Particle Flow Calorimetry and ILC Detector Design

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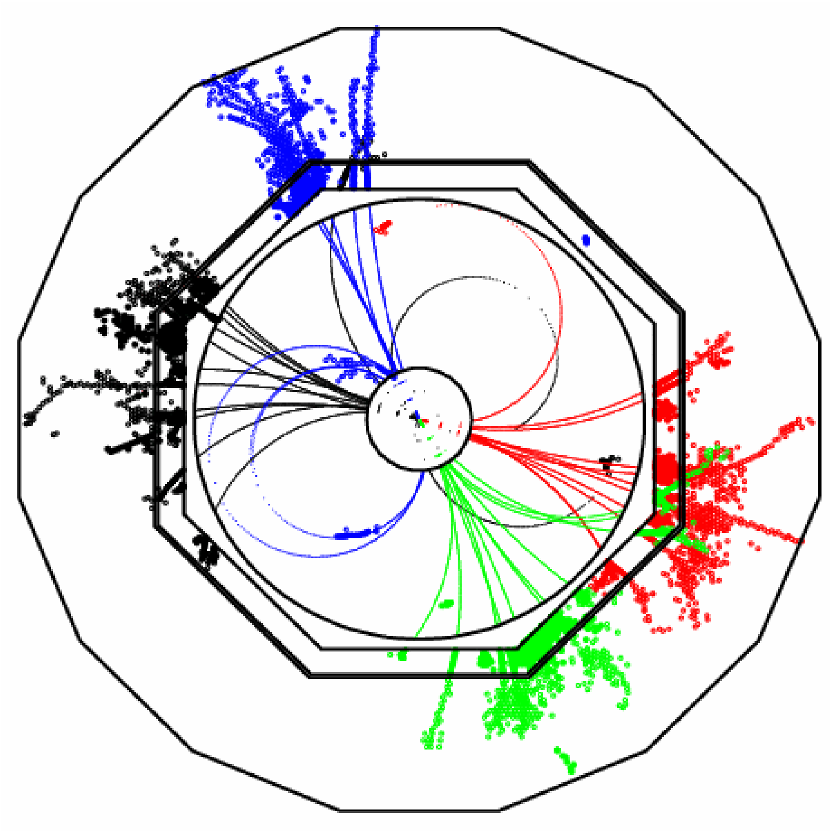
This Talk:



❶ Why the ILC
❷ ILC : the Machine
❸ ILC Physics ↔ ILC Calorimetry
❹ The Particle Flow Paradigm
❺ Calorimetry in the ILC Detector Concepts
❻ PFA and Detector Design
❼ "Realistic" Particle Flow Reconstruction
❽ Current Performance and Detector Optimisation Studies
❾ Conclusions

➊ Why the ILC ?

★ The **LHC** and **ILC** provide a complimentary approach to studying the physics of **EWSB** and beyond

The LHC

- ★ Will open the door to new physics !
- ★ Pushes the **energy frontier** with **proton-proton** collisions at 14 TeV
  - *qq*, *qg* and *gg* collisions in the energy range 0.5-5 TeV

The ILC

- ★ A different approach:
  very high precision as opposed to **very high energy**
- ★ **Electron-positron** collisions in the energy range 0.1-1 TeV
- ★ Very clean final states + high resolution detectors
  - ⇨ very precise measurements (as at LEP)
  - ⇨ detailed understanding of new physics + tight constraints on theory (as at LEP)

★ The case for having both the **LHC** and **ILC** very well studied:

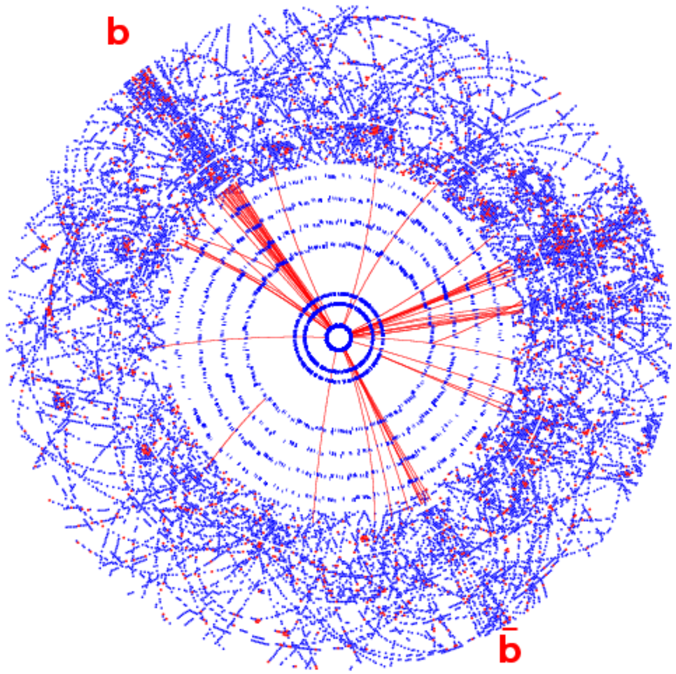
e.g. "Physics Interplay of the LHC and ILC", G. Weiglein et al., Phys. Rept. 426 (2006) 47-358

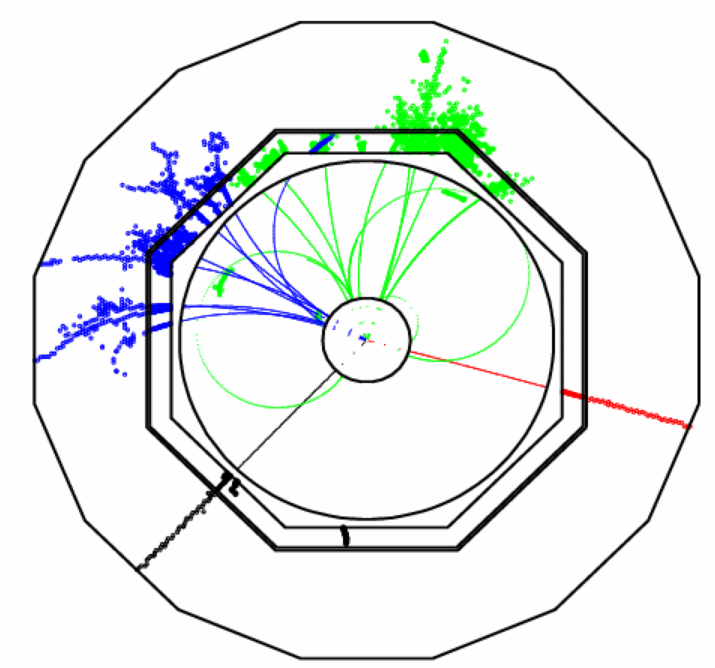
$e^+ e^- \equiv$ precision

★ Electron-positron colliders provide clean environment for precision physics

The LHC $\mathrm{pp} \to \mathrm{H} + X$

The ILC $\mathrm{e^+e^-} \to \mathrm{HZ}$





★ At electron-positron the final state corresponds to the underlying physics interaction, e.g. above see $\mathrm{H} \to b\bar{b}$ and $\mathrm{Z} \to \mu^+\mu^-$ and nothing else…

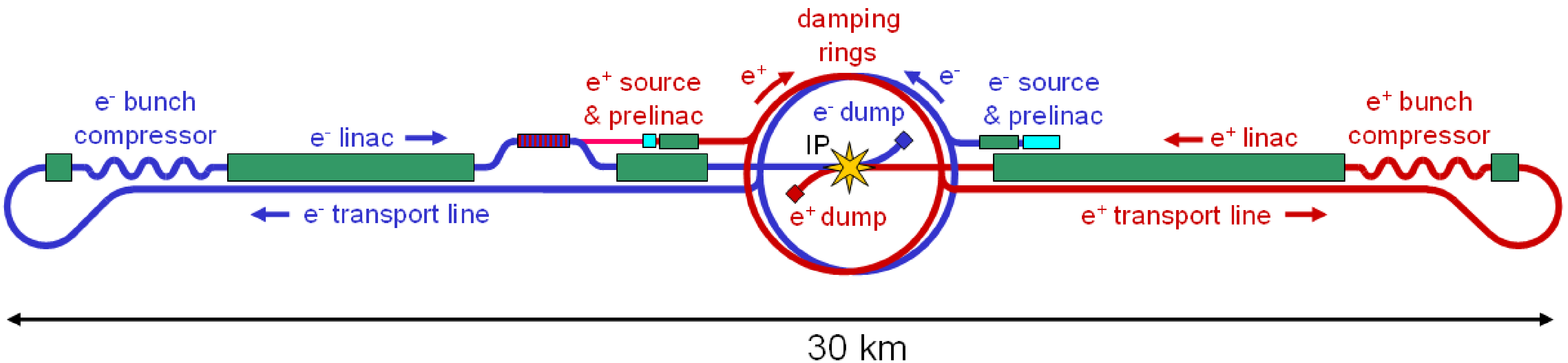
❷ ILC : the machine

Basic Machine Design Parameters

- ★ Centre-of-mass energy adjustable from **200-500 GeV**
  - upgradeable to **1 TeV** (i.e. make it longer)
- ★ Integrated luminosity of **500 fb^{-1}** in first **4 years** operation
  - require high luminosity: **2×10^{34} cm^{-2}s^{-1}**
- ★ Energy stability **<0.1 %** for precision measurements
- ★ Electron polarization of **>80 %** at interaction point

Baseline design for the ILC now exists in the form of the "The ILC Reference Design Report (2007)"

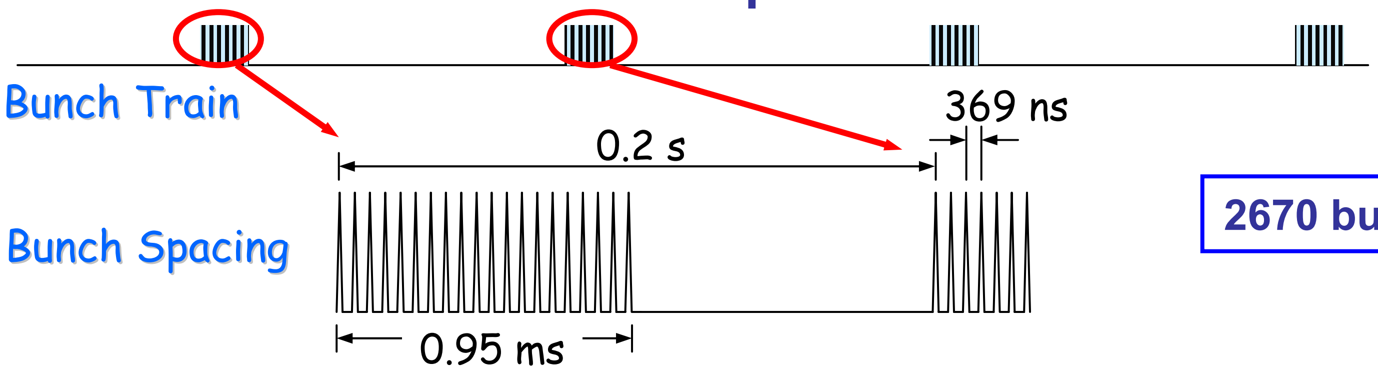
The ILC is much more than the "linear bit"…



Physics at the ILC

★ Main "baseline" features of ILC now fixed

- Luminosity : ~ 10^{34} $cm^{-2}s^{-1}$ (1000xLEP)
- Time Structure : 5 Bunch-trains per second



2670 bunches/train

- Modest physics event rates

  $e^+e^- \to qq$ ~100/hr $e^+e^- \to W^+W^-$ ~1000/hr
  $e^+e^- \to tt$ ~50/hr $e^+e^- \to HX$ ~10/hr

- "Backgrounds" low

  $e^+e^- \to qq$ ~0.1 /Bunch Train
  $e^+e^- \to \gamma\gamma \to X$ ~200 /Bunch Train
  ~500 hits/BX in Vertex det.
  ~5 tracks/BX in TPC

★ Very clean physics environment: Event rates low, backgrounds modest, "large" time between collisions

Machine Impact on Detector Design

- ★ Radiation hardness does not dictate detector design
- ★ Modest timing requirements (~300 ns)
- ★ Must be able to cope with modest gamma-gamma background

★ PHYSICS, not the machine, drives ILC Detector design

❸ ILC Physics ↔ Calorimetry

ILC PHYSICS:

Precision Studies/Measurements

- ★ Higgs sector
- ★ SUSY particle spectrum (if there)
- ★ SM particles (e.g. W-boson, top)
- ★ and much more...

