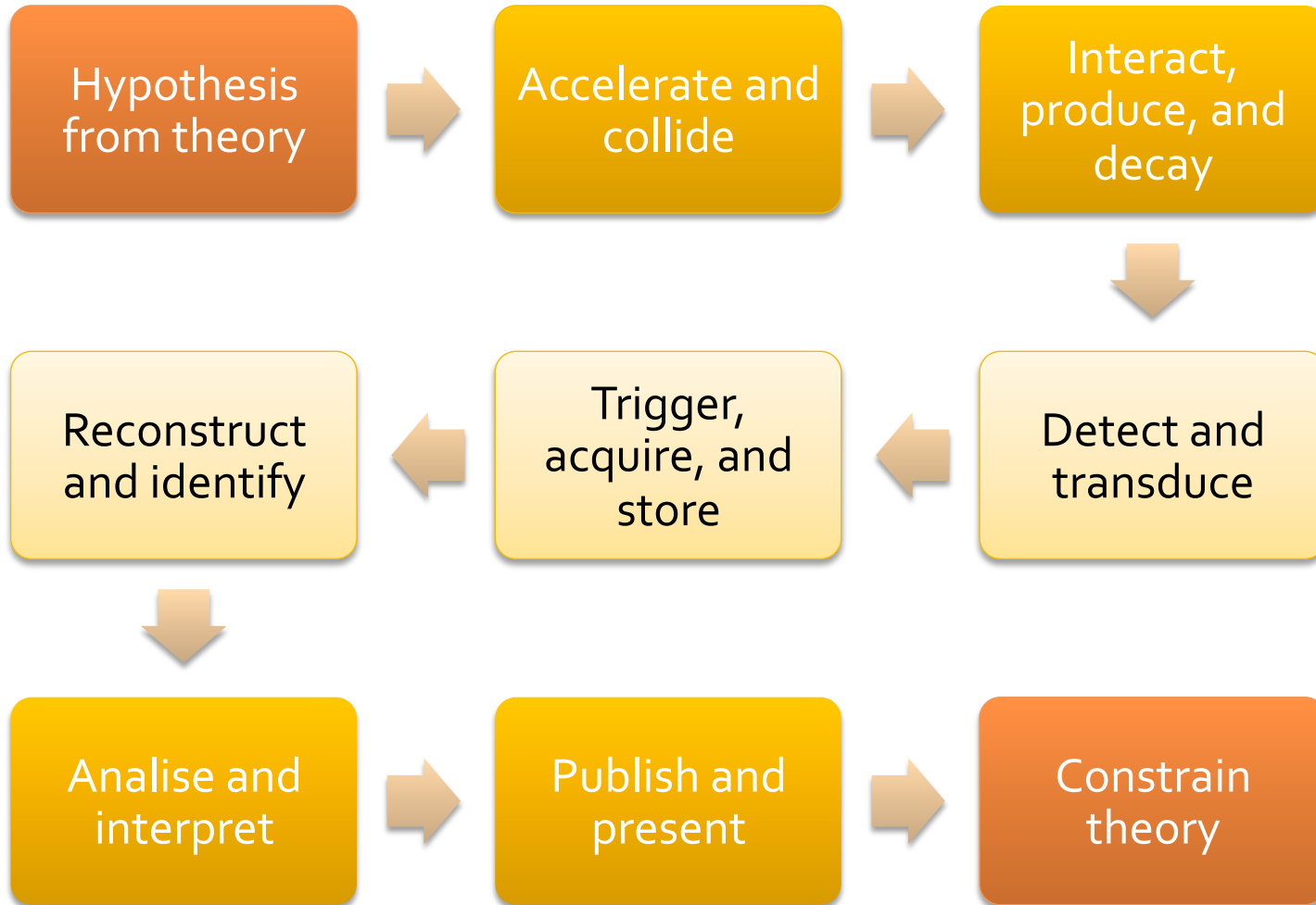


After the collisions, before the analysis.

Detectors, reconstruction, and trigger

You are here



You are here

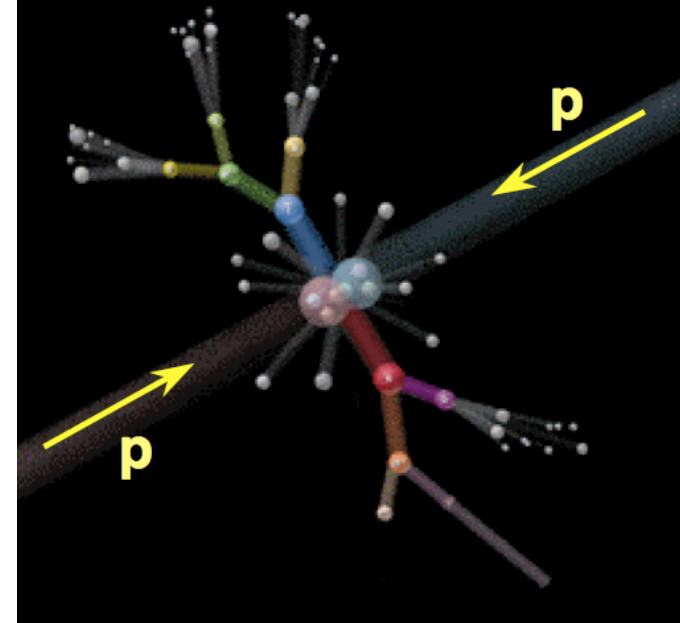


- Particles, interactions and detectors.
- Calorimetry and energy.
- Trackers and momentum.
- Trigger and acquisition.

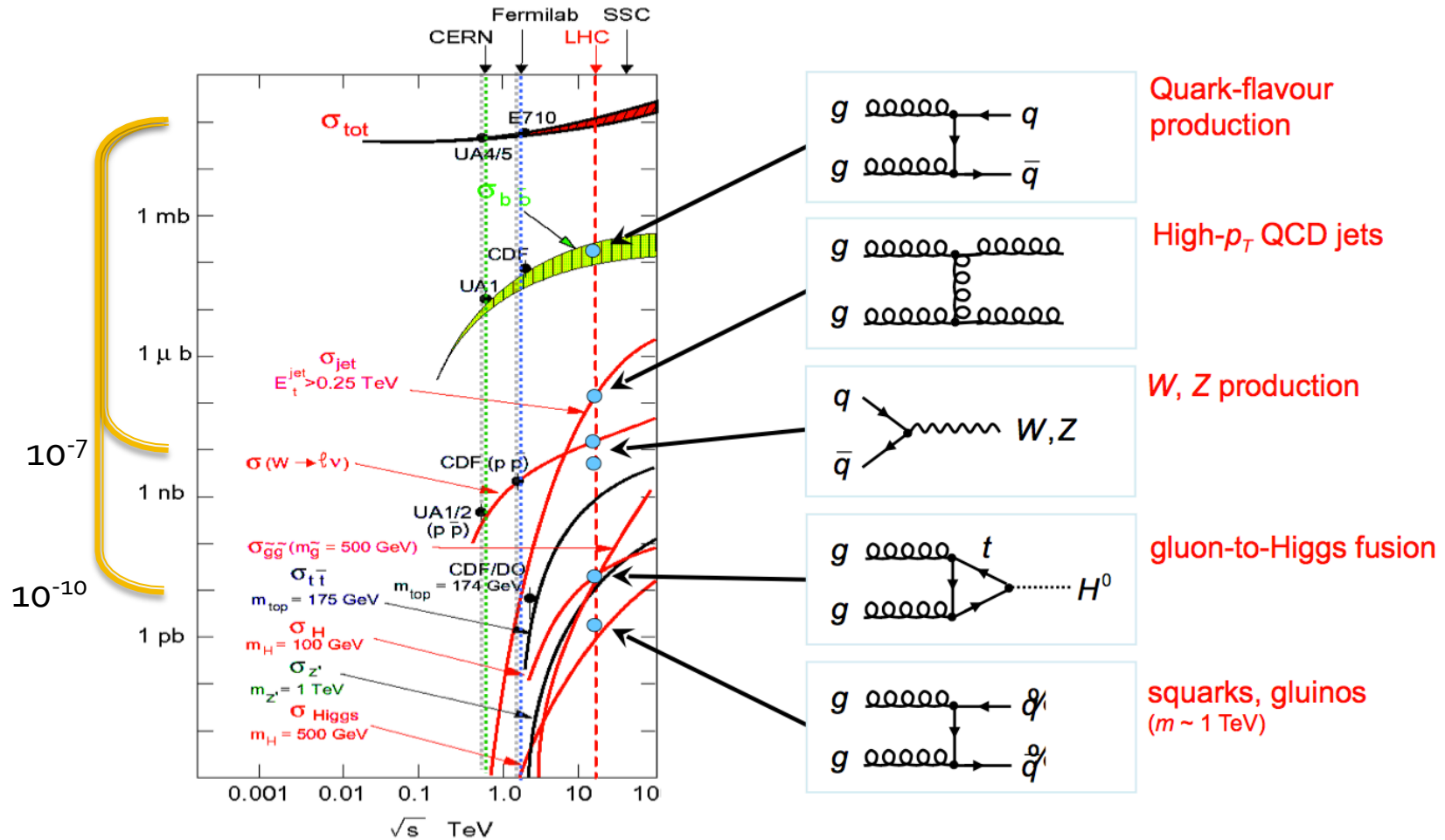
Particles, interactions and detectors

What gets produced in collisions

- Mostly pions.
 - The cheapest way to rearrange quarks and gluons.
 - 2/3 charged: $c\tau \sim 8$ m decay in $\mu\nu$.
 - 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...

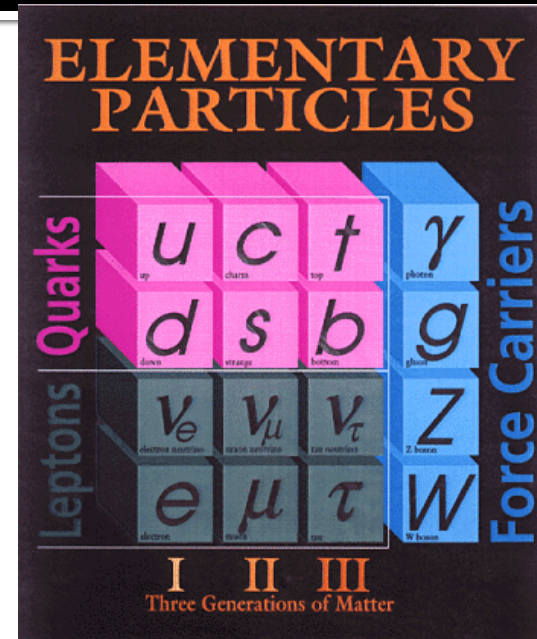


What gets produced in collisions



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**



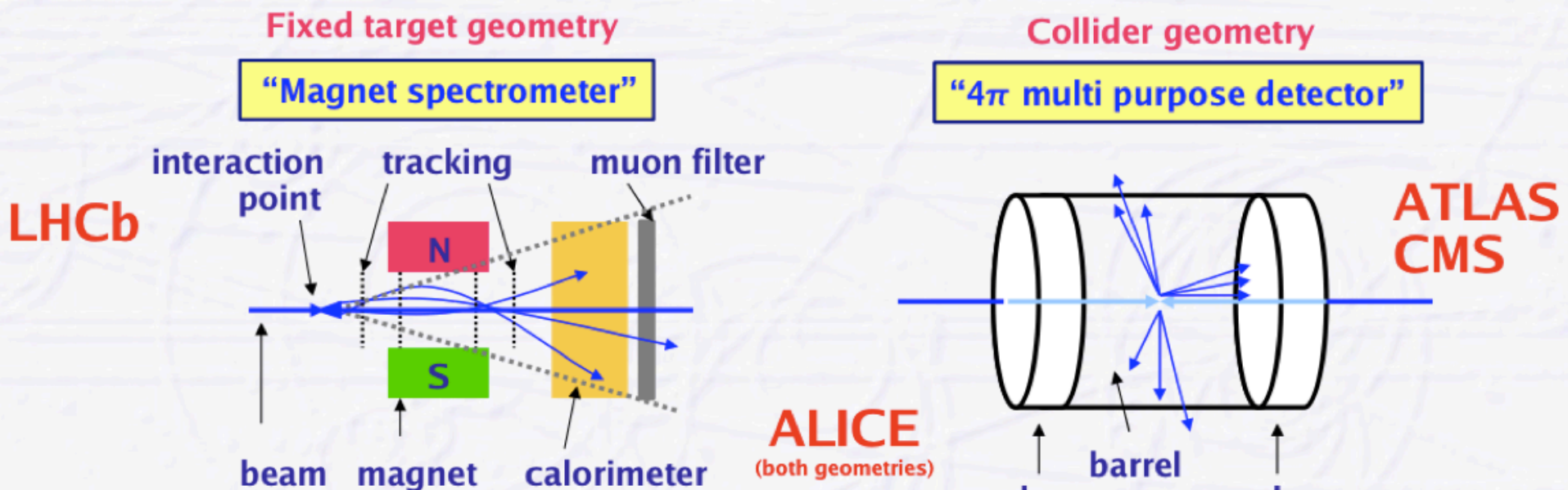
What we can detect

- 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) %
$(u\bar{u} + c\bar{c})/2$	(11.6 ± 0.6) %
$(d\bar{d} + s\bar{s} + b\bar{b})/3$	(15.6 ± 0.4) %
$c\bar{c}$	(12.03 ± 0.21) %
$b\bar{b}$	(15.12 ± 0.05) %
W ⁺ DECAY MODES	Fraction (Γ_j/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) %

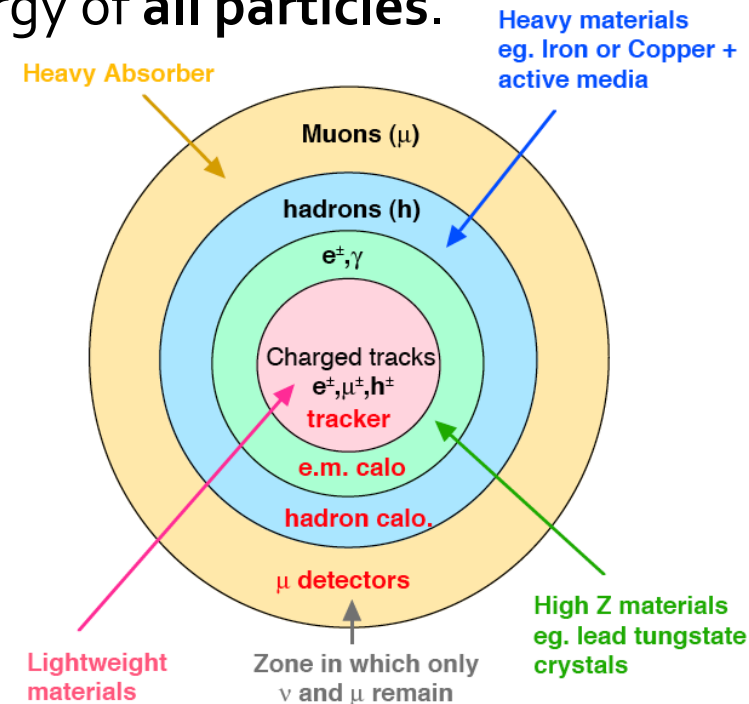
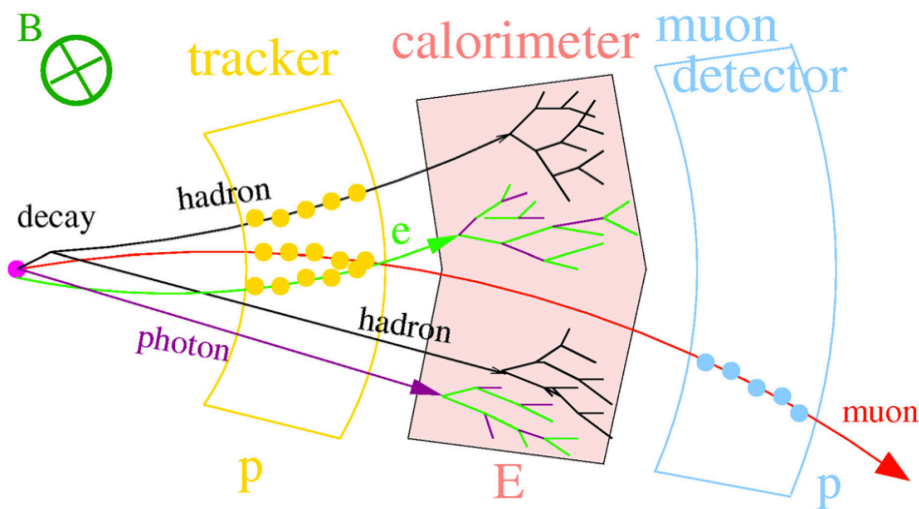
Shapes of experiments

