# Calorimetry and Missing $E_T$

**Frank Simon**
**MPI for Physics & Excellence Cluster 'Universe'**
**Munich, Germany**

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(Werner-Heisenberg-Institut)

TUM
LMU
Excellence Cluster
Universe

# The Universe: Open Questions

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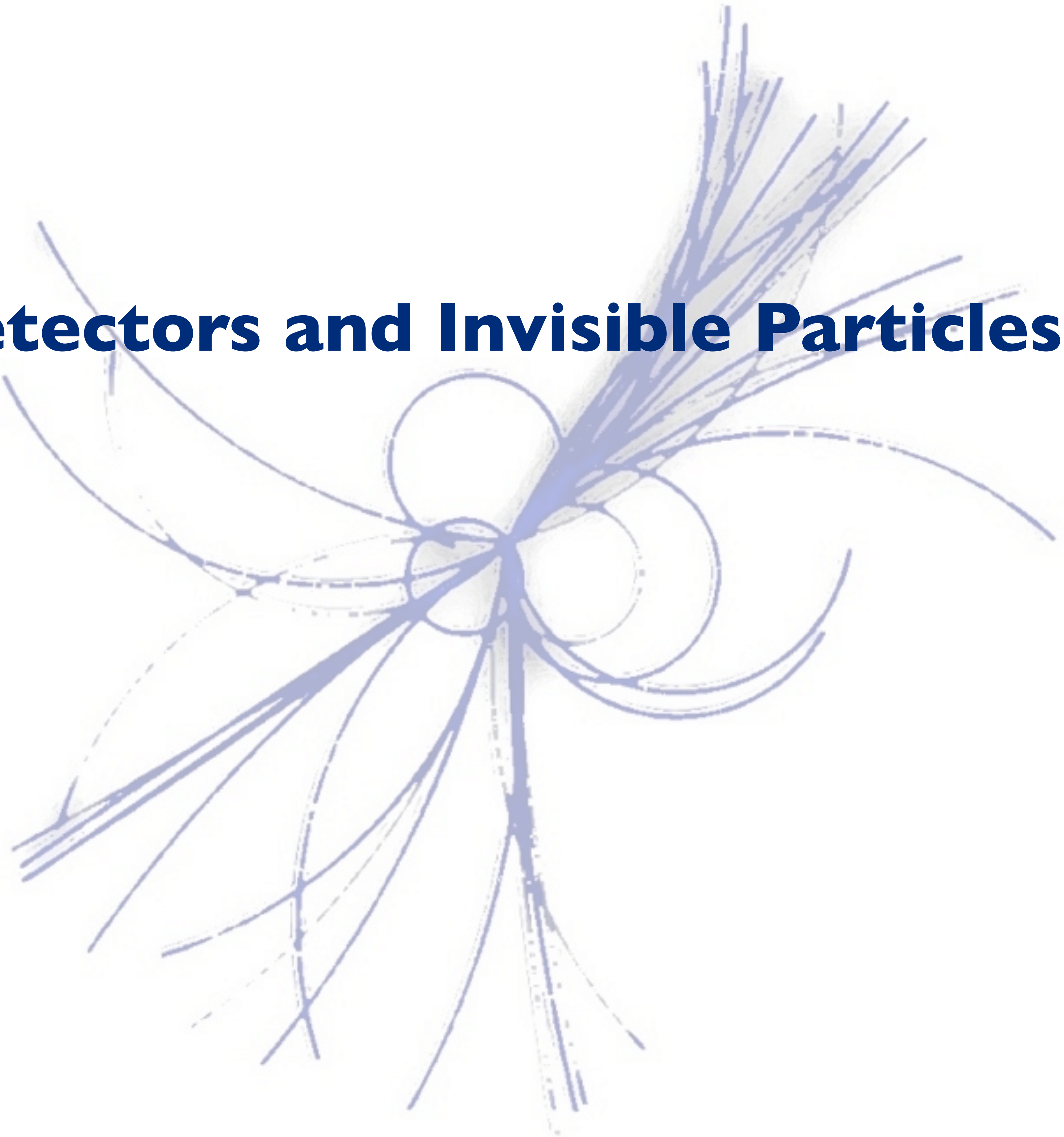
How do you see those guys in a detector?

How do you get precise measurements of particle masses, in particular in hadronic decays?

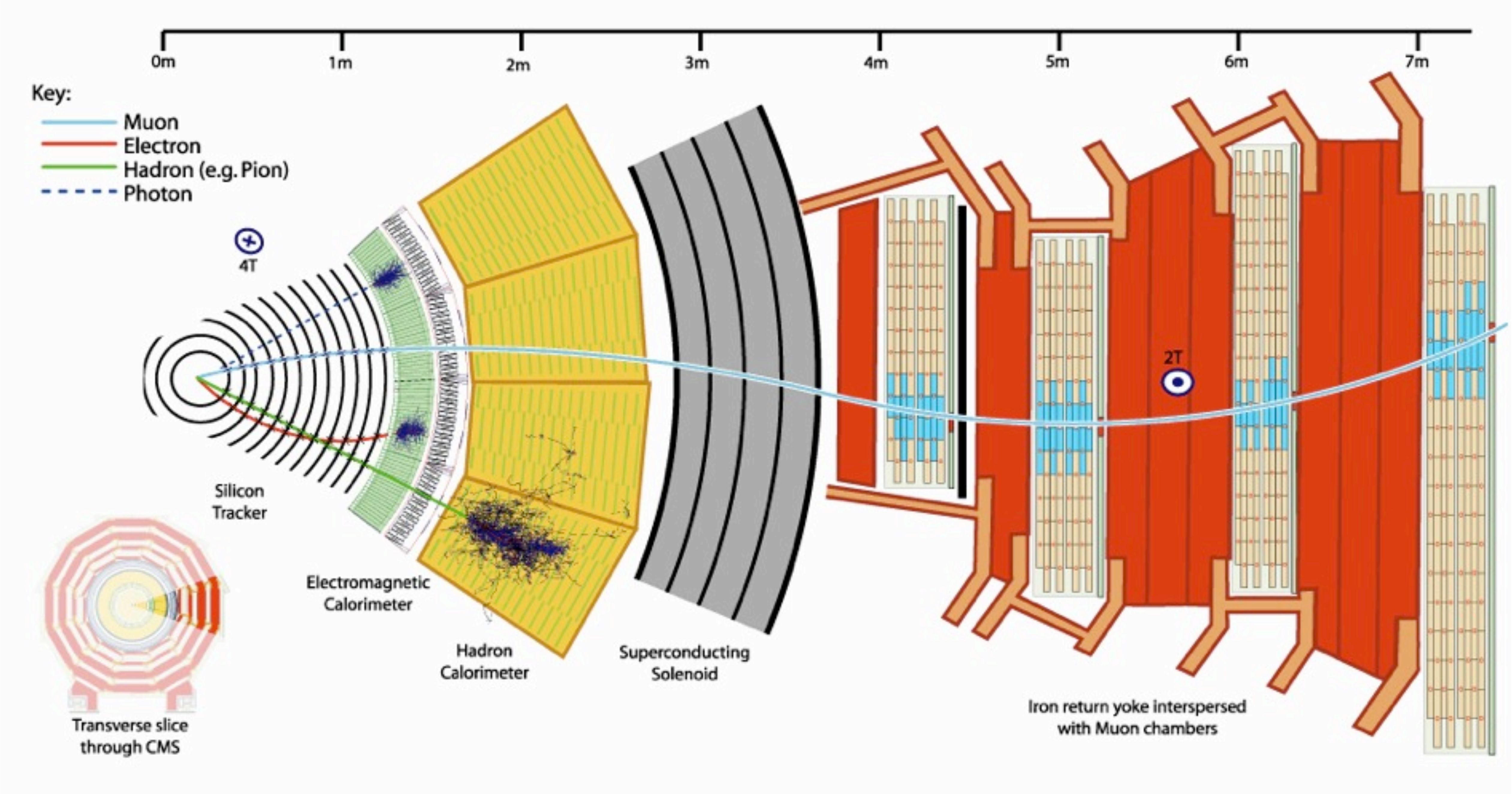
# Outline

- Missing $E_T$: Techniques to see "invisible" Particles
- Calorimetry in Collider Physics
- Advanced Reconstruction Techniques at future Colliders: Particle Flow
- Particle Flow at LHC
- Summary

# Detectors and Invisible Particles



# The Generic Collider Detector




- The CMS detector as an example: Measurements of
  - Charged particles (hadrons, electrons, muons): dE/dx energy loss
  - Neutral particles (photons, long-lived neutral hadrons): em or hadronic showers

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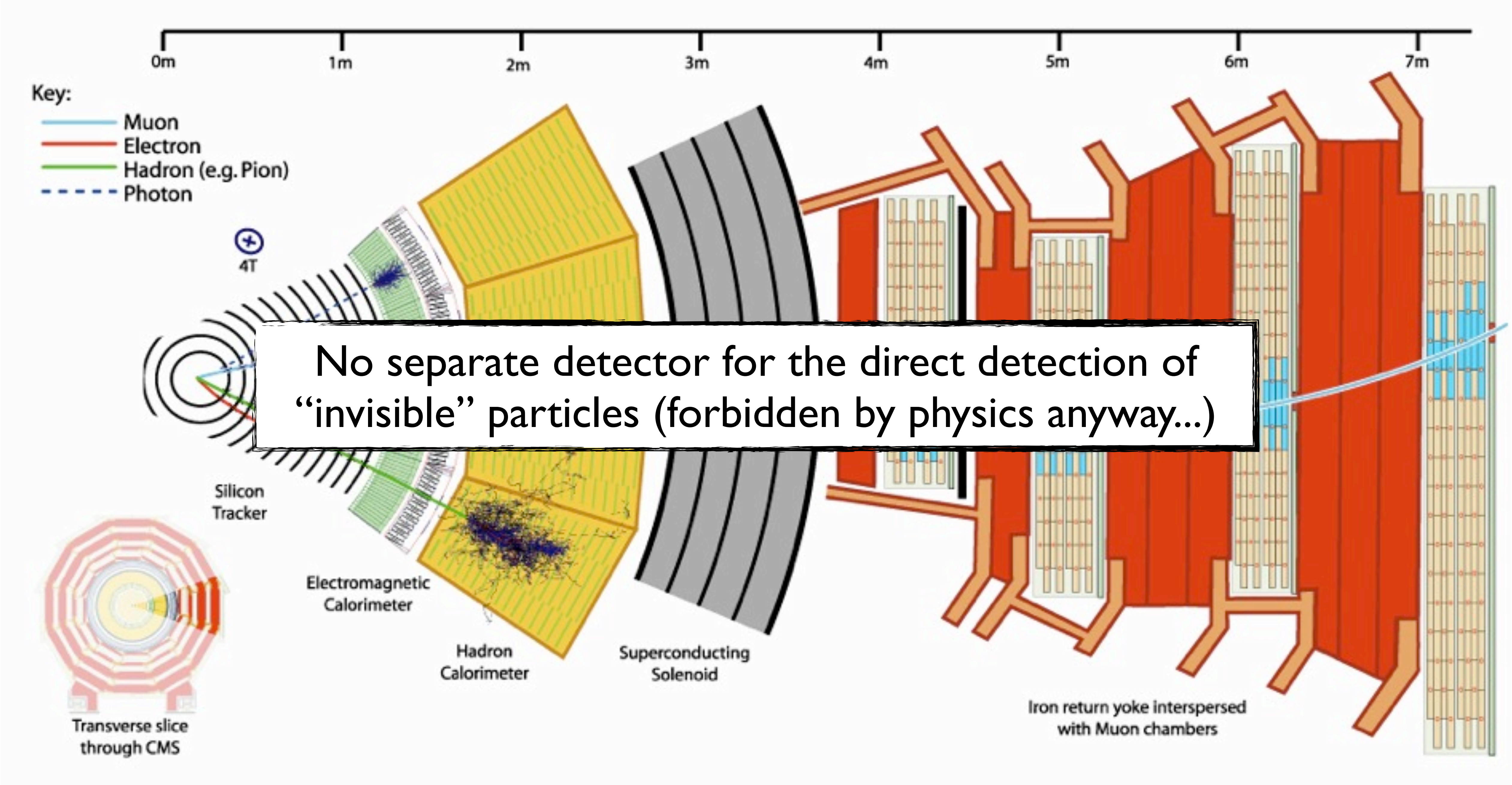


No separate detector for the direct detection of "invisible" particles (forbidden by physics anyway...)

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- What we know:
  - Head-on collision of beam particles: both travel along the detector axis
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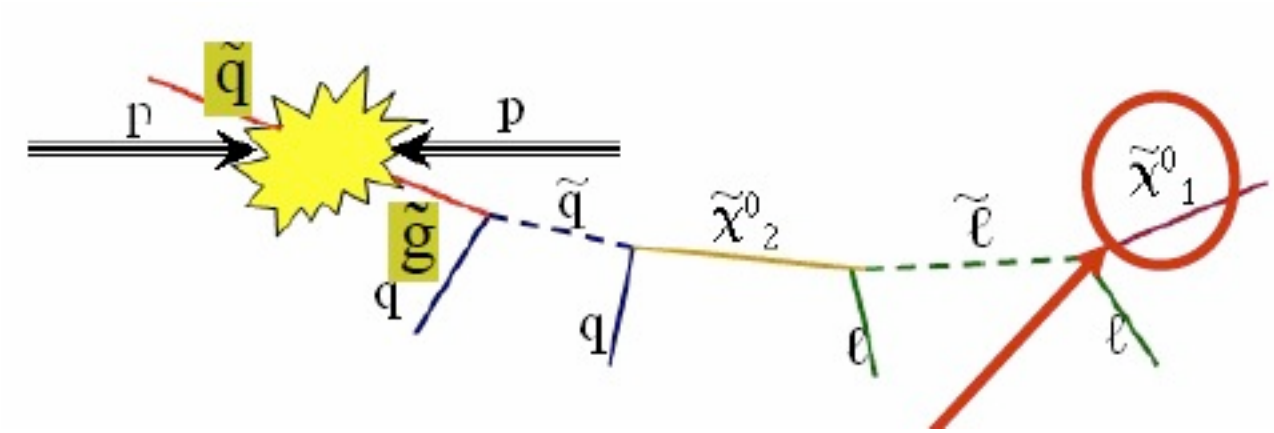
➯ Circumstantial evidence: Apparent energy and momentum violation in the final state

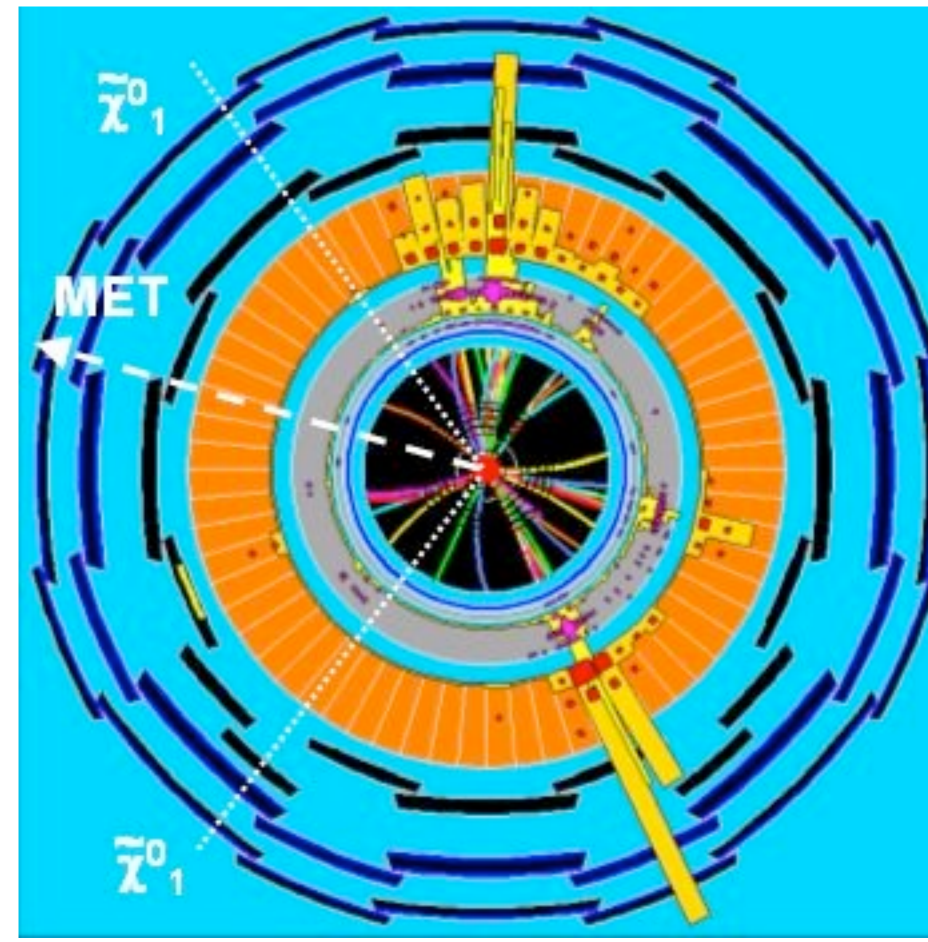
the sum of transverse momenta does not add up to zero: one (or more) particles escaped the detector undetected

# Seeing Invisible Particles: SUSY Example




LSP: "invisible particle", dark matter candidate

ATLAS Simulation

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  - multiple hadronic jets
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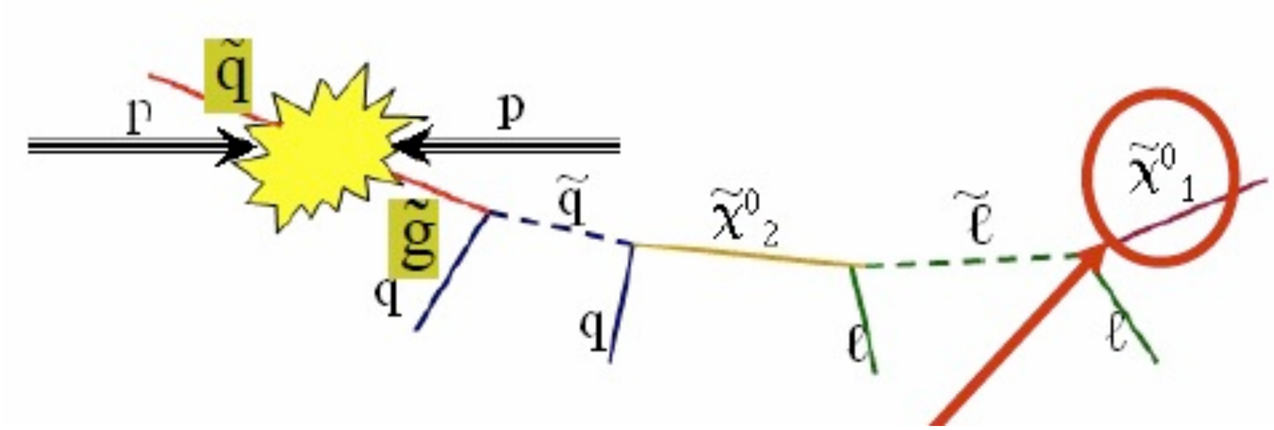


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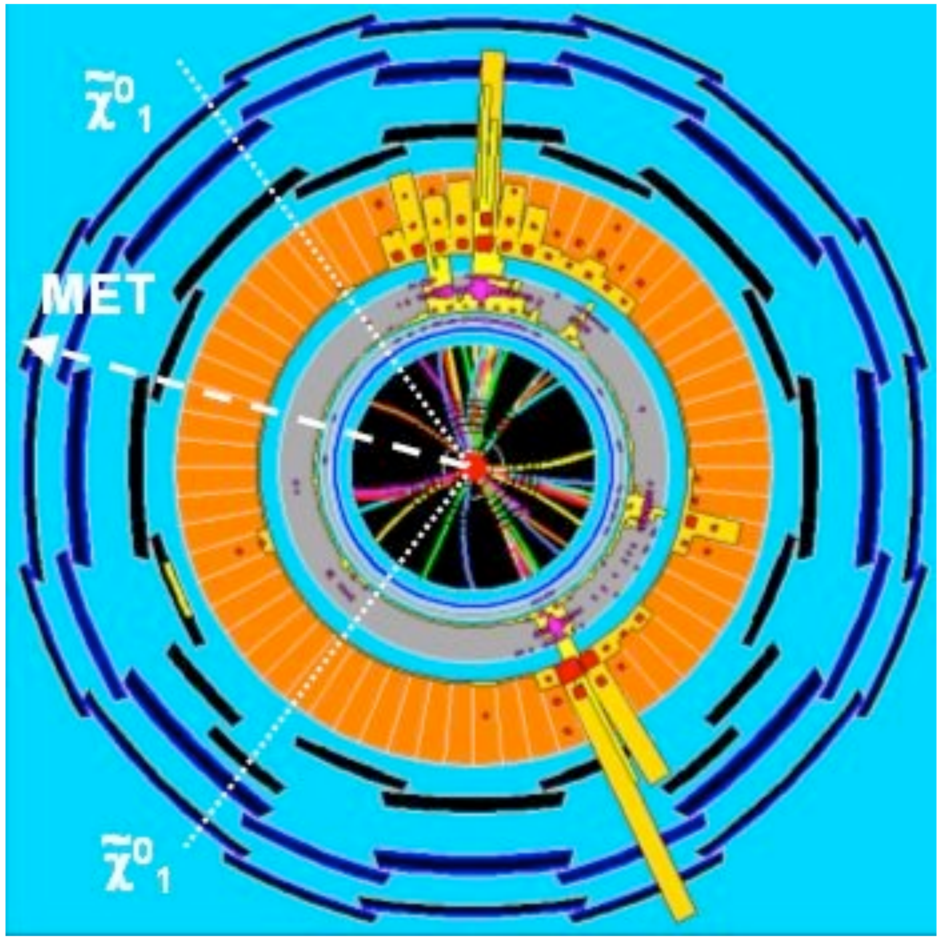


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Of particular importance: The complete energy measurement, performed in the calorimeters

# Reconstructing the Energy Flow in an Event

- In a typical event at a high energy collider:
  - Final-state quarks: Give rise to hadronic jets
    - Photon component from the decay $\pi^0 \rightarrow \gamma\gamma$
  - Final-state leptons: muons and electrons
    - Taus are special: Decay almost instantaneously, large BR in hadrons: Belong more in the jet than in the lepton category, with the added problem of missing energy from a neutrino
  - Final state photons: Direct photon production
  - Final-state neutrinos (and long-lived neutral NP particles): Missing $E_T$

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The recipe for a good measurement:

- highly efficient, high resolution tracking for muons
- high resolution electromagnetic calorimeters for photons
- high resolution jet measurement in the calorimeter system

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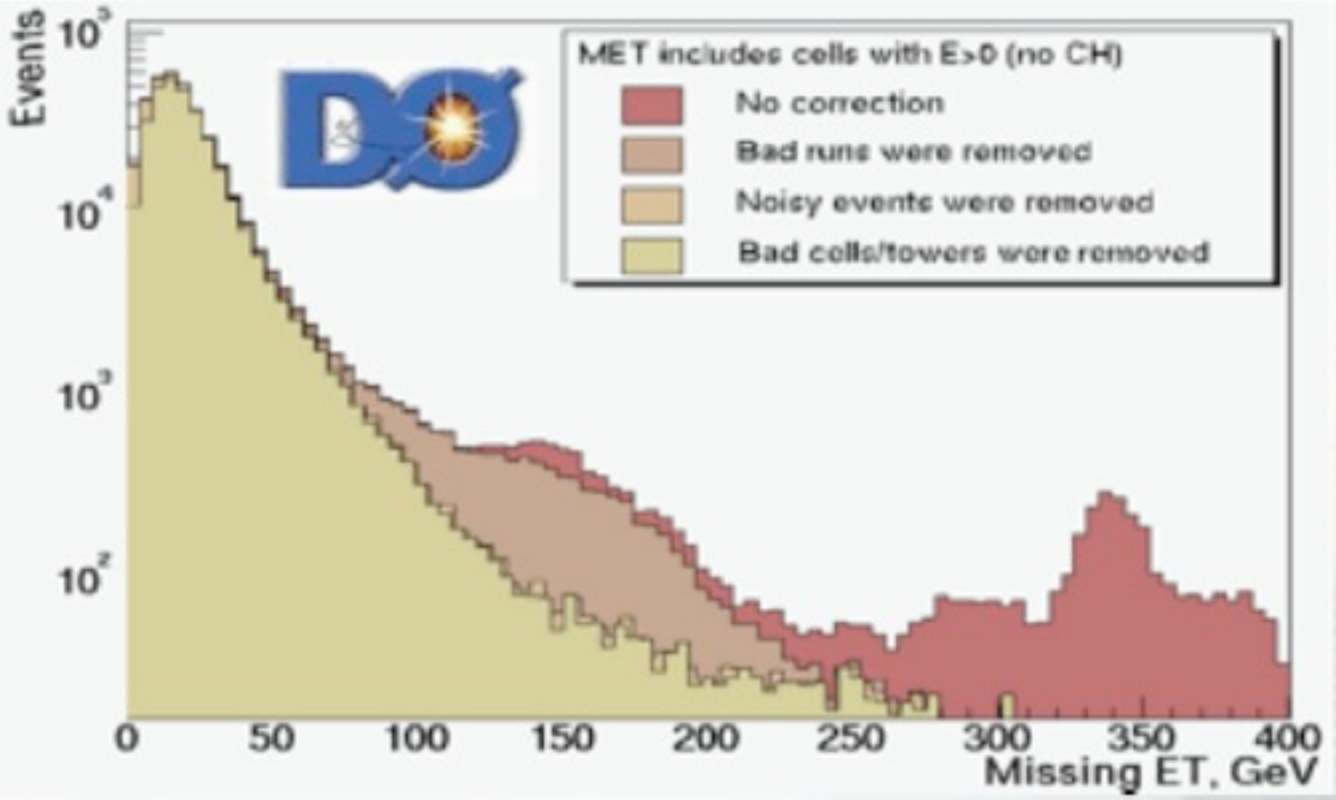
➯ Requirements for the detector:

- Hermetic coverage down to extremely low angles
- Very good understanding of detector performance, also at the interfaces between subsystems
- Good energy resolution, also for jets and neutral hadrons: Defines the resolution for missing $E_T$

# Missing $E_T$ at the Tevatron: Not just New Physics

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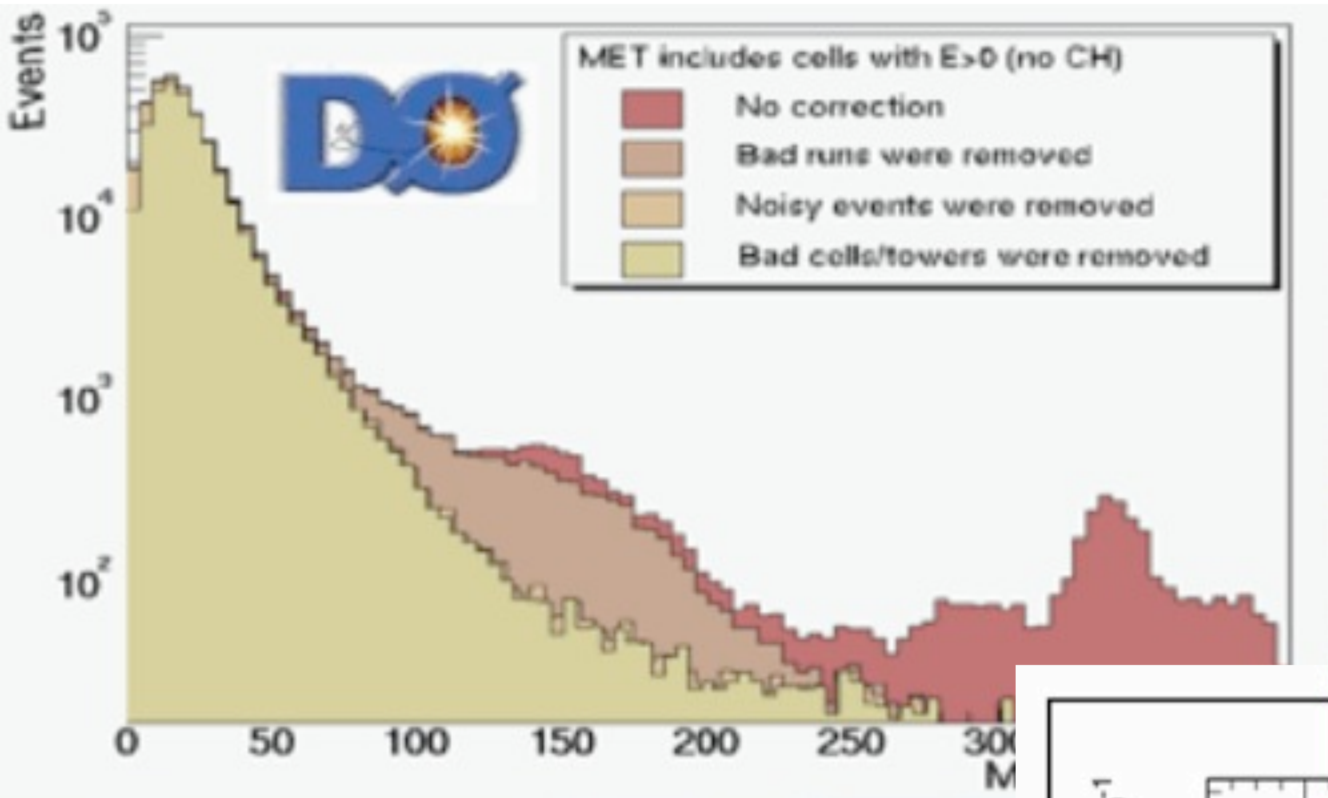


