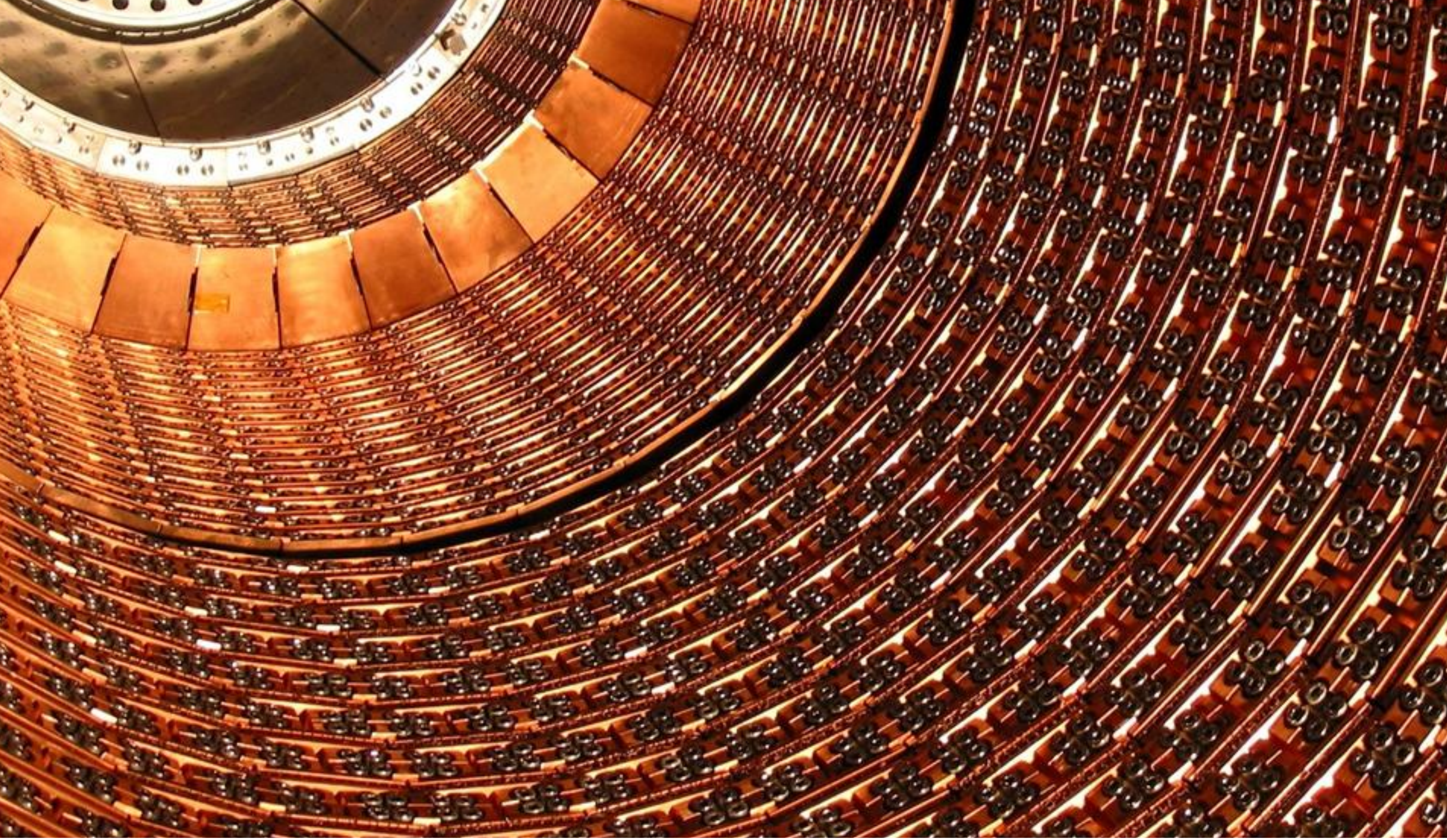


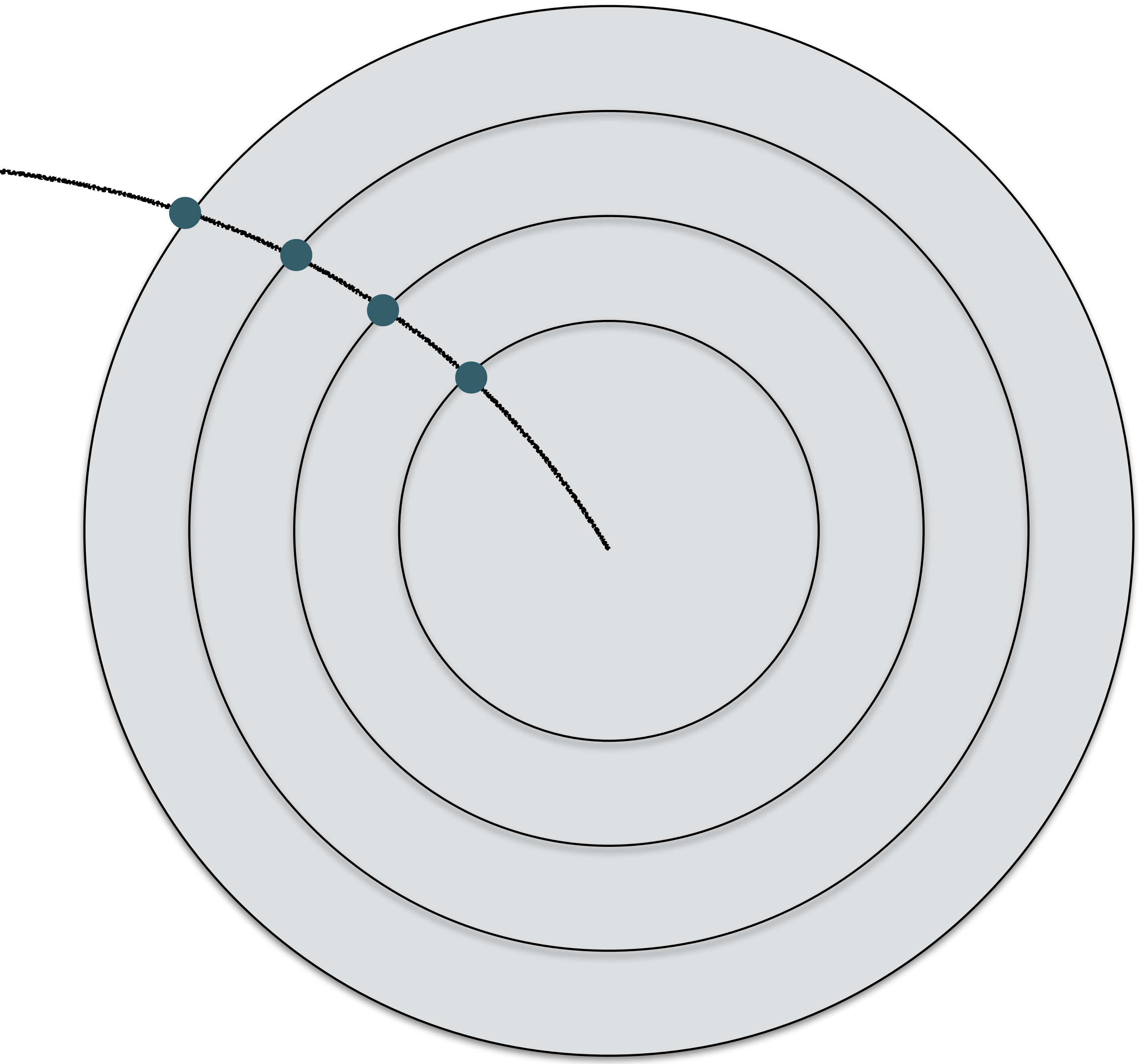
Calorimetry and particle ID

Kate Pachal
TRIUMF

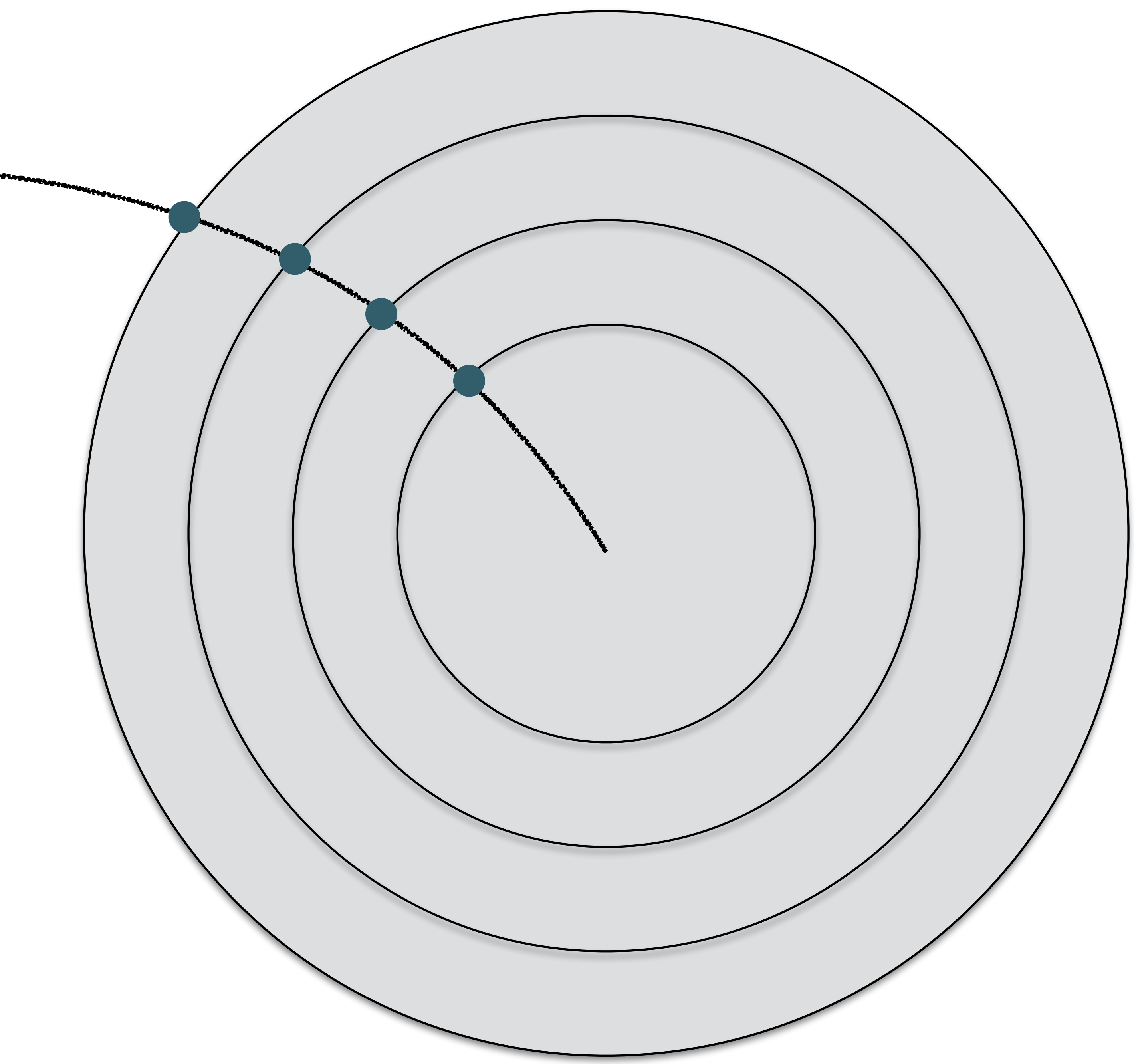
Overview

- This lecture is meant to *introduce* you to the main concepts in calorimetry and particle ID (PID)
- I am a high-energy particle physicist and work on the ATLAS experiment at CERN's LHC
    - This talk will inevitably be a bit biased towards my experience in this environment! I know a lot more about high energy than low energy calorimetry.
- Max Swiatlowski gave this talk last year and made some updates to my slides, so shout out to him for portions of this content!

Trackers: The Good and the Bad



Trackers: The Good and the Bad



- Non-destructive measurement: measure trajectory → momentum from B-field
  - Can be very high resolution!
- Only measures charged particles: no neutrals
- Difficult to build to 4π coverage

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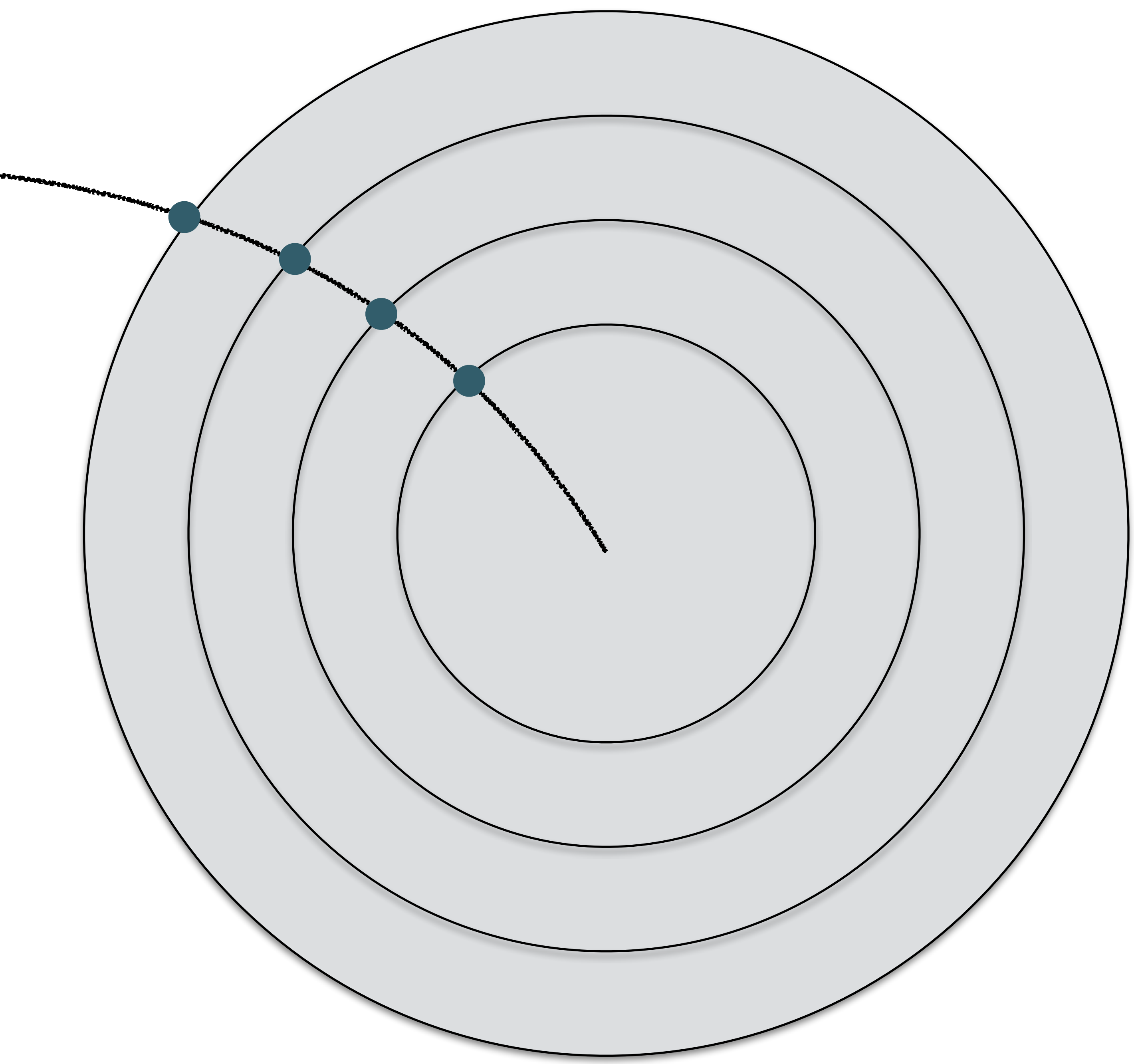
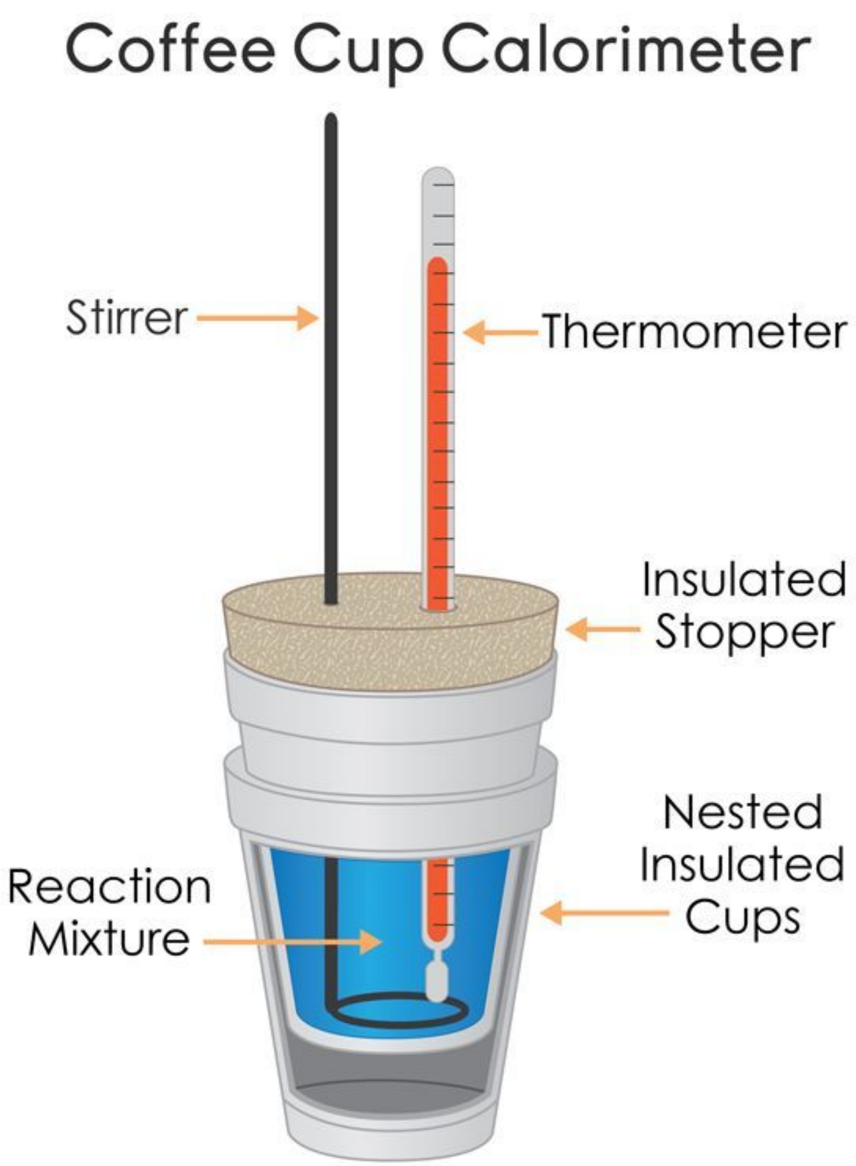


- Non-destructive measurement: measure trajectory → momentum from B-field
  - Can be very high resolution!
- Only measures charged particles: no neutrals
- Difficult to build to 4π coverage
- What's the alternative to non-destructive measurements?
  - Destructive!

Calorimeters

What’s a calorimeter?



- Calorimeters measure amount of energy output by some process
    - Simplest calorimeters measure the energy of some chemical process
- Calorimeters in subatomic physics are destructive: incoming particle vanishes in reaction with material. If it’s a good calorimeter, nothing comes out the other side: all energy is absorbed
    - So put it after your tracker!!

Goals and needs of a calorimeter

- Must be **thick enough and as close to 4π** to contain all of the energy you're trying to measure
- Must **record a signal** that gives you accurate information about how much energy was lost
  - Signal recorded by calorimeter should be predictably **proportional (linear)** to deposited energy
- Must be sufficiently **granular** to tell you not just how much energy was deposited, but where: want to reconstruct 4-vectors
- Additional **practical concerns**: small enough to fit in your detector, not too expensive, able to survive radiation conditions of your experiment, read-out fast enough for your event rate, …

Particles in matter

- A photon in space is pretty happy to just keep going! Atoms provide interaction potential that causes energy loss
- Higher density of atoms and higher atomic number both lead to greater potential for interaction

BREMSSTRAHLUNG

PAIR PRODUCTION

Particles in matter

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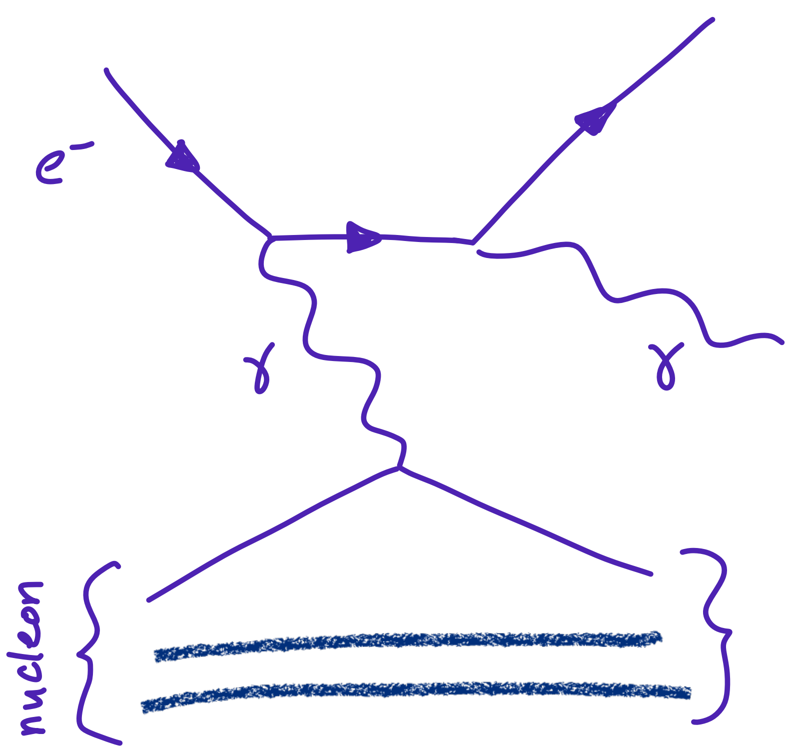

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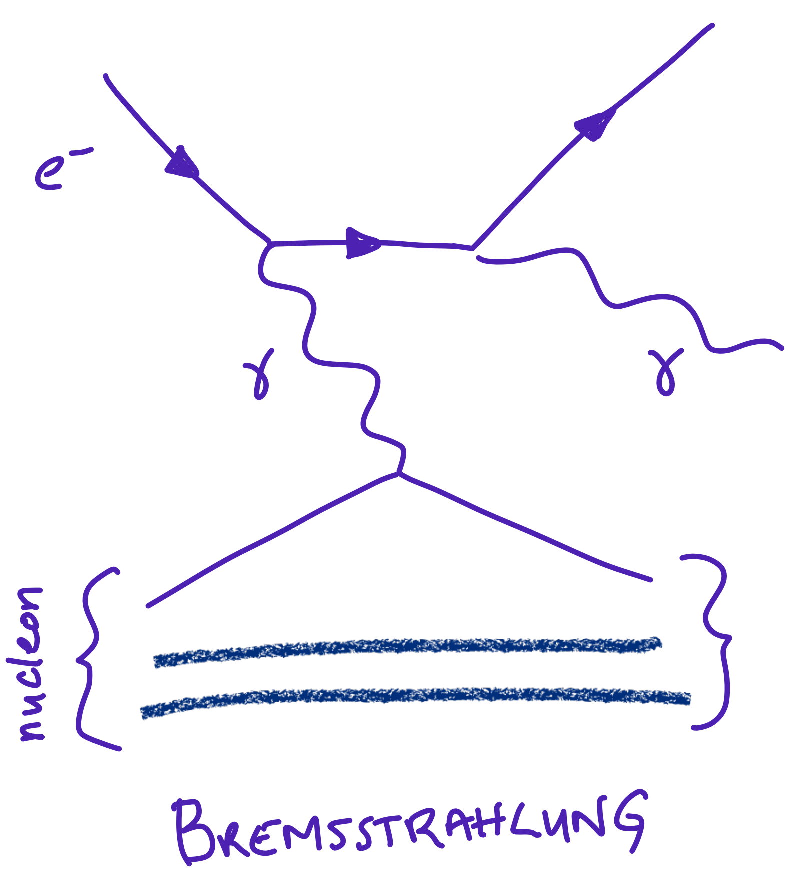
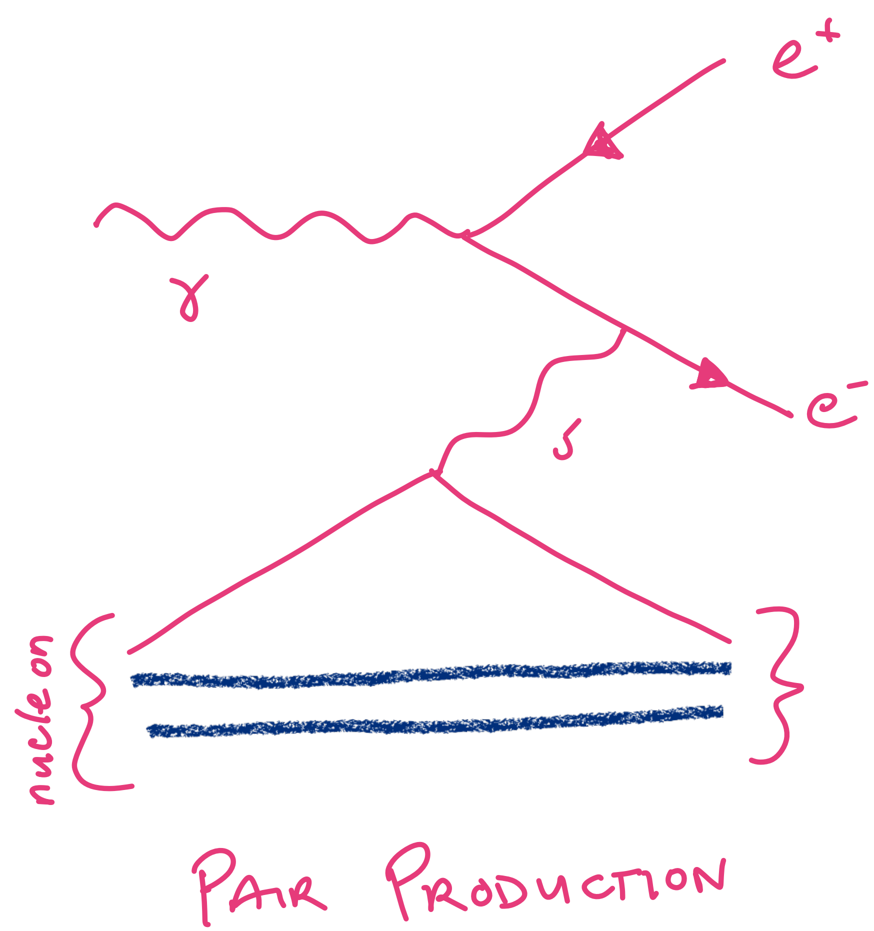
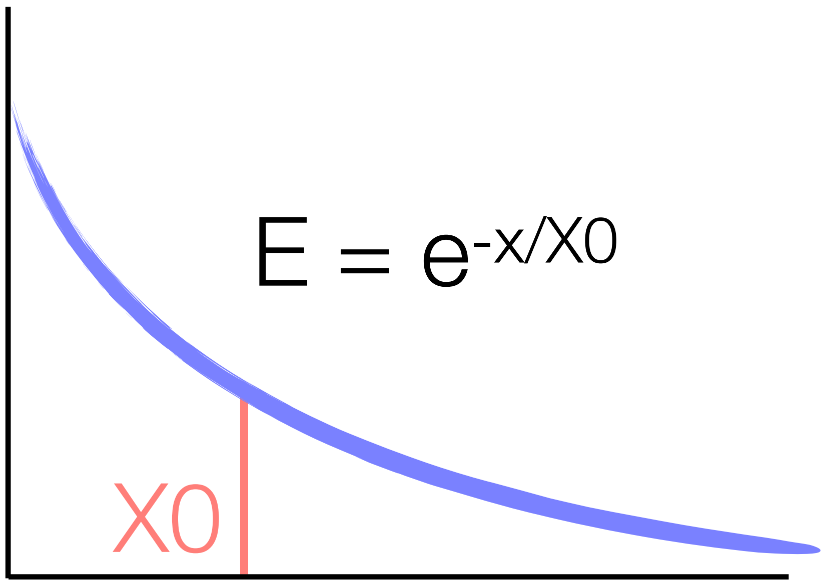




Glossary of terms

- Z = atomic number of detector material
- A = mass number (~ 2 Z)
- X_0 = radiation length. Distance after which all but 1/e of an electron's energy is lost via bremsstrahlung
- t = depth in radiation lengths
- Critical energy = energy at which an electron interacts equally via bremsstrahlung and ionisation.
- Shower maximum = depth of calorimeter shower where there is maximum particle multiplicity



$$X_0 \simeq \frac{180A}{Z^2}\ \text{g/cm}^2$$

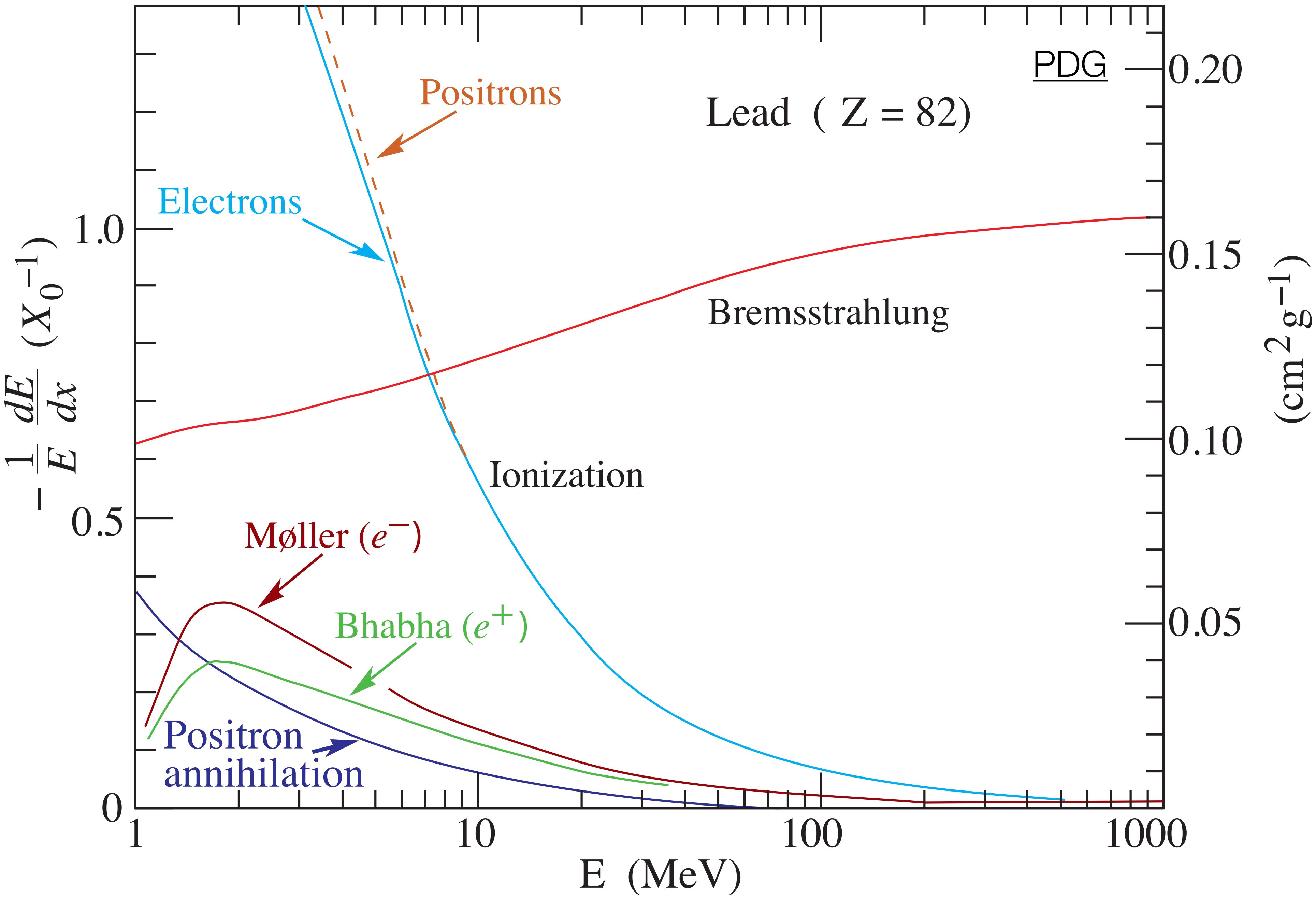
$$t = \text{distance}/X_0$$

$$E_C \simeq \frac{610\ MeV}{Z + 1.24}$$

$$t_{max} = \ln\left(\frac{E}{E_C}\right) - [1.0,\ 0.5]$$

e⁻ γ

Electron interactions



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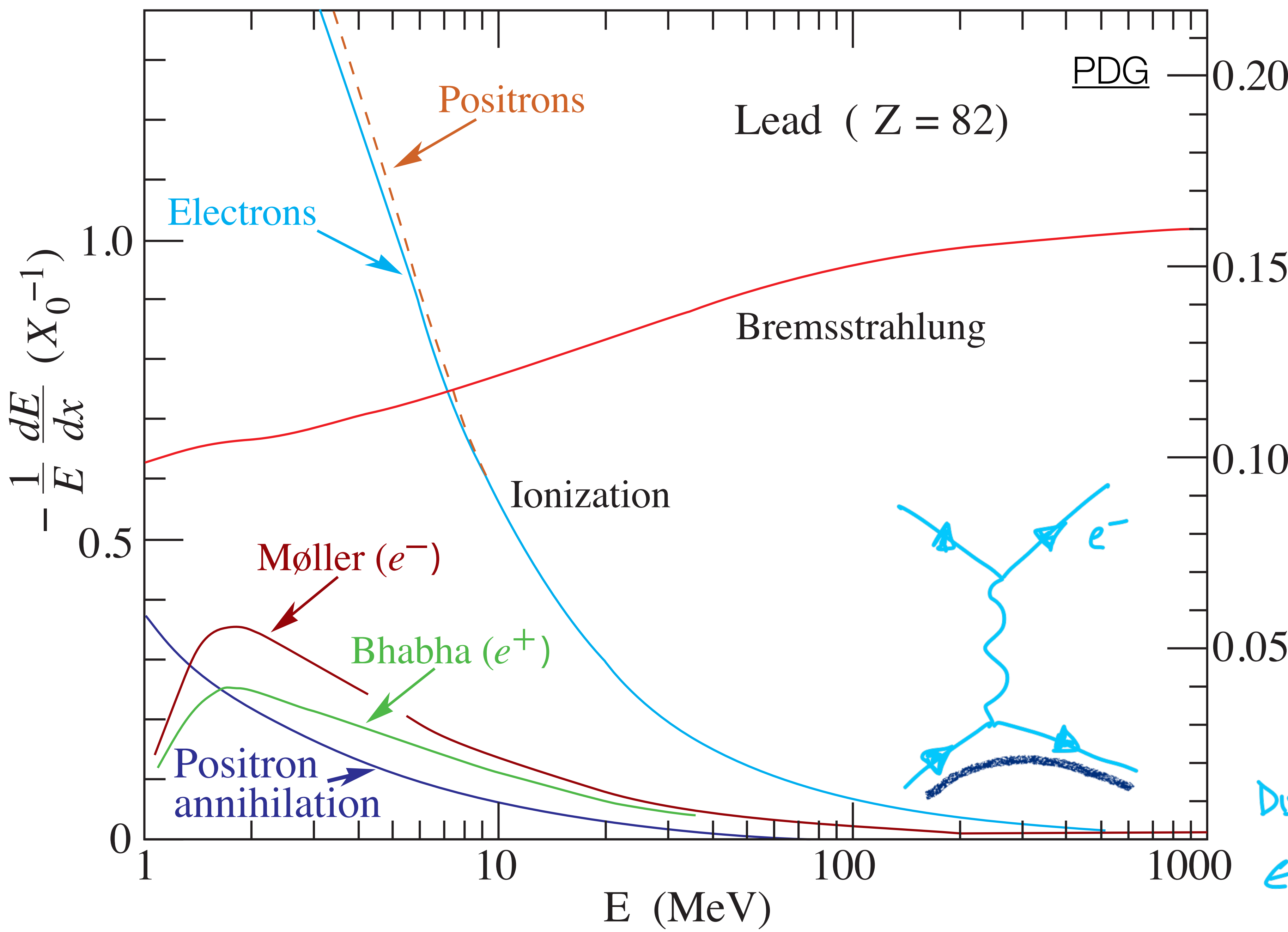
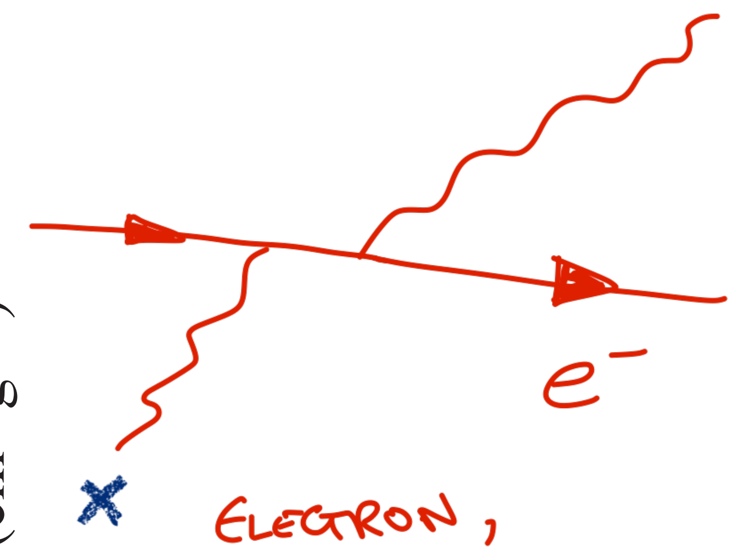


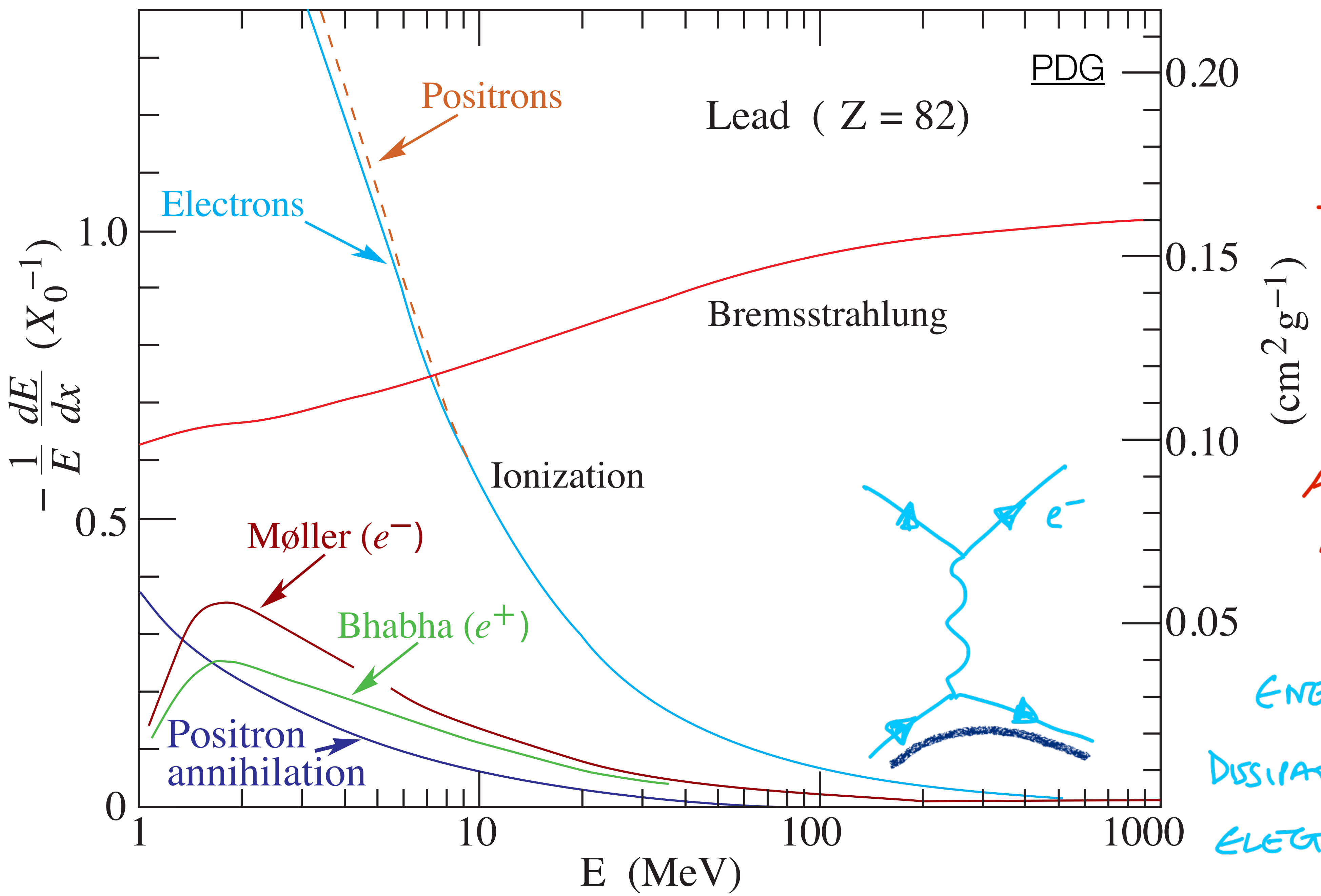


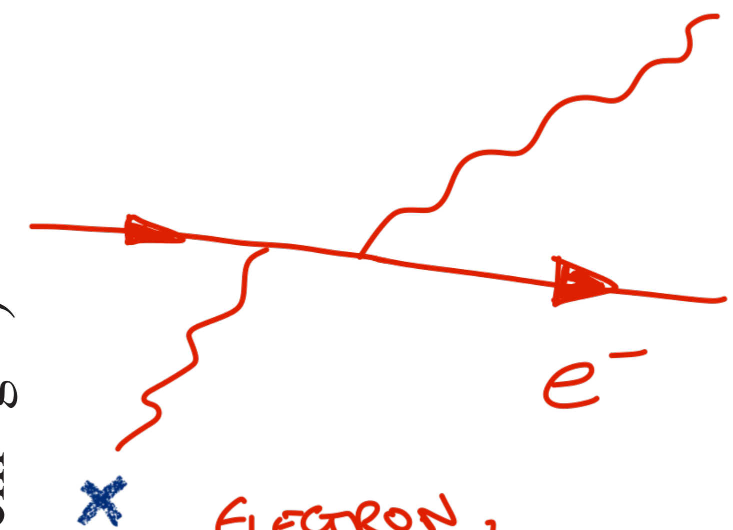
ELECTRON, ACCELERATED BY FIELD OF ATOM, RADIATES A PHOTON

ENERGY OF ELECTRON DISSIPATED WHILE FREEING ELECTRON FROM NEIGHBOURING ATOM

Electron interactions

Reminder: electron needs to accelerate to radiate





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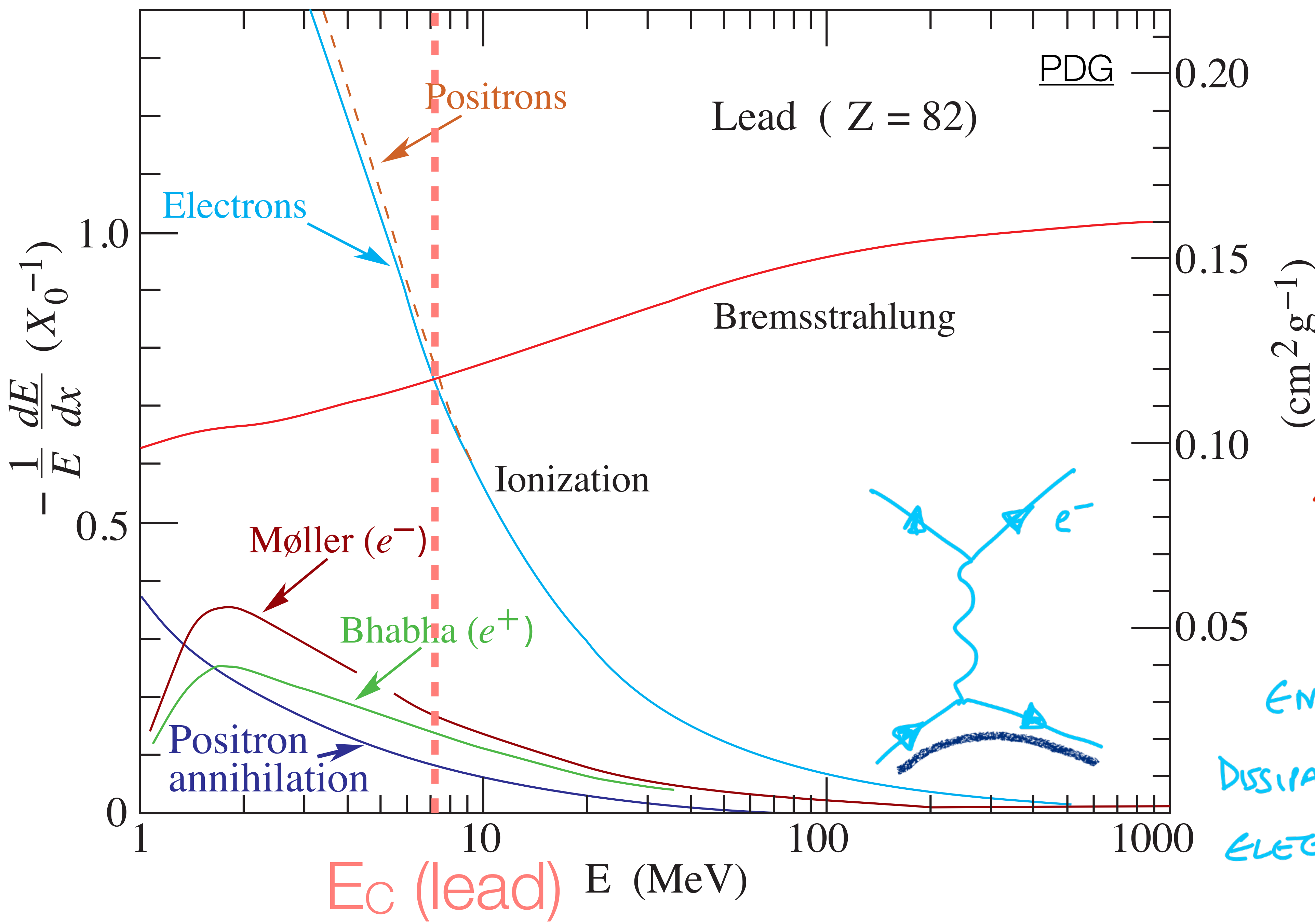

