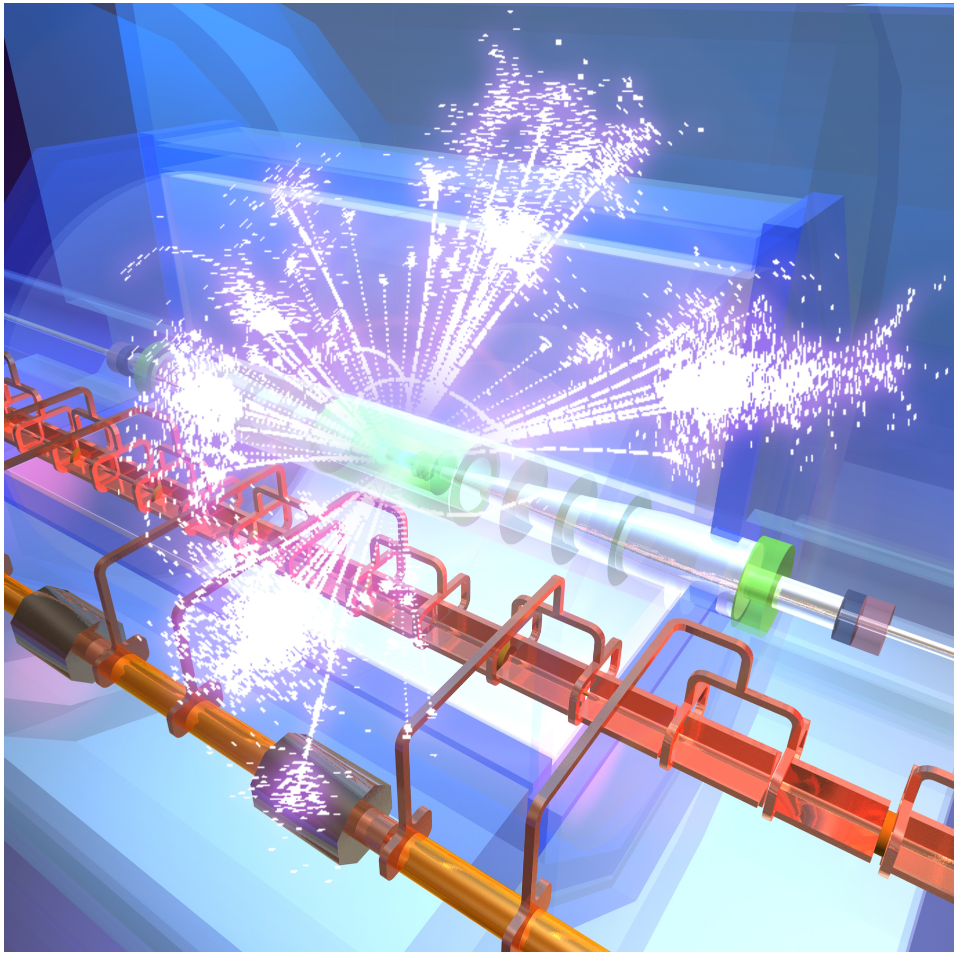
Particle Flow Calorimetry

Mark Thomson
University of Cambridge



Outline

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

1) Calorimetry

Precision Physics

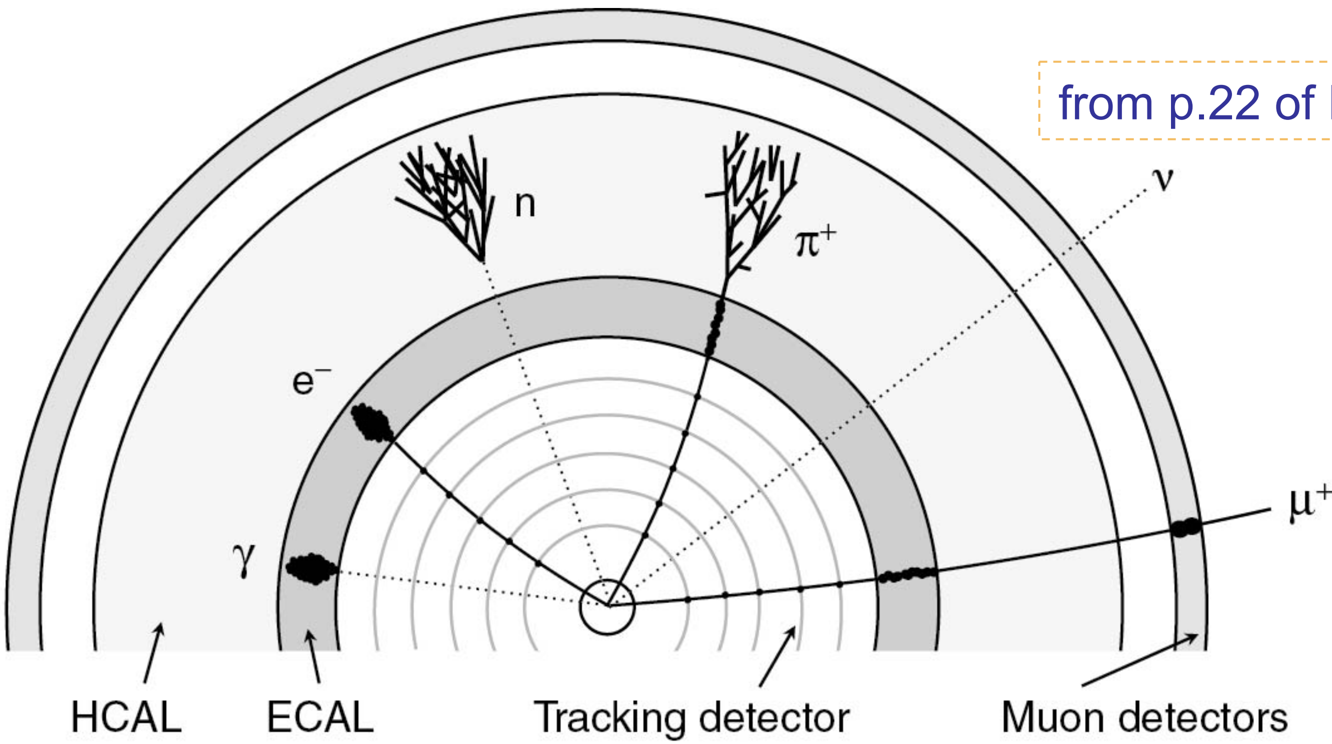
★ **From yesterday:**
- ♦ Should be clear that the ILC lives/dies on precision physics
- ♦ Has implications for detector design
- ♦ Detector needs to be matched to physics goals

★ **Previous talk:**
- ♦ Implications for tracking systems
- ♦ Reconstruction of charged particles

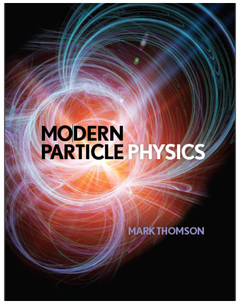
★ **This talk:**
- ♦ Implications for calorimeter systems
- ♦ Reconstruction of neutrals and jets

Calorimetry for beginners

- Calorimeters consist of two main systems:
  - **ECAL**: electromagnetic calorimeter: photons
  - **HCAL**: hadron calorimeter: neutral hadrons
  - tracker + ECAL + HCAL ⇨ particle ID

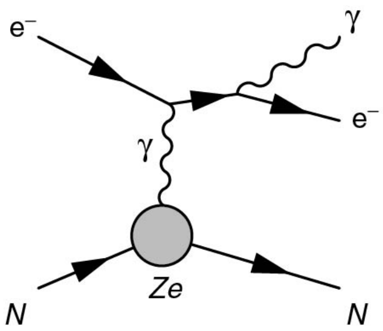


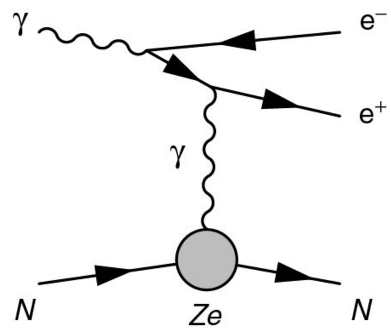
from p.22 of MPP

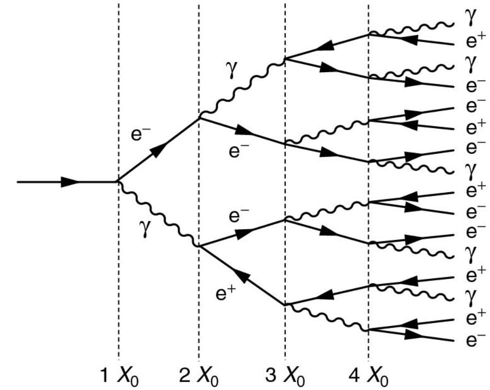


★ Electromagnetic calorimetry

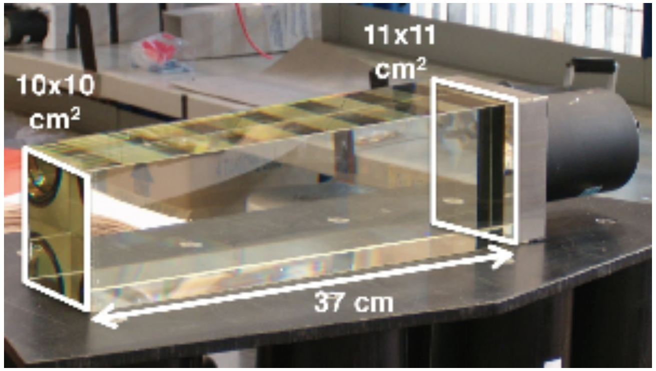
- High-energy electrons/photons produce EM showers via Bremsstrahlung and pair-production processes





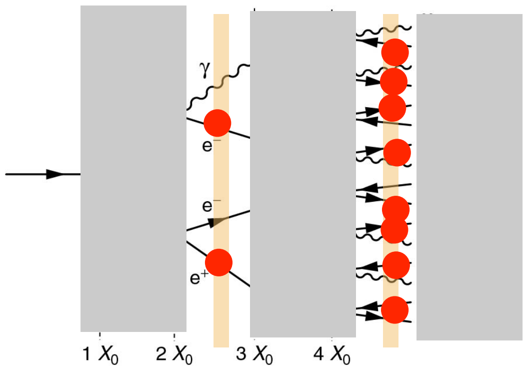


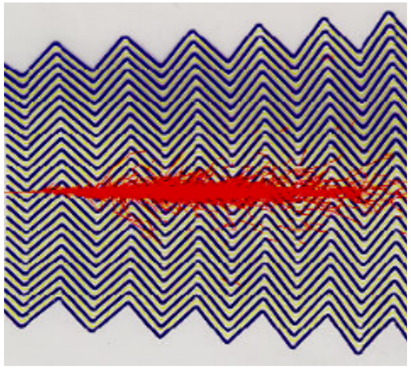
- Totally active



~ total e+/e- path length

- Sampling: dense absorber + active



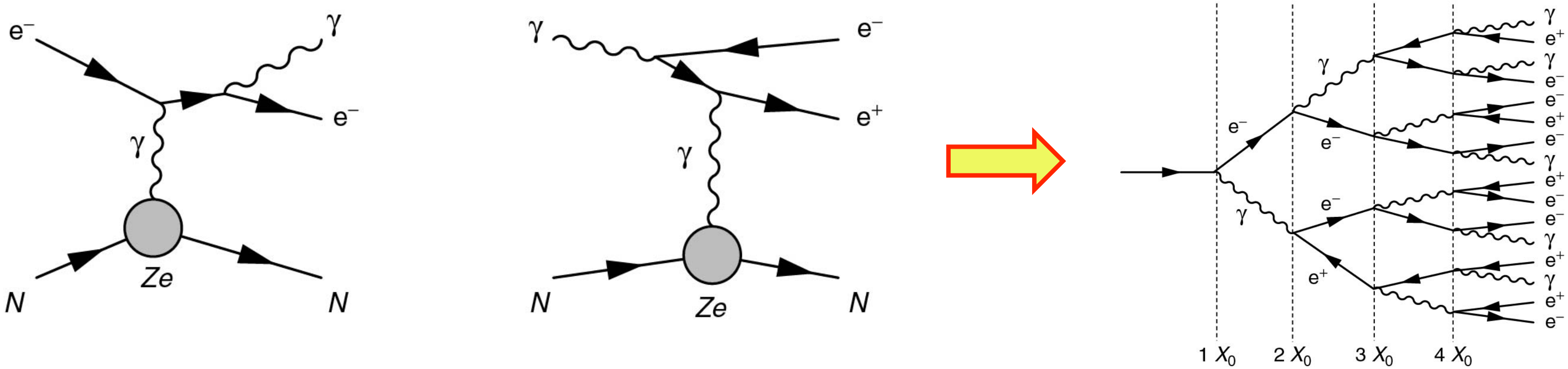


~ numbers of e+/e- Xing active layers

ECAL

★ **Electromagnetic calorimetry**

♦ **High-energy electrons/photons produce EM showers via Bremsstrahlung and pair-production processes**



- **Totally active**

e.g. CMS crystals
Good resolution
Not very compact
Limited segmentation

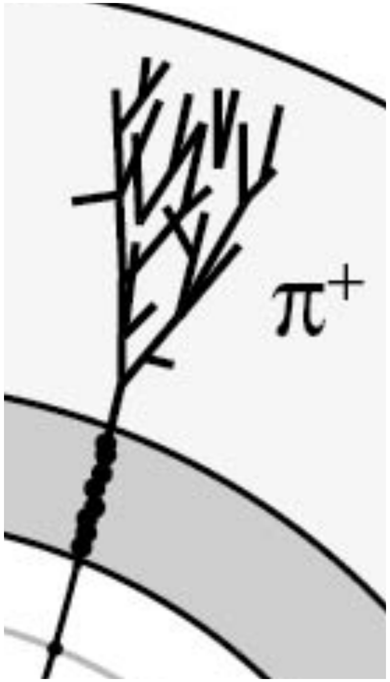
- **Sampling: dense absorber + active**

e.g. ATLAS LAr
OK resolution
More compact
More segmentation

HCAL

- **Hadron calorimetry**
  - **High-energy hadrons interact via strong interactions through many processes: much more shower-to-shower variation**
  - **Energy observed depends on EM fraction (neutral pions), energy lost to nuclear excitation, …**
  - **Hadronic showers are large – need dense material to contain**

