Status of
Particle Flow Calorimetry

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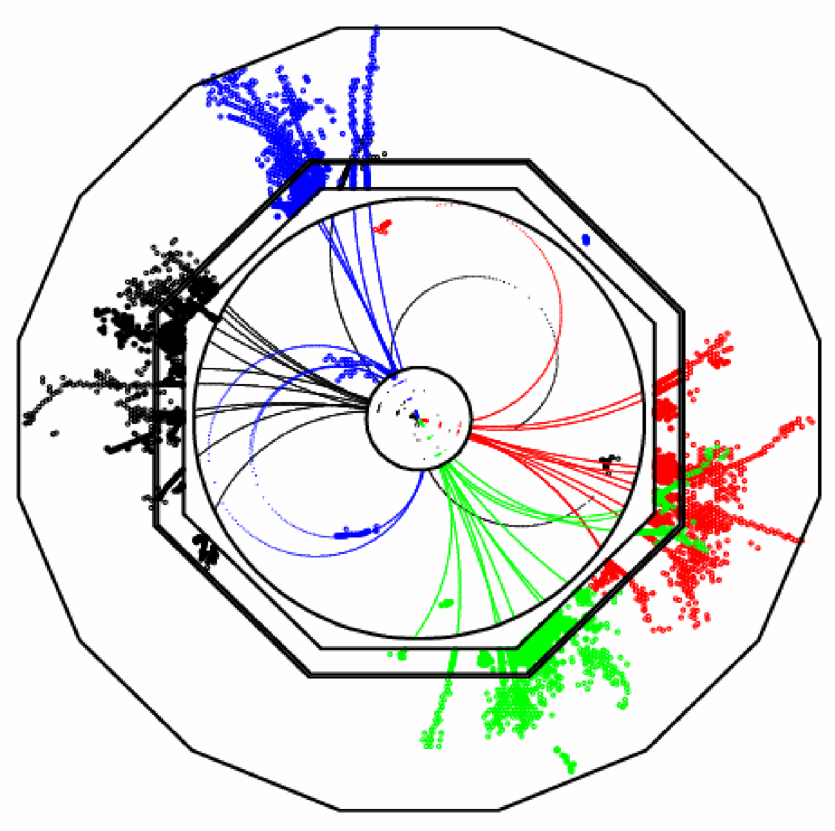
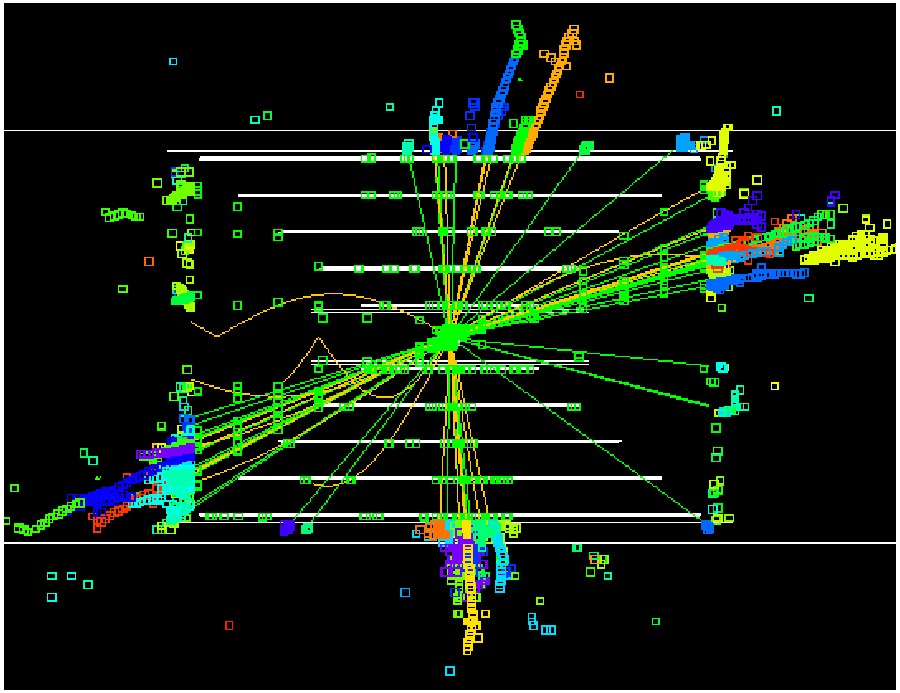
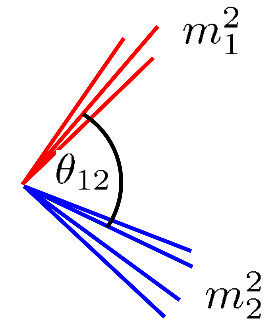


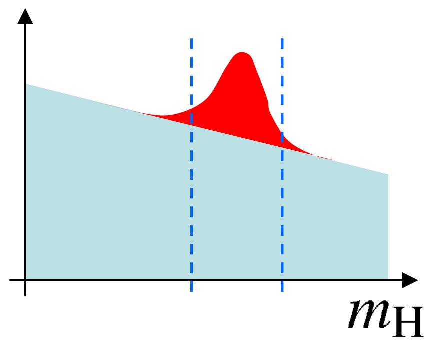


➊ LC Jet Energy Requirements

- ★ What are the real jet energy requirements at the LC ?
  - not 30 %/√E
- ★ Primarily interested in di-jet mass resolution



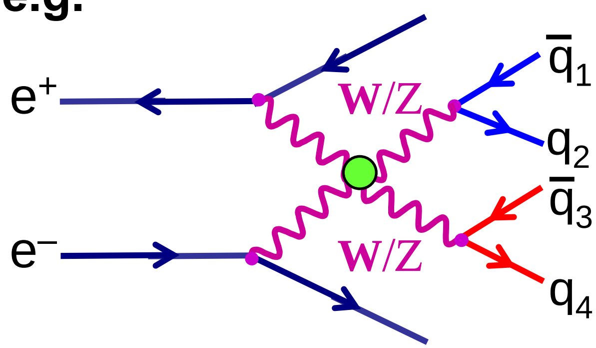
  - For a narrow resonance, want best possible di-jet mass resolution

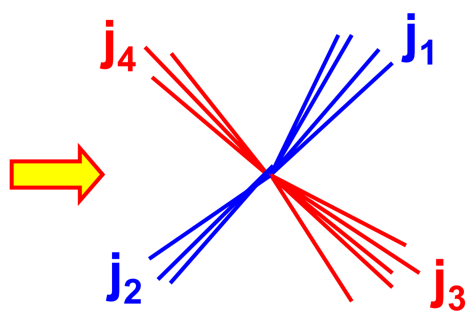


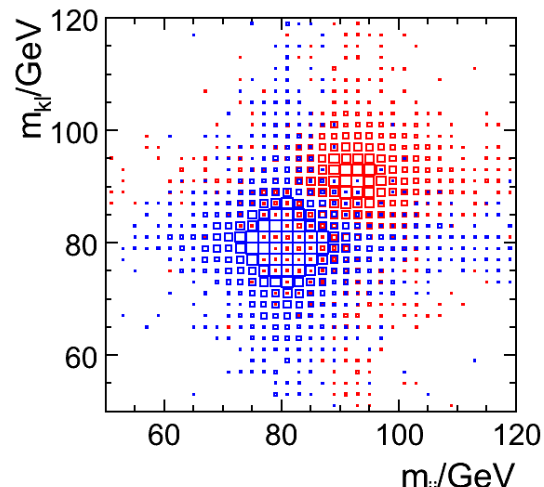
$$\text{signif.} \propto \frac{S}{\sqrt{B}} \propto (\text{resolution})^{-\frac{1}{2}}$$

  - At very least, need to separate W/Z hadronic decays

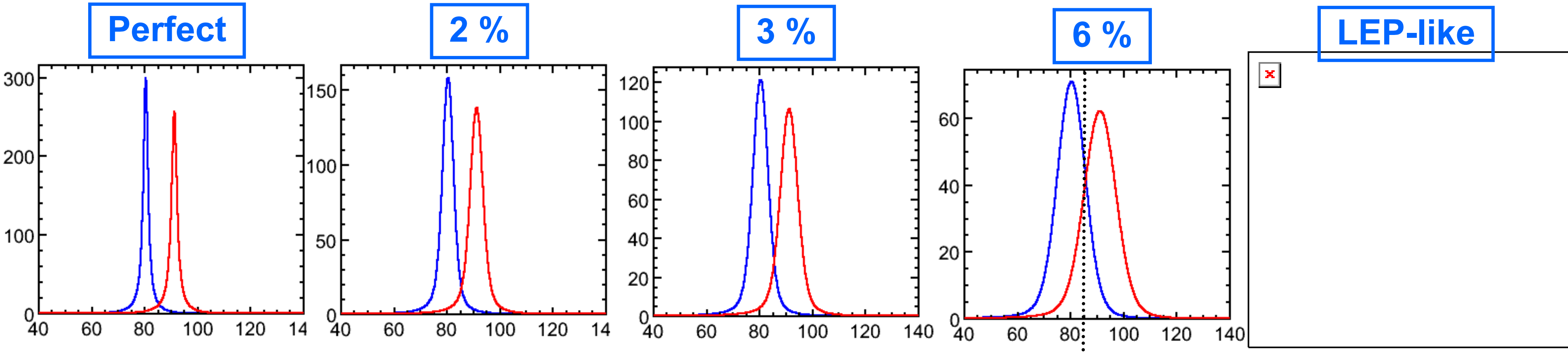
e.g.







