PandoraPFA

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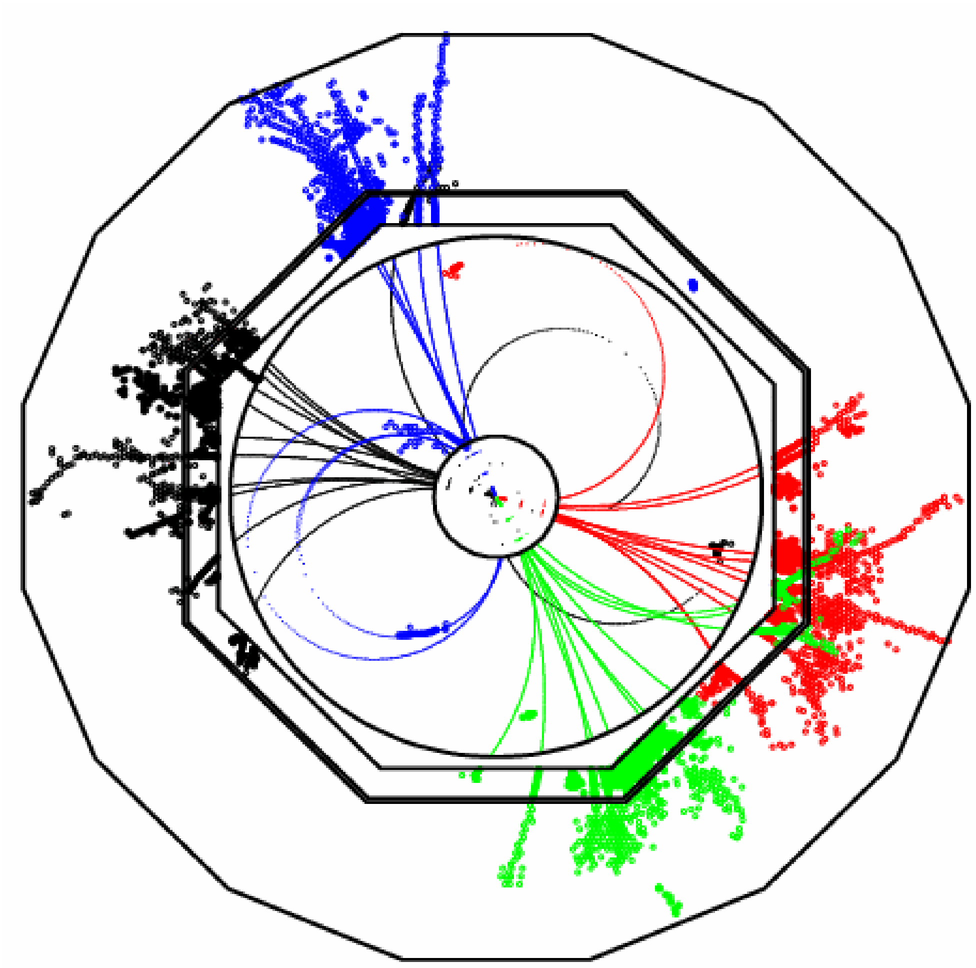
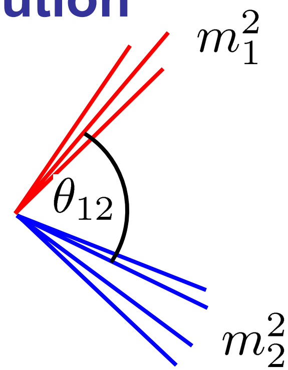


This Talk:

- ❶ PFA Goals
- ❷ Algorithm Overview
- ❸ Status at LCWS07
- ❹ From LCWS to Sendai
- ❺ Ongoing work
- ❻ Summary/Outlook

❶ PFA Goals : revision

★ Aim for jet energy resolution giving di-jet mass resolution similar to Gauge boson widths



★ For a pair of jets have:

$$m^2 = m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta_{12})$$

★ For di-jet mass resolution of order $\Gamma_{W/Z}$

$$\frac{\sigma_m}{m} \approx \frac{2.5}{91.2} \approx \frac{2.1}{80.3} \approx 0.027$$

⇨ $$\sigma_{E_j}/E_j < 3.8\%$$

+ term due to θ_{12} uncertainty

★ Assuming a single jet energy resolution of normal form

$$\sigma_E/E = \alpha(E)/\sqrt{E(\mathrm{GeV})}$$

⇨ $$\sigma_m/m \approx \alpha(E_j)/\sqrt{E_{jj}(\mathrm{GeV})}$$

⇨ $$\alpha(E_j) < 0.027\sqrt{E_{jj}(\mathrm{GeV})}$$

E_{jj}/GeV	$\alpha(E_{jj})$
100	< 27 %
200	< 38 %

★ Typical di-jet energies at ILC (100-300 GeV) suggests jet energy resolution goal of $\sigma_E/E < 0.30/\sqrt{E_{jj}(\mathrm{GeV})}$

But Not The End

- What jet energy resolution is really needed at the ILC ?
  - NOT 30%/√E, NOT 3.8 %
  - Ideally reach point where dominated by Z/W width
  - NOT the same as

