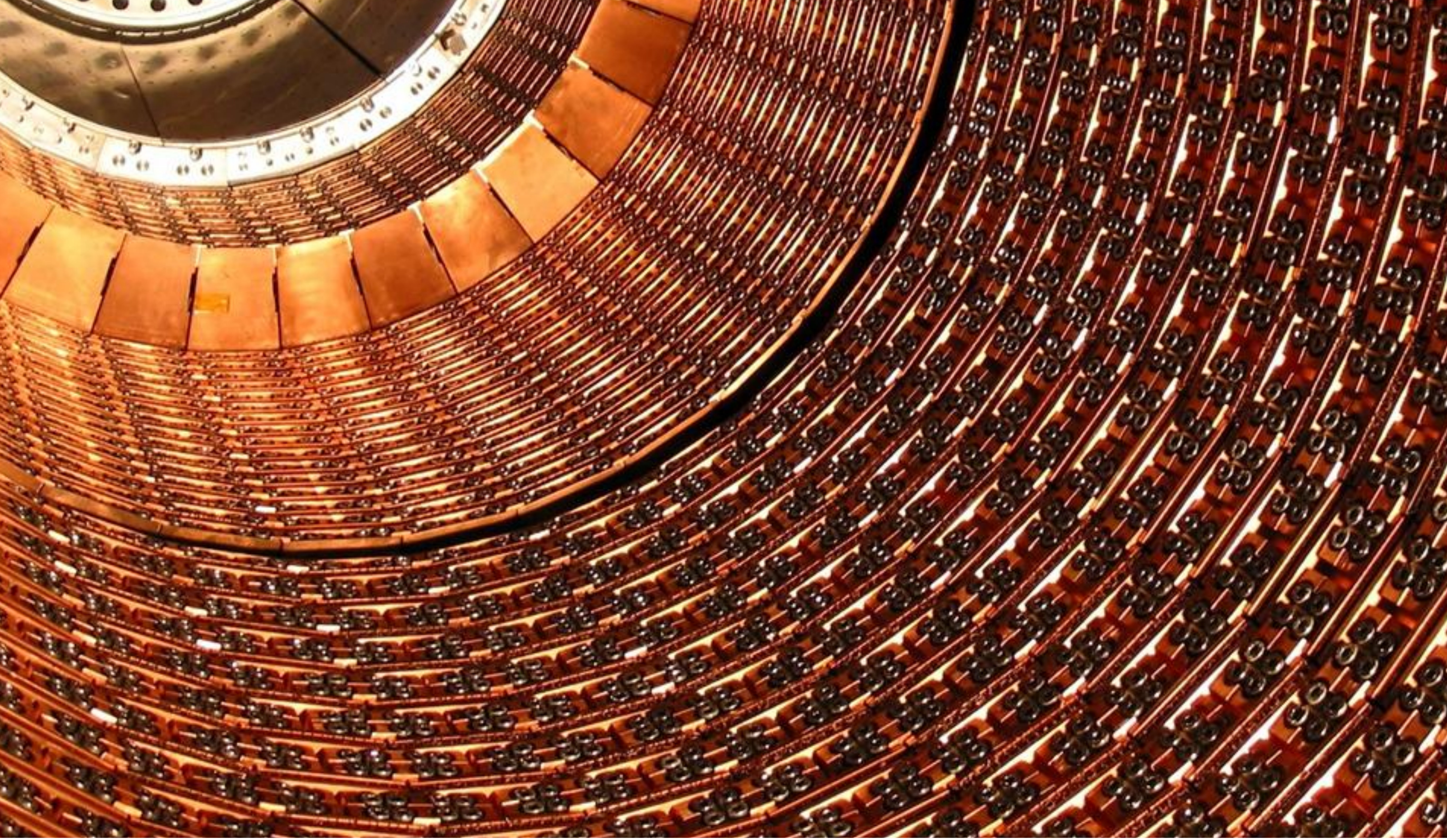


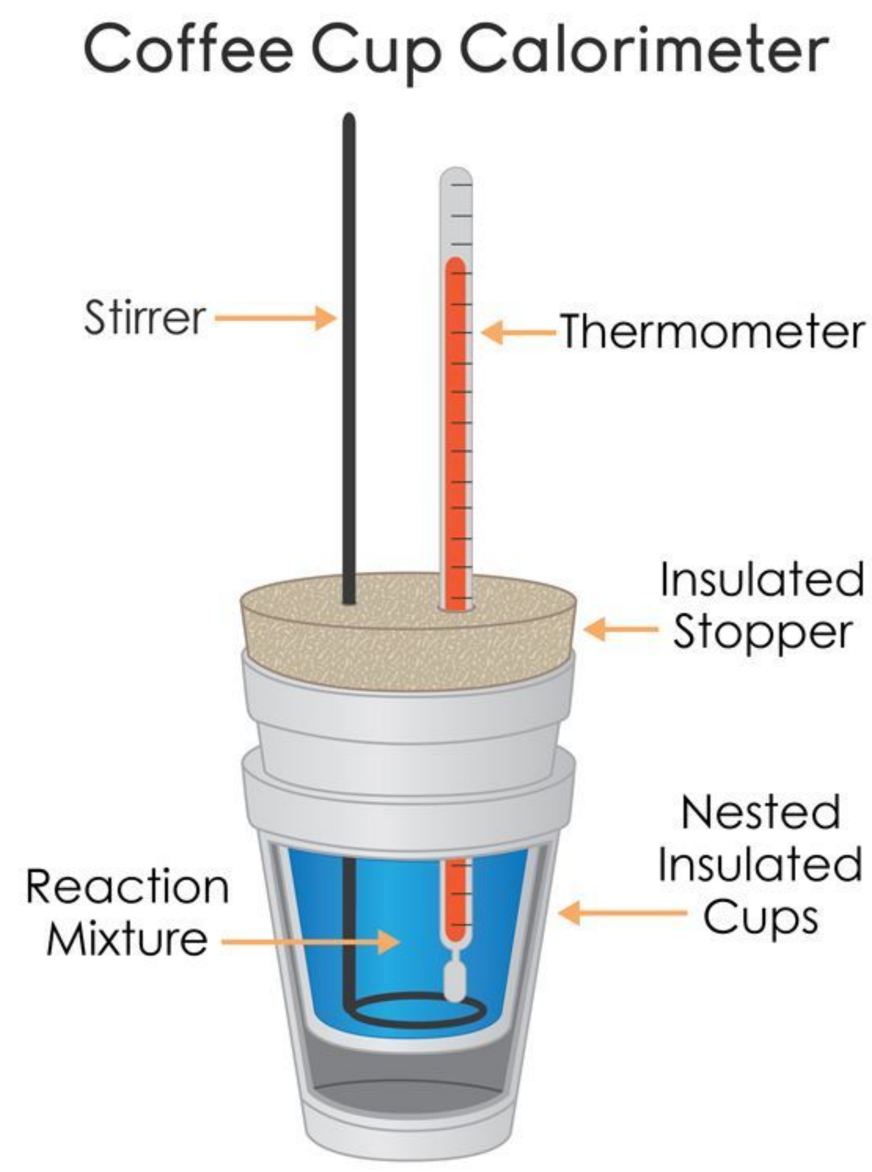
Calorimetry and particle ID

Kate Pachal
Duke University

Calorimeters

What's a calorimeter?

- Calorimeters measure amount of energy output by some process
- Have discussed trackers already - these are critical to an all-purpose particle detector!
- But with only momentum information you don't have a full 4-vector. Need a calorimeter to tell you energy of your particle



- Calorimeters are destructive: incoming particle vanishes in reaction with material. If it's a good calorimeter, nothing comes out the other side
  - So put it after your tracker!!

Goals and needs of a calorimeter

- Must be **thick enough** 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** to deposited energy
- Must be sufficiently **granular** to tell you not just how much energy was deposited, but where
- 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, …

Glossary of upcoming 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

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

- t = depth in radiation lengths

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

- Critical energy = energy at which an electron interacts equally via bremsstrahlung and ionisation. E_C ~= 610 MeV/(Z+1.24)

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

- Shower maximum = depth of shower where there is maximum particle multiplicity

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

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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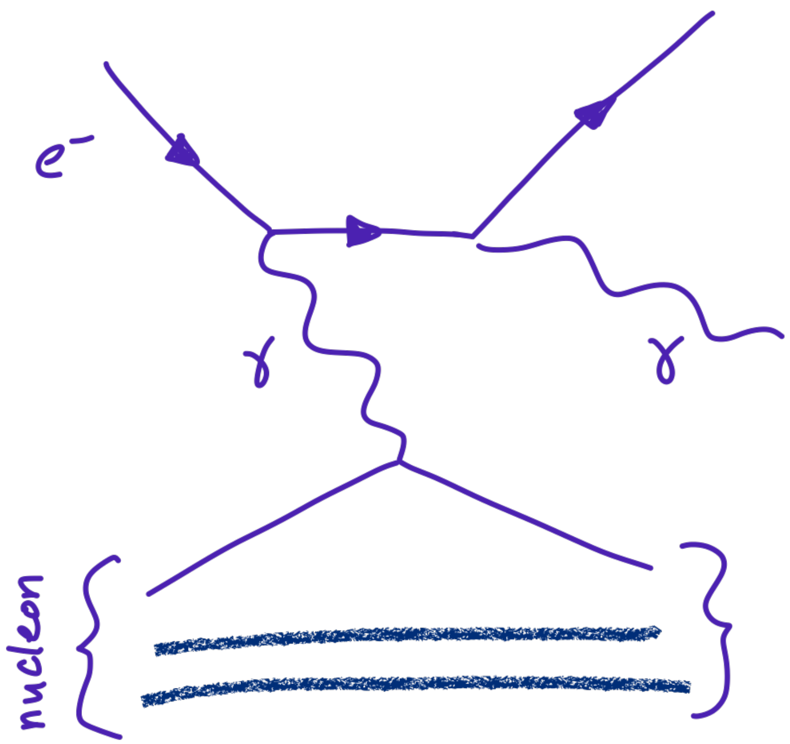

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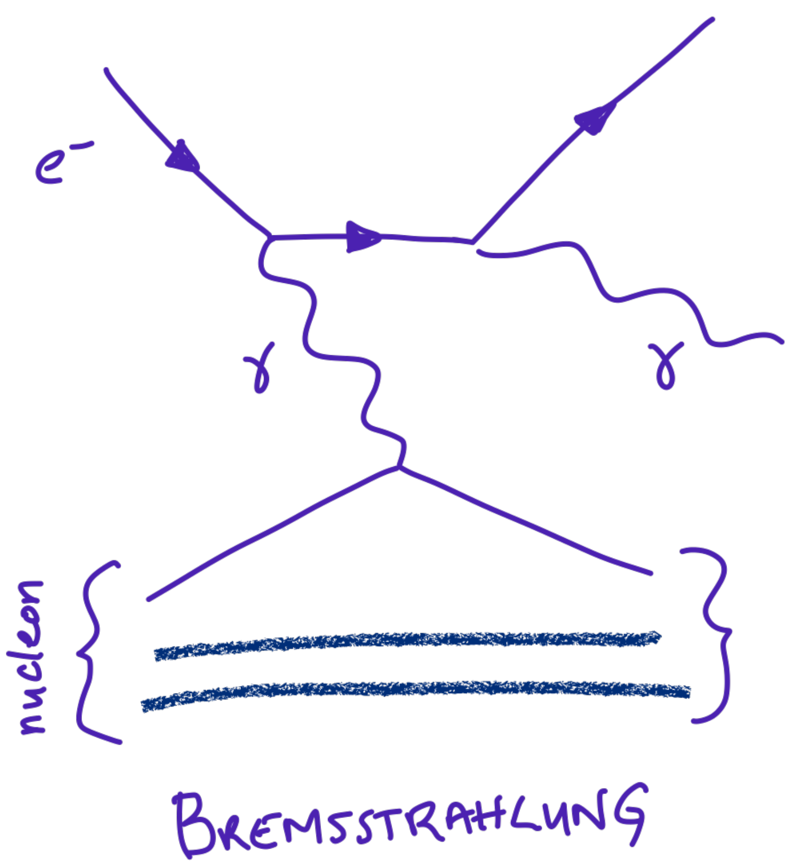

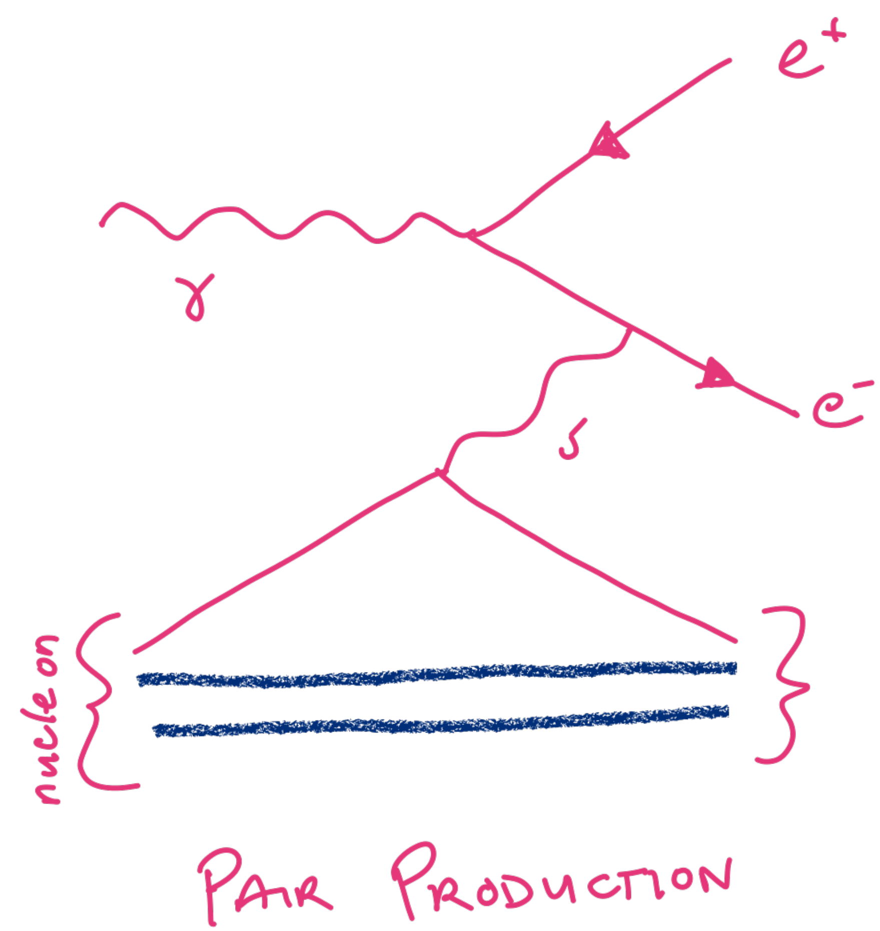

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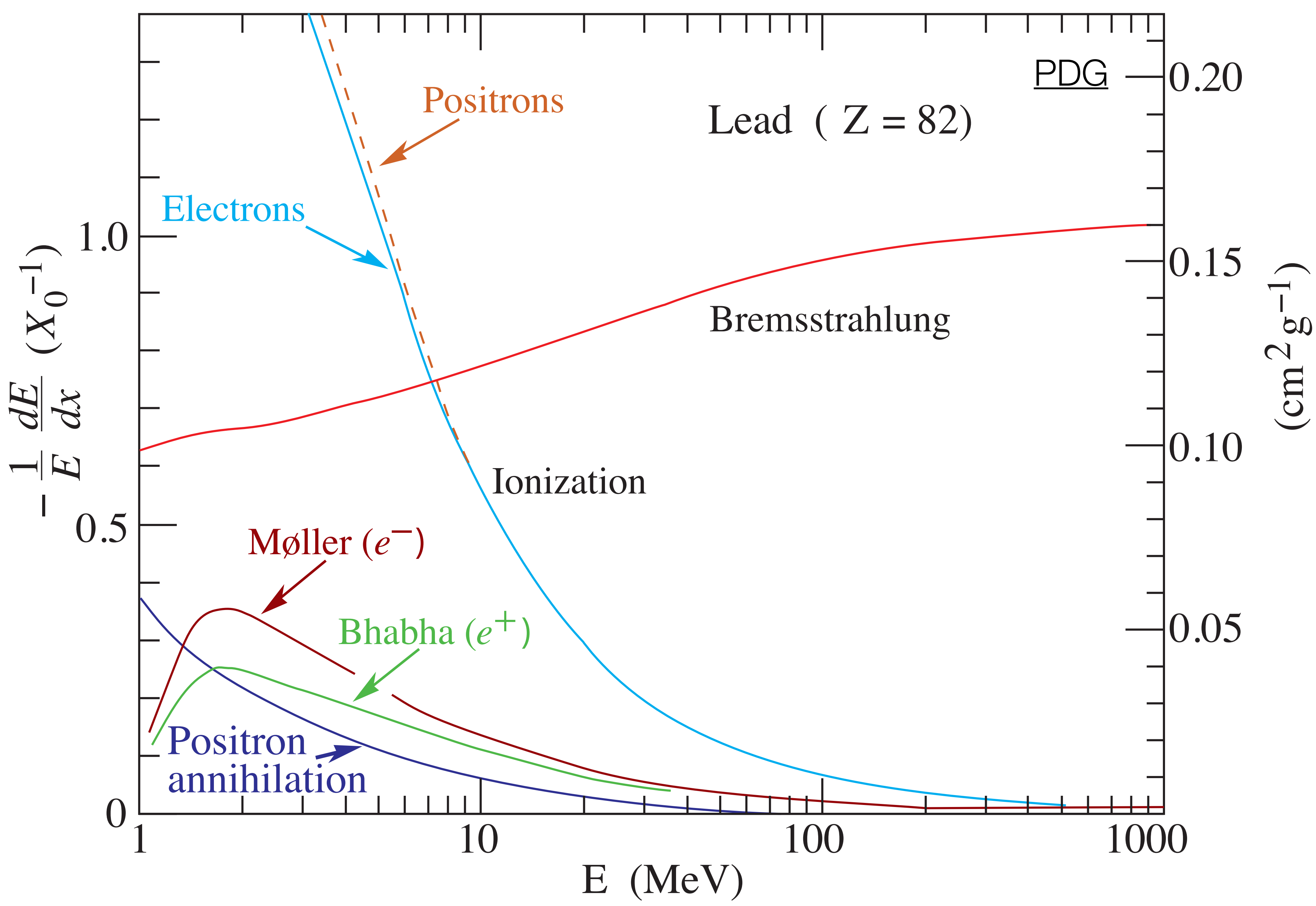

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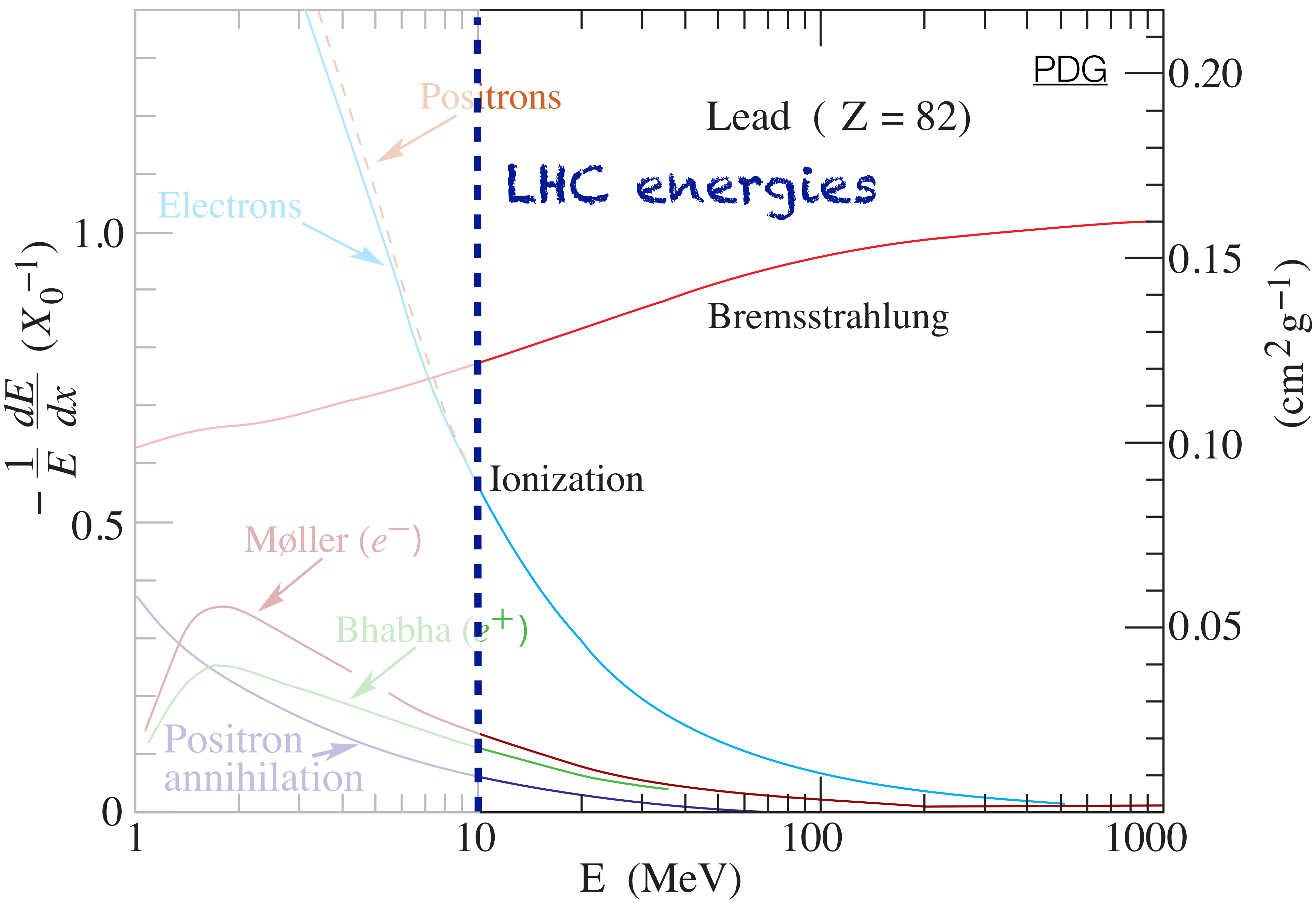

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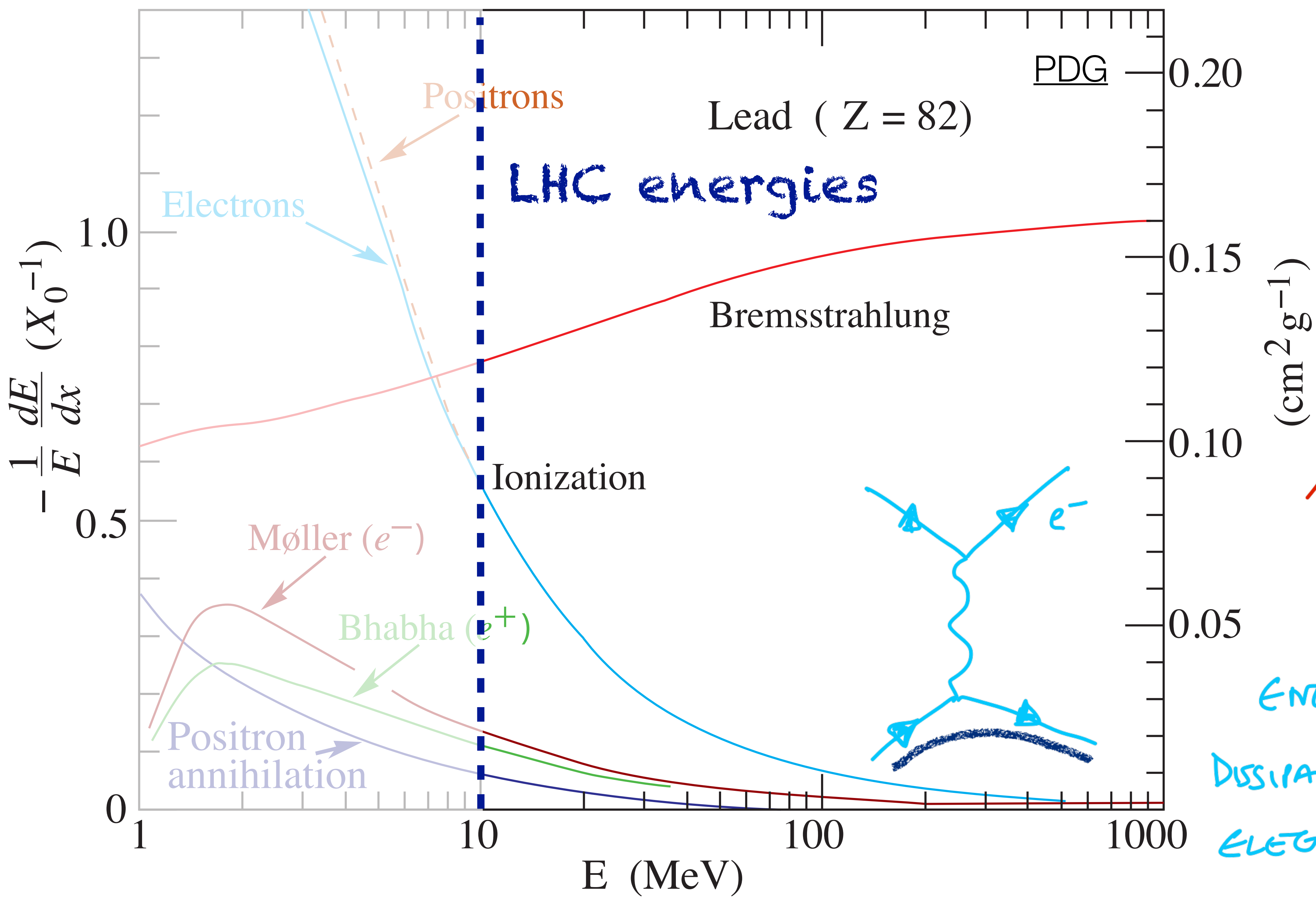
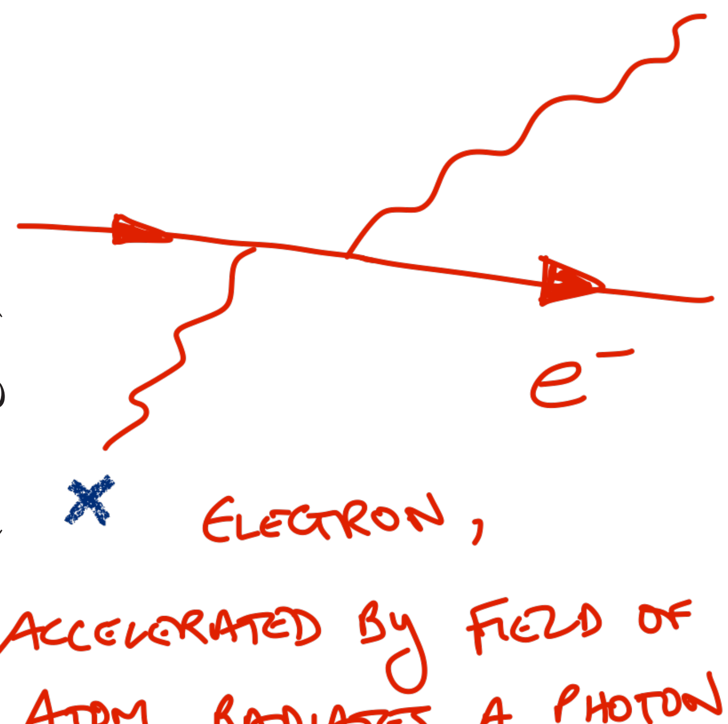
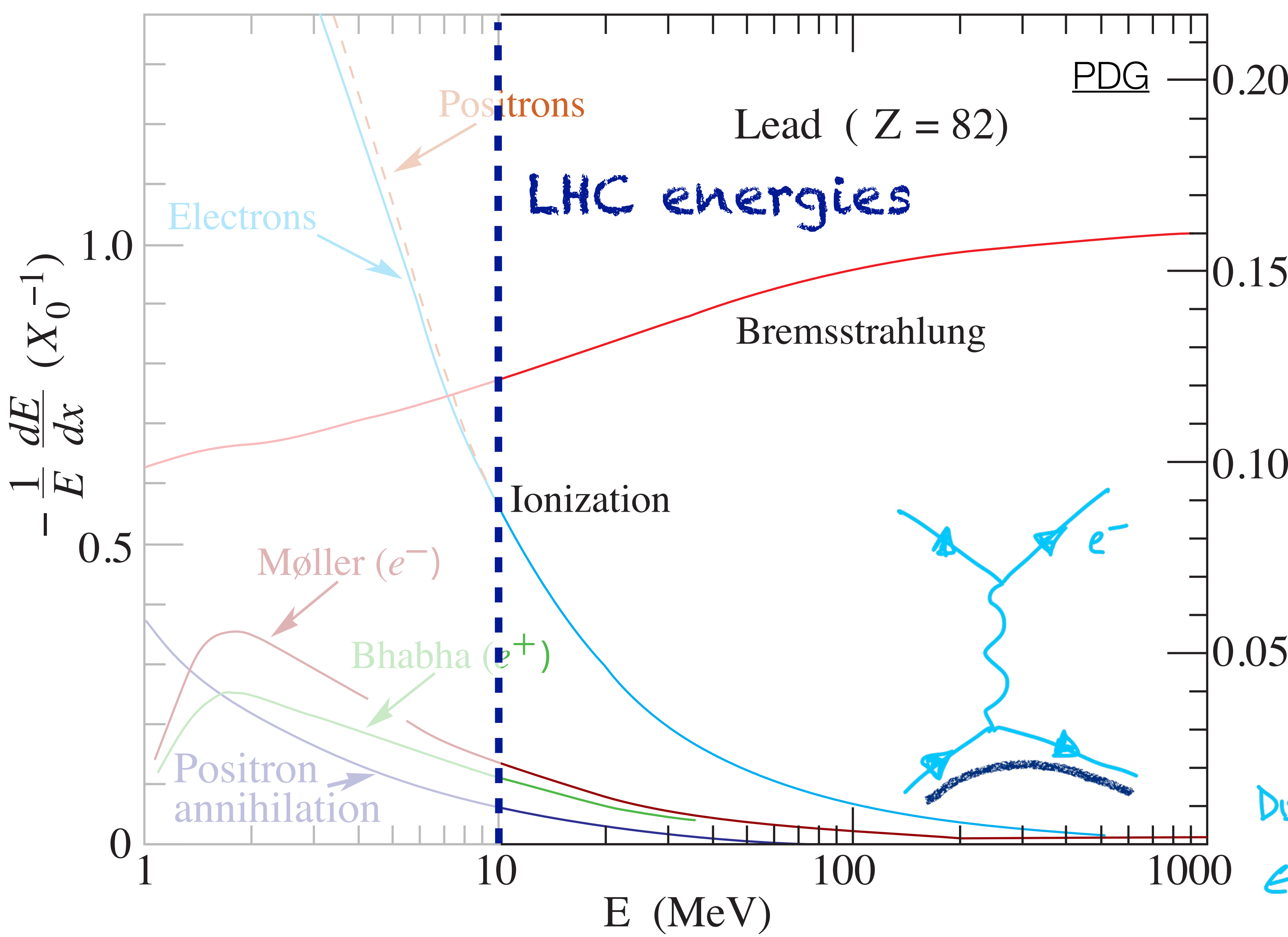


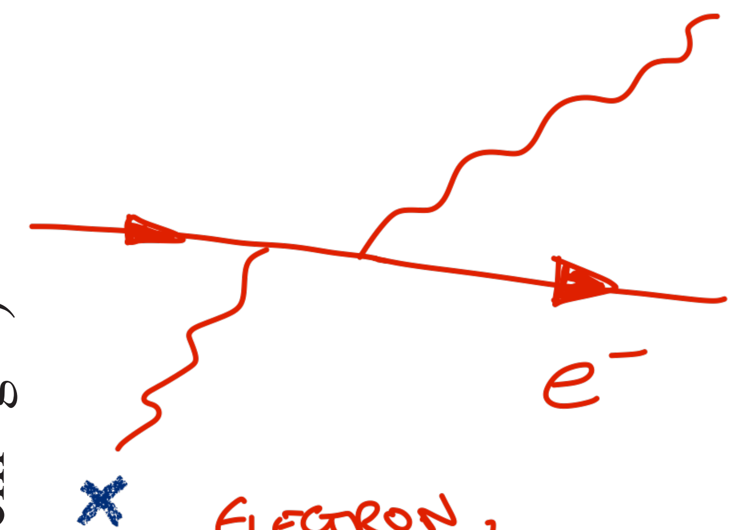


ENERGY OF ELECTRON DISSIPATED WHILE FREEING ELECTRON FROM NEIGHBOURING ATOM

Electron interactions

Reminder: electron needs to accelerate to radiate





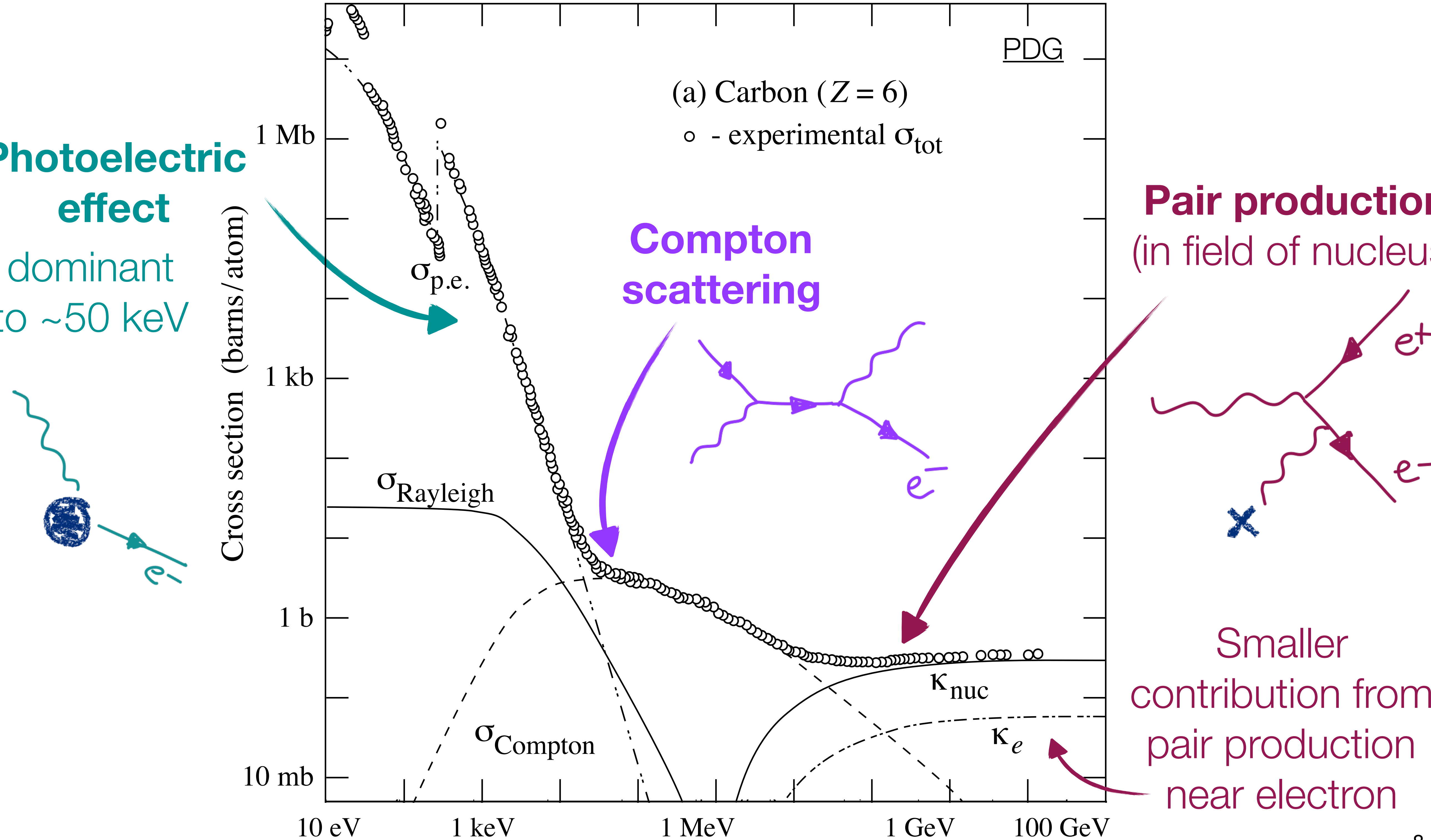
ELECTRON, ACCELERATED BY FIELD OF ATOM, RADIATES A PHOTON

ENERGY OF ELECTRON DISSIPATED WHILE FREEING ELECTRON FROM NEIGHBOURING ATOM

Photon interactions

Photoelectric effect

dominant to ~50 keV



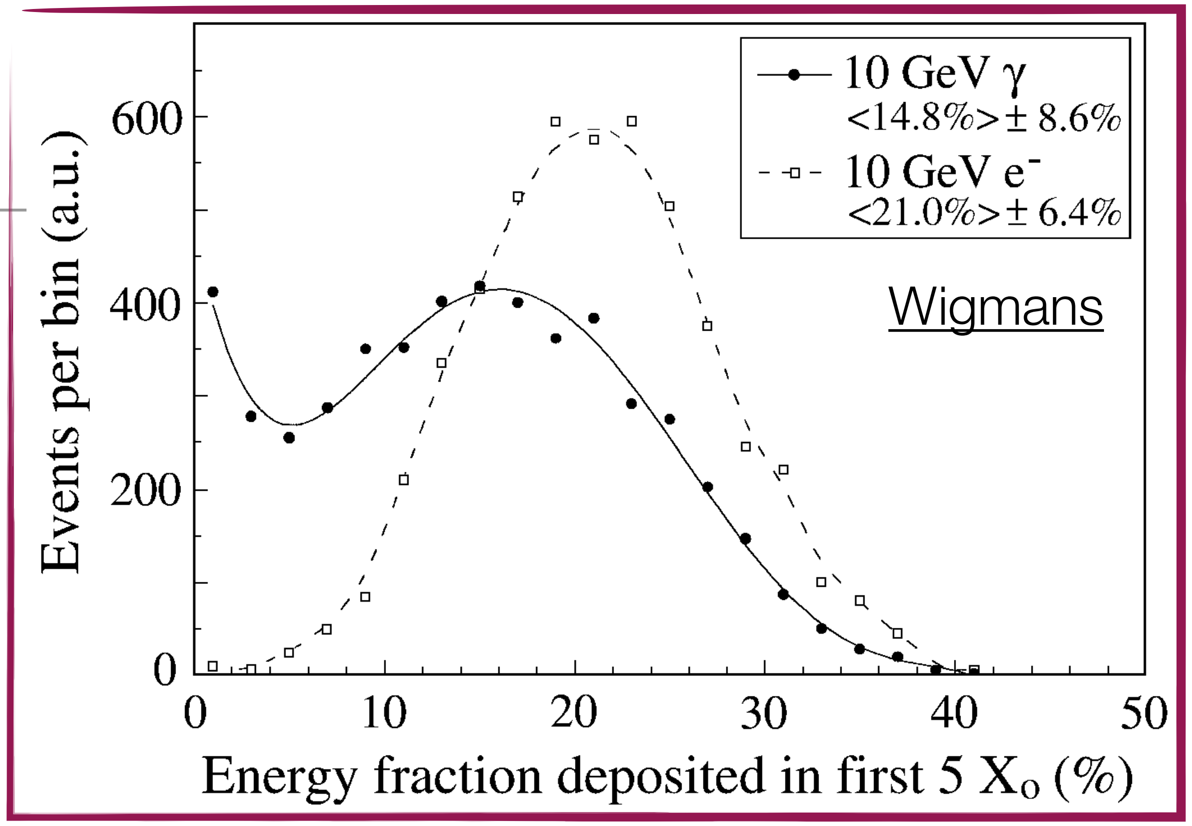
Compton scattering

Pair production

(in field of nucleus)

Smaller contribution from pair production near electron

Electromagnetic showers in matter



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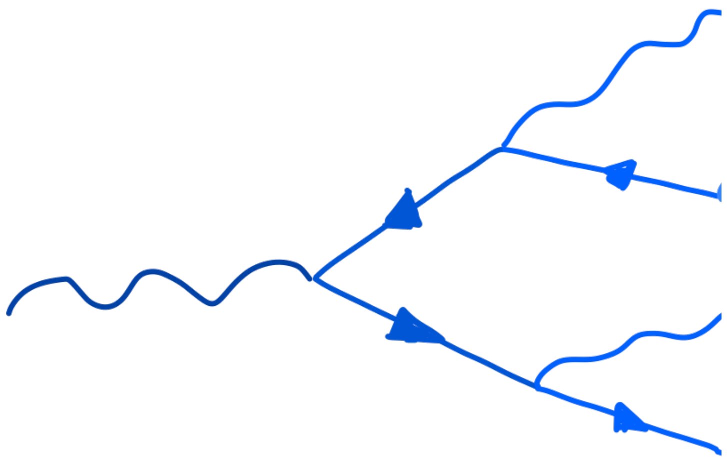

