# Important CMS Upgrade: Particle-Flow Event Reconstruction

Colin Bernet
(LLR, École Polytechnique/CNRS),

for the CMS collaboration.

What is particle flow?

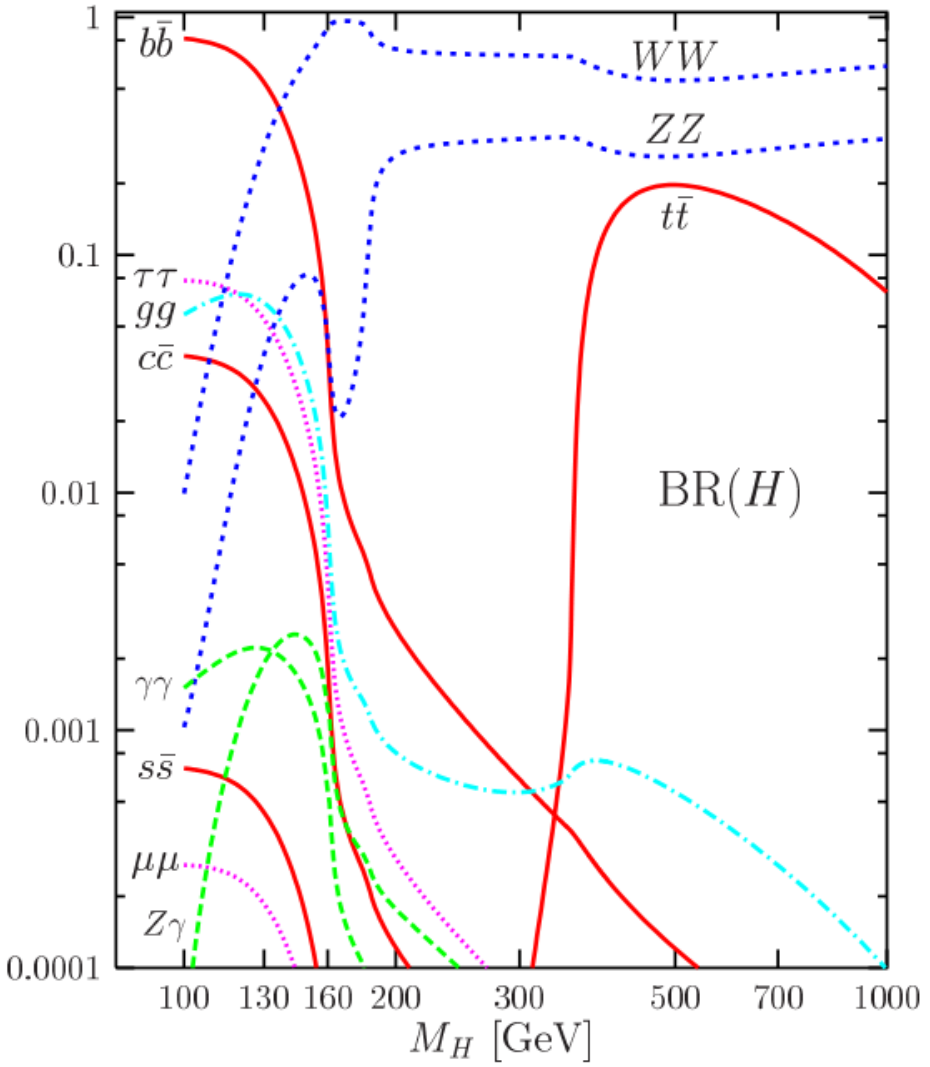
How does it work?

How well does it perform?

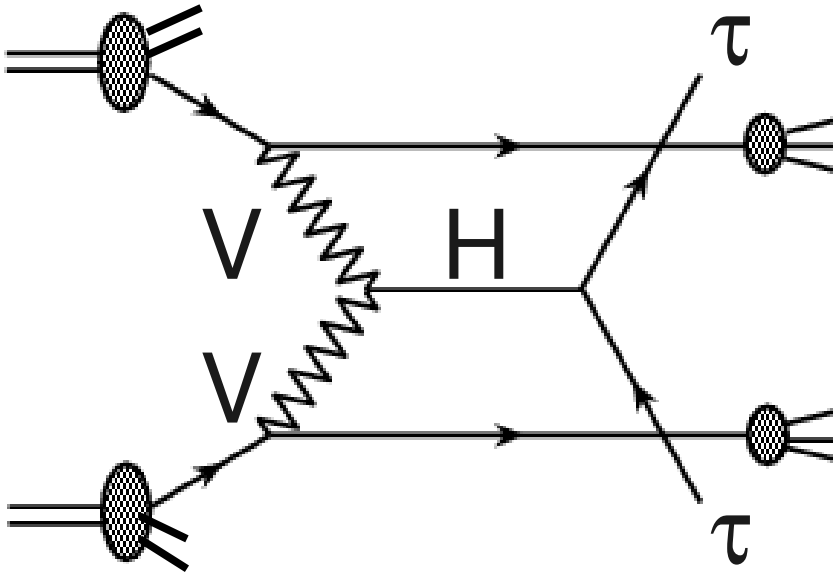
# Example analysis

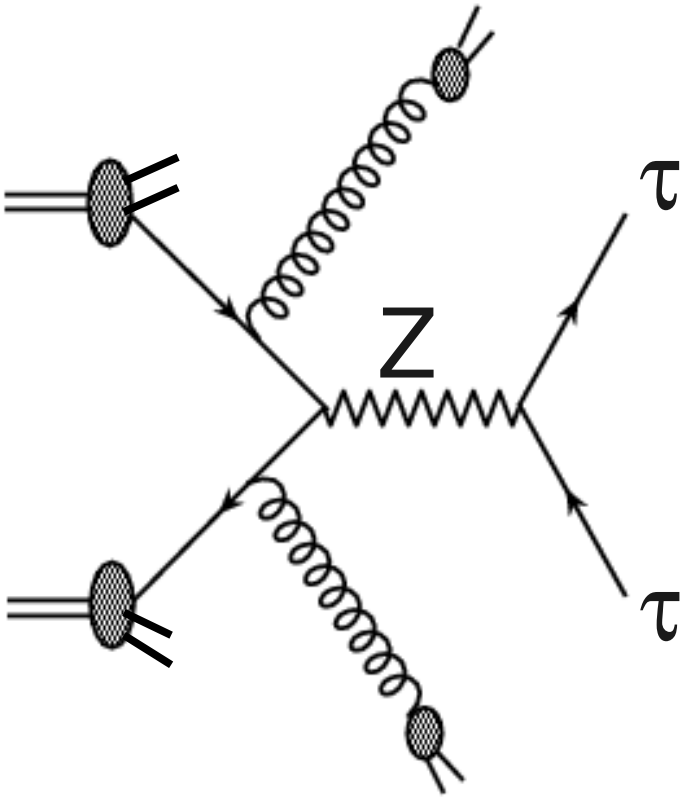
- Search for H → τ τ
- τ's have a fairly high mass
  - Sizeable branching ratio for a low mass SM Higgs
- They are leptons
  - Can be reasonably well identified w/r to jets

    → Get rid of most of the QCD background
  - Main remaining irreducible background:
    - Z → τ τ



# Vector-boson fusion production

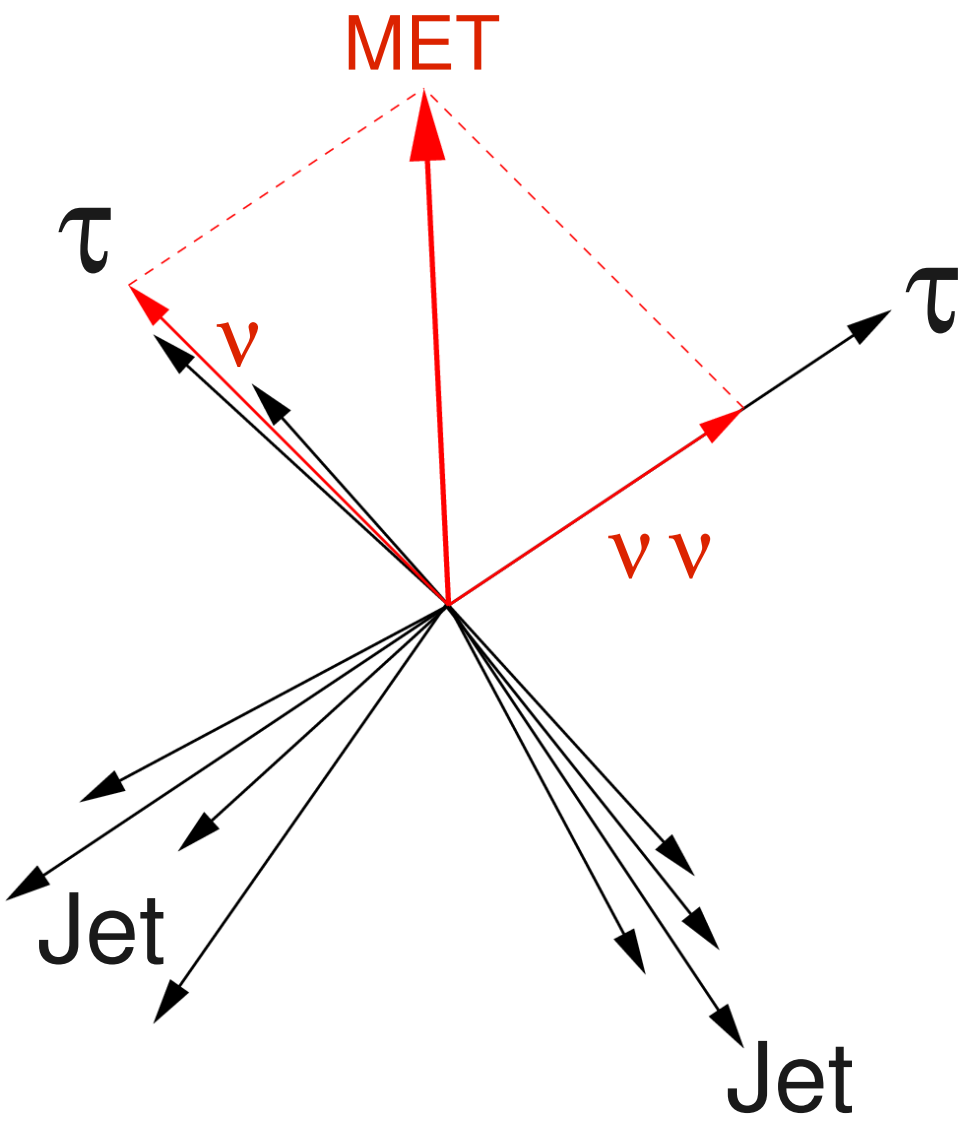


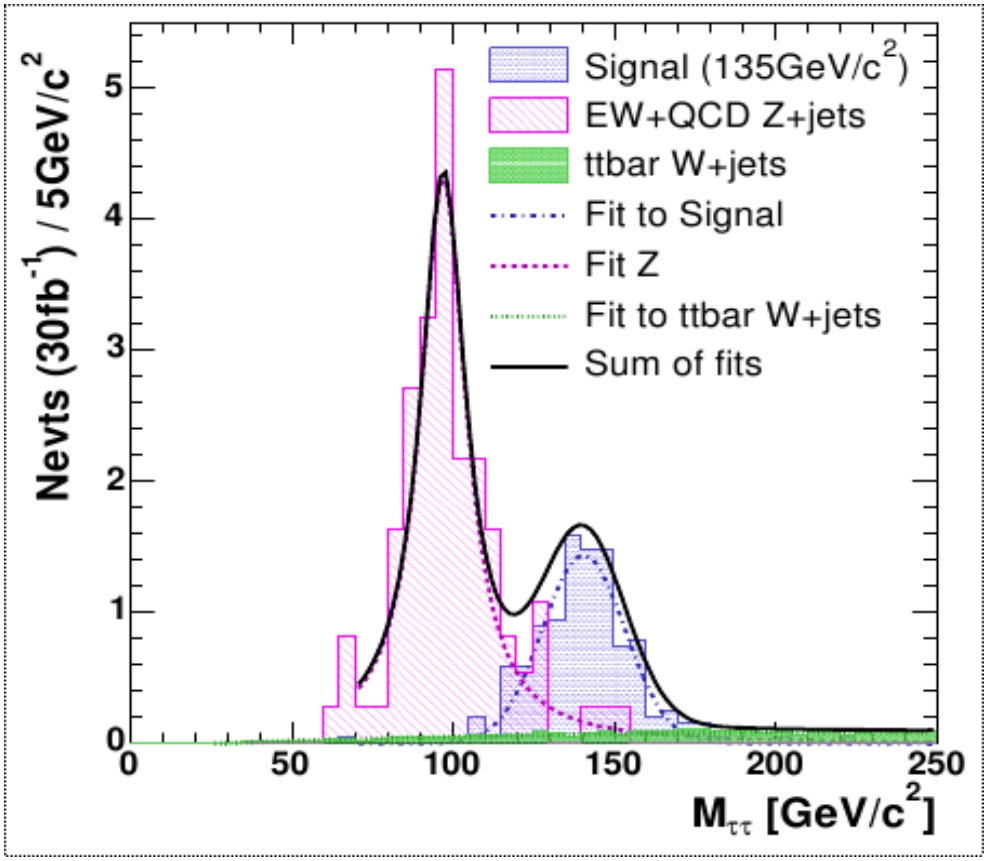




- Signal: no colour exchange between the 2 protons
- Rapidity gap between the 2 jets

- Main irreducible background: QCD $Z \rightarrow \tau\,\tau$
- No rapidity gap between the 2 jets

# Di-τ mass reconstruction



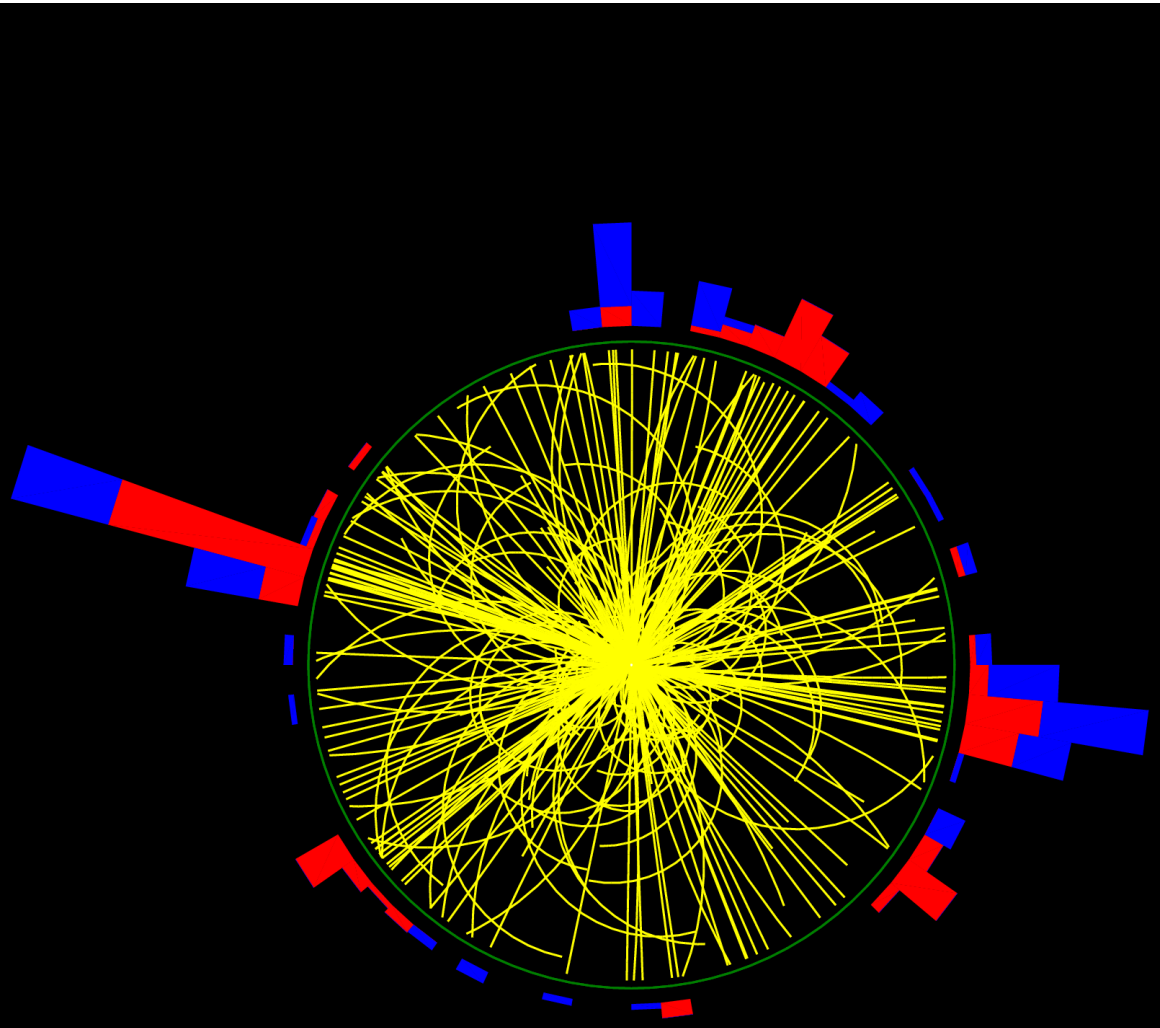




- Crucial to have a good resolution on the MET and on the visible decay products of the τ's
  - both in energy and angle

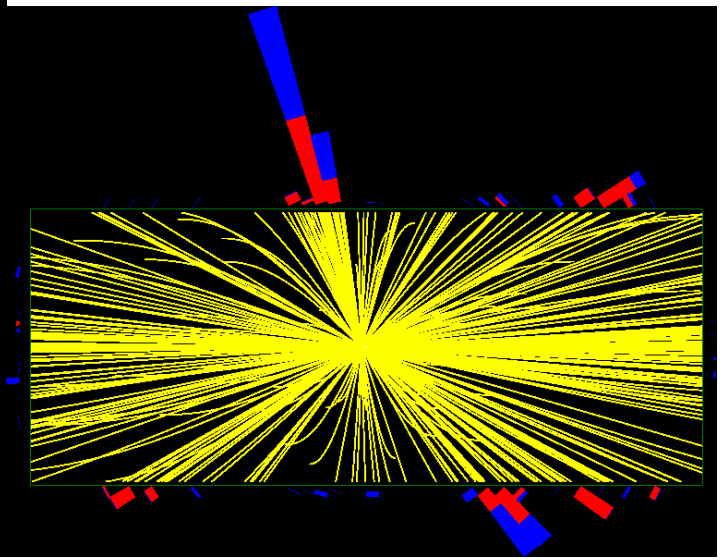
# Shopping list

- For a good $H \rightarrow \tau\,\tau$ analysis, we need the following ingredients
  - A good MET resolution
  - A good $\tau$ reconstruction and identification
  - A good jet reconstruction
- Many other analyses feature at least one of these ingredients
- Let us see what particle flow can do
  - Next slides:
    - what is particle flow?
    - why should it improve, e.g., jets?

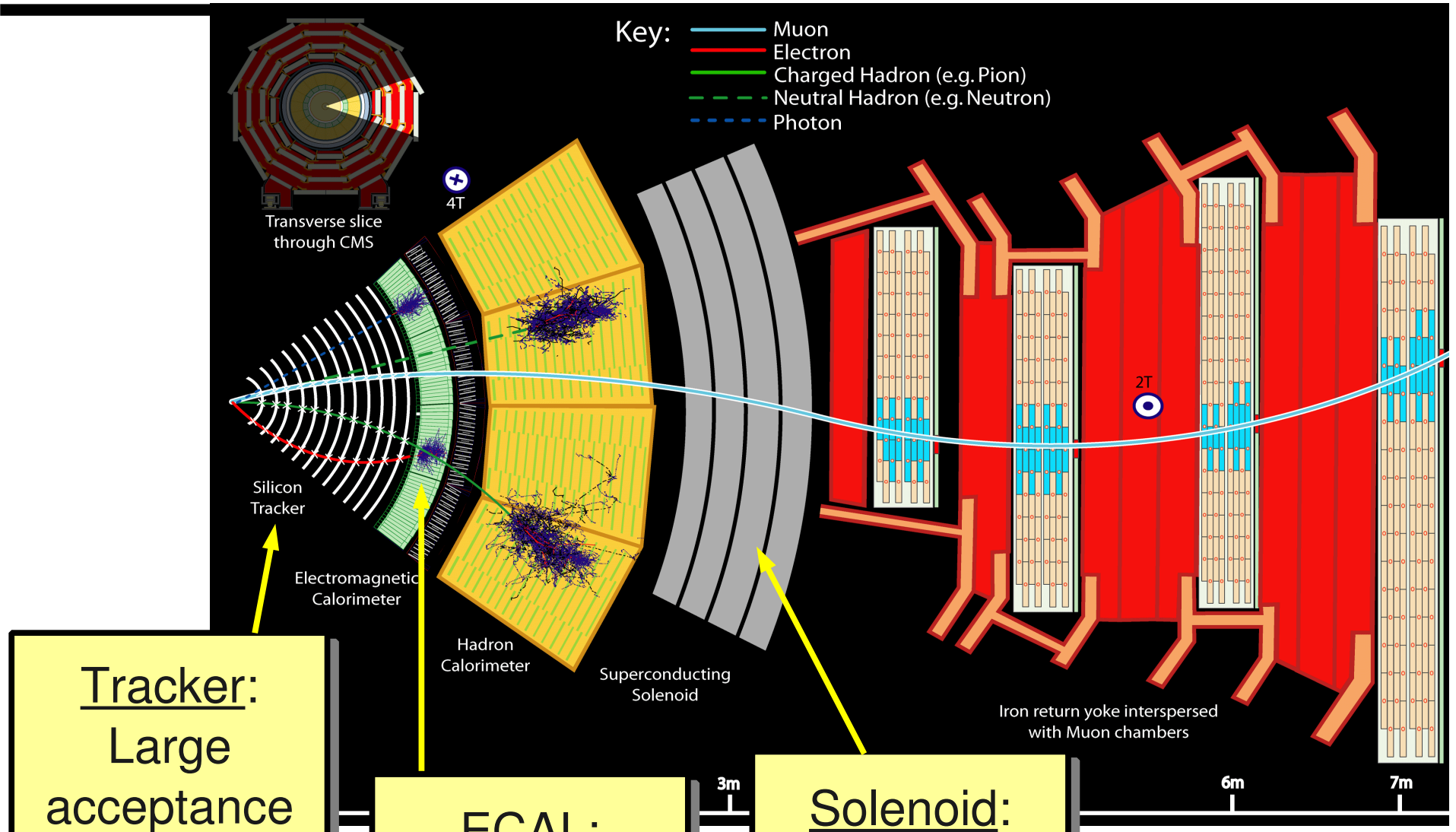
# What is particle flow?



- "Simply" an attempt to reconstruct all particles in the event.
- From these particles, *higher level Physics objects* (Jets, MET, ...)
- Analysis



# The CMS experiment

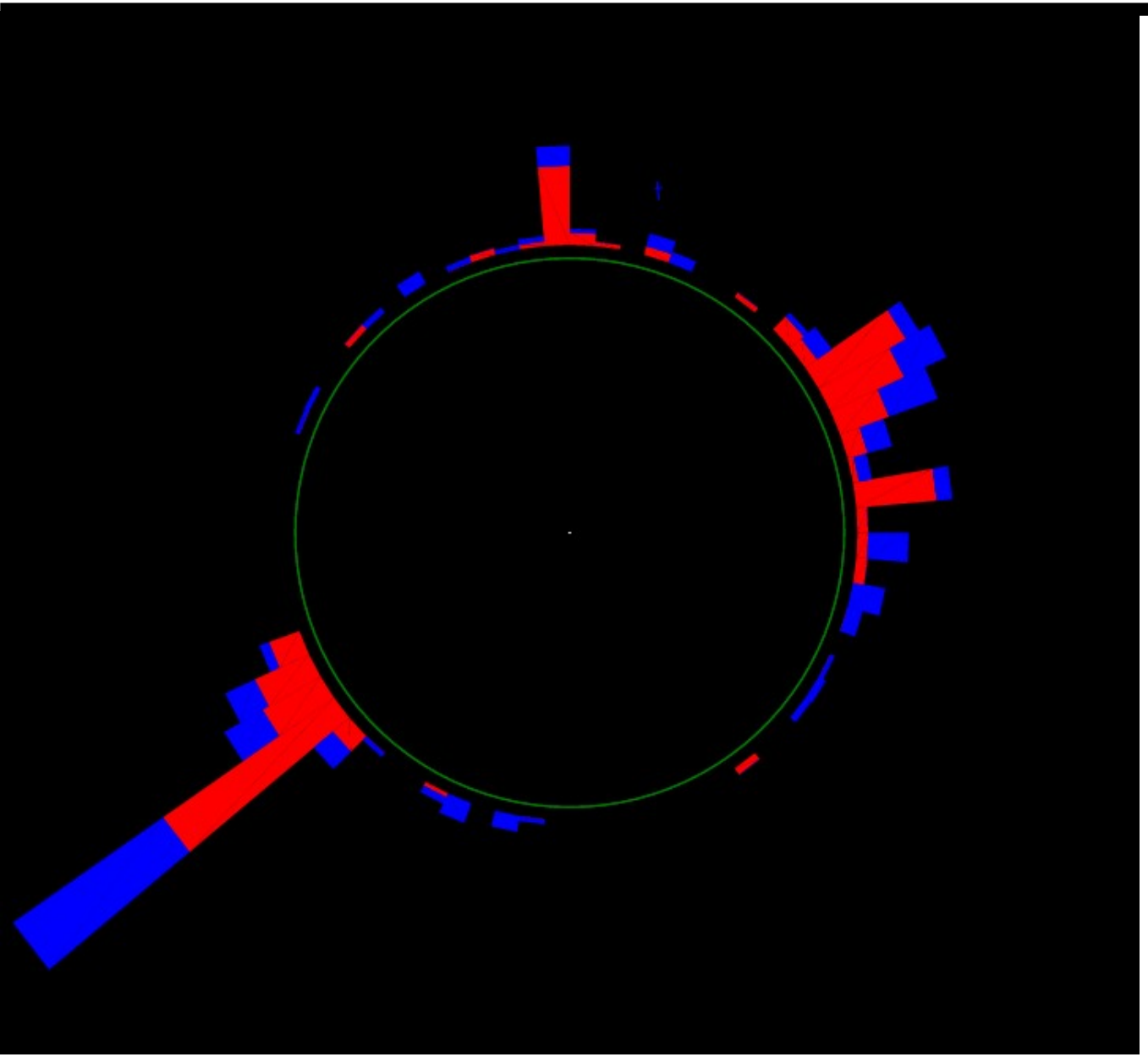



**Tracker**: Large acceptance and efficiency

**ECAL**: Good granularity

**Solenoid**: Large field

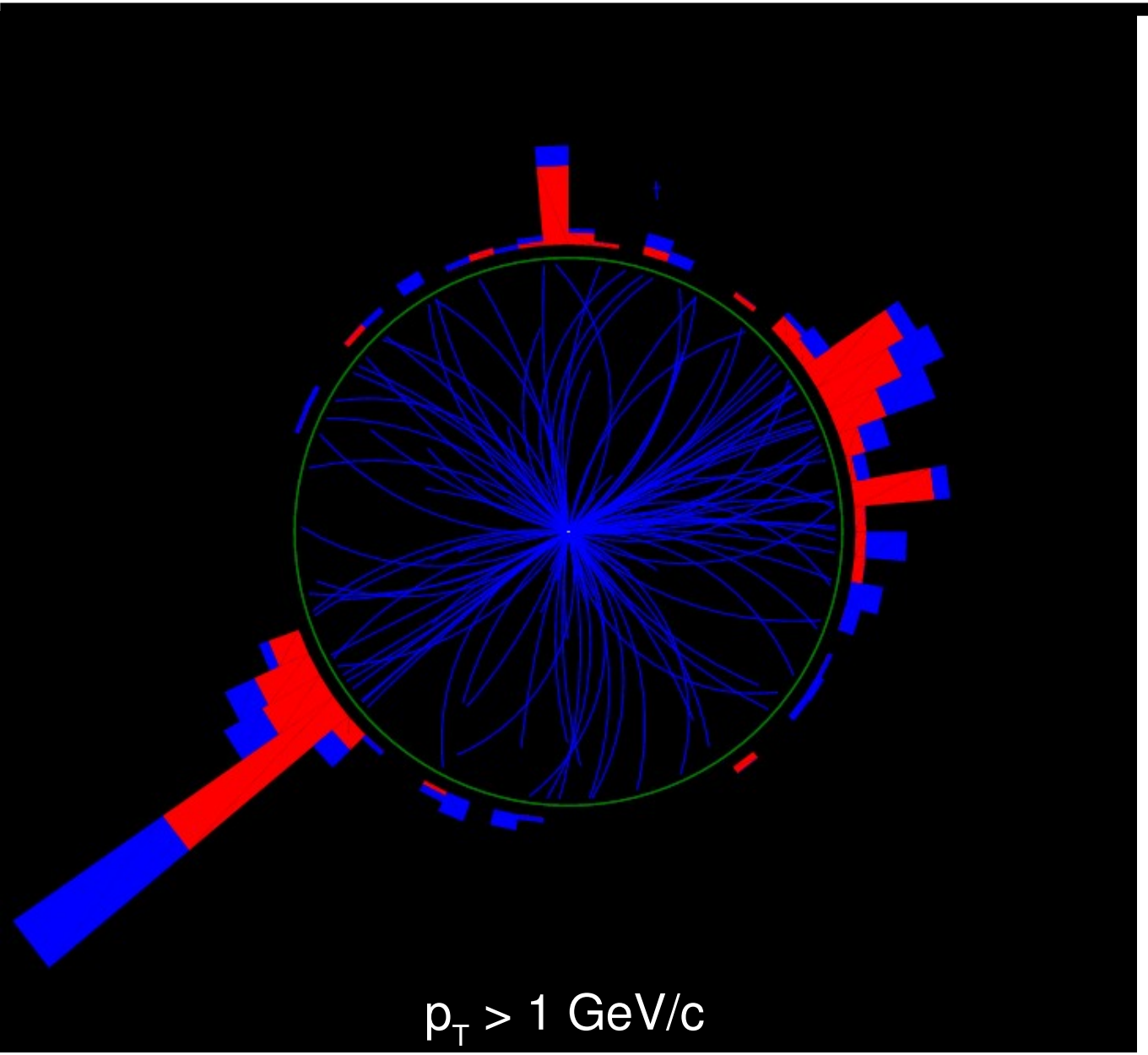
# Traditional, calorimeter jets



- CaloTower:
  - 1 HCAL tower
  - 25 ECAL crystals underneath
- Iterative cone algorithm
- Loosing ECAL granularity
- Jet energy corrections needed
- Resolution of HCAL:

$$\frac{\sigma}{E} \sim \frac{100\%}{\sqrt{E}}$$

# Traditional, calorimeter jets

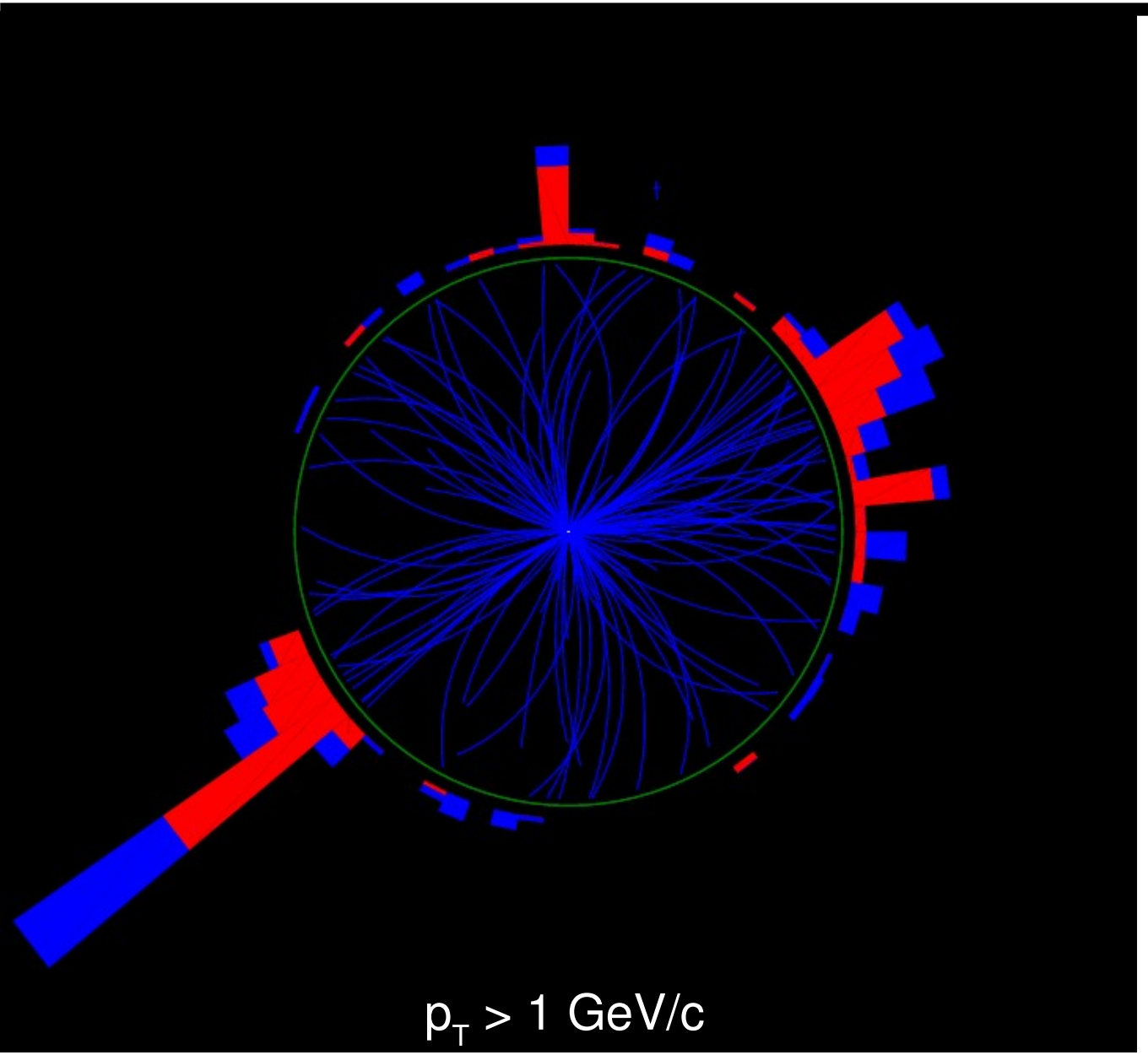



- CaloTower:
  - 1 HCAL tower
  - 25 ECAL crystals underneath
- Iterative cone algorithm
- Loosing ECAL granularity
- Jet energy corrections needed
- Resolution of HCAL:

$$\frac{\sigma}{E} \sim \frac{100\%}{\sqrt{E}}$$

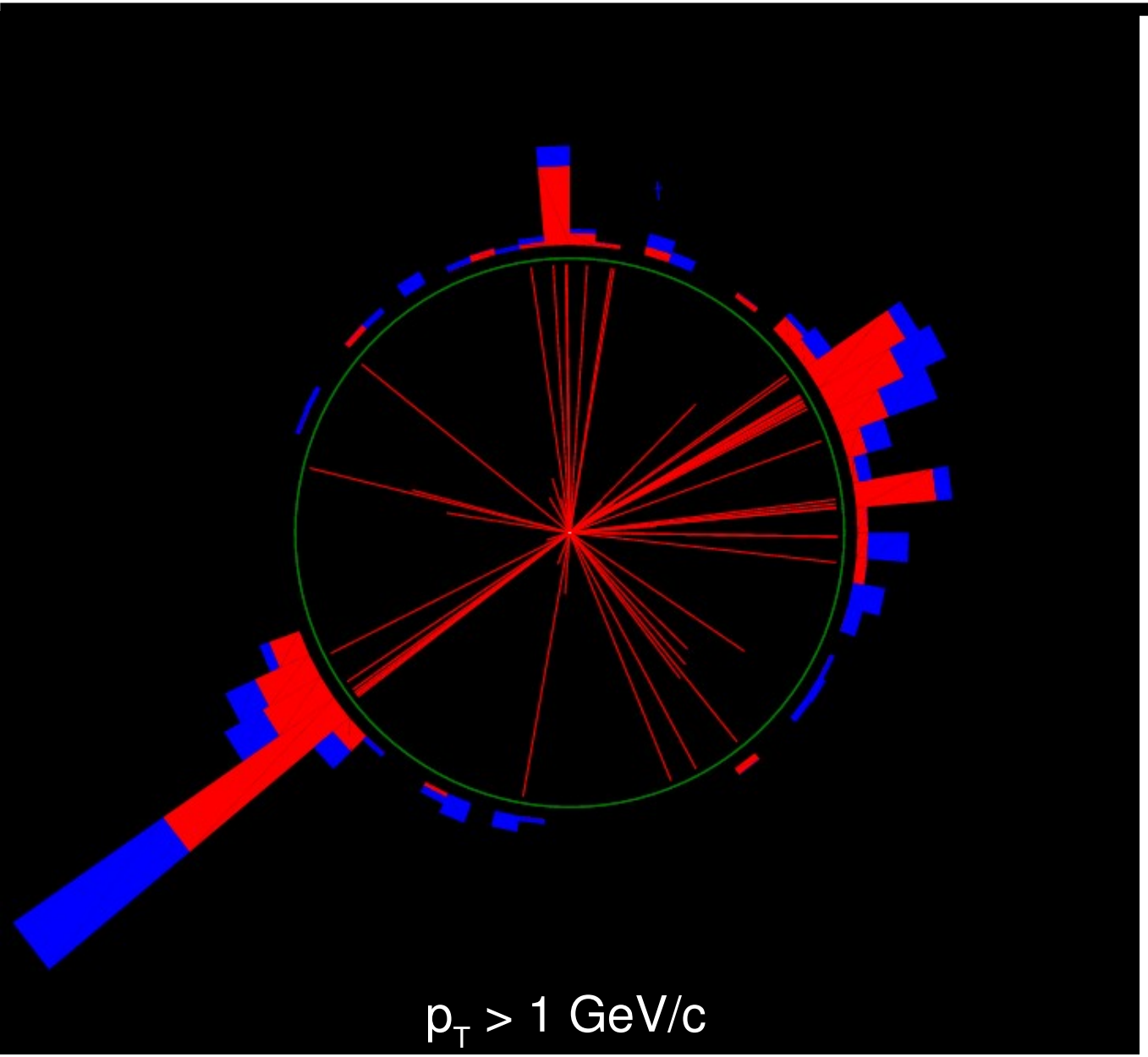
- Charged hadrons spread by the field
  - degradation of the angular resolution

# Jets of particles



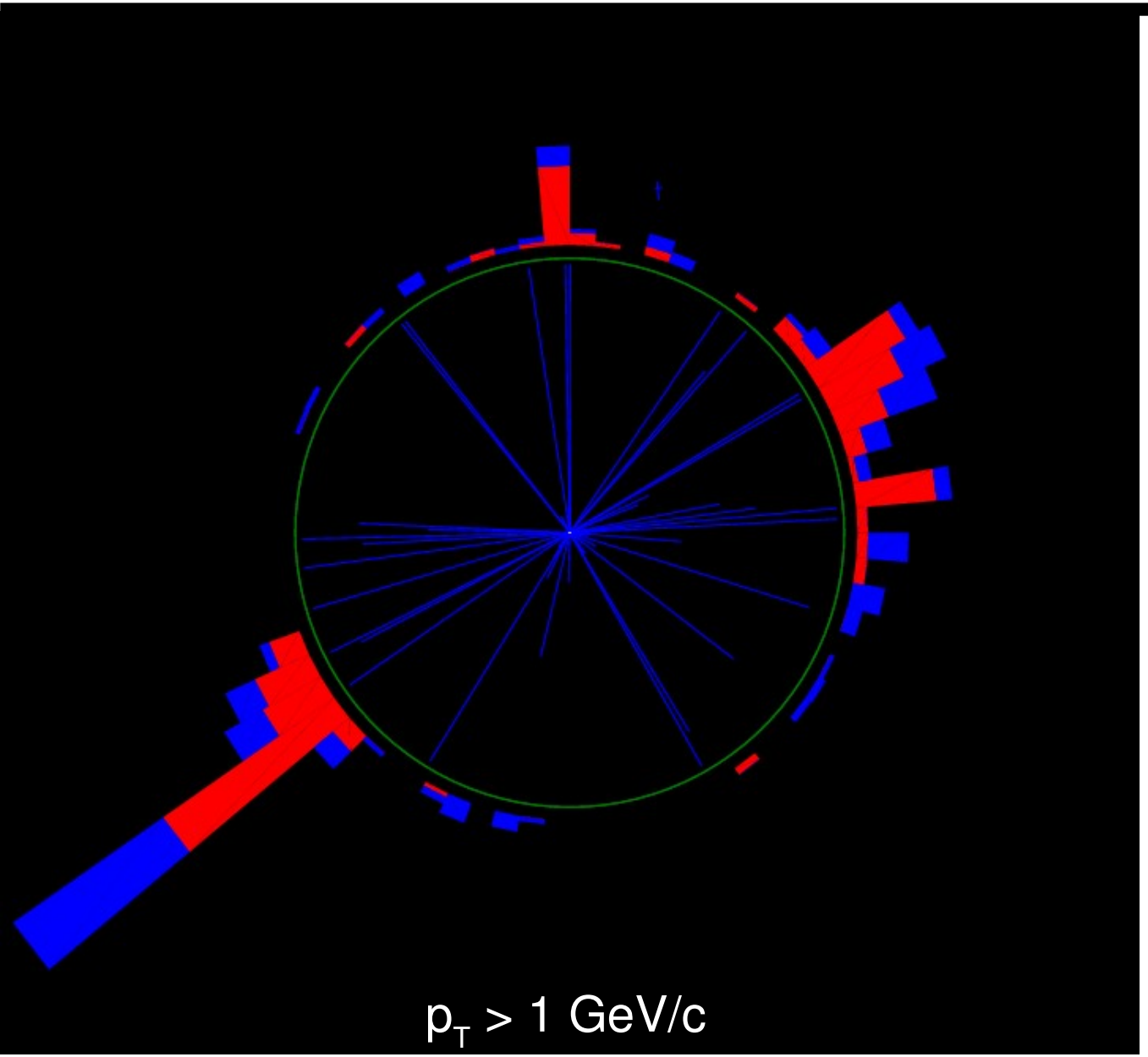

- reconstructed or generated
- Same Iterative cone algorithm
- Charged hadrons
  - 65% of jet E
  - direction at vertex
  - resolution tracker

# Jets of particles




- reconstructed or generated
- Same Iterative cone algorithm
- Charged hadrons
  - 65% of jet E
  - direction at vertex
  - resolution tracker
- + Photons
  - 25% of jet E
  - resolution ECAL

# Jets of particles




- reconstructed or generated
- Same Iterative cone algorithm
- Charged hadrons
  - 65% of jet E
  - direction at vertex
  - resolution tracker
- + Photons
  - 25% of jet E
  - resolution ECAL
- + Neutral hadrons
  - 10% of jet E
  - resolution HCAL

# What is to be expected?

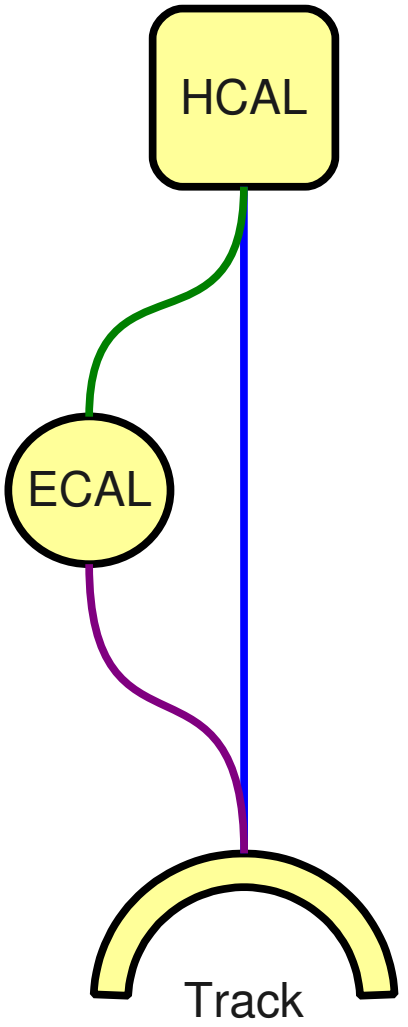
- Improvements in the reconstruction of jets, MET, taus
  - Energy and direction
- Historical example: ALEPH
  - Particle flow was used everywhere, with great success
- Historical example: All experiments on hadron colliders
  - It never worked...
- In CMS, the work started three and a half years ago
  - Did we manage??

# The Particle Flow Algorithm

# Overview

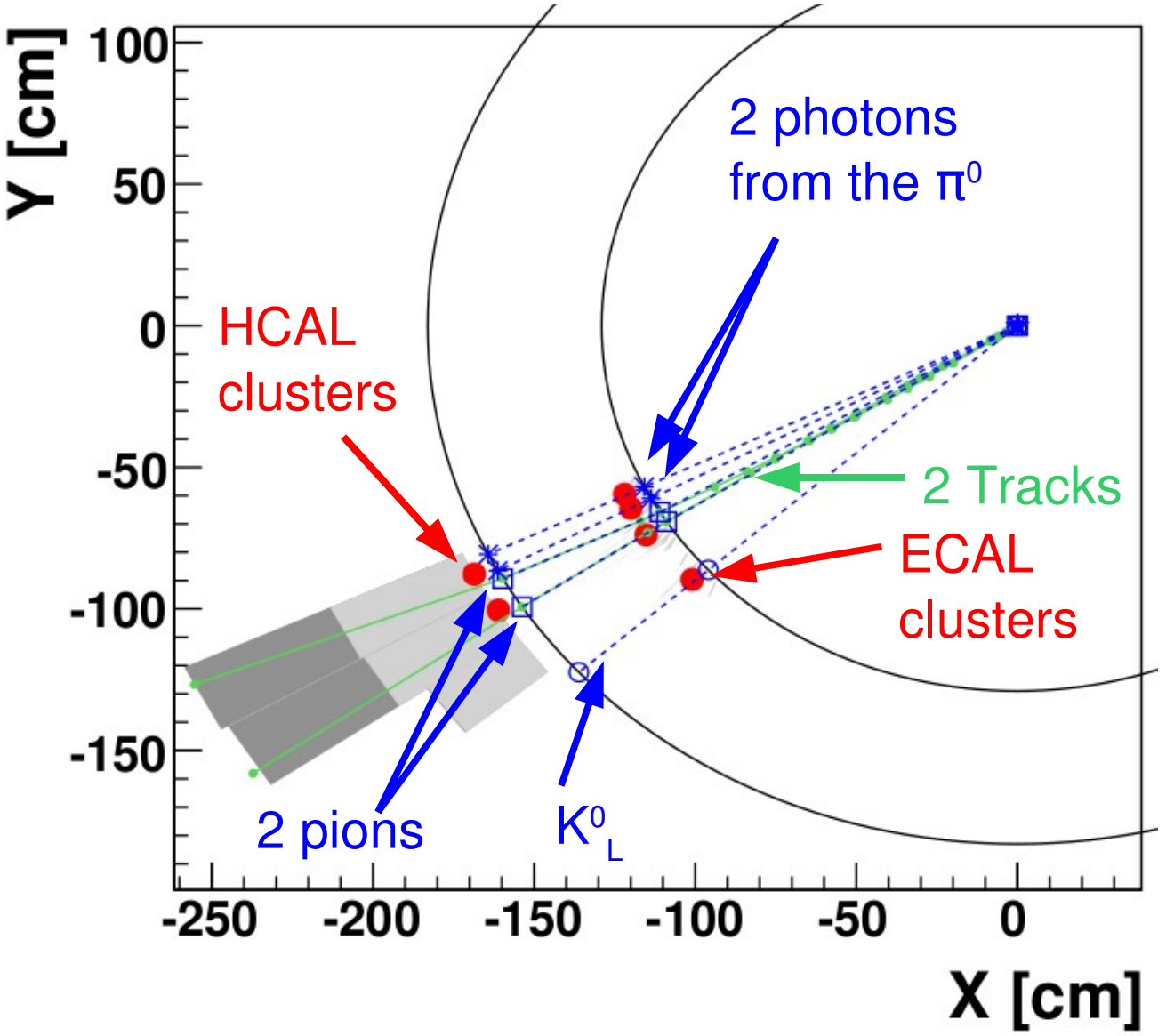
- Reconstruct *elements*
  - Tracks, clusters, muon tracks
- Link them into *blocks*
  - example: 1 charged hadron

→ block: 1 track
1 ECAL cluster
1 HCAL cluster




- Interpret the blocks in terms of *particles*
  - Charged hadrons, photons, neutral hadrons, ...
- Reconstruct *higher level Physics objects*,
  - Jets, MET, Taus...
- Do the analysis

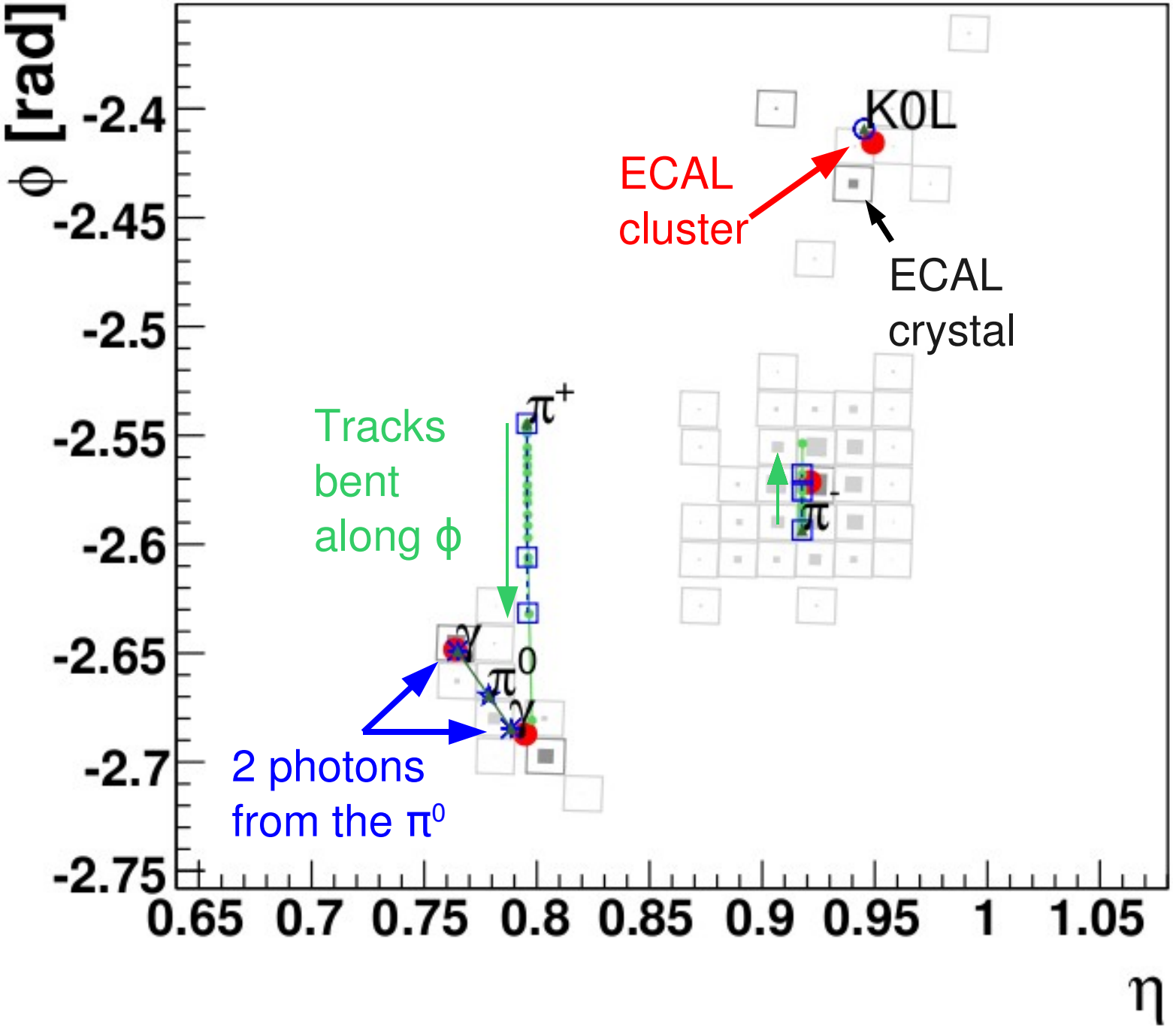
# Simple jet - (X,Y)



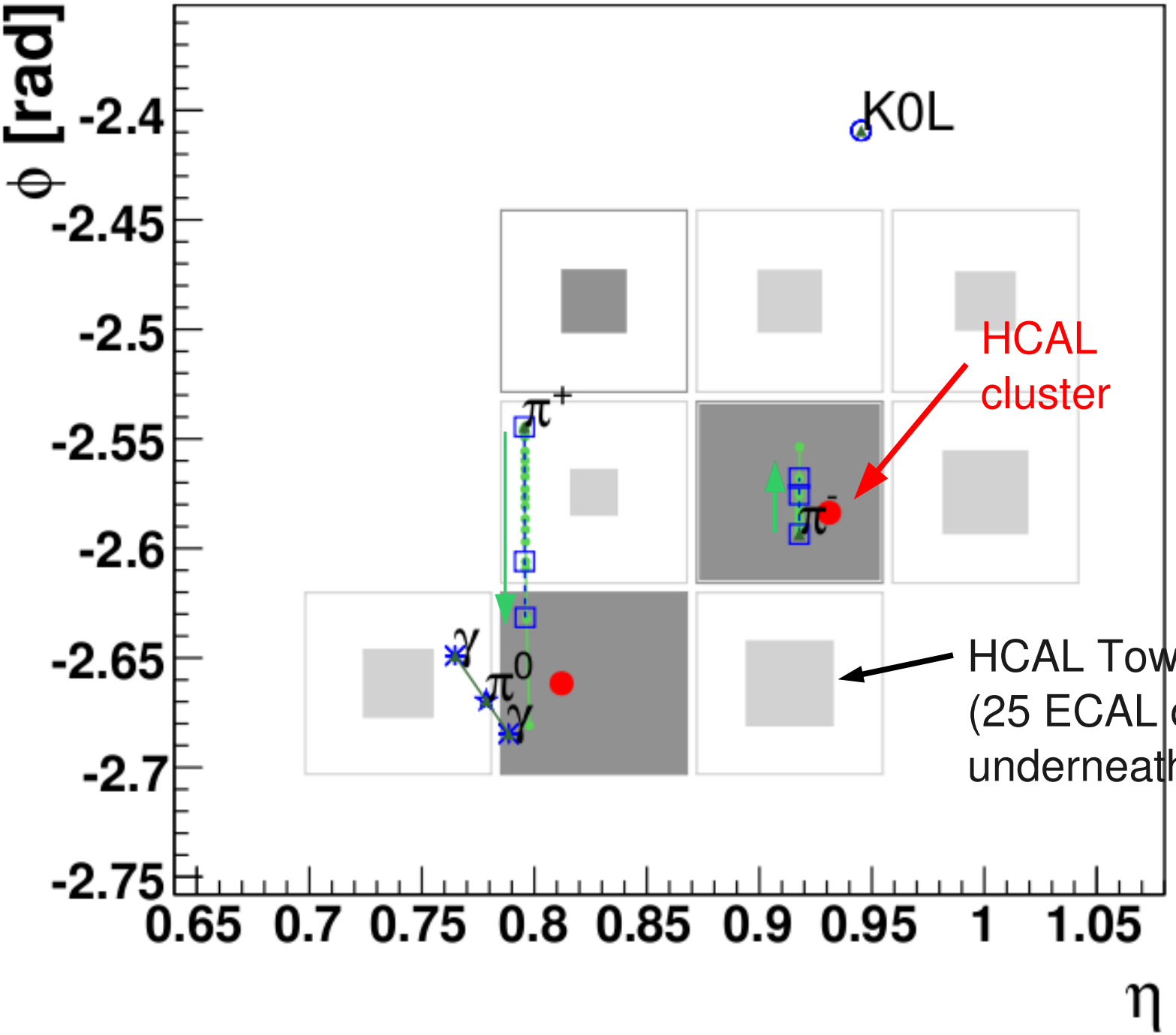

- Jet $p_T$ = 65 GeV/c
- 4 true particles:

$$(\pi^+, \pi^-, \pi^0, \mathrm{K}^0_\mathrm{L})$$

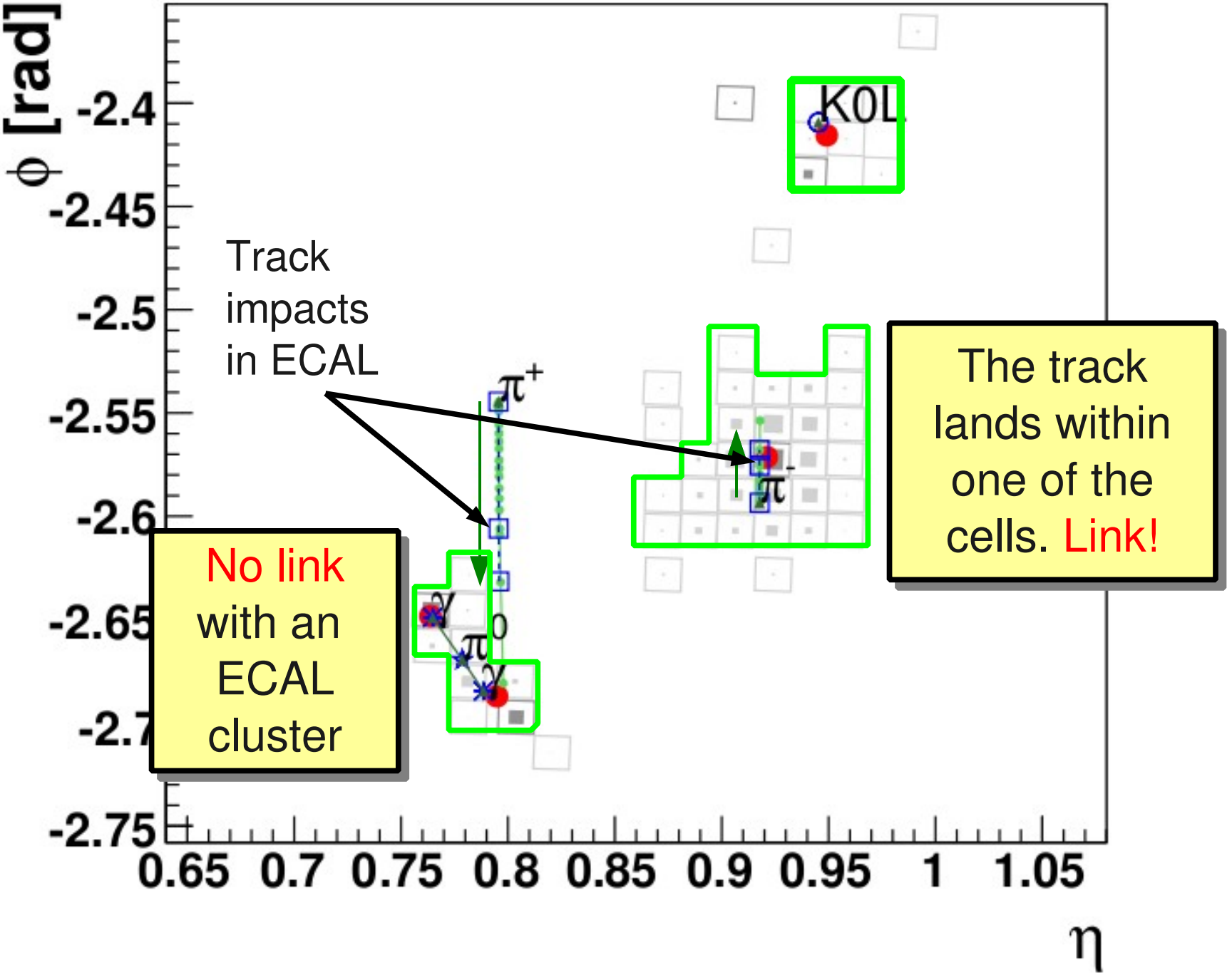
# Simple jet - (η,ϕ) - ECAL



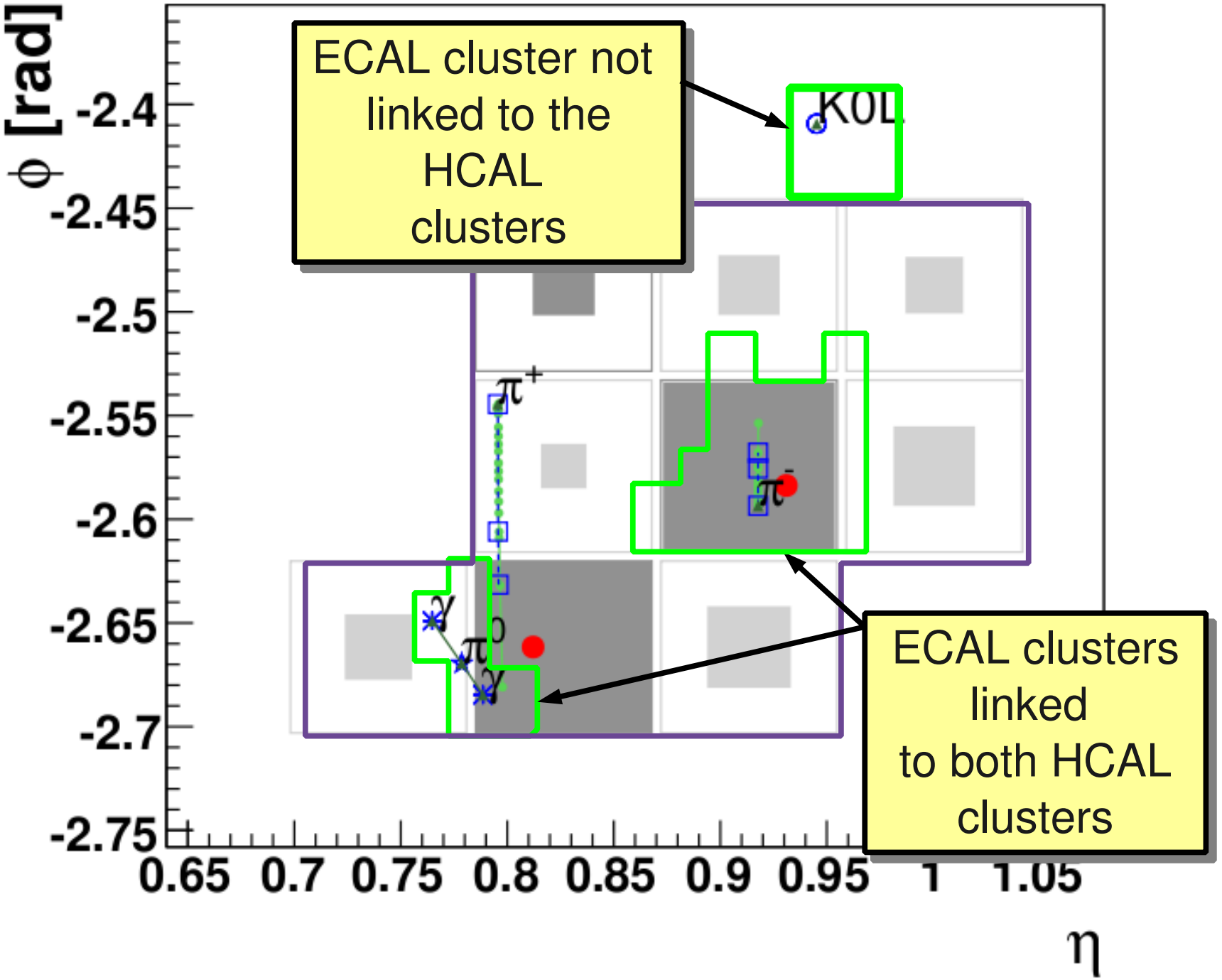
# Simple jet - (η,ϕ) - HCAL



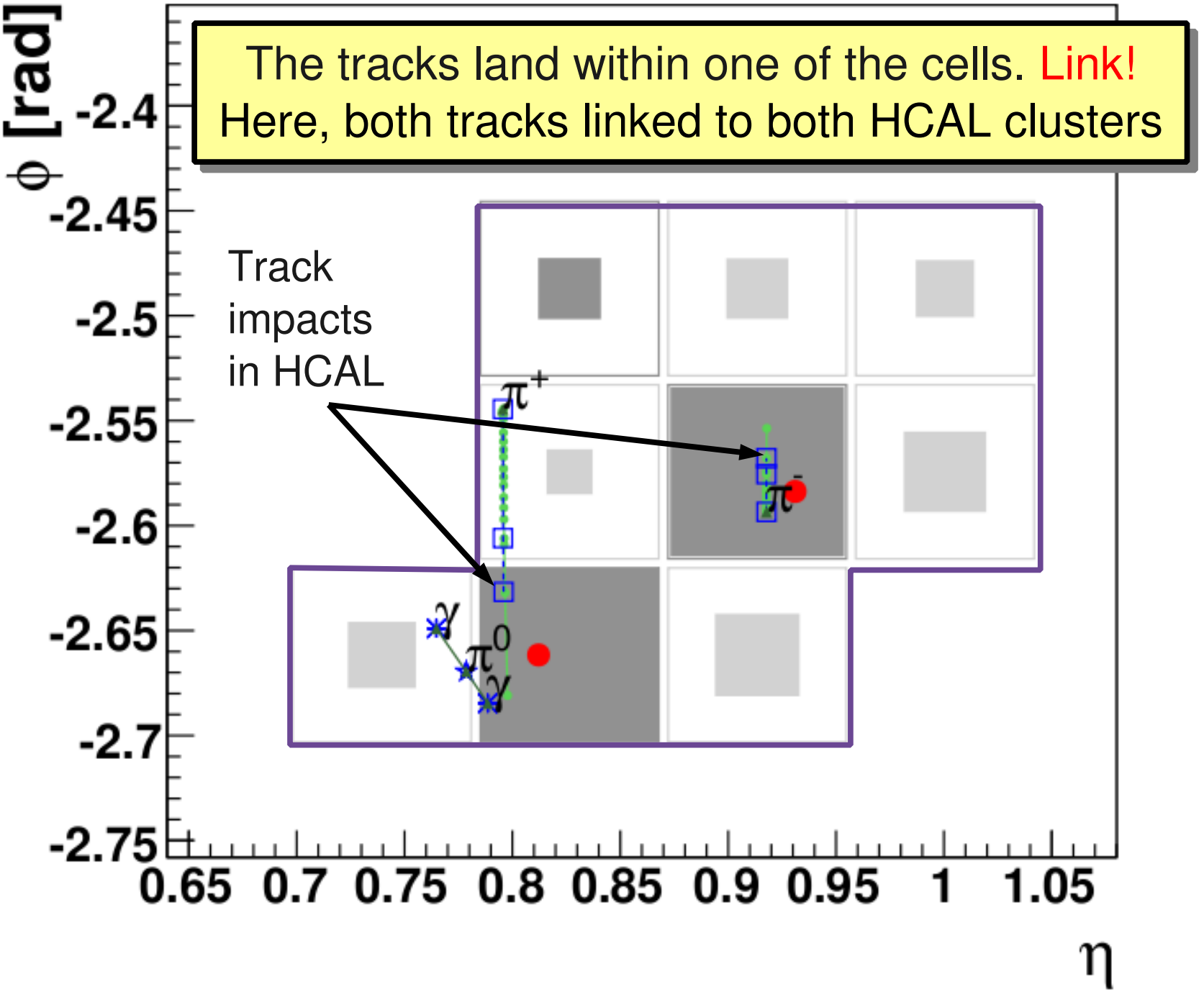
# Track-cluster link, ECAL



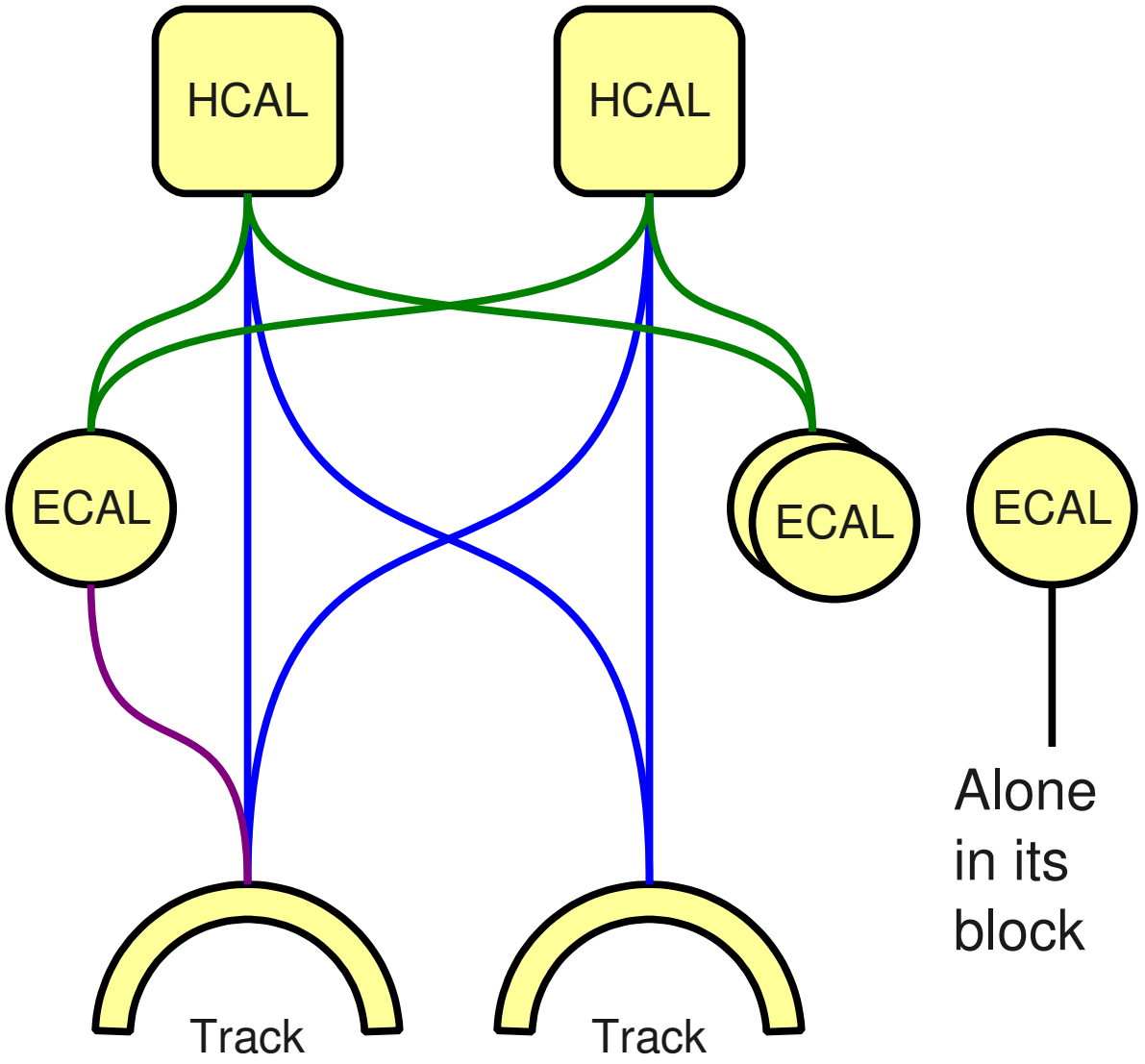
# ECAL-HCAL cluster link

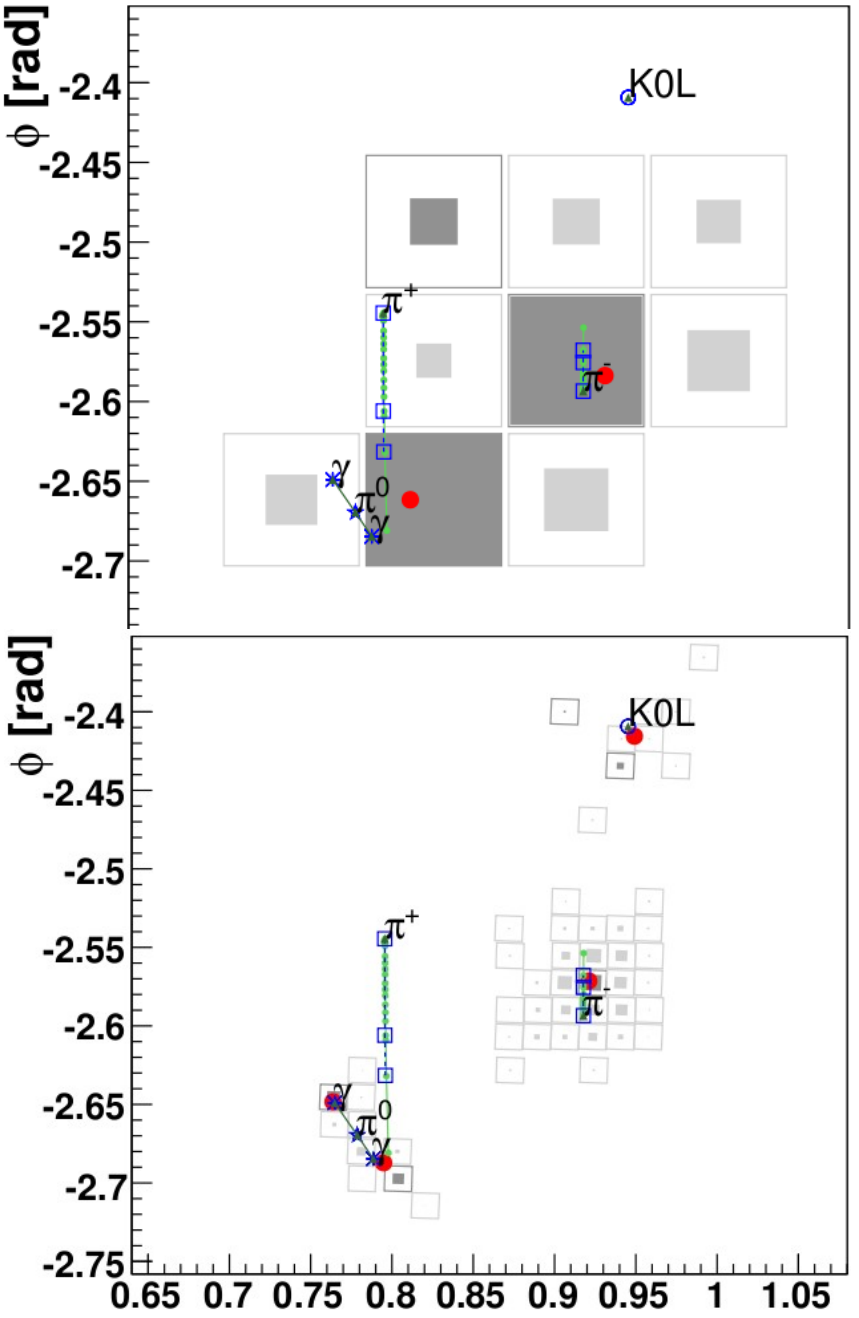


# Track-cluster link, HCAL



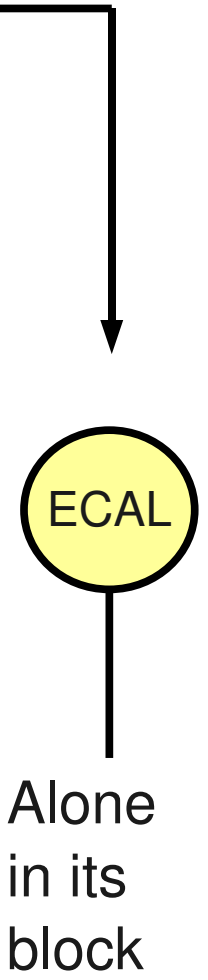
# Linking done → 2 blocks



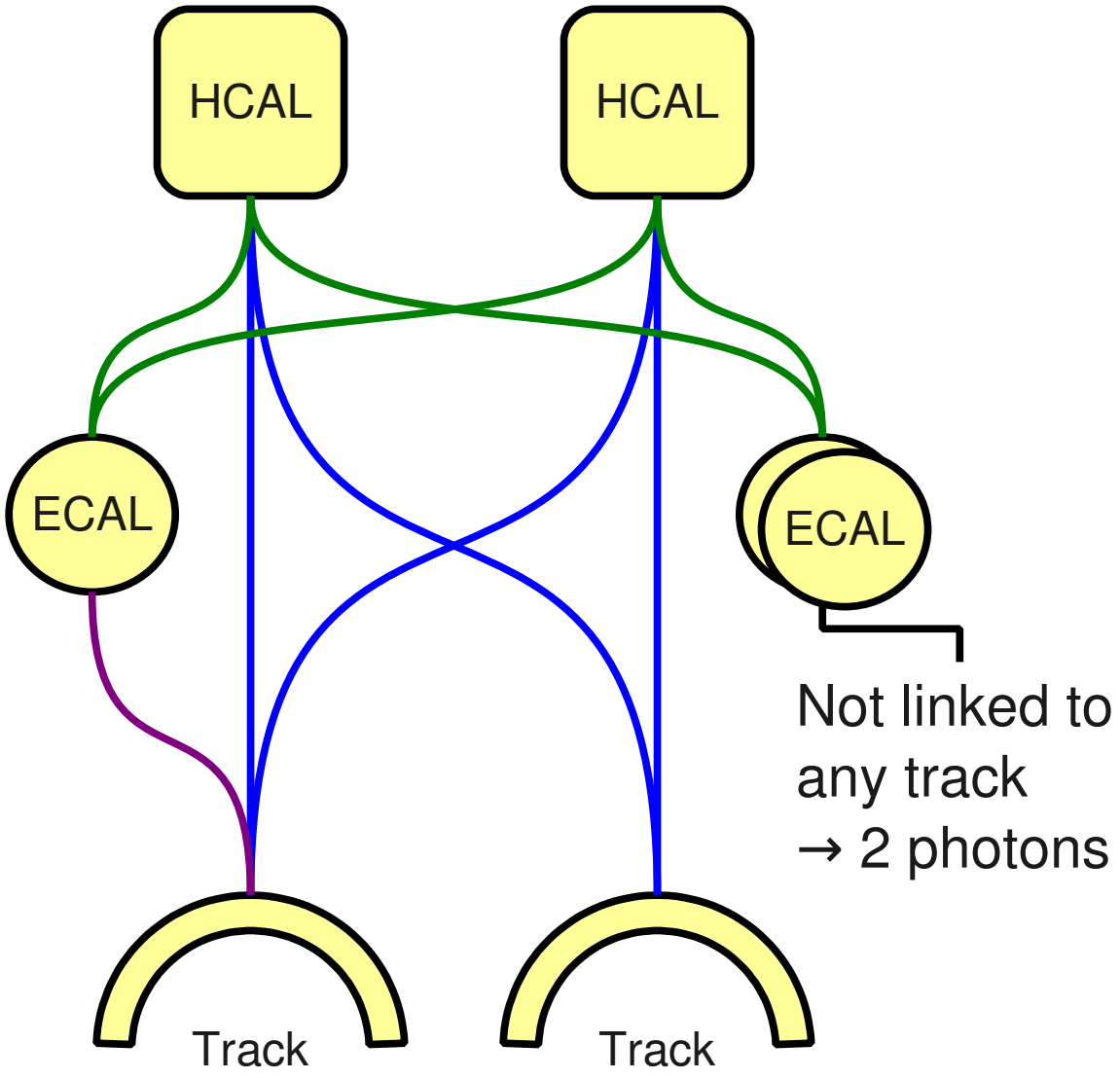



# Single elements

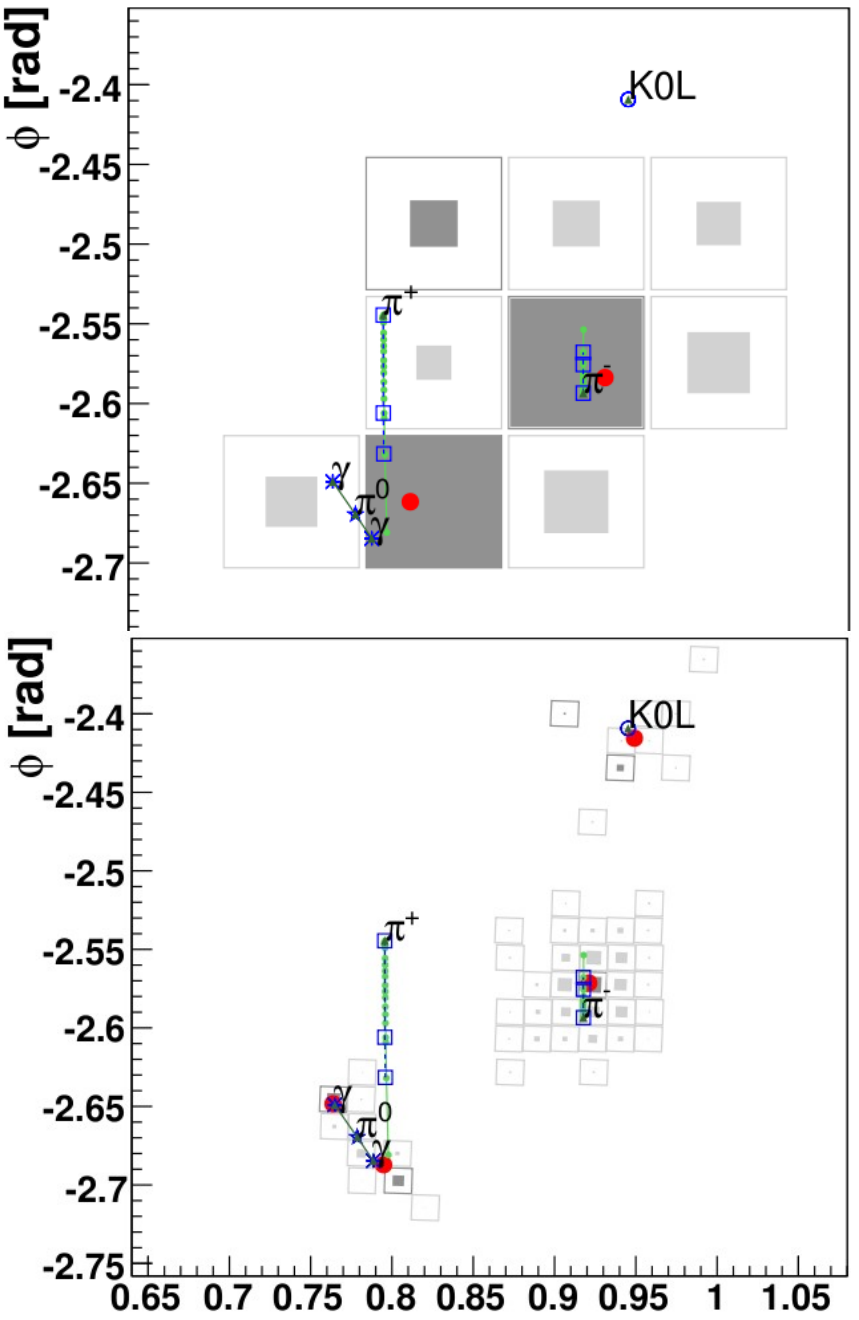
- Single ECAL
  → photon
  - residual, small "photon" calibration
- Single HCAL
  → neutral hadron
  - residual, "hadron" calibration
  - factor ~ 1.1
  - important for neutral hadrons only (10% of the jet energy)
- Single Track
  → charged hadron
  - pion mass hypothesis



