Recent Progress with PFA and Detector Optimisation

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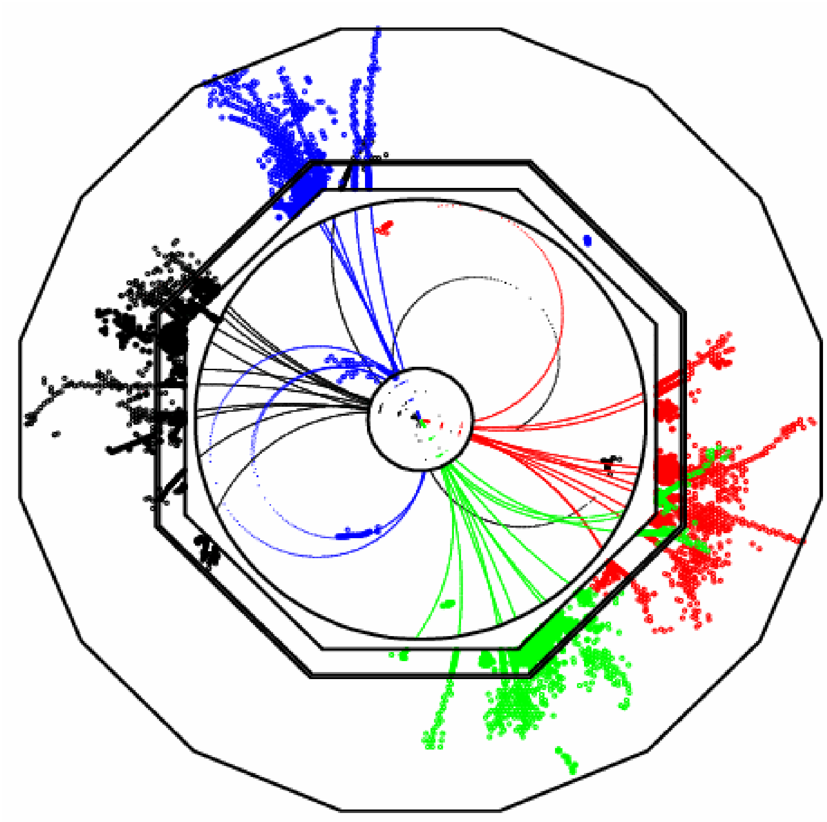


This Talk:

❶ Status of PandoraPFA
❷ PandoraPFA and ILD
❸ Understand the performance
❹ PFA Optimisation Studies
❺ PFA at a multi-TeV Collider
❻ Outlook

➊ Status of PandoraPFA

- ★ The PandoraPFA algorithm is still evolving
- ★ Recent developments have included
  - ▪ Inclusion of Muon chamber hits as a “tail-catcher”
  - ▪ Improvements in photon identification
  - ▪ Possibility of re-ordering algorithm, i.e. run photon finding first
  - ▪ Compatibility with ILD detector model including new forward calorimetry
  - ▪ Implementation of new levels of “Perfect Particle Flow”
- ★ As a result, the performance is still improving, particular for
  - ▪ higher energy jets
  - ▪ forward jets
- ★ Progress is still limited by effort rather than ideas…
- ★ A new version (**3.0**) will be released shortly for reconstruction of ILD MC samples
- ★ The previous version was used extensively in the optimisation of the ILD detector parameters

In this talk, will summarise recent “highlights”

❷ PandoraPFA and ILD

★Results obtained with the very new Mokka model of the ILD concept

Performance (ILD) $Z \rightarrow d\bar{d}, Z \rightarrow u\bar{u}, Z \rightarrow s\bar{s}$

rms90 PandoraPFA v03-β

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	24.5 %	3.6 %
100 GeV	29.2 %	2.9 %
180 GeV	39.7 %	2.9 %
250 GeV	49.6 %	3.2 %

- Full G4 simulation
- "Realistic" detector, gaps etc.
- Full reconstruction inc. tracking
- Not yet optimised for ILD
- Calibration not final

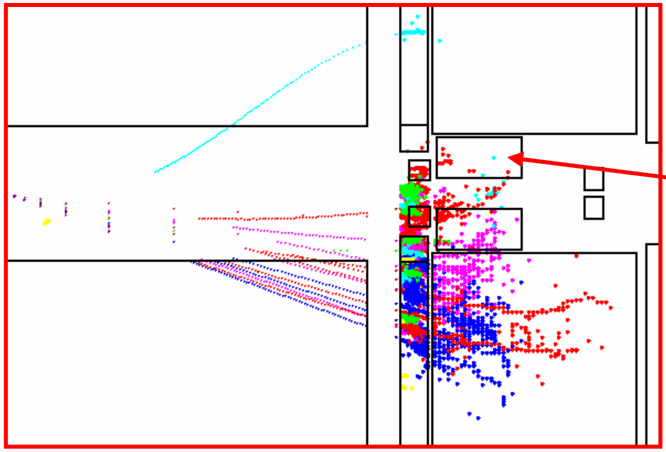
★ Comfortably achieve ILC "goal" of $\sigma_E/E_j < 3.8$ % over full range of jet energies of interest at a **TeV collider**

★ For lower energy jets (< 100 GeV) calorimetric resolution more important than confusion – PFA is doing its job

