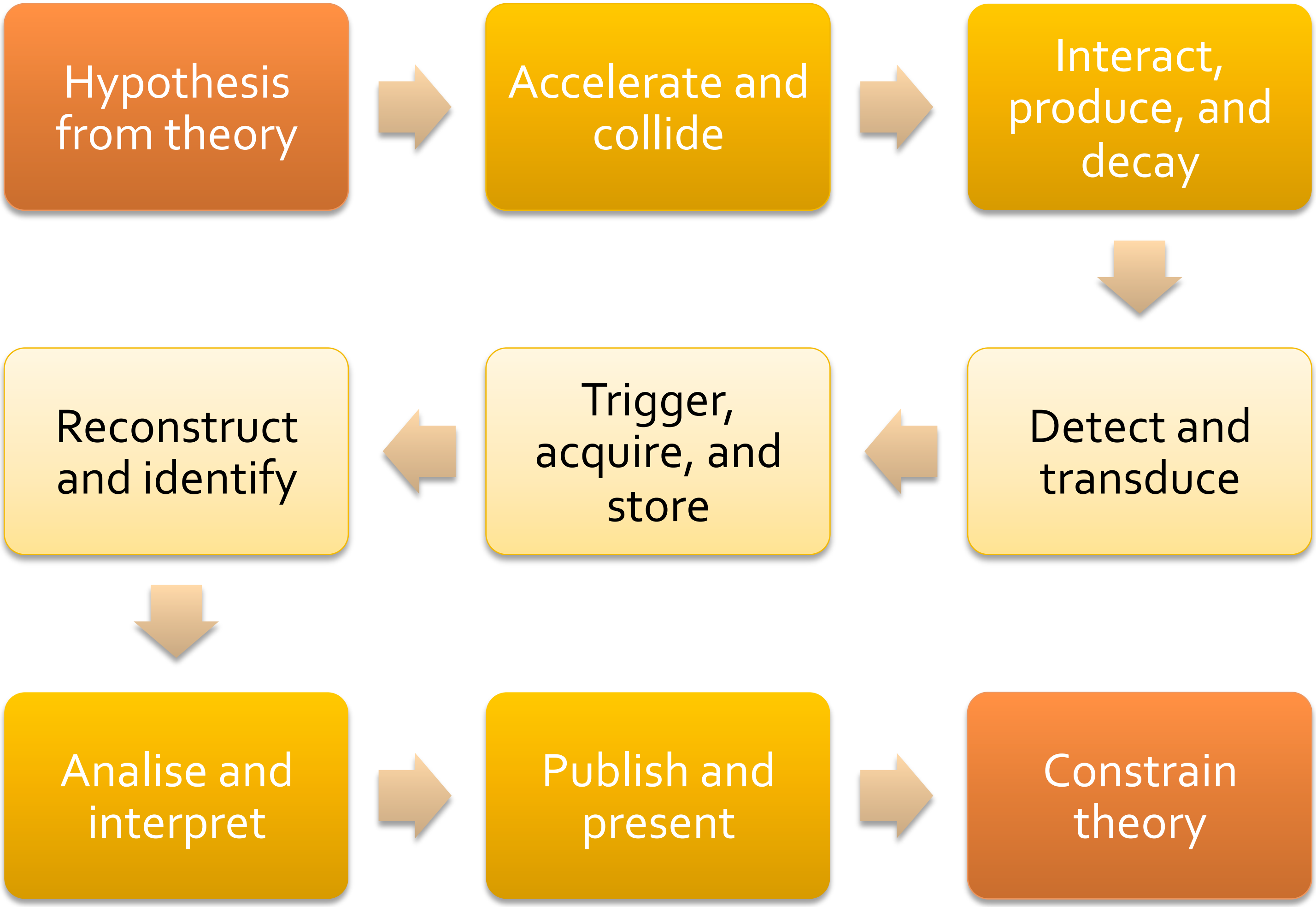
After the collisions, before the analysis.

Detectors, reconstruction, and trigger

andre@lip.pt

You are here



Hypothesis from theory

Accelerate and collide

Interact, produce, and decay

Detect and transduce

Trigger, acquire, and store

Reconstruct and identify

Analise and interpret

Publish and present

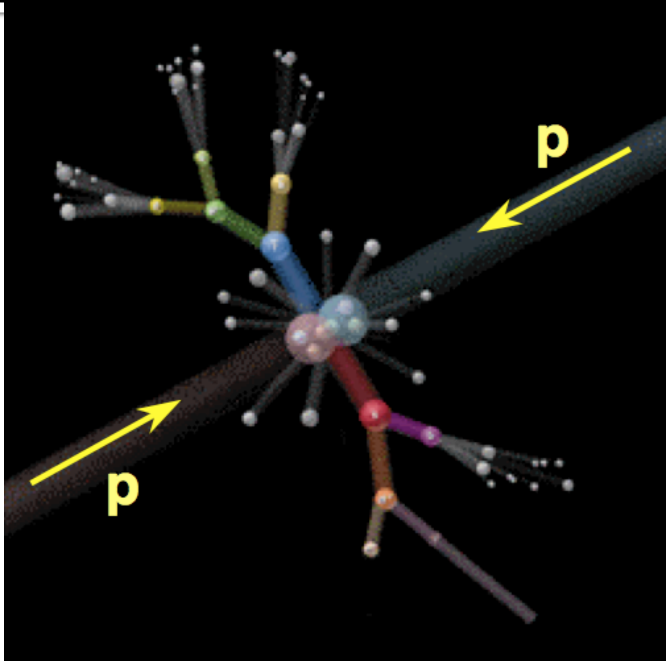
Constrain theory

You are here

- Particles, interactions and detectors.
- Calorimetry and energy.
- Trackers and momentum.
- Trigger and acquisition.

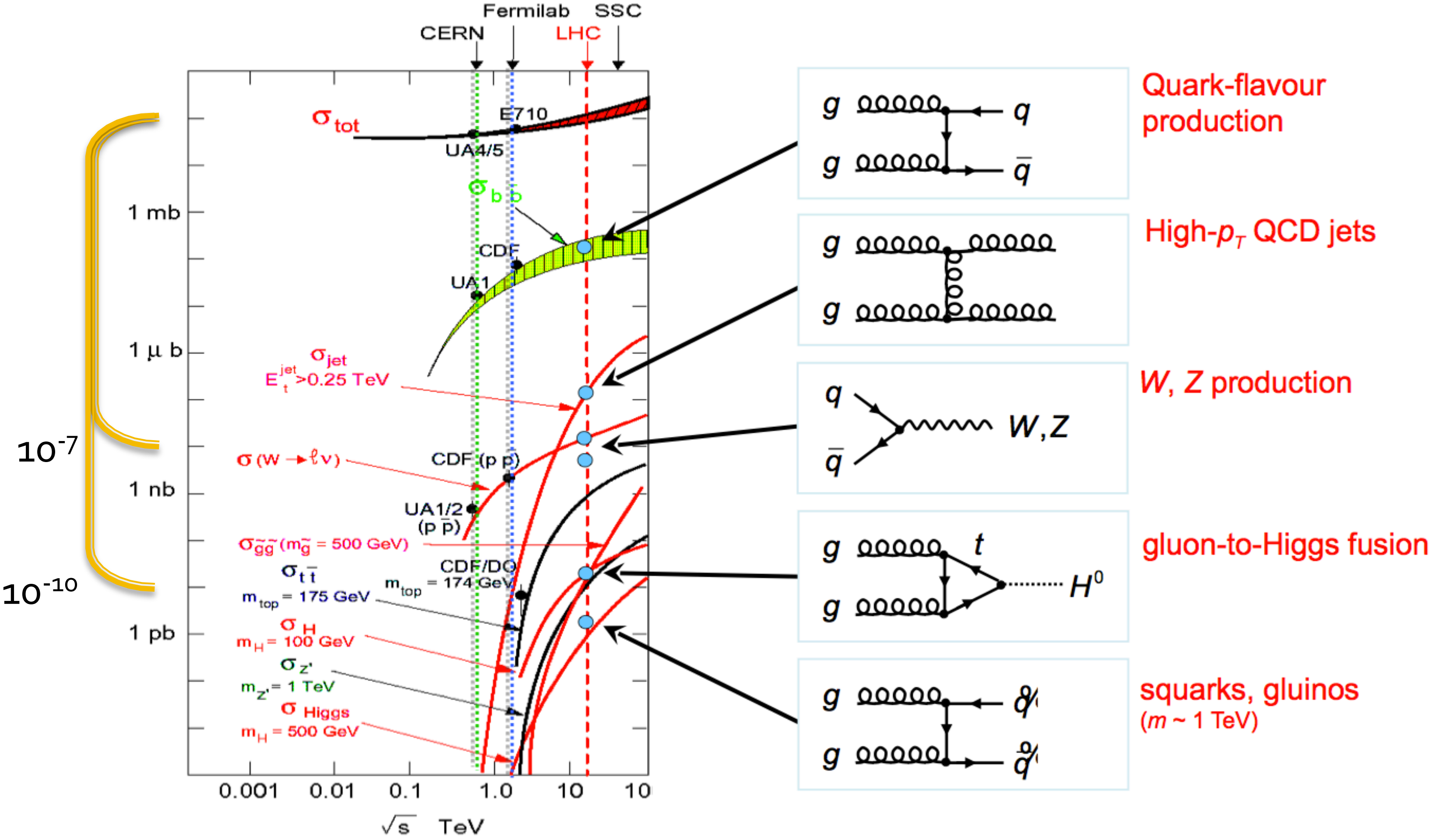
Particles, interactions and detectors

What gets produced in collisions



- Mostly pions.
  - The cheapest way to rearrange quarks and gluons.
    - 2/3 charged: cτ~8 m decay in μν.
    - 1/3 neutral: promptly decay in diphotons.
- The things we look for.
  - From 10^7 (W, Z) to 10^{10} (Higgs) times less often.
  - And less…

What gets produced in collisions



Quark-flavour production

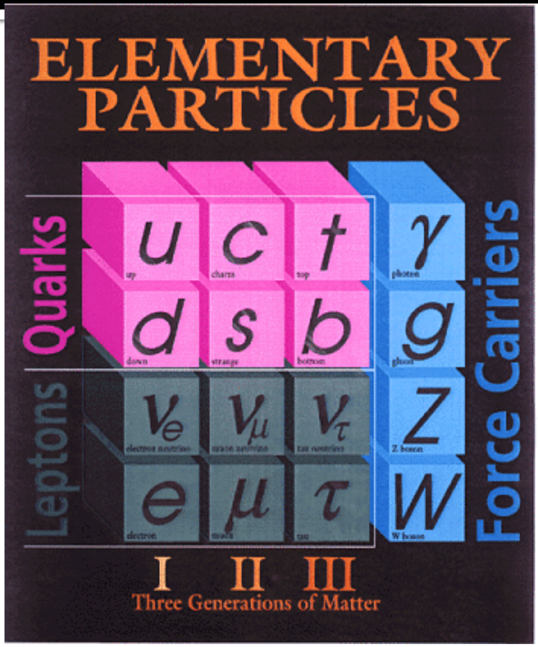
High-p_T QCD jets

W, *Z* production

gluon-to-Higgs fusion

squarks, gluinos
(*m* ~ 1 TeV)

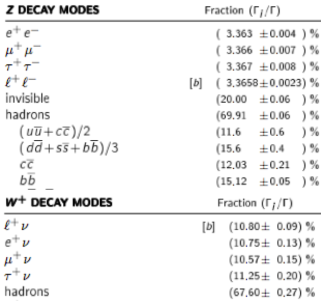
What we can detect



- Directly observable particles must:
  - Undergo strong or EM interactions.
  - Be sufficiently long-lived to pass the detectors.
- We can directly observe:
  - Electrons, muons, photons.
  - Neutral or charged hadrons:
    - Pions, protons, kaons, neutrons, …
    - Many physics analyses treat **jets** from quark hadronization collectively as single objects.
    - Use **displaced secondary vertices** to identify jets originating from b-quarks.
- We can indirectly observe long lived weakly interacting particles (e.g. neutrinos) through **missing transverse energy**

What we can detect

- Short-lived particles decay to long-lived ones.
  - Neutral pion: diphoton.
  - u, d, s quarks and gluons: jets of mostly pions.
  - c, b quarks: jets with long-lived mesons.
  - W, Z bosons, tau leptons: multiple decay topologies.
  - "Everyone" else in the Review of Particle Physics "phonebook" [http://goo.gl/ASrmh].

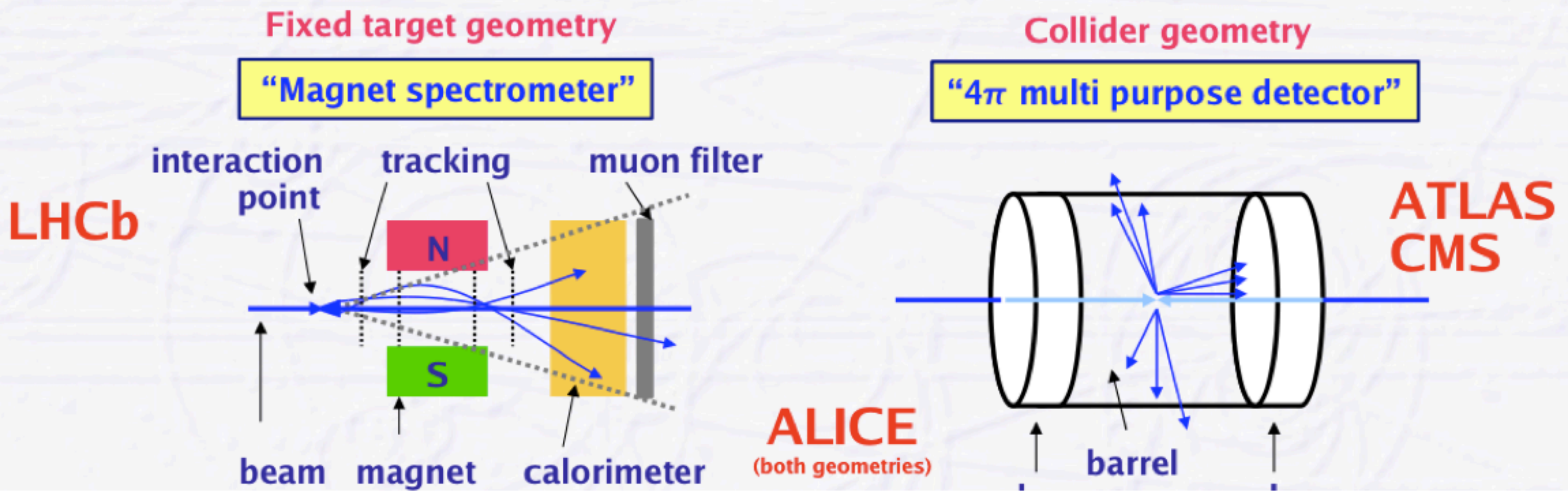


Z DECAY MODES		Fraction (Γ_i/Γ)
e^+e^-		(3.363 ±0.004) %
$\mu^+\mu^-$		(3.366 ±0.007) %
$\tau^+\tau^-$		(3.367 ±0.008) %
$\ell^+\ell^-$	[b]	(3.3658±0.0023) %
invisible		(20.00 ±0.06) %
hadrons		(69.91 ±0.06) %
$(u\overline{u}+c\overline{c})/2$		(11.6 ±0.6) %
$(d\overline{d}+s\overline{s}+b\overline{b})/3$		(15.6 ±0.4) %
$c\overline{c}$		(12.03 ±0.21) %
$b\overline{b}$		(15.12 ±0.05) %

W^+ DECAY MODES		Fraction (Γ_i/Γ)
$\ell^+\nu$	[b]	(10.80± 0.09) %
$e^+\nu$		(10.75± 0.13) %
$\mu^+\nu$		(10.57± 0.15) %
$\tau^+\nu$		(11.25± 0.20) %
hadrons		(67.60± 0.27) %

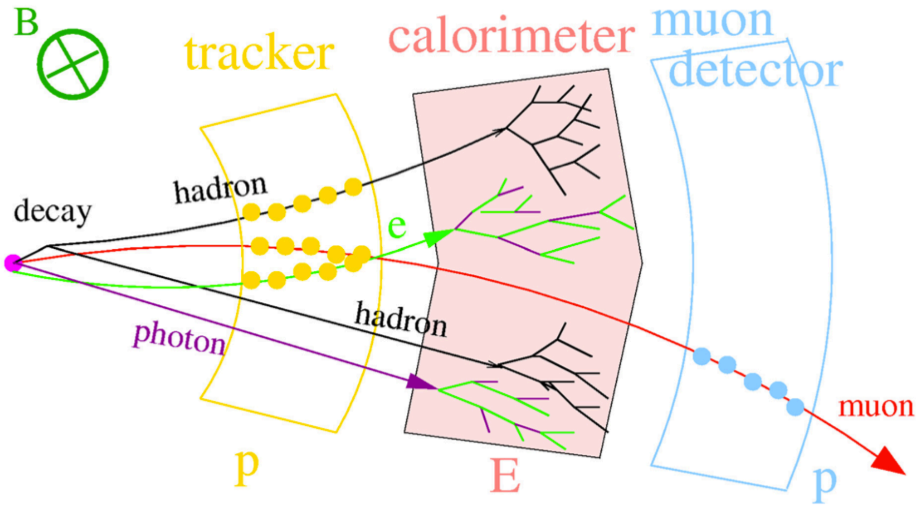
Shapes of experiments

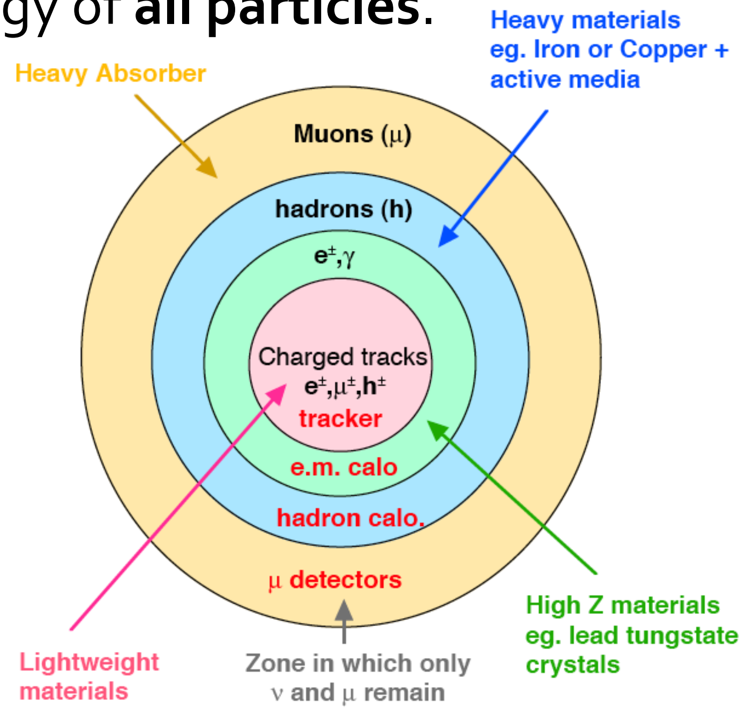
- Fixed-target geometry
  - Easy access, smaller, less expensive.
- Collider geometry
  - Hermiticity, larger, more expensive.



