After the collisions, before the analysis.

Detection and detectors

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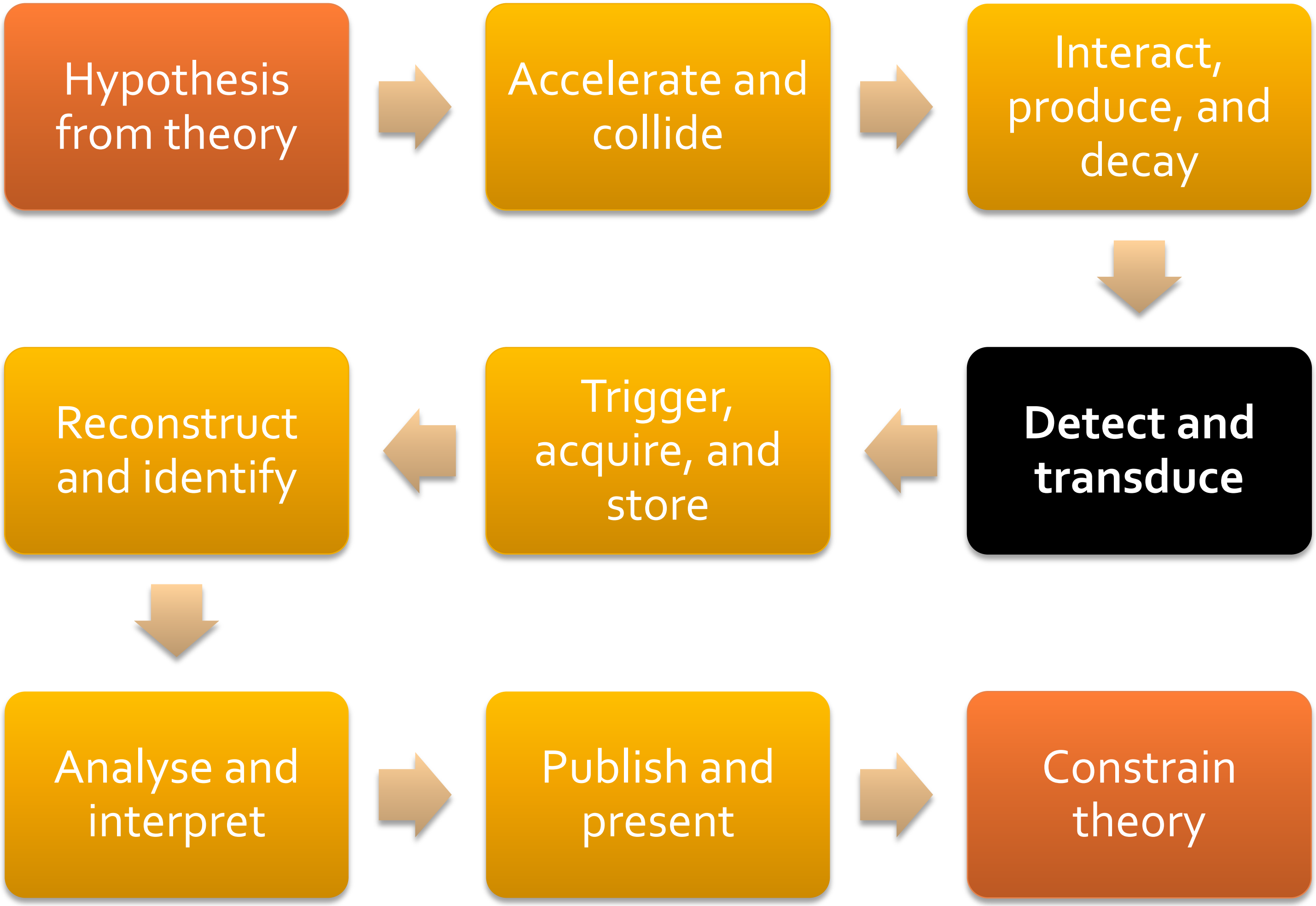
Who is this guy?

- Experimental physicist
  - Detector builder, Nature scrutiniser, Engineer botherer, and Theory disprover.

You are here



Hypothesis from theory

Accelerate and collide

Interact, produce, and decay

Detect and transduce

Trigger, acquire, and store

Reconstruct and identify

Analyse and interpret

Publish and present

Constrain theory

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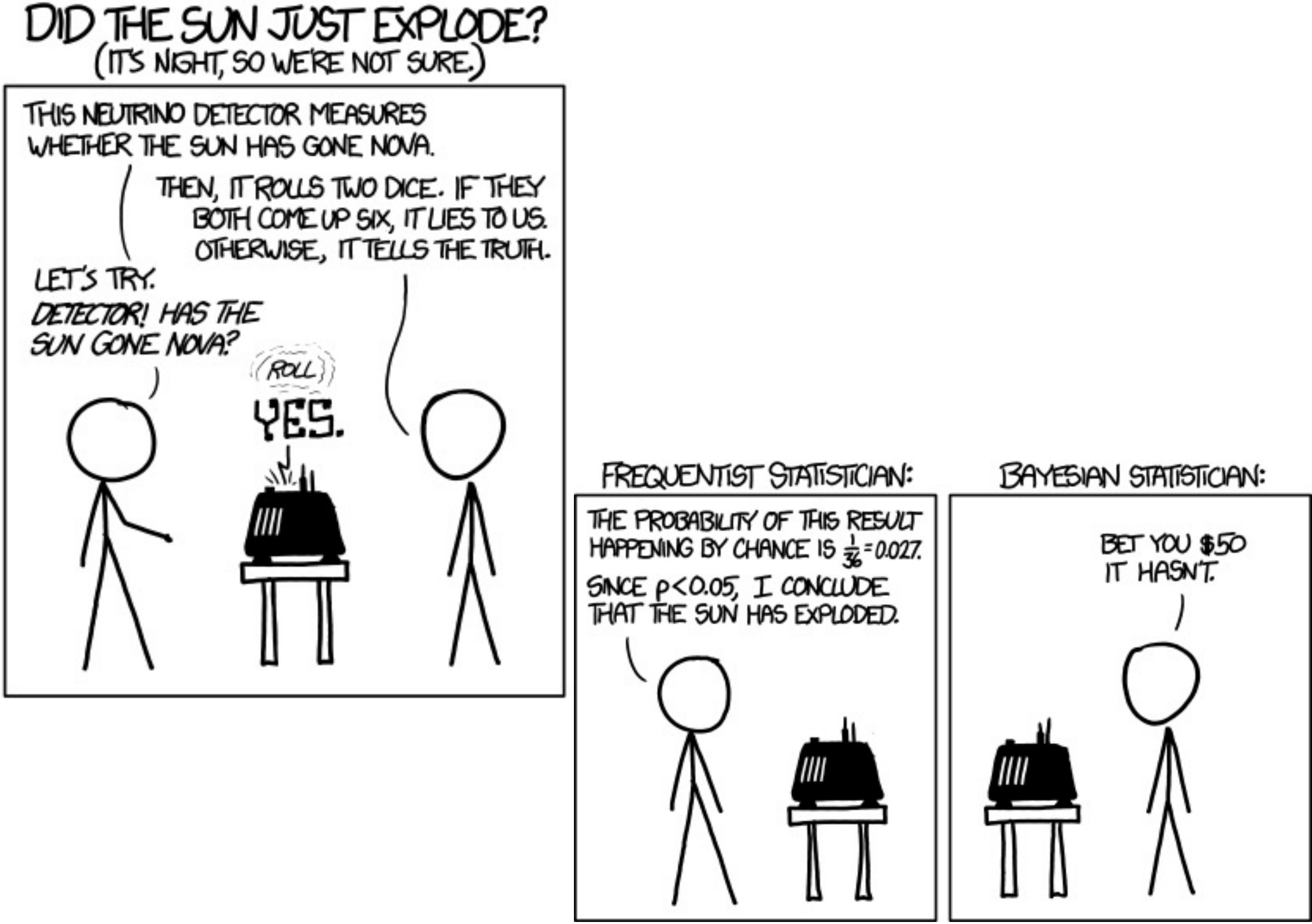
DID THE SUN JUST EXPLODE?
(IT'S NIGHT, SO WE'RE NOT SURE.)
THIS NEUTRINO DETECTOR MEASURES WHETHER THE SUN HAS GONE NOVA.
THEN, IT ROLLS TWO DICE. IF THEY BOTH COME UP SIX, IT LIES TO US. OTHERWISE, IT TELLS THE TRUTH.
LET'S TRY. *DETECTOR! HAS THE SUN GONE NOVA?*
(ROLL)
YES.
FREQUENTIST STATISTICIAN:
THE PROBABILITY OF THIS RESULT HAPPENING BY CHANCE IS $\frac{1}{36}=0.027$. SINCE $p<0.05$, I CONCLUDE THAT THE SUN HAS EXPLODED.
BAYESIAN STATISTICIAN:
BET YOU $50 IT HASN'T.

“Rivelatori”

- The Italian for detector is “**rivelatore**”.

- Detectors **reveal** the presence of particles:
  - **What** kind of particle.
  - **Where** the particle came from and went through.
  - **How much energy** the particle had.

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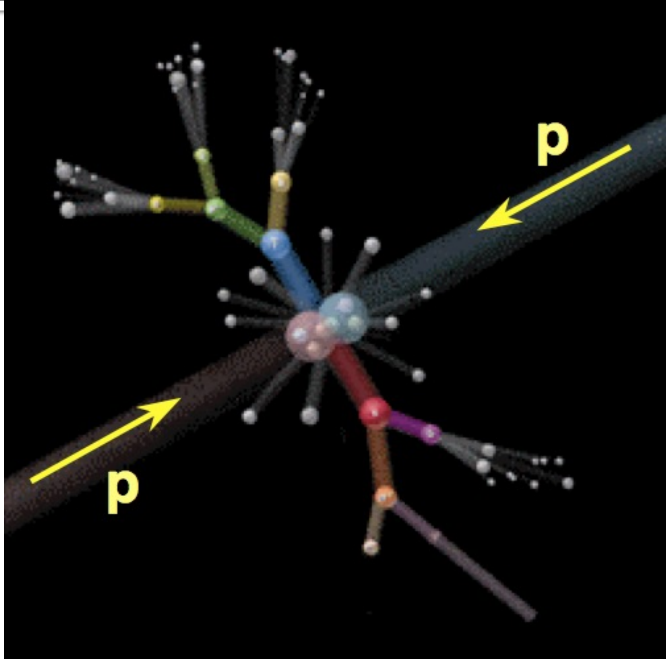
What gets produced in collisions



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

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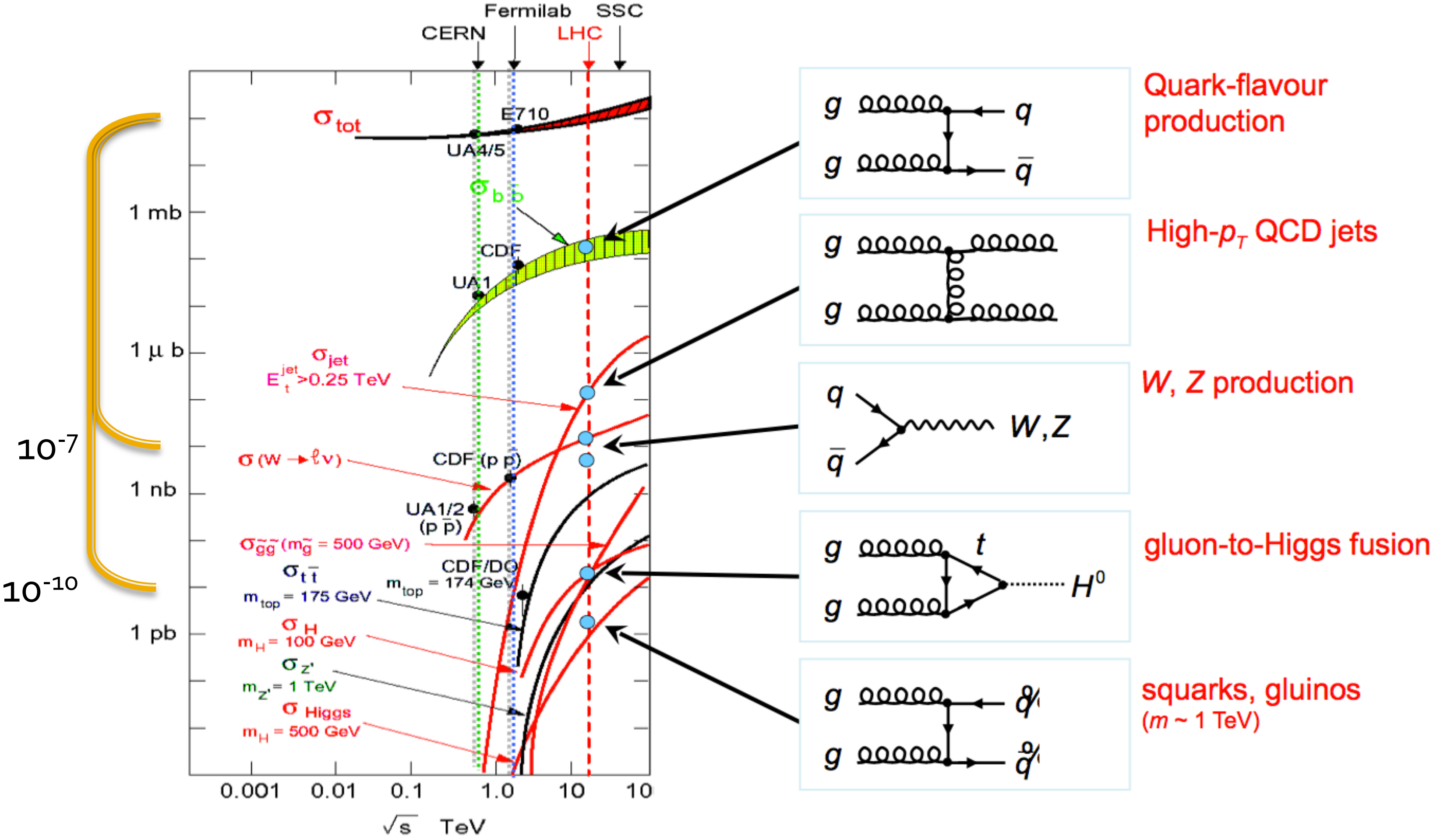
What gets produced in collisions



Quark-flavour production

High-p_T QCD jets

W, *Z* production

gluon-to-Higgs fusion

squarks, gluinos
(*m* ~ 1 TeV)

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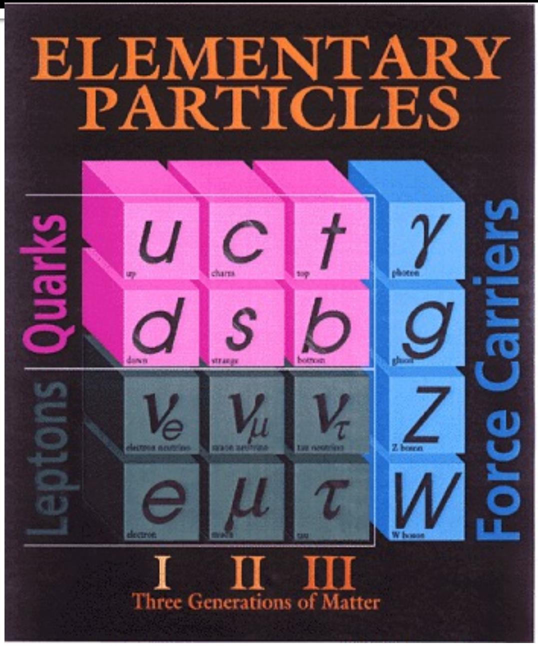
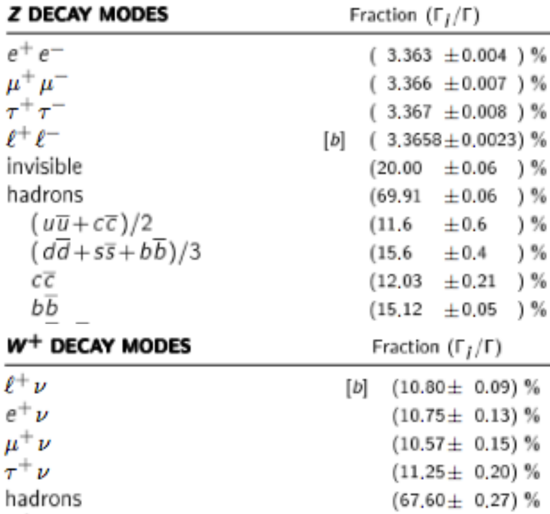
What we can detect



- 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: two **photons**.
  - u, d, s quarks and gluons: **jets** of mostly **pions**.
  - c, b quarks: jets with long-lived **mesons**.
  - W, Z bosons, τ leptons: **multiple decay** topologies. →
  - “Everyone” else in the Review of Particle Physics “phonebook”: https://pdglive.lbl.gov/.



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) %

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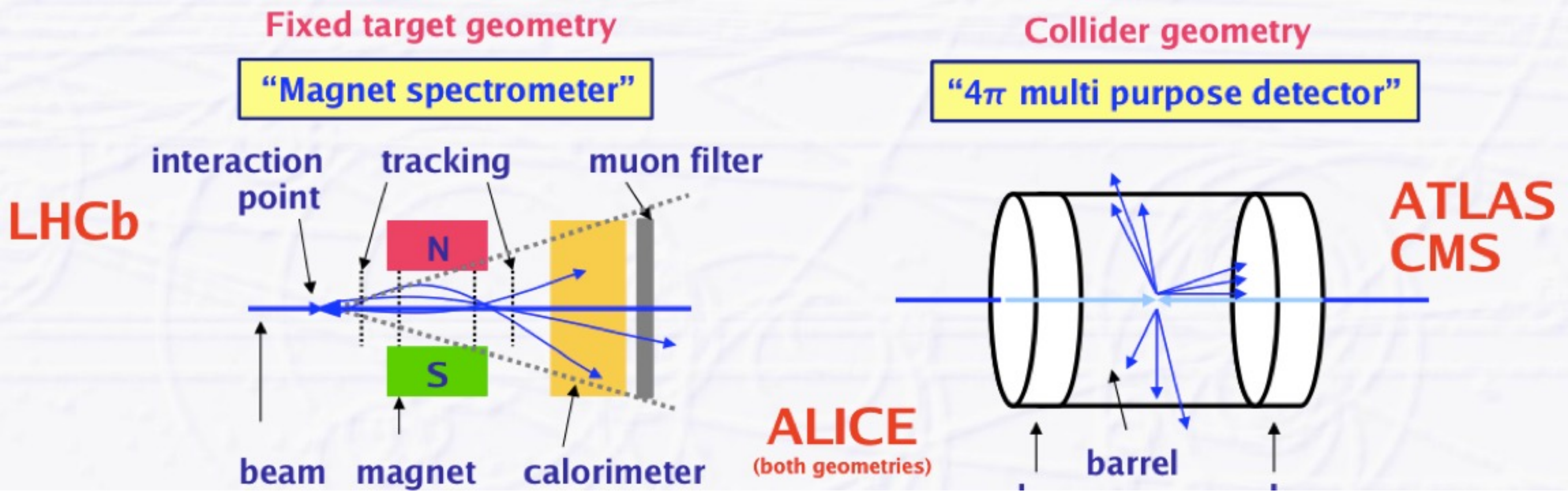
Shapes of experiments

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



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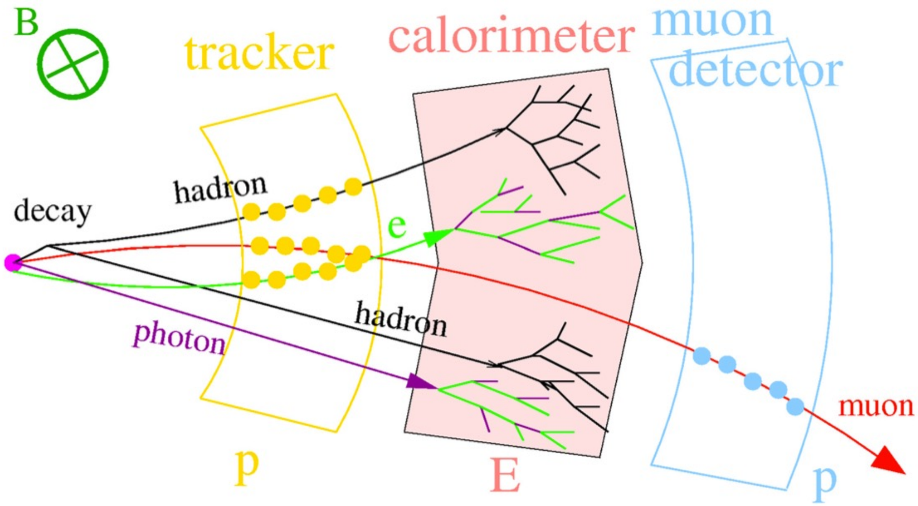
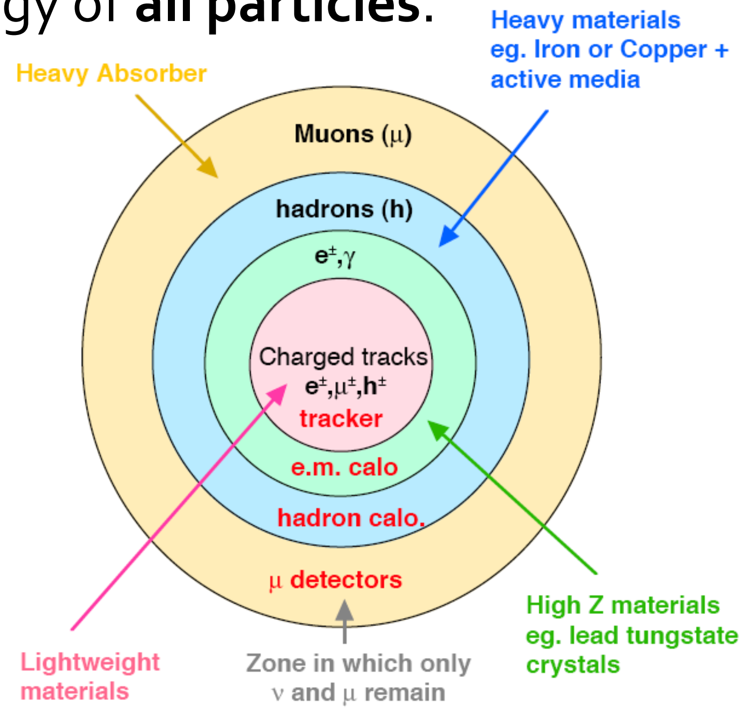
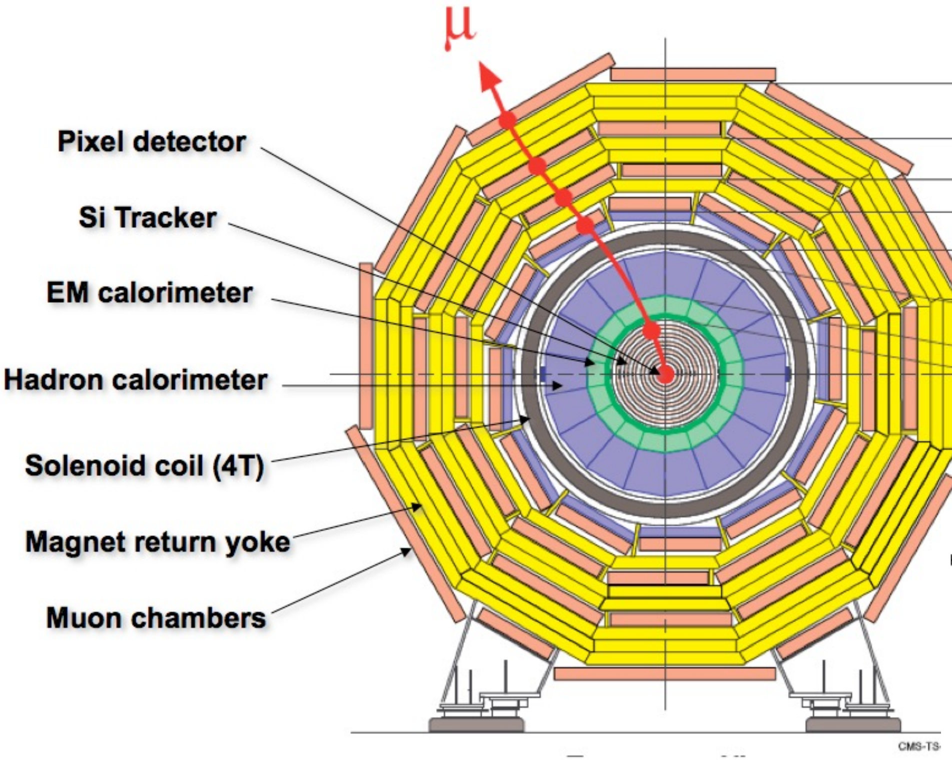
Peeling the hermetic onion

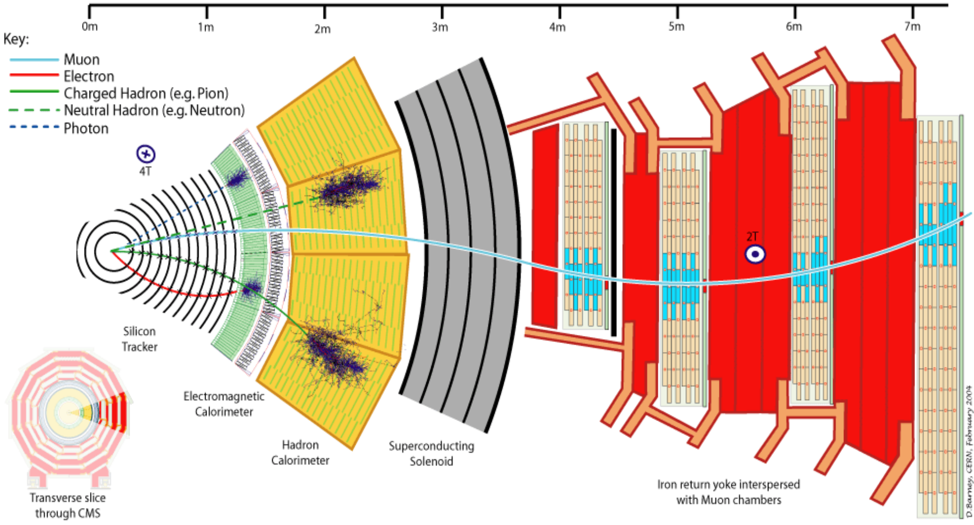
- Inner tracking
  - Measure charged particles **disturbing them the least possible**.
- Calorimetry
  - Measure as much as possible the energy of **all particles**.
- Outer tracking
  - Measure and identify **muons**.





CMS example





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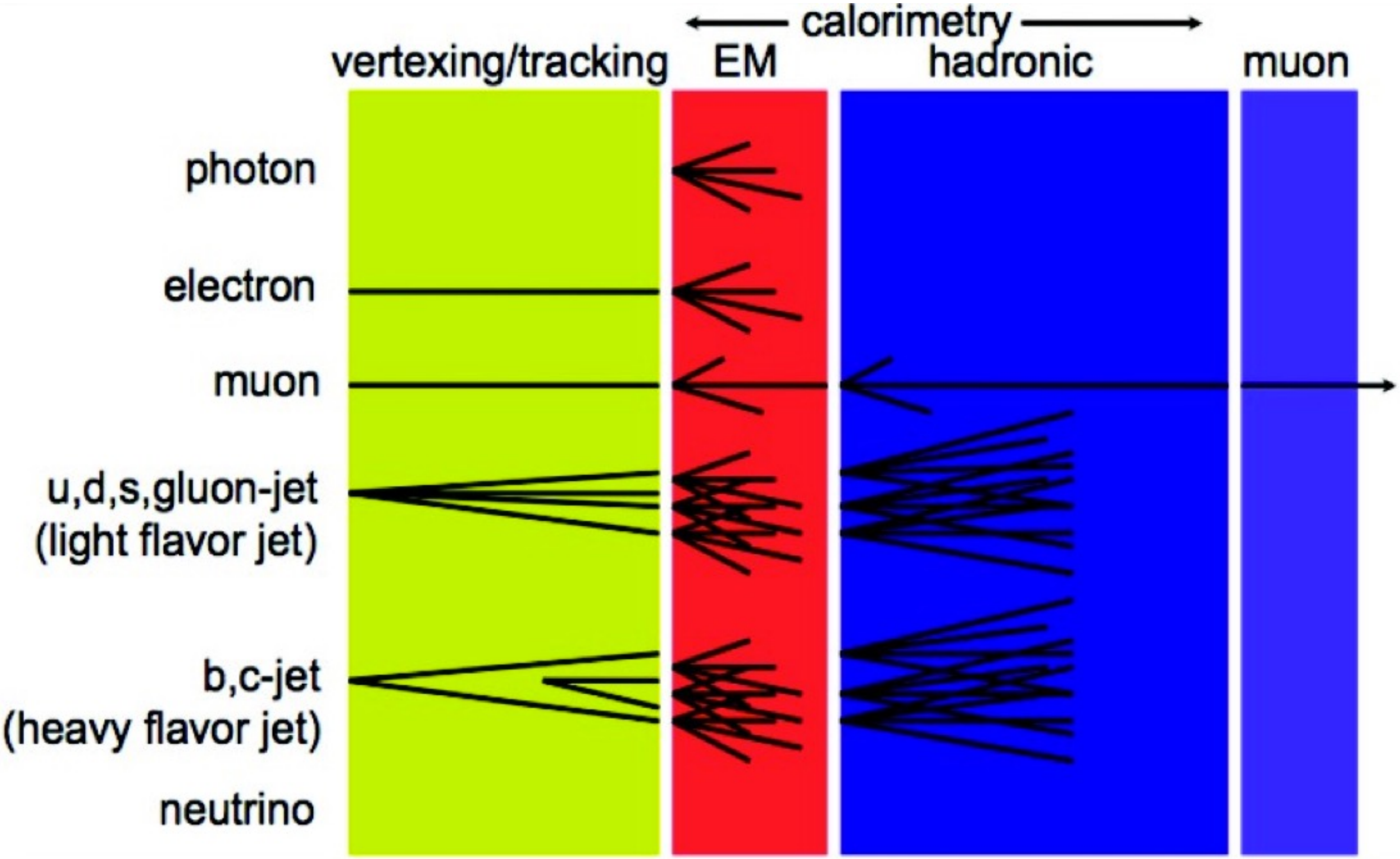
Particles and their decays



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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.

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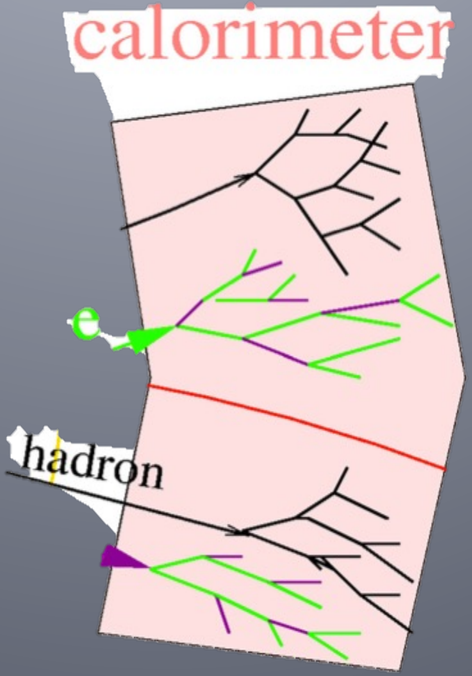
Calorimetry

Trying to measure the energy of everything except muons.



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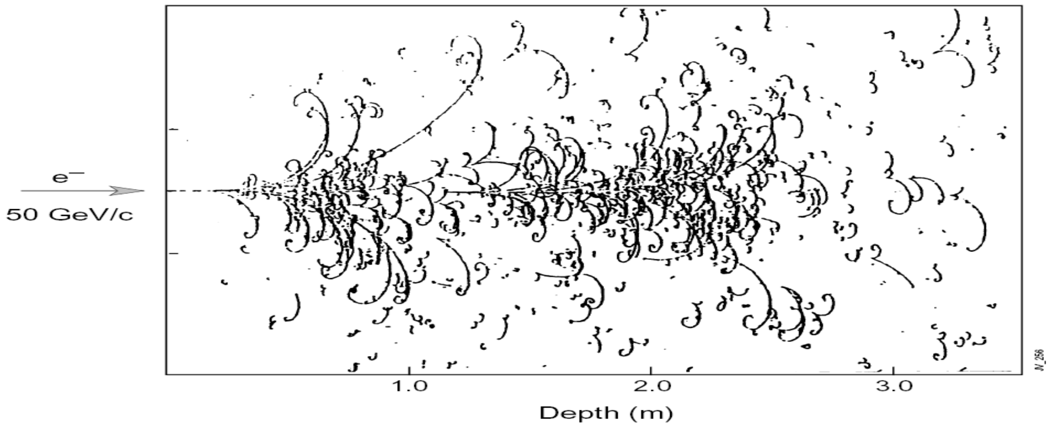
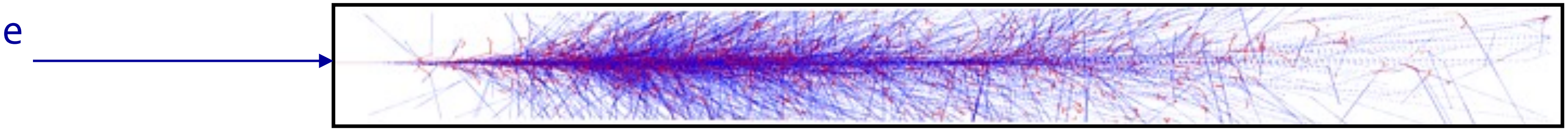
Calorimetry: what?

- 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)

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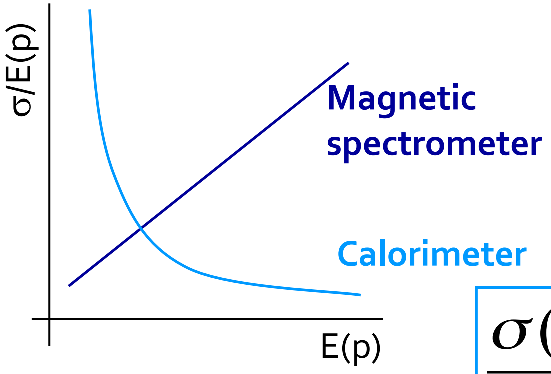
Calorimetry: why?

- 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.

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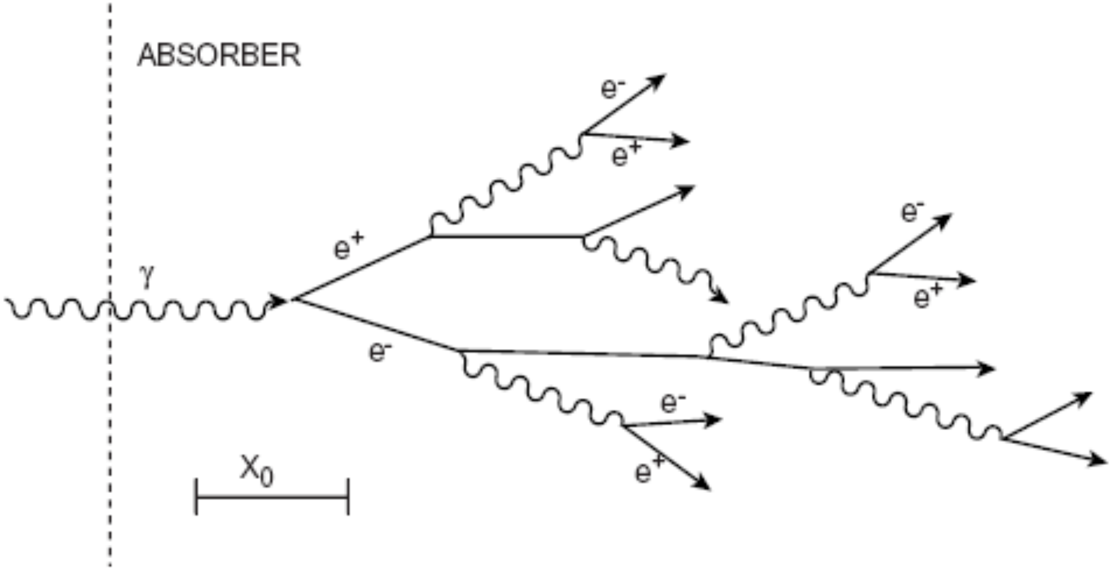
Electromagnetic showers

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

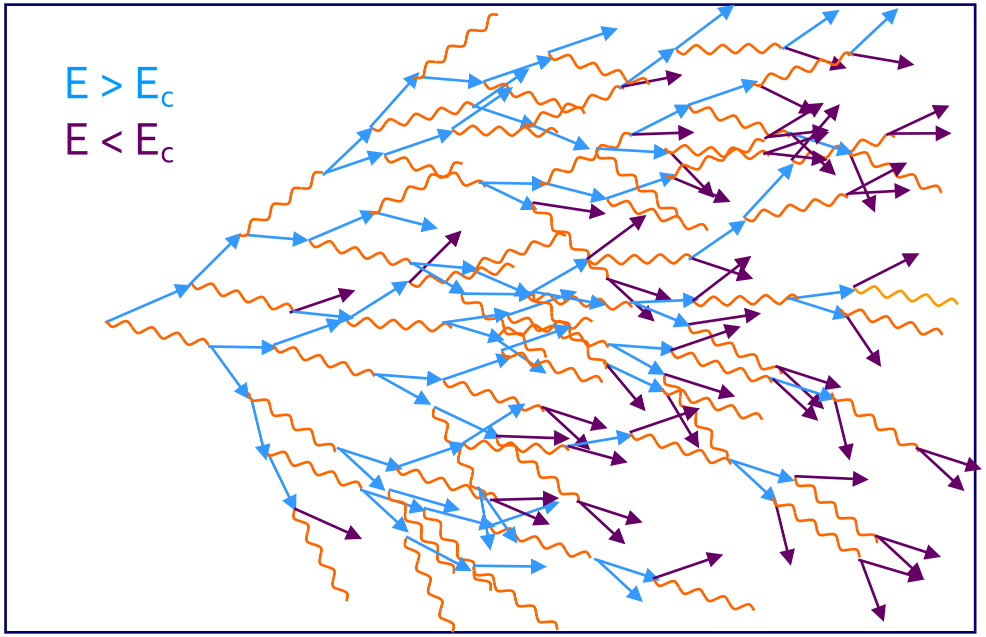
- Radiation length (X_0) defined to be the distance over which an electron loses all but 1/e of its energy.
- Useful approximation ➔
  - Rough derivation in [Cal1]; more precise approximation in [Cal2].

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

- **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].**



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Hadronic showers

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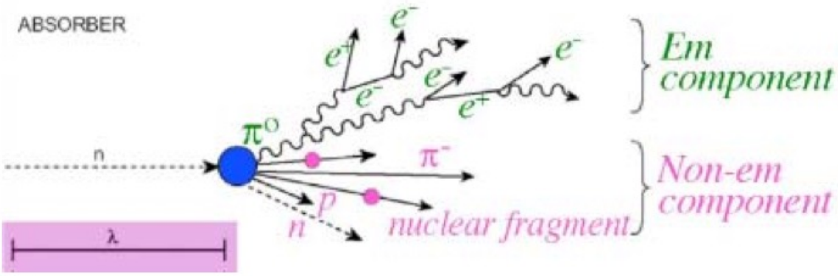
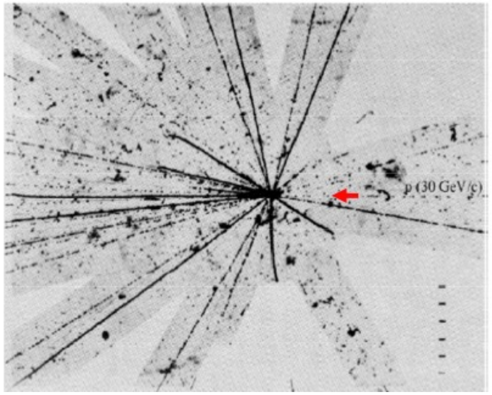
Hadronic cascade

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



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

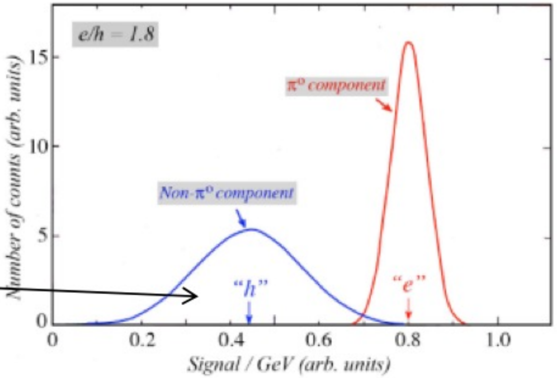
Charged hadrons	(20%)
Nuclear fragments , p	(25%)
Neutrons, soft γ's	(15%)
Breakup of nuclei	(40%)



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

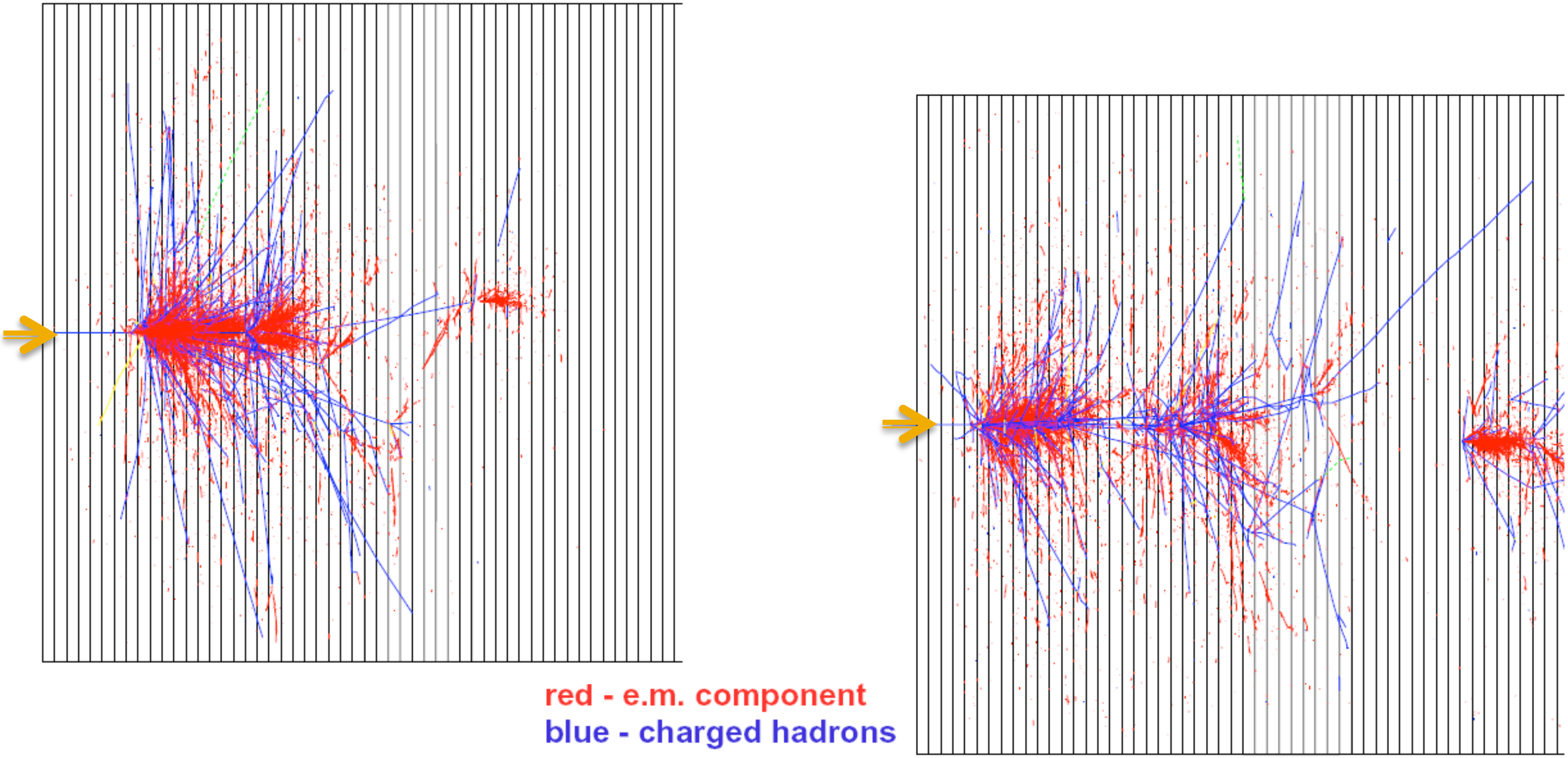
= Invisible energy

e/h > 1



Hadron showers

- Individual hadron showers are quite dissimilar



red - e.m. component
blue - charged hadrons

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 $\sigma_{\text{inel}} \approx \sigma_0 A^{0.7}$, $\sigma_0 = 35$ 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.

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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.

Comparison of stochastic performance

Scintillating crystals

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

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

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

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

Cherenkov radiators

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

$$\approx 10 \div 30 \; \gamma / \mathrm{MeV}$$

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

Homogeneous LKr calorimeter NA48/62

Ionisation signal

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

ATLAs Pb-LAr sampling

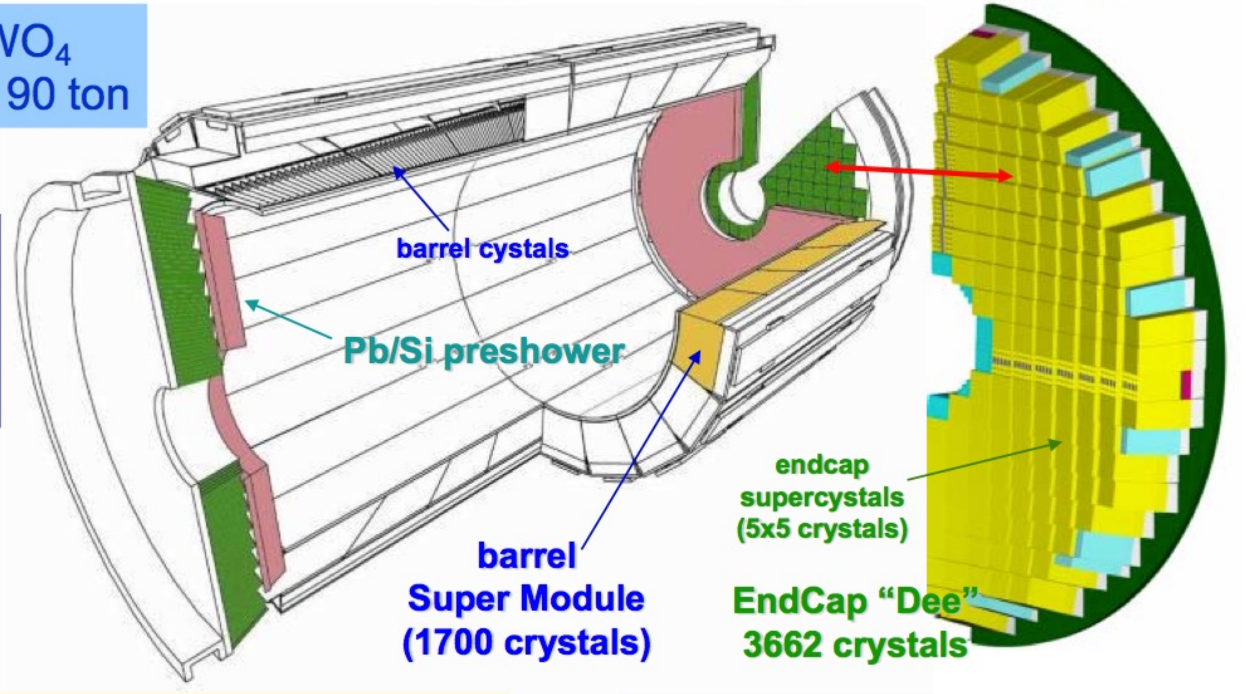
$$t = d/X_0 \approx 0.4$$

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

CMS ECAL

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

Previous Crystal calorimeters: max $1m^3$


Precision electromagnetic calorimetry: 75848 PWO crystals

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

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

Transparency monitoring

The Solution:

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

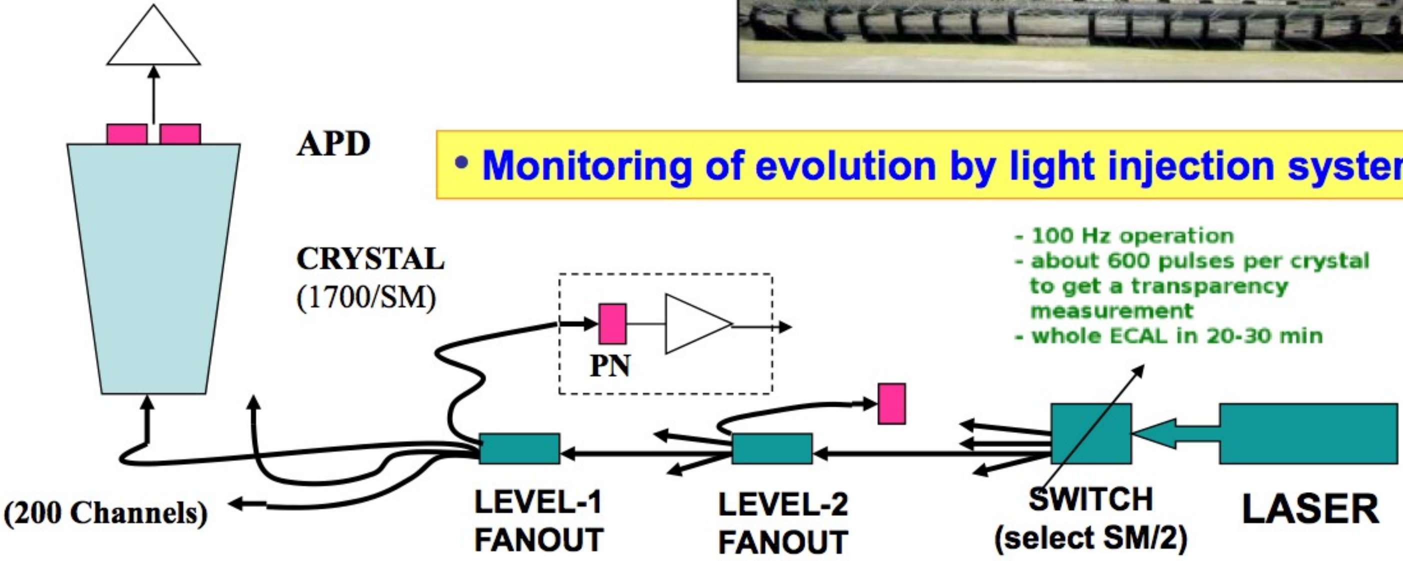
2 wavelengths are used:

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



APD

CRYSTAL
(1700/SM)

PN

(200 Channels)

LEVEL-1
FANOUT

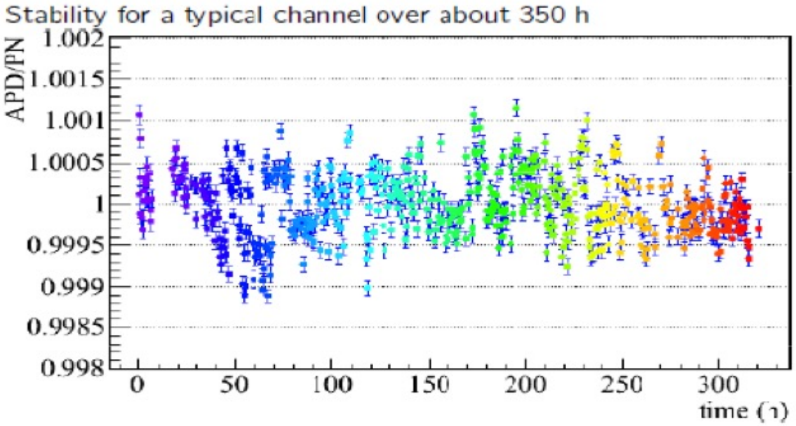
LEVEL-2
FANOUT

SWITCH
(select SM/2)

LASER

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

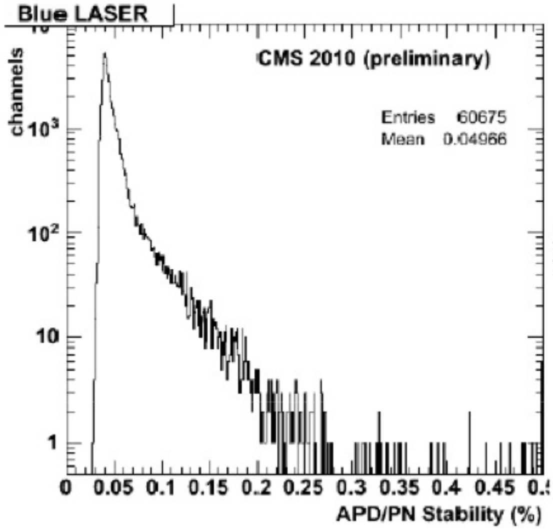
Transparency monitoring

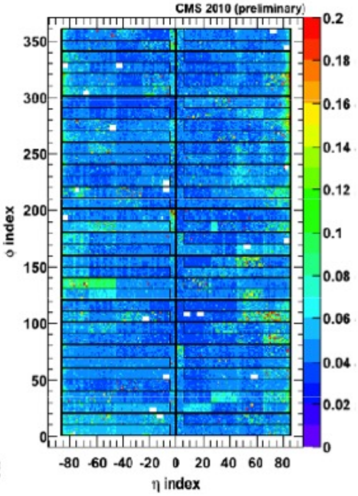


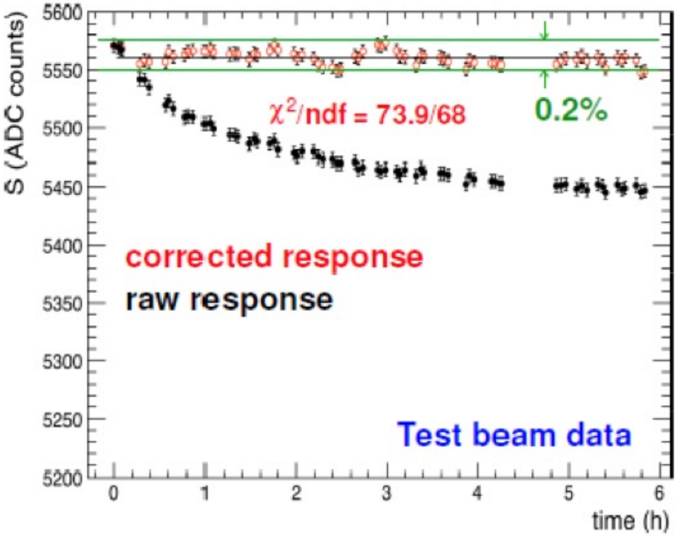
Measure a loss of transparency:
S (particle signal) and R(laser signal)

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

NB: α is ~ the same for all crystals!







