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Introduction to particle flow in ATLAS

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ATLAS Hadronic Calibration Workshop

14-18 September 2015

Outline

- Introduction to particle flow
  - How does it work in general?

- Why particle flow in ATLAS?

- ATLAS particle flow algorithm step by step:
  - Input Objects (track and all topoclusters)
  - Track-Cluster matching
  - E/p performance
  - Charge shower subtraction
  - Output objects (tracks and neutral clusters)

- Particle flow performance studies (8 TeV data)

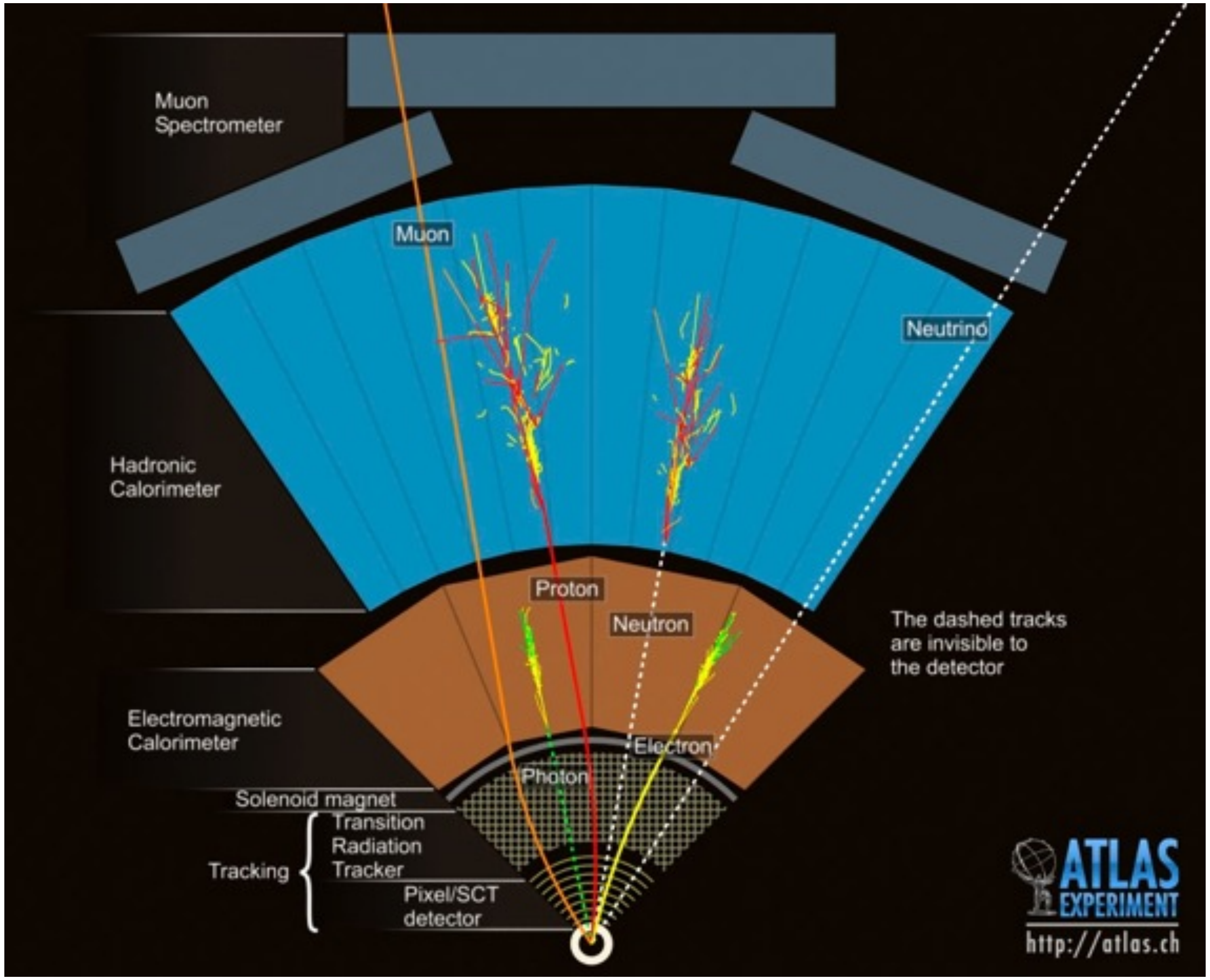
Introduction to Particle Flow

Particle Flow algorithms try to follow the path of the particles through the detector.

Main goal is to improve the energy resolution of the hadronic objects

How to do it? combining the information from different sub-detectors

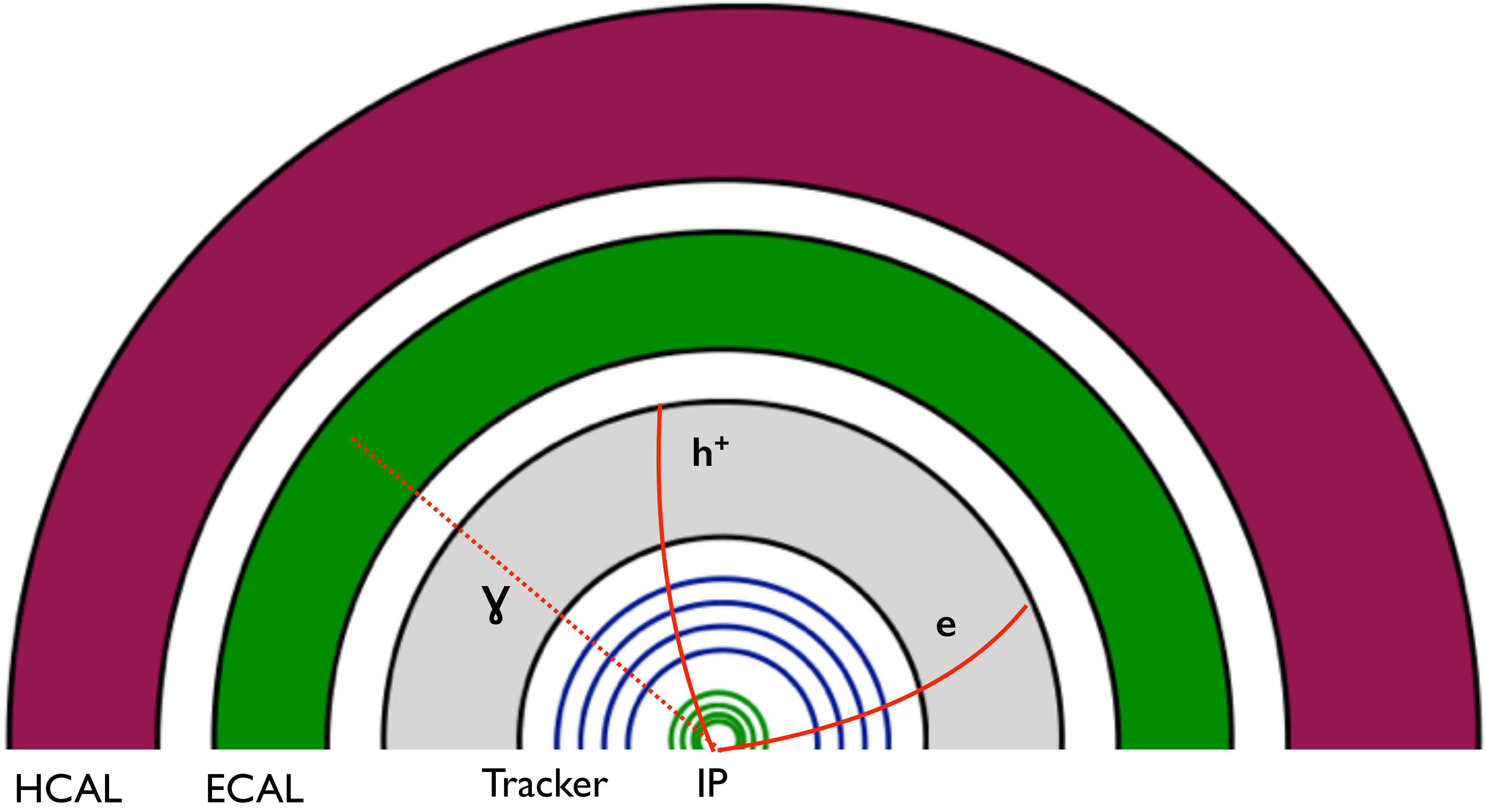
➡ Emphasise the role of the tracker in jet physics.



Introduction: Particle Flow principle

How does Particle Flow work?

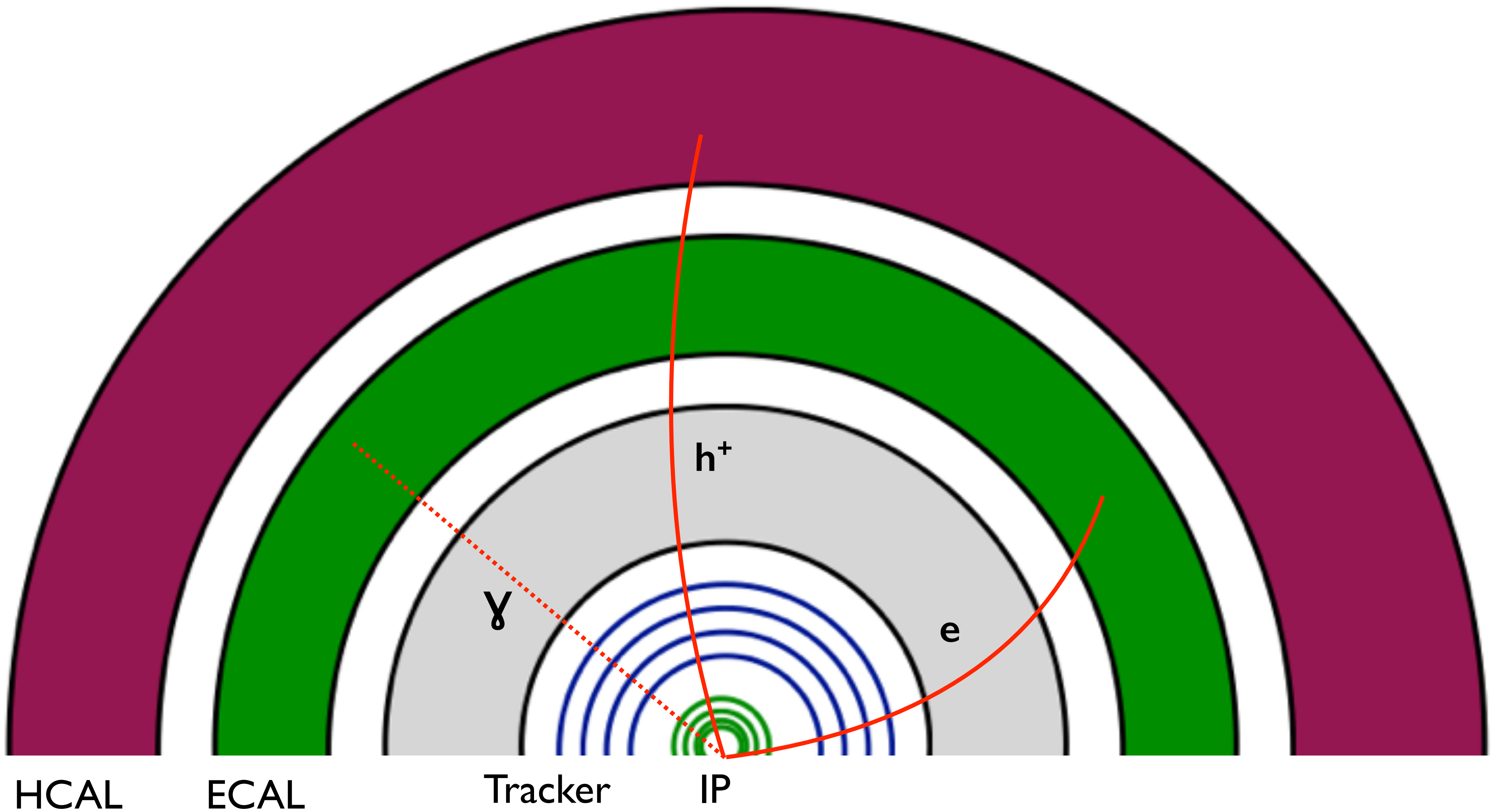
- Track reconstruction in the Inner Detector



Introduction: Particle Flow principle

How does Particle Flow work?

- Track reconstruction in the Inner Detector
- Extrapolate the tracks to the calorimeter system



Introduction: Particle Flow principle

How does Particle Flow work?

