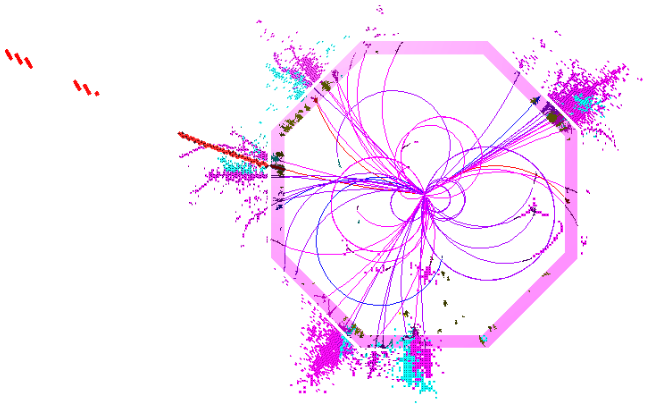


Particle flow performance at CLIC

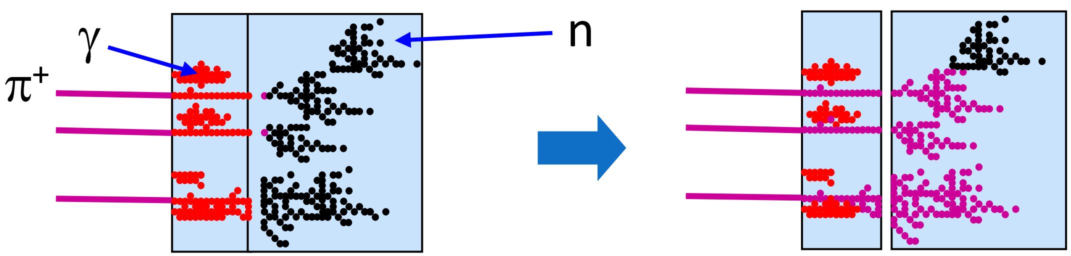
J.S. Marshall
A. Muennich, M.A. Thomson

CLIC CDR Review, Manchester, October 19 2011

Overview

- The particle flow paradigm.
- Introduction to Pandora particle flow algorithms.
- Technical performance study:
  - Jet energy resolution as a function of jet energy and angle,
  - Influence of timing cuts on jet energy resolution.
- Physics performance study:
  - *W* energy and mass reconstruction,
  - *W* and *Z* separation,
  - Separation of gaugino pair production final states.

Particle Flow Calorimetry

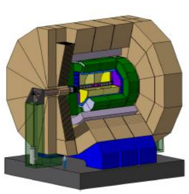


$E_{JET} = E_{ECAL} + E_{HCAL}$ → $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

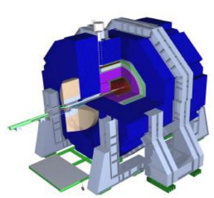
- Measure charged particle energies (60% of jet) in tracker.
- Measure photon energies (30%) in ECAL, $\sigma E/E < 20\%/\sqrt{E(GeV)}$
- Measure only neutral hadron energies (10%) in HCAL.

Reconstruction implemented in Pandora, allowing reuse of same particle flow algorithms for ILD/SiD:

Pandora Client Apps



CLIC_ILD/Marlin



CLIC_SiD/org.lcsim

Pandora APIs

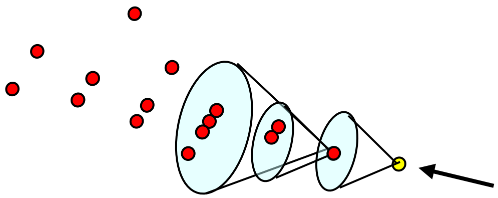
Pandora Framework

Pandora APIs

Pandora Algorithms

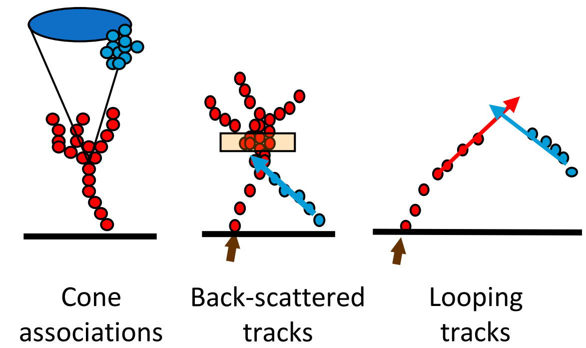
- Clustering Algs
- Particle Id Algs
- **Library of 60+ reusable Algs...**

