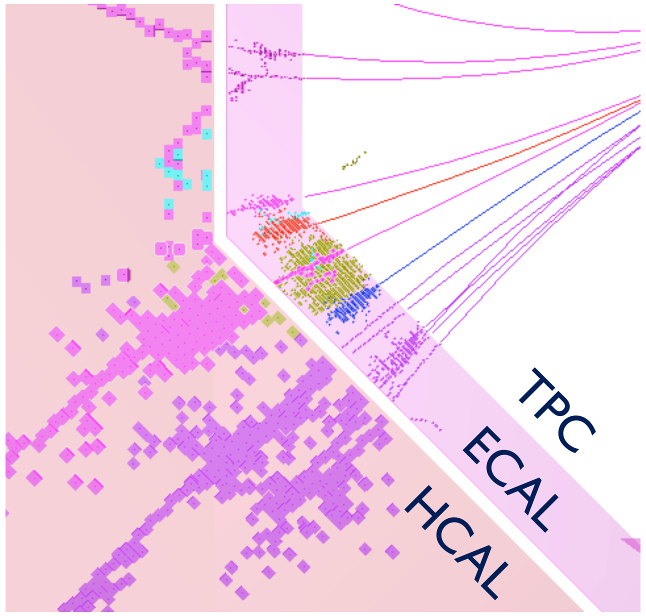
Pandora

LC Reconstruction



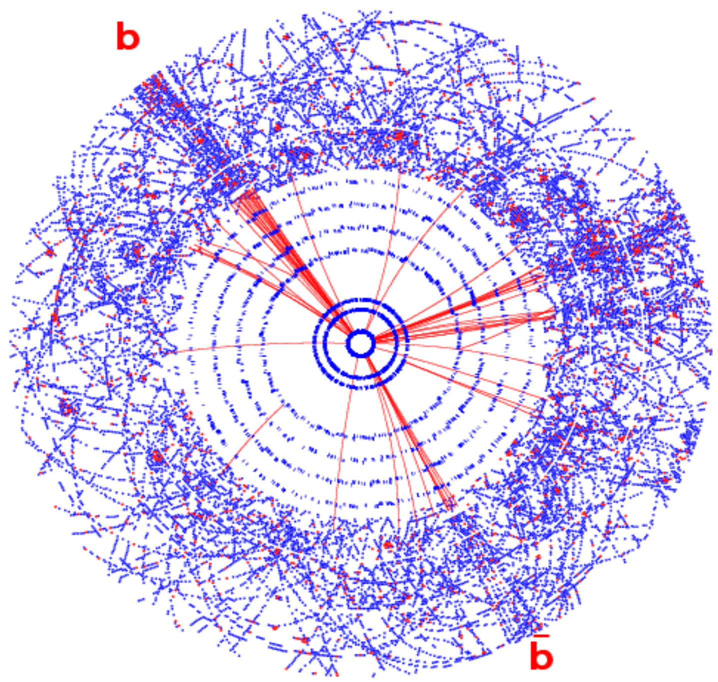
Overview

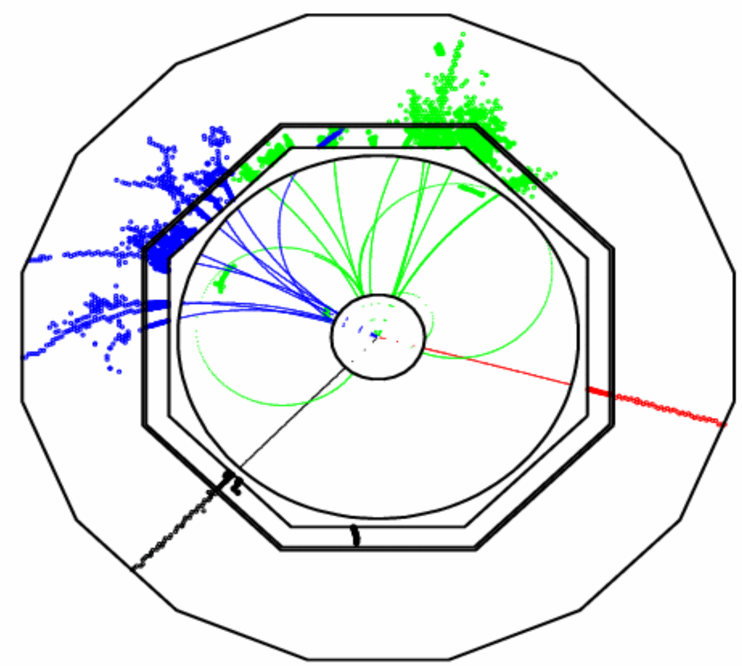
1. Calorimetry Goals at a Linear Collider
2. Fine Granularity Particle Flow Calorimetry
3. Pandora Particle Flow Algorithm
4. Particle Flow Performance at ILC
5. Optimising ILC Detector Design
6. From ILC to CLIC Energies
7. Particle Flow Performance at CLIC
8. Summary

e^+e^- Physics

- Electron-positron colliders provide a clean environment for precision physics:

LHC
pp → H + X





Future Linear Collider
$e^+e^- \to HZ$

- Precision studies/measurements:
  - Higgs sector and other SM particles (esp. W, top), SUSY particle spectra and more.
- Physics characterised by:
  - High Multiplicity final states, often 6/8 jets
  - Small cross-sections, e.g. $\sigma(e^+e^- \to ZHH) = 0.3\text{fb}$
- Require high luminosity, i.e. ILC/CLIC
- Require detector optimised for precision physics in multi-jet environment.

Comparison with LEP

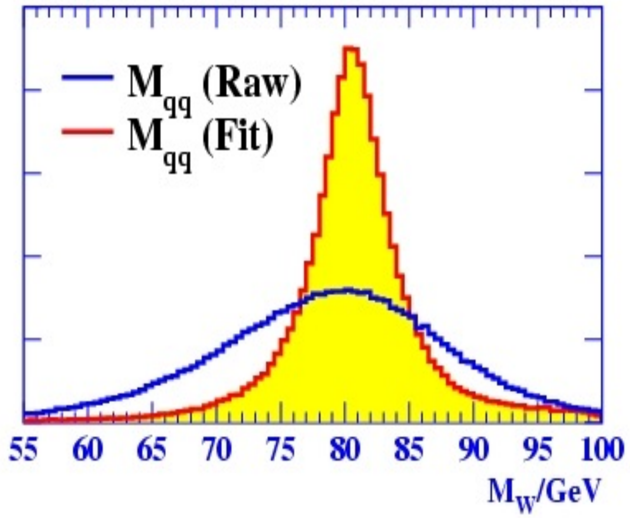
At LEP

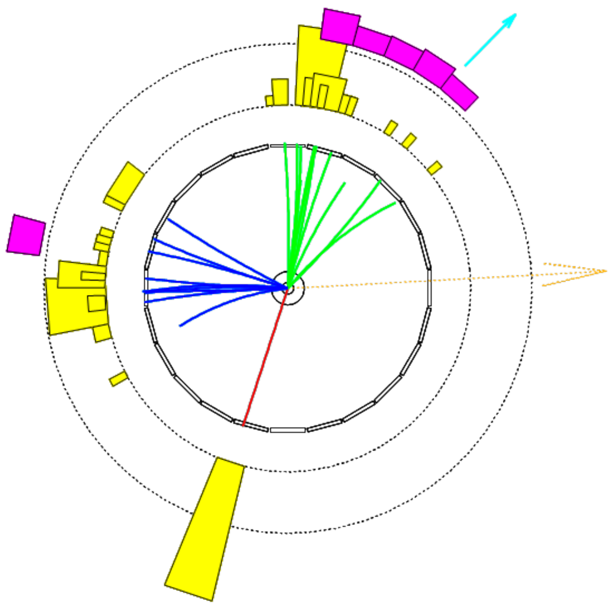
- Signal dominates: $e^+e^- \rightarrow Z$ and $e^+e^- \rightarrow W^+W^-$
- Backgrounds not too problematic
- Even for W mass measurement, jet energy resolution not too important

Kinematic Fits

$$\sum E_i = \sqrt{s}$$

$$\sum \vec{p}_i = 0$$





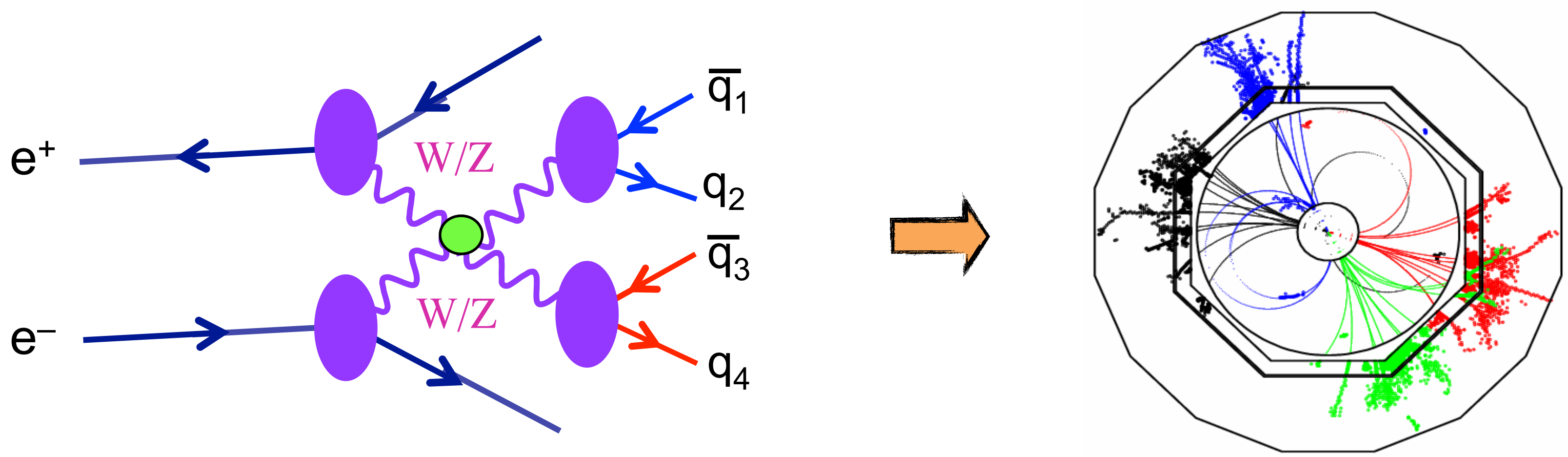
At ILC/CLIC

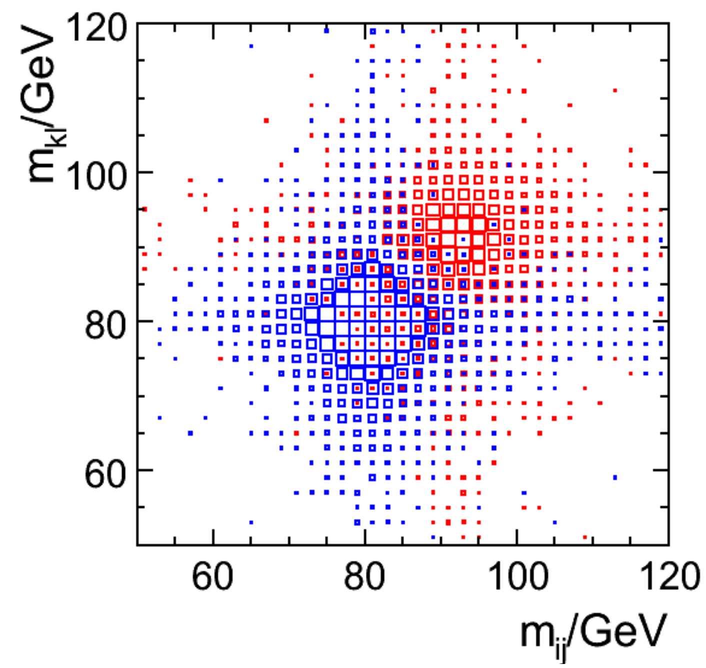
- Backgrounds dominate interesting physics
- Kinematic fitting much less useful: Beamstrahlung + many final states with > 1 neutrino

- Physics performance depends critically on detector performance (not true at LEP)
- Places stringent requirements on LC detectors

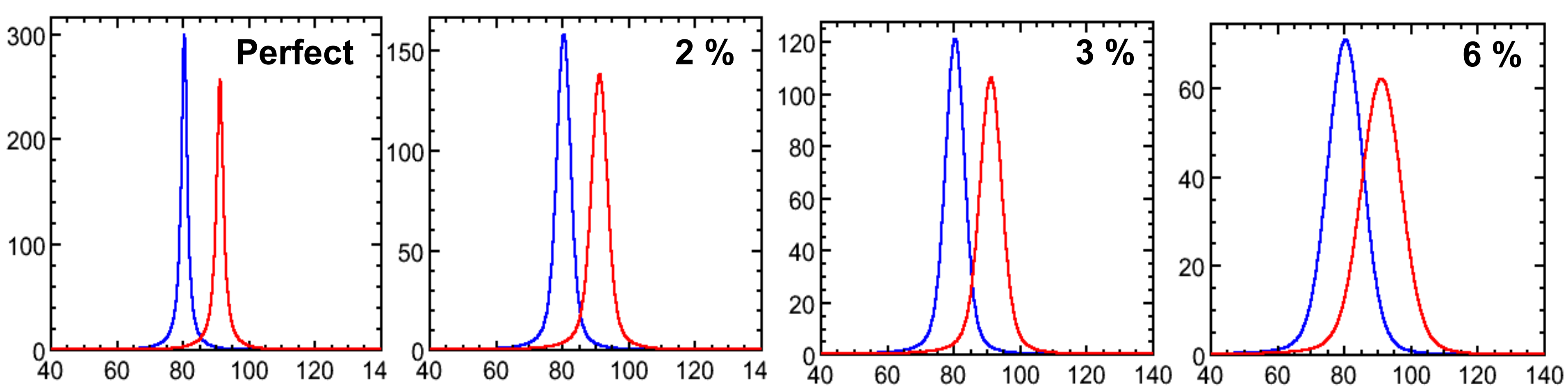
LC Calorimetry Goals

- Jet energy resolution requirements depend on physics...
- Likely to be primarily interested in di-jet mass resolution.
- Strong desire to separate W/Z hadronic decays.





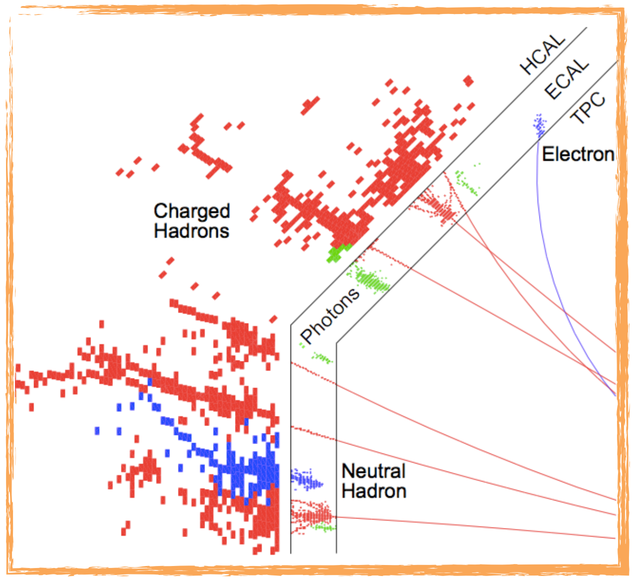
- 3-4% jet energy resolution gives decent 2.6-2.3σ W/Z separation.
- Sets a reasonable choice for LC jet energy minimal goal ~3.5%.
- For W/Z separation, not much further gain; limited by natural widths.



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

Fine Granularity Particle Flow

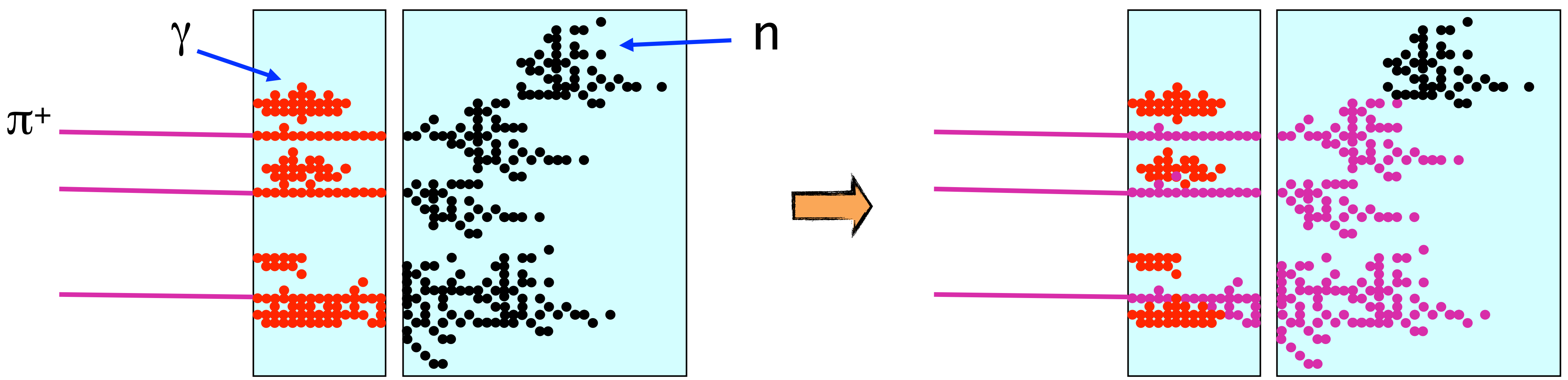


In a typical jet:

- 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
- Approximately 70% of energy measured in HCAL: $\sigma_E/E \approx 60\% / \sqrt{E(\text{GeV})}$



$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

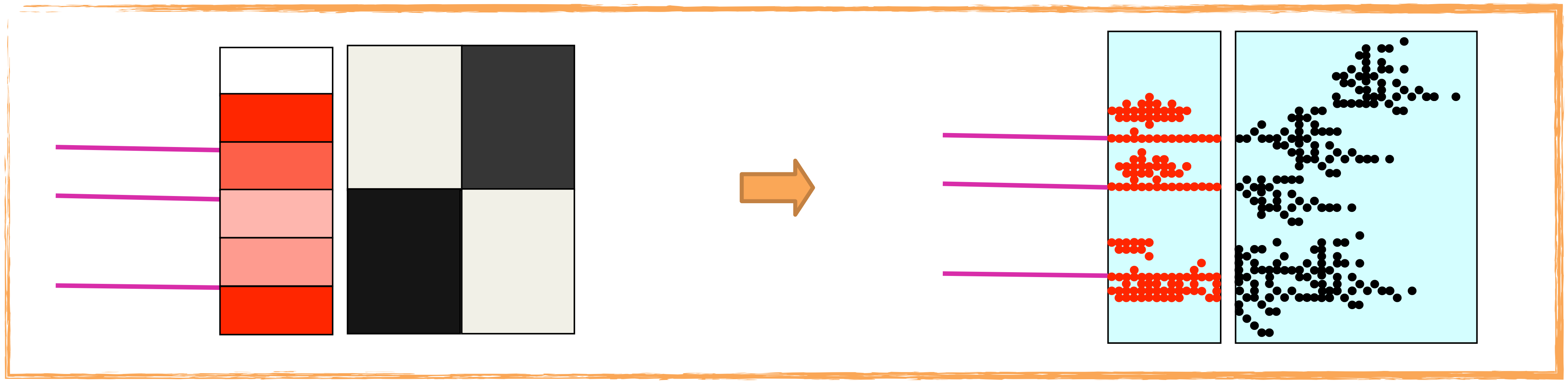
Fine granularity Particle Flow Calorimetry: reconstruct individual particles.

- Charged particle momentum measured in tracker (essentially perfectly)
- Photon energies measured in ECAL: $\sigma_E/E < 20\% / \sqrt{E(\text{GeV})}$
- Only neutral hadron energies (10% of jet energy) measured in HCAL: much improved resolution.

Fine Granularity Particle Flow

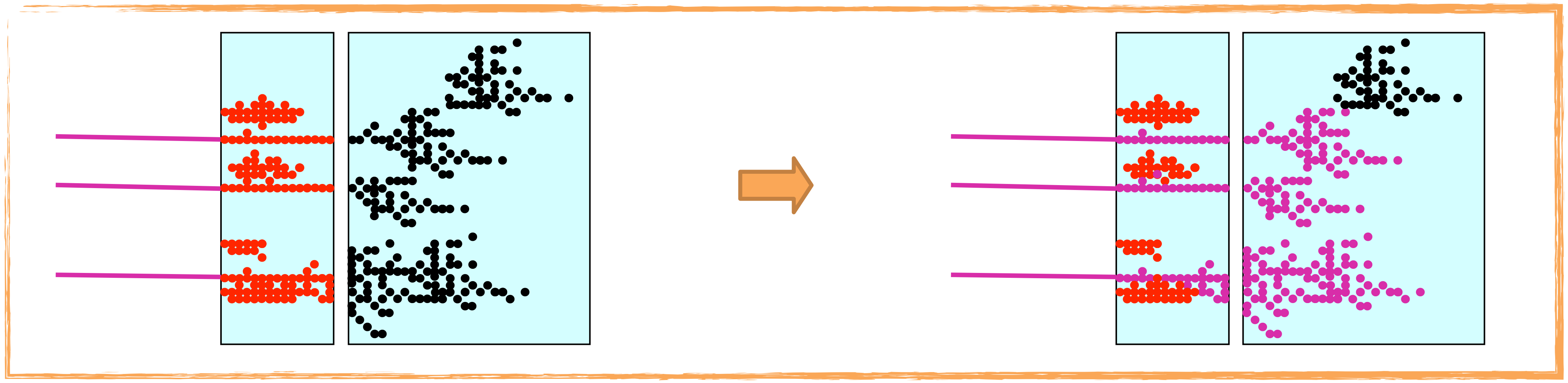
<u>Hardware:</u> need to be able to resolve energy deposits from different particles.

- Require highly granular detectors (as studied by CALICE).



<u>Software:</u> need to be able to identify energy deposits from each individual particle.

- Require sophisticated reconstruction software to deal with complex events, containing many hits.



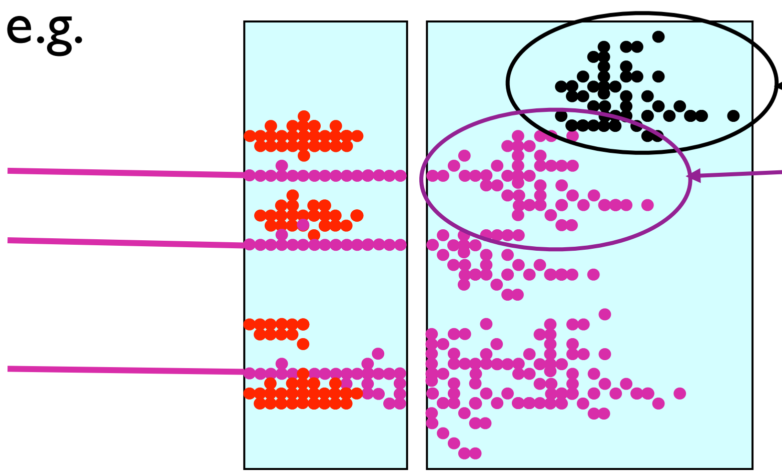
Particle Flow Calorimetry = HARDWARE + SOFTWARE

Particle Flow Algorithms

The challenge for fine granularity particle flow algorithms:

- Avoid double counting of energy from same particle
- Separate energy deposits from different particles

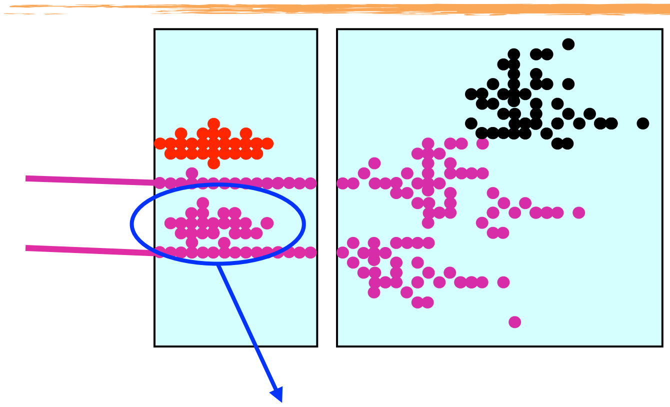
e.g.