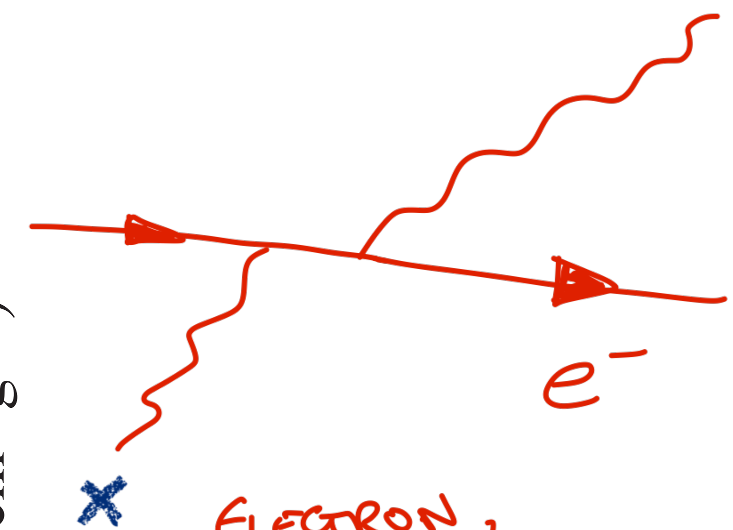

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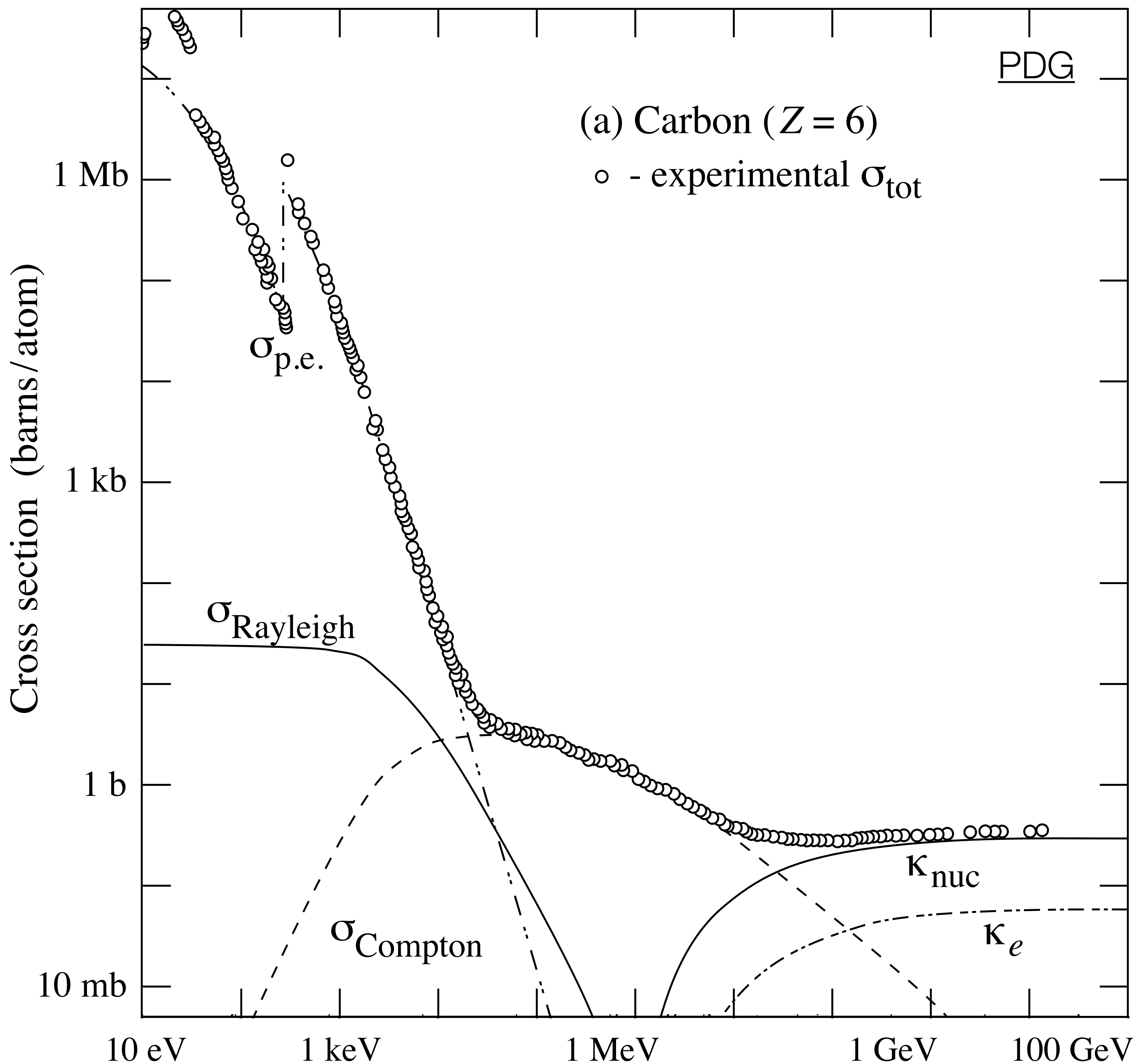
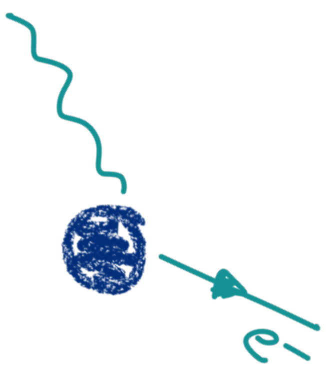
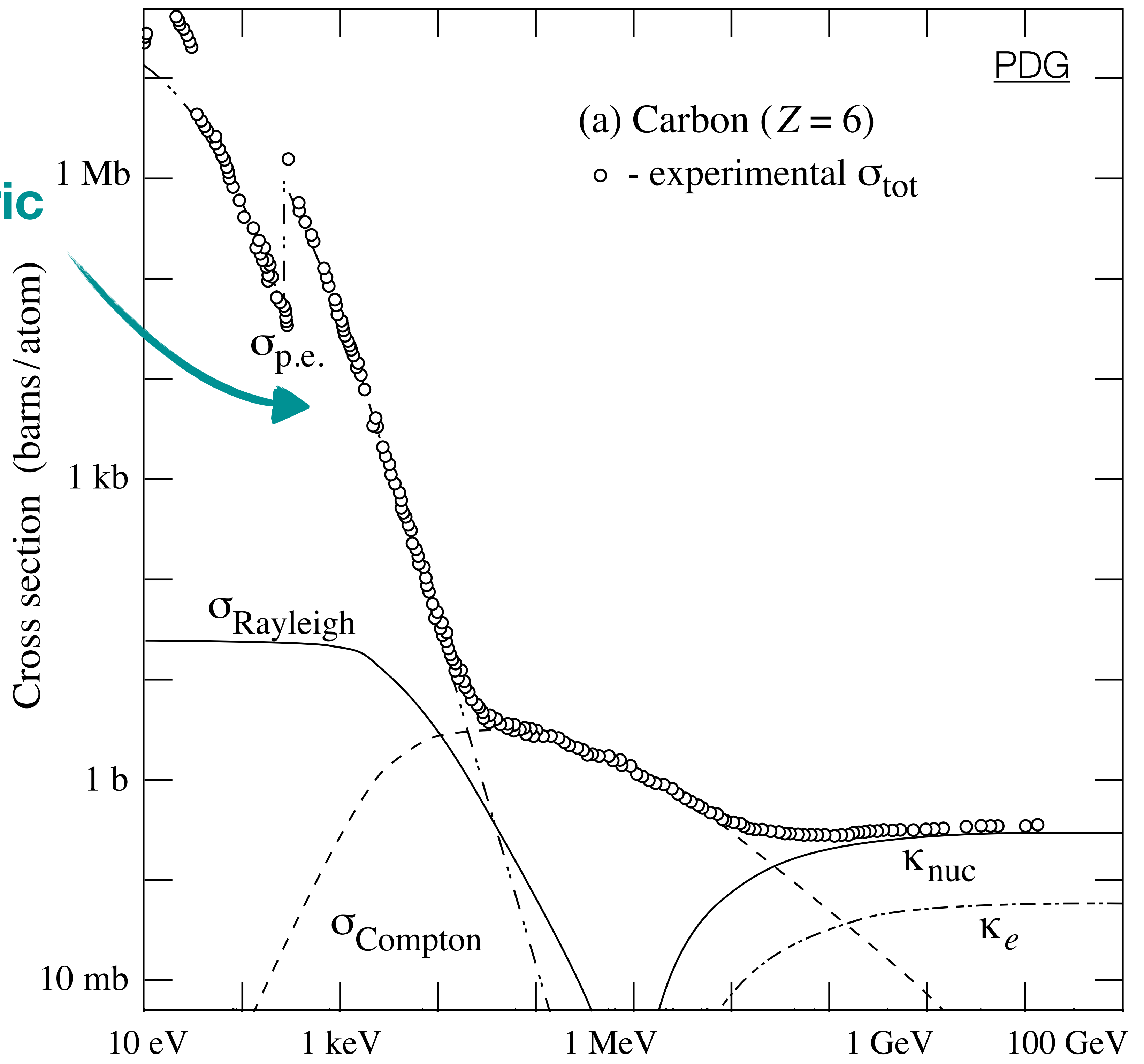


Photon interactions

Photoelectric effect

dominant to ~50 keV





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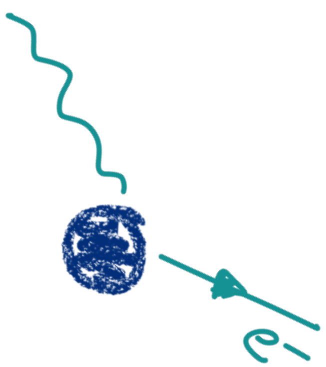

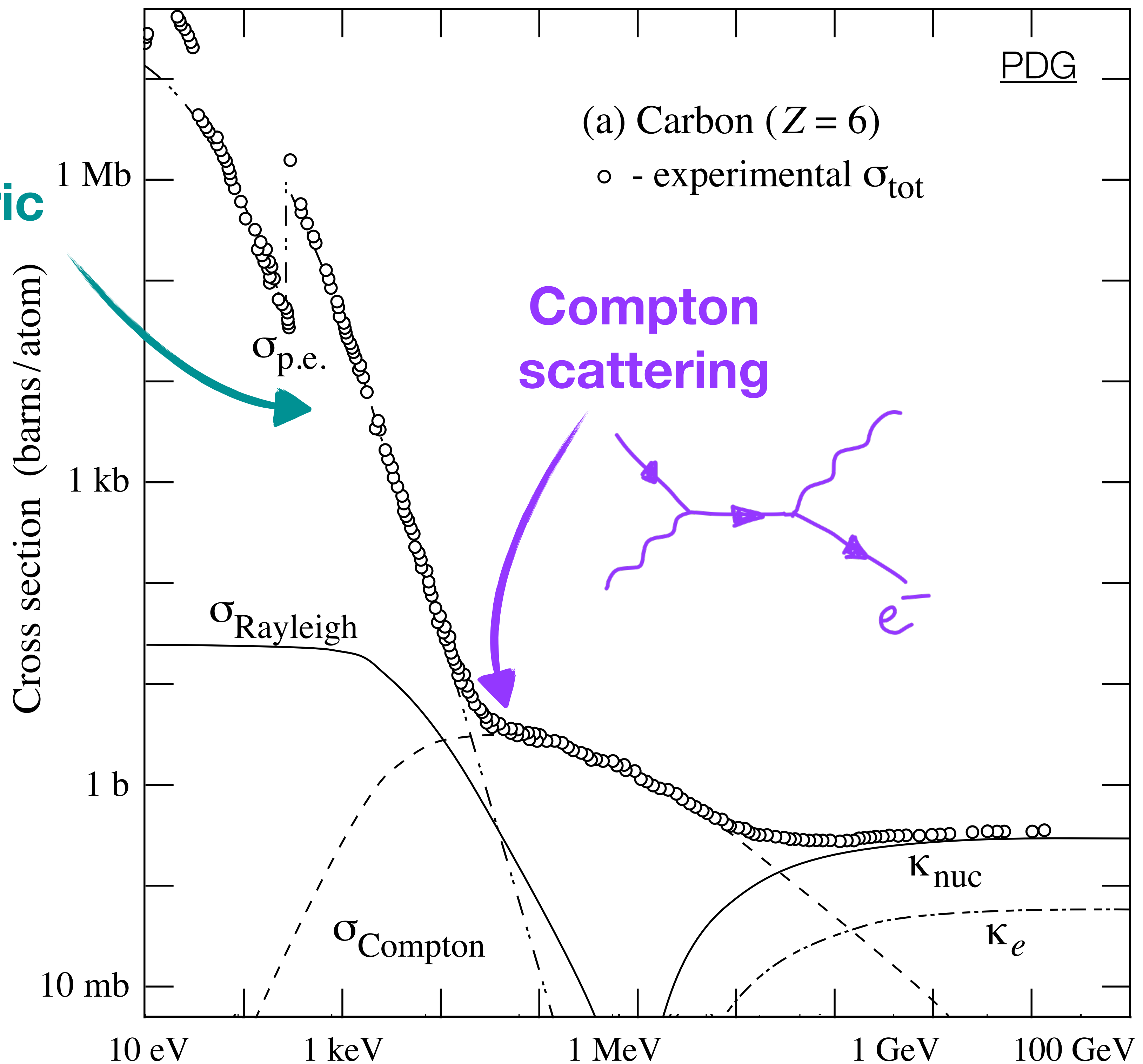

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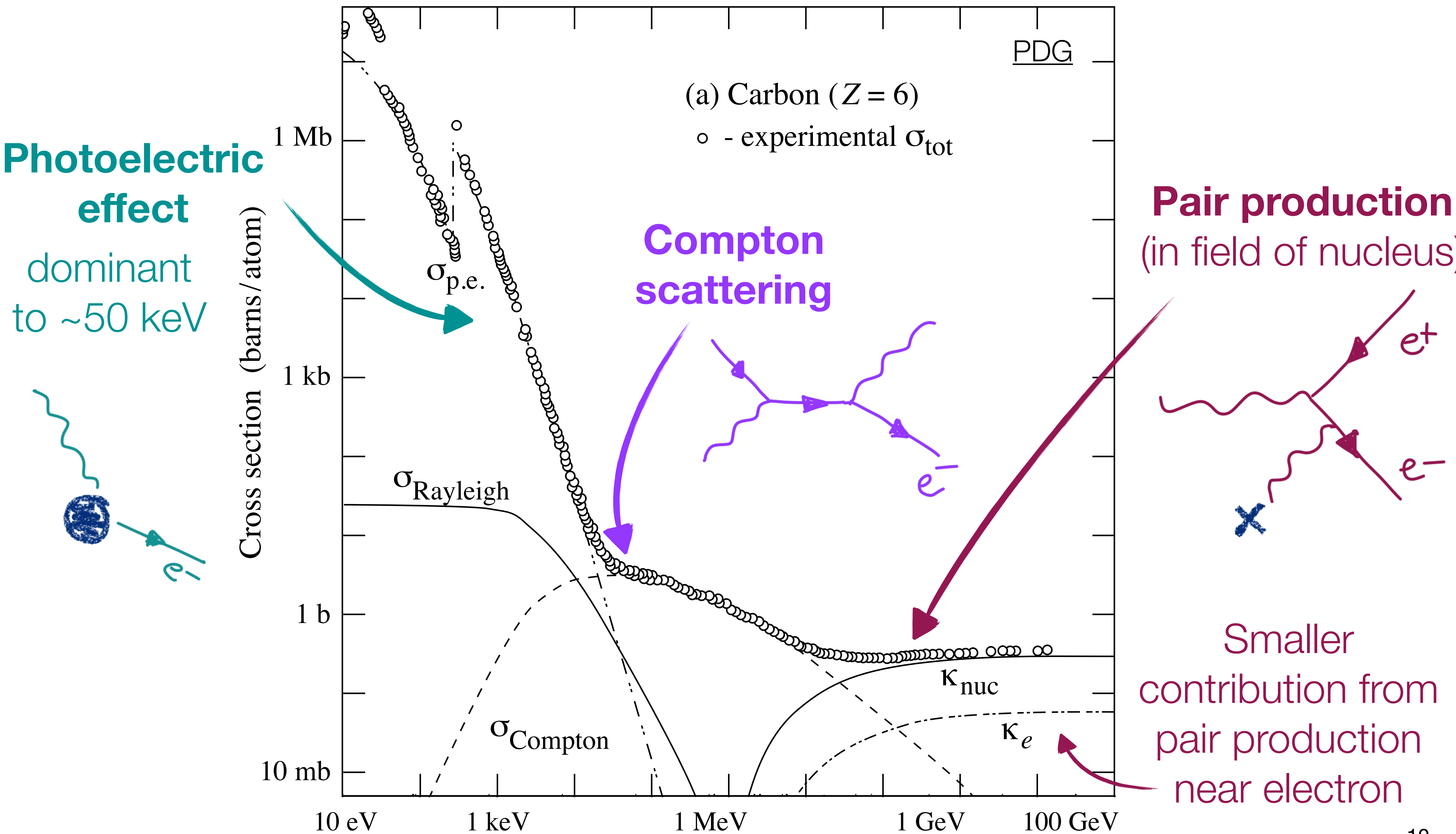
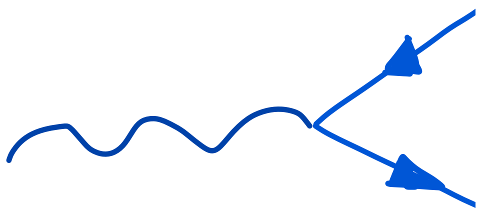
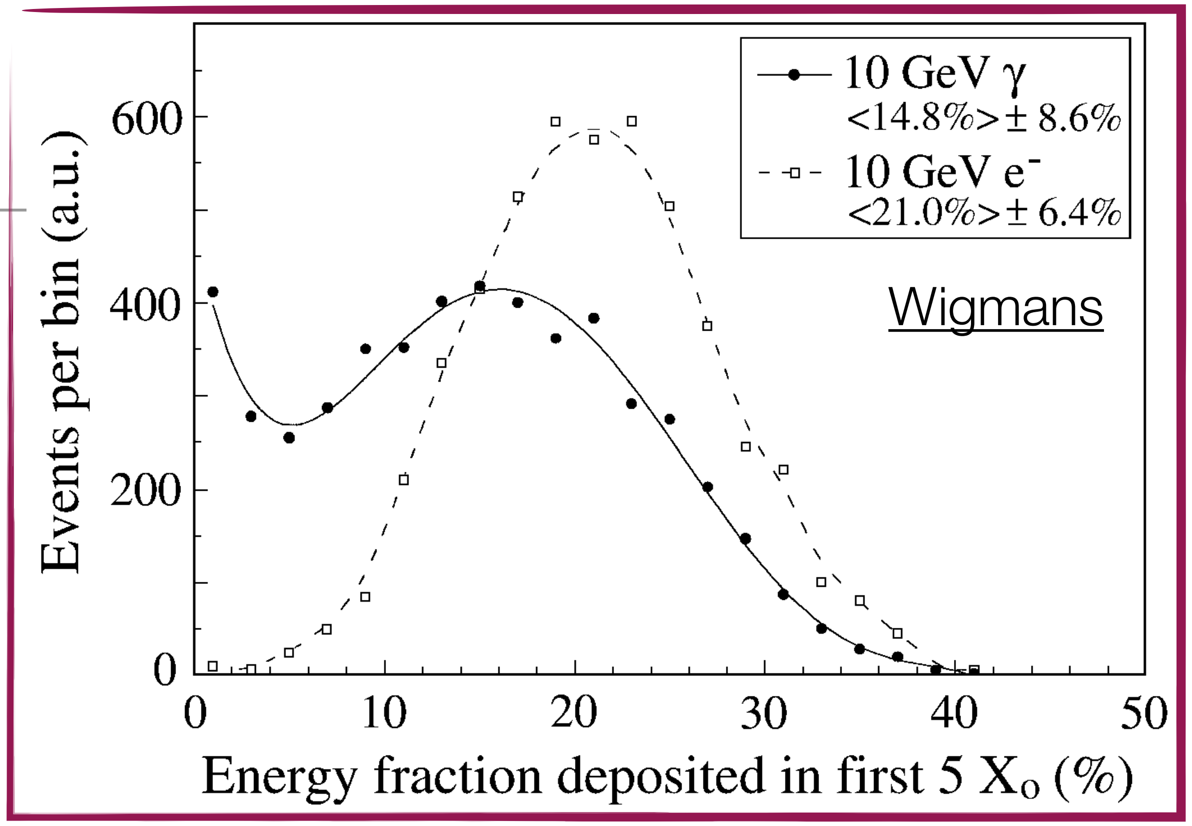


Electromagnetic showers in matter





- High-energy photons pair produce electrons and positrons, vanishing in the process
    - Lower energy photons measured by photoelectric effect

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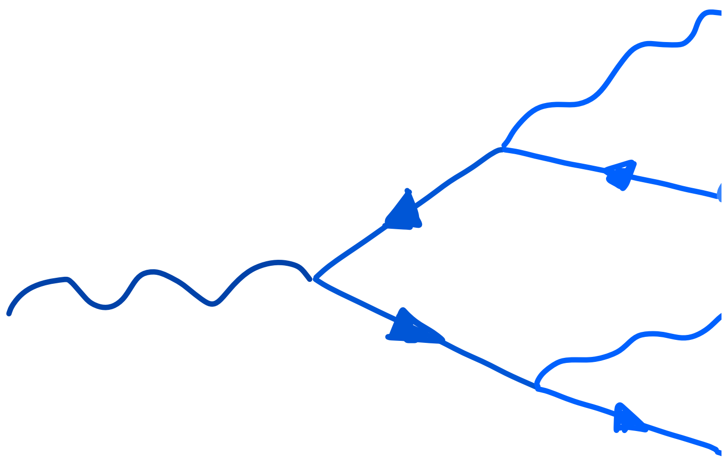

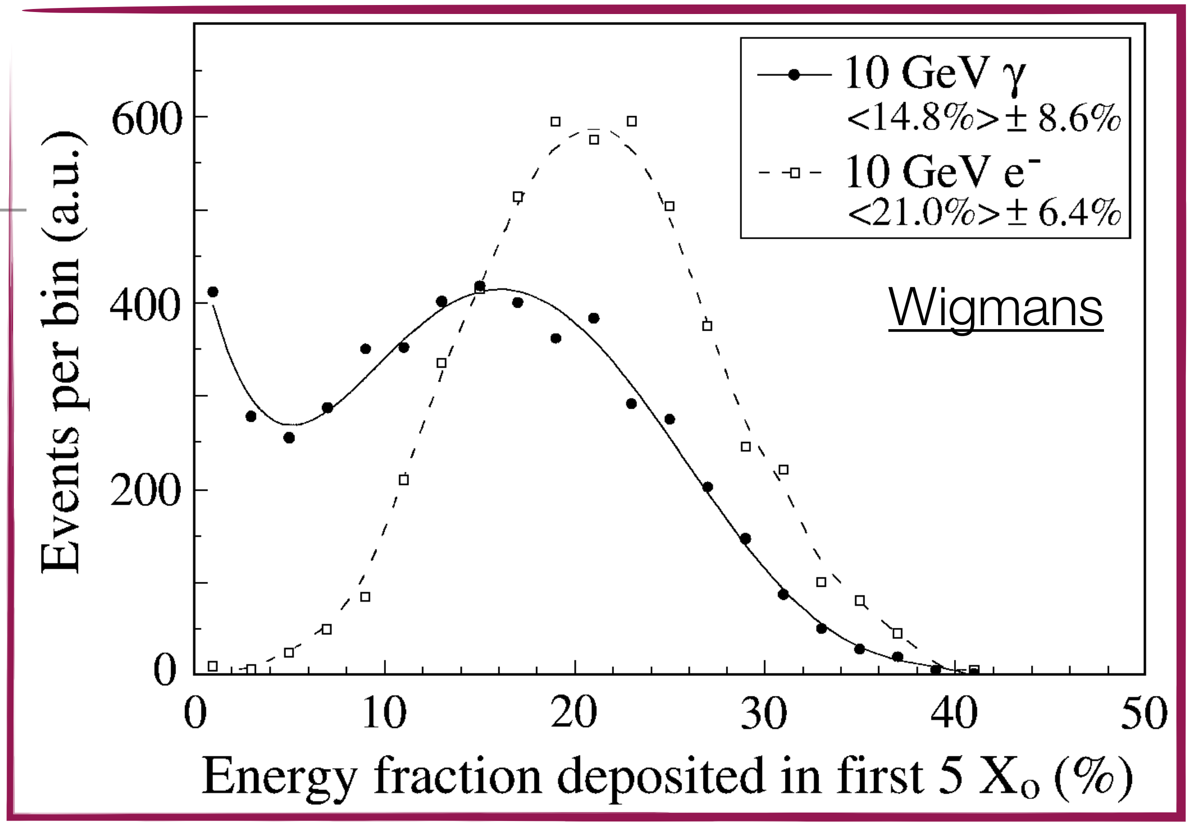

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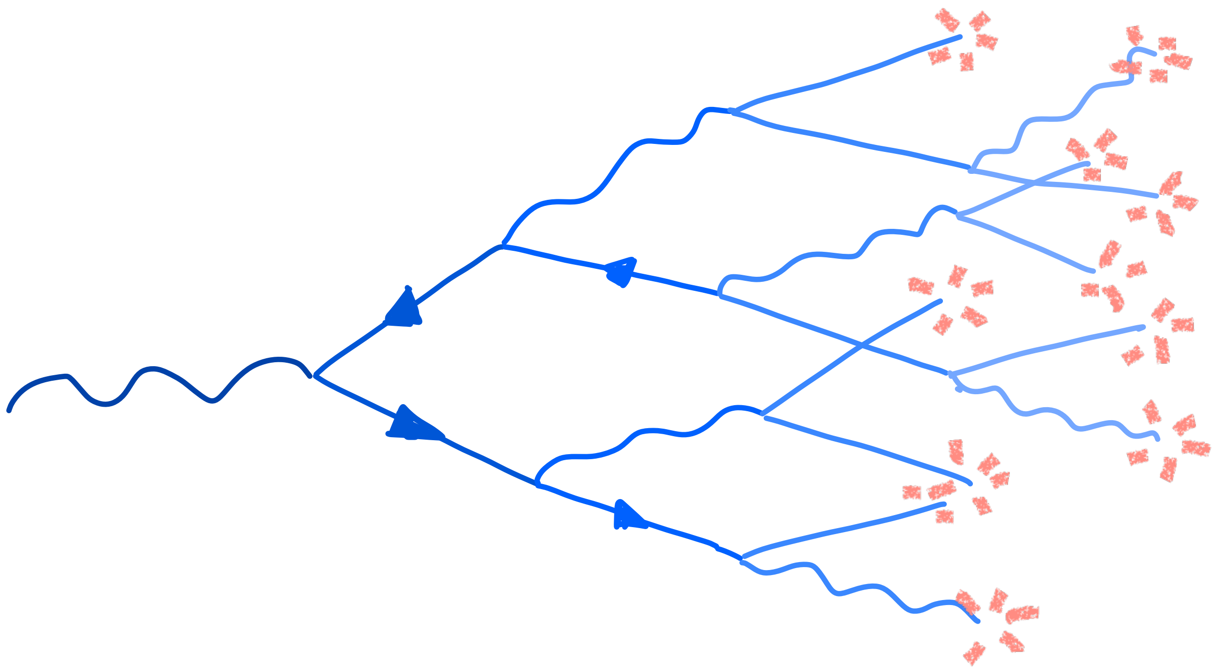

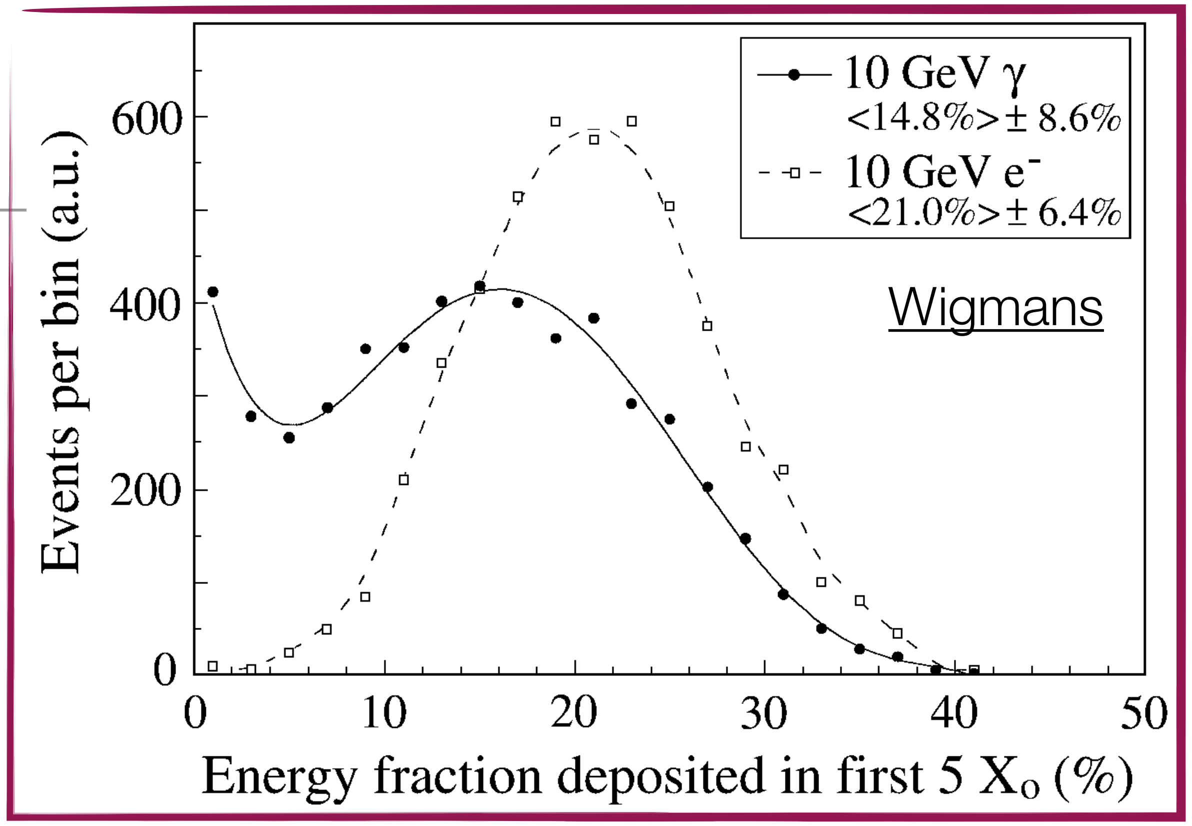

- High-energy photons pair produce electrons and positrons, vanishing in the process
  - Lower energy photons measured by photoelectric effect
- Electrons and positrons radiate photons via bremsstrahlung as they travel through matter, interacting with fields of atoms
- Once electrons fall below *critical energy*, more energy lost via ionisation than bremsstrahlung and the shower stops growing
- Shower maximum occurs where we have largest number of particles: $E \sim E_C$

Let's do some approximations!

$t = X/X_0$
X_0 = radiation length
E_0 = initial energy

- Interaction ~ once per X_0:
  $N(t) = 2^t$

- Energy shared equally at each interaction: particle at t has

$$E \sim E_0/N(t) = E_0/2^t$$

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$$E_C = E_0/2^{t_{max}}$$

$$t_{max} = \log_2(E_0/E_C)$$

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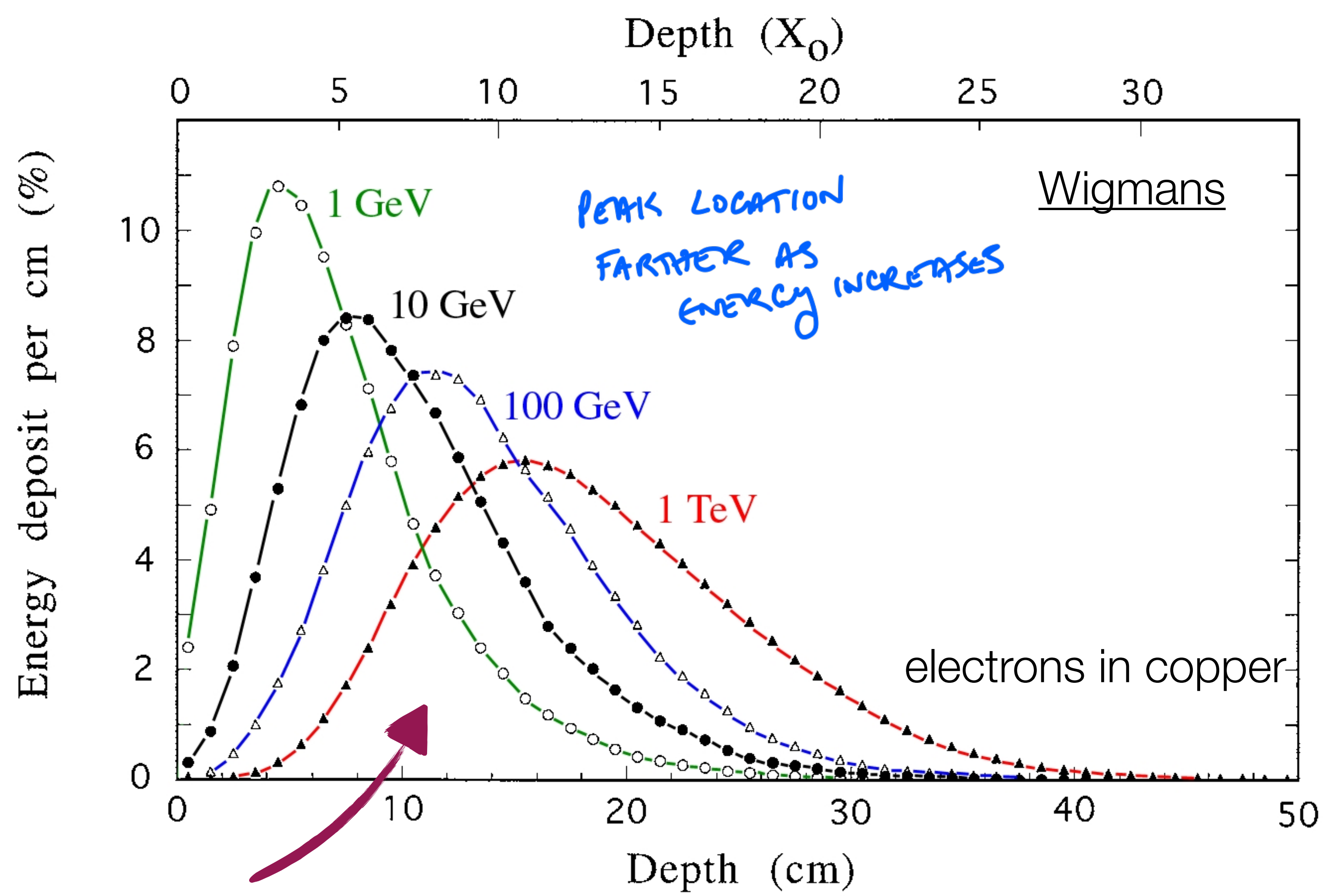

t_{max} proportional to E_0

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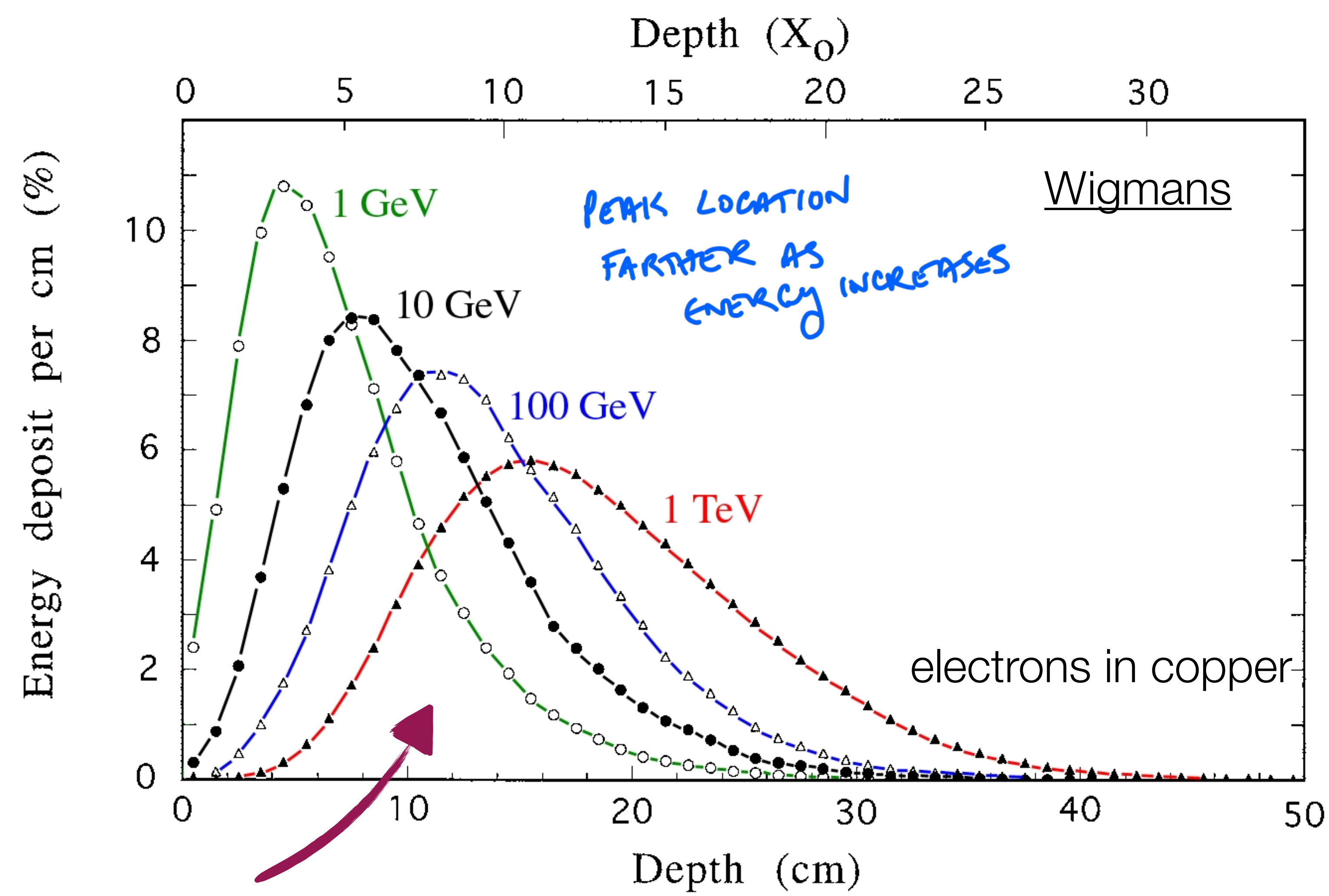
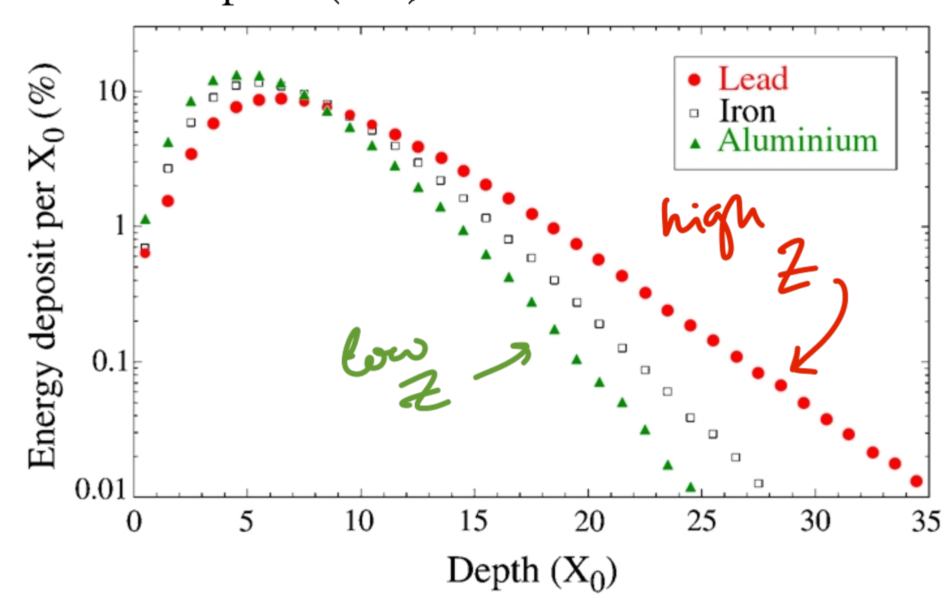
t_{max} proportional to E_0

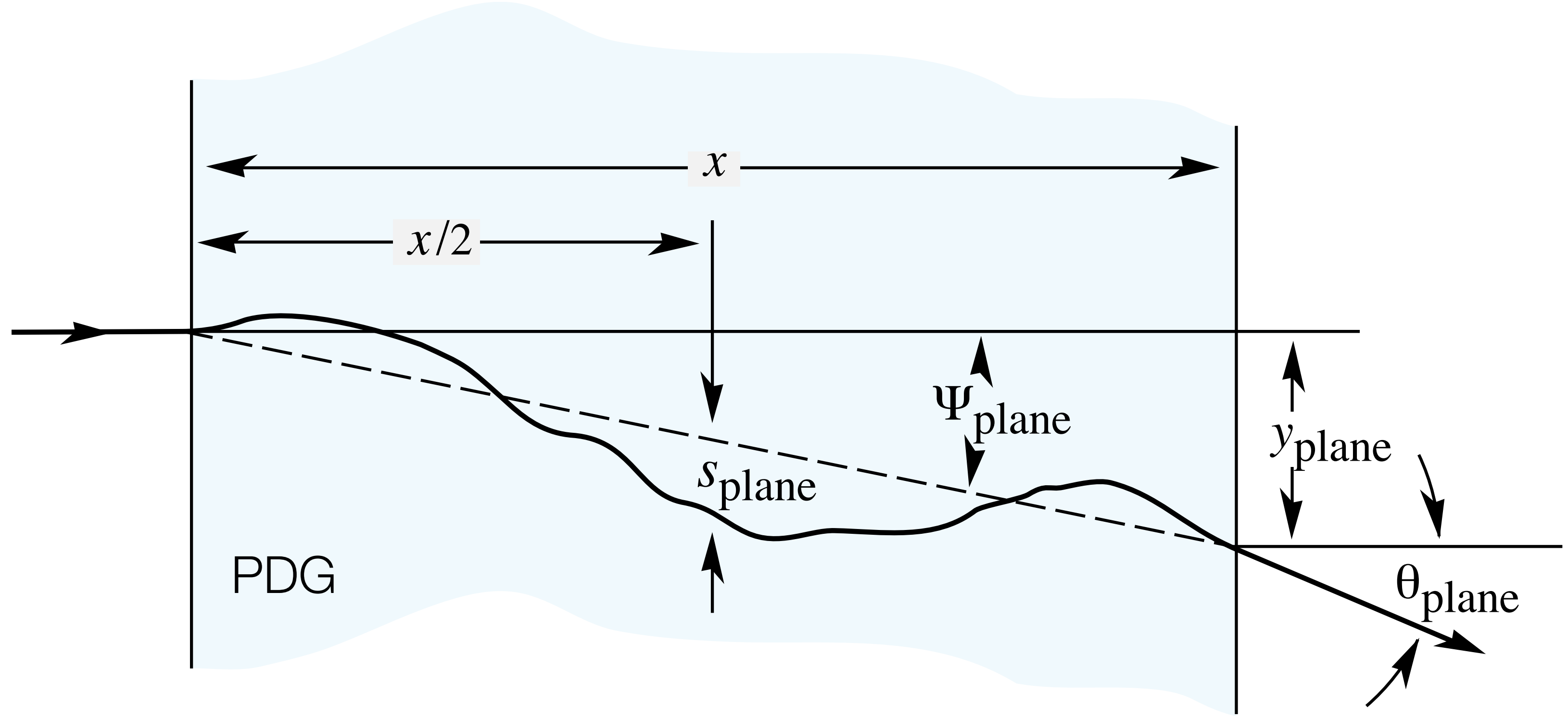
$E_C \propto 1/Z$, so shower profile varies a bit too

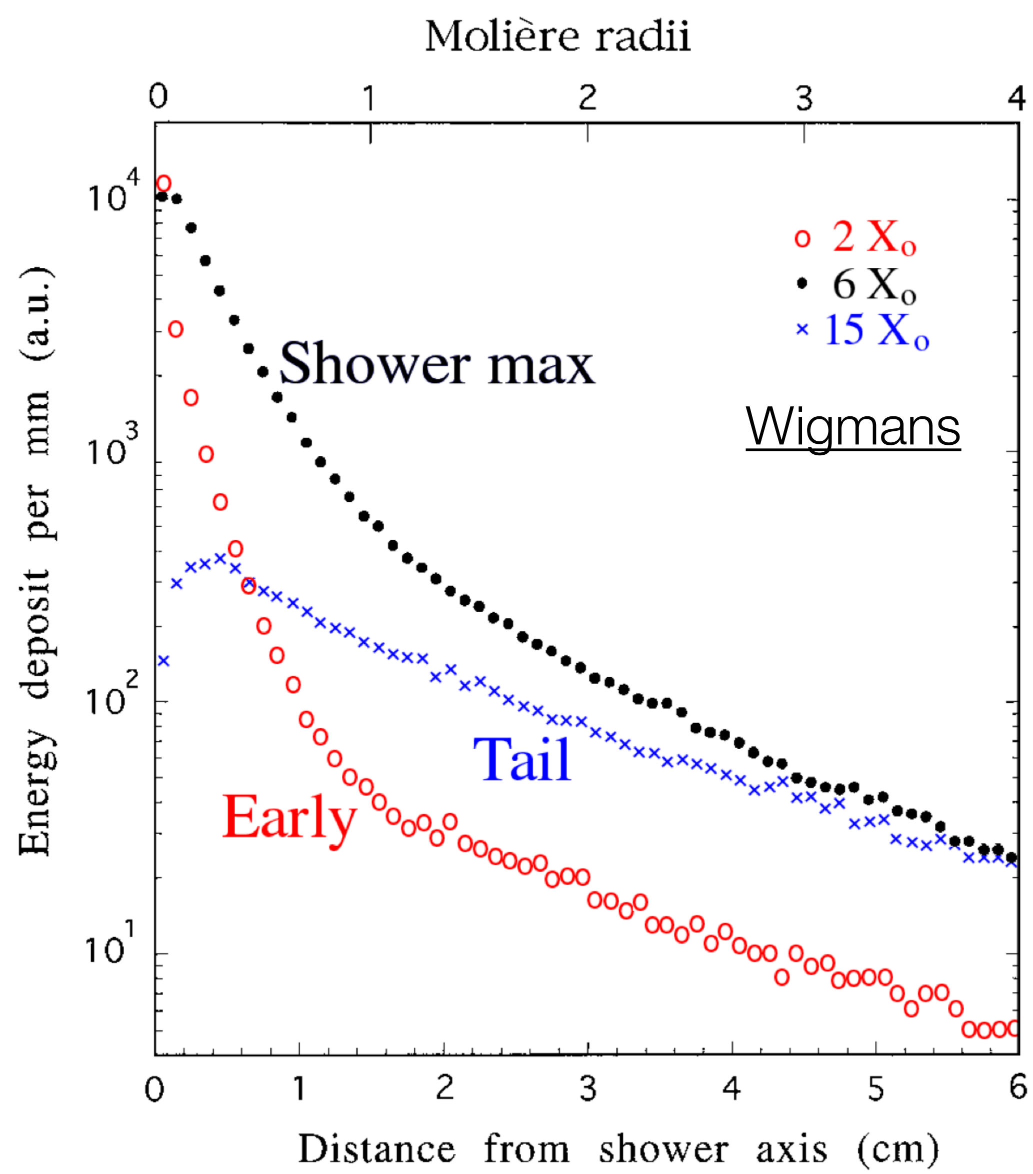




Shower width

- Multiple Coulomb scattering of electrons - elastic, but changes direction.
    - Dominant at high energies, used to derive Moliere radius
- Compton scattering and photoelectric effect produce new particles isotropically
    - Relevant at lower energies