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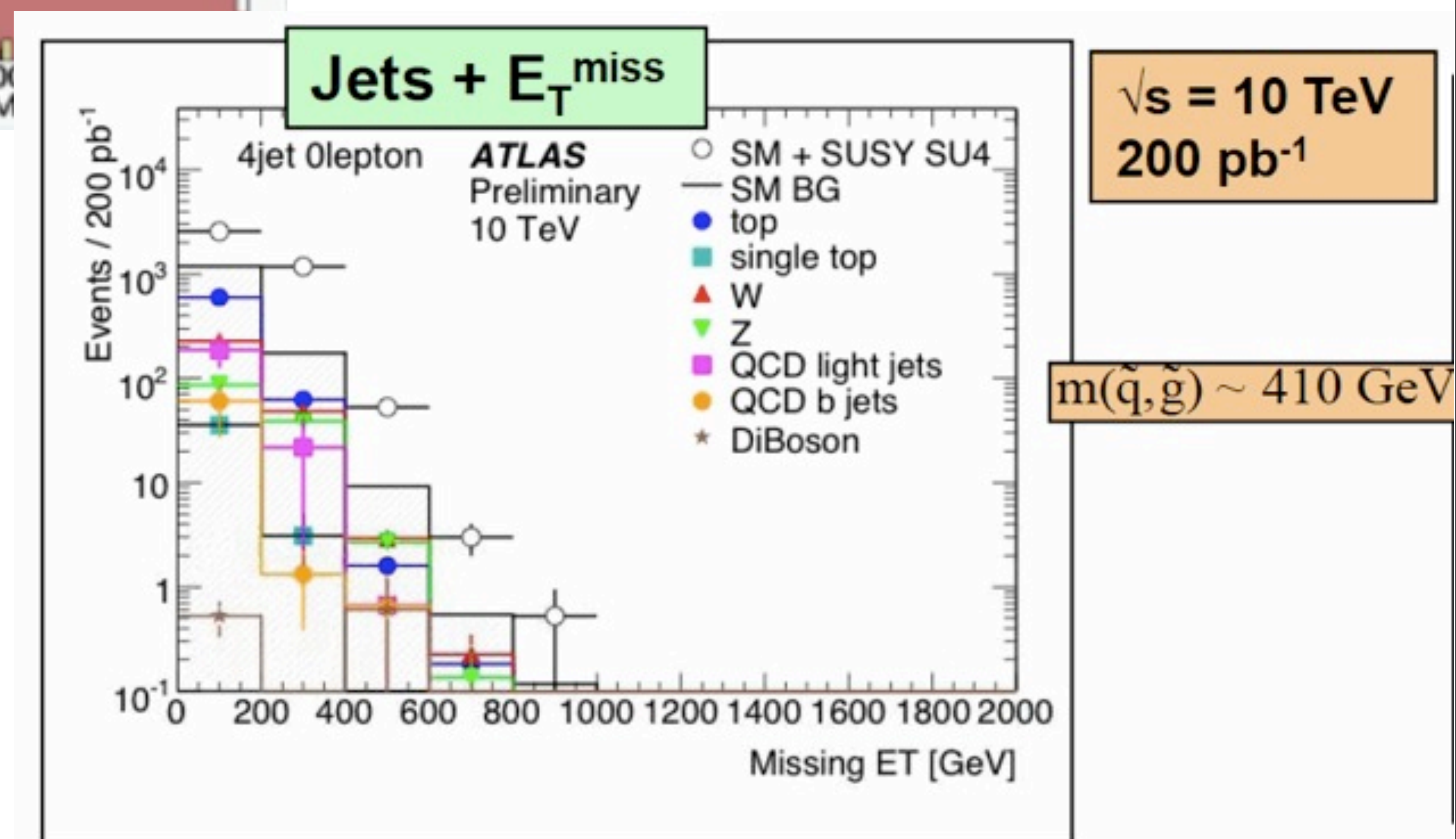
- Also standard-model physics leads to missing $E_T$:
  - Neutrinos in the final state
  - Fake missing $E_T$ due to fluctuations in reconstruction



# LHC: Amazing Performance

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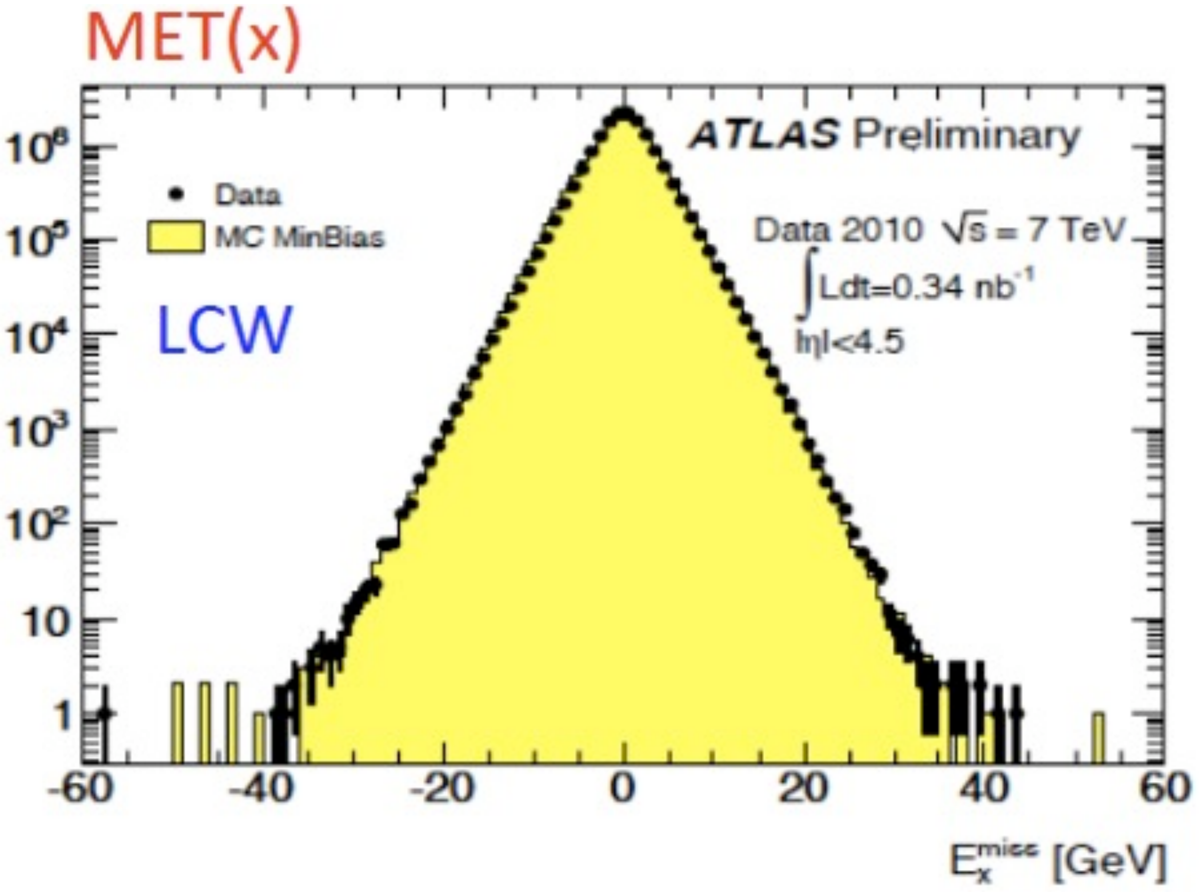


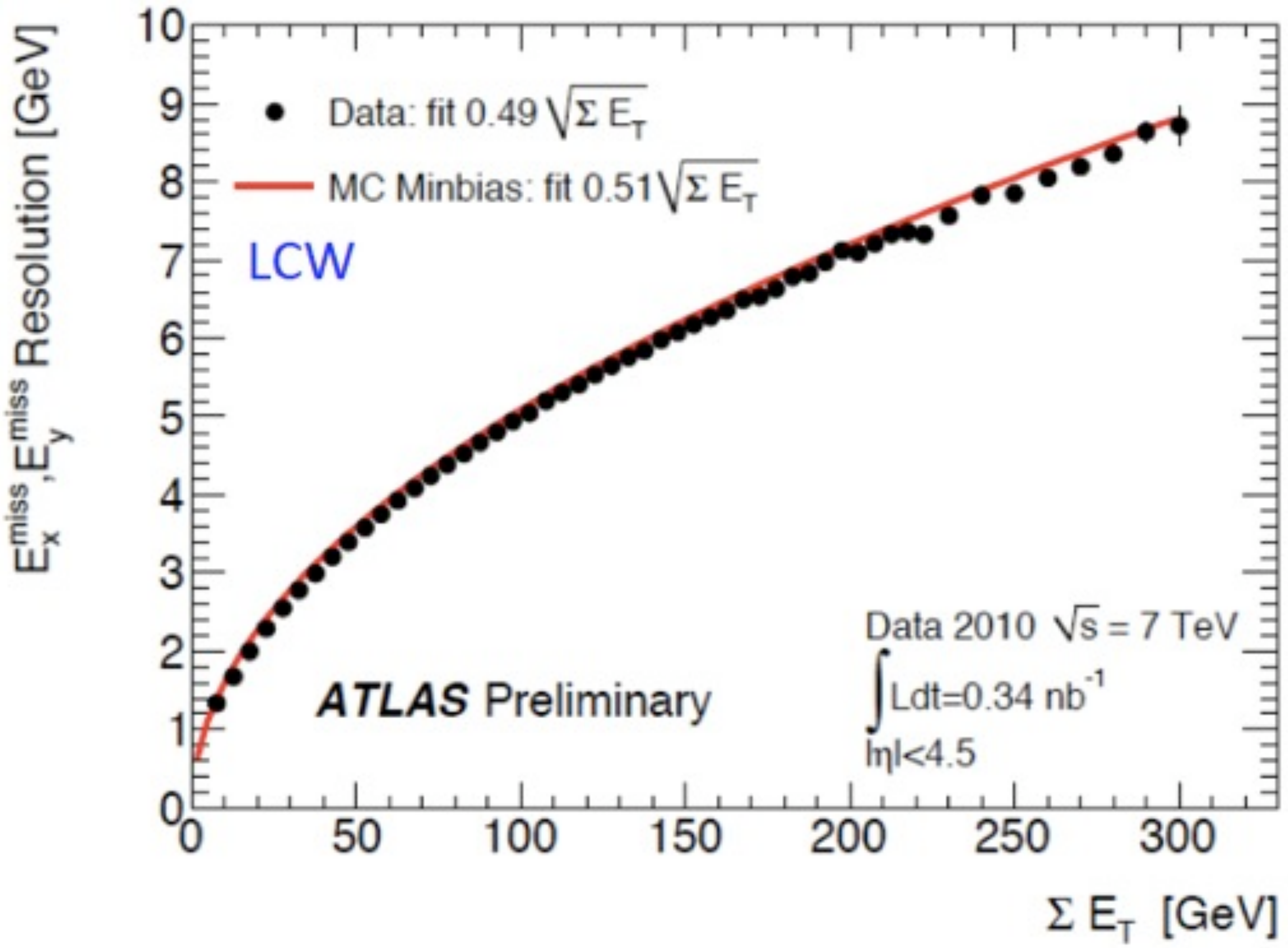

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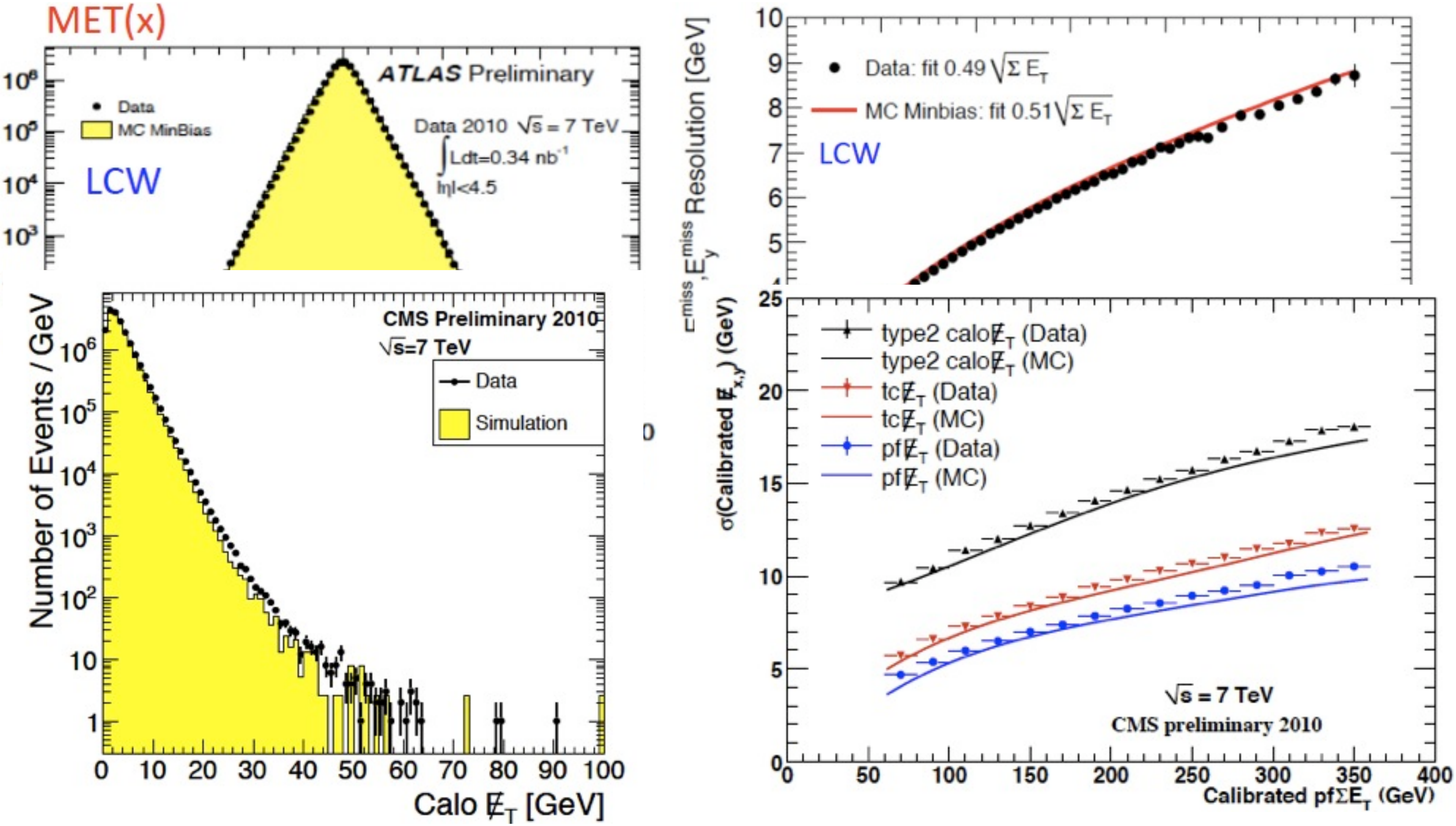
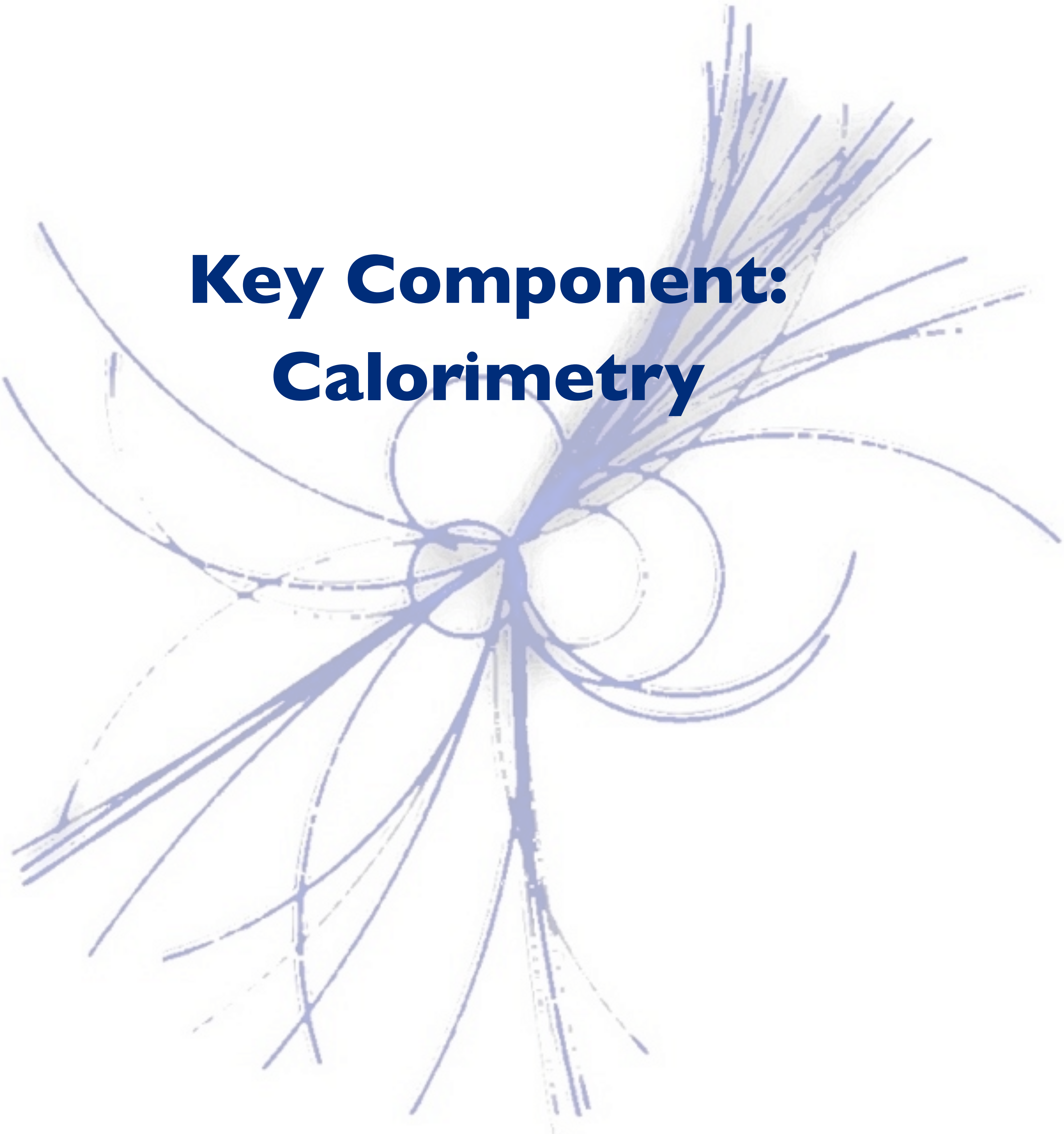


# Key Component: Calorimetry



# Calorimeters in Collider Physics

- Measure the energy of particles by total absorption via em or hadronic showers: also neutral particles are measured (not for neutrinos, muons)
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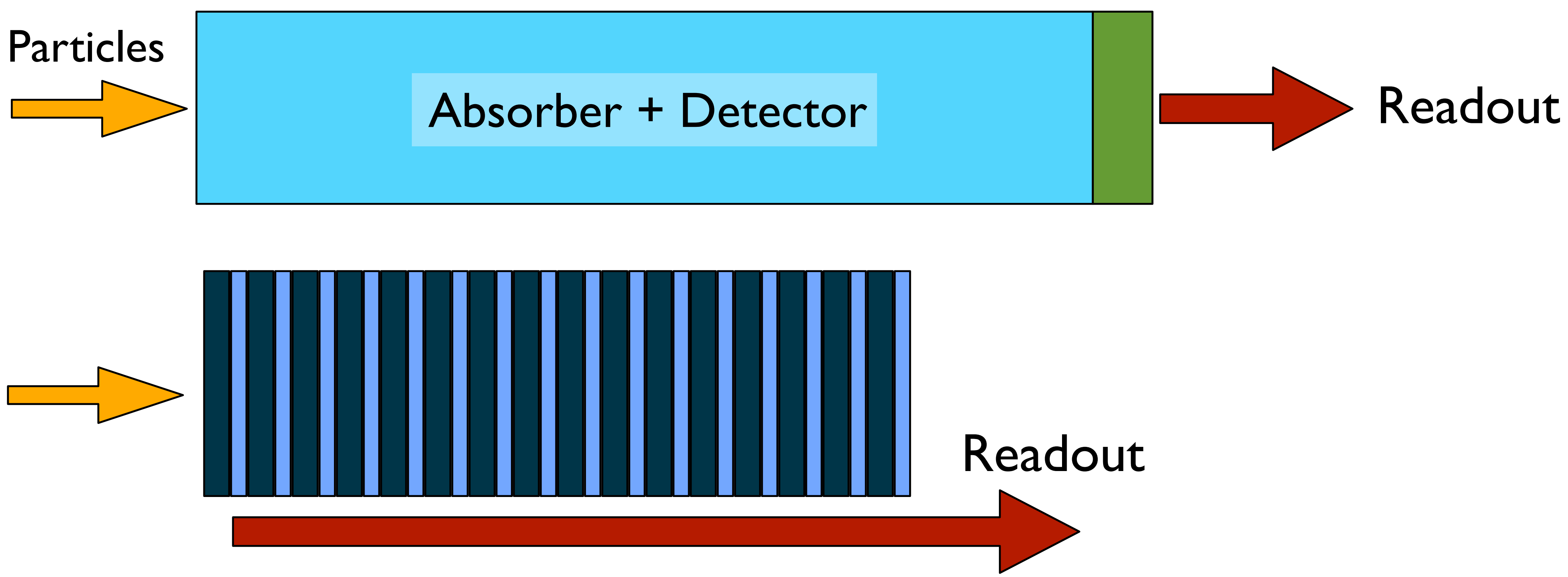

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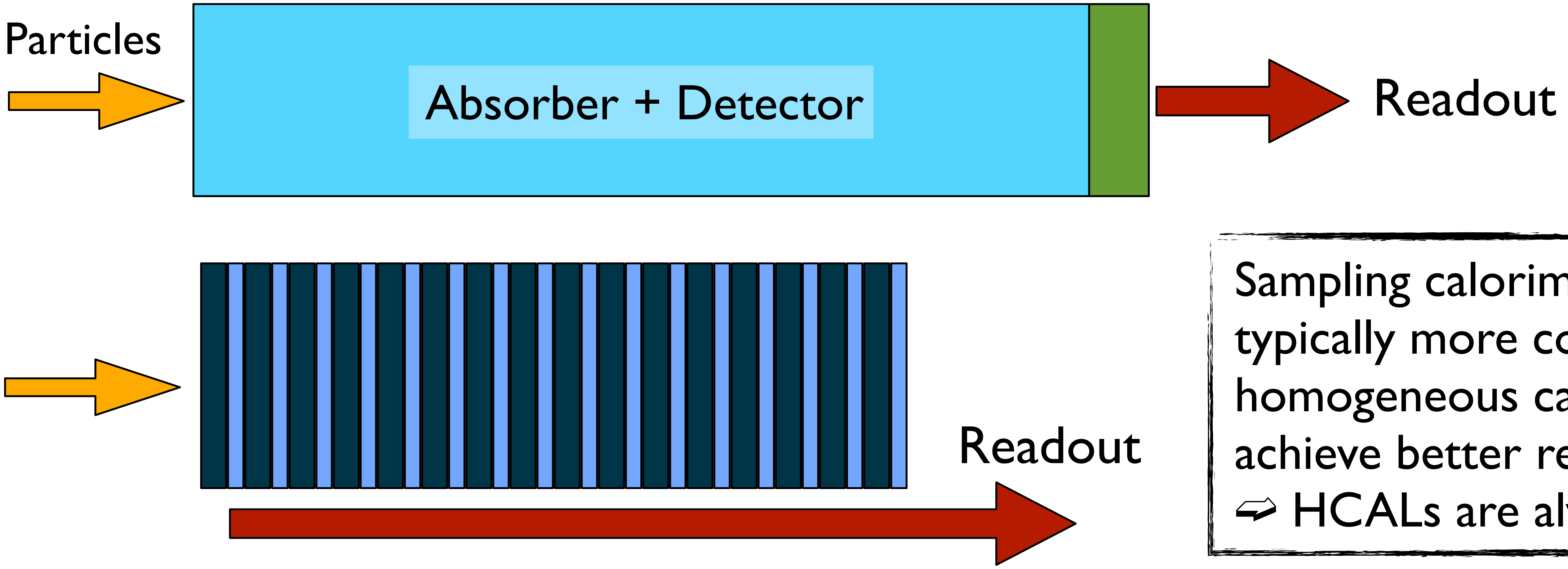


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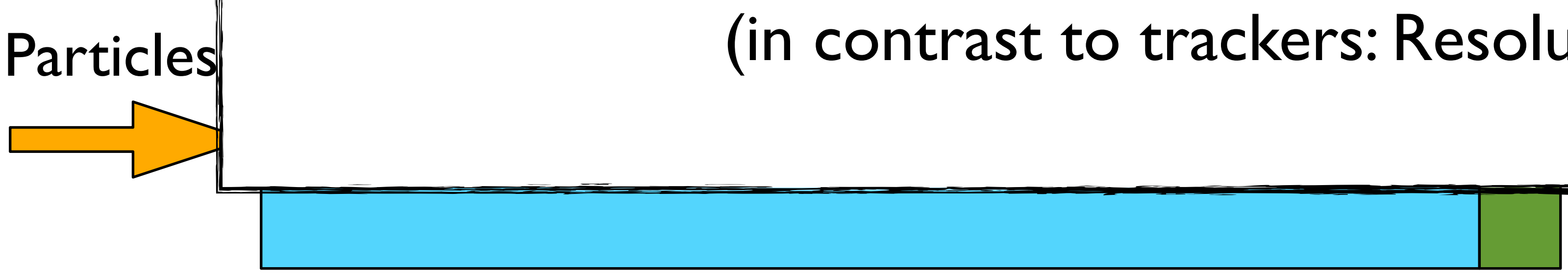
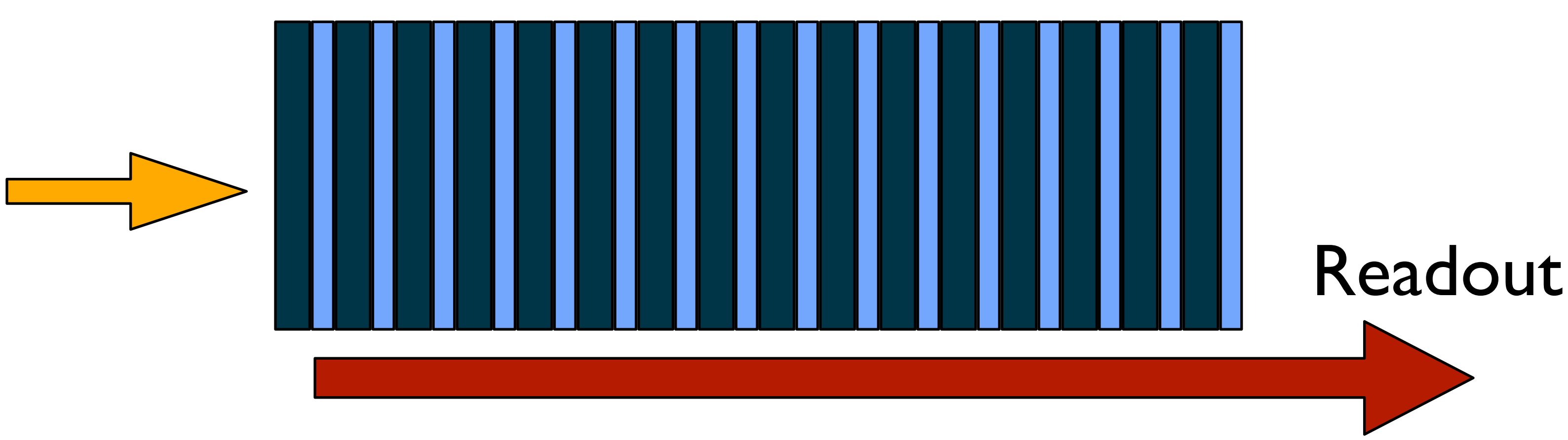
  - tc

Differe … adronic

Energy measurement based on counting of secondary particles within shower: Resolution gets better with energy, scales as $1/\sqrt{E}$
(in contrast to trackers: Resolution ~ E)

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# Of Particular Importance: Hadron Calorimeter

- Usually: Multiple hadronic jets in the final state
- Typical composition:
  - 62% charged particles (mainly hadrons)
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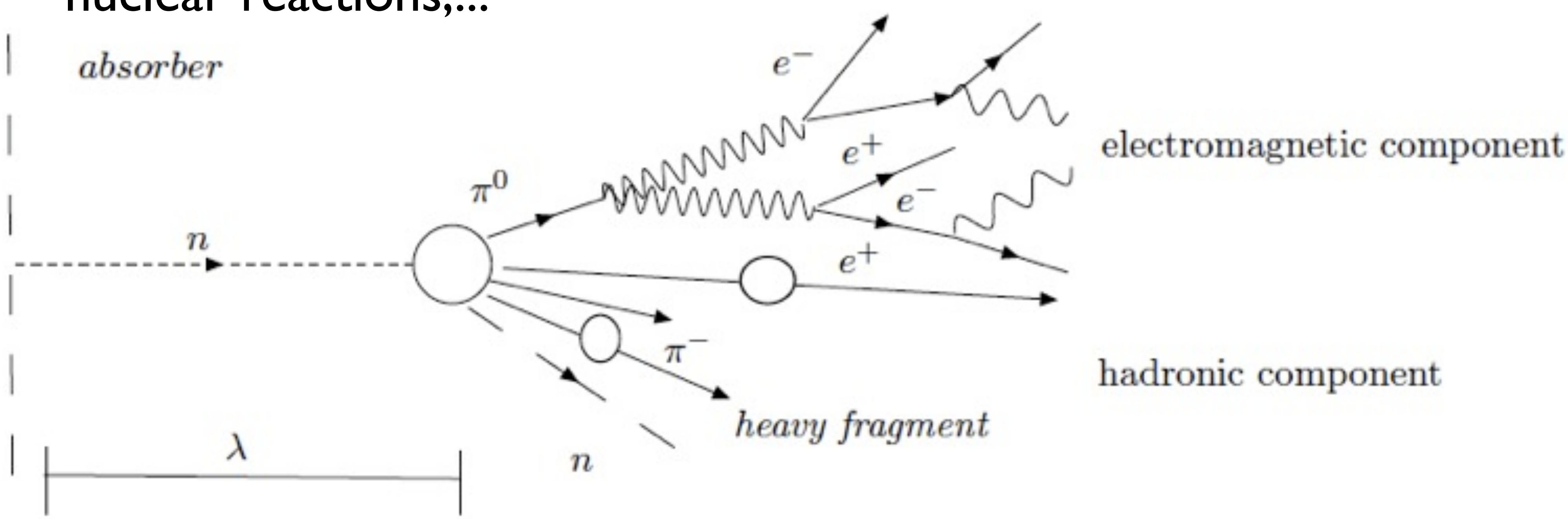
The downside: Hadronic showers are complicated!

➯ A mix of electromagnetic and purely hadronic components, lost energy due to nuclear reactions,...



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  - The response of the calorimeter to electromagnetic showers is higher than that to purely hadronic showers
  - ▸ Reconstructed energy depends on the electromagnetic fraction within the hadronic shower
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Every shower is different: Fluctuations and limited resolution can lead to sizable fake missing $E_T$ signals!

