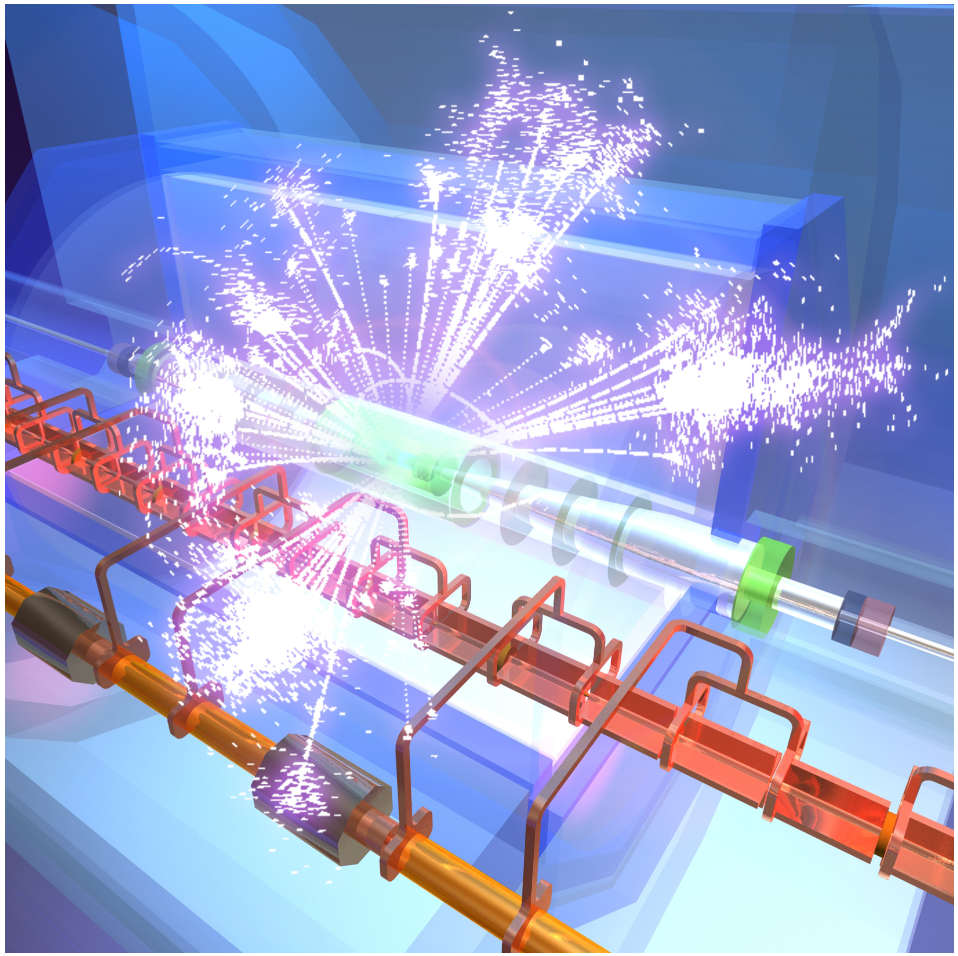
Particle Flow Calorimetry*

Mark Thomson
University of Cambridge



*with an LC bias

Outline

This talk:
1) What is Particle Flow Calorimetry ?
2) Calorimetry Goals at the ILC
3) Linear Collider Detector Concepts
4) Particle Flow Reconstruction
5) Particle Flow Performance
6) Beyond Particle Flow
7) Summary

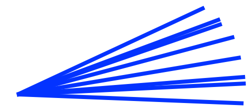
1) What is Particle Flow?

What is Particle Flow ?

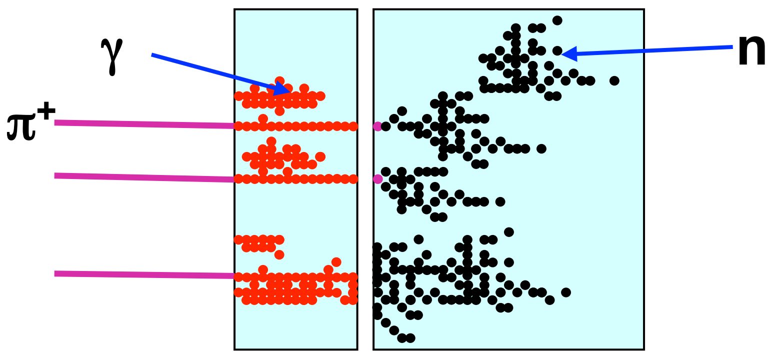
- ★ No strict definition of particle flow calorimetry…
  - Move away from pure calorimetry
  - Move towards full event reconstruction
    - Use tracks to correct/determine jet energies
- ★ Used in three main contexts:
  - "Energy flow"
    - Use tracks to correct jet energies
  - "Particle flow/Full event reconstruction" e.g. CMS
    - Aim to reconstruct particles not just energy deposits
  - "High granularity particle flow" e.g. ILC
    - Technique applied to detector concept optimised for particle flow

Traditional 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



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

High quality tracking information not used

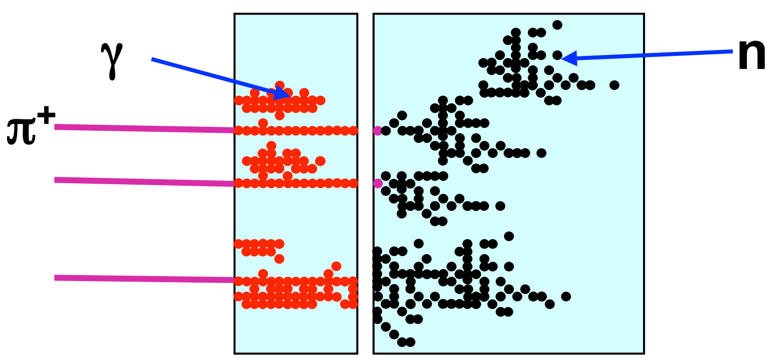
Particle Flow Paradigm

★ **Particle flow approach:**

- Try and measure energies of individual particles
- Reduce dependence on intrinsically "poor" HCAL resolution

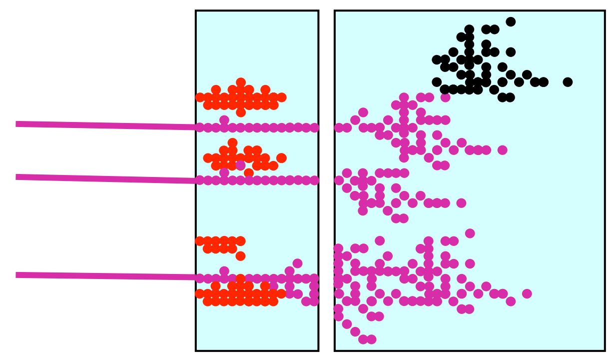
★ **Idealised Particle Flow Calorimetry paradigm:**

- charged particles measured in tracker (essentially perfectly)
- Photons in ECAL
- Neutral hadrons (and ONLY neutral hadrons) in HCAL
- Only 10 % of jet energy from HCAL ⇒ improved jet energy resolution



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

⇒

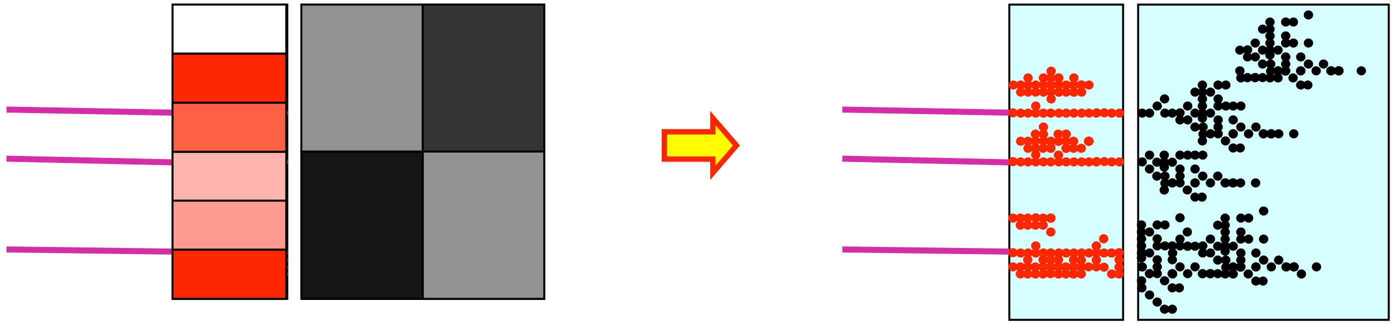


$$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$$

Realising Particle Flow

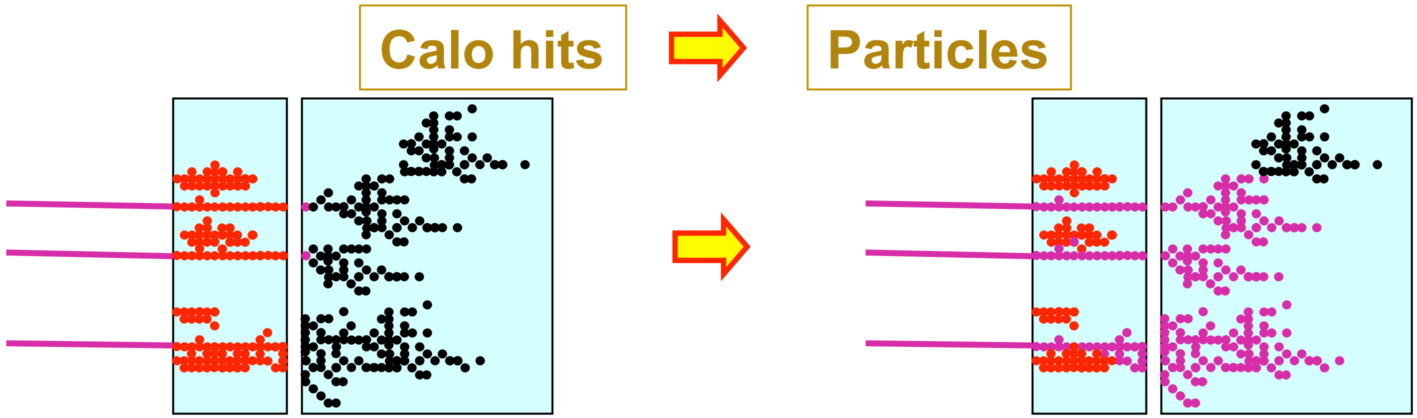
<u>Hardware:</u> need to be able to resolve energy deposits from different particles

- Requires highly granular detectors (as studied by CALICE)



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

- Requires sophisticated reconstruction software



Particle Flow Calorimetry = HARDWARE + SOFTWARE

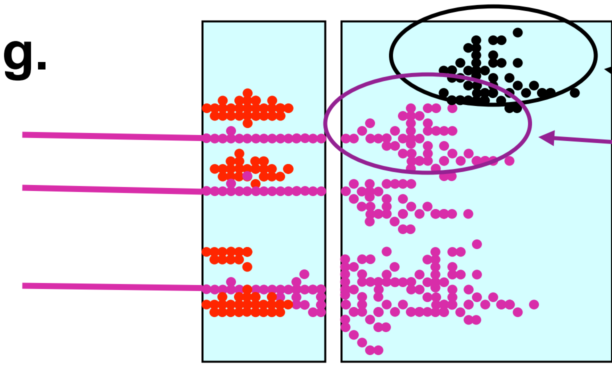
Particle Flow Reconstruction

Reconstruction of a Particle Flow Calorimeter:

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

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

e.g.

