Event reconstruction at the LHC

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With some slides from
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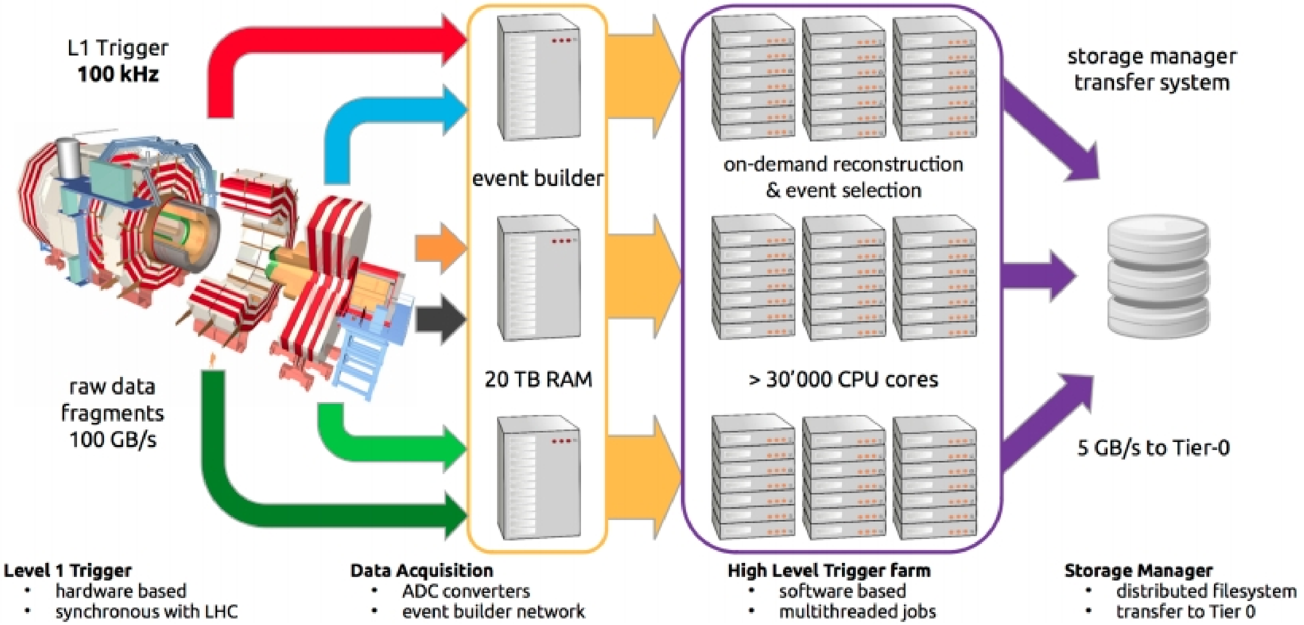
What is reconstruction?

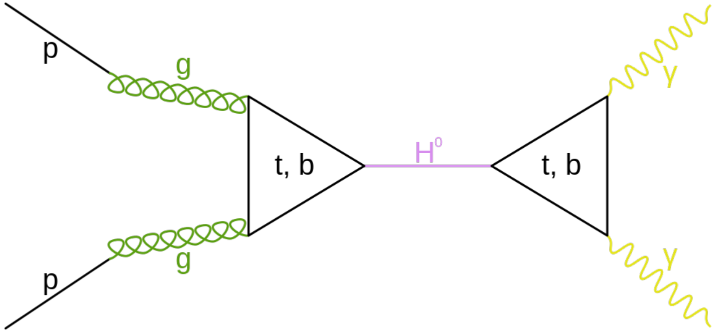
- Events passing the trigger are stored on tape at CERN
- But one event, like a picture from your camera phone, is just a collection of numbers
- As I physicist, I want information like “a 10 GeV electron was emitted at 30 degrees from the beam” rather than 011010100101...
- Reconstruction is what transforms digitised electrical signals from the detector into physics objects



When particles collide

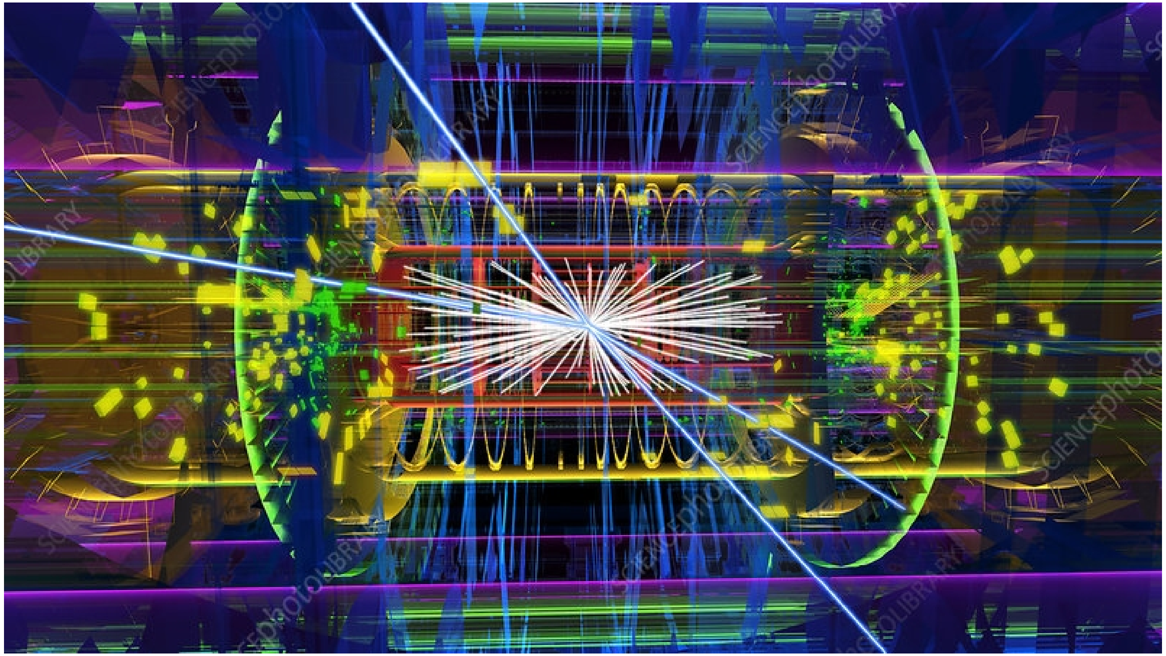
- Production of heavy states that decay into lighter states, measured by the detector
- I like to say as a half-joke that collider physics is like sending two apples (protons) at full speed against each other, and produce a water melon (heavy state, eg. Higgs boson)

- The water melon explodes immediately, the only thing we can measure are the little black seeds from its explosion
- We have to reconstruct the shape of the water melon by measuring the black seeds
- → we have to reconstruct the properties of the Higgs from the two photons from its decay