Peeling the hermetic onion

- Inner tracking
  - Measure charged particles **disturbing them the least possible**.
- Calorimetry
  - Measure as much as possible the energy of **all particles**.
- Outer tracking
  - Measure **muons**.




Heavy materials eg. Iron or Copper + active media

Heavy Absorber

Muons (μ)

hadrons (h)

$e^\pm,\gamma$

Charged tracks
$e^\pm,\mu^\pm,h^\pm$
tracker

e.m. calo

hadron calo.

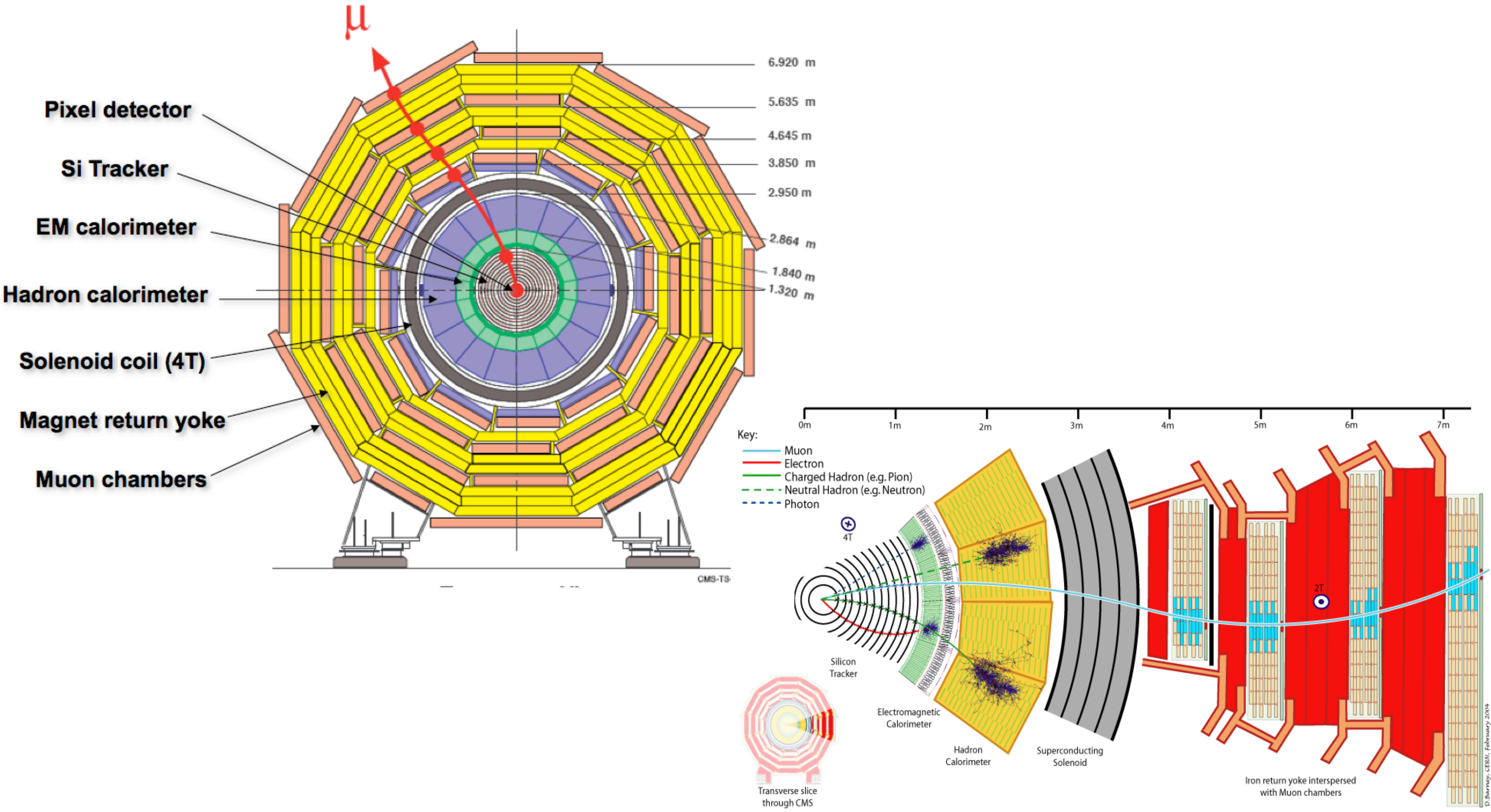
μ detectors

High Z materials eg. lead tungstate crystals

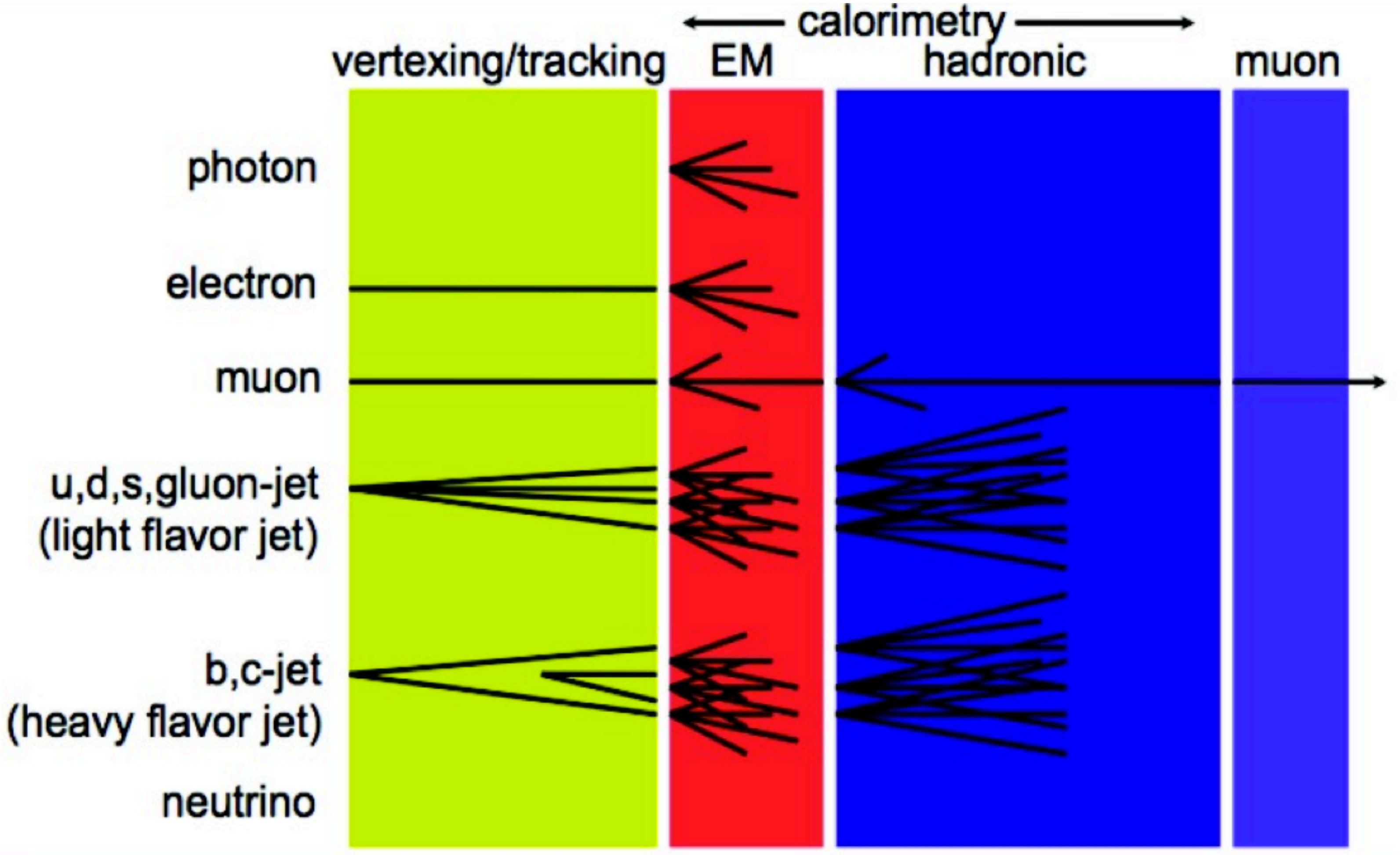
Lightweight materials

Zone in which only ν and μ remain

CMS example


μ
Pixel detector
Si Tracker
EM calorimeter
Hadron calorimeter
Solenoid coil (4T)
Magnet return yoke
Muon chambers
6.920 m
5.635 m
4.645 m
3.850 m
2.950 m
2.864 m
1.840 m
1.320 m
CMS-TS
0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Particles and their decays

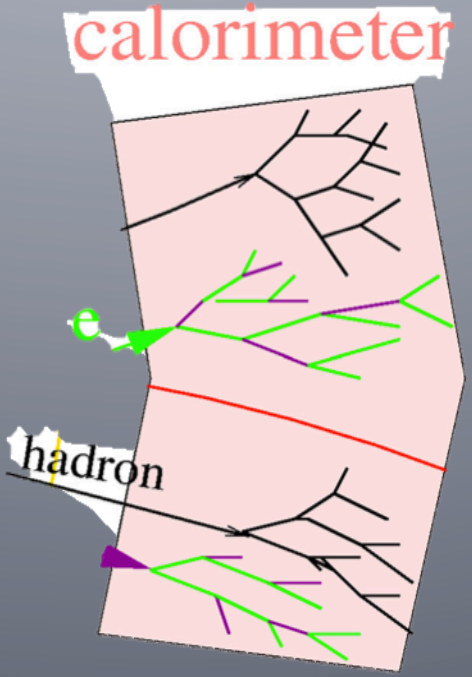


In the end it is all charged particles

- Ultimately all detectors end up detecting charged particles:
  - Photons are detected via electrons produced in different ways.
  - Neutrons are detected through transfer of energy to charged particles in the detector medium (shower of secondary hadrons).
- Charged particles are detected via EM interaction with electrons or nuclei in the detector material:
  - Inelastic collisions with atomic electrons → energy loss.
  - Elastic scattering from nuclei → change of direction.

Calorimetry

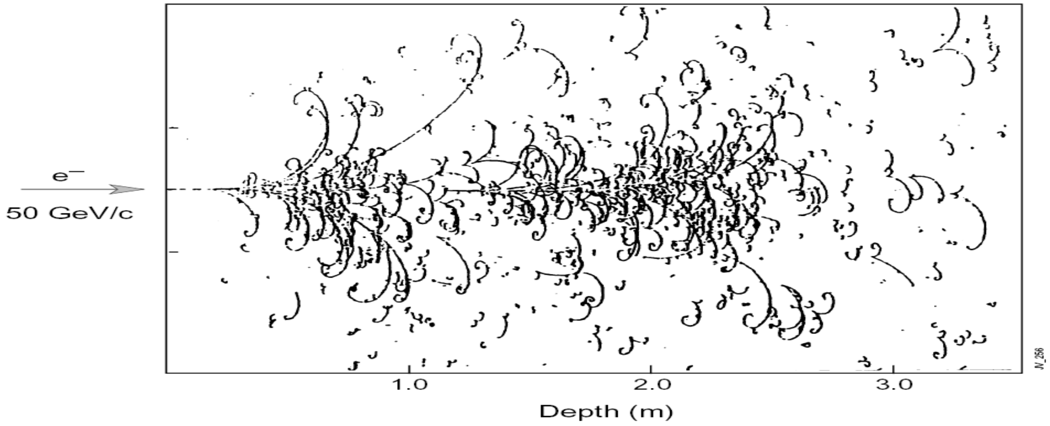
Trying to measure the energy of everything except muons.

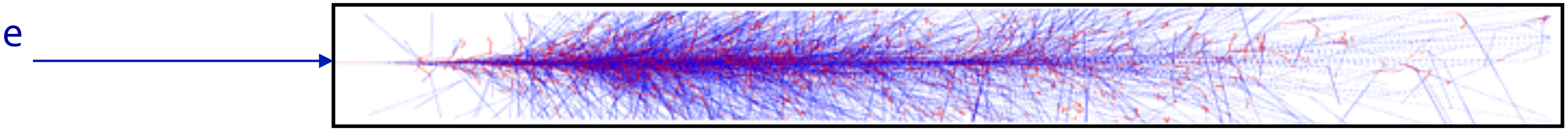


Calorimetry: what?

- Measure energy deposited in material by particles which give rise to electromagnetic or hadronic showers.
  - Electrons, photons and hadrons (including neutral hadrons)

Big European Bubble Chamber filled with Ne:H_2 = 70%:30%, 3T Field, L=3.5 m, $X_0 \approx 34$ cm, 50 GeV incident electron



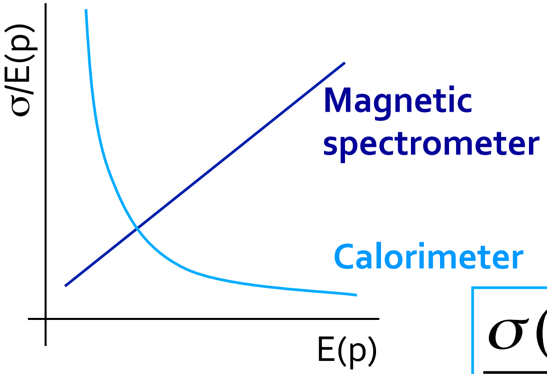


GEANT shower Monte Carlo ($PbWO_4$ crystal)

Calorimetry: why?

- Fractional, or relative, energy resolution improves with energy — in contrast to measurements of a magnetic spectrometer
  - The size required increases only like log(E)

- Calorimeters can:
  - Measure energy of jets
  - Measure missing transverse energy
    - Neutrinos etc
  - Provide fast, efficient, and selective trigger output
  - Measure position
  - Measure time



$$\frac{\sigma(p)}{p} \approx ap$$

$$\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}$$

Calorimetry: how?

- Need material in which shower takes place, and a way to obtain a signal to measure the shower – for example:
  - Ionization
    - Liquid argon, silicon wafer, various gasses and gas mixtures…
  - Scintillation
    - Plastic scintillator, various (inorganic) crystals…
  - Cerenkov radiation
    - Lead glass, water, air…

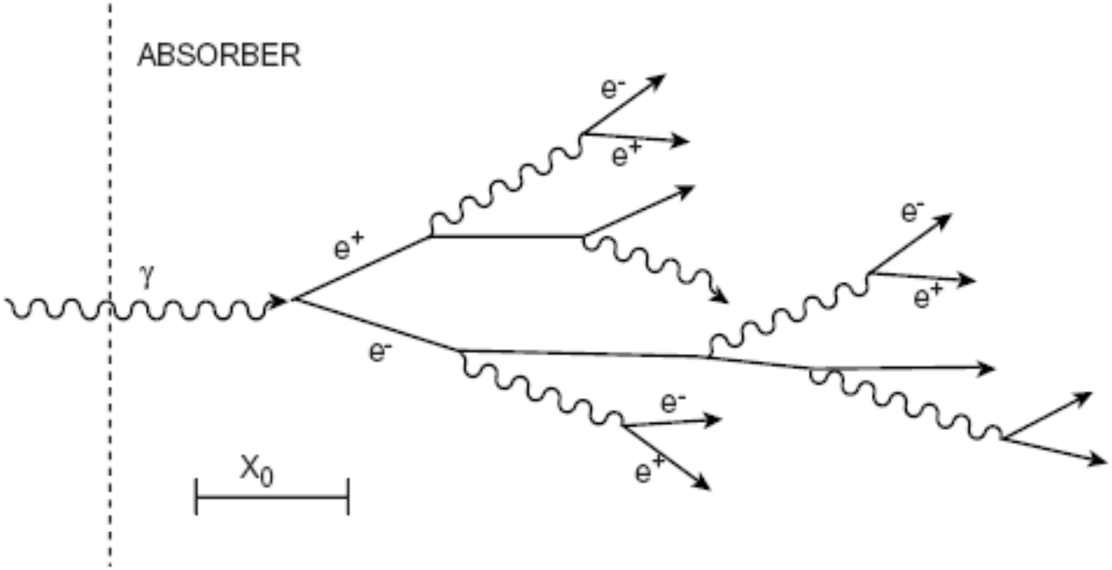
- Sampling calorimeter has dense material to keep the shower compact, and the shower is sampled with an active material.
  - e.g. plastic scintillator, liquid argon, silicon wafer, etc.
- Homogeneous calorimeter is entirely composed of active material
  - e.g. lead glass, lead tungstate crystals, water…

- Electromagnetic calorimeters designed to measure electrons and photons.
- Hadron calorimeters designed to measure hadronic showers.

Electromagnetic showers

Electromagnetic showers

- Electromagnetic showers result from electrons and photons undergoing bremsstrahlung and pair creation.