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

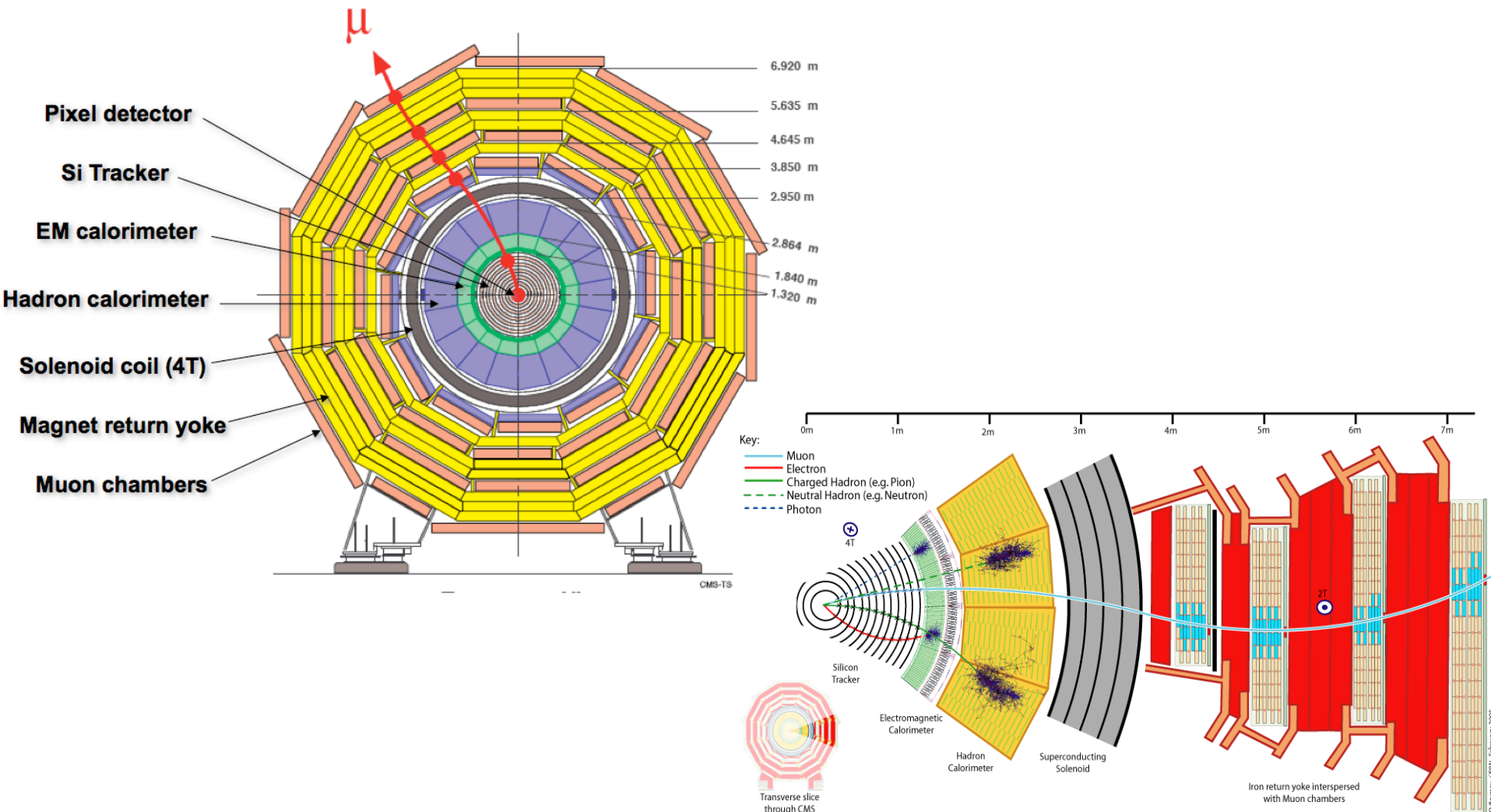


Peeling the hermetic onion

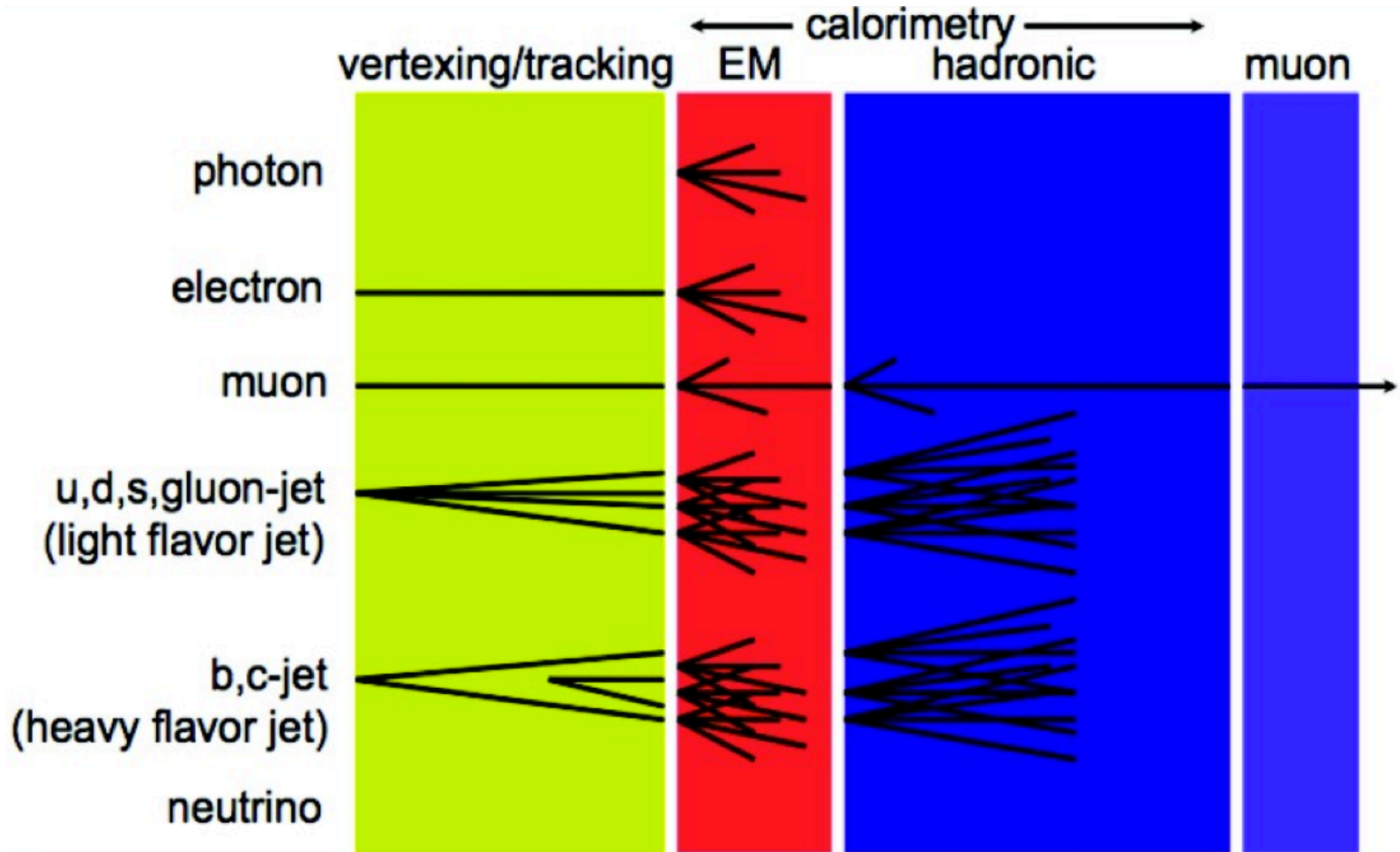
- Inner tracking
 - Measure charged particles **disturbing them the least possible.**
- Calorimetry
 - Measure as much as possible the energy of **all particles.**
- Outer tracking
 - Measure **muons.**



CMS example



Particles and their decays

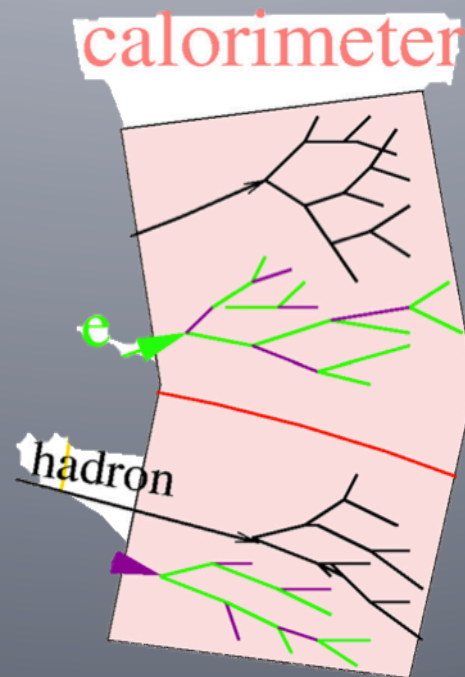


In the end it is all charged particles

- 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

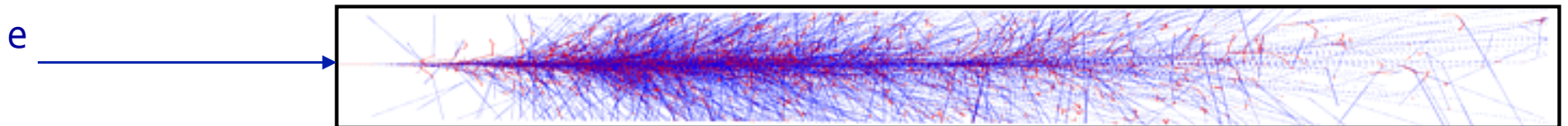
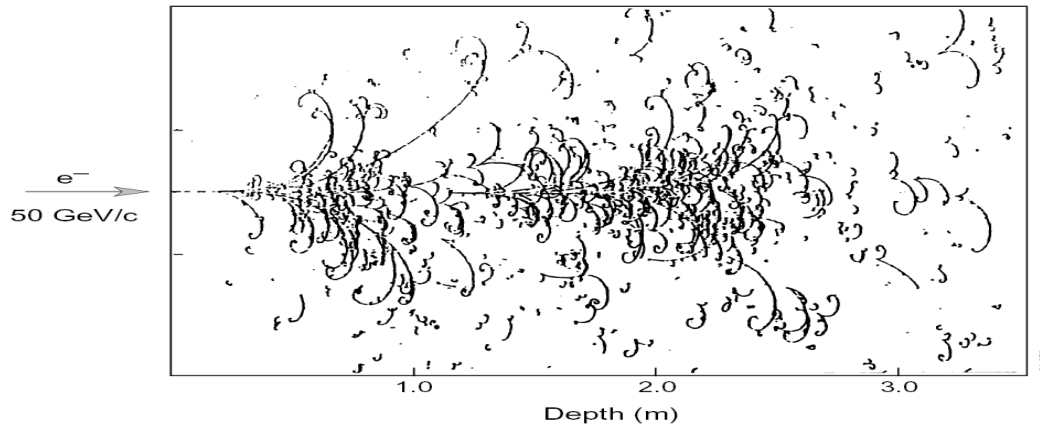
Trying to measure the energy of everything except muons.



Calorimetry: what?

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

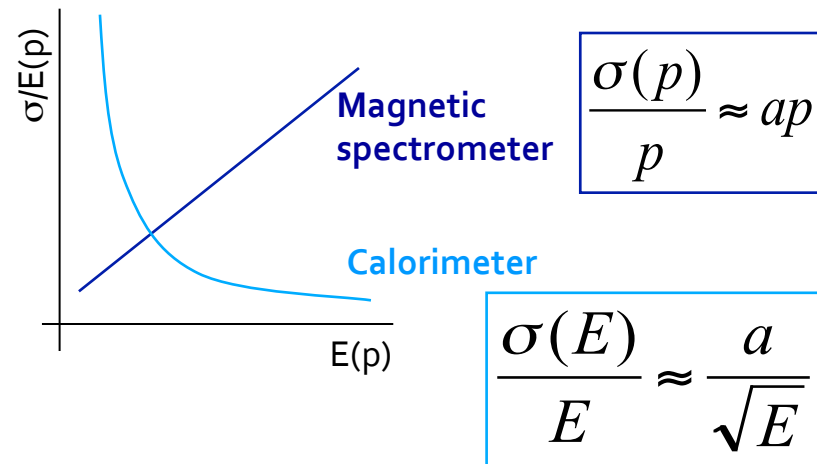
Big European Bubble Chamber filled with Ne:H₂ = 70%:30%,
3T Field, L=3.5 m, X₀≈34 cm, 50 GeV incident electron



GEANT shower Monte Carlo (PbWO₄ 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



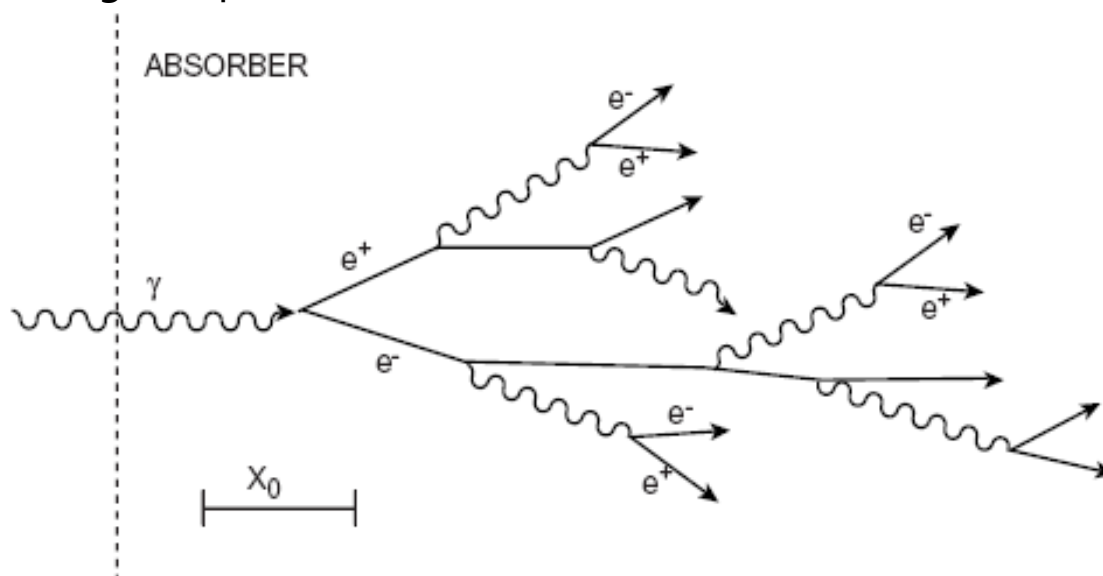
Calorimetry: how?

- 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 absorption mechanism.
 - Shower development governed by these processes.

Electromagnetic shower development

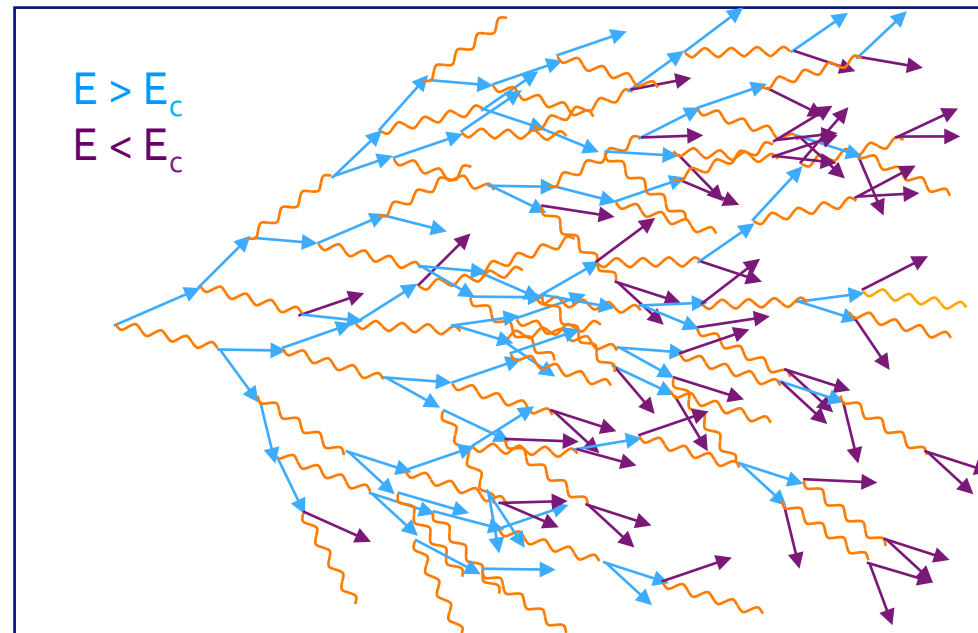
- Radiation length (X_0) defined to be the distance over which an electron loses all but $1/e$ of its energy.
- Useful approximation →
 - Rough derivation in [Cal1]; more precise approximation in [Cal2].

