Physics 214 UCSD/225a UCSB

Lecture 3

- Particles going through matter
  - –PDG 2006 chapter 27
  - –Kleinknecht chapters:
    - •1.2.1 for charged particles
    - •1.2.2 for photons
    - •1.2.3 bremsstrahlung for electrons
- Collider Detectors
  - –Kleinknecht chapters:
    - •7. Momentum measurement
    - •6. Energy measurement

What do we need to detect?

- Momenta of all stable particles:
  - Charged: Pion, kaon, proton, electron, muon
  - Neutral: photon, K^0_s , neutron, K^0_L , neutrino
- Particle identification for all of the above.
- "Unstable" particles:
  - Pizero
  - b-quark, c-quark, tau
  - Gluon and light quarks
  - W,Z,Higgs
  - … anything new we might discover …

All modern collider detectors look alike

Increasing radius

beampipe

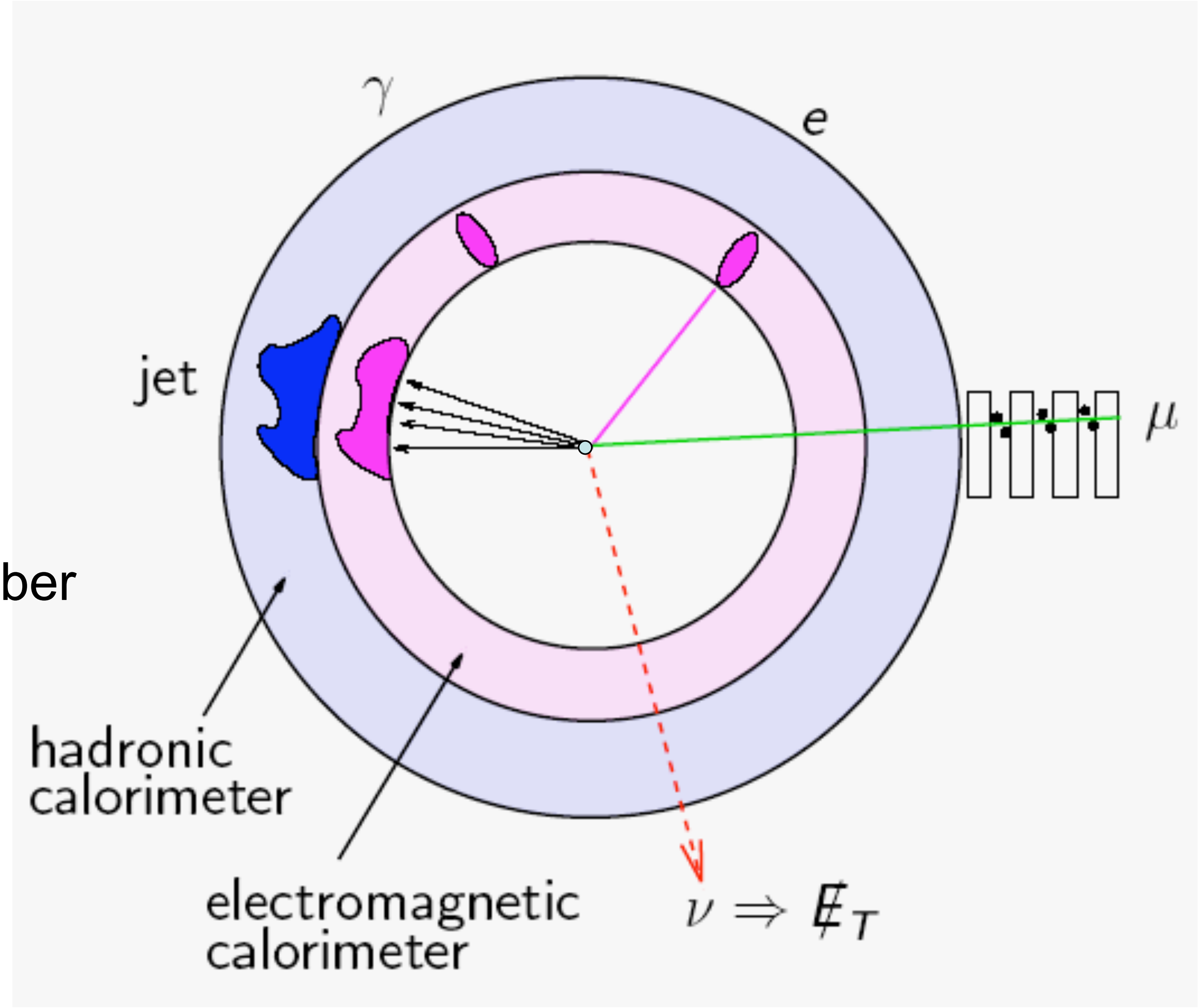
tracker

ECAL

solenoid

HCAL

Muon chamber



Order we proceed:

- First look at the physics underlying the detector concepts.
  - We will be very superficial!
  - Much more detail is available in Kleinknecht and PDG 2006, and their references.
- Second look at the resulting detector concepts, and what limits their resolution.
  - Again, more info in Kleinknecht. We only provide useful equations but don’t derive them.
  - Some more depth in next homework assignment.

