Summary on PFA

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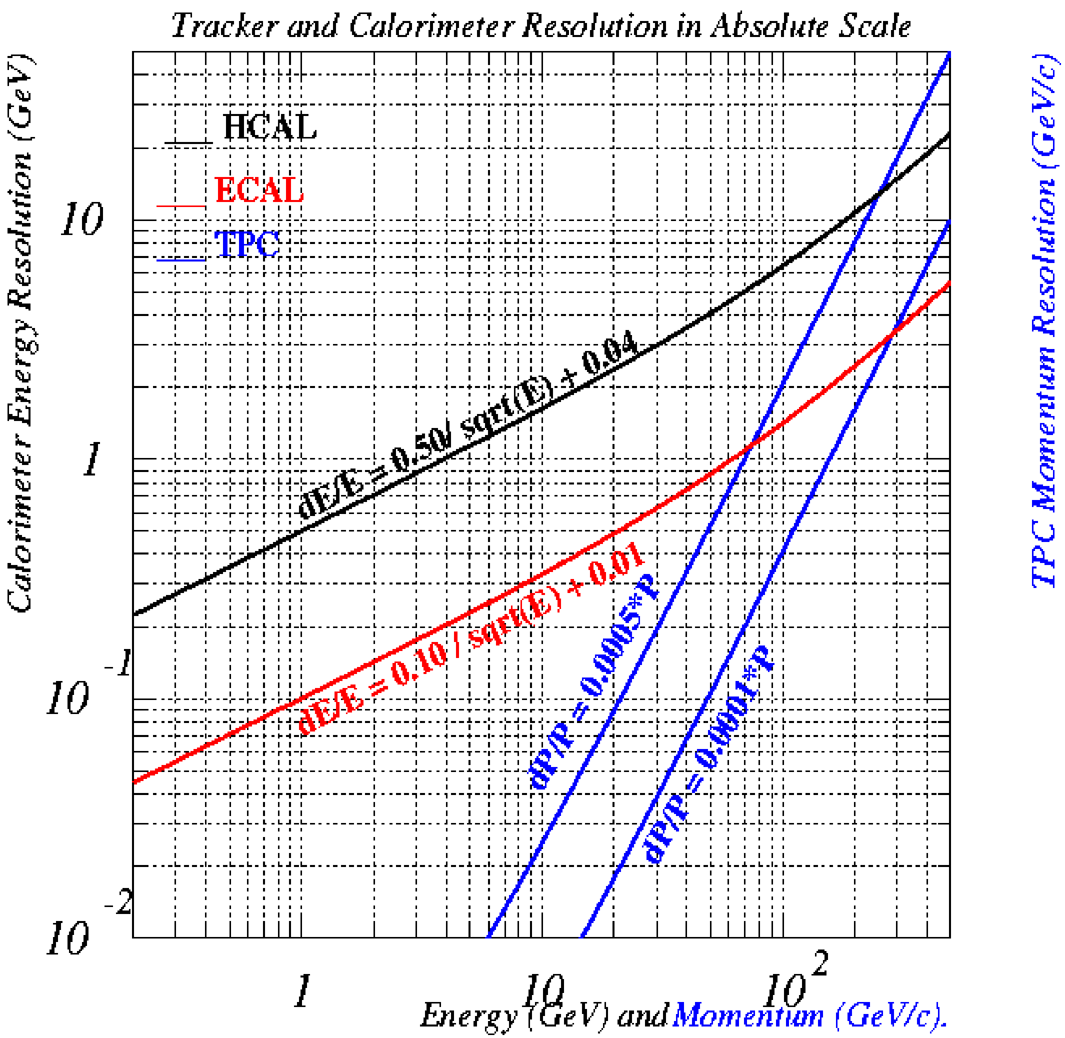
ILC Workshop,
Snowmass
August 26, 2005

Introduction

- PFlow concept has found wide acceptance as an optimal approach for event reconstruction in the LC experiment
  - PFA performance is one of the main factors, driving detector design
- ILC collaboration enters the phase of detector optimization
  - we desperately need tools to perform detector optimization studies (realistic PFA is one of these tools)
- At the stage of detector optimization, flexibility of reconstruction software is favored over performance
  - PFA should have minimal dependence on detector geometry to enable detector optimization
  - PFA can be further optimized once the detector configuration is chosen and fixed

Particle Flow Concept

- Basic idea : optimal reconstruction of every measurable particle in an event
- Track momentum resolution is much better than calorimeter energy resolution :
  - use tracker to estimate 4-momenta of charged objects (e, μ, $h^{\pm}$)
  - use calorimeters for reconstruction of neutral objects (γ, h0)
- Implications for detector
  - good pattern recognition in tracking device to facilitate efficient track reconstruction in jets with high local particle densities
  - imaging capabilities of calorimeters are favored over compensation; one needs highly granular calorimeters to ensure good separation between charged and neutral particles



Perfect PFA : What theory predicts

- Jet energy resolution

  $\sigma^2(E_{jet}) = \sigma^2(ch.) + \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(conf.)$

- Excellent tracker :

  $\sigma^2(ch.) << \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(conf.)$

- Perfect PFA : $\sigma^2(conf.) = 0$

- $\sigma^2(E_{jet}) = A_\gamma^2 E_\gamma + A_h^2 E_{h0} = w_\gamma A_\gamma^2 E_{jet} + w_{h0} A_h^2 E_{jet}$

  $\sigma(E_{\gamma,h})/E_{\gamma,h} = A_{\gamma,h}/\sqrt{E_{\gamma,h}}$

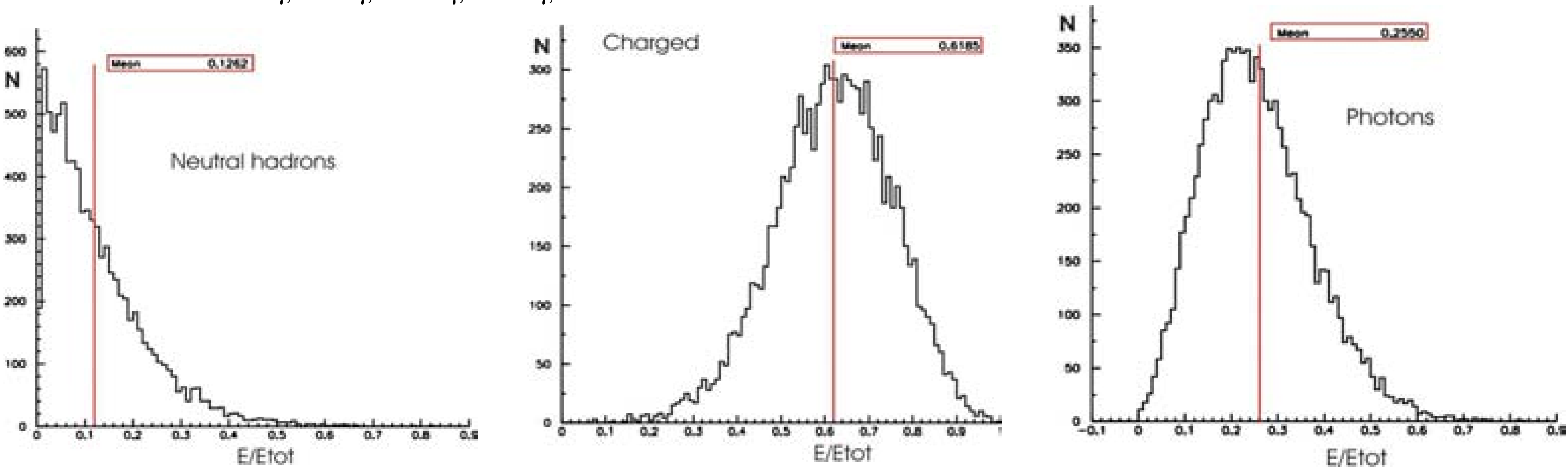
Typically $w_\gamma = 25\%$; $w_{h0} = 13\%$

$A_\gamma = 11\%$; $A_{h0} = 34\%$

$\Rightarrow \sigma(E_{jet})/E_{jet} = 12\%/\sqrt{E_{jet}}$

$A_\gamma = 11\%$; $A_{h0} = 50\%$

$\Rightarrow \sigma(E_{jet})/E_{jet} = 17\%/\sqrt{E_{jet}}$



Factors Contributing to Z Mass Resolution. Studies for LDC

$$e^+ e^- \rightarrow Z^0 \rightarrow q\bar{q} \text{ at } 91.2\text{GeV}$$

Studies by P. Krstonosic

Effect	σ [GeV] separate	σ [GeV] not joined	σ [GeV] total ($\%/\sqrt{E}$)	σ to total
$E_\nu > 0$	0.84	0.84	0.84 (8.80%)	12.28
$Cone < 5^o$	0.73	1.11	1.11(11.65%)	9.28
$P_t < 0.36$	1.36	1.76	1.76(18.40%)	32.20
σ_{HCAL}	1.40	1.40	2.25(23.53%)	34.12
σ_{ECAL}	0.57	1.51	2.32(24.27%)	5.66
M_{neutral}	0.53	1.60	2.38(24.90%)	4.89
M_{charged}	0.30	1.63	2.40(25.10%)	1.57