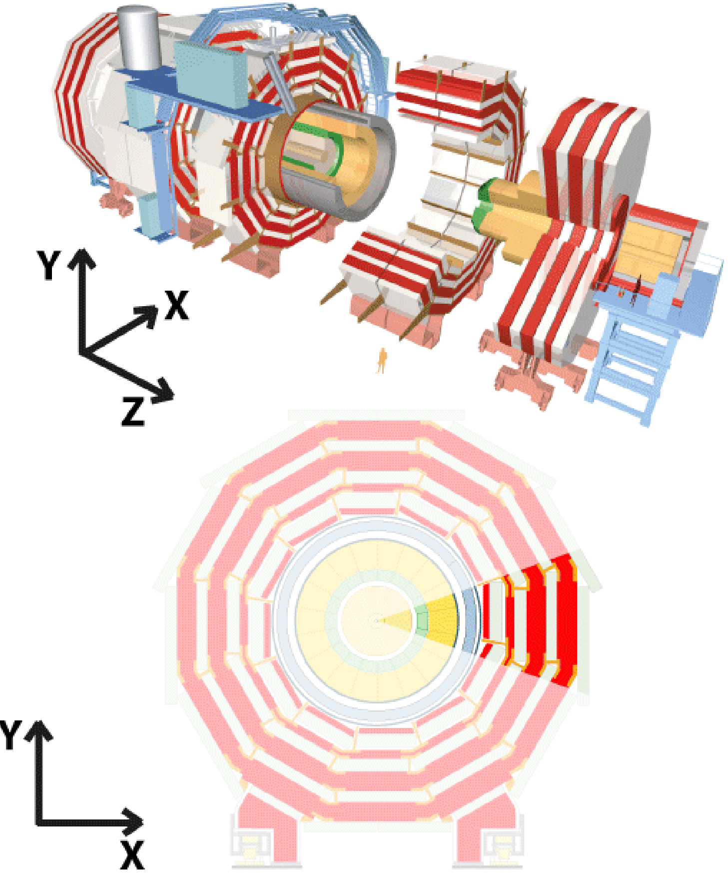


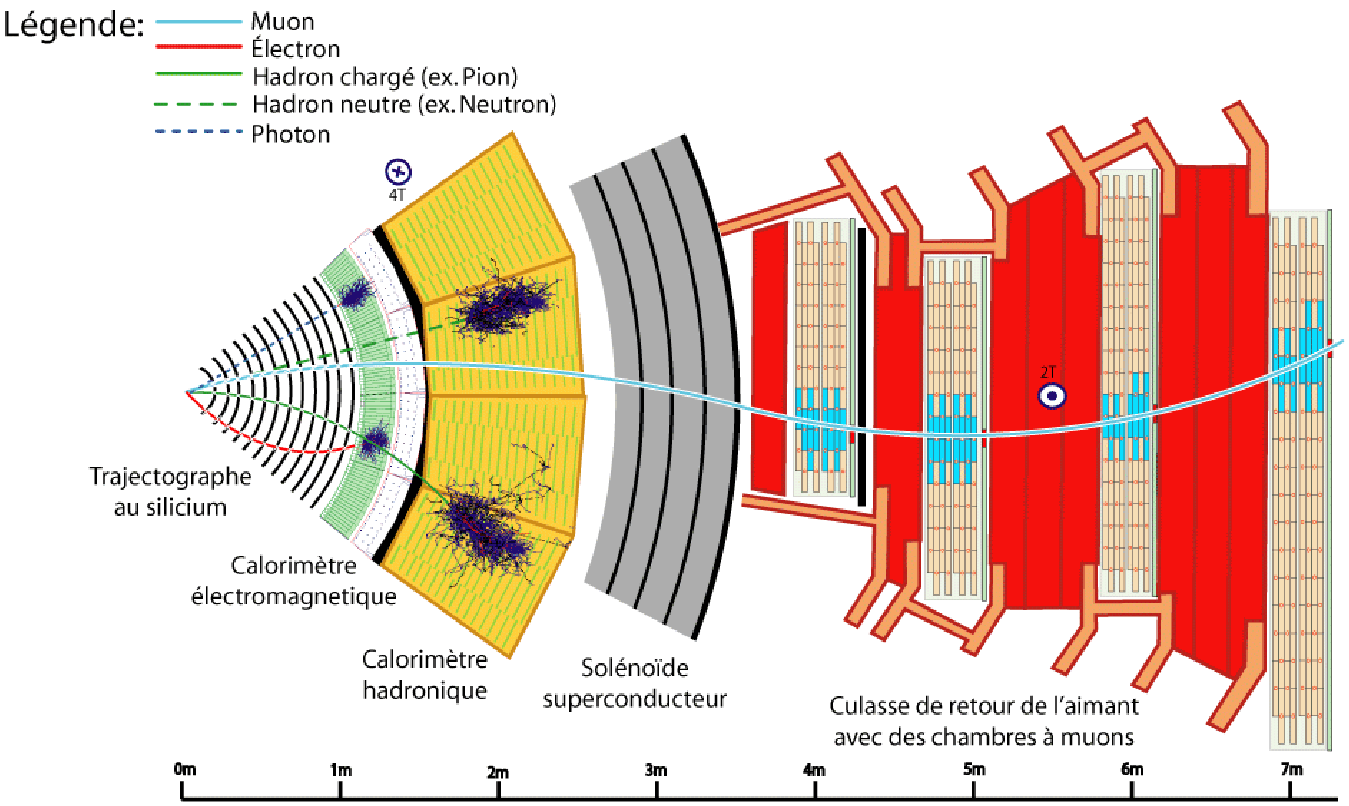
What can we detect?

- We can only measure directly particles with $c\tau >\sim 1$m (muons, pions, kaons, but not charm or beauty hadrons)
- Detector around collision point to measure decay products, and reconstruct short-lived states from them
- In a collider, detectors have cylindrical shape with several independent layers

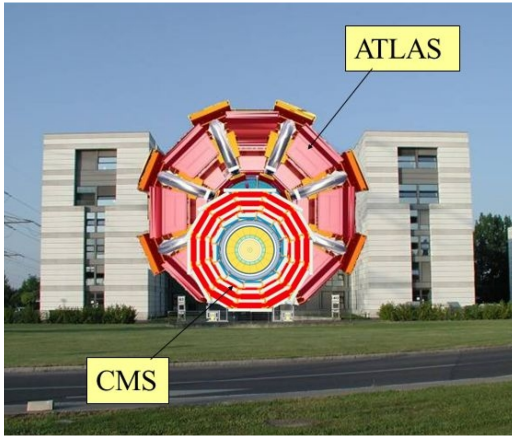


A typical detector slice (CMS)





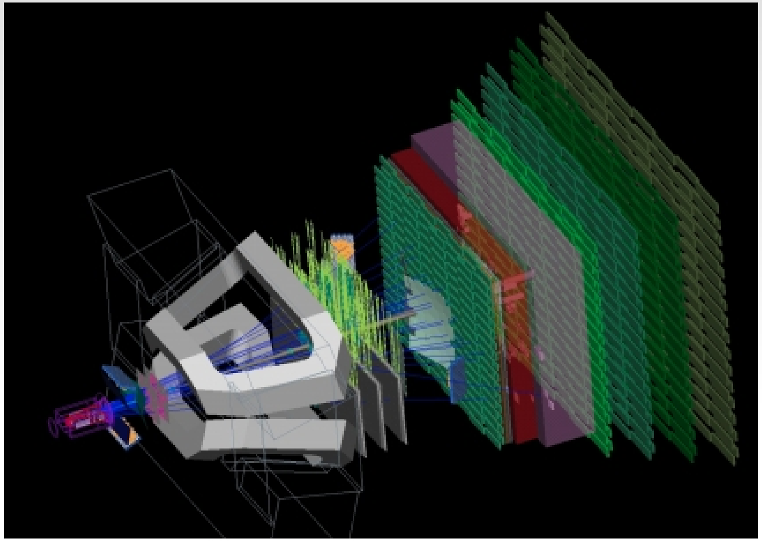
Differences between ATLAS and CMS



- Size:
  - ATLAS is 43m long 25m high
  - CMS 25m long 15m high
- Magnetic field:
  - ATLAS 9 magnets (1 2T solenoid, 8 ~1T air-core toroids, 2 FWD toroids)
  - CMS 1 4T solenoid
- Detector technologies:

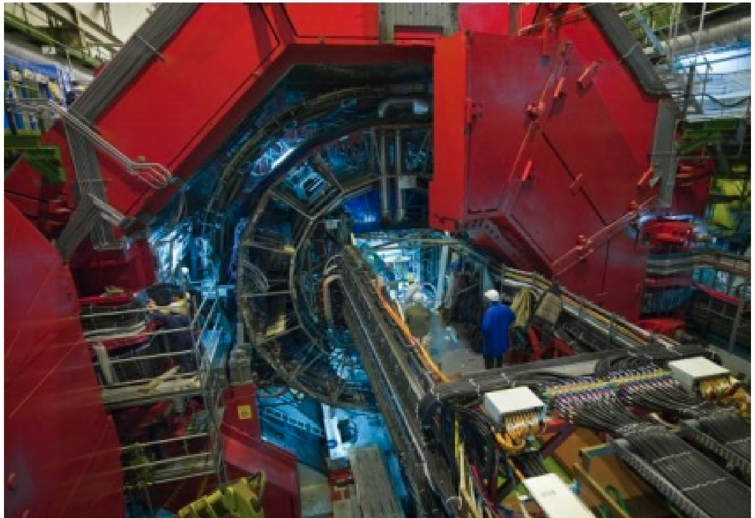
	ATLAS	CMS
tracking	Silicon/gas	Silicon
EM calo	Liquid Argon	PbWO cristals
Had calo	Steel/scint, LAr	Brass/scint
Muon	RPCs / drift	RPCs / drift

LHCb and ALICE



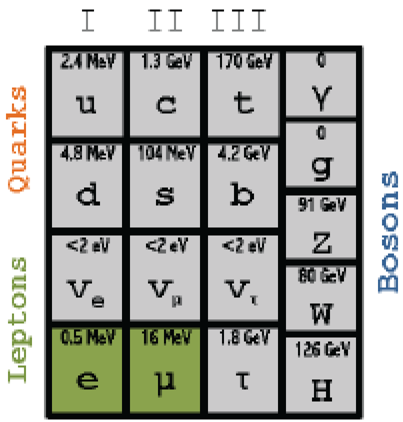
LHCb dedicated to forward low-andgle physics (especially b-quark production) looks like a pyramid with axis on the beam

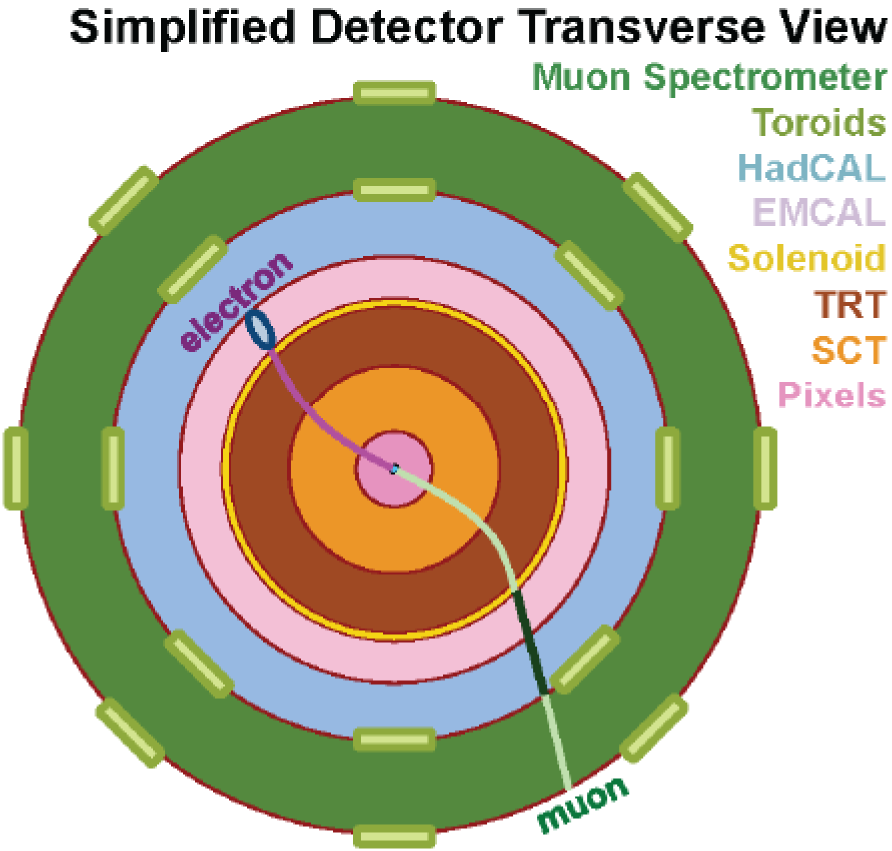
Very good particle identification



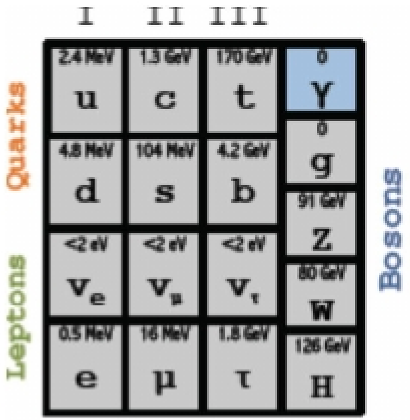
Alice looks for high-mutiplicity events in nucleus-nucleus collisions- the only LHC detector to have a gas tracker due to low-lumi and high-occupancy operation