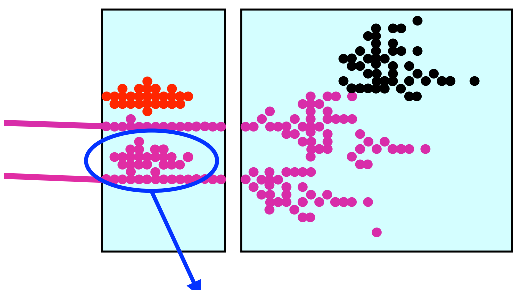


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution

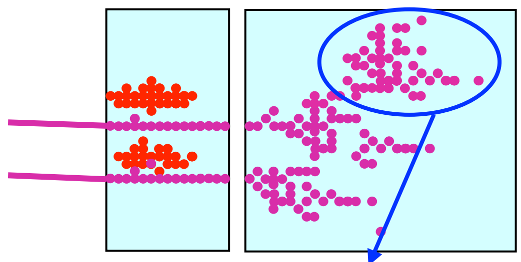
Three types of confusion:

i) Photons



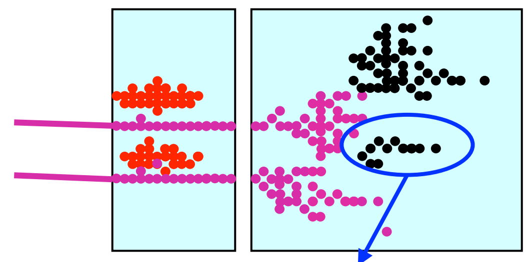
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

iii) Fragments



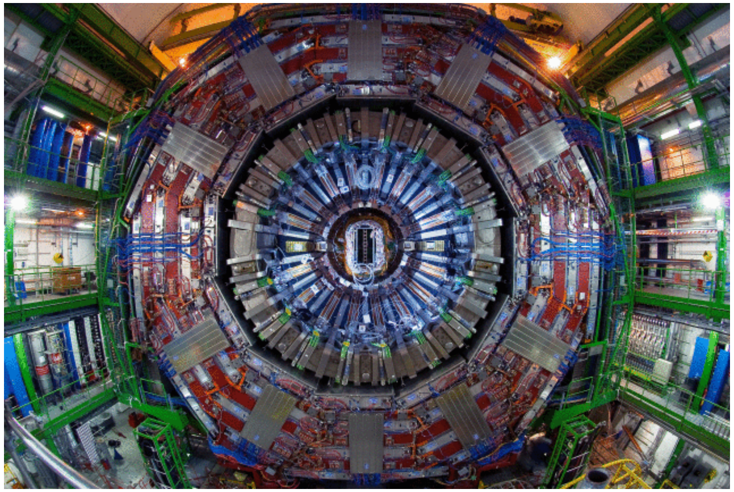
Reconstruct fragment as separate neutral hadron

Practical Particle Flow

★ **Particle flow reconstruction**

- In practice, what one means by particle flow reconstruction depends on the detector

i) **Reality** **CMS**

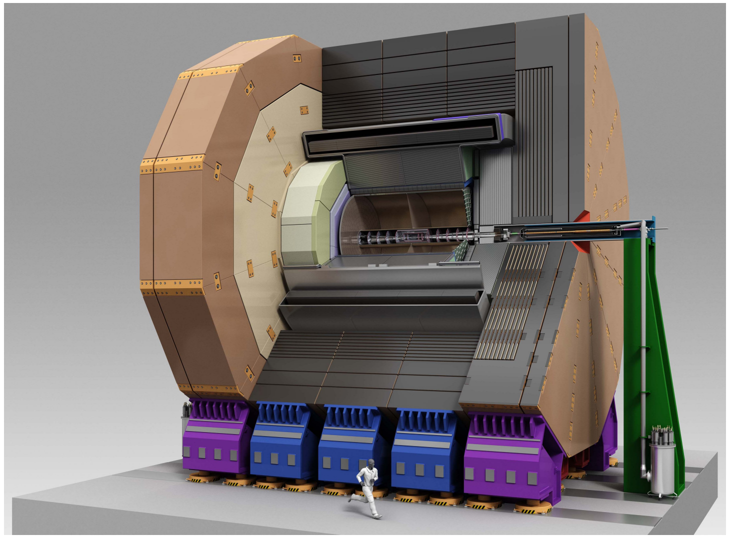


★ Apply particle flow techniques to an existing detector – **see next talk**

ii) Our dreams..

Soon to become reality?

ILD Concept for the ILC



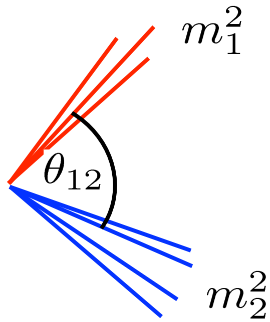
★ Design the "ultimate" particle flow detector – **this talk**

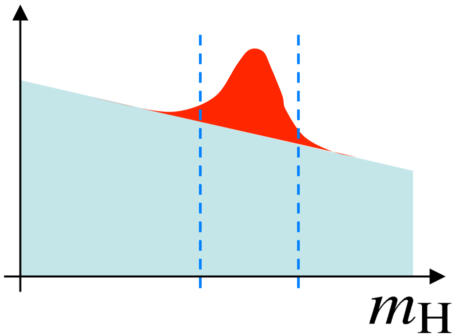
2) Calorimetry Goals for the ILC*

*or CLIC

Calorimetry at a Future e^+e^- Collider

- ★ What motivates the jet energy requirements at a future LC ?
  - in part, depends on physics..
- ★ Likely to be primarily interested in di-jet mass resolution
  - For a narrow resonance, want best possible di-jet mass res.

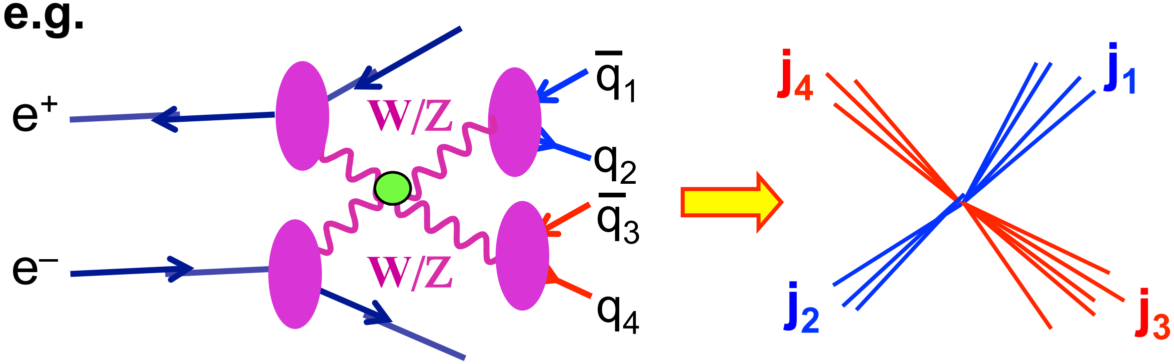


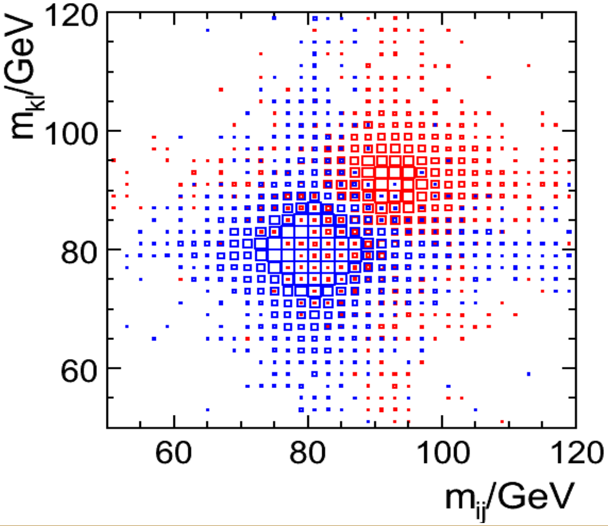


$$\text{signif.} \propto \frac{S}{\sqrt{B}} \quad \propto (\text{resolution})^{-\frac{1}{2}}$$

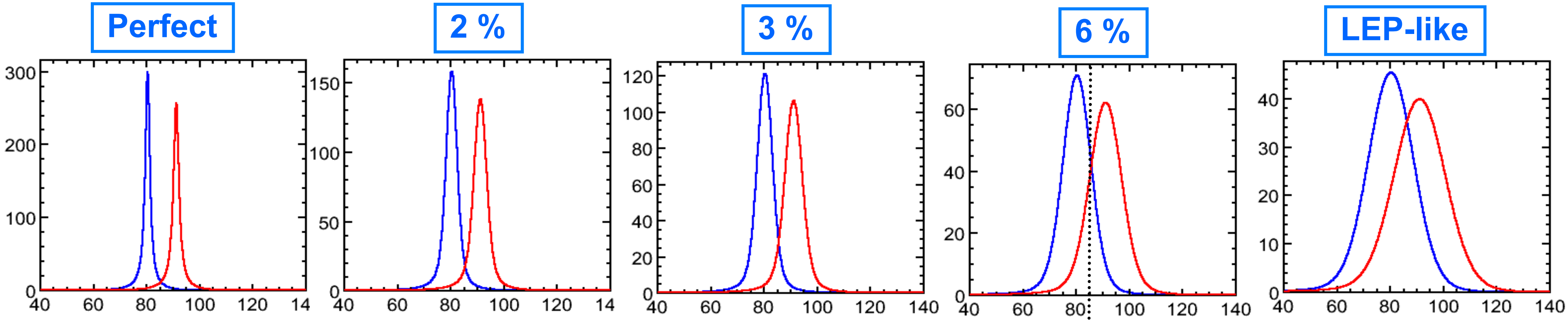
- + strong desire to separate W/Z hadronic decays

e.g.



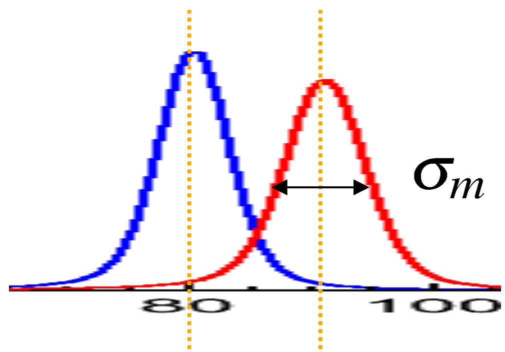


Gauge boson reconstruction



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

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 Lepton Collider jet energy minimal goal ~3.5 %**
- **for W/Z separation, not much to gain beyond this as limited by W/Z widths**

LC Jet Energy Goals

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 not be achieved with conventional calorimetry !