PandoraPFA

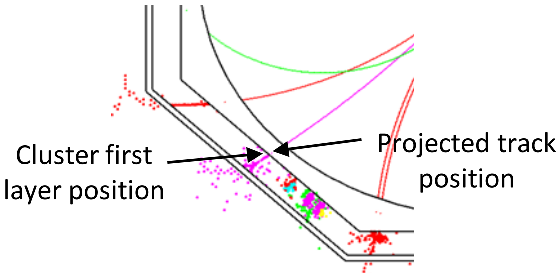


ConeClustering Algorithm

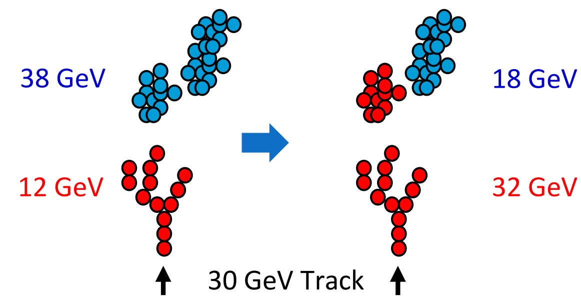
Topological Association Algorithms



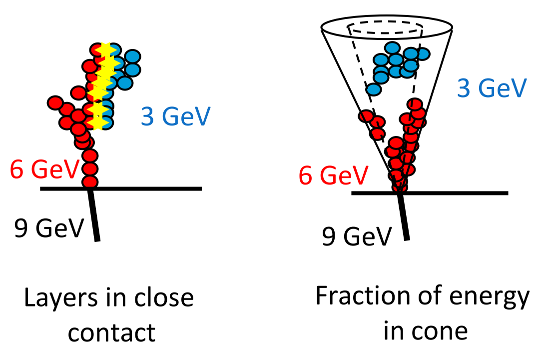
Track-Cluster Association Algorithms



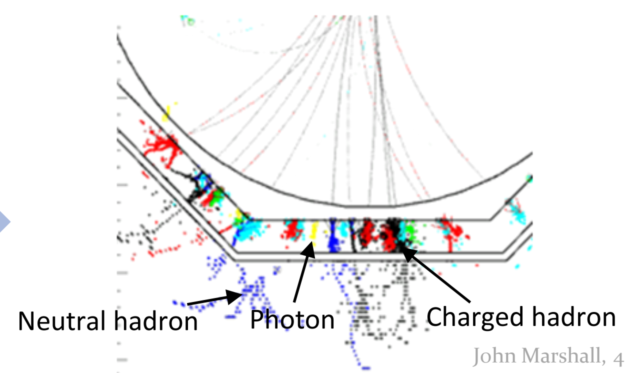
Reclustering Algorithms



Fragment Removal Algorithms



PFO Construction Algorithms



Technical Study

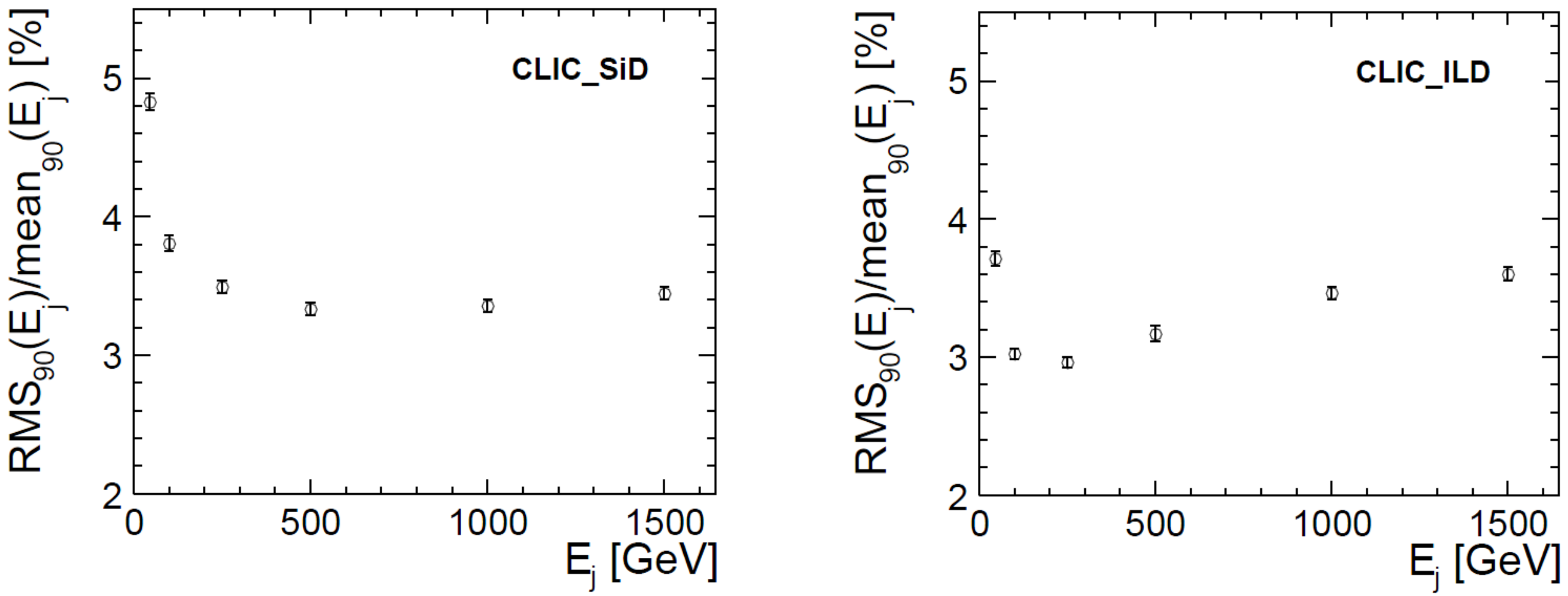
- Particle flow performance has been assessed using fully simulated and reconstructed events with *Z*s at different energies (91GeV to 3TeV) decaying at rest into light quarks.
- Backgrounds are not included and no jet reconstruction is carried out. The full energy deposited in the detector, E_{jj}, is analysed to avoid any bias from jet reconstruction.
- Performance is evaluated by examining resolution of the jet energy, E_j:

$$\frac{\text{RMS}_{90}(E_j)}{\text{mean}_{90}(E_j)} = \frac{\text{RMS}_{90}(E_{jj})}{\text{mean}_{90}(E_{jj})}\sqrt{2}$$

- $\text{RMS}_{90}(E_{jj})$ and $\text{mean}_{90}(E_{jj})$ are calculated from the reconstructed total energy distribution.

Resolution vs. Jet Energy

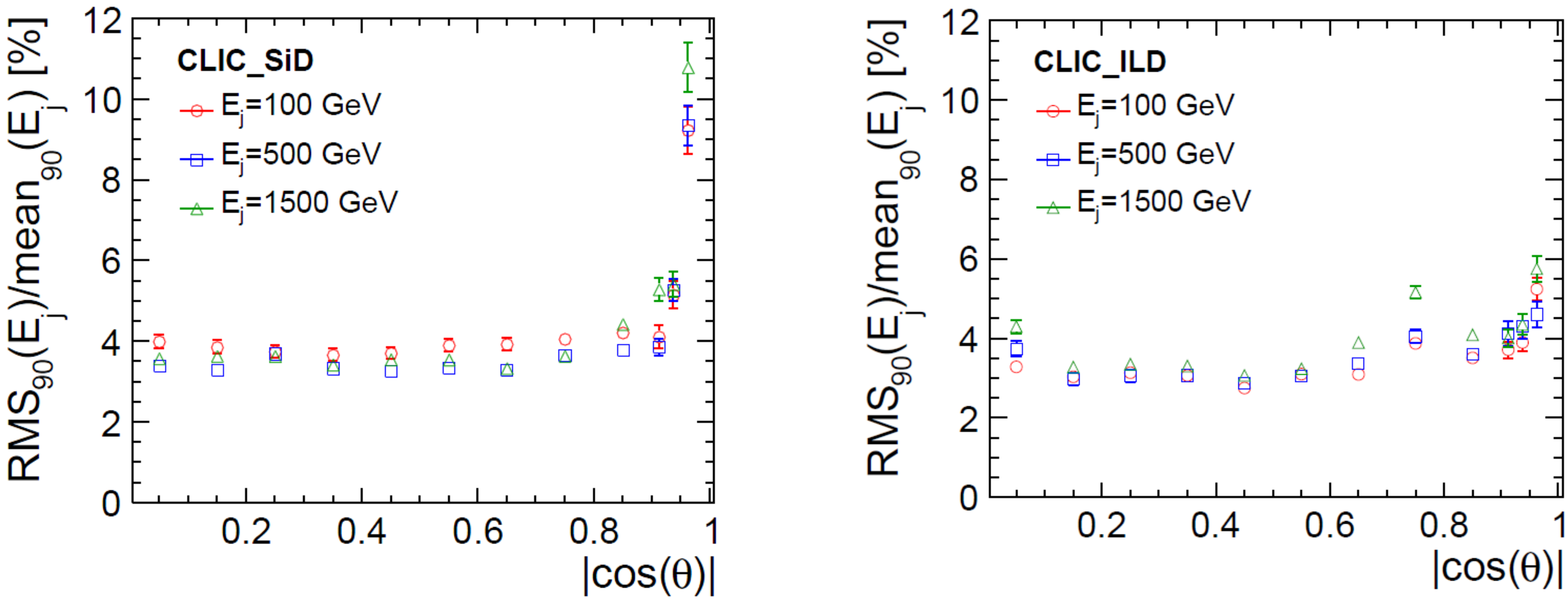
- Barrel region |cos θ| < 0.7, no background, no jet reconstruction:



- At lower energies, CLIC_ILD benefits from its larger radius.
- At higher energies, particle separation becomes more difficult; confusion term dominates energy resolution; particle flow can become energy flow. Both detectors show similar performance.