# Detector Understanding: ATLAS

- Precise knowledge of the calorimeter performance, in particular at the interfaces between detector subsystems, is crucial for missing $E_T$ measurements:
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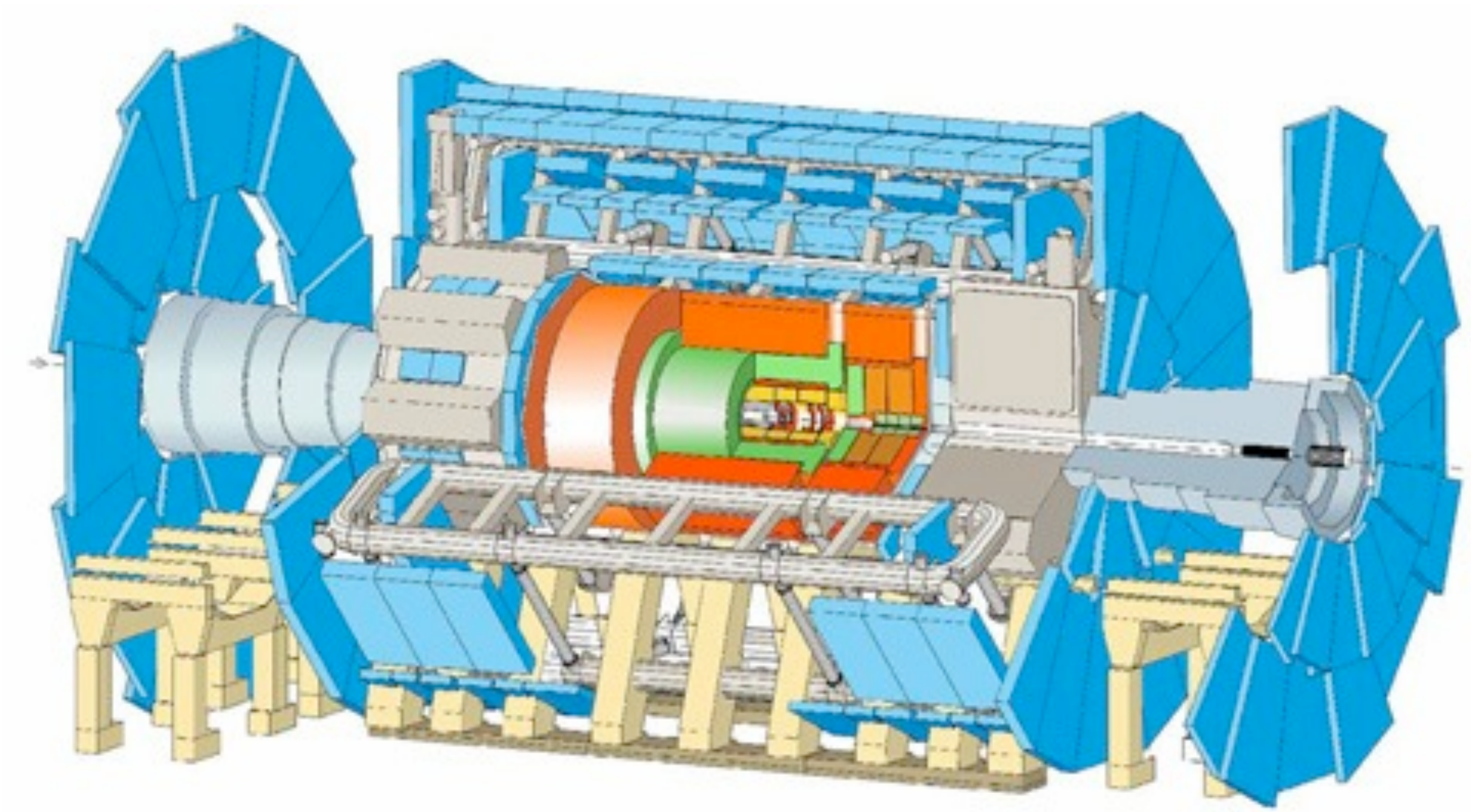

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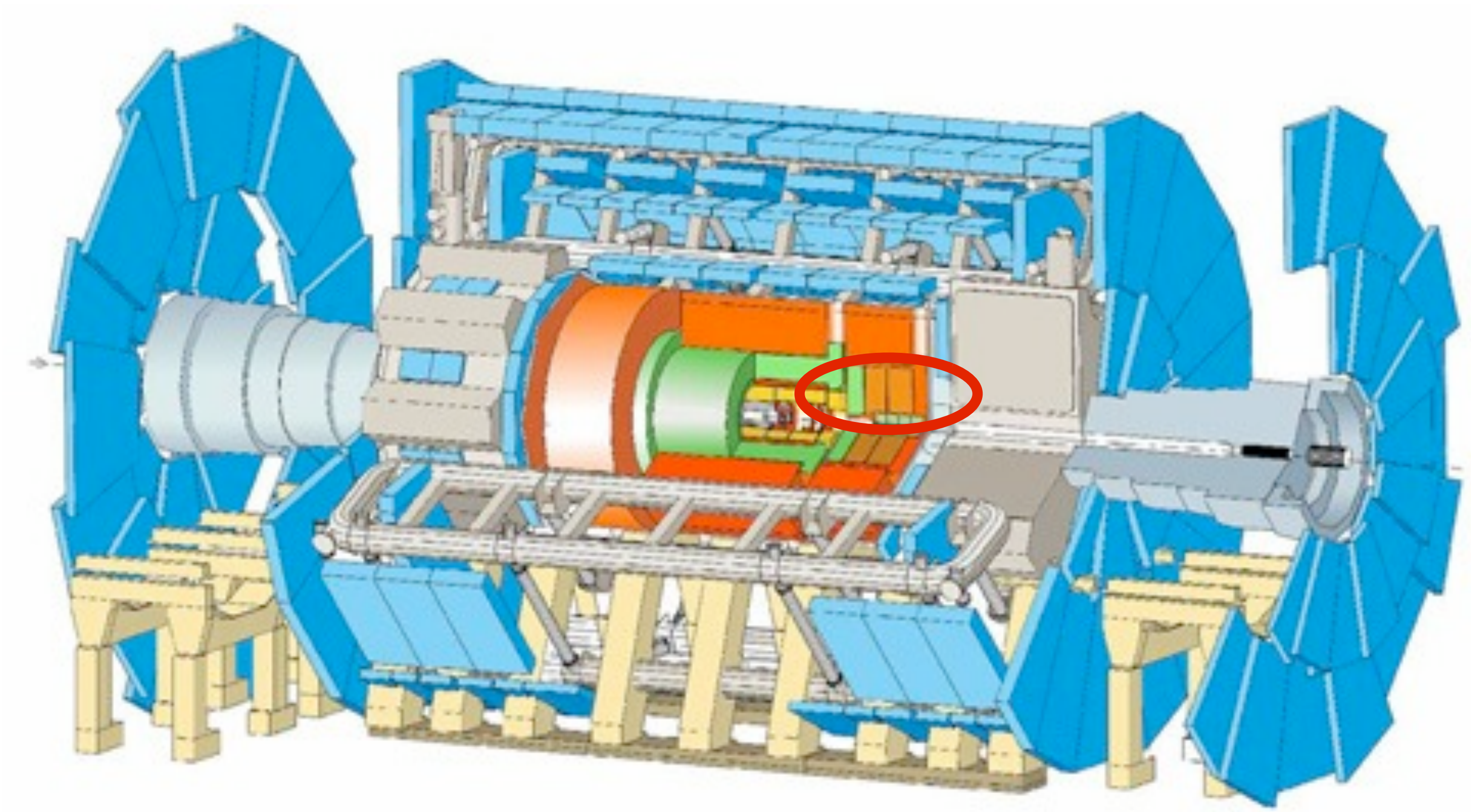

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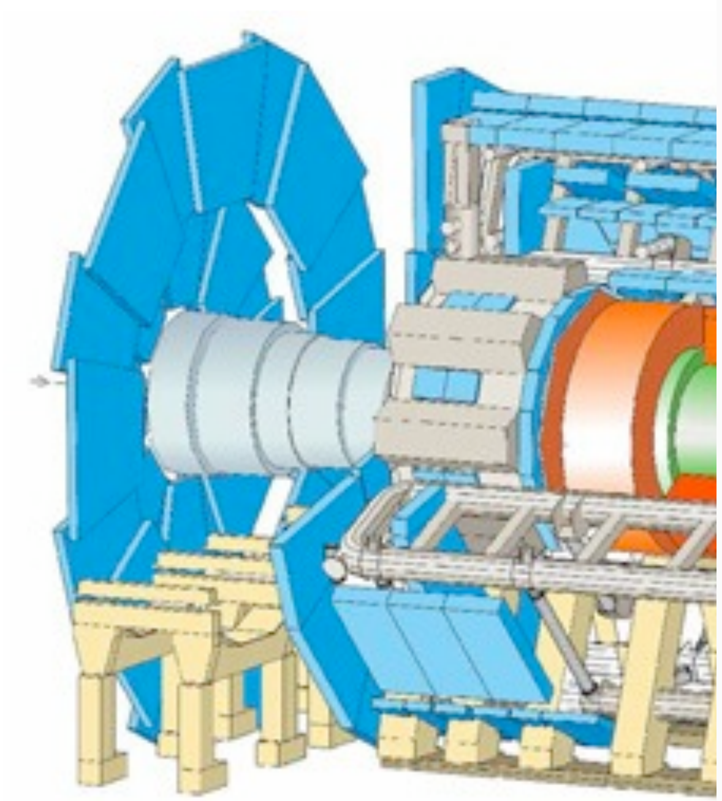

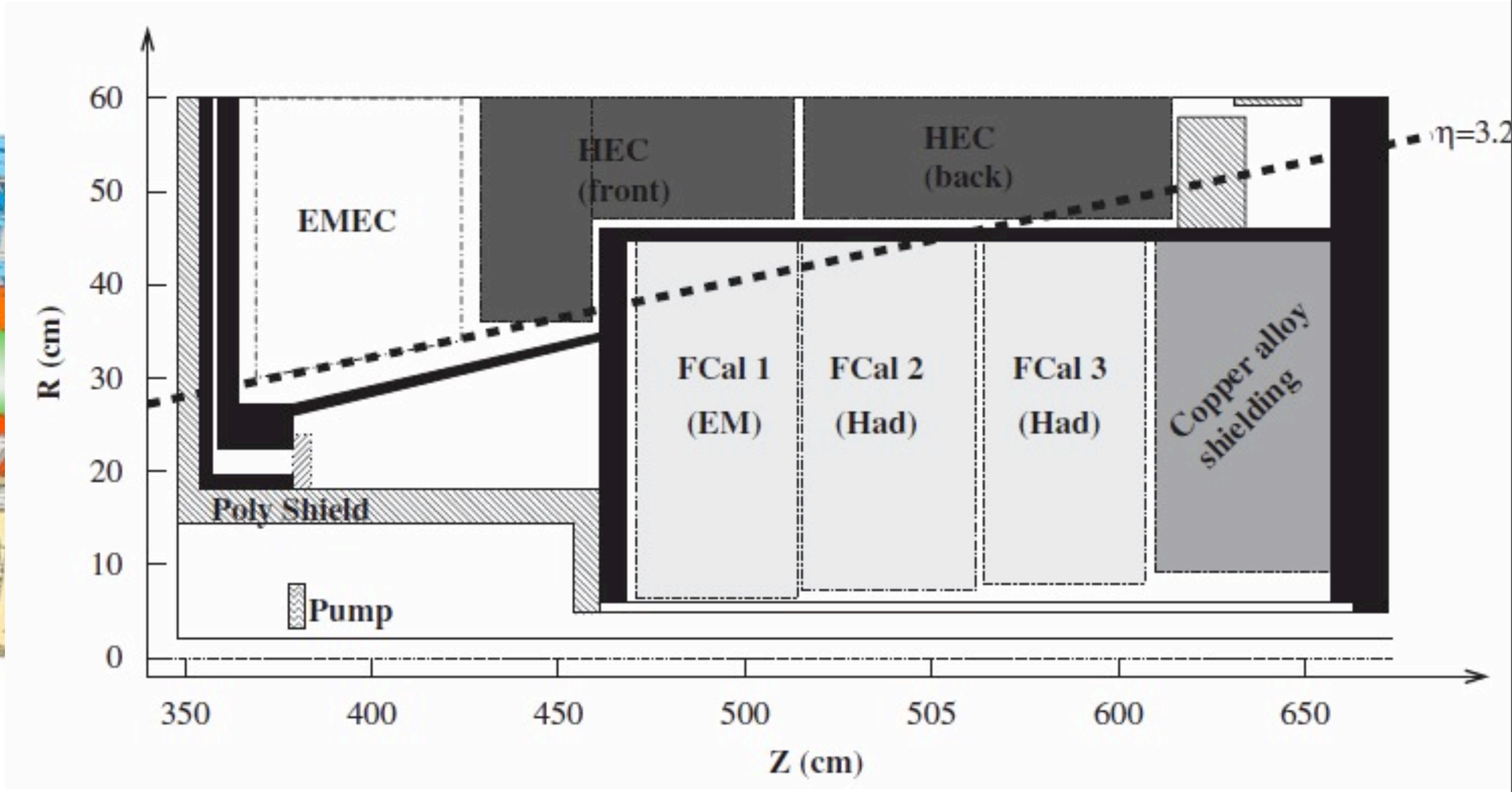

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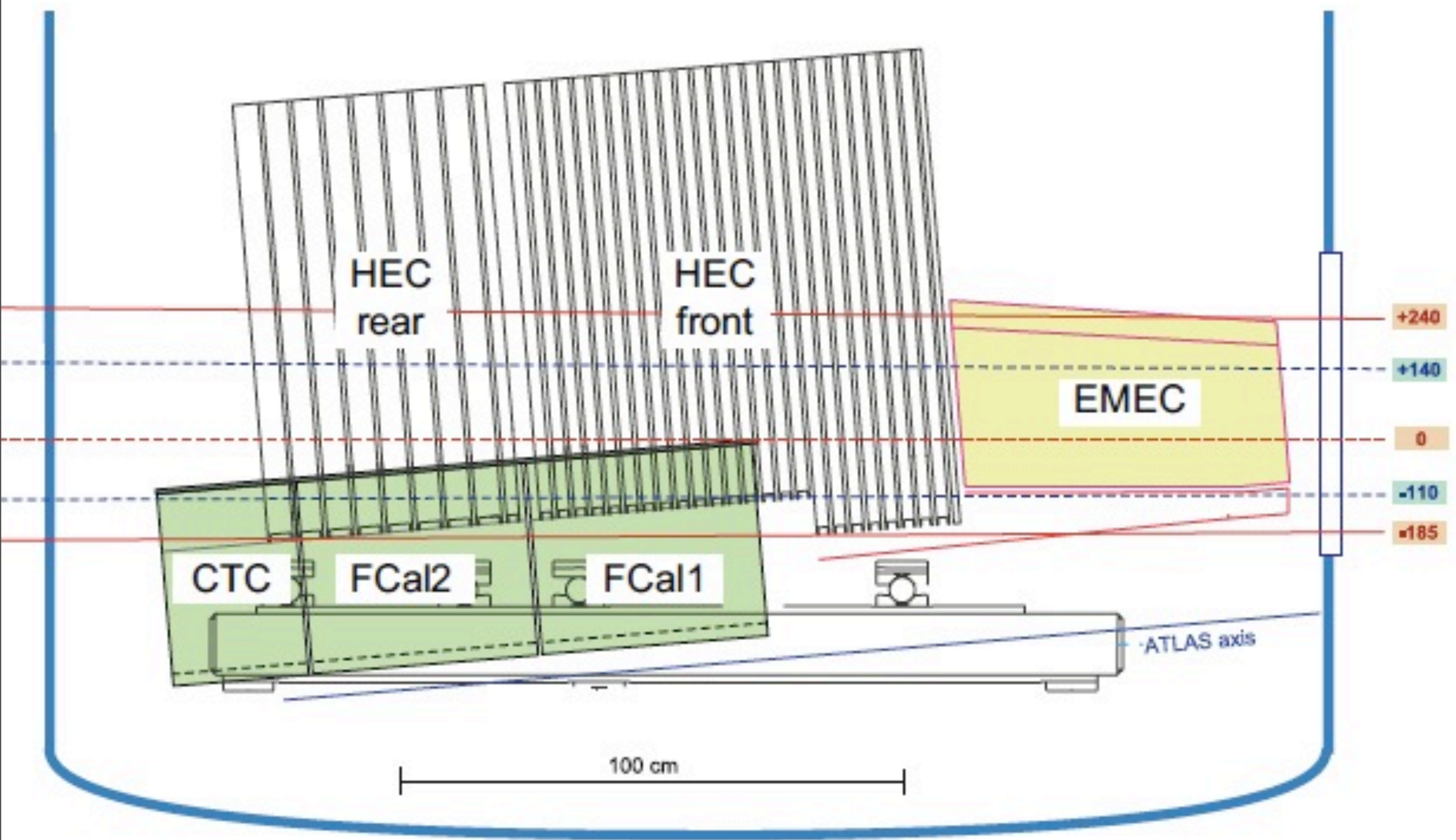


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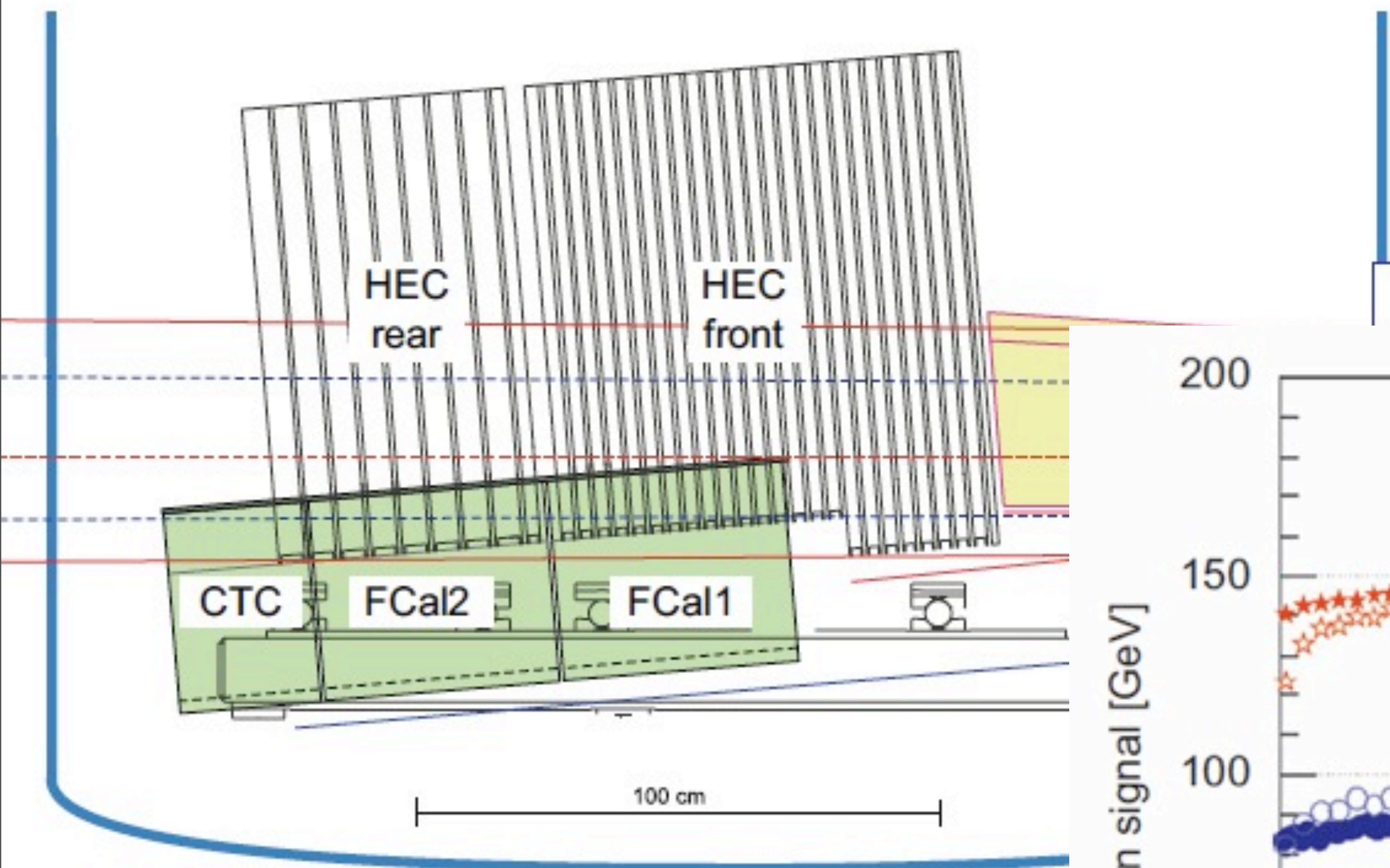


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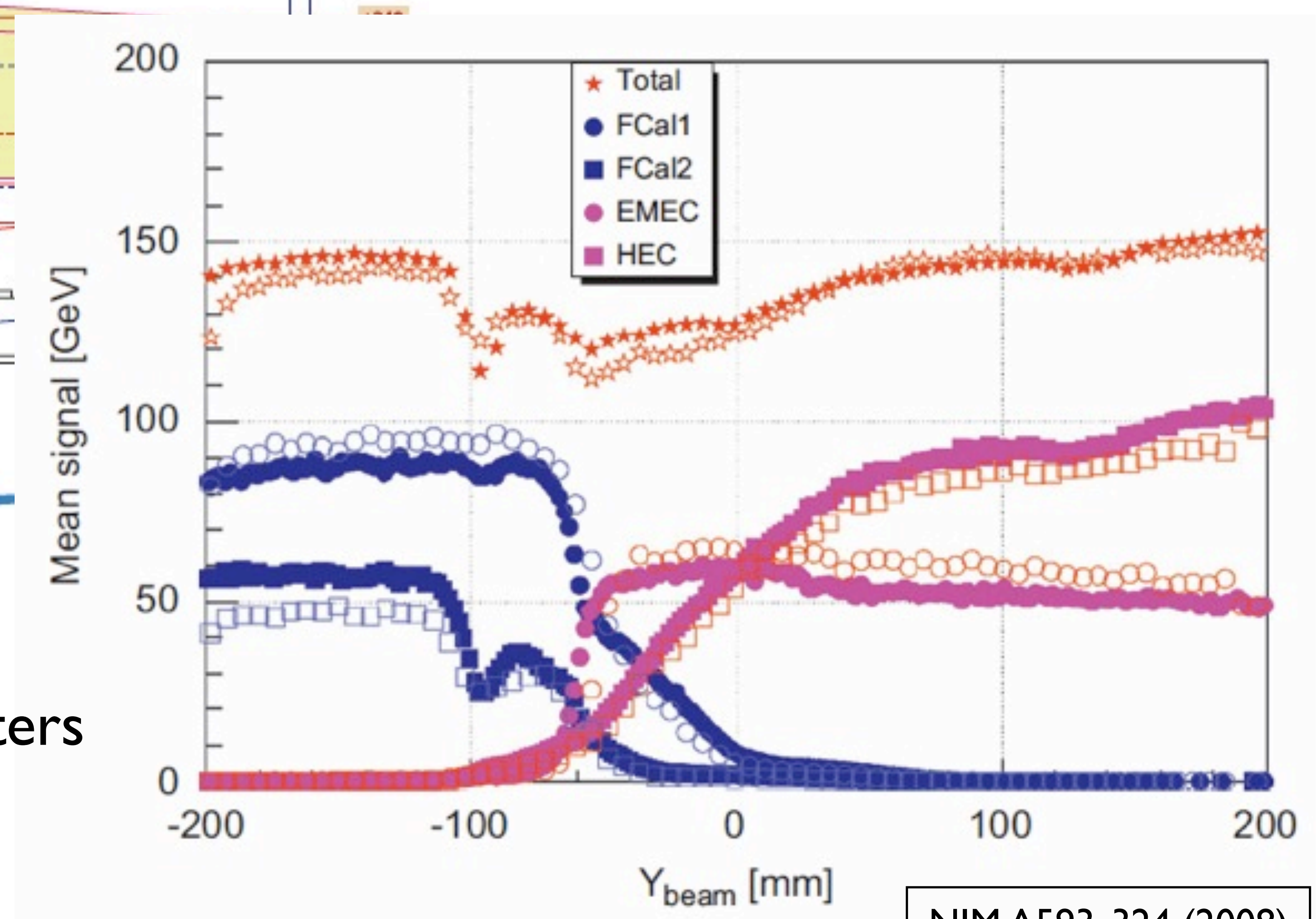


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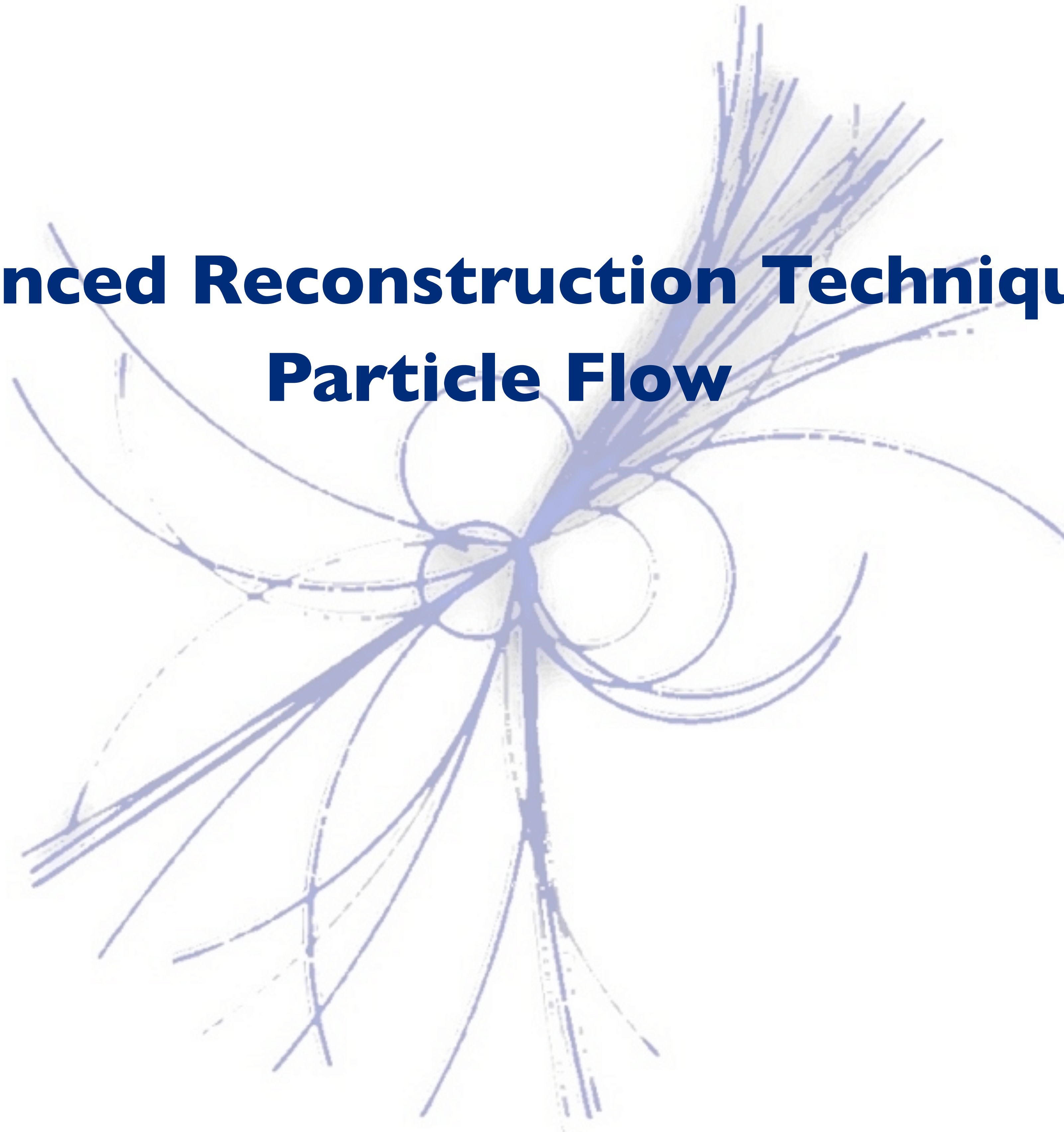
- Reconstructed energy on the em scale: non-compensating calorimeters
- position dependence of signal
- good reproduction by simulations

# Advanced Reconstruction Techniques: Particle Flow



# Jet Reconstruction at Next Generation Colliders

- Possible future colliders beyond LHC: Best candidate: high energy $e^+e^-$ collider
  - Well established concept: ILC (International Linear Collider) - 500 GeV
  - In development: CLIC (Compact Linear Collider) - 3 TeV
- Events at lepton colliders are clean:
  - No underlying event (reactions of other projectile constituents)
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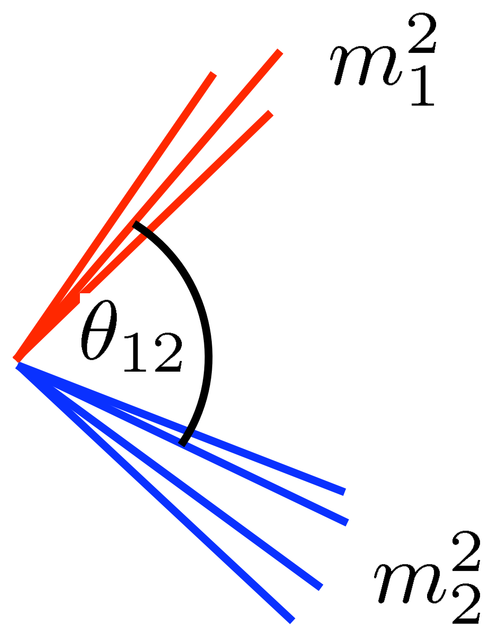
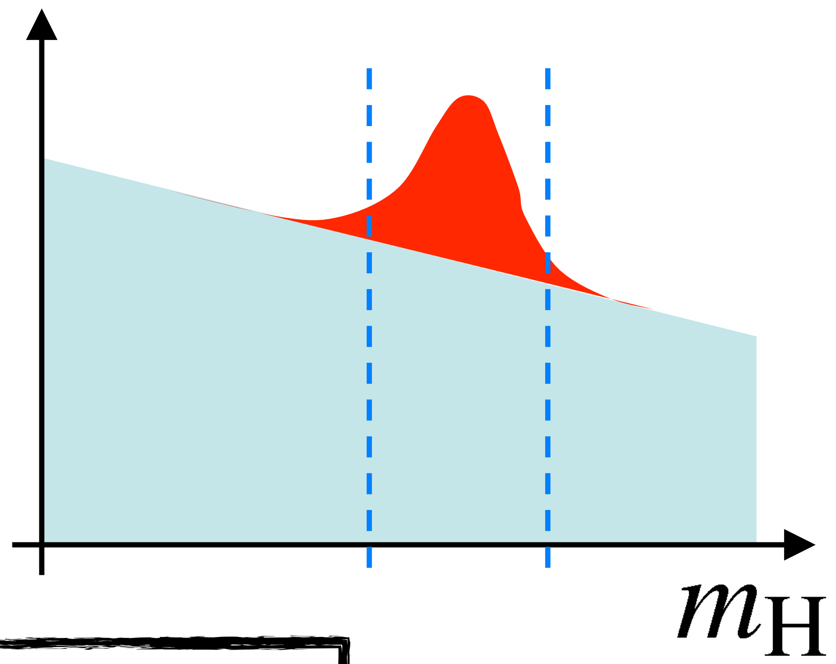
But beware: No pile-up and no underlying event does not mean no background! High energy $e^+e^-$ colliders also present a challenging environment for detectors!

