Commissioning of the ATLAS experiment towards first LHC physics

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Contents and lectures

- What is ATLAS?
- The complete operation chain
- Reconstruction: from raw data to physics input objects

Lecture 1: M.J.Costa

- Track reconstruction and alignment

Lecture 2: S. Martí

- How the full operation chain is being commissioned?
- Results from cosmic rays analysis and single beam data
- Strategy towards first LHC physics results

Lecture 3: M.J.Costa

The ATLAS experiment

What is ATLAS?

- A gigantic multi-purpose detector for the LHC

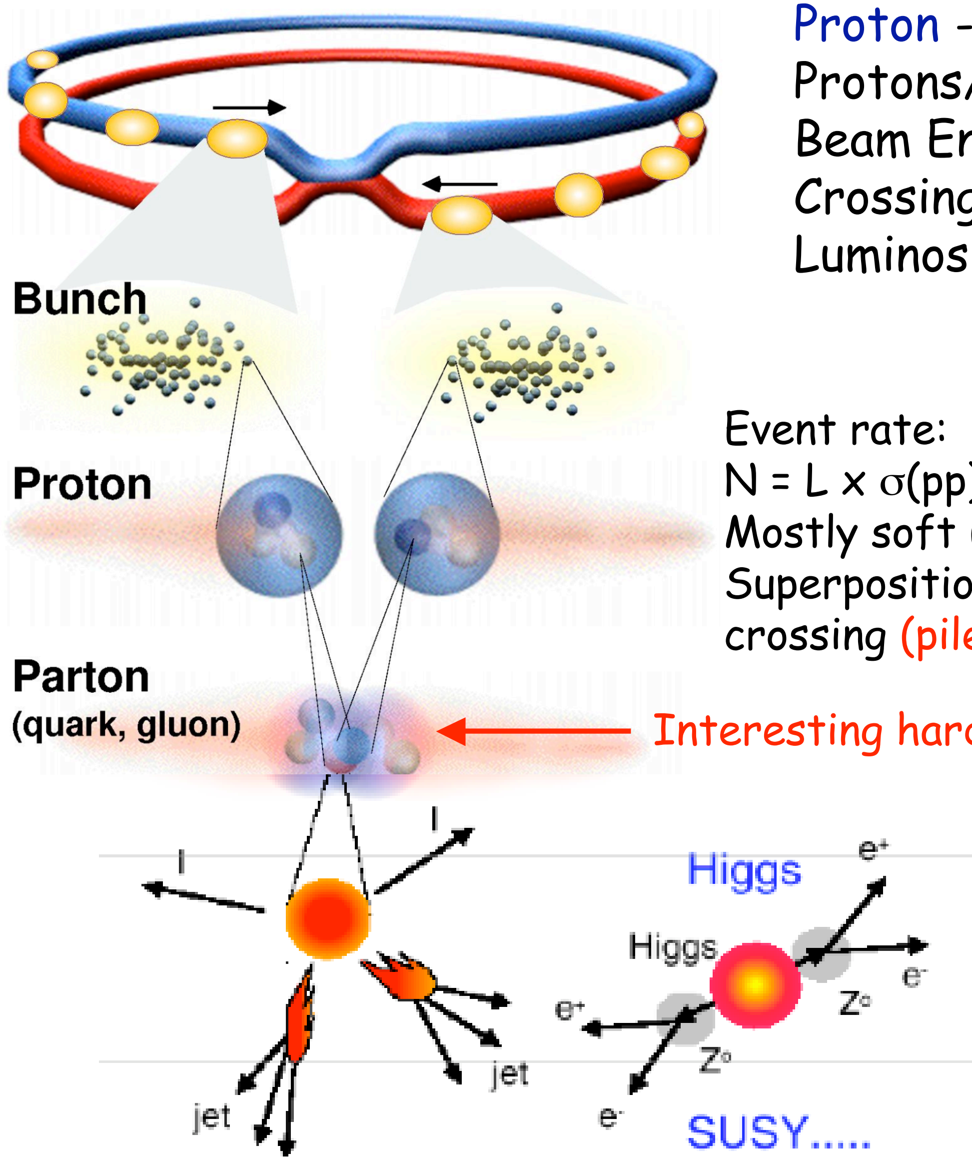
A scientific and technical challenge well beyond previous particle physics experiments

- A large scientific collaboration effort (37 nations)

- A project which started beginning of the 90's and will be collecting data until ~ 2020.

A lot of new physics for the next 12 years to come!

What is needed for the TeV physics?



Proton - Proton
Protons/bunch 10^{11}
Beam Energy 7 TeV
Crossing rate 40 MHz
Luminosity 10^{34} $cm^{-2}s^{-1}$

Event rate:
$N = L \times \sigma(pp) \approx 10^{9}$ interactions/s
Mostly soft (low $p_{\perp}$) events
Superposition of 23 pp interactions per bunch crossing (pile-up)

Interesting hard (high $p_{\perp}$) events are rare

Selection of 1 in
10,000,000,000,000 events

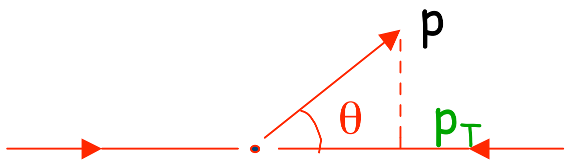
Very powerful detectors needed!

What is needed for the TeV physics?

Important variables used in the analysis of pp collisions

Transverse momentum

In the plane perpendicular to the beam

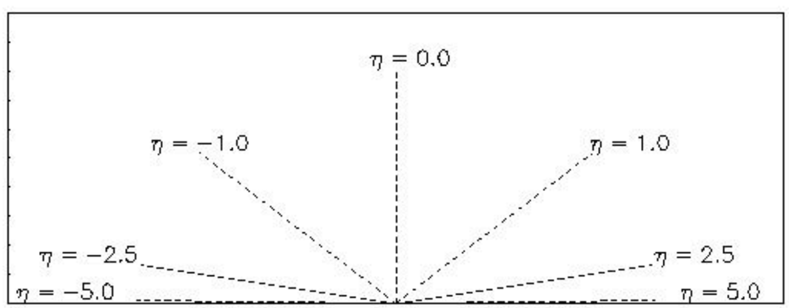


$p_T = p \sin\theta$

- ☞ $d\sigma/dp_T dy$ is Lorentz-invariant
- ☞ $\eta = y$ for $m \sim 0$
- ☞ Physics is ~ constant versus η at fixed p_T

pseudorapidity

$\eta = -\ln \tan(\theta/2)$



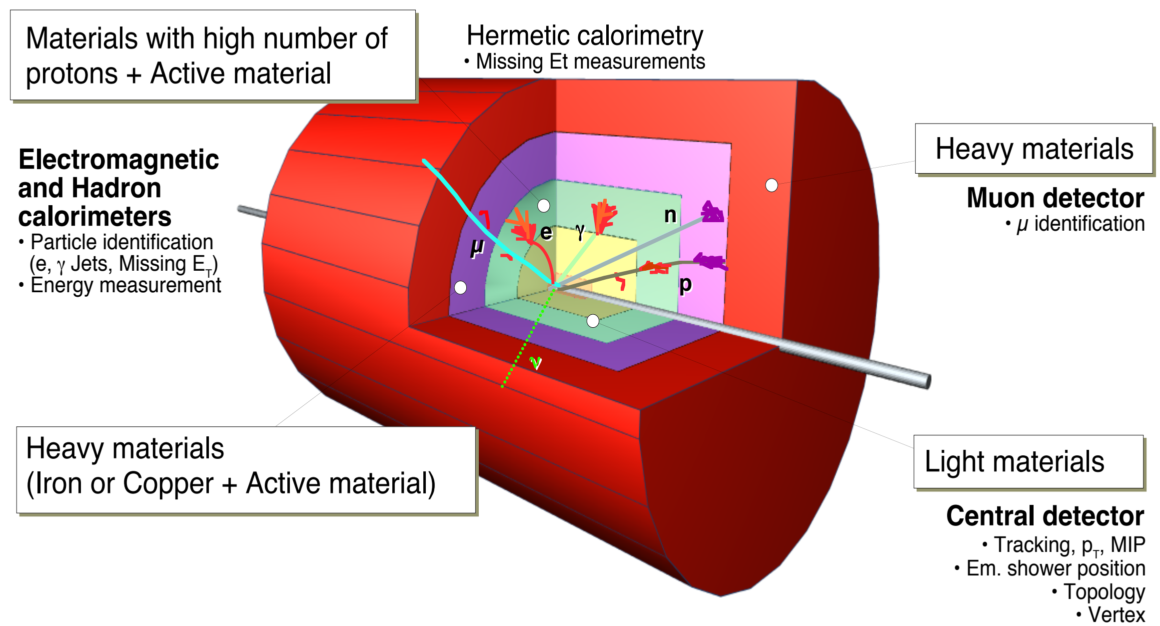
$\theta = 90^o \rightarrow \eta = 0$
$\theta = 10^o \rightarrow \eta \cong 2.4$
$\theta = 170^o \rightarrow \eta \cong -2.4$
$\theta = 1^o \rightarrow \eta \cong 5.0$

What is needed for the TeV physics?

Features required by the detector:

- Survive 10 years of operation
→ radiation hardness
- Provide precise timing and have fast response
25 ns is the time interval
- Excellent spacial resolution
to minimize pile-up effects
- Identify extremely rare events, mostly in real time
  - σ_{signal} as low as 10^{-14} σ_{tot}
  - Online rejection: 10^7
- Detectors must measure and identify according to certain specifications driven by physics

Typical elements of a collider detector



Each layer identifies and enables the measurement of the momentum or energy of the particles produced in a collision

- Tracking and vertexing (ttH, H→bb)
- em calorimetry (H→γγ, H→ZZ→eeee)
- Muon identification and measurement (H→ZZ→μμμμ)
- Missing transverse energy (SUSY, H→ττ)

The ATLAS as built detector

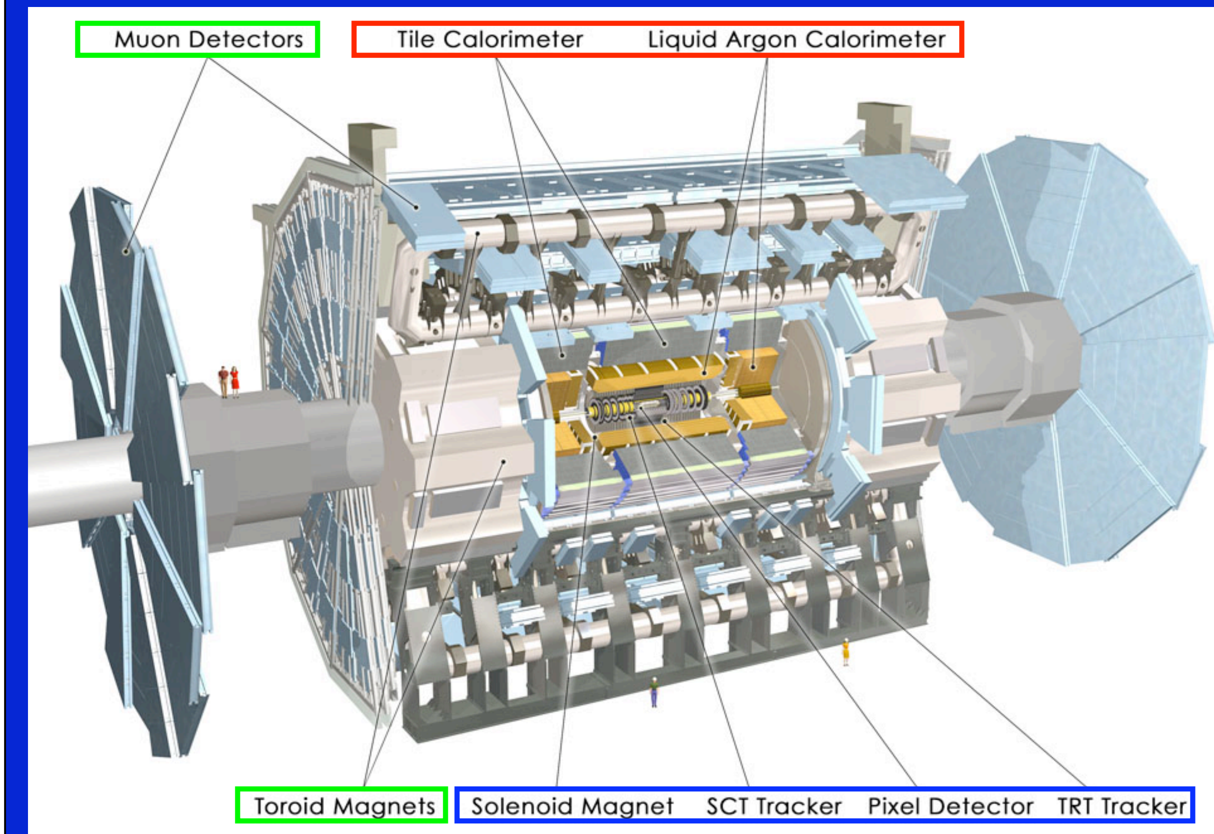
Size of the detector

- Weight: 7000 tons
- Diameter: 25 m
- Length: 26 m
- Volume: 20 000 m^3

Why so big?

Directly related to energies of particles produced:

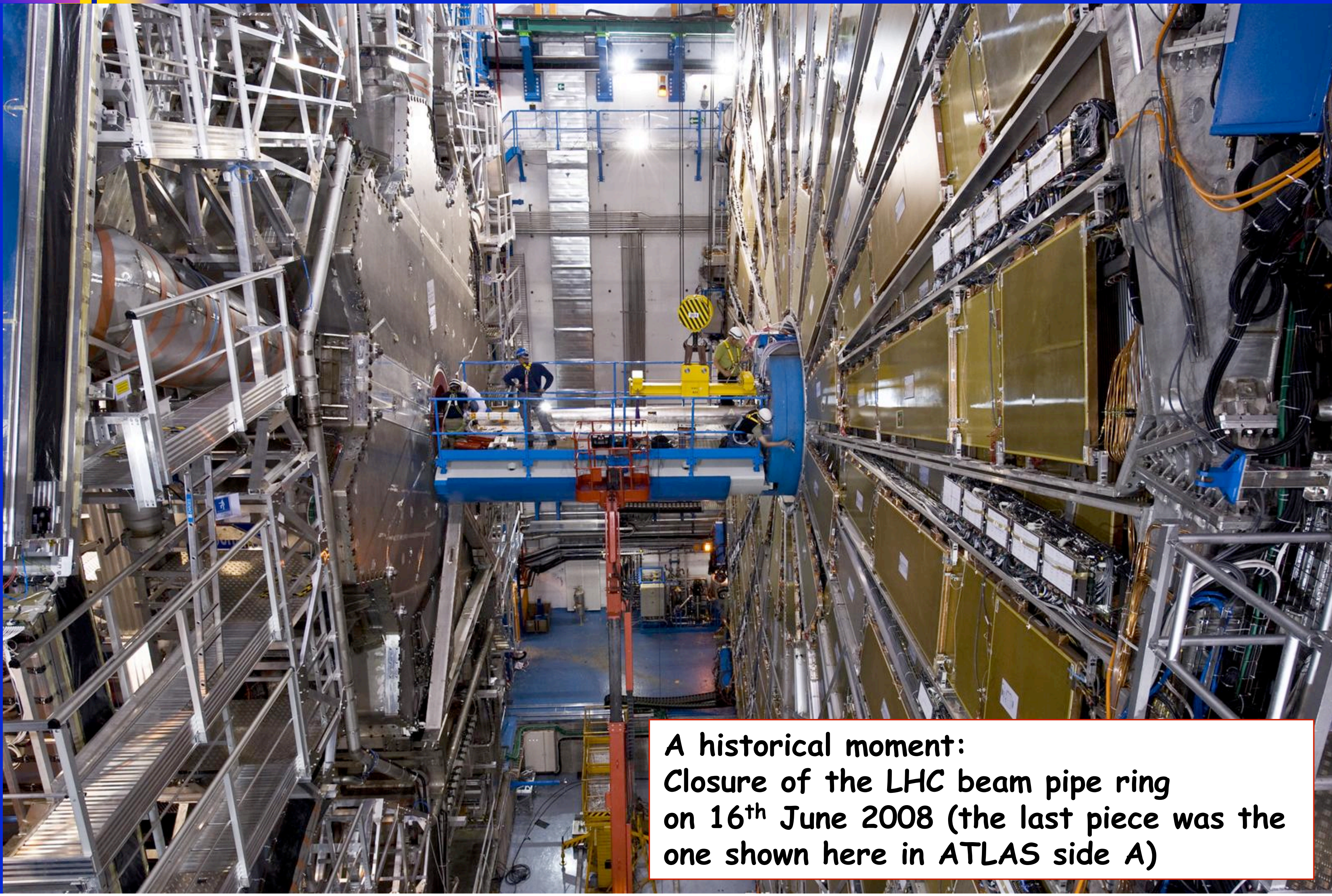
- Need to absorb E of 1 TeV electrones → 30 X_0 or 18 cm of Pb
- E of 1 TeV pions → 11 λ or 2 m Fe
- Need to measure momenta of 1 TeV muons outside calorimeters → BL^2 is key factor to optimise



More than 25 years from first conceptual studies (Lausanne 1984) to solid physics results!