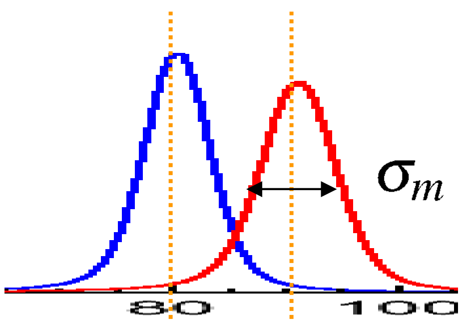
- Gauge boson width sets "natural" goal for jet energy resolution



- Quantify by effective W/Z separation

$$\mathrm{W/Z\ sep} = (m_Z - m_W)/\sigma_m$$

Jet E res.	W/Z sep
perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ



Defined as effective Gaussian equivalent Mass resolution

- 3 – 4 % jet energy resolution give decent W/Z separation 2.6 – 2.3 σ
- sets a reasonable choice for ILC jet energy goal ~3.5 %
- limited by Gauge boson widths at 2 % (but W/Z already well separated)

Context : LC jet energies

- ★ What jet energies are we interested in ?
- ★ Little need to reconstruct two fermion di-jet mass…
- ★ At 500 GeV primarily interested in 4-fermion/6-fermion final states
  - e.g. $e^+e^- \to ZH \to q\bar{q}b\bar{b}$ and $e^+e^- \to t\bar{t} \to bq\bar{q}\bar{b}q\bar{q}$
- ★ For higher centre-of-mass energies, fermion multiplicities will tend to be higher, e.g. SUSY cascade decays
- ★ Sets scale of typical jet energies:

√s	#fermions	Jet energy	
250 GeV	4	~60 GeV	ILC - like
500 GeV	4 – 6	80 – 125 GeV	ILC - like
1 TeV	4 – 6	170 – 250 GeV	ILC - like
3 TeV	6 – 8	375 – 500 GeV	CLIC - like

ILC Goals: ~3.5 % jet energy resolution for 50 – 250 GeV jets

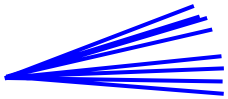
CLIC Goals: ~3.5 % jet energy resolution for 100 – 500 GeV jets

Can particle flow calorimetry achieve this ?

❷ Particle Flow Calorimetry

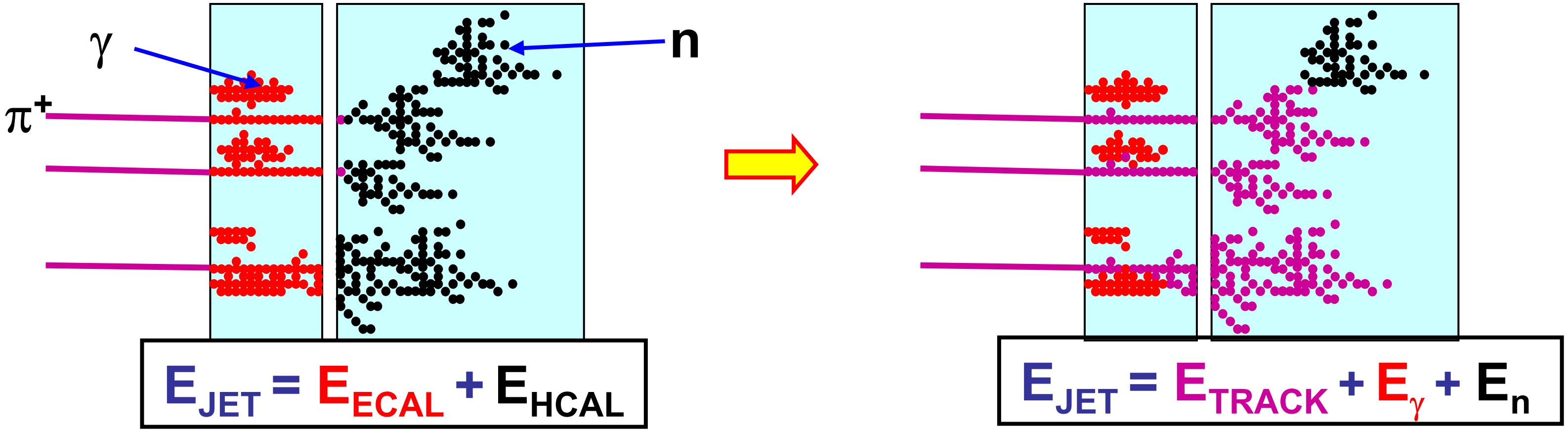
★ **In a typical jet :**

- **60 % of jet energy in charged hadrons**
- **30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)**
- **10 % in neutral hadrons (mainly n and K_L)**



★ **Traditional calorimetric approach:**

- **Measure all components of jet energy in ECAL/HCAL !**
- **~70 % of energy measured in HCAL:** $\sigma_{\mathrm{E}}/\mathrm{E} \approx 60\,\%/\sqrt{\mathrm{E(GeV)}}$
- **Intrinsically "poor" HCAL resolution limits jet energy resolution**



★ **Particle Flow Calorimetry paradigm:**

- **charged particles measured in tracker (essentially perfectly)**
- **Photons in ECAL:** $\sigma_{\mathrm{E}}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
- **Neutral hadrons (ONLY) in HCAL**
- **Only 10 % of jet energy from HCAL ⇨ much improved resolution**

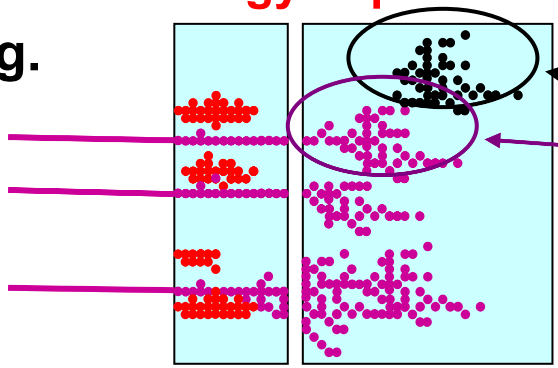
Particle Flow Algorithms (PFA)

Reconstruction of a Particle Flow Calorimeter:

★ Avoid double counting of energy from same particle

★ Separate energy deposits from different particles

e.g.

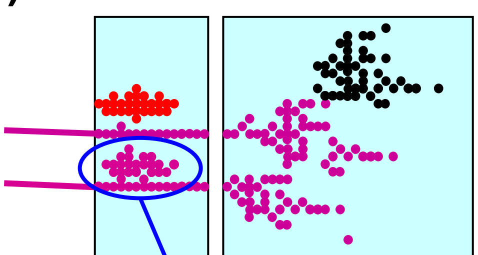


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution
not the intrinsic calorimetric performance of ECAL/HCAL

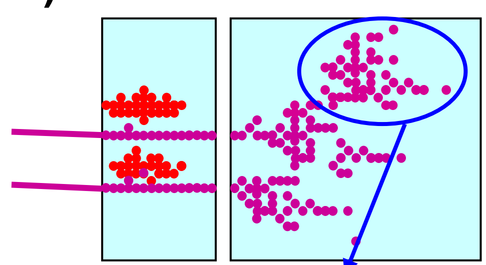
Three types of confusion:

i) Photons



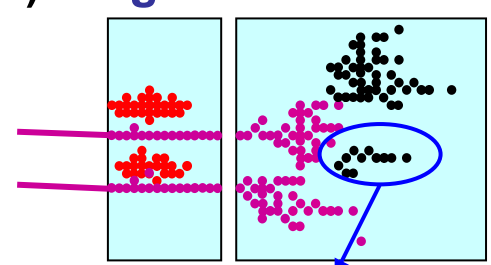
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

iii) Fragments



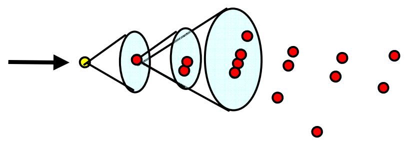
Reconstruct fragment as separate neutral hadron