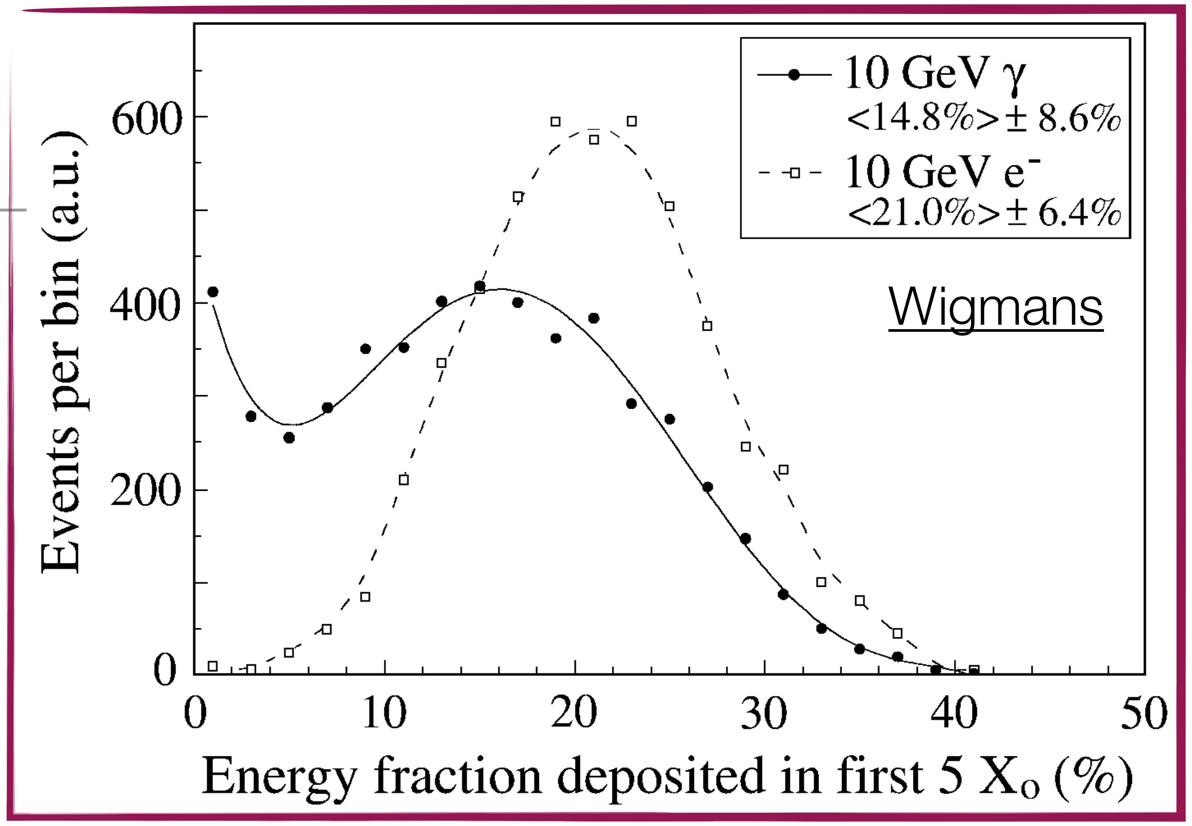

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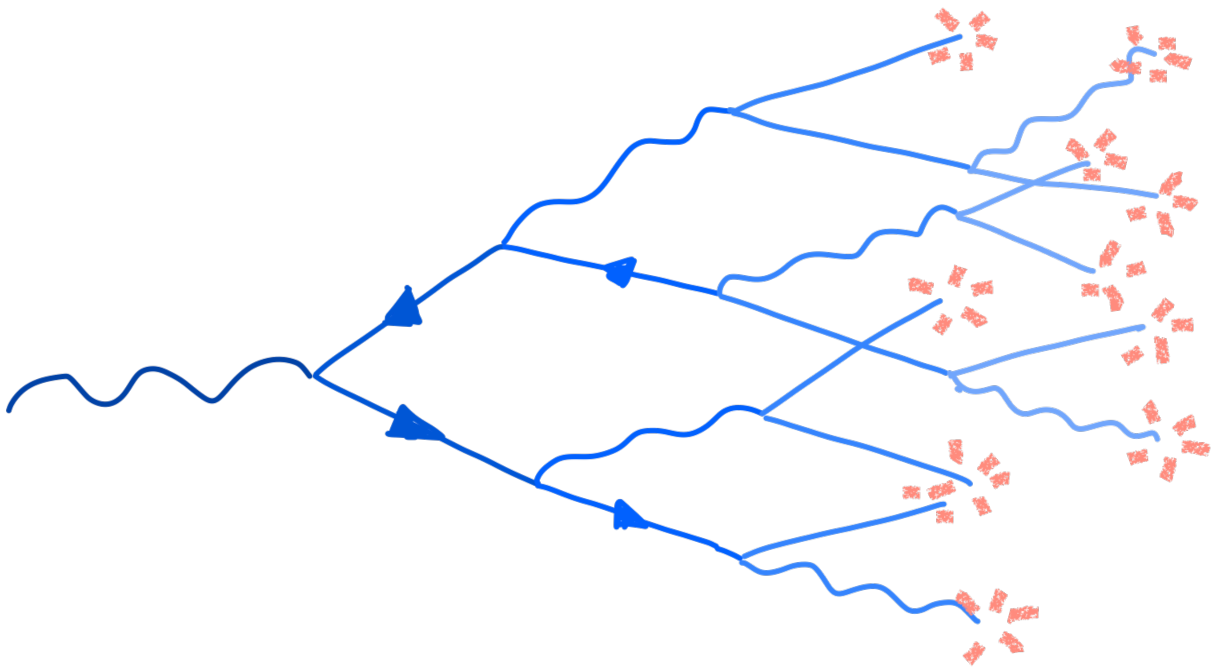

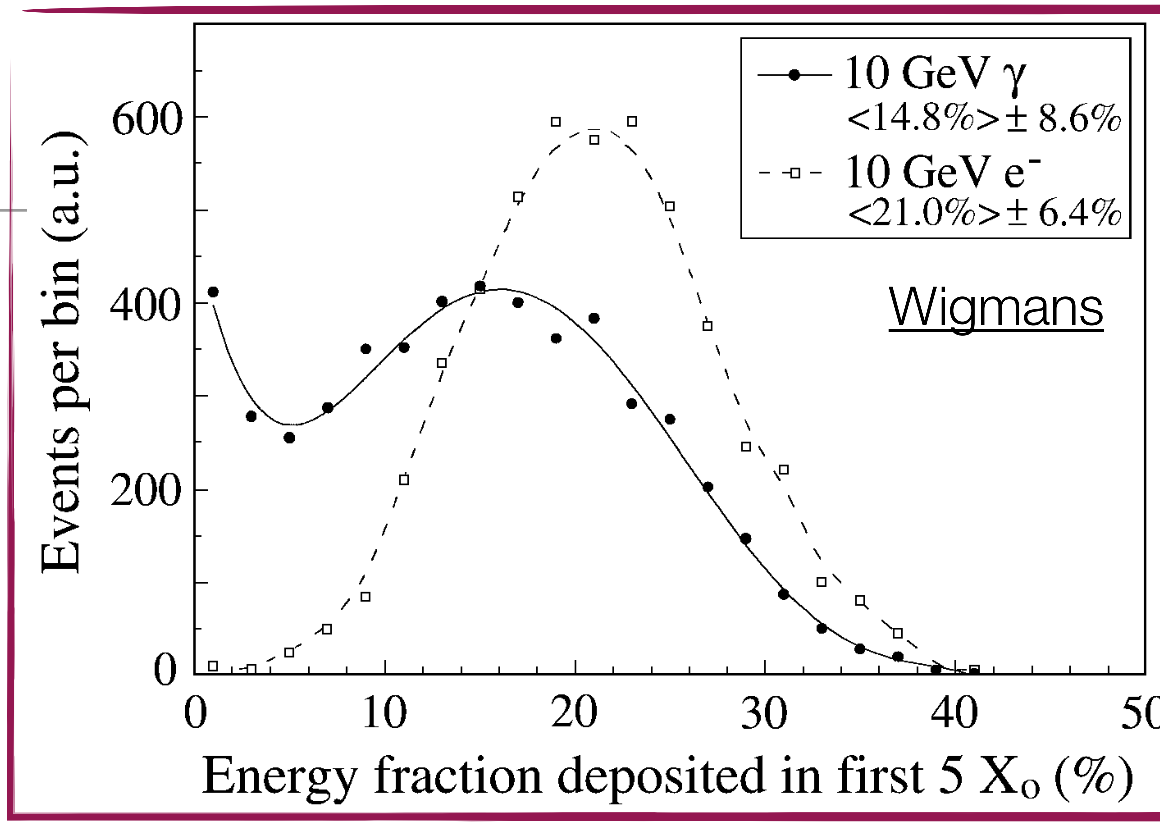

- High-energy photons pair produce electrons and positrons, vanishing in the process
- Electrons and positrons radiate photons via bremsstrahlung as they travel through matter, interacting with fields of atoms
- Once electrons fall below *critical energy*, more energy lost via ionisation than bremsstrahlung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

$t = X/X_0$
E_0 = initial energy

Let's do some approximations!

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

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

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

- Shower maximum occurs when $E = E_C$:

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

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

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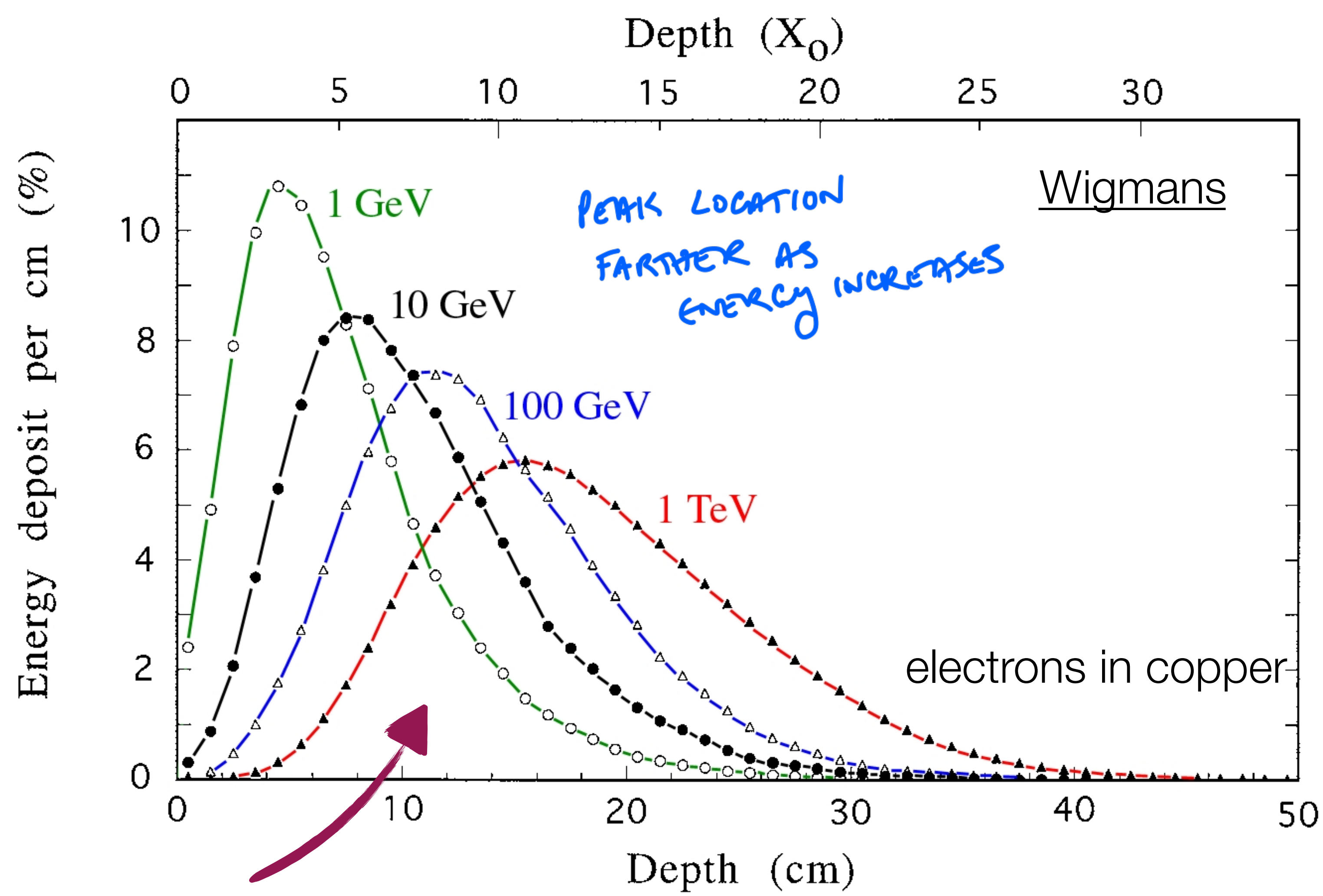

t_{max} proportional to E_0

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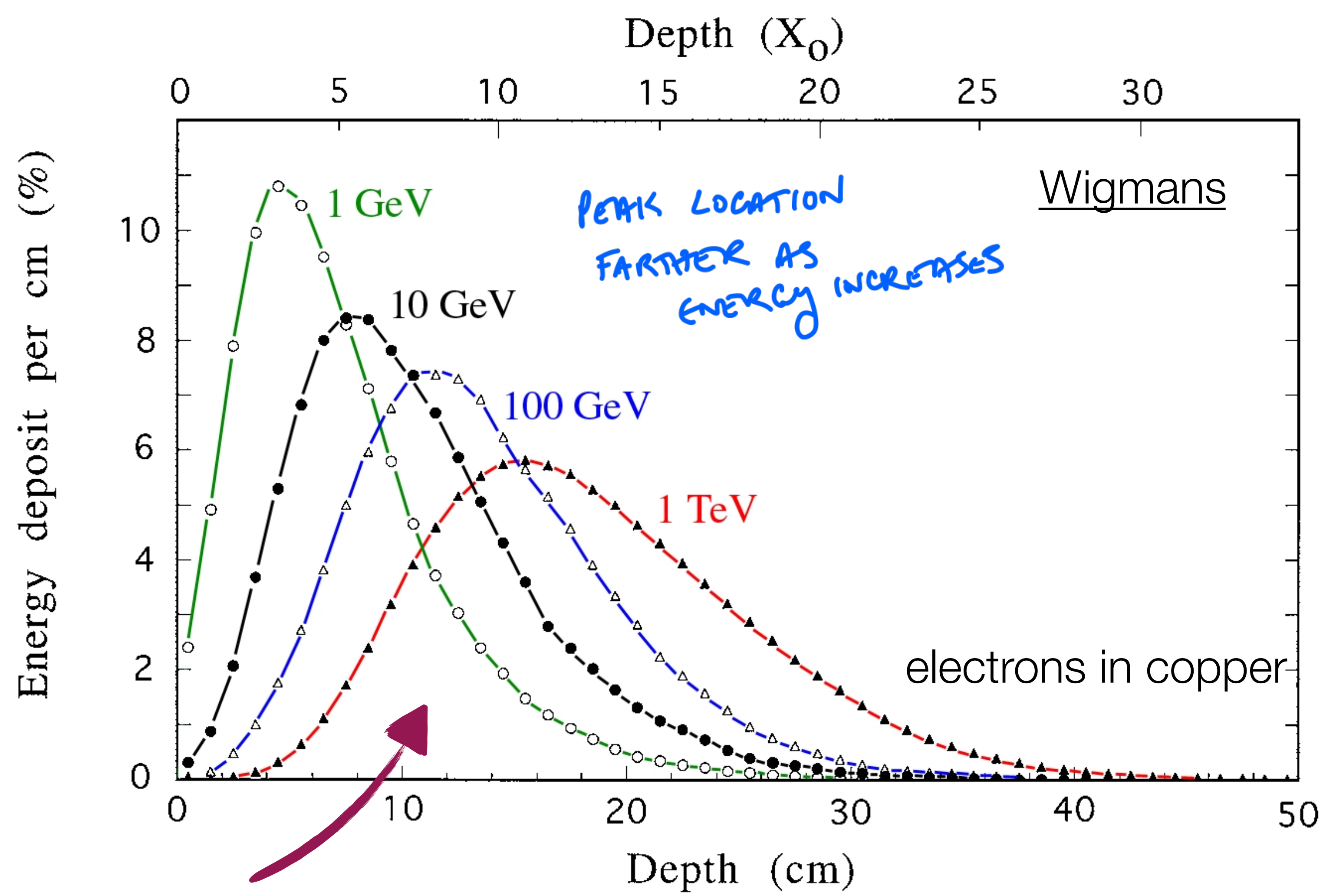
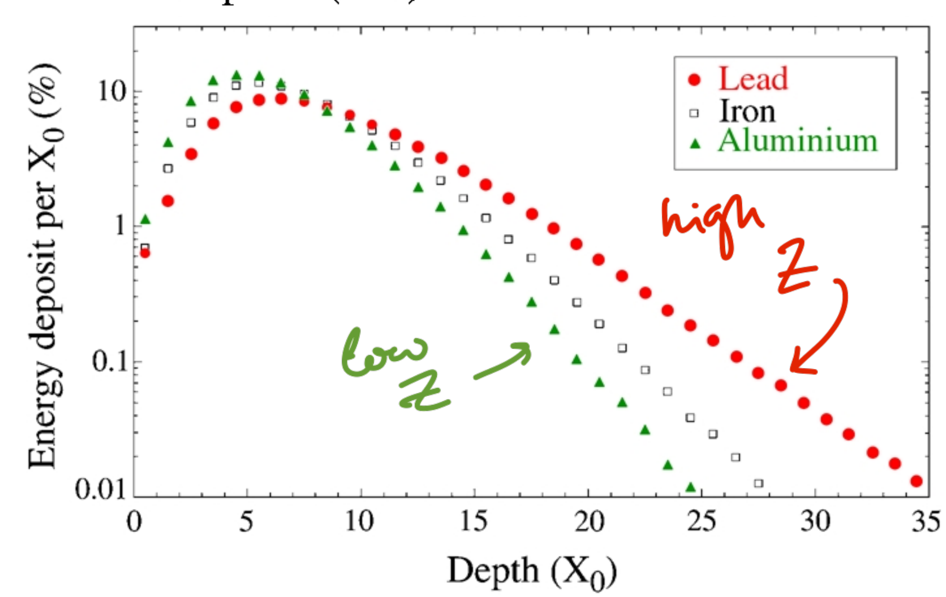
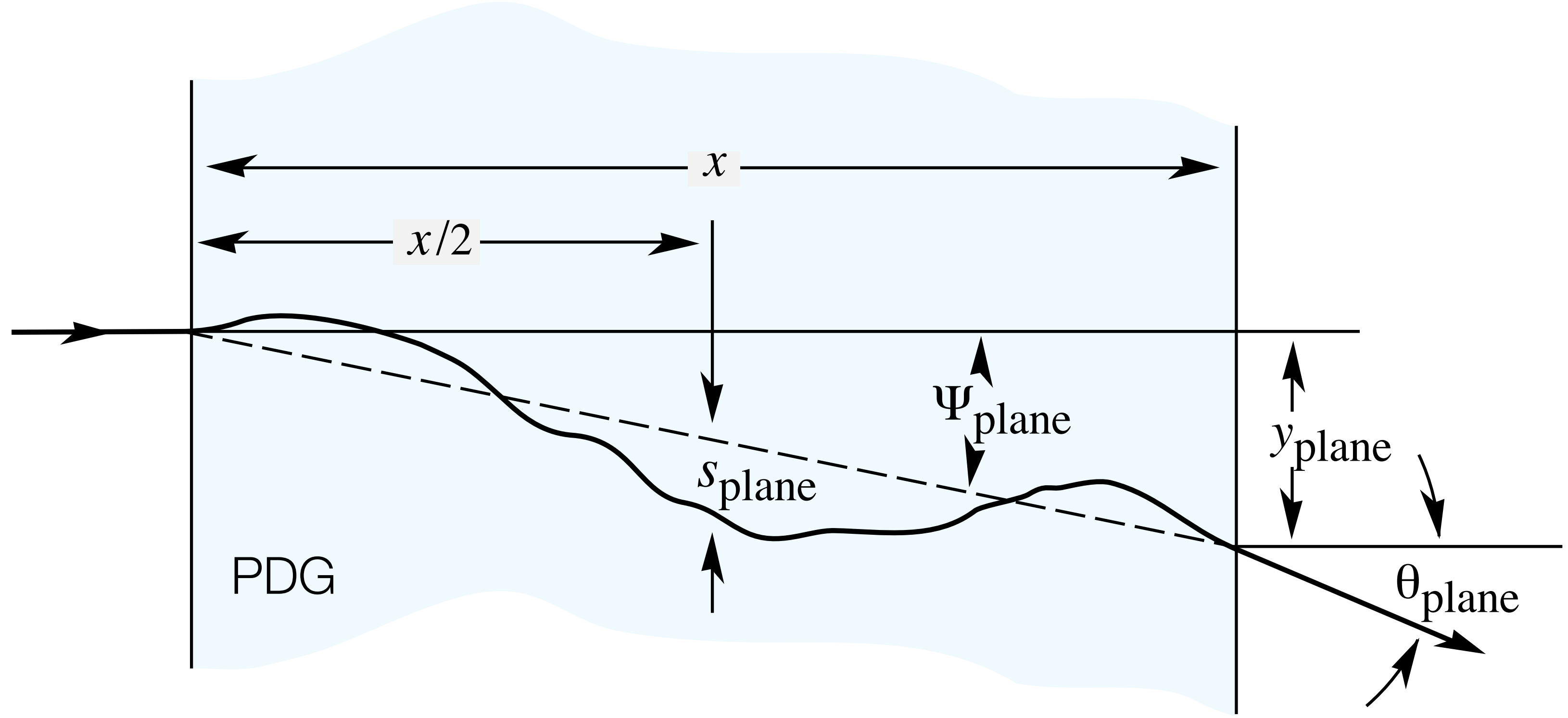
E_C varies with Z, so shower profile varies a bit too

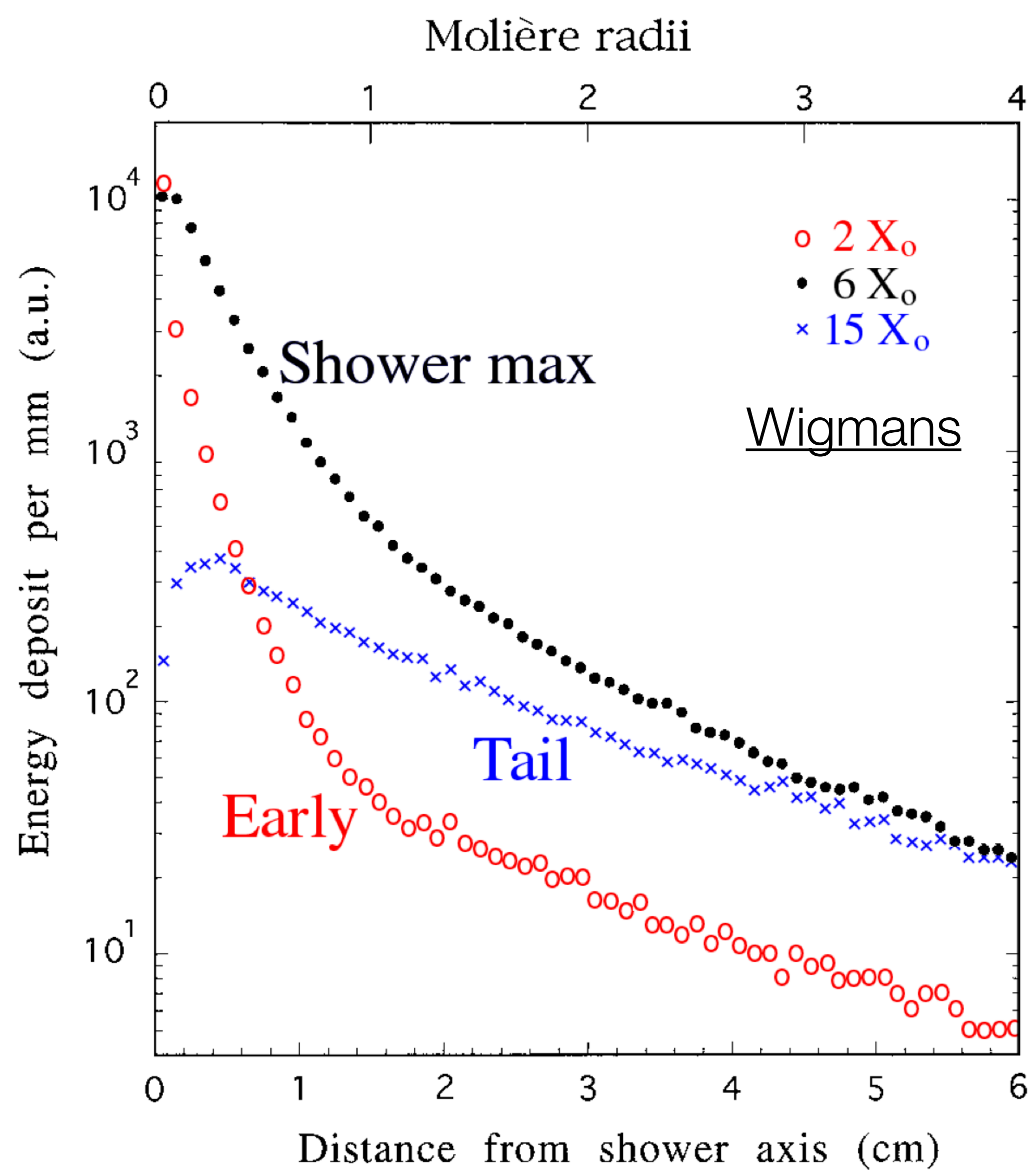




Shower width

- 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





Define Moliere radius

$$R_M \propto X_0/E_C$$
$$\propto A/Z$$

Cylinder containing 90% of shower

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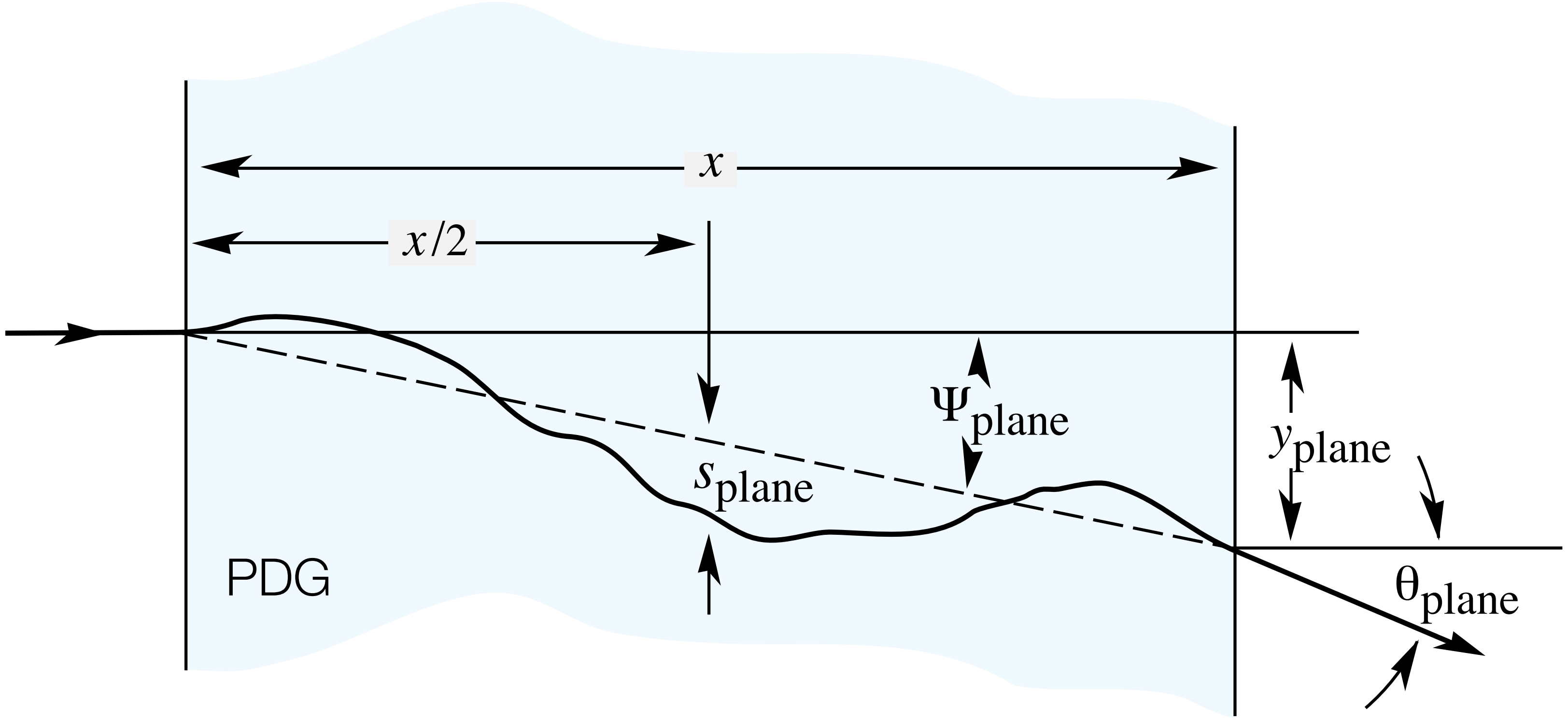

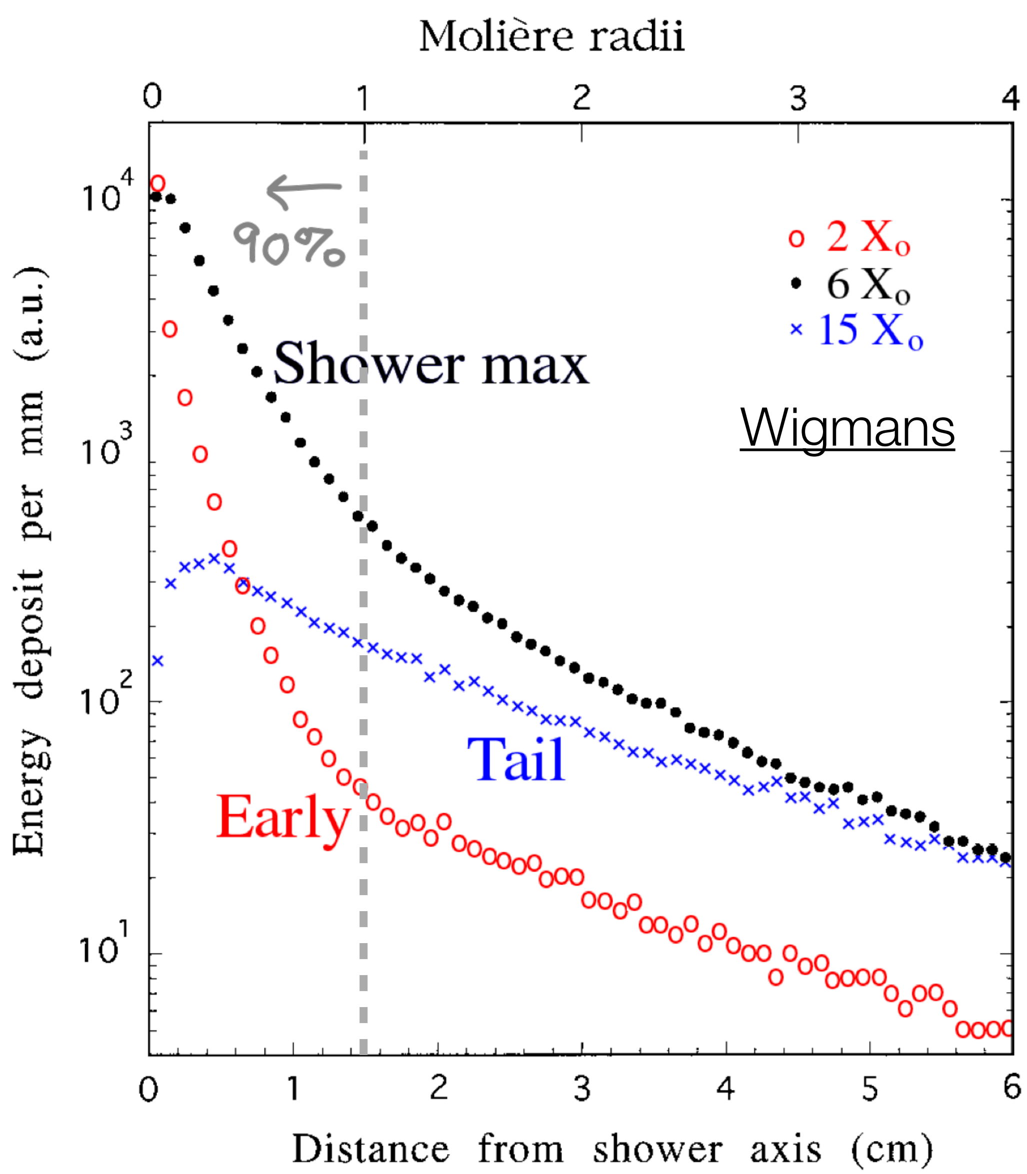

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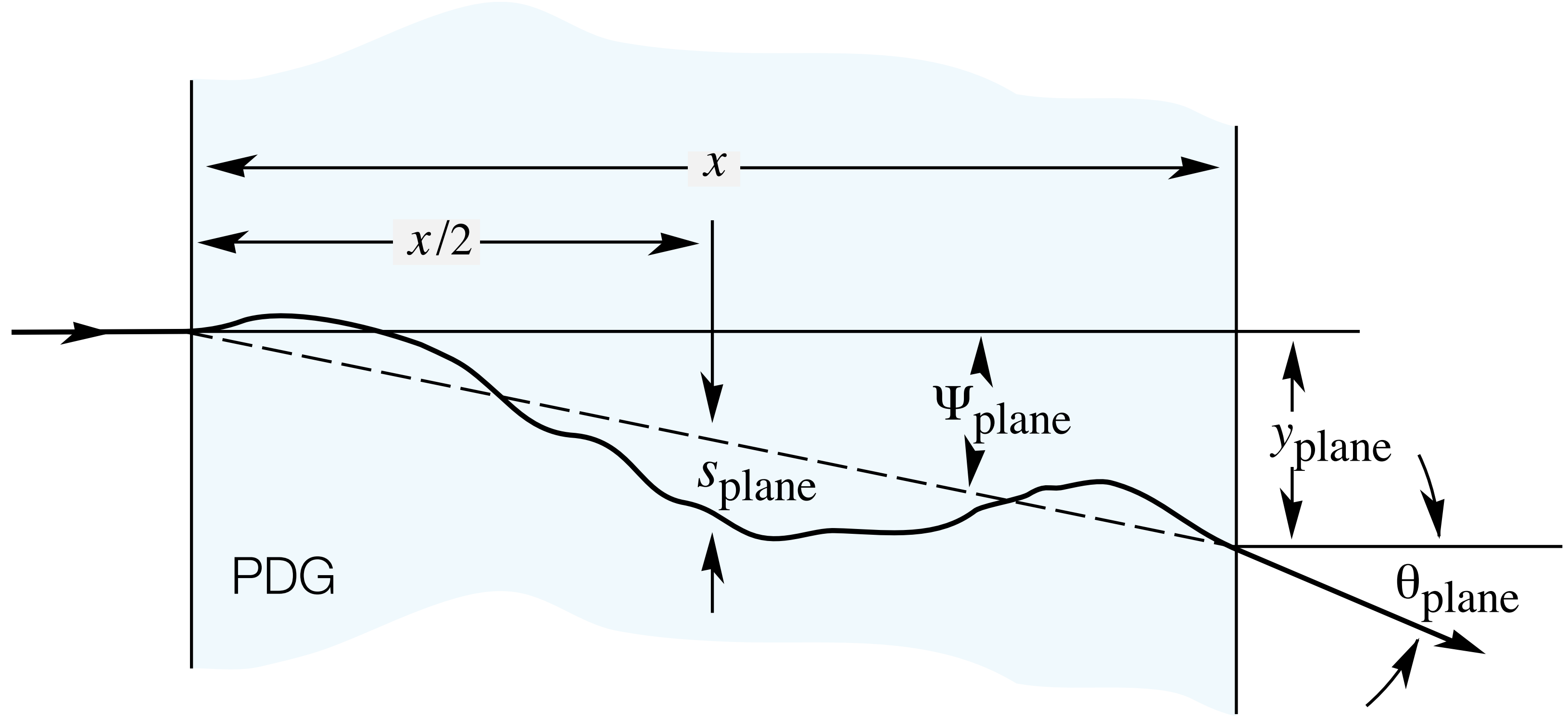

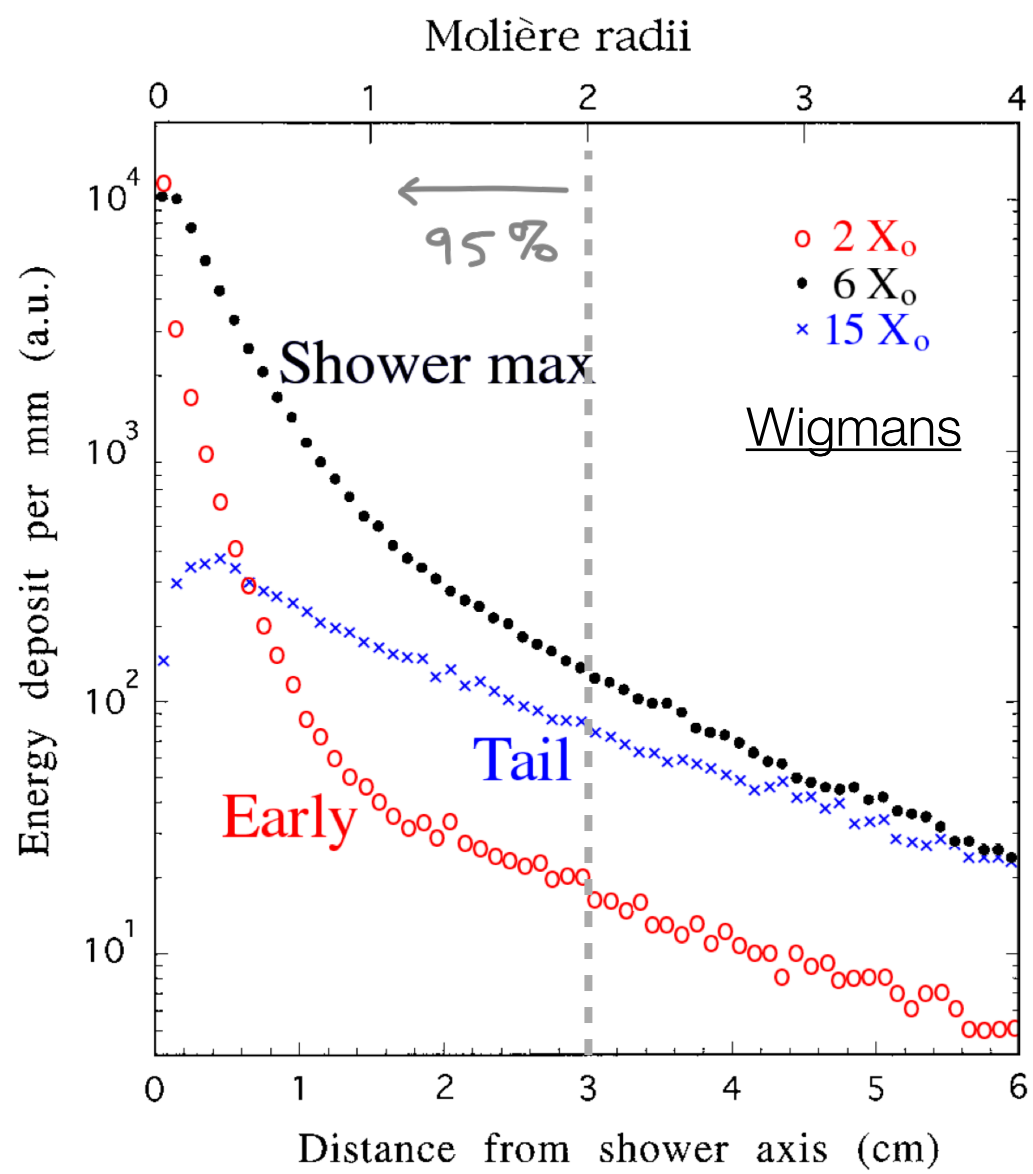

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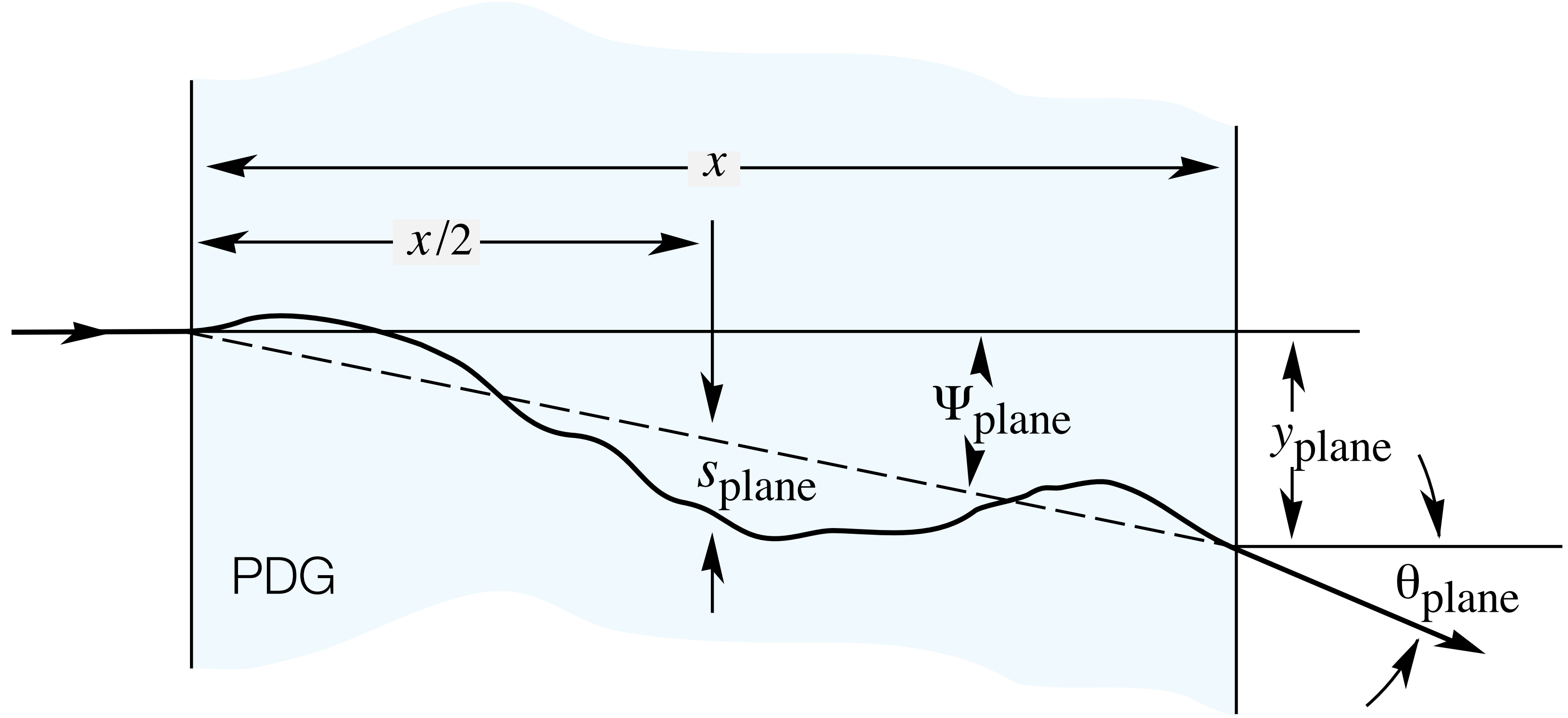