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

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

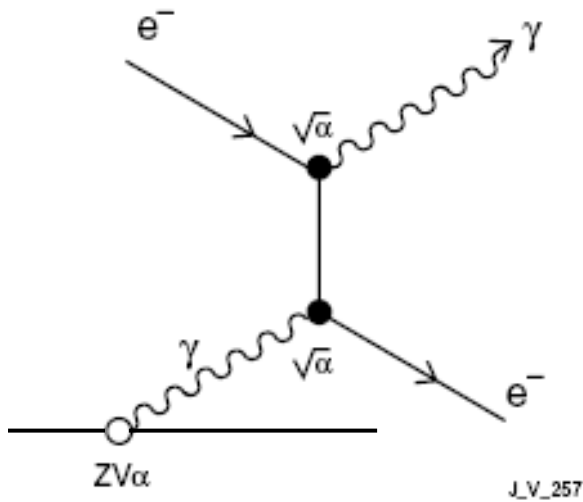
$$E_c \approx \frac{560}{Z} \text{MeV}$$

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

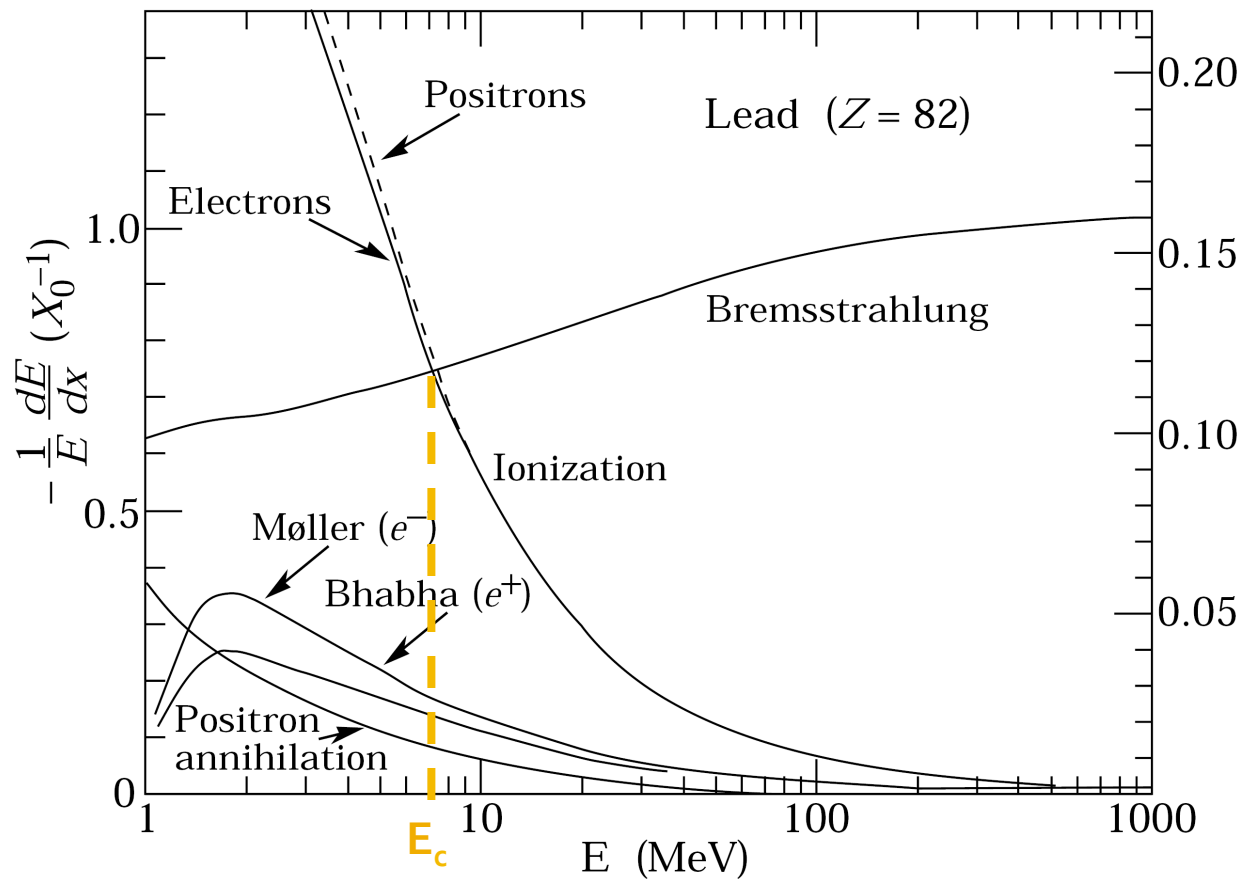


Energy loss in matter: electrons

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 $E_\gamma > 2m_e c^2$)

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

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

Can define mean free path:

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

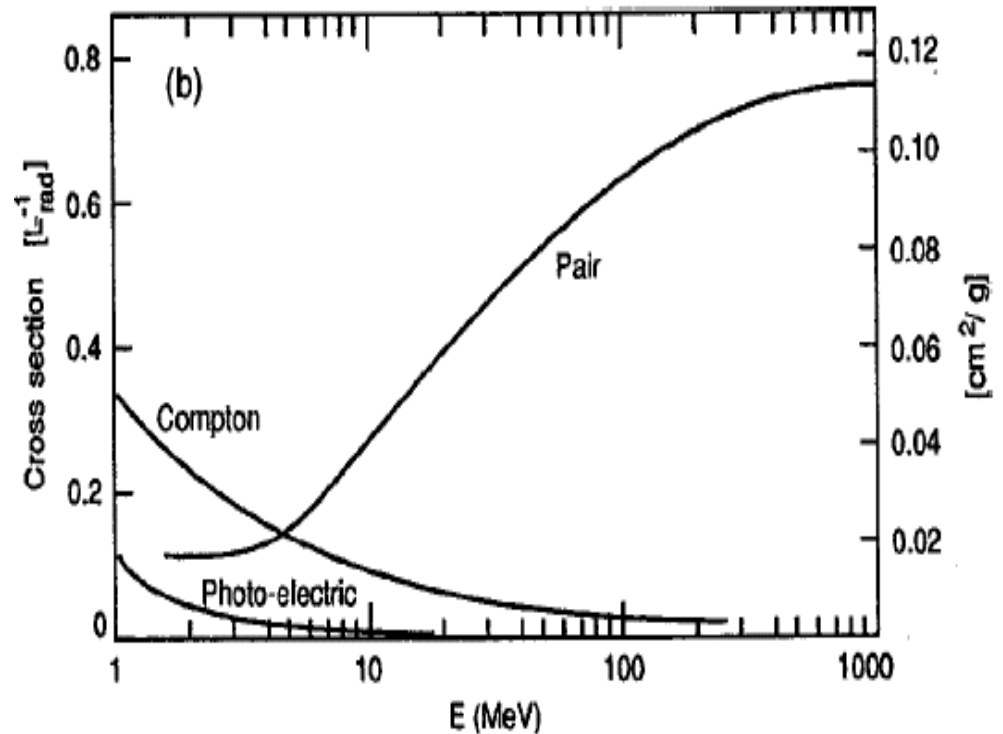
Compton scattering

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

Photoelectric effect

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

Fractional energy loss: photons



Contributions to Photon Cross Section in Carbon and Lead

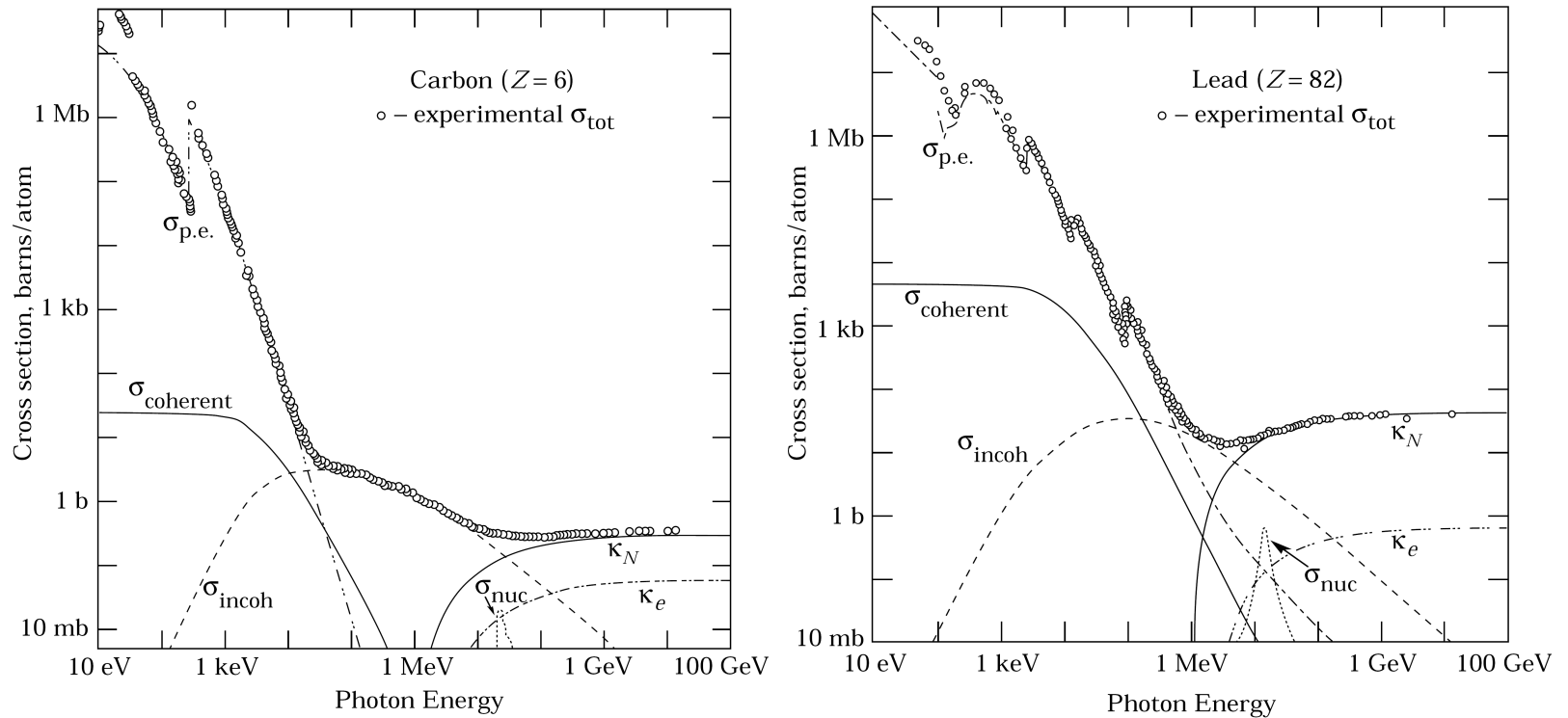


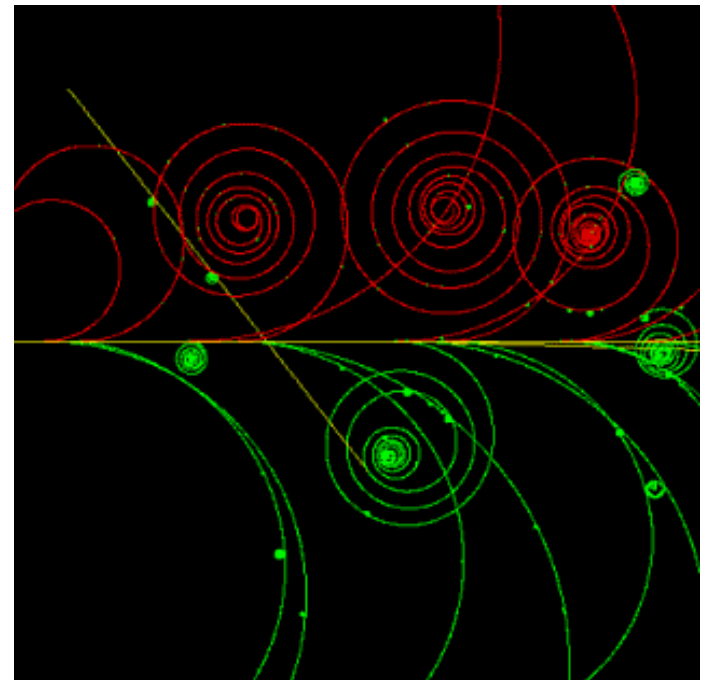
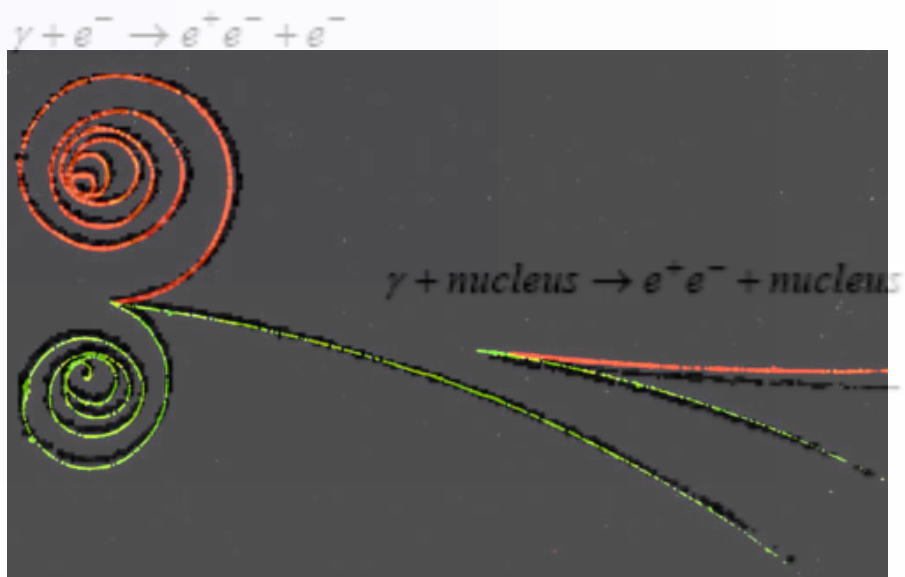
Figure 24.3: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes:

- $\sigma_{\text{p.e.}}$ = 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 emitted 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 :

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

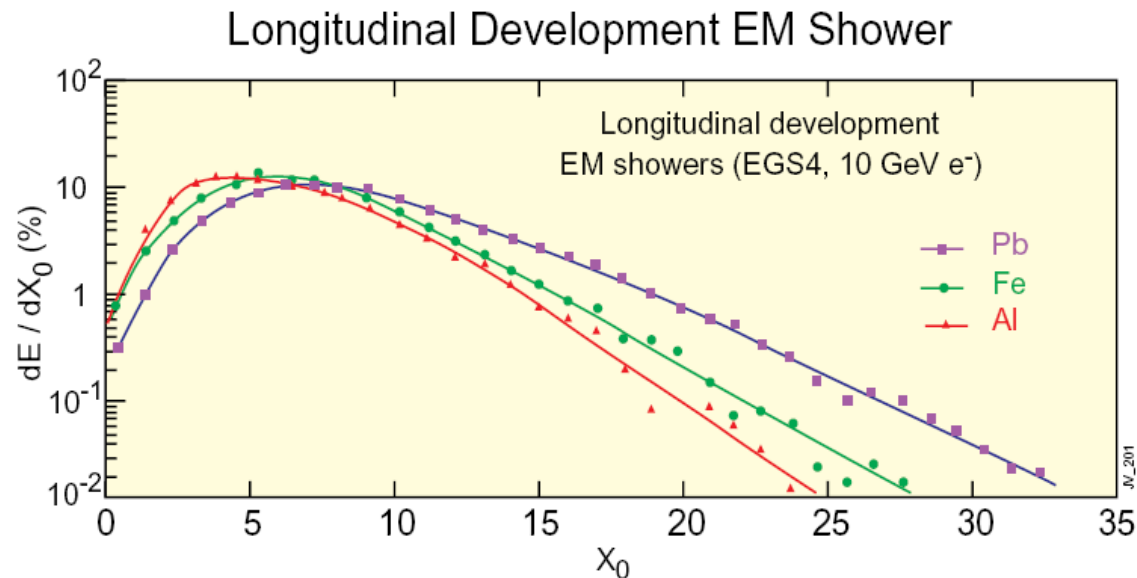
- Electrons lose about 2/3 of their energy in $1X_0$, and the photons have a probability of 7/9 for conversion: $X_0 \sim$ generation length

- After distance t :
 - number of particles, $n(t) = 2^t$
 - energy of particles, $E(t) \approx \frac{E}{2^t}$

- When $E = E_c$, \sim 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_0 only holds approximately:
 - Lower $E_c \Rightarrow$ multiplication continues to lower energies and electrons continue radiating down to lower energies

