Particle Flow Calorimetry At ILC Experiment

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LCWS07 @ DESY
May 29th-June 4rd, 2007

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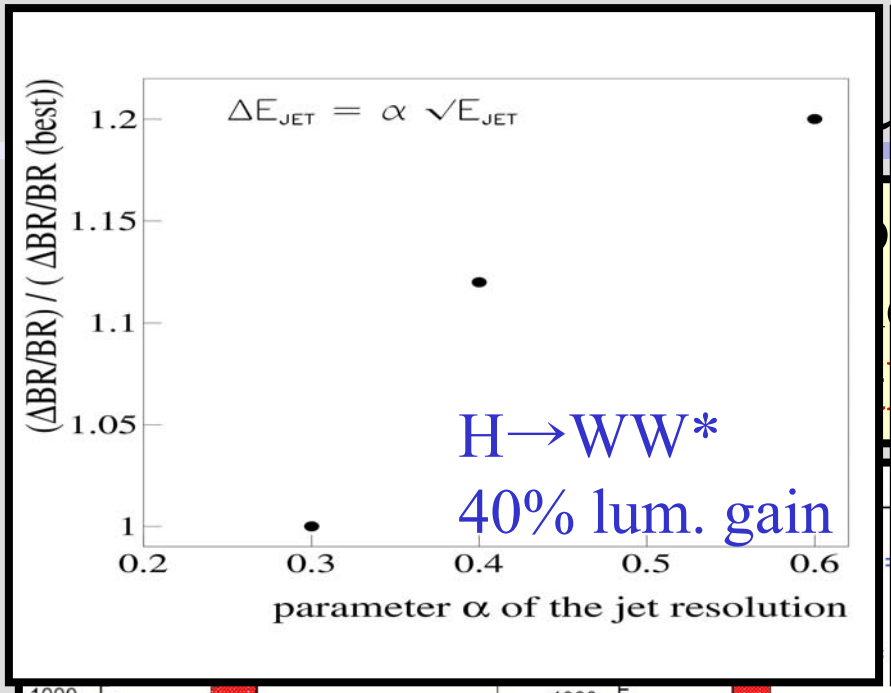
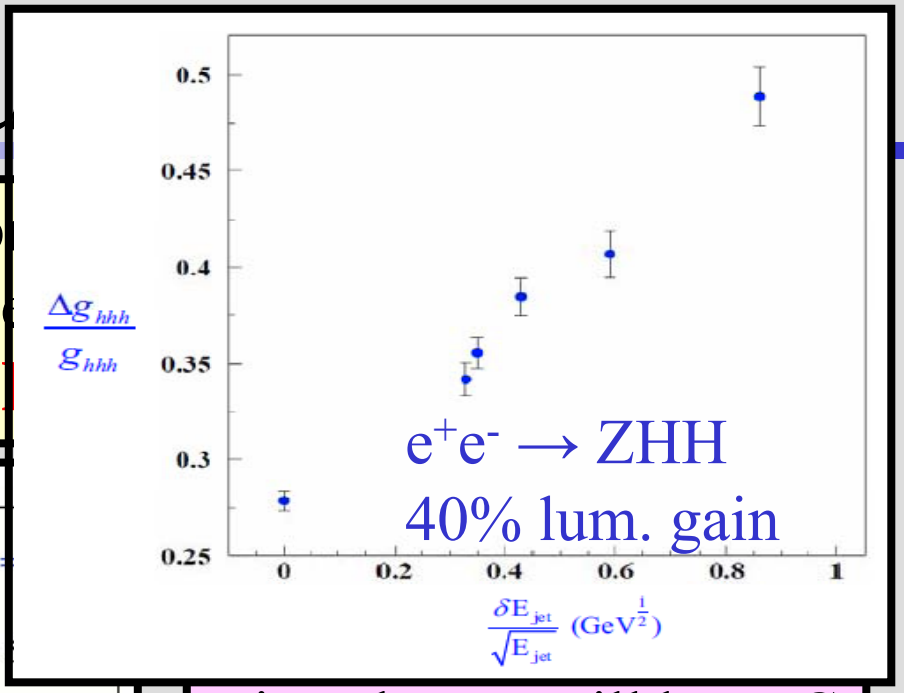
Introduction

- Most of the important physics processes to be studied in the ILC experiment have multi-jets in the final state.

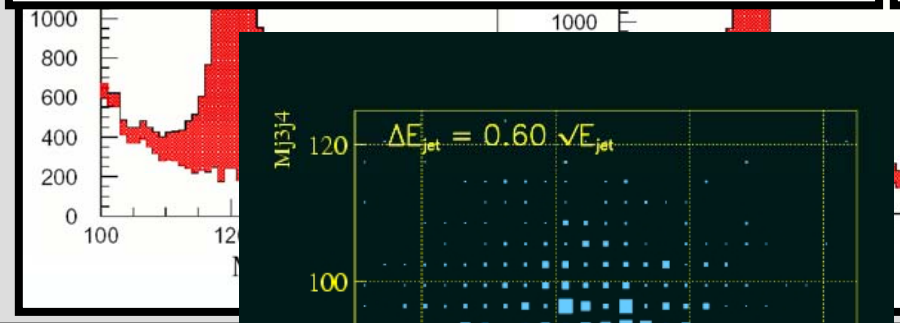
  → **Jet energy resolution is the key in the ILC physics.**

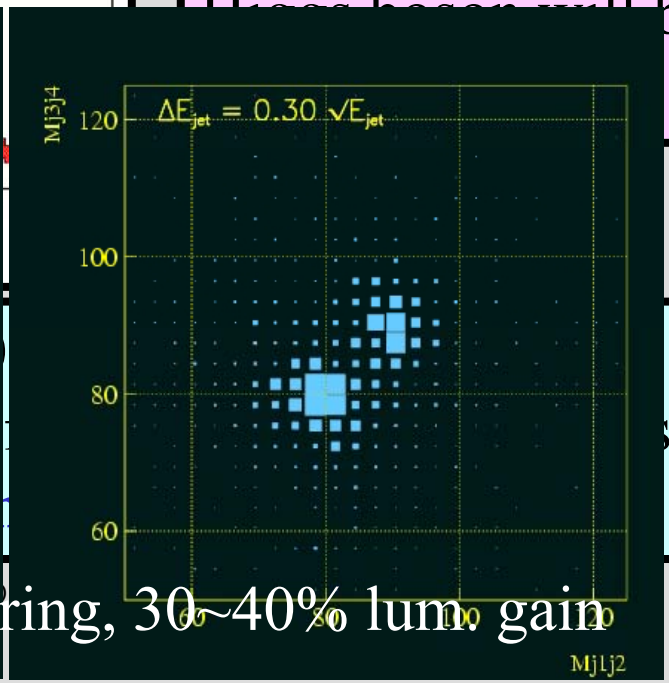


H→WW*
40% lum. gain

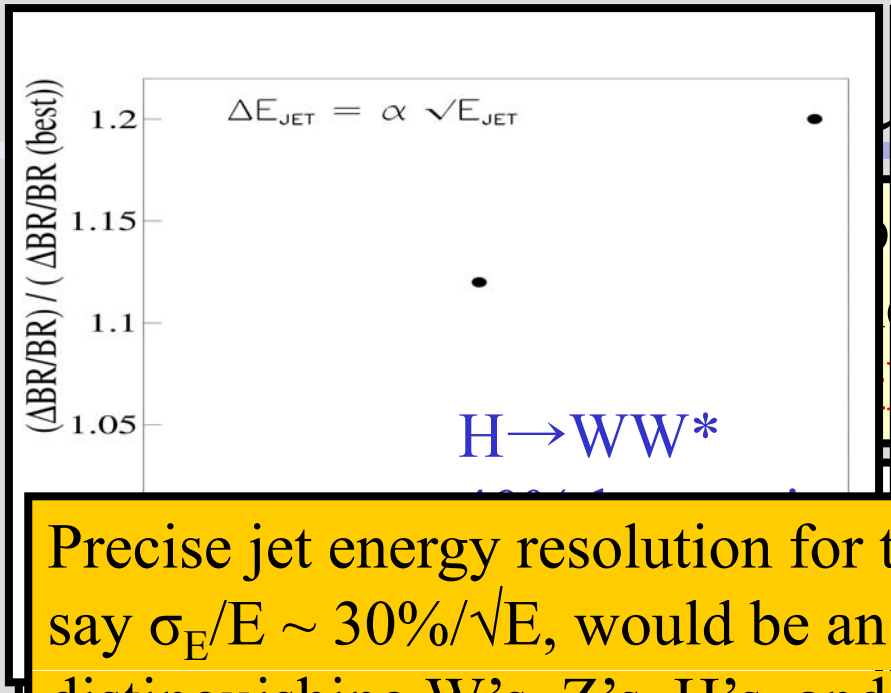


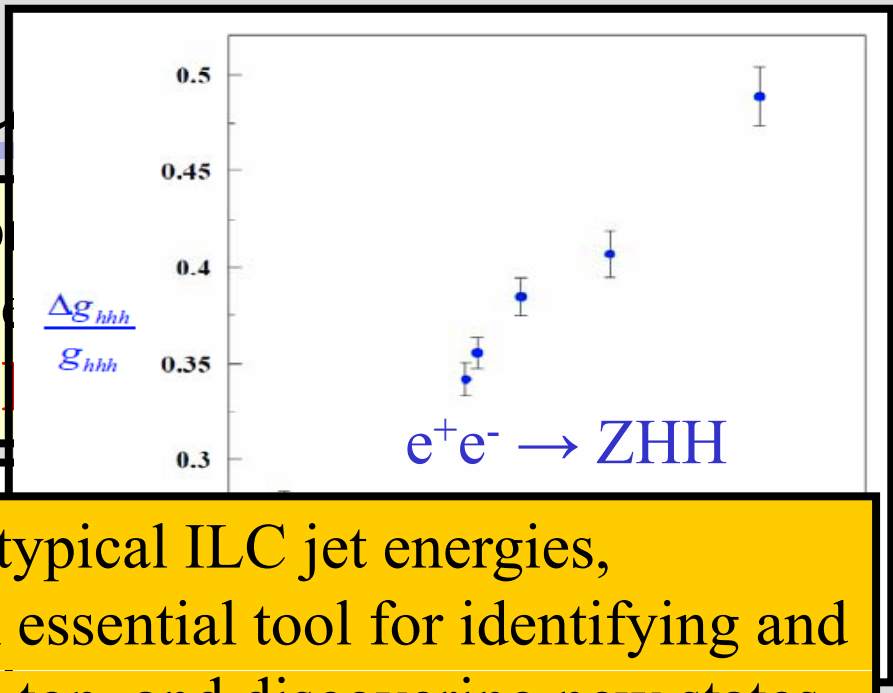
$e^+e^- \rightarrow ZHH$
40% lum. gain



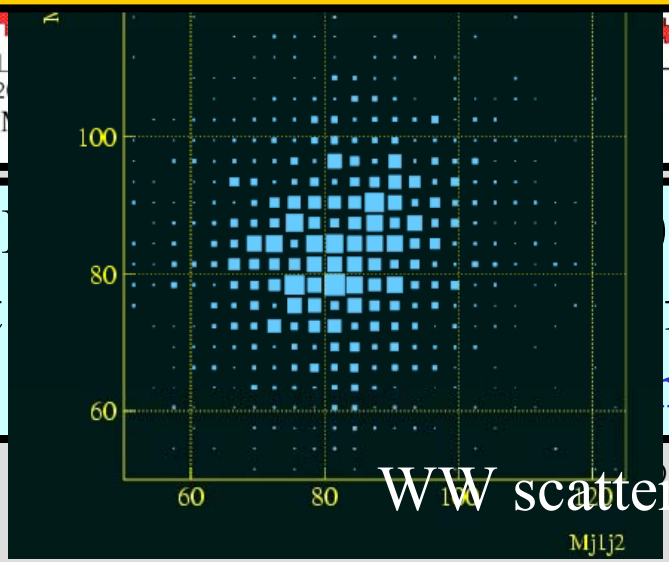


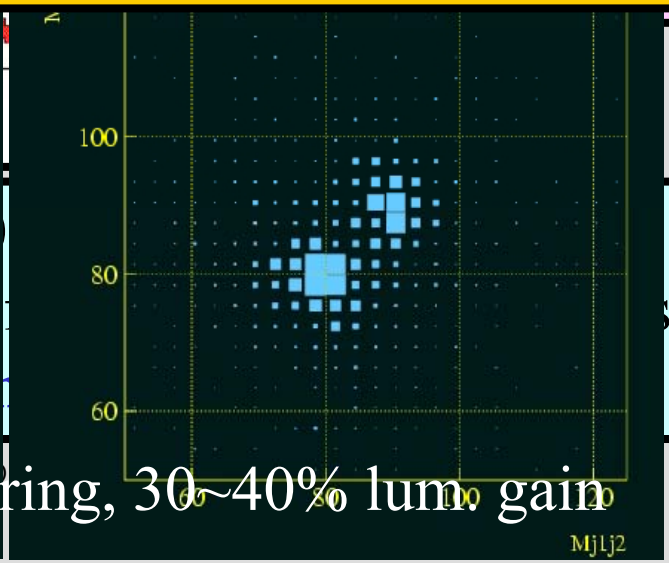
WW scattering, 30~40% lum. gain





Precise jet energy resolution for typical ILC jet energies, say $\sigma_E/E \sim 30\%/\sqrt{E}$, would be an essential tool for identifying and distinguishing W's, Z's, H's, and top, and discovering new states or decay modes.