ATLAS in 2003

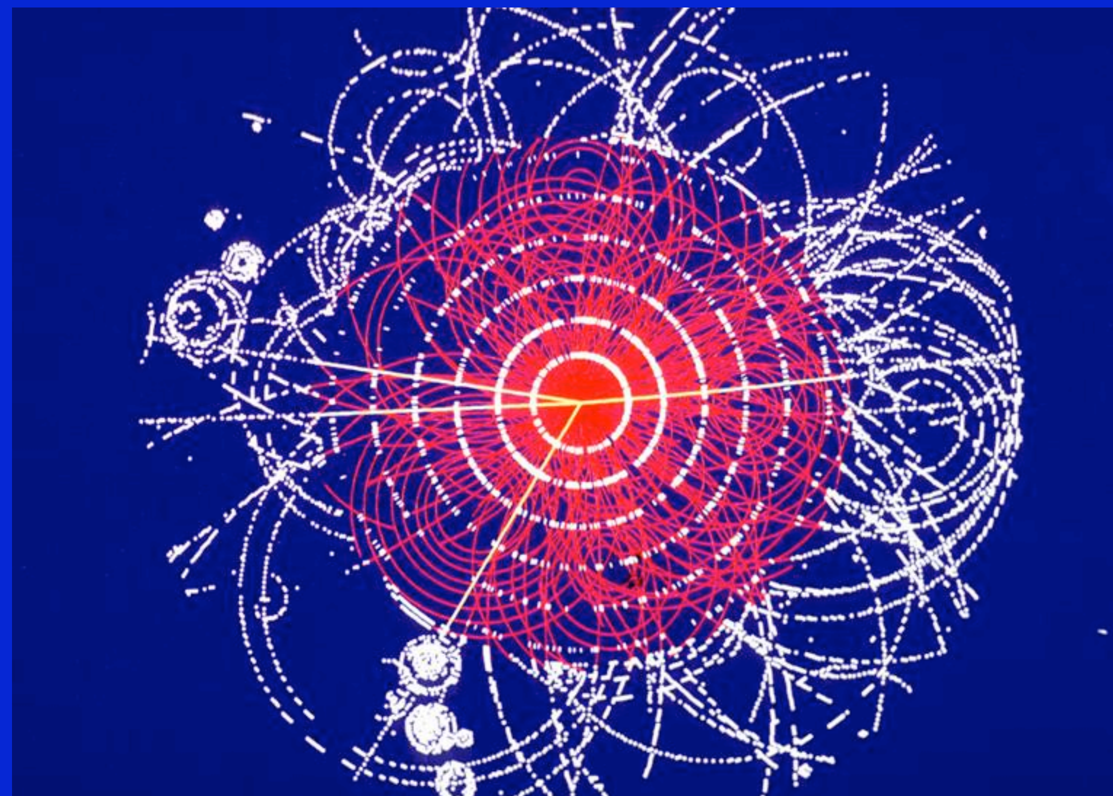
ATLAS after 5 years of construction



A historical moment:
Closure of the LHC beam pipe ring
on 16th June 2008 (the last piece was the one shown here in ATLAS side A)

Inner Detector

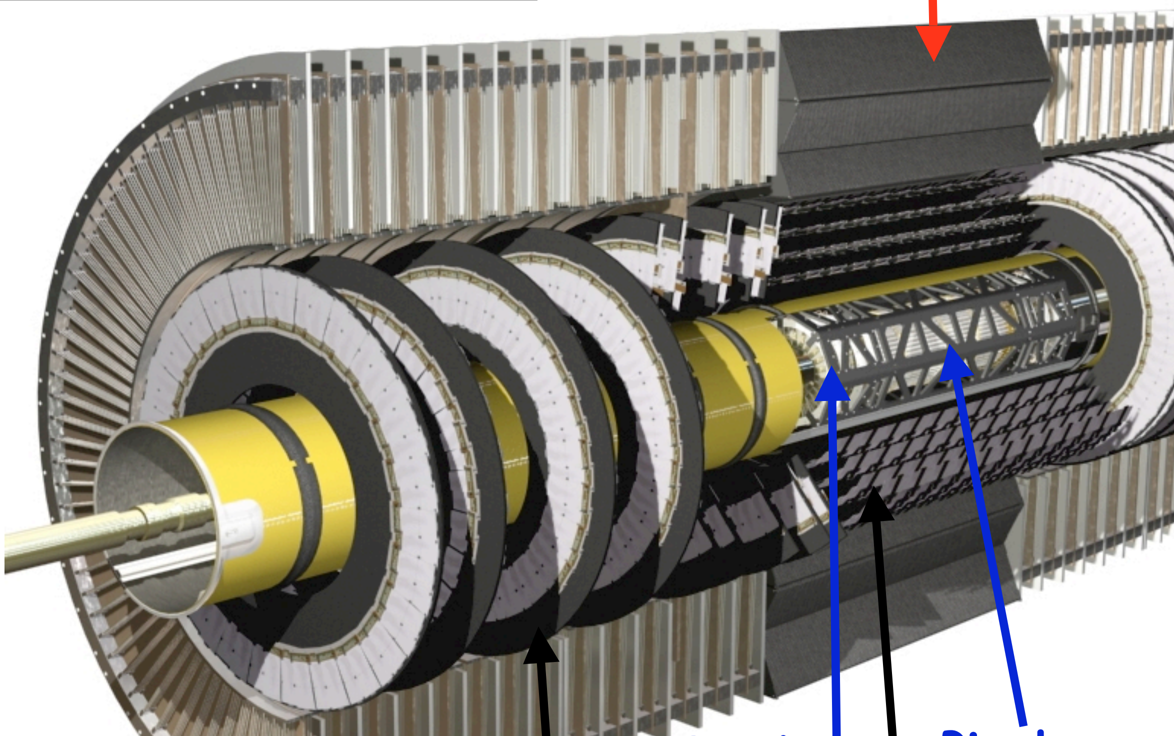
- ~1000 charged particles over $|\eta|<2.5$ produced at each beam crossing @ $10^{34}cm^{-2}\ s^{-1}$ → huge track density
- Some challenging requirements imposed by physics:
  - Measure leptons from decays of heavy gauge bosons
  - Tagging of b-quarks

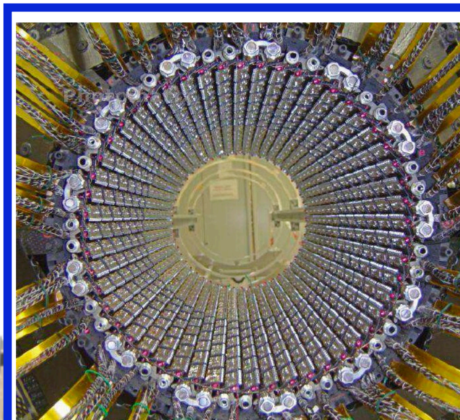


To achieve the momentum and vertex resolution requirements imposed by the benchmark physics processes, high-precision measurements must be made with fine detector granularity.

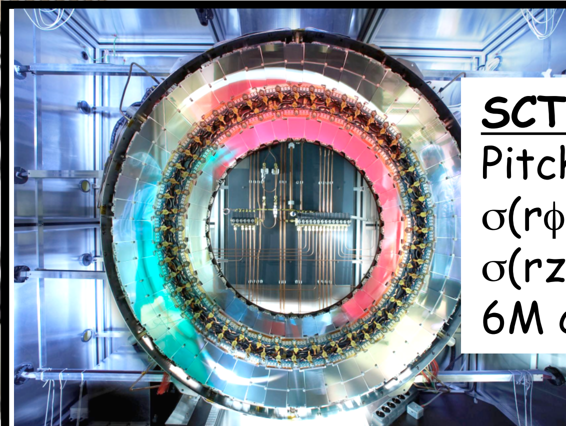
Inner Detector

R = 115 cm, L = 7 m
$|\eta|<2.5$
Solenoid B = 2 T

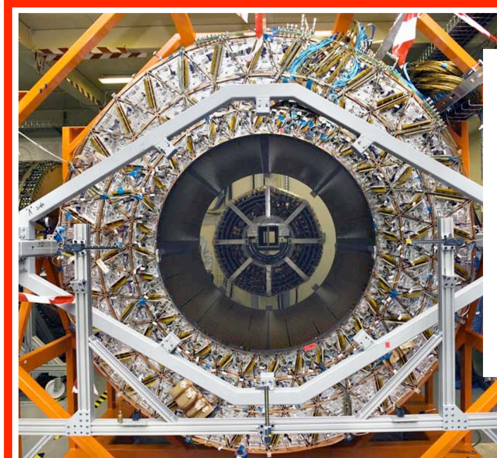




Pixels:
50x400 μm
$\sigma(r\phi)$=12 μm
$\sigma(rz)$=110 μm
80M channels



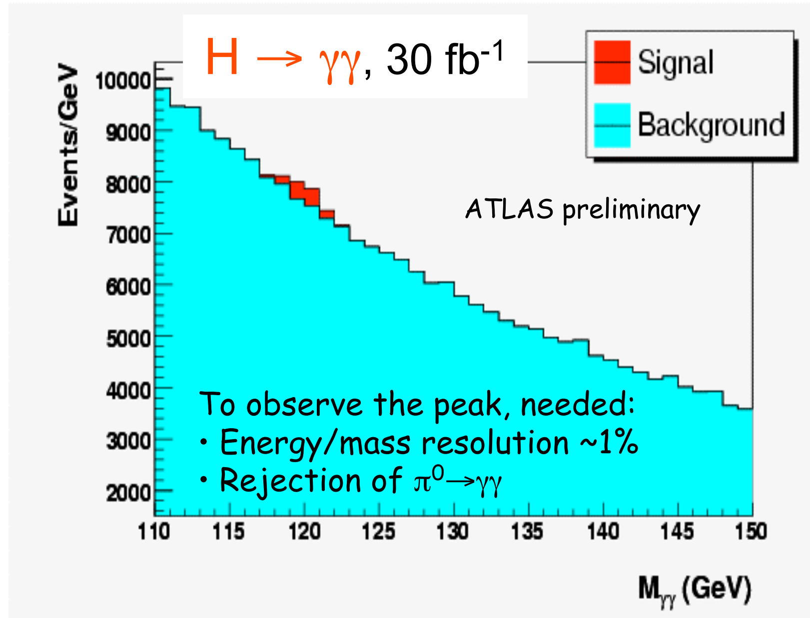
SCT:
Pitch: ~57-90μm
$\sigma(r\phi)$=16 μm
$\sigma(rz)$=580 μm
6M channels

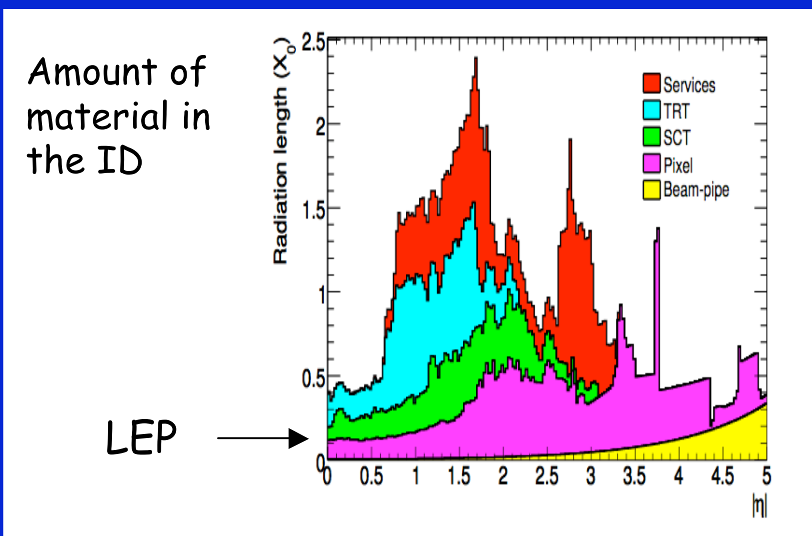


TRT:
Straw tubes:
d=4mm
Gas: $Xe:CO_2:O_2$
$\sigma(r\phi)$=130 μm
351K channels

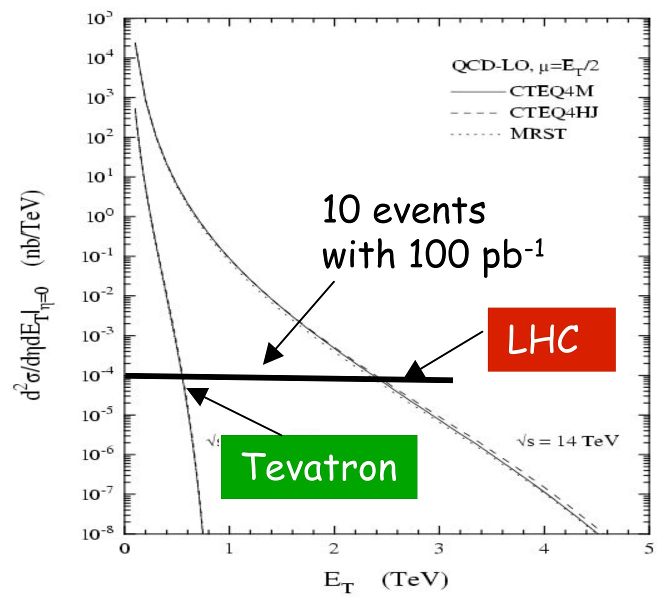
Calorimetry

- Need to trigger and measure γ, e and hadron energies by total absorption.
- Need to allow particle identification:
  - γ vs π^0, e, jets, γ conversions
- Efficient and accurate reconstruction of electrons and photons will be an unprecedented challenge at the LHC
  - e/QCD jets ~10^{-5} ~100 worse than @ Tevatron
  - Large amount of material in front of the EM Cal
- Good jet reconstruction and missing energy measurements



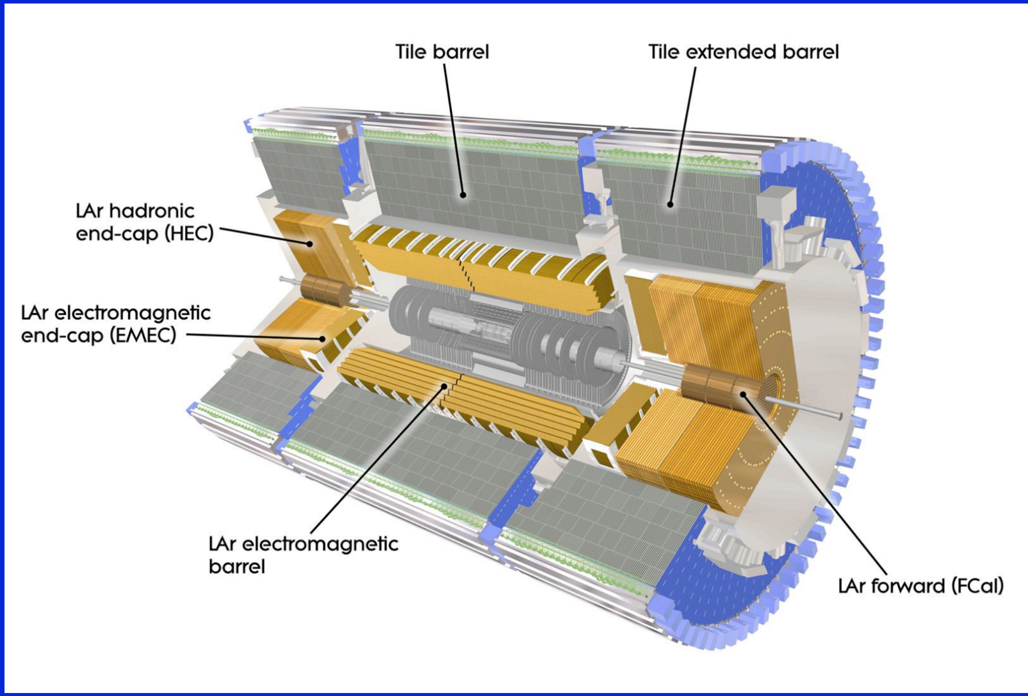


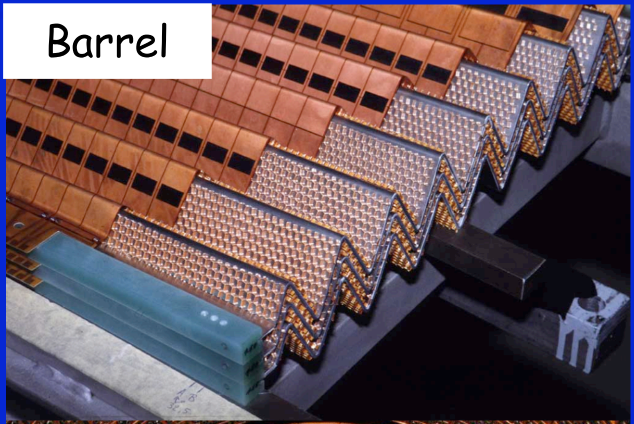
QCD Jet cross-sections

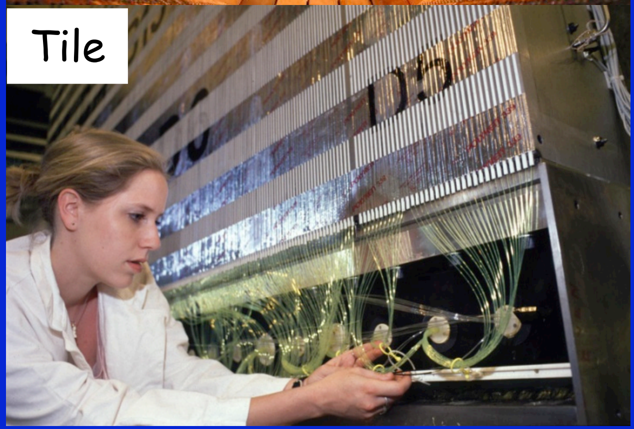


Will jump immediately into a new territory!

