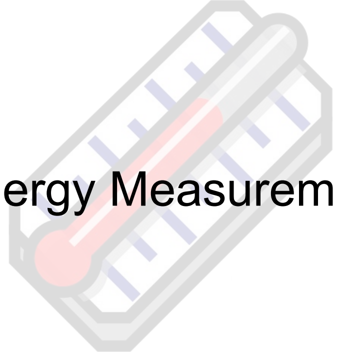
Calorimetry

Grace E. Cummings

With a lot of influence from Richard Wigman's HCSS 2018 Talk!

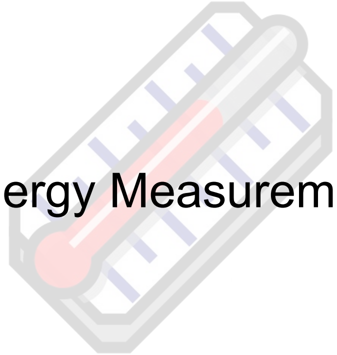
EDIT School - November 15, 2024

What is calorimetry?



Energy Measurement

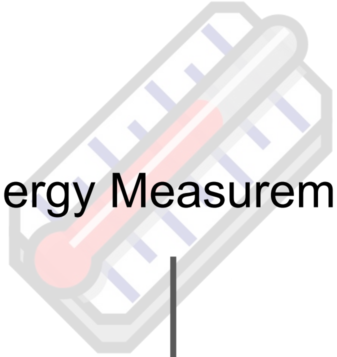
What is calorimetry?



Energy Measurement

Every particle detection technology can be used for calorimetry!

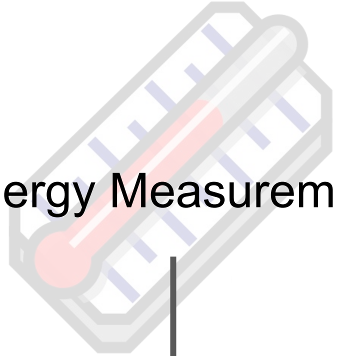
What is calorimetry as *an instrumentation discipline*?



Energy Measurement

How to build a detector to **specifically** measure energy

What is calorimetry as *an instrumentation discipline*?



Energy Measurement

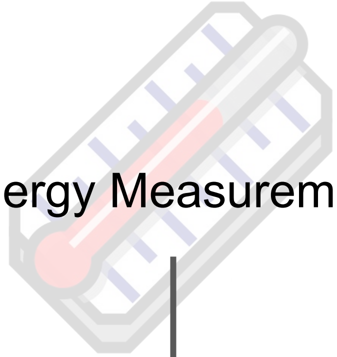
↓

How to build a detector to **specifically** measure energy

Q1

What energy regime are we trying to measure?

What is calorimetry as *an instrumentation discipline*?



Energy Measurement

How to build a detector to **specifically** measure energy

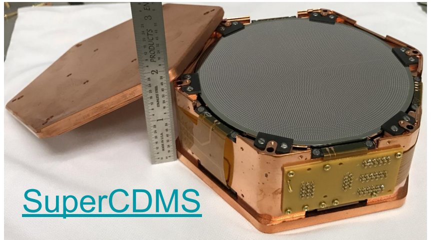
Q1

What energy regime are we trying to measure?

ULTRA-LOW!

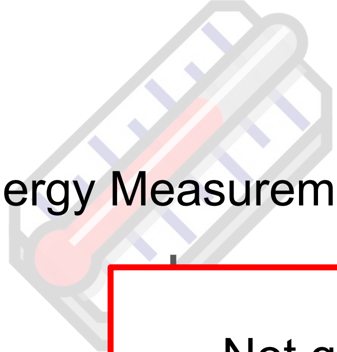
Cryogenic detectors/quantum sensors

- Phonon detection
- Cooper-pair dissociation
- Etc…
- For more info
  - See Monday's talk!
  - See Thursday's talk!



SuperCDMS

What is calorimetry as *an instrumentation discipline*?



Energy Measurement

Q1

What energy regime are we trying to measure?

ULTRA-LOW!

Not going to cover this today!

Cryogenic
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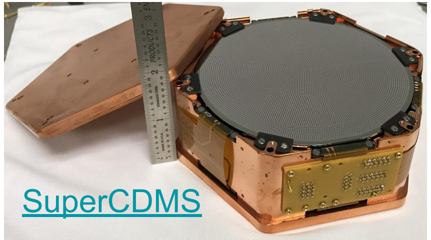


SuperCDMS

Can we extract energy transfer?

What is calorimetry as *an instrumentation discipline*?

Energy Measurement

How to build a detector to **specifically** measure energy

Q1

What energy regime are we trying to measure?

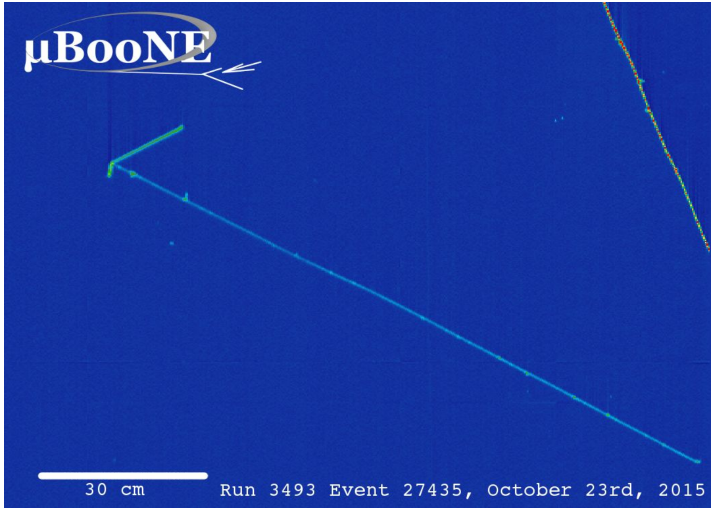
LOW-MEDIUM

Time projection chambers

Ionization/excitation for dE/dx

Particle range out!

See detailed talk on Monday!



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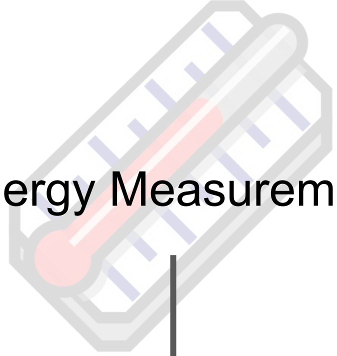


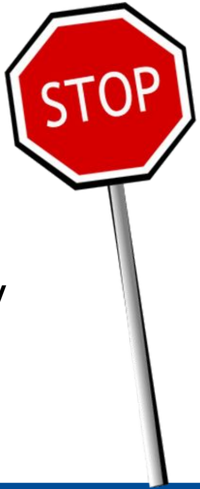
Energy Measurement

How to build a detector to **specifically** measure energy

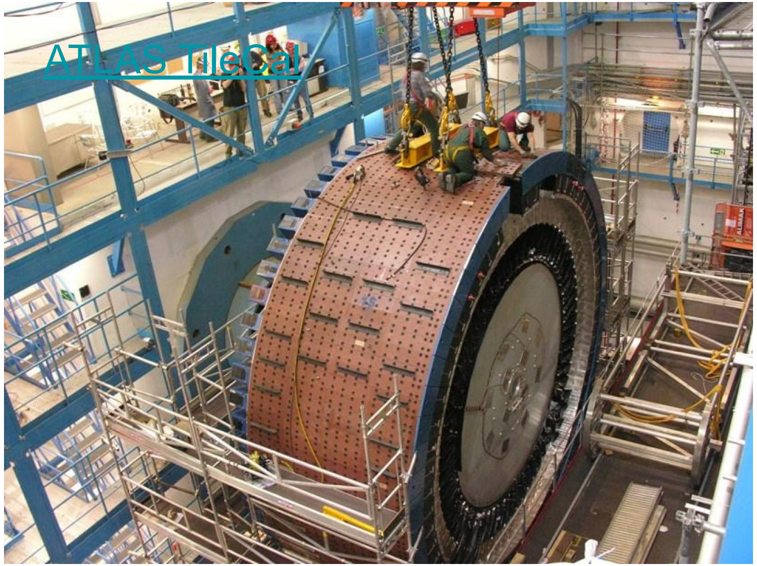
Q1

What energy regime are we trying to measure?

HIGH ENERGY!



Stop those particles!



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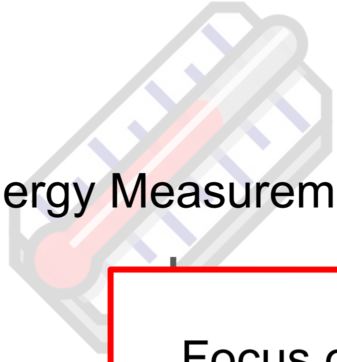


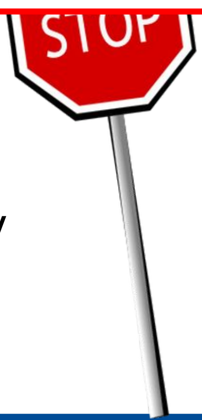
Energy Measurement

Q1

What energy regime are we trying to measure?

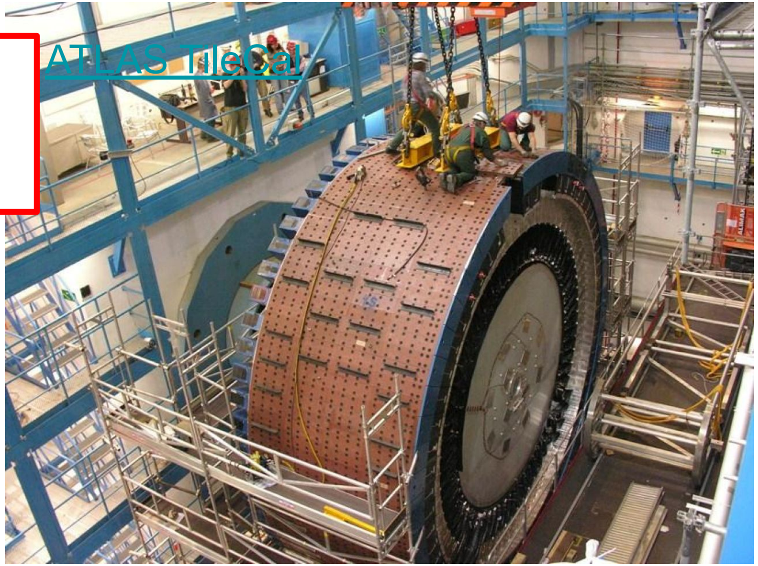
HIGH ENERGY!

Focus of the examples I will give!



Stop those particles!

How to build a detector to **specifically** measure energy



ATLAS TileCal

Role of calorimetry/calorimeters - see *everything*

UA2 Lead+Scintillating Plastic Calorimeter

Journal of Physics: Conf. Series 928 (2017) 012001

- Measure charged and neutral particles
    - Give enough space for this interaction
    - Allows for “missing energy” reconstruction
- Particle Flow and Particle ID
    - Either alone or w/ other subdetector info, can ID particles
- Good for *trigger*
    - Quick, large analog signal

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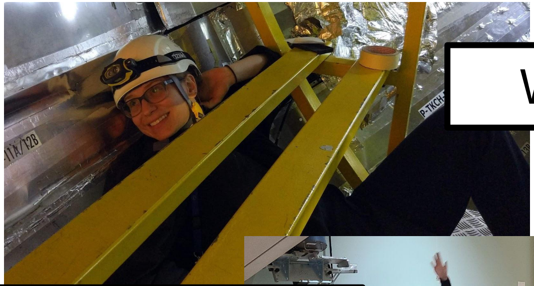
Not all calorimeters do everything - so you have to think about what you want!

Outline

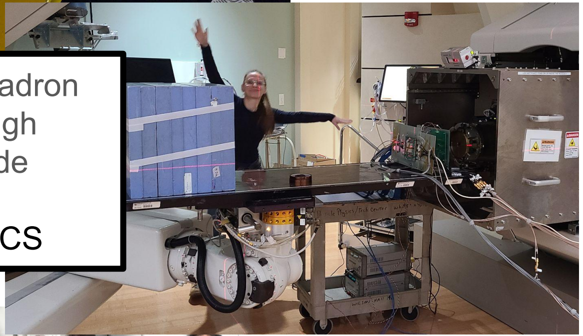
1. What is calorimetry
   a. How particles deposit energy
   b. General designs
   c. Some limitations
2. Calorimeter Technologies
   a. Ionization Calorimetry
   b. Optical Calorimetry
3. What I have left out, but you should be aware of

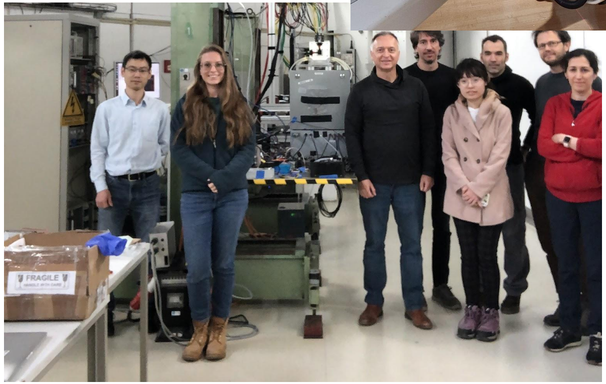
Who am I?