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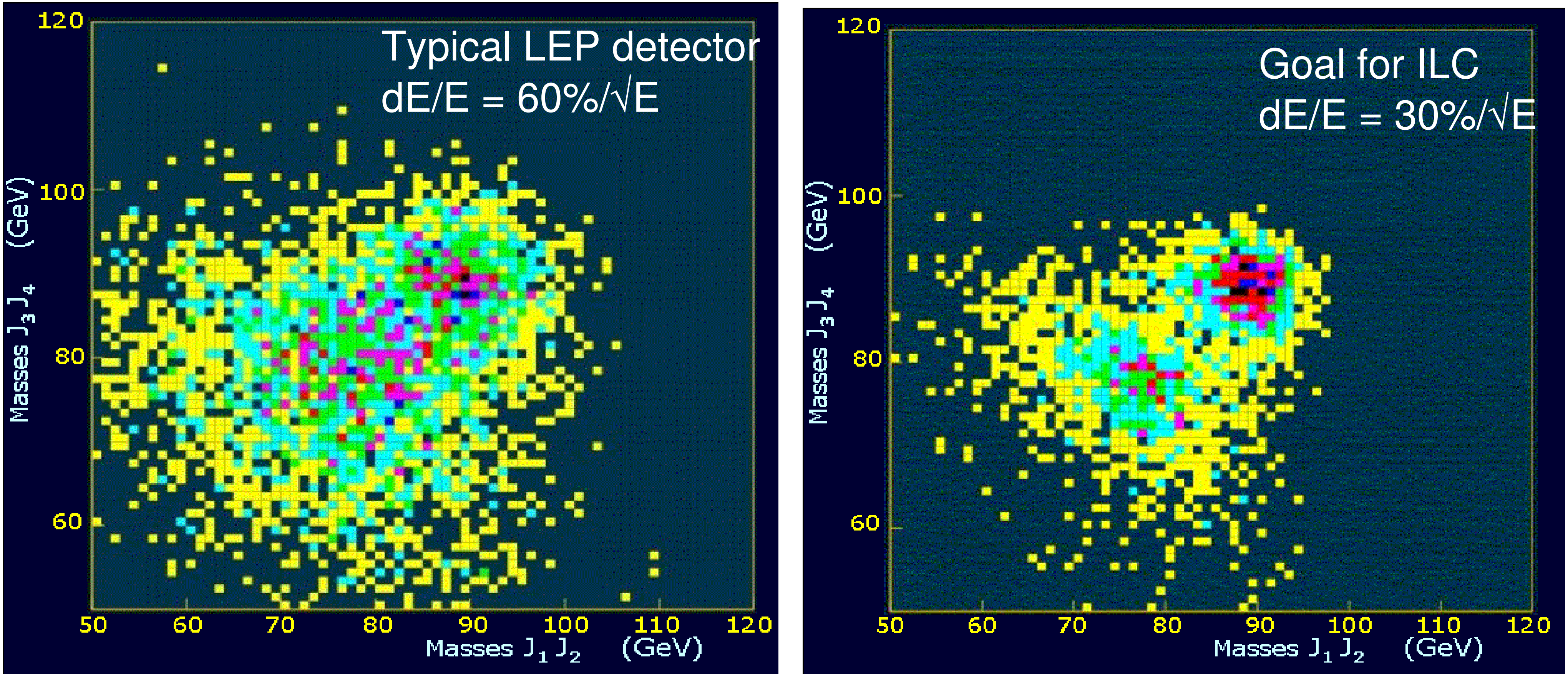
What Jet Energy Resolution Do We Need

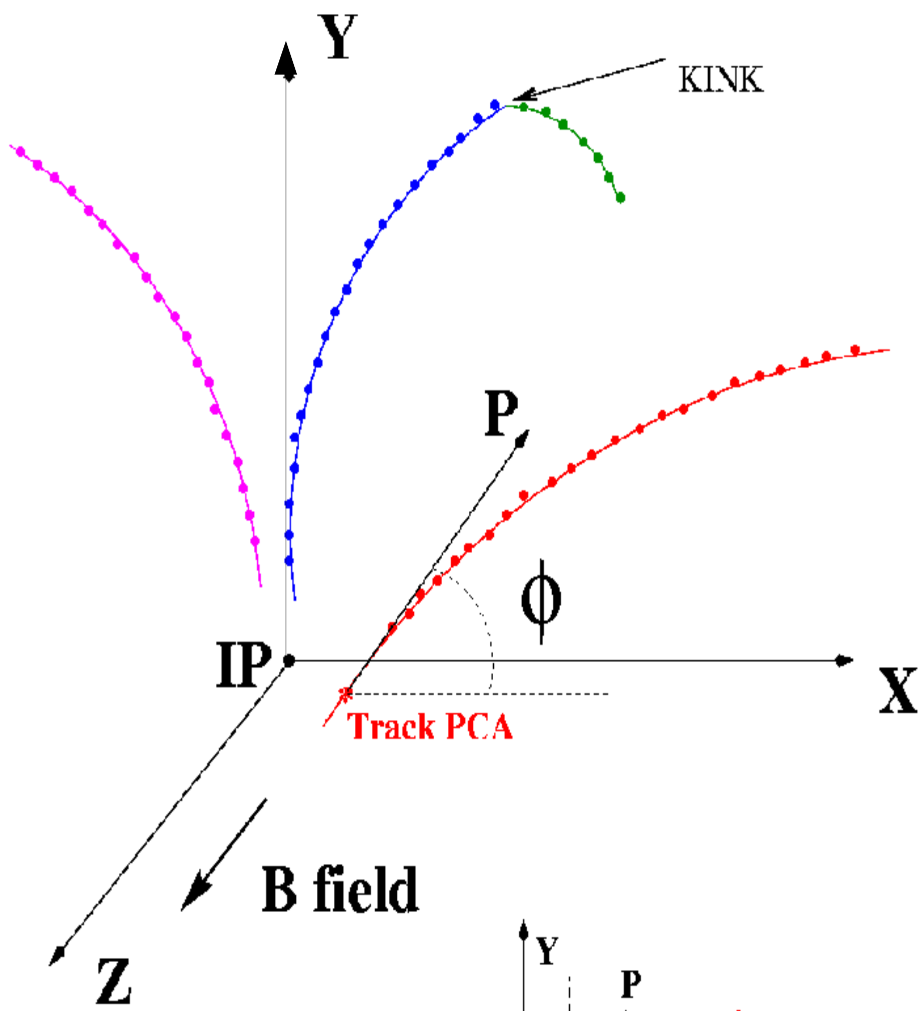
Separability of WW=>4j and ZZ=>4j final states in processes $e^+e^- \Rightarrow WW\nu\nu$, $ZZ\nu\nu$ (Signal for strong EWSB!)

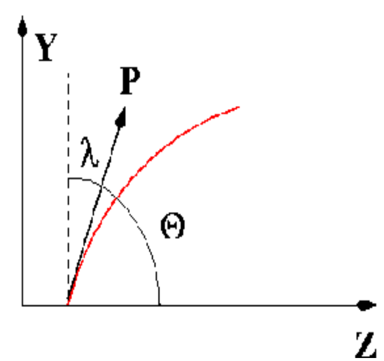


Benchmark goal : $dE_{jet}/E_{jet} = 30\%/\sqrt{E_{jet}}$

1^{st} Step of PFA. Tracking

- Pattern recognition in tracking system (there exist corresponding codes for TPC (MarlinReco) and Si tracker (org.lcsim))
- Track fitting using Kalman fitter.
- Procedures of fitting
  - Simple helix model (used for tracking in Si detector)
  - Model accounting for energy loss (used in TPC code)
- Track parameters extracted from fit are used to estimate momentum of charged objects @ point of closest approach to IP and their charge:
  - $P_T = 0.3\ B[T]\ R[m]$
  - $P_x = P_T \cos\phi$; $P_y = P_T \sin\phi$
  - $P_z = P_T \tan\lambda$
- Special handle of kinks and V0's



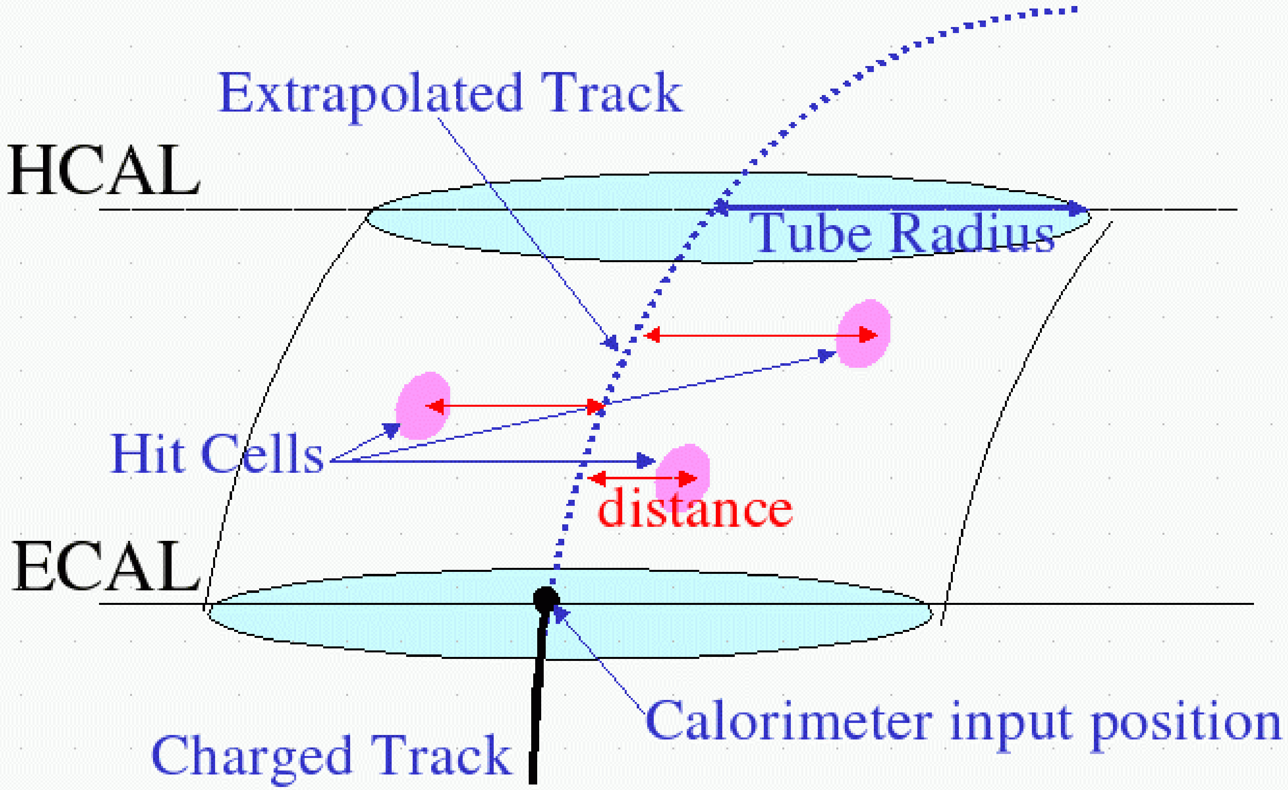


Two Strategies of PFA

- First approach (org.lcsim, PFA for GLD)
  - Track supported clustering => association of calorimeter hits to close-by track; iterative procedure to match energy of cluster and track momentum
  - dedicated photon cluster finding
  - clustering on remaining hits => neutral hadrons
- Second approach (MarlinReco)
  - Clustering based solely on spatial information (relies heavily on imaging capabilities of detectors, no use of hit amplitude information, no use of tracking information)
  - Track – cluster matching based on proximity criterion
  - Particle ID based on cluster shape analysis

Track Matching Procedure

- ***Basic Concept*** :
  Extrapolate the charged track and calculate a distance between a calorimeter hit cell and the extrapolated track. Connect the cell that in a certain tube radius (clustering).