    ⇨ **HCAL is always a sampling calorimeter**



HCAL

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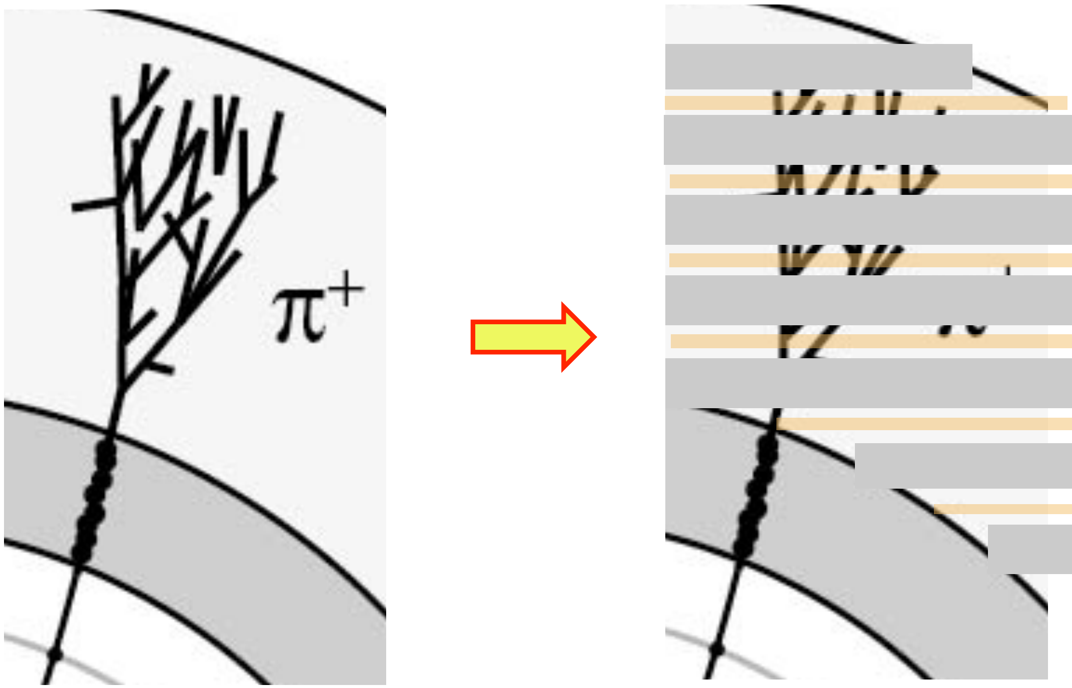

~ total ionization in active sampling layers

Resolutions

EM and hadronic showers are stochastic processes

- ★ "typical" ECAL energy resolutions

$$\boxed{\frac{\sigma_E}{E} \sim \frac{2\,\% - 10\,\%}{\sqrt{E(\mathrm{GeV})}}}$$

- ★ "typical" HCAL energy resolutions

$$\boxed{\frac{\sigma_E}{E} \sim \frac{50\,\% - 100\,\%}{\sqrt{E(\mathrm{GeV})}}}$$

Resolutions

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★ "typical" HCAL energy resolutions

$$\frac{\sigma_E}{E} \sim \frac{50\,\% - 100\,\%}{\sqrt{E(\mathrm{GeV})}}$$

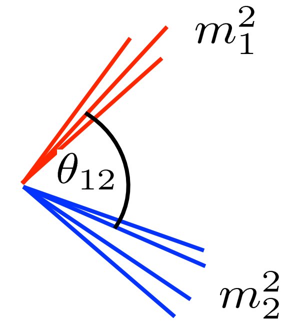
This is **bad** for a LC !

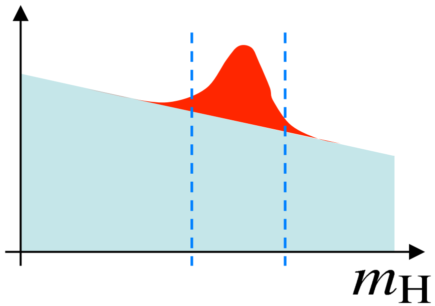
2) Calorimetry Goals for the ILC*

*or CLIC

Calorimetry at a Future e⁺e⁻ Collider

- ★ What motivates calorimetry requirements at a future LC ?
  - depends on physics measurements
- ★ **NOT** driven by single particle resolution
- ★ Jet energy resolution much more important
- ★ Likely to be primarily interested in di-jet mass resolution
  - For a narrow resonance, want best possible di-jet mass res.

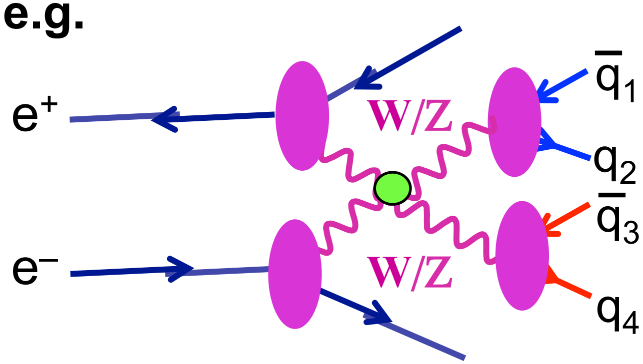


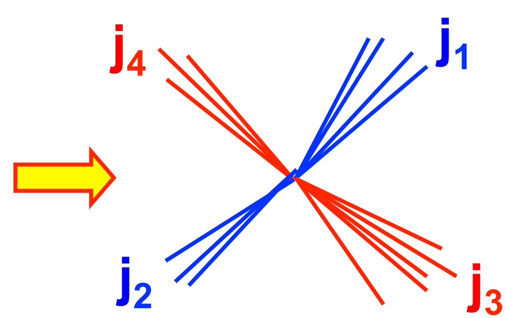


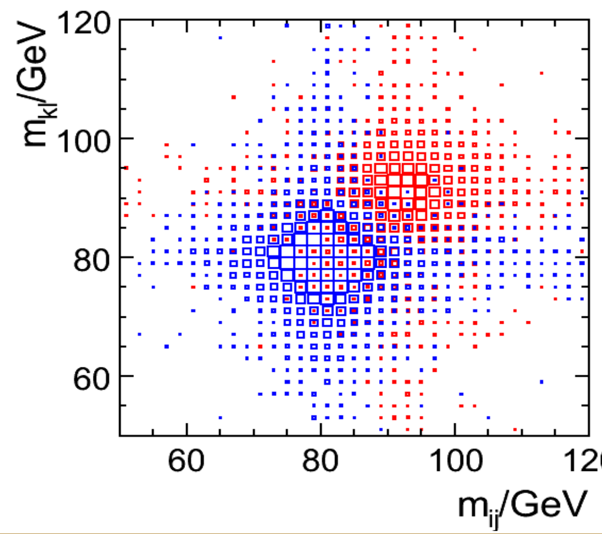
$$\text{signif.} \propto \frac{S}{\sqrt{B}} \quad \propto (\text{resolution})^{-\frac{1}{2}}$$

  - + strong desire to separate W/Z hadronic decays

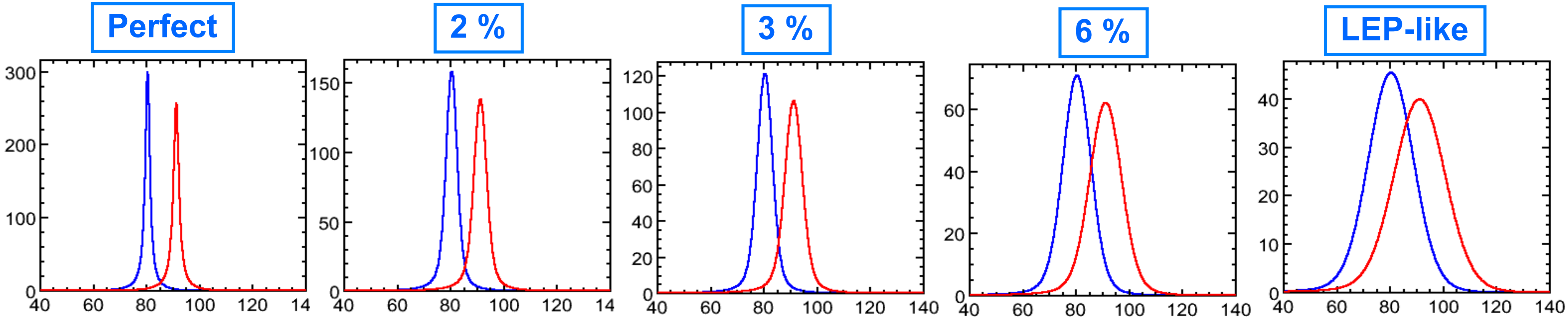
e.g.





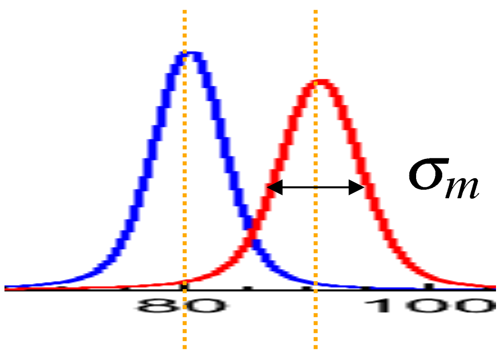


Gauge boson reconstruction



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**

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



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

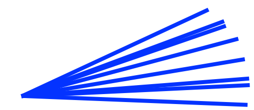
Dual Readout

Unproven, not clear if viable for a collider detector

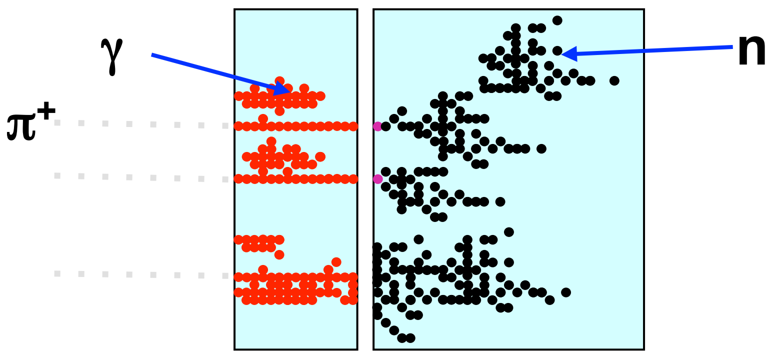
3) What is Particle Flow?

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



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

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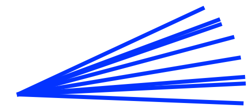

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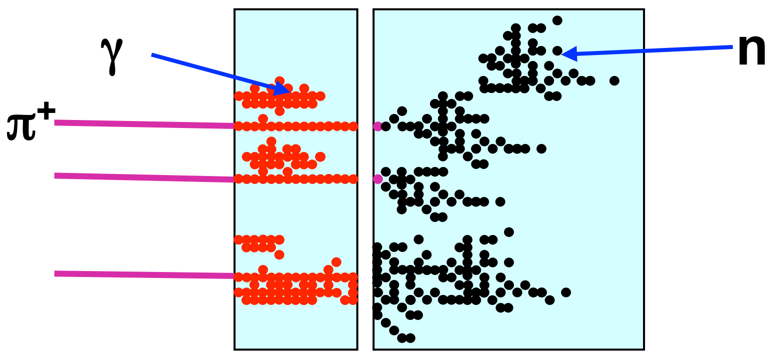


$\mathrm{E}_{\mathrm{JET}} = \mathrm{E}_{\mathrm{ECAL}} + \mathrm{E}_{\mathrm{HCAL}}$

High quality tracking information not used

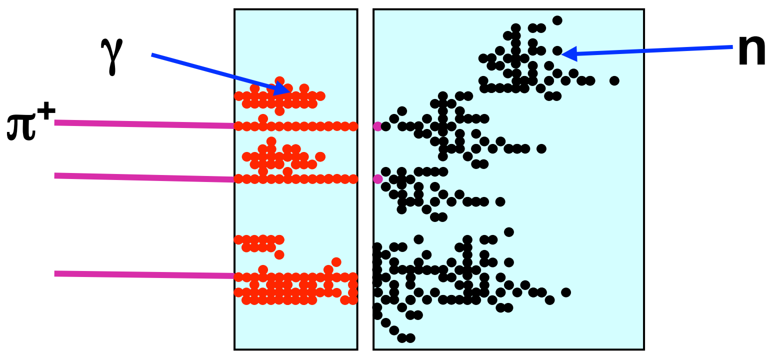
Particle Flow Paradigm

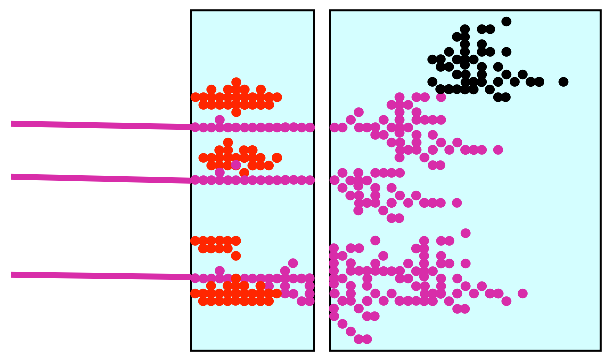
★ **Particle flow approach:**

- 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





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

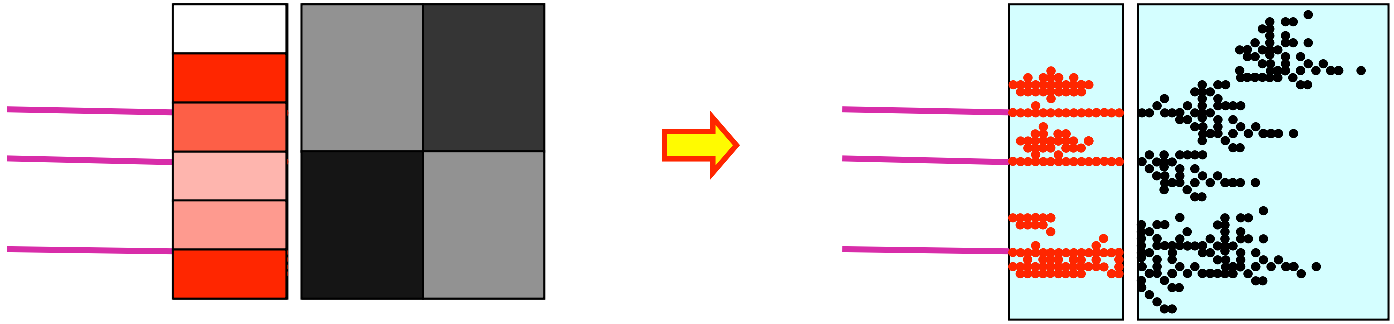
⇒

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

Realising Particle Flow

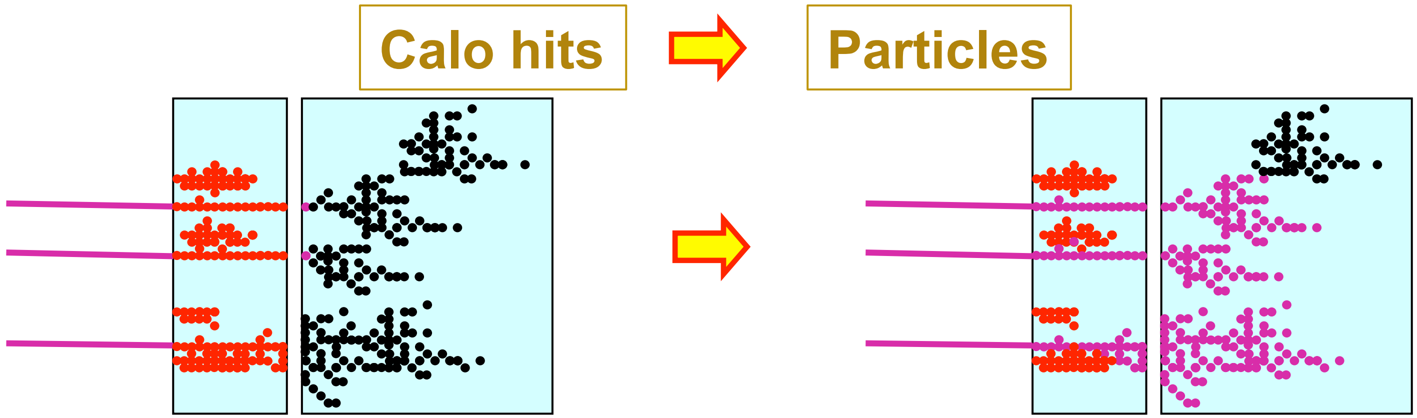
<u>Hardware:</u> need to be able to resolve energy deposits from different particles

- Requires highly granular detectors



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

- Requires sophisticated reconstruction software



Particle Flow Calorimetry = HARDWARE + SOFTWARE

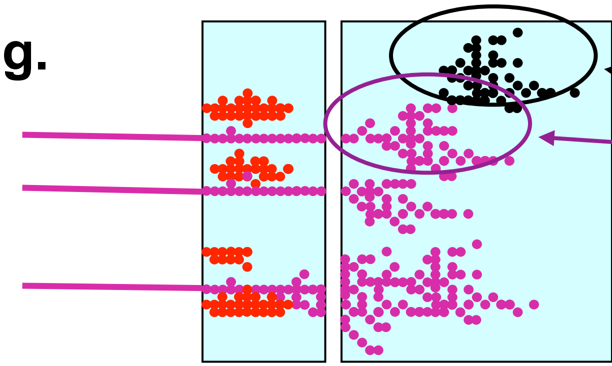
Particle Flow Reconstruction

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.