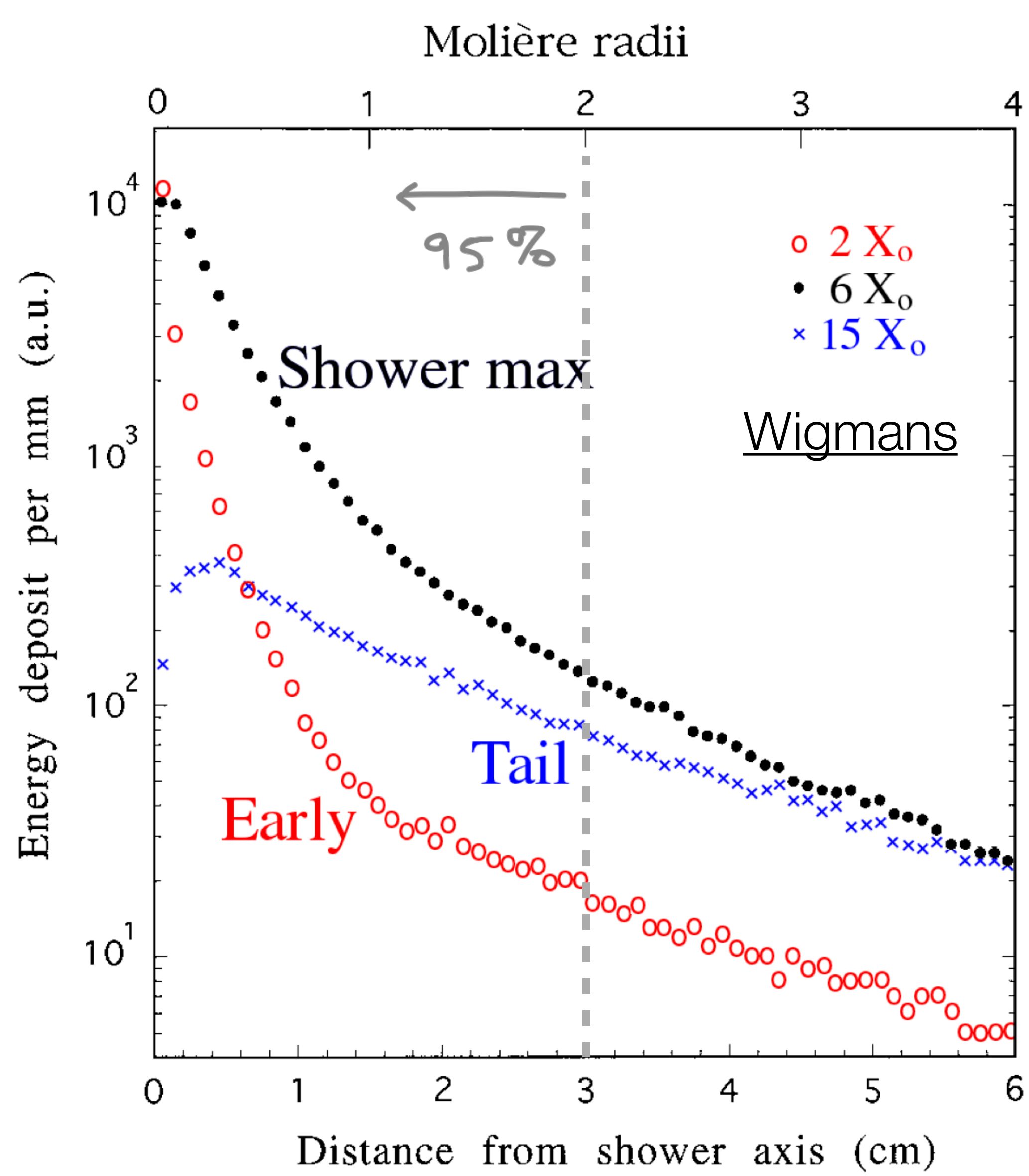

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$$\propto A/Z$$

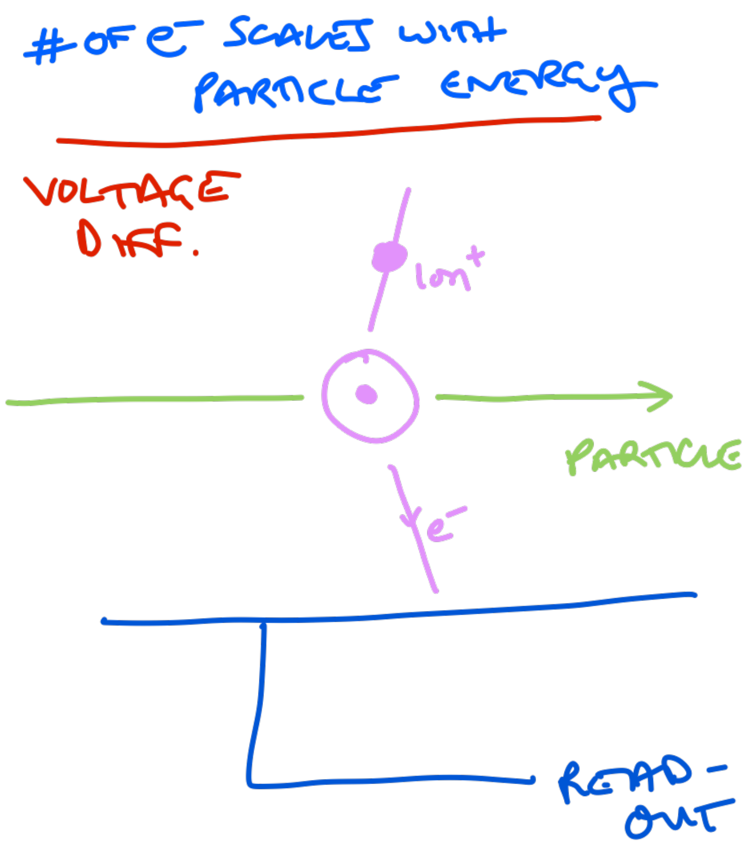
Recall $X_0 \propto A/Z^2$

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

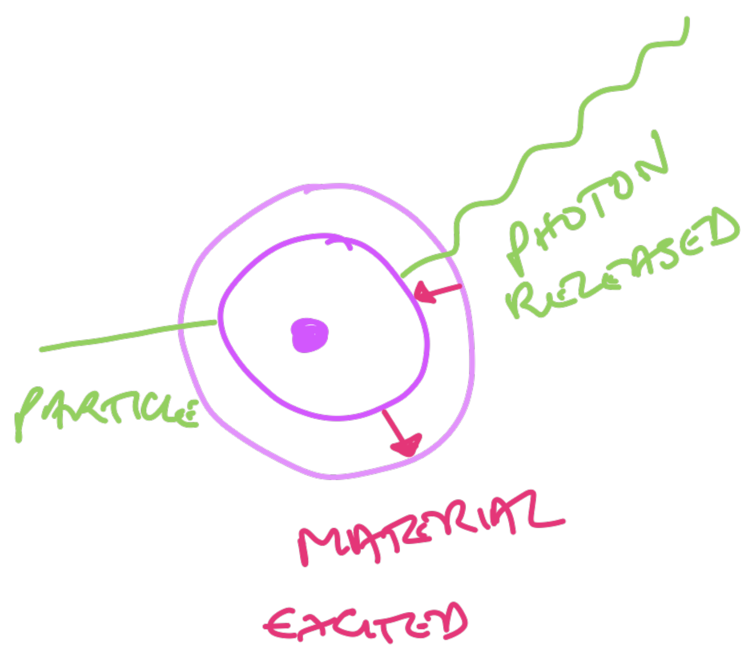
What happens at the end of the shower?

- In most materials, not much! In a block of lead, energy ultimately dissipates as heat. For us, this constitutes lost information.
- In other materials, well-defined process makes this energy visible to us.

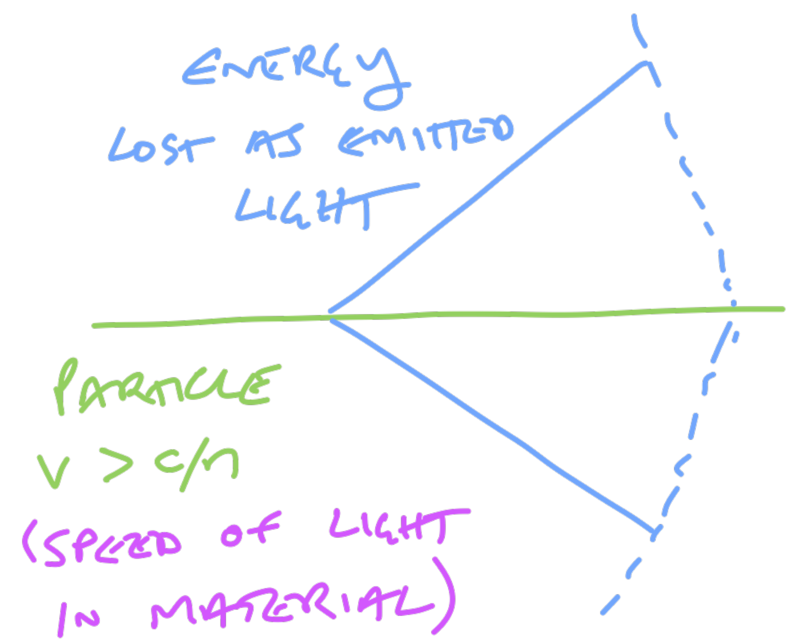
Ionisation

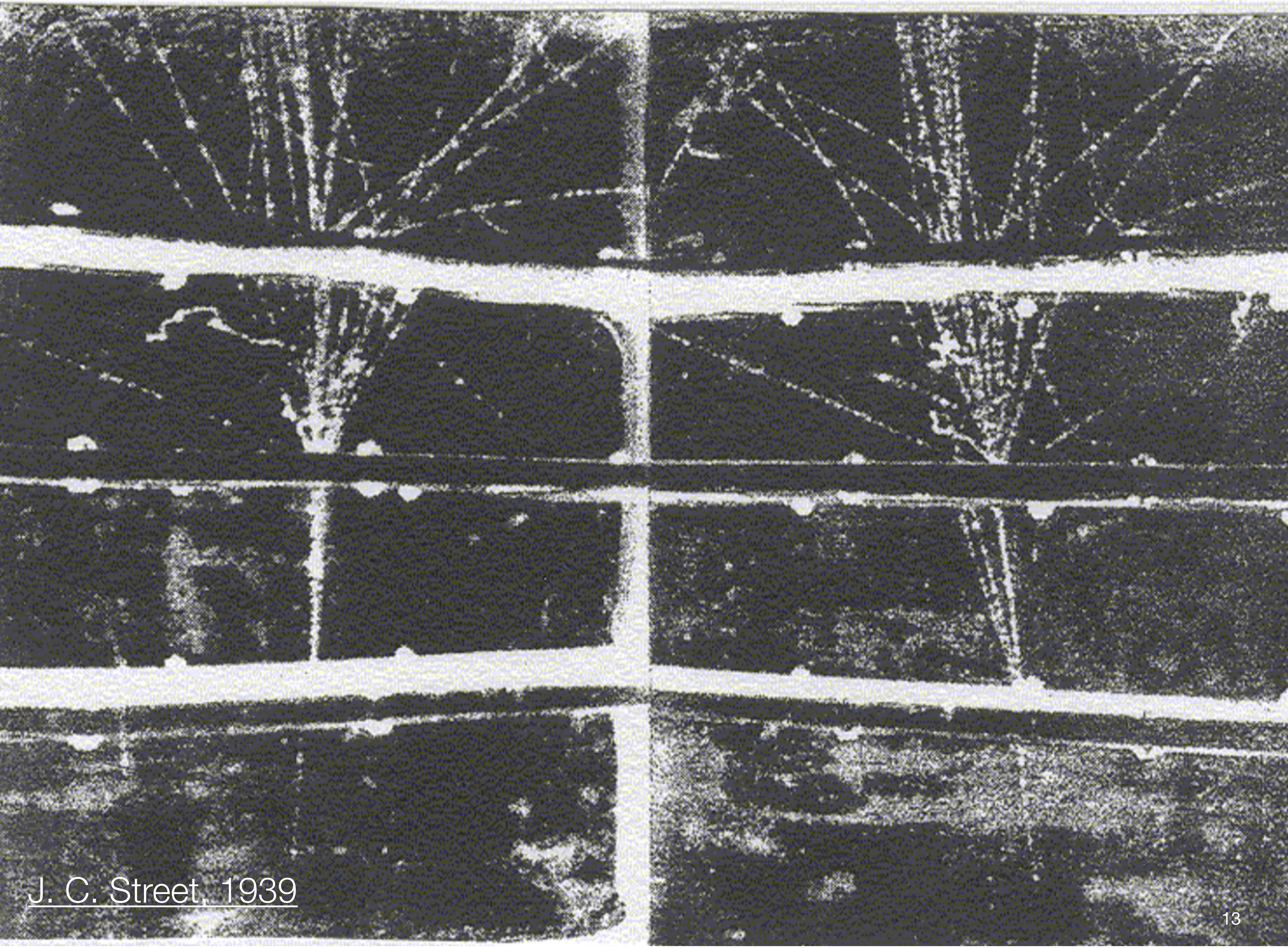


Scintillation



Cherenkov radiation



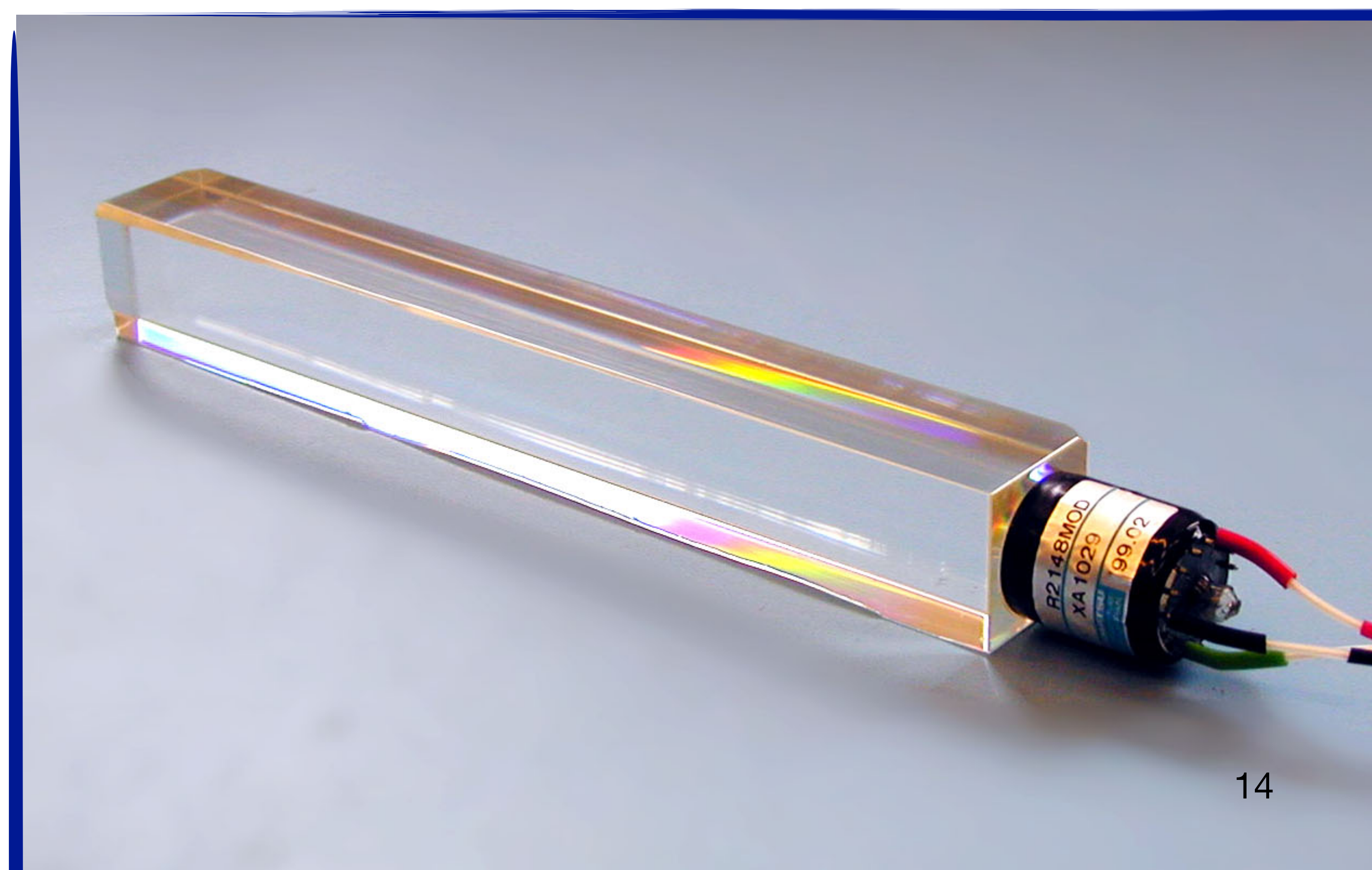


J. C. Street, 1939

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)



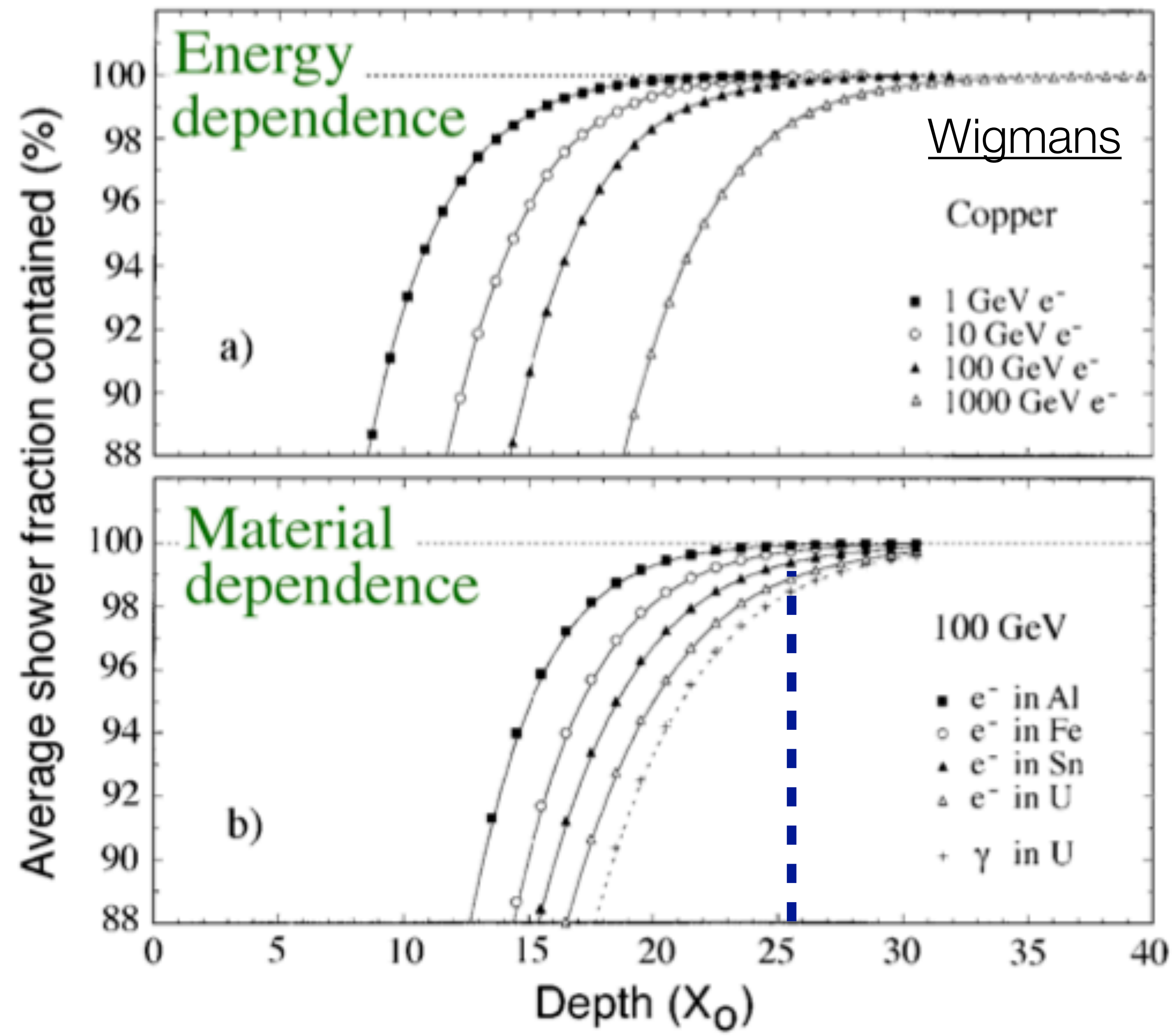
Scale of a *homogeneous* calorimeter

	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)



99% of shower contained after 19-26 X_0

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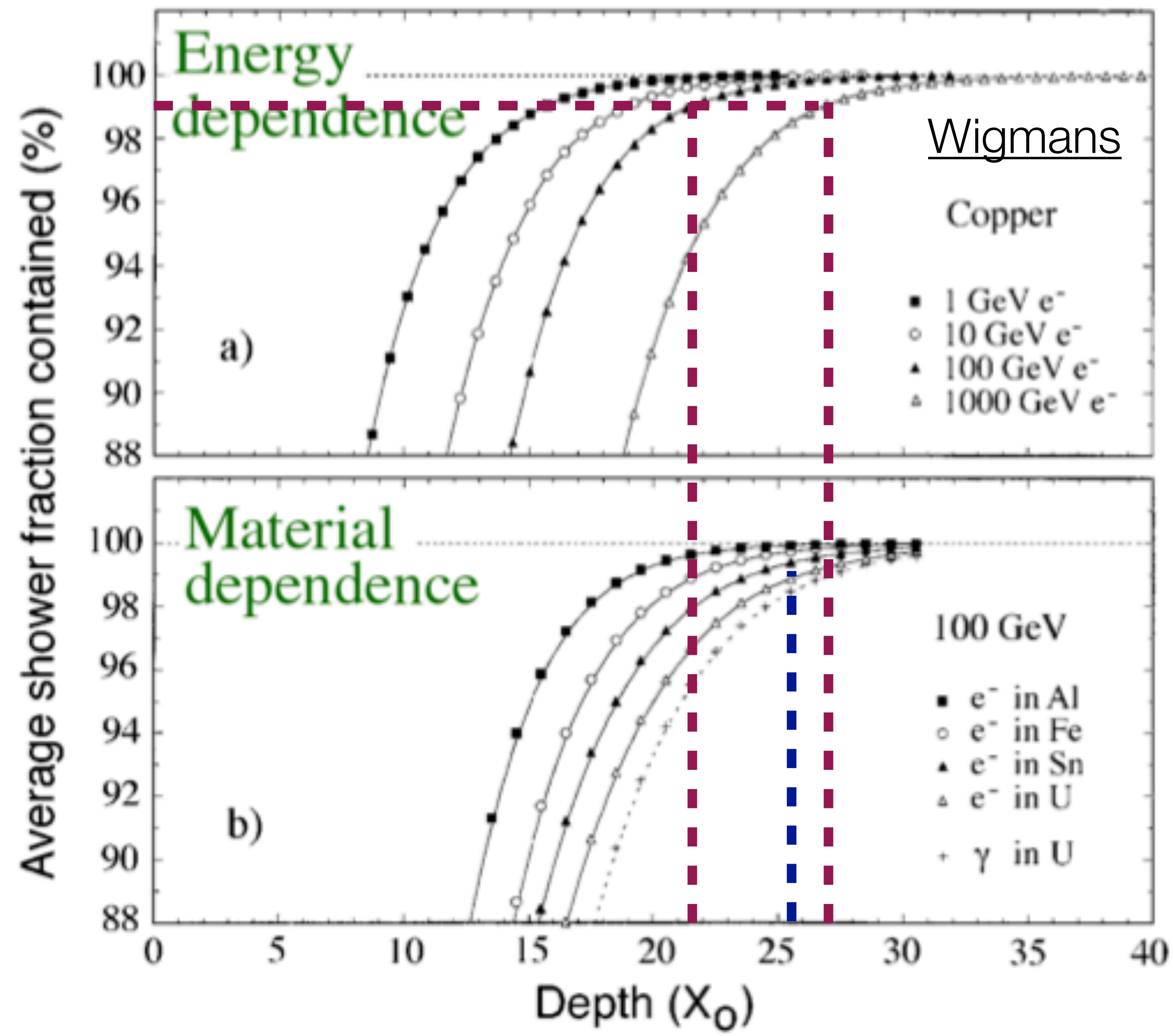

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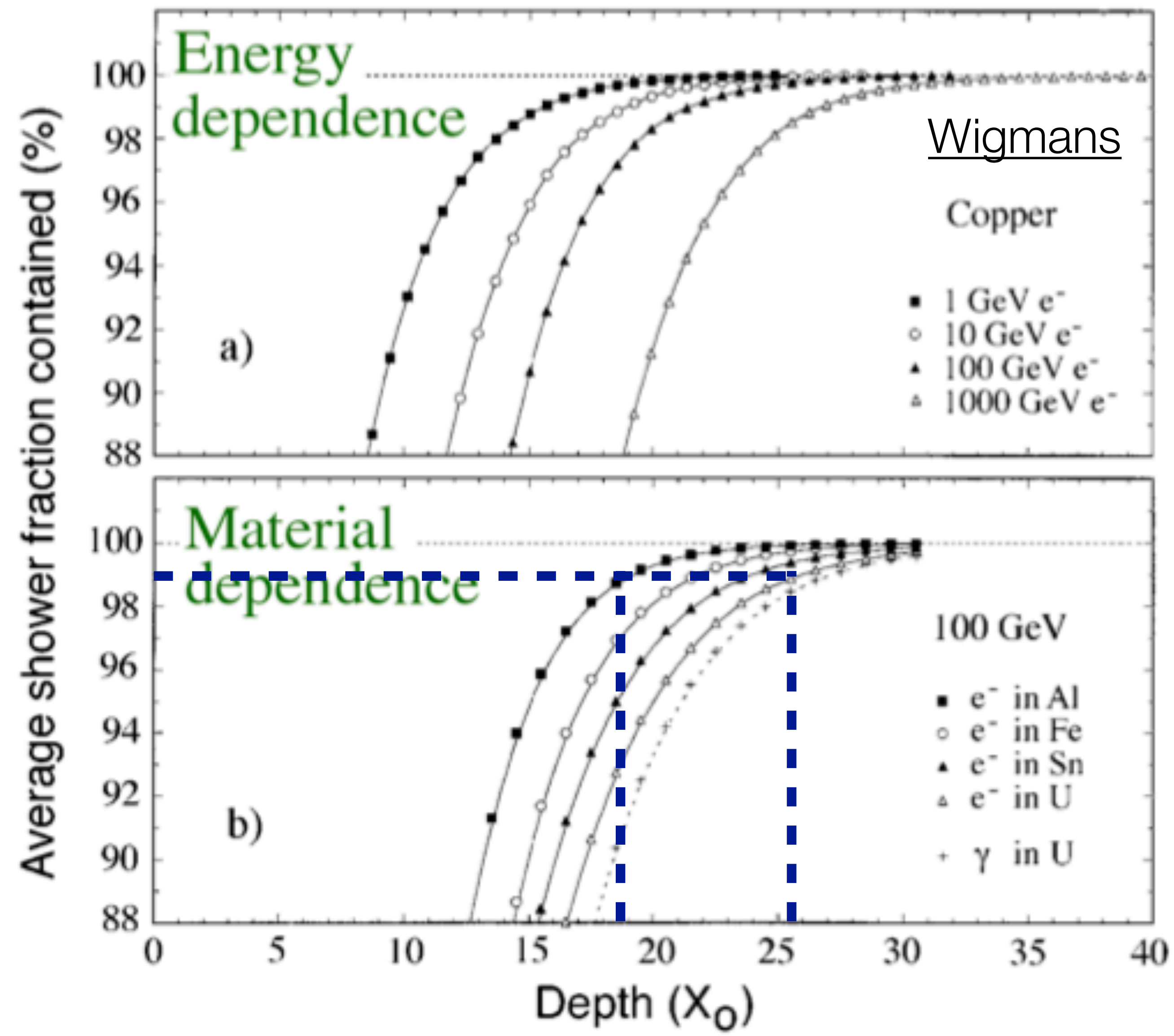

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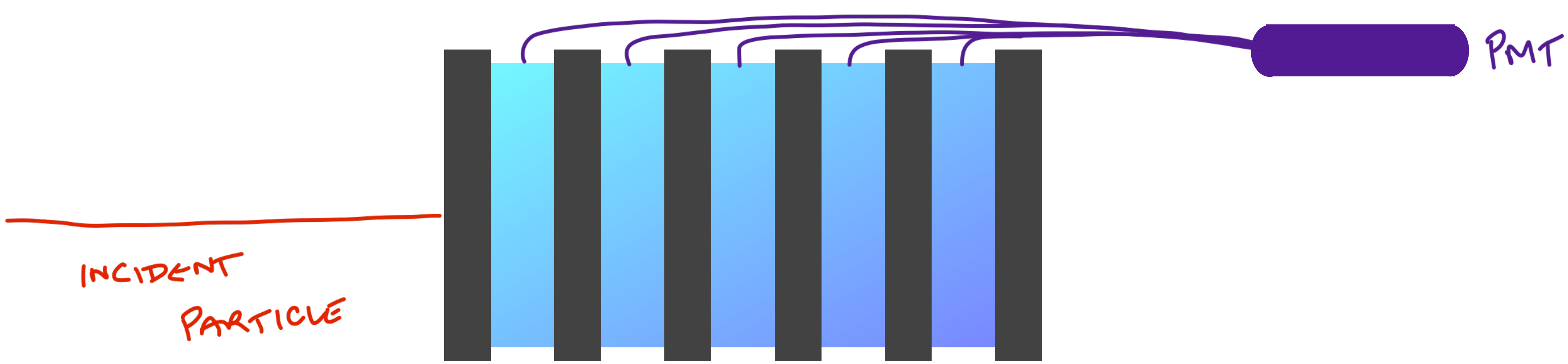
What if I don't have enough space/money?

- 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



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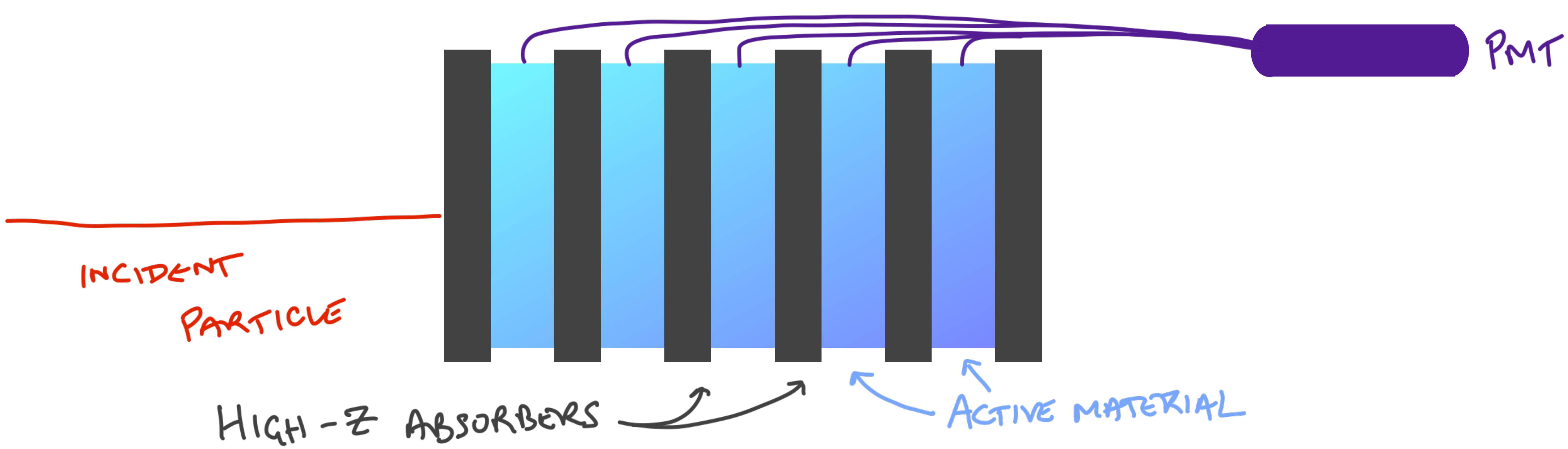

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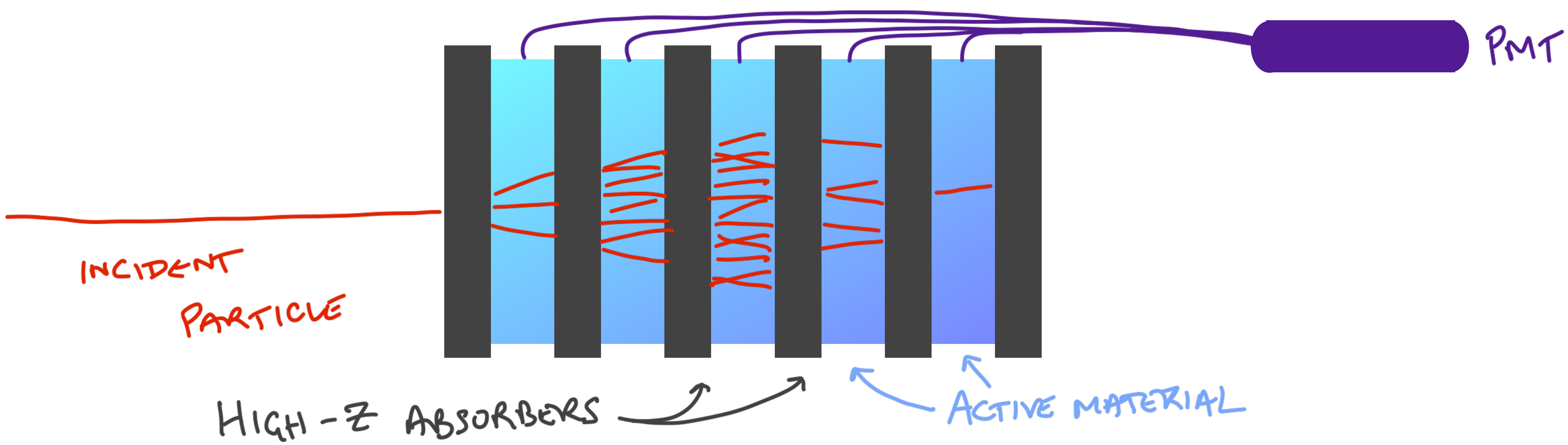

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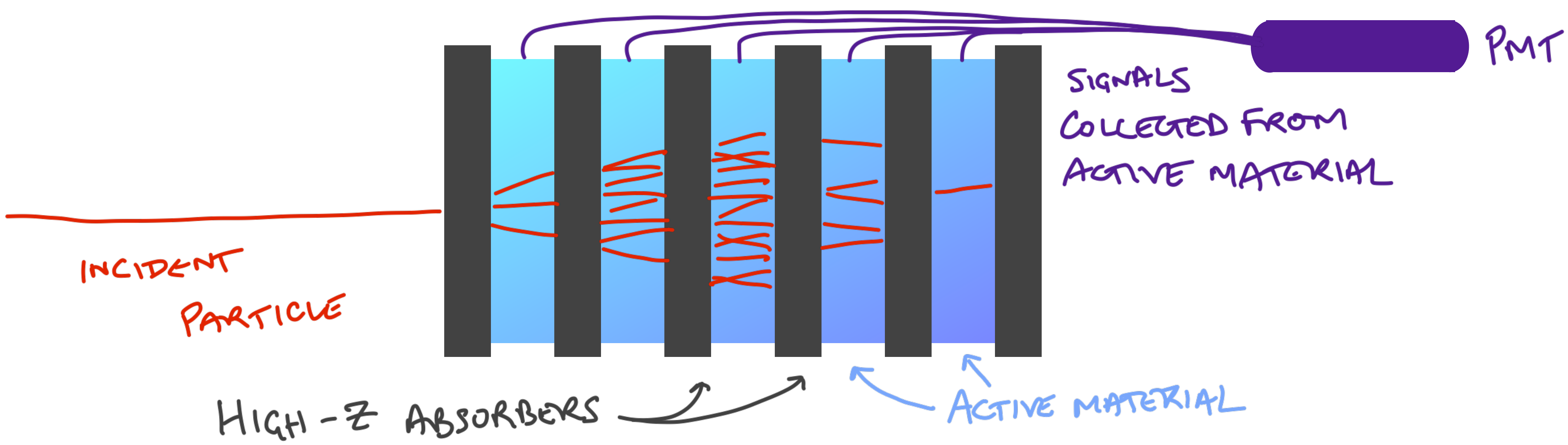

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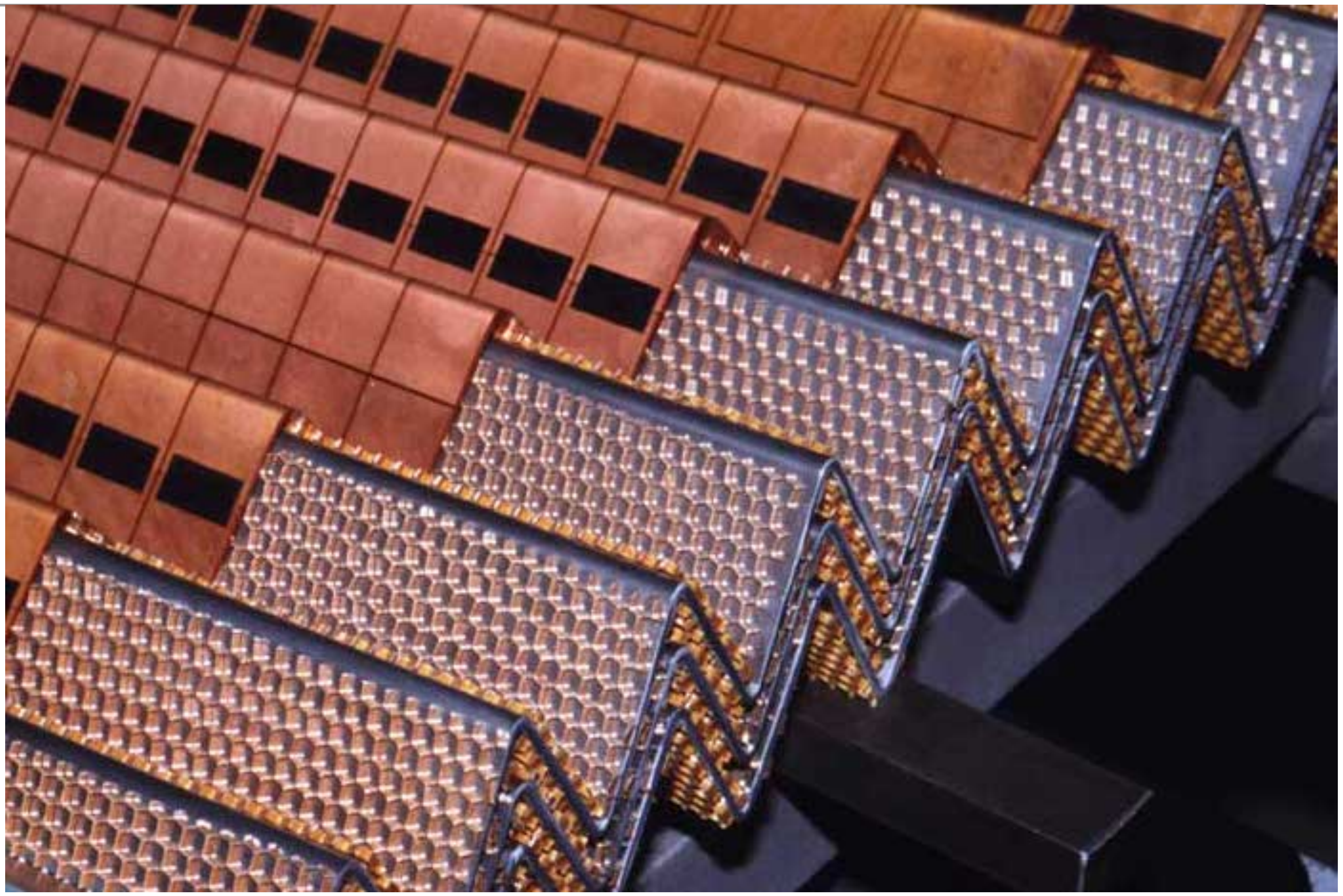
Example of a *sampling* calorimeter

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 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
- **Sampling calorimeters** have additional contribution from fluctuations in amount sampled

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~2 to 3%

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- **Sampling calorimeters** have additional contribution from fluctuations in amount sampled

Calorimeter resolution

Resolution contributions

Showering fluctuations and 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
- **Sampling calorimeters** have additional contribution from fluctuations in amount sampled