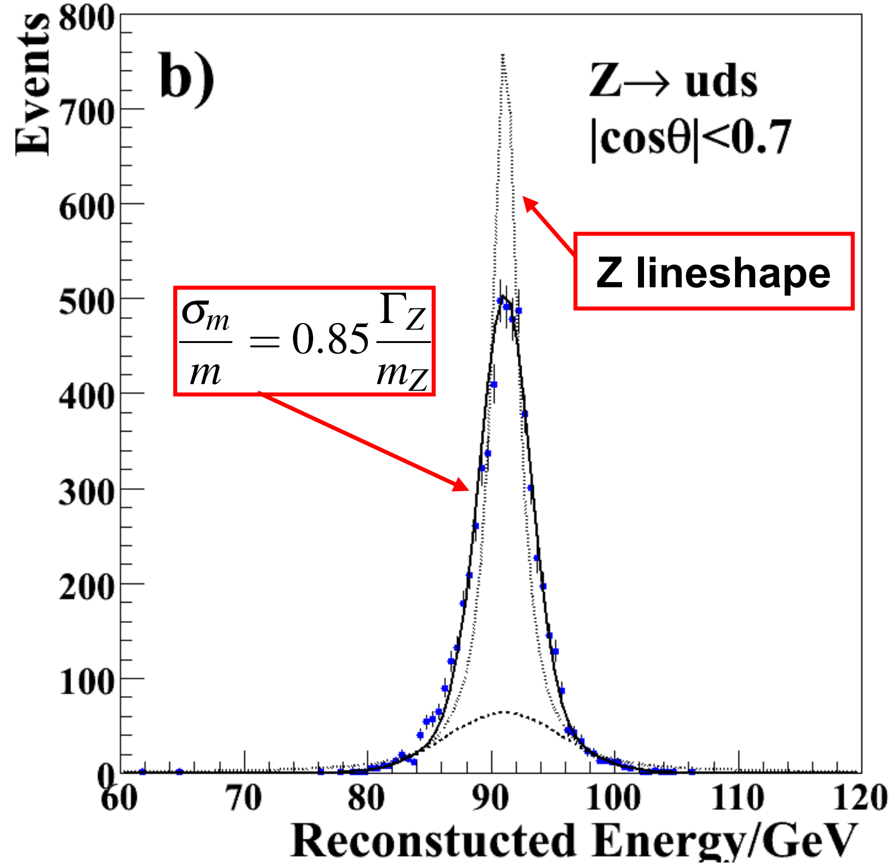
$$\frac{\sigma_m}{m} \sim \frac{\Gamma_Z}{m_Z}$$

FWHM

  - Suggests

$$\frac{\sigma_m}{m} < \frac{\Gamma_Z}{m_Z}$$

  - Significant advantages in further improvements ?



- Push as hard as possible on jet energy resolution
- Ultimate criterion – "physics performance"…

❷ The PandoraPFA Algorithm

- ★ ECAL/HCAL reconstruction and PFA performed in a single algorithm
- ★ Keep things fairly generic algorithm
  - applicable to multiple detector concepts
- ★ Use tracking information to help ECAL/HCAL clustering

- ★ Fairly "sophisticated" algorithm : 10^4 lines of code
  - of order 4 orders of magnitude less lines of documentation

Eight Main Stages:

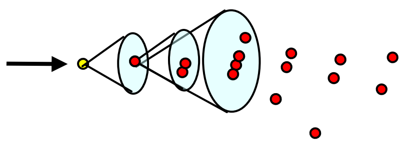
i. Preparation
ii. Loose clustering in ECAL and HCAL
iii. Topological linking of clearly associated clusters
iv. Courser grouping of clusters
v. Iterative reclustering
vi. Photon Identification/Recovery
vii. Fragment removal
viii. Formation of final Particle Flow Objects (reconstructed particles)

algorithm overview

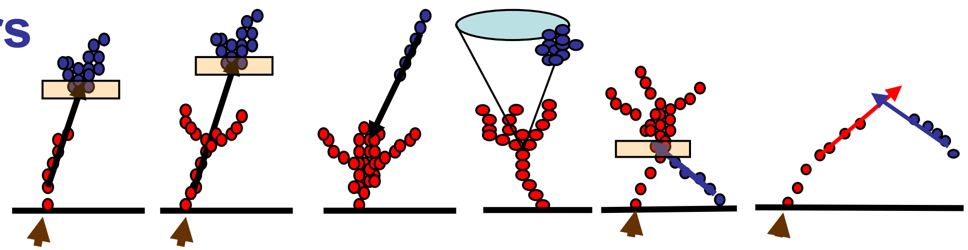
The Eight Main Stages:

i. Preparation/Tracking

ii. Loose clustering in ECAL and HCAL

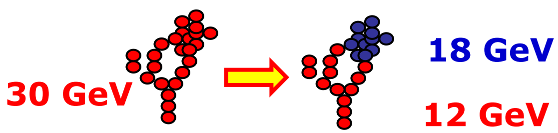


iii. Topological linking of clearly associated clusters

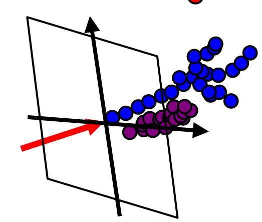


iv. Courser grouping of clusters

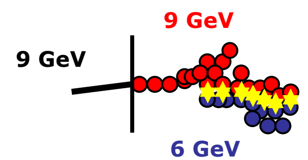
v. Iterative reclustering (using tracks)