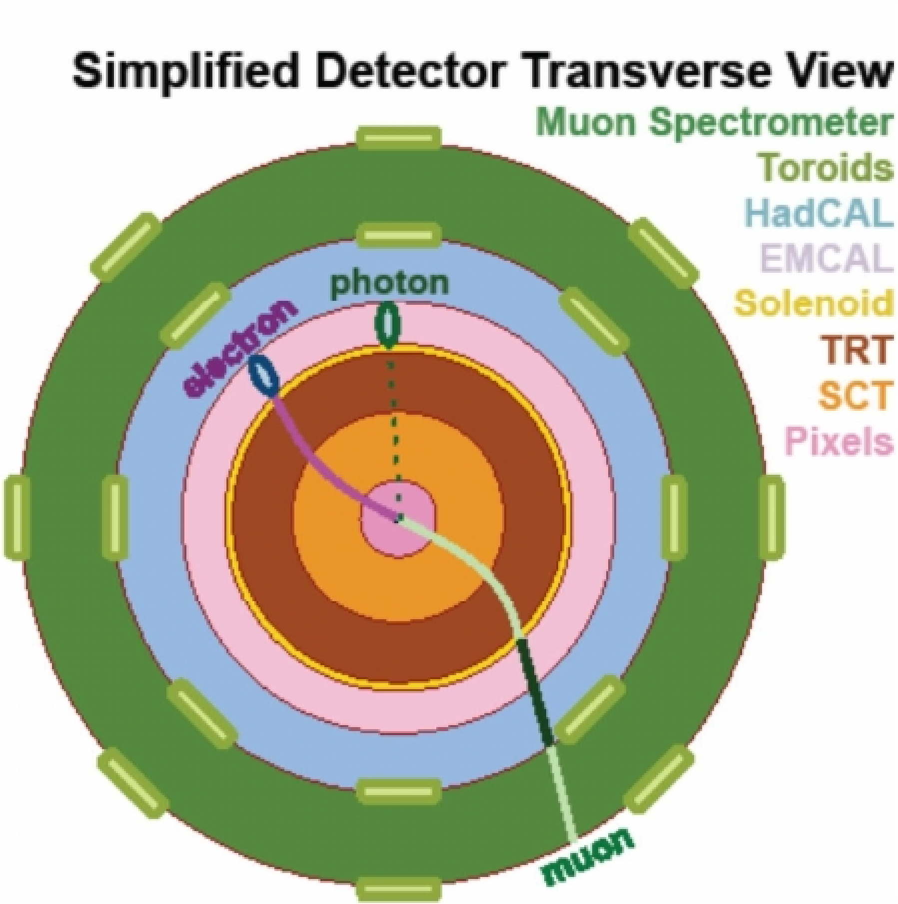
Detecting electrons and muons



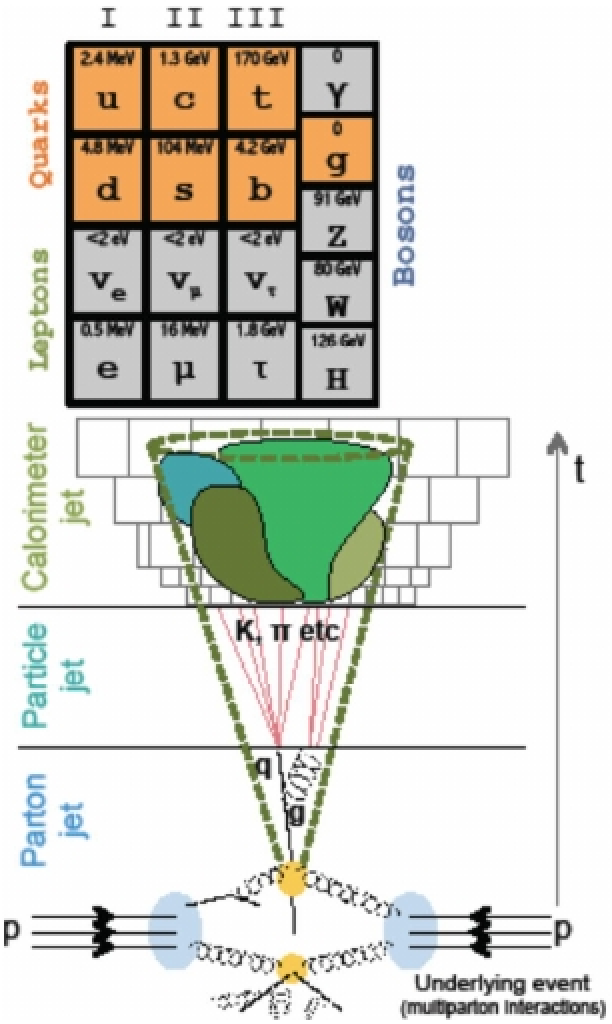


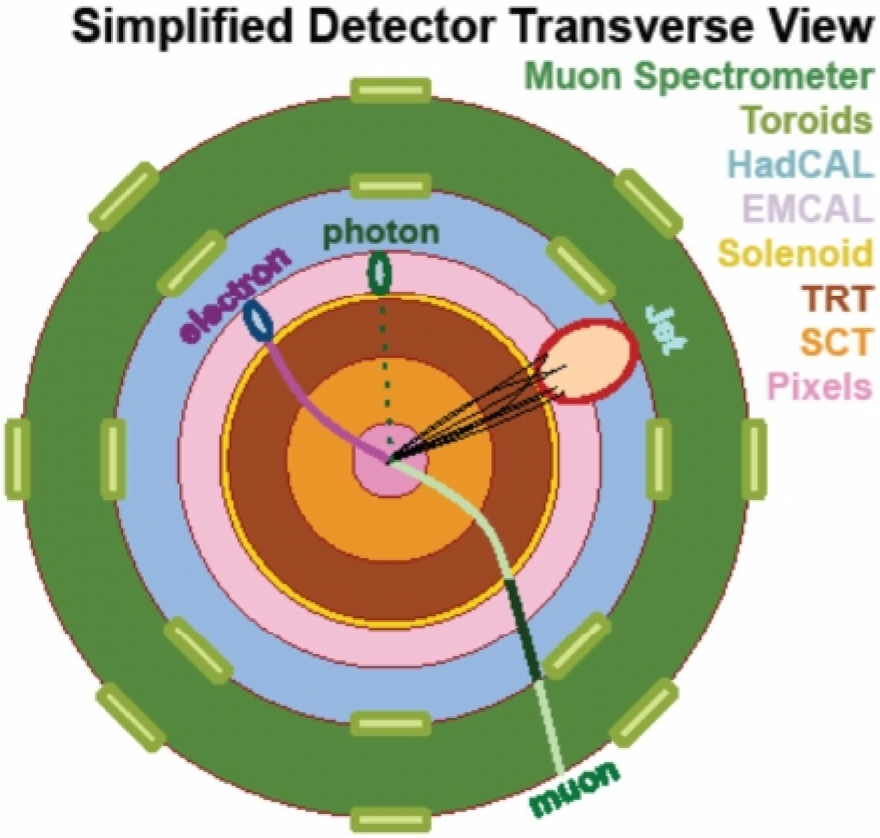
Detecting photons



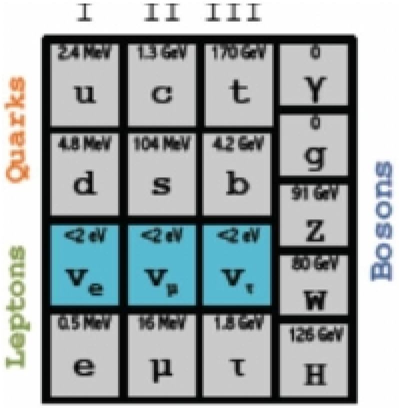


Detecting jets (hadrons)





Detecting what you can’t detect (neutrinos, DM etc)

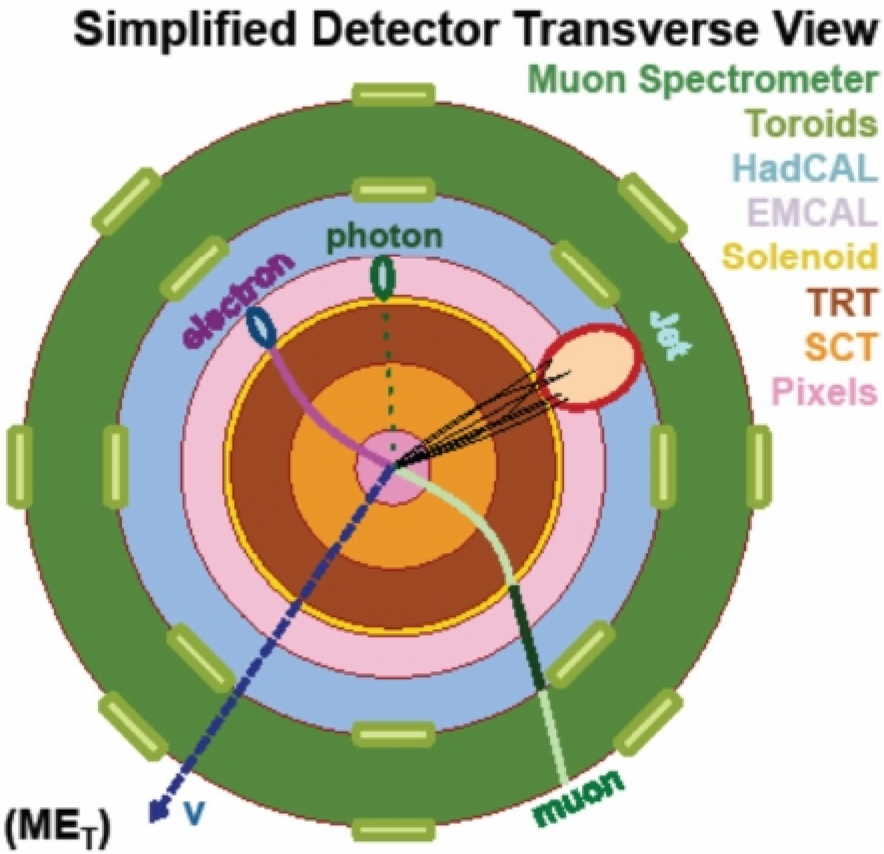


Also “invisible” particles from DM, SUSY…

In the transverse plane:

$$\sum \vec{p}_T = 0$$

Missing Transverse Momentum (ME_T)



