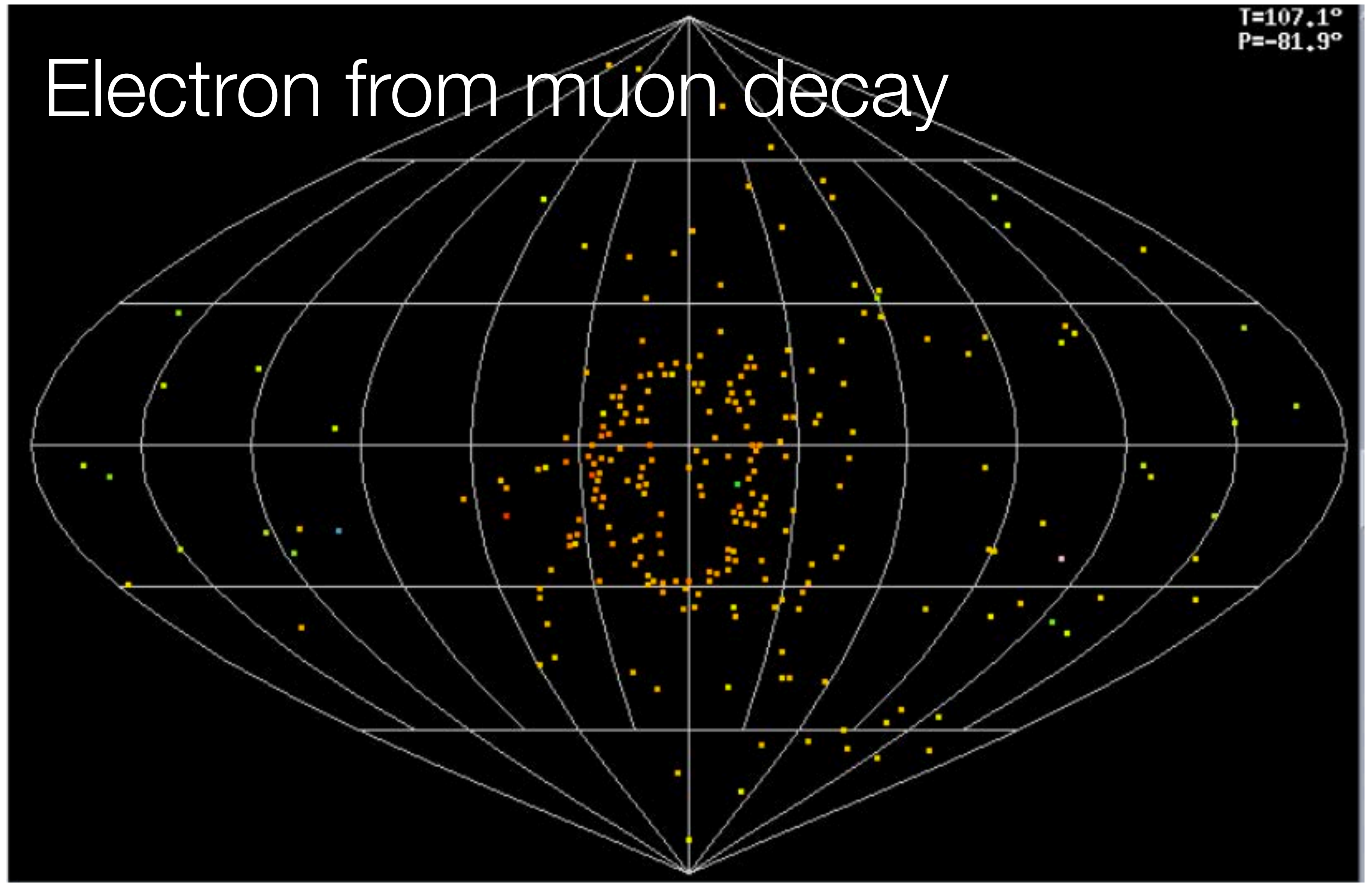


Charged particle ID : **Cherenkov radiation**

Sudbury Neutrino Observatory



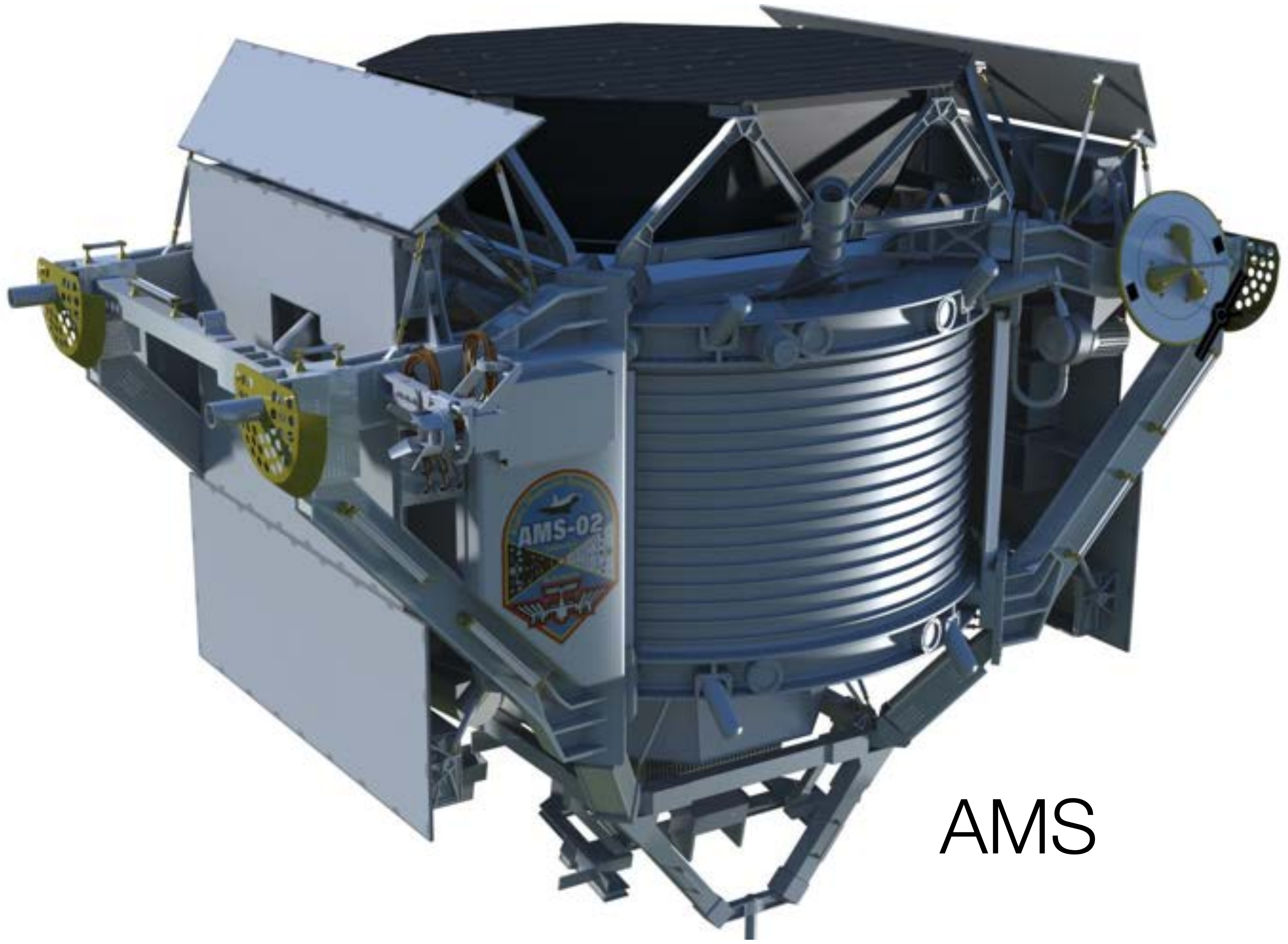




Charged particle ID : **Transition radiation**

- Energy radiated via transition-radiation photons increases