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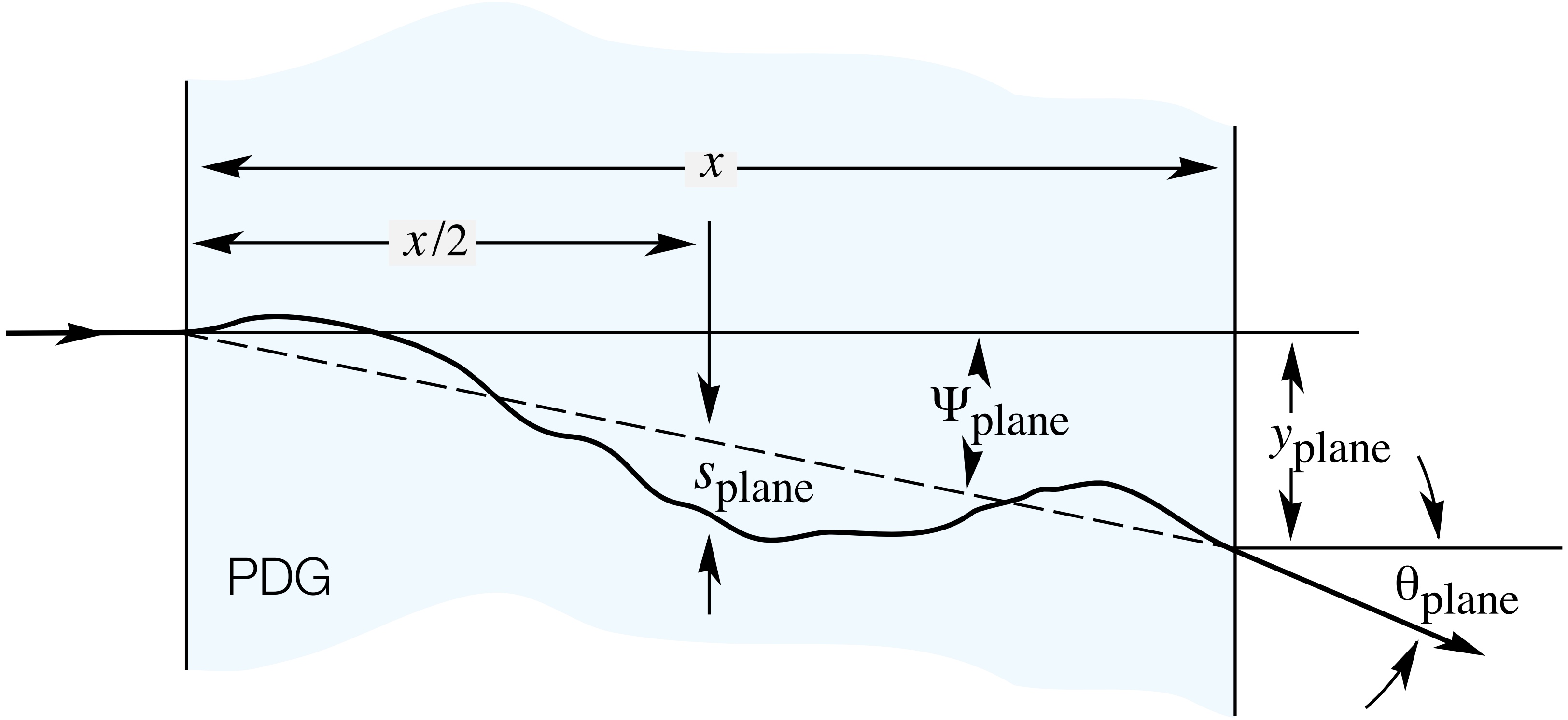

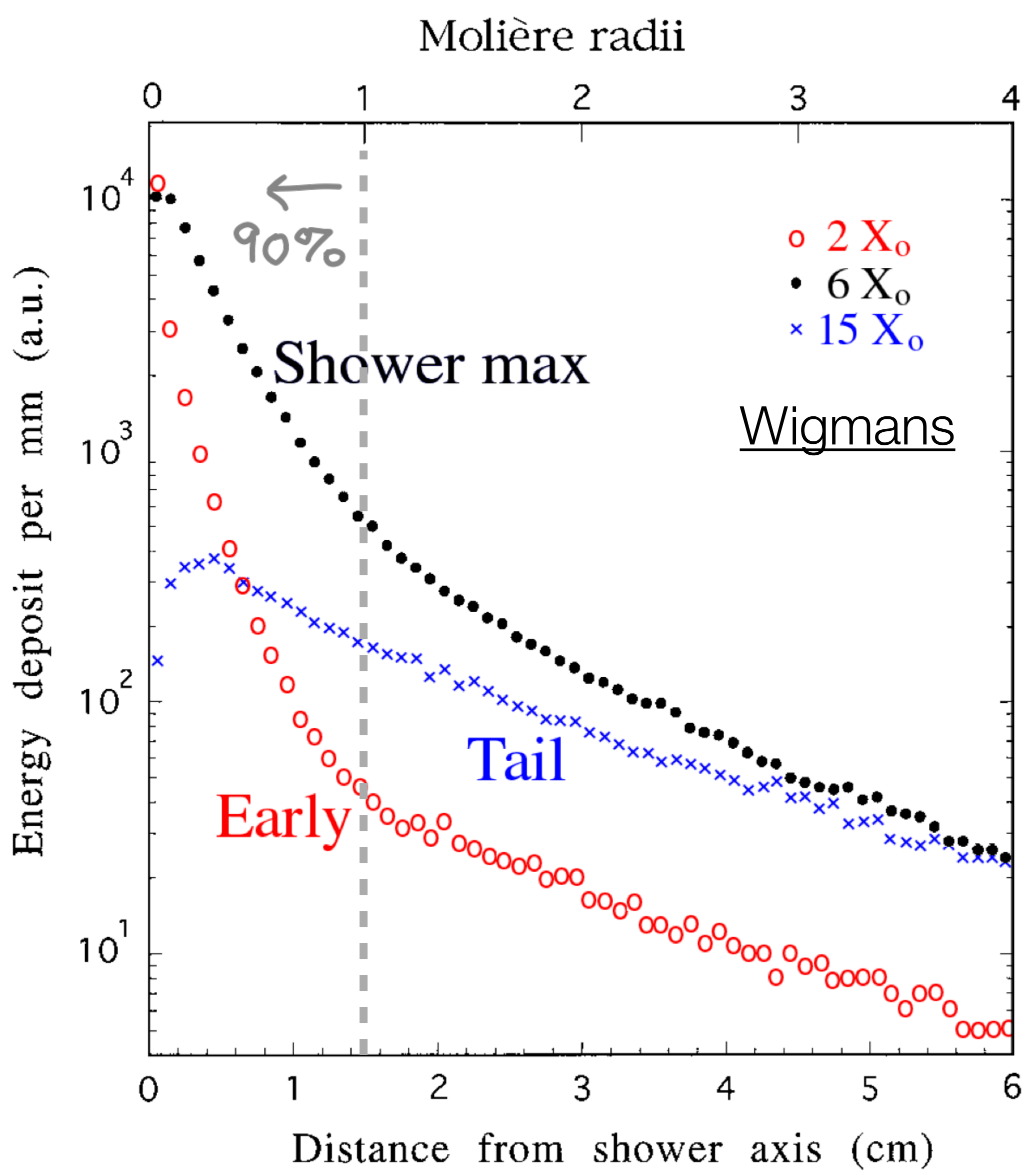

Define Moliere radius

$$R_M \propto X_0/E_C$$

Cylinder containing 90% of shower

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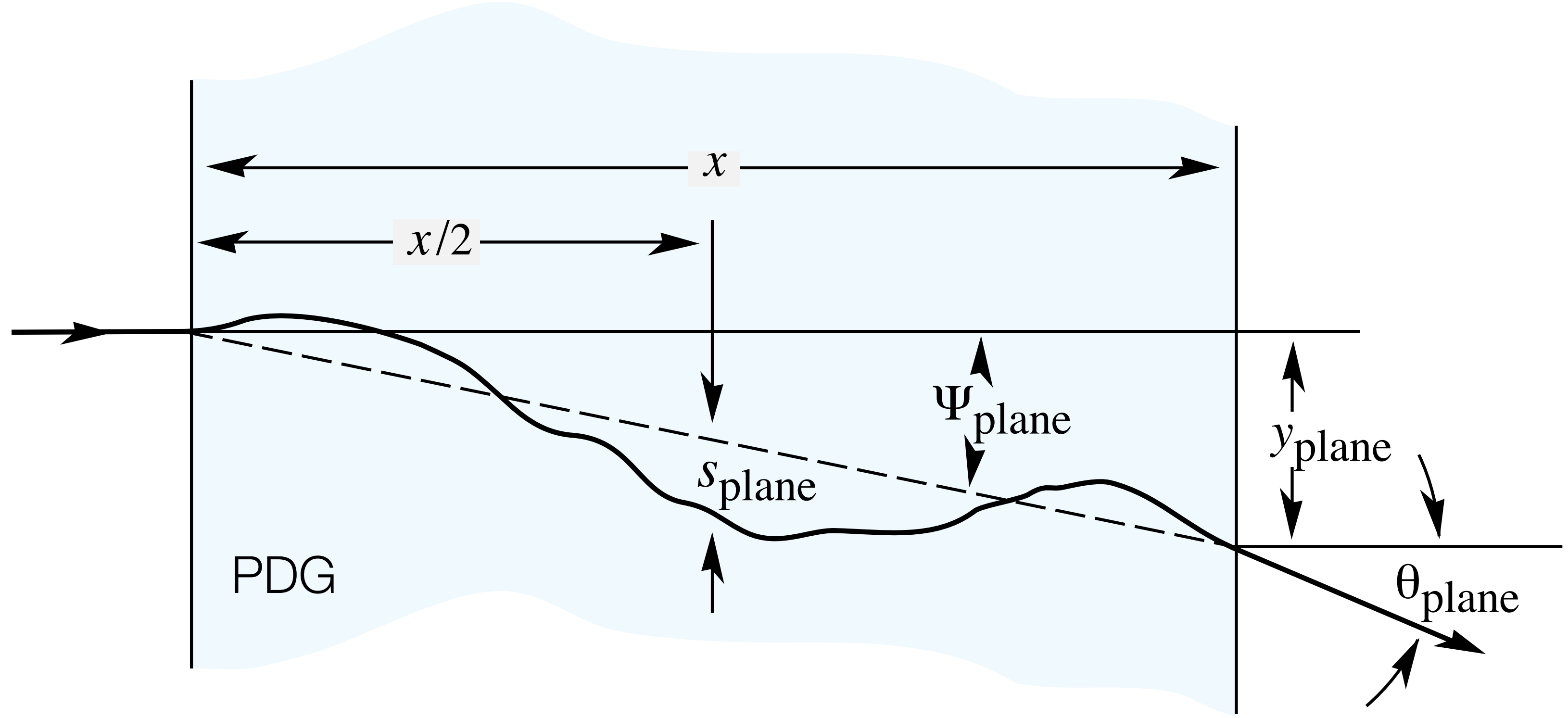

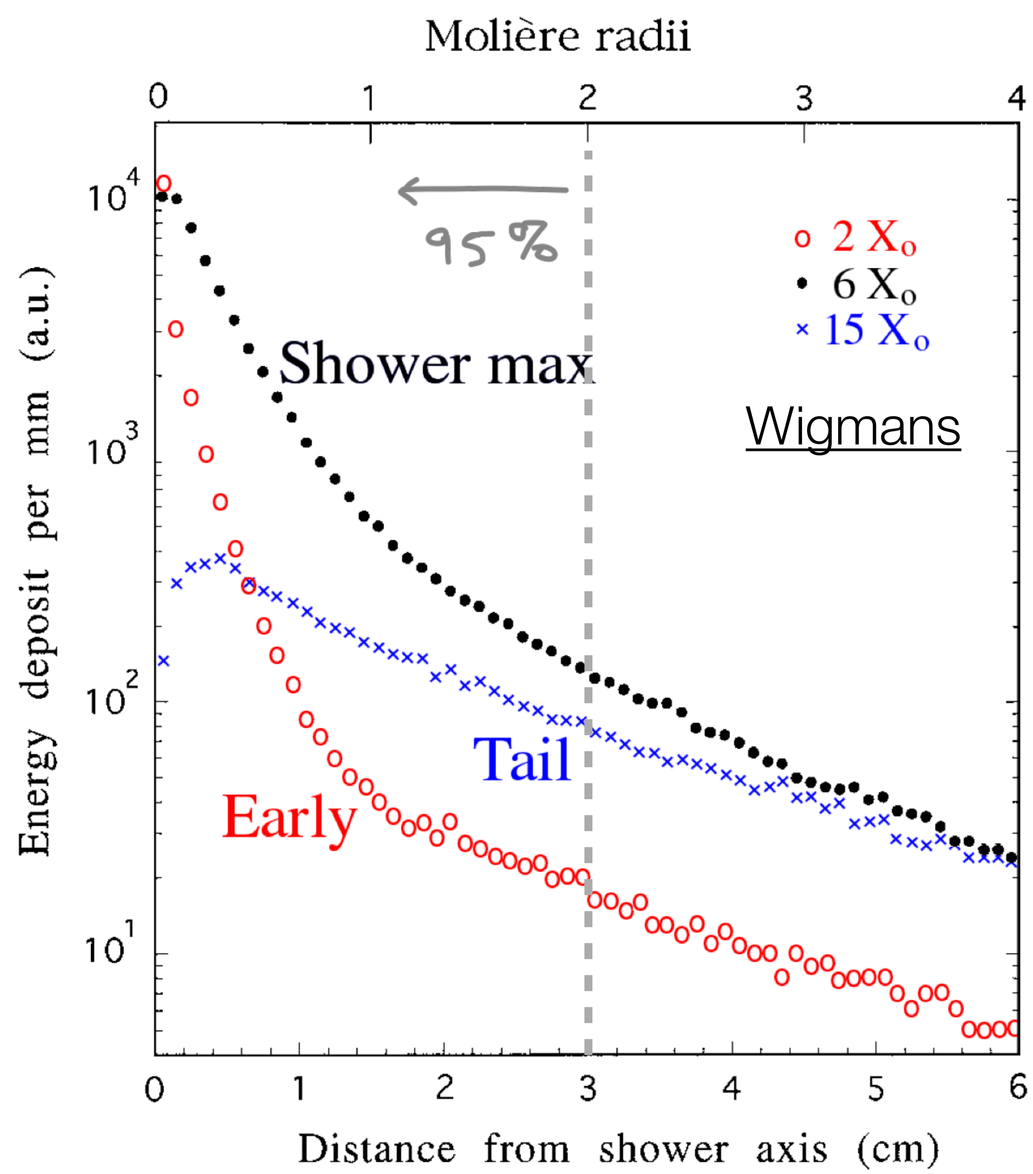

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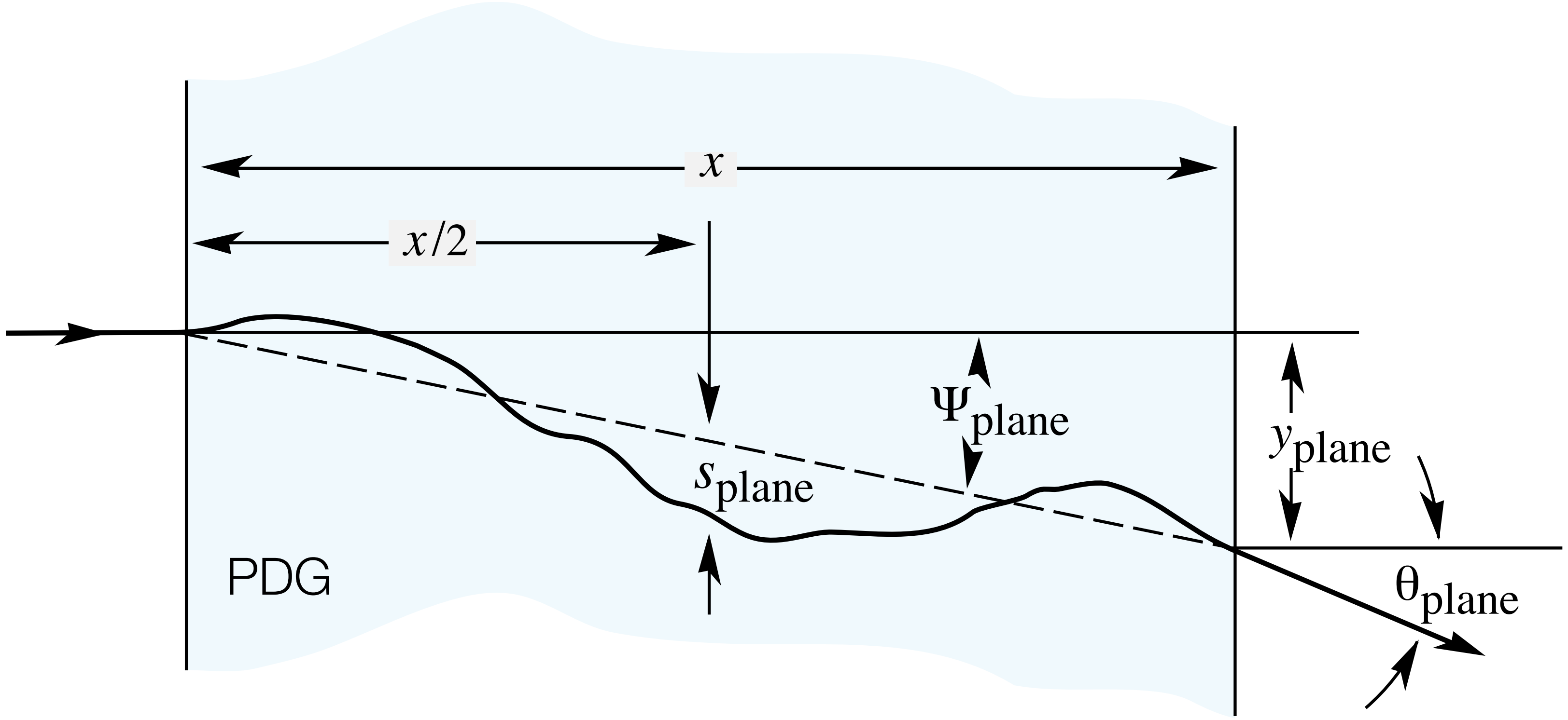
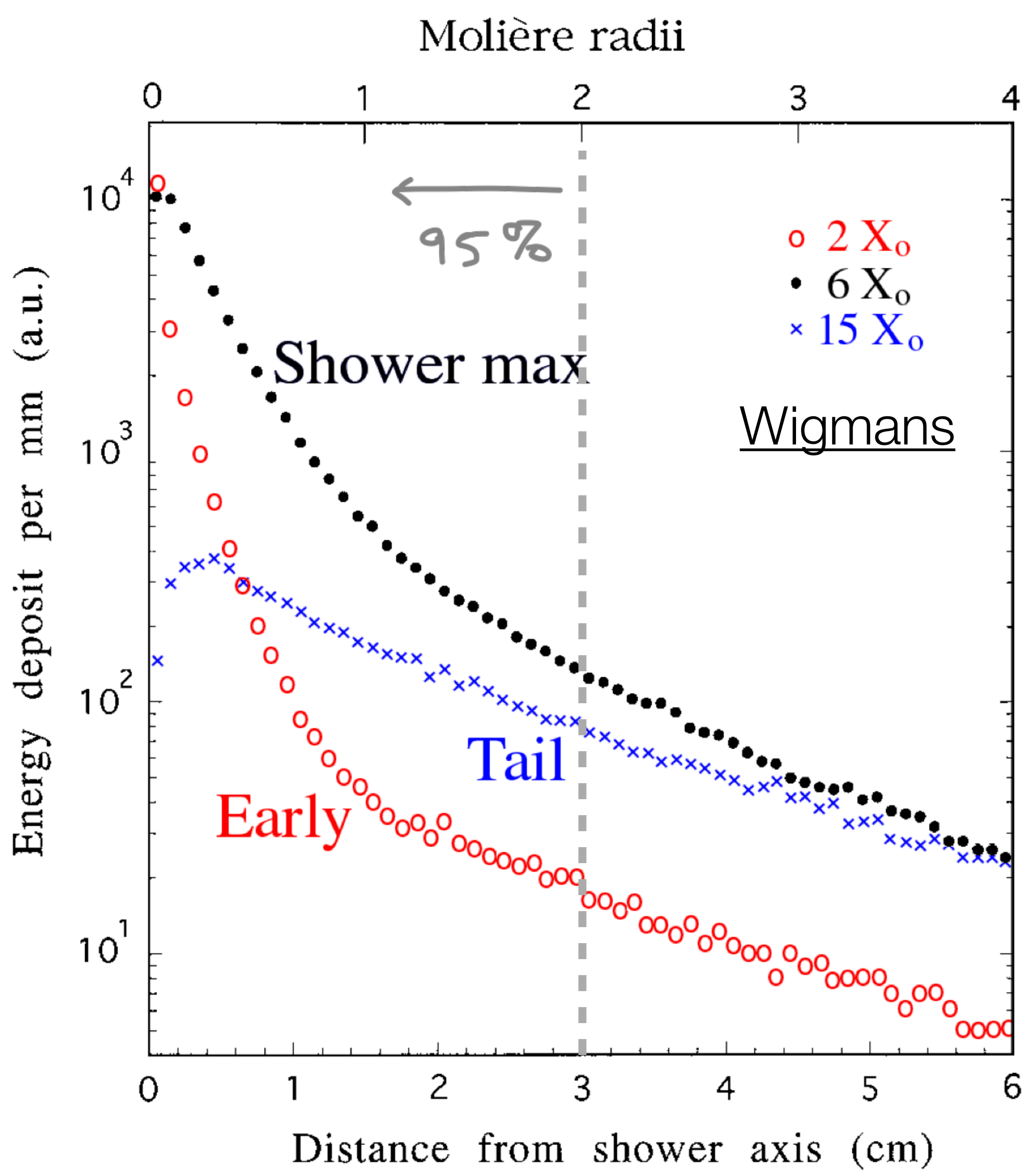




Define Moliere radius

$$R_M \propto X_0/E_C$$

Recall $X_0 \propto A/Z^2$

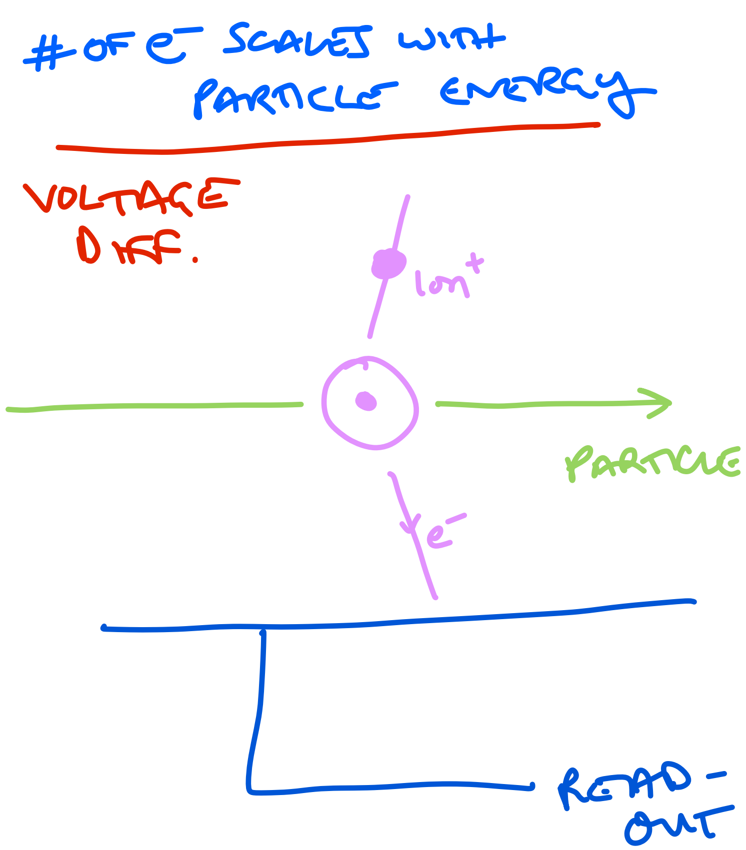
$$R_M \propto A/Z$$

→shower depth changes a lot with material, but R_M only changes a little

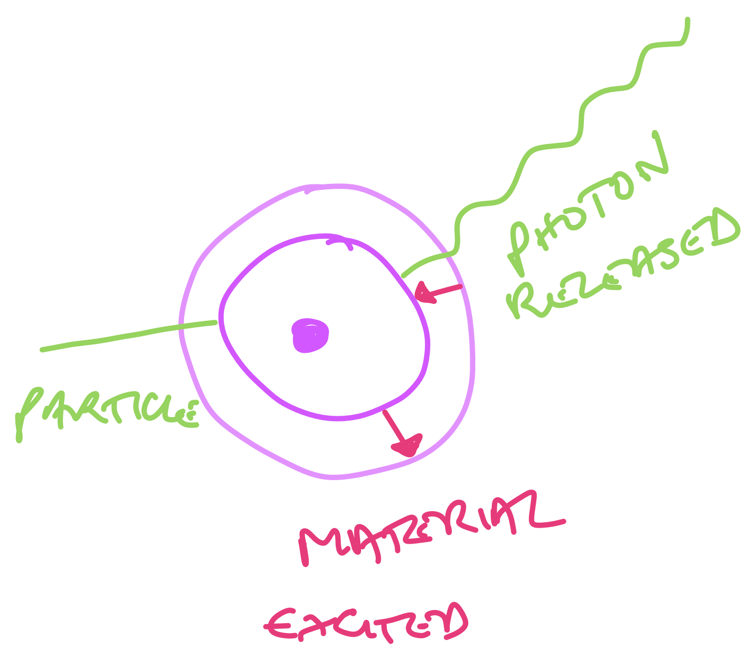
What happens at the end of the shower?

- In passive materials, not much! In a block of lead, energy ultimately dissipates as heat. For us, this constitutes lost information.
- In active materials, well-defined processes makes this energy visible to us.
    - Particles are also ionizing/scintillating/radiating through the shower evolution: we don't only measure the "end"!

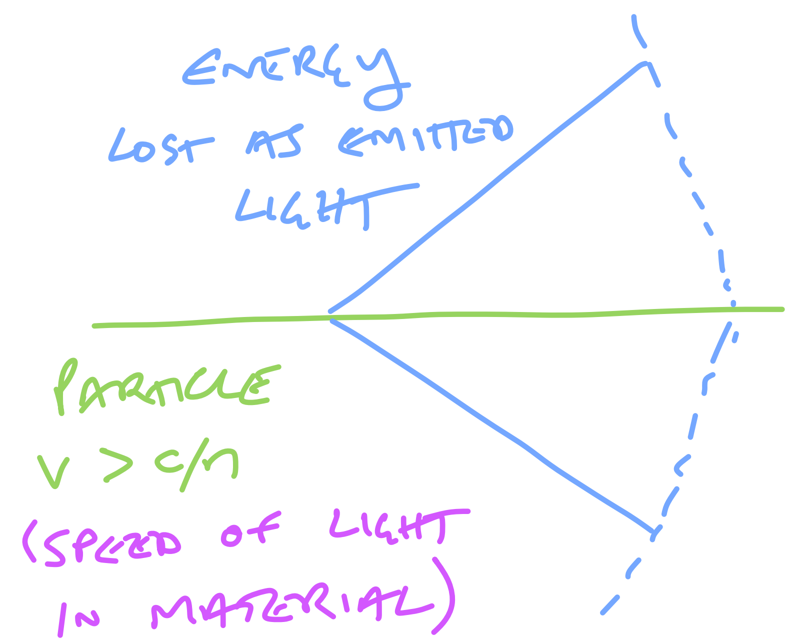
Ionisation

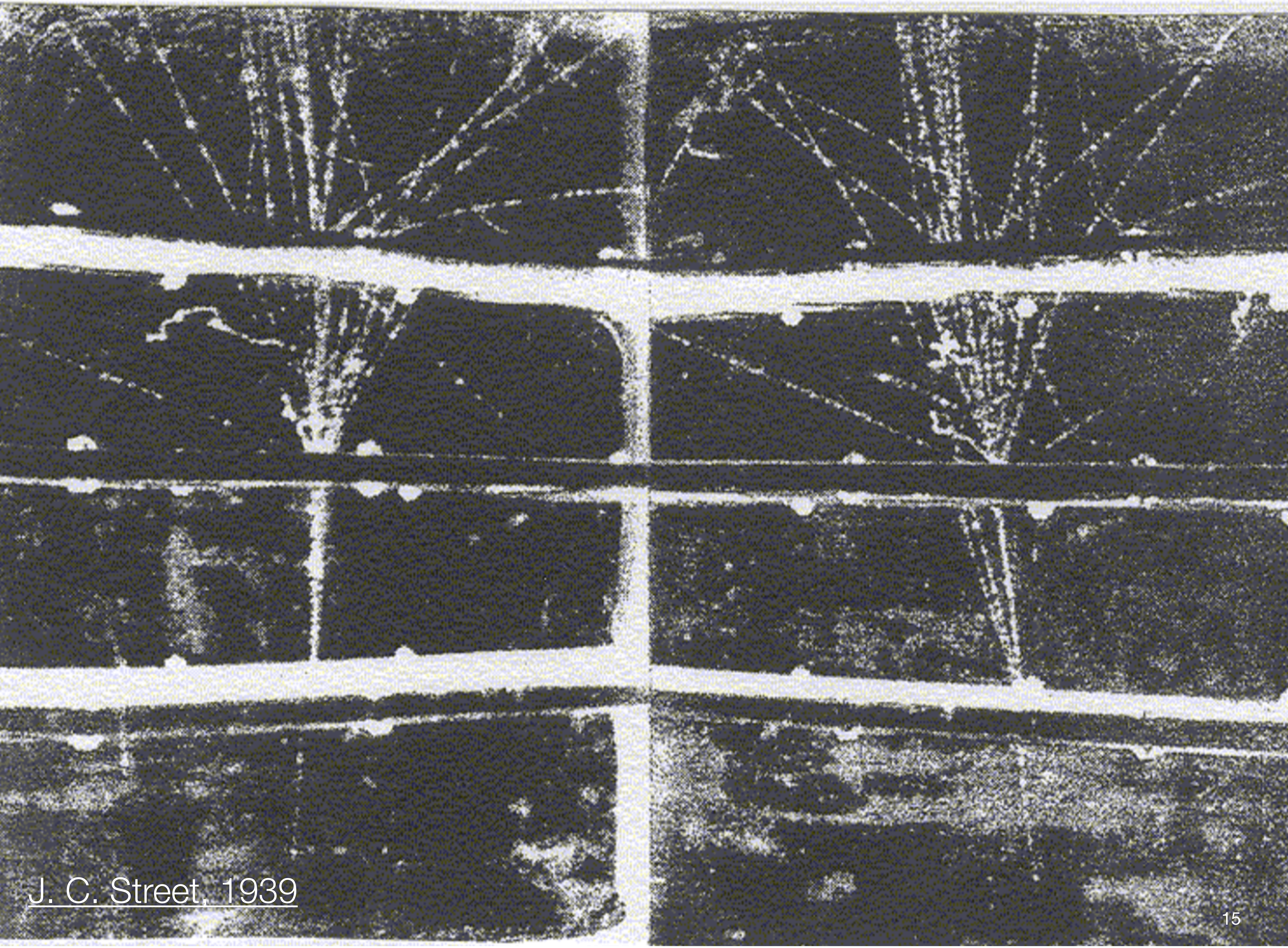


Scintillation



Cherenkov radiation





J. C. Street, 1939

Materials for the detector

Also important: high granularity, fast response, affordable…

- Now to design a calorimeter to contain and measure shower energy! Two key (physics) features for the material we want to build it from.
  - Has to cause the shower to develop: favour high Z
  - Has to make deposited energy detectable and proportional to initial particle energy: needs to ionise or scintillate (see "end of the shower" slide!)
- It's possible to get a material that can do both!
  - Examples: solid lead tungstate crystals (CMS ECAL), large volume of liquid scintillator (KamLAND, Daya Bay)

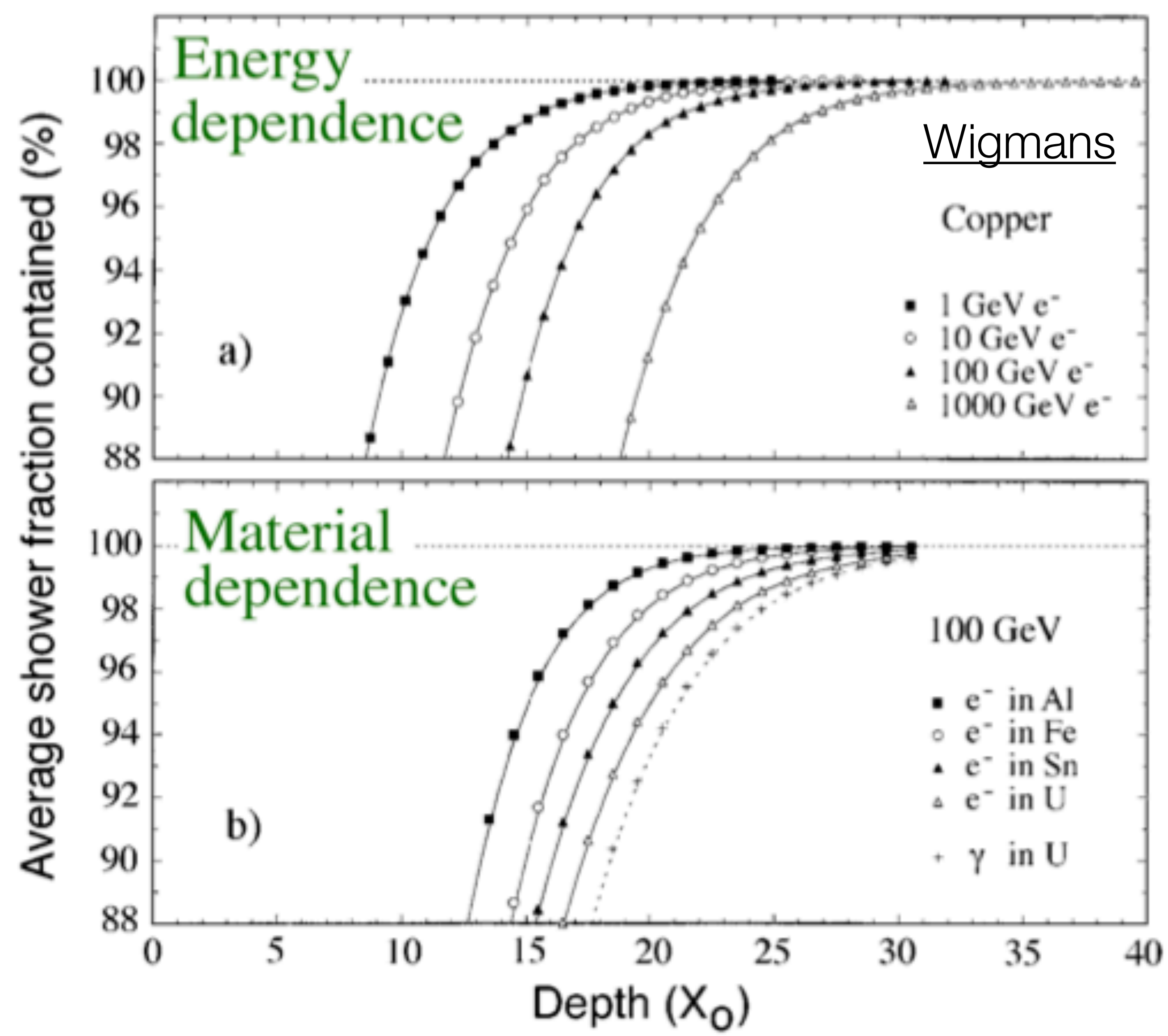
Scale of a *homogeneous* calorimeter

	NaI(Tl)	BGO	CsI(Tl)	$PbWO_4$
density (g/cm^3)	3.67	7.13	4.53	8.28
X_0 (cm)	2.59	1.12	1.85	0.89
R_M (cm)	4.5	2.4	3.8	2.2
dE/dx_{mip} (MeV/cm)	4.8	9.2	5.6	13.0
light yield (photons/MeV)	$4 \cdot 10^4$	$8 \cdot 10^3$	$5 \cdot 10^4$	$3 \cdot 10^2$
energy resolution σ_E/E	$1\%/\sqrt{E}$	$1\%/\sqrt{E}$	$1.3\%/\sqrt{E}$	$2.5\%/\sqrt{E}$

Masciocchi

- CMS EM calorimeter made of $PbWO_4$
- Each crystal 2.2 x 2.2 x 23 cm: equivalent to R_M x R_M x 25 X_0
- Therefore, contains 99% of shower depth and is sufficiently granular to measure shower's position well

Electron induced showers
(photon requires a bit more)



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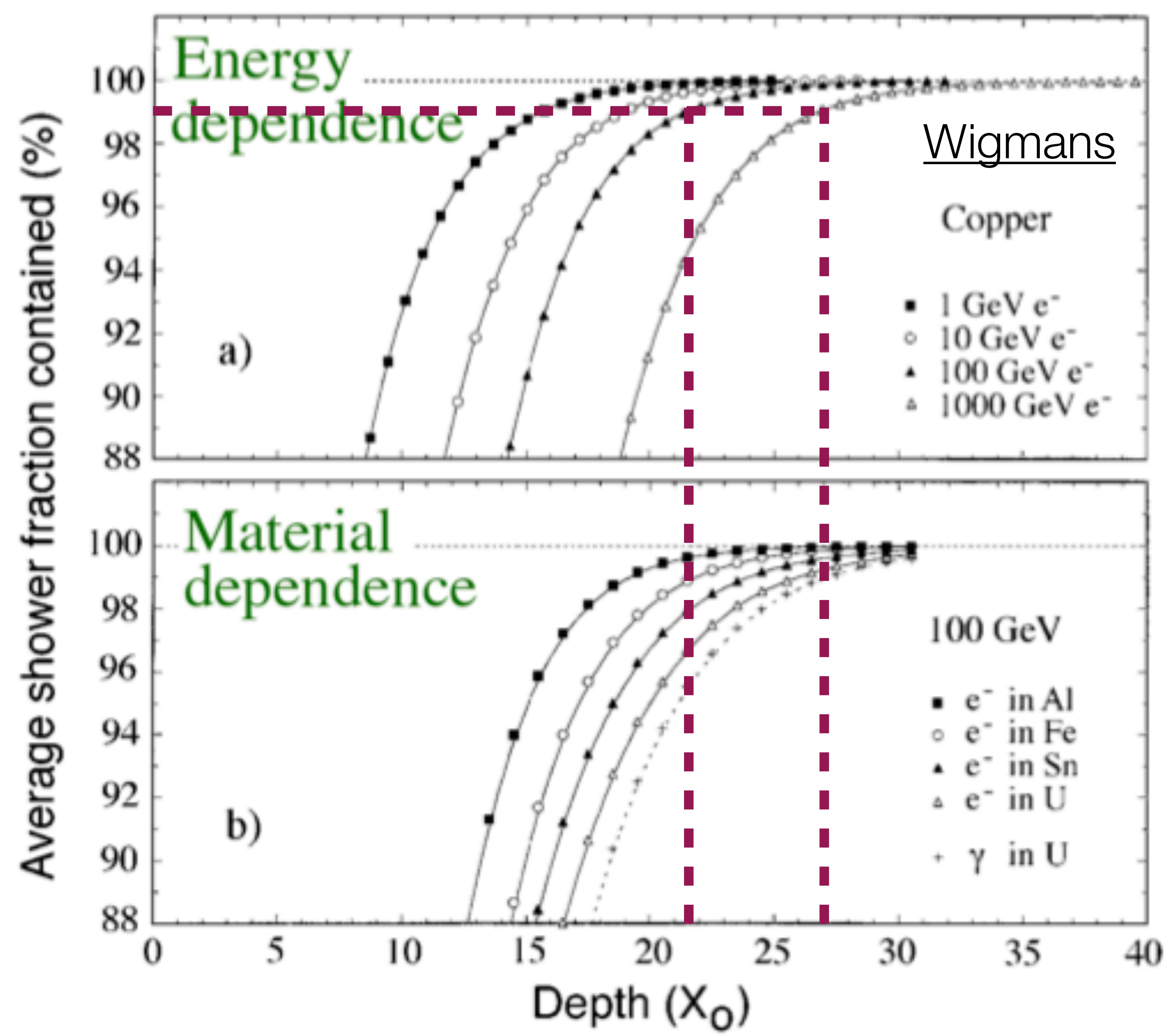

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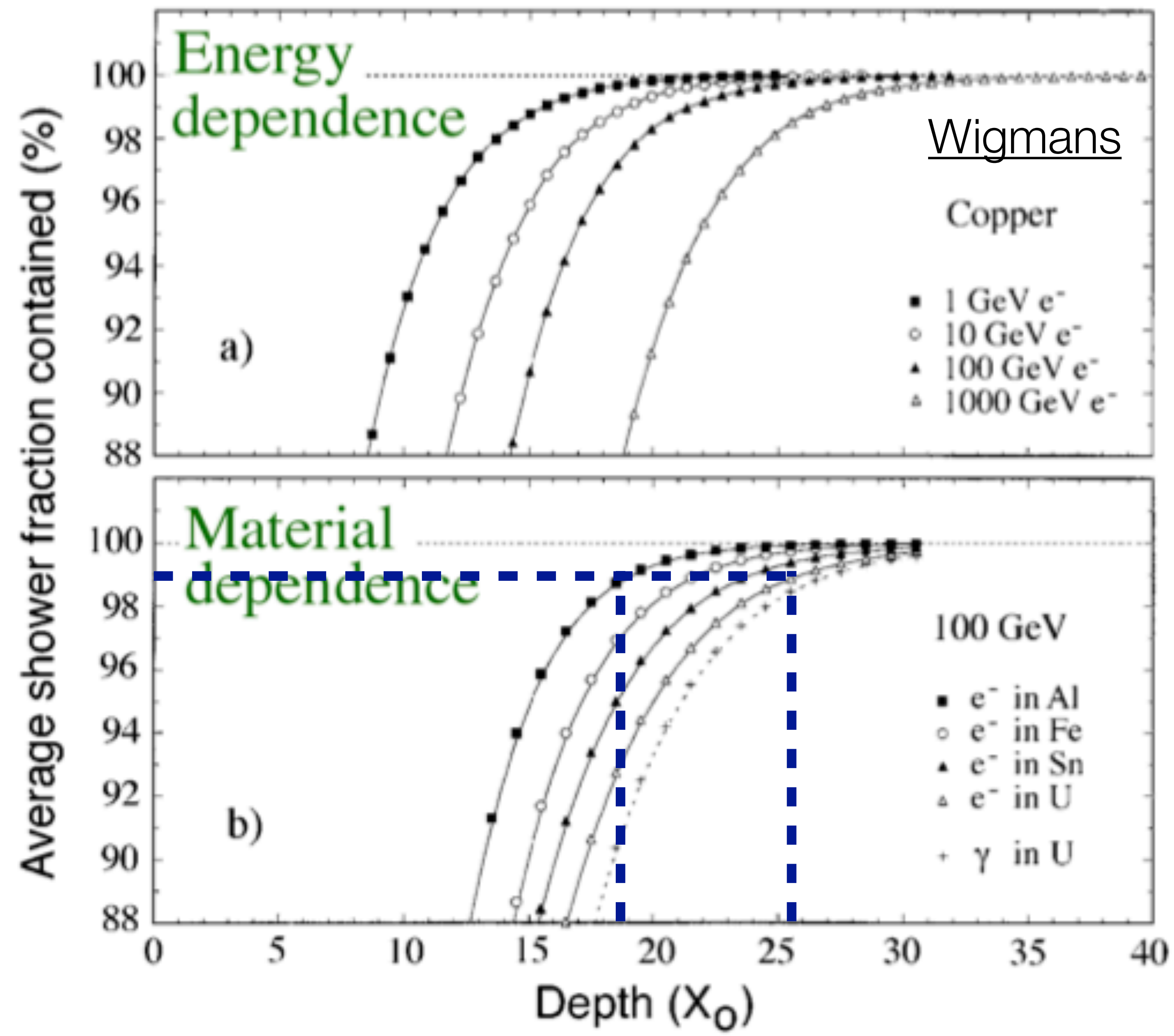
dE/dx_{mip} (MeV/cm)	4.8	9.2	5.6	13.0
light yield (photons/MeV)	$4 \cdot 10^4$	$8 \cdot 10^3$	$5 \cdot 10^4$	$3 \cdot 10^2$
energy resolution σ_E/E	$1\%/\sqrt{E}$	$1\%/\sqrt{E}$	$1.3\%/\sqrt{E}$	$2.5\%/\sqrt{E}$

Masciocchi

- CMS EM calorimeter made of $PbWO_4$
- Each crystal 2.2 x 2.2 x 23 cm: equivalent to R_M x R_M x 25 X_0
- Therefore, contains 99% of shower depth and is sufficiently granular to measure shower's position well

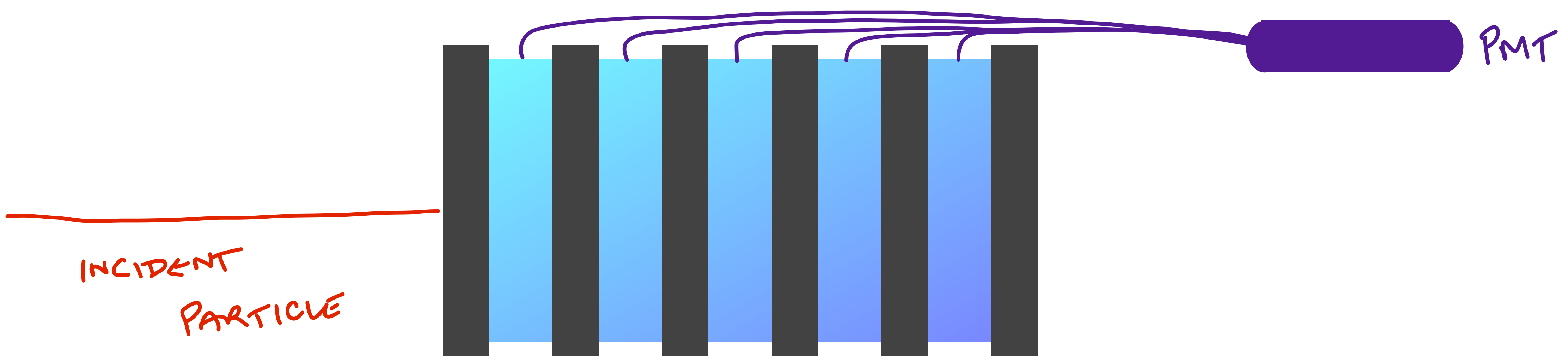
Electron induced showers (photon requires a bit more)



99% of shower contained after 19-26 X_0

What if I don't have enough space/money?