- **For high energy (GeV scale) electrons, bremsstrahlung is the dominant energy loss mechanism.**
- **For high energy photons, pair creation is the dominant absorbtion mechanism.**
  - **Shower development governed by these processes.**

Electromagnetic shower development

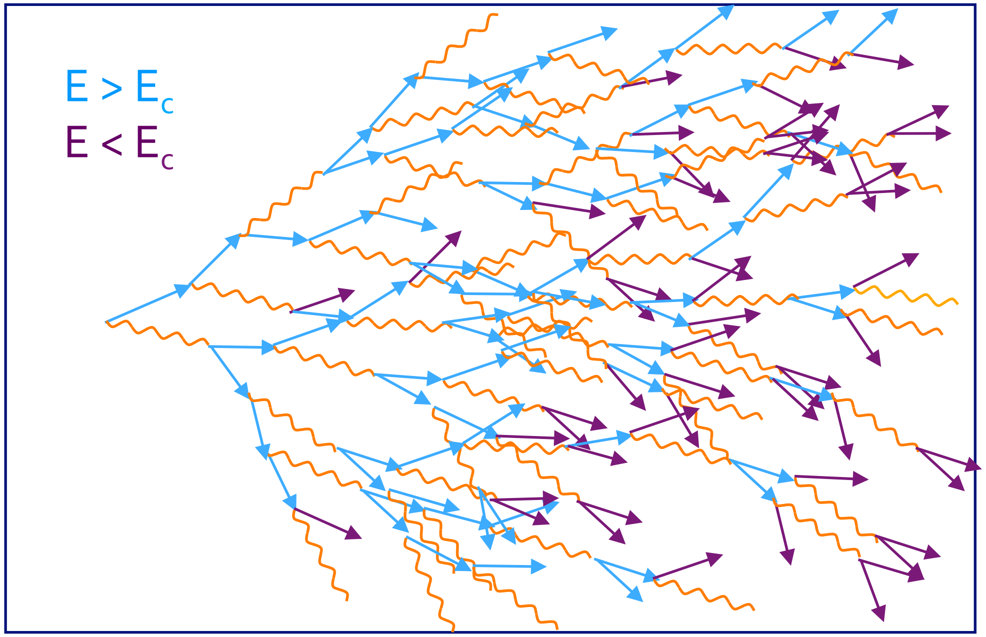
- Radiation length (X_0) defined to be the distance over which an electron loses all but 1/e of its energy.
- Useful approximation ➔
  - Rough derivation in [Cal1]; more precise approximation in [Cal2].

$$\boxed{X_0 \approx \frac{180A}{Z^2} g \cdot cm^{-2}}$$

- **Critical energy (E_c) defined to be where energy loss due to radiation and energy loss due to ionization are equal**

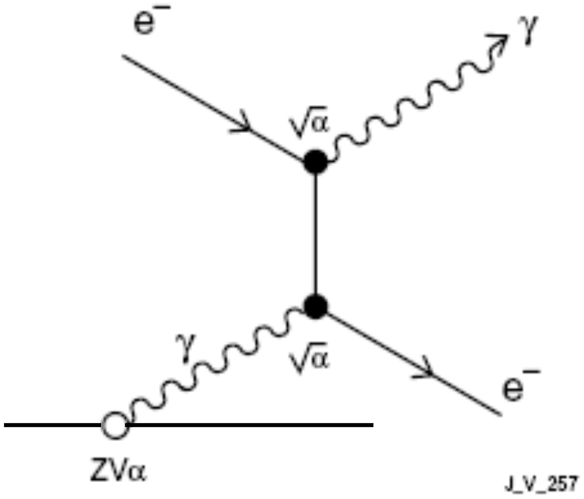
$$\boxed{E_c \approx \frac{560}{Z} \mathrm{MeV}}$$

  - **Other, more precise, approximations in [Cal2].**

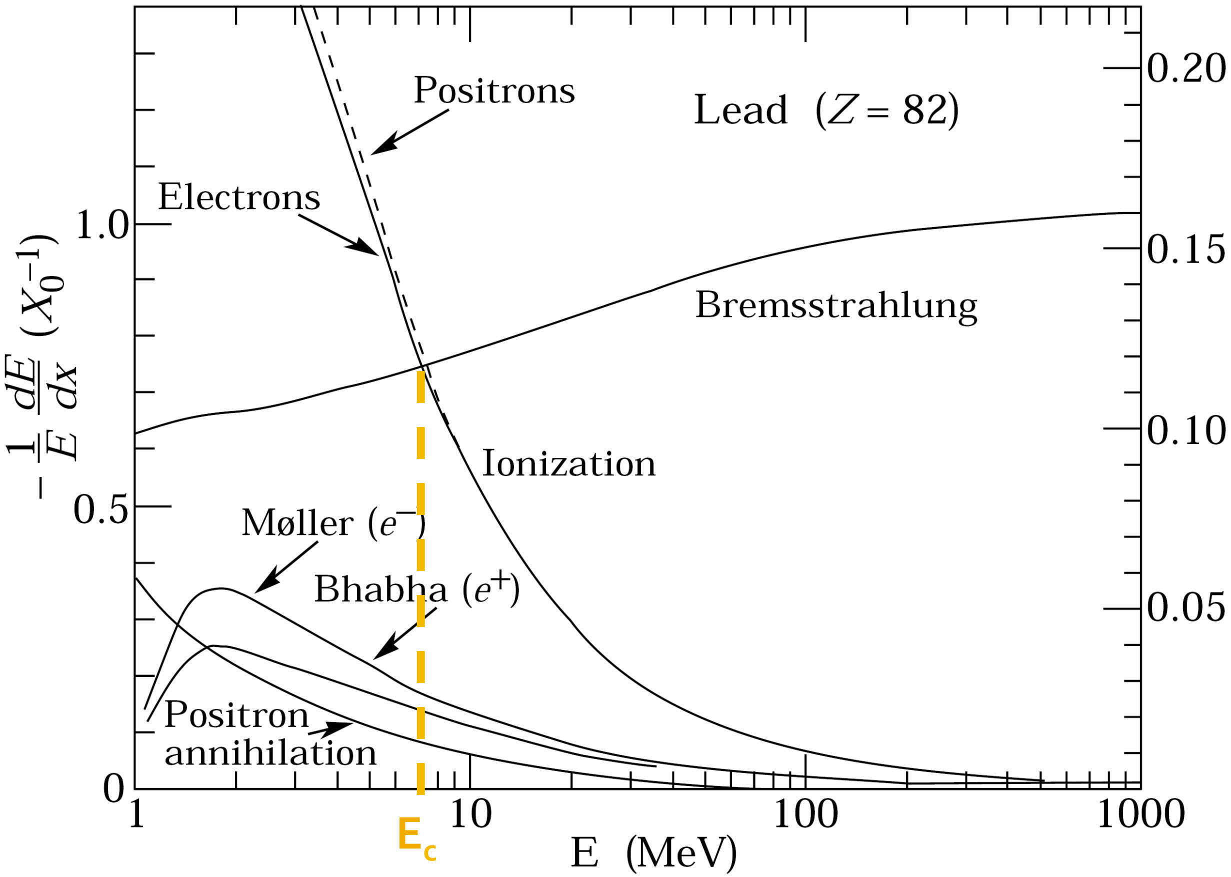


Energy loss in matter: electrons

Bremsstrahlung in the
Coulomb field of the nucleus



Fractional energy loss: electrons



Energy loss in matter: photons

Pair Production

Occurs in the electric field of the nucleus (if $E_\gamma > 2m_ec^2$)

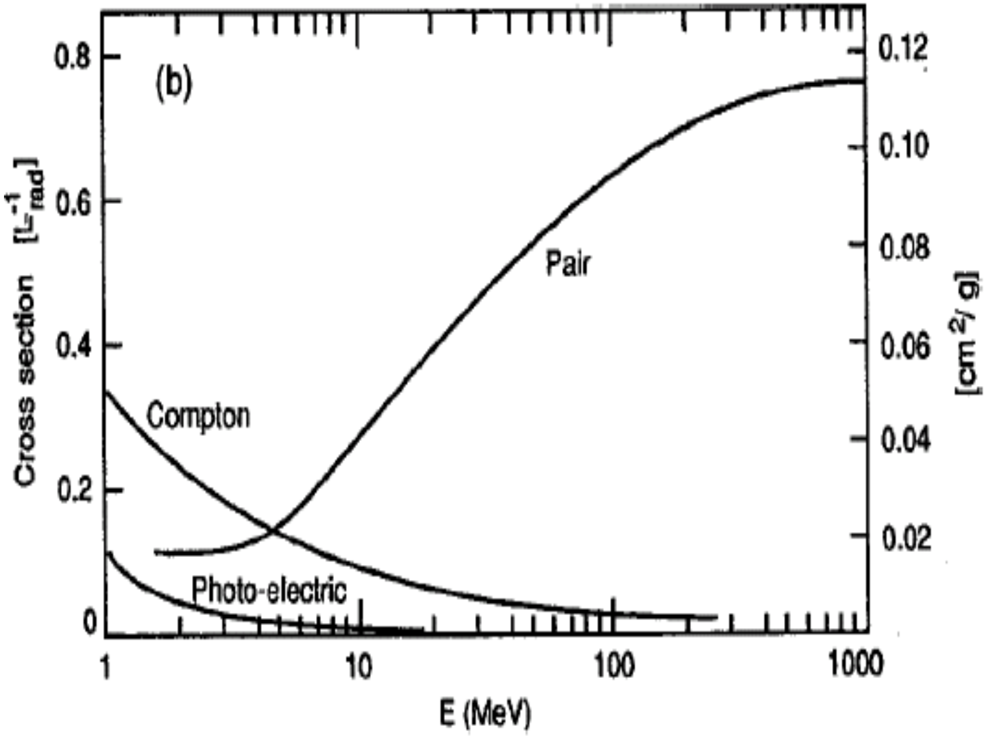
$$\boxed{\sigma_{pair} \approx \frac{7}{9} \cdot \frac{A}{N_A} \cdot \frac{1}{X_0}}$$

Probability of conversion in 1 X_0 is $e^{-7/9}$

Can define mean free path:

$$\boxed{\lambda_{pair} \approx \frac{9}{7} X_0}$$

Fractional energy loss: photons



Compton scattering

$$\boxed{\sigma_C \approx \frac{\ln E_\gamma}{E_\gamma}}$$

Photoelectric effect

$$\boxed{\sigma_{pe} \approx Z^5 \alpha^4 \left(\frac{m_ec^2}{E_\gamma} \right)^{\frac{7}{2}}}$$

Contributions to Photon Cross Section in Carbon and Lead

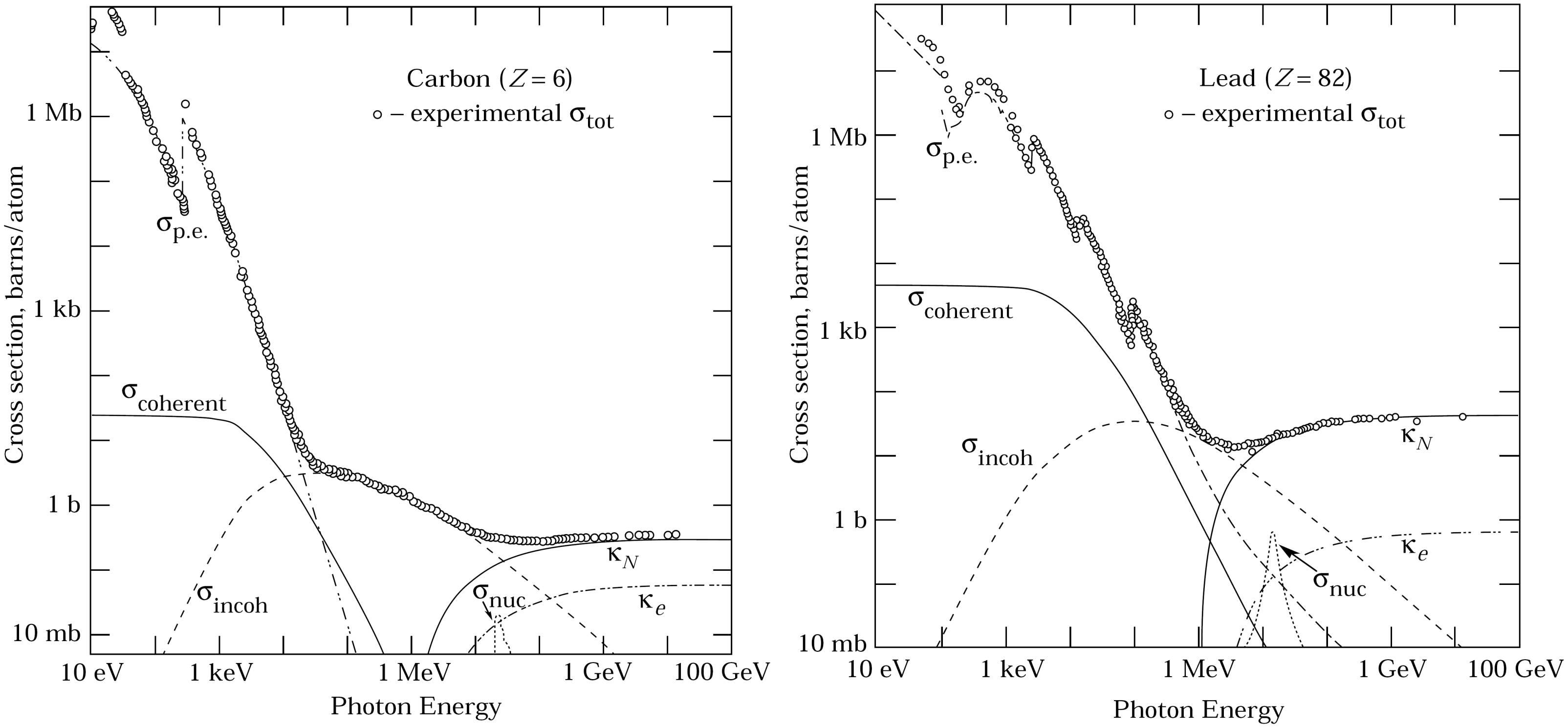


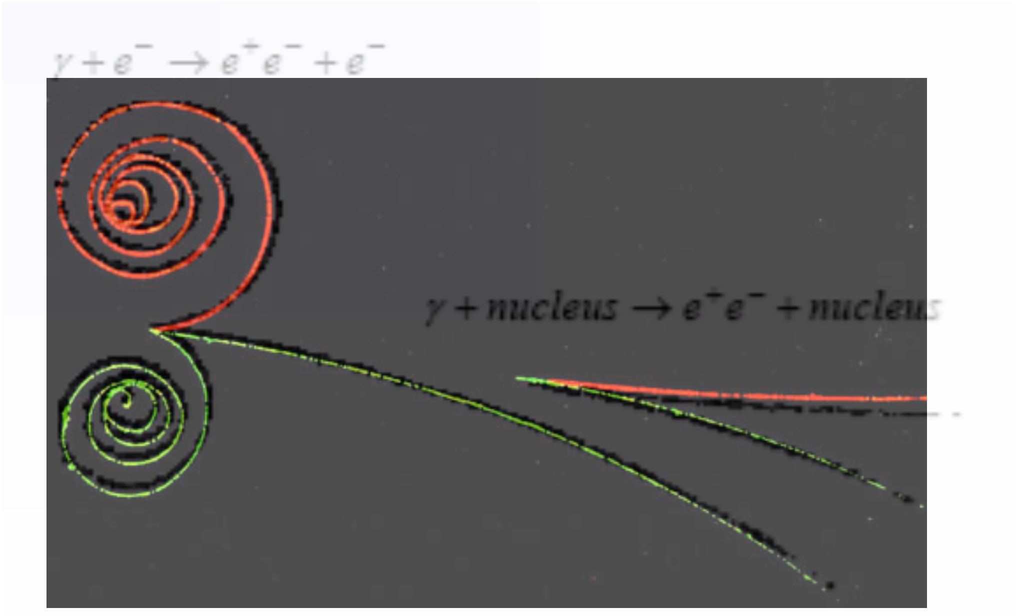
Figure 24.3: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes:

$\sigma_{\text{p.e.}}$ = Atomic photo-effect (electron ejection, photon absorption)
σ_{coherent} = Coherent scattering (Rayleigh scattering—atom neither ionized nor excited)
$\sigma_{\text{incoherent}}$ = Incoherent scattering (Compton scattering off an electron)
κ_n = Pair production, nuclear field
κ_e = Pair production, electron field
σ_{nuc} = Photonuclear absorption (nuclear absorption, usually followed by emission of a neutron or other particle)

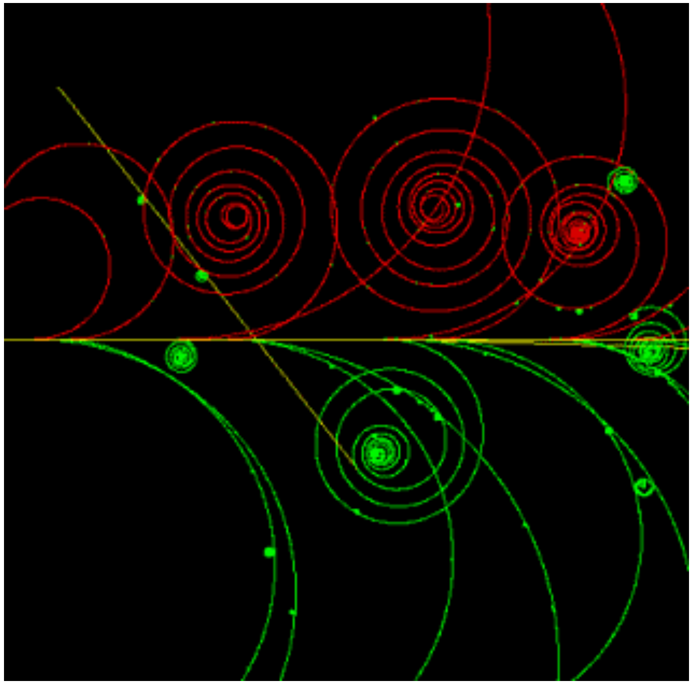
From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data **9**, 1023 (80). Data for these and other elements, compounds, and mixtures may be obtained from `http://physics.nist.gov/PhysRefData`. The photon total cross section is assumed approximately flat for at least two decades beyond the energy range shown. Figures courtesy J.H. Hubbell (NIST).

Pair production/conversion

- The pairs are emmitted in the direction of the photon: $\theta \sim m_e/E_\gamma$.



- Electrons from the photoelectric effect and from Compton scattering are more or less isotropic.