Compact Muon Solenoid Hadron Calorimeter Upgrade/ High Granularity Calo Upgrade

READOUT ELECTRONICS

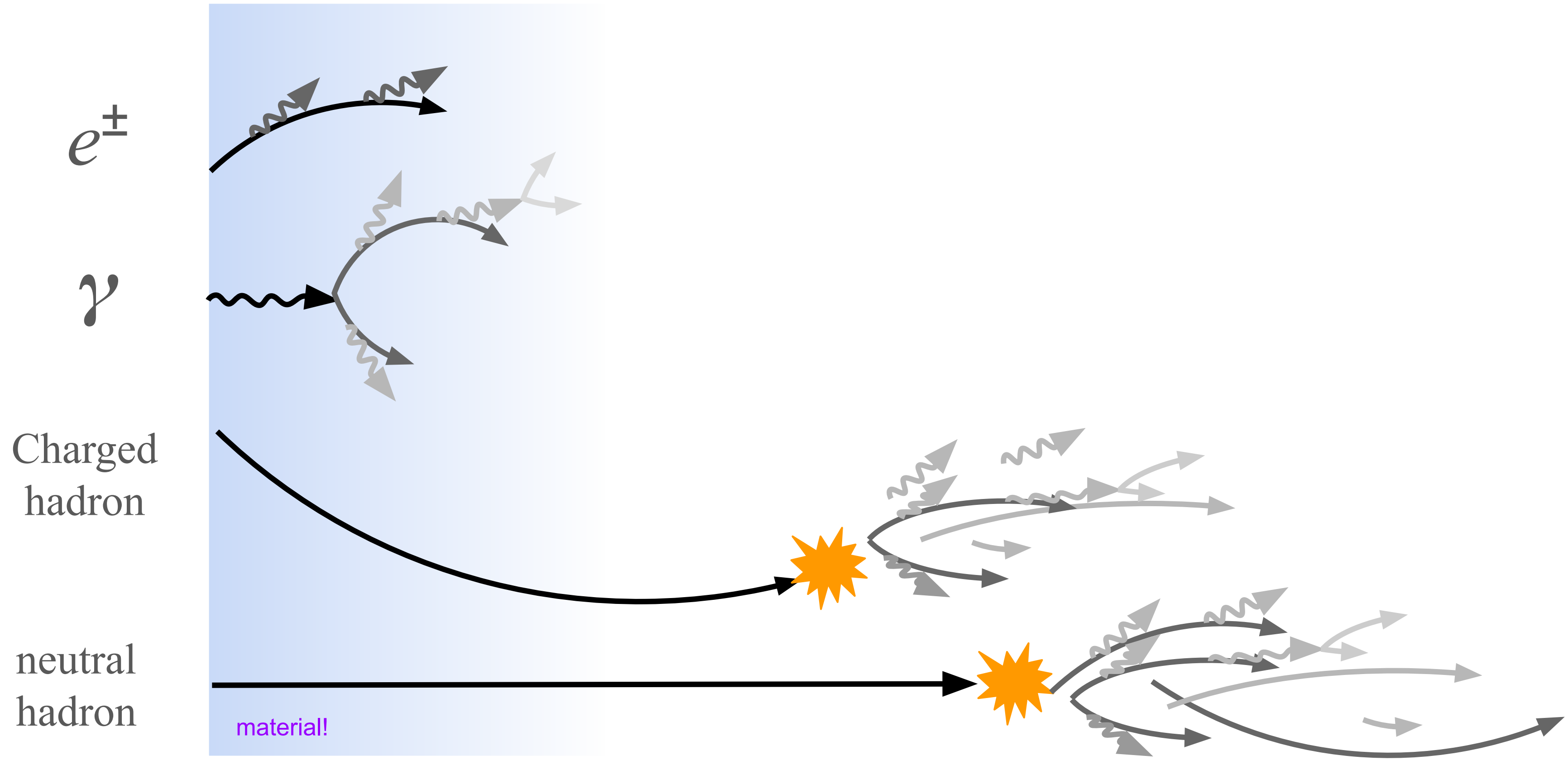




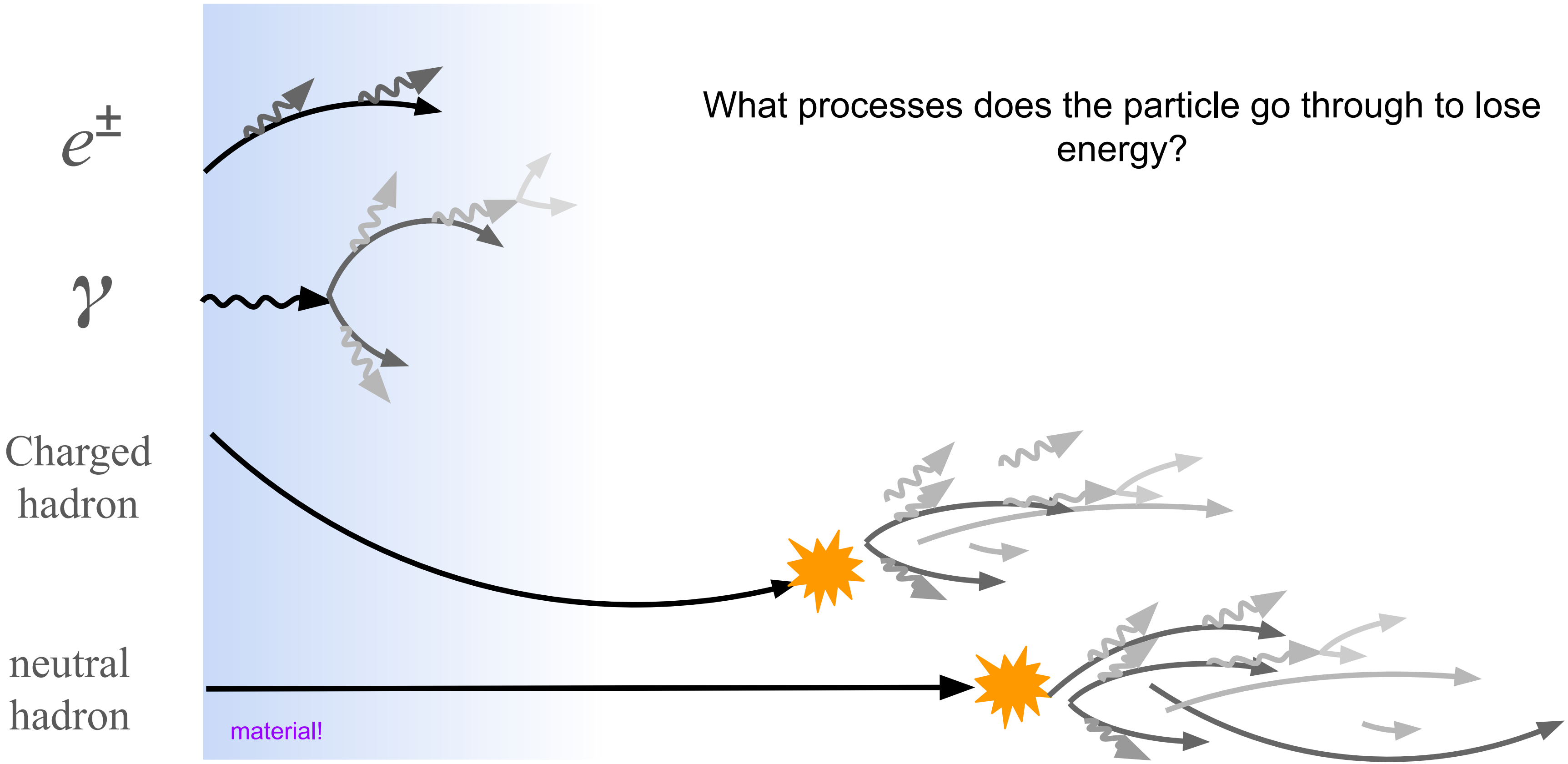
Dual Readout for future collider R&D w/ CalVision

How do particles lose/deposit energy?

Particle Energy Loss

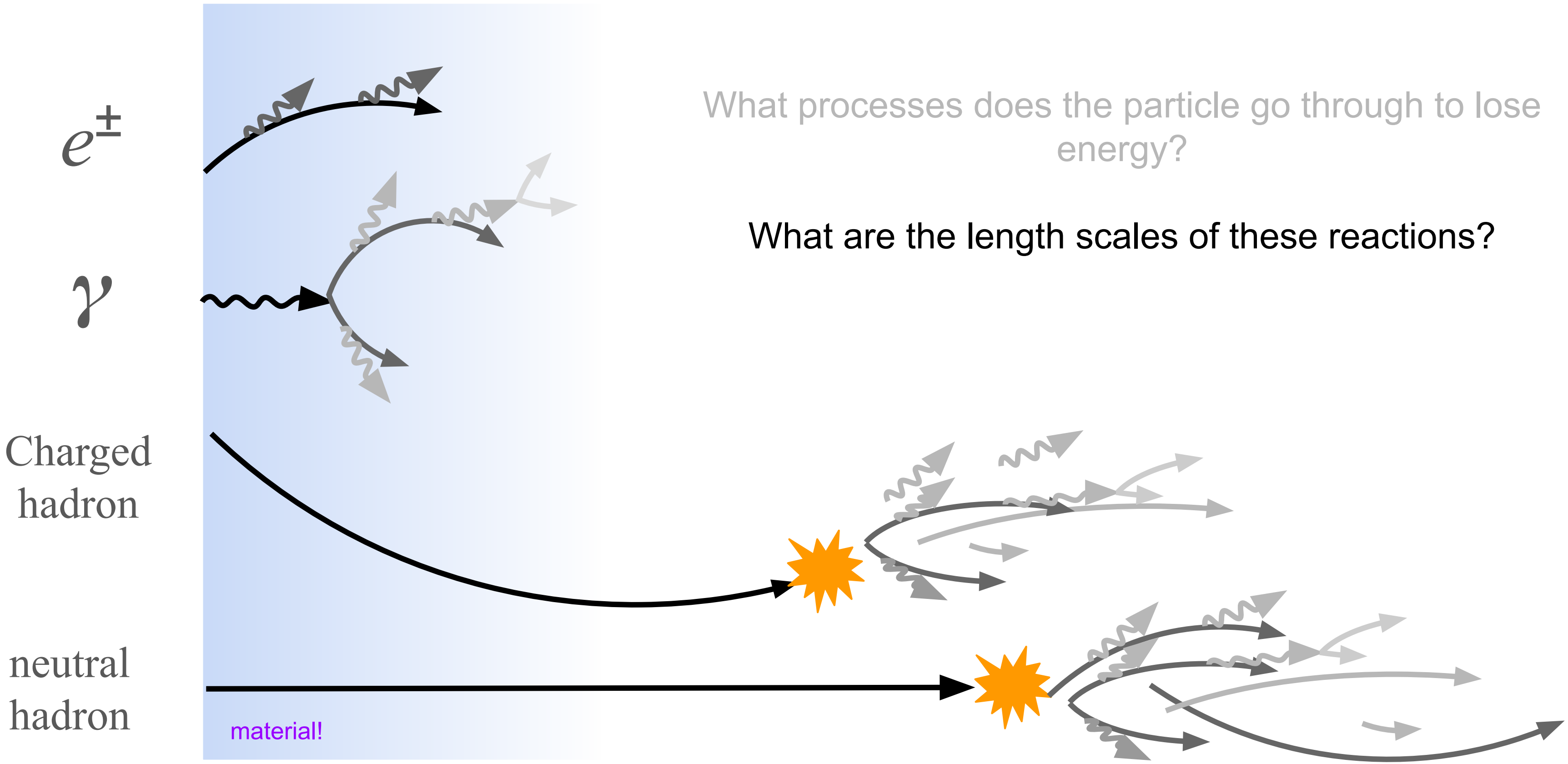


Particle Energy Loss



What processes does the particle go through to lose energy?

Particle Energy Loss



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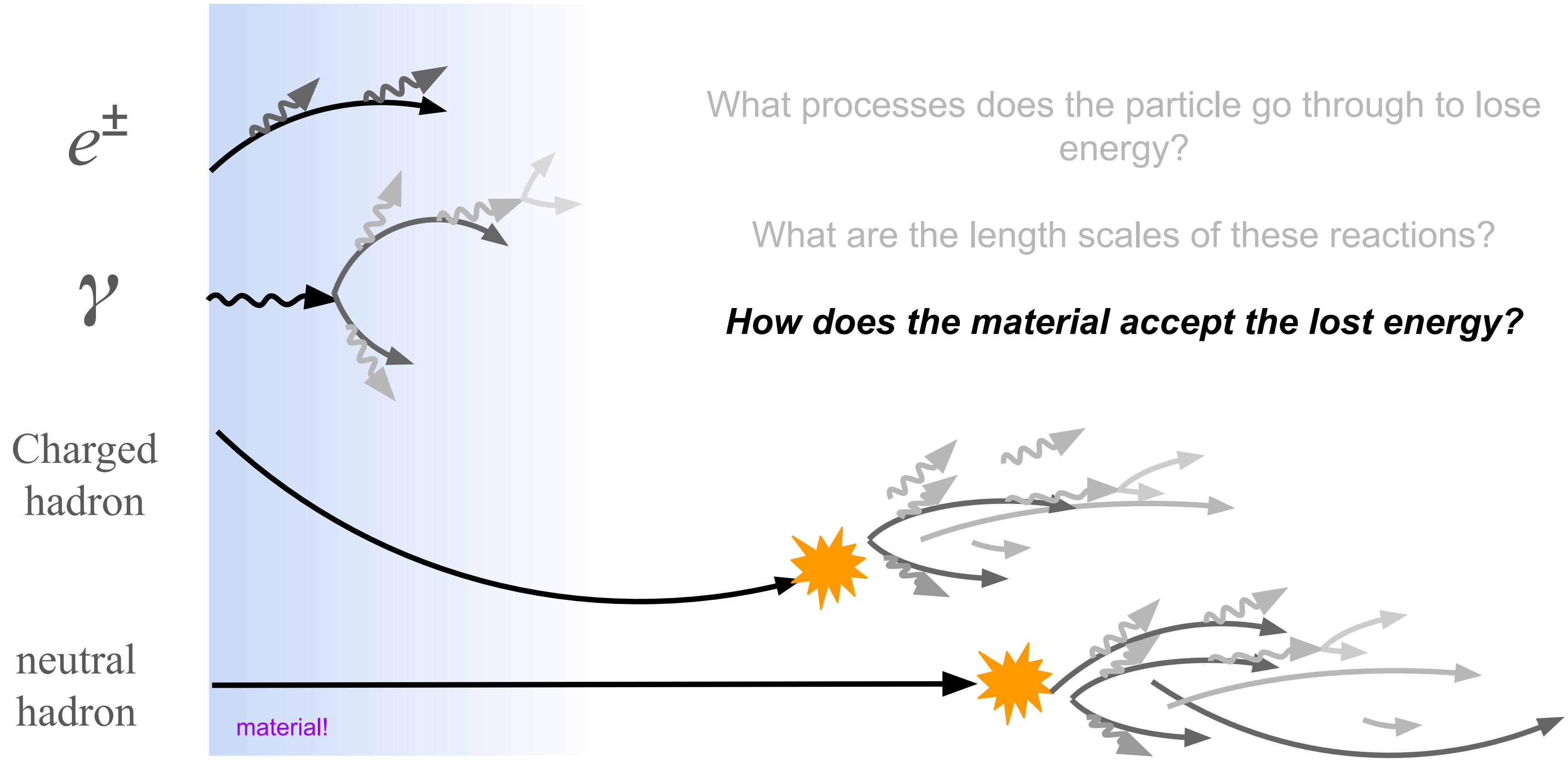
What are the length scales of these reactions?

Particle Energy Loss



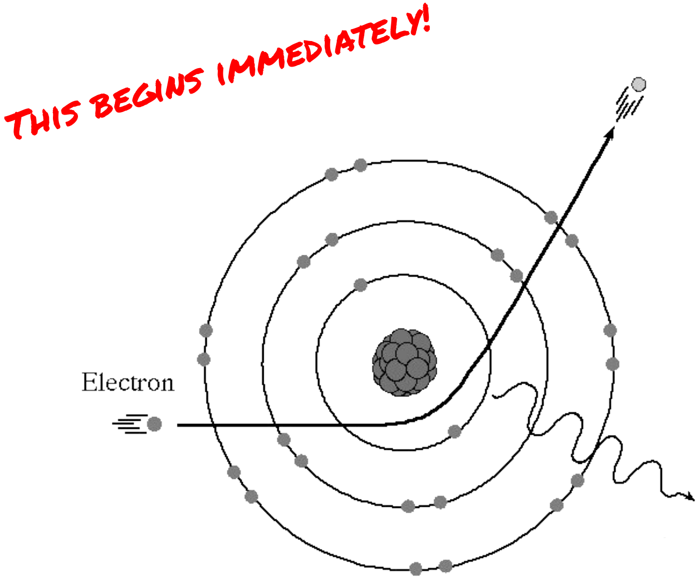
What processes does the particle go through to lose energy?

What are the length scales of these reactions?

How does the material accept the lost energy?