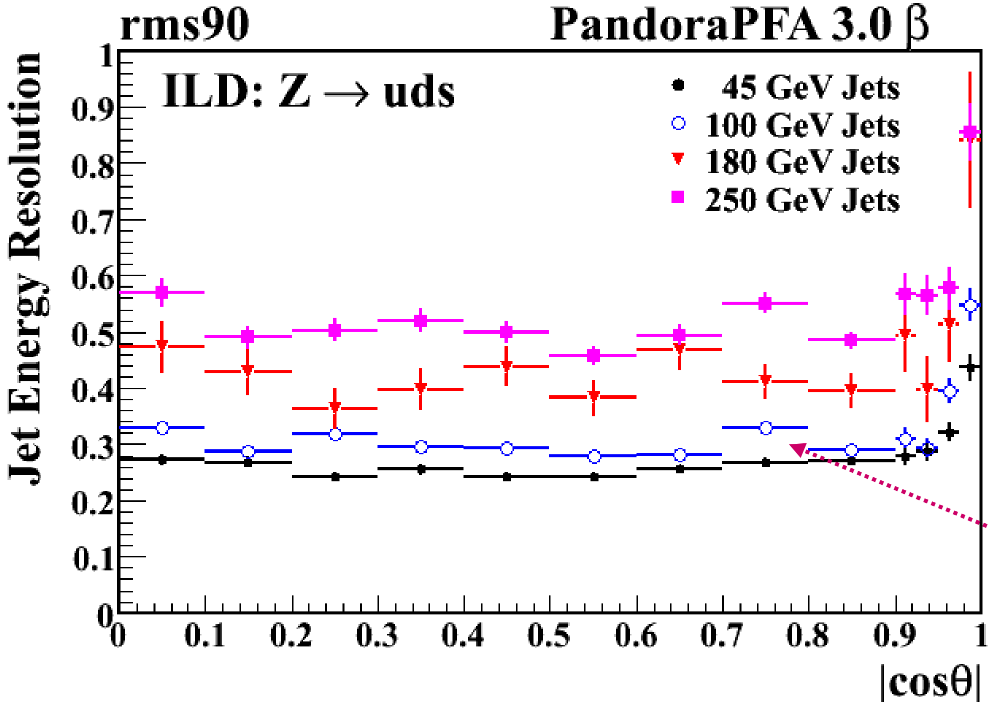
★ Current PFA code is not perfect – lower limit on performance

★ Believe moderate improvements will be obtained soon for higher energy jets, "work in progress"

Angular Dependence



- ★ ILD model includes a more detailed simulation of forward region
- ★ Including LHCAL
- ★ Implemented a first (imperfect) attempt to include in reconstruction
- ★ Also sensitive to forward tracking



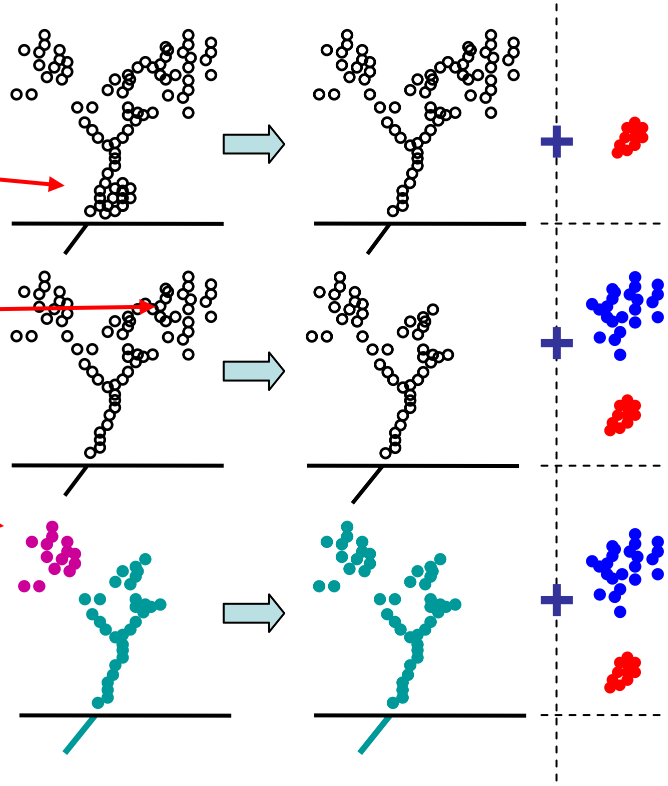
Results

- PFA performance now almost flat out to |cosθ| = 0.975
- Performance worse for |cosθ| > 0.975, but not bad !
  (> factor 2 improvement wrt LDC)
- Some degradation in barrel/ endcap overlap

❸ Understanding PFA

★ Try to use various "Perfect PFA" algorithms to pin down main performance drivers (resolution, confusion, …)

★ New version of **PandoraPerfectPFA**



PandoraPFA options:

- **PerfectPhotonClustering**
  hits from photons clustered using MC info and removed from main algorithm
- **PerfectNeutralHadronClustering**
  hits from neutral hadrons clustered using MC info…
- **PerfectFragmentRemoval**
  after PandoraPFA clustering "fragments" from charged tracks identified from MC and added to charged track cluster
- **PerfectPFA**
  perfect clustering and matching to tracks

★ By comparing results from different options can empirically determine main contributions to **PandoraPFA** jet energy resolution

