From Raw Data to Physics Results I & II

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Outline

- To present the essential ideas on how to use HEP detectors measurements to extract physics results at the LHC
  - Emphasis put on methods used mostly in ATLAS
- Introduction
- Basic mesurements with HEP detectors
  - Tracks
  - Calorimeter cluster energy
  - Reconstruction of Physics objects
- HEP data
- Physics analysis example

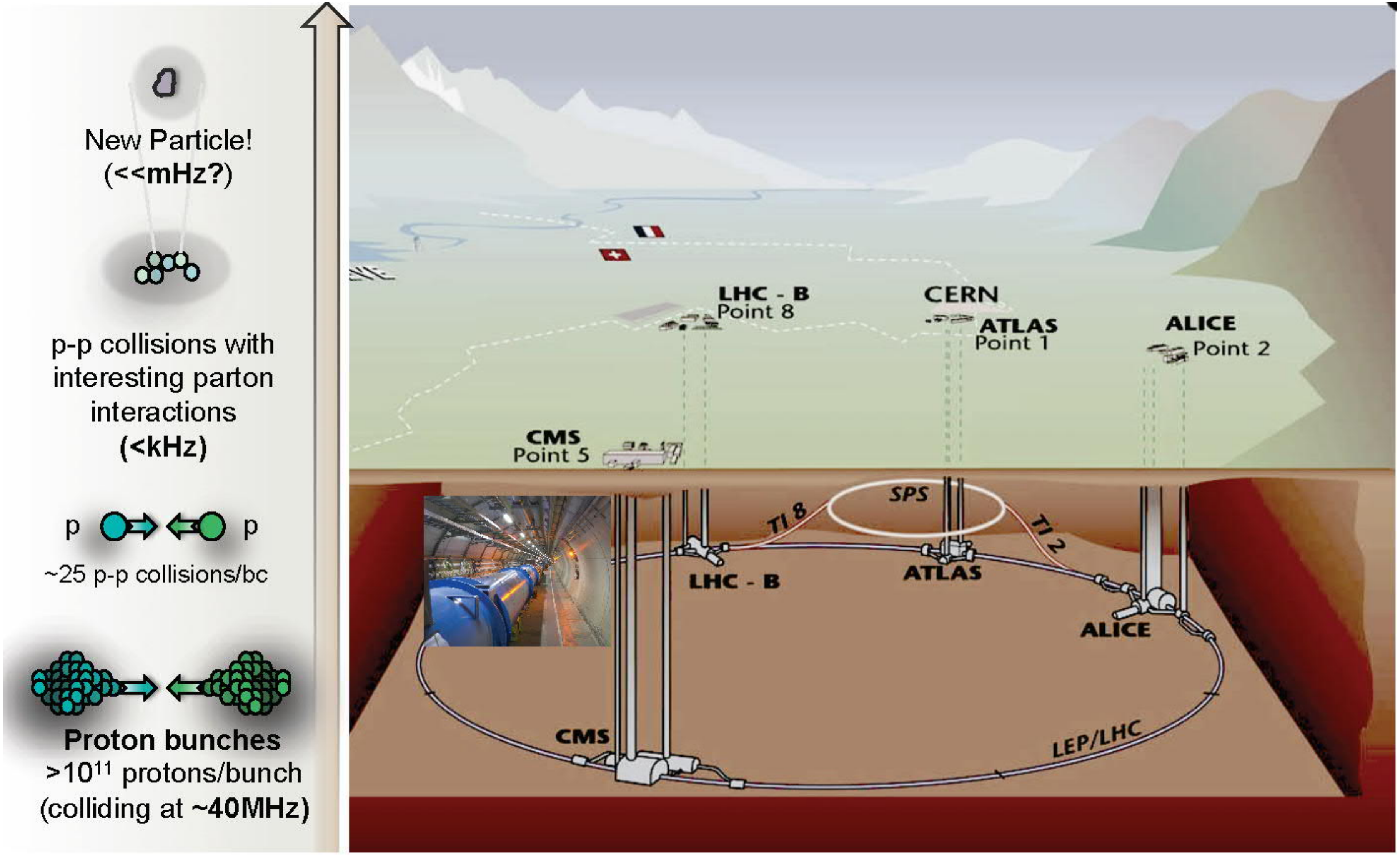
Data analysis in HEP experiments

- Collect data from sub-detectors channels (millions)
- Decide to read out everything or only interesting events (Trigger)
- Build the event (put info together)
- Store the data
- Analyze them
  - reconstruction, user analysis algorithms, data volume reduction
- Compare data and theory

This lecture !!

- Other components of physics analysis are part of other lectures:
  - Monte Carlo detector simulation
  - Event Generators
  - Statistical analysis

The Large Hadron Collider (LHC)



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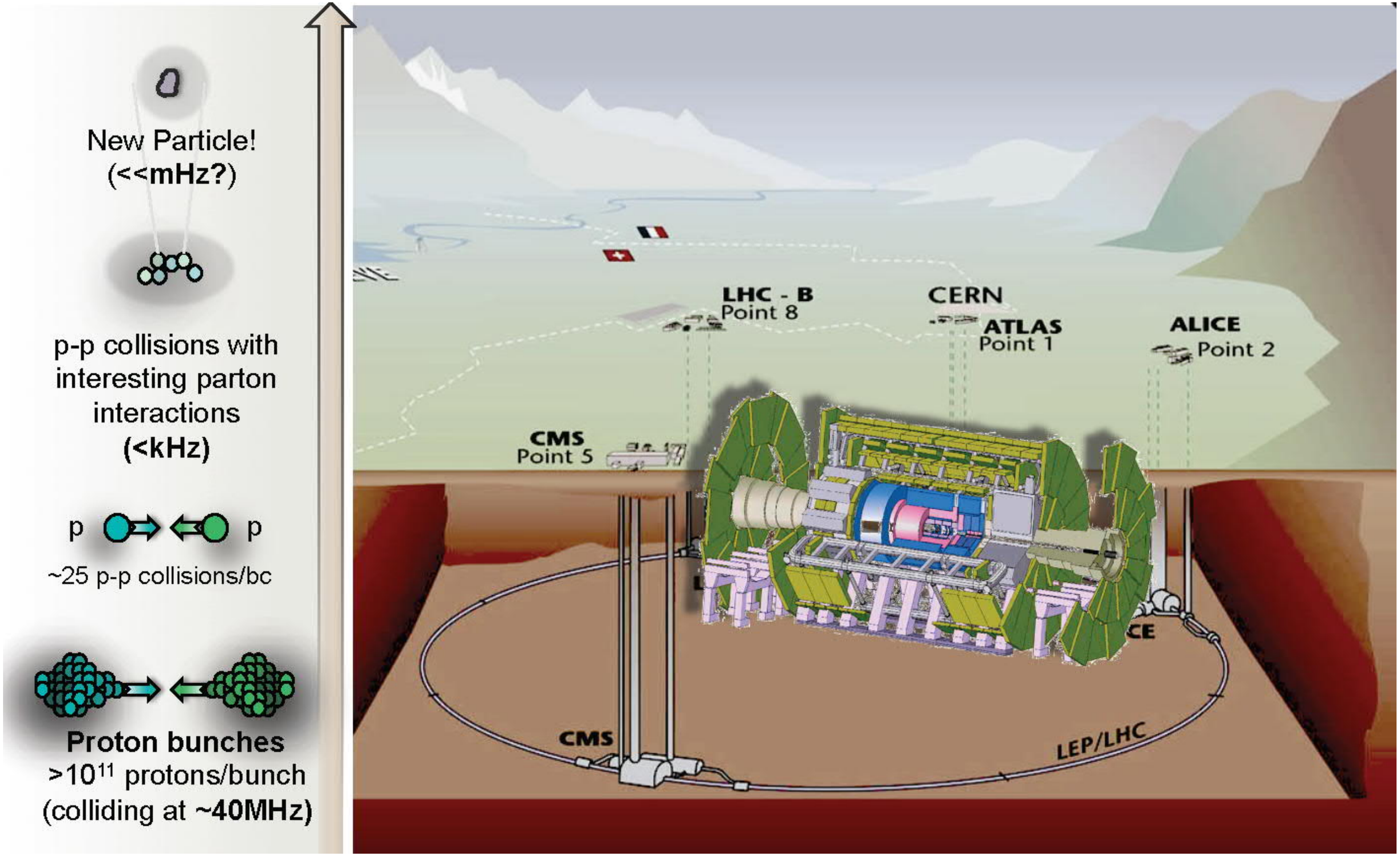
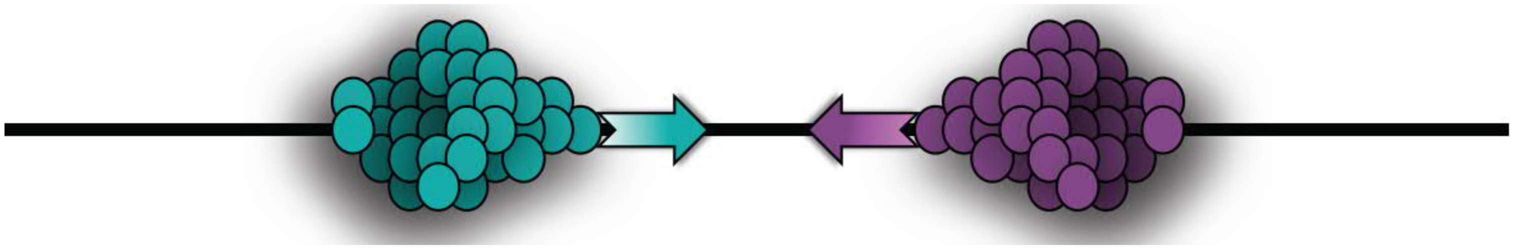


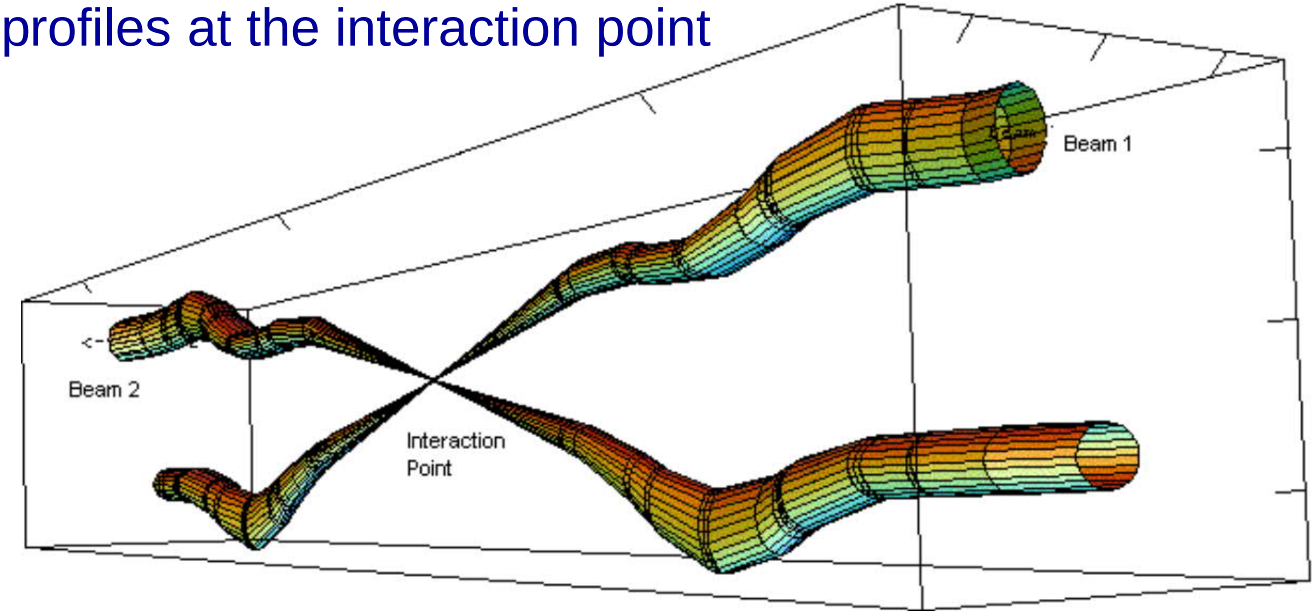
Proton-proton collisions at the LHC



Proton bunches >10^{11} protons/bunch

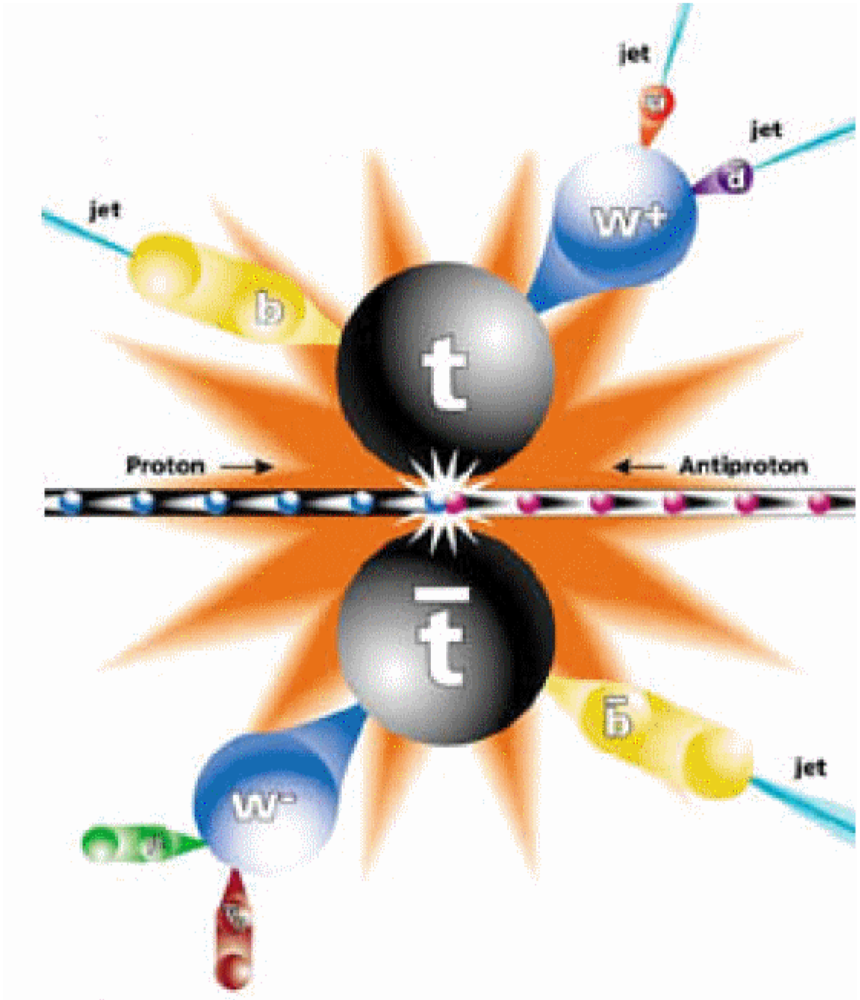
- colliding at 13TeV and at 40MHz in Run-2
- collided at 7/8TeV and at 20MHz in Run-1

LHC beam profiles at the interaction point

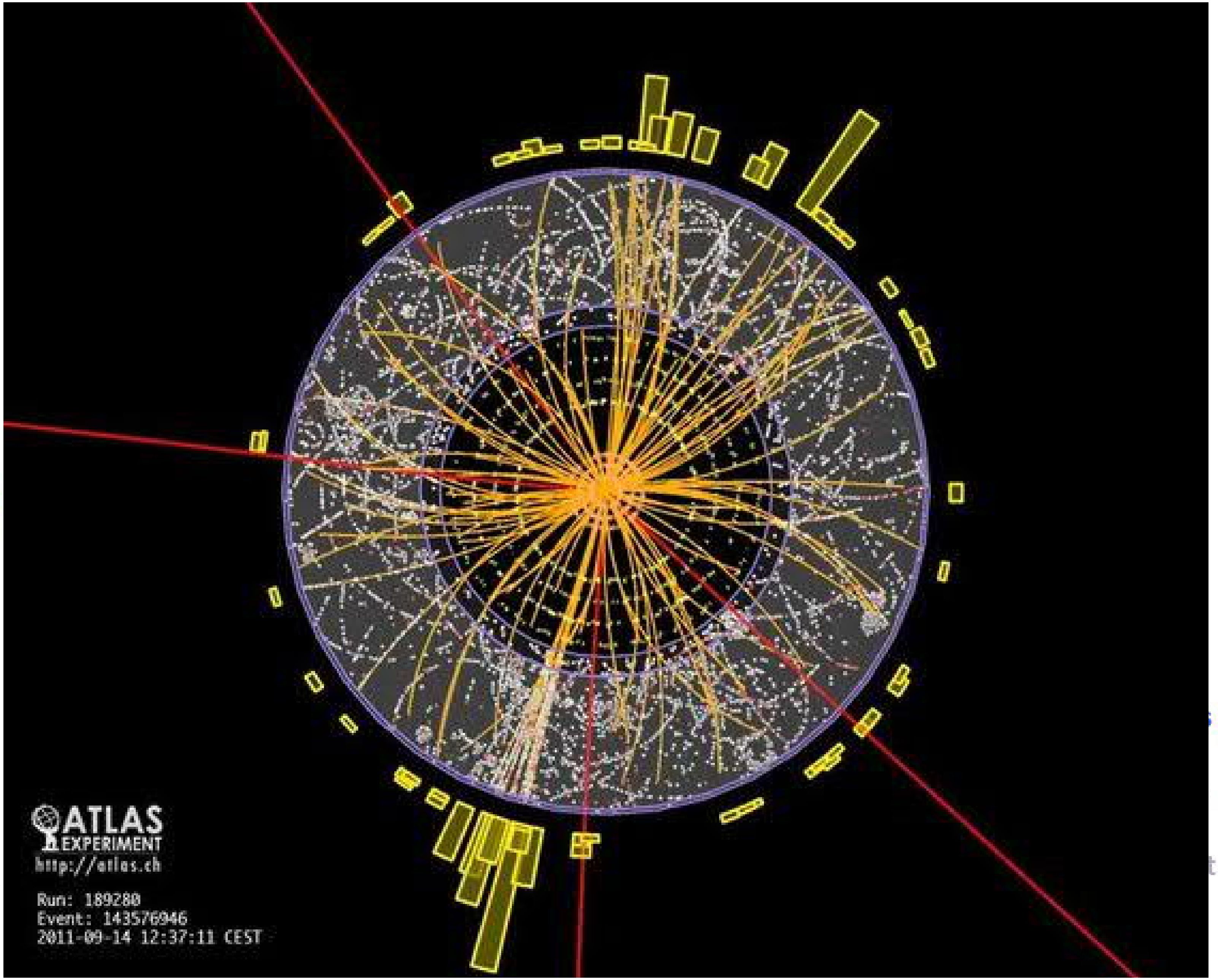


Collision: What happens?

- 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
- Cascade of particles is produced
- Therefore
  - We cannot “see” the interaction
  - We need to identify all final particles and their properties in order to retrieve the “history” of the physics process. In HEP words, we need to **reconstruct the event**.
- HEP detectors have to give us all needed information



A more realistic collision picture



Detectors in HEP experiments

Global Detector Systems

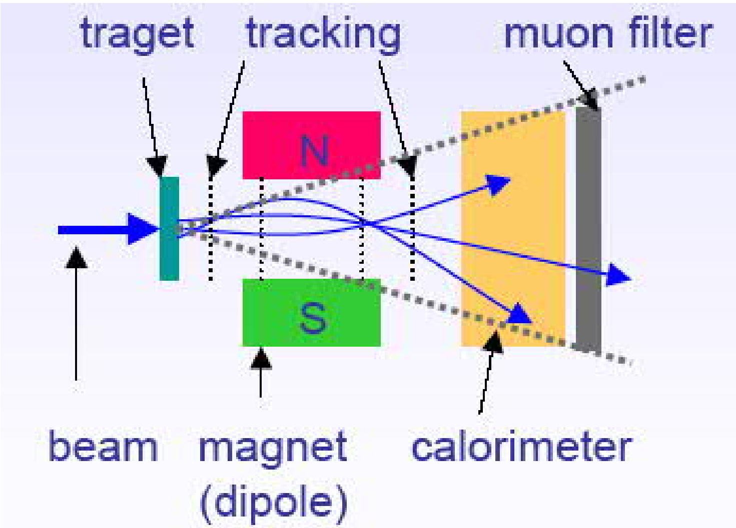
Overall Design Depends on:

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

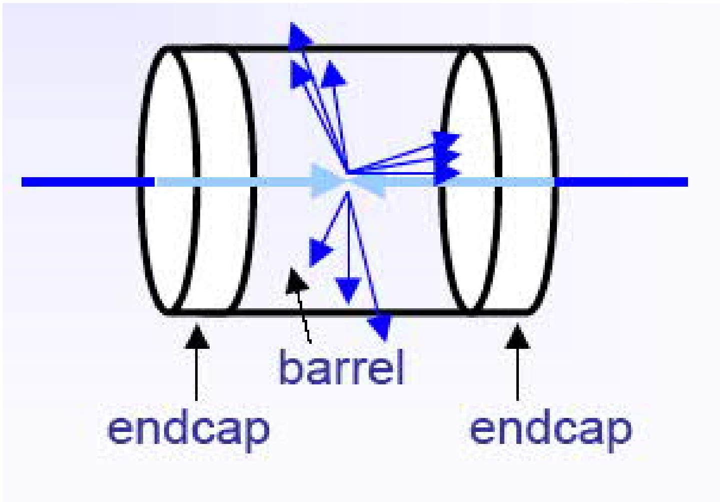
No single detector does it all…

→ Create detector systems

Fixed Target Geometry



Collider Geometry



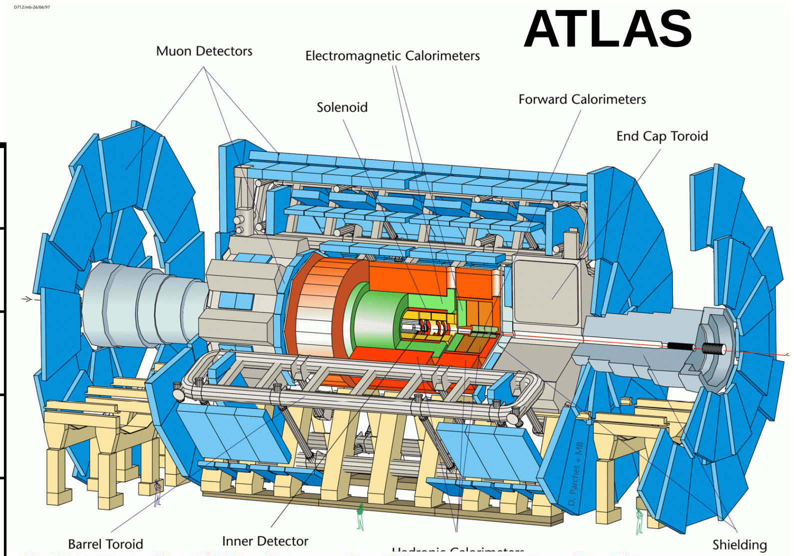
- **Limited solid angle (dΩ□ coverage (forward)**
- **Easy access (cables, maintenance)**

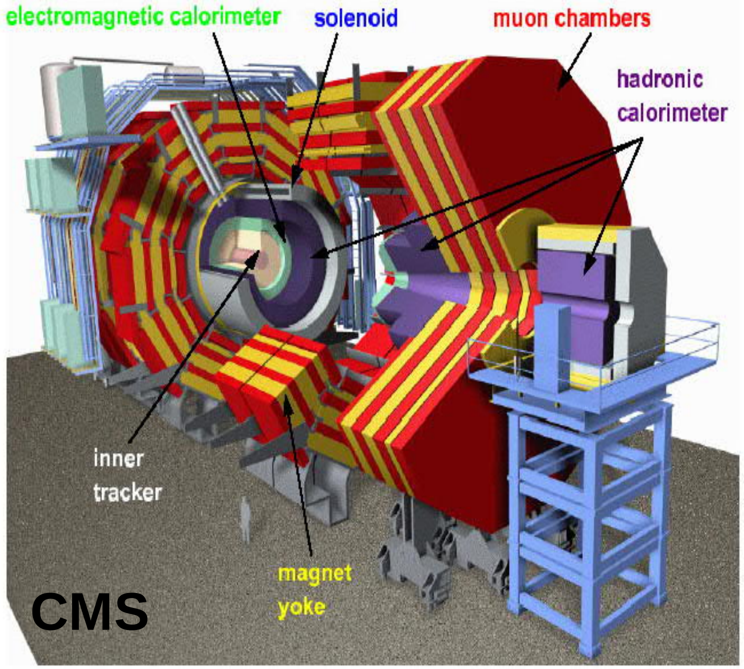
- **"full" solid angle dΩ coverage**
- **Very restricted access**

The ATLAS and CMS Detectors

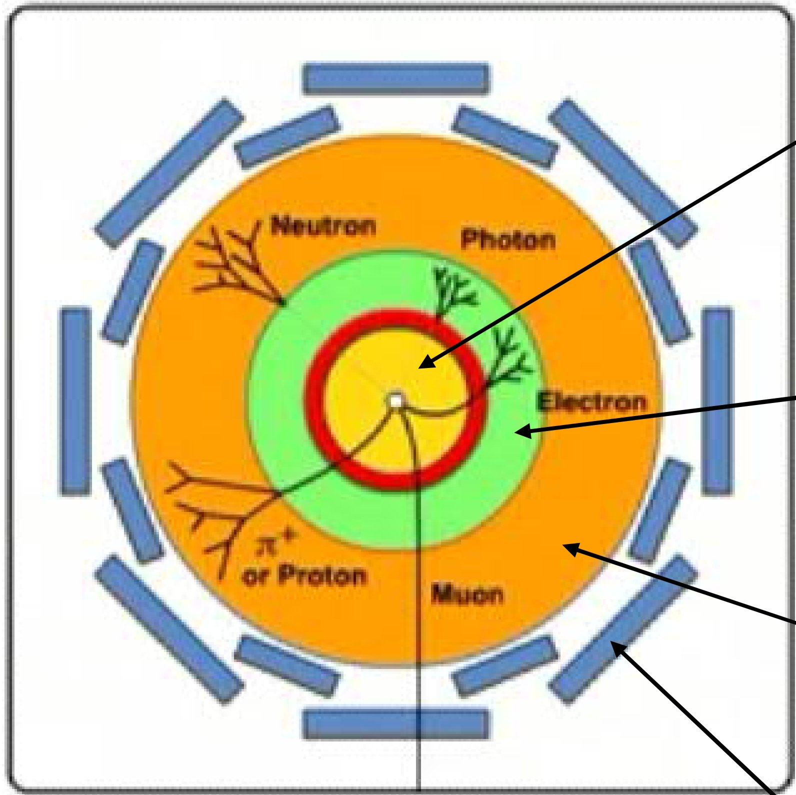
- Two different approaches for detectors

	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





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

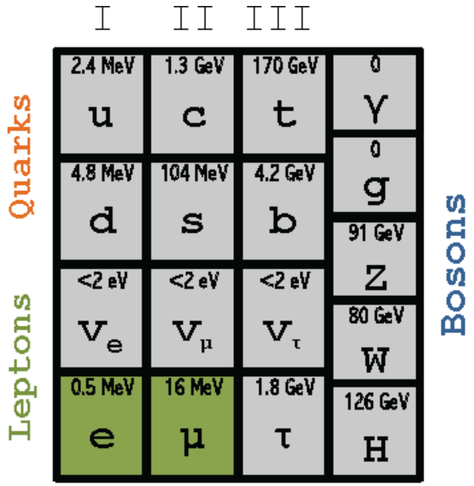
−Measure energy of hadrons (particles containing quarks), such as protons, neutrons, pions, etc.