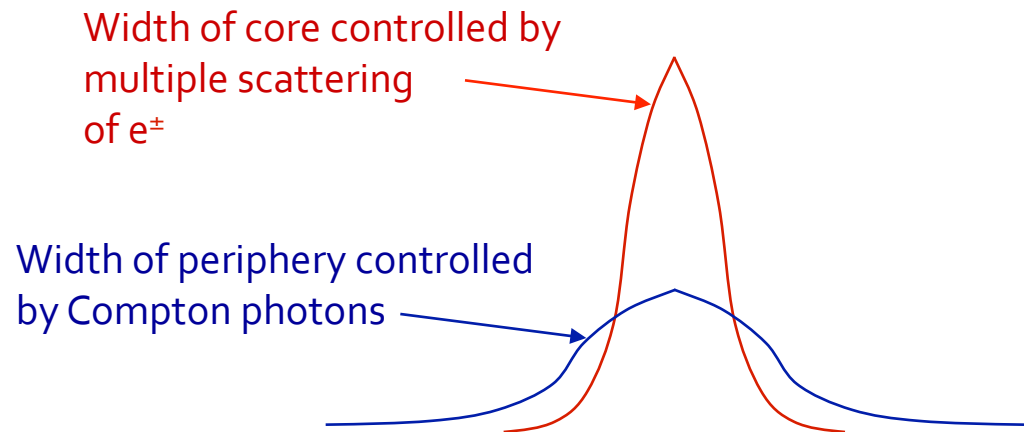


Lateral development

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

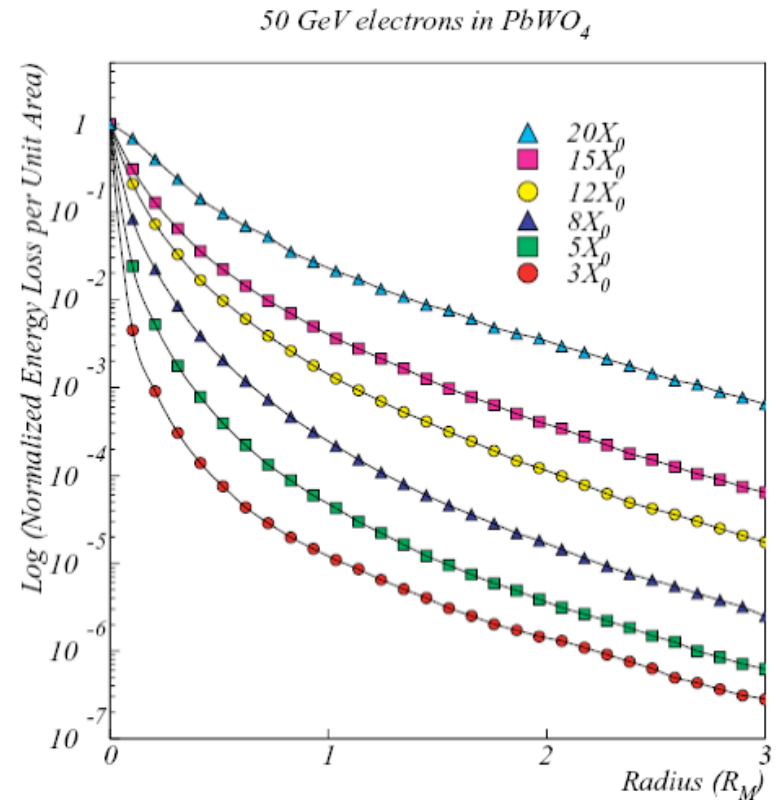
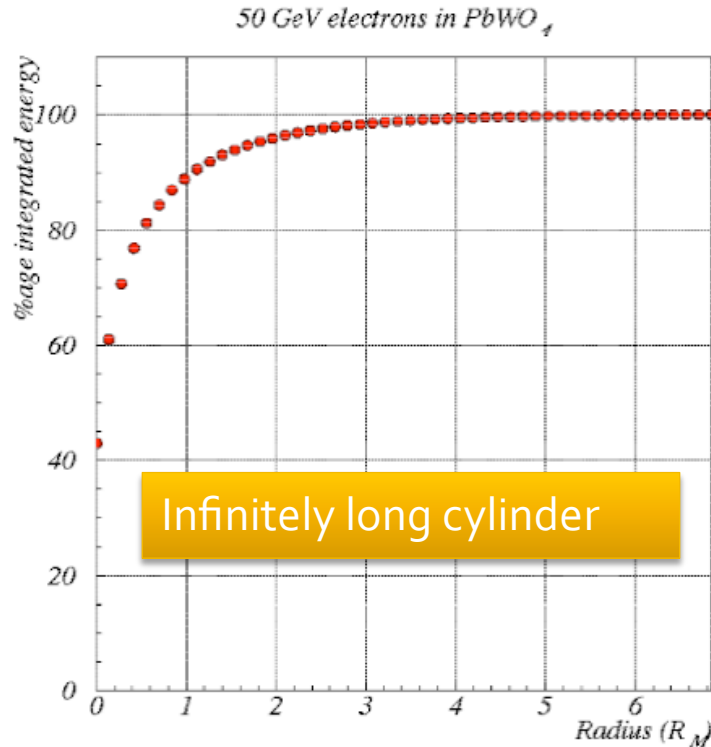
$$R_M = \frac{21 \text{MeV} \cdot X_0}{E_c} \approx \frac{7A}{Z} \text{g} \cdot \text{cm}^{-2}$$

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



EM showers: lateral spread

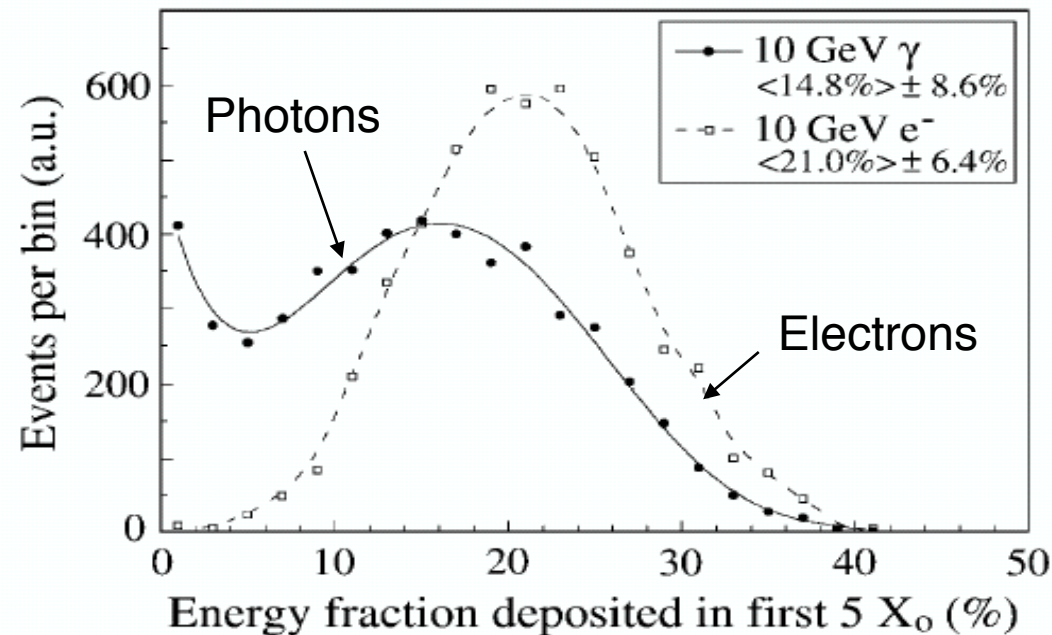
- Lateral shower shape: to very good approximation is invariant with energy.



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:

$$\lambda_{pair} \approx \frac{9}{7} X_0$$
- 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.
 - $E \sim 2m_{\pi} = 0.28 \text{ GeV}/c^2$.
 - 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

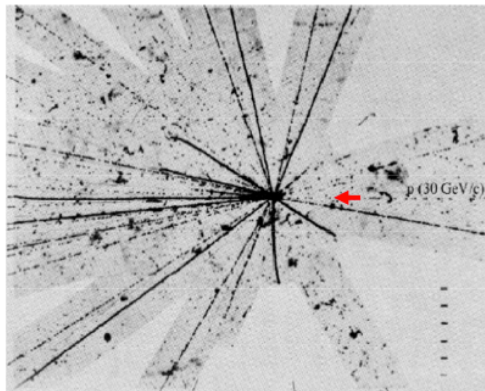
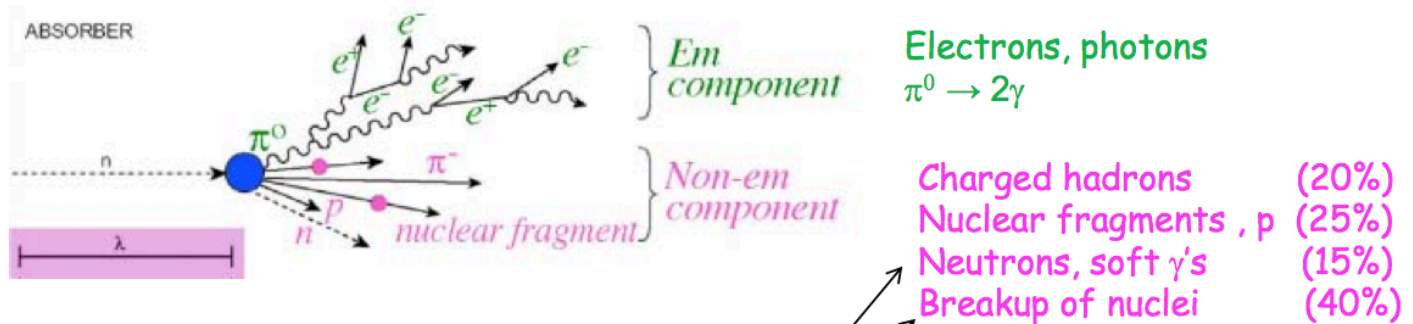
- Simple model of interaction on a disk of radius R:
 - $\sigma_{\text{int}} = \pi R^2 \propto A^{2/3}$
 - Compare to $\sigma_{\text{inel}} \approx \sigma_0 A^{0.7}$, $\sigma_0 = 35 \text{ mb}$.
- **Nuclear interaction length**: mean free path before inelastic interaction:

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

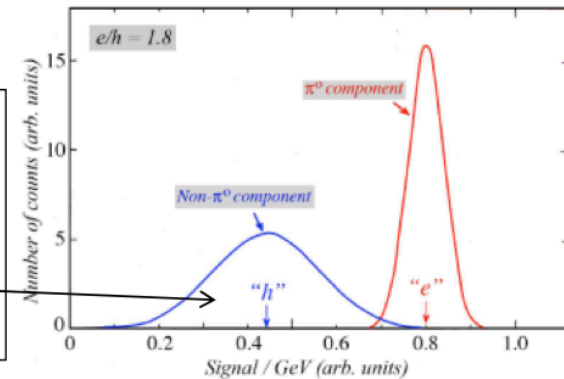
- Mean transverse momentum resulting from interaction:
 - $\langle p_T \rangle \sim 300 \text{ MeV}$.
 - This is about the same magnitude as the energy lost traversing 1λ for typical materials.

Hadronic cascade

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

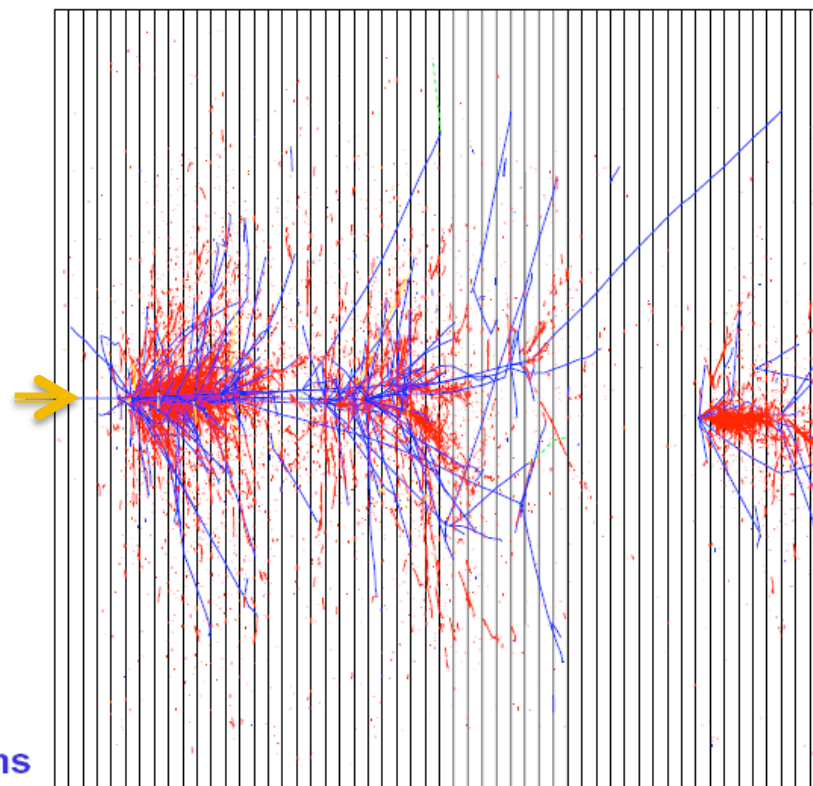
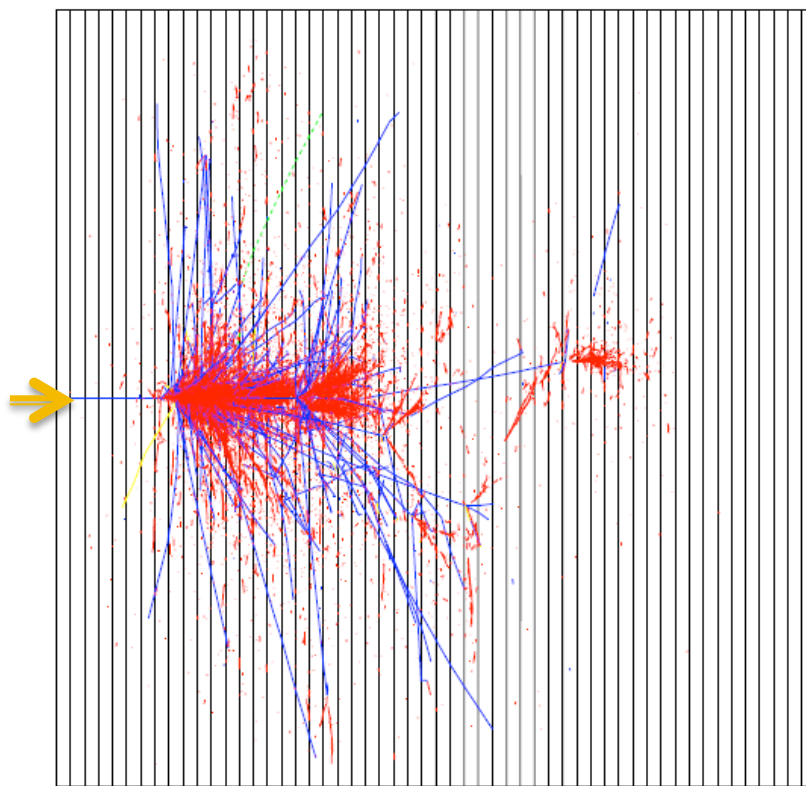


Either not detected
or often too slow to be
within detector time
window
= **Invisible energy**
 $e/h > 1$



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

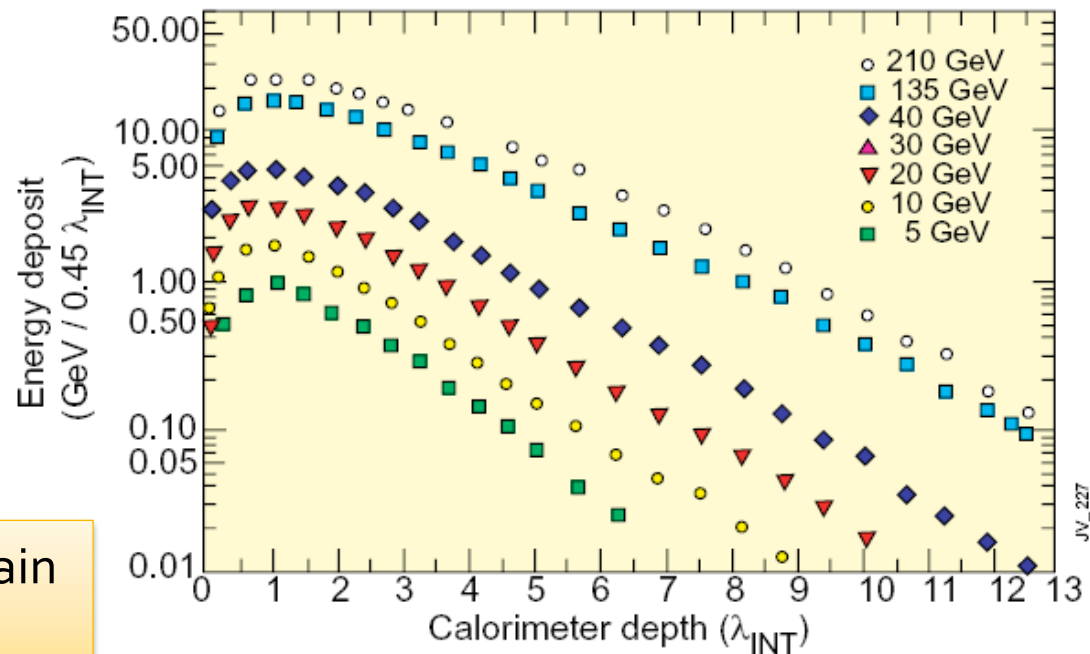
PDG booklet a good source for more/similar numbers