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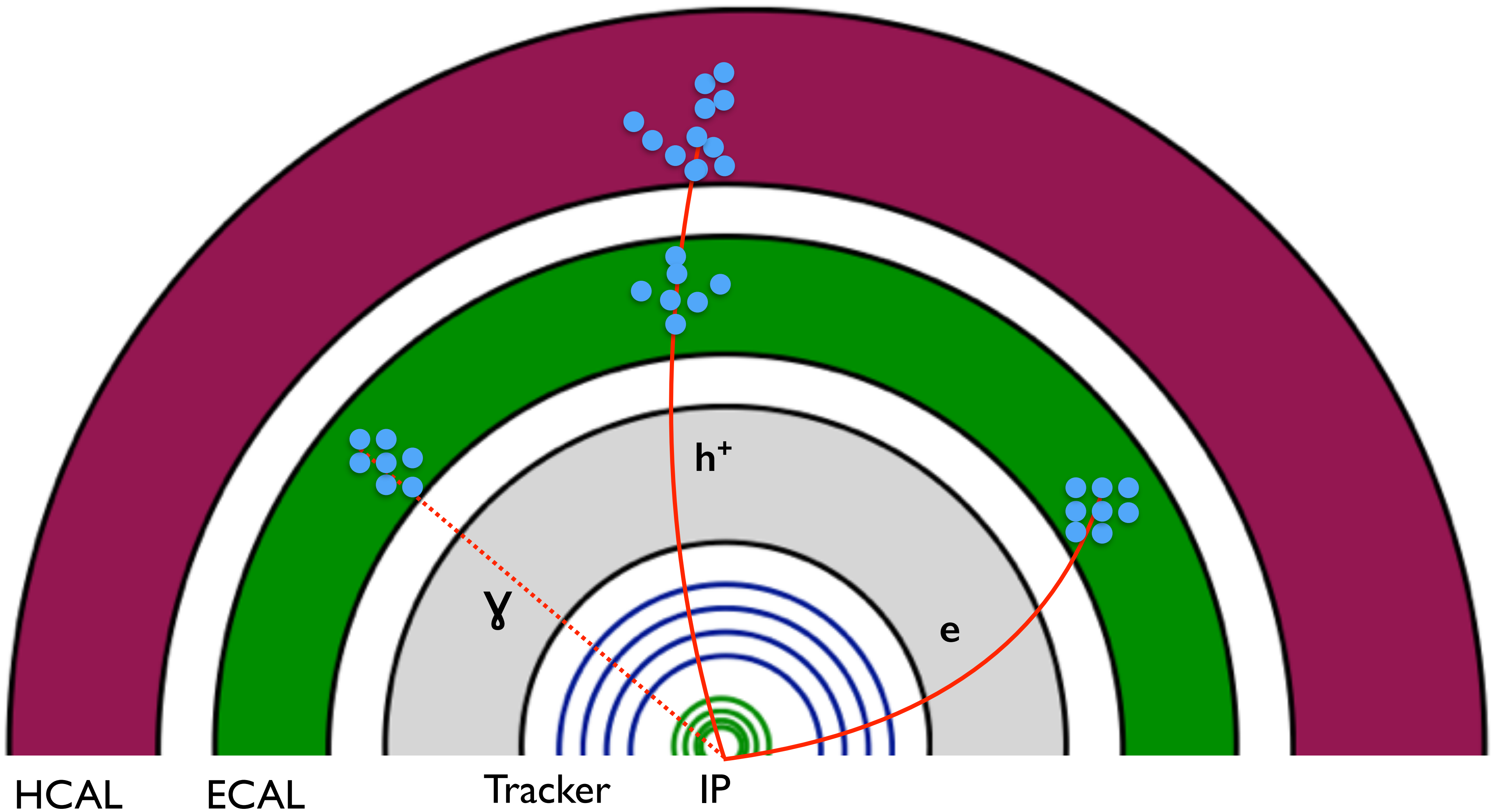
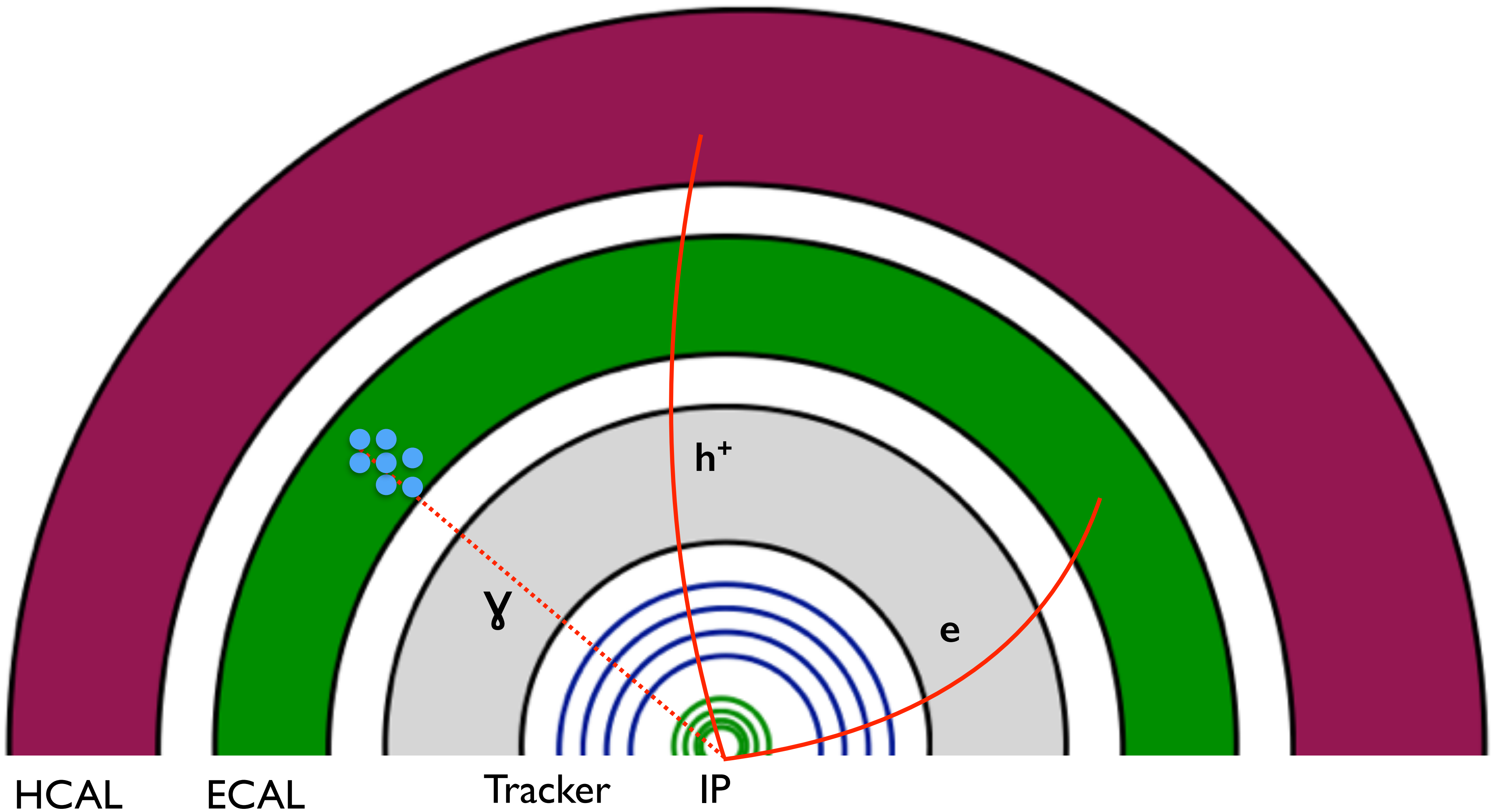
- Extrapolate the tracks to the calorimeter system
- Match the tracks to the calorimeter clusters



Introduction: Particle Flow principle

How does Particle Flow work?

- Track reconstruction in the Inner Detector
- Extrapolate the tracks to the calorimeter system
- Match the tracks to the calorimeter clusters
- Remove energy from charge particle in the calorimeter: tracks and energy clusters from neutral particles are kept

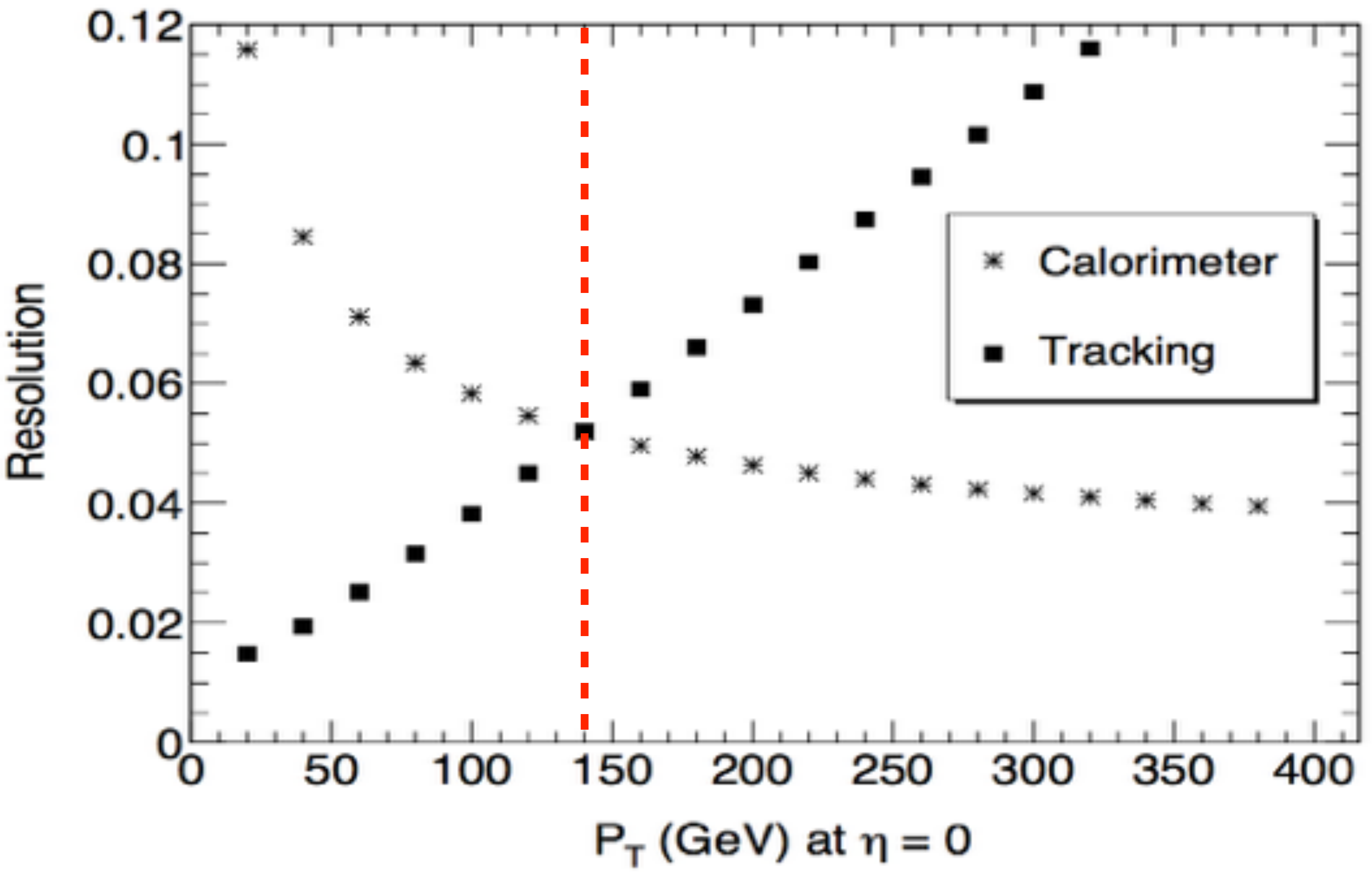


Why Particle flow in ATLAS?

Some reasons for using particle flow in ATLAS:

- The tracker resolution is significantly better than the calorimeter resolution at low p_T
- Low p_T particles, which not pass the threshold required to create a topocluster, can be measured by the tracker
- Better angular resolution of the tracker compared with the calorimeter for single particles
- When the track is reconstructed, the vertex information from which the track comes, can be used to mitigate the pileup contribution
- Calorimeter's ability to reconstruct neutral particles

Particle flow algorithm (eflowRec) decides to use the tracker information or the calorimeter information or a combination of both



Particle flow low-level performance studies

Important quantities for pflow performance studies

Useful for track-cluster matching:

- **Efficiency**: sum of the energy deposited by the true particle in the topo-cluster divided by the total energy deposited by the particle in the calorimeter

$$\epsilon = \frac{\Sigma E_{CalHit}(cluster)}{\Sigma E_{CalHit}(all\ clusters)}$$

- **Purity**: sum of the energy deposited by the true particle in the topo-cluster divided by the sum of the energy of all true particles in this cluster

$$\rho = \frac{\Sigma E_{CalHit}(cluster)}{\Sigma E_{CalHit}(all\ true\ particles\ in\ the\ clusters)}$$

Useful for subtraction studies:

- **R^0**: true neutral energy left after subtraction

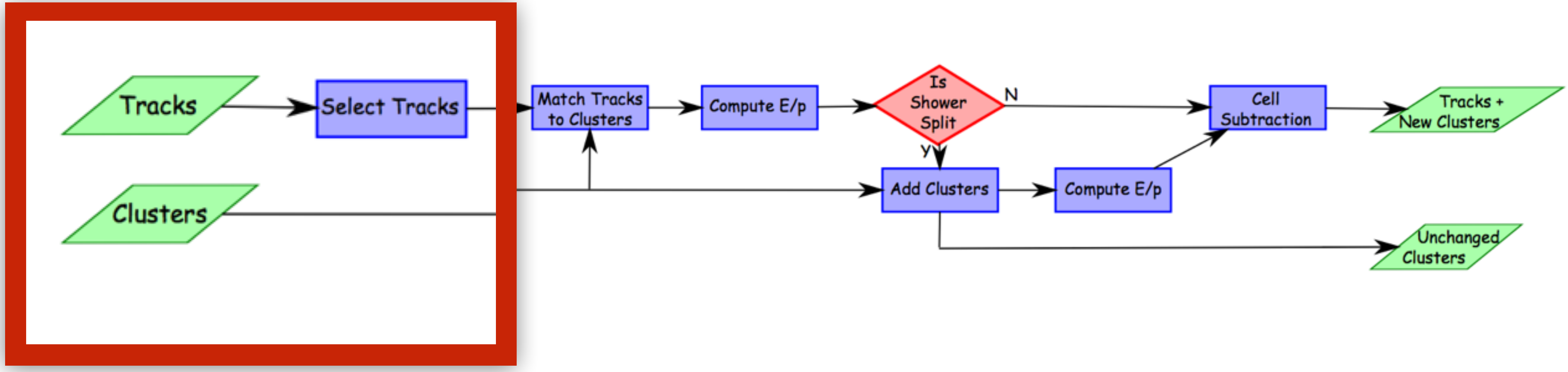
$$R^0 = \frac{\sum_{\text{neutral}} E_{\texttt{CalHit}}(\text{after subtraction})}{\sum_{\text{neutral}} E_{\texttt{CalHit}}(\text{before subtraction})}$$