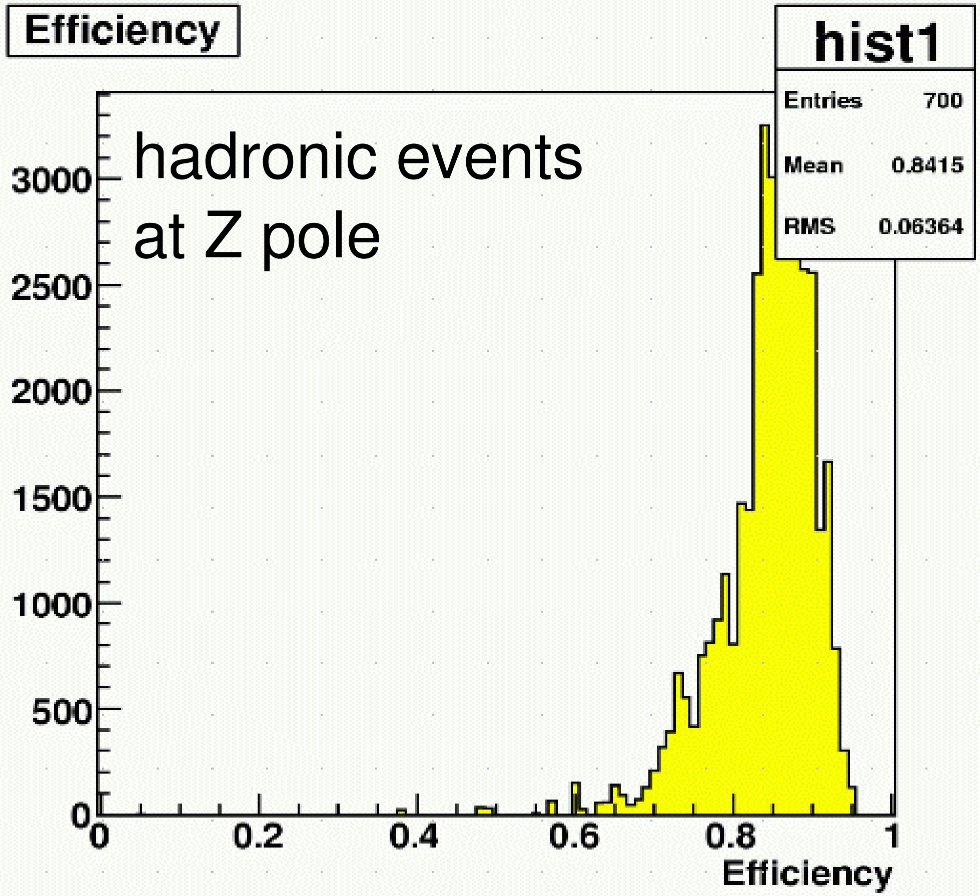
- Calculate the distance for any track/calorimeter cell combination.

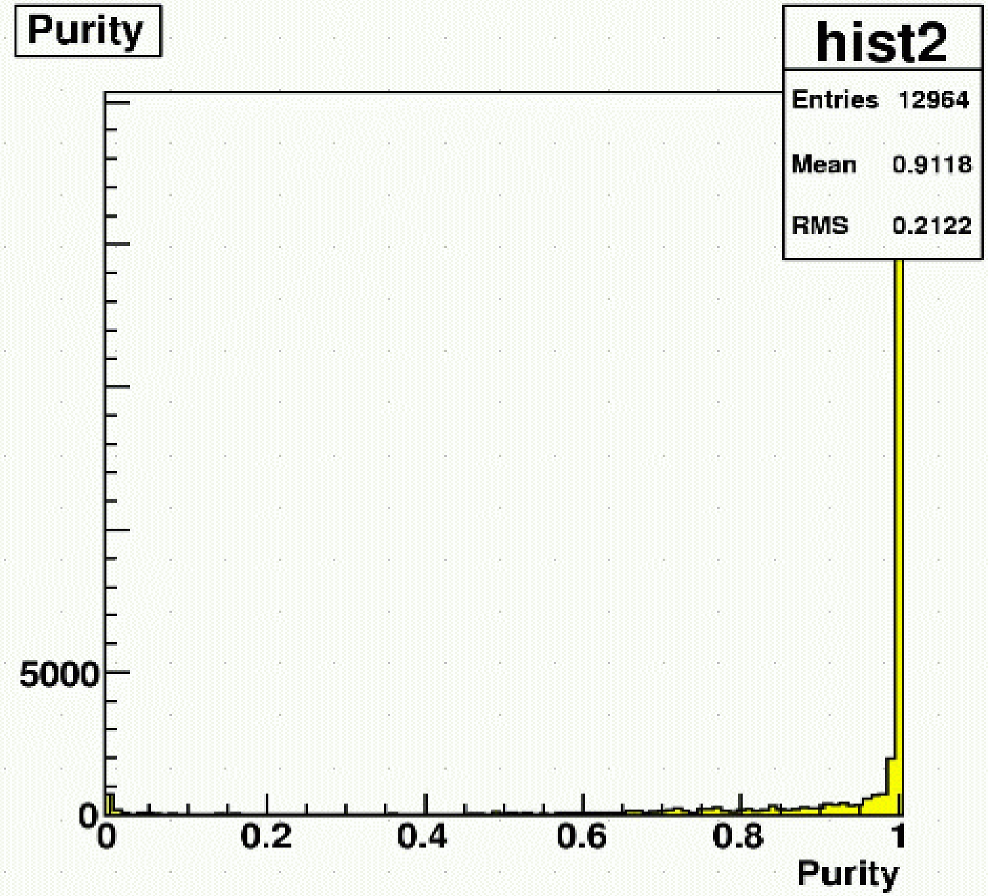
- Tube radius for ECAL and HCAL can be changed separately.

T. Yoshioka

Energy Weighted Efficiency/Purity

- Efficiency/Purity of Track Matching is checked by cheating method.