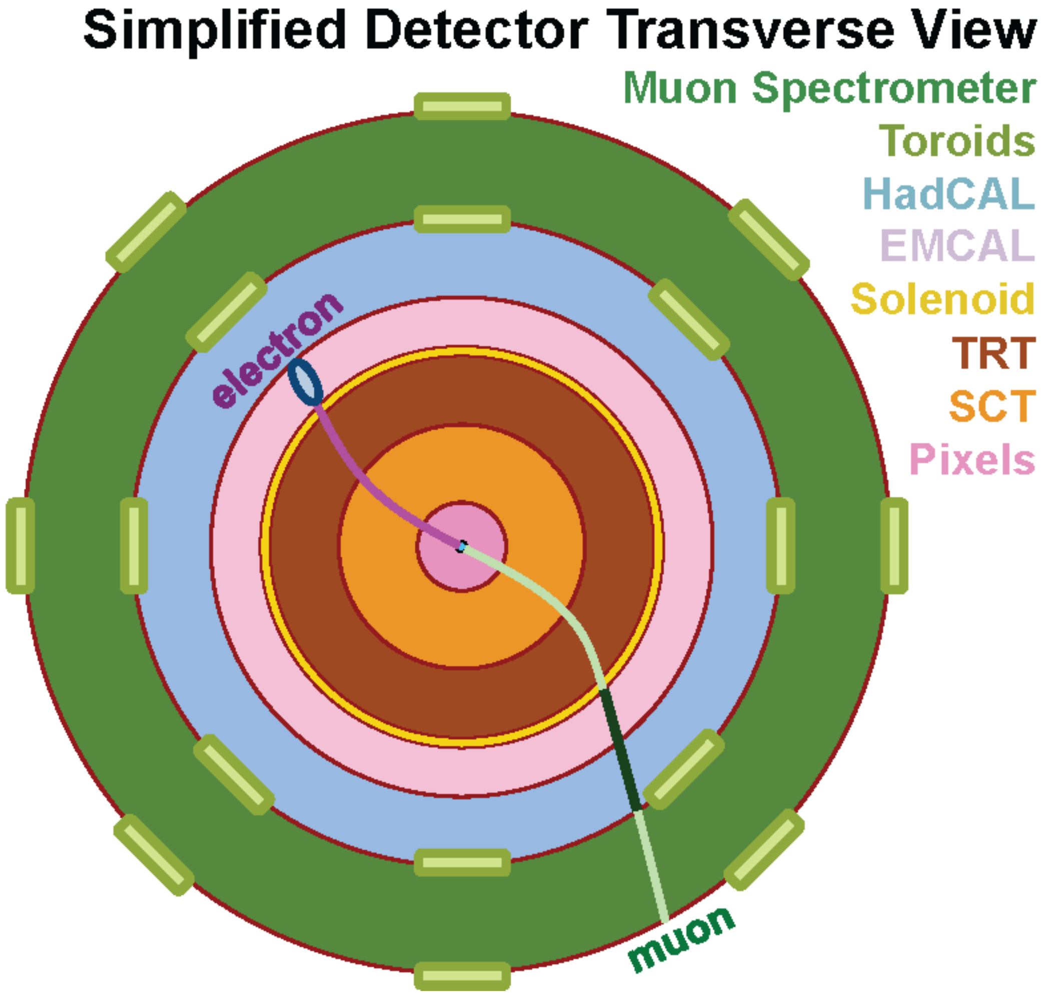
Neutrinos are only detected indirectly via 'missing energy' not recorded in the calorimeters

Muon detector

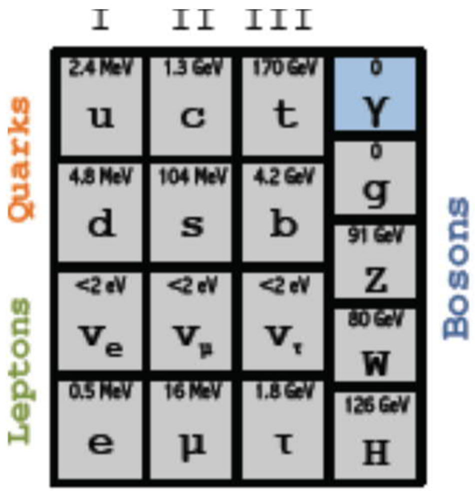
−Measure charge and momentum of muons

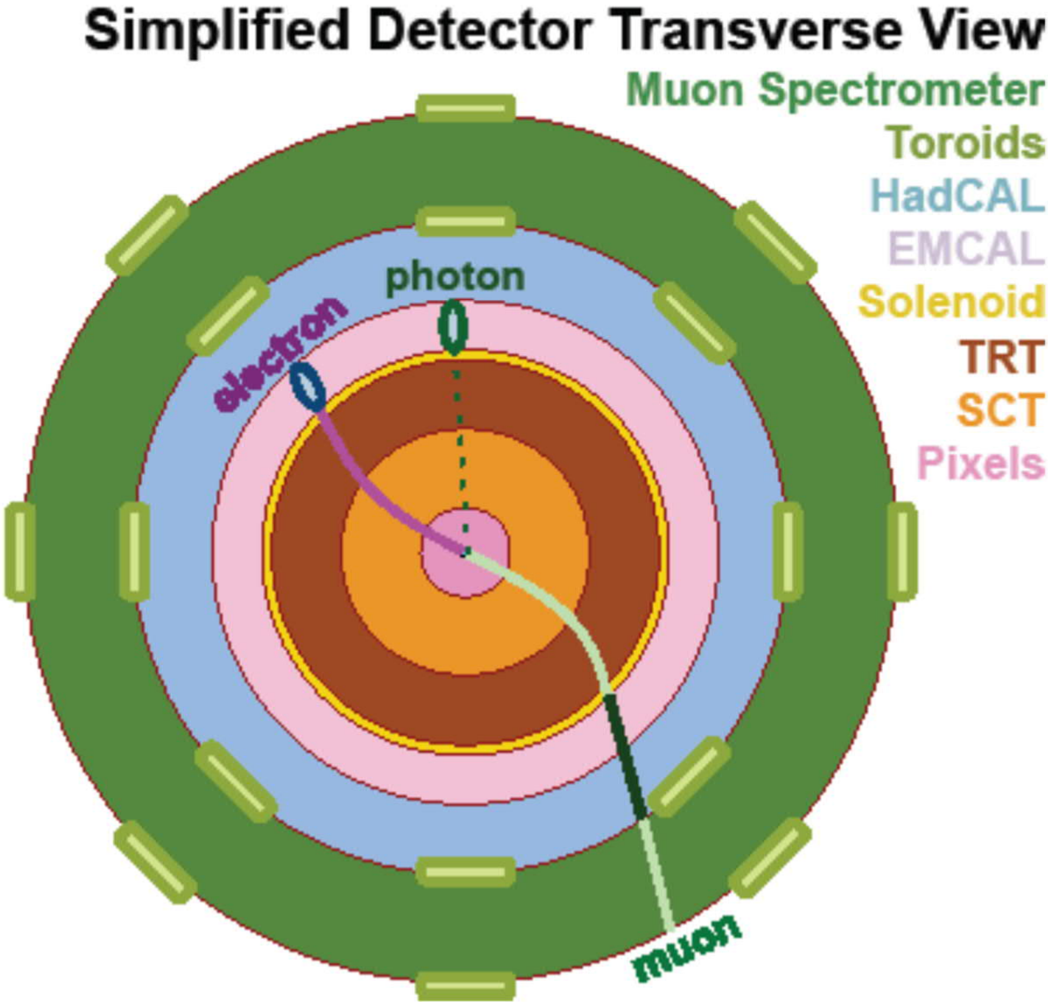
Detecting particles: electrons and muons



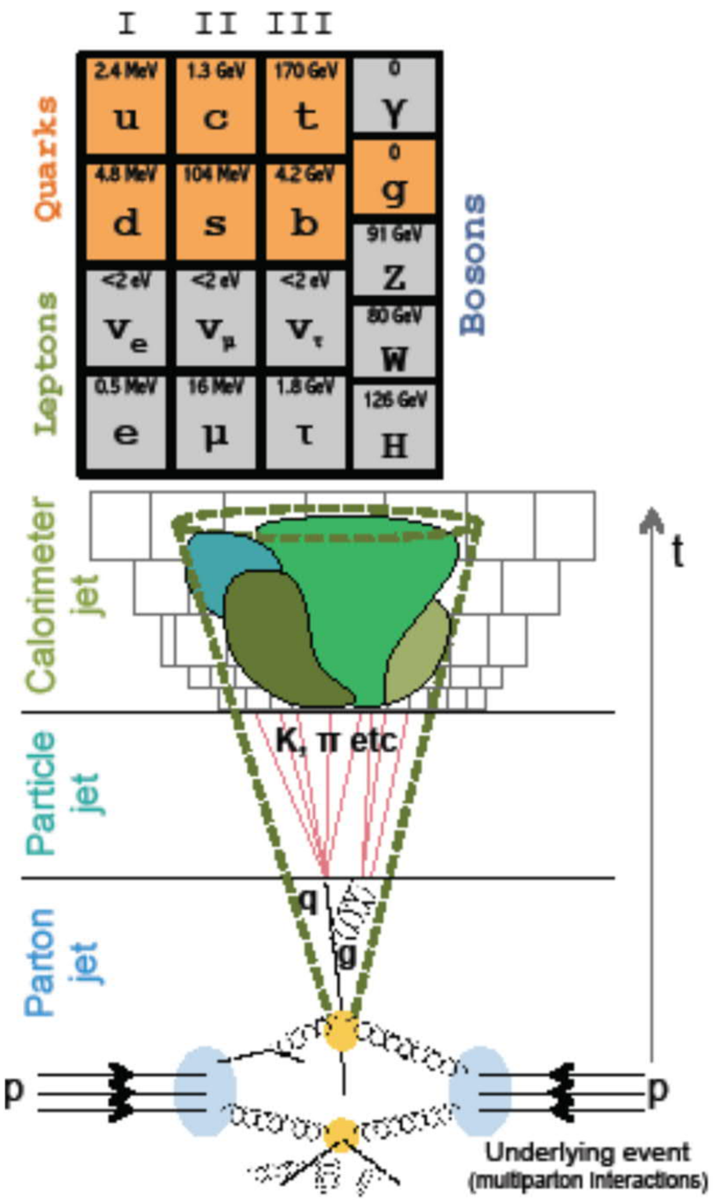


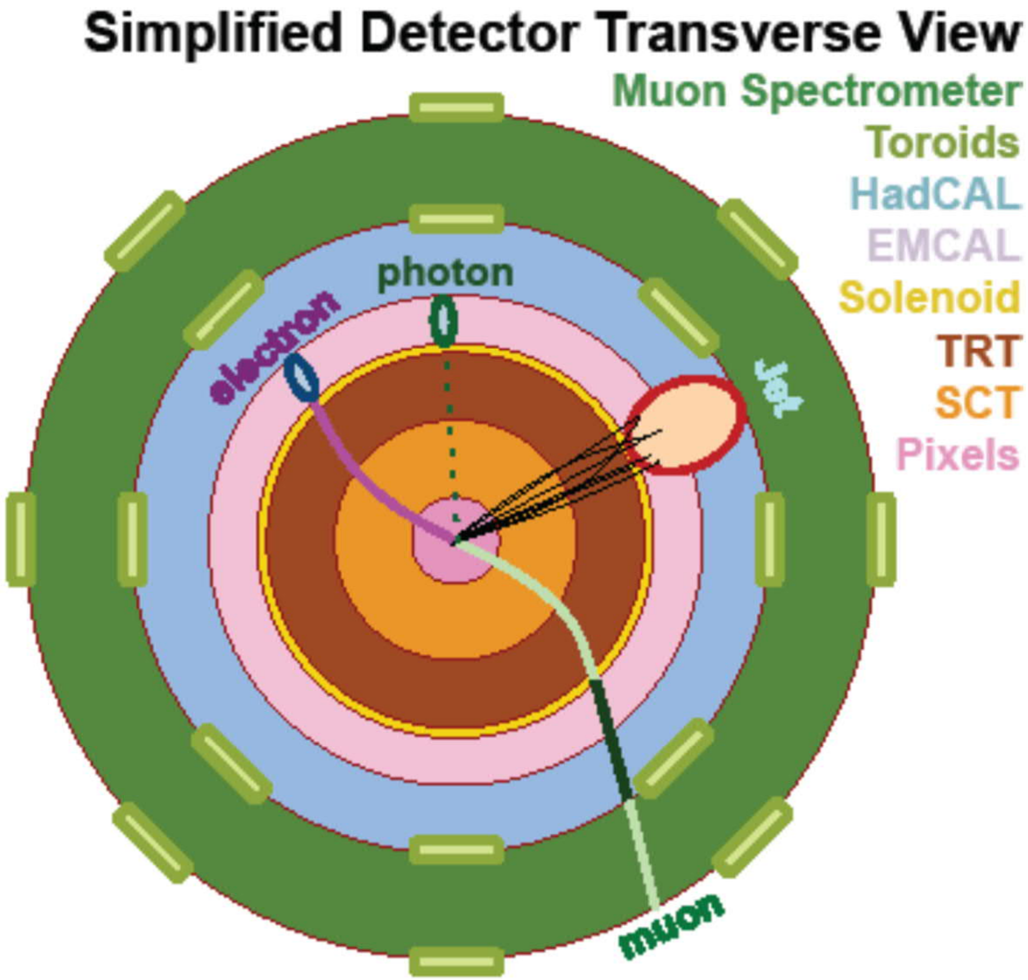
Detecting particles: photons



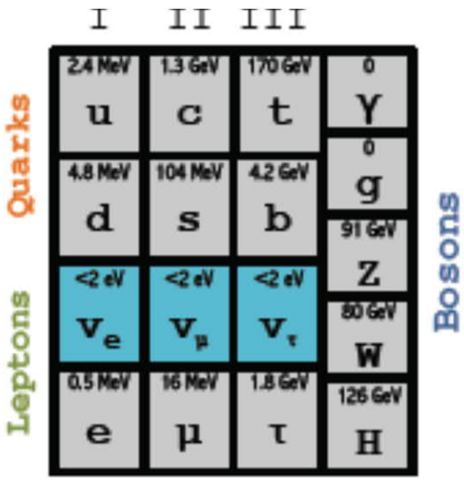


Detecting particles: jets





Detecting particles: non interacting particles

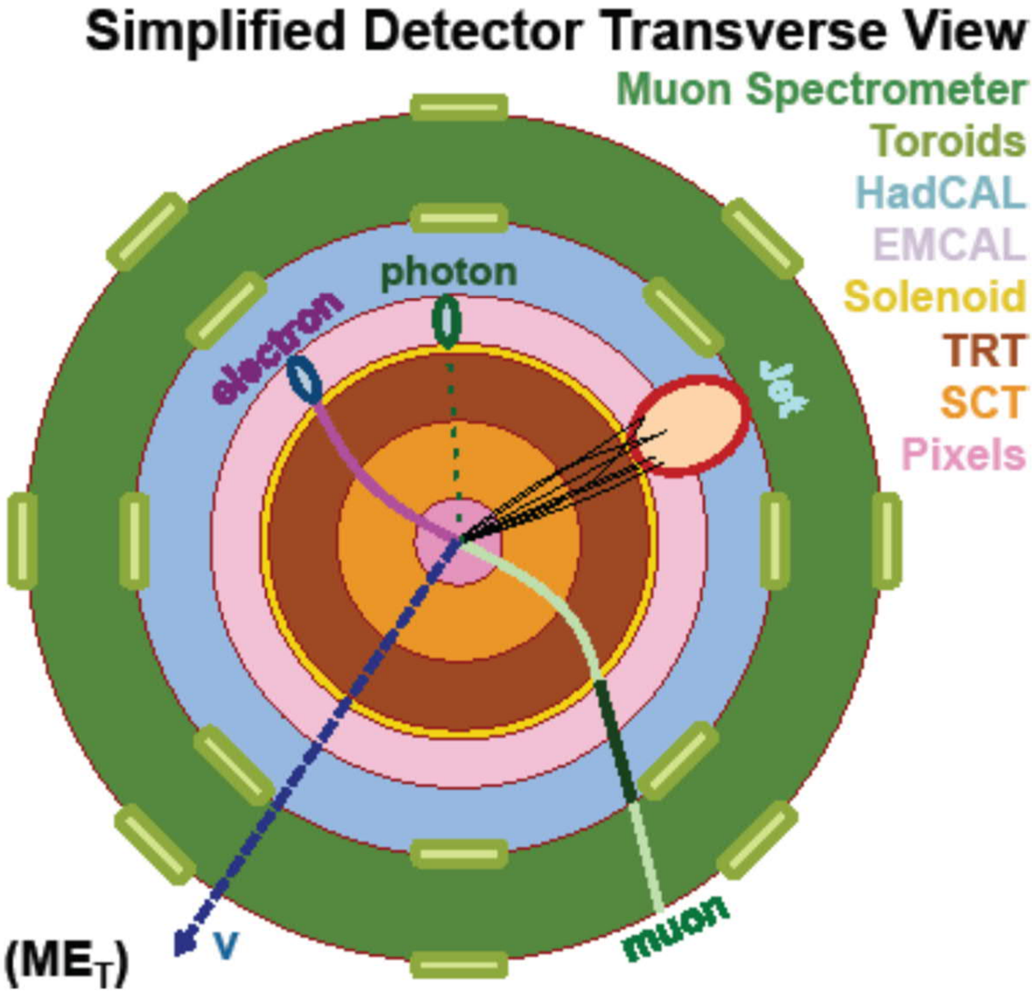


Also “invisible” particles from DM, SUSY…

In the transverse plane:

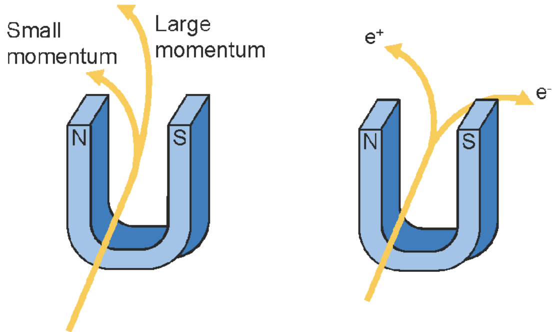
$$\sum \vec{p}_T = 0$$

Missing Transverse Momentum (ME_T)

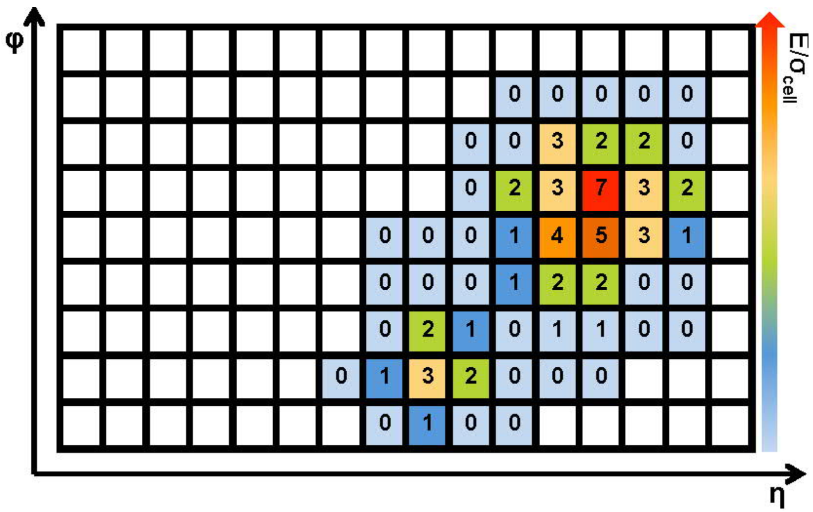


What do we really measure in HEP detectors?

Tracks: charges, momentum, Time-of-flight, energy loss



Energy deposit in calorimeter: clusters



Example: Tracking in ATLAS in Inner Detector

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

Sequence:

1. Creation of 3-dimensional Space Points in Pixel and SCT (Si-Layers)

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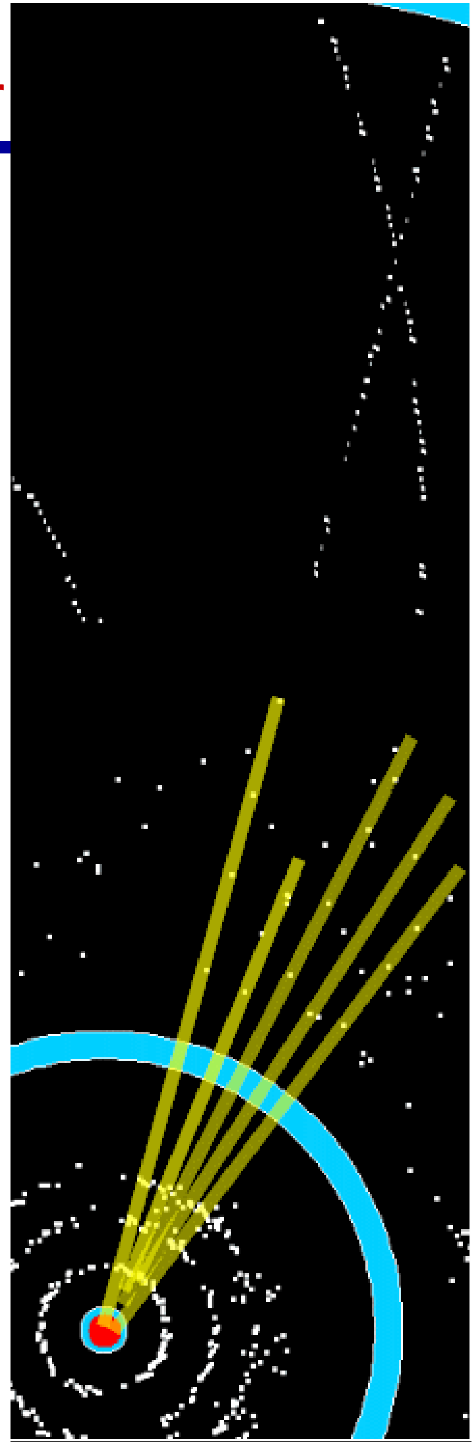

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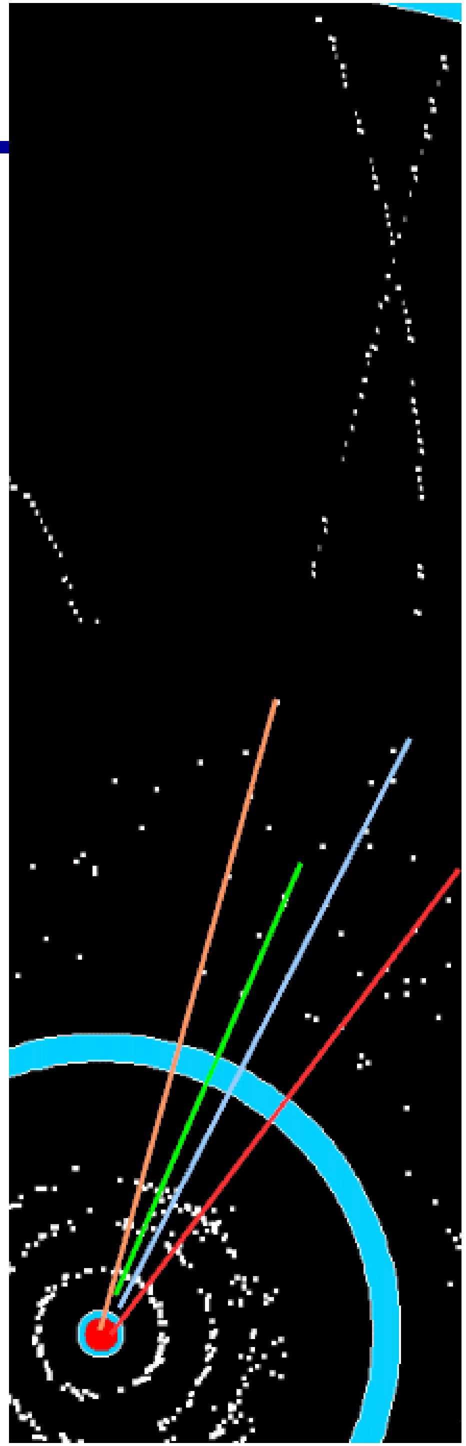

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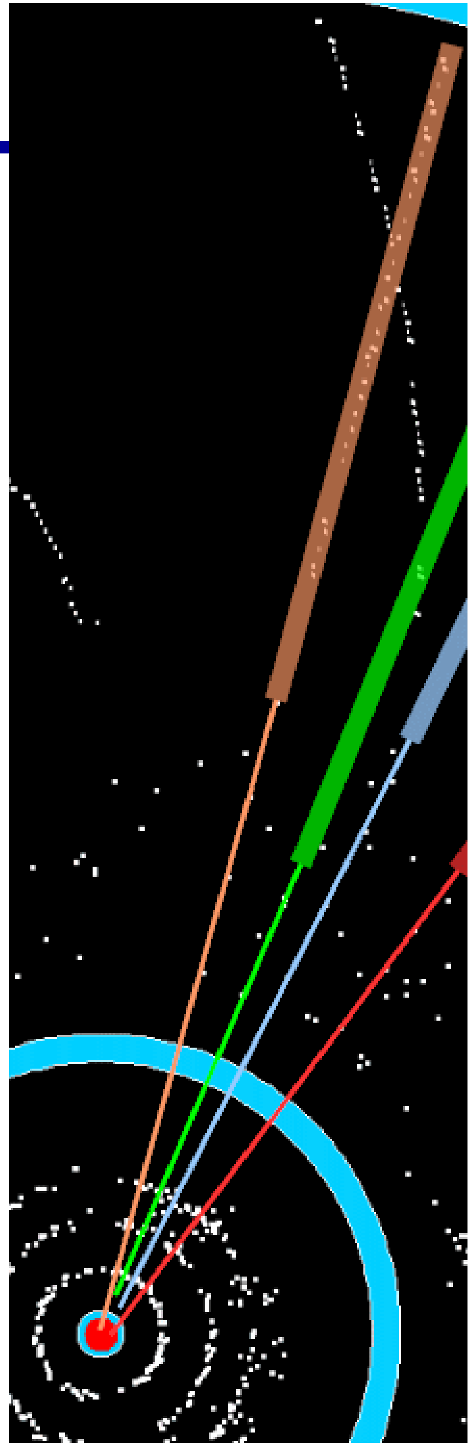