Particle Flow Algorithms in practice

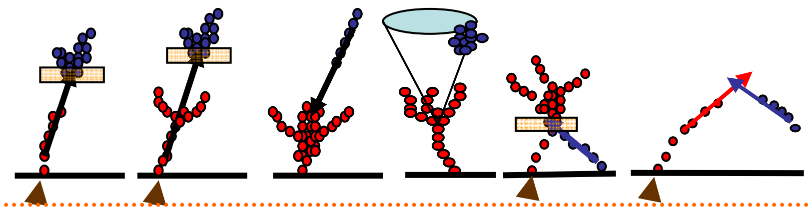
★ **Highly non-trivial !**

e.g. **PandoraPFA** consists of a number complex steps (not all shown)

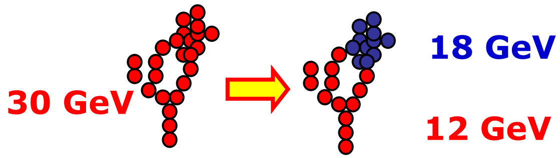
Clustering

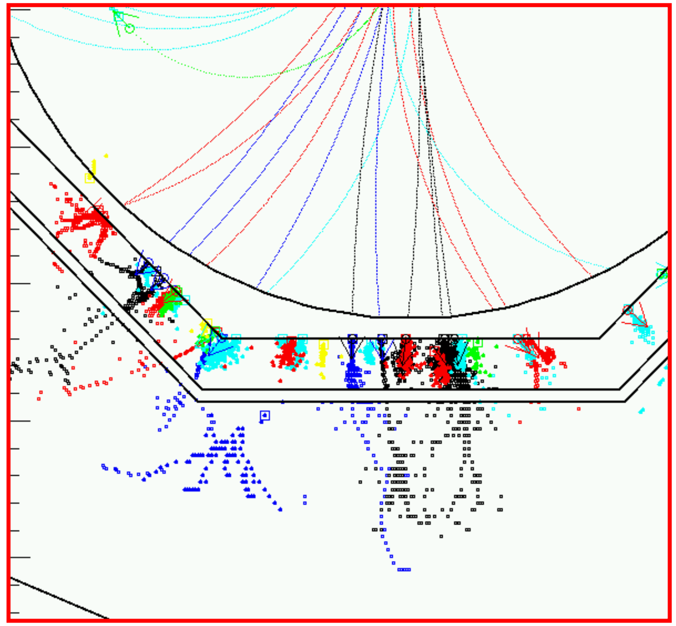


Topological Association

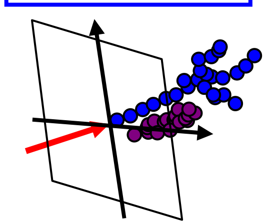


Iterative Reclustering

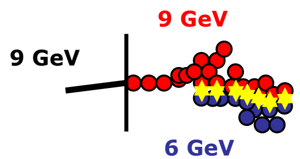




Photon ID



Fragment ID



Status of PFA for the ILC

- Since last ALCPG meeting, there has been a lot of progress
  - I believe principle of Particle Flow now proven beyond all reasonable doubt; it will deliver at ILC energies
- Both ILD and now SiD have dedicated PFA algorithms used for LoIs:
  - PandoraPFA (ILD):
    - most mature, gives best performance
    - now well understood
    - now even "documented"… paper accepted by NIMA
  - IowaPFA (SiD):
    - looks promising (real progress in last year)
    - further improvements possible
- LoI performance:

E_{JET}	σ_E/E (rms_{90})	
	ILD	SiD
45 GeV	3.7 %	5.5 %
100 GeV	2.9 %	4.1 %
180 GeV	3.0 %	4.1 %
250 GeV	3.1 %	4.8 %

- ILD/PandoraPFA meets ILC goal for all relevant jet energies
- SiD/IowaPFA getting close (encouraging)
- The difference? Probably:
  - in part detector (size)
  - in part algorithm

❸ Understanding PFA Performance

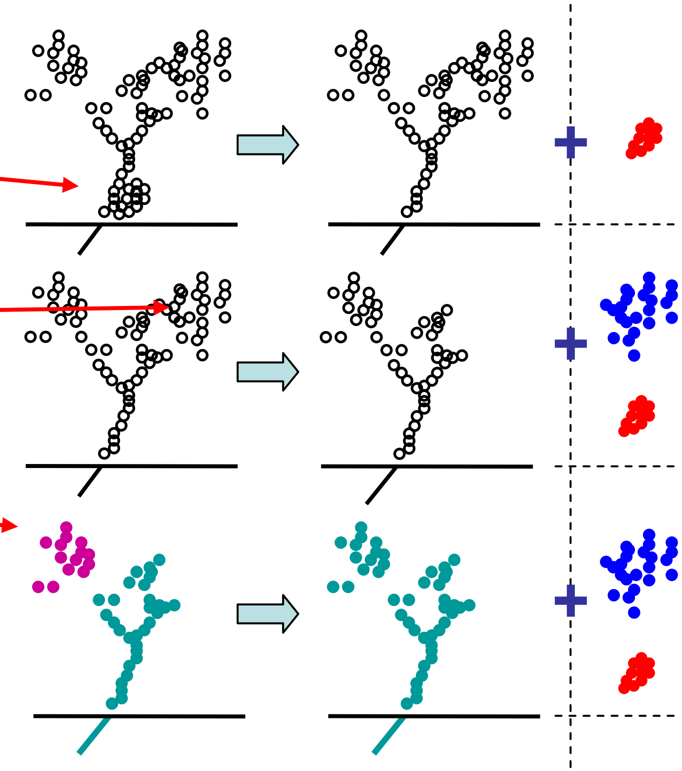
What drives Particle Flow performance ?

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

★ Use MC to "cheat" various aspects of **Particle Flow**

<u>PandoraPFA options:</u>

- **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



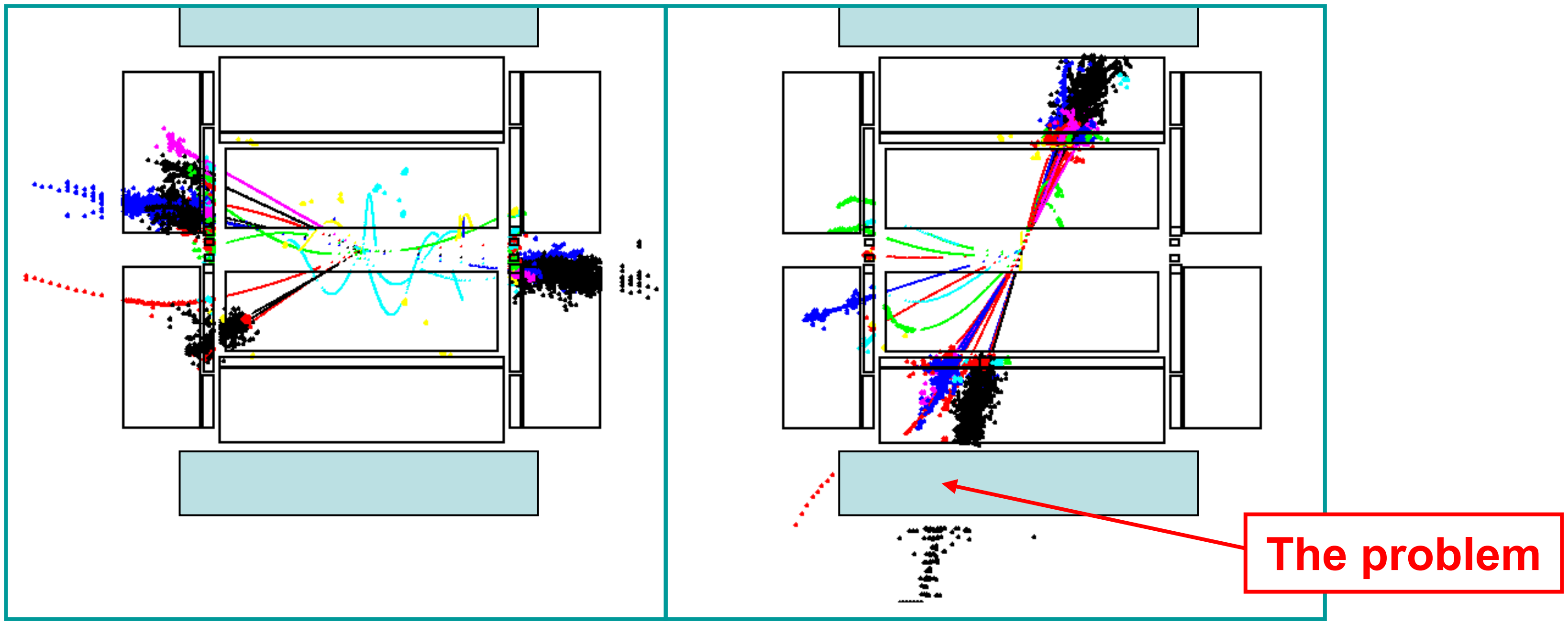
★ Also consider leakage (non-containment) of hadronic showers