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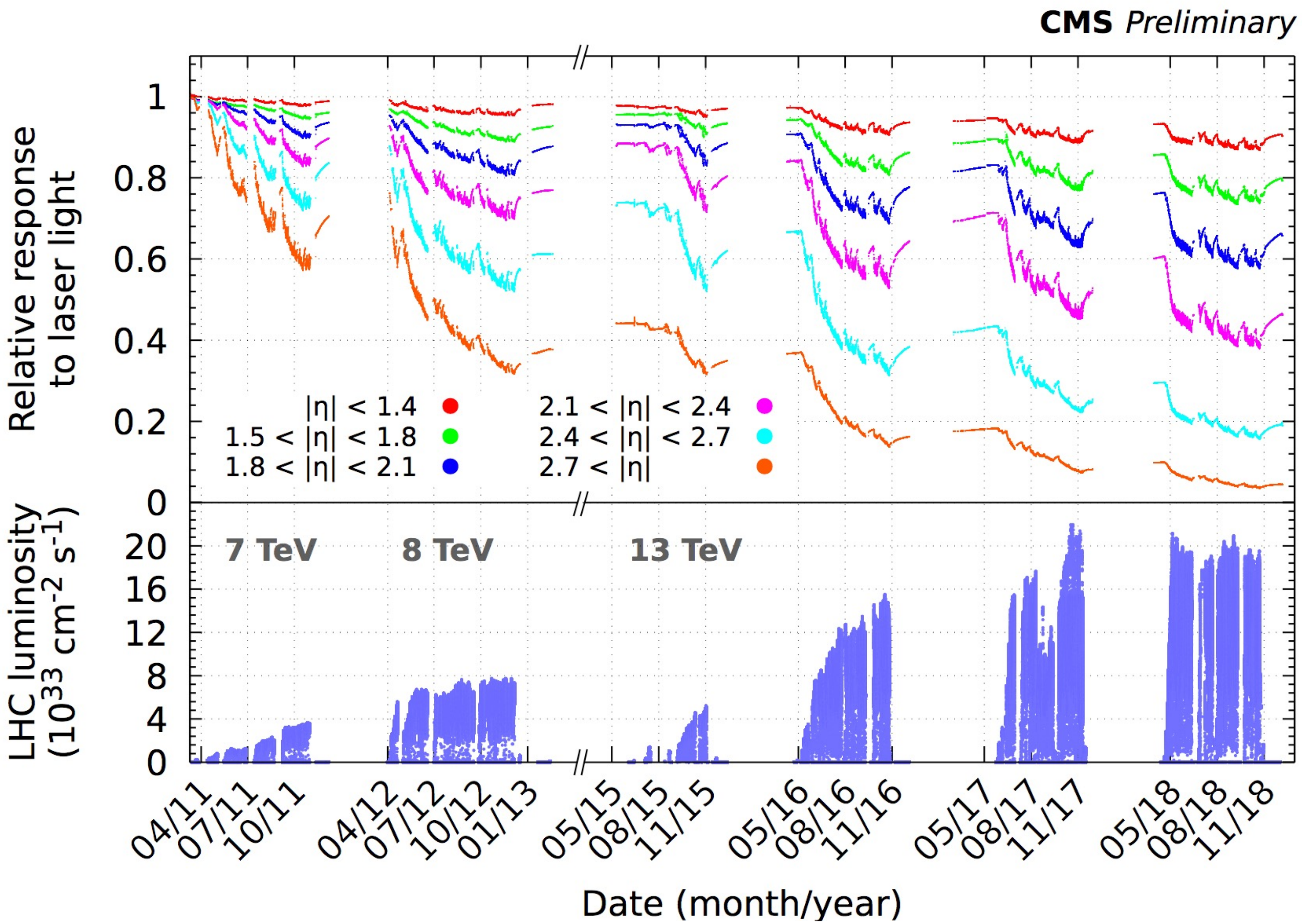
Transparency monitoring



Hadronic energy resolution

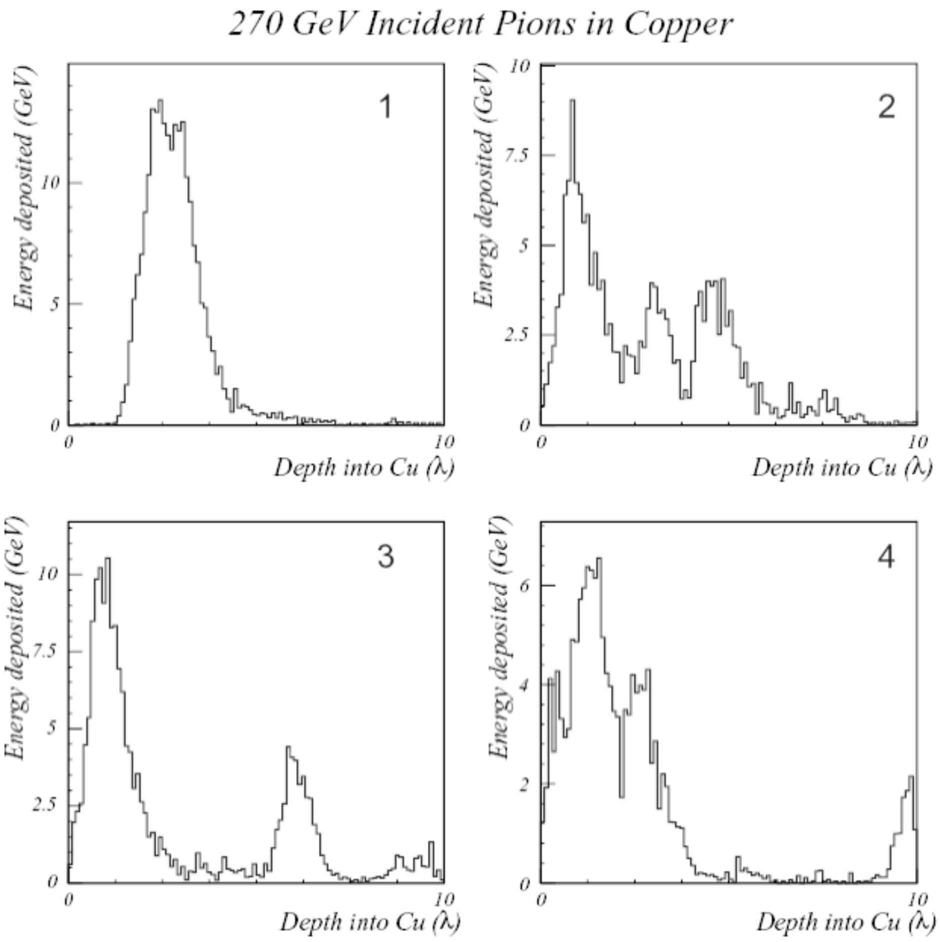
- Hadronic calorimeters are (almost) always sampling calorimeters.

- 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:



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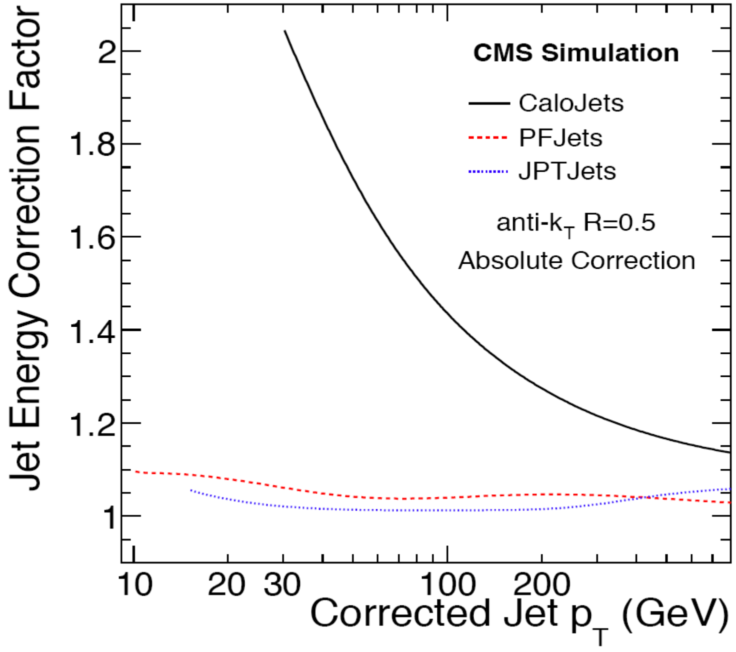
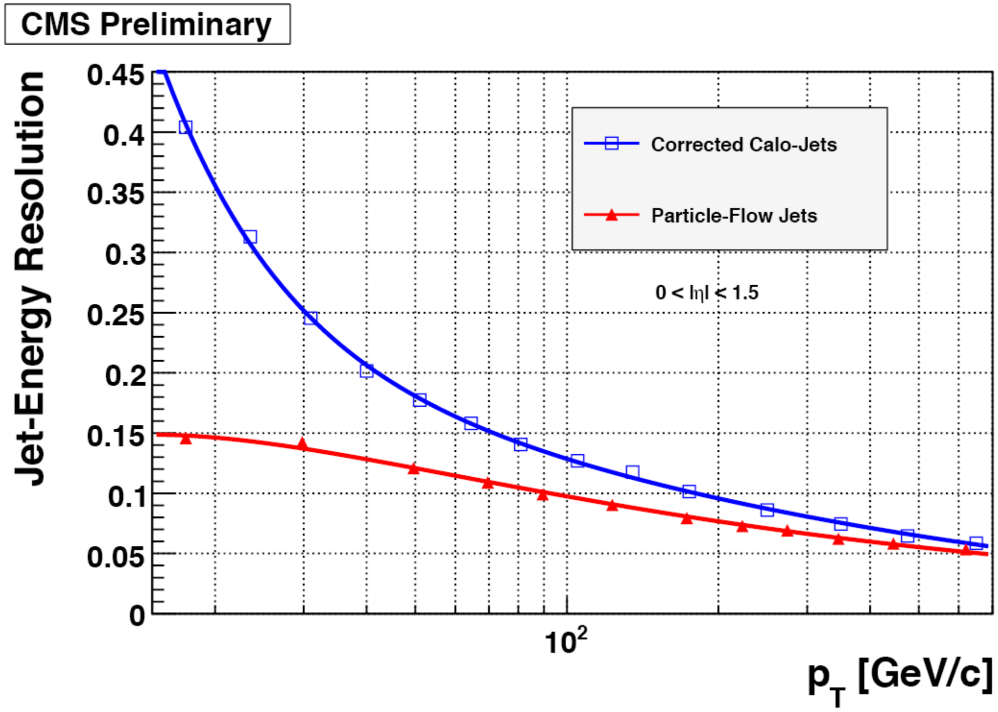
Example of particle flow in CMS

- 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.





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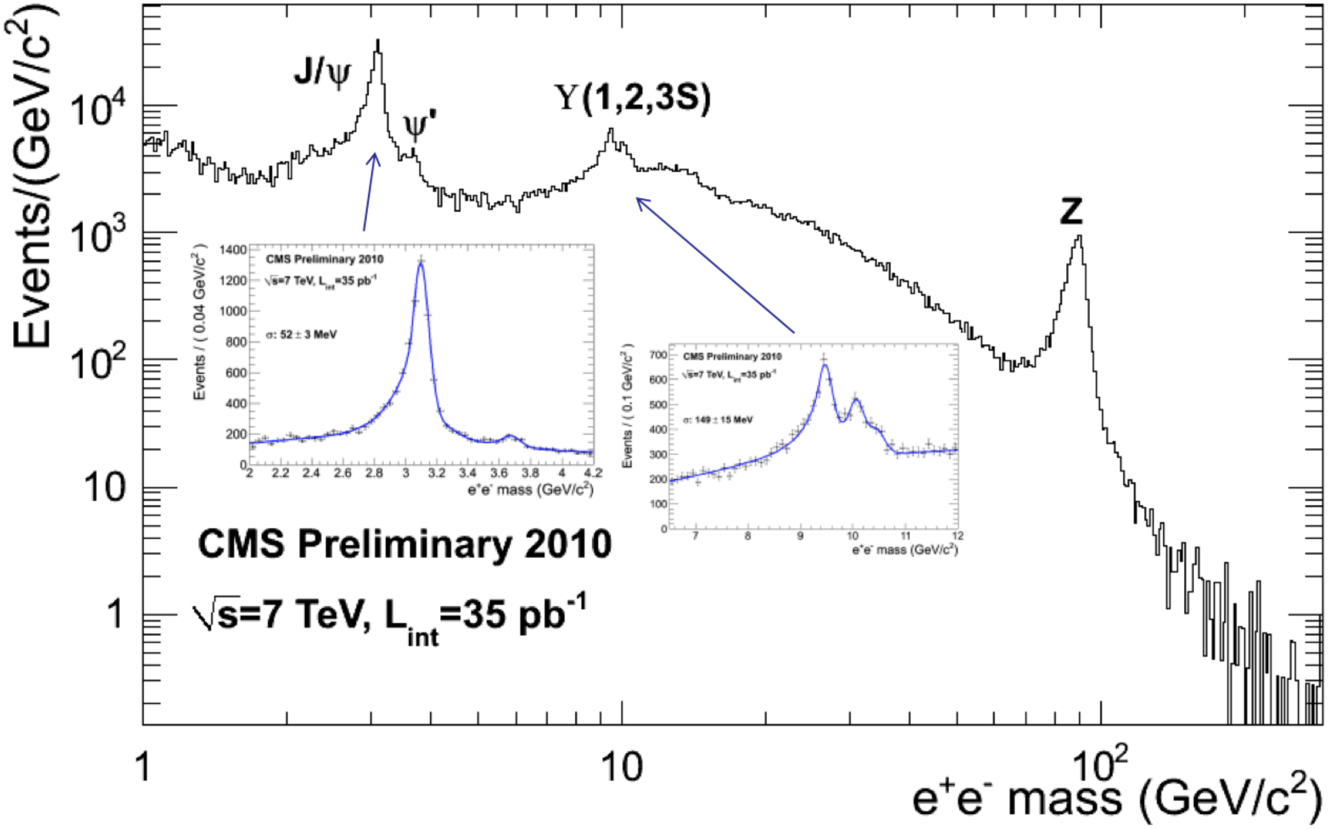
CMS ECAL performance

- Dielectrons from J/ψ to Z



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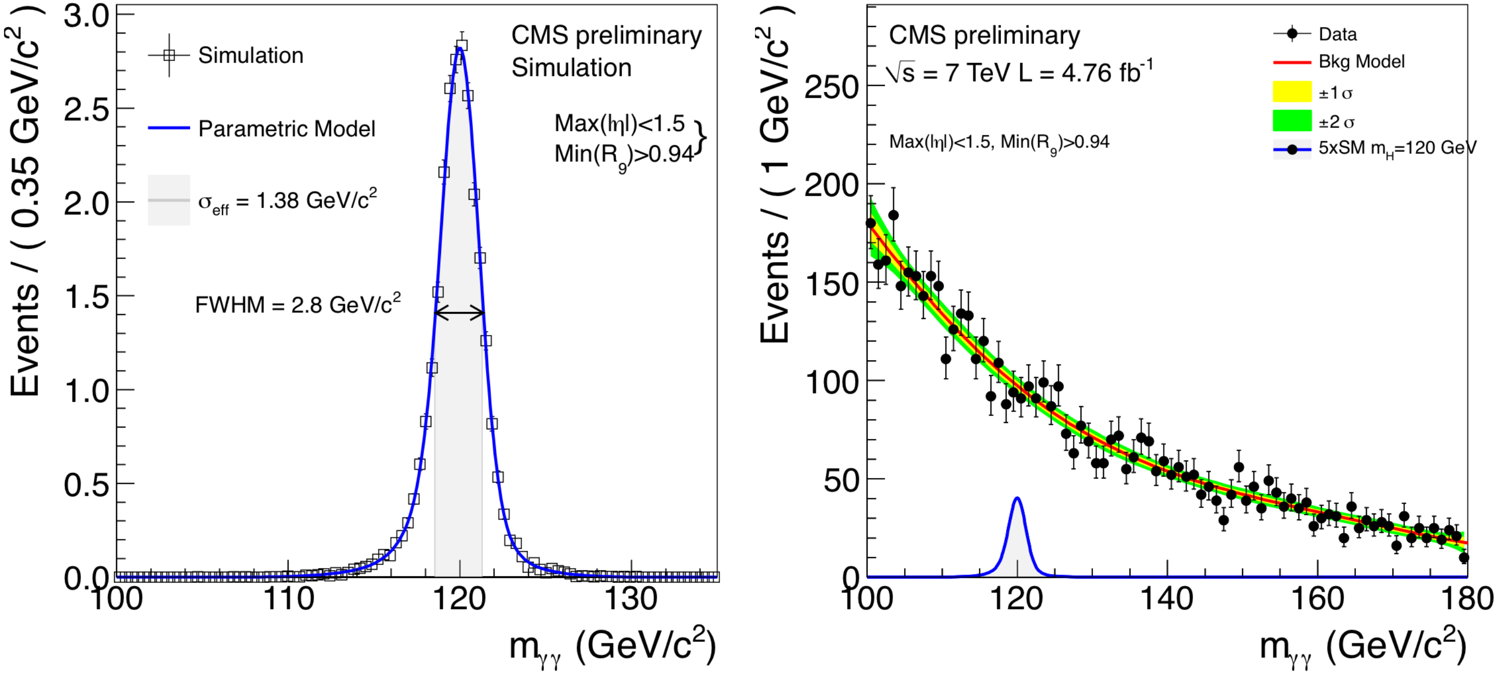
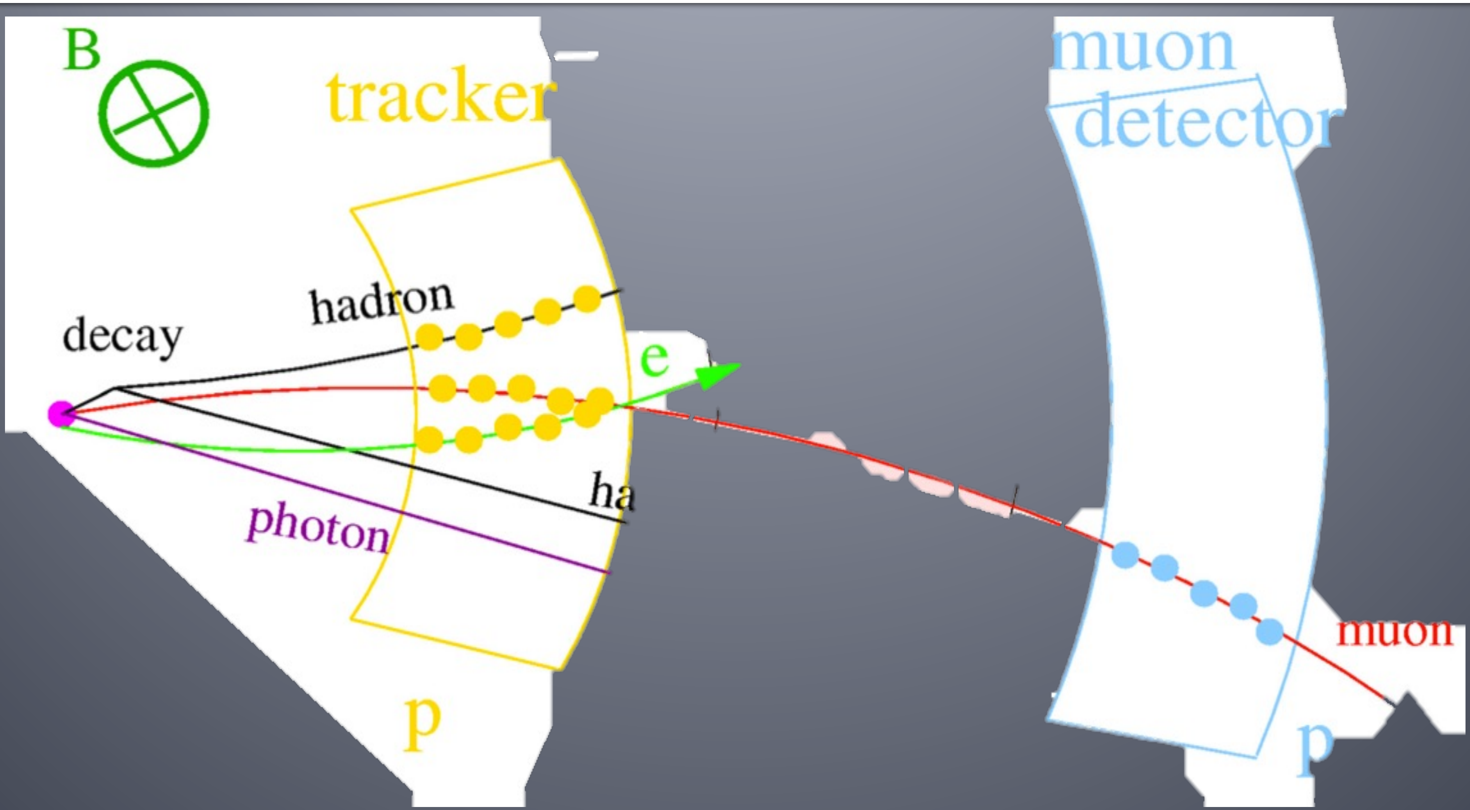
CMS ECAL performance

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



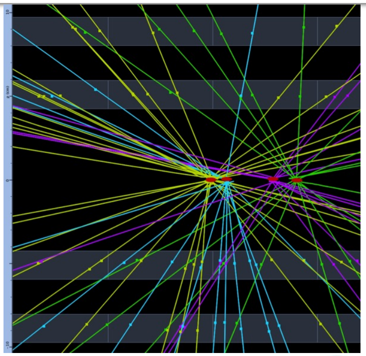
Tracking

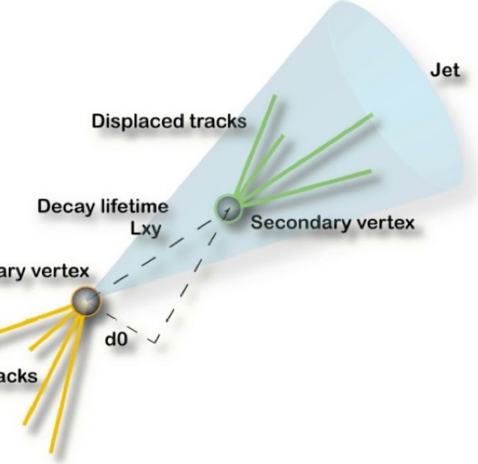
Trying to retrace the path of charged particles, including far-reaching muons.

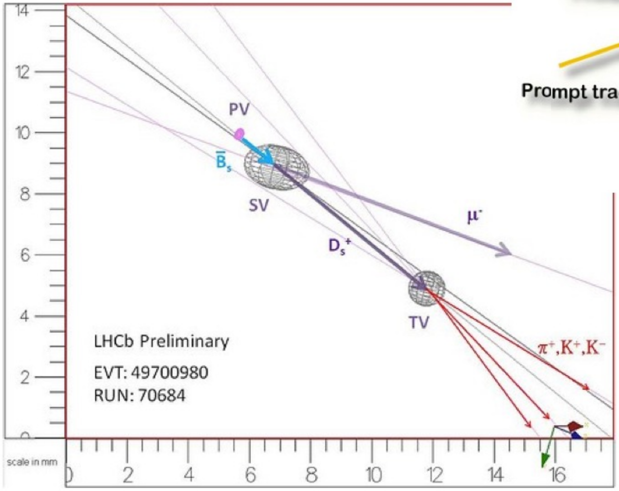


Tracking: why?

- To find the hard interaction vertex. ➔
- To identify secondary vertices. ➘
  - Longer-lived particles.
- To measure trajectory of particles.
  - Momentum and energy loss of charged particles.
  - Connection to showers in calorimeters (electrons, photons).
  - Provide inner leg for muon reconstruction.

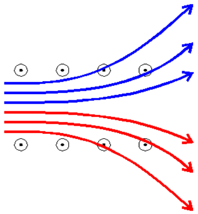






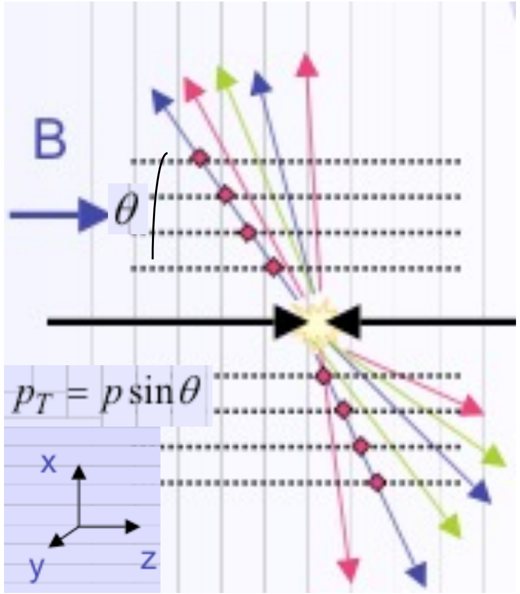
Tracking: what?

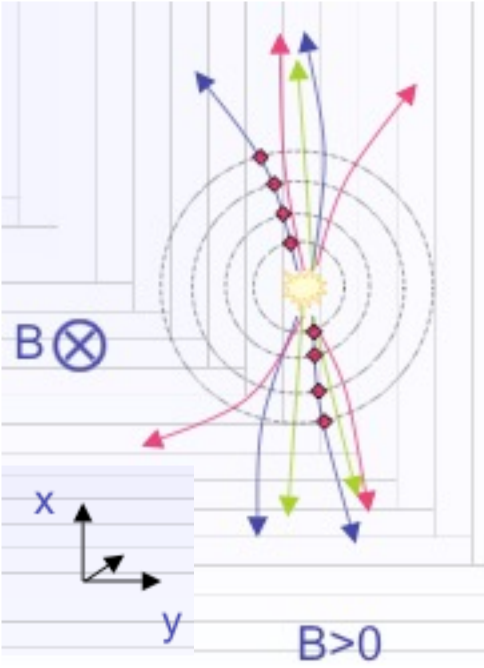
- Solid state detectors.
  - Pixels for vertexing.
  - Strips for tracking.
- Gaseous detectors.
  - Drift tubes, etc for outer tracking.



$$F = q\cdot v\cdot B = m\cdot \frac{v^2}{R}$$

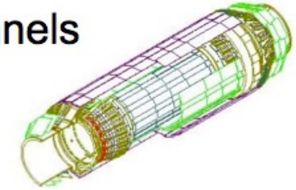
$$\Rightarrow q\cdot B\cdot R = m\cdot v = \left|\vec{p}\right|$$



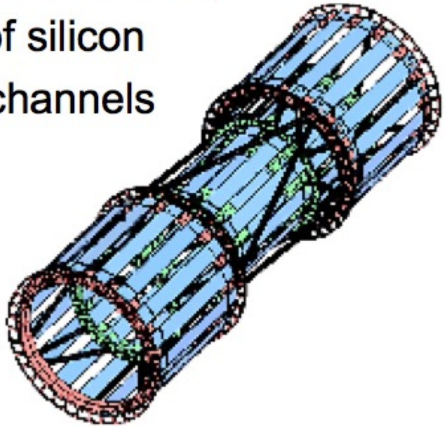


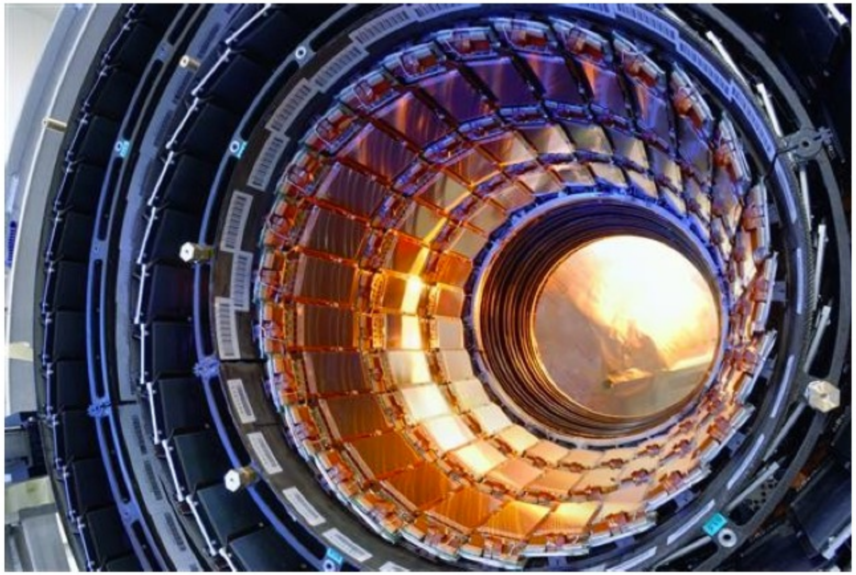
Tracking: how?

- LEP eg. DELPHI (1996)
  - 1.8 m^2 of silicon
  - 175k readout channels



- CDF SVX IIa (2001)
  - 6 m^2 of silicon
  - 175k channels





- CMS tracker
  - full silicon tracker
  - 210 m^2 of silicon
  - 10.7 M channels

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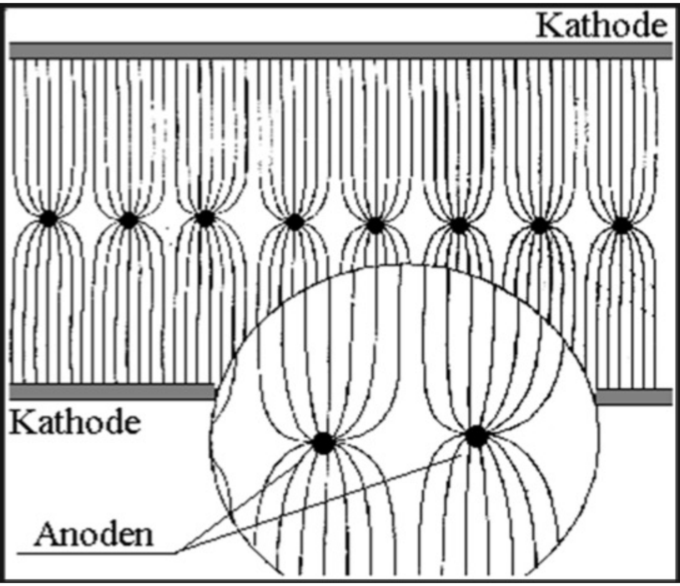
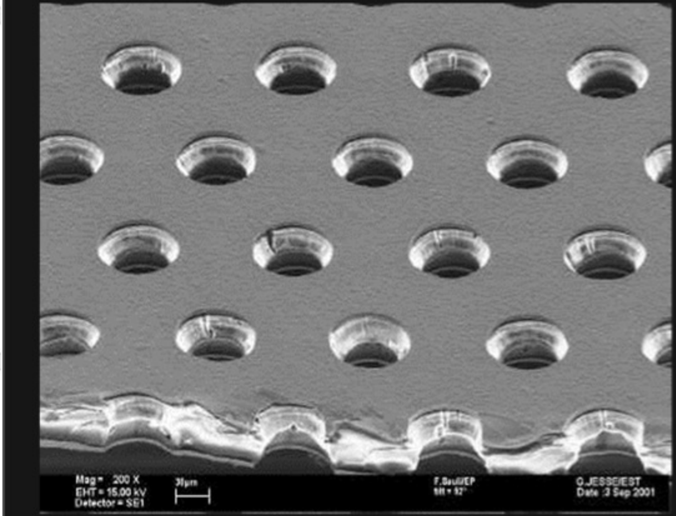
Tracking: how?

- Drift Tubes.
- Microstrip Gas Counters.
- Gas Electron Multipliers.





Inner trackers

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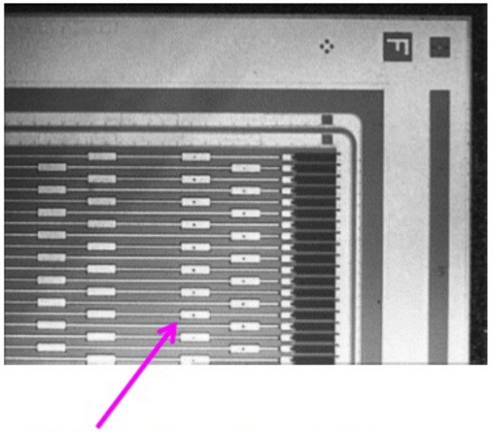
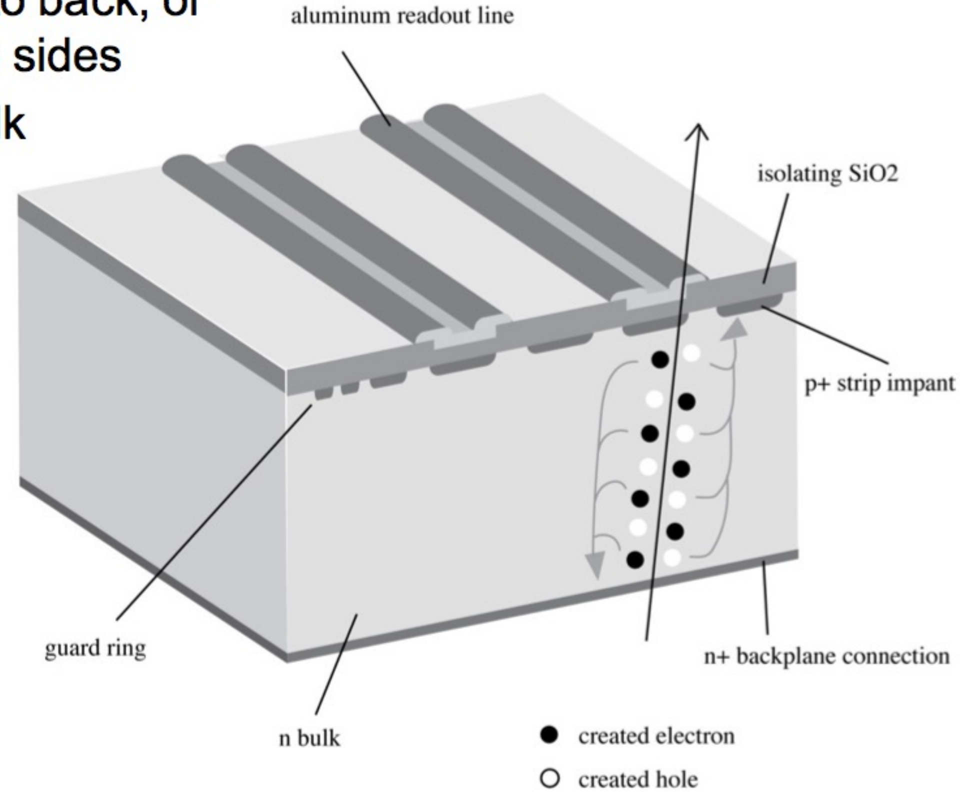
Microstrips sensors

- Make many diodes on one wafer
  - ~50 μm strip pitch (possible with planar fabrication process)
  - Glue wafers back-to back, or make strips on two sides
  - eg. p strips in n bulk



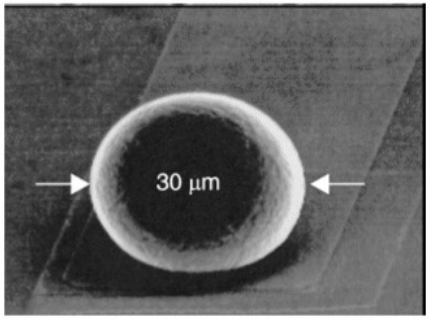
Metalisation above strips, with bond pads

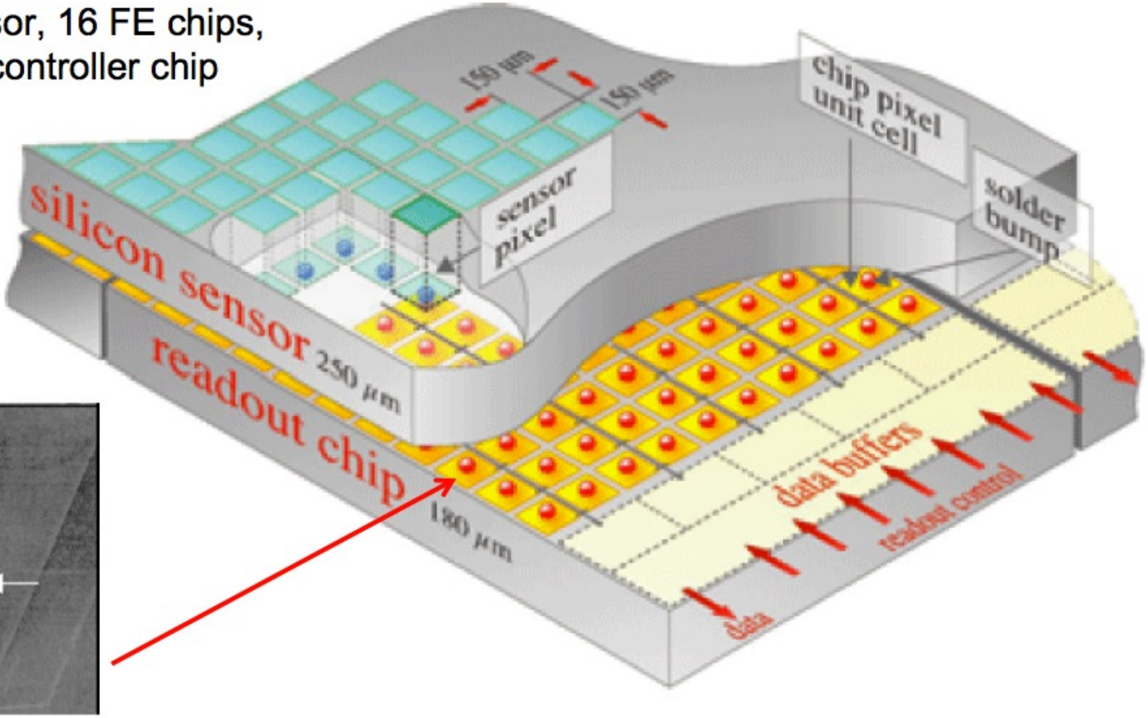


Pixel sensors

- 2-d position information with high track density.
  - Back-to-back strips give “ghost” hits. Pixels give unambiguous point
- Hybrid pixel detectors with sensors and readout chips bump-bonded together in a module
  - eg. one sensor, 16 FE chips, one master controller chip

bump bond





Tracks

Momentum measurement

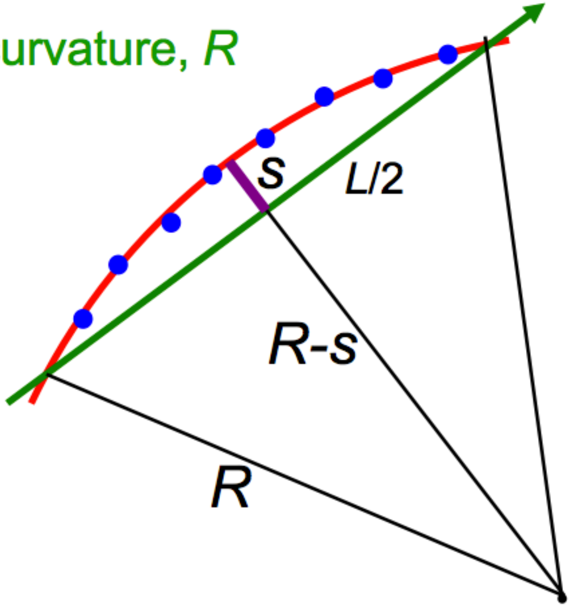
- Circular motion transverse to uniform B field:

$$p_T[\mathrm{GeV/c}] = 0.3 \cdot B[\mathrm{T}] \cdot R[\mathrm{m}]$$

- Measure sagitta, s, from track arc → curvature, R

$$R = \frac{L^2}{2s} + \frac{s}{2} \approx \frac{L^2}{2s}$$

- $$\frac{\sigma_{p_T}}{p_T} = \frac{8 p_T}{0.3 B L^2} \sigma_s$$



- Relative momentum uncertainty is proportional to p_T times sagitta uncertainty, σ_s. Also want strong B field and long path length, L

Measuring momentum

Sagitta uncertainty, σ_s, from N points, each with resolution $\sigma_{r\phi}$ is:

$$\sigma_s = \sqrt{\frac{A_N}{N+4}}\,\frac{\sigma_{r\phi}}{8}$$

Statistical factor $A_N = 720$:
(Gluckstern)

The point error, $\sigma_{r\phi}$ has a constant part from intrinsic precision, and a multiple scattering part.

Multiple scattering contribution:
(L is in the transverse plane)

$$\sigma_s \propto \frac{L}{p_T \sin^{1/2}\theta}\sqrt{\frac{L}{X_0}}$$

$$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T \cdot \sigma_s}{0.3BL^2} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2}\theta}$$

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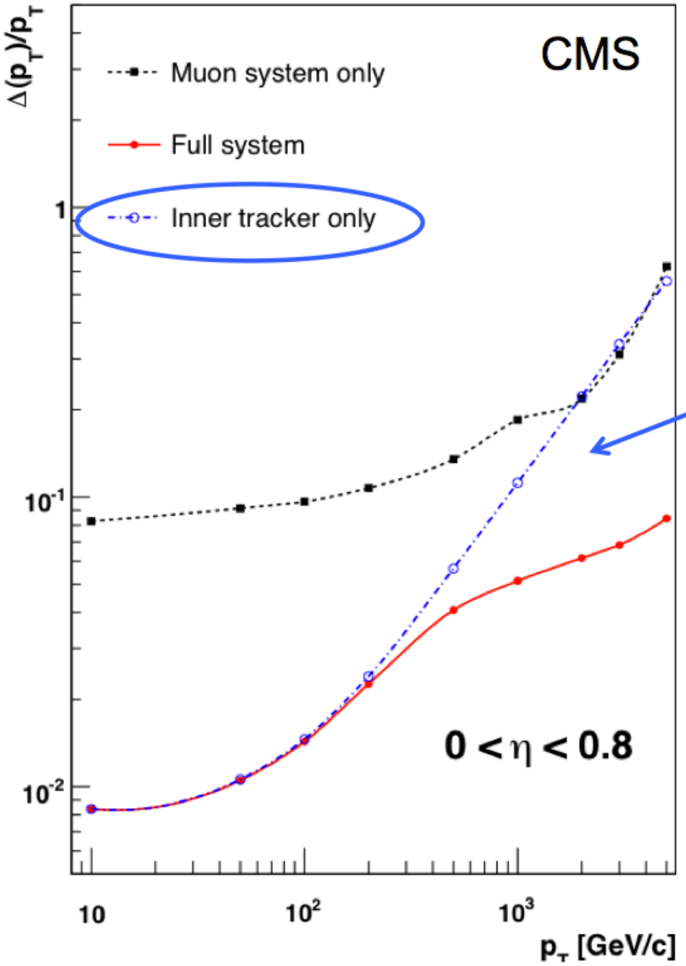
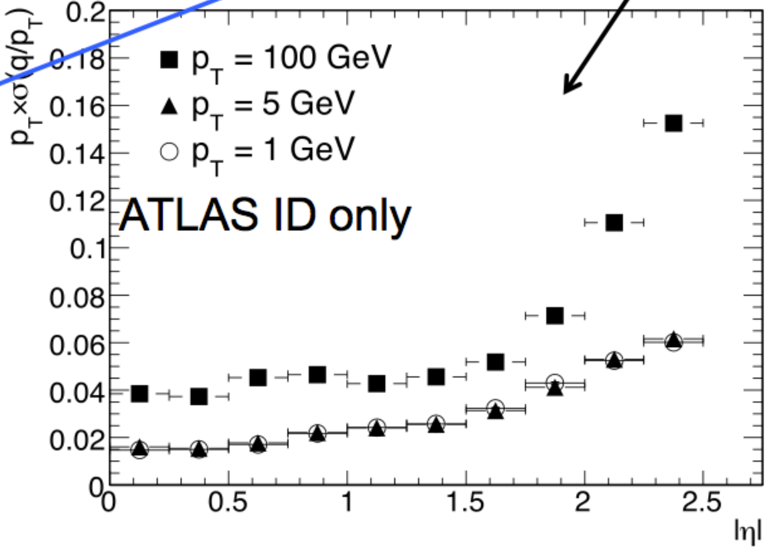
Momentum resolution



Expected relative p_T resolution for muons vs |η| and p_T.

$$\frac{\sigma_{p_T}}{p_T} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2}\theta}$$



(More material) →

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Calibration and alignment

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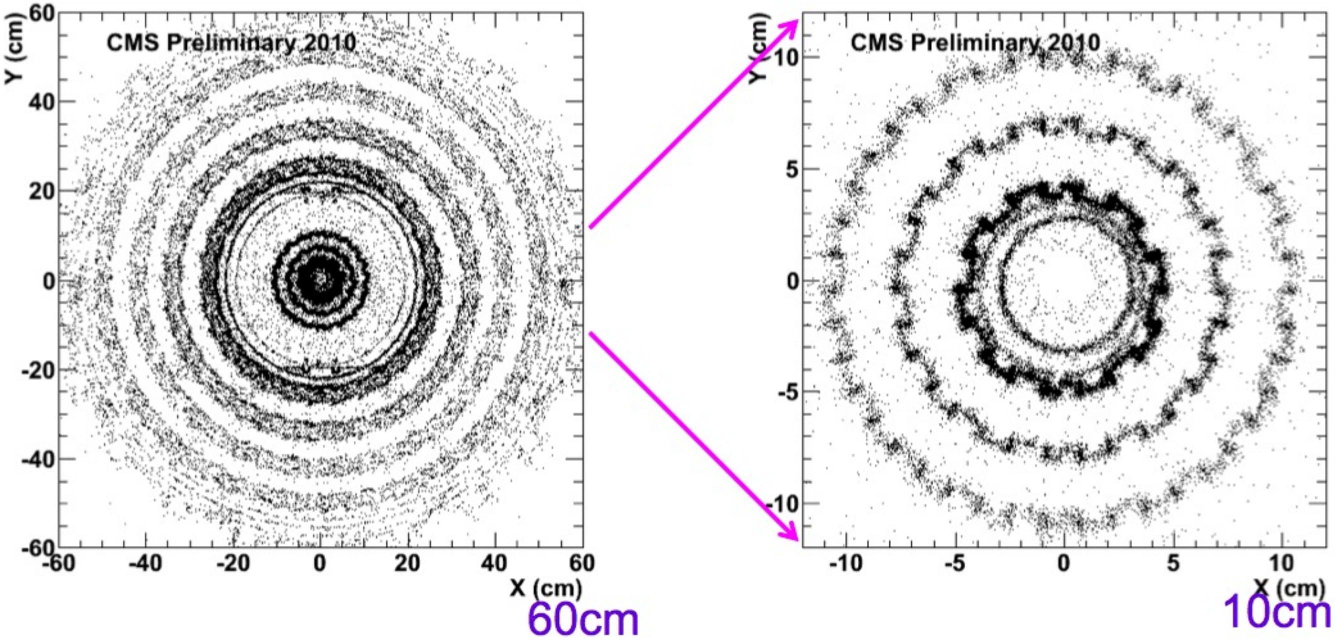
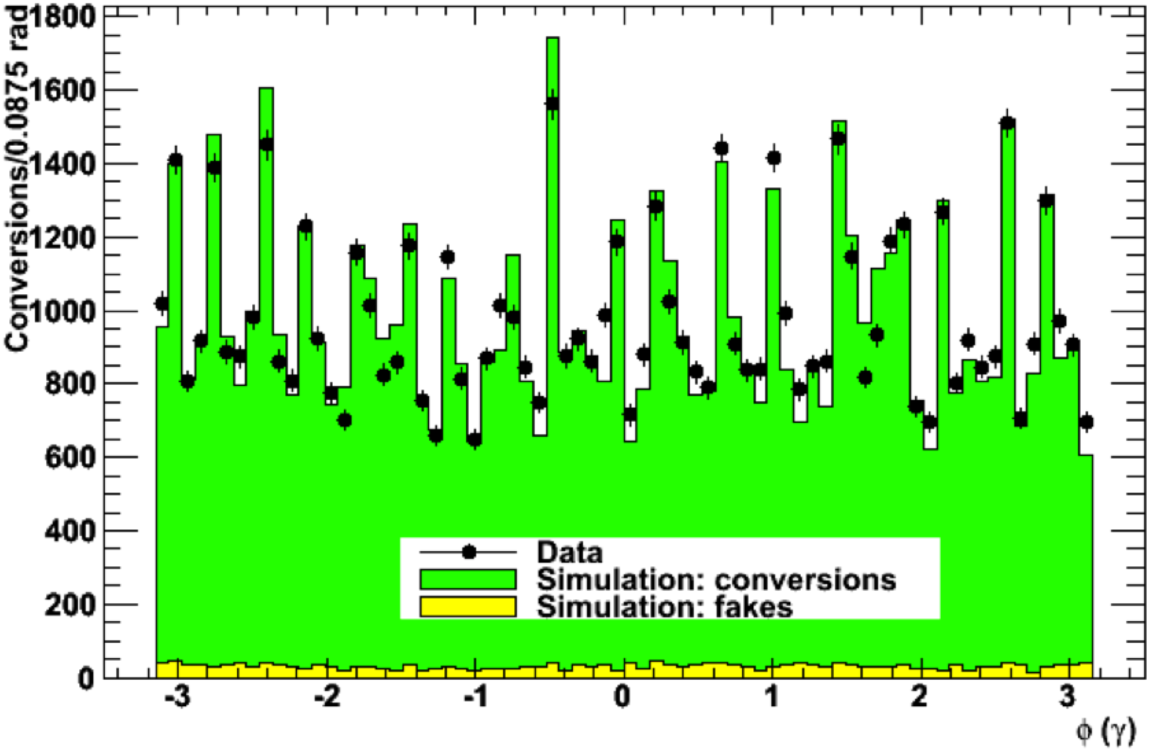
Checking material

- Conversions, $\gamma \rightarrow e^+e^-$, example from CMS
  - Two oppositely charged tracks
  - Consistent with coming from the same point
  - Consistent with fit to a common vertex, imposing zero mass



Checking material description

- ϕ distribution for conversions with |z|< 26cm, R< 19cm
- → Compare pixel barrel structure in data and simulation
- Spikes due to cooling pipes



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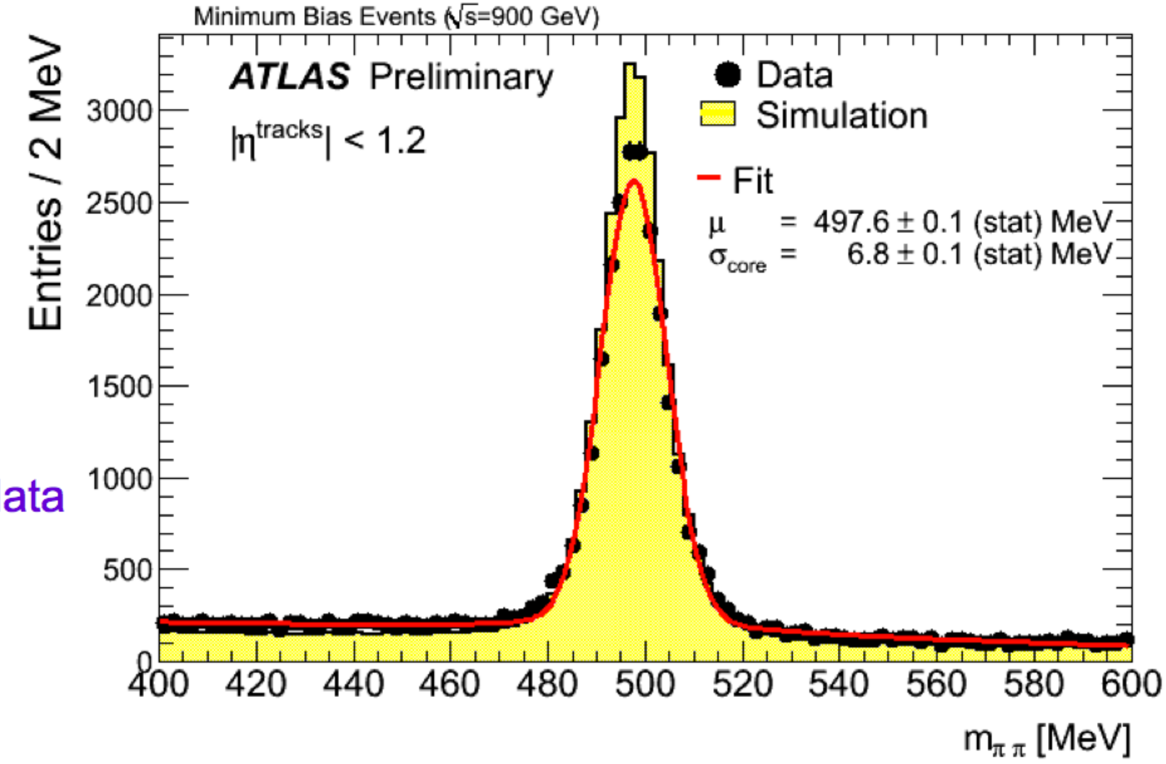
Checking alignment

$K^0 \rightarrow \pi^+\pi^-$

Two oppositely charged tracks, consistent with the same vertex.