- Homogeneous calorimeters can be bulky or very expensive. More common to separate absorbing material from active material
- *Sampling calorimeters* alternate an absorber to force showering with active material which ionises or scintillates



- Only a fraction of deposited energy is recorded, but the fraction is predictable so the recorded signal is still proportional to incident particle energy

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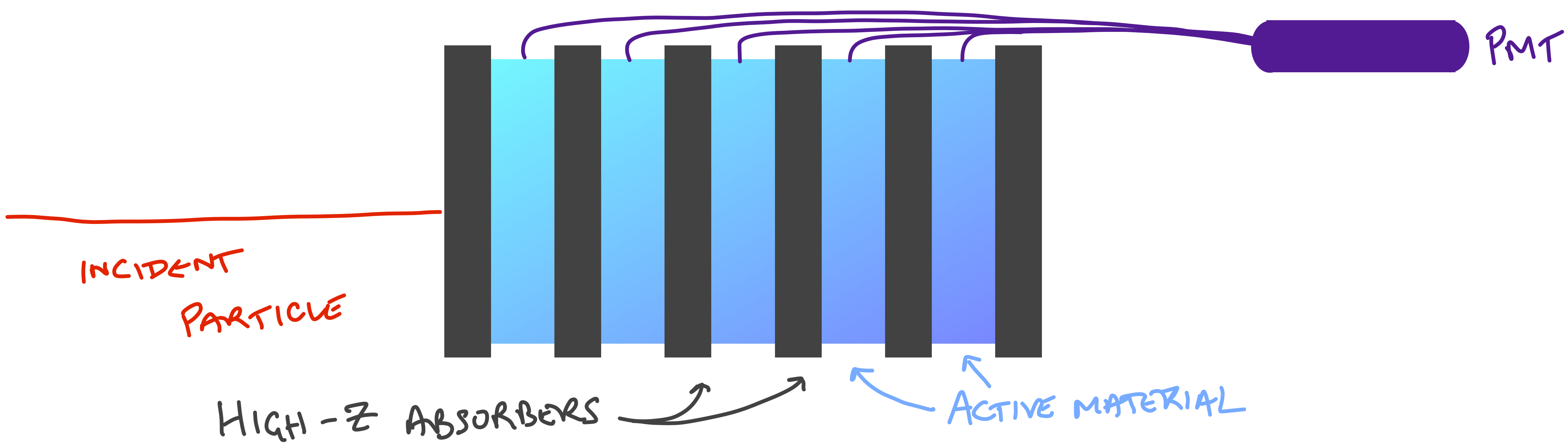

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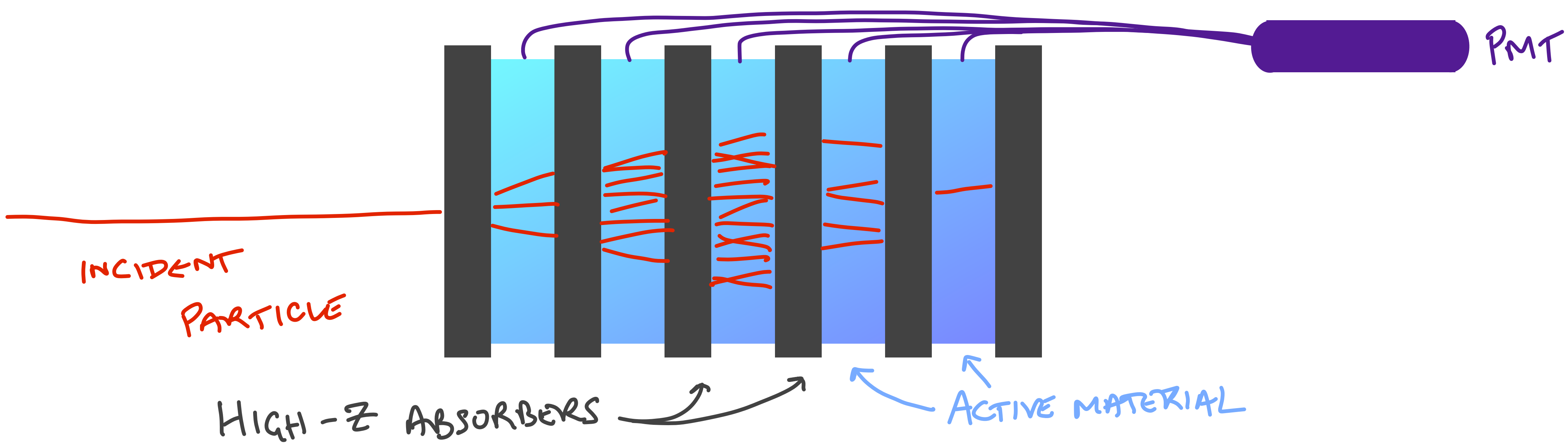

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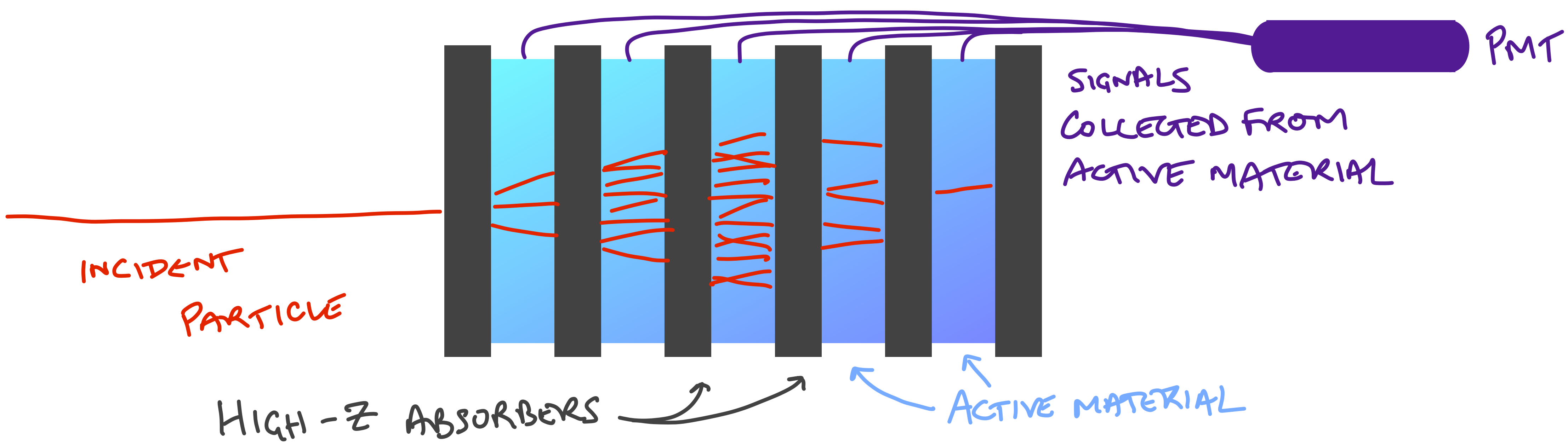

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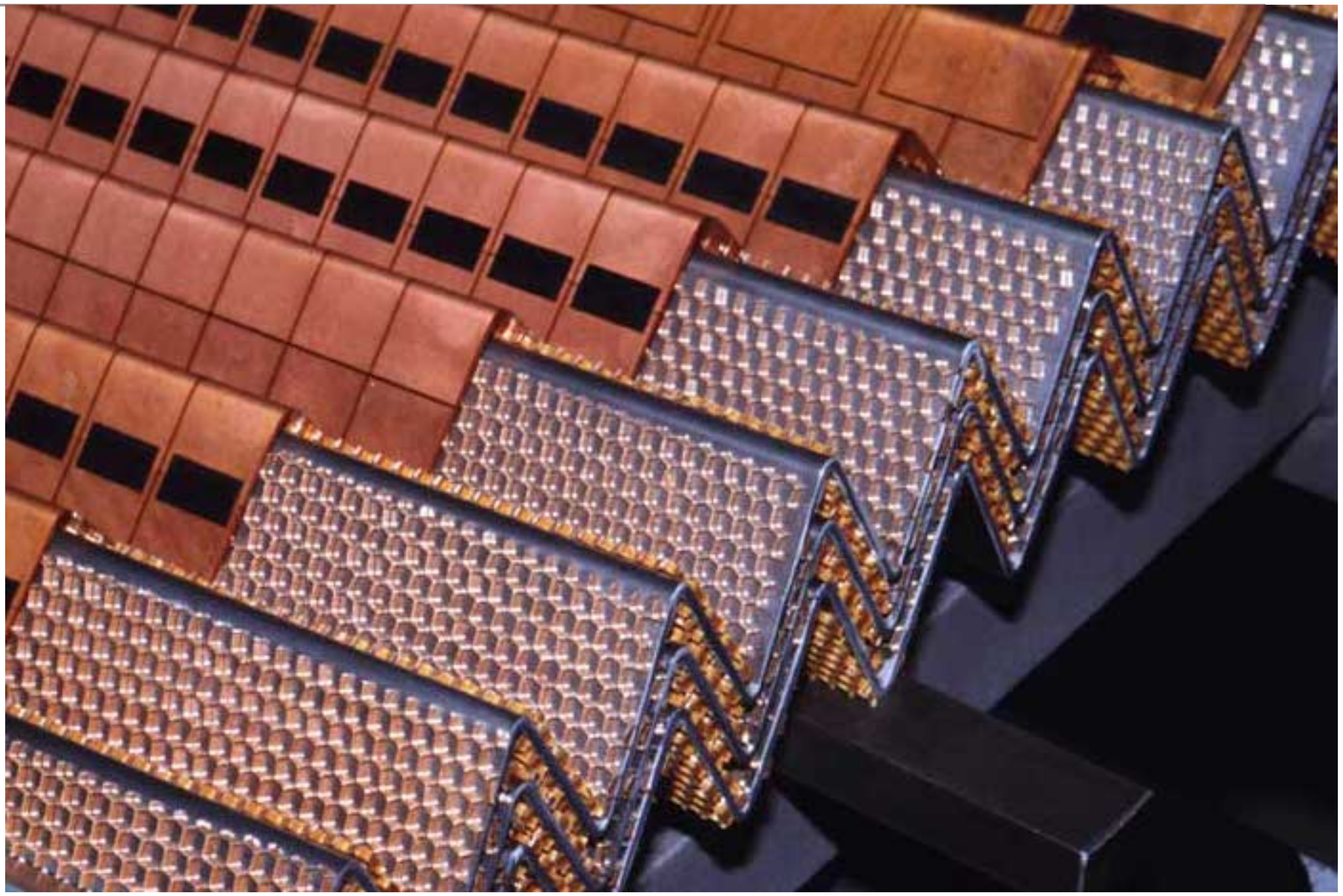
Example of a *sampling* calorimeter

Dimensions from
ATL-COM-LARG-2008

ATLAS EM calorimeter made of lead mixture as absorber (X_0 = 0.75 cm) and liquid argon active material (X_0 = 14 cm)



Calorimeter thickness: 46 cm
Lead layers: 1.1-1.5 mm
LAr layers: 2.1 mm
Total Pb thickness ~ 17 cm = 22.7 X_0
Total LAr thickness ~ 29 cm = 2.0 X_0
Total X_0 is about 25
… enough to contain 99% of an electromagnetic shower.

If we wanted the same X_0 with LAr alone, the calorimeter would have to be 3.5 m deep!

Calorimeter resolution

Resolution contributions

Showering fluctuations and $1/\sqrt{N}$ statistics	$\propto 1/\sqrt{E}$
Noise	$\propto 1/E$
Shower leakage	~ constant

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

Resolution is better for higher E!

- **Homogeneous calorimeters** have great resolution because all deposited energy is recorded

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~2 to 3%

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Calorimeter resolution

Resolution contributions

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Resolution is better for higher E!

- **Homogeneous calorimeters** have great resolution because all deposited energy is recorded
- **Sampling calorimeters** have additional contribution from fluctuations in amount sampled

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

d = active layer thickness
f_{samp} = sampling fraction

~ 5 to 15%

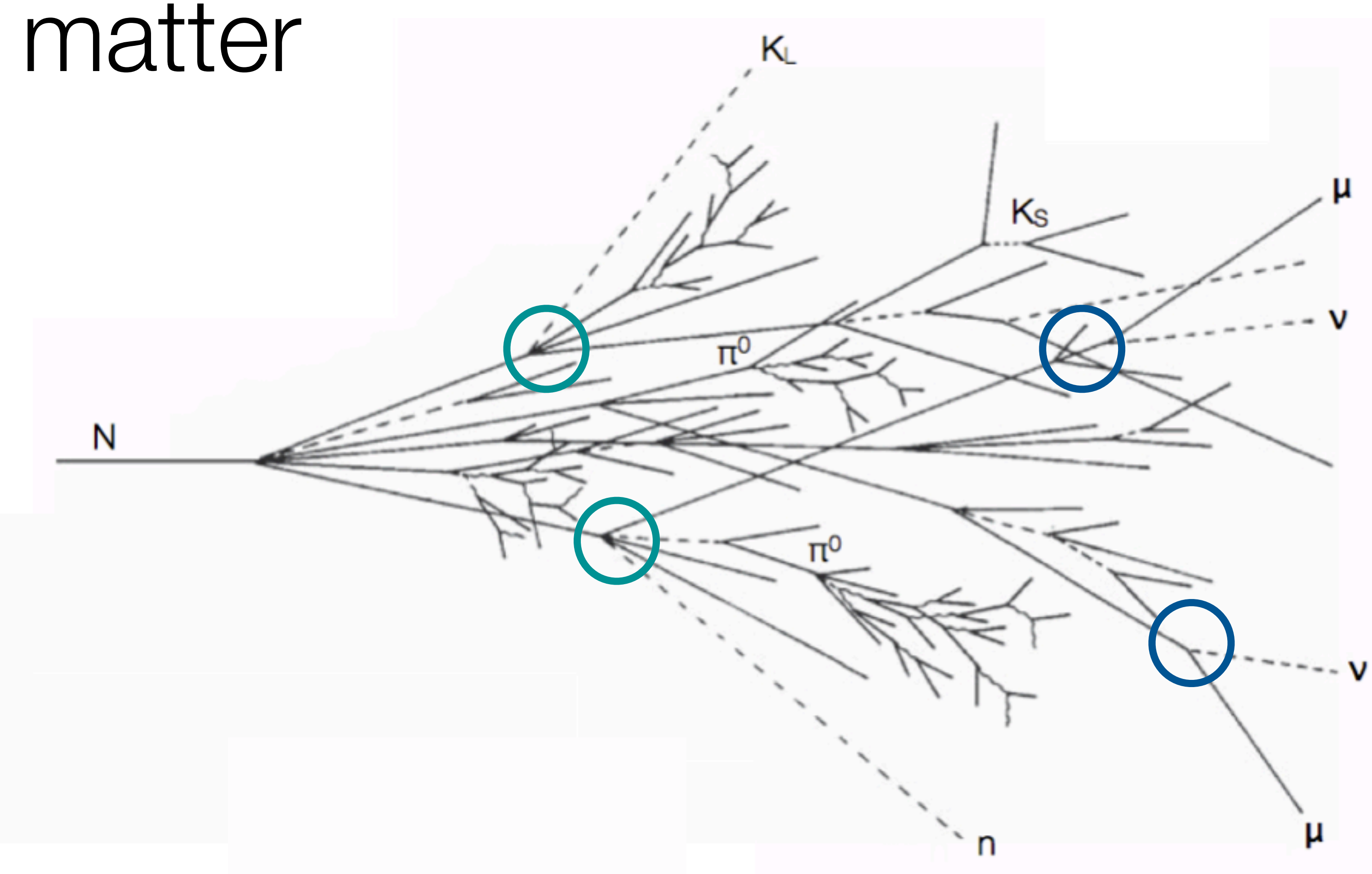
Grupen & Shwartz, 2008

Hadronic showers in matter

- Strongly charged particles generate **much** more complicated showers

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

- Produced fission fragments can undergo **β decays**, creating non-measured neutrinos



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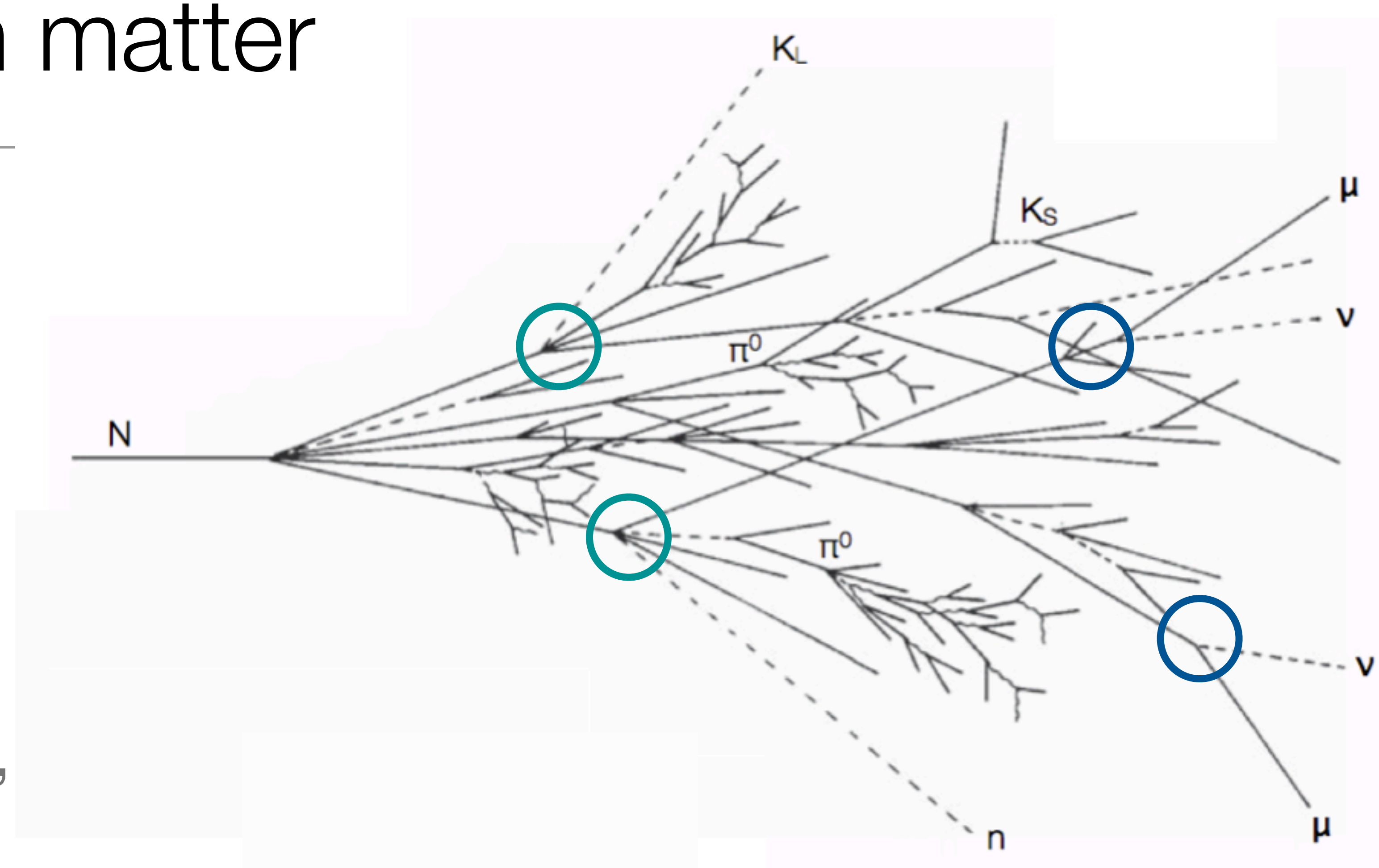
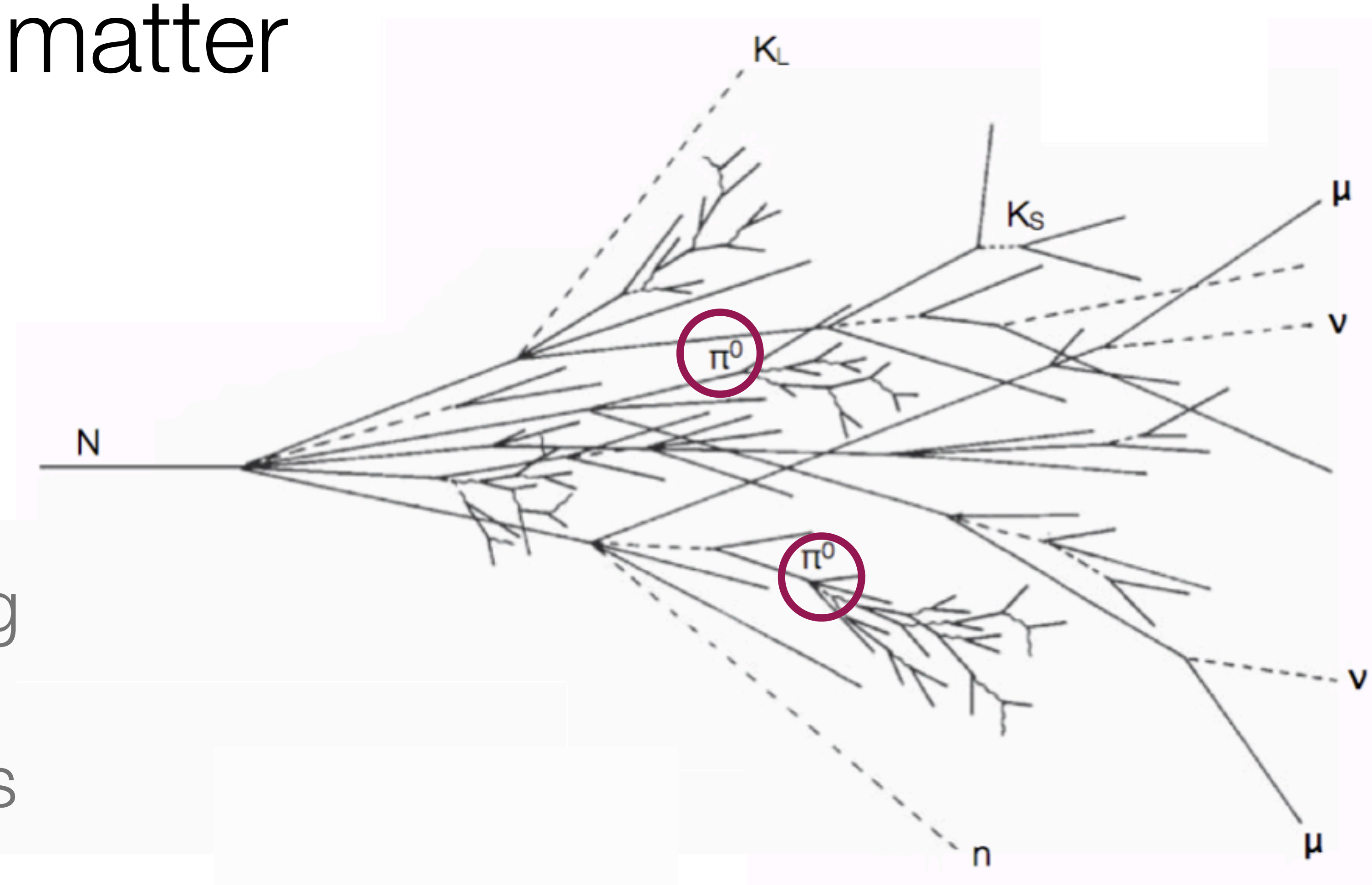


Non-compensation:
Response will always be < 1

(Sometimes said: $e/h \gg 1$)

Hadronic showers in matter

- Strongly charged particles generate more complicated showers
- Main products of showering are pions. Produce π^+, π^-, π^0 in roughly equal fractions
- **π^0 decays to $\gamma\gamma$** which initiates electromagnetic sub-cascade. The more interactions take place in a shower, the more chances to create a π^0 (no chance to convert back to hadron!)

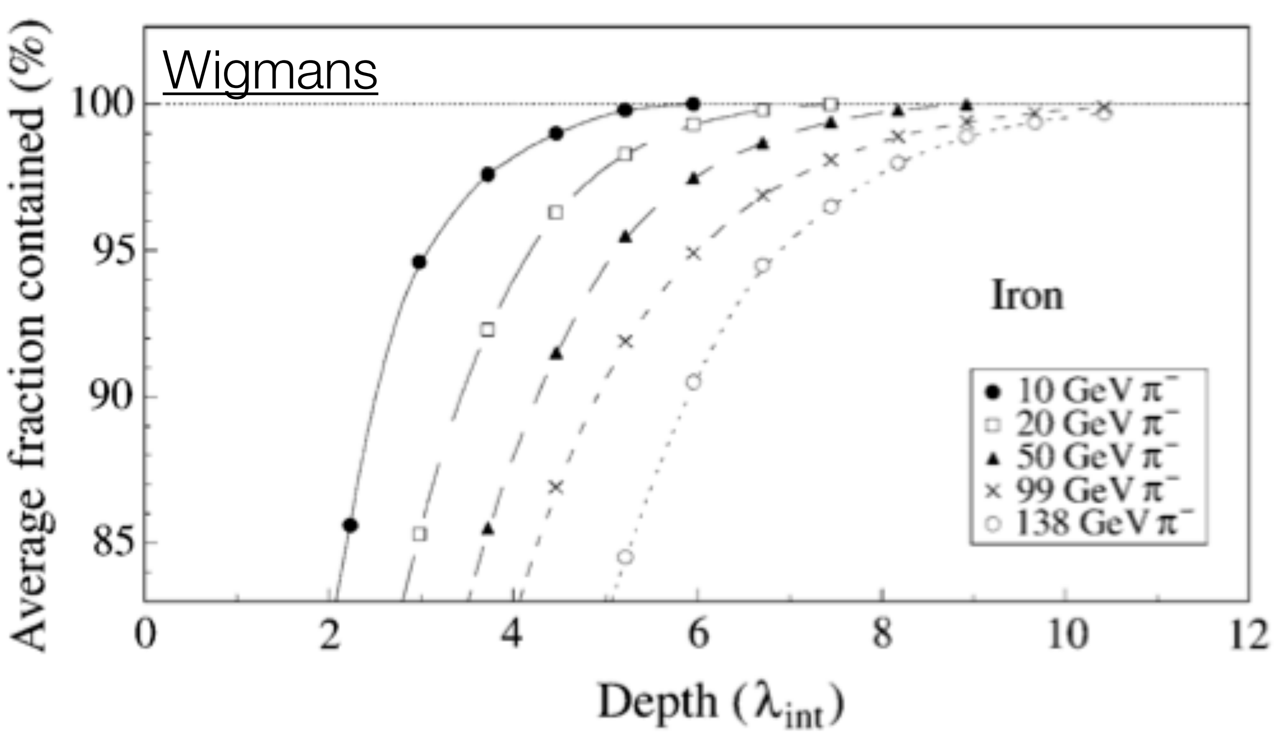


Non-linearity:
Response is higher (better) for higher-energy jets

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

Size of a hadronic shower

- Equivalent of radiation length is *interaction length* λ_{int}
- Hadronic shower 99% contained within **9 λ_{int} longitudinally** and 1 λ_{int} transversely



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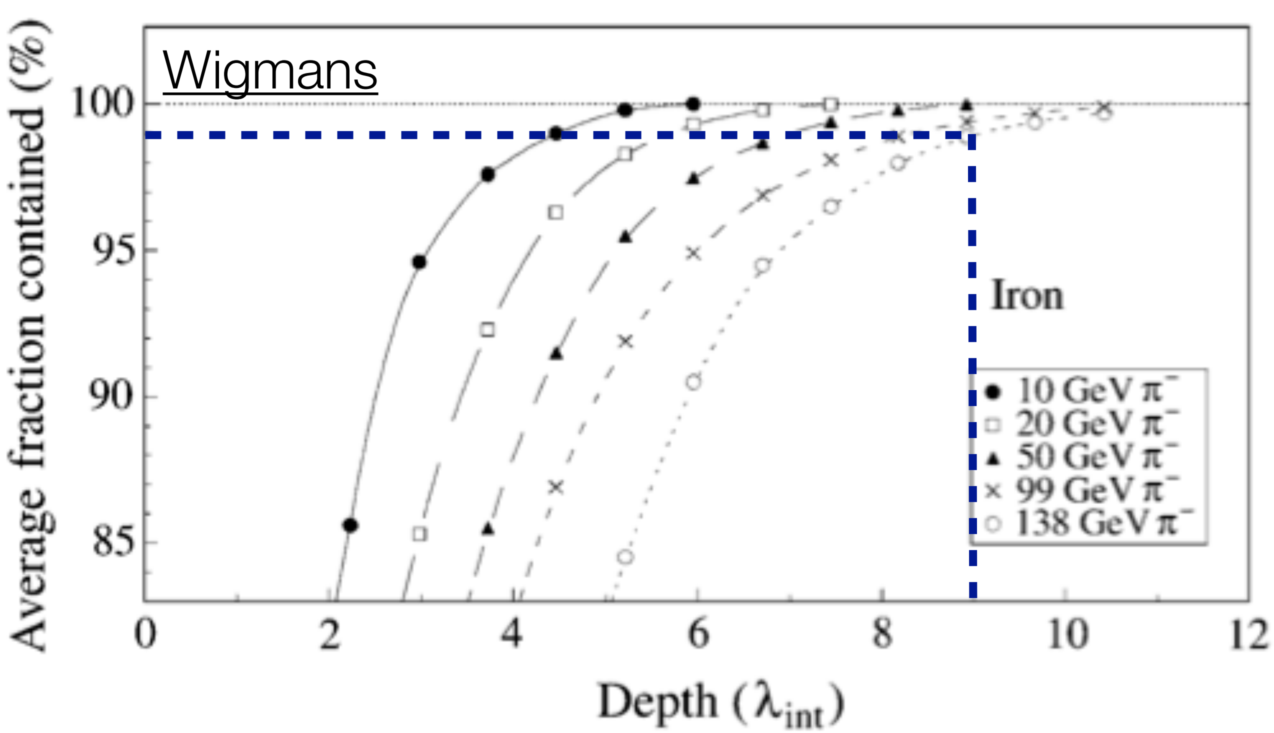

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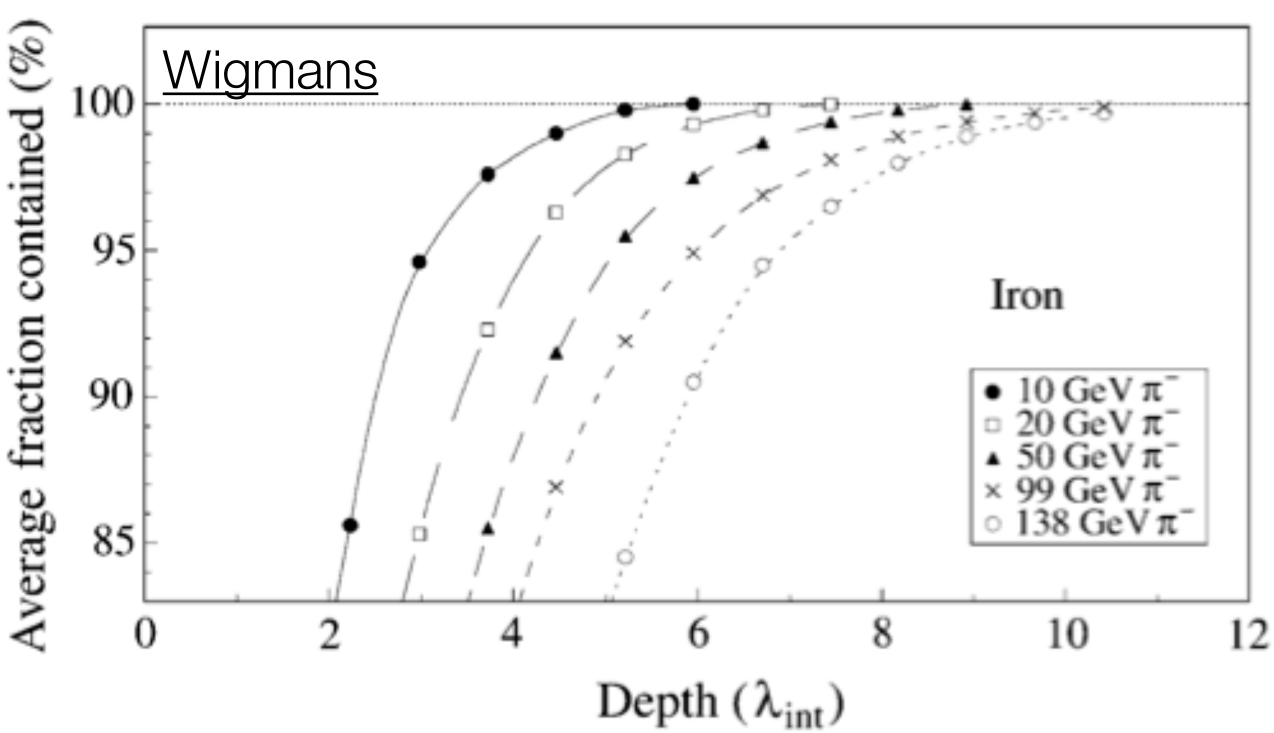

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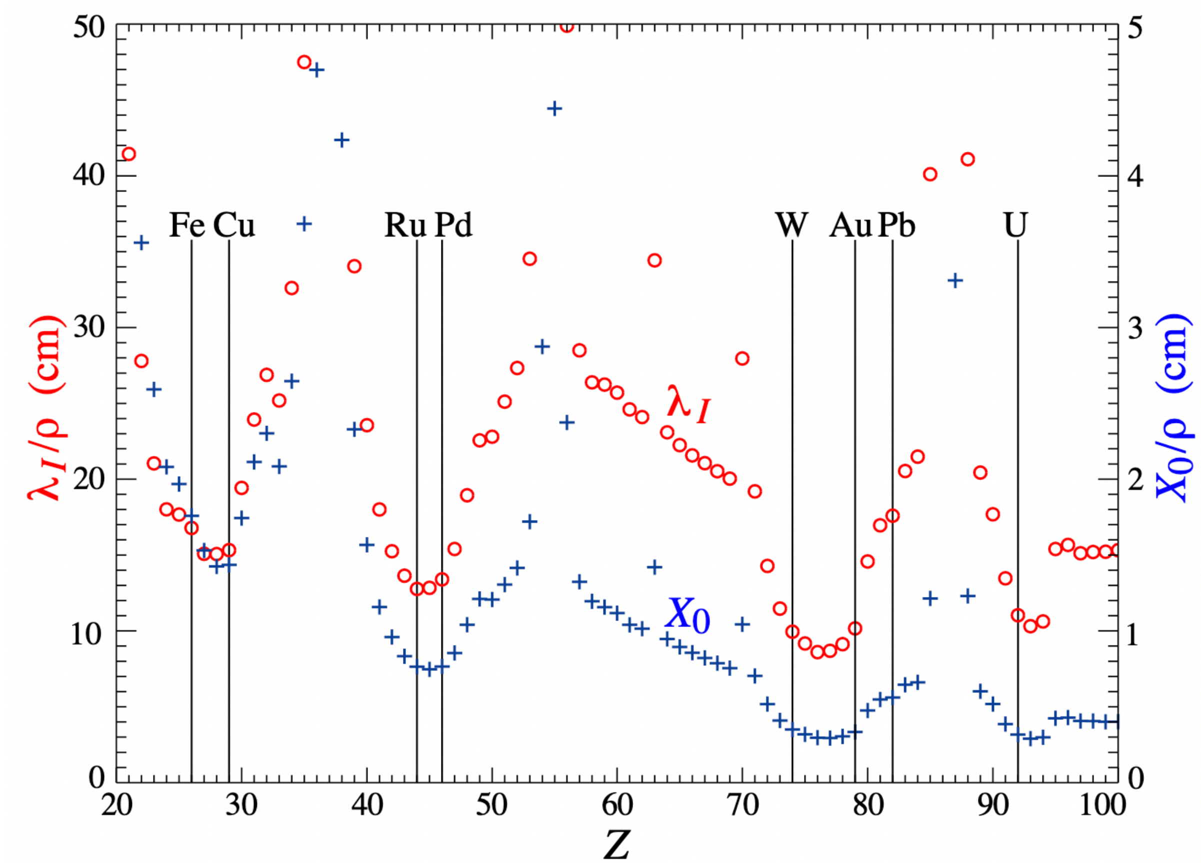
If $X_0 \propto 1/A$ and $\lambda_{int} \propto A^{1/3}$, then

$$\lambda_{int}/X_0 \propto A^{4/3}$$

→ Interaction length is a lot longer than X_0 for most materials!



Material	C	Al	Fe	Pb
X_0 (cm)	18.9	8.9	1.8	0.56
λ_{int} (cm)	26.1	25.8	10.4	10.1

PDG 2019

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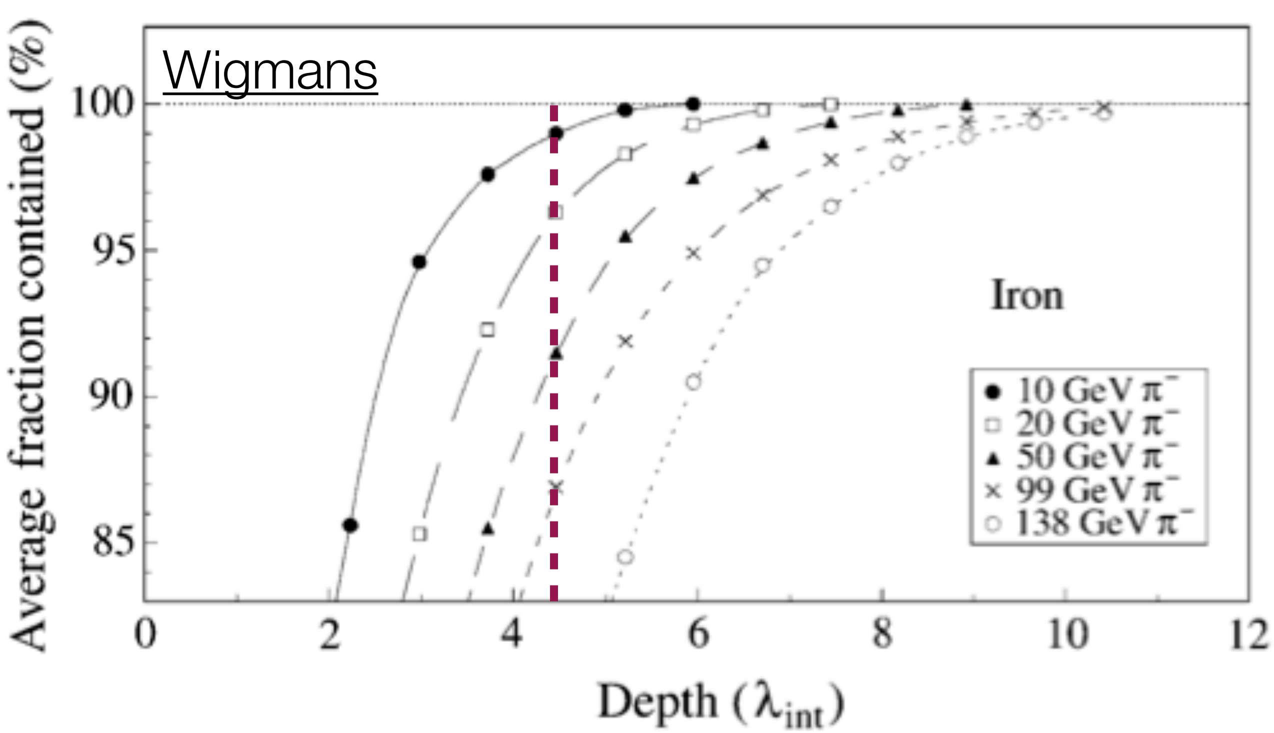

25 X_0: EM shower fully contained by here

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

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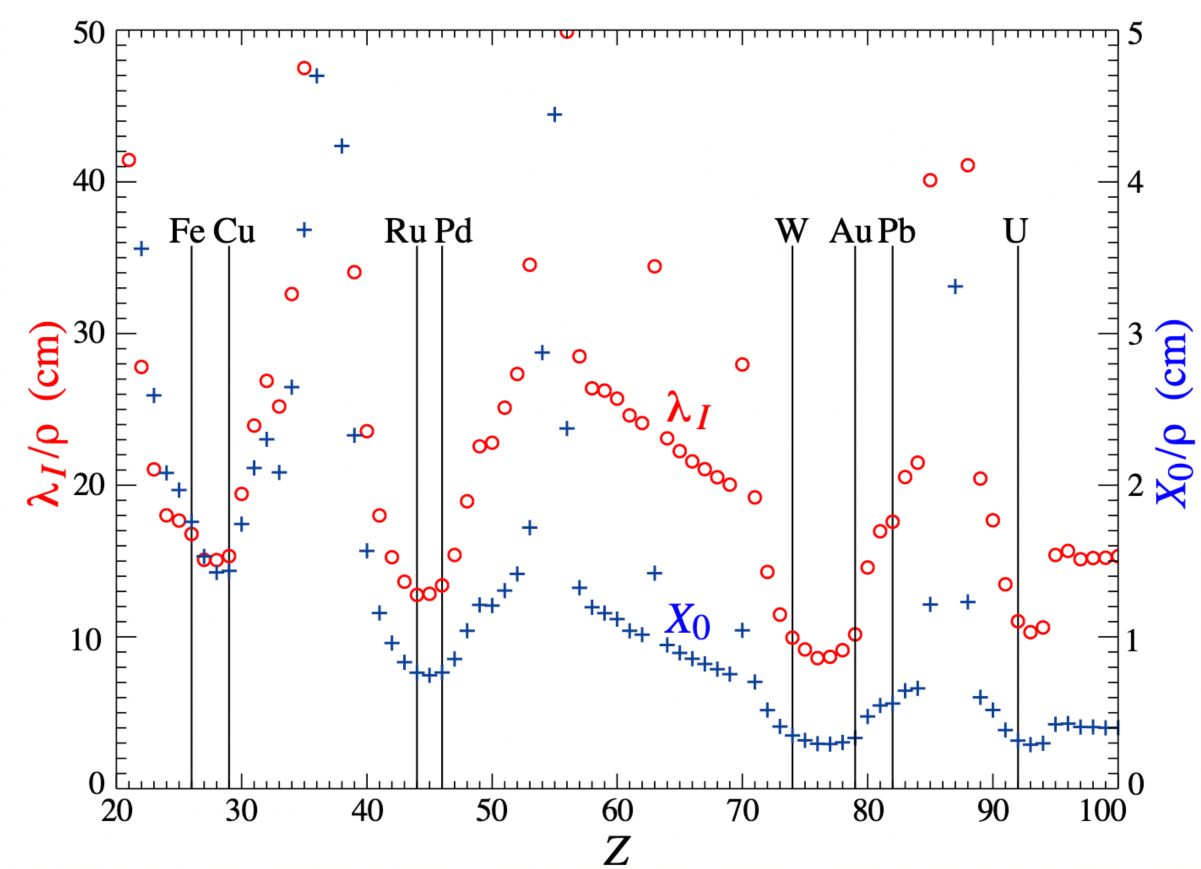

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PDG 2019

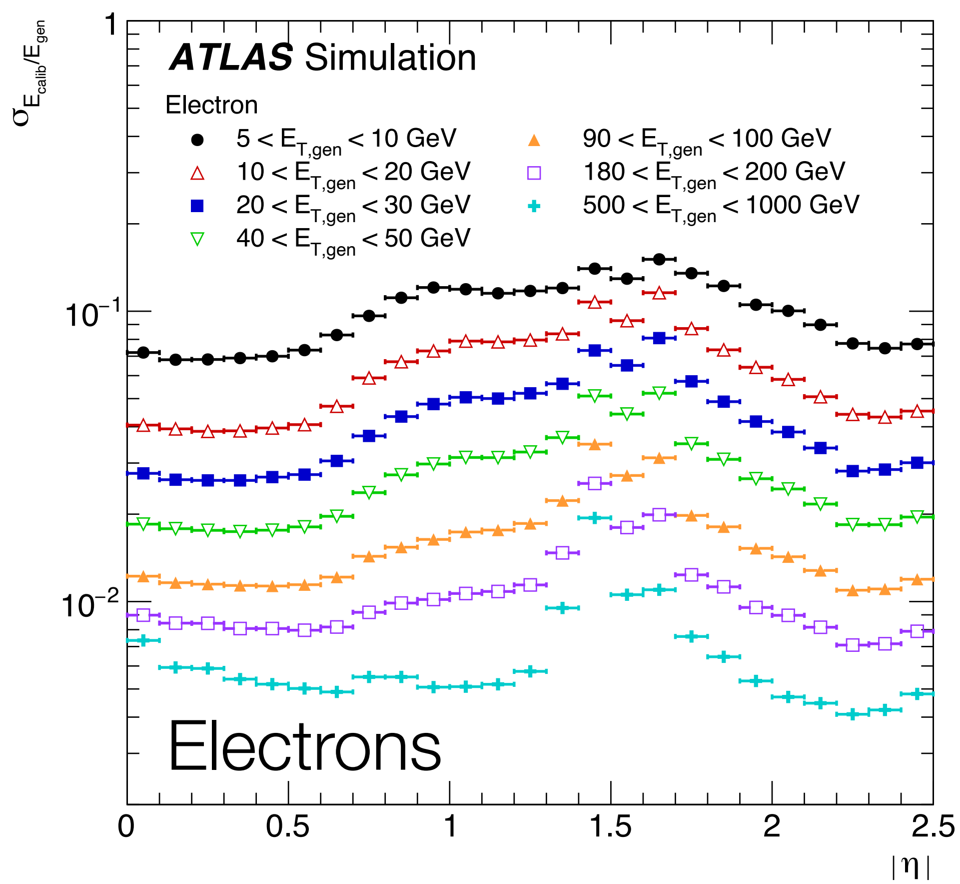
Hadronic calorimeter resolution

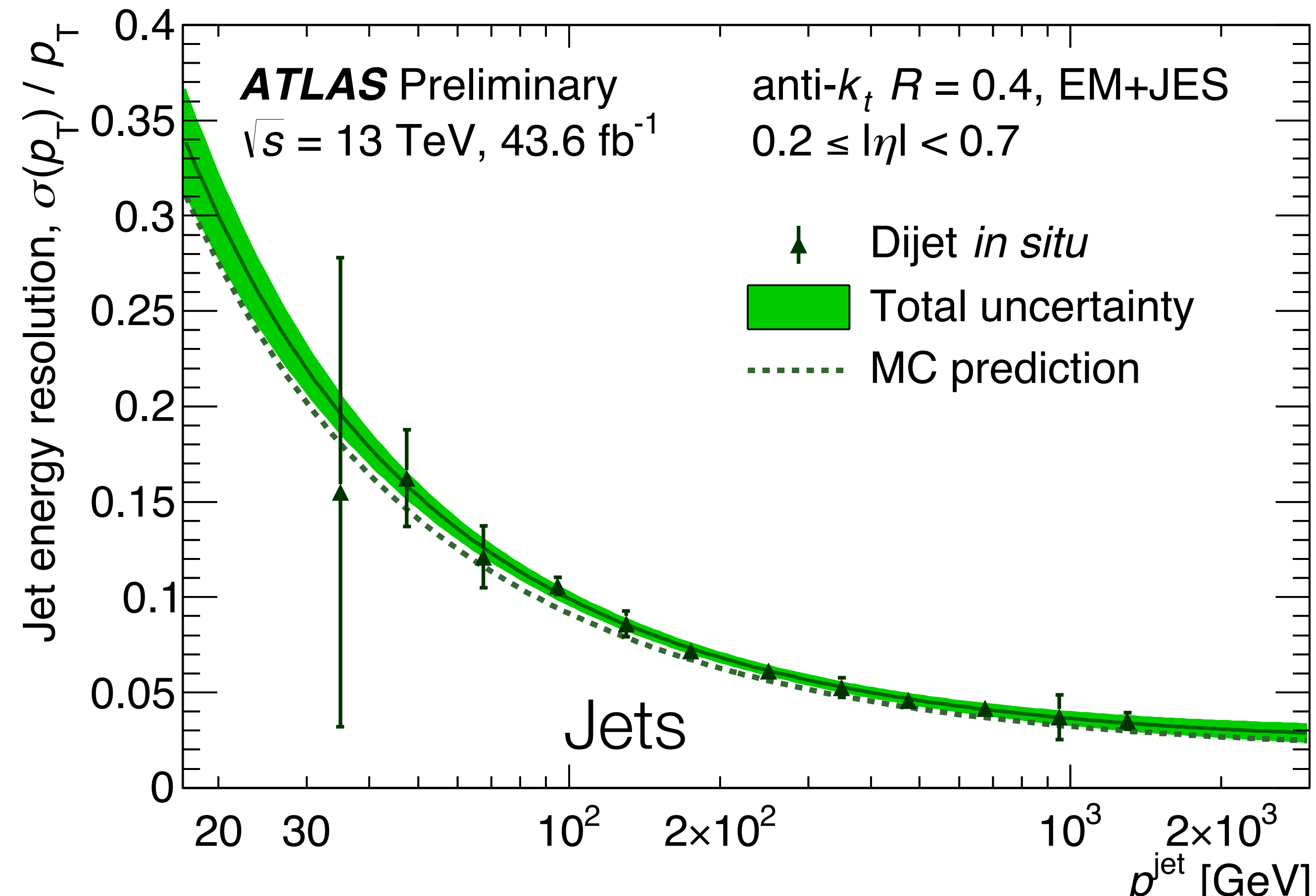
- Resolution worse for hadronic showers due to:
  - Fluctuations in lost energy (neutrinos, muons, nuclear excitation energy, …)
  - Fluctuations in EM fraction of showers
  - Varying degrees of shower leakage