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

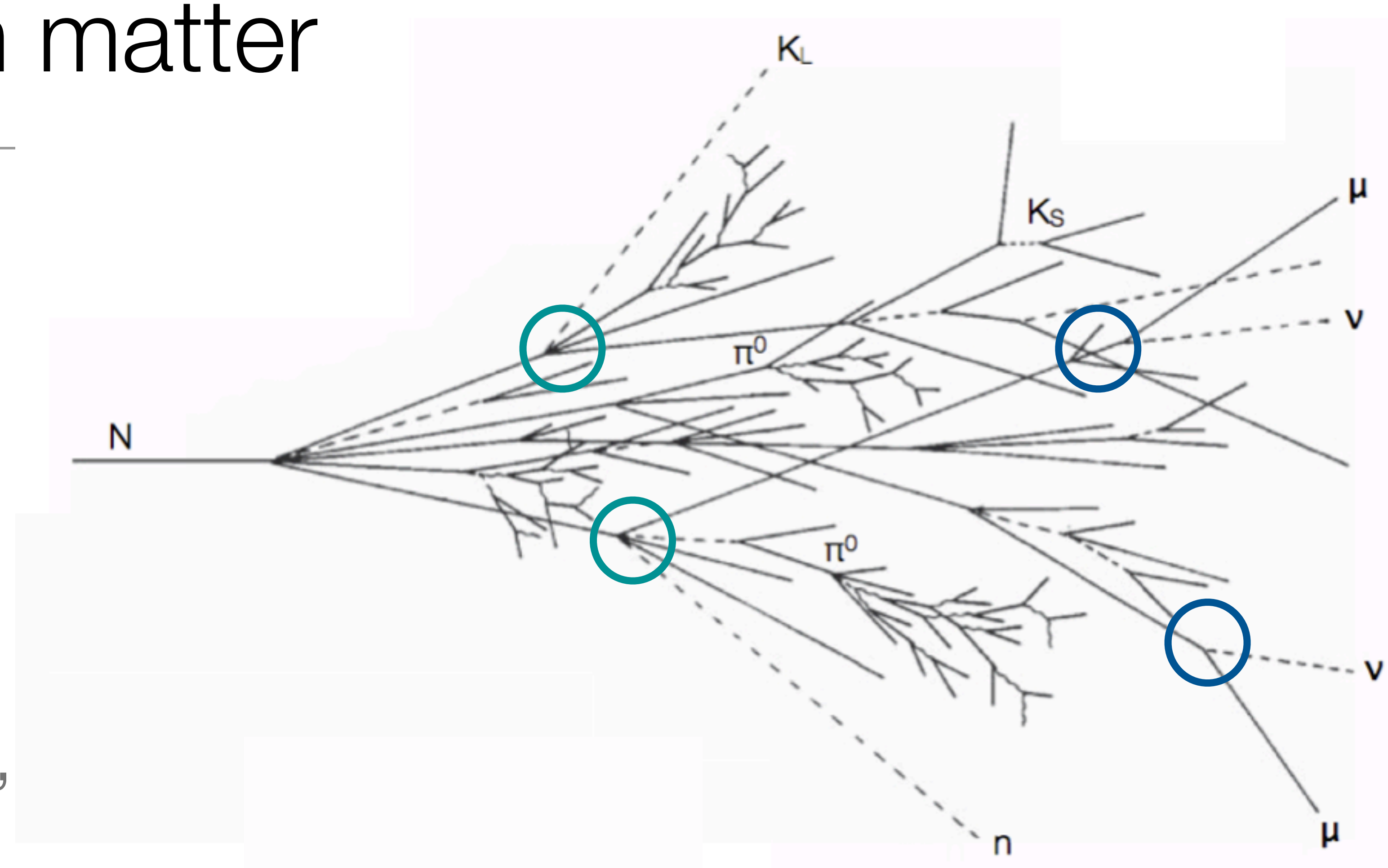
d = active layer thickness

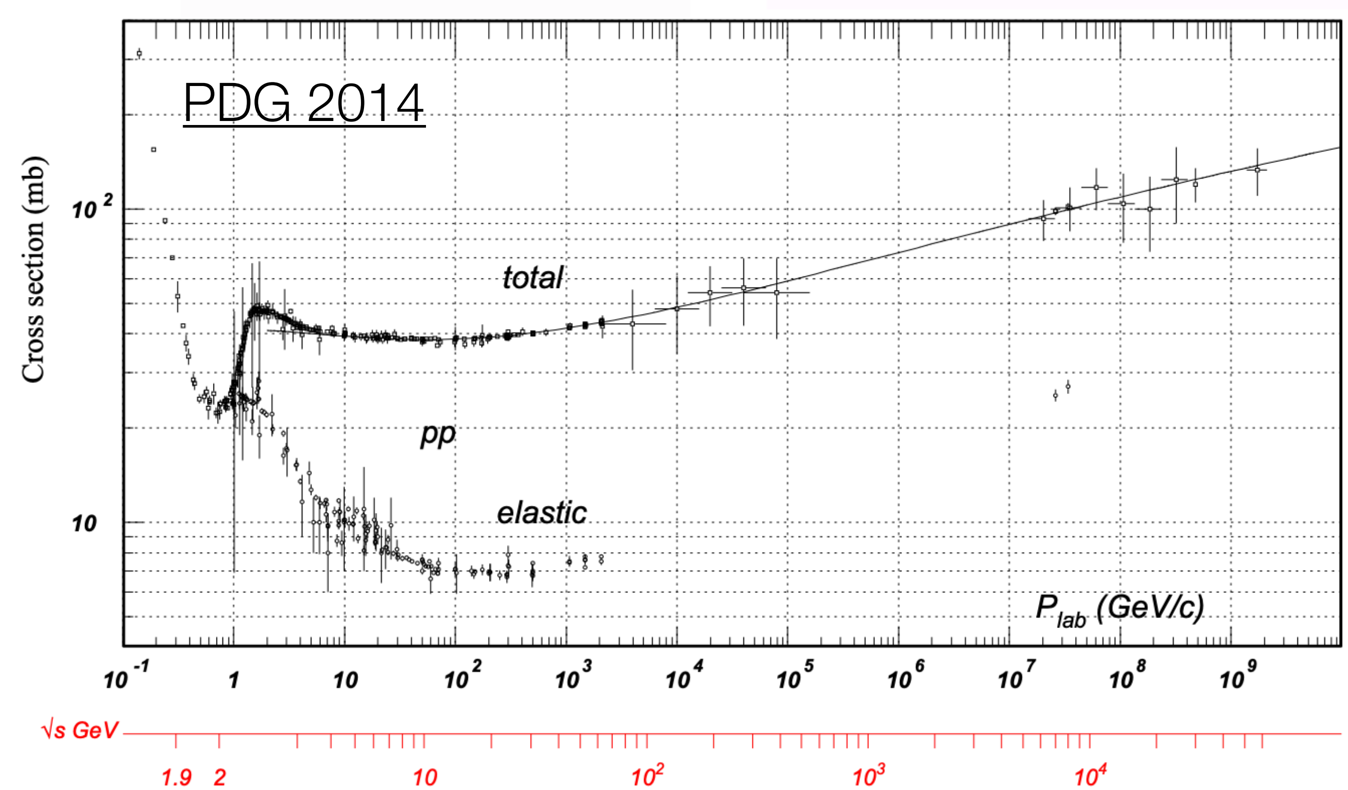
f_{samp} = sampling fraction

~ 5 to 15%

Hadronic showers in matter

- Strongly charged particles generate 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





Grupen & Shwartz, 2008

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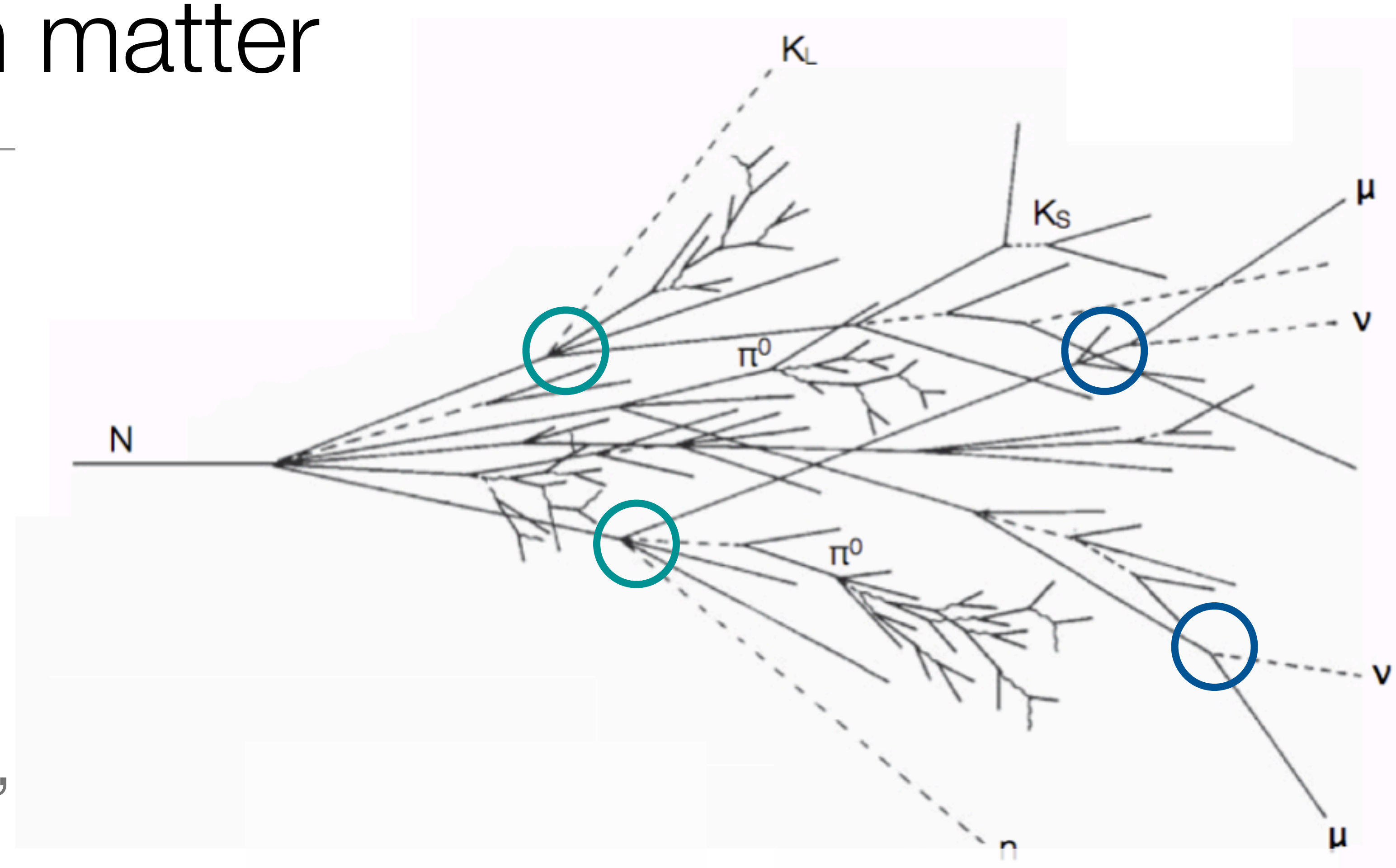
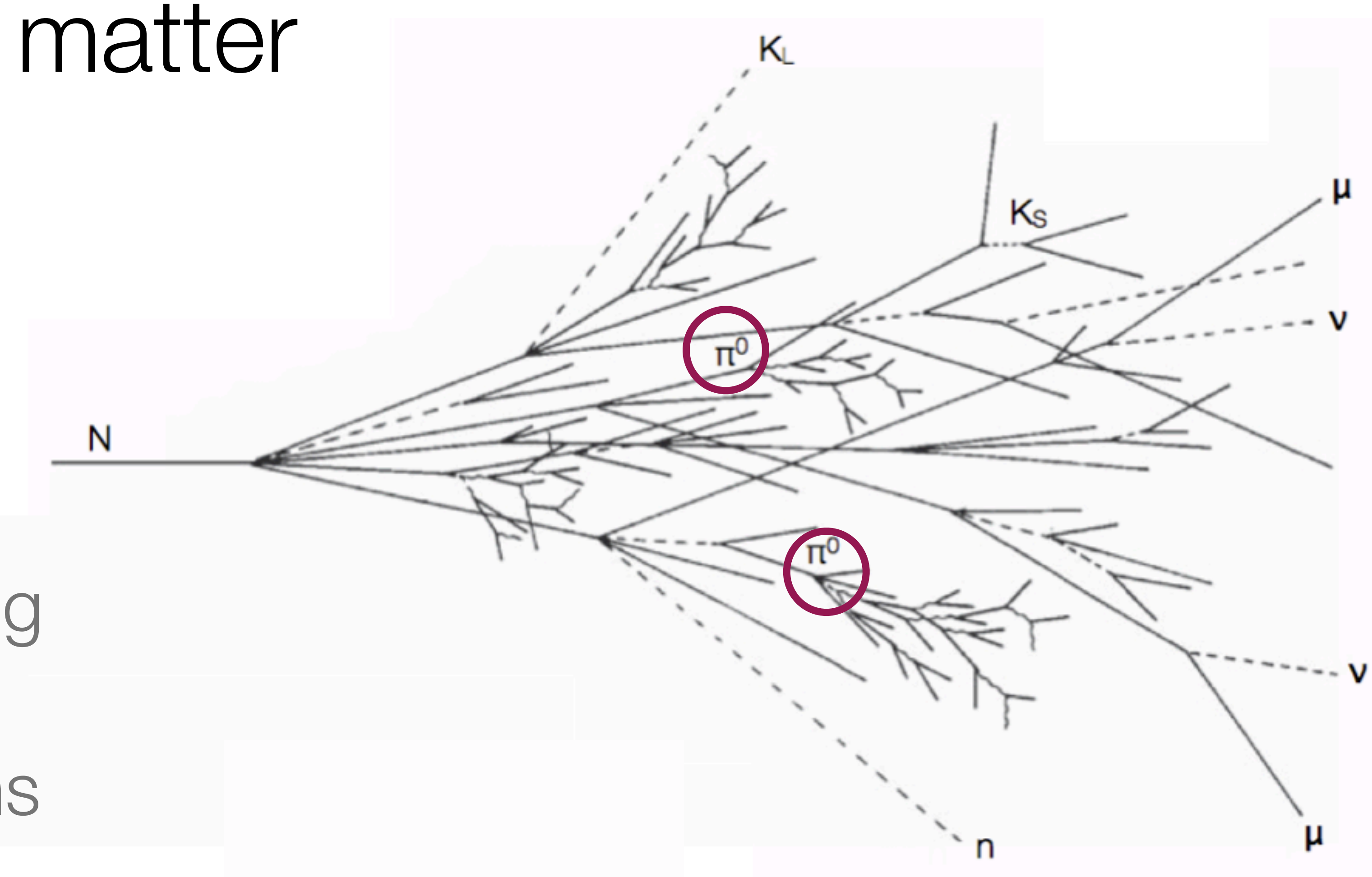


Non-compensation:

Response will always be < 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



Non-linearity:

Response is different (better) for higher-energy jets

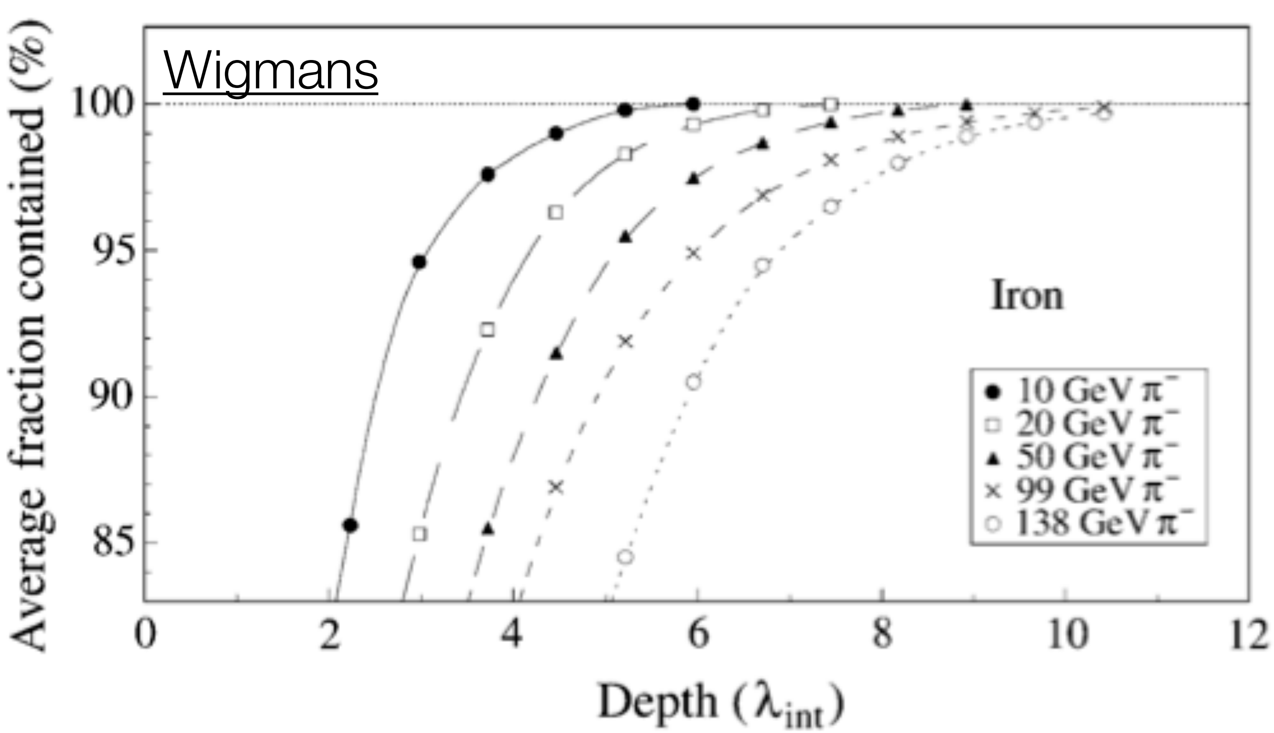
Size of a hadronic shower

- Equivalent of radiation length is *interaction length* λ_{int}
- Hadronic shower 95% contained within **9 λ_{int} longitudinally** and 1 λ_{int} transversely

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$$
$$\sim \sigma_{pp} \cdot A^{2/3}$$

$$\lambda_{\text{int}} = \frac{1}{\sigma_{tot} \cdot n} \approx \frac{A}{\sigma_{pp} A^{2/3} \cdot N_A \rho}$$

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



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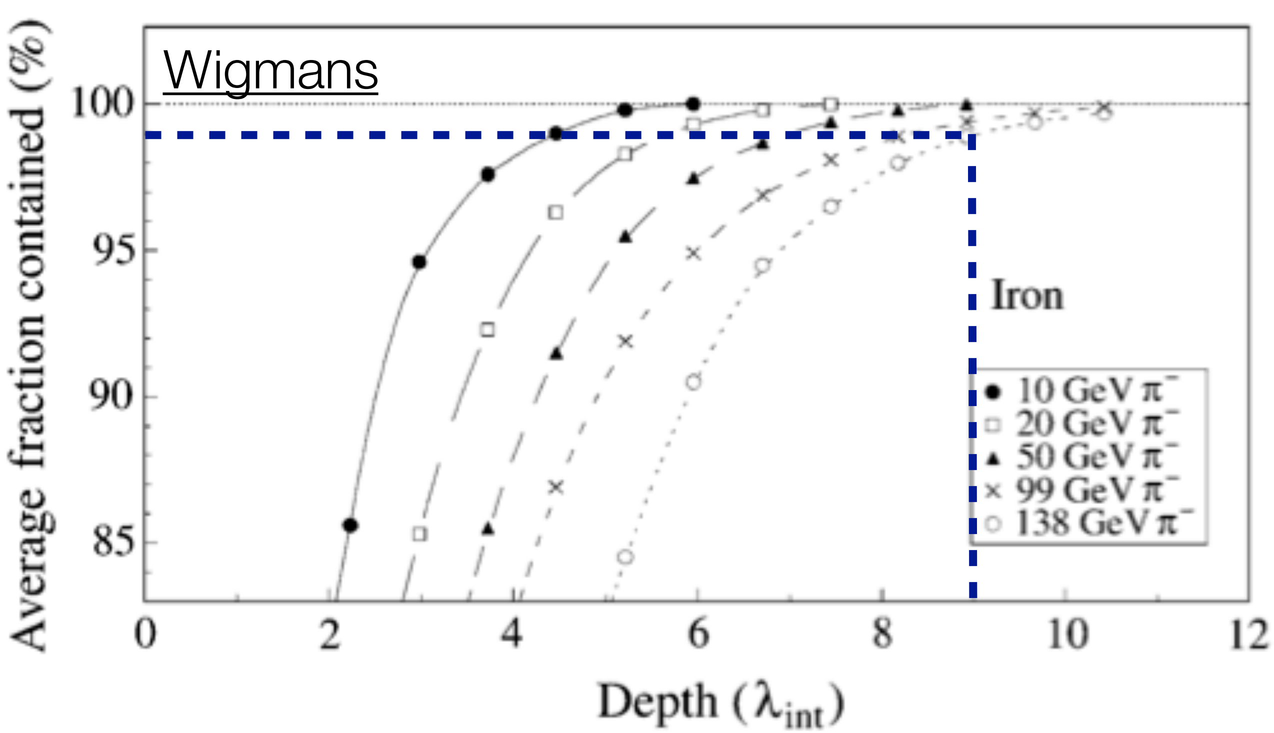

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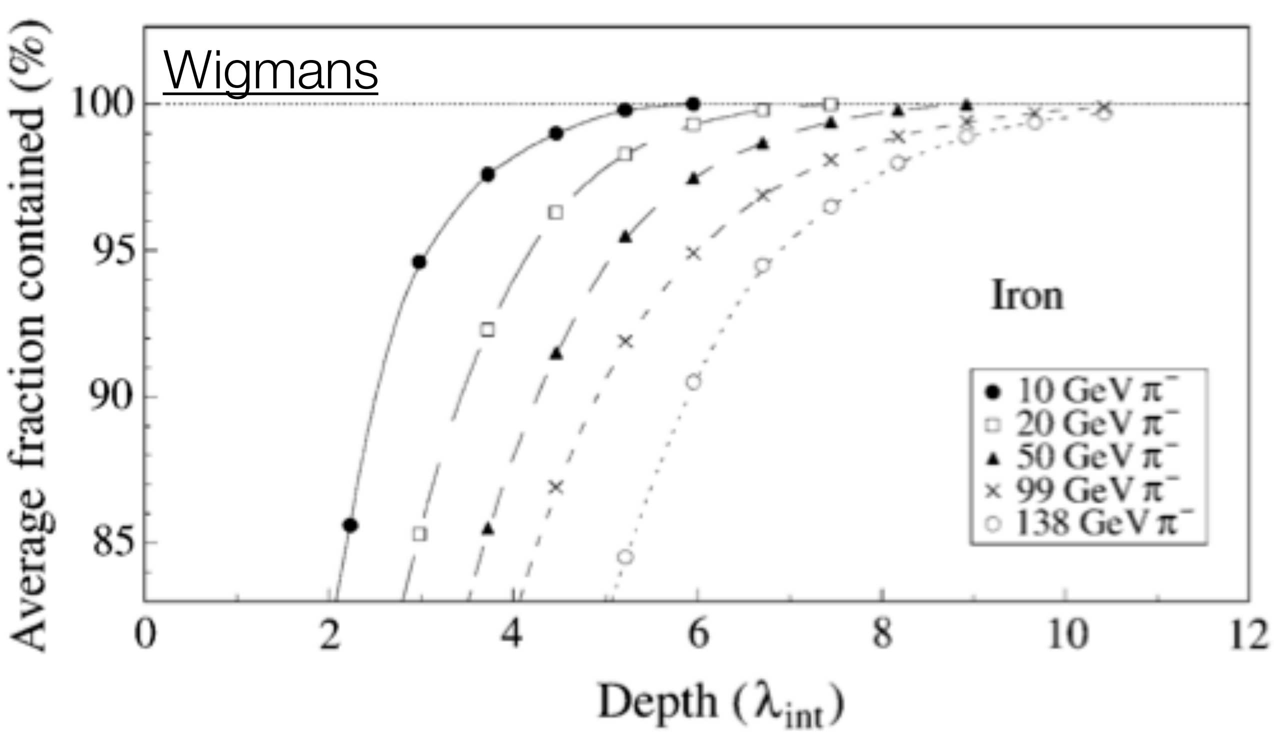

If $X_0 \propto 1/A$ and $\lambda_{int} \propto A^{1/3}$, then

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

→ 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 2014

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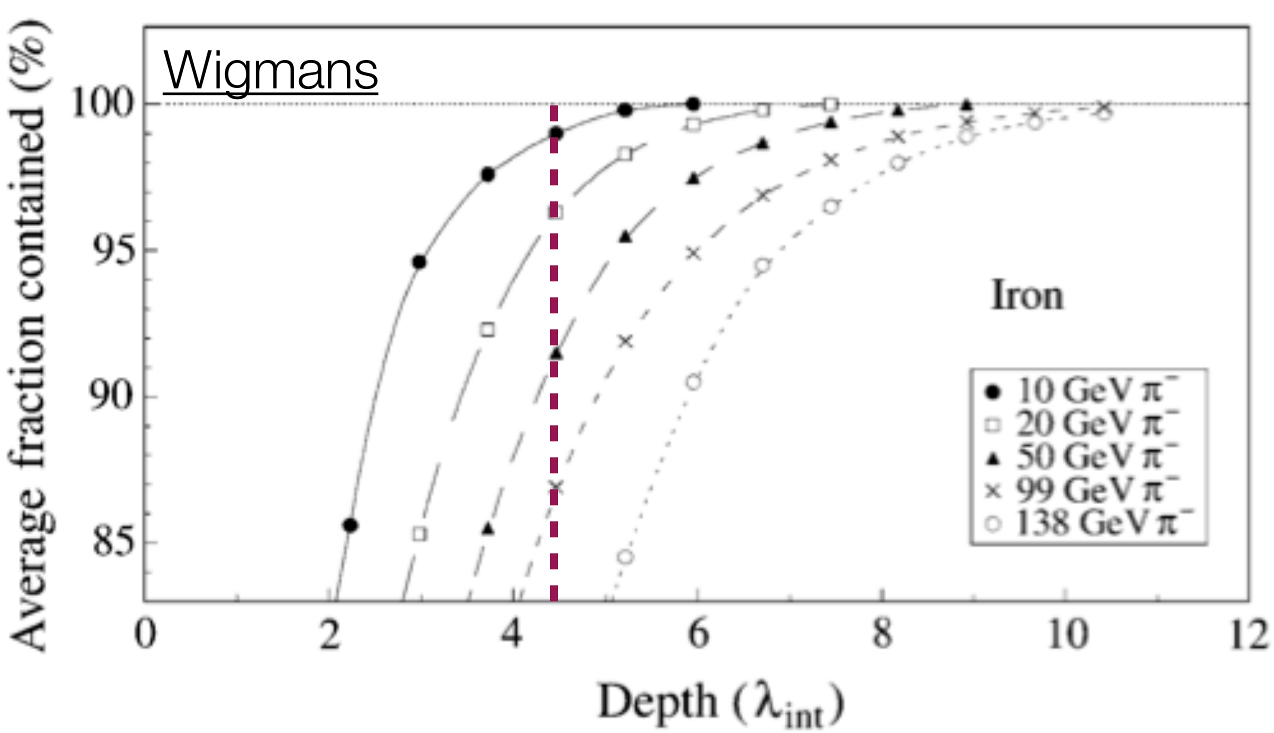

25 X_0: EM shower fully contained by here

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PDG 2014

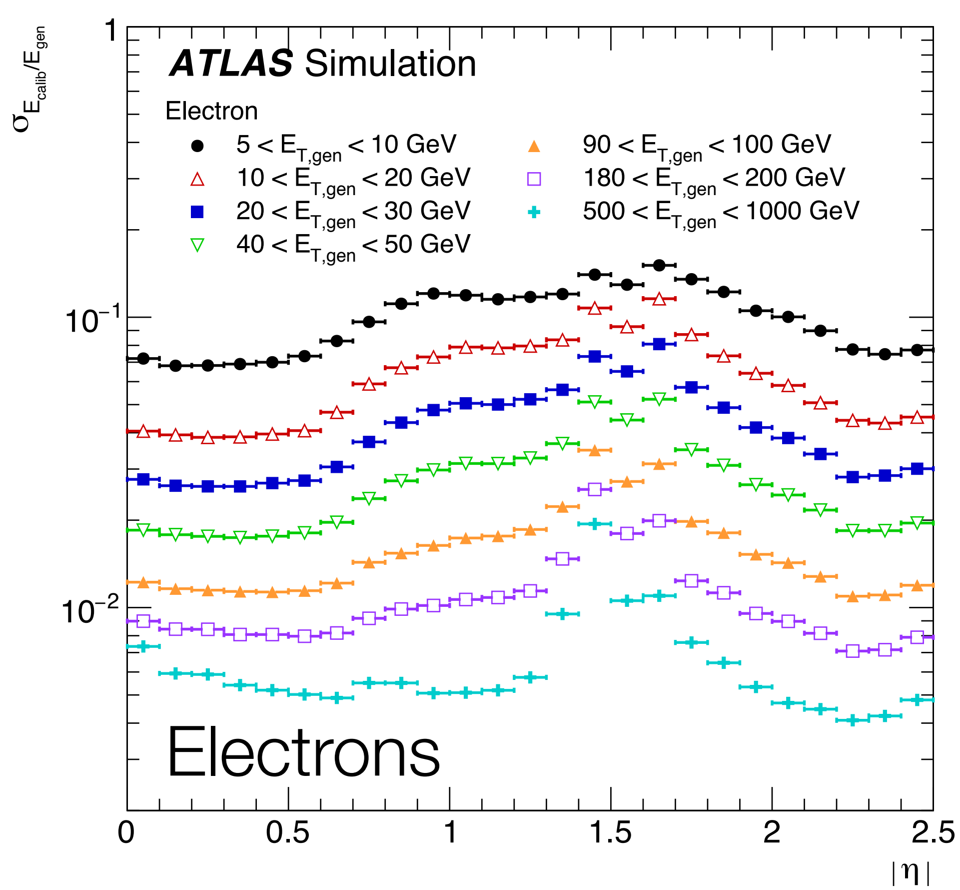
Hadronic calorimeter resolution

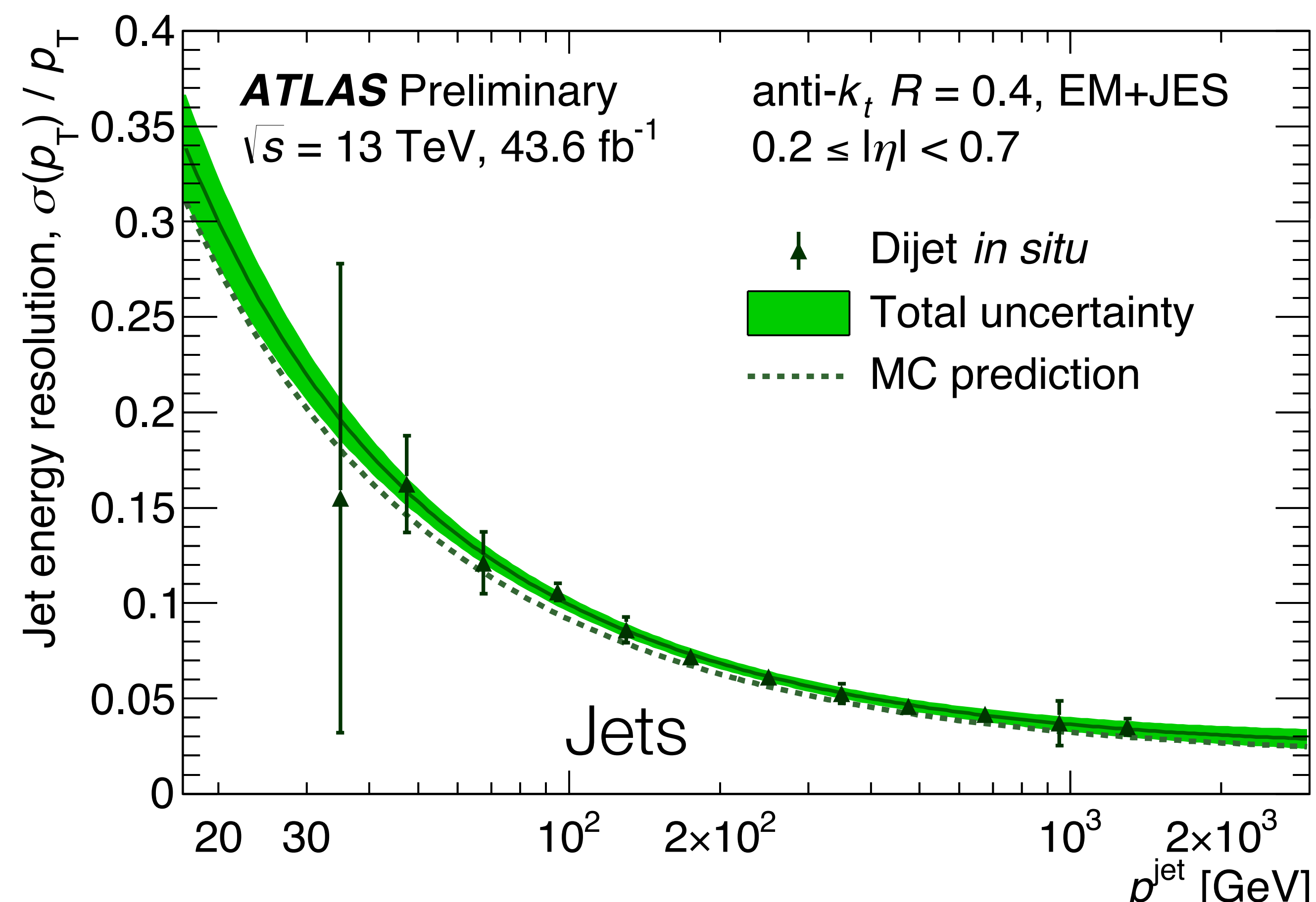
- Resolution worse for hadronic showers due to:
  - Fluctuations in amount of lost energy (neutrinos, muons, neutral hadrons, nuclear excitation energy, …)
  - Fluctuations in EM fraction of showers
  - Varying degrees of shower leakage

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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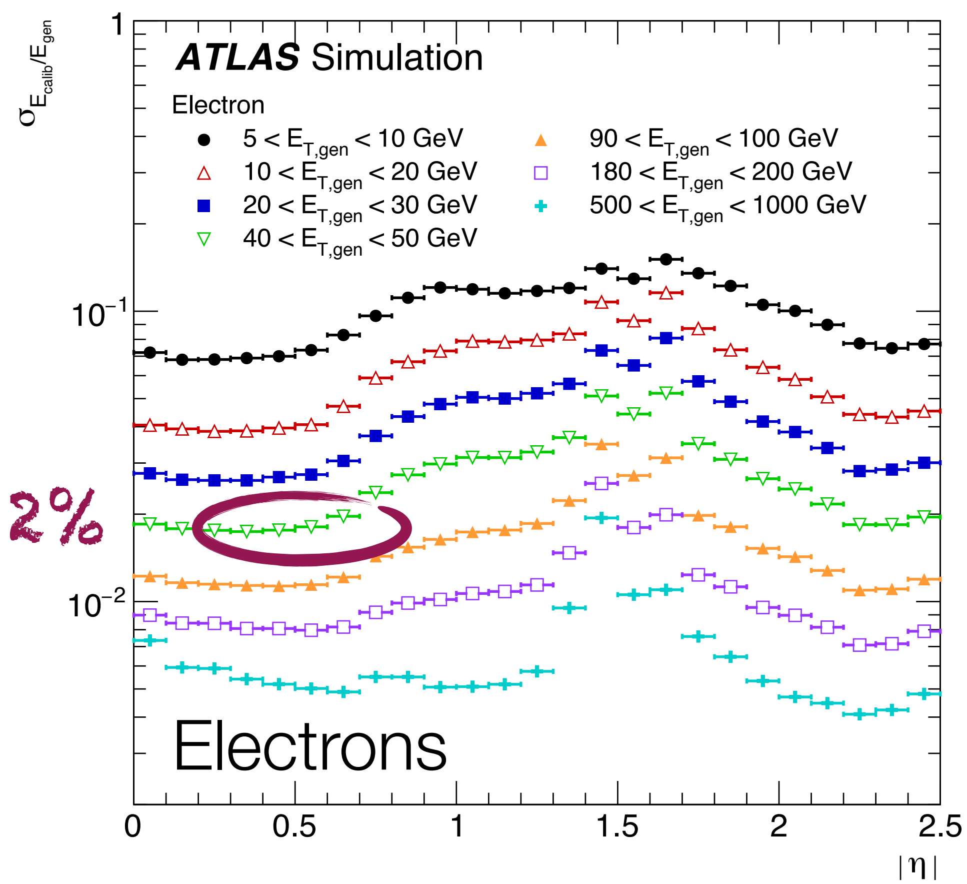

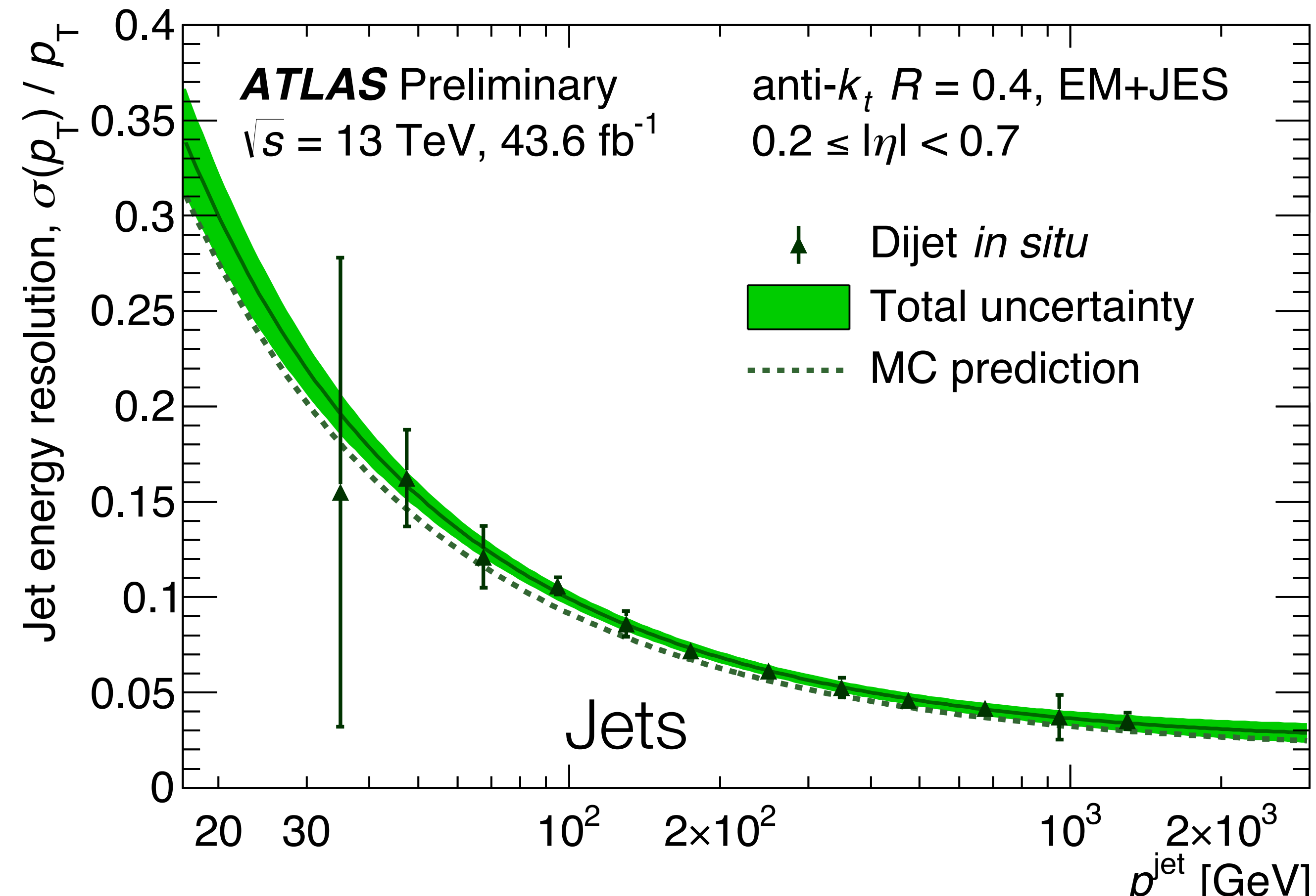

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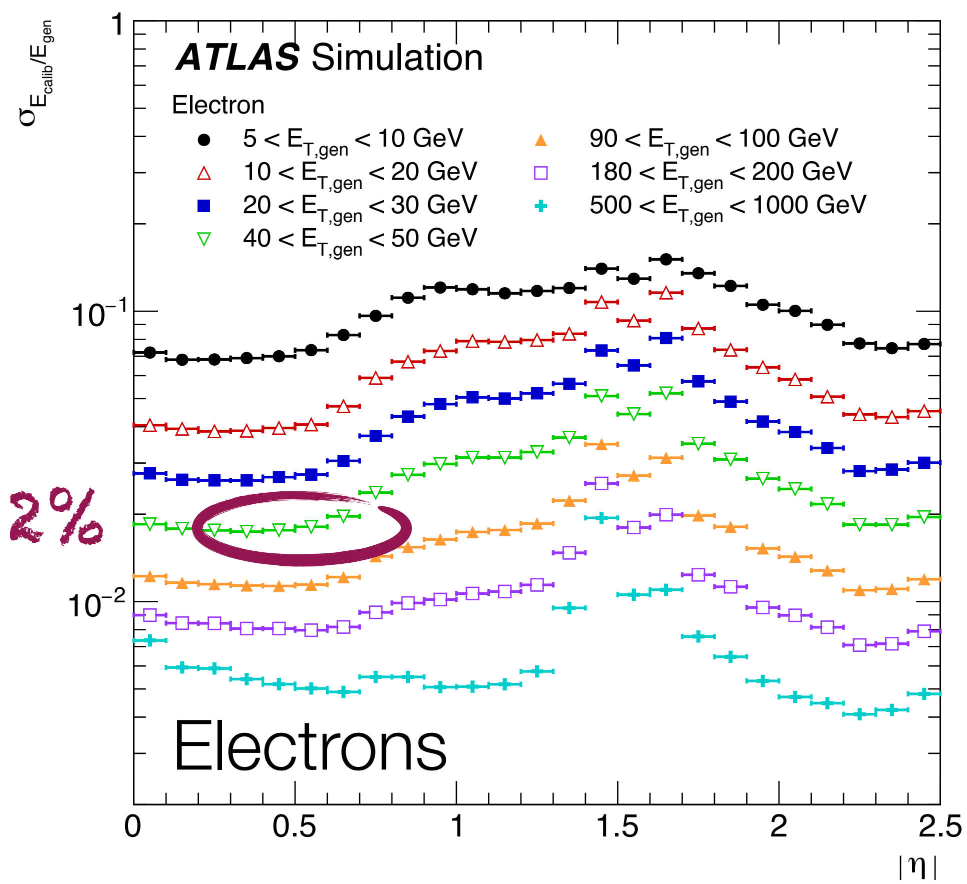
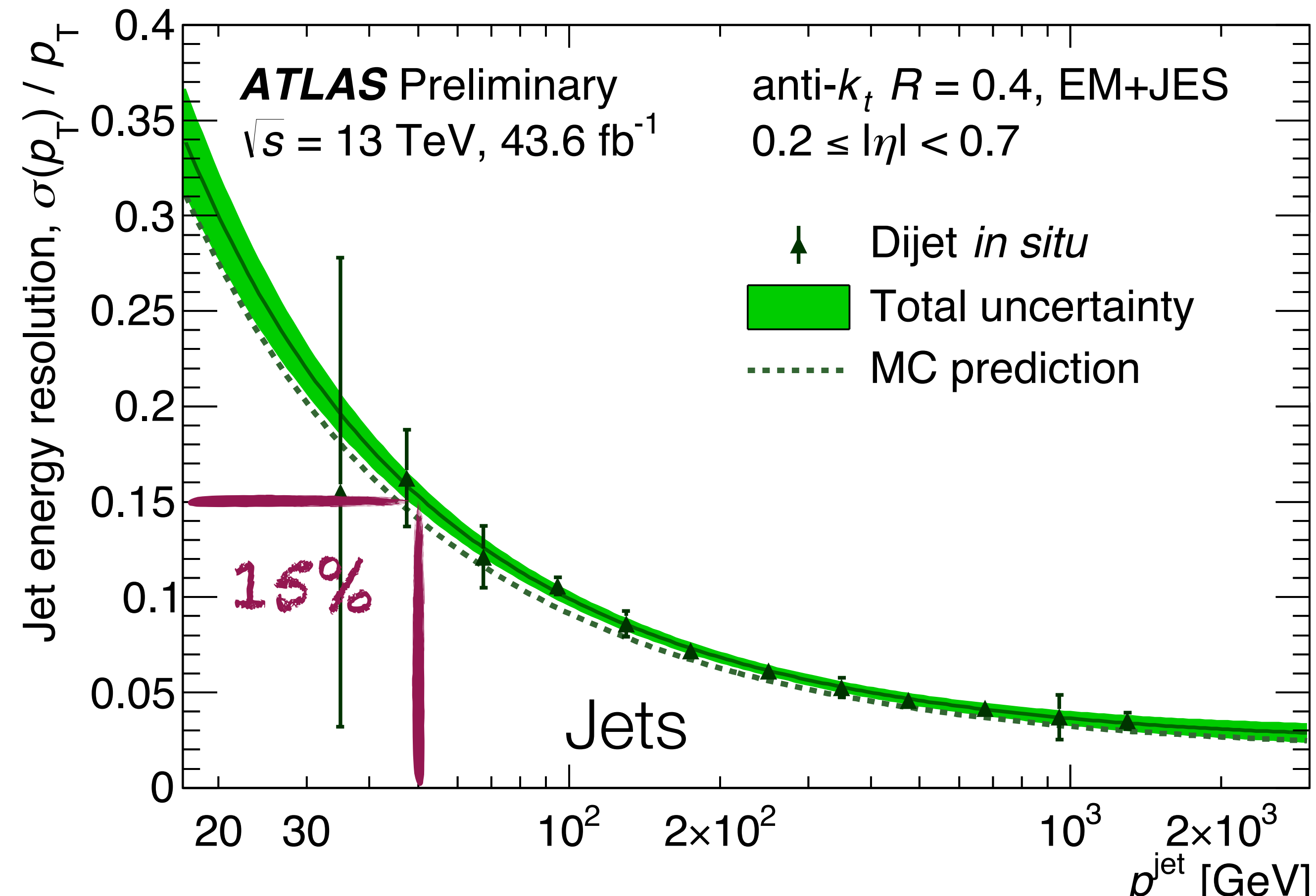
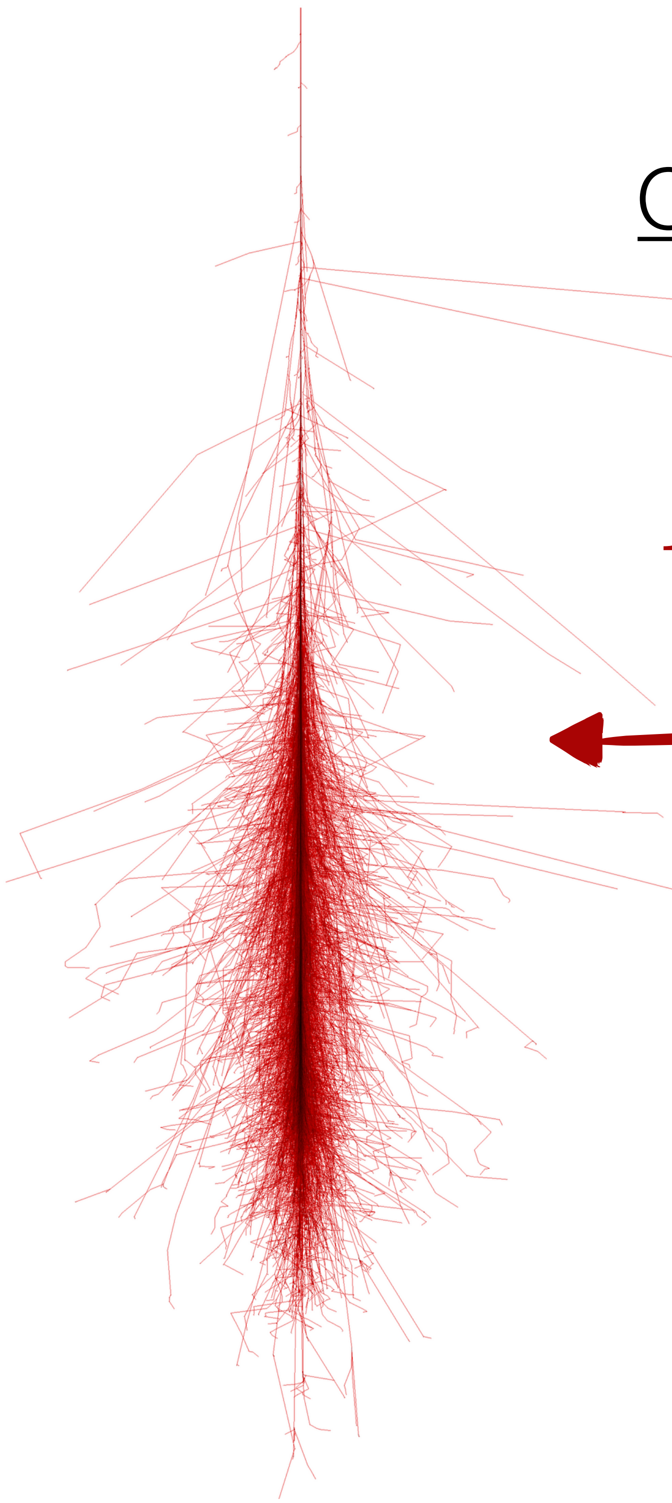