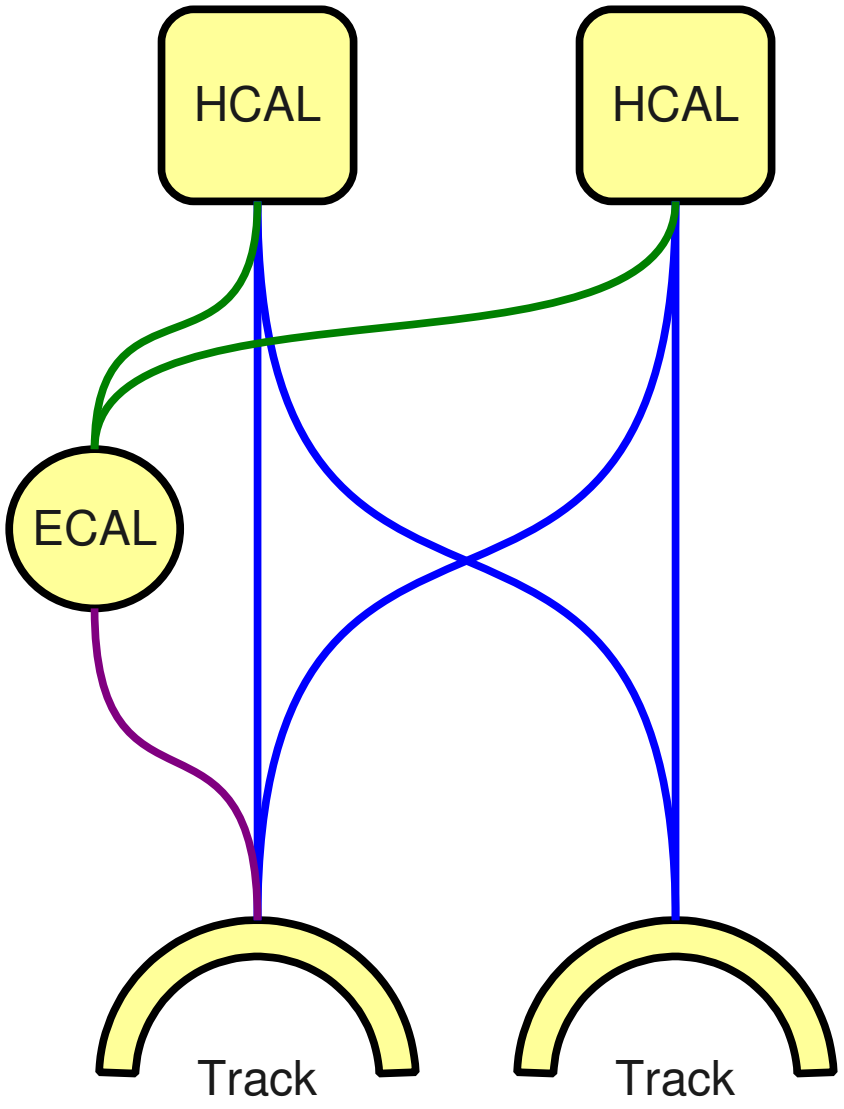
# Block summary

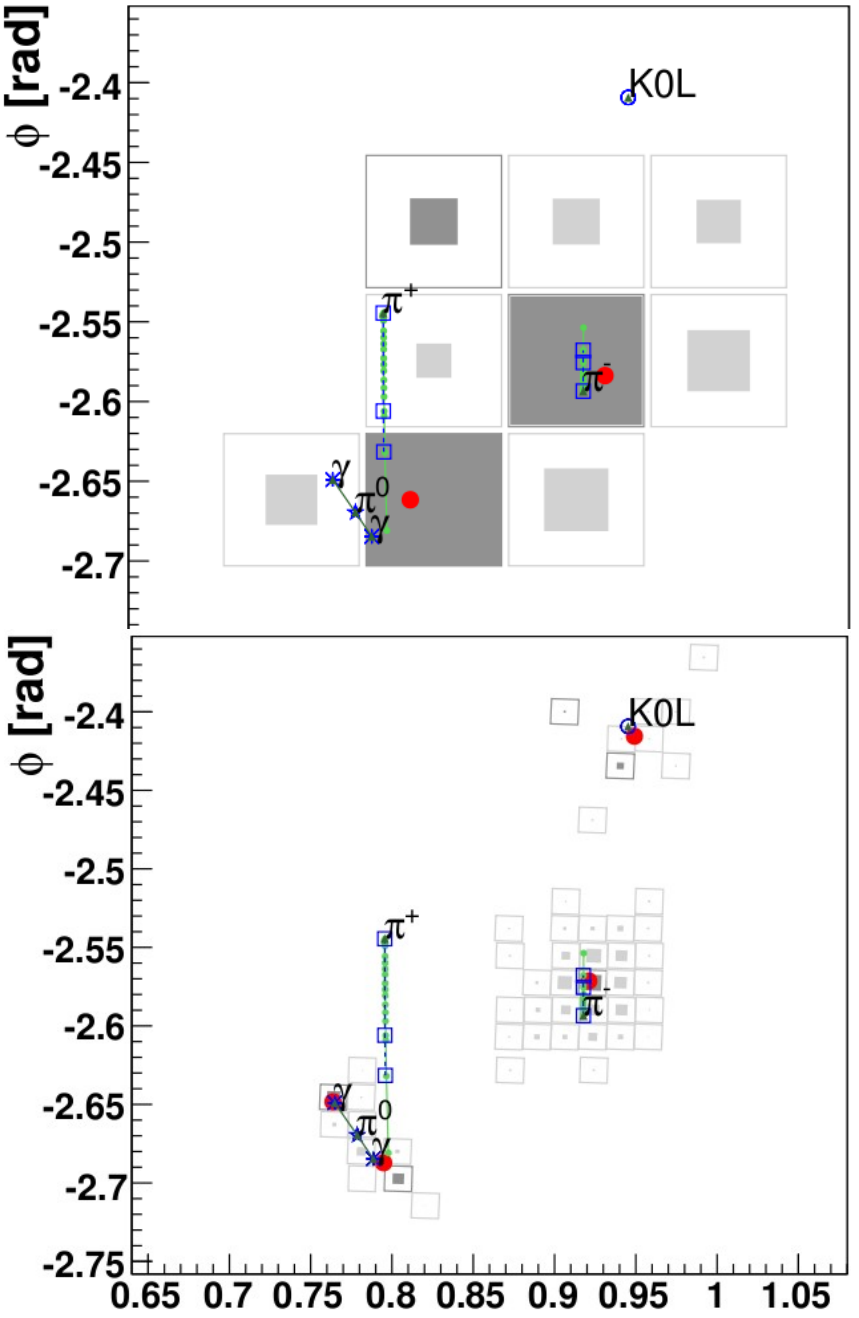



Not linked to
any track
→ 2 photons

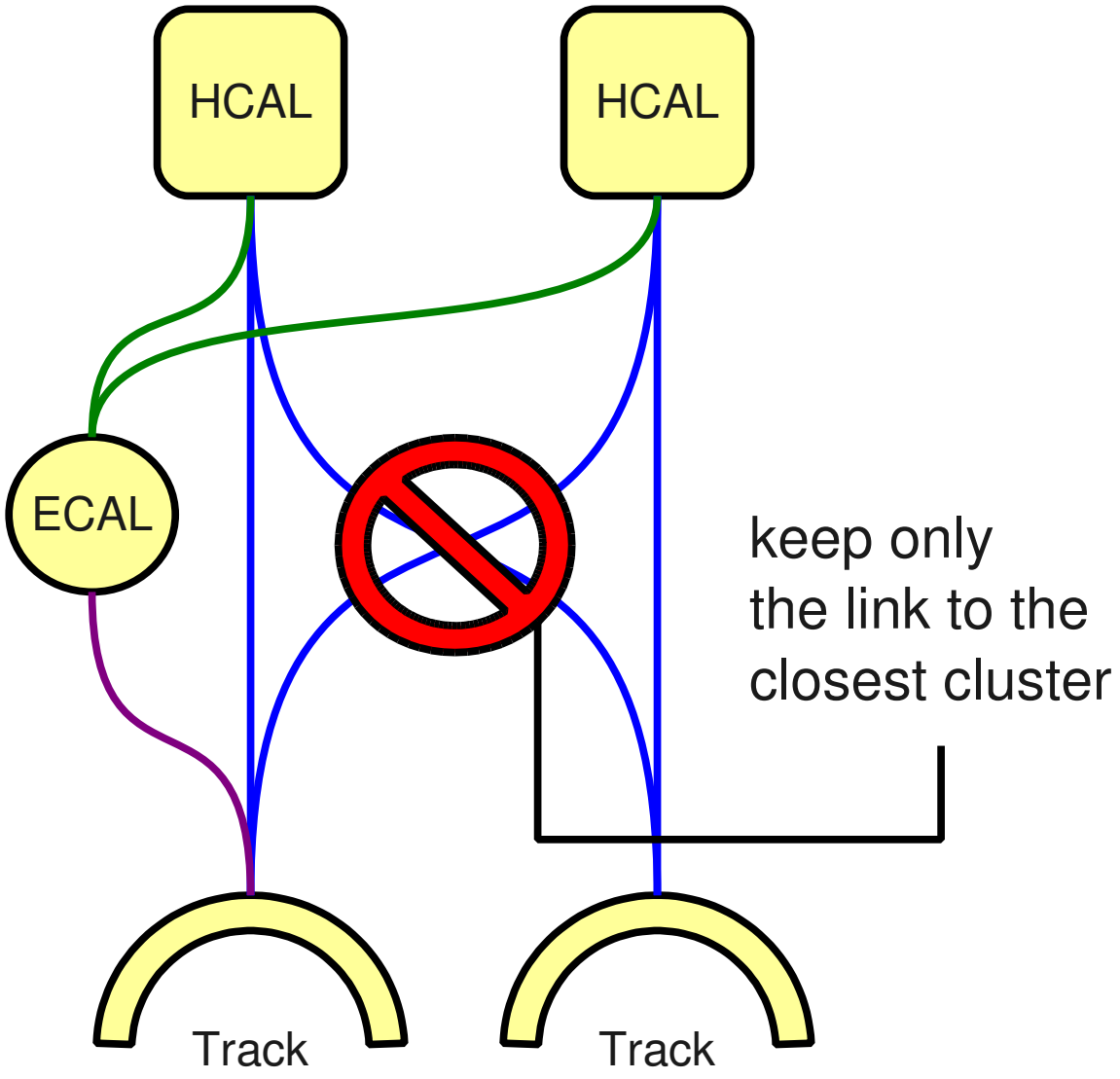


# Block summary

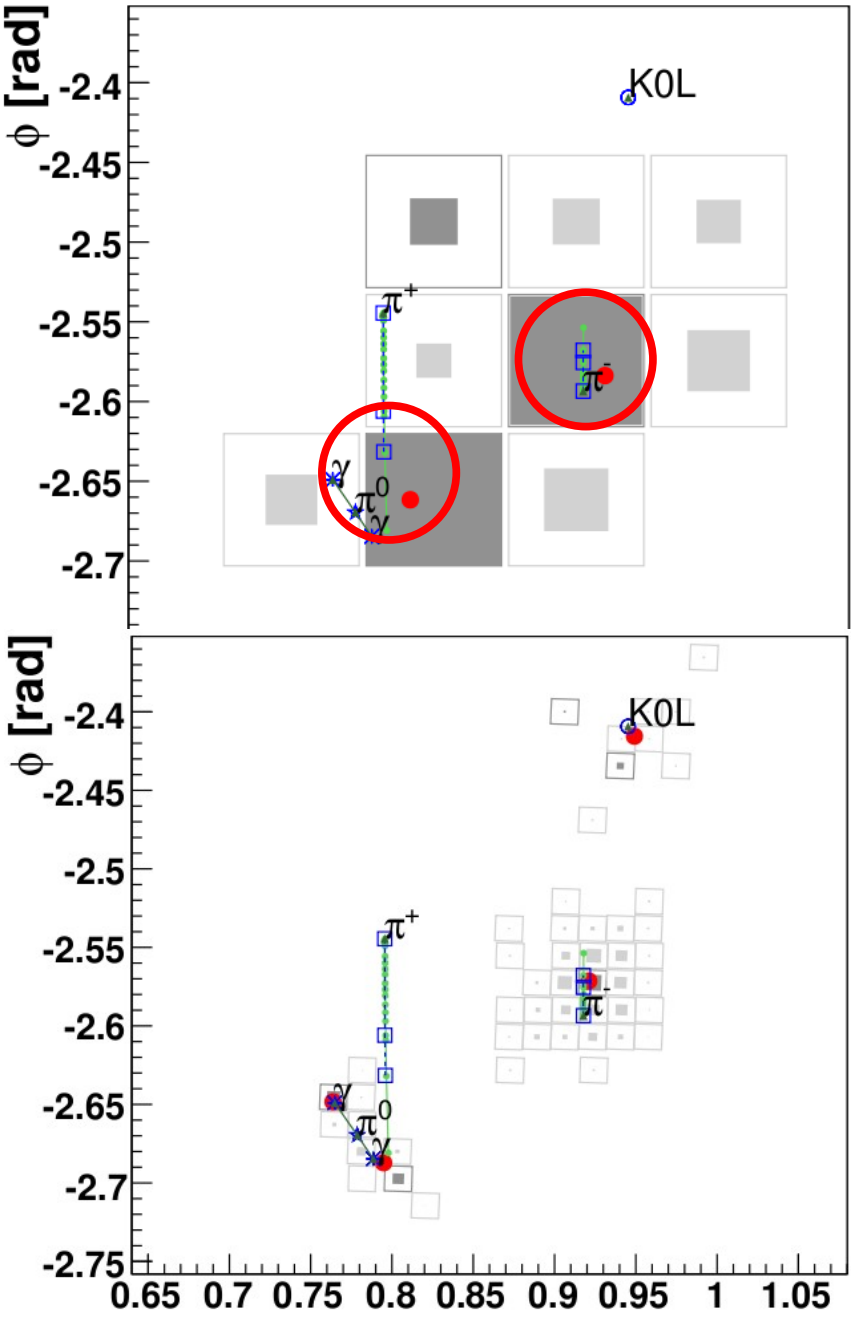


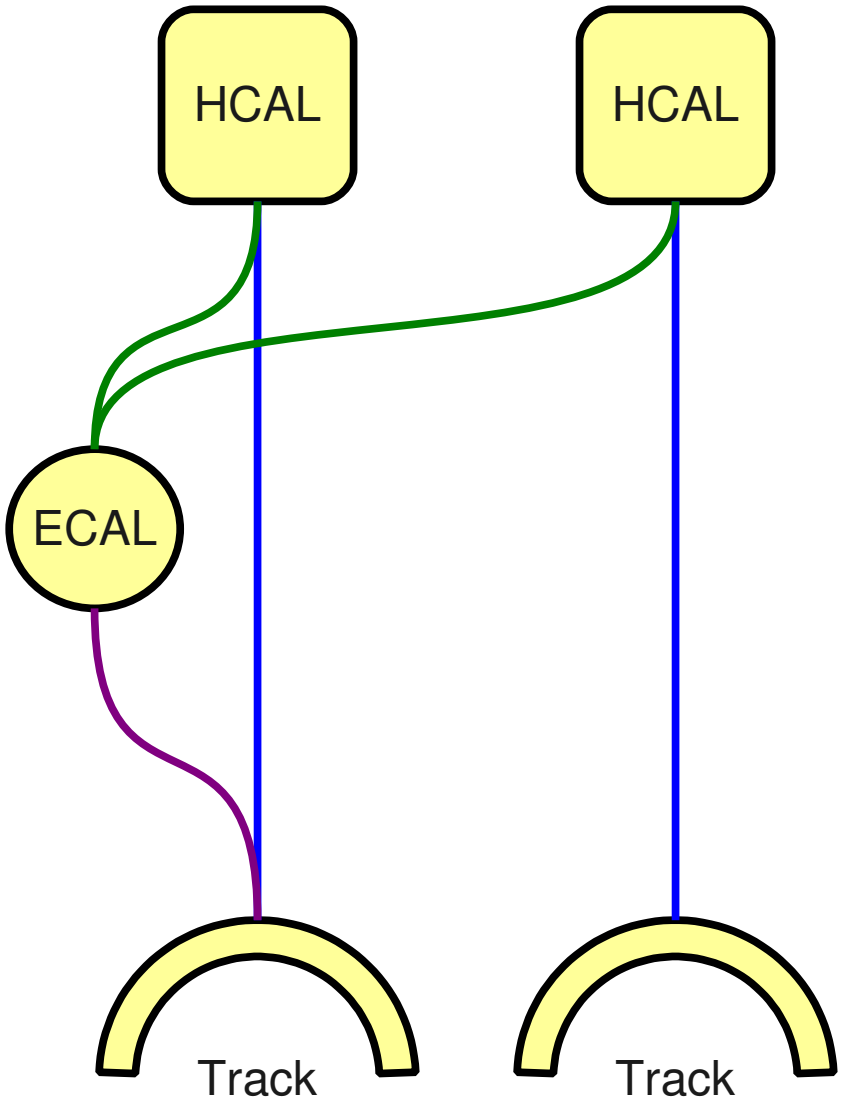
# Block summary

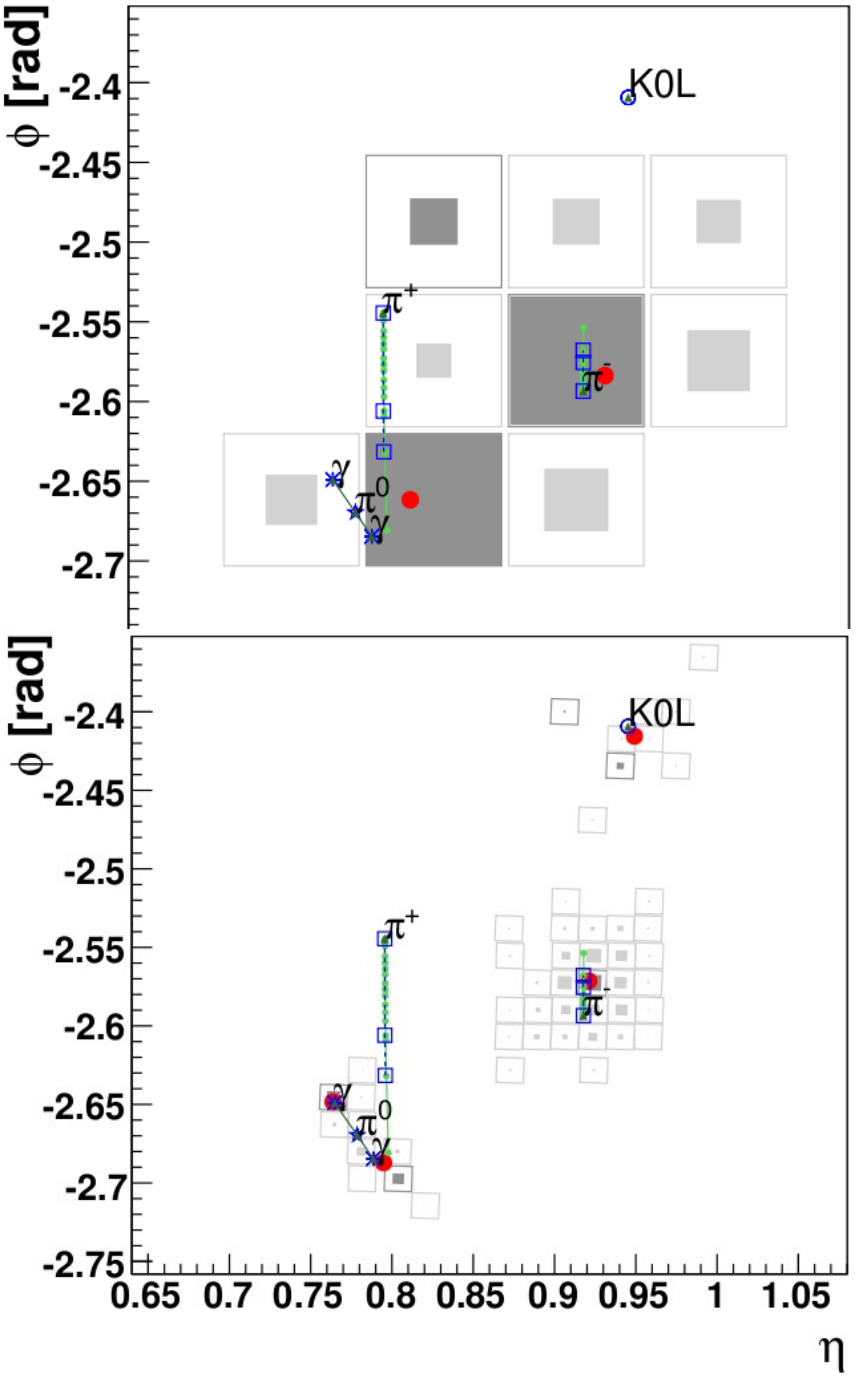



keep only
the link to the
closest cluster

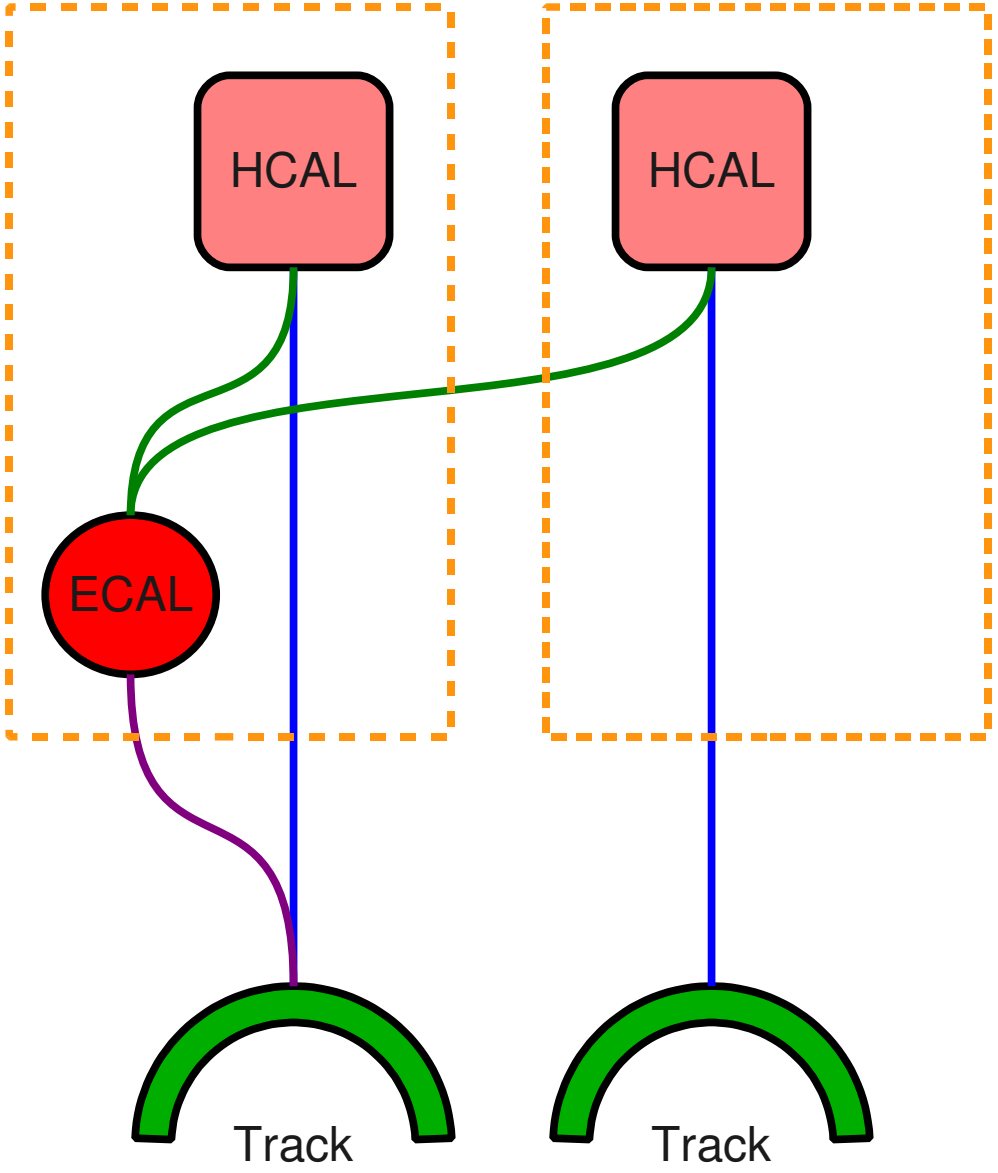


# Block summary



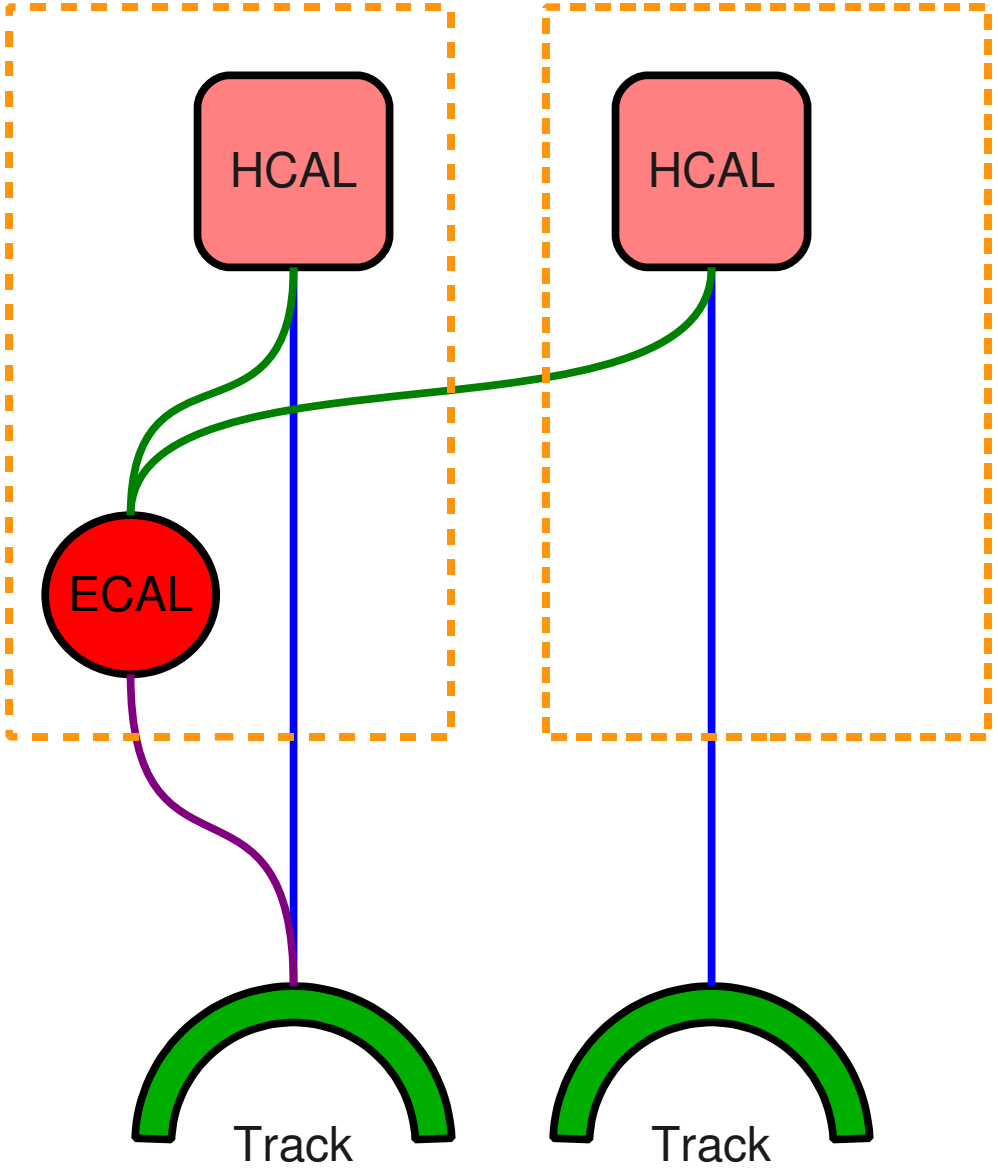



# Detect merged neutrals




- For each HCAL
  - Compute
    1- calorimetric energy
    linked to the track
    - Hadron calibration of HCAL (+ECAL)
  - Compare to
    2- track momentum
  - 1 > 2 + $\sigma_{calo}$
    - $\sigma_{calo}$ : resolution of the calorimeter system.
    - additional photon or neutral hadron.
    - tracks → charged hadrons

# Photon or neutral hadron?




- HCAL only
  - excess → n. hadron

hadron calib.

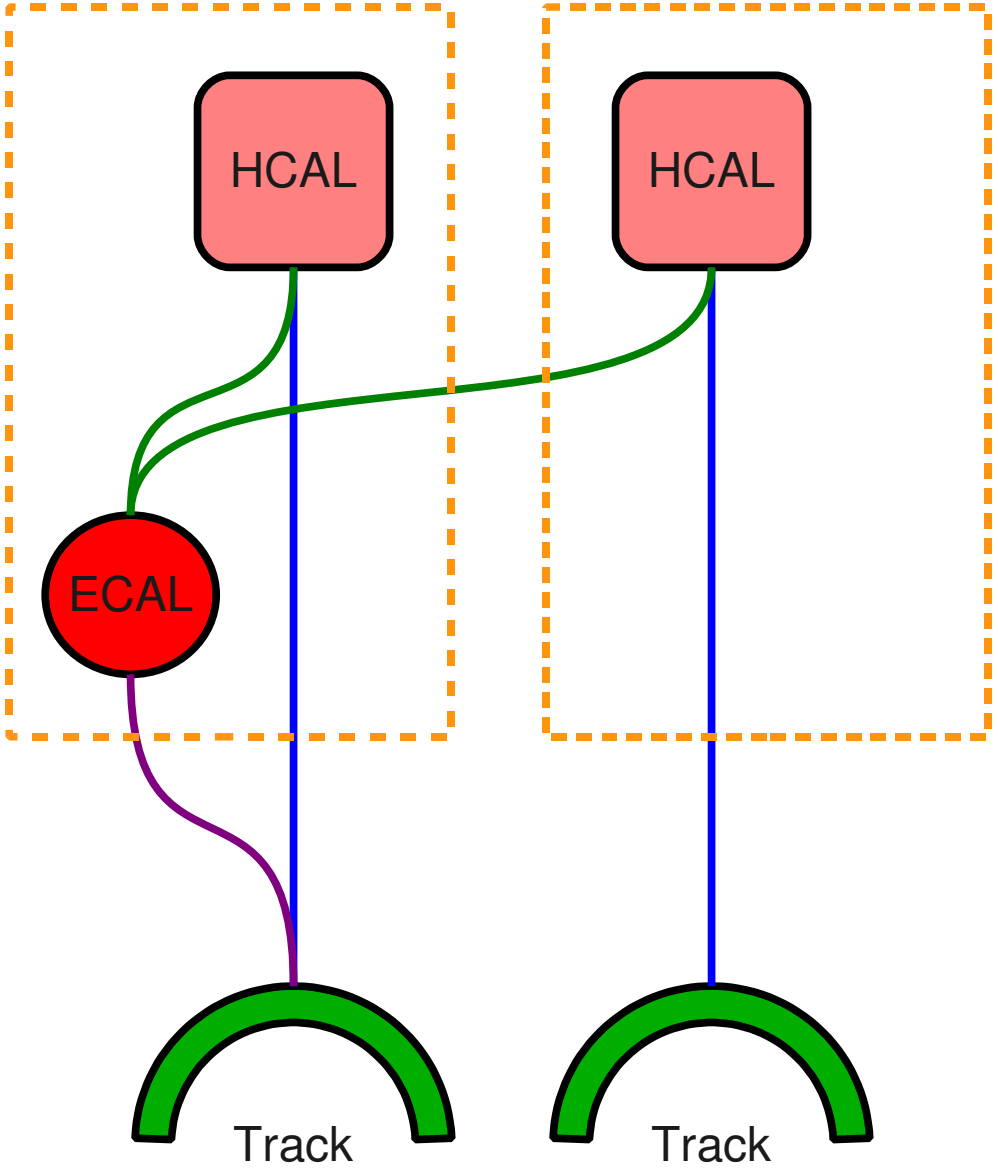
- ECAL only
  - excess → photon

- ECAL + HCAL
  - excess > $E_{ECAL}$
    $E_{ECAL}$ → photon
    remaining excess → n. hadron

hadron calib.

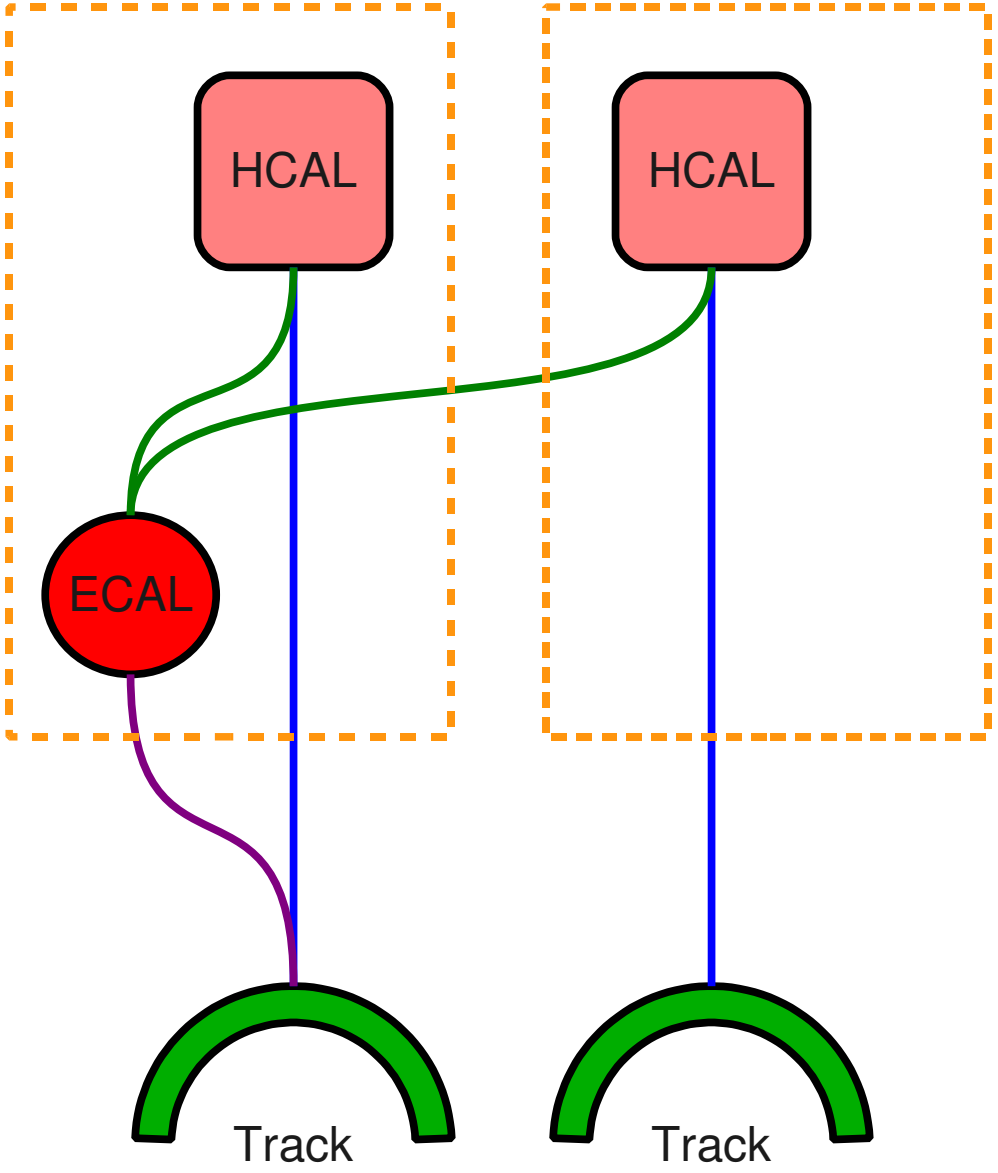
  - excess < $E_{ECAL}$
    excess → photon

# Detect merged neutrals




- For each HCAL
  - Compute
    1- calorimetric energy
    linked to the track
    - Hadron calibration of HCAL (+ECAL)
  - Compare to
    2- track momentum
  - $1 > 2 + \sigma_{calo}$
    - $\sigma_{calo}$ : resolution of the calorimeter system.
    - additional photon or neutral hadron.
    - tracks → charged hadrons

# Charged-hadron momentum



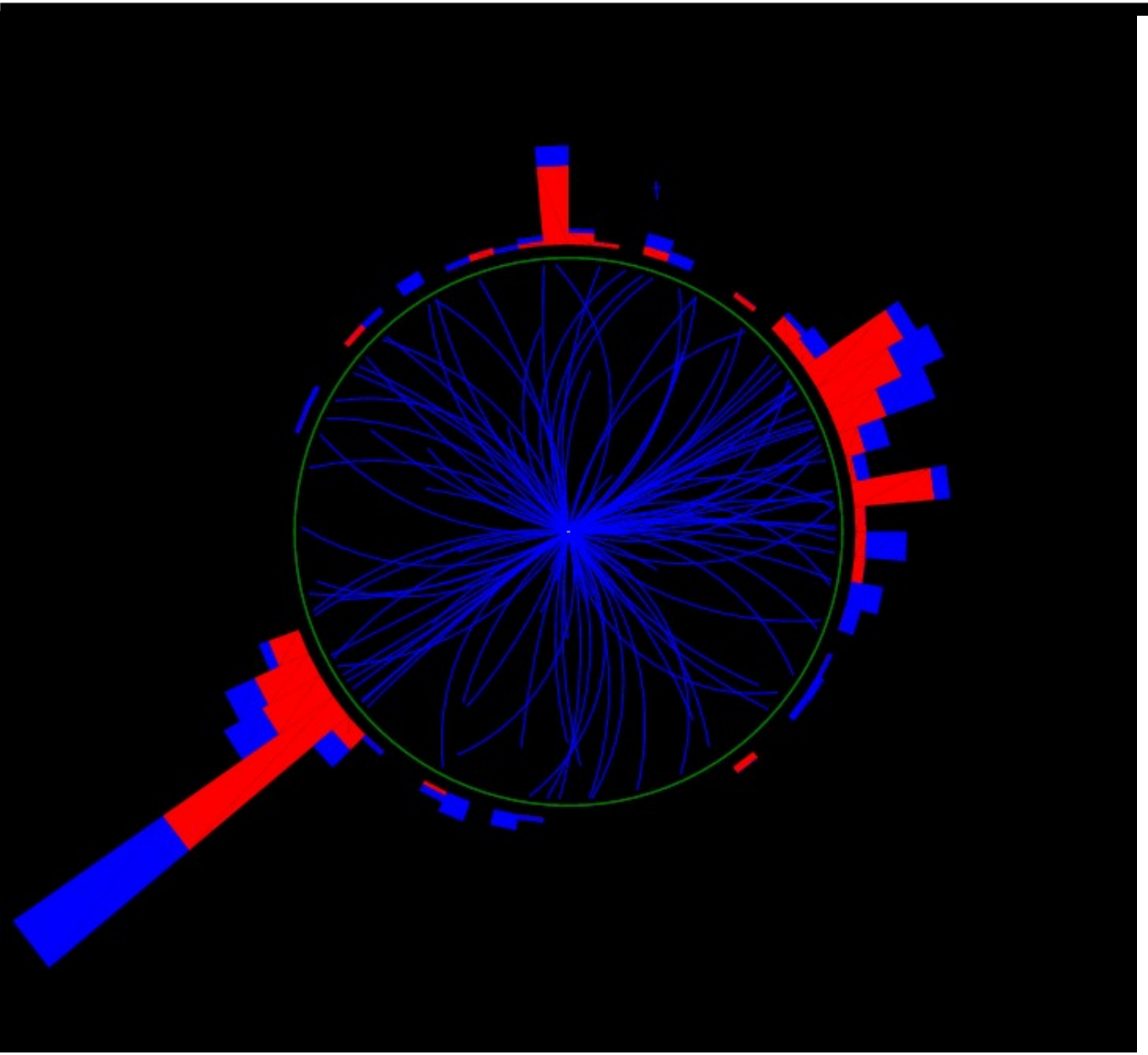

- For each HCAL
  - Compute
    1- calorimetric energy
    linked to the track
    - Hadron calibration of HCAL (+ECAL)
  - Compare to
    2- track momentum
  - 1 compatible with 2 ?
    - tracks → charged hadron
      - **weighted average** of calorimetric energy and the track momentum
      - **Goal: tend to a calorimetric measurement at high energy**

# The devil is in the details

- What if 1- calorimetric energy is much smaller than 2- charged energy
  - Don't consider poorest quality tracks (fakes?)
  - Identify and reconstruct more muons
- Several tracks linked to a given HCAL cluster
- Several ECAL clusters linked to a given tracks
- Use of the preshower
- Muons, Electrons
- New clustering algorithm
  - ECAL, HCAL, PS
- New iterative tracking strategy
  - 90% efficiency, 1% fake
- ...