0.5 – 1.0

~4%, 2nd largest now

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





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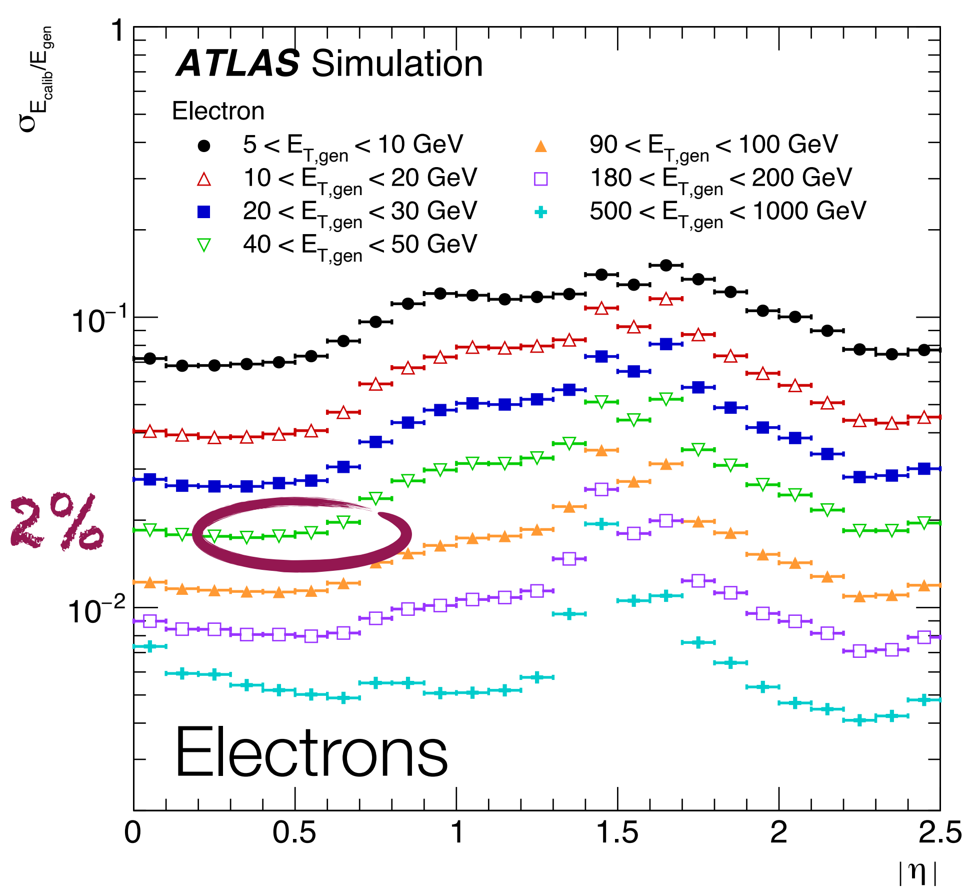

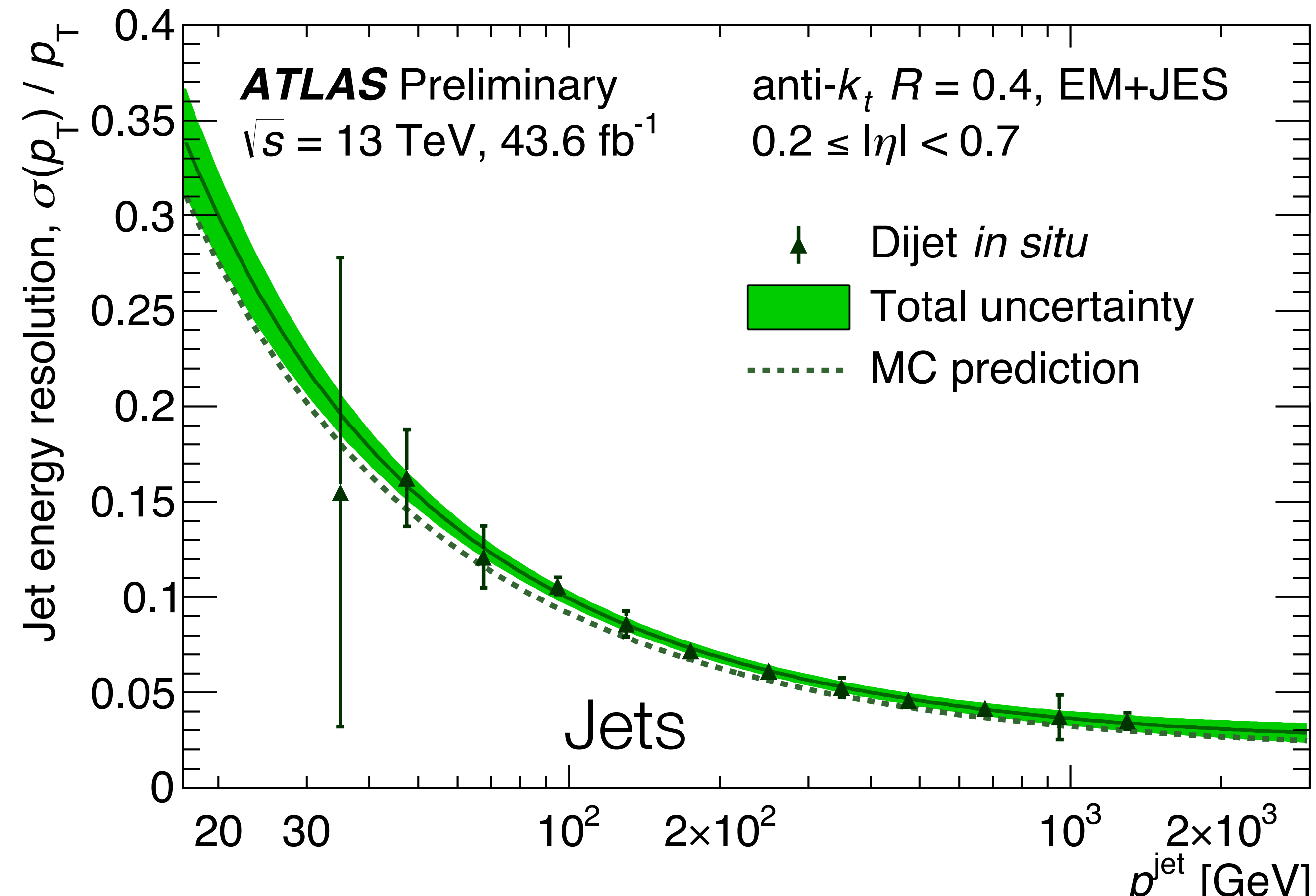

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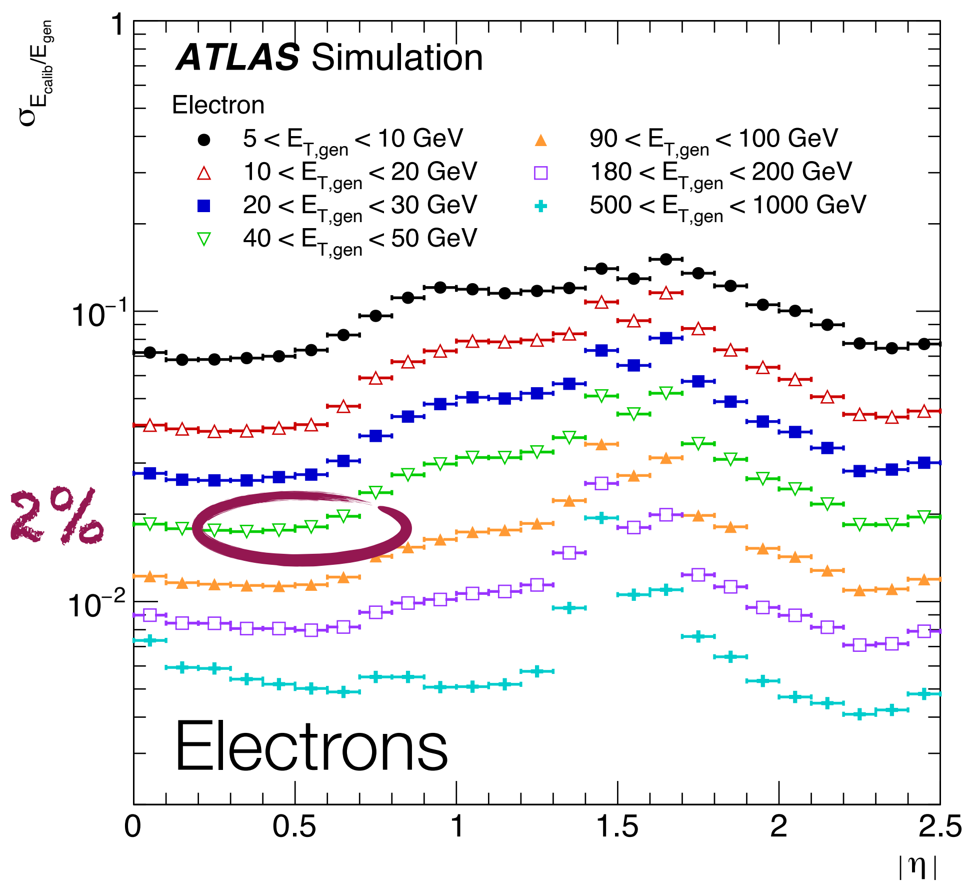
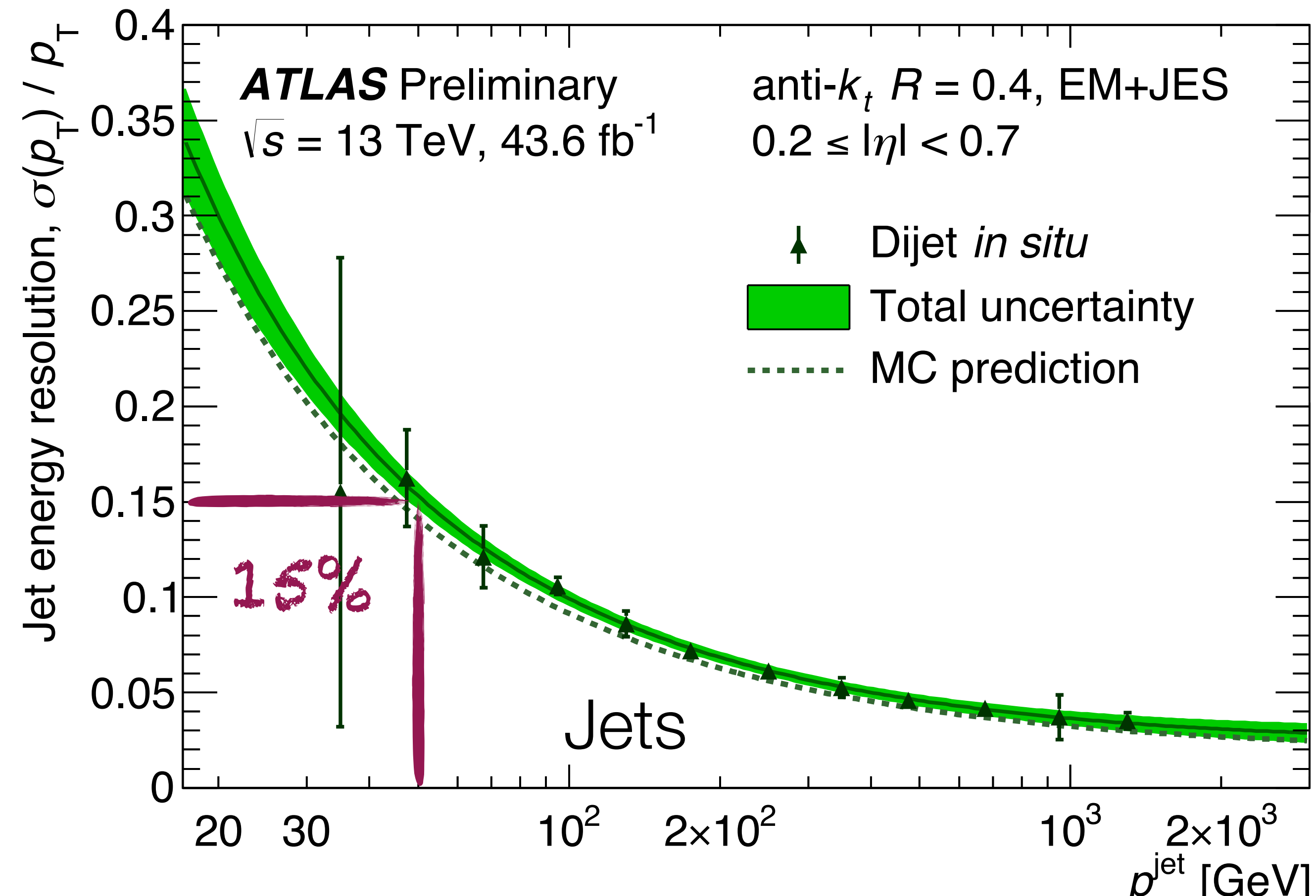
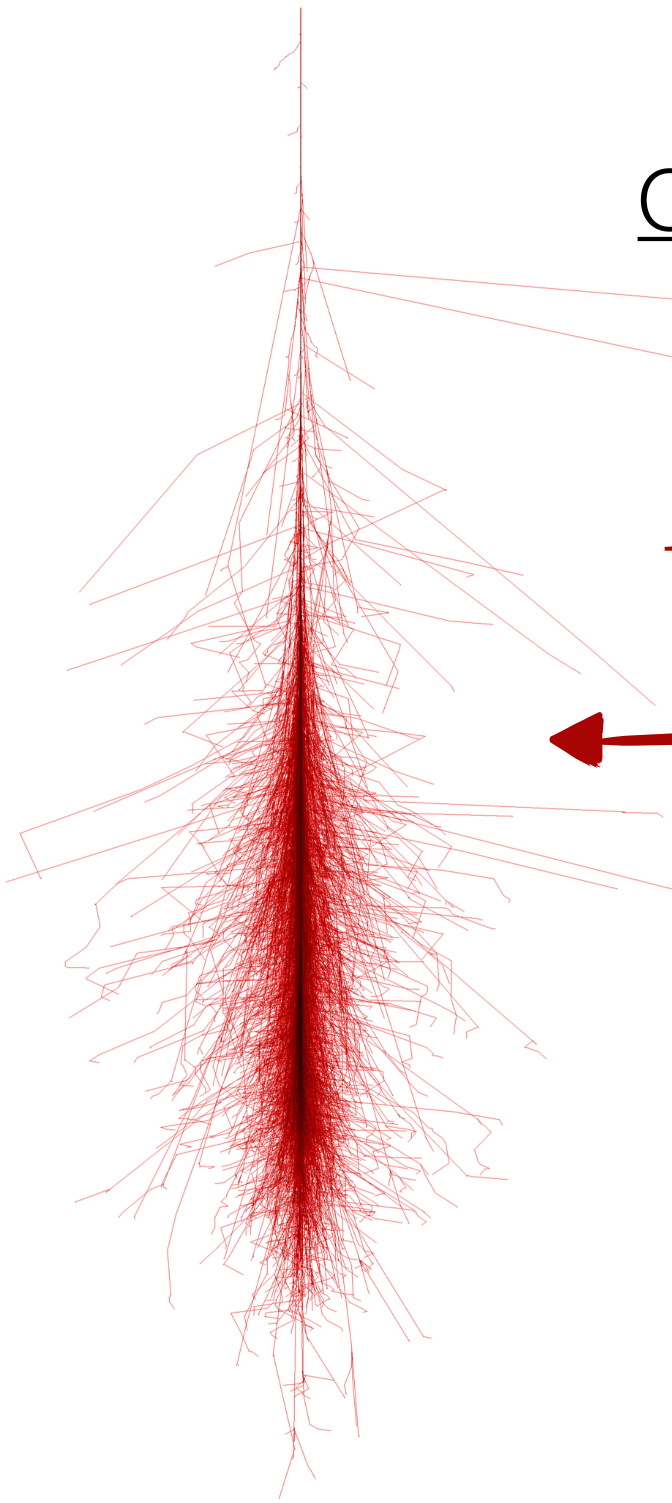




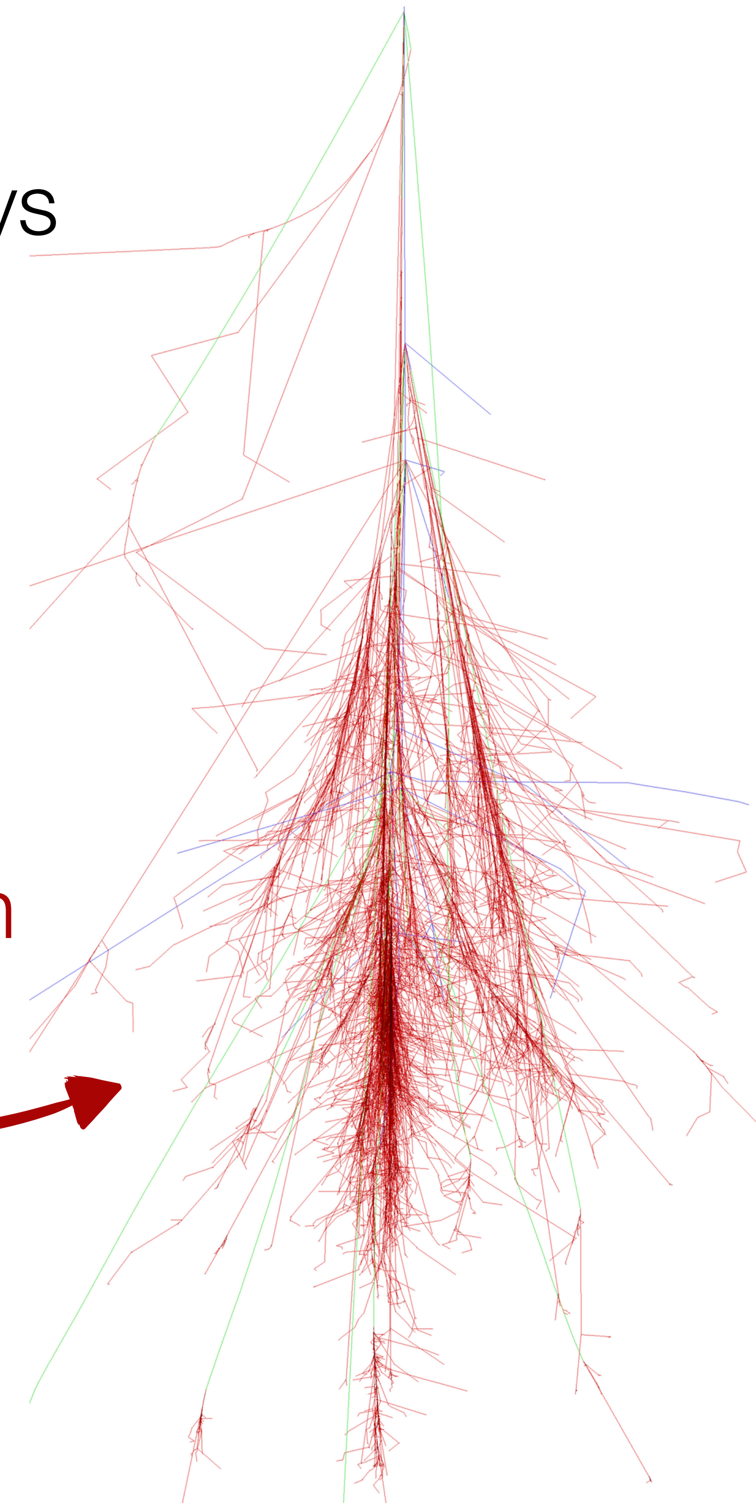
Hadronic versus electromagnetic showers

Simulations from
CORSIKA of cosmic rays
showering in air



100 GeV photon

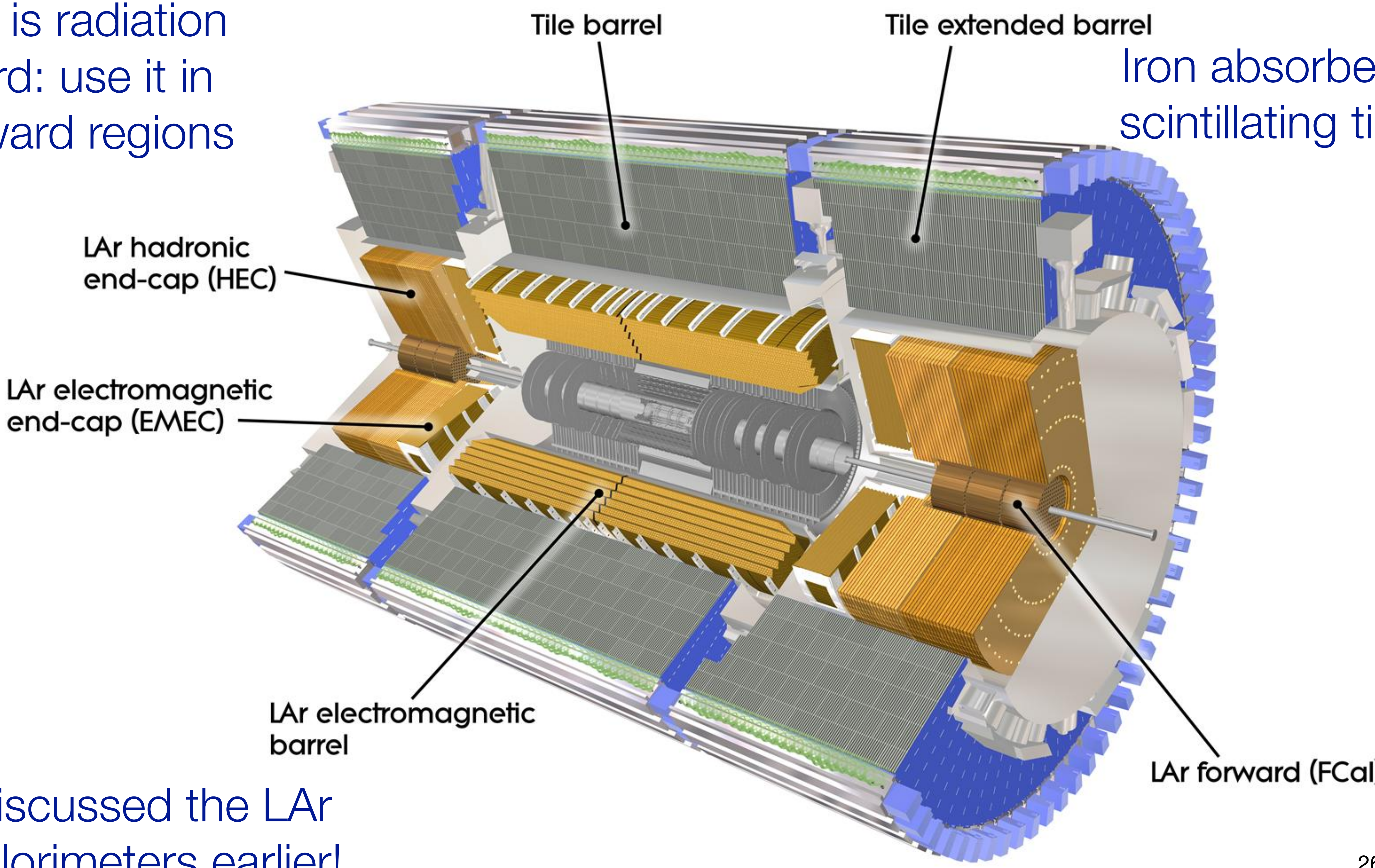
100 GeV proton



Two layered calorimeters, EM then hadronic

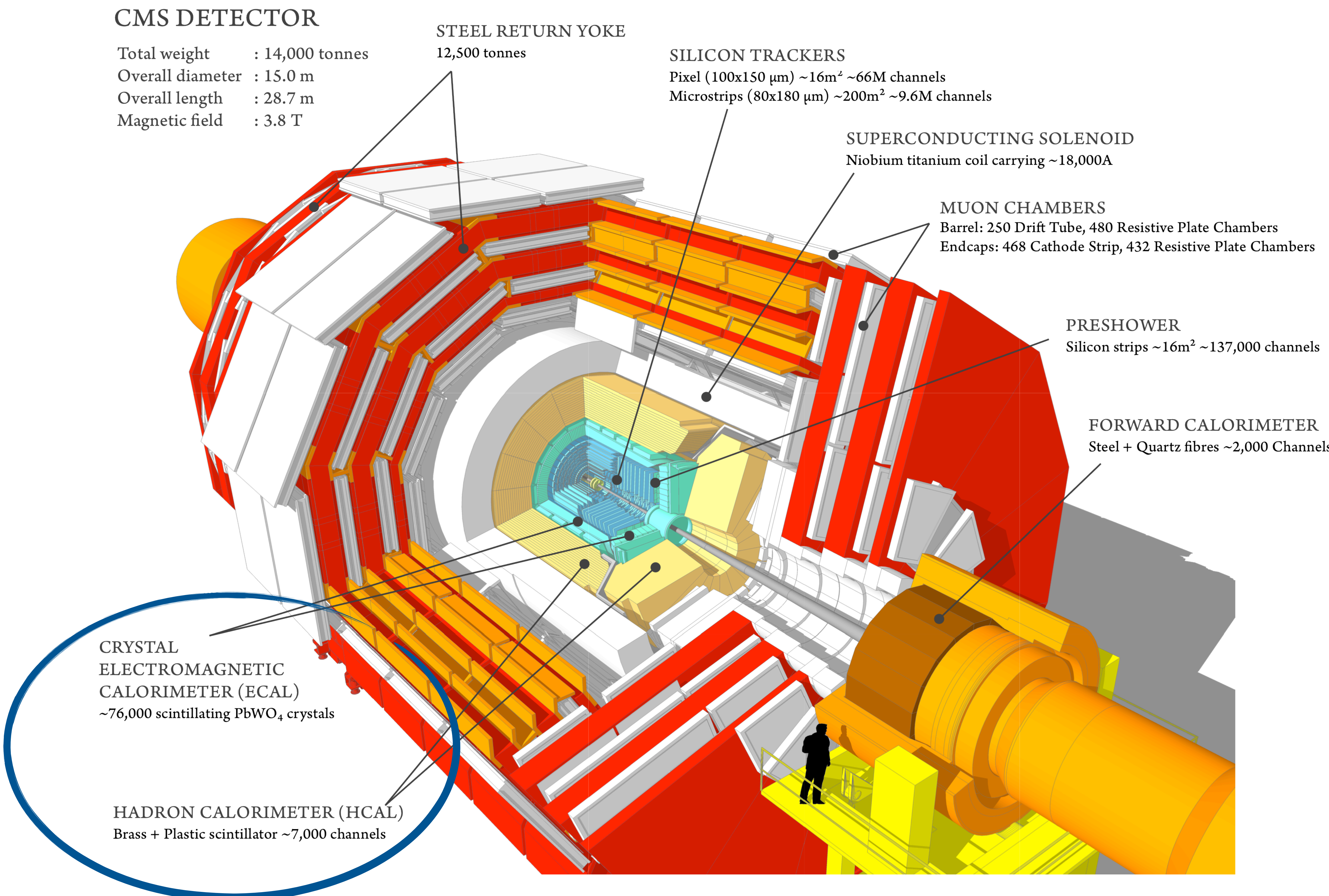
LAr is radiation hard: use it in forward regions

Iron absorbers, scintillating tiles



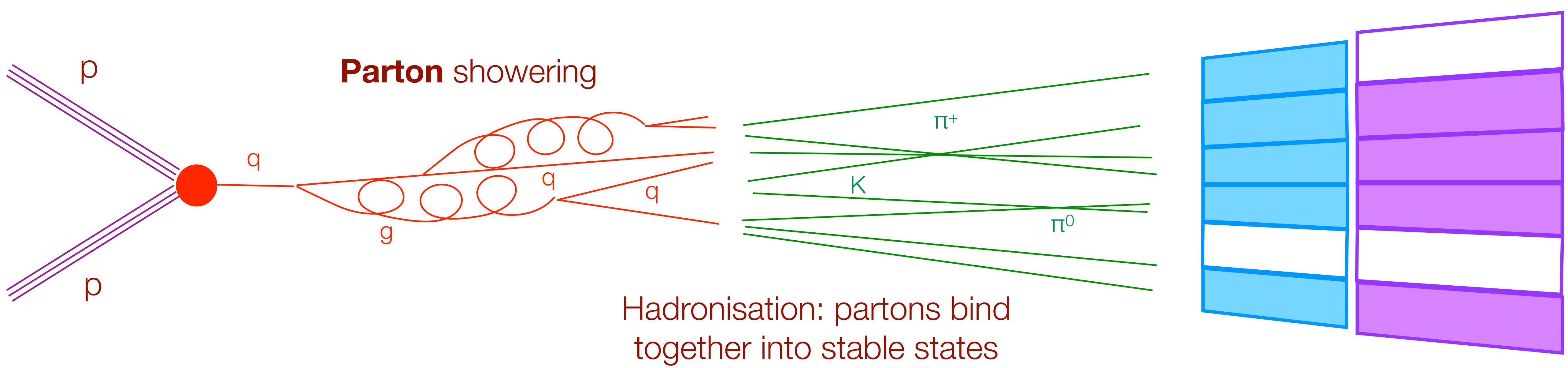
Discussed the LAr calorimeters earlier!

Two layered calorimeters, EM then hadronic



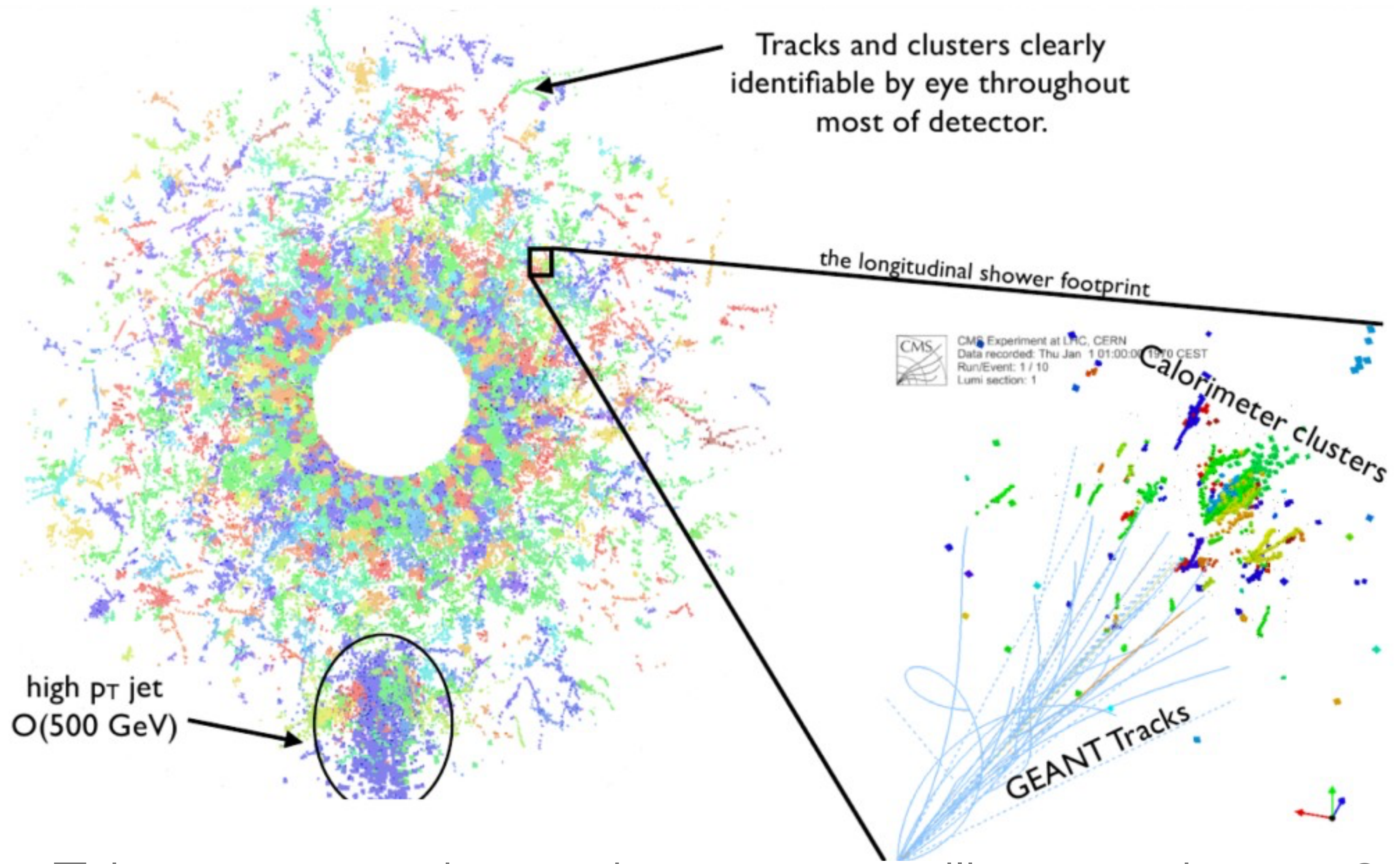
An aside: Parton showers versus particle showers

- Heads up: the word "shower" is confusingly overloaded when we talk about strongly charged particles interacting
- In a high energy physics, the process by which a single quark or gluon produced in a Feynman diagram generates additional particles before forming stable hadrons is also often called **parton** showering
- Consequence is the emergence of "**jets**": when you produce a q or g at high energy, you get a large group of pions, kaons, etc arriving at your calorimeter together, and each of these will start a **particle** shower in the material



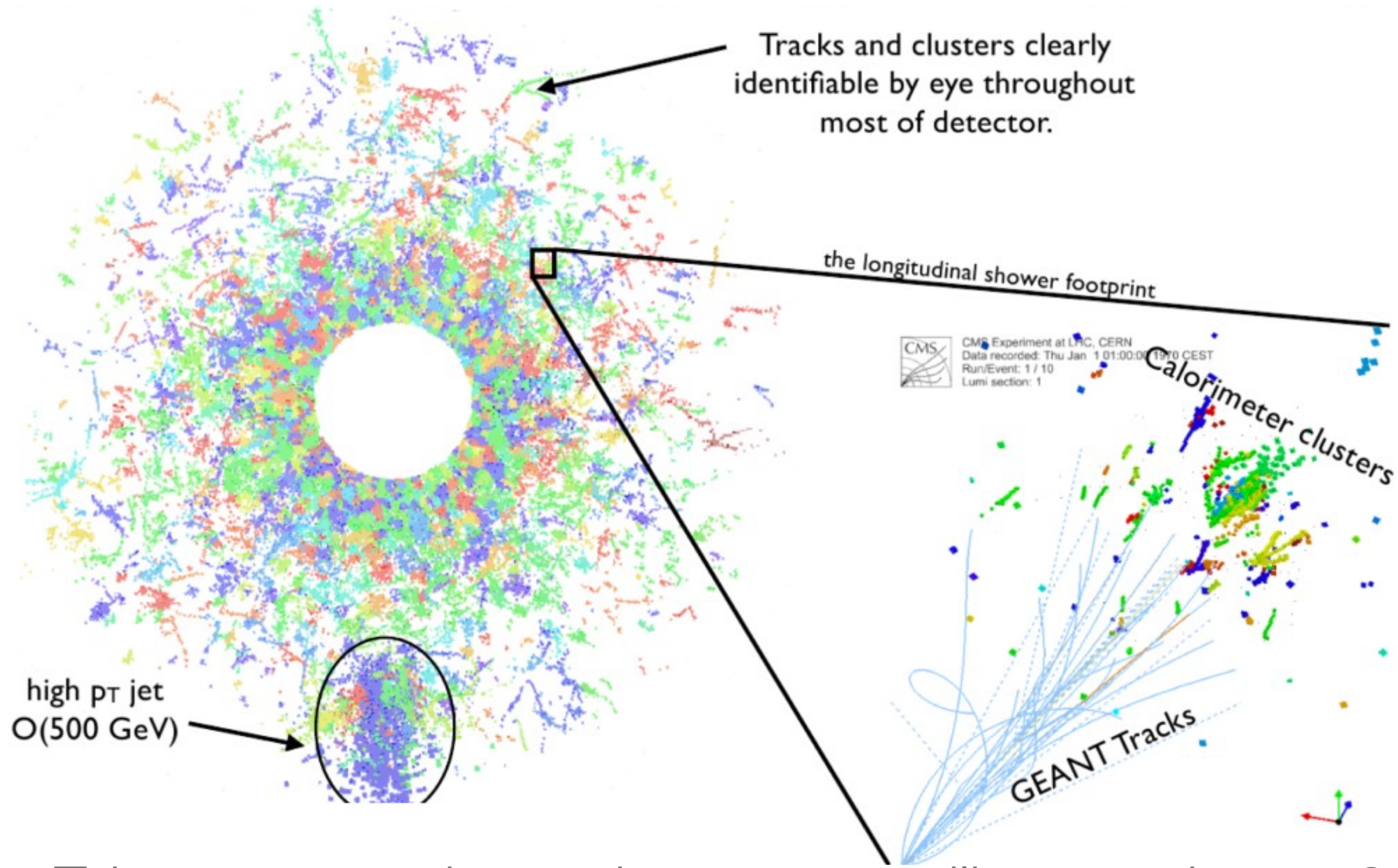
Now they hit the calorimeter and each starts a **particle** shower

High Granularity Calorimetry



- Take segmentation to the extreme: silicon readout at 0.5cm^2!
- Image individual portions of the shower evolution

High Granularity Calorimetry

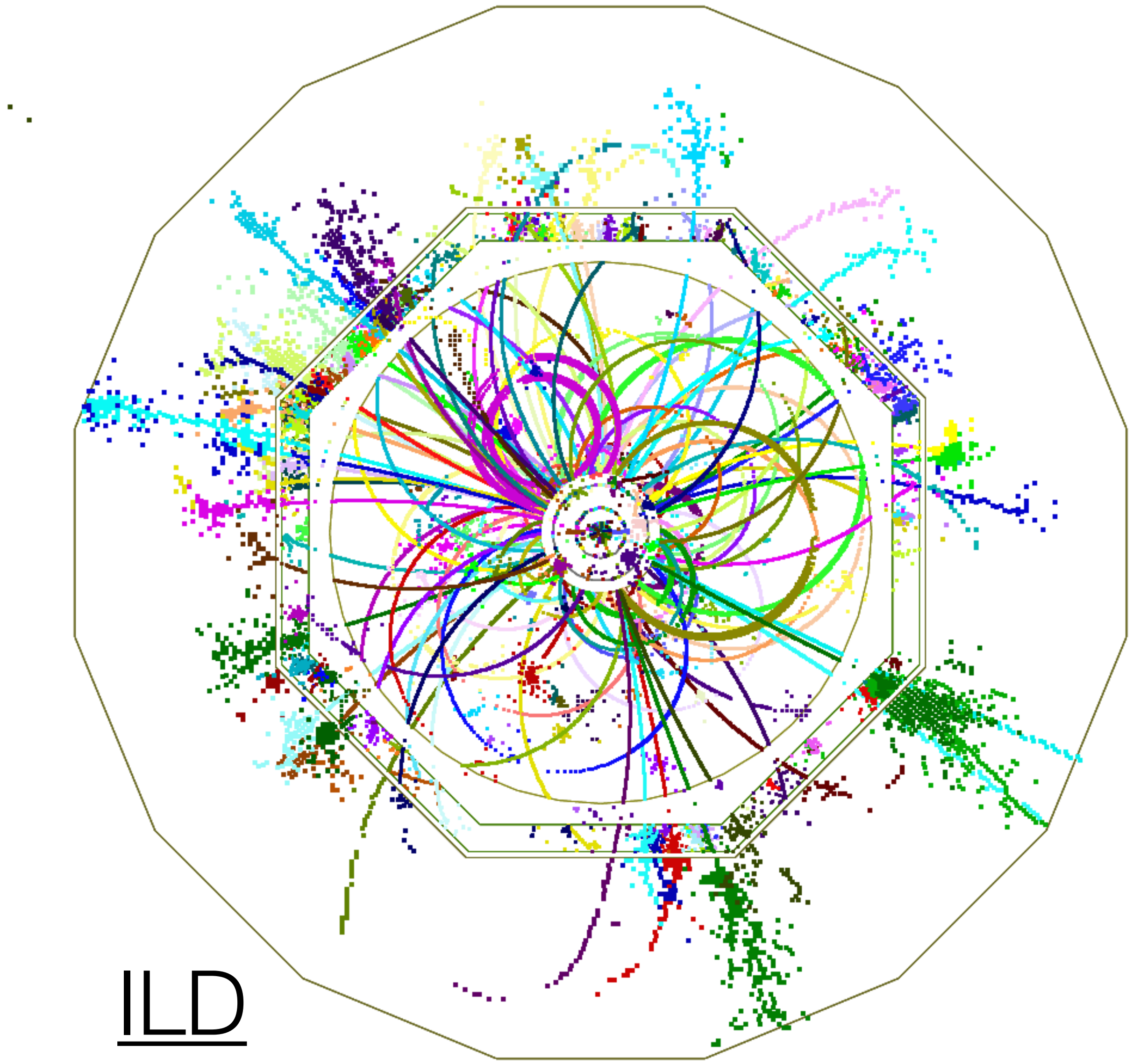


$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

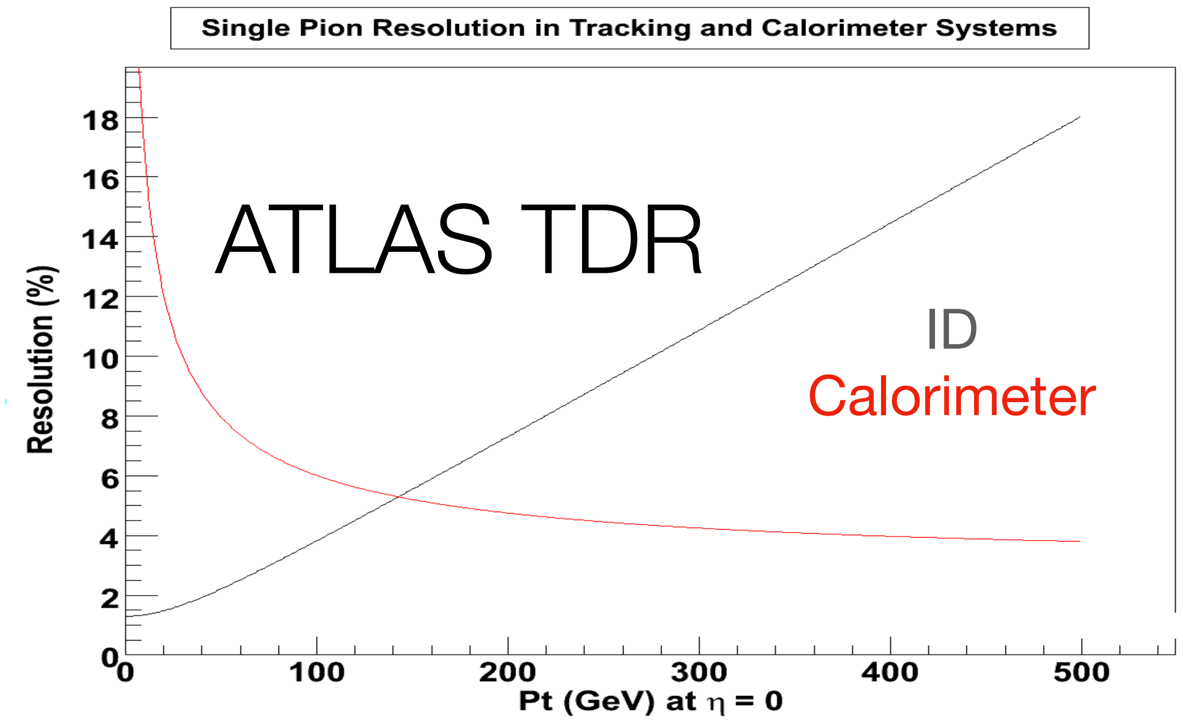
usually ~ 5 to 15%

- Take segmentation to the extreme: silicon readout at 0.5cm^2!
- Image individual portions of the shower evolution
  - **Extremely high** stochastic term: 22%! **So why bother?**

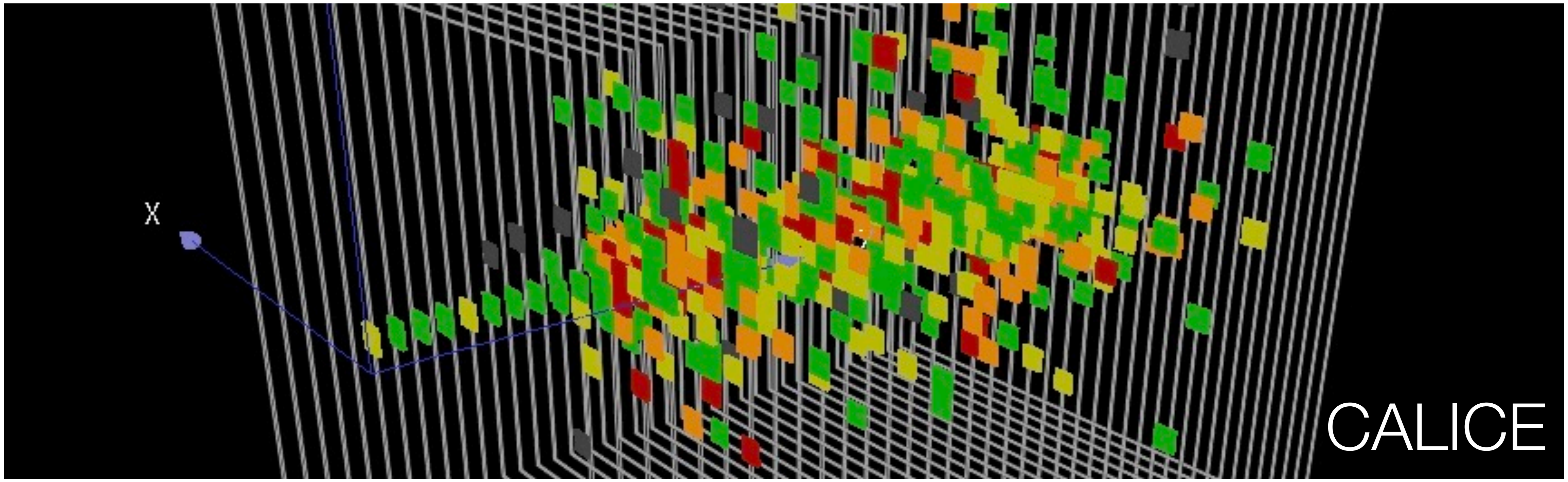
Particle Flow



- Calorimeter is not your only detector!
- In HEP (and often nuclear) detectors, you have *trackers* as well: much better resolution for charged hadrons
  - And hadrons are ~2/3rds of particles striking calorimeter (particles in jets)
- Combining tracker and calorimeter: “Particle Flow”
  - Main challenge: double counting
  - More granular calorimeter: less confusion!



