# Particle Flow Calorimetry for a High Energy Lepton Collider

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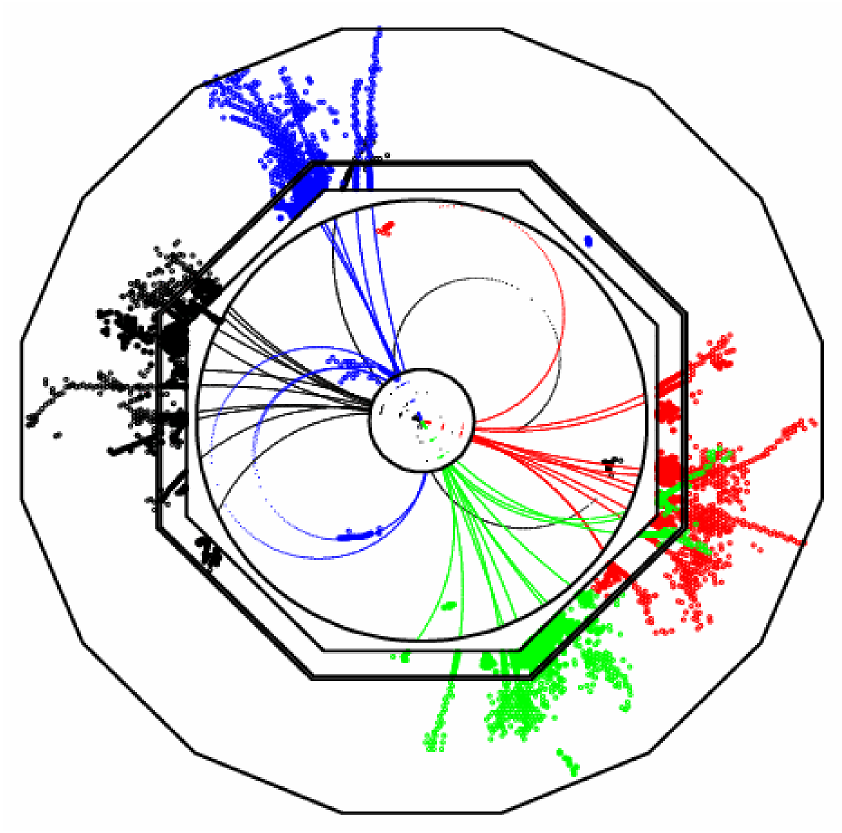
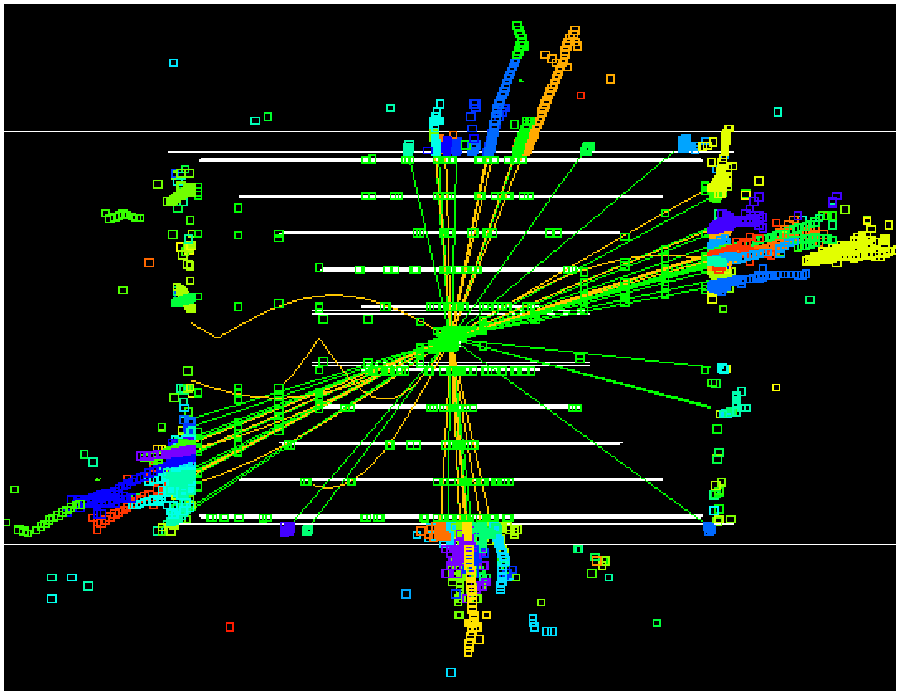




# This Talk

★ **Four Main Topics:**

- Particle Flow jet energy reconstruction: 45 GeV – 1.5 TeV
- Understanding Particle Flow at High Energy
- Di-Jet Mass reconstruction
- Particle Flow and timing at CLIC

★ **Preliminaries:**

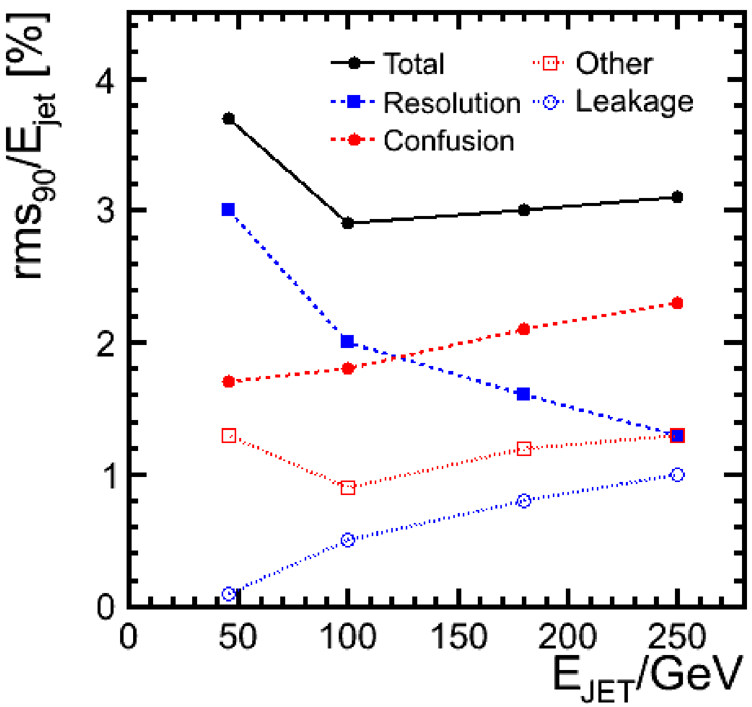
- All studies use latest version of PandoraPFA
  - i.e. the complete rewrite (see John Marshall's talk)
- ILD results refer to ILD00 model (LoI version)
- For high energy studies use CLIC_ILD model
  - 8 interaction length W HCAL
  - 4 Tesla field
  - otherwise very similar to ILD