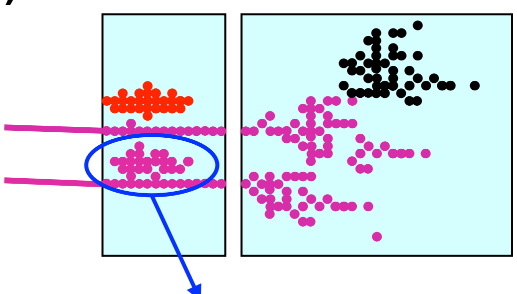


If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

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

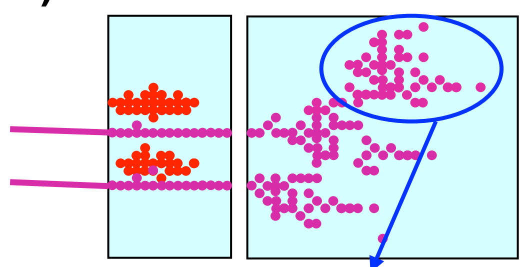
Three types of confusion:

i) Photons



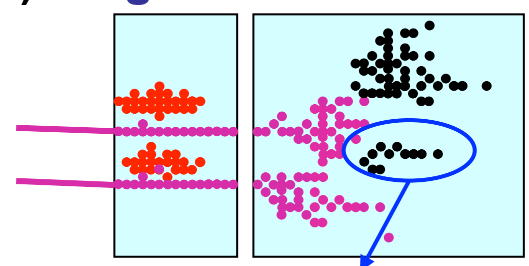
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

iii) Fragments



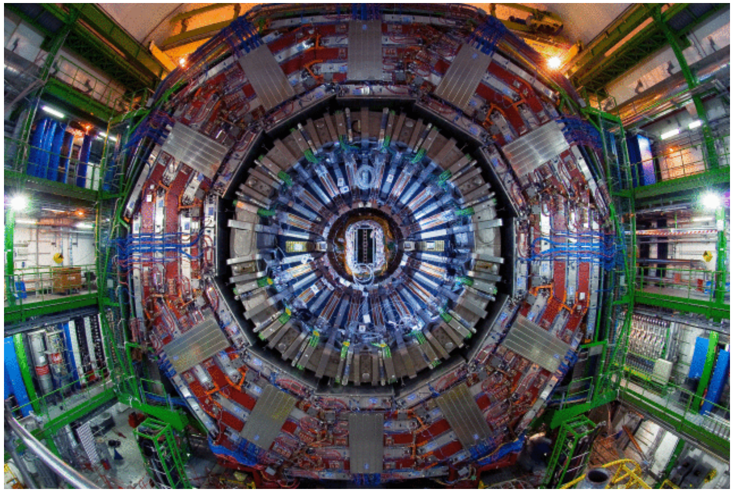
Reconstruct fragment as separate neutral hadron

Practical Particle Flow

★ **Particle flow reconstruction**

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

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

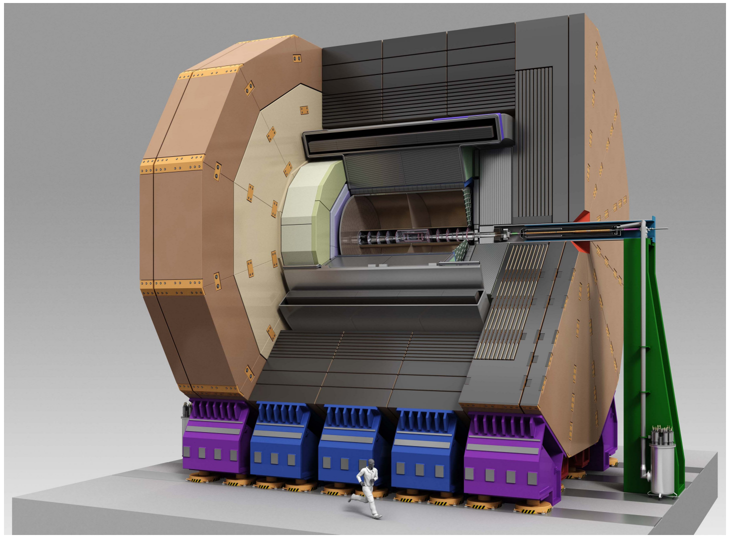


★ Apply particle flow techniques to an existing detector – **see next talk**

ii) Our dreams..

Soon to become reality?

ILD Concept for the ILC



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

4) Linear Collider Detector Concepts

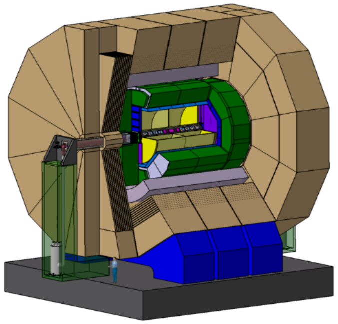
ILC Detector Concepts

★ 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":

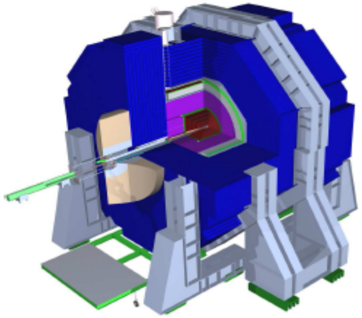
ILD: International Large Detector

"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



ILC Detector Concepts

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- ECAL and HCAL inside solenoid
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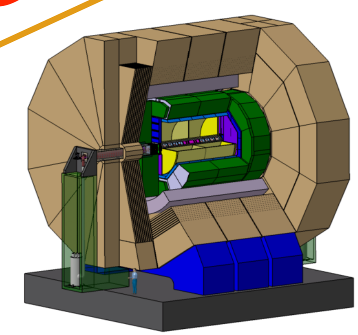
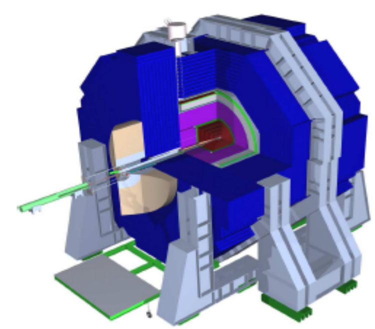
PARTICLE FLOW DICTATES DESIGN OF ~$500M ILC DETECTORS

ILD: International Large Detector

"Large" : trac
B-field
Tracker
Calorimet particle flow



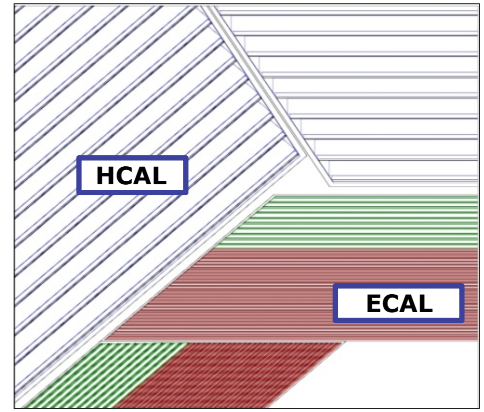
: tracker radius 1.2m
: 5 T
: Silicon
Calorimetry : fine granularity particle flow



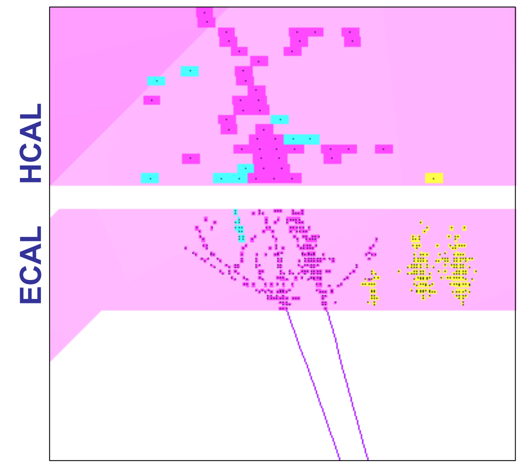
ECAL Considerations

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

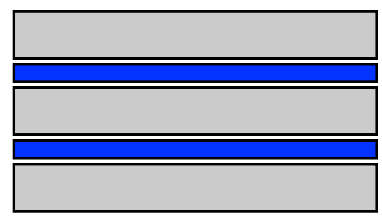
- ★ Want to longitudinally separate EM and Hadronic showers
  - ➤ Require large ratio of λ_I/X_0
  - ➤ Longitudinal segmentation to cleanly ID EM showers



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

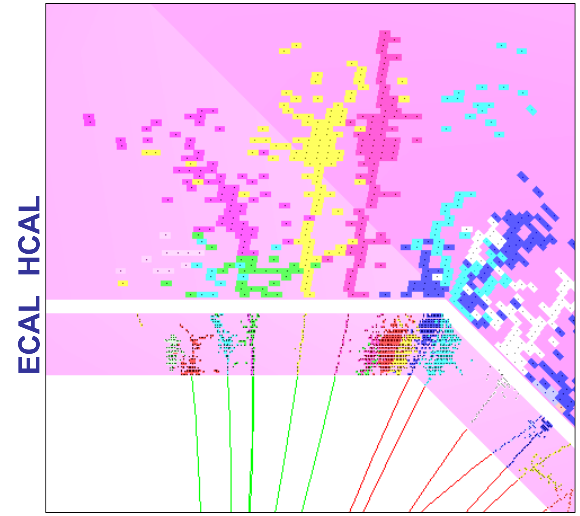


- ★ Favoured option : Tungsten absorber
  - • Need 'thin' sensitive material to maintain small Molière radius



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
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
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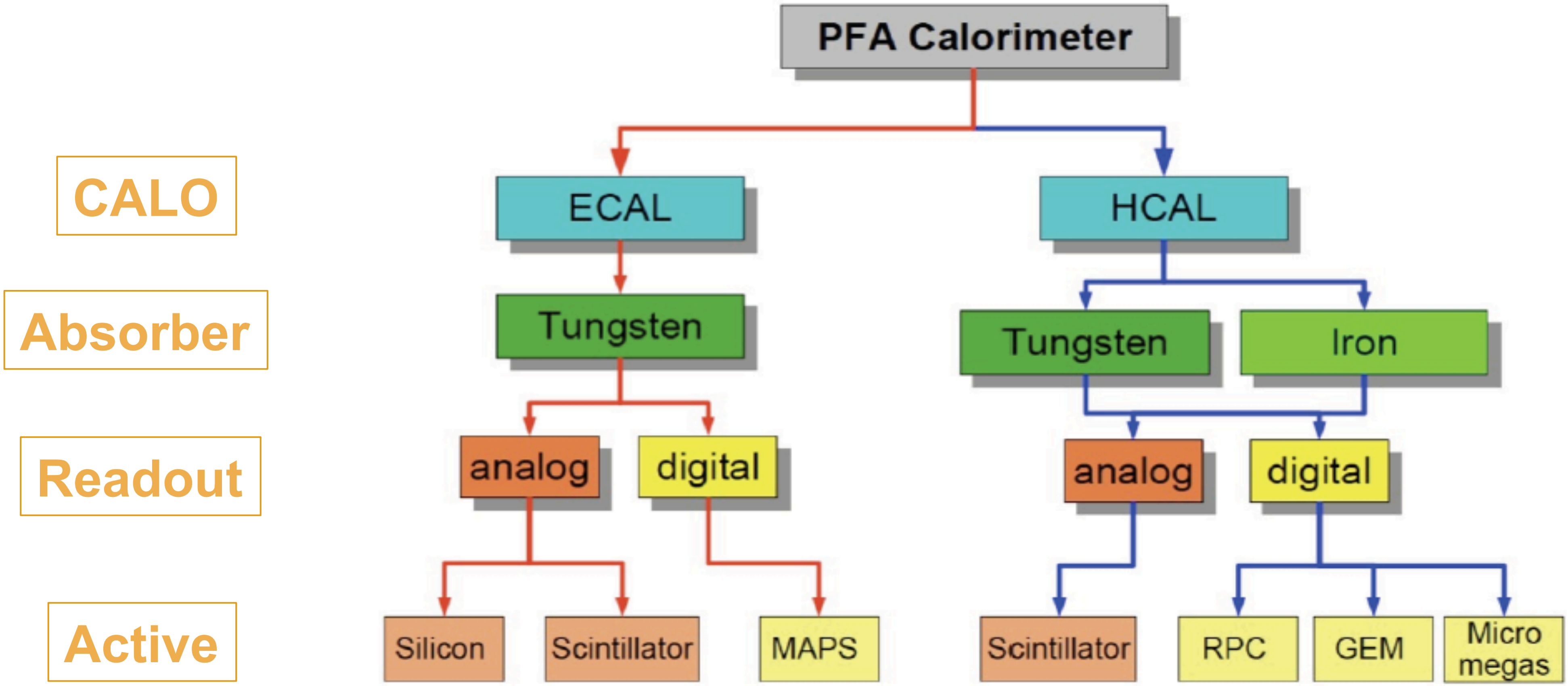
?