$e^+e^- \rightarrow Z$
Invariant
solution.

WW scattering, 30~40% lum. gain

Jet Reconstruction @ ILC

- Q. How to achieve the best attainable jet energy resolution?

- A. Since the momentum resolution for the charged particle measured by trackers is much better than the energy resolution of calorimeters, the best energy resolution is obtained by reconstructing momenta of individual particles avoiding double counting among Trackers and Calorimeters.
  - Charged particles (~60%) measured by Tracker.
  - Photons (~30%) by electromagnetic CAL (ECAL).
  - Neutral hadrons (~10%) by ECAL + hadron CAL (HCAL).

$$E_{TOT} = p_e + p_\mu + p_{\text{charged hadron}} + E_\gamma + E_{\text{neutral hadron}}$$

[tracks only] [calorimeter only]

Particle Flow Algorithm (PFA)

Jet Reconstruction @ ILC

- Q. How to achieve the best attainable jet energy resolution?

The tracks are used instead of making a calorimetric measurement of the energies of the charged hadrons (with large errors).

- the charged particle

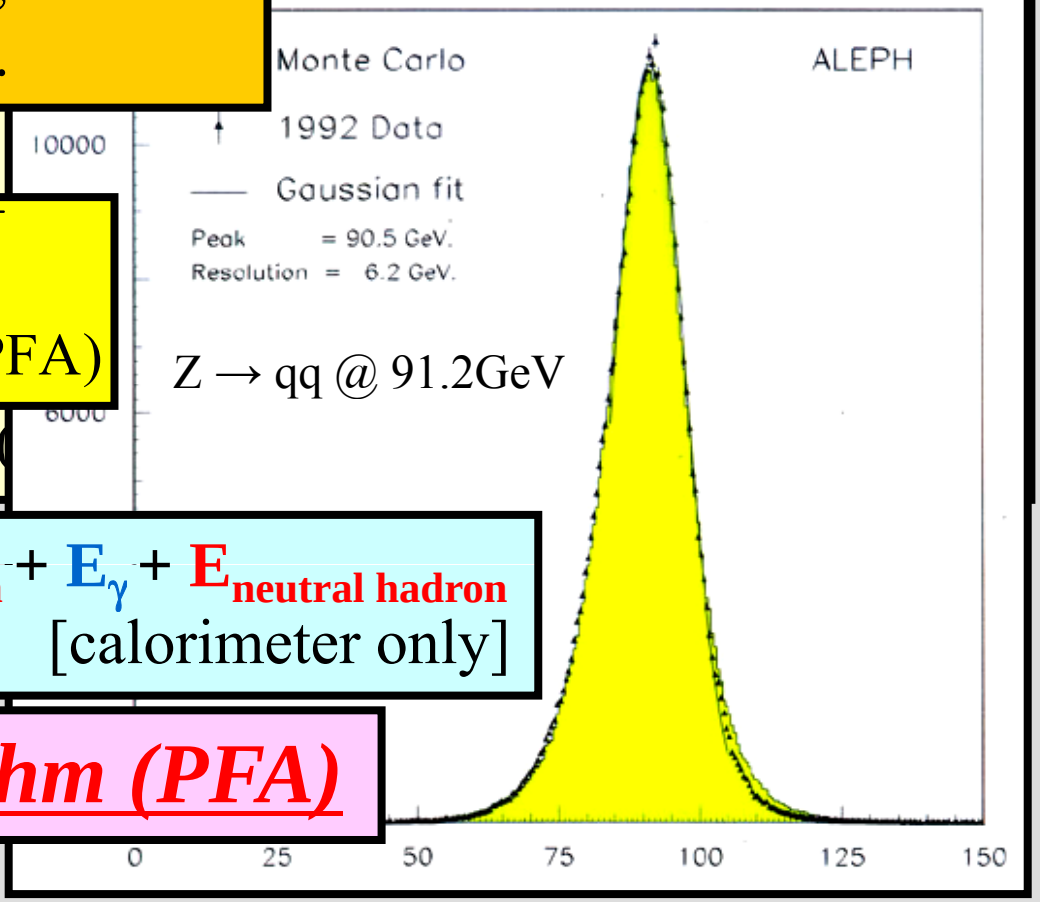
reconstructing momenta of

countin

$\sigma / E = 0.6 / \sqrt{E(\mathrm{GeV})}$

$(1.2 / \sqrt{E(\mathrm{GeV})}$ w/o PFA)

- Neutral hadrons (~1



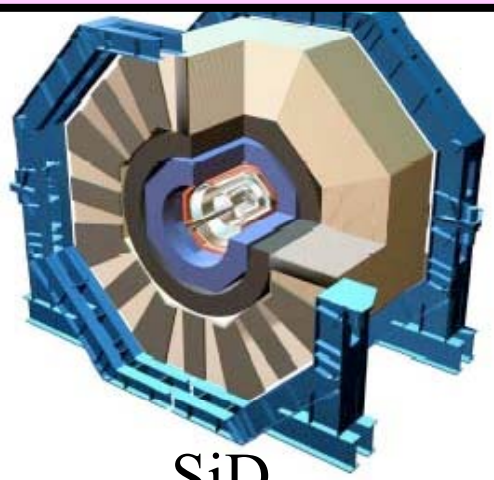
$E_{TOT} = p_e + p_\mu + p_{\text{charged hadron}} + E_\gamma + E_{\text{neutral hadron}}$

[tracks only] [calorimeter only]

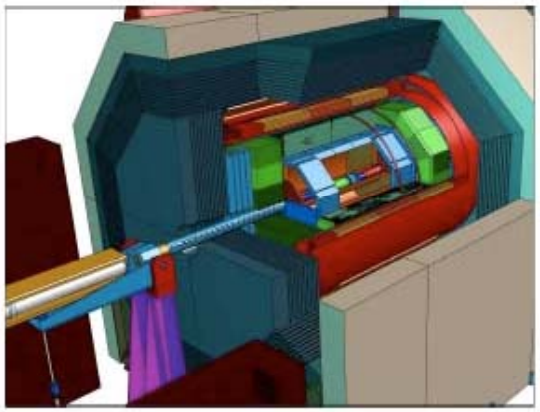
Particle Flow Algorithm (PFA)

Detector Concepts

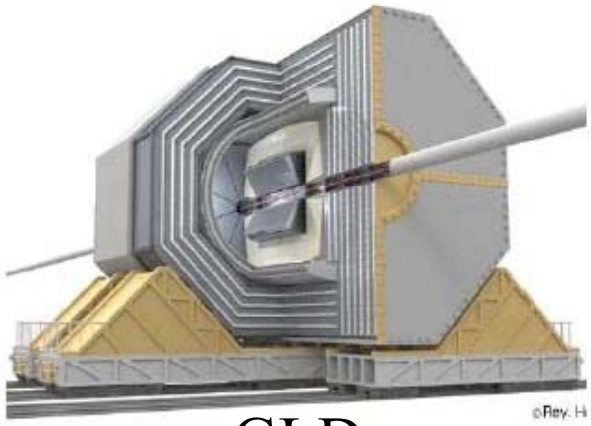
- Particle Flow Algorithm (PFA)



SiD

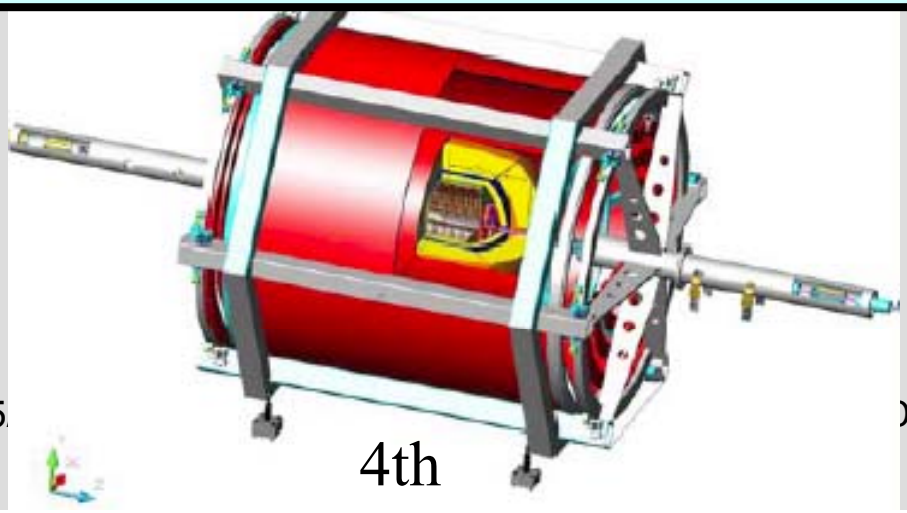


LDC



GLD

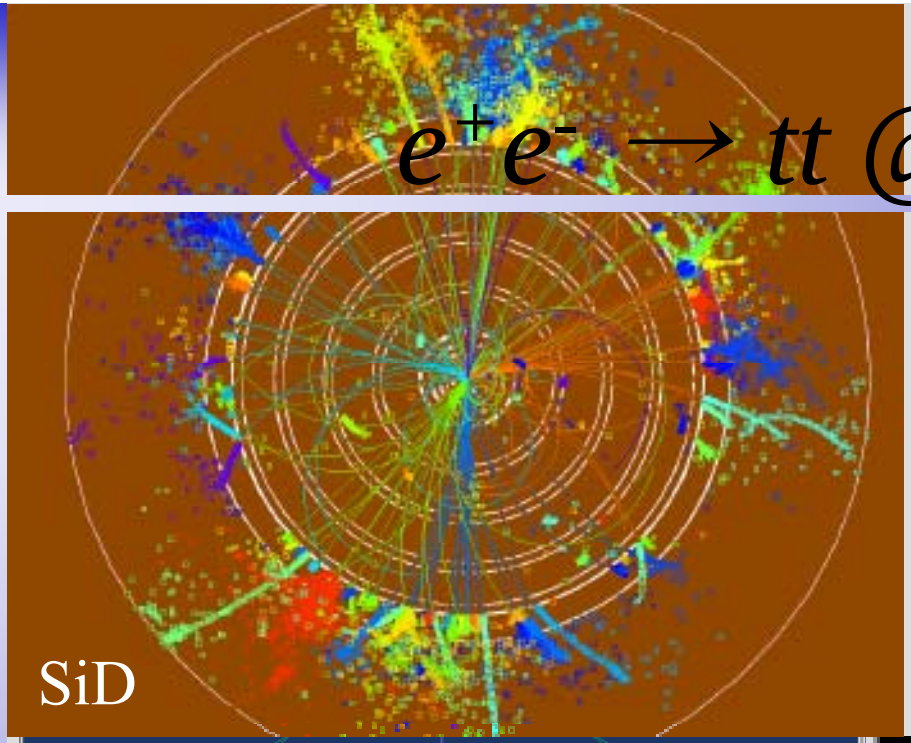
- Compensation (Dual-Readout Calorimeter)