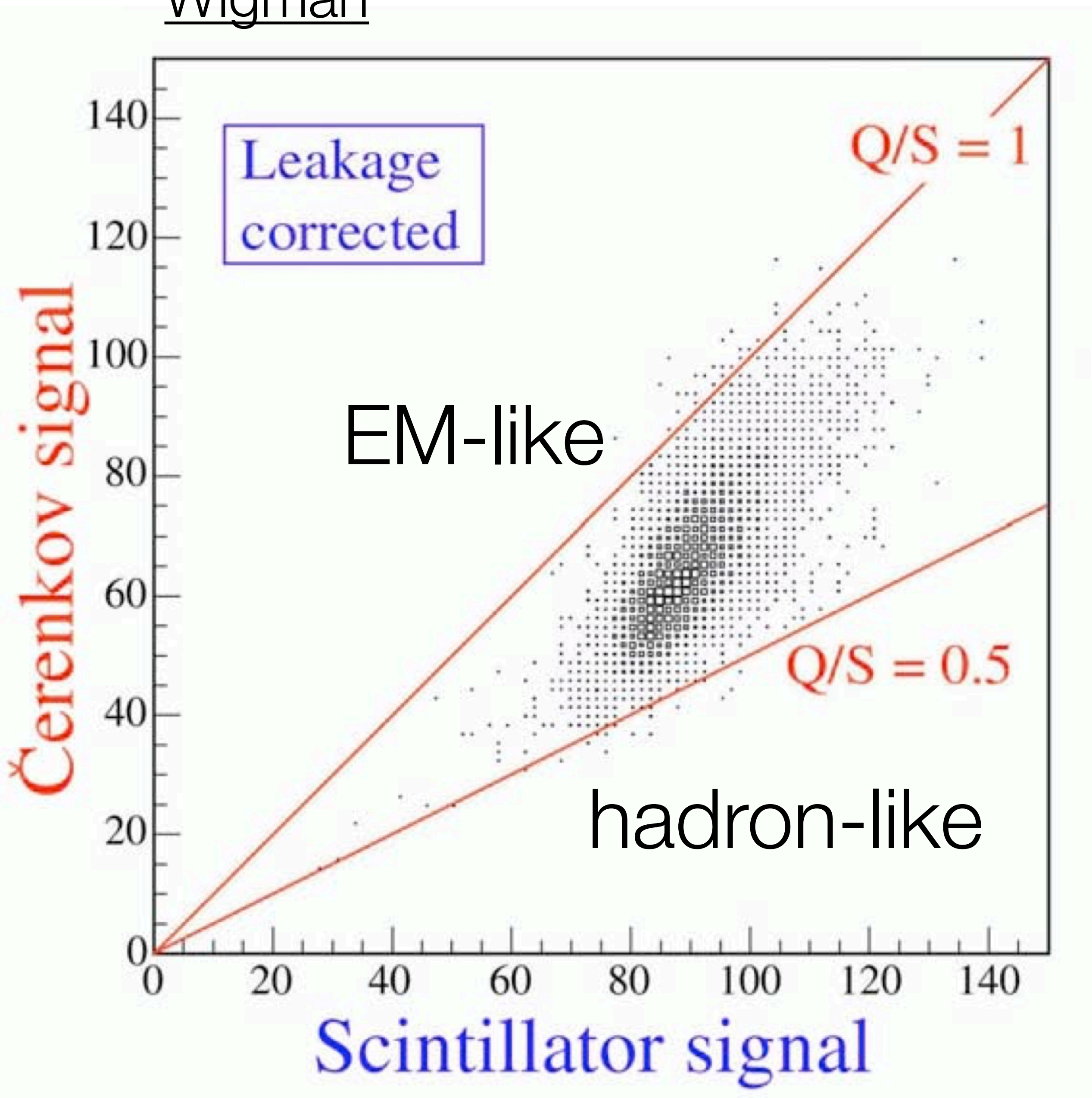
Digital Calorimetry



- Take granularity even more extreme:
  - Energy per read-out gets smaller and smaller
  - Eventually, just reading “presence of signal or not”: **digital signal**
  - Total number of cells $\propto$ total number of MIP interactions $\propto$ energy

Dual Readout

Wigman



- Mostly been talking about single-readout calorimetry
    - (It's cheaper)
- But in many materials, you can get multiple signals
- Can combine signals to *compensate* for $e/h \gg 1$
    - (Many other compensation techniques attempted: historically none super-successful)

Particle ID

… with a calorimeter bias

Particle ID: what and why?

- Critical to be able to **identify** the particles involved in an interaction to understand the processes
- **Long-lived particles** (on the timescale of the detector) are identified by their **unique properties**: mass, charge, interaction types, shower shapes, etc
- **Short-lived massive particles** (W, Z, Higgs, etc) are identified by their **decay products**
- Calorimeters can tell us a lot about particle ID, but need trackers for a full picture! **PID is a full detector project.**
- Different experiments specialise in different physics, so detectors designed for range of PID specialties

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General purpose: decent for everything

ALICE

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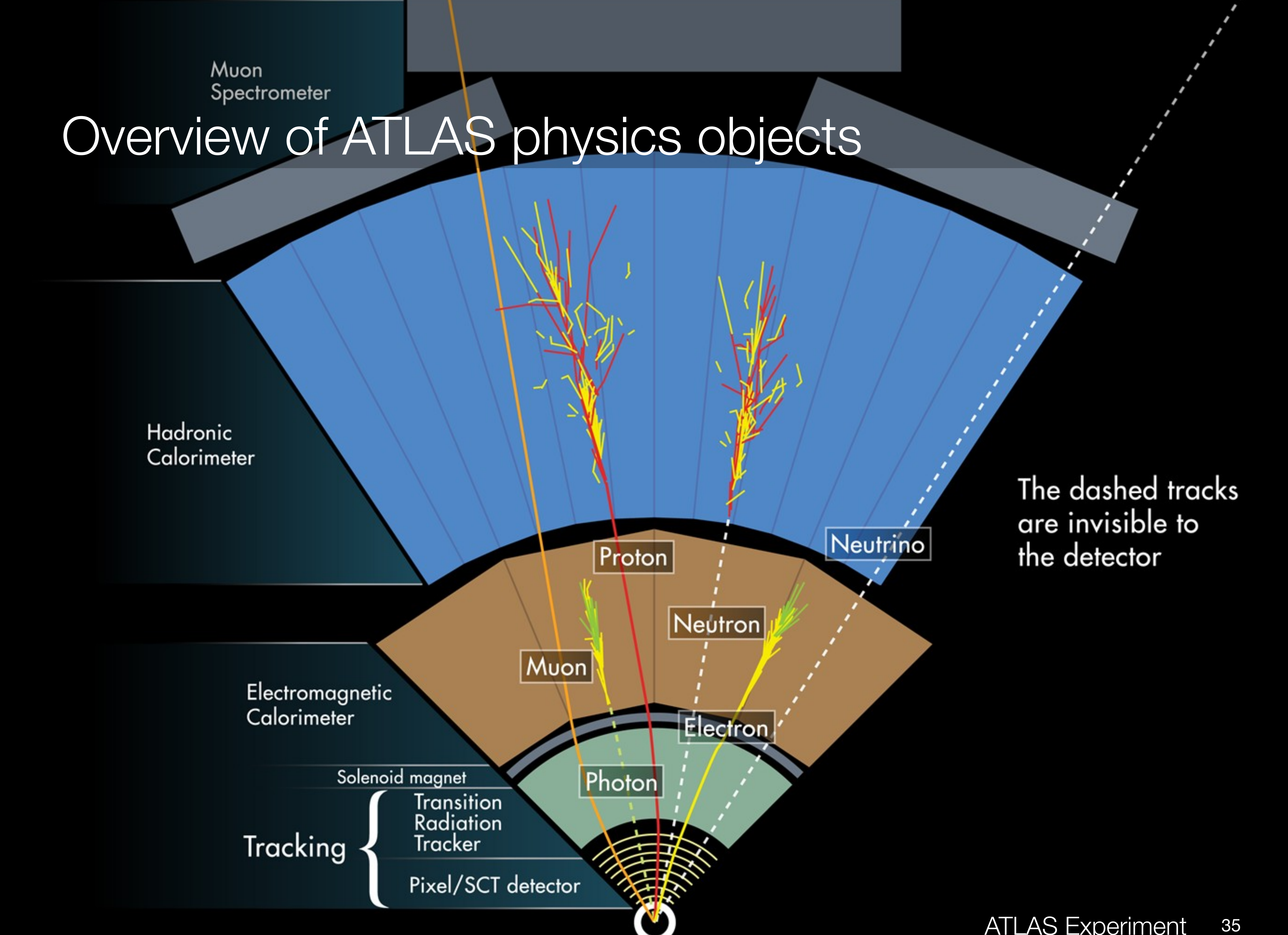
General purpose: decent for everything

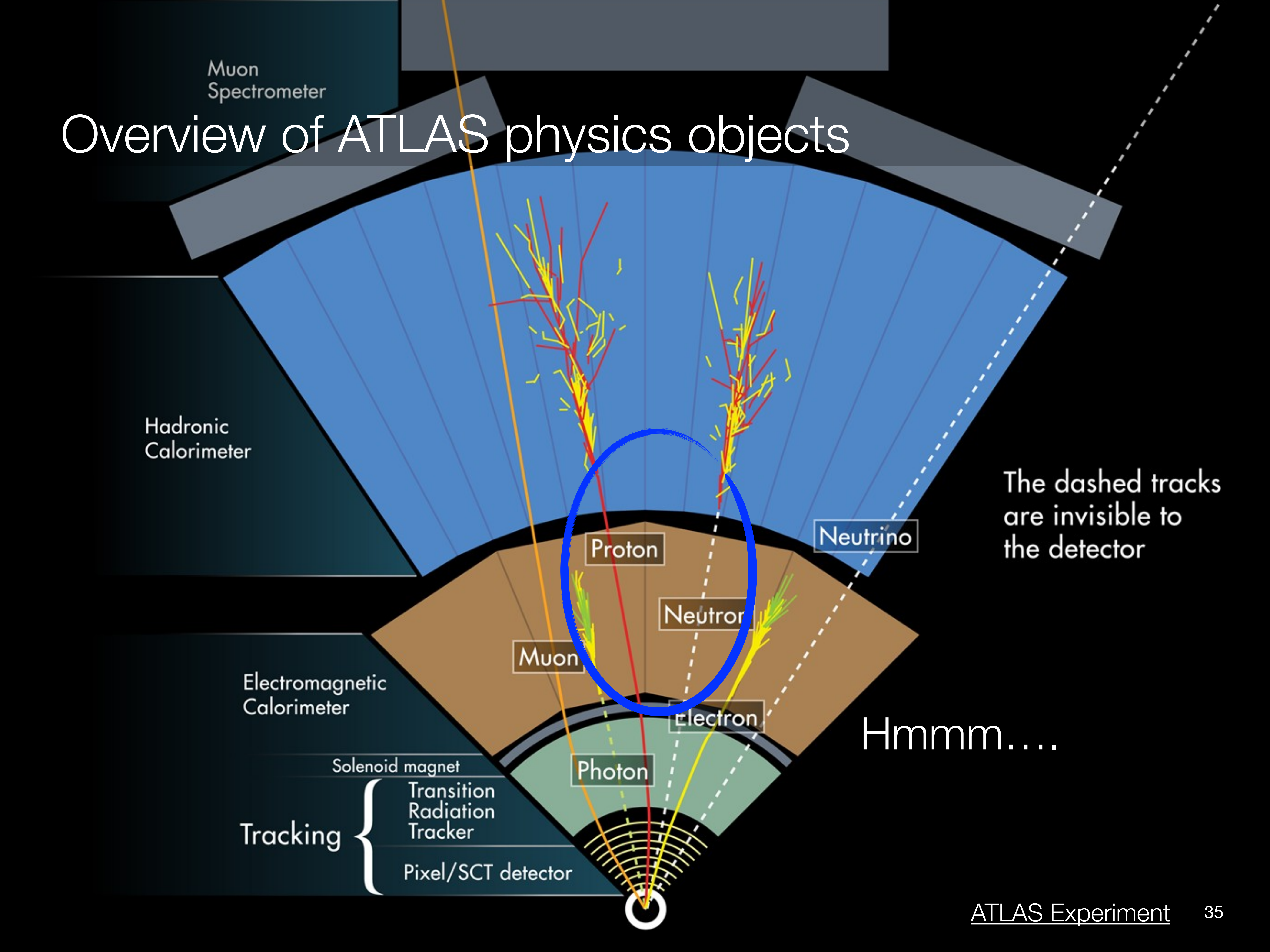
High granularity for busy ion collisions

Overview of ATLAS physics objects



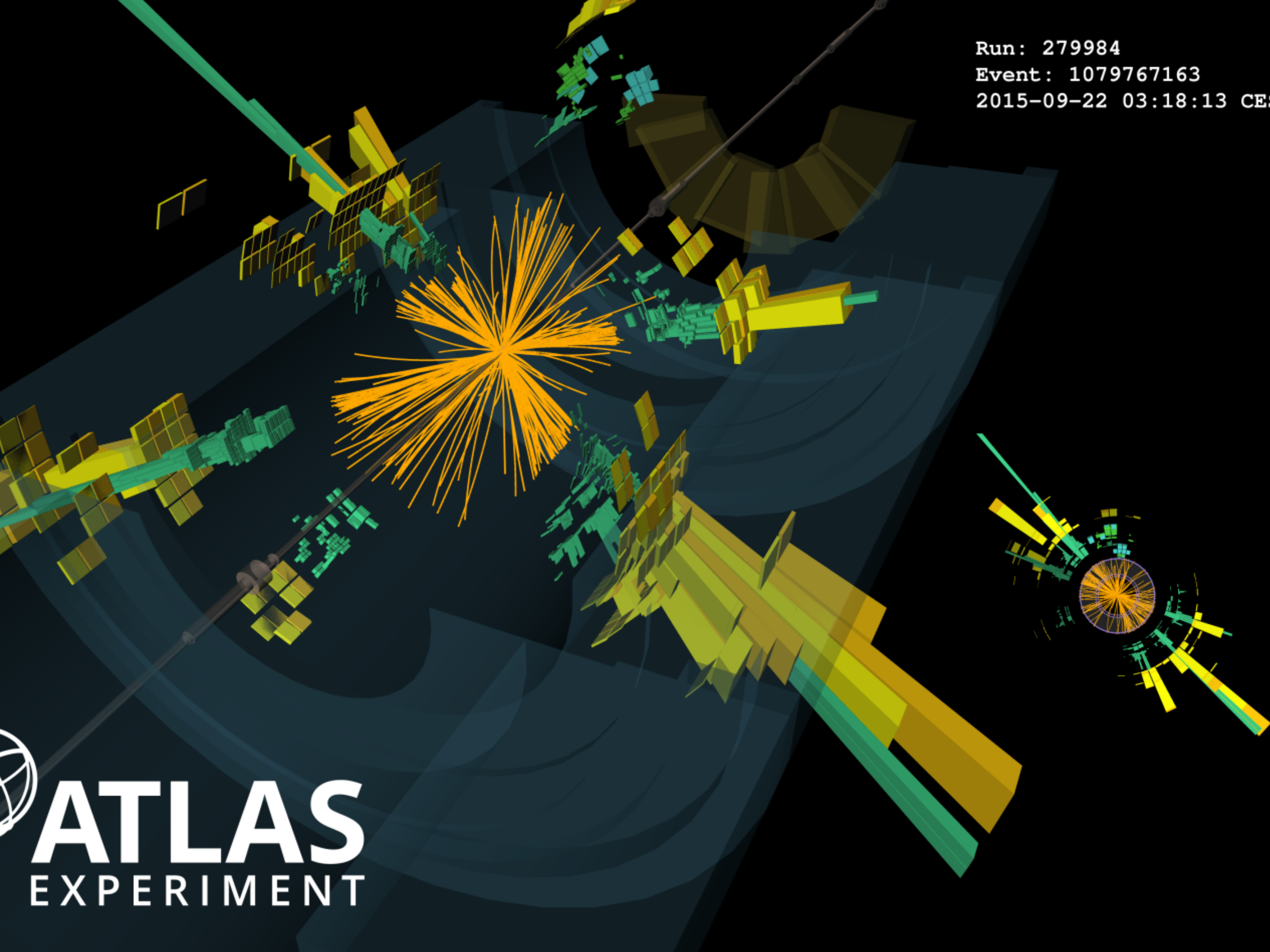
ATLAS Experiment

Overview of ATLAS physics objects



The dashed tracks are invisible to the detector

Hmmm….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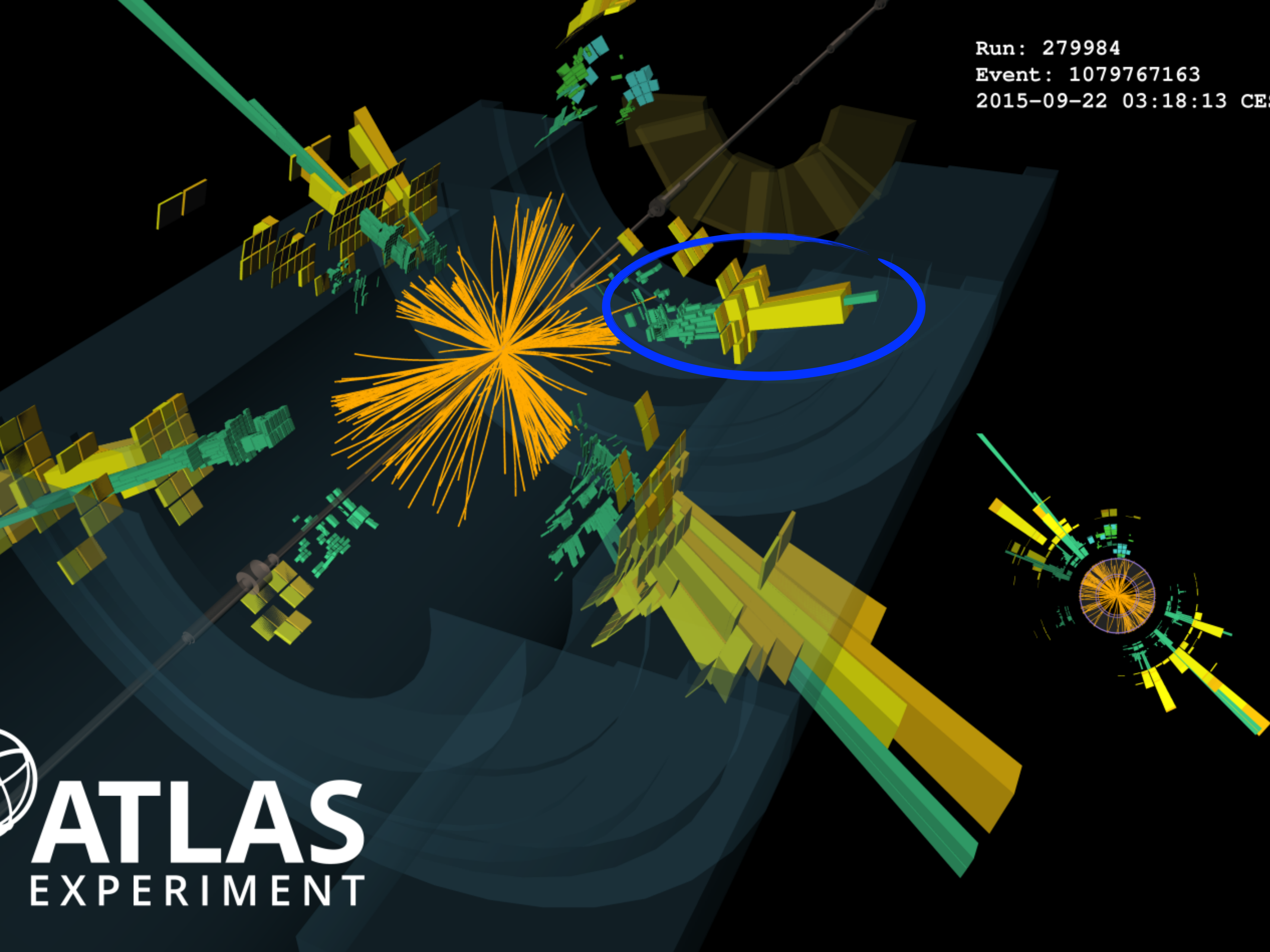
2015-09-22 03:18:13
ATLAS
EXPERIMENT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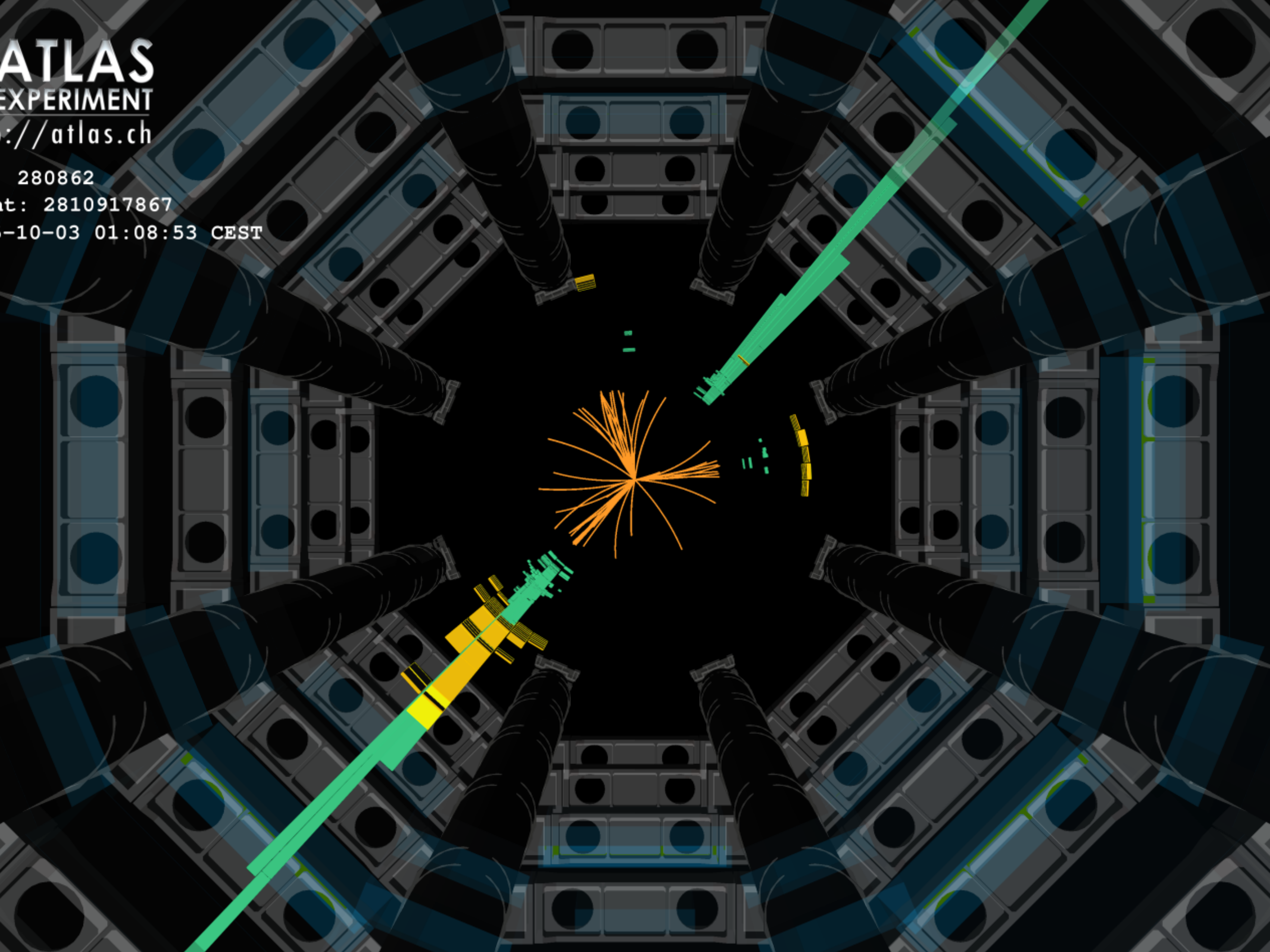
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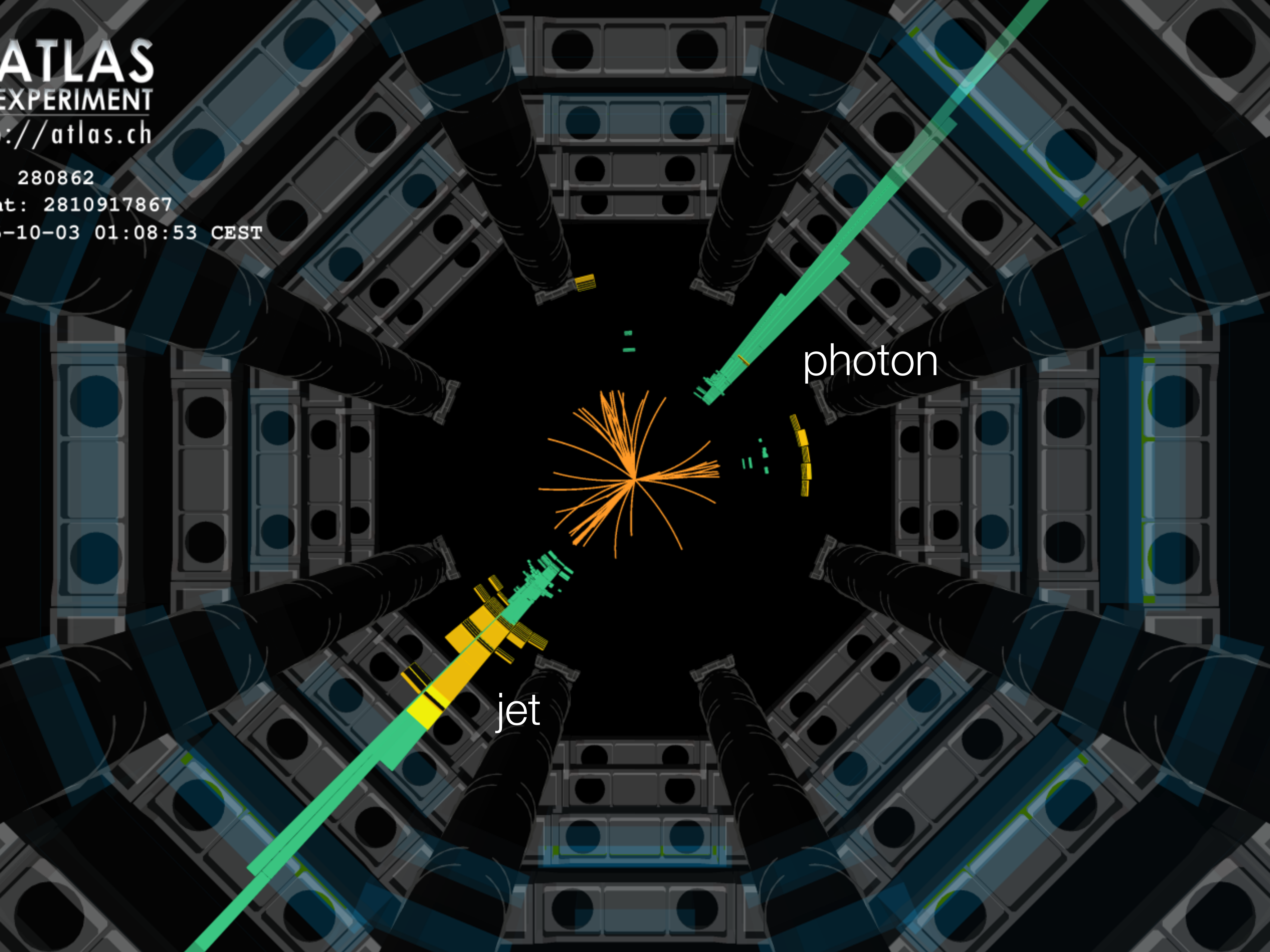

ATLAS
EXPERIMENT
://atlas.ch
280862
t: 2810917867
-10-03 01:08:53 CEST
photon
jet

ID-ing charged particles in material

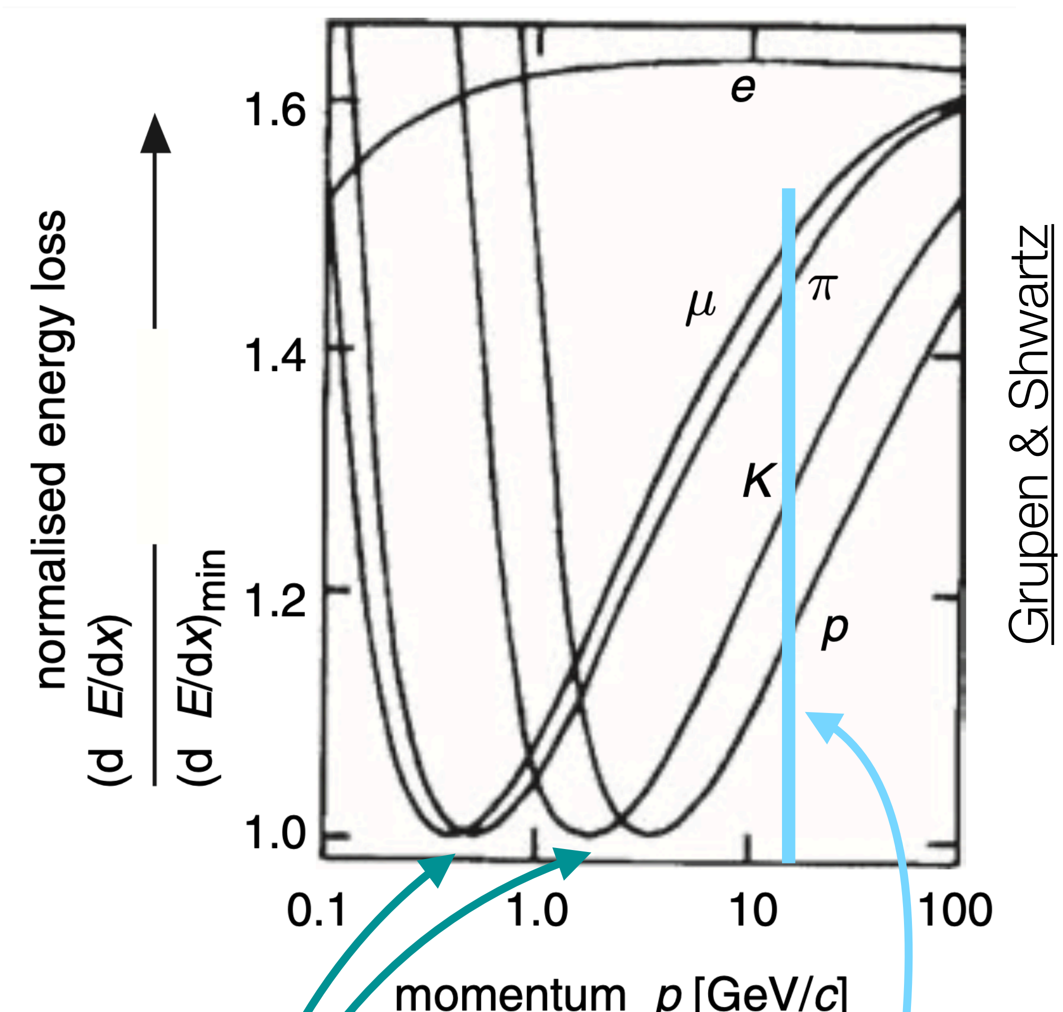
1) Energy loss in material

- Energy loss via ionisation dominates for heavy (non-e) charged particles moving quickly in material
- For relativistic particle,

$$\beta = v/c,\ \gamma = E/m,\ \beta\gamma = p/mc$$

- And we can **approximate** the Beta-Bloch (ionisation E loss) formula as:

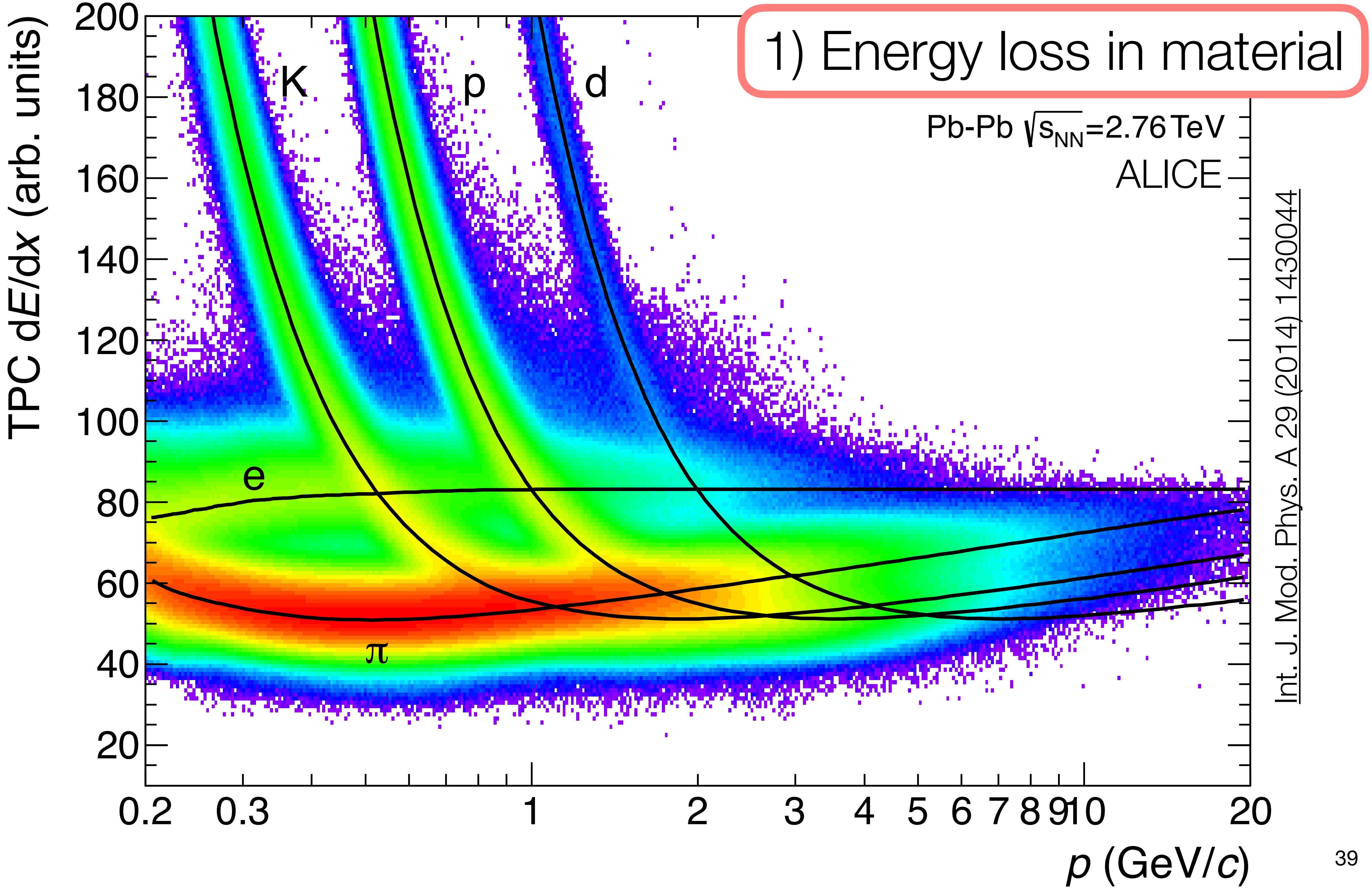
$$dE/dx \propto ln(\beta^2\gamma^2)/\beta^2$$



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

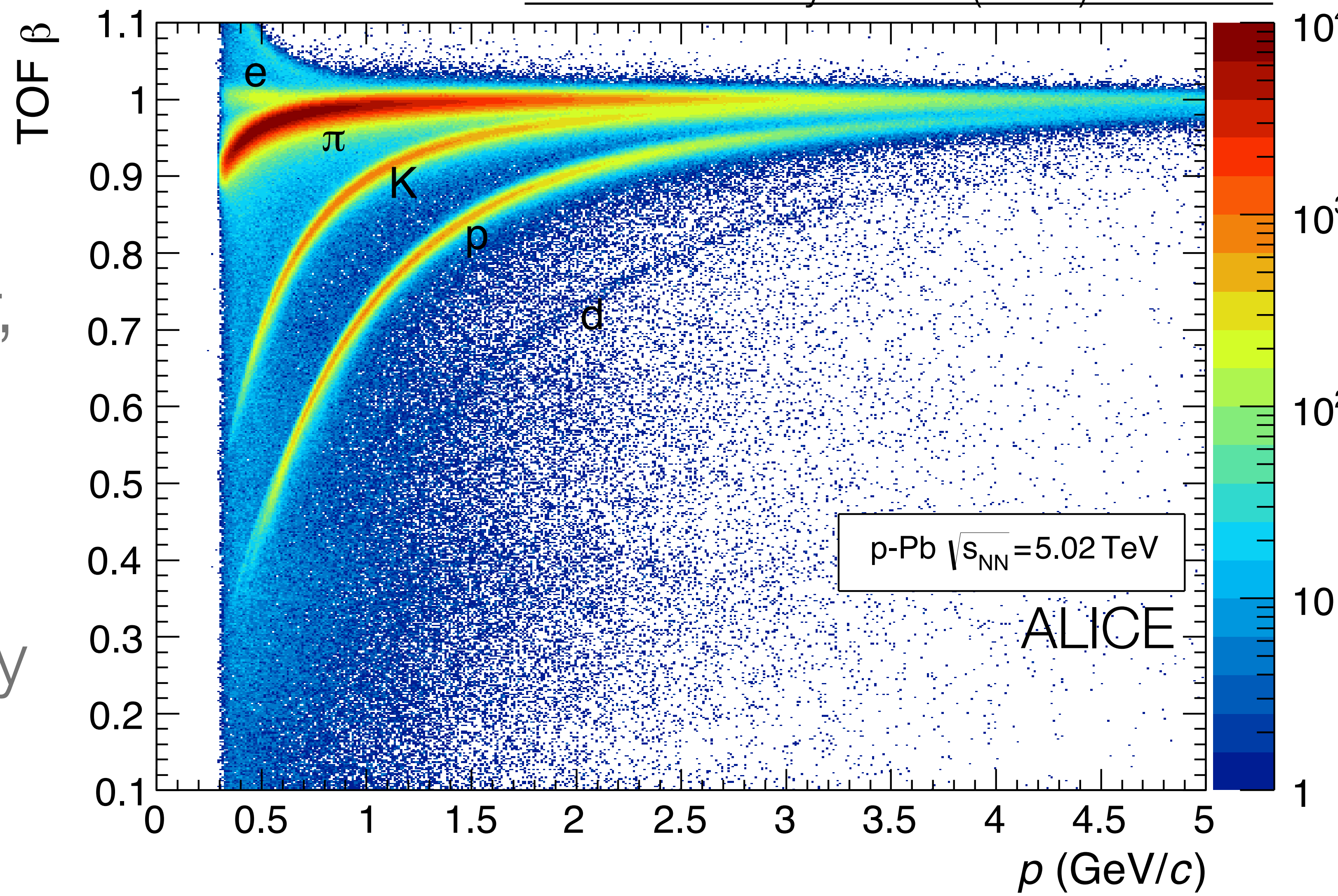
Minimum ionising particle is one near bottom of its curve

ID-ing charged particles in material



ID-ing charged particles in material

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



2) Time of flight

- If you have a very good timing detector, can resolve two particles of the same energy but different masses by when they arrive:

$$\text{tof} = d/\beta c \sim 3\text{ns}/\beta$$

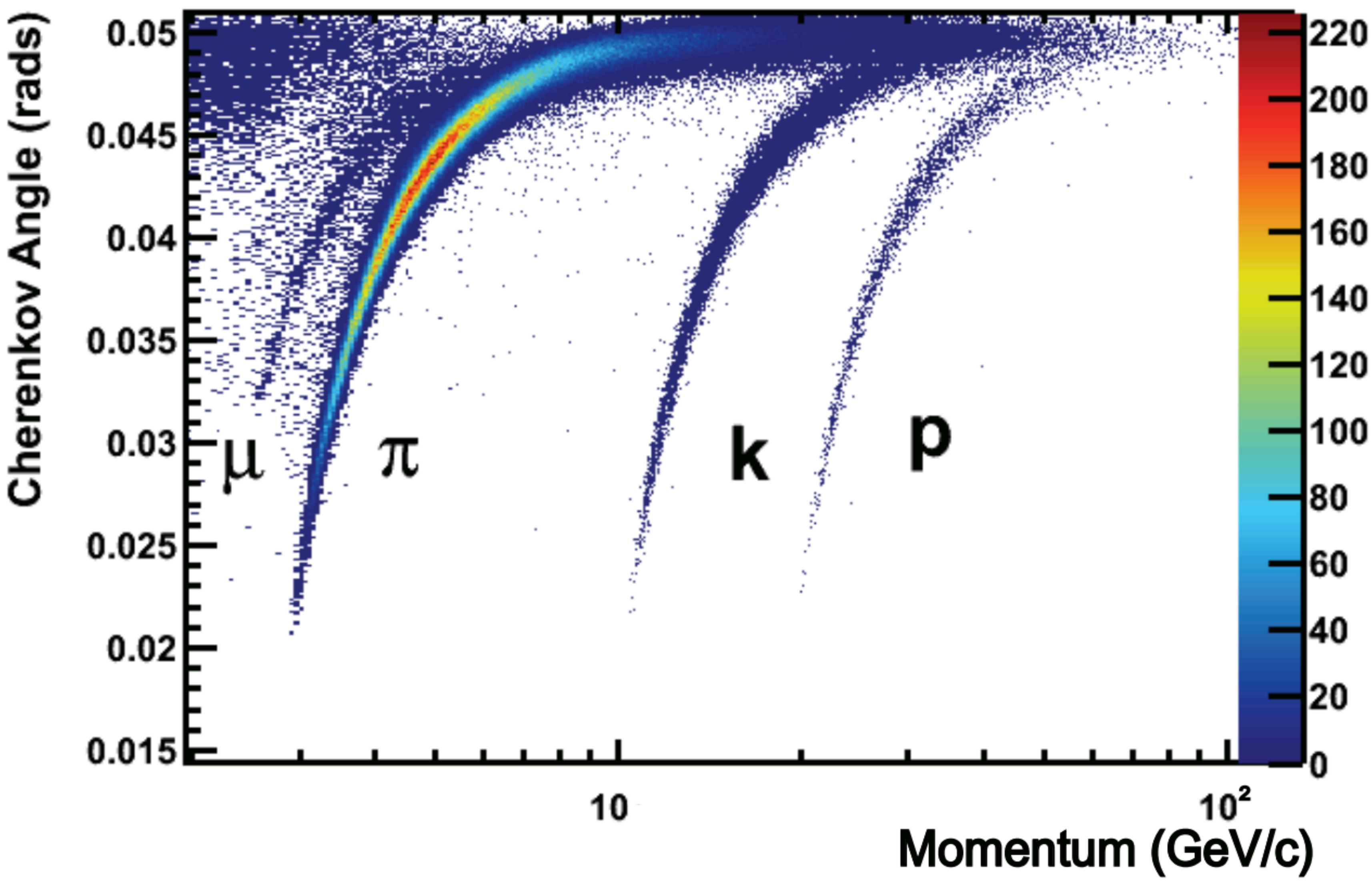
$\beta = v/c \rightarrow$ β to p relationship indicates mass

Flight time differences very small, but feasible!