# PandoraPFA

★ **A few words about PandoraPFA**
- **Basic reconstruction strategy:**
  - **clustering**
  - **topological association**
  - **reclustering**
  - **tidying up (fragment removal)**

★ **For low energy jets (<100 GeV)**
- **Particle flow reconstruction works well (NIMA 611, 25-40, 2009)**
  - **jet energy resolution dominated by HCAL energy resolution**

★ **For high energy jets (100-250 GeV)**
- **Reconstruction becomes increasingly difficult**
  - **clustering imperfect (confusion)**
  - **recovered (in part) by reclustering stage**



# Iterative Reclustering

★ At some point, in high density jets (high energies) reach the limit of "pure" particle flow
  - i.e. can't cleanly resolve neutral hadron in a hadronic shower

★ If track momentum and cluster energy inconsistent : RECLUSTER

**e.g.**


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

**NOTE:**
- clustering "guided" by track momentum
- much more powerful than subtraction (Energy Flow)

**New Implementation:**
- greatly rationalized - fewer, but better defined, steps
- improved treatment when reclustering "fails": the way a a cluster is constructed with just the right energy

# 1) Performance

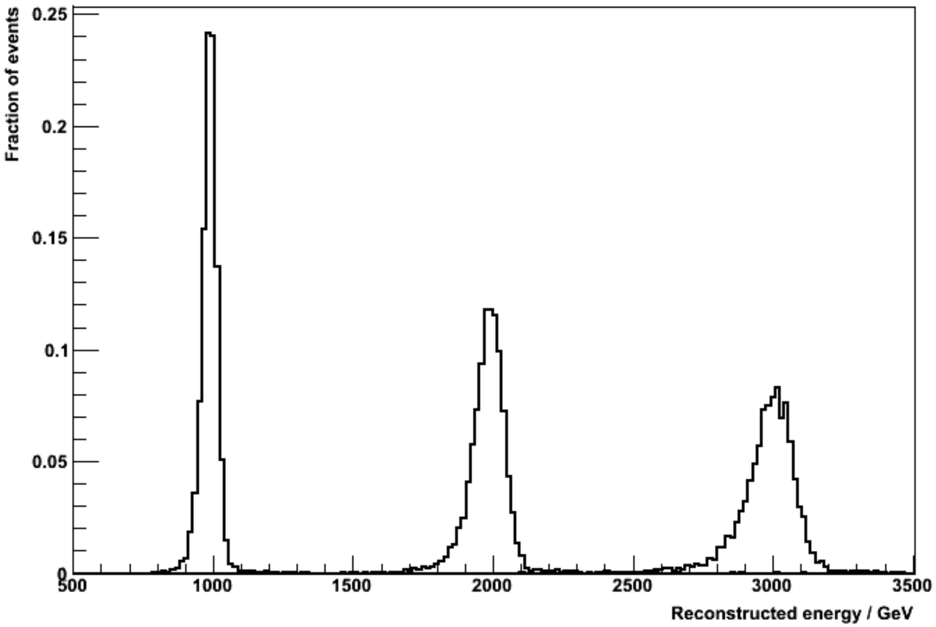
★ **Now tested for jets in range 45 GeV – 1.5 TeV**

**ILD**

| $E_{JET}$ | $RMS_{90}/E_J$ |
|---|---|
| 45 GeV | 3.6 % |
| 100 GeV | 3.1 % |
| 180 GeV | 3.0 % |
| 250 GeV | 3.3 % |

**CLIC_ILD**

| $E_{JET}$ | $RMS_{90}/E_J$ |
|---|---|
| 45 GeV | 3.6 % |
| 100 GeV | 2.9 % |
| 250 GeV | 2.8 % |
| 500 GeV | 3.0 % |
| 1 TeV | 3.2 % |
| 1.5 TeV | 3.2 % |




**Jet Energy Resolution better than 3.6 % over whole range**

# 2) Confusion Matrix

★ Interesting to look at confusion matrix
- fractions of jet energy reconstructed in different classes of PFO

| e.g. 45 GeV | $h^+$ | $\gamma$ | $h^0$ |
|---|---|---|---|
| Reco as $h^+$ | 57 .7% | 0.6 % | 0.7 % |
| Reco as $\gamma$ | 0.6 % | 25.5 % | 1.5 % |
| Reco as $h^0$ | 2.1 % | 1.6 % | 10.7 % |

★ Interpretation
- diagonal is well reconstructed
- "pink" cells represent charged/neutral confusion

Here total confusion = $\boxed{4\ \%}$

★ Can also look at what fraction of the PFO energy is "perfectly reconstructed"
- defined by total energy in PFOs with >90% from correct class

"Pure Fraction" = $\boxed{93\ \%}$

# Confusion Matrix

| 250 GeV | $h^+$ | $\gamma$ | $h^0$ |
|---|---|---|---|
| Reco as $h^+$ | 55 .3% | 2.2 % | 3.0 % |
| Reco as $\gamma$ | 1.0 % | 22.5 % | 2.1 % |
| Reco as $h^0$ | 3.3 % | 1.7 % | 8.8 % |

"Pure Fraction" =

76 %

Confusion still modest !

| 500 GeV | $h^+$ | $\gamma$ | $h^0$ |
|---|---|---|---|
| Reco as $h^+$ | 50 .6% | 4.6 % | 4.5 % |
| Reco as $\gamma$ | 1.3 % | 19.6 % | 2.5 % |
| Reco as $h^0$ | 6.9 % | 2.1 % | 7.8 % |

60 %

| 1 TeV | $h^+$ | $\gamma$ | $h^0$ |
|---|---|---|---|
| Reco as $h^+$ | 40.8 % | 7.6 % | 6.9 % |
| Reco as $\gamma$ | 1.9 % | 15.6 % | 2.4 % |
| Reco as $h^0$ | 11.7 % | 2.6 % | 10.3 % |