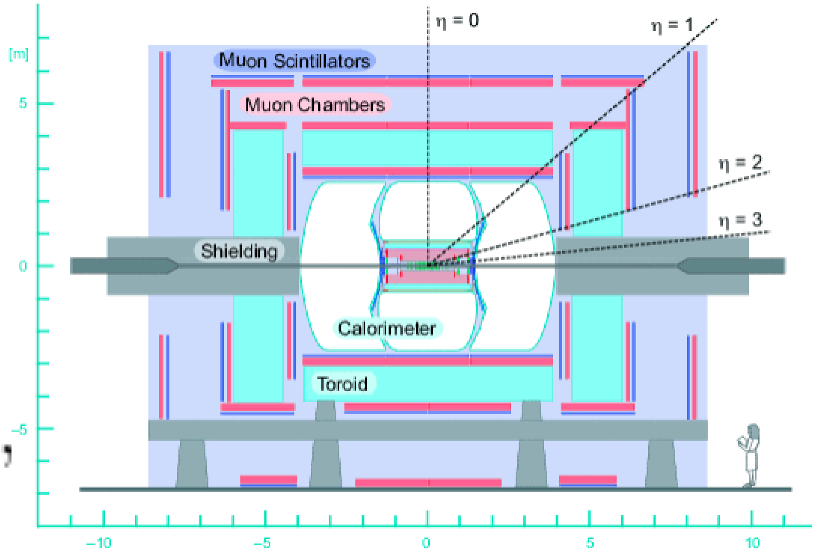
Relevant variables (why transverse plane)

- Only variables invariant under z-boost should be used.
- This is why cuts are expressed in terms of Et and not E, and instead of the angle θ we use rapidity

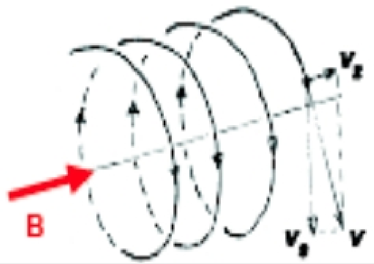
$$\phi_z = \frac{1}{2}\log_e \frac{E + p_z c}{E - p_z c}$$

It depends on the mass of an object, so it cannot directly reference to a detector location; for that we use pseudorapidity, equal to rapidity for massless particles:

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$



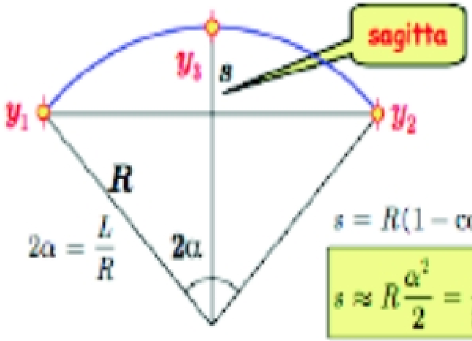
Measuring momentum



$$\boxed{R(m) = \frac{p_\perp(GeV)}{0.3B(T)}}$$

Since the transverse momentum is proportional to the bending radius, the momen resolution depend on the accuracy in measuring R

$$\boxed{R = \frac{p}{0.3B} \qquad \frac{\delta p}{p} = \frac{\delta R}{R}}$$



$$2\alpha = \frac{L}{R}$$

$$s = y_3 - \frac{y_1 + y_2}{2} \qquad \delta s = \sqrt{\frac{3}{2}}\delta y \sim \delta y$$

$$s = R(1 - \cos\alpha)$$

$$\boxed{s \approx R\frac{\alpha^2}{2} = \frac{L^2}{8R}}$$

$$|\delta s| = \frac{L^2}{8R}\frac{\delta R}{R} \sim \delta y \qquad \frac{L^2}{8R}\frac{\delta p}{p} = \delta y$$

$$\frac{\delta p}{p} = \frac{8R}{L^2}\delta y \qquad \frac{\delta p}{p} = \frac{8p}{0.3BL^2}\delta y$$

$$\boxed{\frac{\delta p}{p^2} = \frac{8\delta y}{0.3BL^2}}$$

The ATLAS tracker

Pixel Detector

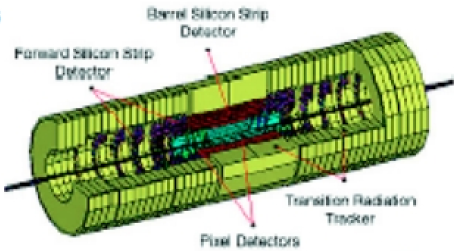
- 3 barrels, 3+3 disks: 80x10^6 pixels
- barrel radii: 4.7, 10.5, 13.5 cm
- pixel size 50x400 μm
- s_{rf}= 6-10 μm s_z = 66 μm

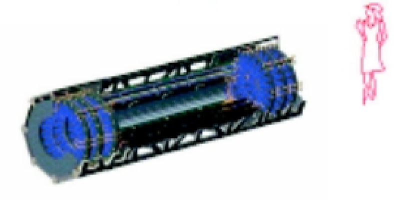
SCT

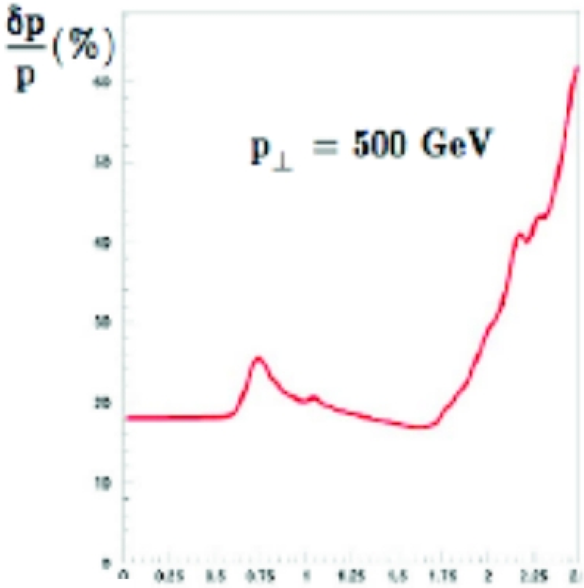
- 4 barrels, disks: 6.3x10^6 strips
- barrel radii:30, 37, 44 ,51 cm
- strip pitch 80 μm
- stereo angle ~40 mr
- s_{rf}= 16 μm s_z = 580μm

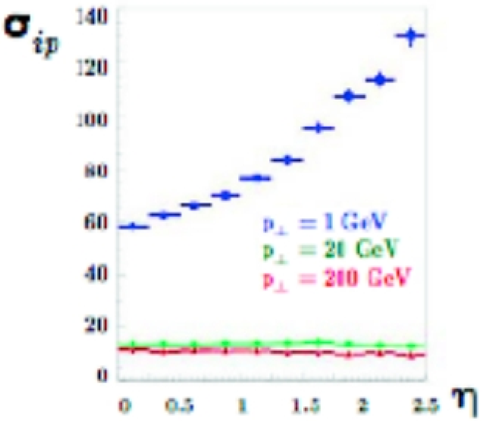
TRT

- barrel: 55 cm < R < 105 cm
- 36 layers of straw tubes
- s_{rf}= 170 μm
- 400.000 channels









The CMS tracker

Pixel Detector

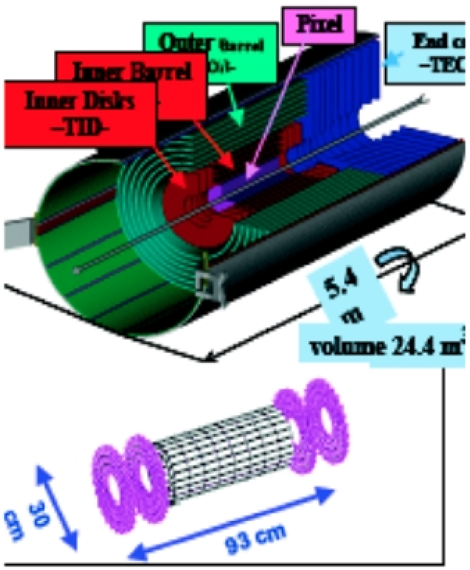
- 2 barrels, 2 disks: 40×10^6 pixels
- barrel radii: 4.1, ~10. cm
- pixel size 100×150 µm
- $\sigma_{r\phi}$ = 10 µm σ_z = 10 µm

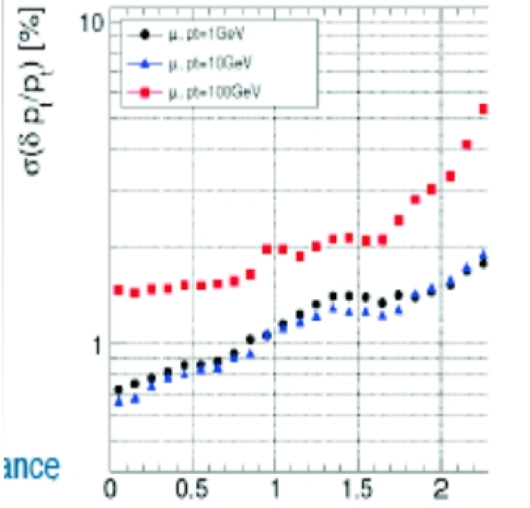
Internal Silicon Strip Tracker

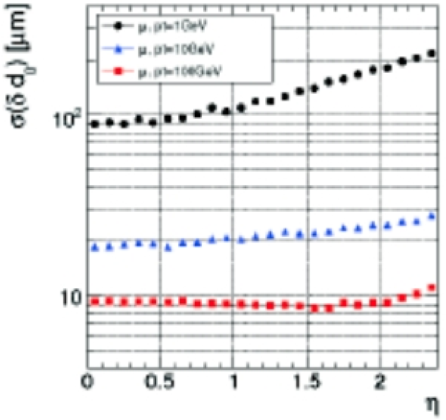
- 4 barrels, many disks: 2×10^6 strips
- barrel radii:
- strip pitch 80,120 µm
- $\sigma_{r\phi}$ = 20 µm σ_z = 20 µm