with Lorentz factor γ (and not just β). Therefore, valuable measurement for PID at higher energy

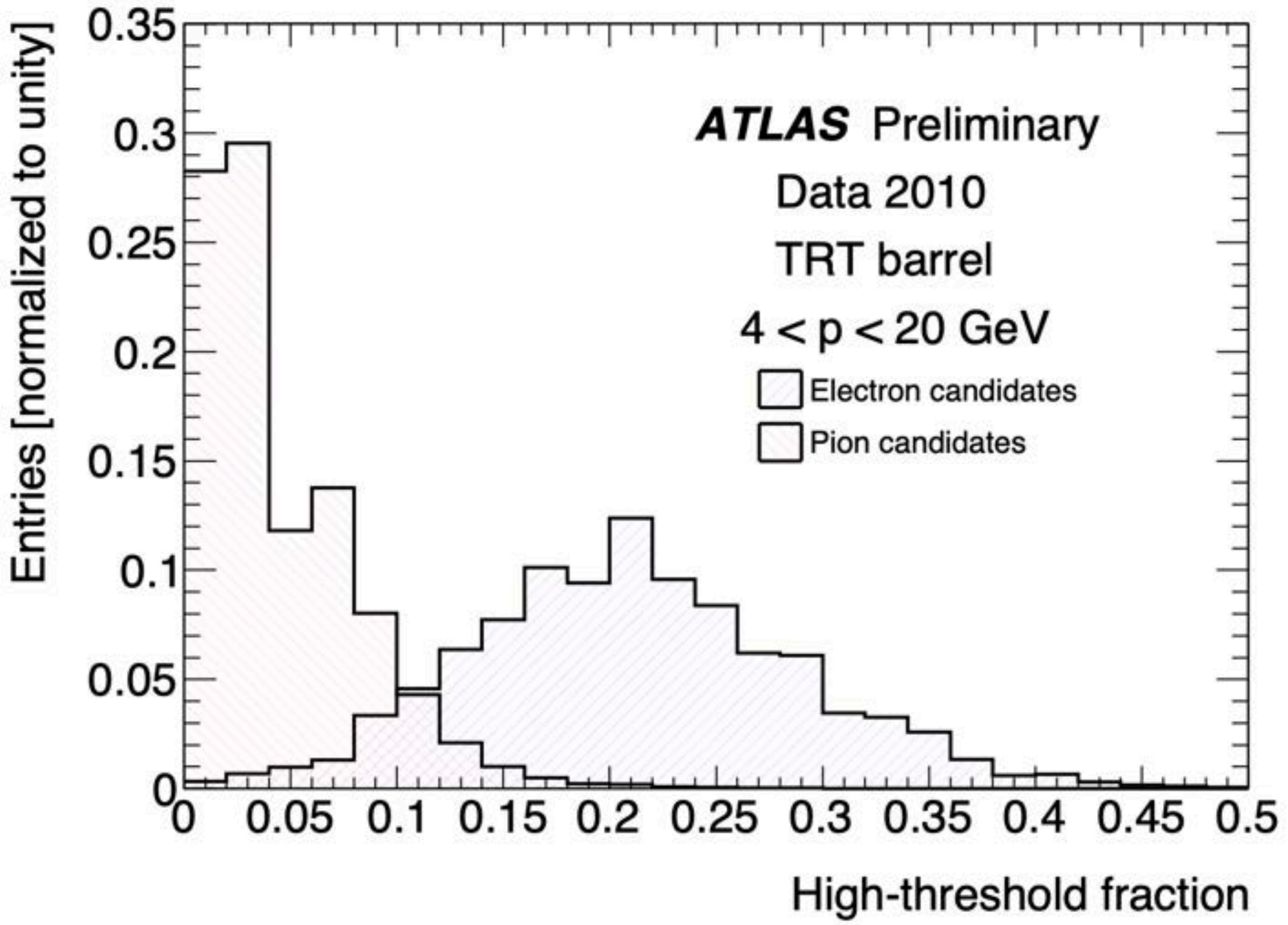
- Number of transition-radiation photons increases with z^2 of incident particle, useful for the identification of high-energy ions