40 %

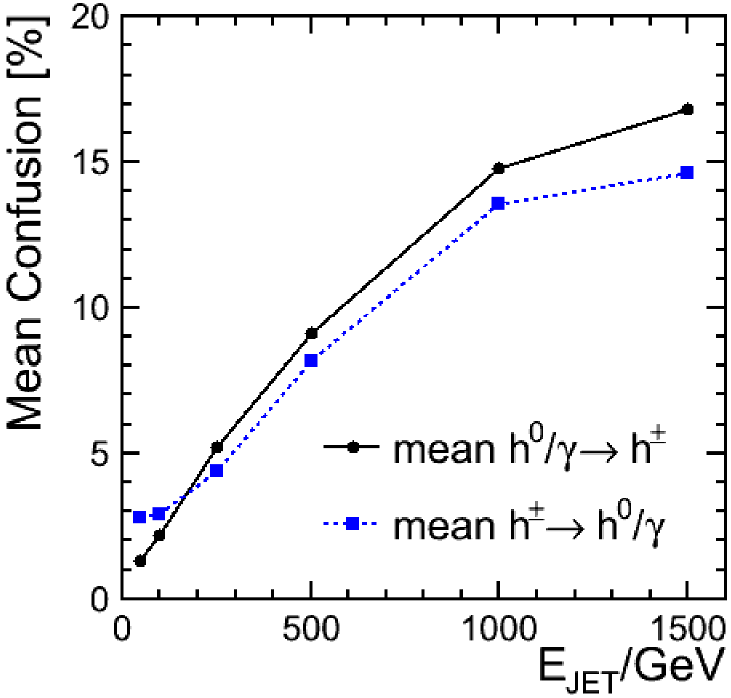
Confusion significant, but 40 % of PFOs still "perfect"

Surprisingly high fraction of lost photons

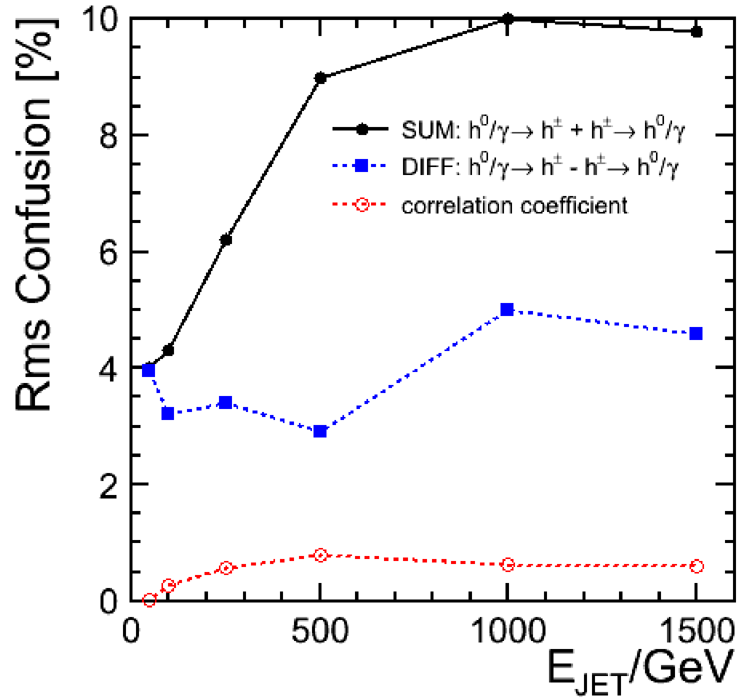
"neutral hadron" fraction Increased – tracking ?

# Confusion vs Energy

**mean**




**rms**

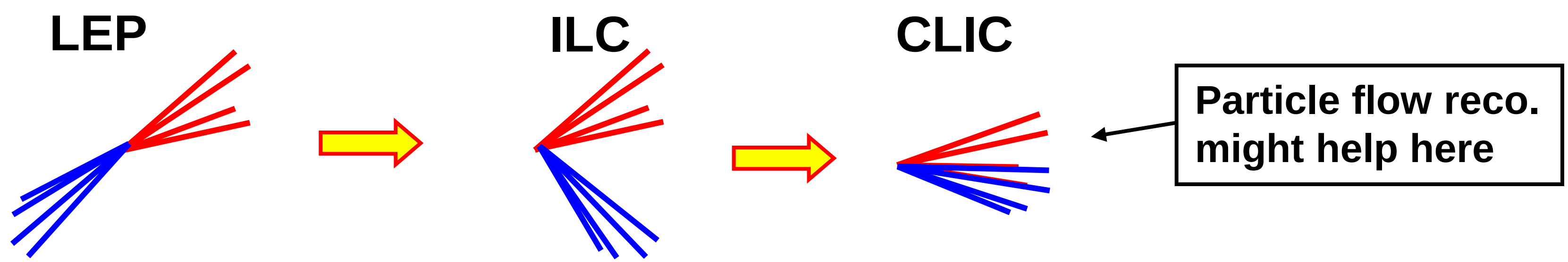



★ **<u>Main points:</u>**

- **confusion rises fairly rapidly with energy – at 1 TeV almost 30 %**
- **two types of confusion highly correlated, i.e. "charged fragments" balanced by "lost" photons/neutral hadrons**
- **Strong correlation due to reclustering – transition from Pflow to Eflow**
- **For very high energy jets: energy flow regime**

# 3) W/Z Separation

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



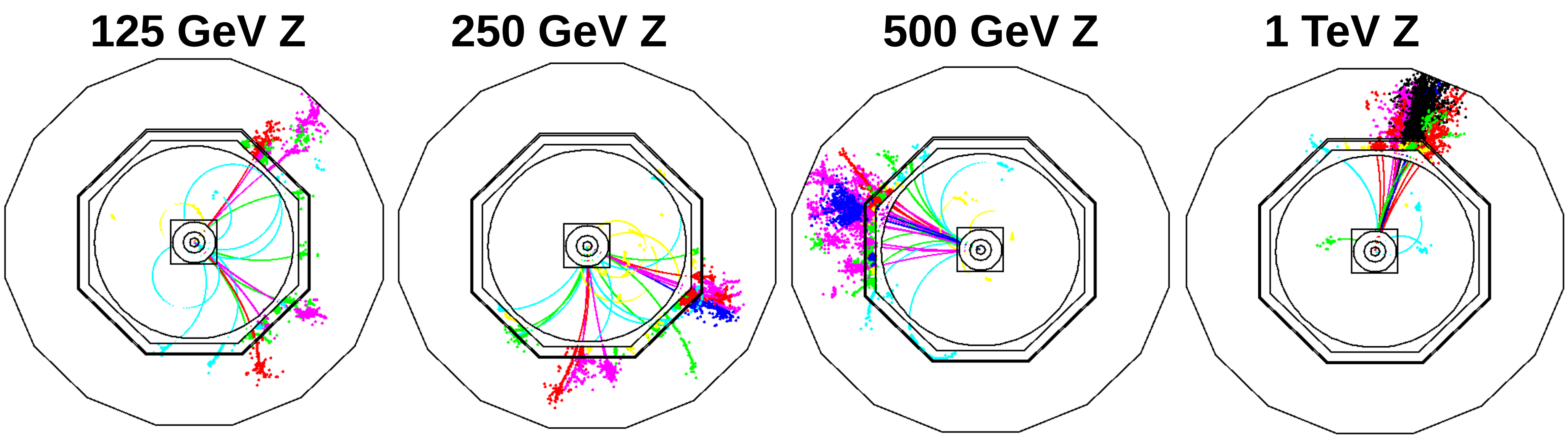

★A few comments:

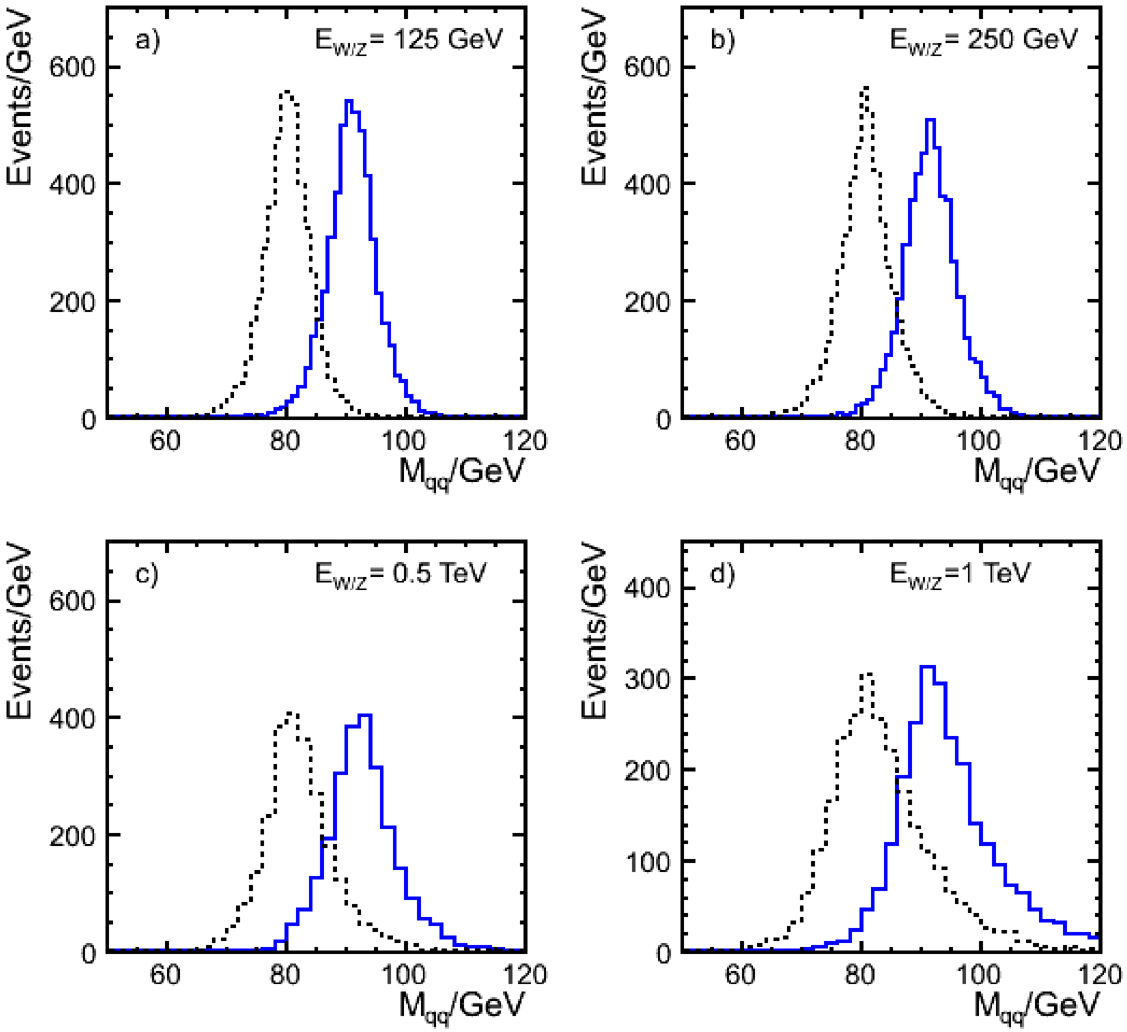
- Particle multiplicity does not change
- Boost means higher particle density

More confusion

- PFA could be well suited for "mono-jet" mass resolution

★PandoraPFA + CLIC_ILD performance studied for:






**Previous results**

**(NIMA 611, 25-40, 2009)**

**Obtained from sum of 4-momenta of all PFOs in event**

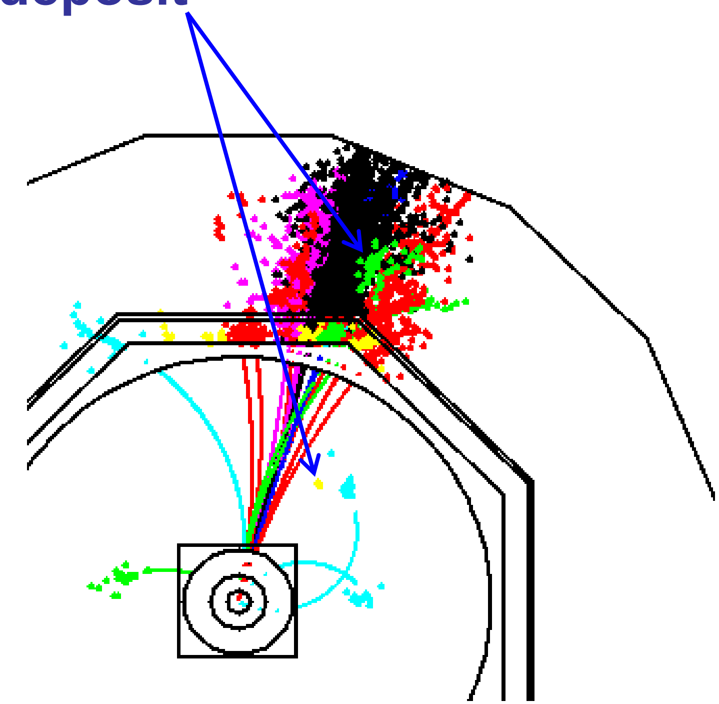
# Mass Resolution

- ★ Impact of fragments, i.e. fake neutral hadrons, on mass reconstruction different is not the same as that for energy reconstruction

- ★ Can show that impact of a false energy deposit of energy $\Delta$ is:

$$\frac{\sigma_E}{E} \propto \frac{\Delta}{E} \qquad \frac{\sigma_m}{m} \propto \frac{\Delta}{m}$$