Assume the tracks are pions. Reconstruct the pair invariant mass.

World Average PDG value 497.614 ± 0.024 MeV



ATLAS example:2009 data slightly broader than simulation

ATLAS-CONF-2010-019

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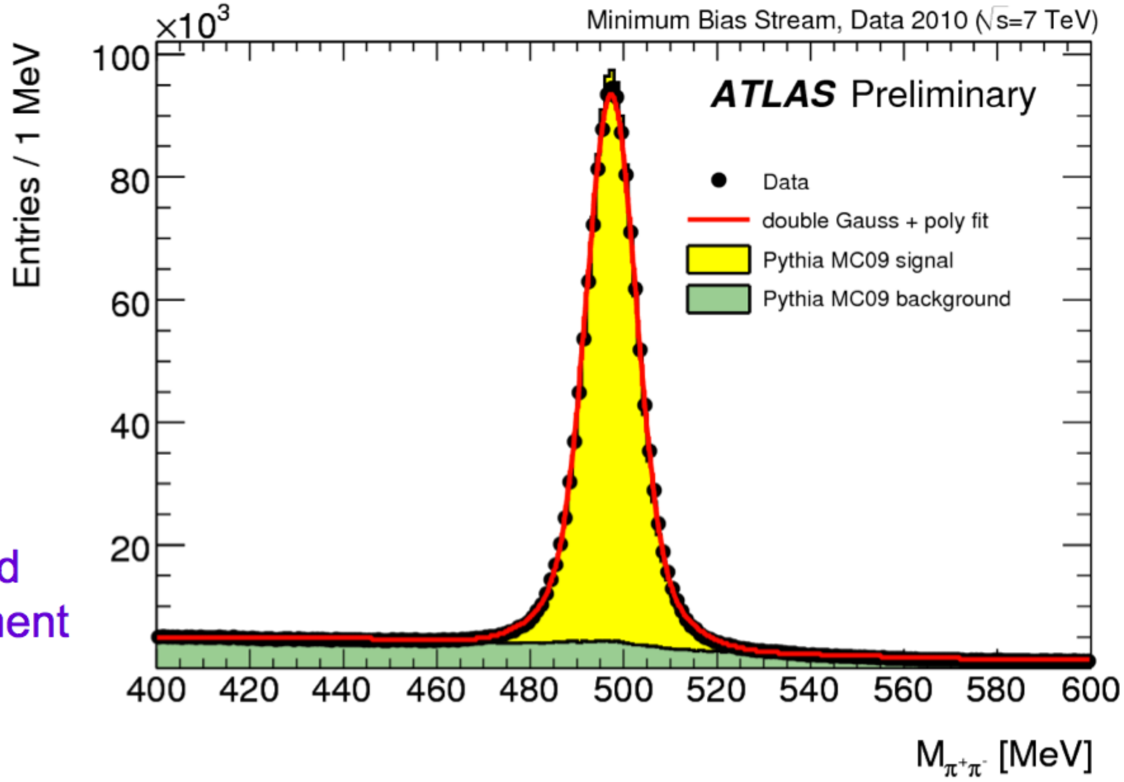
Checking alignment

$K^0 \rightarrow \pi^+\pi^-$

Two oppositely charged tracks, consistent with the same vertex.

Assume the tracks are pions. Reconstruct the pair invariant mass.

World Average PDG value 497.614 ± 0.024 MeV



Much better agreement with 2010 sample and improved alignment

ATLAS-CONF-2010-033

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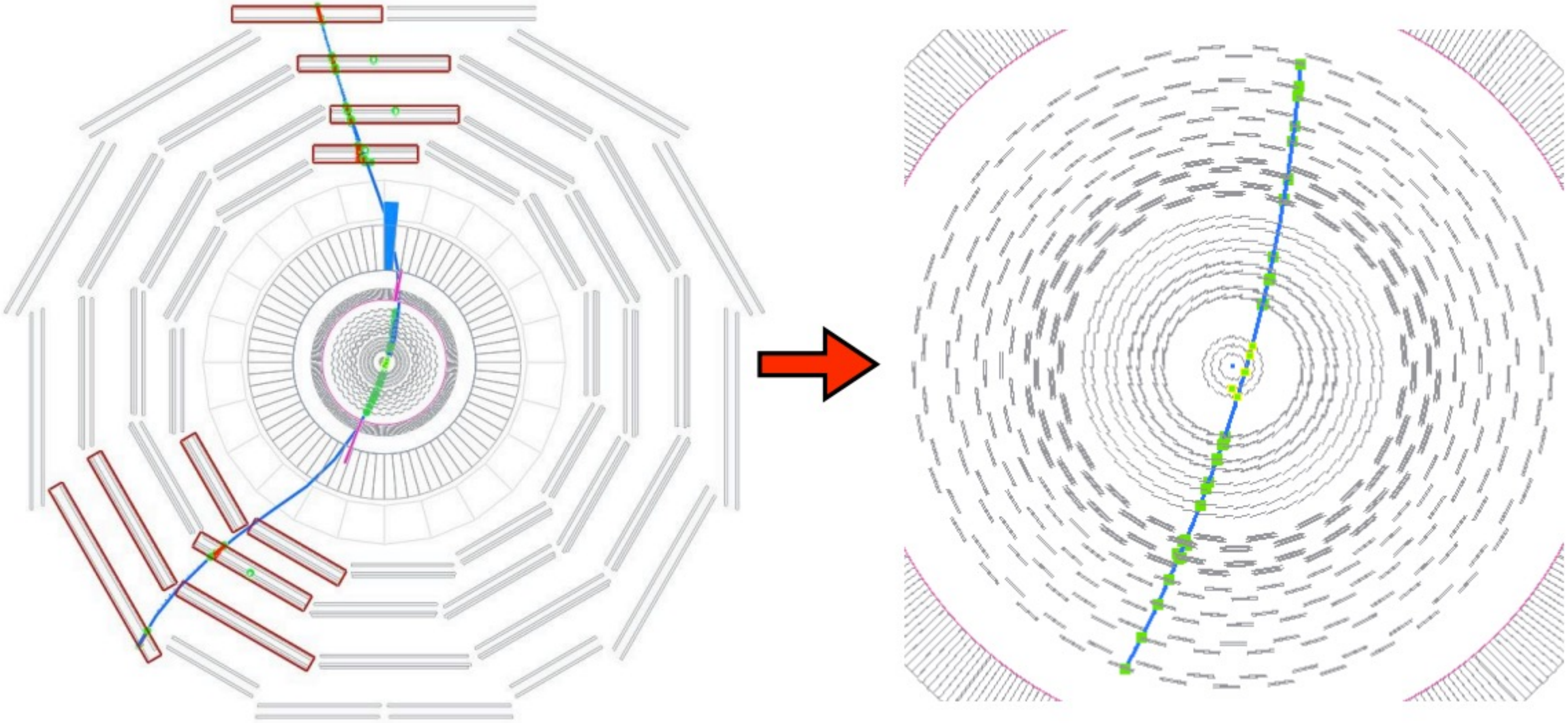
Outer trackers

The cosmic muon that crossed all



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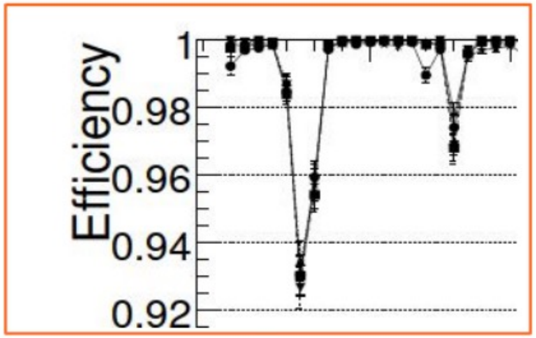
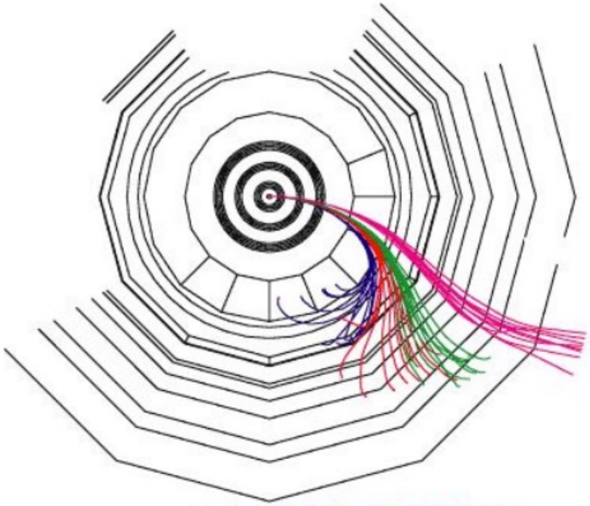
Finding muons: not just outside in

- Standard approach: Outside-in
  - Standalone Muon
  - Combine with tracker track to fit GlobalMuon
- "Muon-ID": complementary Inside-out approach
  - Extrapolate every track outward
  - Find compatible deposits in ECAL, HCAL, HO, muon hits
  - Determine muon 'compatibility'

Recover inefficiencies at muon chamber boundaries and low p_T (e.g. Muons which only reach the first muon station)

Inefficiency at eta cracks





p_t = 3.5, 4.0, 4.5, 6.0 GeV

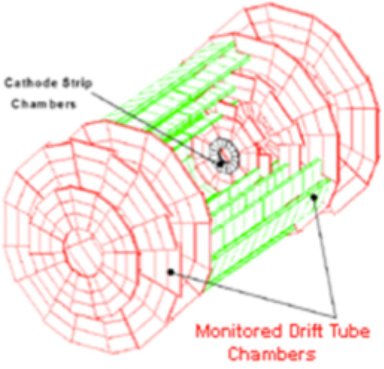
Momentum resolution

ATLAS

$B = 0.7$ T

$L \sim 5$ m

N = 3 Stations * 8 Points



$s = 750\ \mu$m for 1 TeV Track

10% → $\sigma = 75\ \mu$m

$\Delta p/p \sim 6\%$

$$s = \frac{0.3 \cdot B[T] \cdot L[m]^2}{8 \cdot p[GeV]}$$

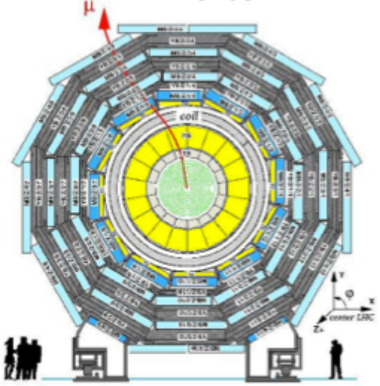
$$\frac{\Delta p_T}{p_T} \propto \frac{1}{s} \cdot \delta_{spatial} \cdot \sqrt{\frac{720}{N_{Stat}}}$$

CMS

$B \sim 2$ T (B-Field in Fe)

$L \sim 3.5$ m

N = 4 Stations * 8 Points in ($r\phi$)



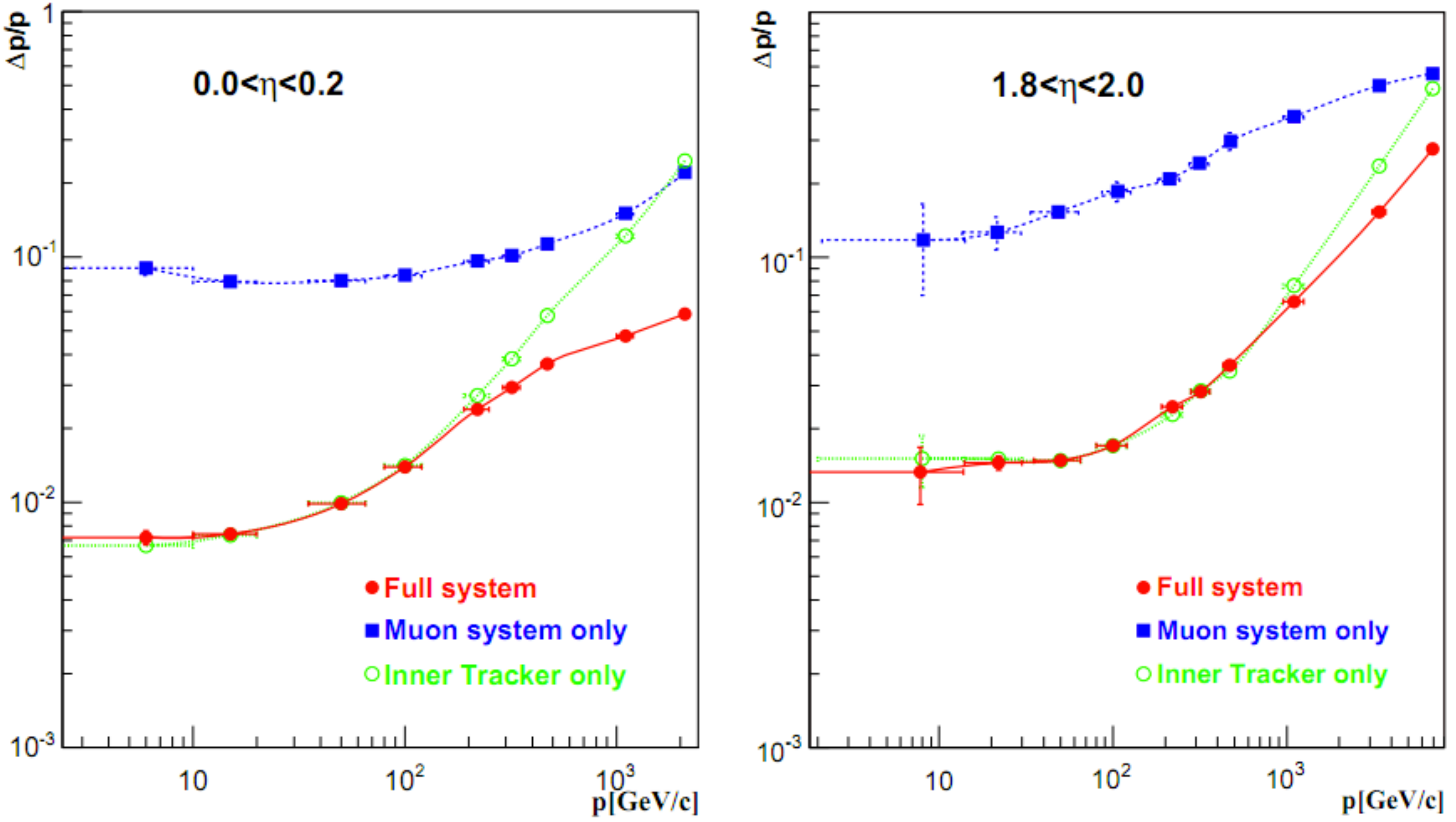
$s = 900\ \mu$m for 1 TeV Track

10% → $\sigma = 90\ \mu$m

$\Delta p/p \sim 12\ \%$ (Multiple scattering in Fe ~100 μm)

Combine with Tracker $\Delta p/p \sim 2\ \%$

Combined performance



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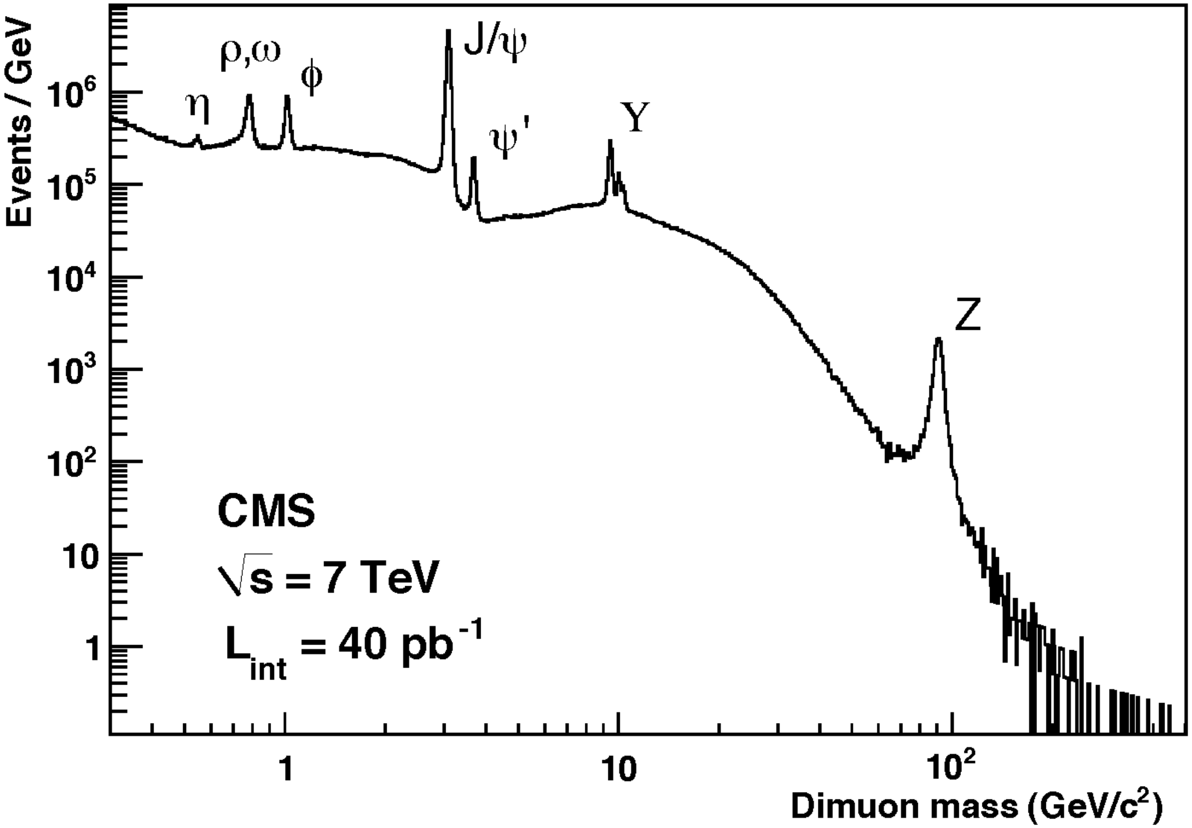
CMS dimuon performance

- Dimuons from η to Z



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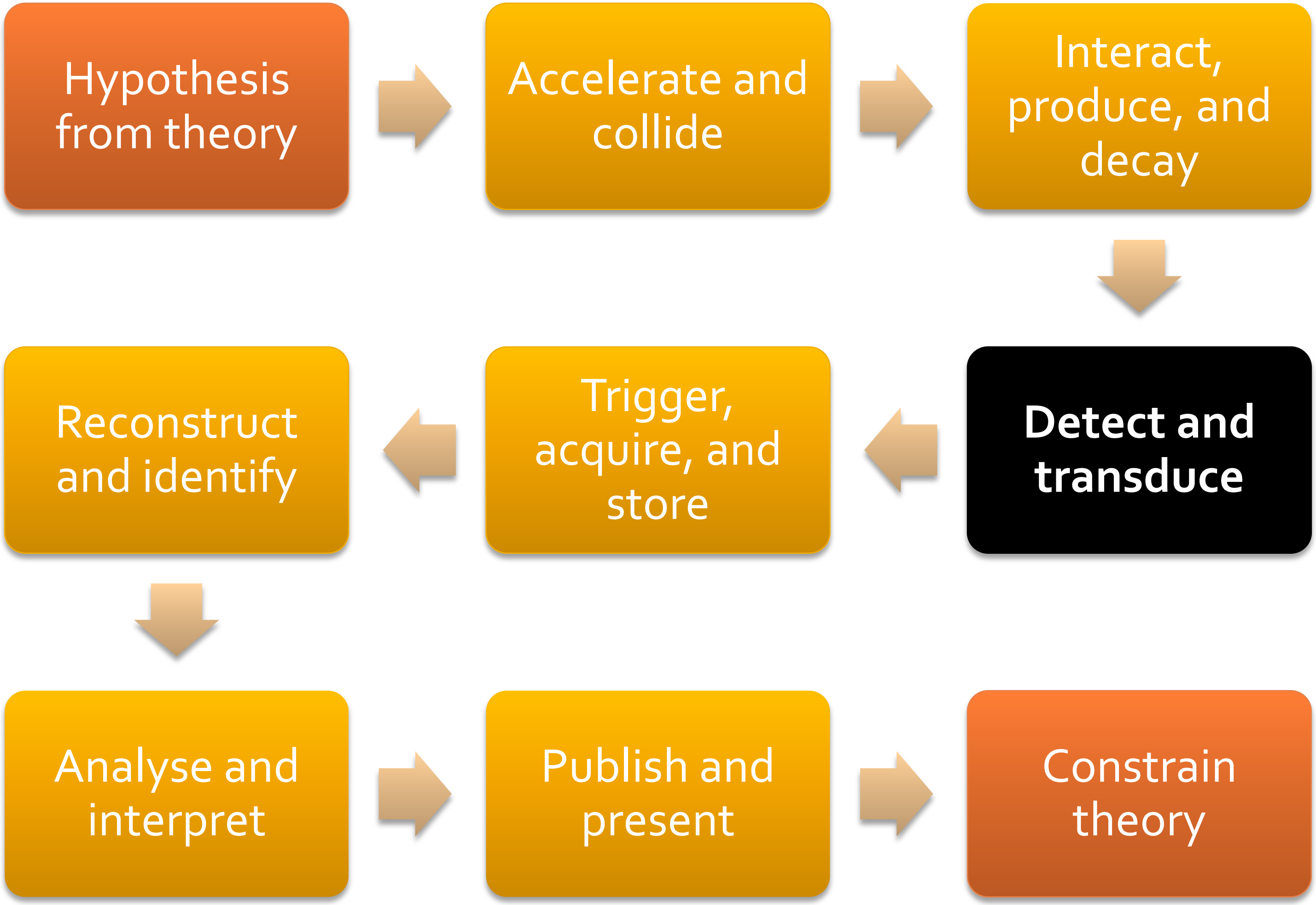
You are here



Hypothesis from theory

Accelerate and collide

Interact, produce, and decay

Detect and transduce

Trigger, acquire, and store

Reconstruct and identify

Analyse and interpret

Publish and present

Constrain theory

IHSTP - 2023

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“Rivelatori”

- 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.

- Tracking systems are crucial.
  - CMS is particularly good at it.
    - Particle flow makes extensive use of tracking to disentangle the calorimeter deposit.

ATLAS vs. CMS – classroom exercise

- **7000 tonnes**
  in a cylinder about **26 m long**
  and **25 m in diameter**.
- **Average density of 0.6 g/cm^3**
  or 30% less than an apple.

- **14000 tonnes**
  in a cylinder about **21.5 m long**
  and **15 m in diameter**.
- **Average density of 3.7 g/cm^3**
  just like a diamond.

- **ATLAS would float in water but CMS would sink.**
  CMS is 7 times denser than ATLAS, hence the C for Compact.
- But first you'd need to get them out of the caverns. ☺

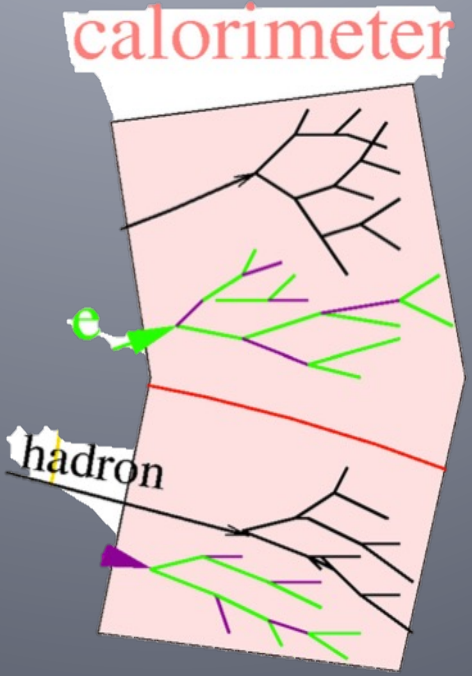
- [http://cern.ch/go/BXt9]
- [http://cern.ch/go/Rfq9]

For discussion, …

…the curious, and the insatiable.

Calorimetry

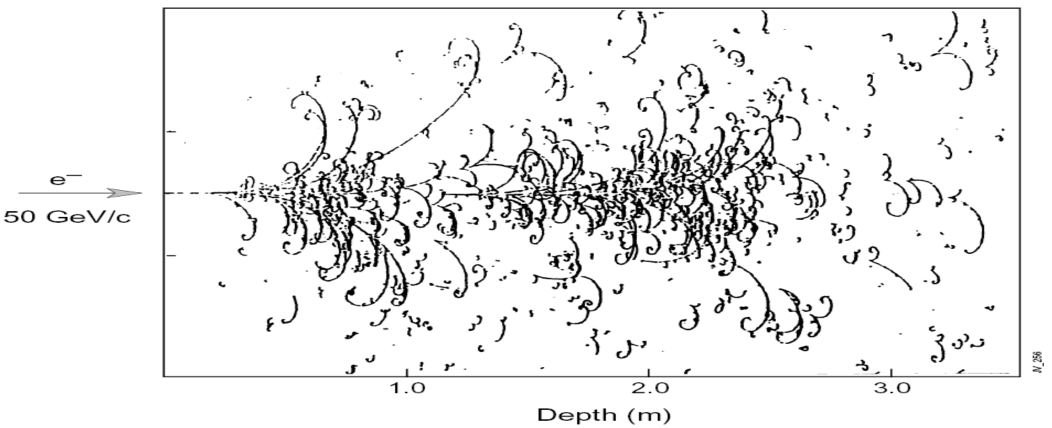
Trying to measure the energy of everything except muons.

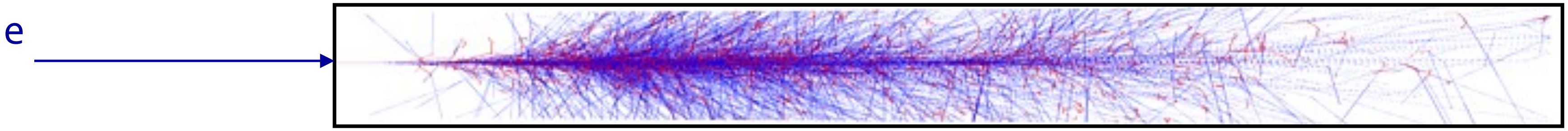


Calorimetry: what?

- 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



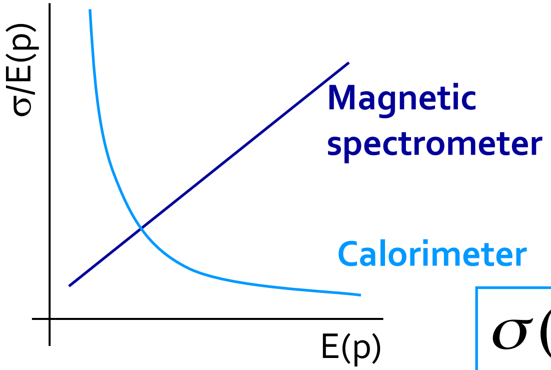


GEANT shower Monte Carlo (PbWO_4 crystal)

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



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

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

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.

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Electromagnetic showers

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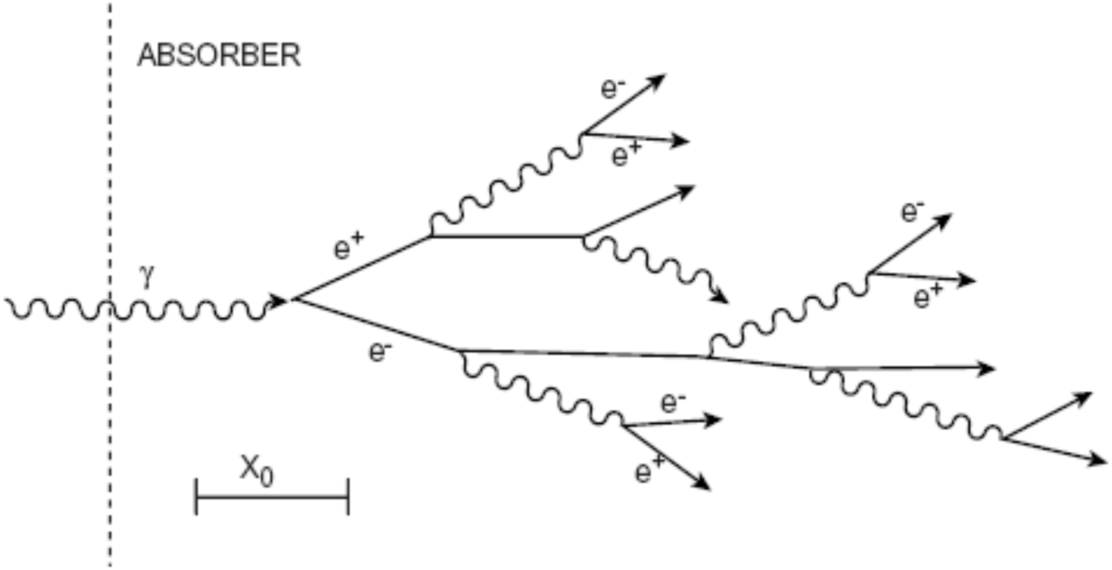
Electromagnetic showers

- 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

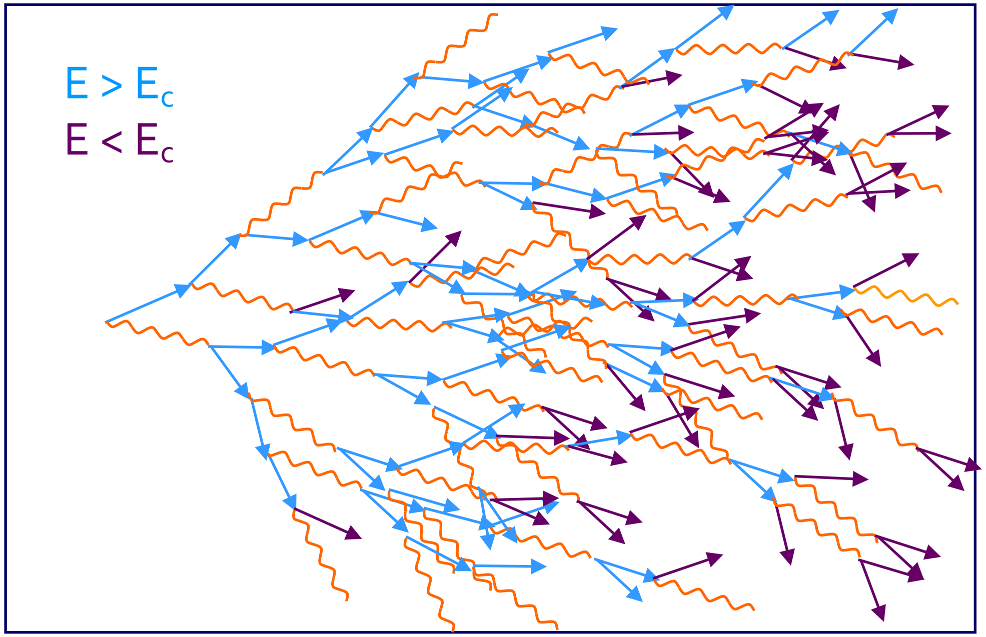
- Radiation length (X_0) defined to be the distance over which an electron loses all but 1/e of its energy.
- Useful approximation ➔
  - Rough derivation in [Cal1]; more precise approximation in [Cal2].

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

- **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].**



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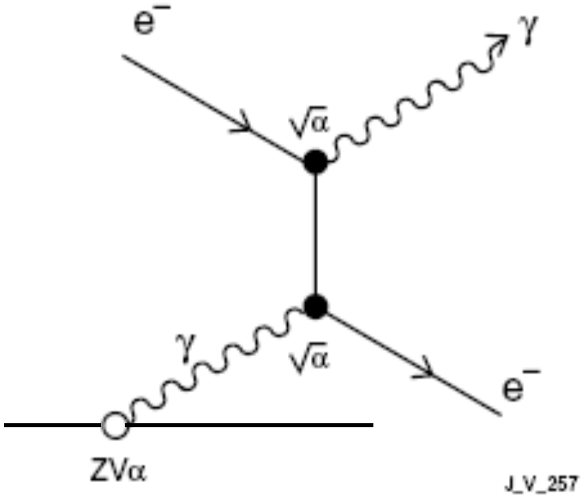
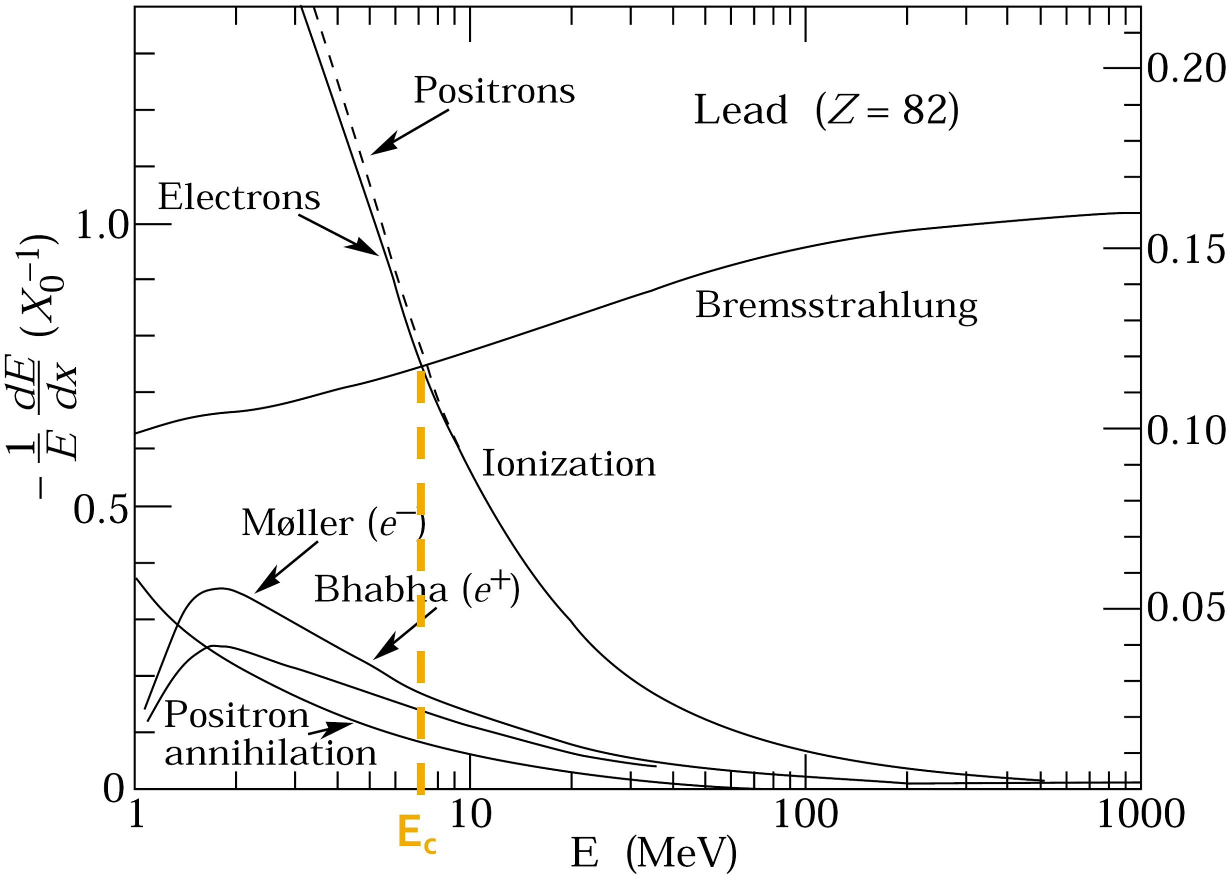
Energy loss in matter: electrons

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 $E_\gamma > 2m_ec^2$)

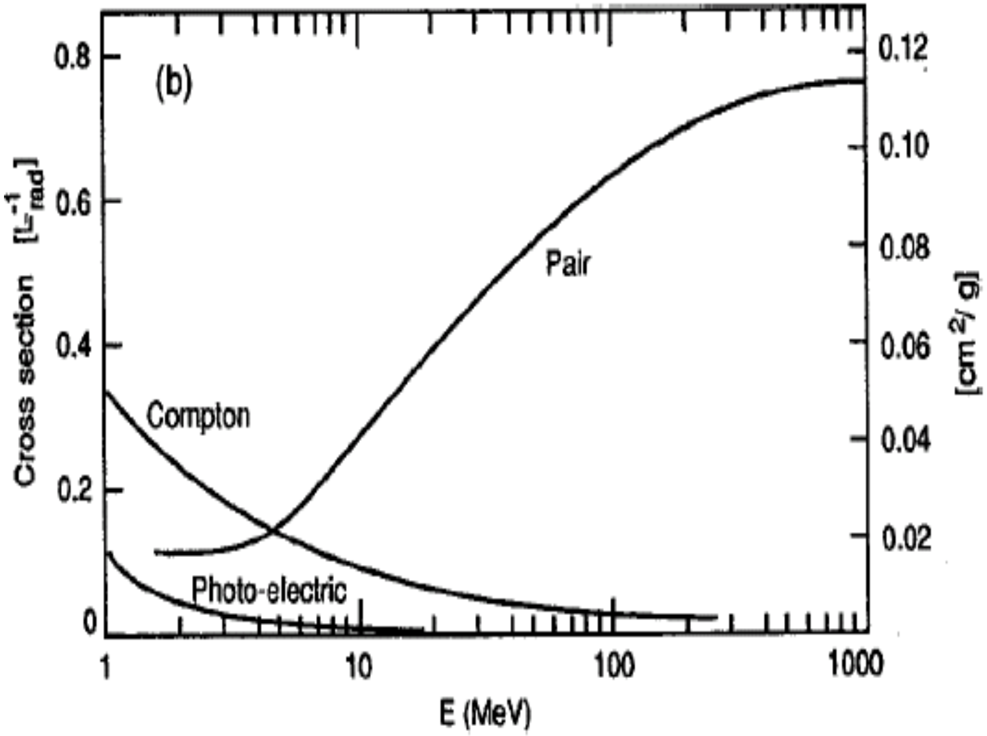
$$\boxed{\sigma_{pair} \approx \frac{7}{9}\cdot\frac{A}{N_A}\cdot\frac{1}{X_0}}$$

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

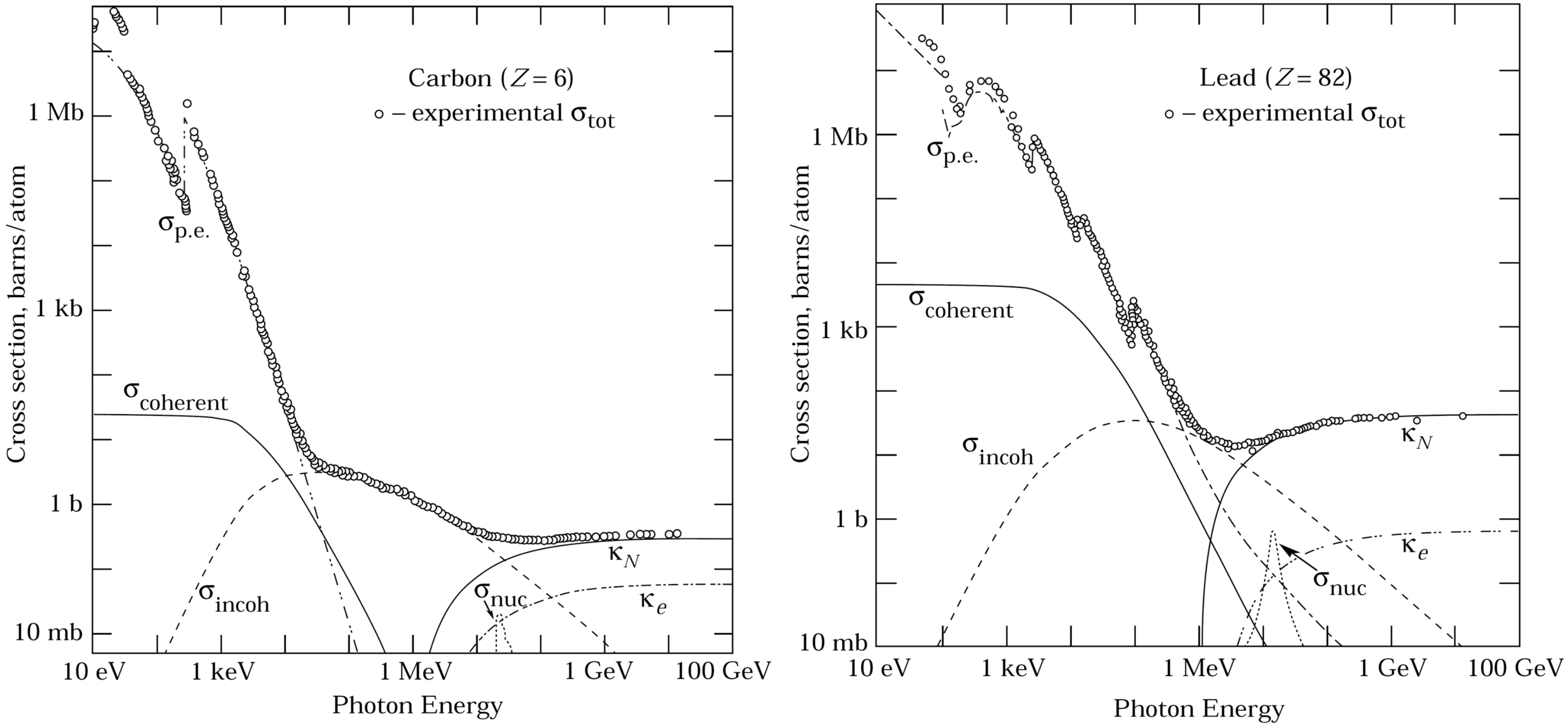


Figure 24.3: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes:

$\sigma_{\text{p.e.}}$ = 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).

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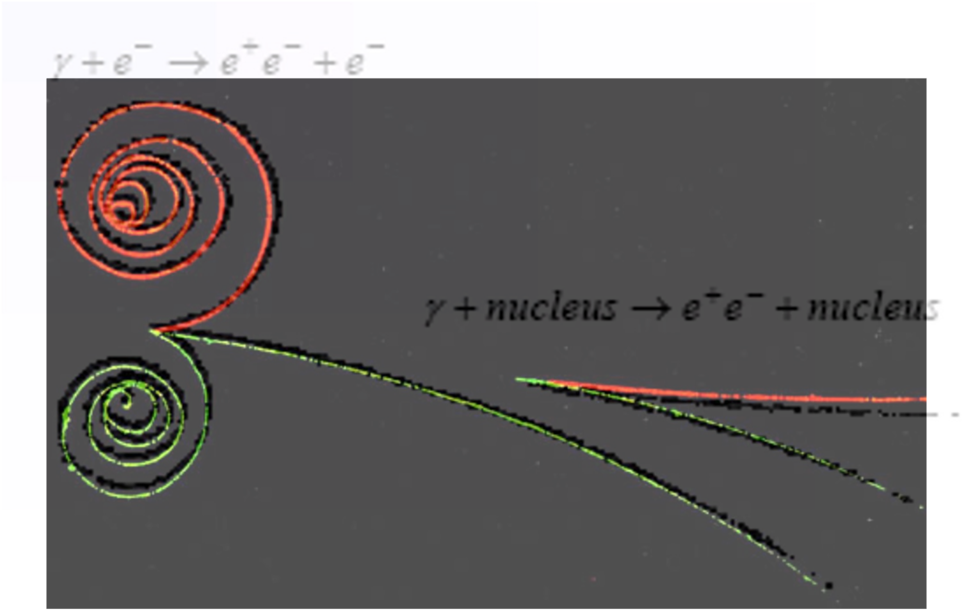
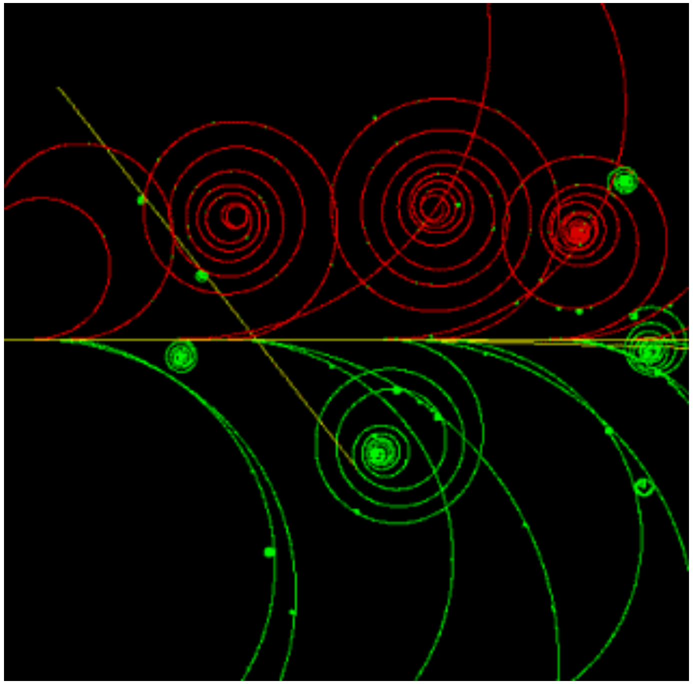
Pair production/conversion

- 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.