# Performance with Jets

# Calorimeter jets

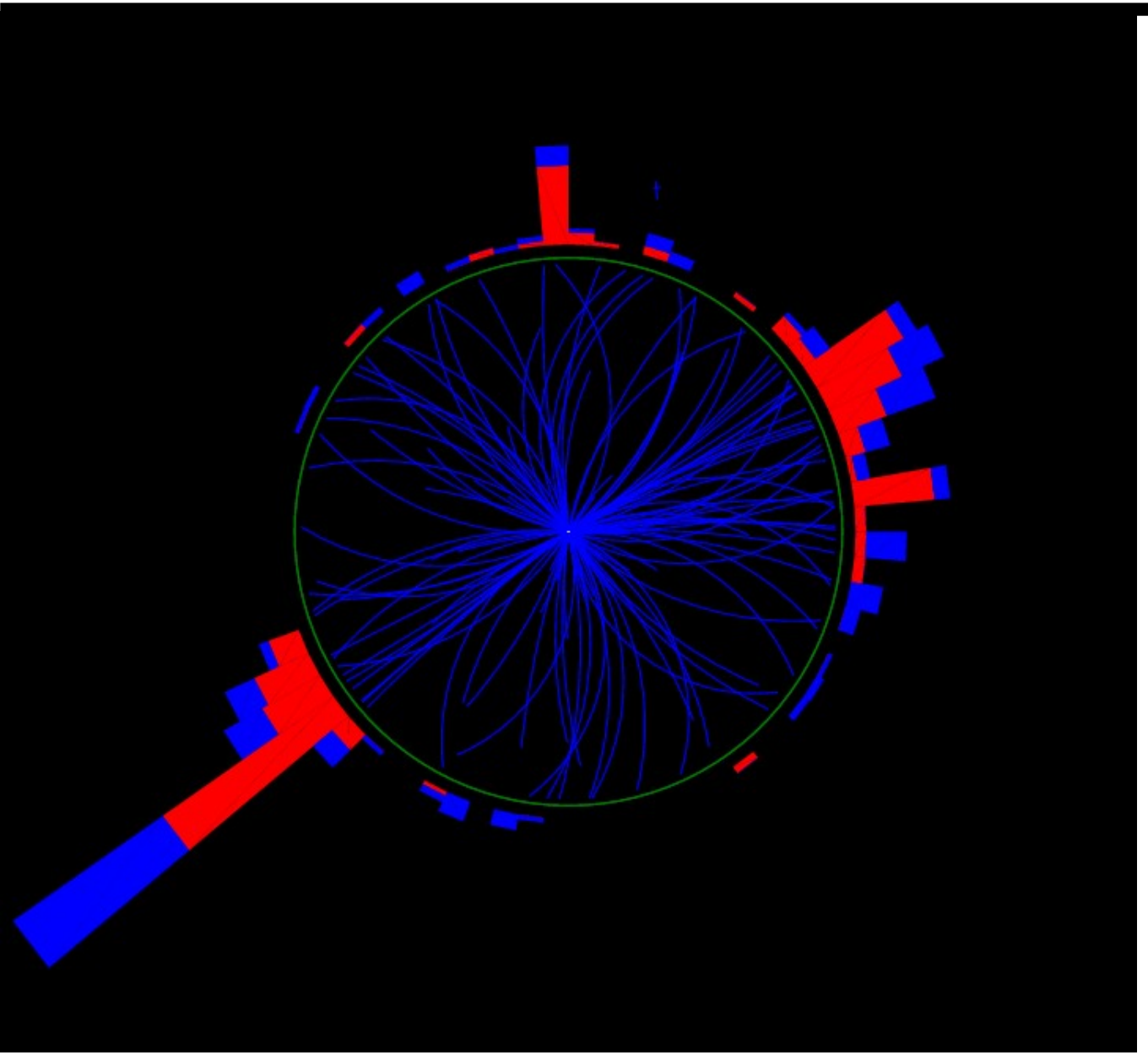


- CaloTower:
  - 1 HCAL tower
  - 25 ECAL crystals underneath
- Iterative cone algorithm
- Loosing ECAL granularity
- Resolution of HCAL:

$$\frac{\sigma}{E} \sim \frac{100\%}{\sqrt{E}}$$

- Charged hadrons spread by the field
  - degradation of the angular resolution

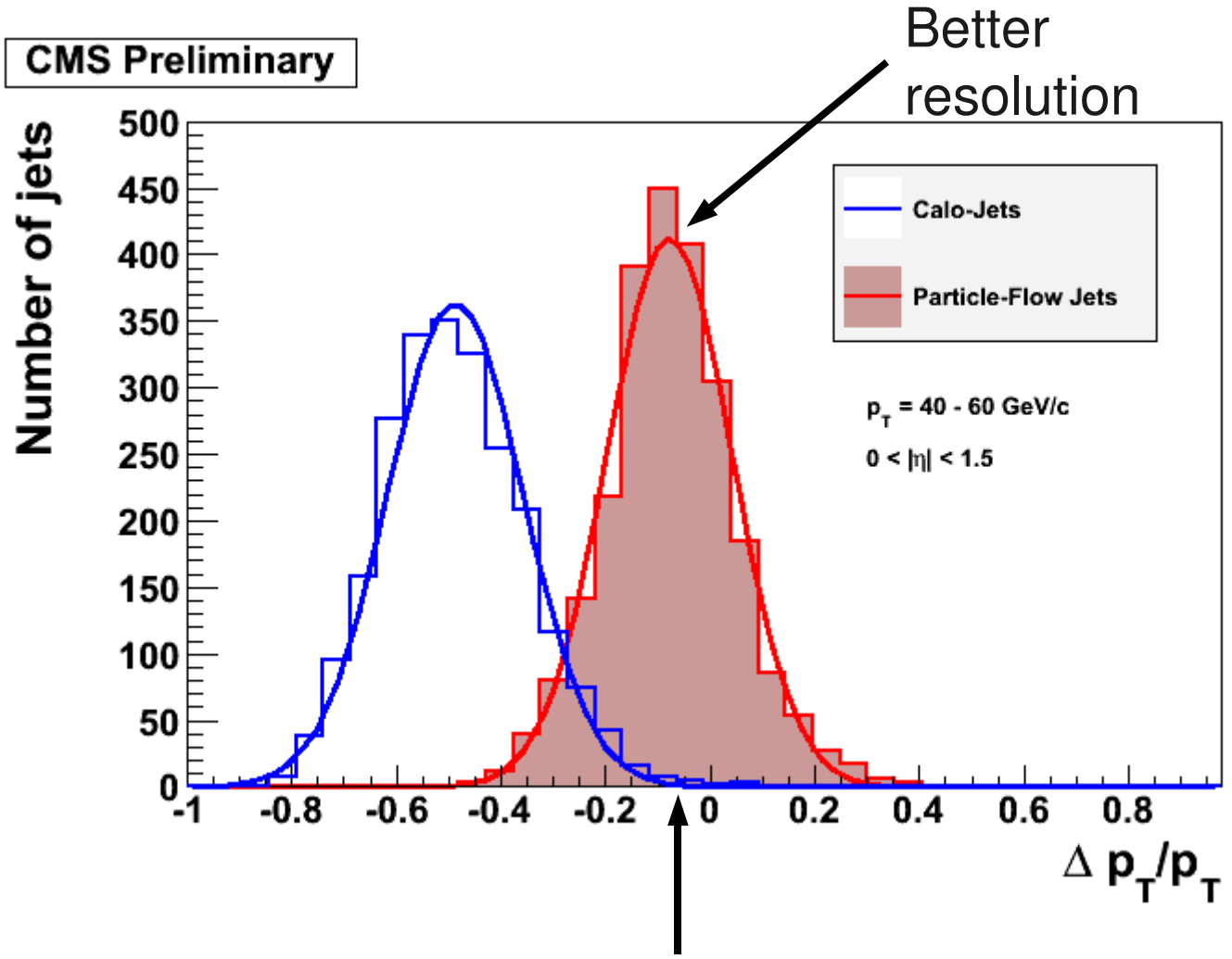
# Jets of particles



- reconstructed or generated
  - no neutrinos
- Same Iterative cone algorithm
- Charged hadrons
  - 65% of jet E
  - direction at vertex
  - resolution tracker
- + Photons
  - 25% of jet E
  - resolution ECAL
- + Neutral hadrons
  - 10% of jet E
  - resolution HCAL

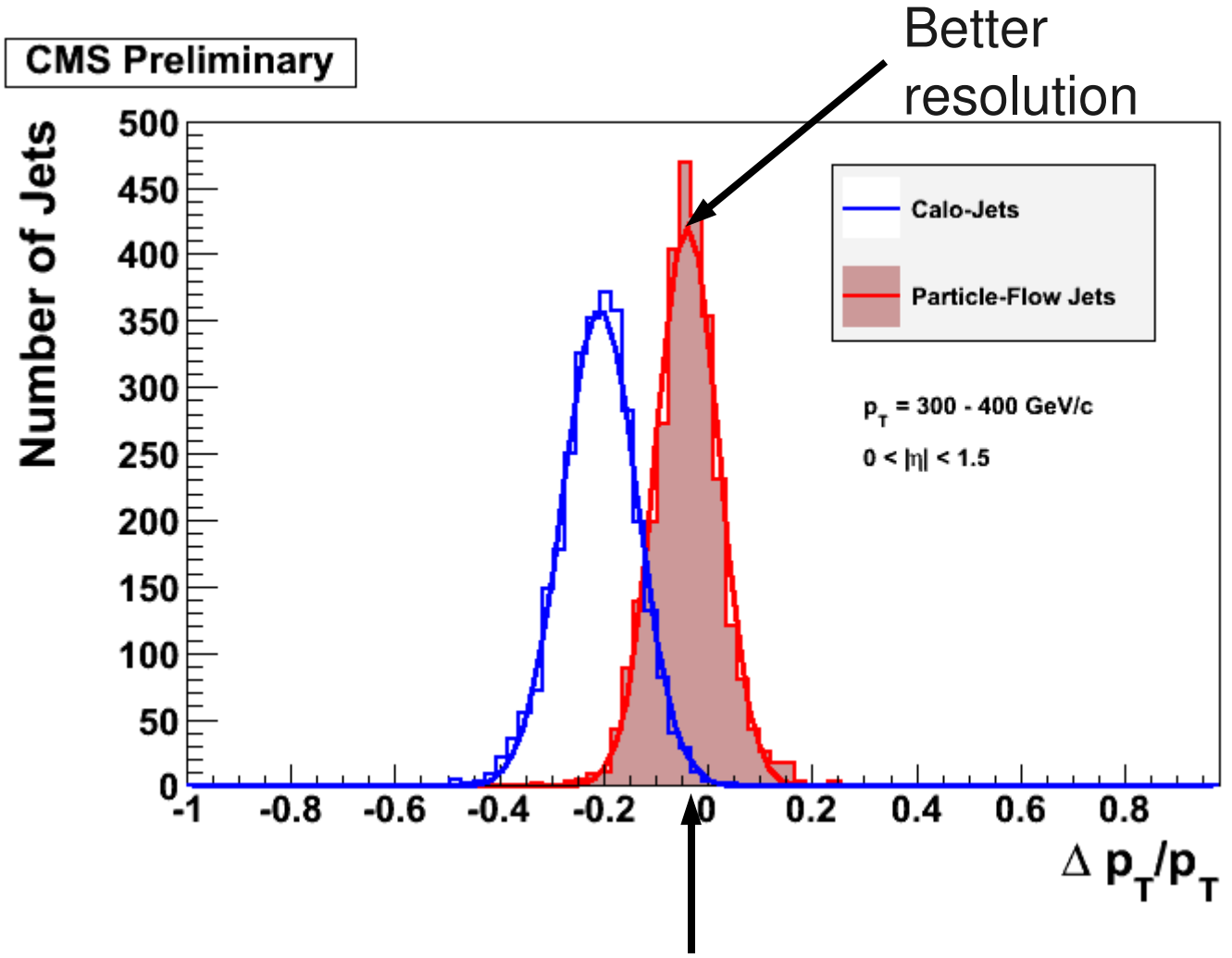
# Reconstruction of jet $p_T$

- Comparison to the closest Gen-Jet, pT = 40 → 60 GeV/c



# Reconstruction of jet $p_T$

- Comparison to the closest Gen-Jet, pT = 300 → 400 GeV/c

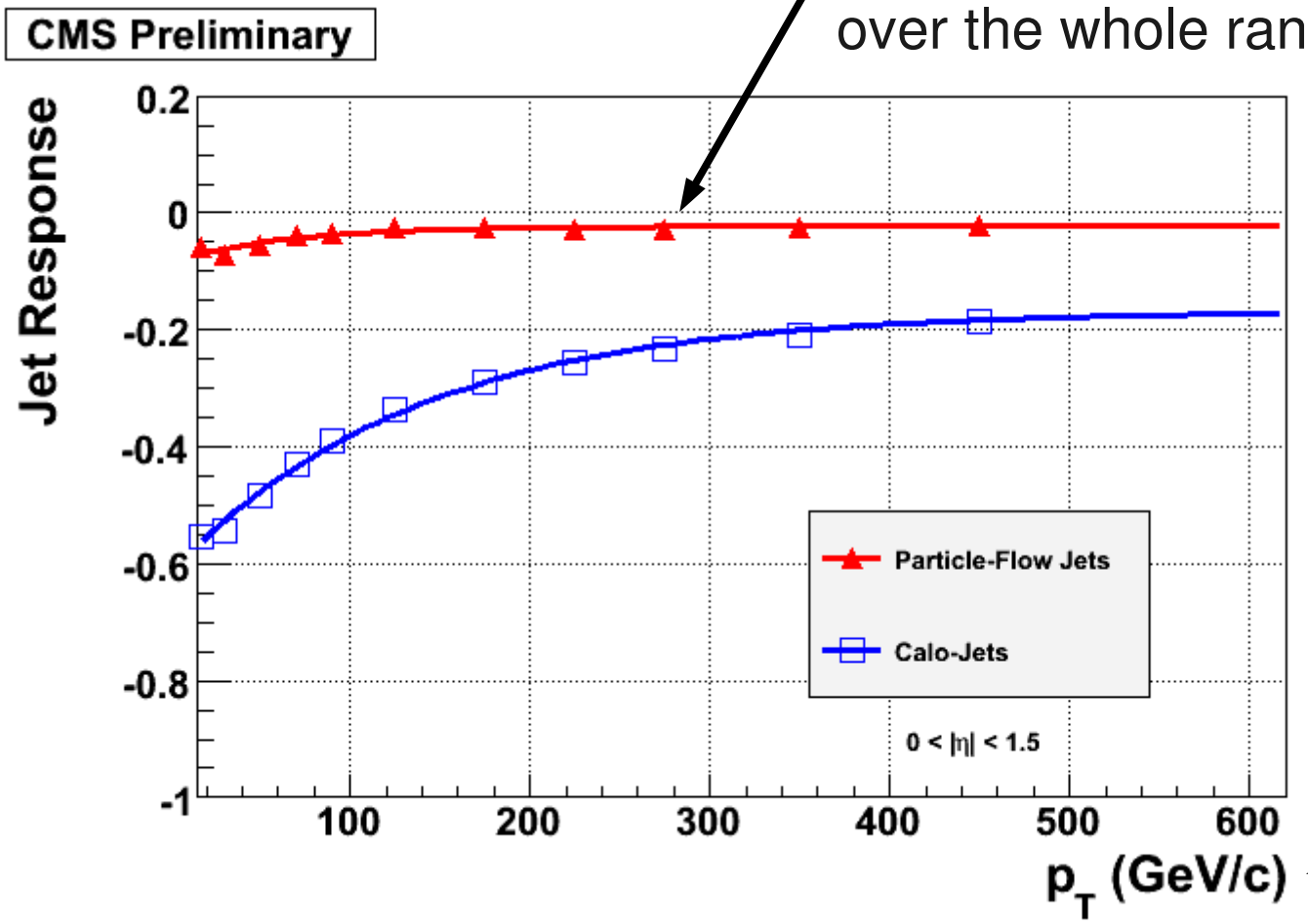



$$\frac{p_T^{rec} - p_T^{gen}}{p_T^{gen}}$$

# Reconstruction of jet $p_T$

95-97% of the $p_T$ reconstructed, over the whole range.

Mean of the fitted Gaussian

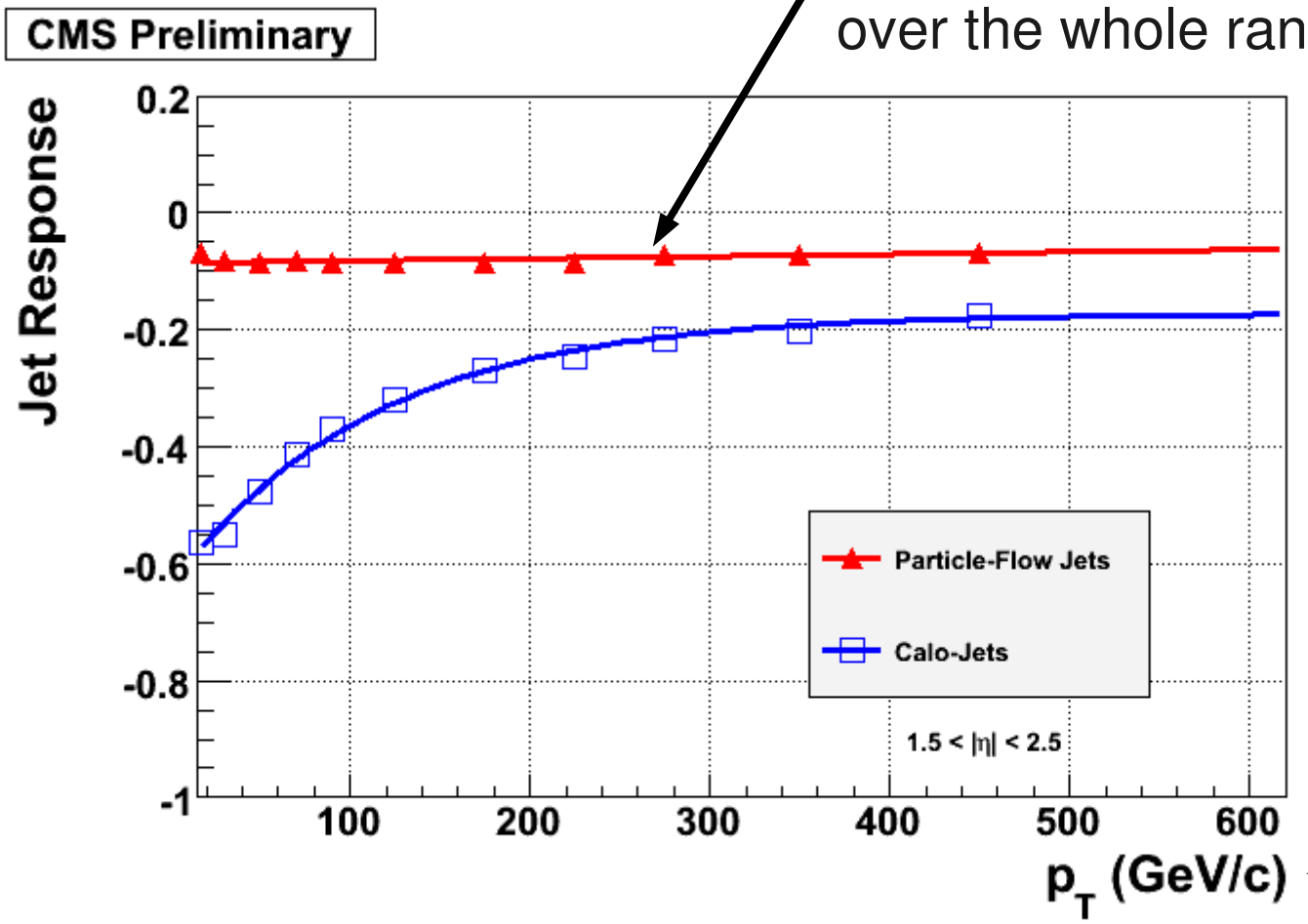



True jet $p_T$

- Barrel: $|\eta| < 1.5$

# Reconstruction of jet $p_T$

90% of the $p_T$ reconstructed, over the whole range!

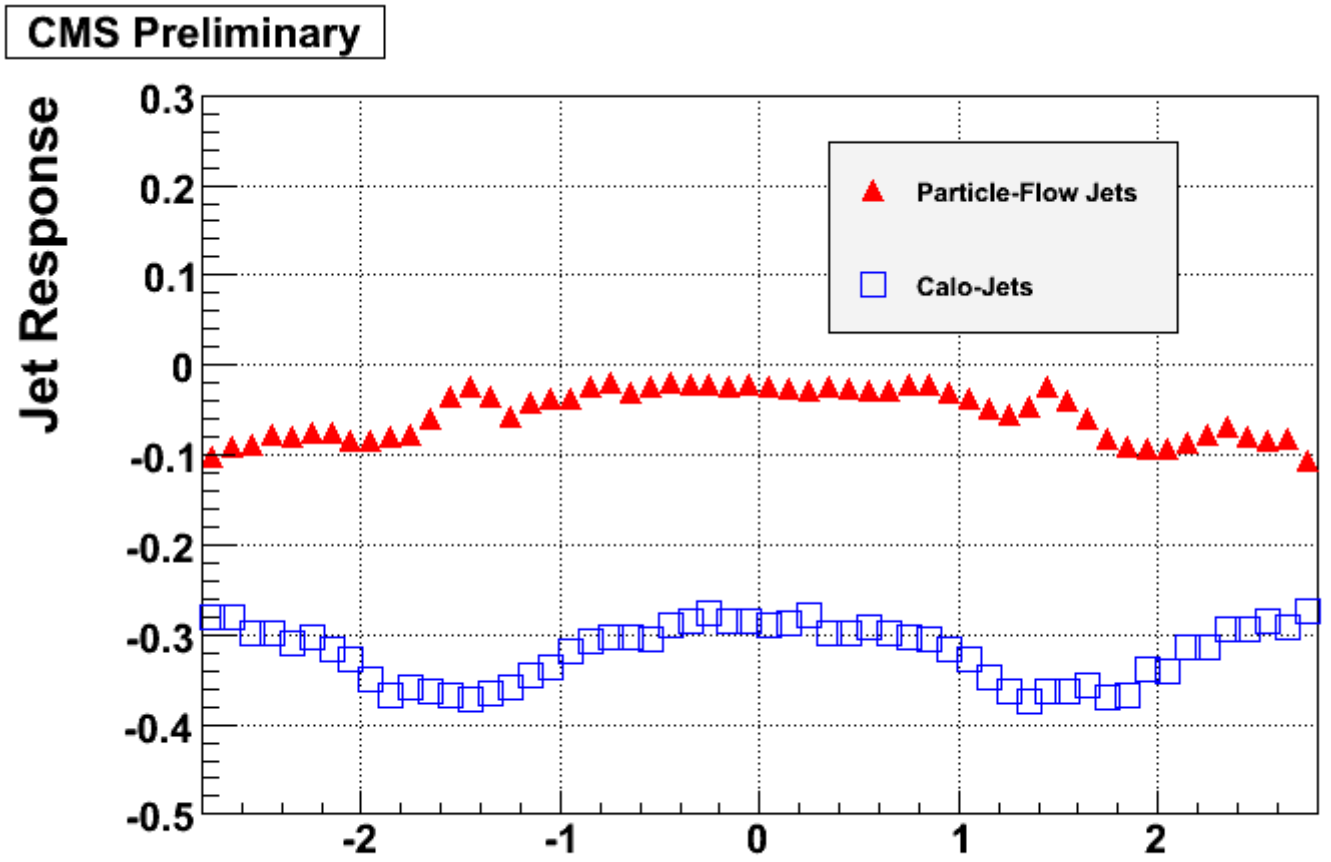



Mean of the fitted Gaussian

True jet $p_T$

- Endcap: $1.5 < |\eta| < 2.5$
  - Lower response than in the barrel. Can still improve!

# Reconstruction of jet $p_T$

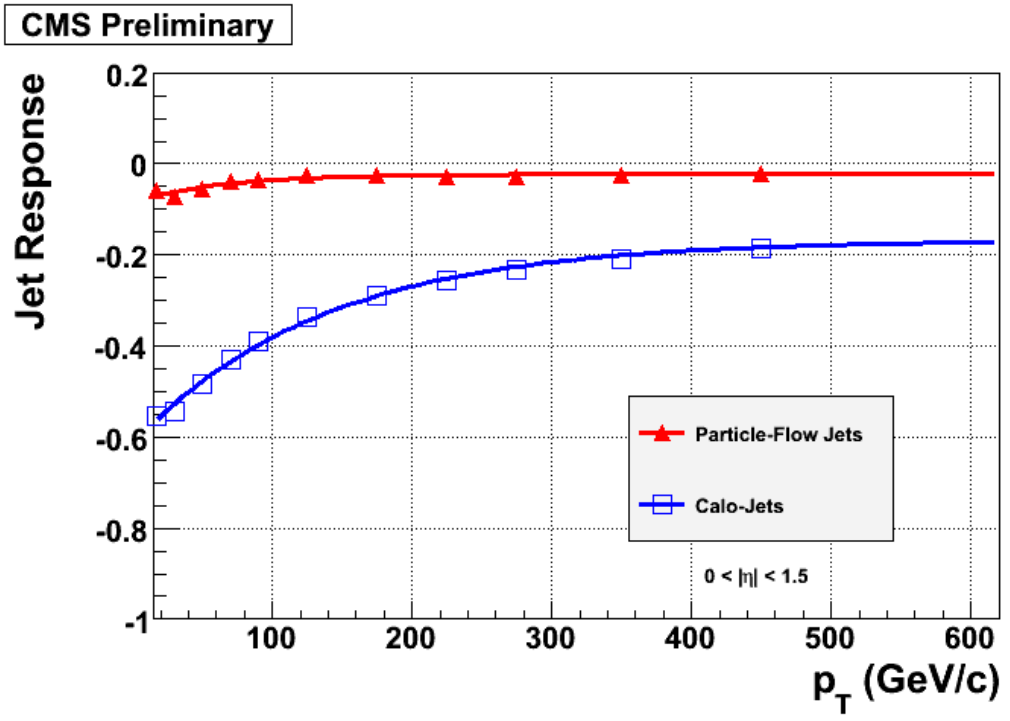


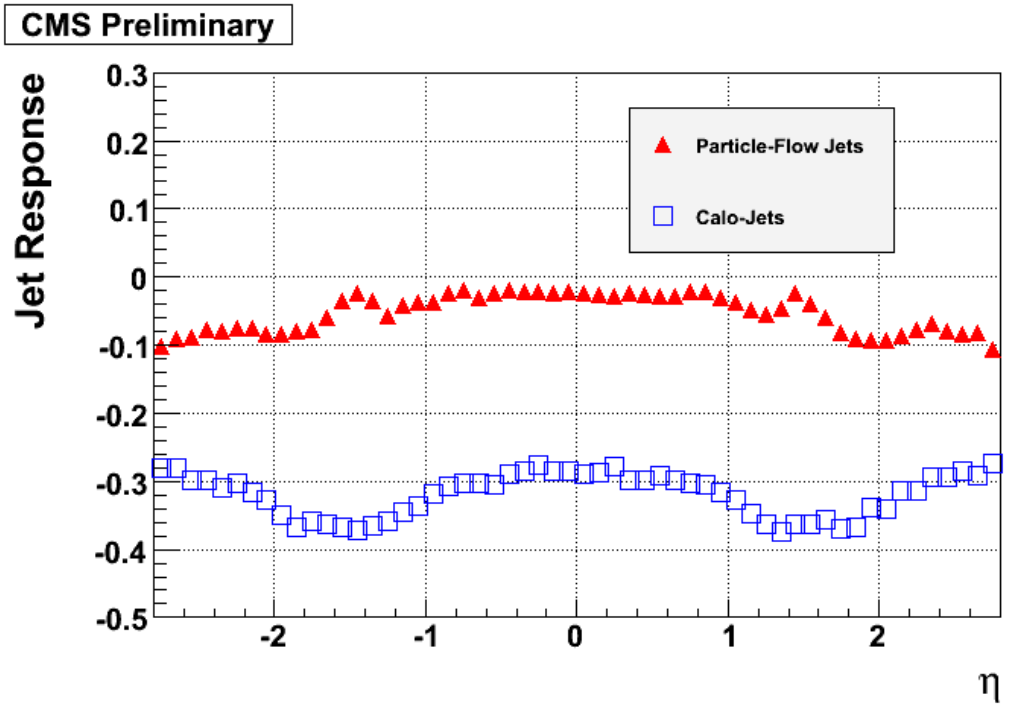

Mean of the fitted Gaussian

- As a function of eta

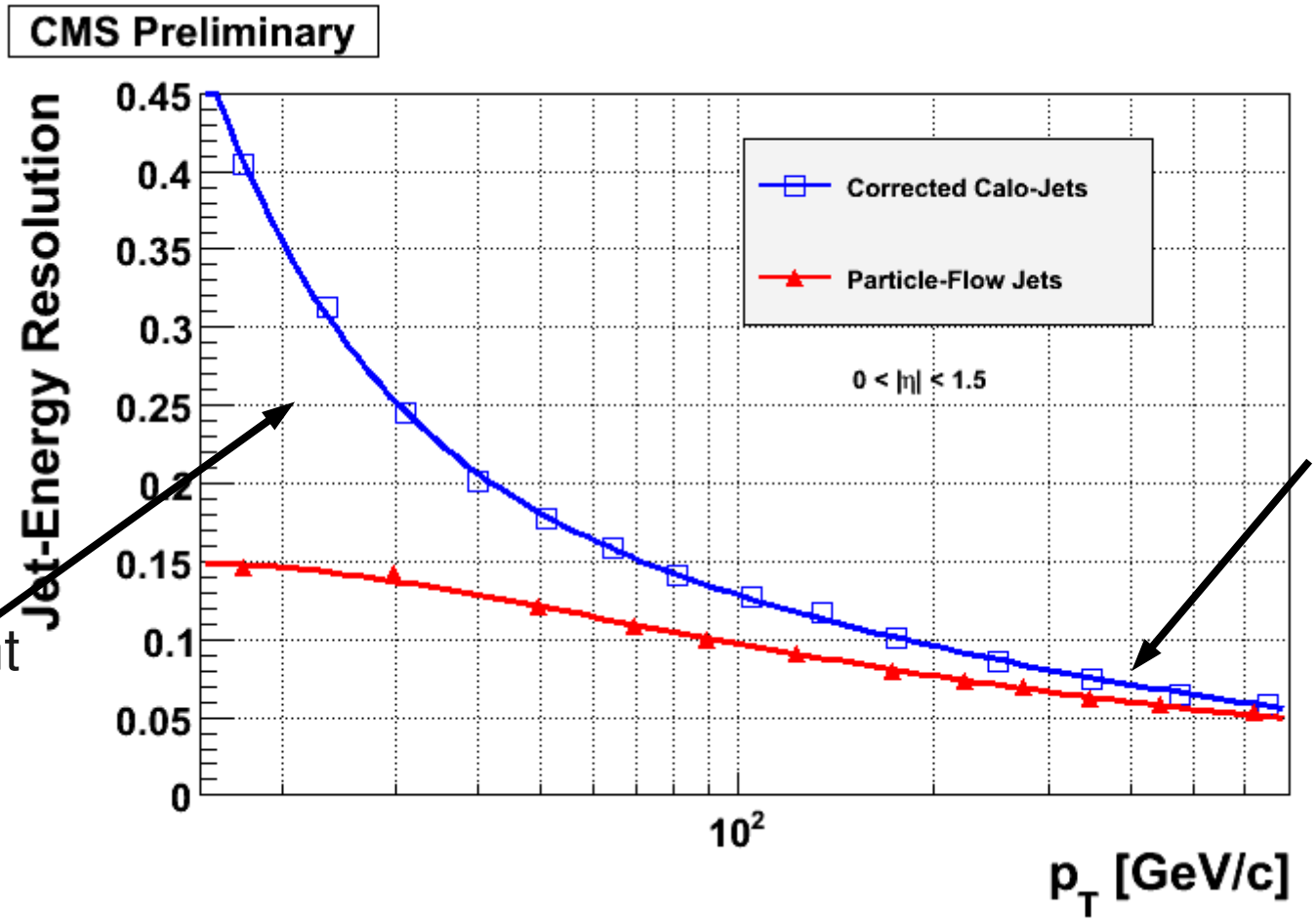
# Jet energy corrections

- Basic idea:
  - Correct the jet $p_T$ to bring the response to 1
  - Correction in bins of $p_T$ and $\eta$
- Particle flow: smaller corrections → smaller systematics