Detection of charged particles

(other than electrons)

- EM interaction in materials

  -> ionization of atoms

  -> cherenkov radiation

  -> transition radiation

Follow discussion as in PDG 2006

We ignore cherenkov & transition radiation because CMS does not exploit either.

Note: Atlas has a transition radiation detector.

Energy loss due to Ionization

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

$K = 4\pi N_0 r_e^2 m_e c^2$ = constant of nature

$Z, A =$ Atomic number and mass number of material

$ze =$ Charge of particle

$I =$ Effective ionization potential

$T_{\max} =$ Max kin.E to transfer on free electron

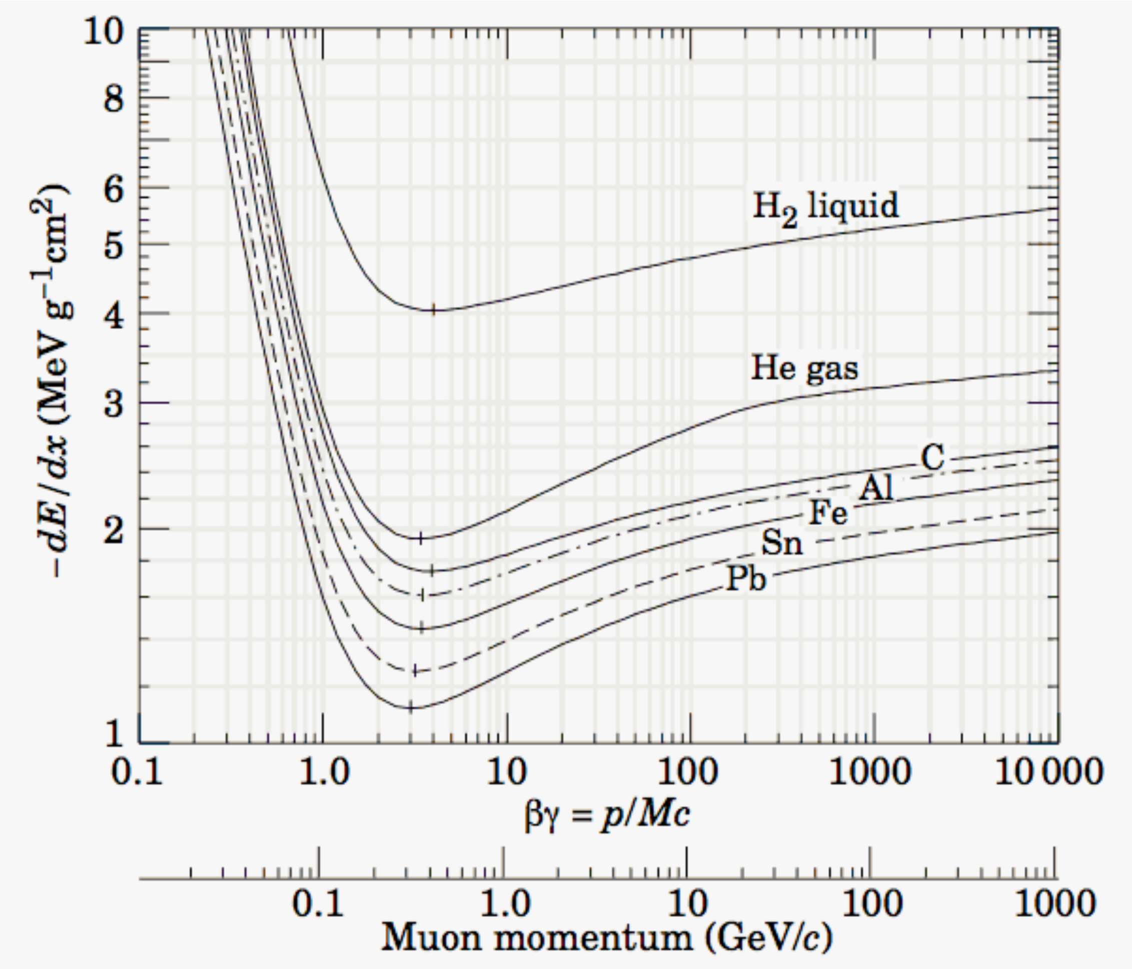
This is the ***Bethe-Bloch*** formula.
Describes average energy loss per length*density.
Depends on material (Z,A), velocity, and charge of particle.