External Silicon Strip Tracker

- 6 barrels, many disks: 8×10^6 strips
- barrel radii: max 110 cm
- strip pitch 80, 120 µm
- $\sigma_{r\phi}$ = 30 µm σ_z = 30 µm





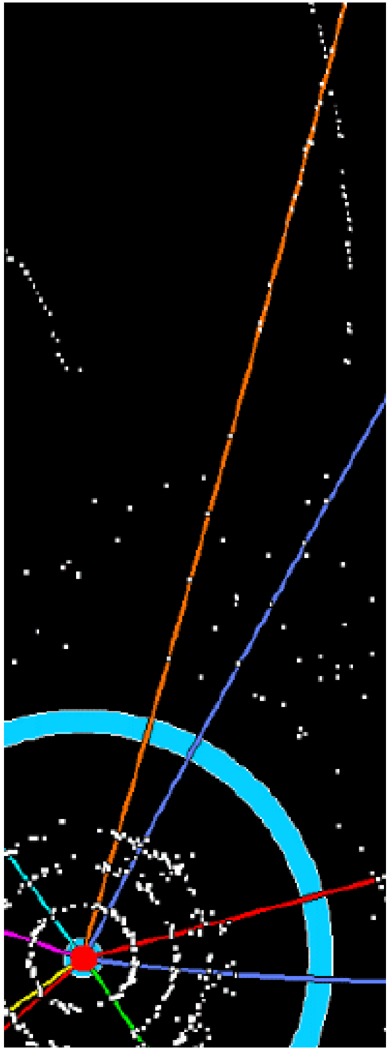


Reconstructing tracks

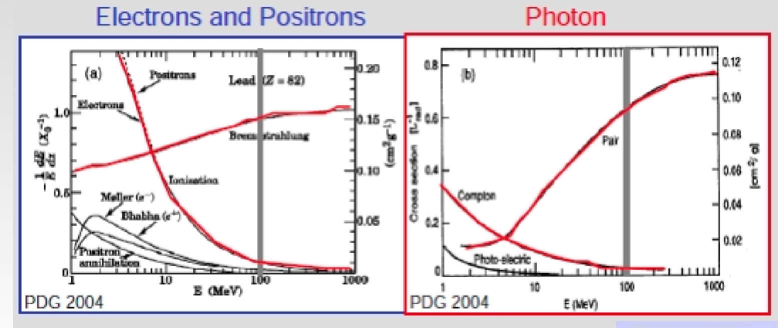
ATLAS has 3 tracking detectors: pixel, SCT, TRT (straw tubes)

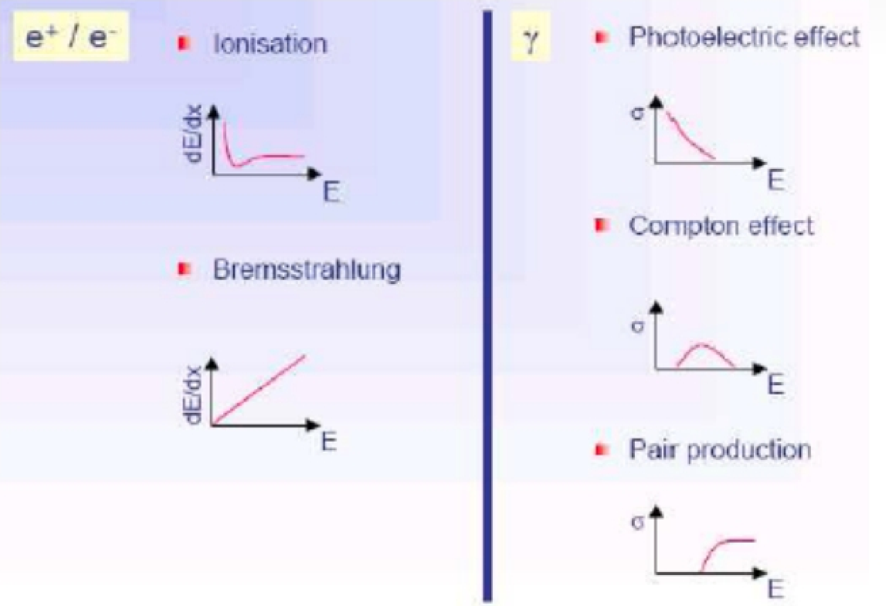
Sequence:

1. Creation of 3-dimensional Space Points in Pixel and SCT (Si-Layers)
2. Search for Track Seeds with Space Points in Si-Layers
3. Track Fit of Seeds found and ambiguity processing
4 Extrapolation into TRT and search for compatible measurements
5. Track fit of Pixel, SCT and TRT measurements
6. Track scoring and track selection



Interactions of electrons and photons in a calorimeter





Reconstructing invariant mass in a calorimeter

Natural width: for $M_H \approx 100$ GeV $\rightarrow \Gamma_H / M_H \leq 10^{-3}$

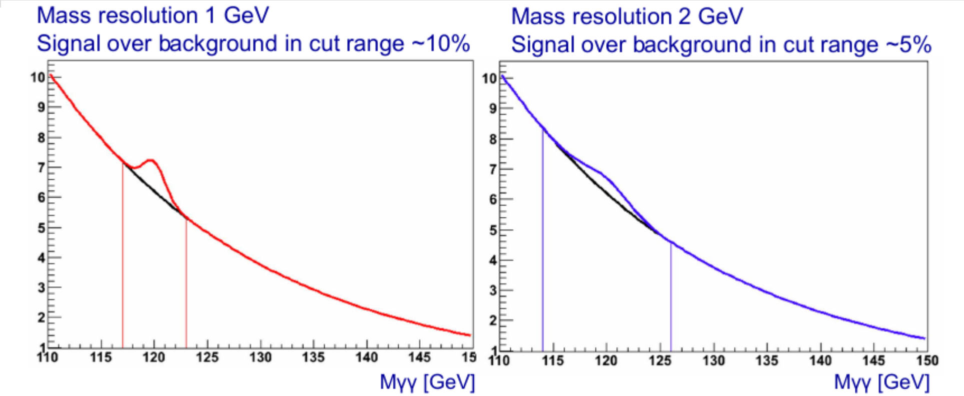
Experimental width of $m\gamma\gamma = 2 E_1 E_2 (1 - \cos\theta_{\gamma\gamma})$:

$$\frac{\sigma_m}{m} = \frac{1}{\sqrt{2}}\left[\left(\frac{\sigma_1}{E_1}\right) \oplus \left(\frac{\sigma_2}{E_2}\right) \oplus \left(\frac{\sigma_\theta}{tg\theta_{\gamma\gamma}/2}\right)\right]$$

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

$$\sigma(\theta) \approx \frac{50\,\mathrm{mrad}}{\sqrt{E}}$$

Same for ATLAS and CMS ...

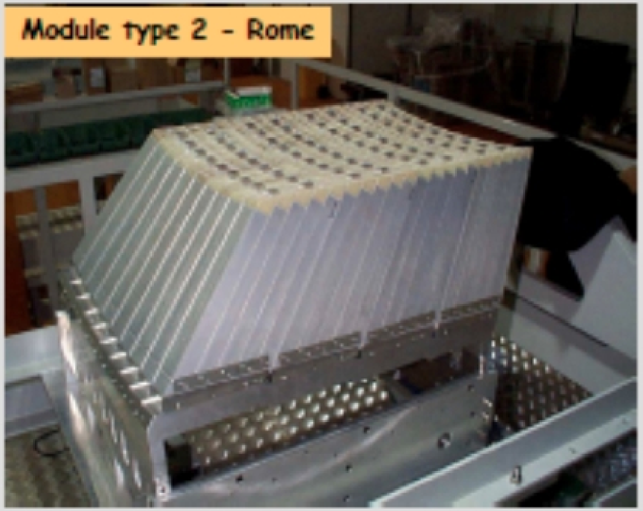


- Can make the difference for a discovery!

CMS Crystal calorimeter

- ✓ Compact
- ✓ Transverse segmentation

Material	X_0/cm	Ec/MeV	R_M/cm
Fe	1.8	22	1.7
Lead	0.56	7.4	1.6
$PbWO_4$	0.89		2.2

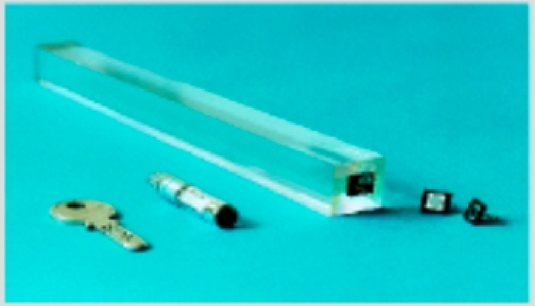


Crystal dimensions:

longitudinal 25 X_0 = 22.2 cm

Transverse 1 R_M = 2.2 cm

95% of the shower contained in 2 R_M



ATLAS Lar calorimeter

- Longitudinal dimension:

$\approx 25\ X_0 = 47$ cm (CMS 22 cm)