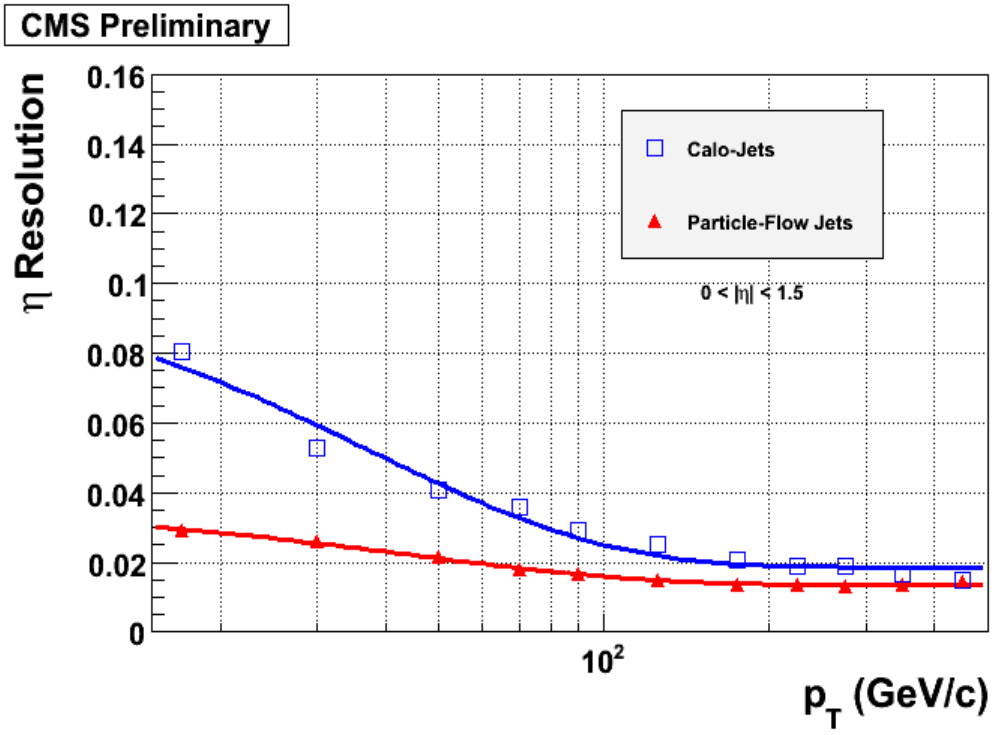
# Jet energy resolution, barrel

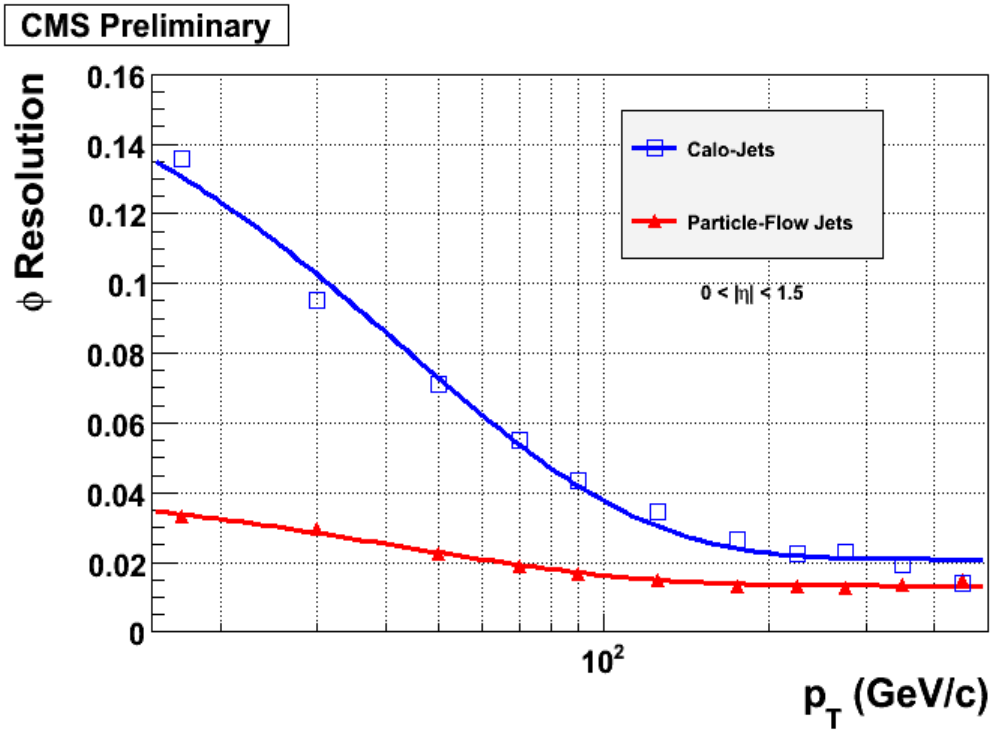



Very large improvement at low pT, thanks to Tracks

Good calorimeter resolution, → Tracks bring less

# Jet angular resolution

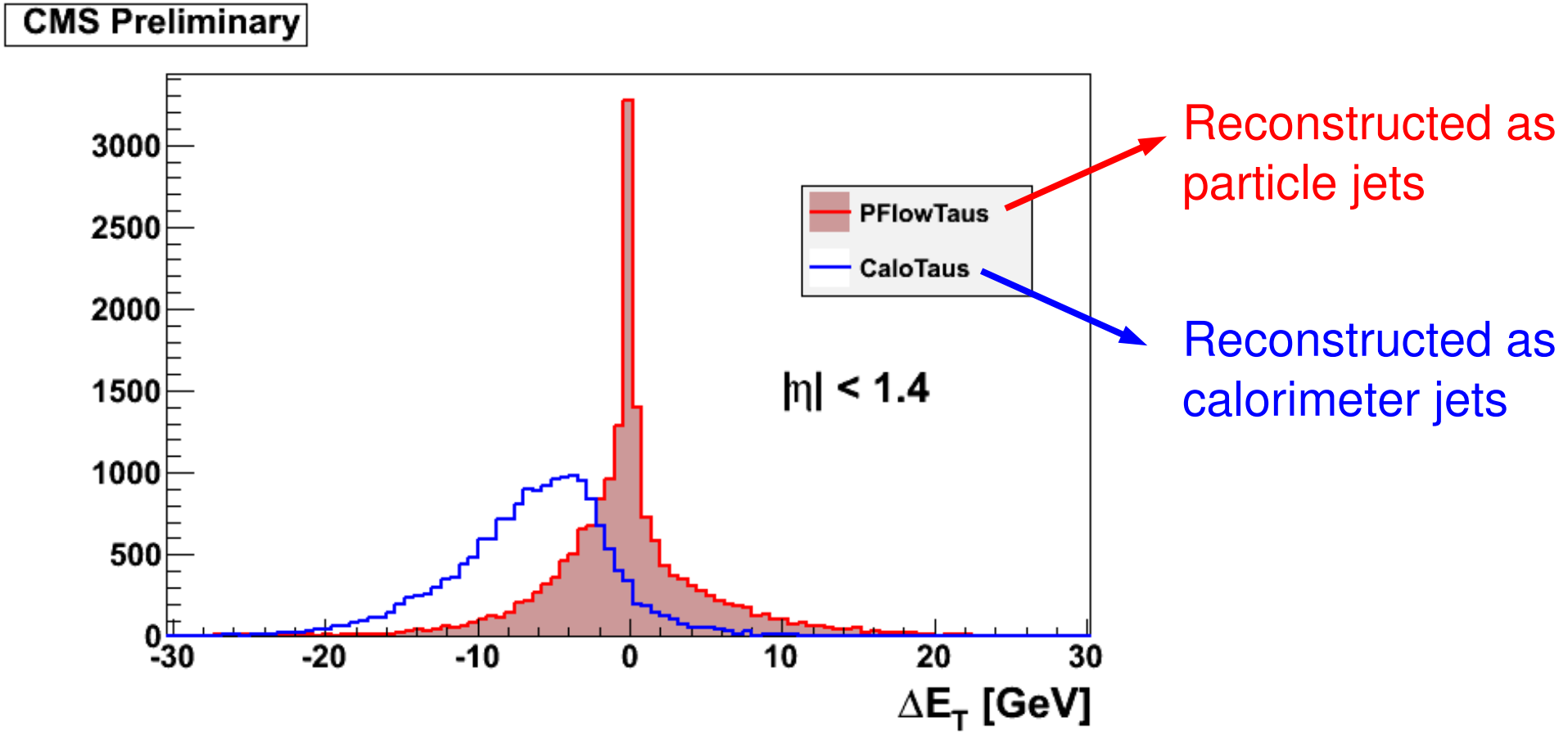



- η
  - Better resolution
    ← tracker and ECAL
- φ
  - No effect of the **B** field
    ← charged hadron direction measured at the vertex.

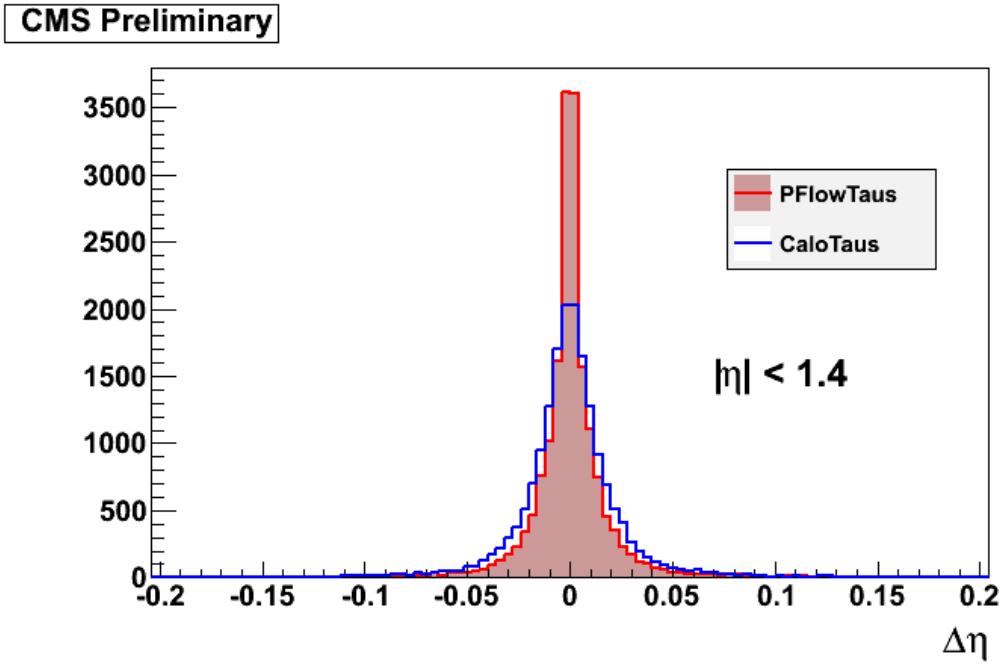
# Performance with Taus

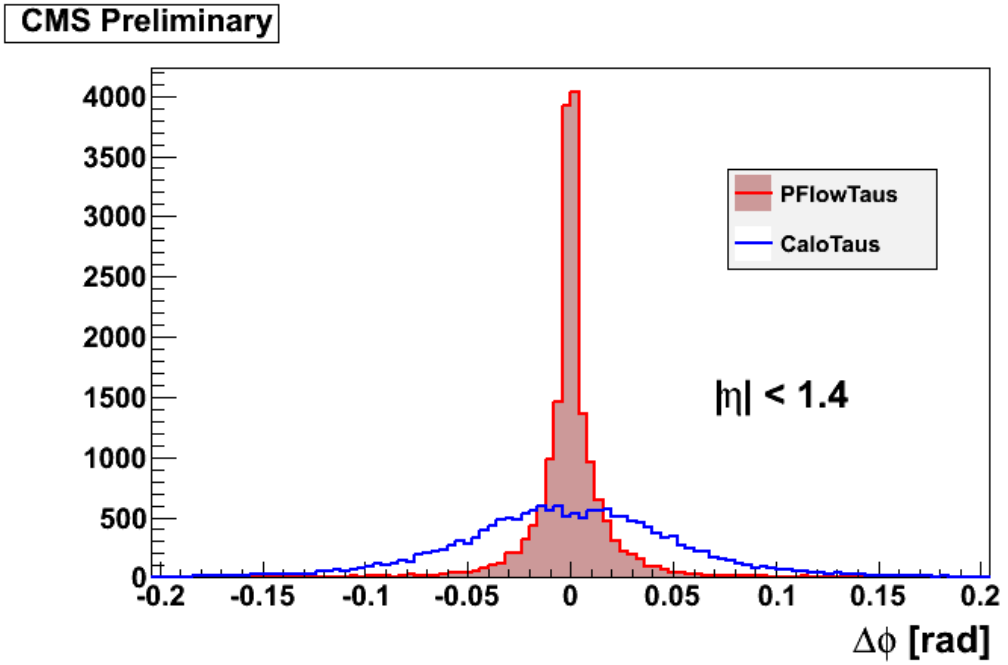
# τ Energy



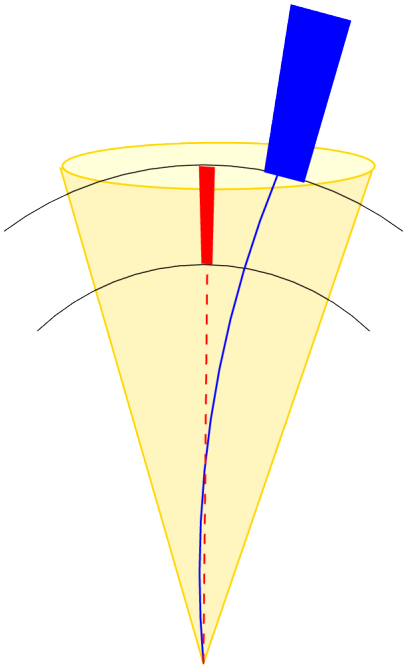

- Even larger improvement than in the case of jets
  - because only 1% of the taus produce neutral hadrons in their decays.

# τ Direction




- η resolution
  - factor 2 improvement
- ϕ resolution
  - CaloTaus: ϕ resolution worse than η resolution



# Performance with MET

# Generated MET

$$\overrightarrow{MET} = -\sum_{i=0}^{N} \vec{E}_T^i$$

Sum over all stable, generated particles, except neutrinos, with $\eta < 5$

# Traditional, calorimeter MET

- Raw MET:
  Sum on all CaloTowers
- The response of the CaloTowers is far from unity
  - For each jet:
    - Add the difference between the corrected and raw jet energy
  - Do the same for each tau
- The muon energy is not measured in the calorimeters
  - Add their $E_T$ *a posteriori*

$$\overrightarrow{MET} = -\sum_{i=0}^{N} \vec{E}_T^{\,i}$$

$$-\sum_{j=0}^{N_{jet}} [\vec{E}_{T,corr}^{\,j} - \vec{E}_{T,raw}^{\,j}]$$

$$-\sum_{k=0}^{N_{\tau}} [\vec{E}_{T,corr}^{\,k} - \vec{E}_{T,raw}^{\,k}]$$

$$-\sum_{m=0}^{N_{\mu}} \vec{E}_T^{\,m}$$

# Particle-flow MET

$$\overrightarrow{MET} = -\sum_{i=0}^{N} \vec{E}_T^i$$

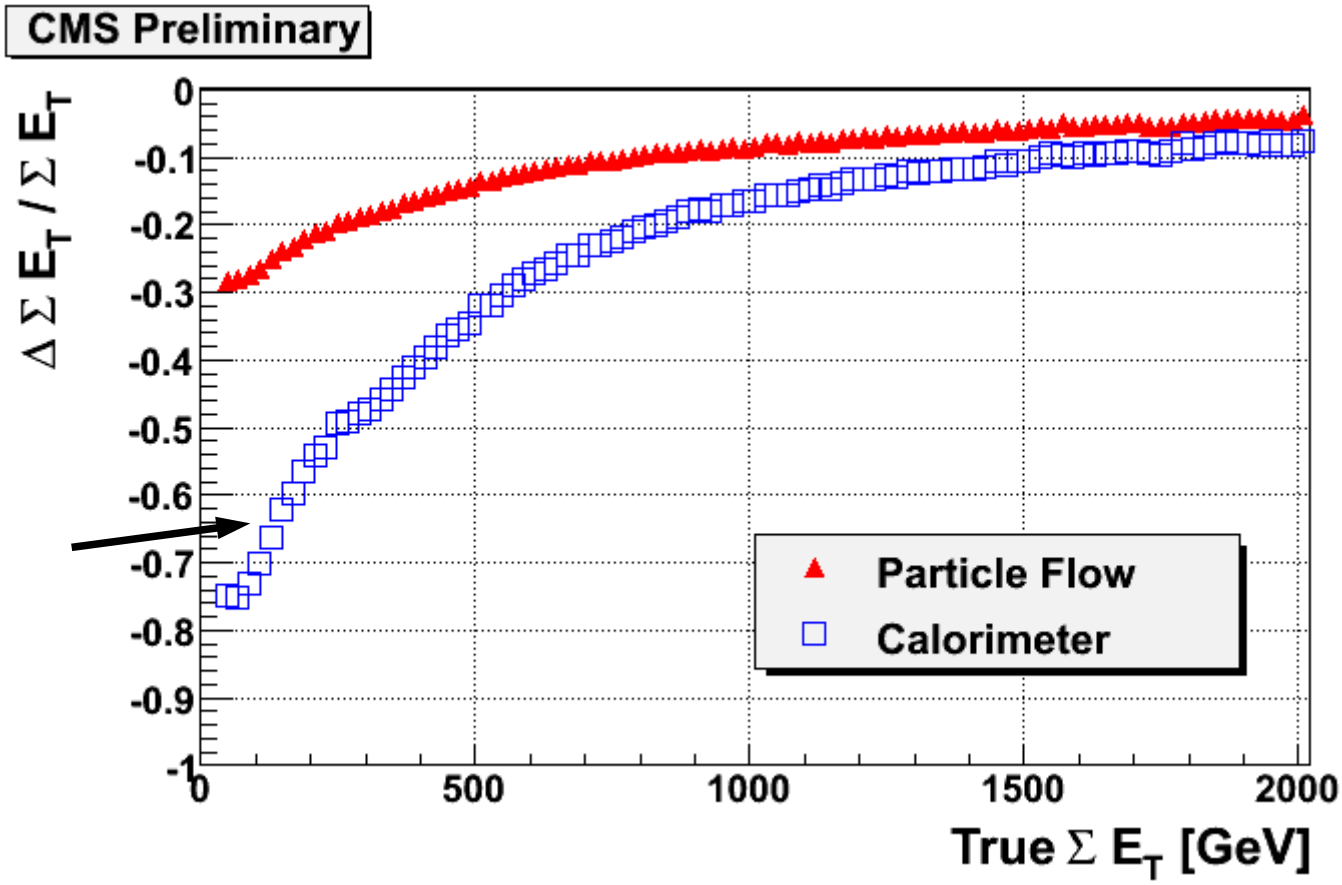
Sum over all particles reconstructed by the particle flow algorithm

# Sum $E_T$ in QCD events

- ~ No MET in QCD events
  → cannot define the MET response
  - would divide by 0

$$\frac{MET^{rec} - MET^{gen}}{MET^{gen}}$$

- Sum $E_T$ :
  - scalar sum of the energy of all particles in the event

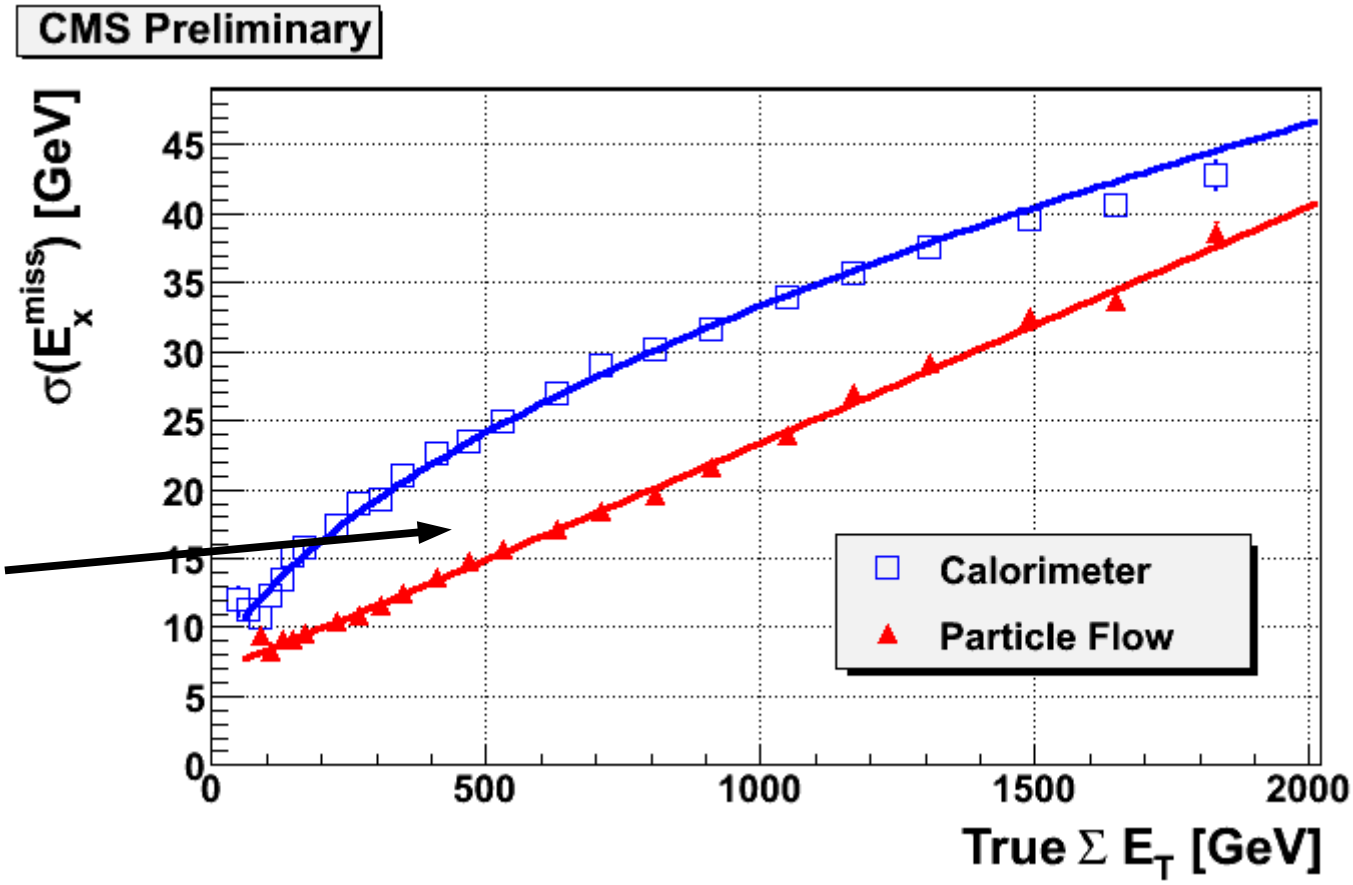



Calorimeters in trouble with low $E_T$ particles (charged hadrons do not reach HCAL; thresholds)

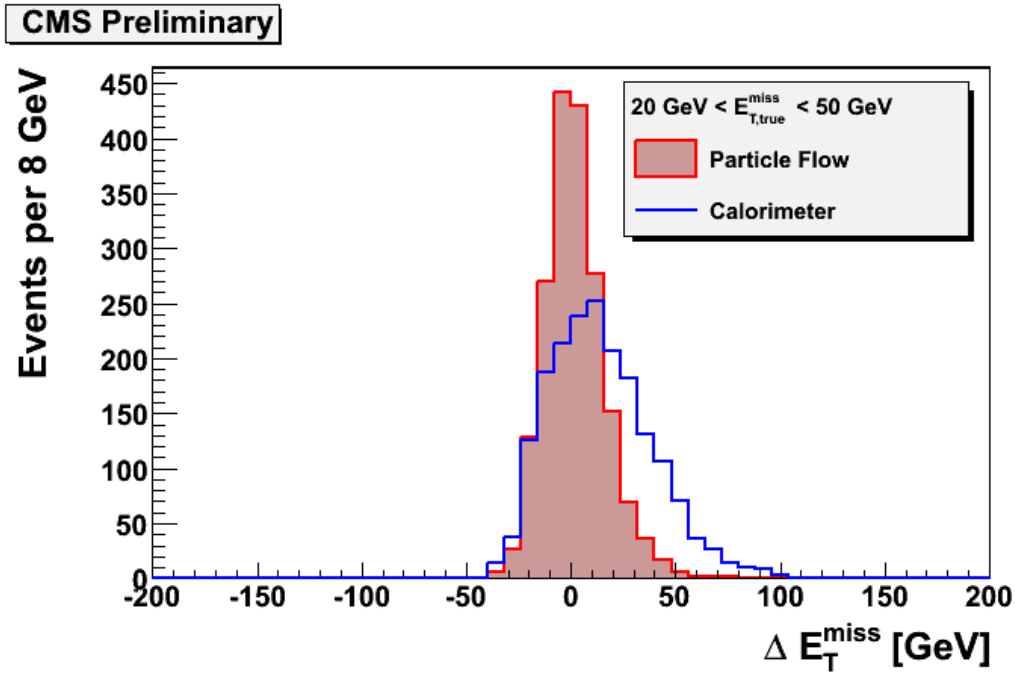
# METX in QCD events

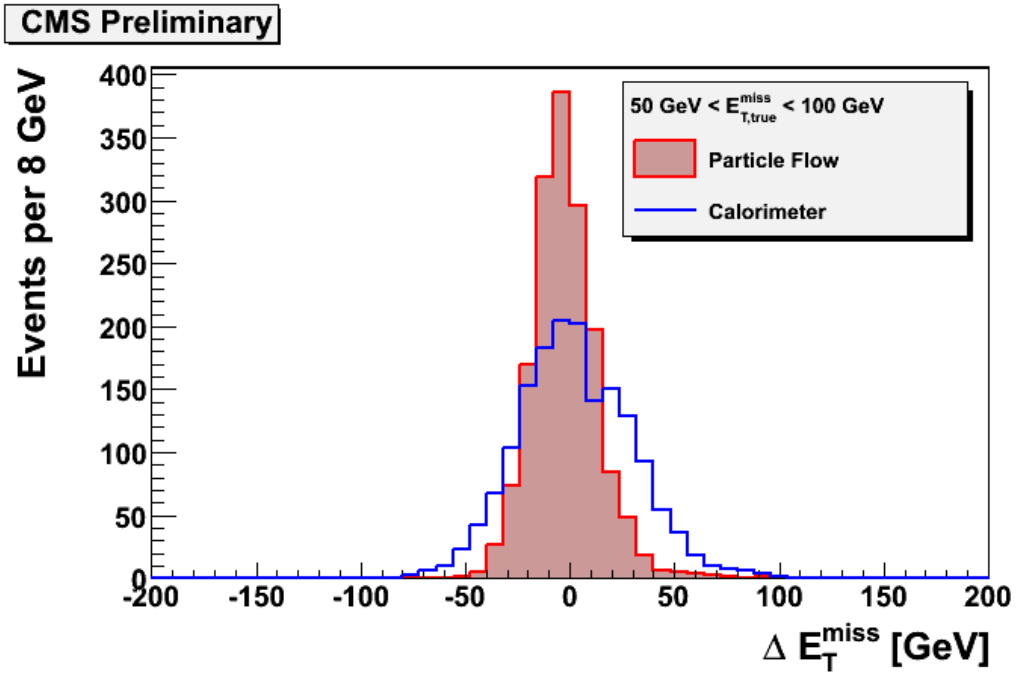
- ~ No MET in QCD events → MET distribution non Gaussian
- METX: MET along a given axis, e.g x
  - METX distribution Gaussian (centred at 0)