Aside on dE/dx units

- Energy / (length*density)

  MeV / (cm * (gram / cm^3) = MeV cm^2 /gram

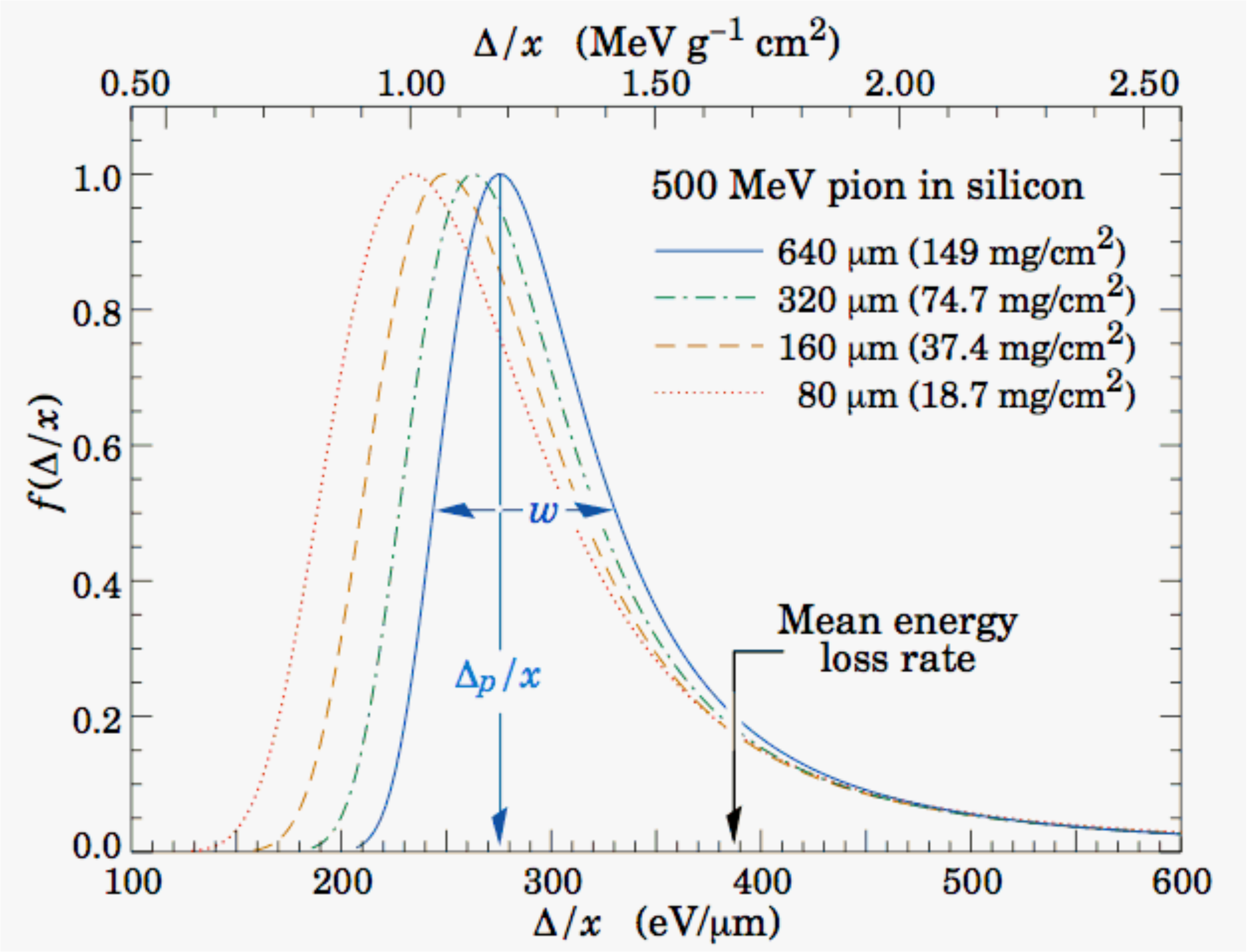
Bethe-Bloch



Min ~ same for all

Relativistic rise:
 -> small
 -> material dependent

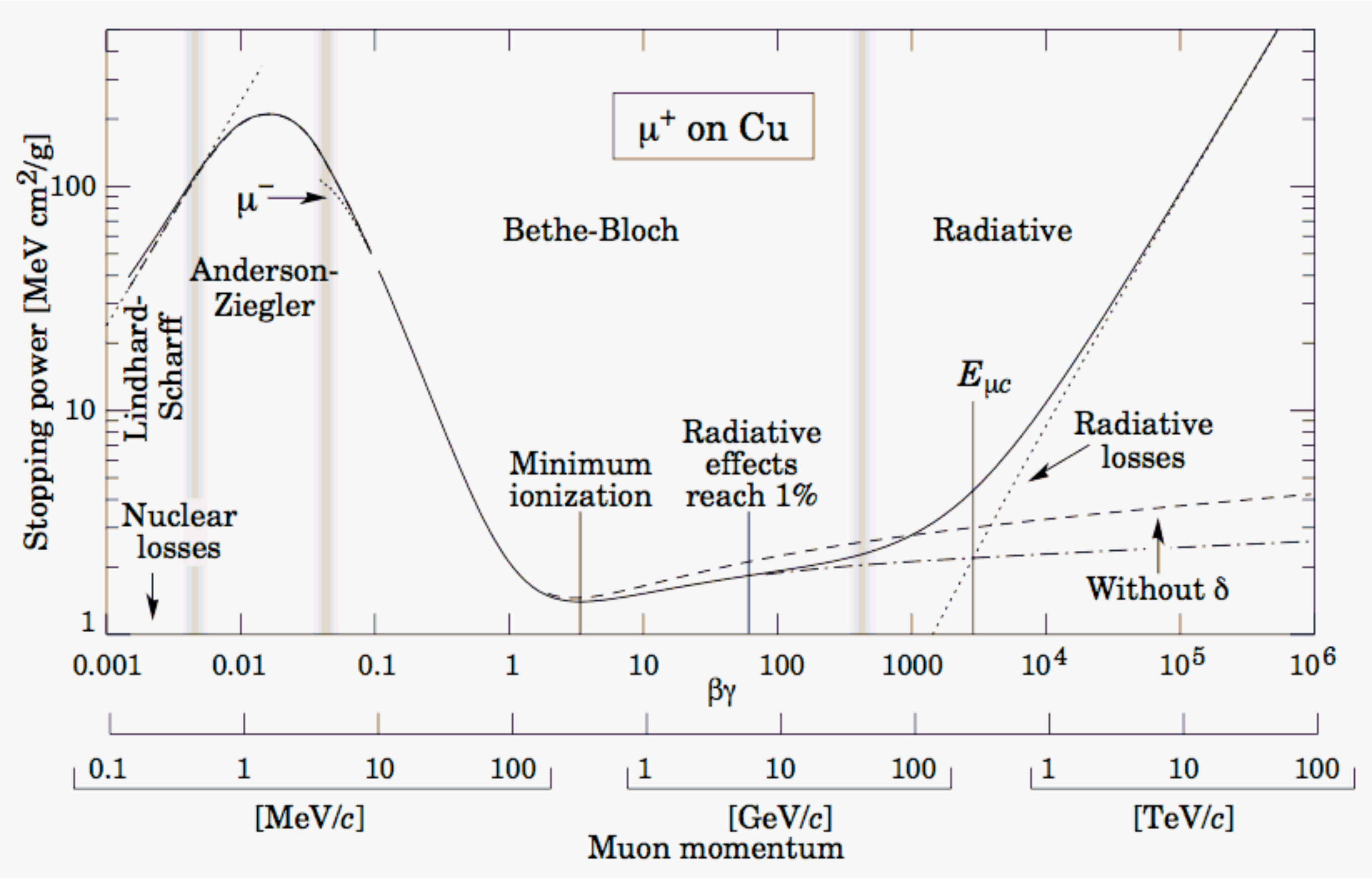