How electrons lose energy

- Bremsstrahlung
  - Photon emitted due to path bending
- Ionization and excitation
  - Liberate or excite electrons in material
  - Can create δ-rays
- Cherenkov Radiation
  - Charged particle moving faster than the speed of light in a media



Electrons actually bend in the electric field of the material's atoms

Brem in material Image credit: https://web2.uwindsor.ca/courses/physics/high_schools/2006/Medical_Imaging/ctphysics.html

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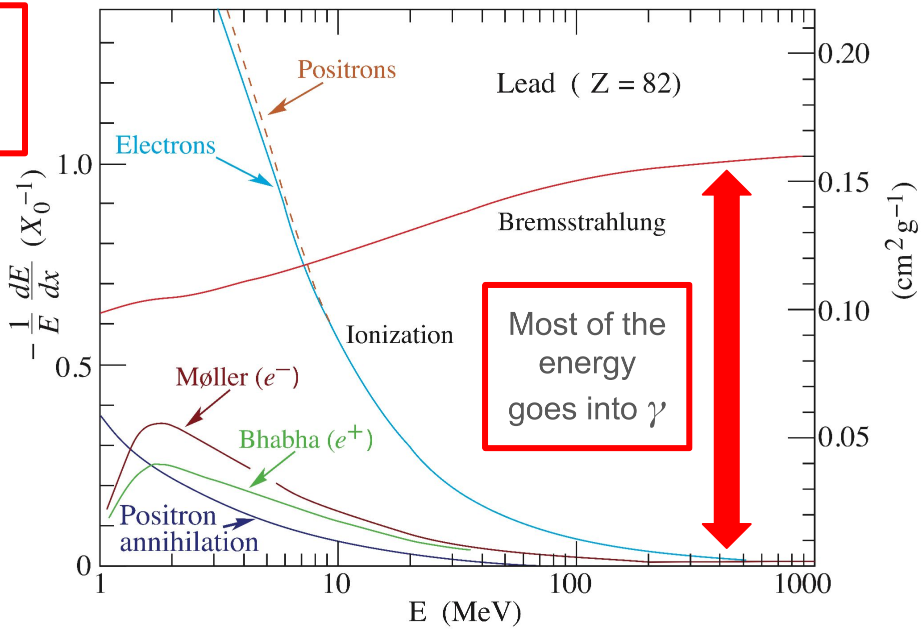
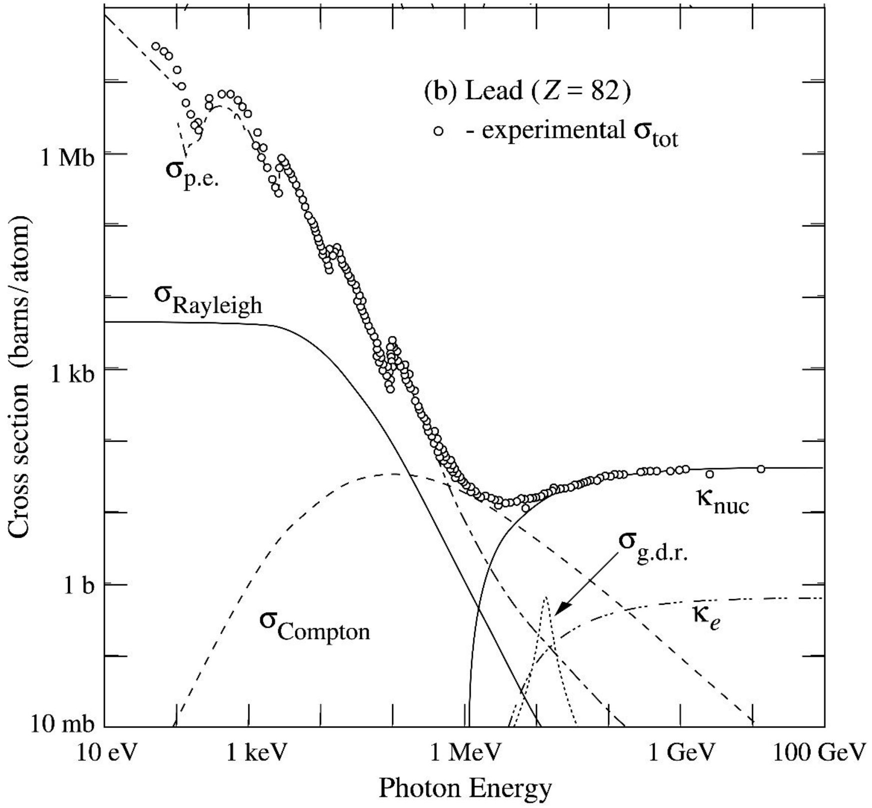


P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2022 update.

How *photons* lose energy

- Pair-production
  - Going into **electron-positron** pairs
    - κ_{nuc}, pp in nuclear field
    - κ_e, pp in electron field
- Compton Scattering
  - Photon scatters off an electron in the material
    - $\sigma_{Compton}$
- Photoelectric effect
  - Photon kicks electron into conduction band
    - $\sigma_{p.e.}$



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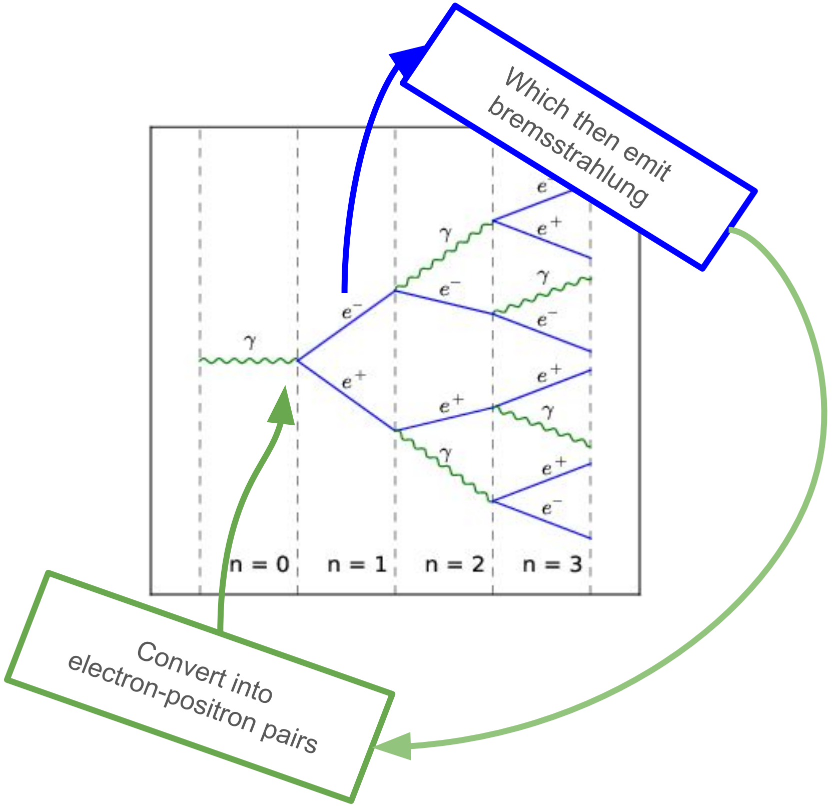
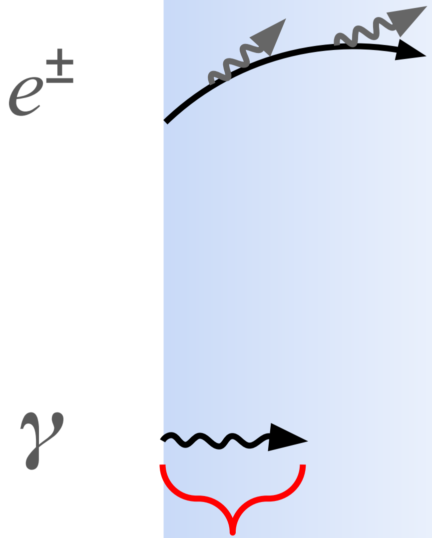


Electromagnetic showers - particle multiplication



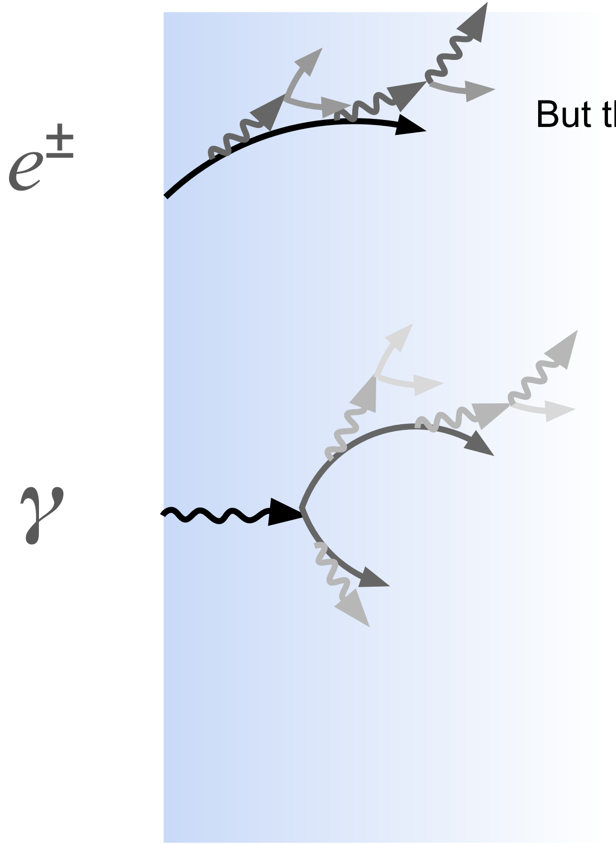
Electrons immediately bremsstrahlung

But photons have to wait until they
have an interaction

“Mean free path”,
~ 9/7 X_0*

*more on this in a second

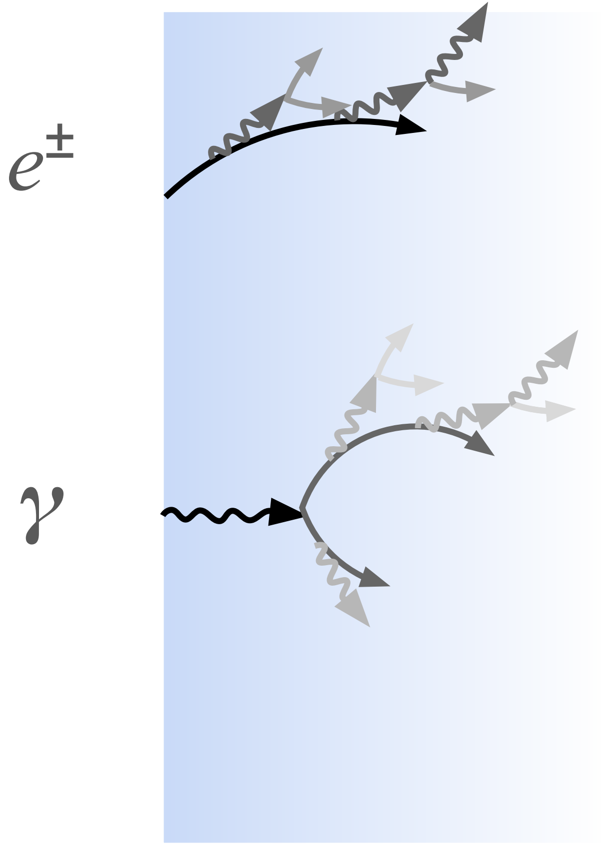
Electromagnetic showers - particle multiplication



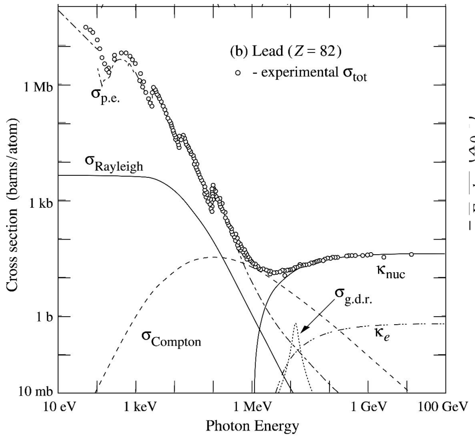
But then the brem-photons pair-produce or scatter

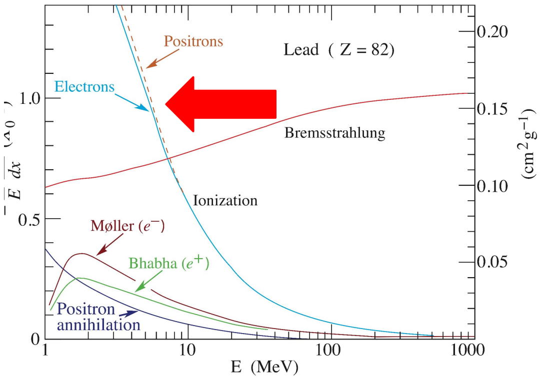
And these electrons brem…

Electromagnetic showers - particle multiplication



And it continues like this until we cross into the regimes where no other particles are produced!

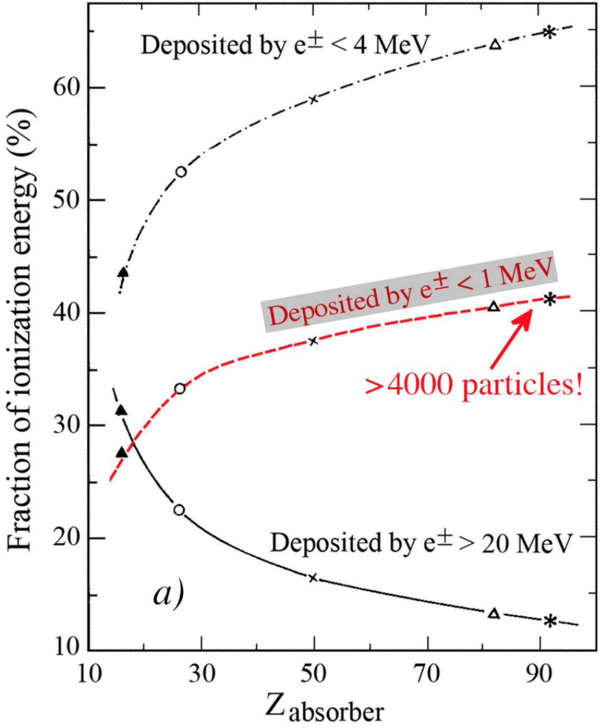




How electromagnetic showers *deposit* energy

ULTIMATELY IONIZATION IN THE END

10 GeV initial Electron
(simulation)



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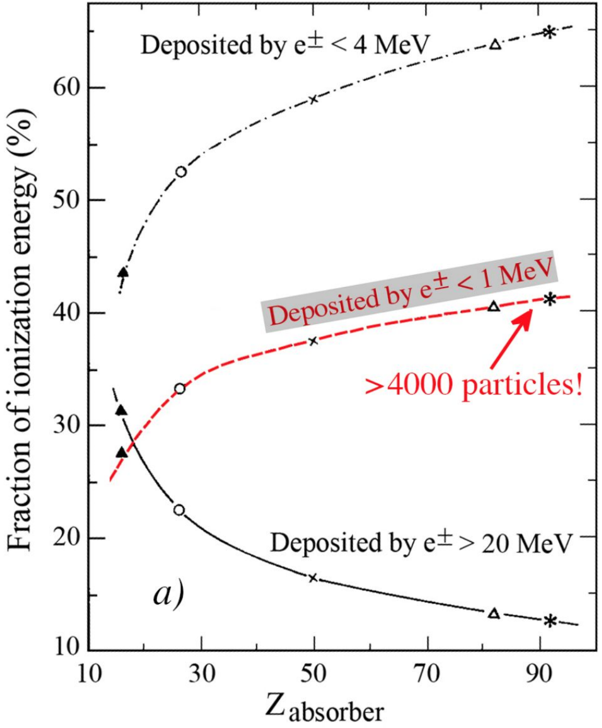
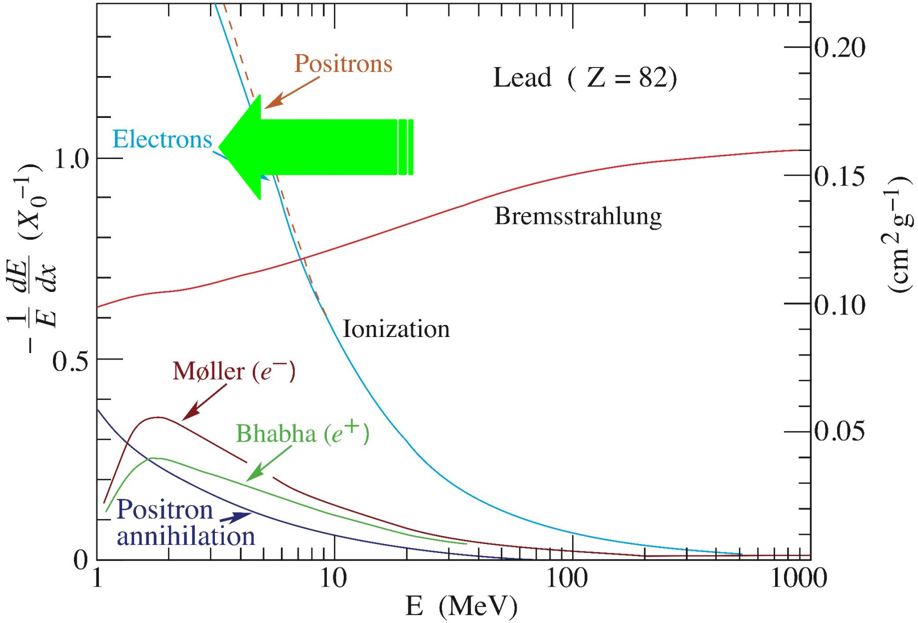




The units of electromagnetic showers

A = mass number
Z = atomic number
N_A = Avogadro's number
V_i = fractional volume

- Radiation Length
  - Distance for which (>> 1 GeV) e± deposit ~63.2% of their energy (1/e)

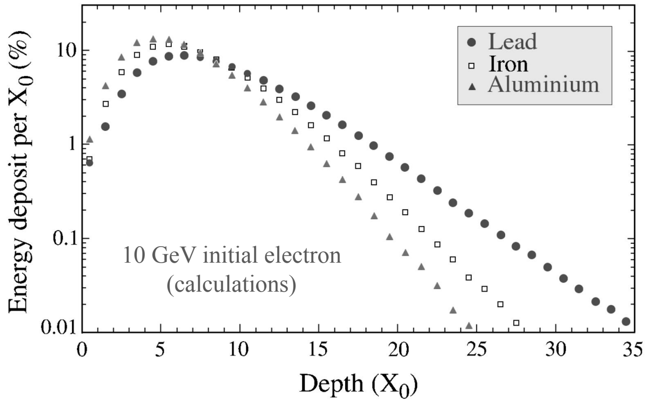
HOMOGENOUS MATERIAL APPROXIMATION:

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

IN A MIXTURE

$$\frac{1}{X_0} = \sum_i V_i/X_i$$

Roughly material independent way to characterize shower development!