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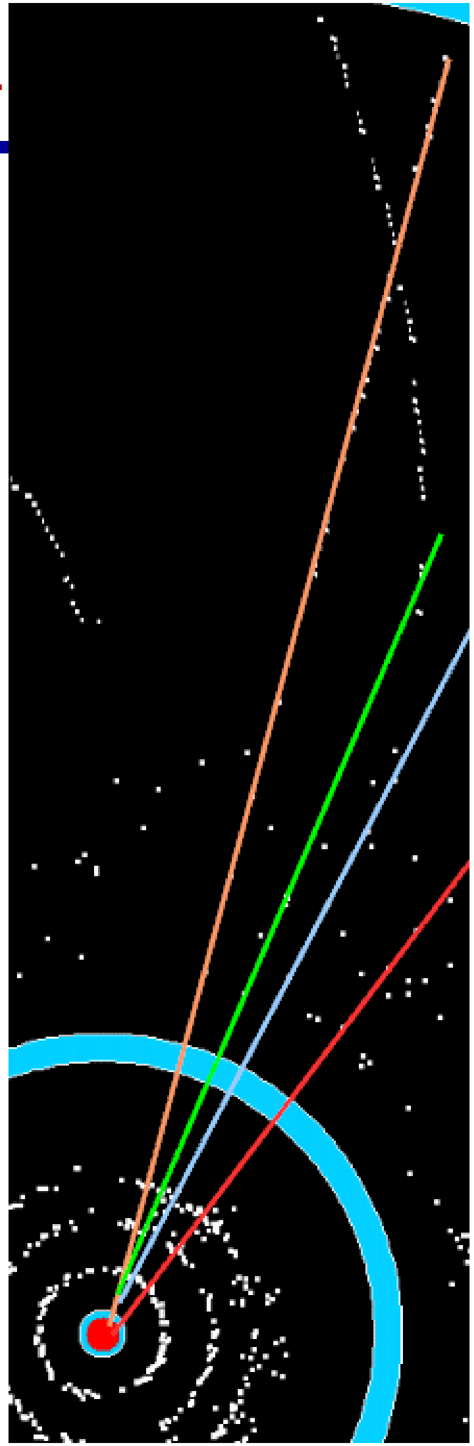
5. Track fit of Pixel, SCT and TRT measurements



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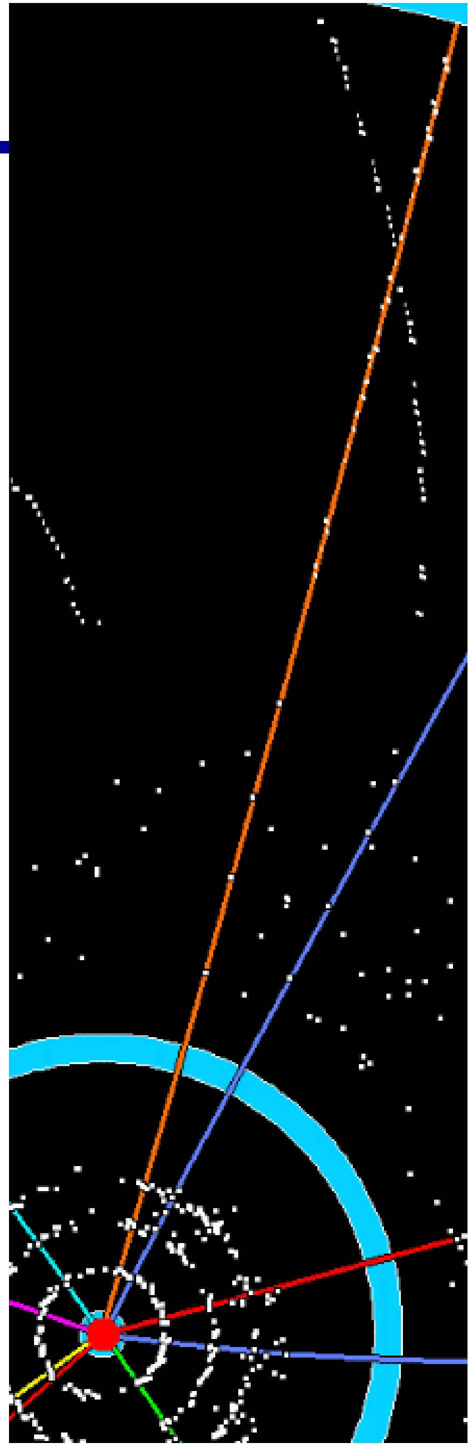
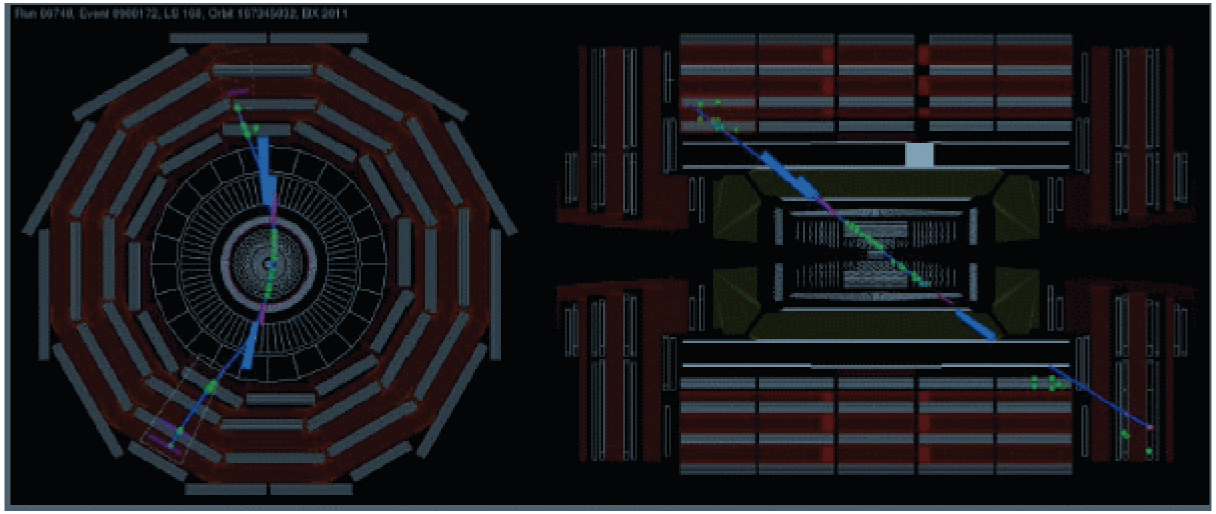
4 Extrapolation into TRT and search for compatible measurements
5. Track fit of Pixel, SCT and TRT measurements
6. Track scoring and track selection



Tracking in Muon Detector

- 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

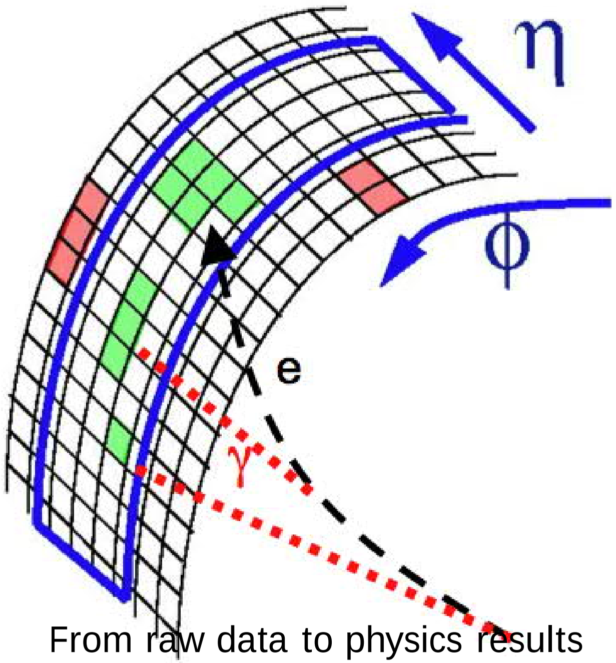


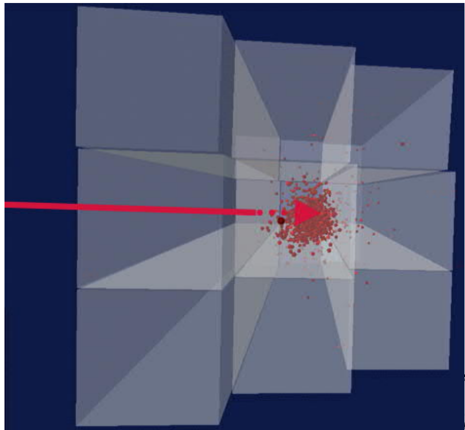
Reconstructing calorimeter energy

- Reconstruct energy deposited by charged and neutral particles
- Determine position of deposit, direction of incident particles
- Be insensitive to noise and un-correlated energy (pileup)

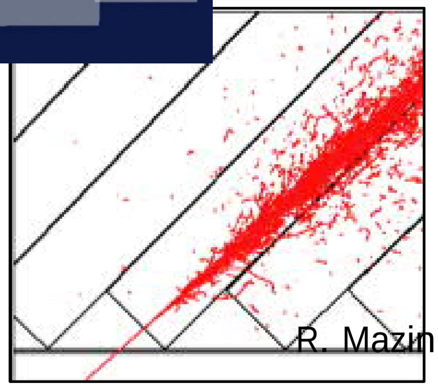
Reconstructing calorimeter energy

- 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

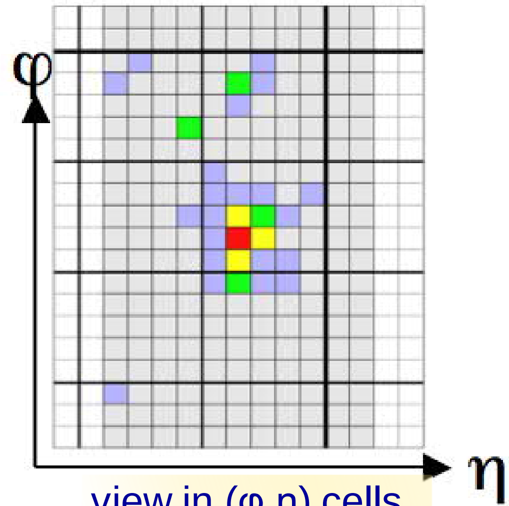




front view



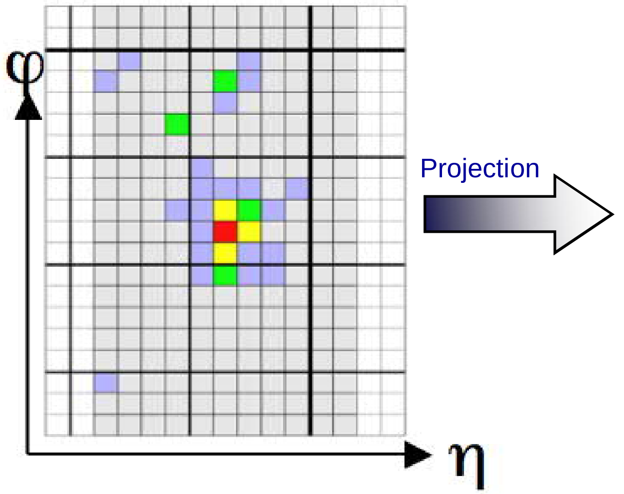
side view

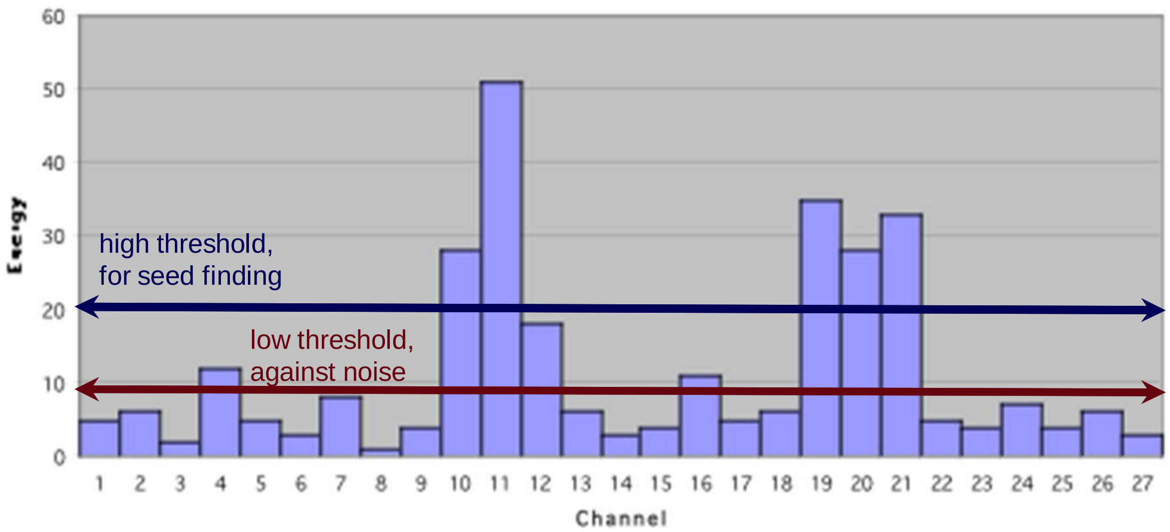


view in (φ,η) cells

Calorimeter 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

Reconstructing physics objects

How to combine all information from the detector to identify final state particles and measure their properties?

Why do we need to reconstruct all of this...

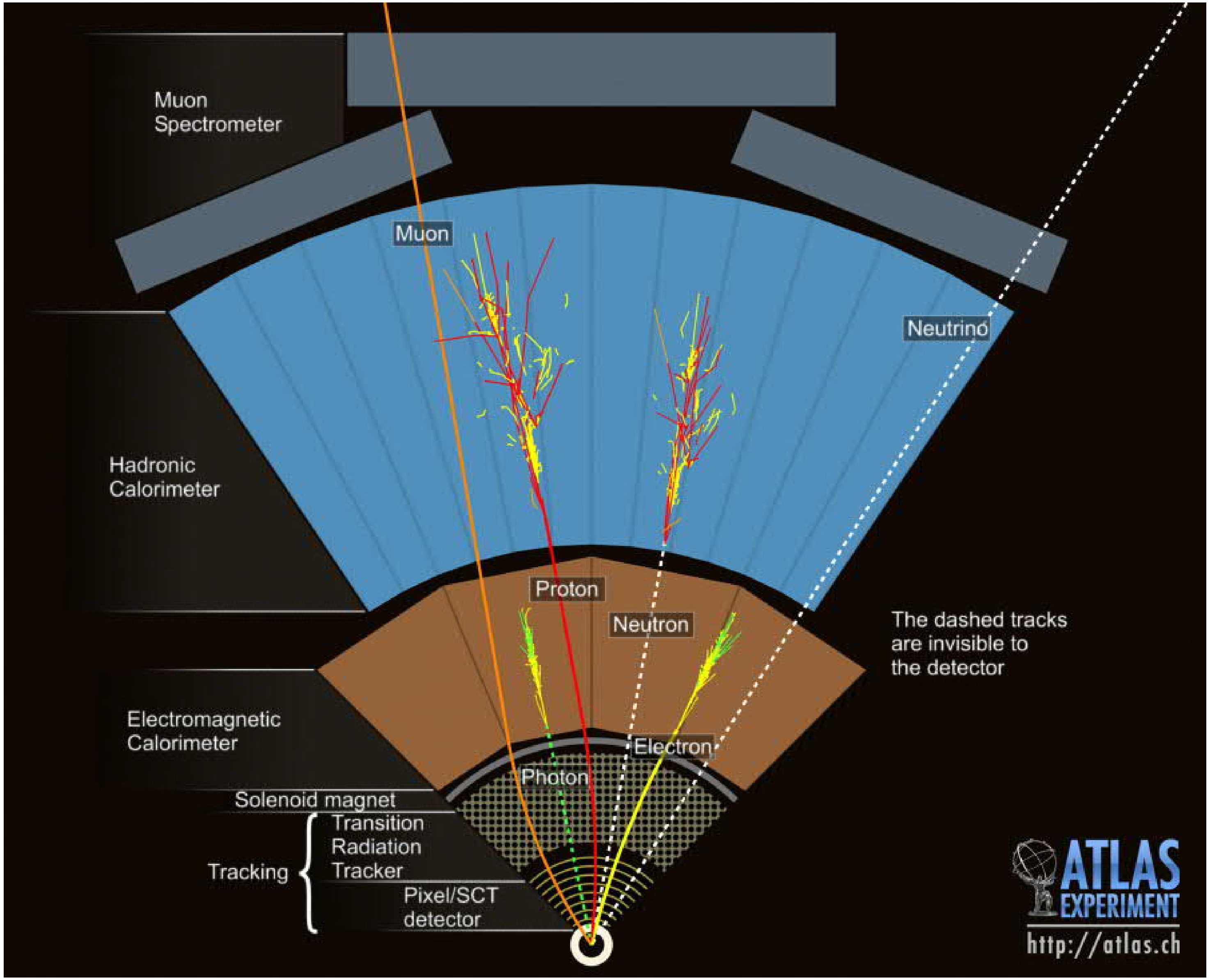
- ... To measure the particles and decays produced in the collisions
- Some important physics channels at the LHC with
  - Electrons and muons ("easy" to identify)
    - Many Standard model measurements such as W/Z, top, di-bosons ...
    - Searches for Higgs, Susy, exotics, e.g. $H \rightarrow 4l$, $Z' \rightarrow 2l$
  - Photons
    - Direct photons, $H \rightarrow \gamma\gamma$, $G \rightarrow \gamma\gamma$...
  - Taus
    - $Z \rightarrow \tau\tau$, $H \rightarrow \tau\tau$, $A \rightarrow \tau\tau$
  - Jets
    - Jet cross-section, jet multiplicies, many Susy channels
  - missing energy
    - $W \rightarrow l\nu$ precision measurements, many Susy channels, indirect Dark Matter searches, Extra dimensions...

How particles are reconstructed?

- Final state SM particles: e, μ, τ, ν, γ, Hadrons
- Each of these particles interact with the detector in a different way:
  - e, μ, τ are theoretically similar, however:
    - e leaves a track and its energy mostly in the EM calorimeter
    - μ leaves a track, passes through all calorimeters into the muons chambers
    - τ, in its hadronic decay channel, looks like a jet
      - Decays within the Inner detector
      - Leaves many tracks (1-3), EM and Hadronic energy

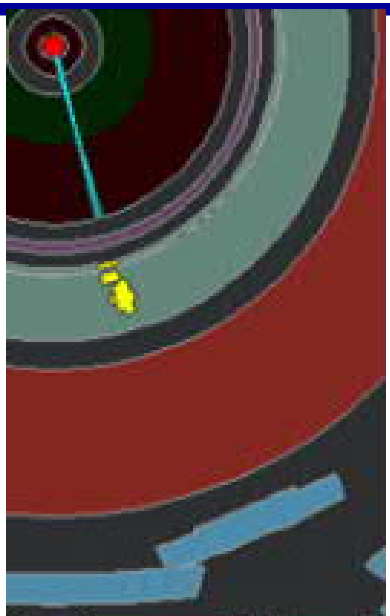
EM energy without a track EM energy with a track	Photon Electron
Hadronic energy without a track Hadronic energy with a track Hadronic energy with many tracks	Neutral Hadron Charged Hadron Collimated hadrons (jet, tau)
ID and muon chambers track	Muon
Missing transverse energy Missing longitudinal energy Displaced secondary vertex	Neutrino Beam remnants In-flight decay, B-mesons

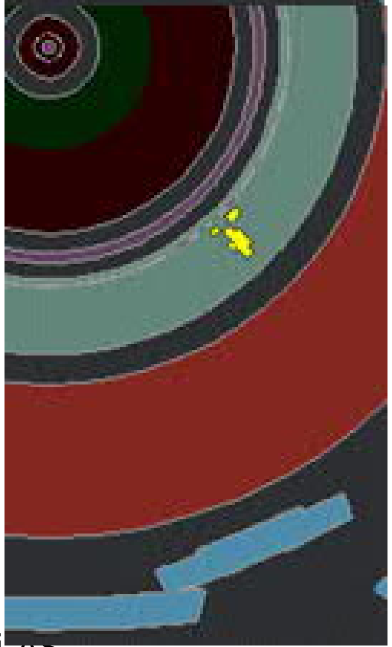
Physics objects reconstruction



Electrons and Photons

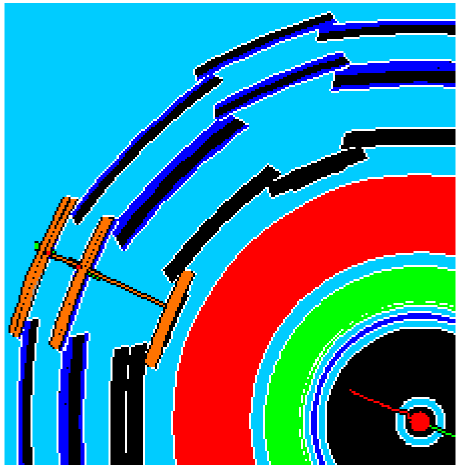
- Energy deposit in calorimeter
  - “Narrow“ shower shape in EM calorimeter
  - Energy nearly completely deposited in EM calorimeter
    - Little or no energy in had calorimeter (hadronic leakage)
- Electrons have an associated track in inner detector
- If there is no track found in front of calorimeter: photon
  - But be careful, photon might have converted before reaching the calorimeter



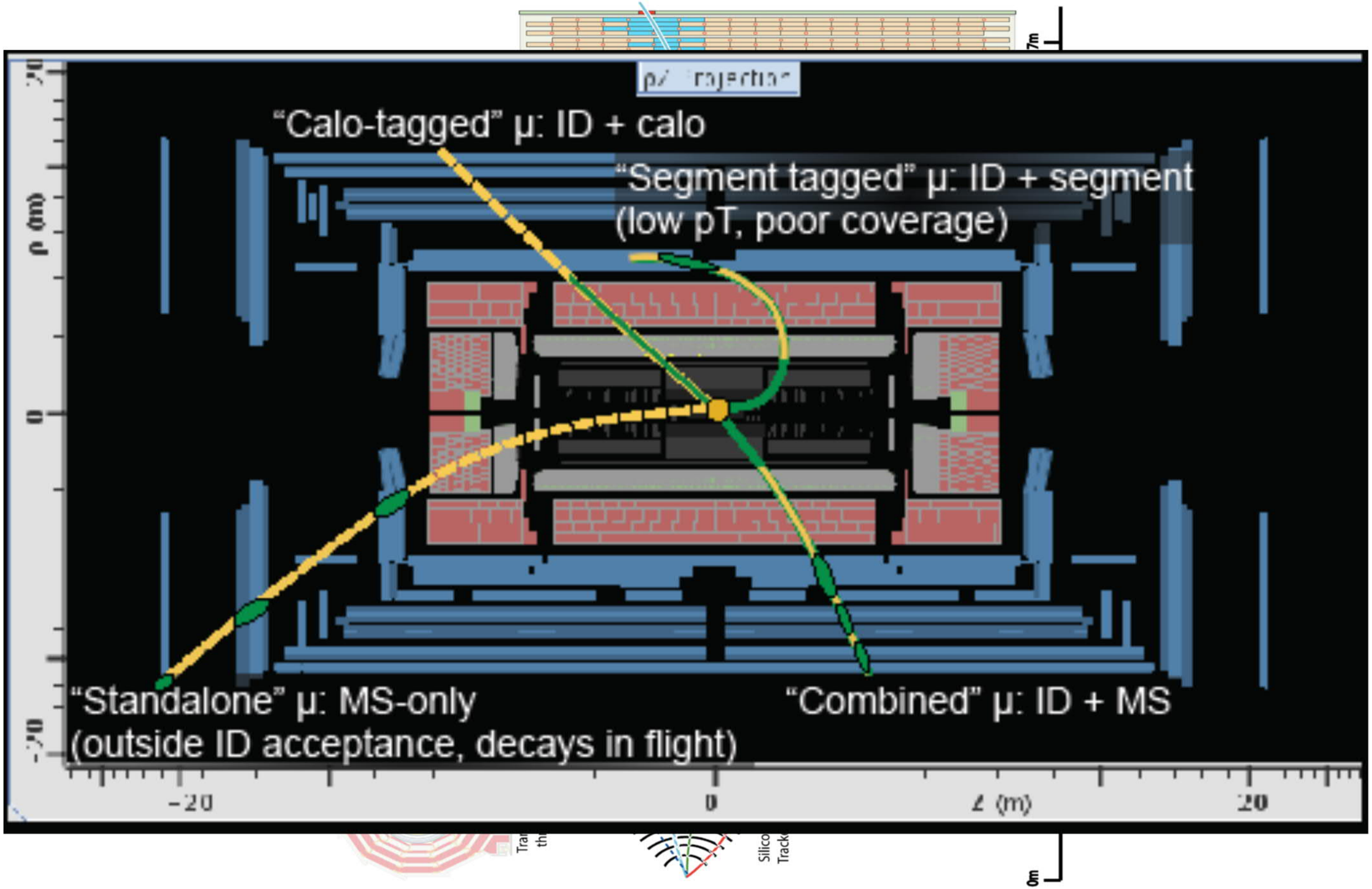


Muons reconstruction

- Because of it's long lifetime, the muon is basically a stable particle for us ($c\tau \sim 700$ 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!
  - 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