Particles that only deposit this are called MIPs.
Minimum ionizing particles.



Fluctuations in dE/dx

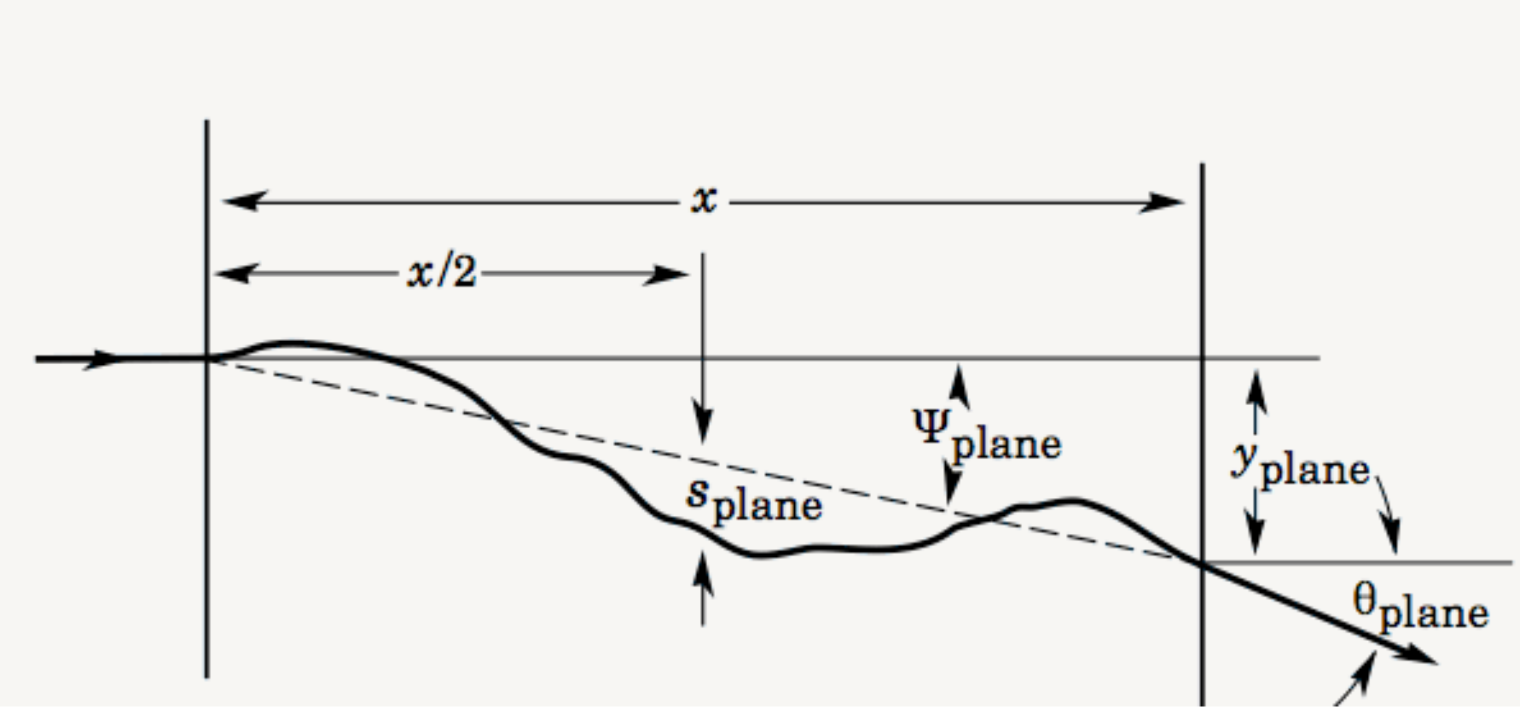
Most likely energy loss rate < mean energy loss rate
Long tail towards larger energy losses.
=> δ-Rays, i.e. “knock-out” electrons with E >> I