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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: $n(t_{\max}) \approx \frac{E}{E_c} = y$

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

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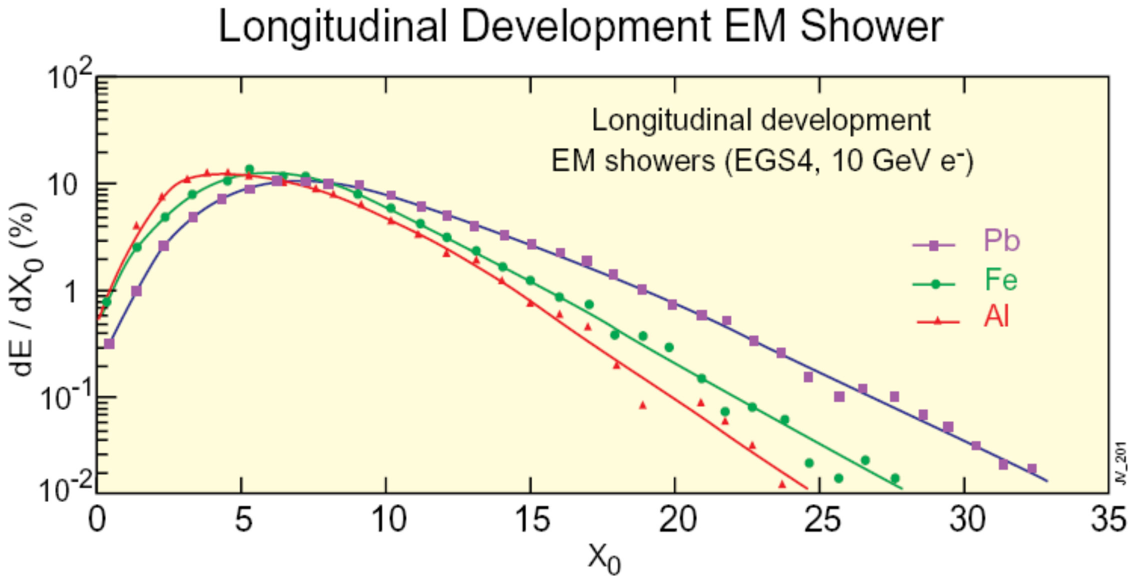
Longitudinal development

- 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



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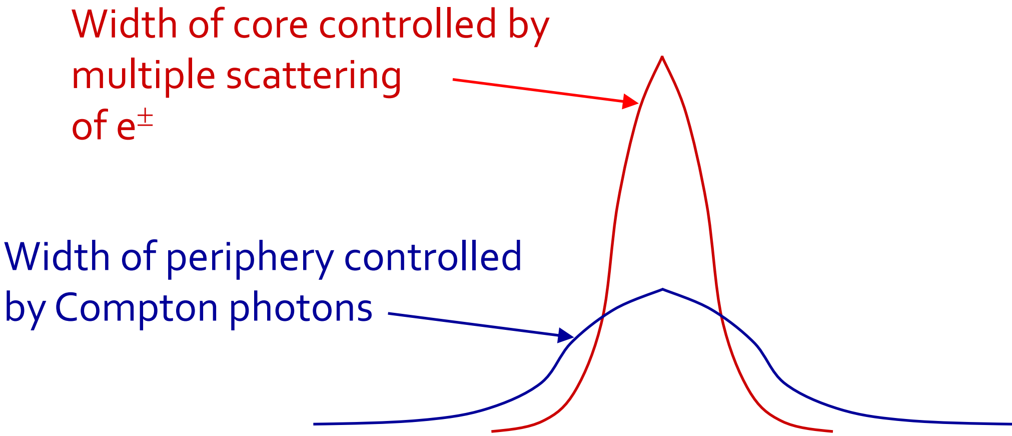
Lateral development

- 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

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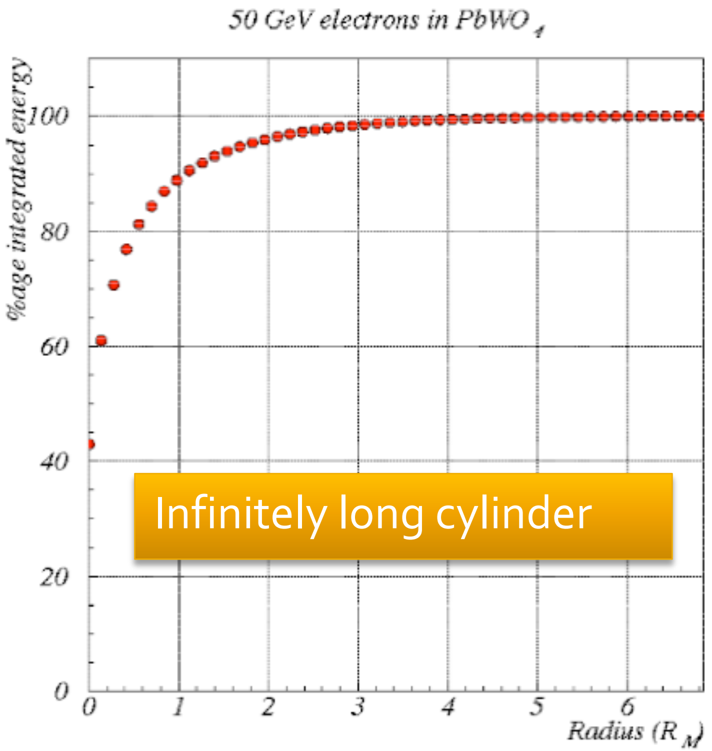
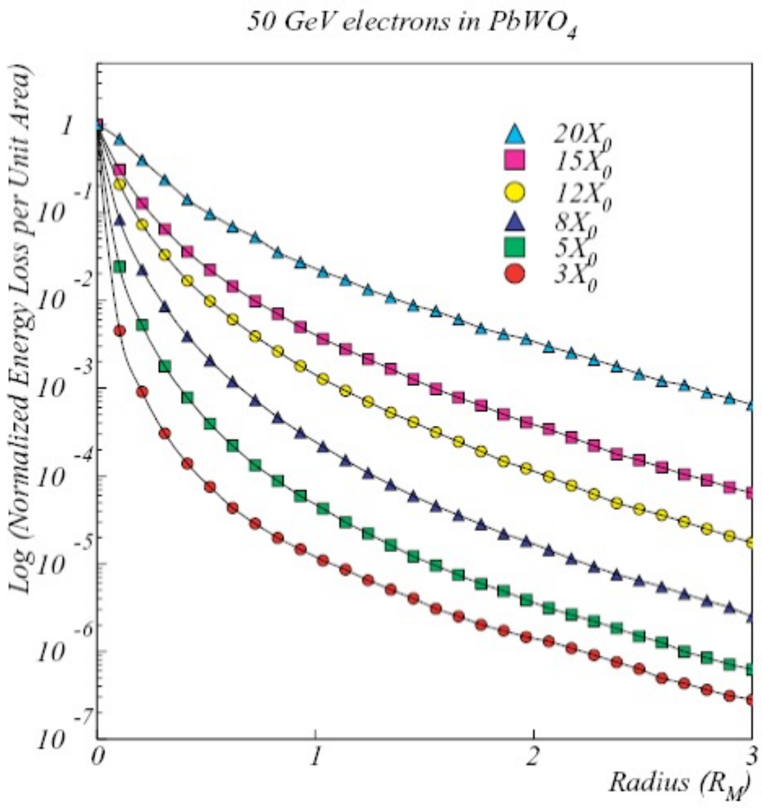
EM showers: lateral spread

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



Infinitely long cylinder



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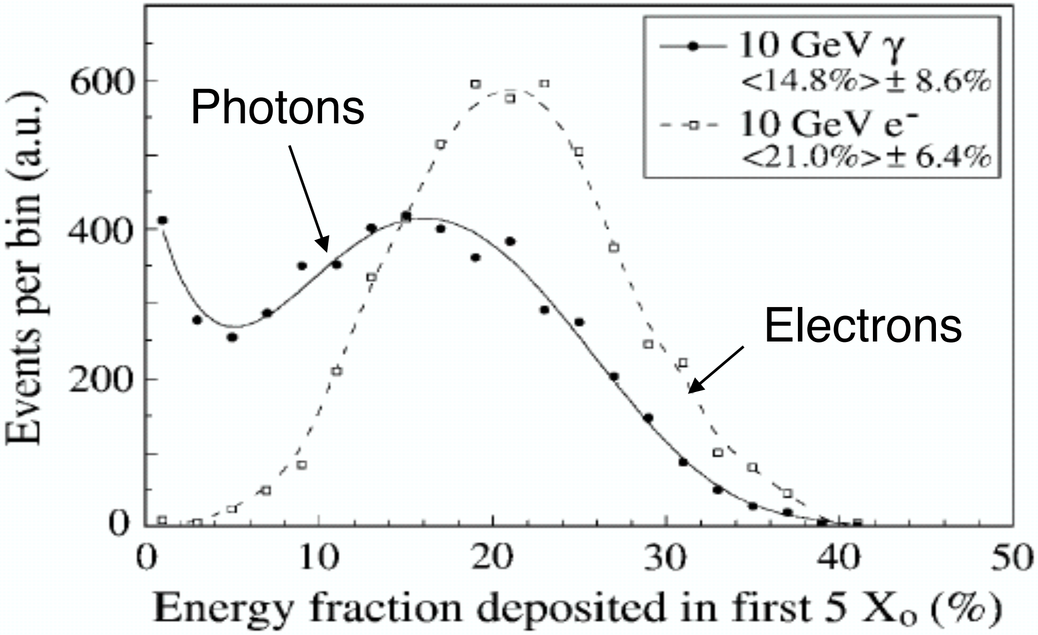
EM showers: further issues

- 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

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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).

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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:

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

- 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.

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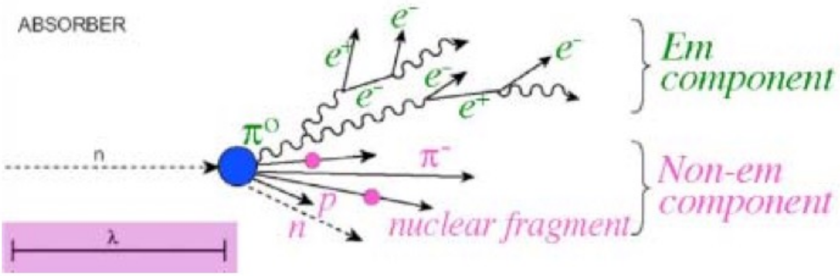
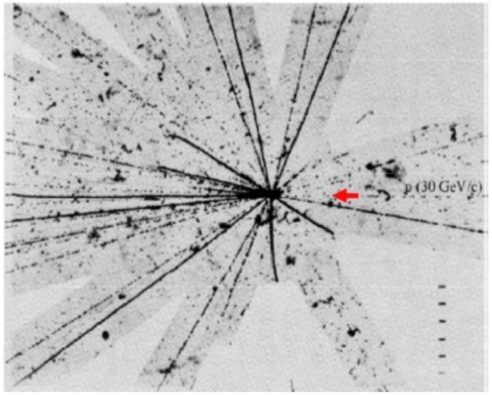
Hadronic cascade

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



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

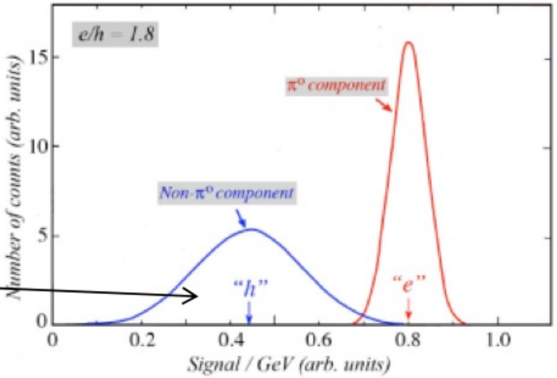
Charged hadrons	(20%)
Nuclear fragments , p	(25%)
Neutrons, soft γ's	(15%)
Breakup of nuclei	(40%)



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

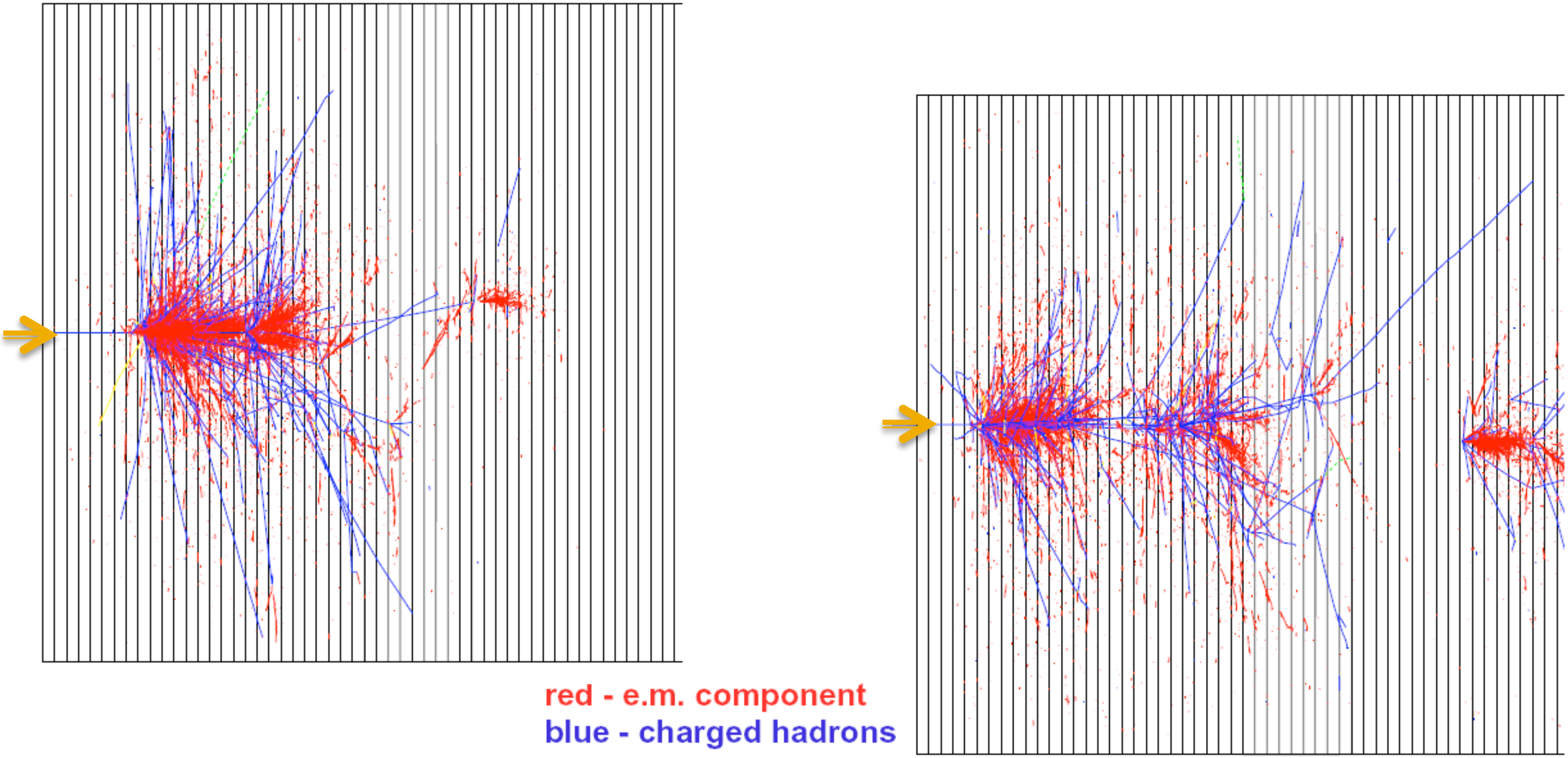
= Invisible energy

e/h > 1



Hadron showers

- Individual hadron showers are quite dissimilar



red - e.m. component
blue - charged hadrons

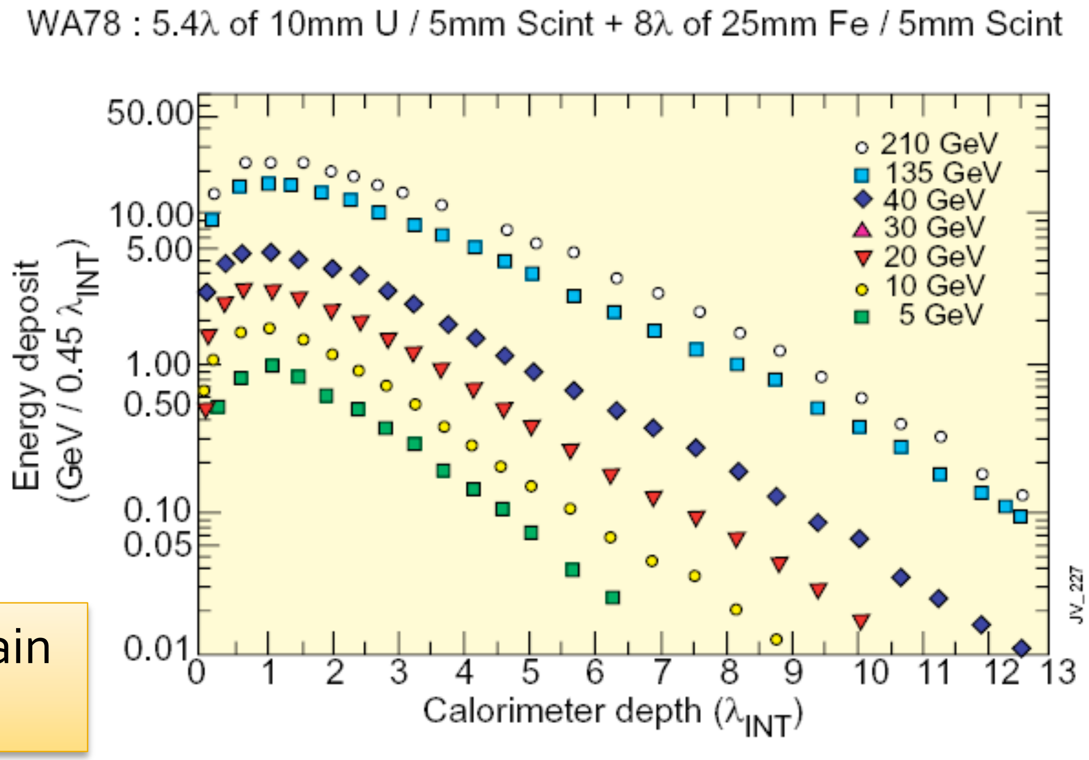
Table of physical properties

	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).

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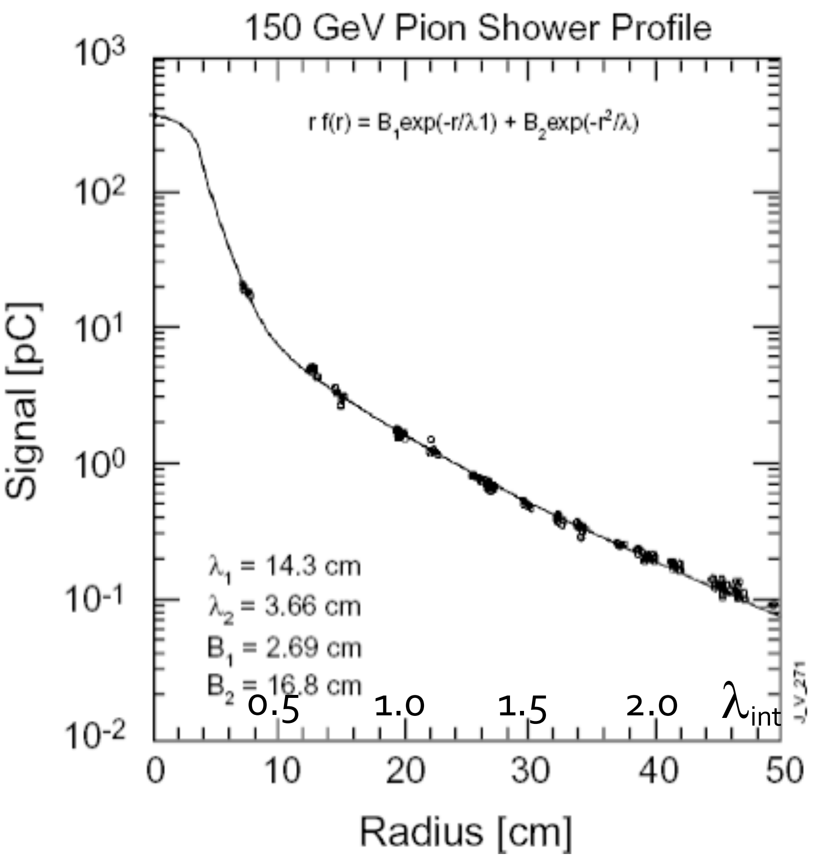
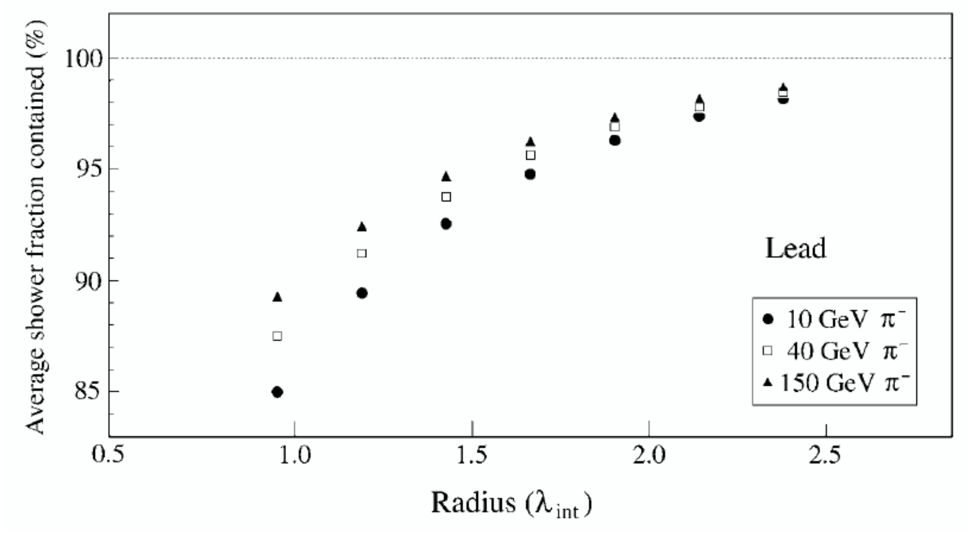
Hadron shower transverse profiles

- 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 ~ **√2 × energy resolution** ⊕ opening angle resolution

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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.

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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: $\sigma/E \approx 5\%/\sqrt{E}$.

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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 $W = 2.96\ \mathrm{eV} \Rightarrow \sigma \approx 540$ eV.

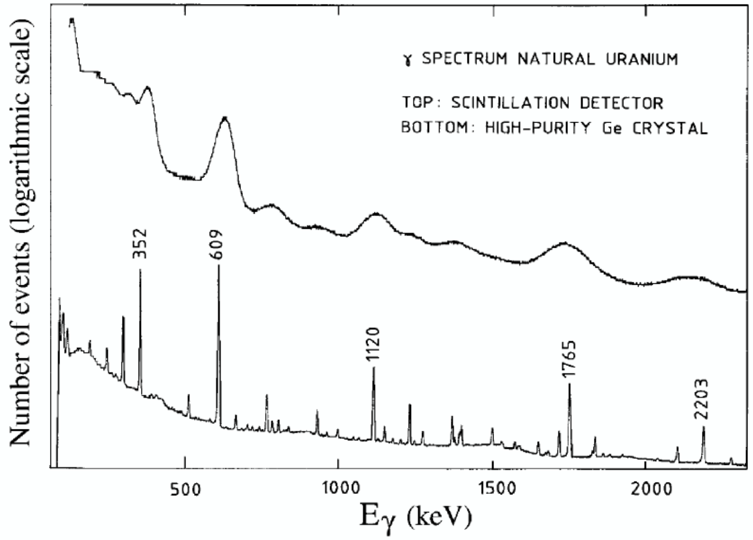

FIG. 1.1. Nuclear γ-ray spectrum of decaying uranium nuclei, measured with a bismuth germaniumoxide scintillation counter (*upper curve*) and with a high-purity germanium crystal (*lower curve*). Courtesy of G. Roubaud, CERN.

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

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

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

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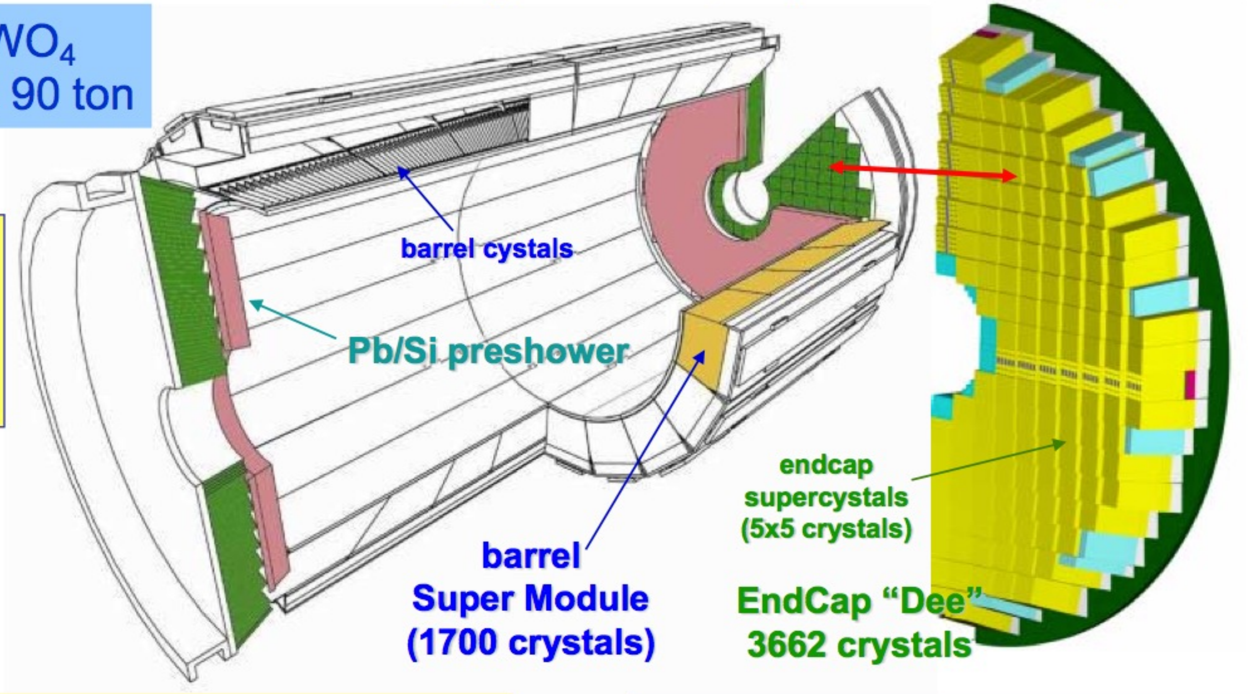
CMS ECAL

Precision electromagnetic calorimetry: 75848 PWO crystals

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

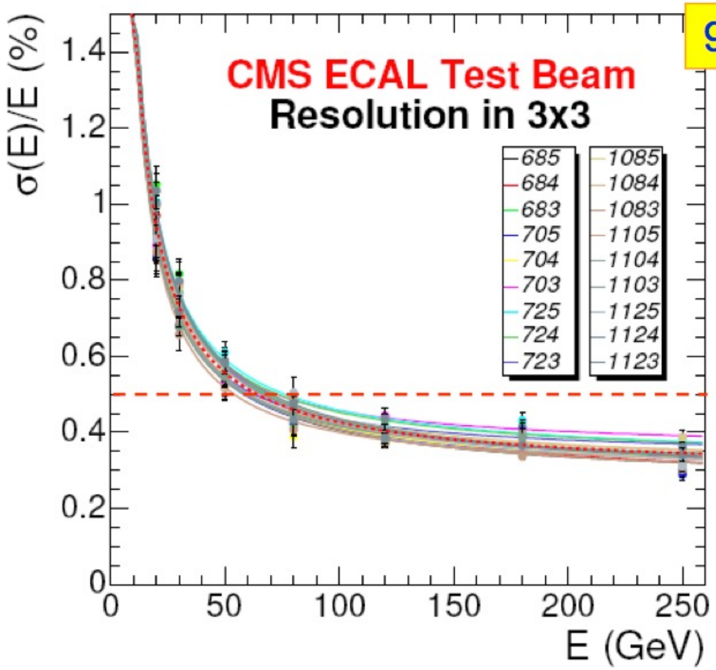
Previous Crystal calorimeters: max $1 m^3$



Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2 \times 2 \times 23 cm^3$)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3 \times 3 \times 22 cm^3$)

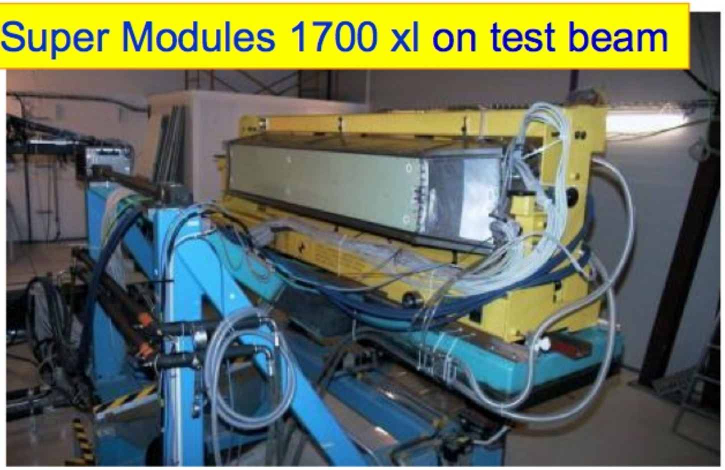
CMS ECAL test beam performance

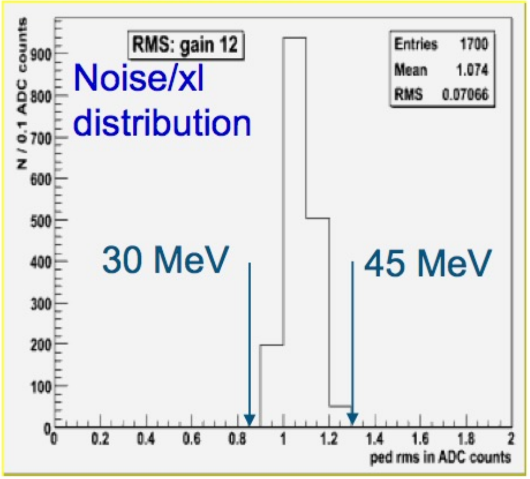


$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

Local resolution

9 Super Modules 1700 xl on test beam





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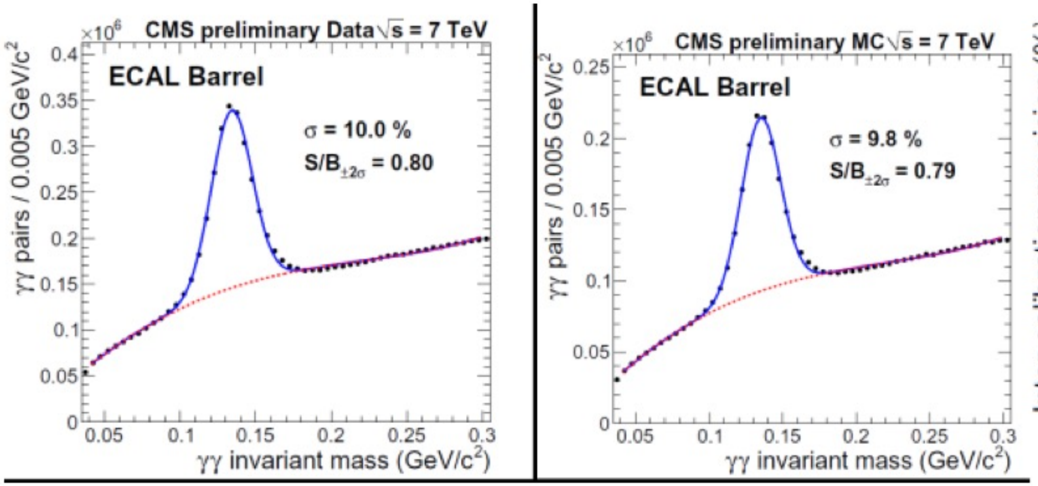
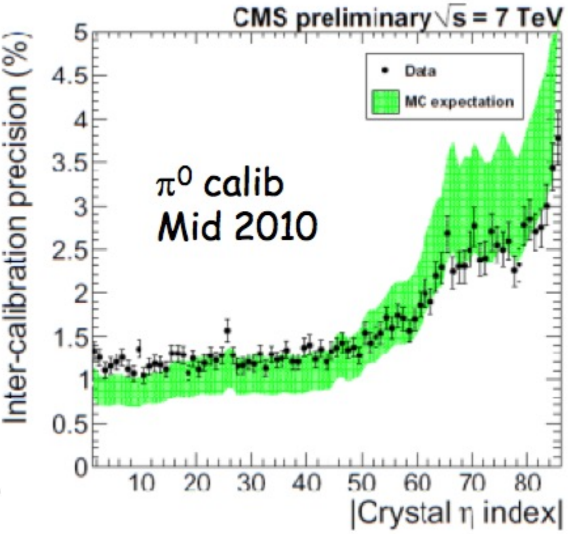
Preserving resolution

- **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





π^0 calib
Mid 2010

Transparency monitoring

The Solution:

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

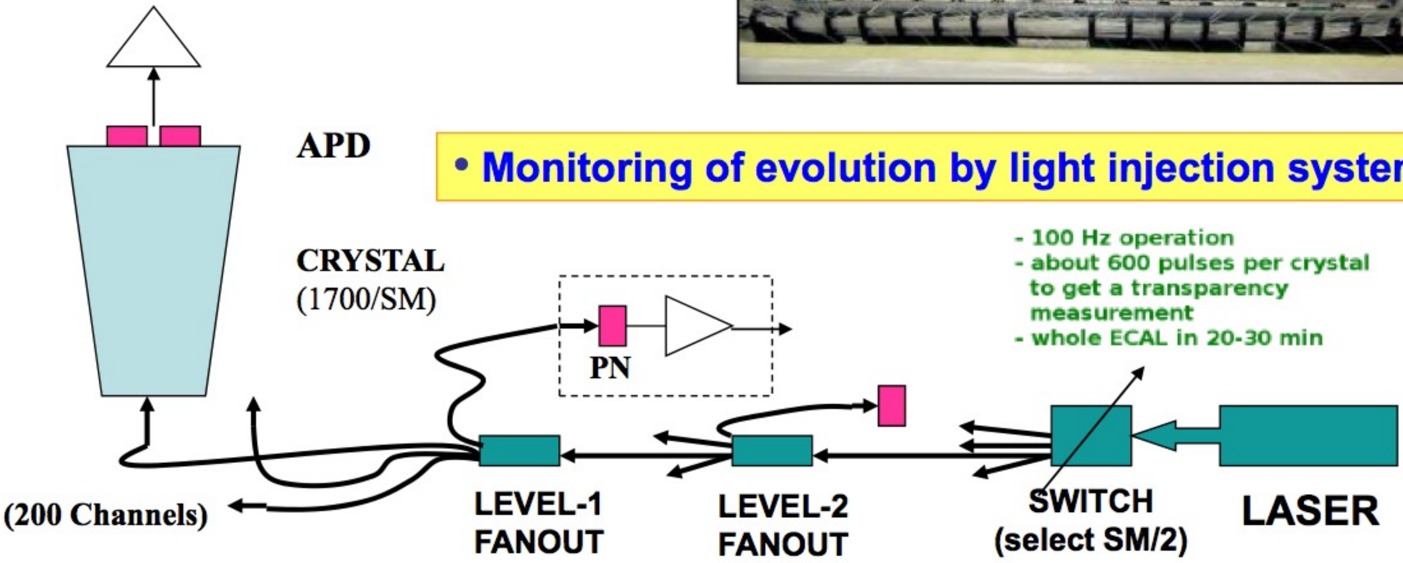
2 wavelengths are used:

440 nm and 796 nm

Light is injected into each crystal

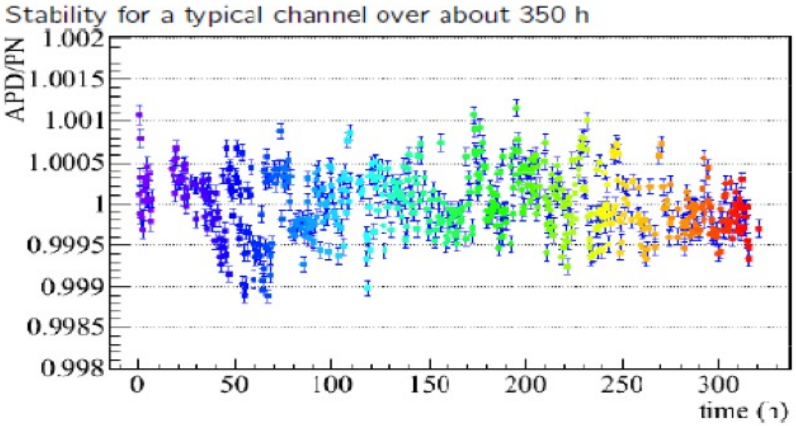
Normalisation given by PN diodes (0.1%)

- 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

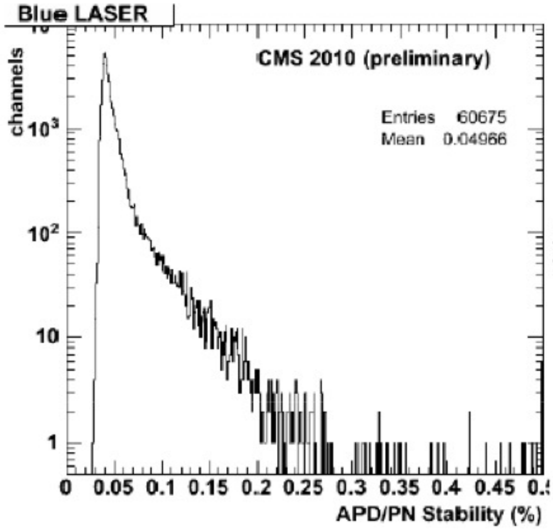
Transparency monitoring

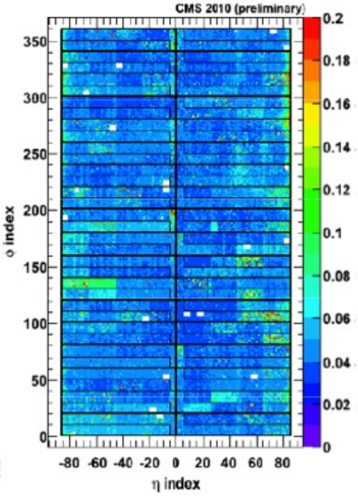


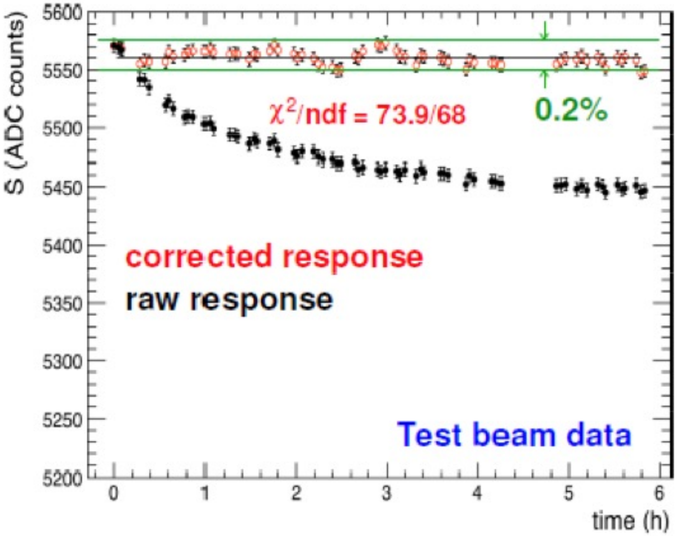
Measure a loss of transparency:
S (particle signal) and R(laser signal)

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

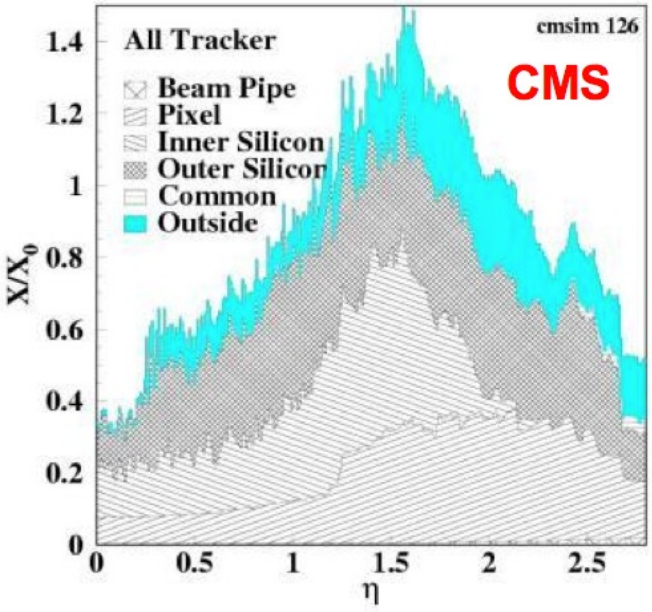
NB: α is ~ the same for all crystals!

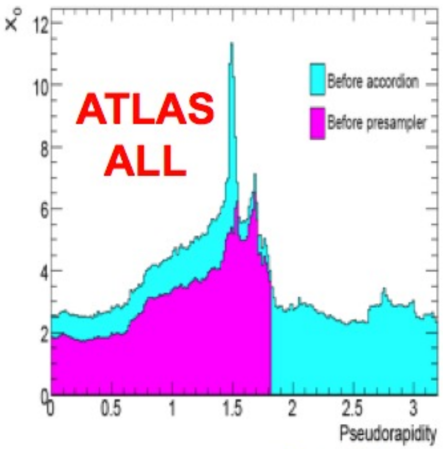


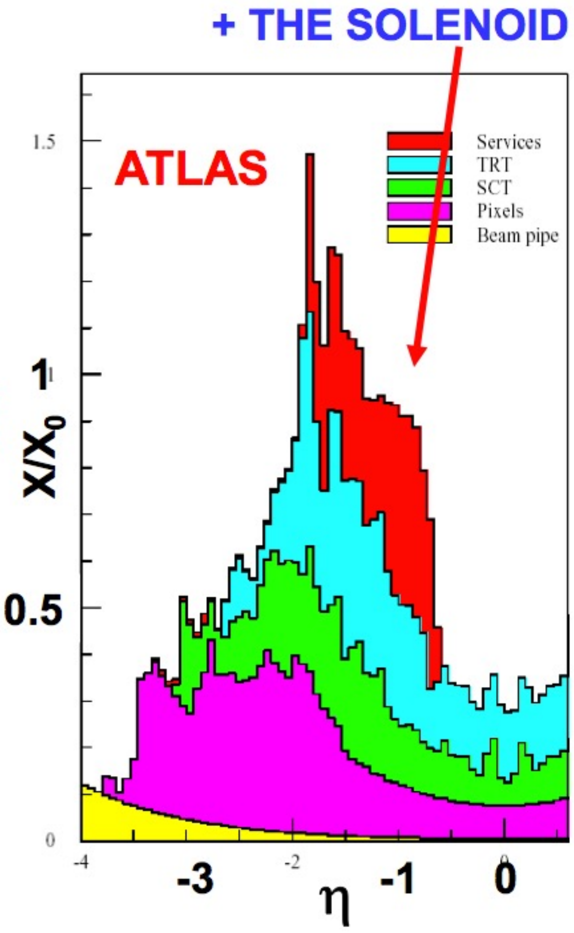


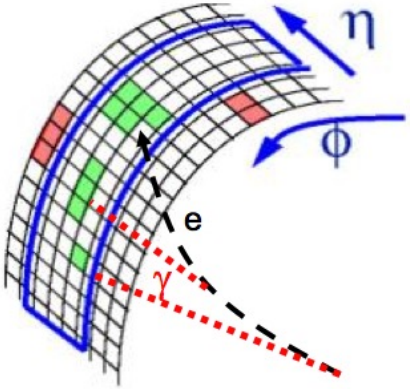


Material in front









Tracker material :

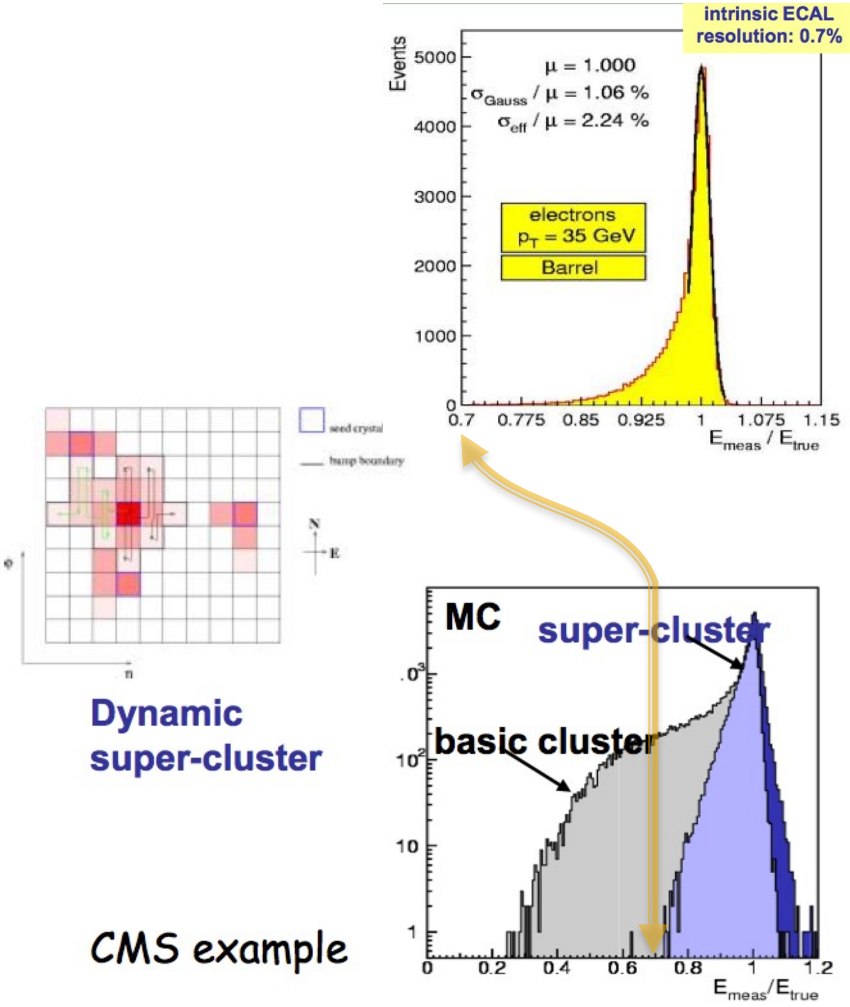
- electrons loose energy via bremsstrahlung
- photons convert

4T (2T) solenoidal B field :

Electrons bend ⇒ radiated energy spread in φ

Material in front

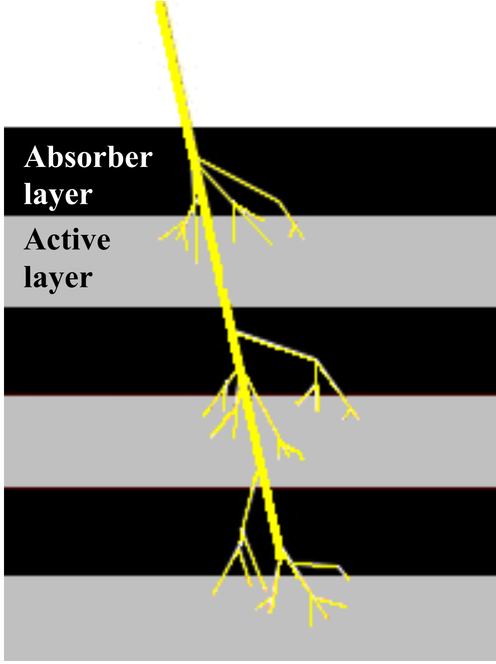
- You can:
  - Widen windows to collect all energy.
  - Or dynamically cluster energy to gather all the bits and pieces. ➔
  - Or identify brems following track kinks (Particle Flow in CMS).
  - Or tag high quality (low brem) electrons, using track curvature info or E/p.



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)

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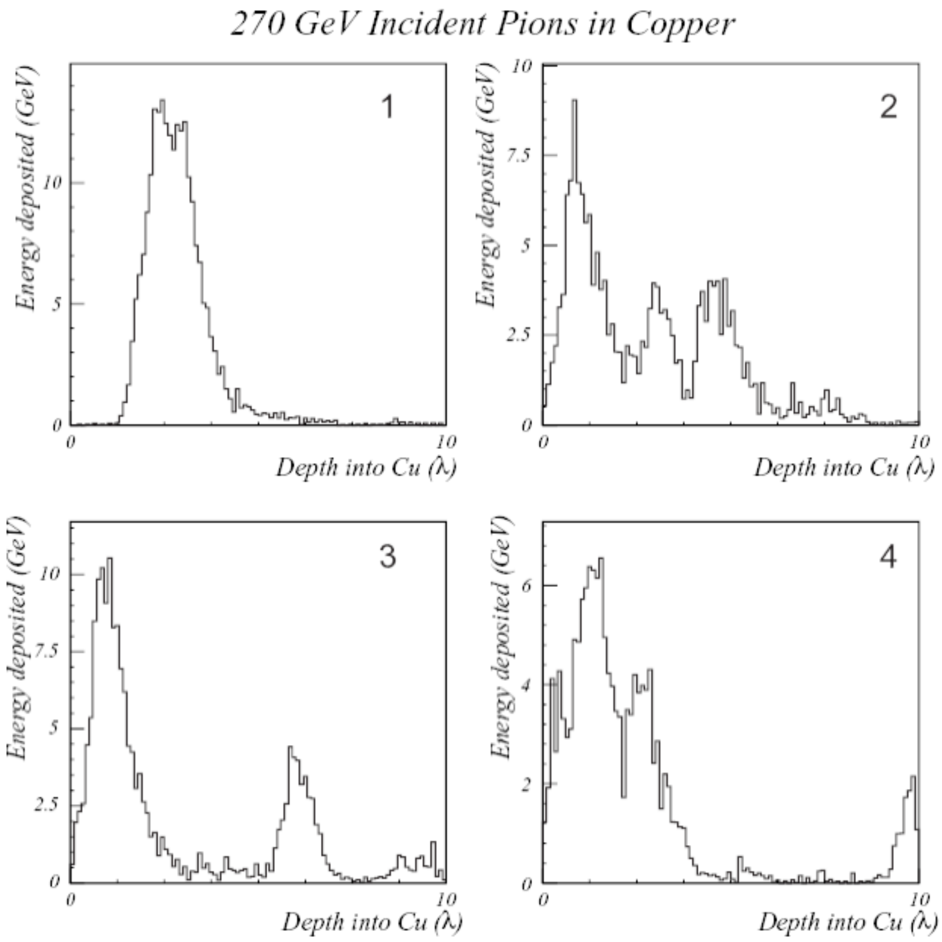
Hadronic energy resolution

- 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

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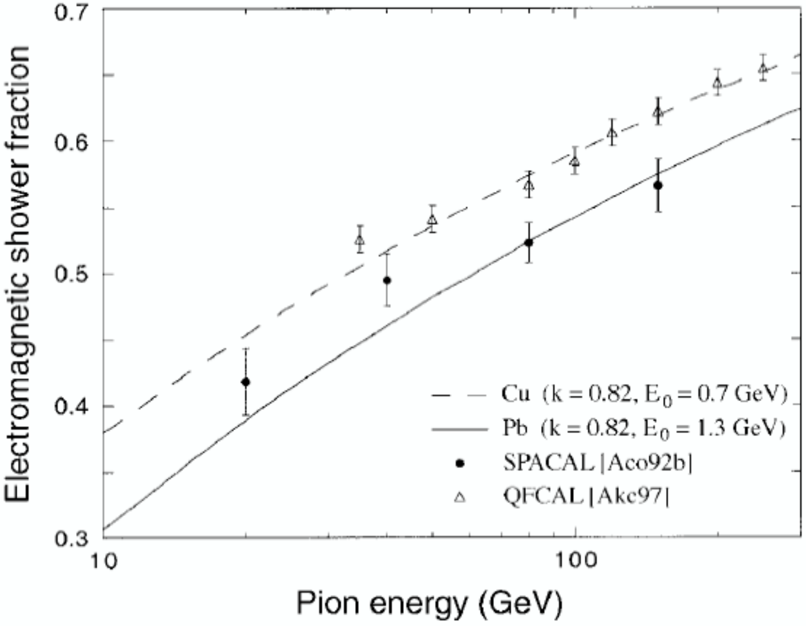
Hadronic showers: EM component

- 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_0.
  - After 2nd step: $f_o + f_0(1-f_0)$, etc.

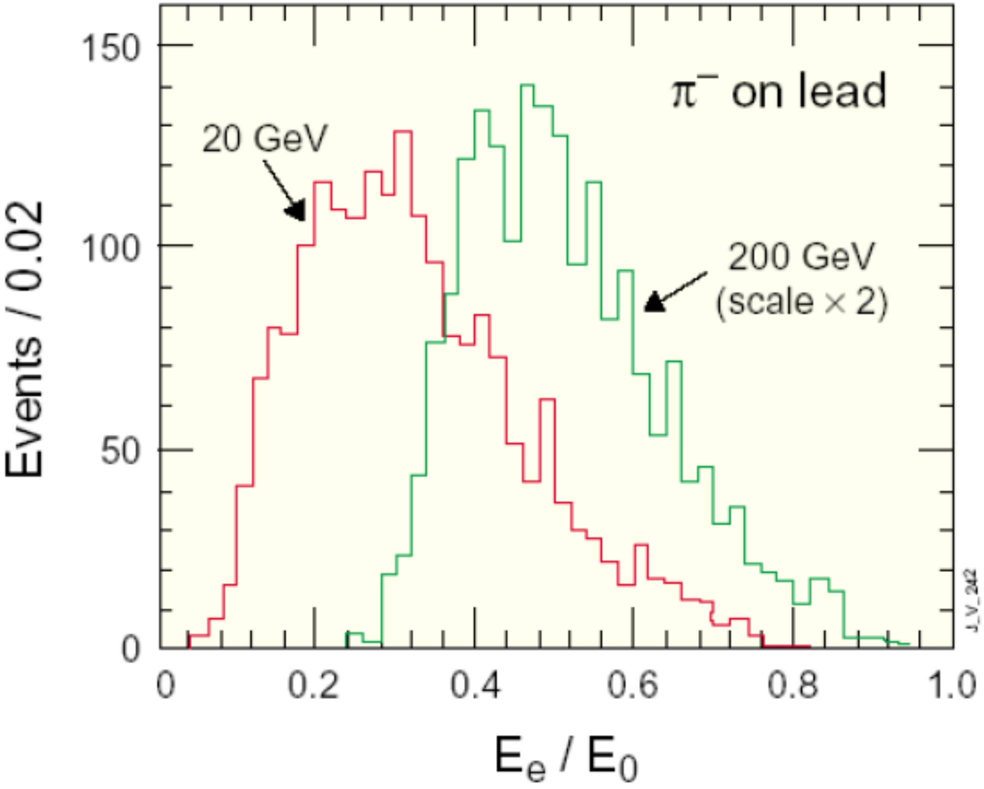
- Call F_o the fraction of EM energy in the shower:
  - $F_0 = f_0\Sigma(1-f_0)^{n-1}$, after n generations.
  - $F_0 = 1 - (1-f_0)^n$.

