Particle Identification

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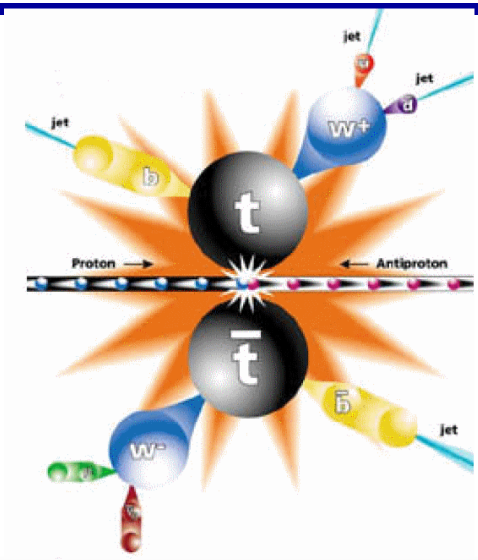
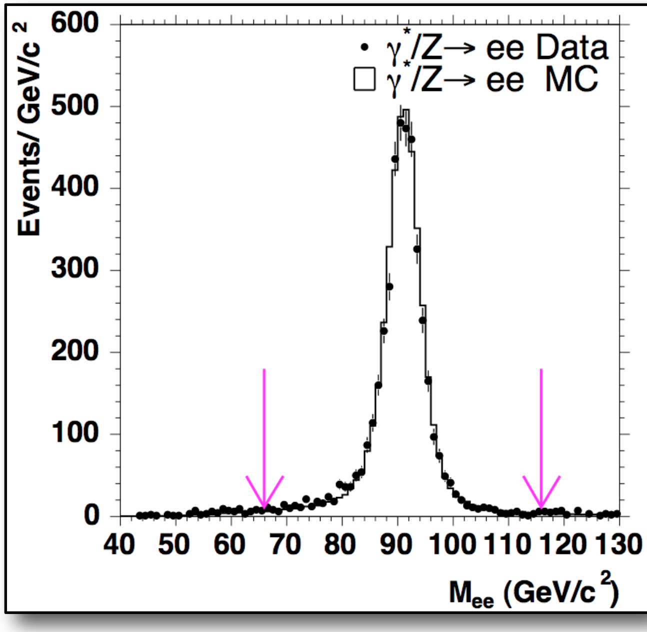
- This talk will cover different methods to do particle identification in a typical multi-purpose detector
  - Emphasis put on LHC detectors
- Outline
  - Introduction
  - Track and calorimeter reconstruction
  - Particle Identification
    - Muons, Electrons, Photons, Taus, Jets, Missing Energy
  - Summary

Introduction

- During collisions of e.g. 2 particles energy is used to create new particles
- Particles produced are non stable and will decay in other (lighter) particles
- The end-product are the basic input to any physics analysis
- E.g. if you want to reconstruct a Z boson, you need to look for events with 2 muons, electrons or jets and then calculate the invariant mass
- There will be events in which you also find 2 objects and which have a similar invariant mass
  - Better do your particle identification right, so that you have to deal with little background





Global Detector Systems

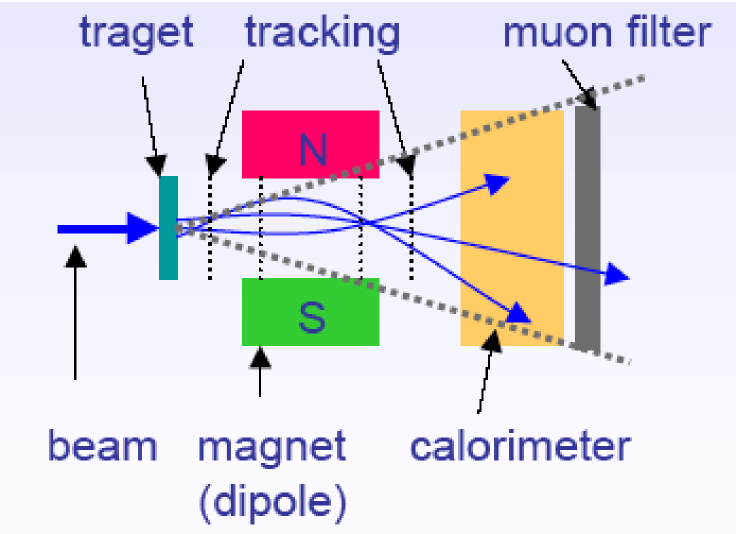
Overall Design Depends on:

- Number of particles
- Event topology
- Momentum/energy
- Particle type

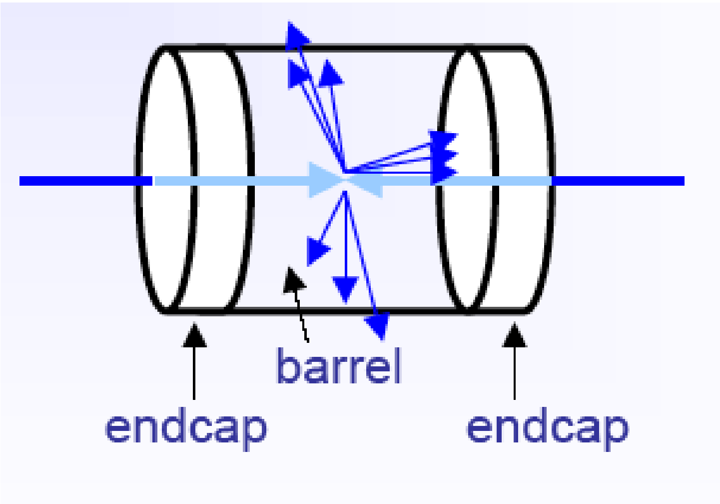
No single detector does it all…

→ Create detector systems

Fixed Target Geometry



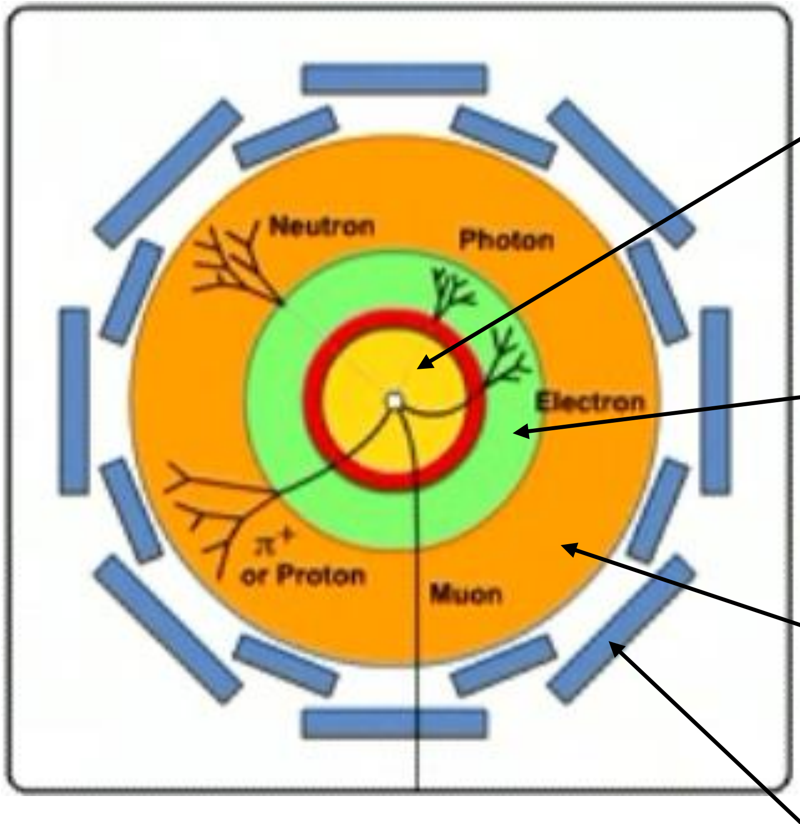
Collider Geometry



•Limited solid angle (dΩ□ coverage (forward)
•Easy access (cables, maintenance)

•“full” solid angle dΩ coverage
•Very restricted access

How to detect particles in a detector



Tracking detector

−Measure charge and momentum of charged particles in magnetic field

Electro-magnetic calorimeter

−Measure energy of electrons, positrons and photons

Hadronic calorimeter

−Measure energy of hadrons (particles containing quarks), such as protons, neutrons, pions, etc.

Muon detector

−Measure charge and momentum of muons

Neutrinos are only detected indirectly via ‘missing energy’ not recorded in the calorimeters

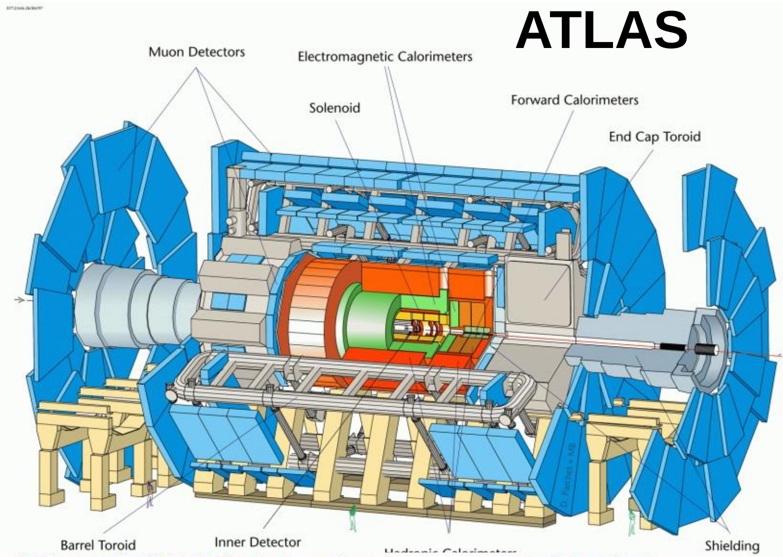
How to detect particles in a detector

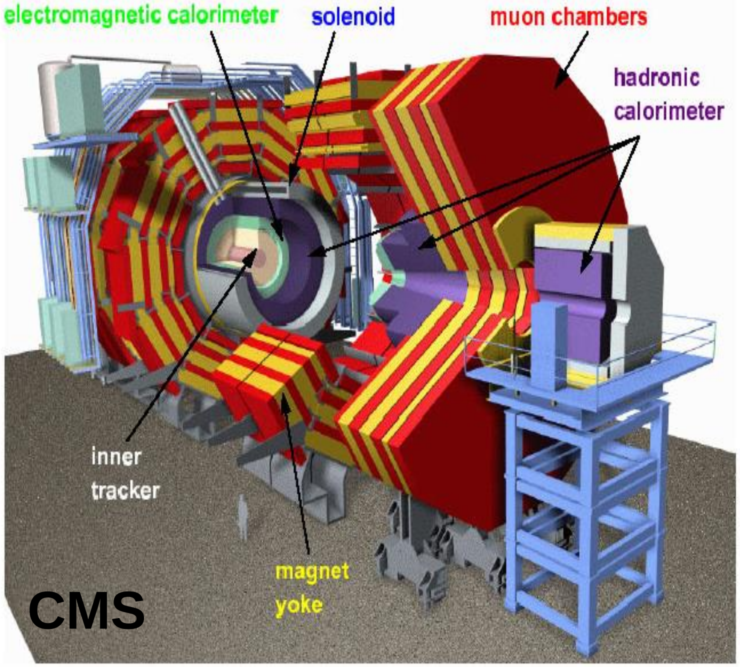
- Use the inner tracking detector, the calorimeters and the muon detector information
- There can be also some special detectors to identify particles
  - π/K/p identification using Cerenkov effect
  - Dedicated photon detector
- There are other things which I won‘t explain
  - Energy loss measurement in tracking detector for π/K/p separation (dE/dx)
  - Transition radiation detectors for e/π separation
  - ...