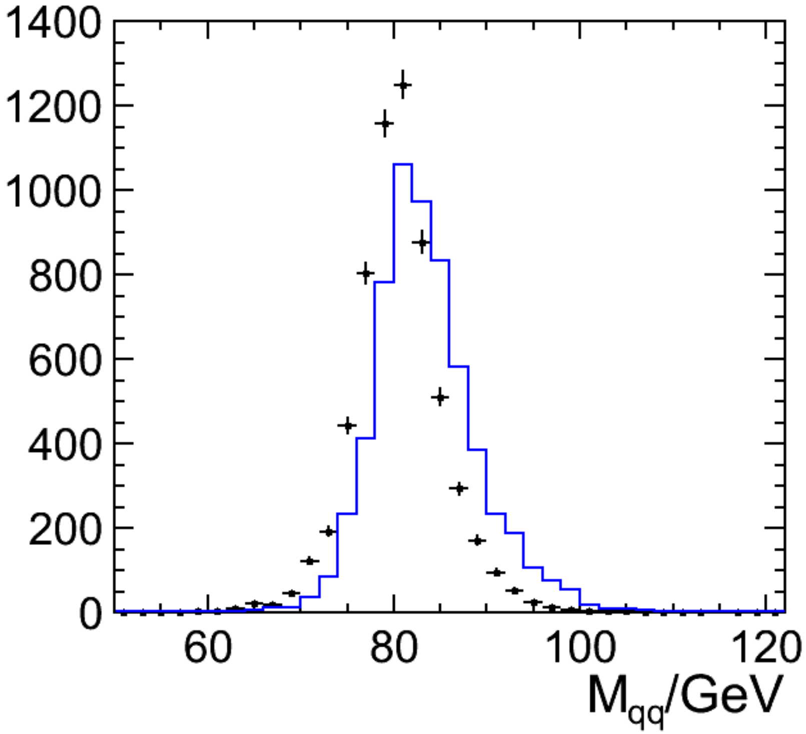
$$\boxed{\frac{\sigma_m}{m} \propto \frac{E}{m}\frac{\sigma_E}{E}}$$