Longitudinal development

- The multiplication of the shower continues until the energies fall below the critical energy, E_c.
- A simple model of the shower uses variables scaled to X_0 and E_c:

$$\boxed{t = \frac{x}{X_0}, y = \frac{E}{E_c}}$$

- Electrons loose about 2/3 of their energy in $1X_0$, and the photons have a probability of 7/9 for conversion: X_0 ~ generation length
- After distance t: number of particles, $n(t) = 2^t$

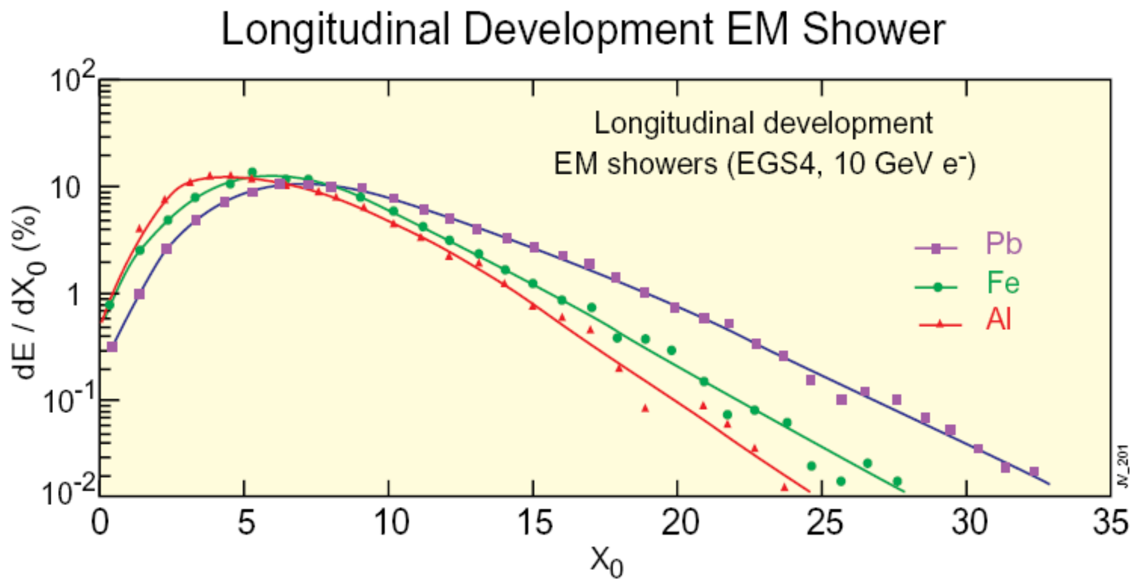
  energy of particles, $E(t) \approx \frac{E}{2^t}$

- When E = E_c, ~shower maximum: $n(t_{\max}) \approx \frac{E}{E_c} = y$

$$t_{\max} \approx \ln\left(\frac{E}{E_c}\right) = \ln y$$

Longitudinal development

- Higher Z materials have lower E_c.
- Scaling of longitudinal development with X_o only holds approximately:
  - Lower $E_c \Rightarrow$ multiplication continues to lower energies and electrons continue radiating down to lower energies

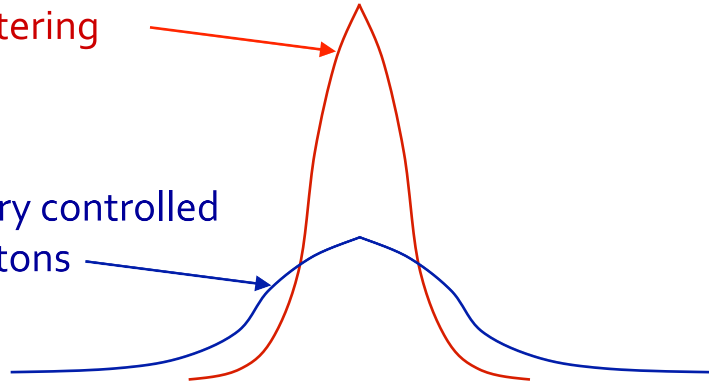


Lateral development

- Molière radius, R_m, scaling factor for lateral extent, defined by:

$$\boxed{R_M = \frac{21 MeV \cdot X_0}{E_c} \approx \frac{7A}{Z} g \cdot cm^{-2}}$$

- Gives the average lateral deflection of electrons of critical energy after 1 X_0
  - 90% of shower energy contained in a cylinder of 1× R_m
  - 95% of shower energy contained in a cylinder of 2× R_m
  - 99% of shower energy contained in a cylinder of 3.5× R_m

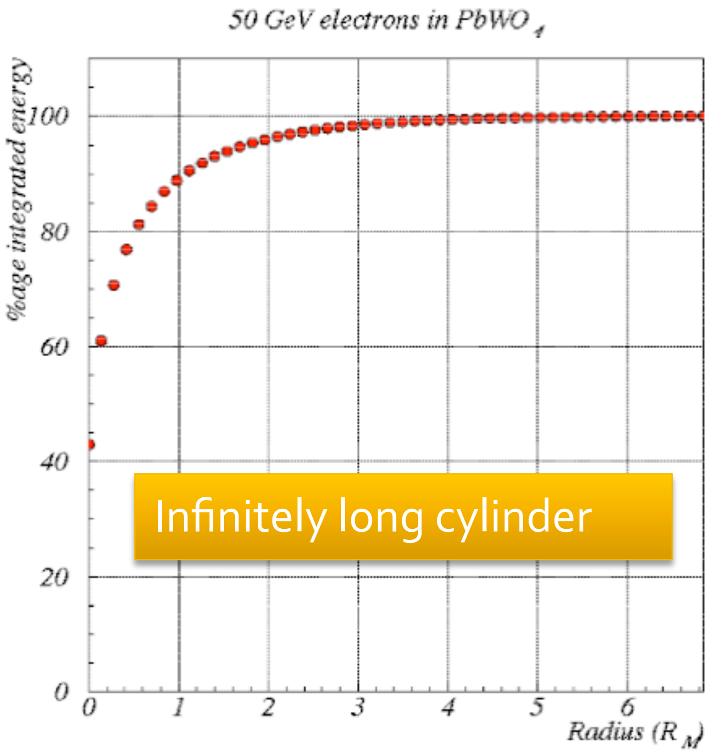


Width of core controlled by multiple scattering of $e^{\pm}$

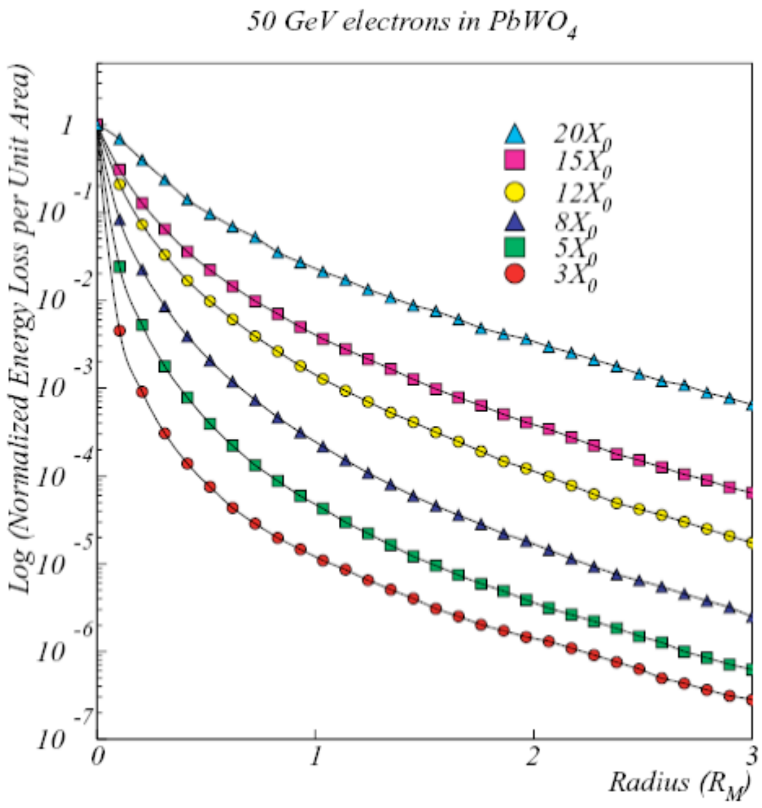
Width of periphery controlled by Compton photons

EM showers: lateral spread

- Lateral shower shape: to very good approximation is invariant with energy.



Infinitely long cylinder



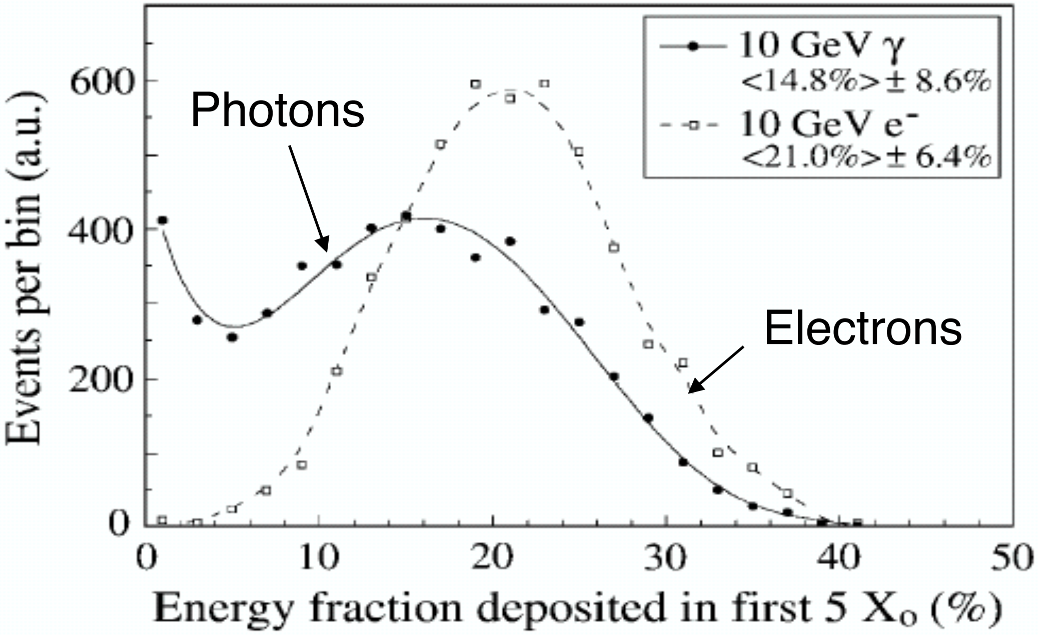
EM showers: further issues

- Shower processes are intrinsically linear and proportional to incoming particle energy:
  - Electromagnetic calorimeters are intrinsically linear.
  - Keeping them so makes demands on: shower containment, readout devices, and associated electronics.

- Photon showers develop slightly deeper than electron showers.
  - Because of distance before first conversion:

$$\boxed{\lambda_{pair} \approx \frac{9}{7} X_0}$$

- Depth of photon showers fluctuates more than electron showers.



Hadronic showers

Hadron showers

- Hadronic cascades develop in an analogous way to EM showers.
  - Strong interaction controls overall development.
  - High-energy hadron interacts with material, leading to multi-particle production of more hadrons.
  - These in turn interact with further nuclei.
  - Nuclear breakup and spallation neutrons.
  - Multiplication continues down to the pion production threshold.
    - $E \sim 2m_\pi = 0.28\ \mathrm{GeV}/c^2$.
  - Neutral pions result in an electromagnetic component.
    - immediate decay: $\pi^0 \rightarrow \gamma\gamma$, also $\eta \rightarrow \gamma\gamma$.

- Energy deposited by:
  - Electromagnetic component (i.e. as for EM showers).
  - Charged pions or protons.
  - Low energy neutrons.
  - Energy lost in breaking nuclei (nuclear binding energy).

Hadronic shower development

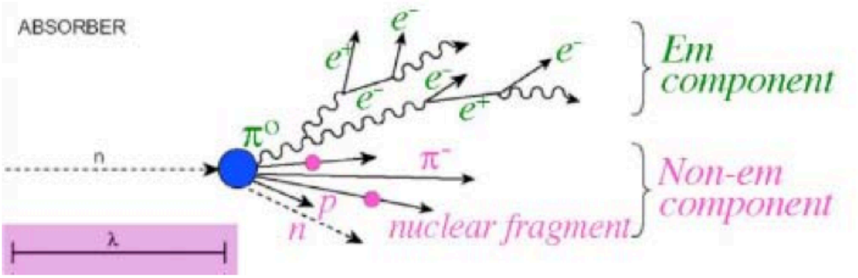
- Simple model of interaction on a disk of radius R:
  - $\sigma_{int} = \pi R^2 \propto A^{2/3}$
  - Compare to $\sigma_{inel} \approx \sigma_0 A^{0.7}$, $\sigma_0 = 35$ mb.
- **Nuclear interaction length**: mean free path before inelastic interaction:

$$\boxed{\lambda_{\text{int}} \approx \frac{A}{N_A \sigma_{\text{int}}} \approx 35 A^{1/3} g \cdot cm^{-2}}$$

- Mean transverse momentum resulting from interaction:
  - $\langle p_T \rangle \sim 300$MeV.
  - This is about the same magnitude as the energy lost traversing 1λ for typical materials.

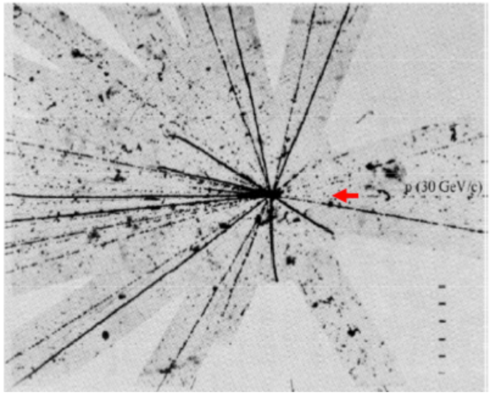
Hadronic cascade

- As compared to EM showers, hadron showers are:
  - Broader and more penetrating.
  - Subject to larger fluctuations – more erratic and varied.



Electrons, photons
$\pi^0 \rightarrow 2\gamma$

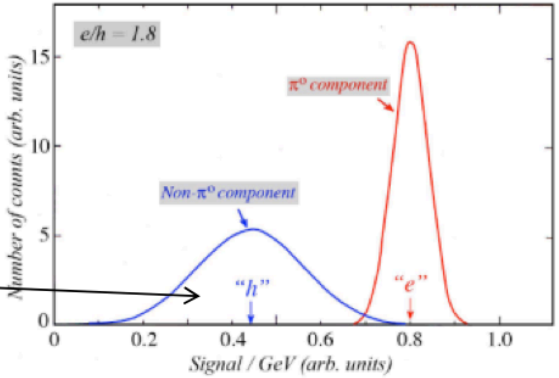
Charged hadrons	(20%)
Nuclear fragments , p	(25%)
Neutrons, soft γ's	(15%)
Breakup of nuclei	(40%)



Either not detected or often to slow to be within detector time window

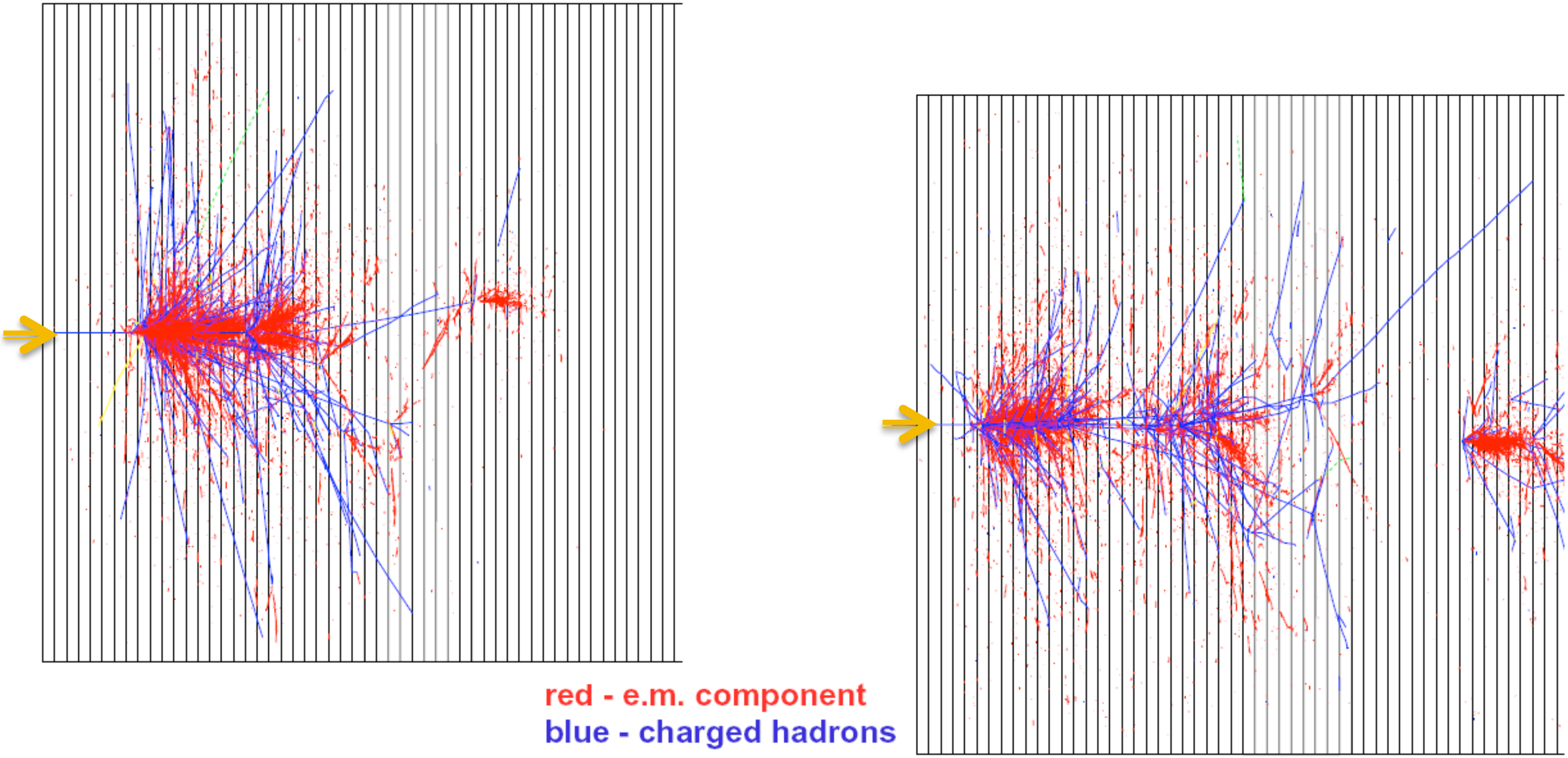
= **Invisible energy**

e/h > 1



Hadron showers

- Individual hadron showers are quite dissimilar



red - e.m. component
blue - charged hadrons

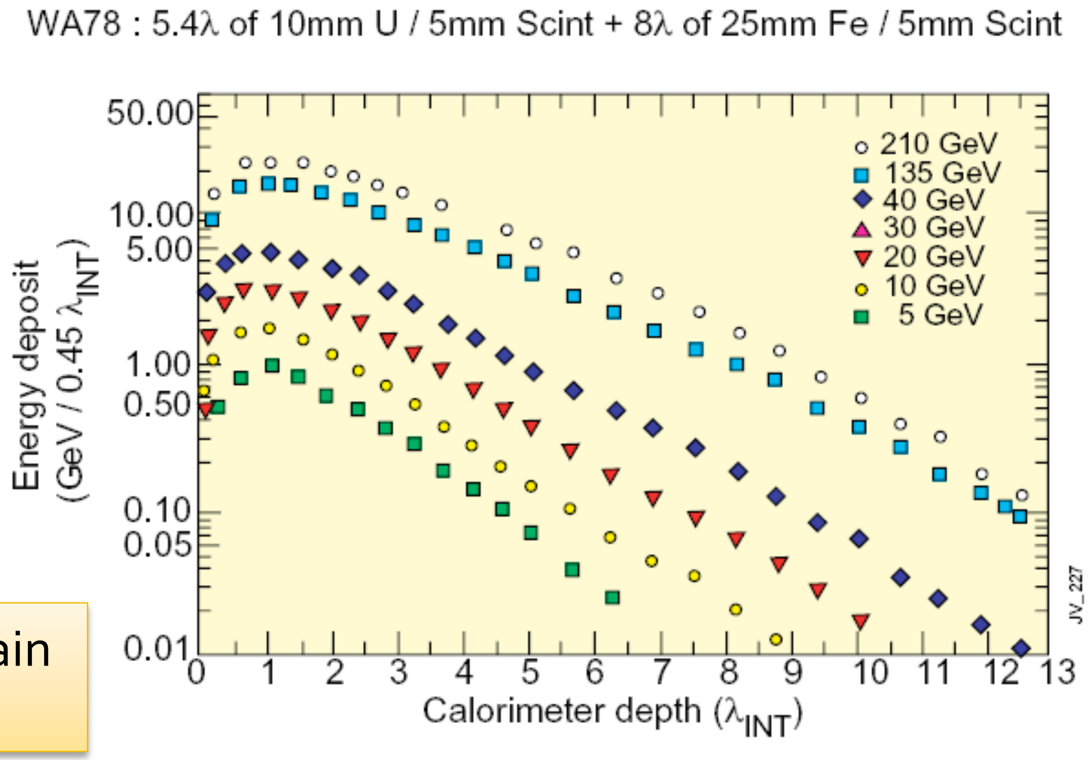
Table of physical properties

	Z	ρ ($g.cm^{-3}$)	E_c (MeV)	X_0 (cm)	λ_{int} (cm)
Air				30 420	~70 000
Water				36	84
$PbWO_4$		8.28		0.89	22.4
C	6	2.3	103	18.8	38.1
Al	13	2.7	47	8.9	39.4
L Ar	18	1.4		14.0	84.0
Fe	26	7.9	24	1.76	16.8
Cu	29	9.0	20	1.43	15.1
W	74	19.3	8.1	0.35	9.6
Pb	82	11.3	6.9	0.56	17.1
U	92	19.0	6.2	0.32	10.5