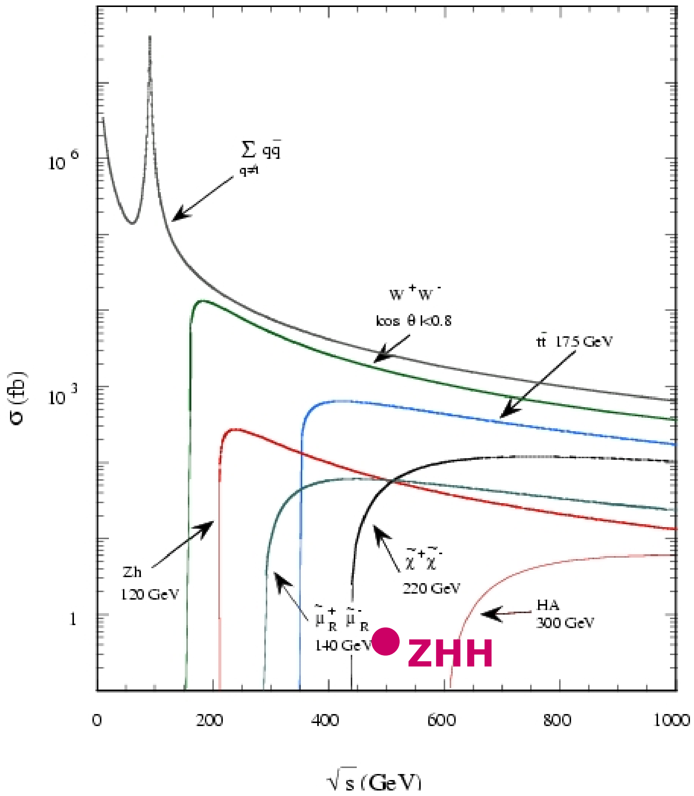
Physics characterised by:

★ High Multiplicity final states

often 6/8 jets

★ Small cross-sections

e.g. $\sigma(e^+e^- \to ZHH) = 0.3$ fb



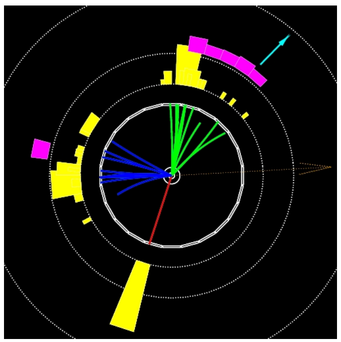
✸ Require High Luminosity – i.e. the ILC

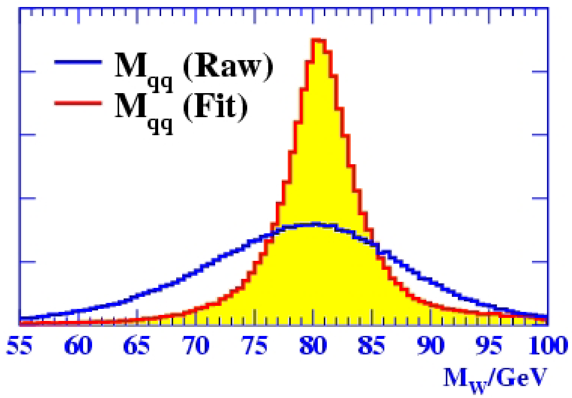
✸ Detector optimized for precision measurements in difficult multi-jet environment

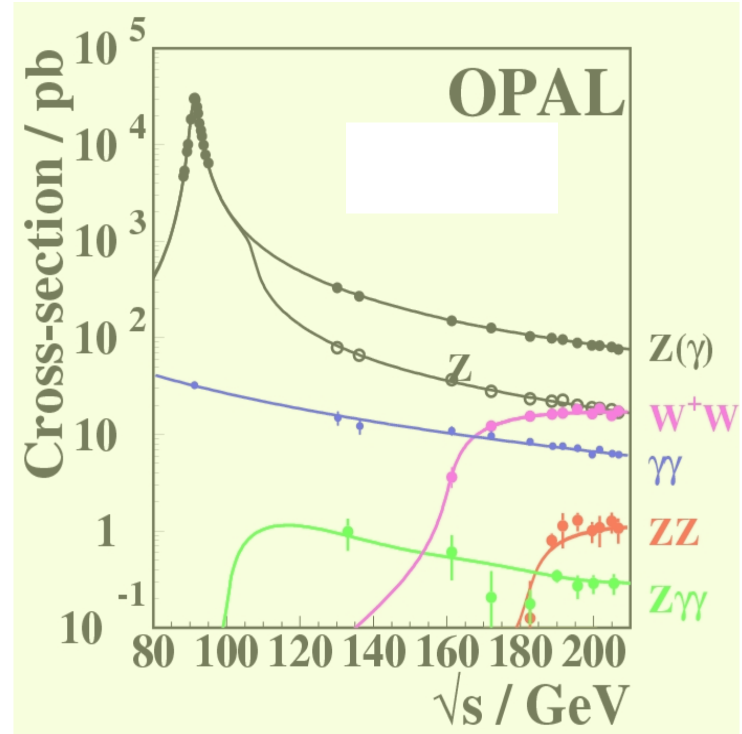
Compare with LEP

★ $e^+e^- \to Z$ and $e^+e^- \to W^+W^-$ dominate
backgrounds not too problematic

★ Kinematic fits used for mass reco.
good jet energy resolution not vital







At the ILC:

★ Backgrounds dominate 'interesting' physics

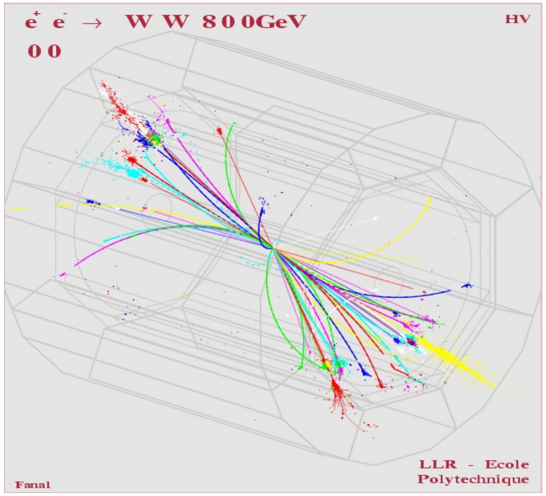
★ Kinematic fitting much less useful: Beamsstrahlung + final states with > 1 neutrino

✸ Physics performance depends critically on the detector performance (not true at LEP)

✸ Places stringent requirements on the ILC detector

ILC Detector Requirements

- ★ **momentum:** $\sigma_{1/p} < 7\times10^{-5}$/GeV (1/10 x LEP)
  (e.g. mass reconstruction from charged leptons)
- ★ **impact parameter:** $\sigma_{d0} < 5\mu m \oplus 5\mu m/p(GeV)$ (1/3 x SLD)
  (c/b-tagging in background rejection/signal selection)
- ★ **jet energy:** $\sigma_E/E = 0.3/\sqrt{E(GeV)}$ (1/2 x LEP)
  (invariant mass reconstruction from jets)
- ★ **hermetic down to :** $\theta = 5$ mrad
  (for missing energy signatures e.g. SUSY)
- ★ Radiation hardness not a significant problem, e.g. 1st layer of vertex detector : 10^9 n cm^{-2} yr^{-1} c.f. 10^{14} n cm^{-2} yr^{-1} at LHC



Must also be able to cope with high track densities due to high boost and/or final states with 6+ jets, therefore require:

- ★ High granularity
- ★ Good two track resolution

★ **Of the ILC goals the most challenging is (probably) that of jet energy resolution:**

$$\sigma_E/E = 30\%/\sqrt{E(\mathrm{GeV})}$$

★ **So why is this important ?**

Calorimetry at the ILC

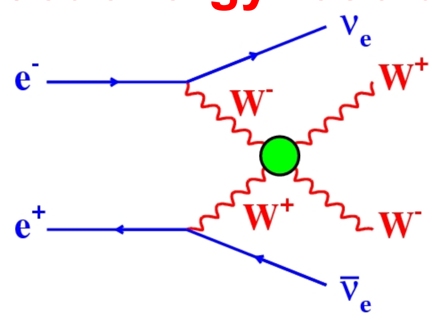
Jet energy resolution:

THIS IS HARD !

Best at LEP (ALEPH):
$\sigma_E/E = 0.6(1+|\cos\theta_{Jet}|)/\sqrt{E(\text{GeV})}$

ILC GOAL:
$\sigma_E/E = 0.3/\sqrt{E(\text{GeV})}$

★ **Jet energy resolution directly impacts physics sensitivity**

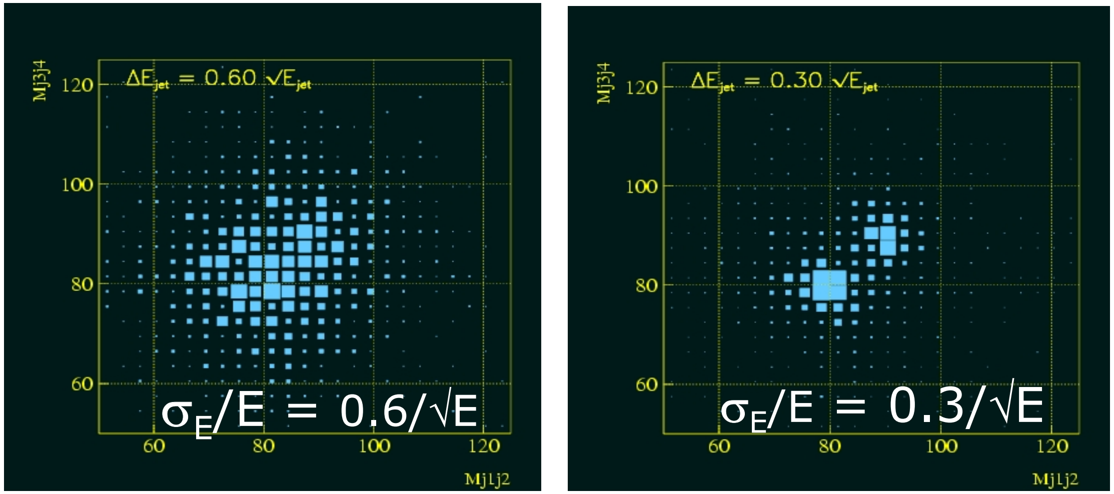


Often-quoted Example:

If the Higgs mechanism is not responsible for EWSB then QGC processes important

$e^+e^- \rightarrow \nu\nu WW \rightarrow \nu\nu qqqq$, $e^+e^- \rightarrow \nu\nu ZZ \rightarrow \nu\nu qqqq$

Reconstruction of two di-jet masses allows discrimination of WW and ZZ final states

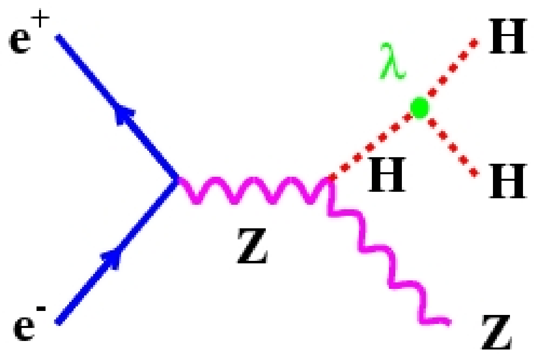


★ **EQUALLY applicable to any final states where want to separate** $W \rightarrow qq$ **and** $Z \rightarrow qq$ **!**

Another example…..

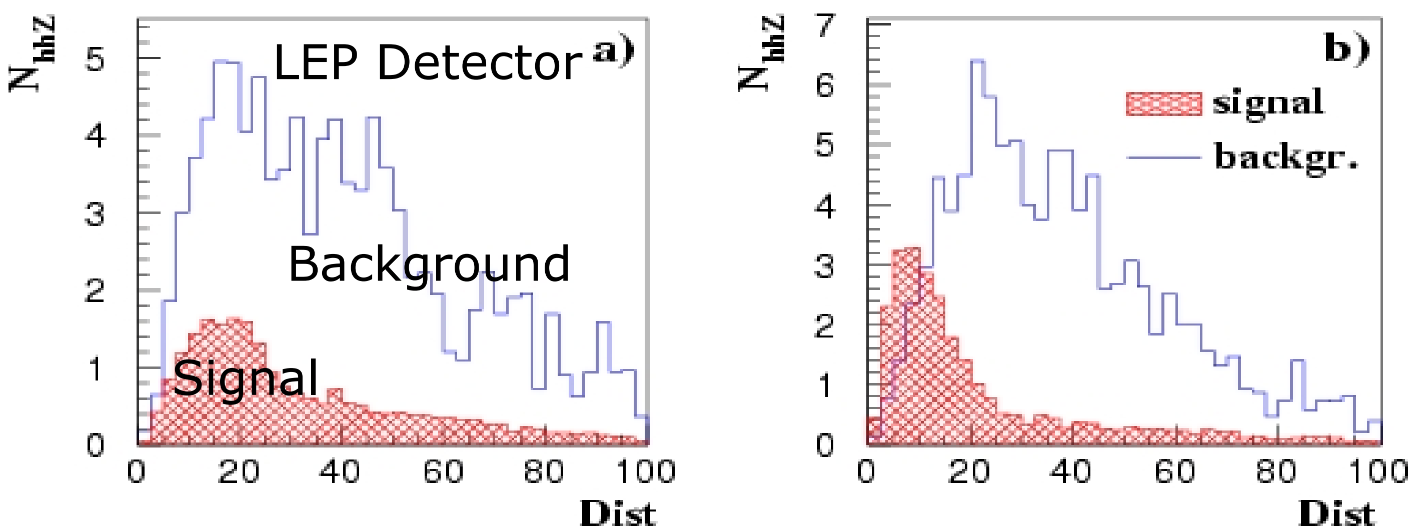
e.g. measurement of trilinear HHH coupling via
$e^+e^- \to ZHH \to qqbbbb$

- ★Probe of Higgs potential
- ★Very small cross-section
- ★Large combinatoric background
- ★6 jet final state



- Use jet-jet invariant masses to extract signal

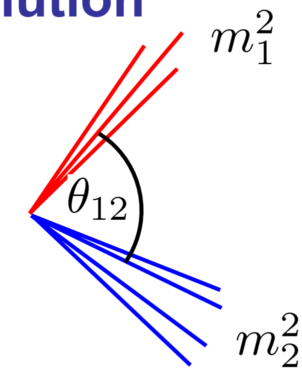
$$Dist=((M_H - M_{12})^2 + (M_Z - M_{34})^2 + (M_H - M_{56})^2)^{1/2}$$



★ **Good jet energy resolution gives much improved signal**

❶ PFA Goals

★ Aim for jet energy resolution giving di-jet mass resolution similar to Gauge boson widths



★ For a pair of jets have:

$$m^2 = m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta_{12})$$

★ For di-jet mass resolution of order $\Gamma_{\mathrm{W/Z}}$

$$\frac{\sigma_m}{m} \approx \frac{2.5}{91.2} \approx \frac{2.1}{80.3} \approx 0.027$$