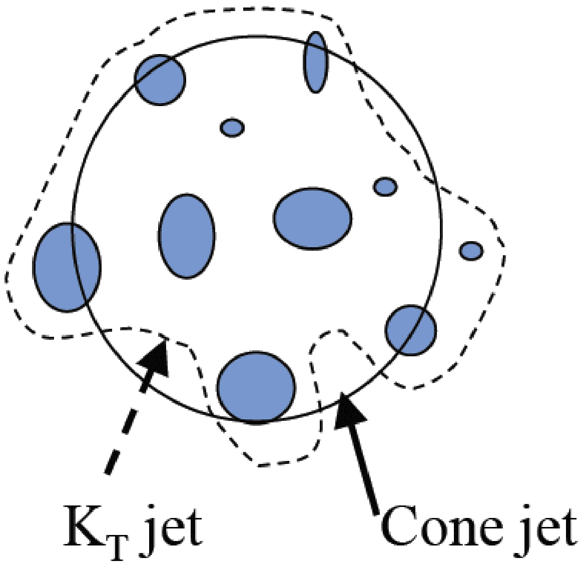
Muons

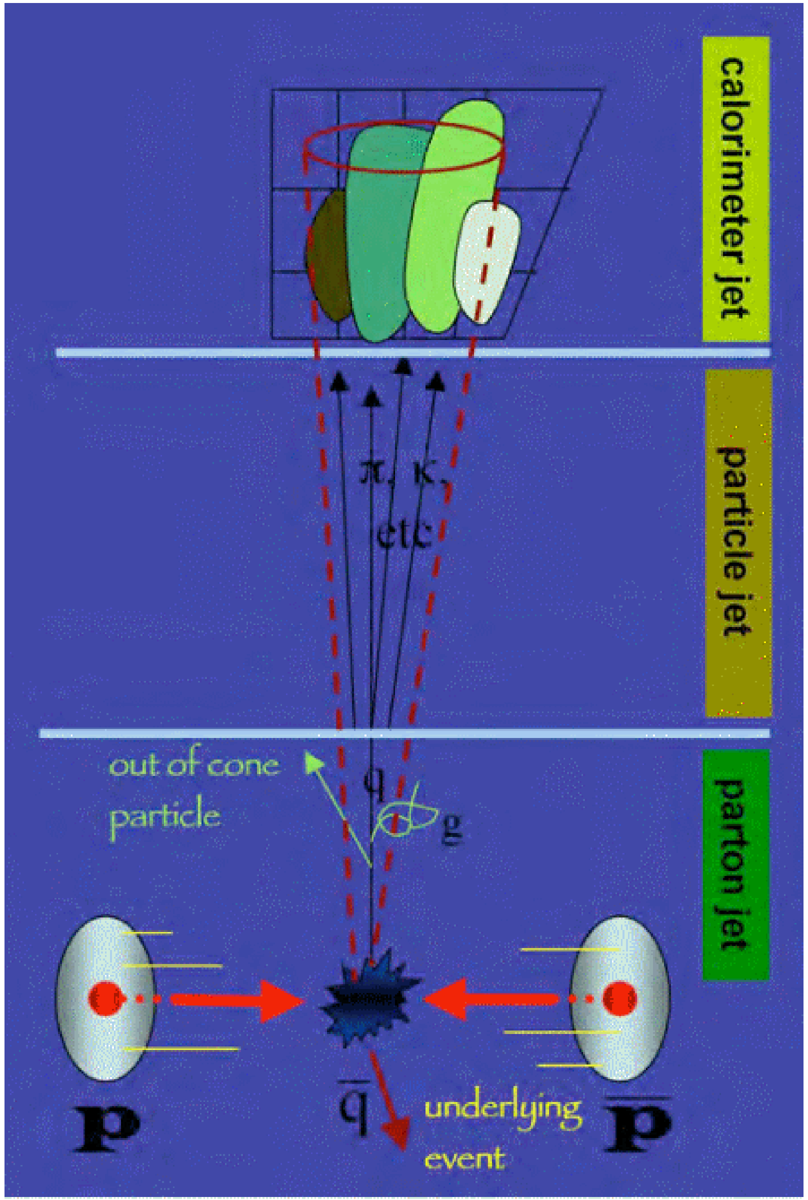


"Calo-tagged" μ: ID + calo
"Segment tagged" μ: ID + segment
(low pT, poor coverage)
"Standalone" μ: MS-only
(outside ID acceptance, decays in flight)
"Combined" μ: ID + MS
ρ (m)
z (m)
-20
0
20

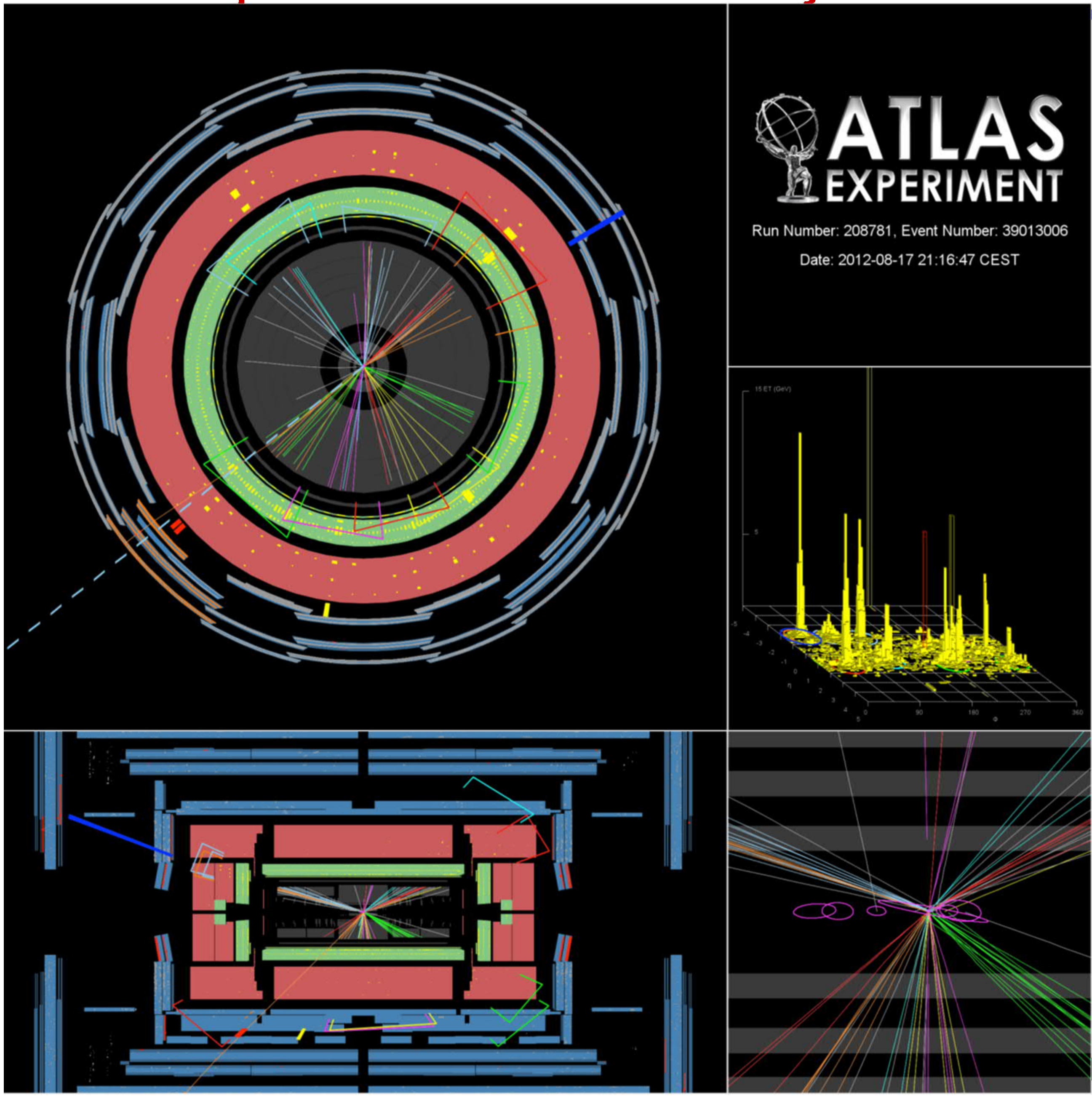
Jet Reconstruction

- A jet is a collection of collimated particles
  - Tracks
  - Energy clusters
- We reconstruct a jet by combining this information in order to „collect the corresponding particles from hadronization
  - 2 main jet algorithms
    - Cone
    - kT





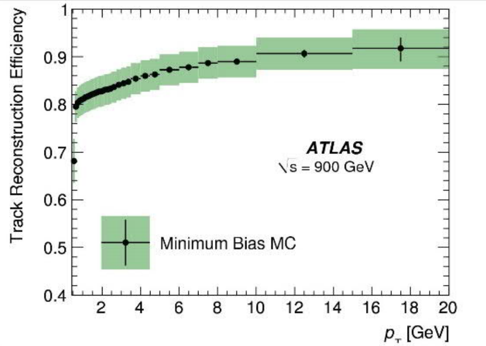
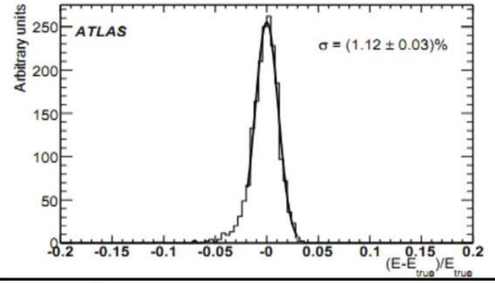
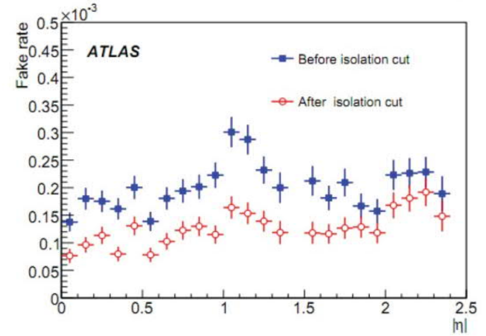
Example of reconstructed jets



Event with 10 reconstructed jets with p_T>50 GeV

Important features for physics object reconstruction

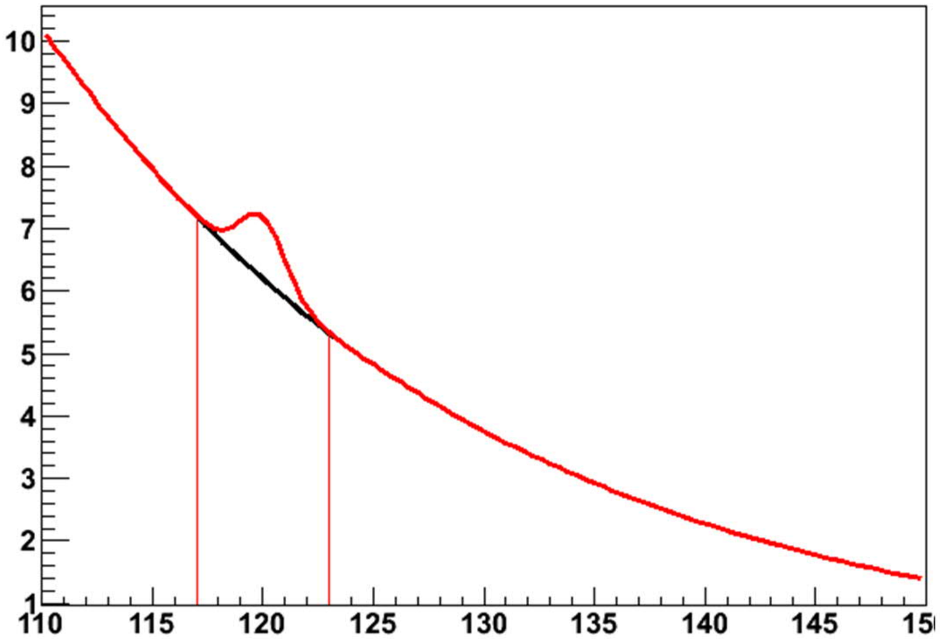
"**true**" quantity:
quantity at MC generator level.

<table>
<tr><th></th><th>Definition</th><th>Example</th><th></th><th>Needs be:</th></tr>
<tr><td>Efficiency</td><td>how often do we reconstruct the object</td><td>tracking efficiency = (number of reconstructed tracks) / (number of true tracks)</td><td>
</td><td>High</td></tr>
<tr><td>Resolution</td><td>how accurately do we reconstruct the quantity</td><td>energy resolution = (measured energy – true energy) / (true energy)</td><td>
</td><td>Good</td></tr>
<tr><td>Fake rate</td><td>how often we reconstruct a different object as the object we are interested in</td><td>a jet faking an electron, fake rate = (Number of jets reconstructed as an electron) / (Number of jets)</td><td>
</td><td>Low</td></tr>
</table>

Importance of energy resolution

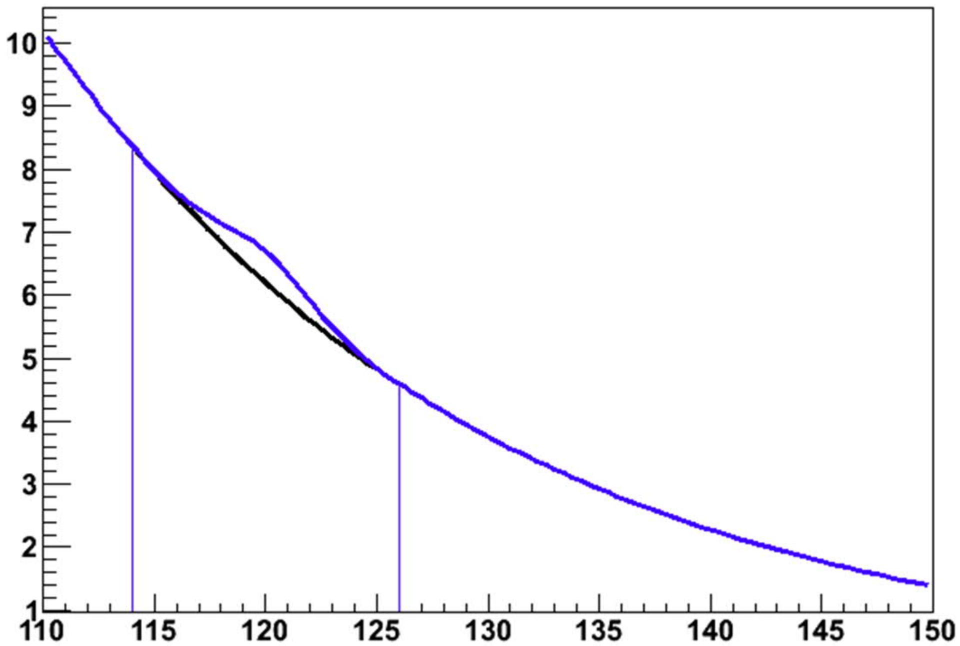
- H→γγ Toy example: Signal peak on exponential background.
- 2 different signal resolutions. Same number of signal events in each peak
- Would discover the left hand signal much quicker!

Mass resolution 1 GeV
Signal over background in cut range ~10%



Mγγ [GeV]

Mass resolution 2 GeV
Signal over background in cut range ~5%

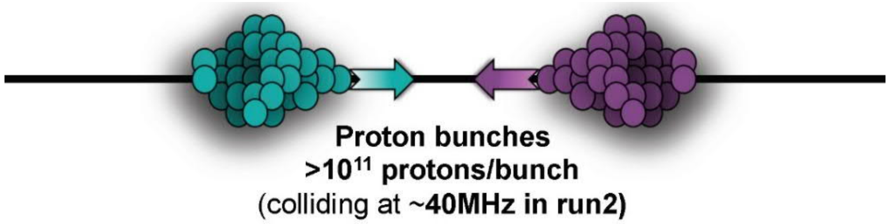


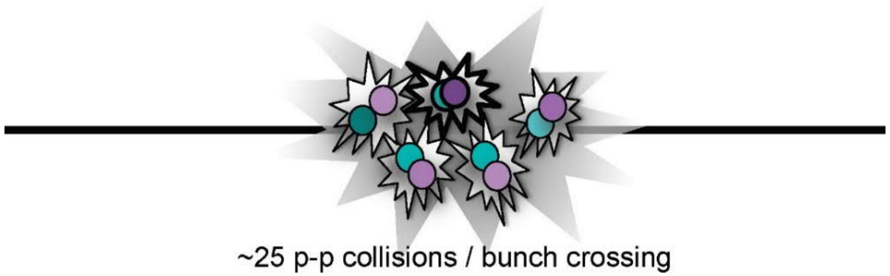
Mγγ [GeV]

Very important to build the detector to give you the best resolution.
But also to optimize the reconstruction algorithms and calibrations to give the best resolution possible for that detector.

Pile up

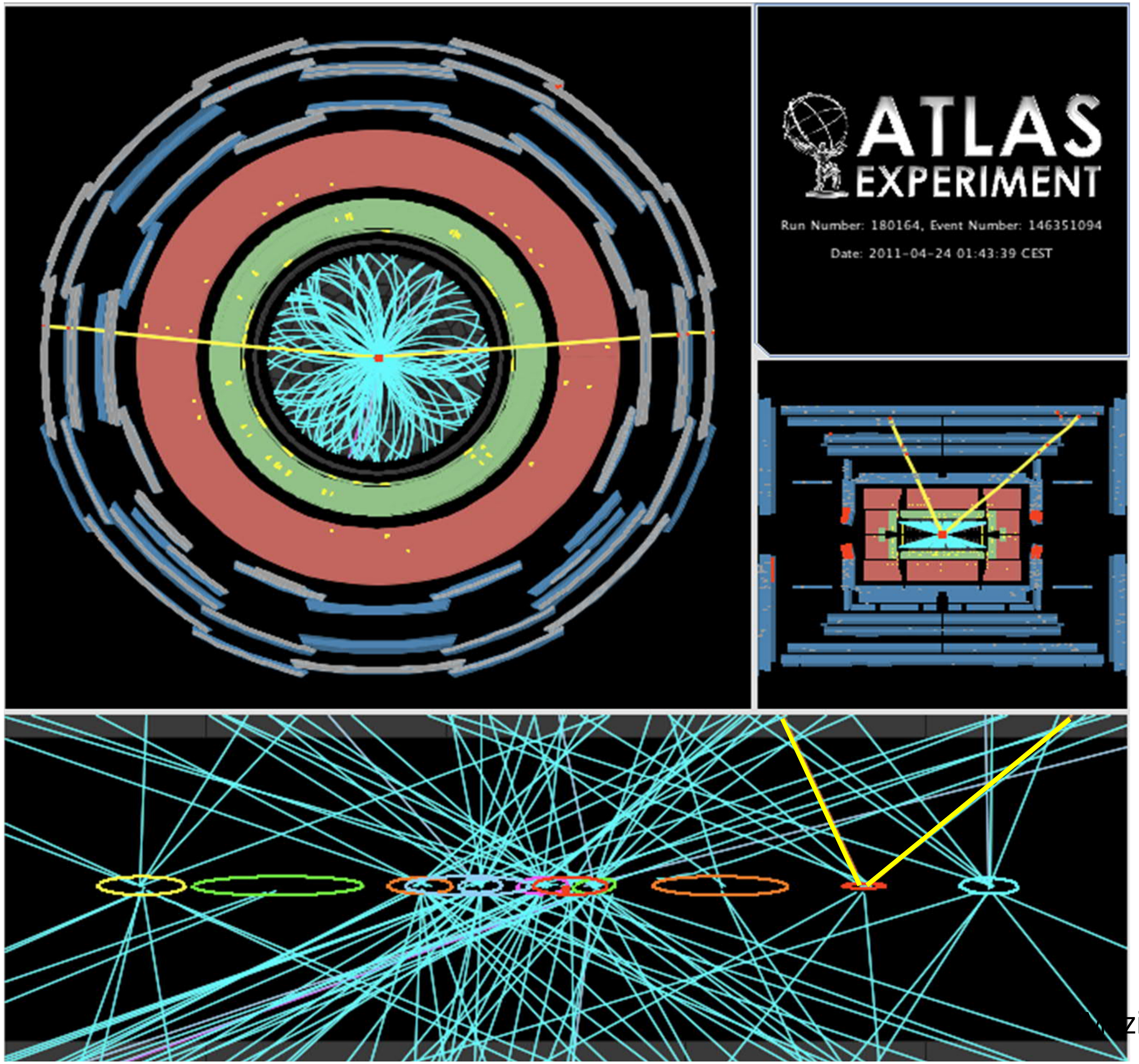
- Increasing luminosity comes with a price
- More interactions per bench crossing





- Interaction with the interesting physics process may be lost

Reconstructing the correct tracks in high pile-up



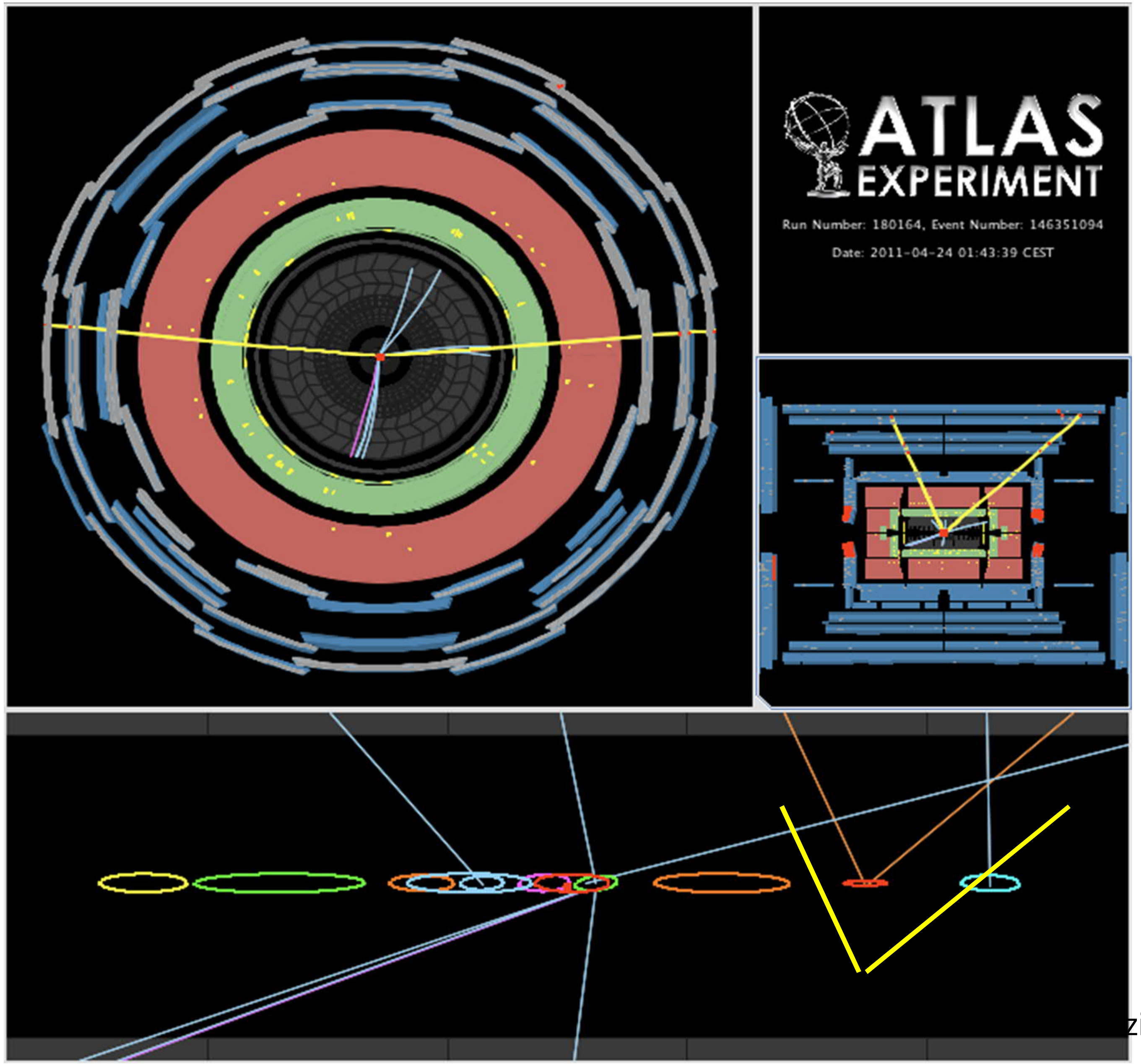
Z->μμ event in ATLAS.

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?

Reconstructing the correct tracks in high pile-up



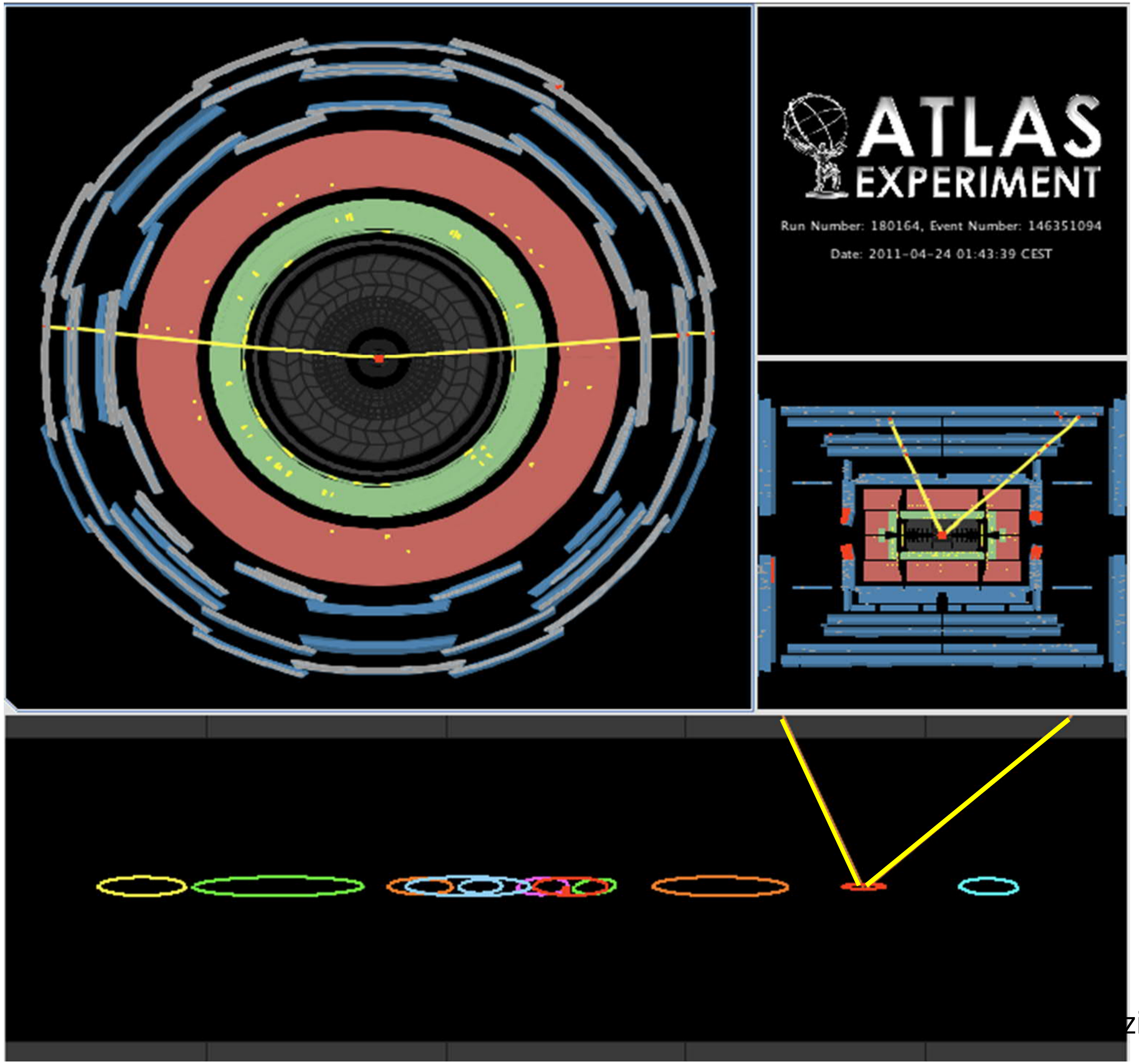
Z->μμ event in ATLAS.