# Missing $E_T$ is not Everything: Di-Jet Mass Resolution

- Required resolution at future colliders: depends to some extend on the physics!
- Very likely of big importance: di-jet mass resolution




Typical case:
A narrow resonance decaying into quark pairs

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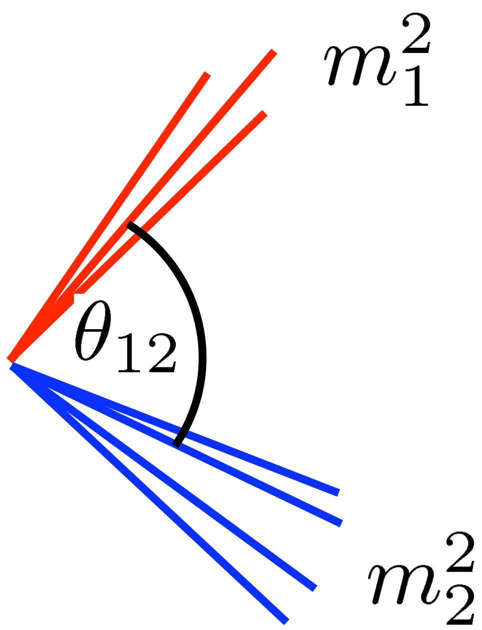


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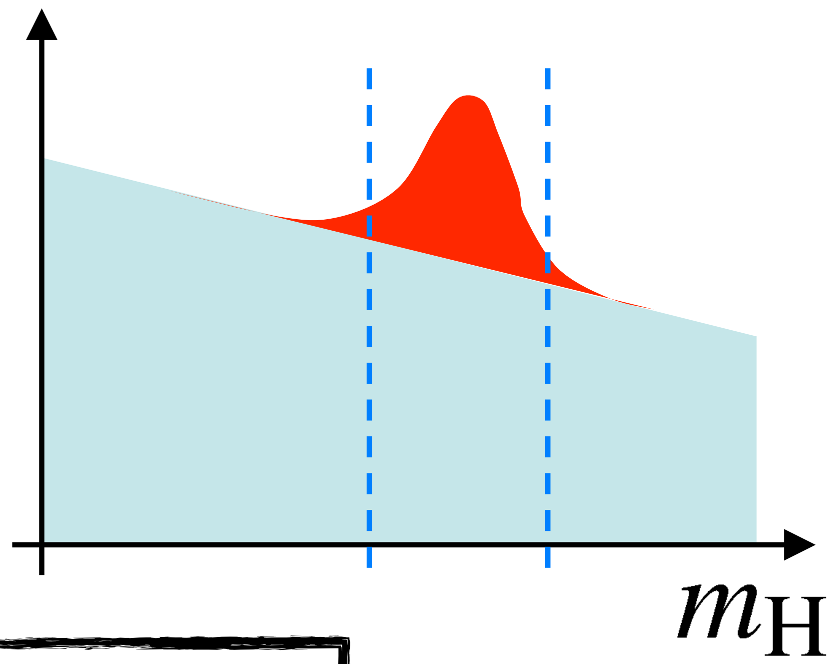


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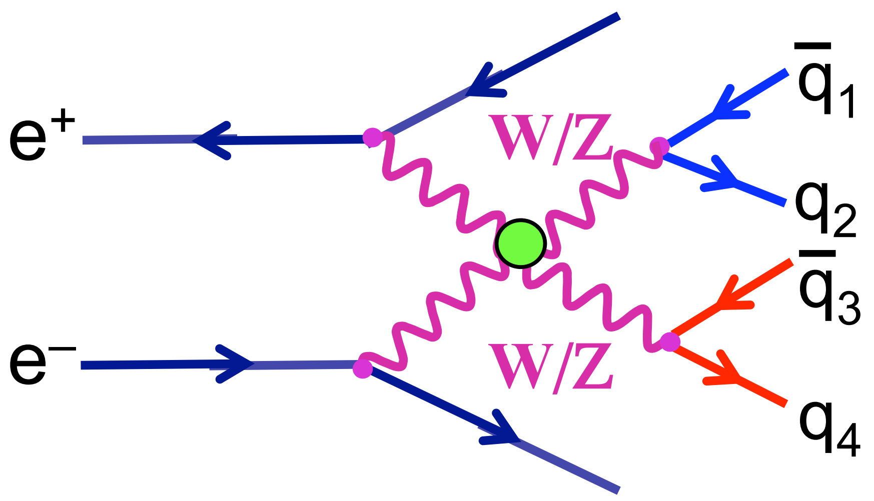
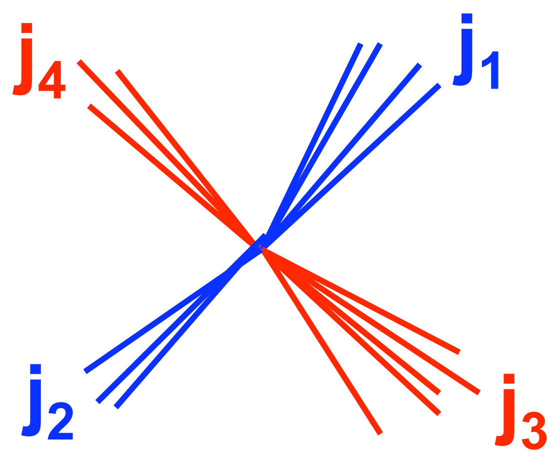
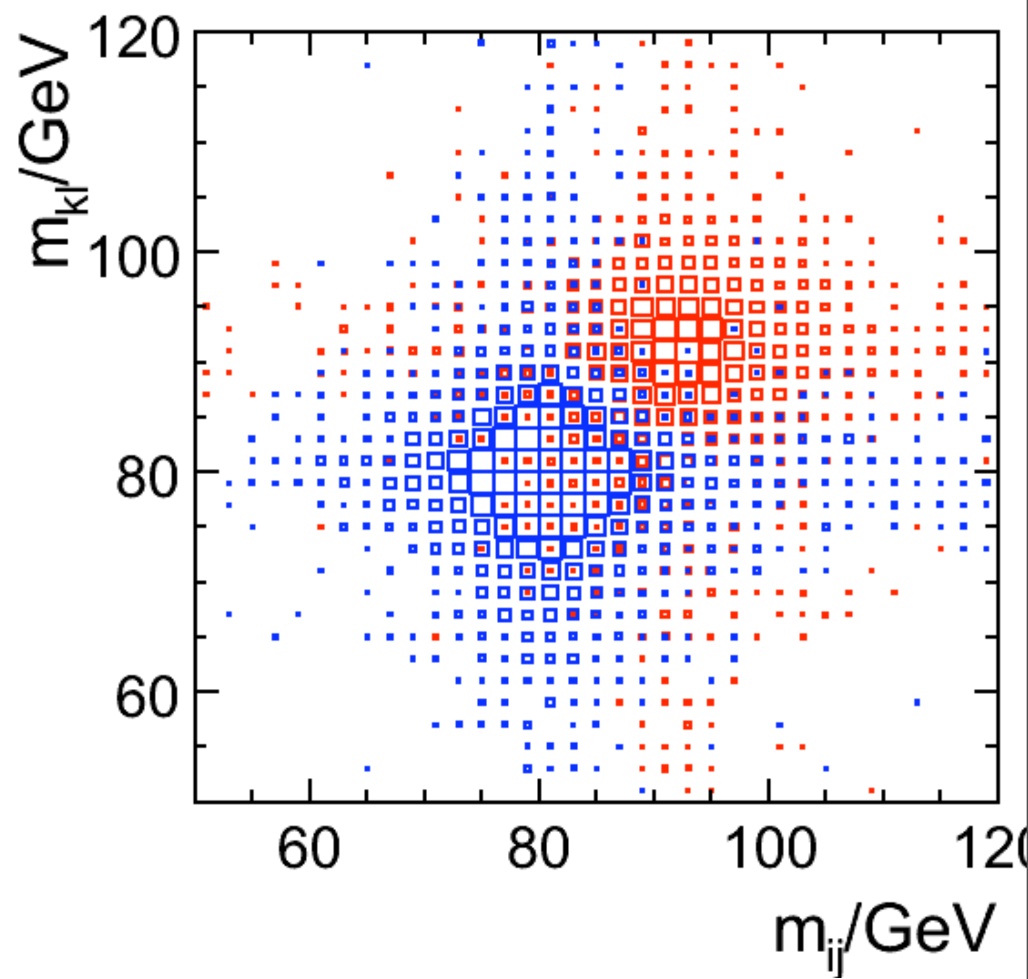
➯ Better resolution means: Less data (less running time = less money) needed for a given measurement or discovery!

# Minimum Requirement: Separate Gauge Bosons

- Gauge bosons (W, Z) are important signatures:
  - Can show up in many final states of heavy particles
  - Potential strong interaction: Scenarios for electroweak symmetry breaking



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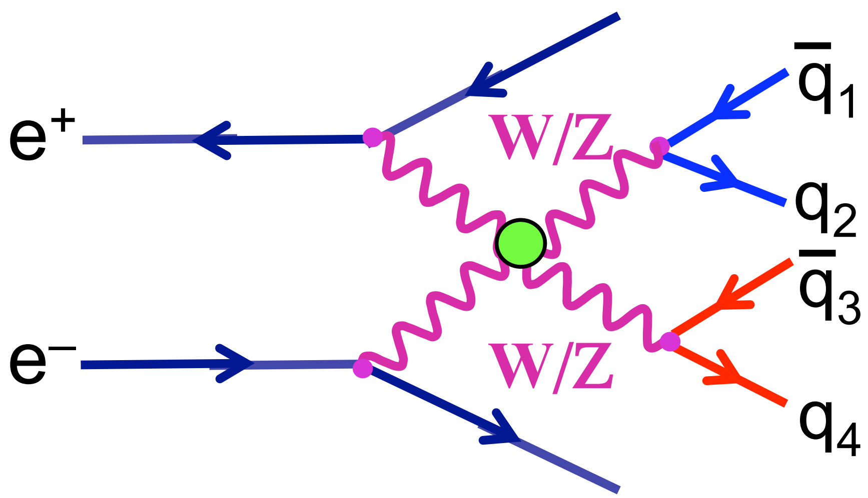
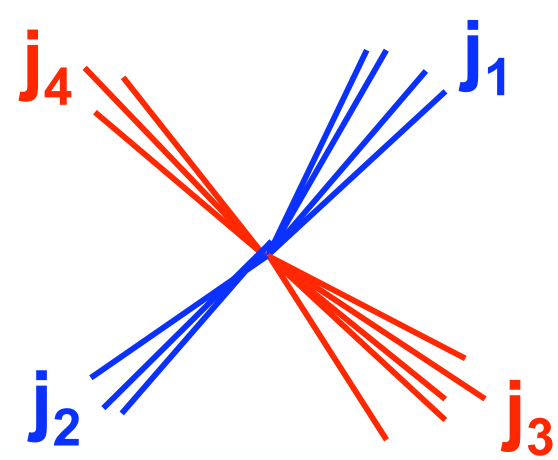
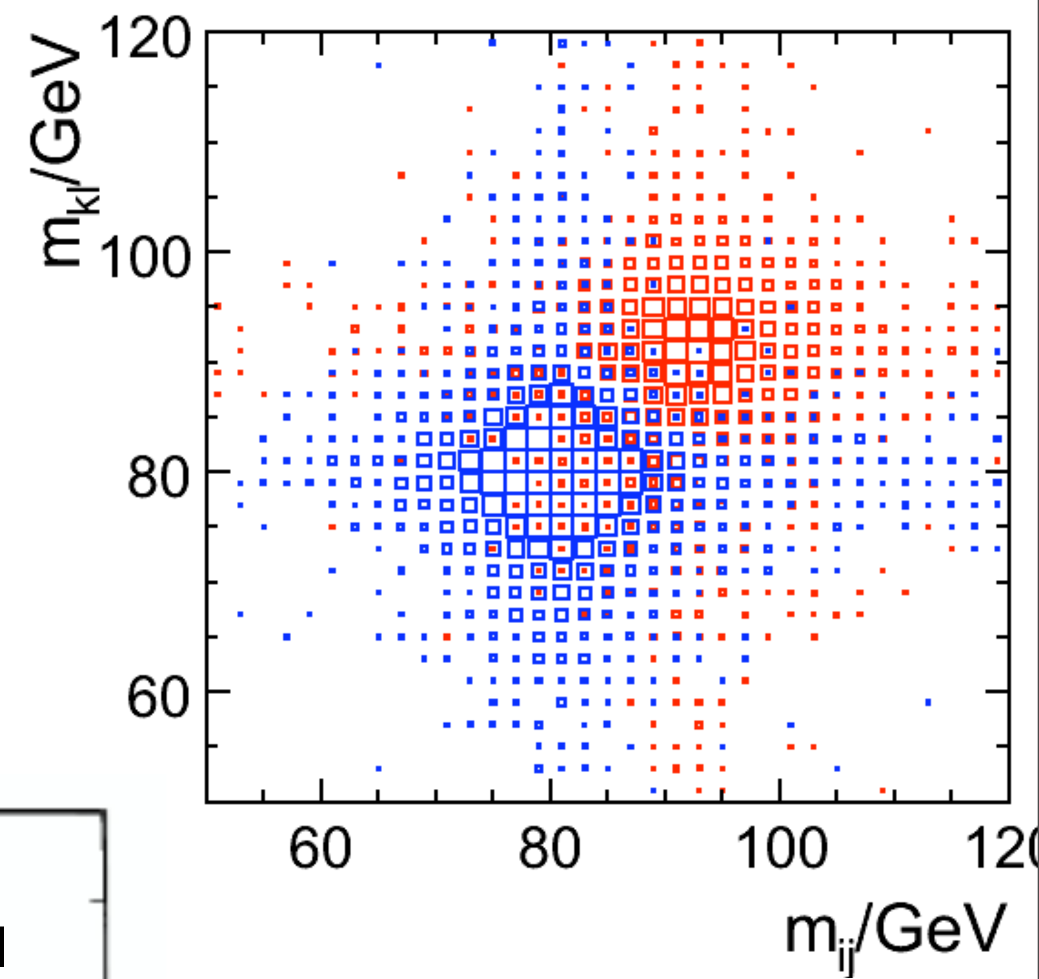
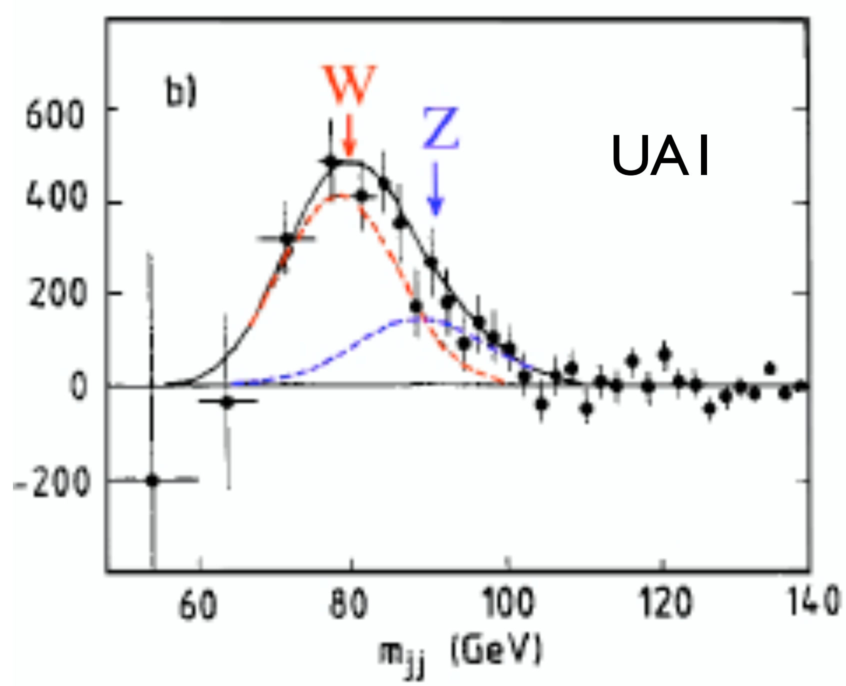


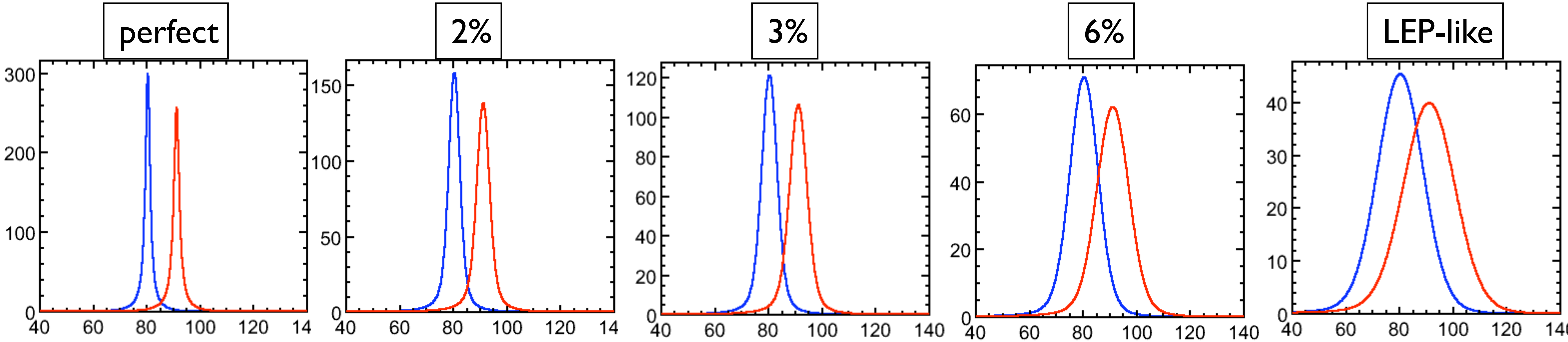




From discovery signal to sensitive tool: a long way to go!



# Mass Resolution: Requirements for separation

- Width of gauge bosons sets a natural scale for the required resolution




| Jet E res. | W/Z sep |
|---|---|
| perfect | 3.1 σ |
| 2% | 2.9 σ |
| 3% | 2.6 σ |
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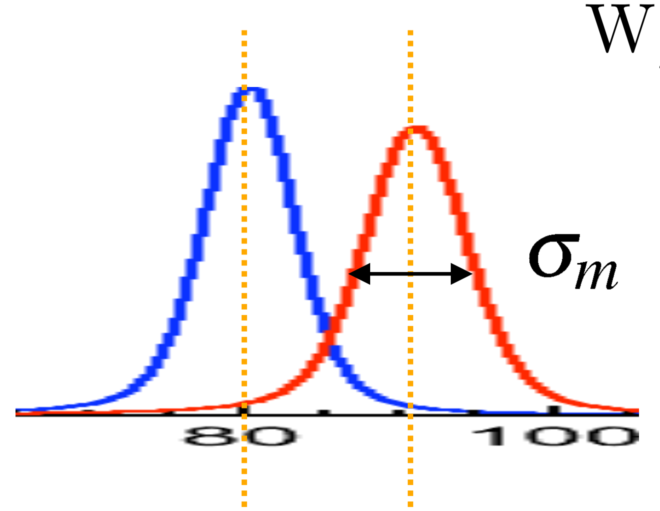
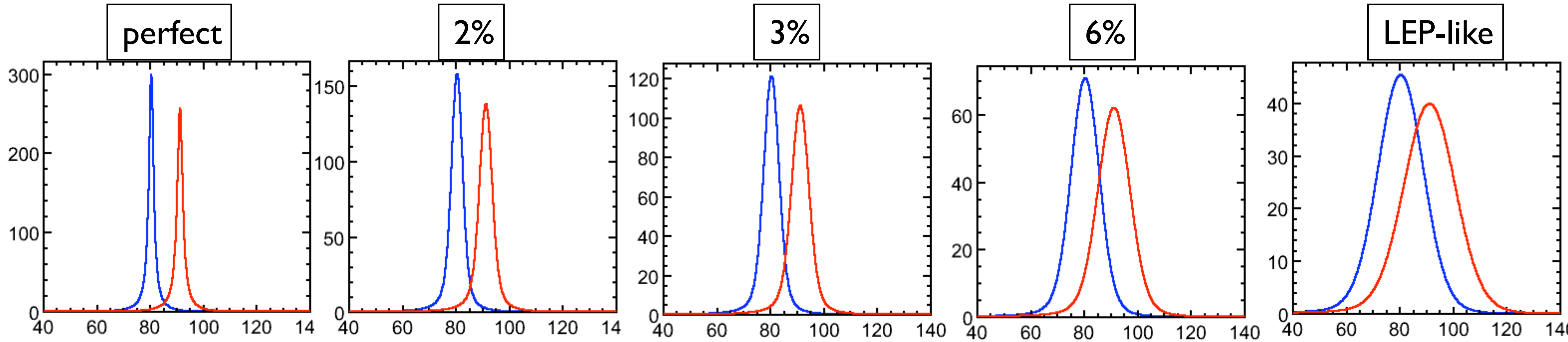



$$\text{W/Z separation} = (m_Z - m_W)/\sigma_m$$

effective gaussian equivalent mass resolution

# Mass Resolution: Requirements for separation

- Width of gauge bosons sets a natural scale for the required resolution

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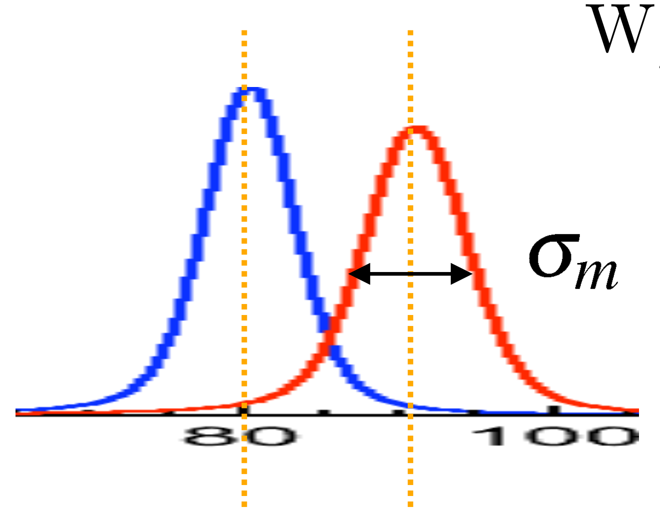


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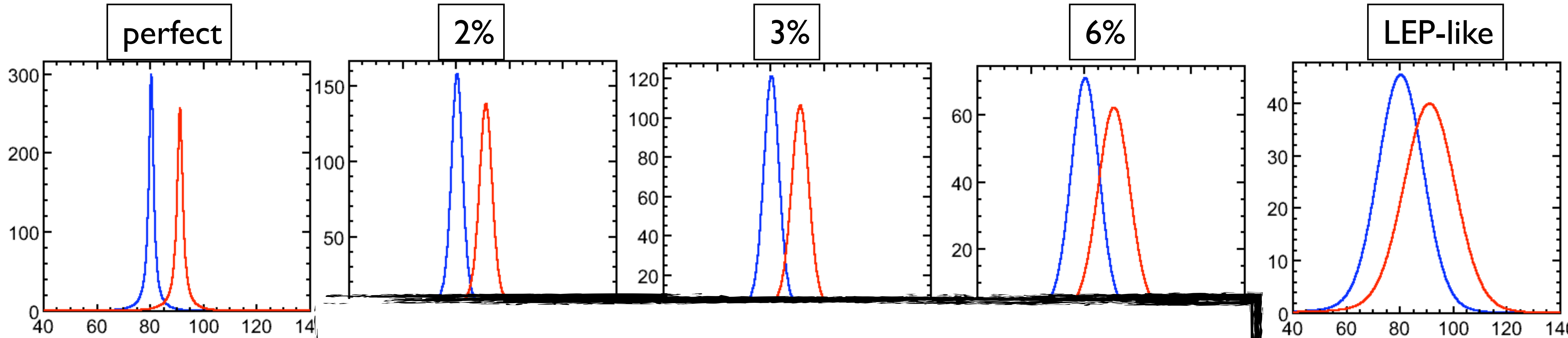


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| perfect | |
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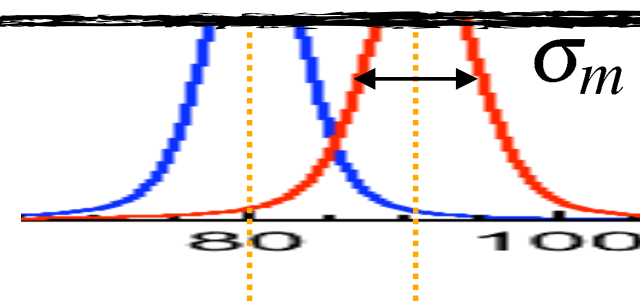
About a factor of 2 better than ATLAS
(state of the art!)

$(m_Z - m_W)/\sigma_m$

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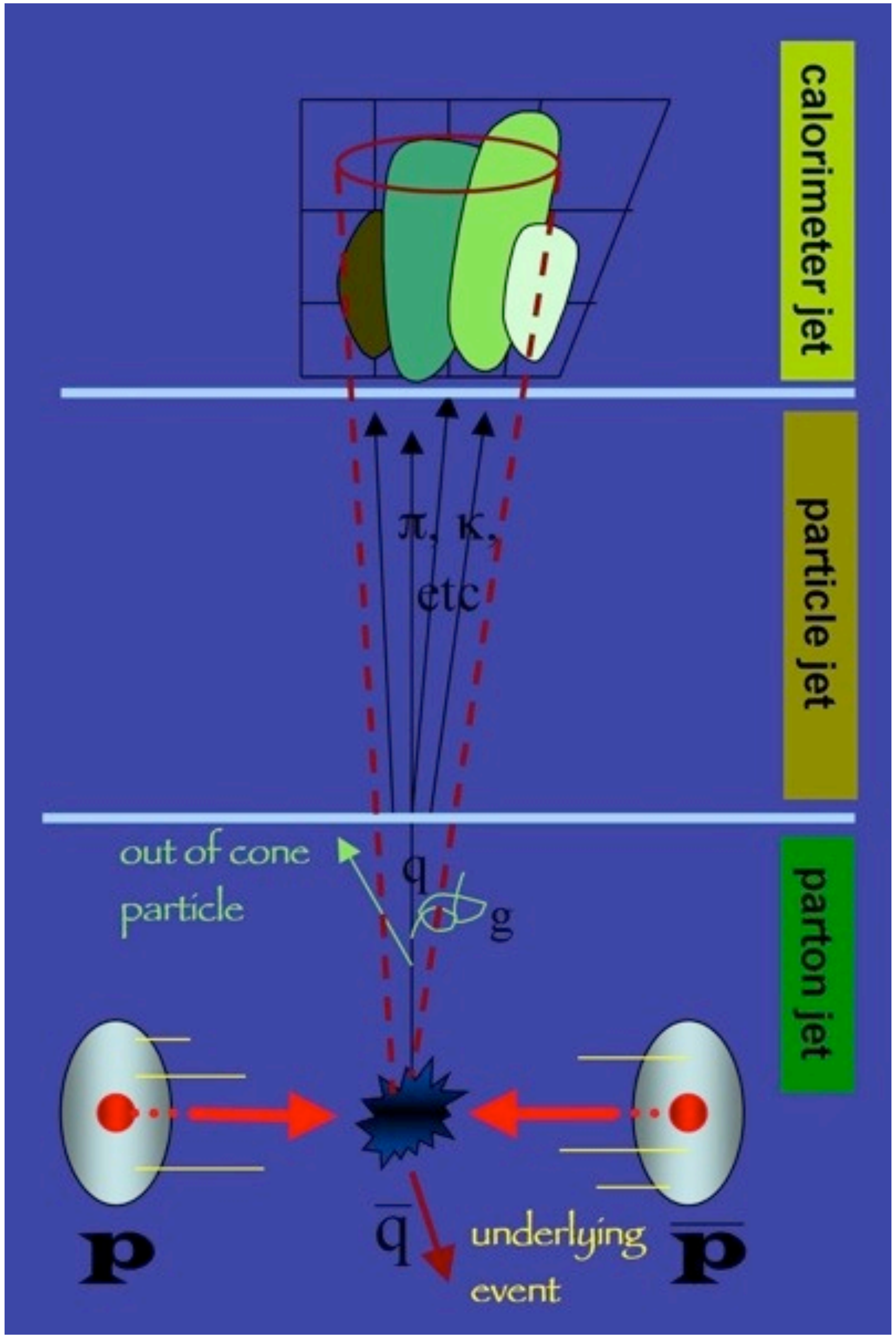
# Where is the Challenge?