High Granularity Particle Flow

Dual Readout

Unproven, not clear if viable for a collider detector

3) Linear Collider Detector Concepts

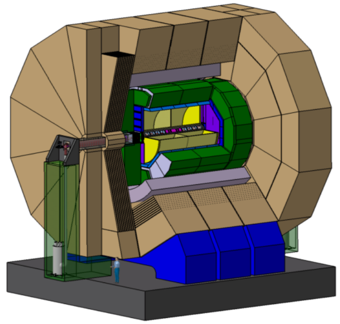
ILC Detector Concepts

★ Designed *from the outset* for Particle Flow Calorimetry
- ECAL and HCAL inside solenoid
- low mass trackers – reduce interactions/coversions
- high granularity imaging calorimeters

★ Design studies based on two concepts “proto-collaborations”:

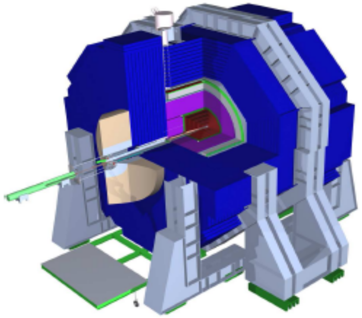
ILD: International Large Detector

“Large”	: tracker radius 1.8m
B-field	: 3.5 T
Tracker	: TPC
Calorimetry	: fine granularity particle flow



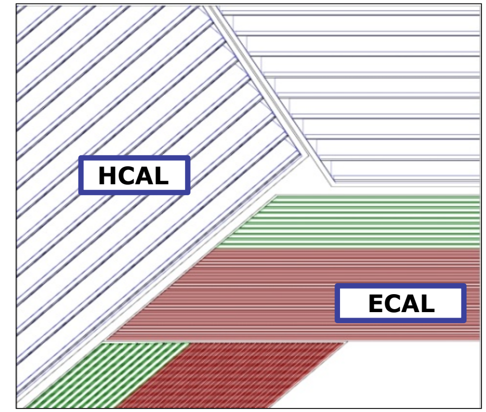
SiD: Silicon Detector

“Small”	: tracker radius 1.2m
B-field	: 5 T
Tracker	: Silicon
Calorimetry	: fine granularity particle flow



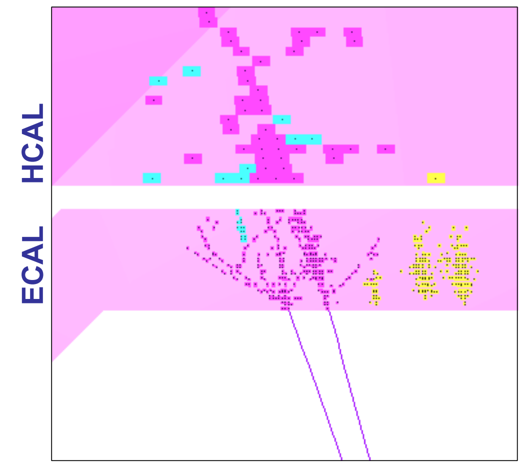
ECAL Considerations

- ★ **Want to minimise transverse spread of EM showers**
  - ➢ **Require small Molière radius**
  - ➢ **High transverse granularity ~Molière radius**

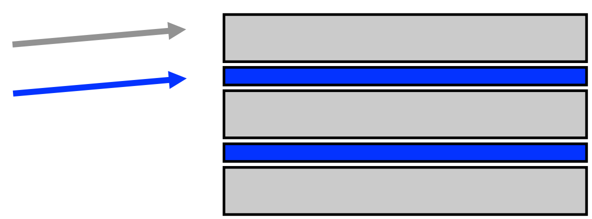


- ★ **Want to longitudinally separate EM and Hadronic showers**
  - ➢ **Require large ratio of λ_I/X_0**
  - ➢ **Longitudinal segmentation to cleanly ID EM showers**

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



- ★ **Favoured option : Tungsten absorber**
  - • **Need 'thin' sensitive material to maintain small Molière radius**

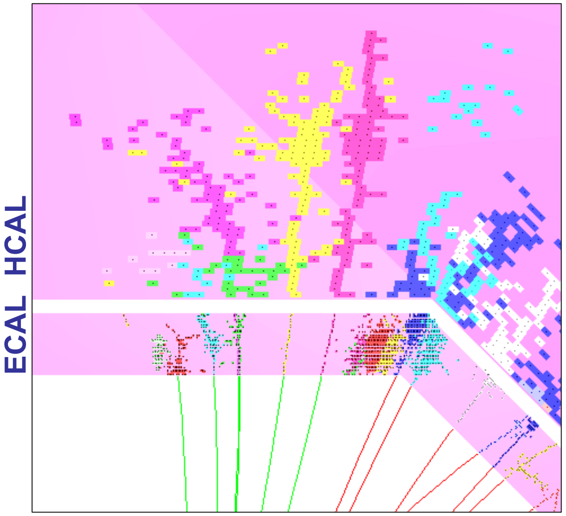


HCAL Considerations

★ Want to resolve structure in hadronic showers
  ➢ Require **longitudinal** and **transverse** segmentation

★ Want to fully contain hadronic showers
  ➢ Require small λ_I

★ HCAL will be large, so absorber cost & structural properties will be important



Material	X_0/cm	ρ_M/cm	λ_I/cm	λ_I/X_0
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?

★ **Technological options under study**, e.g. by **CALICE** collaboration:
CAlorimetry for the **LI**near **C**ollider **E**xperiment

4) Particle Flow Reconstruction

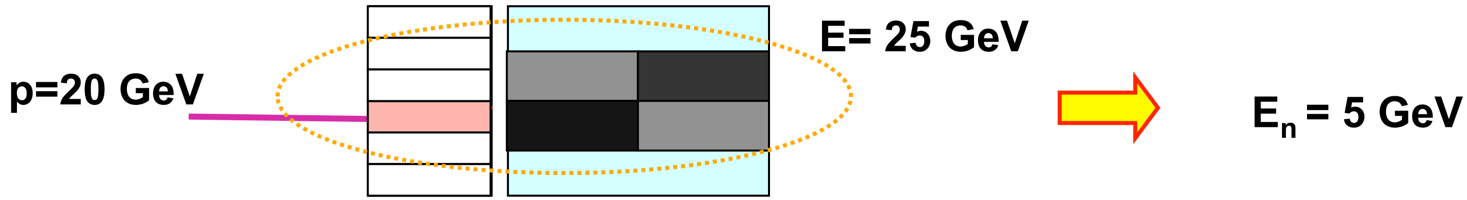
"Energy Flow" vs "Particle Flow"

Energy flow

- ★ The idea *behind* particle flow calorimetry is not new
- ★ a *similar* idea was first (?) used by ALEPH

NIM A360:481-506, 1995

  - Jet energies reconstructed using an "ENERGY FLOW" algorithm
  - Remove ECAL deposits from IDed electrons/photons
  - Left (mostly) with charged and neutral hadrons
  - However, insufficient HCAL granularity to identify neutral hadrons
  - Neutral hadrons identified as significant excesses of CALO energy



  - Energy of neutral hadron obtained by subtraction: $E_n = E_{calo} - p_{track}$

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

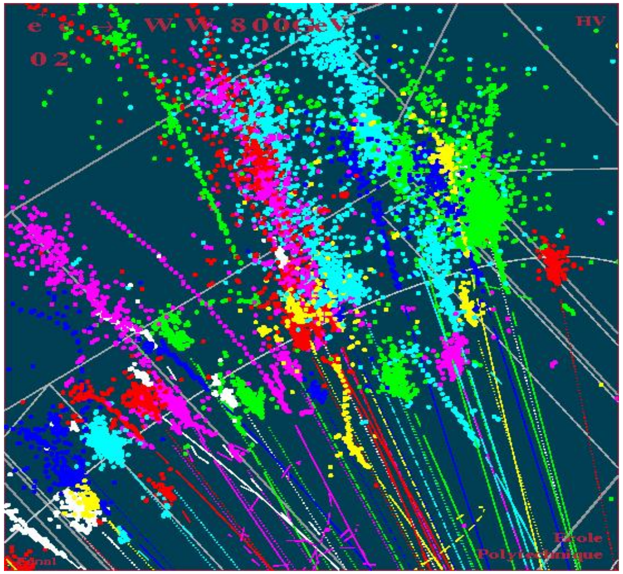
Particle flow

- ★ "PARTICLE FLOW" significantly extends this to highly granular calorimeters
  - Now directly reconstruct neutral hadrons (not subtraction)
  - Potentially much better performance -

Particle Flow Reconstruction

★ High granularity calorimeters – **very different** to previous detectors

★ "Tracking calorimeter" – requires a new approach to ECAL/HCAL reconstruction



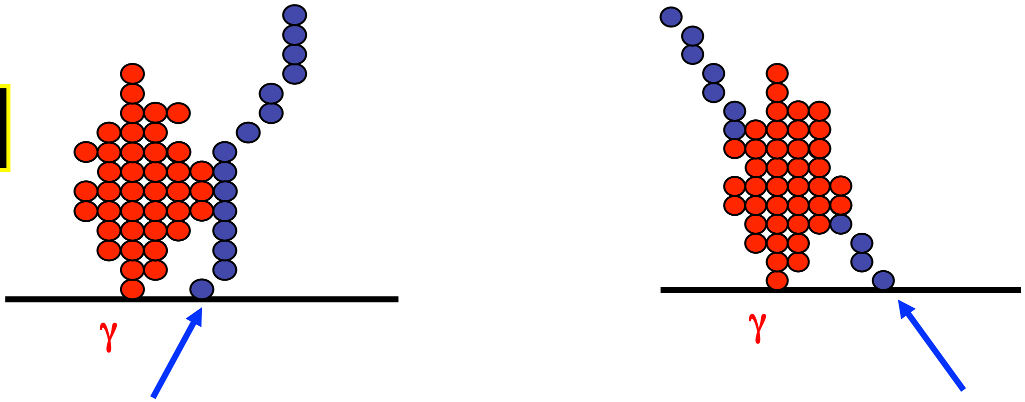
→ **Particle Flow Algorithms (PFA)**

e.g.

★ Need to separate "tracks" (charged hadrons) from photons

hardware

granularity



software

PFlow Algorithm

PandoraPFA

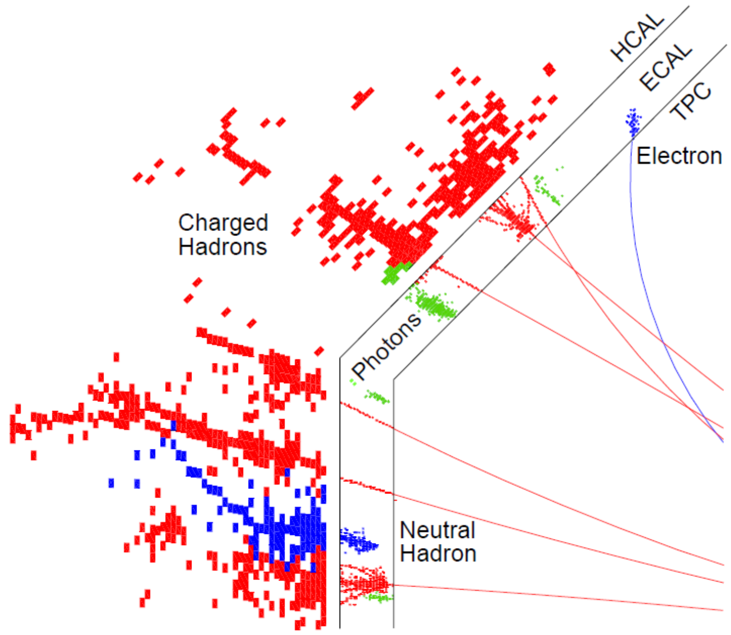
★ High granularity particle flow calorimetry **lives** or **dies** on the quality of the reconstruction of particles

★ Requires high-performance software, both in terms of:
- algorithmic sophistication
- CPU/memory usage – these are complex events with many hits

PandoraPFA

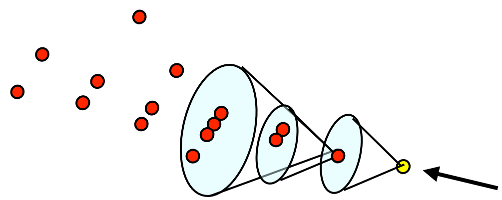
★ Almost all ILC/CLIC studies based on Pandora C++ software development kit