Contribution	σ_E/E			
	45 GeV	100 GeV	180 GeV	250 GeV
Calo. Resolution	3.1 %	2.1 %	1.5 %	1.3 %
Leakage	0.1 %	0.5 %	0.8 %	1.0 %
Tracking	0.7 %	0.7 %	1.0 %	0.7 %
Photons “missed”	0.4 %	0.9 %	1.2 %	1.4 %
Neutrals “missed”	1.0 %	1.6 %	1.7 %	1.8 %
Charged Frags.	1.2 %	0.7 %	0.4 %	0.0 %
“Other”	0.8 %	0.8 %	1.2 %	1.2 %

Comments:

- ★ For 45 GeV jets, jet energy resolution dominated by ECAL/HCAL resolution
- ★ Track reconstruction not a large contribution (Reco ≈ CheatedTracking)
- ★ “Satellite” neutral fragments not a large contribution
  - ▪ efficiently identified in PandoraPFA
- ★ Leakage only becomes significant for high energies
- ★ Missed neutral hadrons dominant confusion effect
- ★ Missed photons, not negligible at higher energies

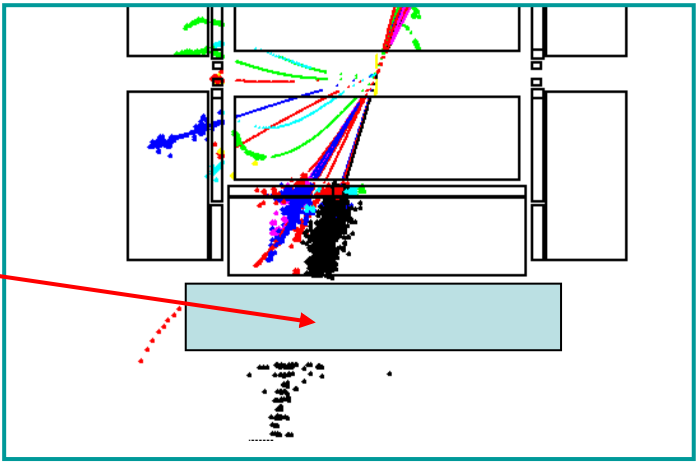
★ No single dominant factor, nevertheless provides guide to future development/algorithm optimisation

❹ ILD Optimisation Studies

- ★ In context of definition of the ILD detector, performed a number of PFA related studies using previous LDC detector concept, e.g.
  - HCAL depth
  - HCAL/ECAL transverse segmentation
  - B field vs. Radius
  - TPC aspect ratio
  - Tau reconstruction (not shown here)
- ★ Conclusions summarised in next few slides

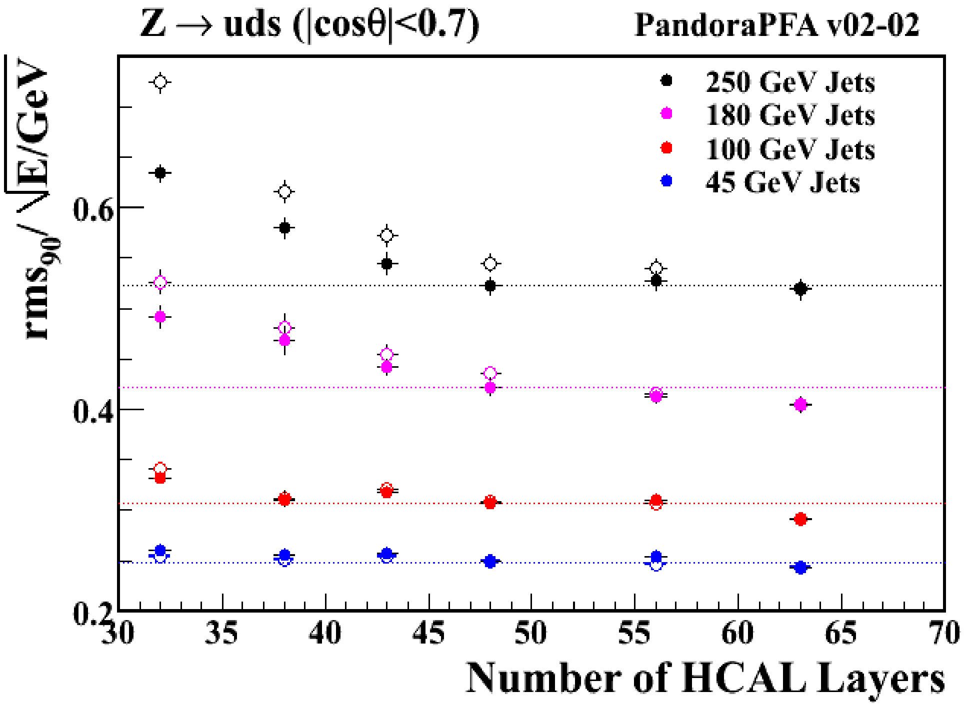
<u>Note:</u> for HCAL studies included first attempt to utilise muon chambers as a "tail catcher"

- Simple standalone MUON clustering
- Fairly simple matching to CALO clusters
- Simple energy estimator (digital) + crude estimate of energy loss in coil



Optimisation Studies : HCAL Depth

- **Open circles** = no use of muon chambers as a "tail-catcher"
- **Solid circles** = including muon chamber as "tail-catcher"



HCAL Layers	λ_I HCAL	λ_I +ECAL
32	4.0	4.8
38	4.7	5.5
43	5.4	6.2
48	6.0	6.8
63	7.9	8.7