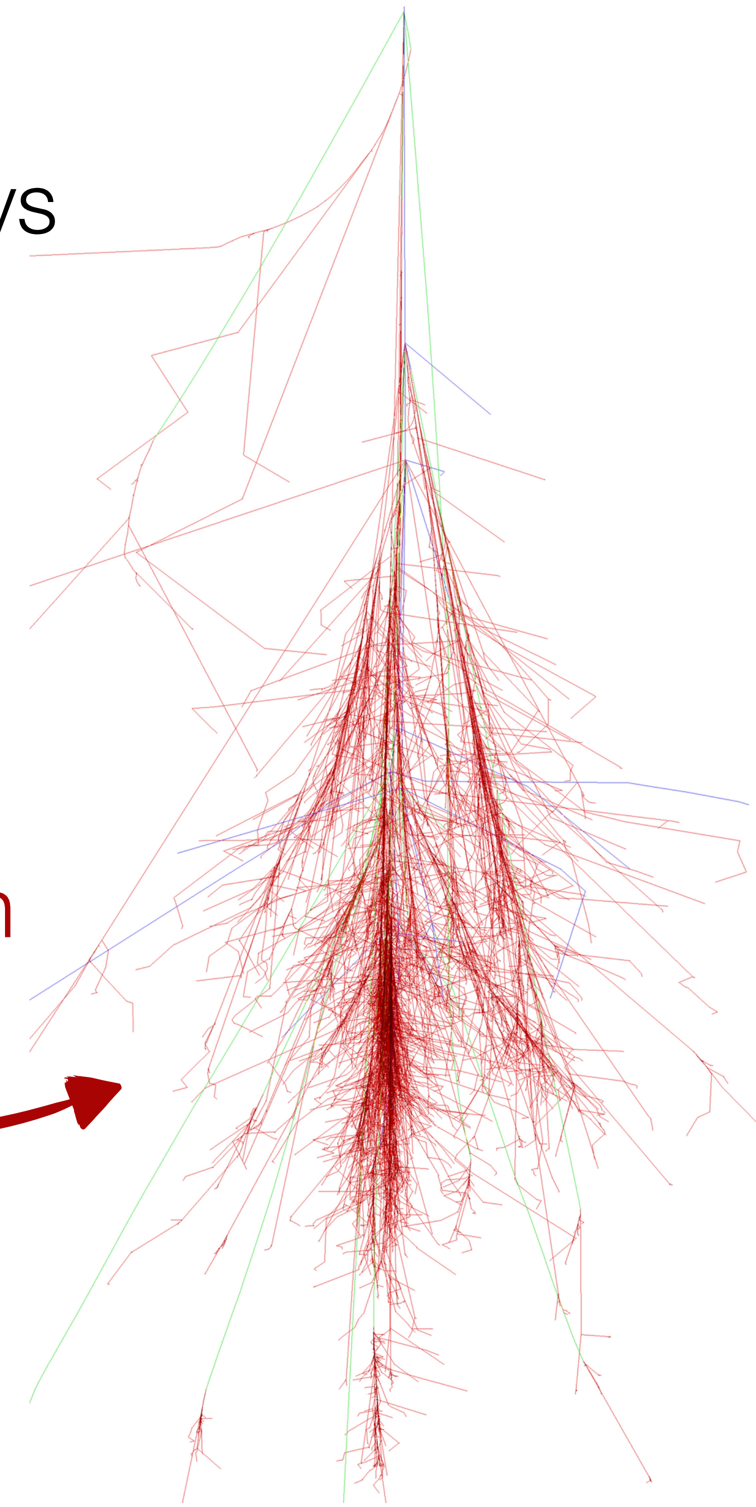
Hadronic versus electromagnetic showers



Simulations from CORSIKA of cosmic rays showering in air

100 GeV photon

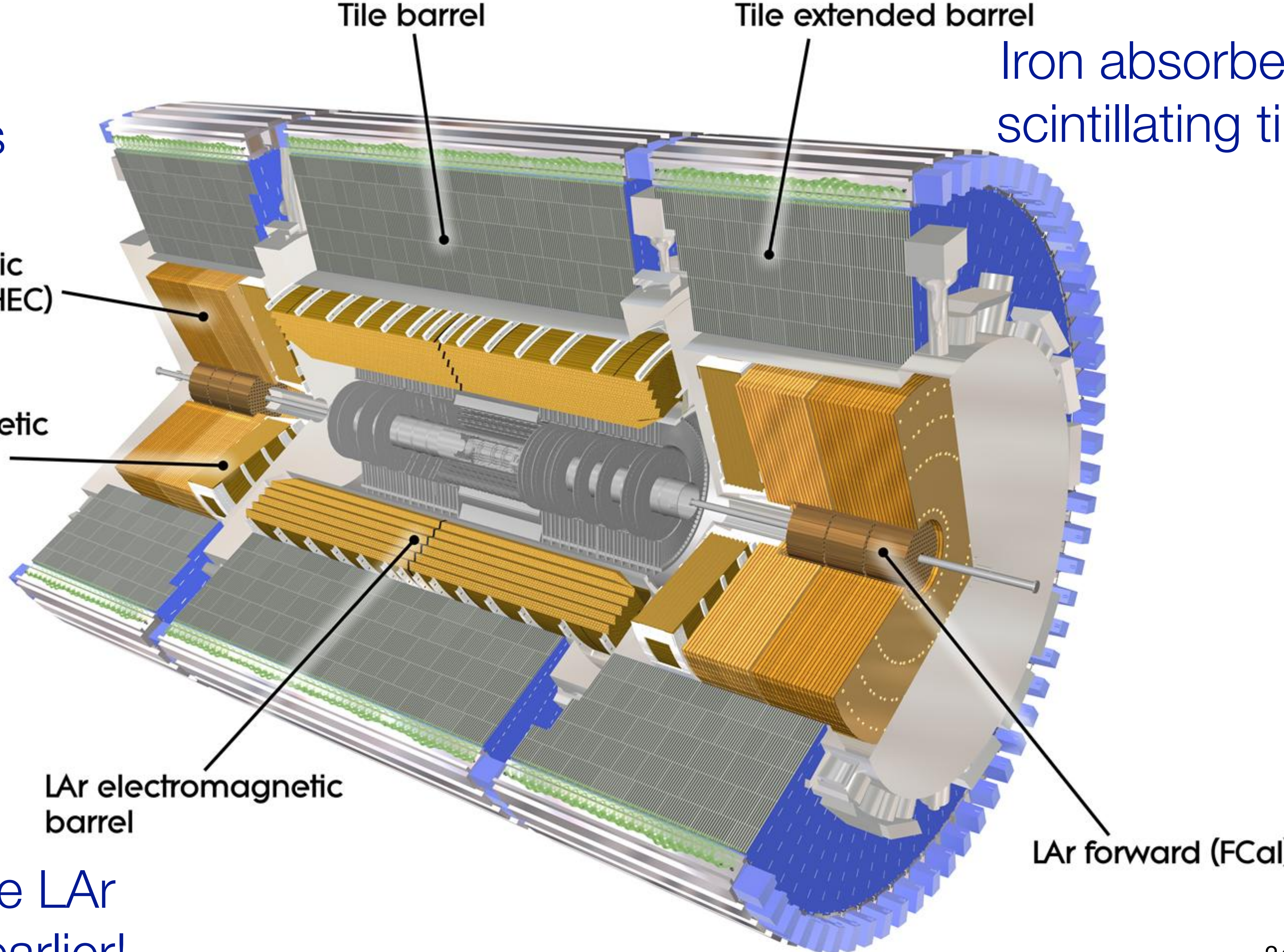
100 GeV proton



Two layered calorimeters, EM then hadronic

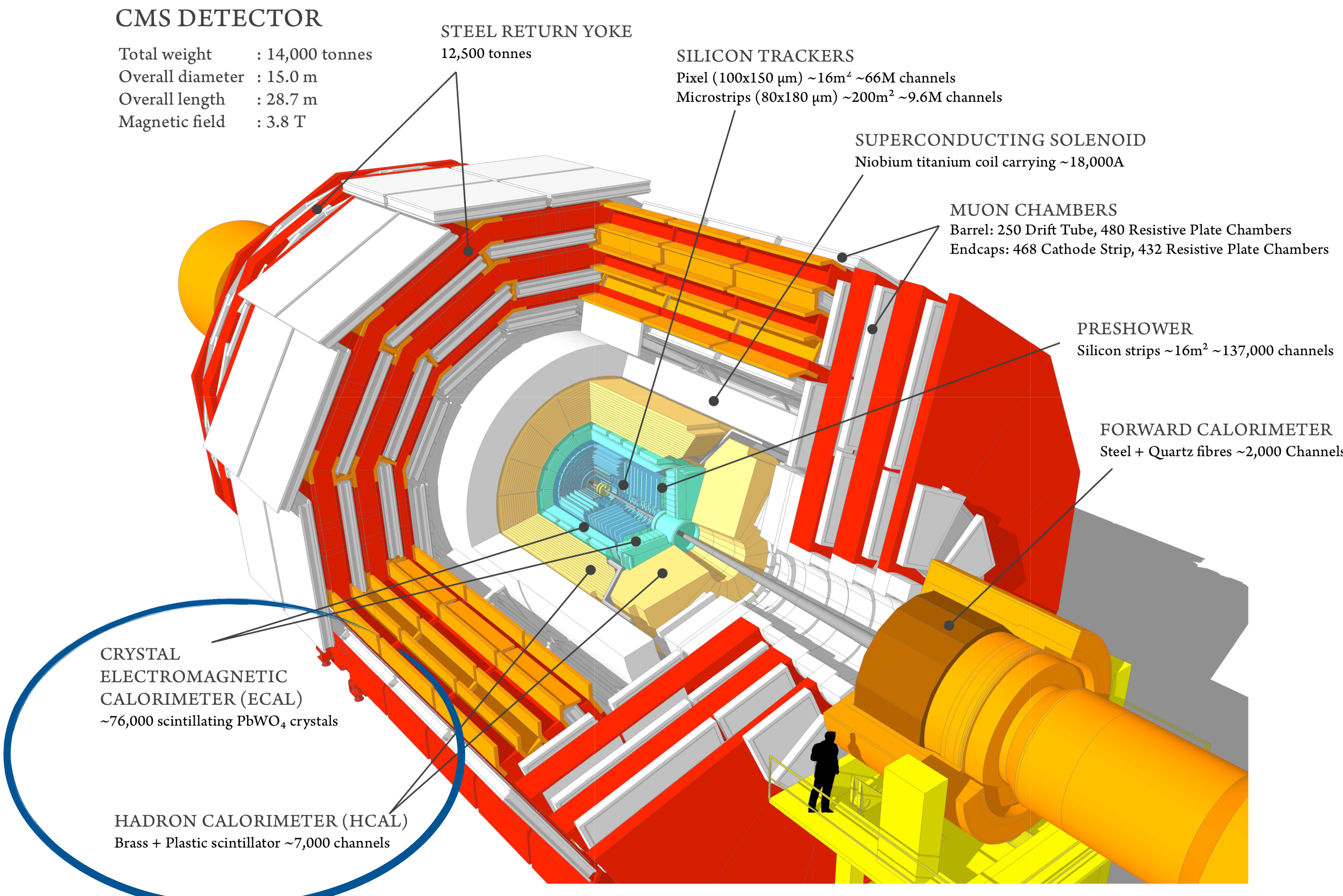
LAr is radiation hard: use it in forward regions

Iron absorbers, scintillating tiles



Discussed the LAr calorimeters earlier!

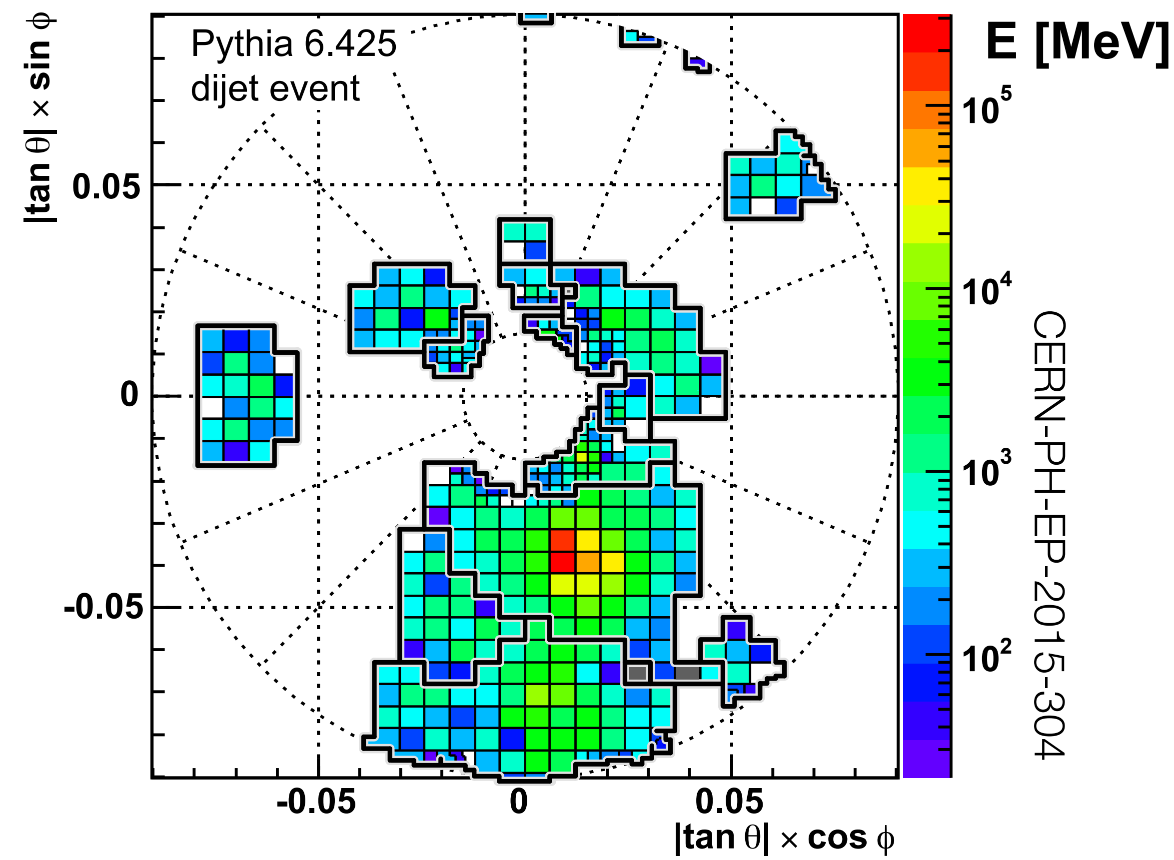
Two layered calorimeters, EM then hadronic

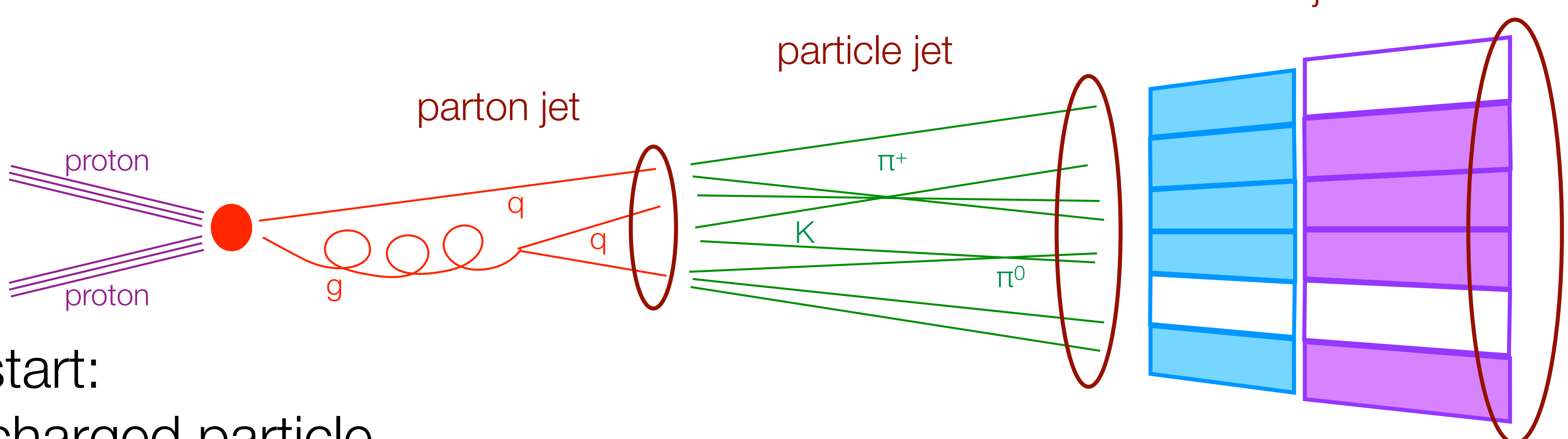


Topoclusters and jets

- What we have in the calorimeter is a bunch of energy deposits at various positions and depths
- What we want is a single unified statement about the incident particle
- Make an "object" we can talk about: from energy depositions reclusters to get jets (electrons and photons expect to have only one cluster)

Detector start:
energy deposits





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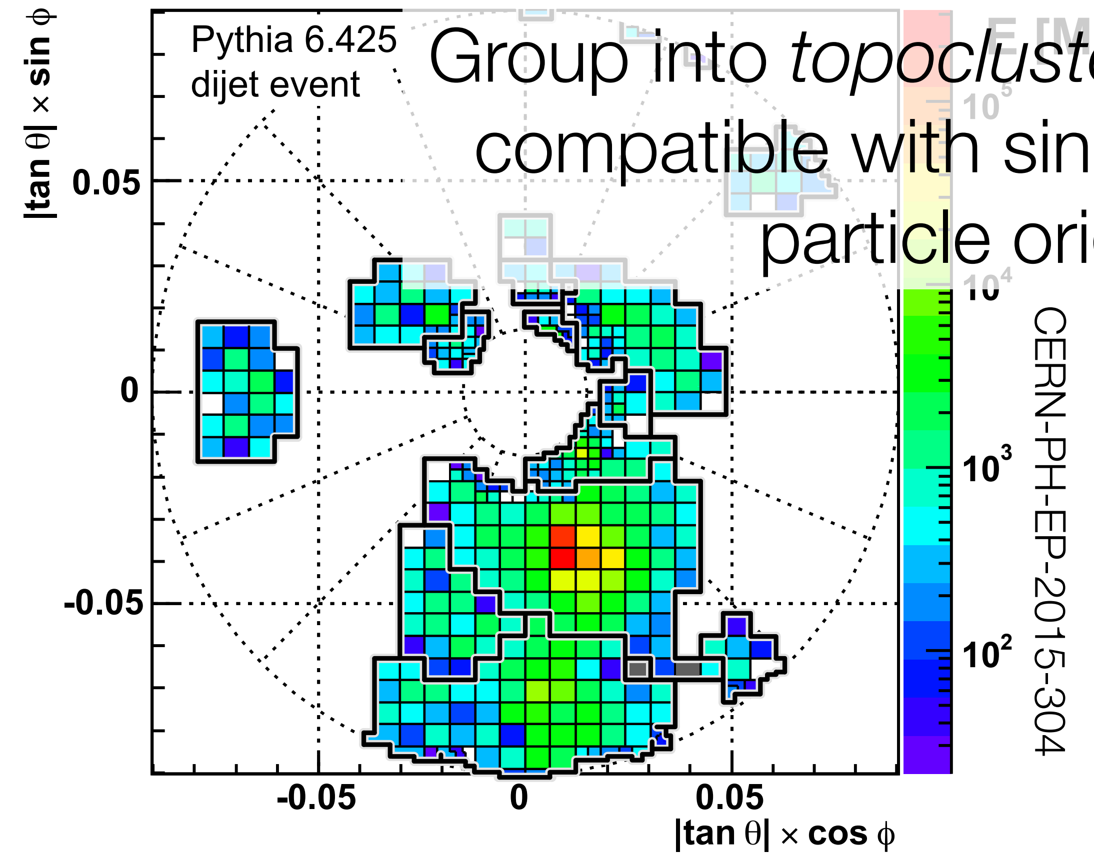
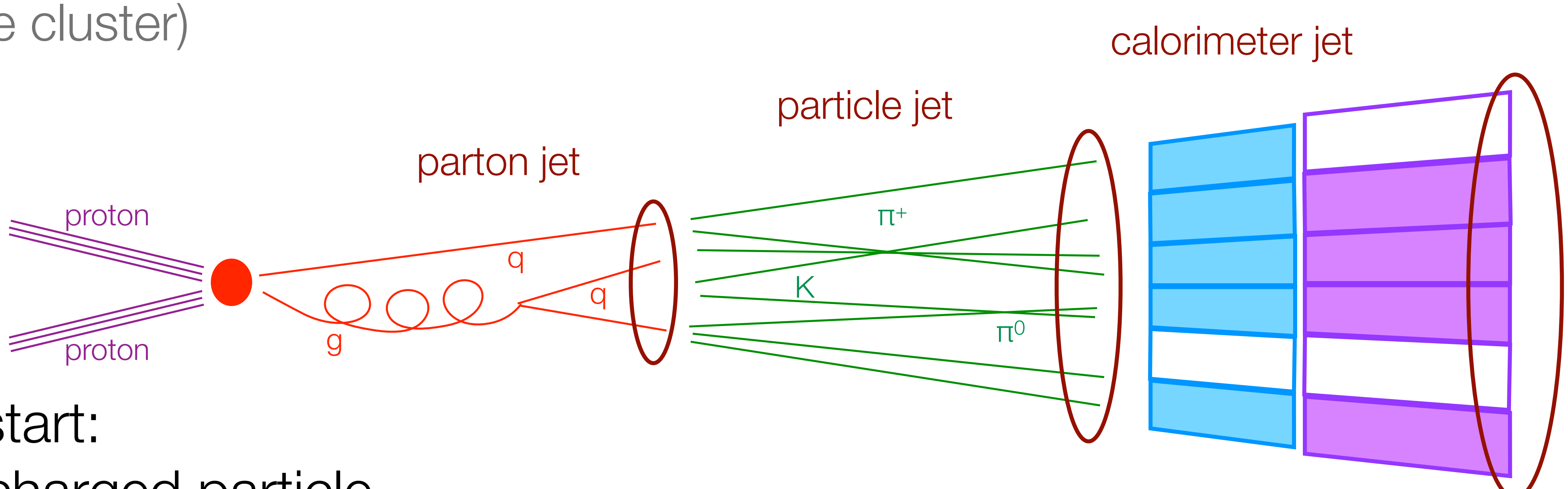


Group into *topoclusters* compatible with single particle origin



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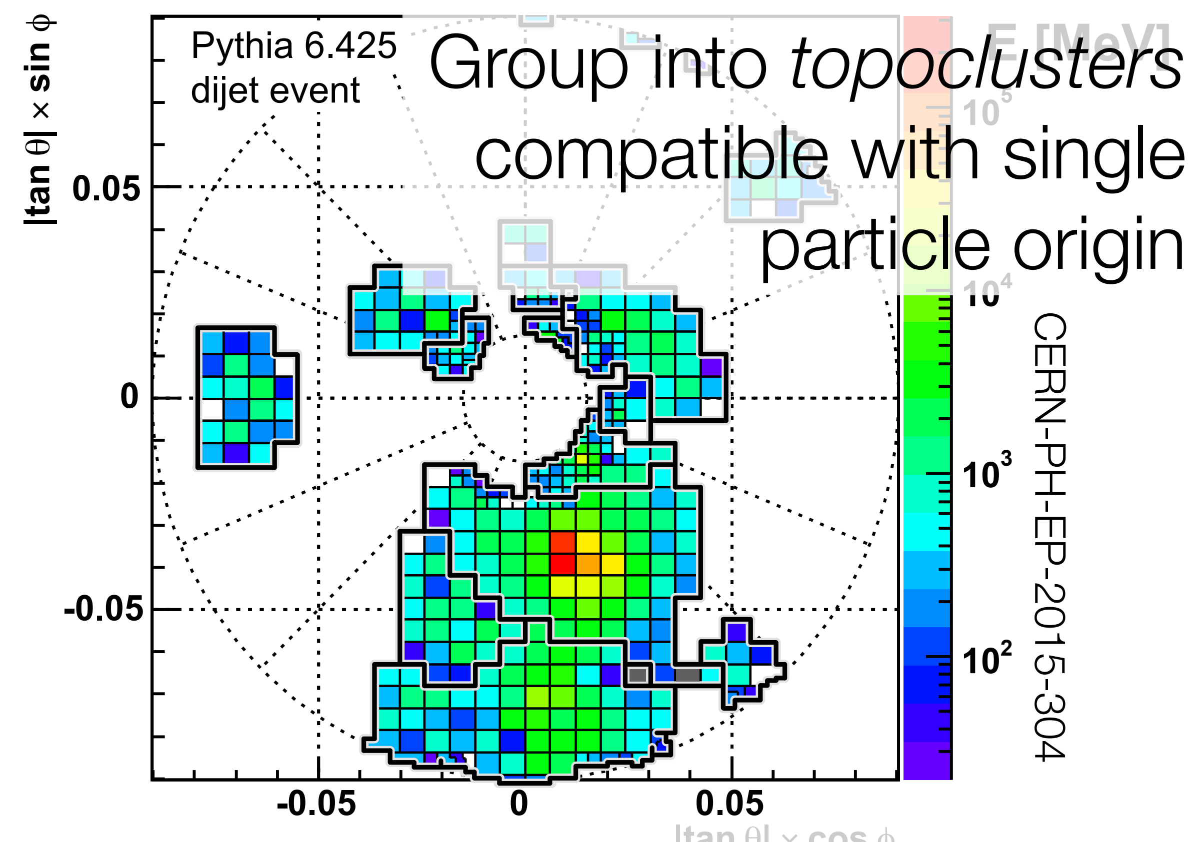

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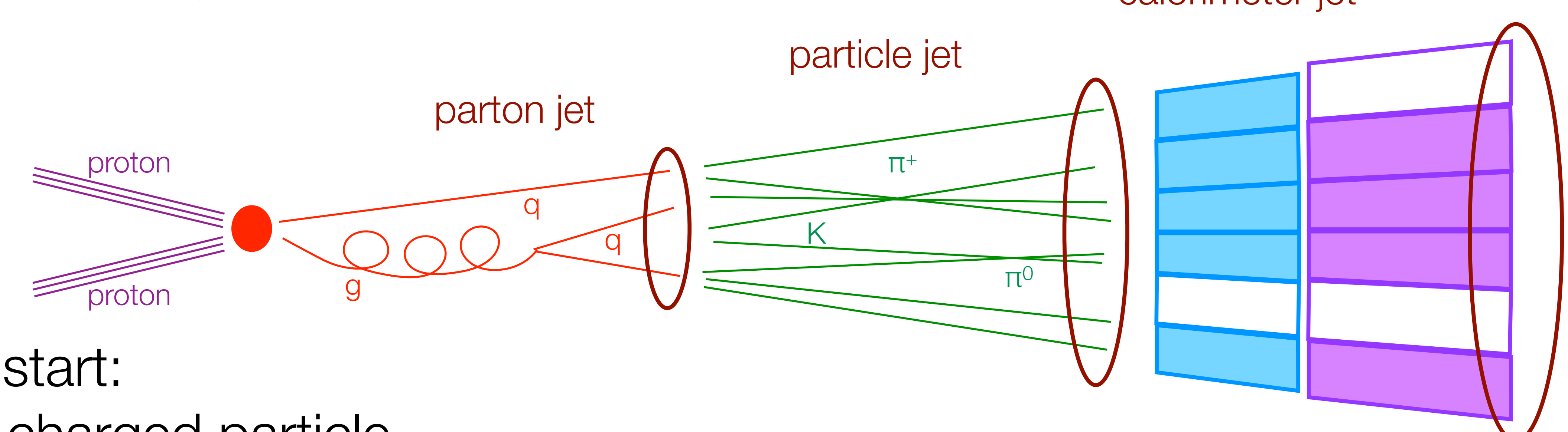
Reclustering algorithm groups topoclusters into jets



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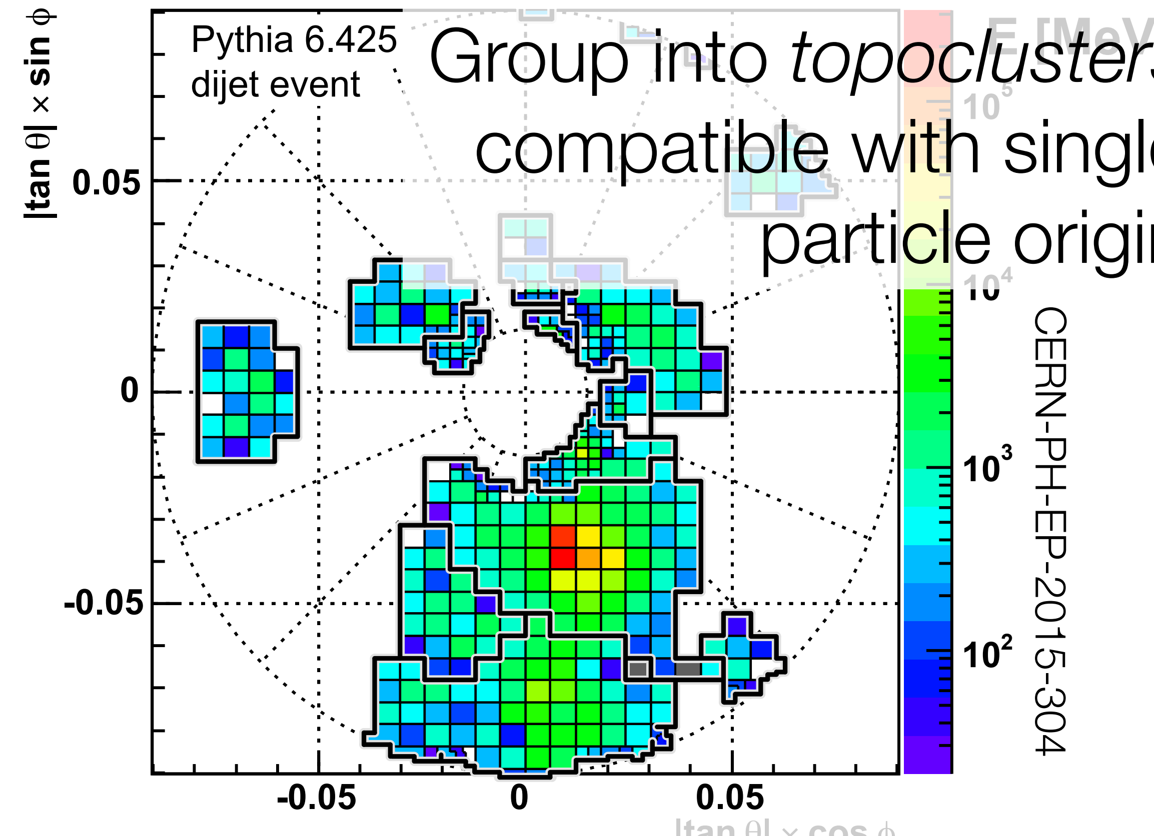

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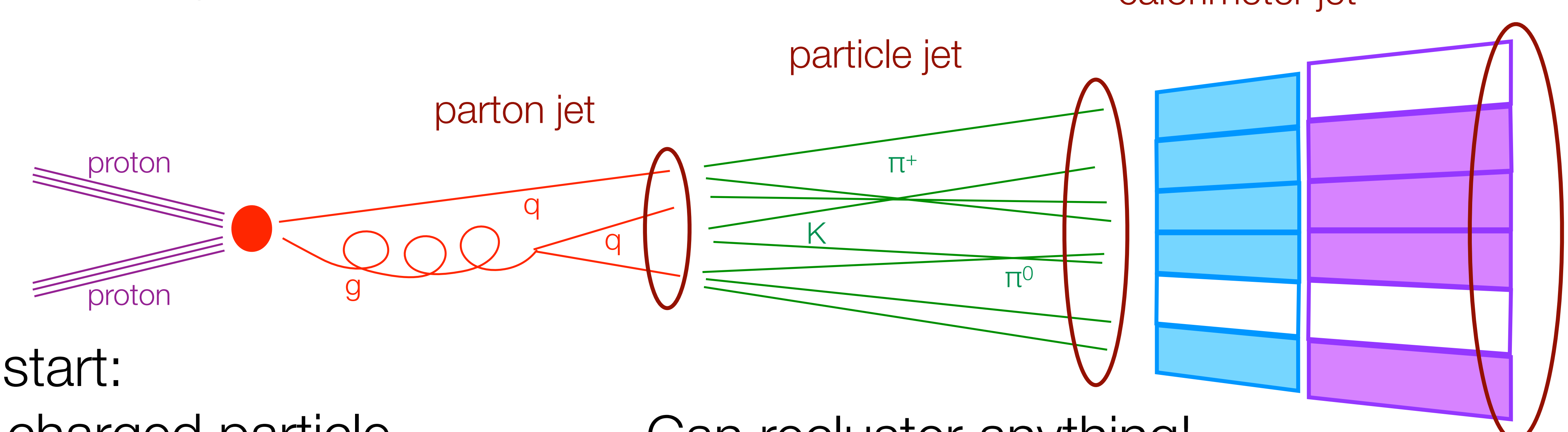


Physics start:
strongly charged particle

Can recluster anything!