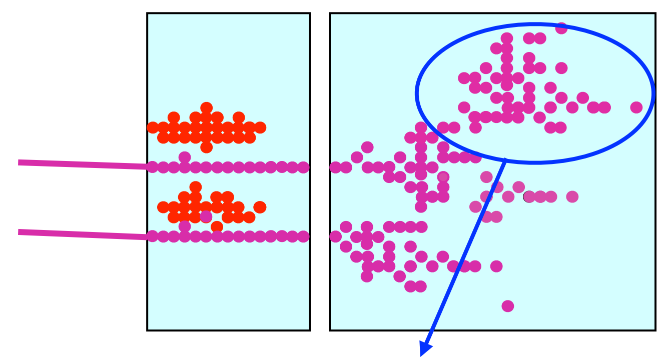
If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution, not intrinsic calorimetric performance

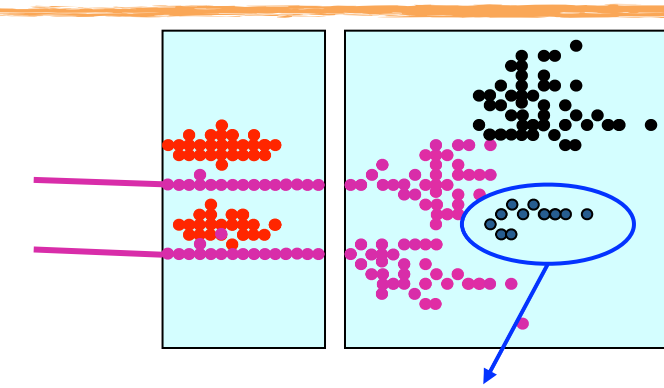
Three basic types of confusion:



Failure to resolve photons



Failure to resolve neutral hadrons



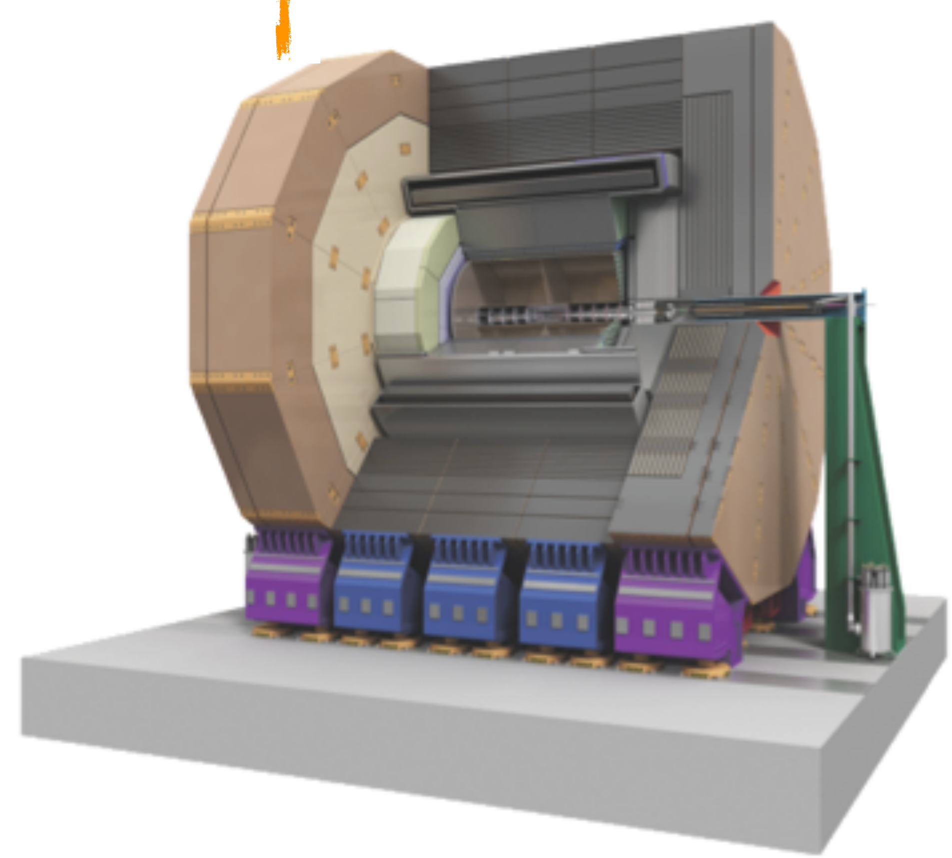
Reconstruct fragments as separate neutral hadrons

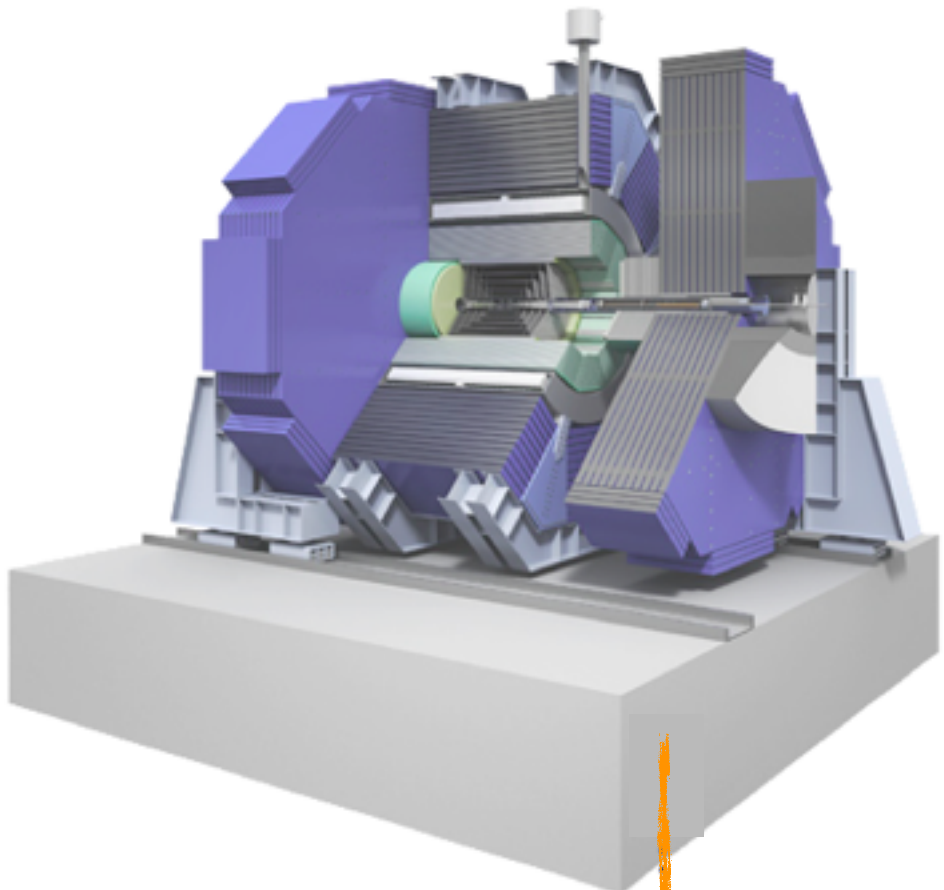
LC Detector Concepts

- Fine granularity Particle Flow must be studied in context of whole detector. Need detailed GEANT4 simulations of potential detector designs, e.g. ILC detector concepts:

“Large” : tracker radius 1.8m
B-field : 3.5 T
Tracker : TPC (220 layers)
Calorimetry : fine granularity particle flow
ECAL + HCAL inside large solenoid

ILD (International Large Detector)





SiD (Silicon Detector)

“Small” : tracker radius 1.2m
B-field : 5 T
Tracker : Silicon (5 layers)
Calorimetry : fine granularity particle flow
ECAL + HCAL inside large solenoid

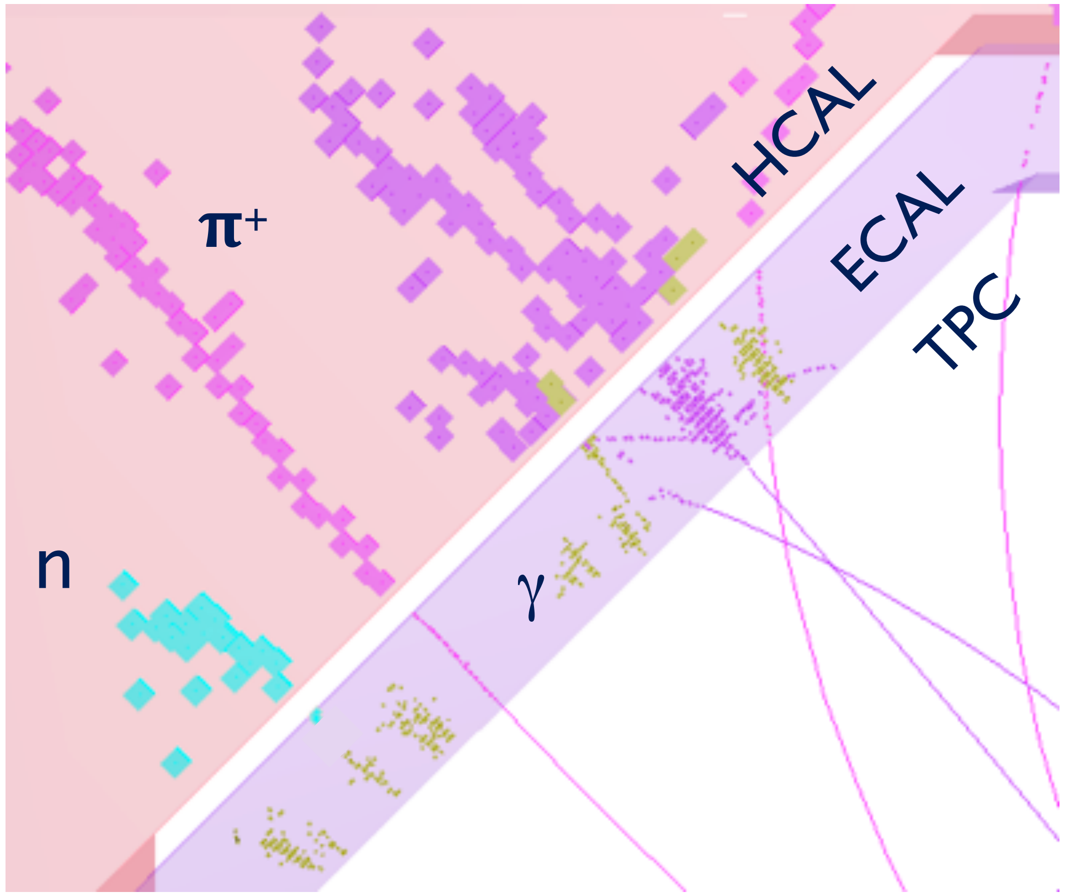
Calorimeter Design

ECAL requirements:

- Minimise transverse spread of EM showers:
  - Small Molière radius & transverse segmentation
- Longitudinally separate EM/Hadronic showers:
  - Large ratio λ_I/X_0
- Identification of EM showers
  - Longitudinal segmentation.

HCAL requirements:

- Fully contain hadronic showers:
  - Small λ_I
- Resolve hadronic shower structure:
  - Longitudinal and transverse segmentation
- HCAL will be rather large:
  - Cost and structural properties important

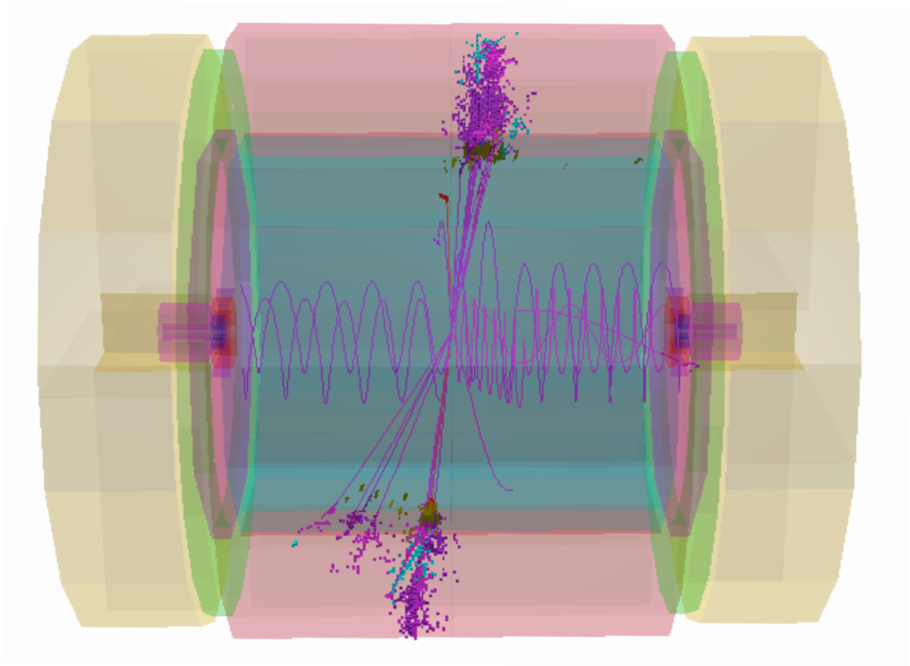


Suitable absorber materials:

Material	X_0/cm	ρ_M/cm	λ_I/cm	λ_I/X_0
Fe	1.76	1.69	16.8	9.5
Cu	1.43	1.52	15.1	10.6
W	0.35	0.93	9.6	27.4
Pb	0.56	1.00	17.1	30.5

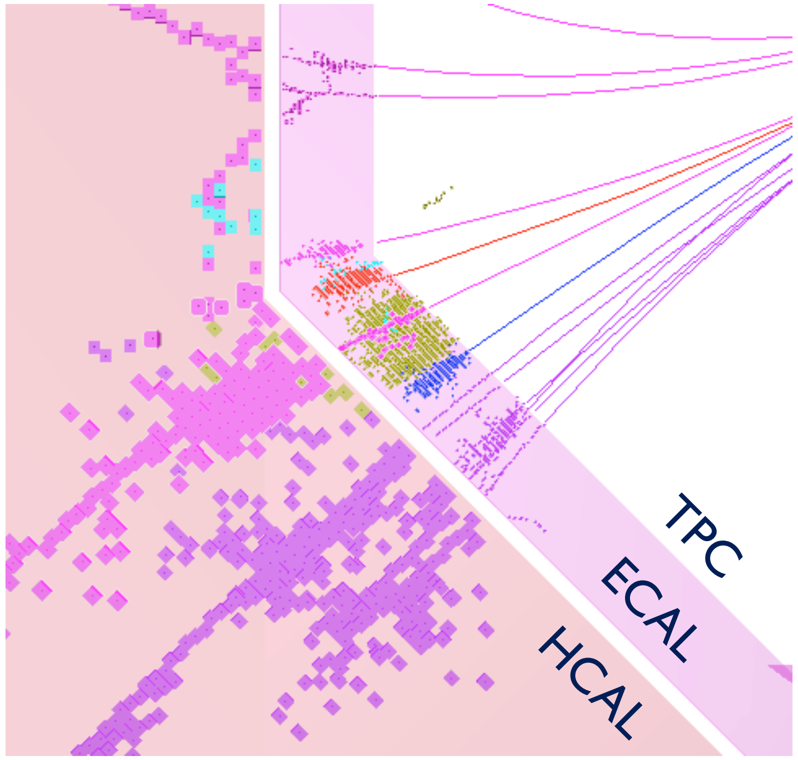
Software Design

- Fine granularity particle flow calorimetry lives or dies on quality of reconstruction of particles.
- Require high-performance software, in terms of:
  - Algorithmic sophistication, with reliable implementation.
  - CPU/memory usage; these are complex events with many hits.



Typical topologies of simulated 250GeV jets in ILD_o1_v05

- Almost all ILC/CLIC studies use code developed with Pandora C++ Software Development Kit.
- Consists of a framework library with carefully designed Application Programming Interfaces.
- Used to implement highly sophisticated particle flow reconstruction algs for LC-style detectors.
- Flexible, reusable with other pat-rec problems.

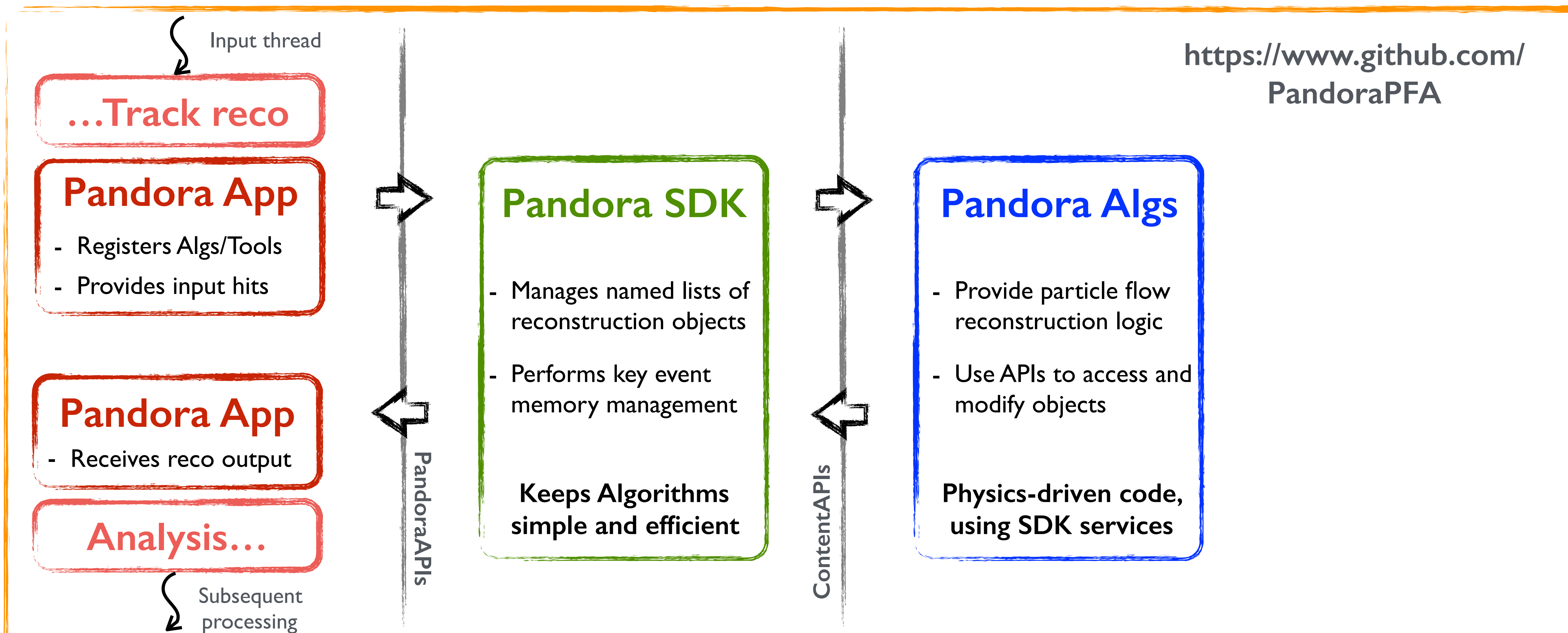


Introducing the Pandora SDK

The **Pandora Software Development Kit** is engineered to provide an environment in which:

1. It is easy for users to provide the building-blocks that define a pattern recognition problem.
2. Logic required to solve pattern recognition problems is cleanly implemented in algorithms.
3. Operations to access or modify building-blocks, or to create new structures, are requested by algorithms and performed by the Pandora framework.

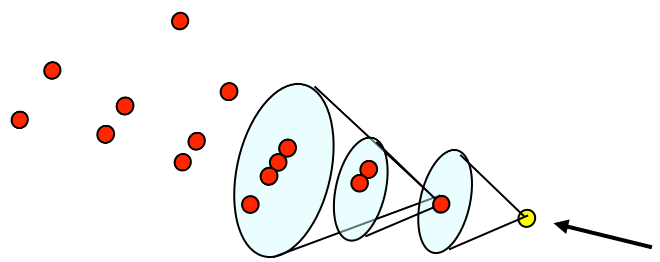
It actively promotes use of large numbers of algorithms, each addressing specific event topologies.



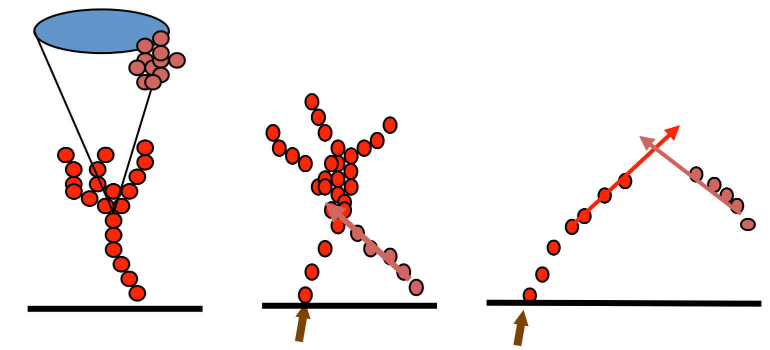
Pandora LC Algorithms

60+ algorithms for fine-granularity detectors

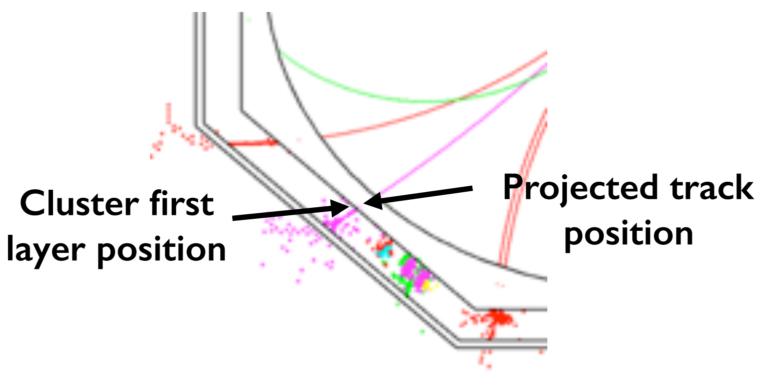
ConeClustering Algorithm



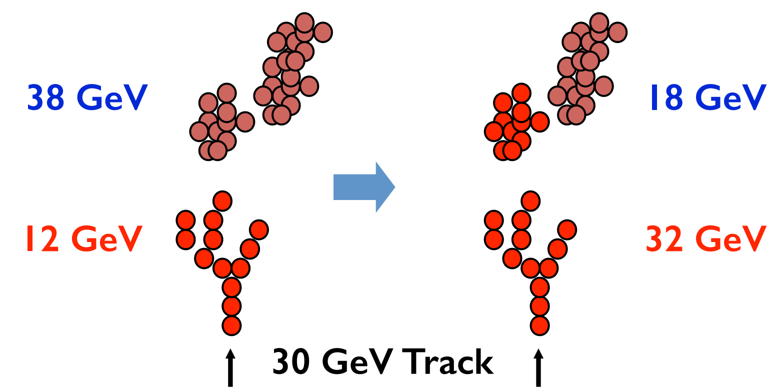
Topological Association Algorithms



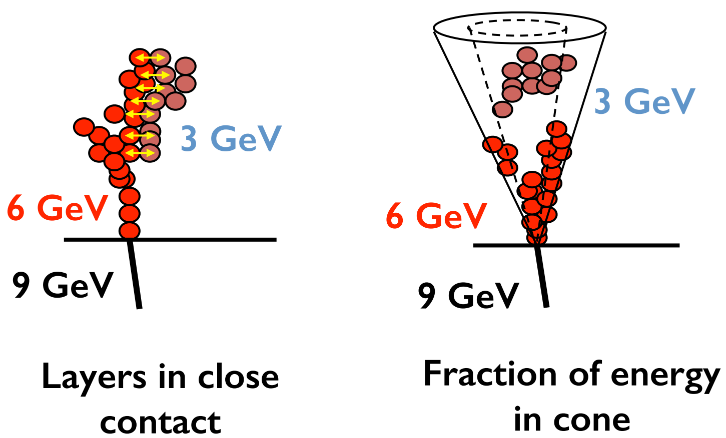
Track-Cluster Association Algorithms



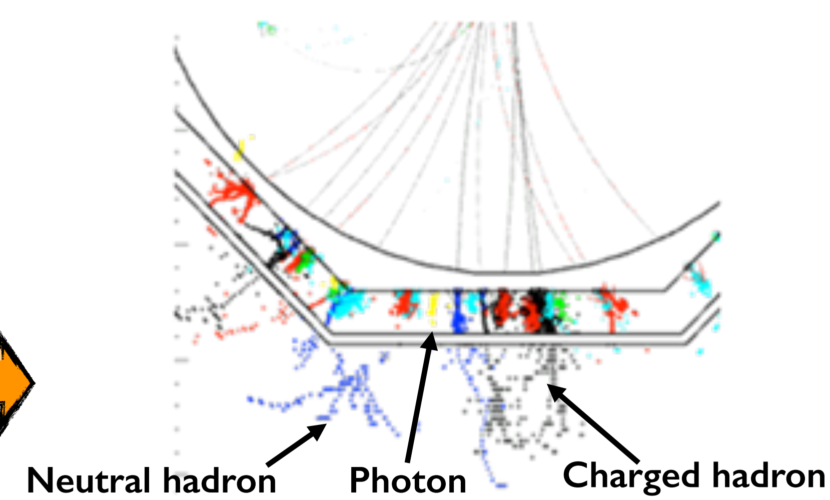
Reclustering Algorithms



Fragment Removal Algorithms



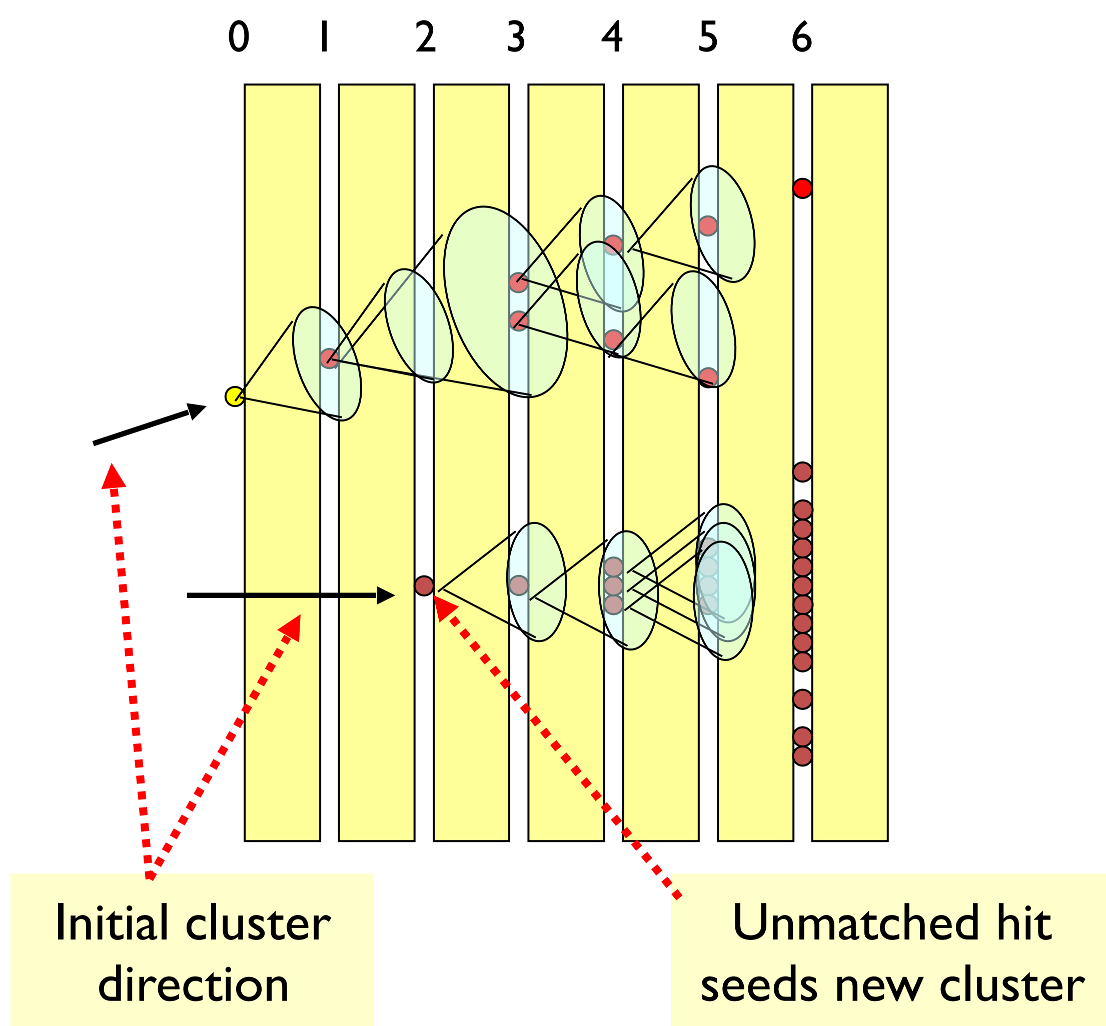
PFO Construction Algorithms

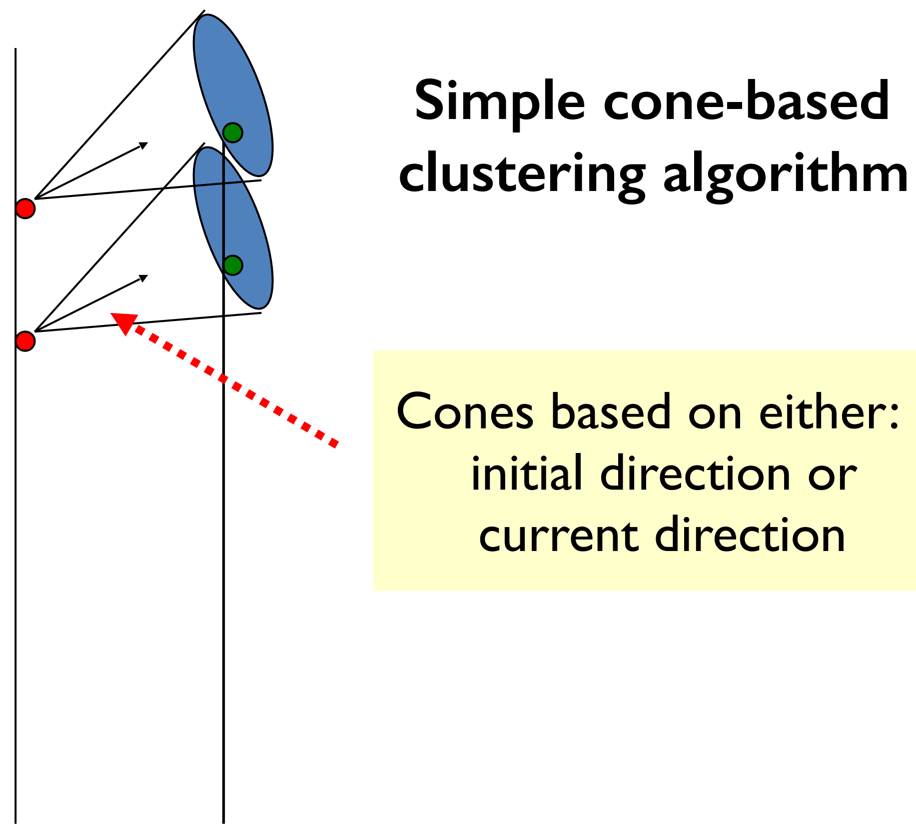


Cone Clustering

- Division of energy deposits into particles starts with simple cone-based clustering algorithm.