Resolution vs. Angle

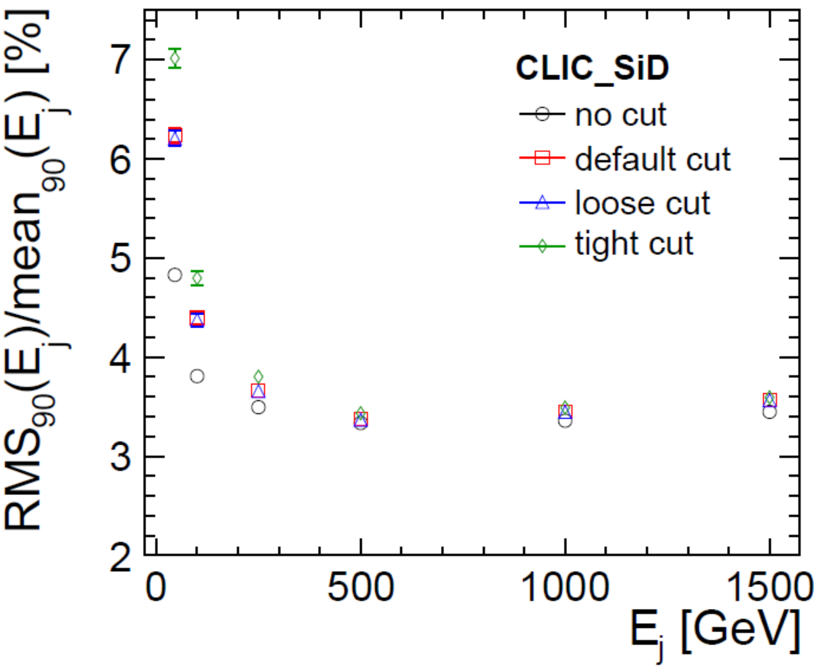
- No background, no jet reconstruction:

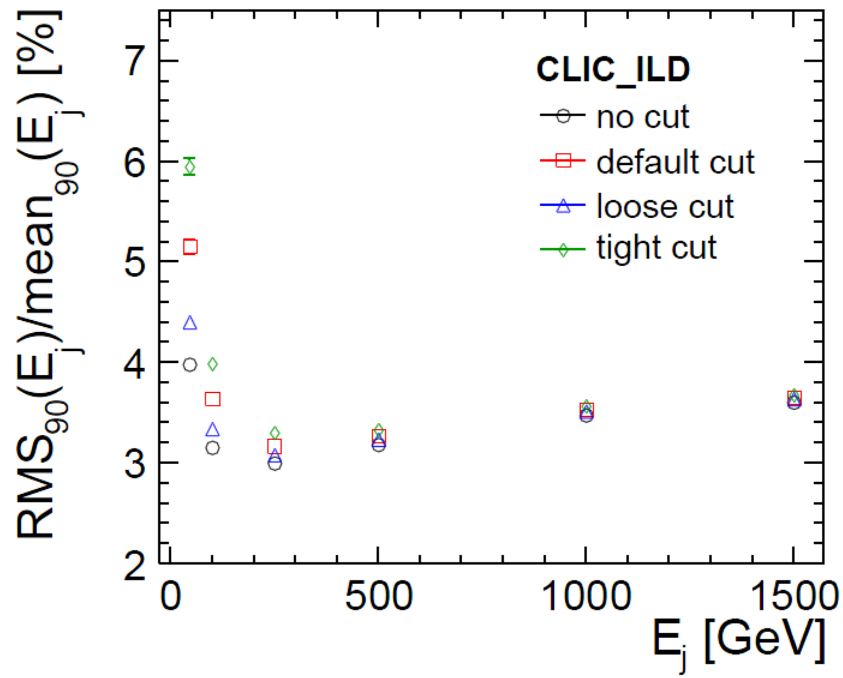


- Resolution for CLIC_SiD is worse in the forward region, due to reduced angular coverage. There is no HCAL coverage below $\theta = 15.5°$.
- Resolution for CLIC_ILD dips in barrel/endcap overlap region, due to gap between ECAL barrel and endcap. Leakage effects due to this gap are more pronounced at higher energies.

Timing Cuts

- No background, no jet reconstruction:





- Impact of **`CLICPfoSelector`** timing cuts on the physics event is studied by applying the cuts without overlaying any background.
- Whilst timing cuts result in degradation of jet energy resolution for low energy jets, the impact is small for jets above 500GeV.

PFA Physics Performance

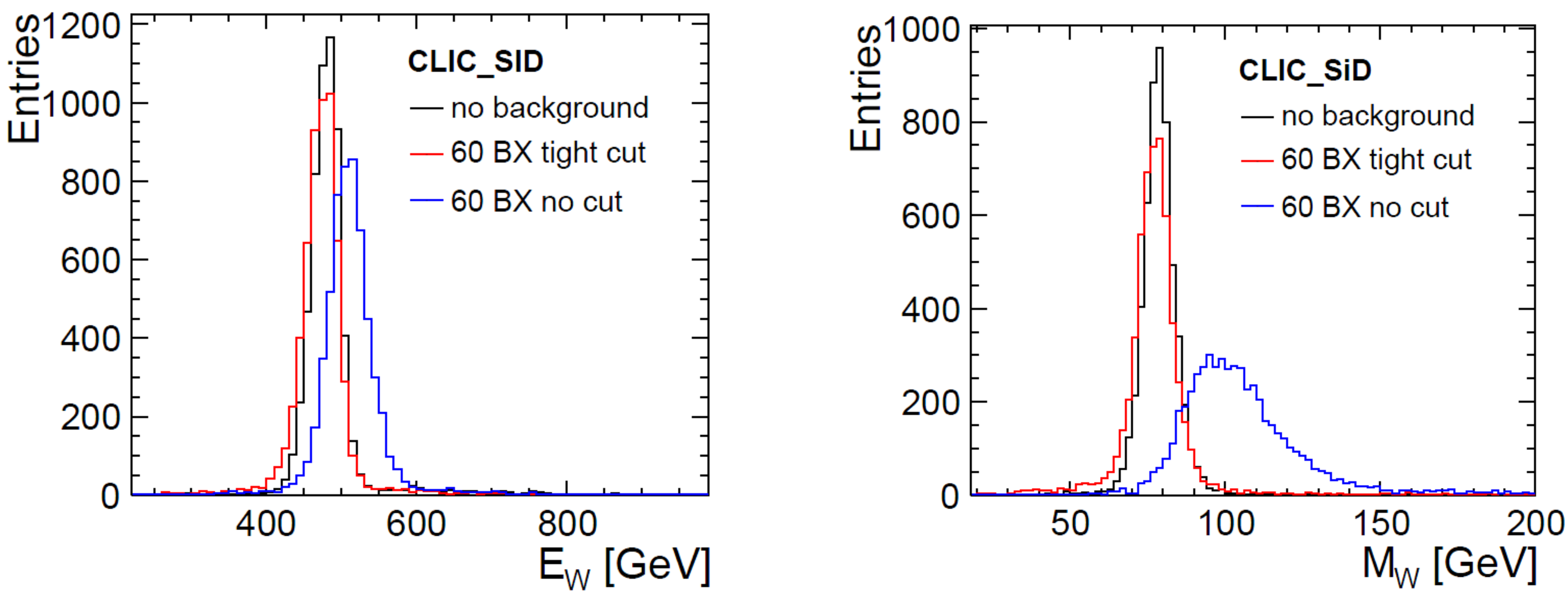
- Study of PFA physics performance carried out by **A. Muennich**. Event sample contains two *W*s, one decaying into muon and neutrino, the other decaying into quarks:
  - $e^+e^- \rightarrow WW \rightarrow \mu\nu qq$
  - *W* energies: 125, 250, 500 and 1000GeV
  - Each energy available without background and with 60BX $\gamma\gamma\rightarrow$hadrons background.