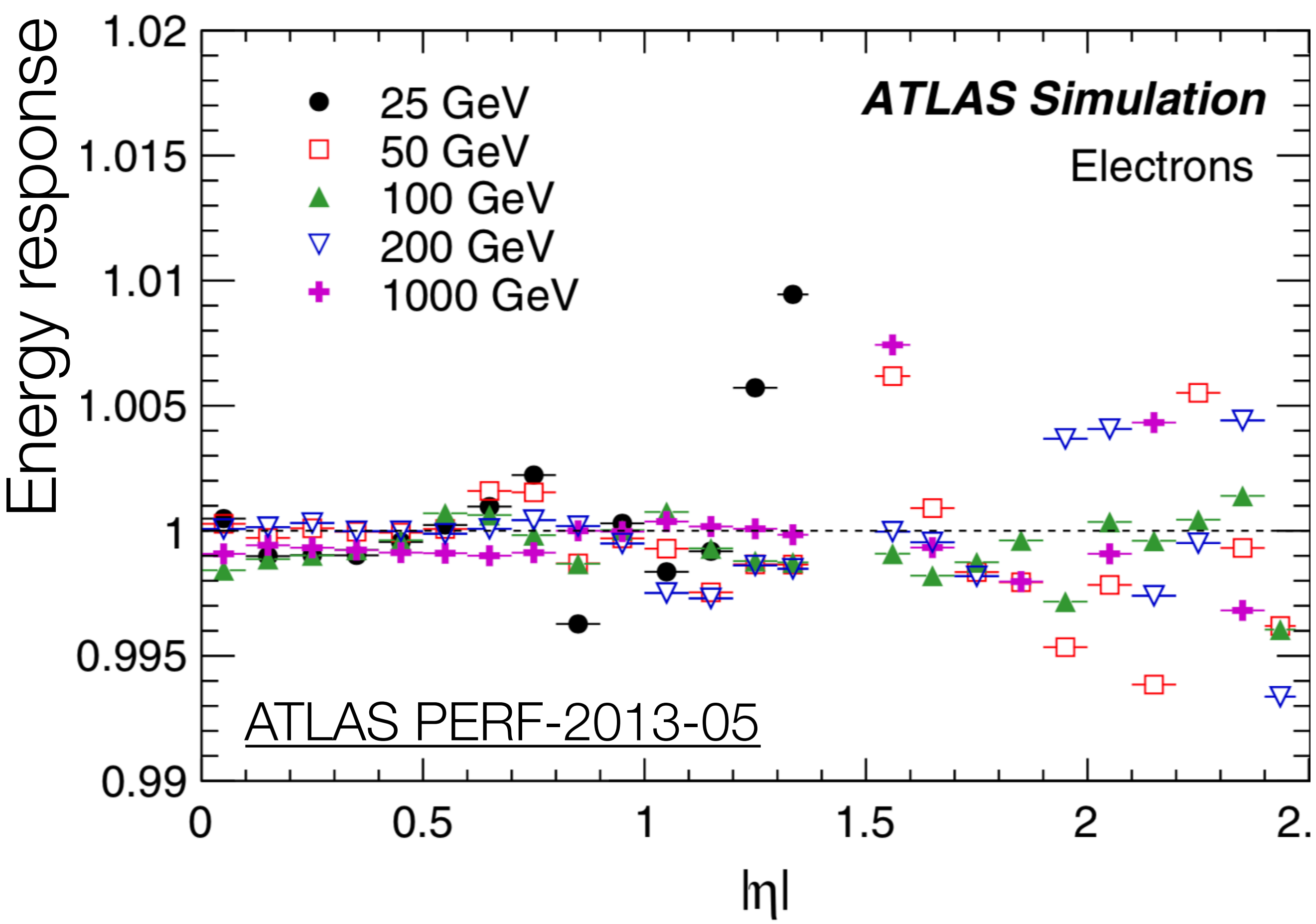
Calibration of energy

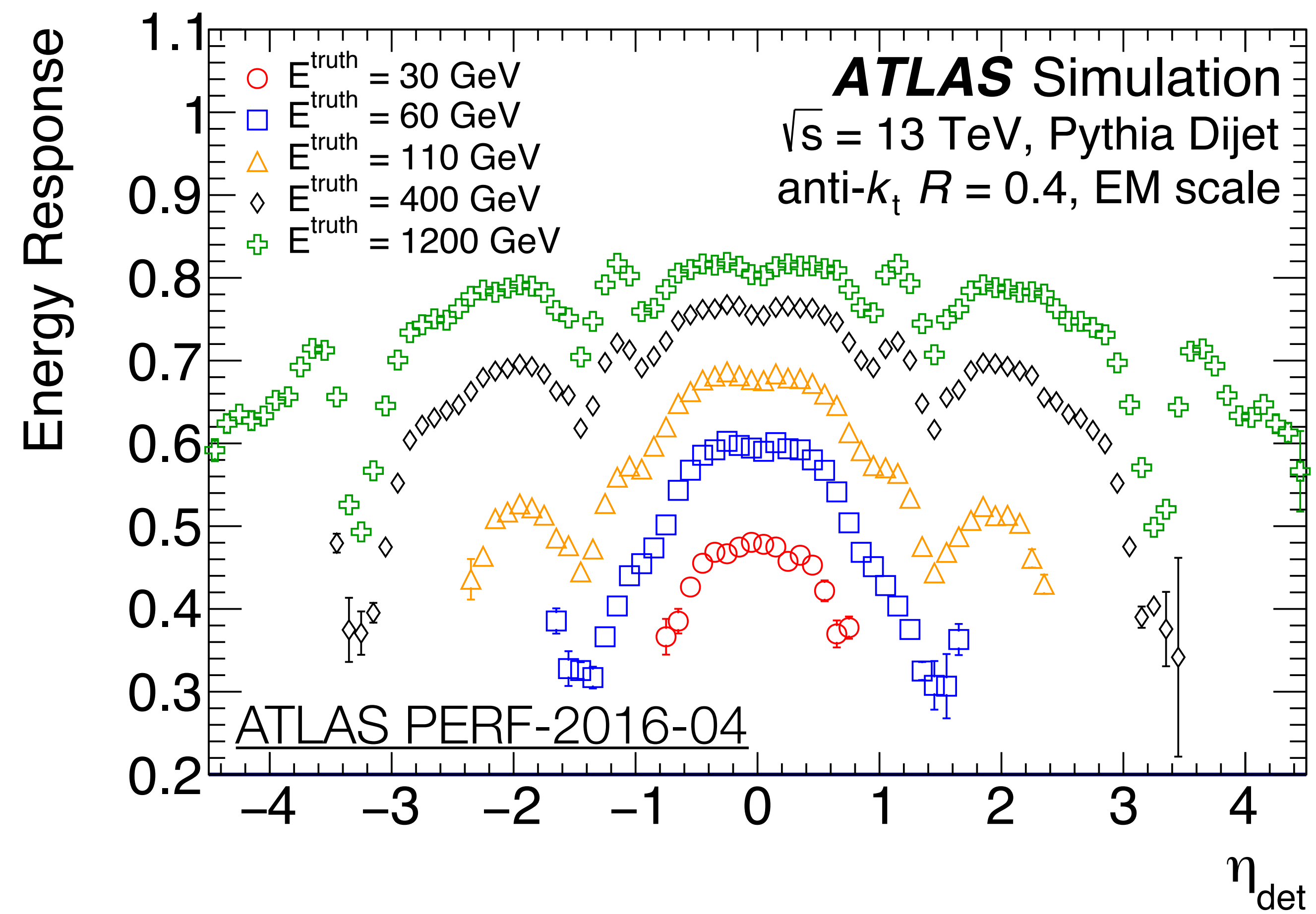
- List of factors we've discussed that calibration needs to account for:
  - Sampling nature of calorimeter: energy deposited in absorber layers not exactly known
  - Non-compensation of calorimeter: smaller fraction of energy from hadronic interactions recorded than from EM
  - Dead material and particles leaking out of calorimeter
  - Truth particles falling outside the reconstructed jet
  - Noise thresholds/reconstruction efficiency
- Can calibrate at calorimeter cluster level or at level of reconstructed object

Simulation-based calibration

- First step in e/γ/jet calibration uses ratio of reconstructed energy to particle-level energy taken from simulations

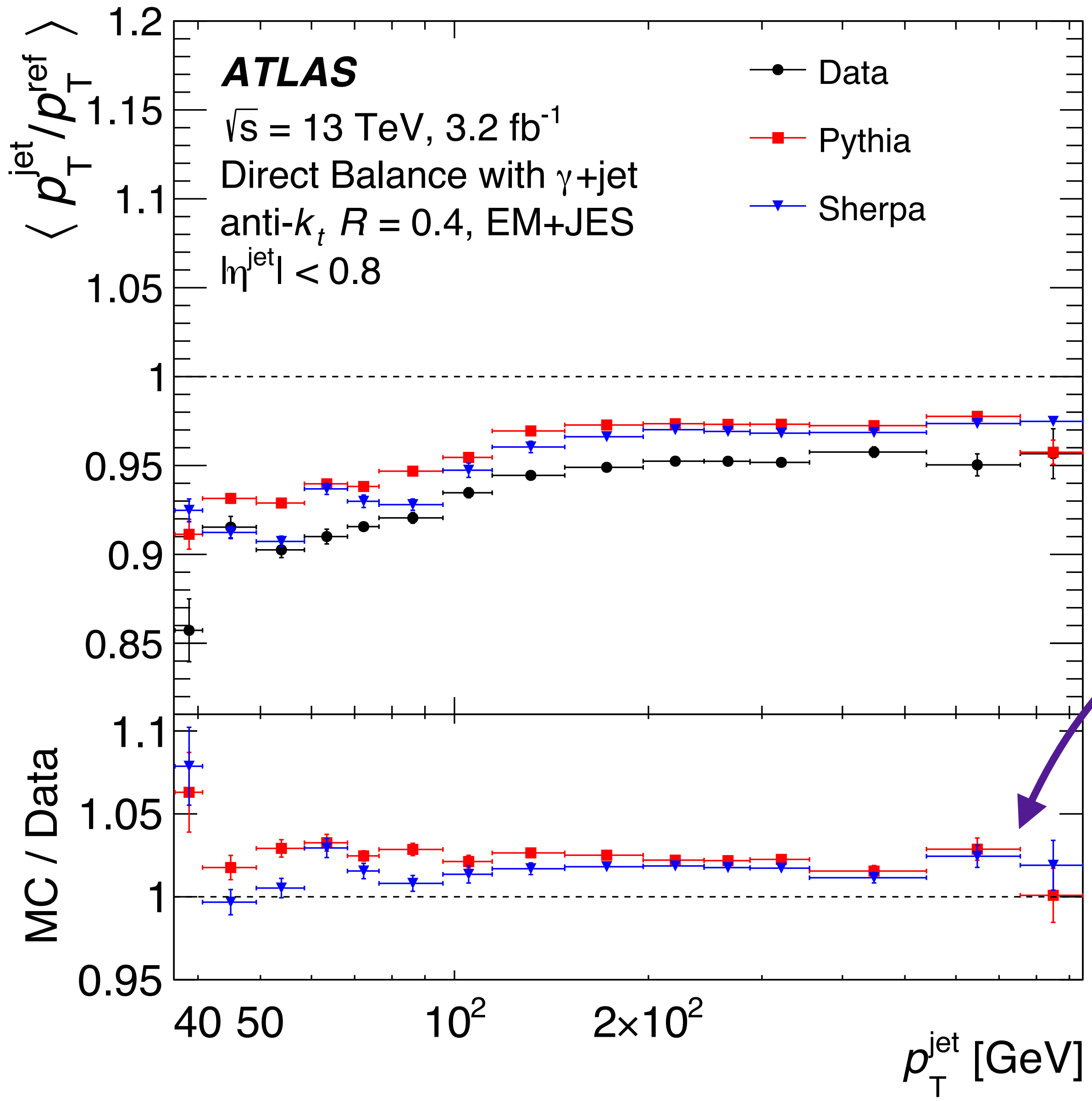
- Goal is to return measured object energy in data to the “true” scale represented to the best of our knowledge by the MC





Data-based calibration

Second stage corrects for residual differences between data and simulation: object in data after MC calibration is momentum-balanced against a well-calibrated standard candle



Ratio of jet momentum to reference object (photon) momentum after calibration

Ratio between blue and black is data/MC difference

→ this defines the residual calibration

Particle ID

… with a calorimeter bias

Particle ID: what and why?

- If our detector observes an interaction, critical to be able to identify the particles involved to understand the processes
- Long-lived particles (on the timescale of the detector) are identified by their unique properties: mass, charge, interaction types, etc
- Promptly decaying particles (W, Z, Higgs, etc) are identified by their decay products
- Calorimeters can tell us a lot about particle ID, but (for more than 1 type of expected particle) 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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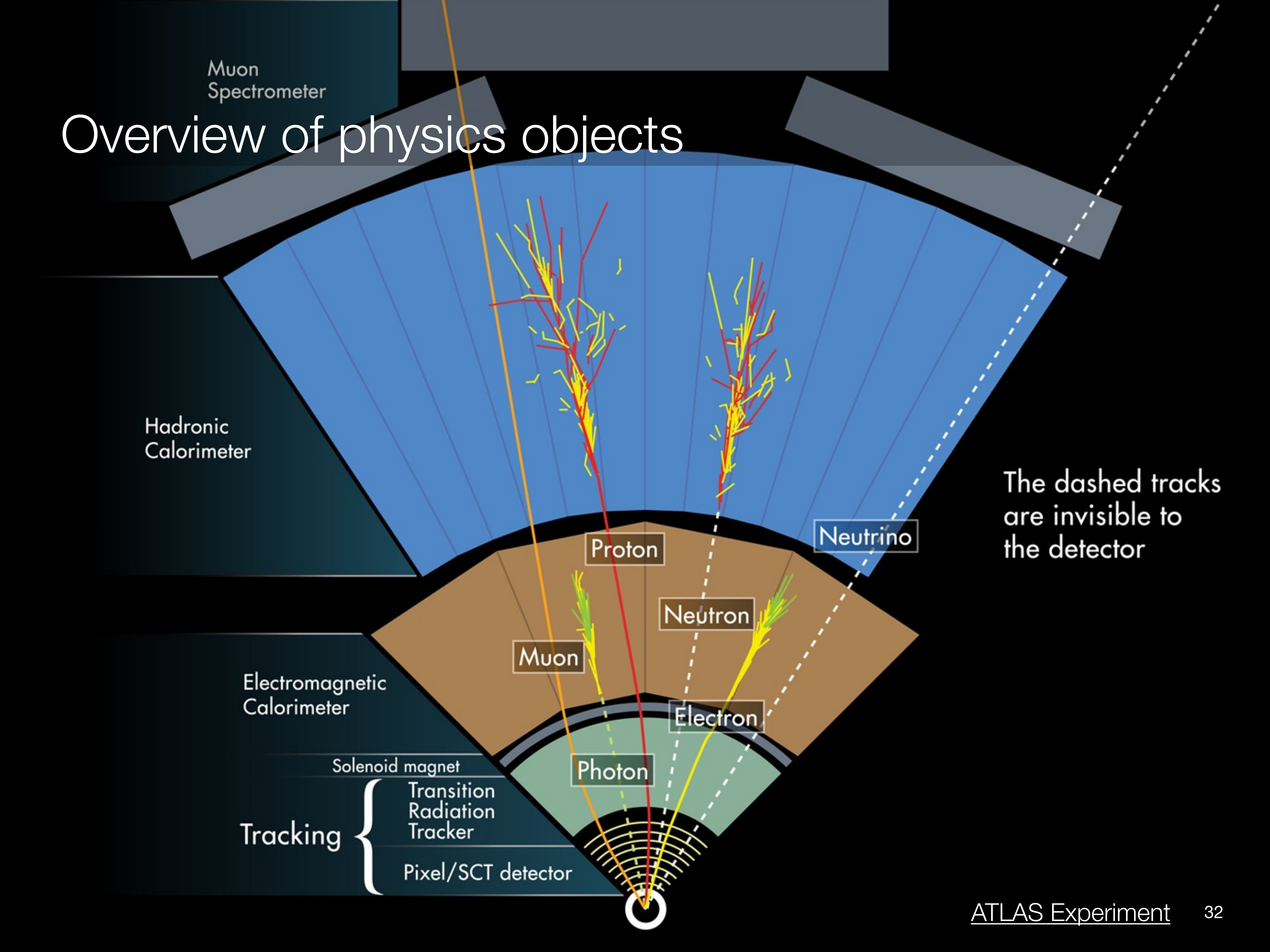
General purpose: decent for everything

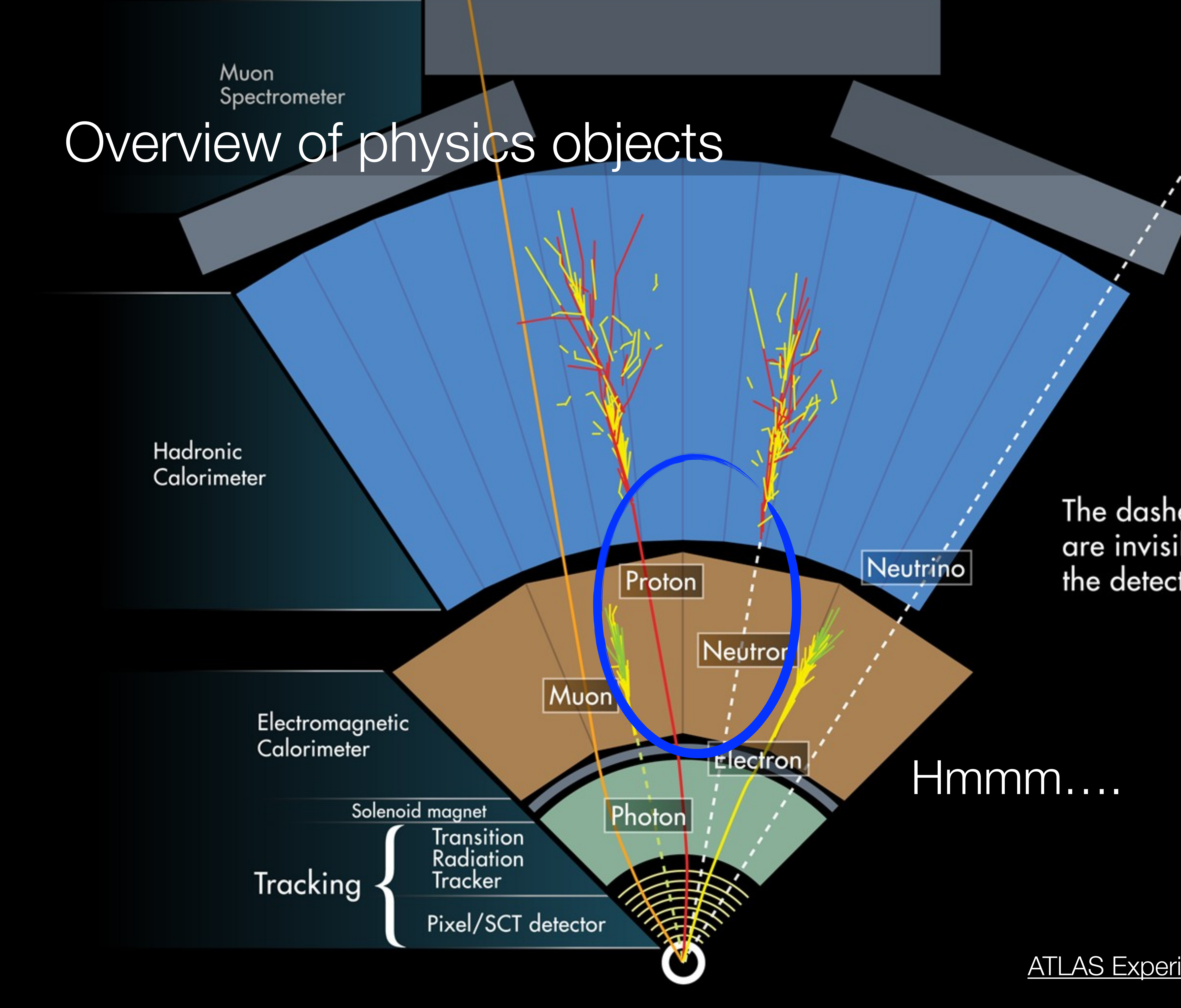
High granularity for busy ion collisions

Overview of physics objects



[ATLAS Experiment](#)

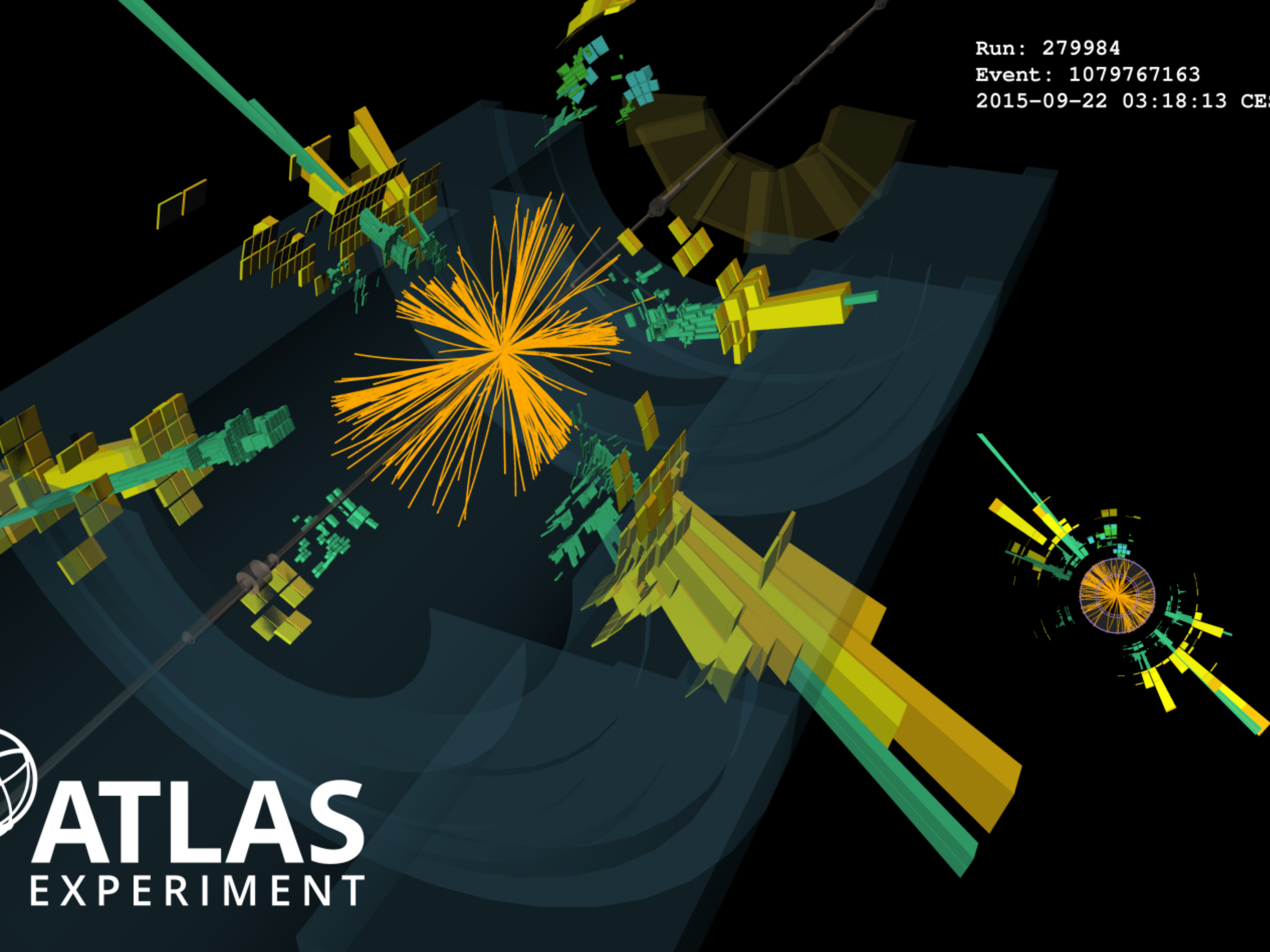
Overview of physics objects



The dashed tracks are invisible to the detector

Hmmm….

ATLAS Experiment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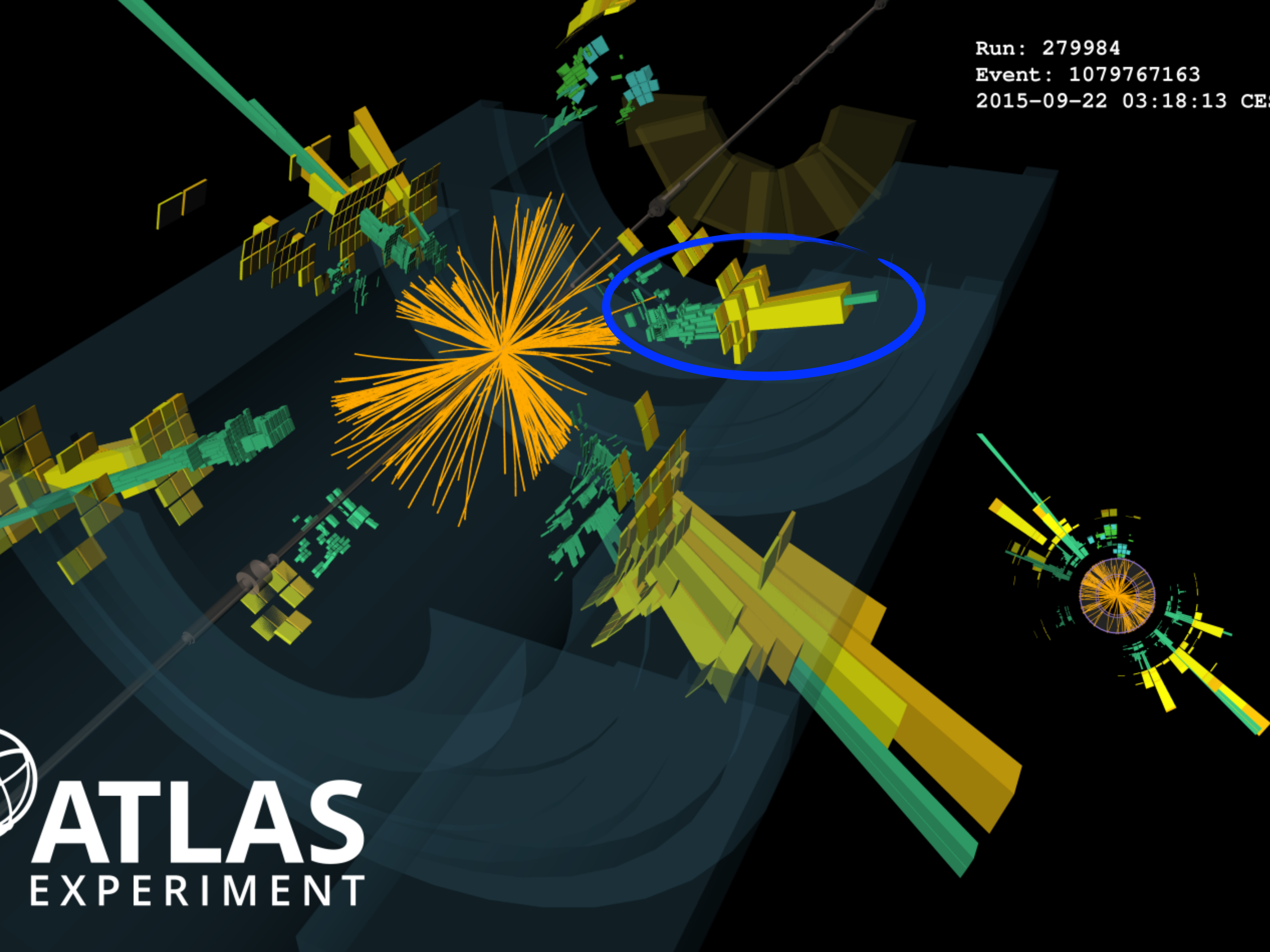
2015-09-22 03:18:13 CE
ATLAS
EXPERIMENT



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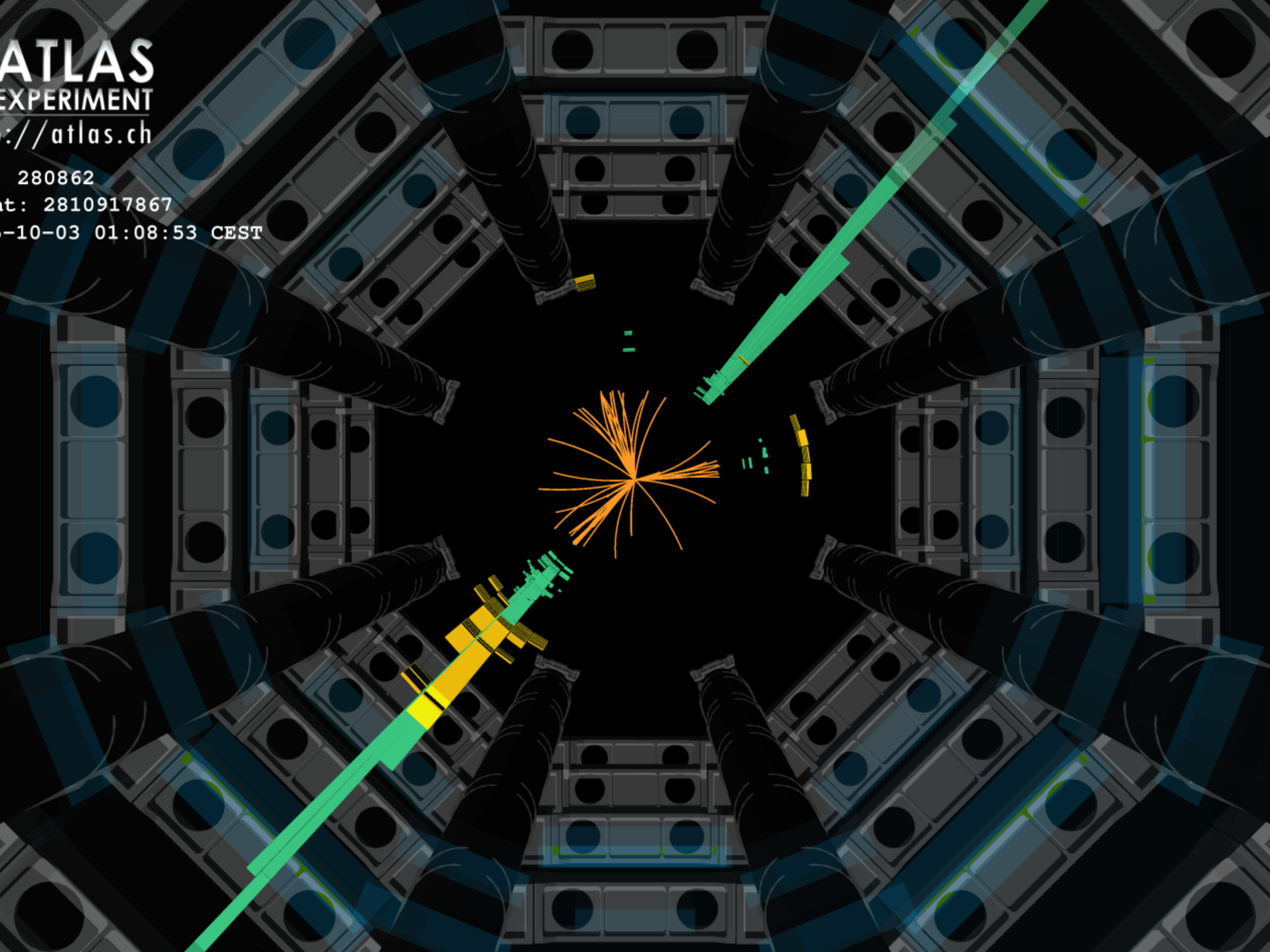
ATLAS
EXPERIMENT
p://atlas.ch
280862
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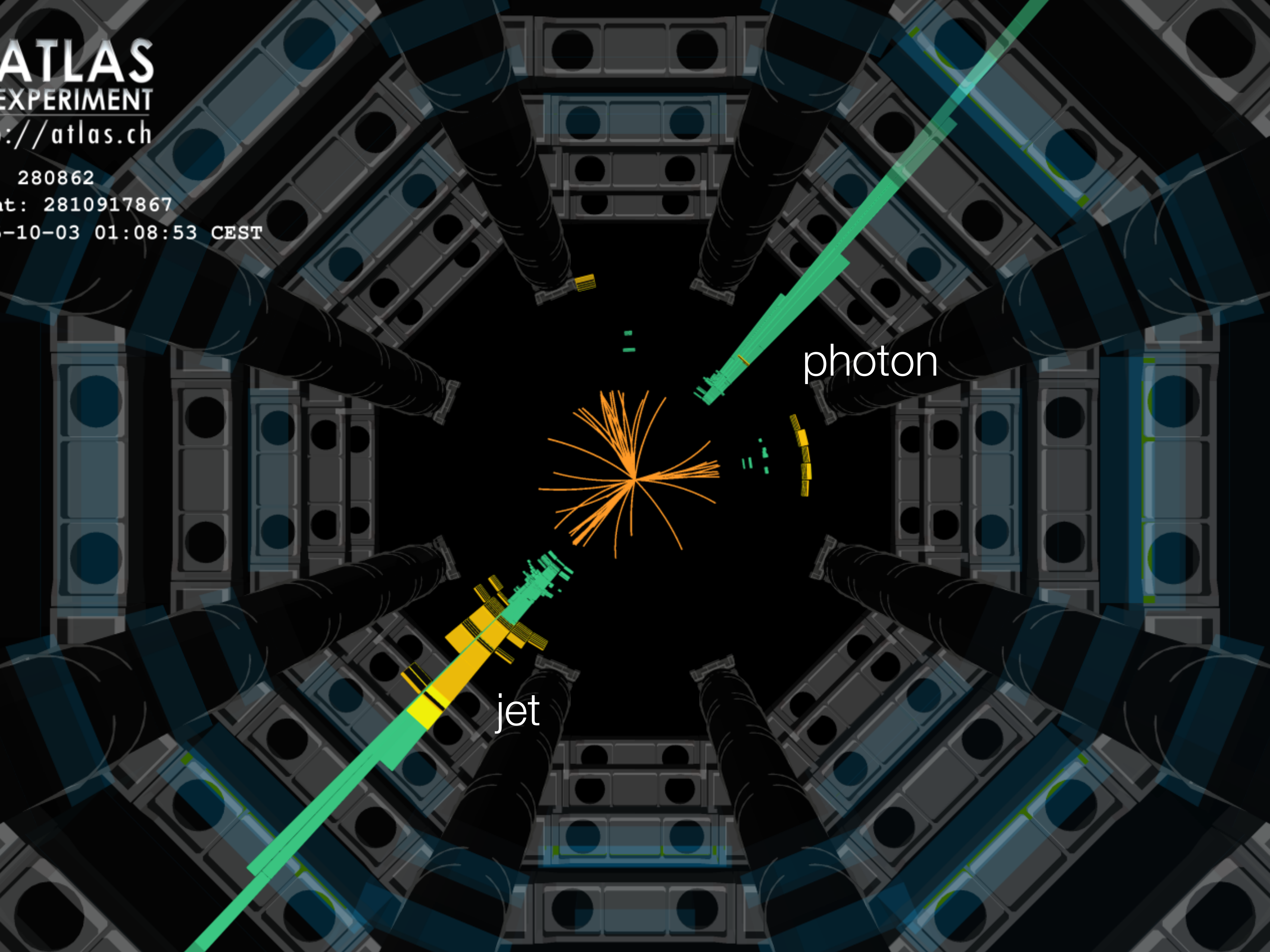
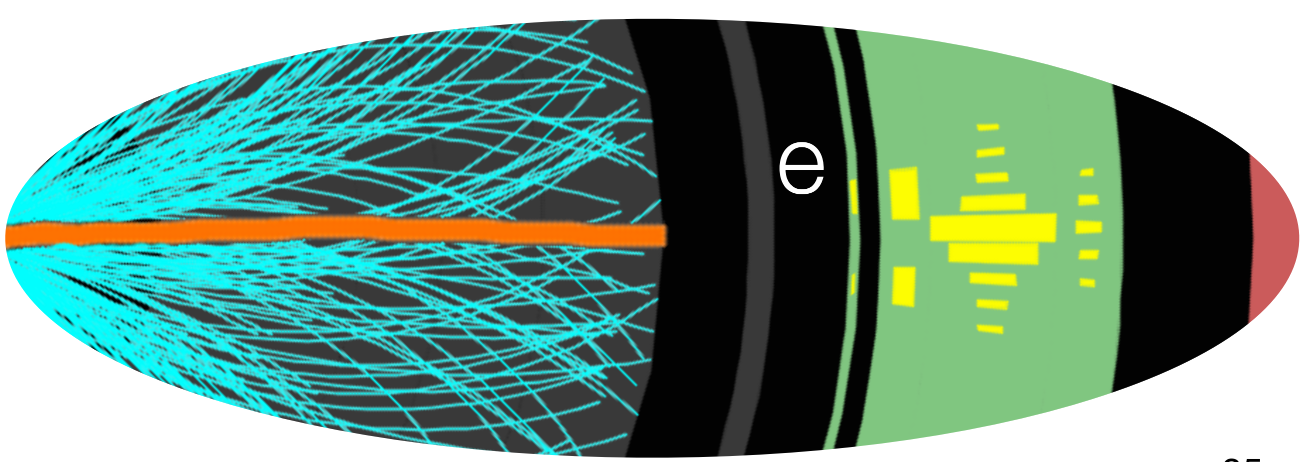

ATLAS
EXPERIMENT
280862
2810917867
01:08:53 CEST
photon
jet

Electrons and photons

- Expect only one energy deposit in EM calorimeter in electrons and photons: no jet-like parton shower
- Distinguish between the two by matching to a track
- But discrimination against backgrounds still tricky
  - e ID backgrounds: mis-ID'd hadrons, non-prompt production, heavy flavour decays
  - γ ID backgrounds: jets with large EM fraction, $\pi^0 \rightarrow \gamma\gamma$
- Use shower shape and width, energy ratios in layers, track to cluster matching information, track details to further discriminate



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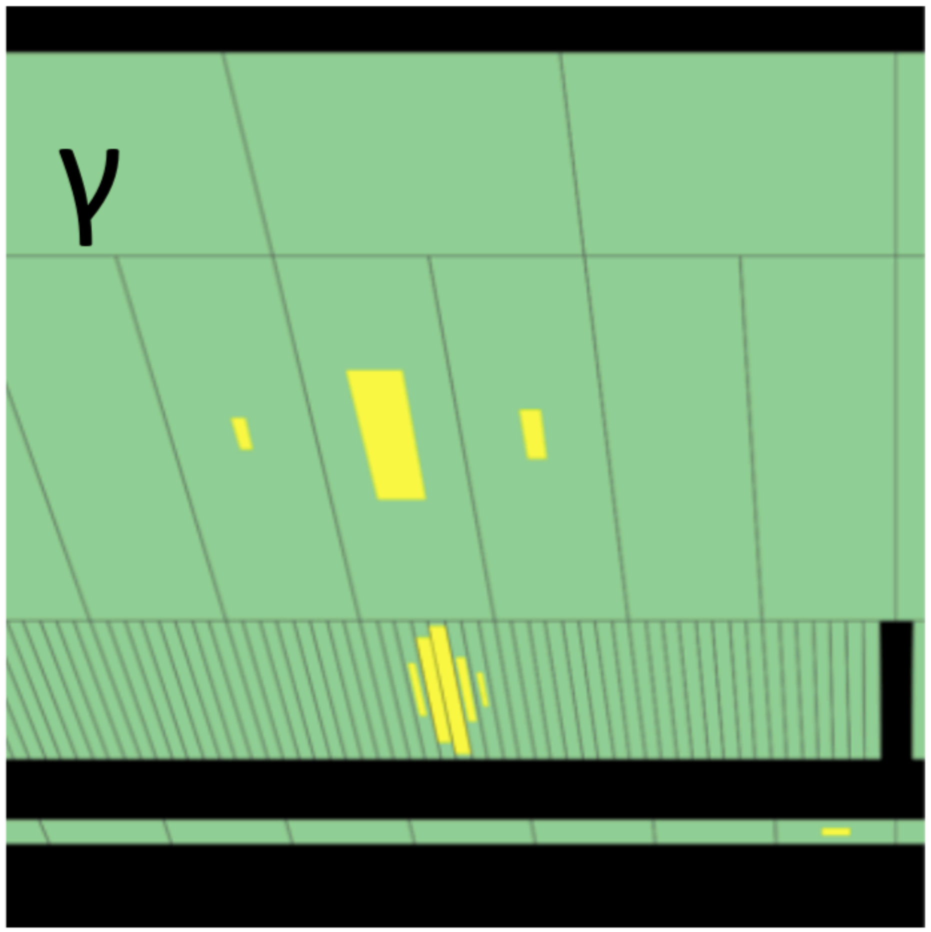
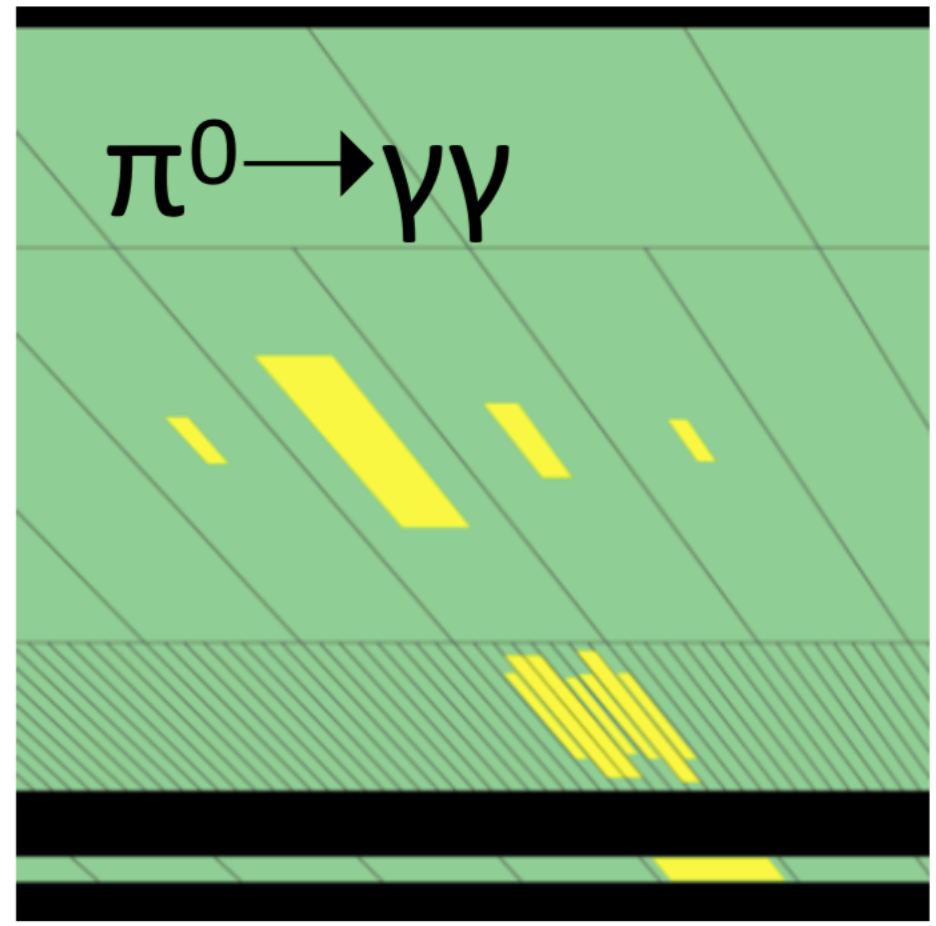
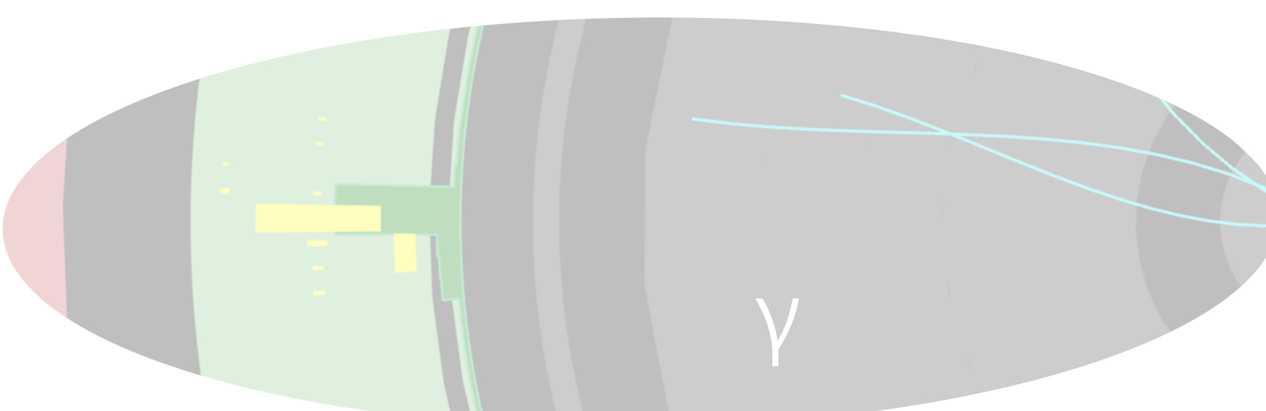
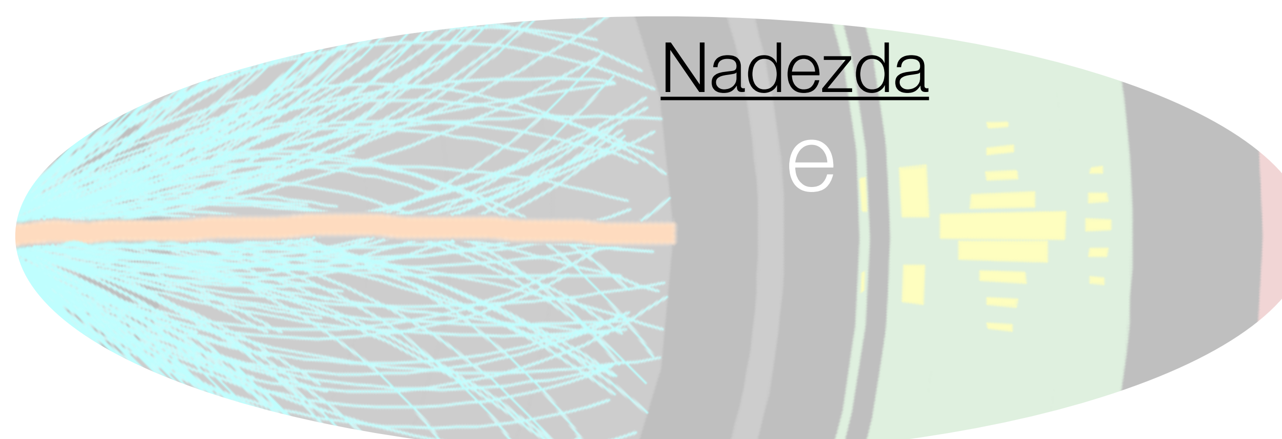