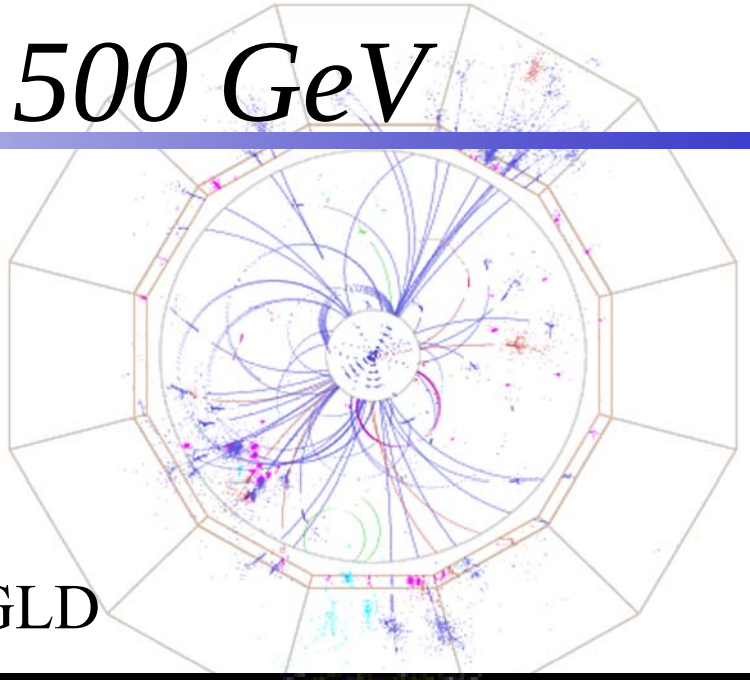


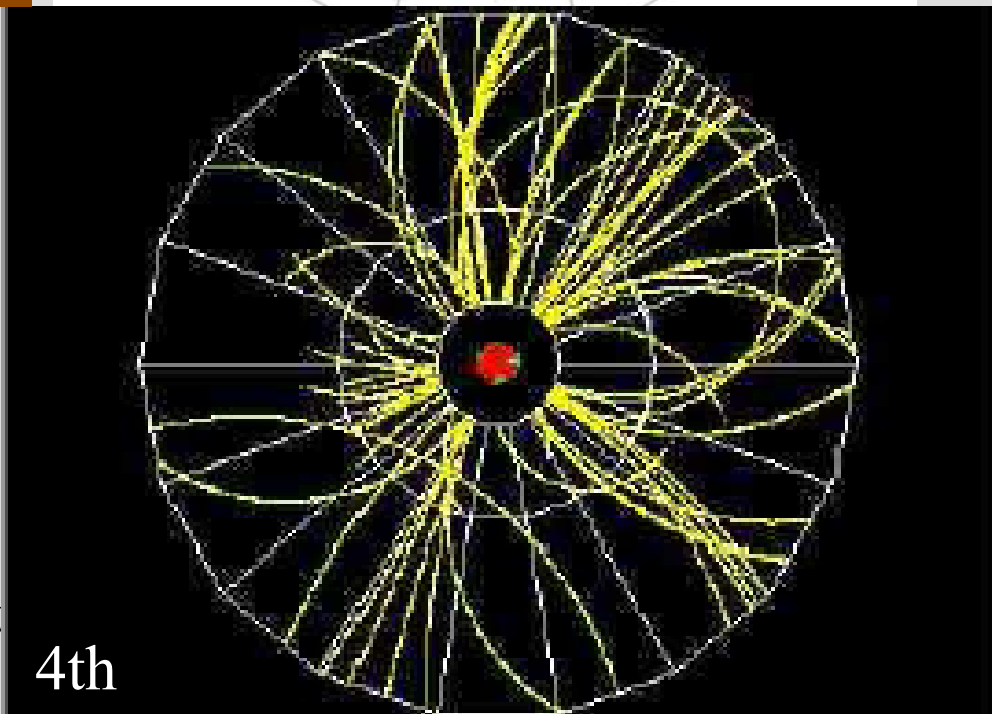
4th

Three out of four are proposing a detector which is optimized for PFA, though the technical realization is quite different.

$e^+e^- \rightarrow tt$ @ 500 GeV

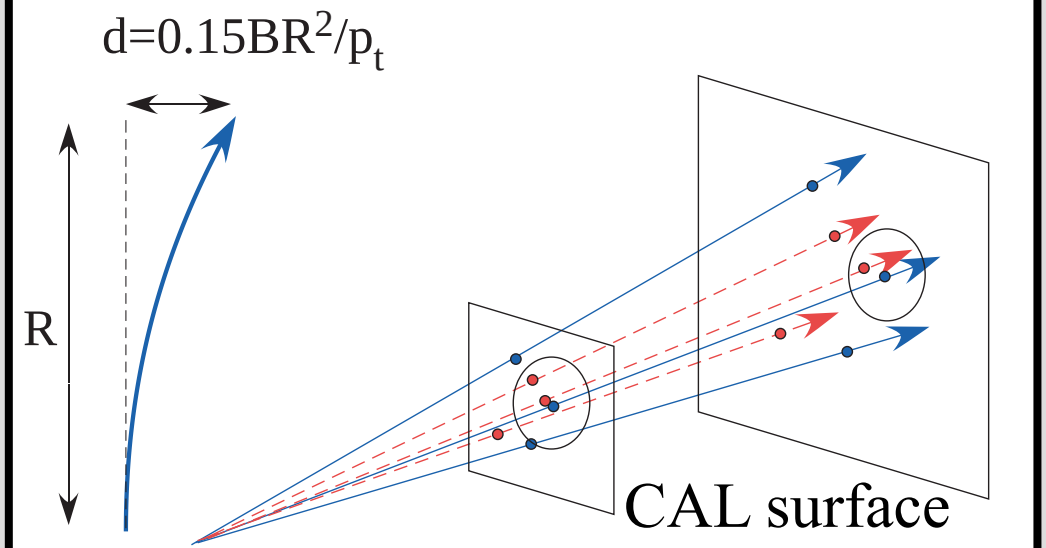






Particle Flow Algorithm

- In order to get good energy resolution by PFA, separation of particles is important. → Reduce the density of charged and neutral particles at calorimeter surface.



Often quoted "Figure of Merit"

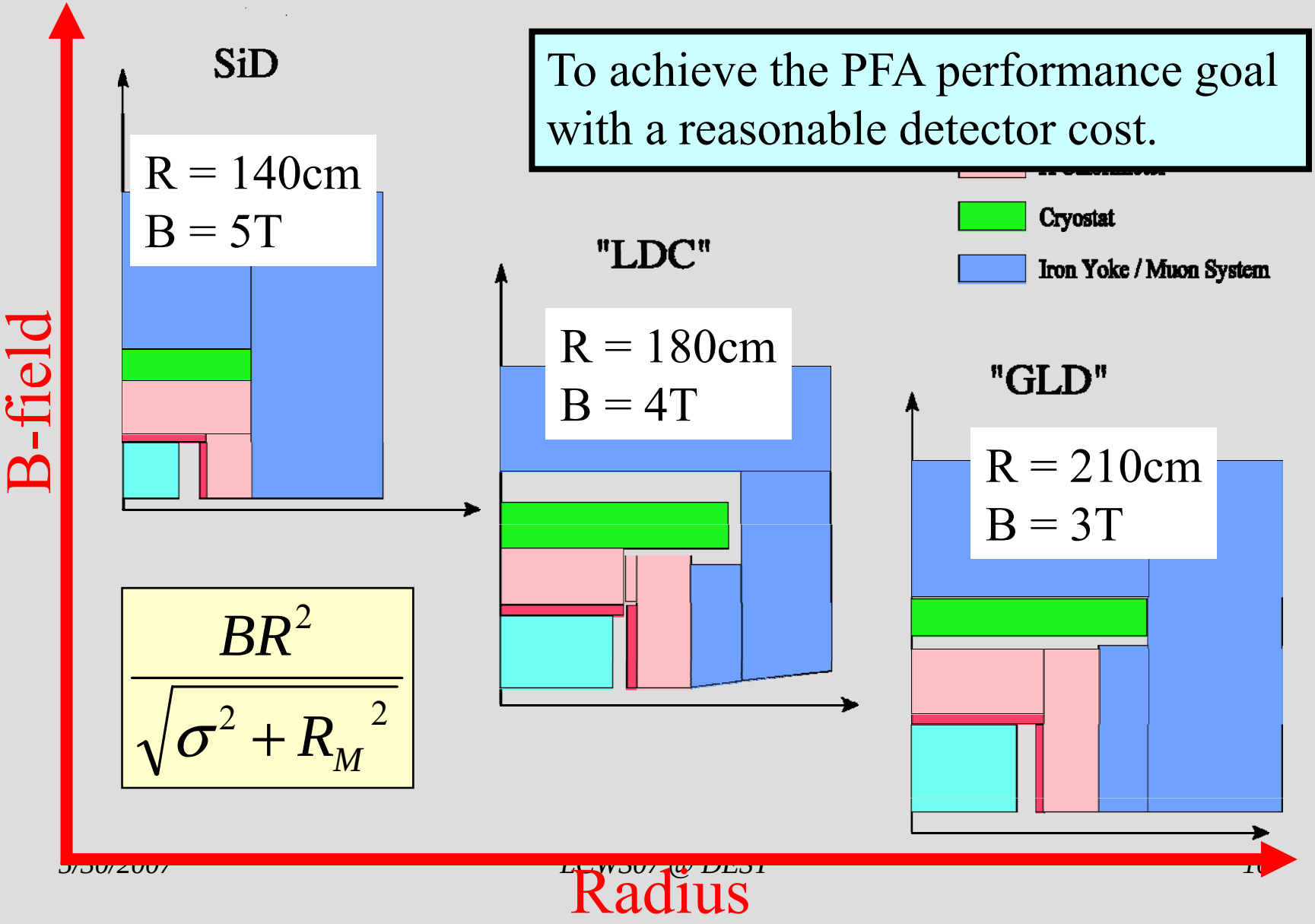
$$\frac{BR^2}{\sqrt{\sigma^2 + R_M{}^2}}$$

B : Magnetic field
R : CAL inner radius
σ: CAL granularity
R_M : Effective Moliere length

- For transverse separation of particles at the ECAL surface, stronger B-field and/or large ECAL radius are preferable.

  * Fine segmentation of CAL is also important for pattern recognition.

Radius vs. B-field



PFA Efforts in the World

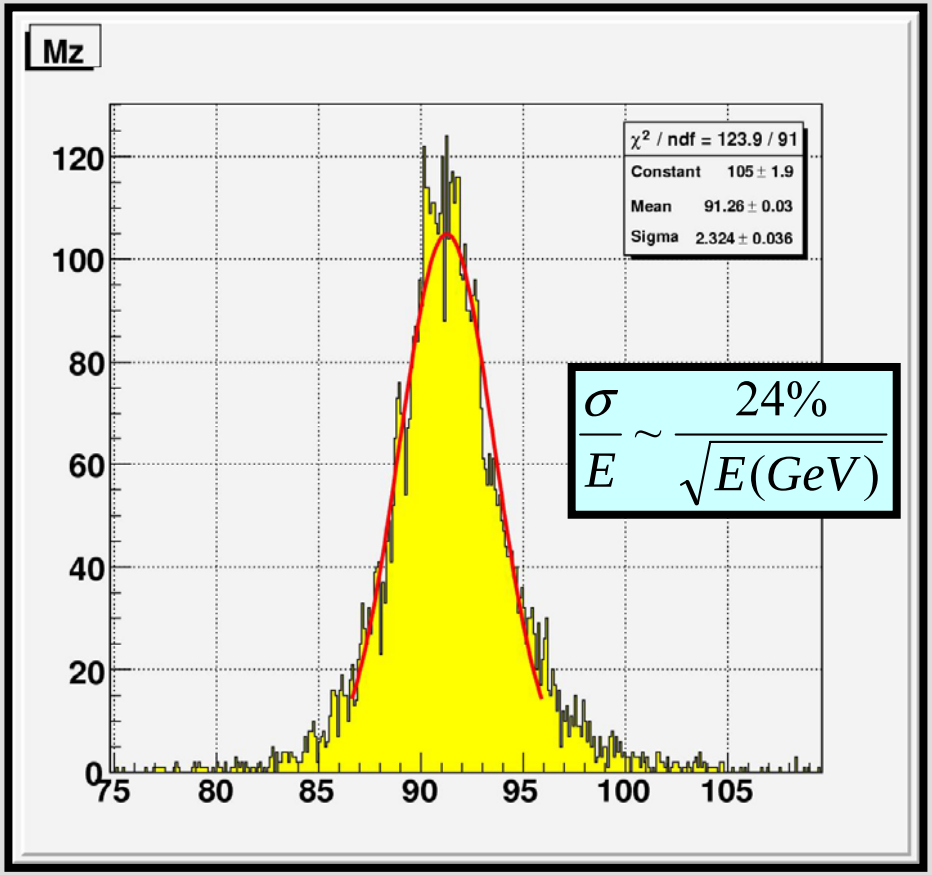
- Several PFAs have been intensively developed in the world so far;
  - SiD
    - PFA for SiD (by N. Graf, S. Magill, L. Xia …)
  - LDC
    - Pandora PFA (by M. Thomson)
    - Wolf PFA (by A. Raspereza)
    - Track-based PFA (by O. Wendt)
  - GLD
    - GLD-PFA (by T. Yoshioka)
  - and others …

→ While the algorithms are distinct, there are a number of features which are common. Details of each algorithm will be presented at on Saturday 02 June.

- Cheated/Perfect PFA studies are also in progress.