With 11 reconstructed vertices.

Tracks with transverse momentum p_T>2GeV are shown

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

Reconstructing the correct tracks in high pile-up



Z->μμ event in ATLAS.

With 11 reconstructed vertices.

Tracks with transverse momentum p_T>10GeV are shown

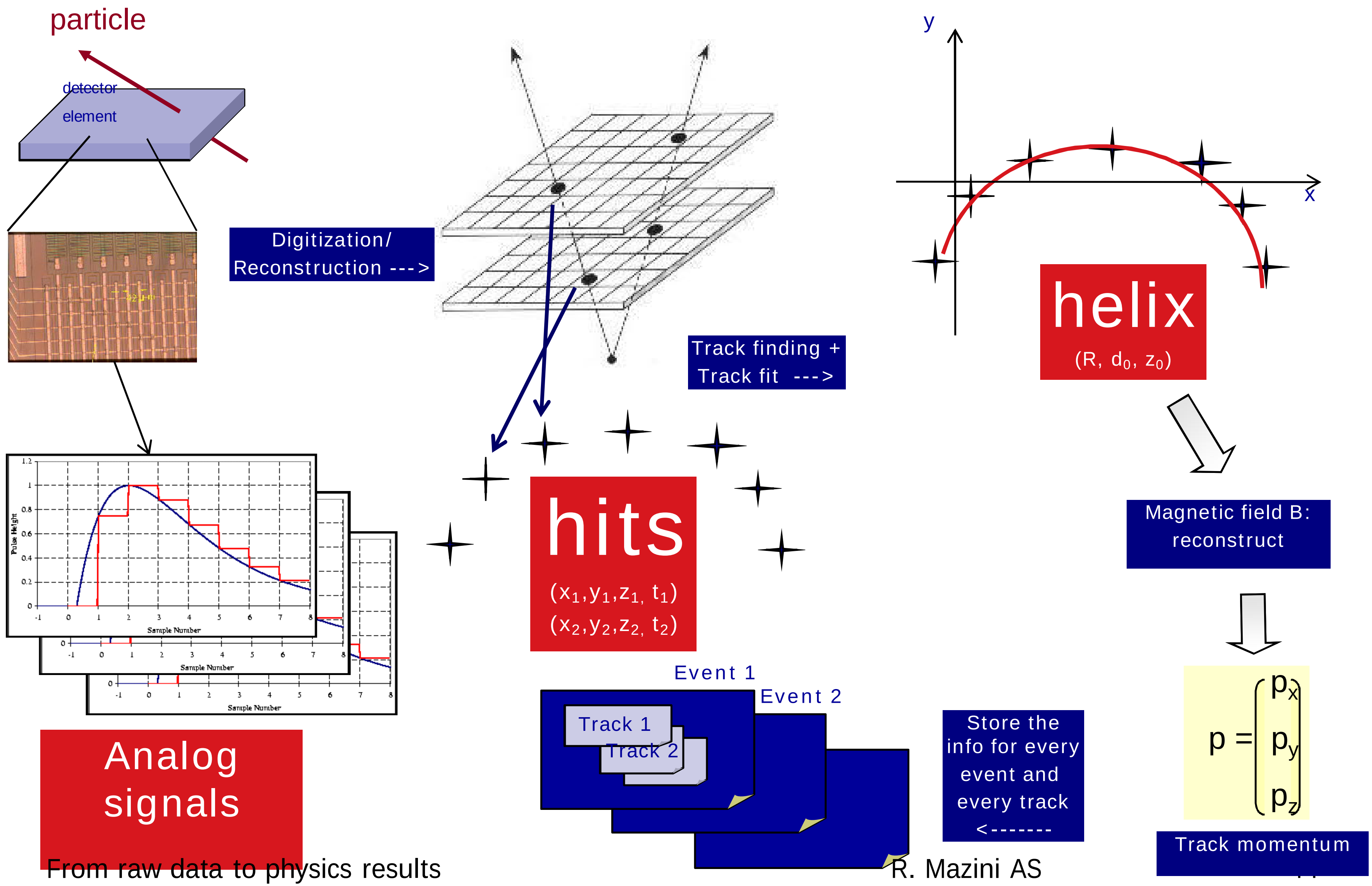
How can we do physics analysis with such a huge number of tracks in the detector?

Selecting high pT tracks, makes the event cleaner, hence easier to analyze.

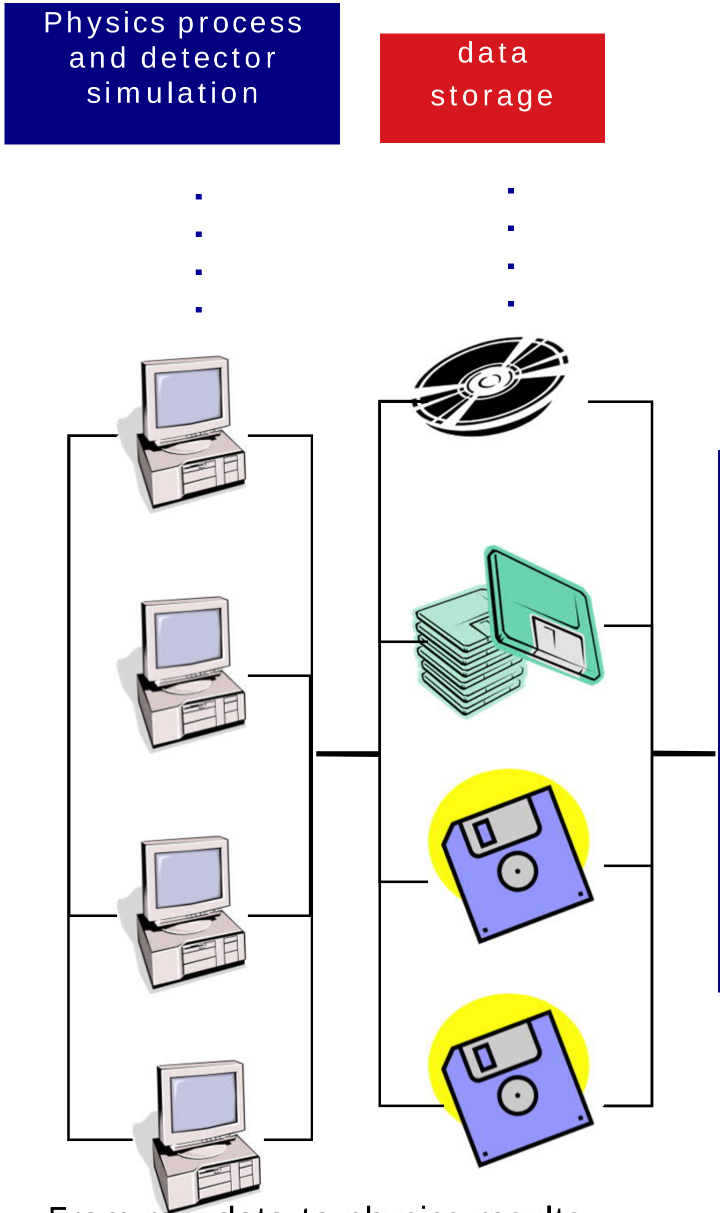
BUT. It might also reduce its physics content.

Important steps from detector measurements to physics analysis

Data handling and reduction in HEP



Monte Carlo Simulation in HEP analysis



Exactly the same steps as for the data

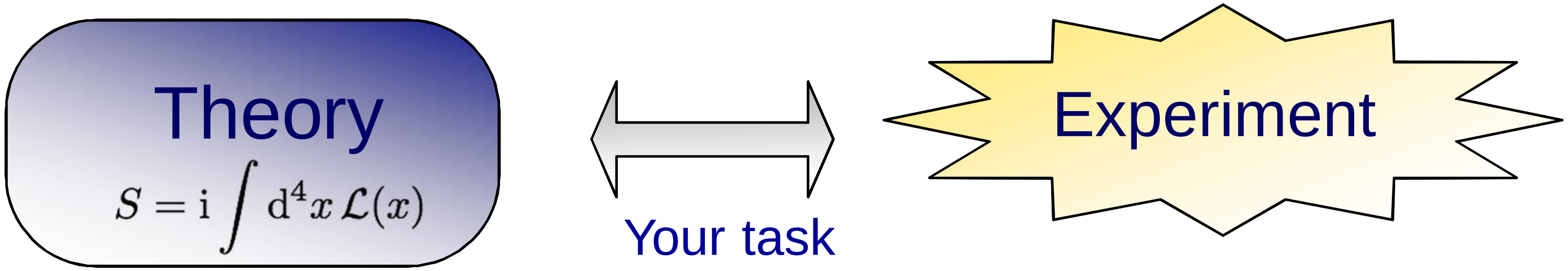
Simulation of many (billions) of events

- simulate physics process

e.g. p p –> Z
or p p –> H

- plus the detector response to the produced particles
- understand detector response and analysis parameters (lost particles, resolution, efficiencies, backgrounds)
- and compare to real data
- Note : simulations present from beginning to end of experiment, needed to make design choices

What do we do?



SM Lagrangian, couplings parameters,..

$$\mathcal{L} = -\tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

{ $W^{\pm}, Z, \gamma$ kinetic energies and self-interactions

$$+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)L$$
$$+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)R$$

{ lepton and quark kinetic energies and their interactions with $W^{\pm}, Z, \gamma$

$$+\left|\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)\phi\right|^{2}$$
$$-V(\phi)$$

{ $W^{\pm}, Z, \gamma$ and Higgs masses and couplings

$$-(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)$$

{ lepton and quark masses and coupling to Higgs

L ... left–handed fermion (l or q) doublet
R ... right–handed fermion singlet

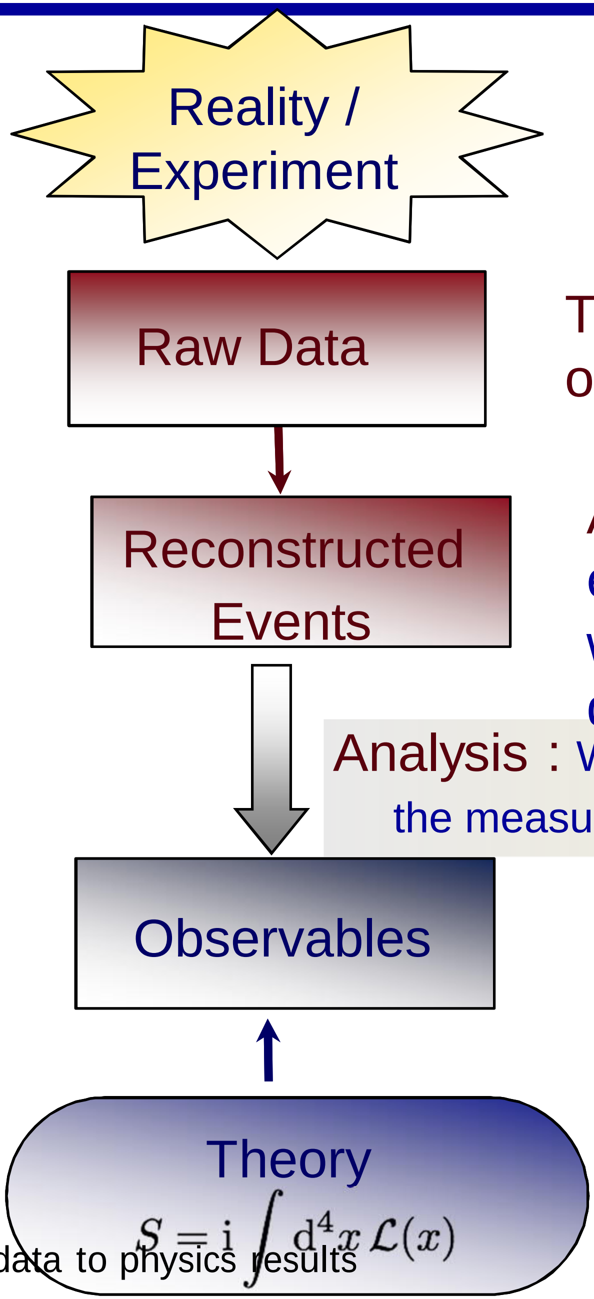
$\mathcal{L}$ from QCD:

$$\mathcal{L} = \underbrace{\bar{q}\,(i\gamma^{\mu}\partial_{\mu} - m)\,q}_{\mathrm{E_{kin}(q)}} - \underbrace{g\,(\bar{q}\gamma^{\mu}T_a q)G^{a}_{\mu}}_{\text{Interaction } q,\,g} - \underbrace{\tfrac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}}_{\mathrm{E_{kin}(g)}\text{ includes self-interaction between gluons}}$$

Digitized detectors output signals

```
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
0x01e84c60:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c70:  0x01e8 0x8824 0x01e8 0x84d8 0x7265 0x6765 0x7870 0x0000
0x01e84c80:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c90:  0x01e8 0x8838 0x01e8 0x8518 0x7265 0x6773 0x7562 0x0000
0x01e84ca0:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cb0:  0x01e8 0x8818 0x01e8 0x8558 0x7265 0x6e61 0x6d65 0x0000
0x01e84cc0:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cd0:  0x01e8 0x8798 0x01e8 0x8598 0x7265 0x7475 0x726e 0x0000
0x01e84ce0:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cf0:  0x01e8 0x87ec 0x01e8 0x85d8 0x7363 0x616e 0x0000 0x0000
0x01e84d00:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d10:  0x01e8 0x87e8 0x01e8 0x8618 0x7365 0x7400 0x0000 0x0000
0x01e84d20:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d30:  0x01e8 0x87a8 0x01e8 0x8658 0x7370 0x6c69 0x7400 0x0000
0x01e84d40:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d50:  0x01e8 0x8854 0x01e8 0x8698 0x7374 0x7269 0x6e67 0x0000
0x01e84d60:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d70:  0x01e8 0x875c 0x01e8 0x86d8 0x7375 0x6273 0x7400 0x0000
0x01e84d80:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d90:  0x01e8 0x87c0 0x01e8 0x8718 0x7377 0x6974 0x6368 0x0000
```

Road from detector measurements to physics results



The imperfect measurement of a (set of) interactions in the detector

A unique happening:
eg. Run 23458, event 1345 which contains a Z $\rightarrow \mu^+\mu^-$ decay

Analysis : We “confront theory with experiment” by comparing the measured quantity (observable) with the prediction.

Cross sections (probabilities for interactions), branching ratios (BR), ratios of BRs, specific lifetimes, ...

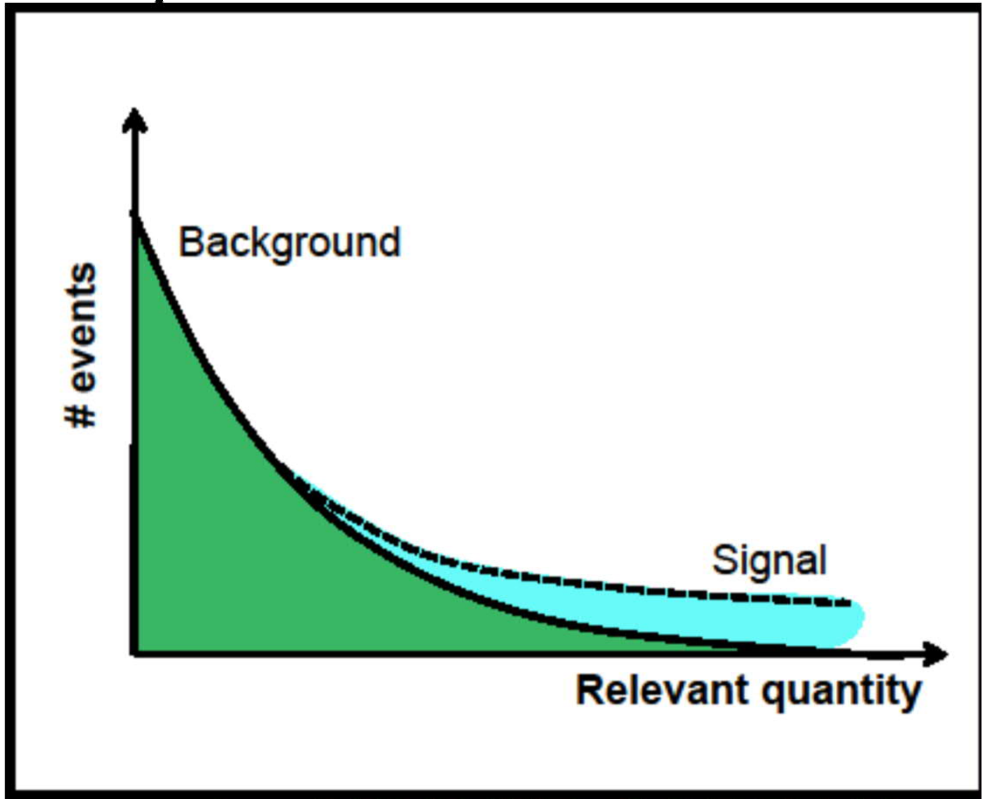
A small number of general equations, with some parameters (poorly or not known at all)

Physics Analysis

Measurements

- Allow important tests of the consistency of the theory.
- Typically limited by systematic uncertainties.

Searches



improve a search.

Cross section

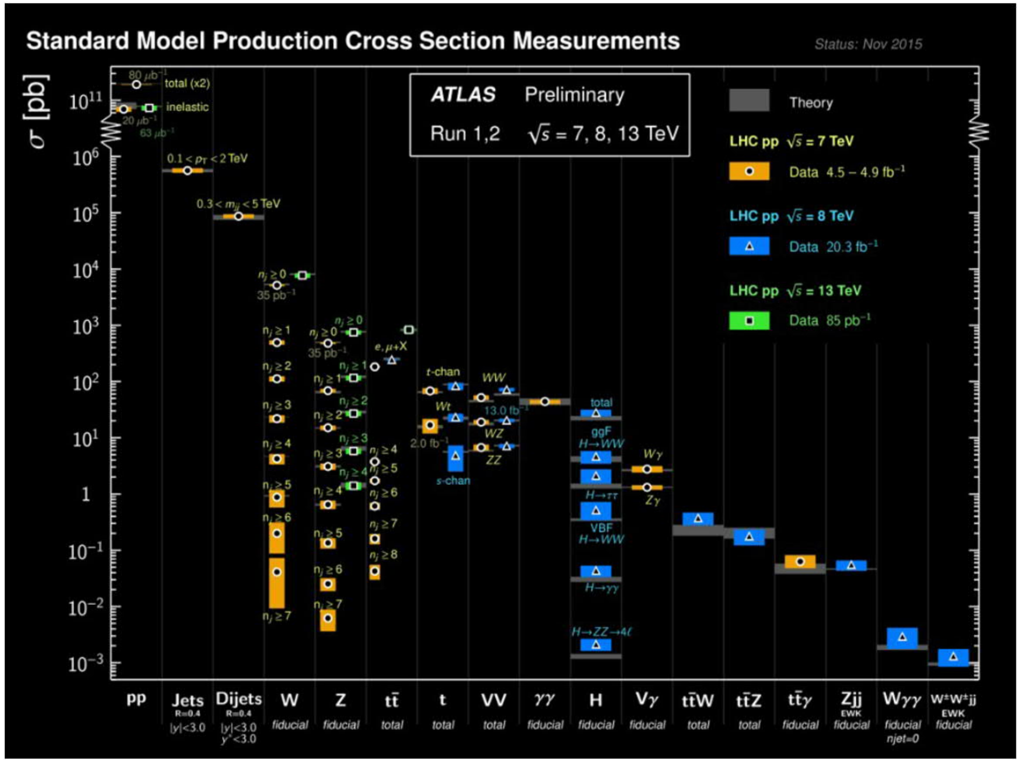
- The cross section represents the probability of a physics process to occur.

$$\sigma = \frac{N}{L}$$

N → Number of events

L → Integrated luminosity

- Measured cross sections In ATLAS



- We can predict the expected number of events of a process for a fixed L

Cross section

- It is too simple to be true!
  - A cross section is not just counting events
  - Not only the studies process occurs $\Rightarrow$ **Background events.**
- A detector is never perfect:
  - Limited geometrical acceptance
    - Coverage, holes, cracks, higher electronic noise…
  - Identification of particles is not 100% efficient
    - Limited by kinematic, resolutions…
  - Interesting event can be missed:
    - Trigger inefficiency
  - Do we really know exactly the physics we are studying?
    - Uncertainty on theoretical models?
    - Monte Carlo simulation of everything?

Cross section measurement

$$\sigma \,.\, BR = \frac{N_{obs} - N_{bkg}}{\alpha \,.\, \varepsilon \,.\, L}$$

Number of observed events

Number of background events
Measured from data
calculated from theory

Branching ratio of the measured final state

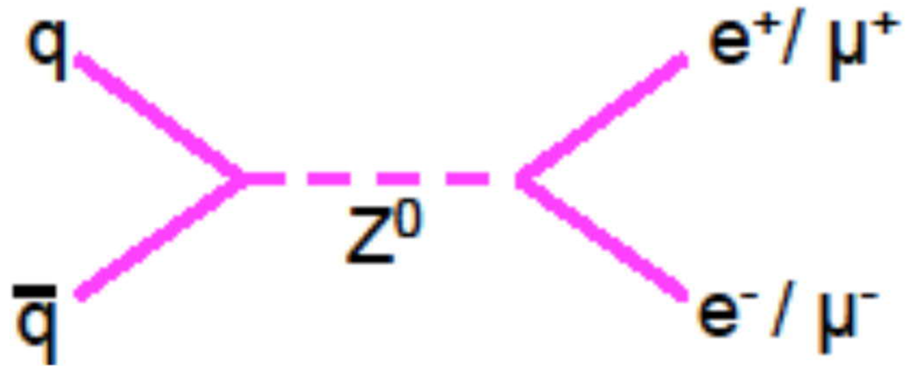
Integrated luminosity.
Provided by accelerator, trigger, specific detectors

Acceptance of selected events

Efficiency of reconstructed objects

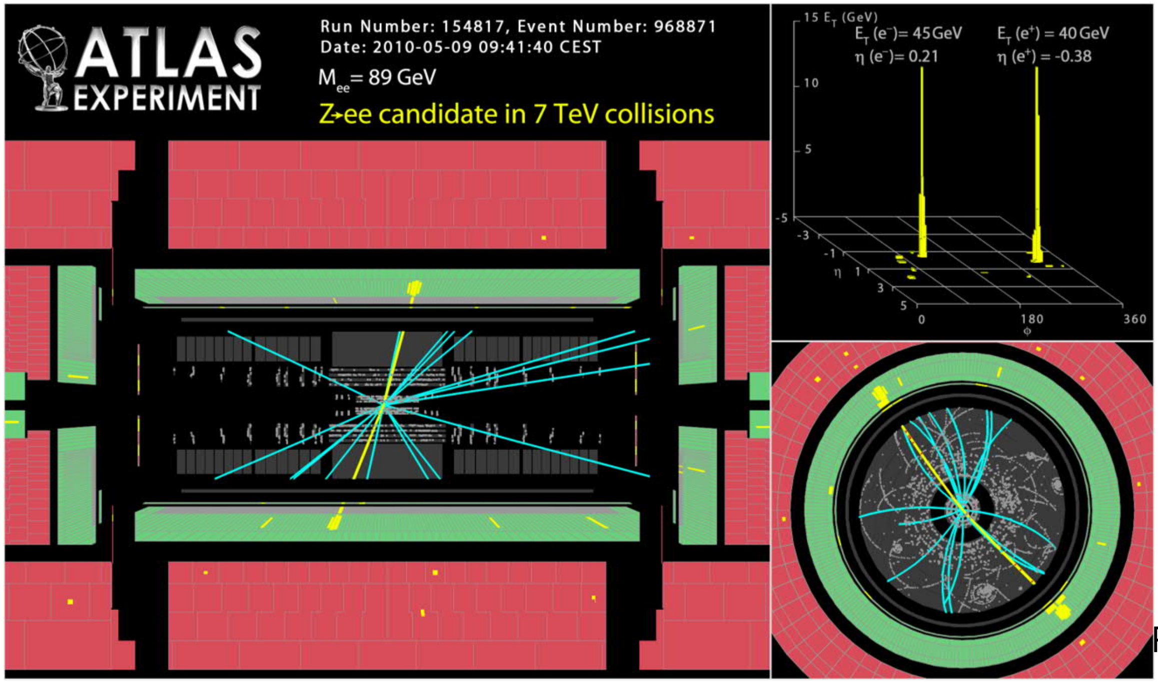
Example of cross section measurement

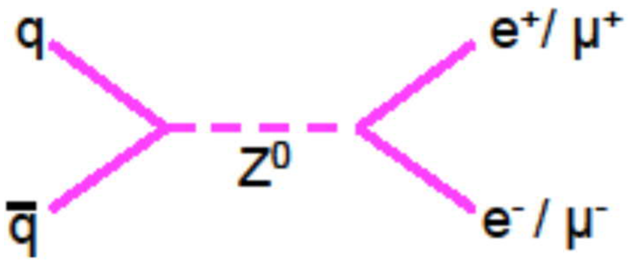
Z^0 production at the LHC



Measuring Z^0 cross section at the LHC

- Z^0 boson decays to lepton or quark pairs
  - We can reconstruct it in the e^+e^- or $\mu^+\mu^-$ decay modes
- Discovery and study of the Z^0 boson was a critical part of understanding the electroweak force
- Measuring the Z^0 cross-section at the LHC important test of theory
  - Does the measurement agree with the theoretical prediction at LHC collision energy?