ATLAS and CMS Detectors Revisited

- Two different approaches for detectors

	ATLAS	CMS
tracking	Silicon/gas	Silicon
EM calo	Liquid Argon	PbWO cristals
Had calo	Steel/scint, LAr	Brass/scint
Muon	RPCs / drift	RPCs / drift
Magnet	Solenoid (inner) / Toroid (outer)	Solenoid
B-field	~ 2 Tesla / 4 Tesla	~ 4 Tesla

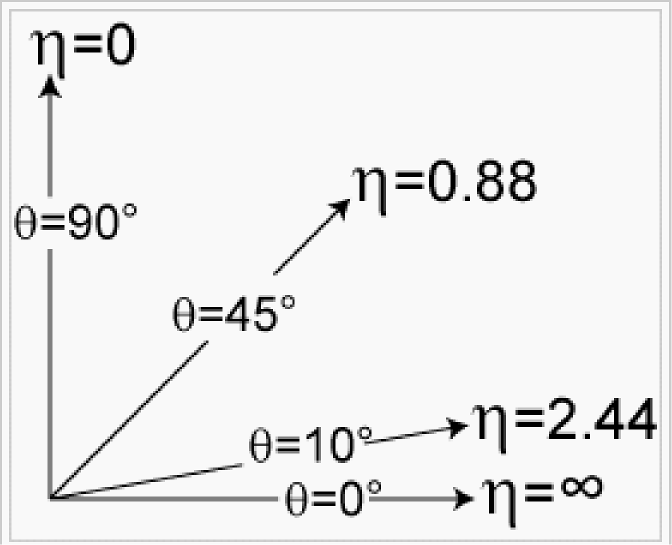




As these terms will crop up during the talk...

Coordinate system used in hadron collider experiments

- Particle can be described as
  - $\vec{p} = (p_x, p_y, p_z)$
- In a hadron collider we use
  - p, η, φ
- η is called “pseudo-rapidity“
  - Angle between particle momentum and beam axis (z-direction)
  - $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$
  - Good quantity as number of particles per η unit is constant
- φ is angle in x-y-plane
  - $p_x = p_T \cdot \cos(\varphi)$, $p_y = p_T \cdot \sin(\varphi)$, $p_T = \sqrt{p_x^2 + p_y^2}$

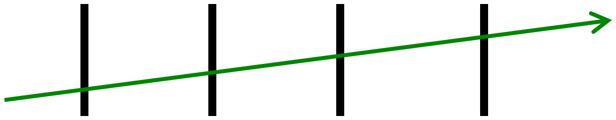


Detector Reconstruction

- Tracking

- Calorimetry

Tracking

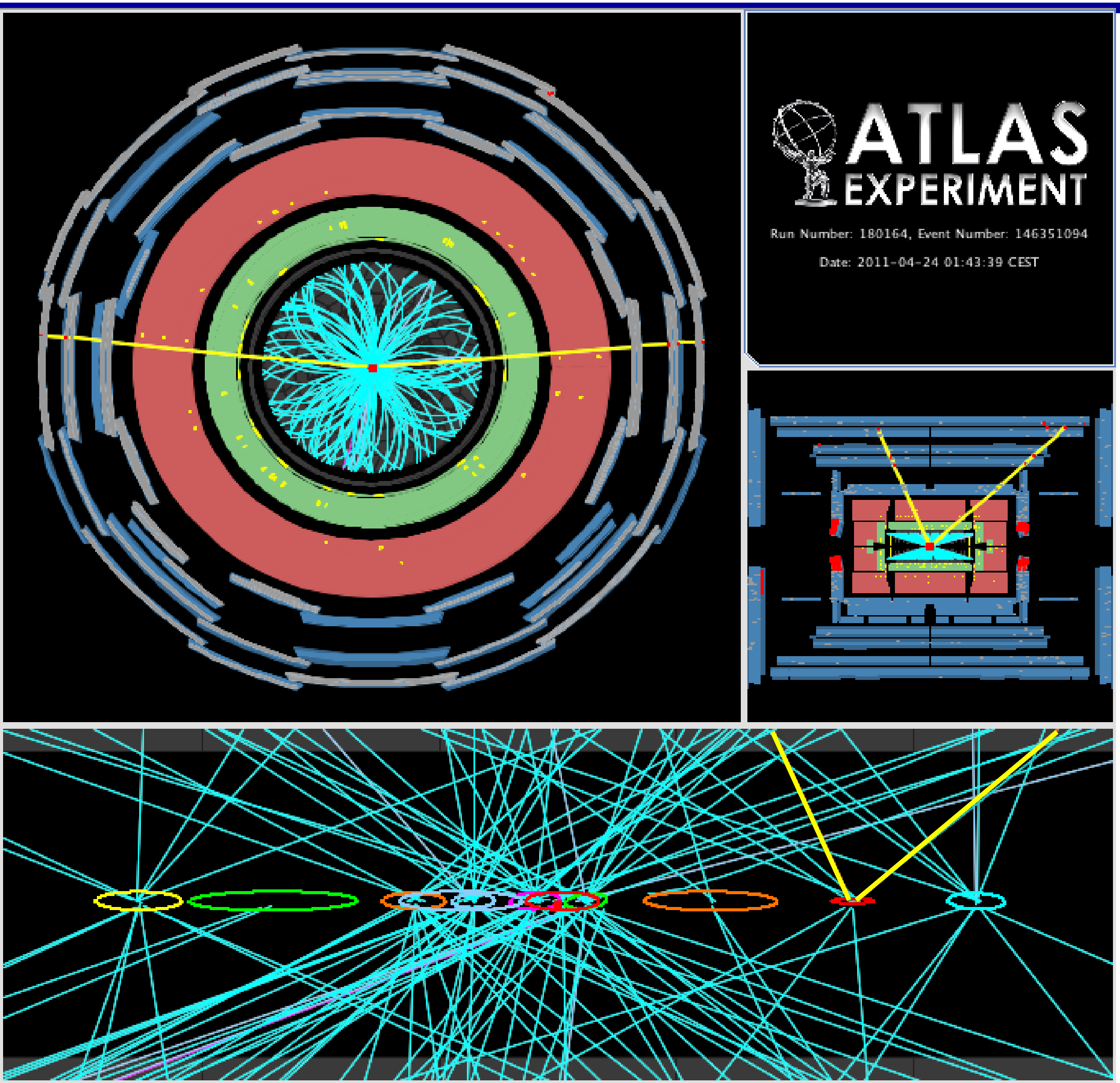


- Inner Detector: Several layers of detectors
- Measure the trajectory of charged particles
  - Fit curve to several measured points (“hits”) along the track
  - Extrapolate track back to the point of origin
  - Measure the momentum of charged particles from their curvature in a magnetic field
- Reconstruct decay vertices
  - Reconstruct primary vertex, point where collision has taken place
    - Typically sum over momenta of tracks from the same vertex, take the one with highest p_T
  - Secondary vertices
    - Identify tracks from tau-leptons, b and c-hadrons, which decay inside the beam pipe, by lifetime tagging
    - Reconstruct strange hadrons, which decay in the detector
    - Identify photon conversions
  - You also have vertices from pile-up (overlapping collisions)

Another Complication: Pileup

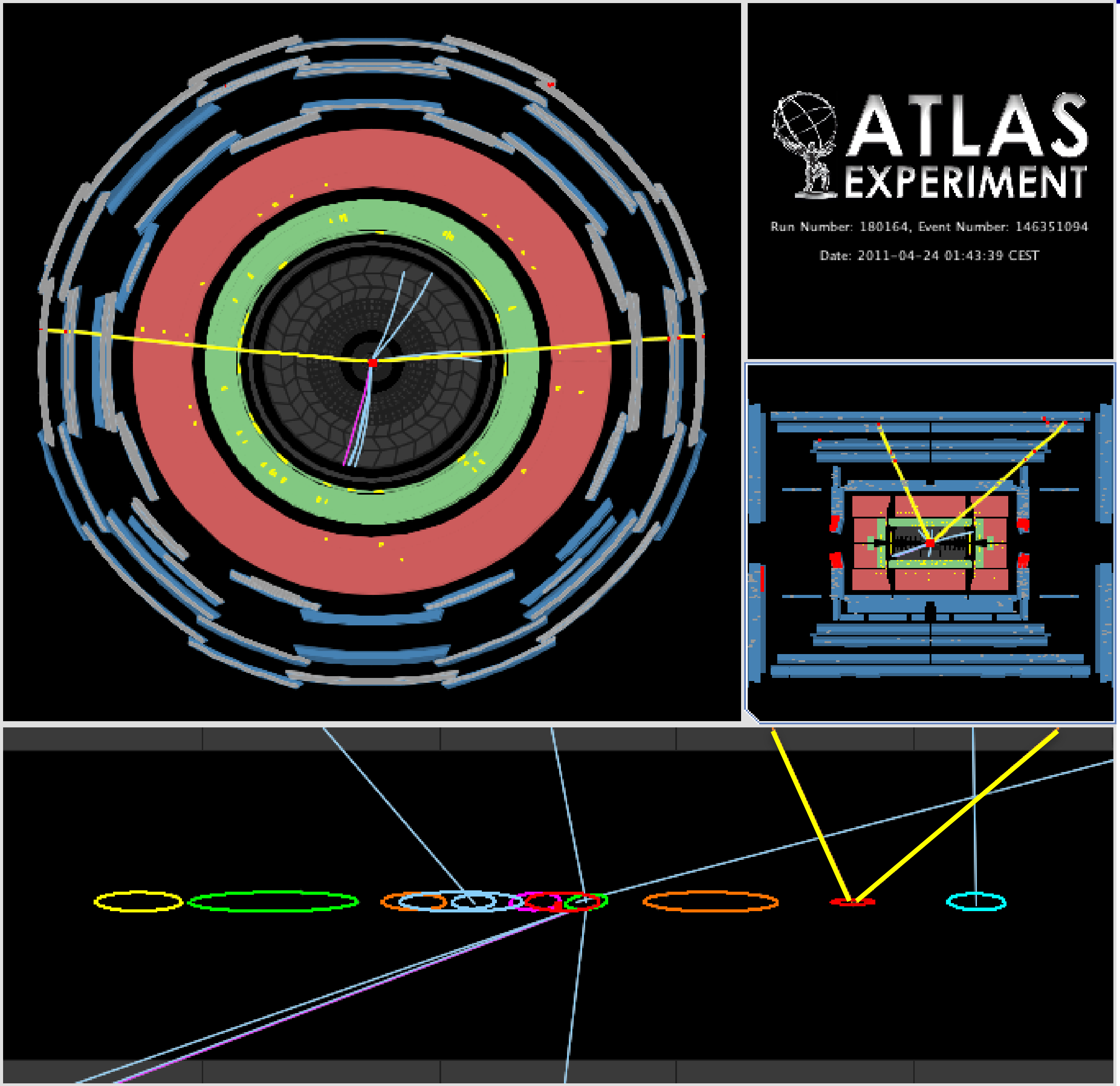
- When the LHC collides bunches of protons we can get more than one p-p interaction – this is called pileup
- These are mainly soft interactions producing low momentum particles
- The number of pileup interactions depends on the LHC parameters
  - How many protons per bunch
  - How small the bunches
- In 2012 we already had up to ~30 overlapping p-p collisions
- We can usually identify which tracks are from which interactions by combining tracks that come from the same vertex