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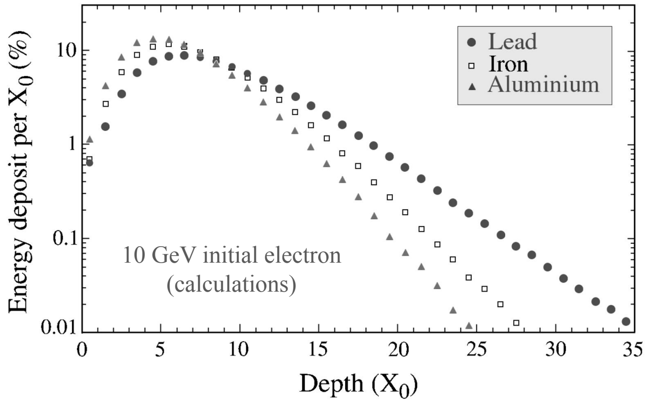

- Mean Free path of very high energy photons

$$\sigma(E \to \infty) = \frac{7}{9} \frac{A}{N_A X_0} \Rightarrow 9/7\, X_0$$

BEFORE AN INTERACTION

The units of electromagnetic showers

A = mass number
Z = atomic number
N_A = Avogadro's number
V_i = fractional volume
E_s = 21.2 MeV = $m_e c^2 \sqrt{4\pi/\alpha}$,
ϵ_c = critical energy → where ionization energy loss per X_0 is equal to the electron's energy

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BEFORE AN INTERACTION

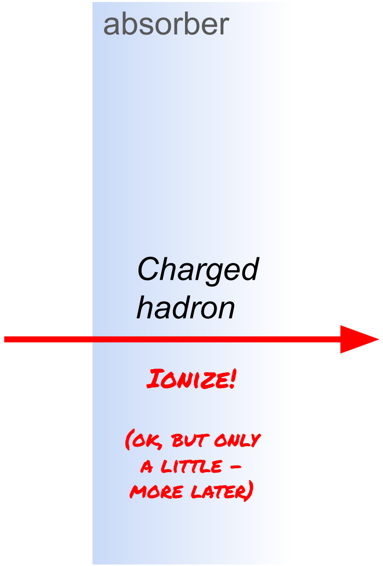
- Molière radius
  - ~85-90% of energy deposited in this radius

$$\rho_M = E_s \frac{X_0}{\epsilon_c}$$

Longer showers → skinnier showers

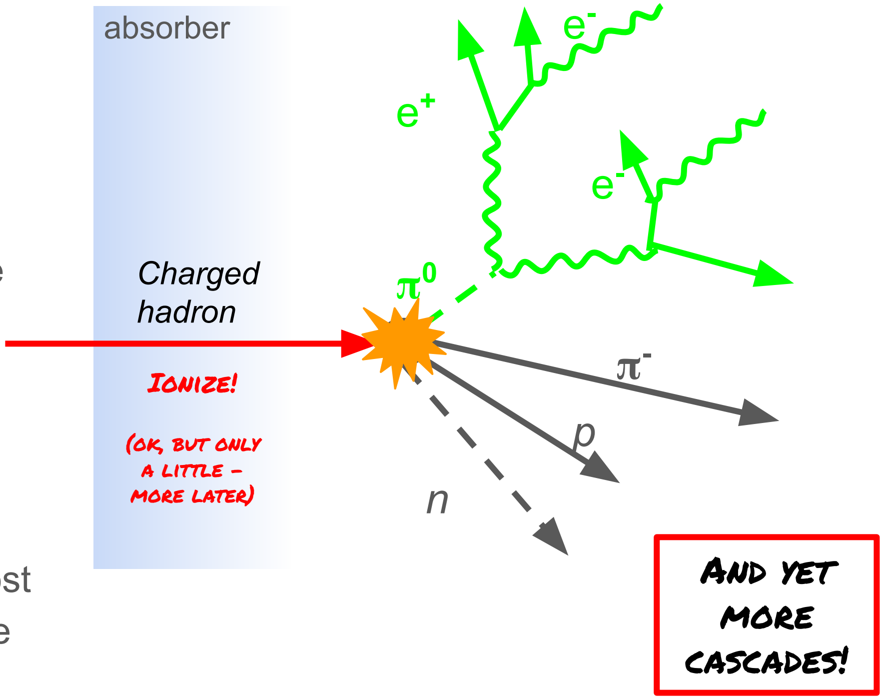
How hadrons lose energy

- Ionization and excitation (if charged)



How hadrons lose energy

- Ionization and excitation (if charged)
- Strong interaction Cascade
  - Hadronization
    - Secondary hadrons from scattering and such
    - These of course ionize, then do the same
  - Nuclear break-ups
    - Lots of secondary protons and neutrons
    - Photons
    - Some of this energy is inherently lost
      - Neutrons very hard to capture



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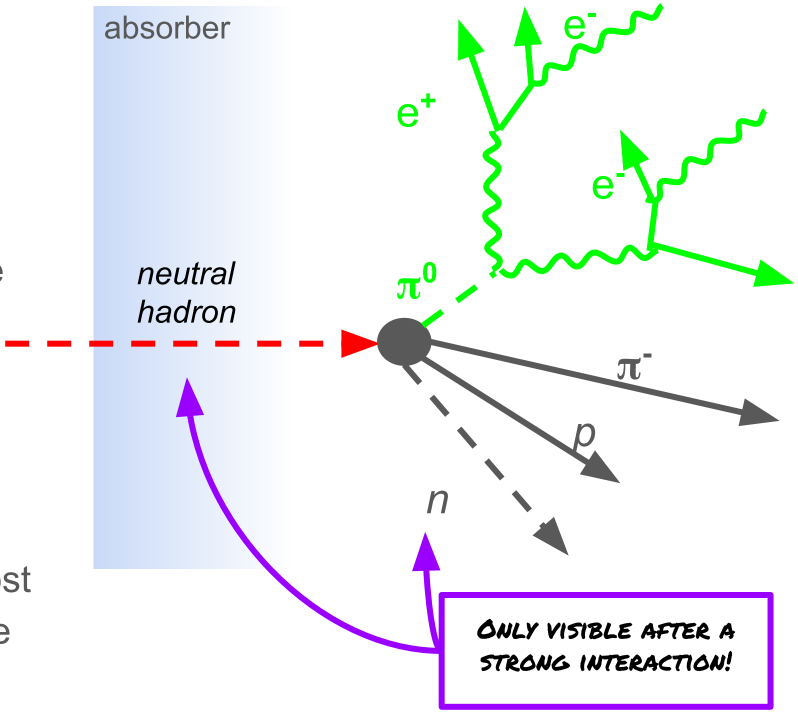

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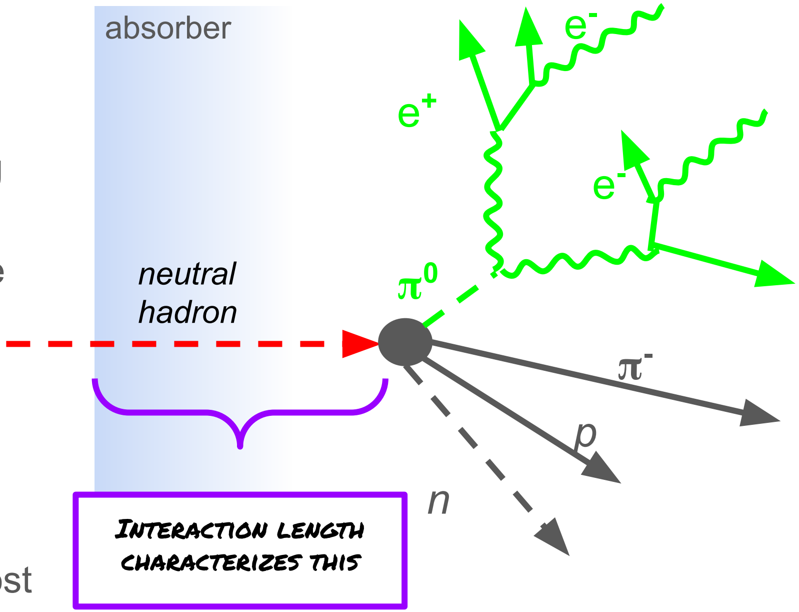
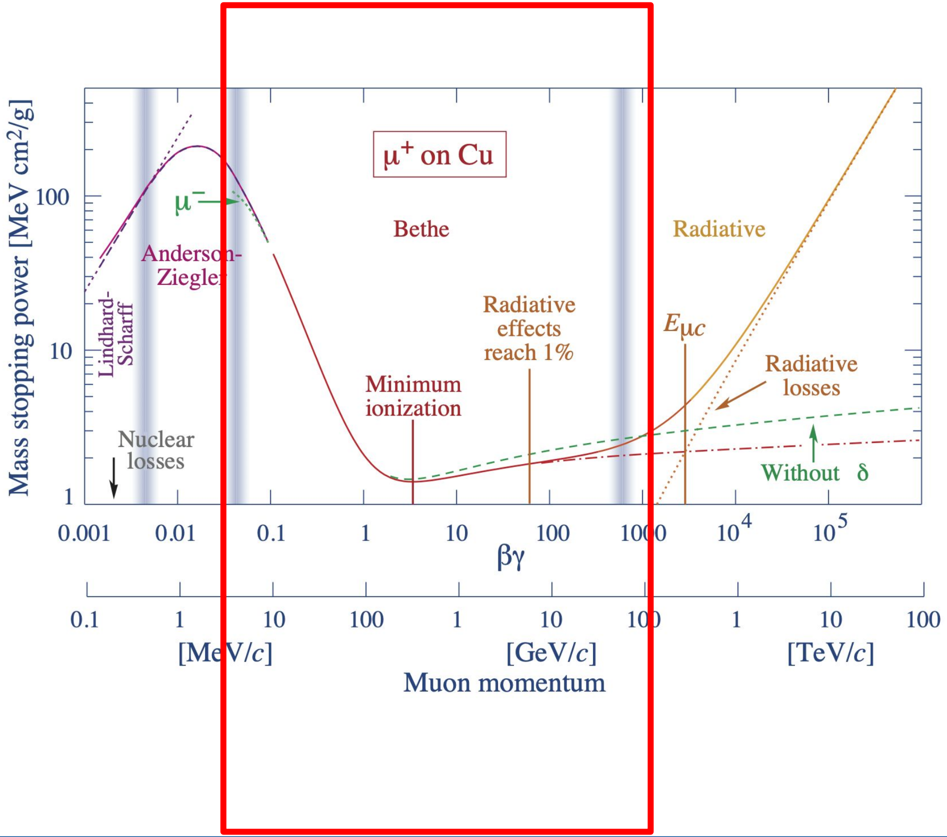
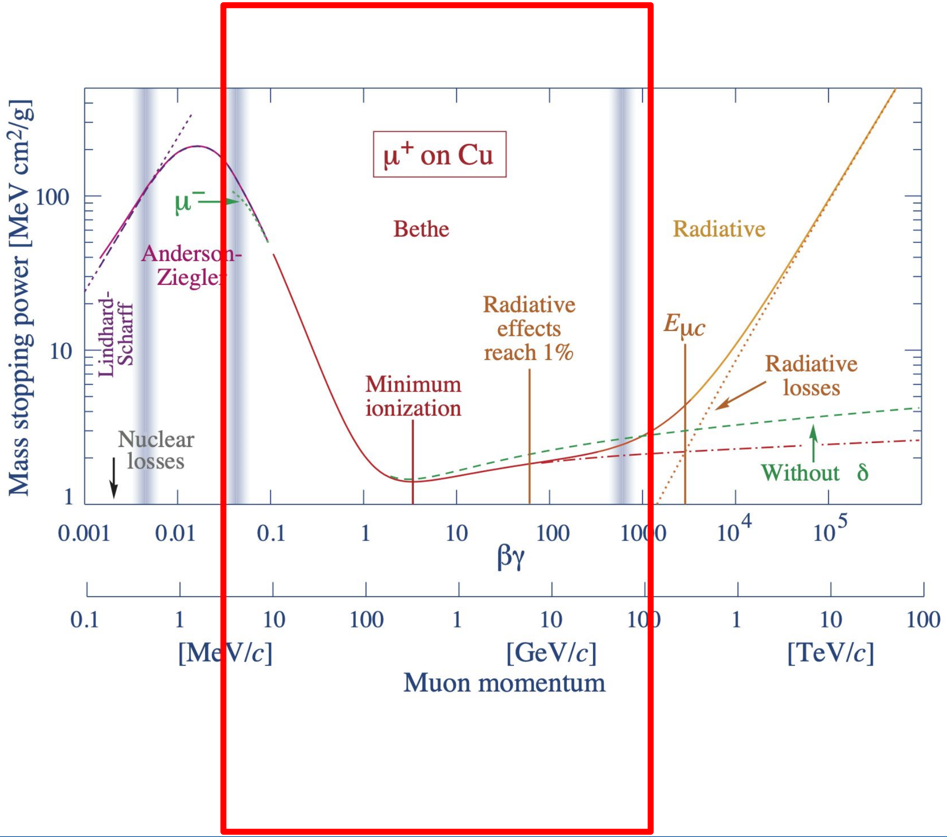


Ionization Energy loss → the energy deposition



δ = density effect correction
$E_{\mu c}$ = critical energy of muon

Ionization Energy loss - Bethe Function



A = mass number
Z = atomic number
z = charge number of incident particle
K = 0.307 MeV mol-1 cm2
T_{max} = maximum energy transfer to an electron in single collision
I = mean excitation energy
δ = density effect correction
$E_{\mu c}$ = critical energy of muon

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

Mainly dependent on the speed of the particle!