⇨ $\sigma_{E_j}/E_j < 3.8\%$

+ term due to θ_{12} uncertainty

★ **Assuming** a single jet energy resolution of normal form

$$\sigma_E/E = \alpha(E)/\sqrt{E(\mathrm{GeV})}$$

⇨ $\sigma_m/m \approx \alpha(E_j)/\sqrt{E_{jj}(\mathrm{GeV})}$

⇨ $\alpha(E_j) < 0.027\sqrt{E_{jj}(\mathrm{GeV})}$

E_{jj}/GeV	$\alpha(E_{jj})$
100	< 27 %
200	< 38 %

★ Typical di-jet energies at ILC (100-300 GeV) suggests jet energy resolution goal of $\sigma_E/E < 0.30/\sqrt{E_{jj}(\mathrm{GeV})}$

★ Want $\sigma_E/E \sim 30\%/\sqrt{E(GeV)}$

or probably more correctly $\sigma_E/E \sim 3.8\ \%$

★ Very hard (may not be possible) to achieve this with a traditional approach to calorimetry

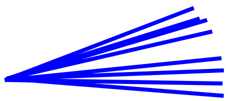
Limited by typical HCAL resolution of $> 50\%/\sqrt{E(GeV)}$

⇒ a new approach to calorimetry

❹ The Particle Flow Paradigm

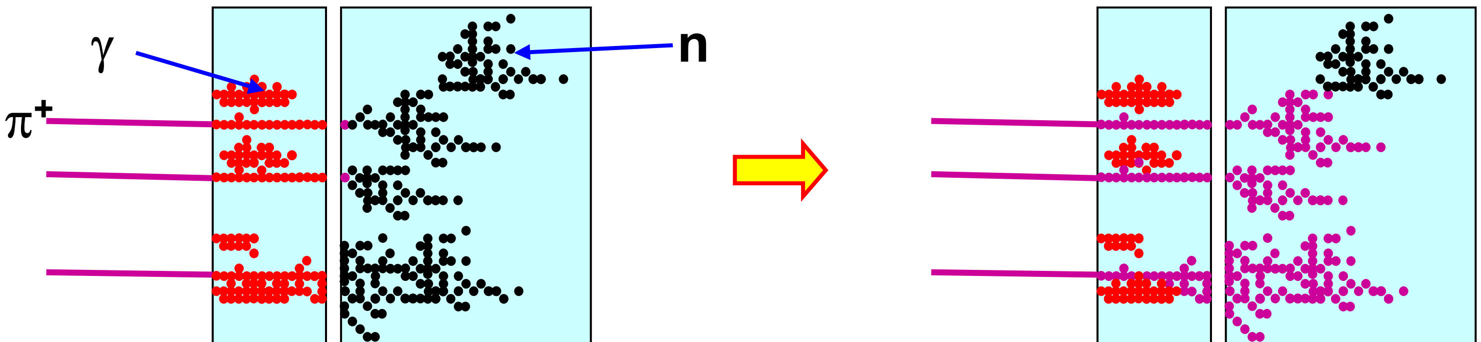
★ **In a typical jet :**

- **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**



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

★ **Particle Flow Calorimetry paradigm:**

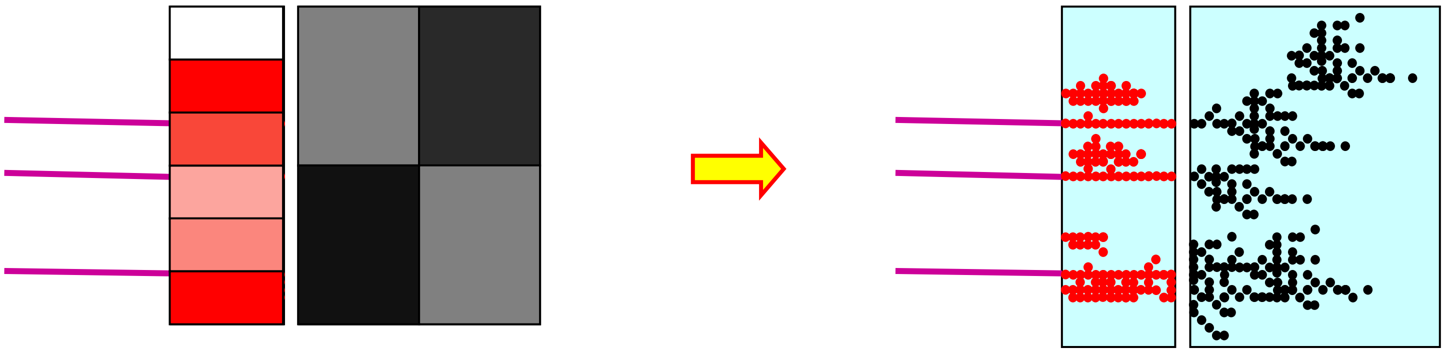
- **charged particles measured in tracker (essentially perfectly)**
- **Photons in ECAL: $\sigma_{\mathrm{E}}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$**
- **Neutral hadrons (ONLY) in HCAL**
- **Only 10 % of jet energy from HCAL ⟹ much improved resolution**

Particle Flow Calorimetry

Hardware:

★Need to be able to resolve energy deposits from different particles

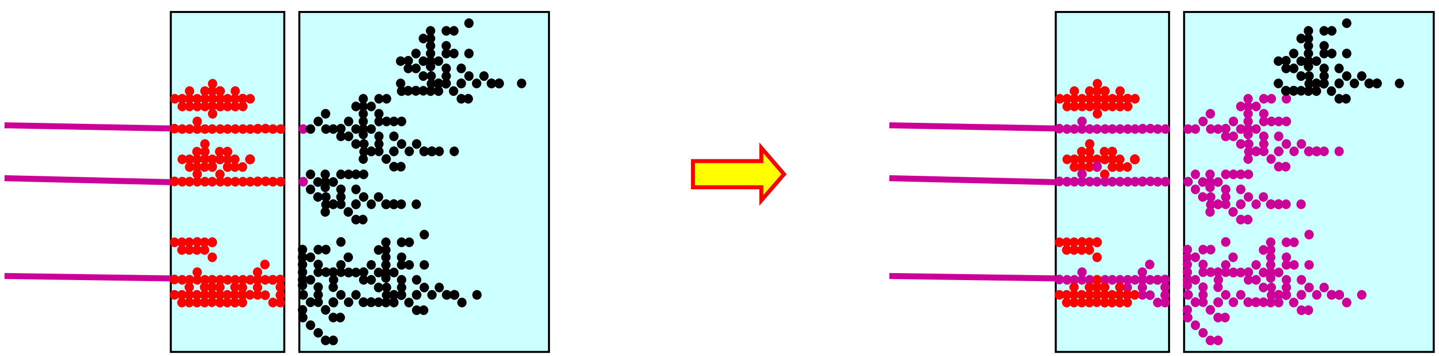
➡ Highly granular detectors (as studied in CALICE)



Software:

★Need to be able to identify energy deposits from each individual particle !

➡ Sophisticated reconstruction software



★**Particle Flow Calorimetry = HARDWARE + SOFTWARE**

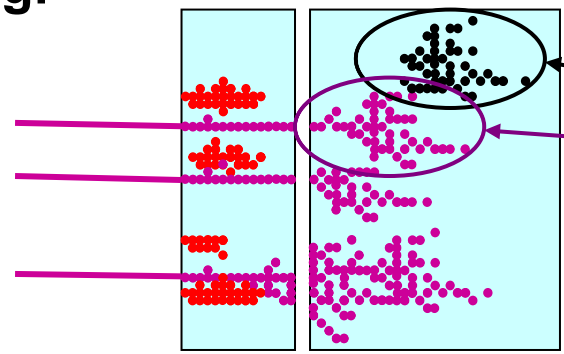
Particle Flow Reconstruction (PFA)

Reconstruction of a Particle Flow Calorimeter:

★ 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** the intrinsic calorimetric performance of ECAL/HCAL

sounds easy….

★ PFA performance depends on detailed reconstruction

★ Studies need to be based on a sophisticated detector simulations

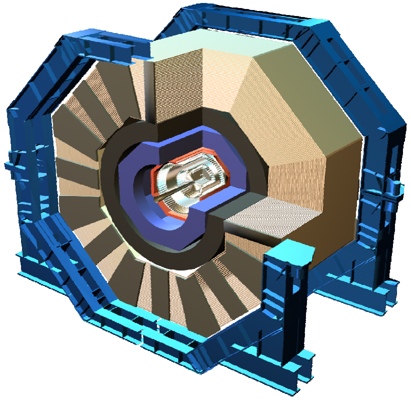
★ Fortunately these exist…

❺ The ILC Detector Concepts

ILC Detector Concepts:

- ★ ILC Detector Design work centred around 4 detector "concepts"
- ★ Ultimately may form basis for TDRs
- ★ Partial "technical designs" ~ 2010 ?
- ★ 3 main concepts "optimised" for PFA Calorimetry SiD, LDC, GLD
- ★ Recently GLD + LDC → ILD

SiD : Silicon Detector



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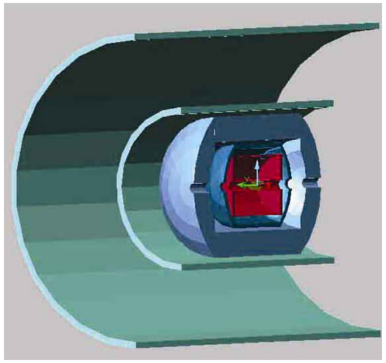
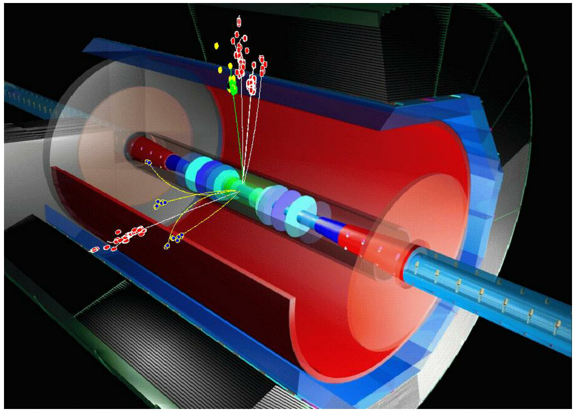


ILD : International Large Detector

LDC : Large Detector Concept (child of TESLA TDR)



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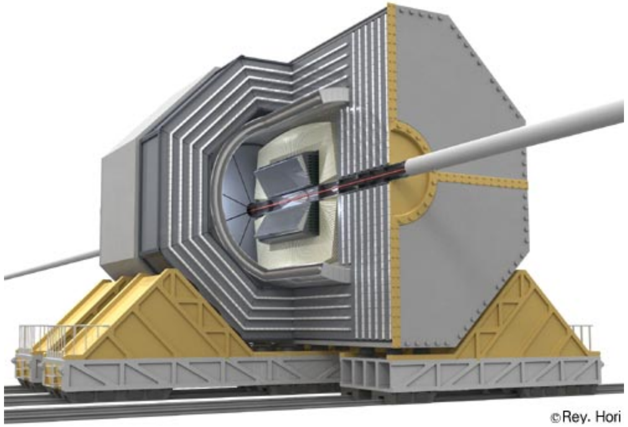
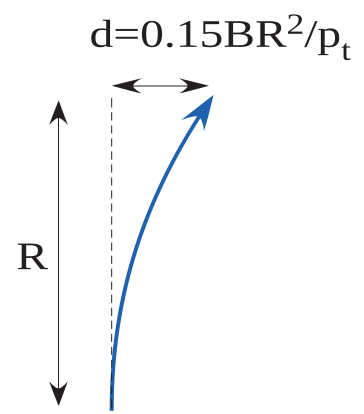
GLD : Global Large Detector

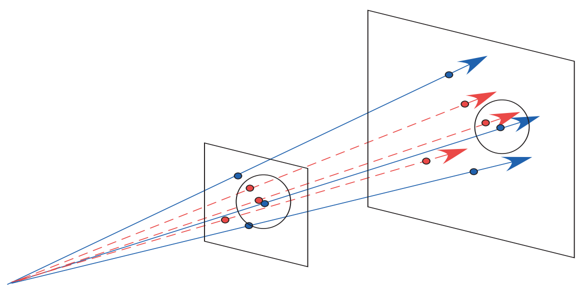


PFA : “Figure of Merit”

- For good jet energy resolution need to separate energy deposits from different particles
  - **Large detector – spatially separate particles**
  - **High B-field – separate charged/neutrals**
  - **High granularity ECAL/HCAL – resolve particles**

  } **HIGH COST**





Often quoted* “figure-of-merit”:

$$\frac{BR^2}{\sigma}$$

- BR^2 ← **Separation of charge/neutrals**
- σ ← **Calorimeter granularity/$R_{Moliere}$**

- **Physics argues for : large + high granularity + ⇧ B**
- **Cost considerations: small + lower granularity + ⇩ B**

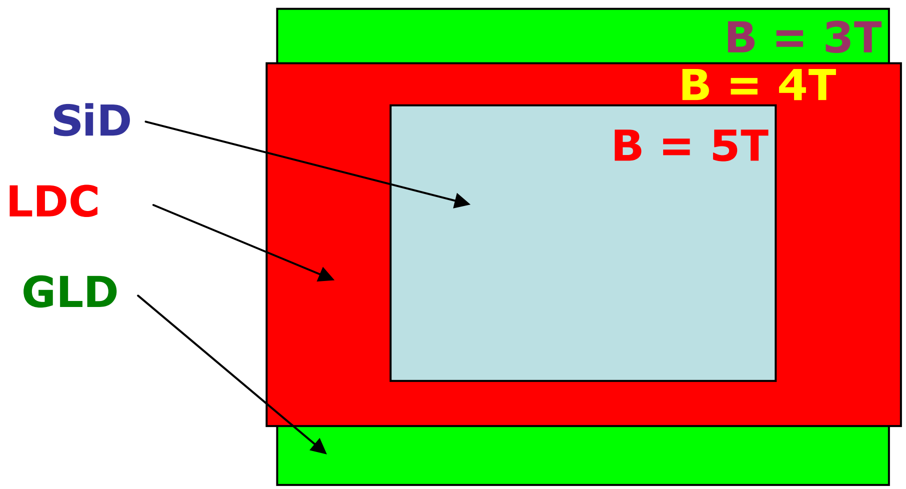
- **Need realistic algorithms to determine what drives PFA performance….**