Z→μμ in pile-up environment



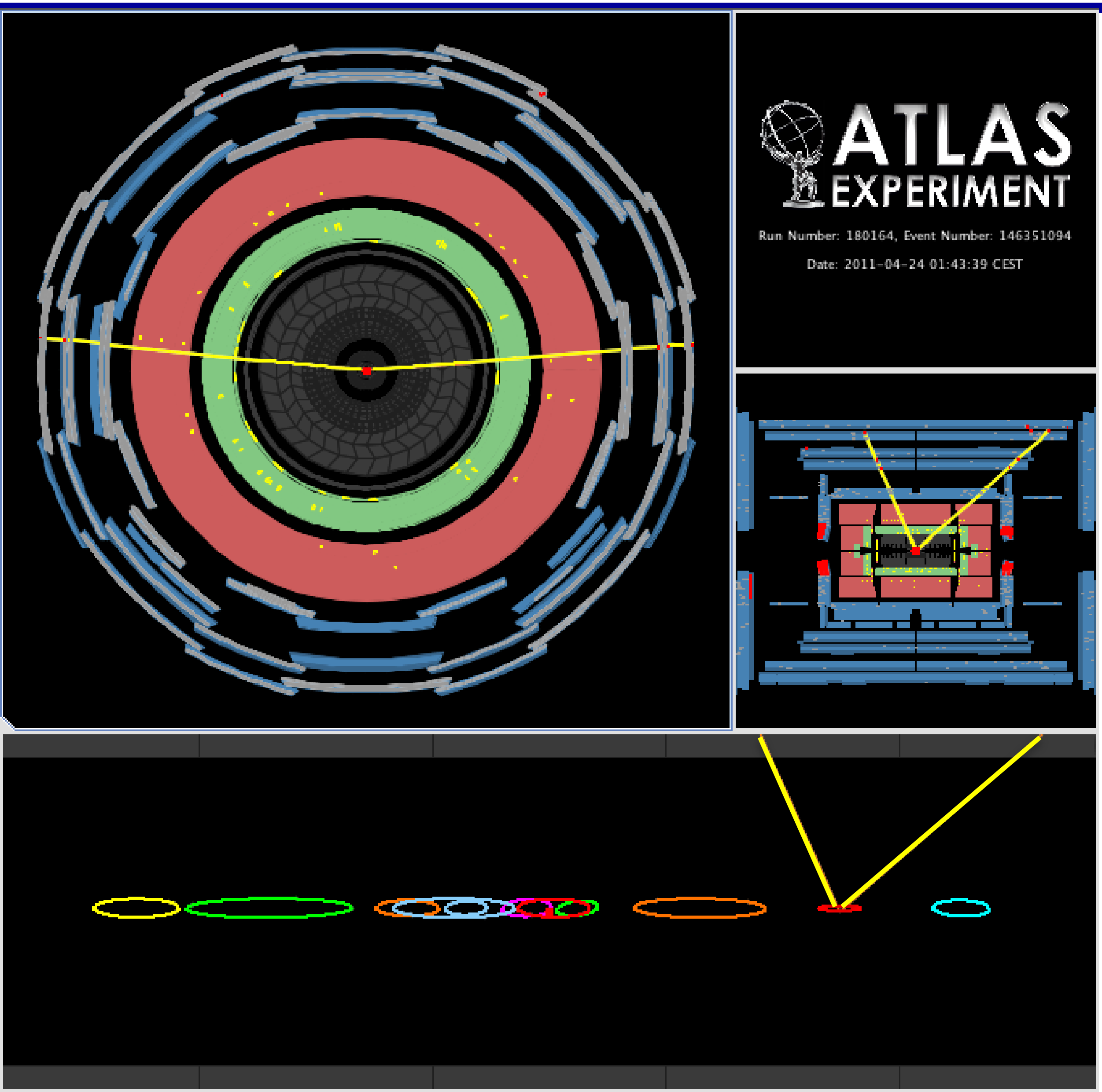
- Z→μμ event with 11 reconstructed vertices.
- Tracks with transverse momentum above 0.5 GeV are shown (p_T>0.5GeV).

Z→μμ in pile-up environment



- Z→μμ event with 11 reconstructed vertices.
- Looks already much better if we increase the p_T cut to 2 GeV

Z→μμ in pile-up environment

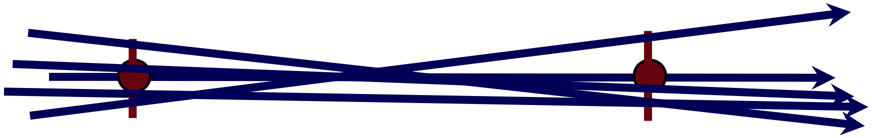


- Z→μμ event with 11 reconstructed vertices.
- Even better if we increase the p_T cut to 10 GeV

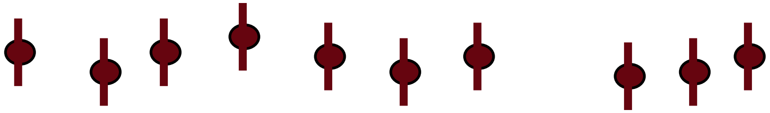
Track reconstruction

- 1D straight line fit as simple case
- Two perfect measurements in 2 layers of the detector
  - No measurement uncertainty
  - Just draw a straight line through them and extrapolate

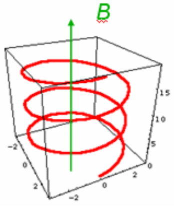
- Imperfect measurements give less precise results
  - The farther you extrapolate, the less you know



- Smaller errors and more points help to constrain the possibilities.



- But how to find the best point from a large set of points?
  - Parameterise track $y(x) = \theta x + d$ (helix is you have magnetic field)
  - Find track parameters by Least-Squares-Minimisation
  - Gives you errors δΘ, δd



$$\chi^2 = \sum_{i=1}^{n_{\text{hits}}} \frac{(y_i - y(x_i))^2}{\sigma_i^2}$$

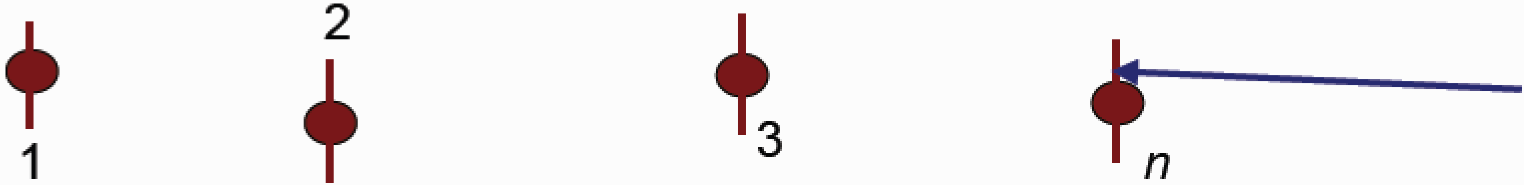
position of ith hit

predicted track position at ith hit

uncertainty of ith measurement

Track Reconstruction

- Reality is a bit more complicated
- Particles interact with matter
  - Energy loss
  - Change in direction
  - This is multiple scattering
- Your track parameterisation needs to take this into account
- Do calculate very precisely would take too long, therefore, work outward N times



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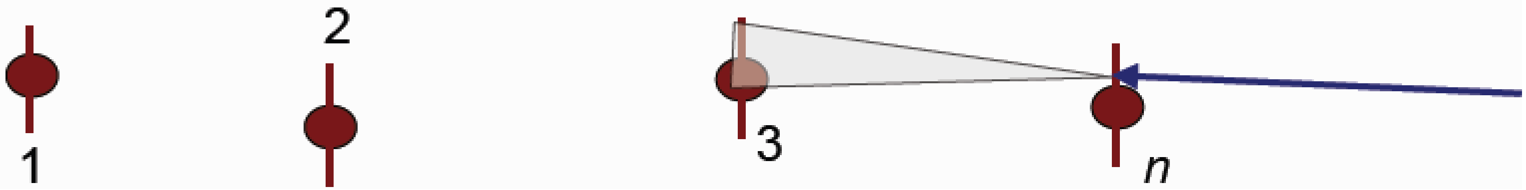

- In each step extrapolate to next layer, using info from current track parameters, expected scattering error, and measurement in next layer
- Needs starting estimate (seed) and may need some iterations, smoothing

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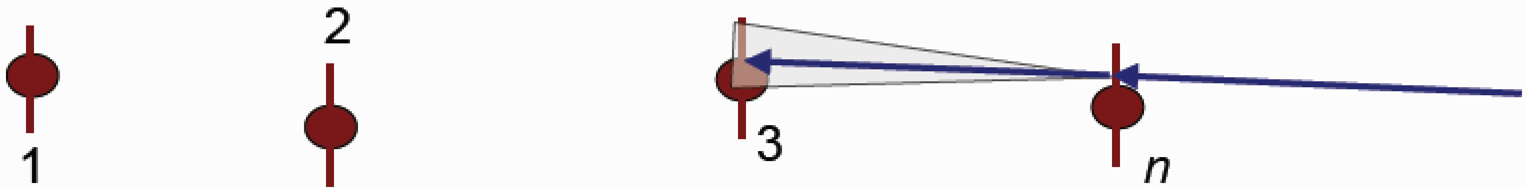

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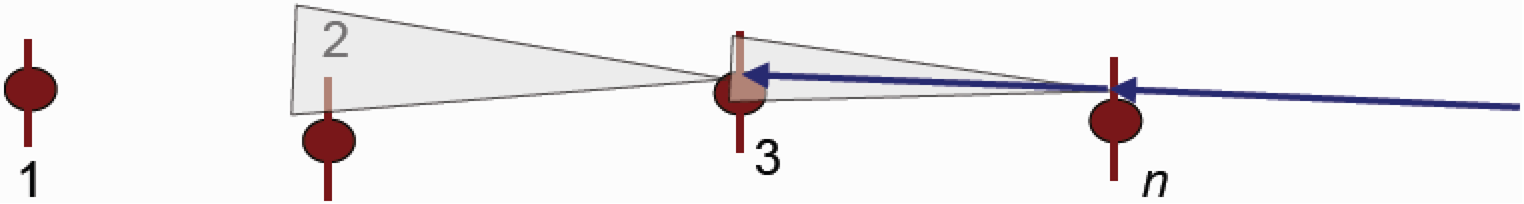

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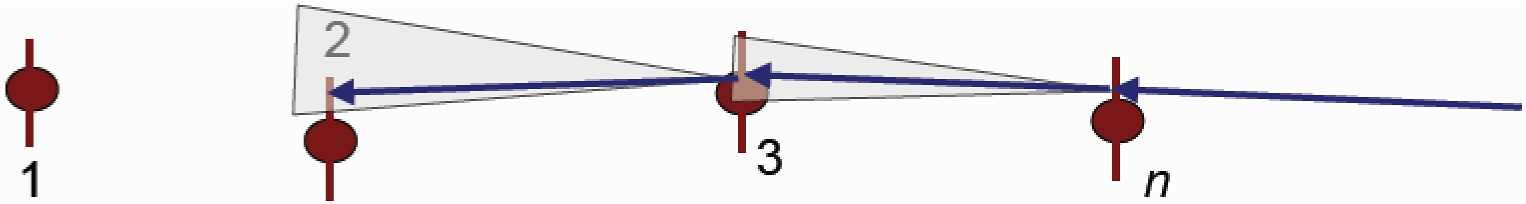