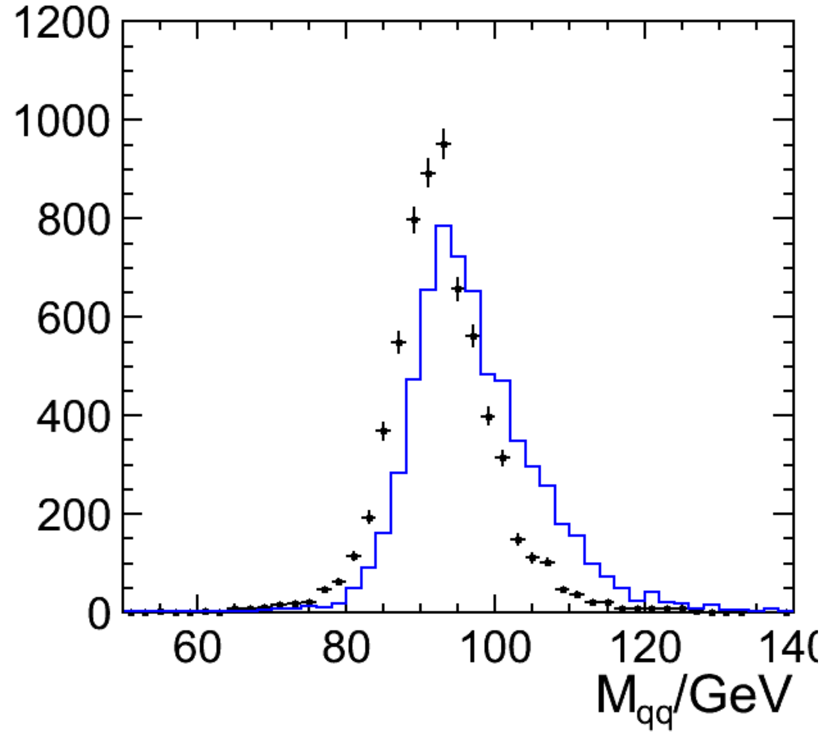

- ★ For high energy jets, neutral fragments have disproportionate effect on mass

- ★ Investigate effect of cuts on minimum neutral hadron PFO energy

**0.5 TeV W**



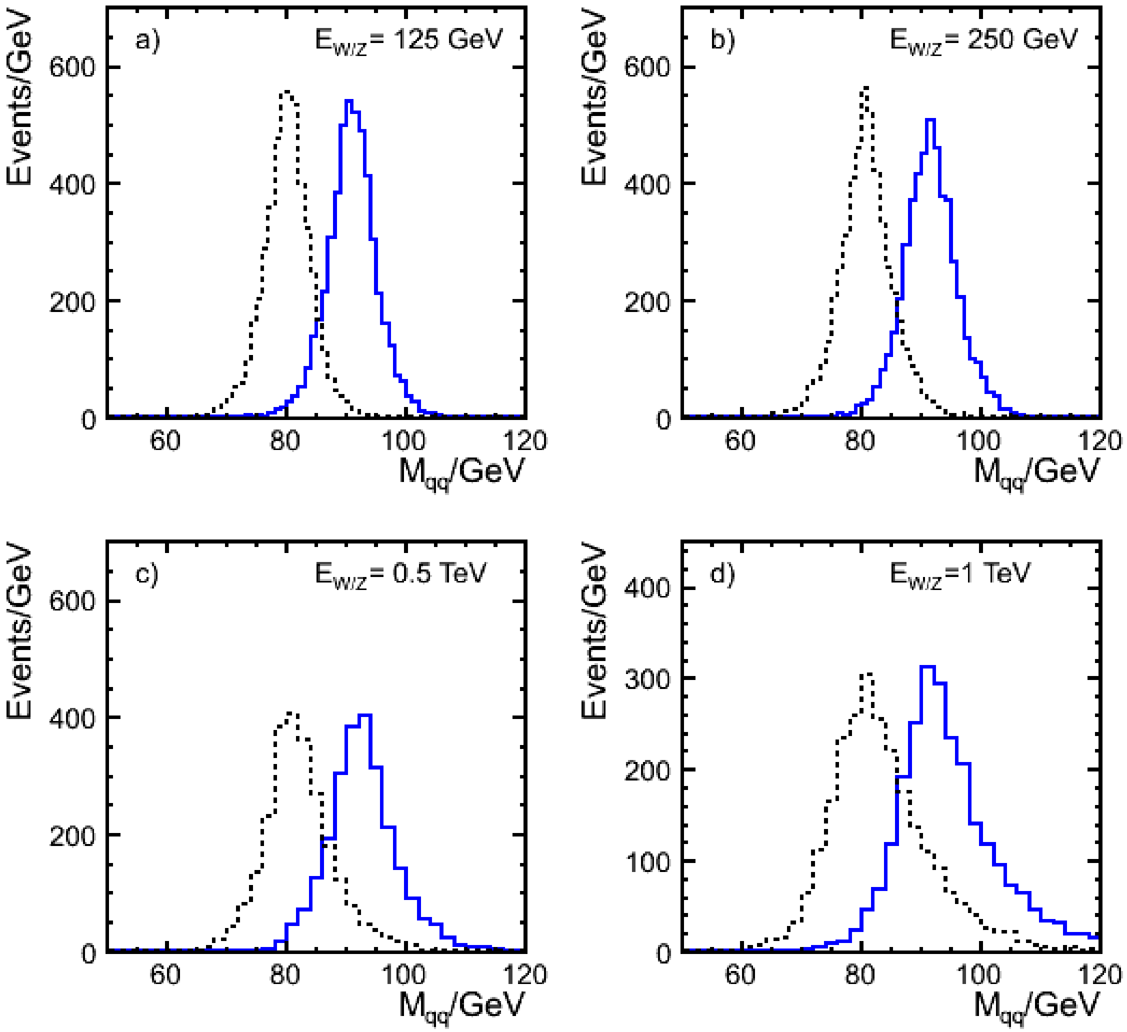

**1 TeV W**




| | 0.5 TeV W | 1 TeV W |
| --- | --- | --- |
| ——— | **All PFOs** | **All PFOs** |
| + | $E_{h^0} > 2.5$ **GeV** | $E_{h^0} > 5.0$ **GeV** |

★ **Optimal cut represents a compromise between jet energy resolution and suppression of fake "mass generating" effects**