- Reconstruction was performed in two steps:
  1. **Lepton removal.** Muon and every particle around it within tight cone removed, leaving only hadronic decaying *W* in the event.
  2. **Jet reconstruction.** Without background, ee_kt algorithm used. In presence of background, kt algorithm performed best. Algorithms used in exclusive mode, forcing event into two jets.

- The analysis used PFOs passing tight timing cuts (found minimal performance difference between timing cuts). Results are shown for jets in the region $|\cos\theta| < 0.9$

W Reconstruction

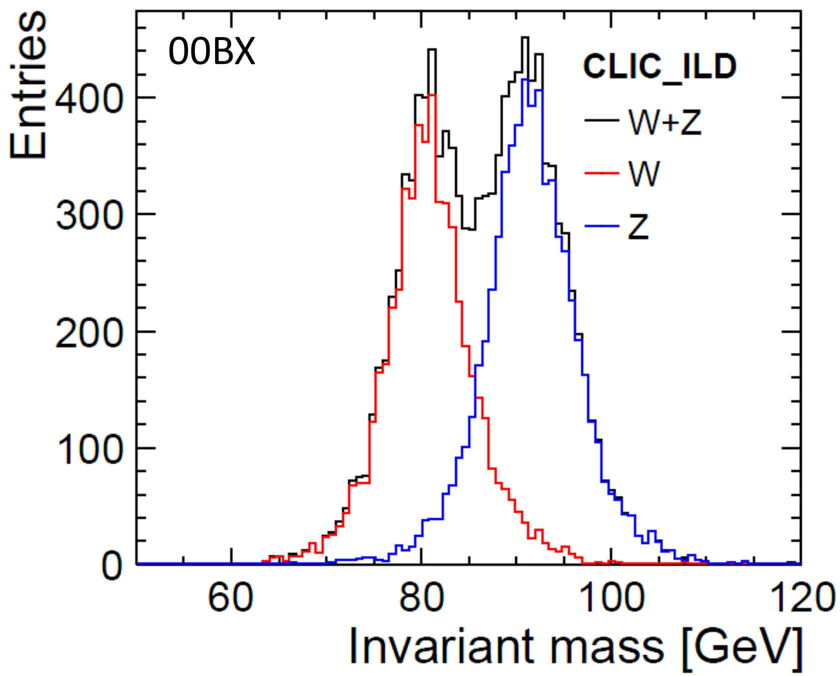
- Energy and mass distributions for the reconstructed *W*, with energy of 500GeV:

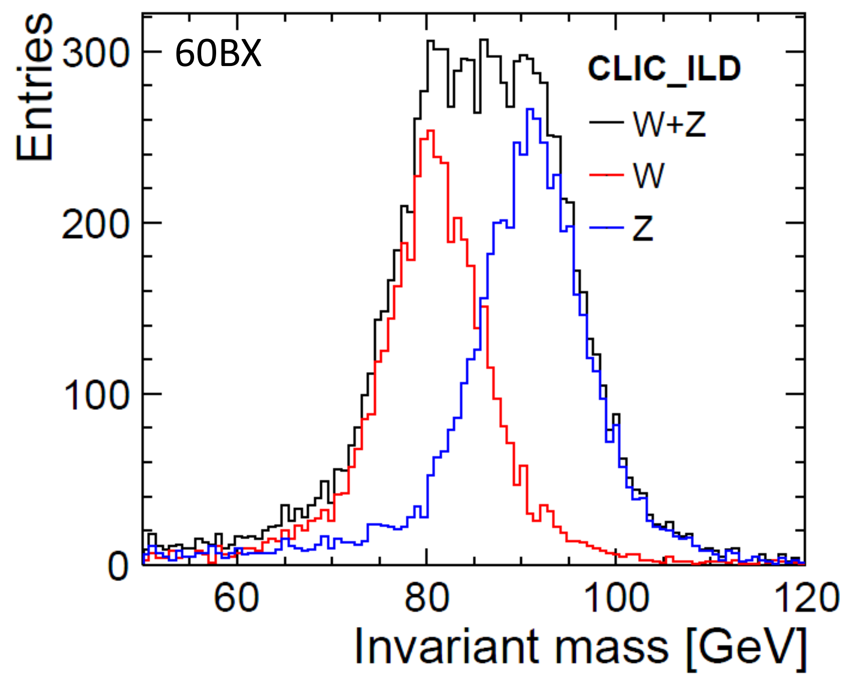


- Without background, the energy resolution is comparable to that obtained in the technical study, without jet reconstruction.
- With background, and without timing cuts, many background particles remain in the event and are reconstructed as part of the jet, shifting the energy and mass distributions to higher values.

W/Z Separation

- One of the goals of PFA and fine granularity calorimetry is separation of *W* and *Z* particles.
- To study this separation, used *W* samples already described and samples of $e^+e^- \rightarrow ZZ \rightarrow \nu\nu qq$
- Mass distributions of the reconstructed *W* and *Z* for CLIC_ILD at $E_{W/Z}$ = 500GeV:

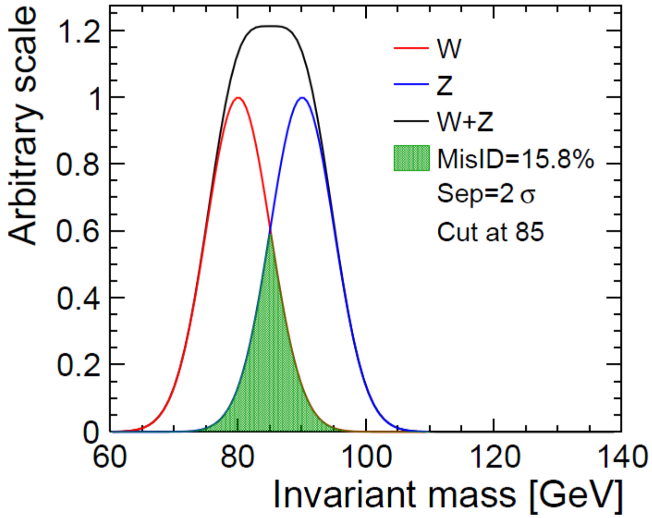


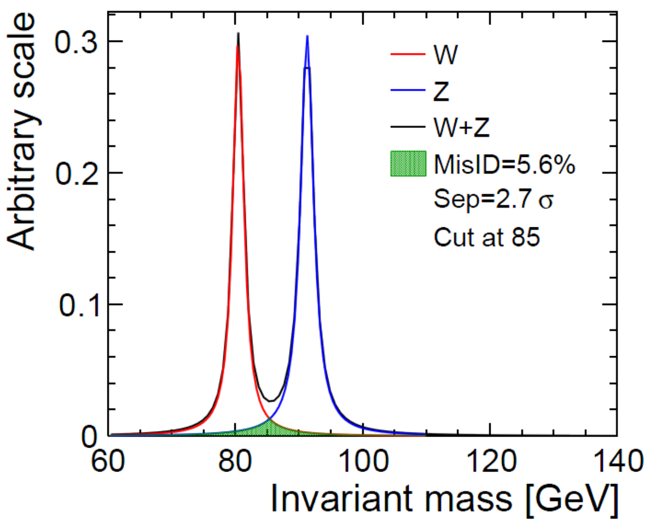


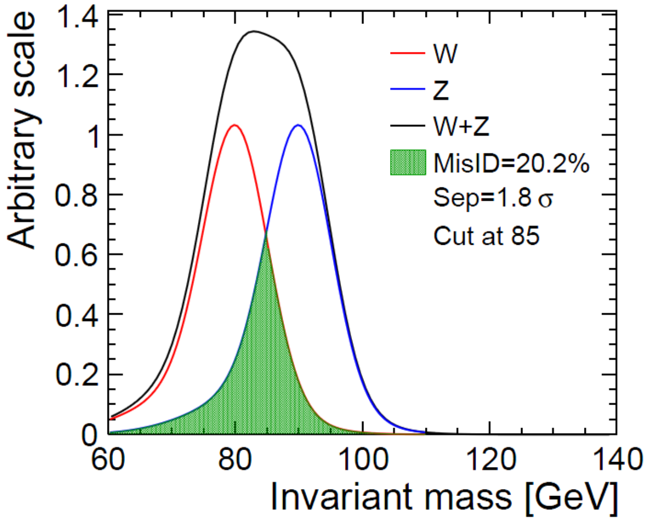
- Without background, the two peaks remain clearly separated. With 60BX, see significant overlap.

W/*Z* Separation

- Separation calculated by applying optimal cut, minimising number of misidentified events.
- For ideal Gaussian distributions, misidentification of 15.8% corresponds to 2σ separation.
- If tails present in distribution, separation drops below 2σ even if main peaks remain 2σ apart.
- Obtainable separation limited by natural width of *W* and *Z* to identification efficiency of 94%.

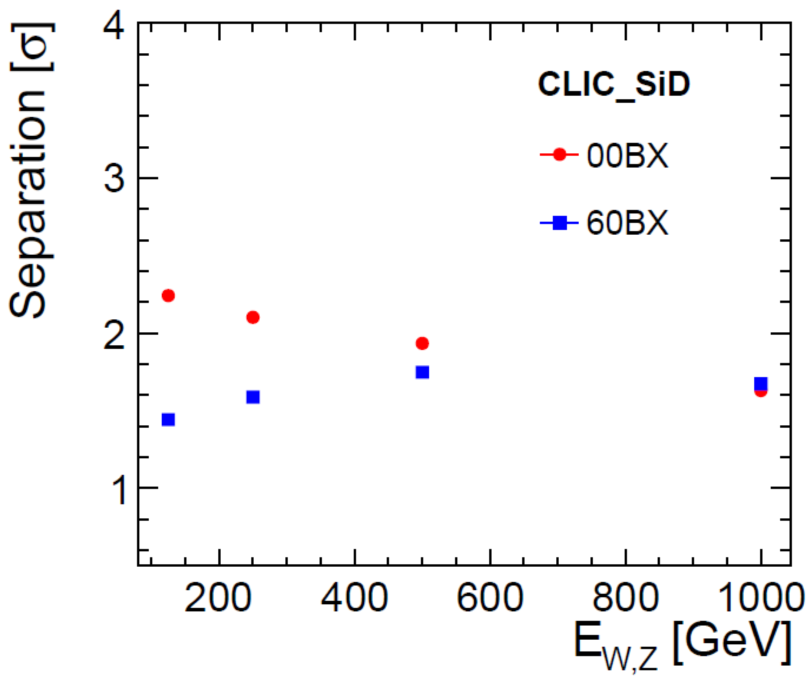


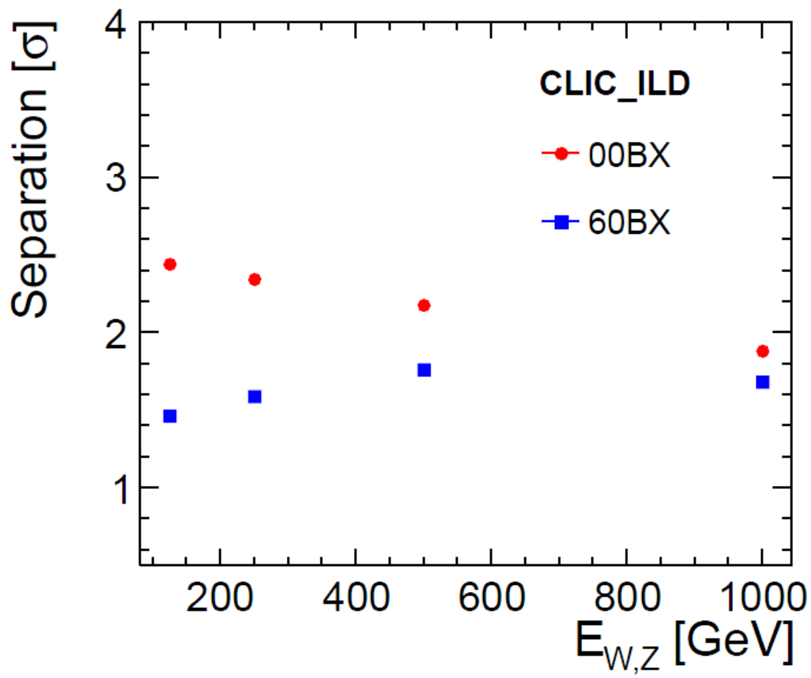




W/Z Separation

- Separation between *W* and *Z* peaks with no background and with 60BX of background:





Gaugino Pair Production

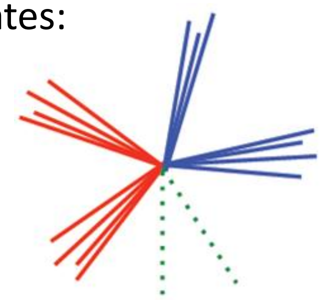
- Test particle flow reconstruction of boosted low mass (EW scale) states in presence of background:

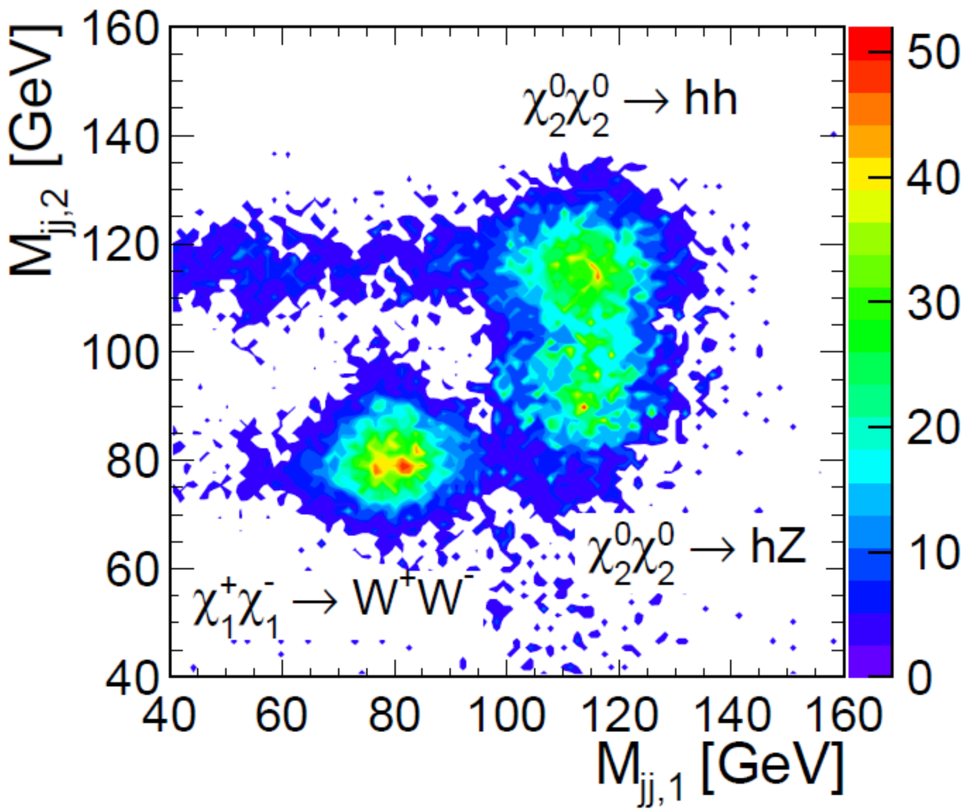
$m(\tilde{\chi}_1^0) = 340\,\text{GeV} \quad m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643\,\text{GeV}$

- Pair production and decay:

$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow hh\,\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad \textbf{82 \%}$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow Zh\,\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad \textbf{17 \%}$$

- Largest BR decay has same topology for all final states:





- Use kt jet-finder and tight PFO collection. **Separate using di-jet invariant mass.**

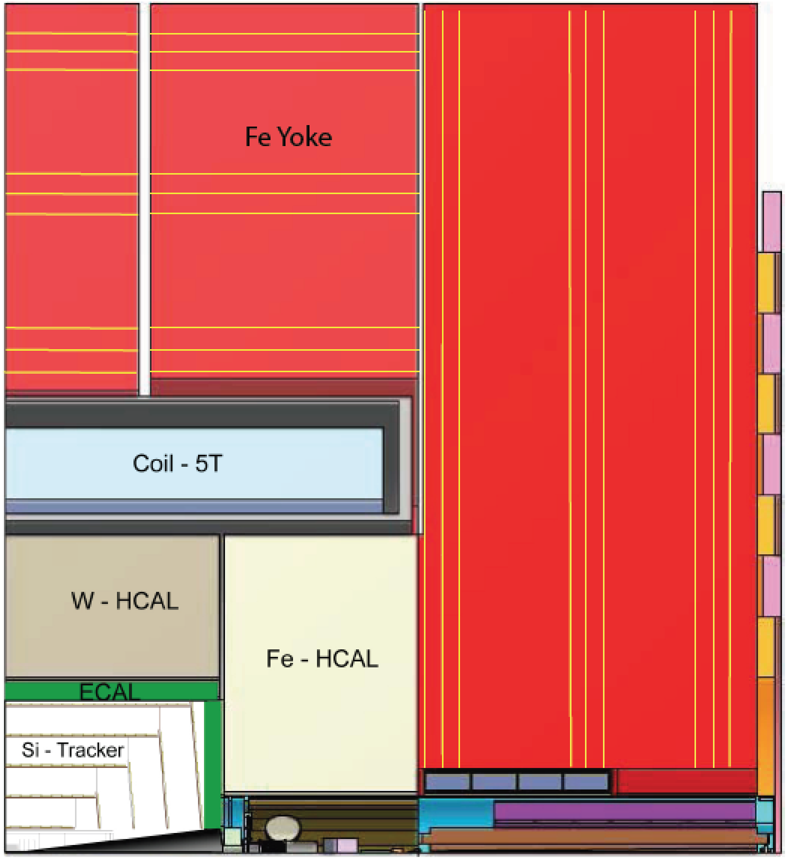
Summary

- Technical performance study shows that PandoraPFA provides impressive jet energy resolution at CLIC. The behaviour of the reconstruction is well-understood.
- Physics performance study reveals that it is possible to separate final states (with identical topologies) based on invariant mass reconstruction.

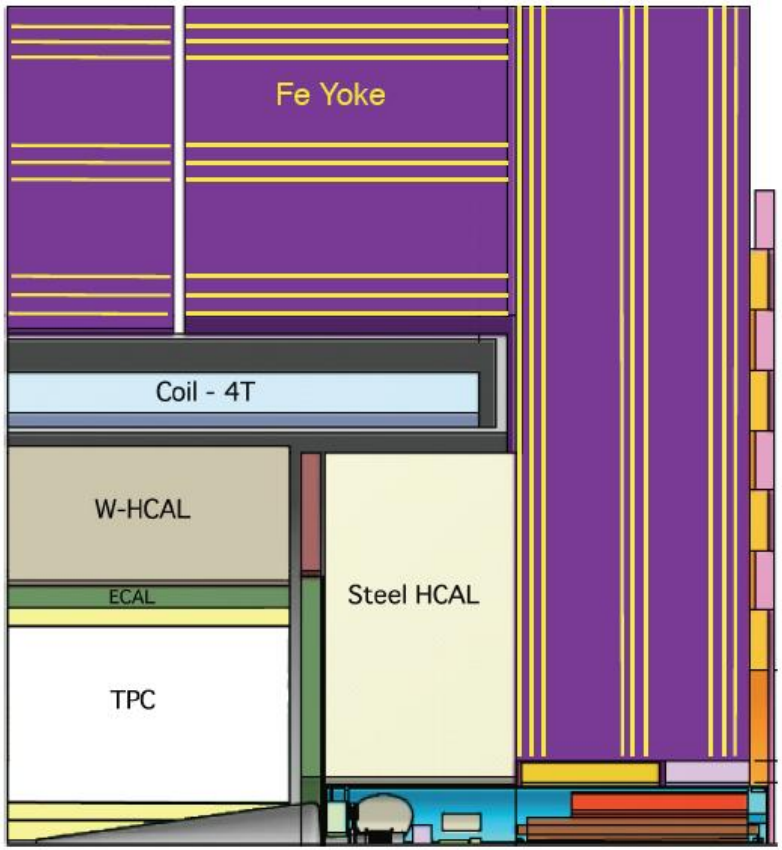
- Background from $\gamma\gamma\rightarrow$hadrons can be addressed using timing cuts at PFO level.
- Influence of background on reconstructed energy and mass resolutions is evident, but decreases at higher jet energies.
- CLIC_ILD and CLIC_SiD show similar performance in the presence of background.