Z^0 cross-section is related to the probability that we will produce a Z^0 at the LHC

Analysis chain for Z^0 cross section measurement

Data

Detector & Trigger

↓

Reconstruction

↓

Physics Analysis

Monte Carlo

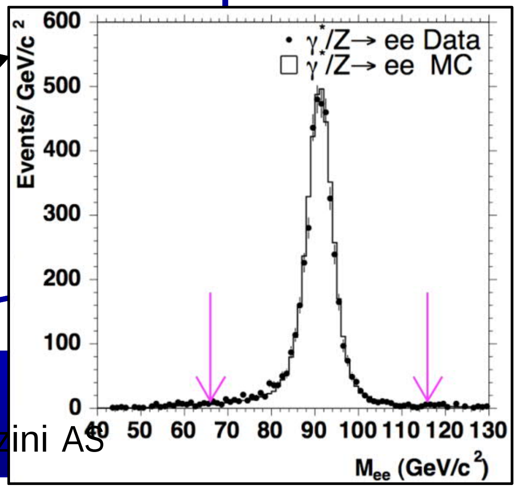
Simulated data

↓

Reconstruction

Reconstruct e and μ candidates

1. Select events with 2 oppositely charged e/ μ
2. Calculate mass
3. Select events with mass close to Z mass



Compare theory and experiment

Z^0 cross section measurement

How do we know if it's a Z^0:

Identify Z decays using the invariant mass of the 2 leptons
$M^2 = (L_1+L_2)^2$ where $L_i = (E_i,\underline{\mathbf{p}}_i)$ = 4-vector for lepton i
Under assumption that lepton is massless compared to mass of Z^0
=> $M^2 = 2\,E_1\,E_2\,(1-\cos\vartheta_{12})$ where ϑ_{12}= angle between the leptons

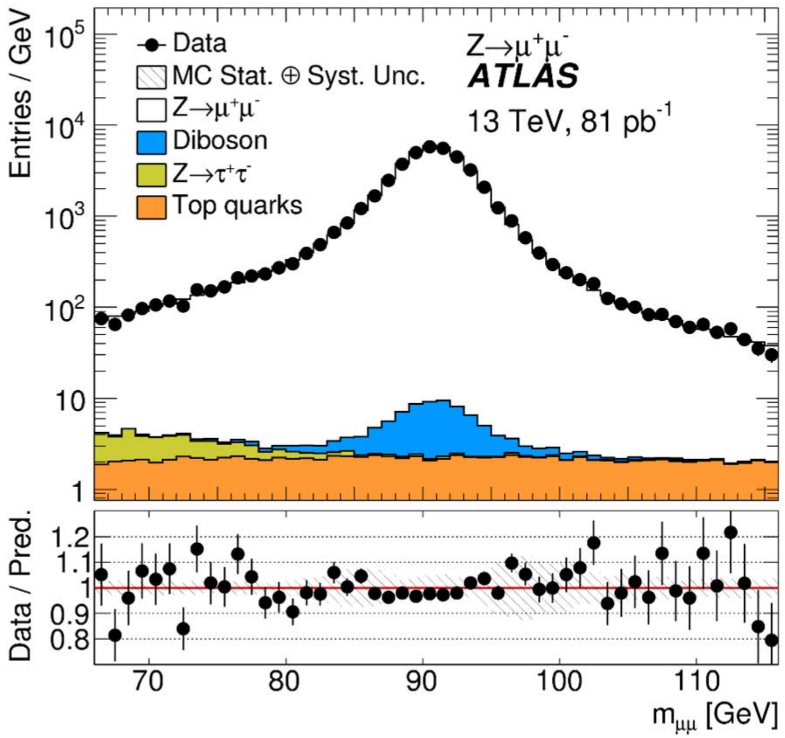
Reconstruct the electron and muon energy and direction. Then can calculate the mass.

Select Z^0 events with analysis cuts':

-Events with 2 high momentum electrons or muons

-Require the electrons or muons are of opposite charge

- With di-lepton mass close to the Z^0 mass (e.g. $70<m_{l+l-}<110$ GeV)



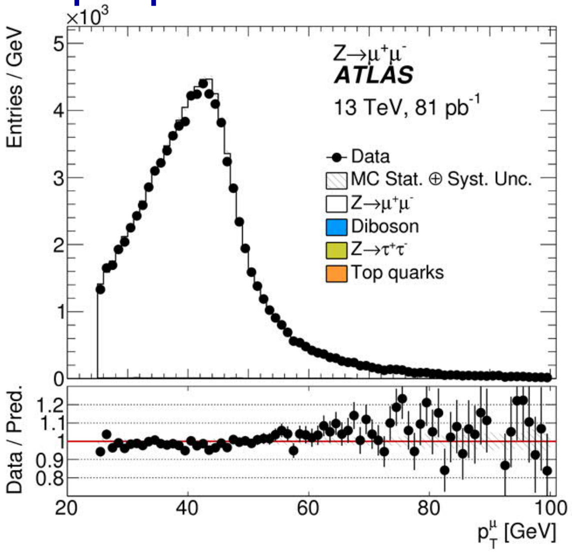
Very little background in the Z^0 mass region

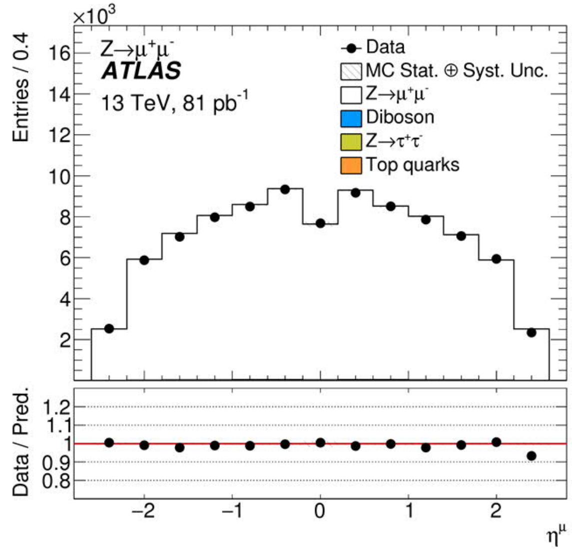
Estimation of background events

- MC estimation of the background
  - MC is used to estimate the number of background events
  - Have to trust MC cross section calculation
  - Have to trust MC generation process and detector simulation
  - Simply count number of MC events expected:
  - Normalised MC events to data Luminosity
  - Put MC samples through event selection
  - Done foe WW.WZ,ZZ, top
- Data-driven estimation of the background
  - There are processes where we don't trust the MC
  - W+Jets process:
    - Very difficult to calculate
    - Large theoretical uncertainties in normalization
    - Very difficult to model the rate of jets faking electrons
  - QCD Multijet processes:
    - Standard Model processes involving light quarks and gluons
    - Dominates all events at the LHC
    - We do not trust the MC

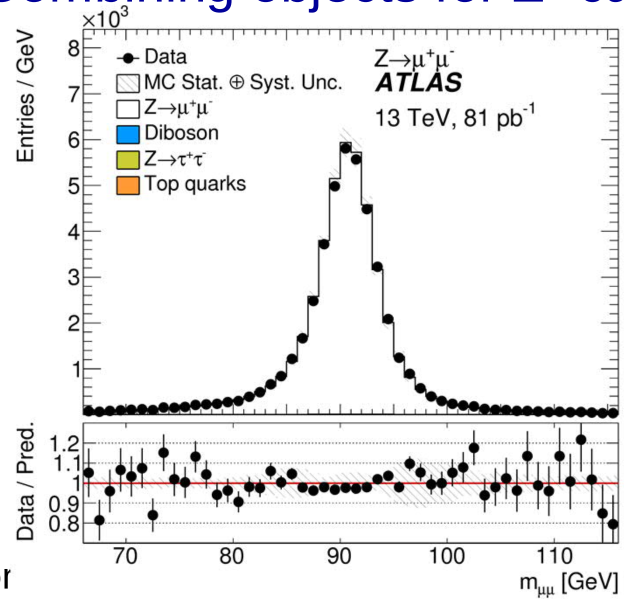
Other kinematic variables for Z^0 analysis

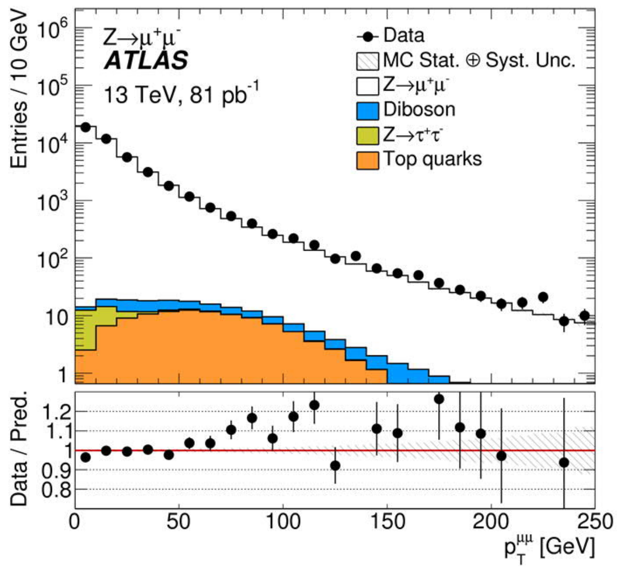
Some properties of reconstructed muons::





Combining objects for Z^0 candidates kinematics:





Fror

Z^0 cross section measurement

Theoretically:

Cross-section calculated for:

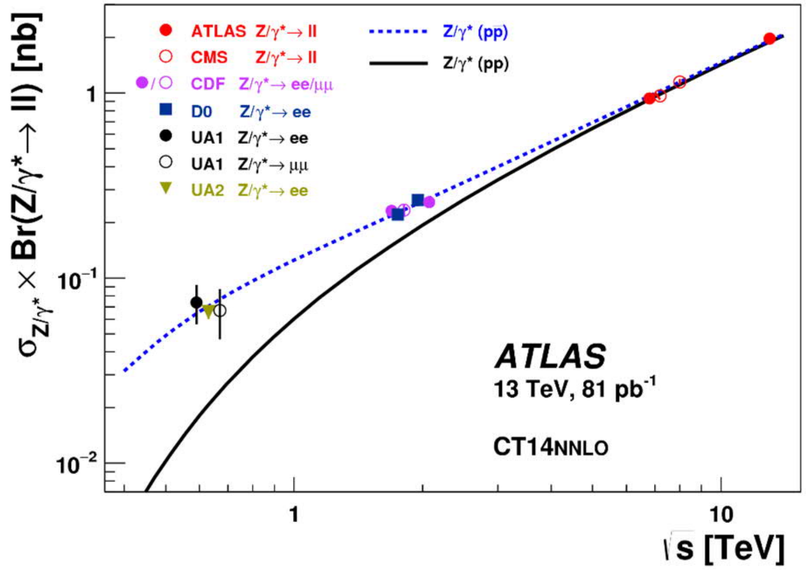
- Specific production mechanism (pp, pp, e^+e^-)
- Centre-of-Mass of the collisions

Experimentally:

$\sigma(pp \to Z) = (N_{OBS} - N_{BKG}) / L\ \varepsilon$

Looks like simple counting experiment.

But need to also calculate **uncertainty** on the cross-section – measurement without an uncertainty is useless.



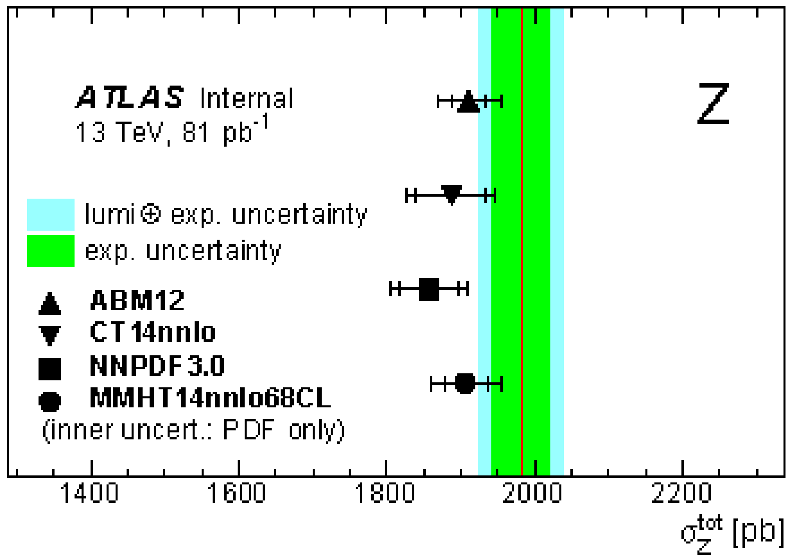
Two components to the uncertainty:

Statistical: $\sim\sqrt{N_{OBS}}$

Systematic:

- How well do we know the background?
- How well do we know the efficiency?
- How well do we know the luminosity?

Most of the work in the physics analysis is trying to understand the systematic uncertainties related to the above questions.



Principal steps towards physics results

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event selections
- Background determination
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

Principal steps towards physics results

- ◎ Data-set and Monte Carlo samples
- ◎ Trigger
- ◎ Object definitions
- ◎ Background dete
- ◎ Systematic uncer
- ◎ Statistical metho
- ◎ Results
- ◎ [Interpretations]

The data and simulation samples used in the analysis. Data for the measurement / search, simulation to compare data to predictions.

Data-set specifics:

◎ Data quality ⇒ Good run list.
◎ Luminosity.

Monte carlo sample specifics:

◎ Generator, tunes.
◎ Statistics.

Principal steps towards physics results

- Data-set and Monte Carlo samples
- Trigger
- Object defin
- Background dete
- Systematic uncer
- Statistical metho
- Results
- [Interpretations]

The trigger used to collect the data with.

Trigger specifics:

- Prescales; typically unprescaled triggers are used, prescaled triggers for QCD / high stat measuments.
- Trigger (in)efficiencies.

Principal steps towards physics results

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event selections
- Backg
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- [Inter

The exact definition of objects (electrons, muon, jets, …) and how these are combined in selecting events to be analyzed.

Object definition specifics:

- "Flavor" of the identification (loose, medium, tight).
- Calibrations.

Event selection specifics:

- Event cleaning (e.g. from noise and cosmics).
- Momentum, geom. acceptance and multiplicity of objects.
- Higher level cuts, such as invariant mass.
- "**Signal regions**".

Principal steps towards physics results

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event
- Background determination
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

Events that are imitating the signal we are searching for or measuring.

Background determination specifics:

- Can/must be **data-driven** or **simulation-based**.
- "**Validation regions**" and "**control regions**" required. These can use different triggers wrt signal regions.

Principal steps towards physics results

- Data-set and Monte Carlo
- Trigger
- Object definitions and eve
- Background determinatio
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

- Any 'intermediate' measurement we have performed carries uncertainties (statistical and systematic).
- **"Systematic" uncertainties are introduced by inaccuracies in the methods used to perform the measurement.**
- Efficiencies, acceptance, number of events, luminosity, cross sections used in Monte Carlo scaling…
- Some of them are "centrally" assessed by the performance groups of an experiment. Some of them are analysis-specific.

Principal steps towards physics results

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event
- Background determinatio
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

Dealing with large data-sets, we use statistical methods to make sense of the numbers we measure.

Typical method:

- Do a fit to extract signal from background.

Methodologies can vary a lot, but nowdays they are pretty unified within and across experiments.

Principal steps towards physics results

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event selections
- Background determination
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

Produce the results in tables and plots. These include details of what is found in the signal region.

Principal steps towards physics results

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event selections
- Background determination
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

Put the results into context: interpret them in theoretical models.

Summary

- We have seen a very simplified picture on the road from data to physics results
- Fundamental measurements from HEP detectors are somehow simple. Tracks from tracking detectors and energy from calorimeters
- Combinations of these pieces of information are used in complicated reconstruction algorithms to identify particles and measure their properties.
- Physics analysis consists on exploiting all information in order to do:
  - Precision measurements for known physics processes
  - Searches for new physics
- An important part of the analysis consists of estimating all sources of systematic uncertainites and minimizing them.
  - Experimetal uncertainties related to detector properties, reconstruction algorithms, calibration, object properties, pile-up
  - Theoretical uncertaities: event generators, background estimation.

Back-up

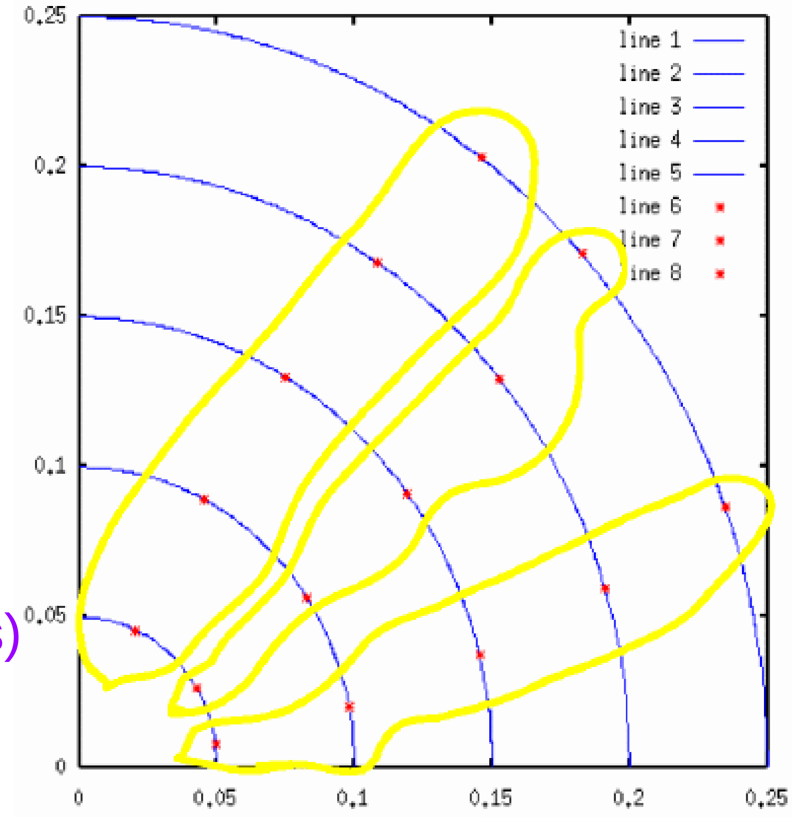
How to detect particles in a detector

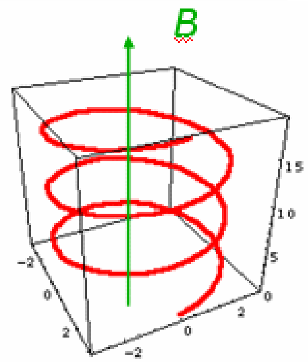
- There can be also some special detectors to identify particles
  - π/K/p identification using Cerenkov effect
  - Dedicated photon detector
  - Luminosity detectors
- There are other things which I won‘t explain
  - Energy loss measurement in tracking detector for π/K/p separation (dE/dx)
  - Transition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

Tracking

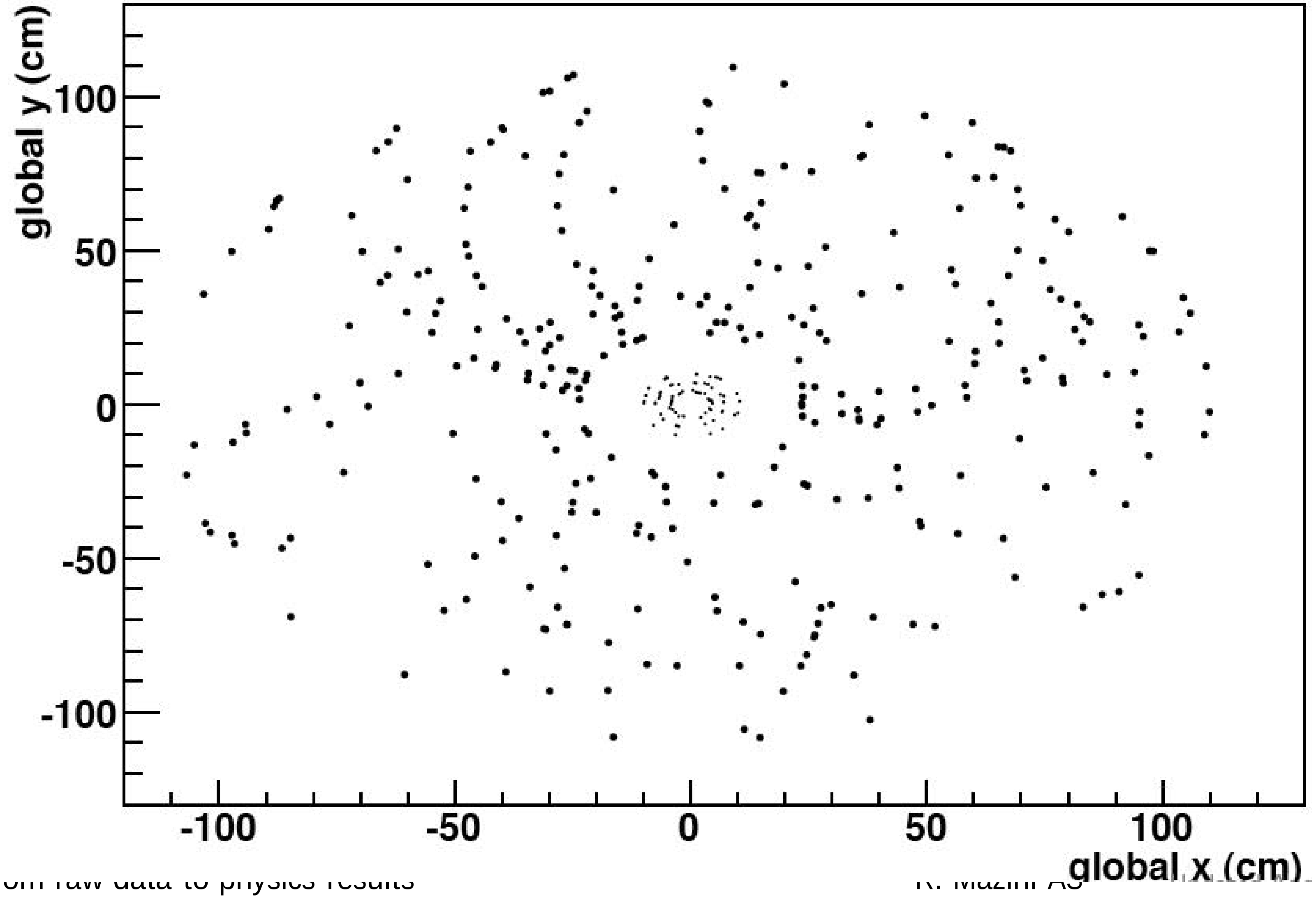
- This task is divided into different subtasks:
  - Hit reconstruction
  - Track finding/pattern recognition
  - Track fitting/parameter estimation
  - Note, often the steps are not separated but integrated for best performance
- Hit reconstruction
  - space points, sometimes called clusters (set of position measurements)
  - determine space point uncertainties
- Track finding
  - find track seeds in “rough“ way
  - The aim is to group these measurements together in subsets, each subset containing measurements orginating from one charged particle

Track finding



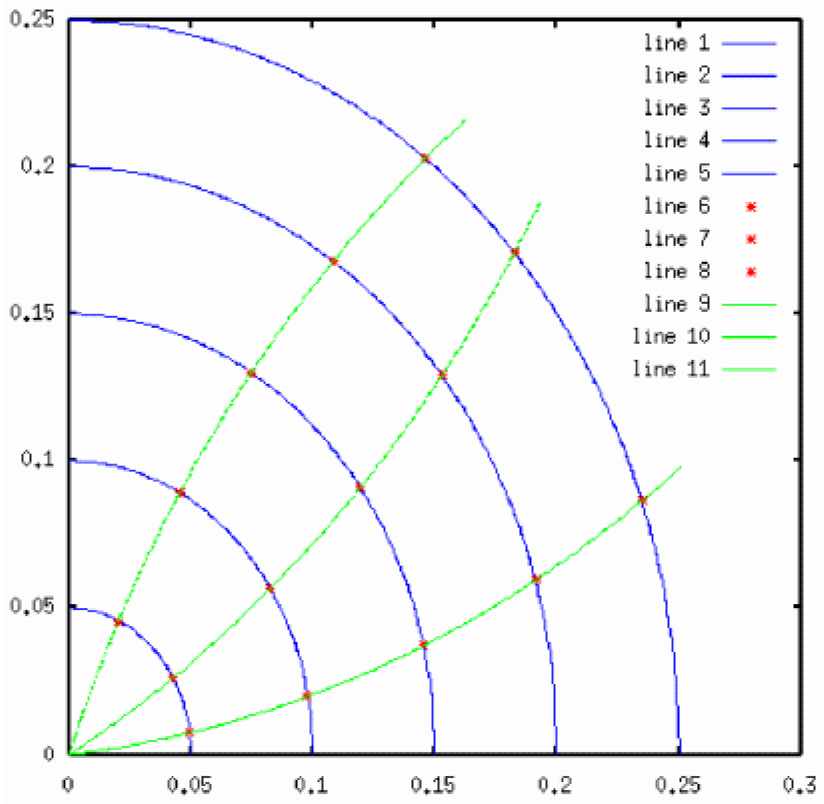


Tracking by eye - Can you find the 50 GeV Track?