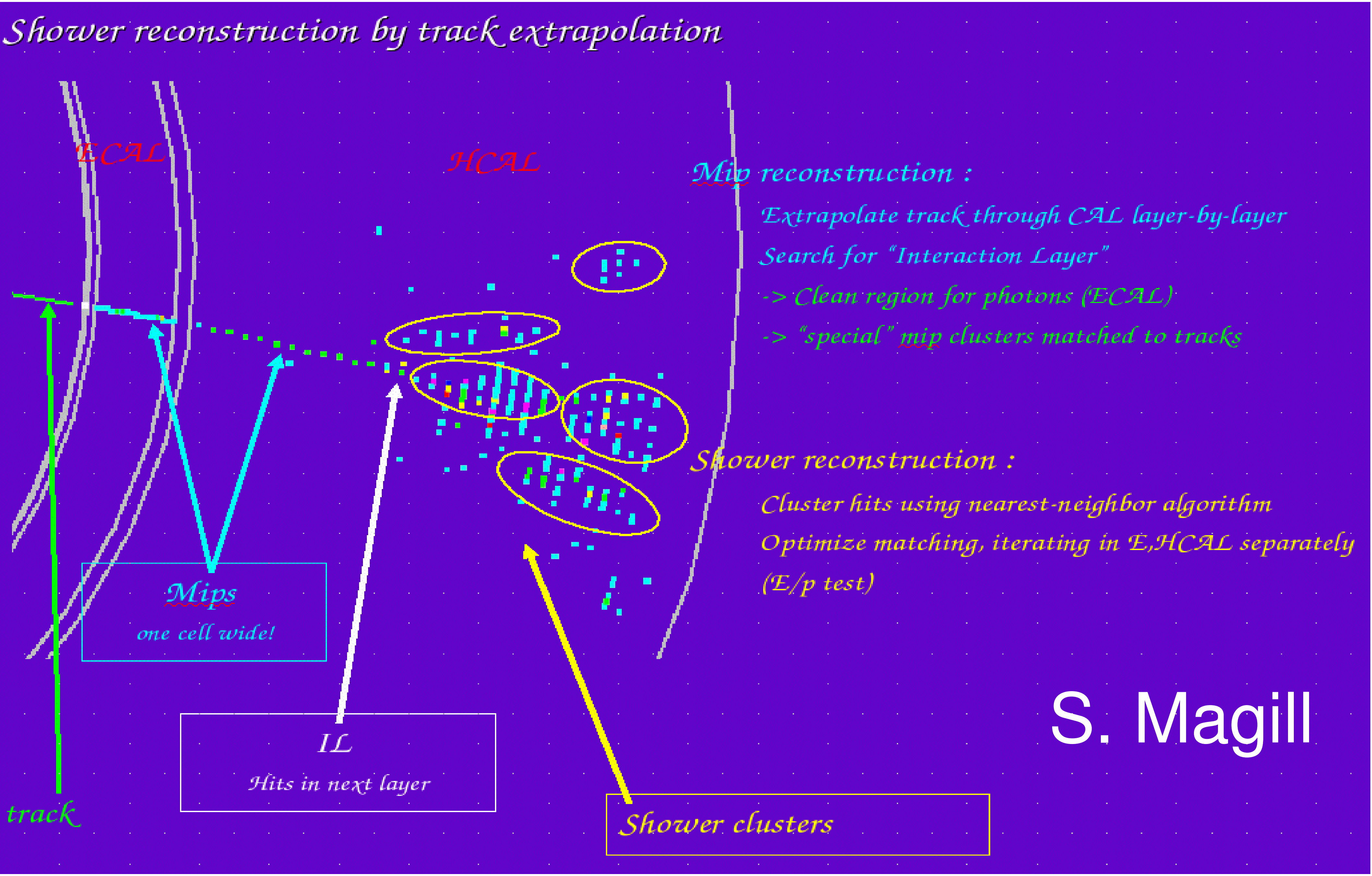


Efficiency : 84.2%

Purity : 91.2%

T. Yoshioka

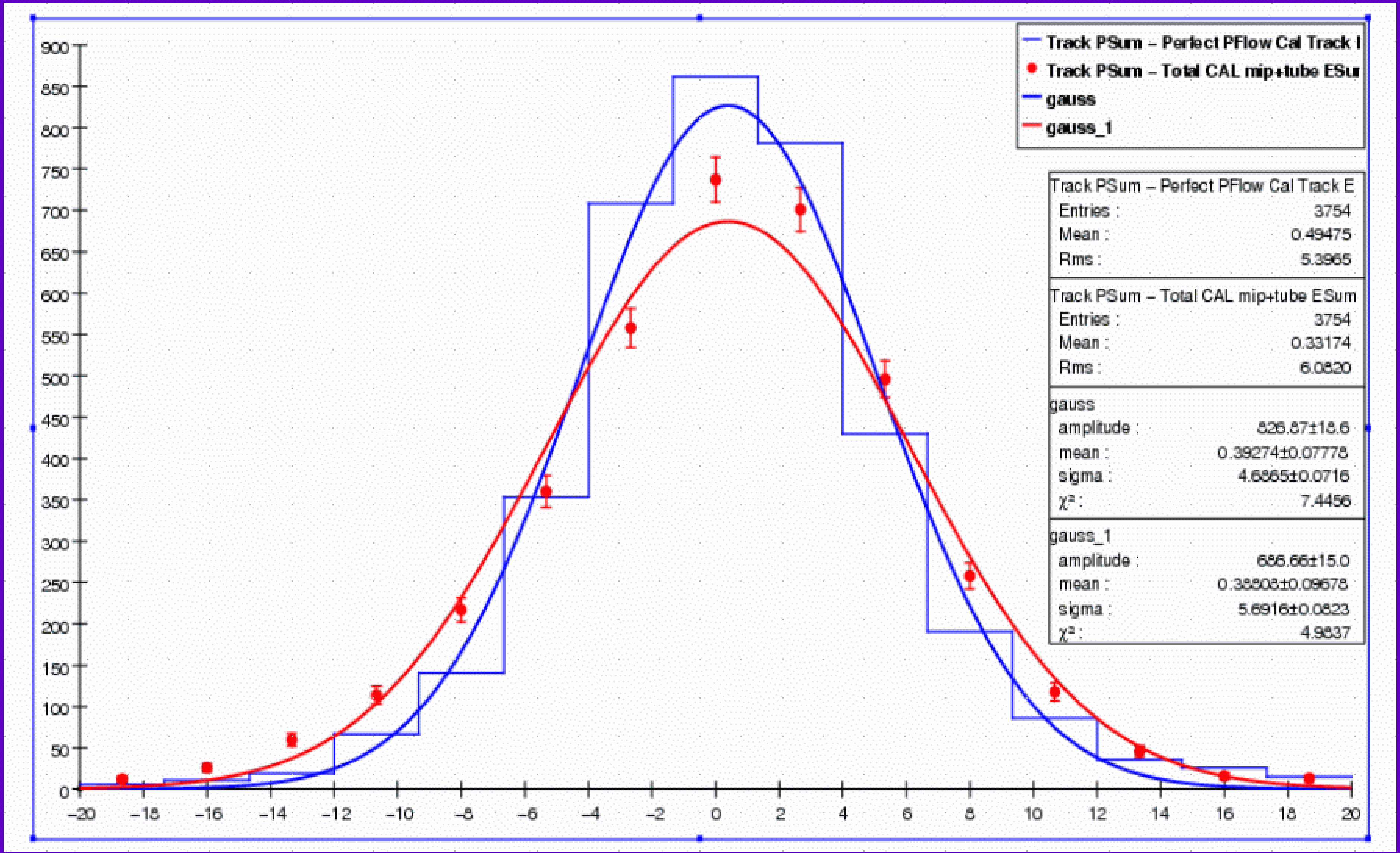
Alternative Approach Realized in org.lcsim



S. Magill

Track/CAL Cell Association Algorithm

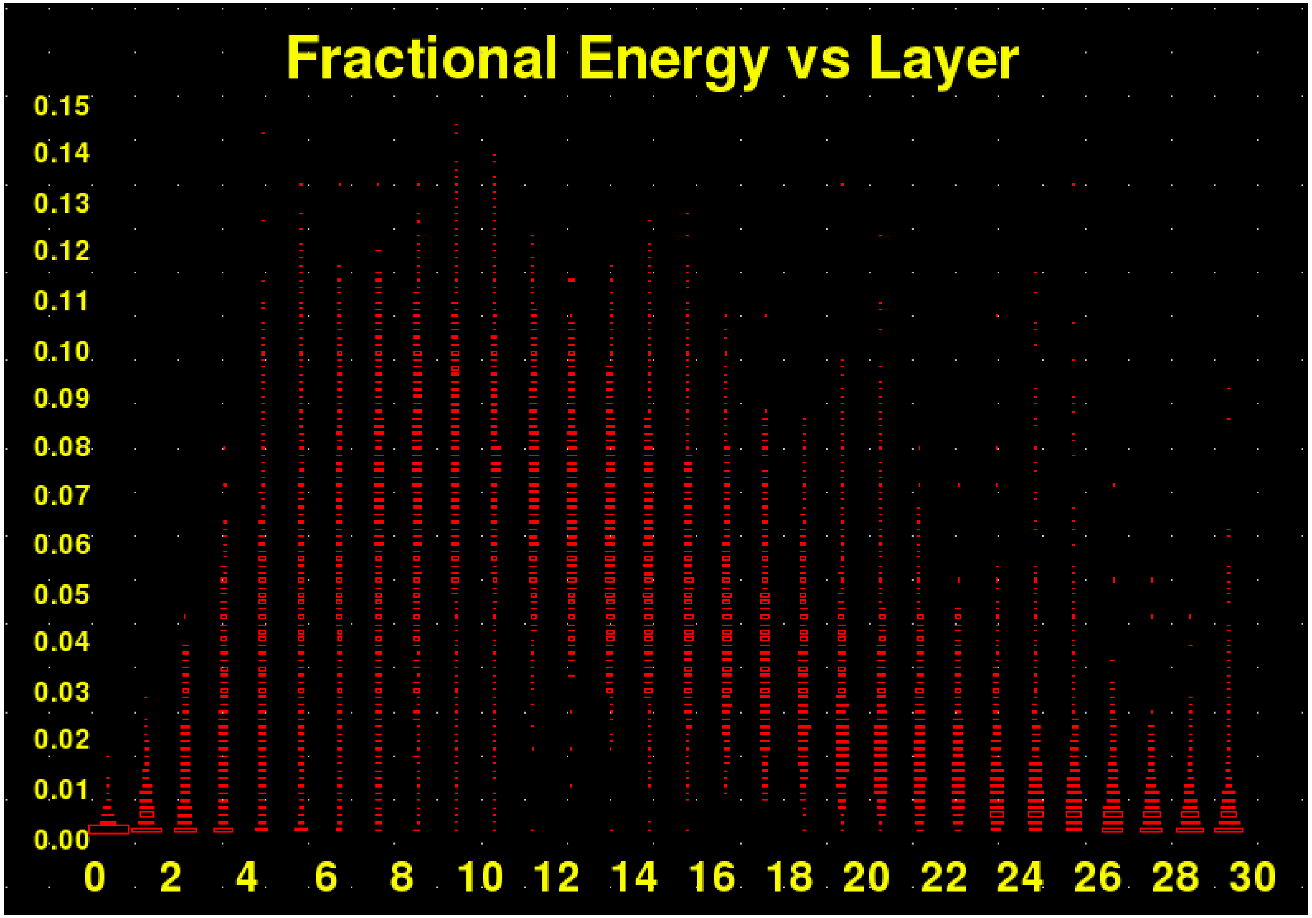
S. Magill



Track/Cell association algorithm reproduces perfect ID

Example of Photon Finding (org.lcsim approach).

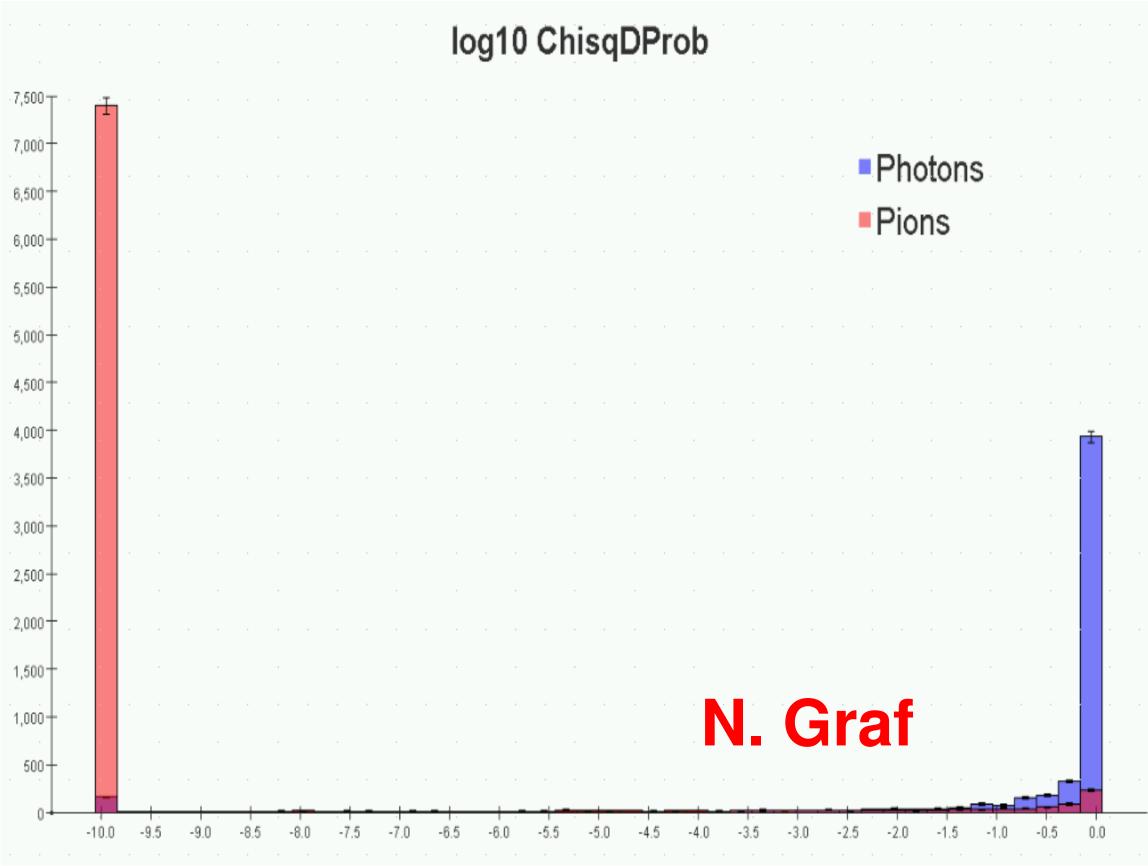
- Hits associated to tracks are removed : clean the region for photons
  - Photon finding employs cone clustering performed on EM hits
  - Photon ID based on analysis of long. shower profile



N. Graf

Photon ID. Neutral Clusters

- Use longitudinal energy depositions and their correlations to create a cluster χ^2 (HMatrix approach)
  - $M_{ij} = \{\Sigma_n(E_i(n)-\langle E_i\rangle)(E_j(n)-\langle E_j\rangle)\}/N$
  - $H = M^{-1}$
  - $\chi^2 = \Sigma_{ij}(E_i-\langle E_i\rangle)H_{ij}(E_j-\langle E_j\rangle)$