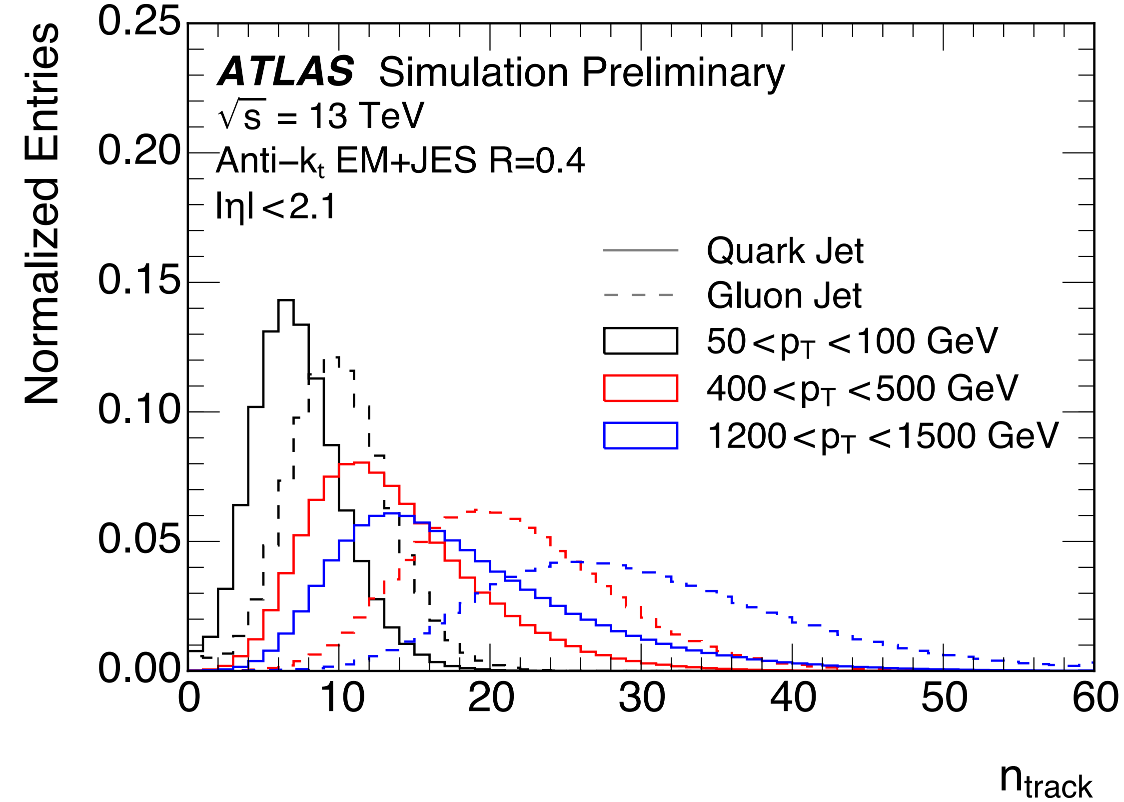


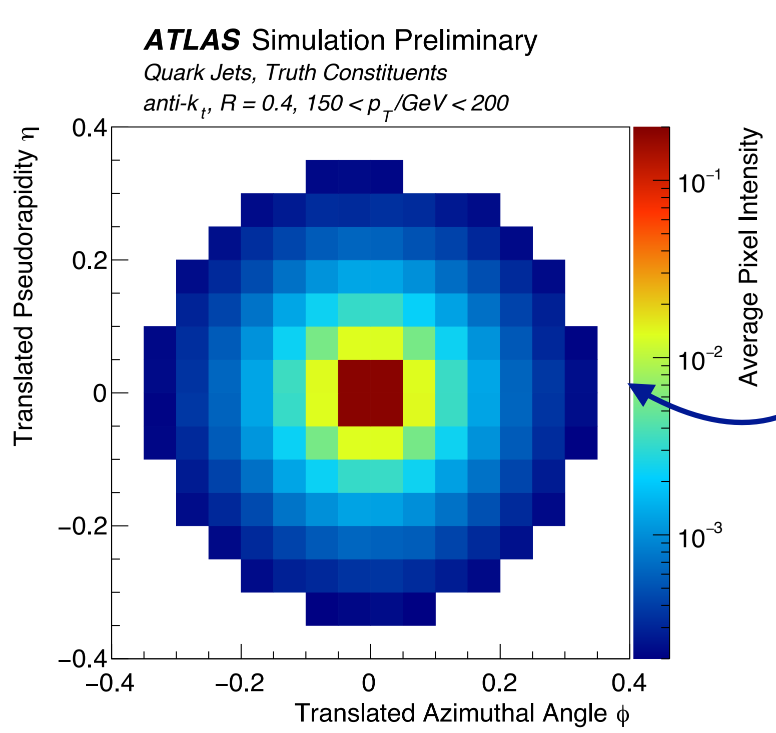
Nadezda

Quarks and gluons

ATL-PHYS-PUB-2017-017
ATL-PHYS-PUB-2017-009

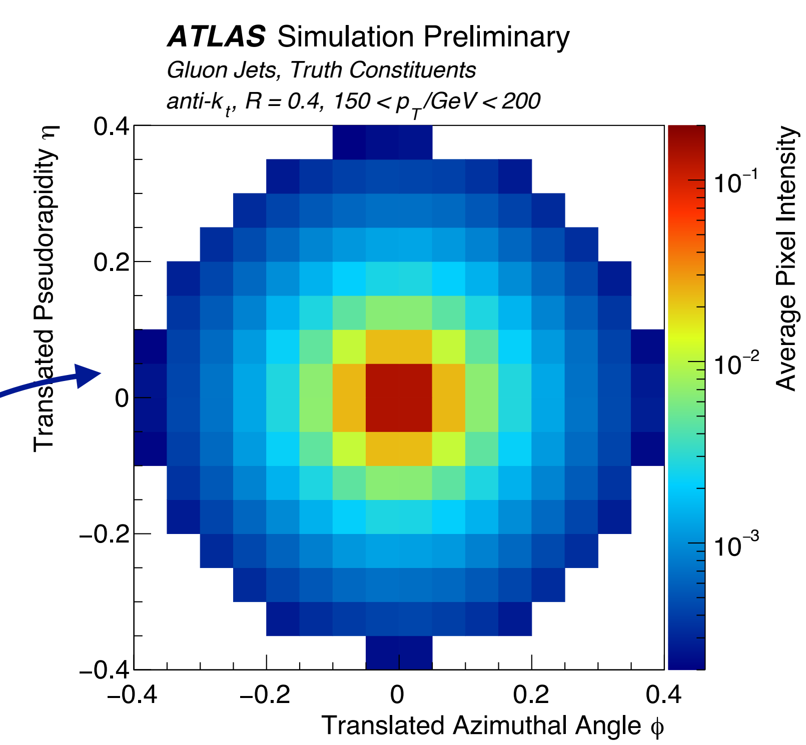
- Quarks and gluons showering immediately and hadronize shortly afterwards
- Once anything reaches the detector, there's no longer just one particle: track multiplicity ~ 6 to 10
- Hard to tell quark and gluon jets apart! Gluon jets are a little wider and tend to include more particles. Ongoing q/g tagging efforts in ATLAS & CMS





Average quark jet

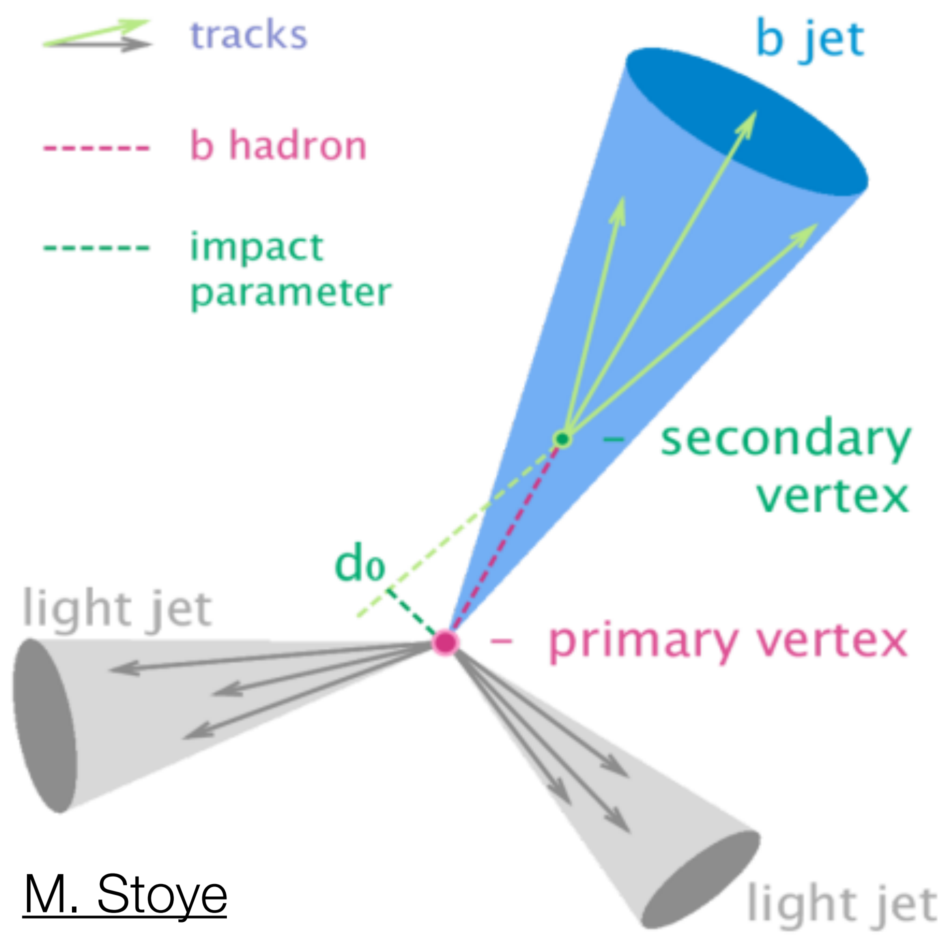
Average gluon jet



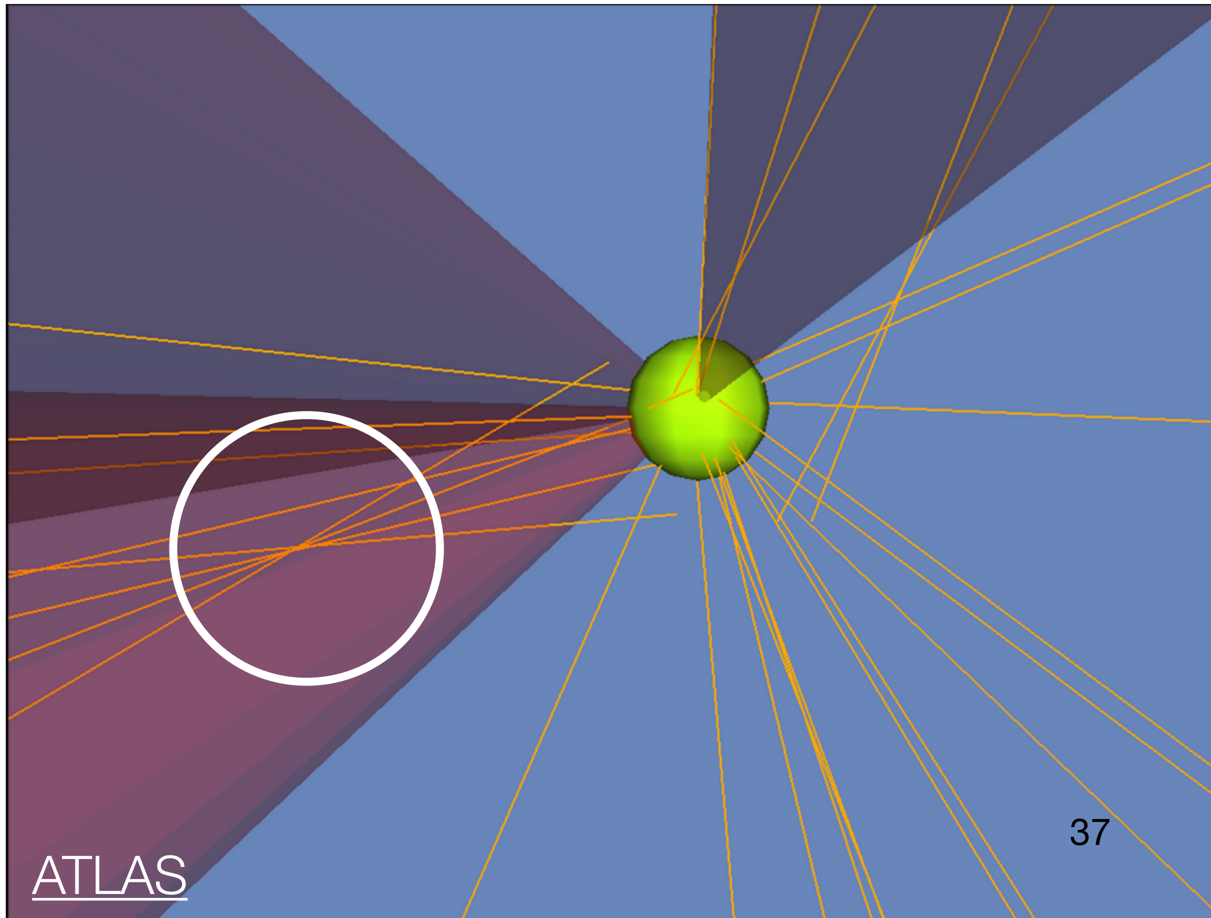
Example: use jet image in calorimeter to train NN

B-jets

- Exception to the above: 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

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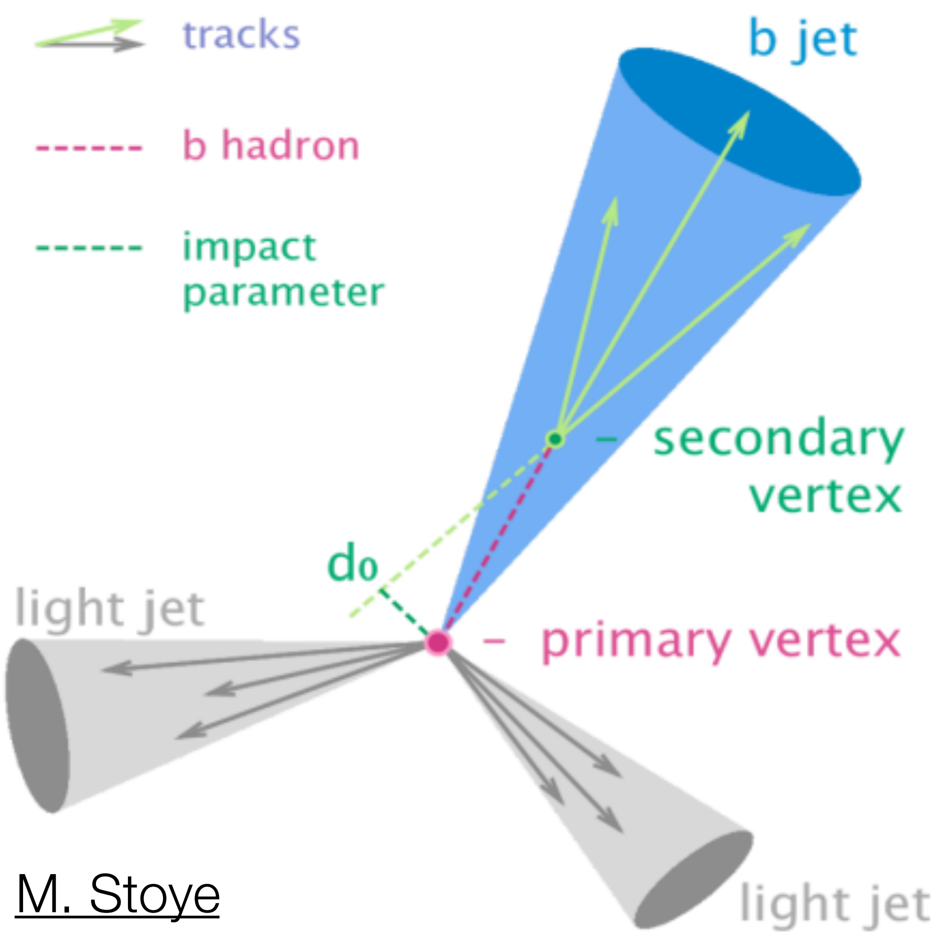


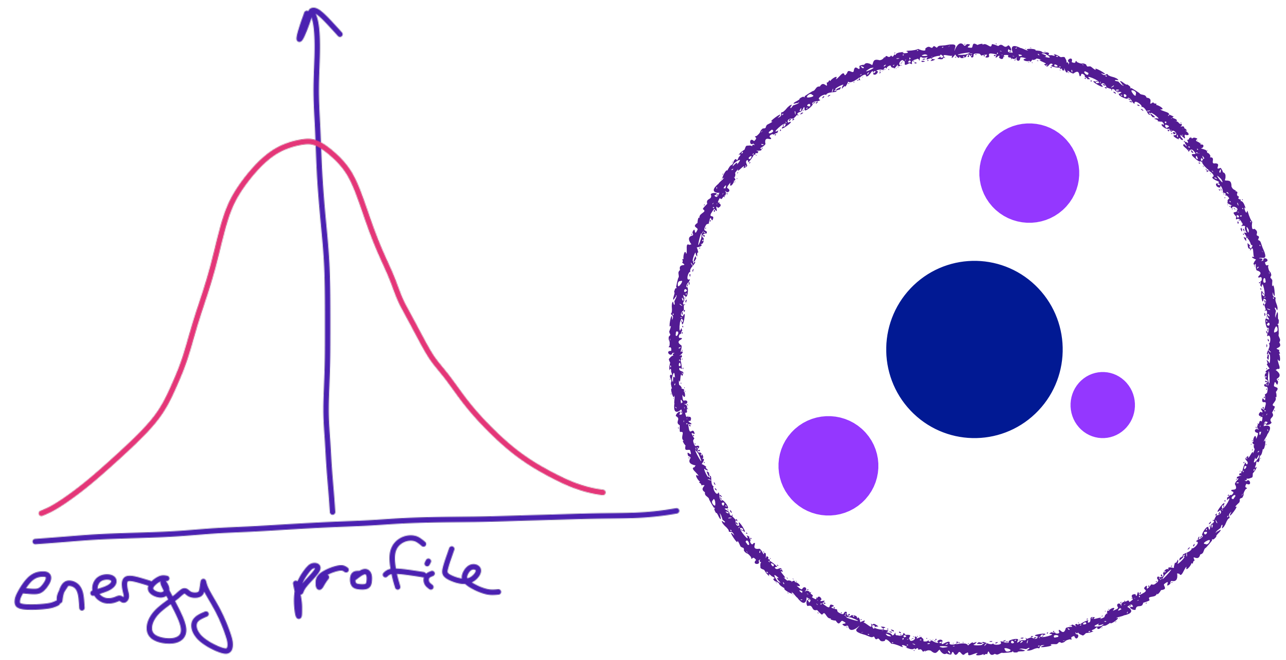
M. Stoye

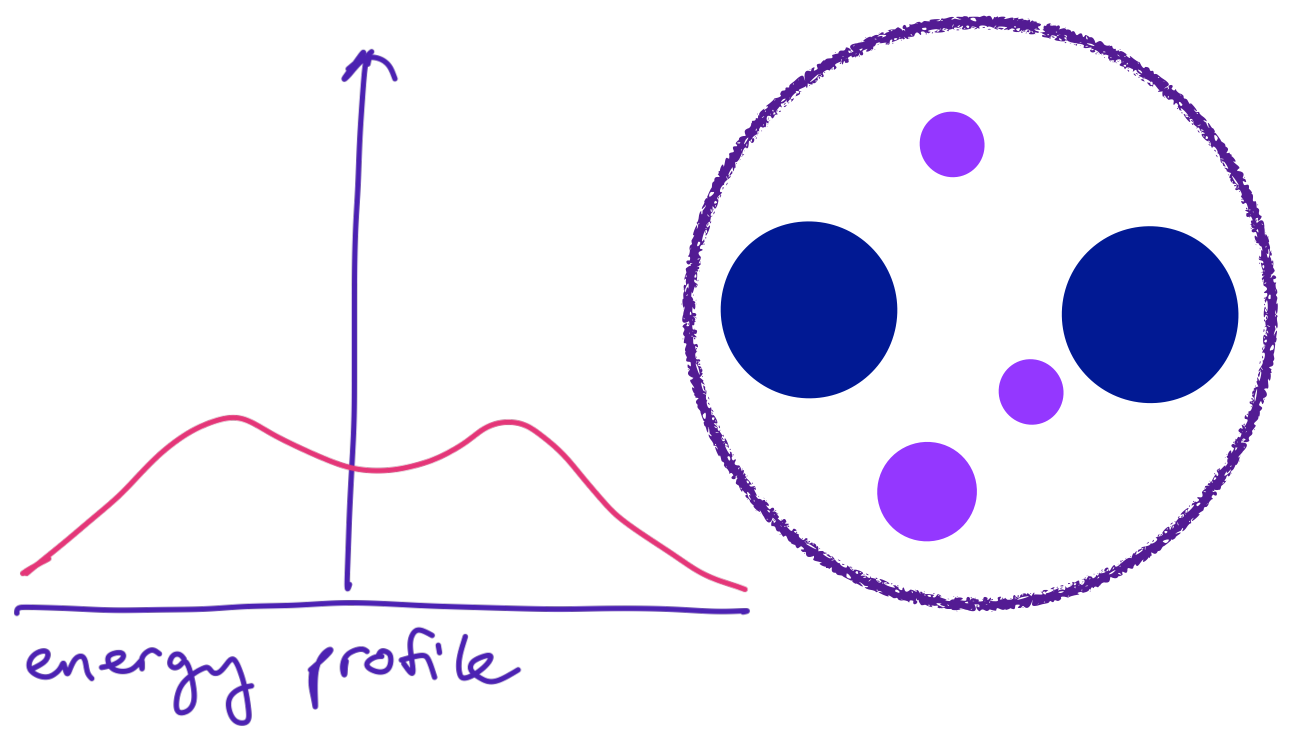
Why do we care?

- Heavy flavours could couple preferentially to new physics
- Needed for identifying top quark events
- Highest rate decay of the Higgs!

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

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) %		–

PDG

- 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	(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) $\times 10^{-6}$		45594
invisible	[h]	(20.000 ± 0.055) %		–
hadrons	[h]	(69.911 ± 0.056) %		–

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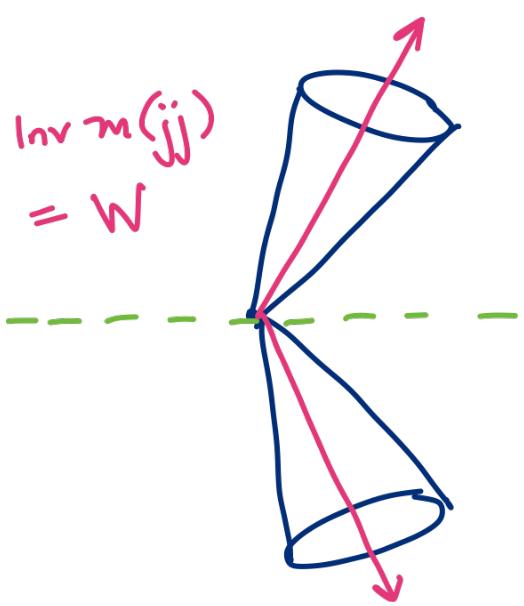
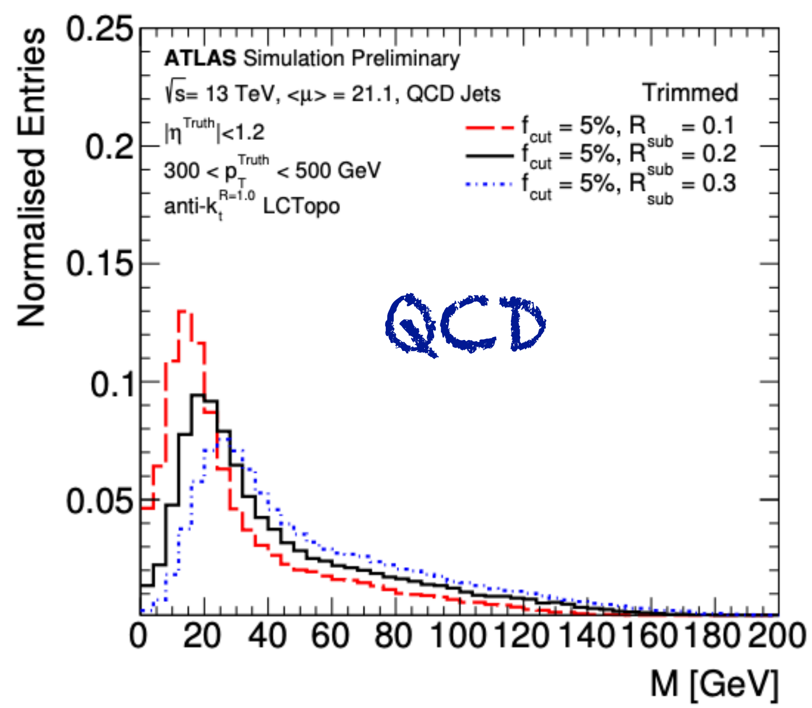
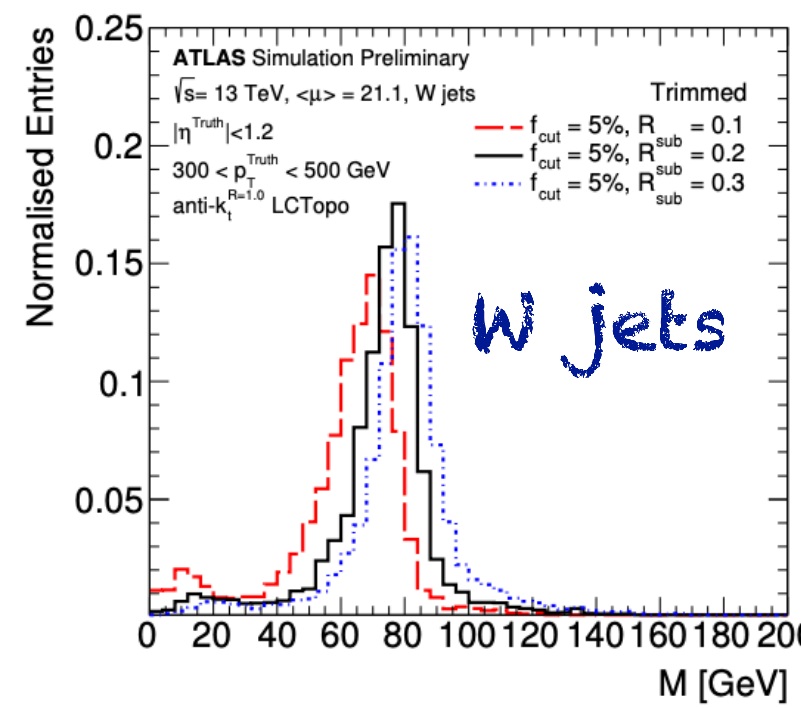
PDG

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



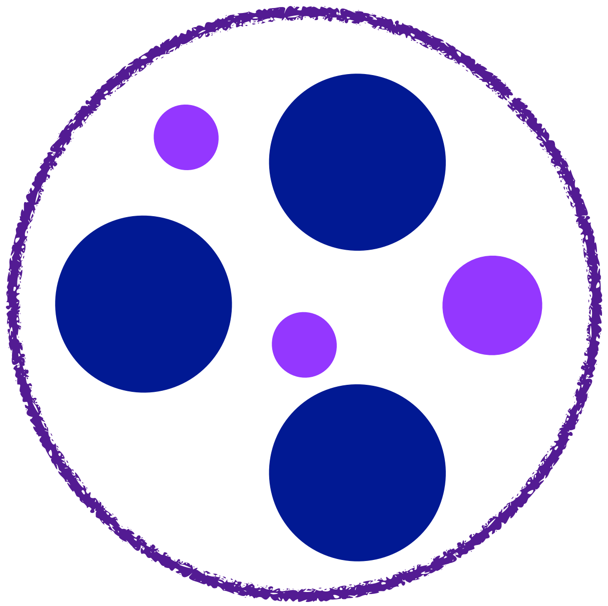
or

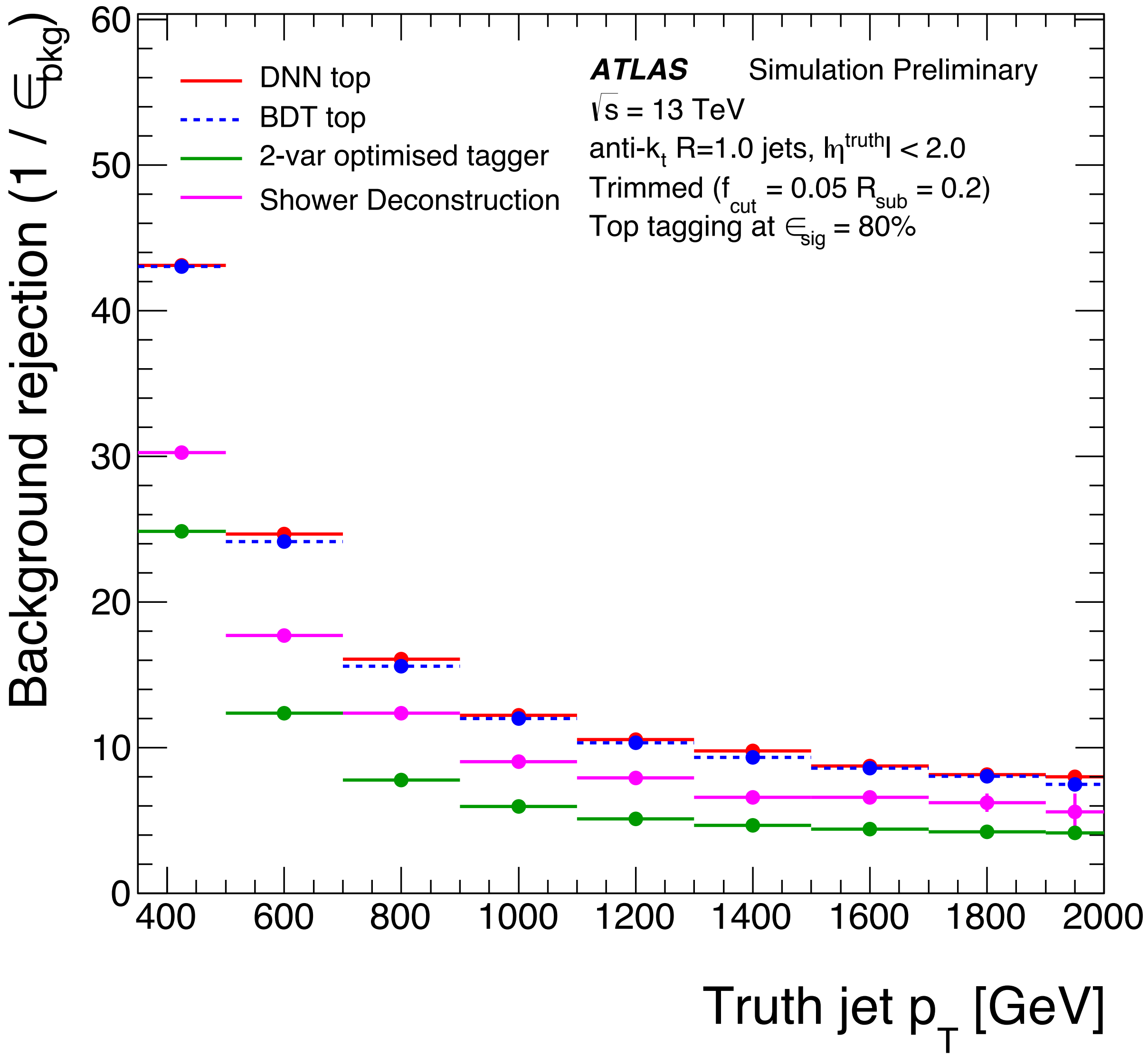




Top tagging

- Like with W and Z, mass and distribution of energy inside the jet are the strongest discriminants
- With hadronic tops, expect ~three energy groups. Basic selection with mass and “n-subjettiness” does well, but adding extra substructure variables in a BDT or DNN can do better still
- Extra useful: one of the decay products should be a b-jet!





ATLAS-CONF-2017-064

Stop talking about calorimeters!

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	(MeV/c)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %		–
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hadrons		(67.41 ± 0.27) %		–

PDG

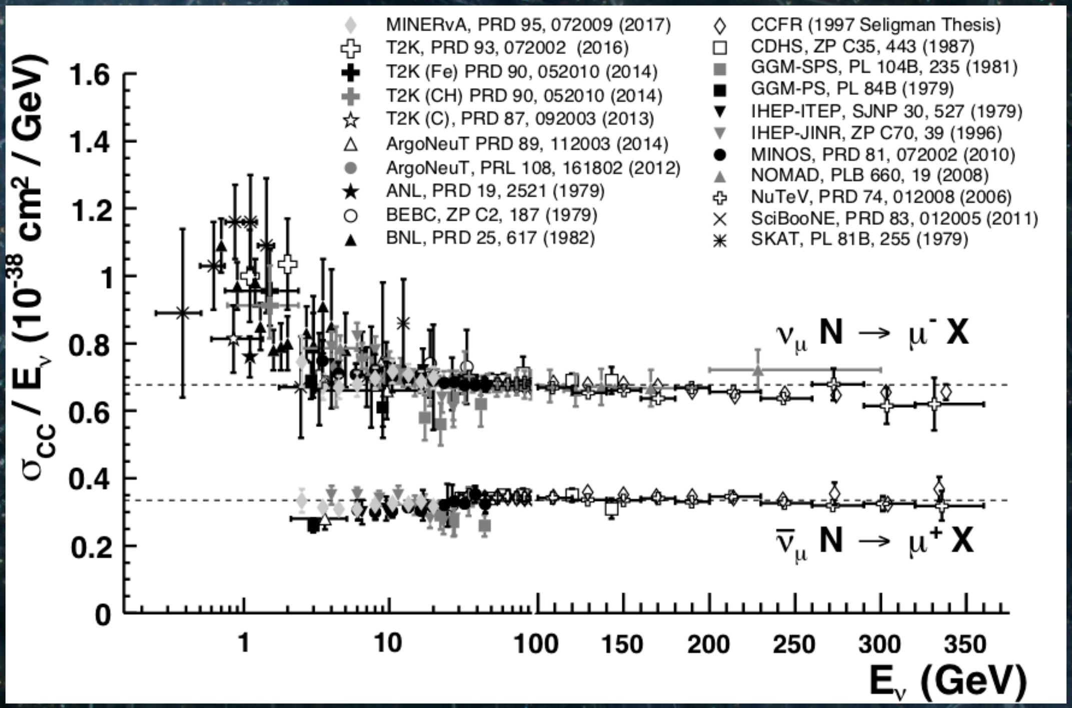
- Z decays to leptons are easy because resolution for leptons is good: if the invariant mass matches a Z, it's probably a Z
- W decays are harder: the ν escapes the detector, leaving missing energy.
- Missing energy is transverse p_T imbalance and is a 3-vector. If you have only 1 neutrino in your event, can reconstruct W *transverse mass*:

$$m_T = \sqrt{2 p_T^{\ell} p_T^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$

Sno+: 800 tonnes of scintillator

Neutrino ID

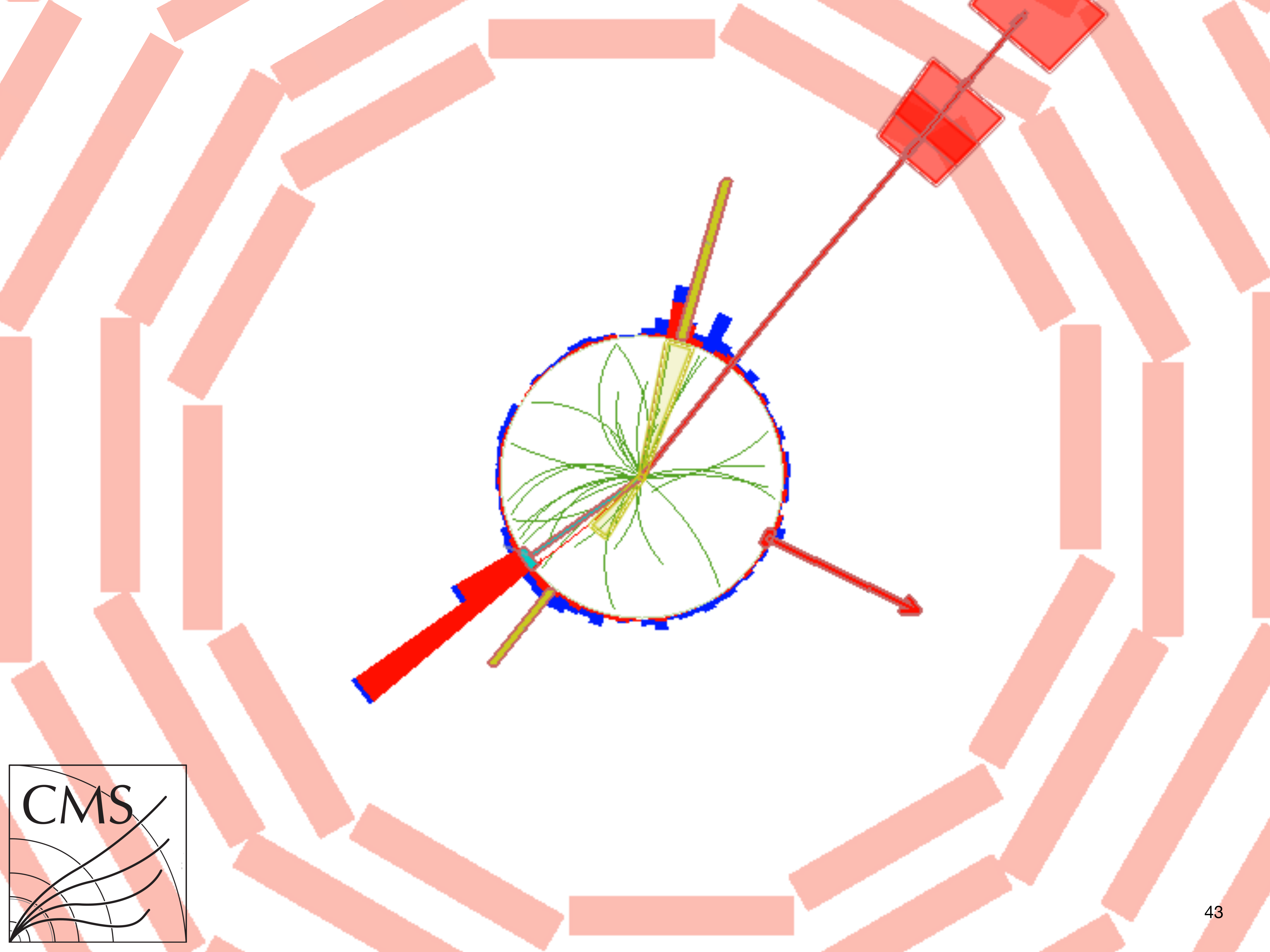
- Neutrino interaction cross section is ridiculously small



- 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

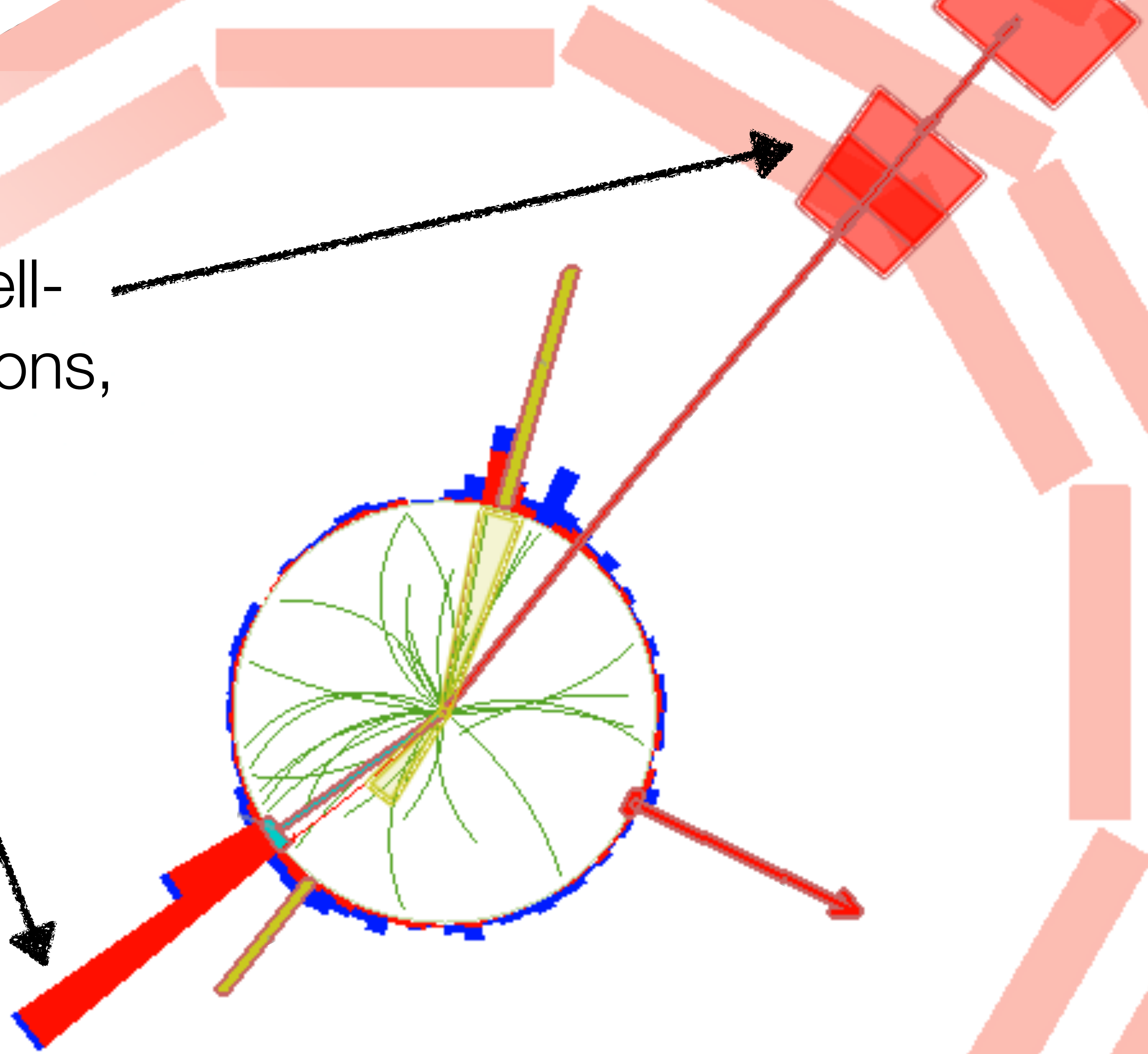
- If you're a collider experiment, you are out of luck! Neutrinos will pass all the way through the detector leaving no trace.