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

5) Calorimeter Options

CALICE Activities

★ CALICE = "Umbrella R&D collaboration for LC calorimetry"
- studies encompass a number of technological options

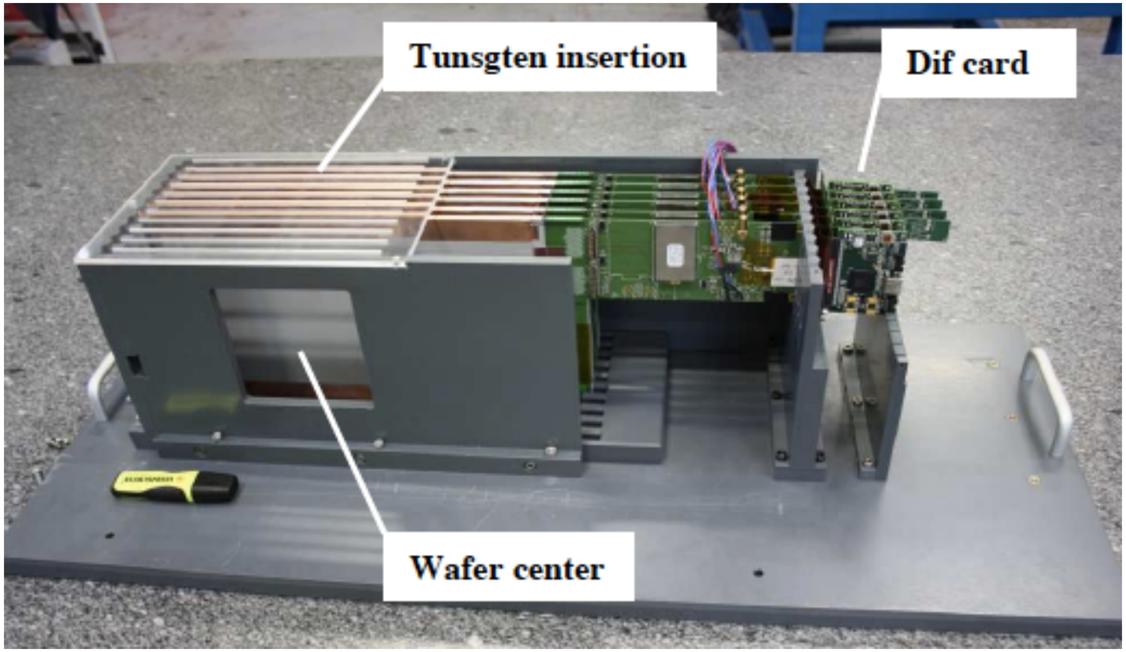


e.g. Si-ECAL prototype

★ **Technological Si-ECAL prototype:**

- **Real-scale detector integration model**
- **Large Si sensors with small 5×5 mm^2 PADs**
- **System with 1200 cells in DESY test beam in 2012**

Full-scale mechanical structure

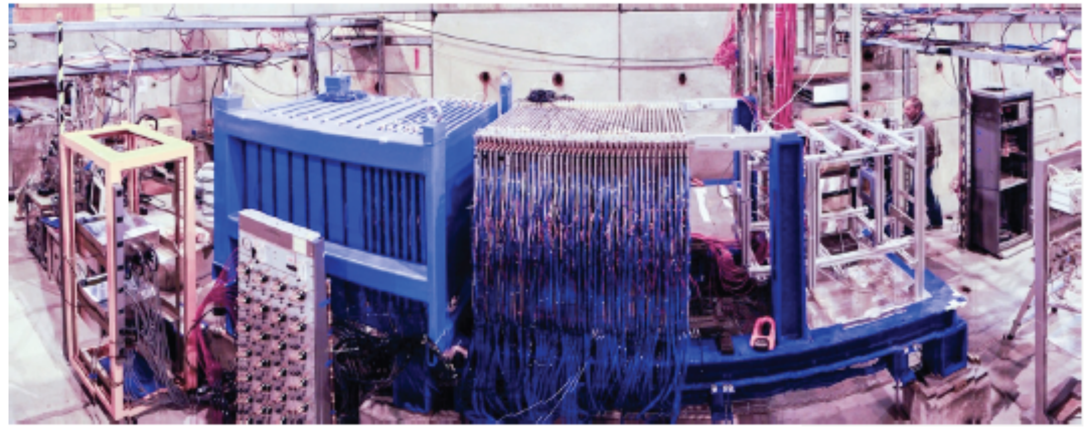


Test beam characterisation of technology

e.g. Digital HCAL

54 glass RPC chambers, 1m^2 each

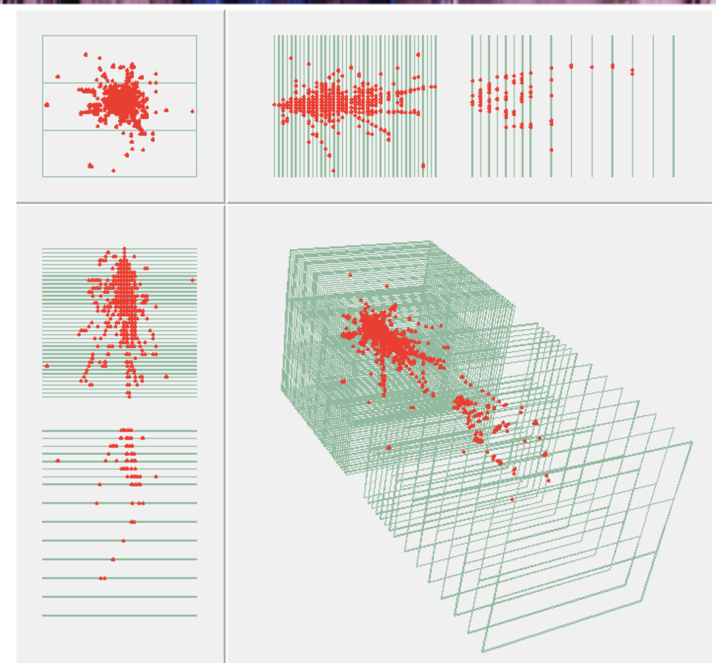
- PAD size 1×1 cm^2
- Digital readout (1 threshold)
- Fully integrated electronics
- Total: 500000 readout channels



⇨ **Detailed 3D images of hadronic showers**

Test beam campaigns:

- Demonstrate technology
- Provide high quality physics data
  ⇨ test GEANT4 models
- Many CALICE publications

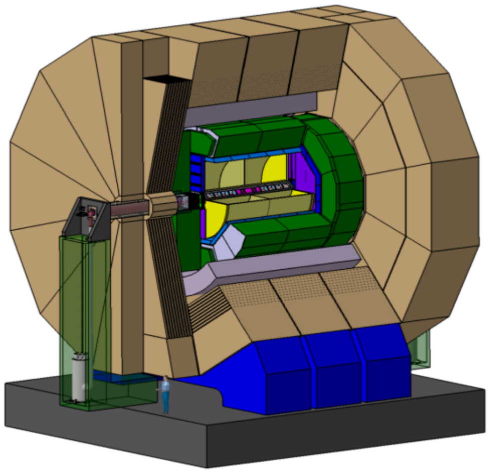


W-DHCAL π^- at 210 GeV (SPS)

Now focus on ILD

ILD: International Large Detector

"Large"	: tracker radius 1.8m
B-field	: 3.5 T
Tracker	: TPC
Calorimetry	: fine granularity particle flow
ECAL	: SiW: 29 layers 5x5 mm^2
HCAL	: ScintW: 48 layers 3x3 cm^2 tiles

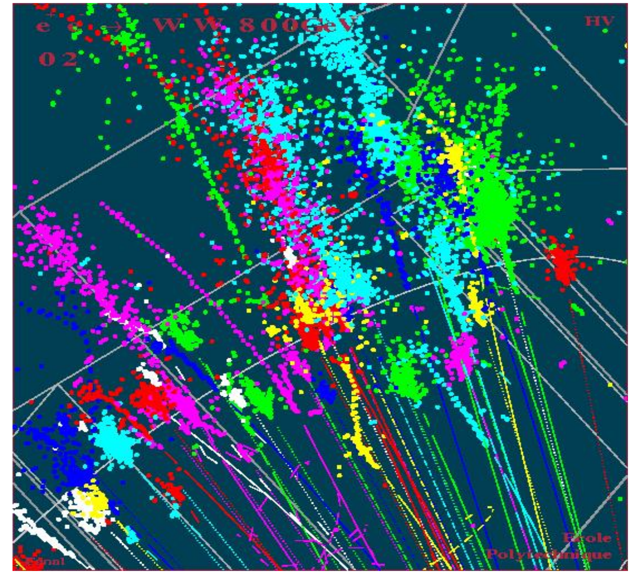


6) Particle Flow Reconstruction aka PFA

Particle Flow Reconstruction

★ **High granularity calorimeters – <u>very different</u> to previous detectors**

★ **“Tracking calorimeter” – requires a new approach to ECAL/HCAL reconstruction**



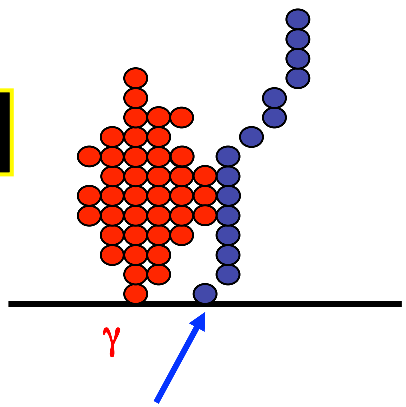
⇨ **Particle Flow Algorithms (PFA)**

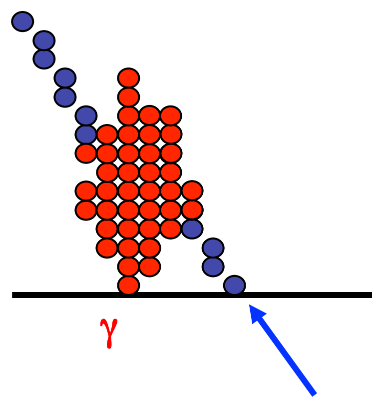
<u>e.g.</u>

★ **Need to separate “tracks” (charged hadrons) from photons**

hardware

granularity





software

PFlow Algorithm

PandoraPFA

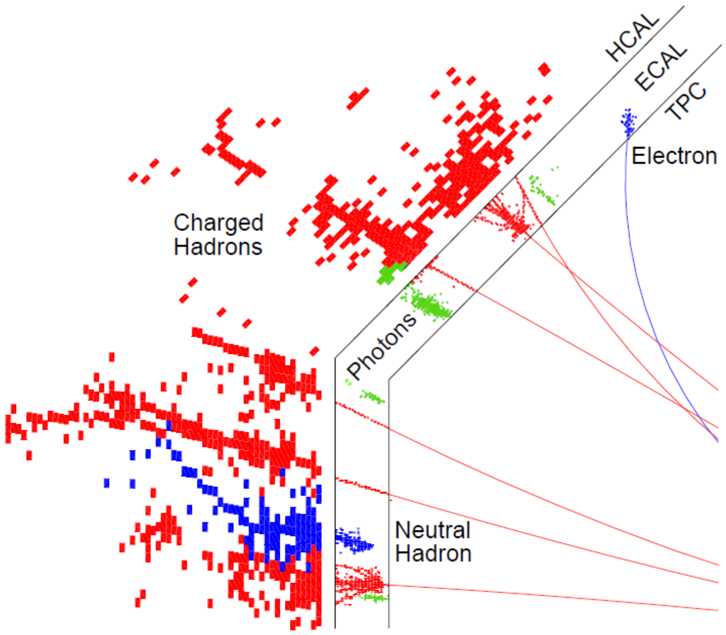
★ High granularity particle flow calorimetry lives or dies on the quality of the reconstruction of particles

★ 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

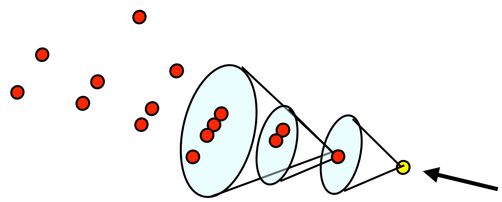
★ Provides highly sophisticated PFlow reconstruction for LC-style detectors
- + flexibility for much more…