Leakage

★ **For high energy jets non-containment of showers is significant**
- **major issue at CLIC energies**

★ **Partially recovered using MUON chambers as a "Tail catcher"**
- **Effectiveness limited by thick (2 λ_I) solenoid**
- **PandoraPFA uses MUON chamber information to estimate leakage and energy deposited in coil**
  - **Reasonably sophisticated – although room for improvement**

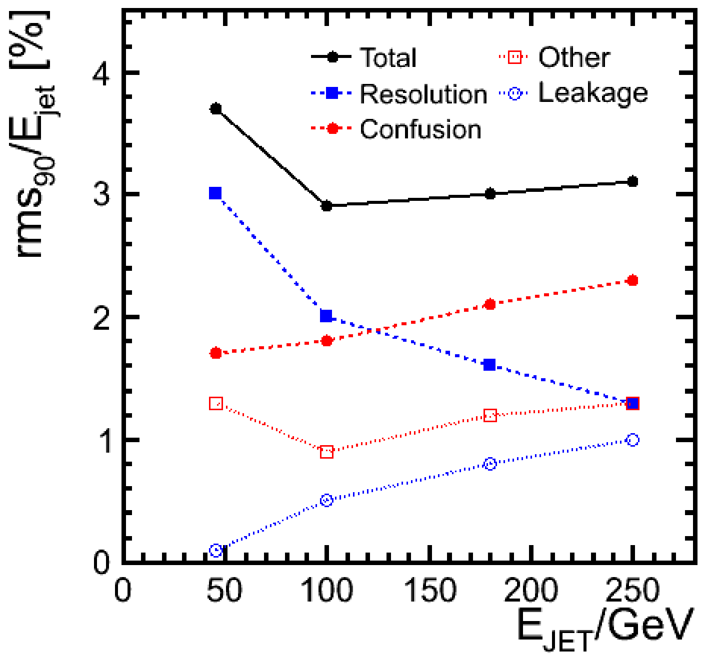
e.g.



★ **Estimate effect by comparing standard PFA with those obtained using a very deep HCAL**

Contributions to resolution

★ **Answer depends on jet energy**
- **Low energy jets: RESOLUTION**
- **High energy jets: CONFUSION**
- **Cross-over at ~100 GeV**
- **For high energies CONFUSION dominates**
- **Very high energy jets: leakage important**



★ **What kind of confusion ?**
- **i) photons**
  (γ merged into charged had. shower)
- **ii) neutral hadrons**
  (K_L/n merged into charged had. shower)
- **iii) charged hadron fragments**
  (fragments of charged had. reconstucted as neutral hadron)

★ **At high energies ii) is the largest contribution, e.g. for 250 GeV jets**

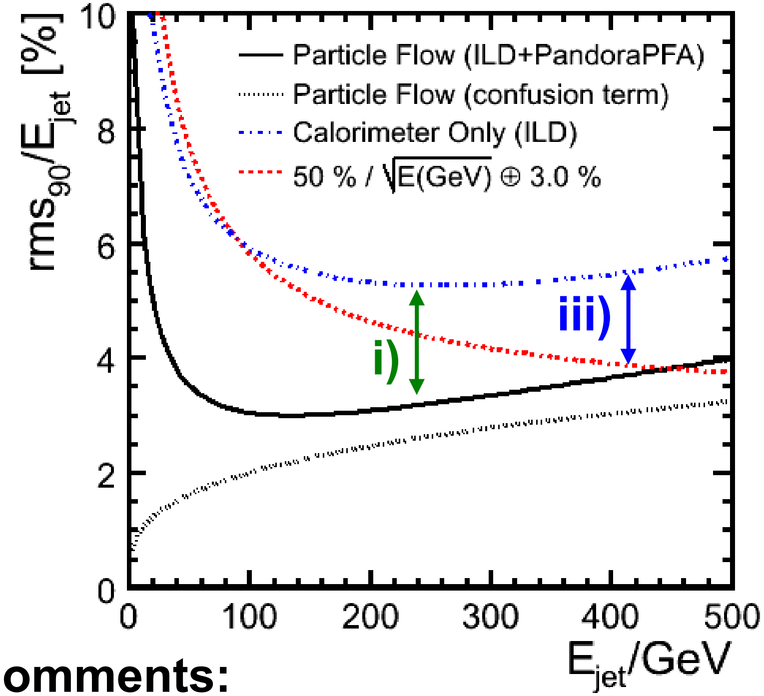
Total Resolution	3.1 %
Confusion	2.3 %
i) Photons	1.3 %
ii) Neutral hadrons	1.8 %
iii) Charged hadrons	0.2 %

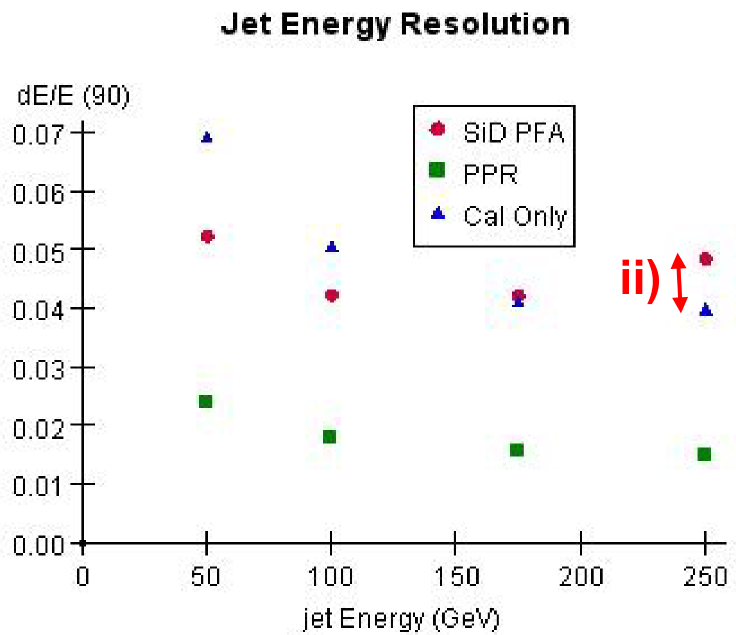
Not insignificant

Largest single contribution, but remember, enters in quadrature

PFA vs Conventional Calorimetry

- ★ **ILD/SiD intended for PFA, but also good conventional calorimeters**
  - ♦ **ECAL ~15%/√E; HCAL ~55%/√E**
- ★ **Interesting to compare PFA and pure energy sum with ILD and SiD**





Comments:

- **i) PandoraPFA: PFA ALWAYS wins over purely calorimetric**
  - **adding information should not make things worse !**
- **ii) SiDPFA: not true – so clear room for improvement (under study)**
- **iii) PandoraPFA: effect of leakage clear at high energies**
- **iv) PandoraPFA/ILD: Resolution better than 4 % for E_{JET} < 500 GeV**

❹ Dependence on hadron shower simulation

★ Modelling of hadronic showers far from perfect, so:

- Can we believe PFA results ?
- Need a dedicated PFA test beam demonstration? [is this even possible?]

★ Have tried to address this by comparing PandoraPFA/ILD performance for 5 very different Geant4 physics lists…

Physics List	Jet Energy Resolution			
	45 GeV	100 GeV	180 GeV	250 GeV
LCPhys	3.74 %	2.92 %	3.00 %	3.11 %
QGSP_BERT	3.52 %	2.95 %	2.98 %	3.25 %
QGS_BIC	3.51 %	2.89 %	3.12 %	3.20 %
FTFP_BERT	3.68 %	3.10 %	3.24 %	3.26 %
LHEP	3.87 %	3.15 %	3.16 %	3.08 %
χ^2	23.3 / 4	17.8 / 4	16.0 / 4	6.3 / 4
rms	4.2 %	3.9 %	3.5 %	2.5 %

Default

~GHEISHA

★ Only a weak dependence < 5 % (but need to connect to CALICE studies)

- NOTE: 5 % is on the total, not just the hadronic confusion term

e.g.