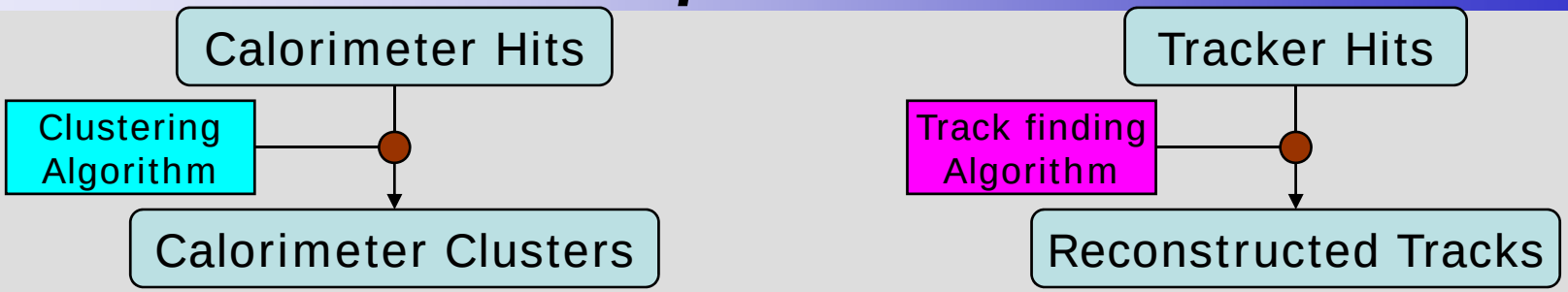
Cheated/Perfect PFA

- Use simulation information to connect track and calorimeter signals.
  → Cheated/Perfect PFA
- Understand factors which affect jet energy resolution
  - Signal sampling fluctuation in calorimeter.
  - Tracker resolution
  - Treatment of V0 decays and interaction before calorimeter.
- Ultimate performance by PFA.

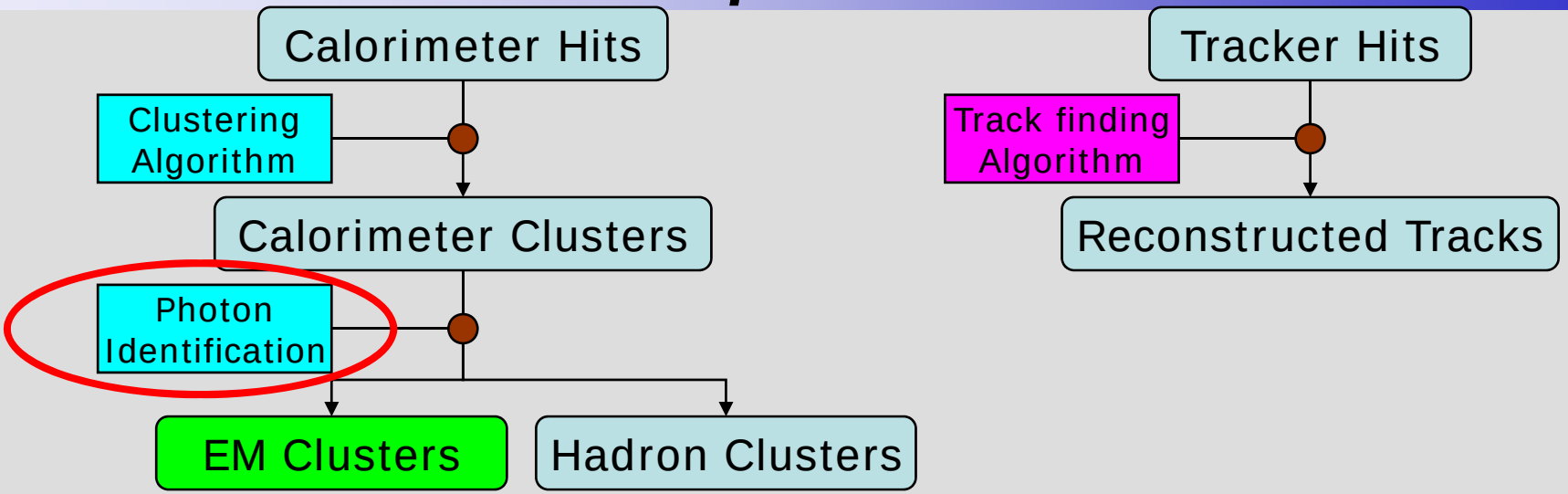


- $e^+e^- \rightarrow Z \rightarrow qq$ @ 91.18GeV

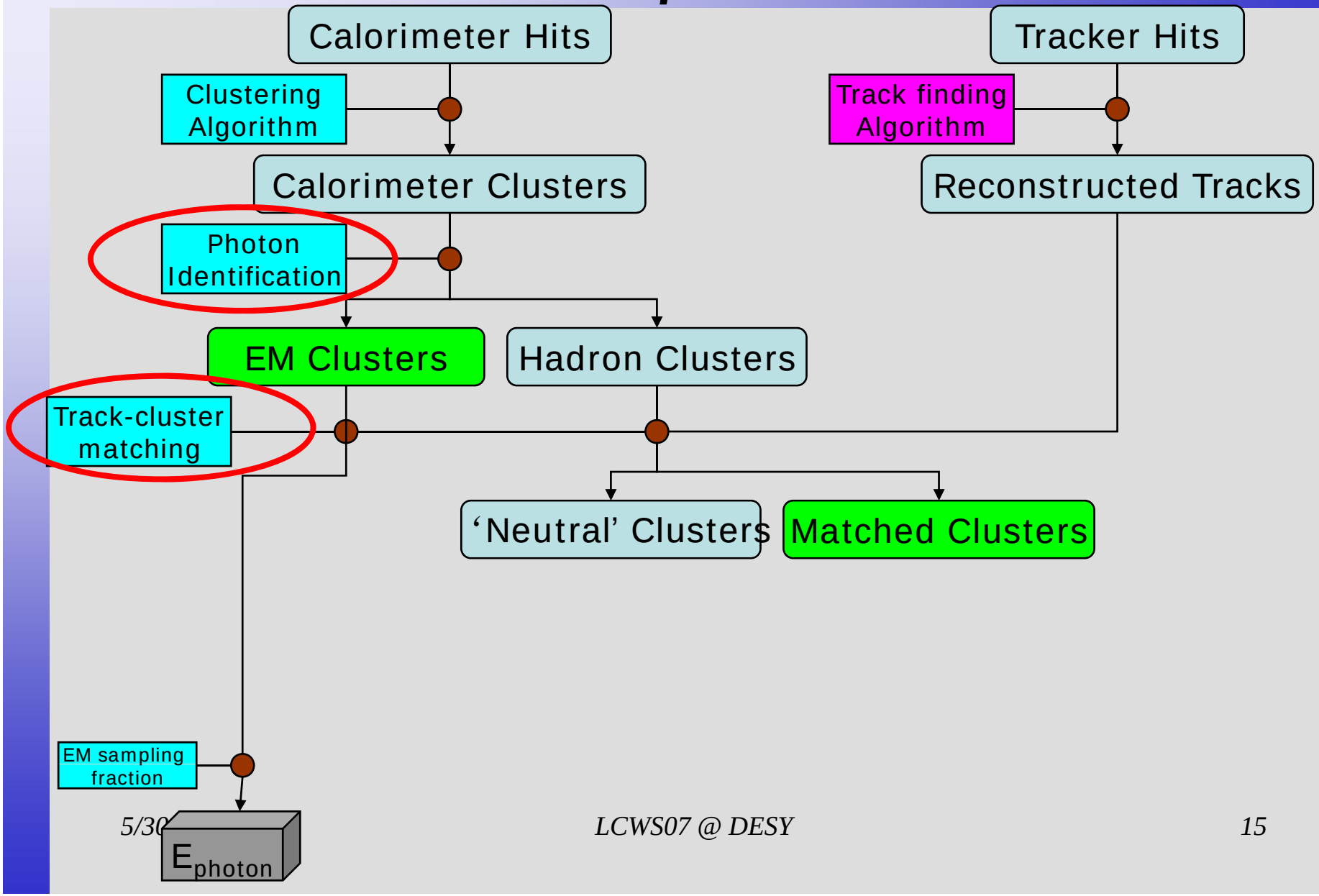
PFA for SiD


Calorimeter Hits
Clustering Algorithm
Calorimeter Clusters
Tracker Hits
Track finding Algorithm
Reconstructed Tracks

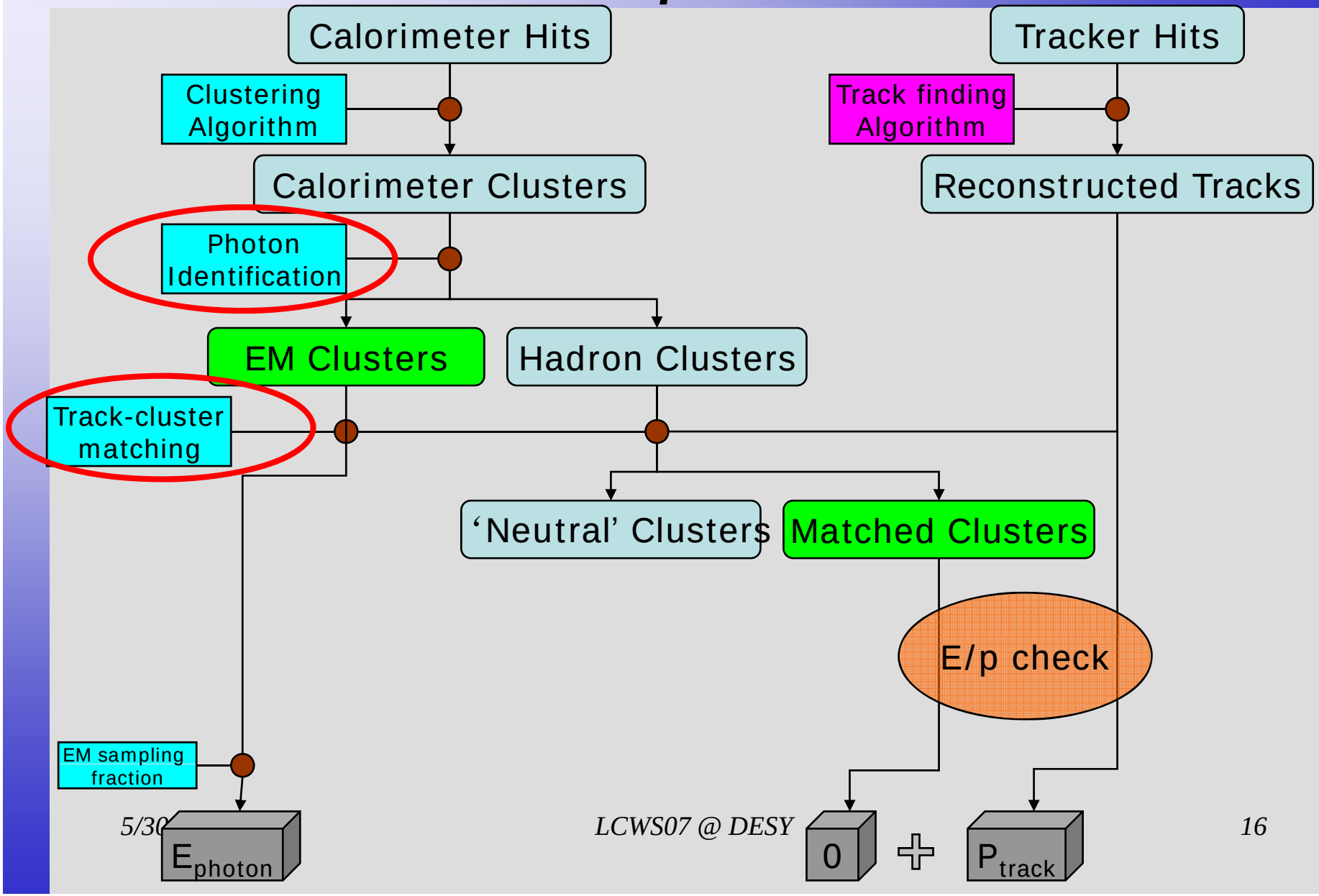
PFA for SiD


Calorimeter Hits
Clustering Algorithm
Calorimeter Clusters
Photon Identification
EM Clusters
Hadron Clusters
Tracker Hits
Track finding Algorithm
Reconstructed Tracks

PFA for SiD


Calorimeter Hits
Tracker Hits
Clustering Algorithm
Track finding Algorithm
Calorimeter Clusters
Reconstructed Tracks
Photon Identification
EM Clusters
Hadron Clusters
Track-cluster matching
'Neutral' Clusters
Matched Clusters
EM sampling fraction
E photon