Typical topology of a simulated 250GeV jet in CLIC ILD

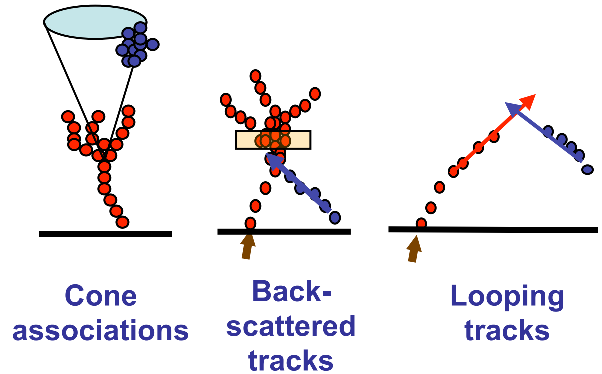
PandoraPFA Algorithms

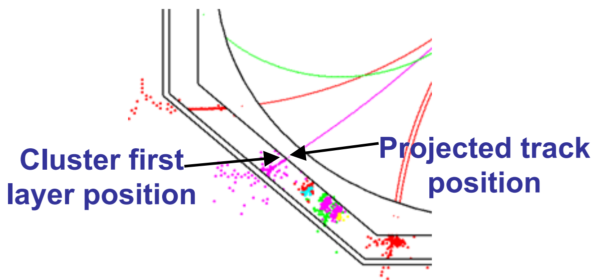
M. Thomson, NIM 611 (2009) 24-40



ConeClustering Algorithm

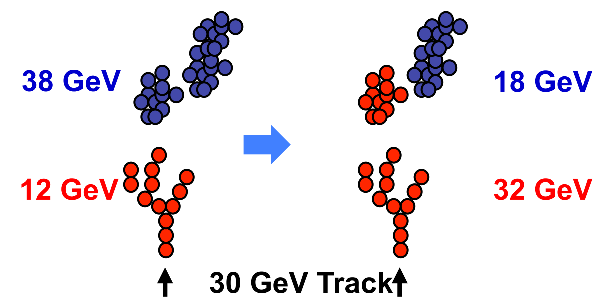
Topological Association Algorithms

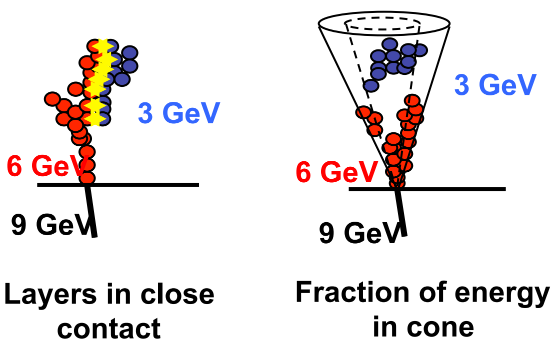




Track-Cluster Association Algorithms

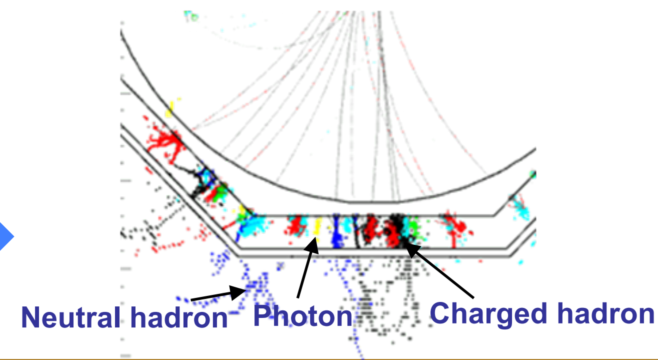
Reclustering Algorithms





Fragment Removal Algorithms

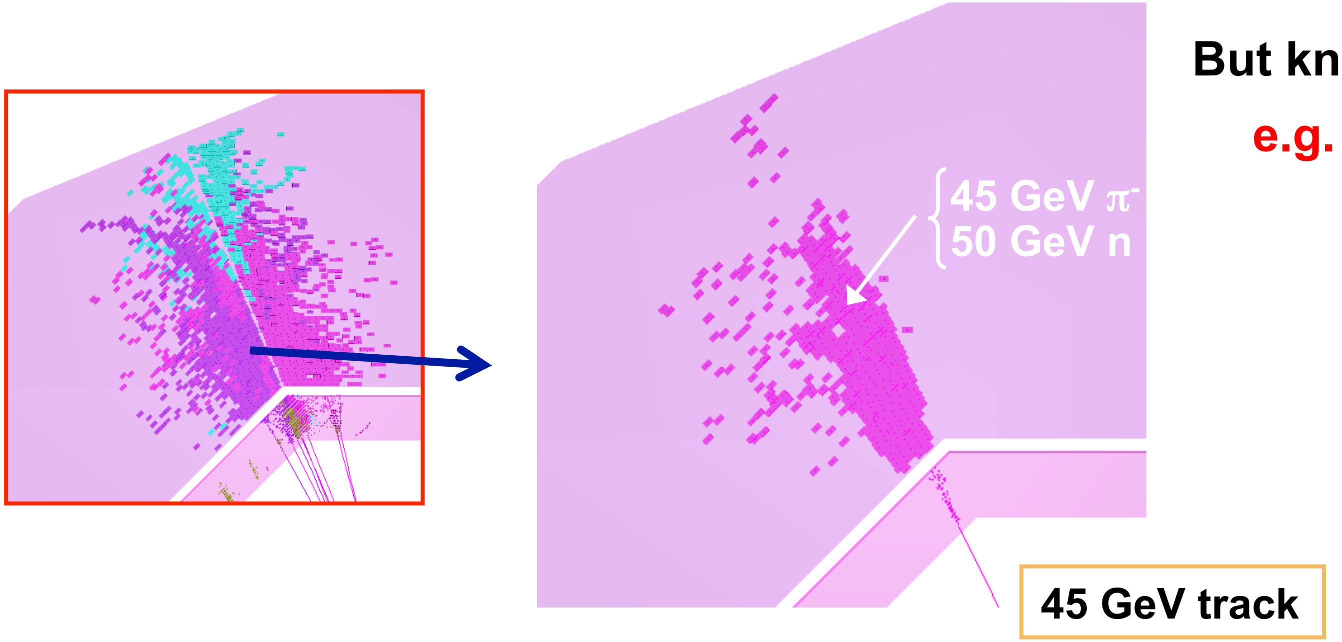
PFO Construction Algorithms



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

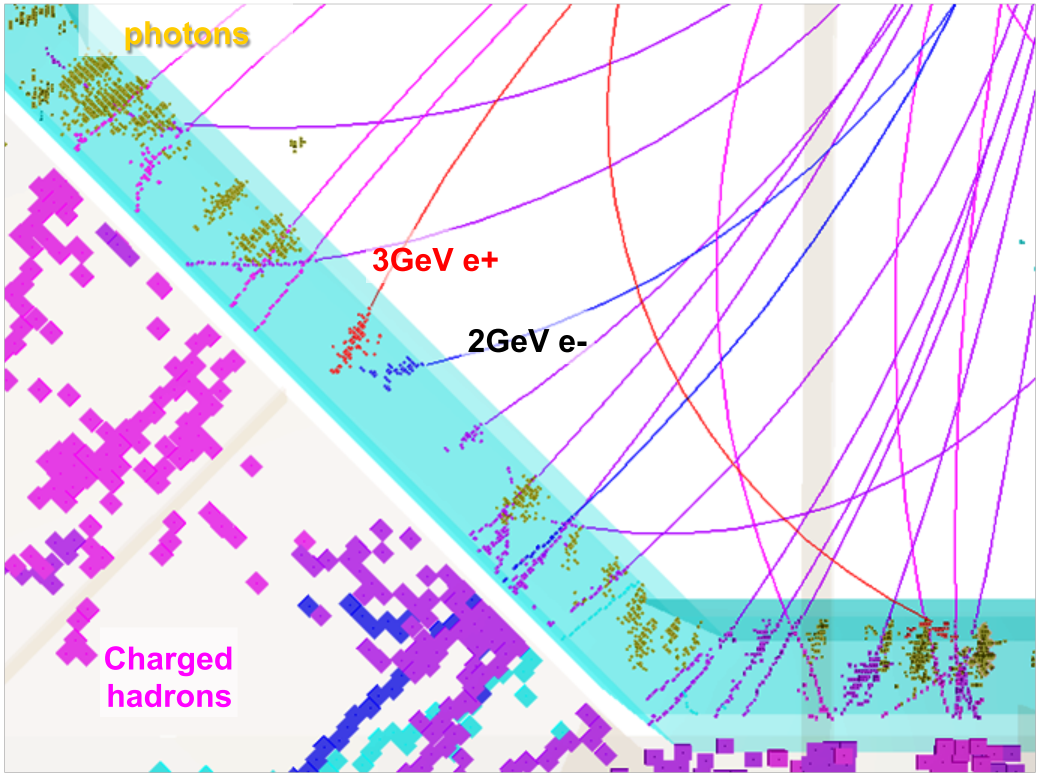
NOTE:

- 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**

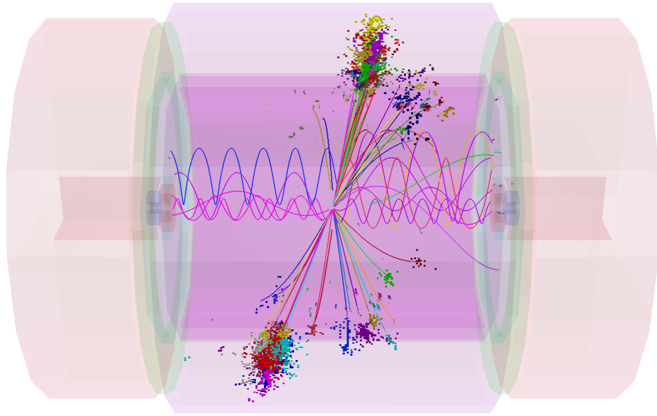
★ **Assess performance of a Particle Flow detector using simulation…**

7) Particle Flow Performance

Performance

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

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

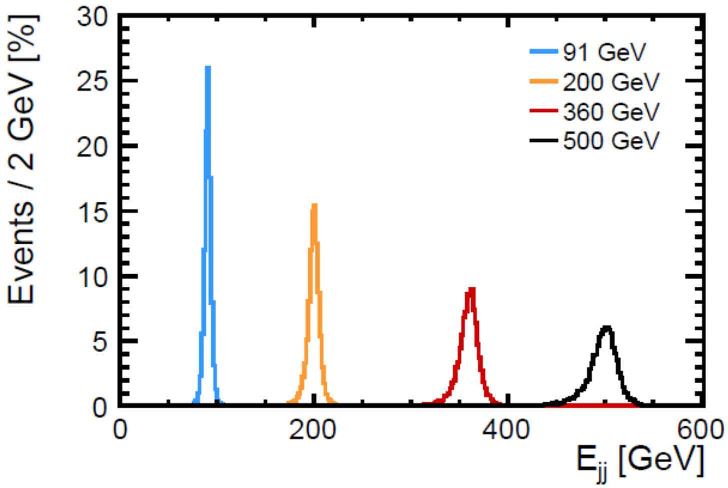


★ **Benchmark** performance using jet energy resolution in Z decays to light quarks

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

★ Current performance (PandoraPFA + ILD)

- uds jets (full GEANT 4 simulations)



rms$_{90}$

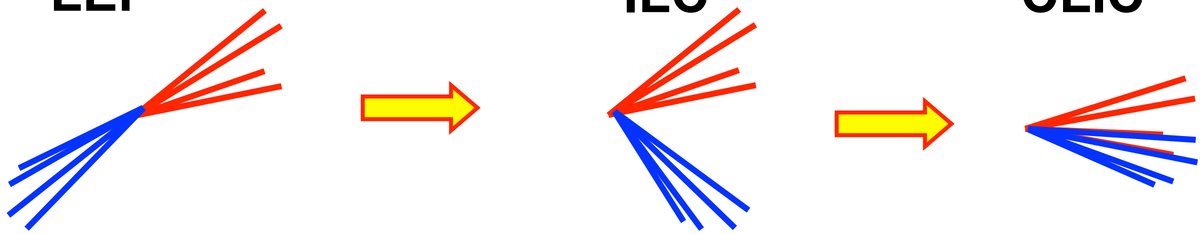
E_{JET}	σ_E/E_j
45 GeV	3.7 %
100 GeV	2.8 %
180 GeV	2.9 %
250 GeV	2.9 %

→ GOAL MET !

★ Factor 2-3 better than traditional calorimetry !

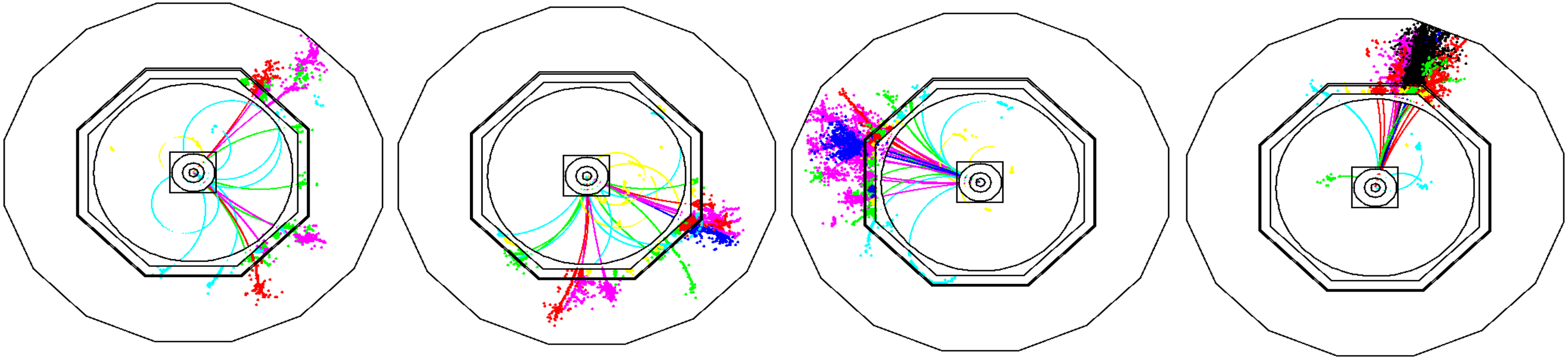
PFA at Higher Energy

- 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 !

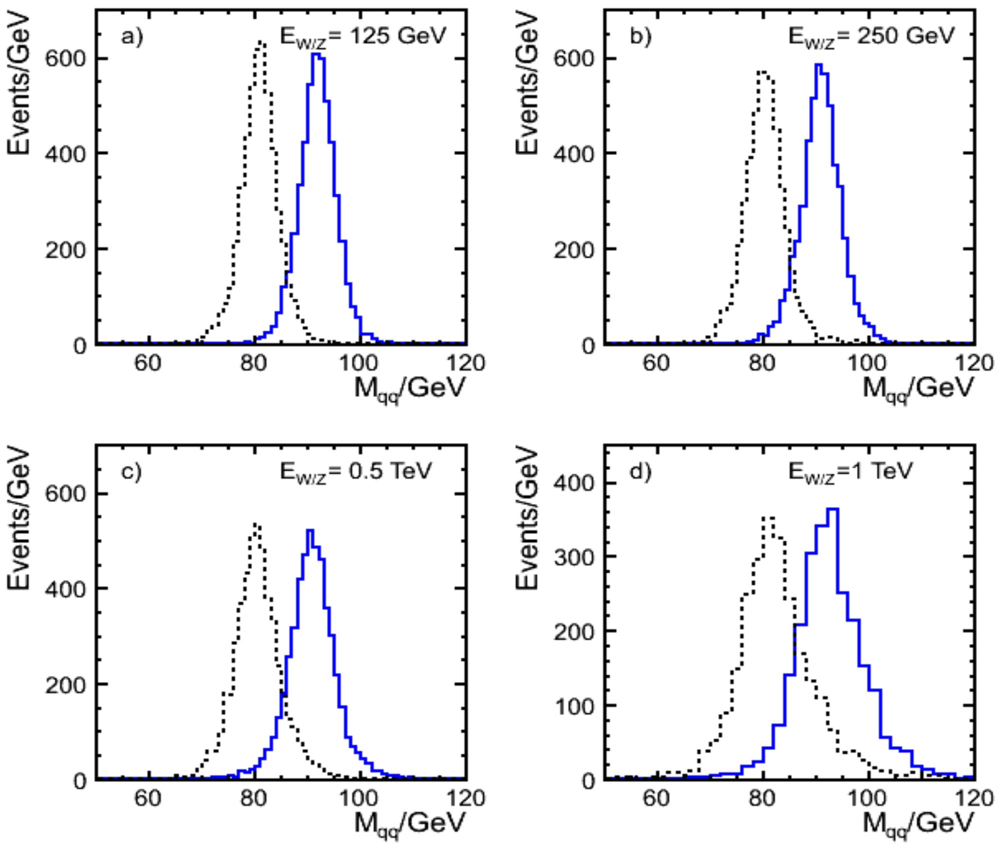
More confusion !