- 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_o.
- Average value of F_o increases with energy. ↓



Hadronic energy resolution

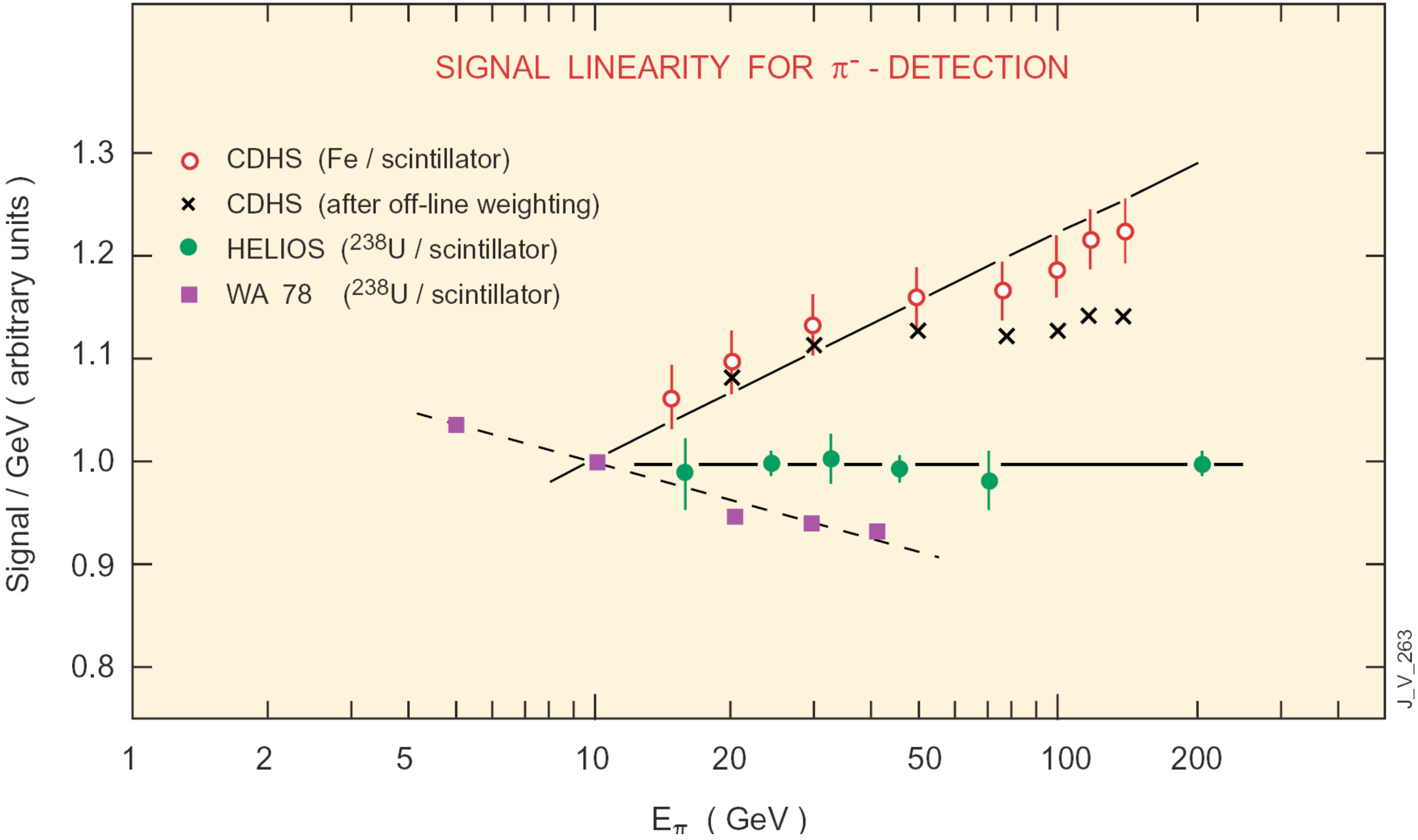
- In general, electromagnetic and hadronic responses of the calorimeter are different.
  - In a calorimeter system the electromagnetic and the hadronic sections may have different values of e/h.
- If e/h = 1 the calorimeter is said to be <u>compensating</u>.
- **If e/h is far from 1, this has serious 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.

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Lack of compensation

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

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

$$F_0 = 0.11 \cdot \ln E \quad \text{R. Wigmans}$$

- 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.

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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).

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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.

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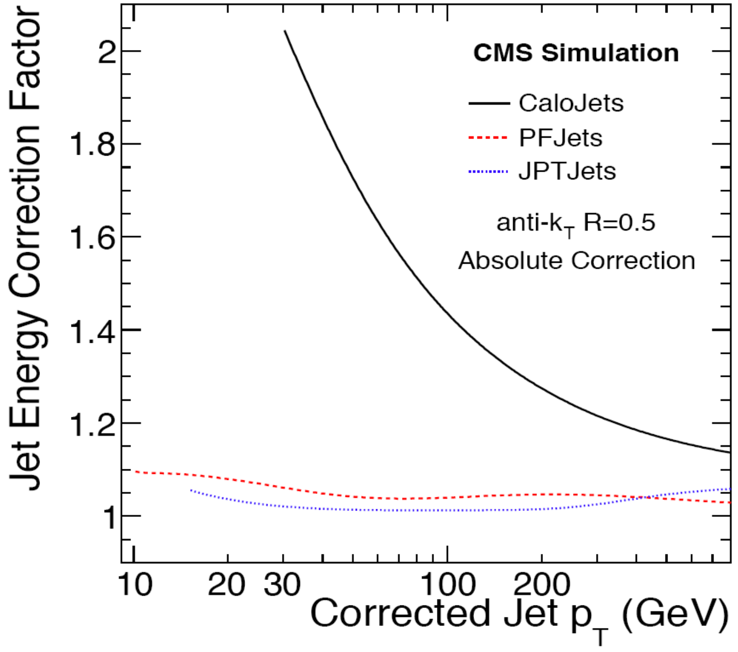
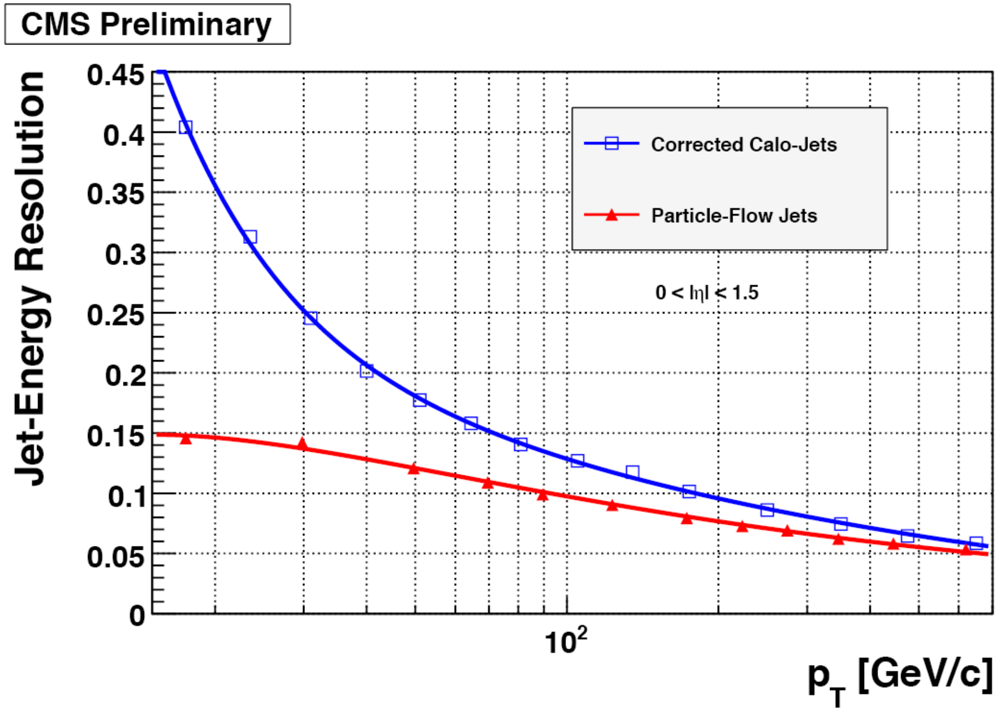
Example of particle flow in CMS

- 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 $W \to l\nu$ events.





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Missing transverse energy

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

- Hermiticity allows to measure the transverse imbalance.

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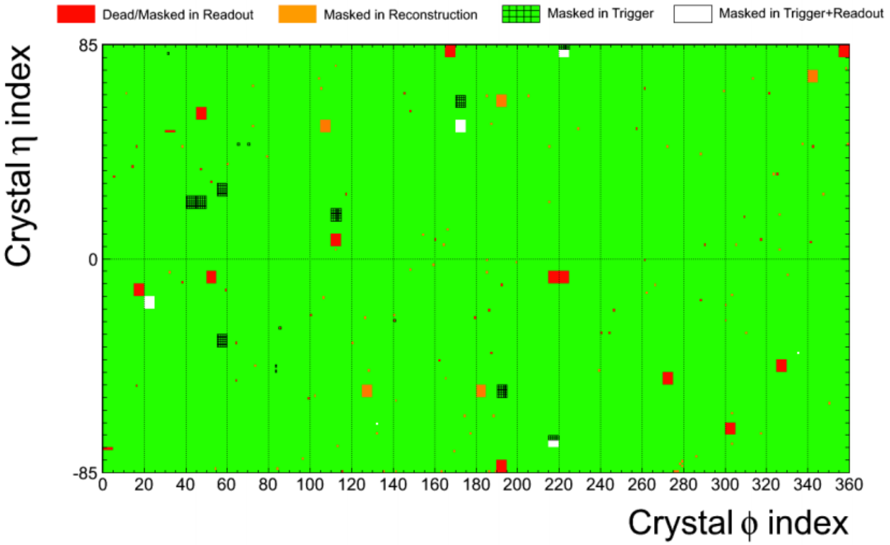
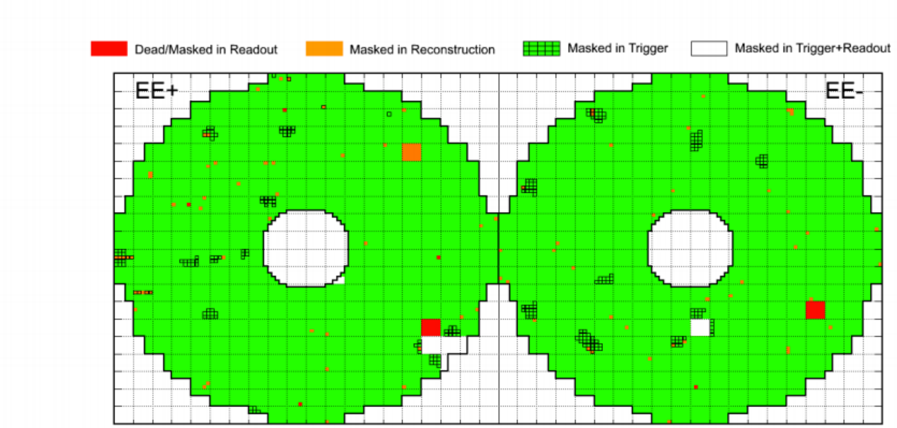
Missing energy

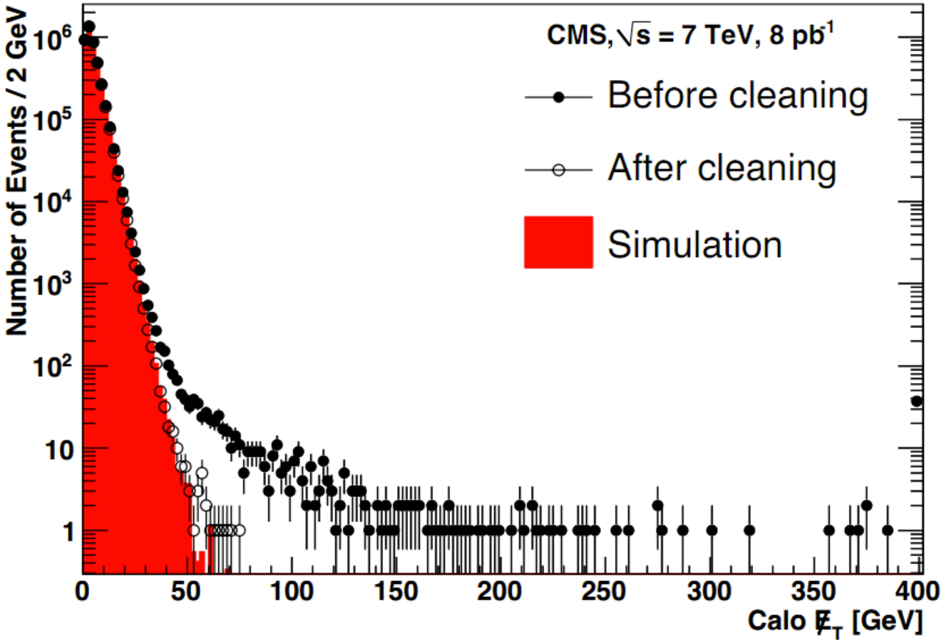
- Sensitive to holes.
  - CMS ECAL map. ➔





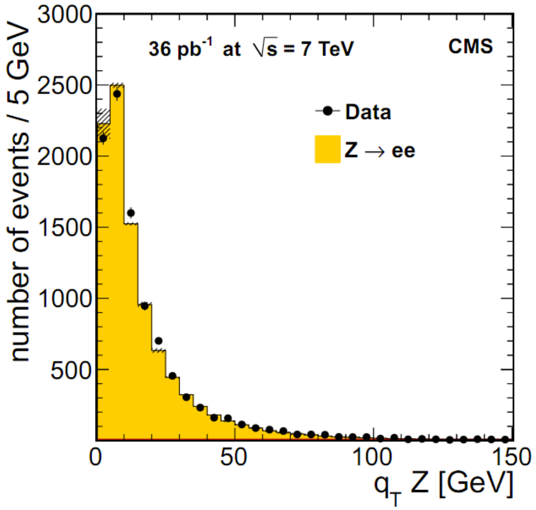
Missing energy

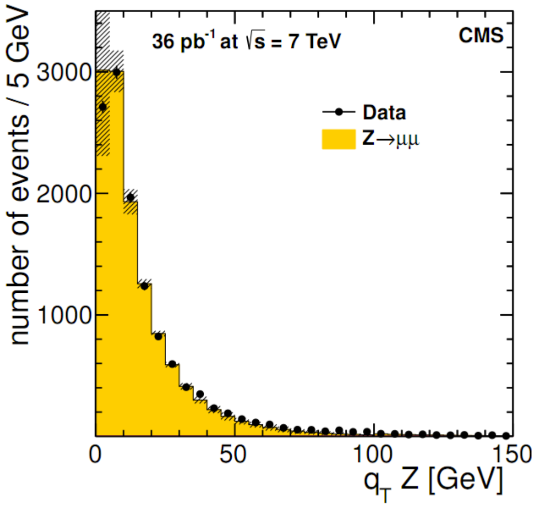
- Sensitive to noise.
  - Electronics regional events.
    - Not global, not local.
  - Direct ionization of photo-detectors.
    - "Spikes".
- Sensitive to beam backgrounds.
  - Beam-halo interactions.

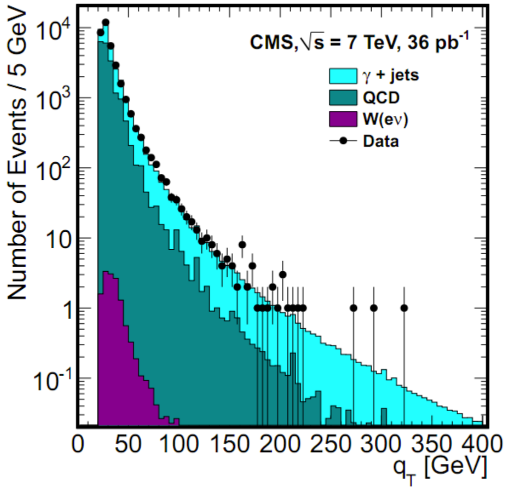


Missing transverse energy

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







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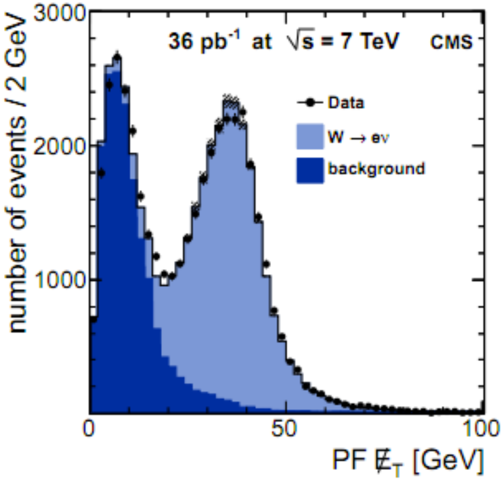
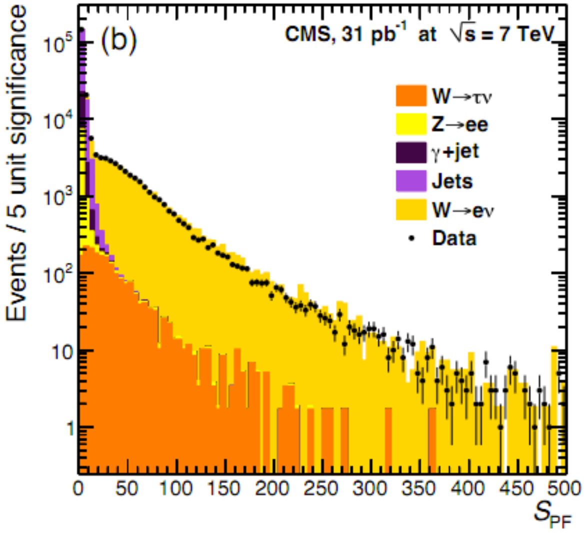
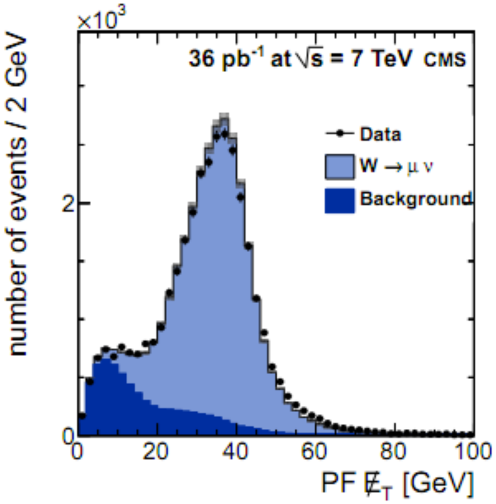
Missing transverse energy

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







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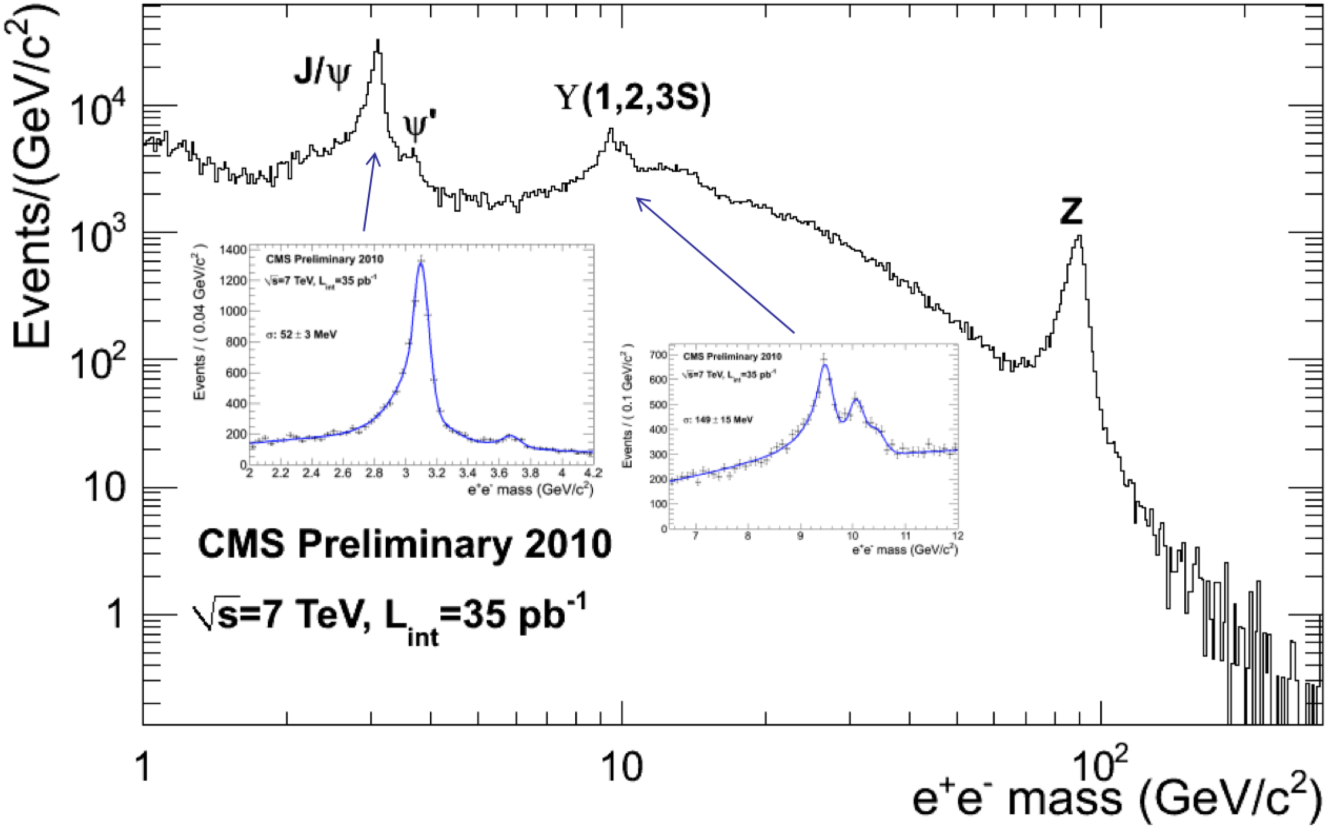
CMS ECAL performance

- Dielectrons from J/psi to Z



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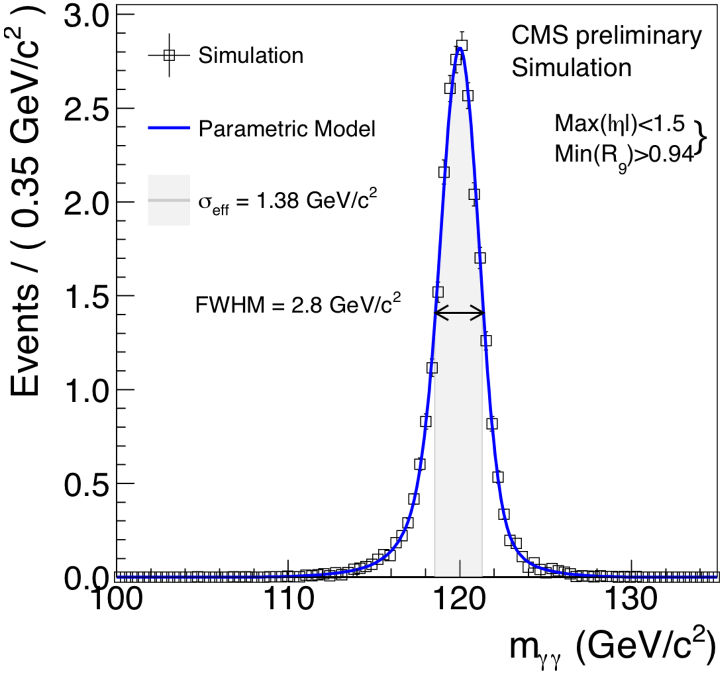
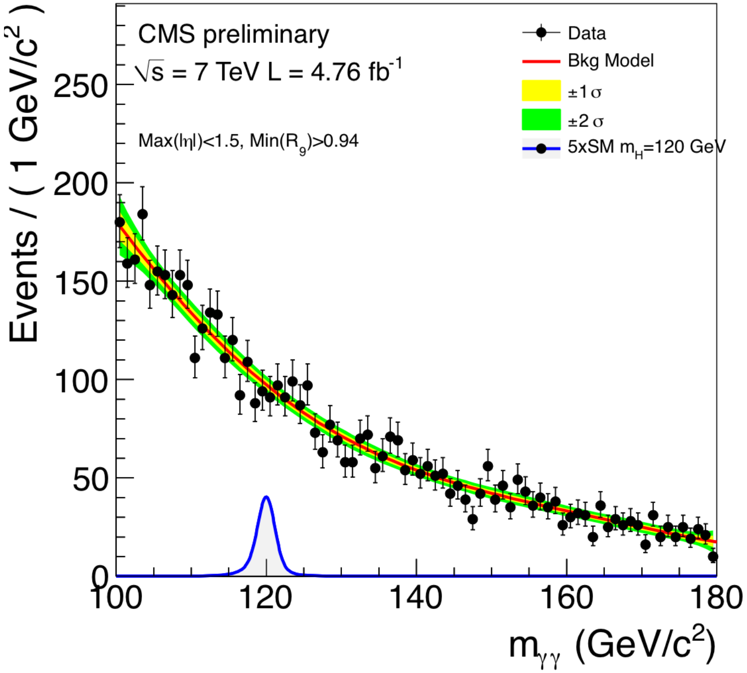
CMS ECAL performance

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

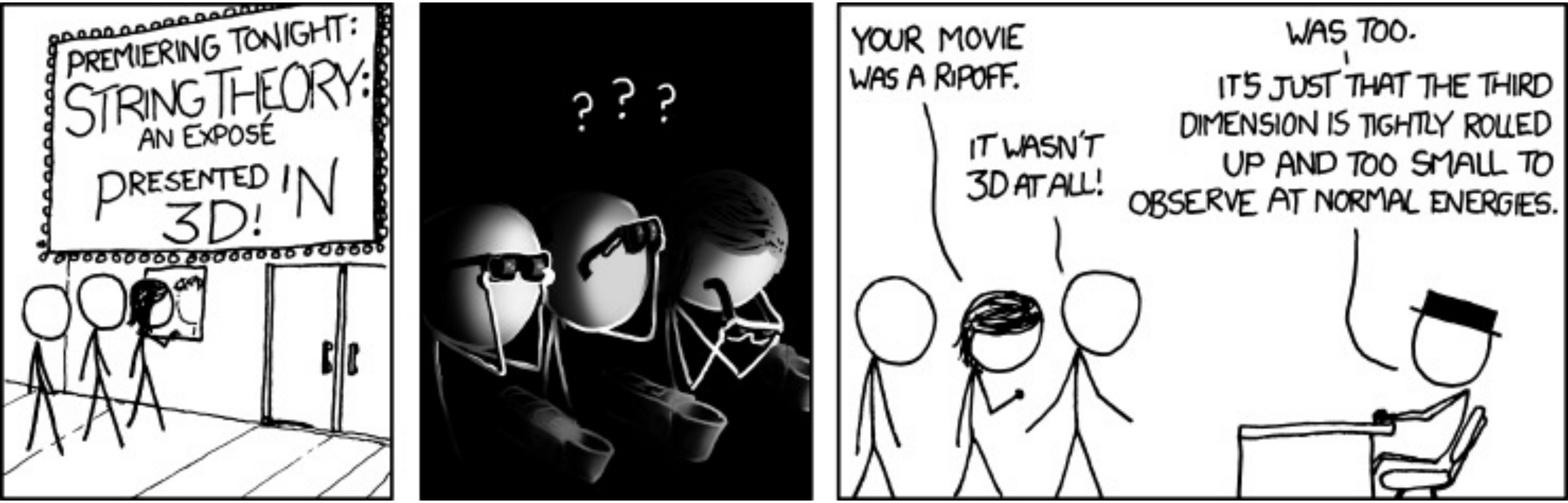




Intro and Calorimetry

- 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.

You are here

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

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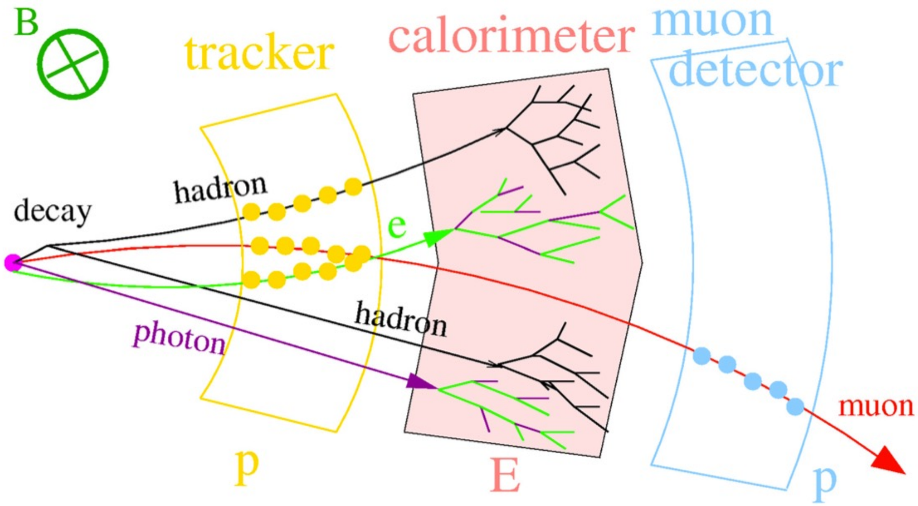
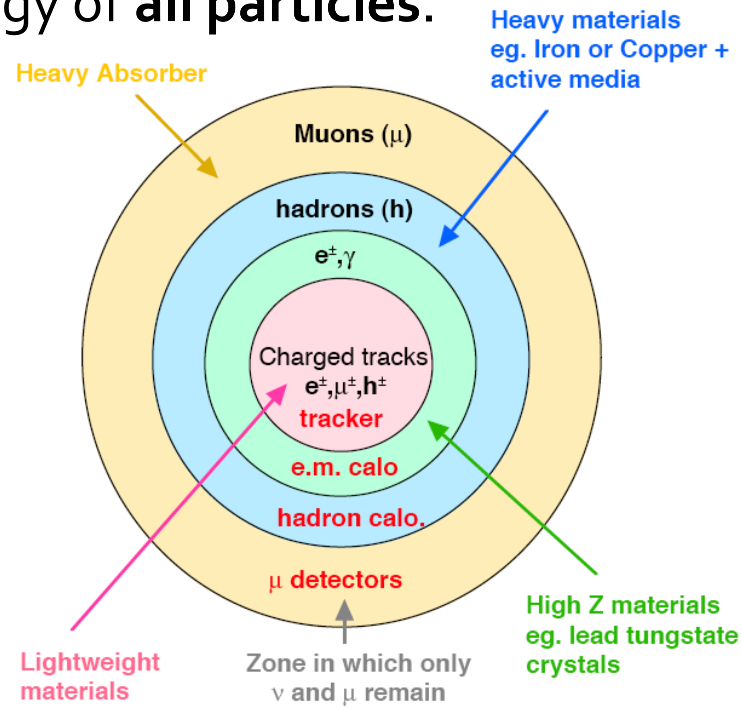
Peeling the hermetic onion

- 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.

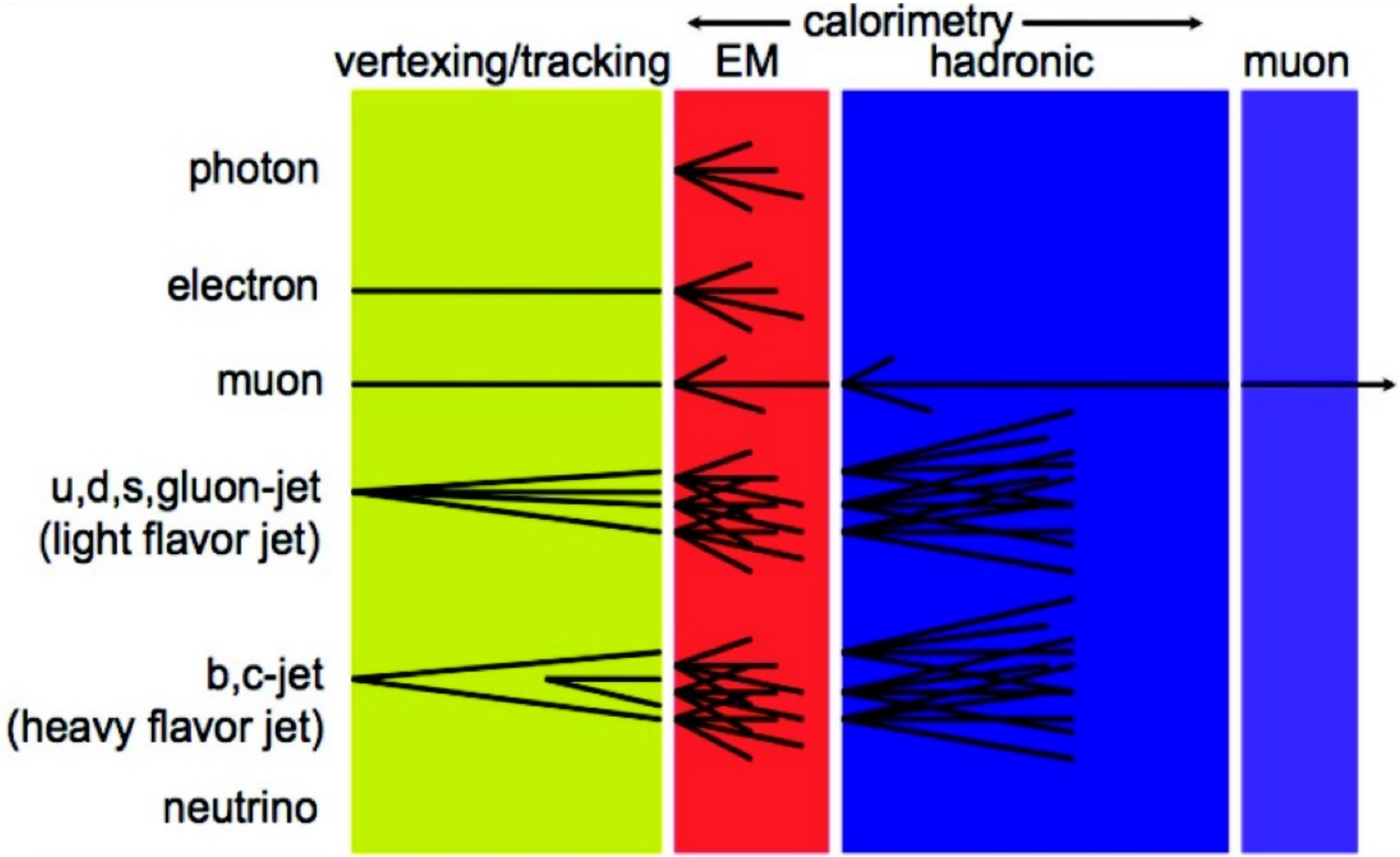
μ detectors

Lightweight materials

Zone in which only ν and μ remain

High Z materials eg. lead tungstate crystals

Particles and their decays



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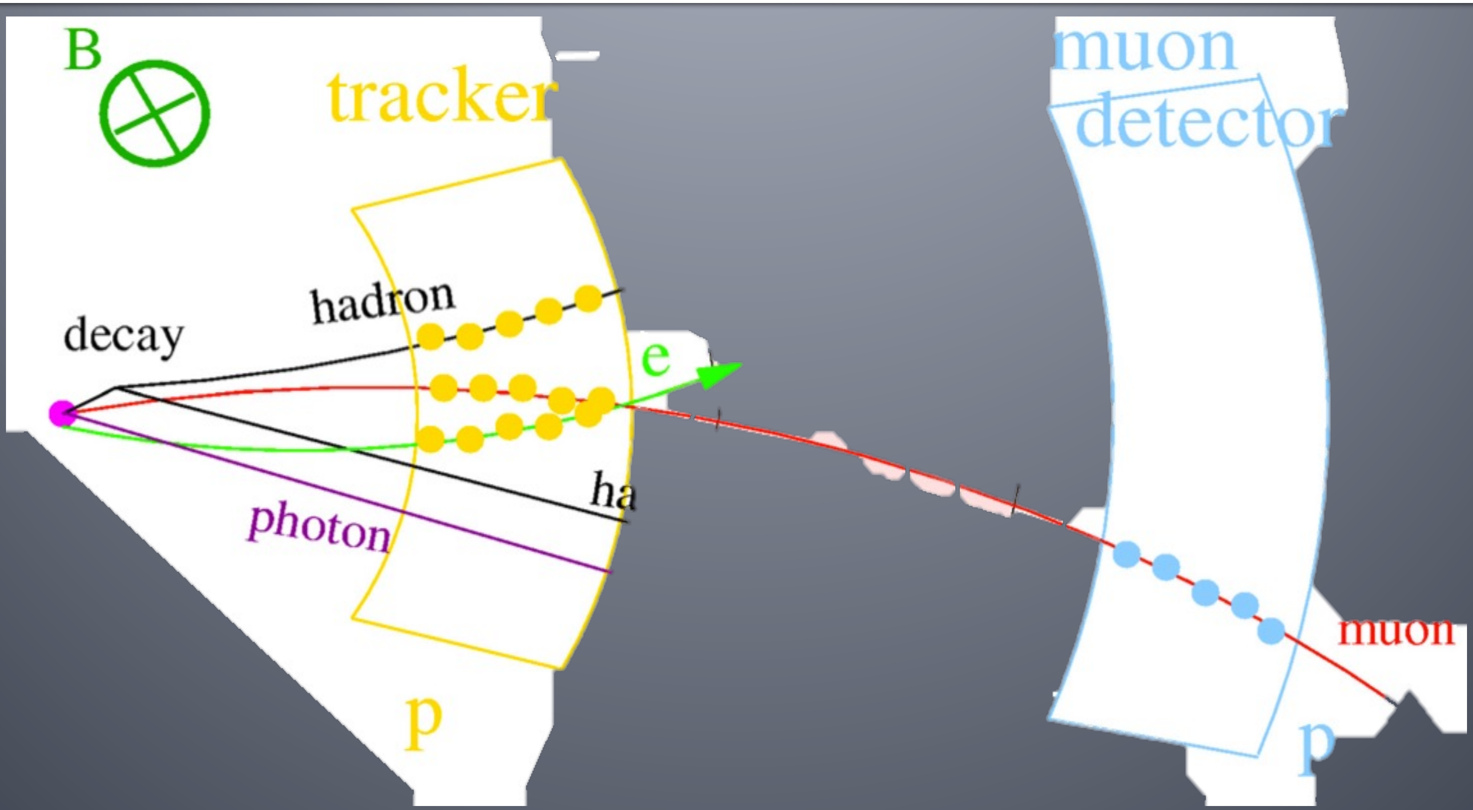
Tracking

Trying to retrace the path of charged particles, including far-reaching muons.



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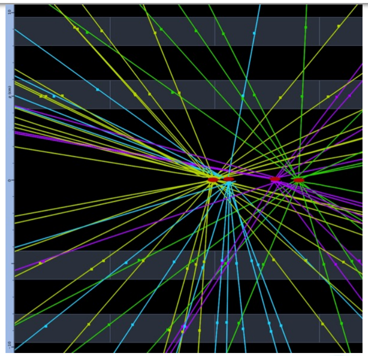
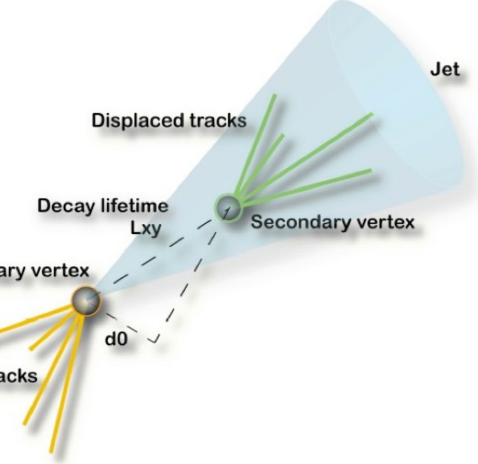
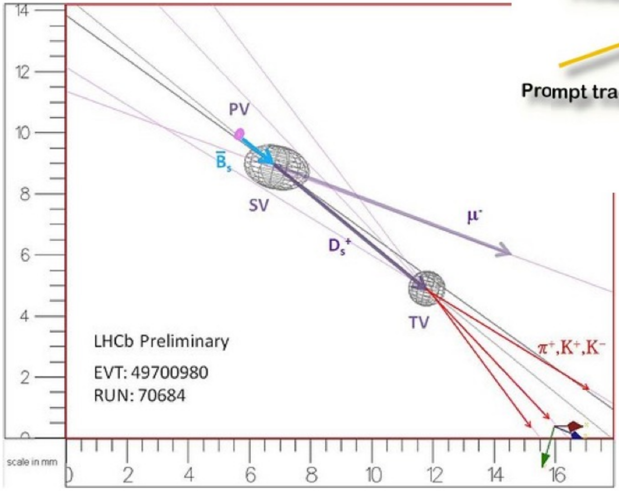
Tracking: why?

- To find the hard interaction vertex. ➔
- To identify secondary vertices. ➘
  - Longer-lived particles.
- To measure trajectory of particles.
  - Momentum and energy loss of charged particles.
  - Connection to showers in calorimeters (electrons, photons).
  - Provide inner leg for muon reconstruction.

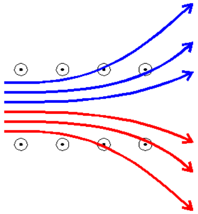






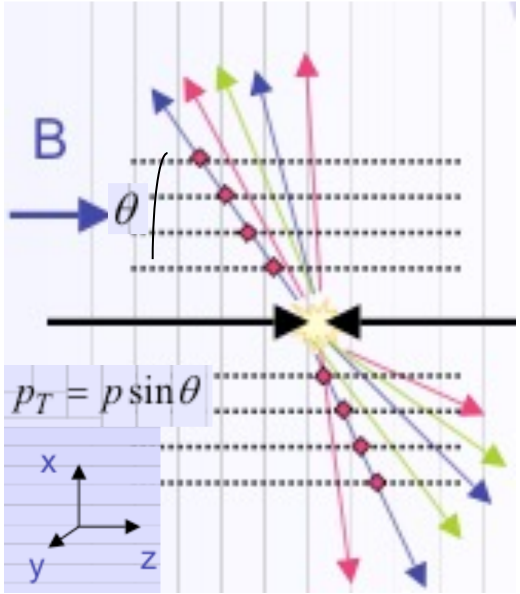
Tracking: what?

- Solid state detectors.
  - Pixels for vertexing.
  - Strips for tracking.
- Gaseous detectors.
  - Drift tubes, etc for outer tracking.



$$F = q \cdot v \cdot B = m \cdot \frac{v^2}{R}$$

$$\Rightarrow q \cdot B \cdot R = m \cdot v = |\vec{p}|$$



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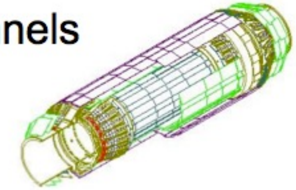
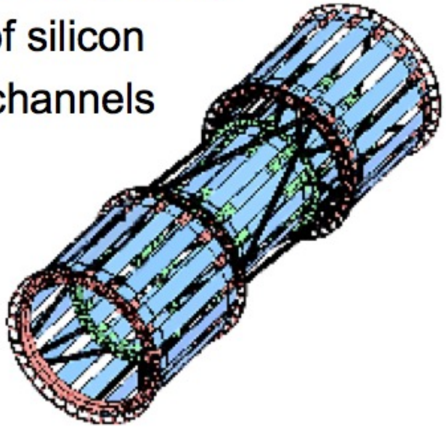
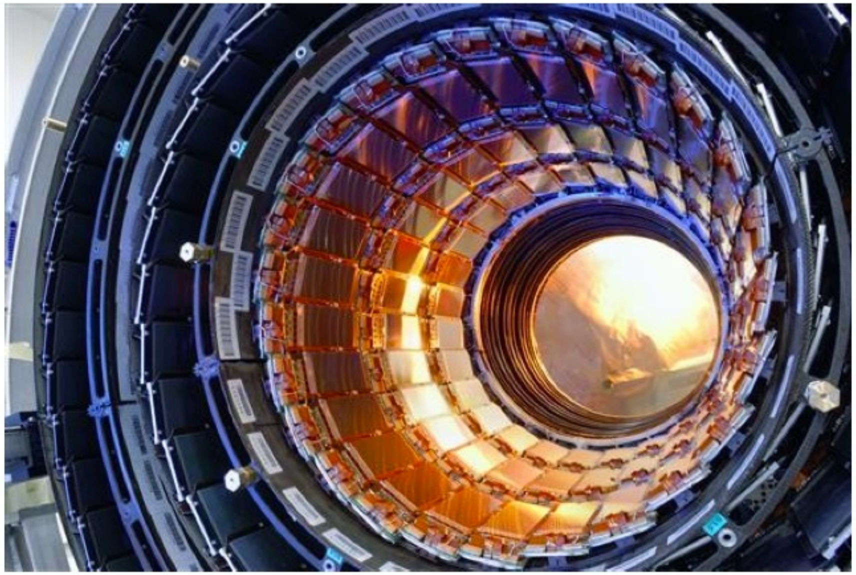
Tracking: how?

- LEP eg. DELPHI (1996)
  - 1.8 m^2 of silicon
  - 175k readout channels



- CDF SVX IIa (2001)
  - 6 m^2 of silicon
  - 175k channels





- CMS tracker
  - full silicon tracker
  - 210 m^2 of silicon
  - 10.7 M channels

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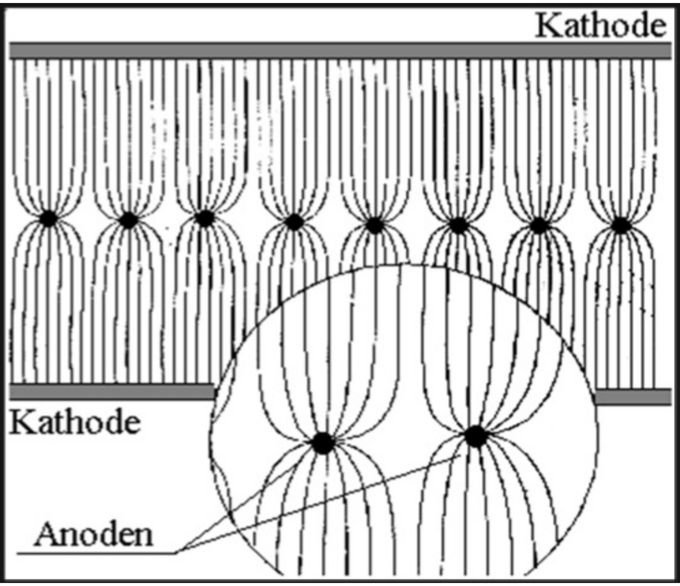
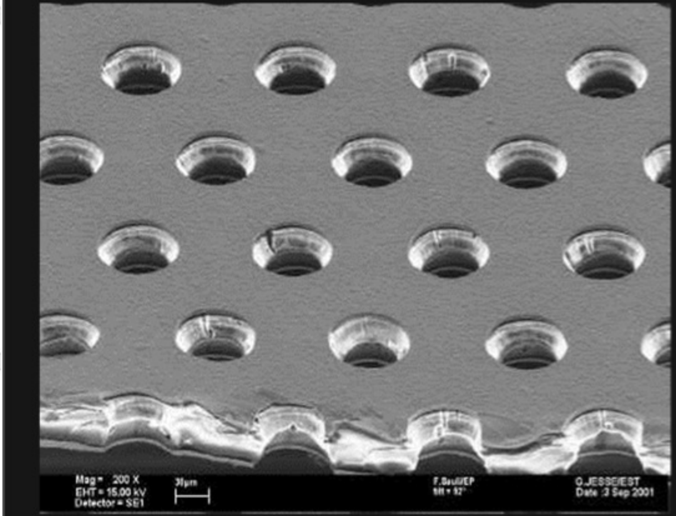
Tracking: how?

- Drift Tubes.
- Microstrip Gas Counters.
- Gas Electron Multipliers.