- **R^+**: true charged energy subtracted

$$(1 - R^+) = 1 - \frac{\sum_{\text{charged}} E_{\texttt{CalHit}}(\text{after subtraction})}{\sum_{\text{charged}} E_{\texttt{CalHit}}(\text{before subtraction})}$$

Overview of the eflowRec chain:

1. Input objects selection:

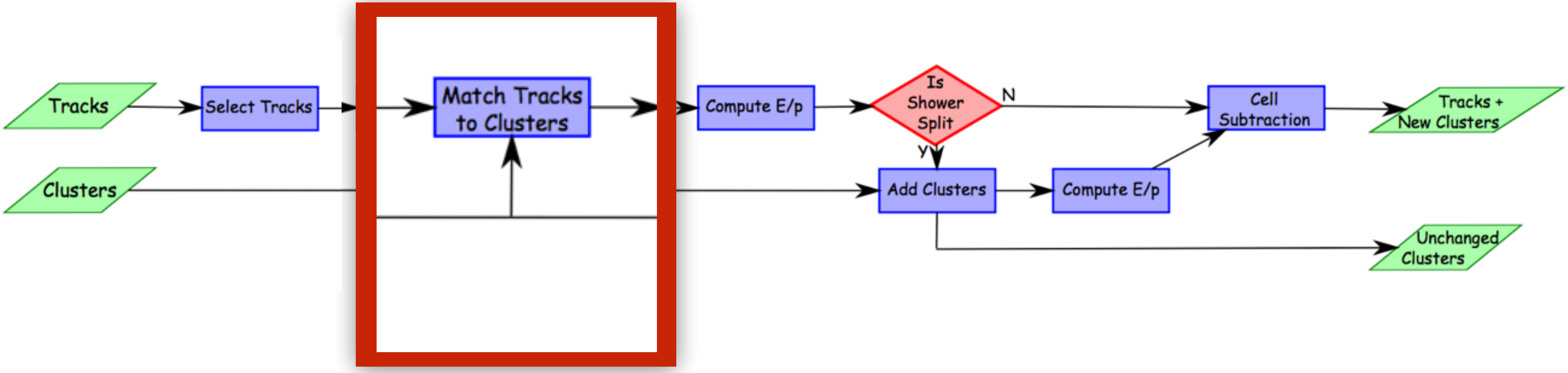


- **Tracks:** selected tracks with a reliable set of properties
  - Run 1:
    - $N_{(PIX+SCT)hits} > 9$ & $N_{(PIX)holes} = 0$ (*minimise the number of fake tracks*)
  - Run 2:
    - Tracking group tight track selection
  - $|\eta|<2.5$ & $p_T > 500$ MeV
  - $p_T < 40$ GeV

- **Topological clusters:** all considered

Overview of the eflowRec chain:

2. Track-Cluster matching:



To remove the energy deposited in the calorimeter → match each track to a cluster

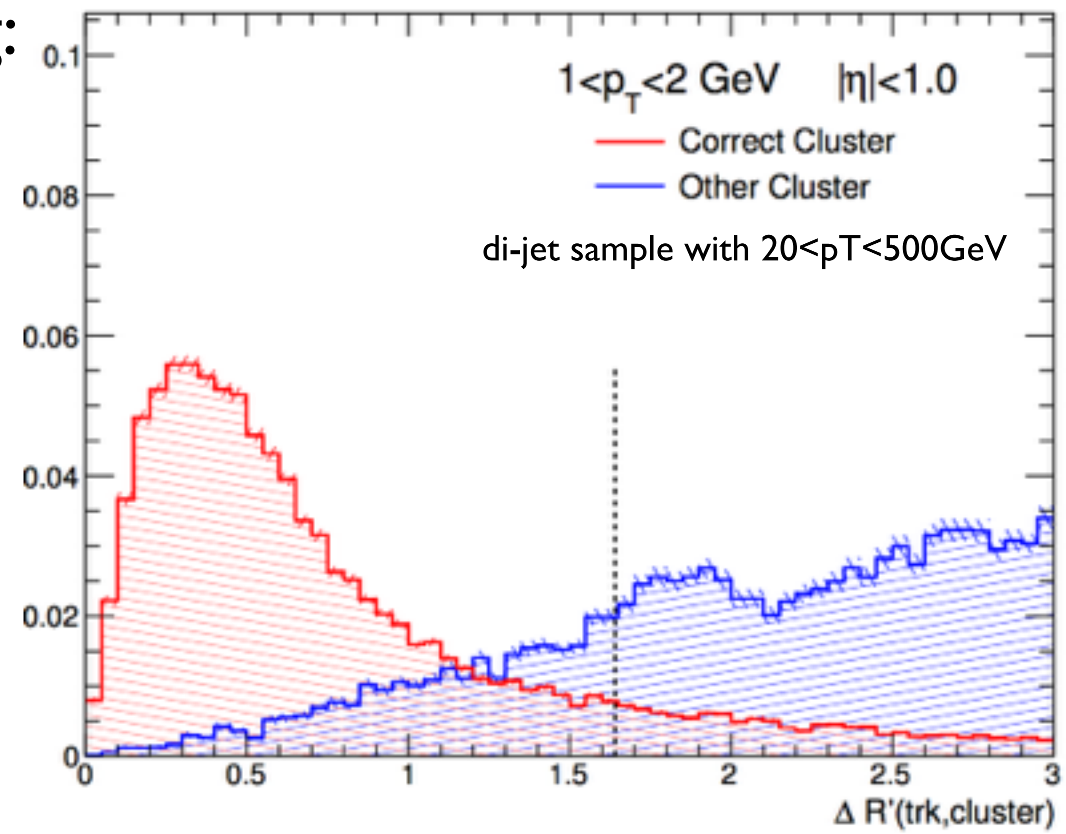
- Each track is extrapolated to the 2nd layer of the EM calorimeter
- The nearest topological cluster is found using:

$$\Delta R' = \sqrt{\frac{(\eta_{\text{track}} - \eta_{\text{clus}})^2}{\sigma_\eta^2} + \frac{(\phi_{\text{track}} - \phi_{\text{clus}})^2}{\sigma_\phi^2}}$$

$\sigma_{\eta,\phi}$ of the cluster width

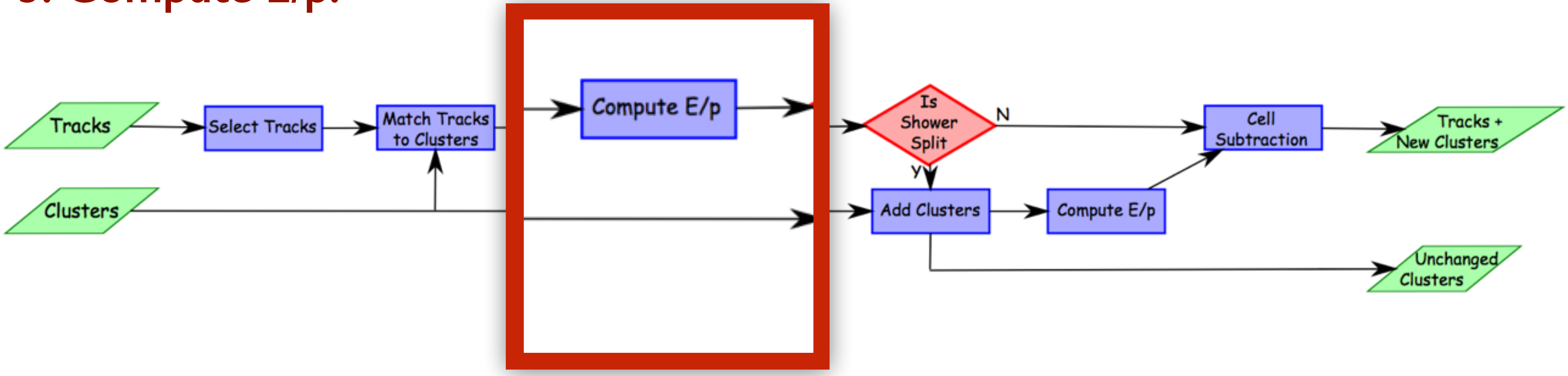
Correct cluster = cluster with E_{cl}>90% E_{true}

Other cluster = next closest cluster



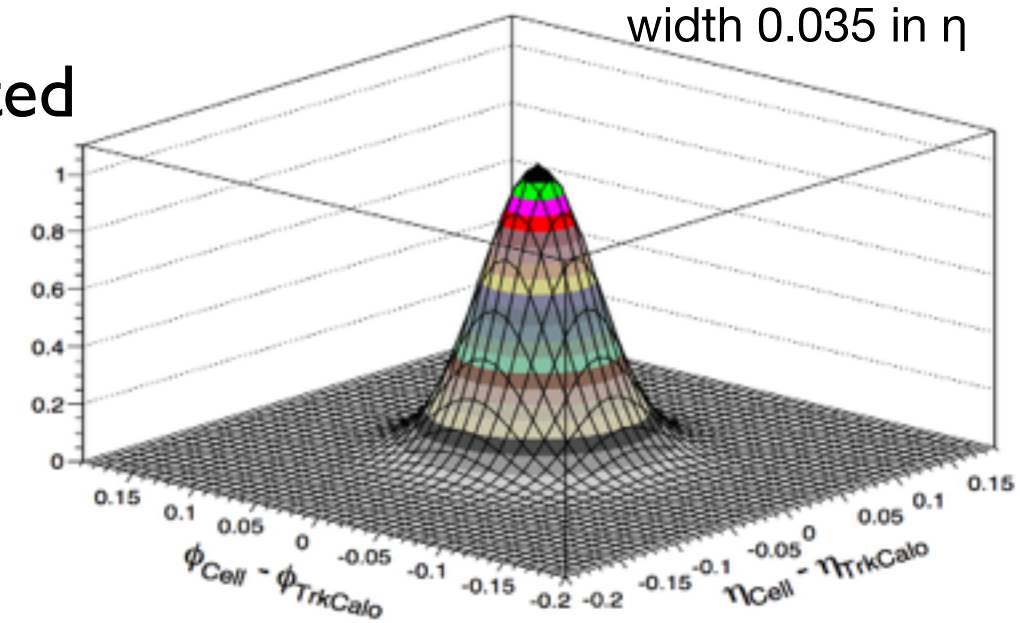
Overview of the eflowRec chain:

3. Compute E/p:



To remove the energy in the calorimeter → how much energy is expected where?

- **LHED** = layer of highest energy density
  - Motivation: find and remove the dense EM core of the shower
  - How to proceed?
    - Scale the cells around the tracks extrapolated position using a Gaussian
    - Calculate the average energy density per radiation length in each layer <ρi'>
    - Take the layer with larges <ρi'>



Overview of the eflowRec chain:

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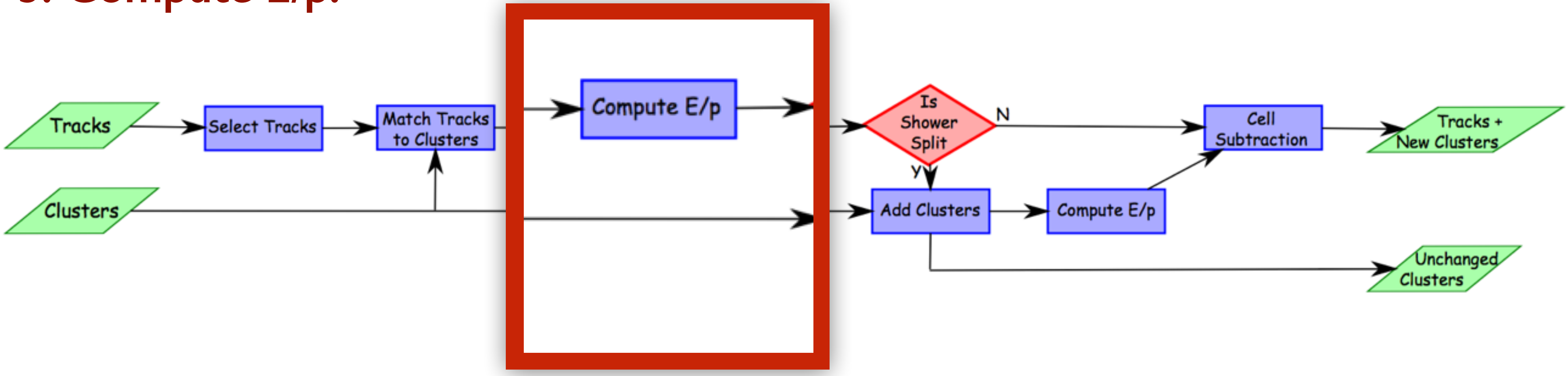
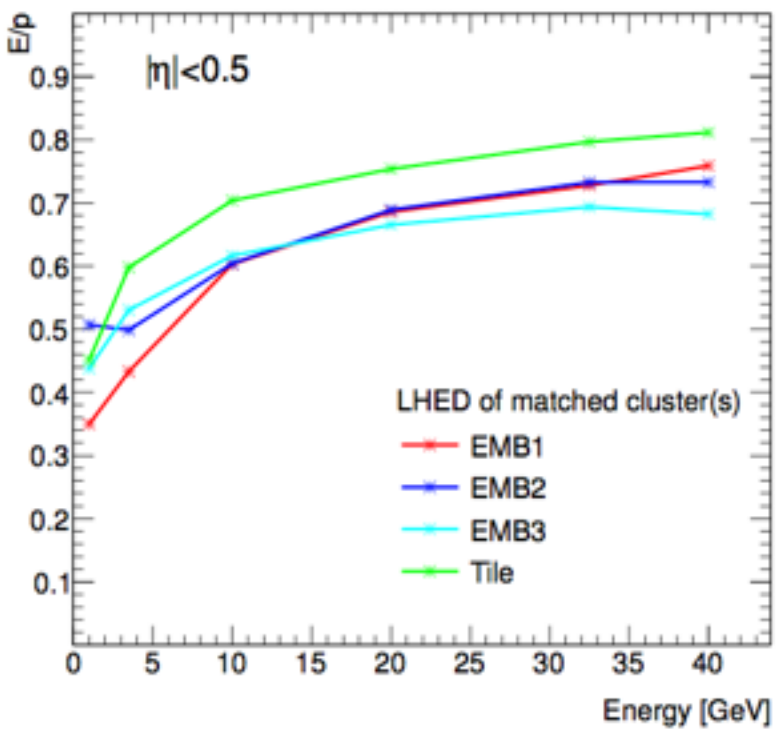
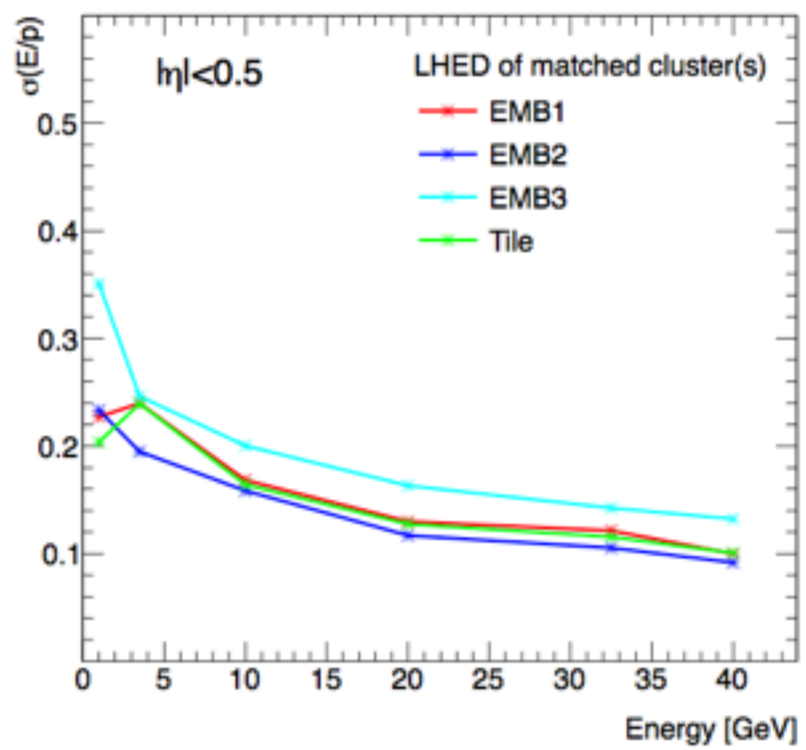