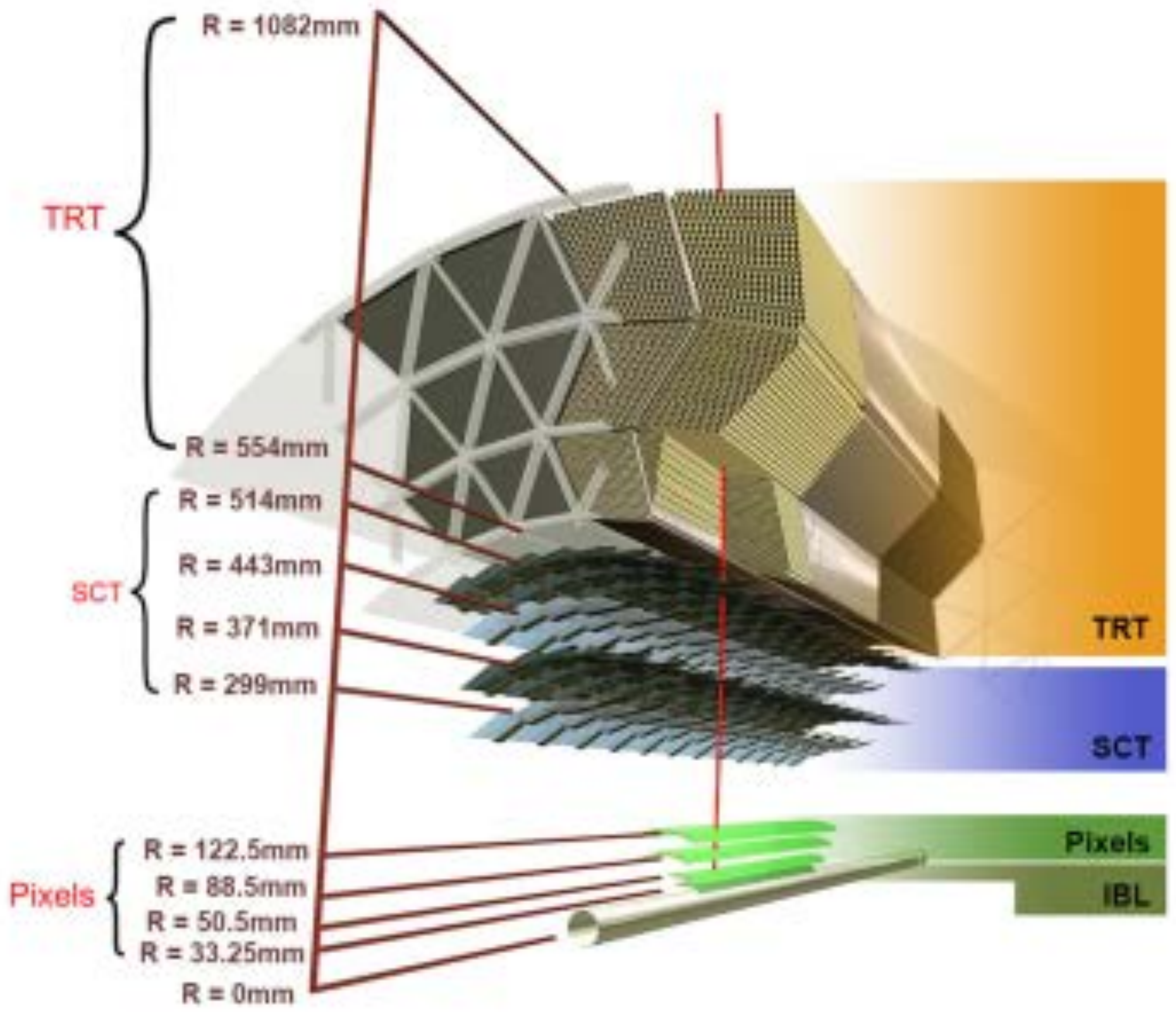


Charged particle ID : **Transition radiation**

- 370 000 cylindrical drift tubes (“straws”) interleaved with polypropylene foils/fibers as radiator
- TR photons detected in drift tubes.
- Use different read-out thresholds to measure charged particle ionization signal from TR signal and discriminate between e/π