Large improvement in MET resolution



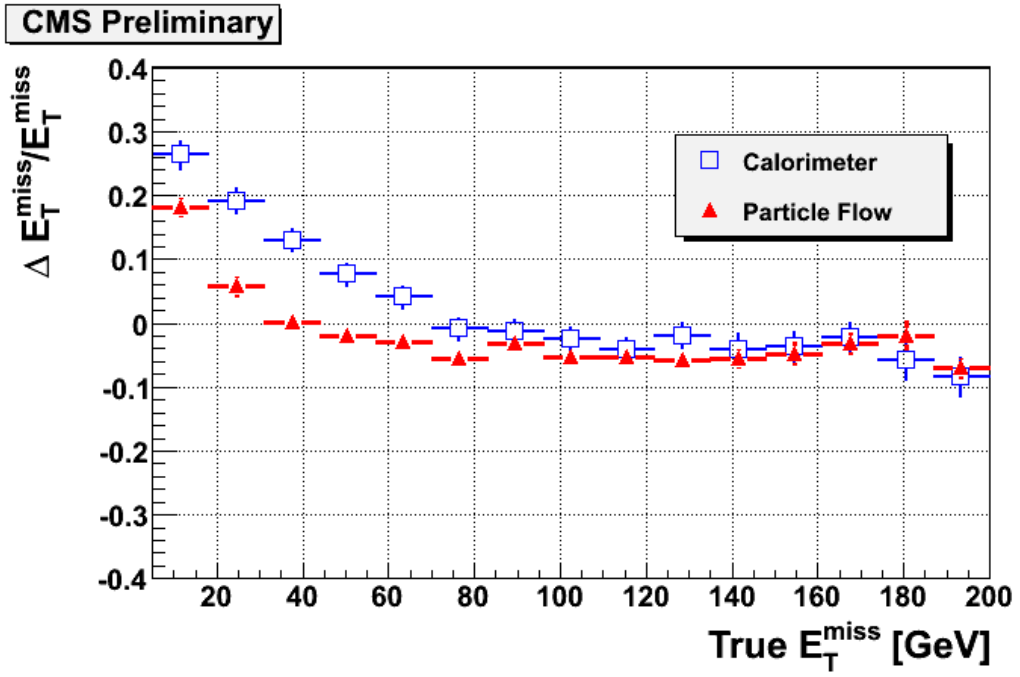
# MET in ttbar events

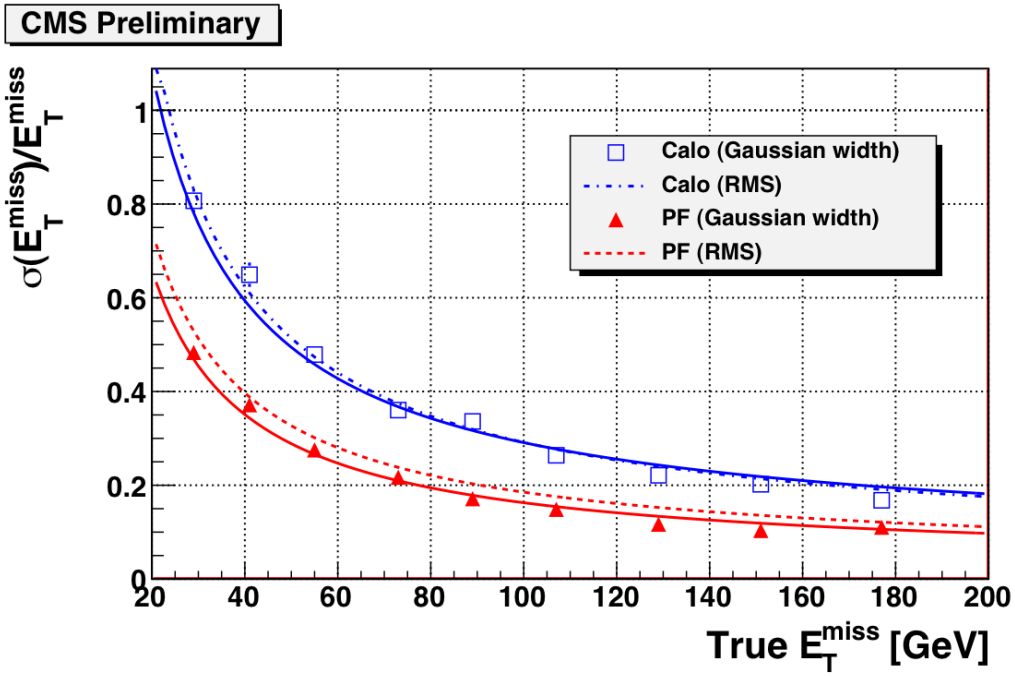



- reconstructed MET – true MET
  - Resolution of particle flow MET ~ twice better.
  - Calorimeter MET overestimated at low MET

# MET in ttbar events

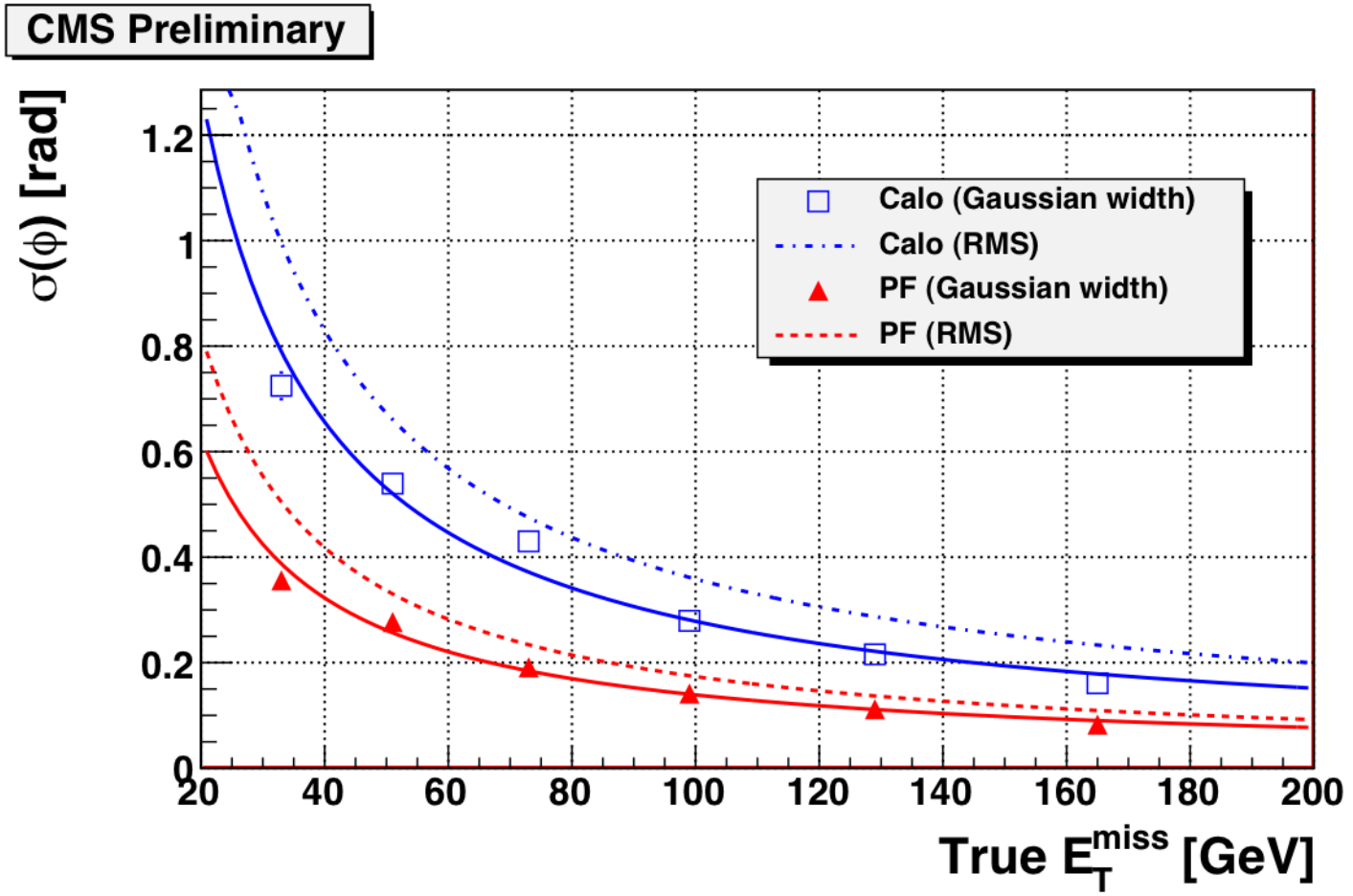



- Response on MET
  - Improved behaviour for low MET events
  - No corrections necessary → lower systematics
- Relative resolution on MET
  - Consistent improvement over the whole range
  - No tails!

# MET angle in ttbar events

- Resolution on MET ϕ
  - important e.g. for the reconstruction of di-τ resonances



# Systematic Studies

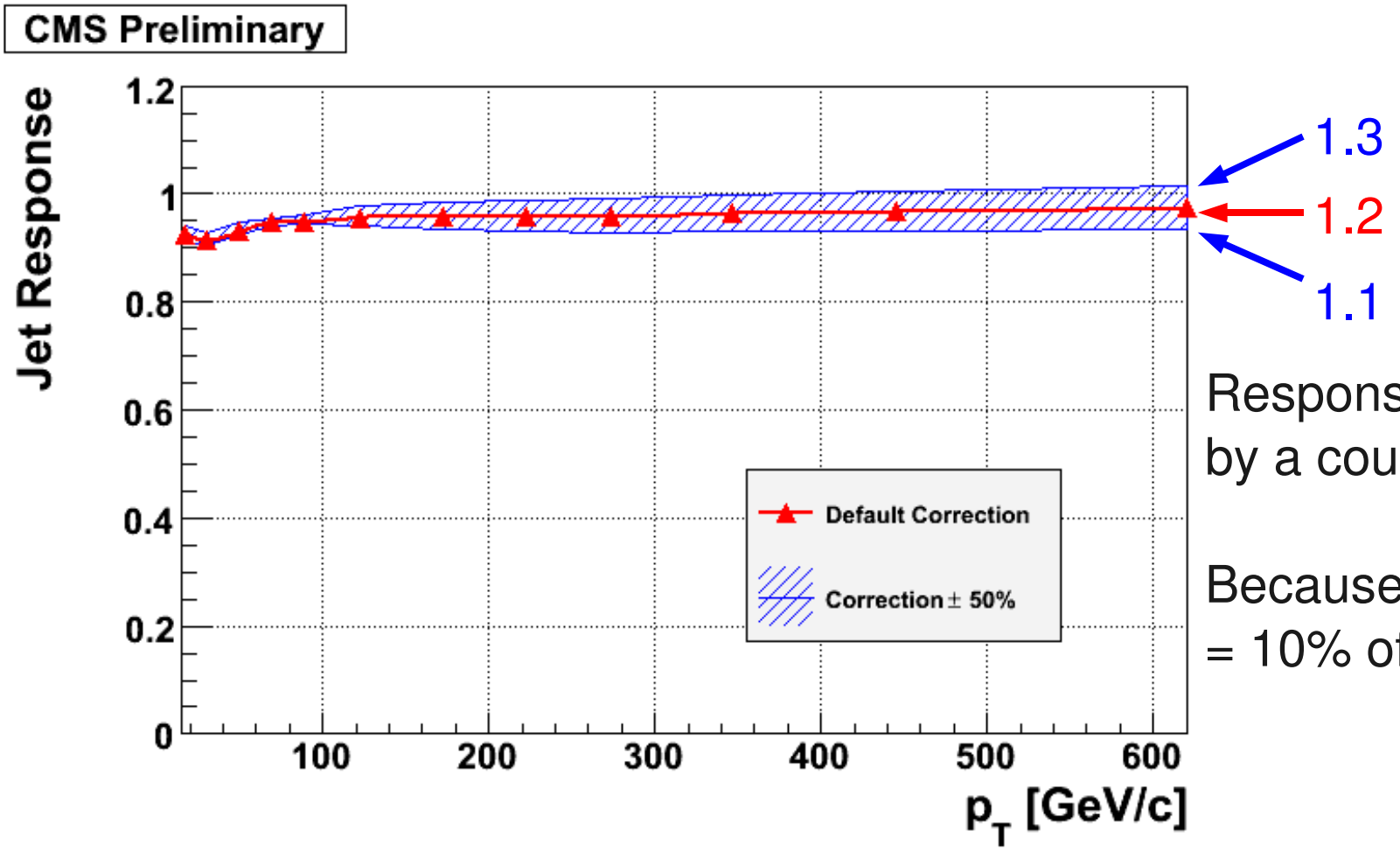
# Systematic effects studied

- Influence of — Very conservative scans parameter scans

| | |
|---|---|
| ◦ a poor modelling of the calorimeter response to hadrons<br>◦ a poor modelling of the calorimeter energy thresholds<br>◦ a poor modelling of the calorimeter energy resolution | Detection of the neutral hadrons and photons |
| ◦ a global reduction of the tracking efficiency. | Detection of charged hadrons |
| ◦ the flavour of the jet-initiating parton | Dominant syst. error on Jet energy correction |

# Systematics: calorimeters

- Poor modelling of the calorimeter response to hadrons
  - Calibration correction factor increased and reduced by 50%.

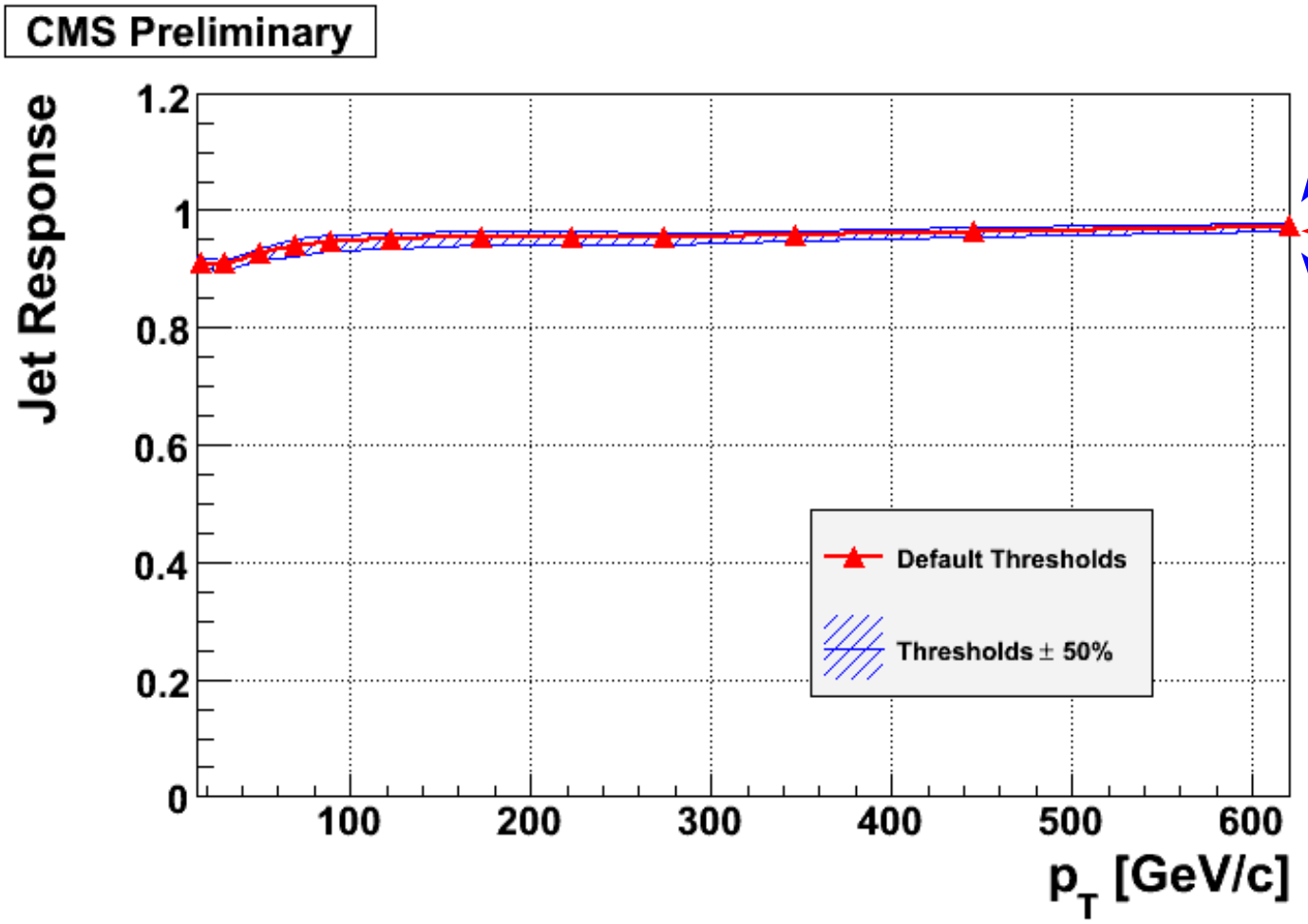



Response changed by a couple % only

Because neutral hadrons = 10% of the jet energy

# Systematics: calorimeters

- Effect of the calorimeter thresholds
  - Thresholds increased and reduced by 50%.




ECAL: 40 MeV
HCAL: 400 MeV

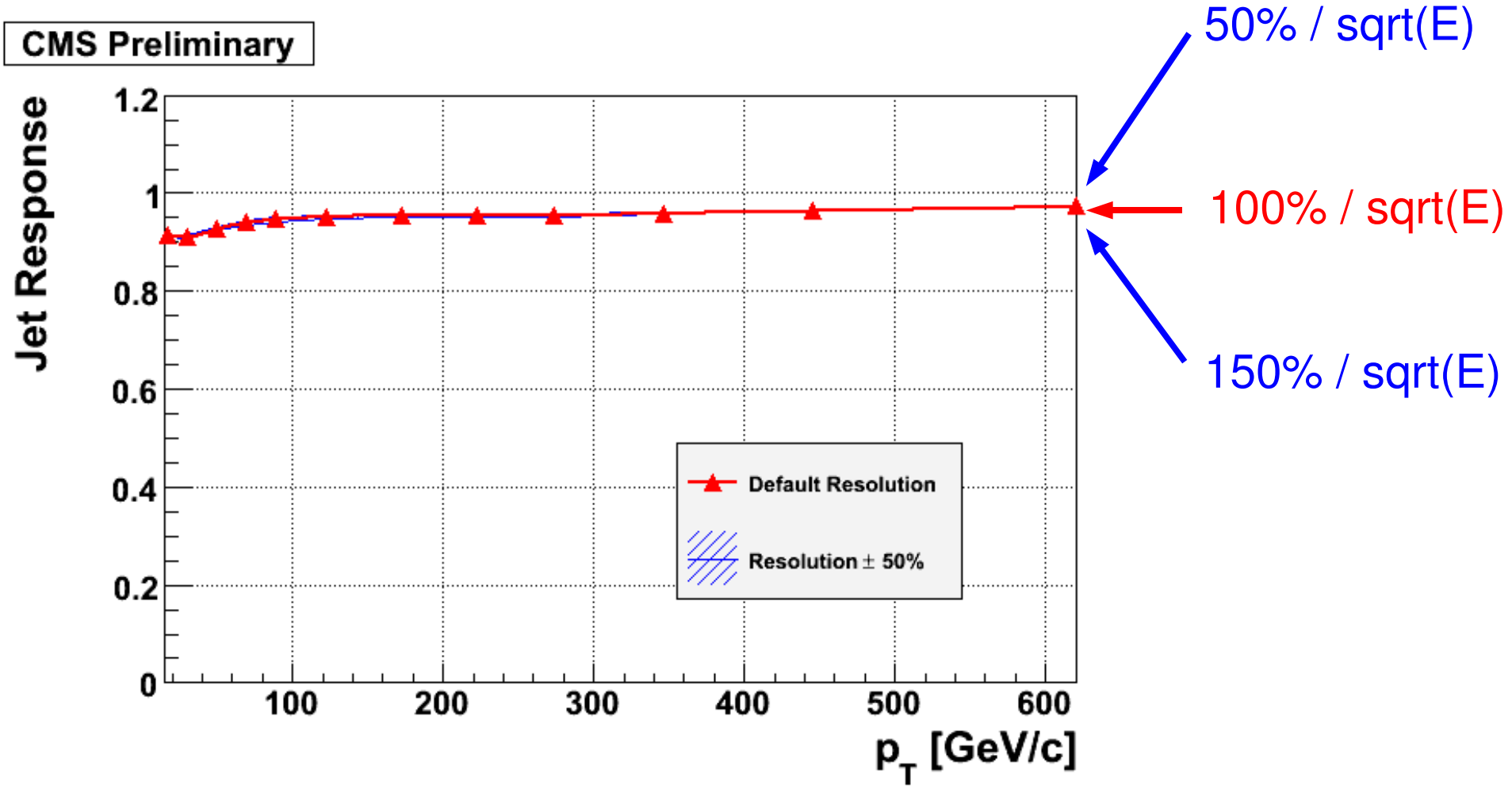
ECAL: 80 MeV
HCAL: 800 MeV

ECAL: 120 MeV
HCAL: 1.2 GeV

Calorimeters supplemented by the tracker

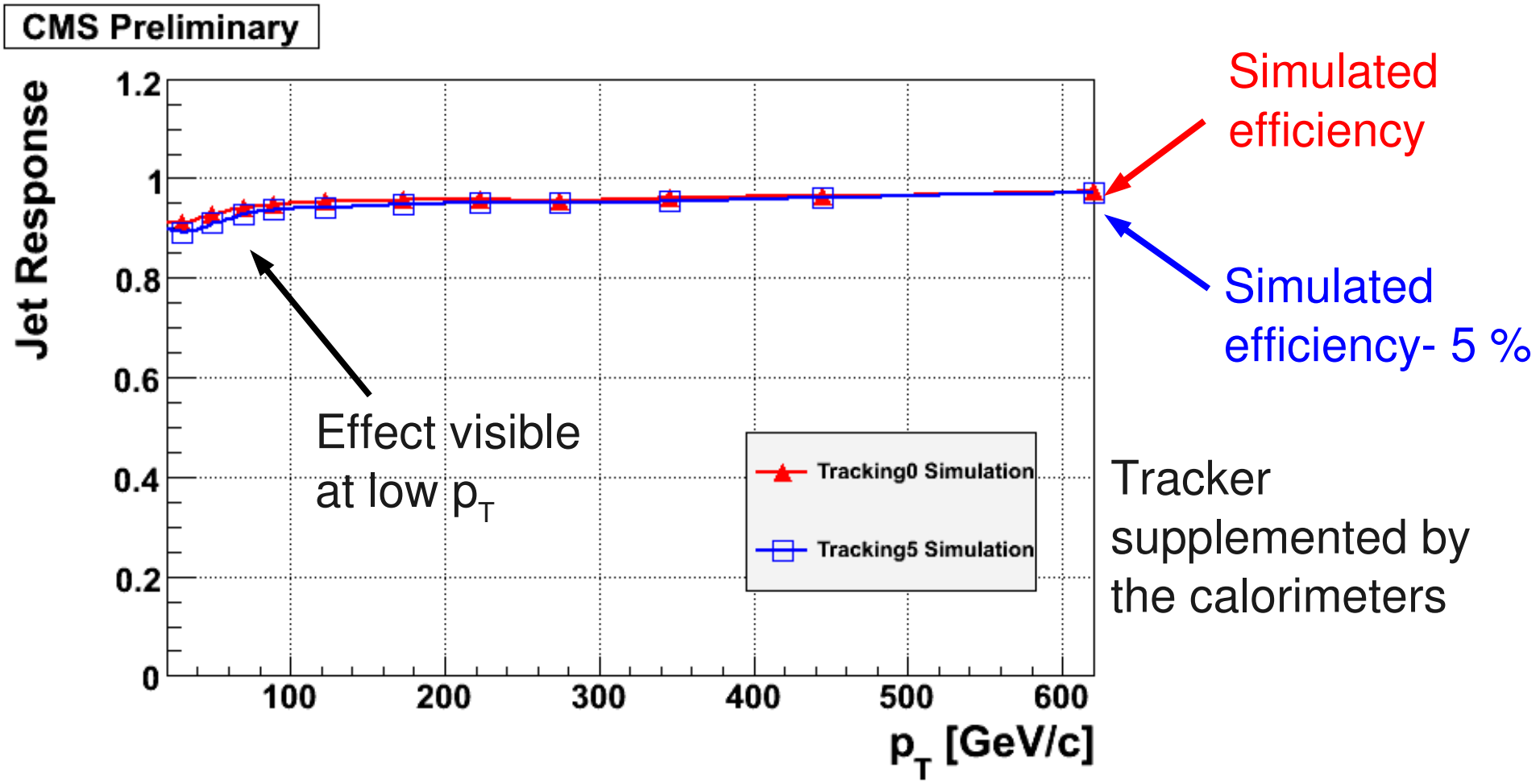
# Systematics: calorimeters

- Effect of a poor modelling of the calorimeter resolution
  - increased and reduced by 50%.



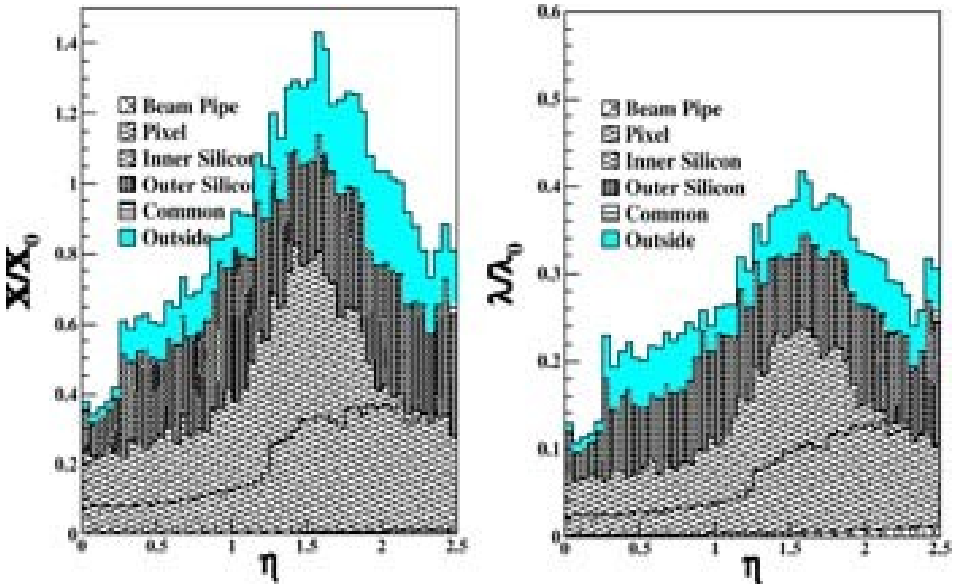
# Systematics: tracking

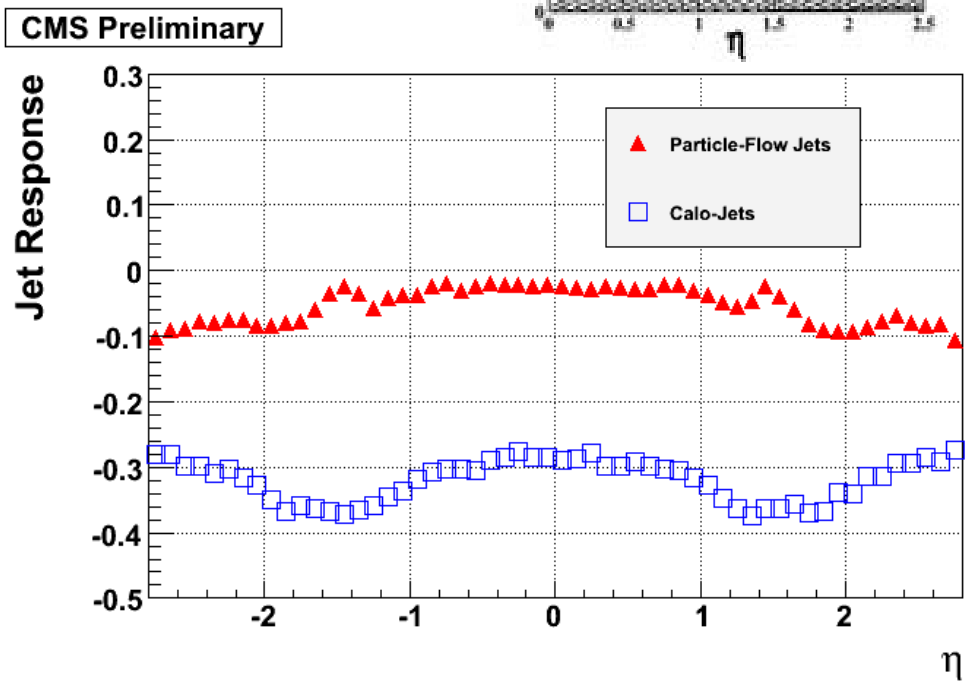
- Global reduction of the tracking efficiency, by 5%



# Systematics: tracking

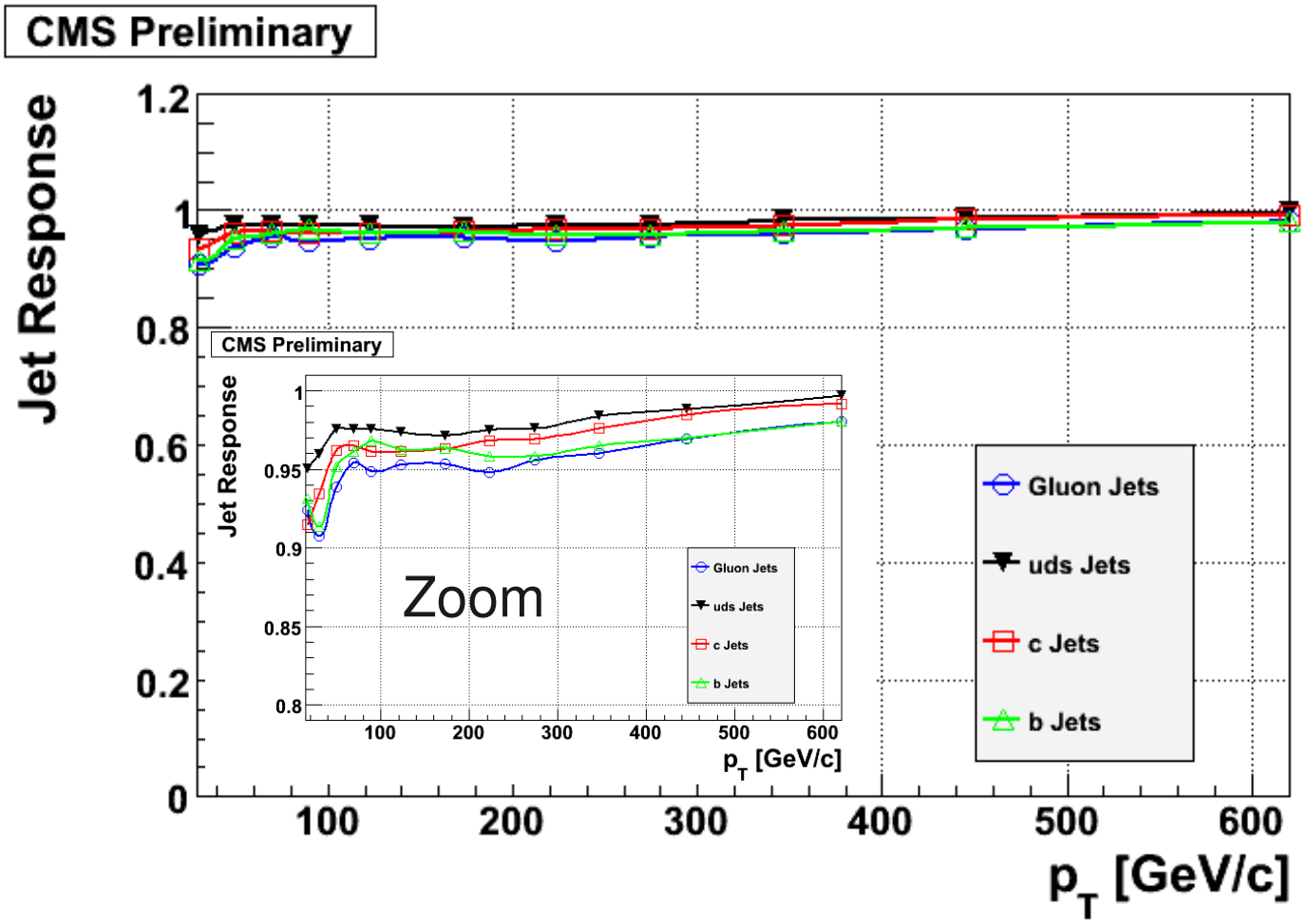
- Effect of the tracker material
  - Factor 4 variation of the amount of tracker material in the barrel
  - No change in the response



# Parton Flavour

- Jet initiators:
  - gluon, light quarks (u,d,s), c quarks, b quarks




Small systematic errors from the unknown flavour of the jet initiating parton!