vi. Photon Recovery



vii. Fragment Removal

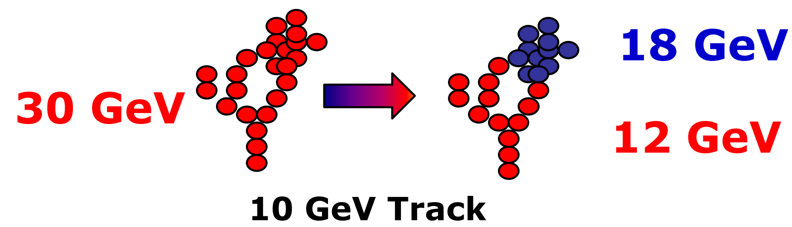


viii. Formation of final Particle Flow Objects

v) Iterative Reclustering Strategies

① Cluster splitting

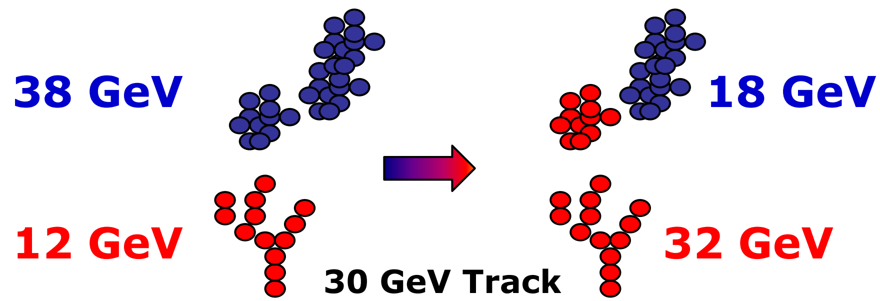
Reapply entire clustering algorithm to hits in "dubious" cluster. Iteratively reduce cone angle until cluster splits to give acceptable energy match to track



★ + plug in alternative clustering algorithms

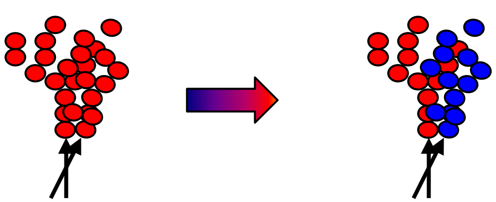
② Cluster merging with splitting

Look for clusters to add to a track to get sensible energy association. If necessary iteratively split up clusters to get good match.



③ Track association ambiguities

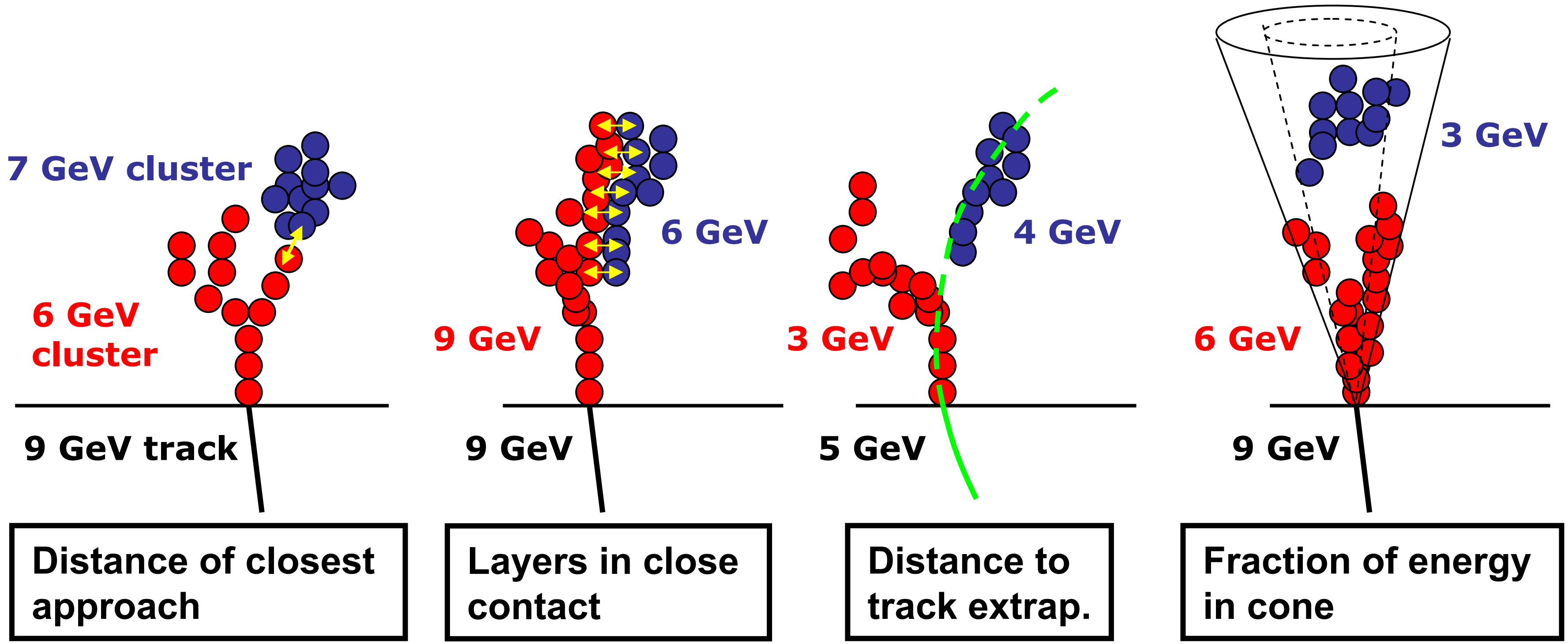
In dense environment may have multiple tracks matched to same cluster. Apply above techniques to get ok energy match.