ATLAS EXPERIMENT

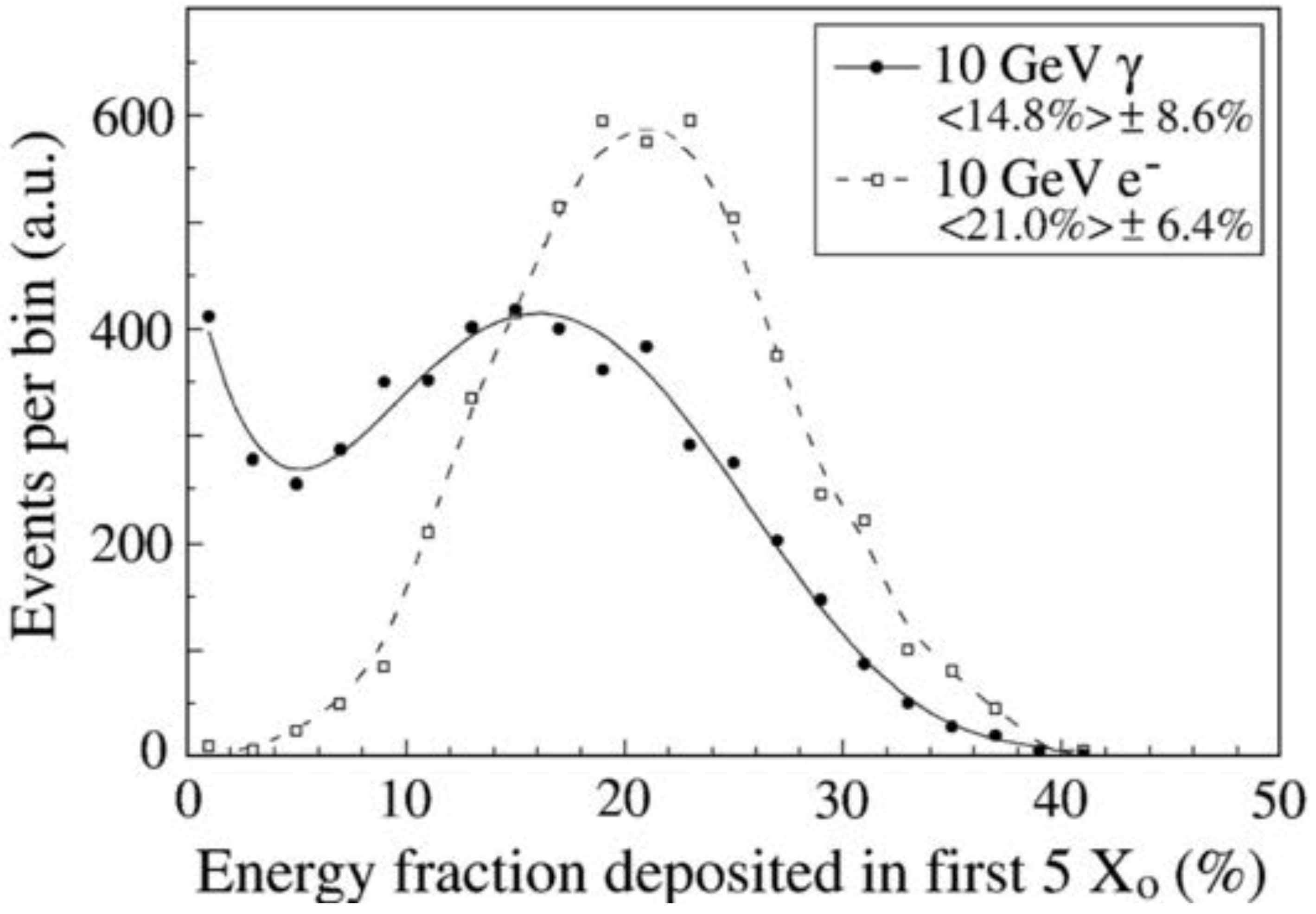


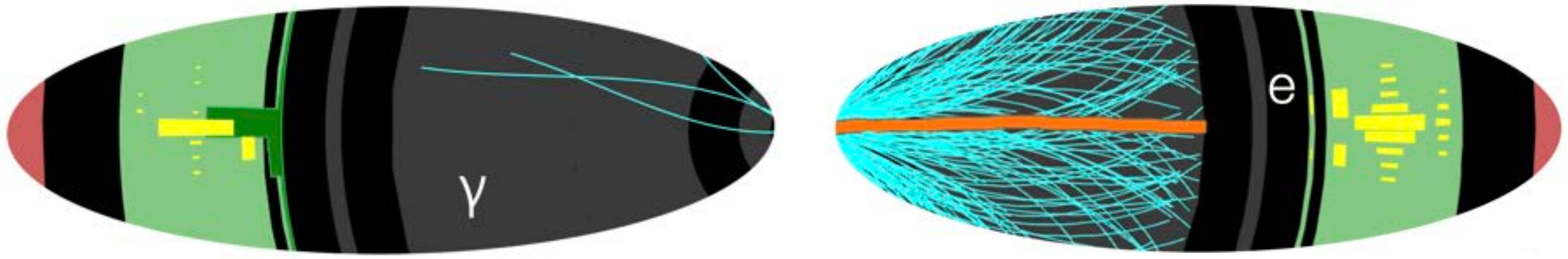


PID in Calorimeter

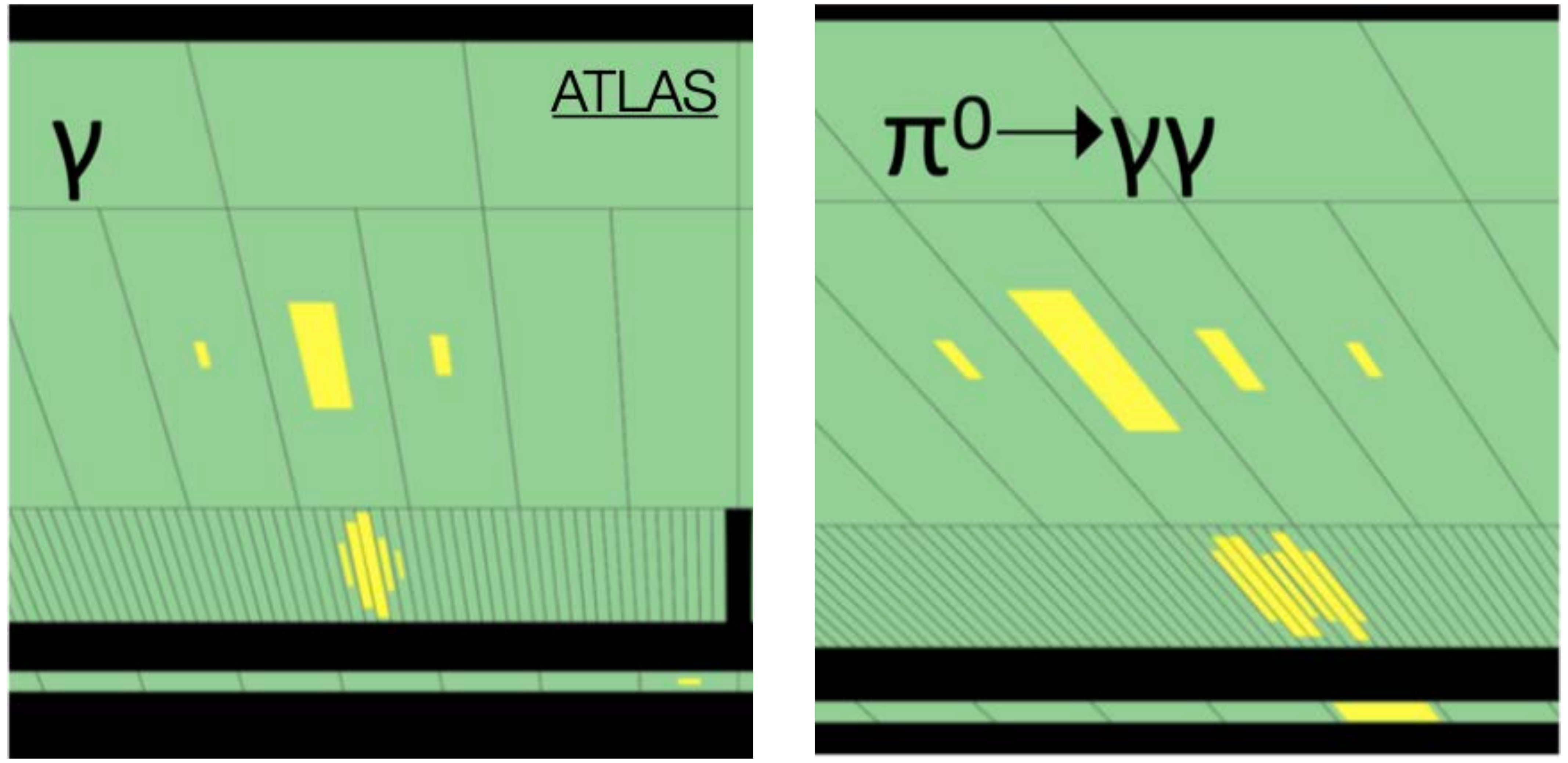
- Expect only one energy deposit in EM calorimeter for electrons and photons - no jet-like pattern