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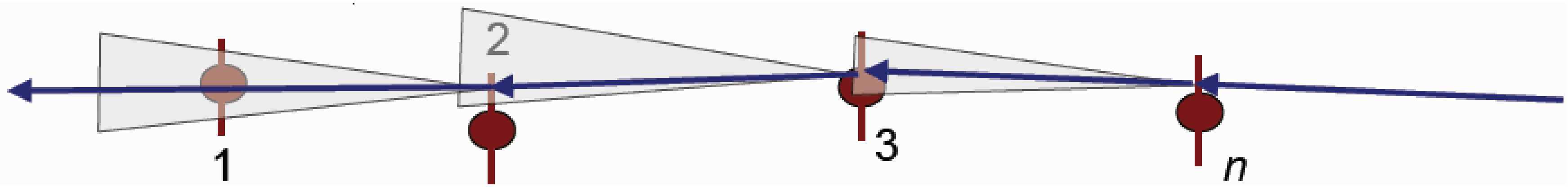
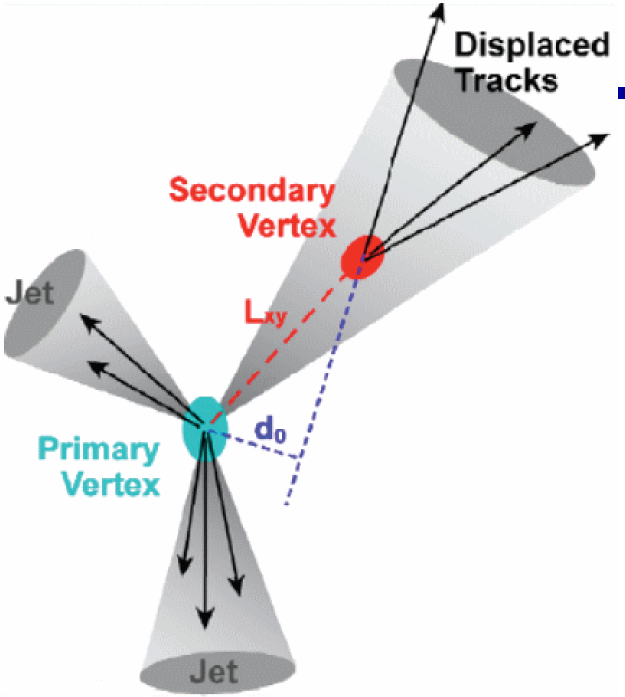
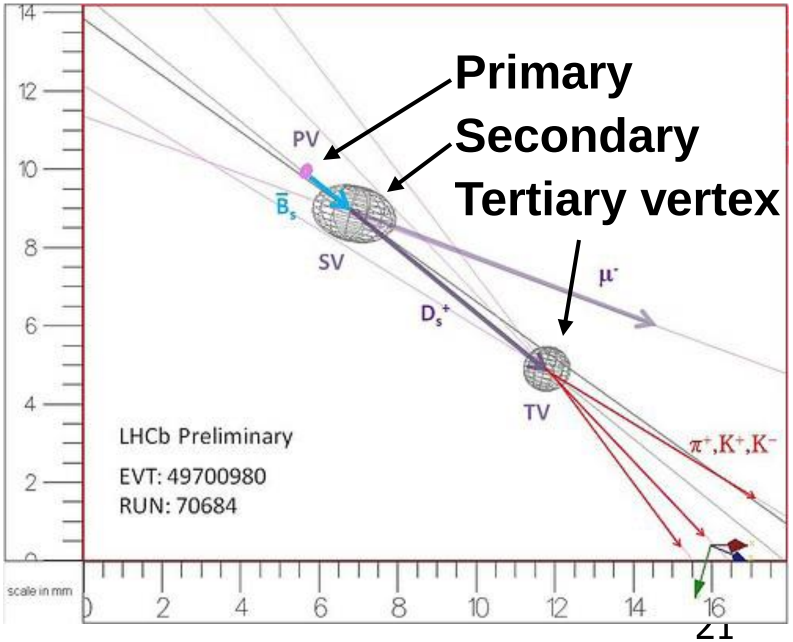


- In each step extrapolate to next layer, using info from current track parameters, expected scattering error, and measurement in next layer
- Needs starting estimate (seed) and may need some iterations, smoothing
- This method is based on theory of the **Kalman Filter**

B-tagging

- b hadrons are
  - long-lived ($c\tau$~450 μm)
  - Massive
- Signature: displaced vertex
  - Important parameters are
    - d_0 = impact parameter (point closest approach in the x-y plane)
    - L_{xy} = distance between primary and secondary vertices
- As LHC is a b- (and even top) factory, b-tagging is a very useful measure





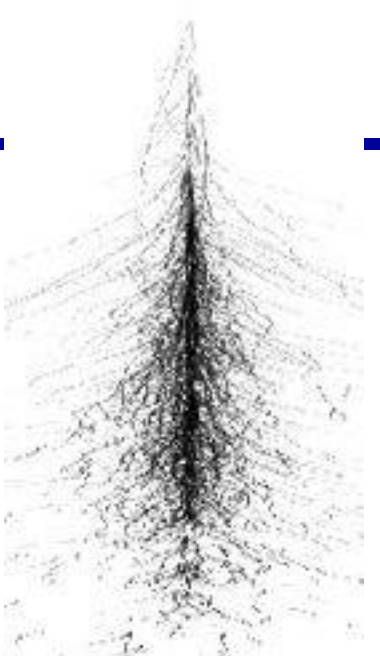
Primary

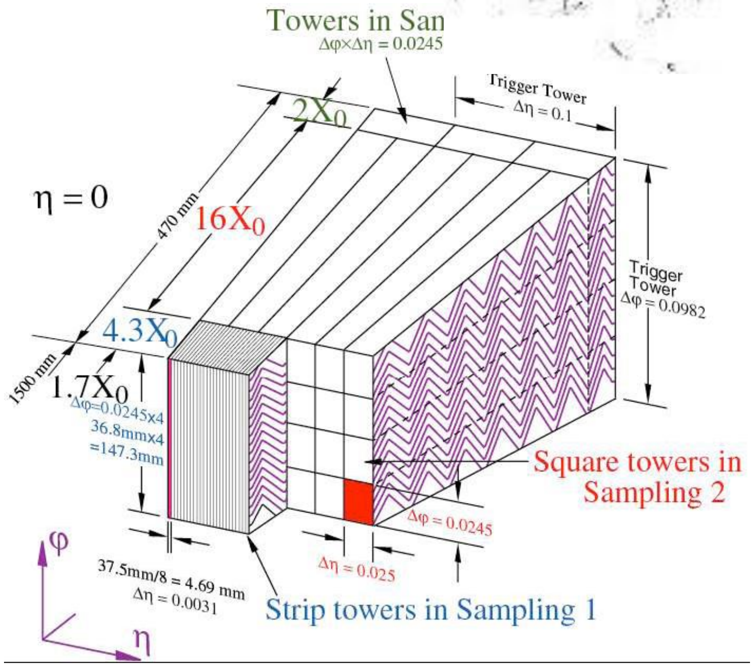
Secondary

Tertiary vertex

Calorimeter

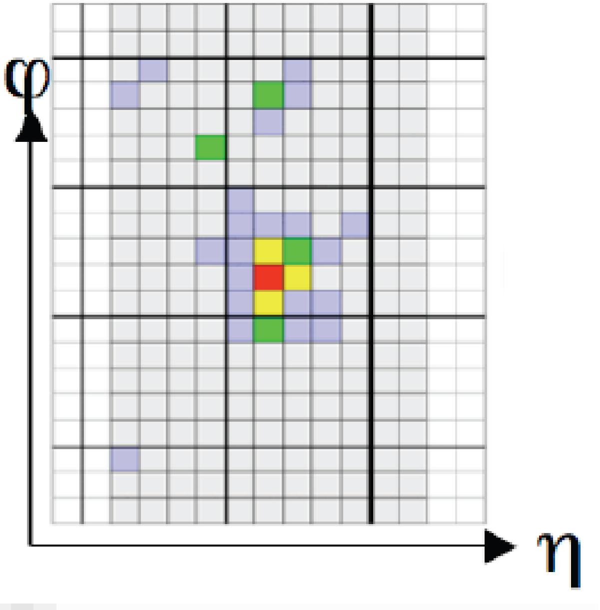
- Measure the total energy of particles
  - Versatile detectors, can measure also position, angle, timing for charged & neutral particles (even neutrinos through missing (transverse) energy (if hermetic))
- Compact detectors: shower length increases logarithmically with E
- Unlike tracking detectors, E resolution improves with increasing E
- Divide into categories: electro-magnetic (EM) calorimeters and hadron calorimeters
- Typically subdivided into several layers and many readout units (cells)
- More on calorimetry in Dave's talk





Cluster Reconstruction

- Clusters of energy in a calorimeter are due to the original particles
  - Clustering algorithm groups individual channel energies
- Ways to do clustering
  - Just scan the calorimeter cell energies and look for higher energetic cells which give local maximum, build cluster around
    - Can used fixed window or cone size or can do it dynamically and add cell if above a given threshold
    - Don’t want to miss any, don’t want to pick up fakes