★ Provides highly sophisticated PFlow reconstruction for LC-style detectors
- + flexibility for much more…



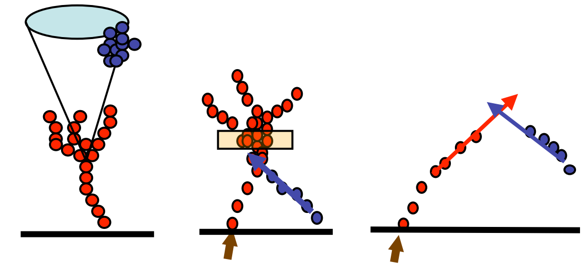
Typical topology of a simulated 250GeV jet in CLIC ILD

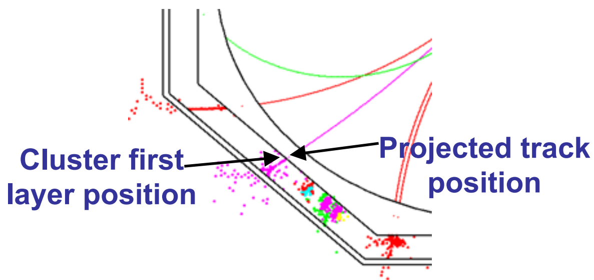
PandoraPFA Algorithms



ConeClustering Algorithm

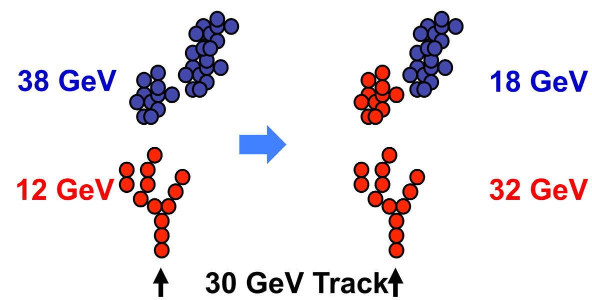
Topological Association Algorithms

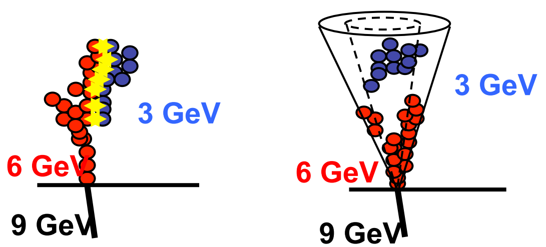




Track-Cluster Association Algorithms

Reclustering Algorithms



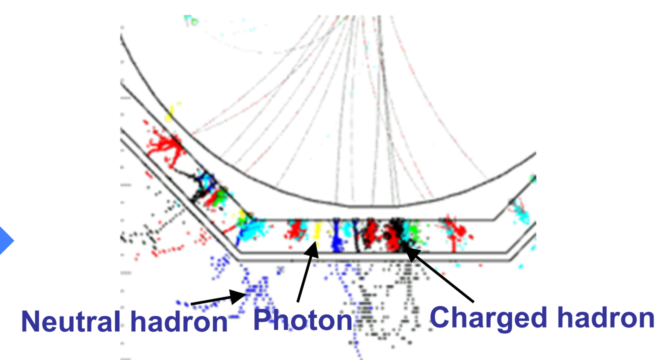


Layers in close contact

Fraction of energy in cone

Fragment Removal Algorithms

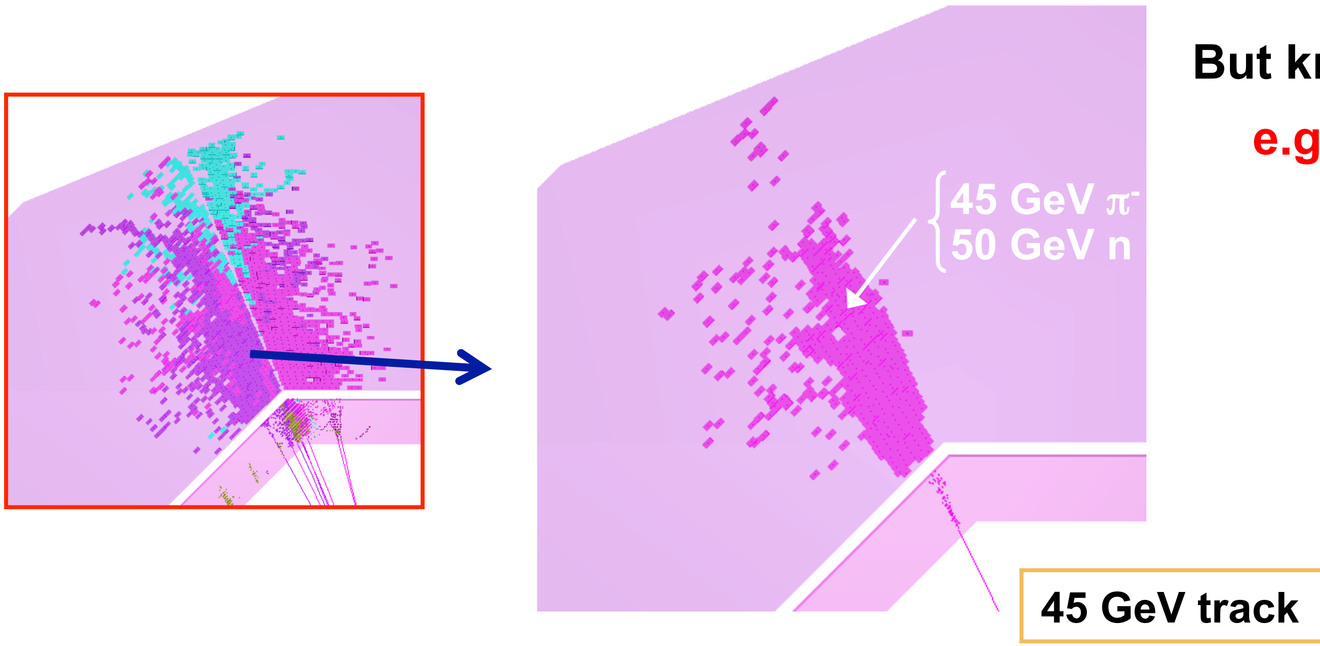
PFO Construction Algorithms



M. Thomson, NIM 611 (2009) 24-40

e.g. Iterative Reclustering

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



But know something is wrong:

e.g. 45 GeV track associated with 95 GeV cluster

This case triggers the "statistical" iterative reconstruction algorithm

⇒ The track comes to the rescue

★ If track momentum and cluster energy inconsistent : RECLUSTER

e.g.

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

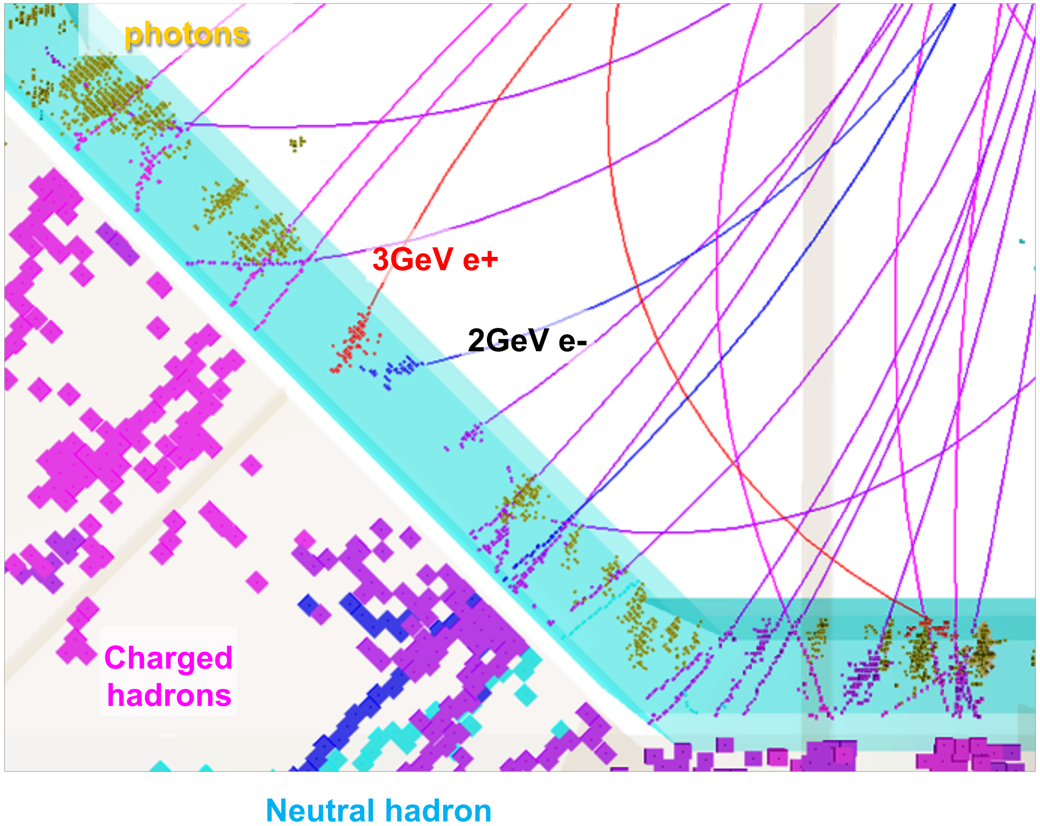
NOTE:

- as a result, clustering *guided* by track momentum
- for "simple cases" works very effectively
- for complex cases tends to energy subtraction "Energy Flow"

★ Smooth transition between pure Particle Flow and Energy Flow

Particle Flow Objects

Typical 250GeV Jet in ILD:



After all that:

Particle flow objects (PFOs) built from tracks and clusters:

- List of reconstructed particles with energies and particle ID
- Build jets…
- Study physics performance

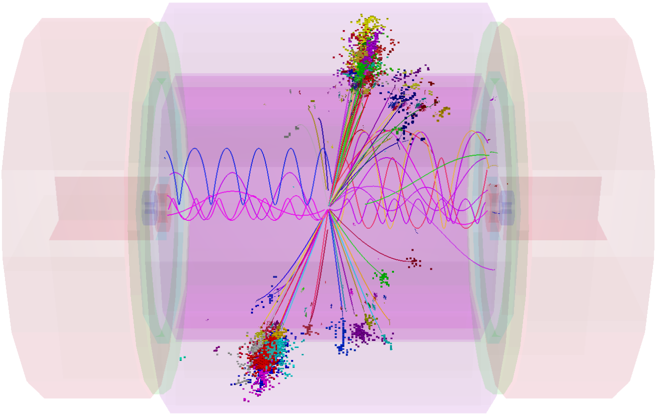
★ Assess performance of a Particle Flow detector using simulation…

5) Particle Flow Performance

Performance

★ **Recall:** motivation for high granularity PFlow Calorimetry

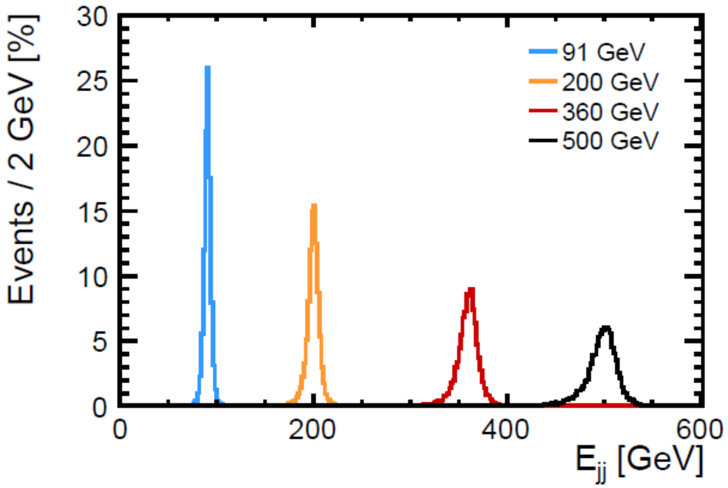
⇒ Jet energy resolution: $\boxed{\sigma_E/E < 3.5\%}$