Limits of applicability for B-B



A 1TeV muon hitting copper is not a MIP !

Multiple scattering through small angles



$$\sigma_\theta \propto \frac{1}{p}\sqrt{\frac{x}{X_0}}$$

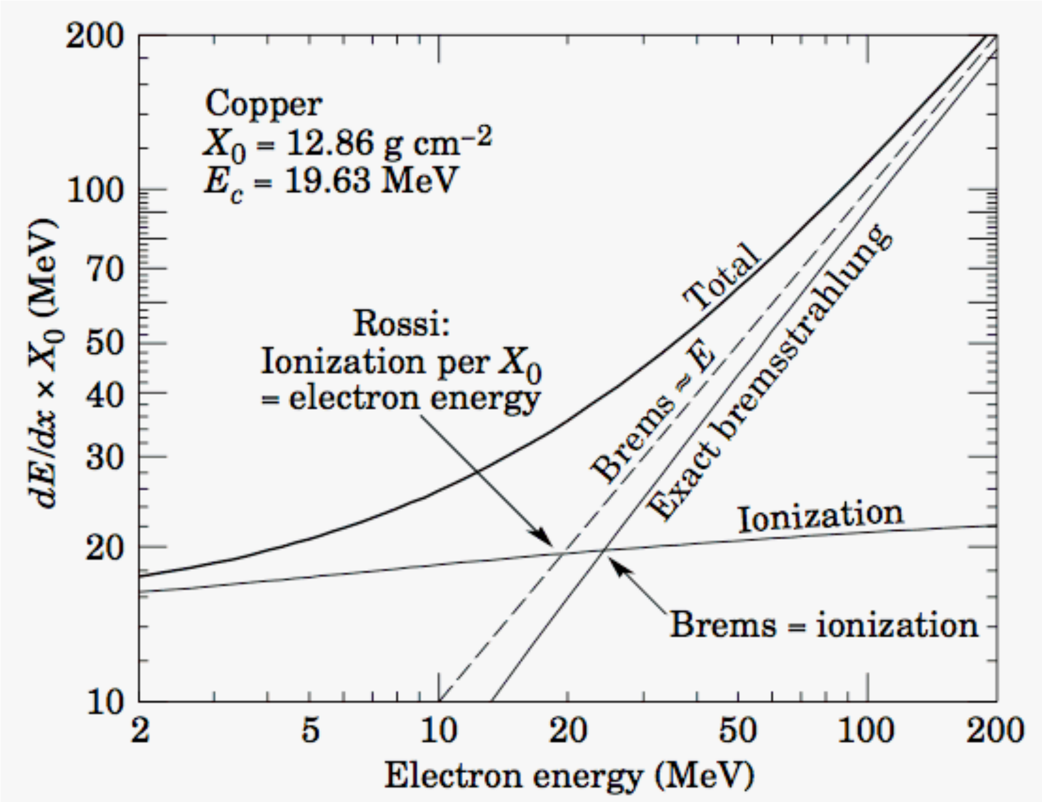
X_0 = ***Radiation length***

Radiation length

- X_0 =
  - -> mean distance over which a high energy electron looses all but 1/e of its energy.
  - -> 7/9 of the mean free path for pair production by a high energy photon.
  - -> appropriate length scale for describing high energy electromagnetic cascades.