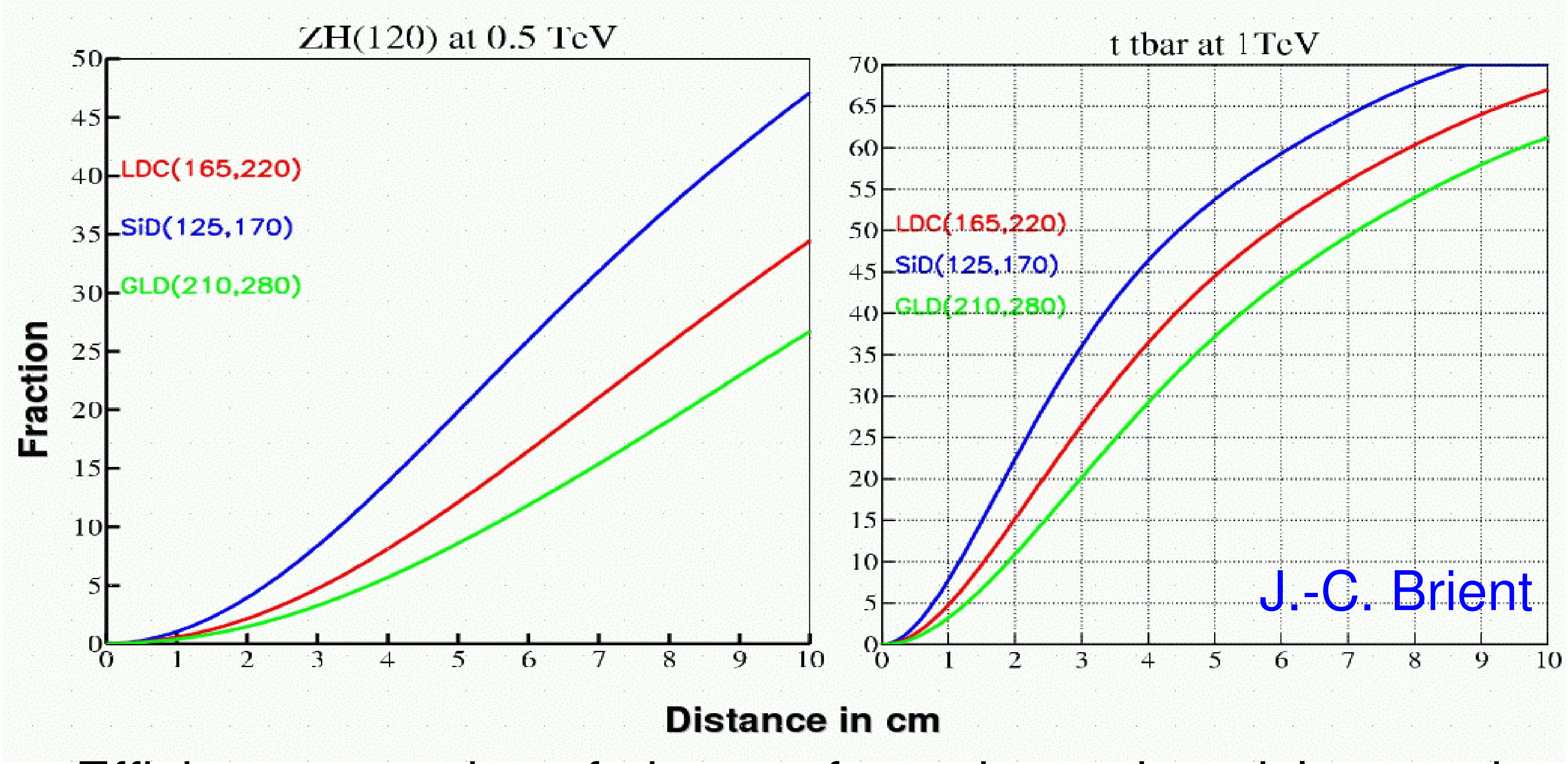
- Final step : clustering on remaining hits

  => neutral hadrons
- Neutral objects : cluster energy as estimate of particle energy; vector connecting IP and cluster starting point (or center-of-gravity) approximates momentum vector

ECAL Granularity

- Most of PFA studies assume highly granular ECAL : (4x4 mm^2 in SiD, 1x1 cm^2 in LDC). Is this high granularity justified?

Fraction of photon(s) energy per event within a given distance to charged tracks

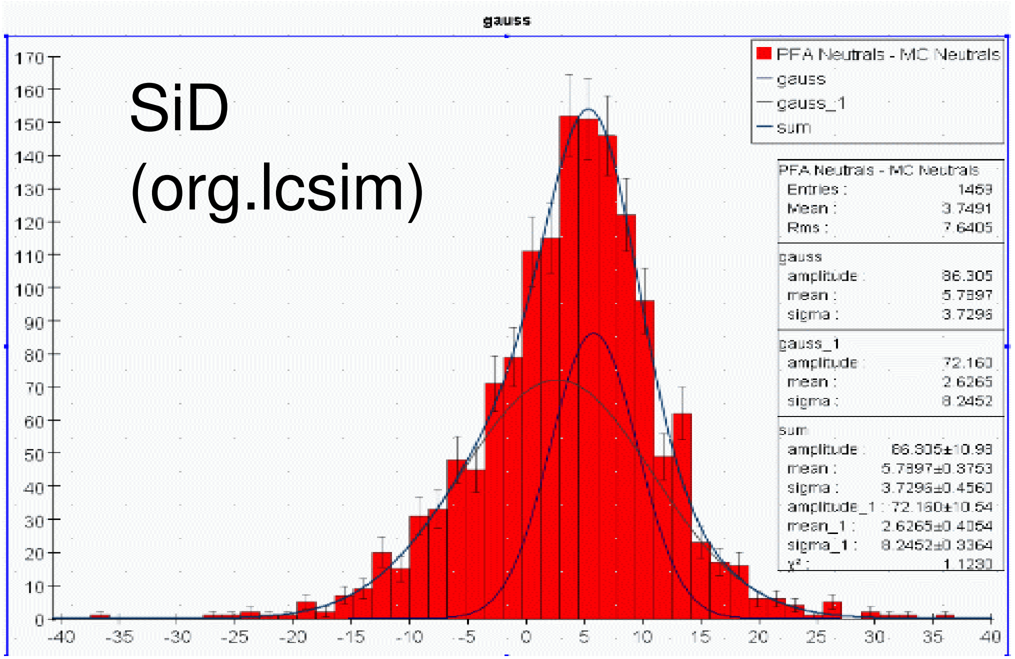


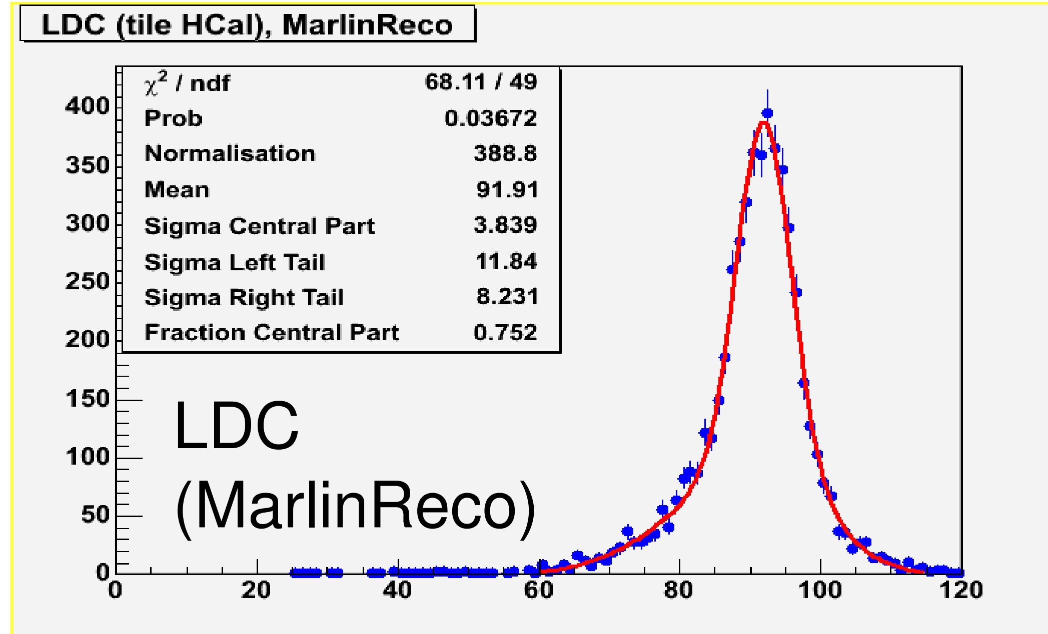
Efficient separation of photons from charged particles requires highly granular ECAL (cell size ≤ 1x1 cm^2)

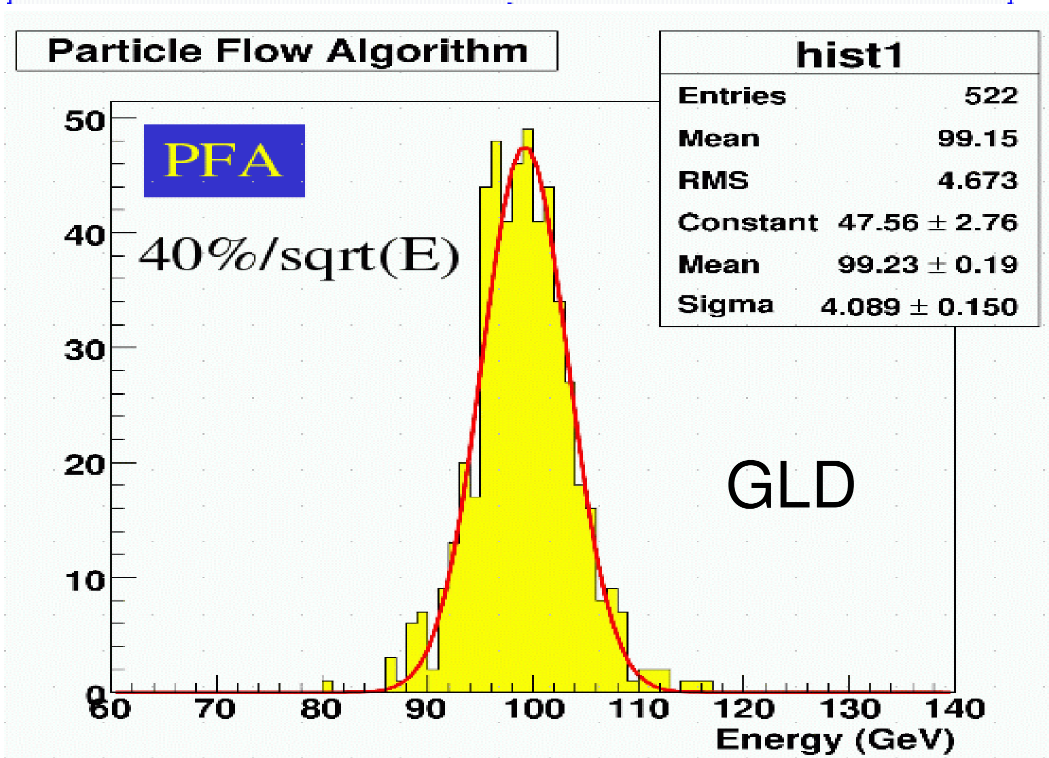
PFA Performance Check

- Hadronic events at Z pole are used to estimate performance of PFA
  - This benchmark process allows for simple analysis ; no need to perform jet clustering, one can easily sum up energies of all particles, calculate momentum imbalance and visible mass of an event => PFA performance is disentangled from the effects related to inefficiency of jet clustering algorithm
  - PFA performance is straightforwardly quantified in terms of resolution on the reconstruction Z mass (or event energy)
  - Study of PFA performance with hadronic events @ Z pole enables direct comparison with LEP detectors and SLD