- Clusters seeded by projections of inner detector tracks to surface of calorimeter.
- Start at innermost layers and work outward, considering each calorimeter hit in turn.
  - If hit lies within cone defined by existing cluster, and is suitably close, add hit to cluster.
  - If hit is unmatched, use it to form a new cluster.



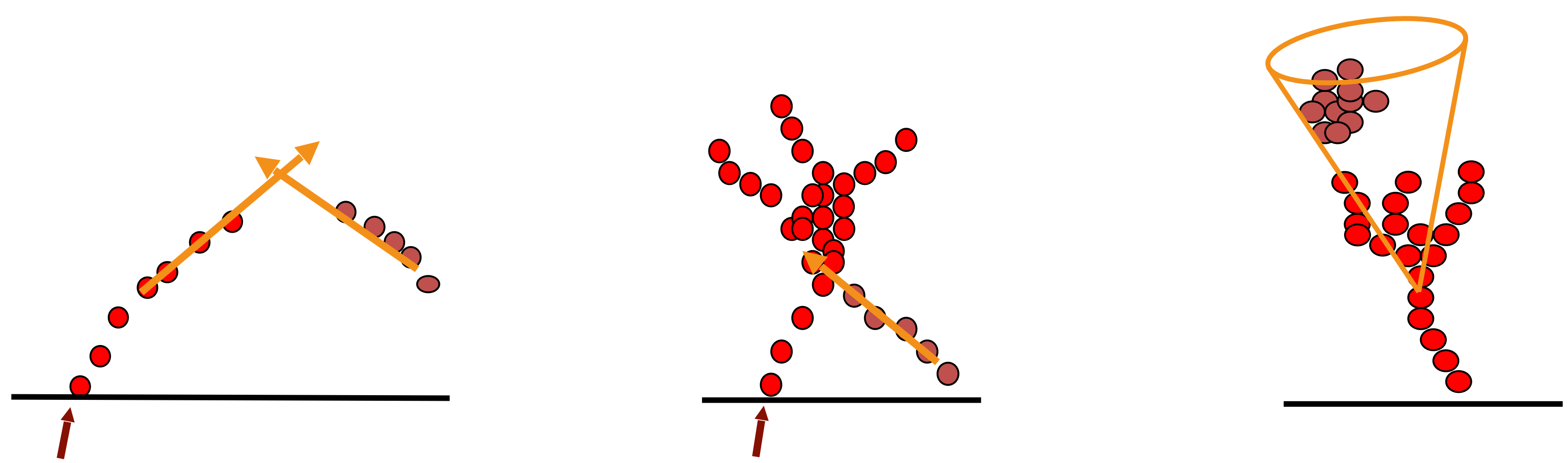


Simple cone-based clustering algorithm

Topological Association

- Pandora reconstruction philosophy:
  - "It's easier to put things together than to split them up."
- Cone based clustering algorithm therefore errs on side of caution; creates clusters that are fragments of single particles, rather than risk merging deposits from separate particles.
- Cluster fragments are then merged together by a series of algorithms, each of which follows well-defined topological rules.

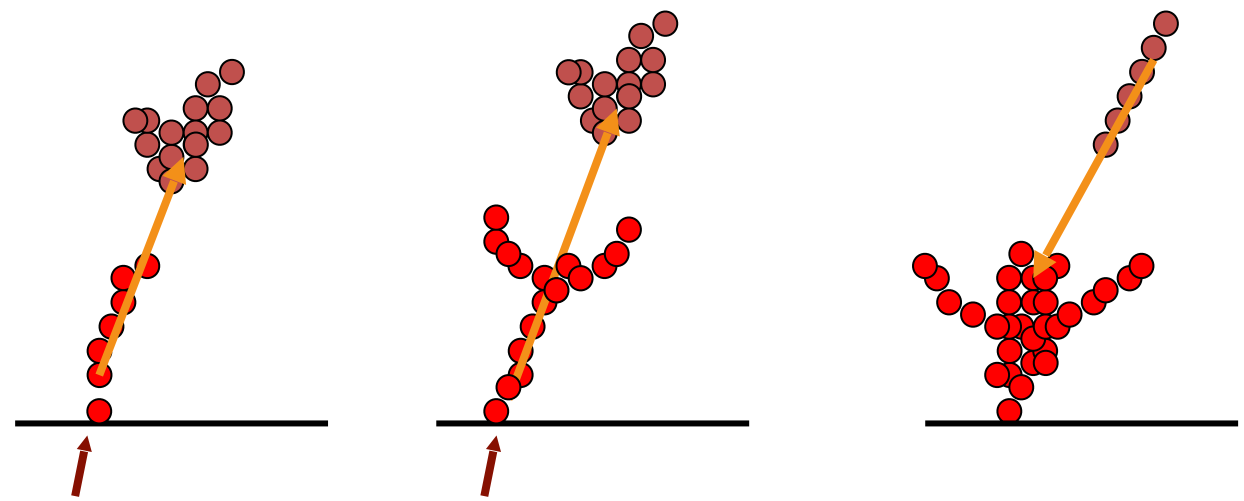
- Clear Associations:
  - The fine granularity and tracking capabilities of the detector are exploited to join clusters that are clearly associated. Very few mistakes are made.



Looping tracks **Back-scattered tracks** **Cone associations**

Topological Association

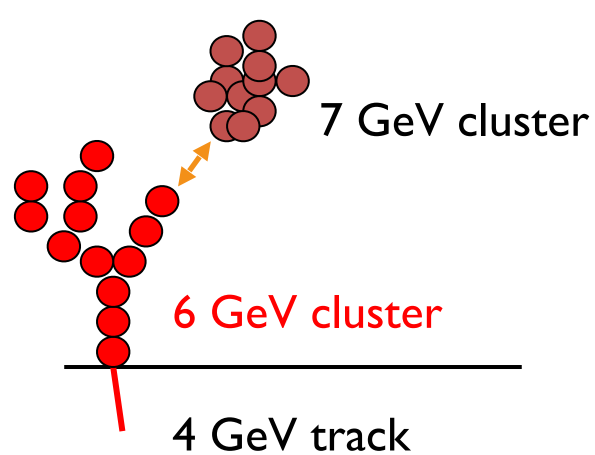
- Clear Associations using cluster mip-segments:
  - Local straight-line fits are performed to hits identified as mip-like and backwards/forward projections are used to identify associations. Tight matching criteria are applied.



Track segment pointing to shower | Proximity | Track-like cluster points back to shower

- Less clear associations:

e.g. Small fragments removed, based on proximity to charged hadron clusters

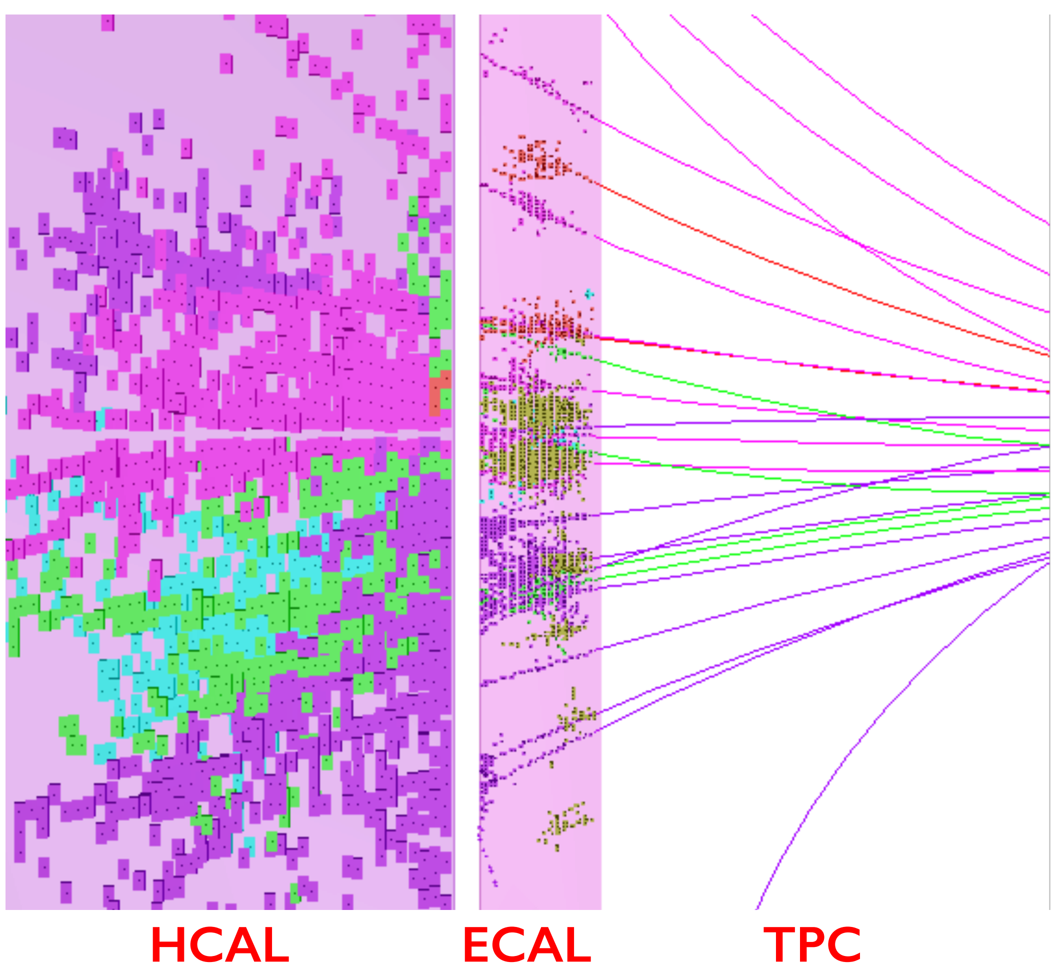


Use E/p consistency to veto clear mistakes

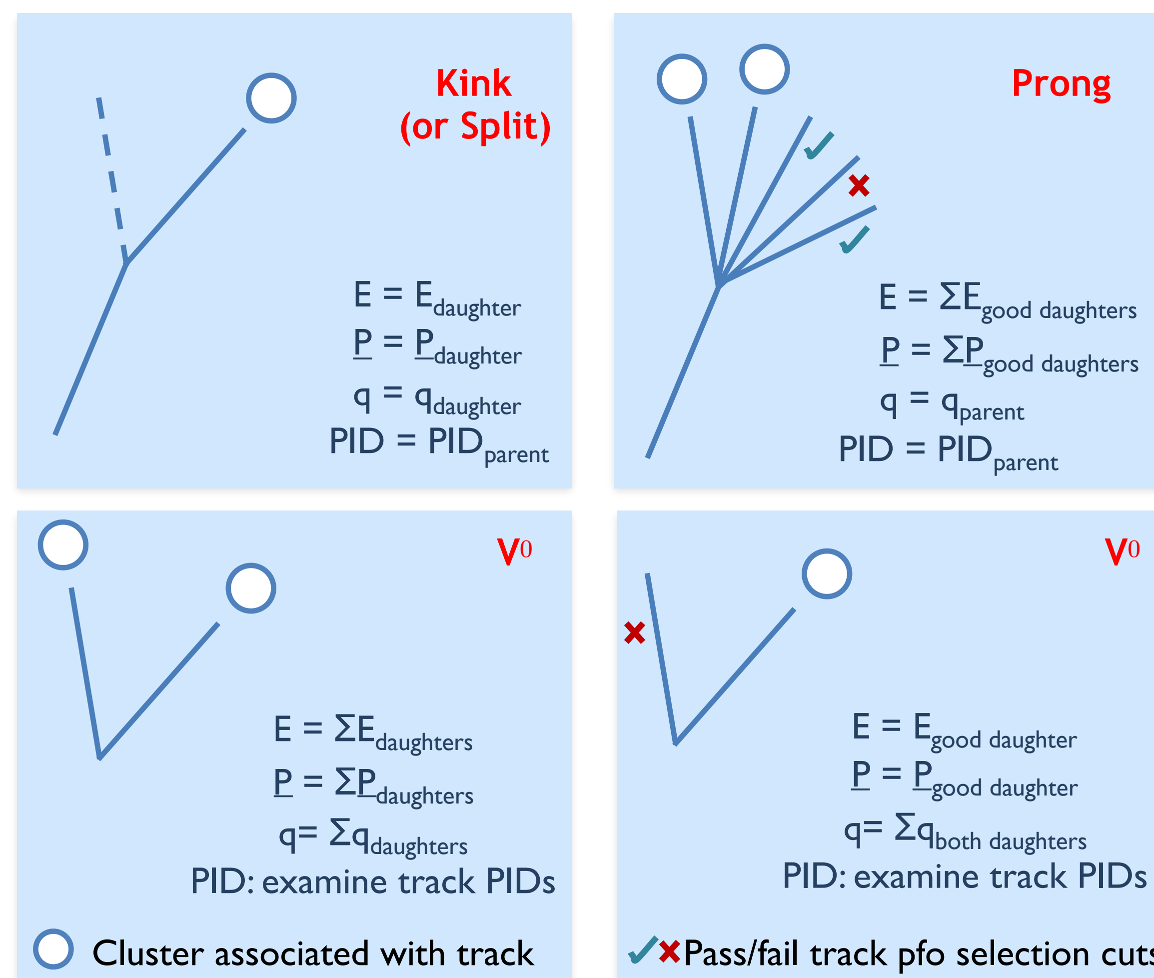
Track-Cluster Associations

- The Pandora track-cluster association algorithms look for consistency between cluster properties and the helix-projected track state at the front face of the calorimeter:
  - Close proximity between cluster and track positions.
  - Consistent track and initial cluster directions.
  - Consistent track momentum and cluster energy.

Clusters ↔ Tracks

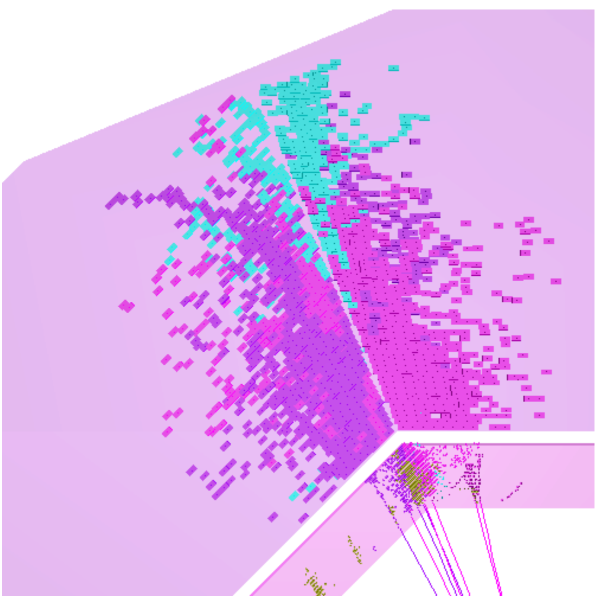


Track-track relationship information also used:



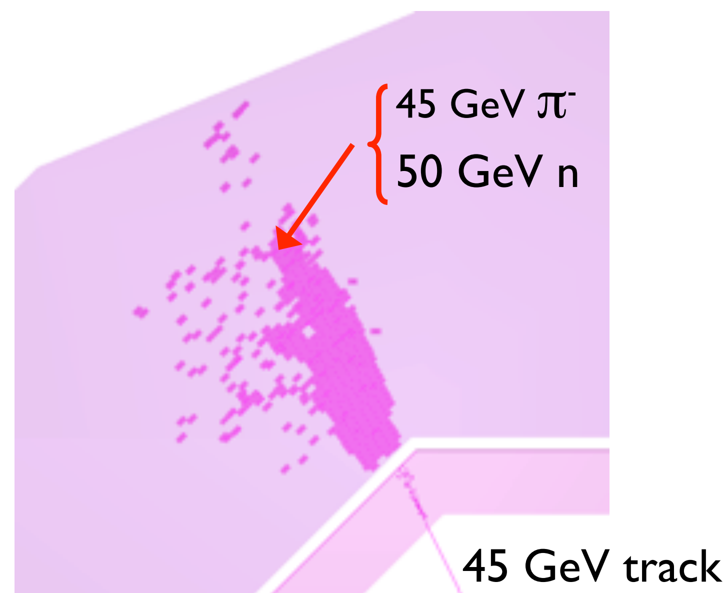
Statistical Reclustering

- At some point, in high density jets (high energies), reach limit of "pure" particle flow.
- Cannot cleanly resolve neutral hadrons in hadronic showers.
- Use information from track-cluster associations to identify pattern-recognition problems:



After topological association

Compare E/p values to find problems



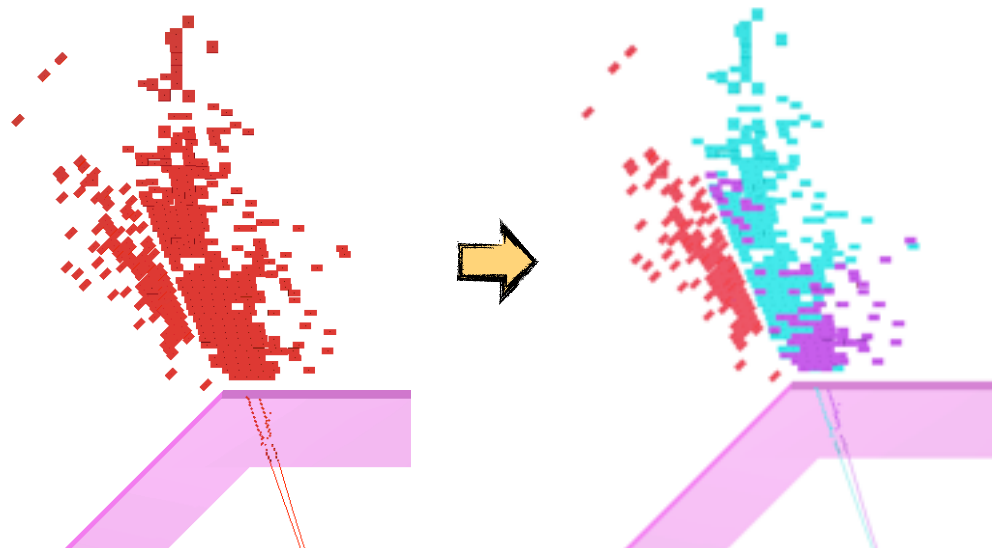
Find n absorbed into π^- cluster

e.g. 45GeV track associated to 95GeV cluster:

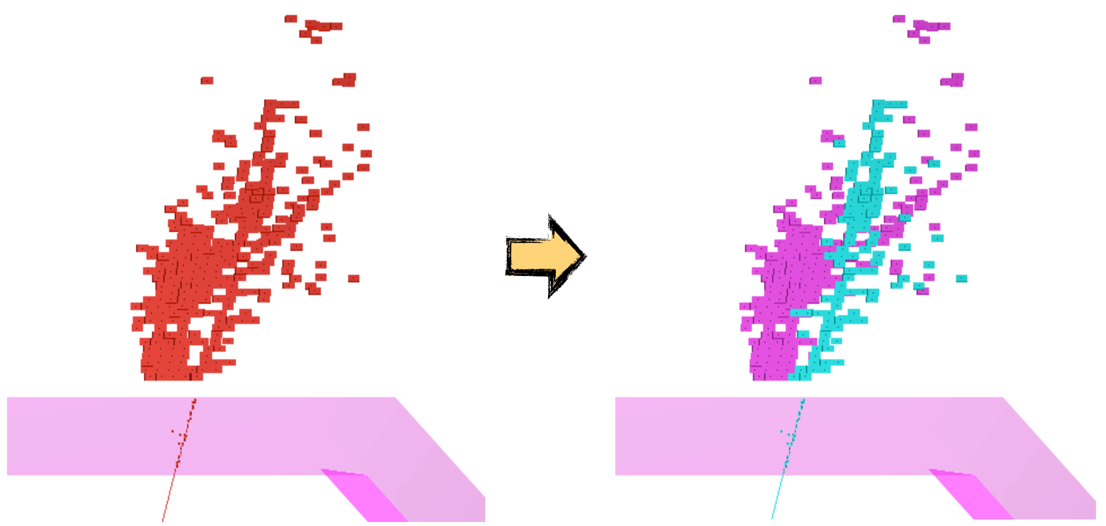
identify and address clustering problem

- Address the problem "statistically"; if we identify significant discrepancy between energy of a cluster and momentum of its associated track, choose to recluster.
- Alter clustering parameters, or change clustering algorithm entirely, until cluster splits in such a way that we obtain sensible track-cluster associations.

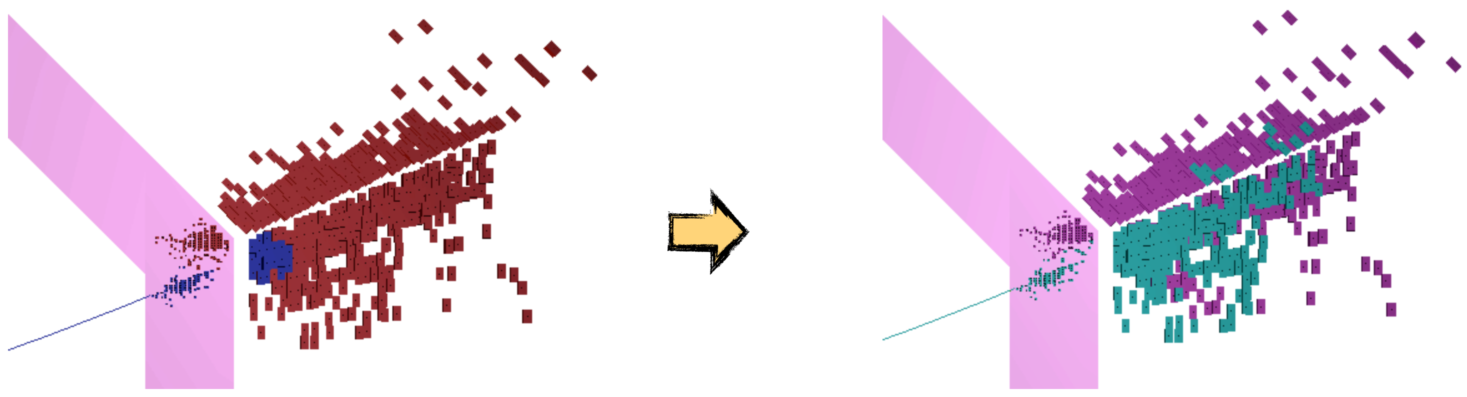
Reclustering Strategies



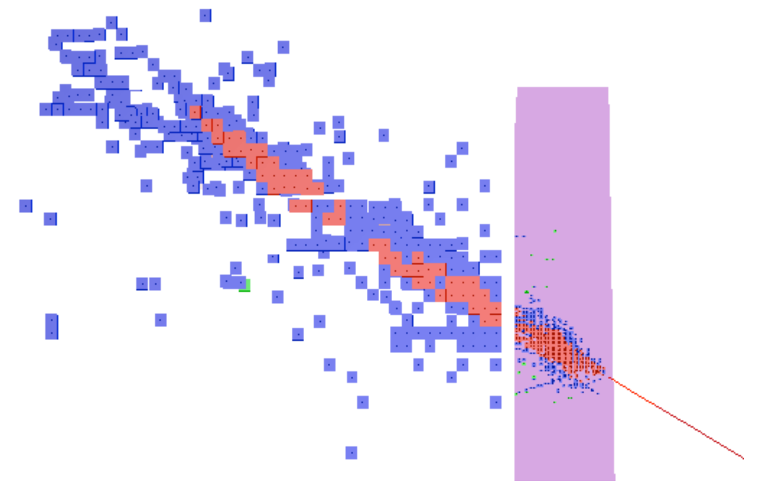
1. Multiple tracks associated to single cluster – split cluster.



2. Cluster energy much greater than track momentum – split cluster.



3. Track momentum much greater than cluster energy – bring in nearby clusters and reconfigure.

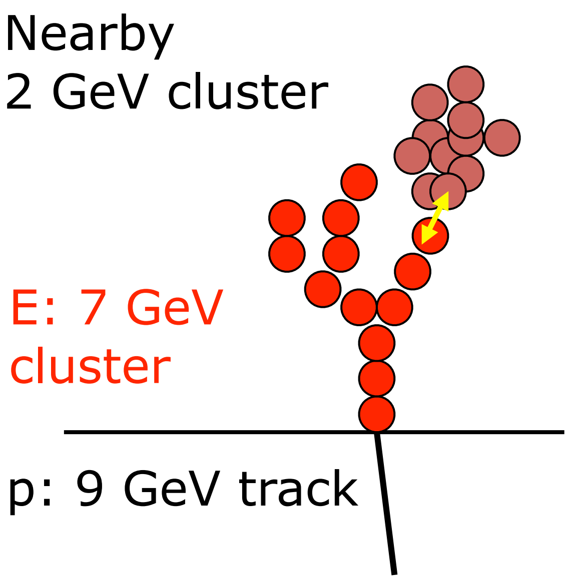


4. If, and only if, no E/p match emerges, can force track-cluster consistency ⇒ energy flow.

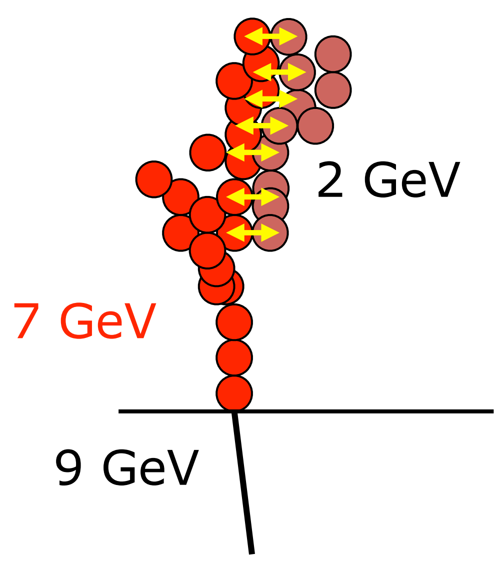
Fragment Removal

- Fragment removal algs aim to remove neutral clusters (those without track-associations) that are really fragments of charged (track-associated) clusters.
- Algs look for evidence of association between nearby clusters, merging the clusters together. In order to merge clusters, the change must bring about a satisfactory change in E/p χ^2.