Total Resolution	3.11 %
Conf: neutral hads	1.80 %
Other contributions	2.54 %

×1.05

×1.14

×1.00

Total Resolution	3.27 %
Conf: neutral hads	2.05 %
Other contributions	2.54 %

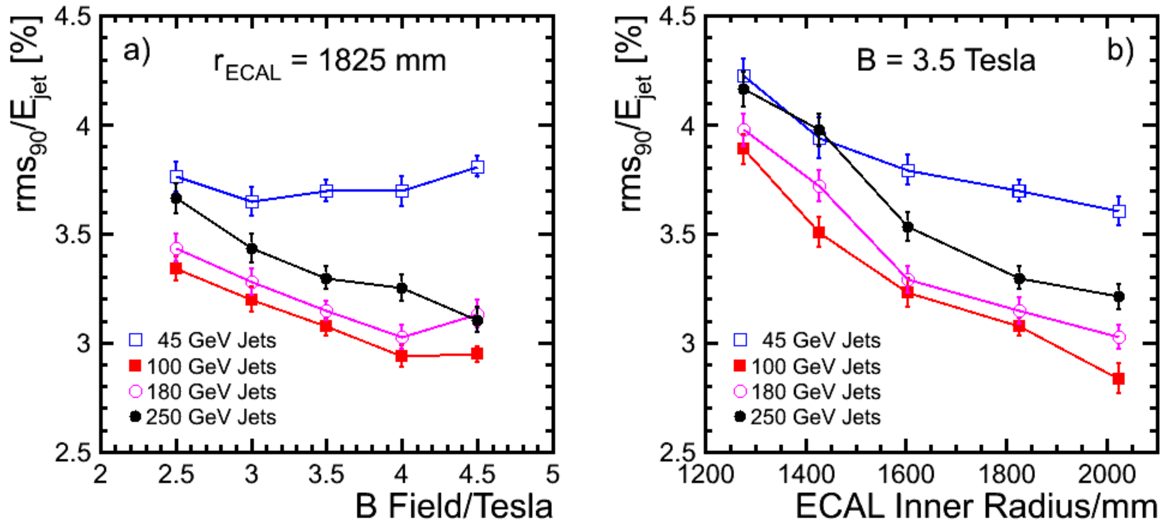
Study suggests PandoraPFA is rather robust to hadronic modelling

- If true, argues against need for dedicated PFA test beam demonstration

❺ PFA Detector Design Issues

★ (Still) often argued that figure of merit for PFA is **BR²**: this is not valid;
- only valid for pairs of collinear neutral/charged particles
- does not account for distribution of particles in jets

★ Empirically find
(PandoraPFA/ILD)



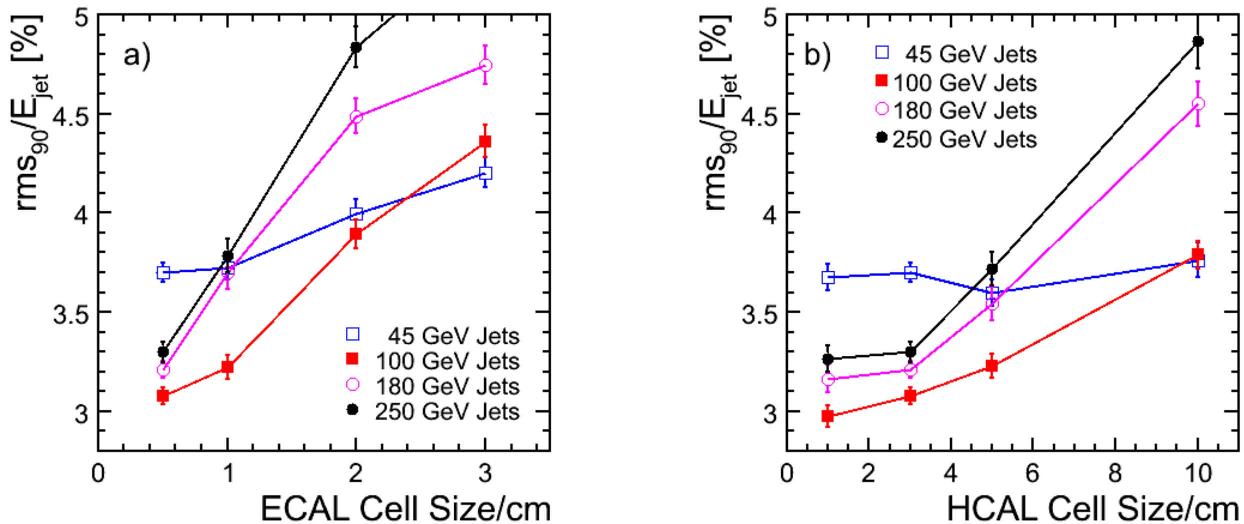
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E/\mathrm{GeV}}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{R}{1825}\right)^{-1.0}\left(\frac{B}{3.5}\right)^{-0.3}\left(\frac{E}{100}\right)^{+0.3}\%$$

Resolution | Tracking | Leakage | Confusion

Conclusions:
- Confusion $\propto$ **B**$^{-0.3}$ **R**$^{-1}$
- 1/R dependence "feels right", geometrical factor !
- Difficult to compensate for **R** with **B**

PFA Optimisation: Calorimeter Segmentation

★ **Starting from LDCPrime vary ECAL Si pixel size and HCAL tile size**



★ **<u>ECAL Conclusions:</u>**

- **Ability to resolve photons in current PandoraPFA algorithm strongly dependent on transverse cell size**
- **Require at least as fine as 10x10 mm^2 to achieve 4.0 % jet E resolution**
- **Significant advantages in going to 5x5 mm^2**
- **For 45 GeV jets resolution dominates (confusion relatively small)**

★ **<u>HCAL Conclusions:</u>**

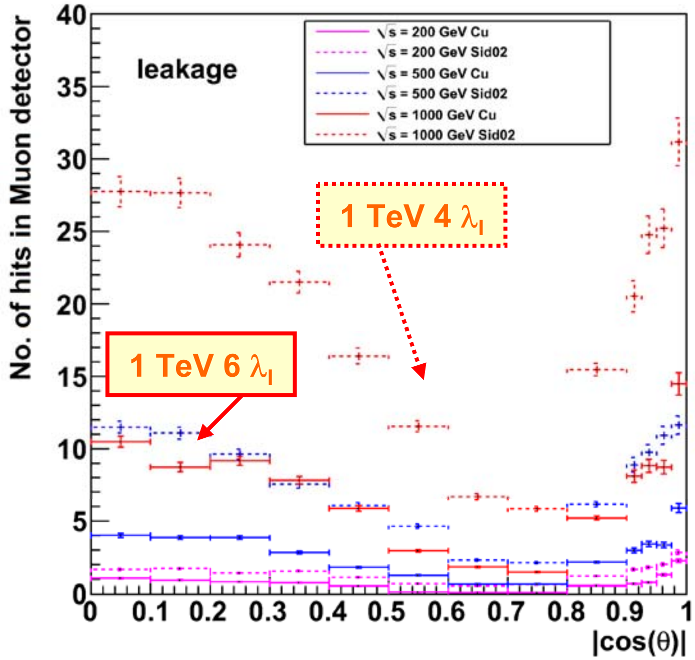
- **For current PandoraPFA algorithm and for Scintillator HCAL, a tile size of 3×3 cm^2 looks optimal**
- **May be different for a digital/semi-digital RPC based HCAL**

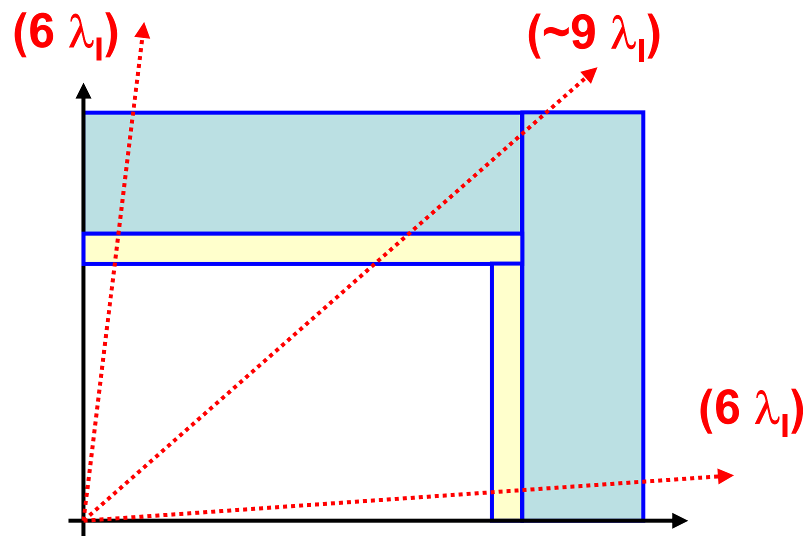
❻ PFA at a multi-TeV collider

★ At a Multi-TeV collider, leakage of hadronic showers is a major issue

★ HCAL in ILD (6 λ_I) and SiD (4 λ_I) concepts too thin to contain 1 TeV showers

- e.g. lowaPFA/SiD with HCAL (4 λ_I and 6 λ_I)





★ Clear dependence on cosθ due to leakage

★ Probably need ~8 λ_I HCAL for CLIC energies

- but needs to be inside Solenoid for PFA – cost/feasibility
- LCD group at CERN, investigating more compact structures e.g. W/Steel

★ In principle, if done correctly, PFA should **REDUCE** impact of leakage

★ But, can PFA deliver at CLIC energies ?