Very Important for higher energy jets

viii) Fragment removal : basic idea

★ Look for "evidence" that a cluster is associated with another



★ Convert to a numerical evidence score **E**

★ Compare to another score "required evidence" for matching, **R**, based on change in E/p chi-squared, location in ECAL/HCAL etc.

★ If **E > R** then clusters are merged

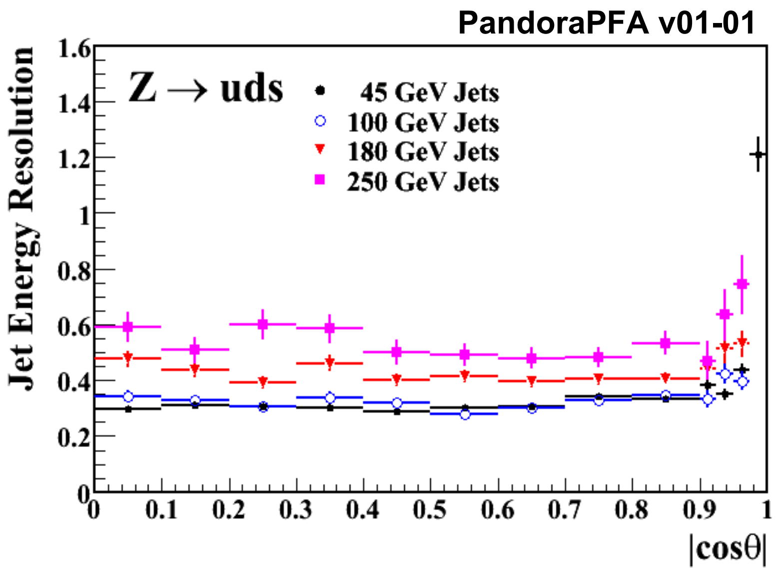
★ Rather *ad hoc* but works well – but works fairly well

❸ Status at LCWS07

★Full simulation studies using the LDC ILC detector concept with the PandoraPFA algorithm. Use $Z \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ decays at rest to benchmark performance

rms90* PandoraPFA v01-01

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	0.295	4.4 %
100 GeV	0.305	3.0 %
180 GeV	0.418	3.1 %
250 GeV	0.534	3.3 %



★For jet energies below 100 GeV achieve $\sigma_E/E < 0.30/\sqrt{E_{jj}(\mathrm{GeV})}$

★Perhaps more importantly, for jet energies above ~75 GeV achieved

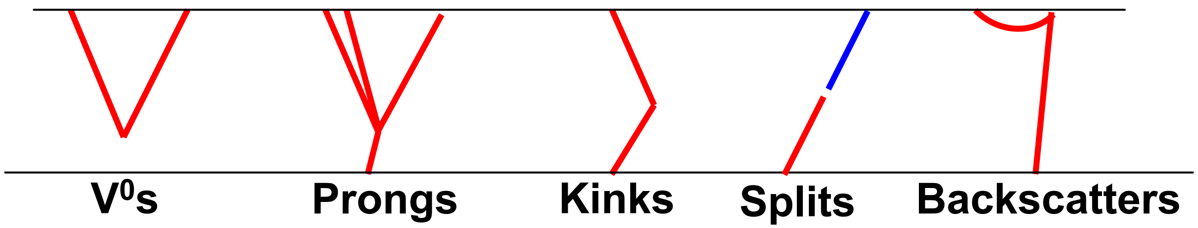
$$\sigma_{E_j}/E_j < 3.8\%$$

★**Post-LCWS emphasis shifted to improving low energy performance**, important in likely initial phase of ILC at **√s ~ 200-500 GeV**