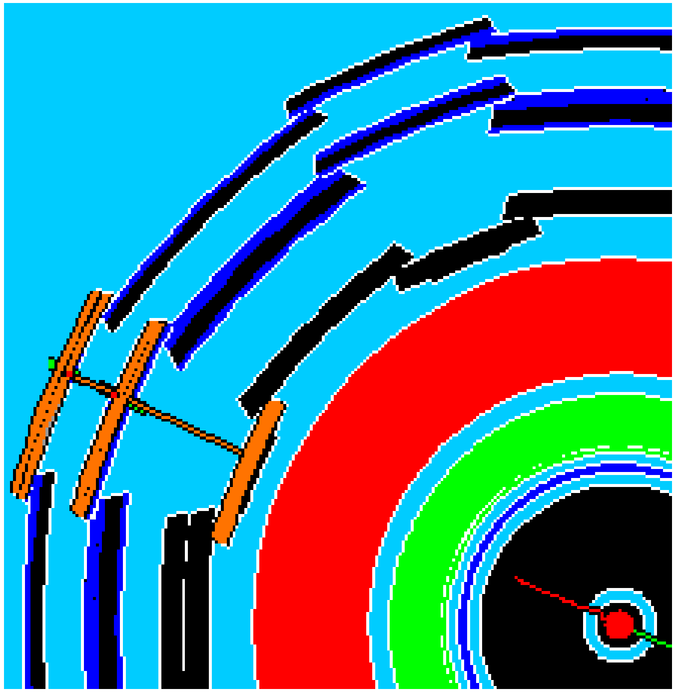


Particle Identification

- Muon
- Electron and Photon
- Taus
- Jets
- Missing transverse energy

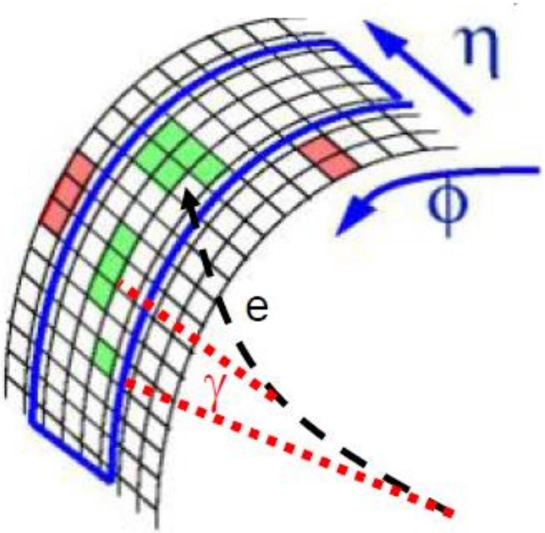
Muon Identification

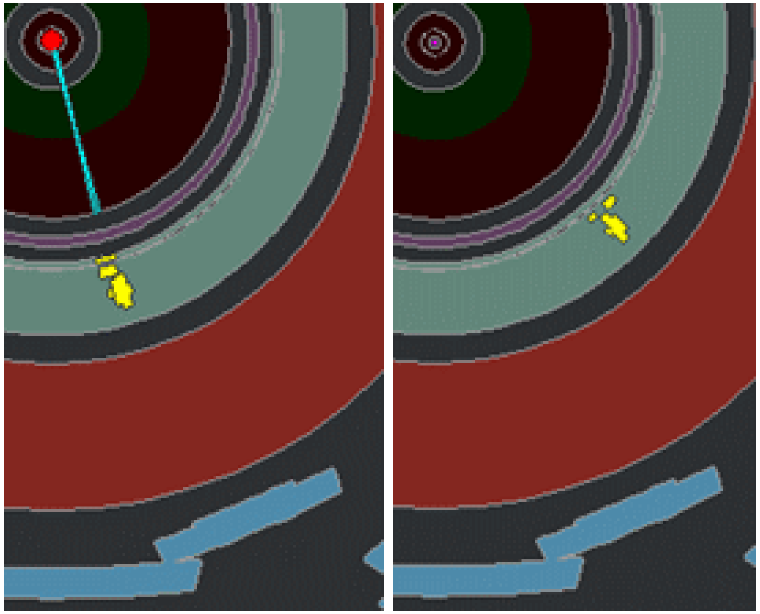
- Because of it’s long lifetime, the muon is basically a stable particle for us (cτ ~ 700 m)
- It does not feel the strong interaction
  - Therefore, they are very penetrating
- Muons are detected in muon detector and inner tracking detector
  - But much less combinatorics to deal with
- Reconstruct tracks in muon and inner detector
- Strategy
  - Find tracks in the muon system
  - Match with track in inner tracker
  - Combine track measurements
  - Consistent with MIP (minimum ionising particle)
    - Little or no energy in calorimeters
- Very clean signal!



Electrons and Photons

- Energy deposit in EM calorimeter
  - Energy nearly completely deposited in EM calorimeter
    - Little or no energy in had calorimeter (hadronic leakage)
  - “Narrow“ cluster in EM calorimeter
- Electrons has a track pointing to the cluster
- If there is no track: photon
  - But be careful, photons can convert before reaching the calorimeter
- Final Electron momentum measurement can come from tracking or calorimeter information (or a combination of both)
- Often want isolated electrons
  - Require little calorimeter energy or tracks in the region near the electron

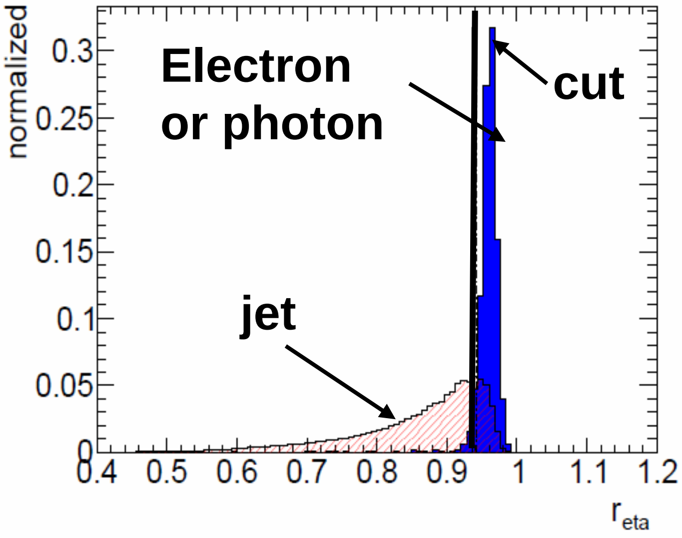


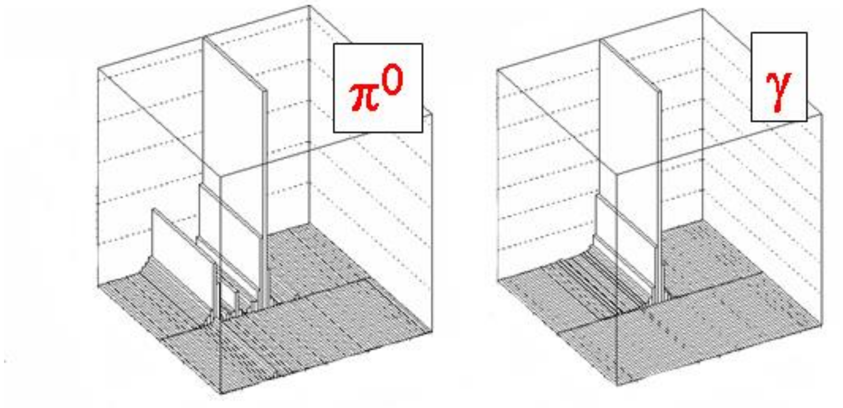


Electron and photon identification

- Leakage into 1st layer of hadronic calorimeter
- Analyse shape of the cluster in the different layers of the EM calo
  - “narrow“ e/γ shape vs “broad“ one from mainly jets
- Look for sub-structures
  - 1st EM layer with very fine granularity in ATLAS
  - Very useful for $\pi^0 \rightarrow \gamma\gamma$ / γ separation, 2 photons from π^0 tend to end up in the same cluster at LHC energies
- Look at how well your track position matches with the one from the calorimeter
- Use E/p

Transverse shower shape in 2nd EM layer (ATLAS)





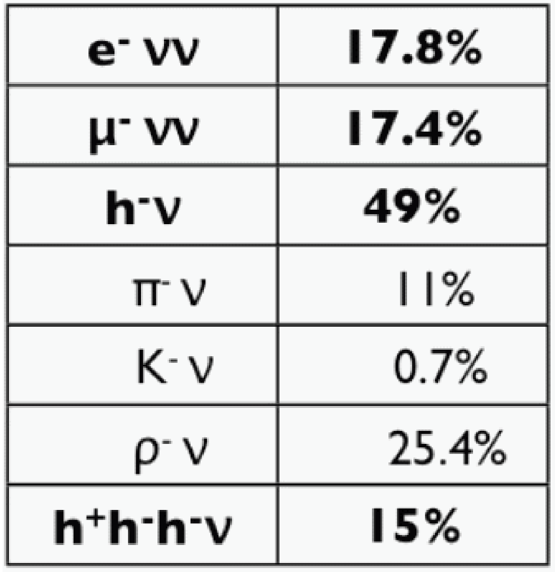
ATLAS

Electron and photon identification

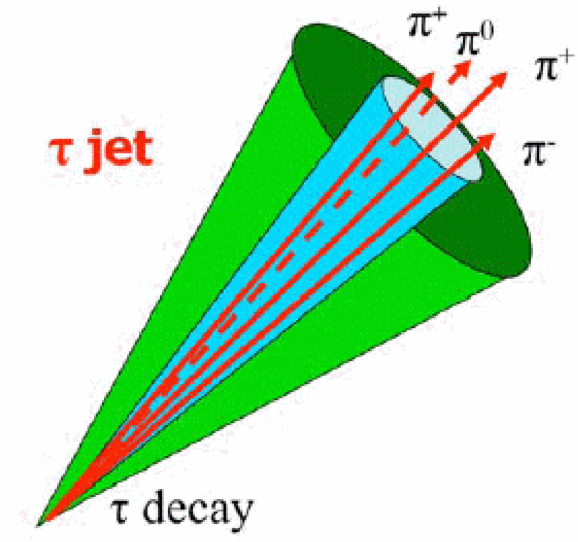
- As shower shape from jets broader it should be easy to separate electrons/photons from jets
- However have many thousands more jets than electrons, so need the rate of jets faking an electron to be very small ~10^{-4} for electrons and several times 10^{-3} for photons
- Need complex identification algorithms to give the rejection whilst keeping a high efficiency

Taus

- Decays
  - 17% in muons
  - 17% in electrons
  - ~65% of τ's decay hadronically in 1- or 3-prongs ($\tau^{\pm}\to\pi^{\pm}\nu$, $\tau^{\pm}\to\pi^{\pm}\nu+n\pi^{0}$ or $\tau^{\pm}\to3\pi^{\pm}\nu$, $\tau^{\pm}\to3\pi^{\pm}\nu+n\pi^{0}$)
- For reconstruct hadronic taus
  - Look for "narrow" jets in calorimeter (EM + hadronic)
    - i.e. measure EM and hadronic radius (measurement of shower size in η-φ): $\sum E_{cell}\cdot R^2_{cell}/\sum E_{cell}$
  - Form ΔR cones around tracks
    - tau cone
    - isolation cone
  - Associate tracks (1 or 3)

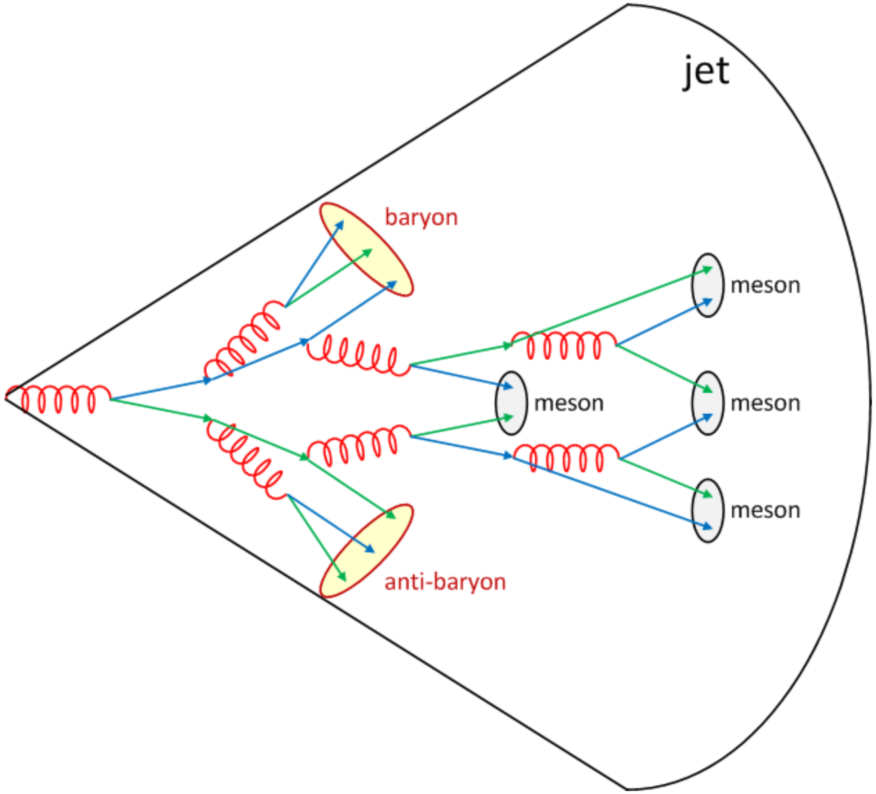


$e^- \nu\nu$	**17.8%**
$\mu^- \nu\nu$	**17.4%**
$h^-\nu$	**49%**
$\pi^- \nu$	11%
$K^- \nu$	0.7%
$\rho^- \nu$	25.4%
$h^+h^-h^-\nu$	**15%**