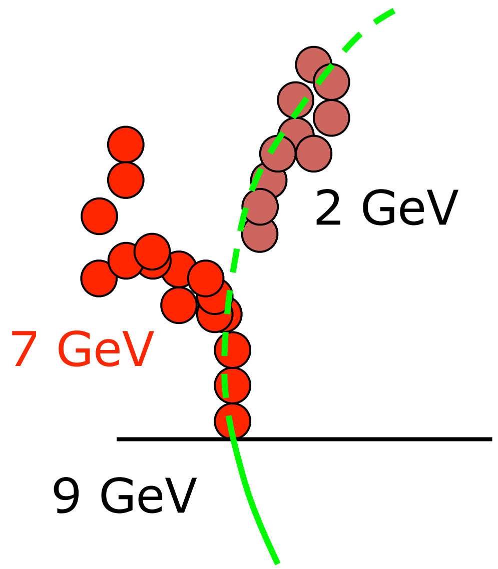
Evidence of association:



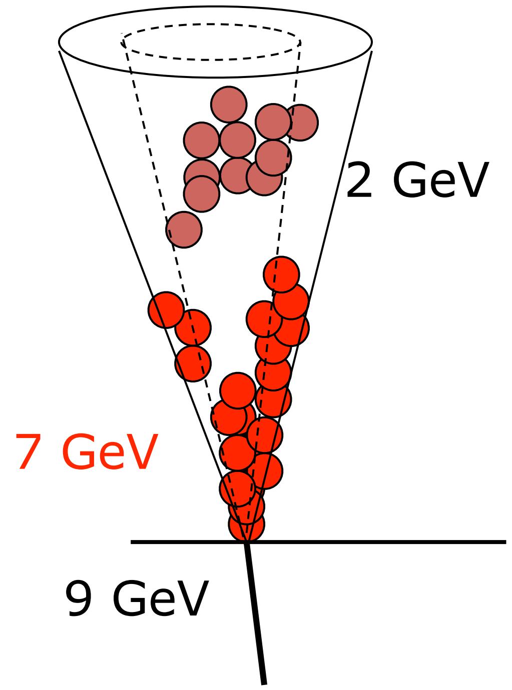
Small distance of closest approach



Multiple layers in close contact



Small distance to track extrapolation



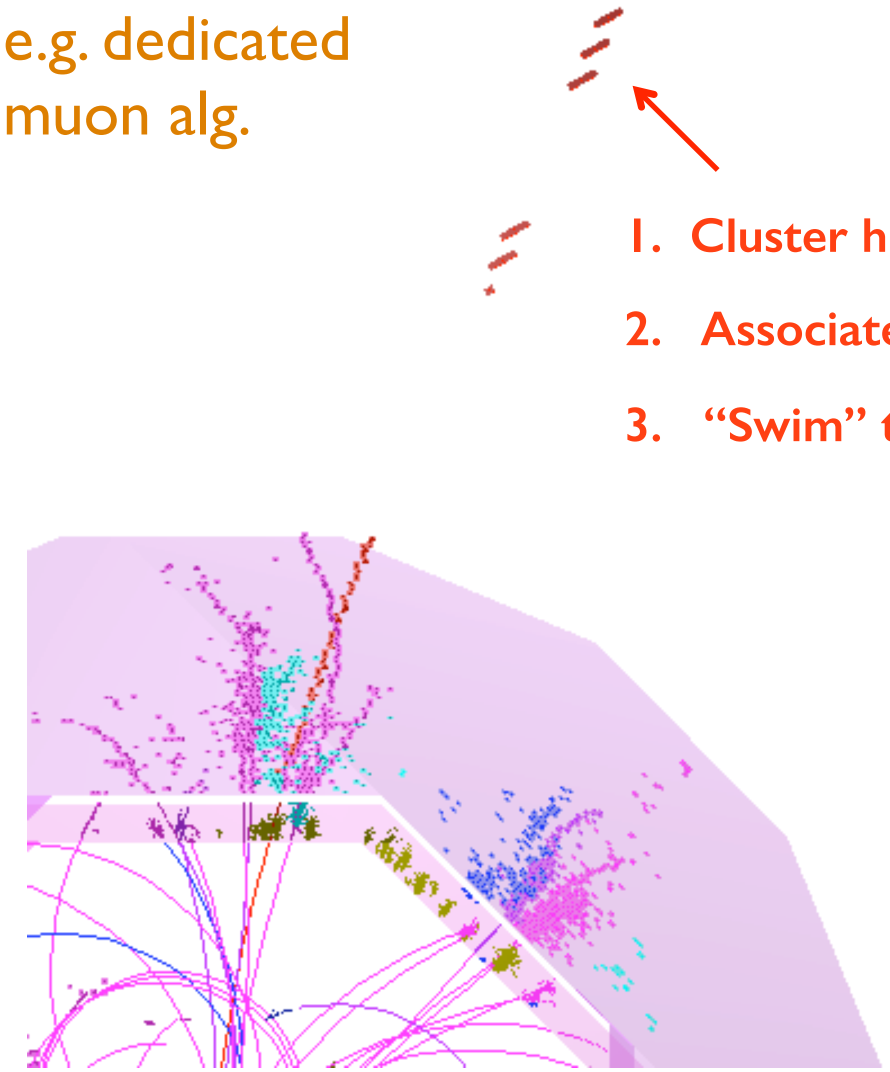
Large fraction of energy in cone

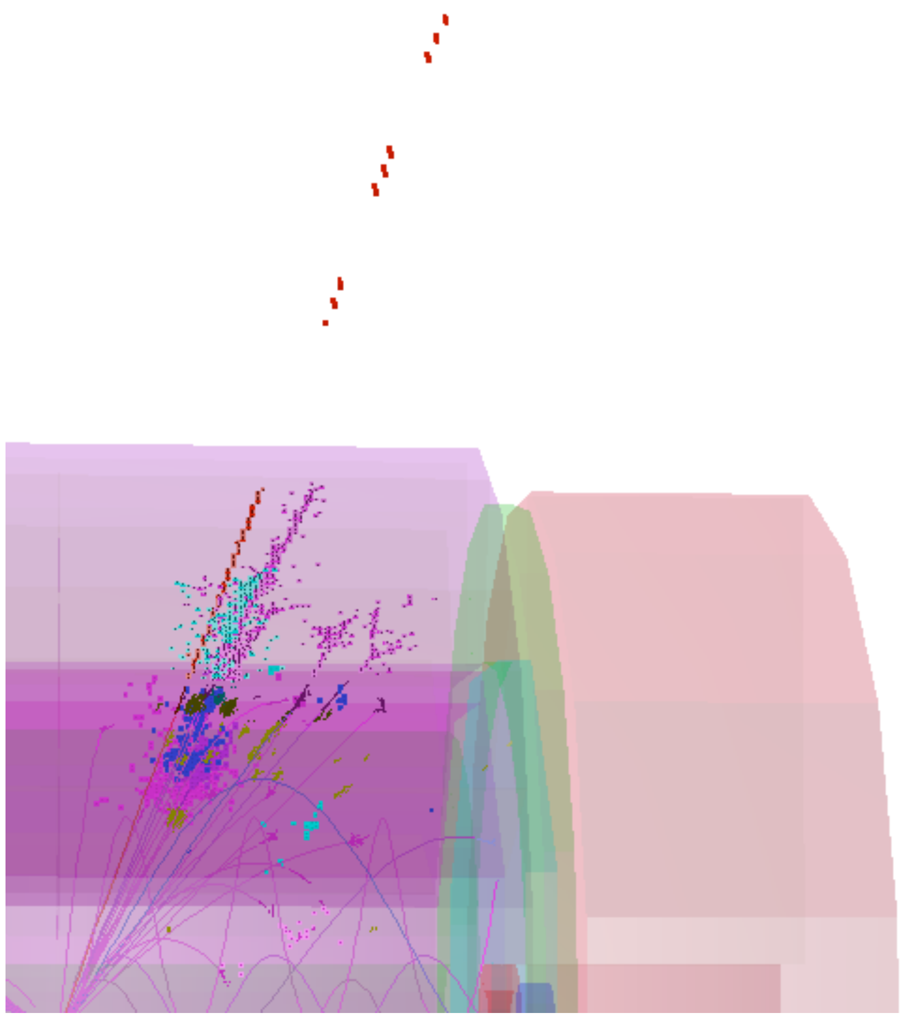
Particle Identification

- Particle ID is crucial for many physics analyses, and photon ID is vital for reconstruction of jet energies in non-compensating calorimeters. Currently available: charged lepton and photon ID.
- Some algs can perform dedicated reconstruction of specific particle types before standard reconstruction. Removal these particles from the event then helps to reduce confusion.

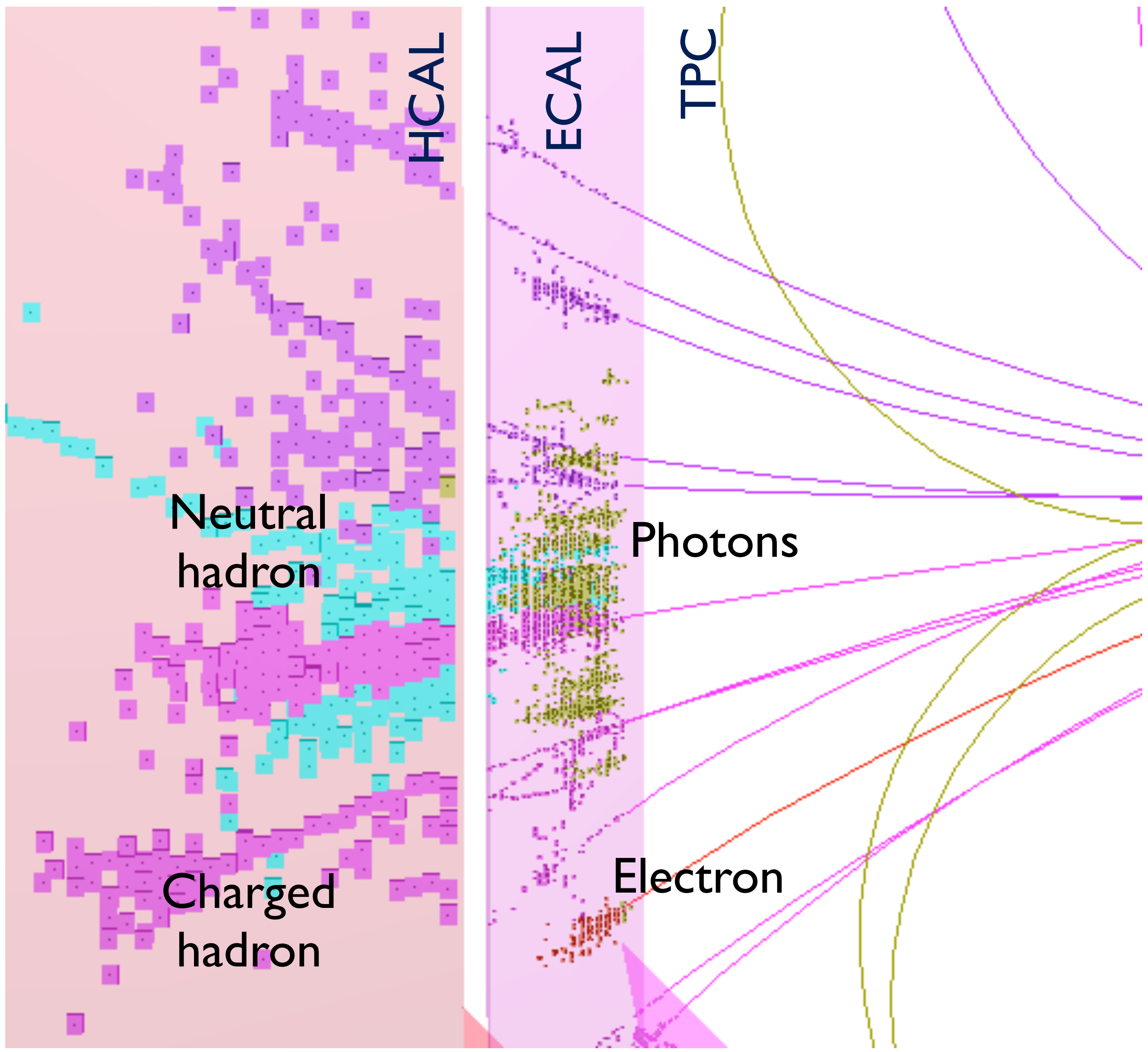
e.g. dedicated muon alg.

1. Cluster hits in muon yoke
2. Associate to inner detector track
3. "Swim" through calorimeter





Typical 250GeV Jet in ILD_o1_v05:



Particle flow objects (PFOs) built from tracks and (associated) clusters using set of simple rules:

- Obtain list of reconstructed particles, with energies and particle ID.
- Calorimeter energy resolution not critical – most energy from tracks.
- Level of mistakes in building particles dominates jet energy resolution.
- Proceed by building jets and studying physics performance.

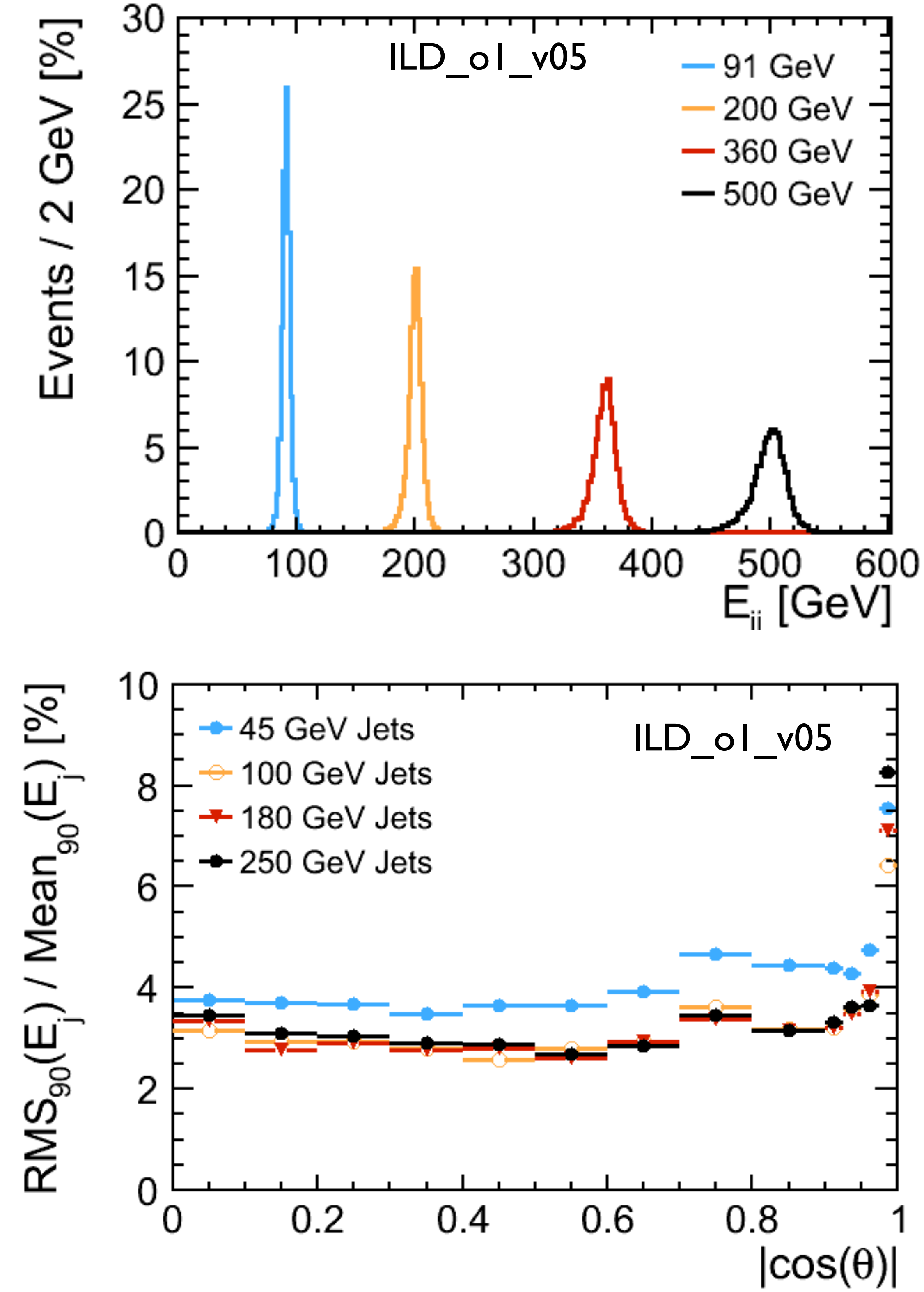
Can now assess performance of fine granularity particle flow using simulation...

Jet Energy Resolution: ILC

- Recall motivation for fine granularity particle flow:
  - Jet energy resolution: $\sigma_E/E < 3.5\%$
- Benchmark performance using jet energy resolution in Z decays to light quarks.
- Use total energy to avoid complications of jet finding and no backgrounds included.
- Current performance, full GEANT4 simulations:

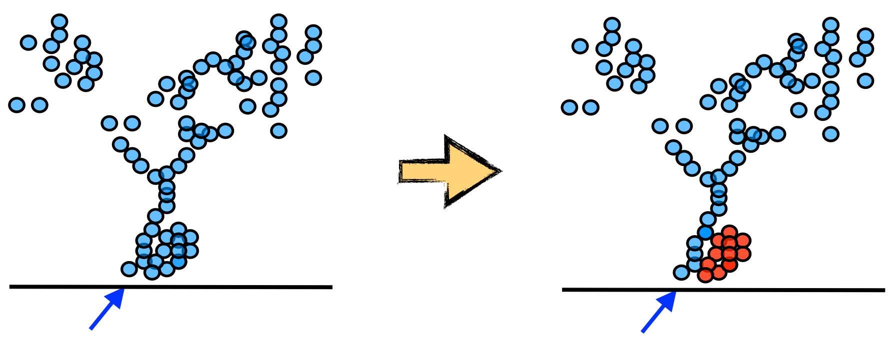
E_j	$RMS_{90}(E_j)$ / $mean_{90}(E_j)$
45 GeV	3.7%
100 GeV	2.8%
180 GeV	2.9%
250 GeV	2.9%

$$\frac{RMS_{90}(E_j)}{mean_{90}(E_j)} = \frac{RMS_{90}(E_{jj})}{mean_{90}(E_{jj})}\sqrt{2}$$



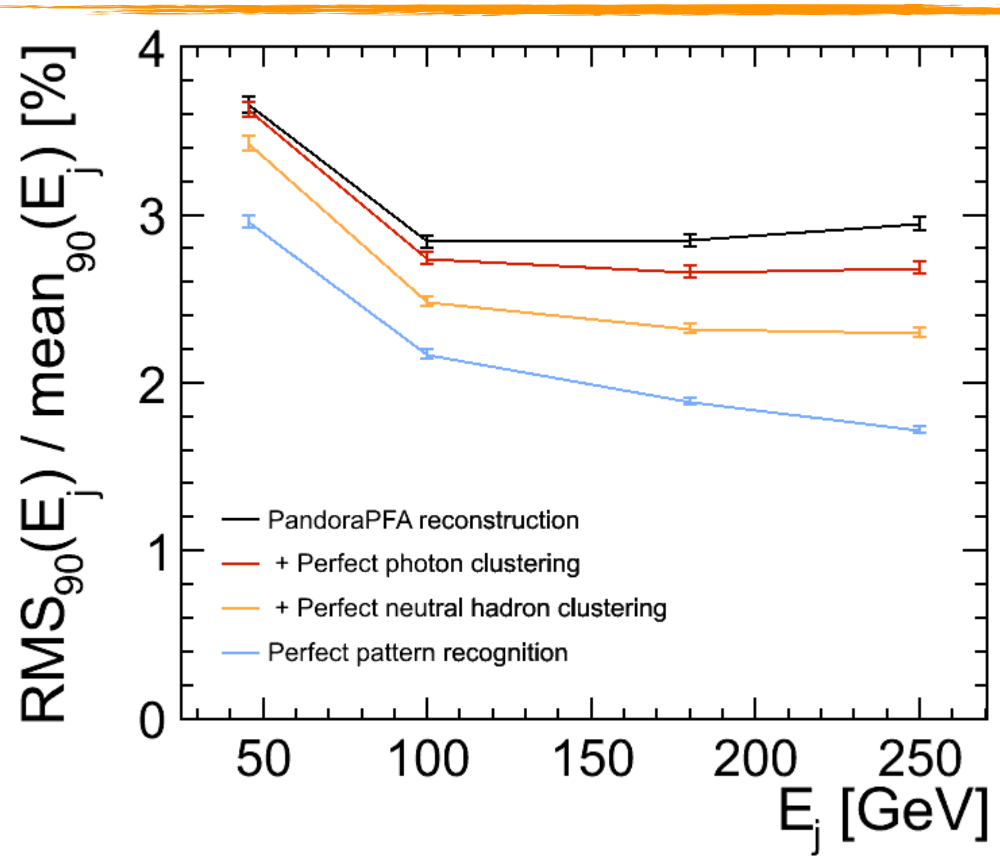
Understanding Resolution

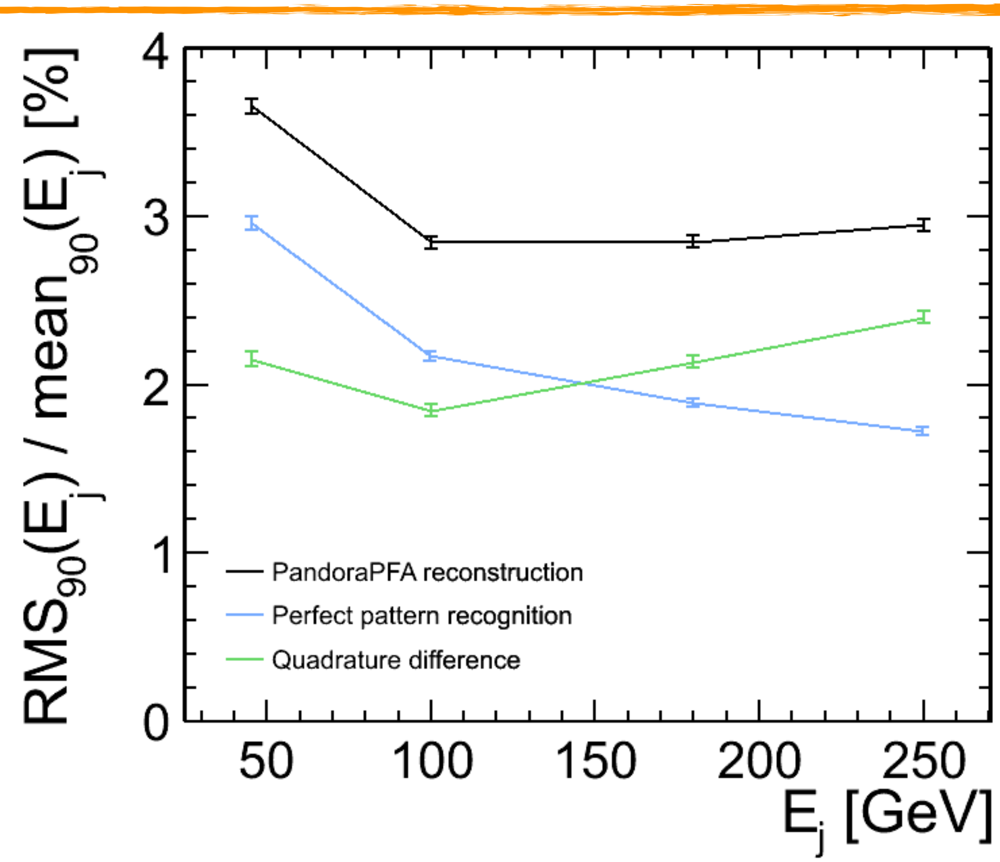
- Switch some standard algs with MC cheating versions to understand resolution:



e.g. Perfect photon reconstruction

- Main performance driver varies with energy:
  - Low energy jets: resolution
  - High energy jets: confusion
  - Cross-over between 100 and 180 GeV
  - Very high energy: leakage will be important





Simulation of Hadronic Showers

- Know that modelling of hadronic showers is far from perfect, so can we believe PFA results?
- Previously compared PandoraPFA/ILD performance using 5 very different GEANT4 physics lists:

Older results, 2010

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 %
rms	4.2 %	3.9 %	3.5 %	2.5 %

- Only a weak dependence < 5% (on the total resolution, not just the hadronic confusion term)

Study suggests Particle Flow is rather robust to modelling of hadronic showers

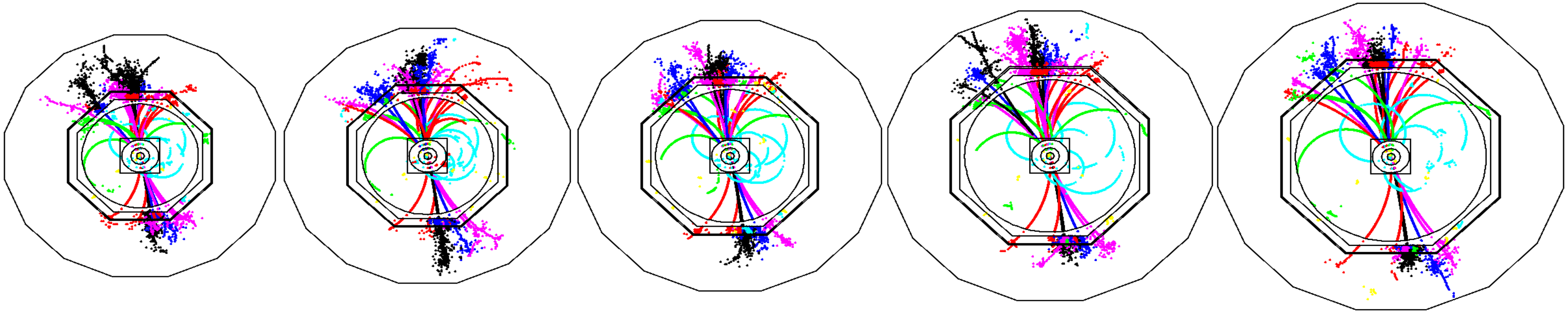
Detector Optimisation

- Calorimeters and solenoid are the main cost drivers for a particle flow detector.