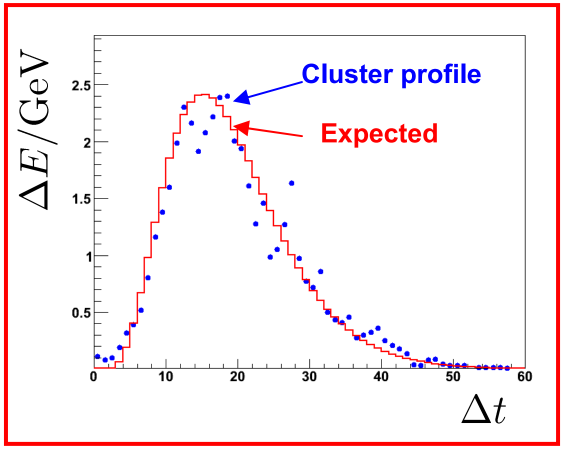
❹ From LCWS07 to Sendai

Step 1: improve low energy performance

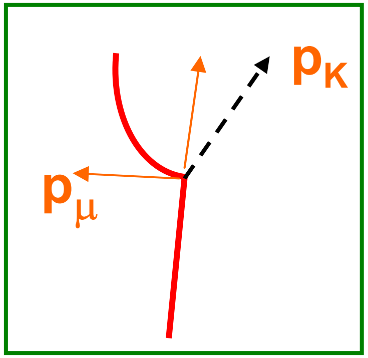
- ★ Technical Improvements/bug fixes
  - ♦ reduced memory footprint (~ factor 2) by on-the-fly deleting of temporary clusters, rather than waiting to event end
- ★ Improved track ID



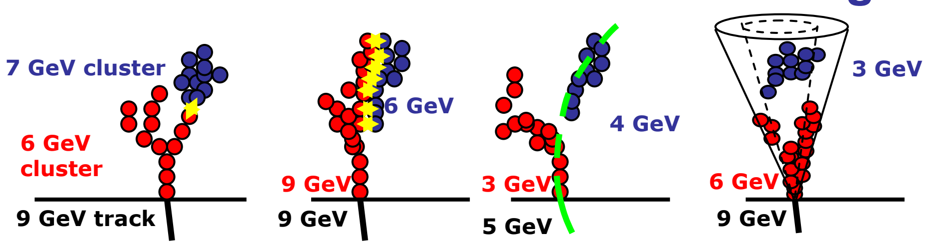
- ★ Much improved photon Identification
  - EM shower profile



- ★ Particle ID
  - ♦ Much improved particle ID : electrons, conversions, $K_S \to \pi^+\pi^-$, $\Lambda \to \pi^- p$ (no impact on PFA)
  - ♦ Some tagging of $K^\pm \to \mu^\pm\nu$ and $\pi^\pm \to \mu^\pm\nu$ kinks



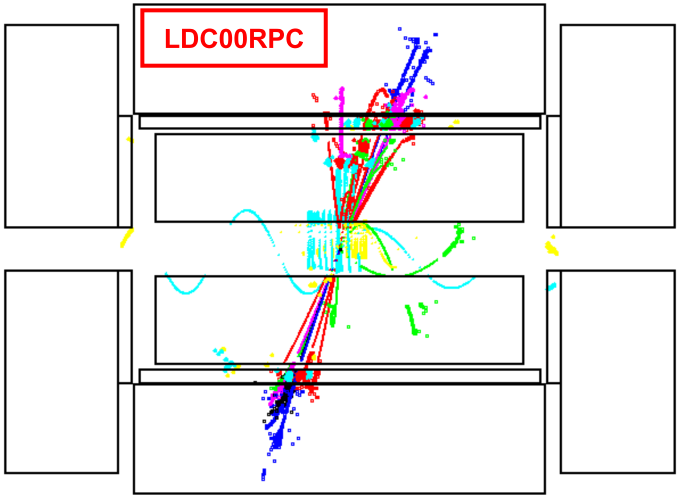
- ★ More sophisticated identification of neutral fragments



From LCWS to Sendai cont.

Step 2: increase functionality

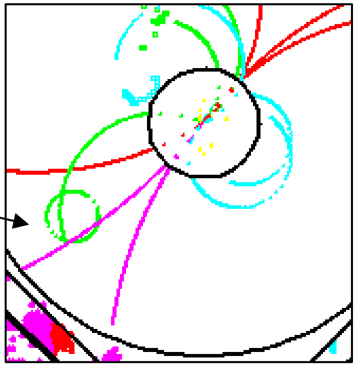
★ Now compatible with digital HCAL (and digital ECAL e.g. MAPs-based)



(PandoraPFAv02 +trackCheater)	E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$
LDC00Sc	100 GeV	29.3 %
LDC00RPC	100 GeV	30.3 %

- very similar performance (digital PFA is not fully optimised)

★ Can now use either TrackCheater or FullLDCTracking
- ♦ required rewrite of V^0 finding + tweaks for kinks
- ♦ note: FullLDCTracking does not find non-vertex curlers, i.e. reduced kink/V^0 efficiency
- ♦ still need to study optimal track quality cuts



Step 3: compatibility with new LDC models

★ Include LCAL, ECAL Plug. + include MUON hits (read but not yet used)

★ Made more robust – better error/warning reporting

LCWS → Sendai: LDC00 (Tesla TDR)

Cheated Tracks

LCWS07 — PandoraPFA v01-01

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	0.295	4.4 %
100 GeV	0.305	3.0 %
180 GeV	0.418	3.1 %
250 GeV	0.534	3.3 %

PandoraPFA v02-α

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	0.226	3.3 %
100 GeV	0.293	2.9 %
180 GeV	0.392	2.9 %
250 GeV	0.534	3.3 %