Hadron shower longitudinal profiles

- Initial peak from π^0 s produced in the first interaction.
- Gradual falloff characterized by the nuclear interaction length, λ_{int} . \rightarrow

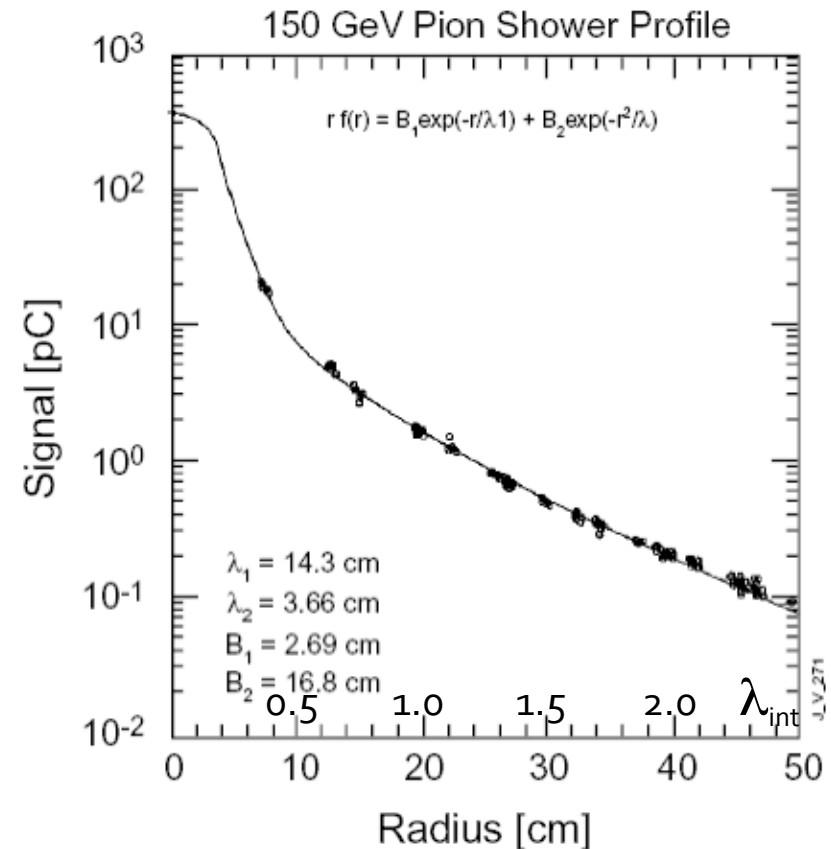
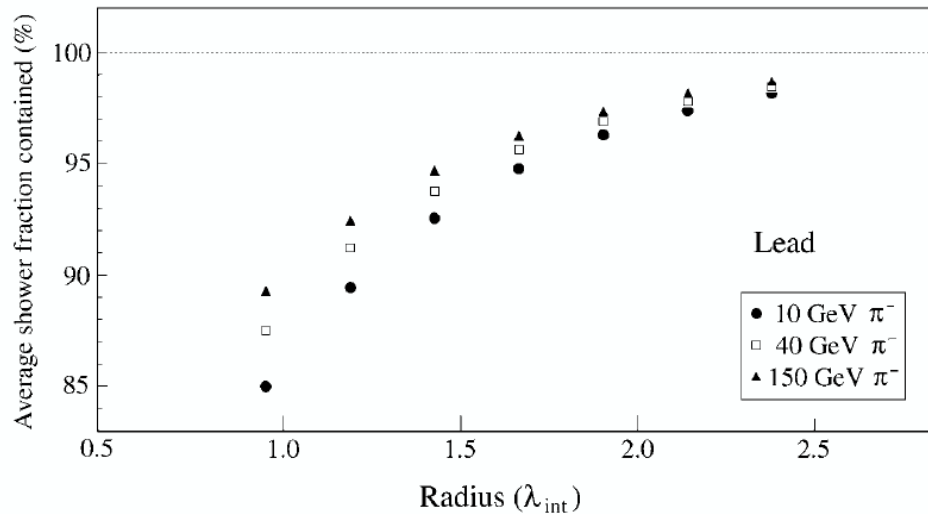
As with EM showers: depth to contain a shower increases with $\log(E)$.

WA78 : 5.4λ of 10mm U / 5mm Scint + 8λ of 25mm Fe / 5mm Scint



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 1λ for many materials. \rightarrow
- Radial extent of the cascade is well characterized by λ . \rightarrow
- The π^0 component of the cascade results in an electromagnetic core. \rightarrow



← Better lateral containment with increasing energy.

Energy resolution

Mass resolution $\sim \sqrt{2} \times$ 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.

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

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).

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

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

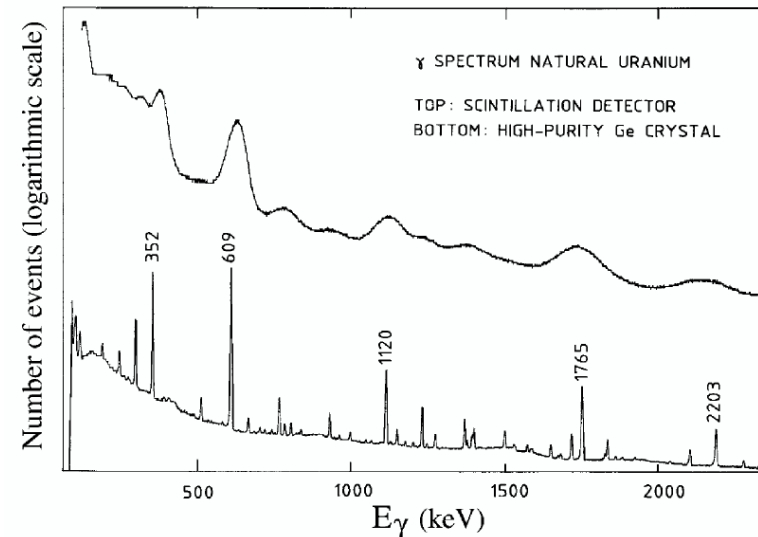


FIG. 1.1. Nuclear γ -ray spectrum of decaying uranium nuclei, measured with a bismuth germaniumoxide scintillation counter (*upper curve*) and with a high-purity germanium crystal (*lower curve*). Courtesy of G. Roubaud, CERN.

Comparison of stochastic performance

Scintillating crystals

$$E_s \cong \beta E_{\text{gap}} \sim \text{eV} \\ \approx 10^2 \div 10^4 \gamma / \text{MeV}$$

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

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

Homogeneous LKr calorimeter NA48/62

Ionisation signal

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

Cherenkov radiators

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

$$\approx 10 \div 30 \gamma / \text{MeV}$$

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

ATLAS Pb-LAr sampling

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

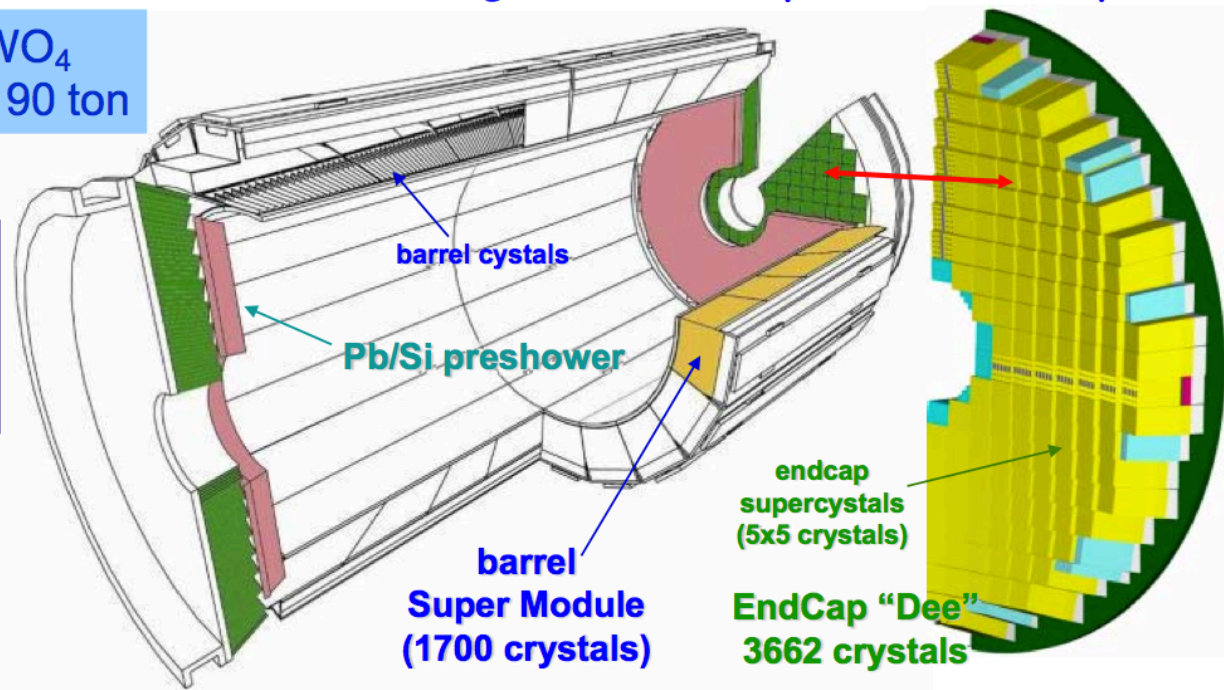
$$\sigma / E \sim 10\% / \sqrt{E(\text{GeV})}$$

CMS ECAL

Precision electromagnetic calorimetry: 75848 PWO crystals

PWO: PbWO_4
about 10 m³, 90 ton

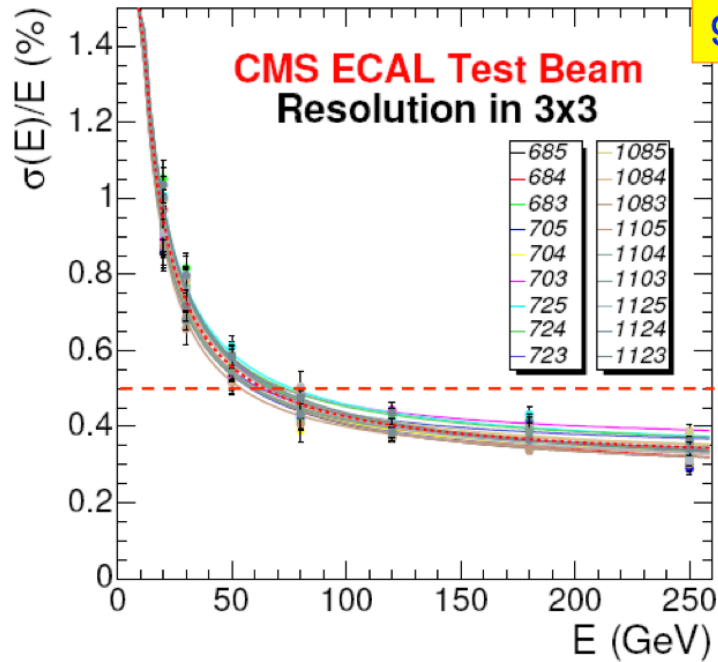
Previous
Crystal
calorimeters:
max 1m³



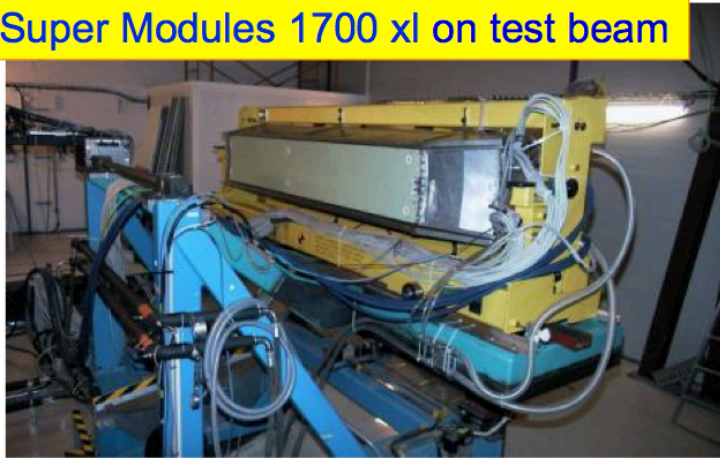
Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2x2x23cm³)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals (3x3x22cm³)

CMS ECAL test beam performance

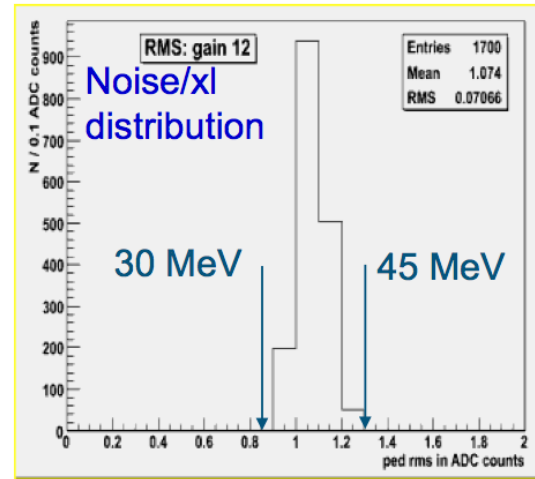


9 Super Modules 1700 xl on test beam



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

Local resolution

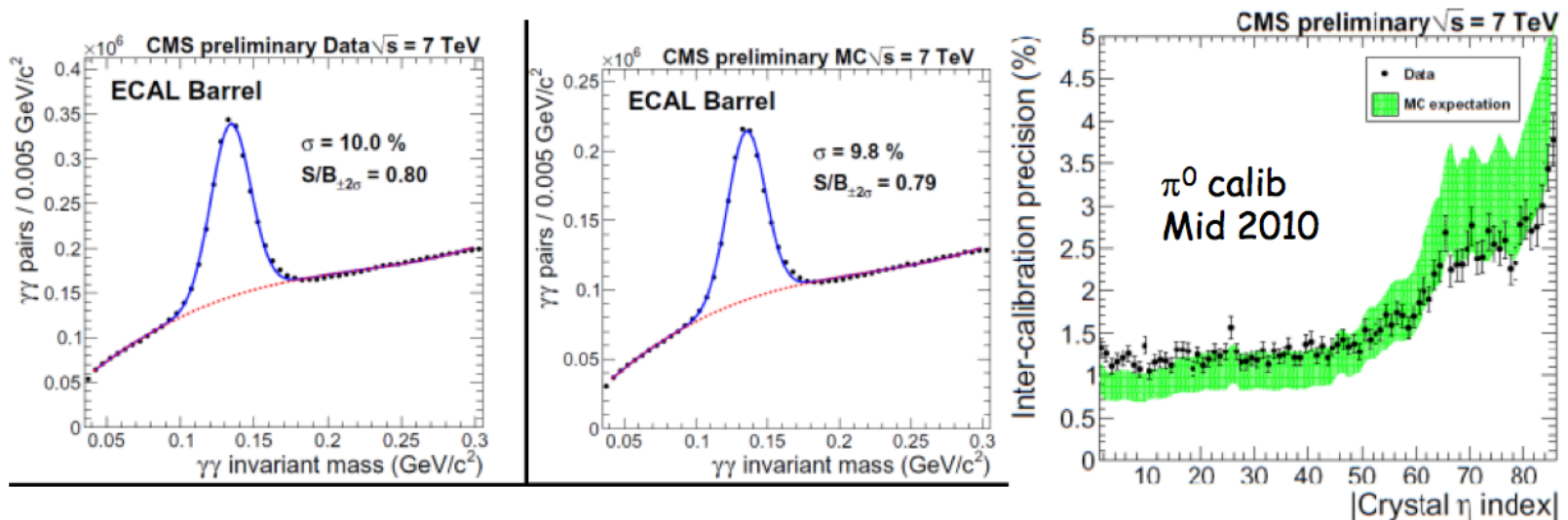


Preserving resolution

- **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:

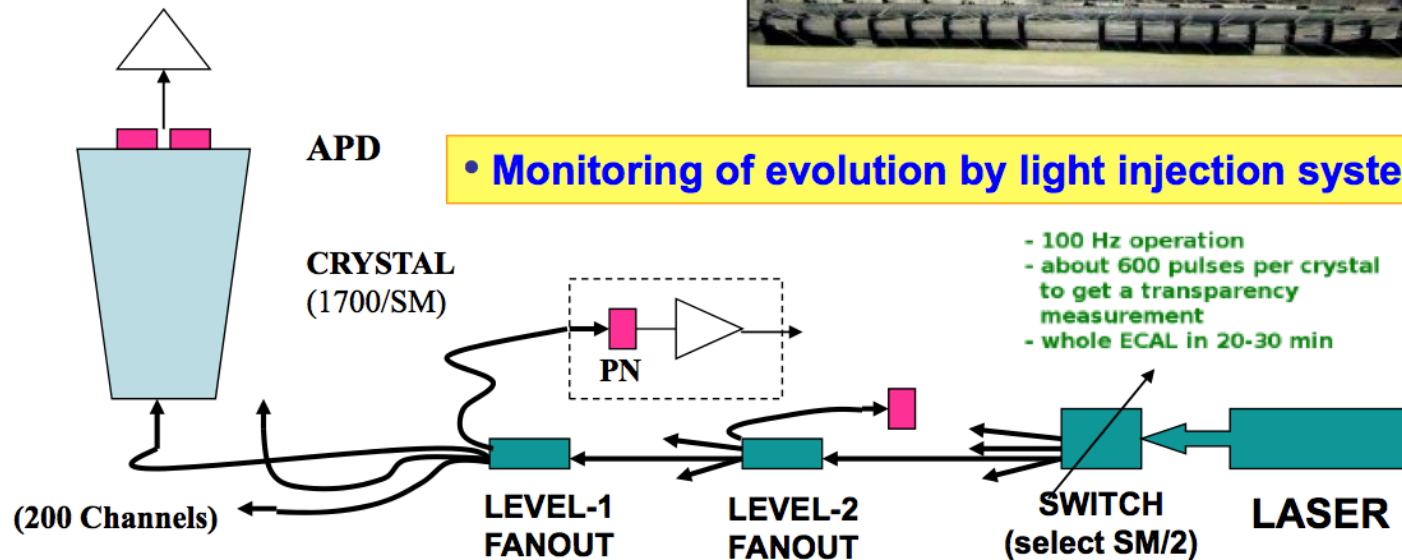
Damage and recovery during LHC cycles tracked with a laser monitoring system

2 wavelengths are used:

440 nm and 796 nm

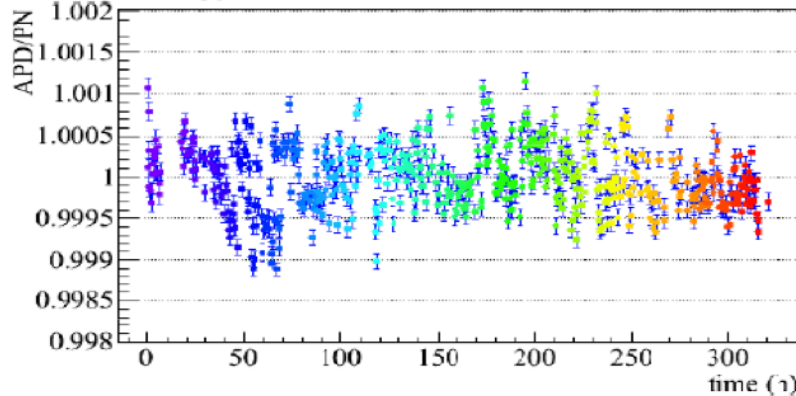
Light is injected into each crystal

Normalisation given by PN diodes (0.1%)



Transparency monitoring

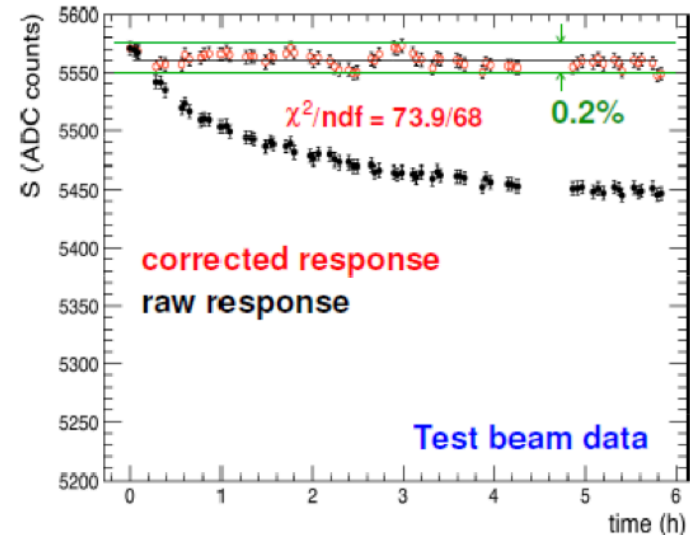
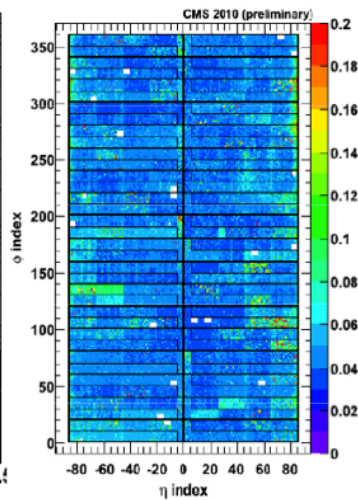
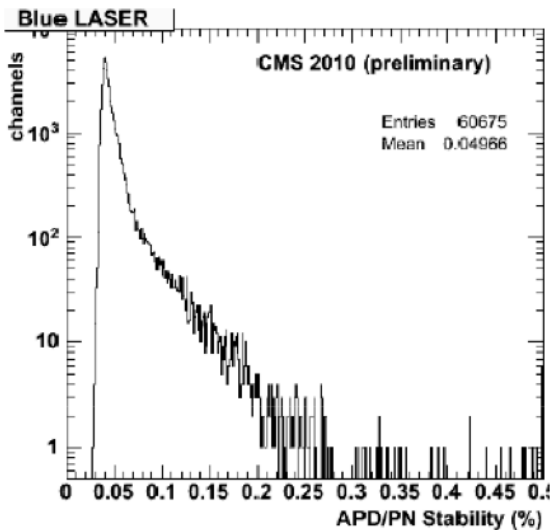
Stability for a typical channel over about 350 h



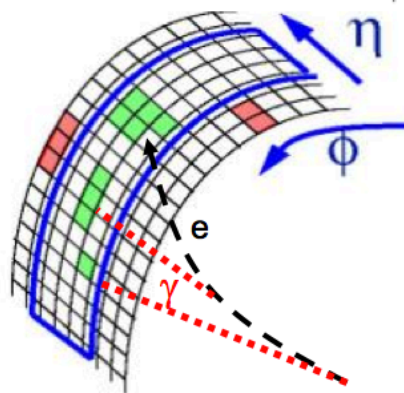
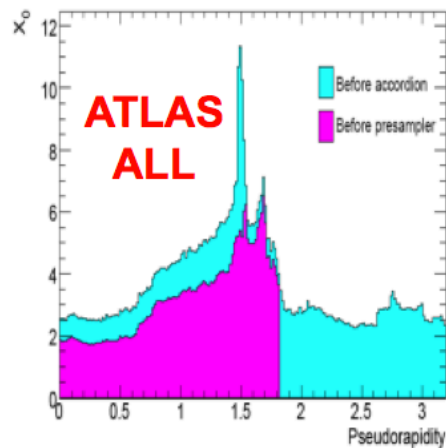
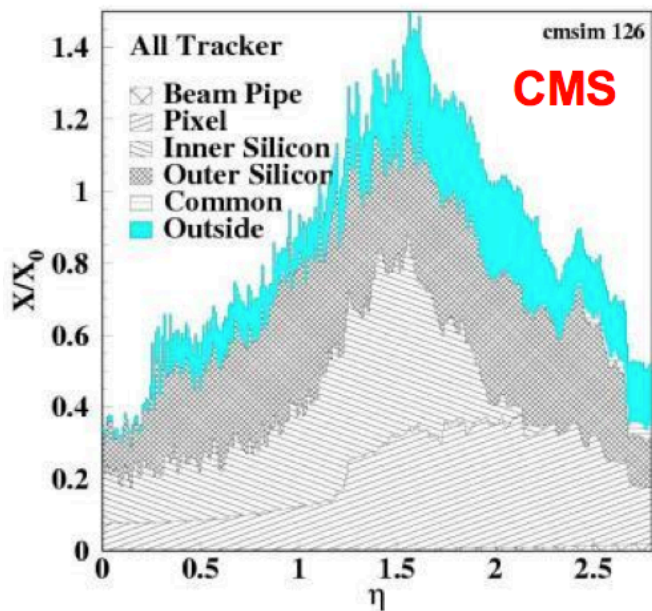
Measure a loss of transparency:
S (particle signal) and R(laser signal)

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

NB: α is ~ the same for all crystals!



Material in front



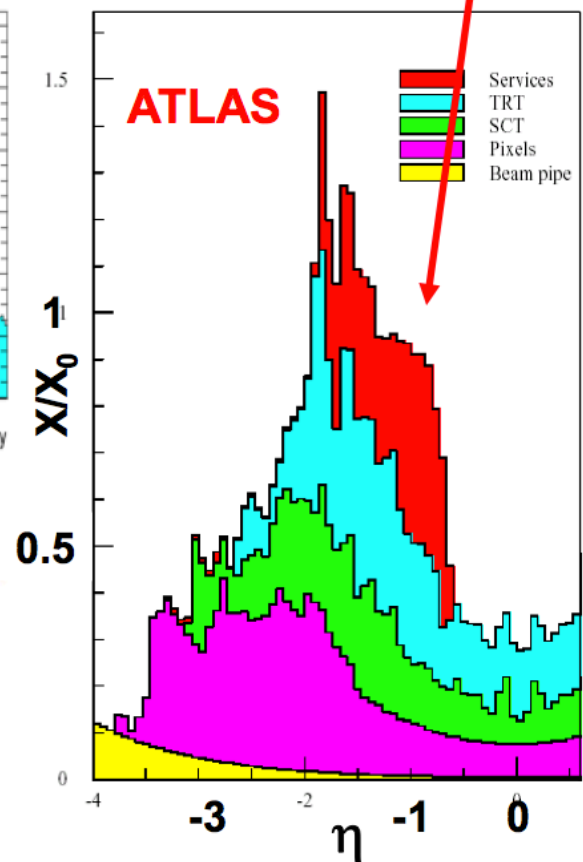
Tracker material :

- electrons loose energy via bremsstrahlung
- photons convert

4T (2T) solenoidal B field :

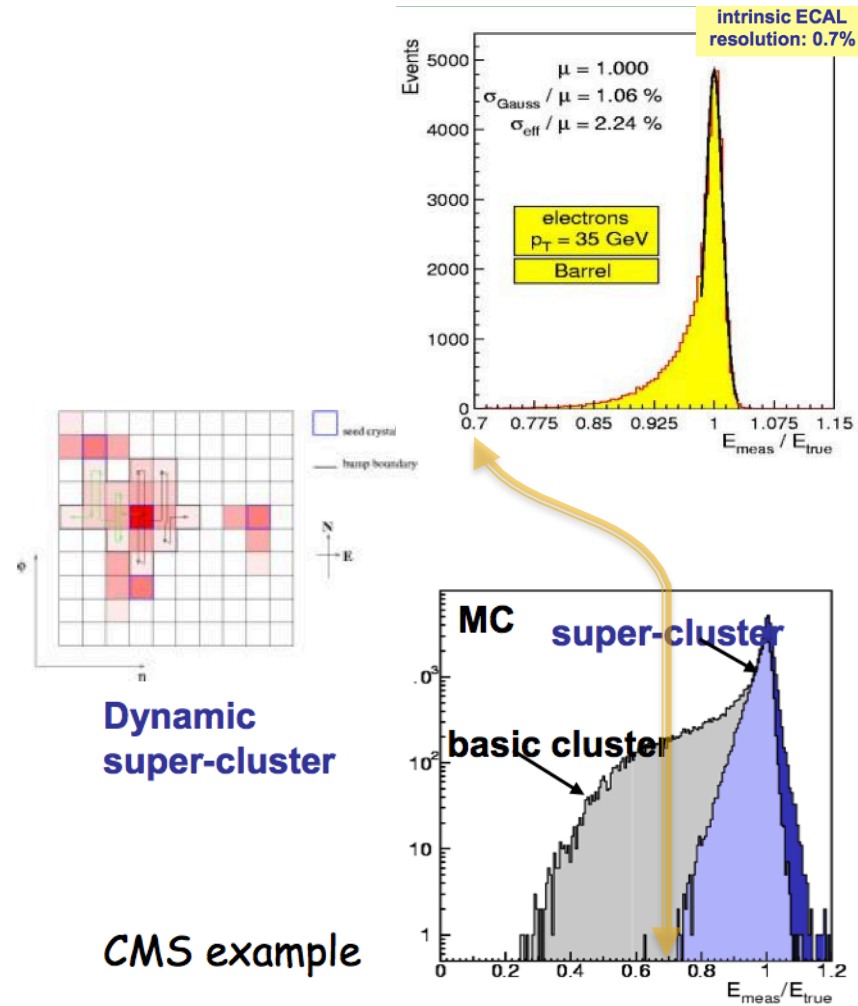
Electrons bend \Rightarrow radiated energy spread in φ

+ THE SOLENOID



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 .

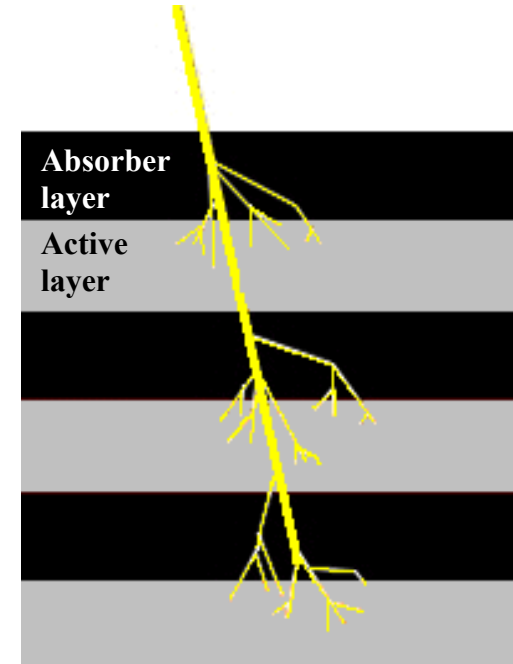


Sampling calorimeters

- 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 $n \approx E/\Delta E_{\text{abs}}$, and $\Delta E_{\text{abs}} = t_{\text{abs}} (dE/dx)$
 - Thus, $\sigma/E = \sqrt{n}/n \approx t_{\text{abs}}/\sqrt{E}$
 - Using the fraction of energy sampled, f_{samp} , as a parameter a generally valid formula for the stochastic contribution is:

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

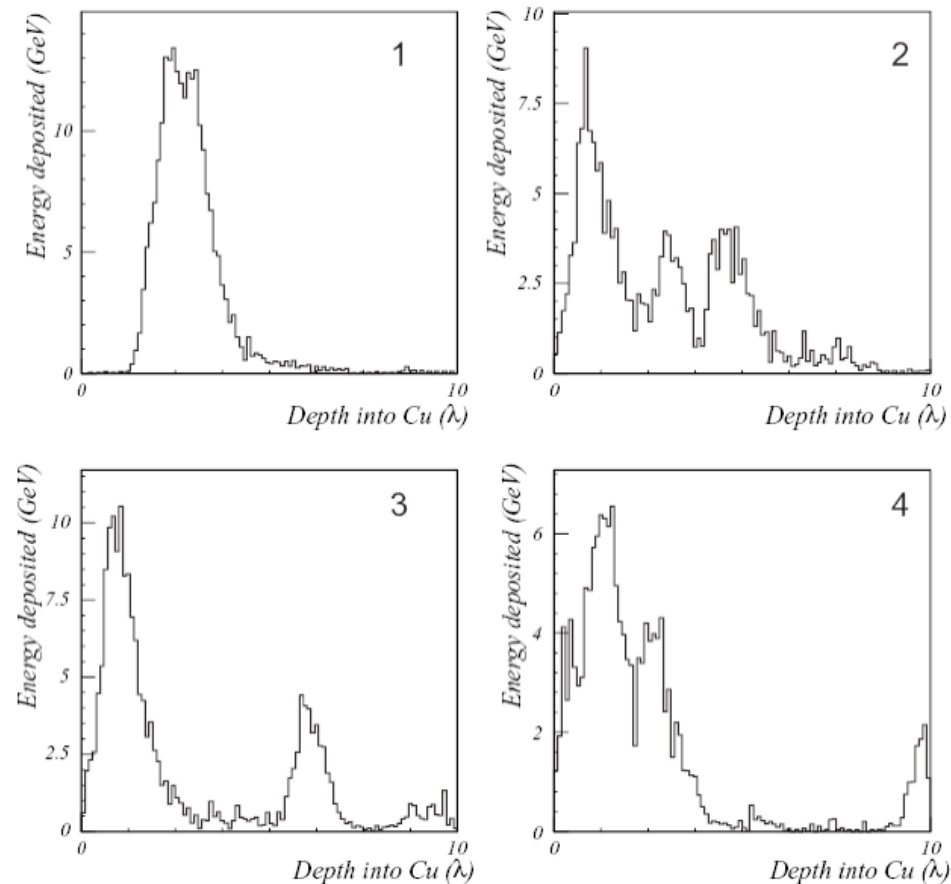
Where ΔE_{cell} is the energy deposited in a unit sample (absorber + active layer)