- 3 longitudinal layers

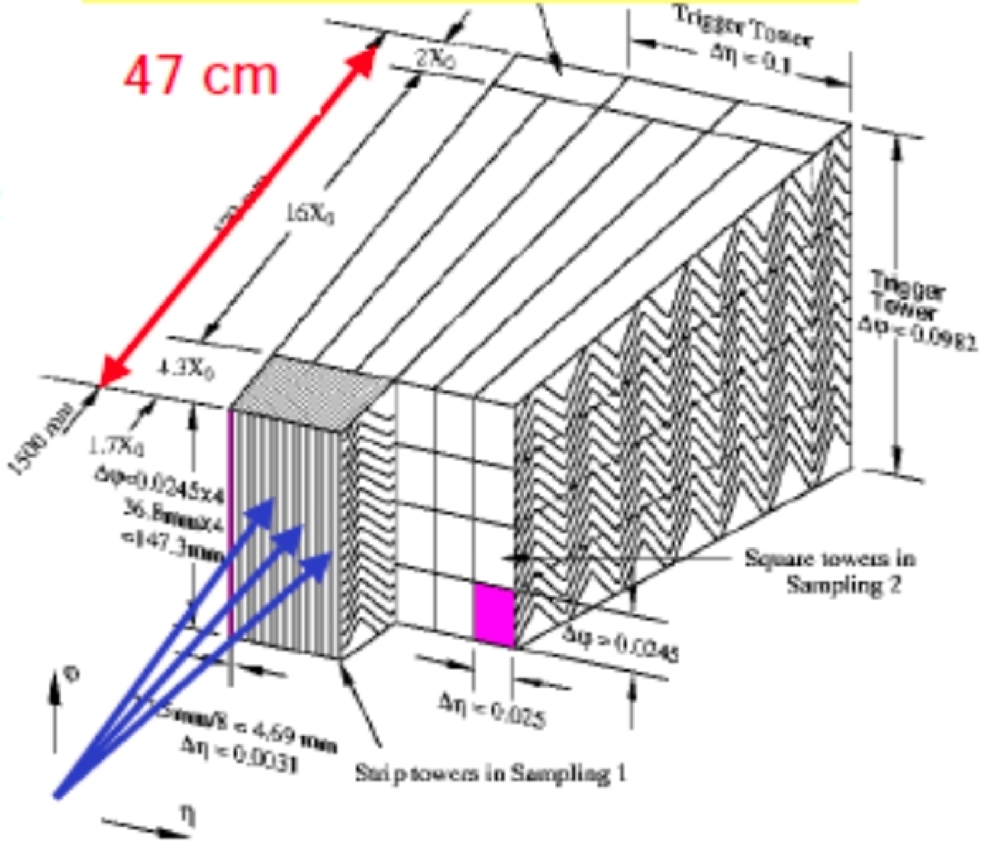
4 X_0 π^0 rejections separation of 2 photons very fine grain in η

16 X_0 for shower core

2 X_0 evaluation of late started showers

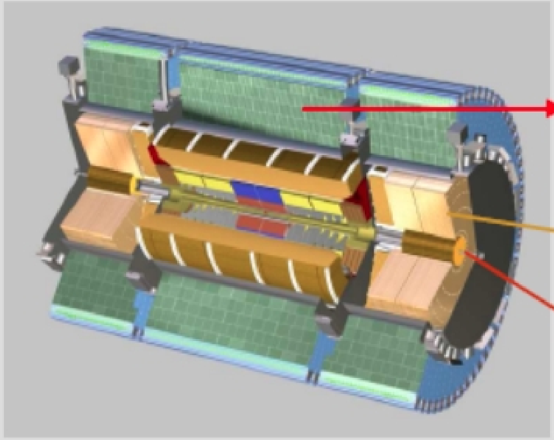
- Total channels = 170000

Sampling: accordion lead structure filled with LAr



Particles from collisions

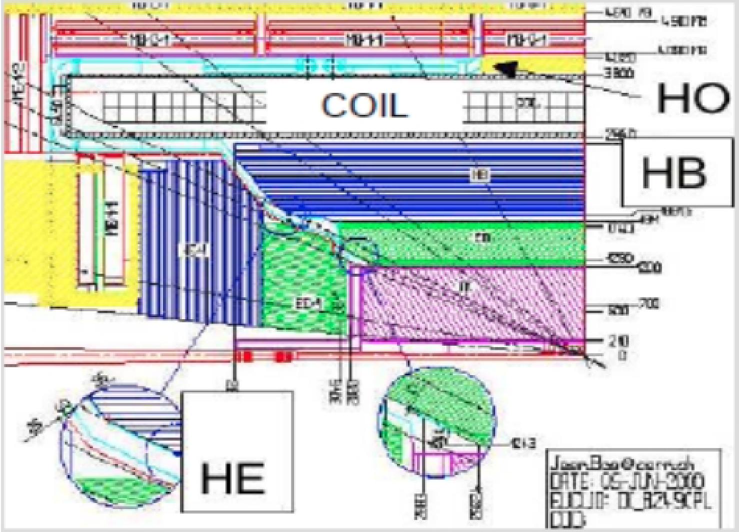
Hadronic calorimetry



Tile Calorimeter $|\eta| < 1.7$
Fe / Scintillator
3 longitudinal sections

LAr/Cu $1.7 < |\eta| < 3.2$
4 longitudinal sections

Both hadronic and em
LAr/Cu or W $3.2 < |\eta| < 4.9$
3 longitudinal sections

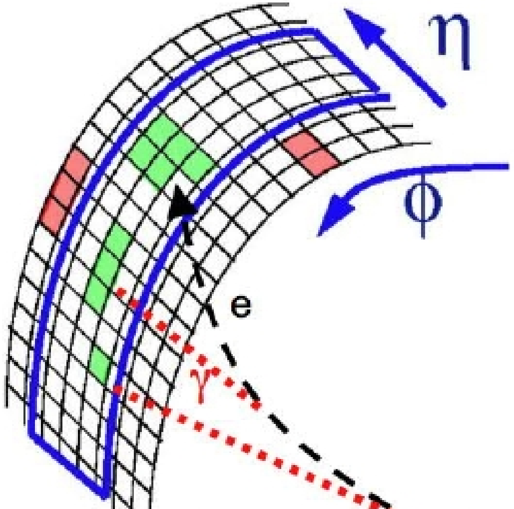


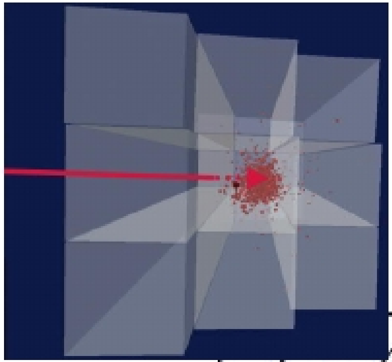
Central Hadronic $|\eta| < 1.7$:
Brass/Scintillator + WLS
2 + 1 (HO) Longitudinal section
$5.9 + 3.9\ \lambda$ ($|\eta| = 0$)
Endcap Hadronic $1.3 < |\eta| < 3$:
Brass/Scintillator + WLS
2/3 Longitudinal sections

Forward calorimeter $2.85 < \eta < 5.19$:
Ferro/fibre di quarzo

Energy reconstruction in calorimeters

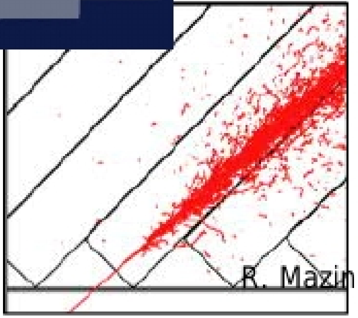
- Calorimeters are segmented in cells
- Typically a shower extends over several cells
  - Useful to reconstruct precisely the impact point from the “center-of-gravity” of the deposits in the various cells
- Example CMS Crystal Calorimeter:
  - electron energy in central crystal ~ 80 %, in 5x5 matrix around it ~ 96 %
- So task is : identify these clusters and reconstruct the energy they contain