FullLDCTracking

PandoraPFA v02-01

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	0.235	3.5 %
100 GeV	0.306	3.1 %
180 GeV	0.427	3.2 %
250 GeV	0.565	3.6 %

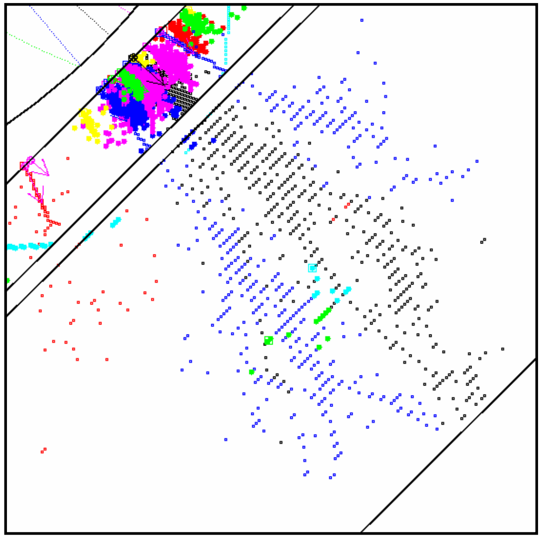
★ For LDC00:

- Slight degradation when using FullLDCTracking
- Small difference may be due to degraded kink finding
- Track cuts not yet optimised

Bottom Line…

- ★ Particle flow can achieve ILC "goal" of $\sigma_E/E_j < 3.8\ \%$
- ★ For lower energy jets Particle Flow gives unprecedented levels of performance, e.g. @ 45 GeV : 3.5% c.f. ~10% (ALEPH)
- ★ "Calorimetric" performance (α) degrades for higher energy jets
  + current code is not perfect - can do better
- ★ would like to investigate the ultimate limit of PFA calorimetry…

PARTICLE FLOW CALORIMETRY WORKS !



… at least in simulation

Hadron Shower Models

- ★ People have rightly expressed concerns about sensitivity to hadron shower models…
- ★ First look at dependence compare **LHEP & QGSP_BERT** models.
- ★ Large model differences
  - 30 % in raw energy deposition
  - longitudinal/transverse development (see Felix's HCAL talk)

(PandoraPFAv02 +trackCheater)		E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$
LDC00Sc	**QGSP_BERT**	**45 GeV**	**22.6 %**
LDC00Sc	**LHEP**	**45 GeV**	**23.2 %**
LDC00Sc	**QGSP_BERT**	**100 GeV**	**29.3 %**
LDC00Sc	**LHEP**	**100 GeV**	**30.2 %**

- ★ Differences rather small (+code not optimised for LHEP)

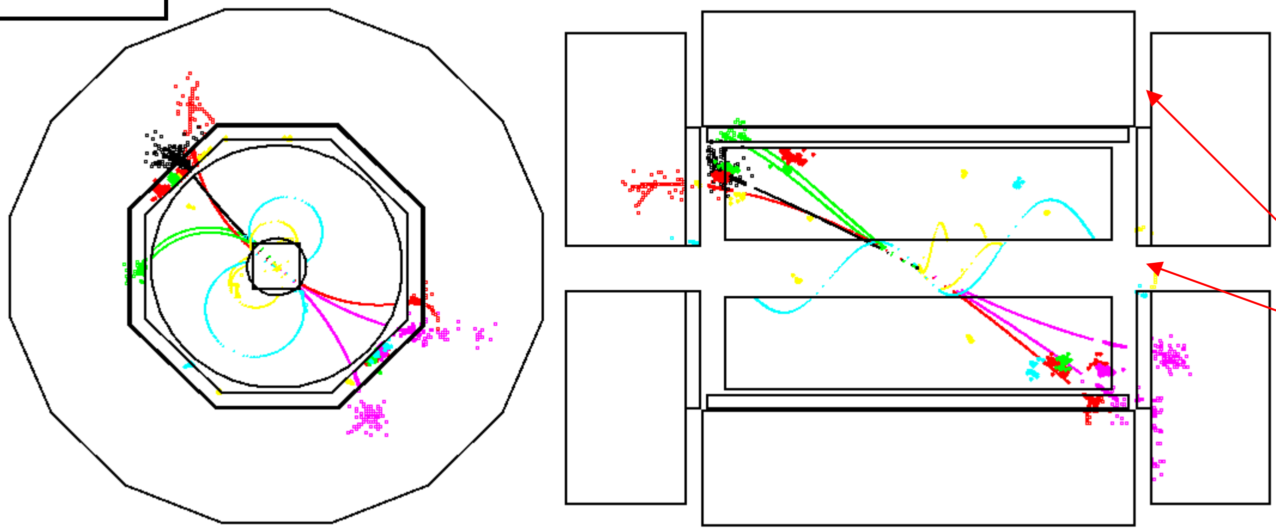
- ★ Sensitivity to Hadronic shower development may not be so large
  - needs more study
  - + CALICE data will show the way

❺ Ongoing Work

★ Main emphasis of recent work
  - Preparation for ILD mass simulation/reconstruction
  - Make PandoraPFA fully compatible with new LDC detector model
    - significant changes to simulation
    - including more realism…
  - This is the first step to moving to LDC' which will be the starting point of the LDC-based part of the ILD optimisation studies