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

Fractional Energy Loss for Electrons and E_c

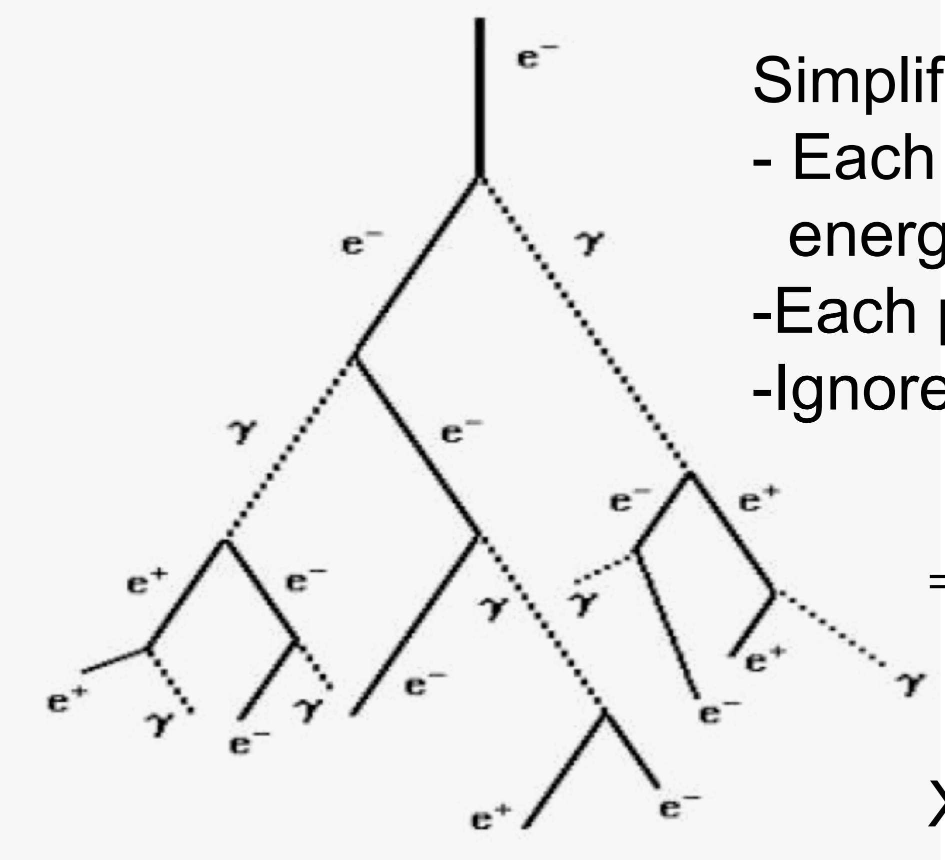


Y-axis:
<Energy lost per X_0>

X-axis:
Electron energy

E_c = electron energy for which ionization matches bremsstrahlung.

EM Showers



Simplified shower model:

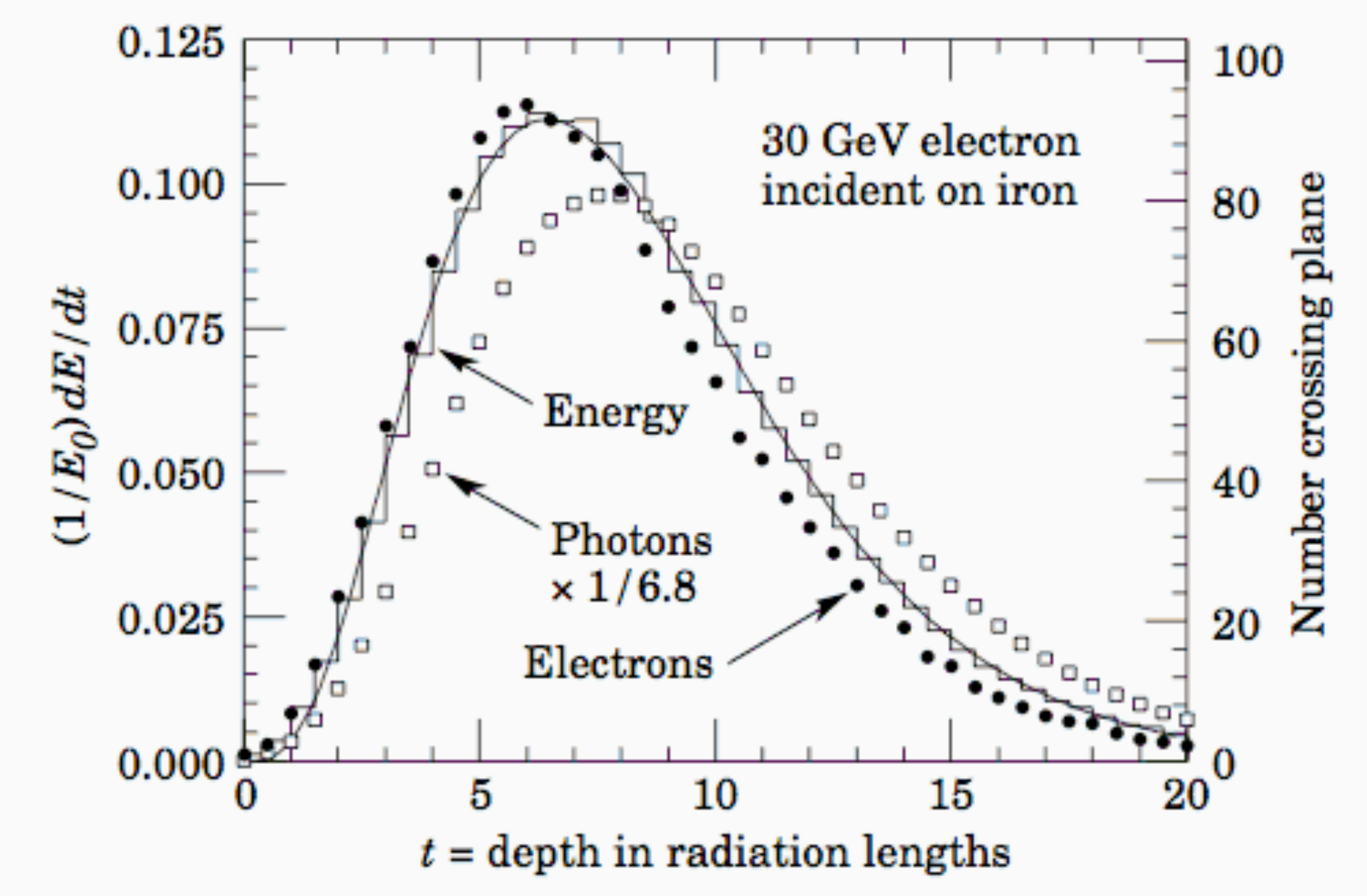
- Each electron looses 1/2 of its energy per X_0 via single hard scatter.
- Each photon pair converts after X_0
- Ignore e/photon with less than E_c