Calorimetry





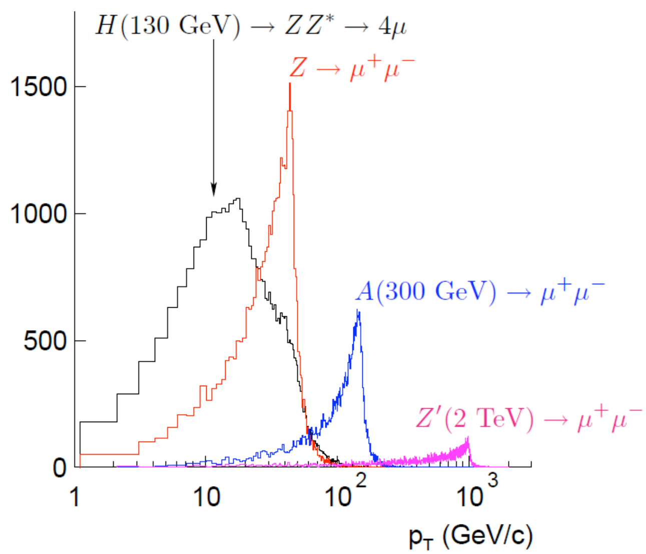


- Coverage: $|\eta|<4.9$
- Using different techniques and granularity
- Over the η covered by the ID, the fine granularity of the EM Cal is ideal for precision measurements of electrons and photons.
- Coarser granularity elsewhere, sufficient to satisfy the physics requirements for jet reconstruction and missing $E_{\perp}$ measurements

The muon spectrometer

- Muons are the only charged primary collision products traversing the calorimeters → clean signature of muonic final states

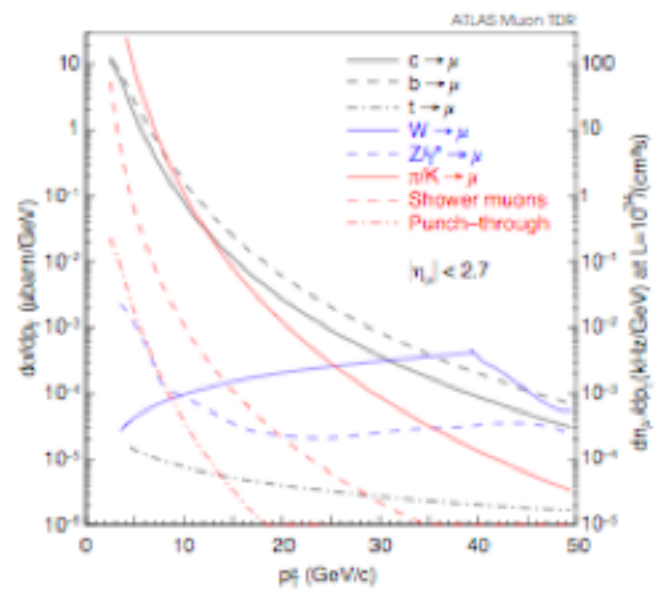
Example of physics processes with muonic final states



Muon Identification

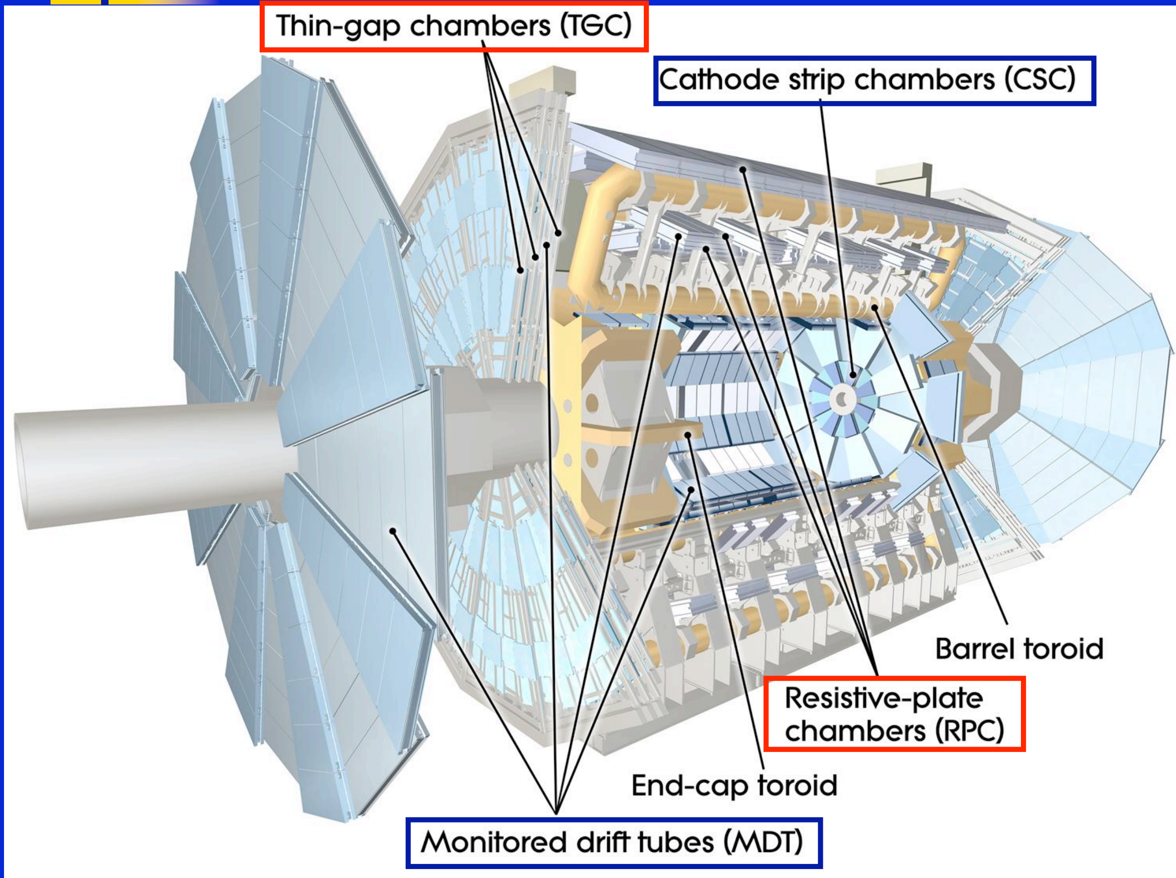
•Identification of "prompt" muons from c, b, t, W and Z/γ decays

• Rejection of muons from π/K decays, shower muons and hadronic punch through.



Clean and efficient muon identification and precise momentum measurement over a wide range of momentum and solid angle is crucial for physics @ LHC

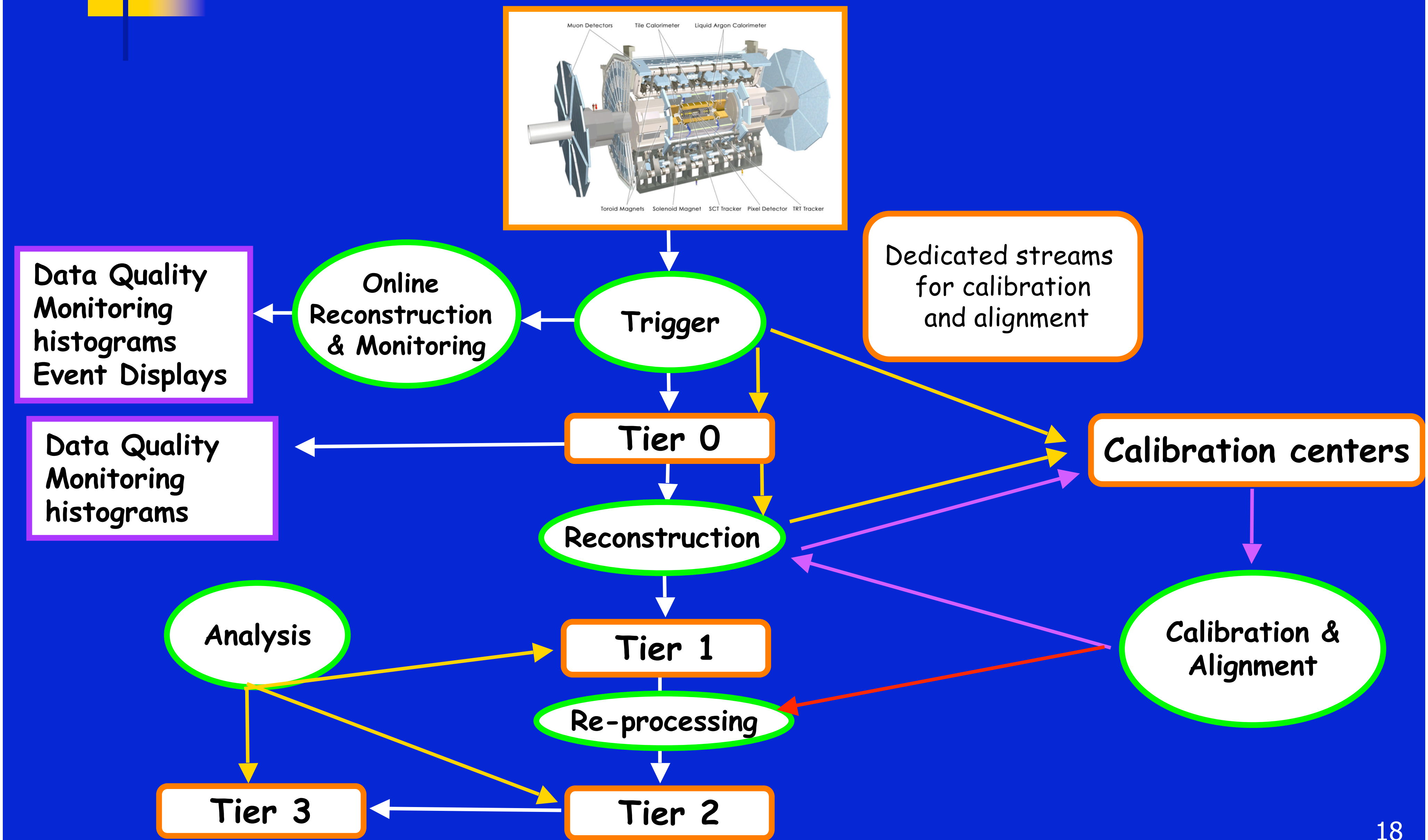
The muon system



- Air core toroid magnet (<B> = 0.4 T) to minimize multiple scattering
- 3 layers of precision tracking chambers (MDT, CSC) for precise momentum measurement (intrinsic spacial resolution ~ 100 μm)
- Fast trigger chambers for muon trigger (intrinsic spacial resolution ~1cm, timing resolution < 10 ns)
- Excellent standalone capabilities and large rapidity coverage: $|\eta| < 2.7$

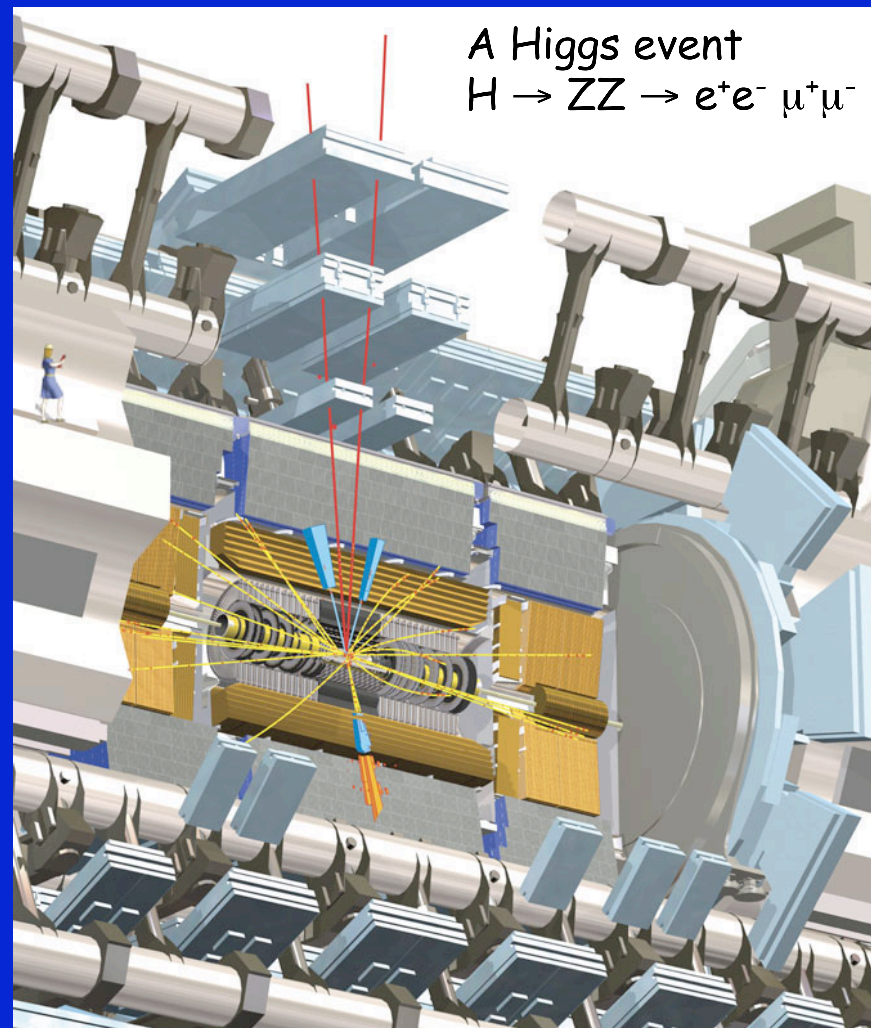
The complete operation chain

Overview of the operation chain



Trigger and data acquisition

- every 25ns: ~ 25 interactions superimpose = 1 event
- 1 event = ~1.5 MByte of data = ~1PB/sec if we store all events
- in every event the chance to find new physics ~ 10^{-11} , 10^{-12}
- today technology will allow us to store and manage on disk ~ 400 MB/sec



so, we need online data selection = trigger

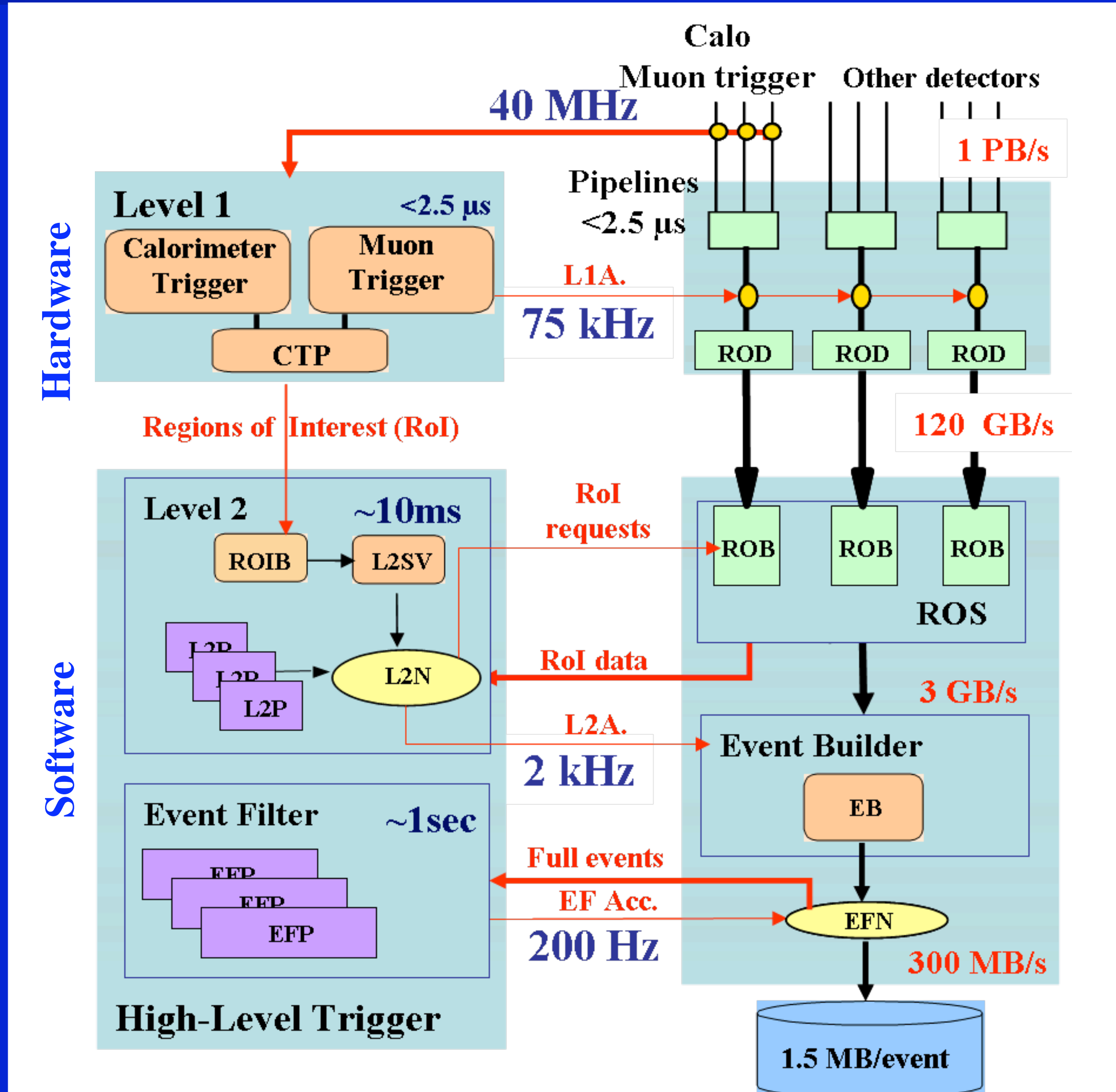
... very smart and fast triggers

Trigger and data acquisition

Level 1
- Based on data from calorimeters and trigger chambers
- synchronous 40 MHz

Level 2
Uses Regions of Interest identified by LVL1 (<10% event) with full granularity from all detectors

Level 3
Has access to full event and can perform more refined event reconstruction

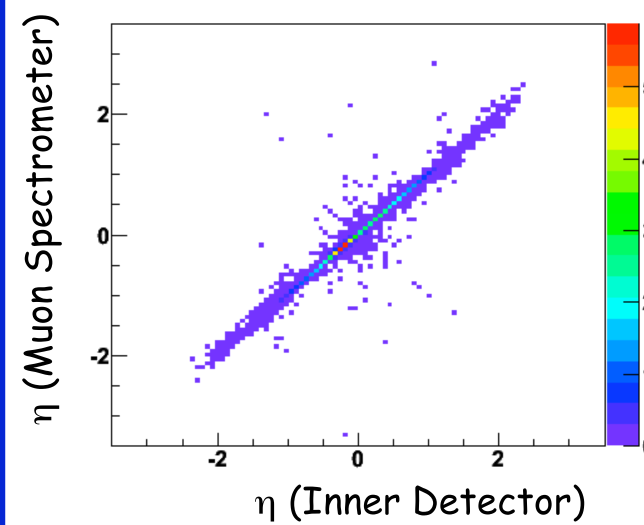


Reduces rate from 40 MHz to 200Hz while retaining the rare, interesting events
Provides streaming of data suited for different physics analysis or calibrations and alignment.