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



MET

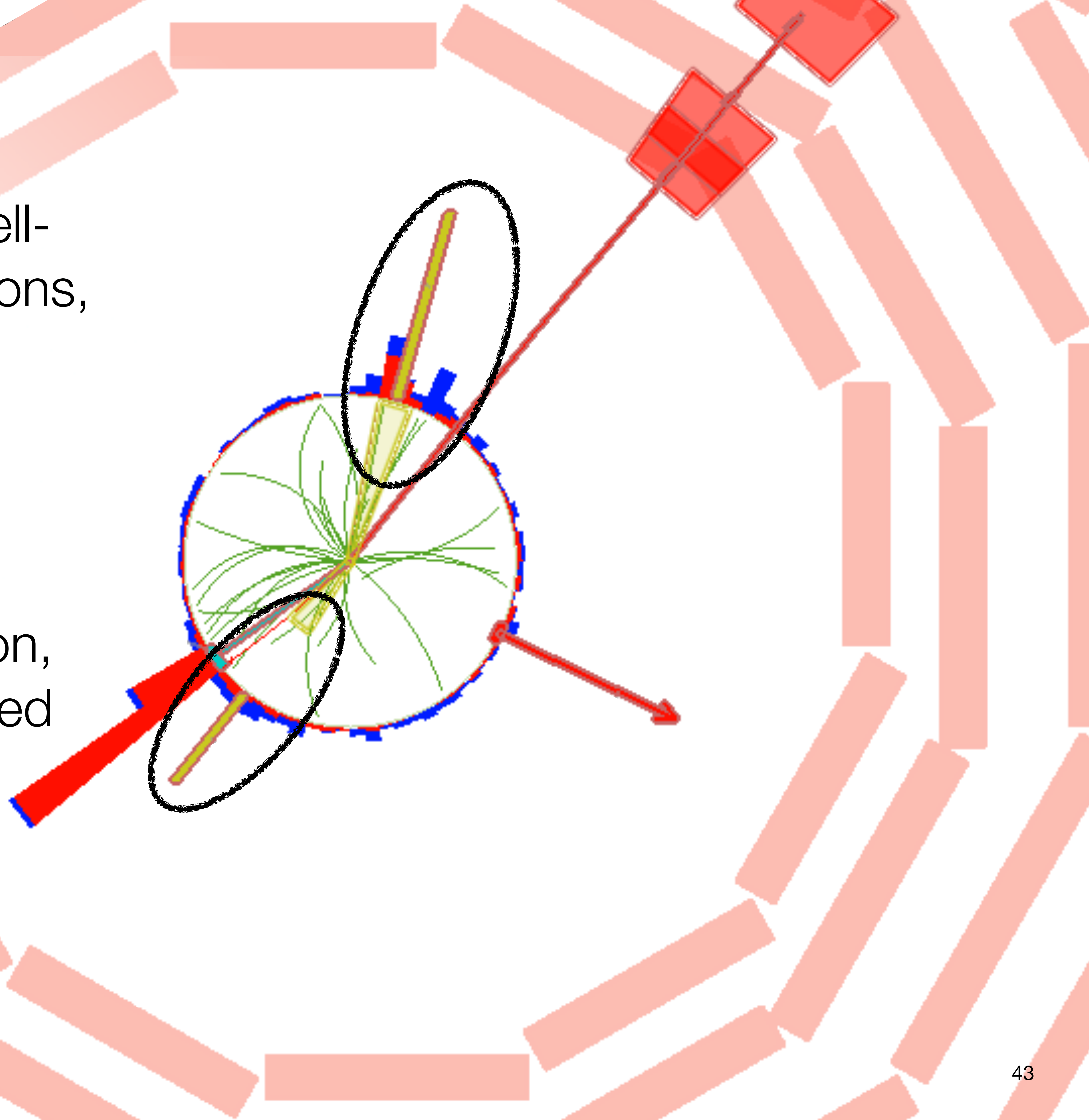
Add together well-calibrated electrons, muons, …



MET

Add together well-calibrated electrons, muons, …

Add all jets passing some threshold criterion, properly calibrated



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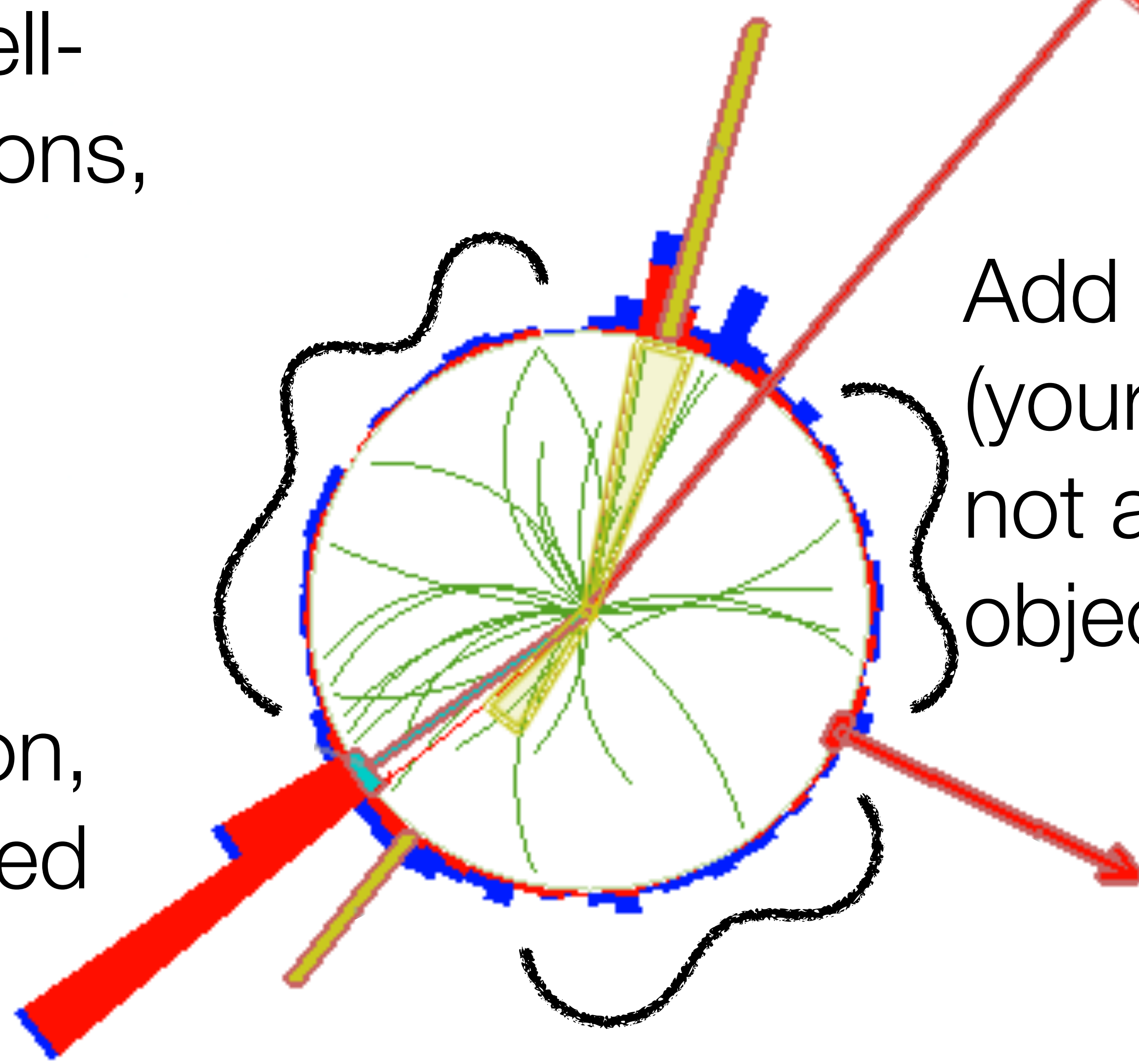


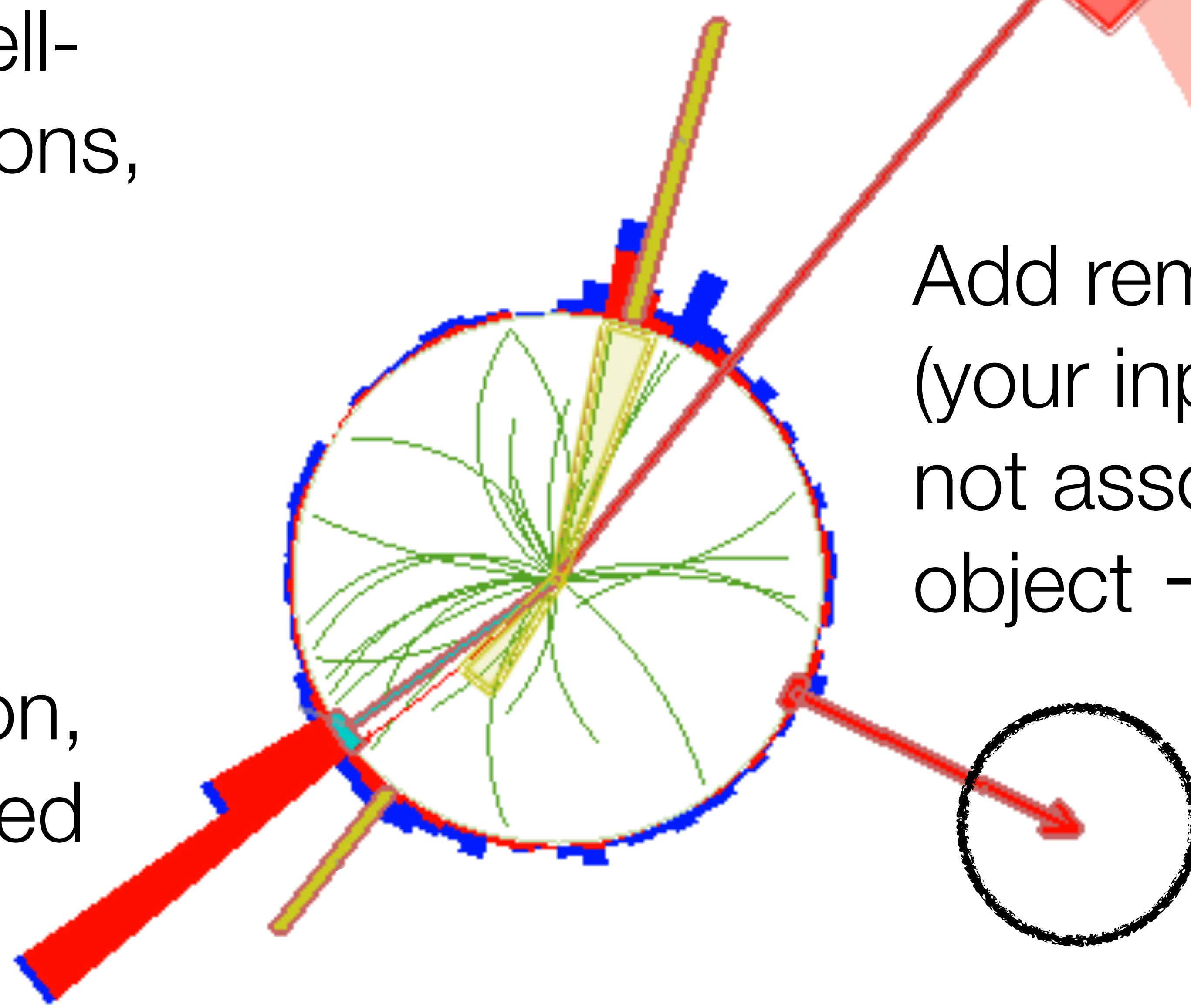
Add remaining activity (your input of choice) not associated to an object → “soft term”

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"

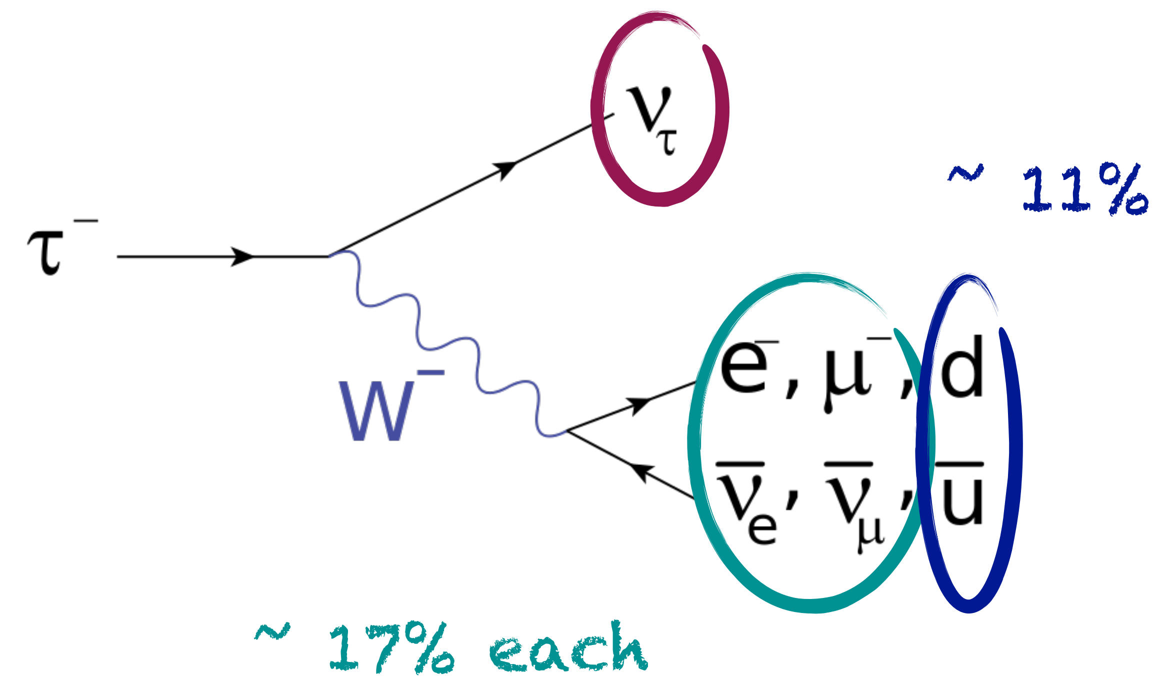
Vector needed for sum to equal zero is the missing transverse momentum (MET)

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



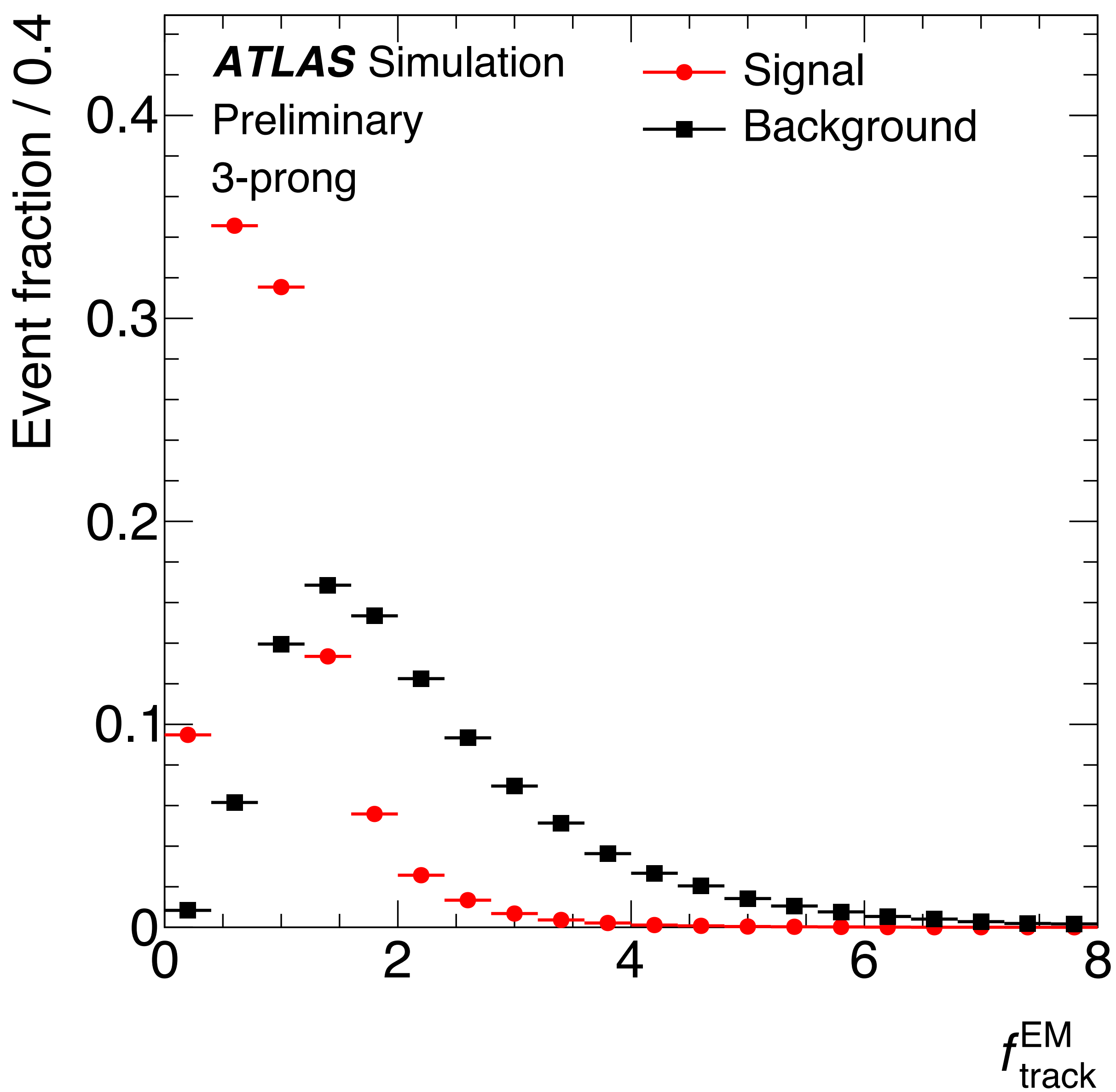
+ 25% $\tau \rightarrow \pi^+ \pi^0 \nu_\tau$

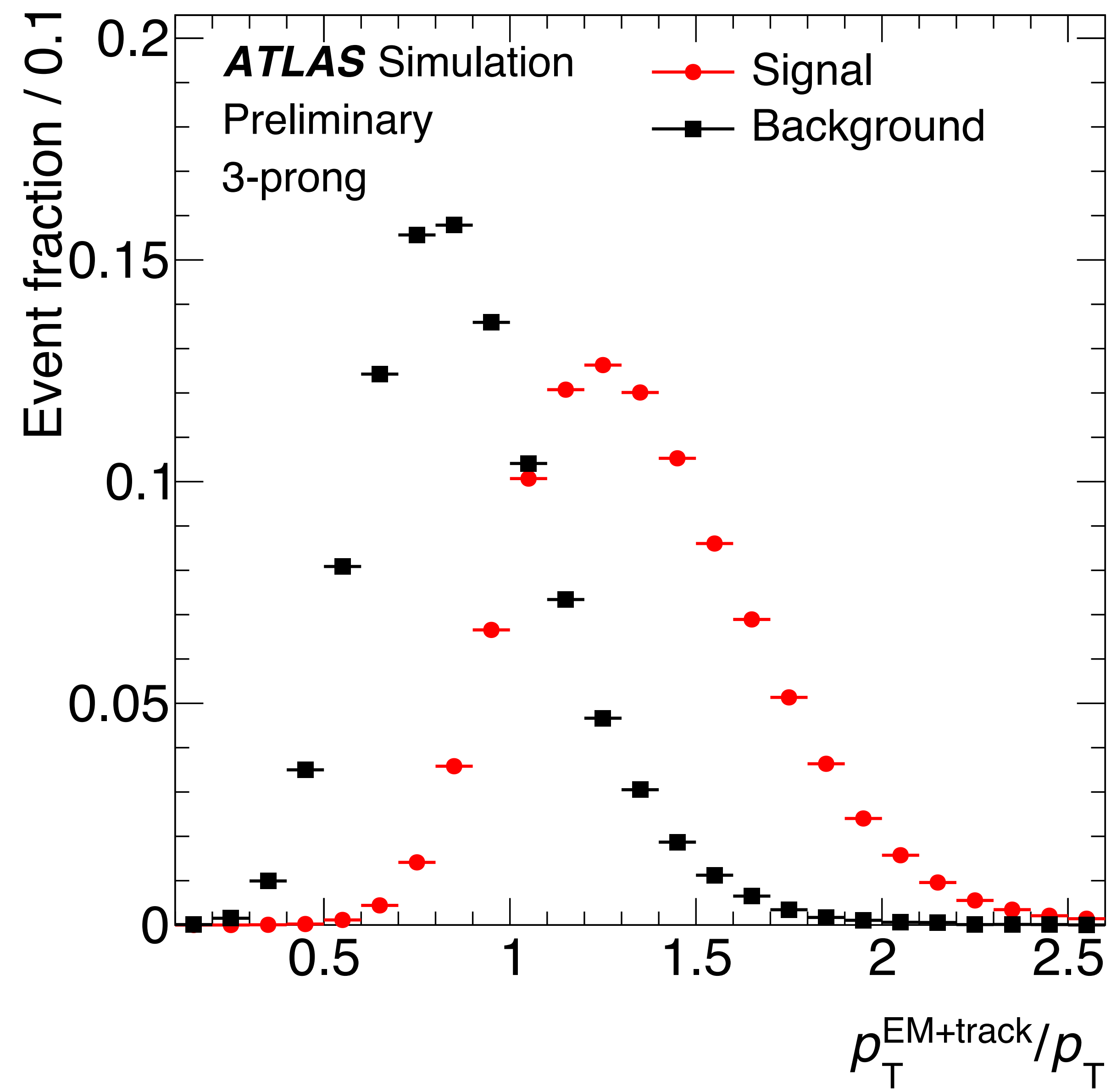
+ 11% $\tau \rightarrow$ 3 charged π

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

Taus

I would paste the PDG decay modes table, but





hadronic fraction, n_{trk}, degree of isolation

[ATL-PHYS-PUB-2015-045]

+ 11% $\tau \rightarrow$ 3 charged π

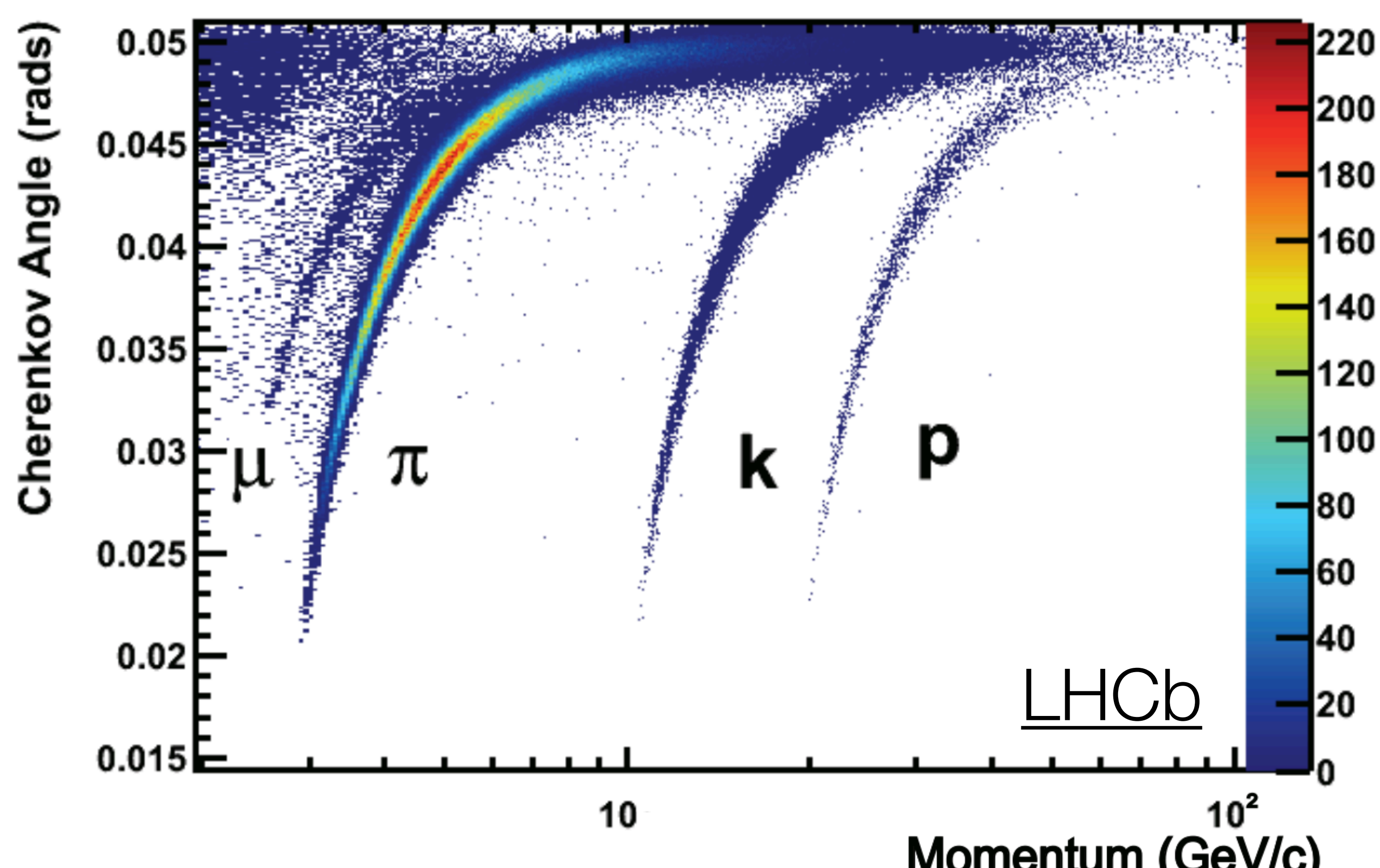
+ 9% $\tau \rightarrow \pi^0\pi^0\pi^+\nu_\tau$

Longer-lived hadrons

Total energy from calo can tell you about mass, but it isn't terribly precise

- If jets aren't enough info and you want to distinguish kaons, pions, and other longer lived mesons, you may need extra information to separate similar masses.
  - Sometimes make an entire dedicated detector (e.g. RICH Cherenkov detector in LHCb)
- For a relativistic particle, $\beta = v/c, \gamma = E/m = (1 - \beta^2)^{-1/2}$
- Cherenkov radiation is one of several ways to get extra information on β which can translate to mass information. Angle of radiated light directly related to β:

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



Longer-lived hadrons, cont'd

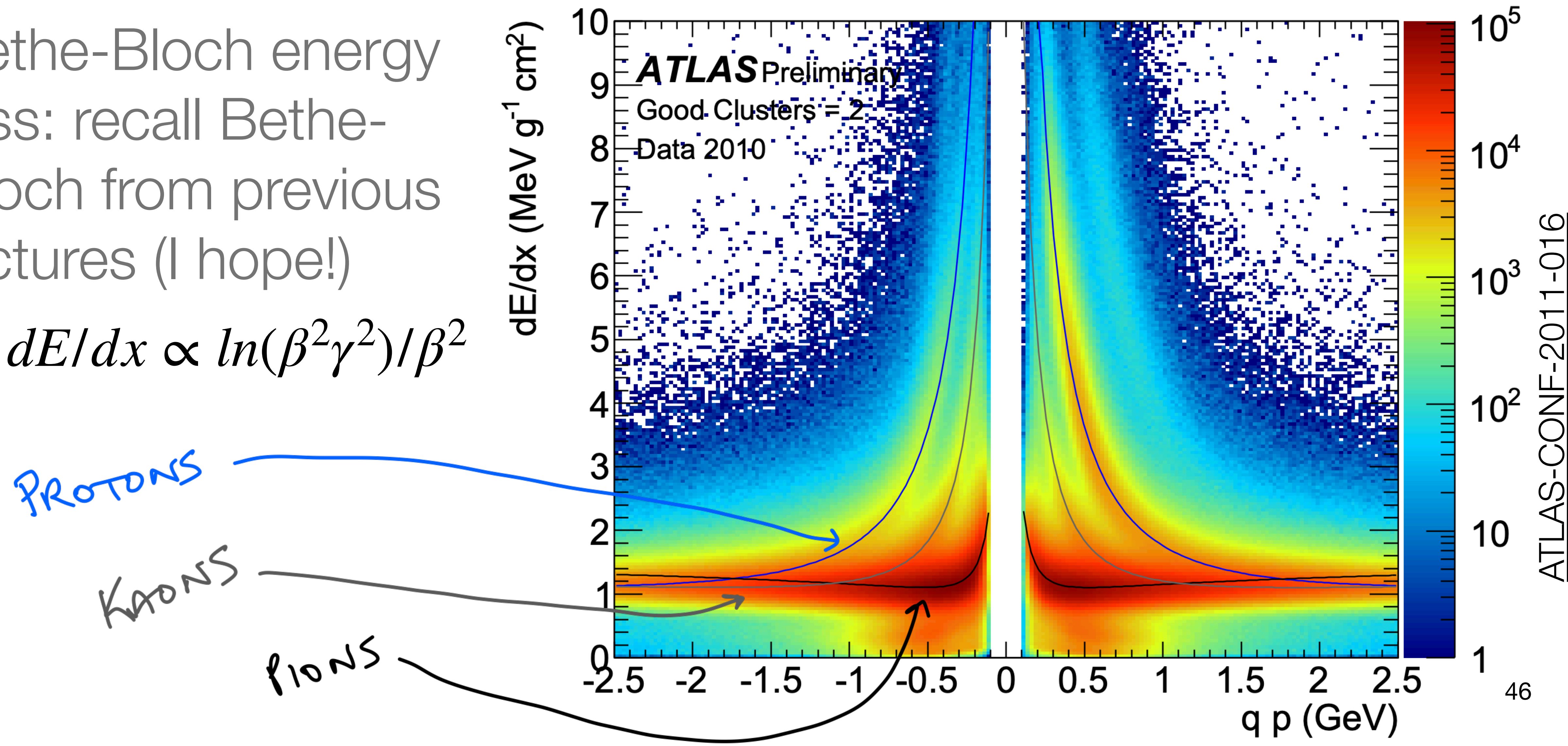
- Time of flight: if you have a very good timing detector, can resolve two particles of the same energy but different masses:

$$\text{tof} = d/\beta c$$

Diff ~ picoseconds, but feasible!

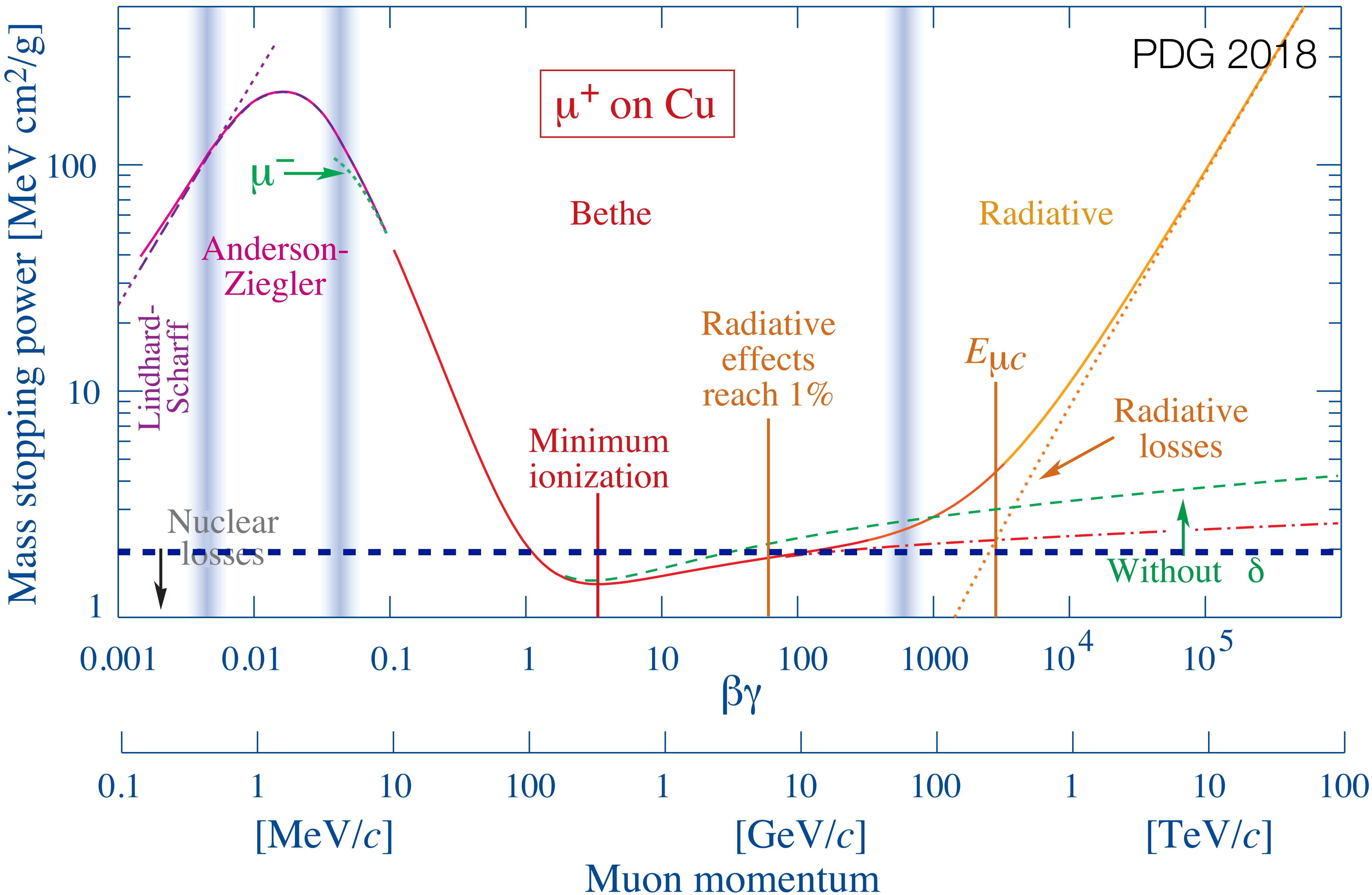
- Bethe-Bloch energy loss: recall Bethe-Bloch from previous lectures (I hope!)

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



Fun with muons

Reminder
$\beta\gamma = p/Mc$



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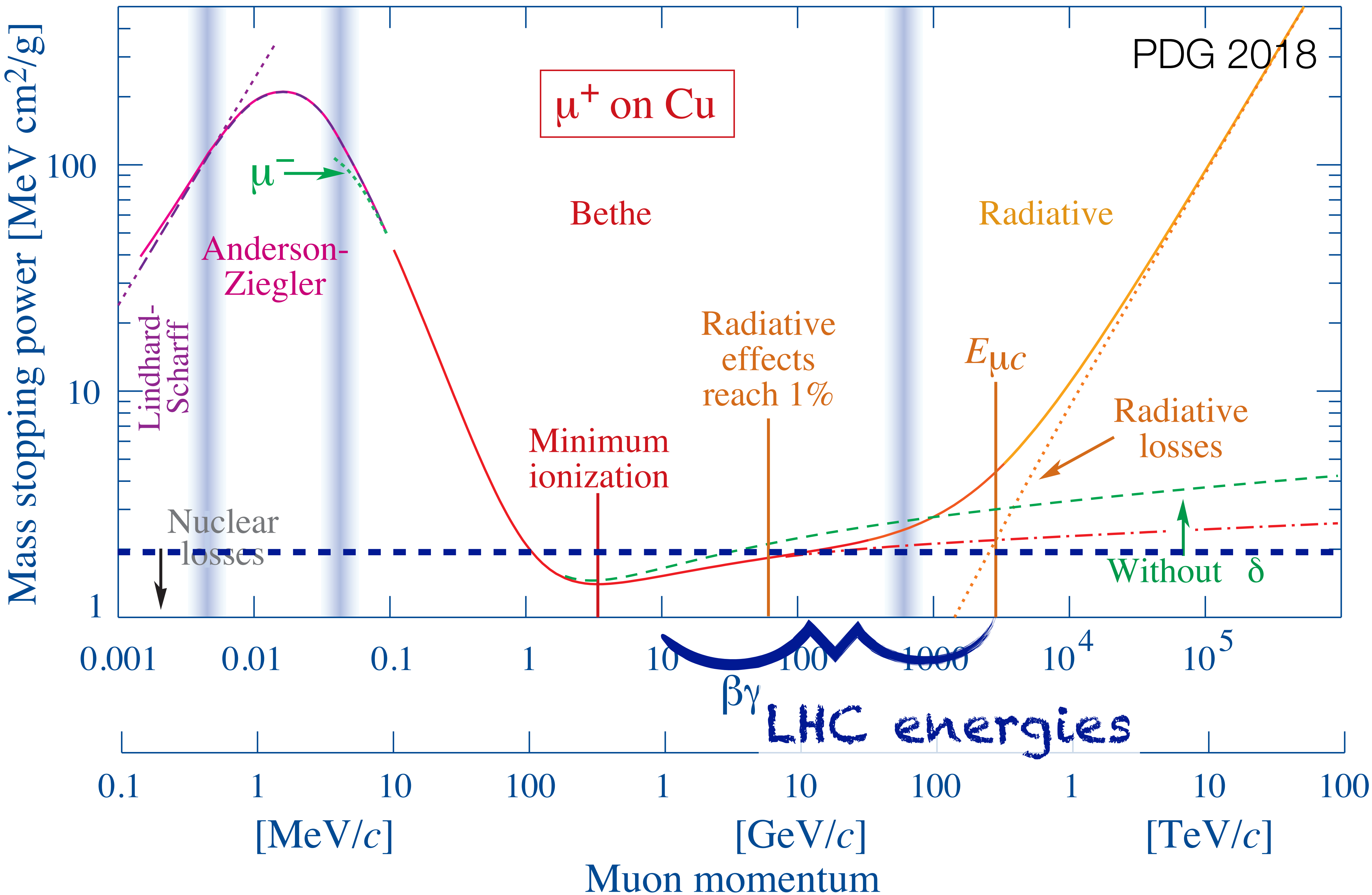

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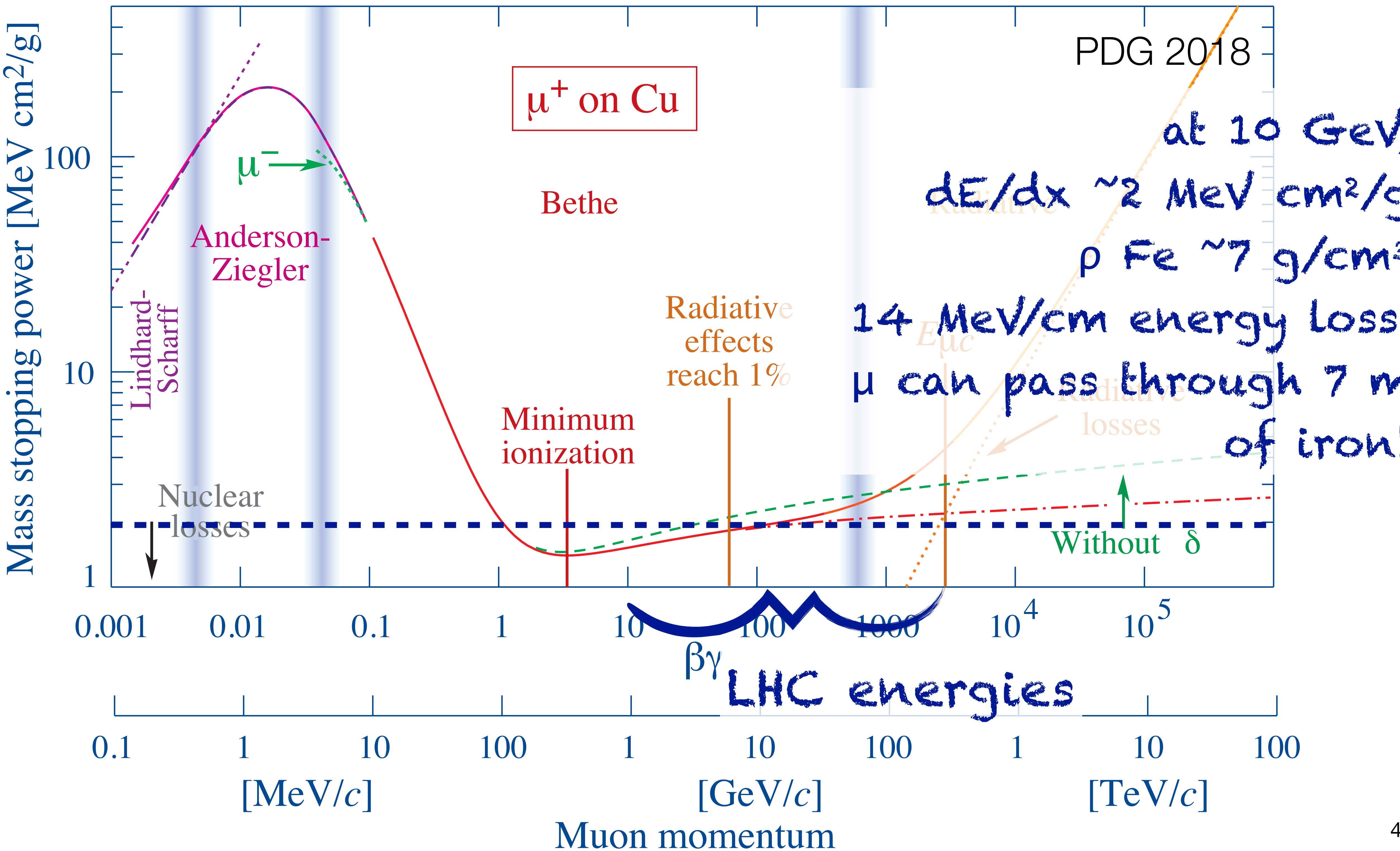

Conclusions

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 LHC energies!

Student problems

Problems

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

- 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 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