- Typical jet composition
  - 60% charged hadrons
  - 30% photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - 10% neutral hadrons (mainly n, $K_L$)
- Classical jet reconstruction relies exclusively on calorimetry: 70% of jet energy measured in the hadron calorimeter



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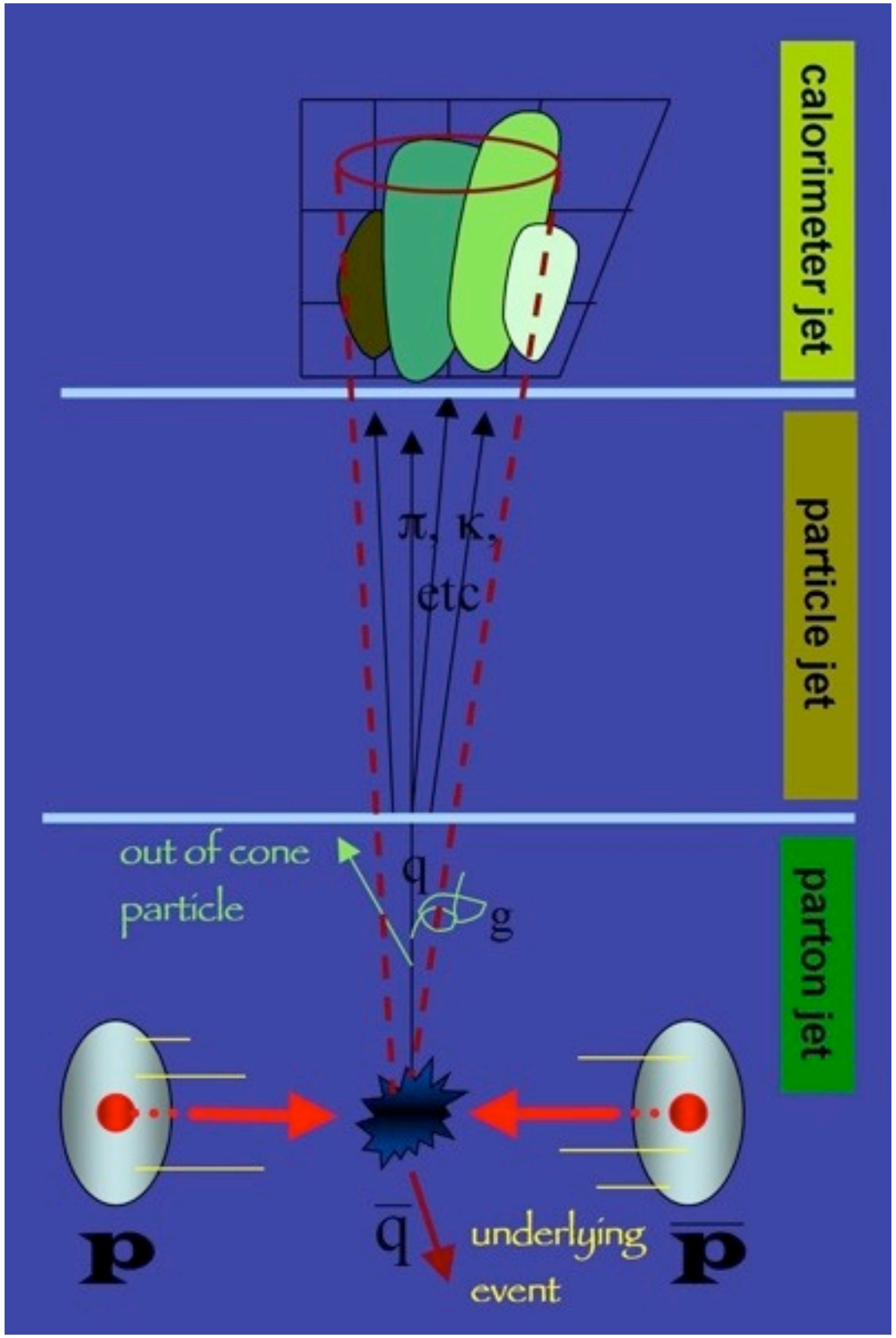


Hadron Calorimeter: Limited energy resolution

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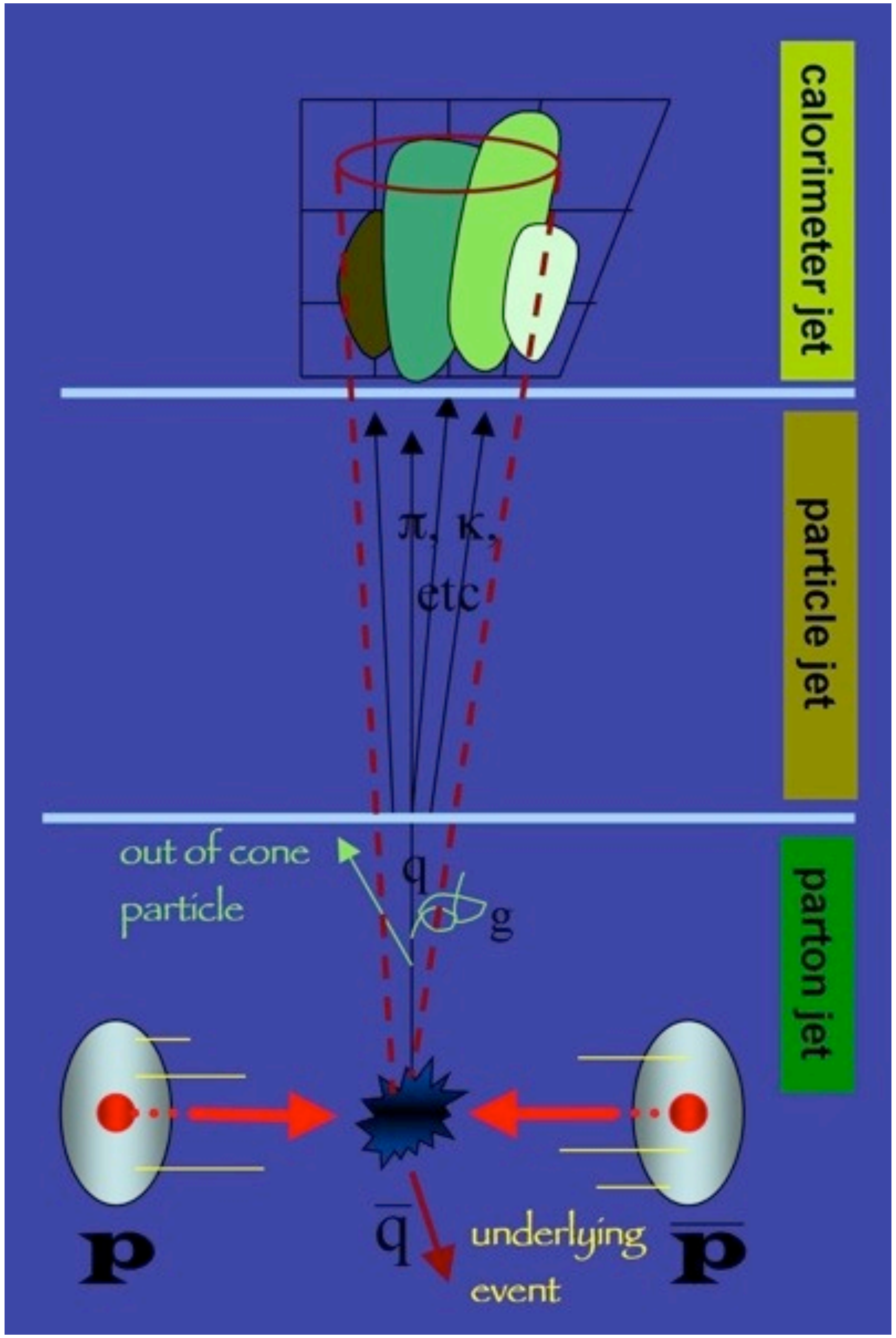
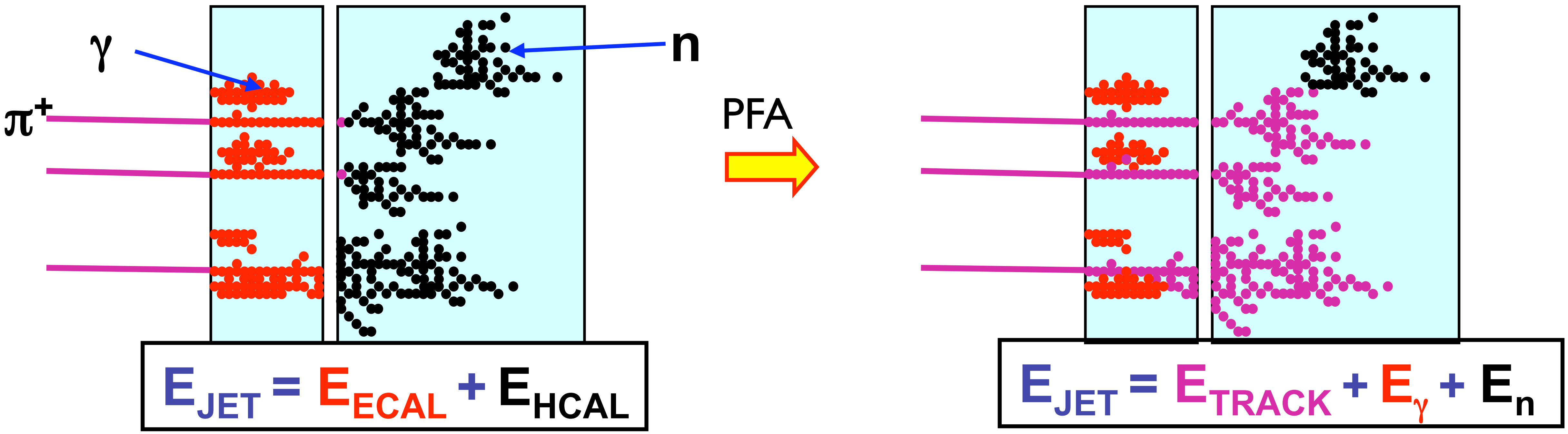
➩ Reduce the importance of the HCAL for jet reconstruction!



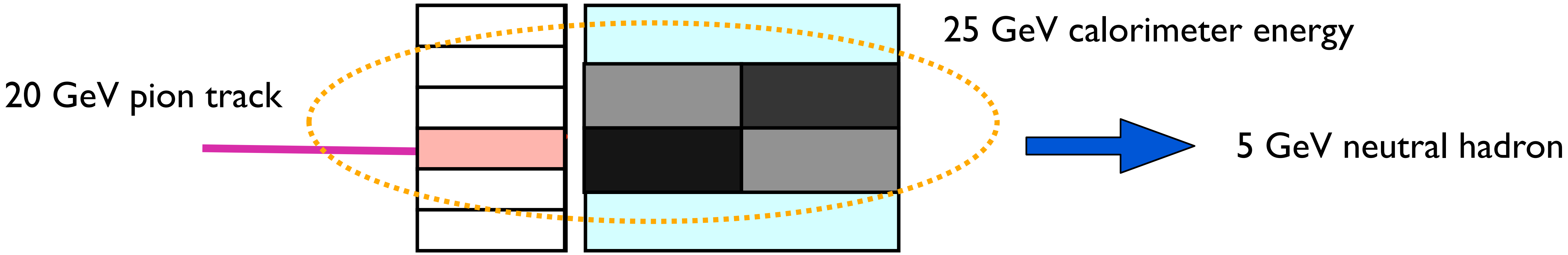
# Particle Flow: A simple Idea

- Improve jet energy reconstruction by measuring each particle in the jet with best possible precision
  - Measure all charged particles in the tracker (remember, 60% charged hadrons!)
  - Significantly reduce the impact of hadron calorimeter performance: Only for neutral hadrons
  - Measure only 10% of the jet energy with the “weakest” detector: significant improvement in resolution



# Energy Flow: A first Step

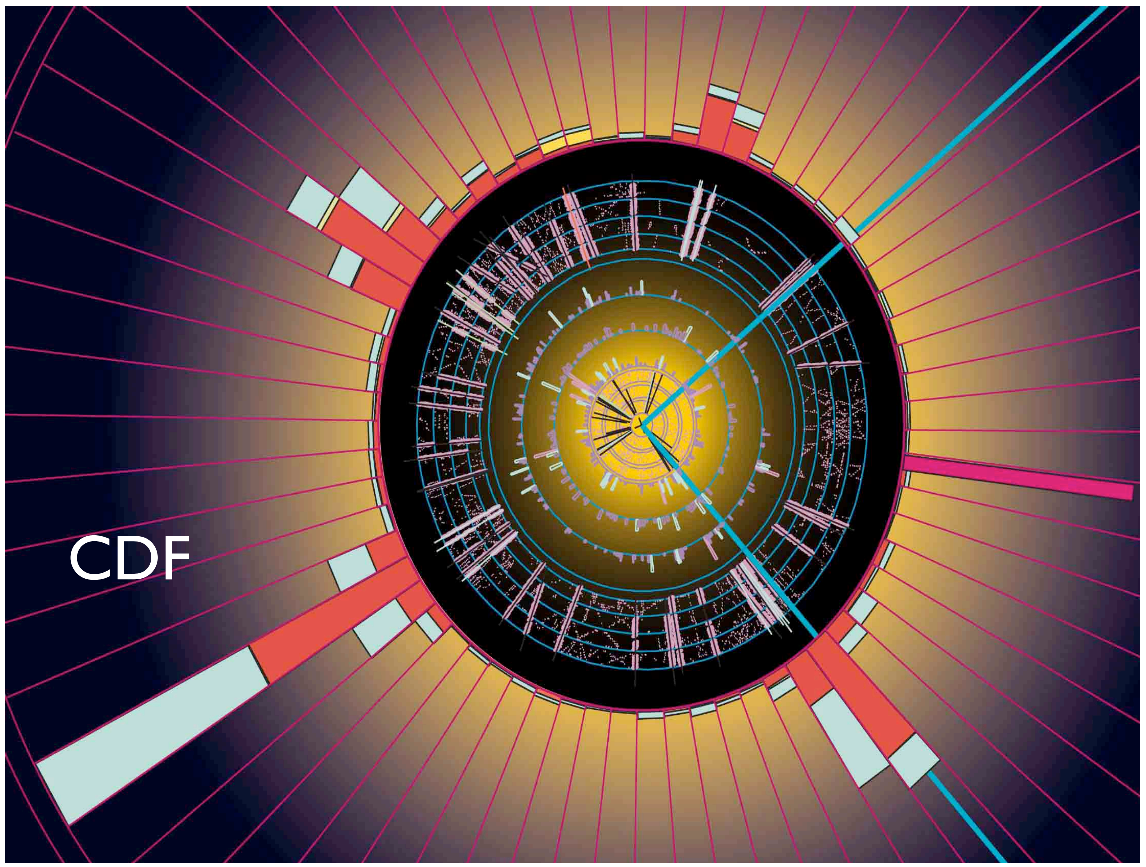
- The idea behind Particle Flow is not new:
  ***Energy Flow*** by ALEPH at LEP (NIM A360, 481 (1995))
  - Identify electrons, photons, muons - remove from calorimeter hits
  - ▸ Left with charged and neutral hadrons in the calorimeter
    - Reconstruction of neutral hadrons by subtraction



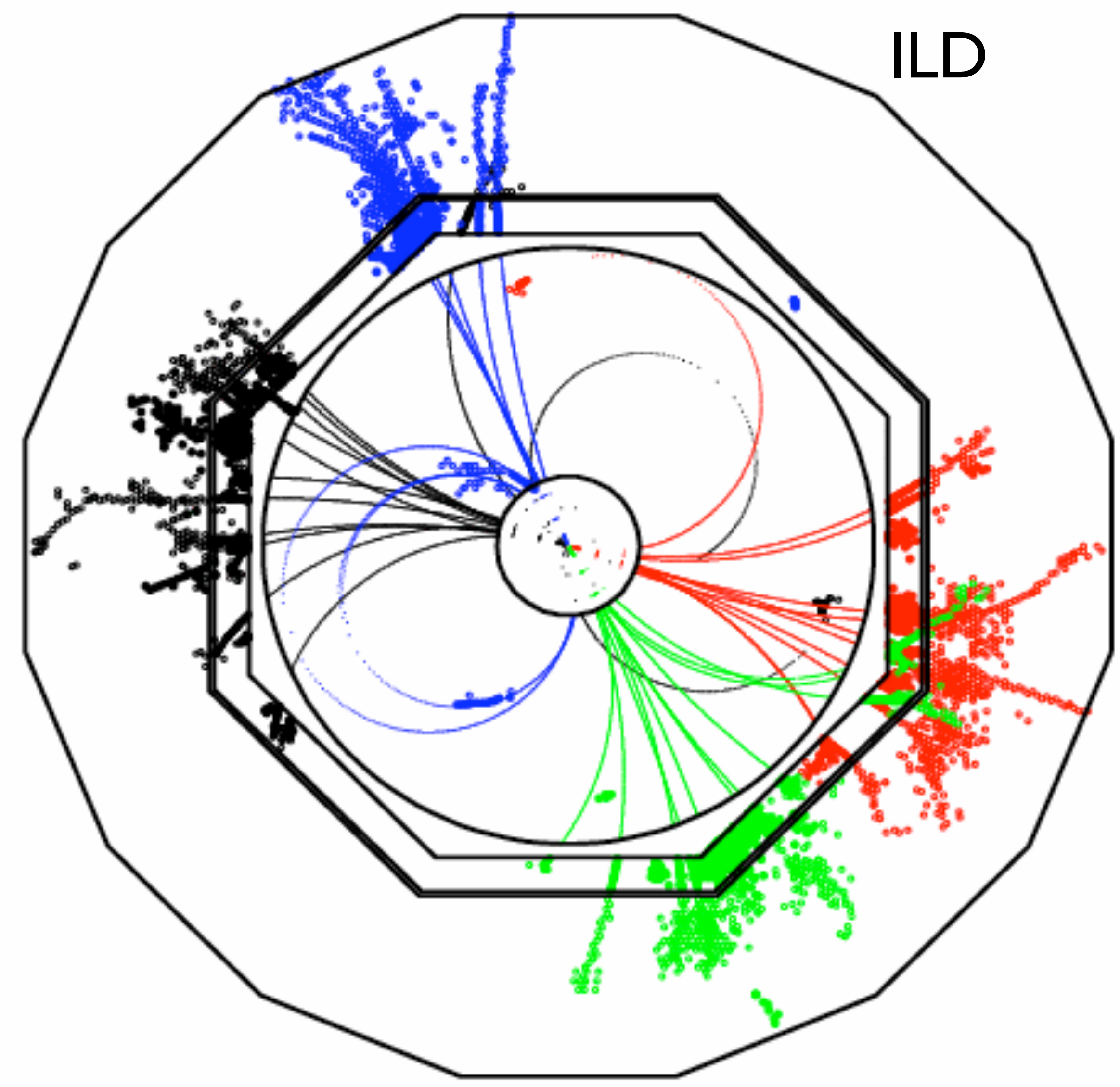

➪ Energy resolution still dominated by hadron calorimeter (electron, photon, muon ID helps to improve jet resolution, neutral hadron ID by subtraction does not help)

# Particle Flow: Very Different Detectors

- Pushing the idea further: Identify neutral and charged hadrons in the calorimeter directly
  - Requires extremely high granularity in the calorimeters for optimum performance



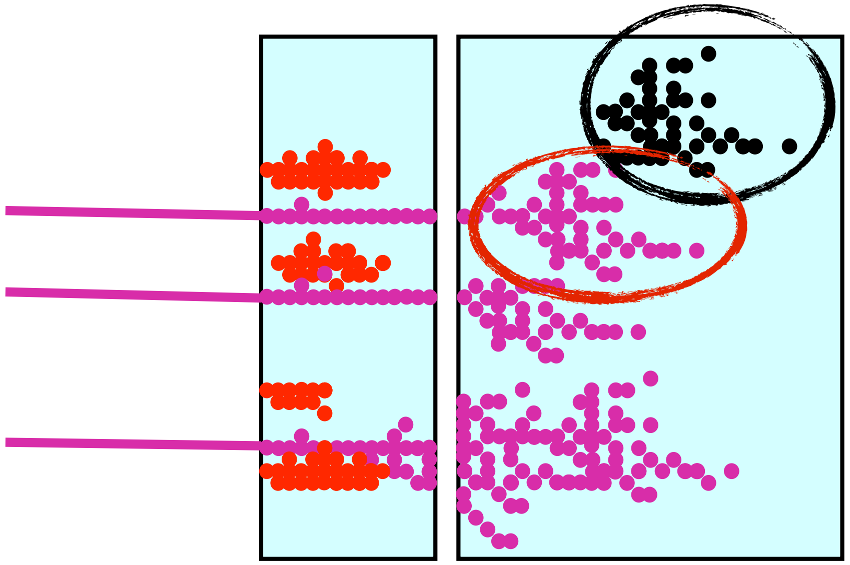

from this...




to this!

# Particle Flow: A Challenging Concept

- Key issues of PFA:
  - Avoid double counting of energy
  - Separate individual particles



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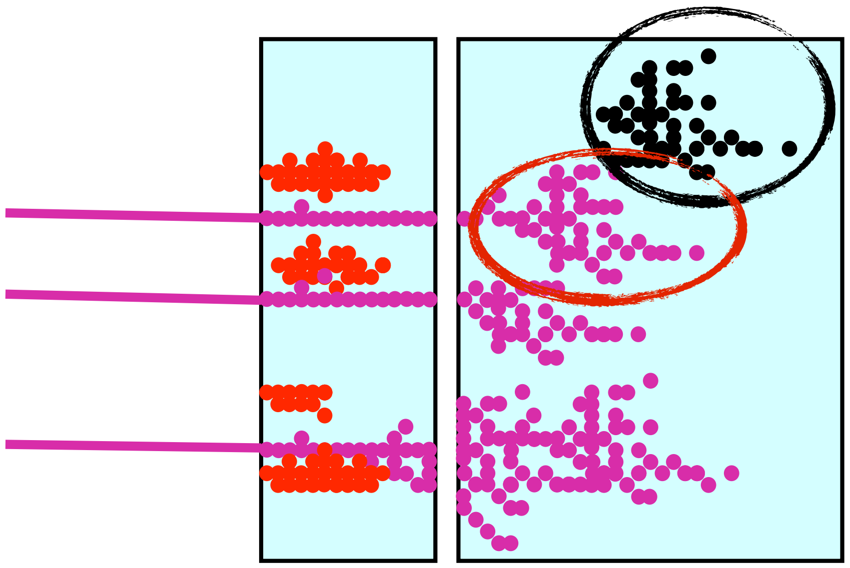

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The level of mistakes, "***confusion***", determines the achievable jet energy resolution, not the intrinsic resolution of the calorimeters!

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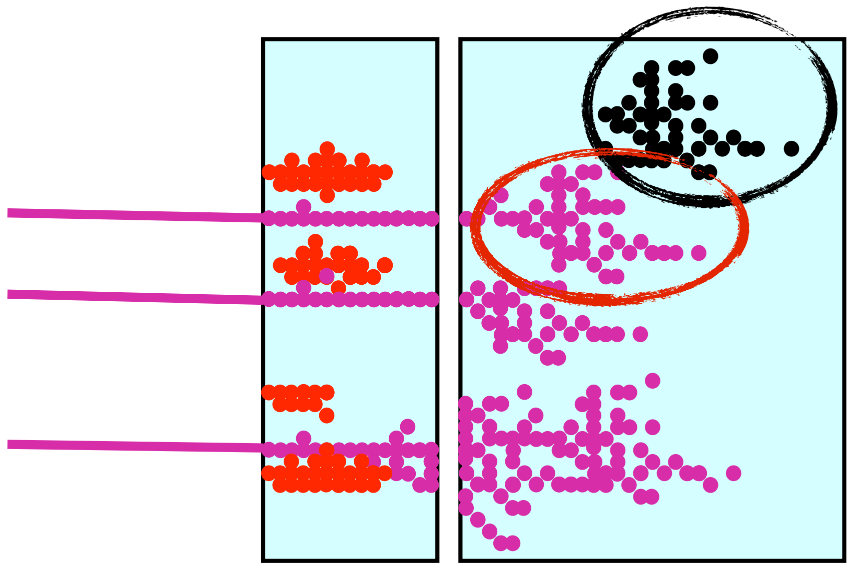

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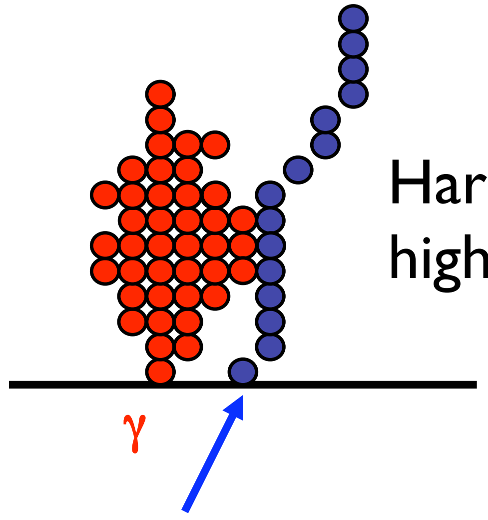
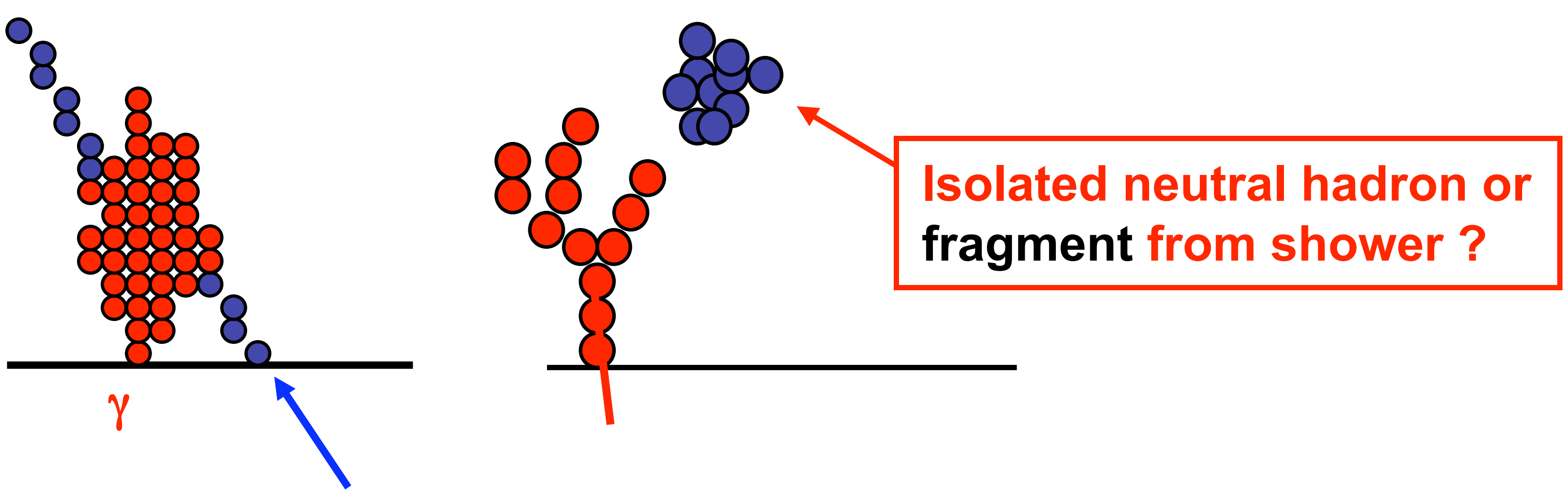
PFA Requirements:



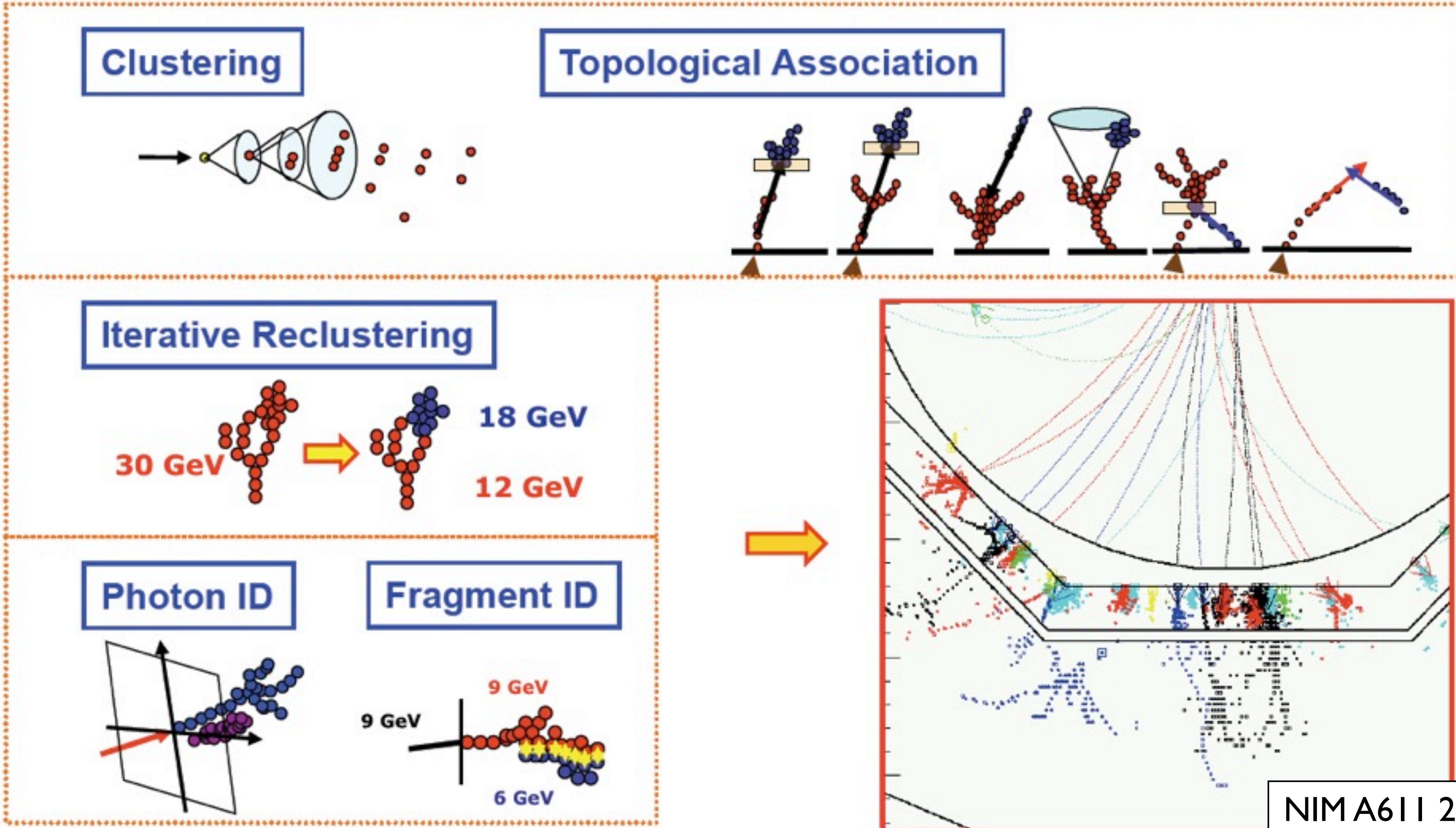

Hardware:
high granularity

Software: very sophisticated algorithms



# Particle Flow Algorithms: Technology

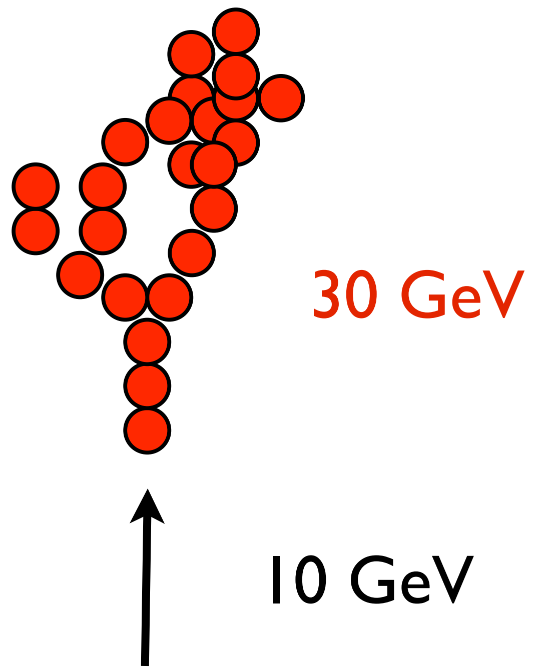
- The most performant PFA at present: PandoraPFA (Mark Thomson, Cambridge)
  - highly complex software package




NIM A611 24, 2009

# PFA Technology: One Example

- Iterative reclustering: Pushing the PFA Concept further
  - In a high-density environment (e.g. high-energy jet), pure PFA hits limits: Showers can not be clearly separated
  - Use consistency of track momentum and shower energy to guide the clustering: recluster if energies are inconsistent