Photons deposit more energy earlier

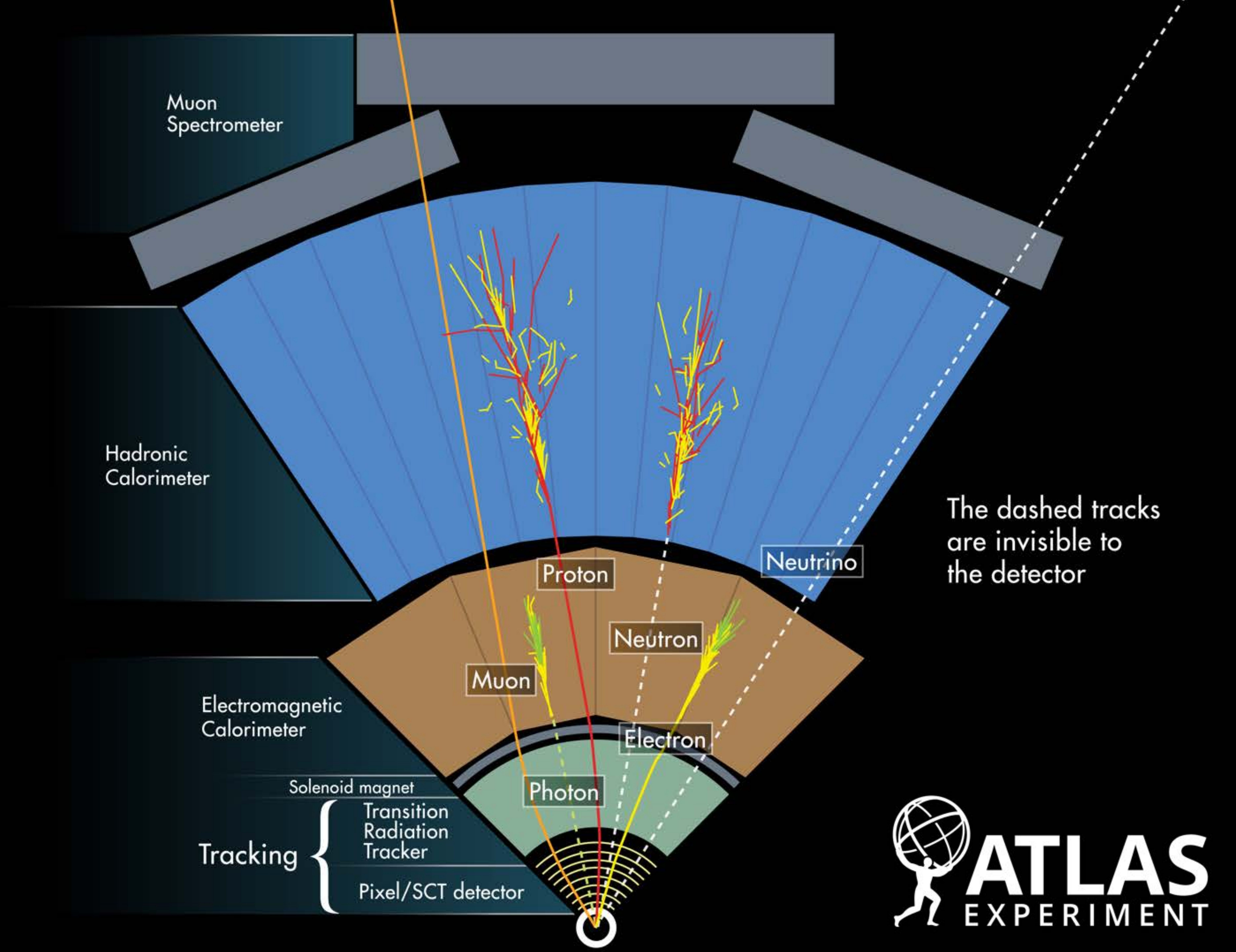




Cluster shape used for γ/π^0

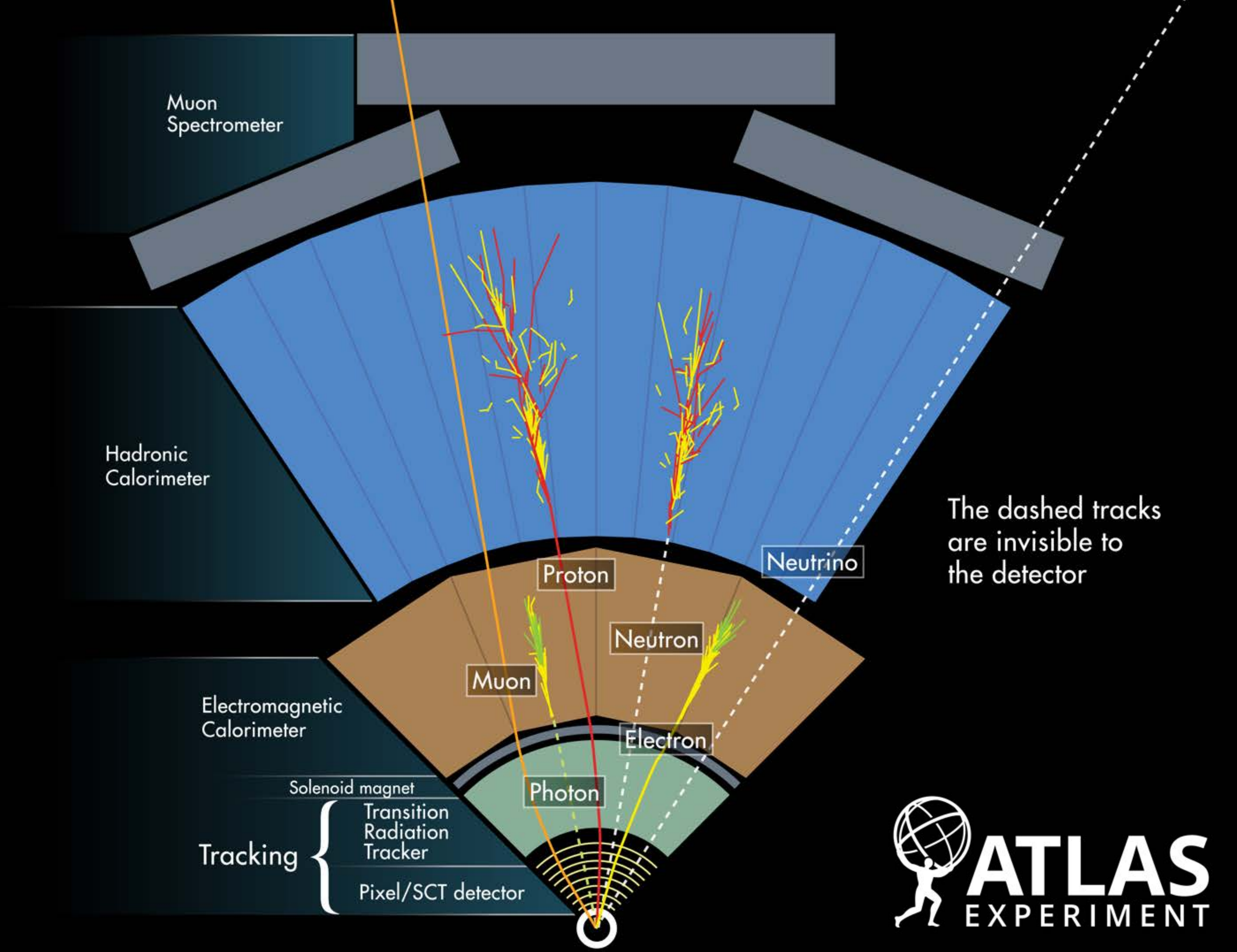


Putting it all together!