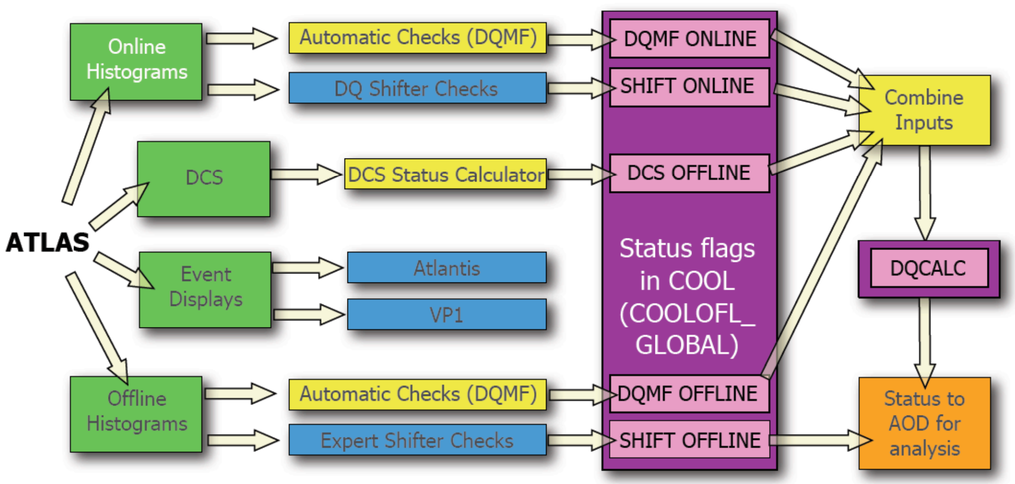
Data quality monitoring

- Essential to continuously check the quality of the data at different levels of the chain (online and offline)
- The results obtained have to be available when doing analysis

Monitoring histograms



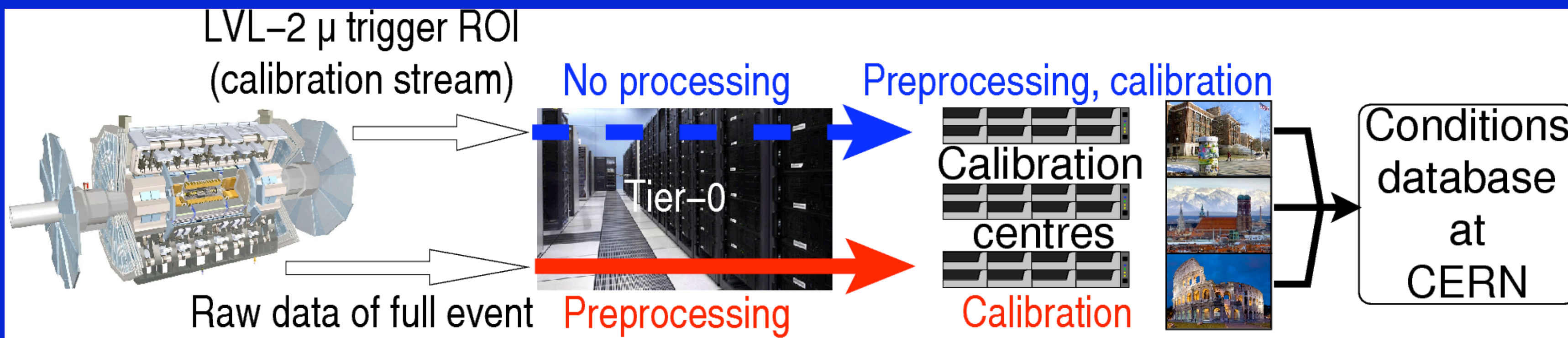
The ATLAS monitoring framework



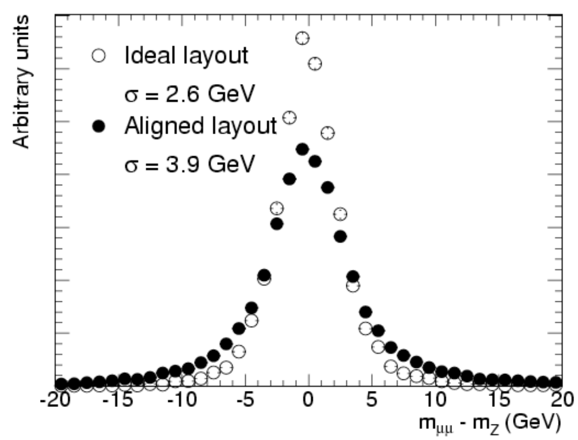

Event displays

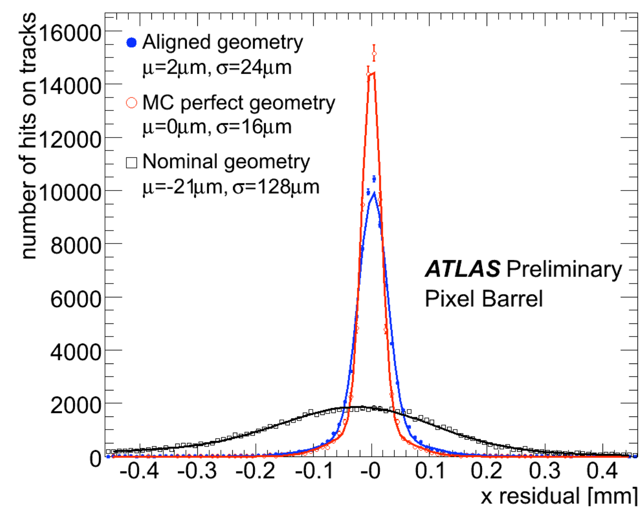
Calibration and alignment

- Calibration and alignment constants should be provided in 24 hours
- The required data (calibration streams) are copied to the different calibration centers around the world and the results obtained are sent back to CERN to be used in the bulk processing at Tier0



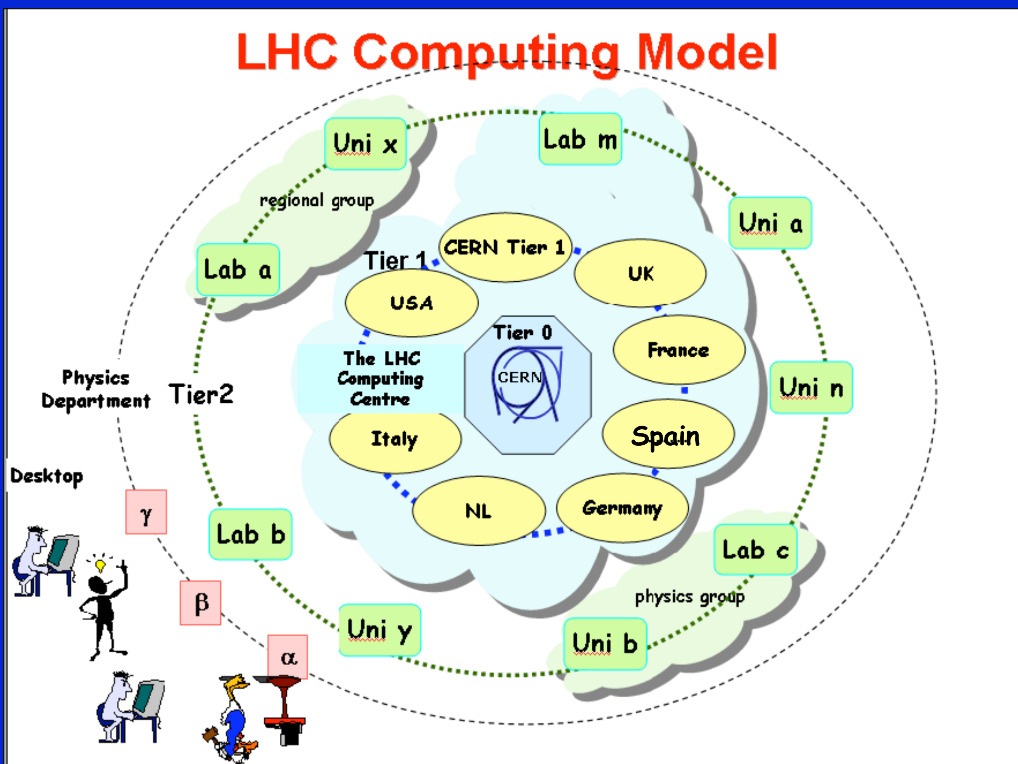
Example: Alignment of the Inner Detector





Offline reconstruction & analysis

- The amount of data to be processed will be huge (a stack of floppy disks of 2,400 Km per year)
- Compute power equivalent to 50,000 today's PCs would be needed to process these data → worldwide LHC computing GRID used (already covered by I.González)



Tier-0 (CERN)
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (11 centers)
- Permanent storage
- Re-processing
- Analysis

Tier-2 (~130 centers)
- Simulation
- End-user analysis

What is actually being run in all these computers centers?

Reconstruction:
from raw data to
physics analysis input objects

How to get physics out of the raw data?

RAW DATA

```
0x01e84c10:    0x01e8 0x8848 0x01e8 0x83d8 0x6c73 0x6f72 0x7400 0x0000
0x01e84c20:    0x0000 0x0019 0x0000 0x0000 0x01e8 0x4d08 0x01e8 0x5b7c
0x01e84c30:    0x01e8 0x87e8 0x01e8 0x8458 0x7061 0x636b 0x6167 0x6500
0x01e84c40:    0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c50:    0x01e8 0x8788 0x01e8 0x8498 0x7072 0x6f63 0x0000 0x0000
…..
```

With the first LHC data, the first task will be to get well reconstructed physics analysis input objects → Let's focus on this first step

Reconstruction

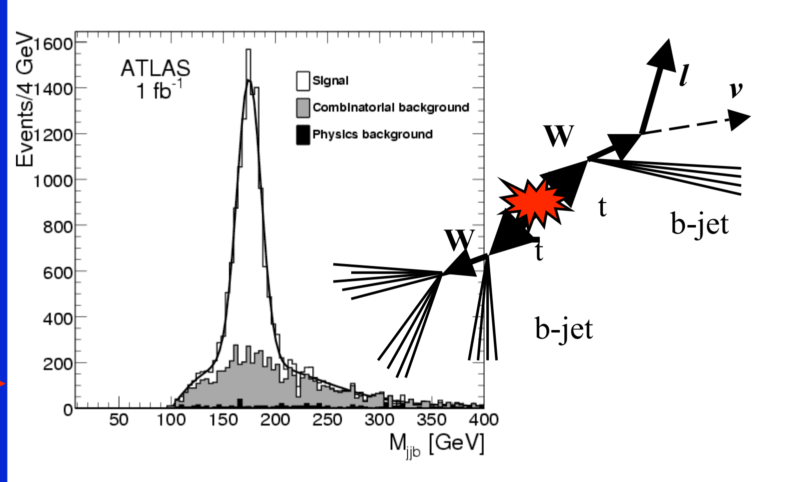
Actually, the first step of analysis
Common algorithms are used here
Calibrations & alignment is crucial

Physics analysis input objects:
Electrons, photons, muons, taus, jets, $E_{\perp miss}$

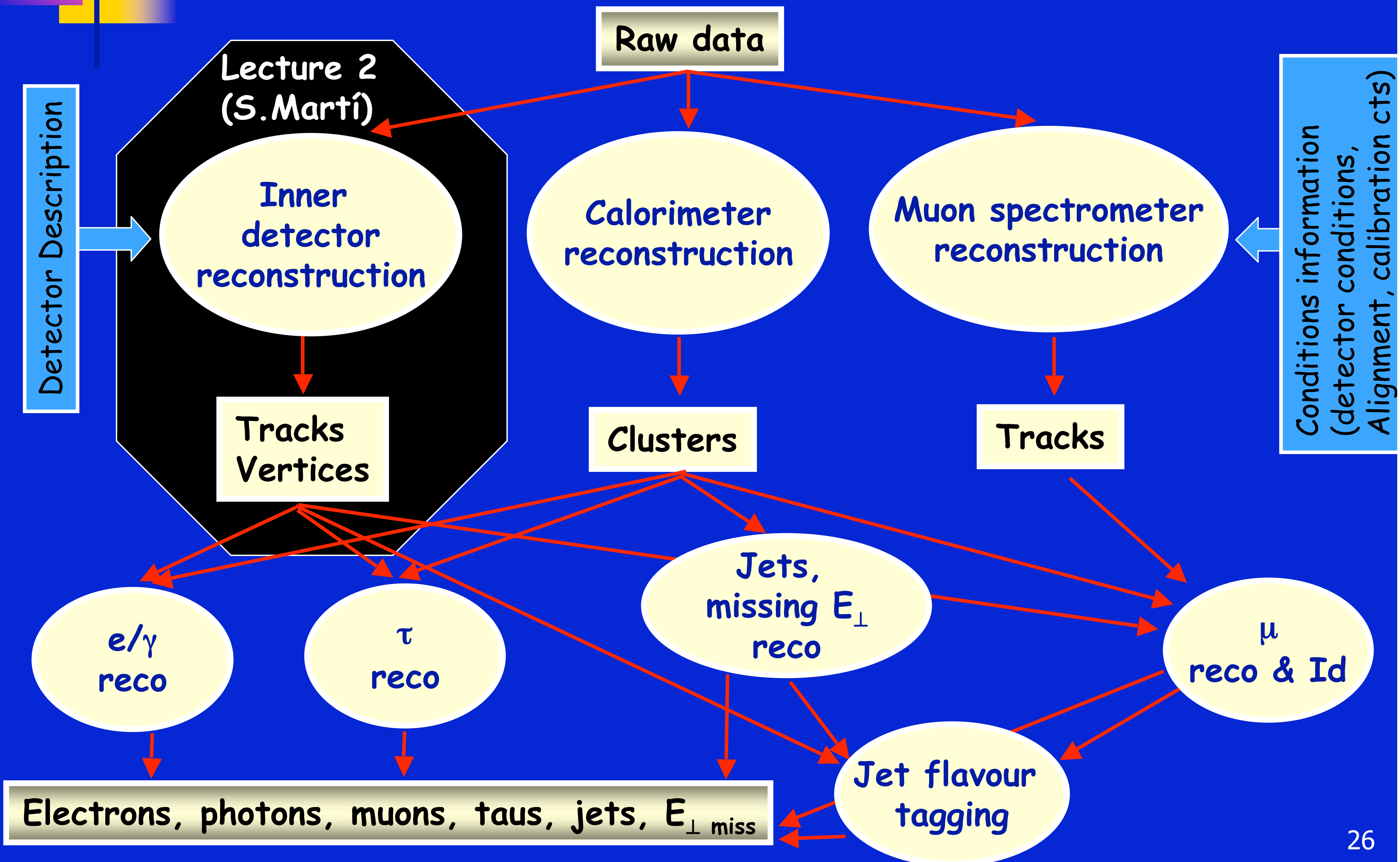
Individual, Provides feedback to the reconstruction as well

Analysis

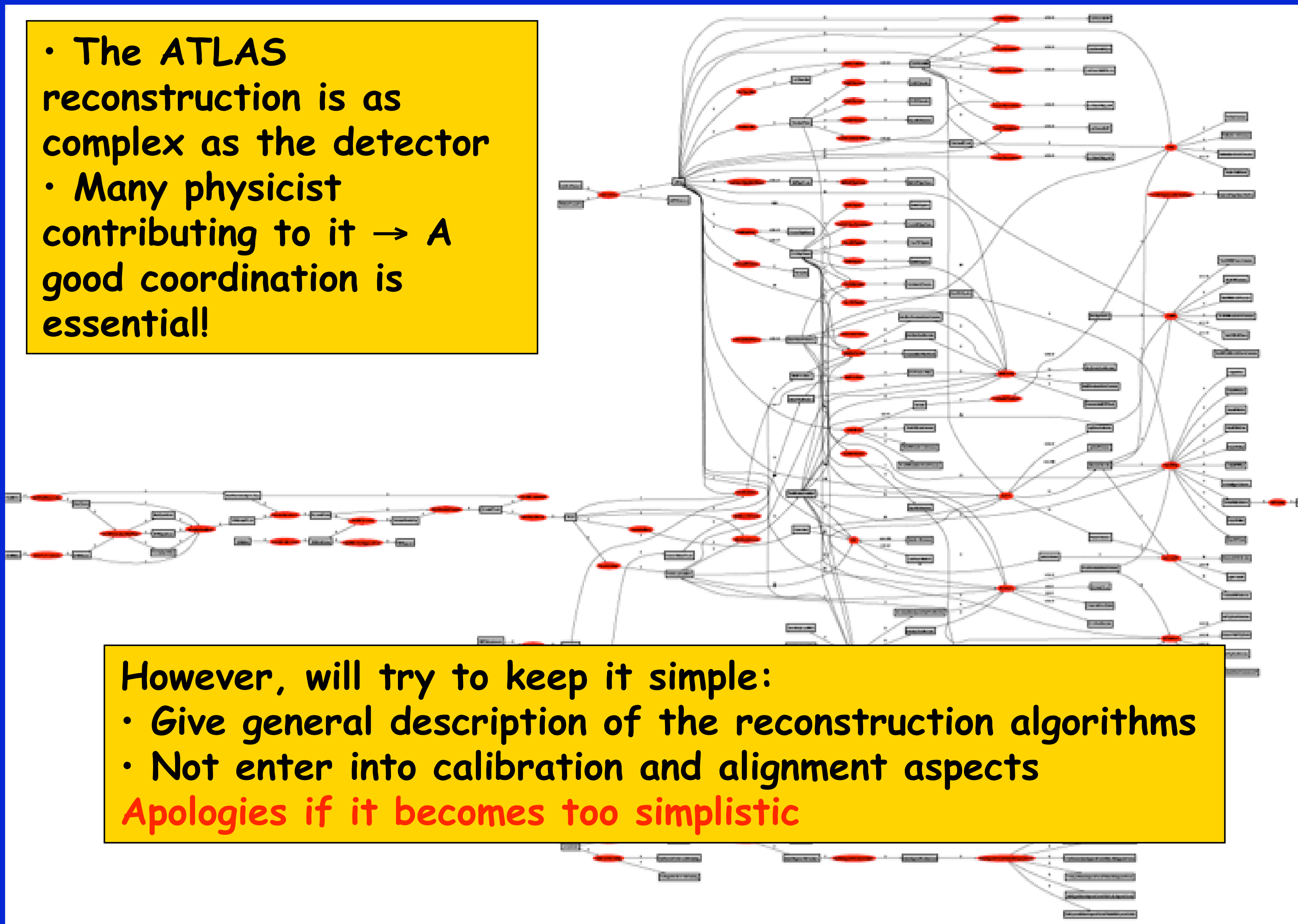
Physics results



Simplified view of the reconstruction chain



A more complicated view



- The ATLAS reconstruction is as complex as the detector
- Many physicist contributing to it → A good coordination is essential!