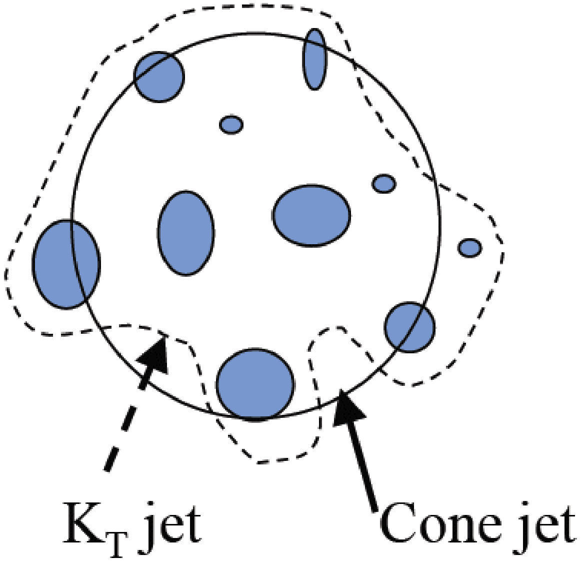
Jets

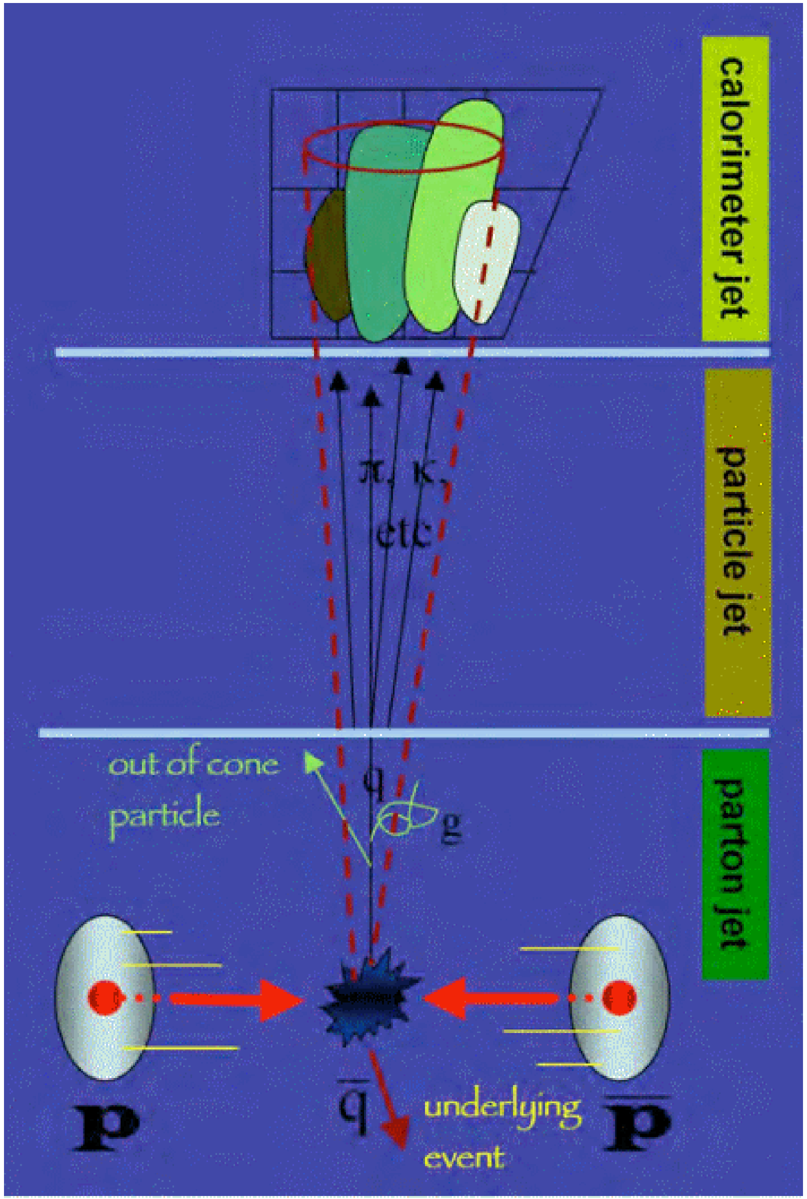
- In “nature” do not observe quarks and gluons directly, only hadrons, which appear collimated into **jets**
- Jet definition (experimental point of view): bunch of particles generated by hadronisation of a common otherwise confined source
  - Quark-, gluon fragmentation
- Signature
  - Energy deposit in EM and hadronic calorimeters
  - Several tracks in the inner detector



Jet Reconstruction

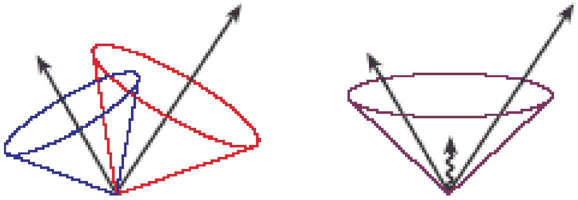
- How to reconstruct the jet?
  - Group together the particles from hadronisation
  - 2 main types
    - Cone
    - kT



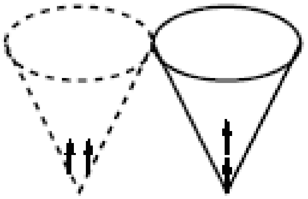


Theoretical requirement to jet algorithm choices

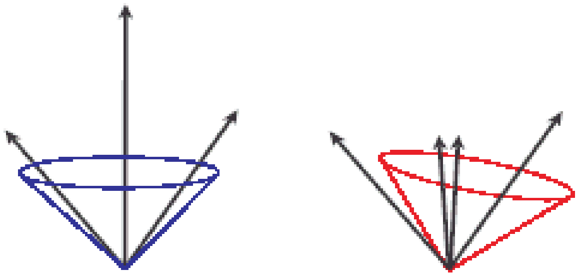
- Infrared safety
  - Adding or removing soft particles should not change the result of jet clustering
- Collinear safety
  - Splitting of large p_T particle into two collinear particles should not affect the jet finding
- Invariance under boost
  - Same jets in lab frame of reference as in collision frame
- Order independence
  - Same jet from partons, particles, detector signals
- Many jet algorithms don’t fulfill above requirements!



infrared sensitivity
(artificial split in absence of soft gluon radiation)

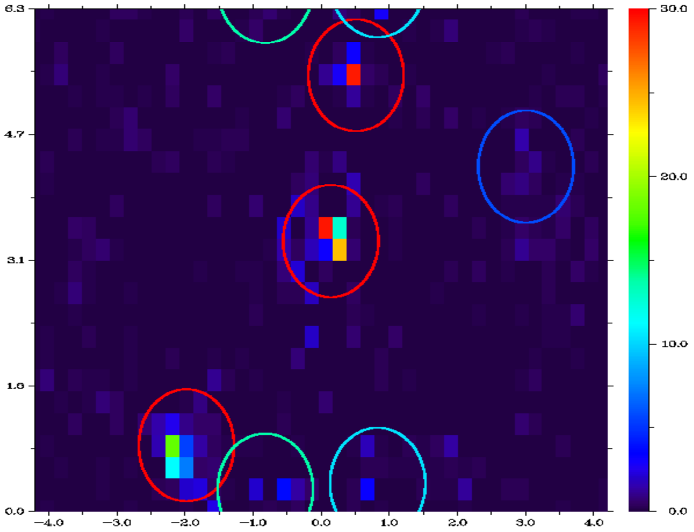


collinear sensitivity (1)
(signal split into two towers below threshold)



collinear sensitivity (2)
(sensitive to E_t ordering of seeds)

Types of jet reconstruction algorithms: cone

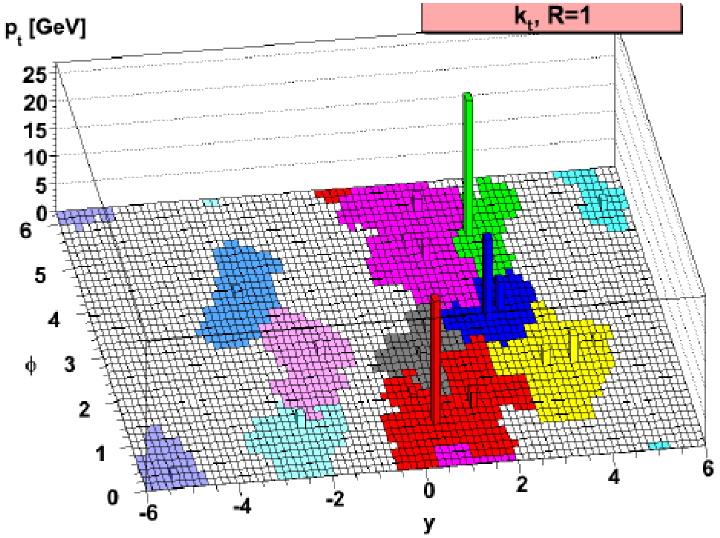


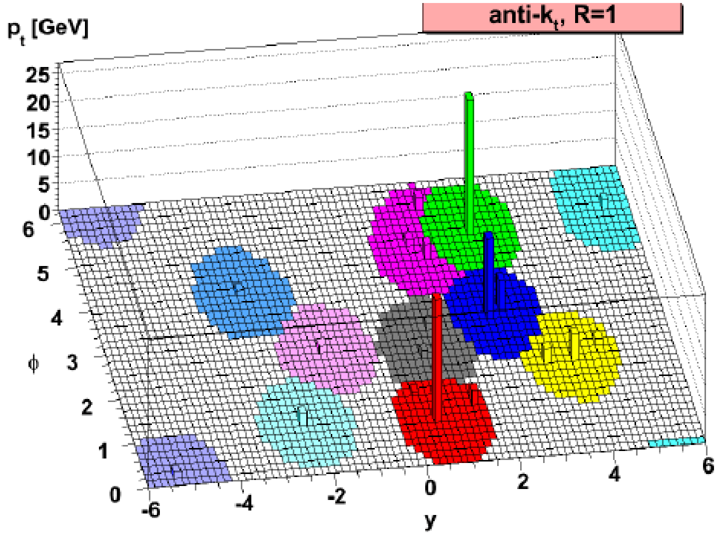
Example: iterative cone algorithms

- Find particle with largest p_T above a seed threshold
- Draw a cone of fixed size around this particle
  - $\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} < R_{\mathrm{cone}}$
- Collect all other particles in cone and re-calculate cone directions
- Take next particle from list with largest p_T seed threshold
- Repeat procedure and find next jet candidate
- Continue until no more jet above threshold can be reconstructed
- Check for overlaps between jets
  - Add lower p_T jet to higher p_T jet if sum of particle p_T in overlap is above a certain fraction of the lower p_T jet (merge)
  - Else remove overlapping particles from higher p_T jet and add to lower p_T jet (split)
- All surviving jet candidates are the final jets
- Different varieties: (iterative) fixed cone, seedless cone, midpoint…