Hadronic energy resolution

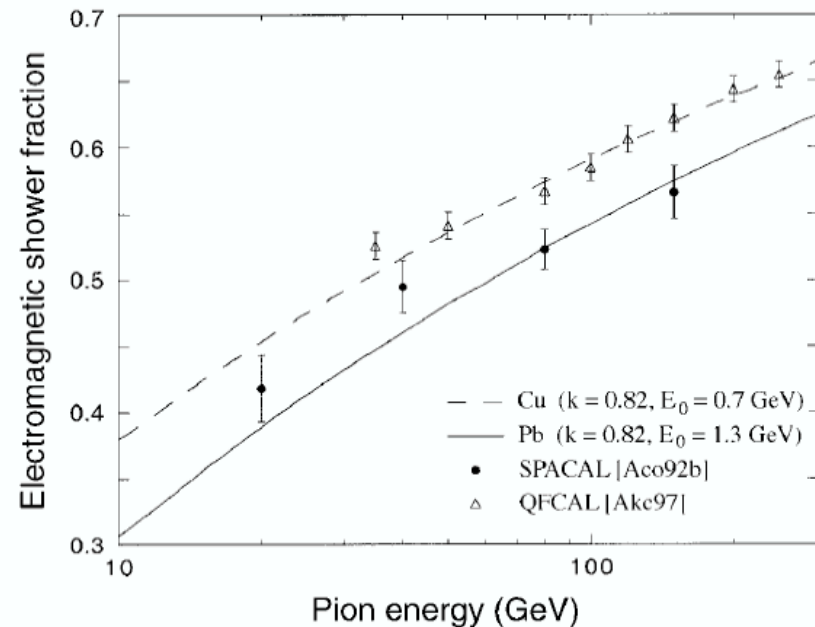
- Hadronic calorimeters are (almost) always sampling calorimeters.
- Fluctuations in the visible energy have more sources:
 - Sampling fluctuations (same as for sampling EM calorimeters).
 - Fluctuations between the electromagnetic and hadronic components.
 - and also between the different elements of 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:
270 GeV Incident Pions in Copper



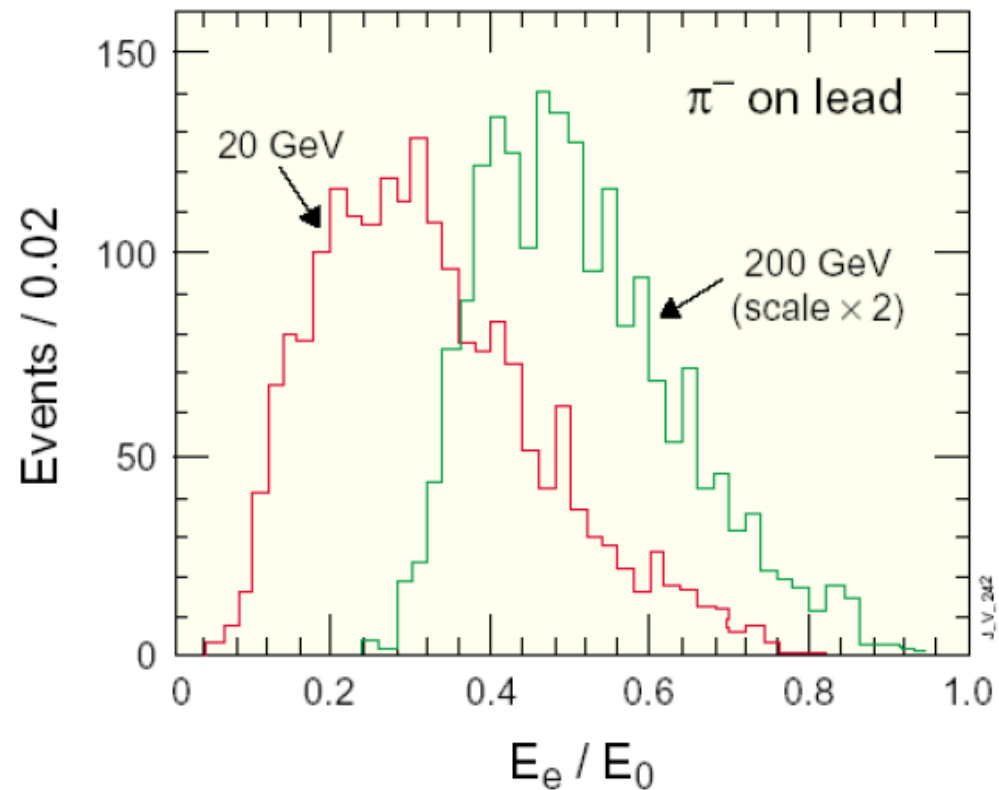
Hadronic showers: EM component

- On average $1/3$ of the mesons produced at each interaction will be π^0 s. (π^+ , π^0 , and π^- equally produced)
 - And then some more in the next step, etc.
- Assume that a fraction of EM energy (f_0) is produced at each step:
 - After 1st step: f_0 .
 - After 2nd step: $f_0 + f_0(1-f_0)$, etc.
- Call F_0 the fraction of EM energy in the shower:
 - $F_0 = f_0 \sum (1-f_0)^{n-1}$, after n generations.
 - $F_0 = 1 - (1-f_0)^n$.
- So:
 - At low energy $F_0 \approx f_0$.
 - At very high energy $F_0 \rightarrow 1$. ↗



Electromagnetic fraction

- Large event to event fluctuations in F_0 .
- Average value of F_0 increases with energy. ↓

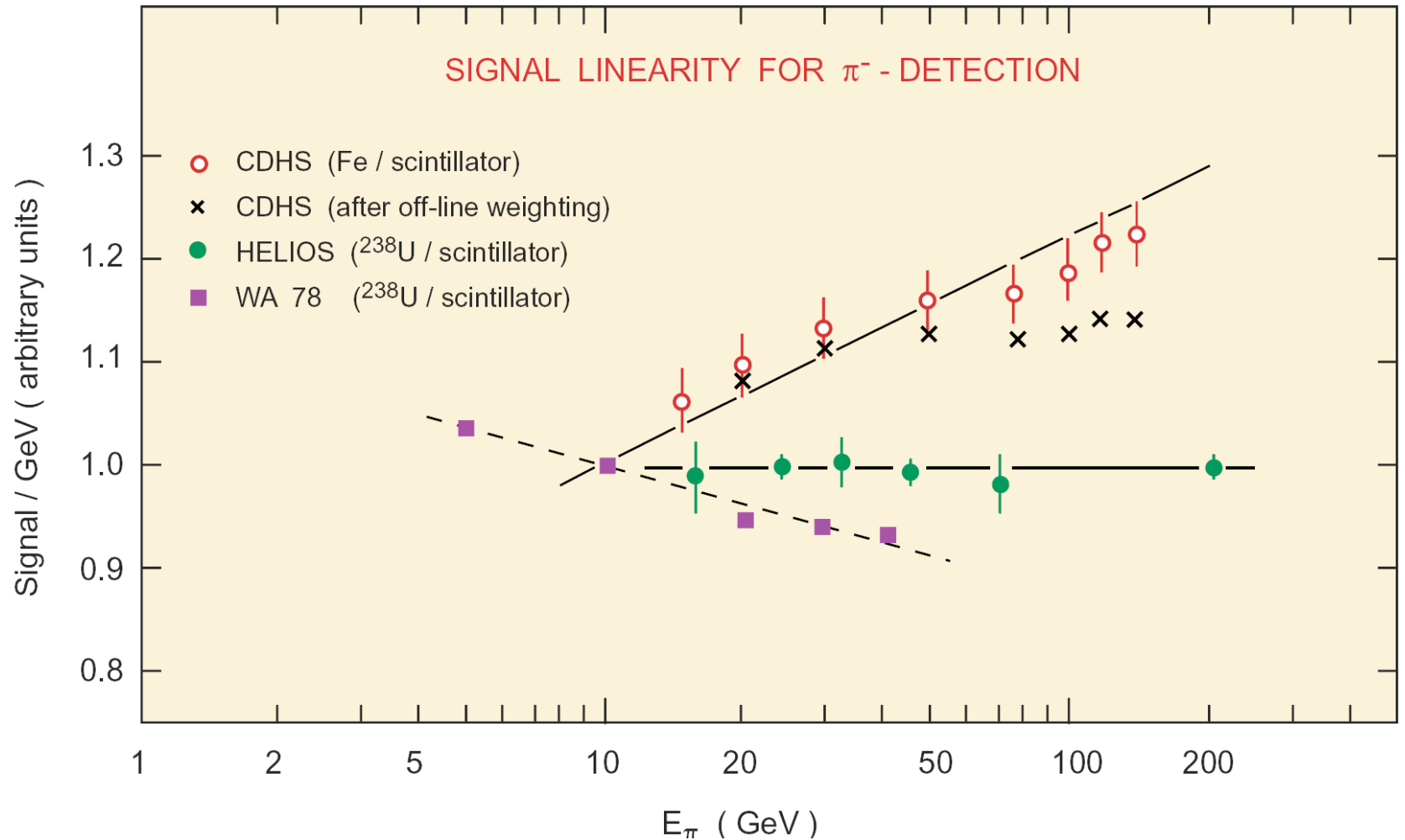


Hadronic energy resolution

- 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.

$$\begin{aligned} E_e &= e \\ E_\pi &= eF_0 + h(1 - F_0) \\ \Rightarrow \frac{E_e}{E_\pi} &= \frac{\frac{e}{h}}{\left[\left(\frac{e}{h} \right) F_0 + (1 - F_0) \right]} \end{aligned}$$

A consequence of $e/h \neq 1$



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_0

$$F_0 = 1 - \left(\frac{E}{0.76} \right)^{-0.13} \quad \text{D. Groom (E in GeV)}$$
$$F_0 = 0.11 \cdot \ln E \quad \text{R. Wigmans}$$

- 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 $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\phi^2)}$.
- Also: missing transverse energy.

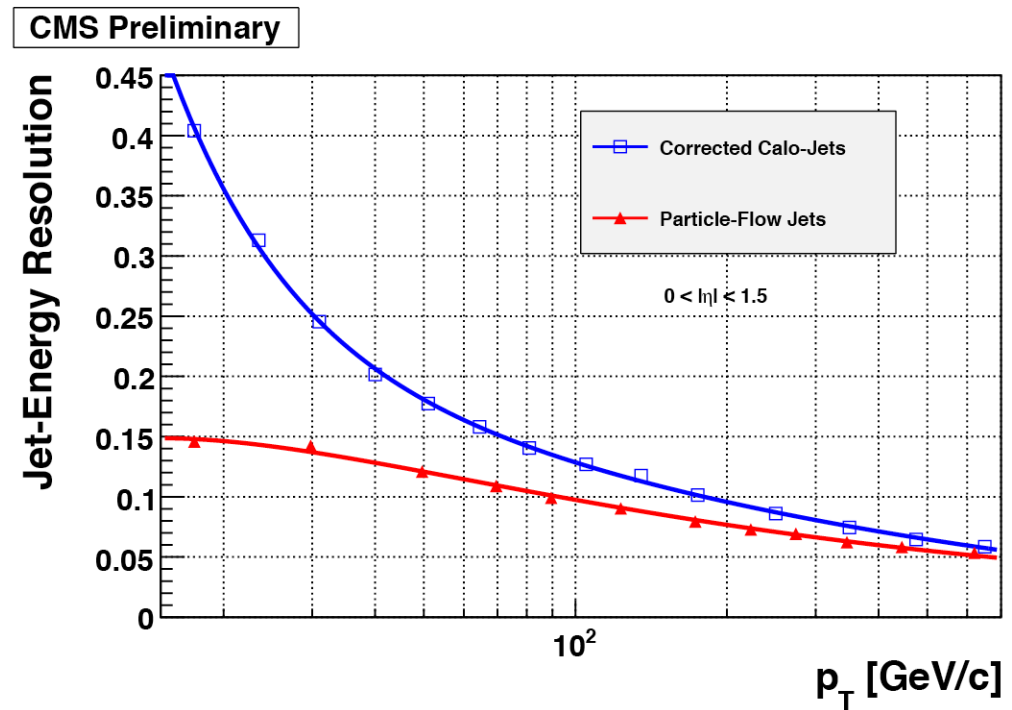
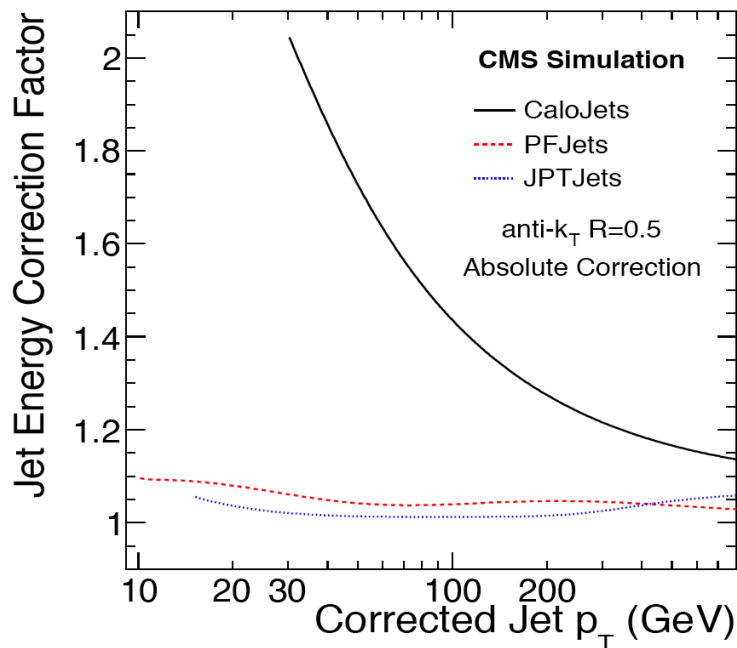
- Jet energy resolution limited by effects from:
 - Details of algorithm used to define the jet (the parameters controlling the algorithm in the example above).
 - Fluctuations in the content of the jet (fluctuation in jet fragmentation).
 - Fluctuations of the underlying event (hadron colliders).
 - 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.

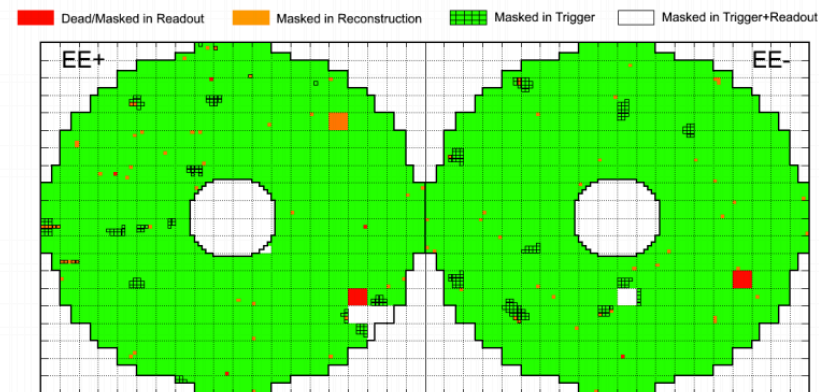
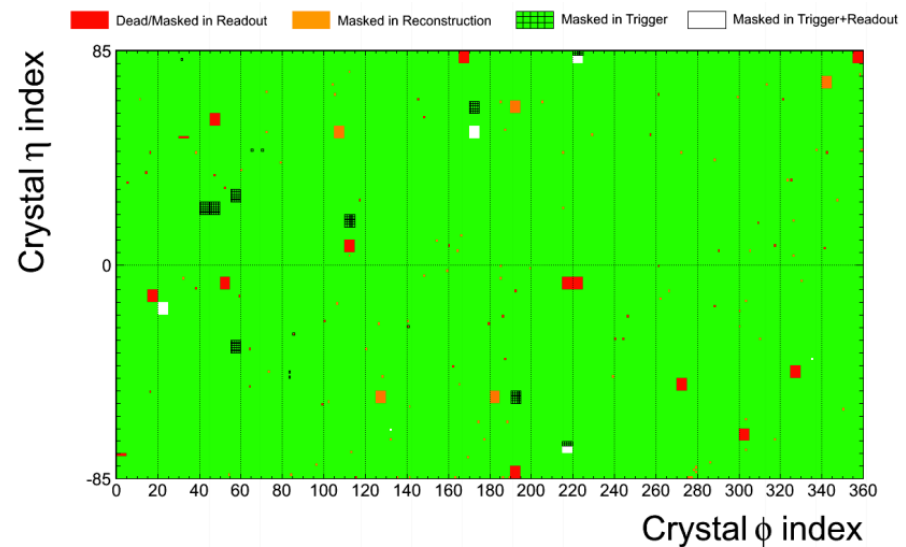


Missing transverse energy

- Longitudinal momentum unknown.
 - Partons are “sampled” from PDFs.
- System must be balanced in the transverse plane.
 - $Q^2 \gg$ parton k_T .
- Hermiticity allows to measure the transverse imbalance.