Results





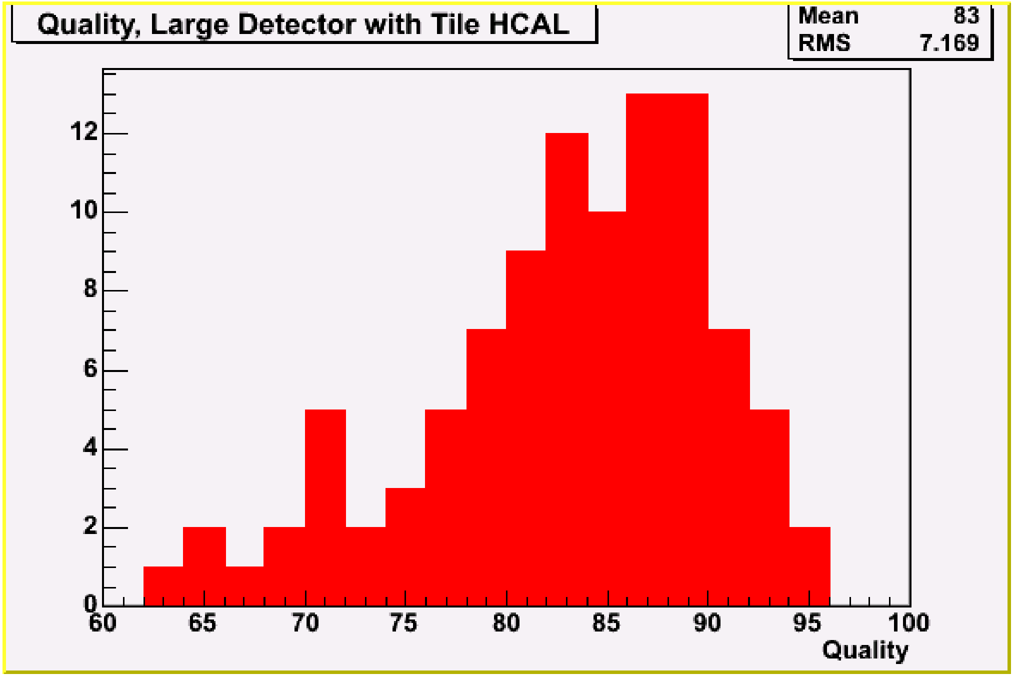


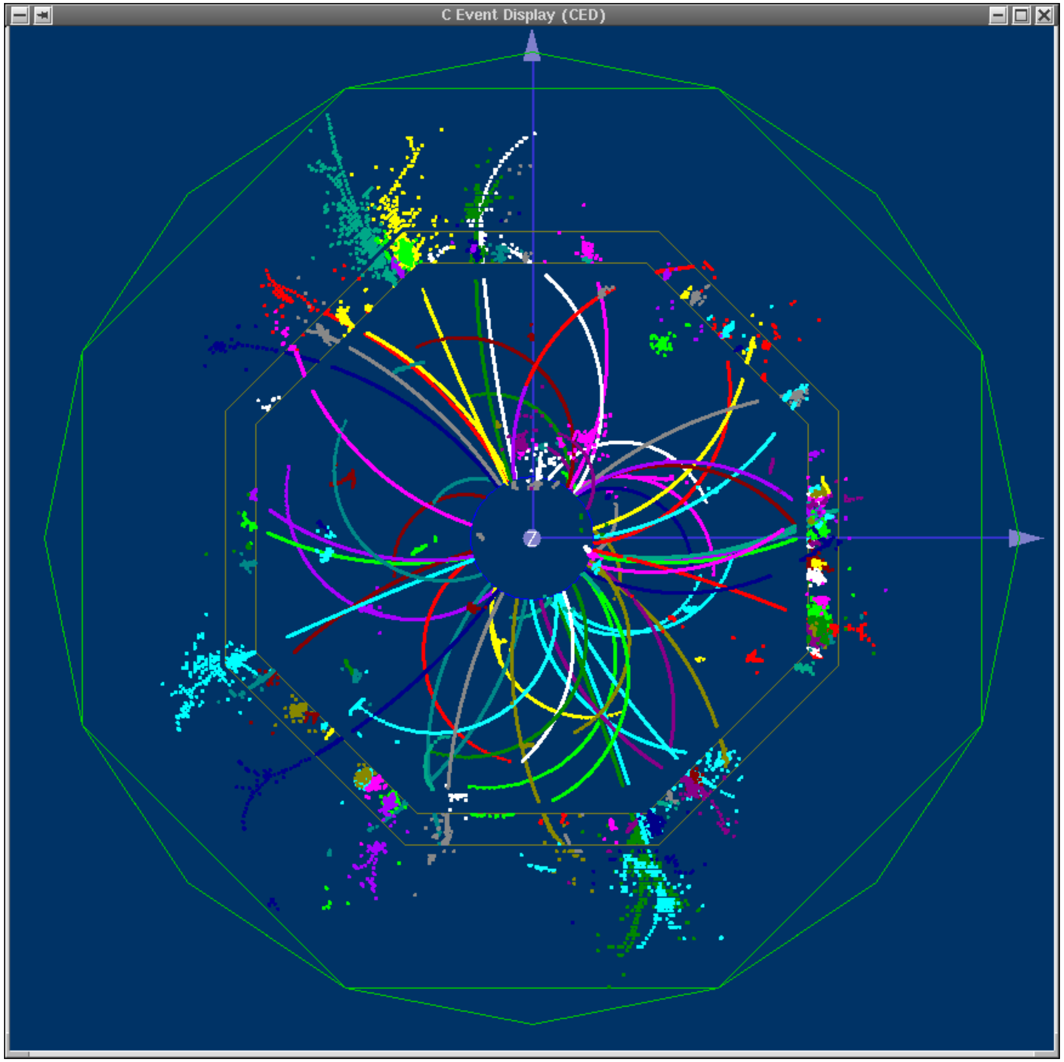
Results obtained by different groups for SiD, LDC and GLD are comparable (dM/M ~ 40%/sqrt(M))

However more pronounced tails are observed in the case of SiD and LDC detectors (needs further investigation)

ttbar => 6jet with Large Detector

- Robustness of PFA is demonstrated also in the reconstruction of events with more complicated topology : ttbar->6jets @ 500 GeV
- Performance of clustering is evaluated in terms of fraction of event energy which is shared between reconstructed and true clusters

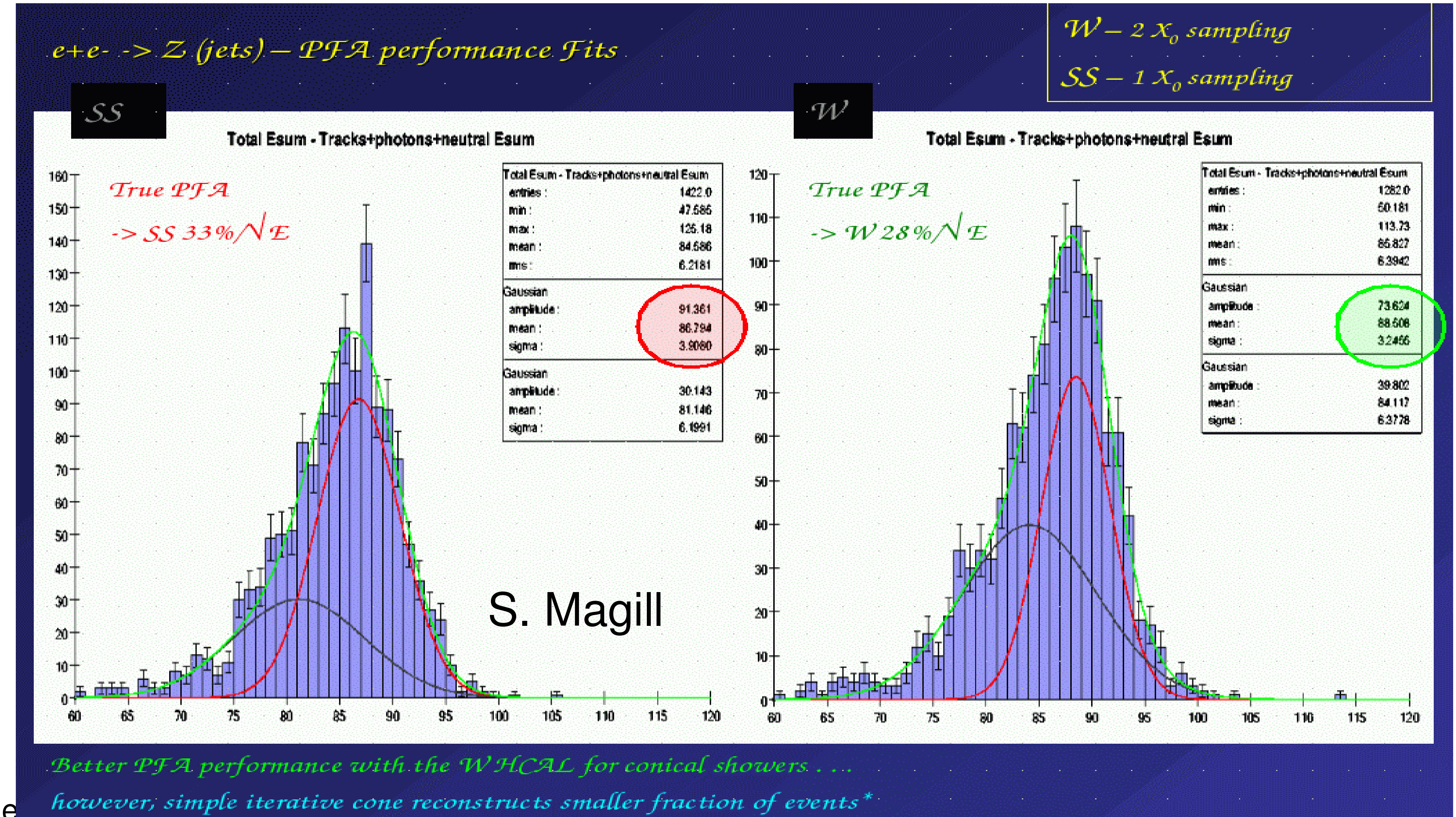




More detailed studies with HZ, ttbar, WW events are planned

Realistic PFA - Tool for Detector Optimization (1)