PFA for SiD


Calorimeter Hits
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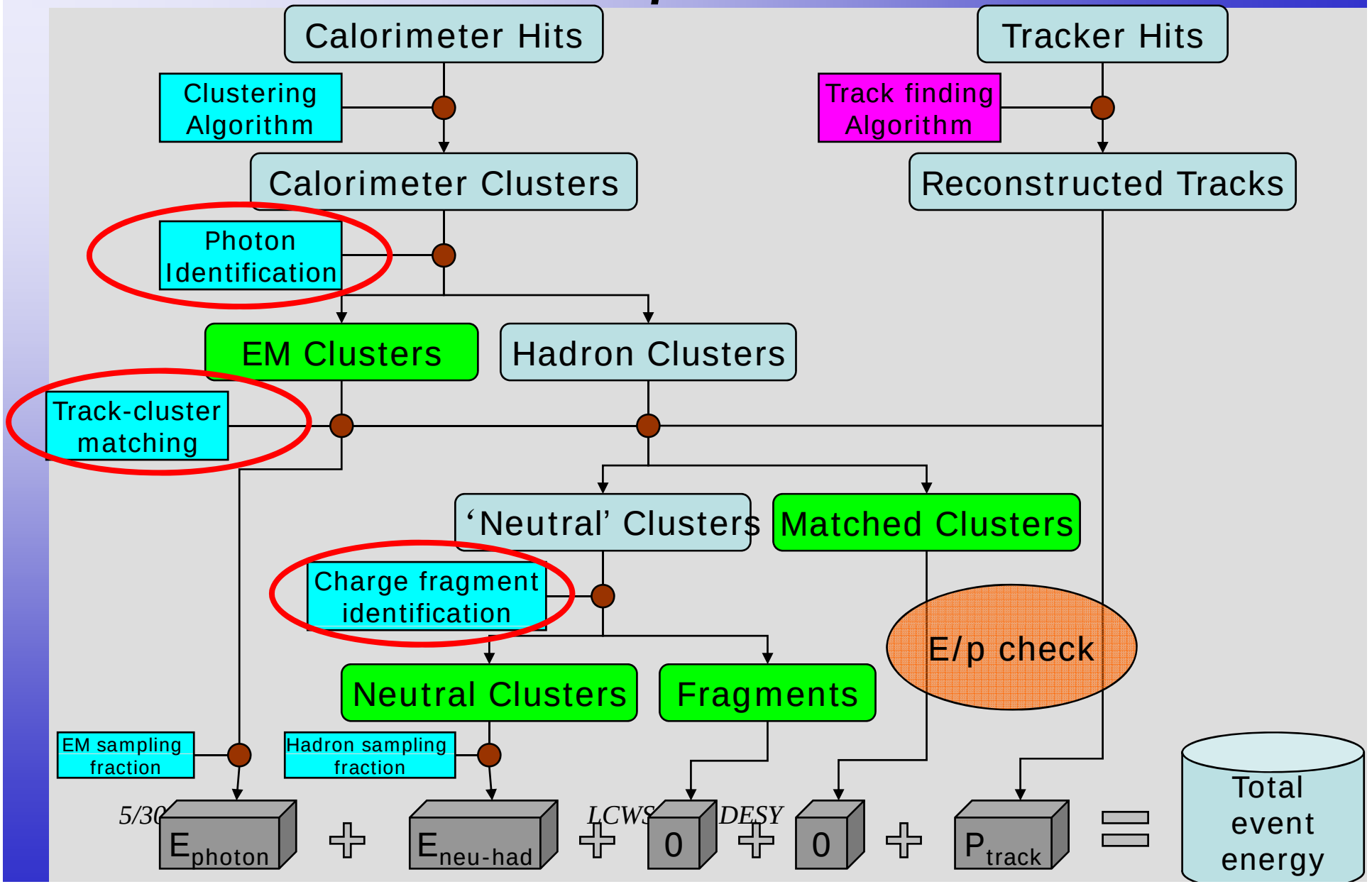
Hadron Clusters
Track-cluster matching
'Neutral' Clusters
Matched Clusters
E/p check
EM sampling fraction
E photon
0
P track

PFA for SiD


Calorimeter Hits
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Reconstructed Tracks
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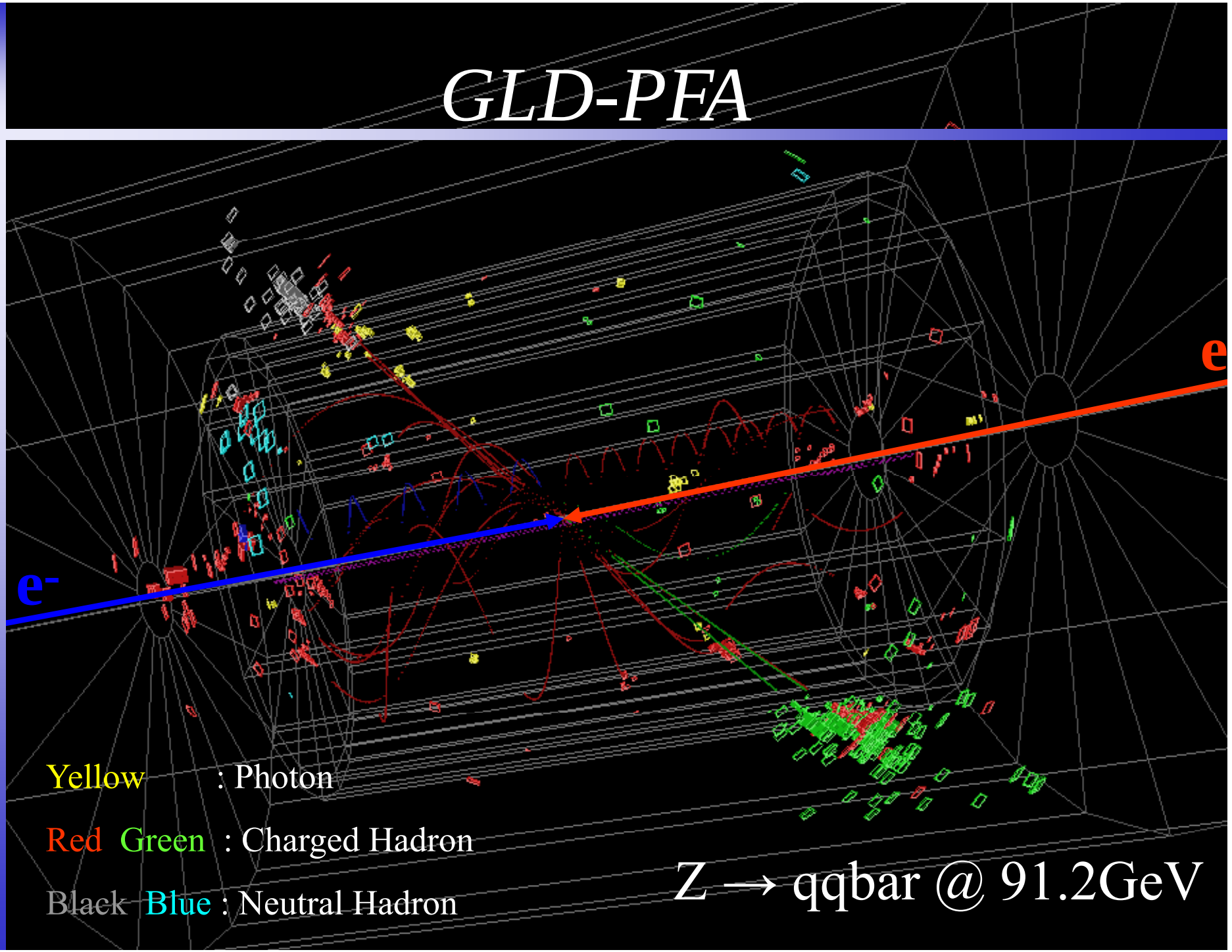
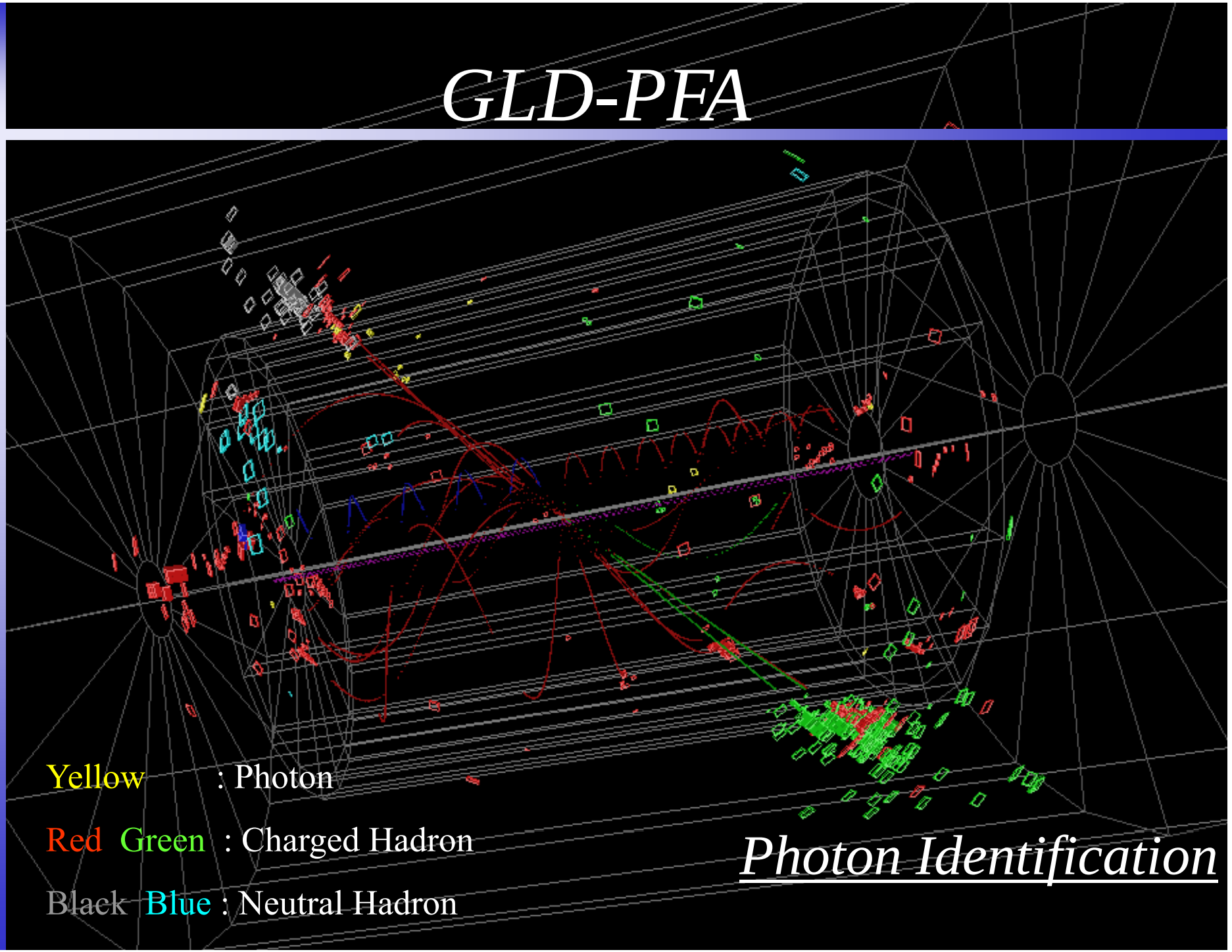
EM Clusters
Hadron Clusters
Track-cluster matching
'Neutral' Clusters
Matched Clusters
Charge fragment identification
E/p check
Neutral Clusters
Fragments
EM sampling fraction
Hadron sampling fraction
E photon
E neu-had
0
0
P track
Total event energy