PDG booklet a good source for more/similar numbers

Hadron shower longitudinal profiles

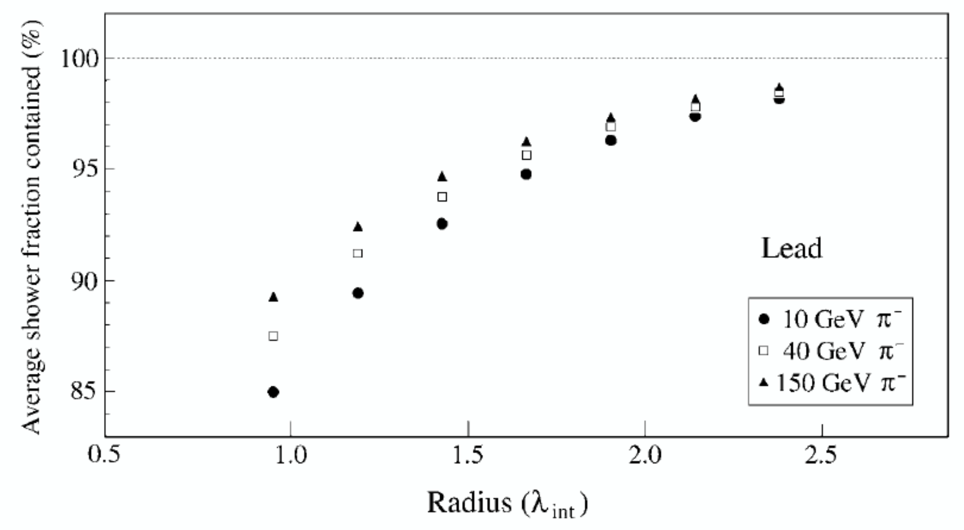
- Initial peak from π^os produced in the first interaction.
- Gradual falloff characterized by the nuclear interaction length, λ_{int}. ➔

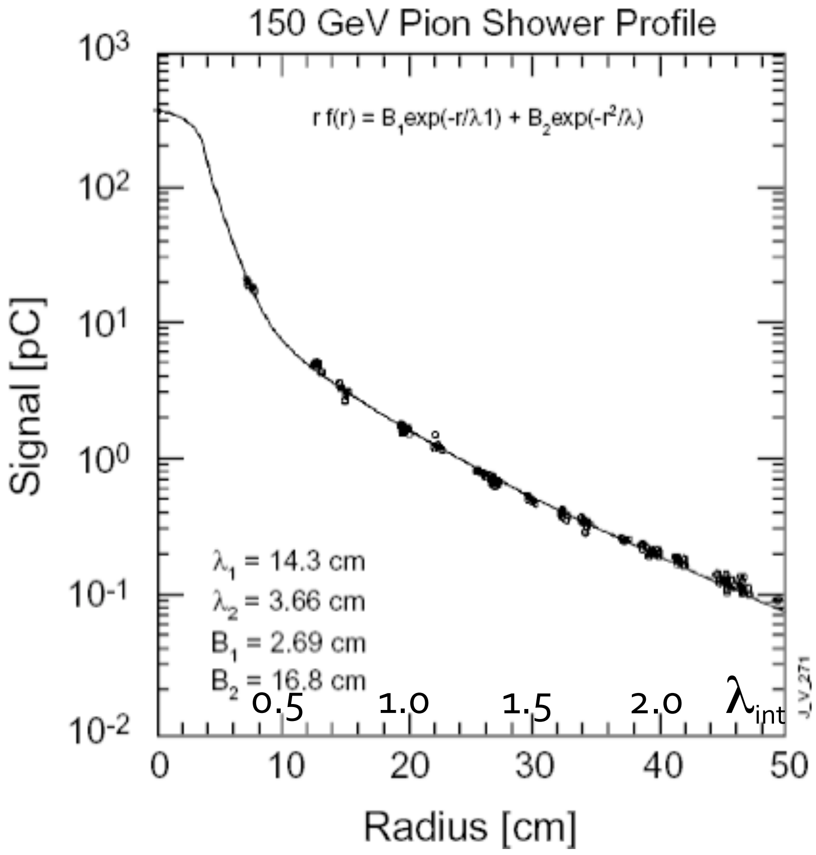


As with EM showers: depth to contain a shower increases with log(E).

Hadron shower transverse profiles

- Mean transverse momentum from interactions, $\langle p_T \rangle \sim 300$ MeV, is about the same magnitude as the energy lost traversing 1 λ for many materials.
- Radial extent of the cascade is well characterized by λ. ➔
- The π^0 component of the cascade results in an electromagnetic core. ➔





← Better lateral containment with increasing energy.

Energy resolution

Mass resolution ~ **$\sqrt{2}$ × energy resolution** $\oplus$ opening angle resolution

Energy resolution

- Usual parameterization for calorimeters:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2 \quad \text{or, more simply} \quad \frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- **a: Stochastic (or "sampling") term**
  - Accounts for statistical fluctuation of the number of primary signal generating happenings.
- **b: Noise term**
  - Electronics noise (i.e. its energy equivalent).
  - Pileup (other energy entering the measurement area).
- **c: Constant term**
  - Non-uniformity of signal generation or collection.
  - Intercalibration errors.
  - Other fluctuations directly proportional to energy; fluctuation in the EM component in hadronic showers.

Stochastic processes

- Even in homogeneous calorimeters where the calorimeter consists entirely of active material, the energy is "sampled".
  - The measurement counts the occurrence of a process.
  - So there is an error proportional to $\sqrt{N}$ (where N is the number of occurrences).

- Example:
  - In a lead glass calorimeter the signal detected is Cerenkov radiation.
  - Cerenkov radiation produced by $e^{\pm}$ with $\beta > 1/n$, i.e $E > 0.7$ MeV.
  - So, at most, $1000/0.7 \approx 1400$ independent particles/GeV produce light.
    - Fluctuation = $\sqrt{1400}/1400 \approx 3\%$.
  - Signal in photodetector is only ~1000 photoelectrons/GeV
    - Further fluctuation (photostatistics) $\sqrt{1000}/1000 \approx 3\%$.
  - Thus, overall resolution from lead glass calorimeter: $\sigma/E \approx 5\%/\sqrt{E}$.

Stochastic term: homogeneous calorimeters

- Smallest stochastic term obtained by counting the most numerous processes
  - Example: collecting electrons liberated by ionization in Ge crystals (at 77°K)

$$n = \frac{E}{W}$$

where W is the mean energy to liberate an electron.

$$\frac{\sigma}{\mathrm{E}} = \frac{\sqrt{n}}{n} = \sqrt{\frac{W}{E}}$$

But the total energy does not fluctuate, and since a large fraction goes into the liberation of electrons the resolution is improved by a factor, F (the Fano factor).

$$\frac{\sigma}{\mathrm{E}} = \sqrt{\frac{FW}{E}}$$

In Ge measure σ = 178 eV for E_γ = 100 keV.
Without Fano factor, expect W = 2.96 eV $\Rightarrow \sigma \approx$ 540 eV.

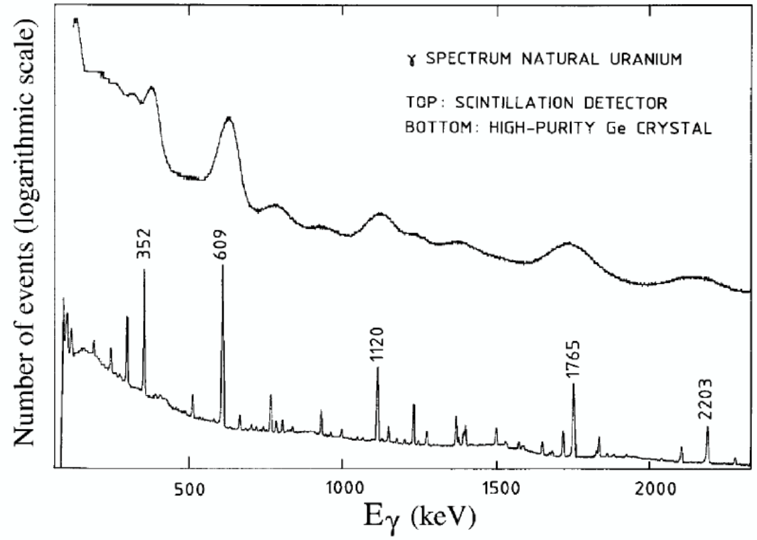


FIG. 1.1. Nuclear γ-ray spectrum of decaying uranium nuclei, measured with a bismuth germaniumoxide scintillation counter (*upper curve*) and with a high-purity germanium crystal (*lower curve*). Courtesy of G. Roubaud, CERN.

Comparison of stochastic performance

Scintillating crystals

$$E_s \cong \beta E_{gap} \sim eV$$

$$\approx 10^2 \div 10^4 \, \gamma / MeV$$

$$\sigma / E \sim (1 \div 3)\% / \sqrt{E(GeV)}$$

In practice dictated by light collection and fluctuations (ENF) at photocathode of photodetector

Cherenkov radiators

$$\beta > \frac{1}{n} \rightarrow E_s \sim 0.7 MeV$$

$$\approx 10 \div 30 \, \gamma / MeV$$

$$\sigma / E \sim (5 \div 10)\% / \sqrt{E(GeV)}$$

Homogeneous LKr calorimeter NA48/62

Ionisation signal

$$\sigma / E \sim 5\% / \sqrt{E(GeV)}$$

ATLAs Pb-LAr sampling

$$t = d/X_0 \approx 0.4$$

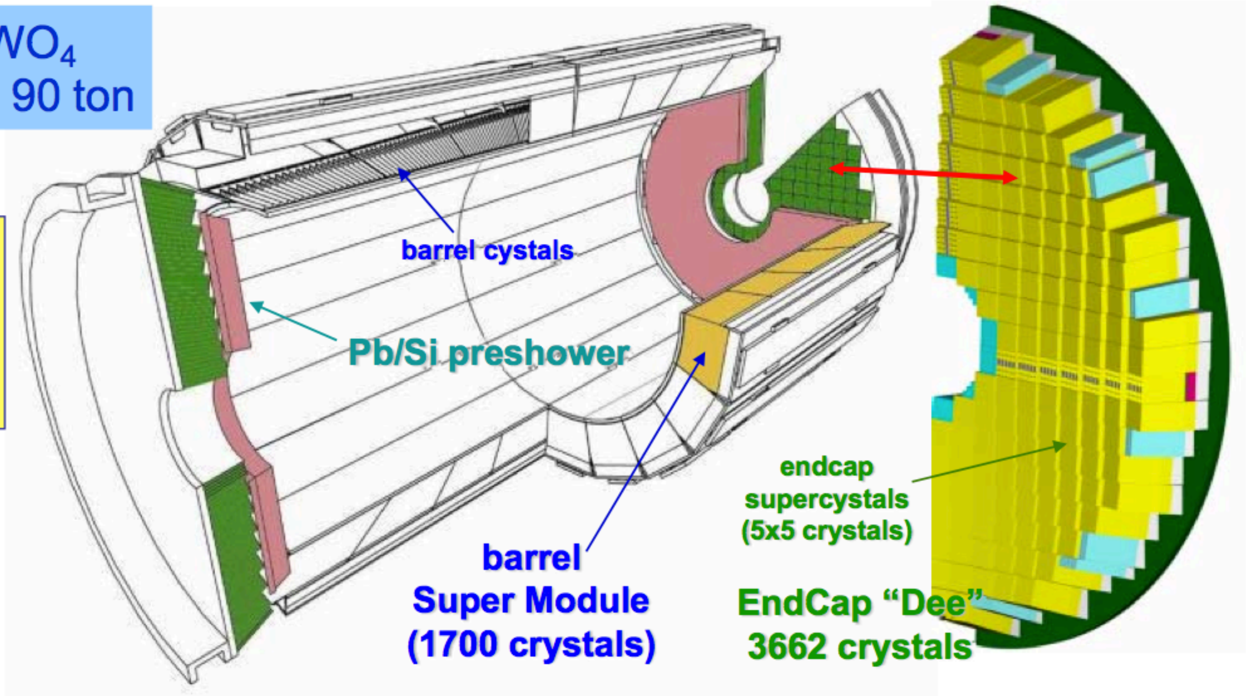
$$\sigma / E \sim 10\% / \sqrt{E(GeV)}$$

CMS ECAL

Precision electromagnetic calorimetry: 75848 PWO crystals

PWO: $PbWO_4$
about 10 m^3, 90 ton

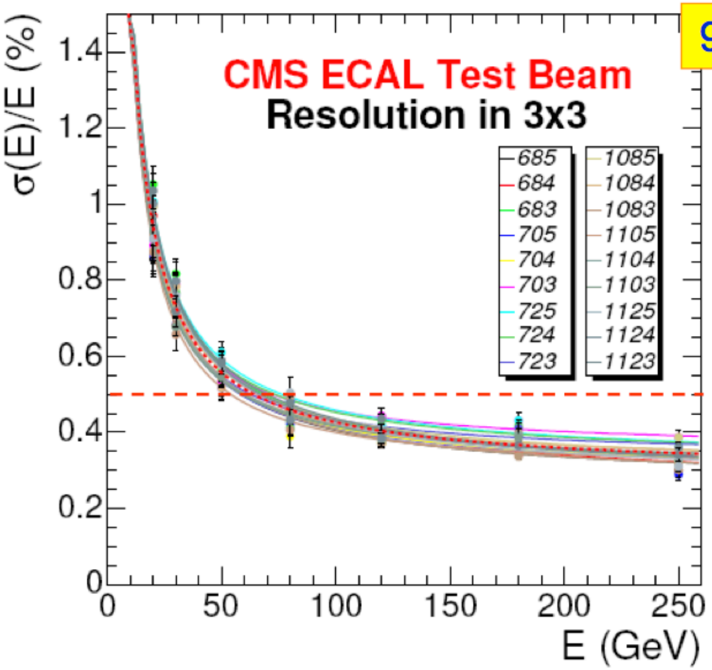
Previous Crystal calorimeters: max $1m^3$



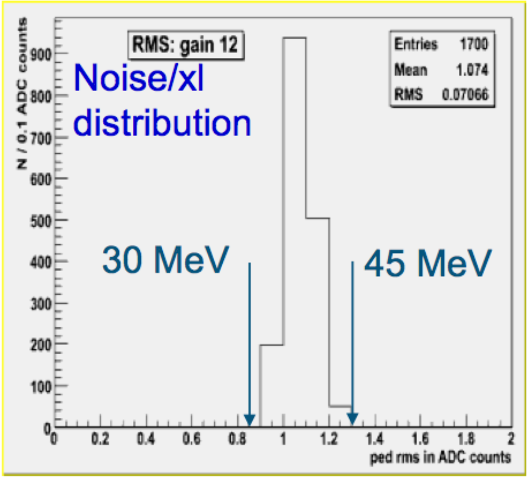
Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2x2x23cm^3$)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3x3x22cm^3$)

CMS ECAL test beam performance



9 Super Modules 1700 xl on test beam

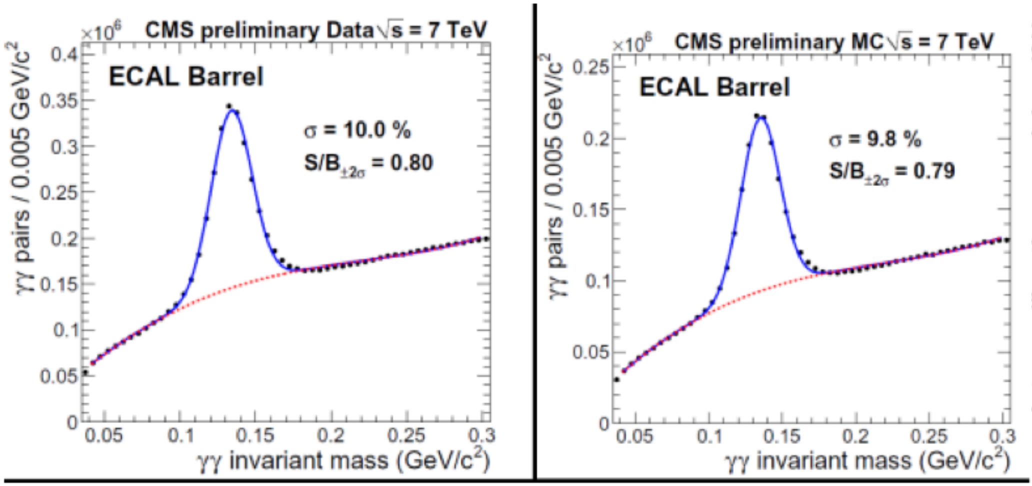


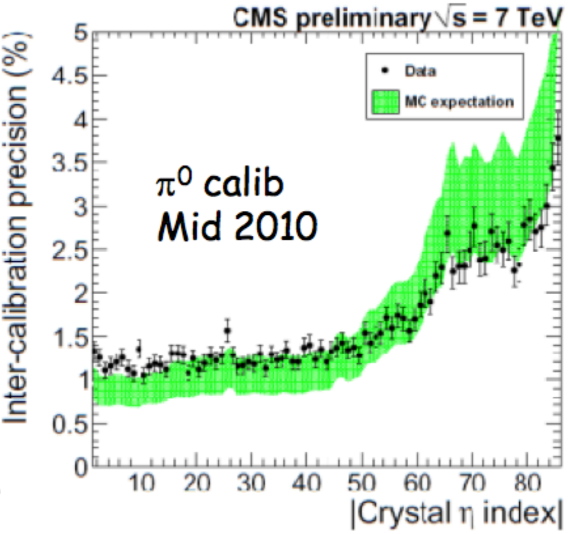
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

Local resolution

Preserving resolution

- **Intercalibration**
  requires several steps before, during and after data taking
  - test beam precalibration
  - continuous monitoring during data taking (short term changes)
  - Intercalibration by physics reactions during the experiment (π^0, η) with specialized data-stream or ϕ symmetry