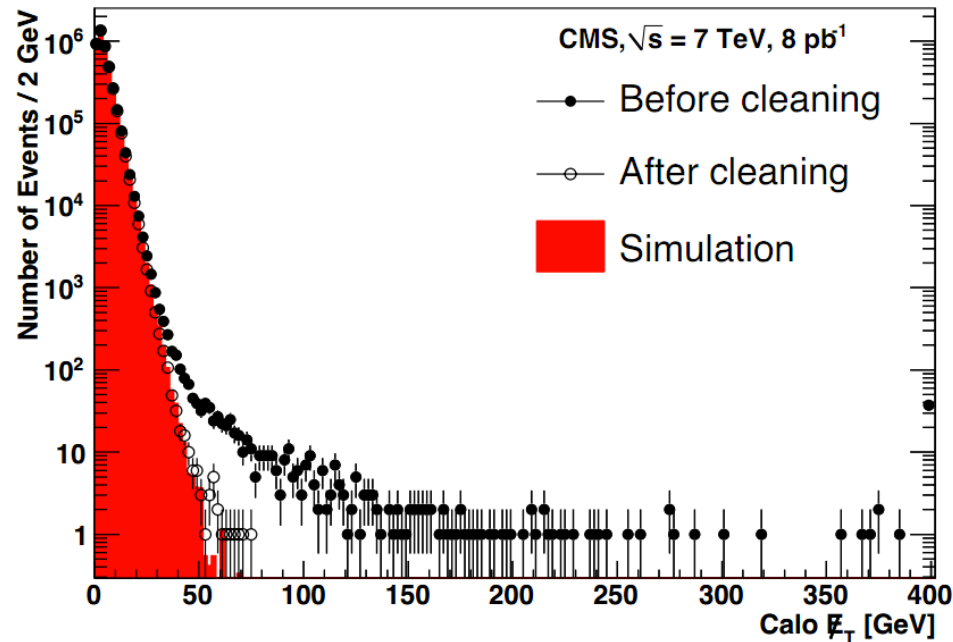
Missing energy

- Sensitive to holes.
 - CMS ECAL map. →



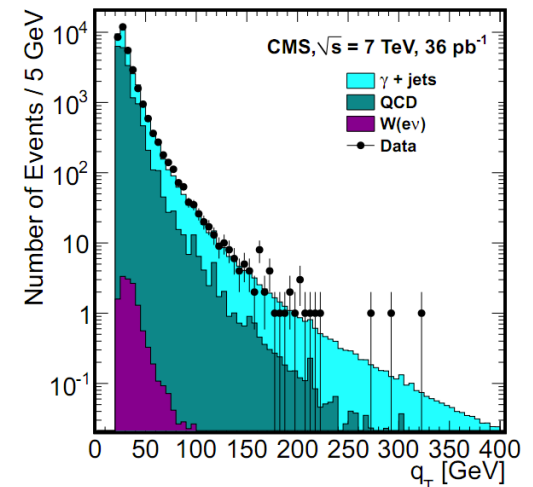
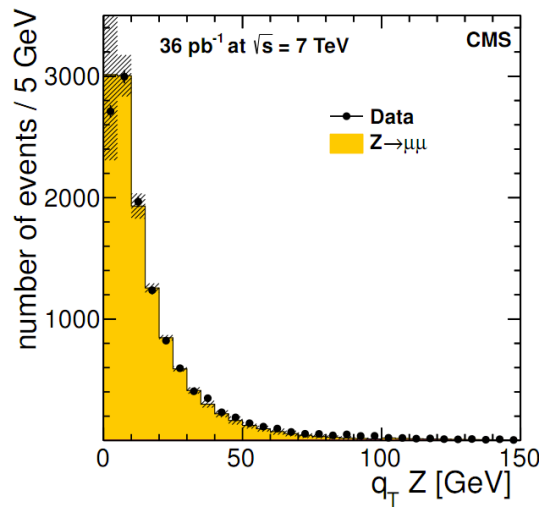
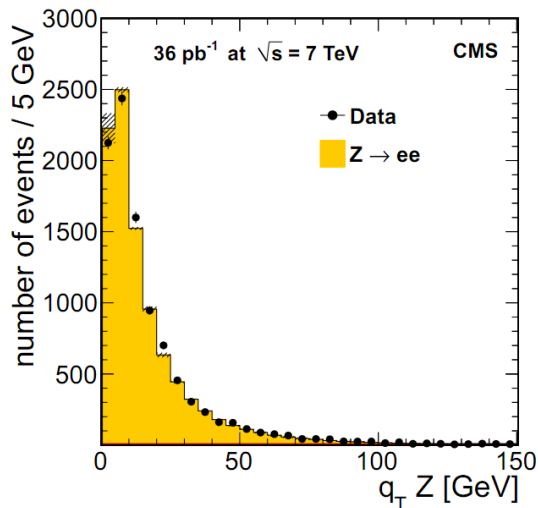
Missing energy

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



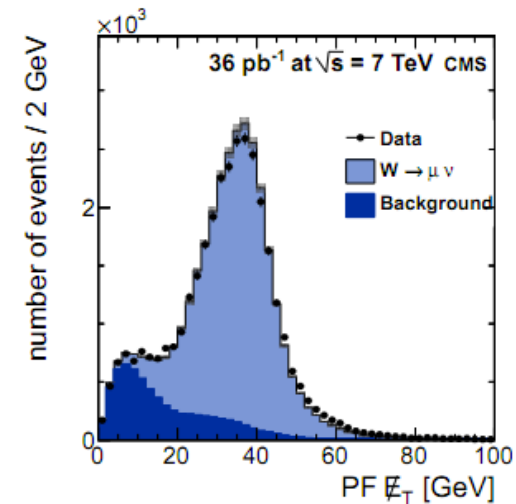
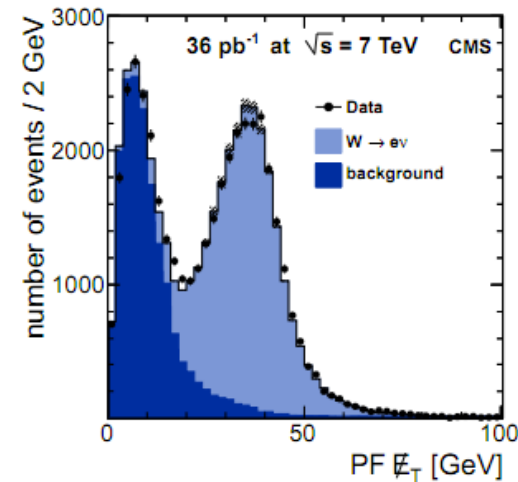
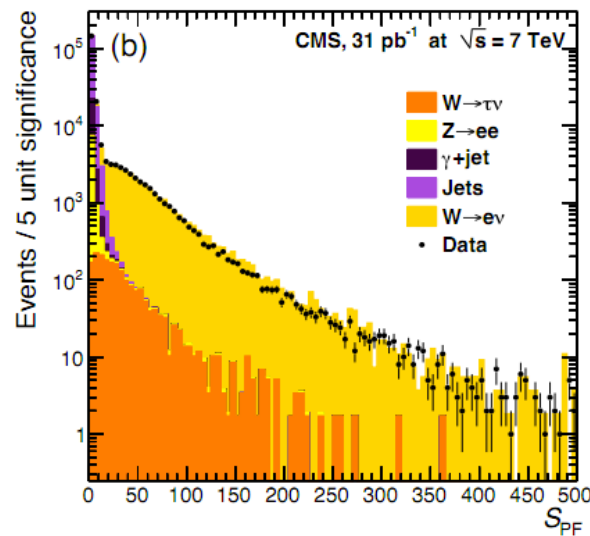
Missing transverse energy

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



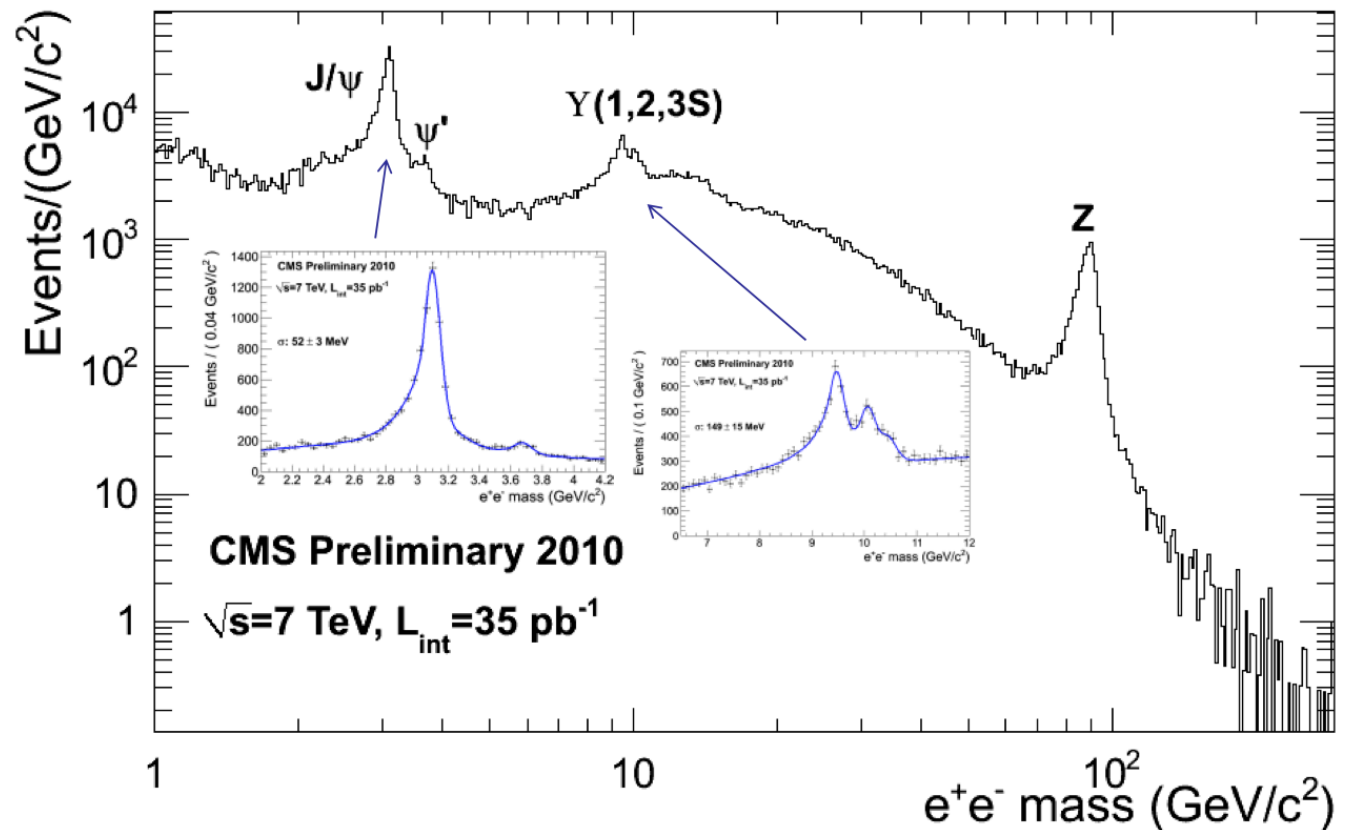
Missing transverse energy

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



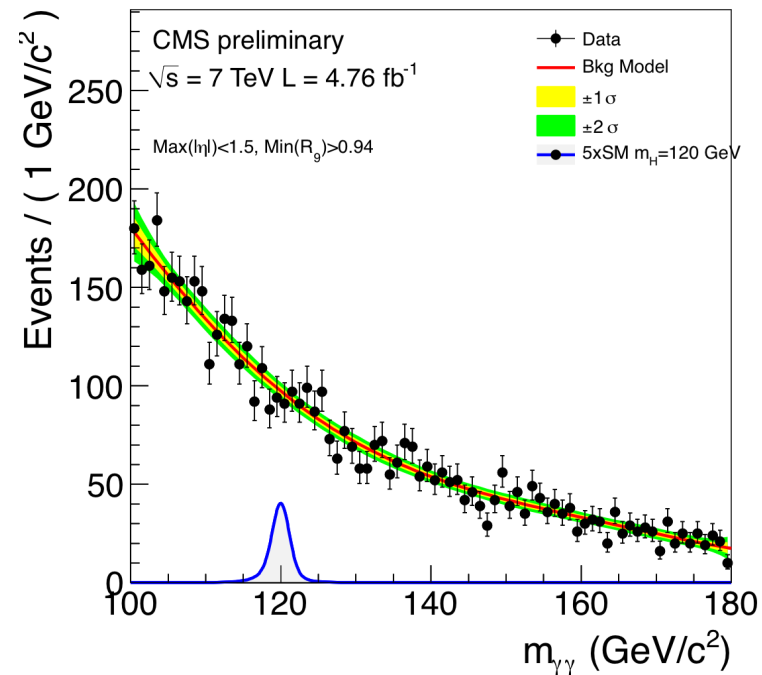
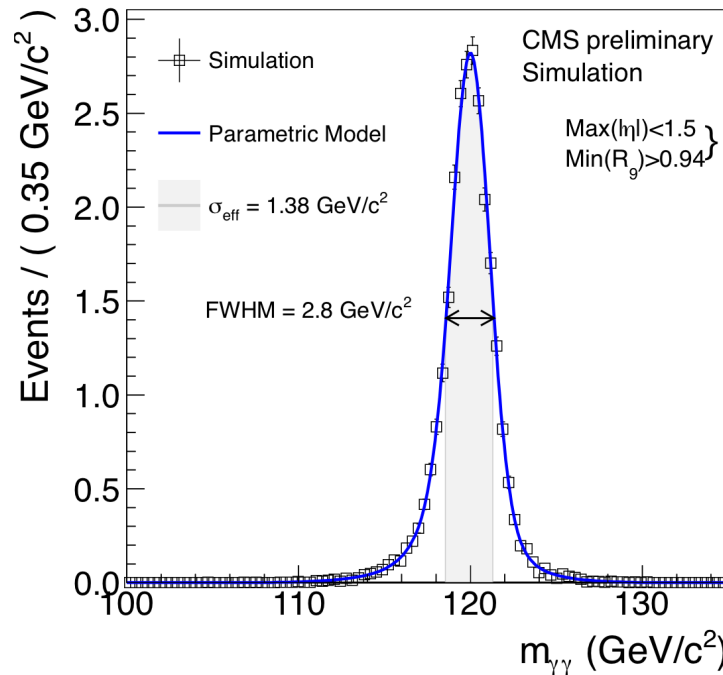
CMS ECAL performance

- Dielectrons from J/psi to Z



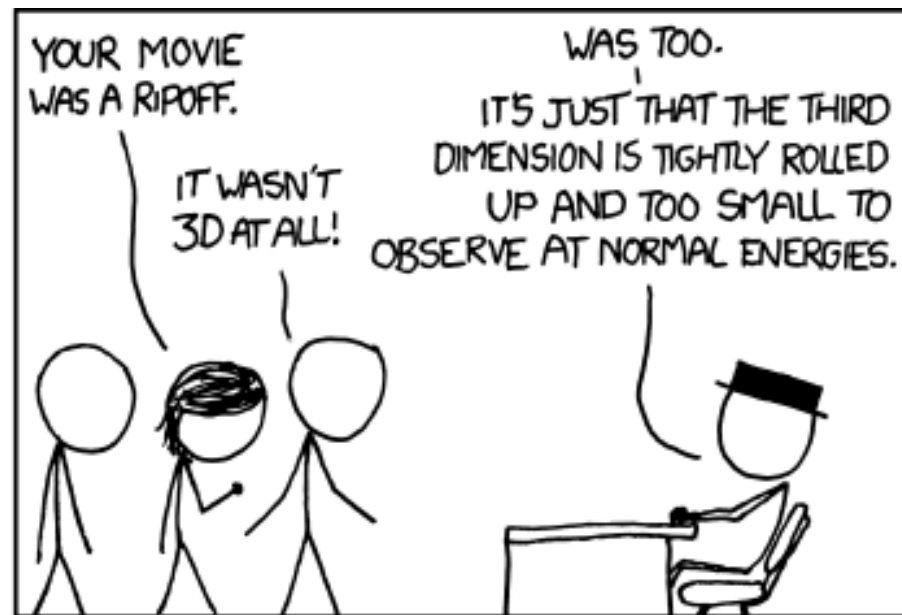
CMS ECAL performance

- SM Higgs to diphoton search.
 - Photon energy resolution crucial to mass peak resolution.
 - Best mass resolution: $\sim 1\%$ (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.



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 Calorimetry 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