Putting it all together!

Q: Why do muons not stop in the detector?



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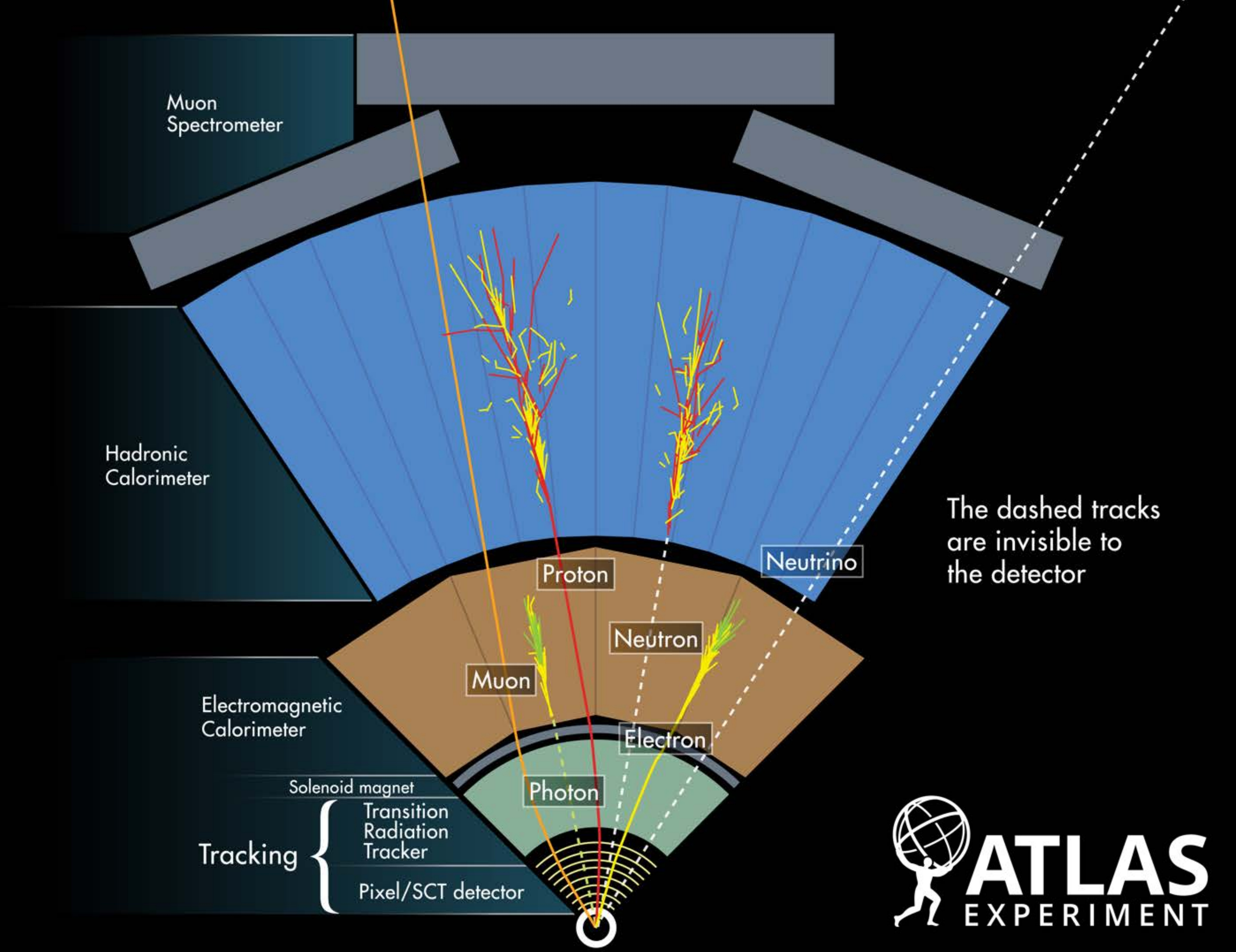
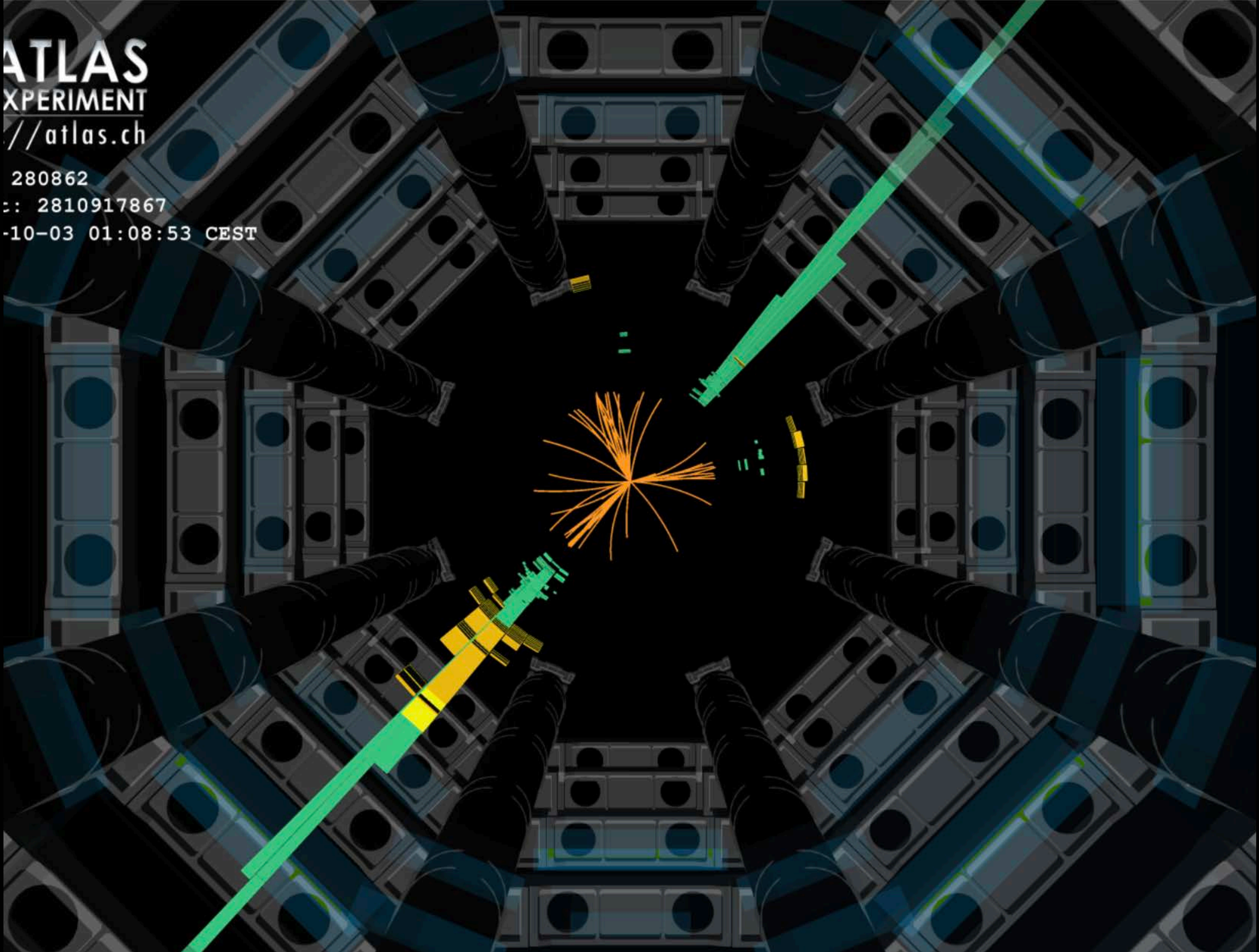