To remove the energy in the calorimeter → how much energy is expected where?

- E/p: ratio of the E deposited in the calorimeter divided by the p of the track.
  - Single particle samples used to determine E/p
  - E obtained as sum of the clustered E in a cone ΔR<0.2
- The E/p is parametrised in terms of η_{part}, E_{part} , LHED

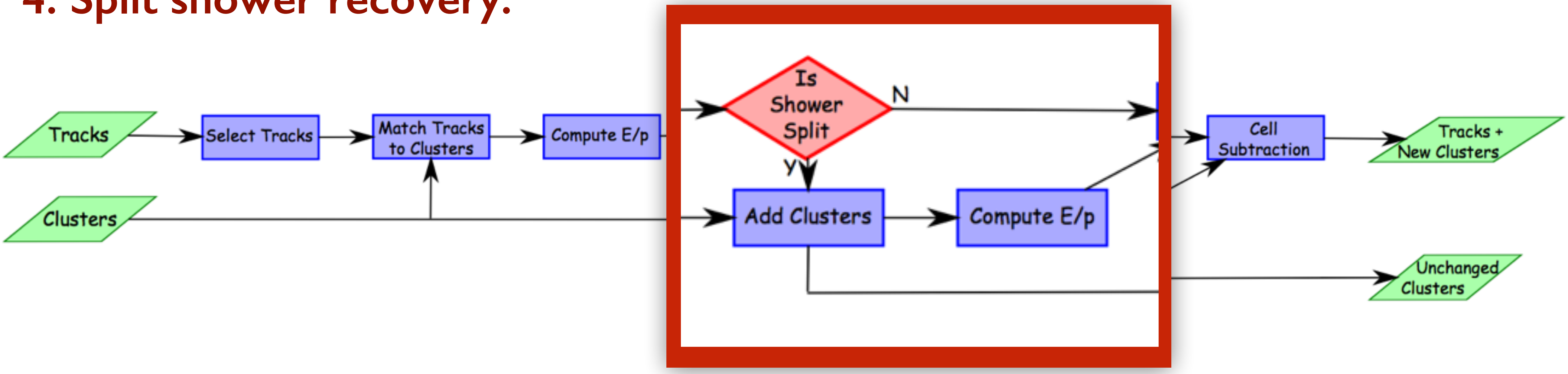




(LHED = layer of highest energy density)

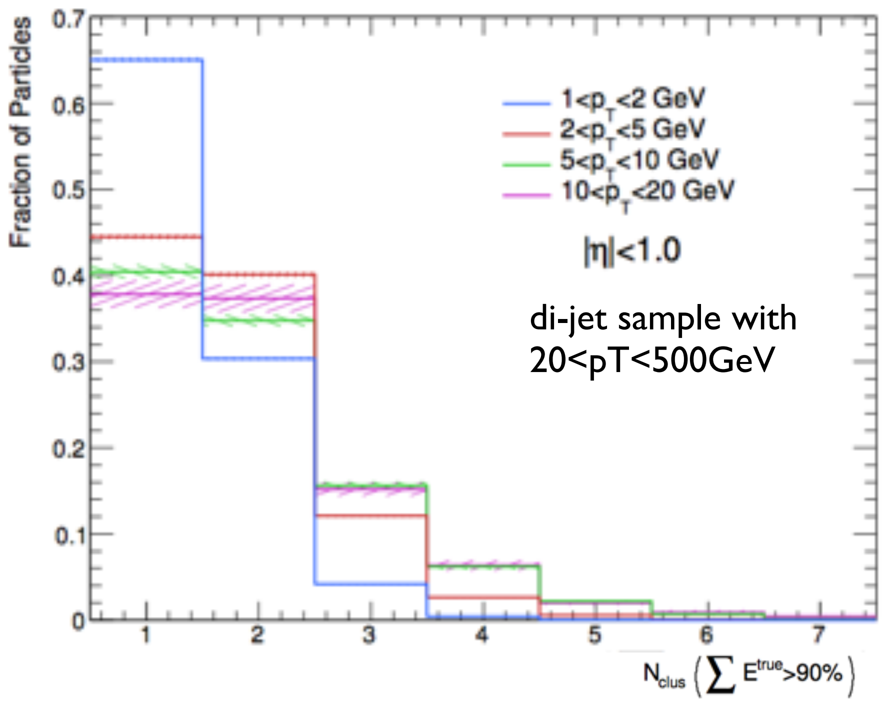
Overview of the eflowRec chain:

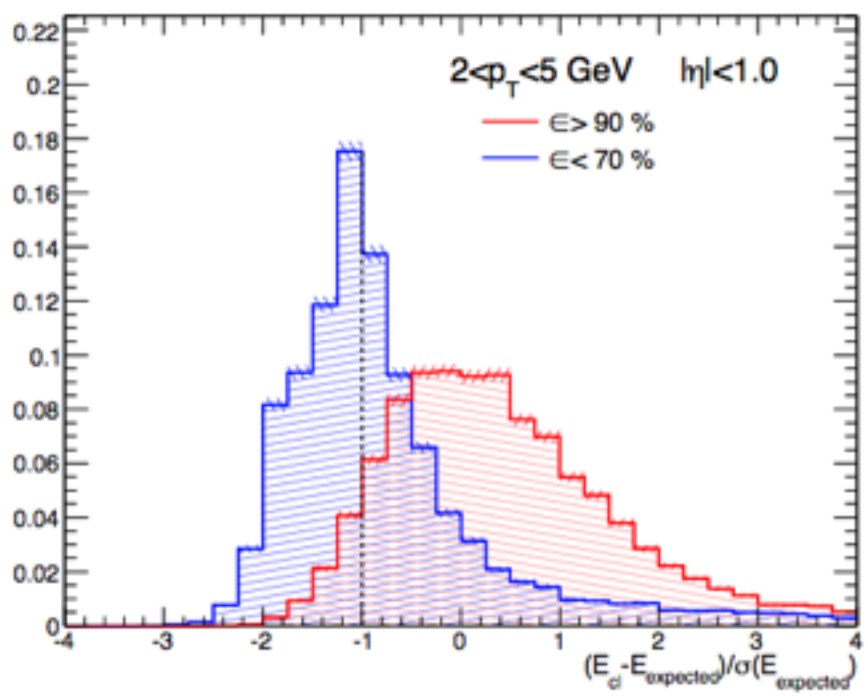
4. Split shower recovery:

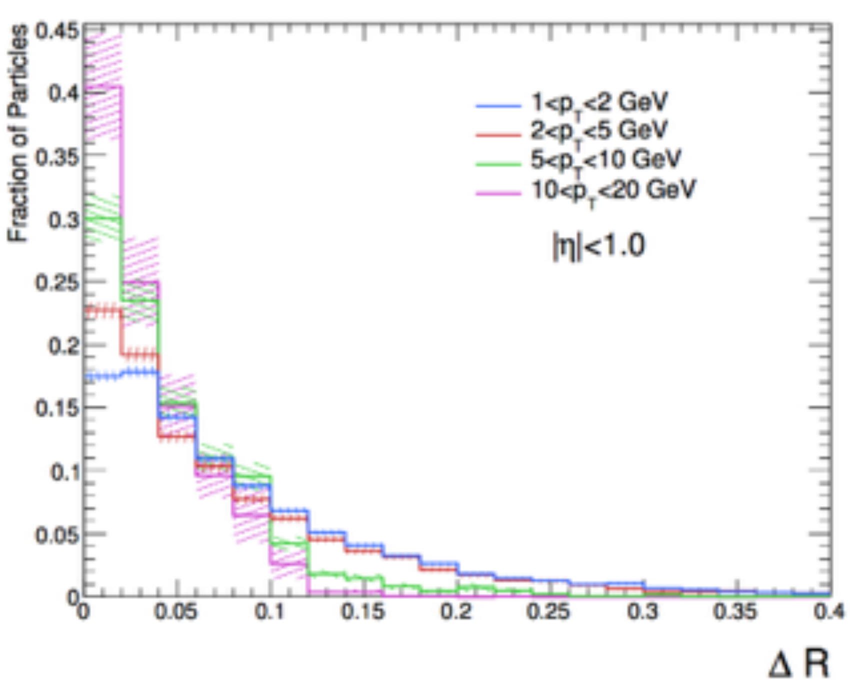


Particles do not always deposit all their energy in a single cluster.

- If E_{clus} is found to be less than E_{exp} by more than $\sigma(E_{exp})$
  - Assume energy has been split over multiple clusters (split shower recovery)
  - All clusters $\Delta R<0.2$ are considered

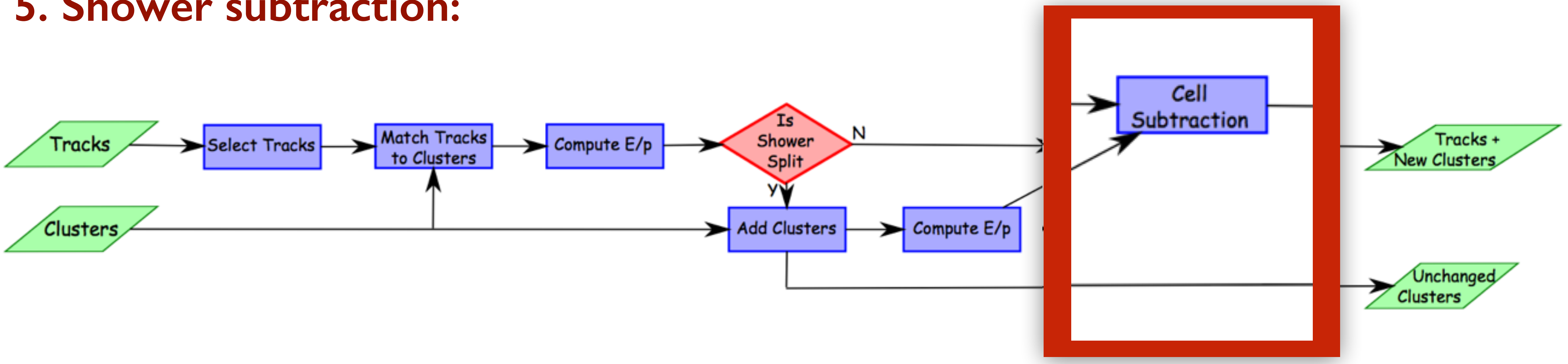






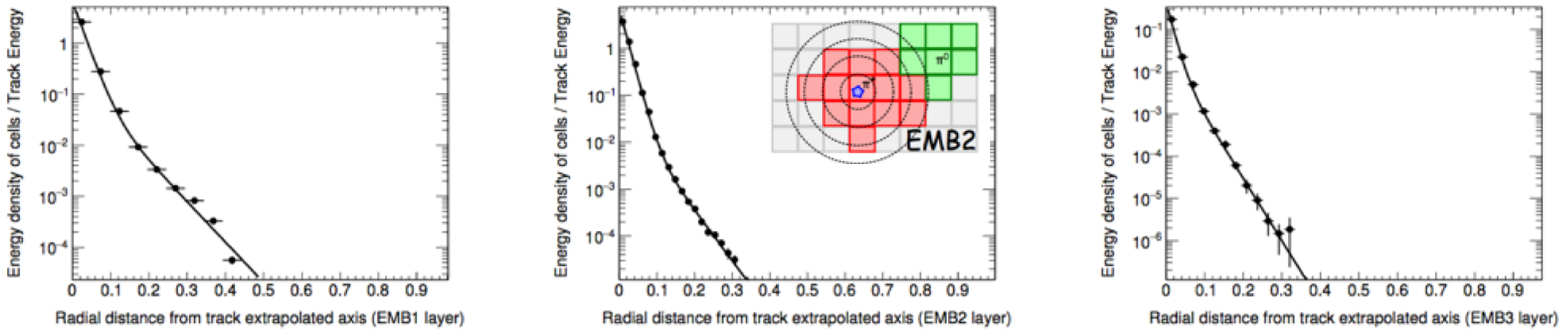
Overview of the eflowRec chain:

5. Shower subtraction:



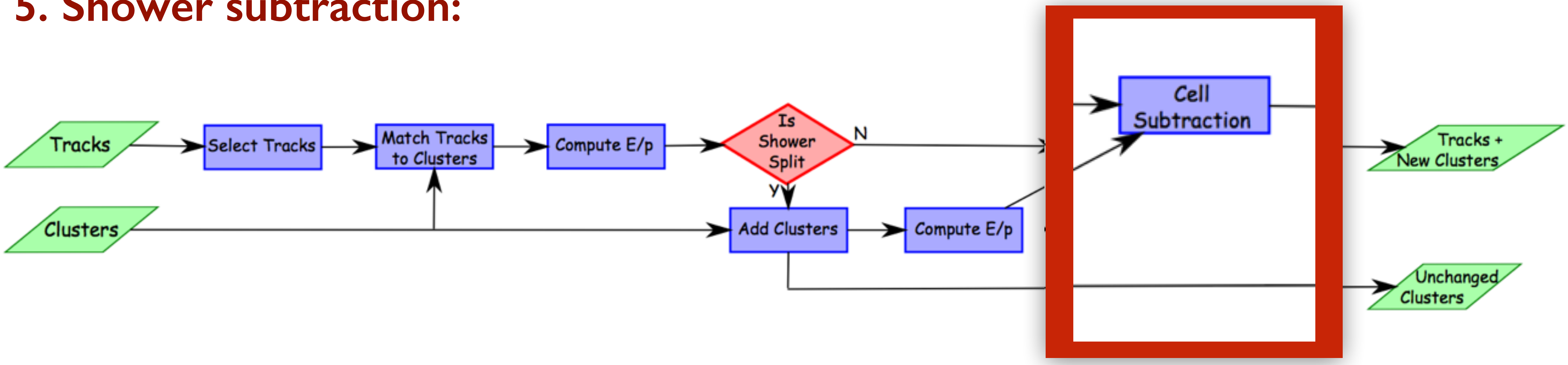
Set of clusters selected → subtraction procedure

- If E_{clus} < expected energy from E/p→ completely subtracted
- If E_{clus} > expected energy from E/p→ ring-by-ring subtraction
  - Parametrised shower shape in each layer (using single pion sample)
  - Using the cell size, rings in (eta, phi) around track direction defined for each layer
  - Average energy density calculated for each ring



Overview of the eflowRec chain:

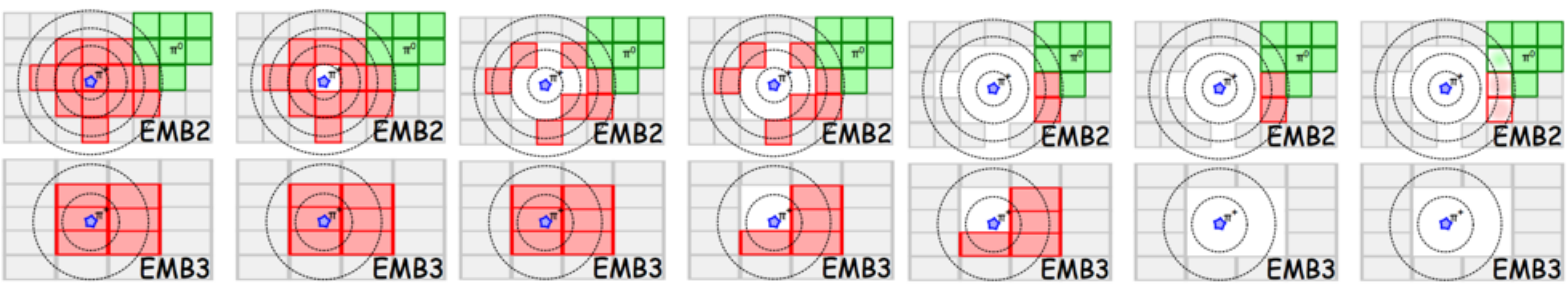
5. Shower subtraction:



Subtraction starts from the highest E density ring

- E_{ring} < E remaining to subtract → removed
- E_{ring} > E remaining to subtract → scaled by the fraction needed

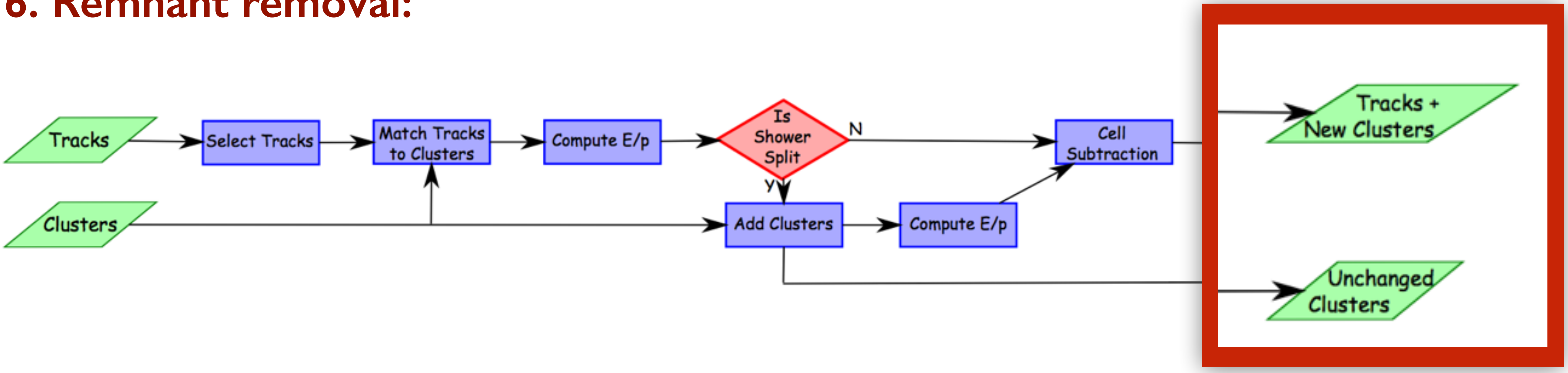
‣ The process of removing cells ring-by-ring is continued until the E_{exp} is subtracted



ring-by-ring subtraction

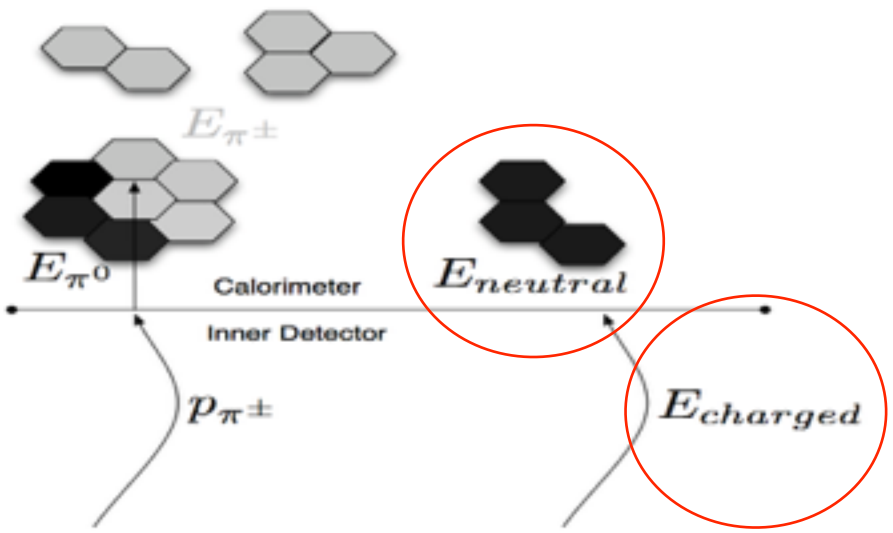
Overview of the eflowRec chain:

6. Remnant removal:

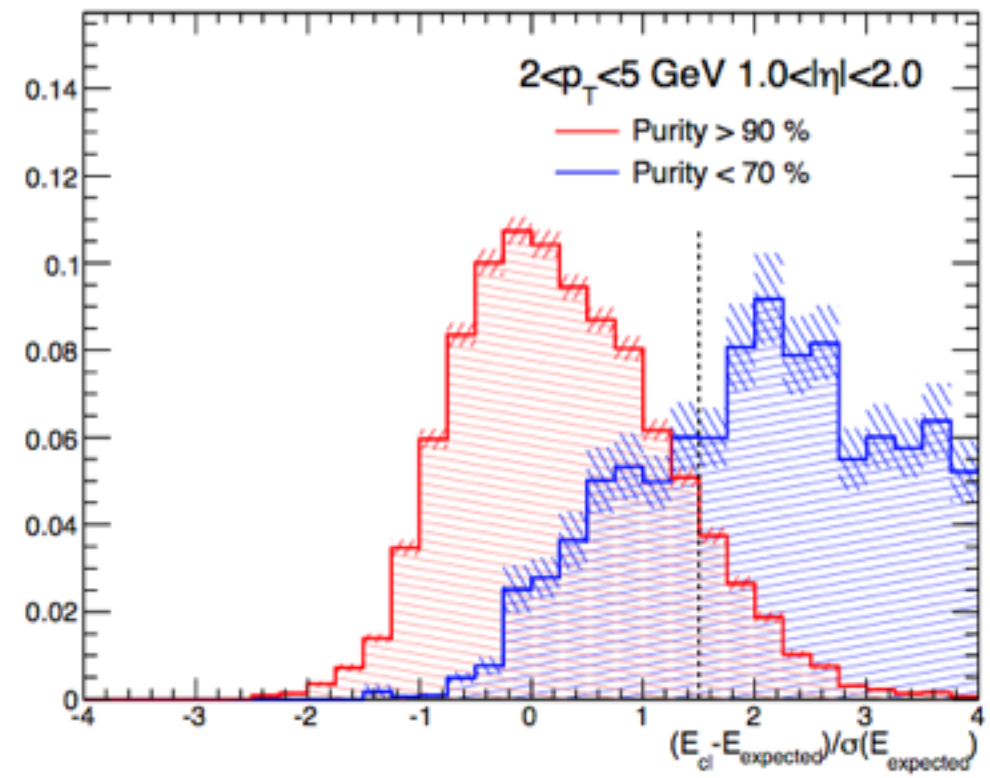


Subtraction stops when E_{exp} has been removed

- If the remaining E is consistent with σ(E/p) → purely noise → totally removed
- If the remaining E larger than σ(E/p) → other particles involved → kept