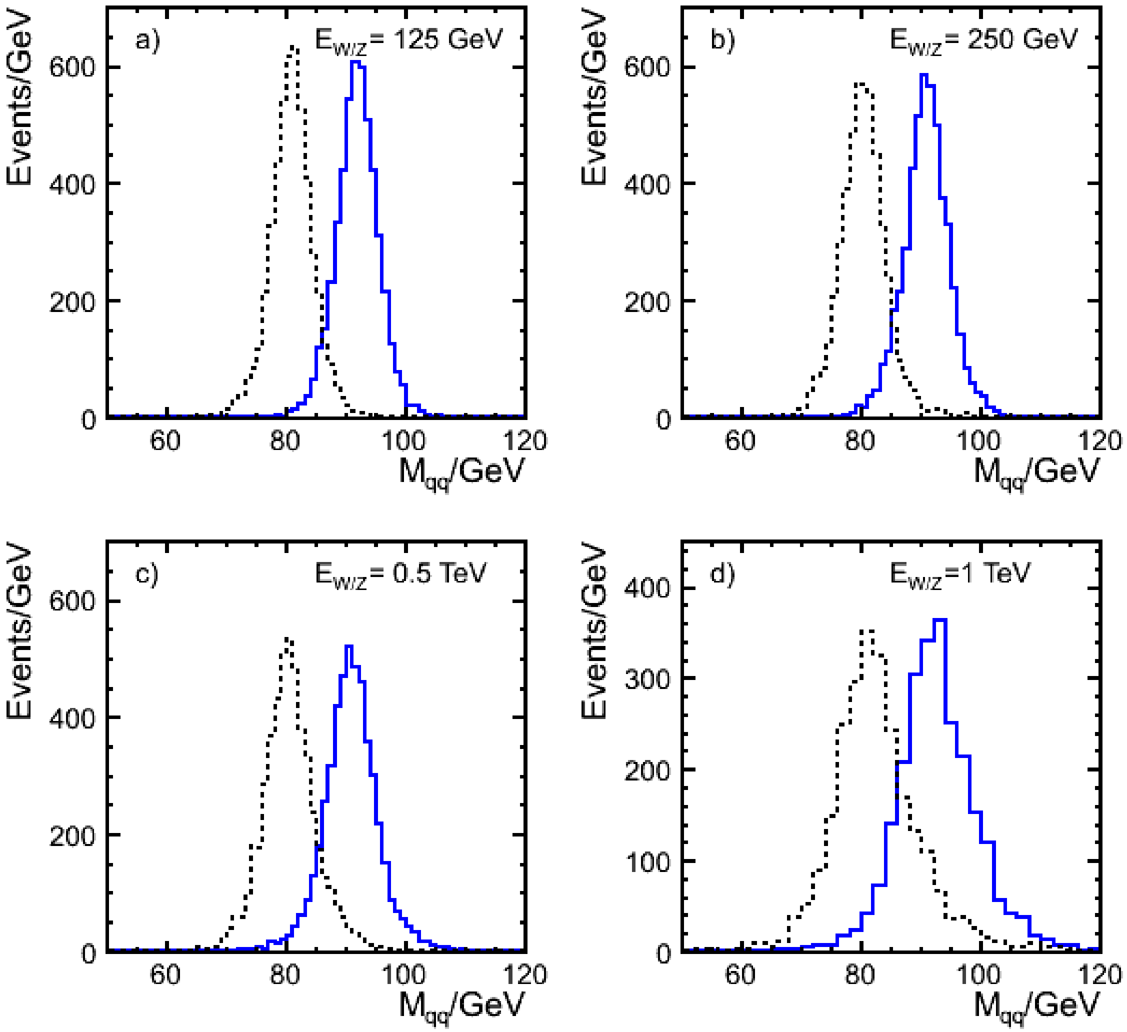
# Old Mass Resolution




**CLIC 09 version**

- **Old Pandora**
- **No neutral cuts**

# New Mass Resolution




**IWLC 10 version**

- New Pandora
- optimal neutral cuts

**Now have clean W/Z separation for 500 GeV W/Zs !**

# W/Z Di-jet Mass Separation

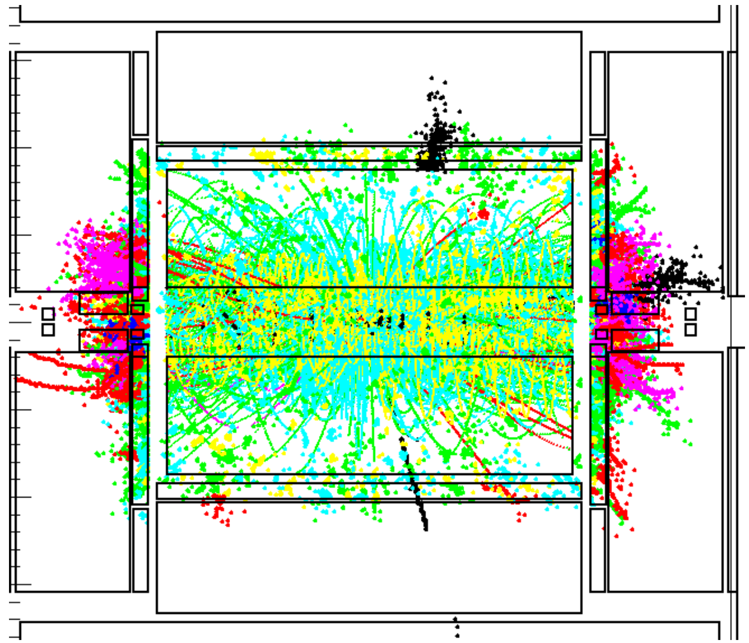
| W/Z Energy GeV | $h^0$ cut GeV | $\sigma_m/m$ w.r.t. $m_{W/Z}$ | $\sigma_m/m$ w.r.t. $m_{gen}$ | W/Z Sep. Efficiency |
|---|---|---|---|---|
| 125 | 0 | 2.8 % | 2.4 % | 92 % |
| 250 | 1.0 | 2.9 % | 2.6 % | 91 % |
| 500 | 2.5 | 3.4 % | 3.2 % | 88 % |
| 1000 | 5.0 | 5.2 % | 5.1 % | 80 % |

- **Note due to Breit-Wigner tails best possible separation is 96 %**
- **Separation of W and Z bosons up to 500 GeV very good**
- **Still need to work on 1 TeV (di)-jet mass resolution, not bad but…**

# 4) PFA and Timing Cuts

★ At CLIC there is significant gamma-gamma to hadrons background

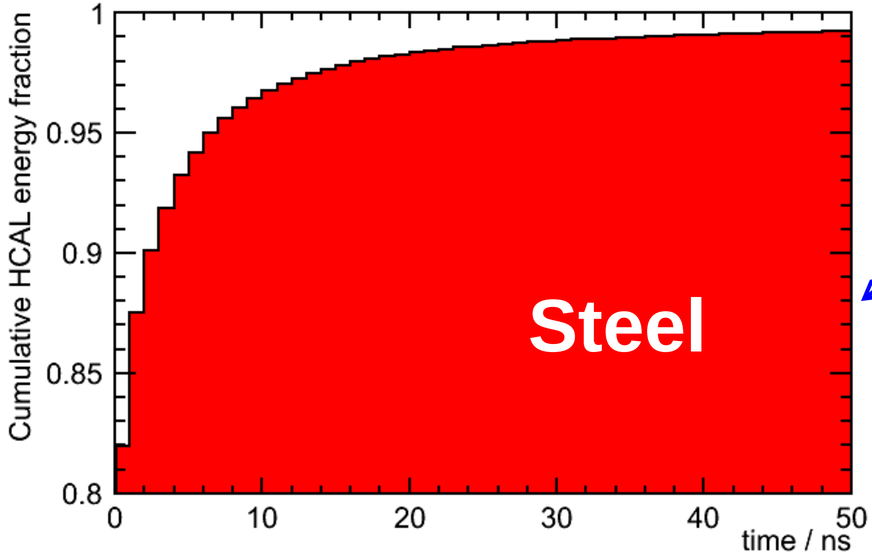
150 BXs



★ Implies tight bunch-tagging capability of a CLIC detector
★ However showers in the calorimeters are not instantaneous
  - propagation times
  - slow neutrons
  - nuclear de-excitations

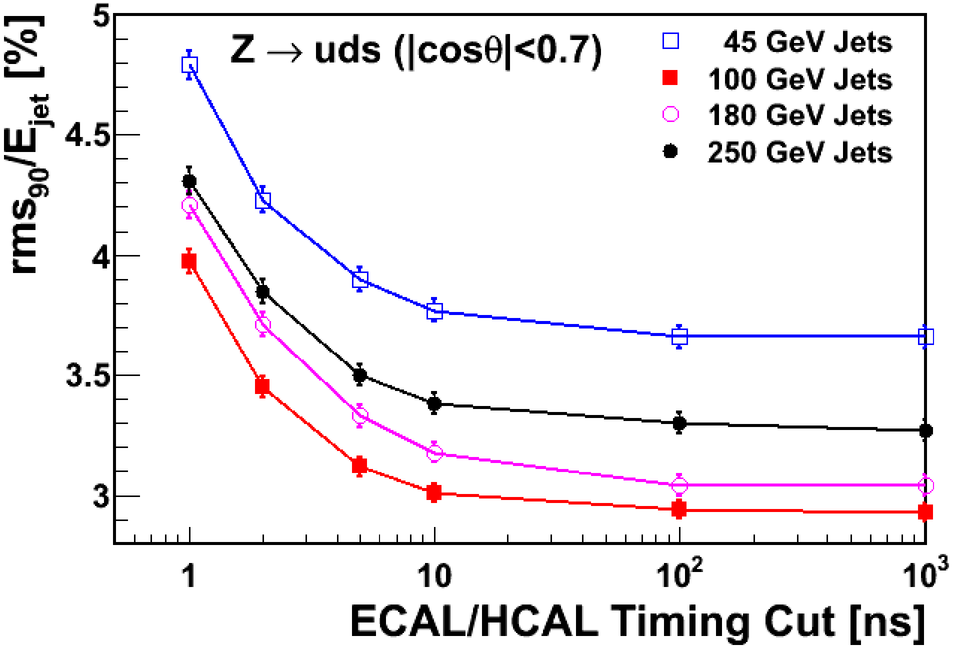
★ HCAL timing studied in context of CLIC_ILD using **QGSP_BERT**