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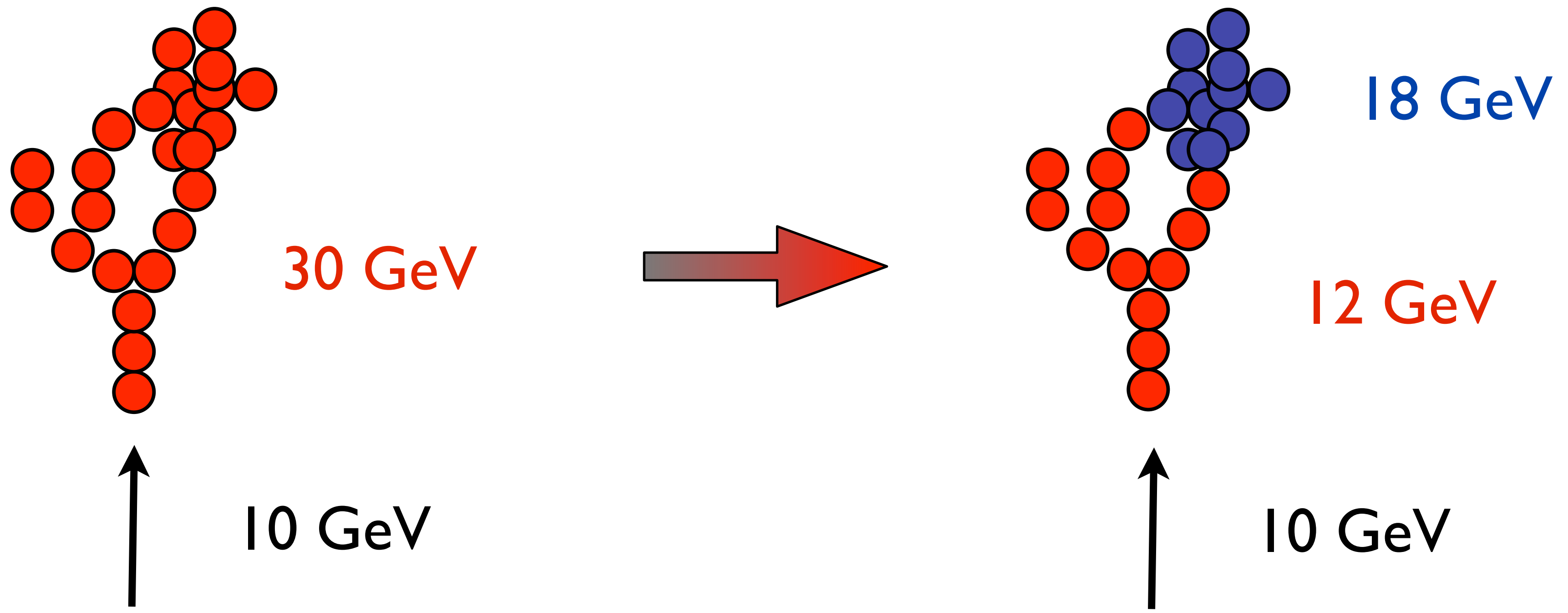
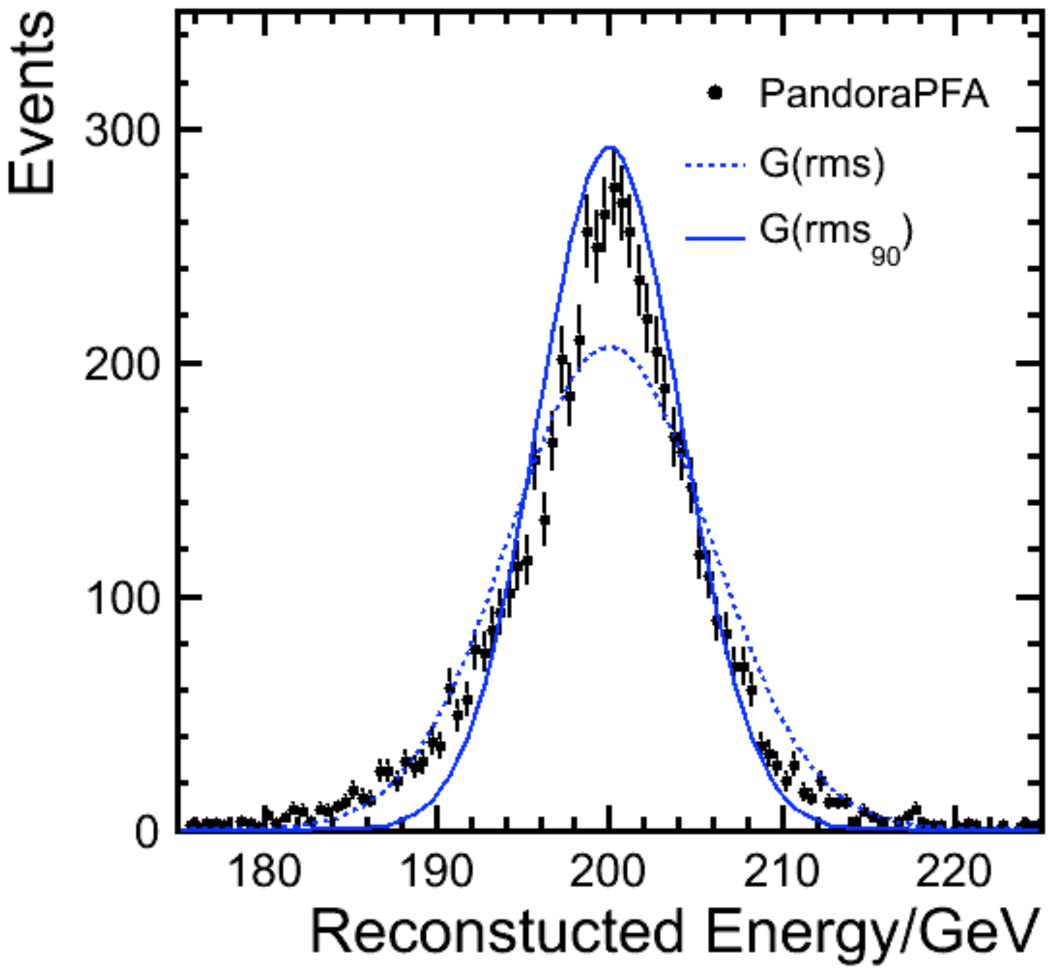



➩ much more powerful than subtraction or one-stage clustering only possible in highly granular calorimeters

# Particle Flow Performance

- Detailed studies with PandoraPFA have been performed for the ILD detector concept

Resolution is given as $RMS_{90}$, the RMS of the 90% most central events:
PFA is inherently non-gaussian (driven by confusion): narrow core, wide tails
In terms of analyzing power: $RMS_{90} \sim 0.9\ \sigma_{Gauss}$




| $E_{JET}$ | $\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$ | $\sigma_E/E_j$ |
|---|---|---|
| 45 GeV | 25.2 % | 3.7 % |
| 100 GeV | 29.2 % | 2.9 % |
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For 45 GeV: Factor 3 better than LEP best (ALEPH)!

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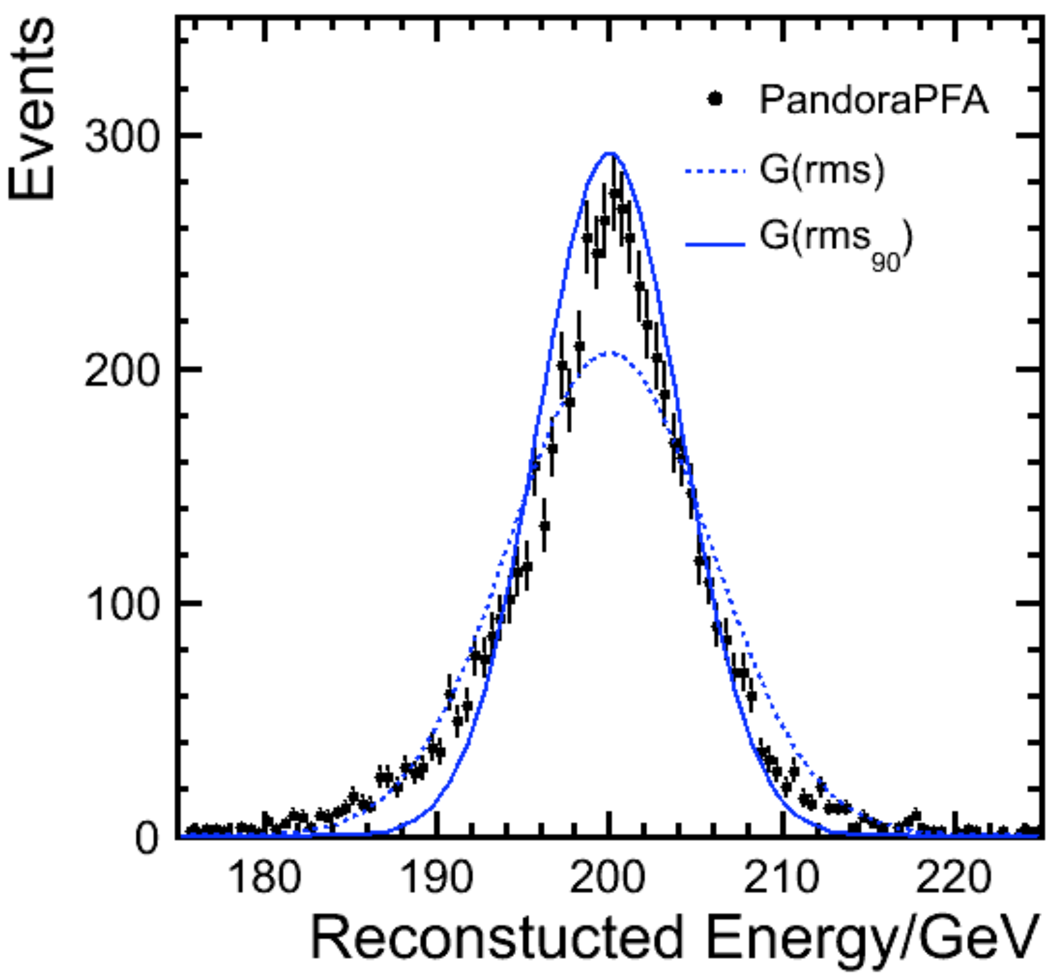


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➩ PFA delivers unprecedented jet energy resolution: Requirements for a Linear Collider are met!

# Particle Flow beyond Linear Colliders

- For best performance:
  - Imaging calorimeters: Best possible shower separation in the calorimeters
- But: Technique can be beneficial also for other detector systems
  - Expect some performance penalties:
    - loose the full power of iterative reclustering
    - default to energy flow (neutral hadrons by subtraction) in some regions

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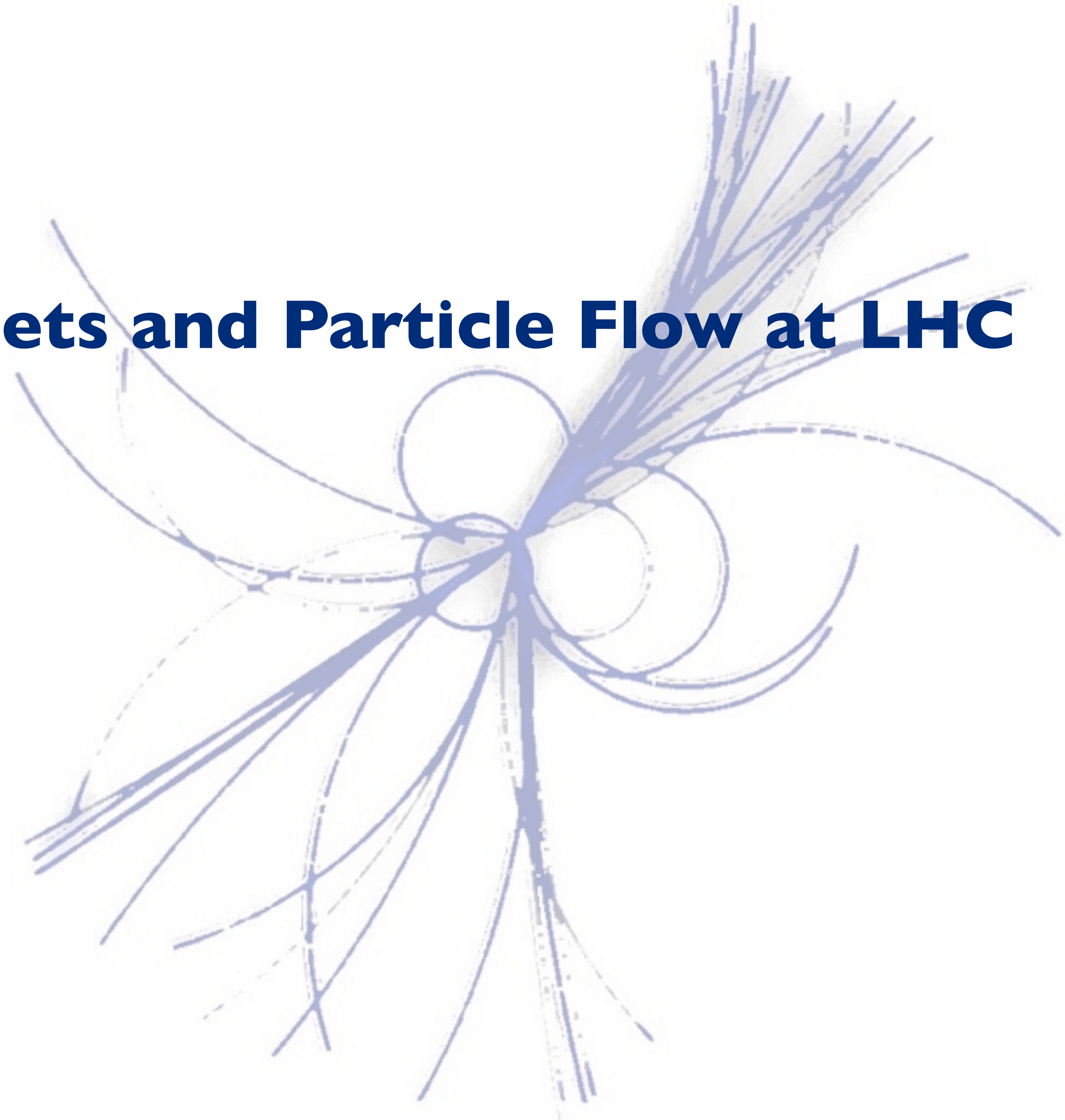
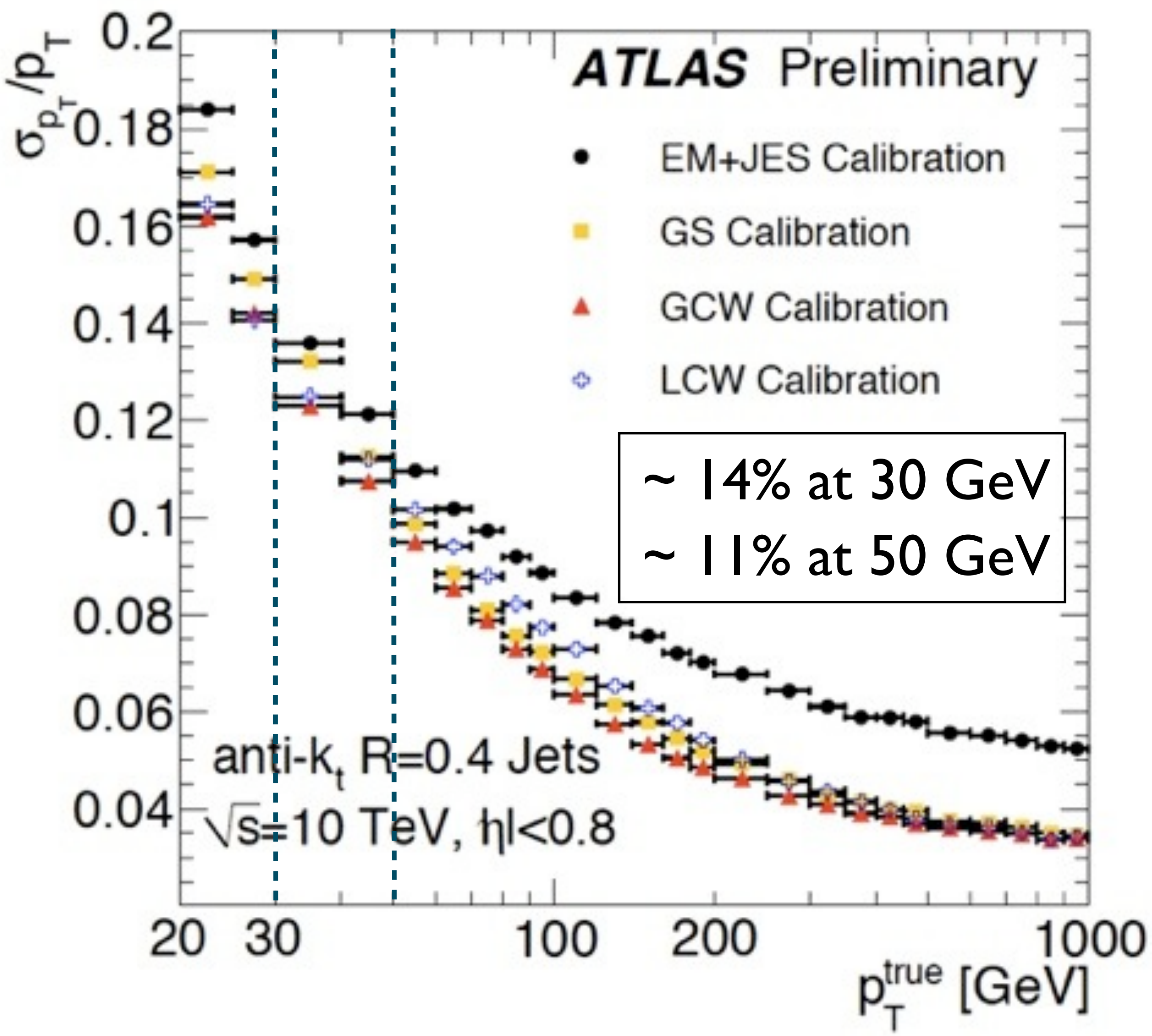
The obvious question:
Are such methods applicable at LHC?

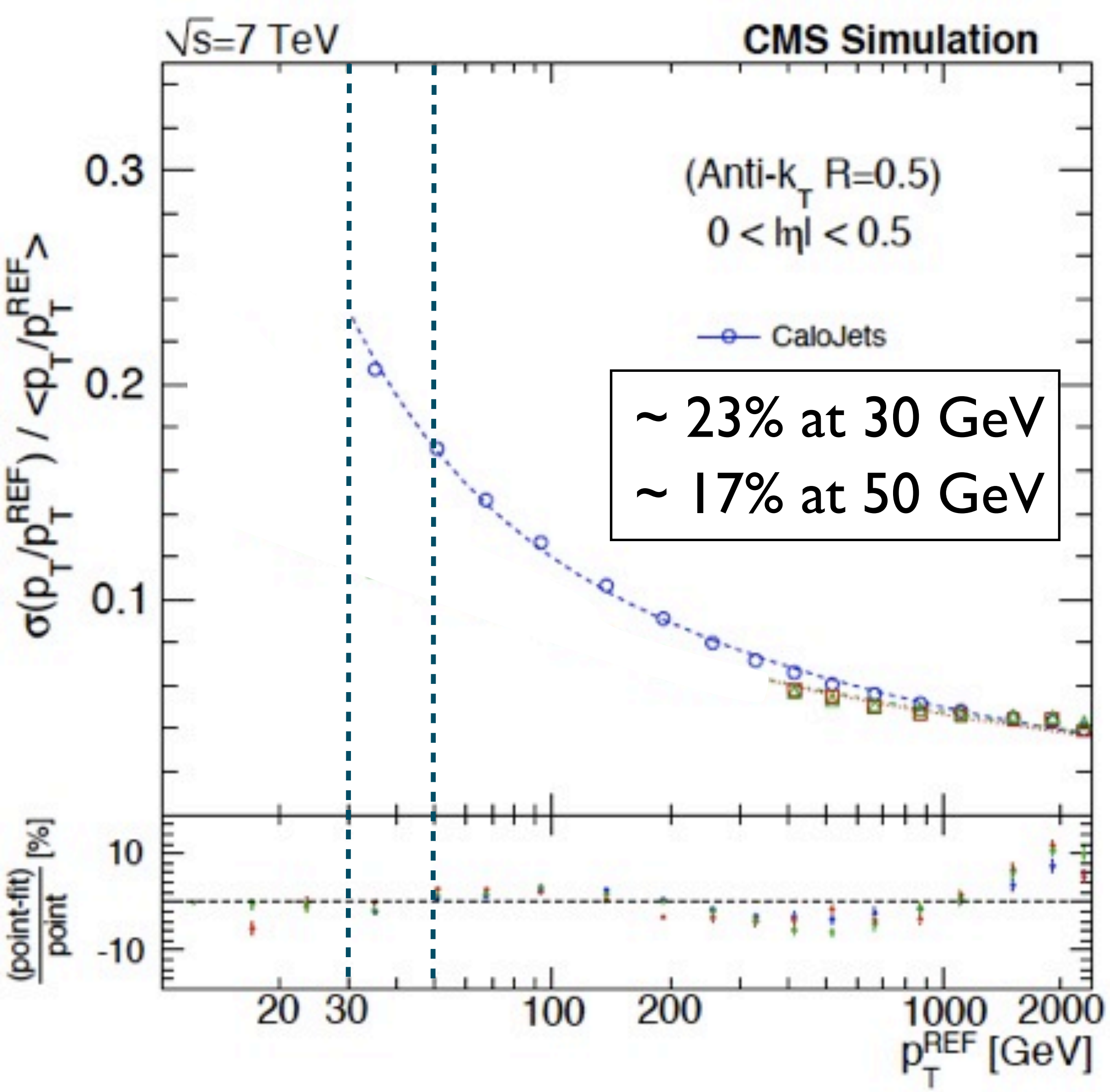
# Jets and Particle Flow at LHC



# Jets at ATLAS and CMS

- Jet resolution expected from simulations
  - Most jets are low energy: particularly important for missing $E_T$!



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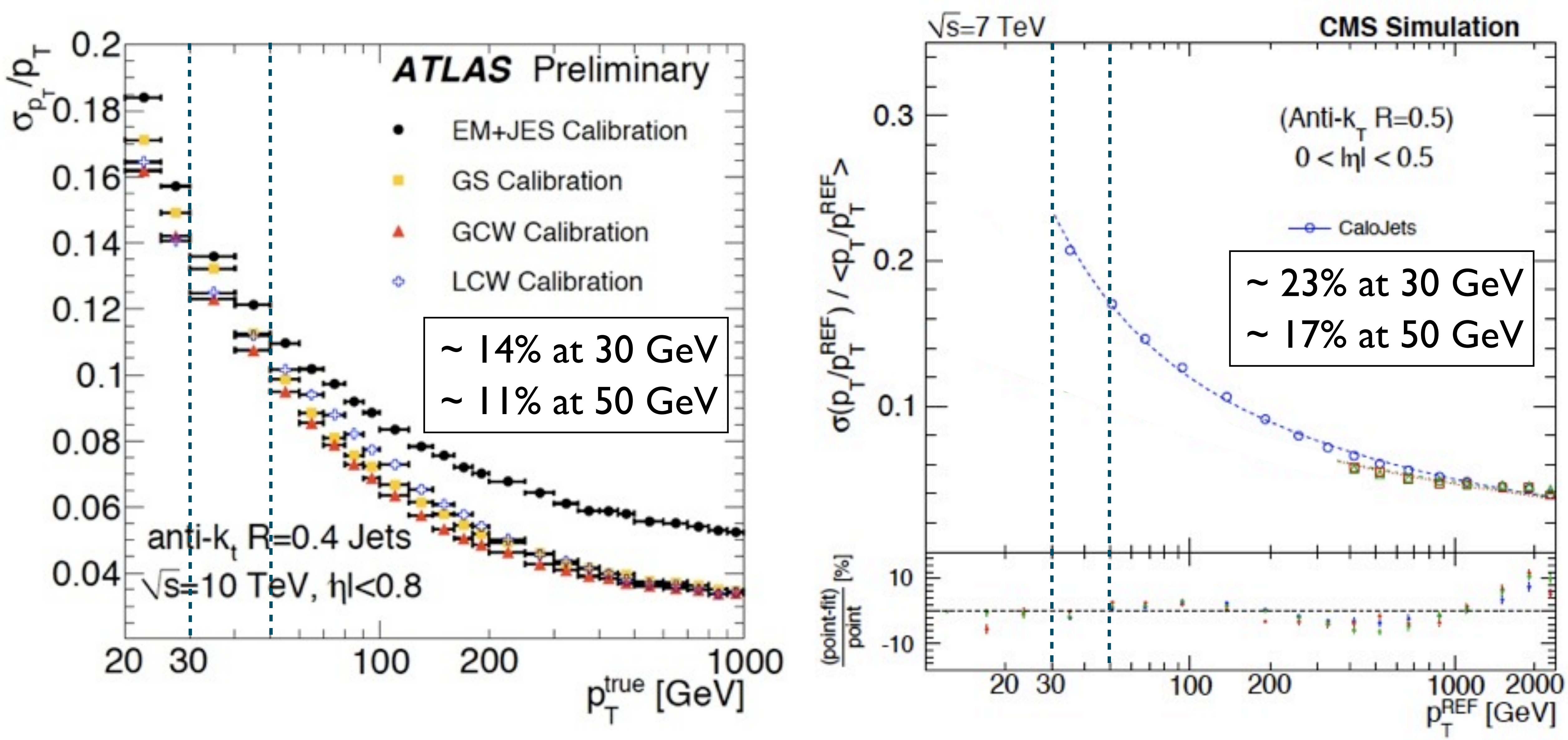
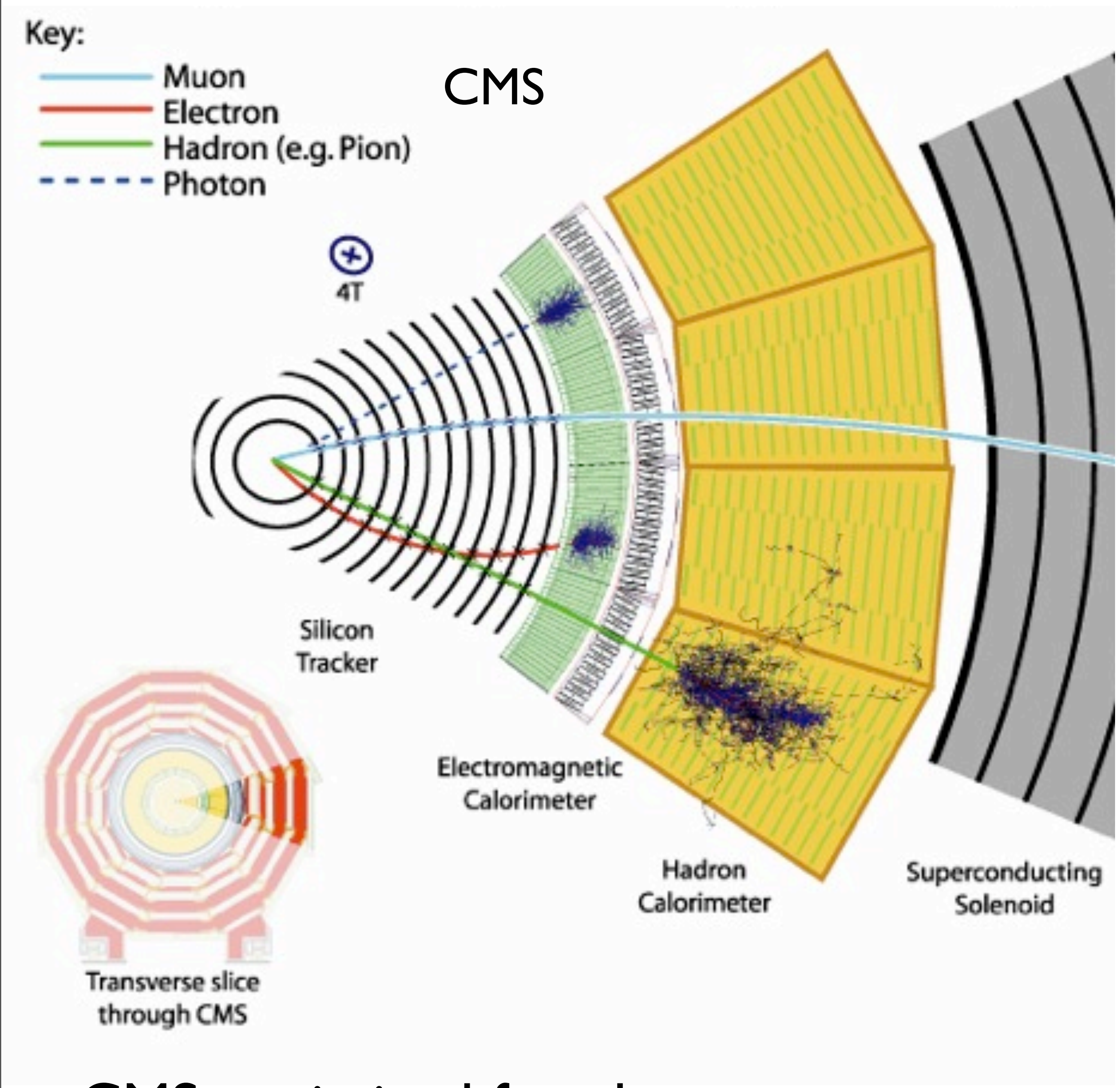
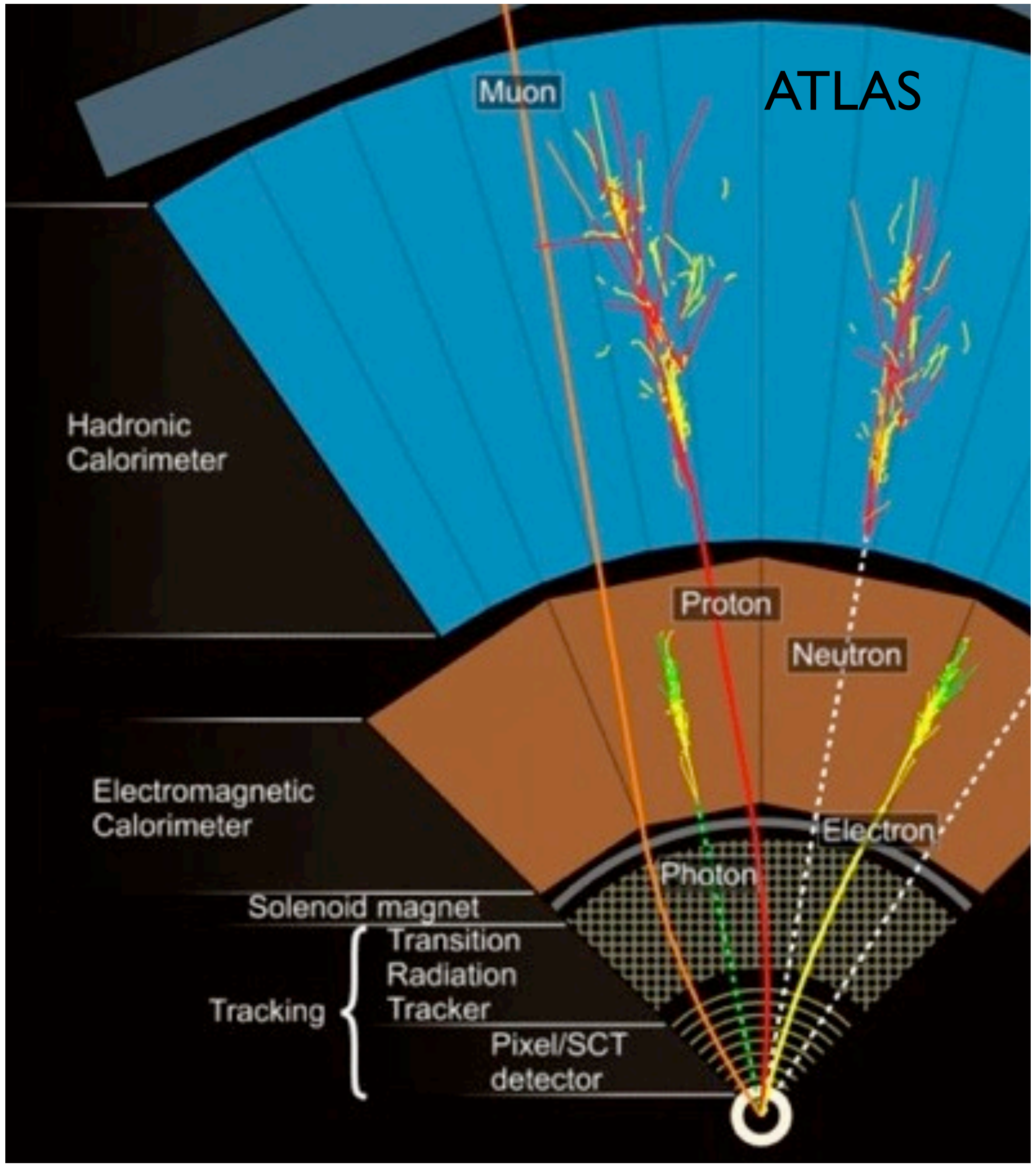



➡ higher degree of "suffering" at CMS - Why?