Stainless steel HCAL vs. Tungsten HCAL
Scintillator as an active element



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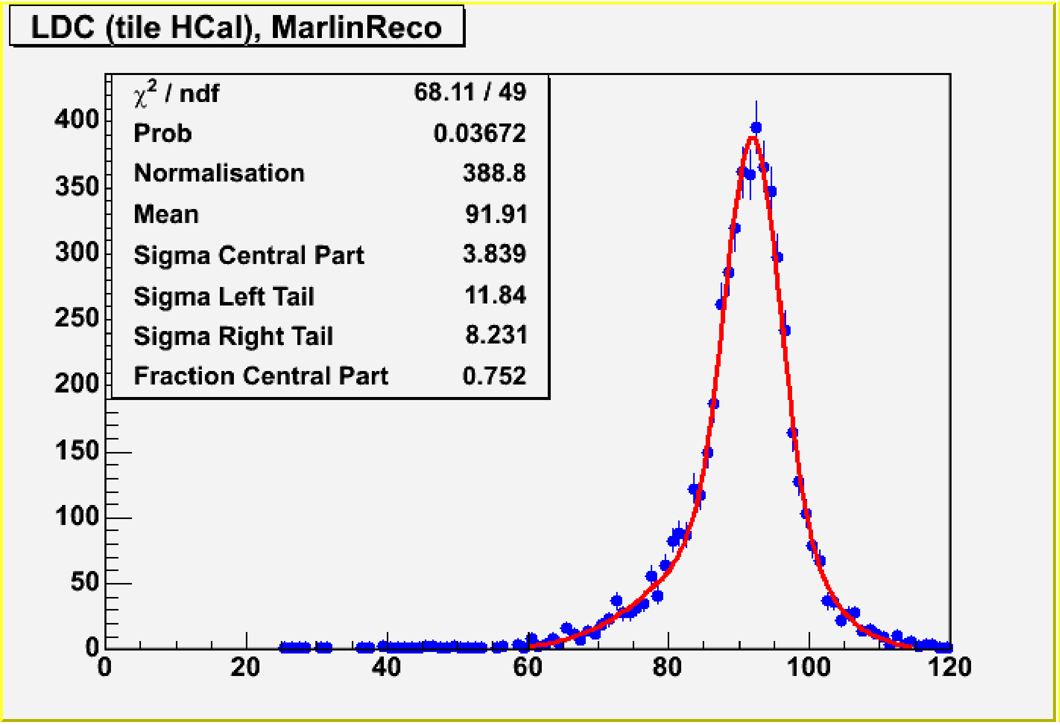
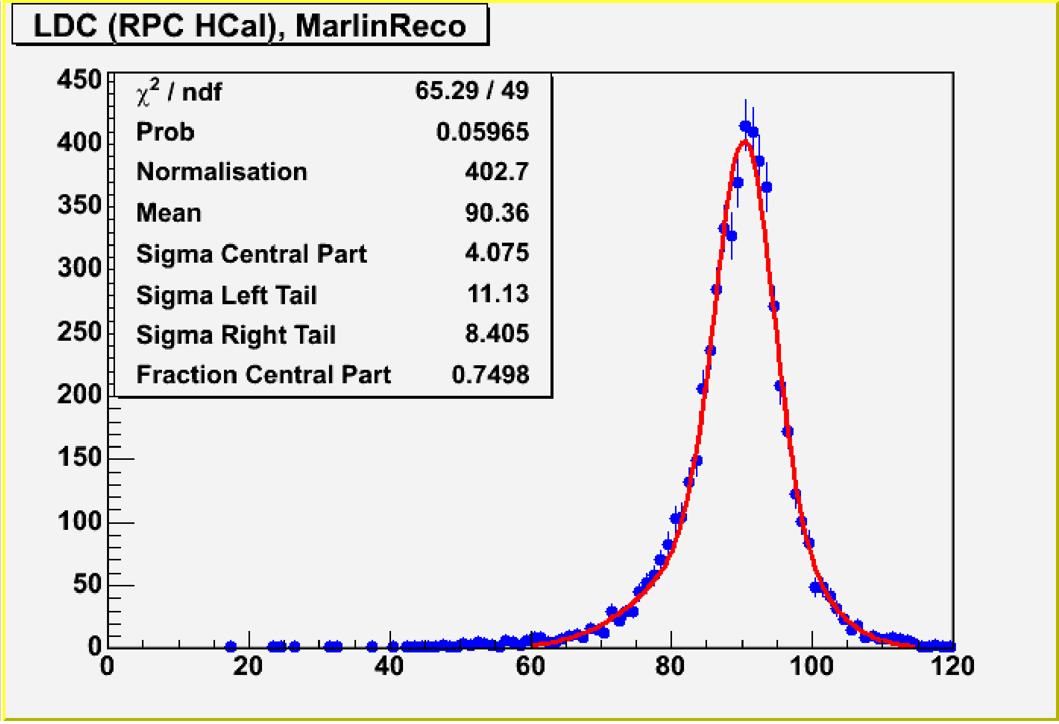
Realistic PFA – Tool for Detector Optimization (2)

Analogue Tile HCal (3x3 cm² tile size)



Digital RPC HCal (1x1 cm² pad size)



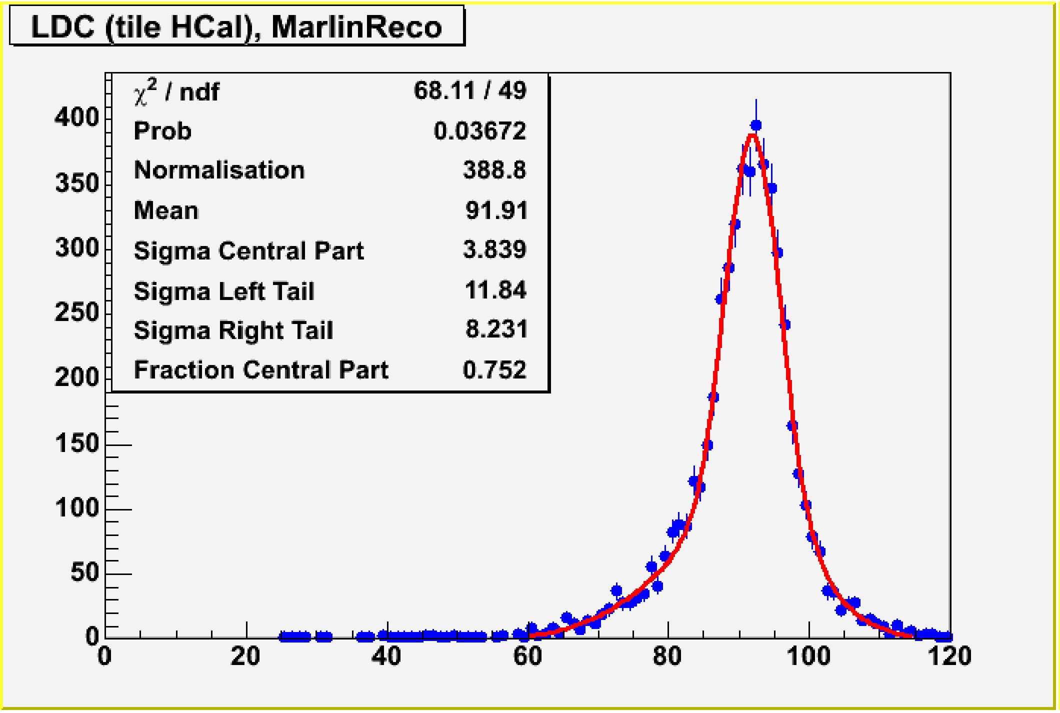
No dramatic difference is found in PFA performance for Large Detector with digital RPC and analogue tile HCAL

Open Issues. Unbiased Comparison Between Different PFA.

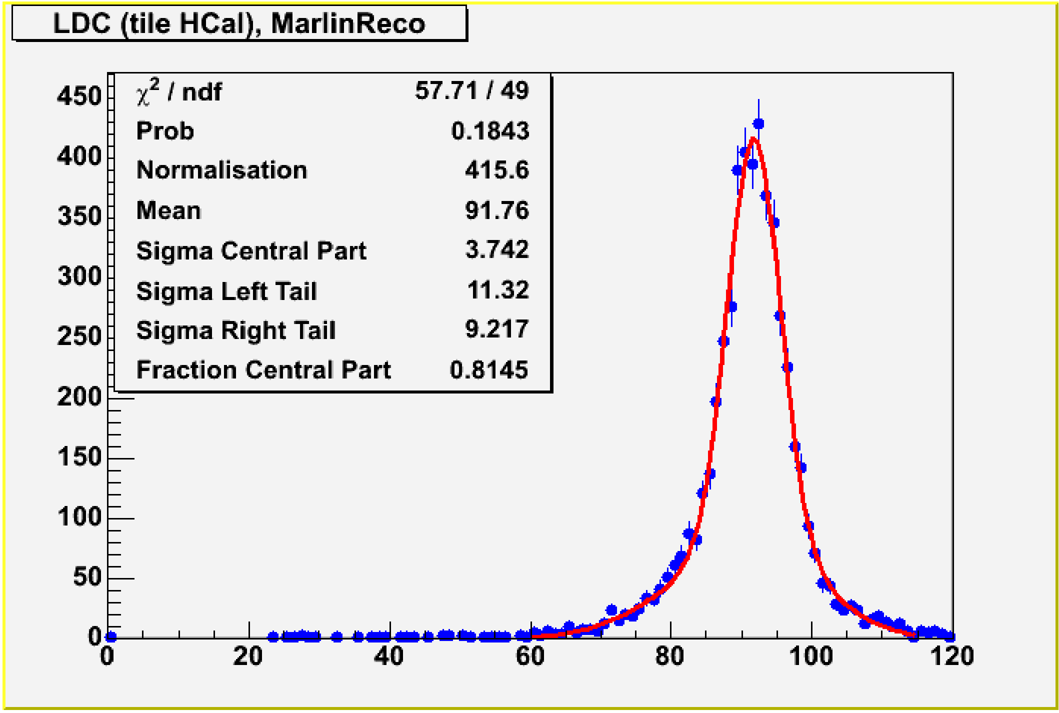
- Various PFA presented @ Snowmass differ in the level of details implemented in the reconstructed procedure
  - SiD : true MC tracks + realistic clustering, photon and neutral hadron identification
  - LDC : realistic tracking (TPC only) + realistic clustering + realistic PID
  - GLD : true MC tracks + realistic clustering + realistic PID + inclusion of neutrino energy
- To enable unbiased comparison we need to agree upon the level of details implemented in PFA.