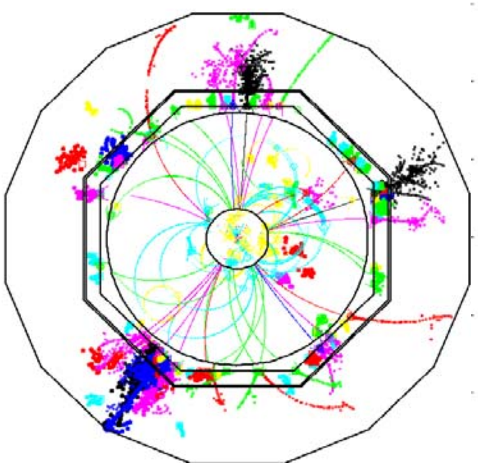
ECAL : λ_I = 0.8
HCAL : λ_I includes scintillator

★ "Tail-catcher": corrects ~50% effect of leakage, limited by thick solenoid

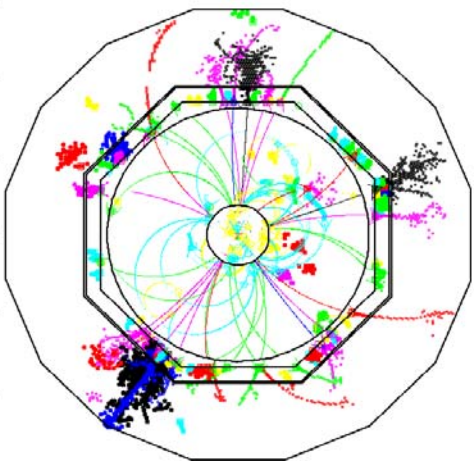
For 1 TeV machine "reasonable range": 5 λ_I - 6 λ_I HCAL