However, will try to keep it simple:

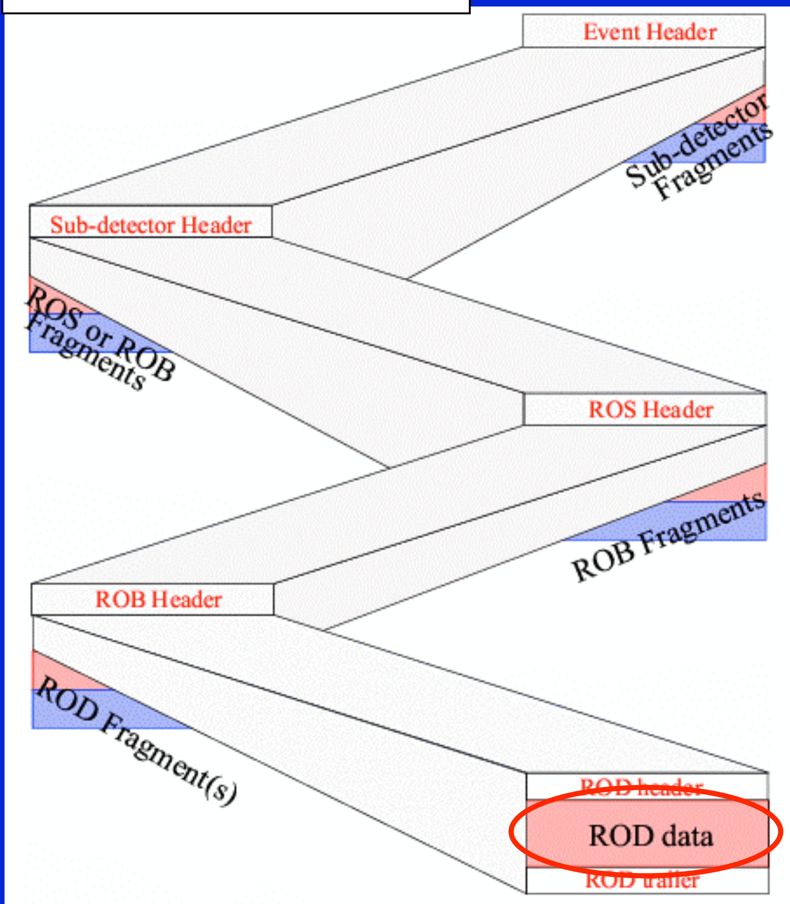
- Give general description of the reconstruction algorithms
- Not enter into calibration and alignment aspects

Apologies if it becomes too simplistic

Commonalities for all sub-systems

- The very first step of the reconstruction is to decode the raw data written out by the detectors

ATLAS Event Format



Byte Stream Converters

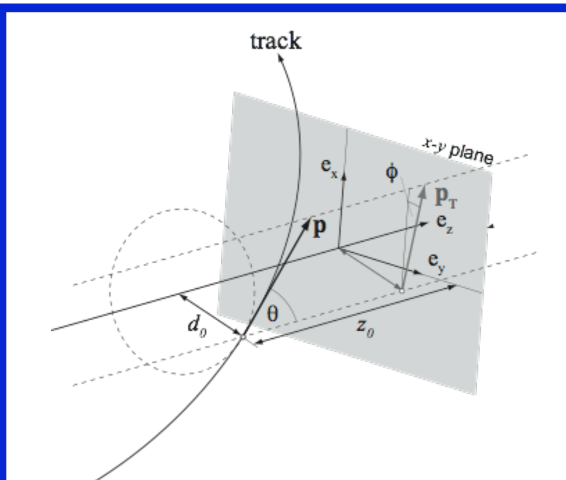
- Detector element identifier (e.g. a given strip in a SCT module)
- Measurement in that element (e.g. if the strip has fired, if there are errors, etc)

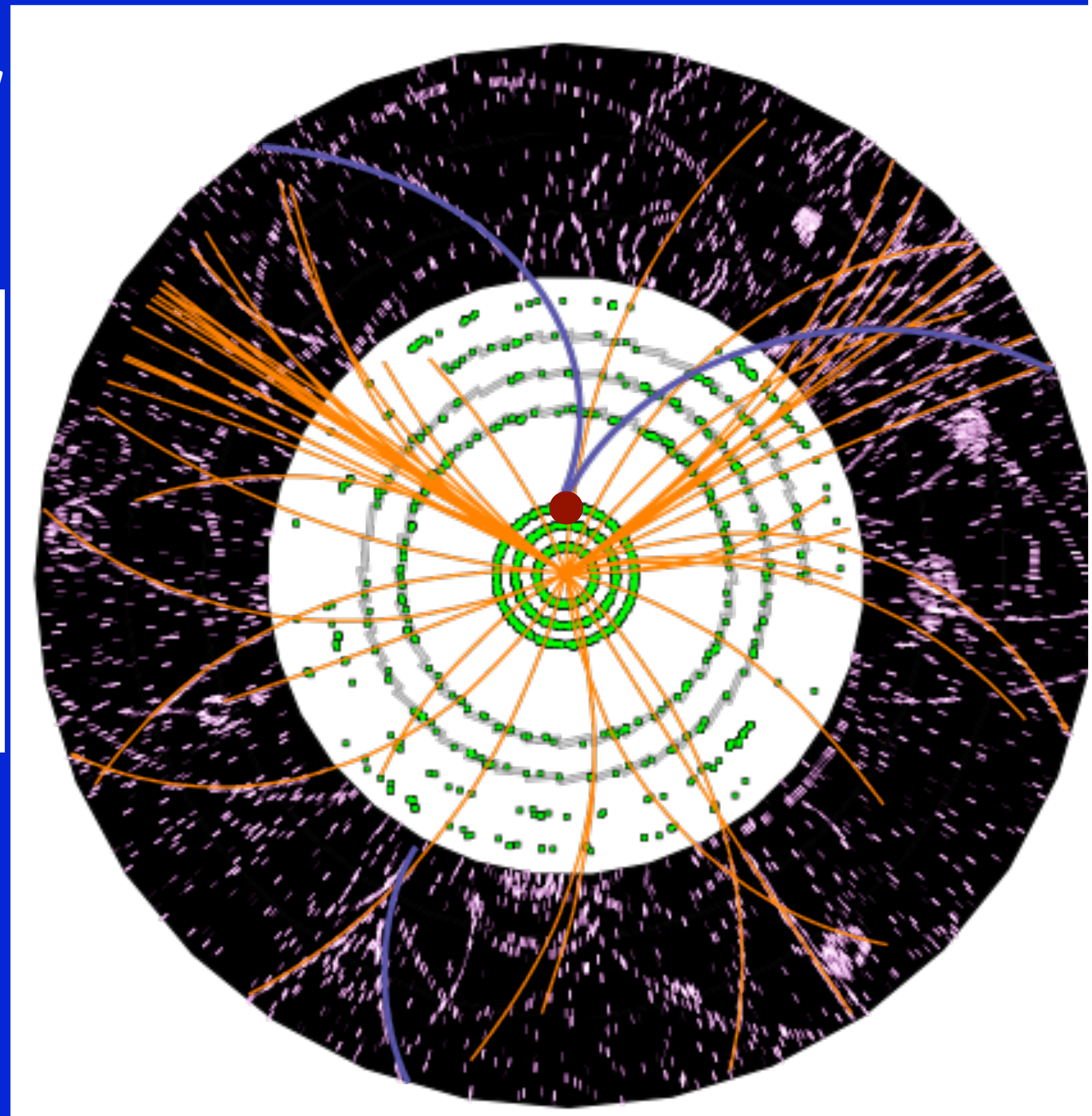
Correct cabling maps are needed to get it right, i.e.:
Where is the readout channel X?

ID and MS reconstruction

- Will be covered in detailed tomorrow by S. Martí focusing on the inner detector but similar techniques are used for the muon spectrometer.

• A trajectory of a charged particle in a magnetic field can be parametrized through 5 parameters (at any point).
•Track parameters @ perigee (point of closest approach to the z-axis): $(\phi_0,\theta_0,d_0,z_0,q/p)$
• For the tracks reconstructed in the muon spectrometer → need to extrapolate through the calorimeters material !!!

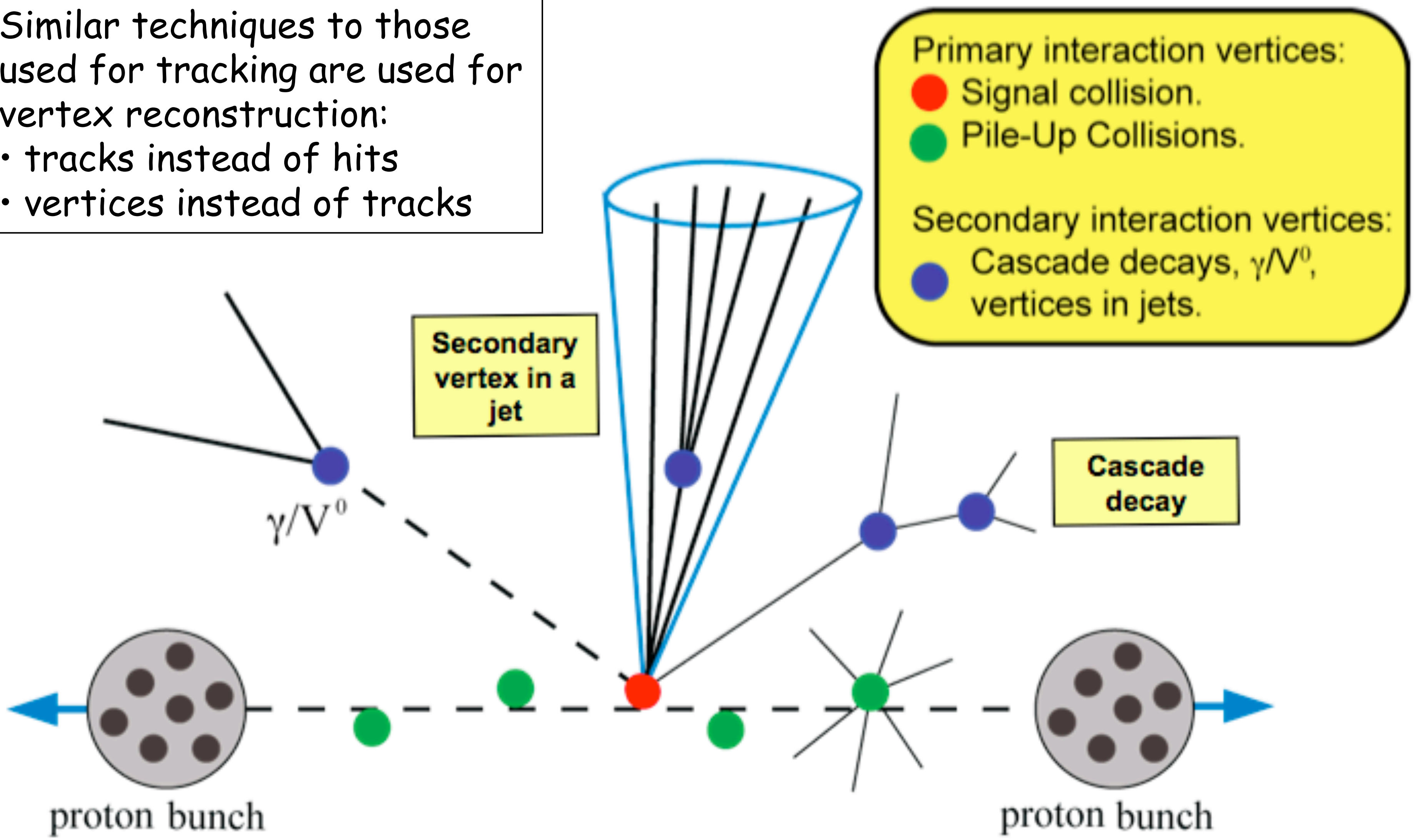




Vertexing in the Inner Detector

Similar techniques to those used for tracking are used for vertex reconstruction:

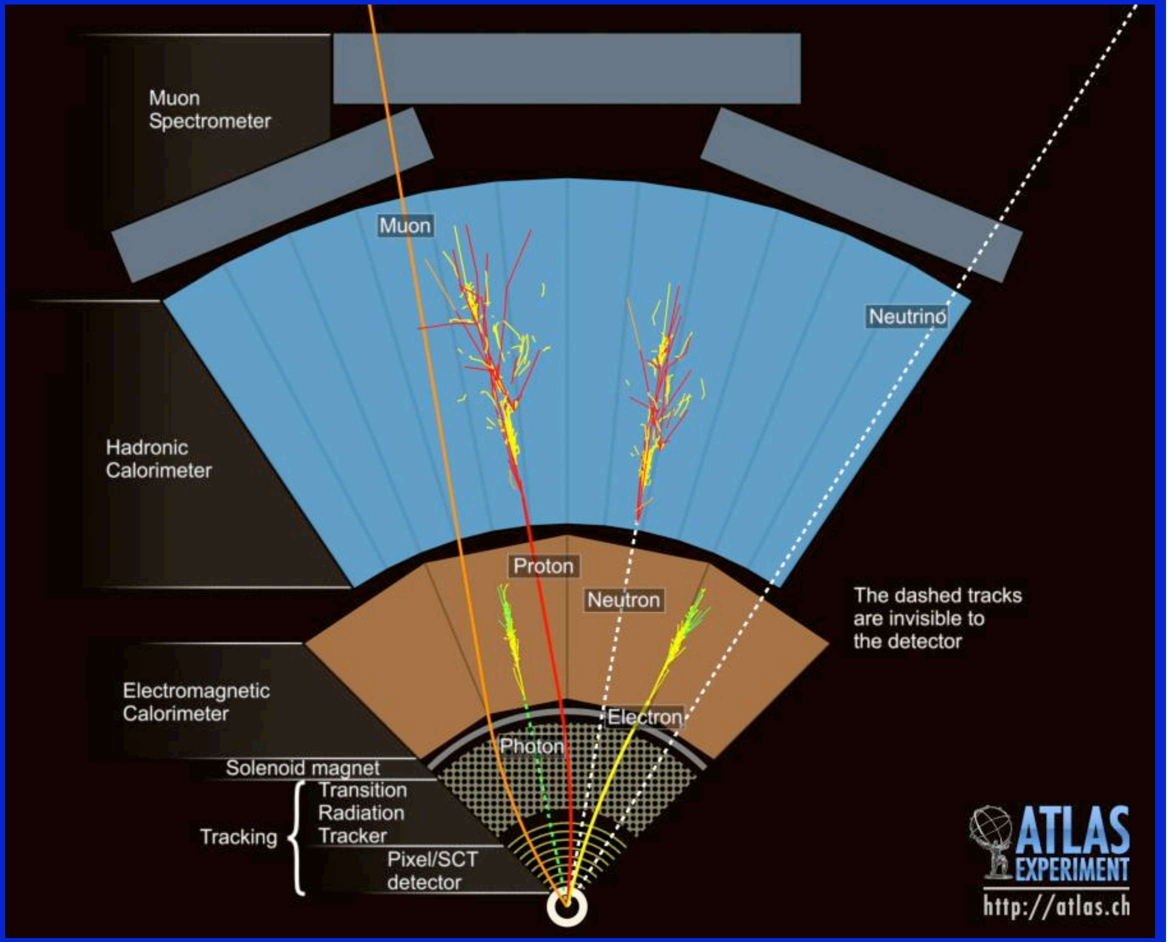
- tracks instead of hits
- vertices instead of tracks



Calorimeter reconstruction

What is the goal?

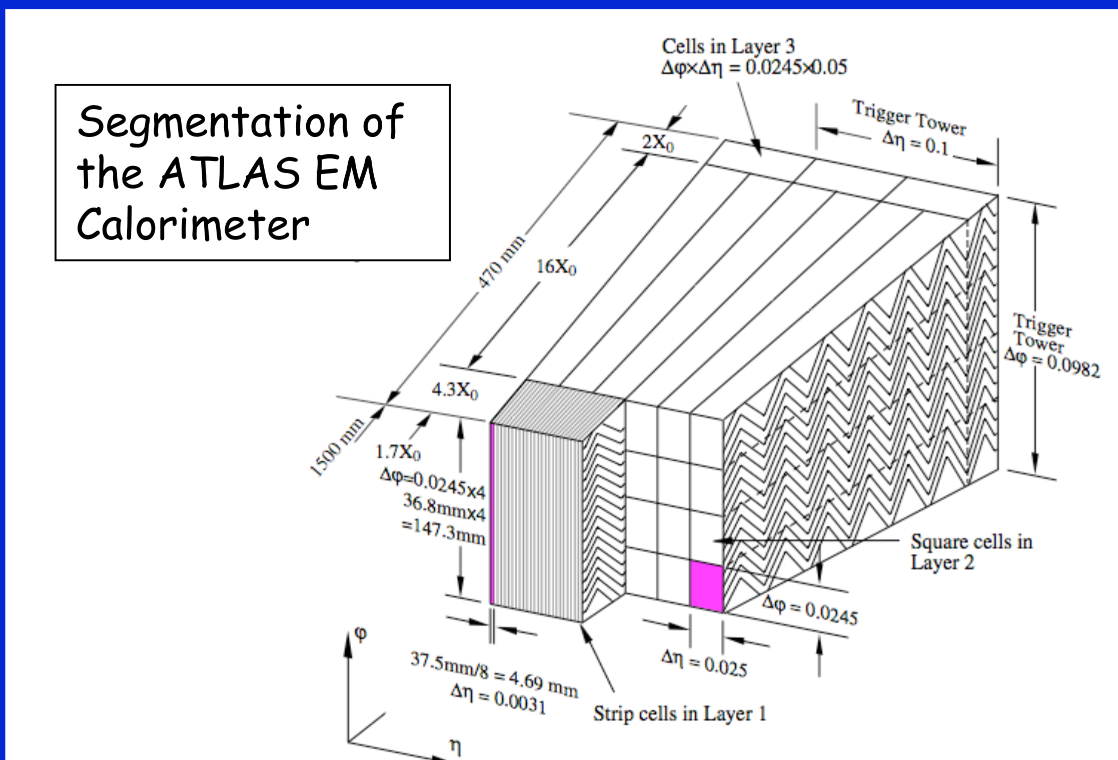
- Reconstruct energy deposited by charged and neutral particles
- Determine position of deposit, direction of incident particles
- Be insensitive to noise and un-wanted (un-correlated) energy
- And obtain best possible resolution!!