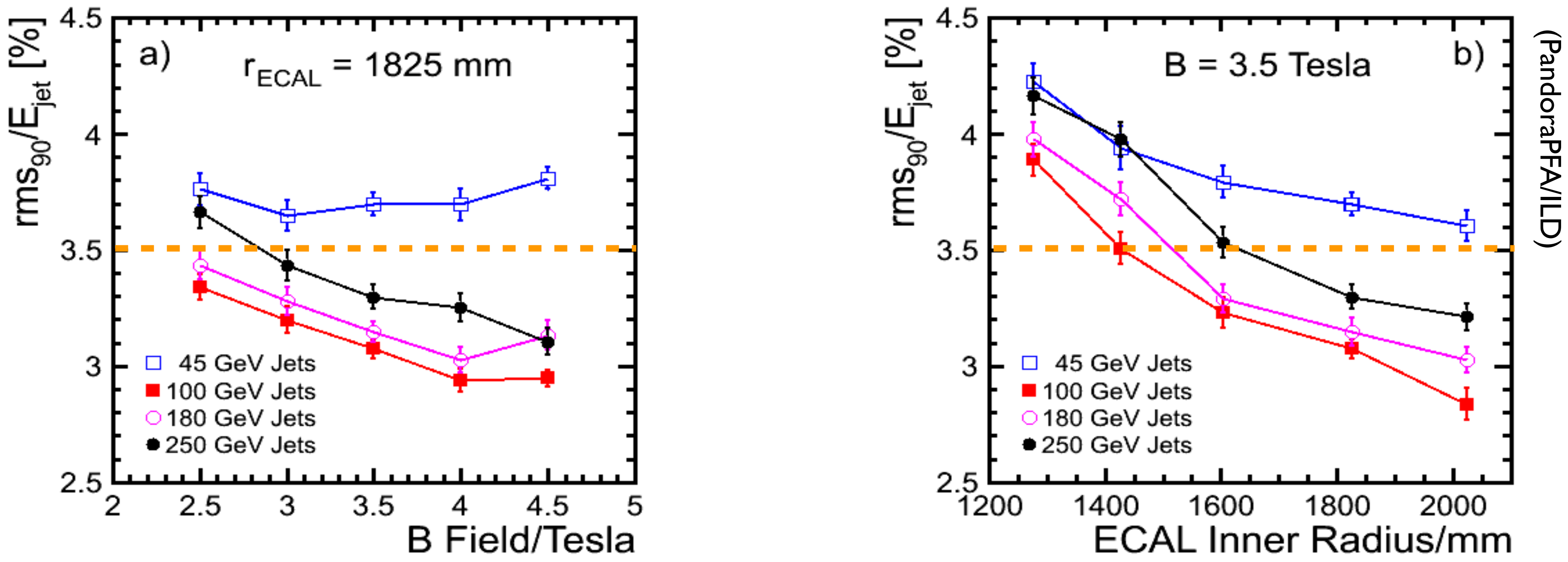
- Most important detector design considerations are:
  - B-field
  - R : inner radius of ECAL
  - L : length, equivalently aspect ratio L/R
  - ECAL and HCAL segmentation
  - HCAL thickness : number of interaction lengths

- Study jet energy resolution as a function of these cost critical issues

e.g. vary ECAL radius and B-field



B-Field and ECAL Inner Radius



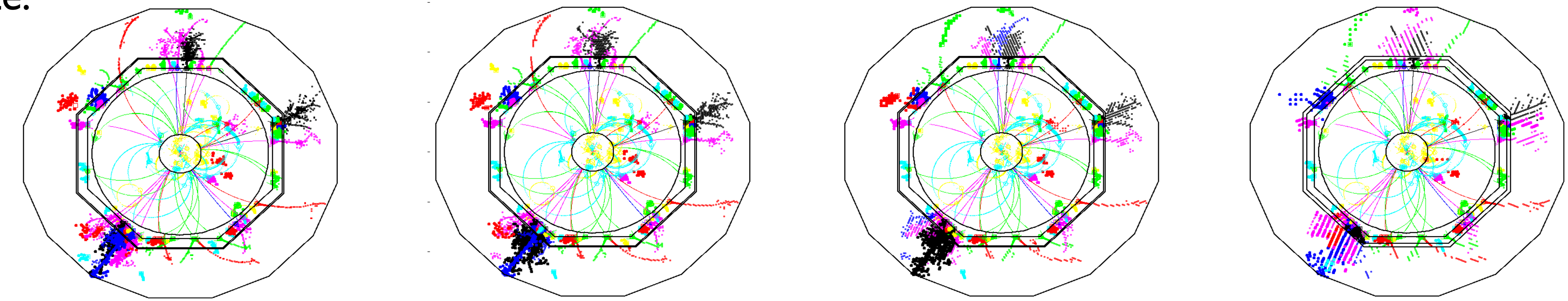
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E/\mathrm{GeV}}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{R}{1825}\right)^{-1.0}\left(\frac{B}{3.5}\right)^{-0.3}\left(\frac{E}{100}\right)^{+0.3}\%$$

Resolution — Tracking — Leakage — Confusion

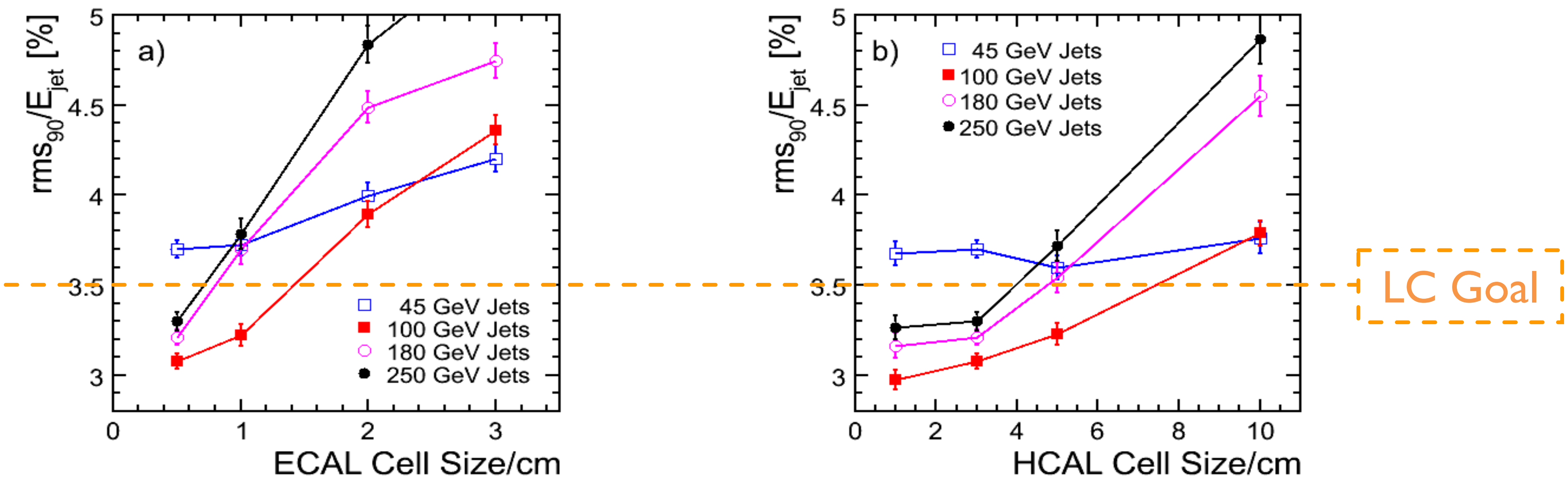
- Confusion $\propto B^{-0.3} R^{-1}$ (1/R dependence "feels right", geometrical factor)
- Detector should be fairly large, very high B-field is less important

Calorimeter Granularity

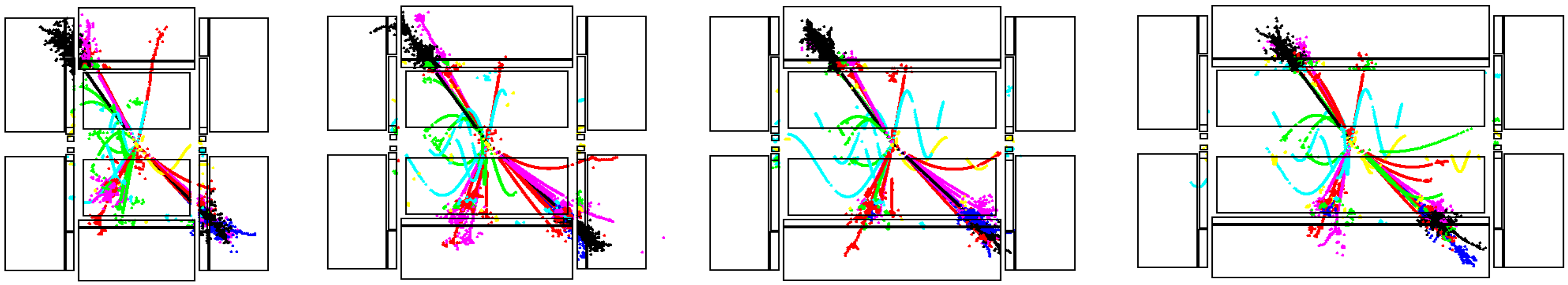
HCAL tile size:

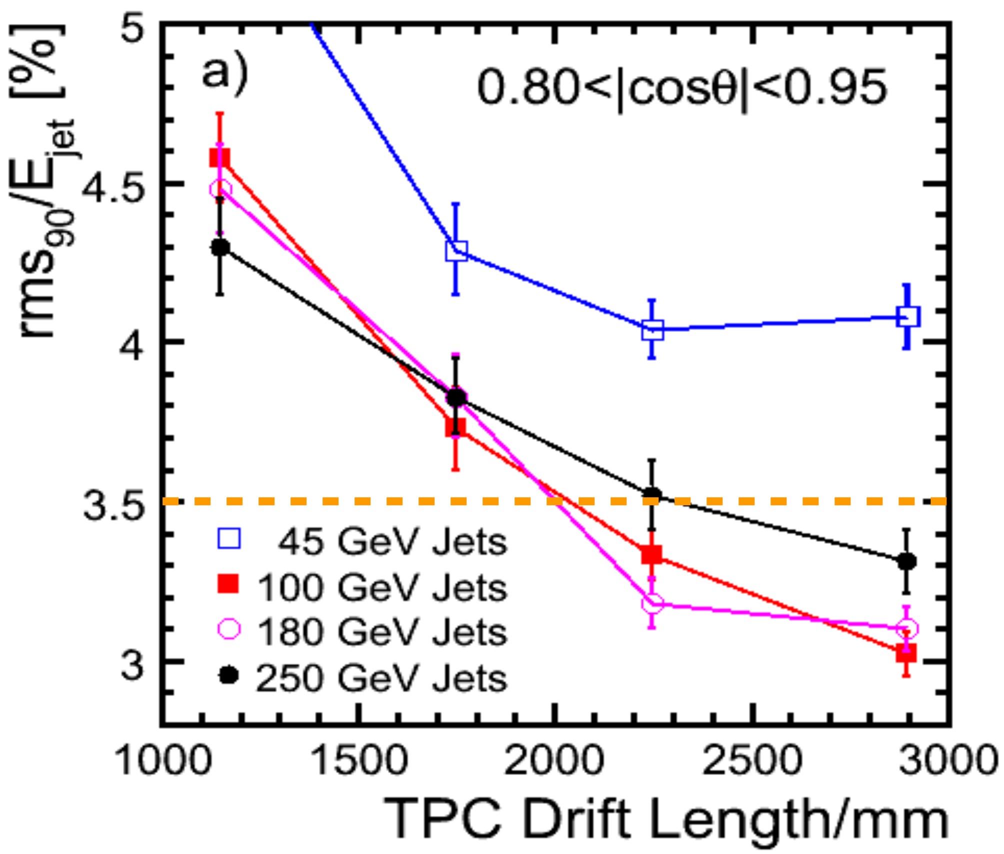


- In ILD detector model vary ECAL Si pixel size and HCAL tile size



Vary detector half-Z:

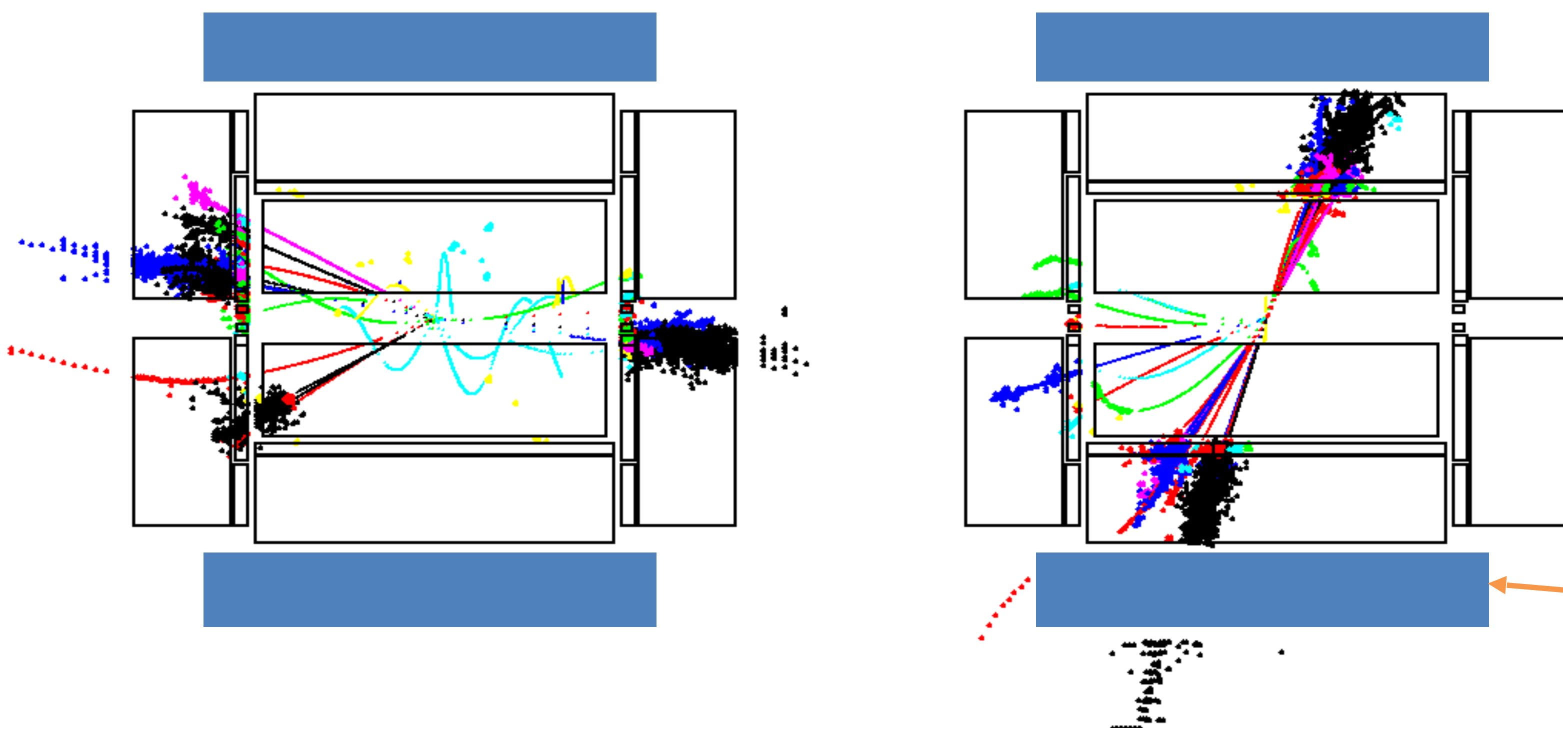




Consider jets in forward region:

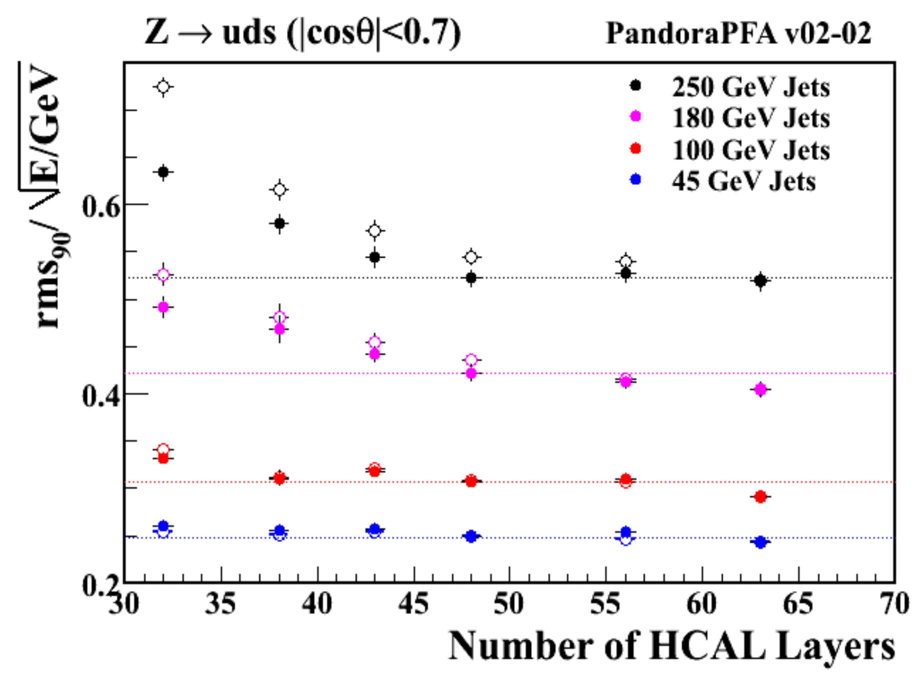
- Performances improves with larger L, as expected
- But diminishing returns in going from 2.2 m → 2.9 m
- Conclude L = 2.2 m is reasonable for ILD

Leakage and HCAL Depth



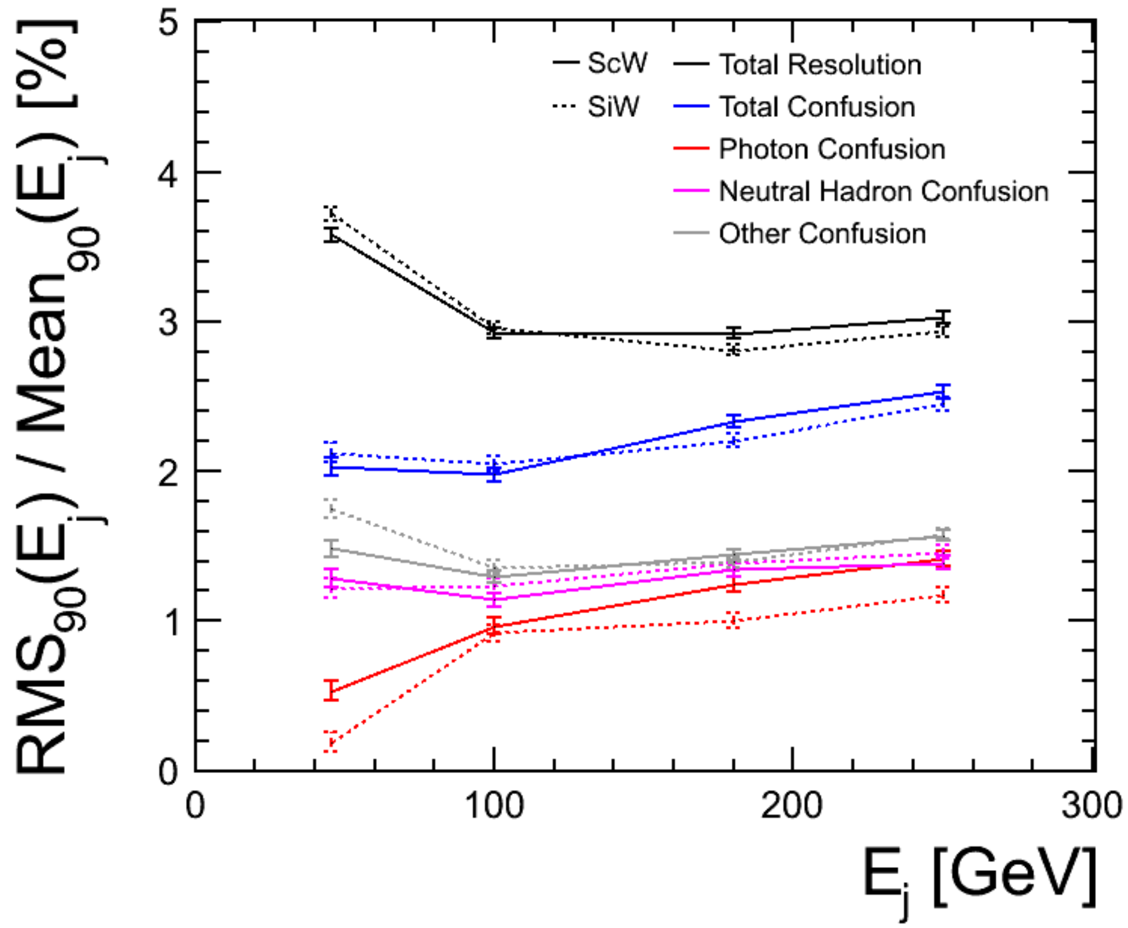
Leakage in coil region

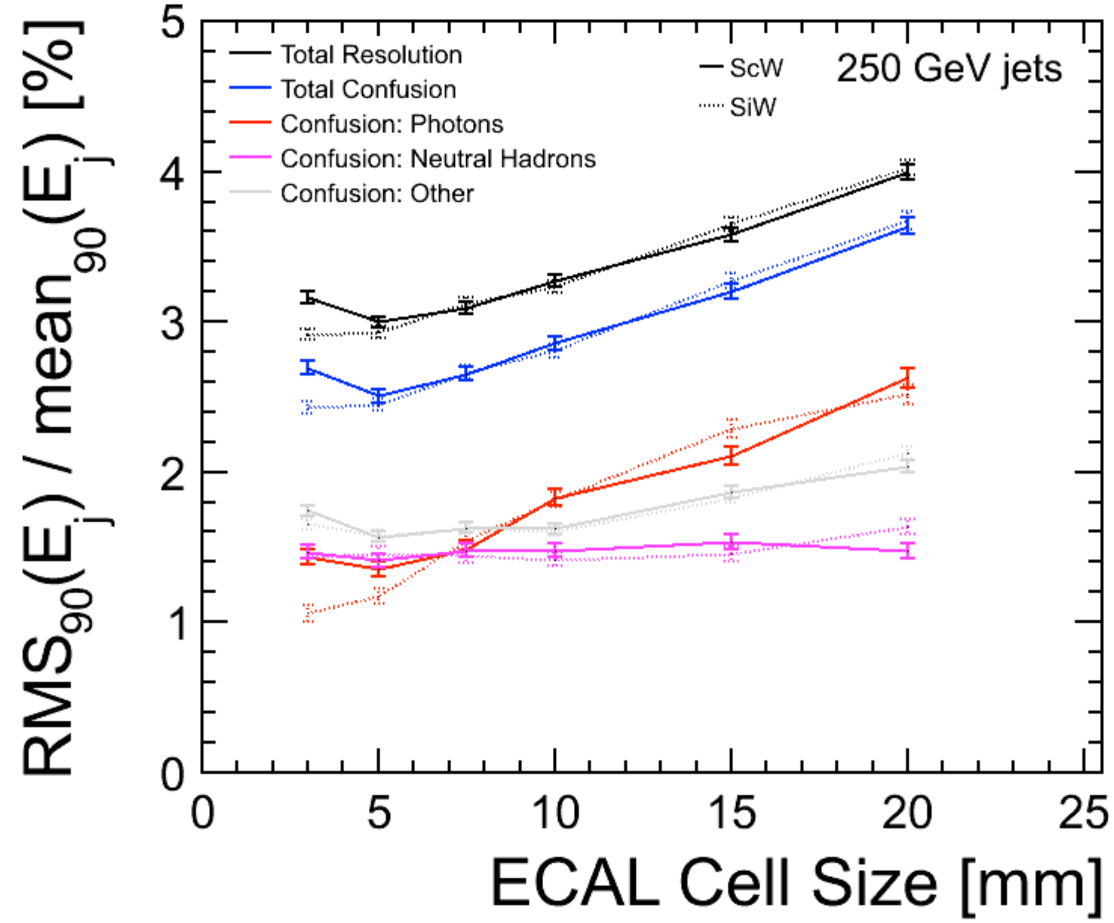
#HCAL Layers	λ_I	
	HCAL	+ECAL
32	4.0	4.8
38	4.7	5.5
43	5.4	6.2
48	6.0	6.8
63	7.9	8.7



- Solid circles: use muon chambers as 'tail-catcher'
- Open circles: no 'tail-catcher'

Current ECAL Studies

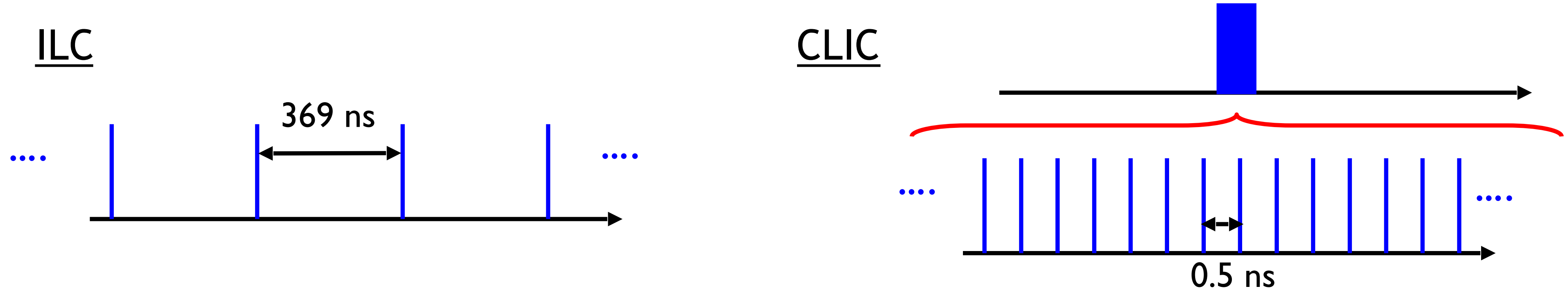




- Studies becoming more sophisticated. Now re-optimising detector, e.g. SiW or ScW ECAL?
- Can examine changes in performance between different algorithm configurations to explicitly determine confusion contributions. Contributions to overall resolution enter in quadrature.
- Total confusion represents difference between best reconstructed resolution and perfect PFA; it comprises neutral hadron confusion, photon confusion and all "other" remaining contributions.

From ILC to CLIC

- Compact Linear Collider provides potential for e^+e^- collisions up to $\sqrt{s}$ = 3 TeV, but the machine environment is much more challenging than ILC:
  - Background levels are high
  - 0.5ns bunch structure means detectors integrate over multiple BX of background



- Significant effort made to complete CLIC Conceptual Design Report. Volume 2 "Physics and Detectors" and Volume 3 "Towards a staged e+e- collider exploring the terascale" now available:
  - http://lcd.web.cern.ch/LCD/CDR/CDR.html
  - Formal physics review, by a panel of experts

- Required detailed simulation and reconstruction, including pile-up from background:
  - Build on existing work developed for ILC.