The selected tracks and the remained clusters represent the reconstructed event

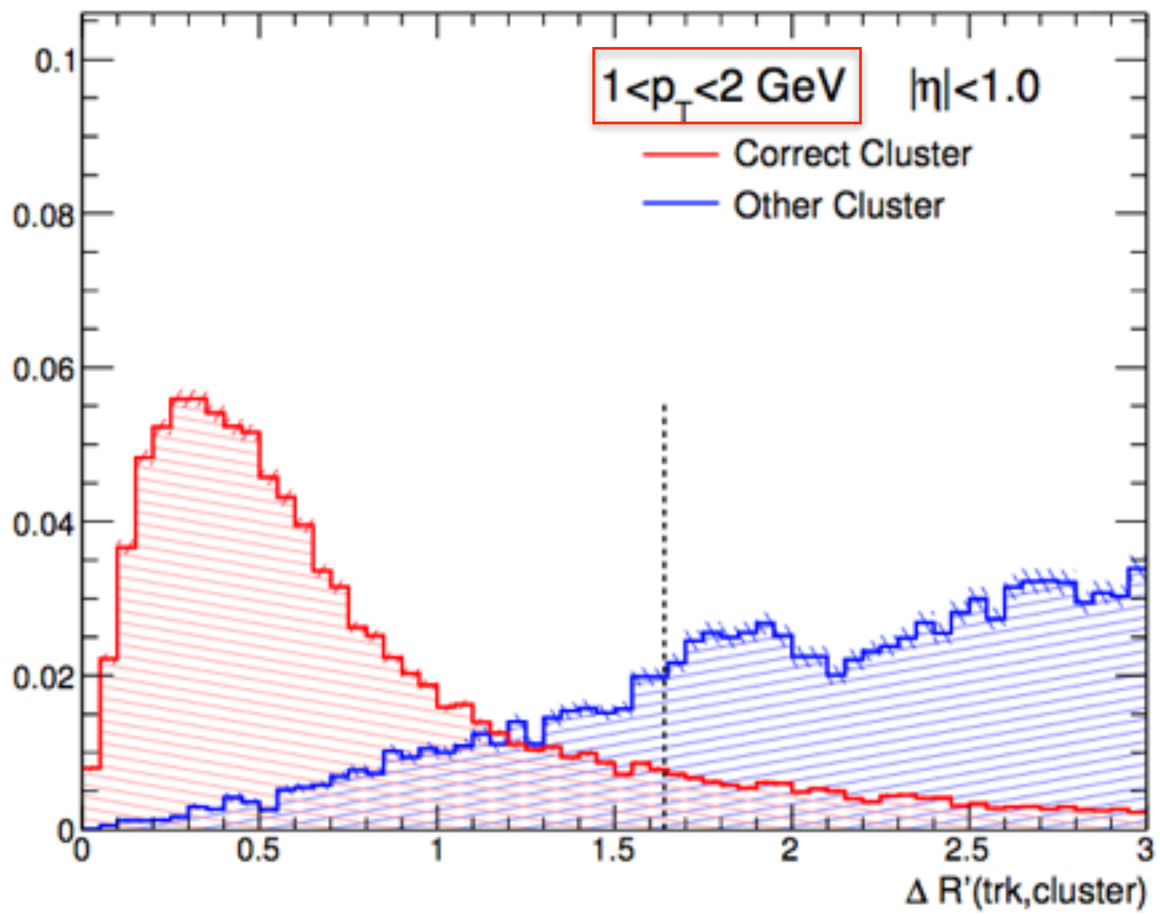


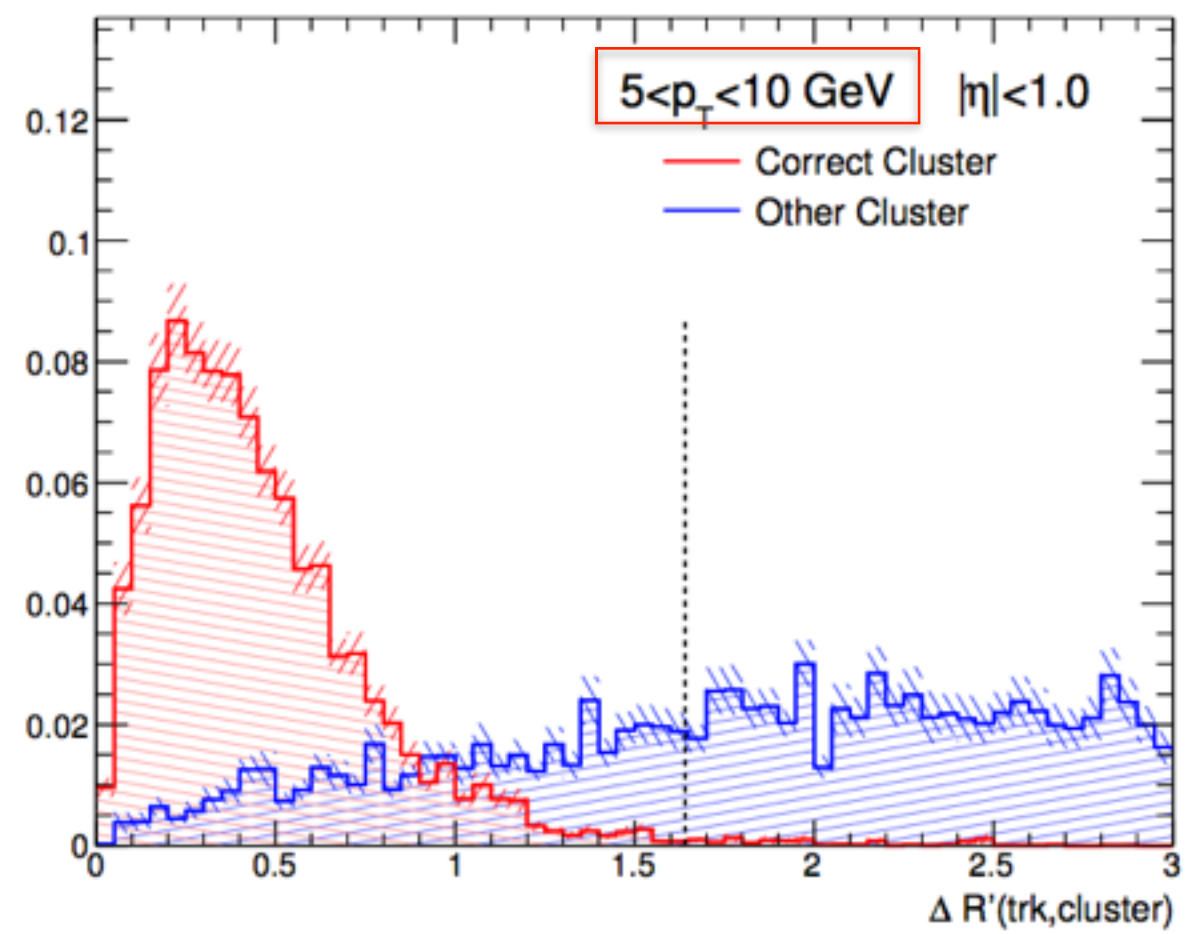
Particle flow low-level performance studies

Track-cluster matching

The optimisation of the track-cluster matching at the first step of the algorithm has been studied:

- Extrapolate low momentum tracks to EM1 instead of EM2 ✗
- Extrapolate to the layer with lower ΔR' ✗
- Extrapolate to the layer where most of the energy is deposited ✗
- Use ΔR instead of ΔR' ✗
- Momentum dependence of the ΔR' ✓ (see Marianna's slides)



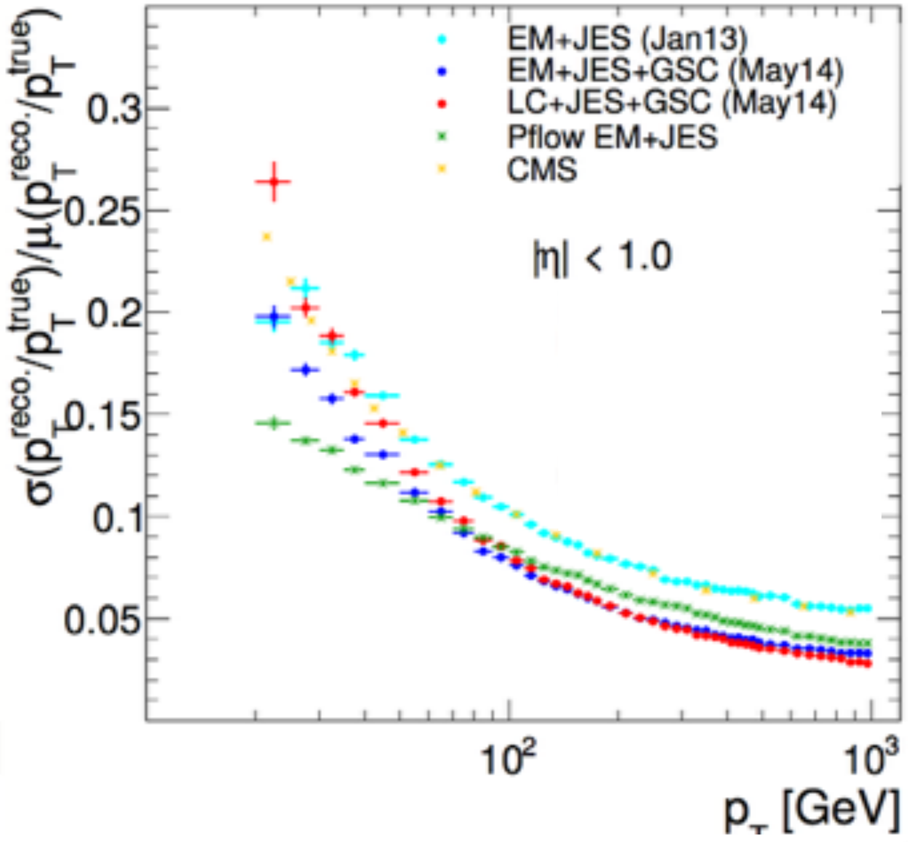


Particle flow performance studies

Results based on √s = 8 TeV (rel 17)

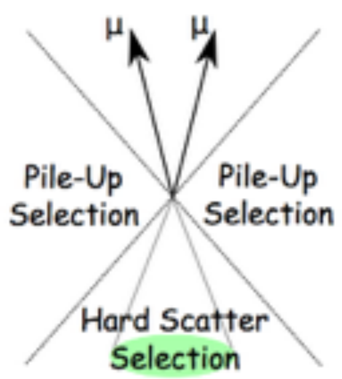
Jet momentum resolution

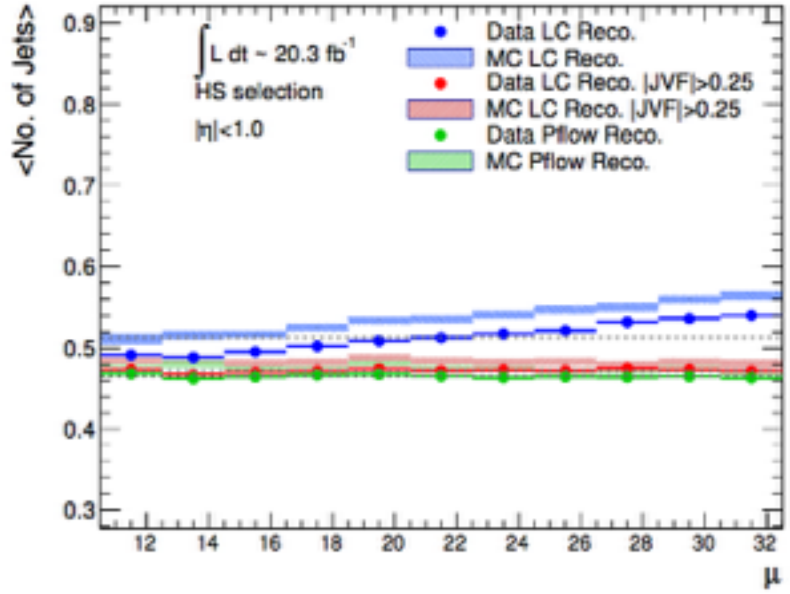
- Most significant improvements at low p_T and central η region
- Resolution high pt will be discussed (Mark's slides)

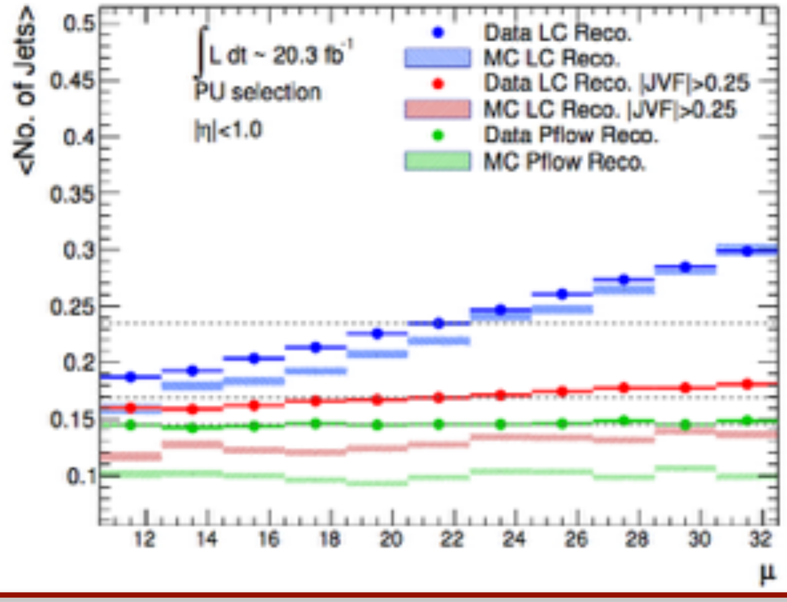


Pile-up

- Average number of particle flow jets originating form pile-up is much suppressed.
- Average number of particle flow jets is stable as a function of pile-up.





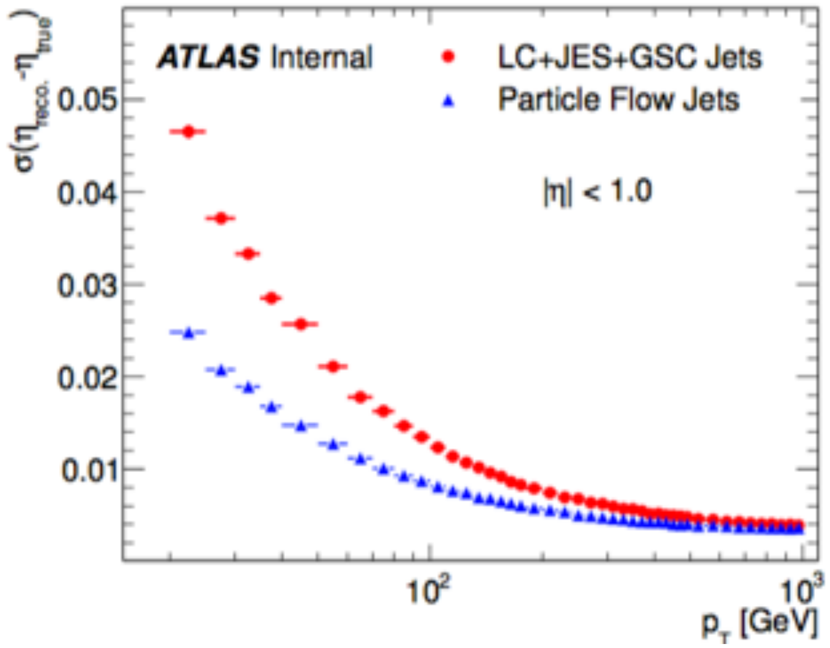


Particle flow performance studies

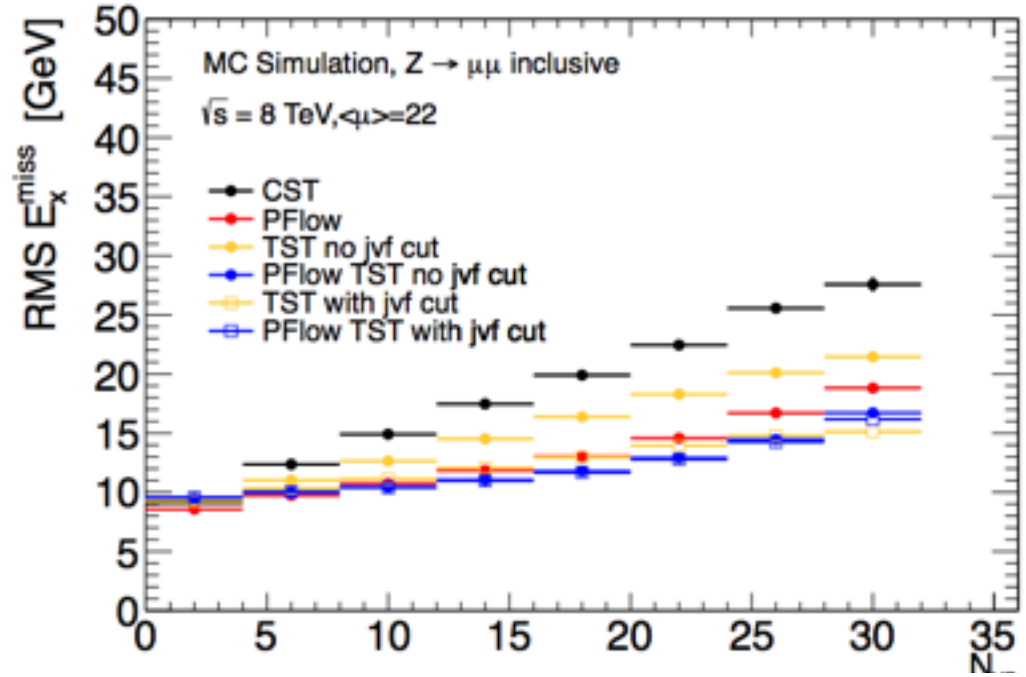
Results based on $\sqrt{s}$ = 8 TeV (rel 17)