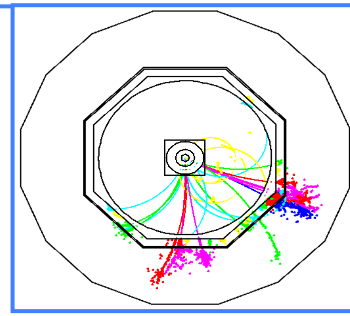
W/Z Separation

★ **Studied di-jet/mono-jet masses in ILD concept**

$$\left\{\begin{array}{l} e^+e^- \rightarrow WW \rightarrow u\bar{d}\nu\mu \\ e^+e^- \rightarrow ZZ \rightarrow d\bar{d}\nu\bar{\nu} \end{array}\right.$$

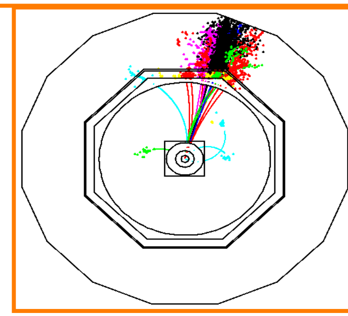


ILC-like energies



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.**

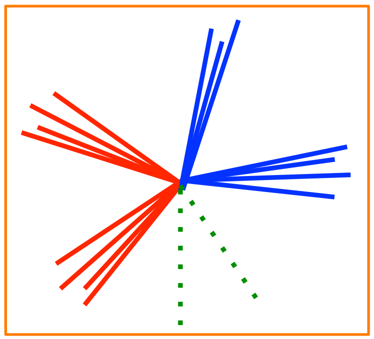
★ **Pair production and decay:**

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

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

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

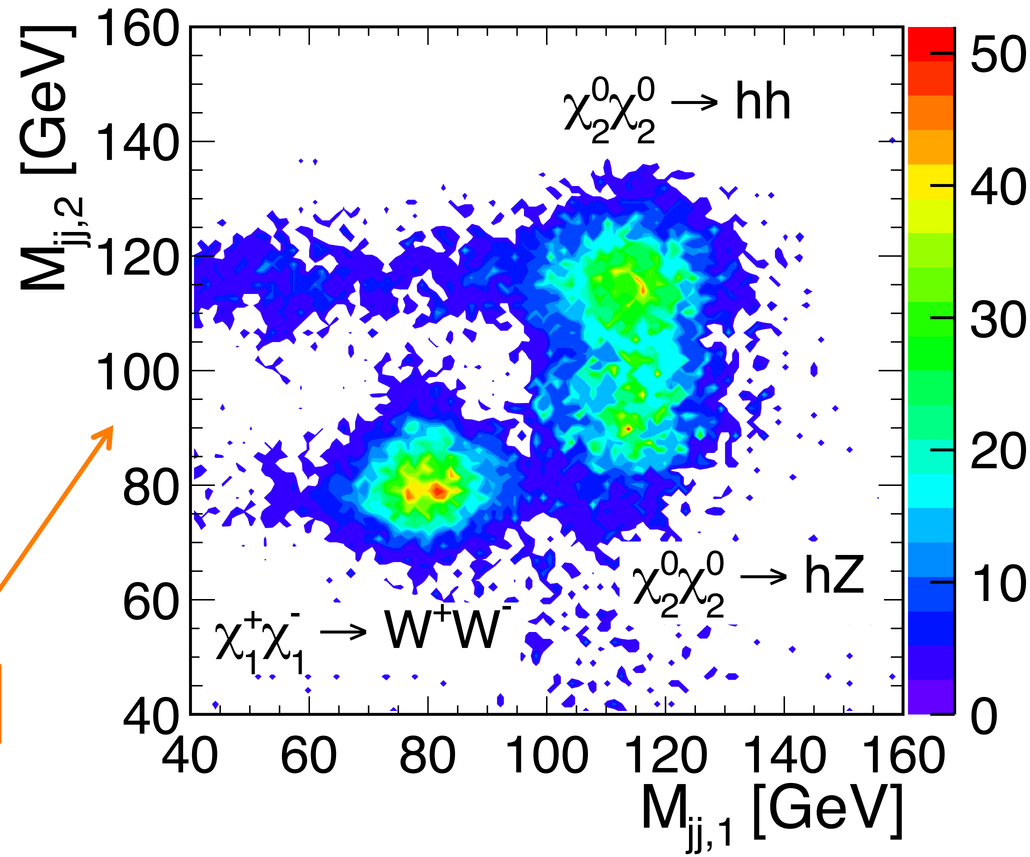
★ **Largest decay BRs have same topology for all final states**



★ **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



8) Understanding Particle Flow

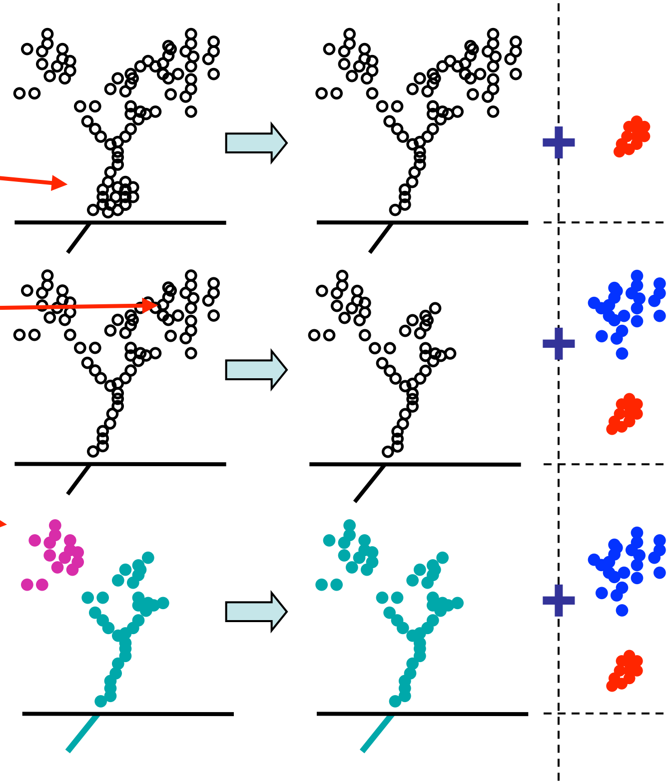
PFlow Limitations

What drives Particle Flow performance ?

- ★ Try to use various "Perfect PFA" algorithms to pin down main performance drivers (resolution, confusion, …)
- ★ Start with full reconstruction (PandoraPFA)
- ★ Then use MC to "cheat" various aspects of Particle Flow

PandoraPFA options:

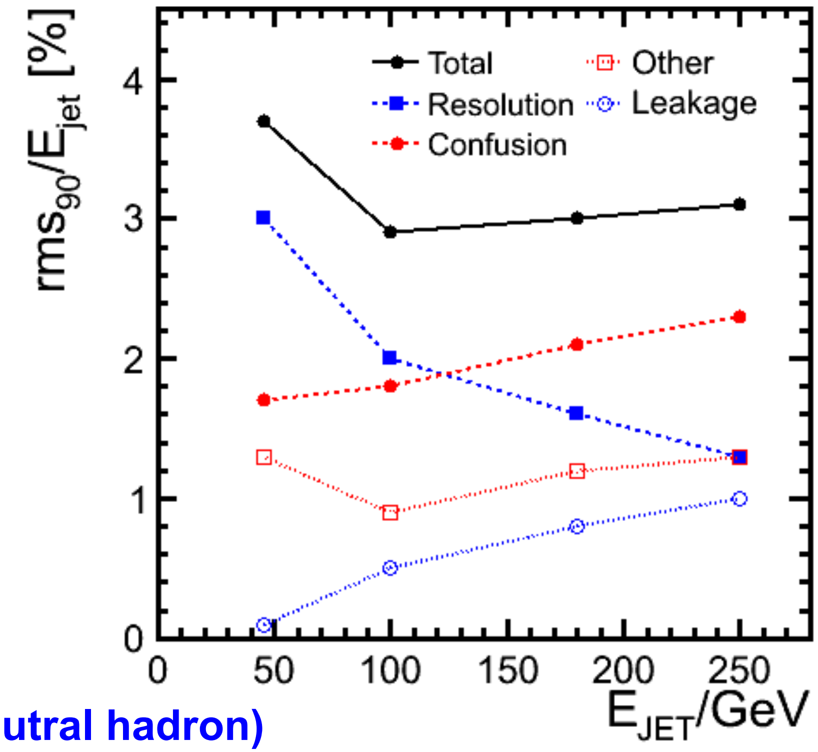
- **PerfectPhotonClustering**
  hits from photons clustered using MC info and removed from main algorithm
- **PerfectNeutralHadronClustering**
  hits from neutral hadrons clustered using MC info…
- **PerfectFragmentRemoval**
  after PandoraPFA clustering "fragments" from charged tracks identified from MC and added to charged track cluster
- **PerfectPFA**
  perfect clustering and matching to tracks



Pflow Limitations

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

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



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

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

Not insignificant

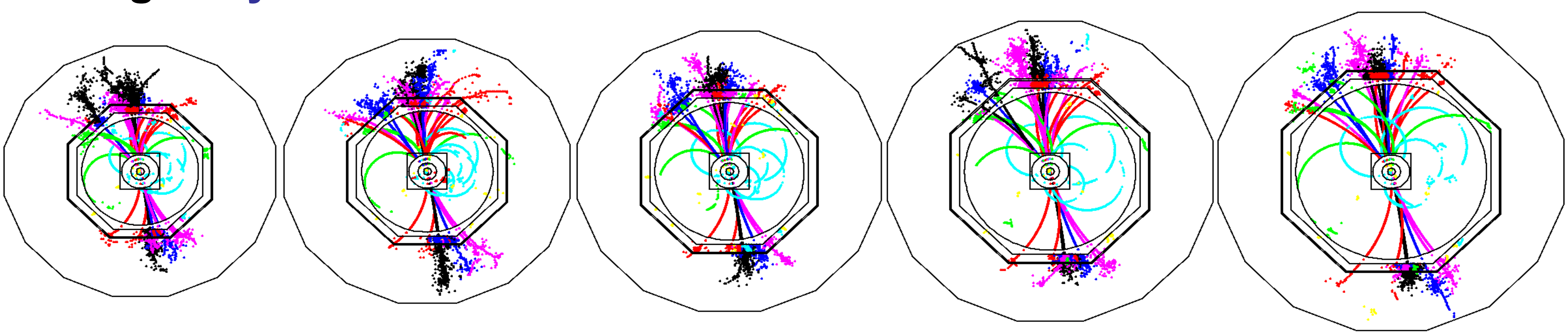
Largest single contribution, but remember, enters in quadrature

But depends on detector

Cost drivers:

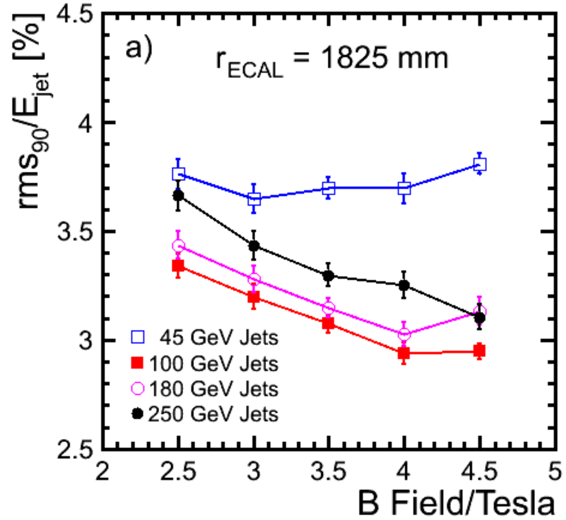
- Calorimeters and solenoid are the main cost drivers of an ILC detector optimised for particle flow
- Most important detector design considerations are:
  - B-field
  - R : inner radius of ECAL
  - HCAL thickness : number of interaction lengths
  - ECAL and HCAL segmentation
- LEVEL OF CONFUSION DEPENDS ON THESE PARAMETERS
- Study jet energy resolution as a function of these cost critical issues

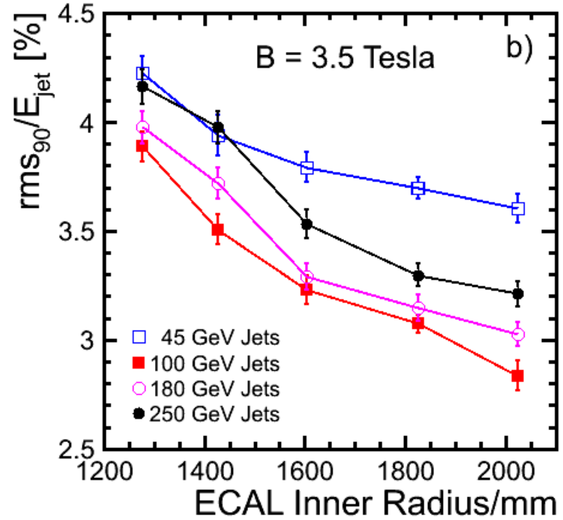
★e.g. vary ECAL radius and B-field



B vs R

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





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

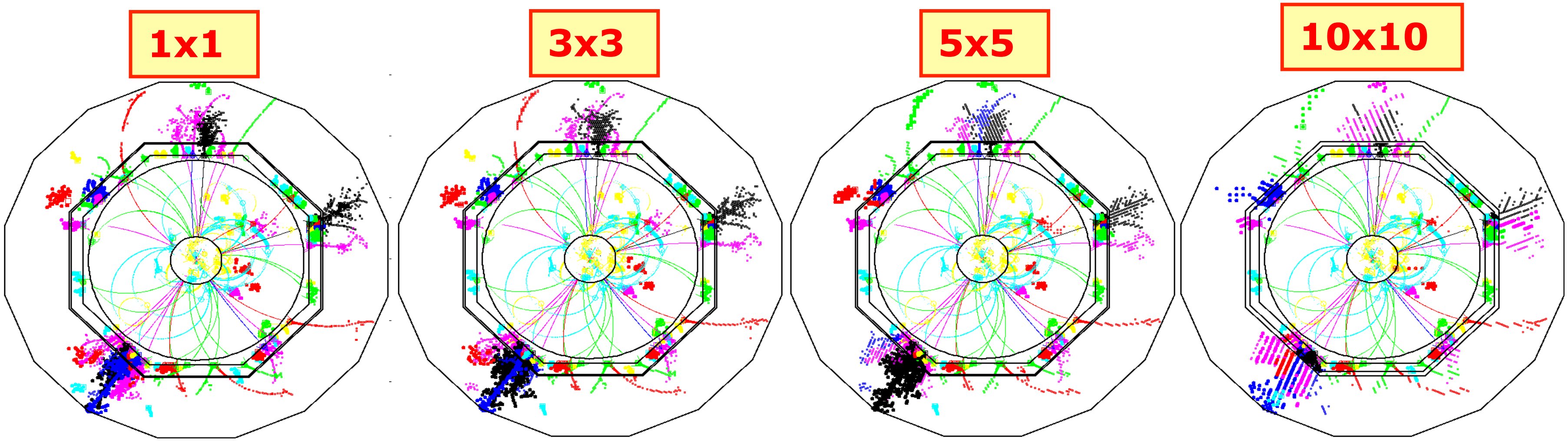
♦ **Confusion ∝ $B^{-0.3}$ R^{-1} (1/R dependence "feels right", geometrical factor !)**

Conclusions:

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

Calorimeter Segmentation

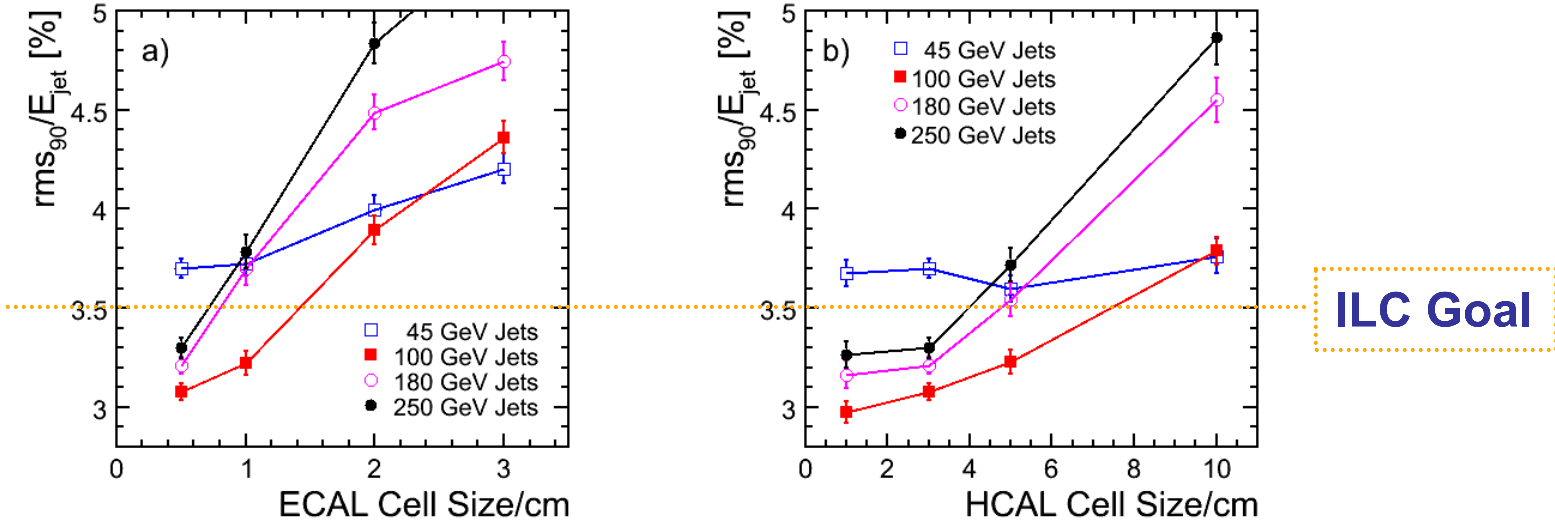
- Assumed particle flow reconstruction requires very highly segmented ECAL and HCAL
- What does this mean ?
- In ILD detector model vary ECAL Si pixel size and HCAL tile size
  - e.g. HCAL tile size [cm^2]



- "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

ECAL and HCAL

★ vary **ECAL Si pixel size** and **HCAL tile size**



★ **ECAL Conclusions:**

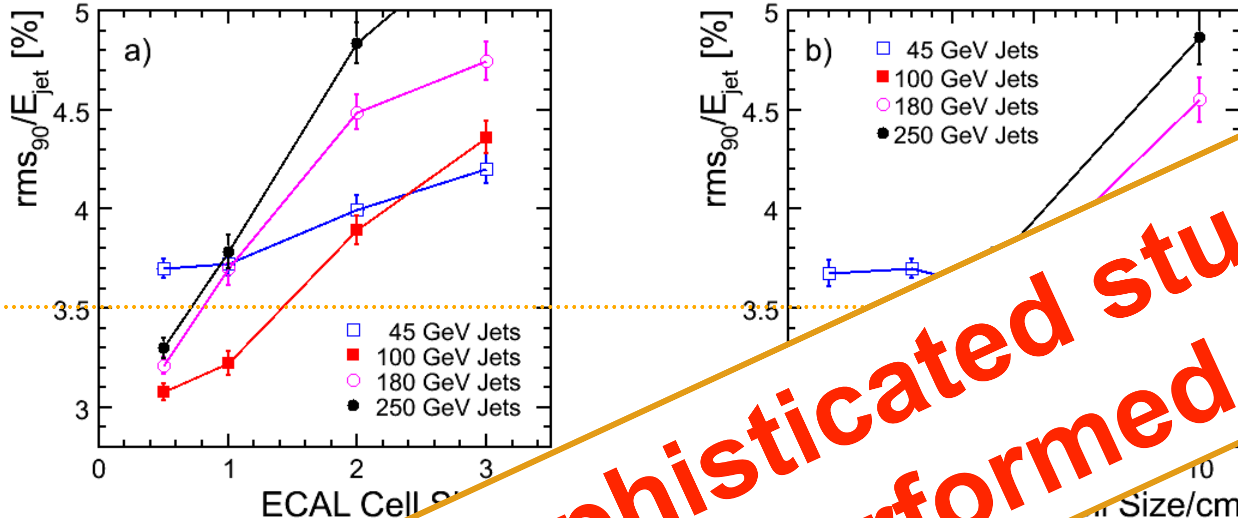
- Ability to resolve photons depends on transverse cell size
- Require at least as fine as **10x10 mm^2** to achieve **4.0 %** jet E resolution
- Significant advantages in going to **5x5 mm^2**

★ **HCAL Conclusions:**

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

ECAL and HCAL

★ **vary ECAL Si pixel size and HCAL tile size**



More sophisticated studies are being performed now

★ **ECAL Con**

- Abil ... pends on transverse cell size
- Requ ... as **10x10 mm²** to achieve **4.0 %** jet E resolution
- Signif ... tages in going to **5x5 mm²**

★ **HCAL Co nclusions:**

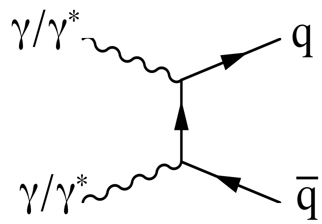
- For Scintillator HCAL, a tile size of **3×3 cm²** looks optimal
- May be different for a digital/semi-digital RPC based HCAL

9) Beyond Particle Flow Calorimetry

Its not just calorimetry

★ Using **reconstructed particles** 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

ECAL 10ns

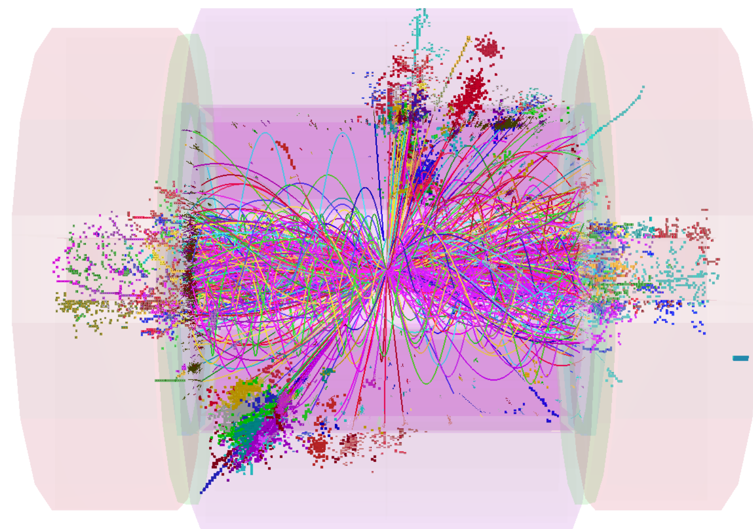
HCAL EndCap 10ns

HCAL Barrel 100ns

10ns of tracks

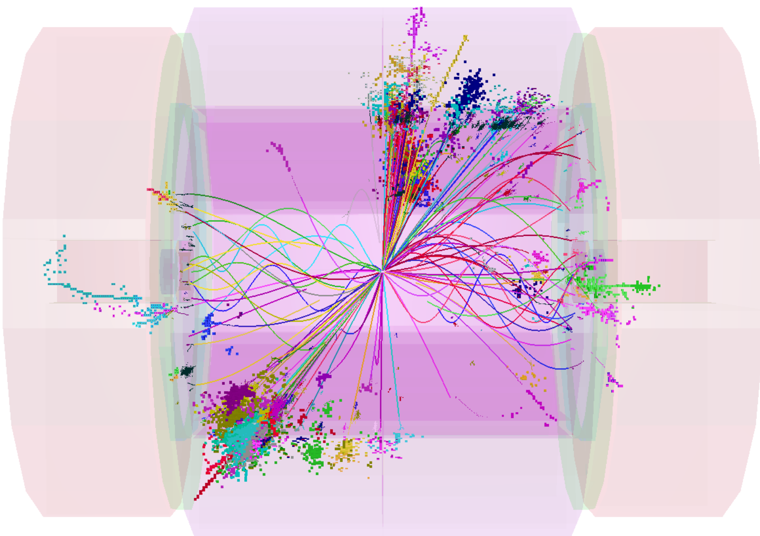
PandoraPFA

2. Reco. particles, total energy 1.2 TeV



Apply timing cuts to reconstructed particles

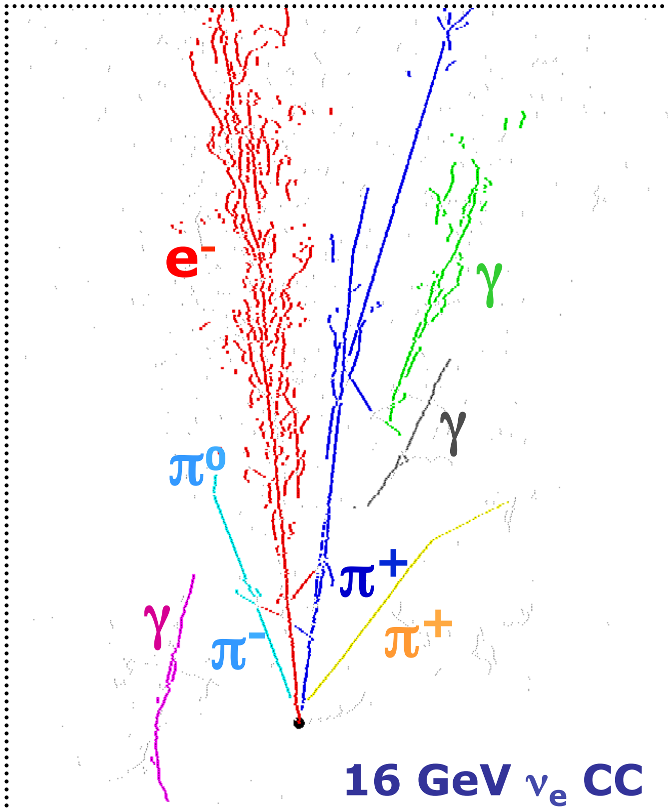
3. Selected particles, total energy 85 GeV

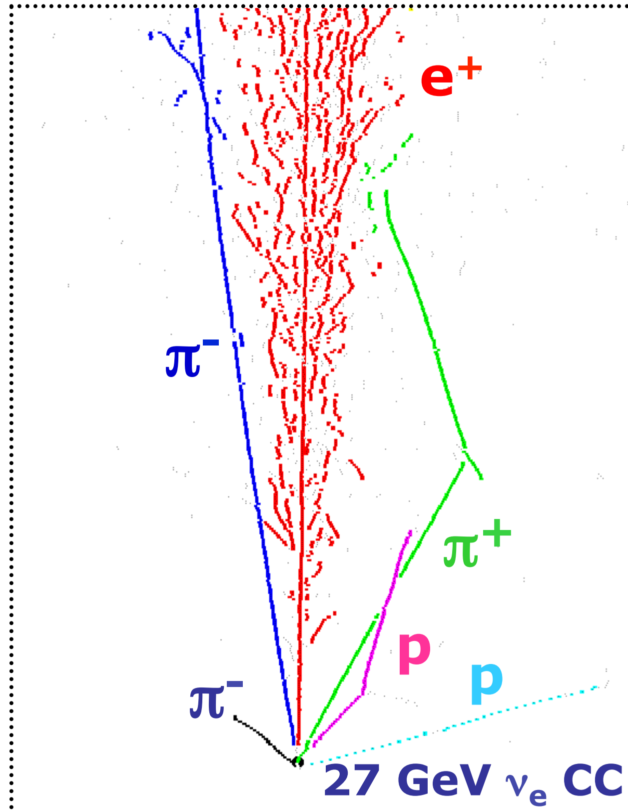


★ PandoraPFA provides now generic reconstruction framework

- developed algorithms for Liquid Argon TPC reconstruction
- another type of imaging calorimeter…

Example simulated electron neutrino interactions in the LBNE detector





★ Looks very promising…

9) Summary

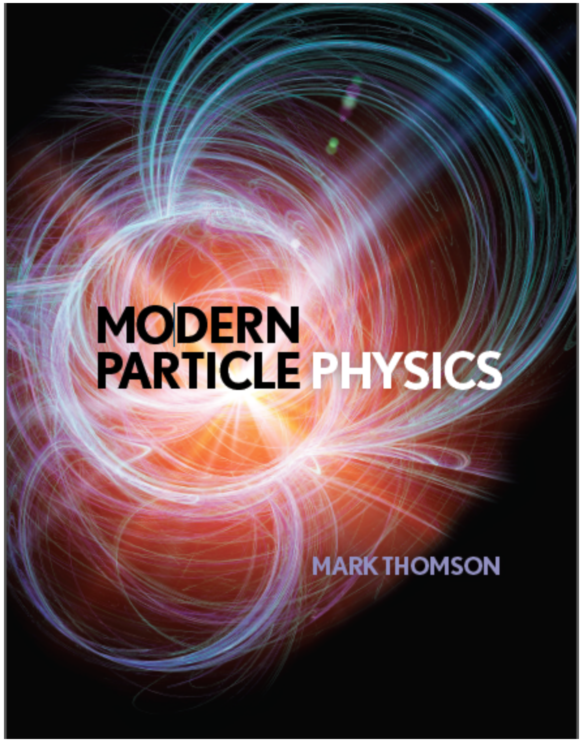
Summary

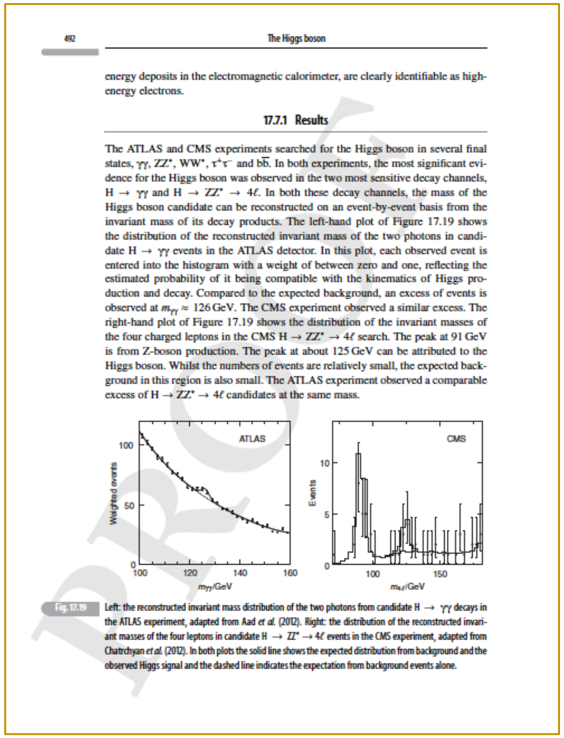
★ High Granularity Particle Flow Calorimetry is **the baseline** for the detector at the ILC (or CLIC)
- ✦ such a detector can be built (at a cost)
- ✦ would provide unprecedented performance

★ 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

The Higgs is out there

★ **Now in all good text books…**





energy deposits in the electromagnetic calorimeter, are clearly identifiable as high-energy electrons.