★ **Benchmark** performance using jet energy resolution in Z decays to light quarks

★ Use total energy to avoid complication of jet finding (mass resolutions later)

★ Current performance (PandoraPFA + ILD)
- uds jets (full GEANT 4 simulations)



rms_{90}

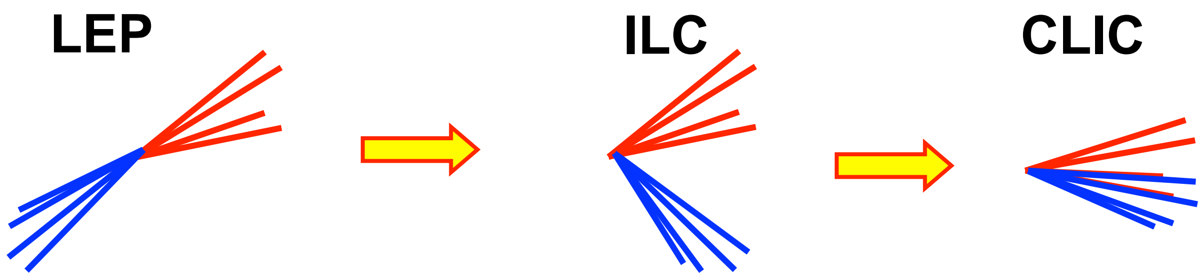
E_{JET}	σ_E/E_j
45 GeV	3.7 %
100 GeV	2.8 %
180 GeV	2.9 %
250 GeV	2.9 %

→ **GOAL MET !**

★ **Factor 2-3 better than traditional calorimetry !**

PFA at Higher Energy

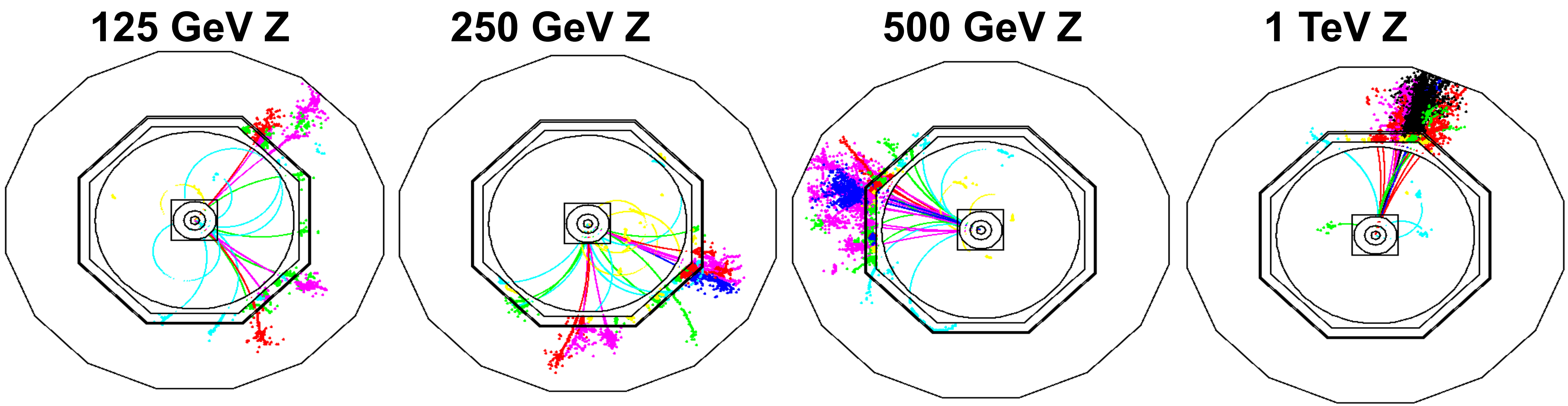
★ **On-shell W/Z decay topology depends on energy:**



★ **Note:**

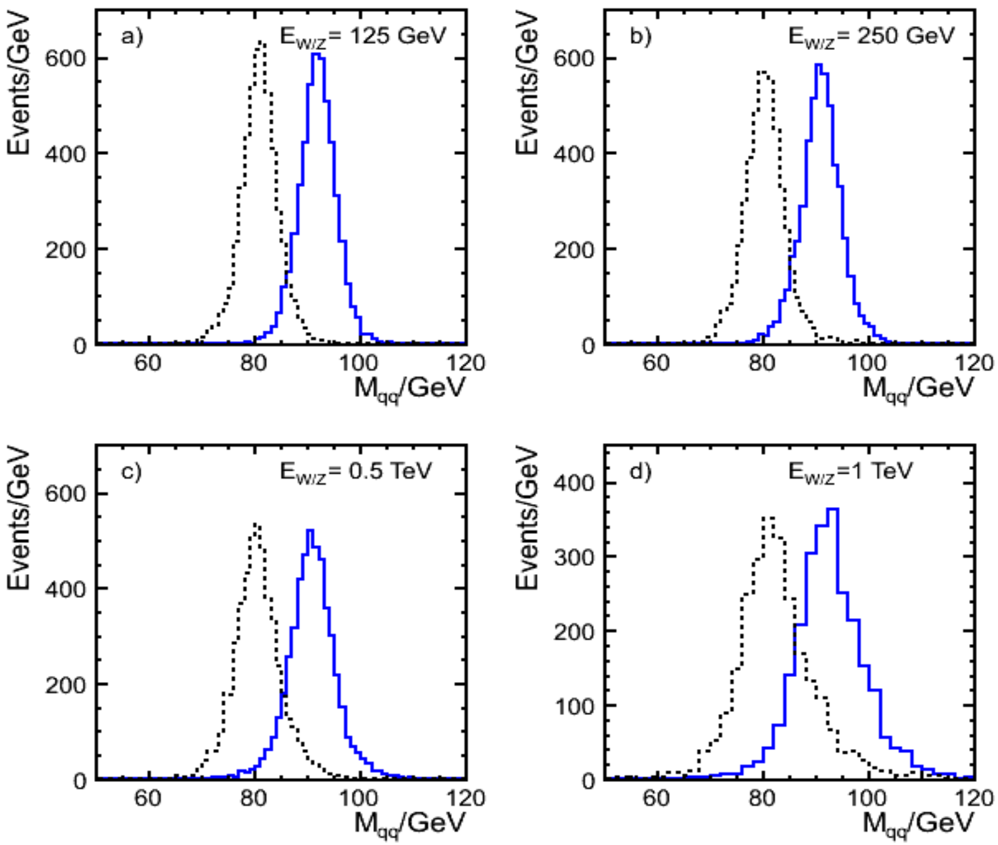
- **Particle multiplicity does not change**
- **Boost means higher particle density**
- **For boosted jets – no sub-jet finding, just sum the 4-momenta of the PFOs !**

More confusion !

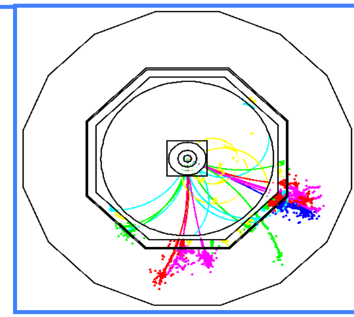


W/Z Separation

★ **Studied di-jet/mono-jet masses in ILD concept**
$$\begin{cases} e^+e^- \rightarrow WW \rightarrow u\bar{d}\nu\mu \\ e^+e^- \rightarrow ZZ \rightarrow d\bar{d}\nu\bar{\nu} \end{cases}$$

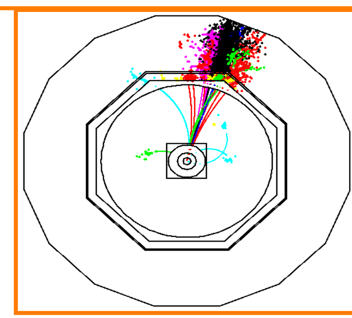


ILC-like energies



Clear separation of W/Z di-jet mass peaks

CLIC-like energies



W and Z still resolved from monojet invariant mass

★ **Impressive demonstration of power of Particle Flow at a Linear Collider**

Gaugino Pair Production at 3 TeV

★ **Have also demonstrated power of particle flow in physics analyses, e.g.**

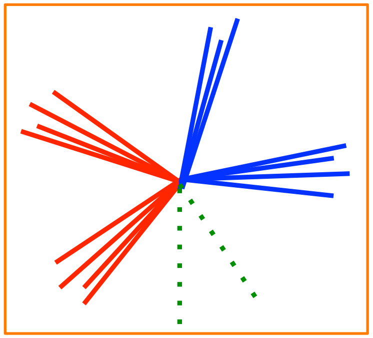
★ **Pair production and decay:**

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$

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

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

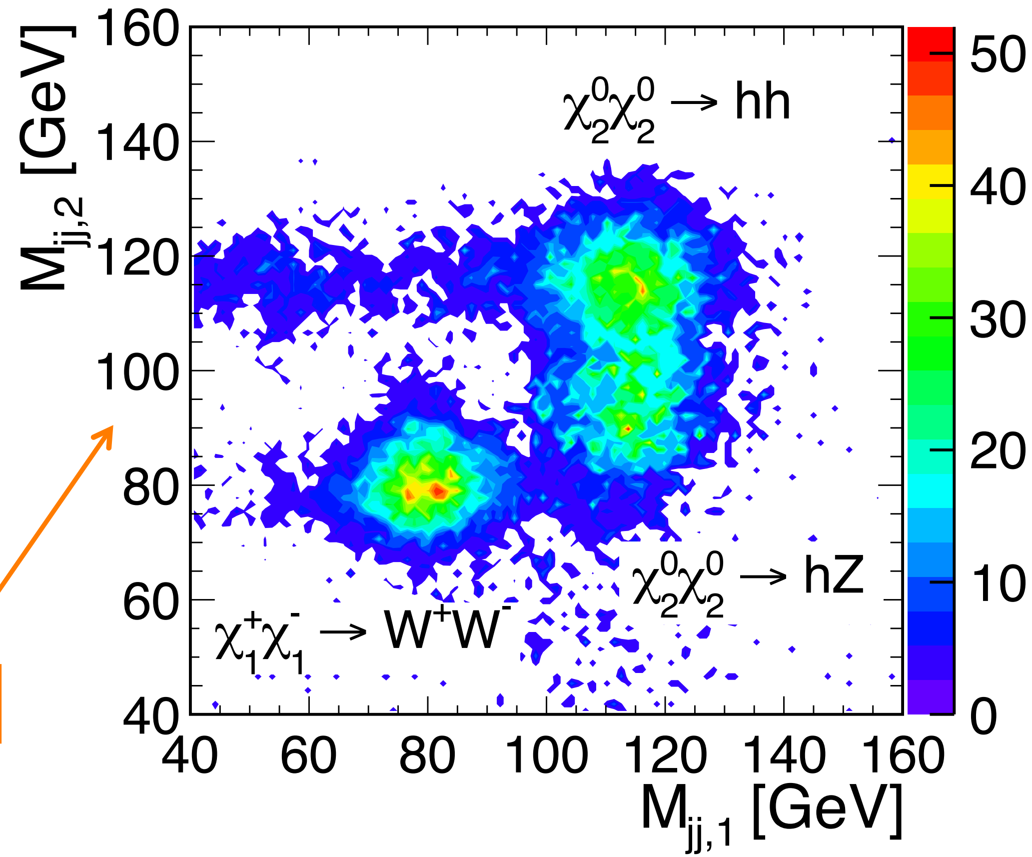
★ **Largest decay BRs have same topology for all final states**