PandoraPFA/ILD Jet Energy Resolution

★ Is an ILD-sized detector suitable for CLIC ?

★ Defined modified ILD+ model:

- B = 4.0 T (ILD = 3.5 T)
- HCAL = 8 λ_I (ILD = 6 λ_I)

★ Effect on jet energy resolution

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	29.2 %	2.9 %
180 GeV	40.3 %	3.0 %
250 GeV	49.3 %	3.1 %
375 GeV	81.4 %	3.6 %
500 GeV	91.6 %	4.1 %

⇨

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	28.7 %	2.9 %
180 GeV	37.5 %	2.8 %
250 GeV	44.7 %	2.8 %
375 GeV	71.7 %	3.2 %
500 GeV	78.0 %	3.5 %

NOTE:

★ Meet "LC jet energy resolution goal [3.5%]" for 500 GeV ! jets

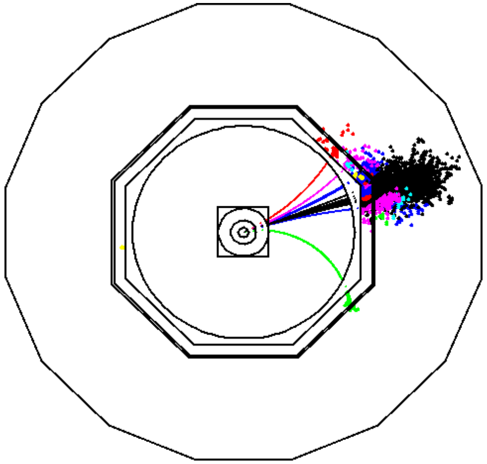
★ Importantly, PFA is still working for 500 GeV jets

- ★ Raw calo. energy : 5.2 %
- ★ PandoraPFA : 3.5 %

Looks promising…

Jet Energy Resolution Goals Revisited

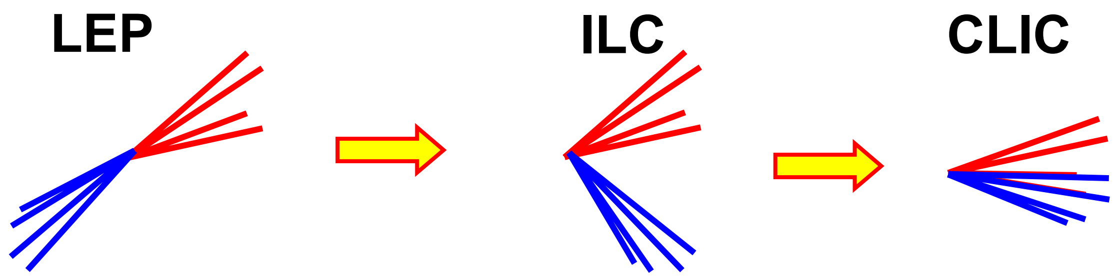
- **But what are the jet energy requirements for CLIC ?**
  - **Assuming two stage operation e.g. 500 GeV followed by 3 TeV**
    - **Need to meet ILC goals – here PFA rules.**
    - **But what about at high energies ?**
- **Multi-TeV jet energy goals:**
  - **BSM physics likely to yield 6-8 fermion final states**
    - **relevant jet energies ~375-500 GeV**
  - **So far have concentrated on jet energy resolution for decays at rest**
  - **If BSM physics close to threshold, not unreasonable**
    - **PFA can achieve <4 % jet energy resolution for new particle decays**
    - **Gives few % mass resolution for new particle decays**
    - **Sufficient to separate W/Z for gauge bosons produced in association with BSM physics**
  - **But, what if W/Z highly boosted e.g. if produced in BSM particle decays**
    - **Now interested in PFA performance for highly boosted jets…**



1 TeV Z

❼ W/Z Separation at high Energies

★On-shell W/Z decay topology depends on energy:



Particle flow reco. might help here

★A few comments:

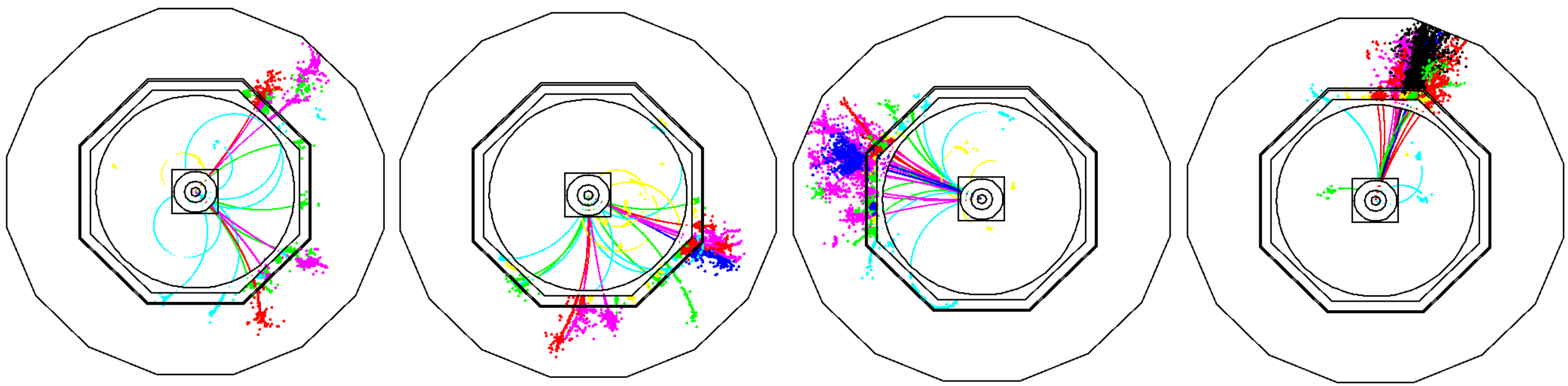
- Particle multiplicity does not change
- Boost means higher particle density

} More confusion

- PFA could be better for "mono-jet" mass resolution

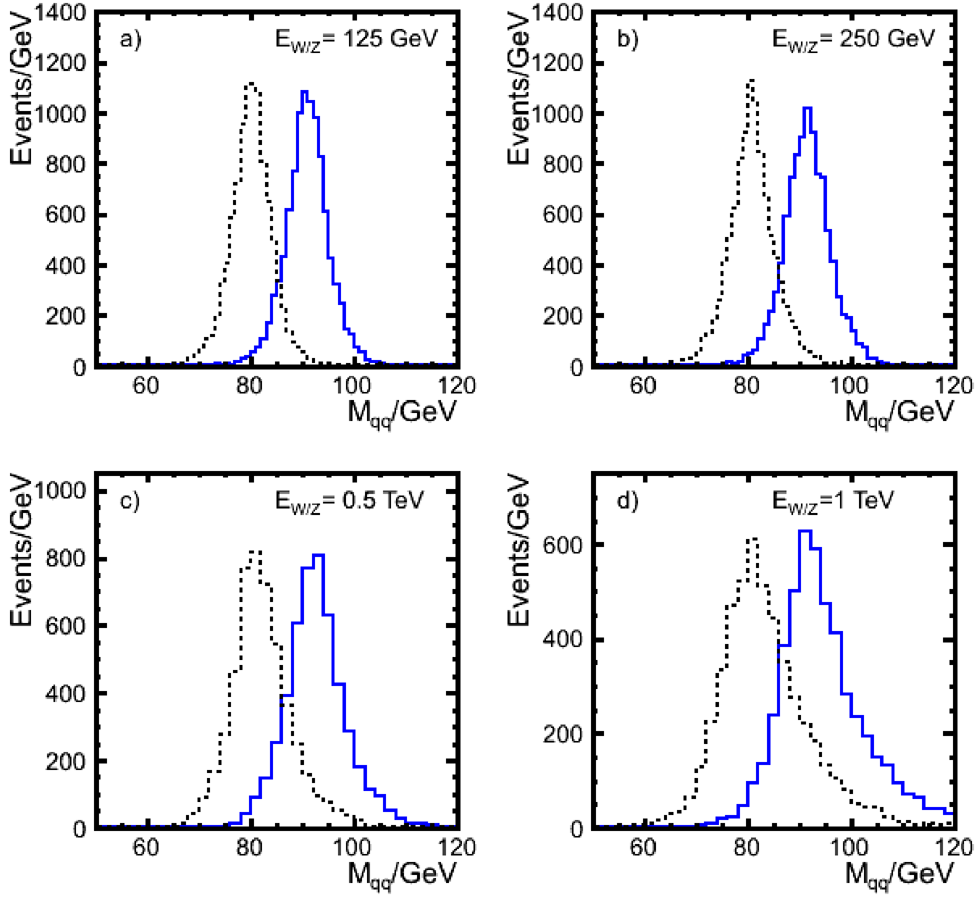
★PandoraPFA + ILD⁺ performance studied for:

125 GeV Z | 250 GeV Z | 500 GeV Z | 1 TeV Z



★ **Studied W/Z separation using ILD+ samples of**

$$e^+e^- \rightarrow WW \rightarrow u\bar{d}\nu\mu \qquad e^+e^- \rightarrow ZZ \rightarrow d\bar{d}\nu\bar{\nu}$$



ILC-like energies

Clear separation

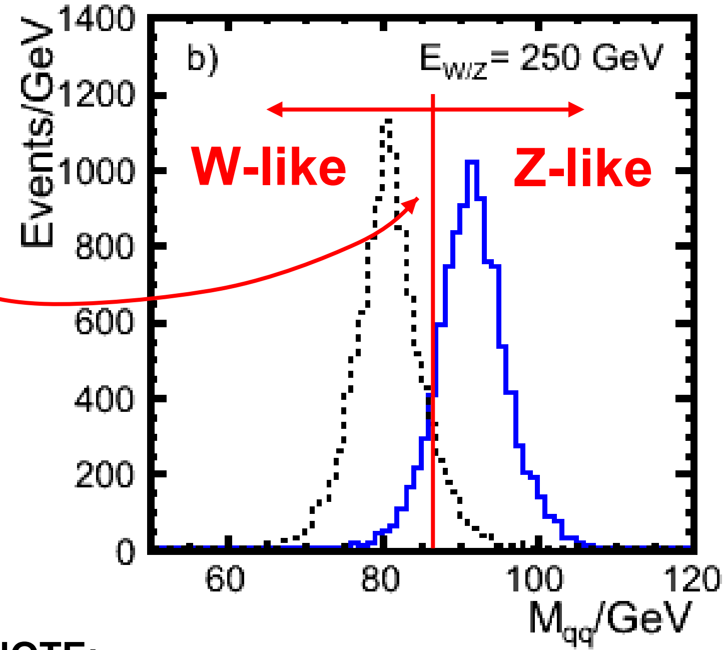
CLIC-like energies

There is separation, although less clear

- **Current PandoraPFA/ILD+ gives good W/Z separation for 0.5 TeV bosons**
- **Less clear for 1 TeV bosons**

★ **Can quantify W/Z separation as:**

- **rms_{90} of mass peaks**
- **Separation in terms of:**
  - **Efficiency of optimal W/Z cut**
  - **Equivalent sigma of W/Z sep.**
  - **Equivalent mass res. to give same separation**



$E_{W/Z}$	$rms_{90}(m)$	σ_m/m	W/Z sep	ε
125 GeV	2.8 GeV	2.9 %	2.7 σ	91 %
250 GeV	3.0 GeV	3.5 %	2.5 σ	89 %
500 GeV	3.9 GeV	5.1 %	2.1 σ	84 %
1000 GeV	6.4 GeV	7.0 %	1.5 σ	78 %

NOTE:

- **Perfect resolution:** ⇨ $\varepsilon = 94\%$
- **No separation:** ⇨ $\varepsilon = 50\%$

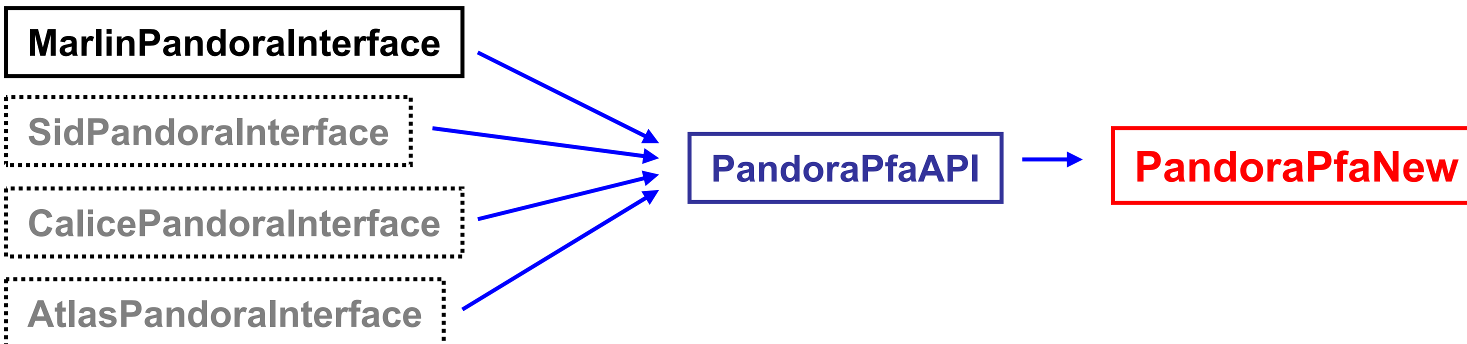
Conclude:

- **Performance almost certainly good enough for 500 GeV W/Zs**
- **Would like better performance for 1 TeV W/Z**
- **Remember, PandoraPFA not tuned for very high energy jets…**

❽ The Future

PandoraPFA

- ★ ILD LoI version frozen, no further development
- ★ New improved version being written from scratch (Cambridge/CERN)
  - Properly designed code
  - Increased flexibility – needed to implement some new ideas…
  - Improved memory footprint/speed
  - Algorithm now independent from framework



  - Constant benchmarking against existing code – ensure performance
  - Aim to have re-implementation of existing code by 1/1/2010

IowaPFA

- ★ Continue development
  - aim to improve high energy performance – already some good ideas
  - important to have a second powerful Particle Flow Algorithm

❾ Conclusions

Solid Conclusions:

★ Clear demonstration that PFA can deliver ILC performance goals
- excellent performance for both $\sqrt{s}$ = 500 GeV and $\sqrt{s}$ = 1 TeV
- modelling uncertainties do not appear to be large
- have not yet reached ultimate PFA performance for ILC energies

★ Have developed a reasonably good understanding of Particle Flow

★ Initial studies demonstrate the Particle Flow Calorimetry will work (to some extent) at $\sqrt{s}$ = 3 TeV:
- For 375-500 GeV jets can achieve 3.2-3.5 % jet energy resolution
- For 0.5-1.0 TeV achieve reasonable (2.1-1.5σ) separation of W/Z bosons
- Full reach of PFA at $\sqrt{s}$ = 3 TeV needs significant algorithm devel.

Particle Flow can deliver unprecedented performance for the next LC

fin

Backup: rms_{90}

★ PFA resolution presented in terms of rms_{90}
- defined as **"rms in smallest region containing 90 % of events"**
- introduced to reduce sensitivity to tails in a well defined manner
- in addition, PFA resolution is inherently non-Gaussian

★ How to interpret rms_{90} ? **With care…**
- how to compare 4 GeV PFA rms90 with 5 GeV Gaussian resolution

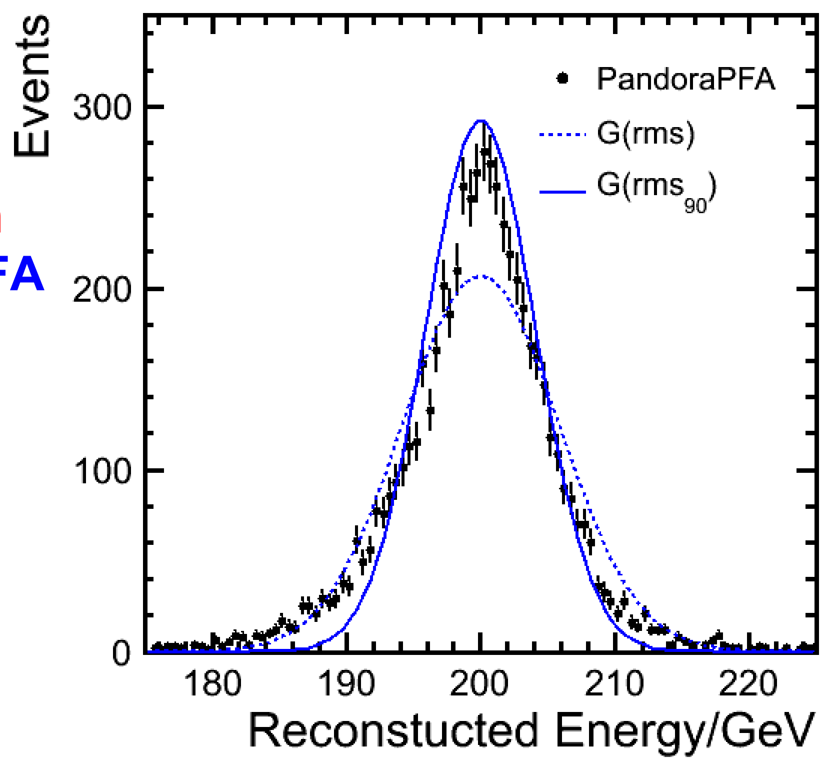
★ For a **true** Gaussian distribution
- $rms_{90} = 0.79\,\sigma$