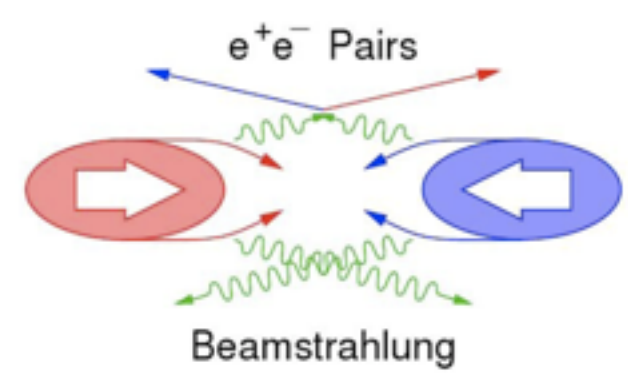
- Performance of Pandora fine-granularity algorithms at CLIC recently documented in publication: **NIM A700:153-162, 2013.** Builds upon original Pandora publication: **NIM A611:025-040, 2009.**

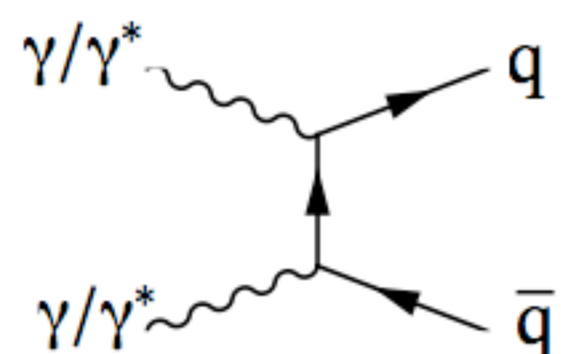
CLIC Machine Environment

	LEP 2	ILC 0.5 TeV	CLIC 0.5 TeV	CLIC 3 TeV
L [$cm^{-2}s^{-1}$]	5×10^{31}	2×10^{34}	2×10^{34}	6×10^{34}
BX/train	4	2670	350	312
BX sep	247 ns	369 ns	0.5 ns	0.5 ns
Rep. rate	50 kHz	5 Hz	50 Hz	50 Hz
L/BX [cm^{-2}]	2.5×10^{26}	1.5×10^{30}	1.1×10^{30}	3.8×10^{30}
$\gamma\gamma\to X$ / BX	neg.	0.2	0.2	3.2
σ_x/σ_y	240 / 4 mm	600 / 6 nm	200 / 2 nm	40 / 1 nm

Drives timing Requirements for CLIC detector

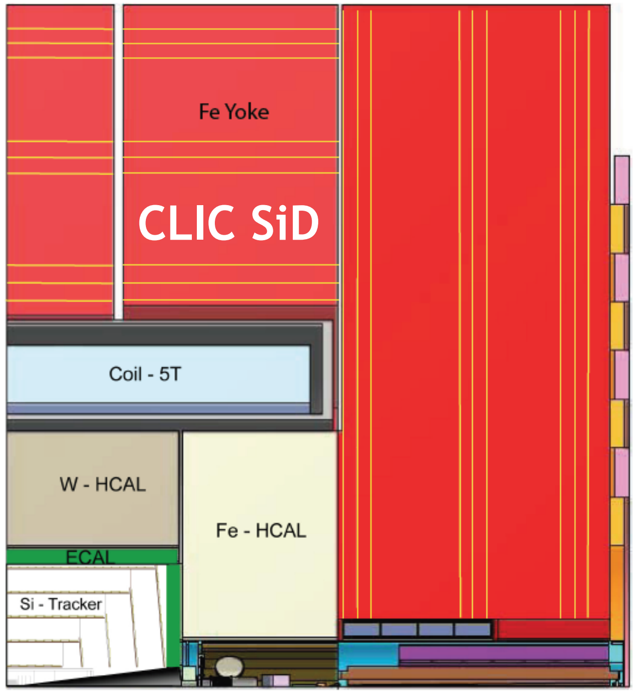
- Beam-related background:
  - Small beam-profile at IP leads to very high E-field
    - Beamstrahlung
    - Pair-background
  - Interactions of real and virtual photons
    - $\gamma\gamma\to$hadrons "mini jets"
    - Integrate over multiple BXs of $\gamma\gamma\to$hadrons
    - 19TeV visible energy per 156ns bunch train

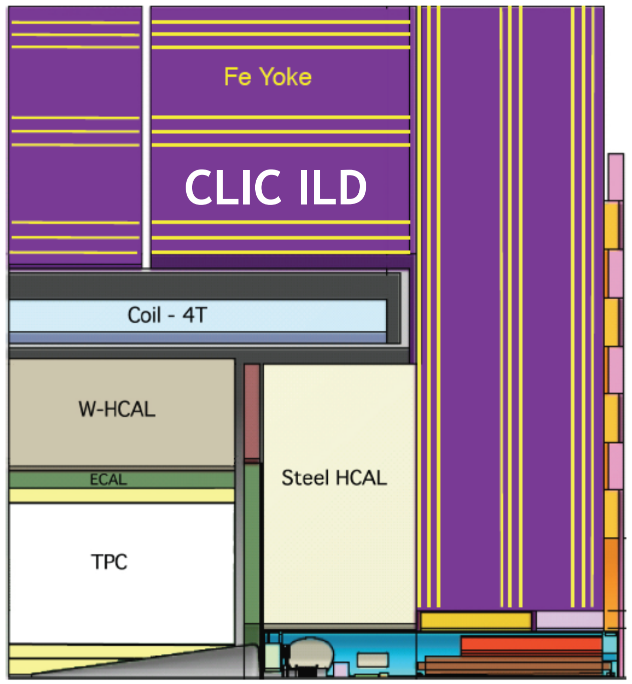




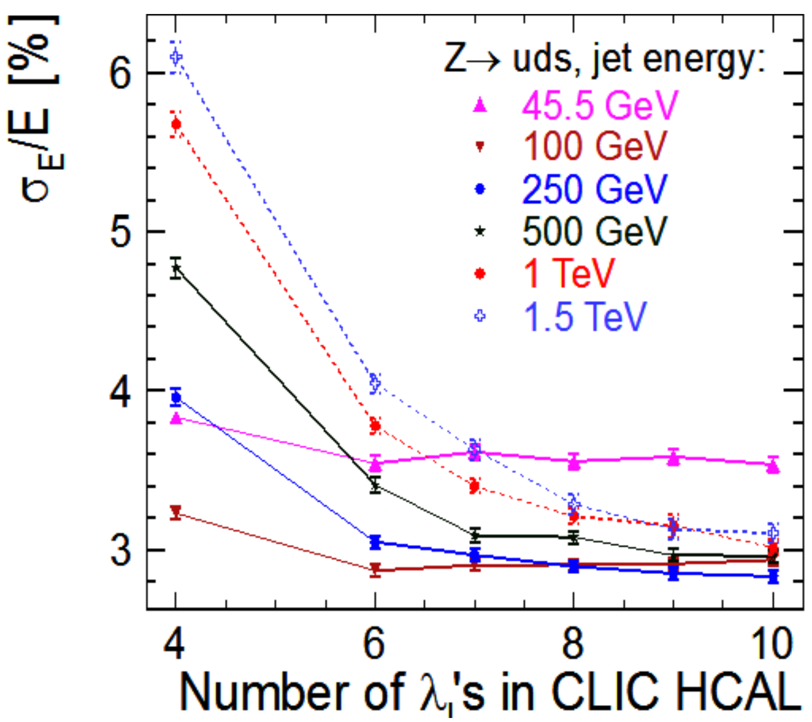
CLIC Detector Modifications

- Detector requirements for CLIC:
  - All those for the ILC + **timing**
  - Optimised for CLIC backgrounds
- Starting point:
  - Validated ILC detectors, ILD and SiD
  - Fine granularity calorimetry:
    - Jet energy resolution
    - Improved background rejection



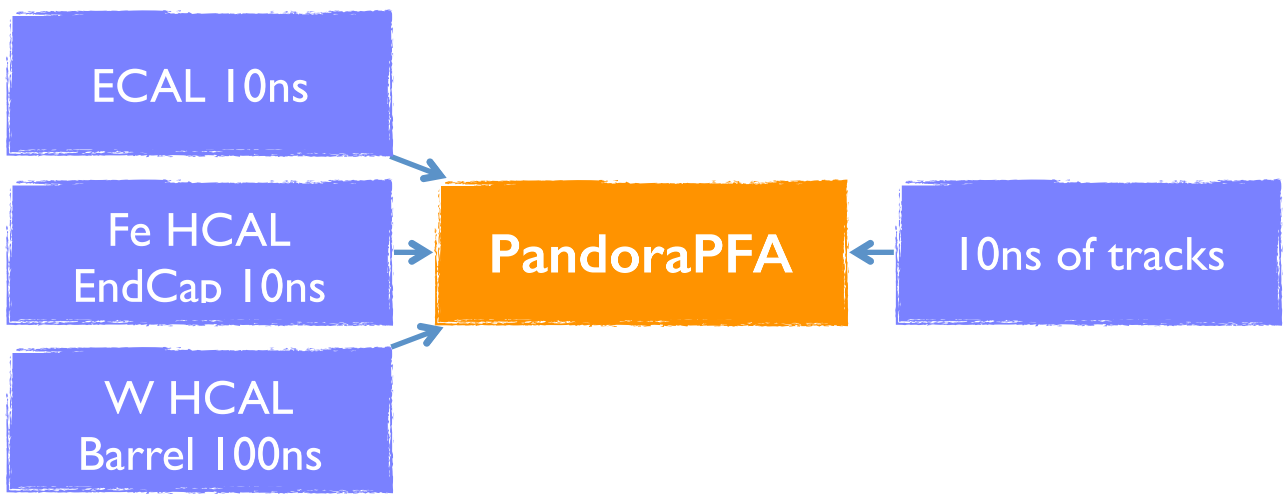


- Main modifications:
  - Location of vertex detector/beam pipe to account for increased backgrounds
  - Increased HCAL depth to contain showers; jet energy resolution studies: 7.5 λ_I HCAL
  - To maintain reasonable solenoid radius, use Tungsten as absorber in barrel



CLIC Background Suppression

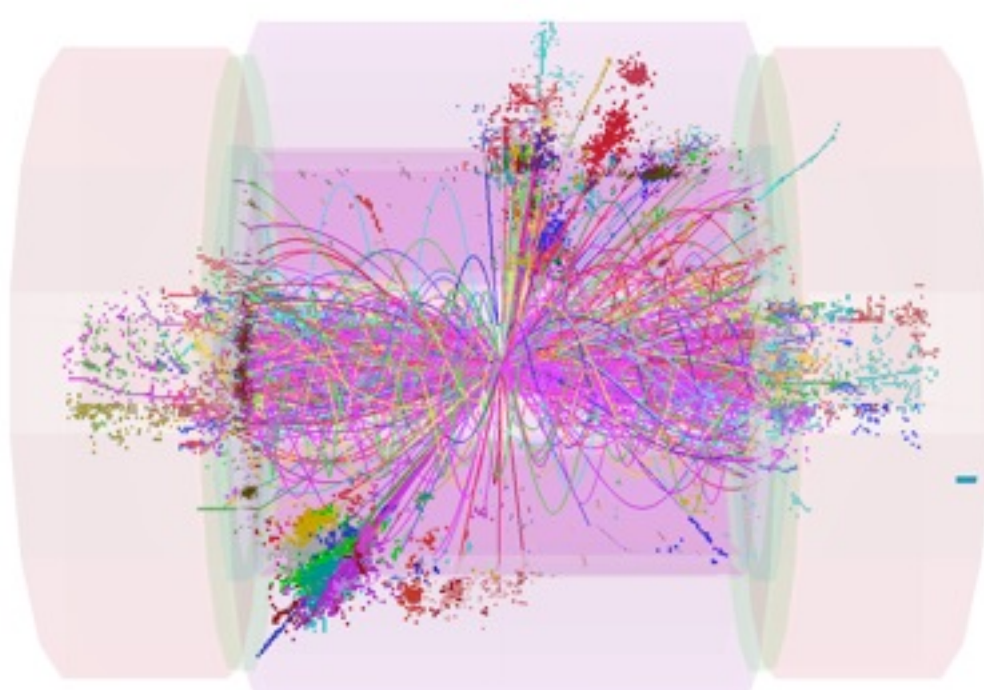
1. CLIC 3TeV input to reconstruction:



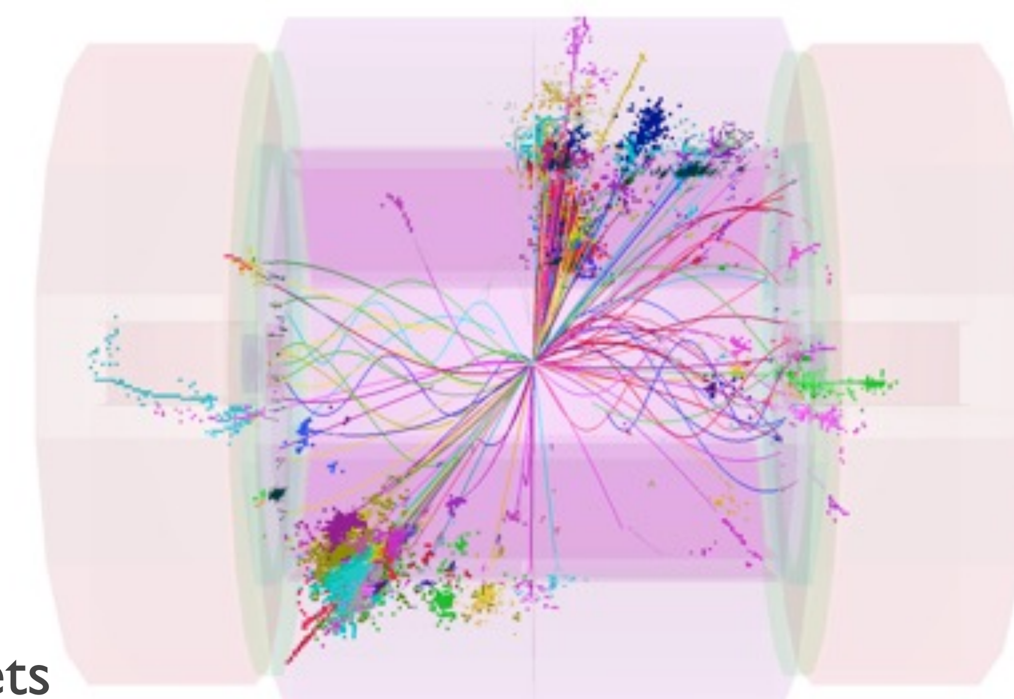
Subdetector	Reco Window	Hit Resolution
ECAL	10 ns	1 ns
Fe HCAL EndCap	10 ns	1 ns
W HCAL Barrel	100 ns	1 ns
Si Detectors	10 ns	$10/\sqrt{12}$
TPC (CLIC_ILD)	Entire train	n/a

2. Reconstructed particles, bkg energy 1.2TeV:

3. Selected particles, bkg energy 85GeV:



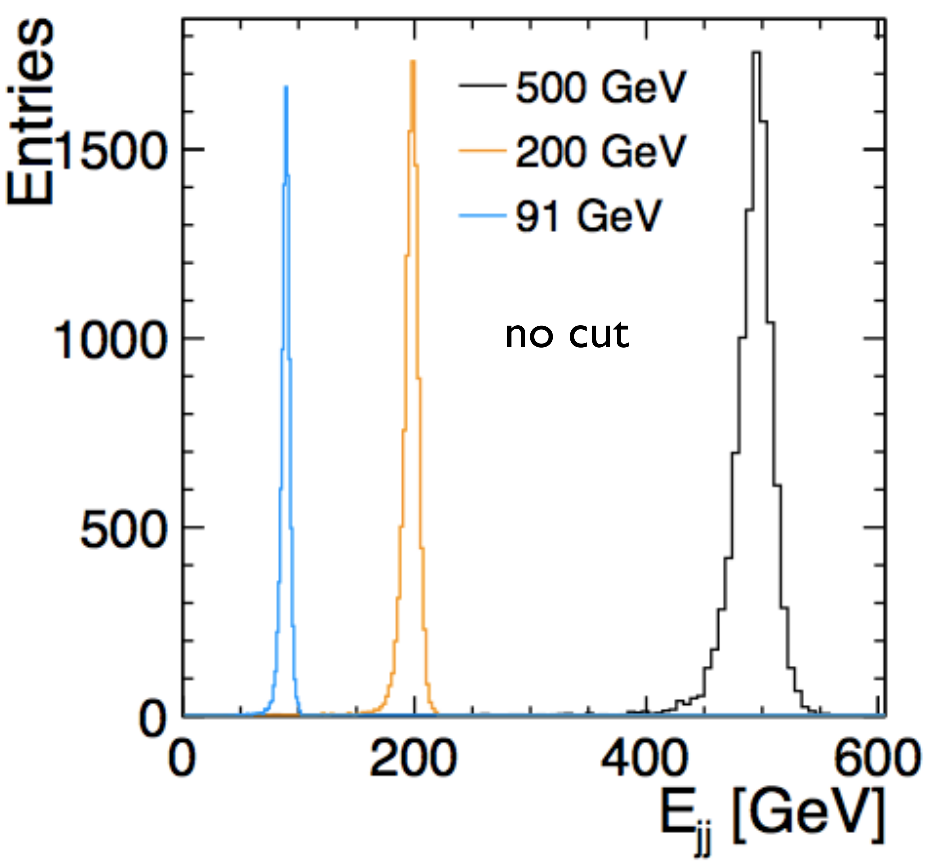
Apply timing and p_T cuts to reject background PFOs

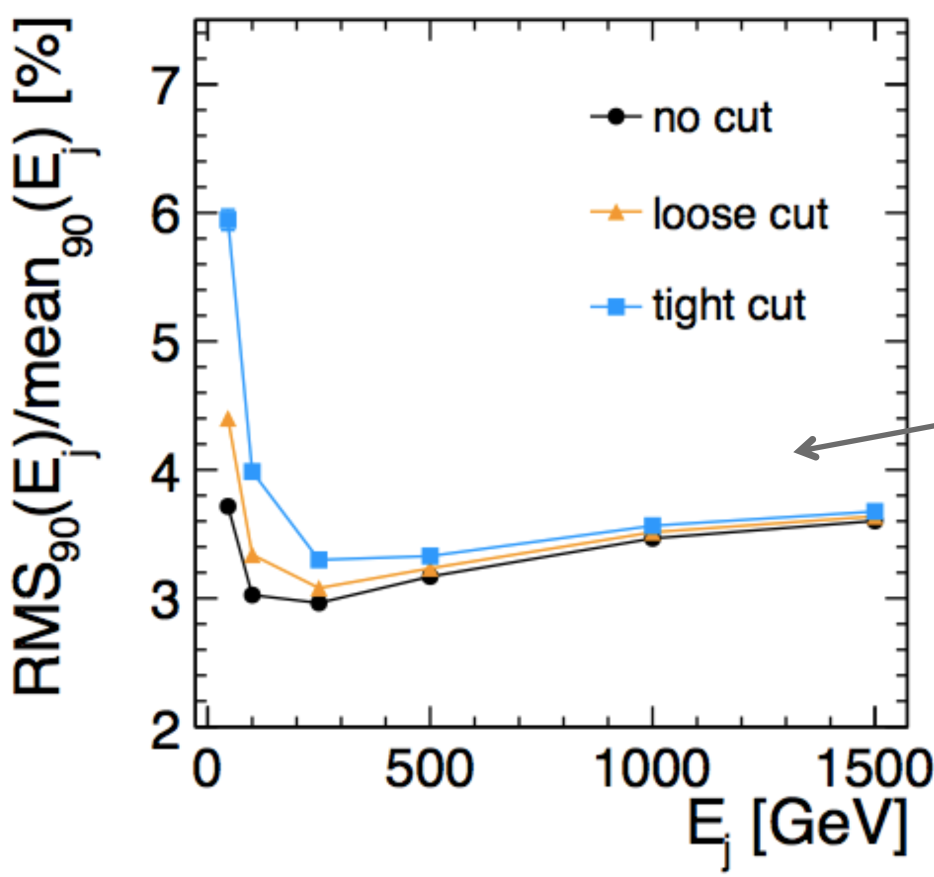


$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t} \to 8$ jets

Jet Energy Resolution: CLIC

- To assess jet energy resolution, and impact of PFO selection cuts, use samples of Z decays to light quarks without any overlaid backgrounds. Consider jet energies in range 45-1500GeV.
- At low energies, PFO selection cuts have significant impact on jet energy resolution. At higher jet energies, the jet energy reconstruction performance is basically unaffected by the cuts.





Jets in barrel region only, $|\cos(\theta)| < 0.7$

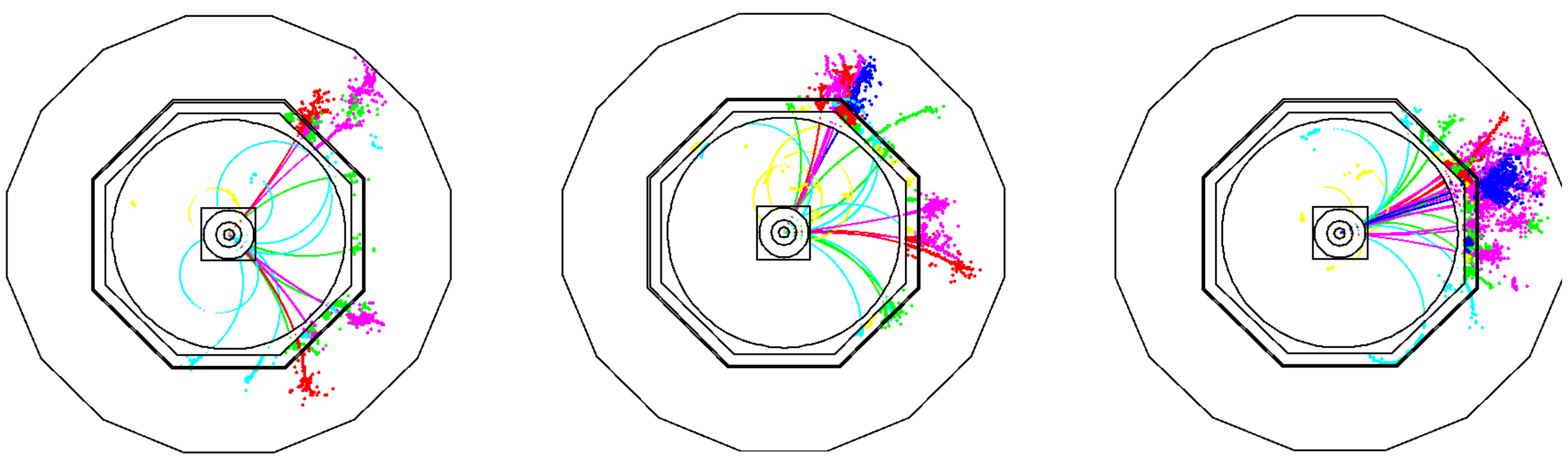
No cuts: resolution better than ~3.7% for all energies considered

CLIC_ILD_CDR

W/Z Reconstruction

- Return to an important aim of fine granularity particle flow calorimetry and examine ability to separate W/Z hadronic decays via di-jet invariant mass reconstruction at CLIC.
- On-shell W/Z decay topology depends on energy, so obtain “mono-jet” topology at high energies:
  - Particle multiplicity does not change
  - Boost means higher particle density

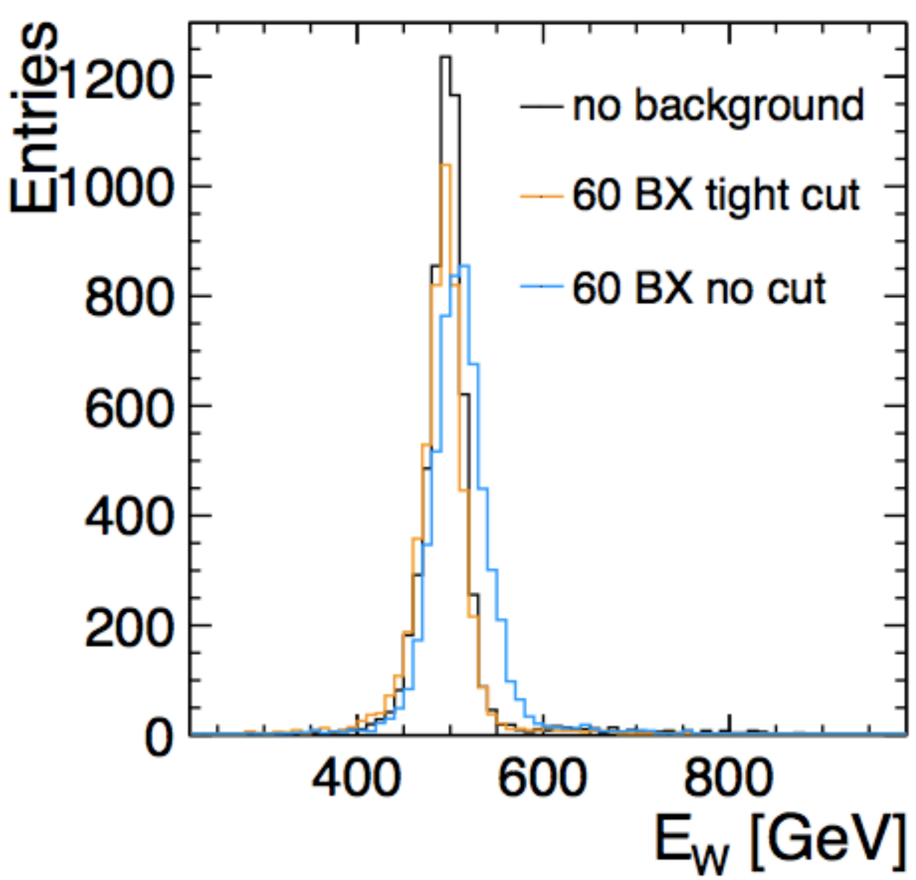
more confusion!

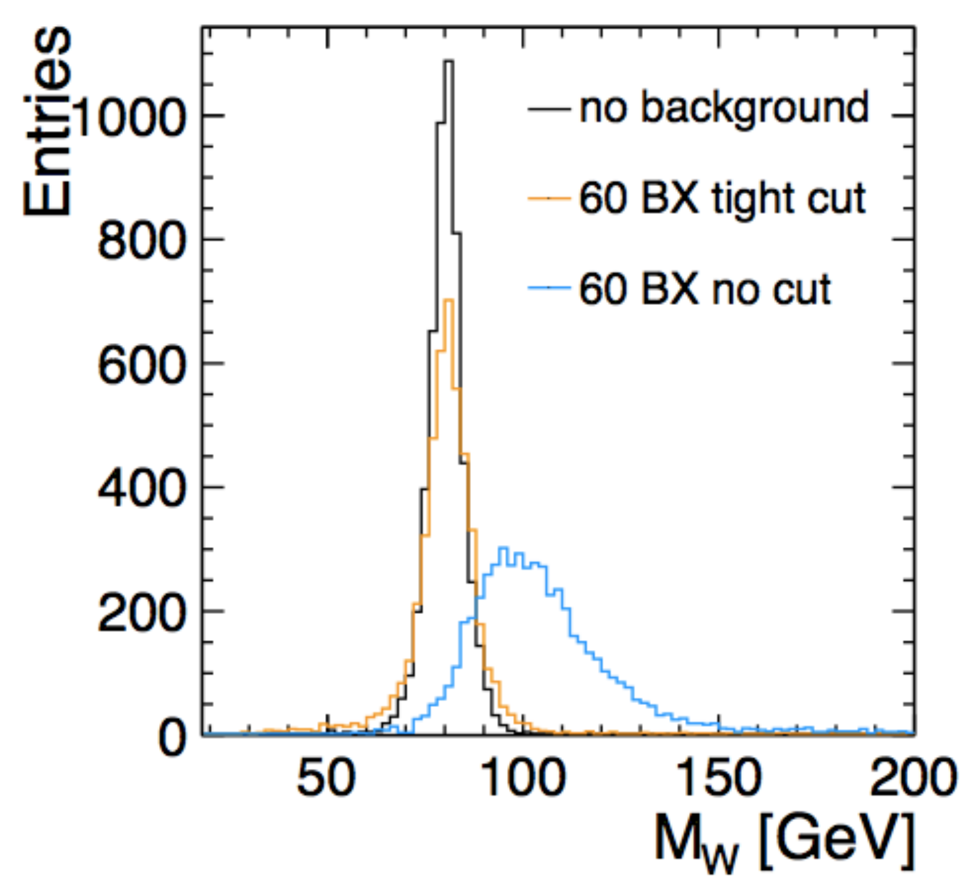


125 GeV Z | 250 GeV Z | 500 GeV Z | 1 TeV Z

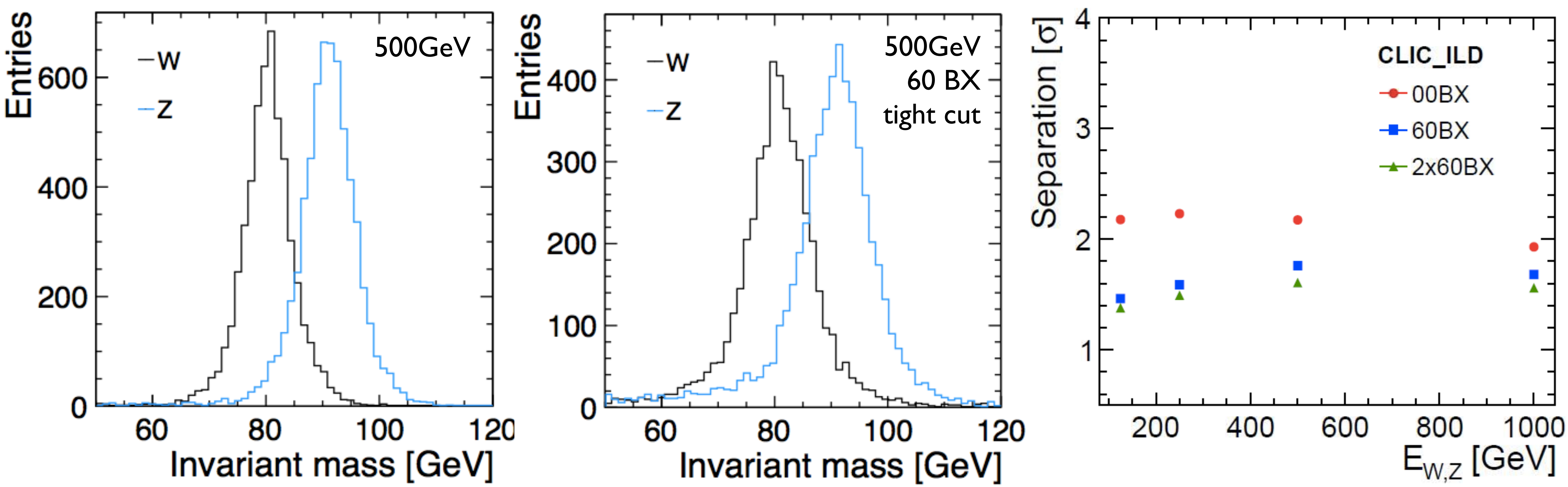
W Reconstruction

- W samples provided by $e^+e^- \rightarrow WW \rightarrow \mu\nu qq$ events in energy range 125-1000GeV. Used full GEANT4 simulation, PandoraPFA reconstruction and considered different levels of background.
- Additional reconstruction and selection procedures: removal of muon, removal of neutral fragments from background, jet reconstruction (`kt` algorithm) and jet angular selection cuts.