***But almost certainly wrong (see later)**

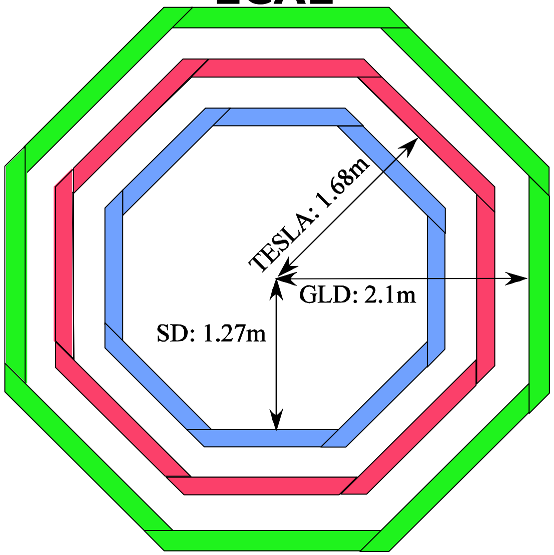
LDC/GLD/SiD

- **SIZE + B-Field**

Tracker



ECAL



- **Central Tracker and ECAL**

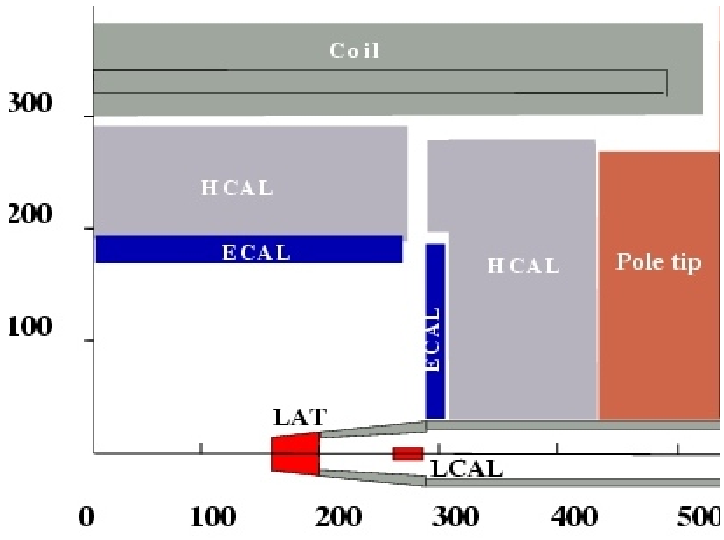
	SiD	LDC	GLD
Tracker	Silicon	TPC	TPC
ECAL	SiW	SiW	Pb/Scint

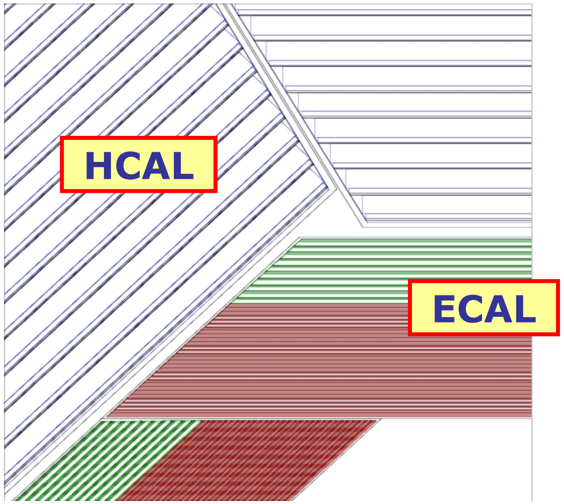
SiD + LDC + GLD all designed for PFA Calorimetry !

★ also "4th" concept designed for more "traditional" approach to calorimetry

LDC/SiD Calorimetry

ECAL and HCAL inside coil





ECAL: silicon-tungsten (SiW) calorimeter:

- Tungsten : X_0 / λ_{had} = 1/25, $R_{Moliere}$ ~ 9mm
  (gaps between Tungsten increase effective $R_{Moliere}$)
- Lateral segmentation: ~1cm² matched to $R_{Moliere}$
- Longitudinal segmentation: 30 layers (24 X_0, 0.9λ_{had})
- Typical resolution: $\sigma_E/E = 0.15/\sqrt{E(GeV)}$

Very high longitudinal and transverse segmentation

Hadron Calorimeter

Again Highly Segmented – for Particle Flow

- Longitudinal: ~40 samples
- 4 – 5 λ (limited by cost - coil radius)
- Would like fine (1 cm^2 ?) lateral segmentation
- For 10000 m^2 of 1 cm^2 HCAL = 10^8 channels – cost !

<u>Two Main Options:</u>

★ Tile HCAL (Analogue readout)

Steel/Scintillator sandwich

Lower lateral segmentation

~ 3x3 cm^2 (motivated by cost)

★ Digital HCAL

High lateral segmentation

~ 1x1 cm^2

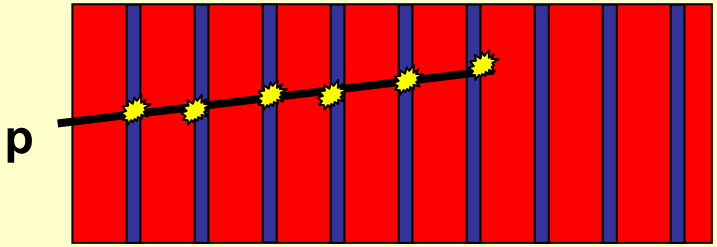
digital readout (granularity)

RPCs, wire chambers, GEMS…

OPEN QUESTION

<u>The Digital HCAL Paradigm</u>

- Sampling Calorimeter:
  Only sample small fraction of the total energy deposition

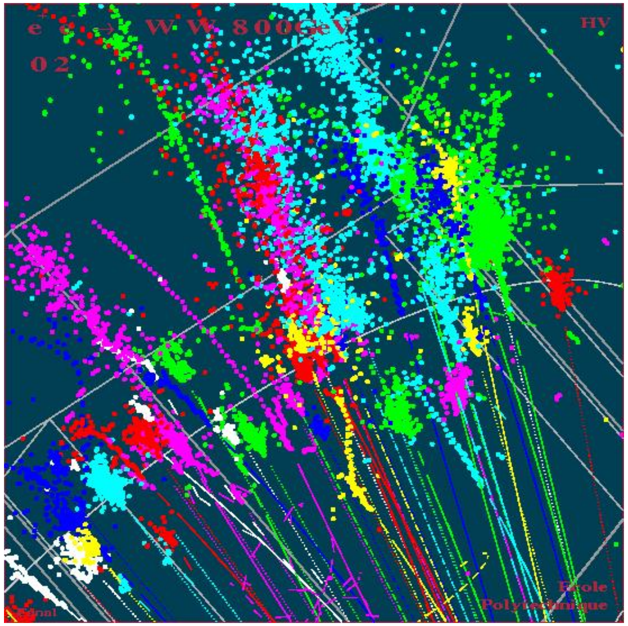


- Energy depositions in active region follow highly asymmetric Landau distribution

Calorimeter Reconstruction

★ High granularity calorimeters – **very different** to previous detectors (except LEP lumi. calorimeters)

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



+PARTICLE FLOW

★ ILC calorimetric performance = HARDWARE + SOFTWARE

★ Performance will depend on the software algorithm

→ Nightmare from point of view of detector optimisation

❻ PFA and ILC detector design ?

PFA plays a special role in design of an ILC Detector

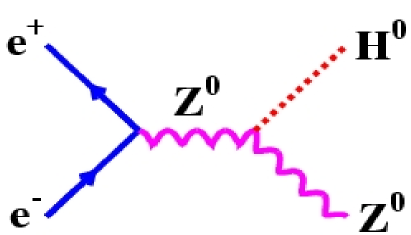
- VTX : design driven by heavy flavour tagging, machine backgrounds, technology
- Tracker : design driven by σ_p, track separation
- ECAL/HCAL : single particle σ_E not the main factor
  - ➡ jet energy resolution ! Impact on particle flow drives calorimeter design + detector size, B field, …

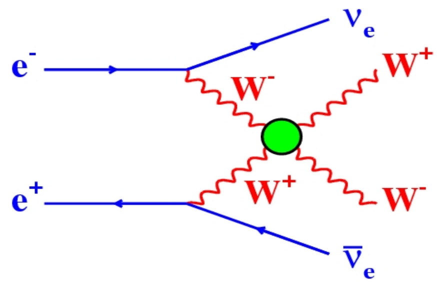
PFA is a (the?) major $$$ driver for the ILC Detectors

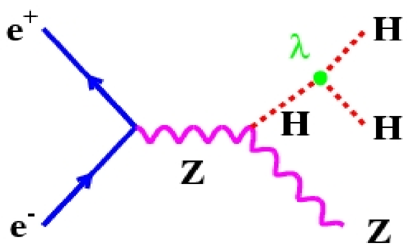
BUT: Nobody really knows what makes a good detector for PFA (plenty of personal biases – but little hard evidence)

How to optimise/compare ILC detector design(s) ?

- Need to choose the key "benchmark" processes (EASY)





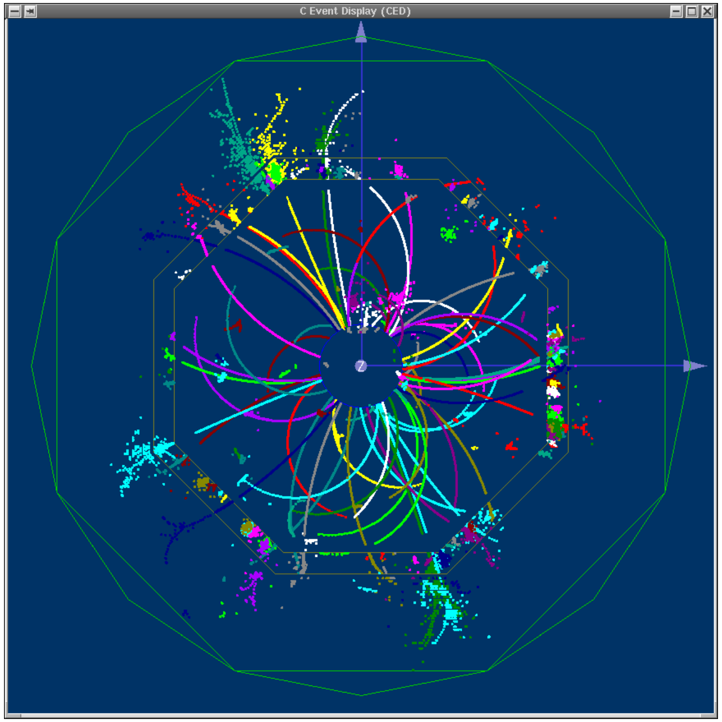


The rest is VERY DIFFICULT !

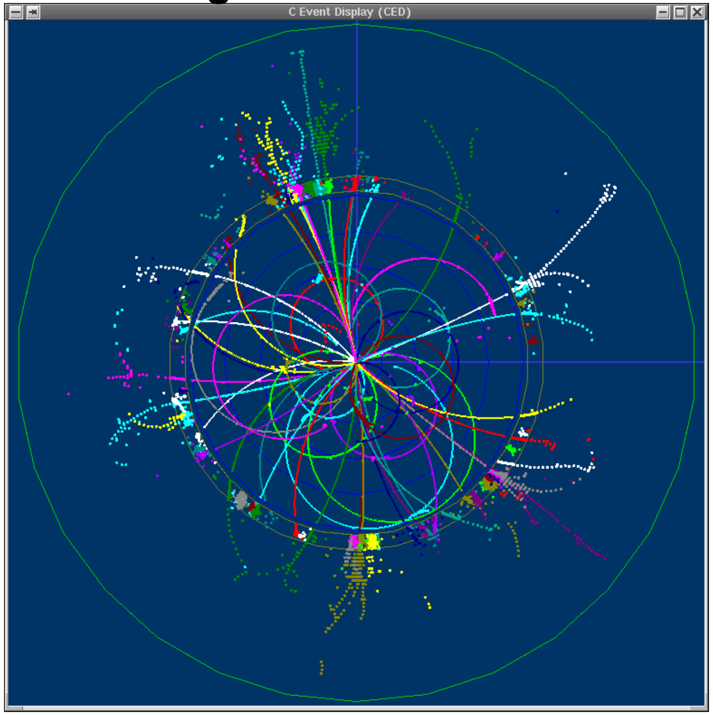
For example:

★ Wish to compare performance of say LDC and SiD detector concepts

e.g. tt event in LDC



e.g. tt event in SiD



★ However performance = DETECTOR + SOFTWARE

★ Non-trivial to separate the two effects

★ NEED REALISTIC SIMULATION + REALISTIC RECONSTRUCTION !

- can't use fast simulation etc.

For design of ILC Calorimetry :

need realistic reconstruction chain

~10 years before start of ILC !!!