ID-ing charged particles in material

3) Cherenkov radiation

LHCb

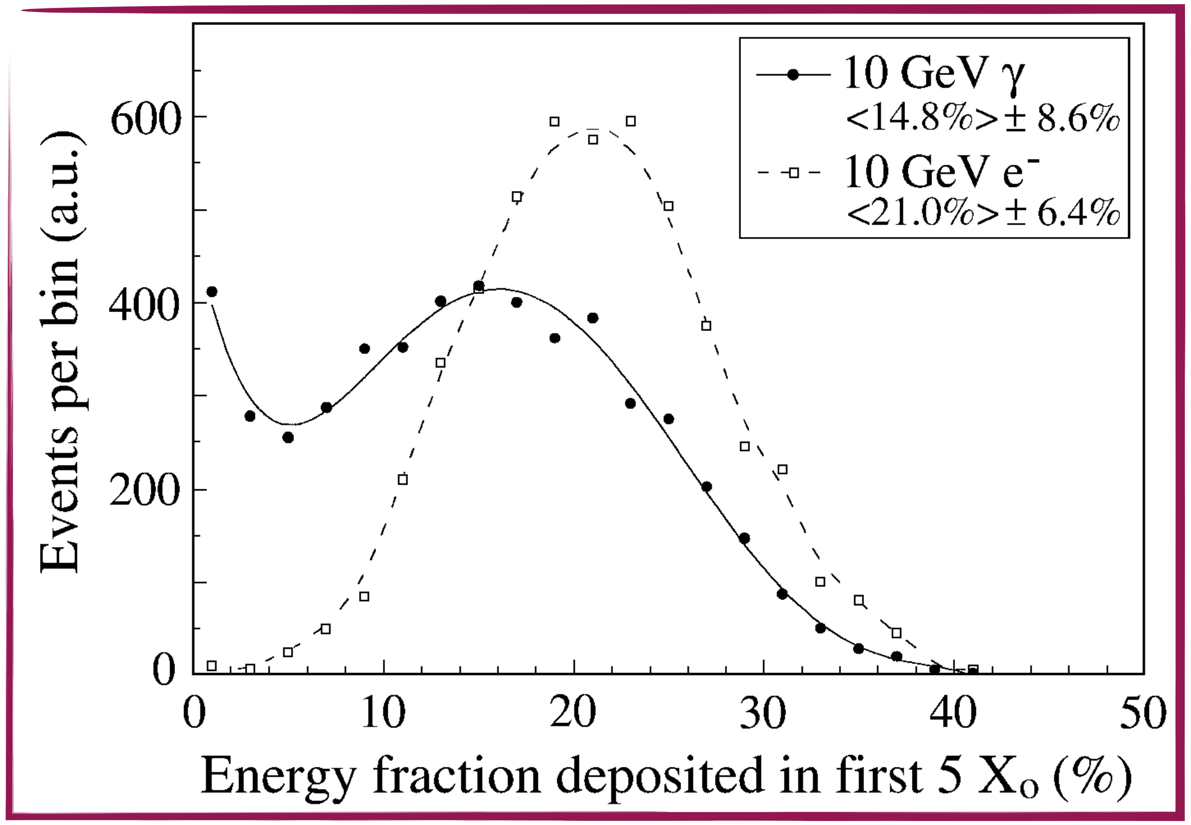


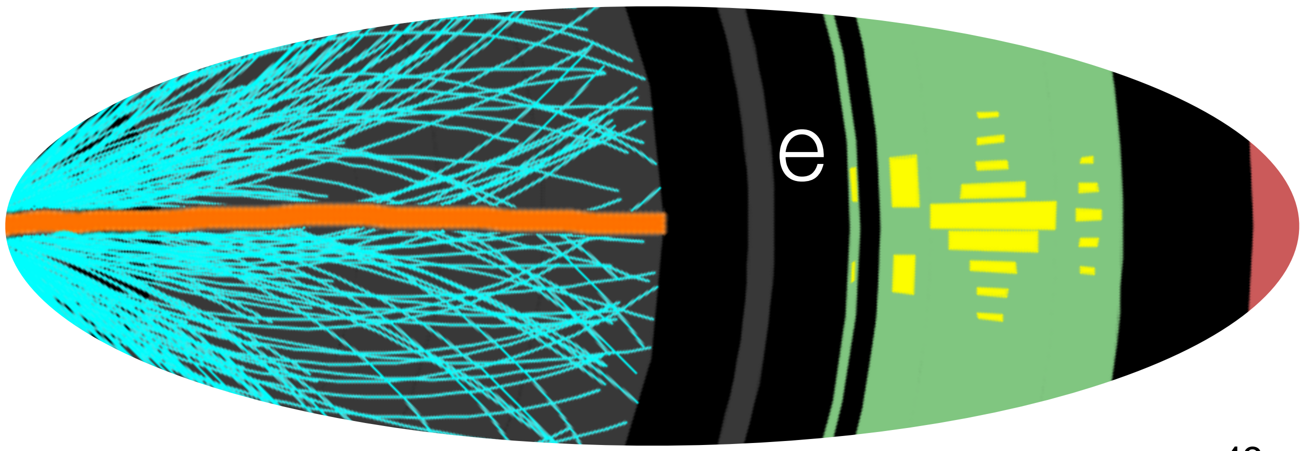
- Charged particle passing through material with refractive index n with v > c/n causes light emission **at specific angle**

$$\cos\theta = 1/\beta n$$

ID with the calorimeter: electrons and photons

- Expect only one energy deposit in EM calorimeter for electrons and photons: no jet-like parton shower
- Full detector ID: match calo to a track
- Use shower shape and width, energy ratios in layers, track to cluster matching information, track details to further discriminate





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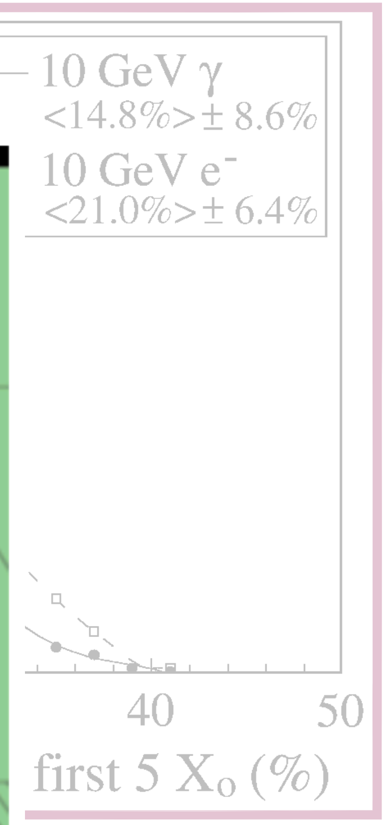
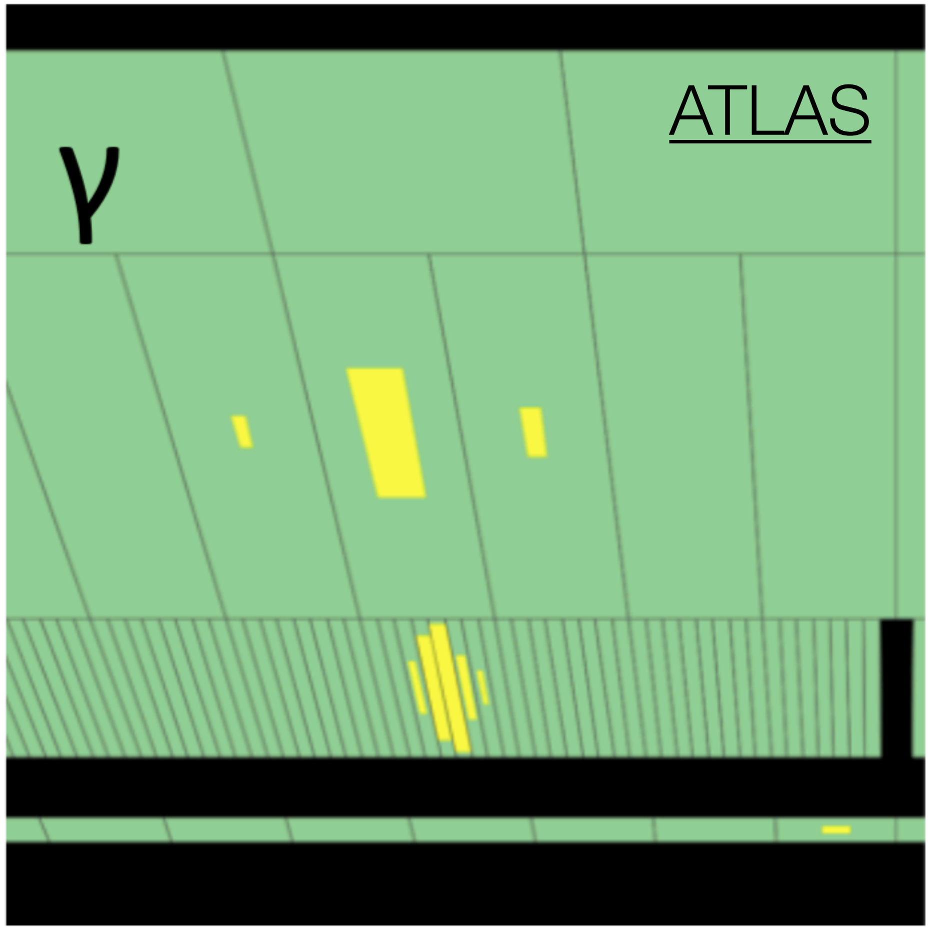
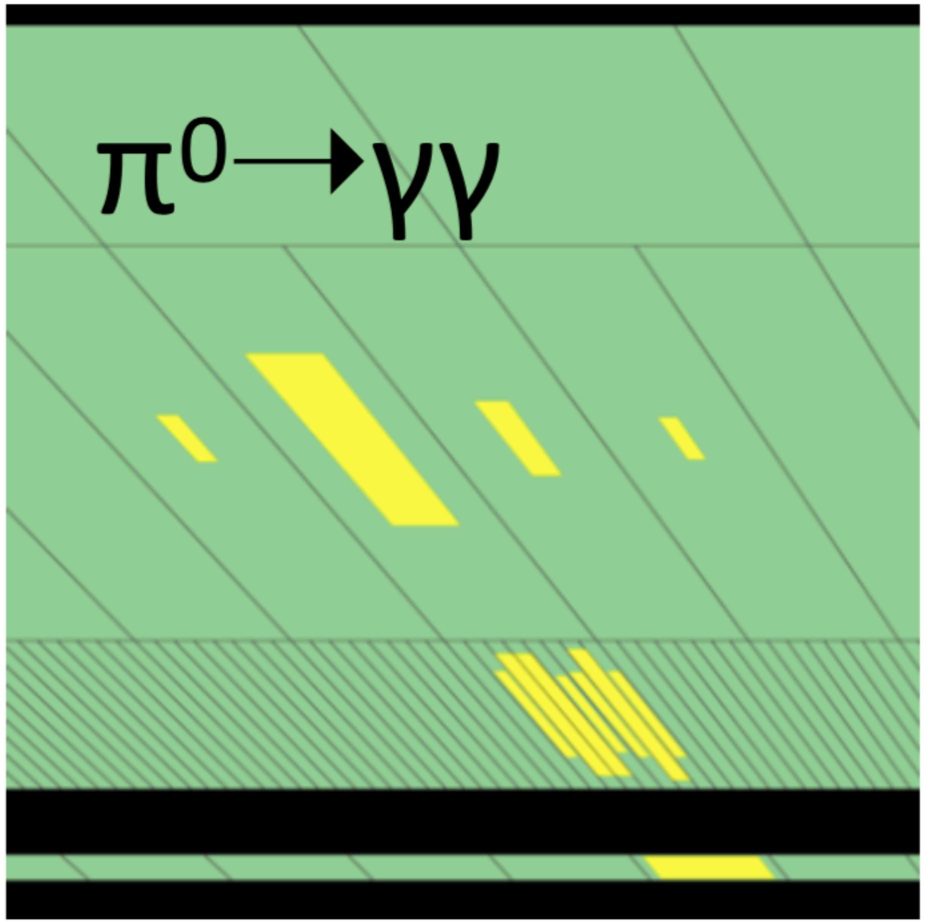
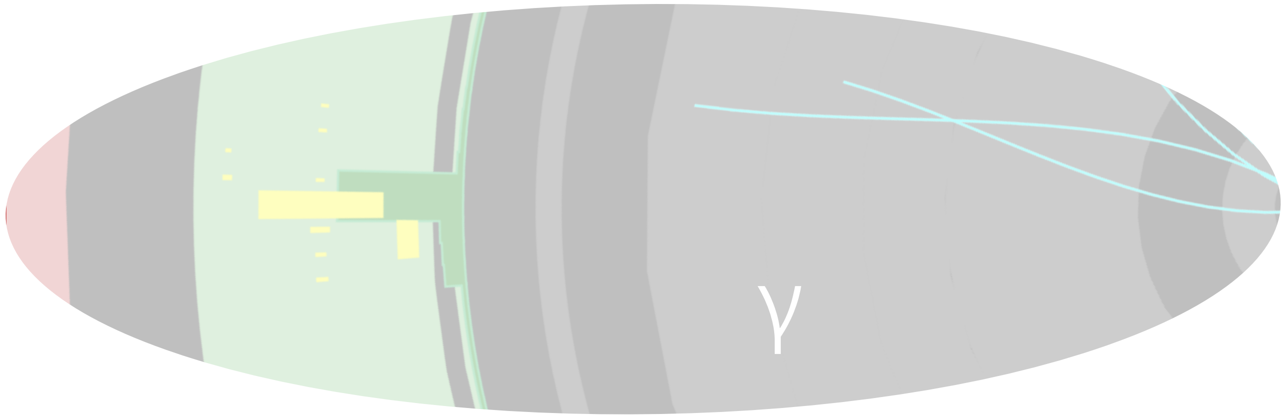
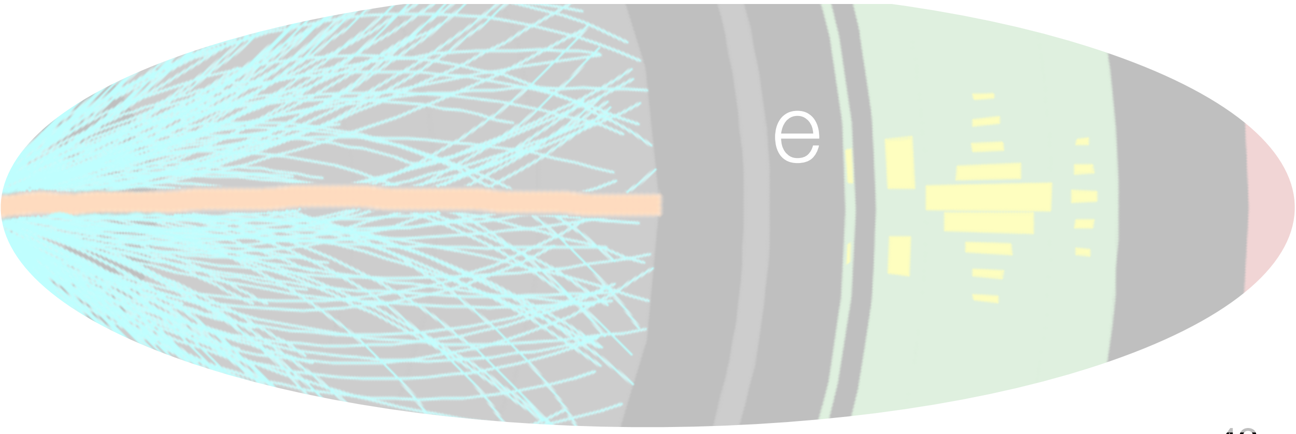




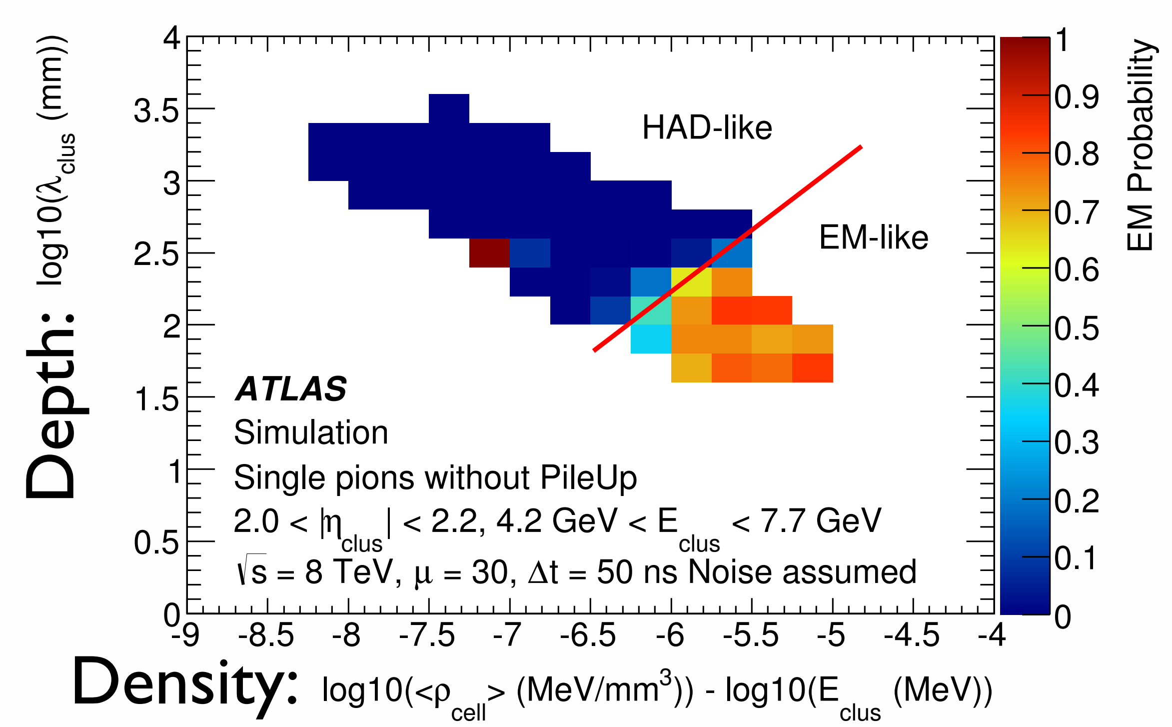






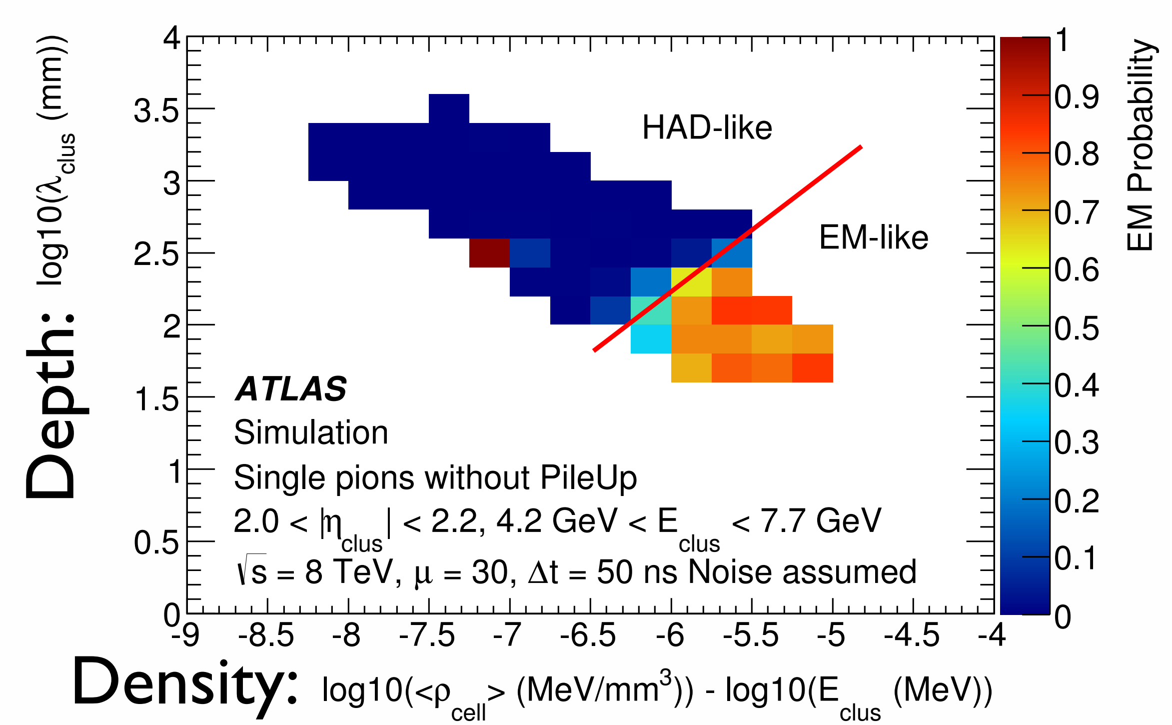
EM vs Hadronic Showers

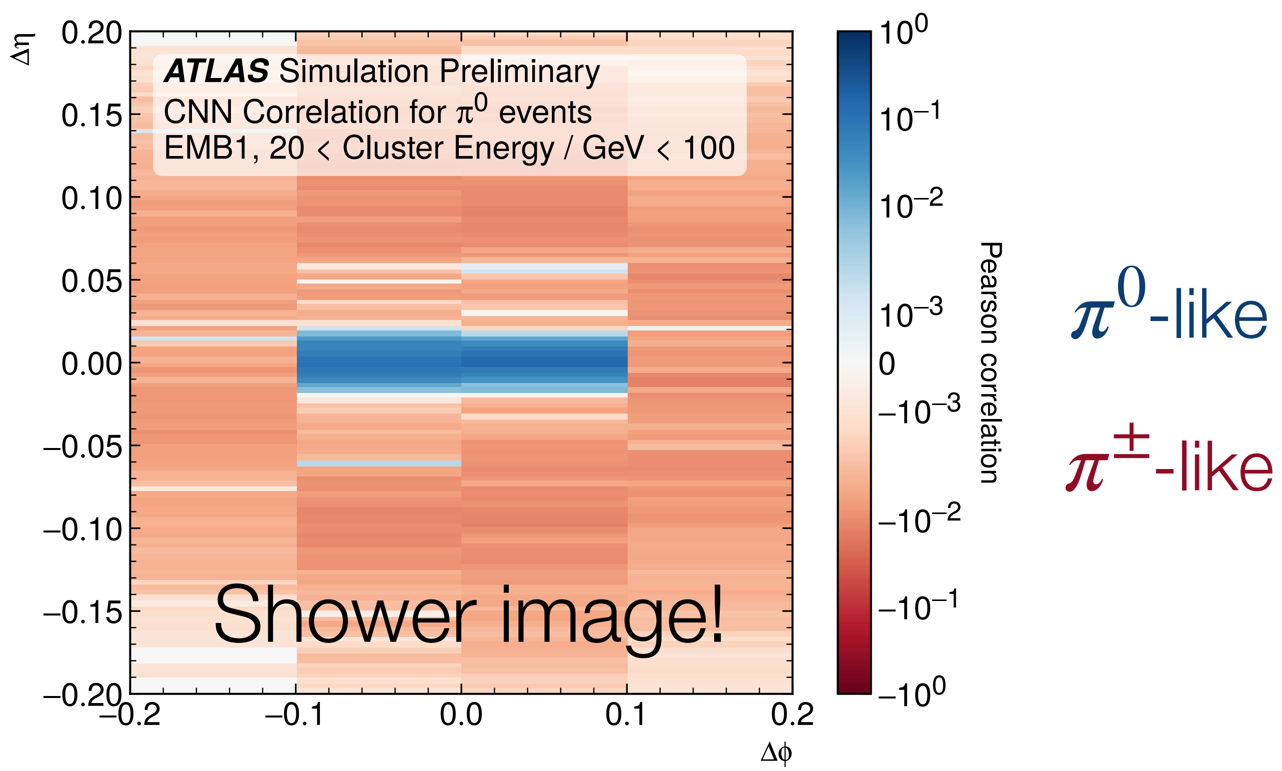
EM vs Hadronic Showers



- Most calorimeters are non-compensating: $e/h \gg 1$
- But we can use information about the shower to calibrate, after-the-fact: "software compensation"
  - Segmentation is key
  - Utilize density+depth for simplest corrections

EM vs Hadronic Showers

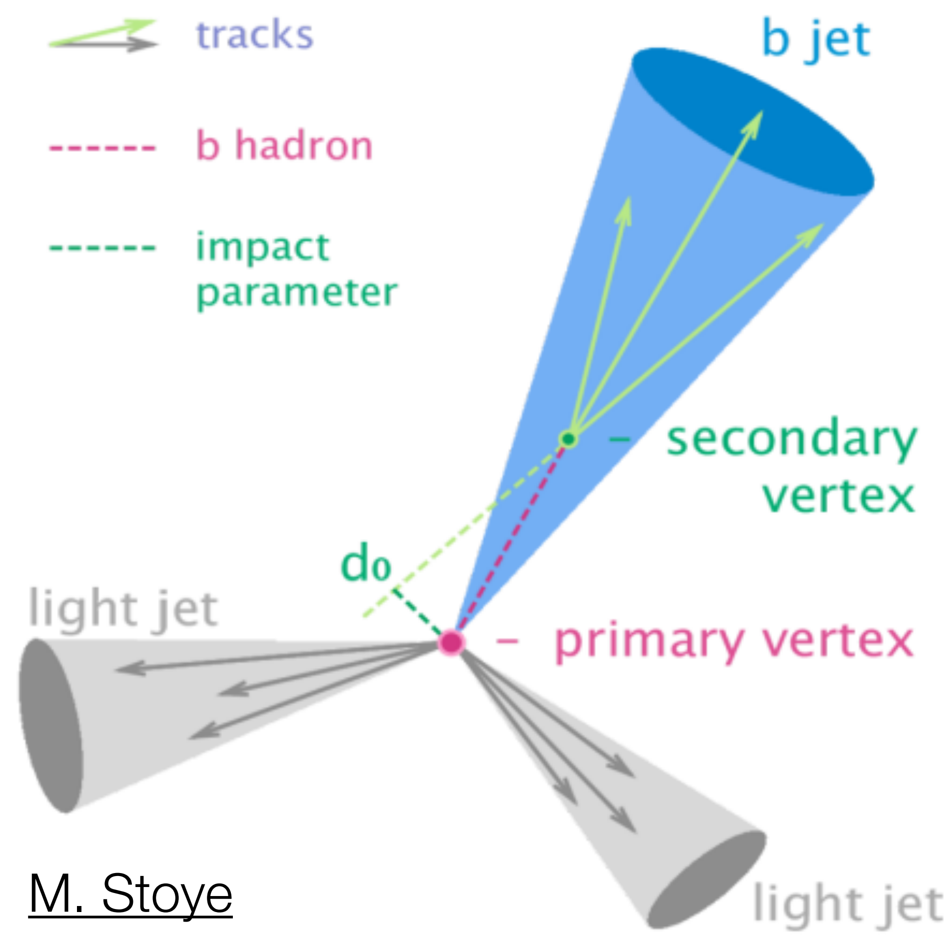




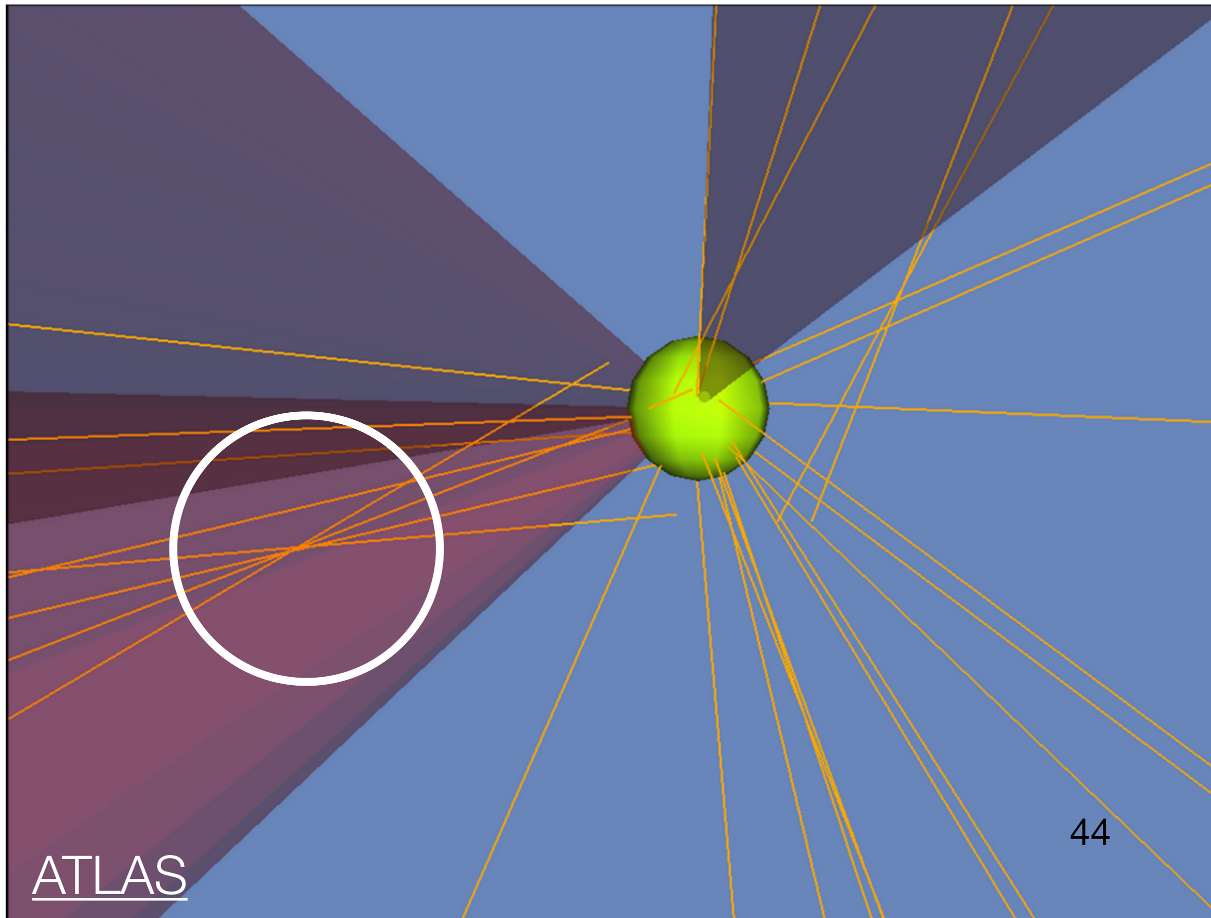
- Most calorimeters are non-compensating: $e/h \gg 1$
- But we can use information about the shower to calibrate, after-the-fact: “software compensation”
  - Segmentation is key
  - Utilize density+depth for simplest corrections
  - These days, utilize neural networks (which extract similar information)

B-jets

- Hadrons containing b-quarks have a longer lifetime and can travel a non-negligible distance before decaying
- Presence of *secondary vertex* used to identify these jets → calorimetry not enough; tracking is critical!
- Other distinguishing features: jets are usually wider with more constituent particles (tracks) than light jets
- Strong machine learning use case!



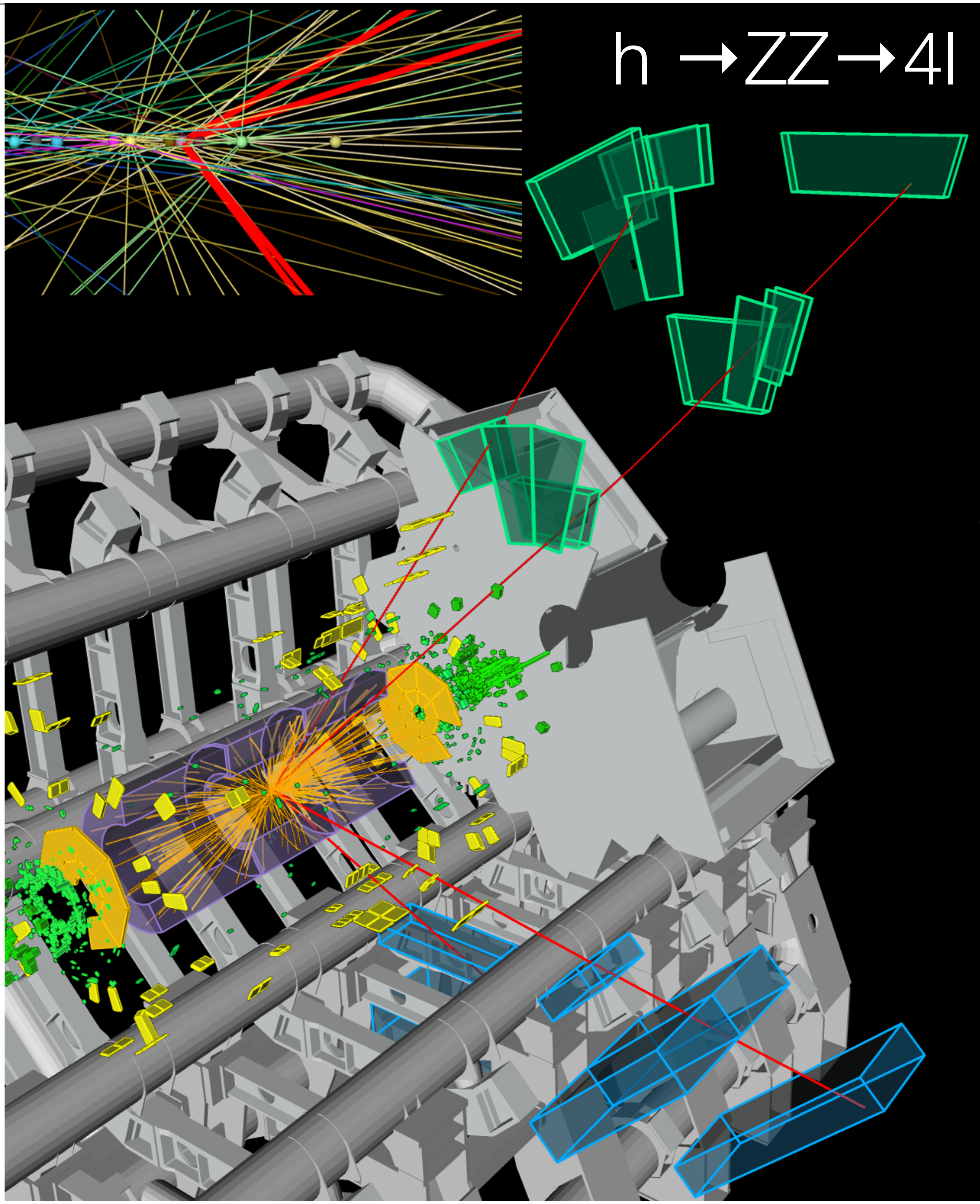
M. Stoye



ATLAS

Identifying short-lived (heavy) particles

- Particles with lifetimes < a picosecond decay "promptly" on detector scales
  - W, Z, Higgs, top quarks, π^0, certain mesons, (taus)
- Identify by their decay products and rest of event in which you find them
- Can reconstruct invariant mass as additional handle



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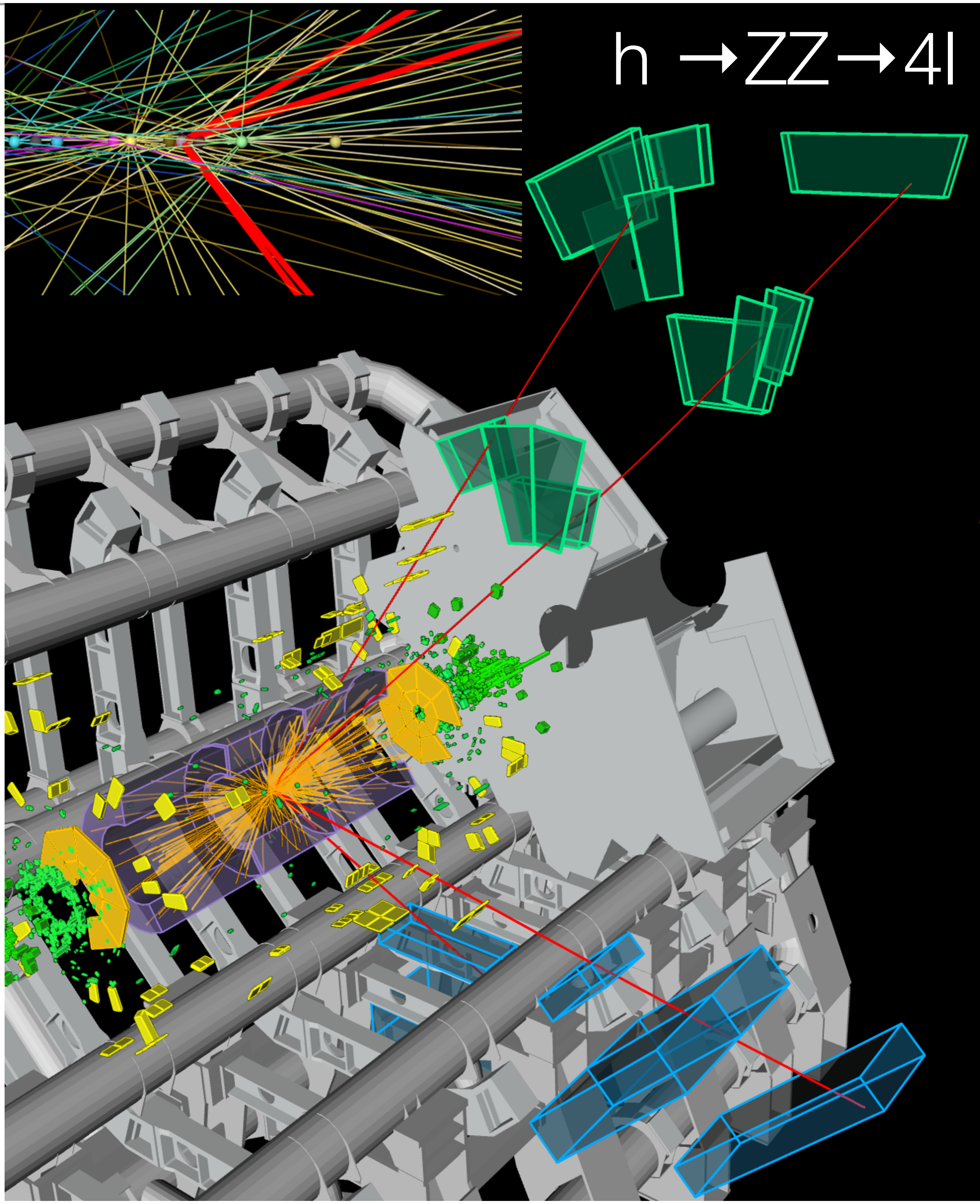
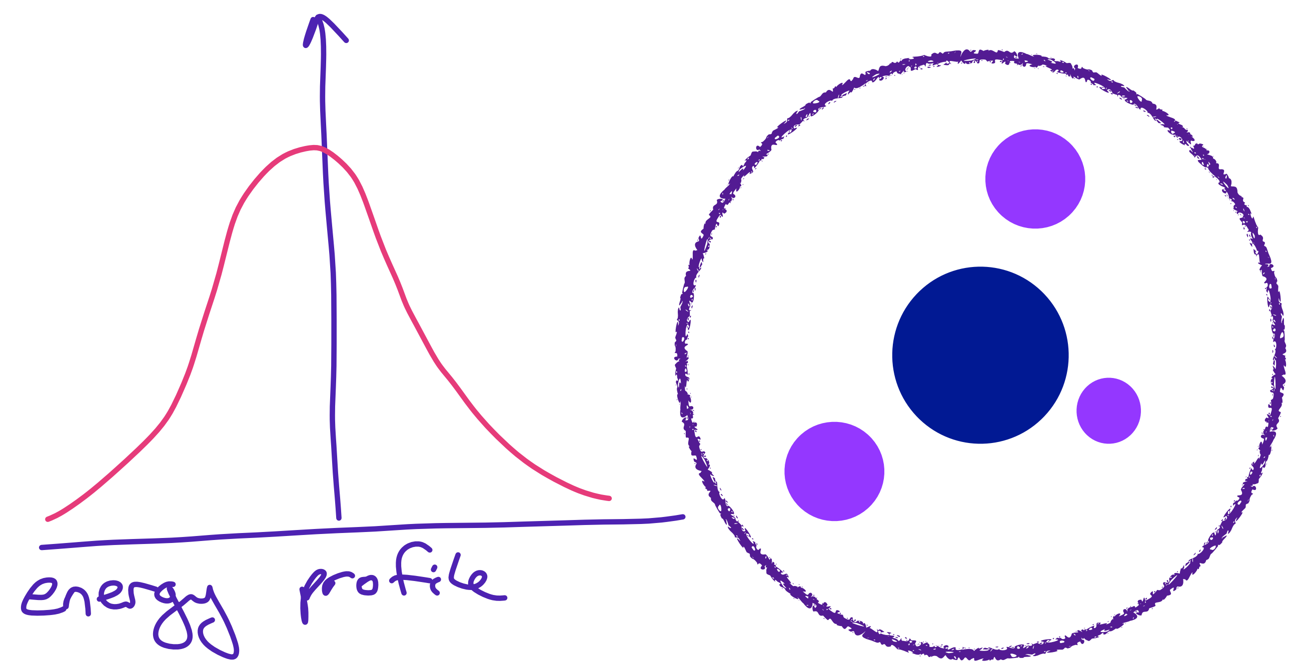
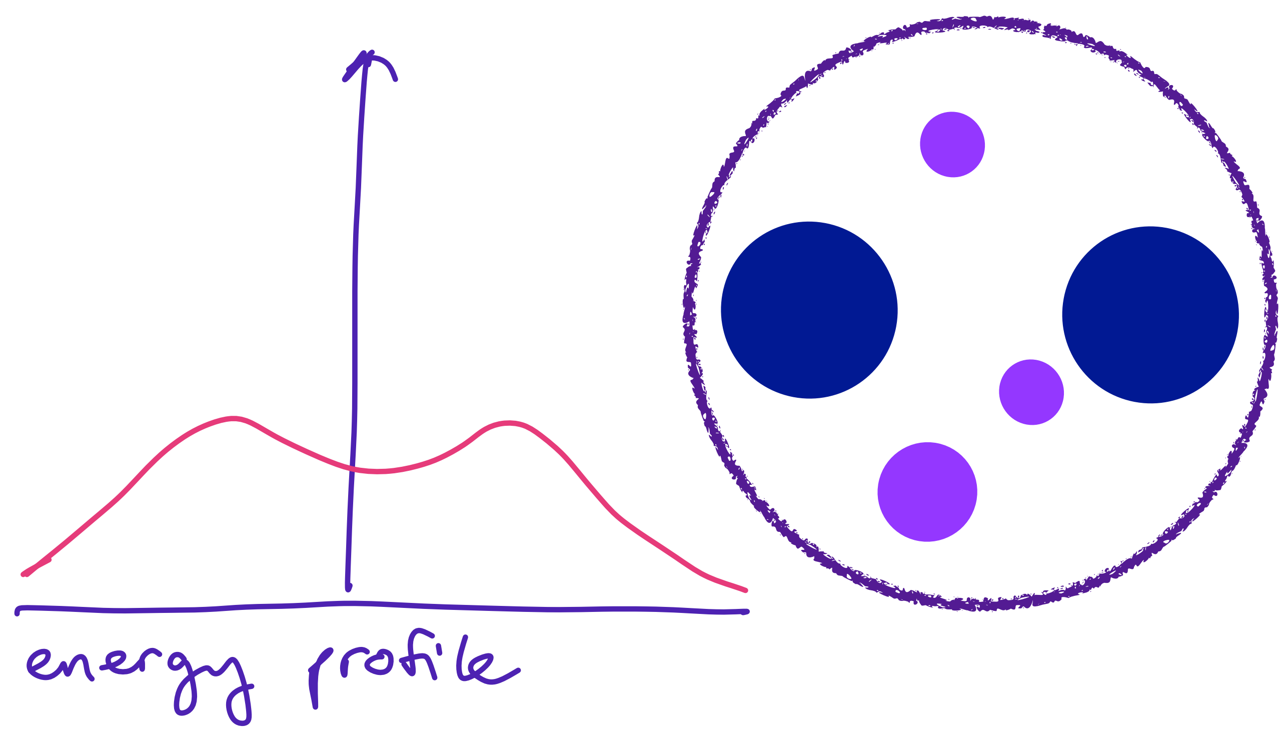
  - W, Z, Higgs, top quarks, π^0, certain mesons, (taus)
- Identify by their decay products and rest of event in which you find them
- Can reconstruct invariant mass as additional handle
- When heavy particles produced at high momenta, decay products still end up nearby: this gives interesting calorimeter consequences



Jet substructure

- Distribution of energy within a jet is a useful source of information!
- Light jets: expect energy distribution in calorimeter to peak at centre, Gaussian-like
- What if we had a boosted initial particle which split into two strongly charged particles, and each initiated its own sub-jet?
- This can help us identify jets which came from the decays of particular parent particles





Heavy bosons

PDG

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %		–
$e^+\nu$		(10.71 ± 0.16) %		40189
$\mu^+\nu$		(10.63 ± 0.15) %		40189
$\tau^+\nu$		(11.38 ± 0.21) %		40170
hadrons		(67.41 ± 0.27) %		–

- W and Z decay to qq most of the time! Need to be able to identify these cases to do effective physics with them.

Heavy bosons

PDG

Z DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^+ e^-$	[h]	(3.3632±0.0042) %		45594
$\mu^+ \mu^-$	[h]	(3.3662±0.0066) %		45594
$\tau^+ \tau^-$	[h]	(3.3696±0.0083) %		45559
$\ell^+ \ell^-$	[b,h]	(3.3658±0.0023) %		–
$\ell^+ \ell^- \ell^+ \ell^-$	[i]	(4.58 ±0.26) × 10^{-6}		45594
invisible	[h]	(20.000 ±0.055) %		–
hadrons	[h]	(69.911 ±0.056) %		–

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Heavy bosons

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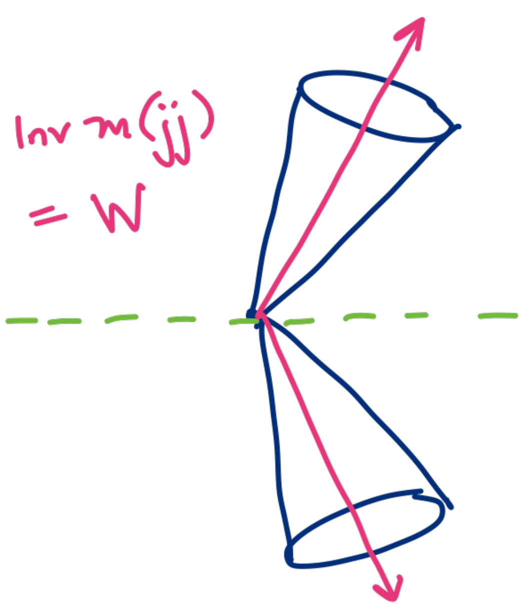
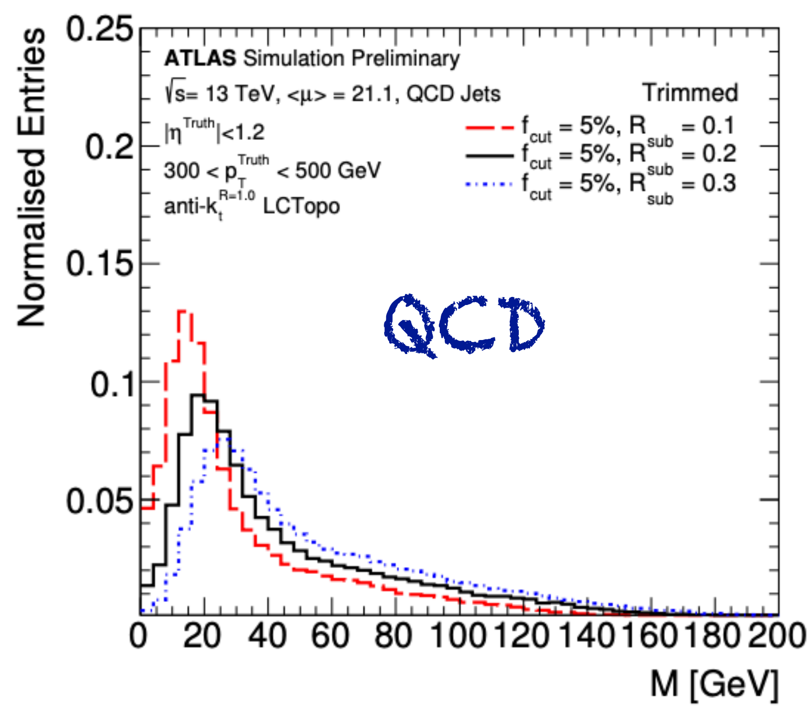
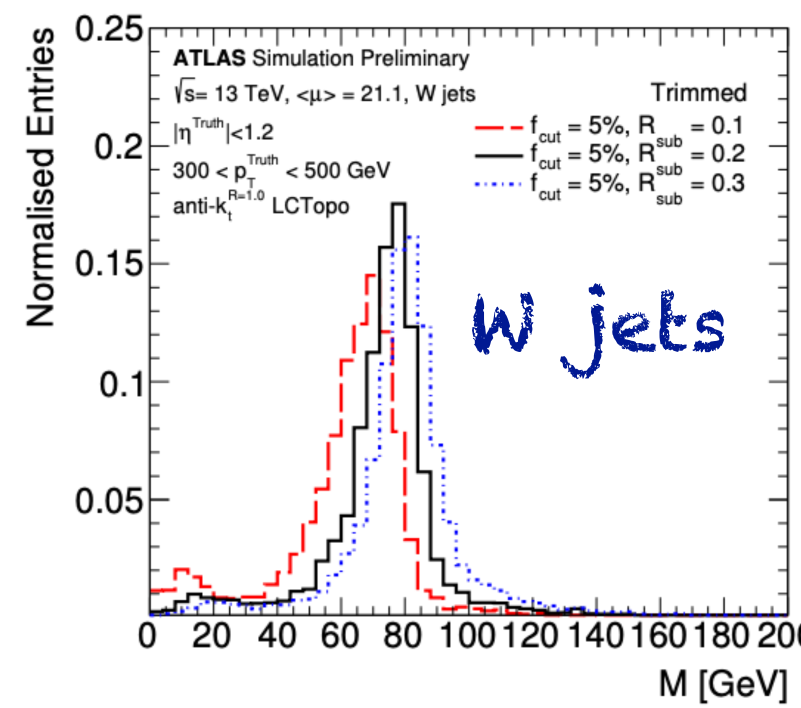
invisible	[h]	(20.000 ±0.055) %		–
hadrons	[h]	(69.911 ±0.056) %		–

- Best identifying feature: mass. Treat constituents of large-radius jet as 4 vectors and add to find their invariant mass



or

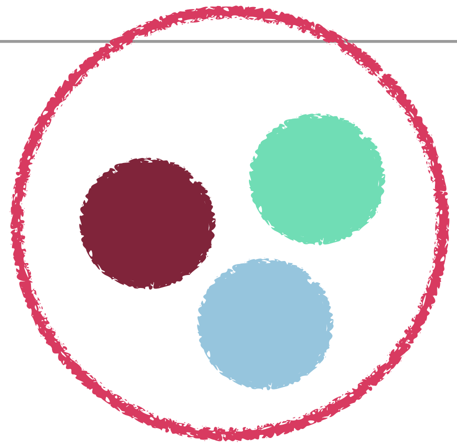




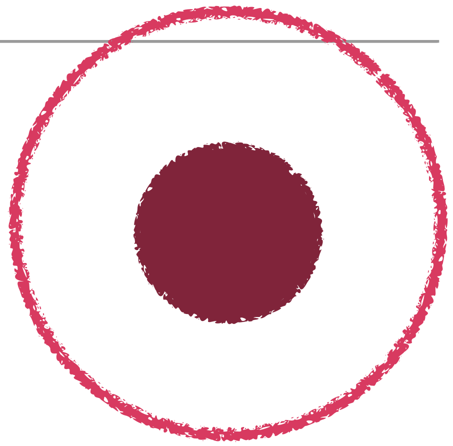
Top tagging

Top tagging

- Like with W and Z, mass and distribution of energy inside the jet are the strong discriminants



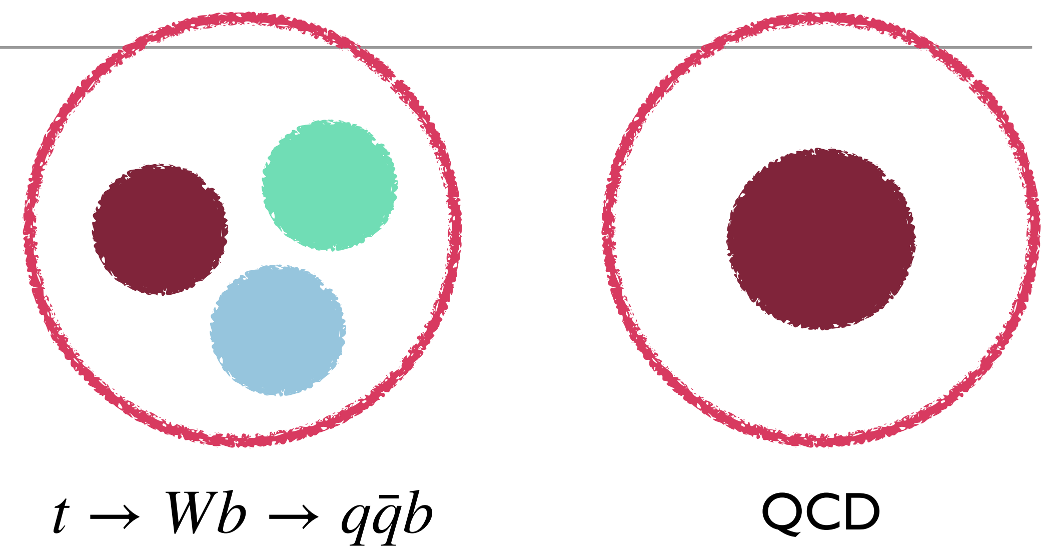
$t \to Wb \to q\bar{q}b$

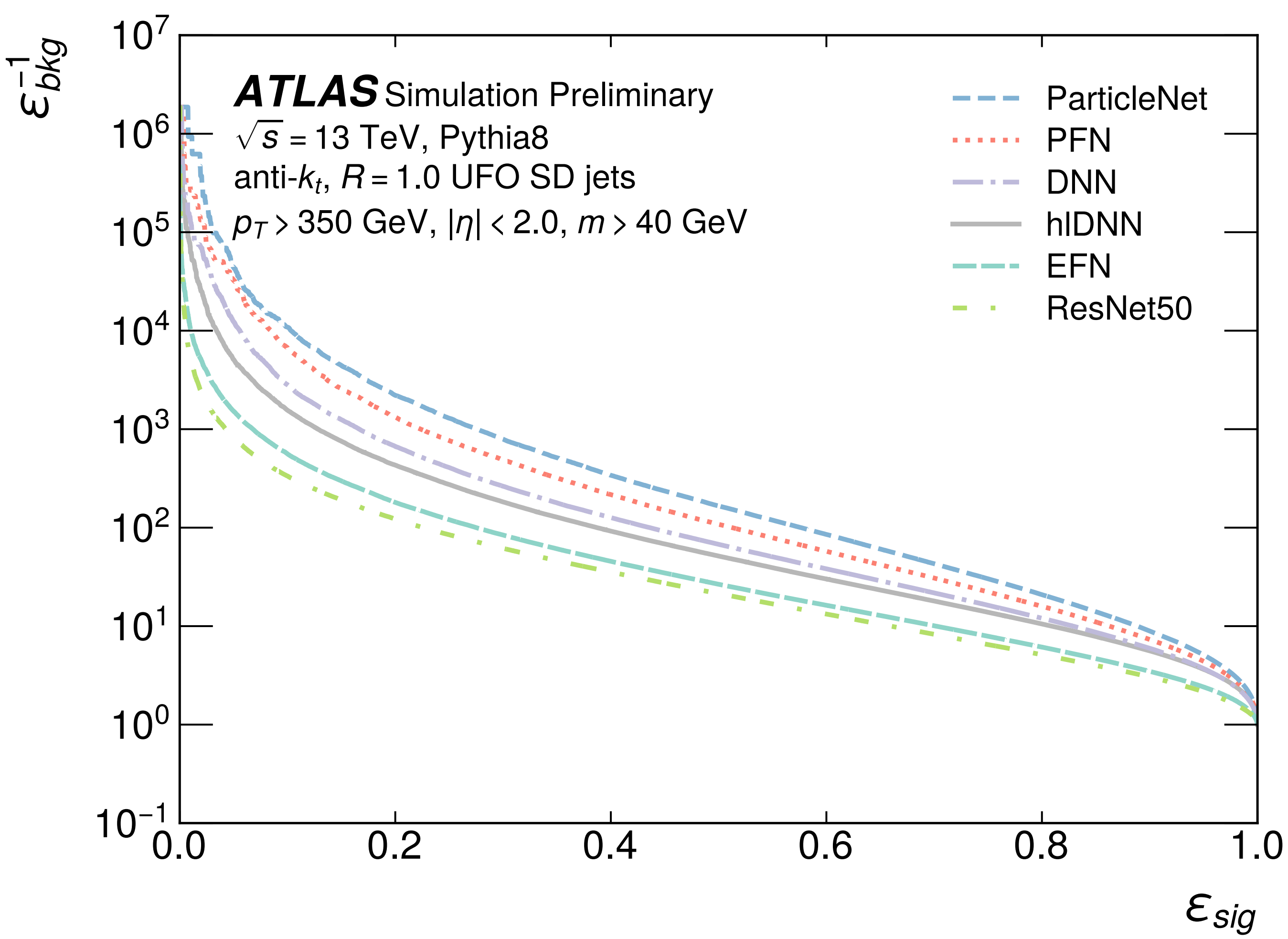


QCD

Top tagging

- Like with W and Z, mass and distribution of energy inside the jet are the strong discriminants
- With hadronic tops, expect ~three energy groups. Neural networks can identify the structure compared to QCD jets!