⇒Shower max at distance X_{max} with:

$X_{max}/X_0 \propto \ln(E_0/E_c)$

E_0 = incident energy of e or γ.

Longitudinal profile example



Transverse profile

- Determined by Molier radius, R_M

$$R_M = 21MeV \bullet \frac{X_0}{E_c}$$

- 99% of energy is within $3R_M$
- E_c and X_0 and thus R_M depend on material.
- Typically, transverse granularity of ECAL is chosen to match R_M .

Hadronic Interactions

- Hadrons create showers via strong interactions just like electrons and photons create them via EM.
- Mean energy of pion with initial energy E_0 after traversing material depth λ:

$$\langle E \rangle = E_0 e^{-X/\lambda}$$

- Mean energy of electron with initial energy E_0 after traversing material depth X_0 :

$$\langle E \rangle = E_0 e^{-X/X_0}$$

X_0 = radiation length
λ = interaction length or hadronic absorption length

X_0 and λ for some materials

Material	X_0	λ
H_2	63	52.4
Argon	18.9	119.7
Iron	13.8	131.9
BGO	8.0	164

Units of g/cm^2

E.g., a pion takes ~10x the depth in Iron to loose its energy than an electron with the same energy.

E.g. within the depth of X_0 in BGO, a pion looses only 5% of its energy, while an electron looses 63% of its energy, on average.

Two comments in HCAL

1. Primary purpose of HCAL is to identify the jets from quarks and hadrons.
    - More than just single particle response!
2. 1/3 of the hadronic shower is in EM energy because of pi0 decay to 2 photons.
    - Want a “compensating” HCAL.

“Compensating” Calorimeter

- Due to isospin, roughly half as many neutral pions are produced in hadronic shower than charged pions.
- However, only charged pions “feed” the hadronic shower as pi0 immediately decay to di-photons, thus creating an electromagnetic component of the shower.
- Resolution is best if the HCAL system has similar energy response to electrons as charged pions.

One of the big differences between ATLAS and CMS is that ATLAS HCAL is compensating, while CMS has a much better ECAL but a much worse HCAL response to photons.

Back to the beginning …

… and discuss detection systems instead of just particle interactions with matter.