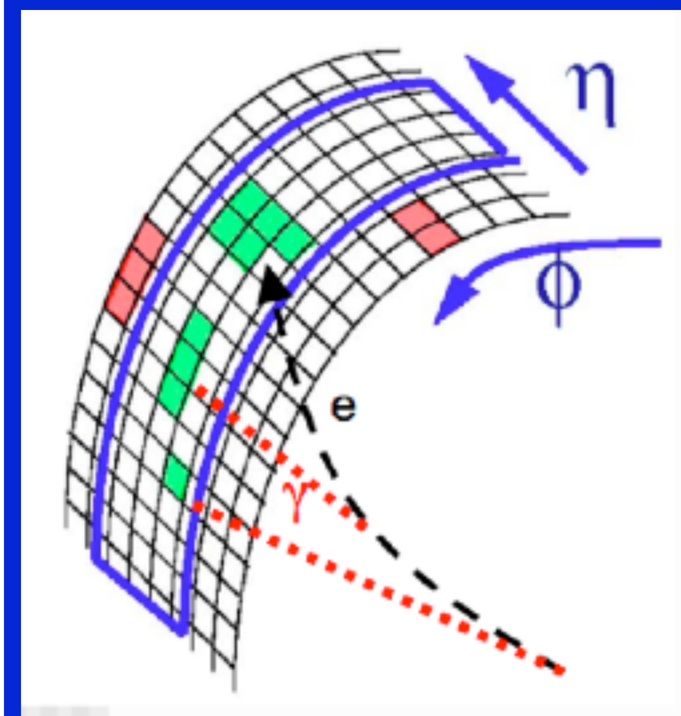
Calorimeter reconstruction

- 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 various cells

Task: identify these clusters and reconstruct the energy they contain

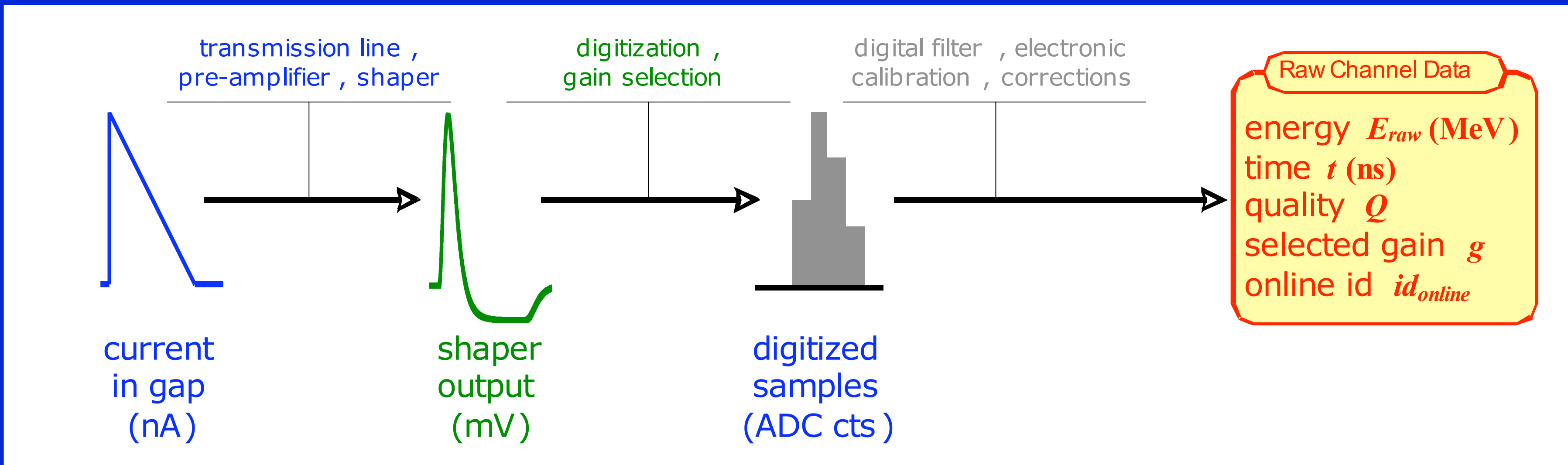


Segmentation of the ATLAS EM Calorimeter



Calorimeter reconstruction

- Ecell: The E in each cell is calculated online in the Readout Drivers (ROD) and some additional corrections are made offline.



- Clusterization: Group cells into clusters to find out the particle energy
  - Don't want to miss any cell, don't want to pick up fakes → tricky!
  - Different algorithms available in ATLAS for different purposes:
    - Electrons
    - Photons
    - Input for jet reconstruction

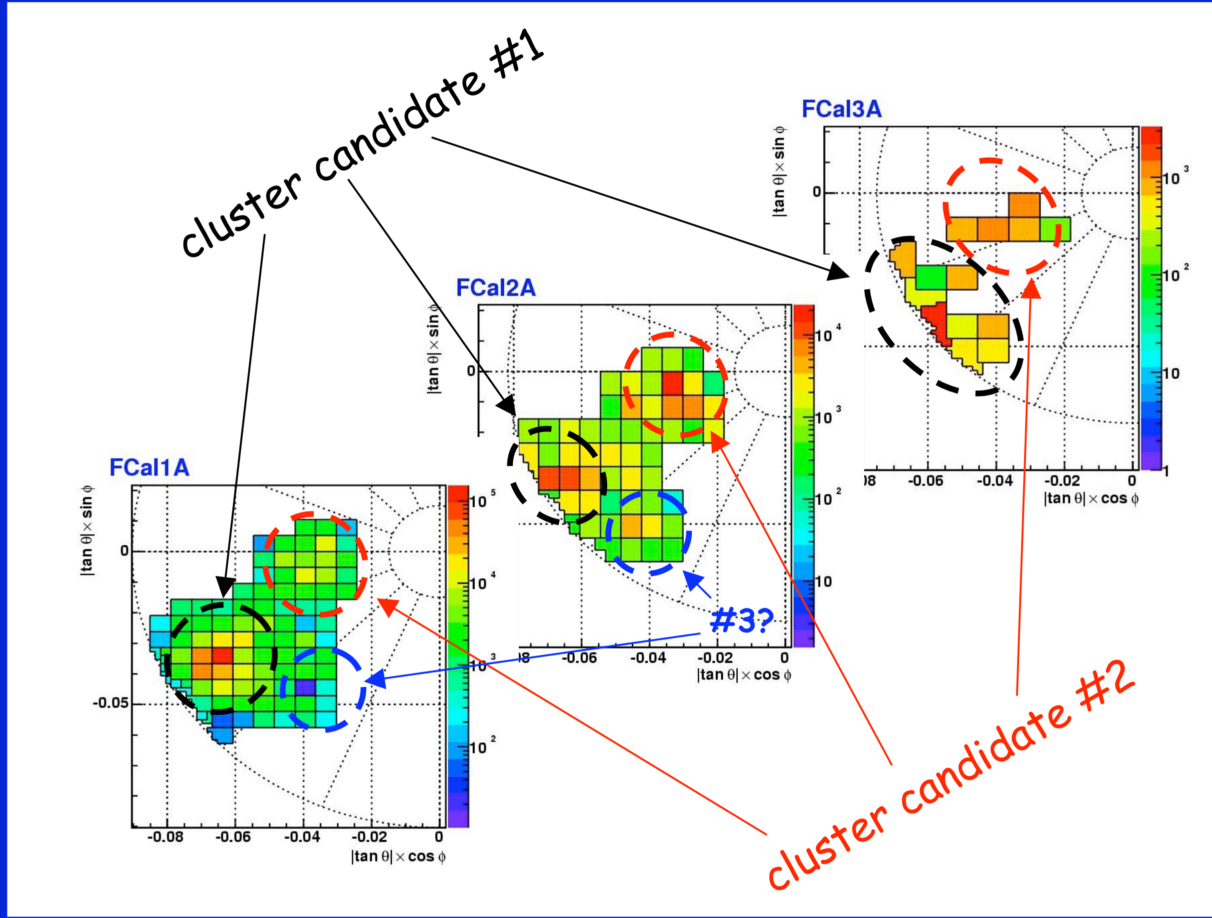
Calorimeter reconstruction

Example: Topological clusters

• Used as input for jet reconstruction.
•Attempt to reconstruct 3D energy blobs representing the showers developing for each particle entering the calorimeter

Method:

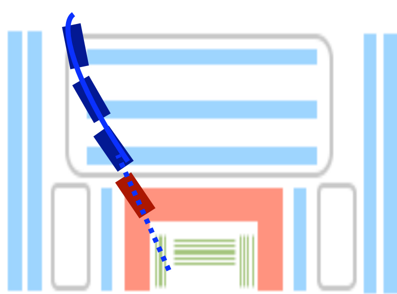
• Find seed with significant signal above primary seed threshold *S*
Significance = $|E_0|/\sigma_{noise} > S = 4$
• Collect all directly neighbouring cells (in 3-d)
• If neighbouring cells have signal above secondary seed *N*, collect neighbours of neighbours if their significance > *P*
• Analyze clusters for local signal maxima and split if more than one found



Muon reconstruction

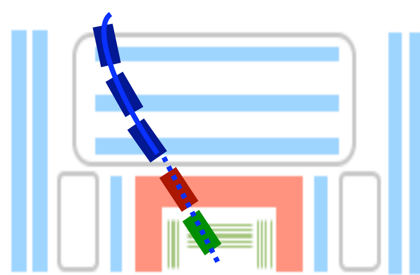
- Muons from 3 GeV up to 3 TeV are identified and measured with optimal acceptance and efficiency through a combination of 3 reconstruction strategies:

Standalone muons



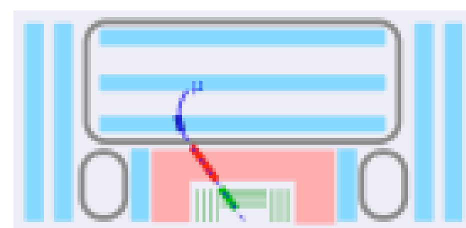
Muon track reconstruction based only on the Muon Spectrometer data
$|\eta|< 2.7$

Combined muons



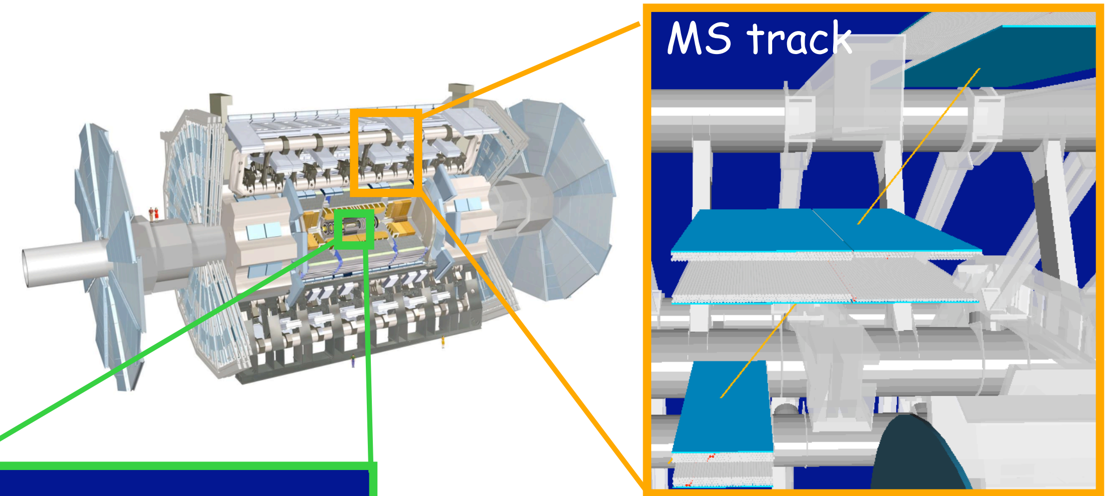
Combination of a muon spectrometer track with an inner detector track
$|\eta|< 2.5$

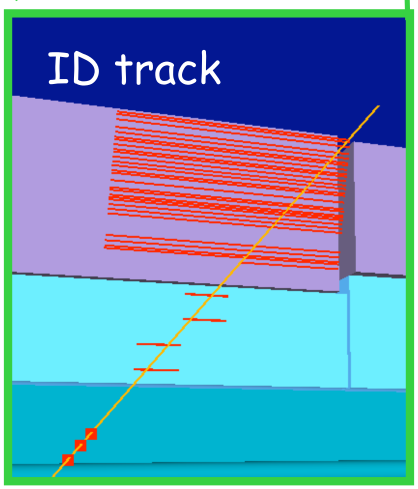
Tagged muons

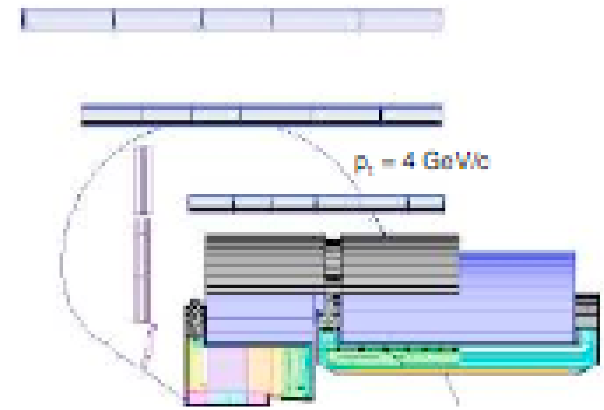


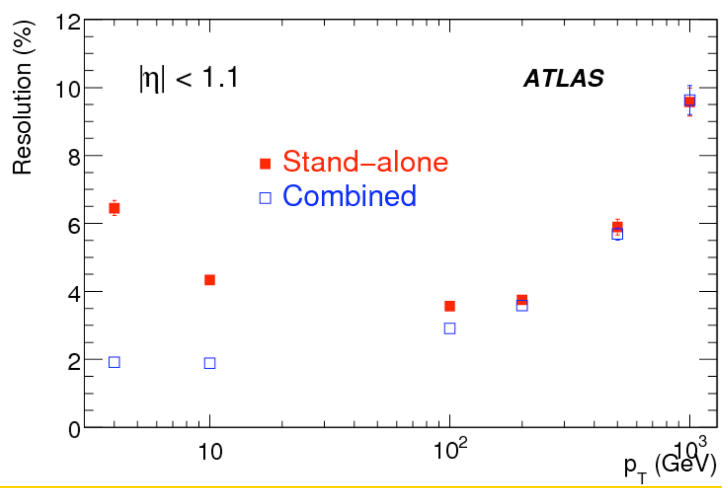
Combination of an inner detector track with a muon spectrometer segment
If no segments: can also be tagged using calorimeter E loss measurement

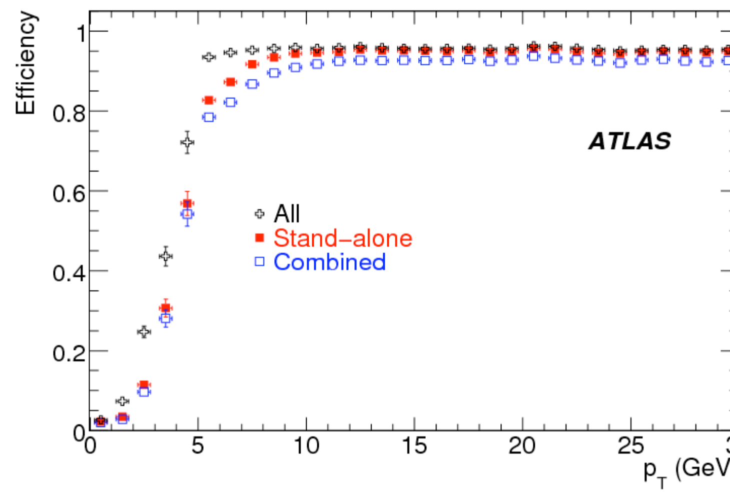
Muon combined reconstruction









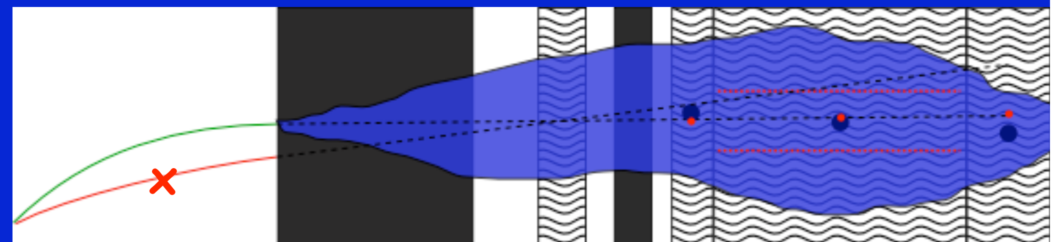


The combined reconstruction allows to:

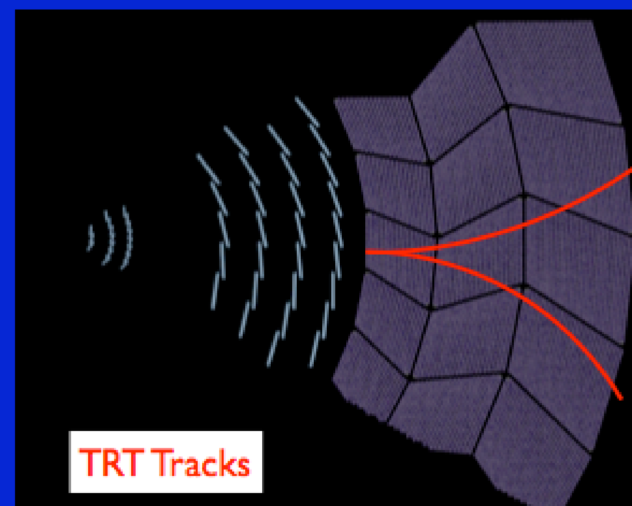
- improve performance in regions of the muon spectrometer with reduced acceptance
- improve the momentum resolution for $p_\perp < 100$ GeV
- high efficiency down to $p_\perp = 5$ GeV
- reduce backgrounds from π punch through or π/K or decays

Electron and photon reconstruction

- Uses as input the output of the ID and EM Calorimeter reconstruction.