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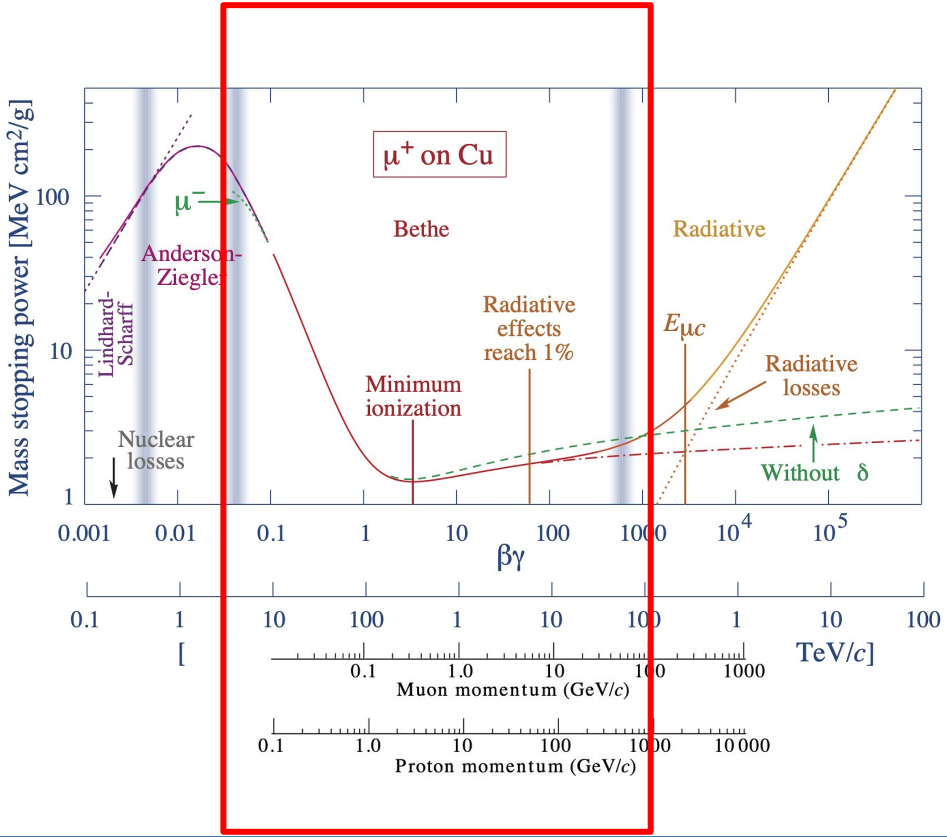
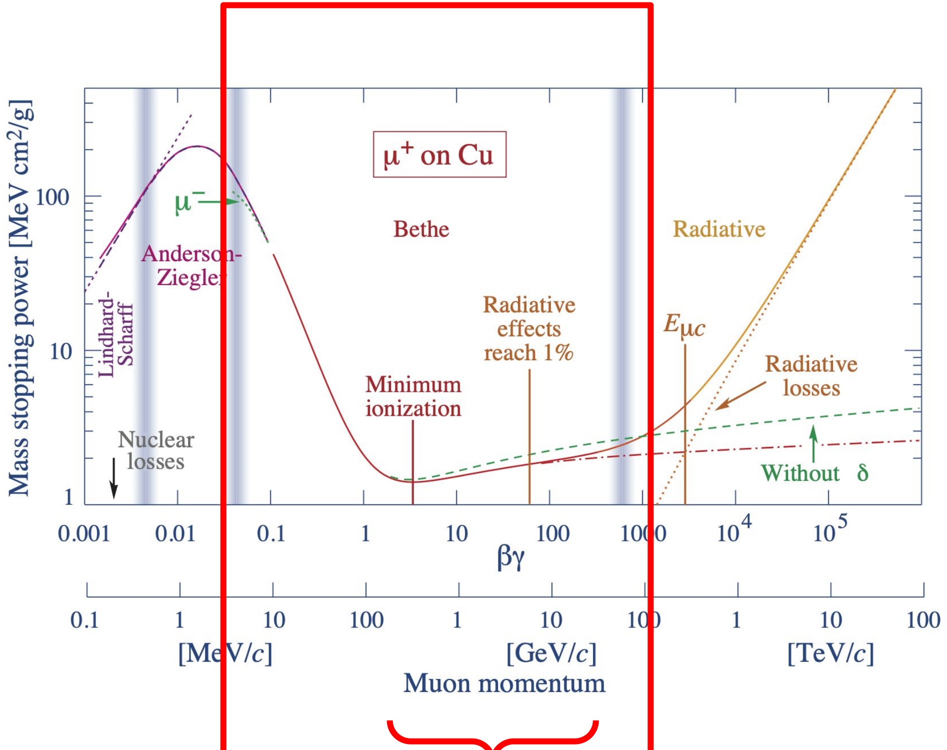


$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

$$T_{\max} = \frac{2m_ec^2\,\beta^2\gamma^2}{1+2\gamma m_e/M + (m_e/M)^2}$$

Mild mass dependence

Ionization Energy loss - Bethe Function



“mip” - minimally ionizing particle

δ = density effect correction
$E_{\mu c}$ = critical energy of muon

For most HEP energies, muons are minimally ionizing → why large TPCs can do muon calorimetry, but LHC experiments cannot!

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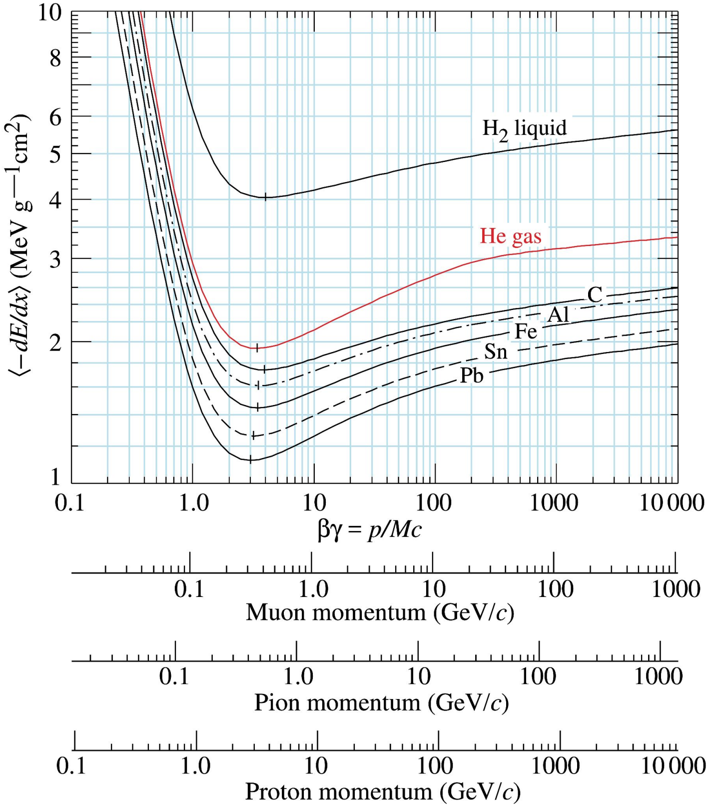
$E_{\mu c}$ = critical energy of muon



$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

Very mild material dependence!

General Designs

What you need to build a calorimeter

- Absorber material
  - Material to initiate cascades!
    - Need a lot for hadrons
    - Need very little for electrons/photons!
  - Desired properties
    - Dense (generally)
    - High Z (generally)

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- Active Material
  - Material to indicate ionization
  - Desired properties
    - Lots of ionization!
    - Transparent to mode of collection
      - i.e., if you want to collect light, it has to be transparent

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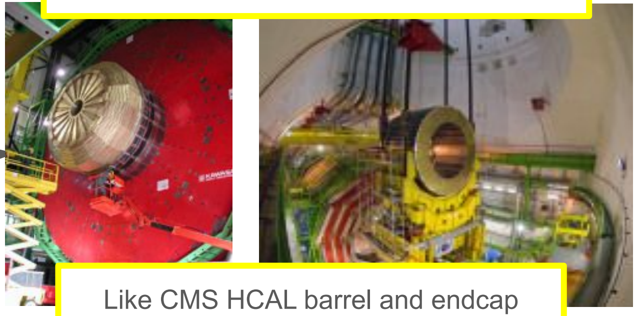
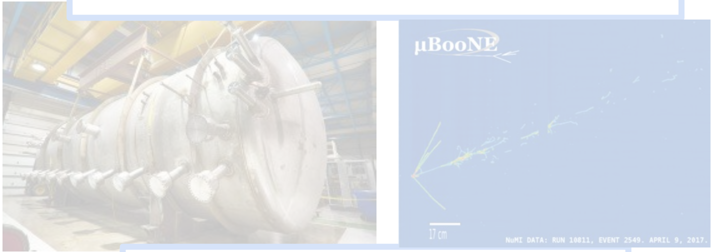
Alternating layers!

Sampling calorimeters



Like CMS HCAL barrel and endcap

Homogenous calorimeters



Like µBooNE liquid Argon TPC

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    - Lots of ionization!
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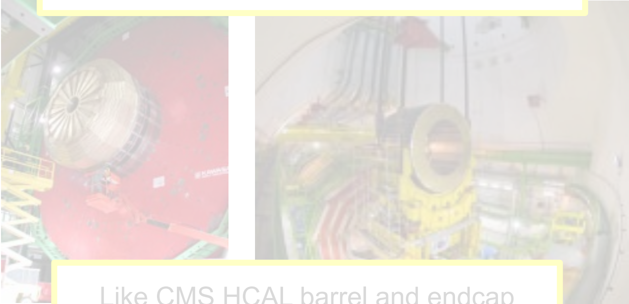
      - i.e., if you want to collect light, it has to be transparent

Same material!

Sampling calorimeters



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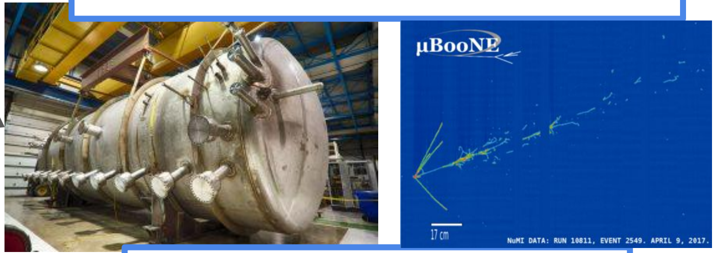
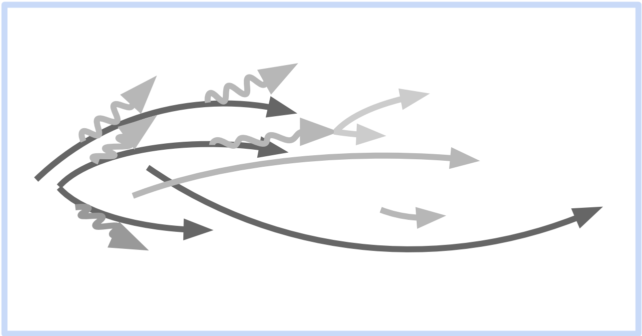


Like µBooNE liquid Argon TPC

The two styles

Homogenous

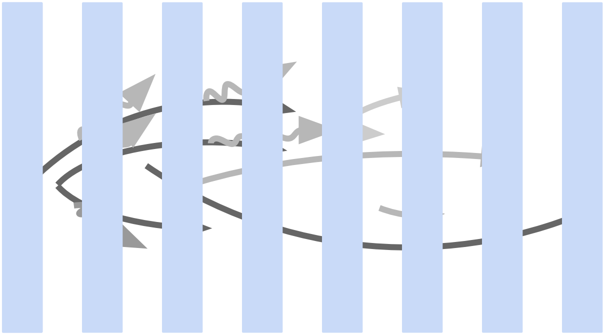
- Everything captured



Great for electrons and photons that deposit all readily deposit energy via ionization

Sampling

- Only get snapshots of the shower



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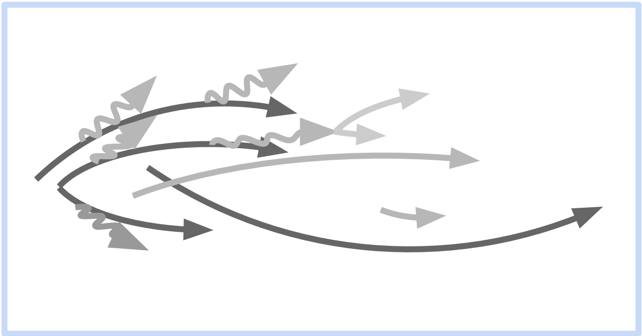

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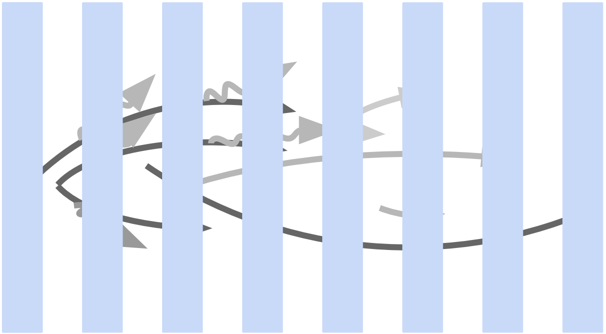


Why would you ever use anything other than homogenous?

The whole rest of the talk will be answering this, in one way or another!

The generic limitations

Challenges to hadronic energy resolution

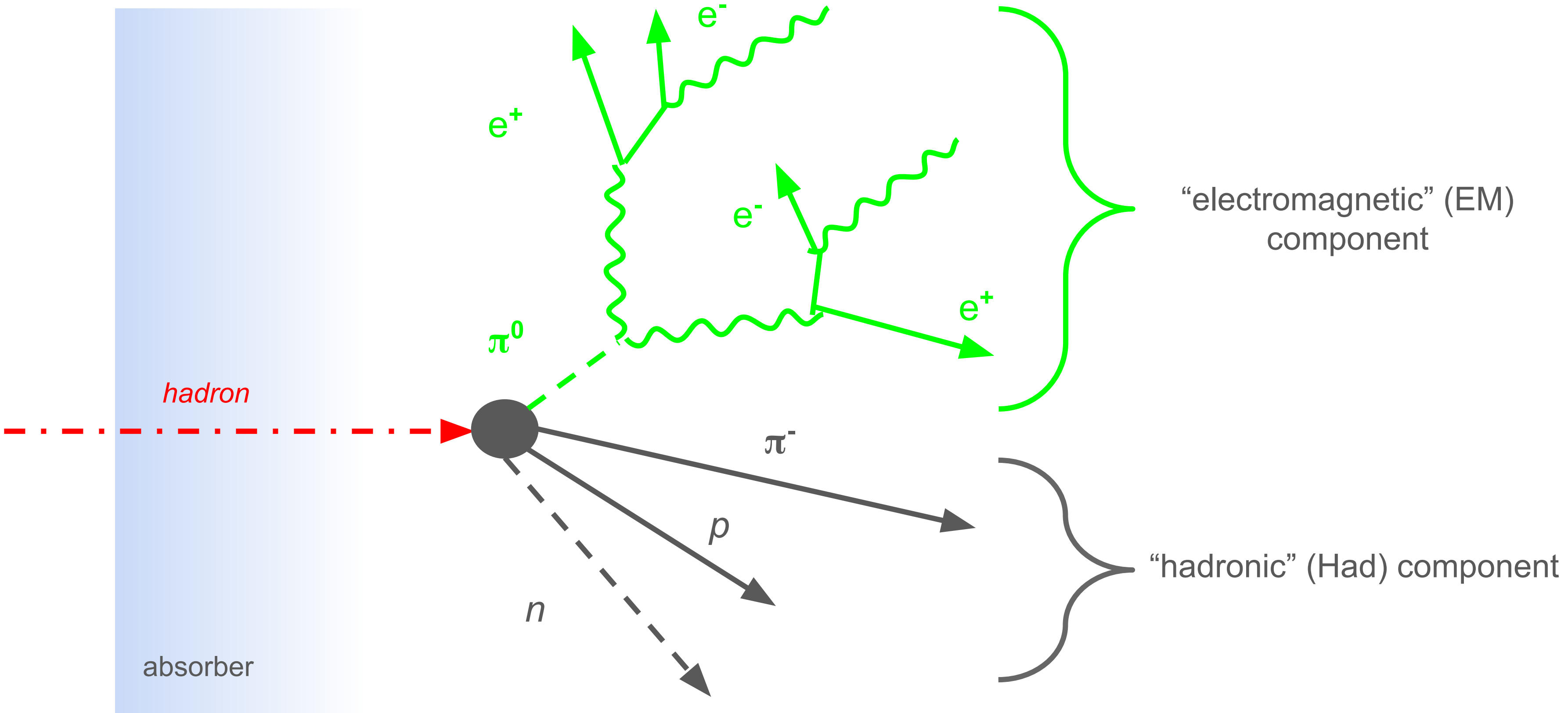
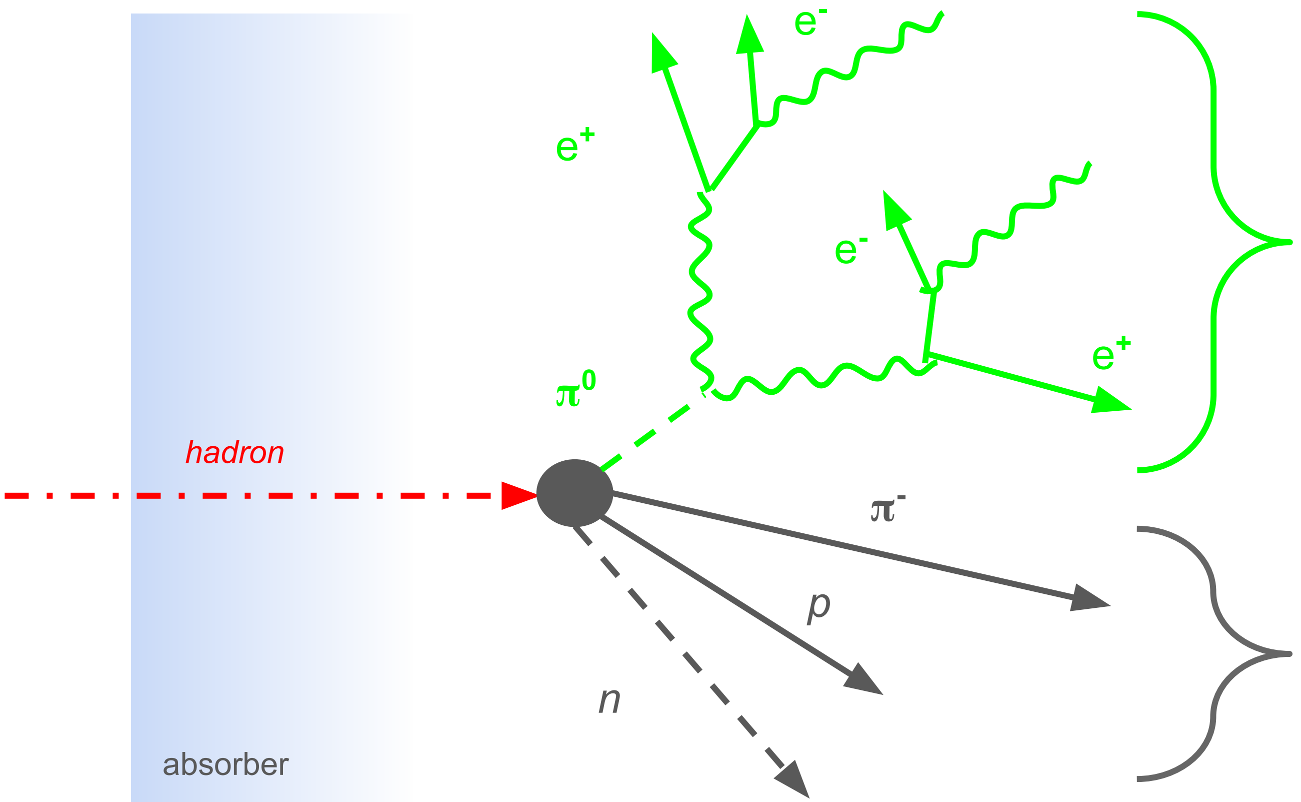


Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

Challenges to hadronic energy resolution



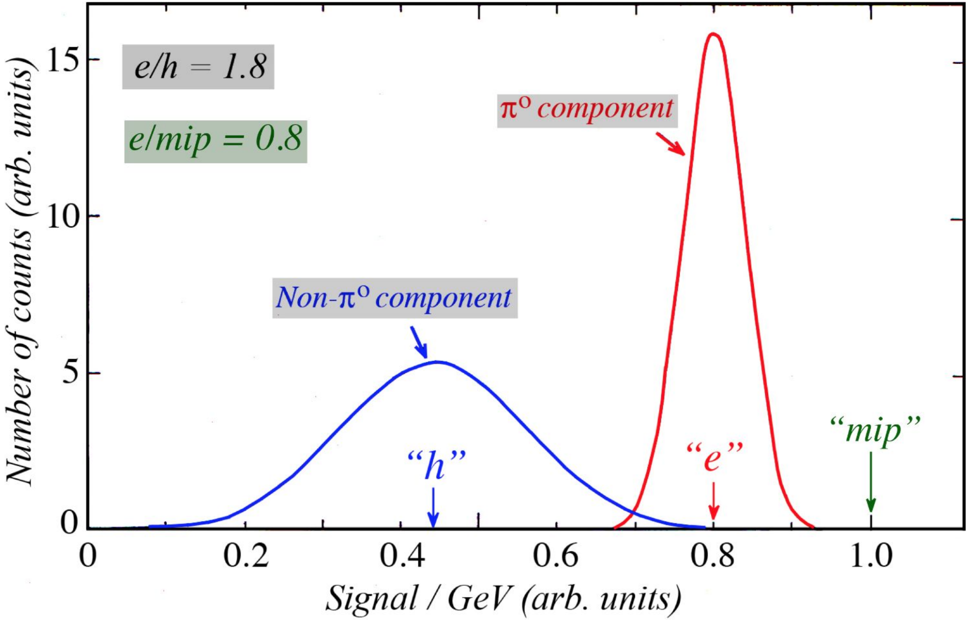
EM/Had ratio fluctuates event-to-event

(ie, what happens to pop out of your strong interaction)

Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

Why is this a problem?

Response to the different shower components is not the same

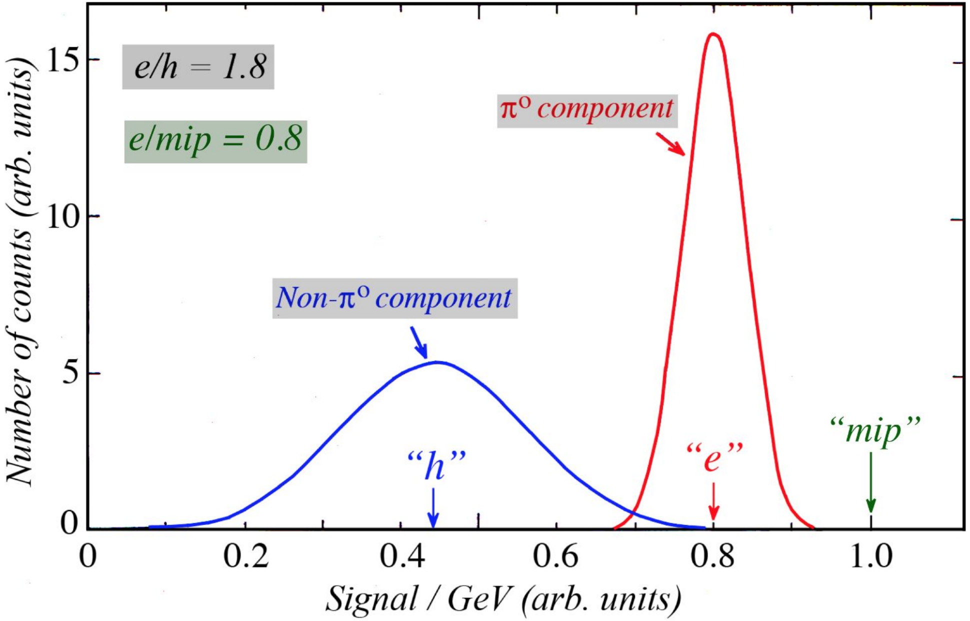


Rev. Mod. Phys. 90, 025002

Why is this a problem?

Response to the different shower components is not the same

1 GeV of an electron does not necessarily look like 1 GeV of a hadron



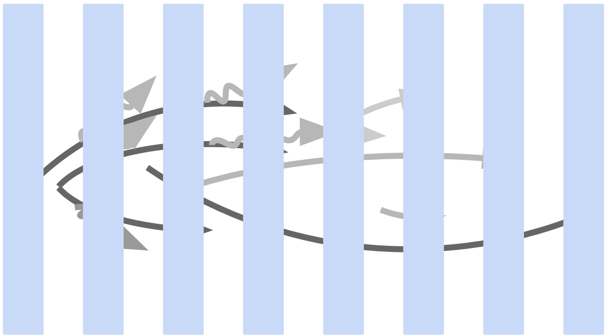
How do you interpret the signal you measure? Directly regrades resolution.

Rev. Mod. Phys. 90, 025002

One of the benefits of sampling

Sampling

- Only get snapshots of the shower



Can tailor absorber material to bring electromagnetic and hadronic responses closer together!

High-Z absorber can reduce the electromagnetic response, and encourage neutron capture!

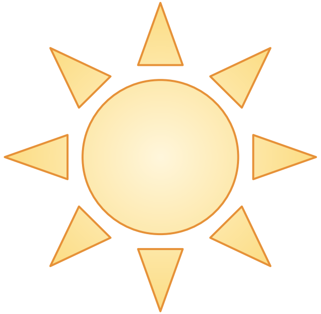
Leveraging this is called *compensation*

Calorimeter Technologies

Two general principles

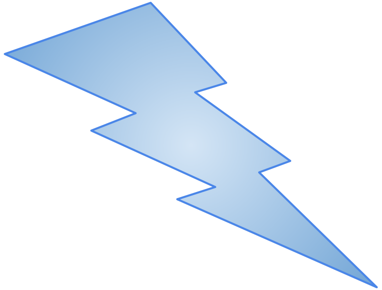
Optical Calorimeters

Use light to indicate energy deposition
Ionization → light



Direct-ionization Calorimeters

Measure the ionization directly



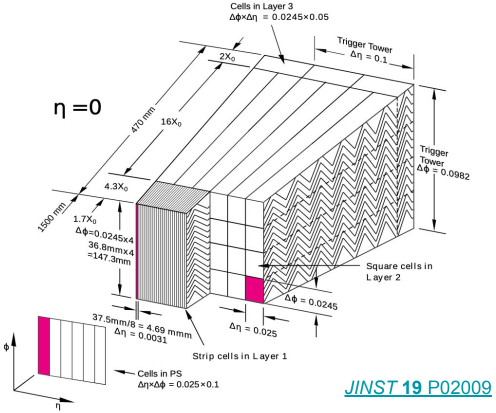
Ionization Calorimeters

Liquid Argon Calorimeters

Example: ATLAS LAr Calorimeter

- Sampling or homogenous
  - Sampling for high energy use
    - Need extra radiation lengths to contain shower
  - Homogenous for TPC
    - Uses the scintillation as well

CERN-GE-0312173-5



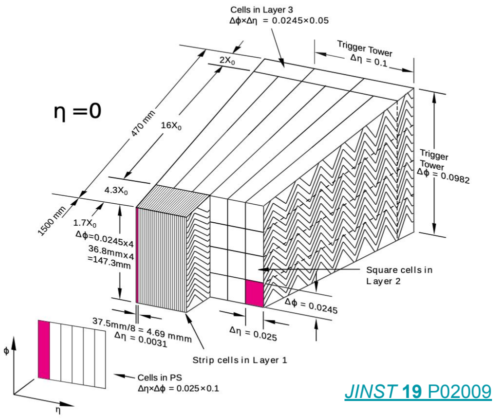
JINST **19** P02009

Liquid Argon Calorimeters

Example: ATLAS LAr Calorimeter

- Sampling or homogenous
  - Sampling for high energy use
    - Need extra radiation lengths to contain shower
  - Homogenous for TPC
    - Uses the scintillation as well
- Require a cryostat
  - This requires a lot of infrastructure!
  - ATLAS LAr calorimeter @ -184 ℃
- Moderate granularity
  - granularity :
    - Smallest volume of energy deposition
  - Couple mm

CERN-GE-0312173-5



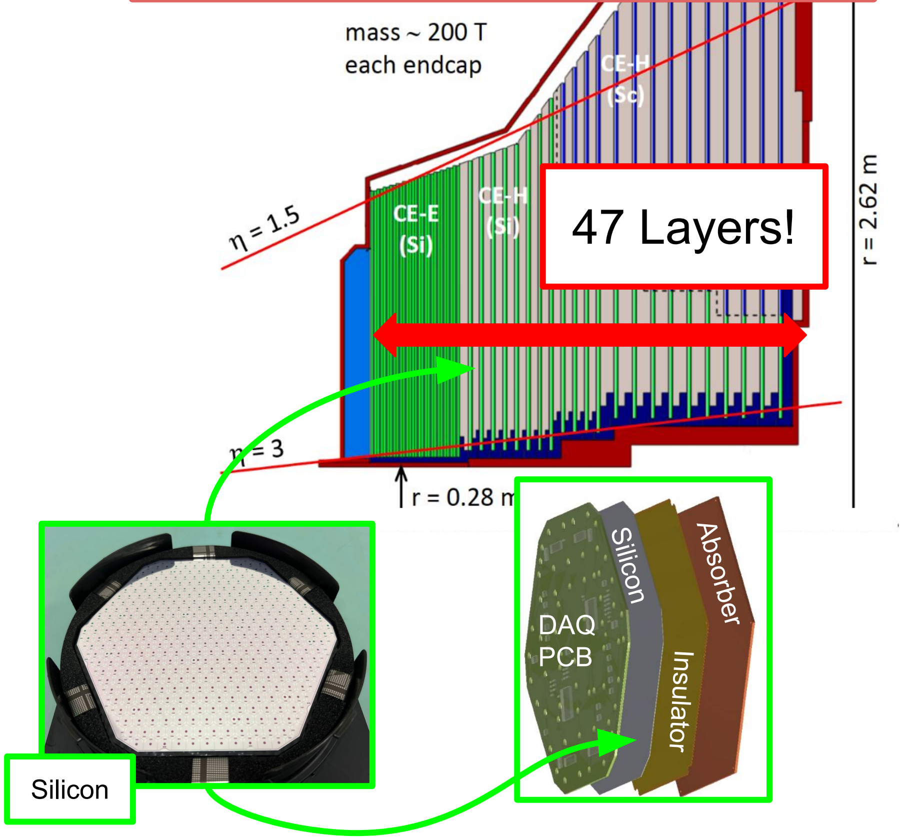
JINST **19** P02009

https://atlas.cern/Discover/Detector/Calorimeter

Silicon-Sandwich Calorimeters

Example: CMS High Granularity Calorimeter Upgrade (ETA 2028)

- Sampling calorimeter
  - Silicon made in wafers industrially
  - Absorber-Si-readout “sandwiches”
- Ultra-high granularity
  - Smallest unit limited by pixel pitch and readout
  - Active layer 100s of microns thick



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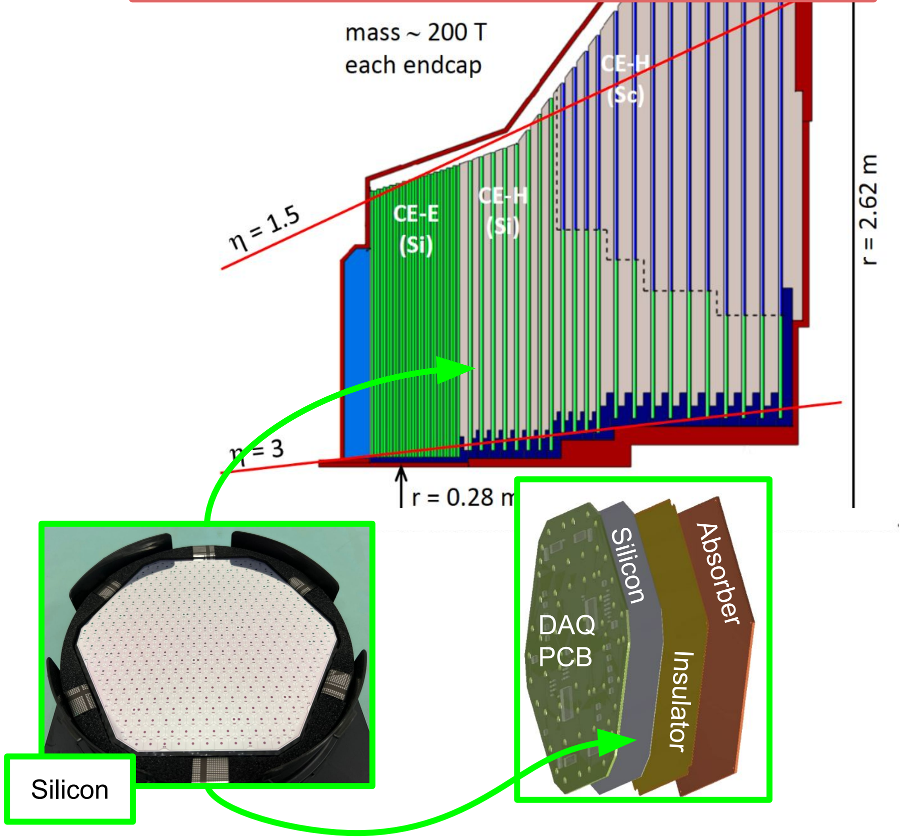
  - Active layer 100s of microns thick
- Requires low-temperature operation
  - CMS high granularity calorimeter will operate at -30 ℃



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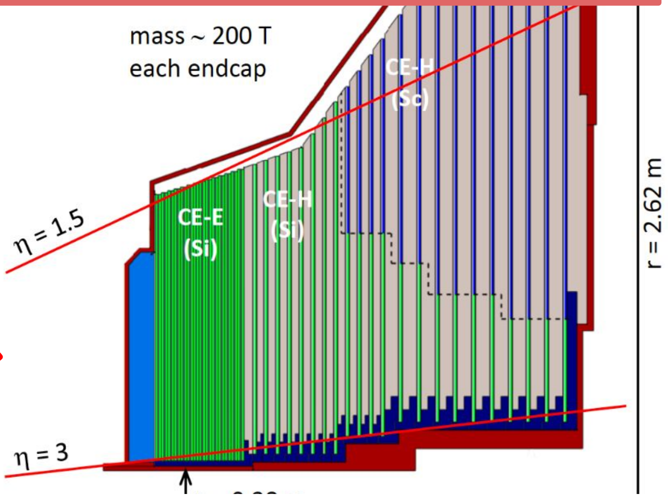
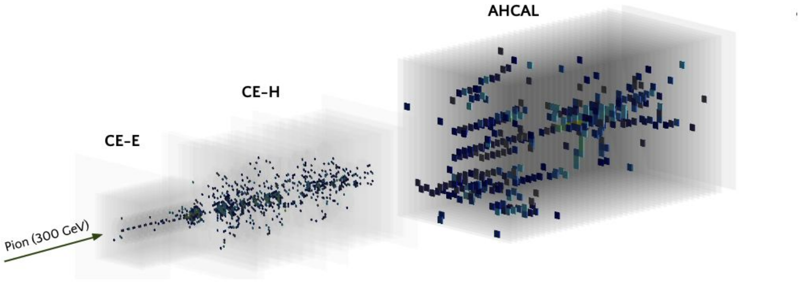
- Ultra-high granularity
  - Smallest unit limited by pixel pitch and readout
  - Active layer 100s of microns thic
- Requires low-temperature operation
  - CMS high granularity calorim operate at -30 °C
- “Imaging”
  - Reconstruct the event in 5D

Excellent for things like jet substructure!