Backup

Detector Concepts



CLIC_SiD



CLIC_ILD

Default PFO Selection

Region	p_T range	Time cut
Photons		
Central $\lvert\cos(\theta)\rvert \leq 0.975$	$0.75\,\mathrm{GeV} \leq p_\mathrm{T} < 4.0\,\mathrm{GeV}$ $0\,\mathrm{GeV} \leq p_\mathrm{T} < 0.75\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$ $t < 1.0\,\mathrm{ns}$
Forward $\lvert\cos(\theta)\rvert > 0.975$	$0.75\,\mathrm{GeV} \leq p_\mathrm{T} < 4.0\,\mathrm{GeV}$ $0\,\mathrm{GeV} \leq p_\mathrm{T} < 0.75\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$ $t < 1.0\,\mathrm{ns}$
Neutral hadrons		
Central $\lvert\cos(\theta)\rvert \leq 0.975$	$0.75\,\mathrm{GeV} \leq p_\mathrm{T} < 8.0\,\mathrm{GeV}$ $0\,\mathrm{GeV} \leq p_\mathrm{T} < 0.75\,\mathrm{GeV}$	$t < 2.5\,\mathrm{ns}$ $t < 1.5\,\mathrm{ns}$
Forward $\lvert\cos(\theta)\rvert > 0.975$	$0.75\,\mathrm{GeV} \leq p_\mathrm{T} < 8.0\,\mathrm{GeV}$ $0\,\mathrm{GeV} \leq p_\mathrm{T} < 0.75\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$ $t < 1.0\,\mathrm{ns}$
Charged particles		
All	$0.75\,\mathrm{GeV} \leq p_\mathrm{T} < 4.0\,\mathrm{GeV}$ $0\,\mathrm{GeV} \leq p_\mathrm{T} < 0.75\,\mathrm{GeV}$	$t < 3.0\,\mathrm{ns}$ $t < 1.5\,\mathrm{ns}$
Track only		
Require $p_\mathrm{T} > 0.5\,\mathrm{GeV}$ and $t_\mathrm{ECAL} < 10\,\mathrm{ns}$		

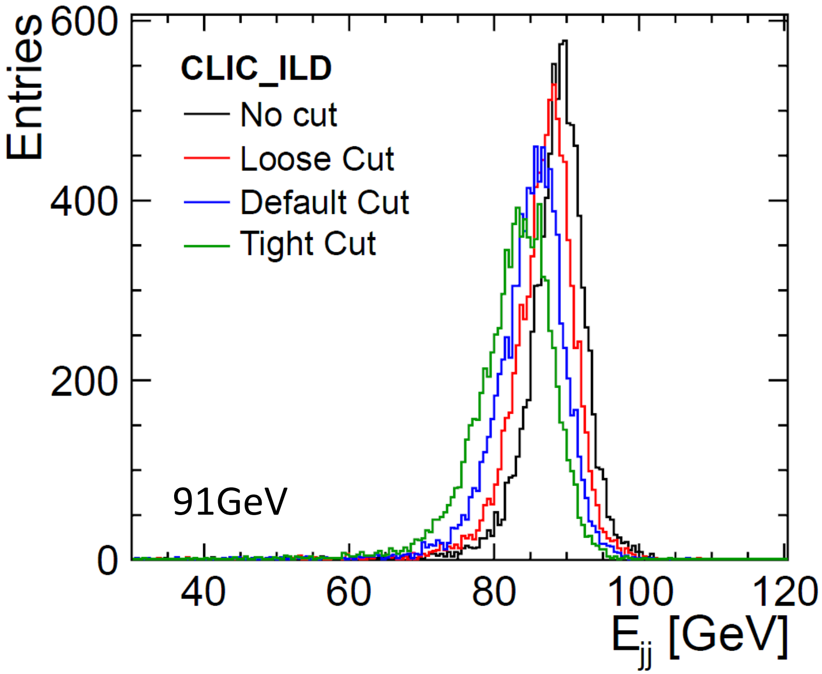
Loose PFO Selection

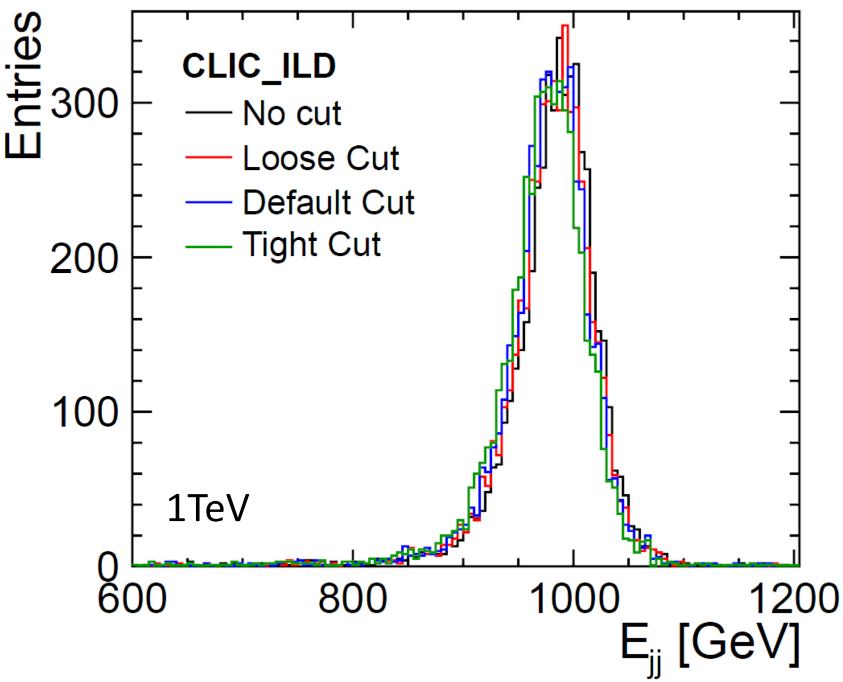
Region	p_T range	Time cut
Photons		
Central $\lvert\cos(\theta)\rvert \leq 0.975$	$0.75\,\mathrm{GeV} \leq p_T < 4.0\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$
	$0\,\mathrm{GeV} \leq p_T < 0.75\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$
Forward $\lvert\cos(\theta)\rvert > 0.975$	$0.75\,\mathrm{GeV} \leq p_T < 4.0\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$
	$0\,\mathrm{GeV} \leq p_T < 0.75\,\mathrm{GeV}$	$t < 1.0\,\mathrm{ns}$
Neutral hadrons		
Central $\lvert\cos(\theta)\rvert \leq 0.975$	$0.75\,\mathrm{GeV} \leq p_T < 8.0\,\mathrm{GeV}$	$t < 2.5\,\mathrm{ns}$
	$0\,\mathrm{GeV} \leq p_T < 0.75\,\mathrm{GeV}$	$t < 1.5\,\mathrm{ns}$
Forward $\lvert\cos(\theta)\rvert > 0.975$	$0.75\,\mathrm{GeV} \leq p_T < 8.0\,\mathrm{GeV}$	$t < 2.5\,\mathrm{ns}$
	$0\,\mathrm{GeV} \leq p_T < 0.75\,\mathrm{GeV}$	$t < 1.5\,\mathrm{ns}$
Charged particles		
All	$0.75\,\mathrm{GeV} \leq p_T < 4.0\,\mathrm{GeV}$	$t < 3.0\,\mathrm{ns}$
	$0\,\mathrm{GeV} \leq p_T < 0.75\,\mathrm{GeV}$	$t < 1.5\,\mathrm{ns}$
Track only		
Require $p_T > 0.25\,\mathrm{GeV}$		