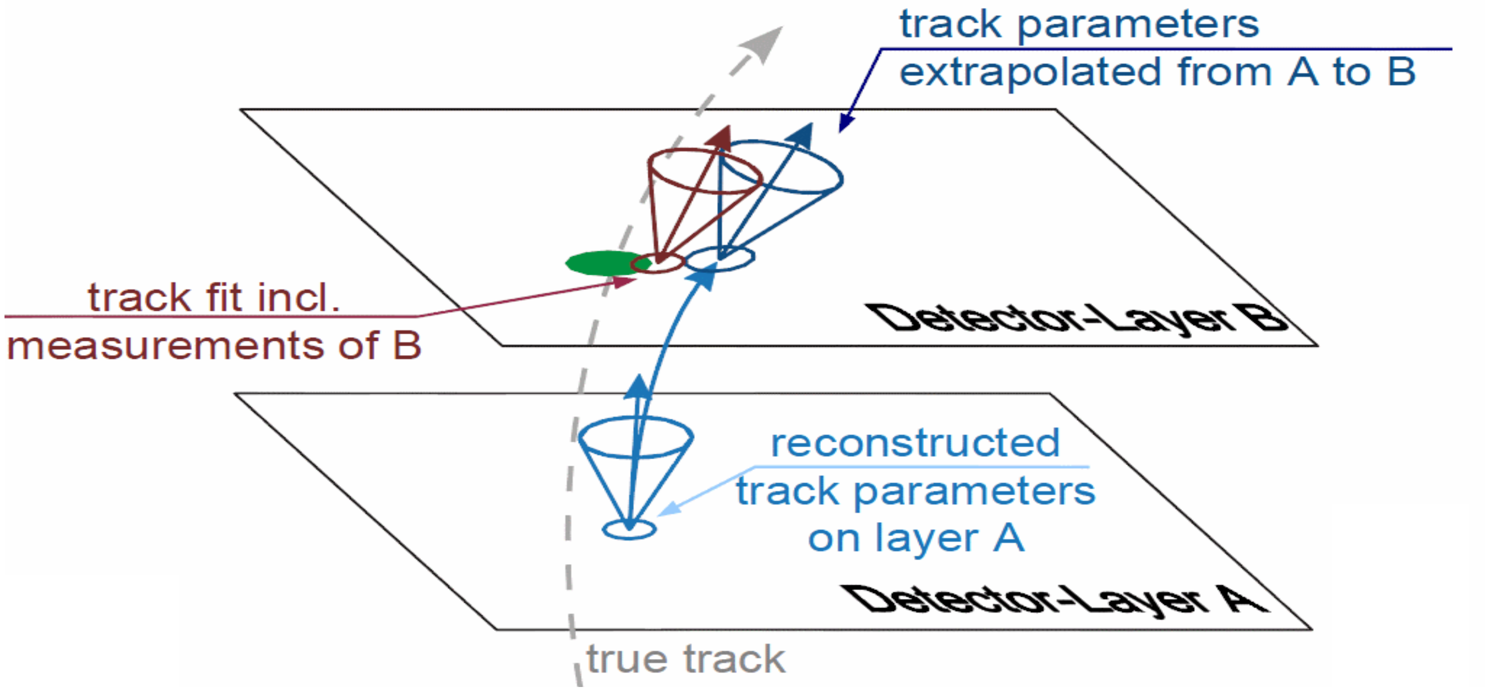
Track Fitting

- Track fitting:
  - Input space points belonging to track candidate
  - Take into account effect due to
    - multiple scattering
    - energy loss
    - magnetic field (use detailed map)
  - This also depends on particle type. Electrons need special treatment due to bremsstrahlung
- Fit output
  - typically momentum (absolute value), direction and position at the surface of the detector unit closest to the beam



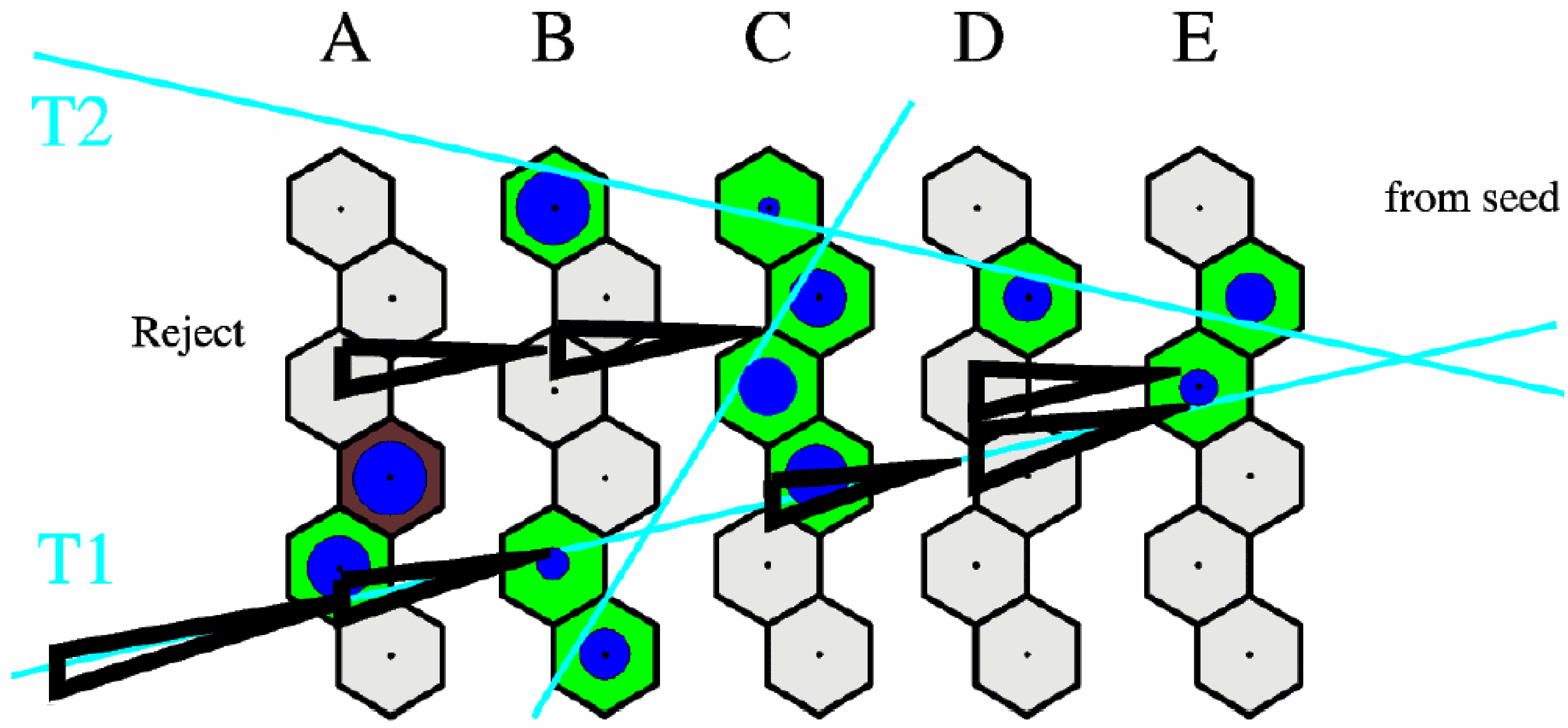
Example: Kalman Filter

- Recursive filter
  - Start from track seed and perform a fit and extrapolate, attach one or more hits
  - add hit(s) based on some criteria, refit, extrapolate and add more hits etc.
  - at some point the recursive algorithm has finished and a final track fit can be applied to the attached hits



Example: Combinatorial Kalman Filter

- Try different possible assignments of measurements



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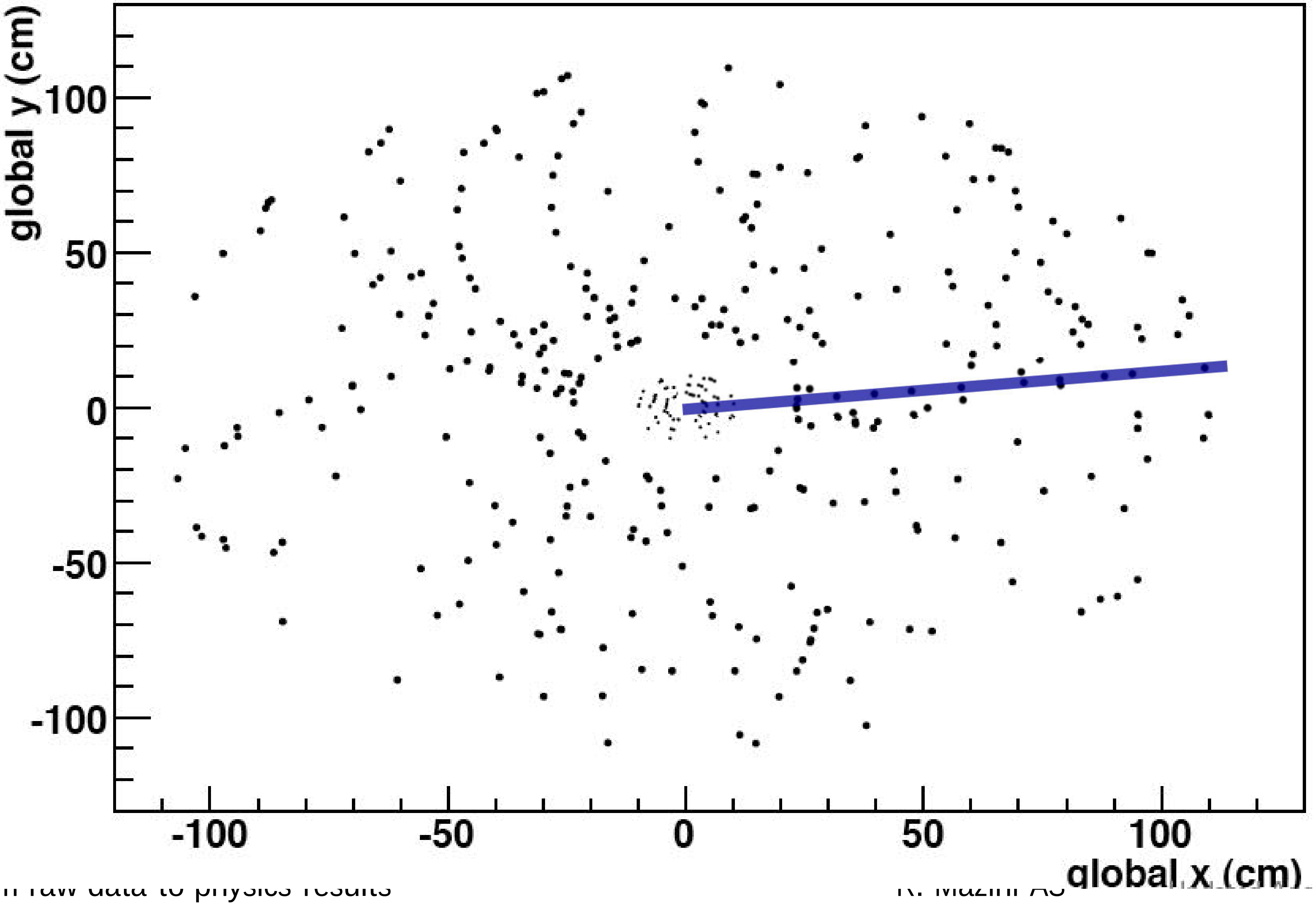
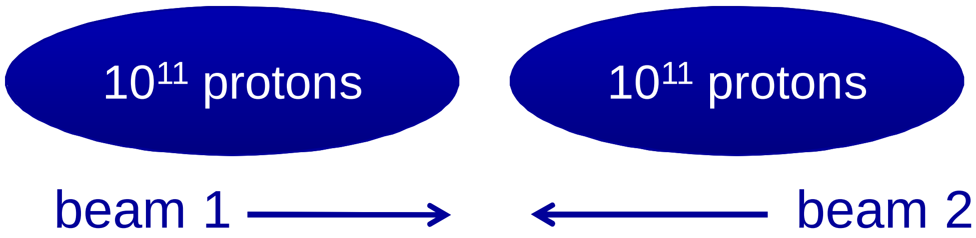


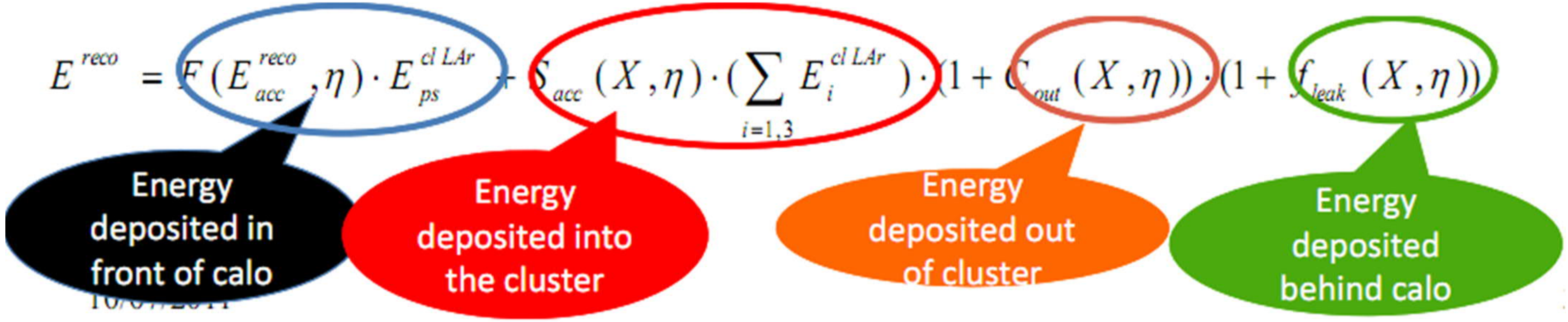
Pile-up: the high luminosity dilema



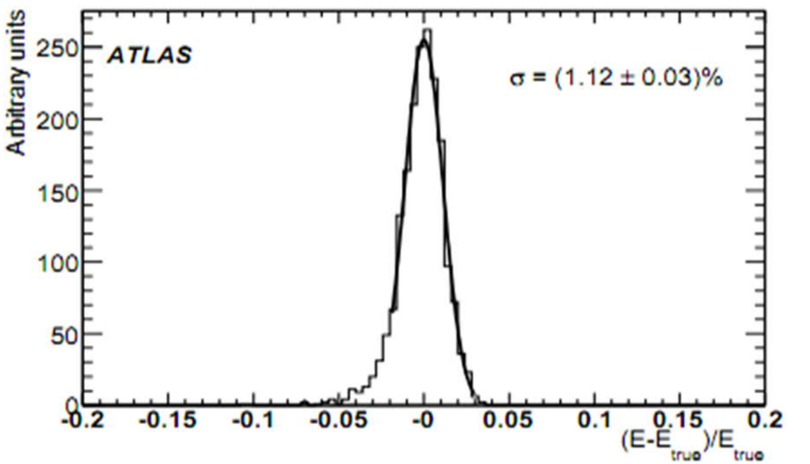
- When the LHC collides bunches of protons we can get more than one p-p interaction – this is called pileup
- The number of pileup interactions depends on the LHC parameters
  - How many protons per bunch
  - How small the bunches have been squeezed
- For last year we have on average ~20 interactions every time the bunches cross
- These pileup interactions give lots of low momentum tracks
- We can usually identify which tracks are from which interactions by combining tracks that come from the same vertex
- Pileup can cause difficulties for some physics analyses
  - Also causes reconstruction to need more computing power
- But allows us to get more luminosity

Cluster Energy calibration

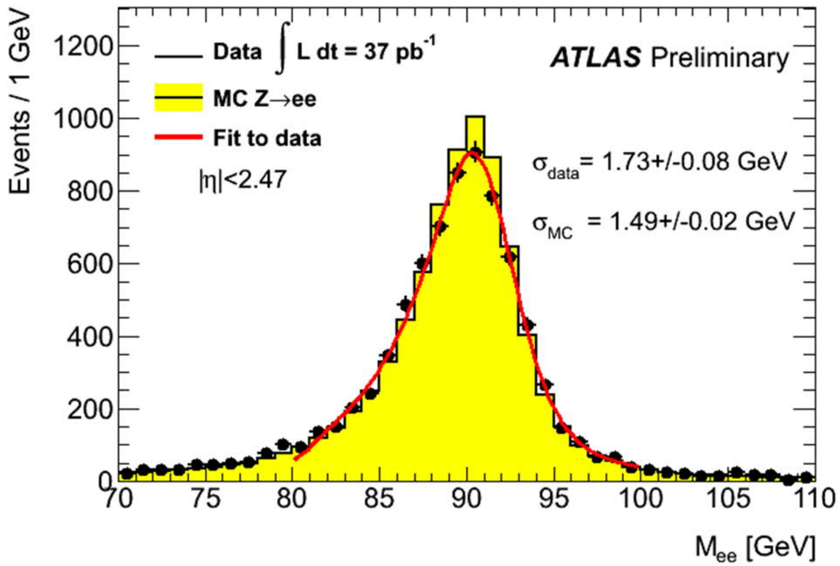
$$E^{reco} = F(E_{acc}^{reco}, \eta) \cdot E_{ps}^{cl\,LAr} + S_{acc}(X,\eta) \cdot \left(\sum_{i=1,3} E_i^{cl\,LAr}\right) \cdot (1 + C_{out}(X,\eta)) \cdot (1 + f_{leak}(X,\eta))$$



- Calibration constants can be complex functions of the position and energy of the cluster
  - $E^{CALIB} = f(E^{MEASURED}, \eta, \phi, \ldots)$, f includes various calibration constants
- Calibration very important to get the be

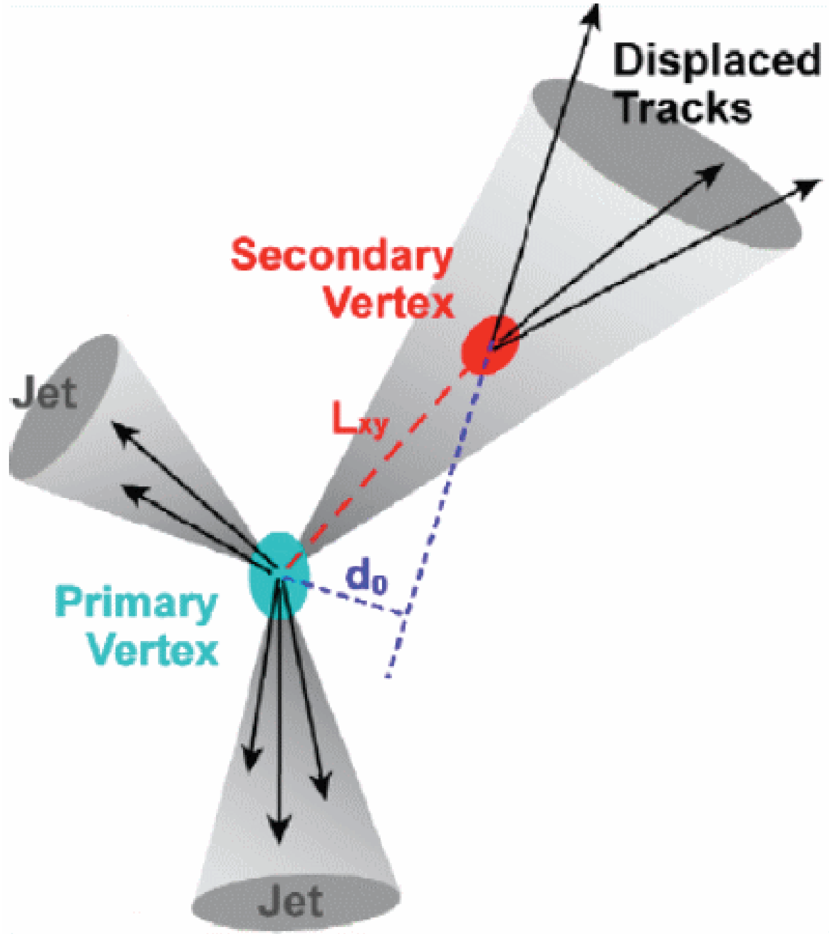


Electron energy resolution from simulation

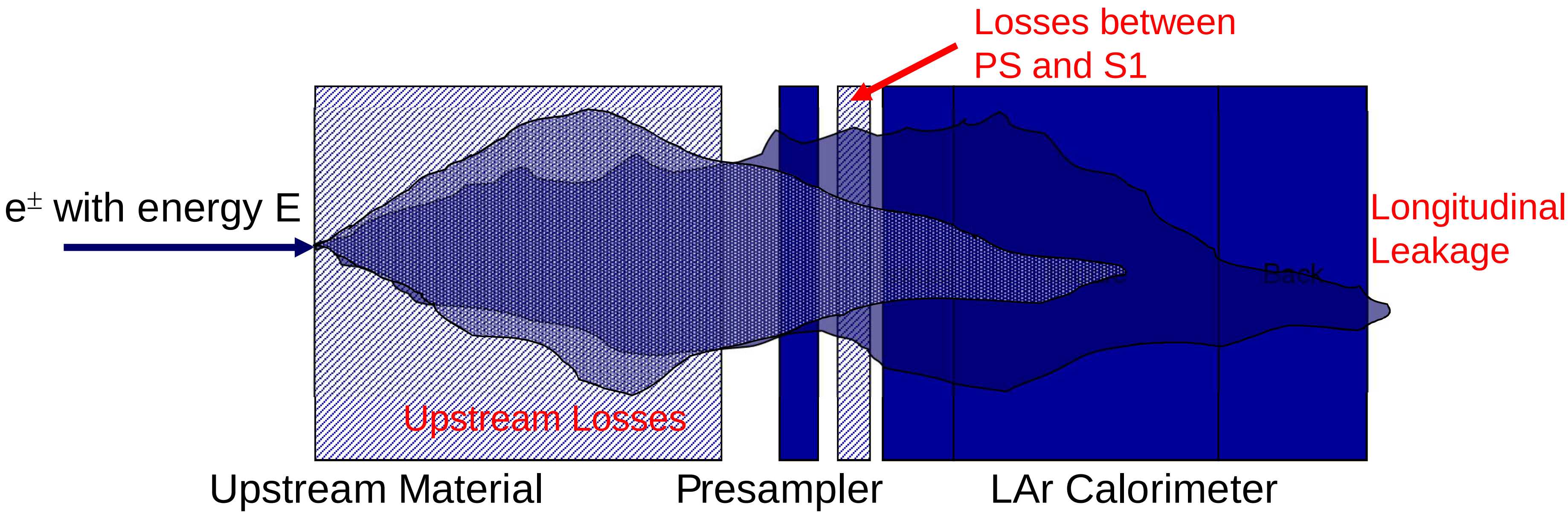


B-tagging

- 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



Cluster reconstruction

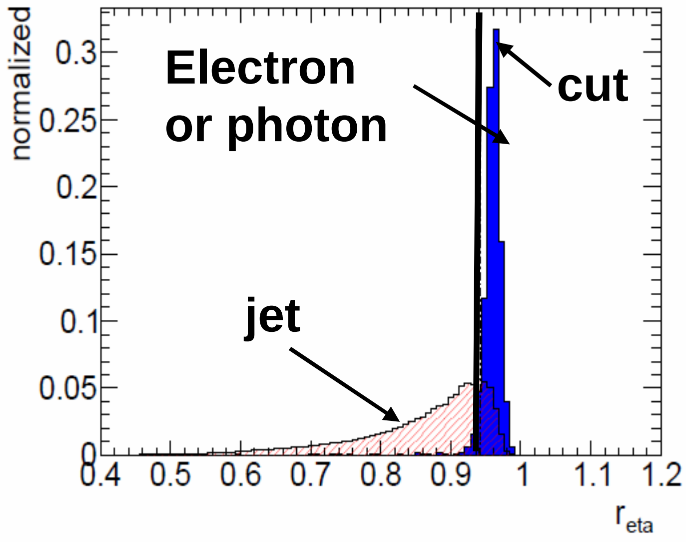


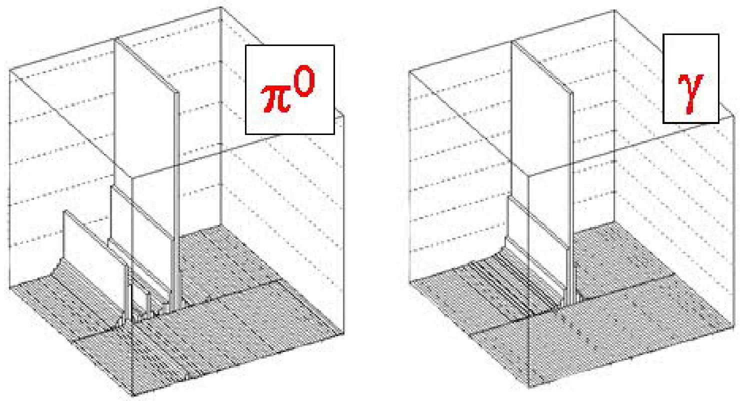
- Input to clustering:
  - Cells calibrated at the EM scale
- Sum energy in EM calo, correct for losses in upstream material, longitudinal leakage and possible other lossses between calo layers (if applicable)
  - e.g. $E_{rec} = \lambda\left(b + W_0 E_{pres} + E_1 + E_2 + W_3 E_3\right)$
- Typically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

e/jet and γ/jet separation

- 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 within one cluster
  - Preshower in CMS, 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

Transverse shower shape in 2nd EM layer (ATLAS)

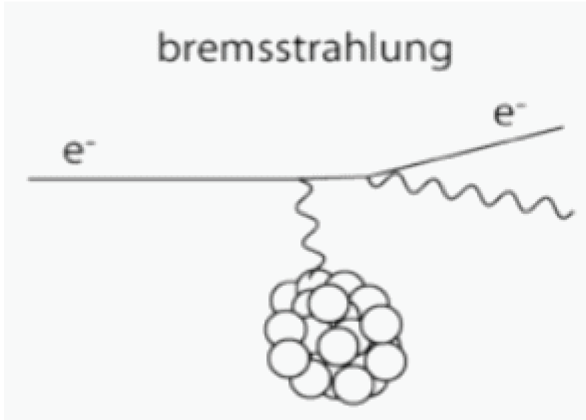


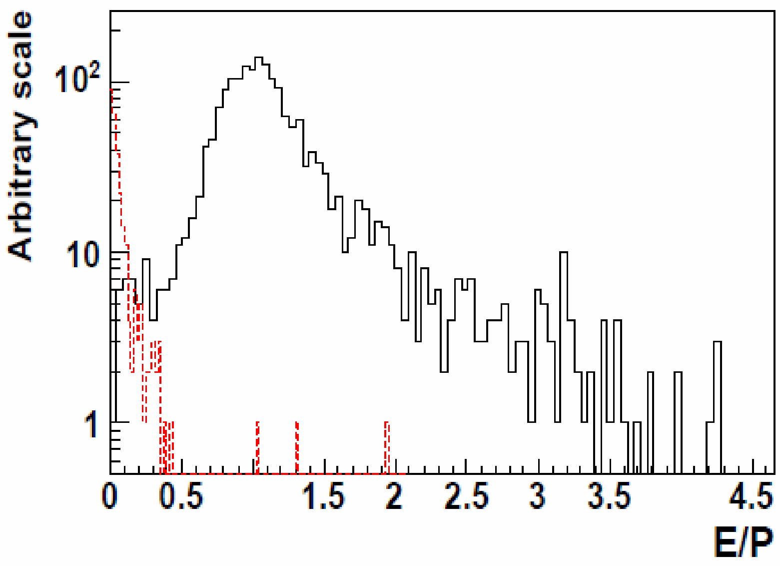


ATLAS

Bremsstrahlung

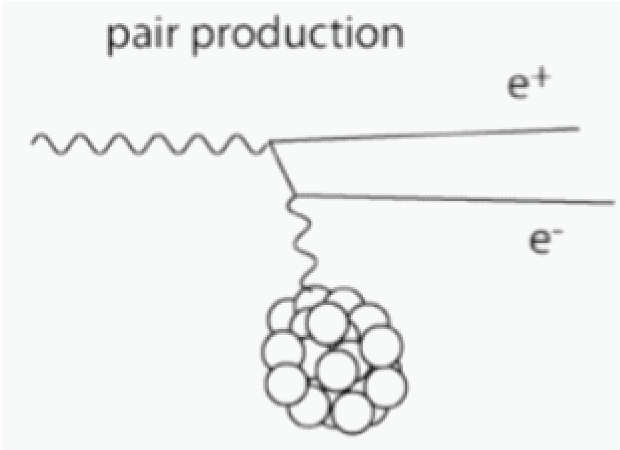
- Electrons can emit photons in the presence of material
- At LHC energies:
  - electron and photon (typically) end up in the same cluster
  - Electron momentum is reduced
  - E/p distribution will show large tails
- Methods for bremsstrahlung recovery
  - Gaussian Sum Filter, Dynamic Noise Adjustment
  - Use of calorimeter position to correct for brem
  - Kink reconstruction, use track measurement before kink