GLD-PFA

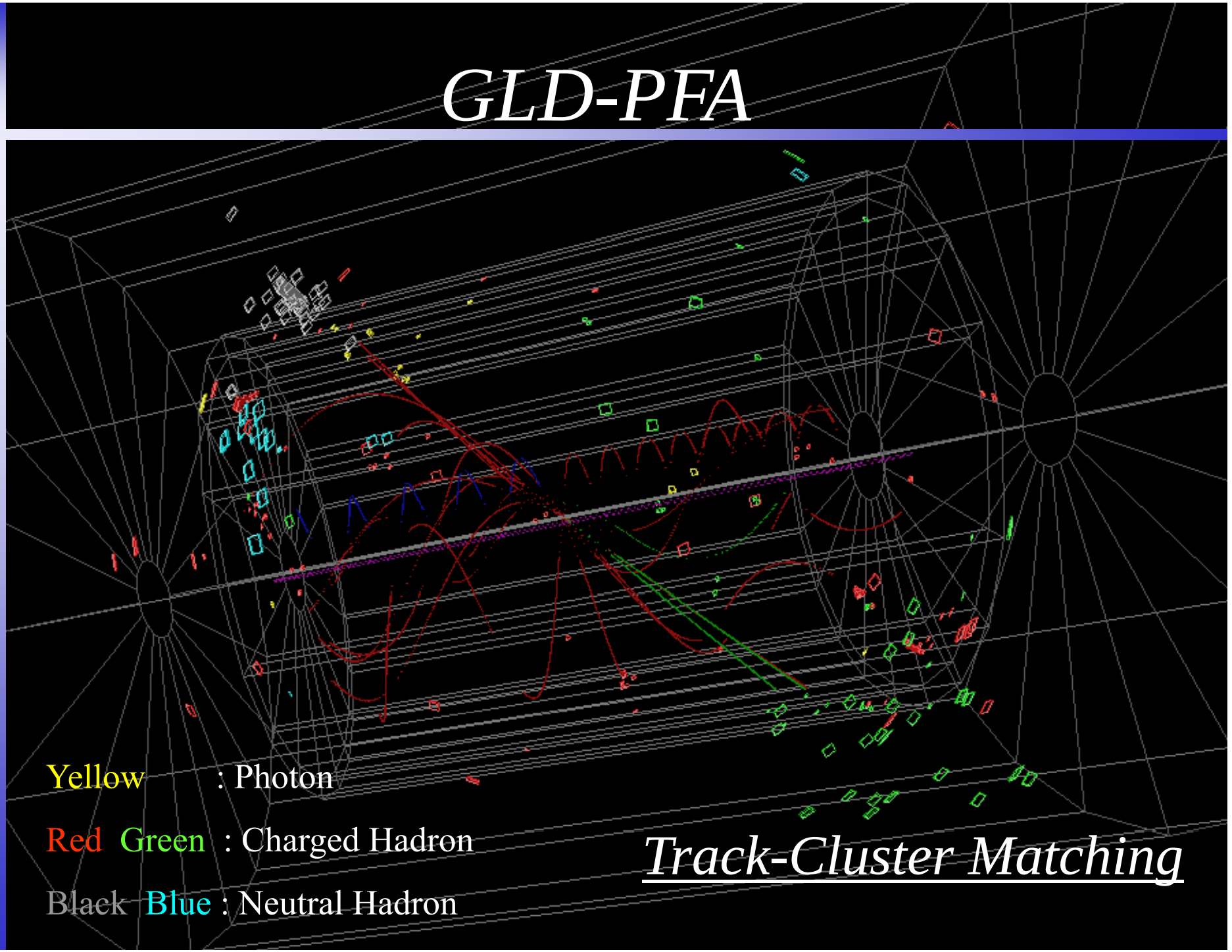

e
e-
Yellow : Photon
Red Green : Charged Hadron
Black Blue : Neutral Hadron
Z → qqbar @ 91.2GeV

GLD-PFA

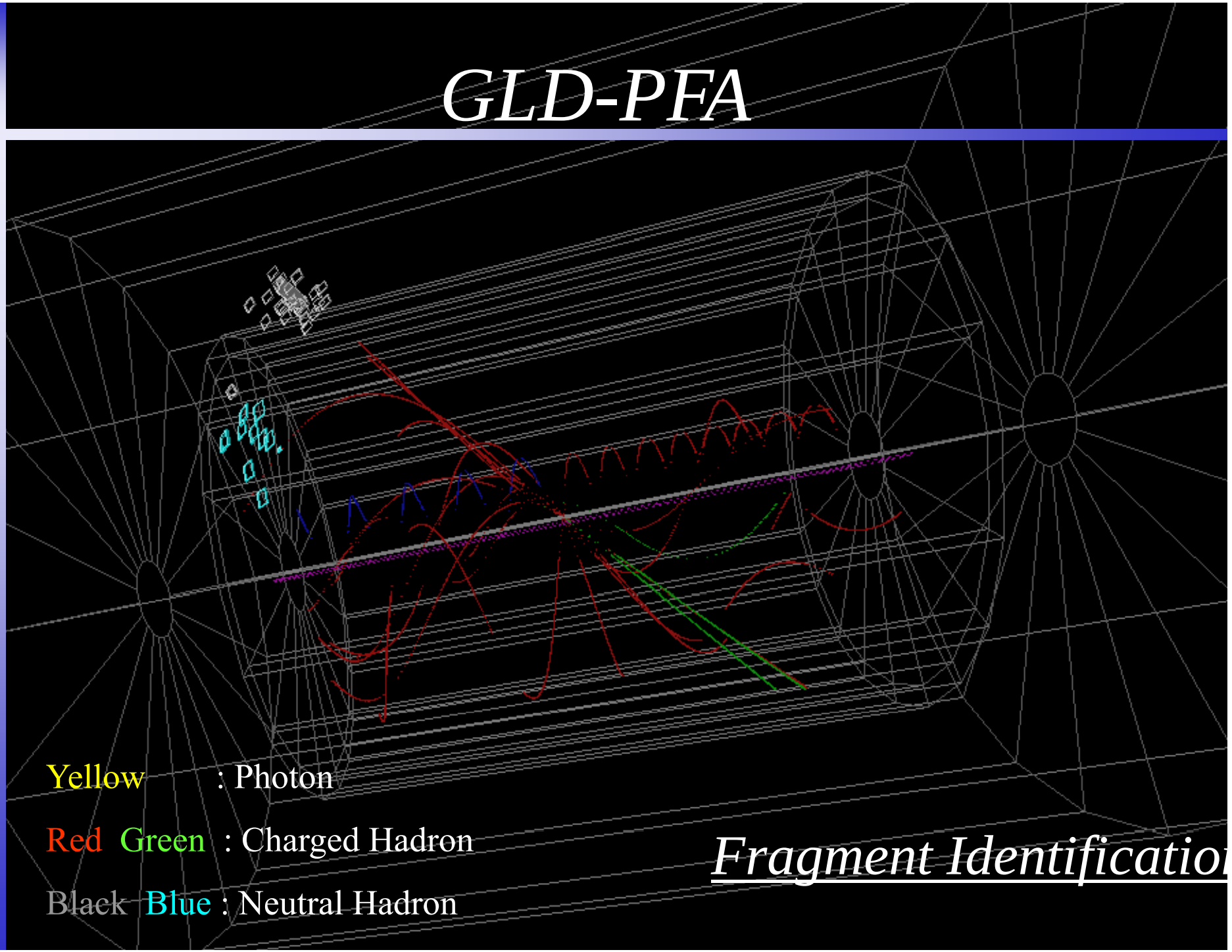


Photon Identification

GLD-PFA


Yellow : Photon
Red Green : Charged Hadron
Black Blue : Neutral Hadron
Track-Cluster Matching