★ **Separate using di-jet invariant masses**

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

Full Simulation with background

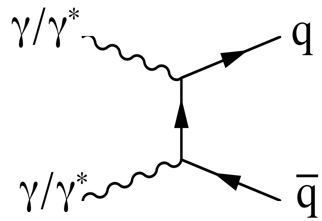


6) Beyond Particle Flow Calorimetry

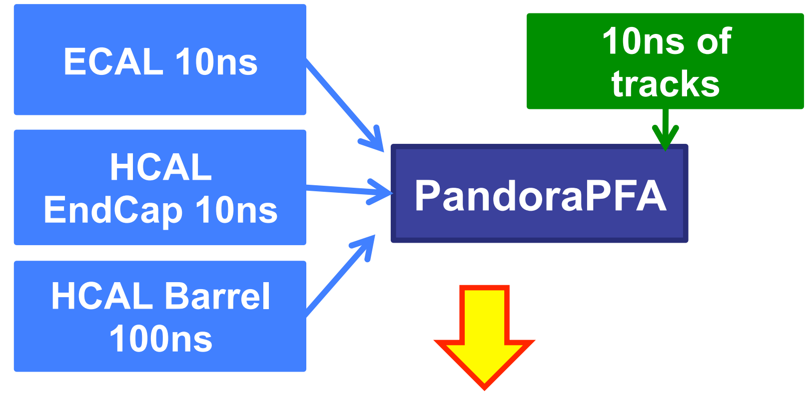
Its not just calorimetry

★ Working at **reconstructed particle** level brings other benefits:

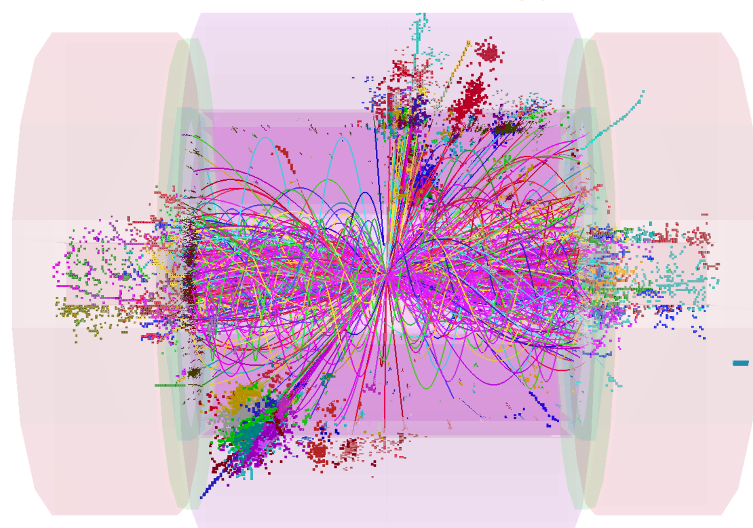
- e.g. at CLIC energies (or ILC at 1 TeV) background from $\gamma\gamma \rightarrow$ hadrons



1. CLIC 3 TeV: input to reconstruction:

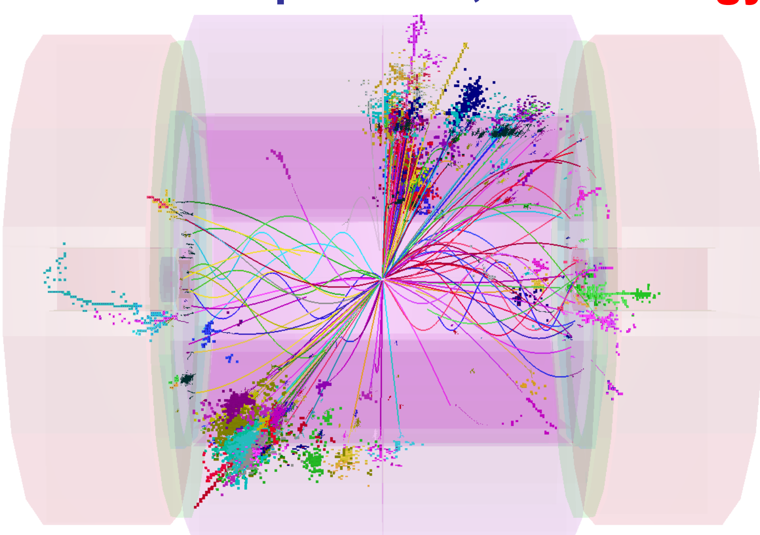


2. Reco. particles, total energy 1.2 TeV



Apply timing cuts to reconstructed particles

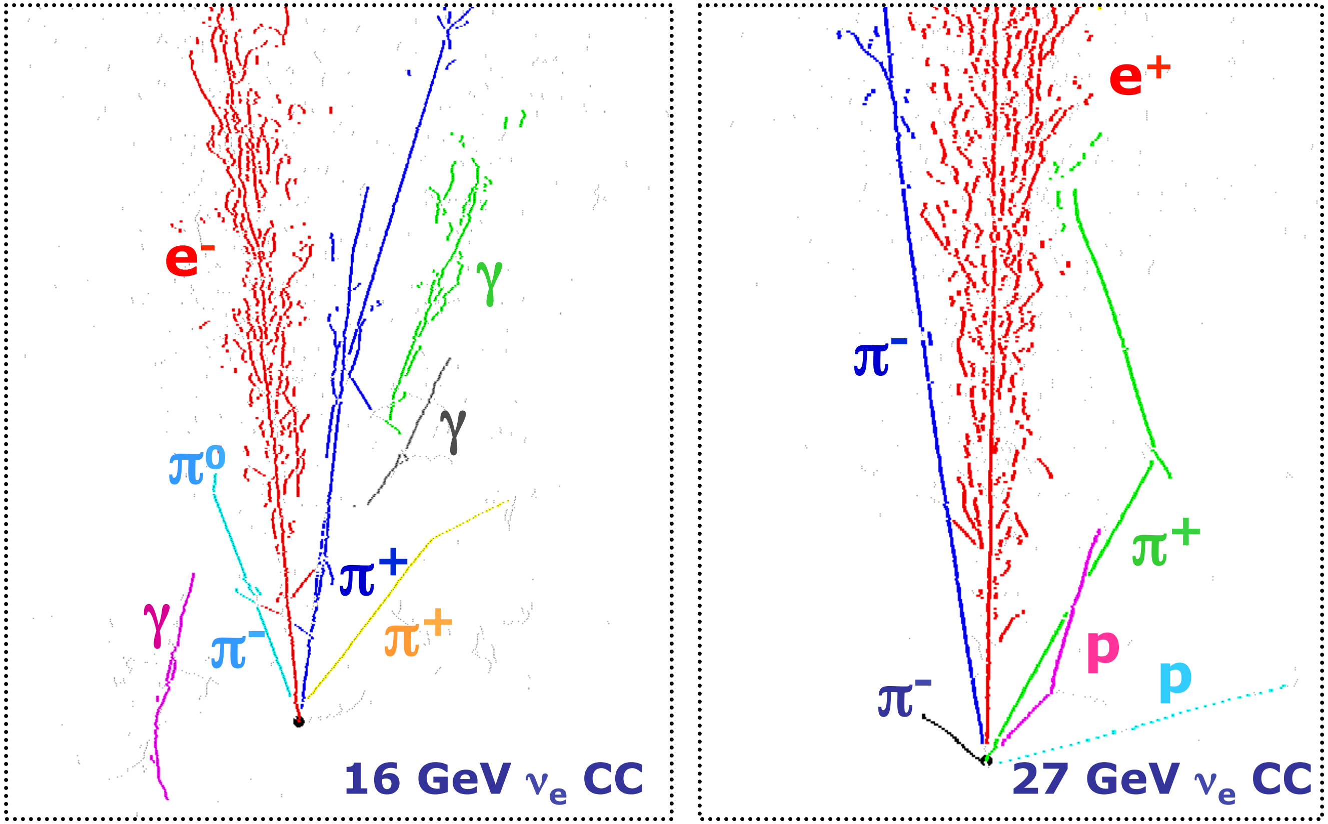
3. Selected particles, total energy 85 GeV



+ not just collider physics

- PandoraPFA provides now generic reconstruction framework
  - developed algorithms for Liquid Argon TPC reconstruction
  - another type of imaging calorimeter…

Example simulated electron neutrino Interactions in the LBNE detector



- Looks very promising…

7) Summary

Summary

★ High 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

★ PandoraPFA reconstruction

- has provided proof of principle over wide range of energies and physics processes
- excellent performance from $\sqrt{s}$ = 500 GeV to $\sqrt{s}$ = 3 TeV
- sufficiently generic to be used elsewhere

Particle Flow techniques already being used in anger

- In particular by the CMS collaboration – next talk…

Thank you

Backup Slides

Dependence on hadron shower simulation

- ★ Modelling of hadronic showers in GEANT4 is far from perfect…
  - Can we believe PFA results based on simulation ?
- ★ 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 %
  - 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

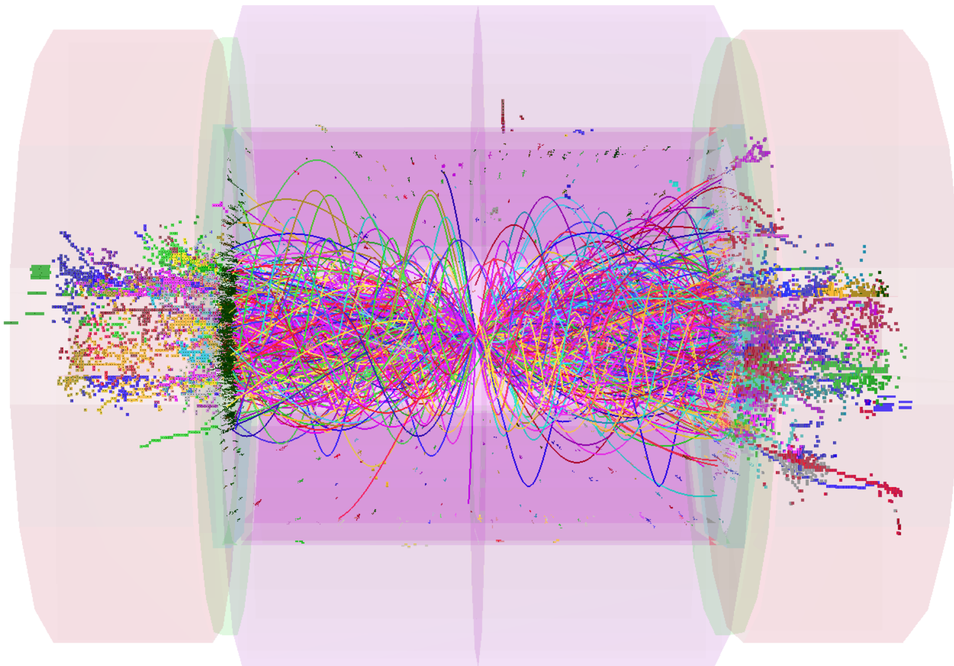
×1.00

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

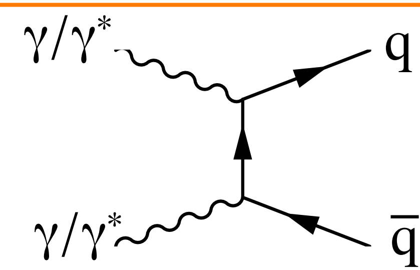
Suggests PFA performance is rather robust
- MC results likely to be reliable, despite shower model uncertainties