17.7.1 Results

The ATLAS and CMS experiments searched for the Higgs boson in several final states, $\gamma\gamma$, ZZ^*, WW^*, $\tau^+\tau^-$ and $b\bar{b}$. In both experiments, the most significant evidence for the Higgs boson was observed in the two most sensitive decay channels, $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$. In both these decay channels, the mass of the Higgs boson candidate can be reconstructed on an event-by-event basis from the invariant mass of its decay products. The left-hand plot of Figure 17.19 shows the distribution of the reconstructed invariant mass of the two photons in candidate $H \to \gamma\gamma$ events in the ATLAS detector. In this plot, each observed event is entered into the histogram with a weight of between zero and one, reflecting the estimated probability of it being compatible with the kinematics of Higgs production and decay. Compared to the expected background, an excess of events is observed at $m_{\gamma\gamma} \approx 126$ GeV. The CMS experiment observed a similar excess. The right-hand plot of Figure 17.19 shows the distribution of the invariant masses of the four charged leptons in the CMS $H \to ZZ^* \to 4\ell$ search. The peak at 91 GeV is from Z-boson production. The peak at about 125 GeV can be attributed to the Higgs boson. Whilst the numbers of events are relatively small, the expected background in this region is also small. The ATLAS experiment observed a comparable excess of $H \to ZZ^* \to 4\ell$ candidates at the same mass.

Fig. 17.19 Left: the reconstructed invariant mass distribution of the two photons from candidate $H \to \gamma\gamma$ decays in the ATLAS experiment, adapted from Aad *et al.* (2012). Right: the distribution of the reconstructed invariant masses of the four leptons in candidate $H \to ZZ^* \to 4\ell$ events in the CMS experiment, adapted from Chatrchyan *et al.* (2012). In both plots the solid line shows the expected distribution from background and the observed Higgs signal and the dashed line indicates the expectation from background events alone.

★ **The ILC is THE machine to study the Higgs**

★ **Let's build a PFlow detector…**

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

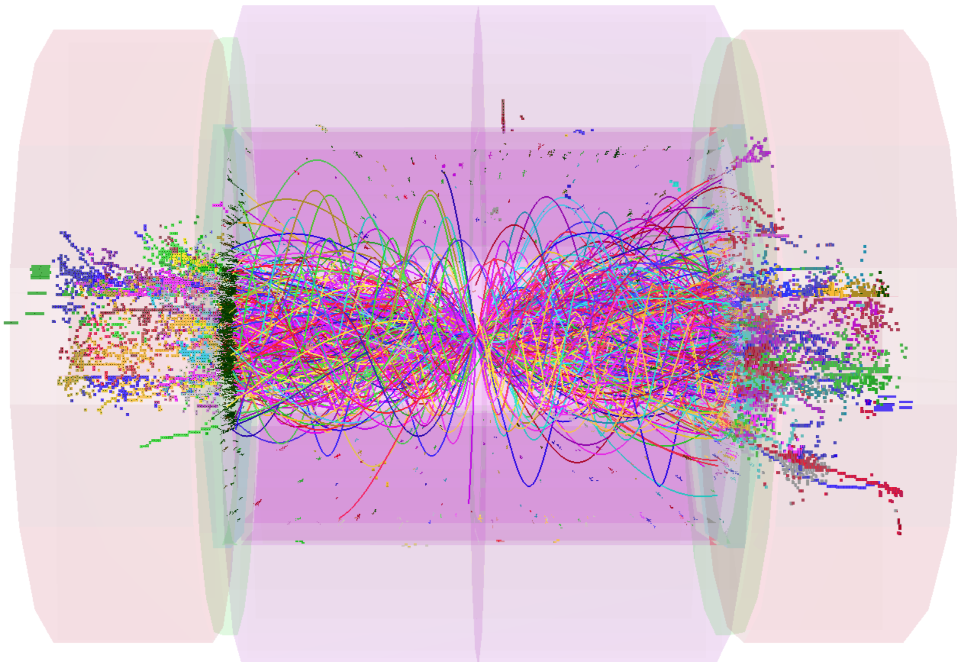
×1.00

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

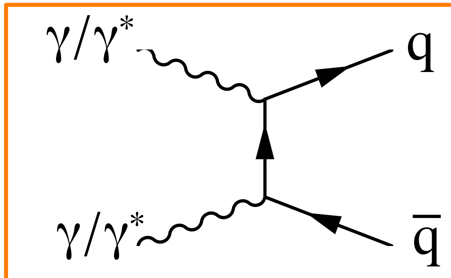
Suggests PFA performance is rather robust
- MC results likely to be reliable, despite shower model uncertainties

CALICE study supports this statement

CLIC: Impact of Background



Pile-up of "mini-jets"

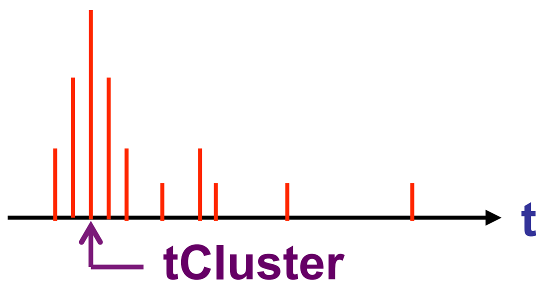


20 BXs = 10 ns of γγ→ hadrons

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

Reconstruction in Time

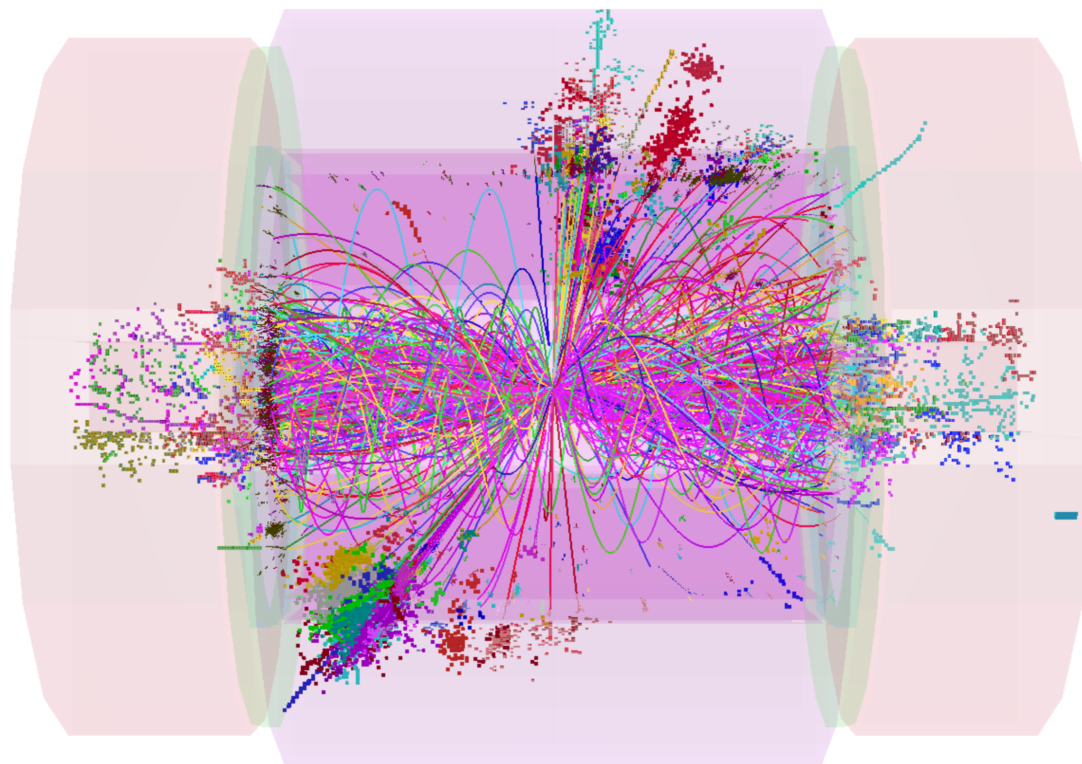
- ★ High granularity calorimetry allows individual particles to be reconstructed
  - with times assigned to each particle based on individual hit times
- ★ Pile-up from $\gamma\gamma \rightarrow$ hadrons can be effectively rejected using spatial and timing information
- ★ Studied at 3 TeV (the worst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



e.g. $e^+e^- \rightarrow H^+H^- \rightarrow 8$ jets

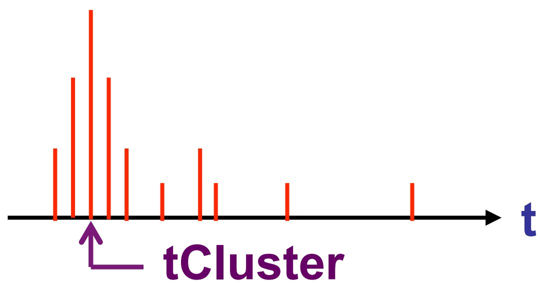
at $\sqrt{s} = 3$ TeV

Before 1.2 TeV



Reconstruction in Time

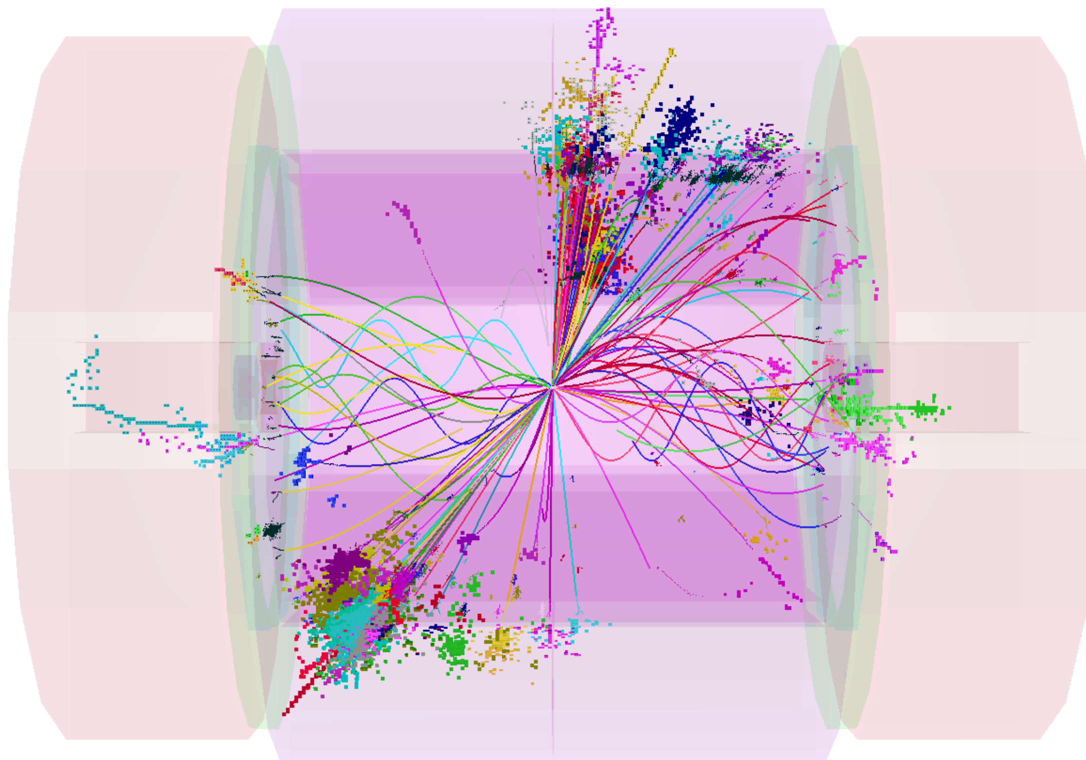
- ★ High granularity calorimetry allows individual particles to be reconstructed
  - with times assigned to each particle based on individual hit times
- ★ Pile-up from $\gamma\gamma \rightarrow$ hadrons can be effectively rejected using spatial and timing information
- ★ Studied at 3 TeV (the worst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



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

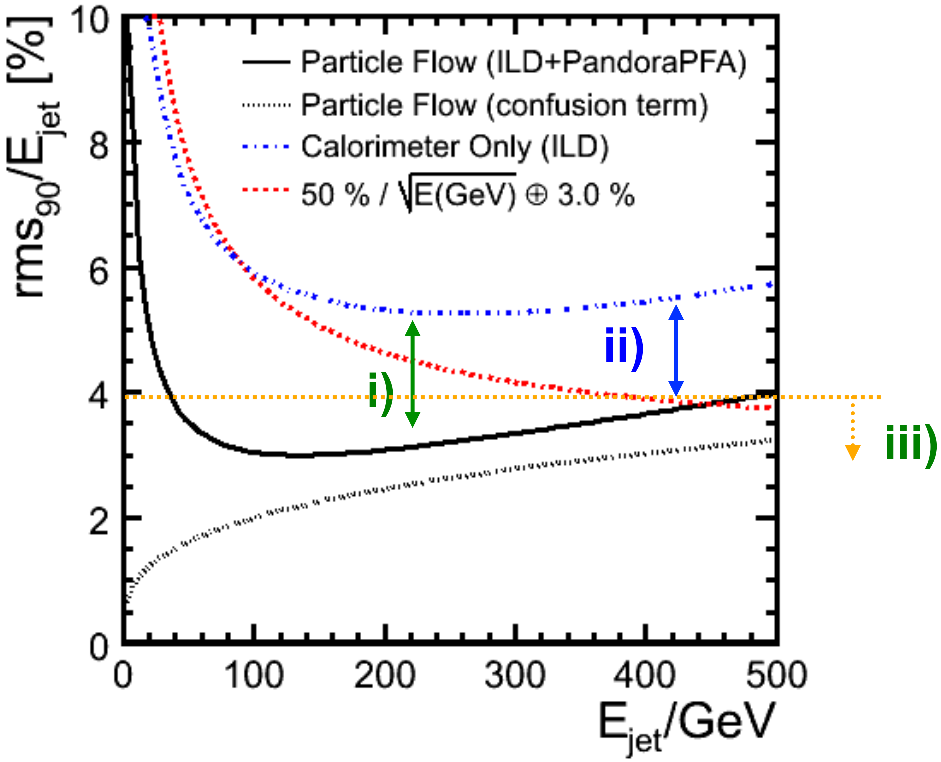
at $\sqrt{s}$ = 3 TeV

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**