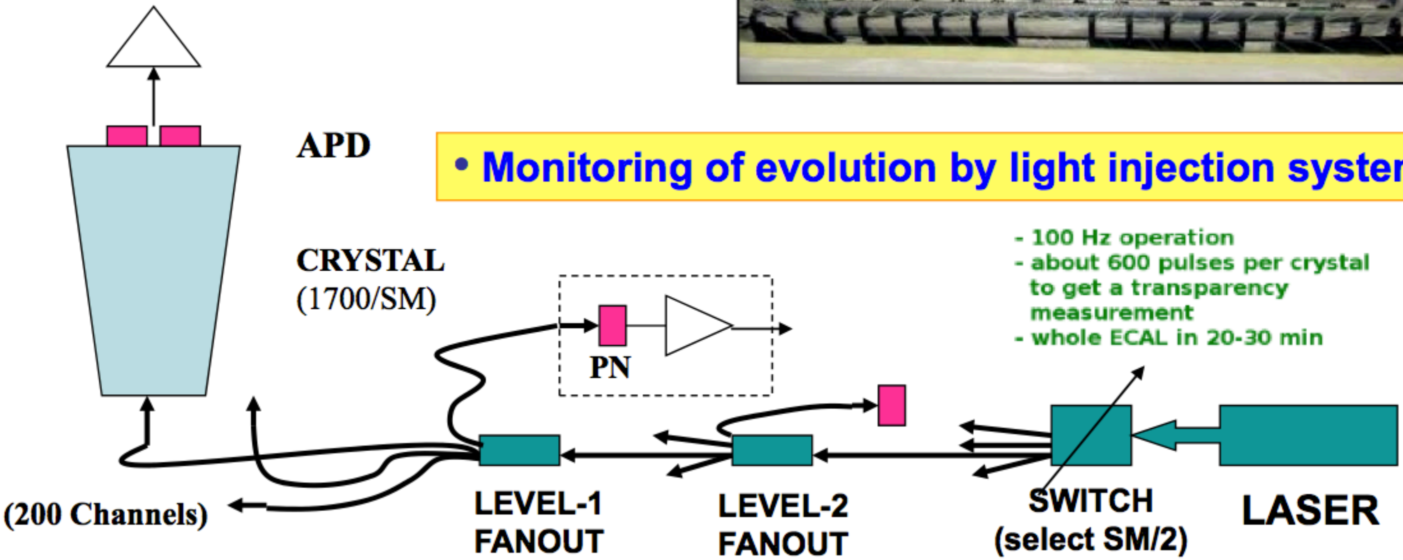




Transparency monitoring

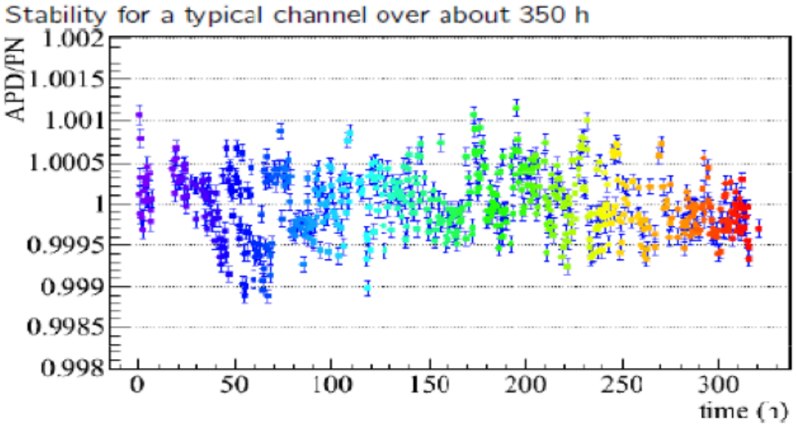
The Solution:
Damage and recovery during LHC cycles tracked with a laser monitoring system
2 wavelengths are used:
440 nm and 796 nm
Light is injected into each crystal
Normalisation given by PN diodes (0.1%)

- **Monitoring of evolution by light injection system**



- 100 Hz operation
- about 600 pulses per crystal to get a transparency measurement
- whole ECAL in 20-30 min

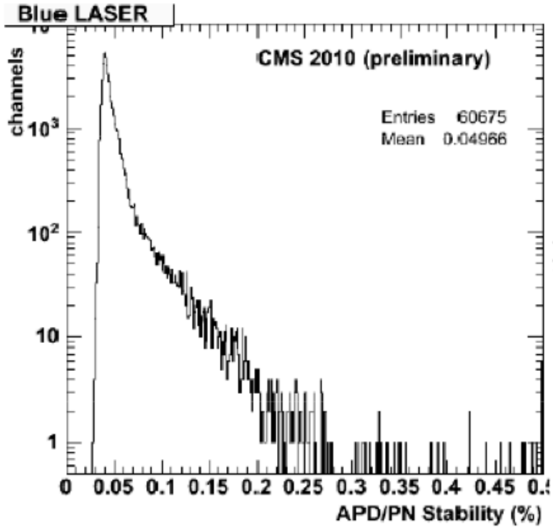
Transparency monitoring

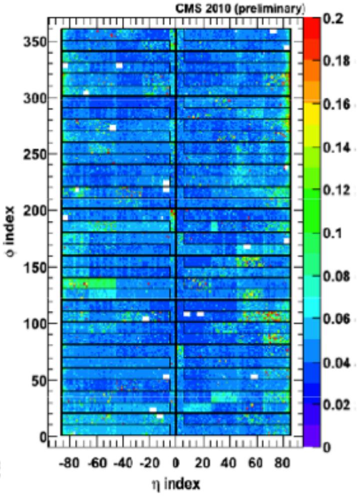


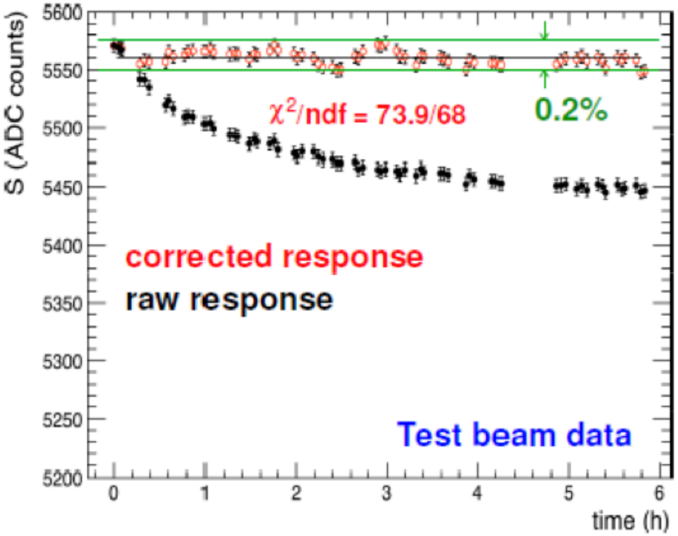
Measure a loss of transparency:
S (particle signal) and R(laser signal)

$$S_{cor} = S\left(\frac{R}{R_0}\right)^{\alpha}$$

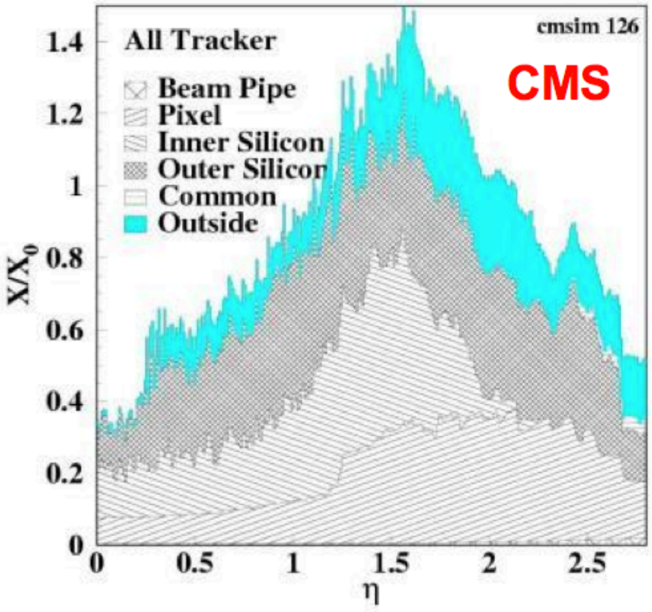
NB: α is ~ the same for all crystals!

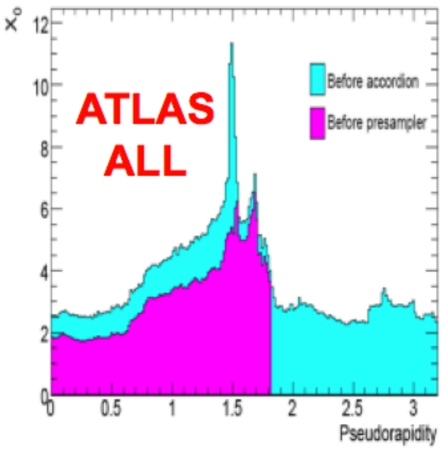


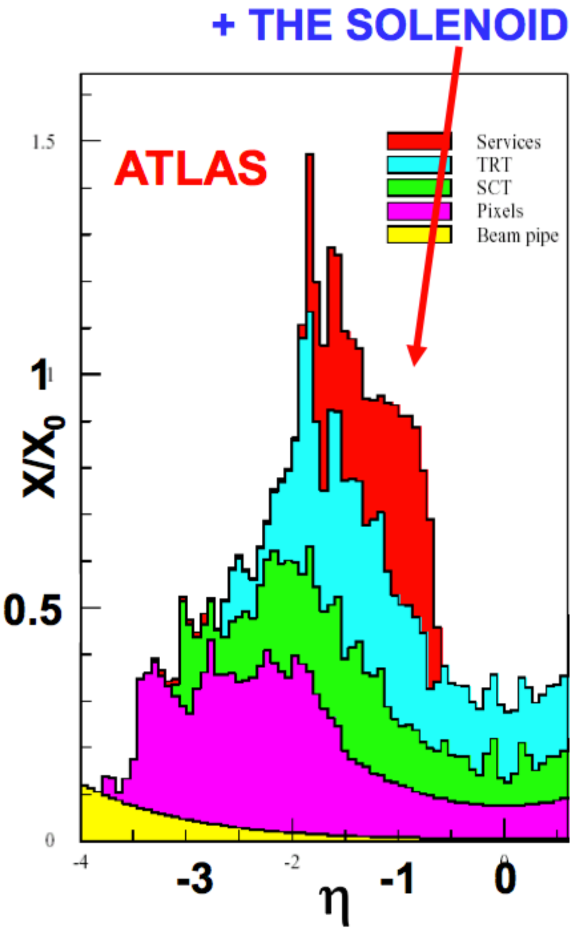


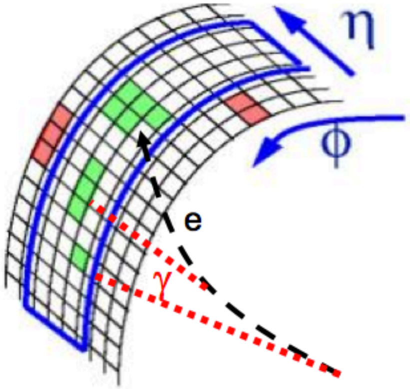


Material in front









Tracker material :

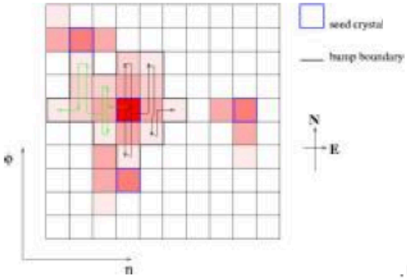
- electrons loose energy via bremsstrahlung
- photons convert

4T (2T) solenoidal B field :

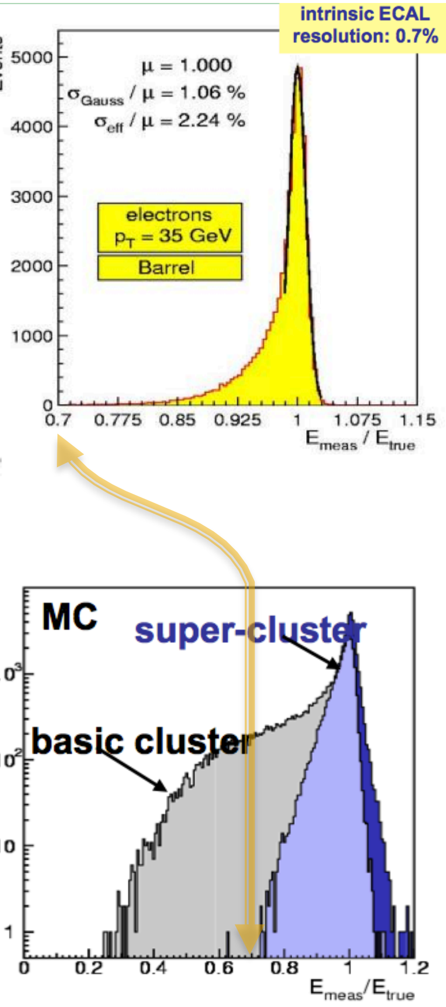
Electrons bend ⇒ radiated energy spread in φ

Material in front

- You can:
  - Widen windows to collect all energy.
  - Or dynamically cluster energy to gather all the bits and pieces. ➔
  - Or identify brems following track kinks (Particle Flow in CMS).
  - Or tag high quality (low brem) electrons, using track curvature info or E/p.

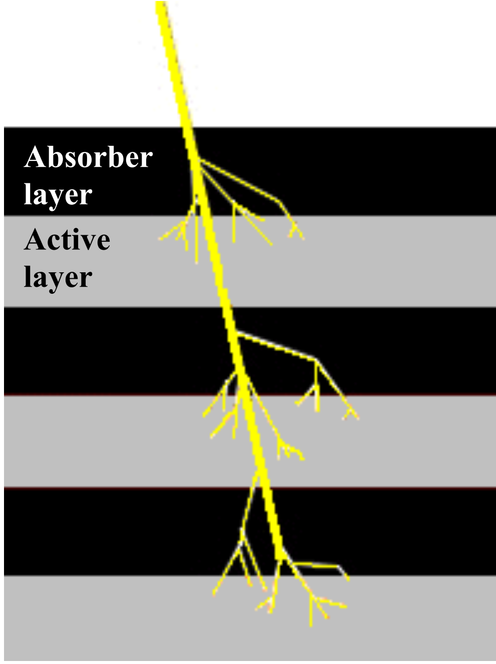


Dynamic super-cluster



CMS example

Sampling calorimeters



- The energy may be sampled by active layers interposed between dense high Z absorber materials. ➔
  - e.g. plastic scintillator layers between layers of Pb, etc.
- All LHC hadronic calorimeters.

- Stochastic term depends on:
  - the granularity of the sampling, and
  - the fraction of energy deposited in the active material.

  - If energy loss in the active layers is small compared to loss in absorber, the number of charged particles crossing the active layer is $n \approx E/\Delta E_{abs}$, and $\Delta E_{abs} = t_{abs}$ (dE/dx)
  - Thus, $\sigma/E = \sqrt{n}/n \approx t_{abs}/\sqrt{E}$
  - Using the fraction of energy sampled, f_{samp}, as a parameter a generally valid formula for the stochastic contribution is:

$$\frac{\sigma}{E} = \frac{5\%}{\sqrt{E}}(1 - f_{samp})\Delta E_{cell}^{0.5(1-f_{samp})}$$

Where ΔE_{cell} is the energy deposited in a unit sample (absorber + active layer)

Hadronic energy resolution

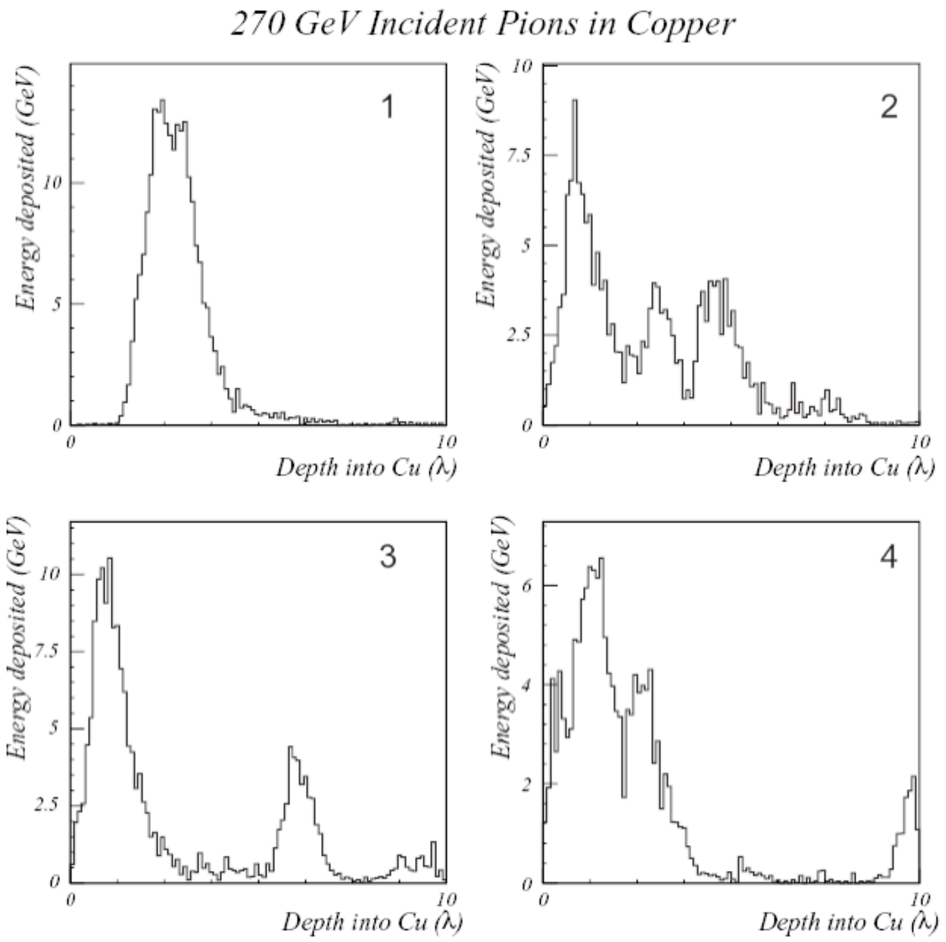
- Hadronic calorimeters are (almost) always sampling calorimeters.

- Fluctuations in the visible energy have more sources:
  - Sampling fluctuations (same as for sampling EM calorimeters).
  - Fluctuations between the electromagnetic and hadronic components.
    - and also between the different elements of the hadronic component.

- Size of EM component, F_0, determined mainly by the first interaction.

- Considerable shower to shower fluctuations. ➔

Four same-energy pion showers:



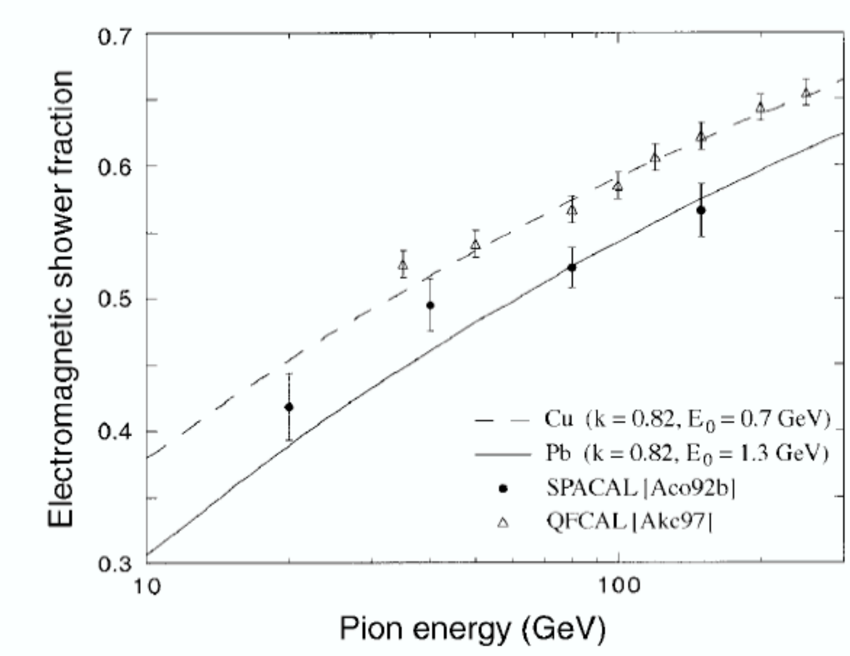
Hadronic showers: EM component

- On average 1/3 of the mesons produced at each interaction will be π^0s.
  (π^+, π^0, and π^- equally produced)
  - And then some more in the next step, etc.