Types of jet reconstruction algo.: Recursive Recombination

- Motivated by gluon splitting function
- Classic procedure
  - Calculate all distances d_{ji} for list of particles / cell energies / jet candidates
    - $d_{ij} = \min(d_i, d_j)\Delta R_{ij}^2 / R^2$ with $d_i = p_{Ti}^{2n}$, n=1
  - Find smallest d_{ij}, if lower than cutoff combine (combine particles if relative p_T < p_T of more energetic particle)
  - Remove i and j from list
  - Recalculate all distances, continue until all particles are removed or called a jet
- Alternatives
  - Cambridge / Aachen (n=0)
    - Uses angular distances only
  - Anti-kT (n= -1, preferred by ATLAS/CMS)
    - First cluster high E with high E and high E with low E particles

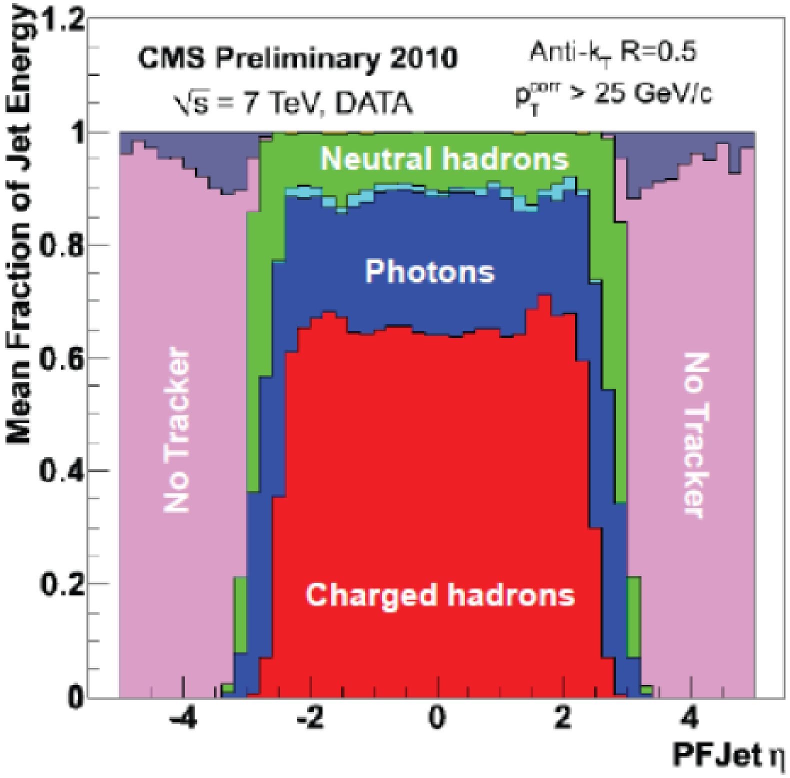




→This keeps jets nicely round

Energy Flow

- You might want to combine tracking with calorimeter information
  - See Dave‘s talk
- Use “best measurement” of each component
  - Charged tracks = Tracker
  - e/photons = Electromagnetic calorimeter
  - Neutral hadrons from hadronic calo: only 10%
- Critical points:
  - Very fine granularity
  - Very large number of channels
  - Confusion due to shower overlaps in calorimeter



- Successfully used for ALEPH experiment and now by CMS experiment (in both case rather poor HCAL)

Missing Transverse Energy

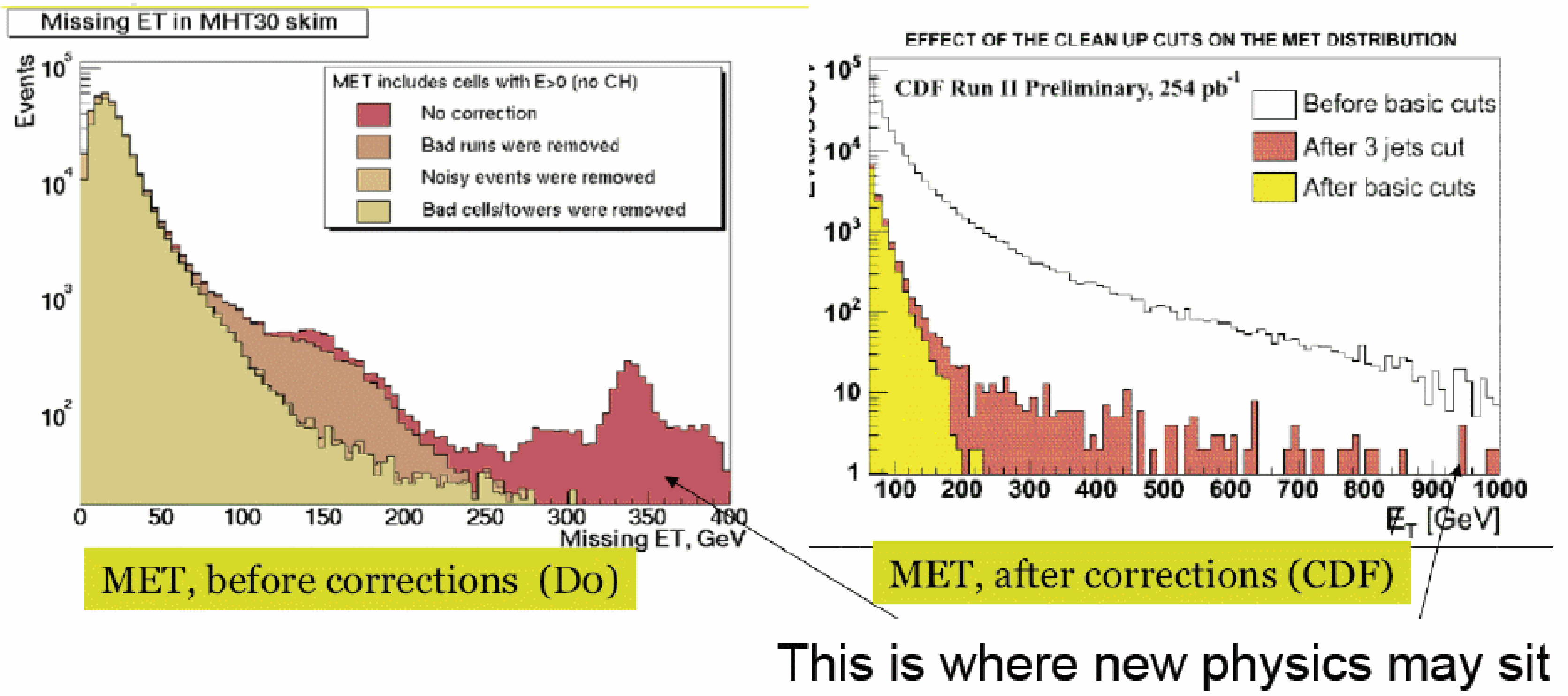
- Missing energy is not a good quantity in a hadron collider as much energy from the proton remnants are lost near the beampipe
- Missing transverse energy (E_T^{miss}) much better quantity
  - Measure of the loss of energy due to neutrinos
- Definition:
  - $\not{E}_T \equiv -\sum_i E_T^i \hat{n}_i = -\sum_{\textit{all}\ \text{visible}} \vec{\mathrm{E}}_\mathrm{T}$
- Best missing E_T reconstruction
  - Use all calorimeter cells which are from a clusters from electron, photon, tau or jet (use particle-type dependent corrections)
  - Use all other calorimeter cells
  - Use all reconstructed particles not fully reconstructed in the calorimeter
    - e.g. muons from the muon spectrometer

Missing Transverse Energy

- But it‘s not that easy...
  - Electronic noise might bias your E_T measurement
  - Particles might have ended in cracks / insensitive regions
  - Dead calorimeter cells
  - Pile-up
- Corrections needed to calorimeter missing E_T
  - Correction for muons
    - Recall: muons are MIPs
  - Correct for known leakage effects (cracks etc)
  - Particle type dependent corrections
    - Each cell contributes to missing E_T according to the final calibration of the reconstructed object (e, γ, μ, jet…)
  - Pile-up effects will need to be corrected for

Missing Transverse Energy

- Difficult to understand quantity



MET, before corrections (Do)

MET, after corrections (CDF)

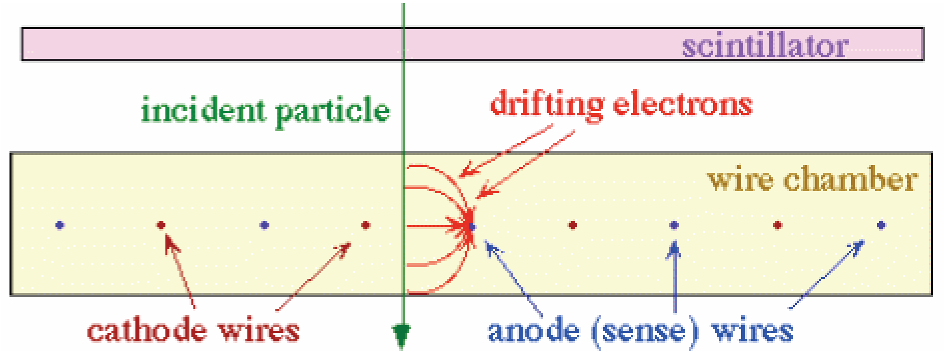
This is where new physics may sit

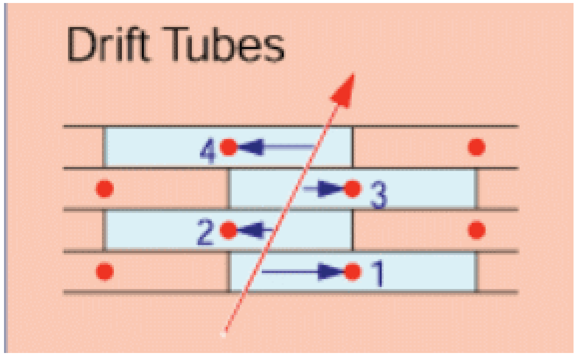
Summary

- Summarise basic features of particle identification
  - Muon, Electron, Photon, Tau, Jet, Missing E_T
  - These are the basic quantities we use as input to any of our analyses

Backup

Gas/Wire Drift Chambers

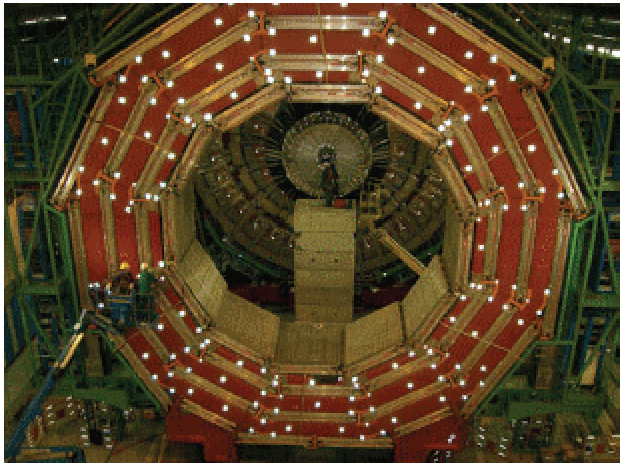


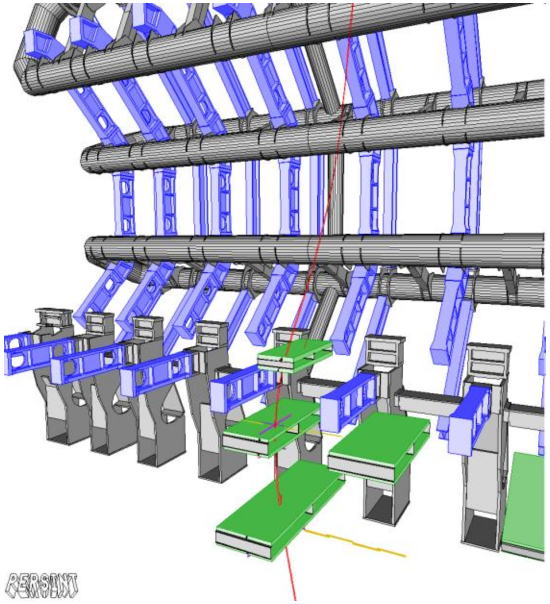


- Wires in a volume filled with a gas (such as Argon/Ethan)
- Measure where a charged particle has crossed
  - charged particle ionizes the gas.
  - electrical potentials applied to the wires so electrons drift to the sense wire
  - electronics measures the charge of the signal and when it appears.
- To reconstruct the particles track several chamber planes are needed
- Example:
  - CDF COT: 30 k wires, 180 µm hit resolution
- Advantage:
  - low thickness (fraction of X0)
  - traditionally preferred technology for large volume detectors