*Note: neutrinos not included in the reference Gen-Jets*

# Concluding Remarks

# Outlook

- Still a preliminary version of the core particle-flow algorithm
  - → Further improvements of jet, MET and τ reconstruction
- Important extensions
  - electron reconstruction in dense environments
- Systematic use of the particle flow in the analysis:
  - τ identification
  - b tagging (improved jets, electrons in jets)
  - particle-based lepton isolation
  - Particle-based physics analyses
- Set-up particle flow on real data
  - Test beam, first collisions.

# Summary

- Combining the strengths of the various CMS sub-detectors, particle flow allows for a much better reconstruction of the jet, τ and MET.
- Both the energy and direction measurements are improved.
- A high stability of the algorithm is guaranteed by the redundancy of the CMS sub-detectors.
- Most CMS analyses will benefit from the gain.
- Particle flow is just starting to be used, it is only the beginning


And thanks to Matt Groening

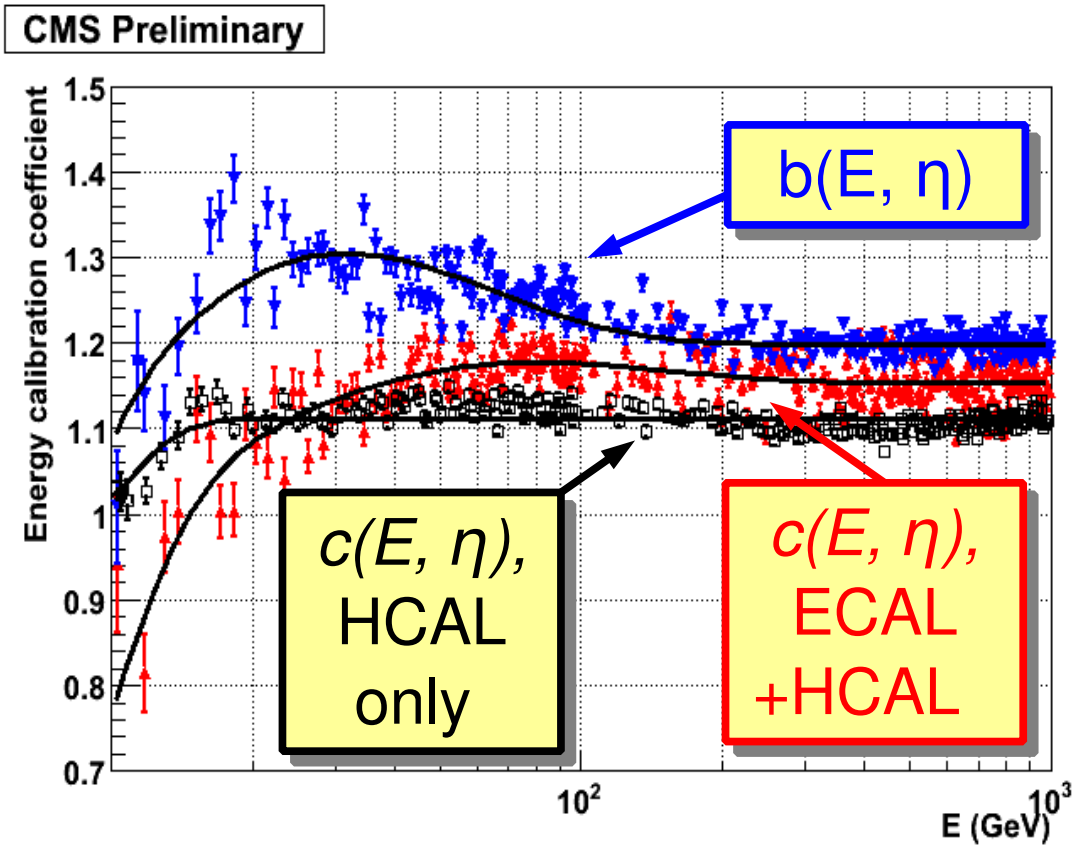
# Back-up

# “Hadron” calibration

- HCAL (+ECAL) cluster energy → estimation of the true energy in the calorimeters

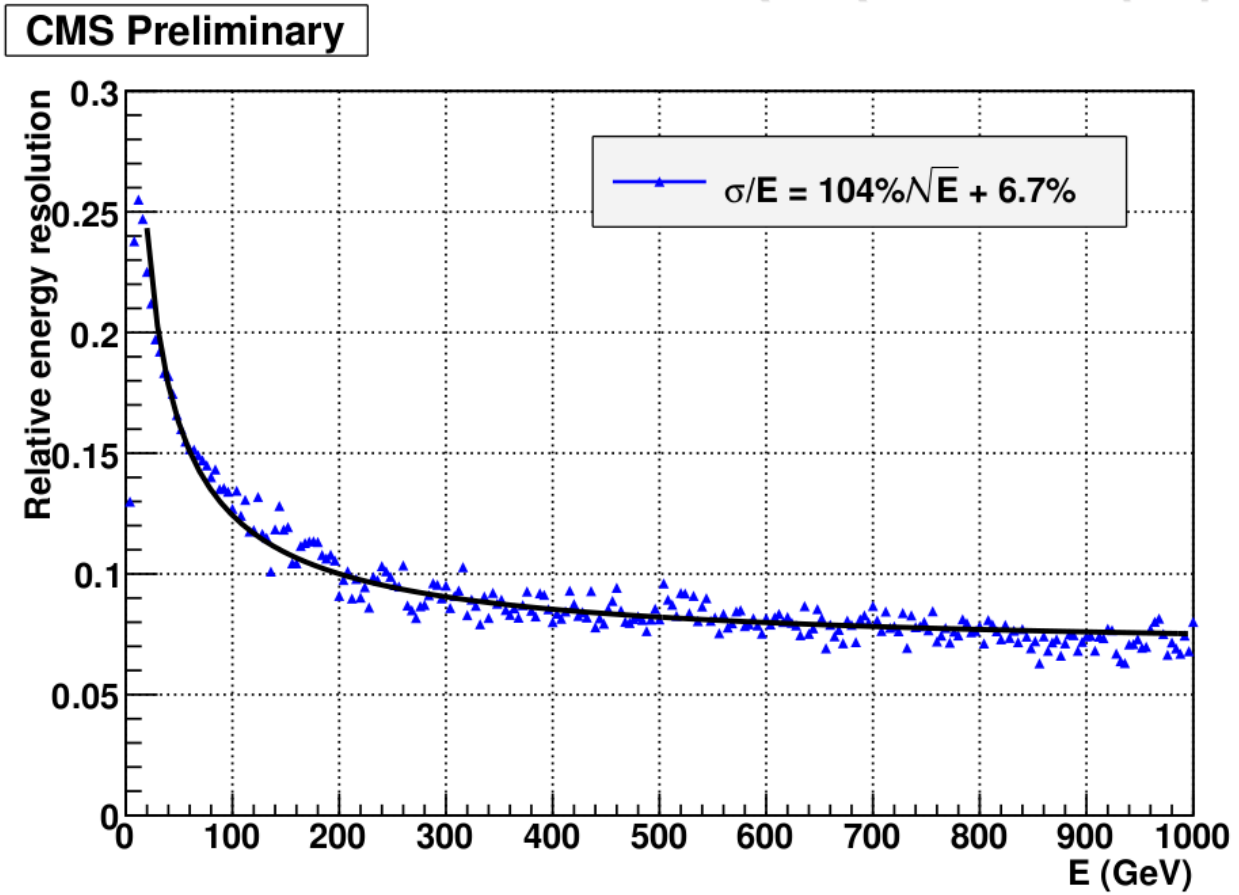
$$E_{\text{calib}} = a + b(E,\eta)E_{\text{ECAL}} + c(E,\eta)E_{\text{HCAL}}$$

- Estimator of the true energy = max of
  - track momentum
  - $E_{ECAL} + E_{HCAL}$
- Parameter determination
  - b and c: fitted
  - a: chosen to minimize the E dependence of b and c

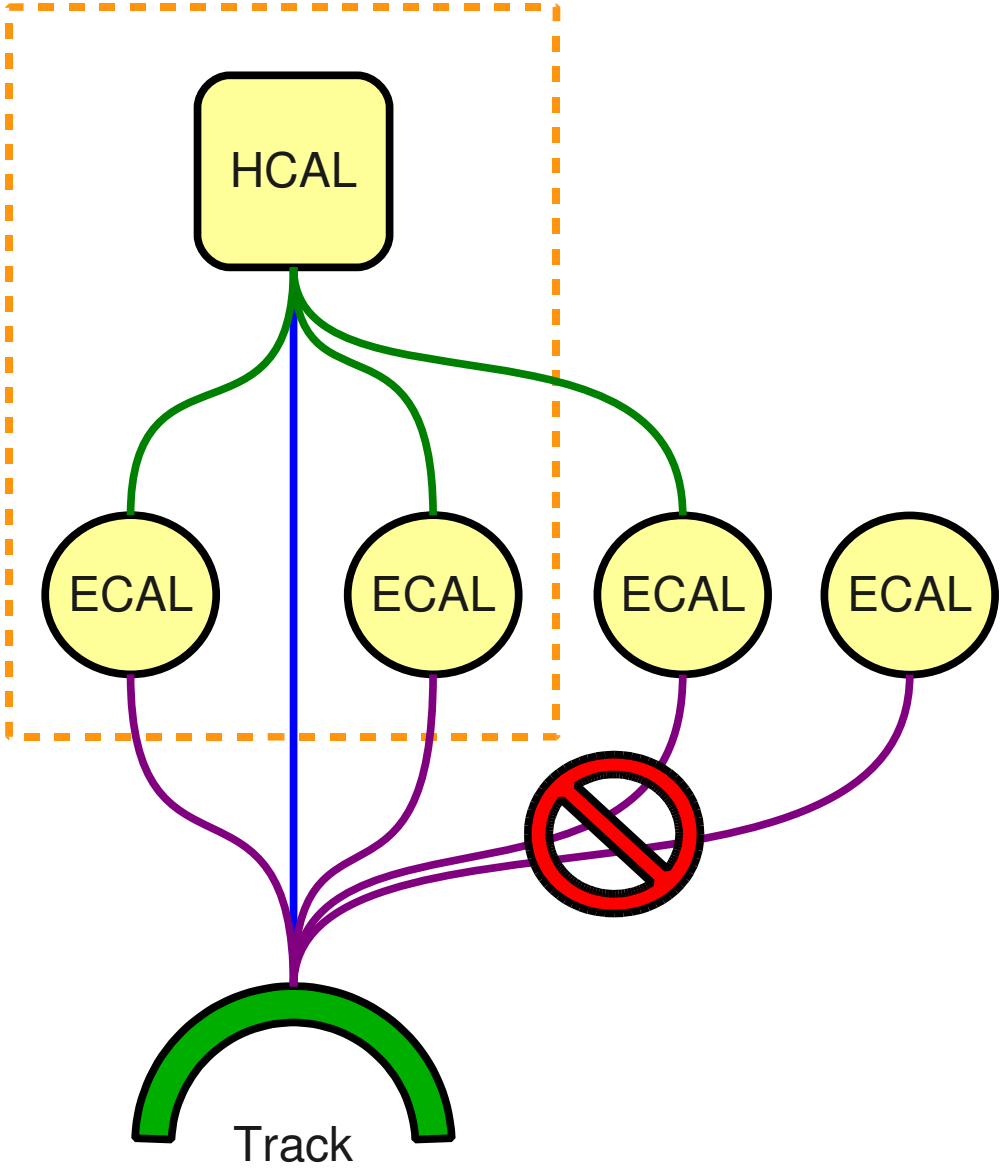


# Single Hadron Resolution

- Relative resolution of the calorimeter system, VS true hadron energy
  - used in the comparison between calorimeter energy and charged energy



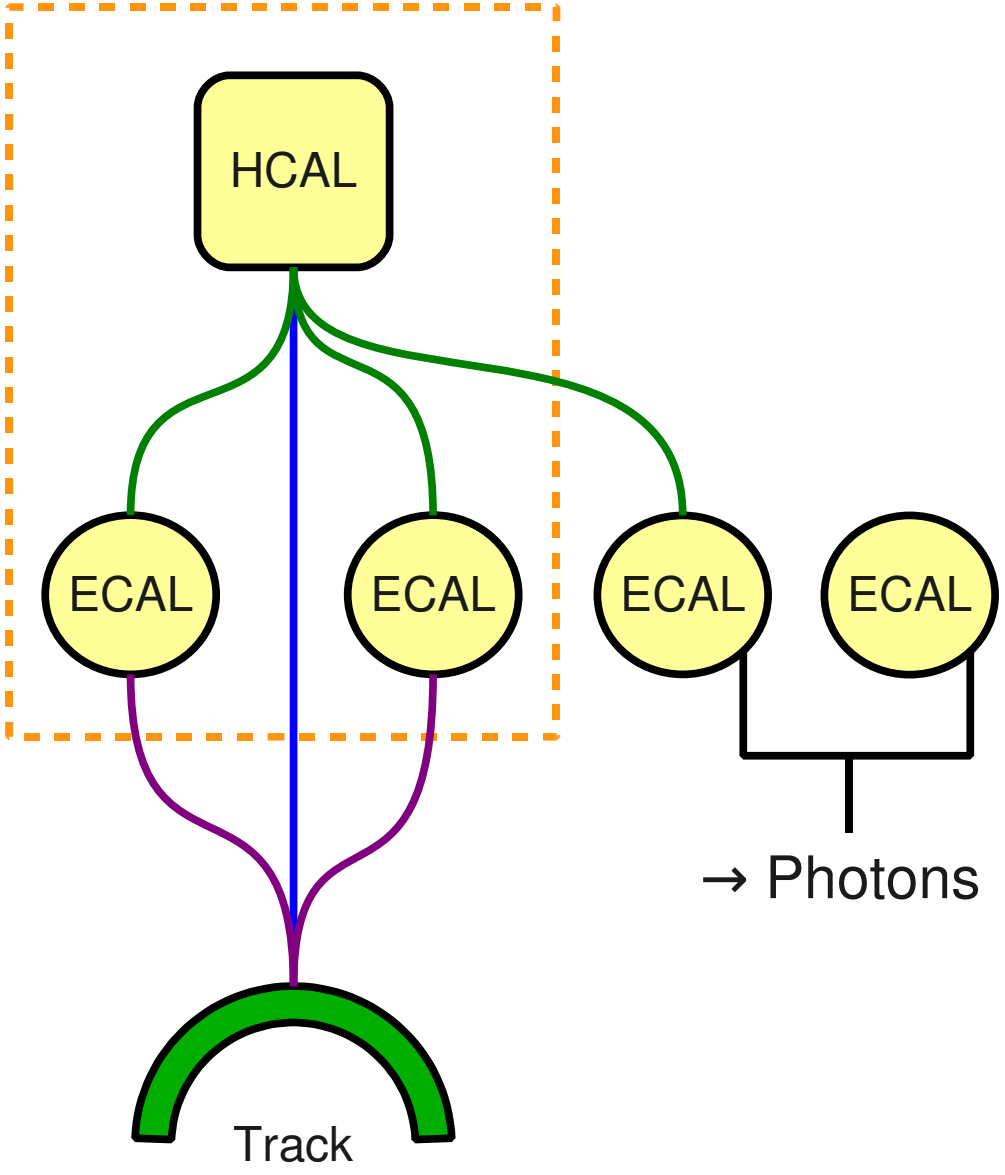
# Subtlety: Multiple ECAL clusters




- For each track
  - Compute
    1- calorimetric energy
    linked to the track
    - Hadron calibration of HCAL (+ECAL)
      *Next slide*
  - Compare to
    2- charged energy
    - track momentum
  - 1 < 2 ?
    - keep the link,
    - add another ECAL, further away from the track

Lines 290-298

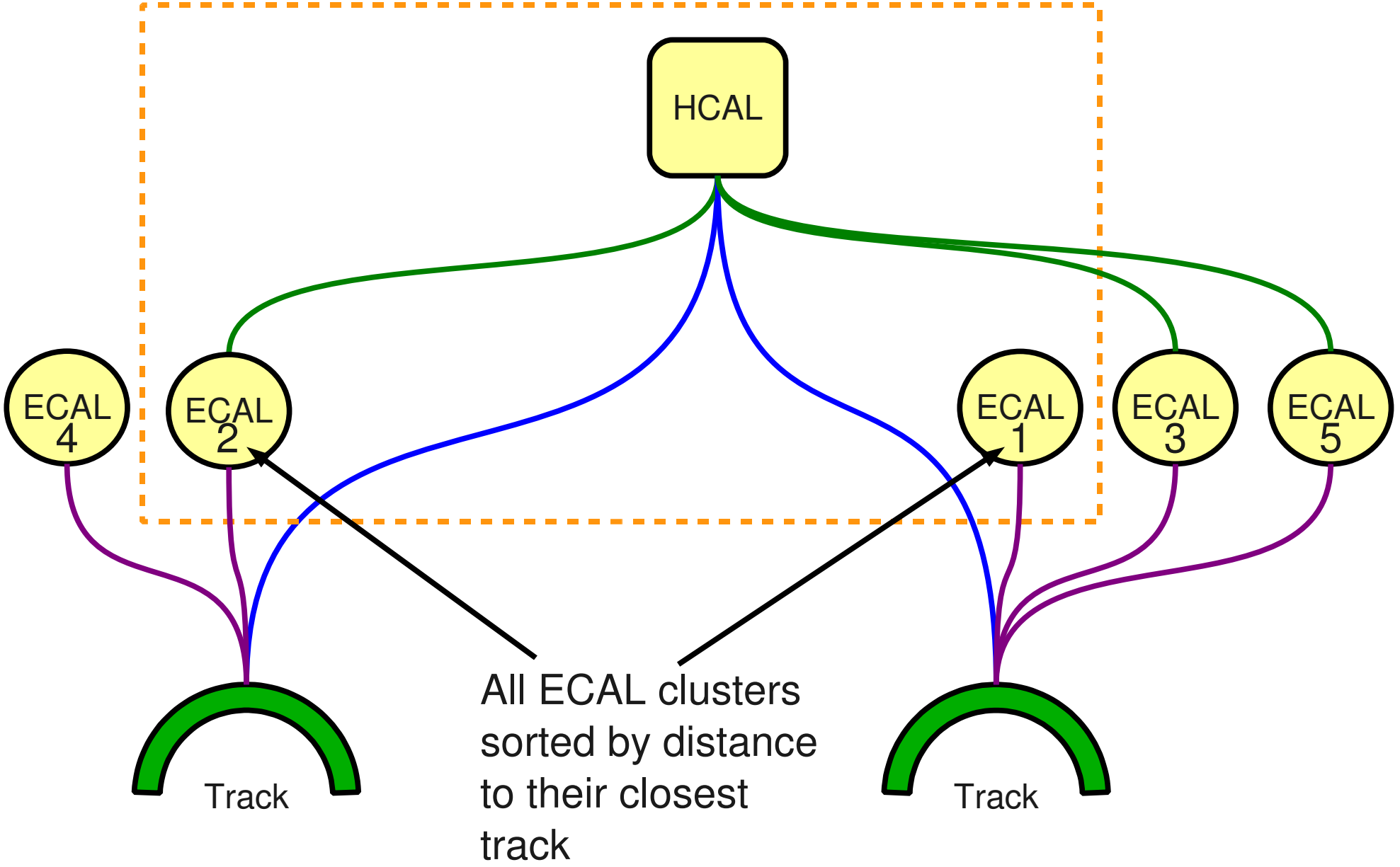
# Subtlety: Multiple ECAL clusters



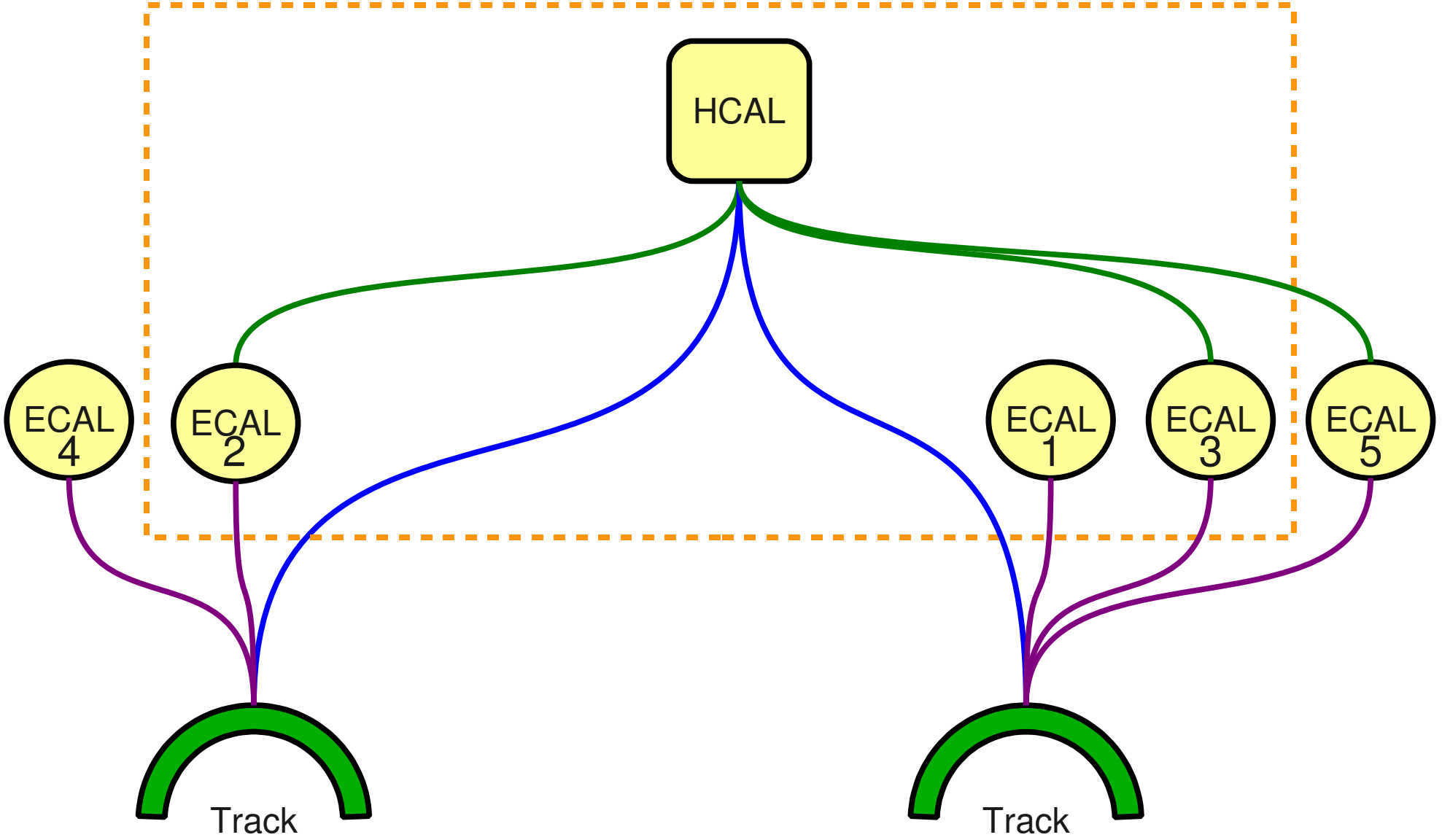

- For each track
  - Compute
    1- calorimetric energy
    linked to the track
    - Hadron calibration of HCAL (+ECAL)
      *Next slide*
  - Compare to
    2- charged energy
    - track momentum
  - 1 < 2 ?
    - keep the link,
    - add another ECAL, further away from the track

Lines 290-298

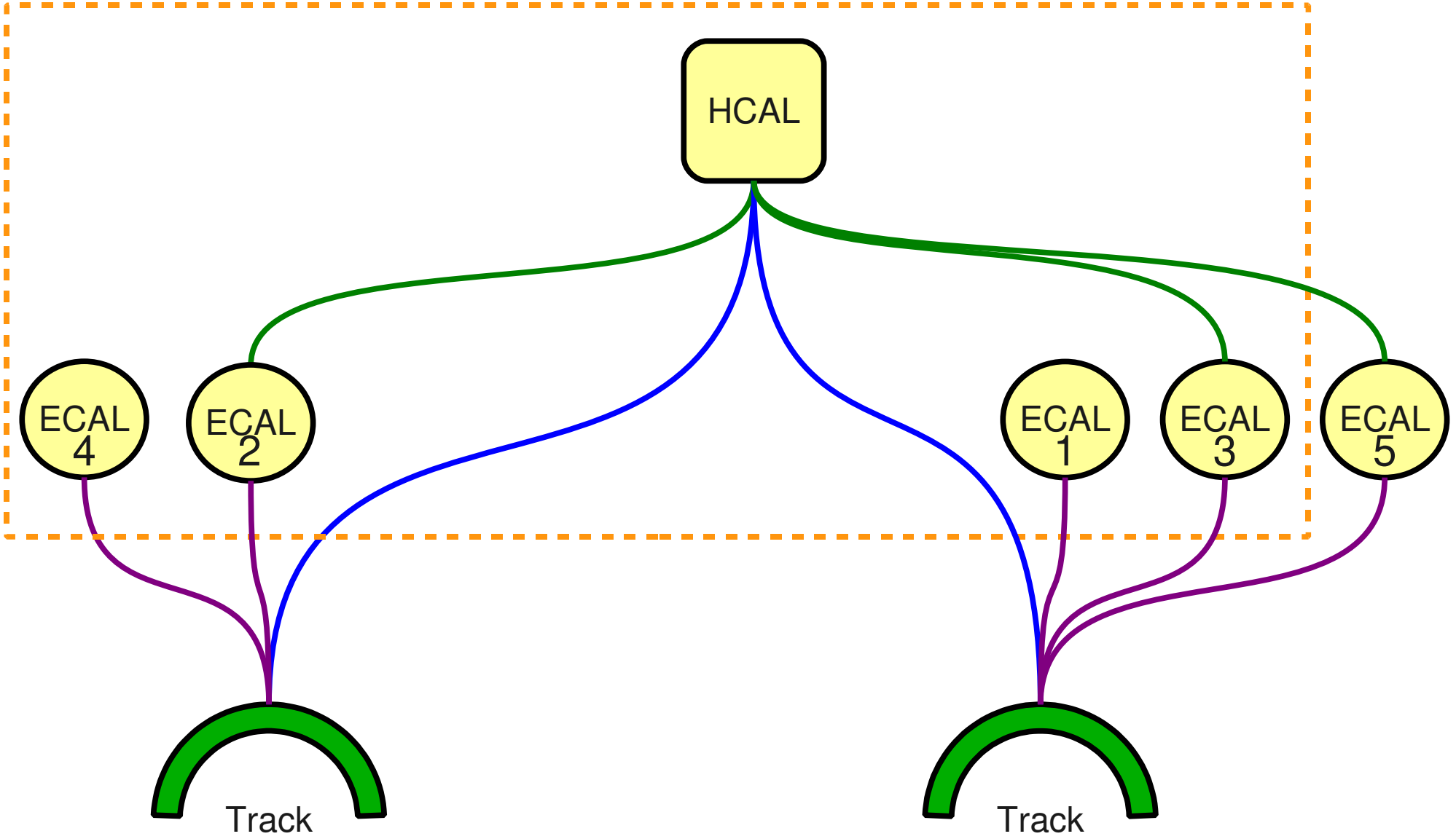
# Subtlety: Multiple Tracks



# Subtlety: Multiple Tracks



# Subtlety: Multiple Tracks



# Subtlety: Multiple Tracks