GLD-PFA



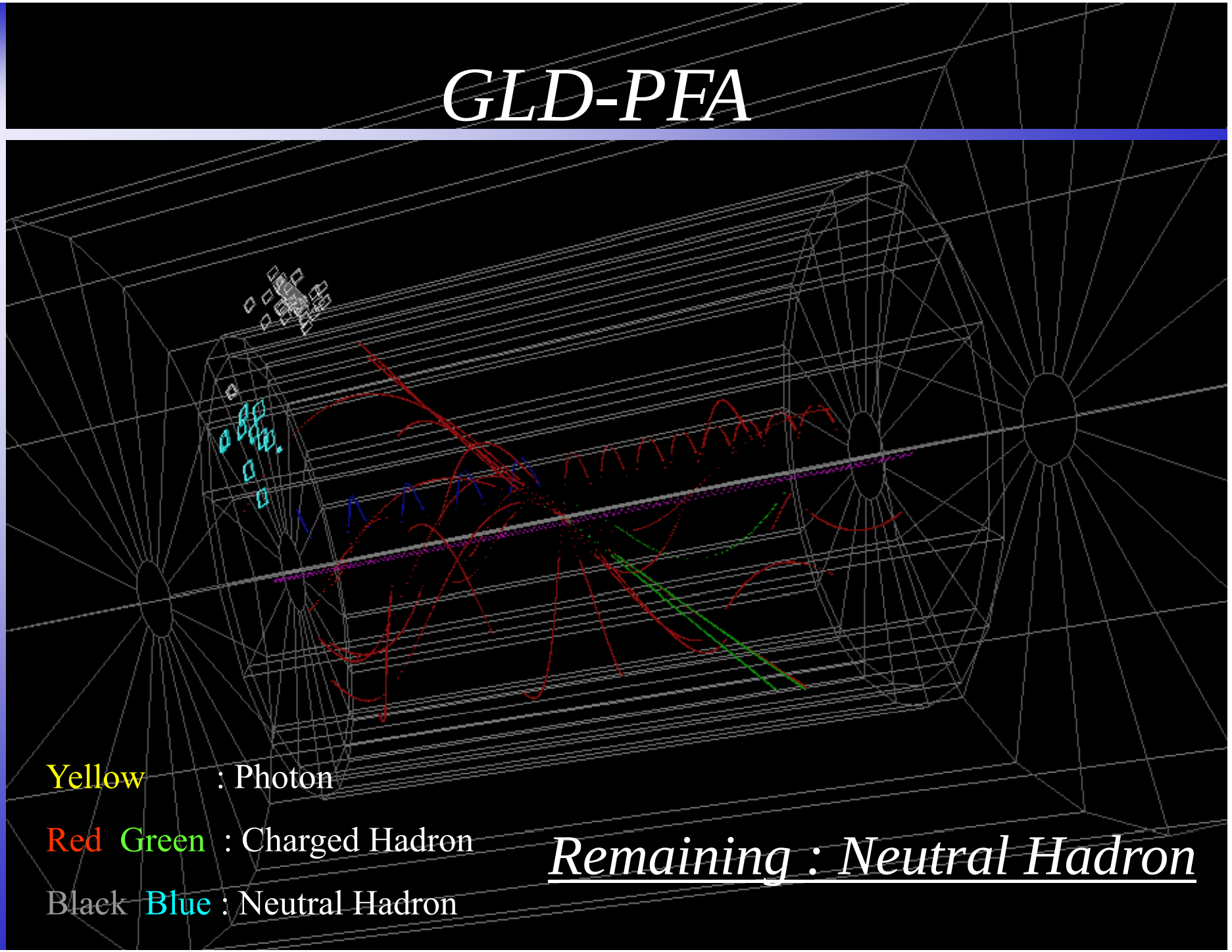
Yellow : Photon

Red Green : Charged Hadron

Black Blue : Neutral Hadron

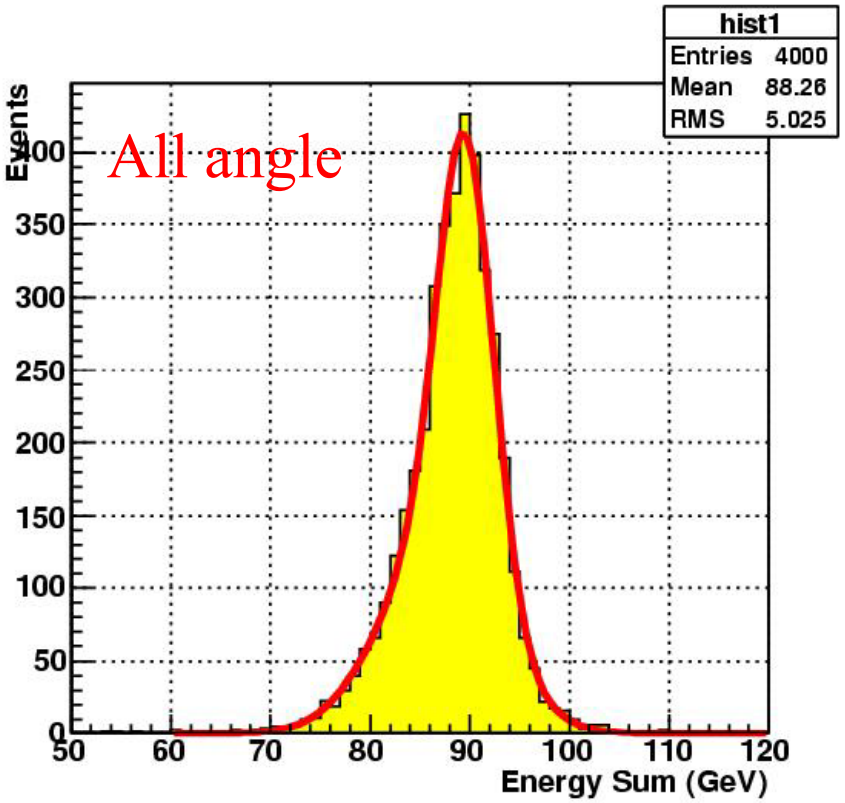
Fragment Identificatio

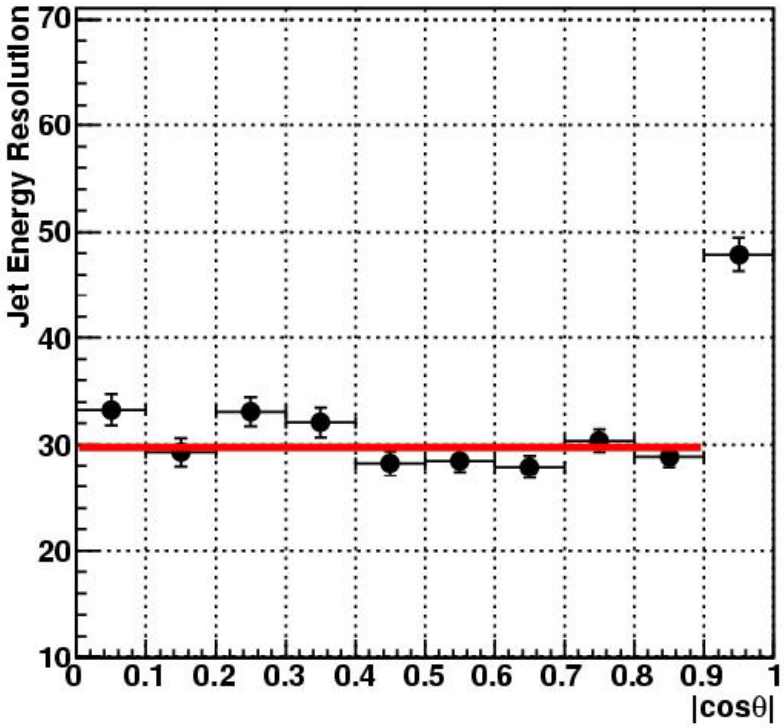
GLD-PFA


Yellow : Photon
Red Green : Charged Hadron
Black Blue : Neutral Hadron
Remaining : Neutral Hadron

Jet Energy Resolution (GLD-PFA)

- Z → uds @ 91.2GeV, tile calorimeter, 1cm x 1cm tile size

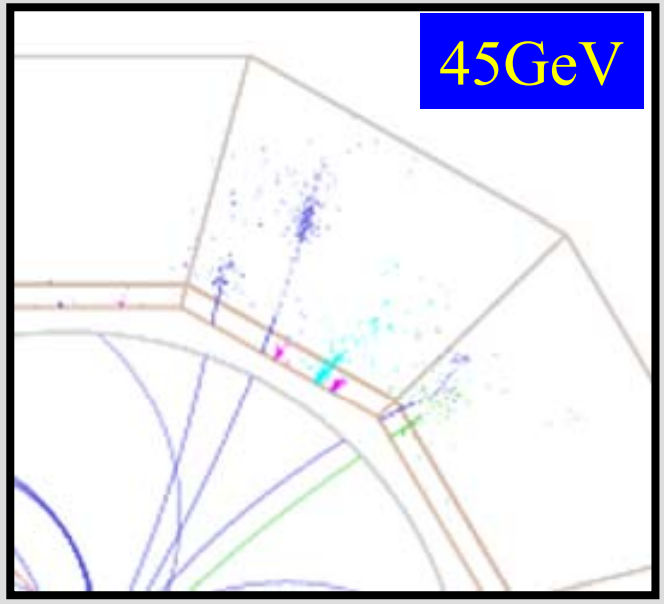


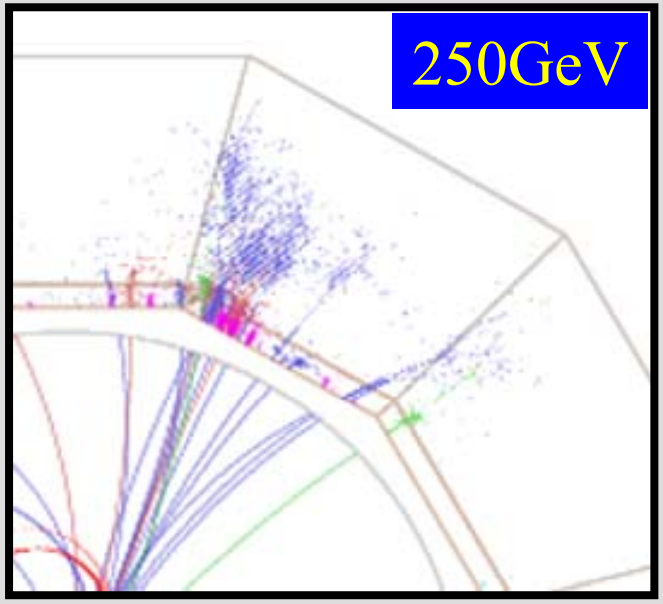


- Almost no angular dependence : ~30%/√E for |cosθ|<0.9.
- cf. 60 %/√E w/o the PFA (sum up the calorimeter energy)

Higher Energy Jets

ILC goal of 30%/√E has been achieved w/ the current PFA at the Z-pole (E_{jet} ~ 45GeV), but PFA becomes more challenging when considering higher energy jets.





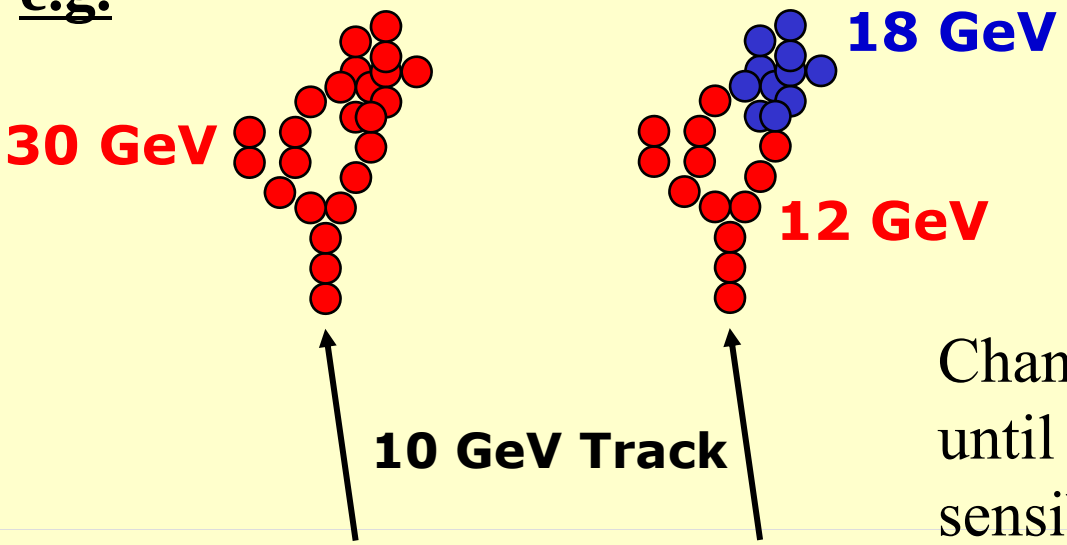
For high energy jets, the opening angles between particles decreases due to the large Lorenz Boost. This makes the separation of the clusters in the calorimeter more difficult. → How to resolve this?

Pandora PFA

- In Pandora PFA, some special tools to take care high energy jets.

- If track momentum and cluster energy inconsistent : RECLUSTER

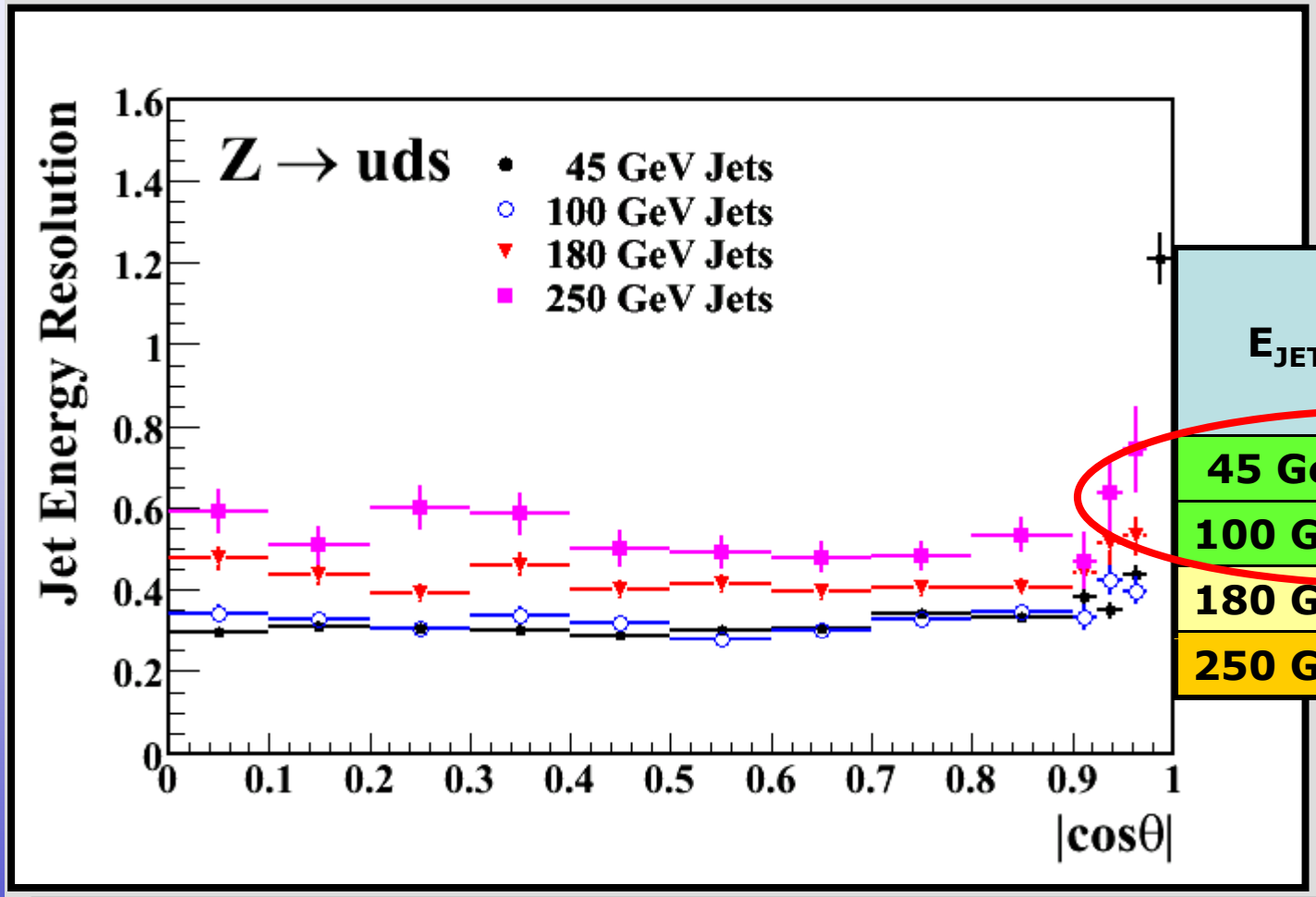
e.g.



Change clustering parameters until cluster splits and get sensible track-cluster match

This is very important for higher energy jets.