New LDC Model – many differences

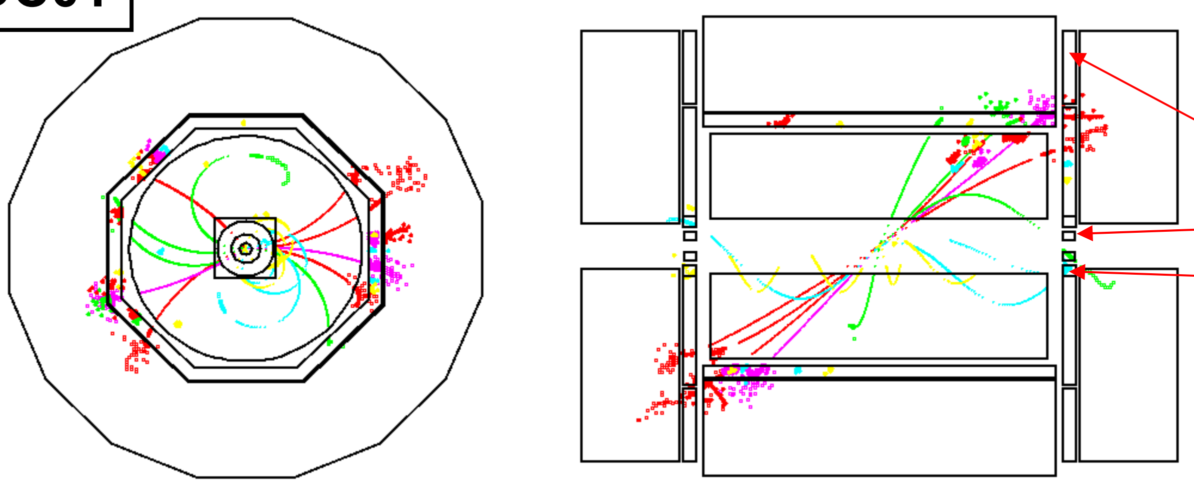
LDC00



Comments

- ~ Tesla TDR
- Large radius ~1.69 m
- Extended barrel
- No HCAL rings
- Hole in FWD region
- "Baseline" for PFA studies to date

LDC01

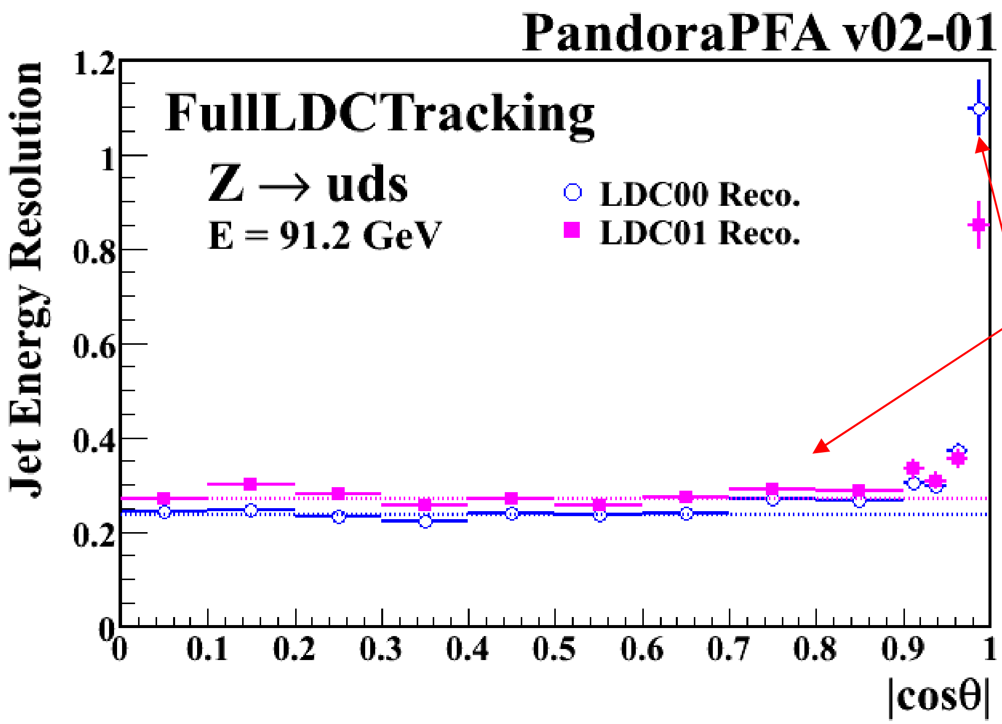


Comments

- Smaller
- TPC radius ~1.58 m
- +HCAL rings
- +LCAL
- +ECAL Plug
- Relatively untested
- Less thick HCAL
  63 → 48 layers