All modern collider detectors look alike

beampipe

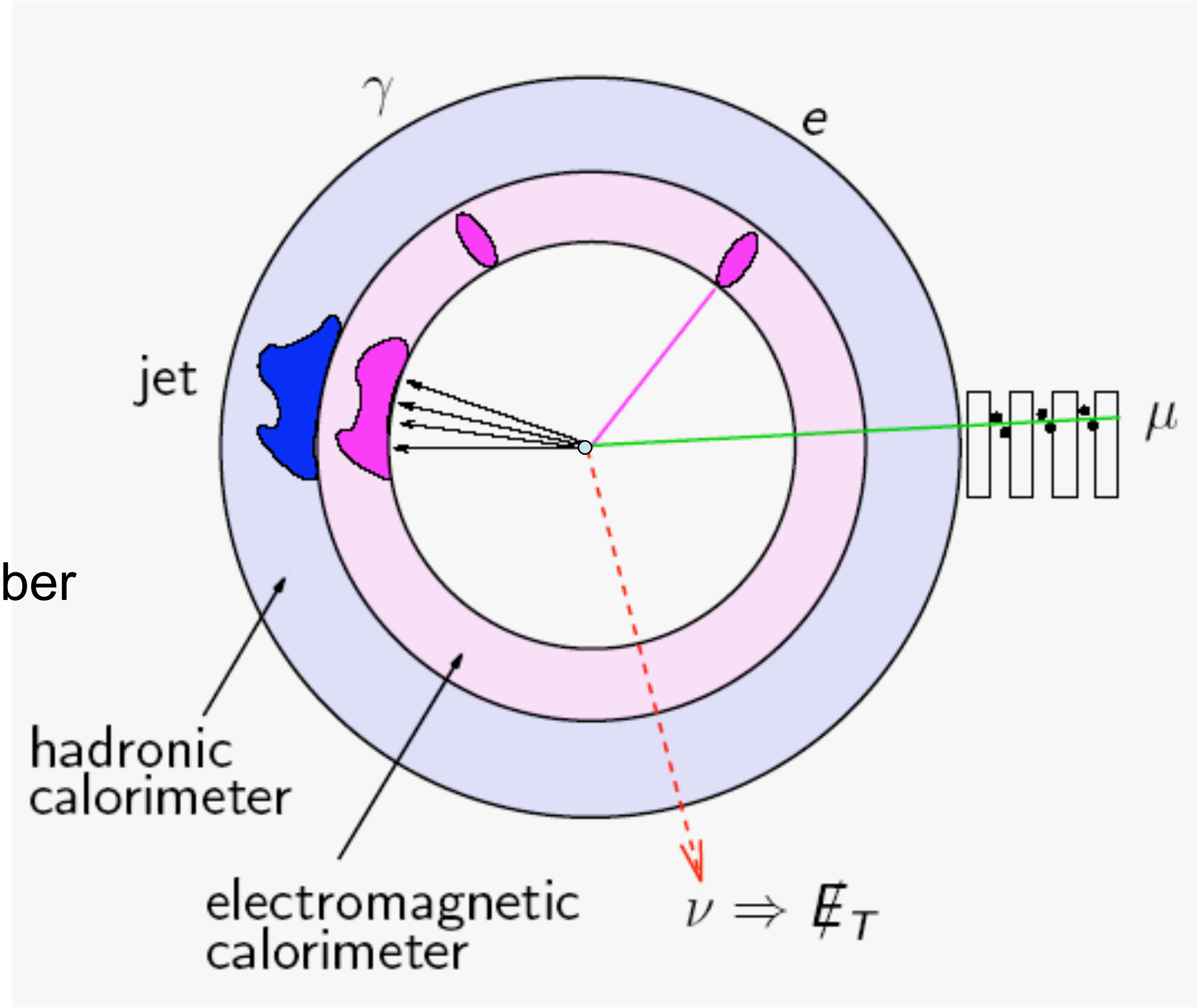
tracker

ECAL

solenoid

HCAL

Muon chamber



Tracking

- Zylindrical geometry of central tracking detector.
  - Charged particles leave energy in segmented detectors.
    - ⇒ Determines position at N radial layers
- Solenoidal field forces charged particles onto helical trajectory
  - Curvature measurement determines charged particle momentum:

$$R = P_T / (0.3B)$$

for R in meters, B in Tesla, P_T in GeV.

E.g. In 4Tesla field, a particle of 0.6GeV will curl in a tracking volume with radius 1m.

Limits to precision are given by:

1. Precision of each position measurement
   => more precision is better
2. Number of measurements => $1/\sqrt{N}$
   => more measurements is better
3. B field and lever arm => $1/BL^2$
   => larger field and larger radius is better
4. Multiple scattering => $1/\sqrt{X_0}$
   => less material is better

Momentum Resolution

Two contributions with different dependence on p_T

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_{r\phi} p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

Device resolution

$$\frac{\sigma(p_T)}{p_T} = \frac{0.05}{BL}\sqrt{\frac{1.43L}{X_0}}$$

Multiple cattering

Small momentum tracks are dominated by multiple scattering.

ECAL

- Detects electrons and photons via energy deposited by electromagnetic showers.
  - Electrons and photons are completely contained in the ECAL.
  - ECAL needs to have sufficient radiation length X_0 to contain particles of the relevant energy scale.
- Energy resolution $\propto 1/\sqrt{E}$

Real detectors have also constant terms due to noise.

HCAL

- Only stable hadrons and muons reach the HCAL.
- Hadrons create hadronic showers via strong interactions, except that the length scale is determined by the nuclear absorption length λ, instead of the electromagnetic radiation length X_0 for obvious reason.
- Energy resolution $\propto 1/\sqrt{E}$

Real detectors have also constant terms due to noise.

Muon Detectors

- Muons are minimum ionizing particles, i.e. small energy release, in all detectors.
- Thus the only particles that range through the HCAL.
- Muon detectors generally are another set of tracking chambers, interspersed with steal or iron absorbers to stop any hadrons that might have “punched through” the HCAL.

What do we need to detect?

- Momenta of all stable particles:
  - Charged: Pion, kaon, proton, electron, muon
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- Particle identification for all of the above.
- "Unstable" particles:
  - Pizero
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  - Gluon and light quarks
  - ***W,Z,Higgs***
  - … anything new we might discover …

Haven't told you how to detect the blue ones!
Three more "detection" concepts missing.

Lifetime tags

Transverse Energy Balance

Reconstruction via decay products.