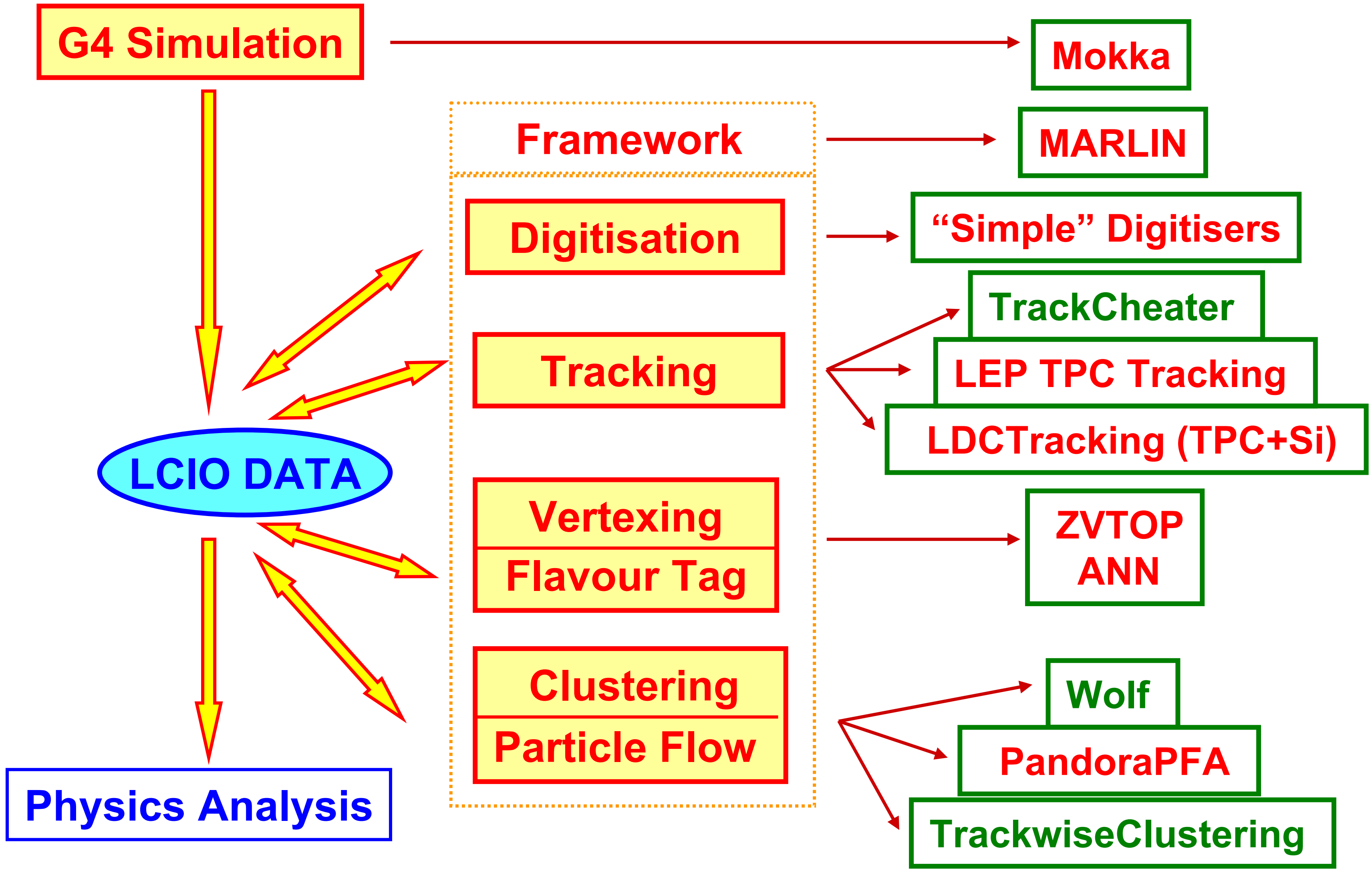
(ideally before start of LHC)

(even more challenging: the software has to work for multiple detector design parameters)

Not far off a first version….

European ILC Software Framework

What software is needed? / What exists now?



❼ Particle Flow Algorithms

- Need sophisticated Particle Flow reconstruction before it is possible to start full detector design studies
- New paradigm – nobody really knows how to approach this
- So where are we now ?
- Significant effort (~6 groups developing PFA reconstruction worldwide)

For this talk concentrate on: PandoraPFA

- This is still work-in-Progress – currently it gives the best performance
- Will give an overview of the algorithm to highlight the most important issues in Particle Flow calorimetry
- Then discuss some first detector optimisation studies

PandoraPFA Overview

★ ECAL/HCAL reconstruction and PFA performed in a **single algorithm**

★ Keep things fairly generic algorithm

- applicable to multiple detector concepts

★ Use tracking information to help ECAL/HCAL clustering

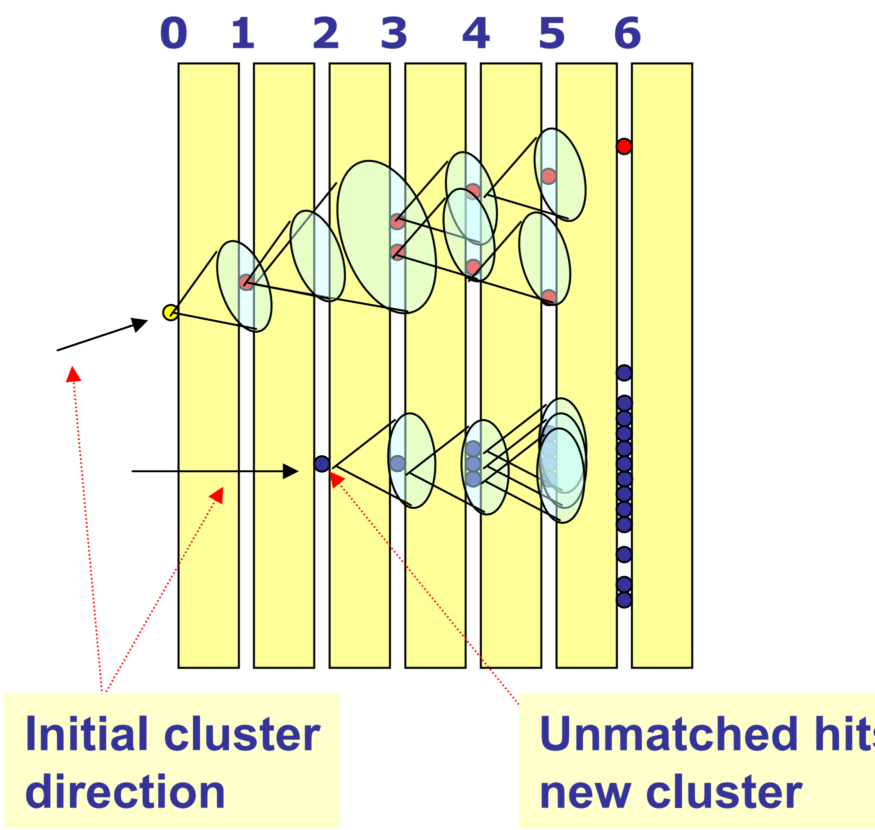
★ This is a fairly sophisticated algorithm : 10^4 lines of code

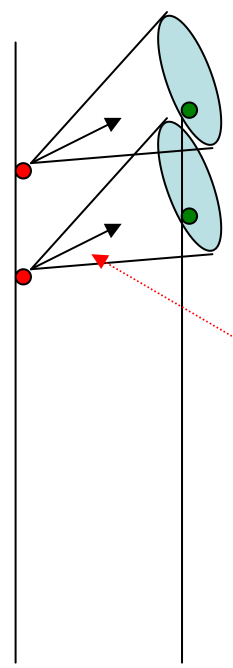
Six Main Stages:

i. Preparation
ii. Loose clustering in ECAL and HCAL
iii. Topological linking of clearly associated clusters
iv. Courser grouping of clusters
v. Iterative reclustering
vi. Photon Identification/Recovery
vii. Fragment removal
viii. Formation of final Particle Flow Objects (reconstructed particles)

ii) ECAL/HCAL Clustering

- Start at inner layers and work outward
- Tracks can be used to "seed" clusters
- Associate hits with existing Clusters
- If no association made form new Cluster
- Simple cone based algorithm





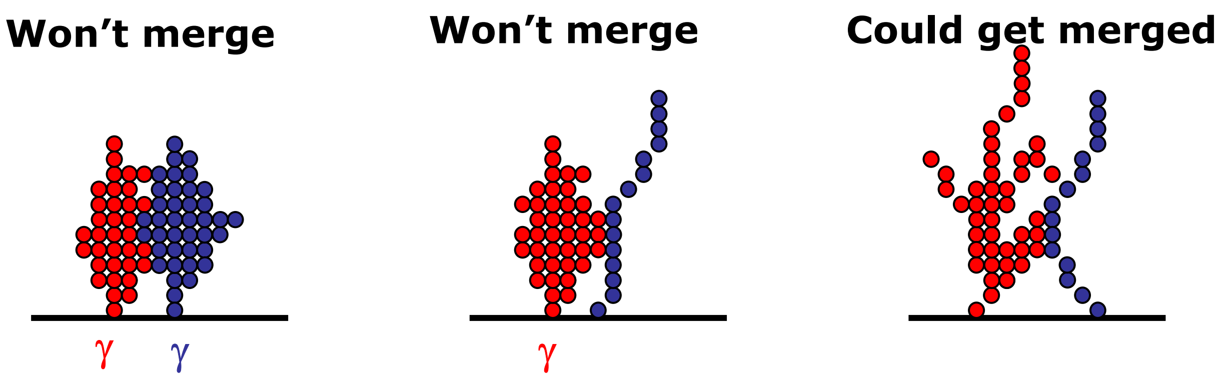
Parameters:
- cone angle
- additional pixels

iii) Topological Cluster Association

- By design, clustering errs on side of caution
  i.e. clusters tend to be split
- **Philosophy:** easier to put things together than split them up
- Clusters are then associated together in two stages:
  - 1) Tight cluster association – clear topologies
  - 2) Loose cluster association – fix what's been missed

Photon ID

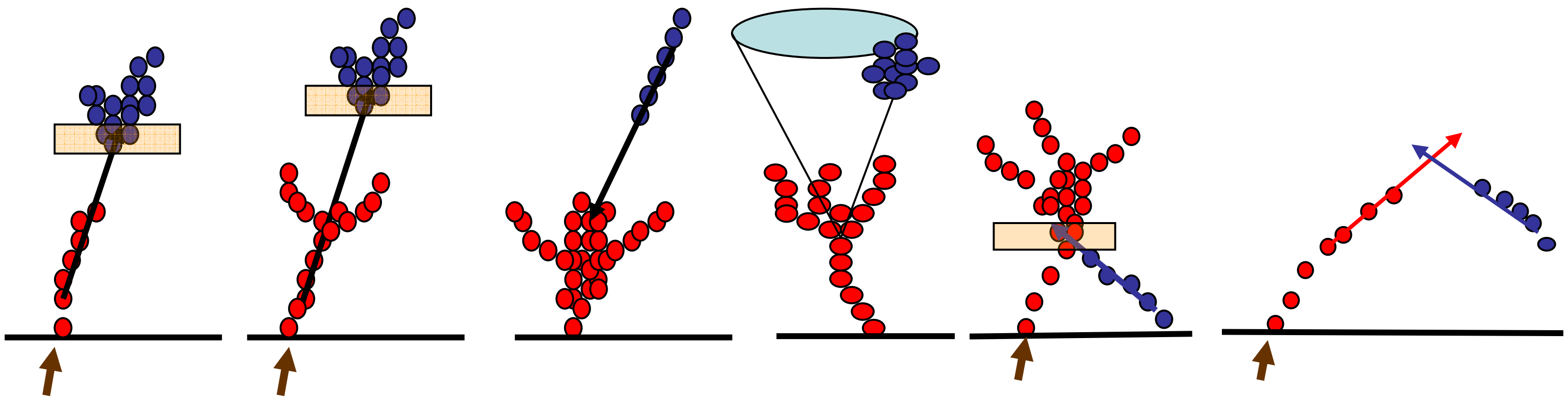
- Photon ID plays important role
- Simple "cut-based" photon ID applied to all clusters
- Clusters tagged as photons are immune from association procedure – just left alone



★ Clusters associated using a number of topological rules

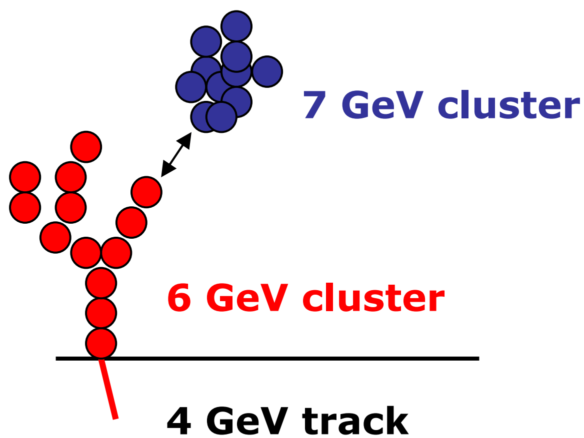
Clear Associations:

- Join clusters which are clearly associated making use of high granularity + tracking capability: very few mistakes



Less clear associations:

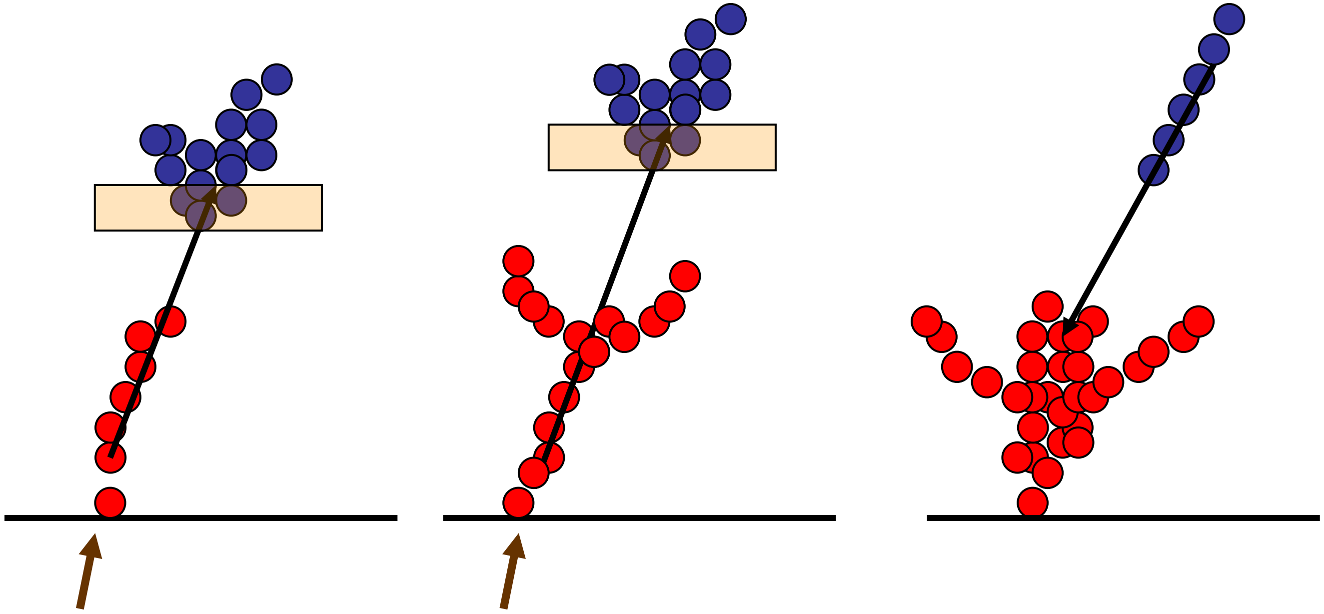
e.g. Proximity



Use E/p consistency to veto clear mistakes

Example : MIP segments

★ Look at clusters which are consistent with having tracks segments and project backwards/forward (defined using local straight-line fits to hits tagged as MIP-like)

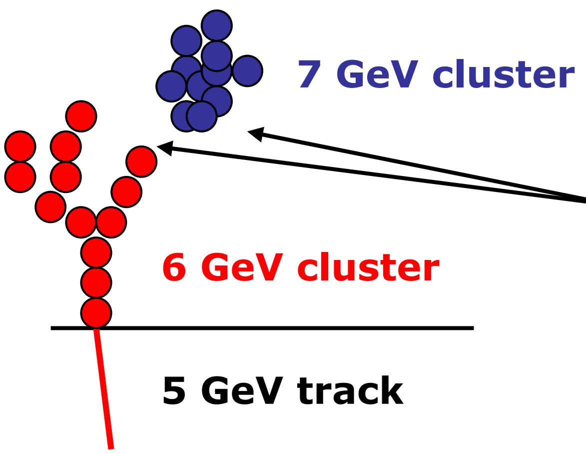


★ Apply tight matching criteria on basis of projected track [NB: + track quality i.e. chi2]

★ Here, association based on “tracking” in calorimeters

iv) Cluster Association Part II

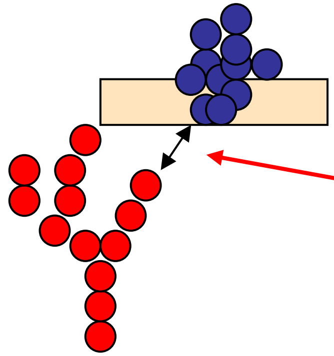
- Have made very clear cluster associations
- Now try "cruder" association strategies
- **BUT** first associate tracks to clusters (temporary association)
- Use track/cluster energies to "veto" associations, e.g.



This cluster association would be forbidden if $|E_1 + E_2 - p| > 3\,\sigma_E$

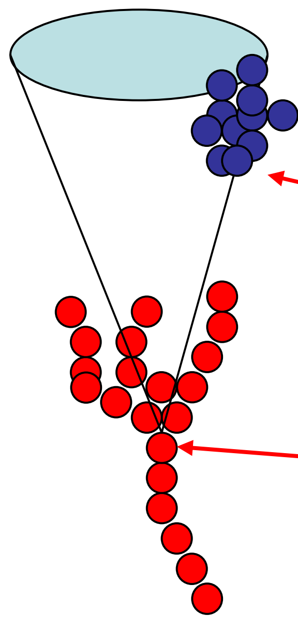
Provides some protection against obvious mistakes

Proximity



Distance between hits : limited to first pseudo-layers of cluster

Shower Cone



Associated if fraction of hits in cone > some value

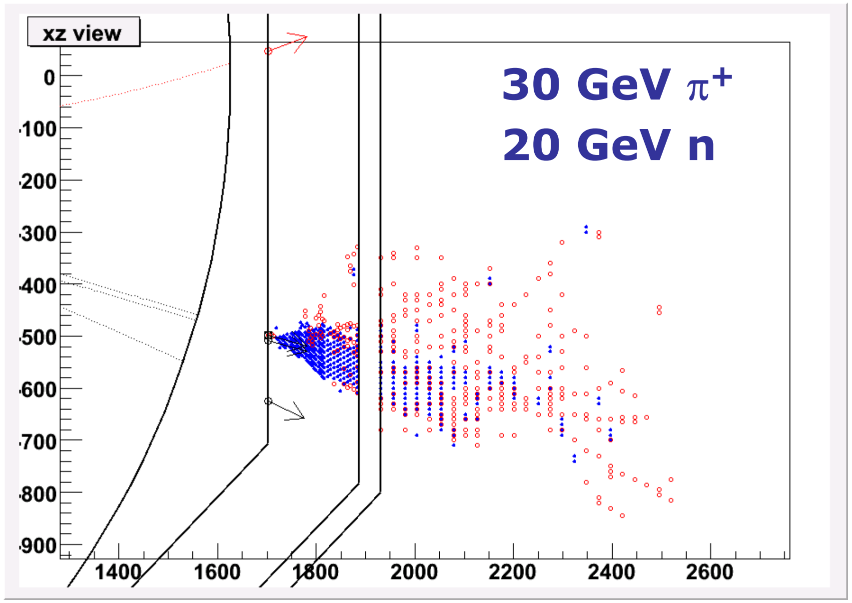
Shower start identified

+Track-Driven Shower Cone

Apply looser cuts if have low E cluster associated to high E track

v) Iterative Reclustering

★ Upto this point, in most cases performance is good – but some difficult cases…



★ At some point hit the limit of "pure" particle flow
- just can't resolve neutral hadron in hadronic shower

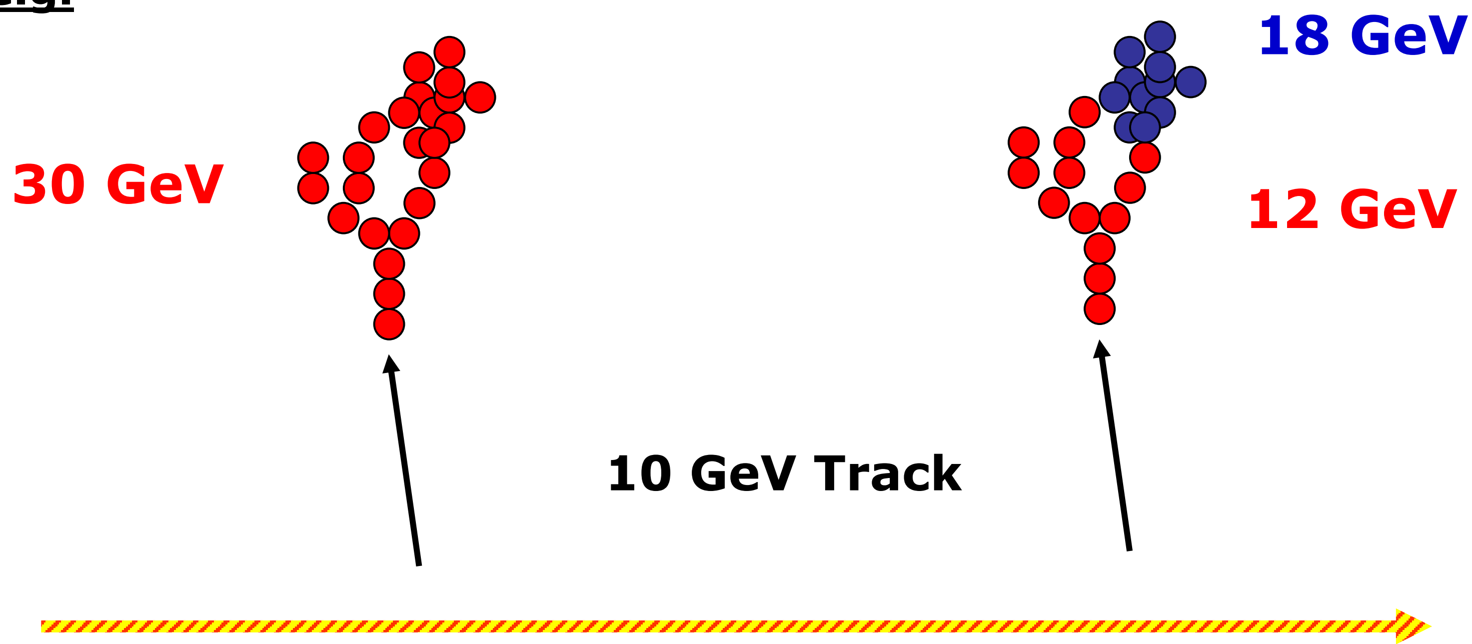
The ONLY(?) way to address this is "statistically"

→

e.g. if have 30 GeV track pointing to 20 GeV cluster
SOMETHING IS WRONG

★ If track momentum and cluster energy inconsistent : RECLUSTER

e.g.



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

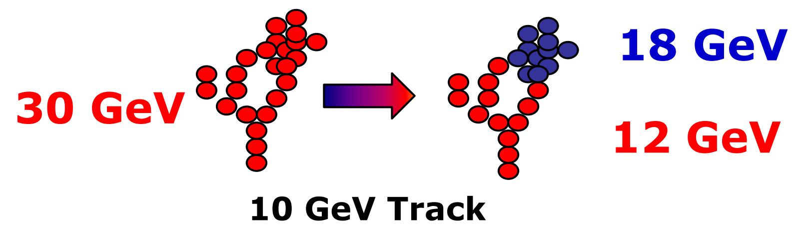
NOTE: NOT FULL PFA as clustering driven by track momentum

This is very important for higher energy jets

Iterative Reclustering Strategies

① Cluster splitting

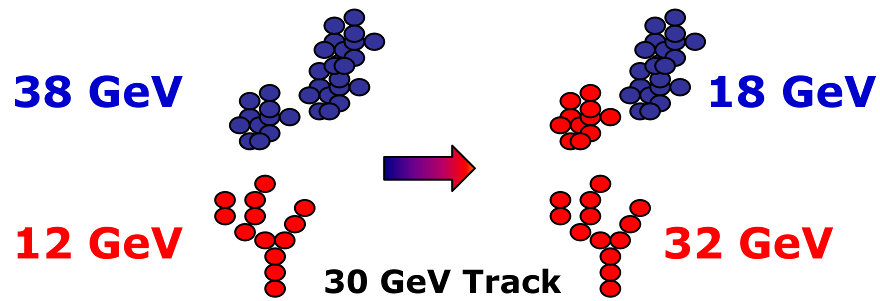
Reapply entire clustering algorithm to hits in "dubious" cluster. Iteratively reduce cone angle until cluster splits to give acceptable energy match to track



★ + plug in alternative clustering algorithms

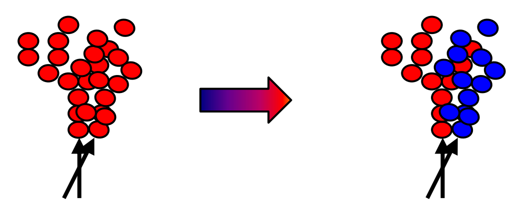
② Cluster merging with splitting

Look for clusters to add to a track to get sensible energy association. If necessary iteratively split up clusters to get good match.



③ Track association ambiguities

In dense environment may have multiple tracks matched to same cluster. Apply above techniques to get ok energy match.