# ATLAS and CMS: The Source of Different Resolutions

- Different focus of the detectors, different calorimeters




CMS: optimized for photons:
fantastic ECAL, but: dead material between ECAL and HCAL
ATLAS: better for hadrons: Less difference in hadronic response of ECAL and HCAL,
sampling calorimeters, with some degree of longitudinal segmentation in both cases

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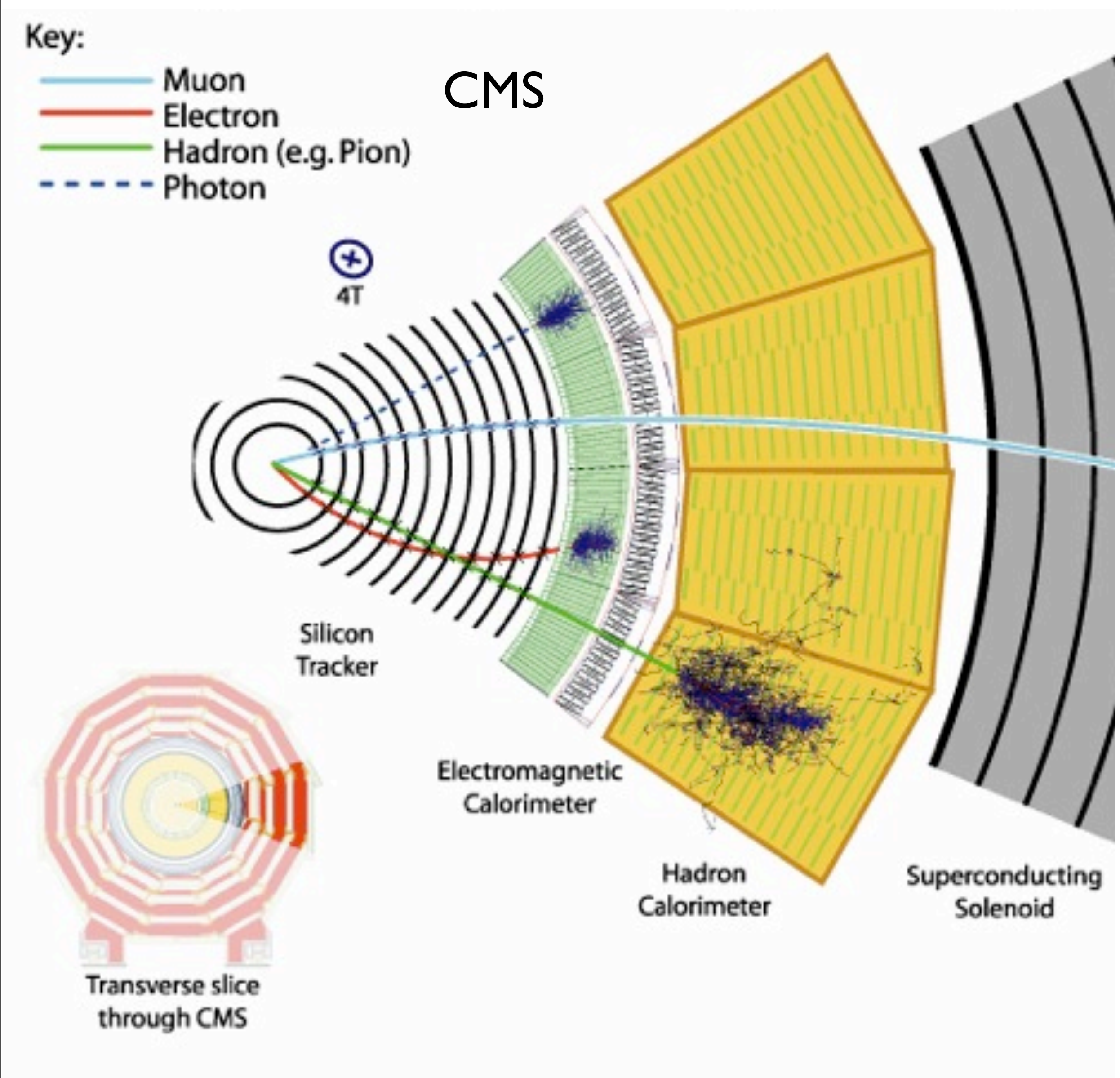


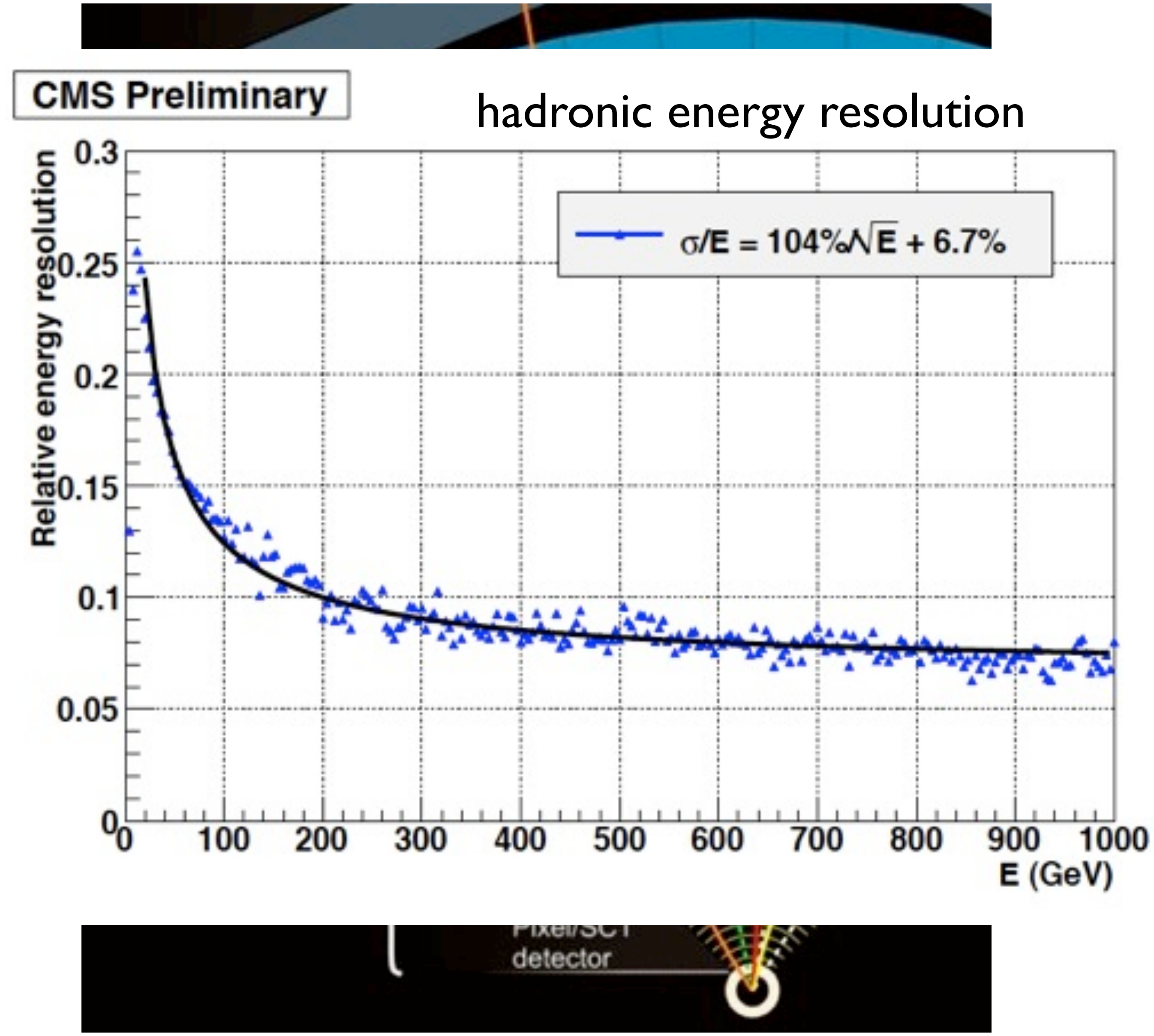


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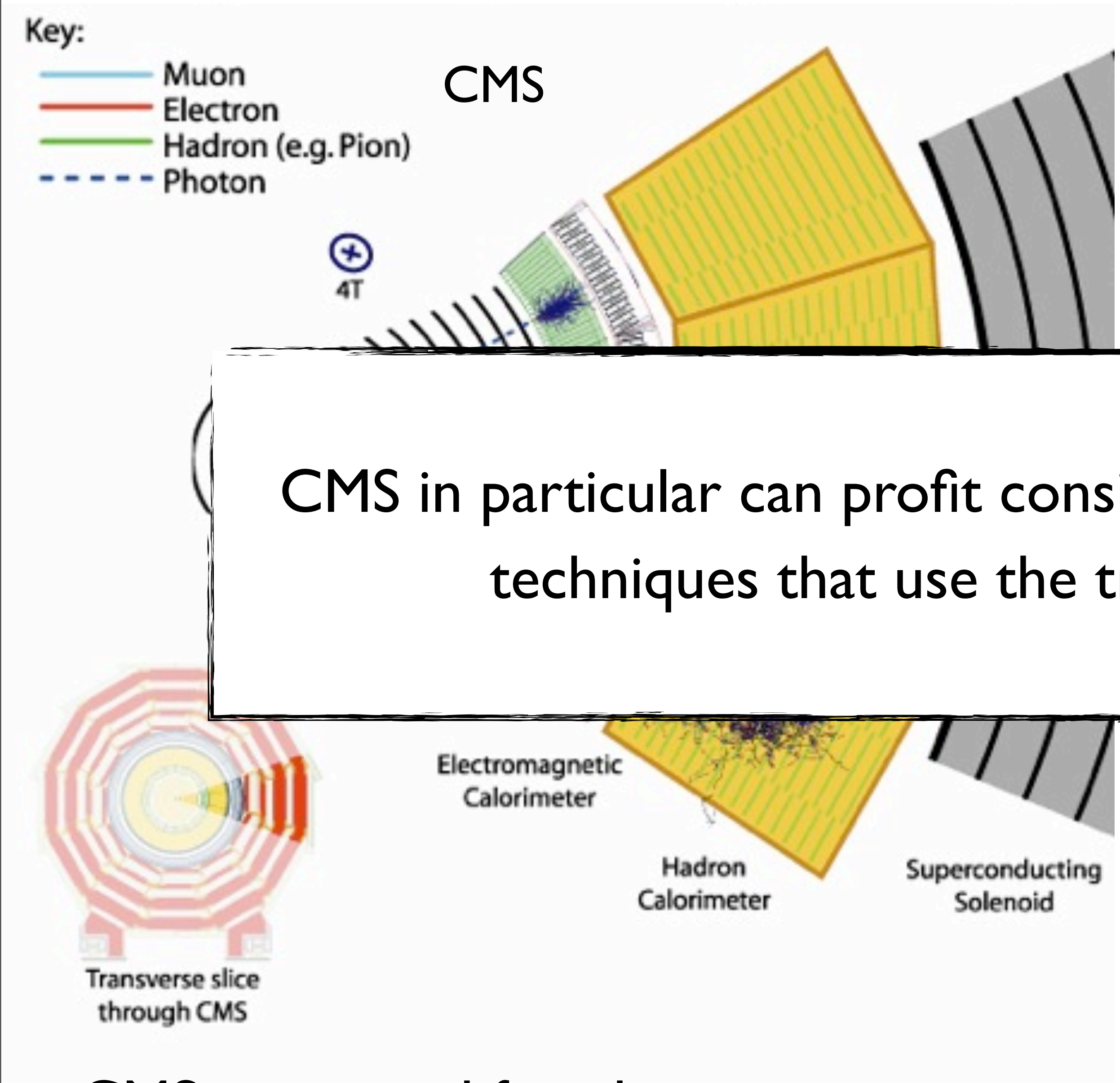


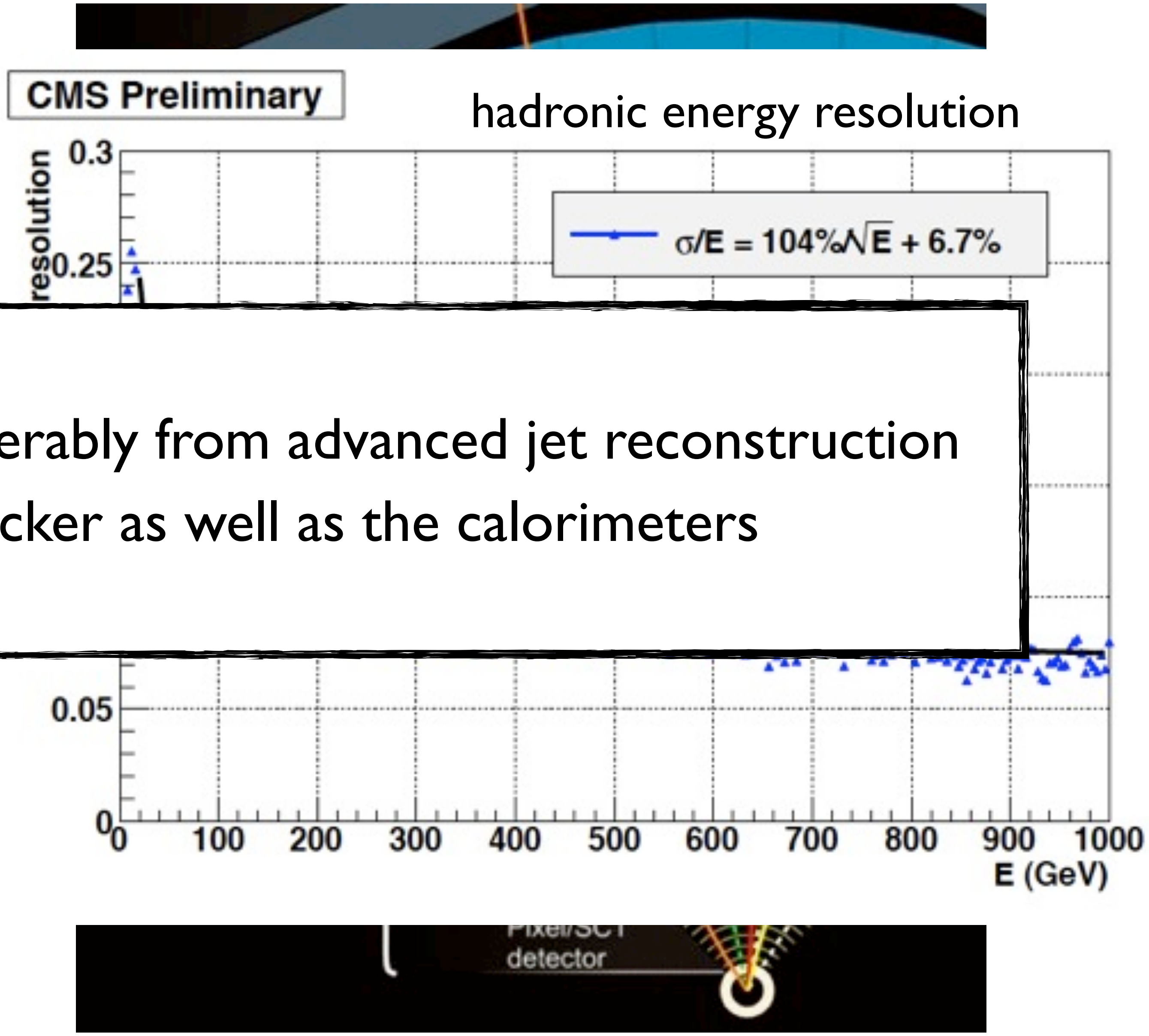


CMS in particular can profit considerably from advanced jet reconstruction techniques that use the tracker as well as the calorimeters

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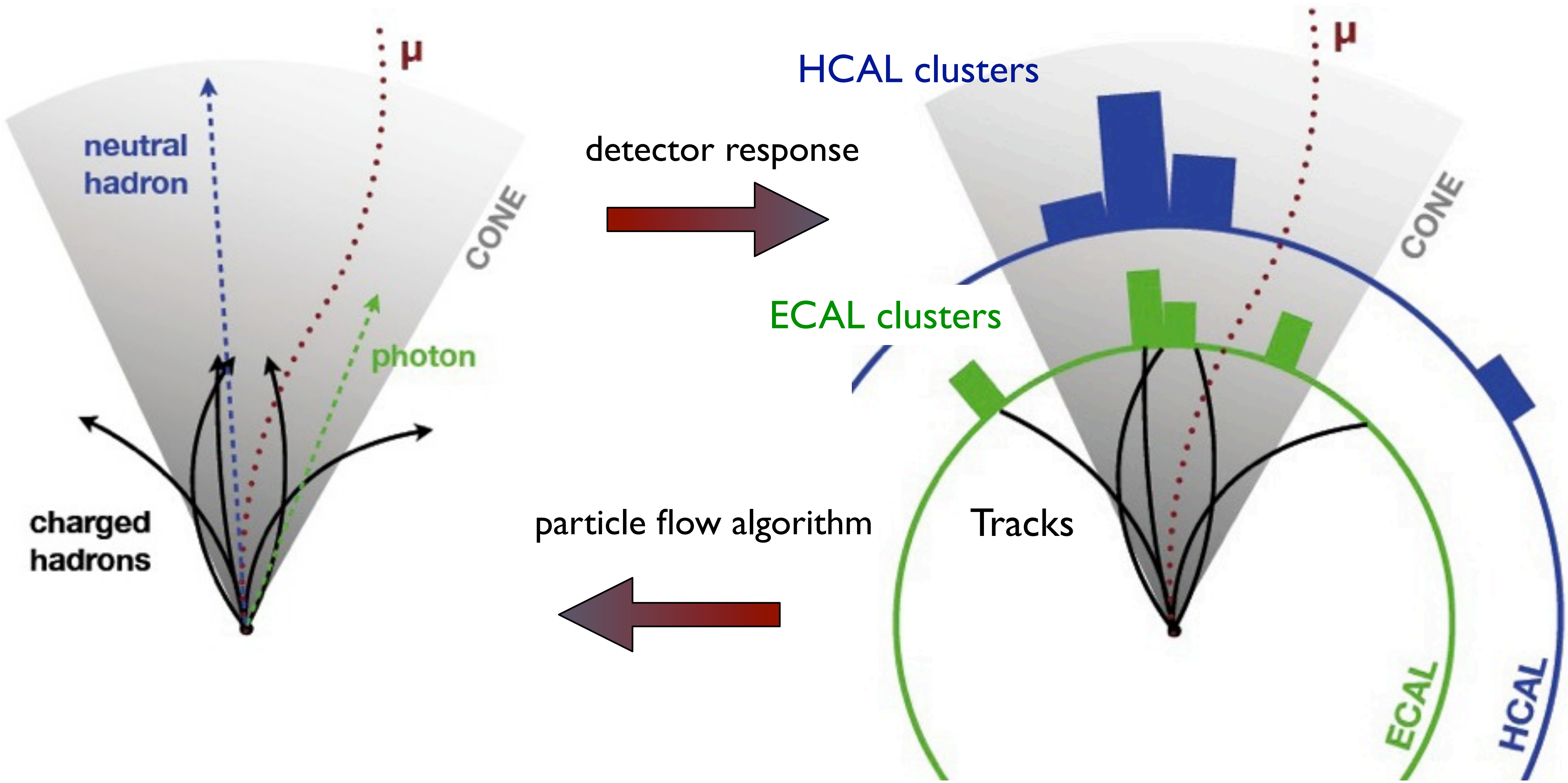
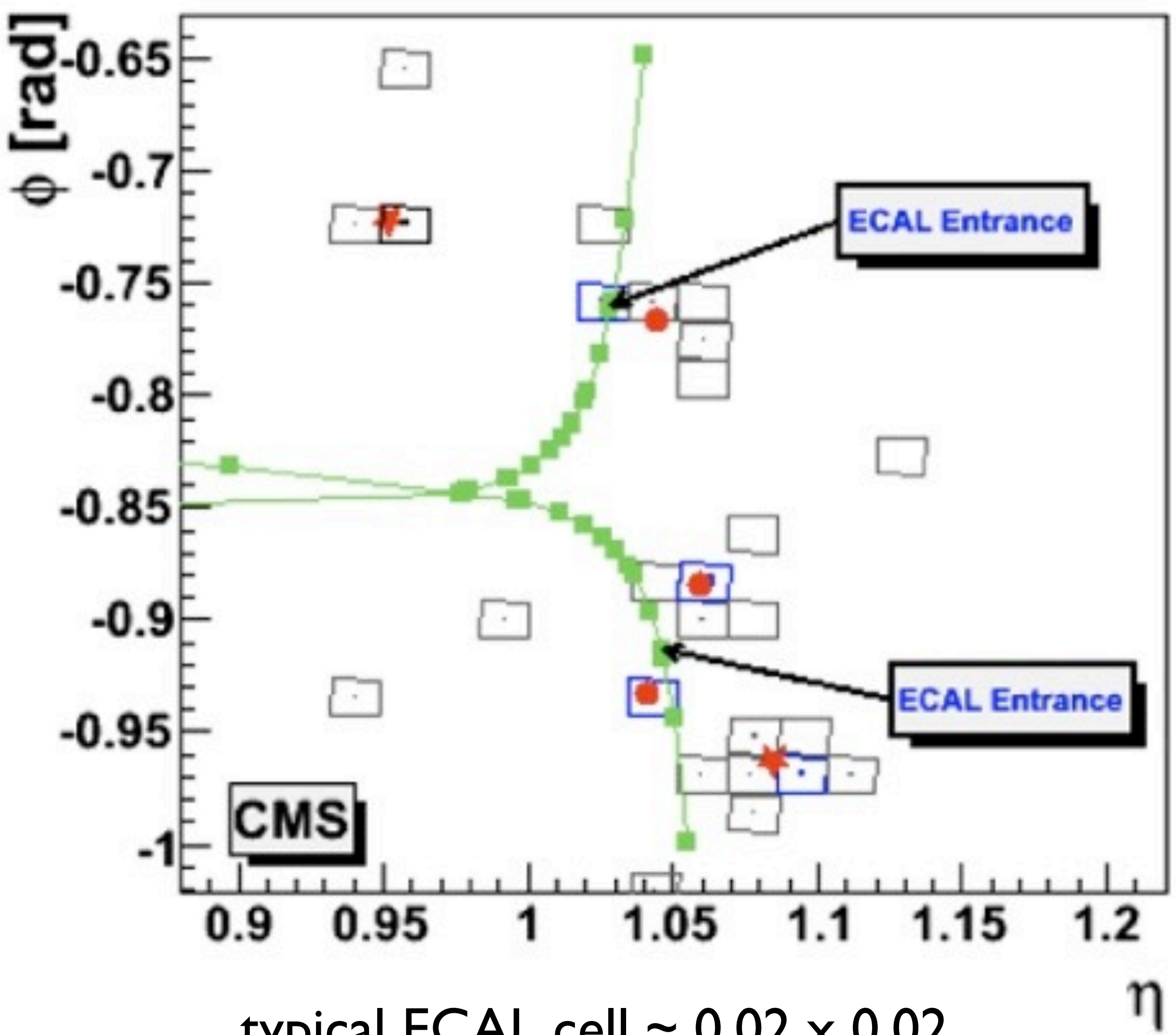
# Particle Flow in CMS



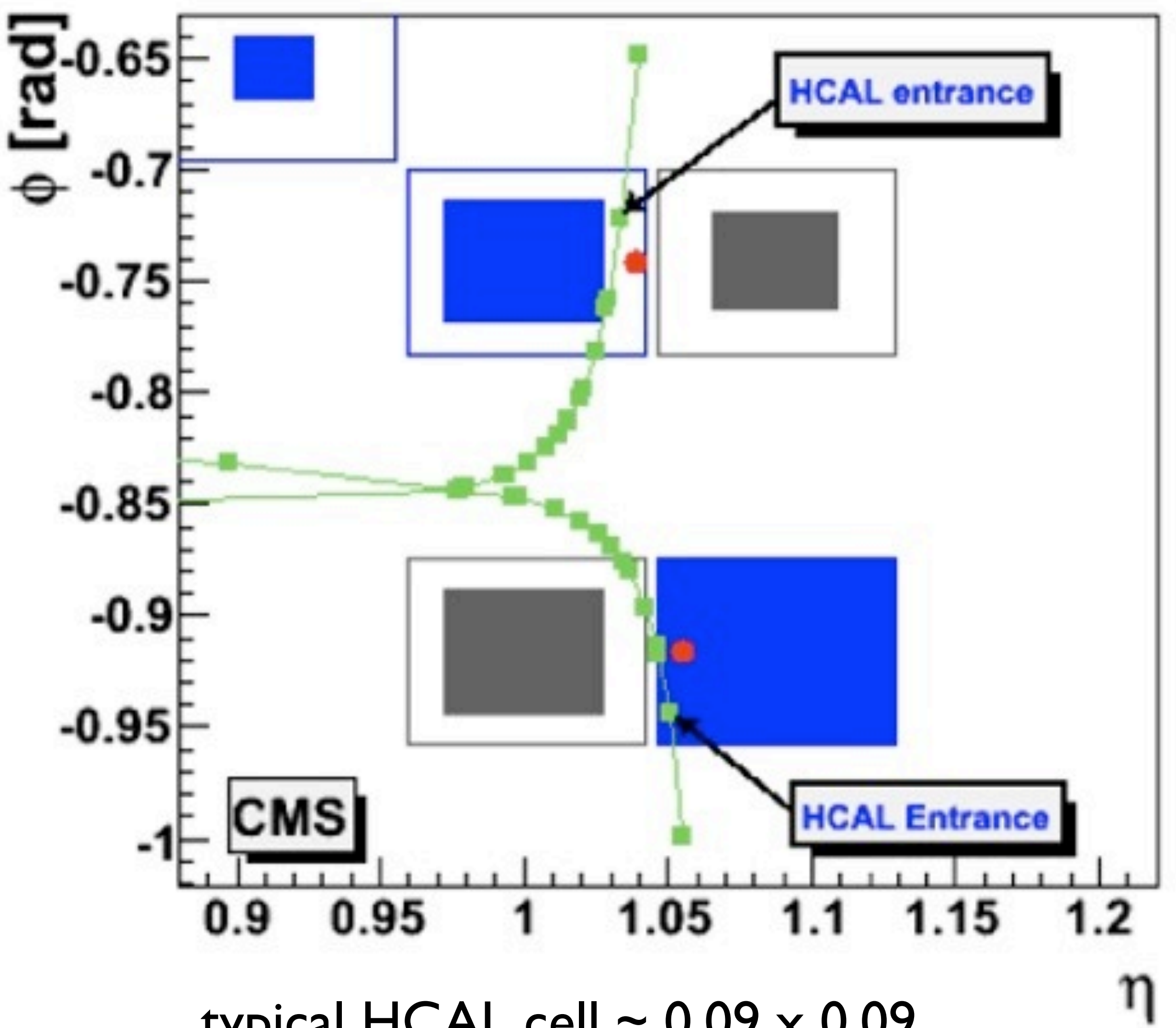

- Exploit the features of CMS:
  - Highly efficient, high resolution tracker, large magnetic field
  - Granular ECAL (in η,φ)

# Particle Flow in CMS - The Algorithm

- The key part of CMS particle flow: The Link Algorithm
  - Link charged tracks to clusters (groups of neighboring cells with around one local maximum) in the calorimeters




typical ECAL cell ~ 0.02 x 0.02
(2.2 x 2.2 $cm^2$, crystals)




typical HCAL cell ~ 0.09 x 0.09
(17 x 17 $cm^2$ at inner layer, tower readout)

for reference: jet cone radius 0.5 in η, φ

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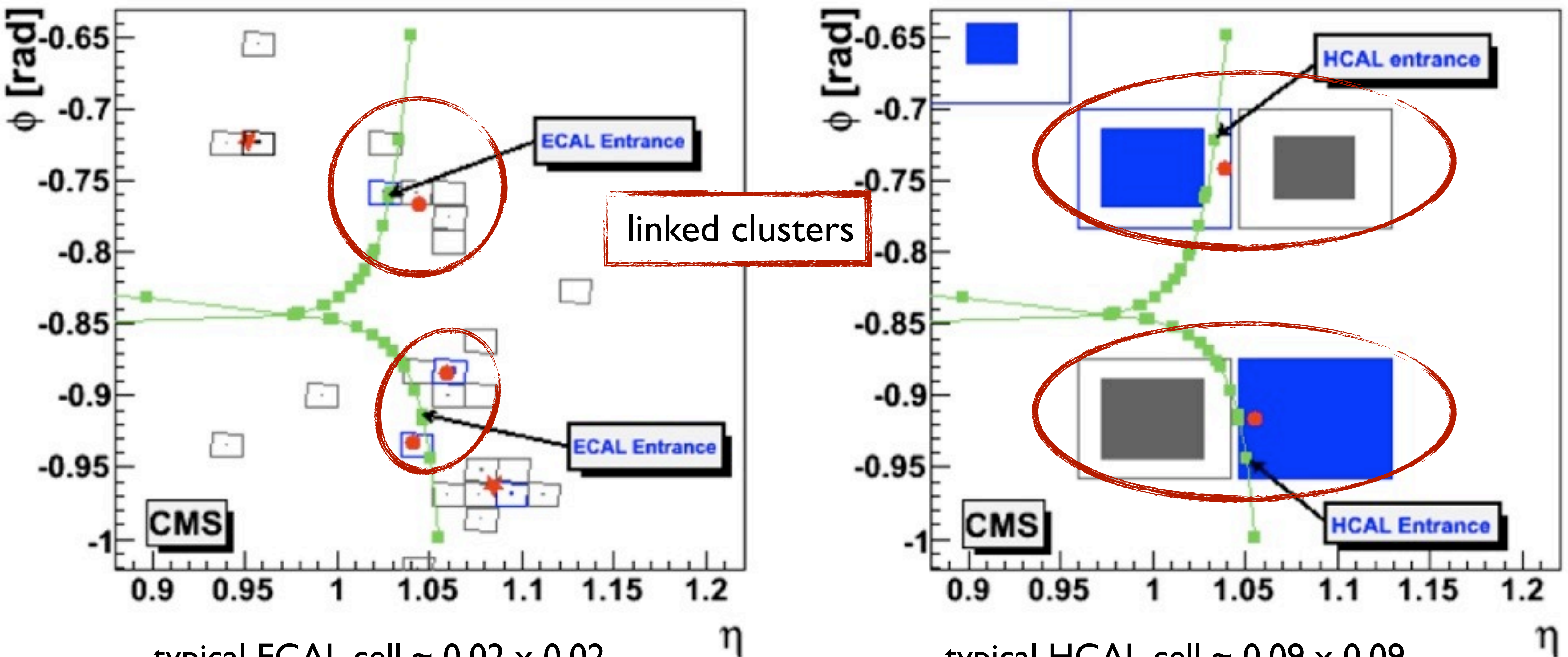