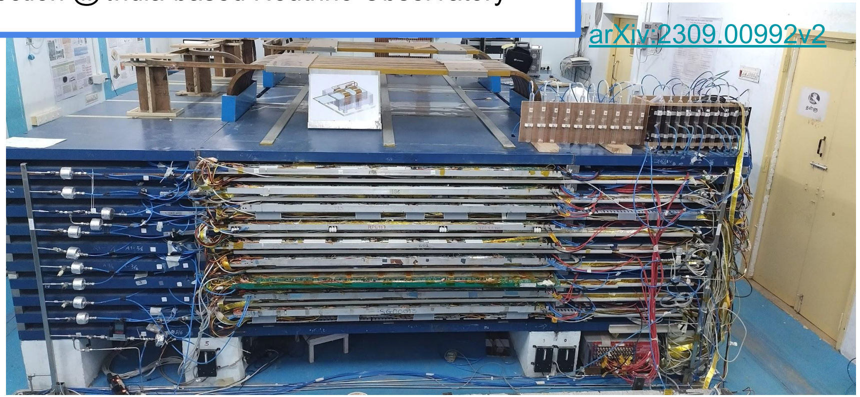
arXiv:2211.04740v2

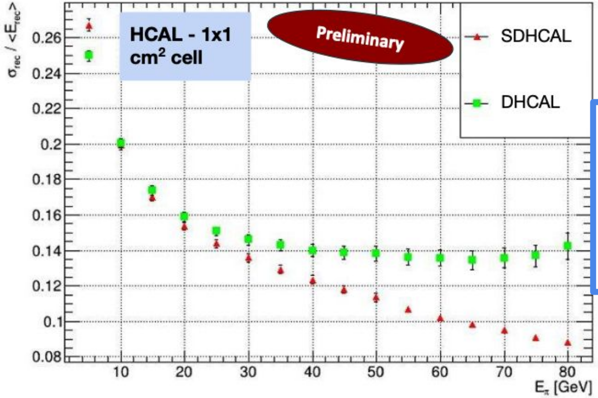
Gaseous Concepts

- Ionized gas as active material
  - Resistive Plate Chamber (RPCs)
  - Micropattern gaseous detectors (MPGD)
- **Fast timing!**
  - Separate neutral and charged hadronic showers
- High granularity possible
  - can allow for "digital calorimetry" → does not measure ionization, but counts MIPs

Example: mini-Iron calorimeter for atmospheric neutrino detection @ India-based Neutrino Observatory

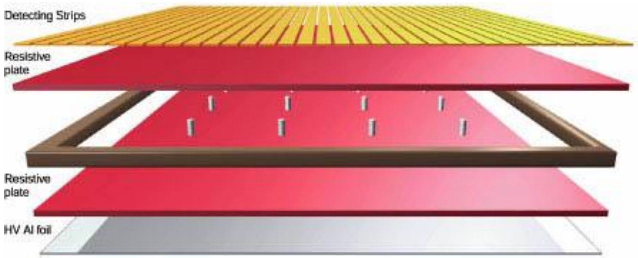
arXiv:2309.00992v2





MPGD Digital (DHCAL) and Semi-Digital (SDHCAL) comparison (L. Lugano, April 2024 DRD6 Meeting)

Example CMS RPC Diagram (used in Muon system)

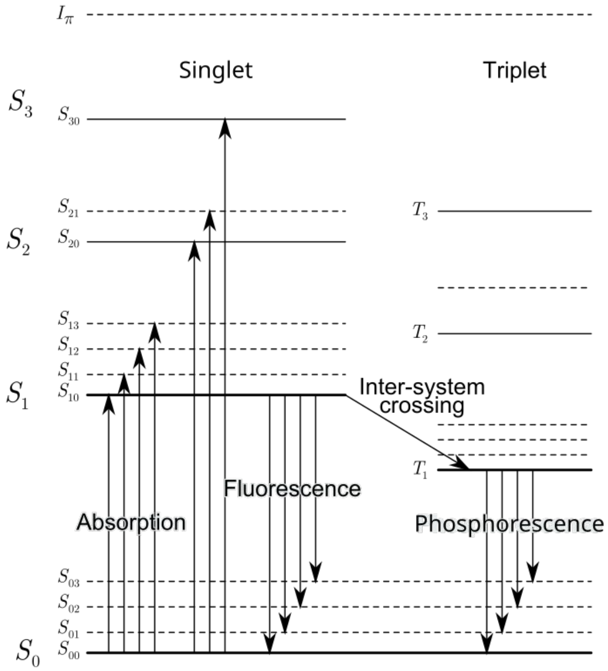


Optical Calorimeters

Physics of optical calorimeters

Cherenkov Light

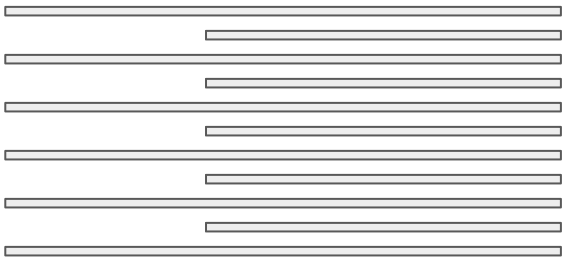
Scintillation Light



Cherenkov Calorimeters

Example: CMS Forward Calorimeter! Quartz fibers in steel absorber - **SAMPLING**

- Capacity to be ultra-fast
  - Cherenkov inherently prompt!
- Radiation hard
  - Simpler materials
- Primarily detect electromagnetic signatures



Uses fiber of different lengths to separate electromagnetic and hadronic showers

CMS-PHO-OREACH-2005-012-10

CMS-PHO-OREACH-2005-012-02

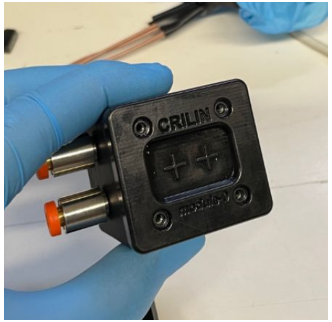
Cherenkov Calorimeters

Example Concept: **Crilin** → **Cr**ystal Calorimeter with **L**ongitudinal **In**formation

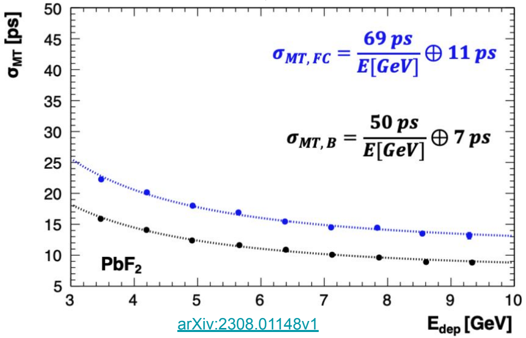
- Capacity to be ultra-fast
  - Cherenkov inherently prompt!
- Radiation hard
  - Simpler materials
- Primarily detect electromagnetic signatures

- PbF_2
- high granularity crystal!
  - 1 cm x 1 cm x 40 cm crystals
  - 3 mm x 3 mm UV-extended SiPMs

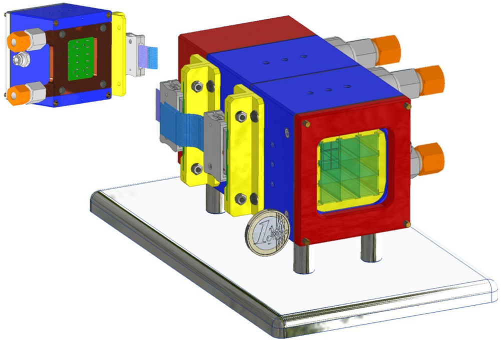
Homogenous calo for muon collider!



arXiv:2206.05838



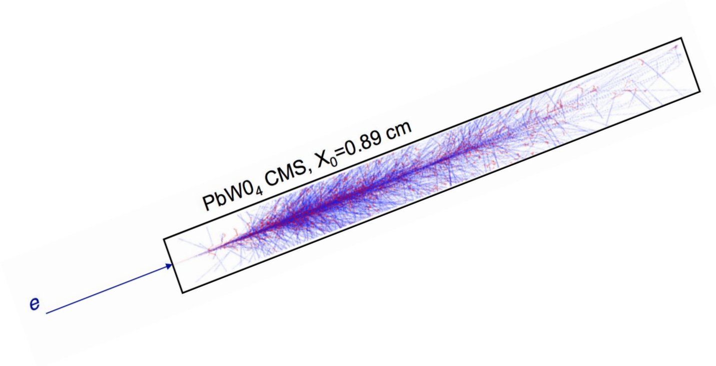
arXiv:2308.01148v1



https://doi.org/10.1016/j.nima.2022.167817

Scintillating Inorganic (crystal/glass) Calorimeters

- Why scintillating?
  - Higher light yield
  - Sensitivity to non-relativistic charged particles
- Homogenous crystal calorimeters
  - best electromagnetic energy resolution

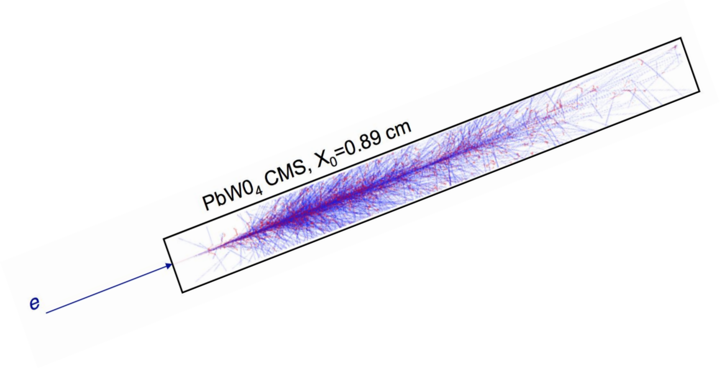


Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
CsI(Tl) (BES III)	$15X_0$	2.5% for $E_\gamma = 1$ GeV	2010
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
$PbWO_4$ (PWO) (ALICE)	$19X_0$	$3.6\%/\sqrt{E} \oplus 1.2\%$	2008

https://pdg.lbl.gov/2022/web/viewer.html?file=../reviews/rpp2022-rev-particle-detectors-accel.pdf

Scintillating Inorganic (crystal/glass) Calorimeters

- Why scintillating?
  - Higher light yield
  - Sensitivity to non-relativistic charged particles
- Homogenous crystal calorimeters
  - best electromagnetic energy resolution
- Complex materials
  - Dense crystals like
    - Lead Tungstate (PbWO4)
    - Bismuth Germanate (BGO)
    - Caesium Iodide (CsI)
  - Can be homogenous or sampling
  - Tend to be less radiation hard and expensive
- Homogenous calorimeter construction challenging



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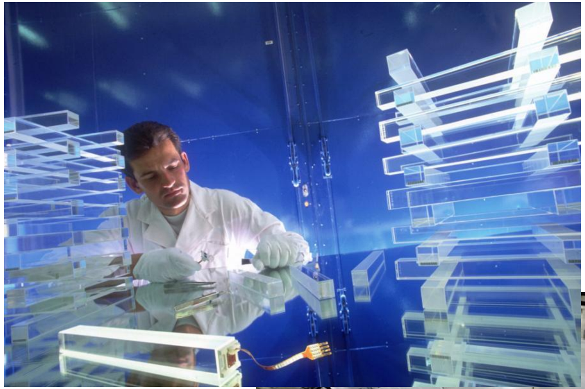
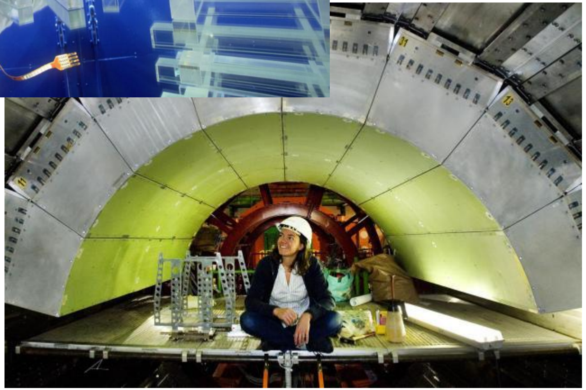
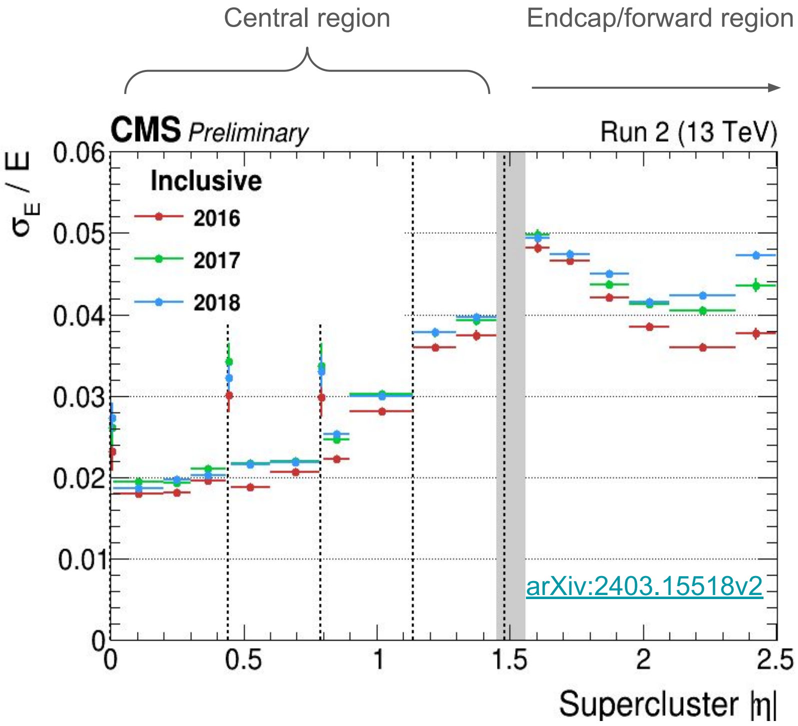
https://pdg.lbl.gov/2022/web/viewer.html?file=../reviews/rpp2022-rev-particle-detectors-accel.pdf

Example: CMS ECAL



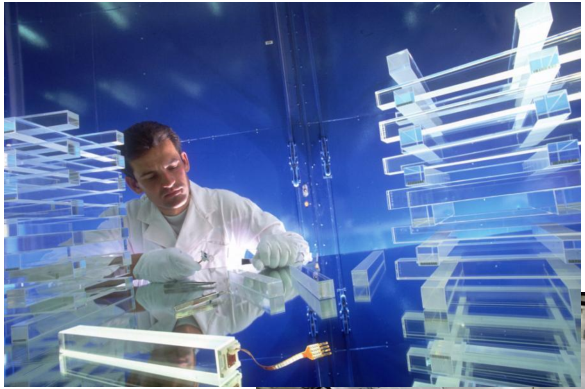


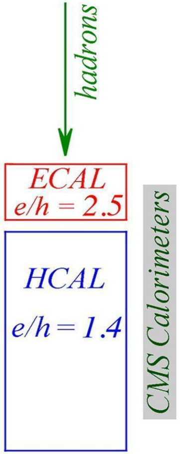
2% γ energy resolution in Run 2!