Optimisation: HCAL Segmentation

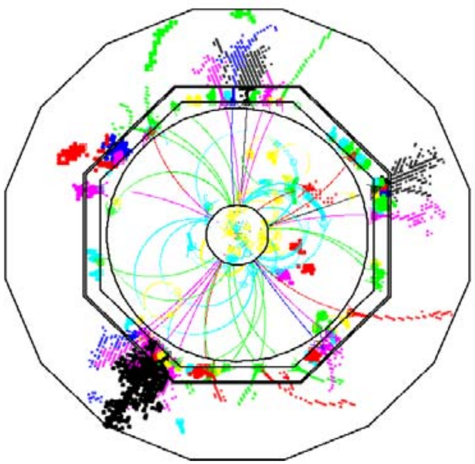
1x1



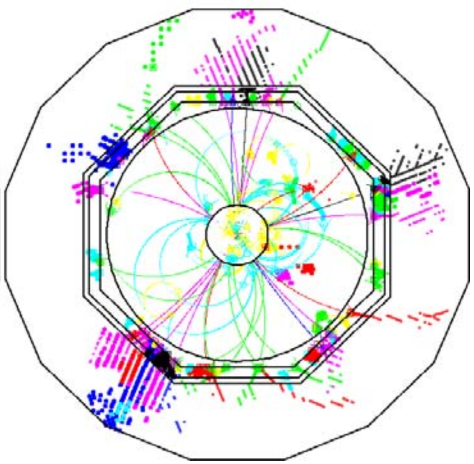
3x3

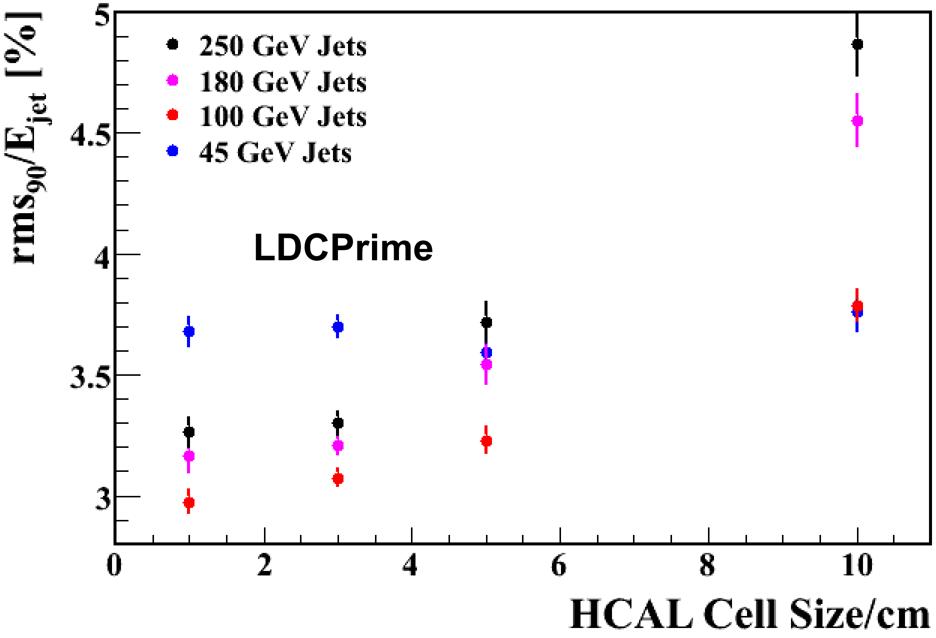


5x5



10x10



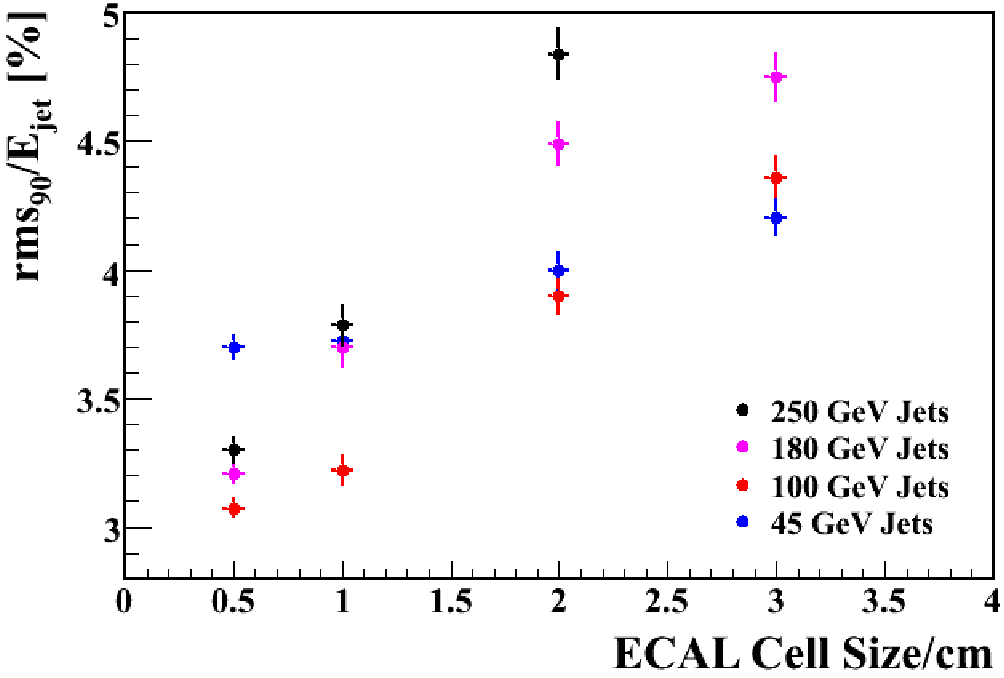


- ★ For now only scintillator HCAL
- ★ $1\times1\text{cm}^2$, $3\times3\text{cm}^2$, $5\times5\text{cm}^2$, and $10\times10\text{cm}^2$ tiles

- $3\times3\text{cm}^2$ looks reasonable
- Hint of small gain going to $1\times1\text{cm}^2$
- Significant degradation for larger tile sizes, e.g. $5\times5\text{cm}^2$

Optimisation: ECAL Segmentation

- Start from **LDCPrime** with **5×5 mm^2** SiW ECAL pixel size
- Investigate **10×10mm^2, 20×20mm^2** and **30×30mm^2**
  - Note: required changes in PandoraPFA clustering parameters



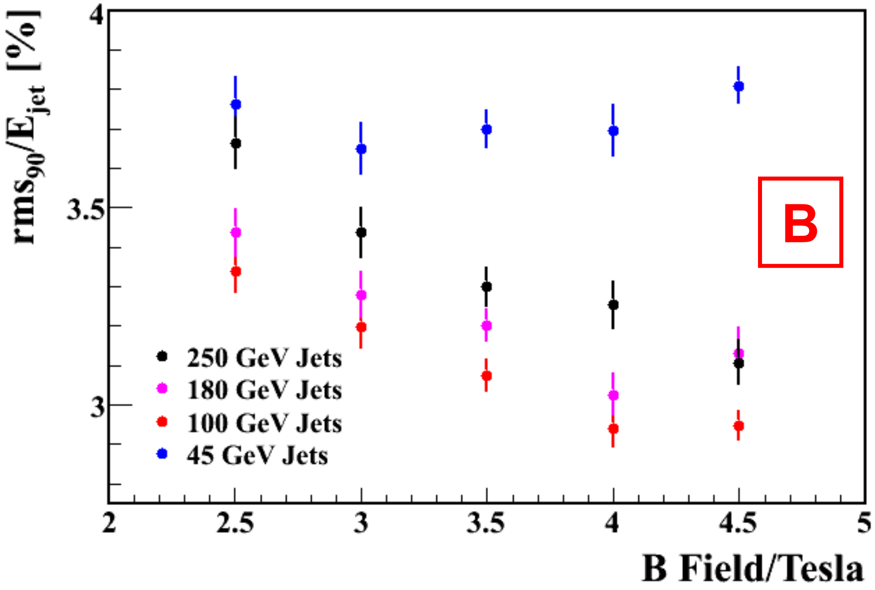
- Performance is a strong function of pixel size
- Probably rules out segmentation of **>10×10mm^2** !!!!

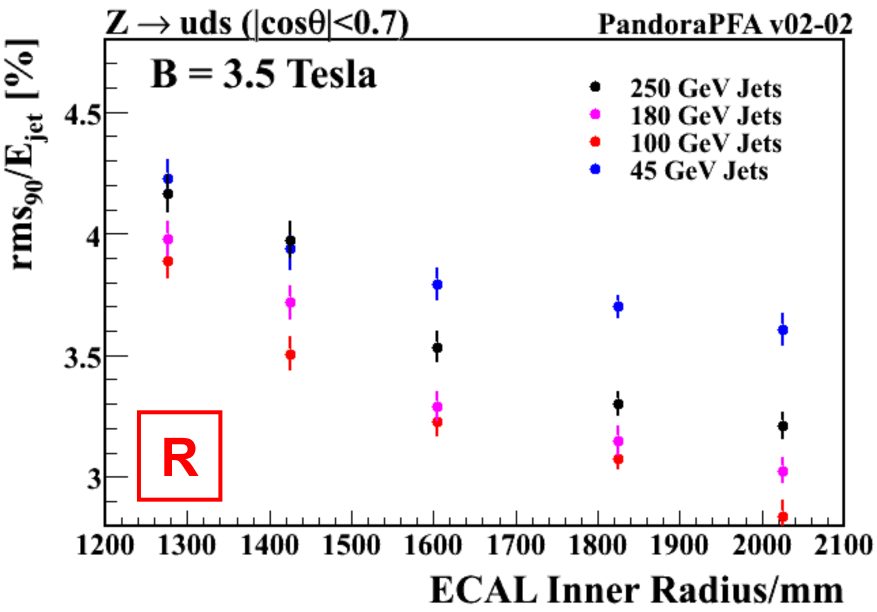
Caveat:

- Remember results are algorithm dependent
- Could reflect flaw in reconstruction

Optimisation: B-field vs Radius

- Studied performance as function of B and R for 45, 100, 180, 250 GeV jets
- Many samples…





Note:

- For low energy jets see little B-field dependence, this is because here resolution not confusion dominates performance
- Dependence on radius is more important than B

★ **Studied 13 combinations of R and B for 4 jet energies (45, 100, 180, 250)**

Test	Change	Parameters				
B and R	Model=	SiD-like	small	LDC	LDCPrime	GLD
B-field	B =	2.5 T	3.0 T	3.5 T	4.0 T	4.5 T
Radius	R_{ECAL} =	1280 mm	1420 mm	1600 mm	1820 mm	2020 mm

★ **Use perfect PFA to estimate non-confusion contributions**

★ **Empirically (for v2.1 of the PandoraPFA algorithm) find**

$$\frac{\sigma_E}{E} = \underbrace{\frac{0.021}{\sqrt{E}}}_{\text{Resolution}} \oplus \underbrace{0.01}_{\text{Tracking/Leakage/Fragments}} \oplus \underbrace{0.02\left(\frac{R}{1825}\right)^{\enclose{circle}{-1.0}}\left(\frac{B}{3.5}\right)^{\enclose{circle}{-0.35}}\left(\frac{E}{100}\right)^{+0.4}}_{\text{Confusion}}$$

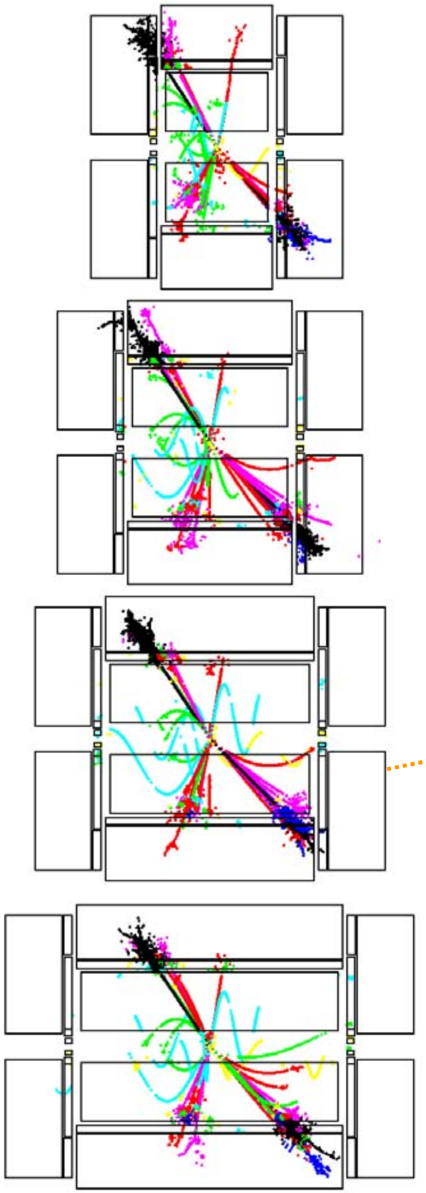
★ **This is a good fit to all 52 data values:** $\chi^2 = 42.6/48\,d.o.f.$