- Electron reconstruction:
- 2 methods to obtain electron candidates:
  - Track seeded: From the ID tracks, energy deposition is looked in the calorimeters (mainly for low $p_\perp$ electrons from J/ψ or from b or c semi-leptonic decays)
  - Calorimeter seeded: when a cluster is found in the calorimeter, a matching to a track not coming from a γ conversion is required (high $p_\perp$ isolated electrons from W/Z, Higgs, SUSY, etc)
- Photon reconstruction:
  - Photon candidates defined when the cluster does not have an associated track or is matched to a reconstructed conversion

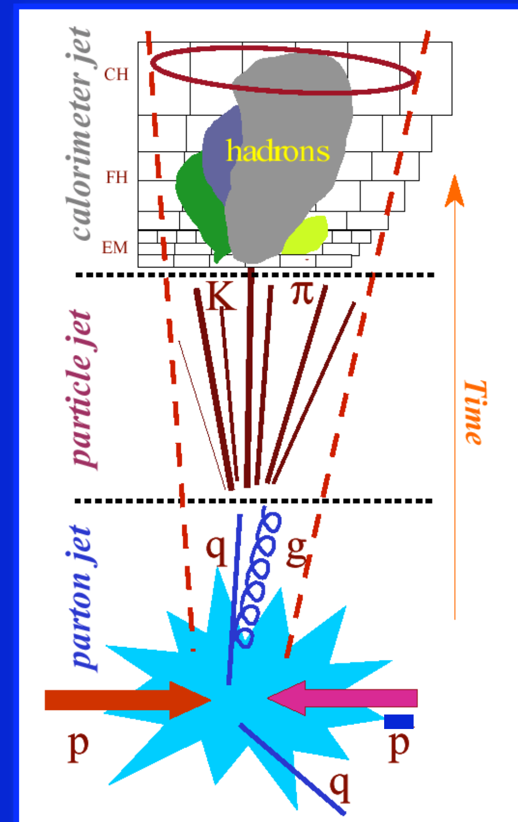


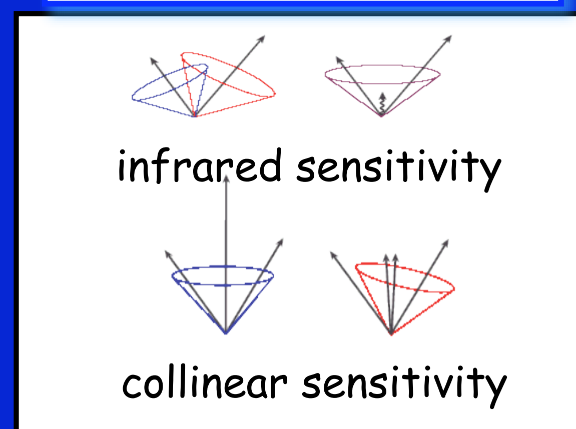
- Additional cuts are applied to reduce fakes
- E, direction measurement:
  - e: E(calorimeters for high $p_\perp$), directions from the ID track
  - γ: from the calorimeters, using the position of the primary vertex

Jet reconstruction

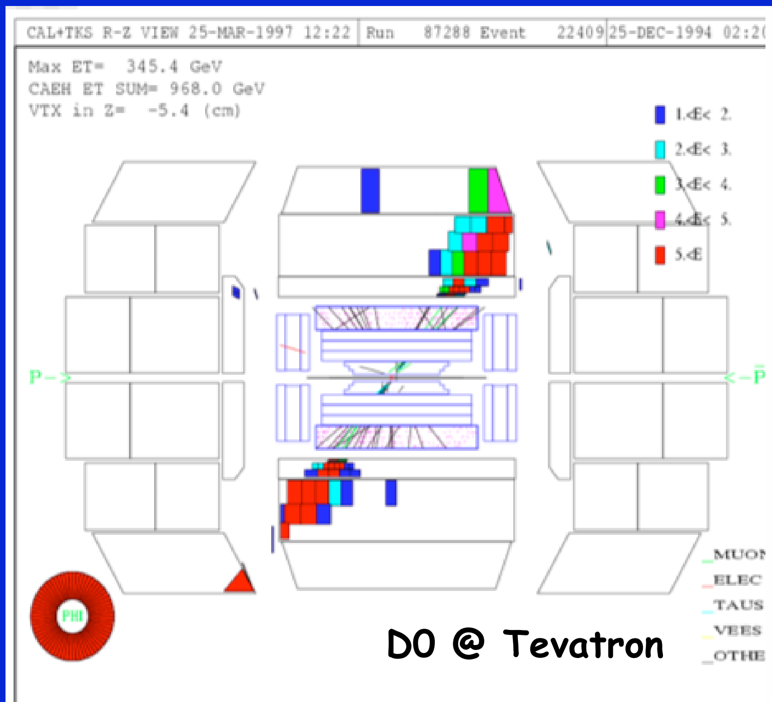
- Quarks and gluons are confined objects → A jet of hadrons is the final state signature of quarks and gluons
- How to define a jet without just guessing? Requirements:
  - Applicable to all levels:
    - Partons
    - Stable particles
    - Measured objects (calorimeter objects, tracks, etc)
  - Independent of the very details of the detector (granularity of the calorimeters, E response, etc)
  - Easy to implement
  - Close correspondence between:

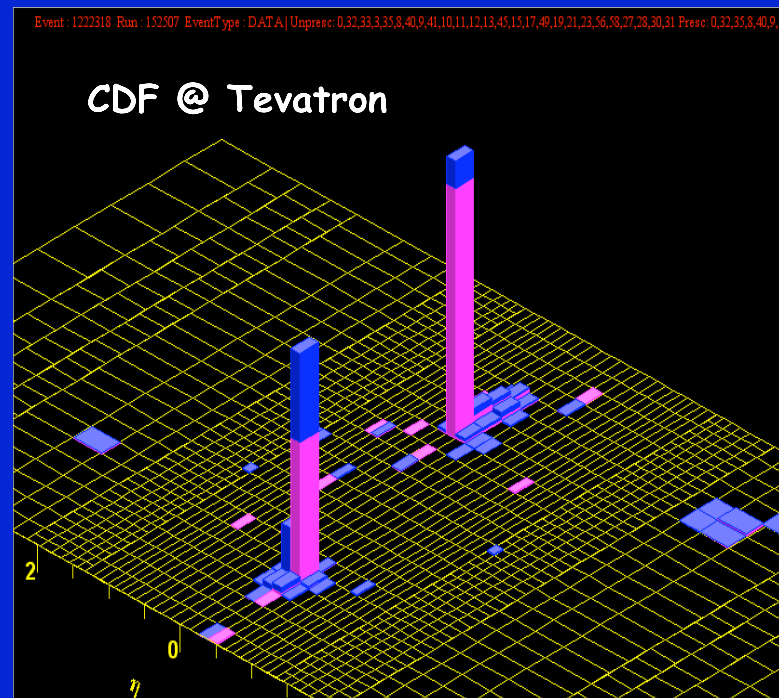
  P (parton) ⇔ P (jet) (Energy, Momentum, Angle)
  - Good from theoretical point of view: Infrared and collinear safe (i.e. insensitive to the emission of arbitrarily soft and collinear particles)

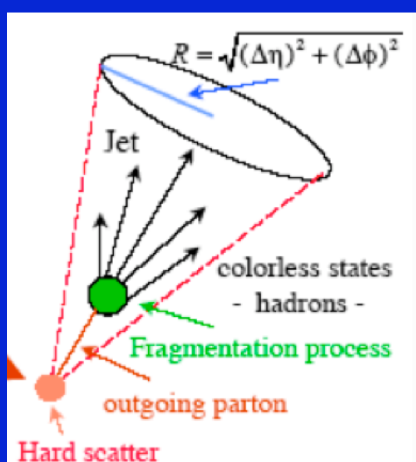




Jet reconstruction





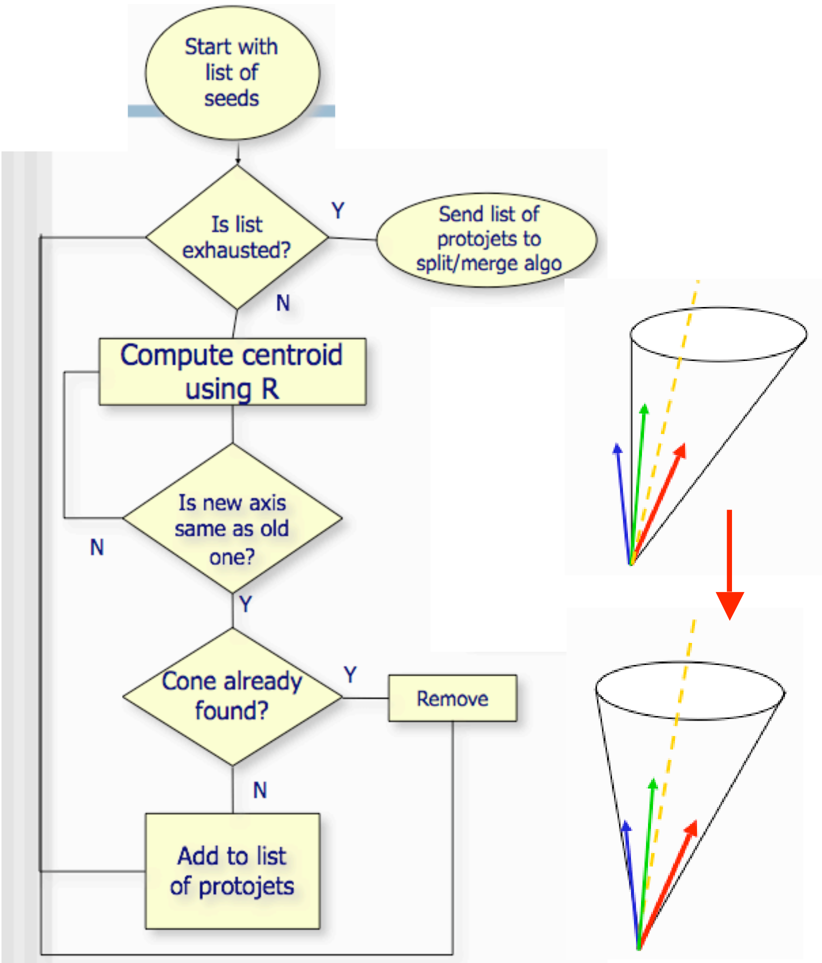


Introducing a cone description seems natural
But how to make it more quantitative?

Jet reconstruction

- Several jet algorithms implemented in ATLAS. 2 main types:

Seeded cone

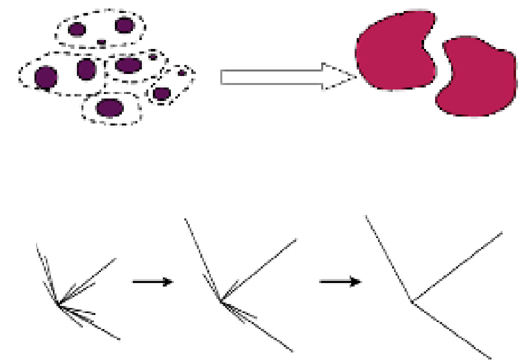


Recursive recombination (kT)

- Calculate for all particles i and pairs ij :

$$d_{ij} = \min(p_{t,i}^2, p_{t,j}^2)\frac{\Delta R_{ij}^2}{D^2} = \min(p_{t,i}^2, p_{t,j}^2)\frac{\Delta y_{ij}^2 + \Delta\varphi_{ij}^2}{D^2}$$

$$d_i = p_{t,i}^2$$

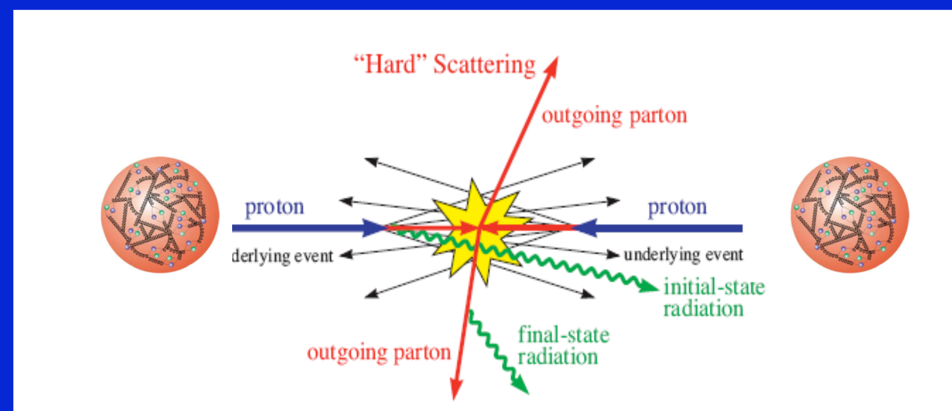


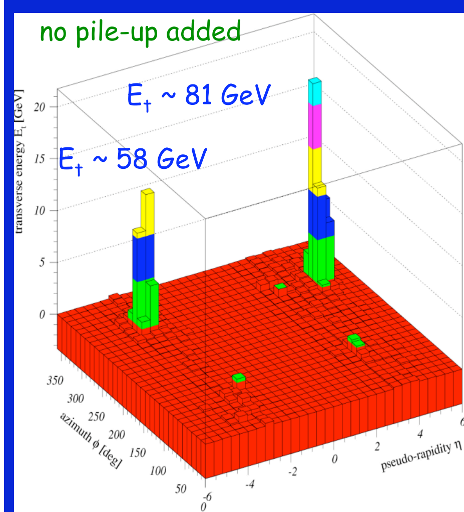
- Find minimum d_{min} from all d_i, d_{ij}
- If d_{min} is a d_i, call i a jet and remove it from the list
- Else combine i and j into a jet
  - 4-momentum recombination
- Calculate new combinations
  - Stop when all particles declared jets
  - Each particle is part of one jet only (exclusive assignment)
- Infrared safe

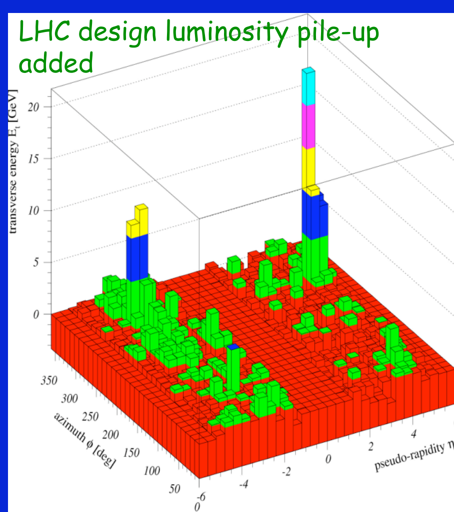
Jet reconstruction

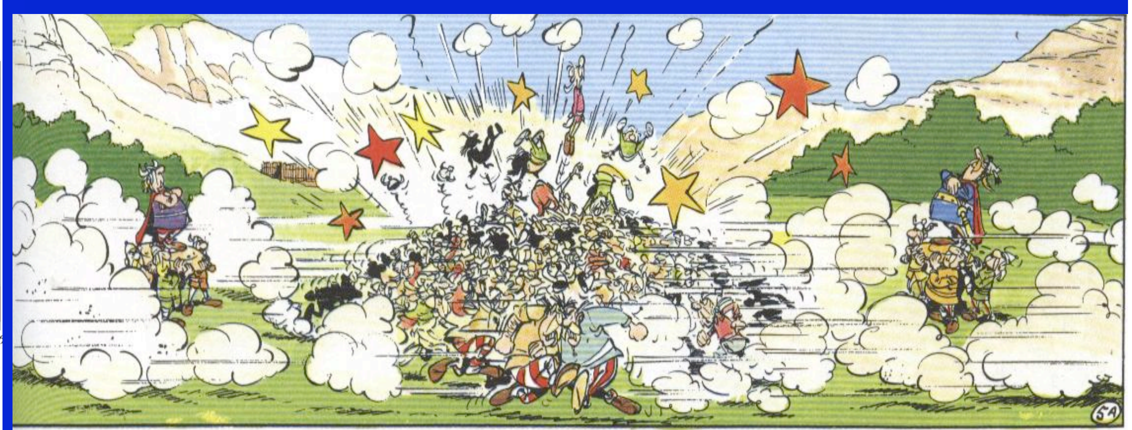
- Further difficulties @ LHC:
- Pile-up:
  - Many additional soft p-p interactions
- Underlying event:
  - Beam-beam remnants, initial state radiation, multiple parton interactions

All this additional energy has nothing to do with jet energies → have to subtract it (essential to measure from data!)









b-tagging

Identification of b-jets takes advantage of the properties that make them different from jets coming from lighter quarks:

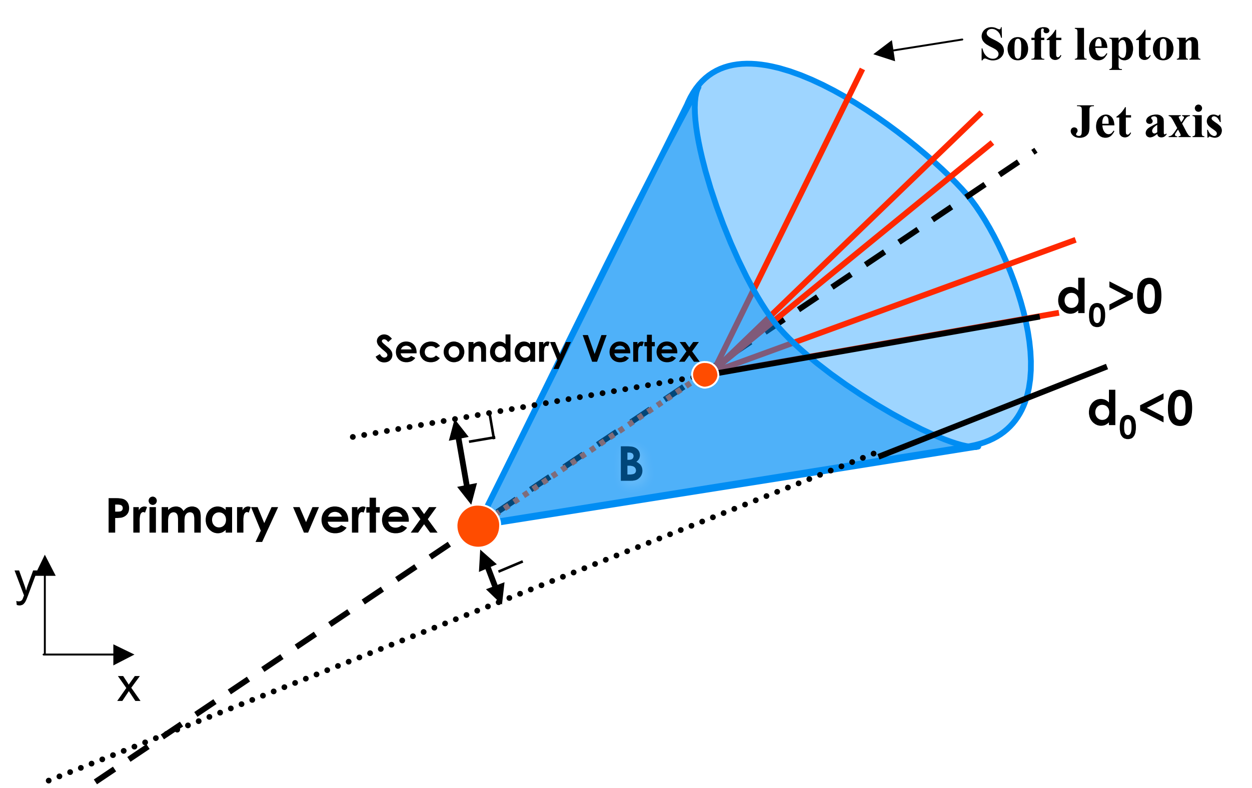
- Hard fragmentation of b quarks $x_B = E_B/E_b \sim 70\%$
- High mass of B-hadrons $m_B \sim 5$ GeV → decay products can be separated
- Semi-leptonic decay of B-hadrons → lepton of large $p_\perp$ and p relative to jet axis
- Long Lifetime of B hadrons: $c\tau \sim 470$ mm (mixture $B^+/B^0/B_s$) , ~ 390 mm (L_b)
  $\langle L \rangle = \beta\gamma c\tau$, for $E_B \sim 50$ GeV, flight length ~ 5 mm, $d_0 \sim 500$ mm

Several taggers of 2 different types have been implemented:

Spacial tagging
- Signed impact parameter of tracks $d_0/\sigma(d_0)$
- Secondary vertex