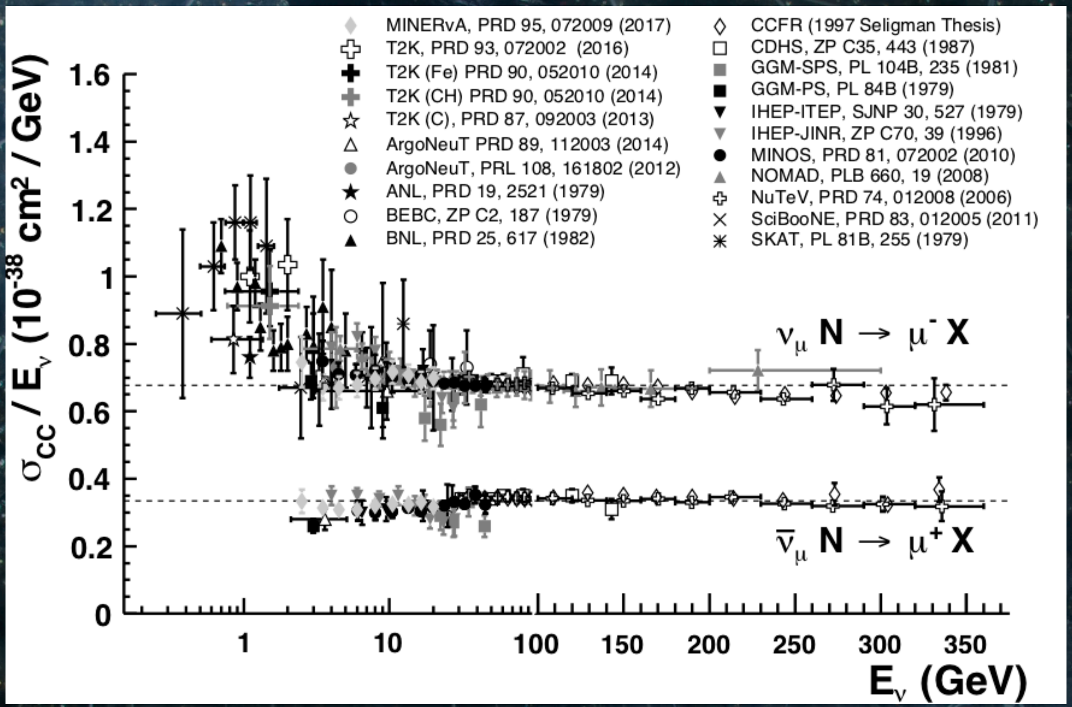




Sno+: 800 tonnes of scintillator

Neutrino ID

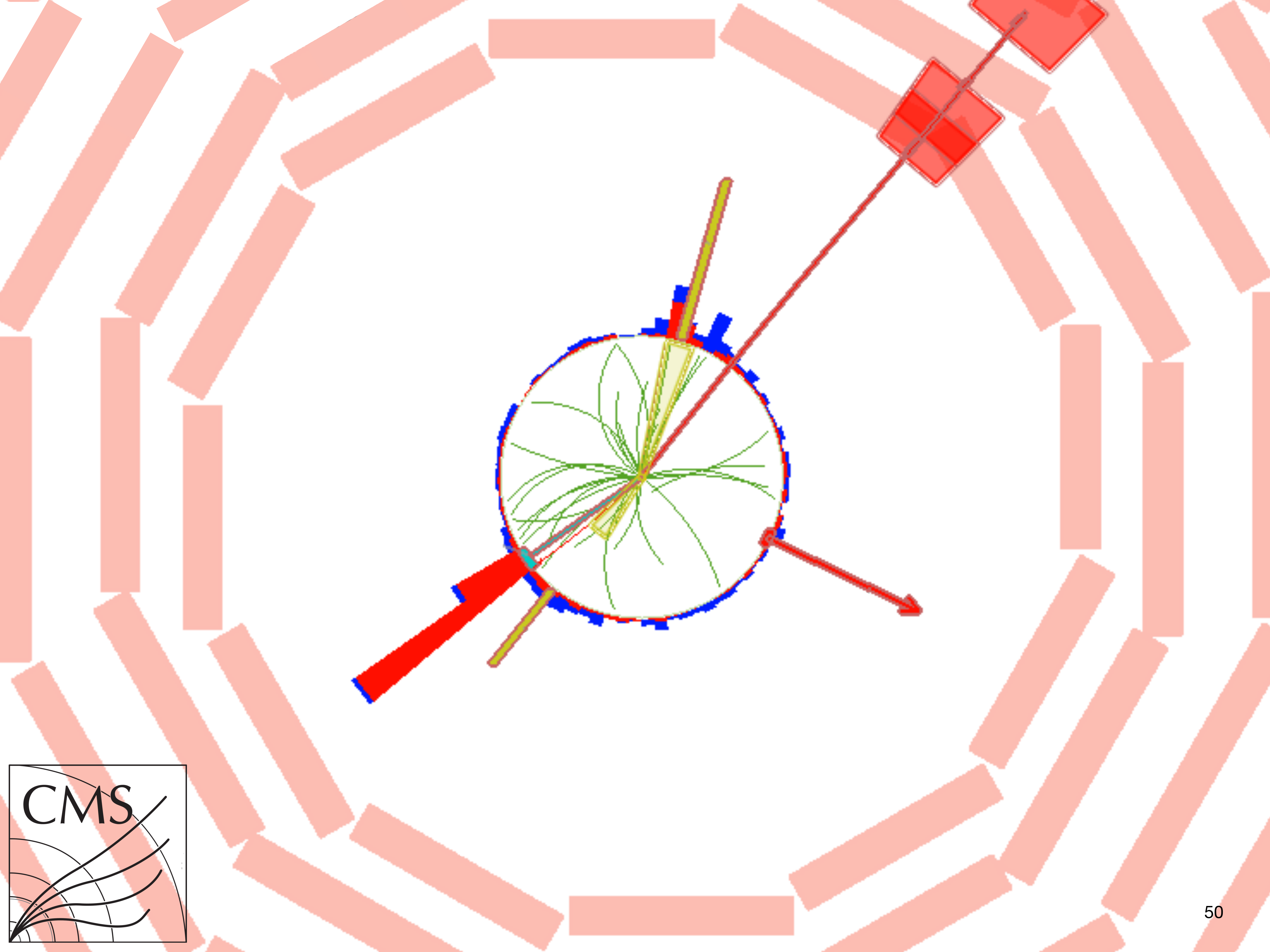
- Neutrino interaction cross section is ridiculously small



- If you are a dedicated neutrino experiment, get as large a volume as possible for the neutrinos to interact in to arrive at a visible rate

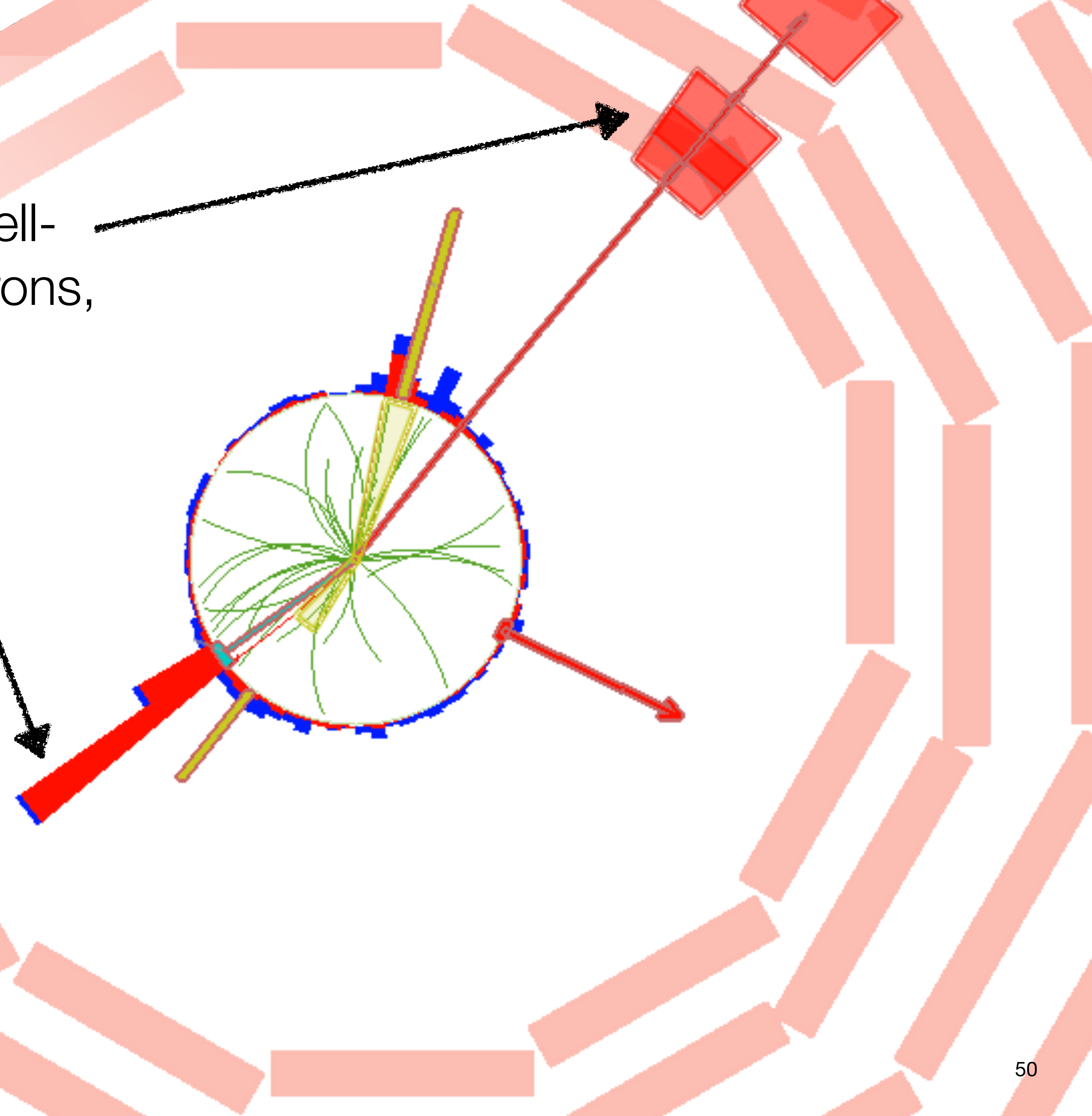
- If you're a collider experiment, you are out of luck! Neutrinos will pass all the way through the detector leaving no trace.

- However, neutrinos carry momentum: p imbalance in transverse plane tells you some particle was not reconstructed


CMS

MET

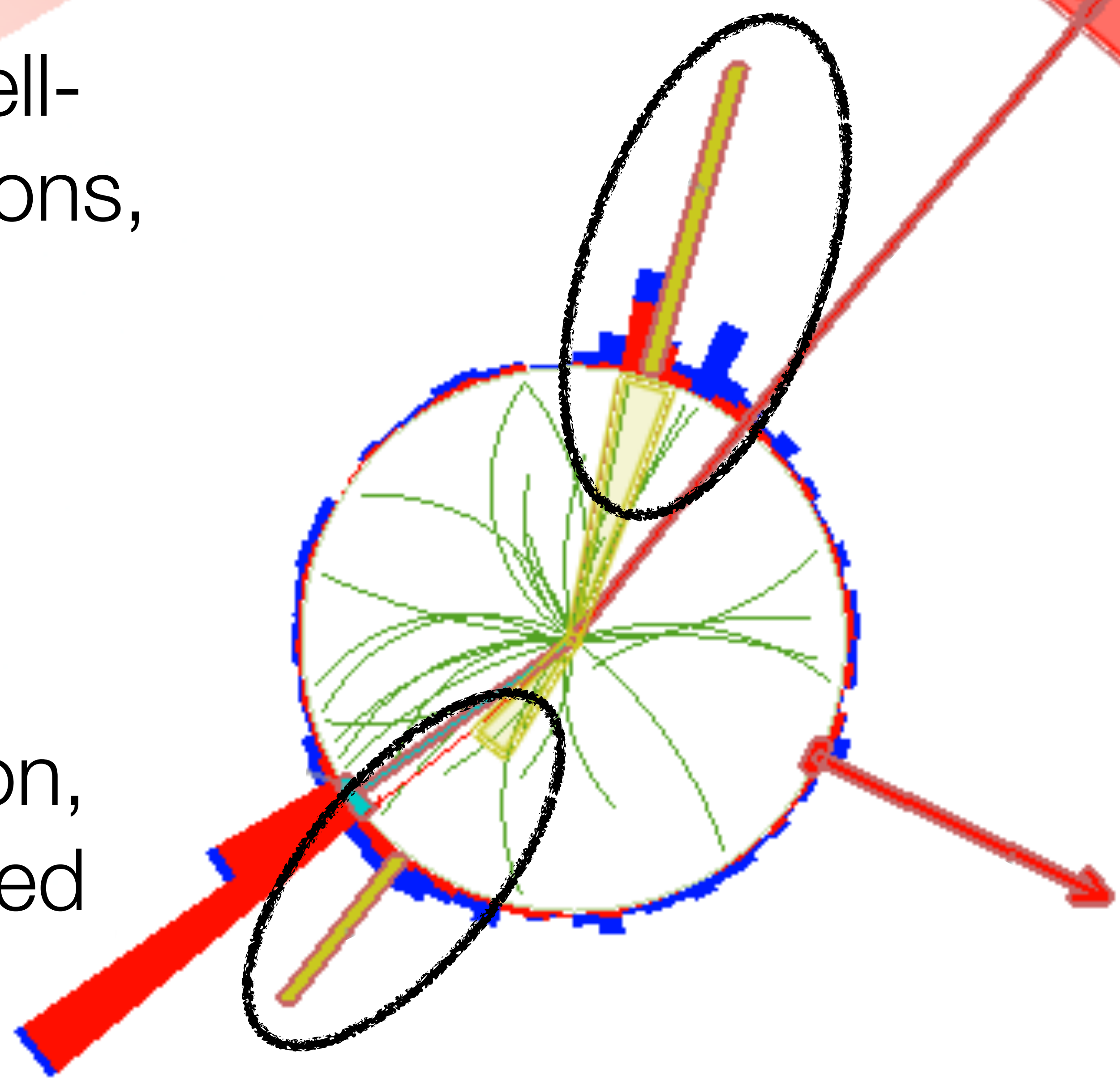
Add together well-calibrated electrons, muons, …



MET

Add together well-calibrated electrons, muons, …

Add all jets passing some threshold criterion, properly calibrated



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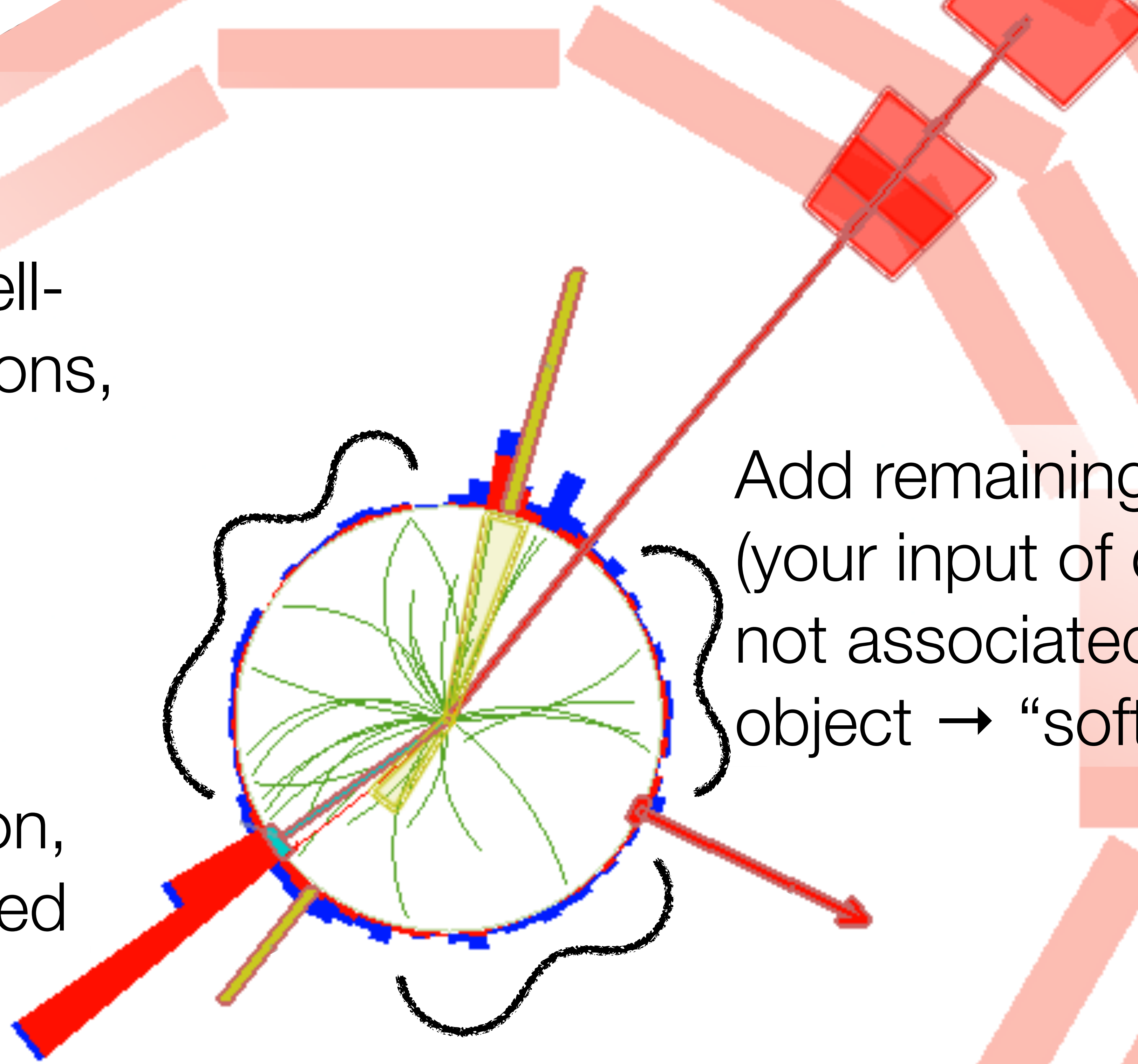


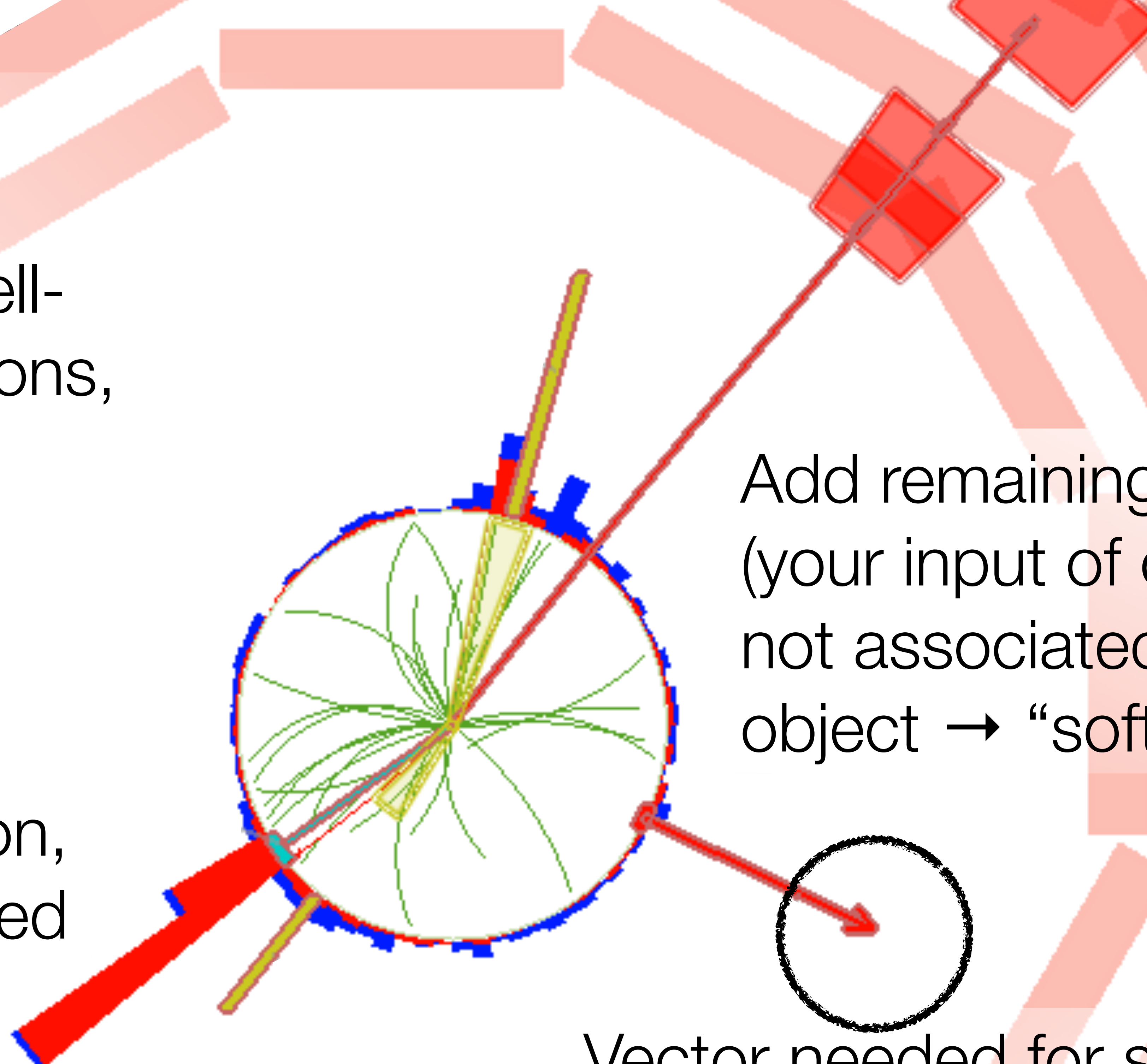
Add remaining activity (your input of choice) not associated to an object → "soft term"

CMS

MET

Add together well-calibrated electrons, muons, …

Add all jets passing some threshold criterion, properly calibrated

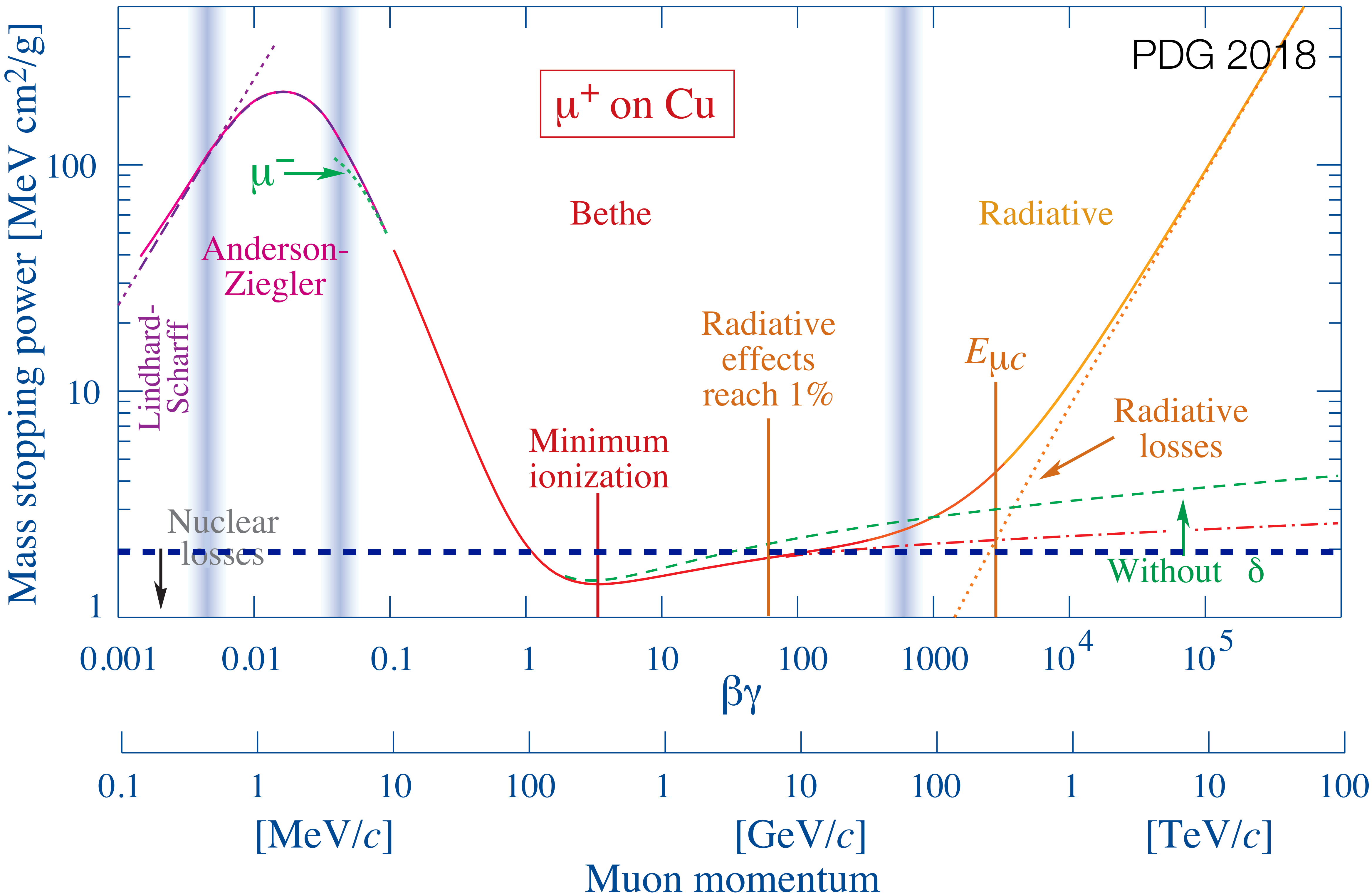


Add remaining activity (your input of choice) not associated to an object → “soft term”

Vector needed for sum to equal zero is the missing transverse momentum (MET): neutrino identification!

Fun with muons

Reminder
$\beta\gamma = p/Mc$



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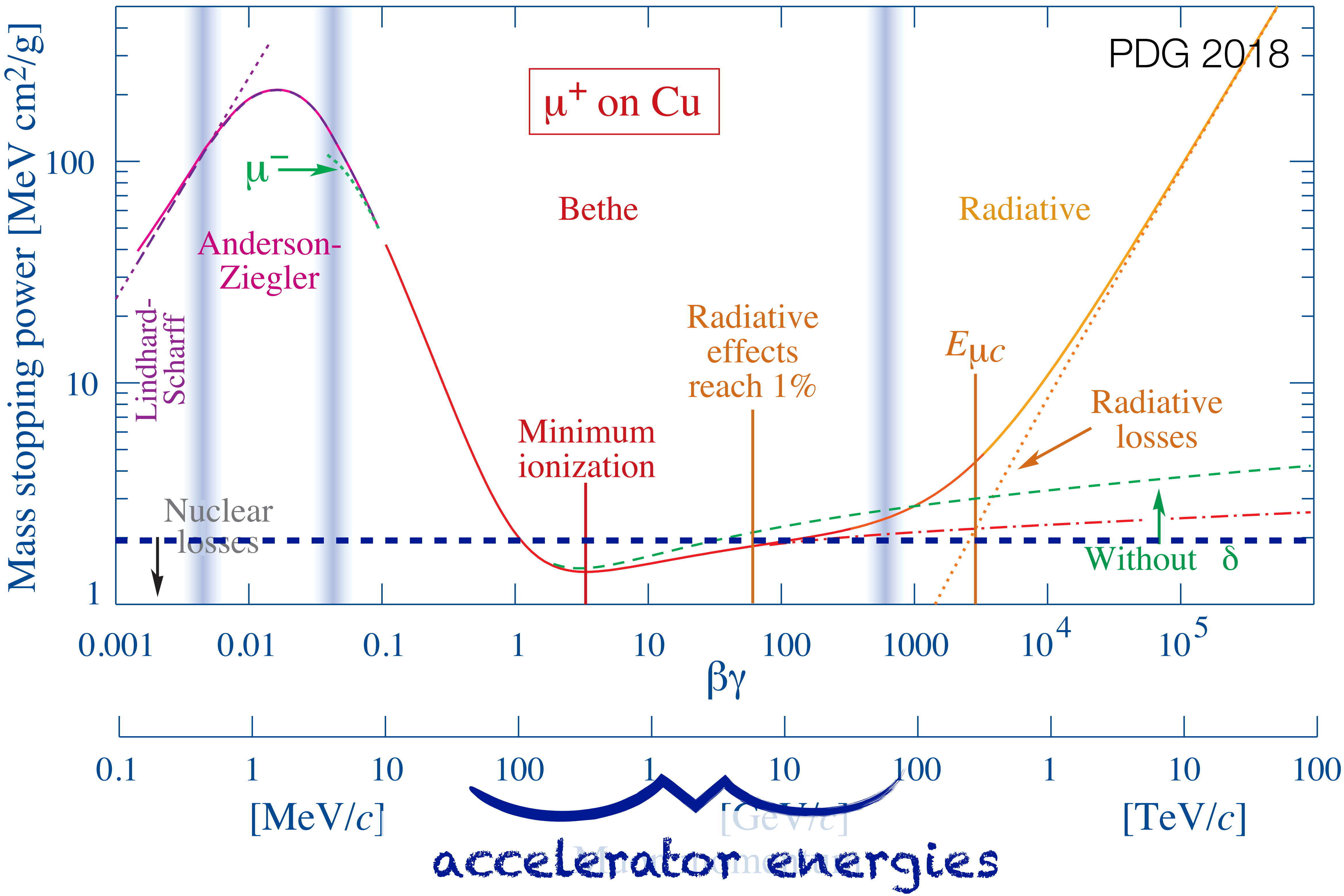

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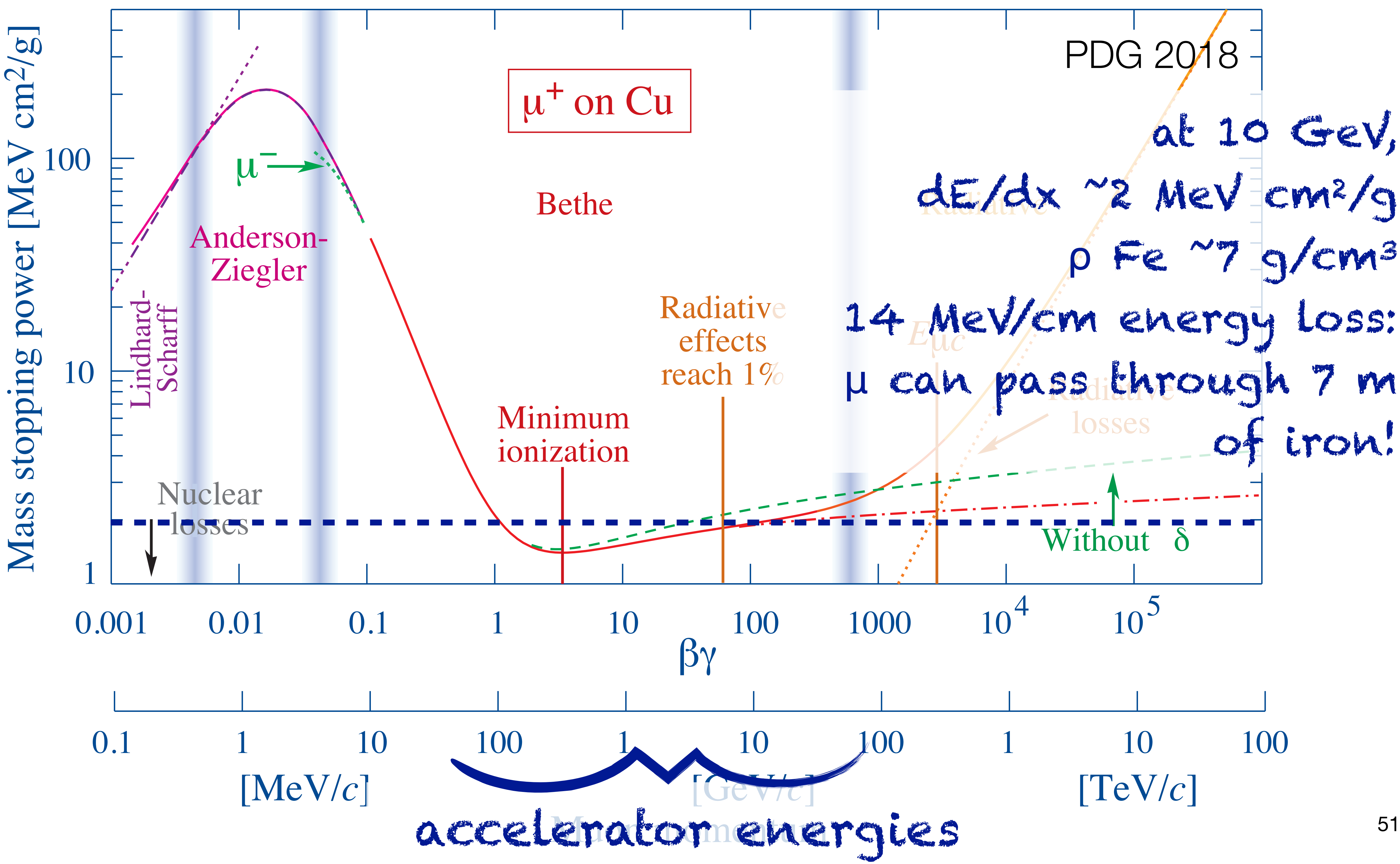


Conclusions

Conclusions

- Detectors need to do two things well:
  - Identify particles entering them
  - Tell us as much as possible about their properties: energy, momentum, charge, mass, …
- Every part of a detector is necessary to get this information!
- We discussed calorimeters: for everything except muons and neutrinos, these give us a measure of the total energy carried by the particle
- Careful calorimeter design lets you balance resolution, size, and expense
- Calorimeters are key for particle identification at high energies!

Student problems

Problems

- Which of these particles will undergo hadronic interactions in my calorimeter? K^0, π^+, γ, μ, n, π^0

- If I want to make a homogeneous electromagnetic calorimeter out of CsI scintillating crystals (density 4.51 g/cm^3, X_0 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?

Backup

Sources and references

- Calorimeter material and explanations taken with many thanks from lectures by M. Vetterli, M. Delmastro, D. Markoff, S. Masciocchi, E. Garutti, P. Loch, G. Gaudio, C. Jessop, M. Battaglieri, M. Nessi,
- Most calorimeter related plots taken from the Particle Data Group or Wigmans' *Calorimetry*, as noted in slides
- PID info relies strongly on *Particle Detectors, 2nd edition* by Grupen & Shwartz
- Non-jetty PID information taken with thanks from N. Proklova, S. Morgenstern, A. Kalinowski, R. Forty
- Most particle ID plots and event displays taken from various ATLAS and ALICE public results
- Some good quick reads on calorimeters and jets: Fabjan & Gianotti, Peter Loch's lectures, Webber

Calorimetric properties of common materials

	X_0 [cm]	E_C [MeV]	R_M [cm]
Pb	0.56	7.2	1.6
Scintillator (Sz)	34.7	80	9.1
Fe	1.76	21	1.8
Ar (liquid)	14	31	9.5
BGO	1.12	10.1	2.3
Sz/Pb	3.1	12.6	5.2
PB glass (SF5)	2.4	11.8	4.3

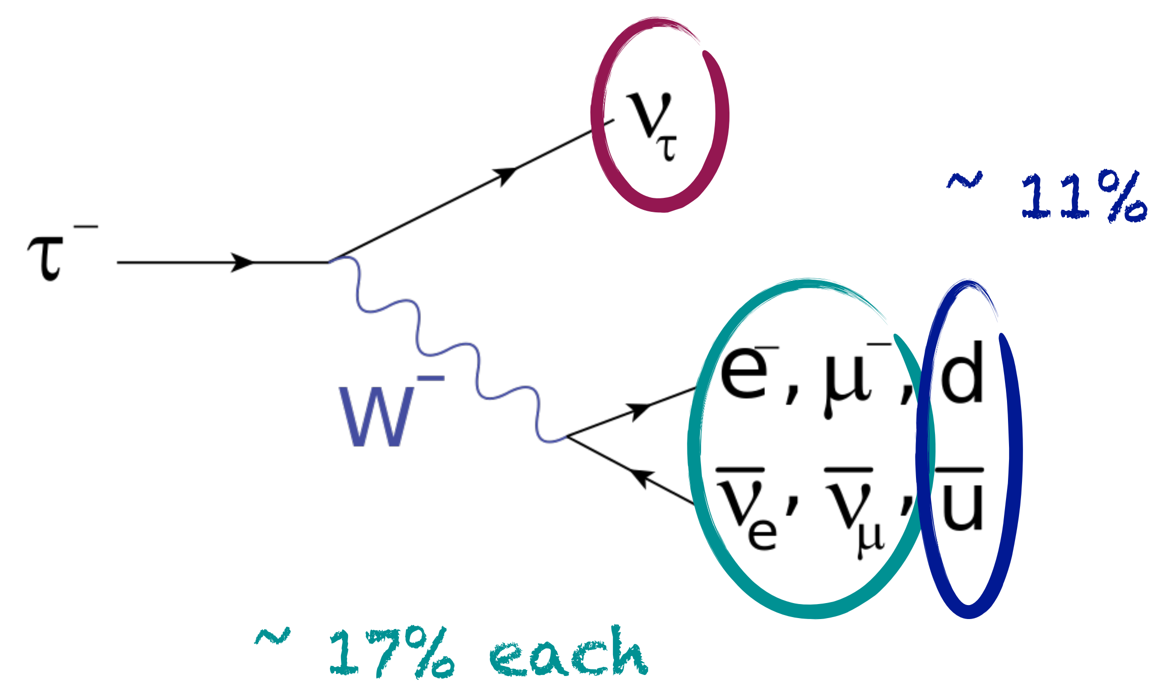
Table from Marco Delmastro

Taus

- Taus are heavy enough to have a huge number of available decays!
- Short lifetime: have to ID by decay products, not directly (though secondary vertex may be visible)
- Two and three charged pion decay modes resemble low-n_{trk} jets
- One-charged-pion decay mode resembles an electron
- Use cluster width and radius, EM to hadronic fraction, n_{trk}, degree of isolation to identify taus

I would paste the PDG decay modes table, but it's 6 pages long!

Lost energy from ν complicates τ energy reconstruction



+ 25% $\tau \rightarrow \pi^+ \pi^0 \nu_\tau$

+ 11% $\tau \rightarrow$ 3 charged π

+ 9% $\tau \rightarrow \pi^0 \pi^0 \pi^+ \nu_\tau$

Taus

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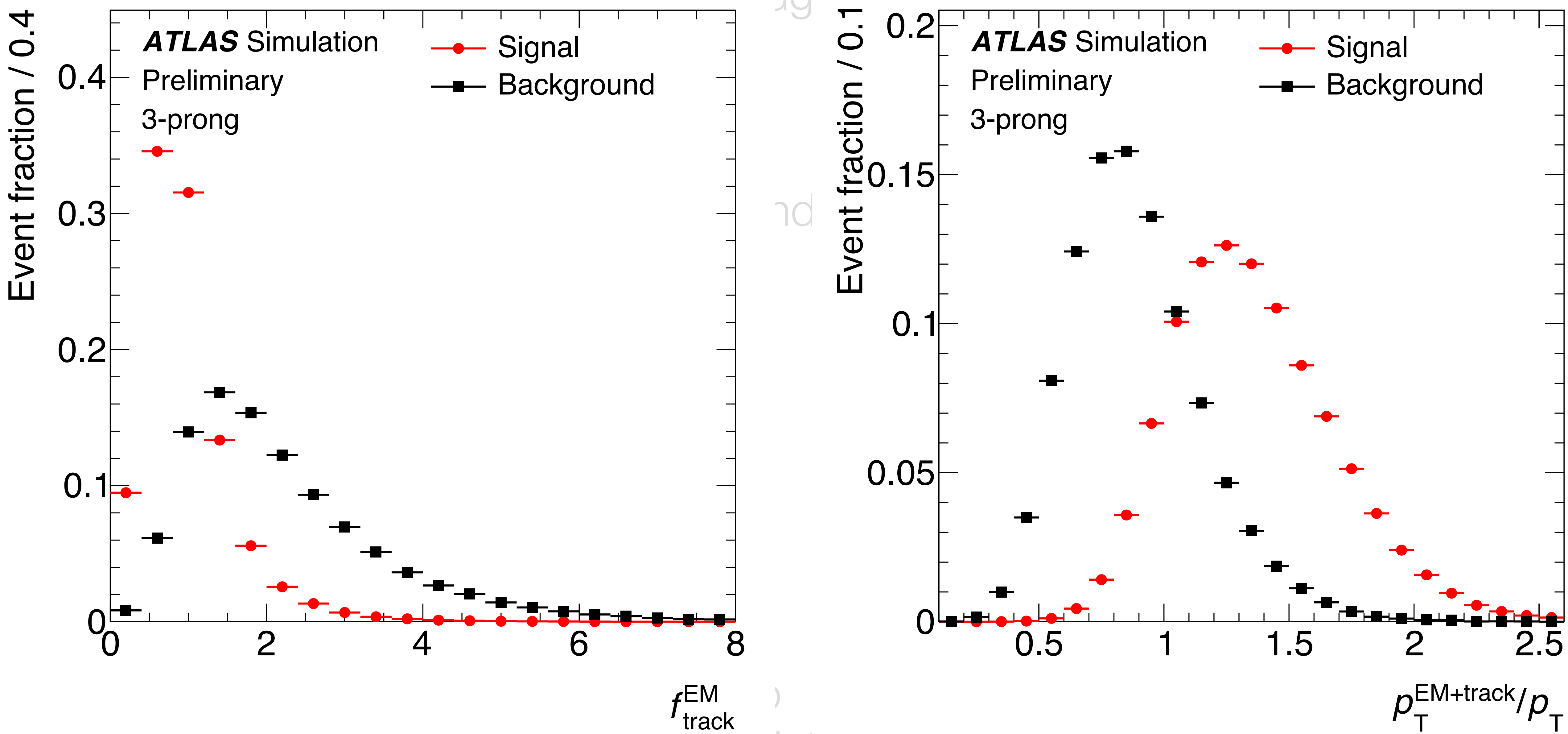

hadronic fraction, n_{trk}, degree of isolation

to identify taus

ATL-PHYS-PUB-2015-045

+ 11% $\tau \rightarrow 3$ charged π

+ 9% $\tau \rightarrow \pi^0\pi^0\pi^+\nu_\tau$

Compensating hadronic calorimeter

- Technically a compensating calorimeter just means EM response == H response. If you can lower EM response enough you get compensation

- Also some crazier tricks you can pull. E.g. the ZEUS experiment built uranium calorimeter that let neutrons/neutral pions trigger fission processes that released more energy

- Result: e/h = 1