Q: Why are neutrinos not detected?


Event: 531676916
2015-08-22 04:20:10 CEST


ATLAS
XPERIMENT
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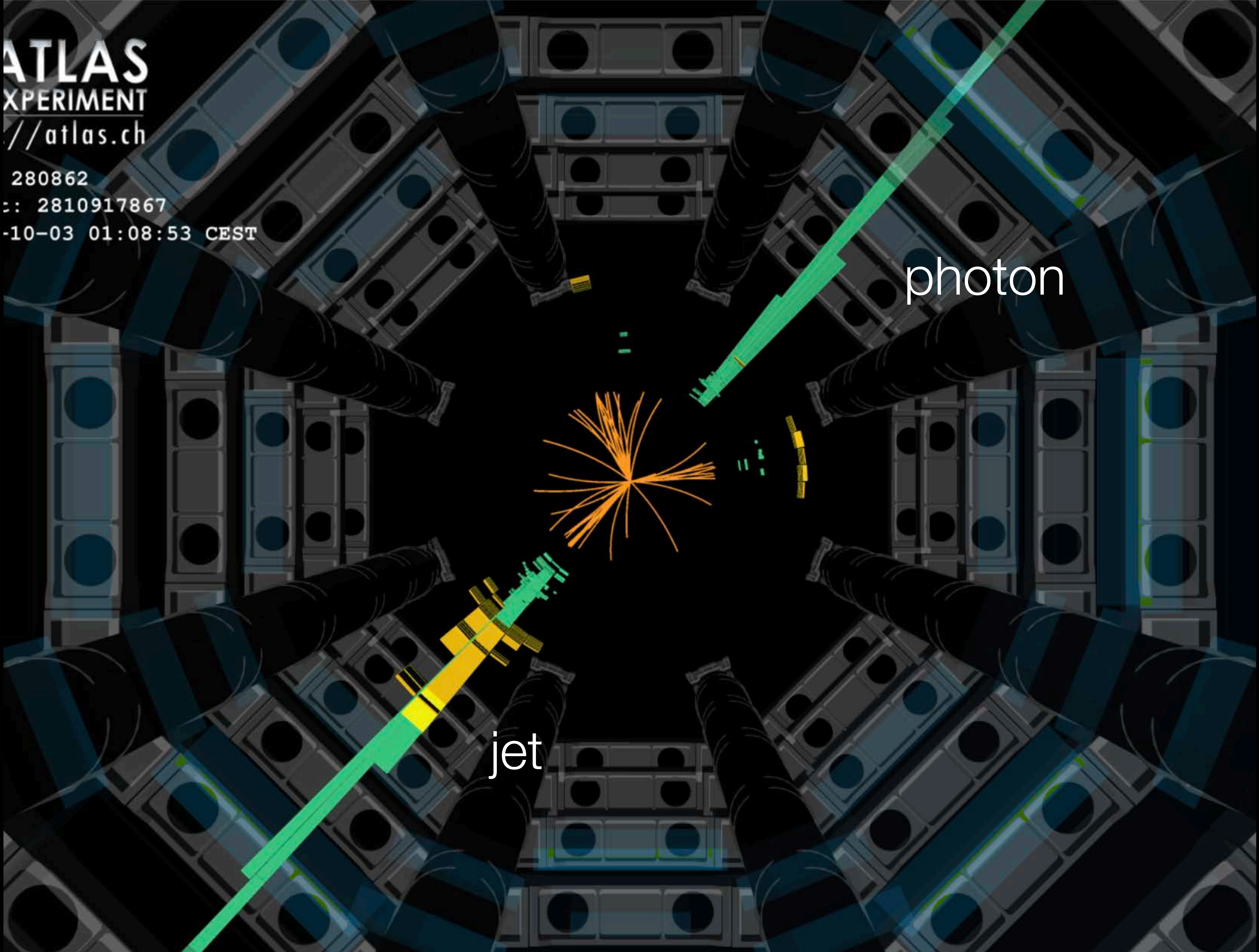
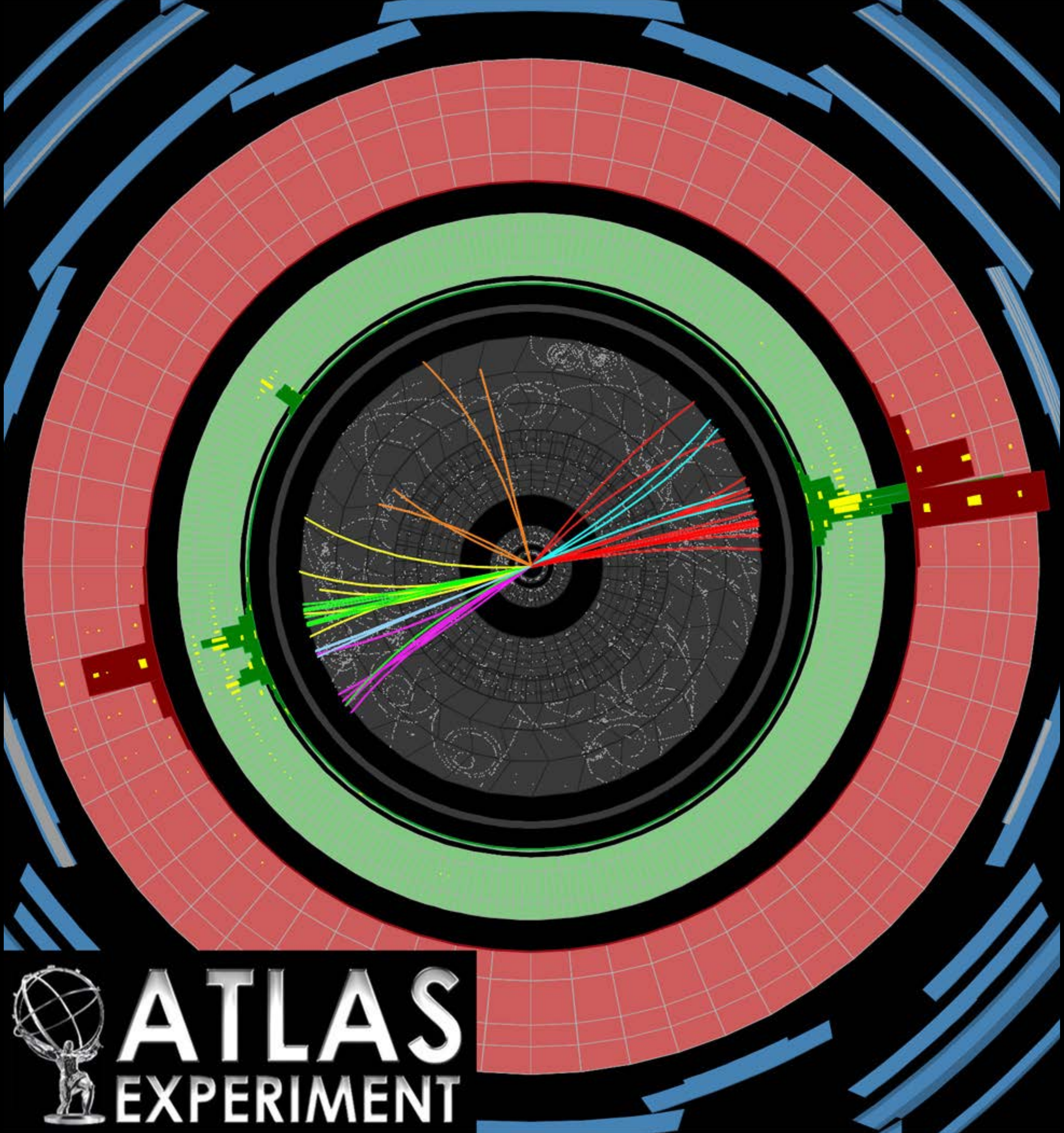