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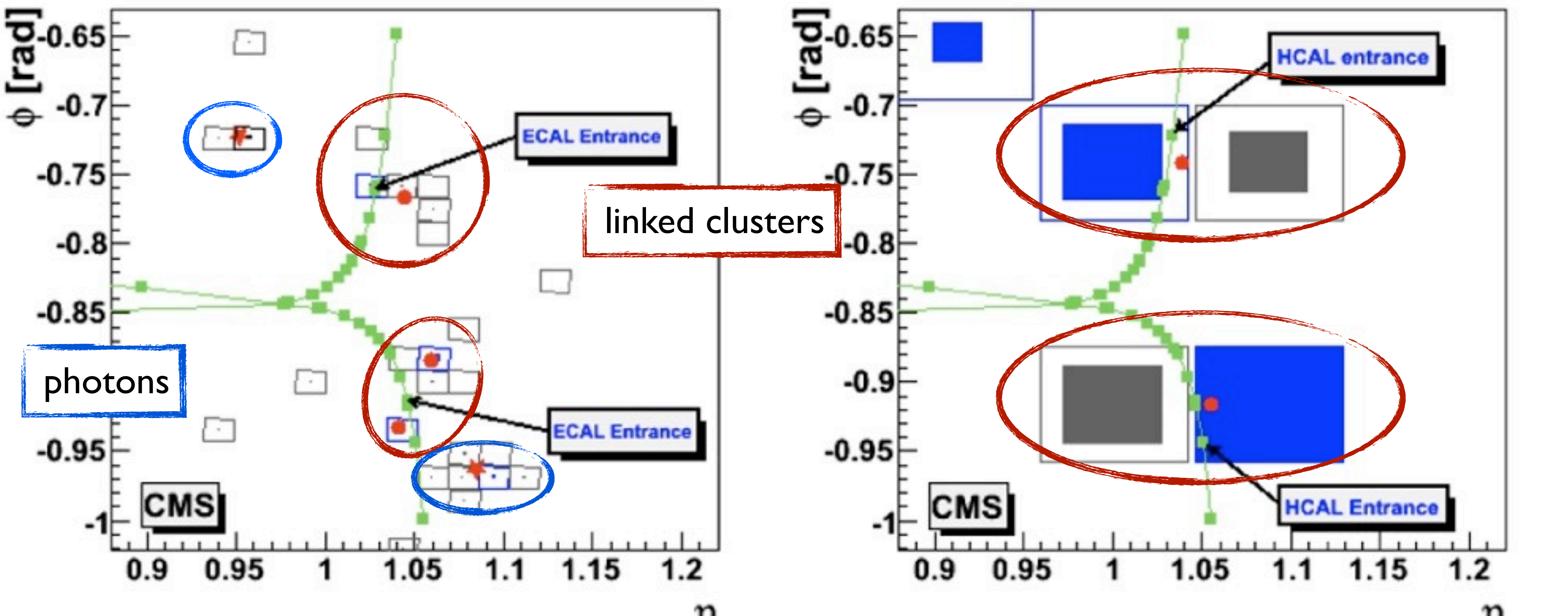


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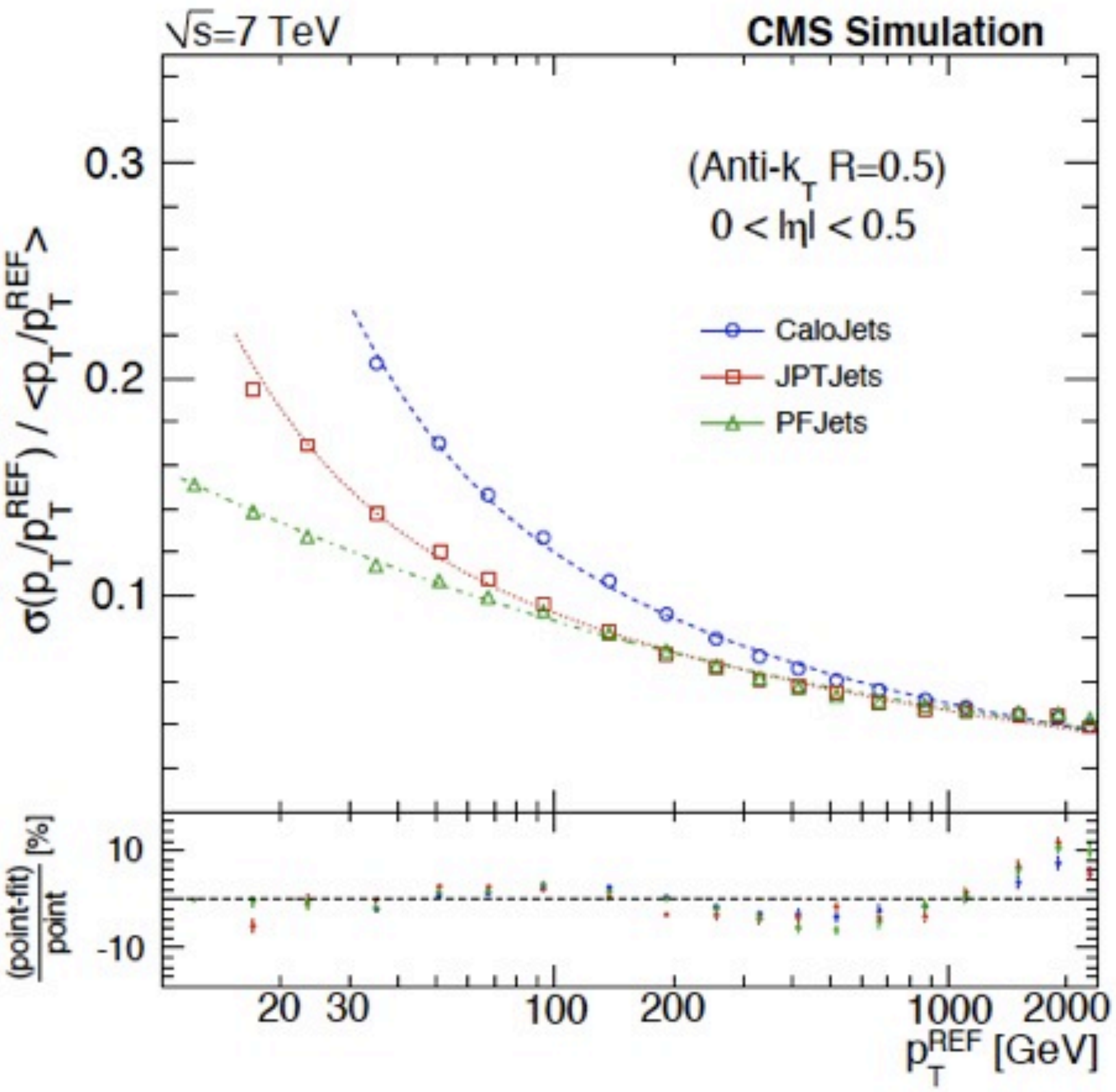
# Particle Flow in CMS - The Algorithm

- Build links between ECAL and HCAL clusters: Based on geometric overlap, cluster in higher granular detector (ECAL) has to be within HCAL cluster area
- For tracks linked to clusters:
  - If calorimeter (ECAL + HCAL) energy is consistent with track energy use all information for best energy measurement (driven by track measurement except at very high energy and/or large rapidity)
  - If calorimeter energy < track energy check for reconstruction problems (rare!)
  - If calorimeter energy > track energy, create photon or neutral hadron based on subtraction
  - For several tracks linked to the same cluster: Use track sum
  - For one track linked to several clusters: Use closest link
- Identify photons and neutral hadrons from calorimeter clusters without links

# CMS Particle Flow Performance




- Substantial improvement, in particular at energies below ~ 300 GeV (where most of the jets are!)
  - A factor of 2 and more below 30 GeV

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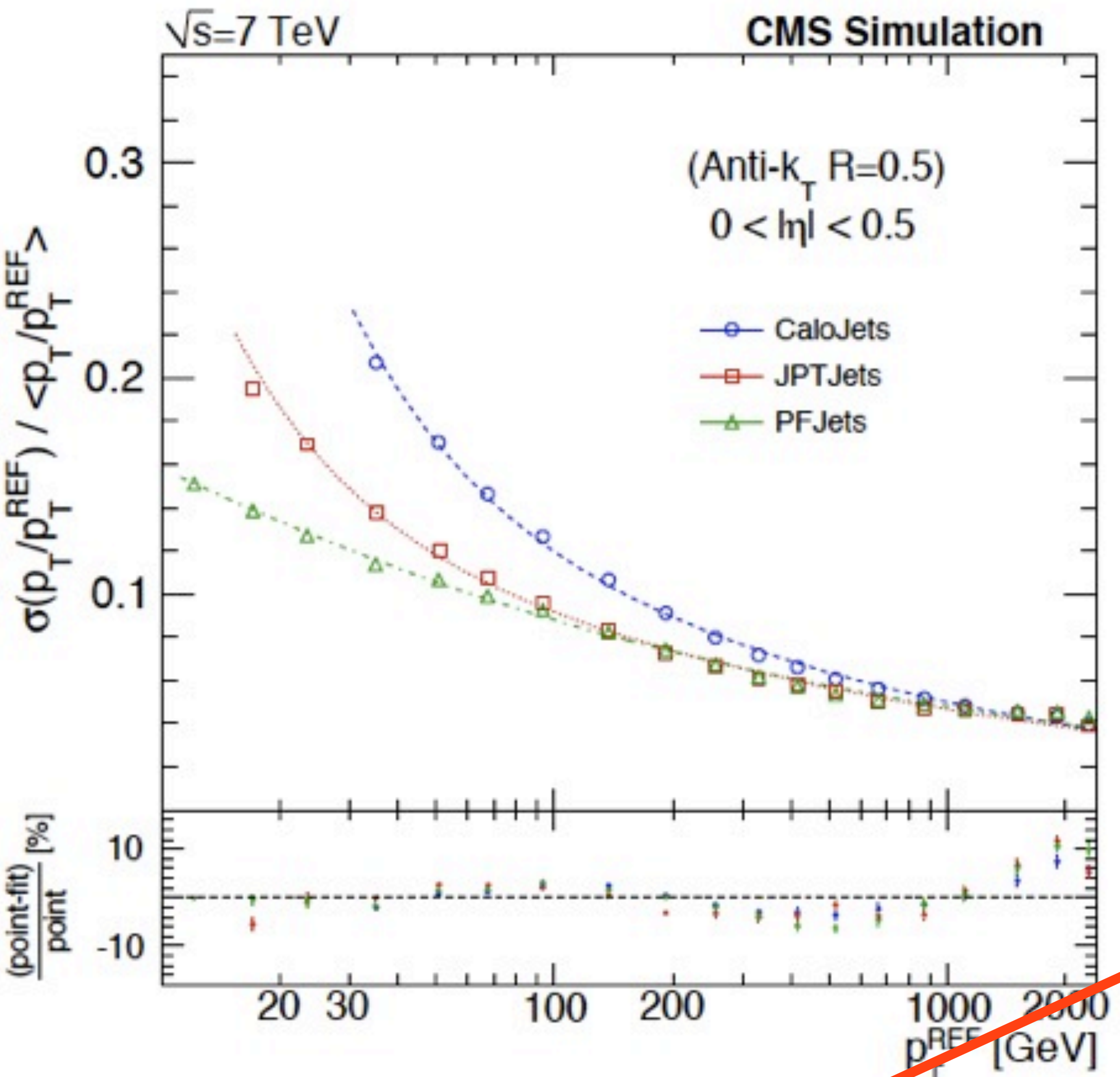


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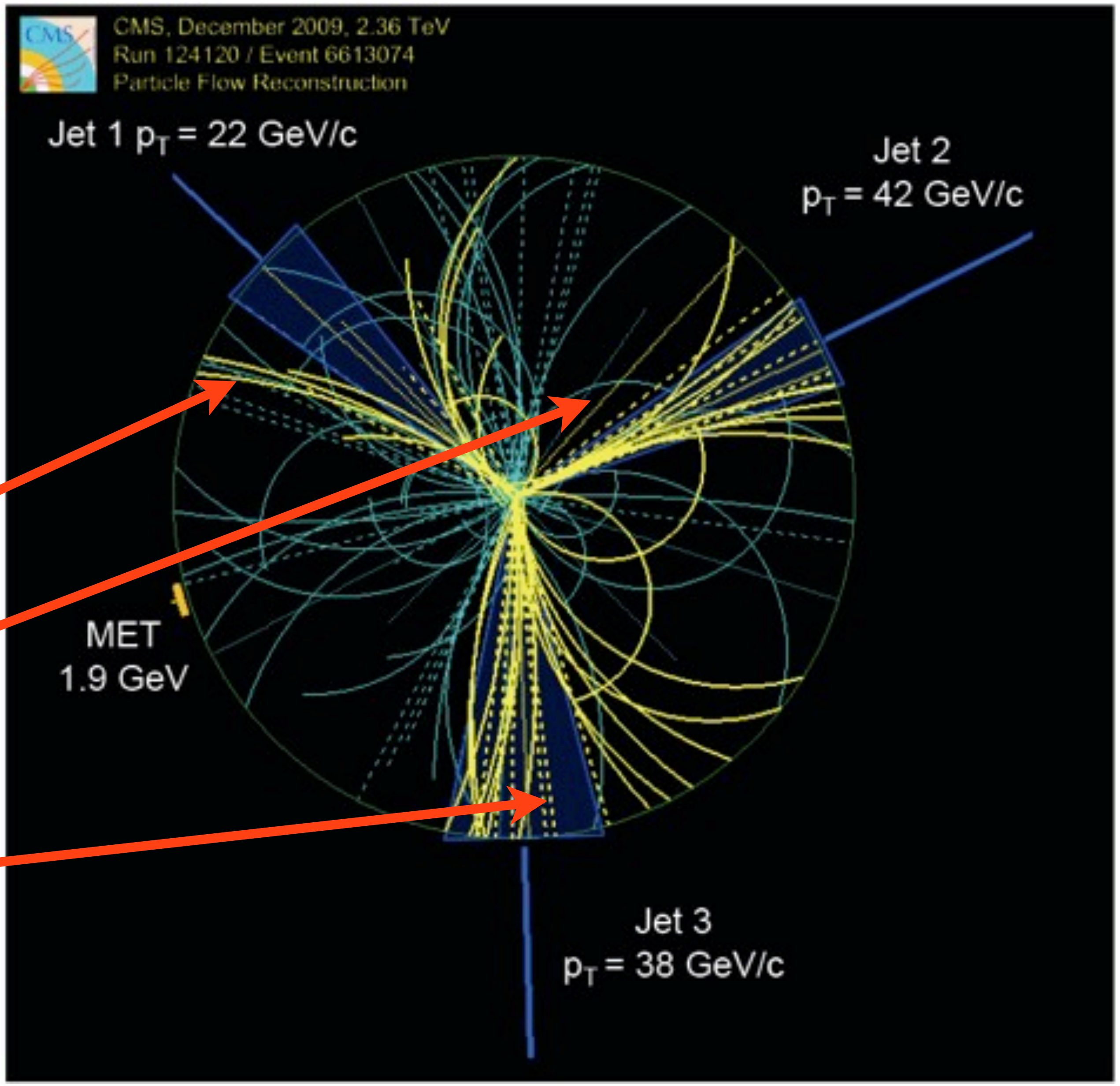


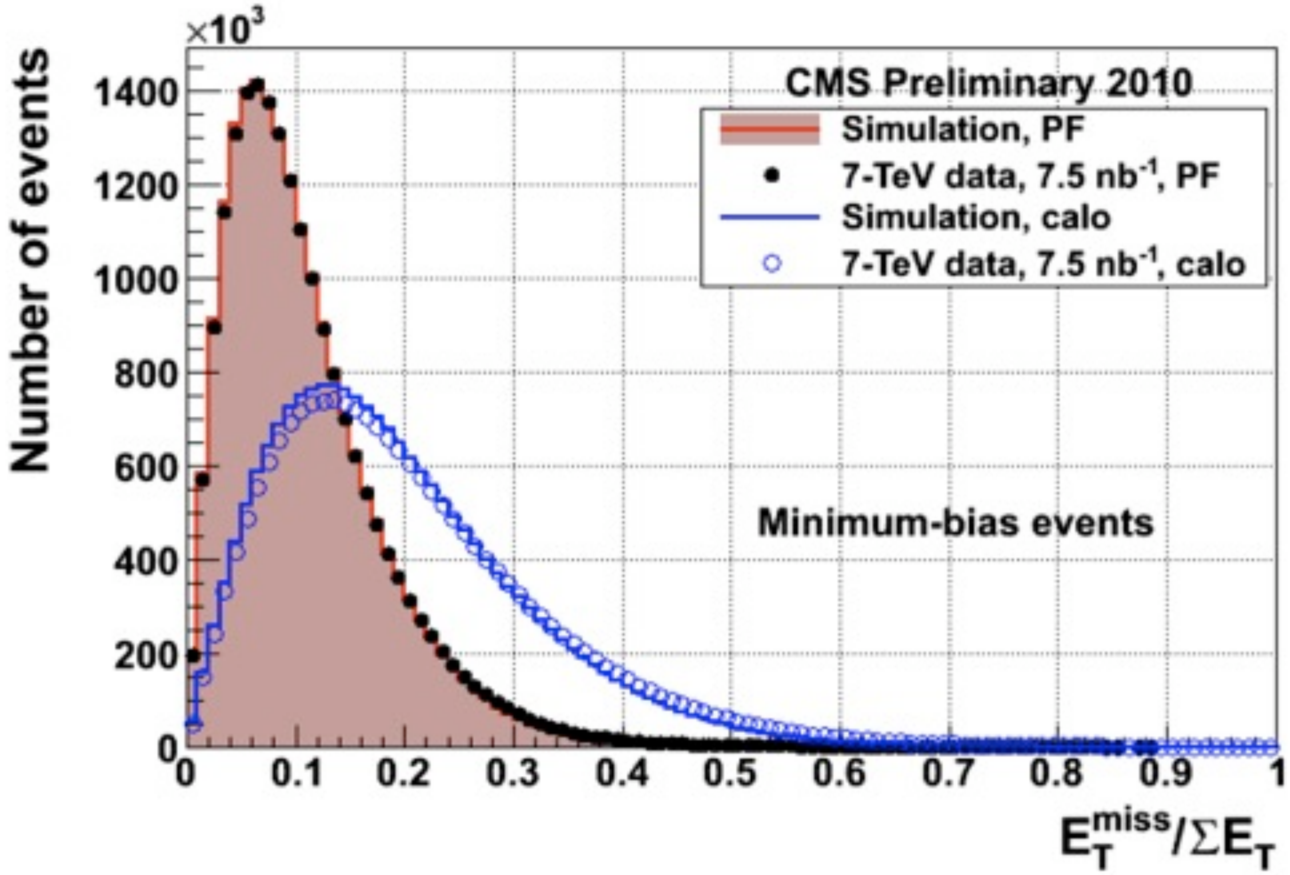

charged hadron

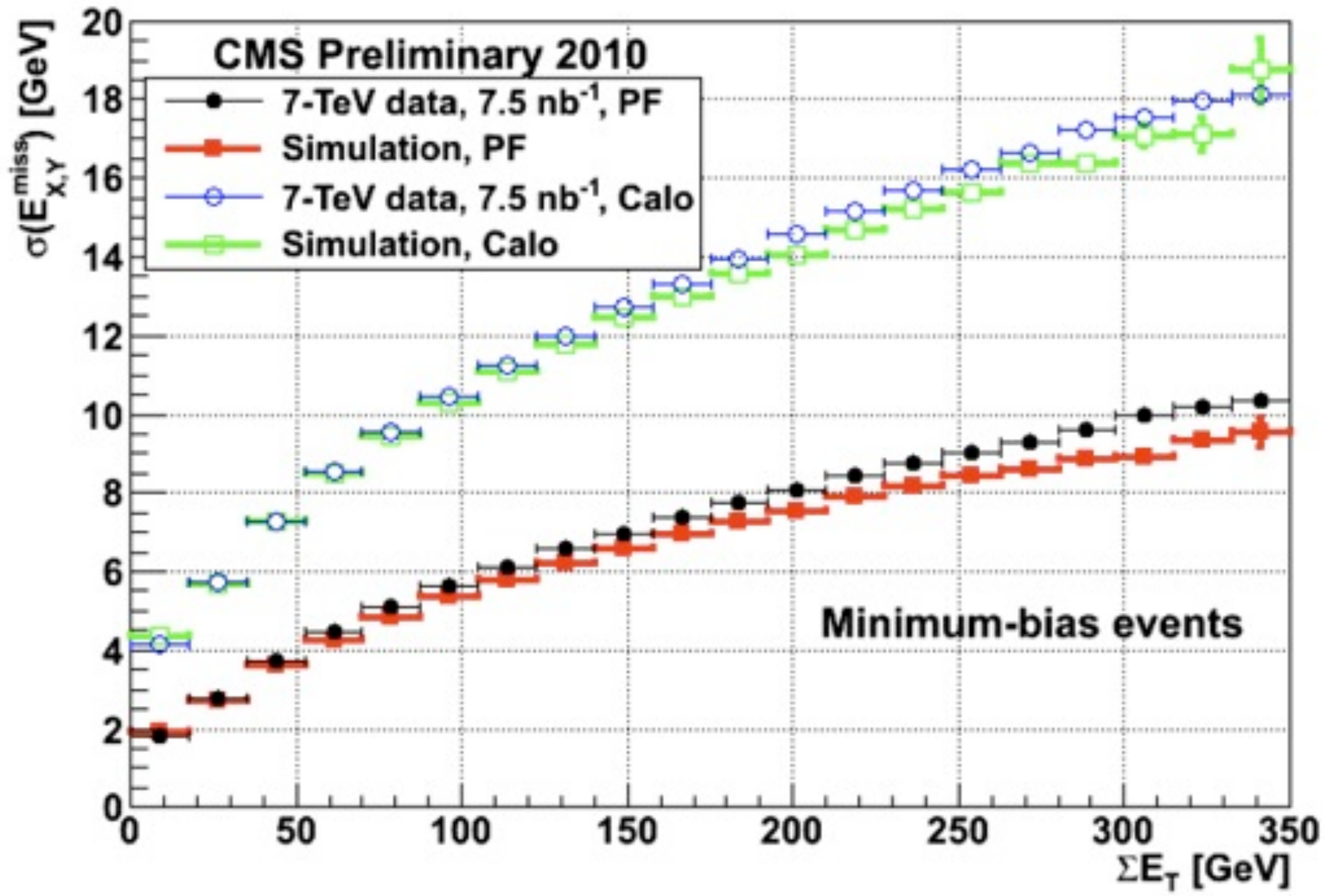
neutral hadron

photon

# CMS Particle Flow Performance

- Factor of 2 improvement for missing $E_T$ reconstruction with PF

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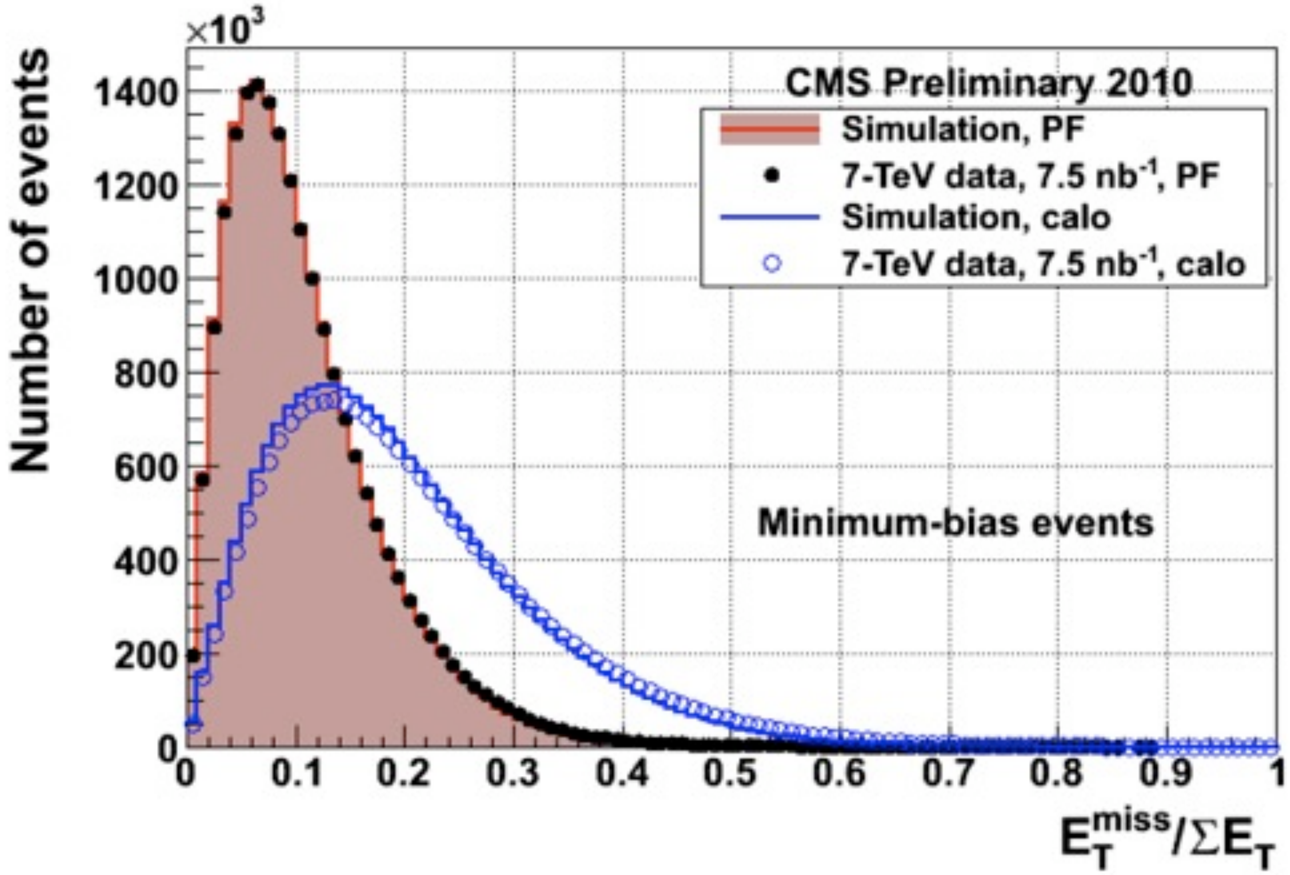


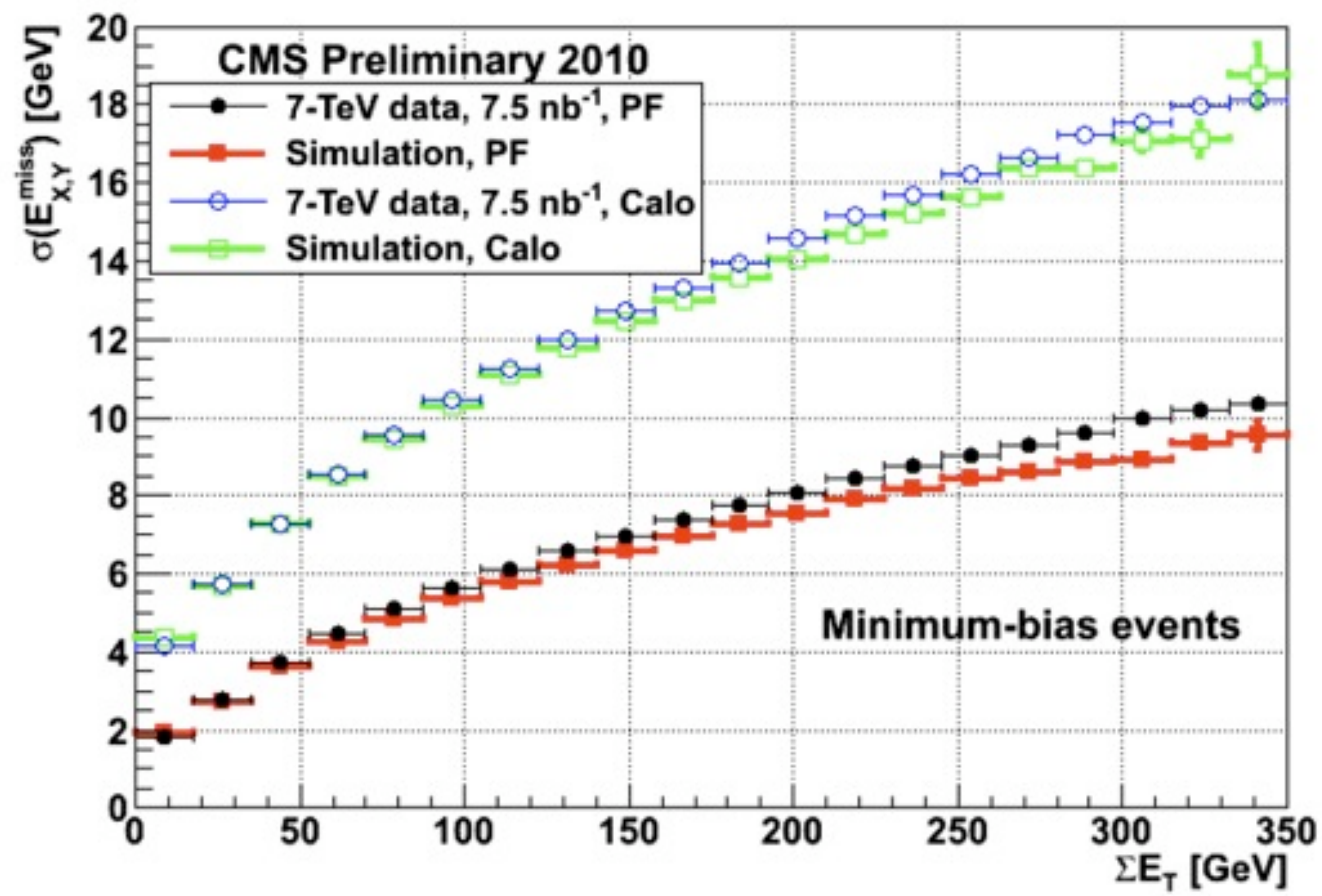


- Stochastic term between 50% and 60% (ATLAS: 51%)

➡ Particle Flow is a powerful technique: Proven to work at CMS (with a detector not designed for this technology)...
... imagine what it can do with a detector designed with Particle Flow in mind!

# Conclusion

- Calorimetry plays a crucial role in high energy collider physics
- One particular application: Missing transverse energy
  - Invisible particles can be detected by a mismatch in the energy balance of the event:
    - Signature for the creation of possible dark matter particles
    - Also: Neutrinos, for example in Top-quark production
  - Important: Good resolution, hermetic coverage, excellent detector understanding
- Particle Flow reconstruction techniques try to make optimal use of information from all detector systems
  - Experiments at future colliders designed for PFA
  - Spectacular performance also at LHC (CMS)