CALICE study supports this statement

CLIC: Impact of Background



Pile-up of “mini-jets”

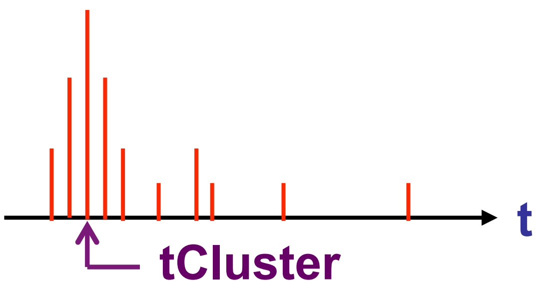


20 BXs = 10 ns of $\gamma\gamma \rightarrow$ hadrons

★ **Background must be accounted for in physics studies**

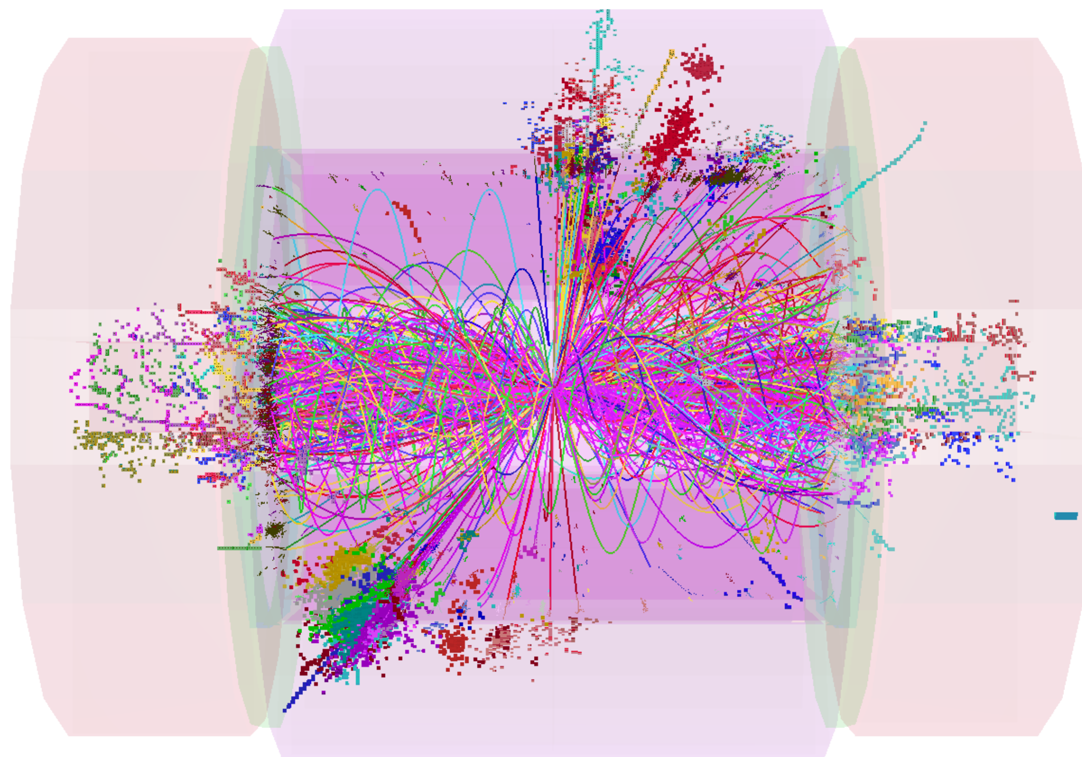
Reconstruction in Time

- ★ High granularity calorimetry allows individual particles to be reconstructed
  - with times assigned to each particle based on individual hit times
- ★ Pile-up from $\gamma\gamma \rightarrow$ hadrons can be effectively rejected using spatial and timing information
- ★ Studied at 3 TeV (the worst case)



e.g. $e^+e^- \rightarrow H^+H^- \rightarrow 8$ jets
at $\sqrt{s}$ = 3 TeV

Before **1.2 TeV**



Reconstruction in Time

- ★ High granularity calorimetry allows individual particles to be reconstructed
  - with times assigned to each particle based on individual hit times
- ★ Pile-up from $\gamma\gamma \to$ hadrons can be effectively rejected using spatial and timing information
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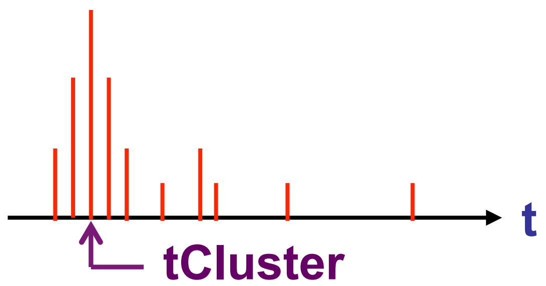
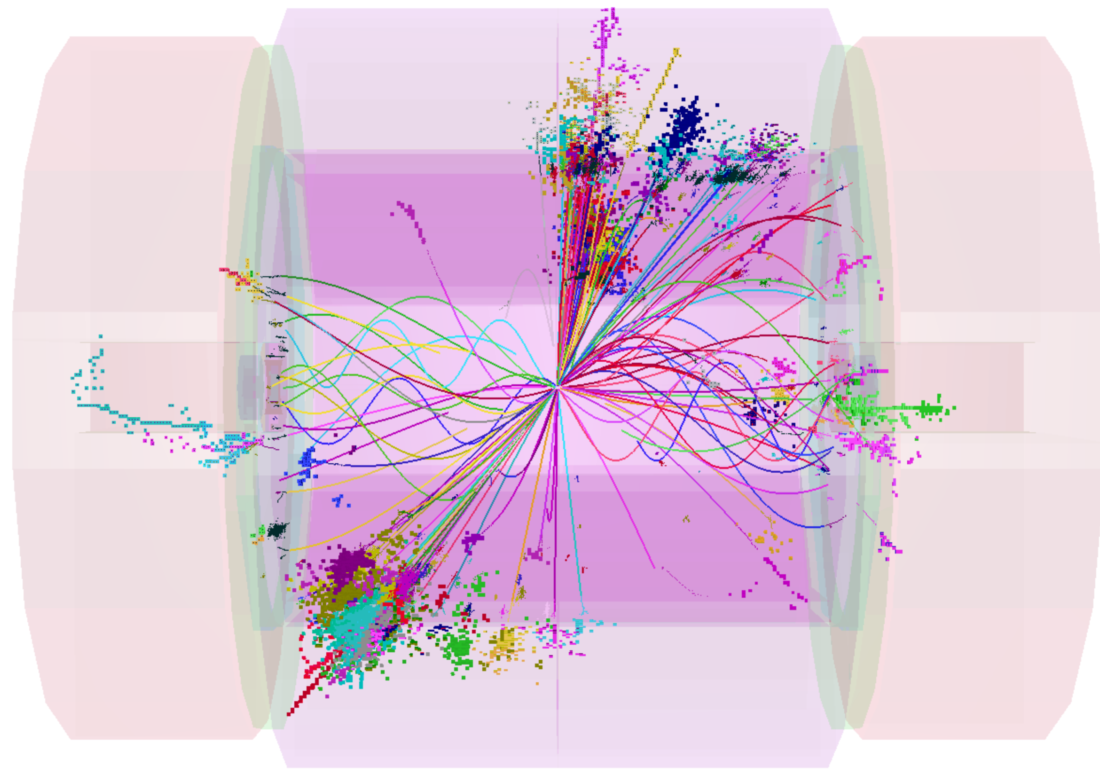


e.g. $e^+e^- \to H^+H^- \to 8$ je

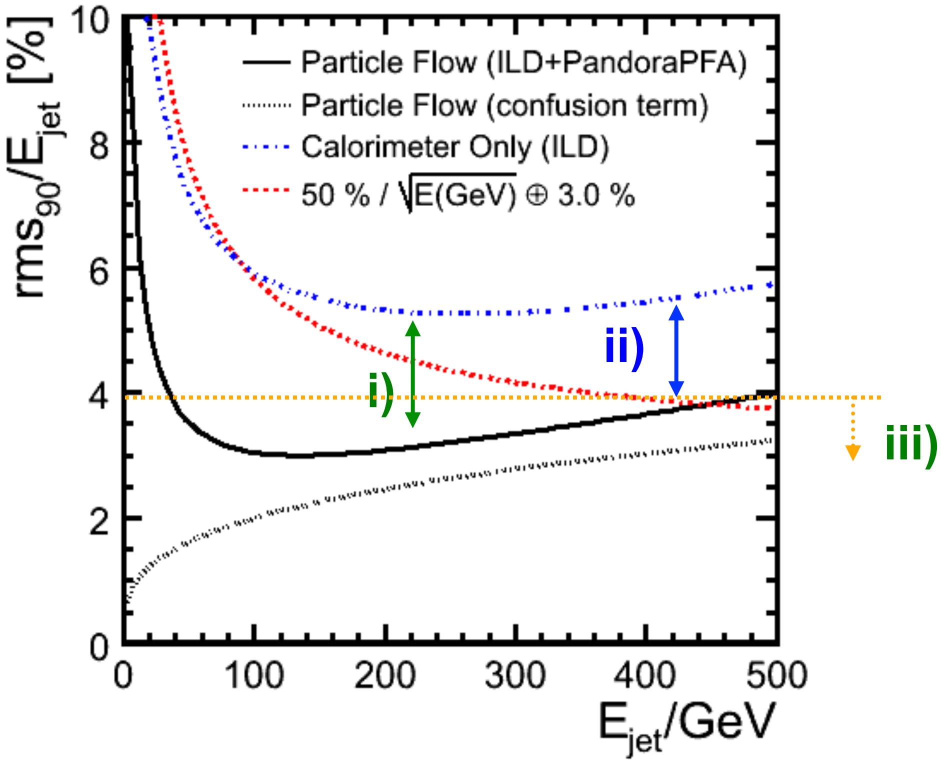
at $\sqrt{s}$ = 3 TeV

After $\boxed{\text{100 GeV}}$



PFA vs. Trad. Cal.