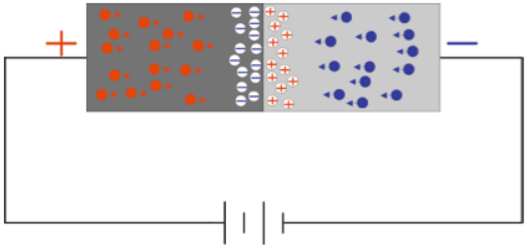


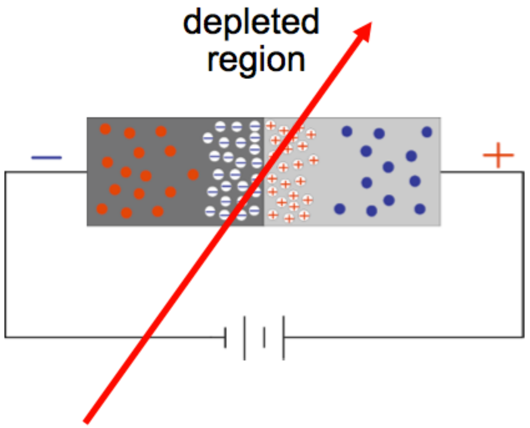


Inner trackers

Silicon detectors

- Silicon detector is a p-n diode
  - p-type (more holes)
  - n-type (more electrons)
  - Current can flow if forward biased





- Reverse bias to create a depletion layer with no mobile charge carriers
  - Passage of a charged particle releases electron-hole pairs by ionisation
  - 20 000 to 30 000 pairs in 300 μm
  - Signal >10 times more than background noise
  - High enough resistivity to allow full depletion (i.e. full depth of sensor) with a few 100V

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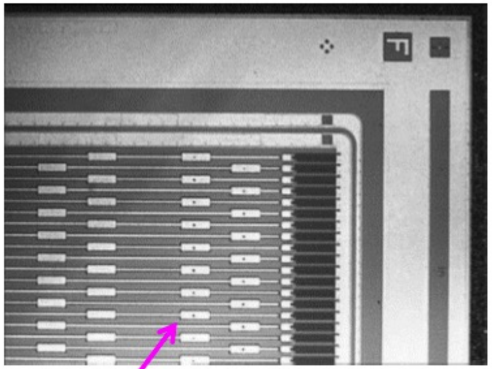
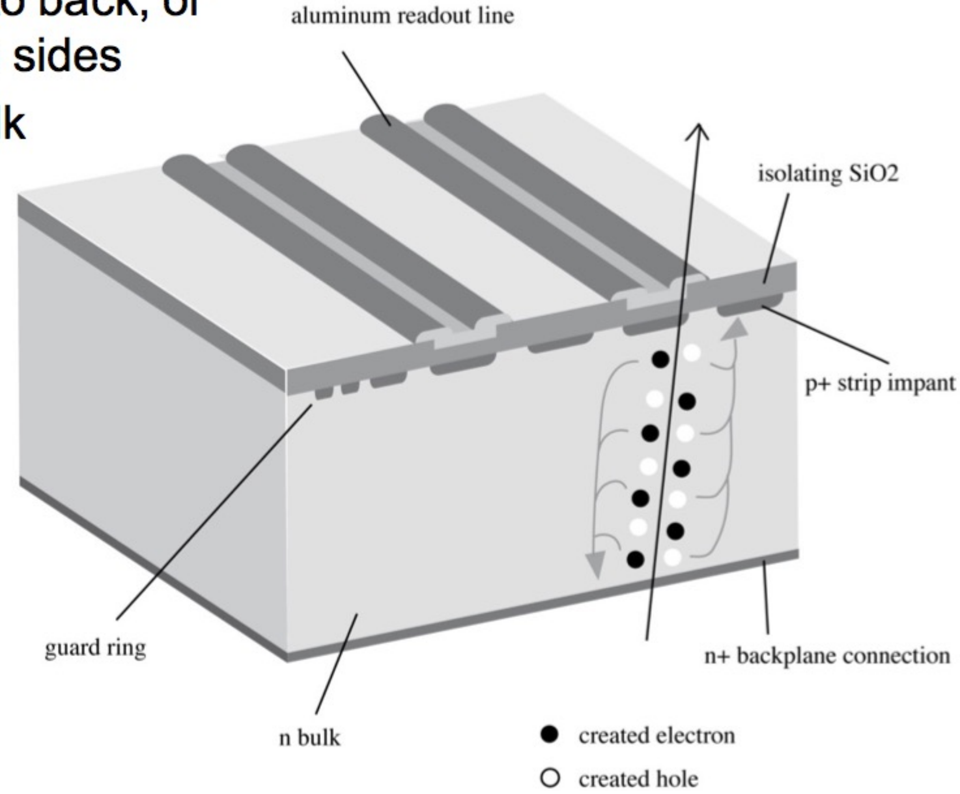
Microstrips sensors

- Make many diodes on one wafer
  - ~50 μm strip pitch (possible with planar fabrication process)
  - Glue wafers back-to back, or make strips on two sides
  - eg. p strips in n bulk

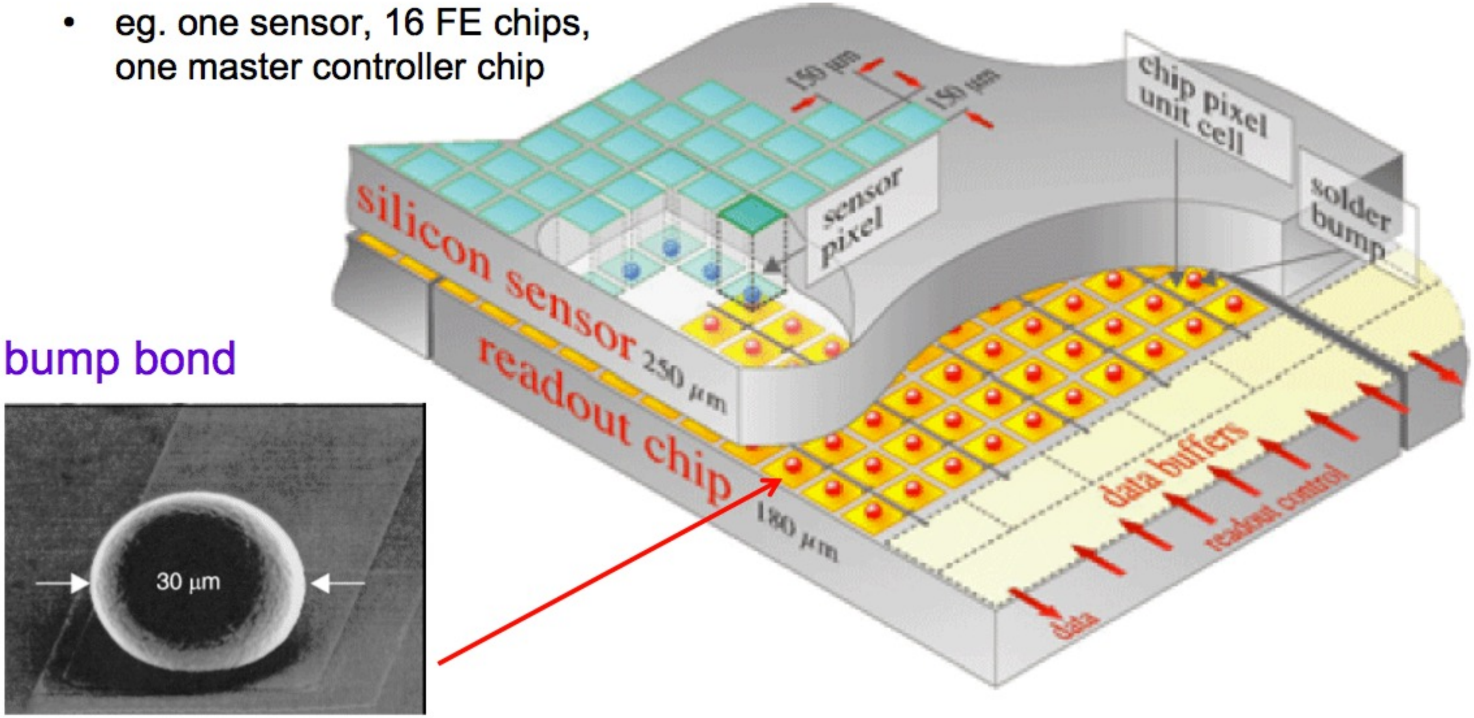


Metalisation above strips, with bond pads



Pixel sensors

- 2-d position information with high track density.
  - Back-to-back strips give “ghost” hits. Pixels give unambiguous point
- Hybrid pixel detectors with sensors and readout chips bump-bonded together in a module
  - eg. one sensor, 16 FE chips, one master controller chip



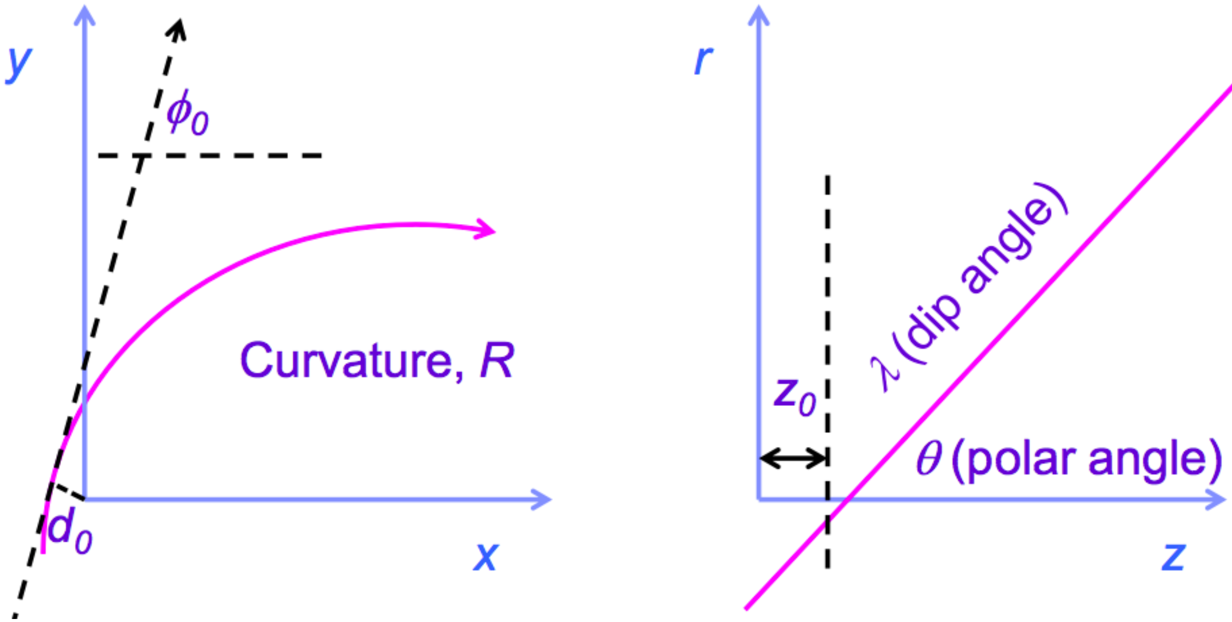
Tracks

Track coordinates

With a uniform B field along the z-axis (= beam line), track path is a helix (i.e. for ALICE, ATLAS or CMS central trackers)

Pseudorapidity, $\eta = -\ln \tan(\theta/2)$. Transverse momentum, $p_T = p \sin\theta$

Transverse (*xy*) and Longitudinal (*rz*) projections. Define impact parameter w.r.t. point of closest approach to origin or PV



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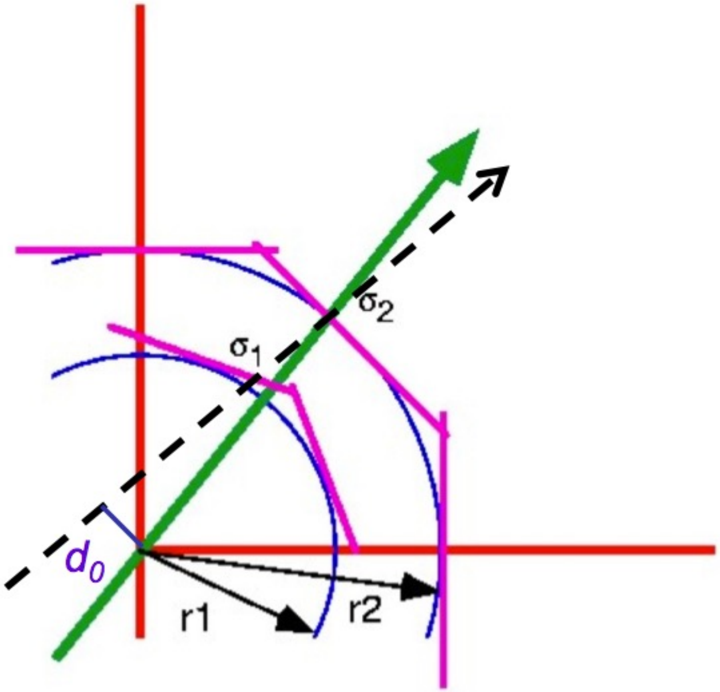
Impact parameter resolution

Uncertainty on the transverse impact parameter, d_0, depends on the radii and space point precision.

Simplified formula for just two layers:



$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$$

Suggests small r_1, large r_2, small σ_1, σ_2

But precision is degraded by multiple scattering…

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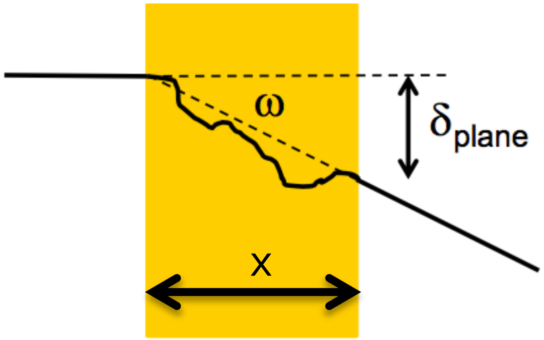
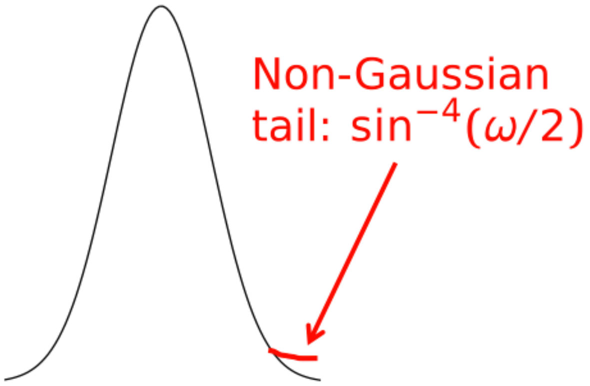
Multiple scattering

- Particle incident on a thin layer, fraction x/X_0 of a radiation length thick, is bent by angle ω




Non-Gaussian tail: $\sin^{-4}(\omega/2)$

- Distribution of ω is nearly Gaussian (central 98%)
- $d_0 = r \tan\omega \approx r\omega$

K. Nakamura et al. (PDG), J. Phys. G 37, 075021 (2010)

$$\sigma_{d_0} = \frac{r}{\beta c p} 13.6\mathrm{MeV} \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \log\left(\frac{x}{X_0}\right)\right]$$

- Higher momentum, p → less scattering
- Best precision with small radius, r, and minimum thickness x

Transverse IP resolution

For a track with $\theta \neq 90°$ $r \rightarrow \frac{r}{sin\theta}, \ x \rightarrow \frac{x}{sin\theta}$

Resulting in:

$$\sigma_{d_0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \oplus \frac{r}{p\sin^{3/2}\theta} 13.6\mathrm{MeV}\sqrt{\frac{x}{X_0}}$$

$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

Constant term depending only on geometry

and term depending on material, decreasing with p_T

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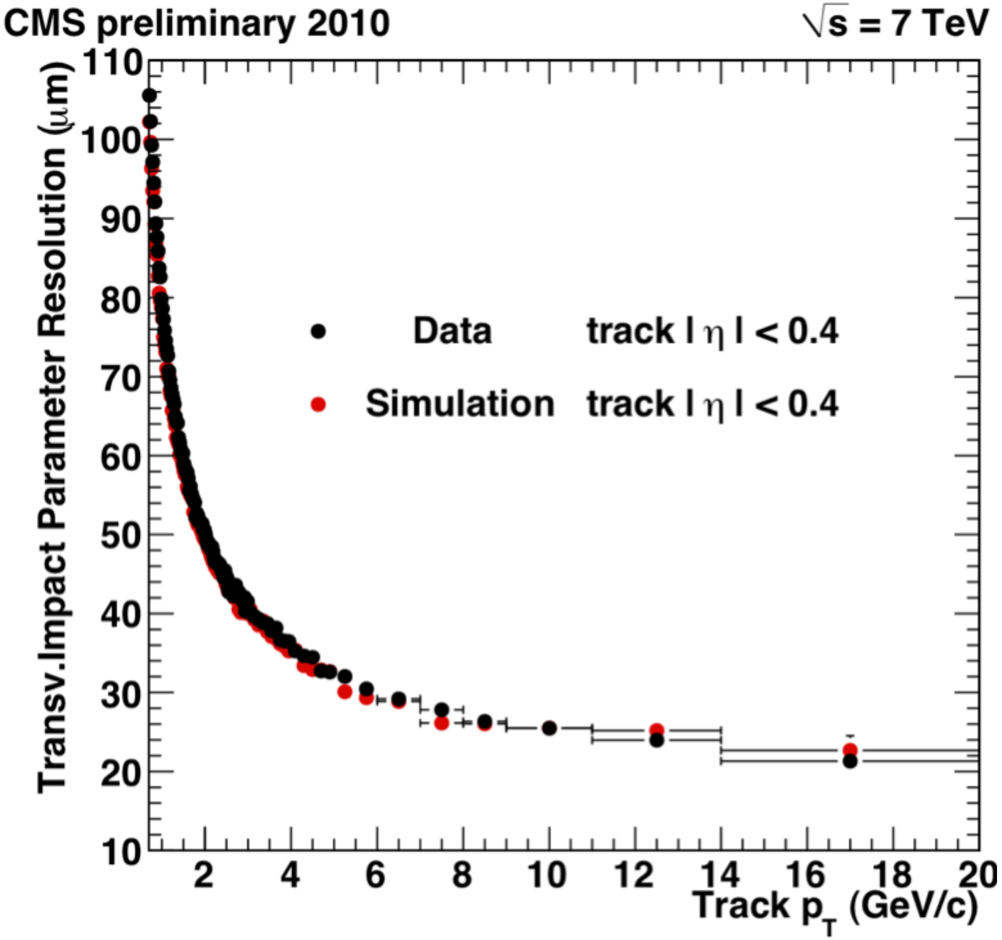
CMS transverse IP resolution

$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

Observed:

100 μm @ 1 GeV,

20 μm @ 20 GeV

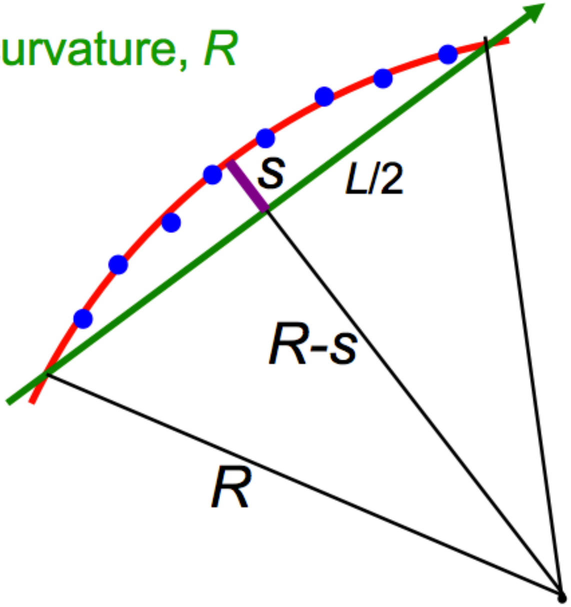


Momentum measurement

- Circular motion transverse to uniform B field:

$$p_T[\mathrm{GeV/c}] = 0.3 \cdot B[\mathrm{T}] \cdot R[\mathrm{m}]$$

- Measure sagitta, *s*, from track arc → curvature, *R*



$$R = \frac{L^2}{2s} + \frac{s}{2} \approx \frac{L^2}{2s}$$

- $$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T}{0.3BL^2}\sigma_s$$

- Relative momentum uncertainty is proportional to p_T times sagitta uncertainty, σ_s. Also want strong B field and long path length, *L*

Measuring momentum

Sagitta uncertainty, σ_s, from N points, each with resolution $\sigma_{r\phi}$ is:

$$\sigma_s = \sqrt{\frac{A_N}{N+4}}\frac{\sigma_{r\phi}}{8}$$

Statistical factor $A_N = 720$:
(Gluckstern)

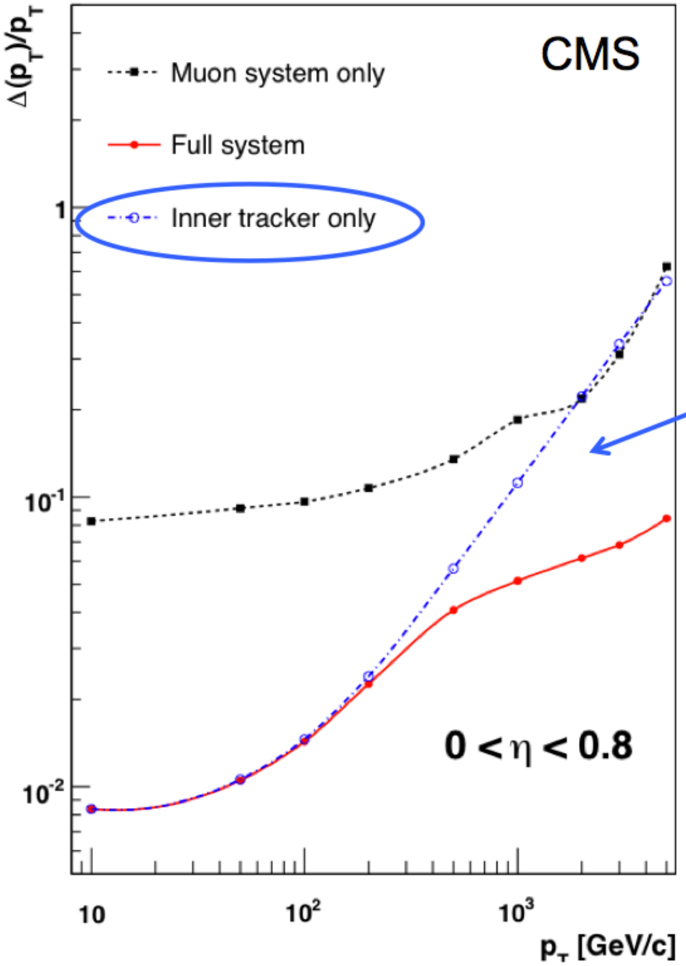
The point error, $\sigma_{r\phi}$ has a constant part from intrinsic precision, and a multiple scattering part.

Multiple scattering contribution:
(*L* is in the transverse plane)

$$\sigma_s \propto \frac{L}{p_T \sin^{1/2}\theta}\sqrt{\frac{L}{X_0}}$$

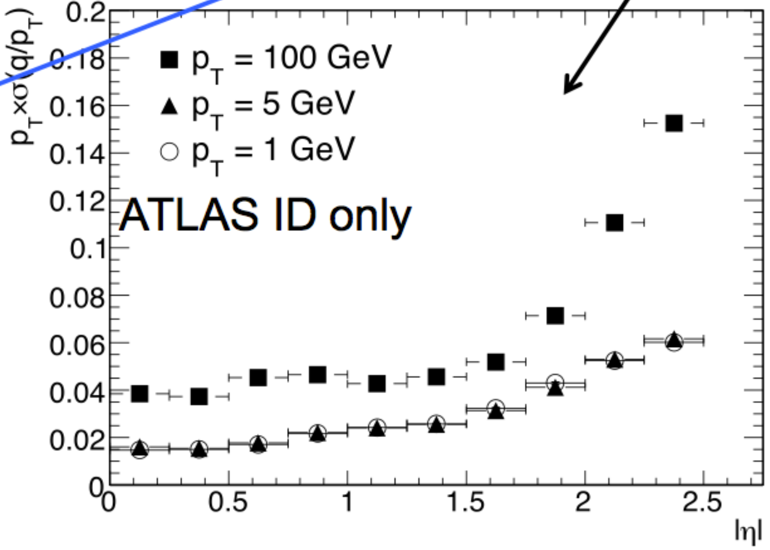
$$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T \cdot \sigma_s}{0.3BL^2} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2}\theta}$$

Momentum resolution



Expected relative p_T resolution for muons vs $|\eta|$ and p_T.

$$\frac{\sigma_{p_T}}{p_T} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2}\theta}$$



(More material) ⟶

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Calibration and alignment

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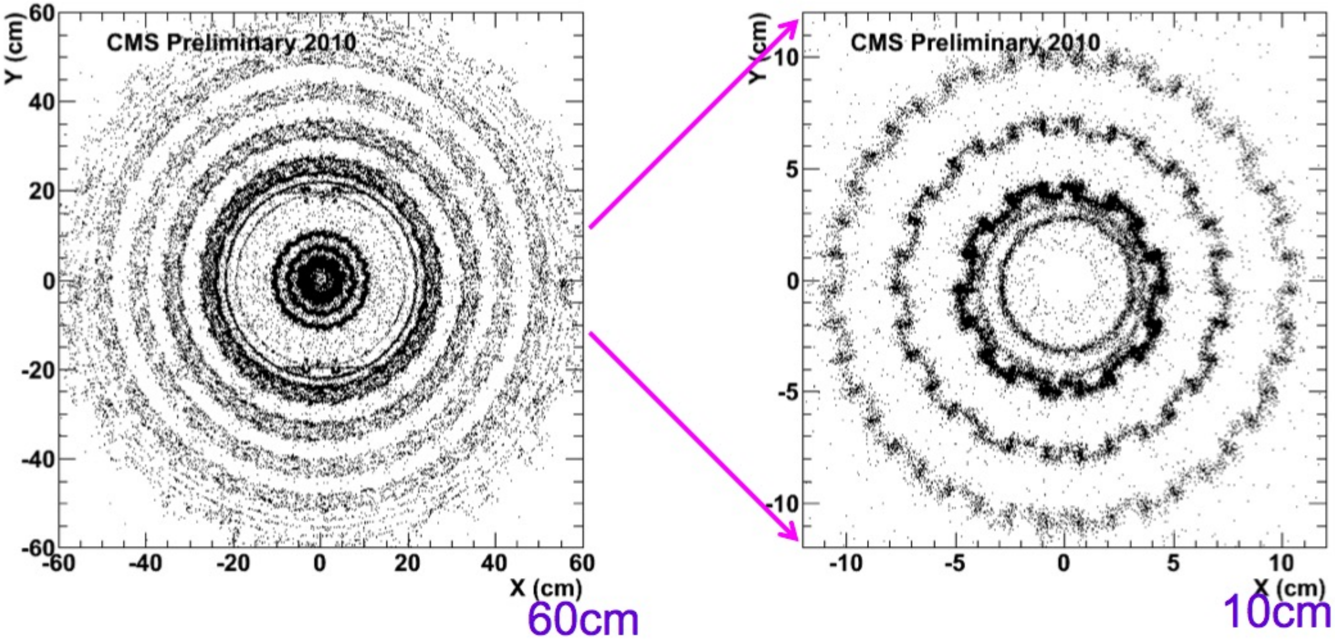
Checking material

- Conversions, $\gamma \rightarrow e^+e^-$, example from CMS
  - Two oppositely charged tracks
  - Consistent with coming from the same point
  - Consistent with fit to a common vertex, imposing zero mass



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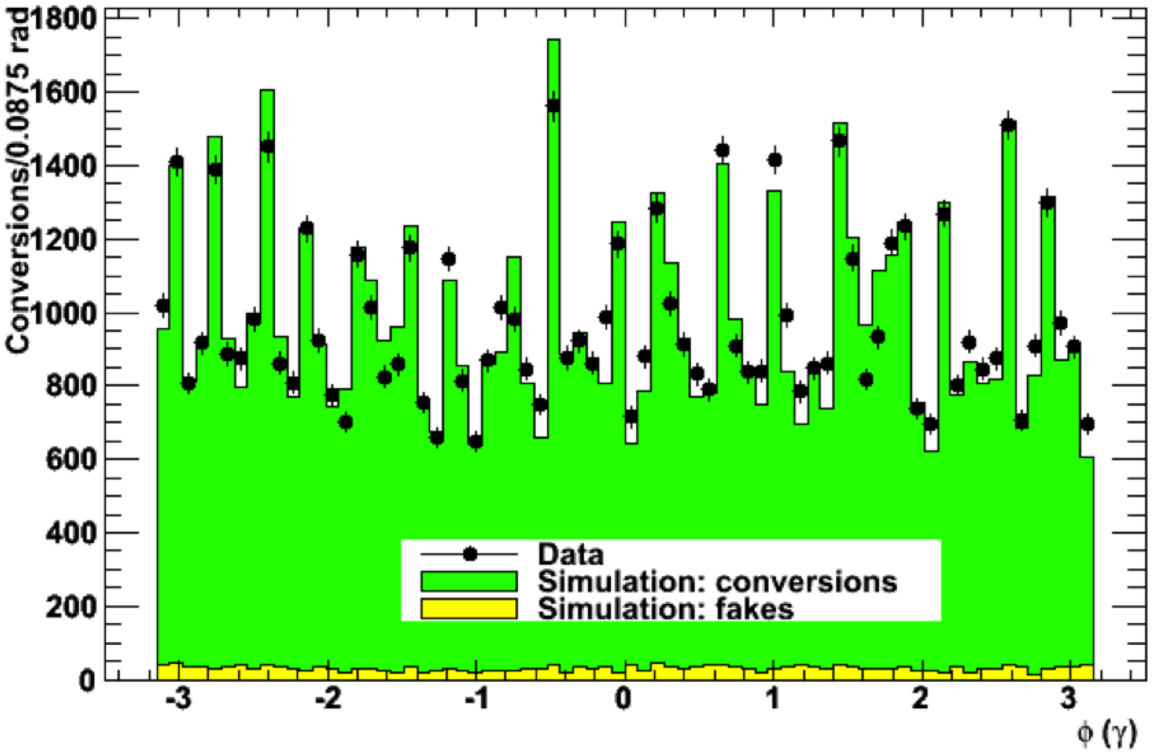
Checking material description

- ϕ distribution for conversions with $|z| < 26$cm, $R < 19$cm
- → Compare pixel barrel structure in data and simulation
- Spikes due to cooling pipes



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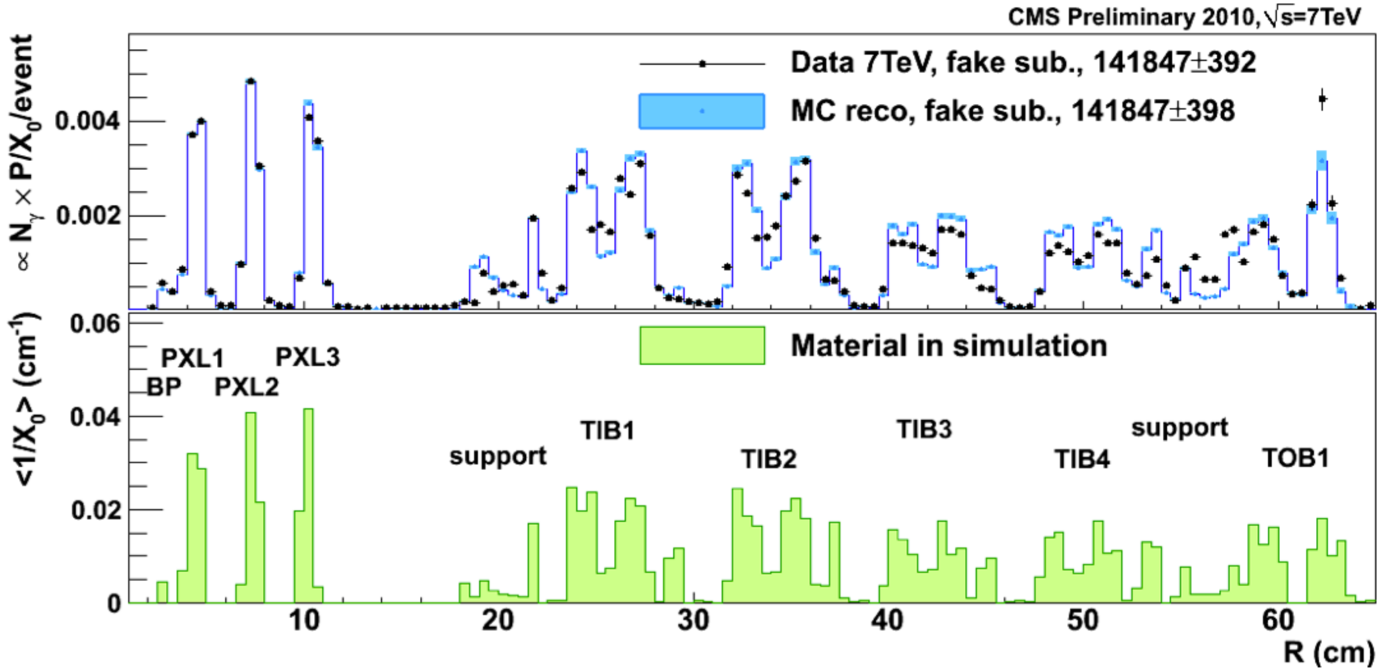
Checking material description

- Correct for identification efficiency to make a quantitative measurement of pixel and inner tracker barrel material
- Relative agreement between data and simulation ~10%
- Local discrepancy for support between TIB and TOB



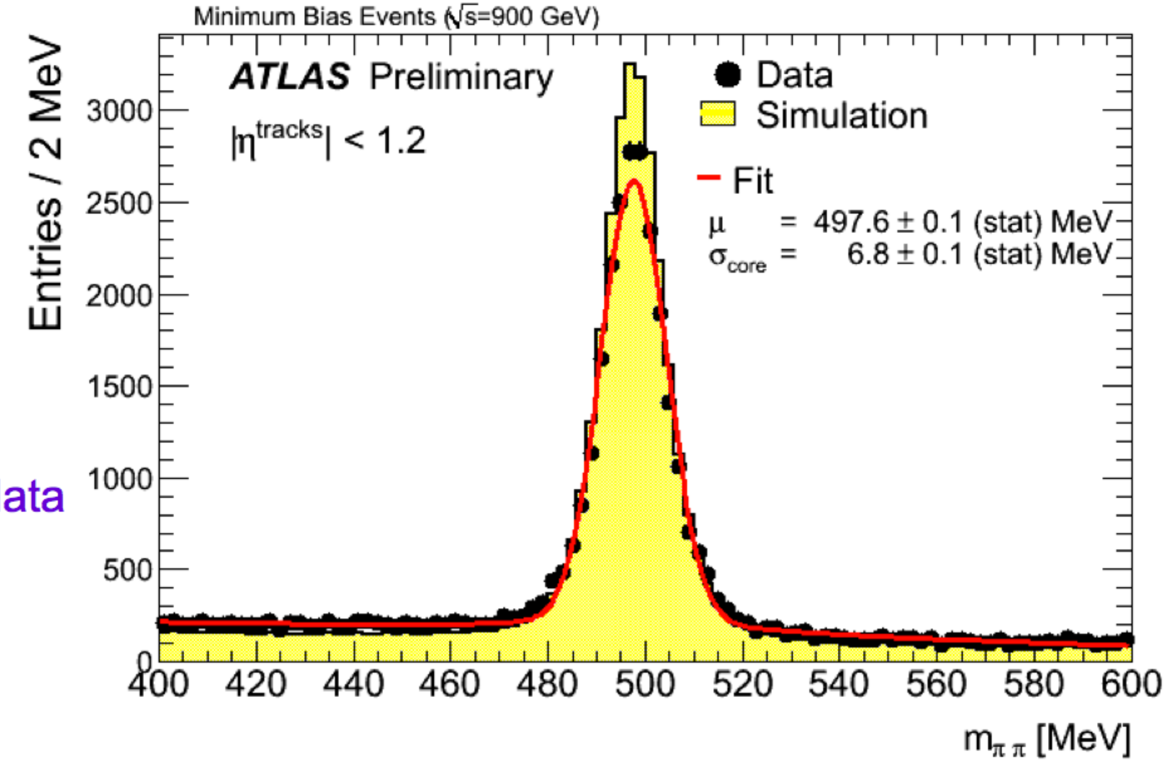
Checking alignment

$K^0 \rightarrow \pi^+\pi^-$

Two oppositely charged tracks, consistent with the same vertex.

Assume the tracks are pions. Reconstruct the pair invariant mass.

World Average PDG value 497.614 ± 0.024 MeV



ATLAS example:2009 data slightly broader than simulation

ATLAS-CONF-2010-019

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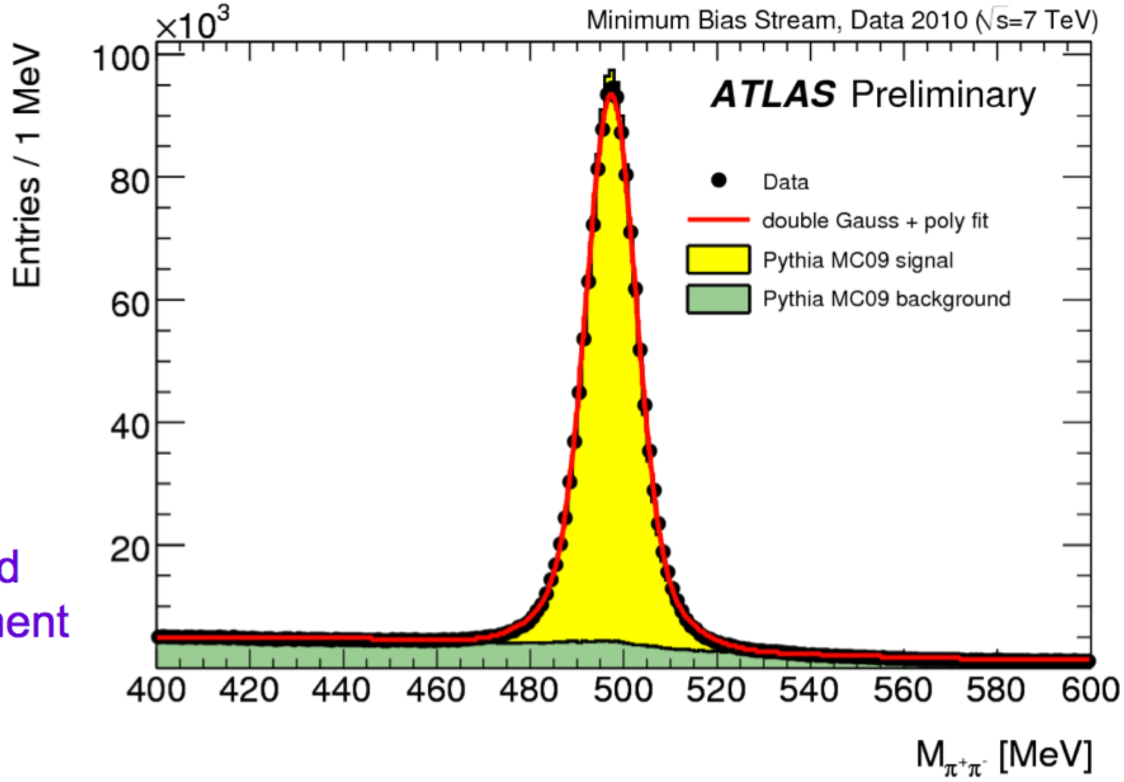
Checking alignment

$K^0 \rightarrow \pi^+\pi^-$

Two oppositely charged tracks, consistent with the same vertex.

Assume the tracks are pions. Reconstruct the pair invariant mass.

World Average PDG value 497.614 ± 0.024 MeV



Much better agreement with 2010 sample and improved alignment

ATLAS-CONF-2010-033

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Outer trackers

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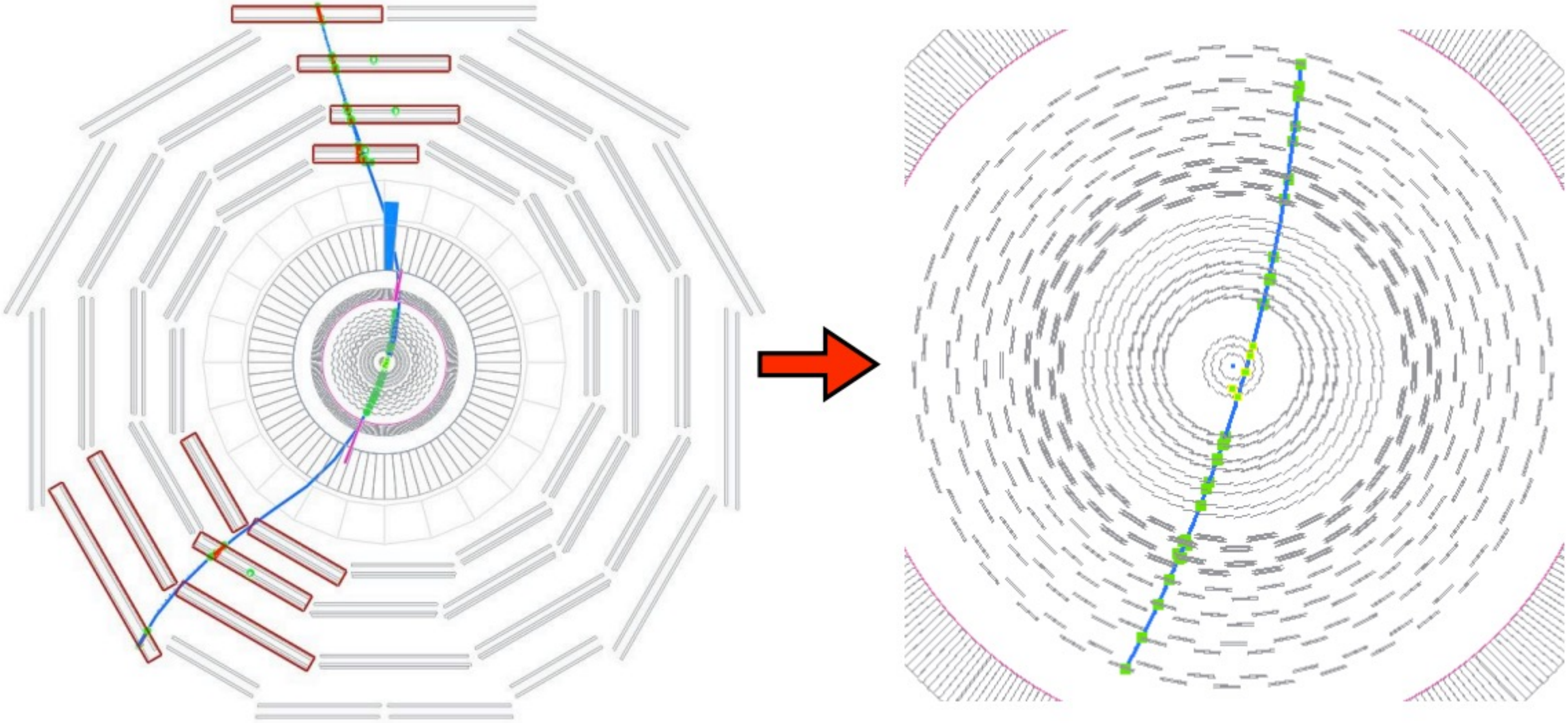
The cosmic muon that crossed all



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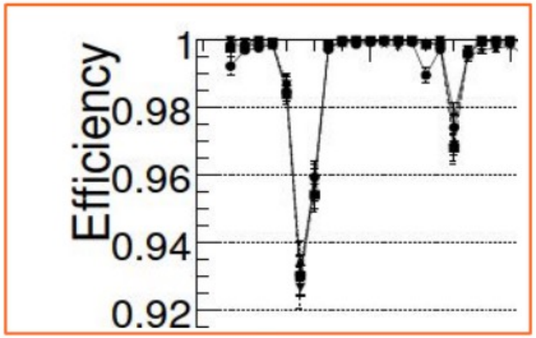
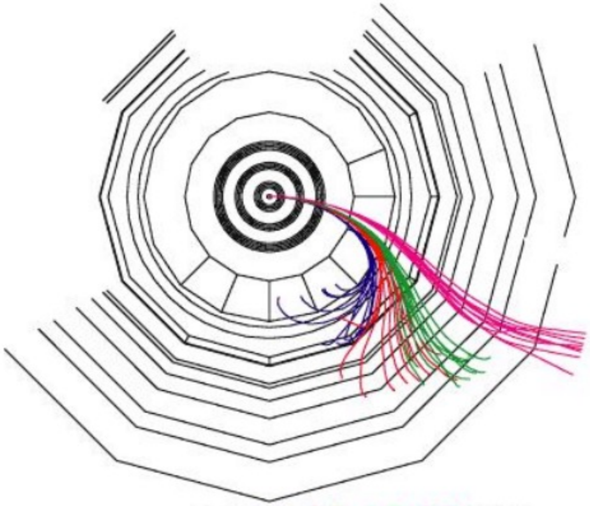
Finding muons: not just outside in

- Standard approach: Outside-in
  - Standalone Muon
  - Combine with tracker track to fit GlobalMuon
- "Muon-ID": complementary Inside-out approach
  - Extrapolate every track outward
  - Find compatible deposits in ECAL, HCAL, HO, muon hits
  - Determine muon 'compatibility'

Recover inefficiencies at muon chamber boundaries and low p_T (e.g. Muons which only reach the first muon station)

Inefficiency at eta cracks





p_t =3.5, 4.0, 4.5, 6.0 GeV

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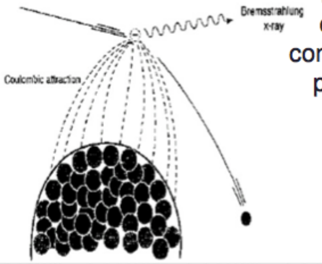
Muon bremsstrahlung

- Main energy loss due to ionization (Bethe-Bloch dE/dx)
- Additional energy loss through electromagnetic interaction in the coulomb field of the nucleus

$$-\left(\frac{dE}{dx}\right)_{brem} = \boxed{4\alpha\cdot N_A\left(\frac{e^2}{4\pi\varepsilon_0 c^2}\right)^2}\cdot\boxed{\frac{Z^2}{A}\cdot\ln\frac{183}{Z^{1/3}}}\cdot\frac{z^2}{m^2}E$$

Constant, independent on material and particle

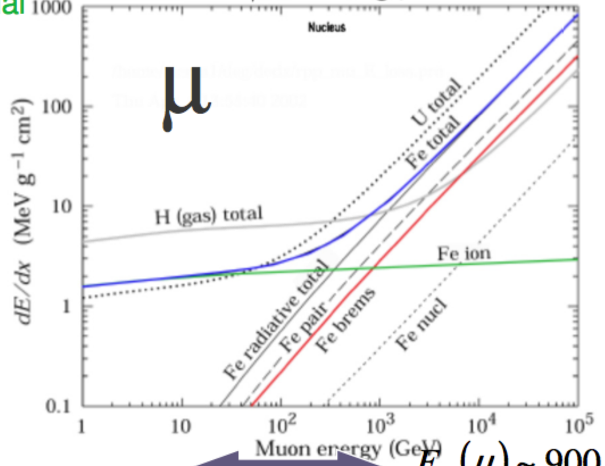
Properties of absorber material



Part of energy converted to photons

- Up to LHC energies, affected mainly electrons (Synch.radiation)

$$\left(\frac{dE}{dx}\right)_{\mu}\Big/\left(\frac{dE}{dx}\right)_{e}\sim\frac{1}{40.000}$$



$$E_C(\mu)\sim 900\ GeV$$

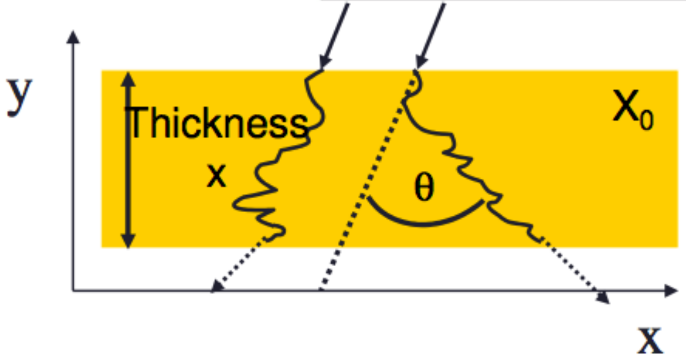
LHC muon energies

Muon multiple scattering

Multiple Rutherford scattering with the nuclei of the detector material

- Small changes per collisions
- Many collisions → in the sum measurable deviation from trajectory

$$\sqrt{<\alpha^2>} = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\left[1 + 0.038\ln(x/X_0)\right]$$

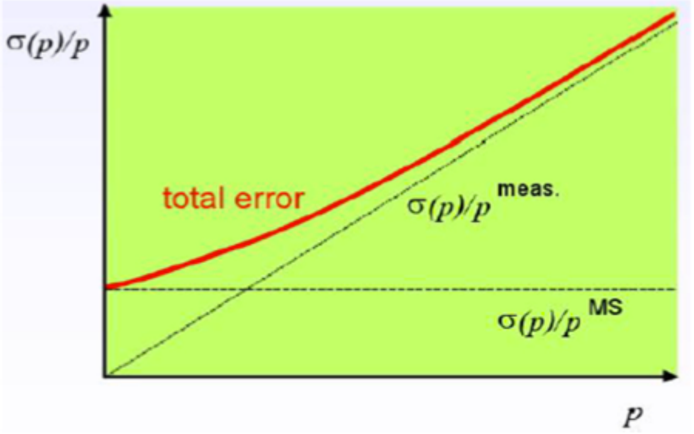


Multiple scattering limits resolution

Example 100 GeV Myon:

1 m Iron = 4 mrad ~ 4 mm

1 m Air = 0.02 mrad ~ 20 μm

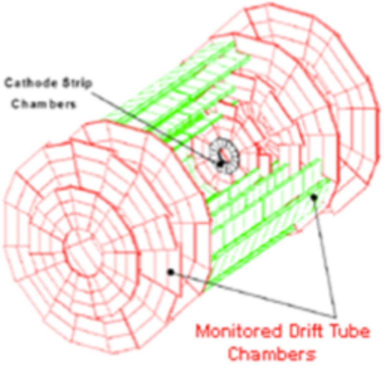


Independent on particle's momentum
At large momenta detector resolution dominating

Momentum resolution

ATLAS

B = 0.7 T
L ~ 5 m
N = 3 Stations * 8 Points



$$s = \frac{0.3 \cdot B[T] \cdot L[m]^2}{8 \cdot p[GeV]}$$

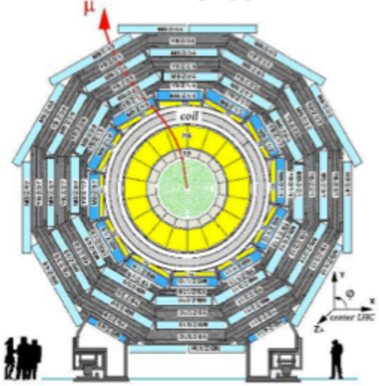
$$\frac{\Delta p_T}{p_T} \propto \frac{1}{s} \cdot \delta_{spatial} \cdot \sqrt{\frac{720}{N_{Stat}}}$$

s = 750 μm for 1 TeV Track
10% → σ = 75 μm

Δp/p ~ 6%

CMS

B ~ 2 T (B-Field in Fe)
L ~ 3.5 m
N = 4 Stations * 8 Points in (rϕ)

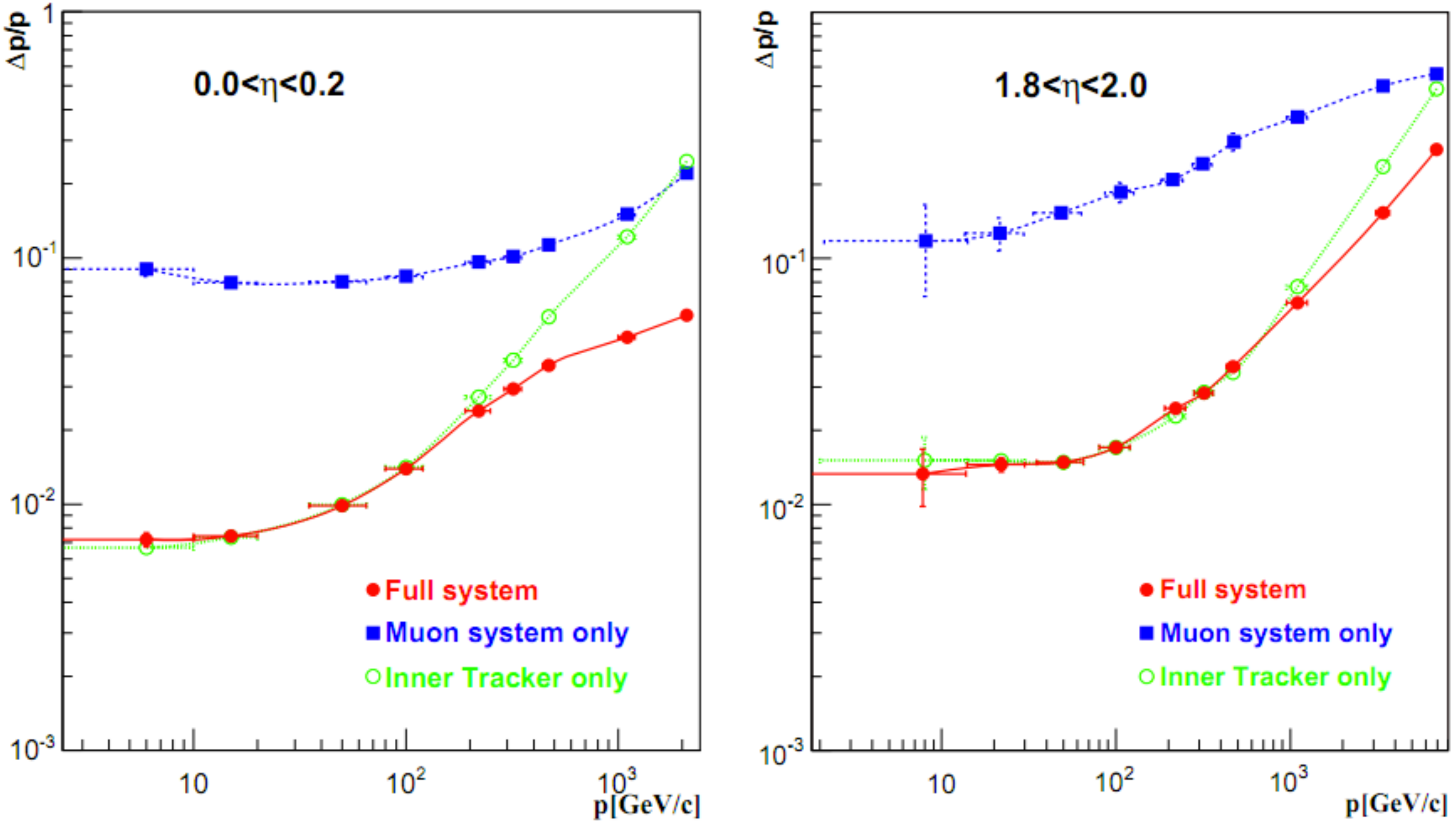


s = 900 μm for 1 TeV Track
10% → σ = 90 μm

Δp/p ~ 12 % (Multiple scattering in Fe ~100 μm)

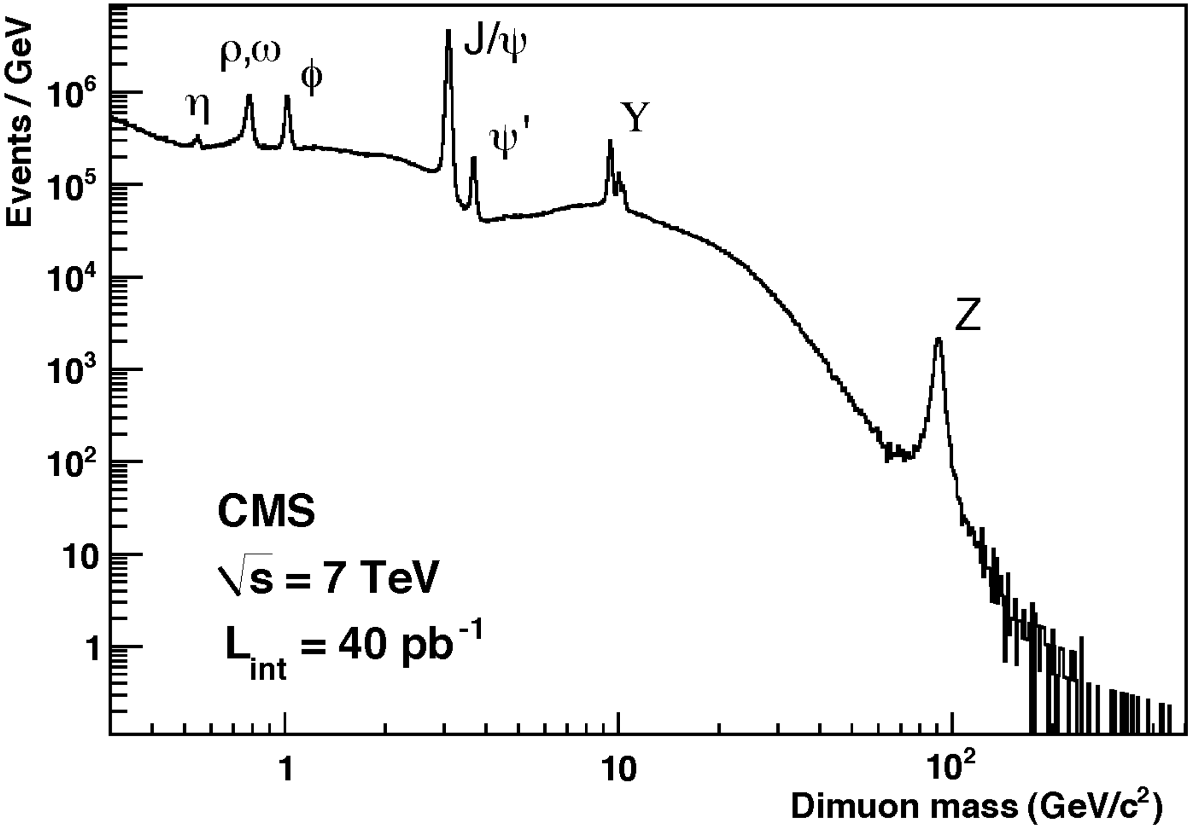
Combine with Tracker Δp/p ~ 2 %

Combined performance



CMS dimuon performance

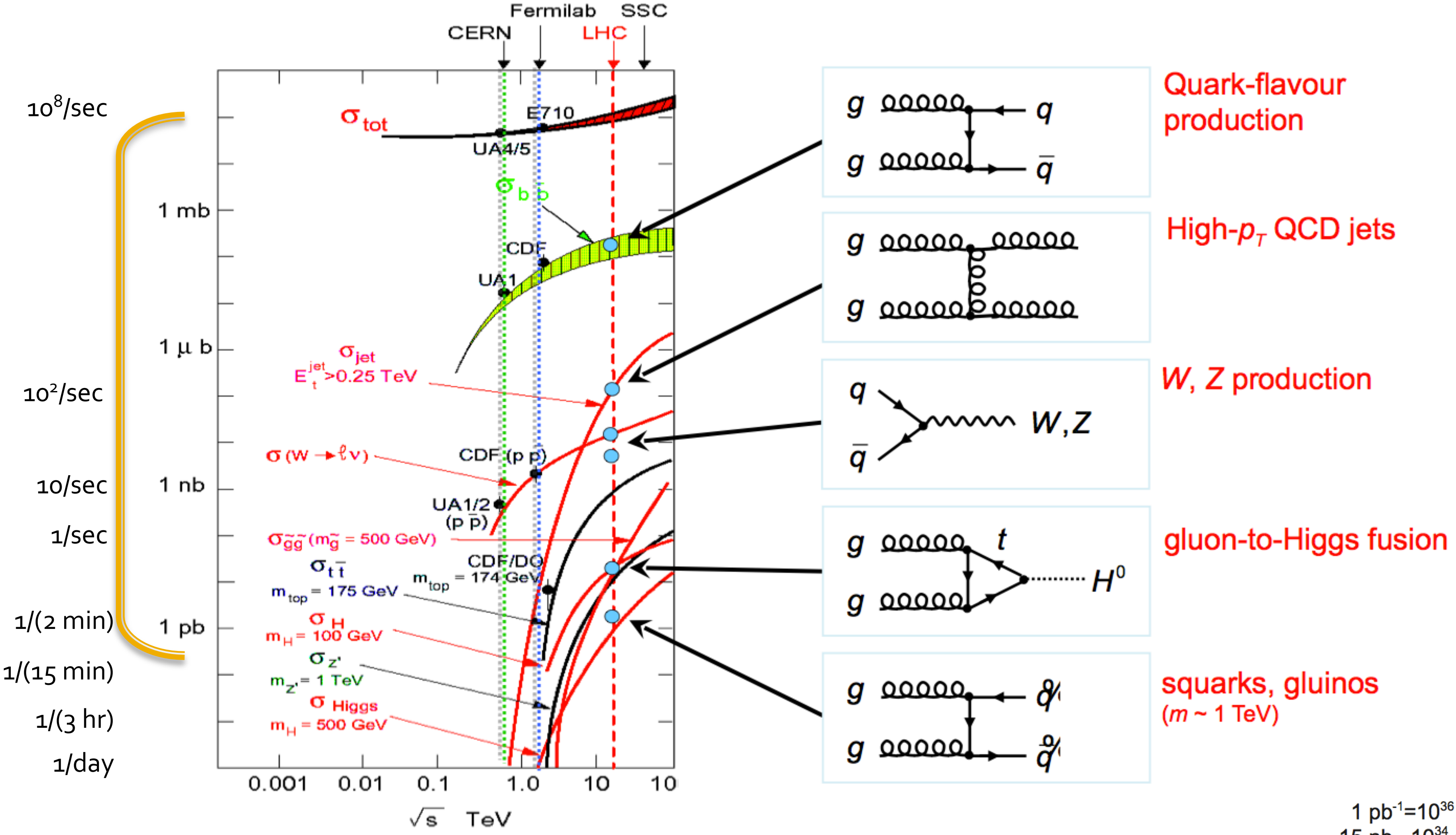
- Dimuons from eta to Z



Trigger

Trying to keep one interesting collision, while rejecting 10^6 others.