★ Highly mis-leading…
- distributions always have tails:
  Gaussian usually = fit to some region
- rms_{90} larger than central peak from PFA
- e.g. for 200 GeV di-jets (from rest):

  rms(E) = 5.8 GeV
  rms_{90}(E) = 4.1 GeV
  fit to 196-205 GeV : 3.8 GeV

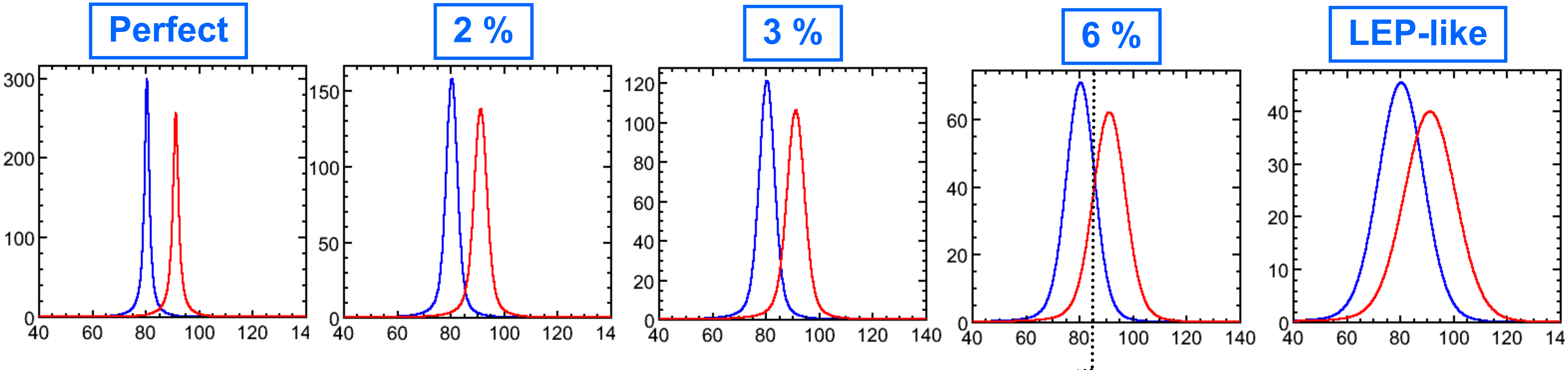
★ MC studies to determine equivalent statistical power show

$$\boxed{\mathrm{rms}_{90} \approx 0.9\sigma_{\mathrm{Gaus}}}$$



Backup: requirements

- Gauge boson width sets “natural” goal for jet energy resolution



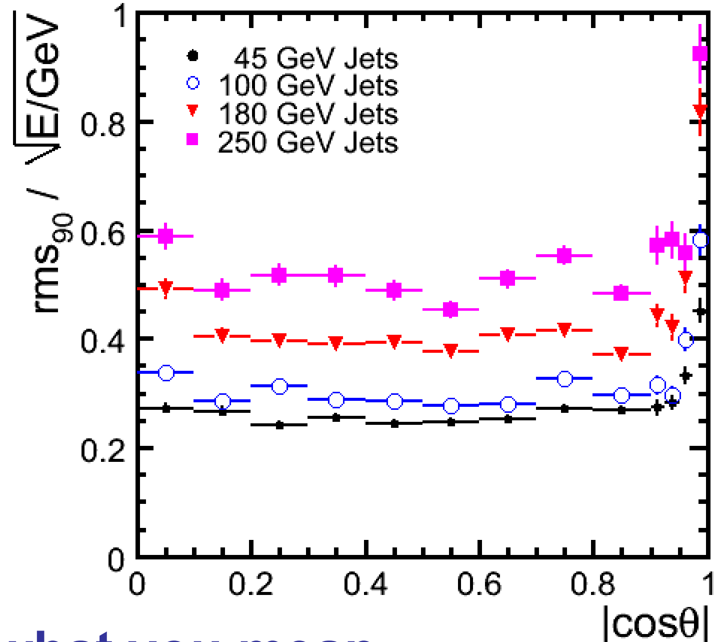
- Quantify by purity of W/Z samples

Jet E res.	Effic.	Back.	Eff*pur	W/Z sep
perfect	94 %	6 %	0.88	**3.1** σ
2%	93 %	8 %	0.86	**2.9** σ
3%	91 %	10 %	0.82	**2.6** σ
4%	88 %	14 %	0.76	**2.4** σ
5%	84 %	19 %	0.68	**2.0** σ
10%	71 %	41 %	0.41	**1.1** σ

Backup: Current Performance (ILD)

- ★ For ILD concept (B=3.5 T, r_{ECAL} = 1.8 m, 6 λ_I HCAL)
- ★ Quote performance in terms of Z decays to uu, dd, ss (at rest)

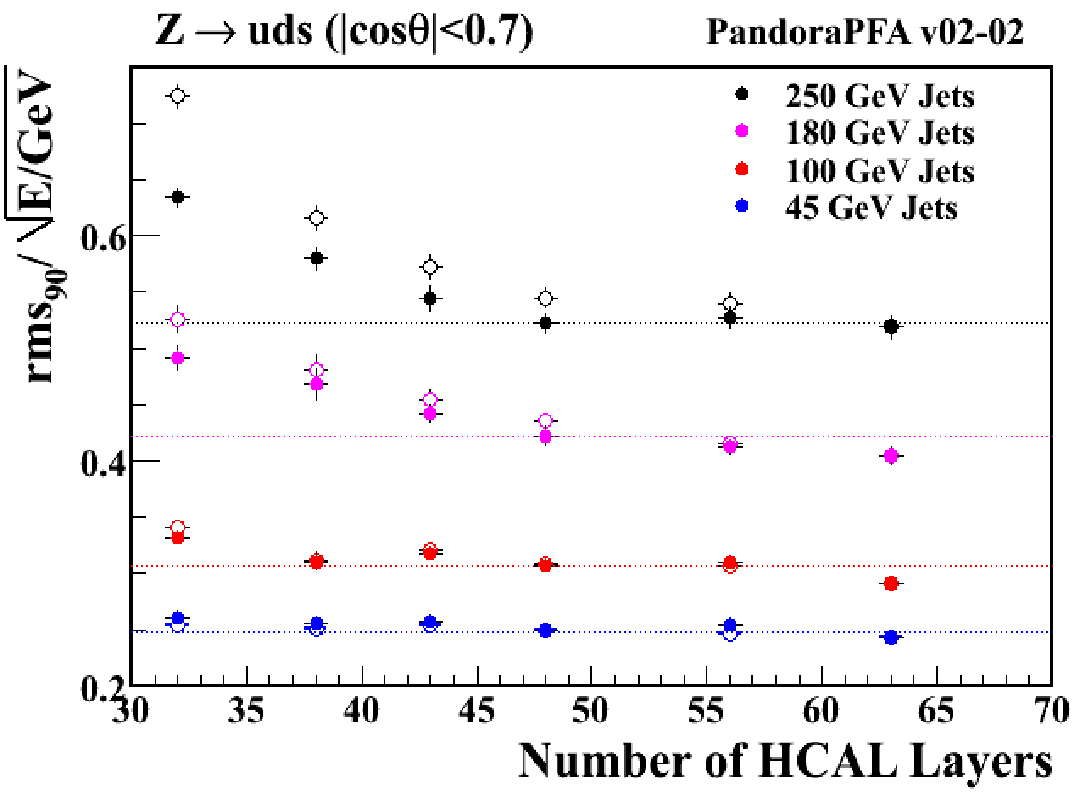
E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	29.2 %	2.9 %
180 GeV	40.3 %	3.0 %
250 GeV	49.3 %	3.1 %
375 GeV	81.4 %	3.6 %
500 GeV	91.6 %	4.1 %



- ★ Is this good enough ? Depends on what you mean…
  - To resolve W and Z bosons need approximately σ_E/E_j < 3.8 %
- ★ What can be achieved with a "traditional" approach to calorimetry?
  - Best at LEP was equivalent to 65 %/$\sqrt{E_{jj}}$ (at 91.2 GeV)
  - Often quoted, but slightly mis-leading:
    - size constant term ?
    - evolution with energy – leakage

Backup: HCAL Depth Results

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



HCAL Layers	λ_I	
	HCAL	+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

★ Little motivation for going beyond a 48 layer (6 λ_I) HCAL
★ Depends on Hadron Shower simulation
★ "Tail-catcher": corrects ~50% effect of leakage, limited by thick solenoid

For 1 TeV machine "reasonable range" ~ 40 – 48 layers (5 λ_I - 6 λ_I)