- ILD/SiD intended for PFA, but also good conventional calorimeters:
  - ECAL ~15%/√E
  - HCAL ~55%/√E



i) **PandoraPFA:** always wins over purely calorimetric approach
ii) **PandoraPFA:** effect of leakage clear at high energies
iii) **PandoraPFA/ILD:** Resolution better than **4 %** for E_{JET} **< 500 GeV**

Optimising a PFlow Detector

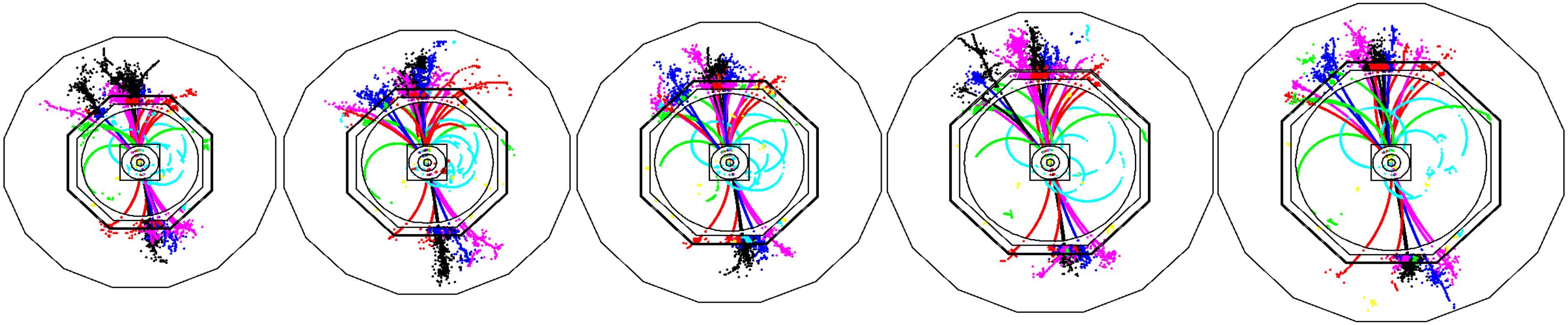
PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Cost drivers:

- Calorimeters and solenoid are the main cost drivers of an ILC detector optimised for particle flow
- Most important detector design considerations are:
  - B-field
  - R : inner radius of ECAL
  - L : length, equivalently aspect ratio L/R
  - HCAL thickness : number of interaction lengths
  - ECAL and HCAL segmentation

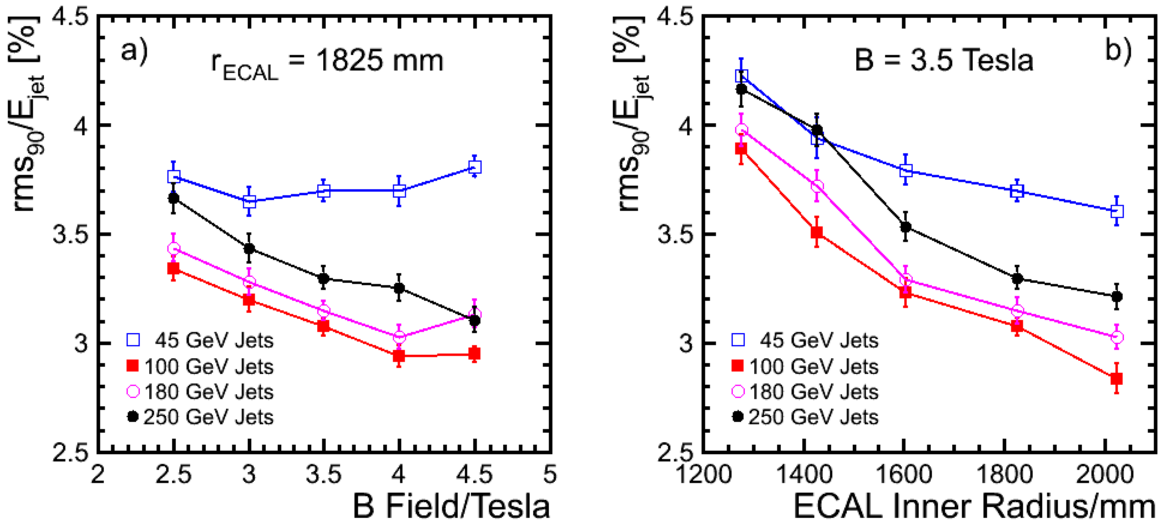
- Study jet energy resolution as a function of these cost critical issues

★ e.g. vary ECAL radius and B-field



B vs R

★ **Empirically find** **(PandoraPFA/ILD)**



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

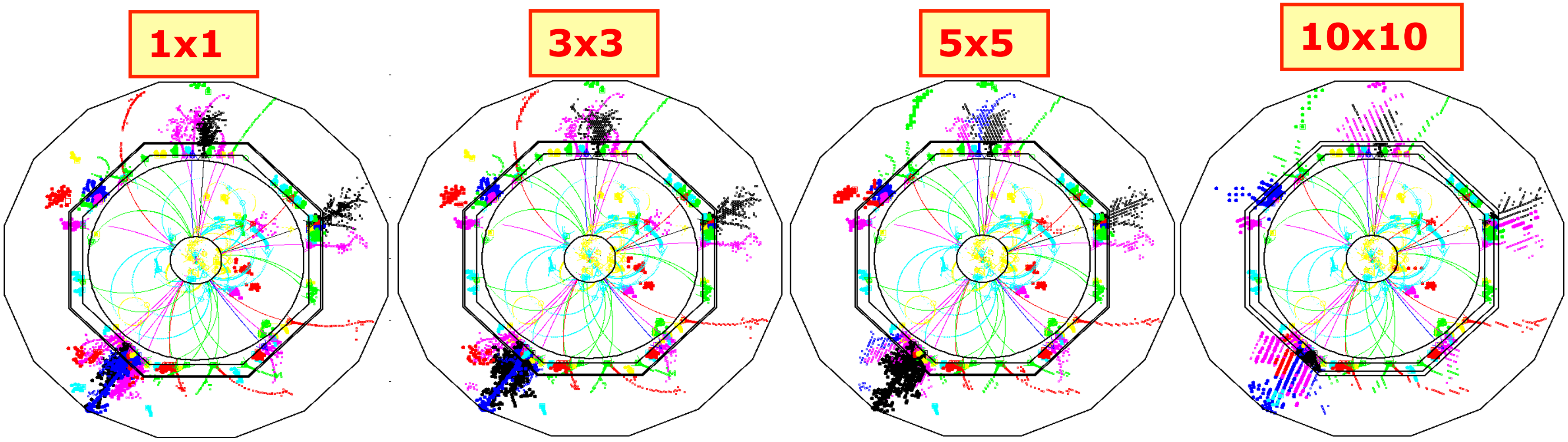
♦ **Confusion ∝ $B^{-0.3}$ R^{-1} (1/R dependence "feels right", geometrical factor !)**

Conclusions:

Detector should be fairly large
Very high B-field is less important

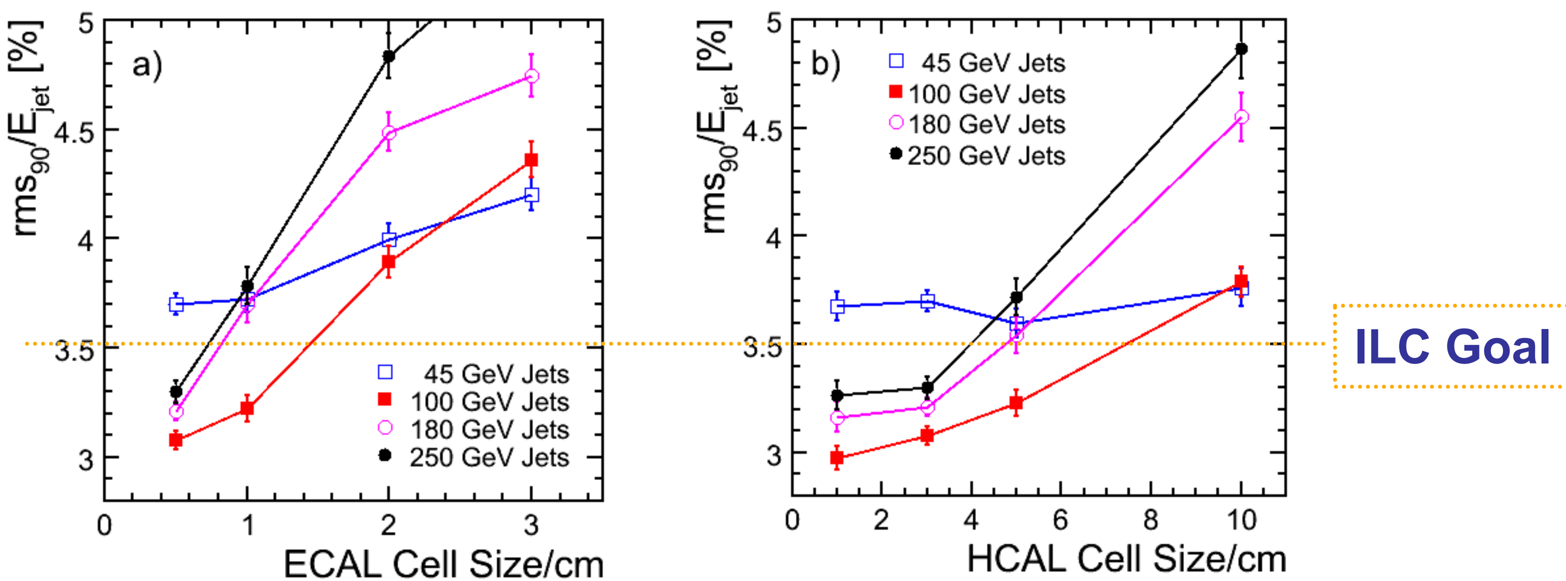
ECAL/HCAL Segmentation

- ★ Assumed particle flow reconstruction requires **very highly segmented ECAL and HCAL**
- ★ What does "highly segmented" mean ?
- ★ In ILD detector model vary **ECAL Si pixel size and HCAL tile size**
  - e.g. HCAL tile size [cm^2]



- ★ "By eye" can see that pattern recognition becomes harder for **10x10 cm^2**
- ★ Dependence of jet energy resolution on segmentation obtained with full particle flow reconstruction

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



★ **ECAL Conclusions:**

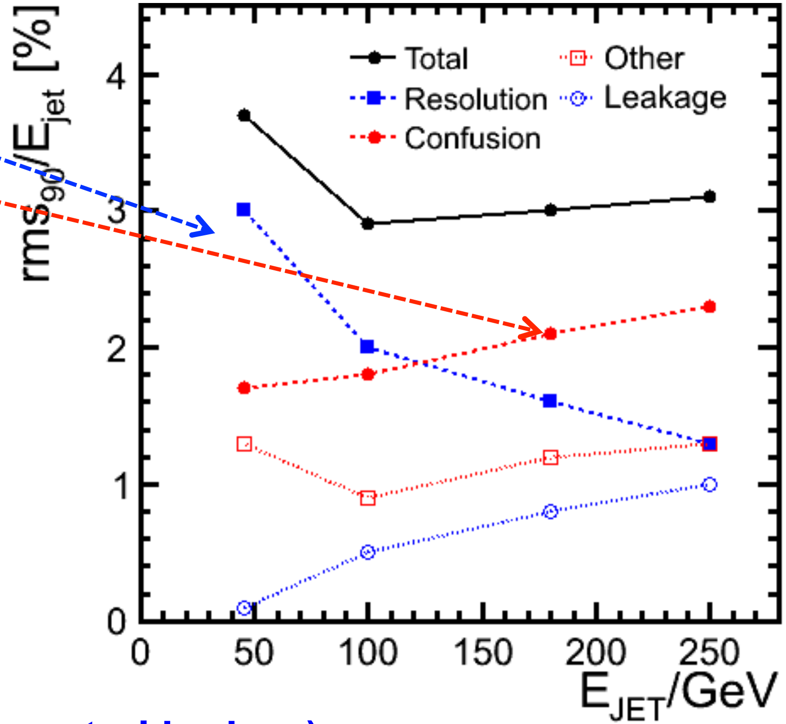
- Ability to resolve photons in current PandoraPFA algorithm strongly dependent on transverse cell size
- Require at least as fine as 10x10 mm^2 to achieve 4.0 % jet E resolution
- Significant advantages in going to 5x5 mm^2

★ **HCAL Conclusions:**

- 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

Contributions to resolution

★ **Answer depends on jet energy**
- Low energy jets: **RESOLUTION**
- High energy jets: **CONFUSION**
- Cross-over at **~100 GeV**
- 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