Jet angular resolution

Improvement in the jet angular resolution for η,Φ



E_T^{miss}



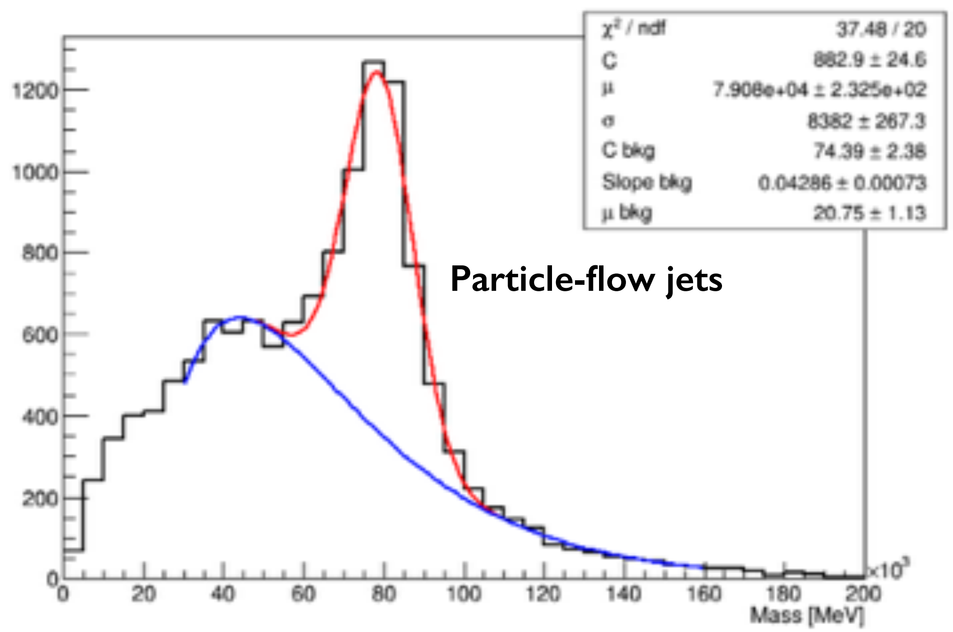
$$E_{x,y}^{\mathrm{miss}} = -\left(\Sigma E_{x,y}^{\text{particle flow jets}} + \Sigma p_{x,y}^{e} + \Sigma p_{x,y}^{\gamma} + \Sigma p_{x,y}^{\mu} + \Sigma p_{x,y}^{\text{trk, unassociated}} + \Sigma E_{x,y}^{\text{clu, unassociated}}\right)$$

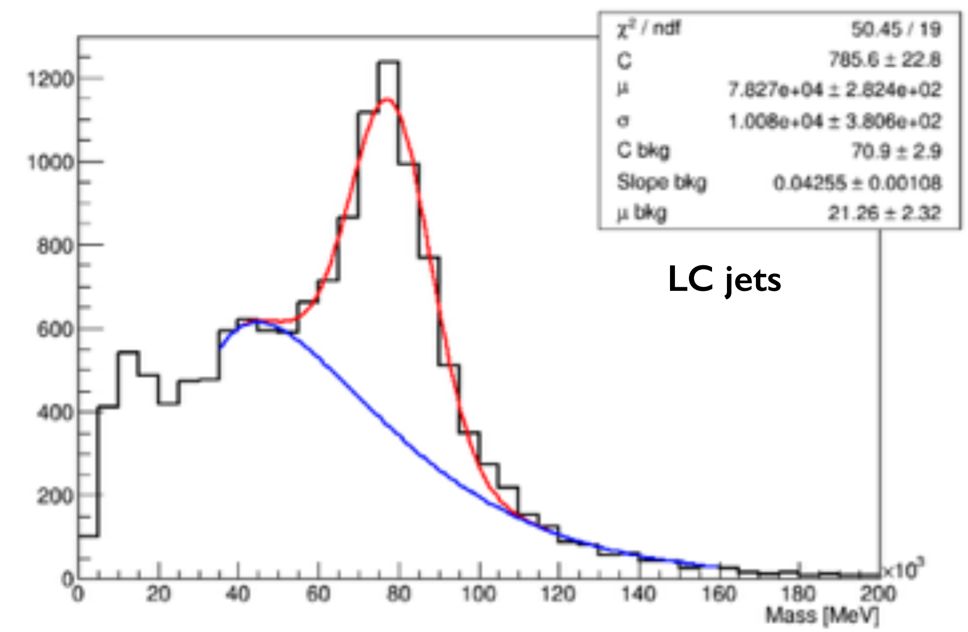
Invariant mass reconstruction of the hadronic W boson in ttbar events

Large R-jets

W mass resolution:

- σ = 11% (Pflow)
- σ = 13% (LC)



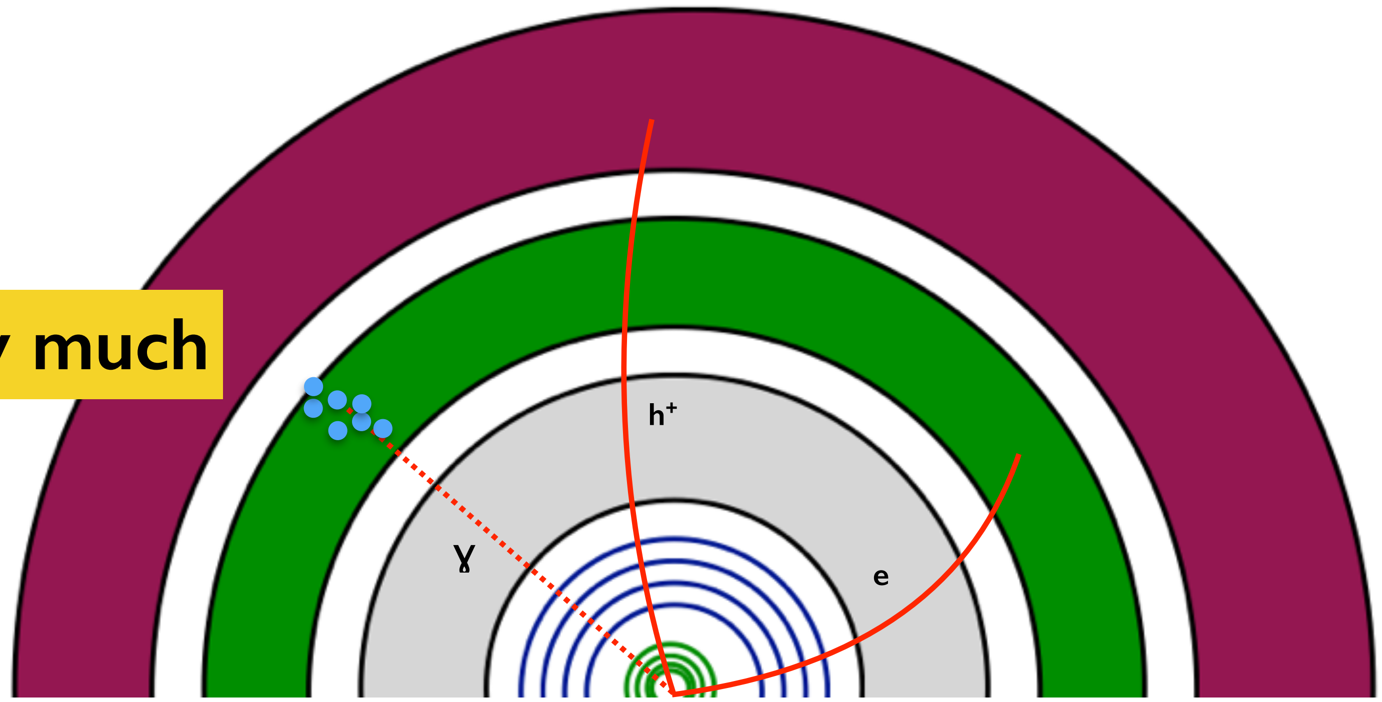


Summary

- Particle flow algorithm (eflowRec) has been studied in depth.
- Performance studies have demonstrated advantages for the particle-flow objects:
  - Particle-flow jet resolution is better than EM (LC) calorimeter jets at low p_T and comparable above ~80 GeV
  - Suppression and stability of the pileup contribution
  - Better angular determination (in η and Φ)
  - Improvements in E_T^{miss} and large-R jets performance

- Run 2 data allows the particle flow algorithm to be further optimised
  Many results already shown during the workshop this week!

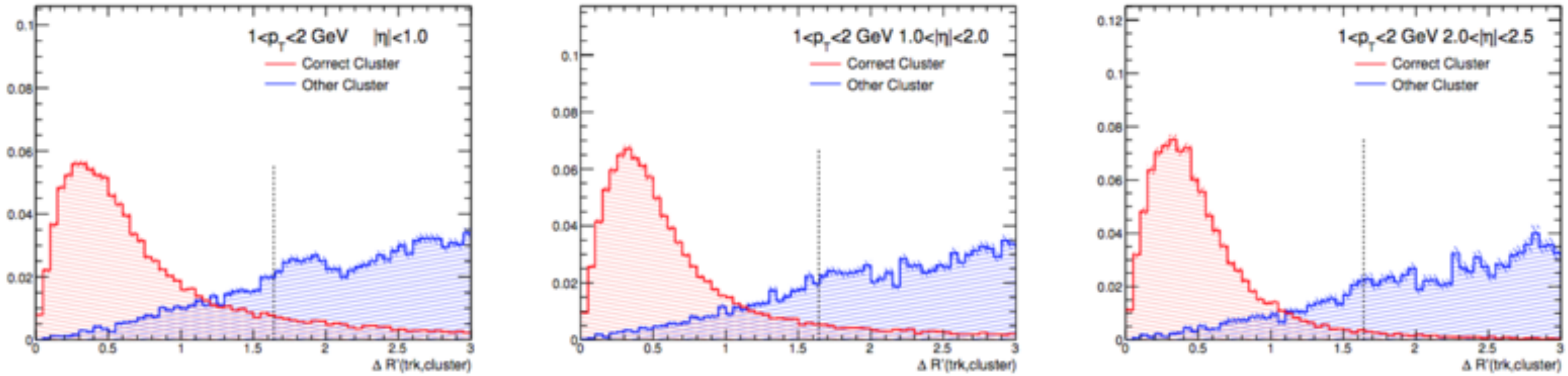
Thank you very much



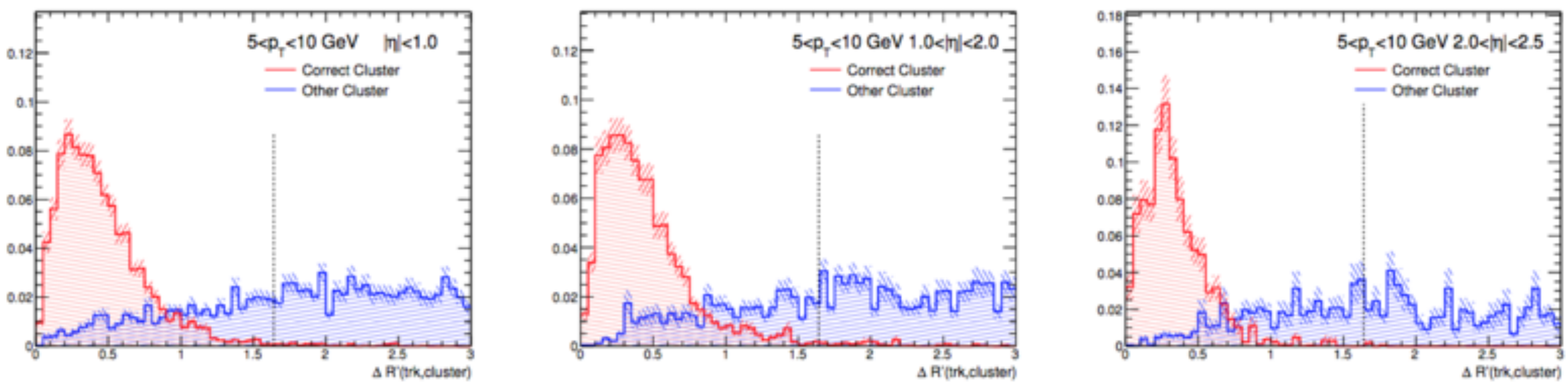
Backup

Track-cluster matching

$$\Delta R' = \sqrt{\frac{(\eta_{\mathrm{track}} - \eta_{\mathrm{clus}})^2}{\sigma_\eta^2} + \frac{(\phi_{\mathrm{track}} - \phi_{\mathrm{clus}})^2}{\sigma_\phi^2}}$$



(a) $1 < p_{\mathrm{T}}^{\mathrm{true}} < 2\,\mathrm{GeV}\ |\eta| < 1.0$ (b) $1 < p_{\mathrm{T}}^{\mathrm{true}} < 2\,\mathrm{GeV}\ 1.0 < |\eta| < 2.0$ (c) $1 < p_{\mathrm{T}}^{\mathrm{true}} < 2\,\mathrm{GeV}\ 2.0 < |\eta| < 2.5$