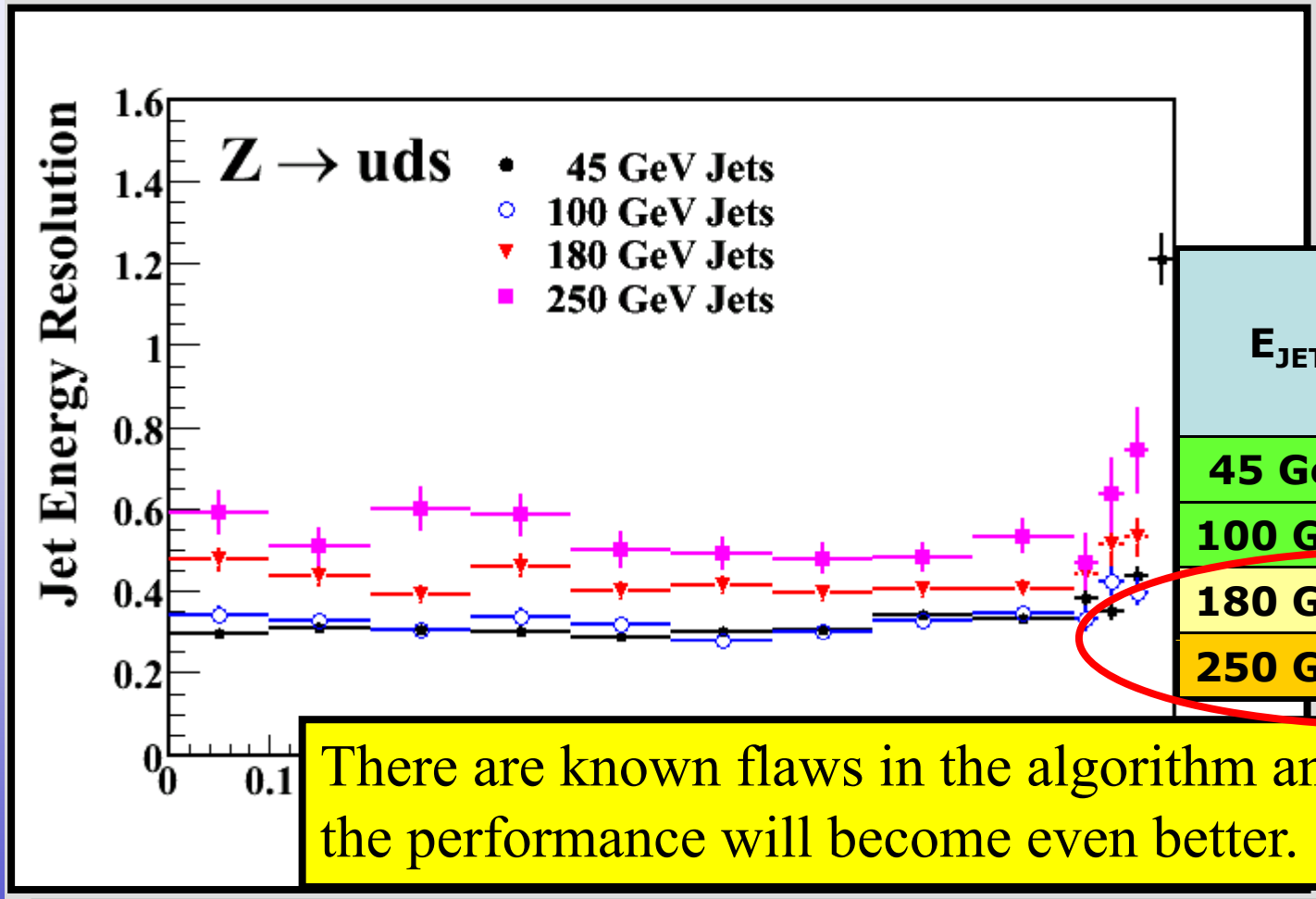
Performance of Pandora PFA



E_{JET}	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$ $\lvert\cos\theta\rvert<0.7$
45 GeV	0.295
100 GeV	0.305
180 GeV	0.418
250 GeV	0.534

For jet energies < 100 GeV ILC goal reached !!!

Performance of Pandora PFA



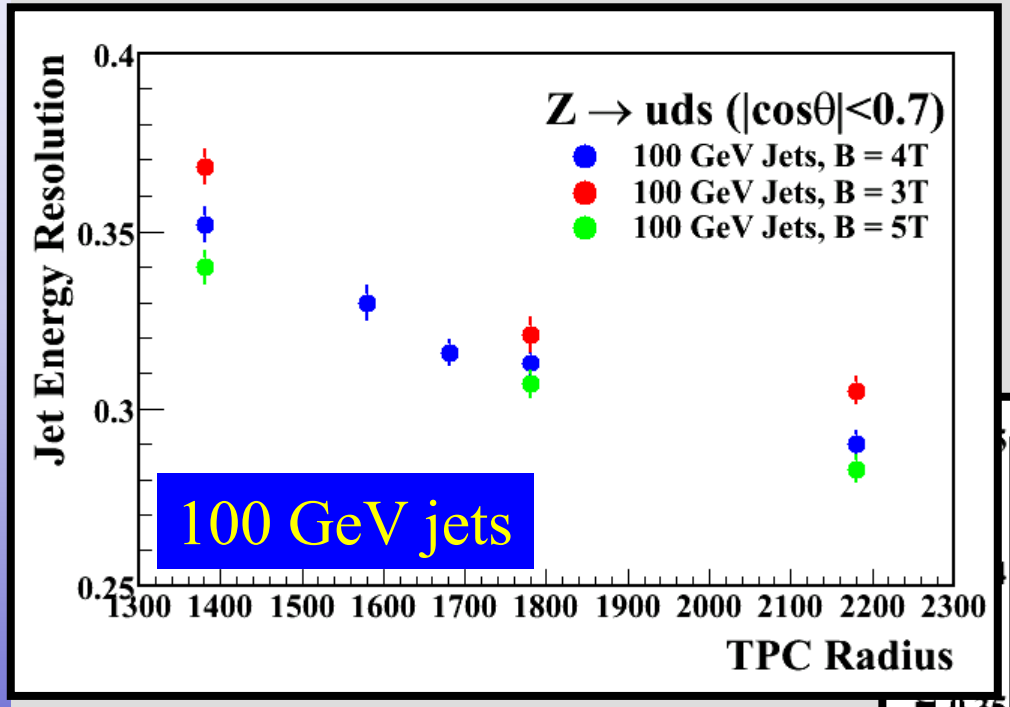
E_{JET}	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$ $\lvert\cos\theta\rvert<0.7$
45 GeV	0.295
100 GeV	0.305
180 GeV	0.418
250 GeV	0.534

There are known flaws in the algorithm and the performance will become even better.

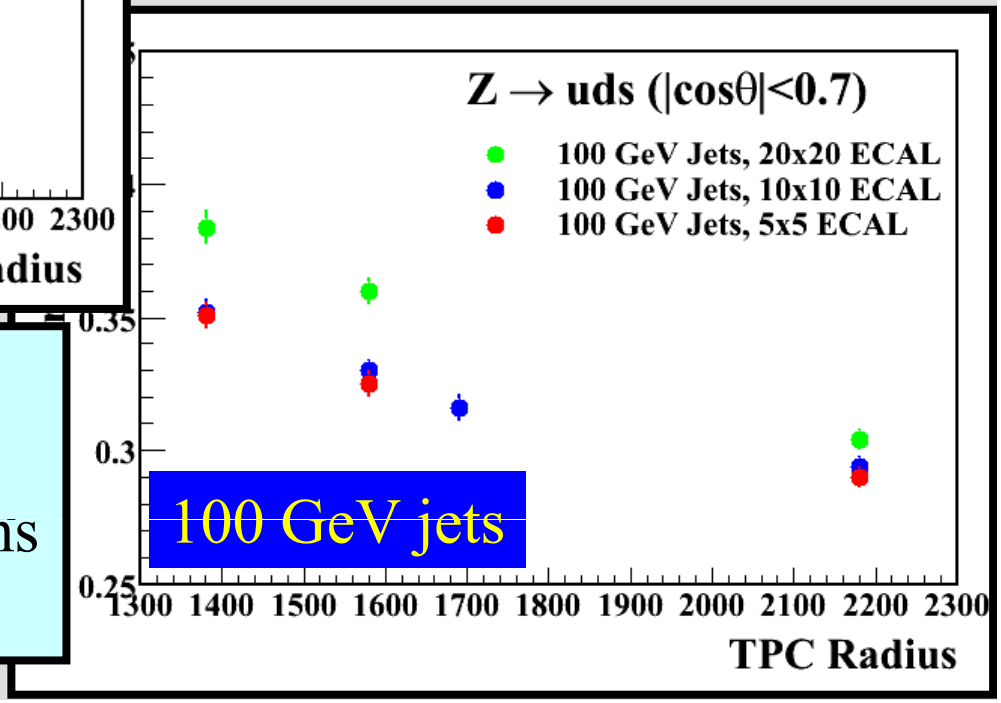
For jet energies < 100 GeV ILC goal reached !!!

Detector Optimization

- Detector optimization study with the PFA has already started.



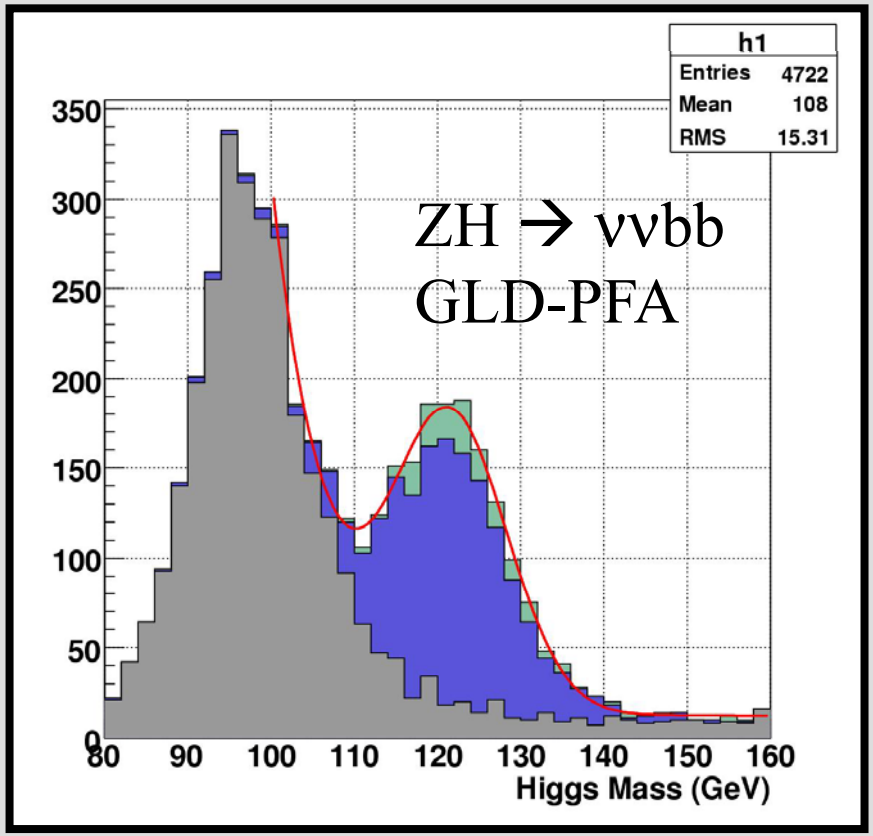
As expected, the resolution improves with increasing radius and increasing magnetic field.

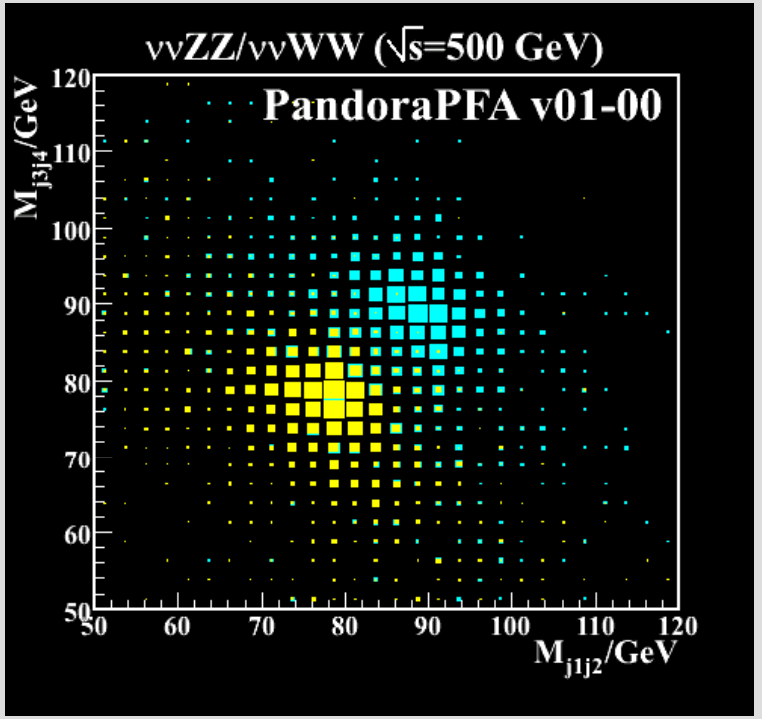


As expected, higher granularity gives better resolution. Previous studies of two particle separations gave similar conclusions.

Physics Study

Lots of physics studies are in progress with the current PFA performance. Results will come soon.





Of course, these are full Simulation results, not fast MC.

Summary

- The Particle Flow Algorithm (PFA) is widely believed that the most promising way to achieve a jet energy resolution of $\sigma_E/E \sim 30\%/\sqrt{E}$.
- We are now confident that PFA can give ILC performance goals for typical ILC jet energies, although there are still plenty of room for improvement.
- Detector optimization study/Physics study with the PFA are now intensively in progress.
- Simulation/Reconstruction parallel session on 31st May and 2nd June.