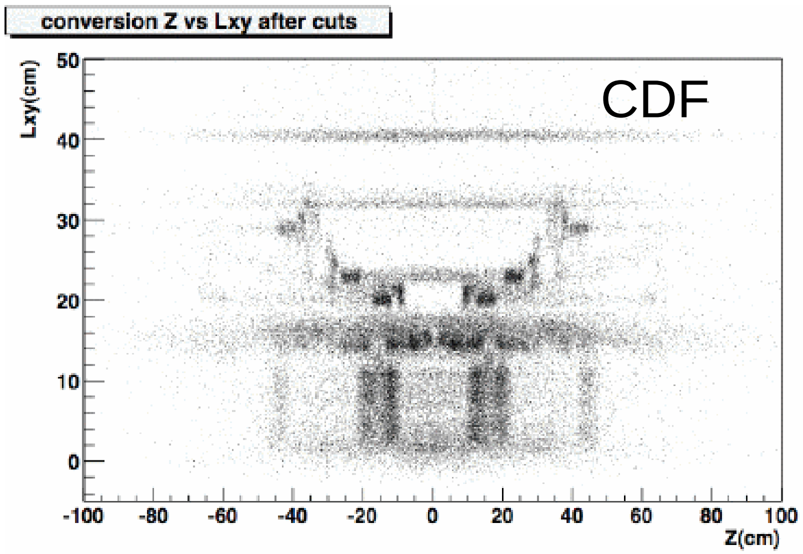


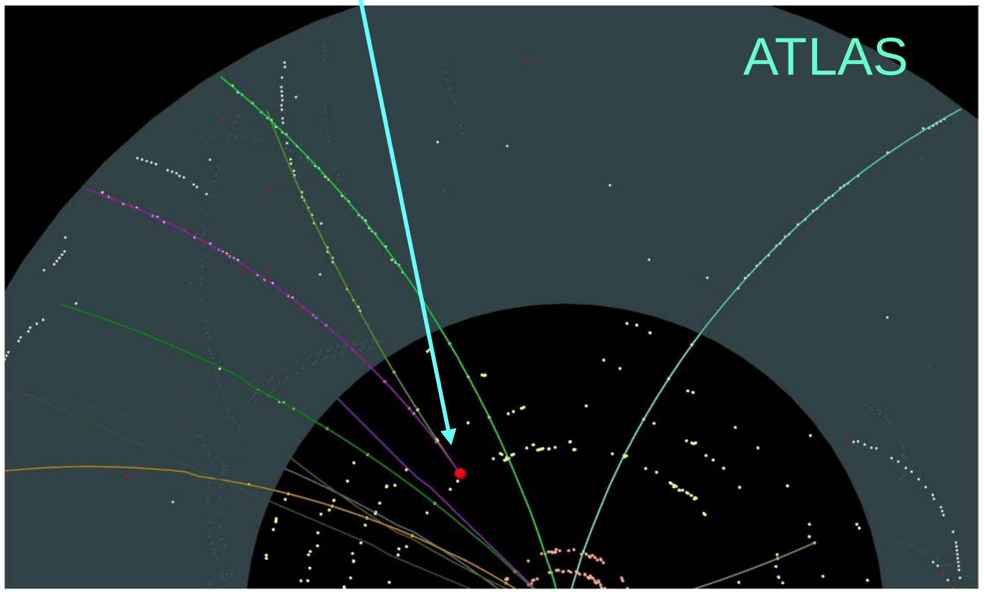


Conversion reconstruction

- Photons can produce electron pairs in the presence of material
- Find 2 tracks in the inner detector from the same secondary vertex
  - Need for outside-in tracking
- However, can be useful:
  - Can use conversions to *x-ray* detector and determine material before calorimeter (i.e. tracker)



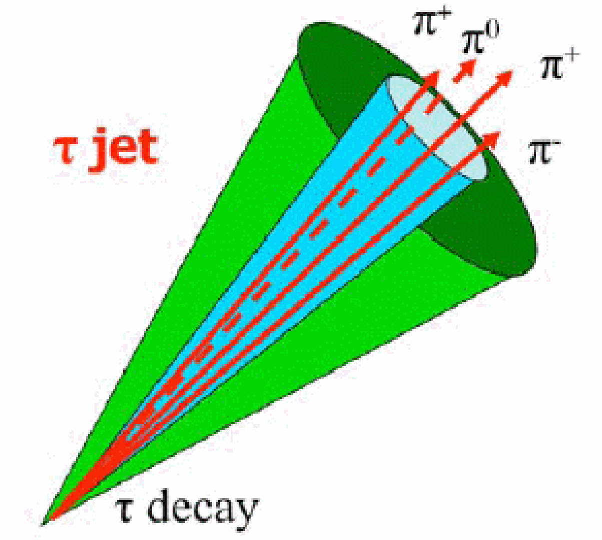




Hadronic decay of tau-lepton

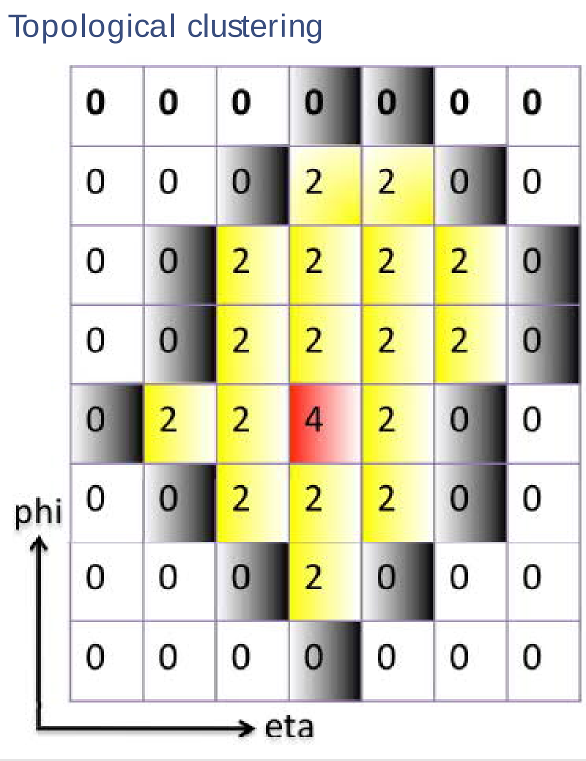
- Decays
  - 17% in muons
  - 17% in electrons
  - ~65% of τ's decay hadronically in 1- or 3-prongs ($\tau^{\pm}\rightarrow\pi^{\pm}\nu$, $\tau^{\pm}\rightarrow\pi^{\pm}\nu+n\pi^{0}$ or $\tau^{\pm}\rightarrow3\pi^{\pm}\nu$, $\tau^{\pm}\rightarrow3\pi^{\pm}\nu+n\pi^{0}$)
- For reconstruct hadronic taus
  - 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)

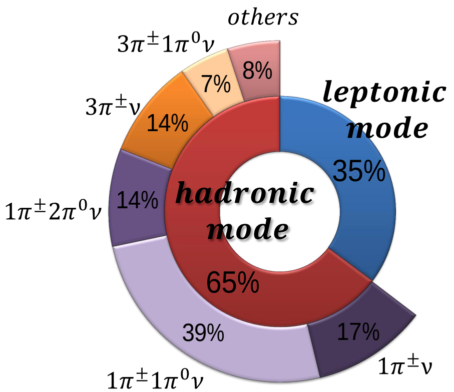
$e^{-}\nu\nu$	**17.8%**
$\mu^{-}\nu\nu$	**17.4%**
$h^{-}\nu$	**49%**
$\pi^{-}\nu$	11%
$K^{-}\nu$	0.7%
$\rho^{-}\nu$	25.4%
$h^{+}h^{-}h^{-}\nu$	**15%**

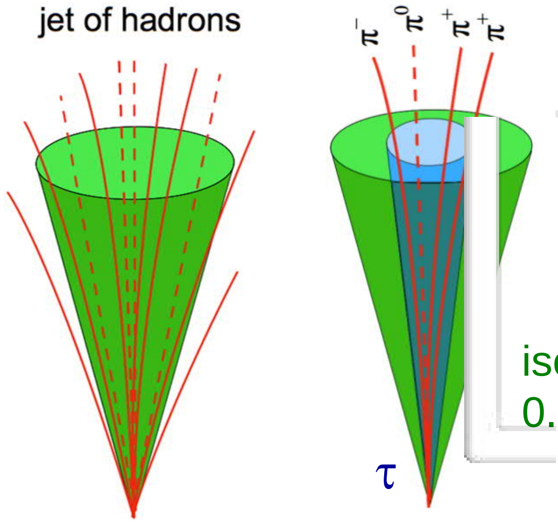


Hadronic decay of tau-lepton

- Hadronic decays of tau: 65%
- Reconstruction seeded by anti-kt jets(R=0.4)
  - p_T > 10 GeV, |η| < 2.5
  - calibrated 3D topological clusters
  - good quality tracks with p_T > 1 GeV
  - discriminating variables
    - combined information from calorimeter and tracking
    - input to multi-variate algorithms







core cone
ΔR < 0.2

isolation cone
0.2 < ΔR < 0.4

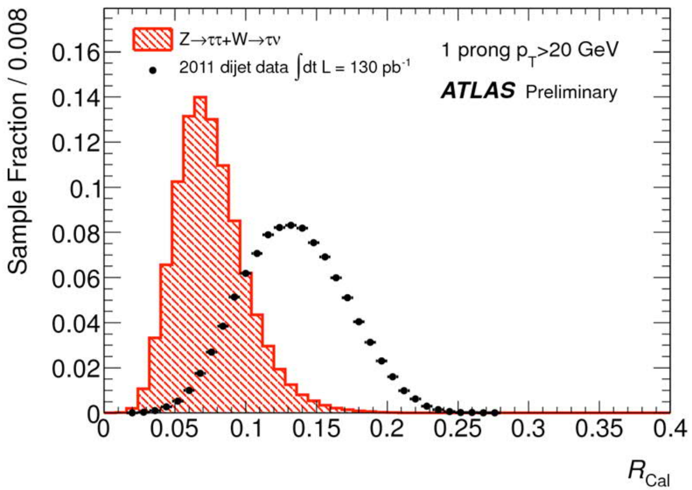
Hadronic decay of tau-lepton

Decay properties of tau	Detector information used
Collimated decay products	Jet width in tracker and calorimeter
Leading charged hadron	Leading track
No gluon radiation	Isolation
Low invariant mass	Invariant mass of tracks and clusters
Lifetime	Impact parameter, secondary vertex
EM energy fraction different from electrons	Longitudinal position of energy deposits
EM component from π^0	LAr strip
Less transition radiation than electrons	TRT

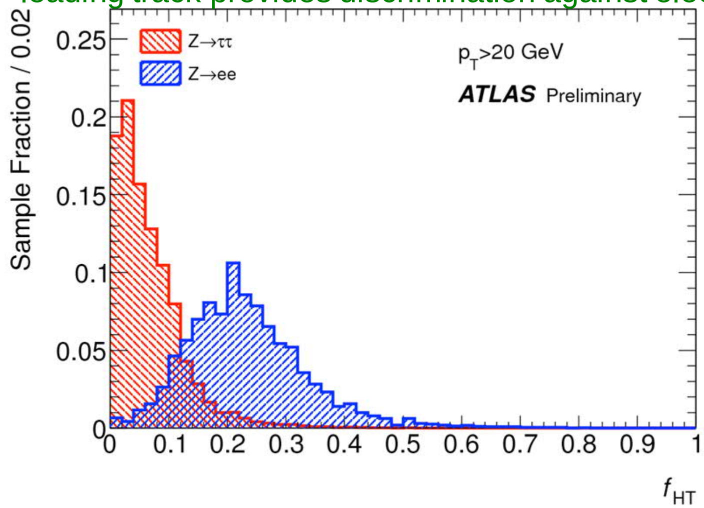
Discrimination against Jets

e

Energy weighted calorimeter radius provides discrimination against jets



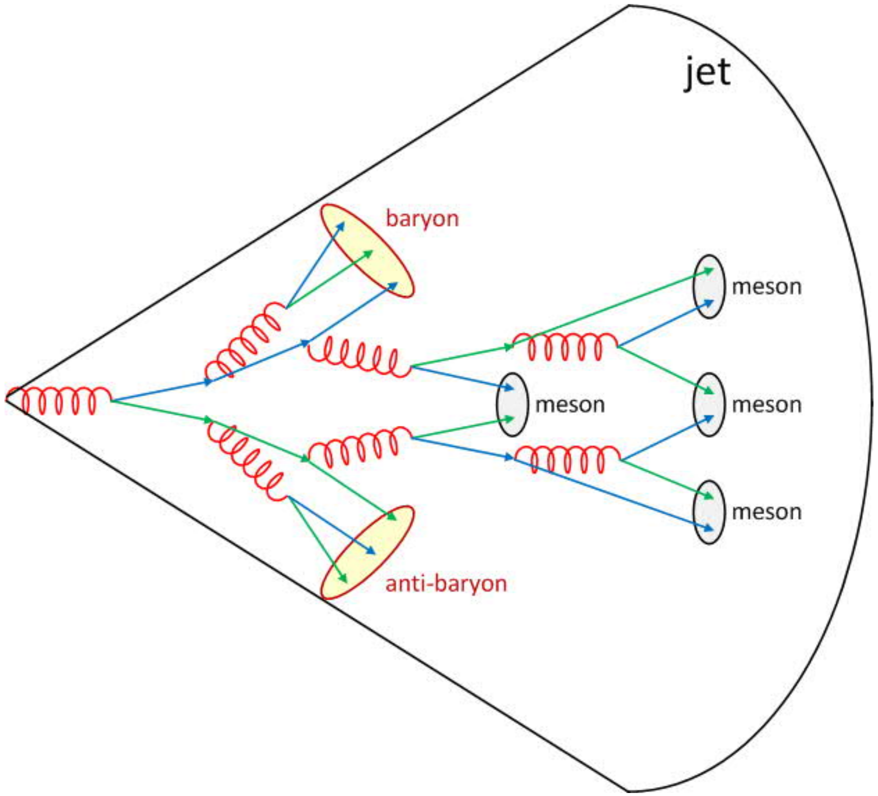
Ratio of high threshold to low threshold hits in TRT for leading track provides discrimination against electrons



Frc

Jets

- 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
- Calorimeter energy measurement
  - Gets more precise with increasing particle energy
  - Gives good energy measure for all particles except μ's and ν's
  - Does not work well for low energies
    - Particles have to reach calorimeter, noise in readout



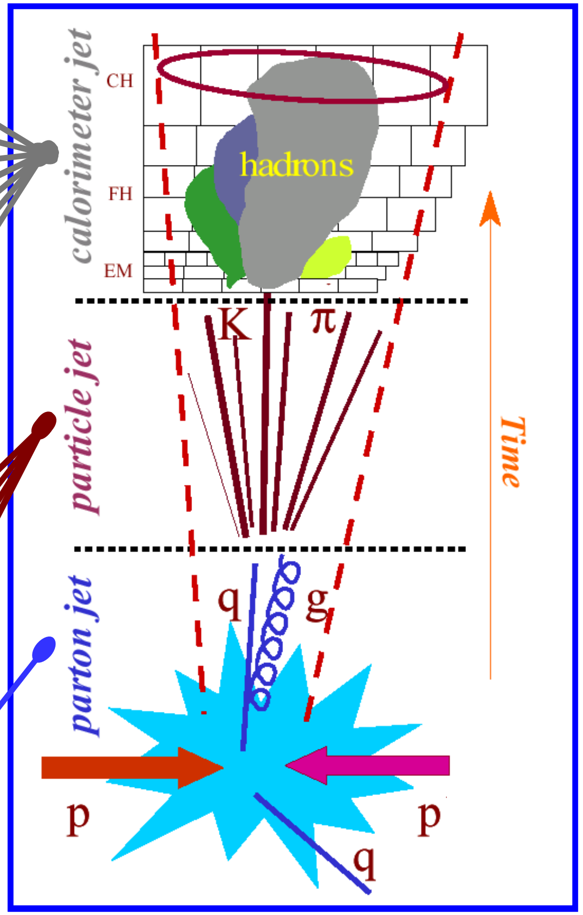
Jet Reconstruction and Calibration

- Contributions to the jet signal:

longitudinal energy leakage
detector signal inefficiencies (dead channels, HV...)
pile-up effects
electronic noise
dead material losses (i.e. cracks)
detector response characteristics (e/h ≠ 1)
jet reconstruction algorithm efficiency

jet reconstruction algorithm efficiency
added tracks from pile-up
added tracks from underlying event
lost soft tracks due to magnetic field

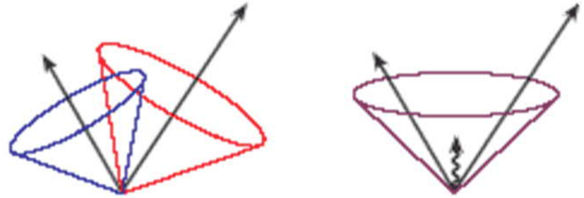
physics reaction of interest (parton level)



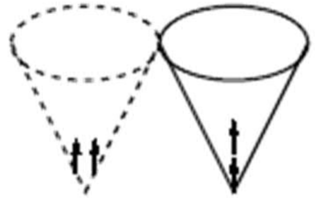
- Try to address reconstruction and calibration through different levels of factorisation

Theoretical requirement to jet algorithm choices

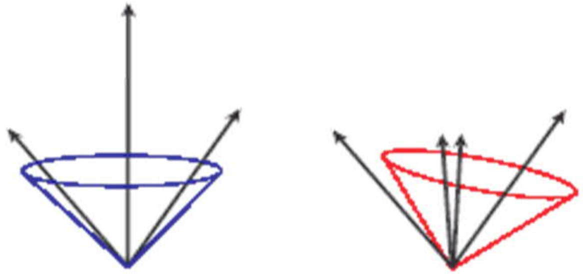
- Infrared safety
  - Adding or removing soft particles should not change the result of jet clustering
- Collinear safety
  - Splitting of large p_T particle into two collinear particles should not affect the jet finding
- Invariance under boost
  - Same jets in lab frame of reference as in collision 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)

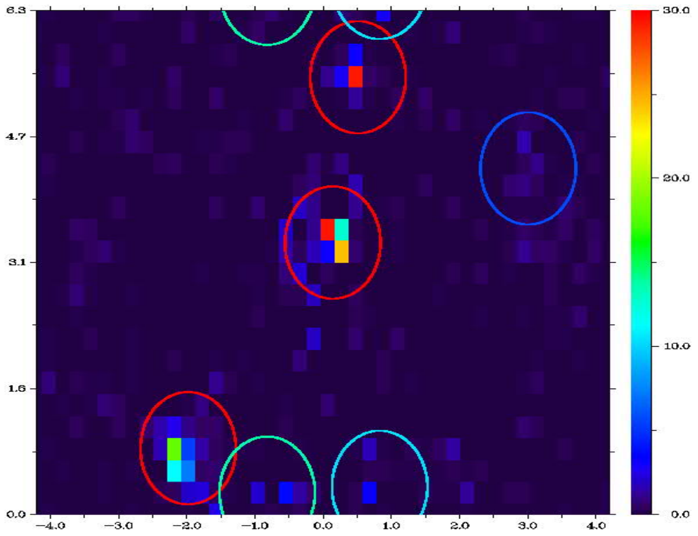


collinear sensitivity (1)
(signal split into two towers below threshold)



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

Types of jet reconstruction algorithms: cone

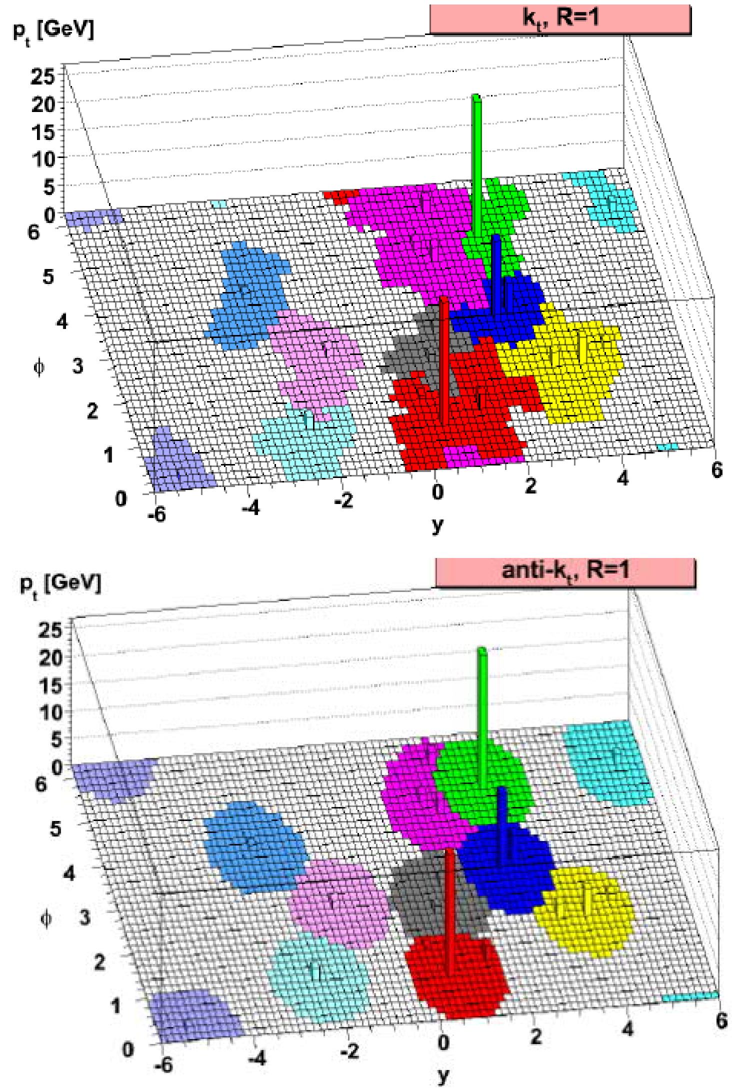


<u>Example: iterative cone algorithms</u>

- Find particle with largest p_T above a seed threshold
- Draw a cone of fixed size around this particle
  - $\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} < R_{cone}$
- Collect all other particles in cone and re-calculate cone directions
- Take next particle from list if above p_T seed threshold
- Repeat procedure and find next jet candidate
- Continue until no more jet above threshold can be constructed
- 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
  - Combine particles if relative p_T is smaller than 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 ATLAS algo.)
    - First cluster high E with high E and high E with low E particles
      - This keeps jets nicely round



Missing Transverse Momentum

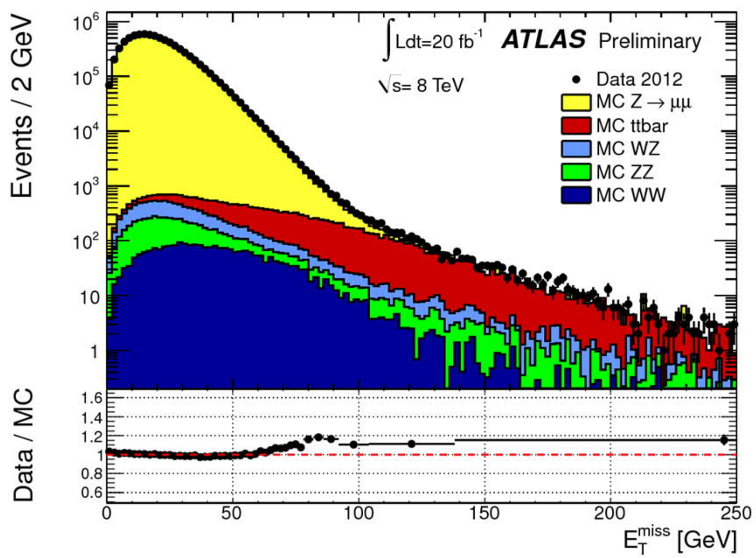
- Missing energy is not a good quantity in a hadron collider as much energy from the proton remnants are lost near the beampipe
- Missing transverse momentum ($\not{E}_T$) much better quantity
  - Measure of the loss of energy due to neutrinos
- Definition:
  - $$\not{E}_T \equiv -\sum_i E_T^i \hat{n}_i = -\sum_{all\ \mathrm{visible}} \vec{\mathrm{E}}_\mathrm{T}$$
- Missing E_T reconstruction algorithms:
  - Use all calorimeter cells or energy clusters above a certain energy threshold
  - Use all reconstructed particles w-r-t their calorimeter and track measurement.
  - Use reconstructed/calibrated particles above a p_T threshold in addition to all remaining calorimeter clusters
  - Use reconstructed particles above a p_T threshold in addition to all remaining reconstructed tracks

Missing Transverse Momentum

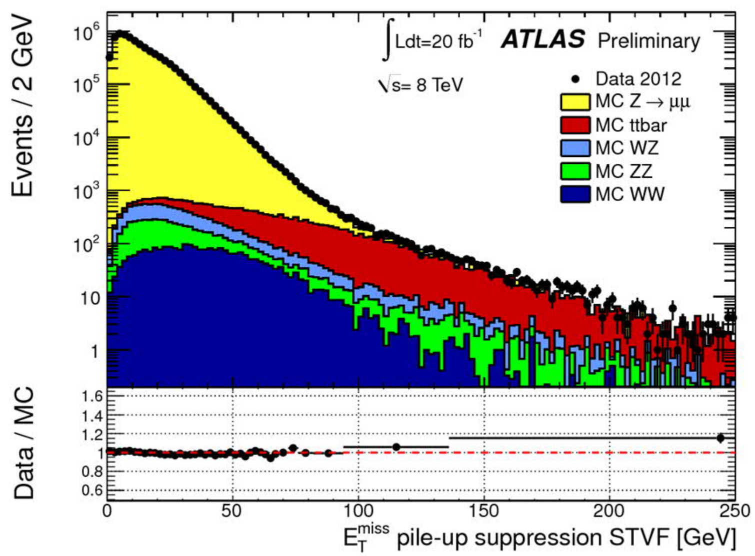
- But it‘s not that easy...
  - Electronic noise might bias missing E_T measurement
  - Particles might have ended in cracks / insensitive regions
  - Dead calorimeter cells
  - Effects from beamhalo events
- Corrections needed to calorimeter missing E_T
  - Correction for muons. Recall: muons are MIPs
  - 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.
  - It is a erious problem at the LHC.
  - Distort smissing E_T scale and direction measurement, worsen its resolution,
  - Increase backgrounds from processes with fake or low missing E_T

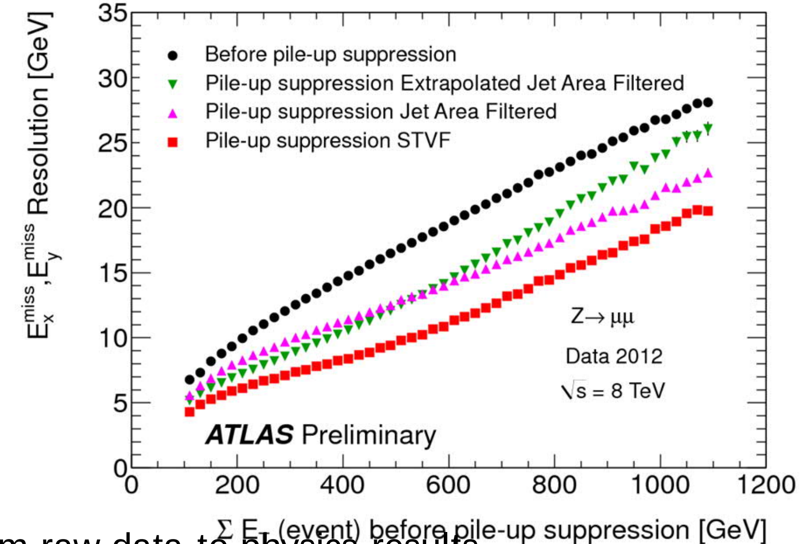
Missing Transverse Momentum

before pile-up suppression



After pile-up suppression





Missing E_T resolution improves with pile-up suppression.
Several methods been developed using tracks or energy subtraction from calorimeter clusters

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