Trigger: why?



Quark-flavour production

High-p_T QCD jets

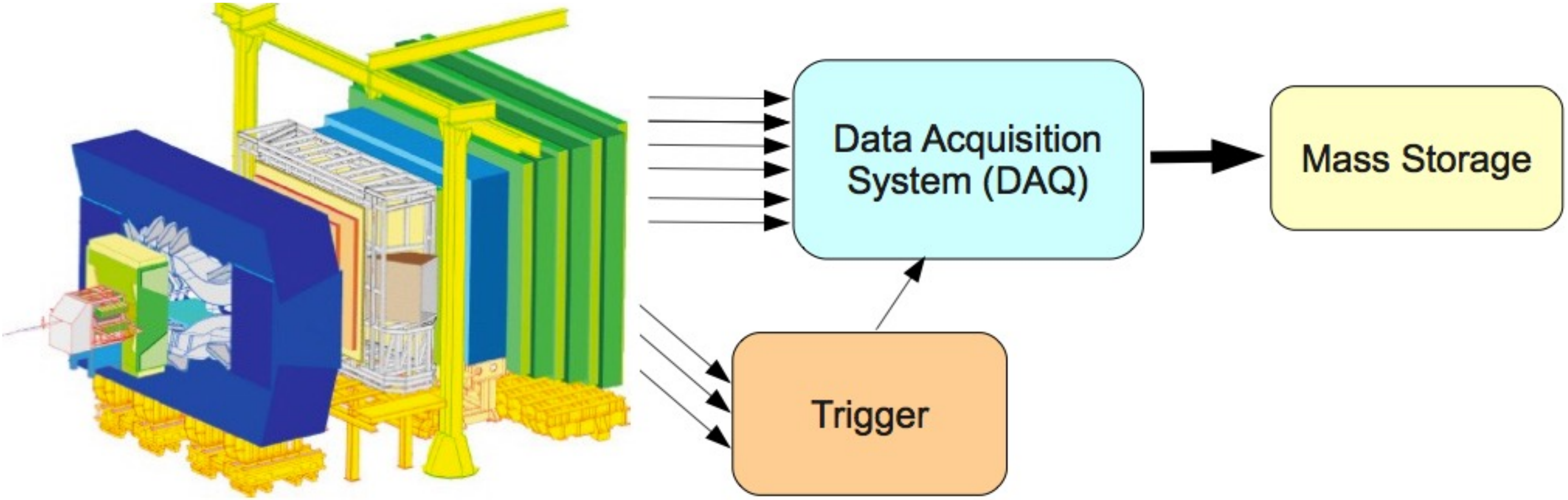
W, *Z* production

gluon-to-Higgs fusion

squarks, gluinos
(*m* ~ 1 TeV)

$1\ \text{pb}^{-1} = 10^{36}\ \text{cm}^{-2}$
$15\ \text{nb} \cdot 10^{34}\ \text{cm}^{-2}\text{s}^{-1} = 150\ \text{Hz}$

Trigger: what?



Data Acquisition System (DAQ)

Mass Storage

Trigger

DAQ is responsible for collecting data from detector systems and recording them to mass storage for offline analysis

Trigger is responsible for real-time selection of the subset of data to be recorded

Trigger: how?

- Data rates are too high record every full event.
  - Reduce rates, typically by factor 10^4-10^5.

	Bunch Crossing Rate	Event size	Trigger Rate Output	Data rate without trigger (PB/year*)	Data rate with trigger (PB/year*)
LEP	45 kHz	~ 100 kB	~ 5 Hz	O(100)	O(0.01)
Tevatron	2.5 MHz	~ 250 kB	~ 50-100 Hz	O(10 000)	O(0.1)
HERA	10 MHz	~ 100 kB	~ 5 Hz	O(10000)	O(0.01)
LHC	40 MHz	~ 1 MB	~ 100-200 Hz	O(100 000)	O(1)

* Assume 50% accelerator duty cycle

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Building an acquisition system

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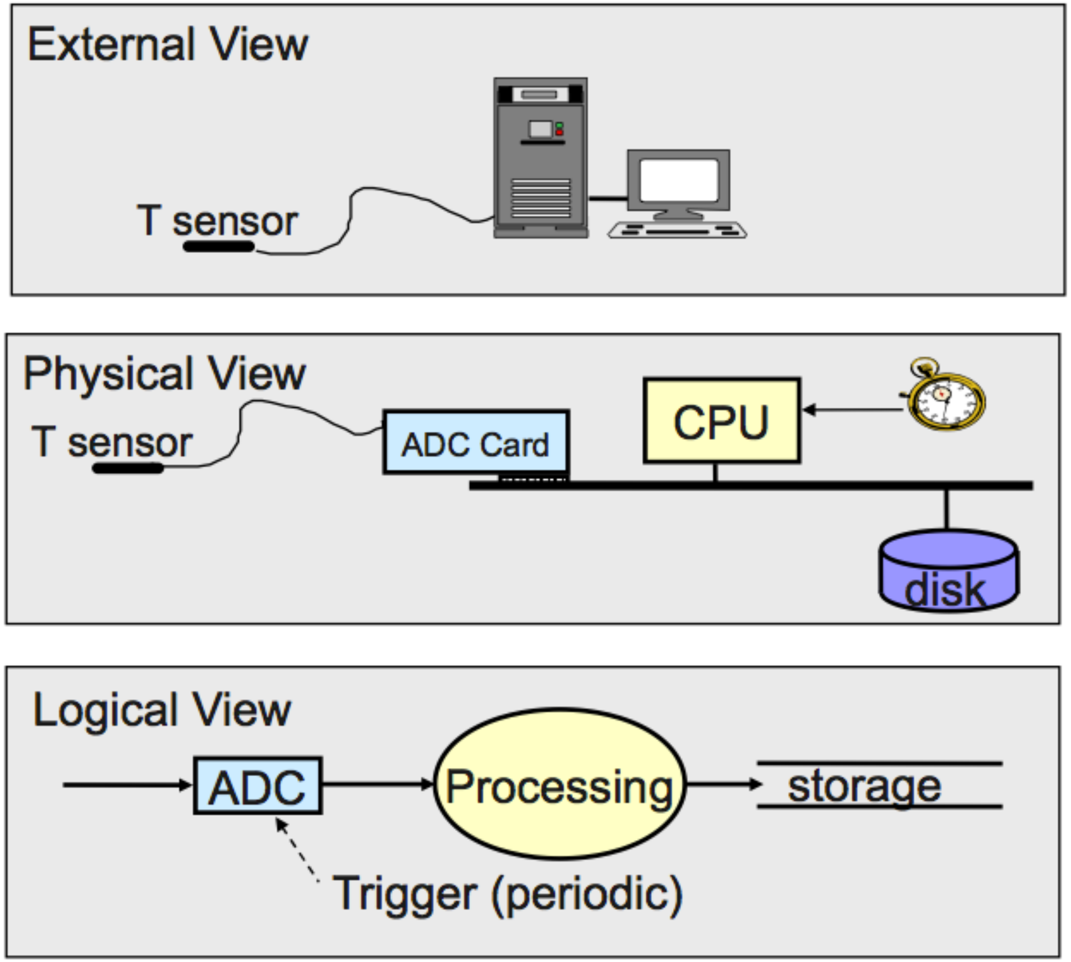
Simple DAQ system



System to measure temperature at fixed rate

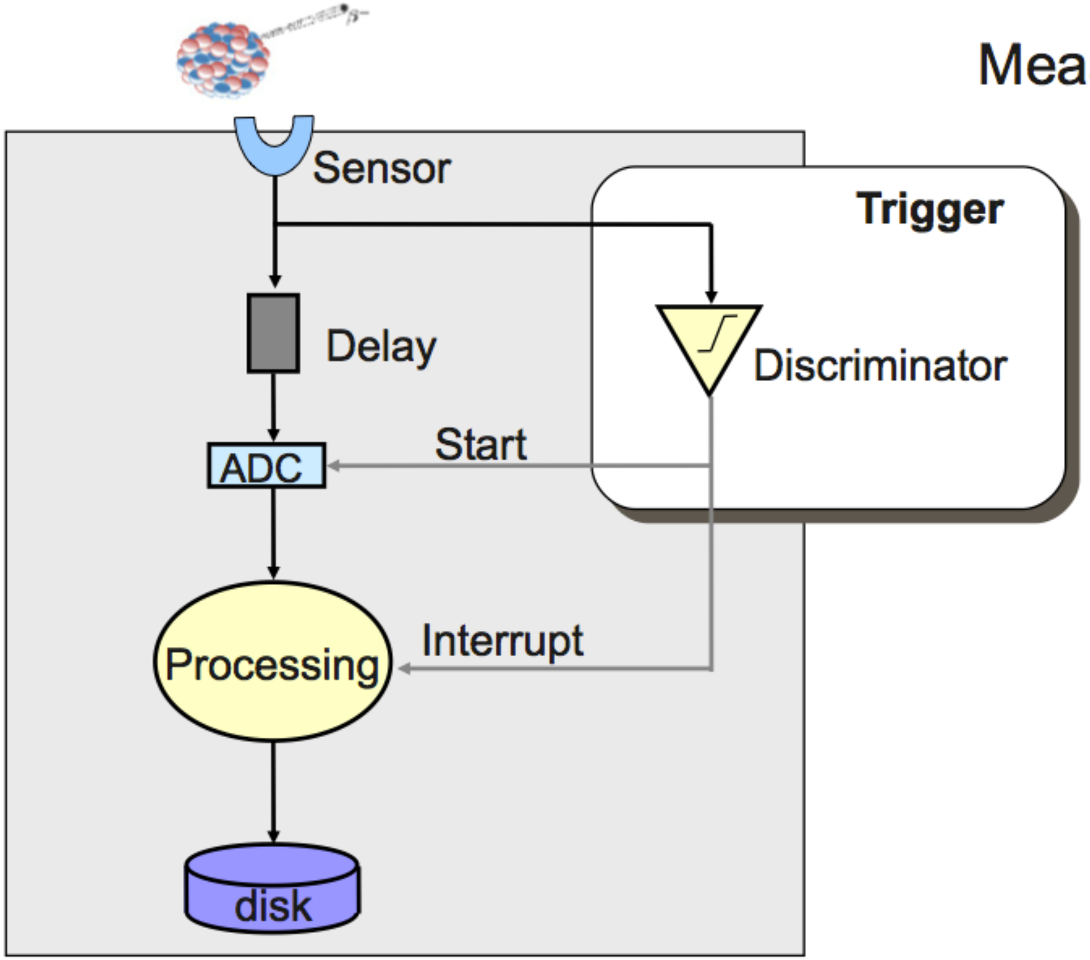
Analog-to-digital converter (ADC) digitizes signal

PC does readout and records data to disk

Rate limited by conversion, readout and data recording

If τ=1ms, max rate is 1 kHz

Adding a trigger



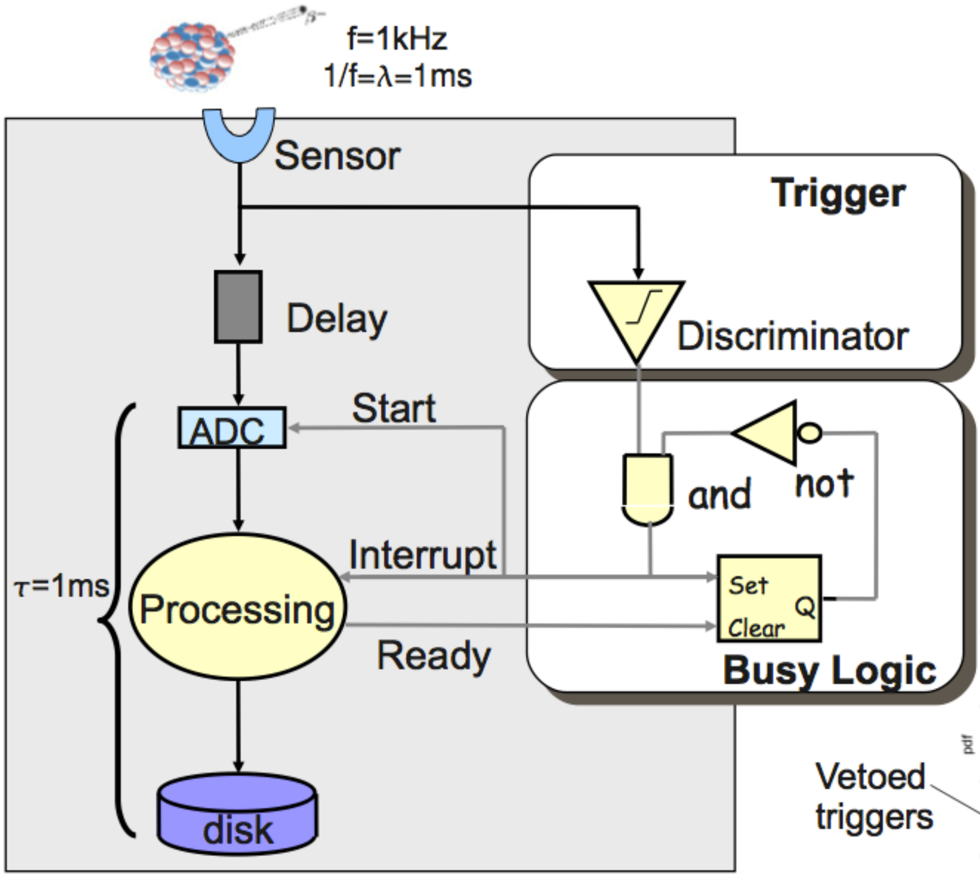
Measurement of β decays

With unpredictable signal, we need a physics based trigger

Delay of signal to ADC needed to synchronize with trigger signal (Trigger Latency)

Delay can be a long cable in simplest cases

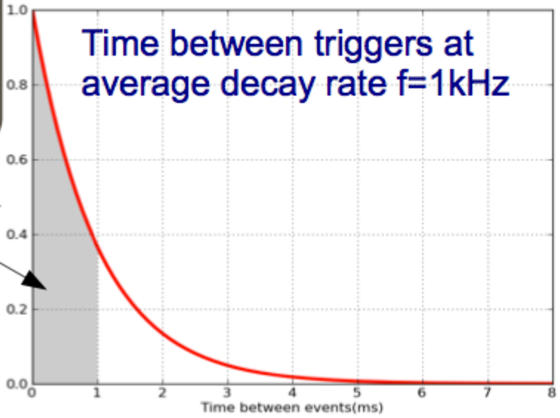
Adding busy logic



With stochastic process, new signals can arrive while system is still processing

Busy logic prevents this

No longer able to process 1 kHz of rate (deadtime)



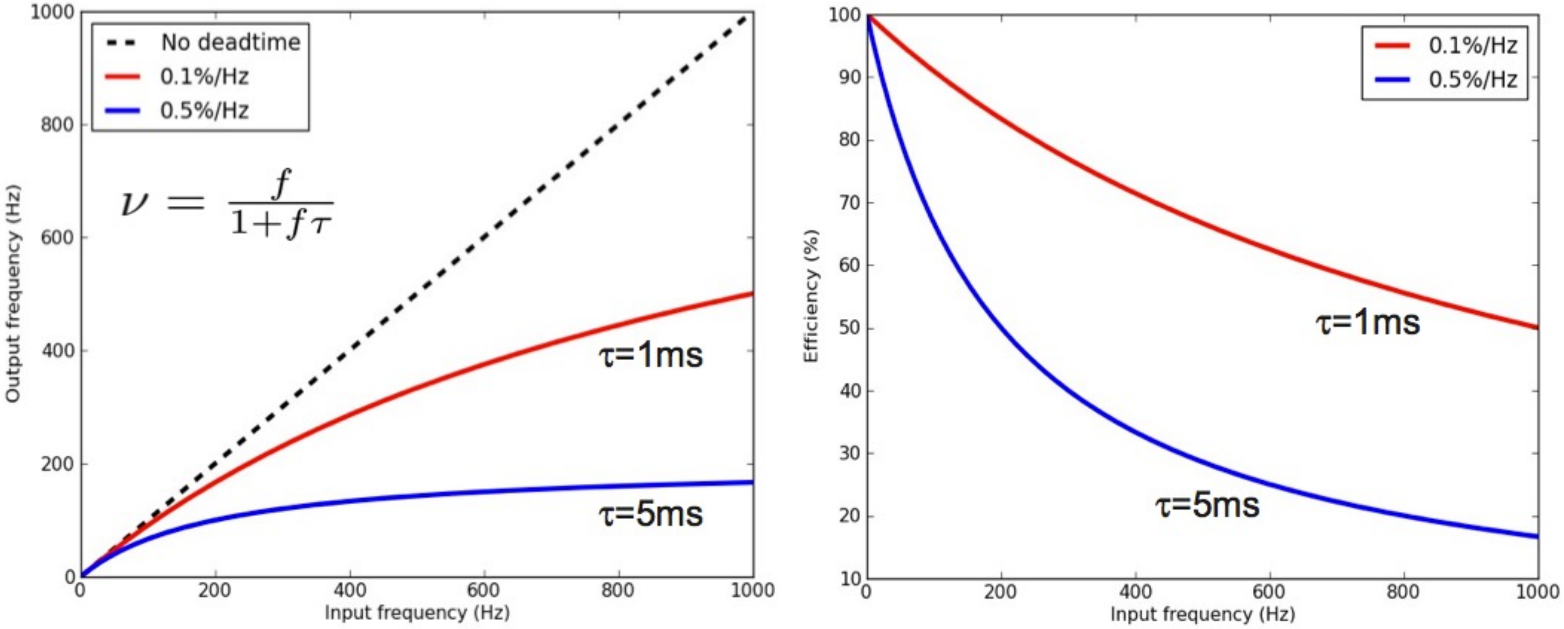
Vetoed triggers

Dead time

At output rate ν, the system will only be accept (1-ντ) of triggers

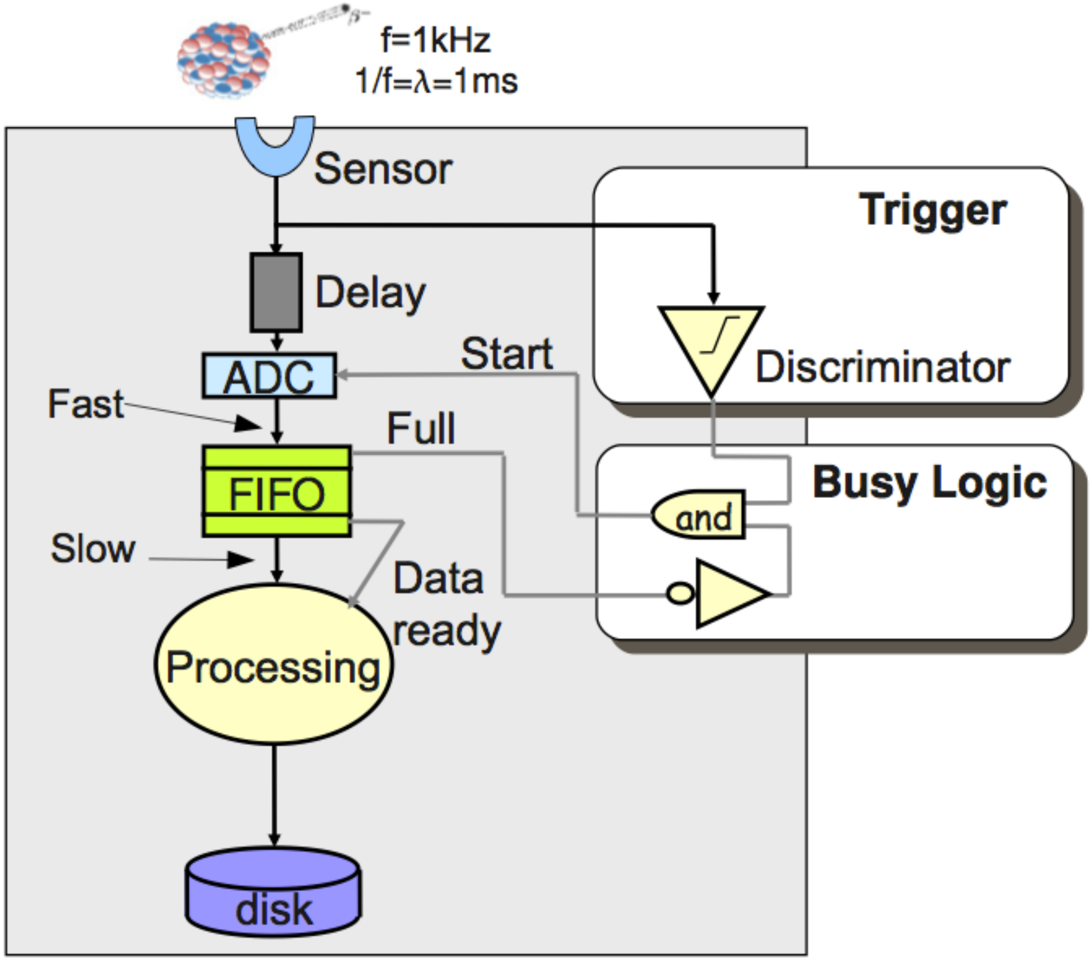
$$\nu = f(1 - \nu\tau) \Rightarrow \nu = \frac{f}{1 + f\tau} < f$$

f input rate
τ readout time



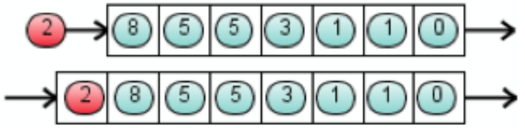
Unless readout time<<time between triggers,
we will have very inefficient system – normally highly undesirable

Derandomizing buffer



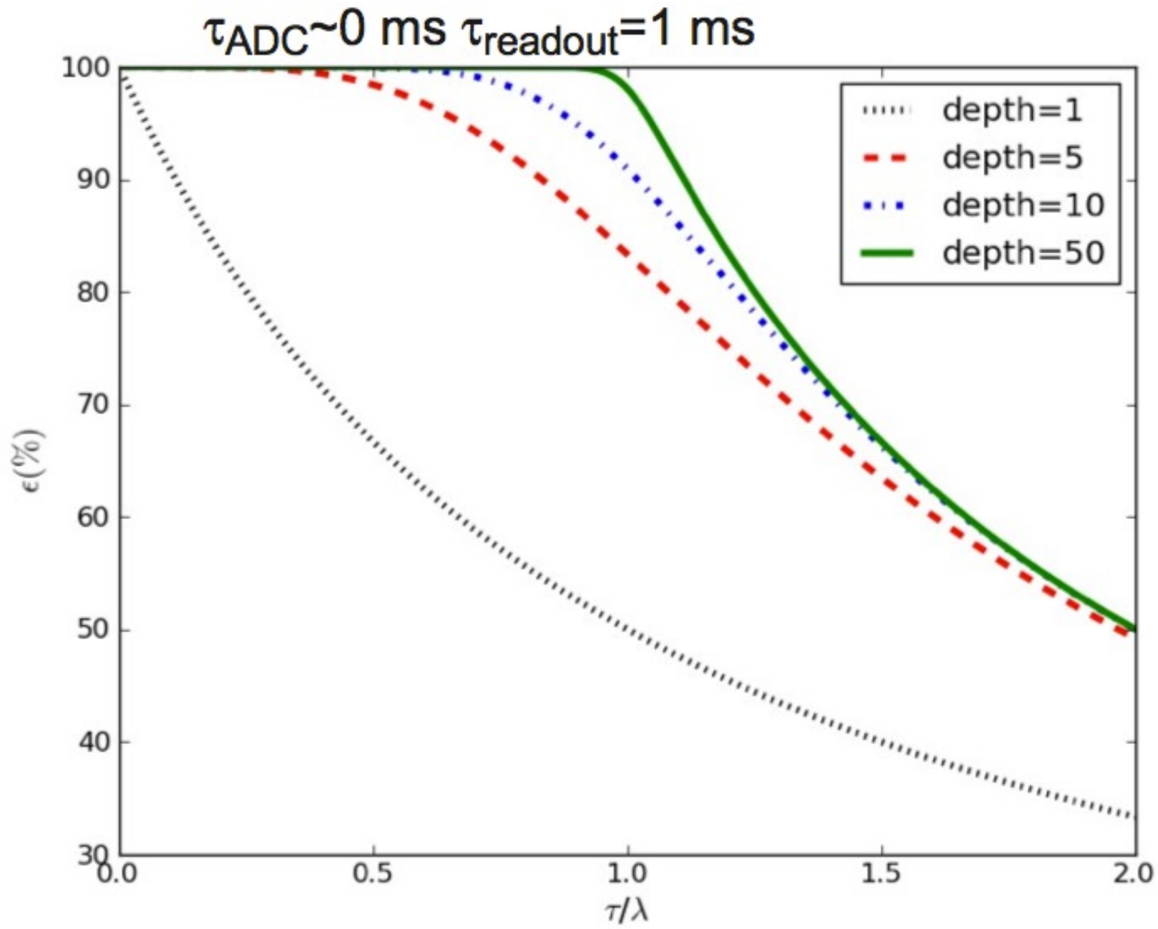
Smooth out fluctuations (derandomize) by introducing an fast, intermediate buffer

Organized as a queue First-In, First-Out (FIFO)



Decouples the fast front-end (ADC) from slow readout

Deadtime with derandomizer



With moderate sized buffer we can retain good efficiency up to f~1/$\tau_{readout}$

Avoids having to over-design the full DAQ system

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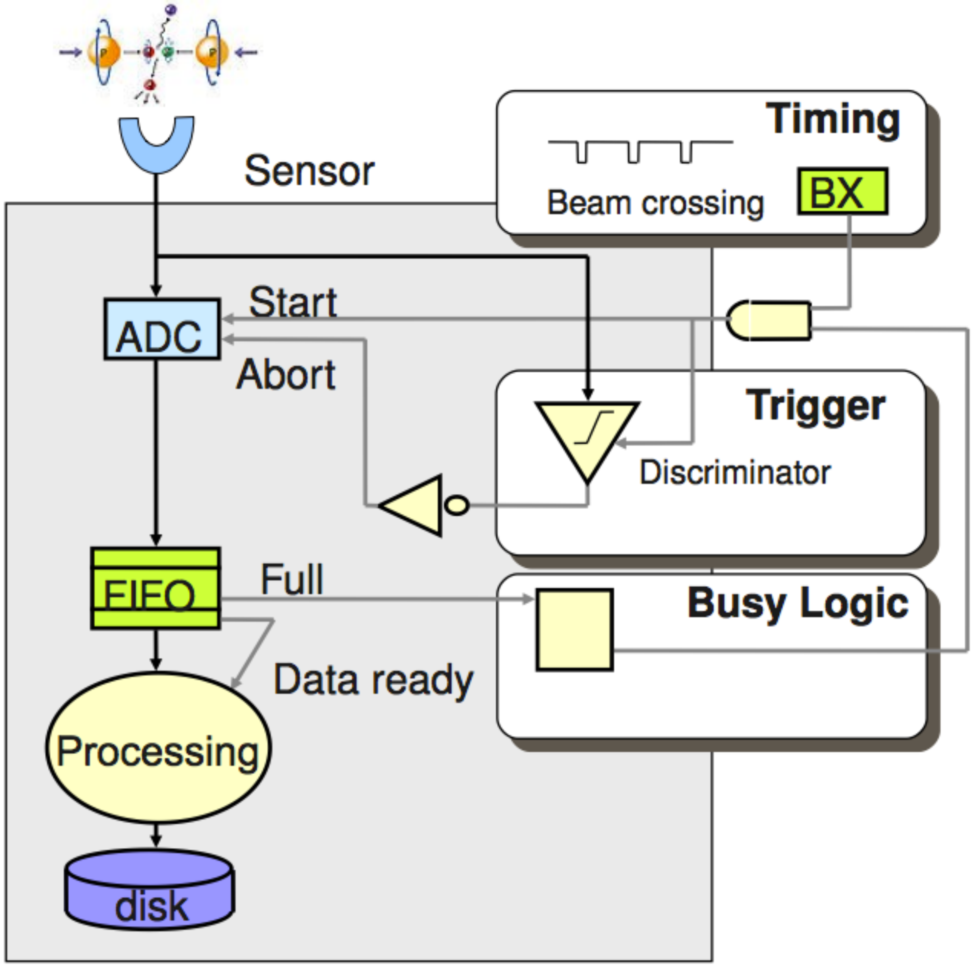
Working with bunched beams



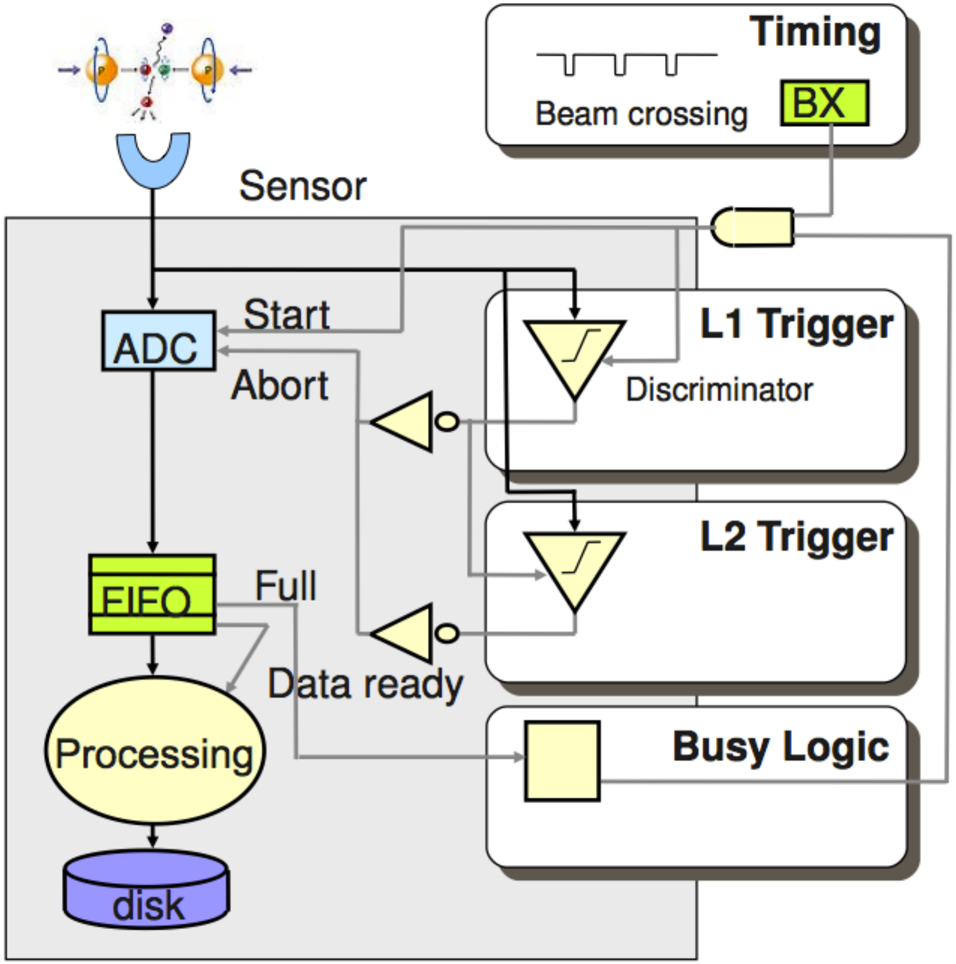
ADC now synchronous with beam crossing

Trigger rejects events

Still need FIFO as trigger output still stochastic

No trigger deadtime if trigger latency below beam crossing interval

Multi-level triggers



For complicated triggers latency can be long

- if $\tau_{trig}>\tau_{BX}$, deadtime>50%

Split trigger in several levels with increasing complexity and latency
All levels can reject events

- with $\tau_{L1}<\tau_{BX}$, trigger deadtime only $\nu_{L1} \cdot \tau_{L2}$

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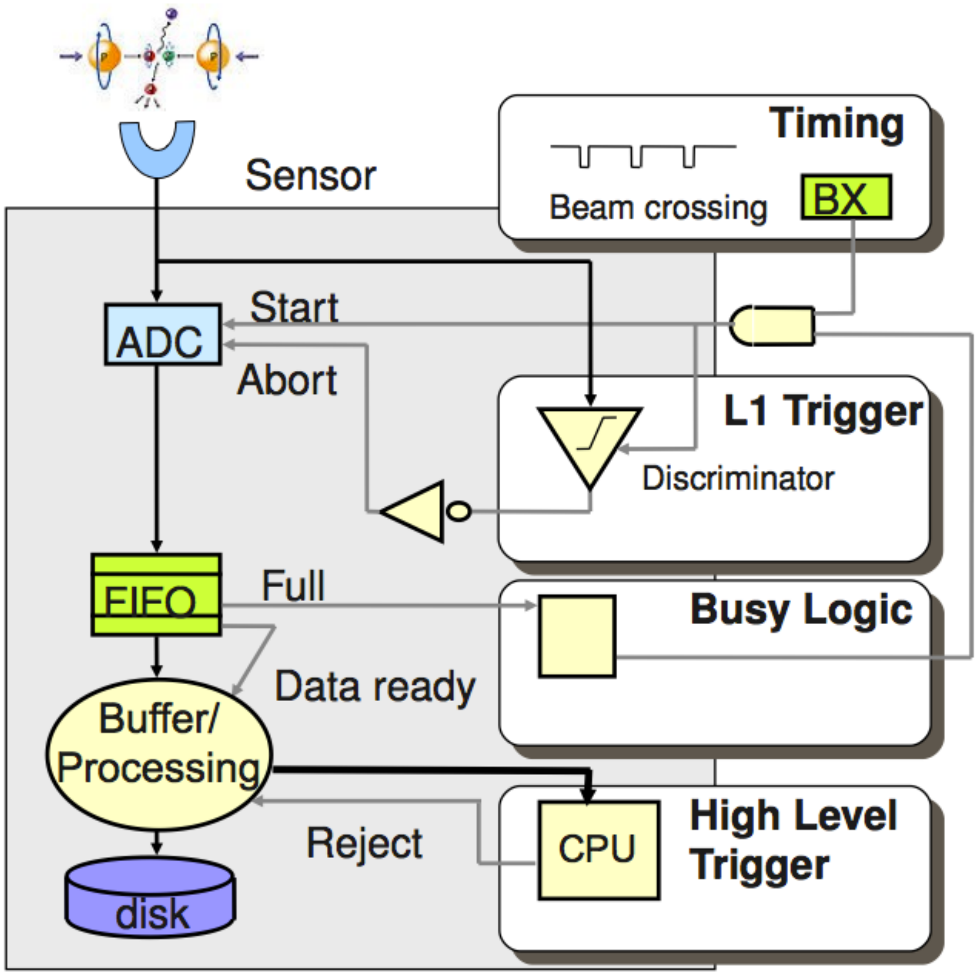
Multi-level trigger



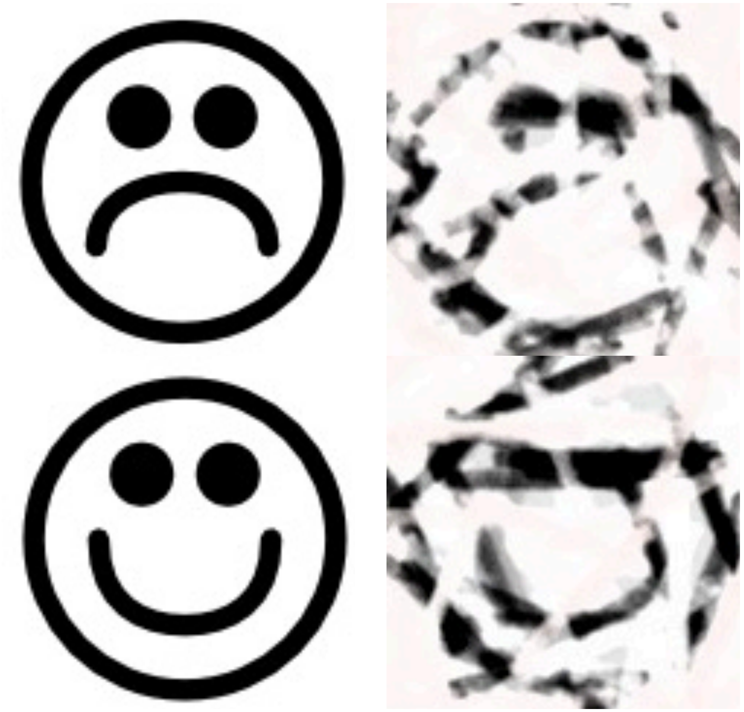
For optimal data reduction can add trigger level between readout and storage (High-level trigger)

Has accessed to some/all processed data

Level-1 trigger

Level-1: a sufficient look

- Not all information is needed to decide to if an event should be kept.



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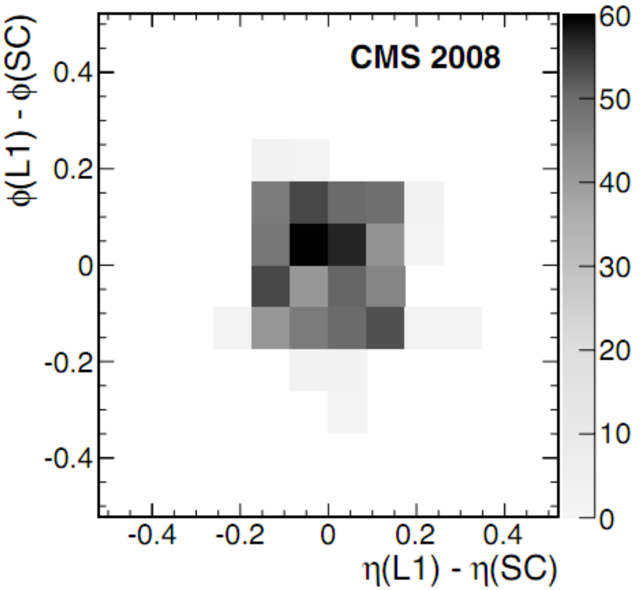
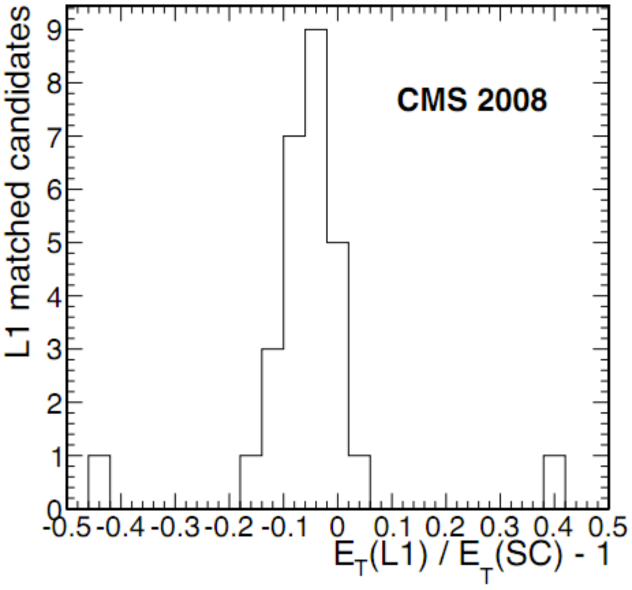
Level-1: a sufficient look

- Information for level-1 decision is kept at a minimum.
  - Spatial resolution and energy resolution are much coarser than offline.