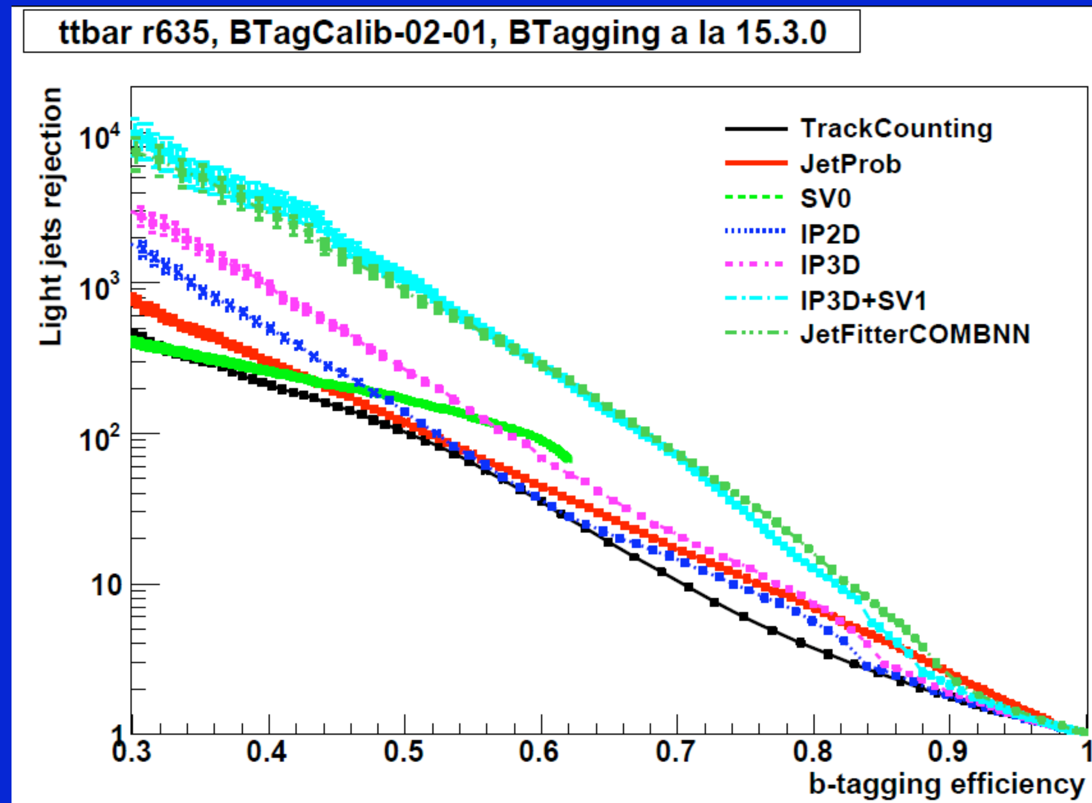
Soft lepton tagging
- Low $p_\perp$ electron from B(D)
- Low $p_\perp$ muon from B(D)

(Limited by BR ≅ 20% each)



b-tagging

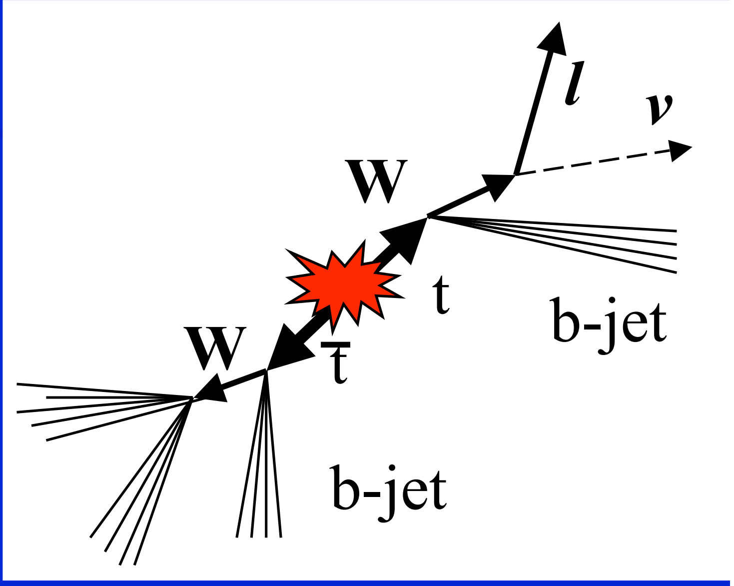
- There are taggers better suited for early data as they can be "easily" calibrated from data or do not require any calibration
- Some others (based on likelihoods) are more powerful but need a very good understanding of the data and tuning of MC



The performance of the b-tagging algorithms directly depends on the good quality of the reconstruction already mentioned:

- Jet reconstruction (direction)
- Tracking in the inner detector (impact parameter resolution, tracking in dense jets)
- Primary vertex reconstruction (mostly along z, @high Luminosity)

Missing $E_\perp$

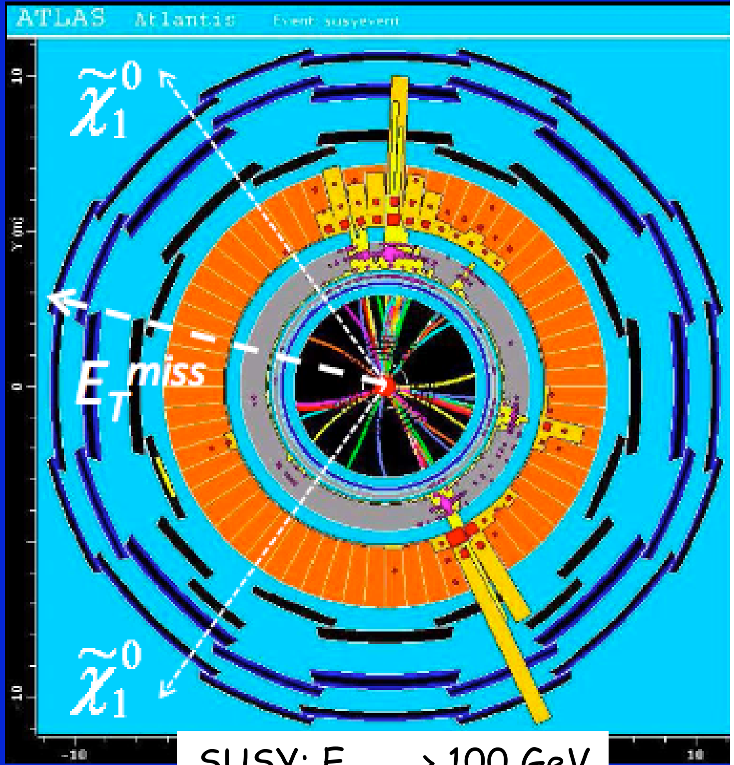


- Neutrinos traverse the detector without interacting → are not directly detected

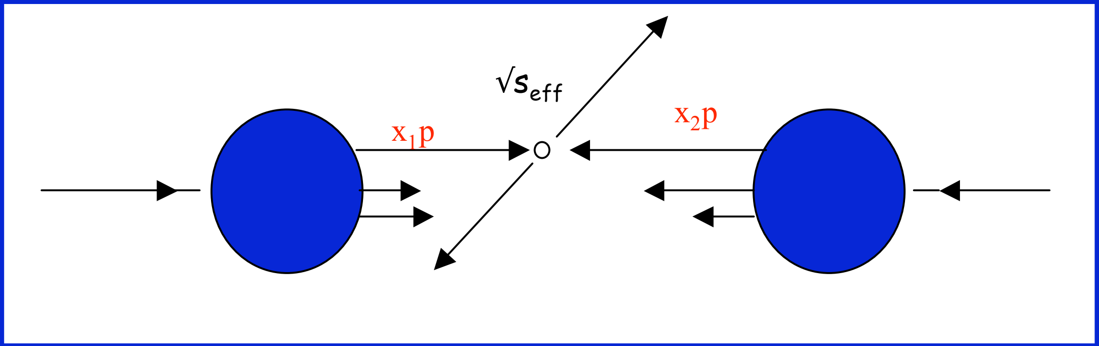
$$(E,\mathbf{p})_{initial} = (E,\mathbf{p})_{final}$$

- In hadron colliders, what it is known is:
  - $p_{\perp\ initial} = 0$
  - → if ν produced: $p_{\perp\ final} \neq 0$ →

$$|\mathbf{p}_{\perp\ \nu}| = |\mathbf{p}_{\perp\ final}| = E_{\perp miss}$$



SUSY: $E_{\perp miss}$ > 100 GeV



Missing $E_\perp$

How to measure it?

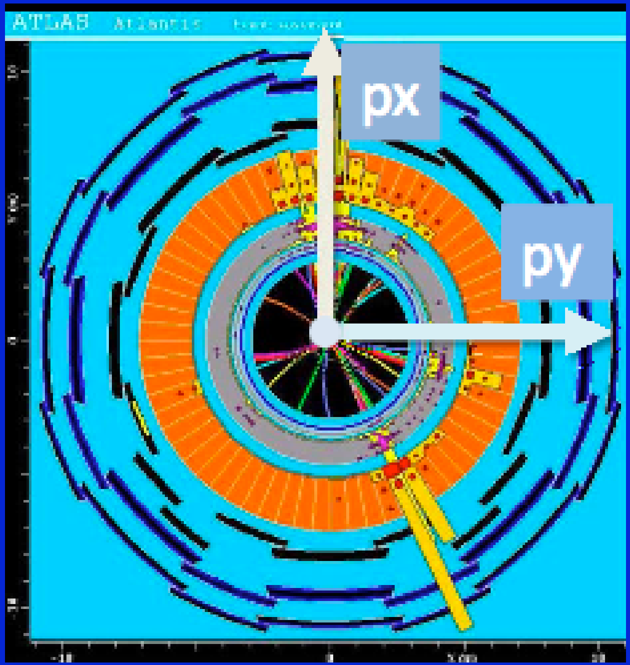
- Can be computed from:
  - The calorimeter cells energies

$$E_\perp^{miss\text{-}Calo} = \sqrt{(\Sigma E_{xcells})^2 + (\Sigma E_{ycells})^2}$$

  - The muons measured standalone

$$E_\perp^{miss\text{-}Muon} = \sqrt{(\Sigma E_{xmuon})^2 + (\Sigma E_{ymuon})^2}$$

  - Correction for the Energy lost in the cryostat between the LAr EM calorimeter and the Tile hadronic calorimeter



Fake Missing $E_\perp$ can have many sources as:
- mismeasurements muons or jets
- hot/dead/noisy cells or regions in calorimeters
- backgrounds:
  - cosmic rays, beam halo, beam-gas

$$E_\perp^{miss\text{-}measured} = E_\perp^{miss\text{-}Calo} + E_\perp^{miss\text{-}Muons} + E_\perp^{miss\text{-}Cryostat} = E_\perp^{miss\text{-}True} + E_\perp^{miss\text{-}Fake}$$

Summary of Lecture 1

- The complexity of the ATLAS experiment required for physics @ LHC:
  - The detector itself
  - The operation chain:
    - Trigger and DAQ
    - Monitoring
    - Reconstruction
    - Computing
- A main focus on the reconstruction algorithms used in ATLAS to provide the input to all physics analysis

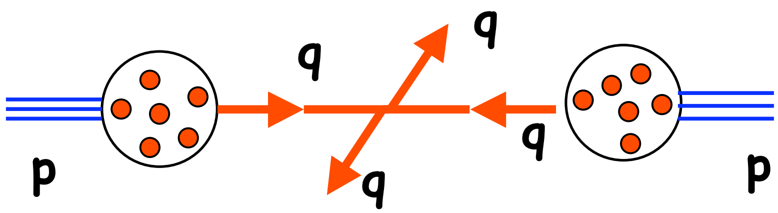
Lecture 2 (S.Martí) will focus on one of the aspects of this chain way:
Tracking and Alignment!

How is ATLAS making sure that the experiment is ready for the LHC startup and what is the strategy for first physics results? (subject of Lecture 3)

Backup slides

What is needed for the TeV physics?

Quark-quark scattering:



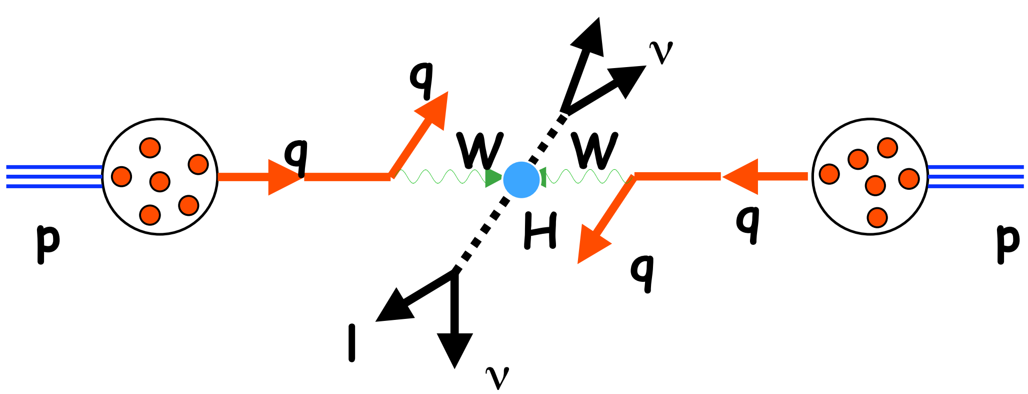
No leptons / photons in the initial and final state

If leptons with high $p_\perp$ are observed $\Rightarrow$ interesting physics!

Important signatures:

- Leptons und photons
- Missing transverse energy

Example: Higgs boson production and decay



Transverse momentum (in the plane perpendicular to the beam)

$p_T = p \sin\theta$

Trigger and data acquisition

Two concepts are used to select data subsets from the readout systems

Region-of-Interest concept:

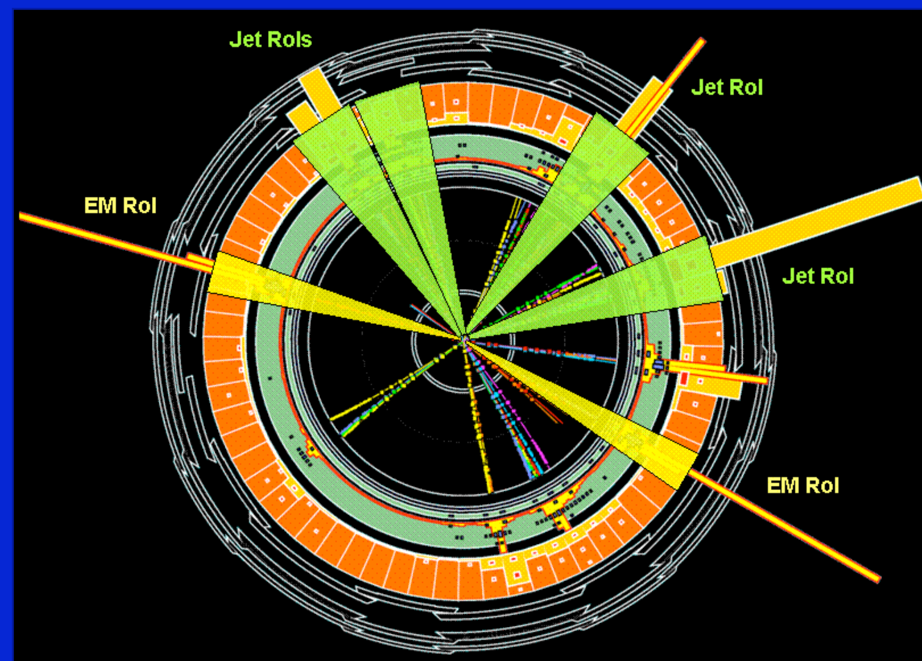
•L1 indicates the geographical location of candidate objects, *e.g.* EM clusters

•L2 only accesses data from RoIs, small fraction of total data

Sequential-selection concept:

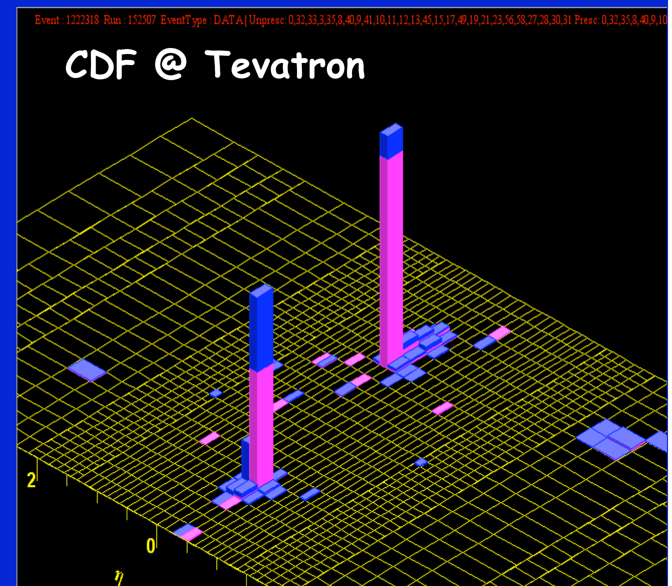
• Data are accessed by L2 initially only from a subset of detectors (*e.g.* muon systems and calorimeters)

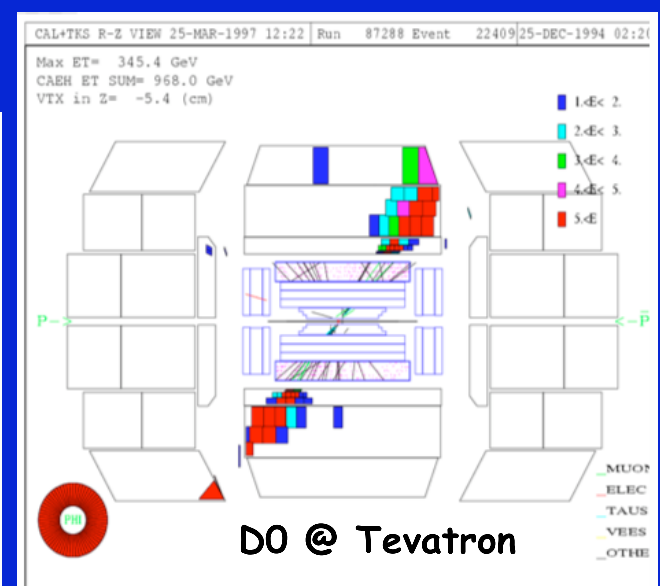
• Many events rejected without accessing, *e.g.*, inner detector



Jet reconstruction

- Several algorithms of 2 different types are available:
- Cones:
  - Seek to find geometric regions which maximize the momentum in a given area (cone)
  - Sort of mimics the "event display+eye" method
  - Traditionally used in hadron-hadron colliders
- Clustering:
  - Starts from all elementary objects available and performs an iterative pair wise clustering to build larger objects
  - Successfully used in e^+e^- and ep





$$E_T^{jet} = \sum E_{T,i}$$

$$\eta_{jet} = \frac{1}{E_T^{jet}} \sum E_{T,i} \cdot \eta_i$$

$$\varphi_{jet} = \frac{1}{E_T^{jet}} \sum E_{T,i} \cdot \varphi_i$$

$$\left(E_{jet}, \vec{p}_{jet}\right) = \left(\sum E_i, \sum \vec{p}_i\right)$$