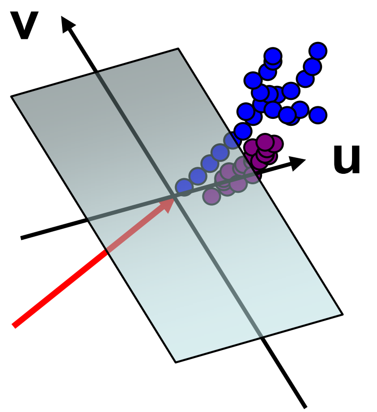


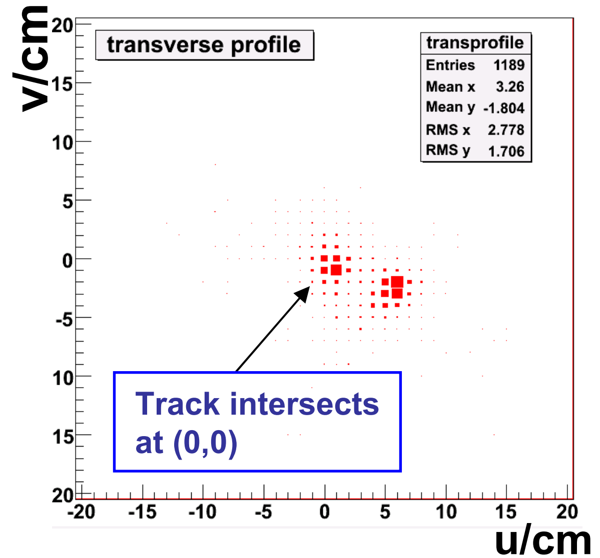
④ "Nuclear Option"

★ If none of above works – kill track and rely on clusters alone

★ **For each cluster associated with a track:**

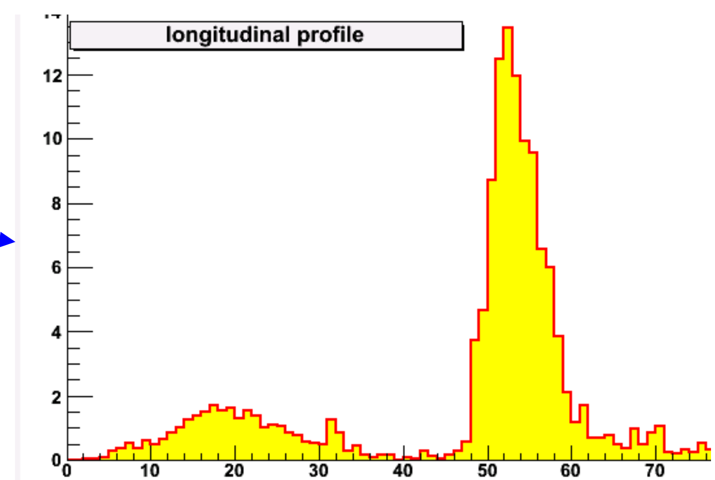
- project ECAL hits onto plane perpendicular to radial vector to point where track intersects ECAL
- search for peaks…





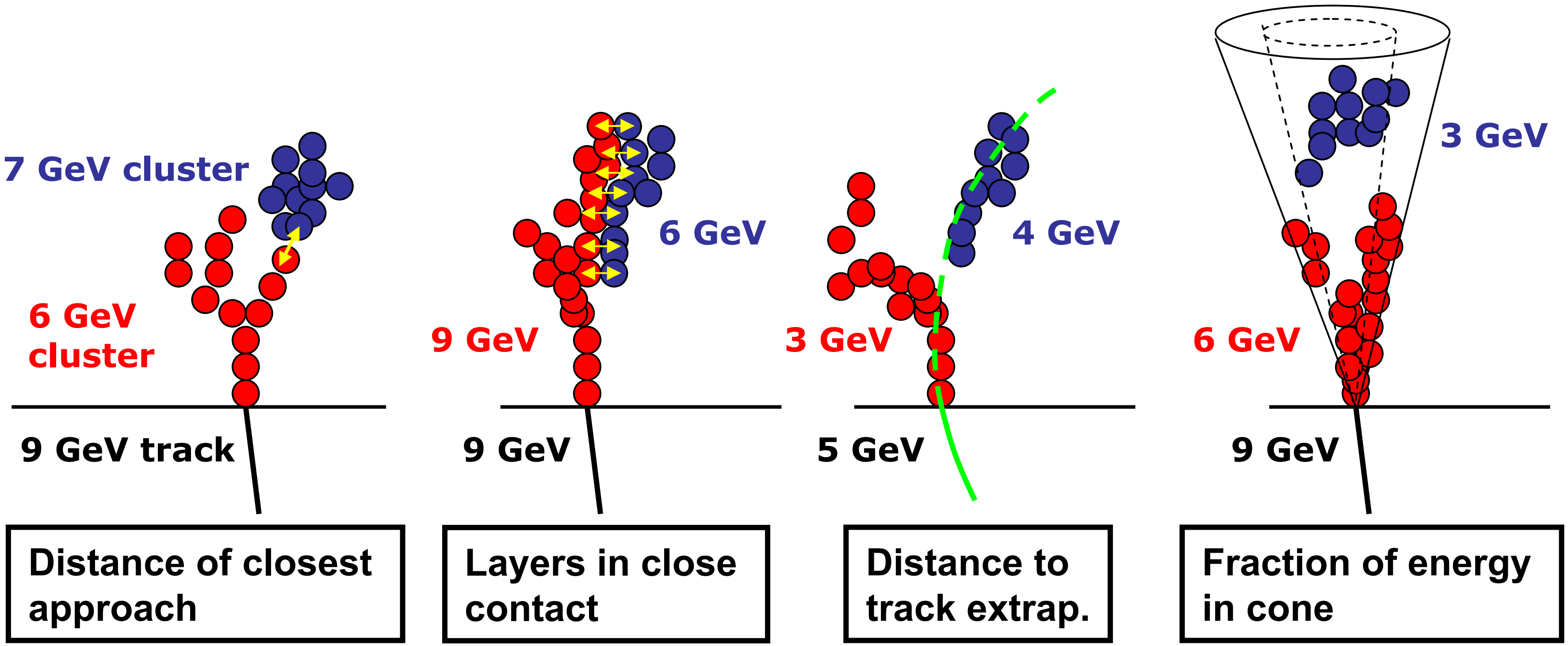
- Also look for photons where only a single peak is found 

- Implemented by looking at longitudinal profile of "shower"



viii) Fragment removal : basic idea

★ Look for "evidence" that a cluster is associated with another



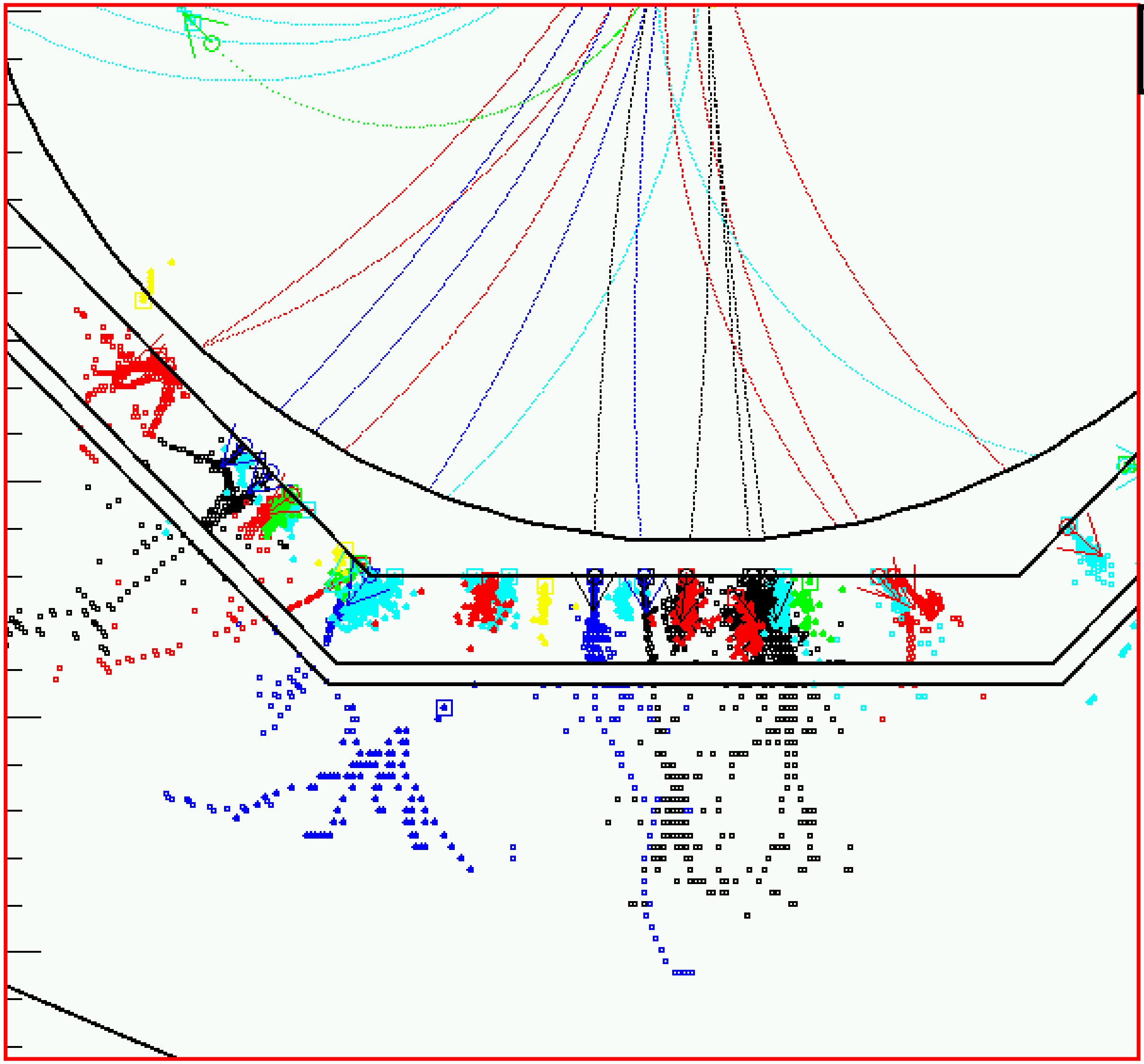
★ Convert to a numerical evidence score **E**

★ Compare to another score "required evidence" for matching, **R**, based on change in E/p chi-squared, location in ECAL/HCAL etc.

★ If **E > R** then clusters are merged

★ Rather *ad hoc* but works well – but works well

Putting it all together…



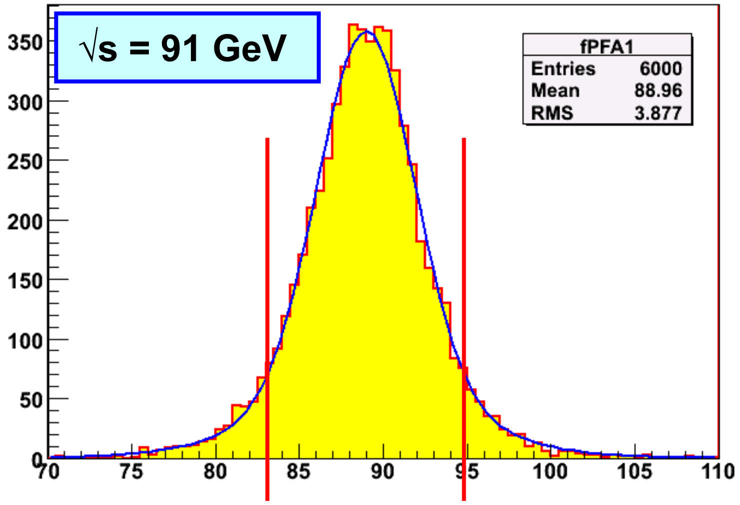
100 GeV Jet

❽ Current Performance

Figures of Merit:

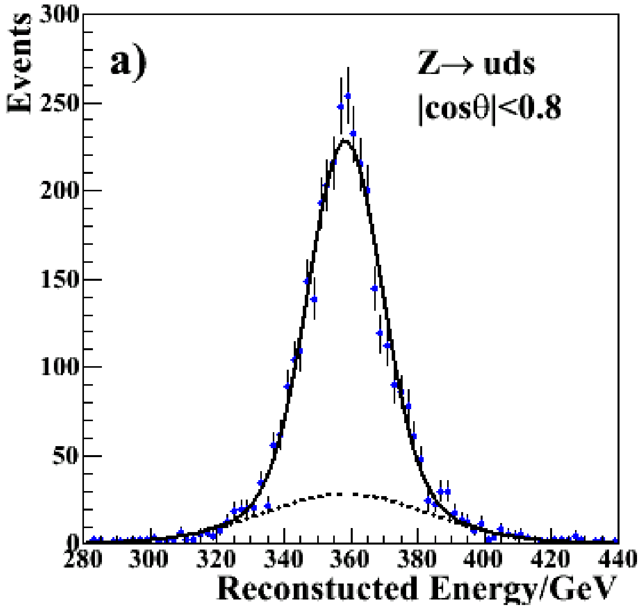
rms_{90}

★ Find smallest region containing **90 %** of events
★ Determine rms in this region



σ_{75}

★ Fit sum of two Gaussians with same mean. The narrower one is constrained to contain 75% of events
★ Quote σ of narrow Gaussian



It is found that $rms_{90} \approx \sigma_{75}$

Performance

rms90 PandoraPFA v02-01

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\vert\cos\theta\vert<0.7$	σ_E/E_j
45 GeV	0.235	3.5 %
100 GeV	0.306	3.1 %
180 GeV	0.427	3.2 %
250 GeV	0.565	3.6 %

- Tesla TDR detector model
- Full simulation
- Full reconstruction

In simulation

★ Particle flow can achieve ILC goal of $\sigma_E/E_j < 3.8\ \%$
★ For lower energy jets Particle Flow gives unprecedented levels of performance, e.g. @ 45 GeV : 3.5% c.f. ~10% (ALEPH)
★ "Calorimetric" performance (α) degrades for higher energy jets
★ + current code is not perfect - can do better

PARTICLE FLOW CALORIMETRY WORKS !

Detector Optimisation Studies

★ From point of view of detector design – what do we want to know ?