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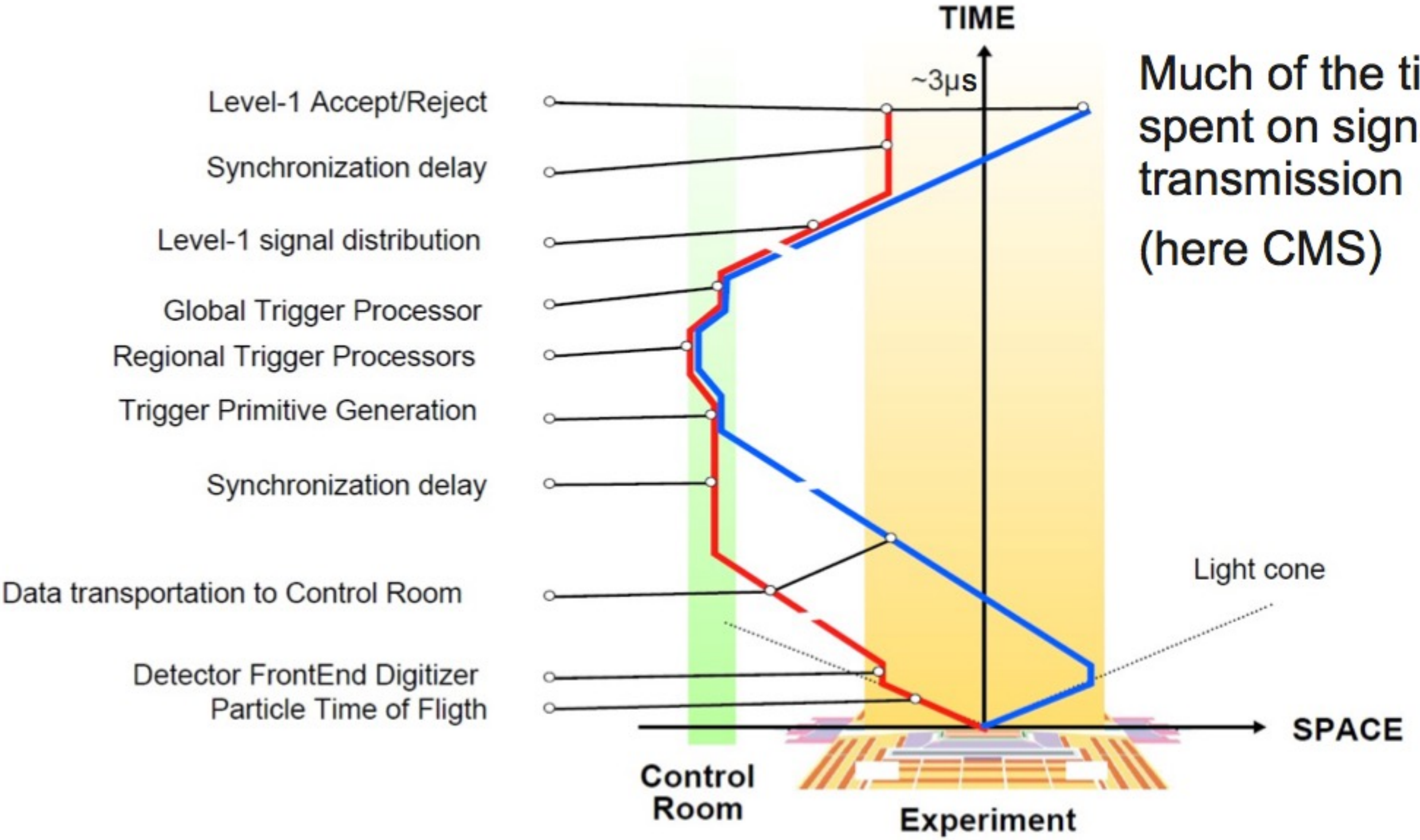
Level-1 Latency

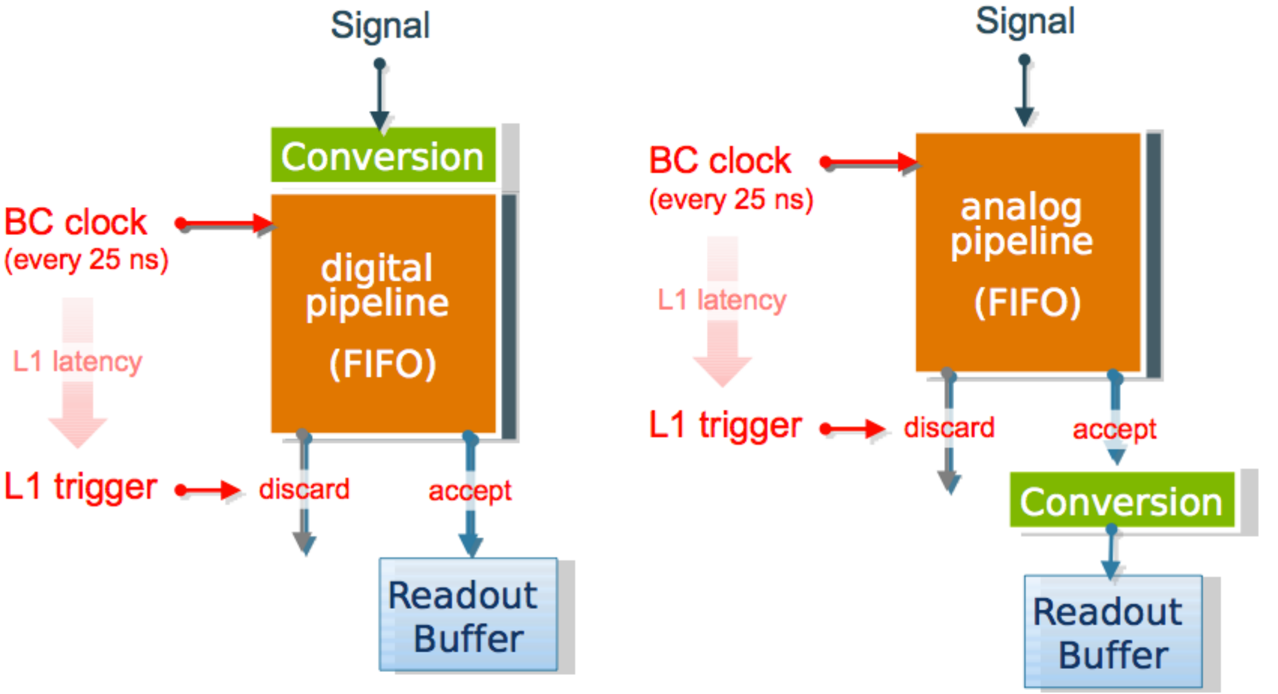


Much of the time spent on signal transmission

(here CMS)

Pipelined front-ends

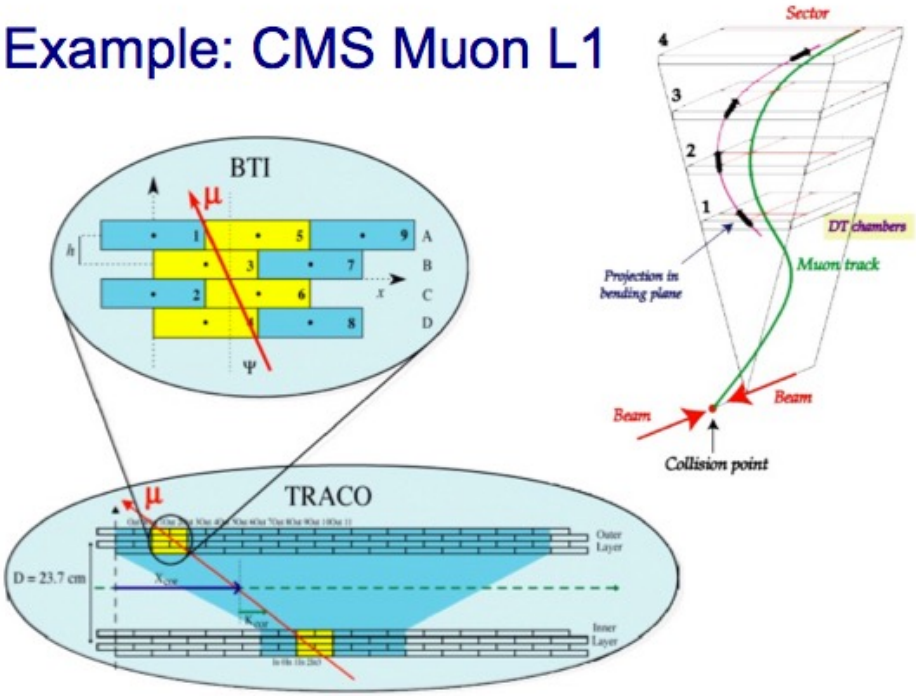
During L1 processing data for all bunch crossings buffered
Use pipeline in data path for holding data
- many variations (analog/digital, on/off detector)
Length of pipeline determines maximum L1 latency

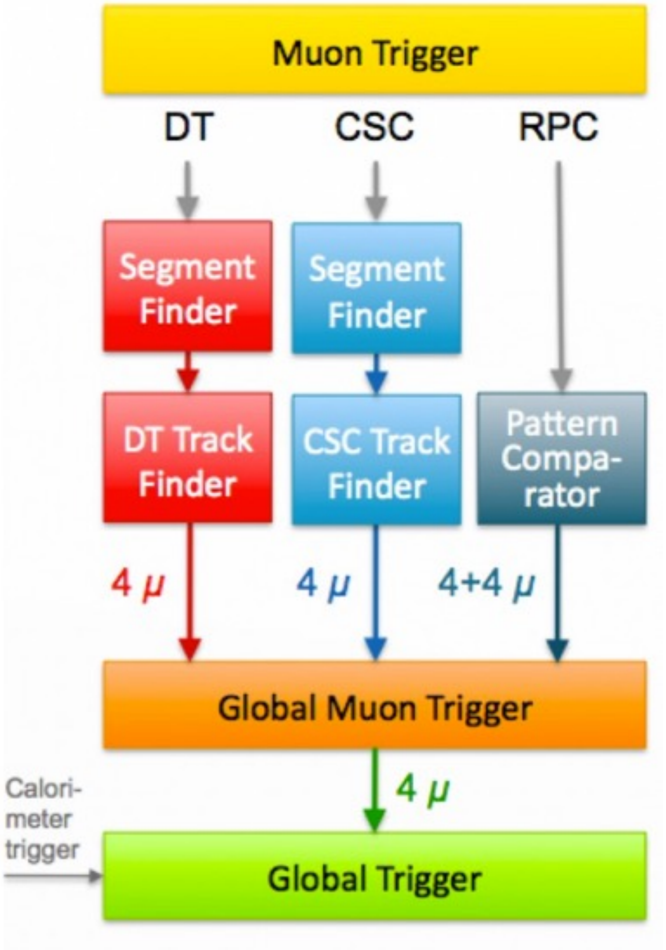


Level-1 Muon trigger

Reconstruct segments in each muon chamber
Combine segments to form track
and measure p_T (rough)

Example: CMS Muon L1




Muon Trigger

DT
CSC
RPC

Segment Finder
Segment Finder

DT Track Finder
CSC Track Finder
Pattern Comparator

4 μ
4 μ
4+4 μ

Global Muon Trigger

Calorimeter trigger
4 μ

Global Trigger

Level-1 Global trigger

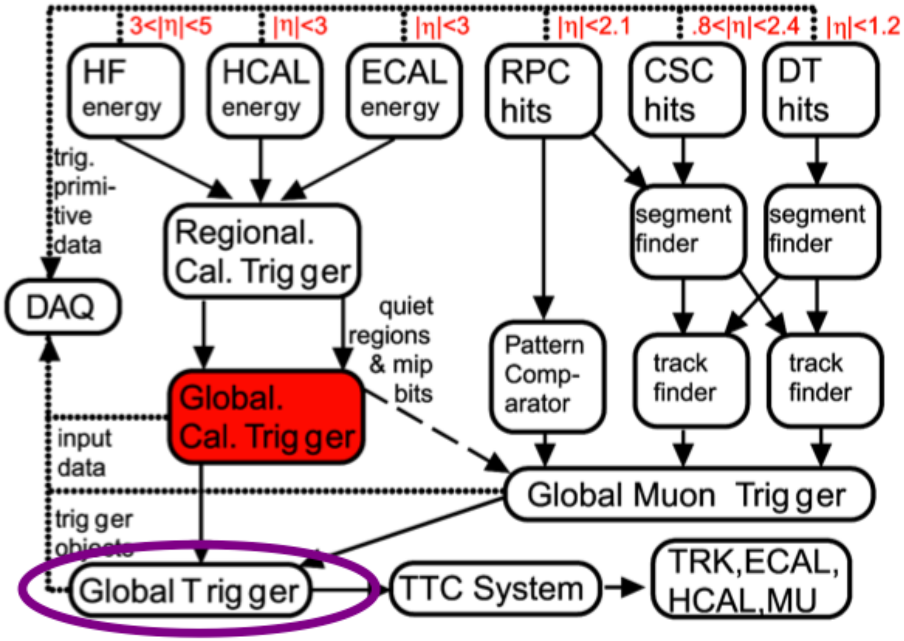
Multiple sources of L1 triggers combined in one place
for final decision of “accept” or “reject” (global/central trigger)
 - also includes busy logic

Can either be big OR of input triggers, require combinations of certain trigger objects or even some topological cuts

Example:

Pass event if:
- 1 muon with p_T>20 GeV, or
- 2 muons with p_T>5 GeV, or
- 1 electron with p_T>7 GeV and 1 muon with p_T>5 GeV, or
- 1 muon above 15 GeV and no jet within $\Delta\phi$ of 0.2 rad,

Example: CMS L1 Trigger



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Event building

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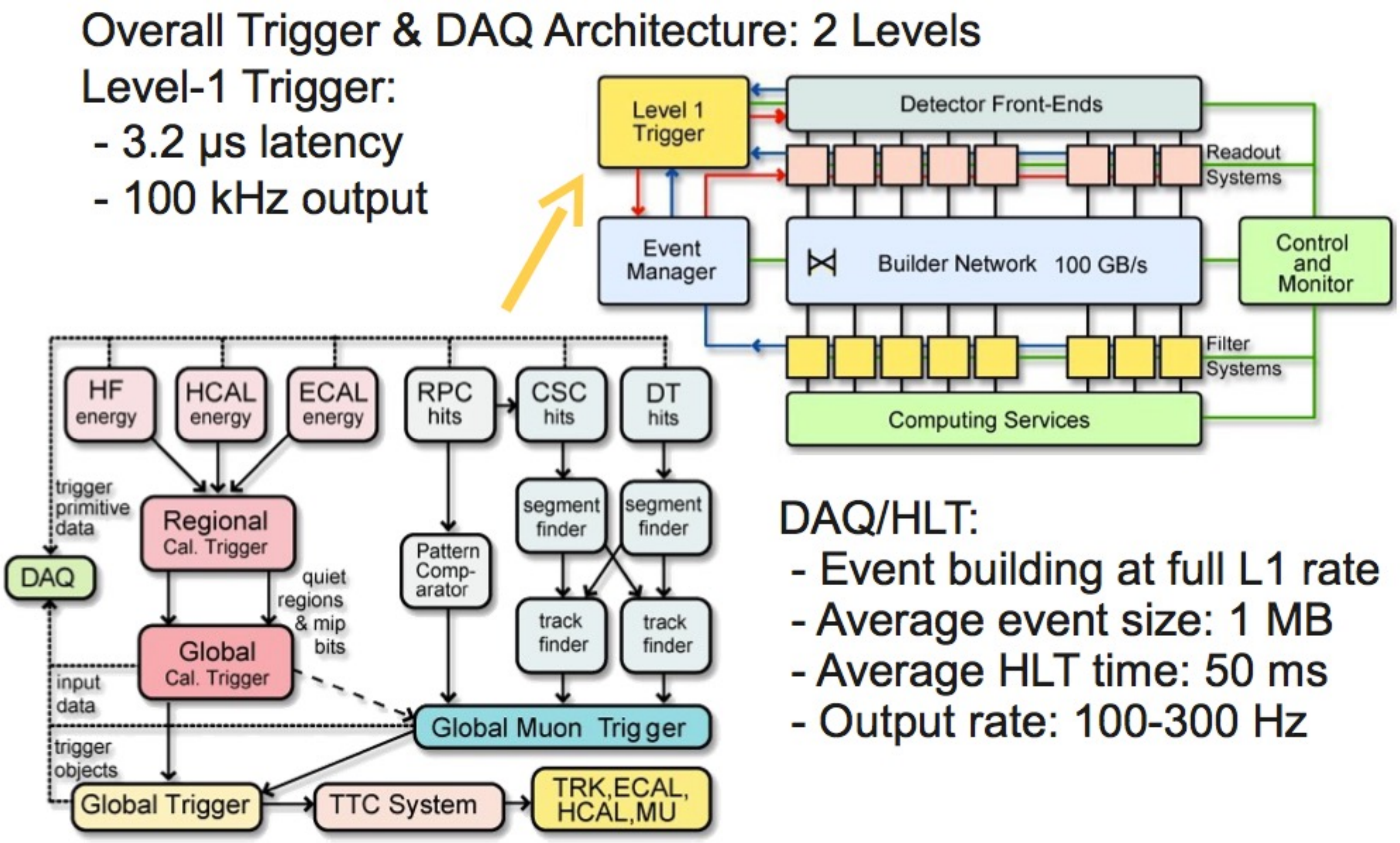
Event building

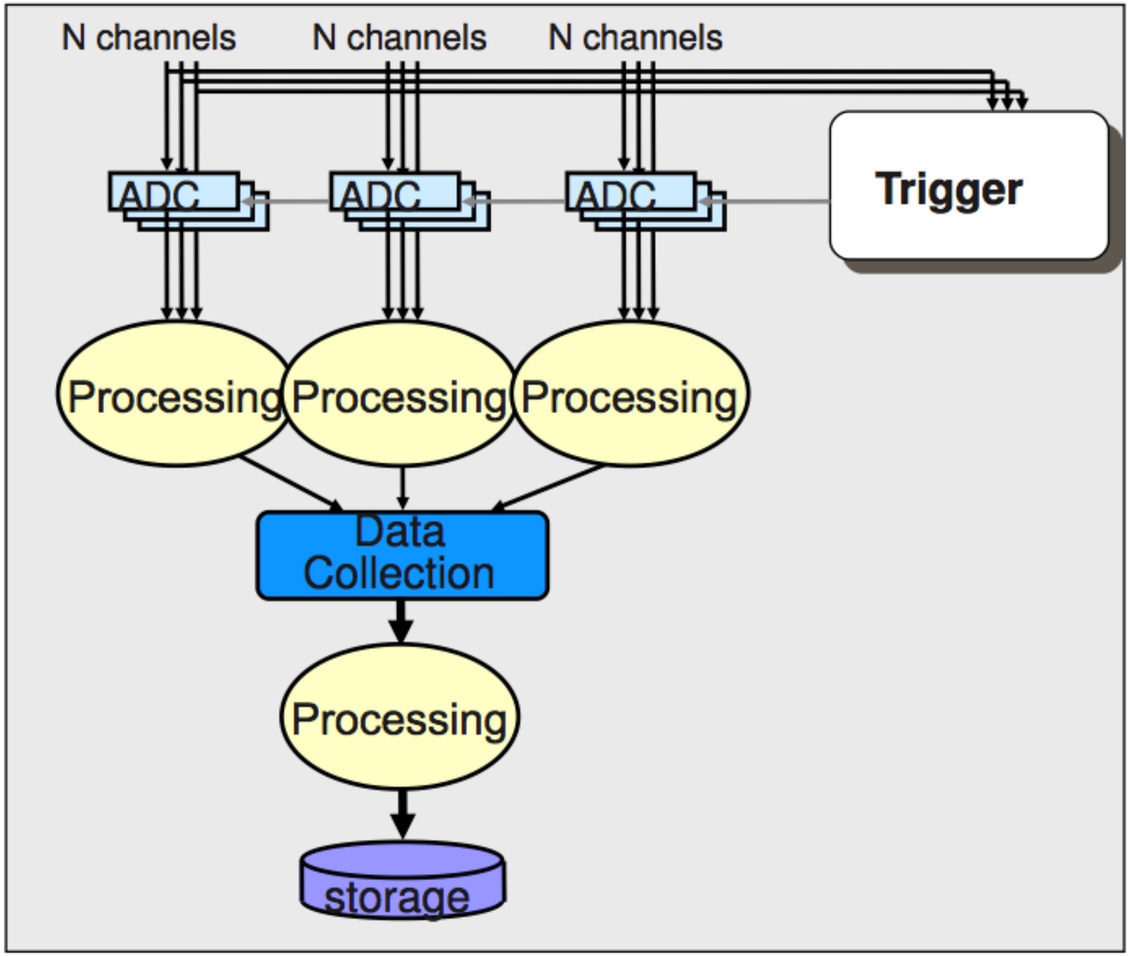


Overall Trigger & DAQ Architecture: 2 Levels

Level-1 Trigger:
- 3.2 μs latency
- 100 kHz output

DAQ/HLT:
- Event building at full L1 rate
- Average event size: 1 MB
- Average HLT time: 50 ms
- Output rate: 100-300 Hz

Scaling up



Increasing the system, complexity starts to enter

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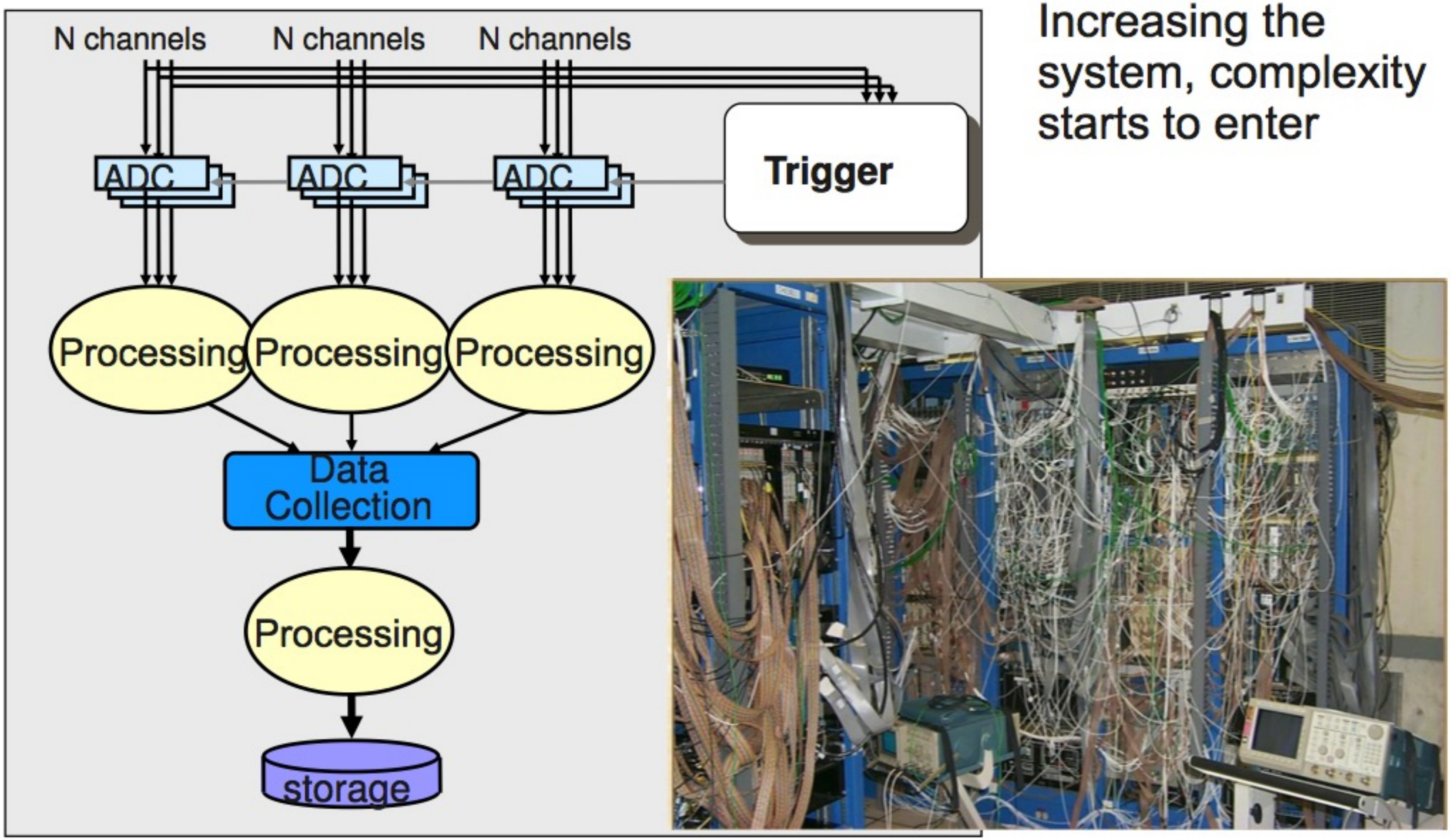
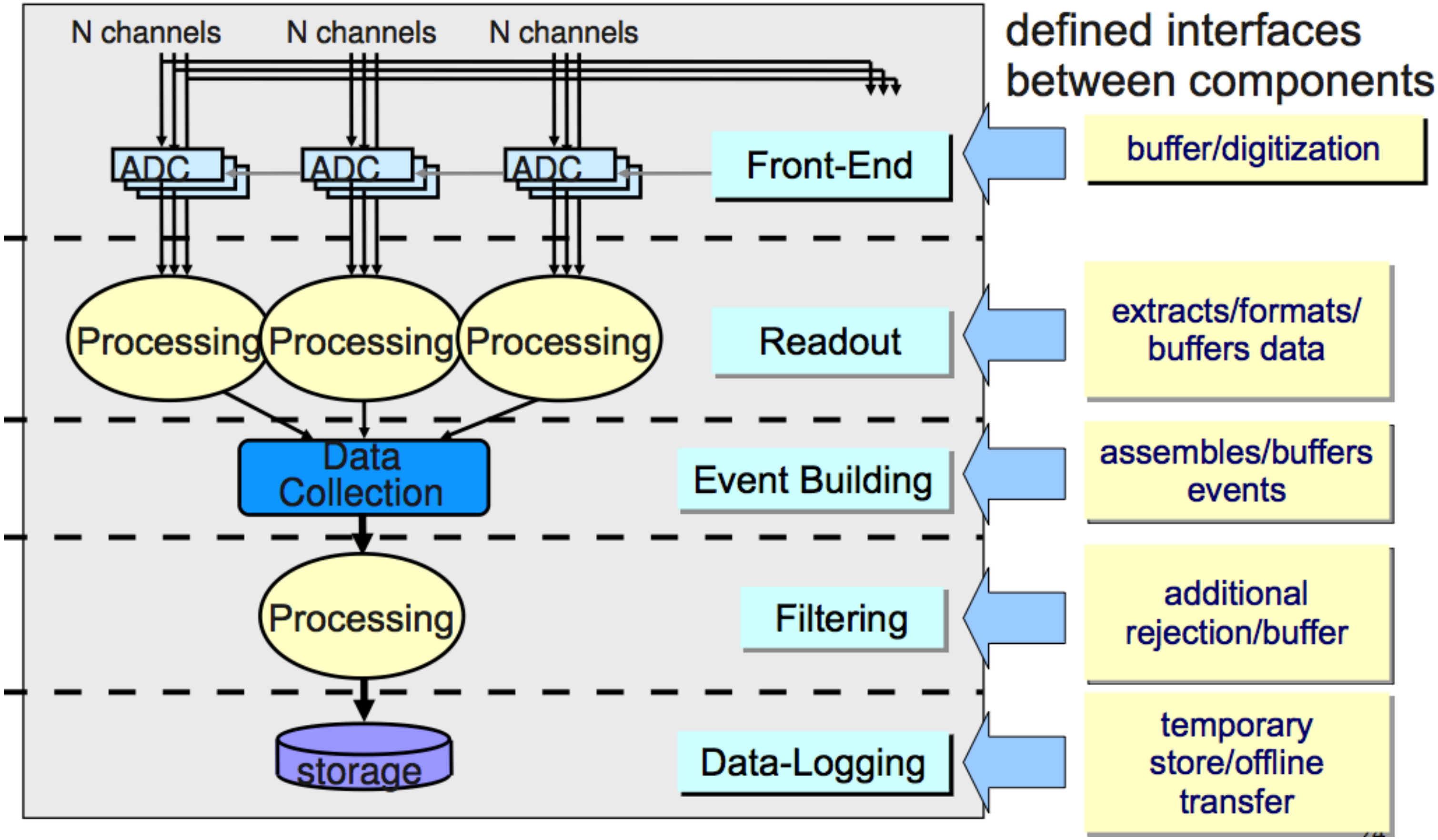
Scaling up



Increasing the system, complexity starts to enter

Scaling up

Need to impose structure with well-defined interfaces between components



N channels

N channels

N channels

ADC

ADC

ADC

Front-End

buffer/digitization

Processing

Processing

Processing

Readout

extracts/formats/ buffers data

Data Collection

Event Building

assembles/buffers events

Processing

Filtering

additional rejection/buffer

storage

Data-Logging

temporary store/offline transfer

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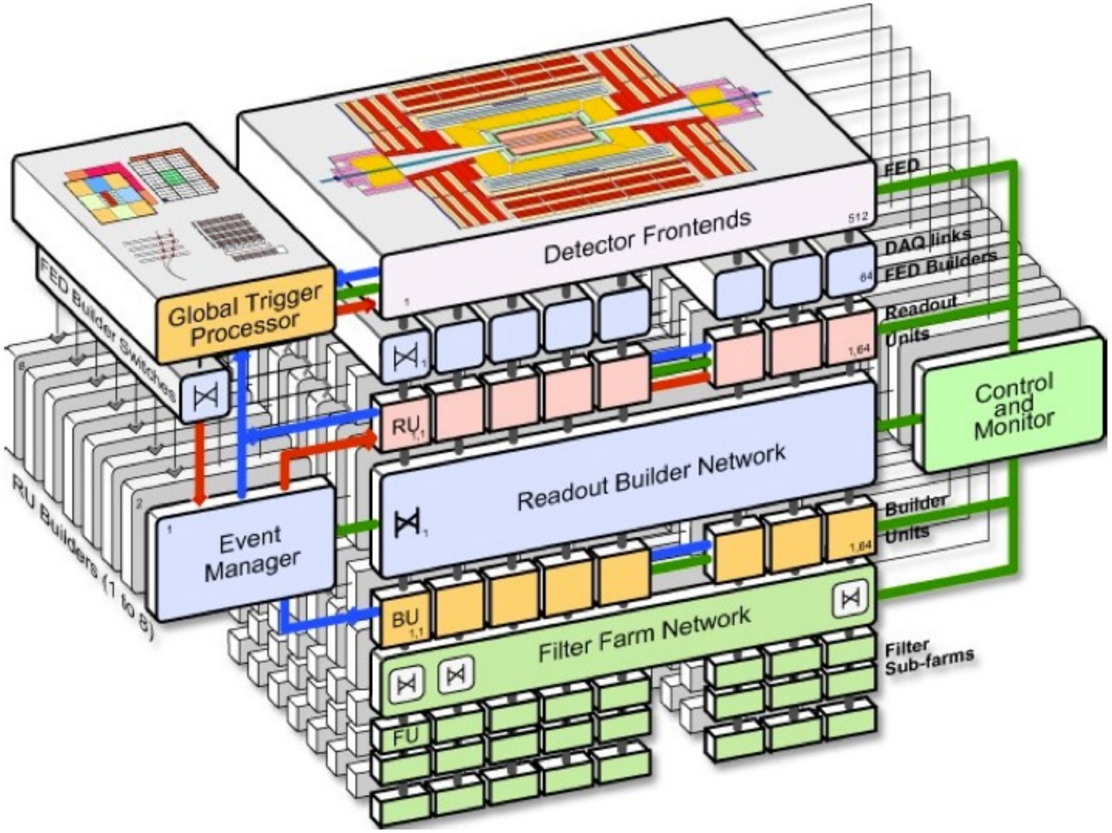
CMS 3D event builder

Event building and filtering done in 8 independent “slices” to facilitate 100 kHz rate



High-level trigger

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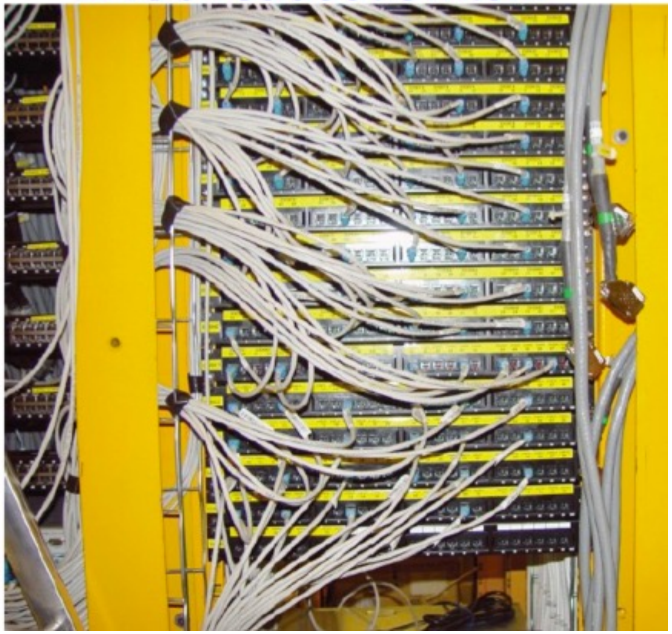
High-level trigger

Final selection in software triggers using large commercial PC farms
- acces to full granularity and offline reconstruction-like algorithms
- extremely flexible
- slow (1-100+ ms latency), so use many PCs at the same time

Events are independent, so trivially parallelizable on PC cluster

ATLAS HLT farm:

LHCb readout switch:



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HLT processing

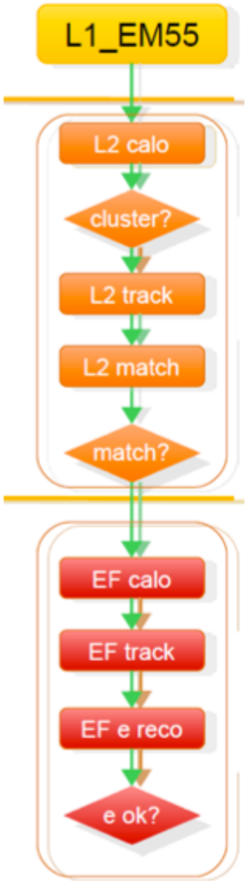
5-100 kHz input rate requires fast algorithms
Processing is typically done multiple steps:

Start by confirming L1 results

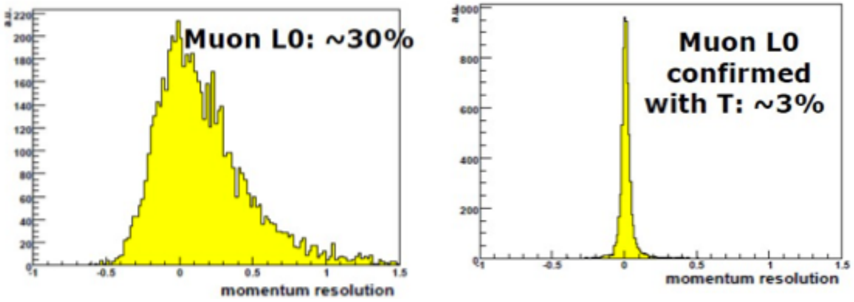
- Only process data in region where L1 found “object”
  - * ATLAS also only reads out detector in region of interest (RoI) at L2 (reduce data traffic)
- Use full granularity of detector readout
- Combine with info from other detectors (trackers)
- reject events as soon as algorithm step fails

Fullscale event reconstruction to find specific B-decay, all jets, etc. is done at lower rates

ATLAS electron trigger



LHCb muon trigger



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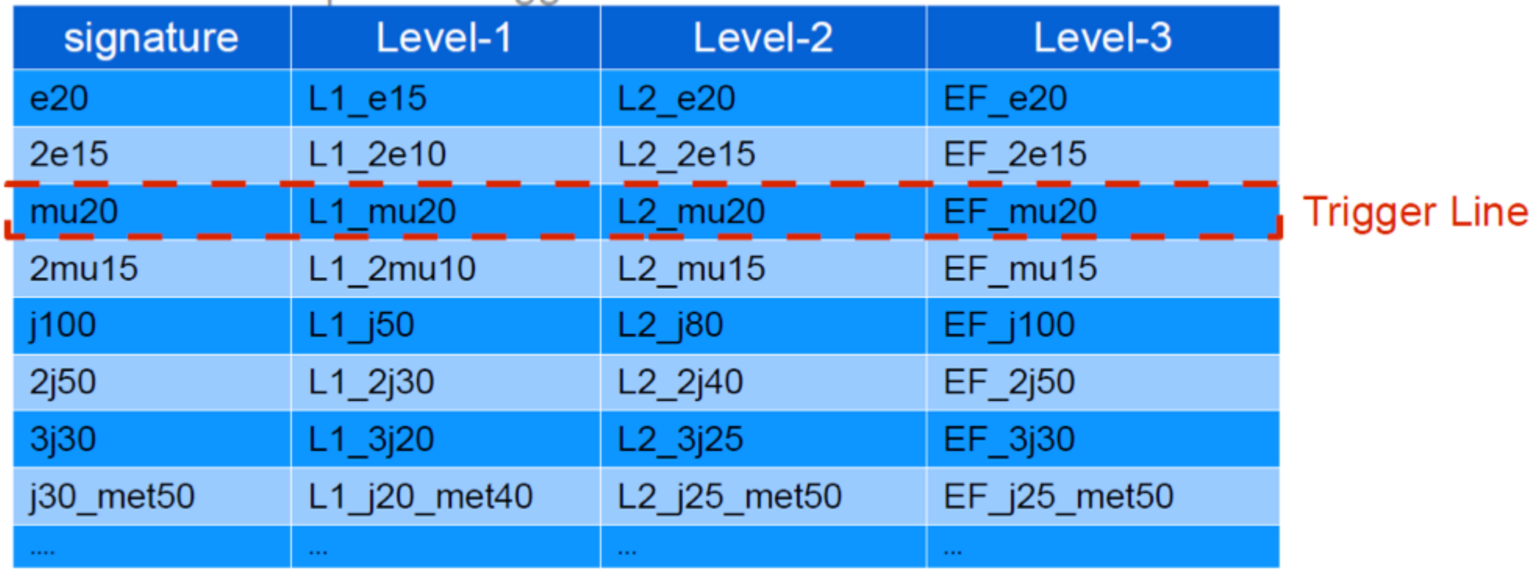
Trigger menus

Each physics signature will one or more “trigger lines” to select it
Collection of trigger lines is “trigger menu” which defines all of the physics the experiment wants to collect events for

Illustrative example of a trigger menu



signature	Level-1	Level-2	Level-3
e20	L1_e15	L2_e20	EF_e20
2e15	L1_2e10	L2_2e15	EF_2e15
mu20	L1_mu20	L2_mu20	EF_mu20
2mu15	L1_2mu10	L2_mu15	EF_mu15
j100	L1_j50	L2_j80	EF_j100
2j50	L1_2j30	L2_2j40	EF_2j50
3j30	L1_3j20	L2_3j25	EF_3j30
j30_met50	L1_j20_met40	L2_j25_met50	EF_j25_met50
....	...	...	...

Trigger Line

Typical to have several hundred trigger lines at hadron collider

Trigger menu varies with luminosity and time

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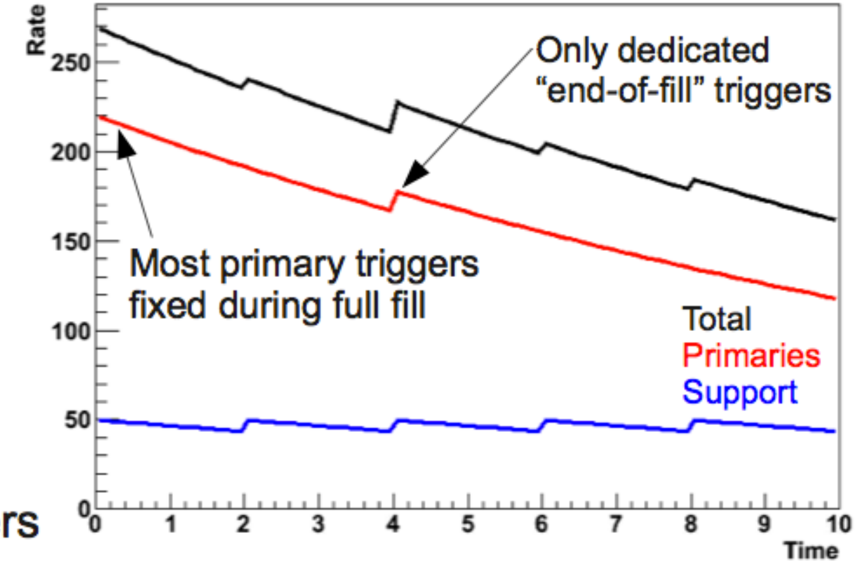
Pre-scaling

Not all triggers need to be recorded at full rate
- often want to just sample low E_T events
- some triggers might just be too high rate

Use prescale for trigger lines

Example:
- prescale of 50 for "e10" line records 2% of 10 GeV electron triggers
- prescale of 1 for "e20" line Records all 20 GeV electron triggers

Simulated rate evolution in an LHC fill



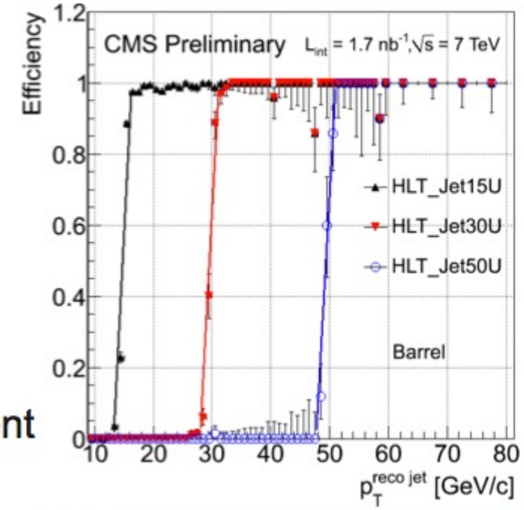
Prescales should be done early to avoid unnecessary rates
Normally implemented in global trigger logic

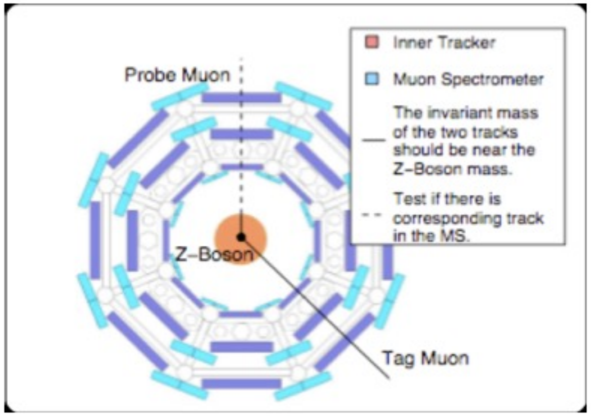
Trigger efficiencies

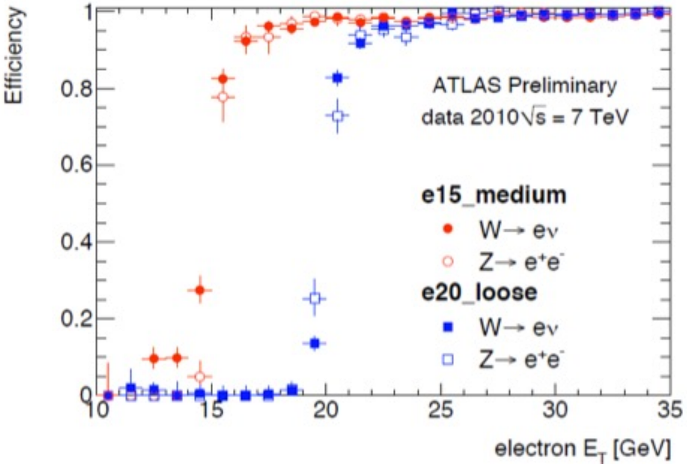
Does the trigger record all signal events?

Different ways to measure trigger efficiency

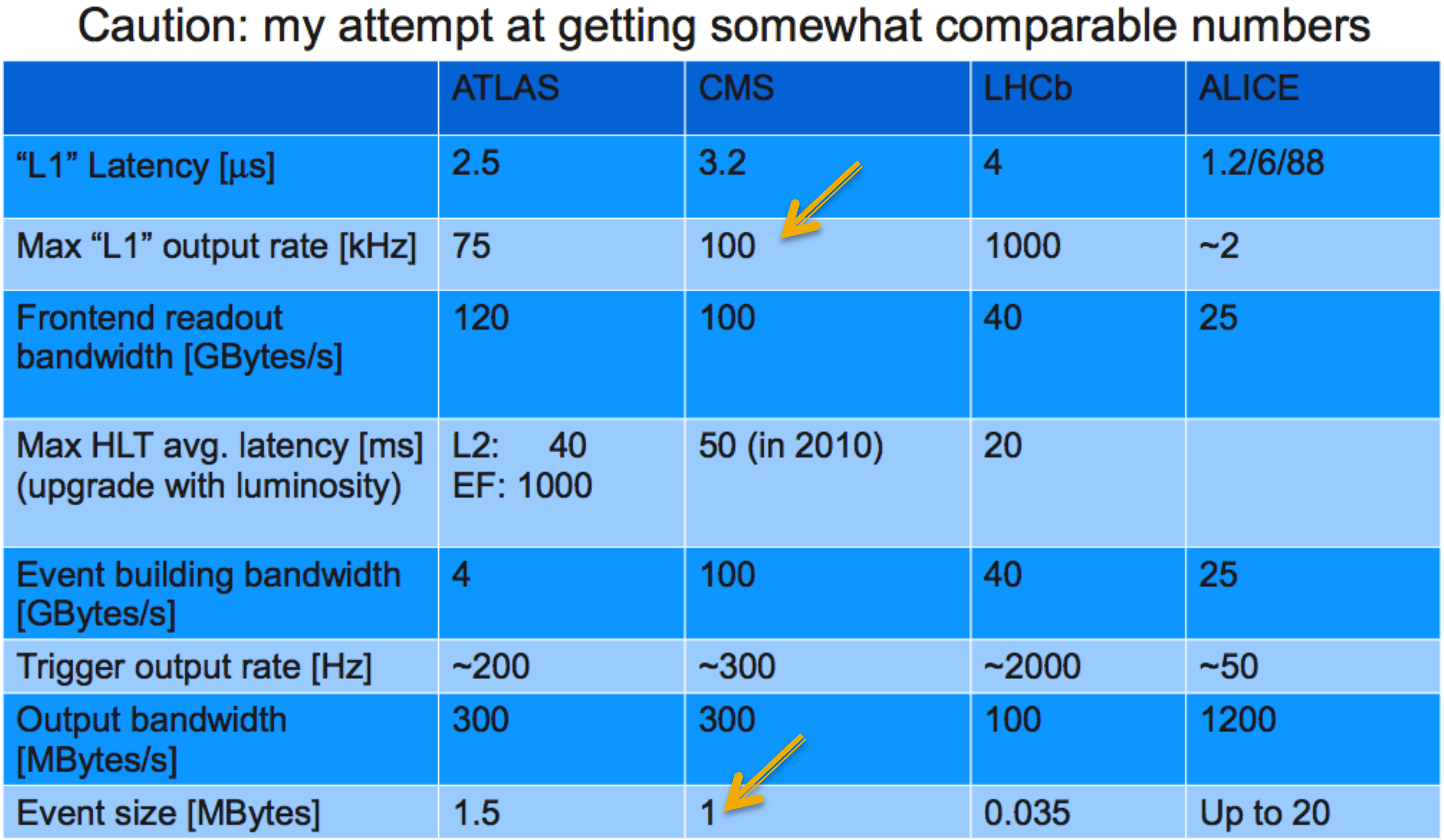
- "tag-and-probe"
  Trigger on 1 particle from resonance and measure how often 2nd particle is triggered
- "Boot-strap"
  Use looser (prescaled) trigger line
- "Orthogonal" trigger
  Trigger on one physics signature, measure a different
- Simulation







2011 LHC Trigger/DAQ comparison



Caution: my attempt at getting somewhat comparable numbers

	ATLAS	CMS	LHCb	ALICE
"L1" Latency [µs]	2.5	3.2	4	1.2/6/88
Max "L1" output rate [kHz]	75	100	1000	~2
Frontend readout bandwidth [GBytes/s]	120	100	40	25
Max HLT avg. latency [ms] (upgrade with luminosity)	L2: 40 EF: 1000	50 (in 2010)	20	
Event building bandwidth [GBytes/s]	4	100	40	25
Trigger output rate [Hz]	~200	~300	~2000	~50
Output bandwidth [MBytes/s]	300	300	100	1200
Event size [MBytes]	1.5	1	0.035	Up to 20

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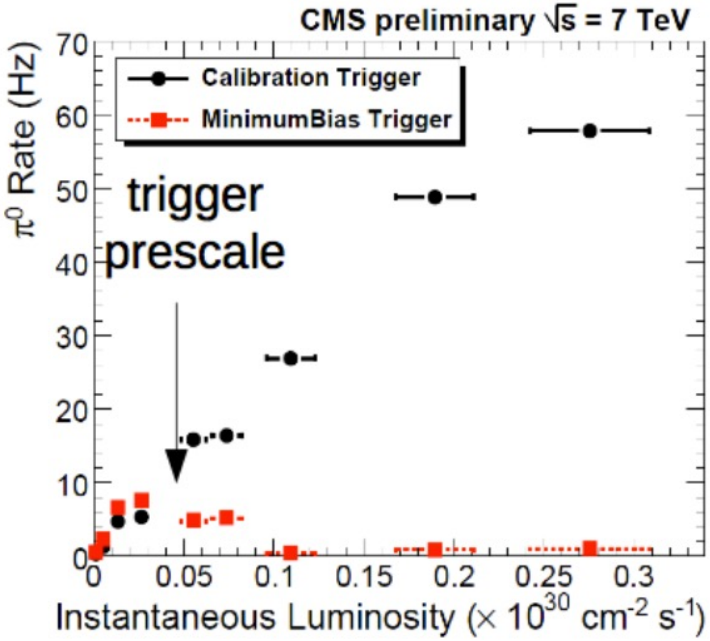
Rules are meant to be bent

- 300 Hz applies to the full event (A) stream.
- If you do not need the full event, **drop content, gain rate**.

- Used mostly in alignment and calibration:
  - Keep only tracks.
  - Keep only pion and eta diphotons clusters. ➔
  - Keep only MET and electron data (W).



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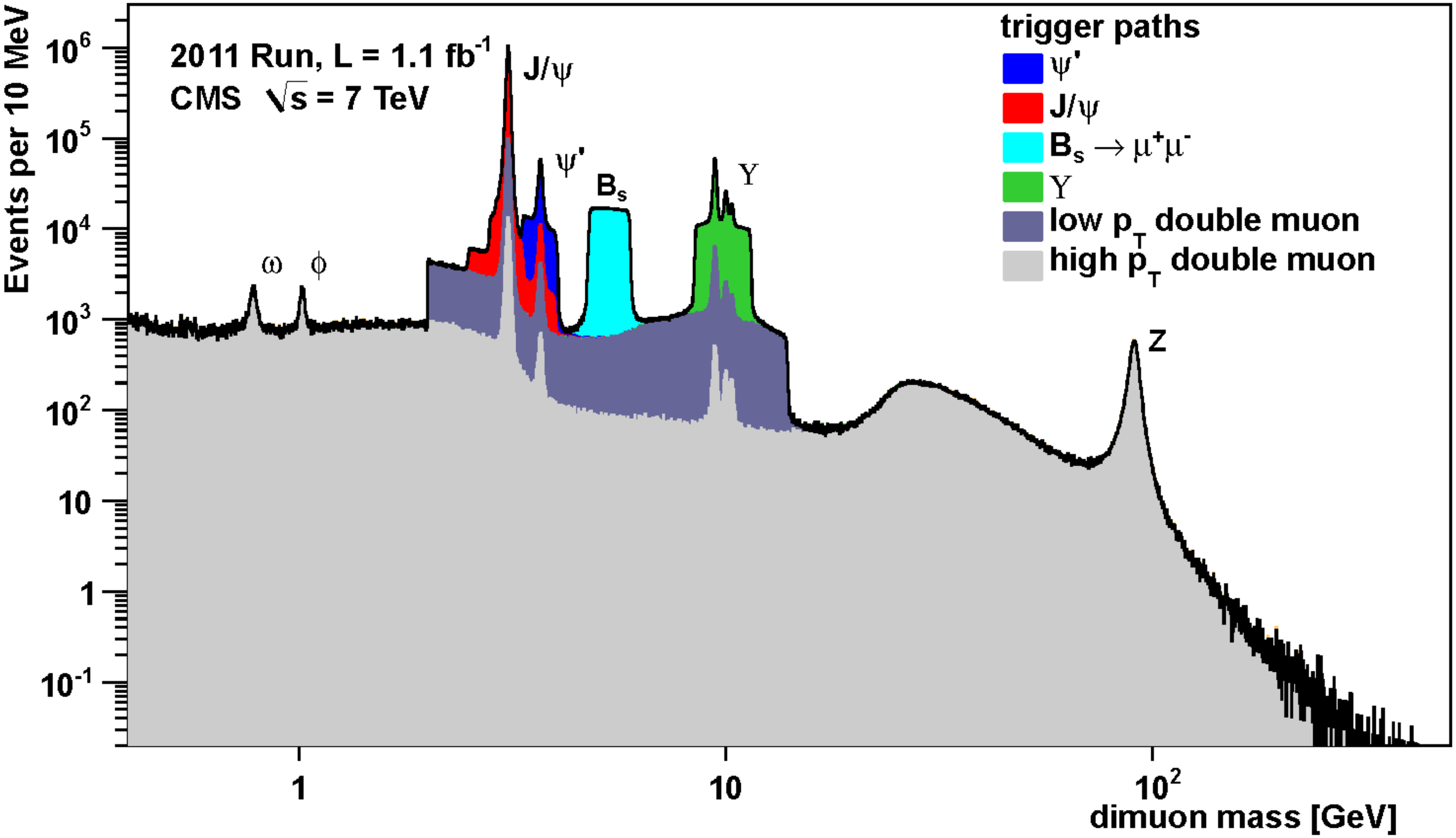
The power of flexibility



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Tracking and trigger

- Tracking systems are crucial.
  - CMS is particularly good at it.
    - Particle flow makes extensive use of tracking to disentangle the calorimeter deposit.

- Trigger is where analysis cuts start.
  - CMS has a simple two-level system.
  - CMS has a flexible system that has shown its trumps in 2011.

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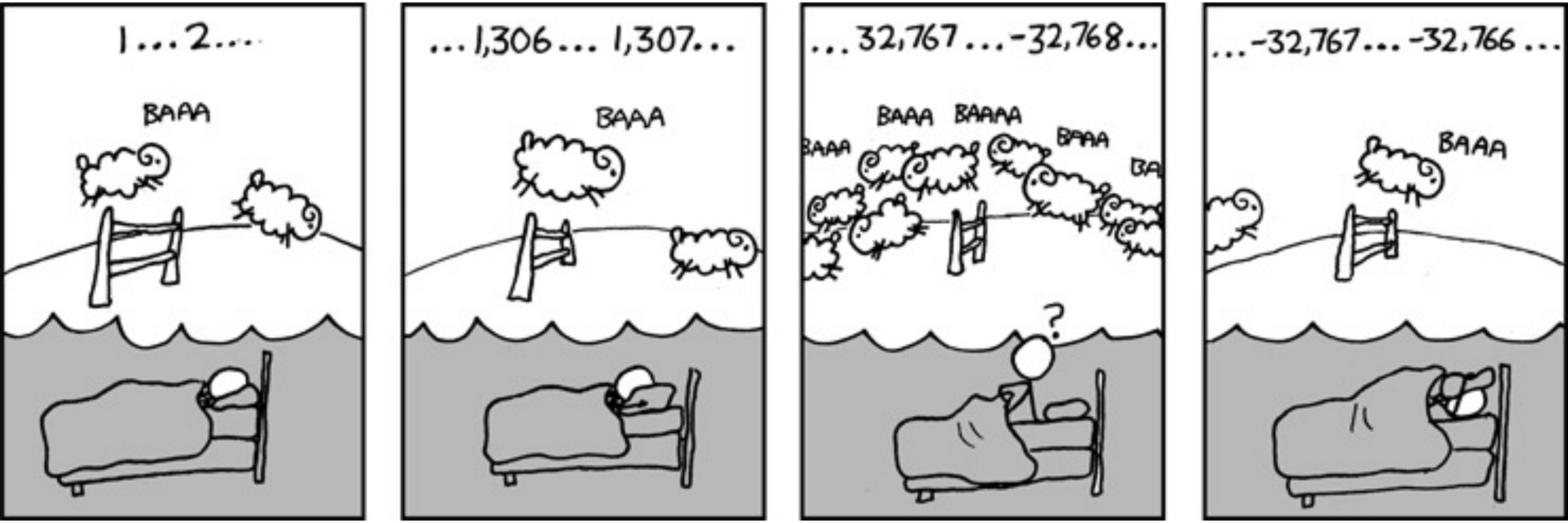
1...2...
BAAA
...1,306... 1,307...
BAAA
...32,767...-32,768...
BAAA BAAAA
BAAA
BAAA
BA
?
...-32,767...-32,766...
BAAA