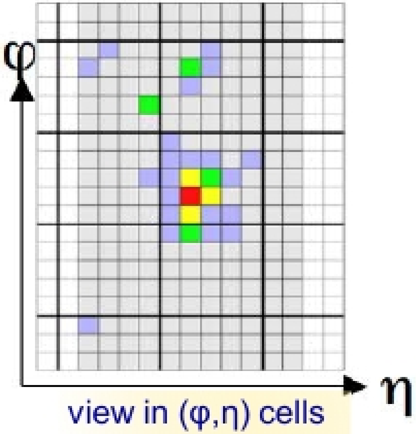




front view

side view

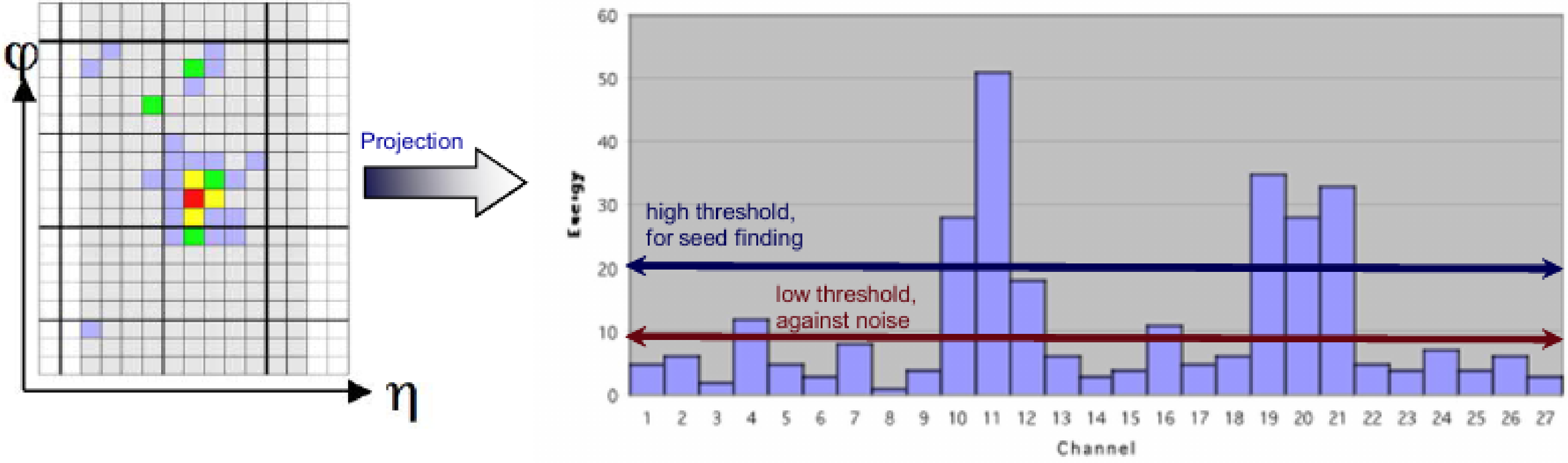




view in (φ,η) cells

Determination of cluster energy

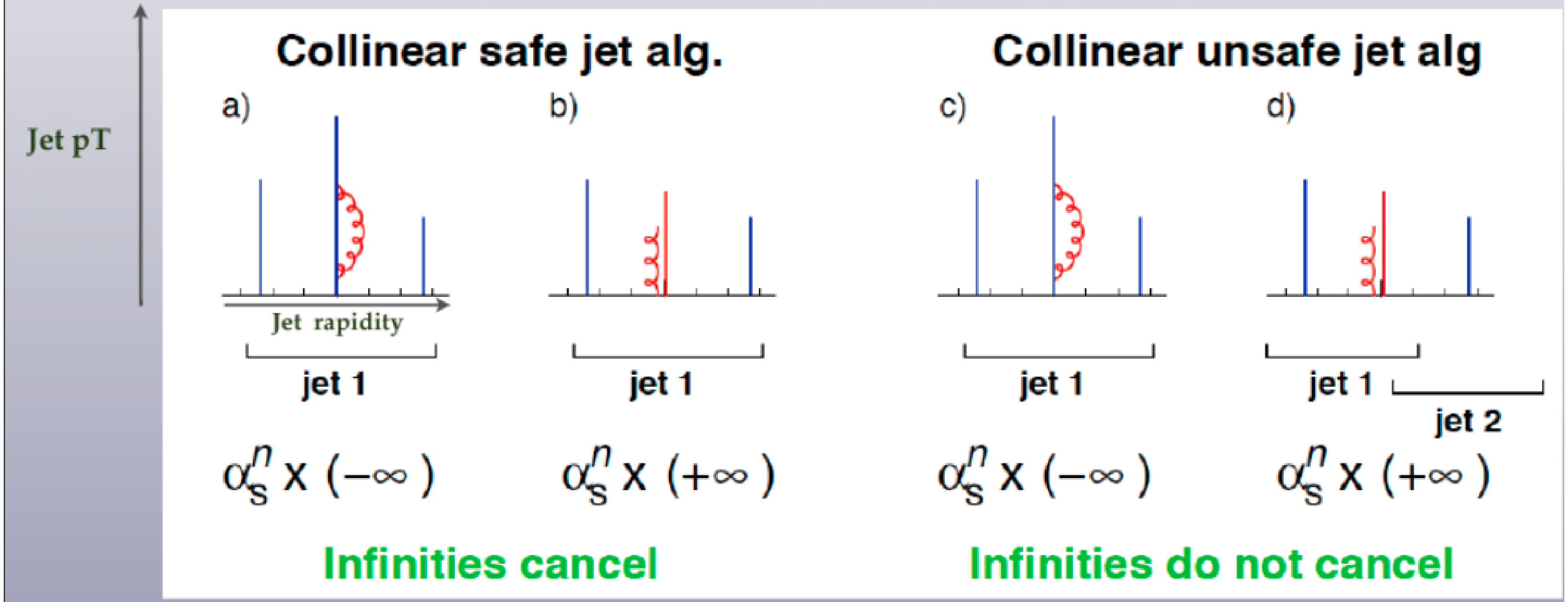
- Clusters of energy in a calorimeter are due to the original particles
  - Clustering algorithm groups individual channel energies
  - Don’t want to miss any; don’t want to pick up fakes



- Careful tuning of thresholds needed
  - needs usually learning phase
  - adapt to noise conditions
  - too low : pick up too much unwanted energy
  - too high : loose too much of “real” energy. Corrections/Calibrations will be larger

Jet algorithms

- In the particular case of jet algorithms, **infrared safety** can be formulated as the requirement that if the **final state particles** are modified by a **soft emission** or a **collinear splitting** then the set of hard jets found should be unchanged
- Failing this criterion, a jet definition will produce **infinite results** at some point in the perturbative expansion because of the **lack of cancellation** of infrared divergences



In the **IRC unsafe algorithm**, a **collinear splitting** leads to a **different set of final state jets** and thus to the lack of cancellation of soft and collinear divergences (KLN theorem)

Sequential recombination algorithms

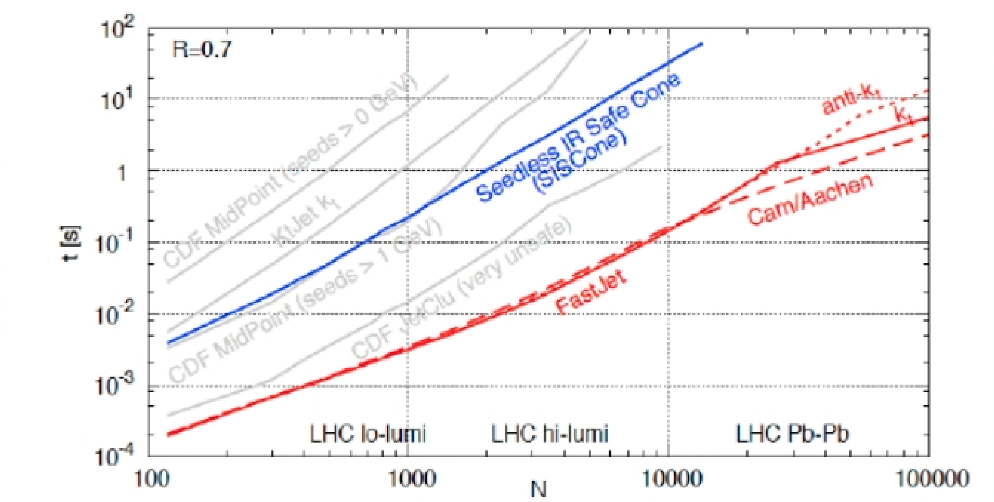
It is possible to **generalize the kt algorithm** by introducing a modified distance as follows

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2,$$
$$d_{iB} = p_{ti}^{2p},$$

- **p = 1 ->** kt algorithm: follows QCD branching structure in pt and in angle
- **p = 0 -> Cambridge/Aachen:** follows QCD branching structure **only in angle**
- **p = -1 -> Anti-kT algorithm:** unrelated to QCD branching structure, with clustering measure favouring recombination of high-pT particles

By construction, these sequential recombination algorithms are **infrared safe**

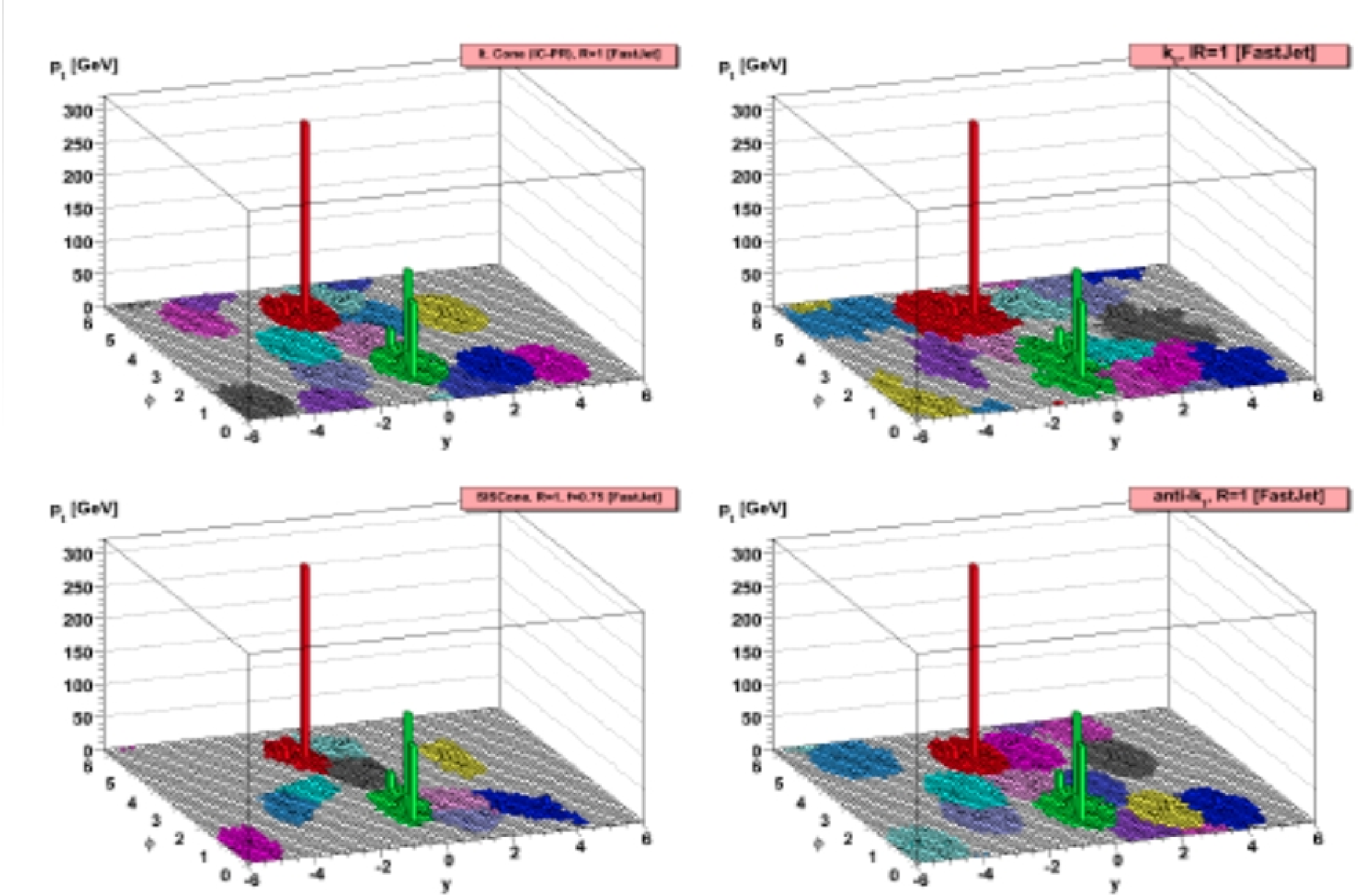
At the LHC, the default jet algorithm is the **Anti-KT** algorithm, for reasons that we discuss now