PandoraPFA : LDC00 vs LDC01_05Sc

★ NOTE: so far mostly looked at 91.1 GeV



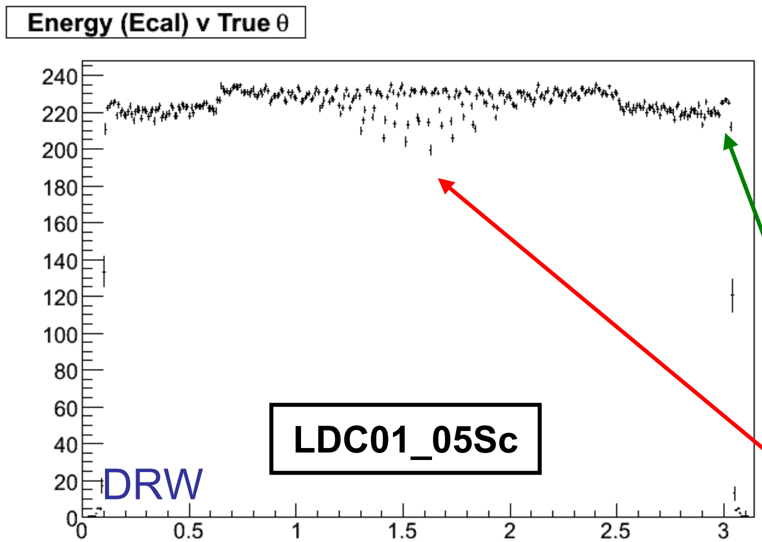
Comments

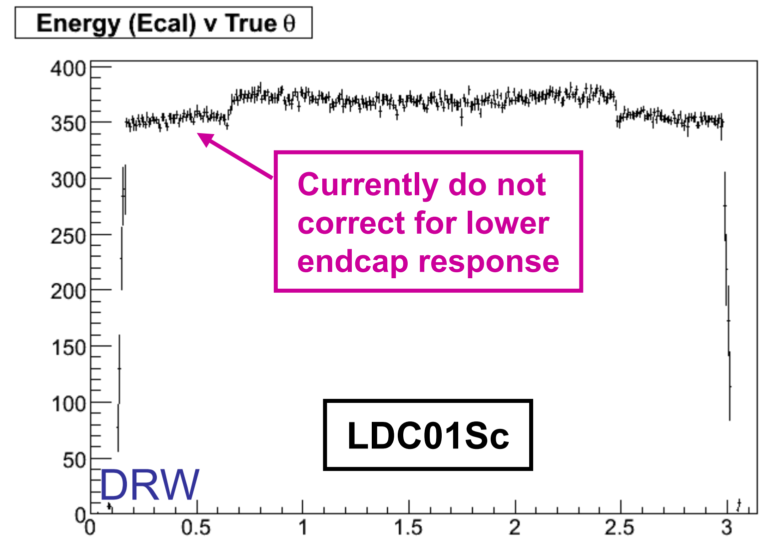
★ Barrel performance worse
23.5%/√E → 27.0 %/√E

★ Less degradation in Barrel/Endcap overlap region for LDC01
HCAL RING ?

★ Far Endcap region LDC01 better !
LCAL/ECAL Plug

★ Degradation in performance understood… ECAL Model
- partly due to decreased Si thickness
- mostly due to conservative gaps in more realistic ECAL model (as described in Frank's talk)





- ★ Gaps not small c.f. Moliere radius
- ★ At small |cosθ| gaps line up
- ★ At the "wrong angle" can miss 30 % of a photon's energy
- ★ Bad for PFA + impact will increase with energy

- Structure around θ=π/2 caused by inter-wafer gaps (2mm) and inter-alveolar gaps (4mm)
- Beneficial effect of endcap rings.

Understanding impact of gaps on PFA

★ Assuming 60% charged particles, 30 % photons, 10 % neutral hadrons, can *estimate* contributions to PFA performance

45 GeV jets: $$\sigma_E = \alpha\sqrt{E}$$

α	ECAL	HCAL	Confusion	Other	Total
LDC00Sc	0.07	0.17	0.11	0.09	0.235
LDC01_05Sc	0.14	0.17	0.12	0.09	0.267

★ For LDC01_05Sc raw ECAL energy resolution (25%/√E) is a significant contribution to jet energy resolution !

★ **NOTE:** this can be fixed in software, but it will introduce an additional complication in the reconstruction chain

★ For ILD optimisation studies the LDC' ECAL model has been modified:
- thicker Si
- more realistic (i.e. less conservative gaps) – but still significant effect

More realism in detector model → more complexity in software
Not all bad, also gives insight into sub-detector design

❻ Summary/Outlook

Performance:

- ★ PandoraPFA with FullLDCTracking achieves good performance

  $\sigma_{E_j}/E_j < 3.6\%$ for 45-250 GeV jets LDC00

- ★ Particle Flow works
- ★ Would like to investigate full potential of PFA for ILC/…

Towards ILD:

- ★ v02-01 works with latest LDC01_05Sc model (minimal re-tuning)
- ★ Realistic simulation of ECAL (good) etc., will introduce additional complexity – need to think how to handle this

Short-term Outlook (i.e. to do list):

- ★ Optimised version for GLD (starting this weekend)
- ★ Minor improvements for LDC version
  - e.g., use of muon hits – tagging/tail-catching ?

Medium-term PFA optimisation:

- ★ Potential for many interesting detector studies
- ★ Intend to start with detailed PFA / HCAL study