- Assume that a fraction of EM energy (f_o) is produced at each step:
  - After 1st step: f_o.
  - After 2nd step: $f_o + f_o(1-f_o)$, etc.

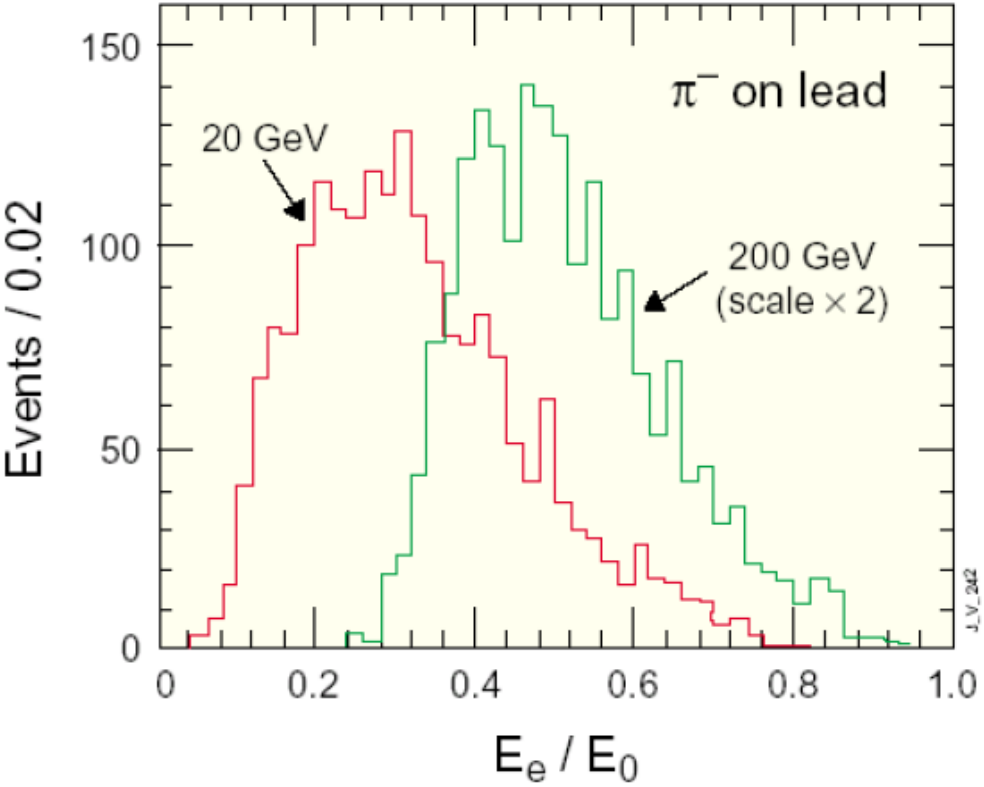
- Call F_o the fraction of EM energy in the shower:
  - $F_o = f_o\Sigma(1-f_o)^{n-1}$, after n generations.
  - $F_o = 1 - (1-f_o)^n$.

- So:
  - At low energy $F_o \approx f_o$.
  - At very high energy $F_o \rightarrow 1$. ↗



Electromagnetic fraction

- Large event to event fluctuations in F_o.
- Average value of F_o increases with energy. ➜



Hadronic energy resolution

- In general, electromagnetic and hadronic responses of the calorimeter are different.
  - In a calorimeter system the electromagnetic and the hadronic sections may have different values of e/h.

- If e/h = 1 the calorimeter is said to be compensating.

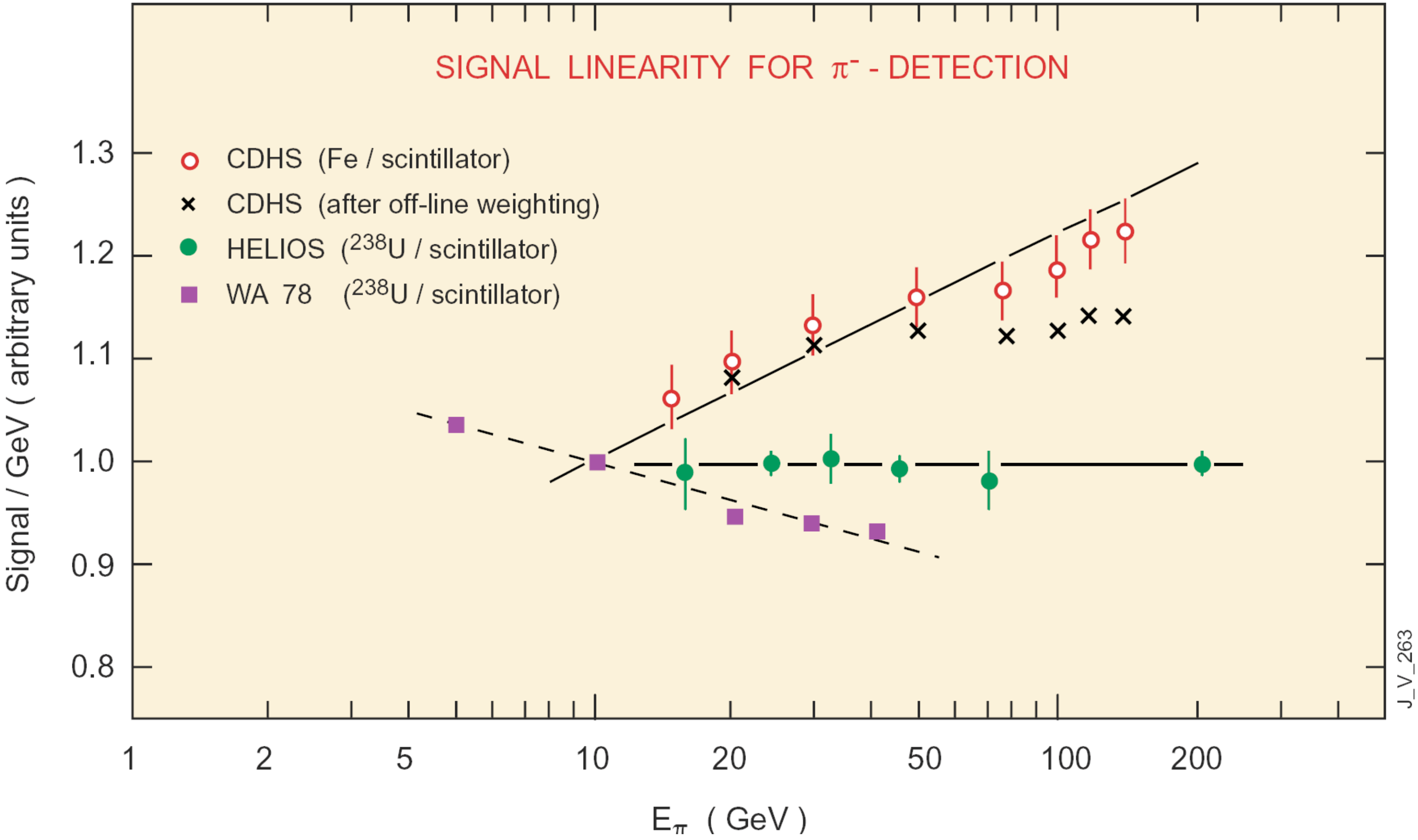
- **If e/h is far from 1, this has serious consequences for performance**:
  - Energy resolution is non-Gaussian.
  - $E_e/E_\pi \neq 1$: the response to hadrons differs from the response to electrons and depends on energy.
    - Non-linear response to hadrons.
  - Event to event fluctuations of F_0 contribute to the energy resolution.

$$E_e = e$$

$$E_\pi = eF_0 + h(1 - F_0)$$

$$\Rightarrow \frac{E_e}{E_\pi} = \frac{\frac{e}{h}}{\left[\left(\frac{e}{h}\right)F_0 + (1 - F_0)\right]}$$

A consequence of e/h ≠ 1



Ways around e/h $\neq$ 1

- **Compensation**
  - Software: Identify EM hot spots and down-weight. Requires high 3D segmentation: H1, (ATLAS).
  - Hardware : Bring the response of hadrons and electrons to the same level (e/h = 1) so that fluctuations do not matter: ZEUS.
- **Dual (or triple) readout**
  - Evaluate the 2 components separately (+ possibly slow neutrons): ILC.
- **Particle flow**
  - Use the calorimeter **only** for the neutral hadron component: (CMS), ILC.

Lack of compensation

- e/h can be inferred from the energy dependent e/π ratio using a formula for F_o

$$F_0 = 1 - \left(\frac{E}{0.76} \right)^{-0.13}$$ D. Groom (E in GeV)

$$F_0 = 0.11 \cdot \ln E$$ R. Wigmans

- Example of energy dissipation in a Pb absorber:
  - **42% invisible energy** (nuclear breakup).
  - 43% charged particles.
  - 12% neutrons with KE ~ 1 MeV.
  - 3% photons with E ~ 1 MeV.
- The large fraction of invisible energy means that hadronic calorimeters tend to be "undercompensating" (e/h>1).

Achieving compensation

- Boost non-EM response by using depleted uranium (^{238}U)
  - Extra energy contribution to the hadronic component from fission of nuclei.
- Suppress the EM response
  - e.g. thin layers of plastic scintillator in a calorimeter with high Z absorber.
- Boost the response to low energy neutrons
  - e.g. active medium containing hydrogen.

Jet energy resolution

- In HEP experiments hadron calorimeters are used primarily for reconstruction of **jets**.
  - Generally: full calorimeter systems (EM + hadronic calorimeter).
- For example: jet energy estimated by summing energy contained in a cone of radius $\Delta R=\sqrt{(\Delta\eta^2+\Delta\varphi^2)}$.
- Also: missing transverse energy.

- Jet energy resolution limited by effects from:
  - Details of algorithm used to define the jet (the parameters controlling the algorithm in the example above).
  - Fluctuations in the content of the jet (fluctuation in jet fragmentation).
  - Fluctuations of the underlying event (hadron colliders).
  - Fluctuations in pileup (hadron colliders at high luminosity).
  - Magnetic field (sweeps charged particles out of cone).

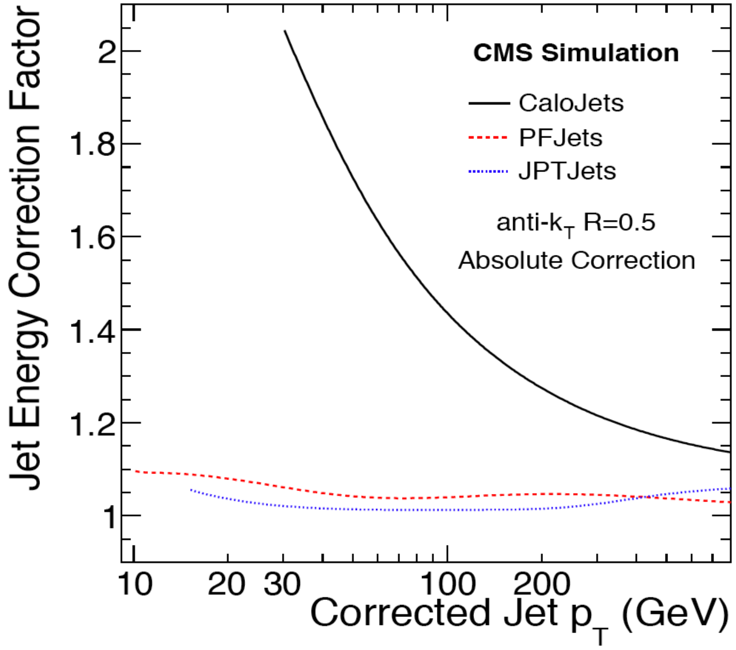
Energy flow

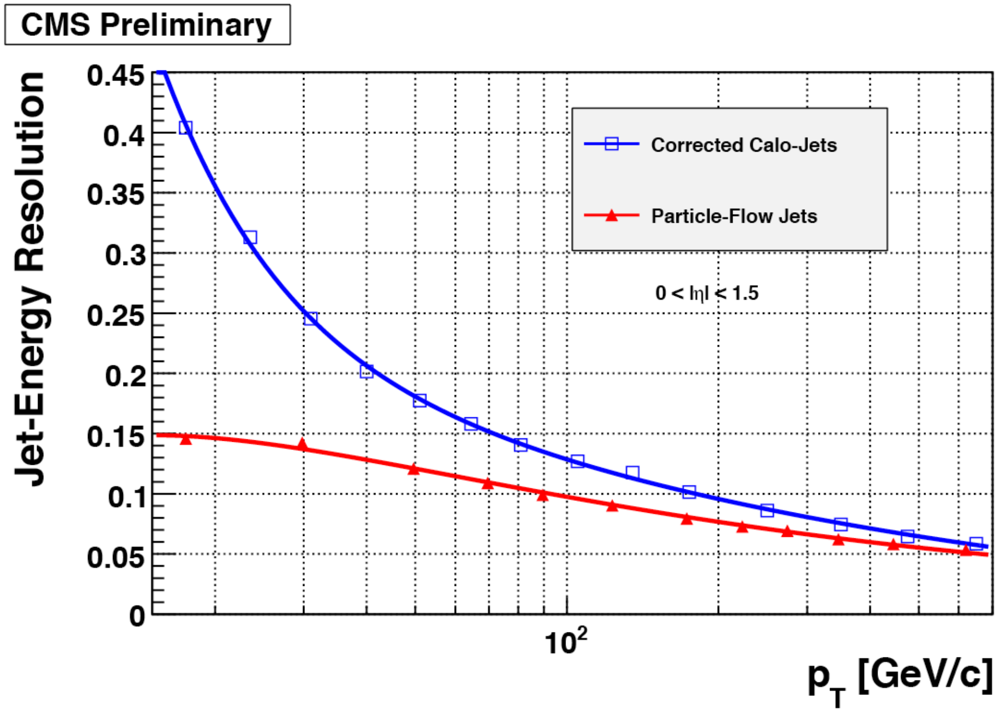
- Another approach to improving jet energy resolution and missing E_T resolution in general purpose detectors is to use the information from the tracker.
  - Low p_T charged hadrons are generally much better measured by tracking system than by the hadron calorimeter.
  - Approach called “energy flow” or “particle flow”.

- Need to sort out calorimetric energy deposited by charged hadrons, from that produced by photons/pizeros – also energy deposited by neutral hadrons.
  - Emphasis of calorimetry for particle flow is fine granular for pattern recognition and separation of individual particle showers.
  - Current R&D for highly granular calorimeters at future possible linear colliders reported at calorimetry conferences e.g. Calor 2010 http://bes3.ihep.ac.cn/conference/calor2010/ have particle flow in mind.

Example of particle flow in CMS

- Both the "jets plus tracks" and the more ambitious particle flow (which aims to give a complete event description in terms of particles) provide an improved jet energy resolution – particularly at lower jet E_T.
- Validated with data – for example in E_T^{miss} resolution for $W \rightarrow l\nu$ events.





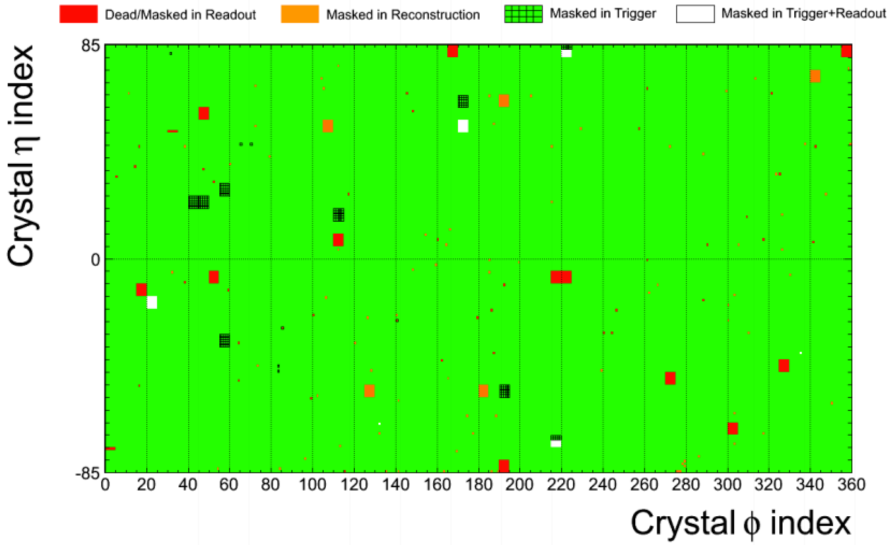
Missing transverse energy

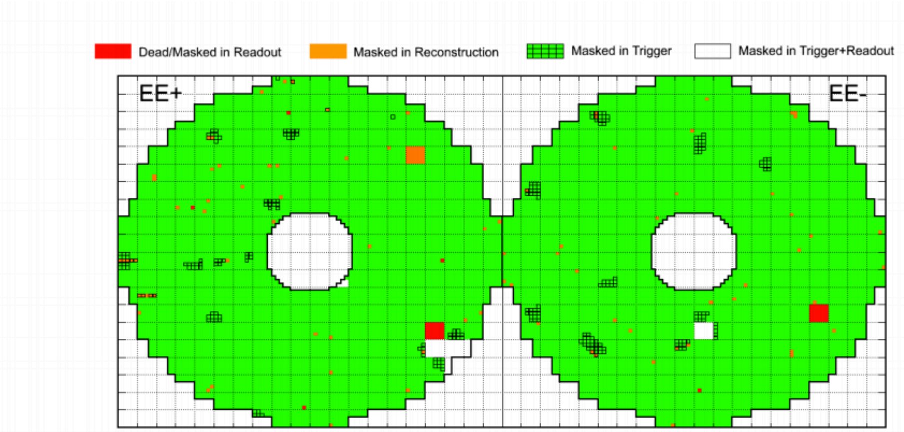
- Longitudinal momentum unknown.
  - Partons are “sampled” from PDFs.
- System must be balanced in the transverse plane.
  - $Q^2 >>$ parton k_T.

- Hermiticity allows to measure the transverse imbalance.