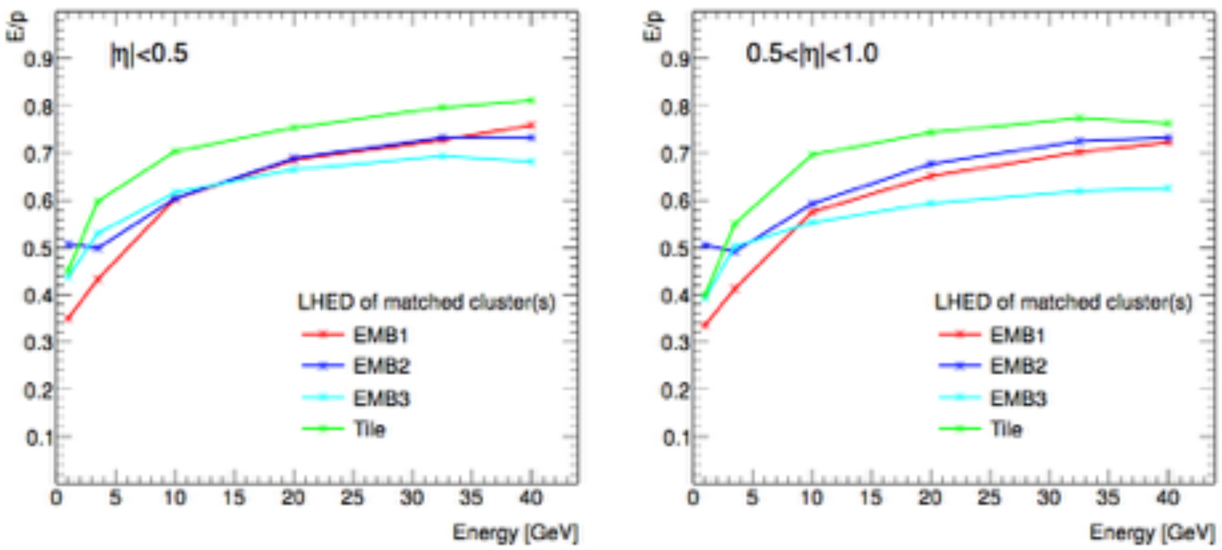


(d) $5 < p_{\mathrm{T}}^{\mathrm{true}} < 10\,\mathrm{GeV}\ |\eta| < 1.0$ (e) $5 < p_{\mathrm{T}}^{\mathrm{true}} < 10\,\mathrm{GeV}\ 1.0 < |\eta| < 2.0$ (f) $5 < p_{\mathrm{T}}^{\mathrm{true}} < 10\,\mathrm{GeV}\ 2.0 < |\eta| < 2.5$

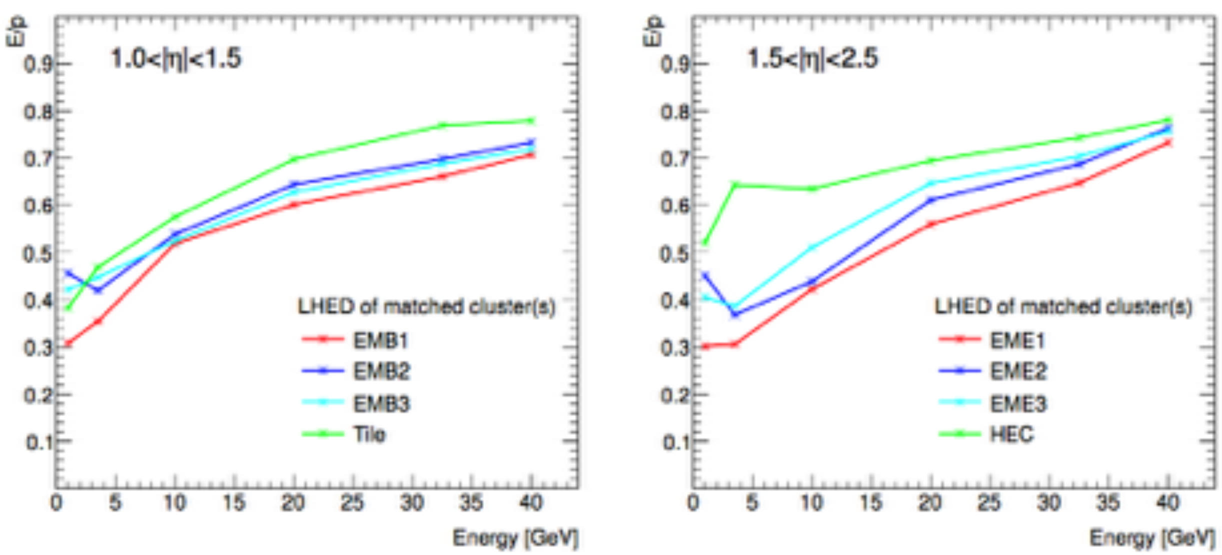
Figure 9: The distribution of $\Delta R'$ for the cluster with the $> 90\,\%$ of the true energy of the particle and the next closest cluster satisfying $E/p_{\mathrm{track}} > 0.1$. The data are taken from a dijet sample with $20 < p_{\mathrm{T}}^{\mathrm{lead}} < 500\,\mathrm{GeV}$ and the errors shown are MC statistics.

E/p

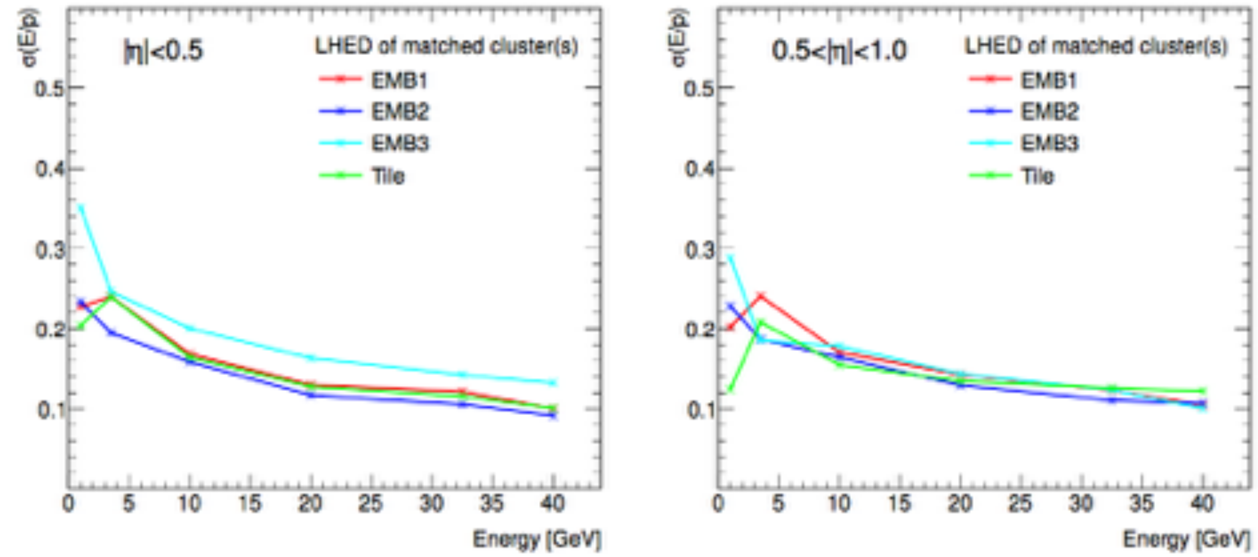
E/p



(a) |η| < 0.5 (b) 0.5 < |η| < 1.0



σ(Eexp)



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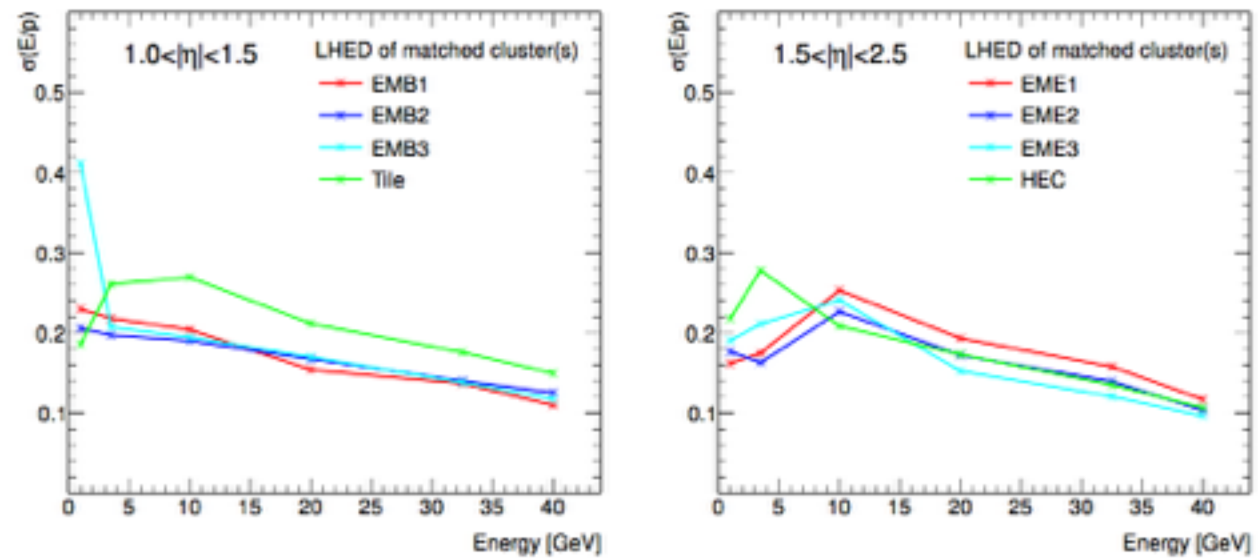


Particle flow low-level performance studies

Subtraction studies

The global performance of the subtraction can be studied using the fraction of:

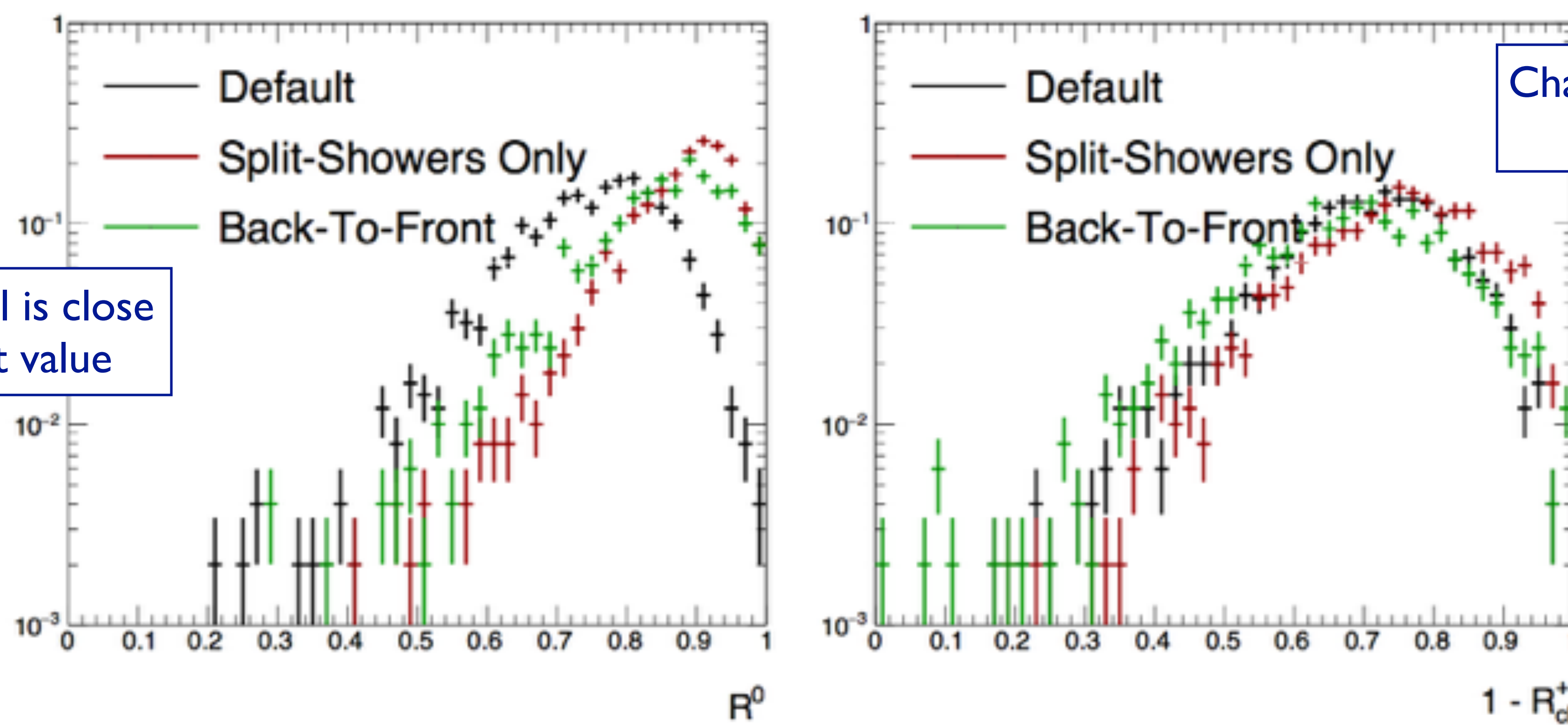
- Neutral energy left in the calorimeters (R0)
- Charged energy subtracted (R+) per event.

$$R^0 = \frac{\sum_{\text{neutral}} E_{\texttt{CalHit}}(\text{after subtraction})}{\sum_{\text{neutral}} E_{\texttt{CalHit}}(\text{before subtraction})}$$

$$(1 - R^+) = 1 - \frac{\sum_{\text{charged}} E_{\texttt{CalHit}}(\text{after subtraction})}{\sum_{\text{charged}} E_{\texttt{CalHit}}(\text{before subtraction})}$$

Strategies tested:

- **Default subtraction**
- Only split shower recovering (all jets in ΔR<0.2)
- Back-to-front (starts the subtraction with the energy in the hadron calorimeter)



Remnant neutral is close to the correct value

Charge particle energy is rarely subtracted

At high p_T, R^+ deteriorates substantially → jet resolution is worse for p_T > 100GeV

➪ New strategy for fixing this problem has been implemented (M.Hodgkinson's talk)