Muon Chambers

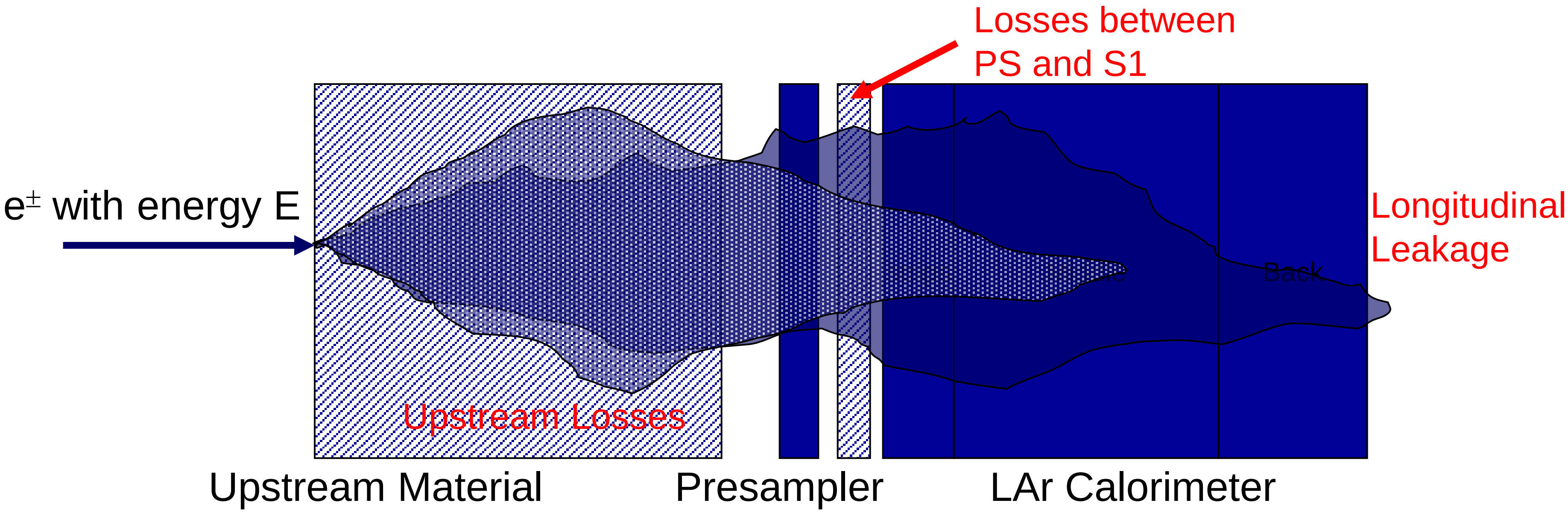
- Purpose: measure momentum / charge of muons
- Recall that the muon signature is extraordinarily penetrating
- Muon chambers are the outermost layer
- Measurements are made combined with inner tracker
- Muon chambers in LHC experiments:
  - Series of tracking chambers for precise measurements
    - RPC’s: Resistive Plate Chambers
    - DT’s: Drift Tubes
    - CSC’s: Cathode Strip Chambers
    - TGC’s: Thin Gap Chambers





Cosmic muon in MDT/RPC

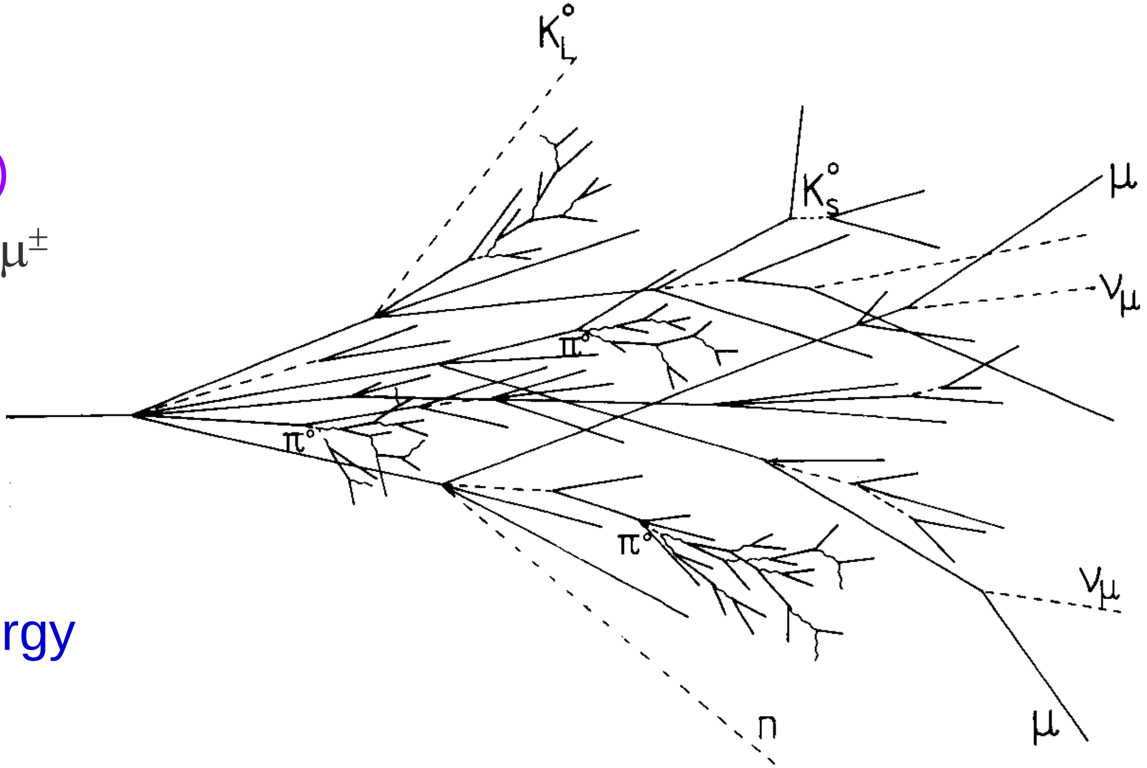
Cluster reconstruction



- Input to clustering:
  - Cells calibrated at the EM scale
- Sum energy in EM calo, correct for losses in upstream material, longitudinal leakage and possible other lossses between calo layers (if applicable)
  - e.g. $E_{rec} = \lambda\left(b + W_0 E_{pres} + E_1 + E_2 + W_3 E_3\right)$
- Typically need to find best compromise between best resolution and best linearity

Calorimeters: Hadronic Showers

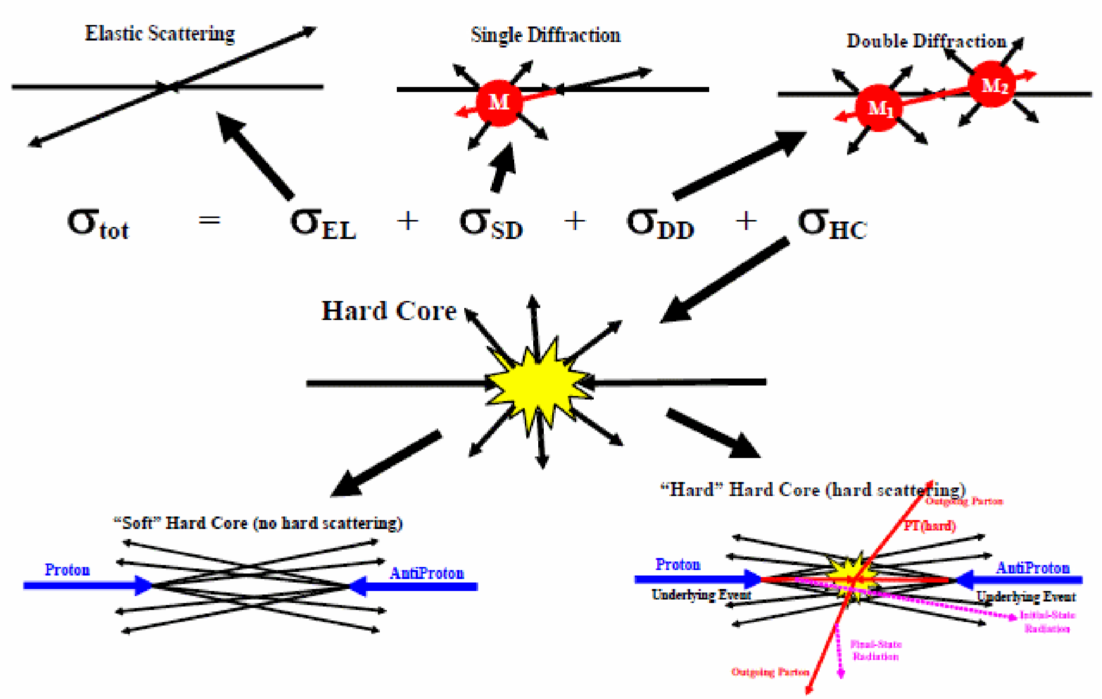
- Much more complex than EM showers
  - visible EM O(50%)
    - $e^{\pm}$, γ, $\pi^{o} \rightarrow \gamma\gamma$
  - visible non-EM O(25%)
    - ionization of $\pi^{\pm}$, p, $\mu^{\pm}$
  - invisible O(25%)
    - nuclear break-up
    - nuclear excitation
  - escaped O(2%)
- Only part of the visible energy is measured (e.g. some energy lost in absorber in sampling calorimeter)
  - calibration tries to correct for it



- Useful things to know in the LHC environment

Minimum bias

- “soft“ partonic interactions
- “all events, with no bias from restricted trigger conditions”
- On average
  - low transverse energy produced
  - low number of particles produced
- Minimum bias contains following processes



Pile-up

- One single bunch crossing may produce several collisions between protons seen in the detector → pile-up
- At design lumi of 10^{34}cm^{-2}s^{-1} we expect ~20 of them (in time pile-up)
- Most of them come from “soft“ interactions and will create minimum bias events
- As readout times at the LHC are typically larger than the bunch spacing pile-up also expected in the previous or following bunches (out of time pile-up)

Underlying event

- In collision we have
  - Hard subprocess
  - Initial and final state radiation
  - Multiple parton-parton interactions
  - Beam remnants and other outgoing partons
  - Pileup
- Underlying event is everything without the hard interaction in leading order
- Nice theoretical recipe, but not trivial for an experimentalist