Missing energy

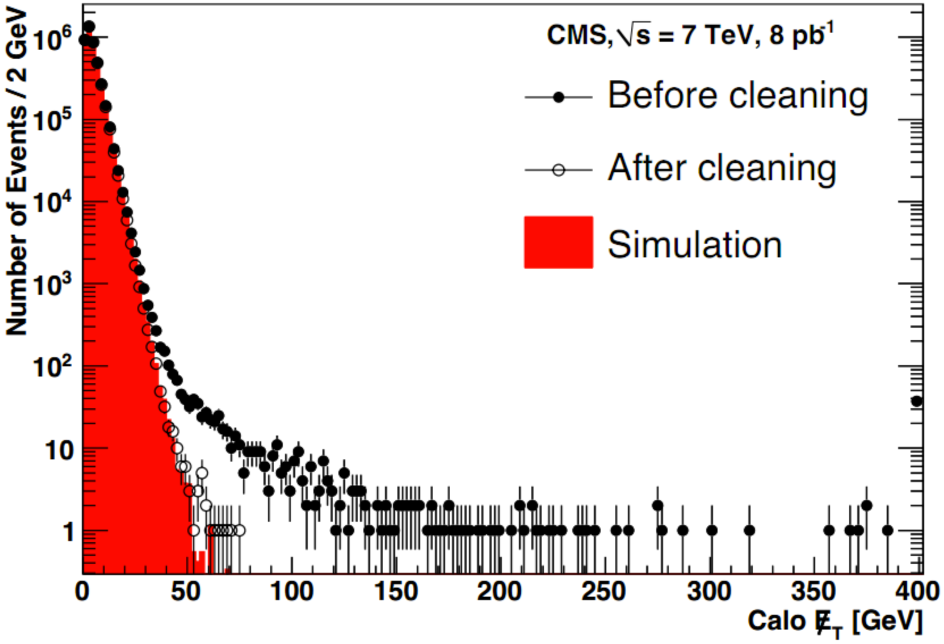
- Sensitive to holes.
  - CMS ECAL map. →





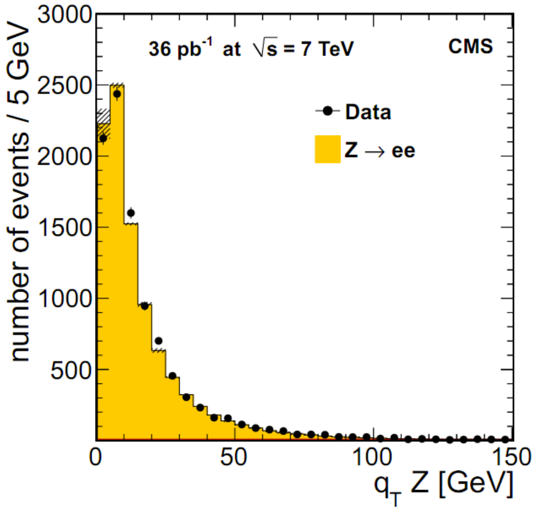
Missing energy

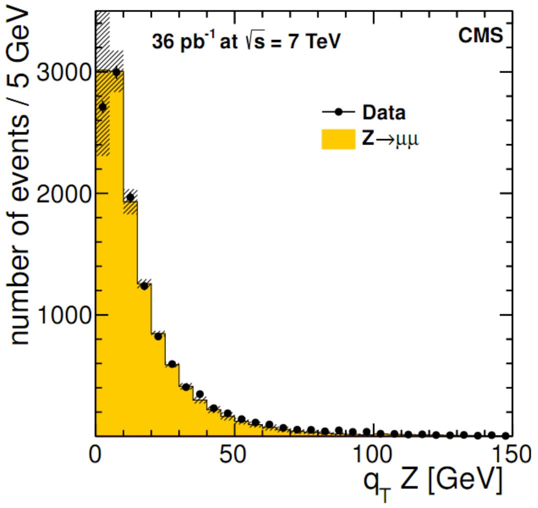
- Sensitive to noise.
  - Electronics regional events.
    - Not global, not local.
  - Direct ionization of photo-detectors.
    - "Spikes".
- Sensitive to beam backgrounds.
  - Beam-halo interactions.

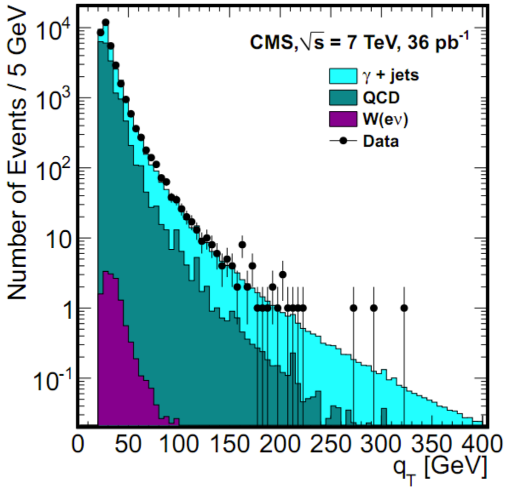


Missing transverse energy

- Check with events with no true missing energy:
  - Z production, photon+jets production.

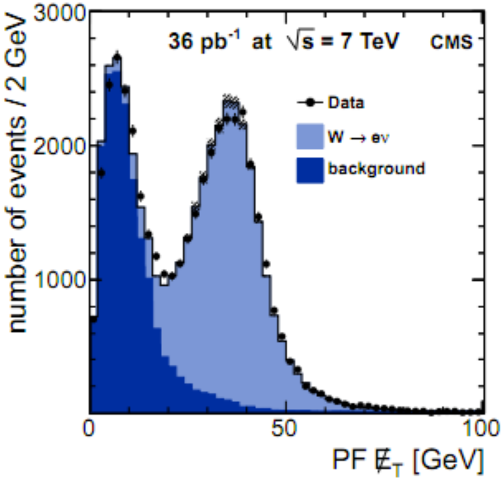


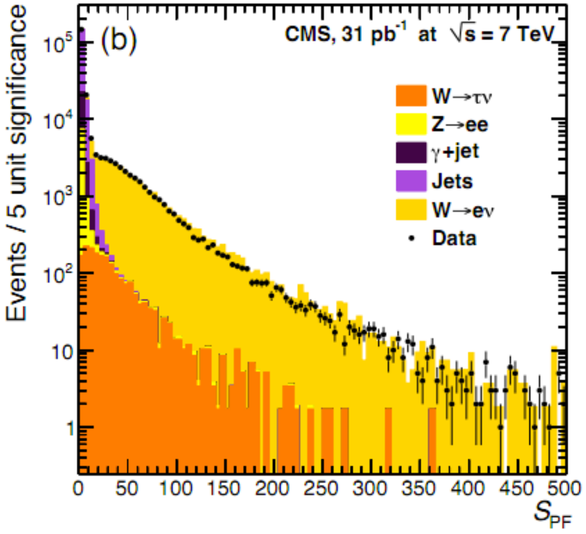


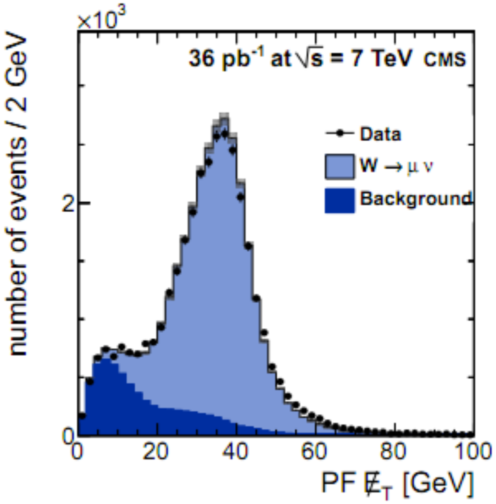


Missing transverse energy

- Events with real missing energy
  - W leptonic decays ➔
- Significance of MET (S_{PF})
  - Good discriminator of events with real MET. ➘

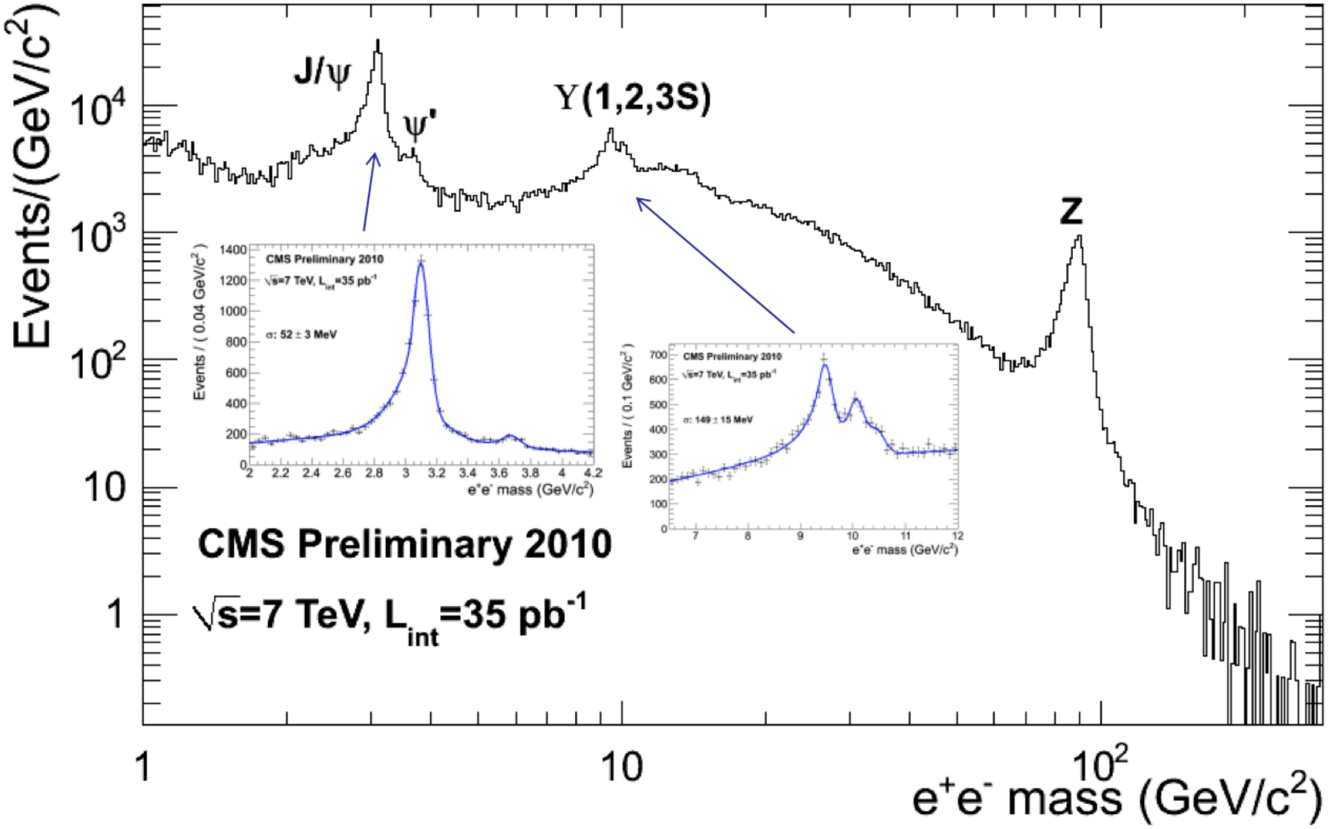






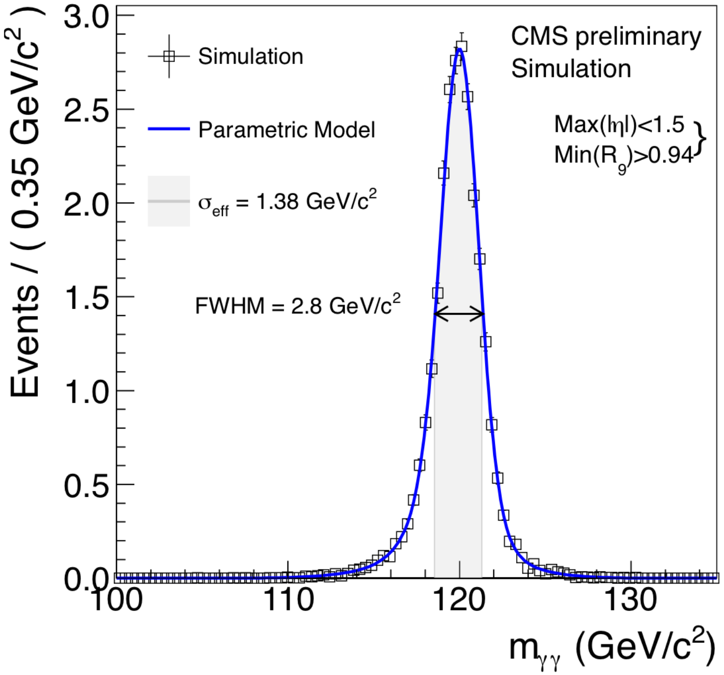
CMS ECAL performance

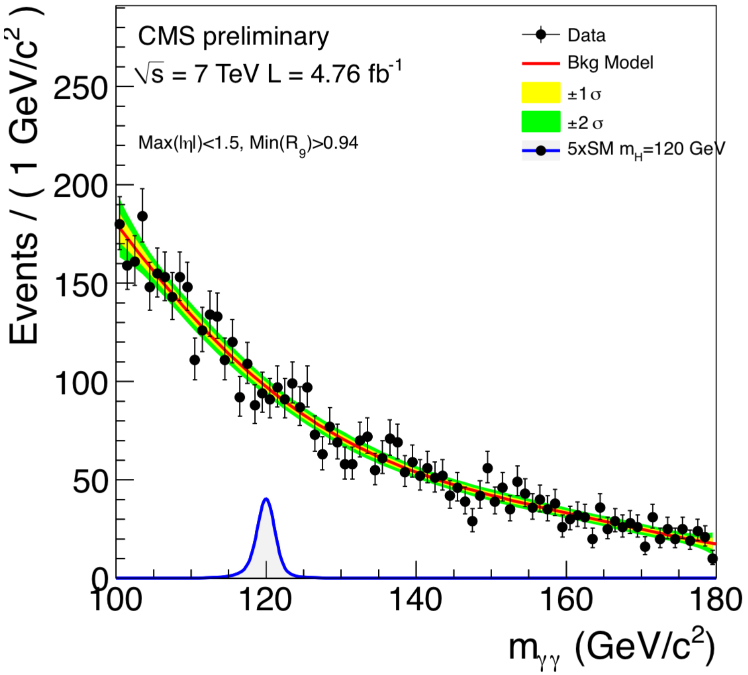
- Dielectrons from J/psi to Z



CMS ECAL performance

- SM Higgs to diphoton search.
  - Photon energy resolution crucial to mass peak resolution.
  - Best mass resolution: ~1% (with just 1 year of running).

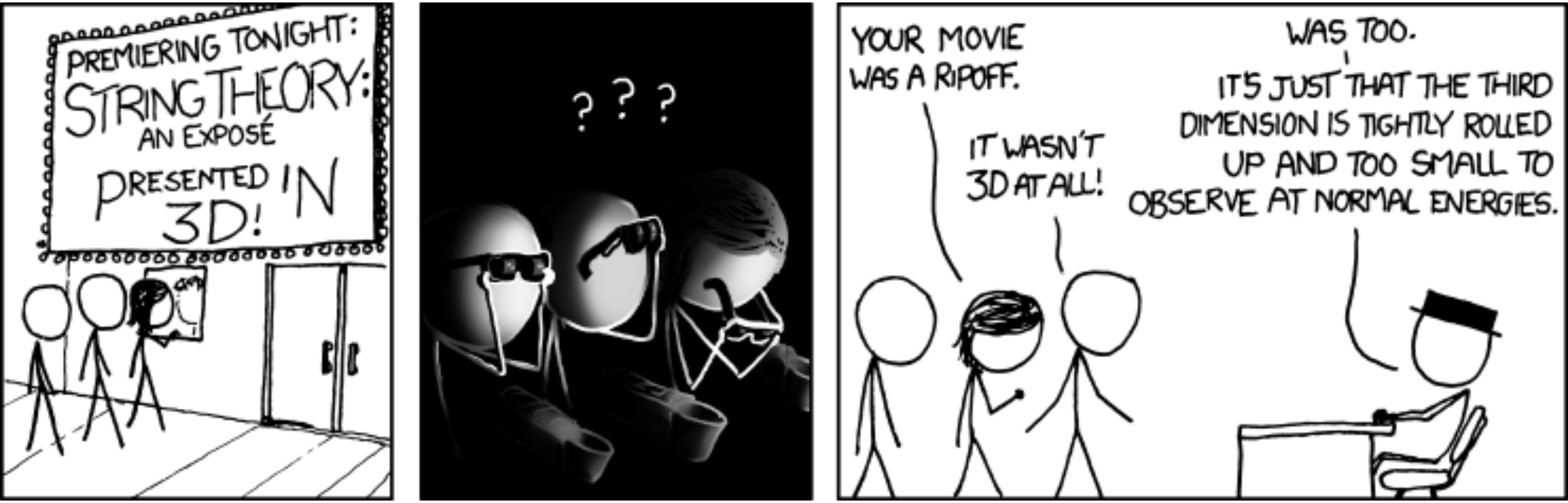




Intro and Calorimetry

- Particles have different interactions with matter.
  - Different detectors exploit those differences.
  - Eventually, it boils down to charged particle interactions, be it directly or through showers.
  - CMS has an excellent array of detectors.

- Calorimetry is quite involved.
  - Focus on energy reconstruction and resolution.
  - Electromagnetic and hadronic showers are very different.
  - CMS has a rather simple HCAL.
    - Performance compensated by excellent tracker, via Particle flow methods.


PREMIERING TONIGHT:
STRING THEORY:
AN EXPOSÉ
PRESENTED IN
3D!
? ? ?
YOUR MOVIE WAS A RIPOFF.
IT WASN'T 3D AT ALL!
WAS TOO.
IT'S JUST THAT THE THIRD DIMENSION IS TIGHTLY ROLLED UP AND TOO SMALL TO OBSERVE AT NORMAL ENERGIES.

Reading material

Intro references

- Text books:
  - W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd edition, Springer, 1994
  - C. Grupen, Particle Detectors, Cambridge University Press, 1996
  - K. Kleinknecht, Detectors for Particle Radiation, 2nd edition, Cambridge University Press, 1998
  - R.S. Gilmore, Single particle detection and measurement, Taylor&Francis, 1992
- Other sources:
  - Particle Data Book (Phys. Rev. D, Vol. 54, 1996)
    https://pdg.web.cern.ch/pdg/2010/reviews/rpp2010-rev-passage-particles-matter.pdf
  - R. Bock, A. Vasilescu, Particle Data Briefbook
    http://www.cern.ch/Physics/ParticleDetector/BriefBook/

Calorimetry references

- [Cal1] T. S. Virdee, Lectures on Calorimetery at Nato Summer School, St Croix: http://cmsdoc.cern.ch/~virdee/stcroix.all.pdf
- [Cal2] Particle Data Group, Review of Particle Physics (the full text form, not the booklet)
- [Cal3] Richard Wigmans, "Calorimetry", Oxford, 2000