ATLAS
XPERIMENT
://atlas.ch
280862
:: 2810917867
-10-03 01:08:53 CEST
photon
jet

Momentum imbalance in the transverse plane



(1) Add 4-vector of well-calibrated objects (electron, muon, etc.)

(2) Add remaining activity not associated to an object → "soft term"

(3) Vector needed to obtain momentum balance is MET: Neutrino ID

Wrap-up

- Detectors need to be able to
  - Identify particles entering them
  - Measure as much of their properties: energy, momentum, charge, etc.
- This is typically achieved by combining information from different parts of a detector (tracker, calorimeter, etc.) and/or different types of signal (scintillation, ionisation, etc.)
- Calorimeters play a crucial role, measuring the total energy carried by all types of particles (except for muons and neutrinos)
  - Also important for particle identification at high energies.
- Key design considerations for calorimeters include energy resolution, position resolution, size, cost, radiation hardness, etc.

Sources and References

- Kate Pachal, “Calorimetry and Particle Identification”, GRIDS 2024.
- Particle Data Group
- Grupen & Shwartz, “Particle Detectors”, 2nd edition, 2008.
- Wigmans, “Calorimetry”.
- Fabjan & Gianotti, Rev. Mod. Phys 75 (2003) 1243.
- And several schematic diagram taken from the public websites of the different collaborations e.g. ATLAS, CMS, LHCb, ALICE, etc.

Problems

- Which of these particles will undergo hadronic interactions in my calorimeter?
  K0, π+, γ, μ, n, π0
- If I want to make a homogeneous electromagnetic calorimeter out of CsI scintillating crystals (density 4.51 g/cm^3, X0 1.86) how thick does it have to be? If I want to instrument 3 m^2 of surface area, how much will my detector weigh?
- Using the approximations on slide 12, what's the maximum number of particles in an electromagnetic shower?
- Estimate the thickness of material (in centimeters) to completely absorb the energy from a 1 TeV gamma ray in: (a) water, (b) CsI(Tl) crystals, (c) Liquid Xenon
- Calculate the longitudinal and lateral size in units of centimeters of a shower in lead induced by the following two types of particles: (a) 100 GeV photon, (b) 100 GeV charged pion.

Properties of common materials

Property	Lead (Pb)	Iron (Fe)	Aluminum (Al)
Atomic Number (Z)	82	26	13
Atomic Mass (A, u)	207.2	55.845	26.981
Ratio A/Z	2.53	2.15	2.08
Molière Radius (cm)	1.6	1.7	3.5
Molière Radius (g/cm²)	18.1	13.4	9.5
Radiation Length (cm)	0.56	1.76	8.9
Radiation Length (g/cm²)	6.37	13.84	24.01
Critical Energy (MeV)	7.4	21	42