Open Issues. Ways of Improving PFA

Realistic tracking (TPC only)



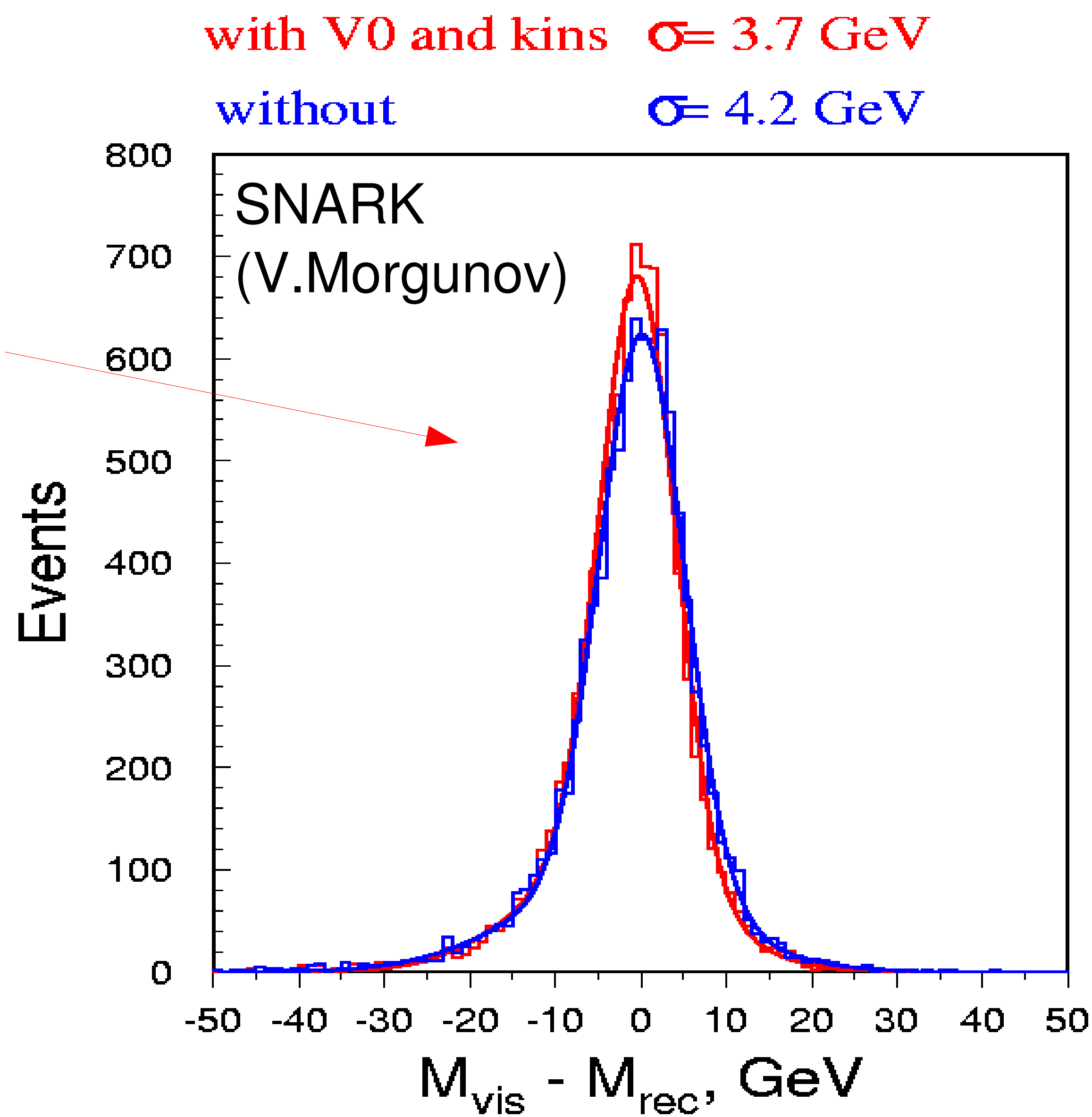
True tracks + realistic track fitting (VTX+SIT+TPC+FTD)



In Large Detector realistic tracking with only TPC does good job
However PFA performance can be slightly improved by including tracking in the vertex detector and forward region (reduced tails)

Open Issues. Does V0 and Kink Finding Improve PFA Resolution

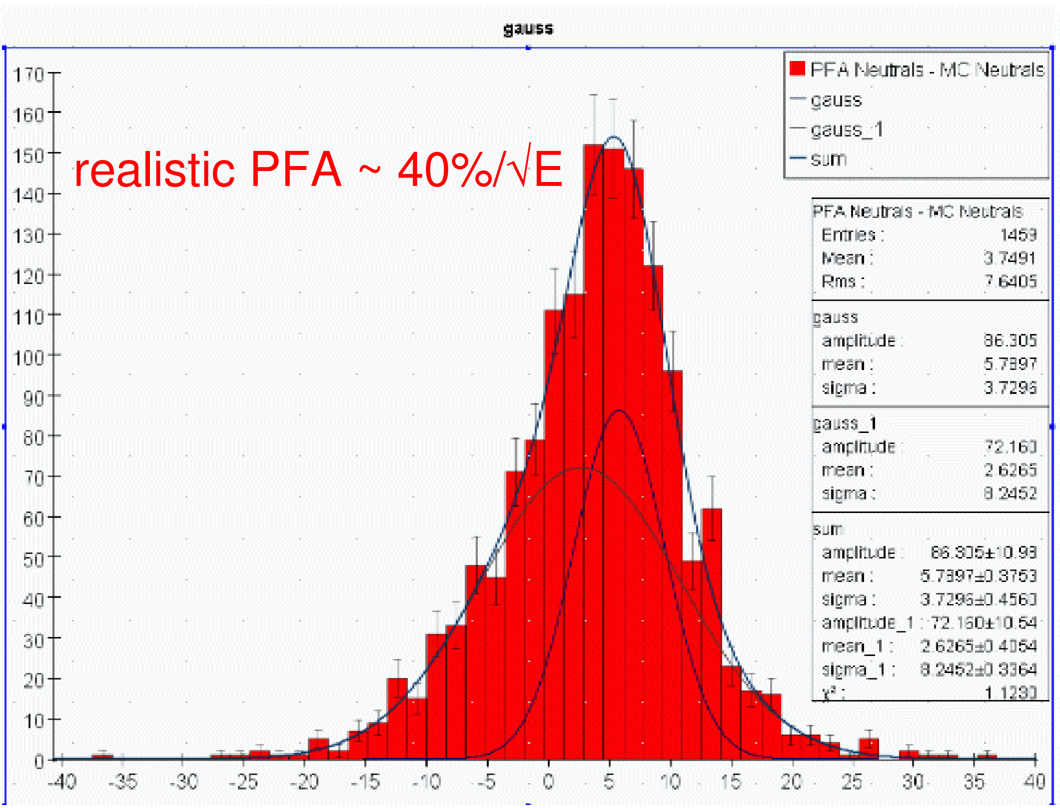
Previous studies with the SNARK package showed that we can gain ~0.5 GeV in the Z mass resolution with dedicated V0 and kink finding procedure



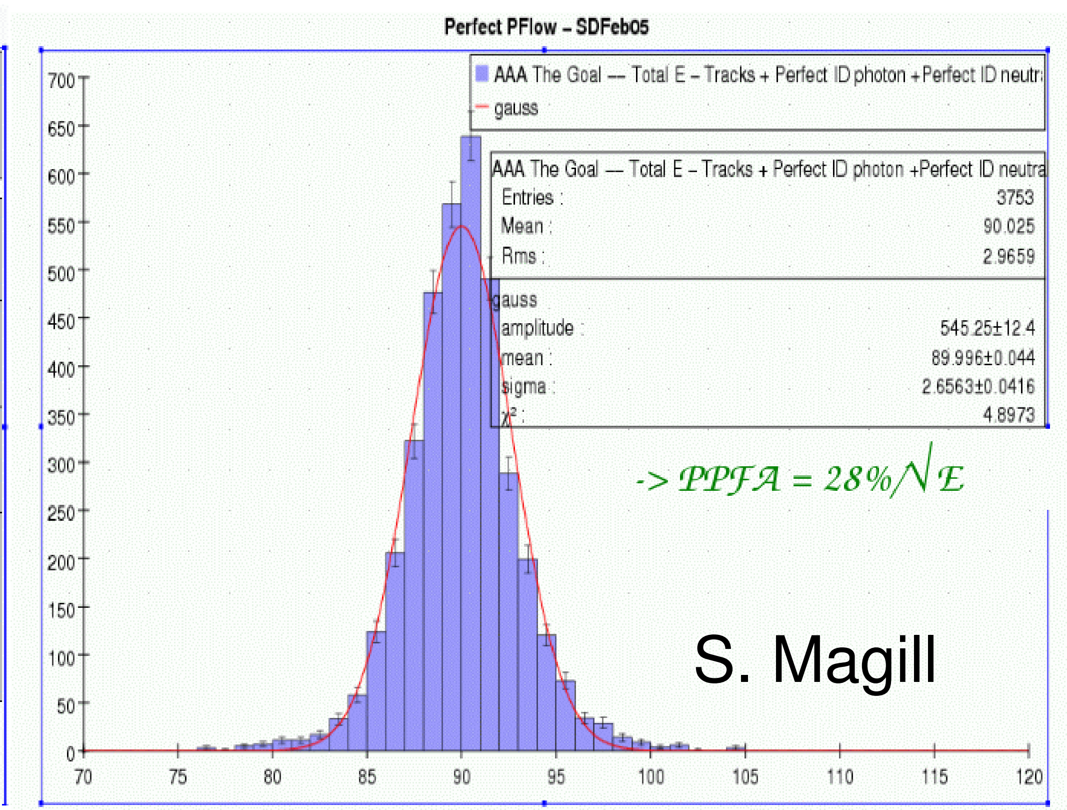
Realistic PFA vs. “Perfect” PFA

Perfect PFA : True MC tracks + true MC clusters + perfect linking between tracks and clusters => estimate of detector resolution effects : useful for detector optimization studies; guideline for PFA developers

Realistic PFA



Perfect PFA



Summary

- Big progress has been made in the development of PFA (org.lcsim, MarlinReco, PFA for GLD, PFA @ NIU)
- Some PFA implementations have minimal dependence on the detector geometry => can be used for detector optimization studies
- Desired performance is not yet achieved but we are already much better compared to LEP detectors (jet energy resolution : $40\%/\sqrt{E}$ vs. 60% @ Z pole) and there is still room for improvements
  - inclusion of V0 and kink finding procedure
  - inclusion of tracking in vertex detector and in the forward region
  - refining clustering procedure (highest priority)
- Issues to be addressed
  - PFA performance vs. ECAL & HCAL granularity
  - PFA performance vs. jet energy (performance checks with HZ, HHZ, ttbar events @ 500 GeV and 1 TeV)
  - Simultaneous optimization of ECAL & HCAL design and reconstruction procedure to obtain best possible resolution for photons and neutral hadrons and reduce confusion term