# Steel HCAL




Corrected for line of sight ToF

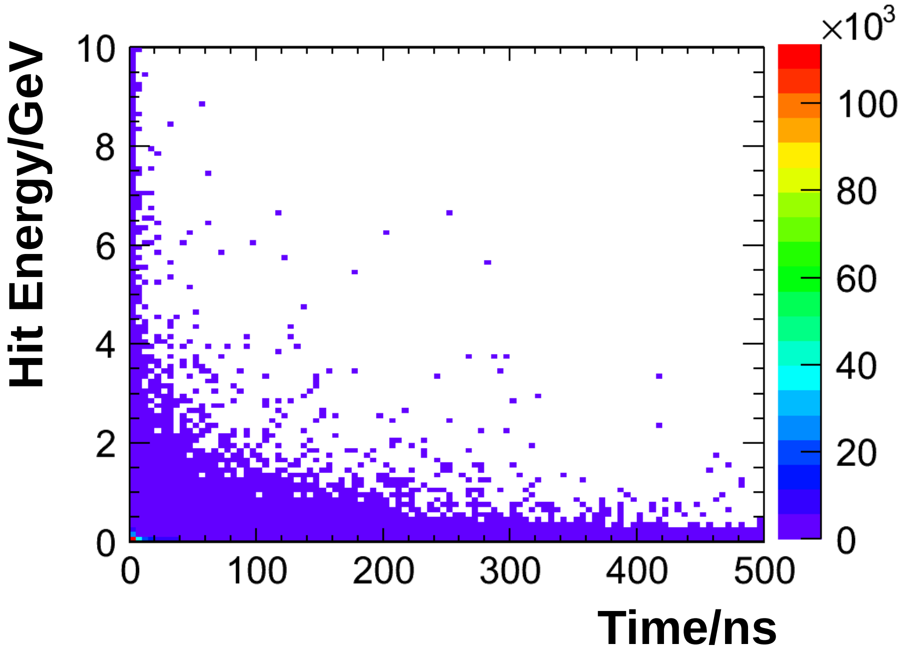
- 95 % of energy in 10 ns
- 99 % in 50 ns

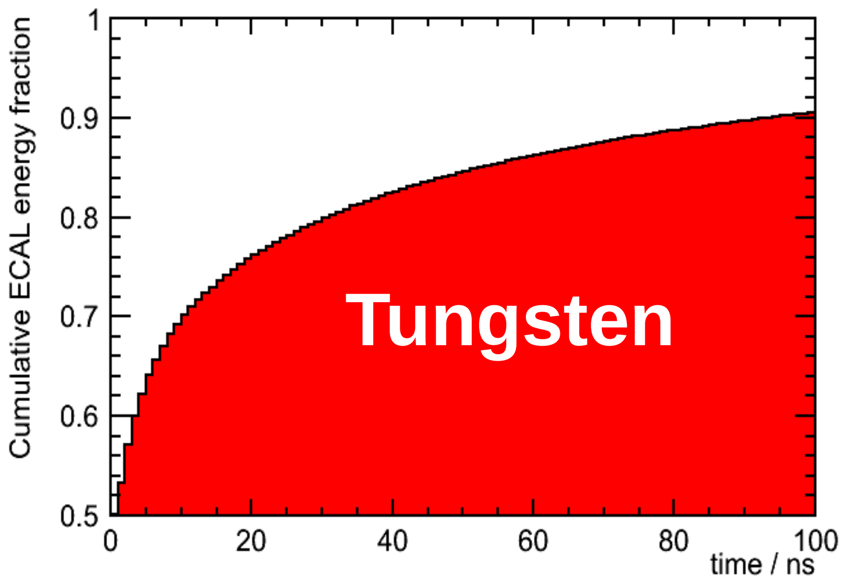



- Impact of timing cuts on PFA
- Suggests optimal timing window in range 5-10 ns

# Tungsten: Time vs Energy

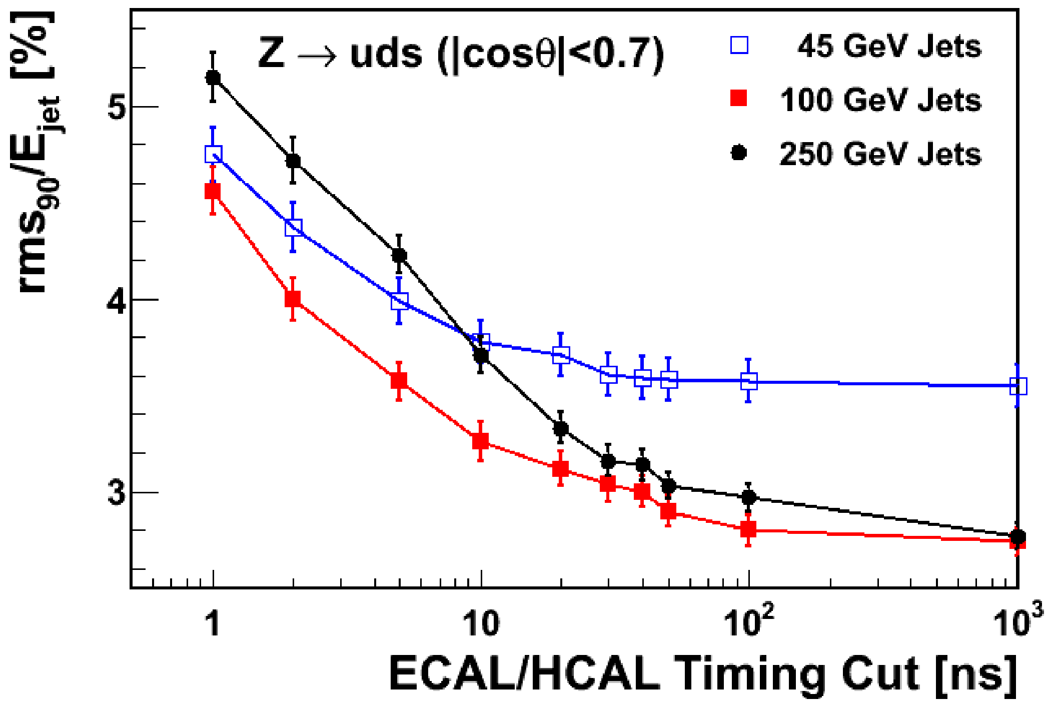
★ Tungsten much "slower", but not the only difference
- distribution of single energy depositions much harder
  - significant number of single hits have energy depositions > few GeV
  - presumably from nuclear fragments



# W HCAL

★ Look at PFA performance for CLIC_ILD with W HCAL (Barrel and Endcap)




★ For no time cut (1000 ns) have standard performance

★ For high(ish) energy jets – fairly strong dependence on time cut

- suggests time window of > 10 ns
- need something like 50 ns to get into "flat region"
- for CLIC need a PFA reconstruction strategy using timing information

# Summary/Conclusions

- ★ PandoraPFA jet energy resolution with ILD-based detector models below 3.6 % entire jet energy range of ILC and CLIC !
- ★ Studies of confusion revealing
  - at high energies smooth transition from PFA to EFlow
- ★ Starting to optimize W/Z Jet mass reconstruction
  - good W/Z separation for E upto 500 GeV
  - 1 TeV W/Z separation much improved – still needs work
- ★ CLIC timing requirements to reduce $\gamma\gamma\rightarrow$hadrons will impact PFA
  - tungsten "slower" than steel (will only be used in barrel)
  - need to develop a PFA reconstruction strategy including timing information

★CLIC studies beginning to push forward PFA development
★Improvements will benefit both CLIC and ILC detector studies

# Fin