Tight PFO Selection

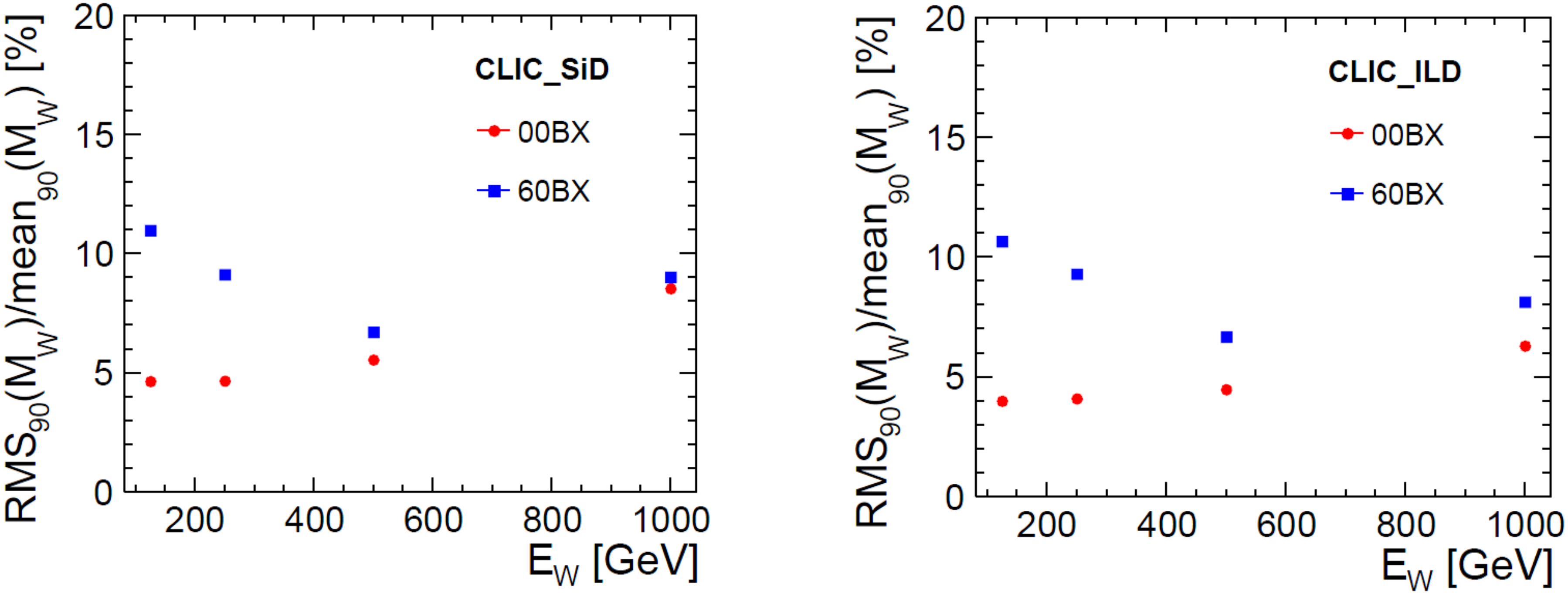
Region	p_T range	Time cut
Photons		
Central $\lvert\cos(\theta)\rvert \leq 0.95$	$1.0\,\mathrm{GeV} \leq p_T < 4.0\,\mathrm{GeV}$ $0.2\,\mathrm{GeV} \leq p_T < 1.0\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$ $t < 1.0\,\mathrm{ns}$
Forward $\lvert\cos(\theta)\rvert > 0.95$	$1.0\,\mathrm{GeV} \leq p_T < 4.0\,\mathrm{GeV}$ $0.2\,\mathrm{GeV} \leq p_T < 1.0\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$ $t < 1.0\,\mathrm{ns}$
Neutral hadrons		
Central $\lvert\cos(\theta)\rvert \leq 0.95$	$1.0\,\mathrm{GeV} \leq p_T < 8.0\,\mathrm{GeV}$ $0.5\,\mathrm{GeV} \leq p_T < 1.0\,\mathrm{GeV}$	$t < 2.5\,\mathrm{ns}$ $t < 1.5\,\mathrm{ns}$
Forward $\lvert\cos(\theta)\rvert > 0.95$	$1.0\,\mathrm{GeV} \leq p_T < 8.0\,\mathrm{GeV}$ $0.5\,\mathrm{GeV} \leq p_T < 1.0\,\mathrm{GeV}$	$t < 1.5\,\mathrm{ns}$ $t < 1.0\,\mathrm{ns}$
Charged particles		
All	$1.0\,\mathrm{GeV} \leq p_T < 4.0\,\mathrm{GeV}$ $0\,\mathrm{GeV} \leq p_T < 1.0\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$ $t < 1.0\,\mathrm{ns}$
Track only		
Require $p_T > 1.0\,\mathrm{GeV}$ and $t_{ECAL} < 10\,\mathrm{ns}$		

Timing cuts: energy distributions





W Mass Resolution



W/Z Separation

BX	$E_{W,Z}$ [GeV]	$\sigma_m(W)/m(W)$ [%]	$\sigma_m(Z)/m(Z)$ [%]	Separation [σ]	ε [%]
00 BX	125	4.6	4.1	2.0	85
	250	4.7	4.5	2.0	85
	500	5.5	4.9	2.0	84
	1000	8.5	7.4	1.7	78
60 BX	125	11.0	10.6	1.4	69
	250	9.1	9.1	1.6	74
	500	6.7	7.0	1.7	78
	1000	9.0	8.5	1.7	76

Separation between W and Z and corresponding mass resolution for CLIC_SiD.

BX	$E_{W,Z}$ [GeV]	$\sigma_m(W)/m(W)$ [%]	$\sigma_m(Z)/m(Z)$ [%]	Separation [σ]	ε [%]
00 BX	125	3.9	3.5	2.2	88
	250	4.1	3.8	2.2	89
	500	4.5	4.2	2.2	88
	1000	6.3	5.6	1.9	87
60 BX	125	11.0	10.1	1.5	70
	250	9.3	9.0	1.6	74
	500	6.7	6.6	1.8	79
	1000	8.1	7.7	1.7	77

Separation between W and Z and corresponding mass resolution for CLIC_ILD.