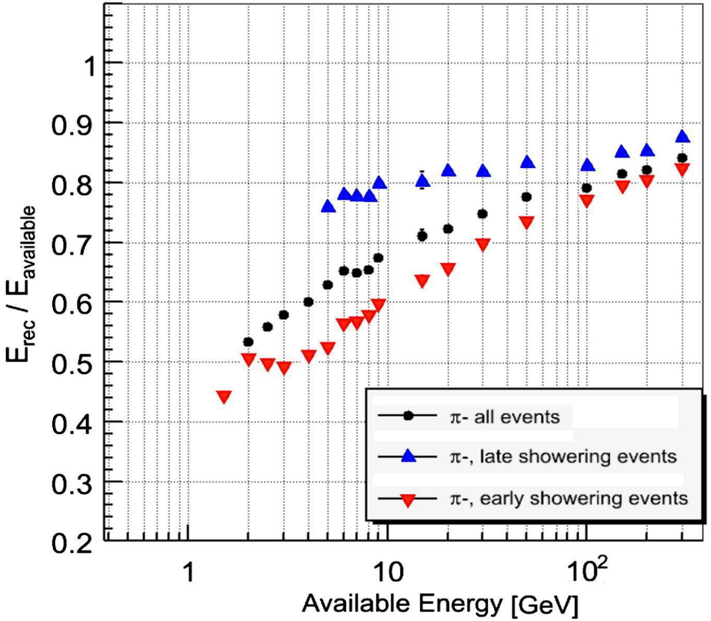


But calorimeters are a system!

CMS ECAL makes the hadron calorimetry WORSE







N. Akchurin, R. Wigmans, (2012) Nucl. Instr. and Meth. **A666** (80)

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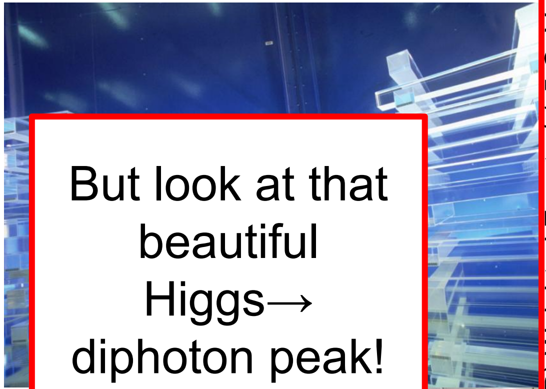
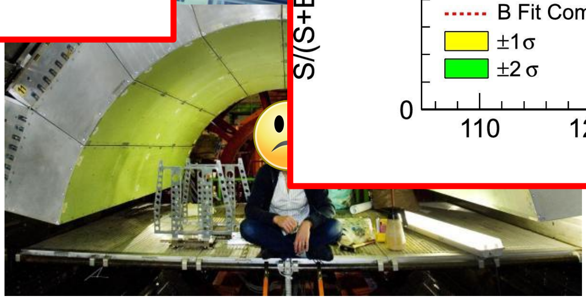
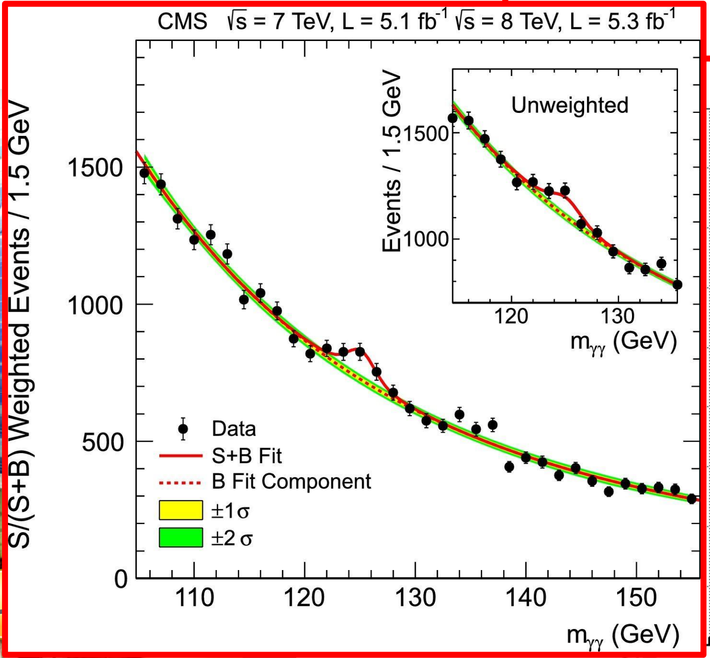
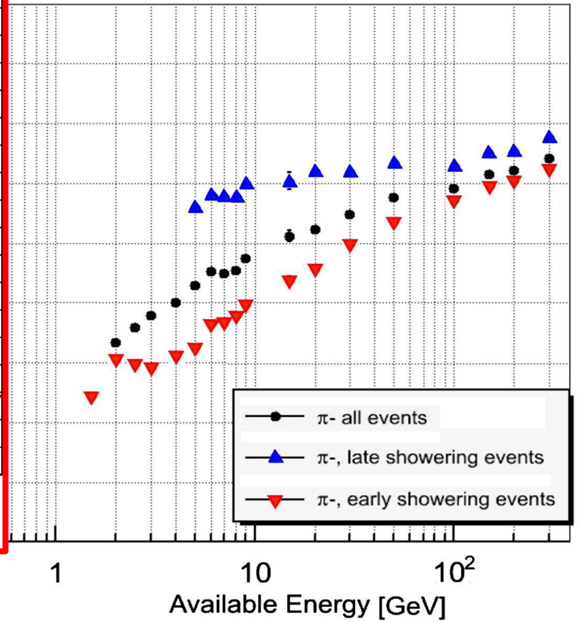


But look at that beautiful Higgs→ diphoton peak!



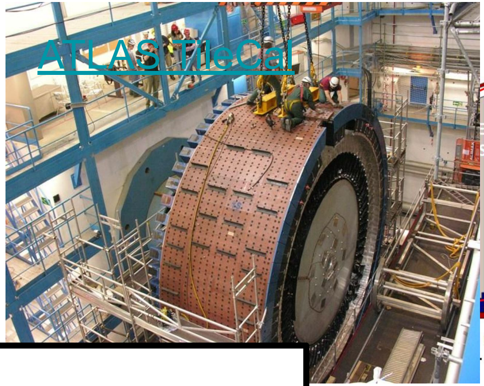




N. Akchurin, R. Wigmans, (2012) Nucl. Instr. and Meth. **A666** (80)

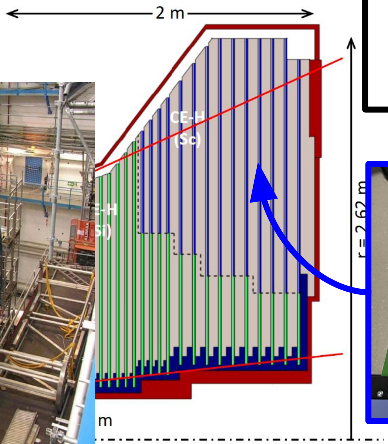
Scintillating Organic (Plastic) Calorimeters

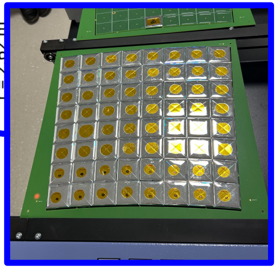
- Plastic is…
  - Less dense
  - Cheaper
  - Customizable!
- For high energy, pretty much always sampling
- Infinitely flexible
  - High granularity
  - Compensating
  - …
- Radiation tolerance can be a problem



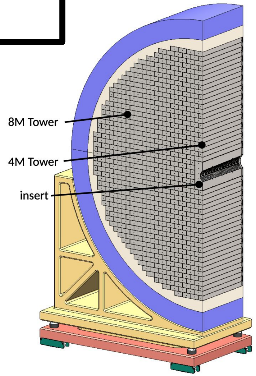
ATLAS TileCal

CMS HGCAL Hadron section



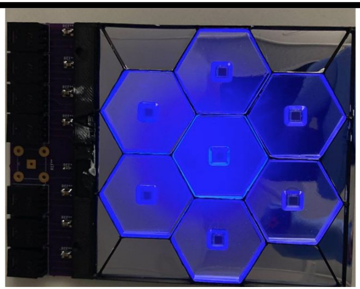


ePIC forward calorimetry



Miguel Arratia CPAD23

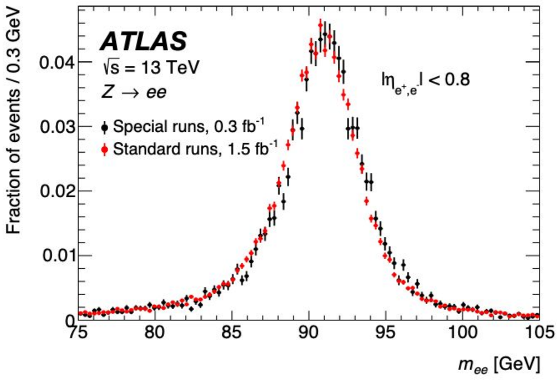
Miguel Rodriguez CPAD23



The things I have not mentioned

Things to think about

- Calibration!
  - Especially in segmented calorimeters
    - where you chop a shower matters
  - Using Standard candles for electromagnetic calorimetry
  - Using radioactive sources
- Readout!
  - Photodetection
    - Wavelength sensitive SiPMs
    - Wavelength Shifting Fibers
    - Optical coupling
  - Readout and bandwidth
    - What info do we keep?
    - Where do we route our fiber optic cables?
    - How much do the electronics heat up?



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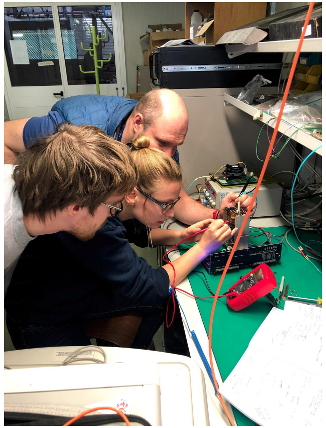
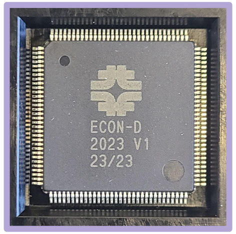
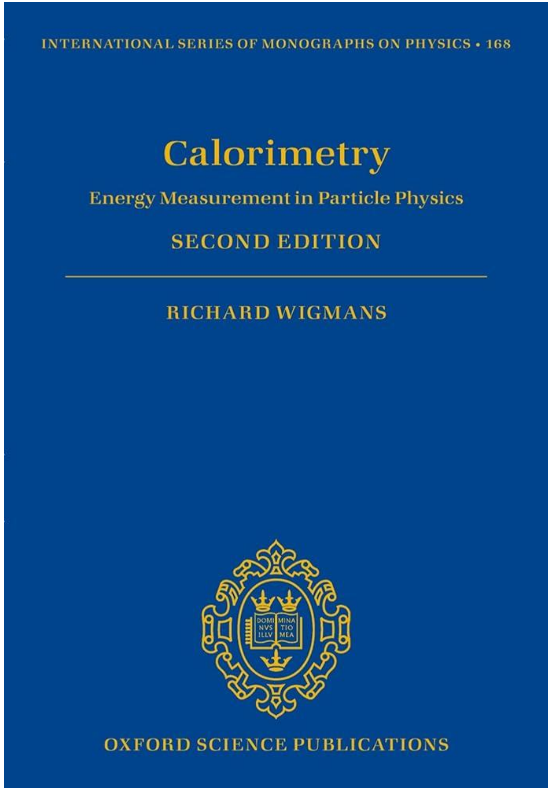




And now the talk has deposited all of its energy

Conclusions and Summary

- Calorimetry is a large and complex field
  - Everything is interrelated
  - Spans
    - material science
    - HEP
    - mechanical and electrical engineering
- Understanding the fundamentals critical to understanding what you are actually measuring!
- There is no "perfect" calorimeter
  - What features are prioritized depend on your needs (and taste)
- Required Reading: R. Wigman's *Calorimetry: Energy Measurement in Particle Physics*

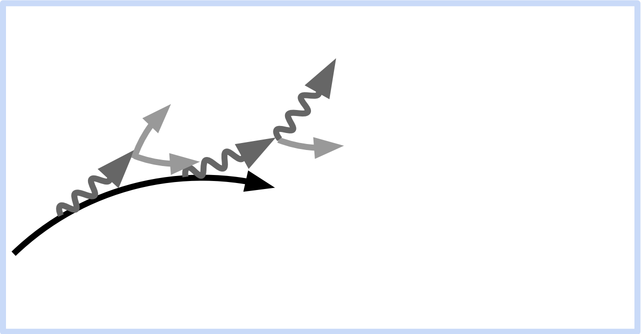


back-up

The two styles

Homogenous

- Everything captured



Great for electrons

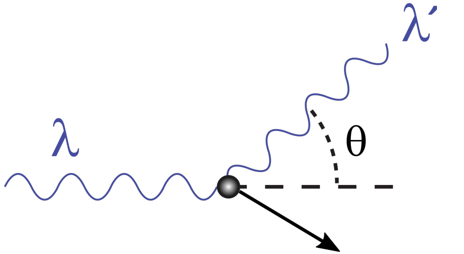
- interact immediately
- possible to contain whole shower in reasonable space

Homogeneous calorimeters

- Active material and absorber the same material
  - All of a particle's energy deposition can result in detector response
- Ideal for electrons and photons
  - All kinetic energy goes into ionization
    - Entire material active = all can be seen
- Traditionally poor for hadrons
  - Generally more nonlinear
  - Cannot contain high energy hadrons at colliders
- Not all materials suitable!
  - Needs to be dense enough to contain the energies you are interested in
  - Need to be able to afford it
  - Hard to balance

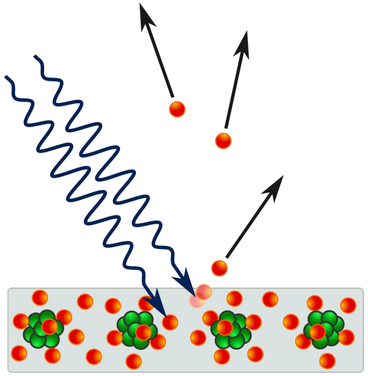
How *photons* lose energy

Compton Scattering

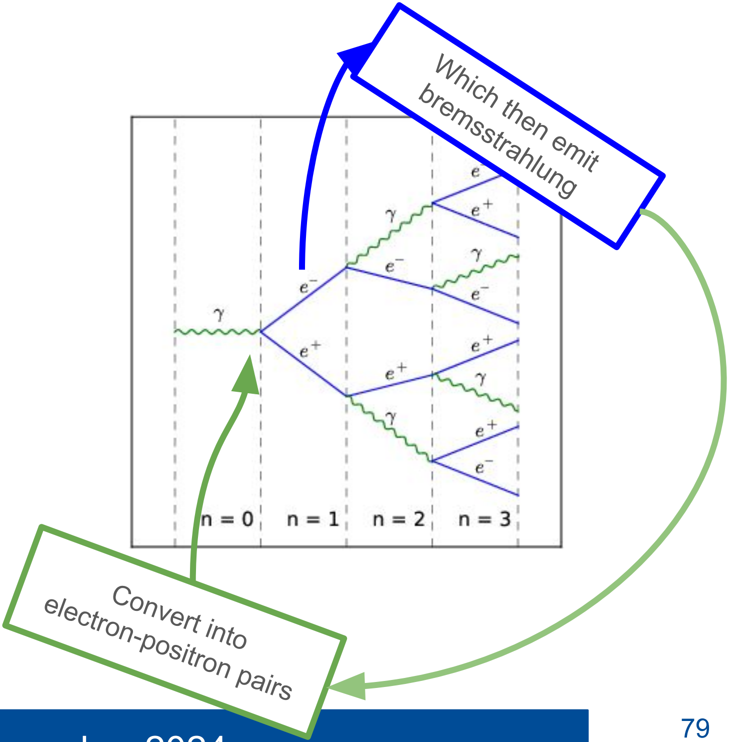


$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

Photoelectric Effect



Pair-production



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