Original implementations of kt algorithm very **slow, T=O(N³)**, making it unpractical for high-multiplicity hadron collisions

Modern implementations (**FastJet**) much more efficient using computational geometry, amd achieve **T=O(N log N)**

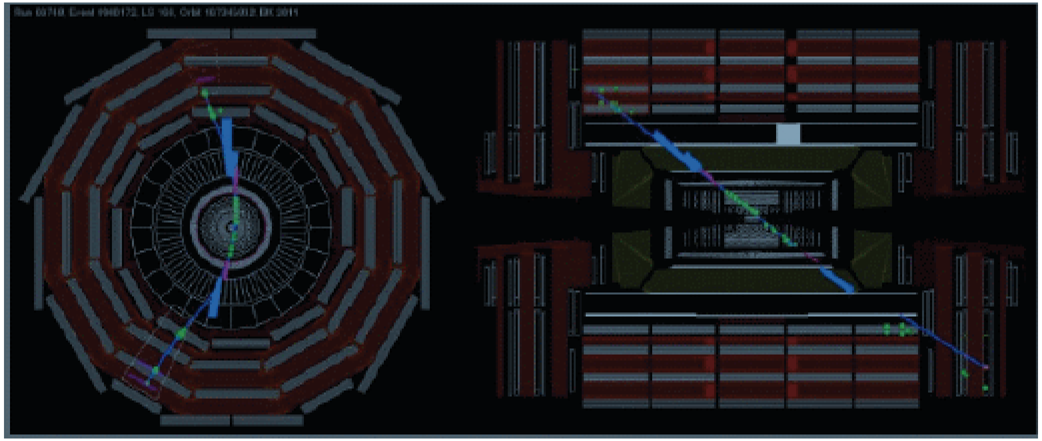
Same event reconstructed by different algorithms



AntiKt, seeded by a combination of calorimeter clusters and tracks (Particle Flow) is default in both ATLAS and CMS

Muon detectors

- Obviously very similar to inner detector tracking
  - But much less combinatorics to deal with
- Reconstruct tracks in muon and inner detector and combine them
- Strategy
  - Find tracks in the muon system
  - Match with track in inner tracker
  - Combine track measurements
  - Consistent with MIP
    - Little or no energy in calorimeters

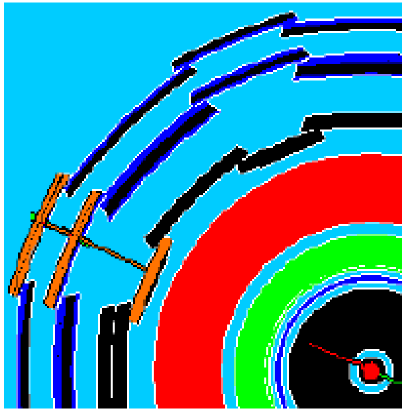


Reconstructing muons

- Because of it's long lifetime, the muon is basically a stable particle for us ($c\tau$ ~ 700 m)
- It does not feel the strong interaction
  - Therefore, they are very penetrating
- It's a minimum ionising particle (MIP)
  - Only little energy deposit in calorimeter
- However, at high energies (E>0.2 TeV) muons can sometimes behave more like electrons!

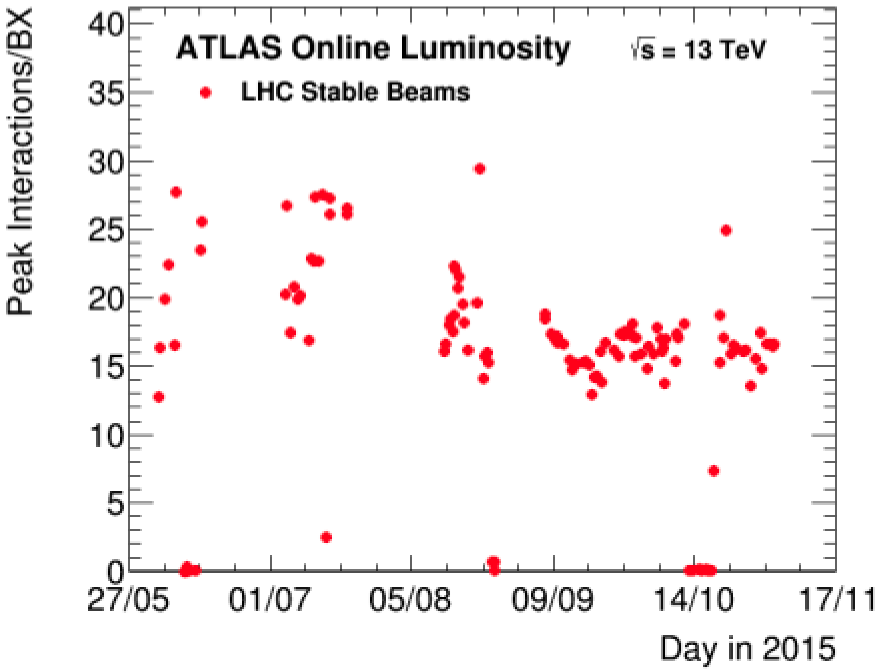
0

  - At high energies, radiative losses begin to dominate and muons can undergo bremsstrahlung
- Muons are identified as a track in the muon chambers and in the inner tracking detectors
- Both measurements are combined for the best track results

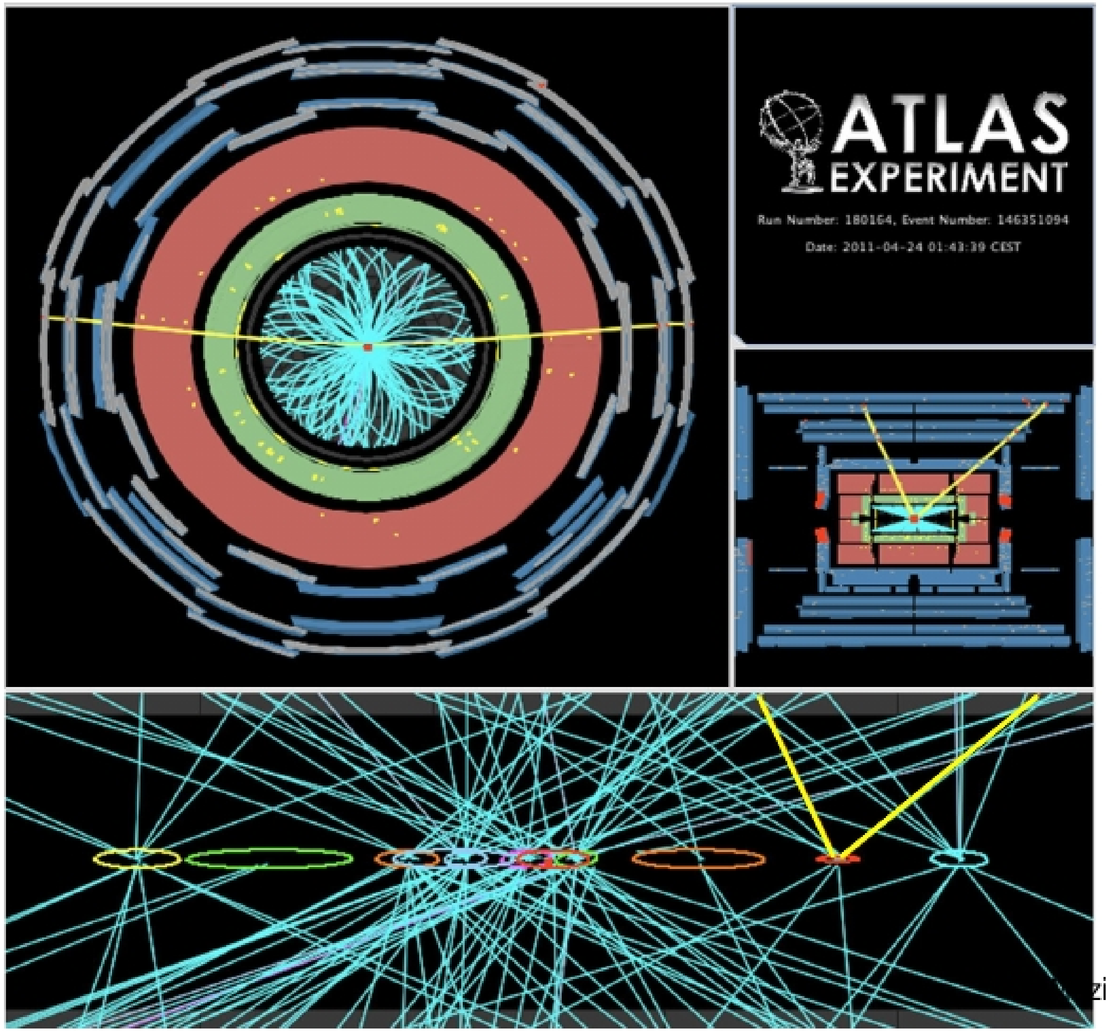


Pileup

- If we have 1E9 events/s, and 40M Bunch Crossings/s, it means there are about 25 events/bunch crossing.
- Analysing an event at the LHC is like making sense of 25 pictures one on top of each other



Analysing data with pileup



Z->μμ event in ATLAS.

With 11 reconstructed vertices.

Tracks with transverse momentum p_T>0.5GeV are shown

How can we do physics analysis with such a huge number of tracks in the detector?

Associate tracks to vertex, and determine PRIMARY vertex, removing tracks not associated with it

Conclusions

- Reconstruction lies in the interface between detector and physics
- Calibrated signals from the detectors are combined to produce physics objects
- Some times (eg electrons) signals from two detectors are combined
- Proper jet reconstruction requires understanding of QCD
- The presence of pileup makes everything more complicated (or interesting!)