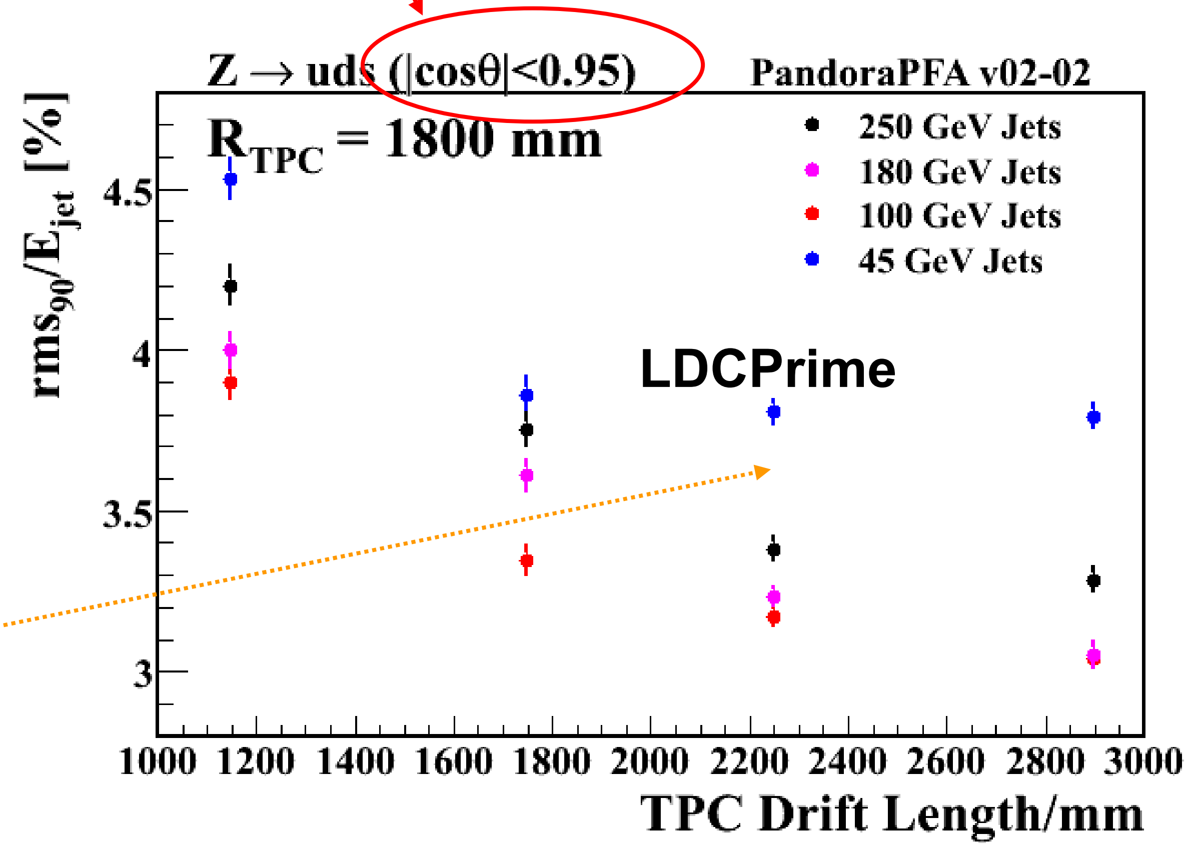
- **As expected, larger + higher field gives best performance**
- **R more important than B**

⇨ **Motivated choice of main ILD parameters**

Optimisation: TPC Aspect Ratio

- ★ Look at “full acceptance”



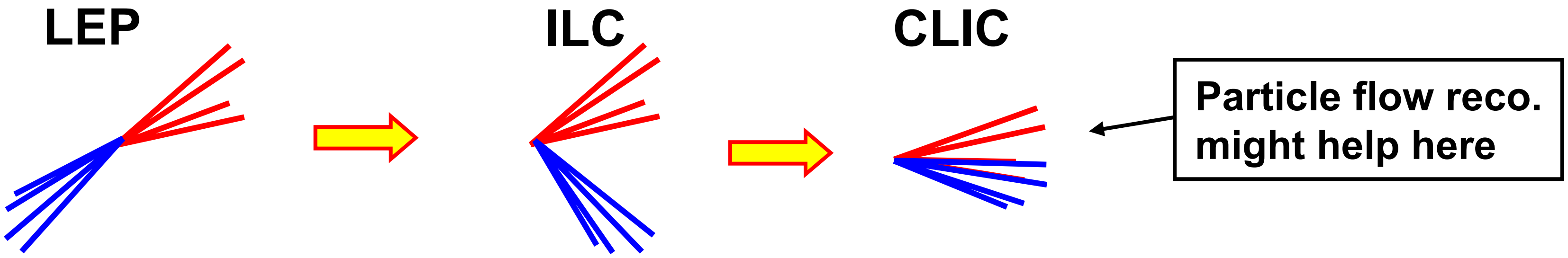


- ★ Little advantage in making TPC longer
- ★ Significant disadvantage in making it shorter

effectively gives smaller “R” for endcap jets

❺ Particle Flow at > 1 TeV

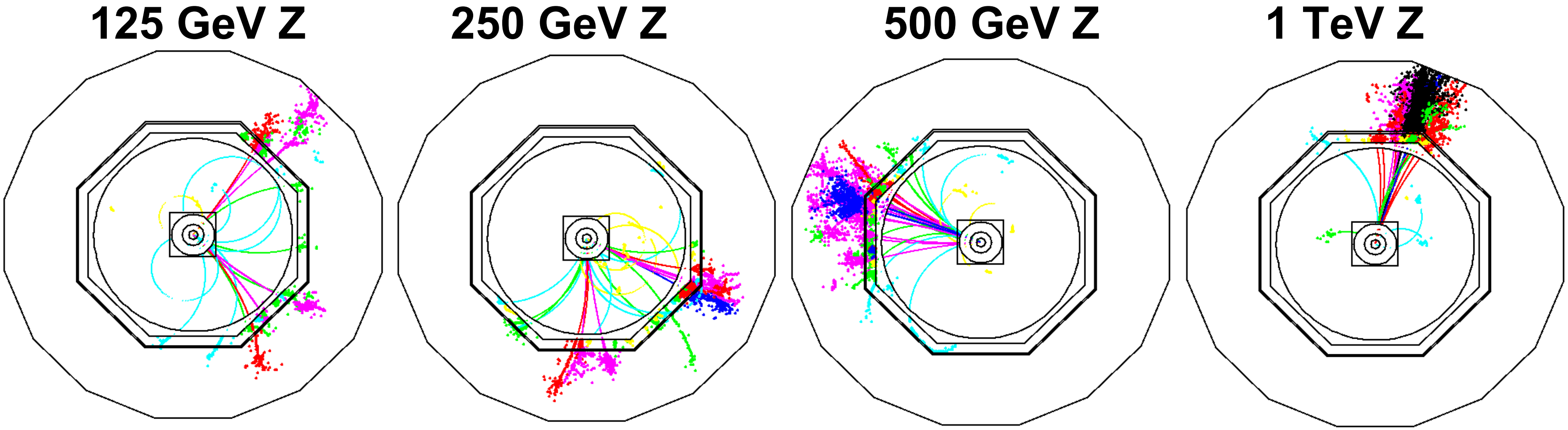
- ★ Whether particle flow is appropriate for a **multi-TeV e^+e^-** collider needs detailed study but depends on <u>physics program</u>, **e.g.**
  - ♦ CLIC is unlikely to operate solely at the highest energy
  - ♦ Likely to be a rich physics program below max. energy
    - ▪ lower $\sqrt{s}$ to study **Higgs**, **SUSY threshold scans**, etc.
    - ▪ Here Particle Flow Calorimetry highly desirable
- ★ Nevertheless want a general purpose detector suitable for collisions at highest centre-of-mass energies
  - Performed some preliminary studies of PandoraPFA performance at higher energies using LDC detector concept + full reconstruction
  - e.g. looked at W/Z separation at highest enegies
  - On-shell W/Z decay topology depends on energy:



Particle flow reco. might help here

W/Z Separation at high Energies

★ Simulated $e^+e^- \rightarrow ZZ \rightarrow u\bar{u}\nu\bar{\nu}$ and $e^+e^- \rightarrow ZZ \rightarrow d\bar{d}\nu\bar{\nu}$ events at 250 GeV, 500 GeV, 1 TeV, 2 TeV and 3 TeV using LDC detector



Note:

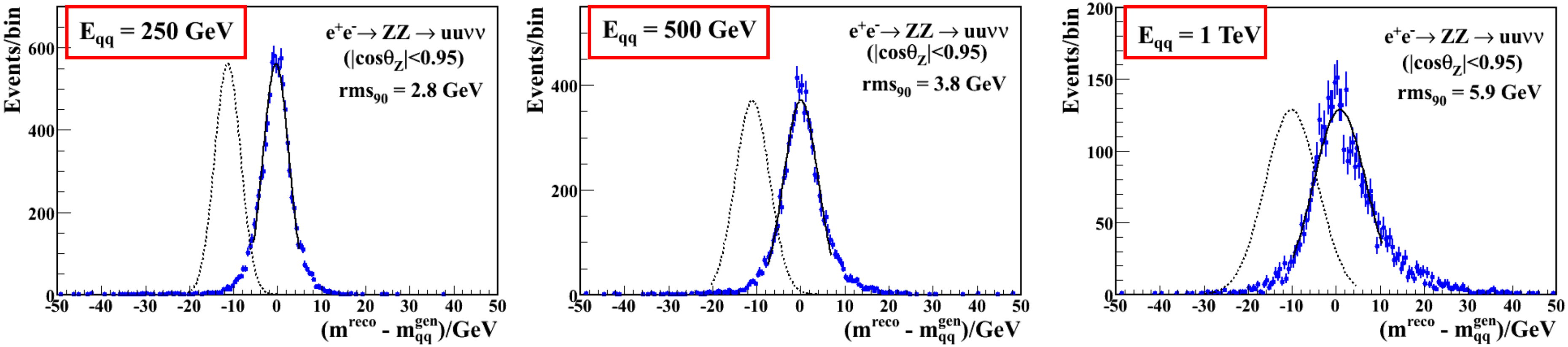
- Particle multiplicity does not change
- Boost means higher particle density

} More challenging for PFA

- PFA could help for high energies where W/Z appear as “mono-jets”

★ Study performance with full reconstruction + PandoraPFA

★ Study Z mass resolution as function of E_Z



(dotted histograms represent approx. W lineshape assuming same resolution)

★ Results are not unpromising

- For 500 GeV Zs resolution still good enough to separate W/Z
- For 1 TeV Zs observe significant degradation
- However, HCAL probably too thin for these energies + algorithm not optimised for very high E

rms90 **PandoraPFA v03-β**

E_Z	σ_E/E	σ_{m}/m
125 GeV	2.4 %	2.7 %
250 GeV	2.5 %	3.1 %
500 GeV	3.1 %	4.1 %
1 TeV	4.2 %	6.2 %
1.5 TeV	5.6 %	8.2 %

Conclude: PFA not ruled for a 3 TeV collider detector

❻ Conclusions

Optimisation

- ★ Understanding of what makes a good PFA detector is improving
  - ▪ radius still appears to be the main PFA performance driver
- ★ PandoraPFA results used extensively in optimisation of ILD

ILD Performance

- ★ First results for ILD detector look very promising:
  - ▪ < 30%/√E for E_{JET} < 100 GeV
  - ▪ < 50%/√E for E_{JET} < 250 GeV
  - ▪ good performance over entire jet angular range

PFA at CLIC ?

- ★ First studies do not rule out a particle flow detector at $\sqrt{s} = 3$ TeV
  - ▪ high energy limitations of PFA need study
  - ▪ also need to consider in light of full physics programme

Outlook

- ★ PandoraPFA is still evolving (limited by available effort)
- ★ Development now concentrating on higher/high energy jets
  - ▪ e.g. adaptive "Particle Flow ↔ Energy Flow ↔ Calorimetry"

Hope for significant progress in next 6 months

Many thanks to David for agreeing to give this presentation