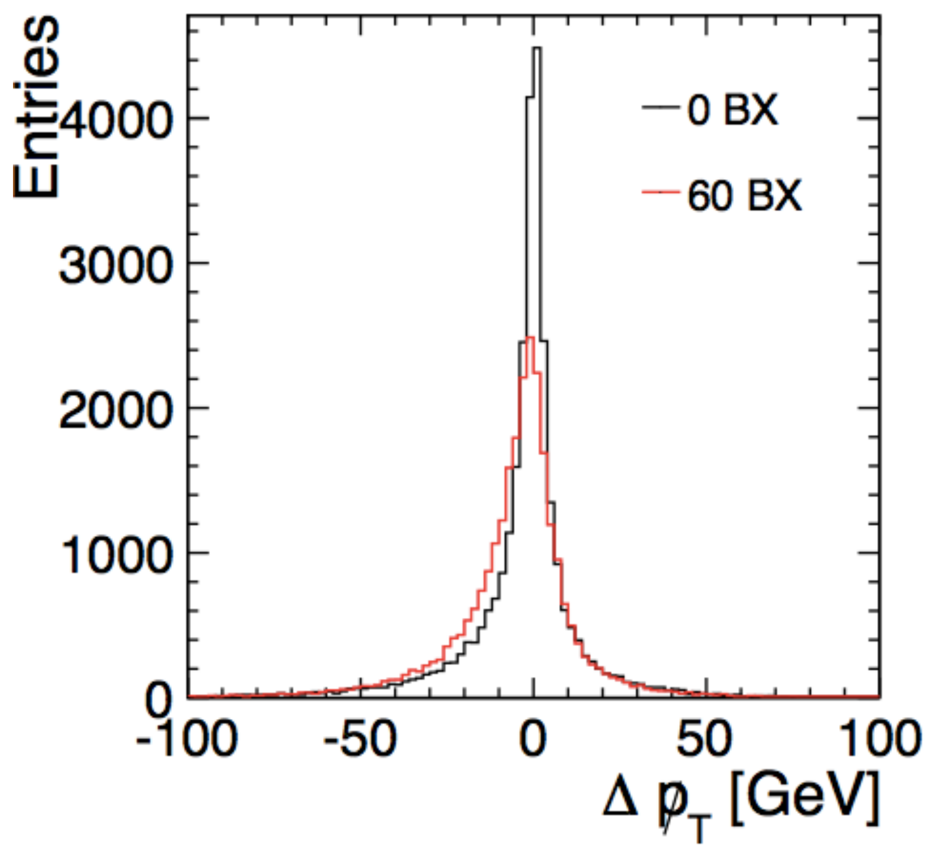


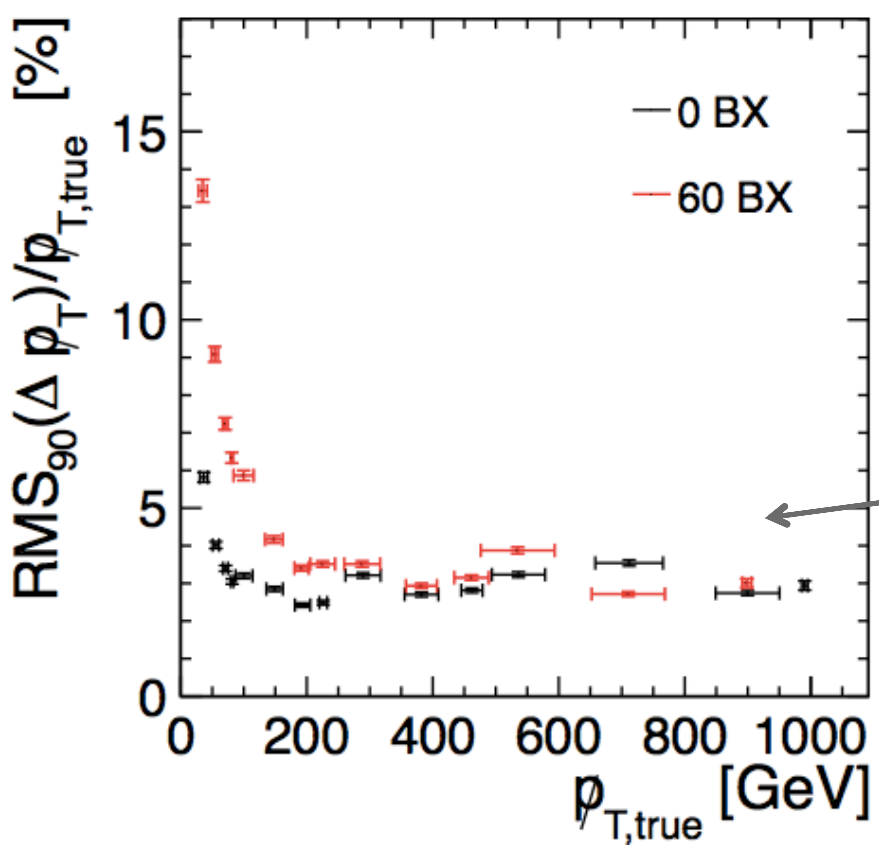
- The di-jet mass distributions obtained from the $e^+e^- \rightarrow WW \rightarrow \mu\nu qq$ event samples were then compared with those obtained from $e^+e^- \rightarrow ZZ \rightarrow \nu\nu qq$ event samples.
- Without background a 2σ separation is maintained for W/Z energies between 125-1000GeV. The separation is reduced to about 1.7σ when 60BX of $\gamma\gamma \rightarrow$ hadrons background is included.



Missing p_T Resolution

- Reconstruction of missing momentum important in many physics analyses. The missing p_T resolution was quantified using $e^+e^- \rightarrow ZZ \rightarrow \nu\nu qq$ samples.
- Missing p_T was calculated from the vector sum of the momenta of all particles in the reconstructed jets. This was compared to the generated missing p_T of the two neutrinos.

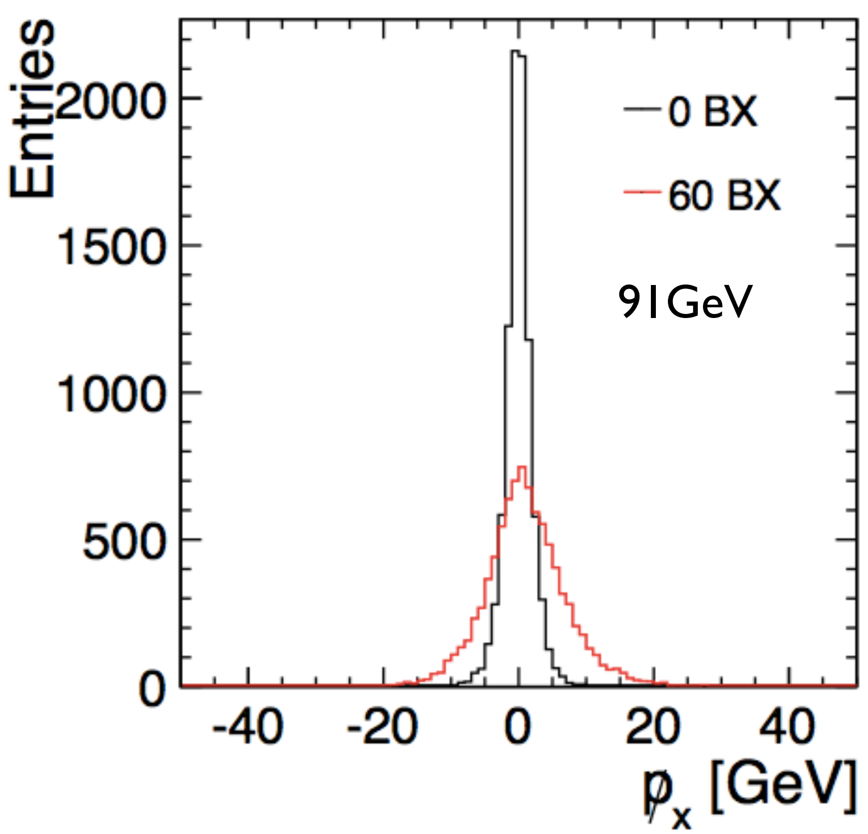


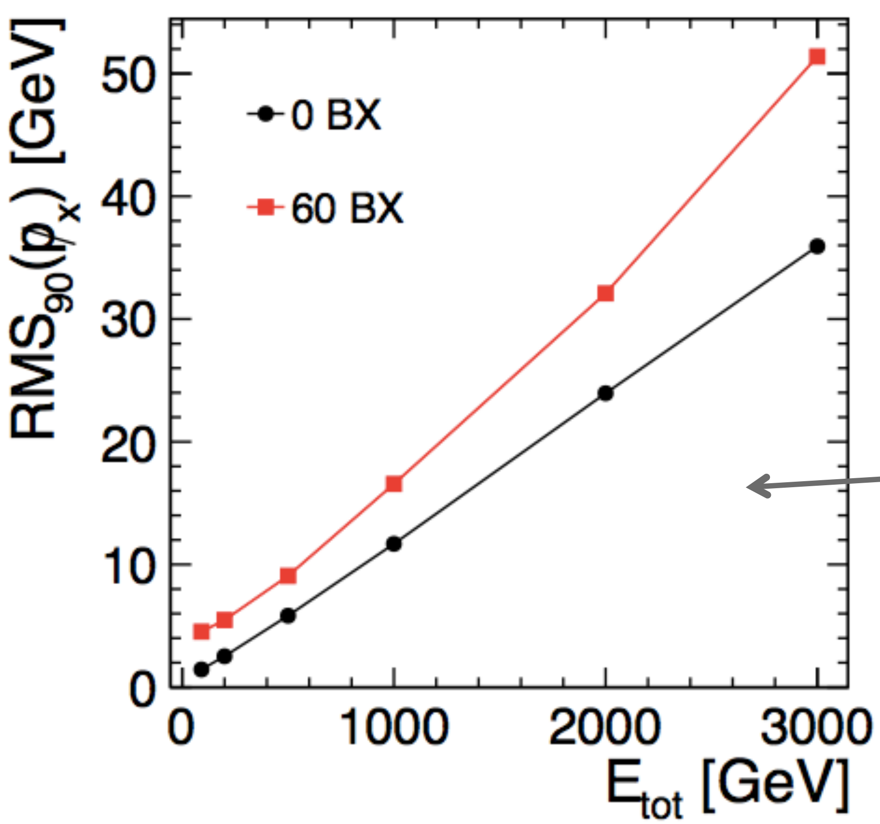


Missing p_T can be measured with an asymptotic precision of ~3% for true missing p_T>100GeV

Fake Missing Momentum

- Fake missing momentum can result from limitations in detector coverage and from failed reconstruction of particle momenta. Quantified using samples of Z decays to light quarks.
- Examine distribution of single component (e.g. x-component) of the fake missing momentum with and without background. Resolution then obtained by calculating RMS_{90} of distribution.





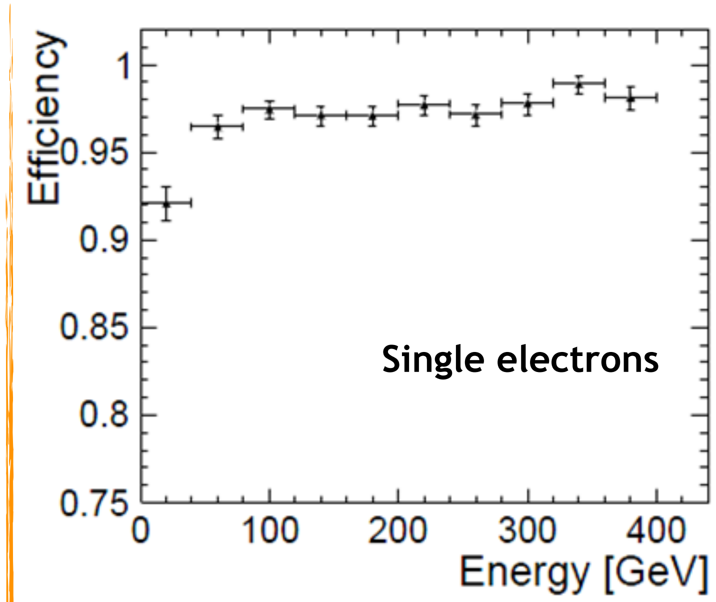
Level of fake missing momentum (in one coordinate) is approx. 1-2% of event energy

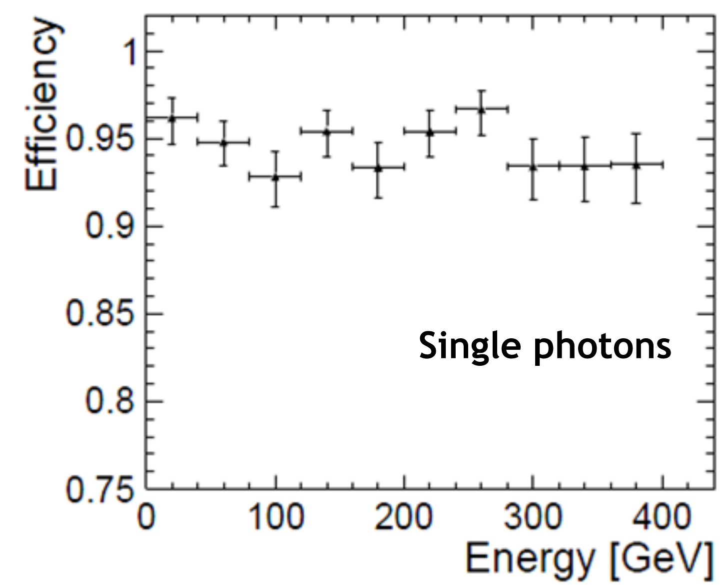
Particle Identification

- Pandora algorithms perform id of charged leptons and photons.
- For CLIC CDR, calculated particle id efficiency for different samples:

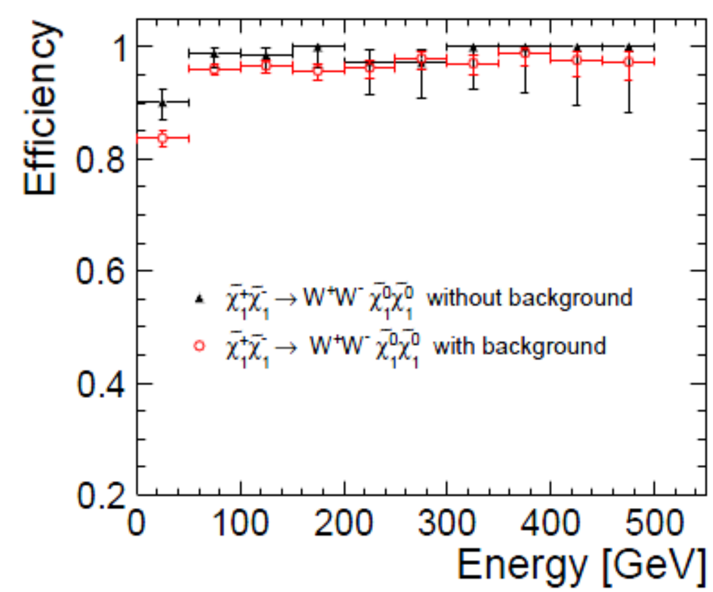
$$\text{Particle ID Efficiency} = \frac{\text{Matched Particles}}{\text{Findable Particles}}$$

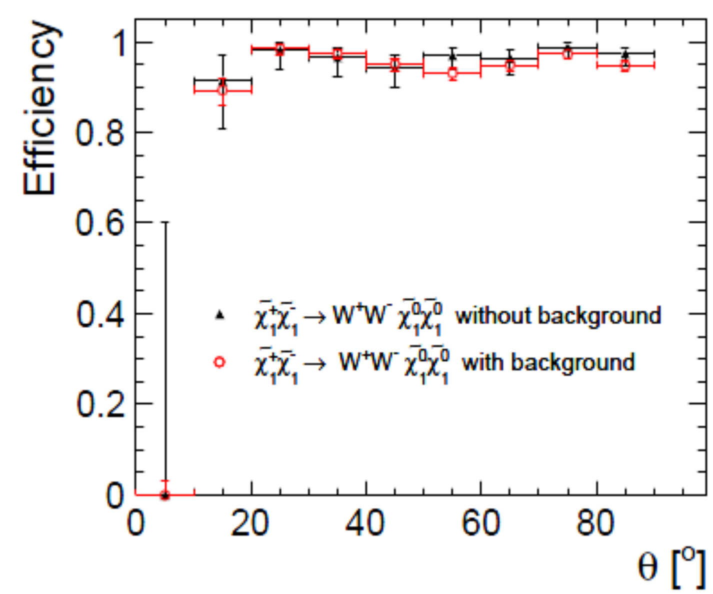
- Matched particle: reconstructed PFO of same type and charge within cone of 2° around a generated particle.
- Findable particle: generated particle of a particular type, with energy > 7.5GeV and 8° < θ < 172°.



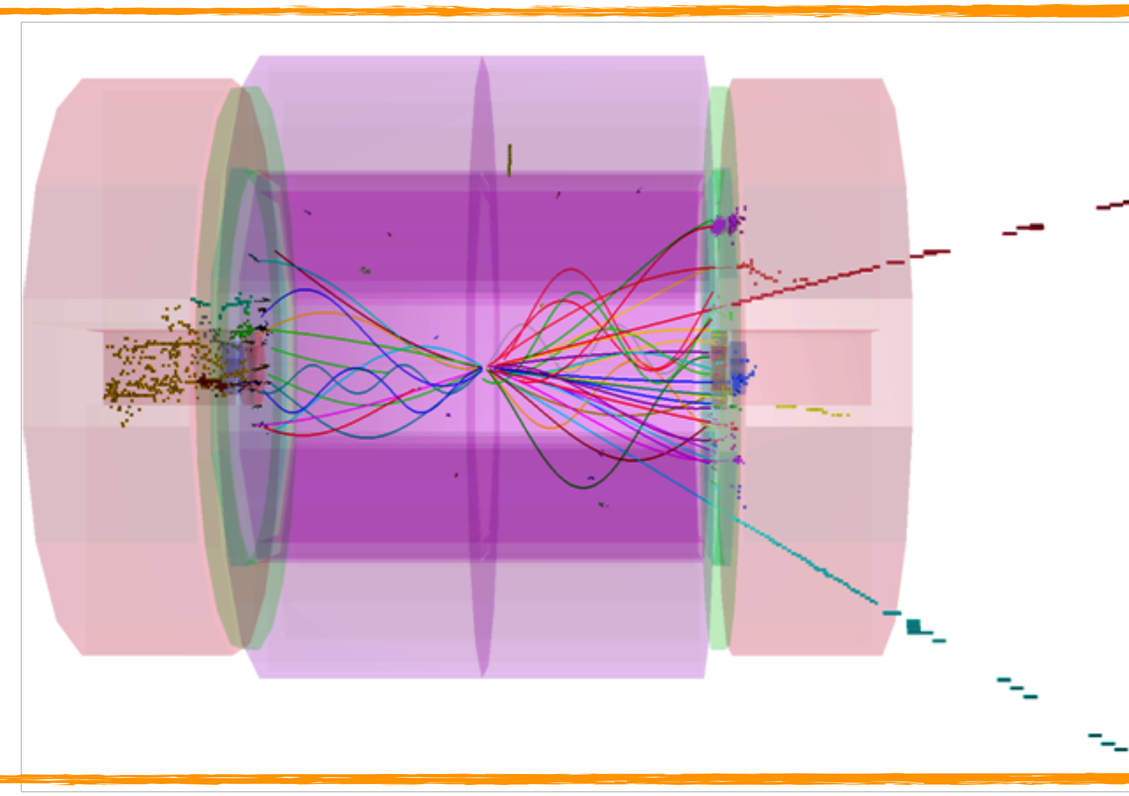


Muon id efficiency, for $e^+e^-\to\tilde{\chi}^+\tilde{\chi}^-\to W^+W^-\chi^0\chi^0$ samples at $\sqrt{s}$=3TeV with and w/o background:



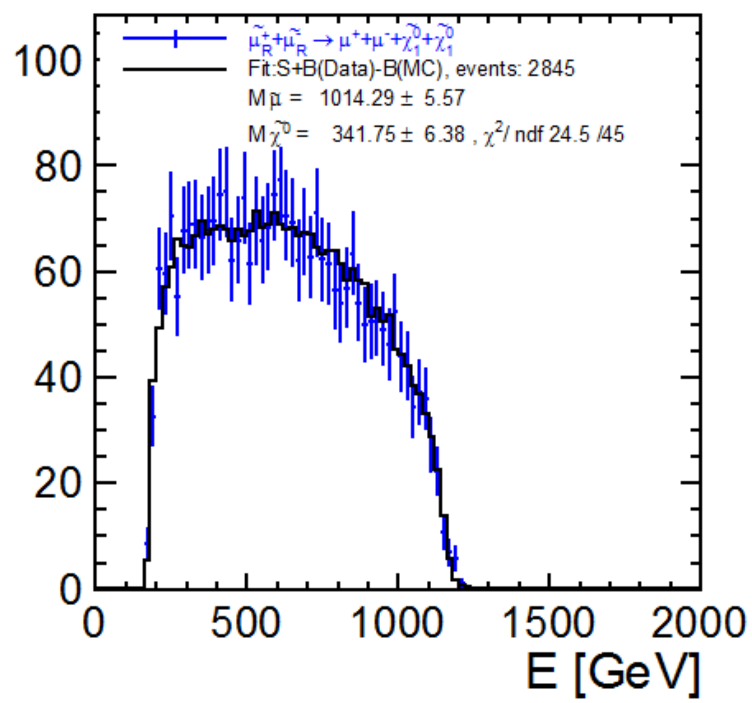


- Slepton production at CLIC very clean
- Use SUSY model II: slepton masses ~1 TeV
- Channels studied include:
  - $e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$
  - $e^+e^- \to \tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$
  - $e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e \to e^+e^-W^+W^-\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$
- Acoplanar leptons and missing energy



- Masses from analysis of endpoints of energy spectra:

e.g. smuon production



All channels combined

$$
\begin{aligned}
m(\tilde{\mu}_R) &: \pm 5.6\,\mathrm{GeV} \\
m(\tilde{e}_R) &: \pm 2.8\,\mathrm{GeV} \\
m(\tilde{\nu}_e) &: \pm 3.9\,\mathrm{GeV} \\
m(\tilde{\chi}_1^0) &: \pm 3.0\,\mathrm{GeV} \\
m(\tilde{\chi}_1^\pm) &: \pm 3.7\,\mathrm{GeV}
\end{aligned}
$$

CLIC Gaugino Pair Production

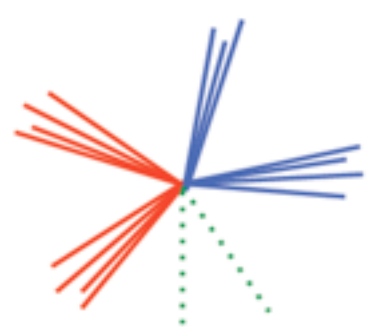
- Have also demonstrated power of particle flow in more demanding physics analyses, e.g.

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

- Pair production and decay:

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

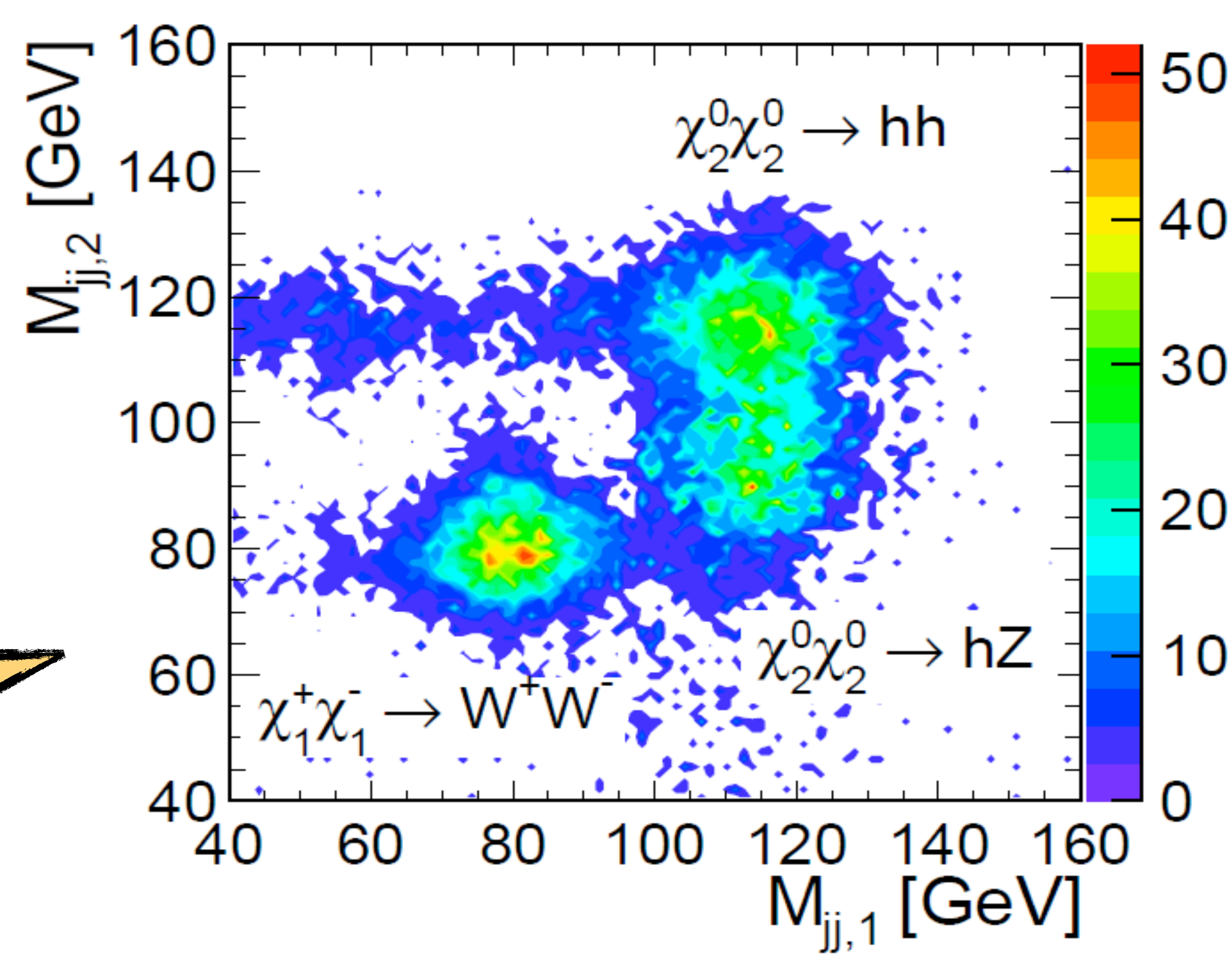
- Largest BR decay has same topology for all final states:



- Separate using di-jet invariant masses:

$$m(\tilde{\chi}_1^\pm) \;:\; \pm 7\,\mathrm{GeV}$$
$$m(\tilde{\chi}_2^0) \;:\; \pm 10\,\mathrm{GeV}$$

Full Simulation with background



CLIC Benchmark Physics Analyses

- Comprehensive list of benchmark physics processes were studied for CLIC CDR, using full reconstruction with background.
- Aim: to demonstrate that an experiment operating at the CLIC accelerator can deliver precision physics measurements.
- Currently working towards comprehensive publication on Higgs physics at CLIC, see e.g. http://arxiv.org/abs/1307.5288
- Role of Pandora Particle Flow Calorimetry crucial.

Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}	 1.4 TeV 1.5 ab^{-1}	 3.0 TeV 2.0 ab^{-1}
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(HZ) \times BR(H \to \text{invisible})$	Γ_{inv}	tbd	–	–
ZH	$H \to b\bar{b}$ mass distribution	m_H	tbd	–	–
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(HZ) \times BR(Z \to \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(HZ) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1%†	–	–
ZH	$\sigma(HZ) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	5%†	–	–
ZH	$\sigma(HZ) \times BR(H \to gg)$		6%†	–	–
ZH	$\sigma(HZ) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	5.7%	–	–
ZH	$\sigma(HZ) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	2%†	–	–
ZH	$\sigma(HZ) \times BR(H \to ZZ^*)$	$g^2_{HZZ}g^2_{HZZ}/\Gamma_H$	tbd	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	3%†	0.3%	0.2%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	–	2.9%	2.7%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		–	1.8%	1.8%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	3.7%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	29%*	16%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		–	15%*	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		–	tbd	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	tbd	1.1%*	0.8%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–	3%†	2%†
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	–	1%†	0.7%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	–	8%	tbd
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	–	7%*	3%*
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	–	28%	16%
$HH\nu_e\bar{\nu}_e$	with -80% e^- polarization	λ	–	21%	12%

Summary

- Fine Granularity Particle Flow Calorimetry is the baseline for the detector at the ILC or CLIC:
  - Such a detector can be built (at a cost).
  - Would provide unprecedented performance.

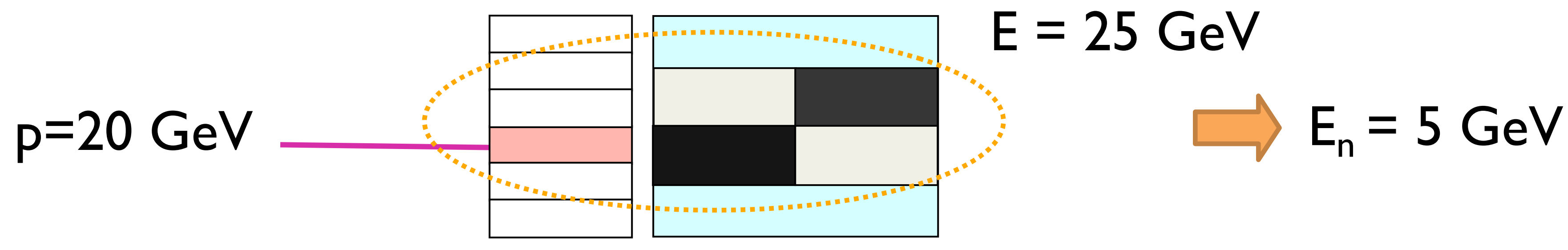
- Pandora Fine Granularity Particle Flow Algorithms:
  - Provide proof of principle over wide range of energies and physics processes.
  - Excellent performance from $\sqrt{s}$ = 500 GeV to $\sqrt{s}$ = 3 TeV.

- Pandora SDK, and many Pandora algorithms, sufficiently generic to be used elsewhere.

Backup Slides

Energy Flow, Particle Flow

- The idea behind particle flow calorimetry is not new, and a similar idea was used by ALEPH:
  - ENERGY FLOW algorithm removes ECAL deposits from identified electrons/photons, leaving (mostly) charged and neutral hadrons.
  - Coarse HCAL granularity means neutral hadrons can only be identified as significant excesses of energy. Neutral hadron energy obtained by subtraction: $E_n = E_{calo} - p_{track}$



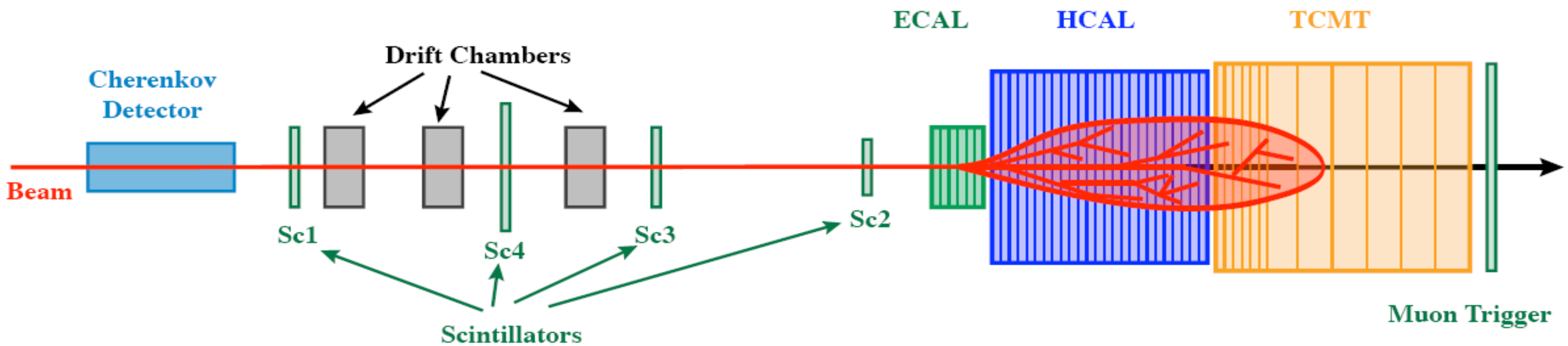
$\sigma_E/E \sim 10\%$ jet E resolution for 45 GeV jets

NIM A360:481-506, 1995

- Similar approach used by a number of other collider experiments.

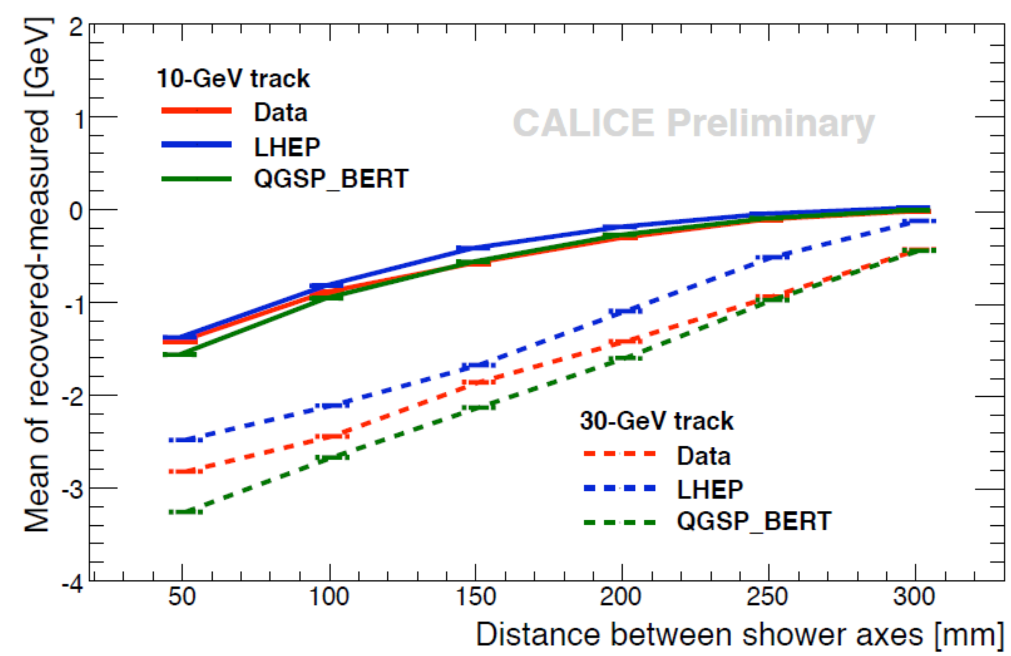
- FINE GRANULARITY PARTICLE FLOW significantly extends this approach:
  - Now directly reconstruct neutral hadrons.
  - Potentially much better performance.
  - But need highly granular calorimeters and sophisticated software.

- The Calice Collaboration is R&D group of around 280 physicists and engineers from around the world, working to develop new, high performance particle flow detectors for future high energy e^+e^- experiments.



- Extensive test beam campaign:
  - 2 GeV to 80 GeV
  - Muons, $e^{\pm}$, $\pi^{\pm}$, unseparated hadrons
  - Different technologies (to date 2 ECAL, 2 HCAL, 1 TCMT)

- **Opportunity to test Pandora with real data**



PFA Performance

- Particle Flow reconstruction inherently non-Gaussian, so 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

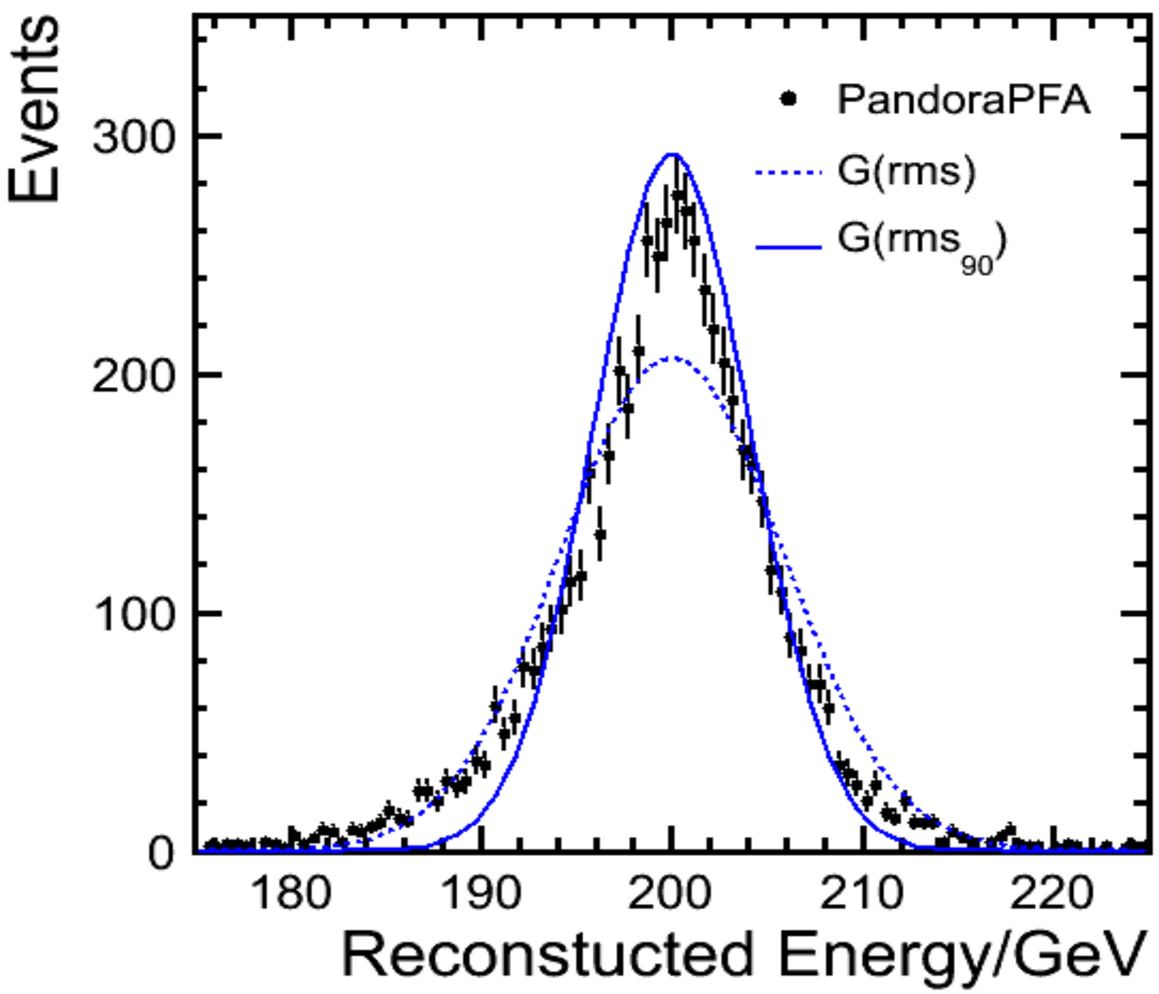
- For a true Gaussian distribution, $\mathrm{rms}_{90} = 0.79\sigma$

- However, this can be highly misleading:
  - Distributions almost always have tails
  - Gaussian usually means fit to some region
  - $G(\mathrm{rms}_{90})$ larger than central peak from PFA

- MC studies to determine equivalent statistical power indicate that:

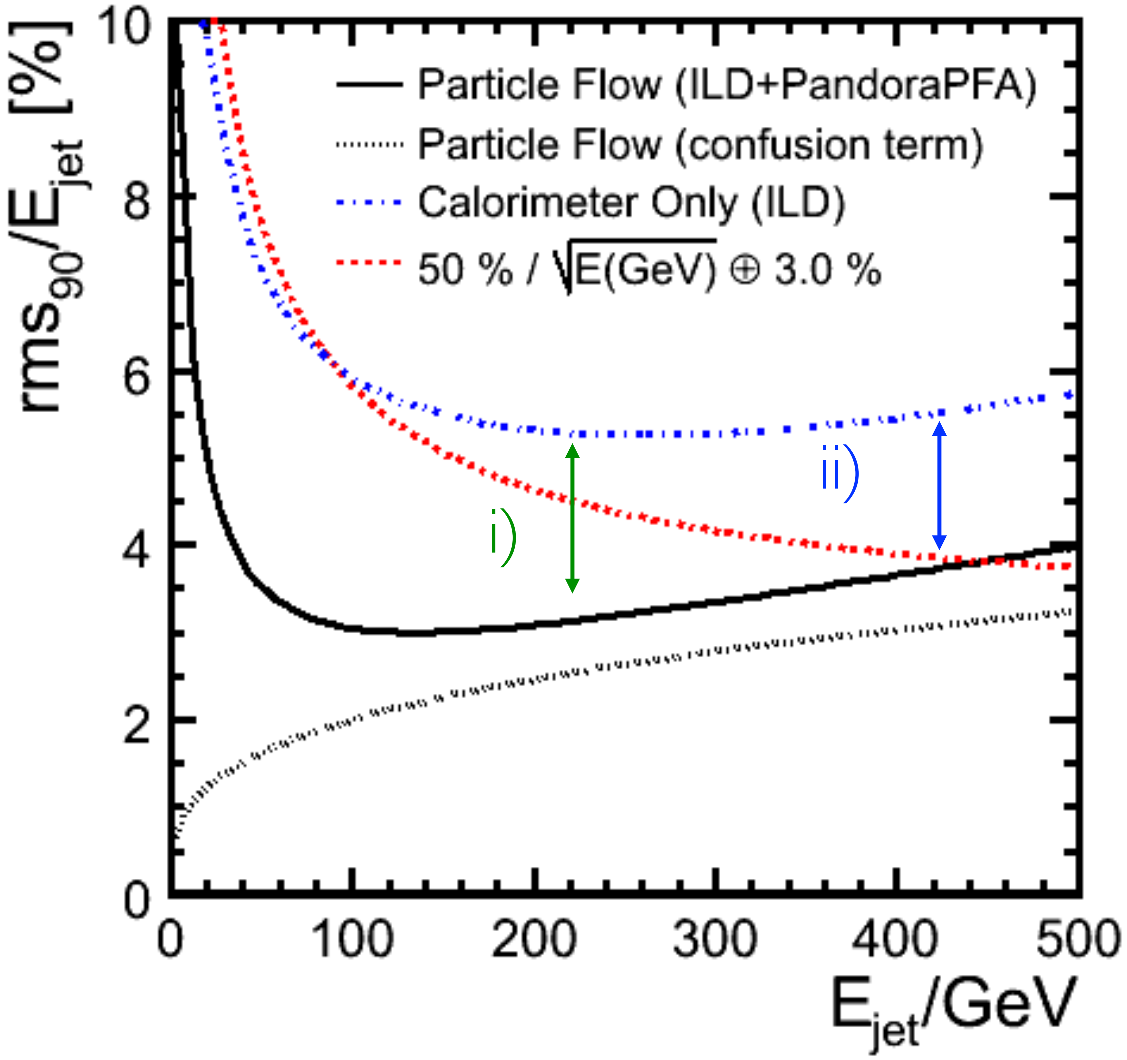
$$\boxed{\mathrm{rms}_{90} \approx 0.9\sigma_{\mathrm{Gaus}}}$$

- Now use rms_{90} as a sensible convention, but does not mean PFA produces particularly large tails.



PFA vs. Conventional Calorimetry

- ILD/SiD intended for PFA, but also good conventional calorimeters:
  - ECAL ~15%/$\sqrt{E}$
  - HCAL ~55%/$\sqrt{E}$

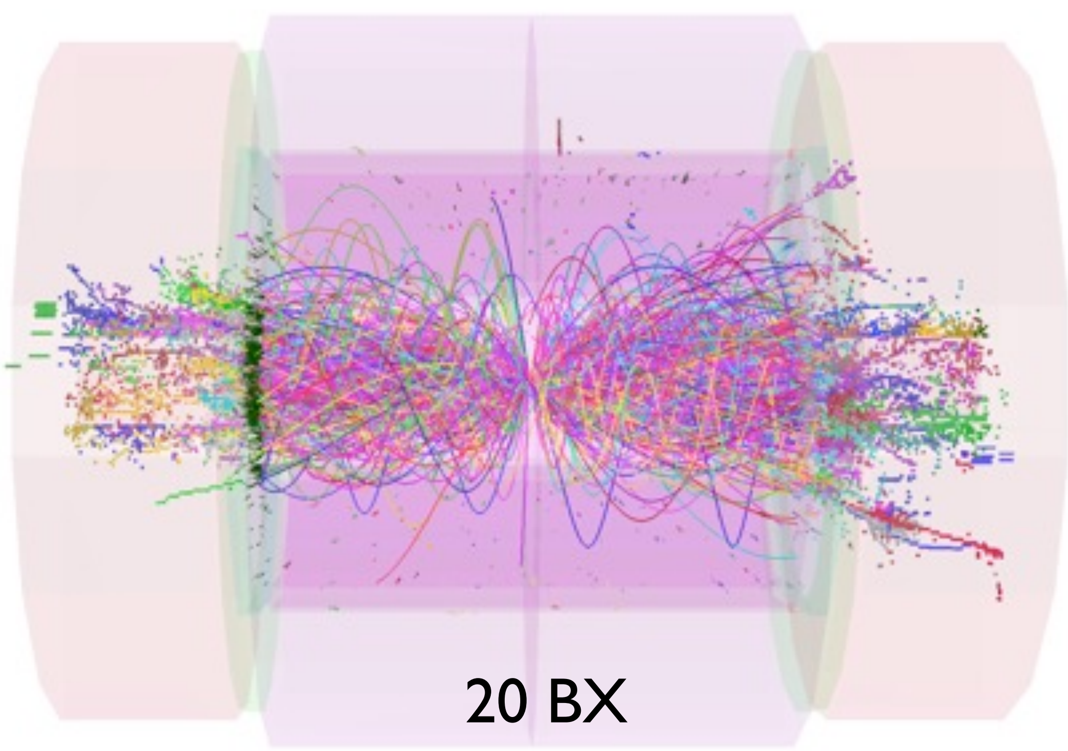


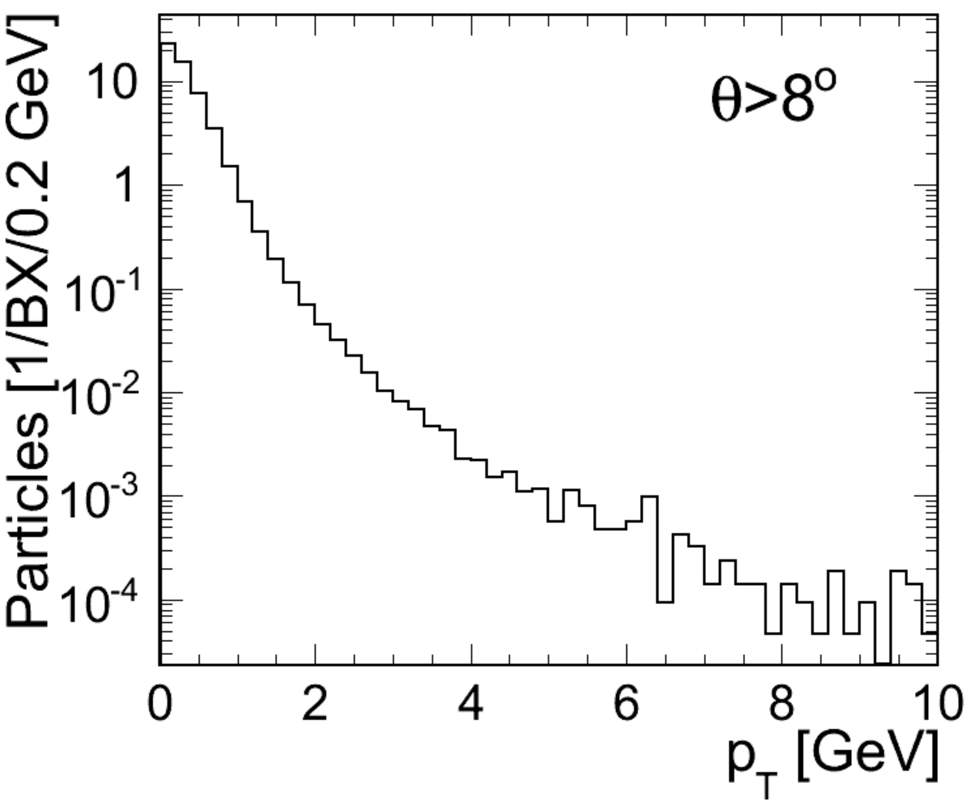
i) PFA always wins over purely calorimetric approach

ii) Effect of leakage clear at high energies

CLIC Backgrounds

- Pair background largely affects very low angle region.
- Background in calorimeters and central tracker dominated by $\gamma\gamma \rightarrow$ hadrons "mini-jets".
- At 3 TeV, average 3.2 events per BX (approximately 5 tracks per event).
- For entire bunch-train (312 BXs):
  - 5000 tracks (mean momentum 1.5 GeV) giving total track momentum : 7.3 TeV
  - Total calorimetric energy (ECAL + HCAL) : 19 TeV
- Largely low p_T particles, but an irreducible background.

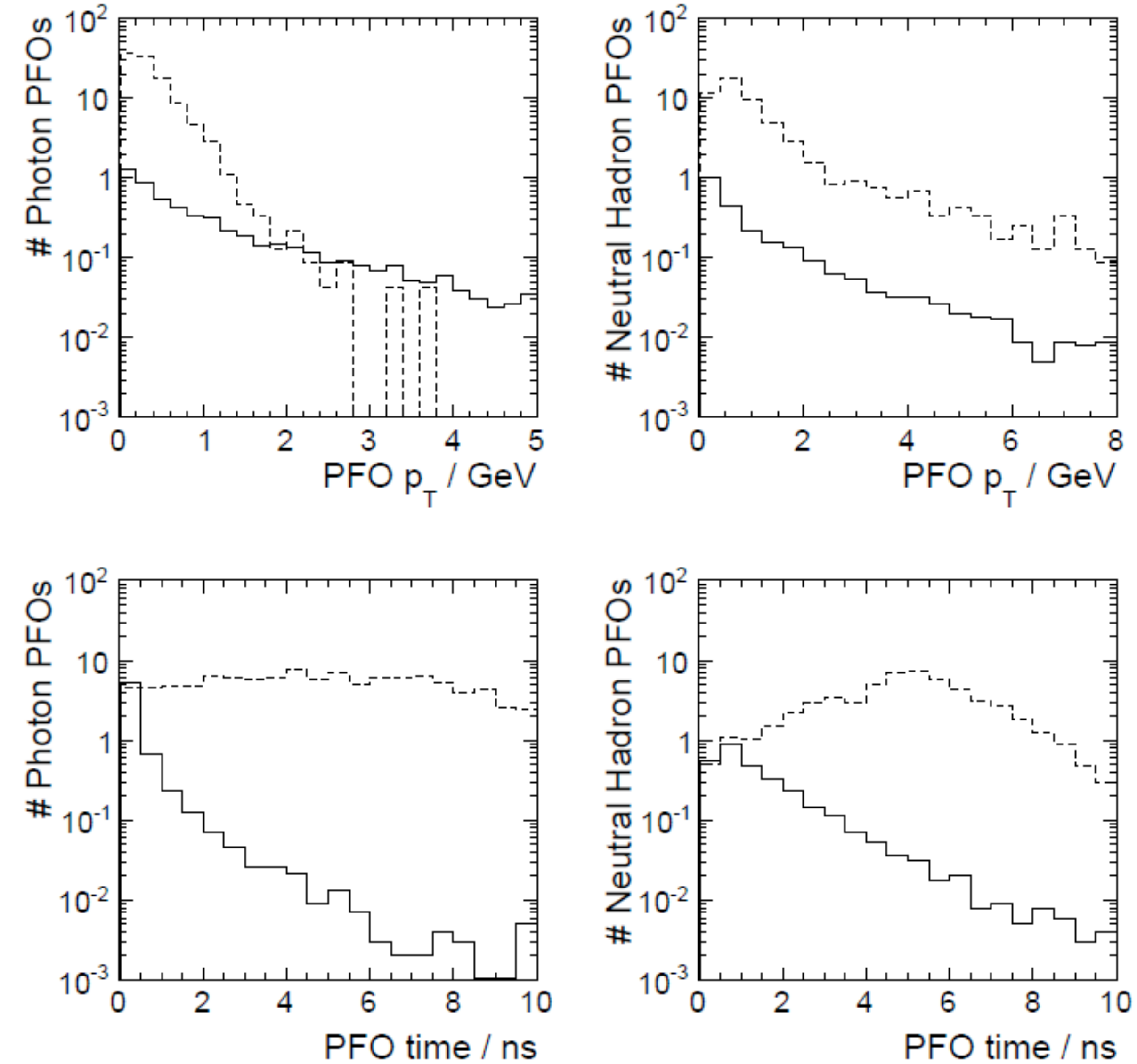




CLIC PFO Selection

- Pandora algs cluster energy in detector into individual particles, which can be identified as background or from underlying interaction.
- Cannot place timing cuts on individual hits prior to reconstruction, but can cut on timing and p_T properties of reconstructed PFOs.
- PFOs from physics event have range of p_T values and times close to t_0.

Cut	$\gamma\gamma \rightarrow$ hadrons Energy (GeV)	500 GeV di-jet Energy (GeV)	500 GeV di-jet Energy loss
No cut	1210	500.2	0%
Loose	235	498.8	0.3%
Default	175	498.0	0.5%
Tight	85	496.1	0.8%
$p_T > 3.0\,\mathrm{GeV}$	160	454.2	9.2%



Solid histograms show distributions for $ZZ \rightarrow qq\nu\nu$ events at $\sqrt{s}$=3TeV, whilst dashed histograms are for pile-up from $\gamma\gamma \rightarrow$hadrons

CLIC Staging Scenarios

- A number of possible staging scenarios, details currently being worked out. For example:

parameter	symbol			
centre of mass energy	E_{cm} [GeV]	500	1400	3000
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	2.3	3.2	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.4	1.3	2
gradient	G [MV/m]	80	80/100	100
site length	[km]	13	28	48.3
charge per bunch	N [10^9]	6.8	3.7	3.7
bunch length	σ_z [μm]	72	44	44
IP beam size	σ_x/σ_y [nm]	200/2.26	$\approx$ 60/1.5	$\approx$ 40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20	660/20
bunches per pulse	n_b	354	312	312
distance between bunches	Δ_b [ns]	0.5	0.5	0.5
repetition rate	f_r [Hz]	50	50	50
est. power cons.	P_{wall} [MW]	271	361	582