Optimise performance vs. cost

★ Main questions (the major cost drivers):

- Size : performance vs. radius
- Granularity (longitudinal/transverse): ECAL and HCAL
- B-field : performance vs. B

★ To answer them use MC simulation + PFA algorithm

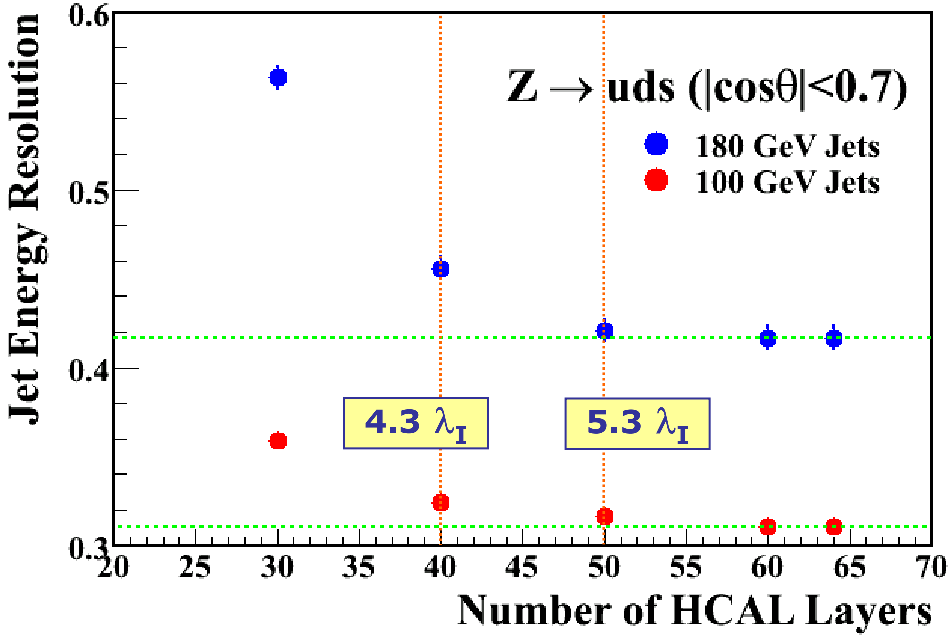
- Need a good simulation of hadronic showers !!!
- Need realistic PFA algorithm
  (want/need results from multiple algorithms)

★ This is important – significant impact on overall design of *xxx* M$ detector !

★ Interpretation of results needs care – observing effects of detector + imperfect software

e.g. HCAL Depth and Transverse segmentation

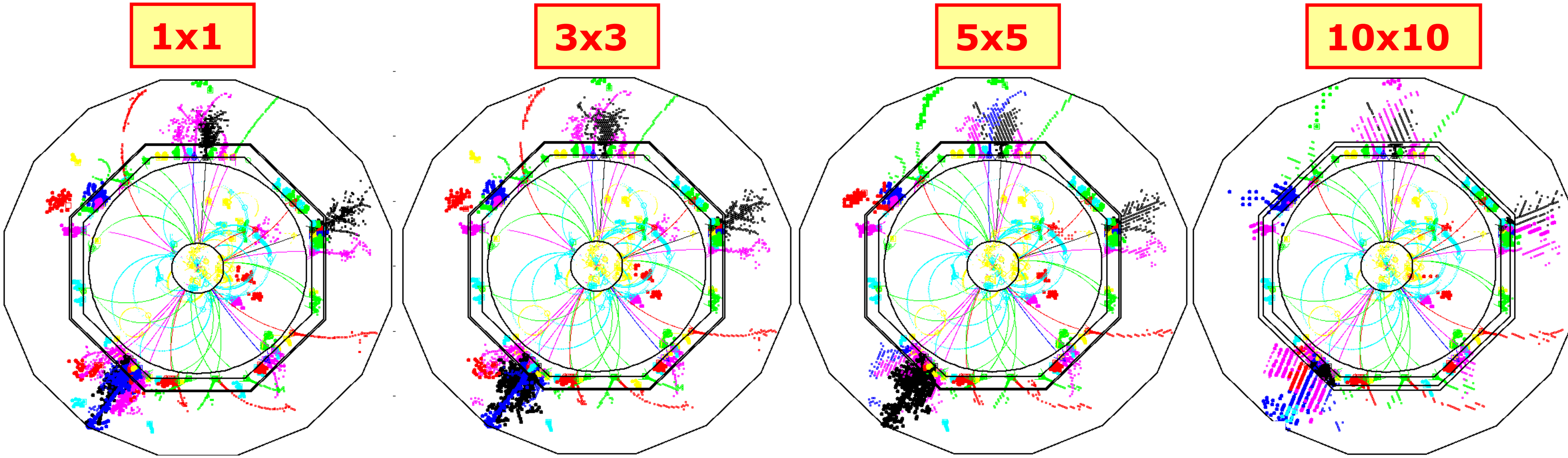
- ★ Investigated HCAL Depth (interaction lengths)
  - Generated **Z→uds** events with a large HCAL (63 layers)
    - approx 7 λ_I
  - In PandoraPFA introduced a configuration variable to truncate the HCAL to arbitrary depth
  - Takes account of hexadecagonal geometry

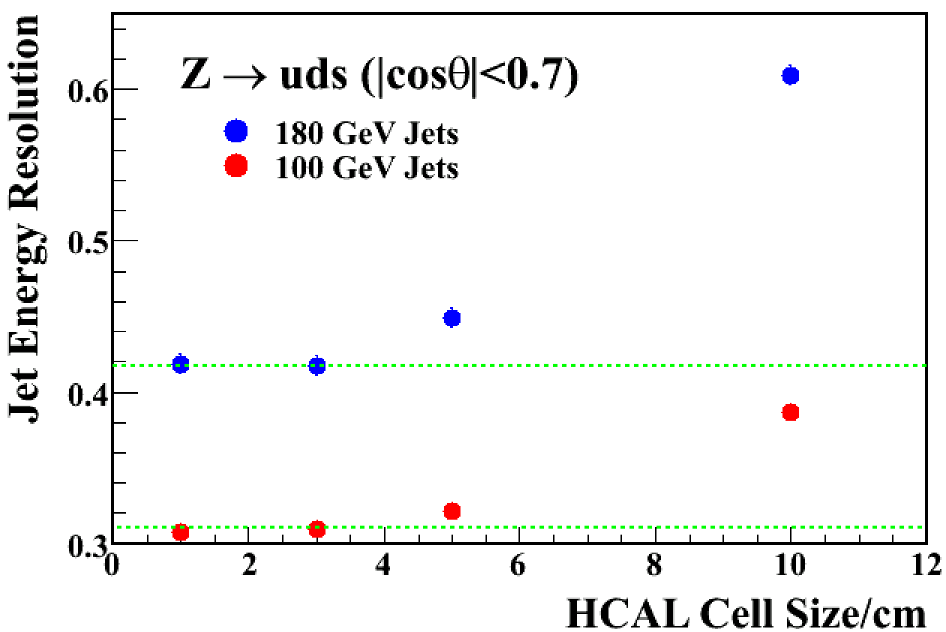


- ♦ HCAL leakage is significant for high energy
- ♦ Argues for ~ **5 λ_I HCAL**

NOTE: no attempt to account for leakage – i.e. using muon hits - this is a worse case

e.g. change HCAL tile size 1x1 → 10x10 mm^2

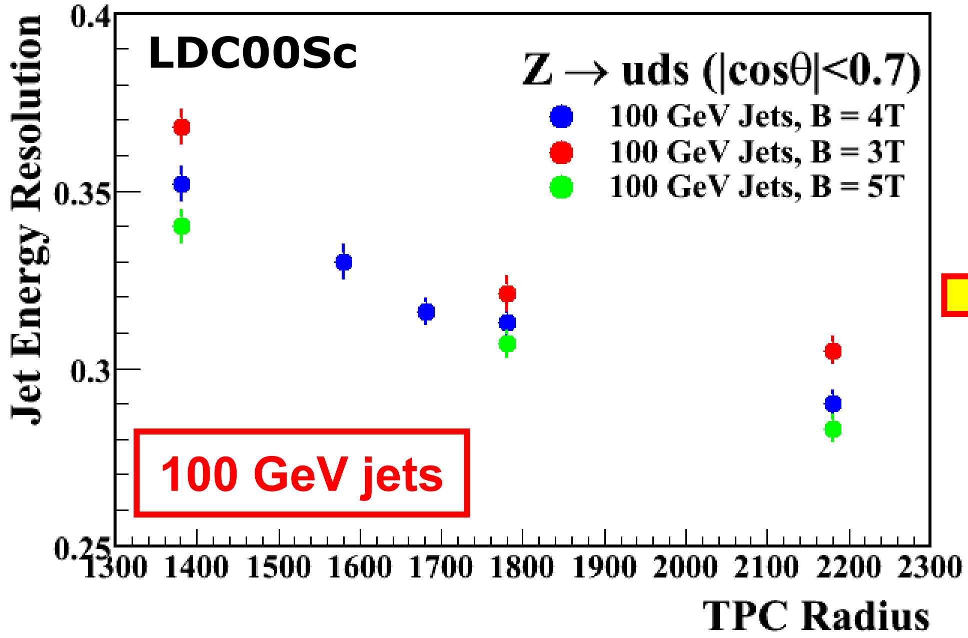




"Preliminary Conclusions"

- 3x3 cm^2 cell size
- No advantage → 1x1 cm^2
  - physics ?
  - algorithm artefact ?
- 5x5 cm^2 degrades PFA
  - Does not exclude coarser granularity deep in HCAL

Radius vs Field



Radius more important than B-field

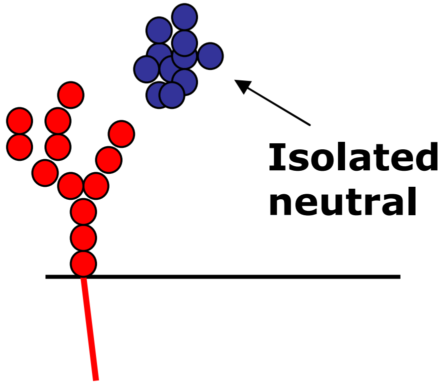
- ✶ Starting to obtain necessary input to optimise detector design from point of view of Particle Flow Calorimetry
- ✶ Currently working on first attempt to match this with detector cost model
- ✶ In very near future should have a much better idea of the parameters of a cost-performance optimized ILC detector

Caveat Emptor I

★ Studies rely on MC simulation
  • Simulation of hadronic showers notoriously difficult
  • All models in GEANT 4 likely to be quite "wrong"

★ What aspects of hadronic showers are most important ?
  • PFA relies on separating calorimeter deposits from different particles in a dense jet environment

★ NOT CLEAR what is most important !
  • NOT just energy resolution
  • Transverse development is important – how much do showers overlap
  • Longitudinal development matters – how well can showers be separated
  • Subtle details like rate and p_T distribution of "neutral fragments" may be important



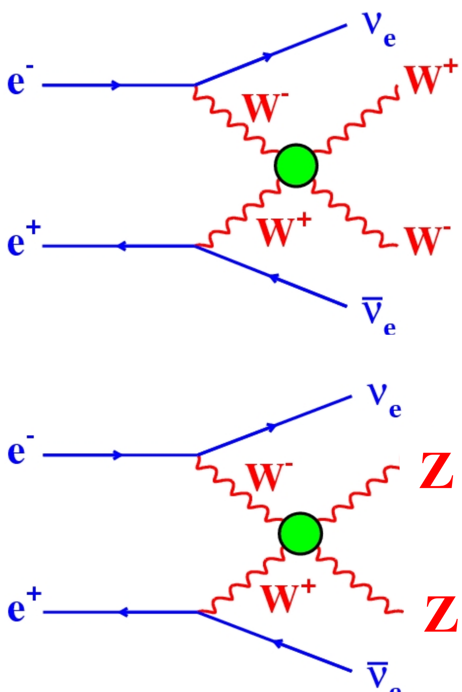
★ What is important for PFA may well be very different from that for traditional HEP calorimetry

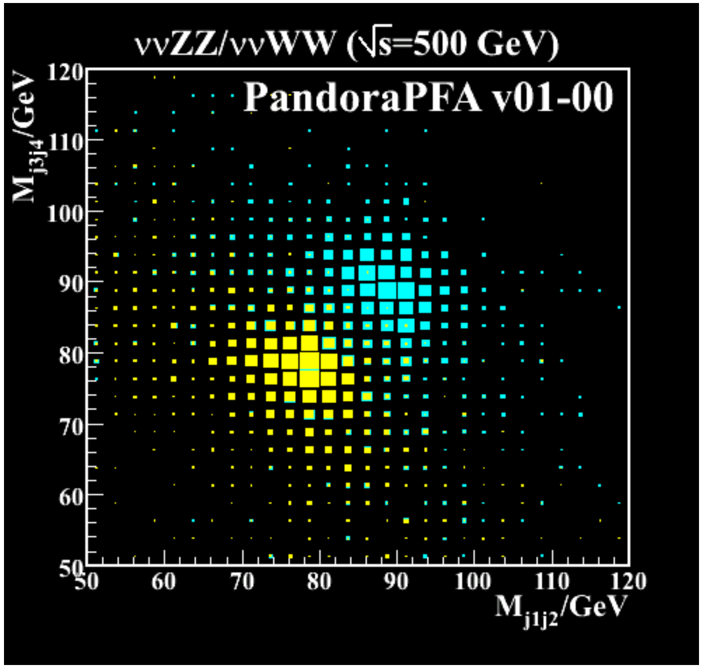
Caveat Emptor II

- ★ Ultimately want to optimise for "physics performance" i.e. di-jet mass resolution in a multi-jet event
- ★ Performance will be degraded by Jet-finding + jet-jet combinatorics
- ★ Need to compare detector performance for analysis chain

e.g.

$e^+e^- \rightarrow \nu\nu WW \rightarrow \nu\nu qqqq$, $e^+e^- \rightarrow \nu\nu ZZ \rightarrow \nu\nu qqqq$





ILD just starting an ambitious programme of physics-based ILC detector optimisation – first results by end of 2008

❾ Conclusions

- ★ Great deal of effort (worldwide) in the design of the ILC detectors
- ★ Centred around 3 "detector concept" groups: ILD (GLD+LDC), SiD + 4th
- ★ Widely believed that calorimetry and, in particular, jet energy resolution drives detector design
- ★ Also believed that it is likely that PFA is the key to achieving ILC goal

THIS IS HARD – BUT VERY IMPORTANT !

- ★ Calorimetry at the ILC = HARDWARE + SOFTWARE (new paradigm)
- ★ It is difficult to disentangle detector/algorithm….
- ★ Can only address question with "realistic algorithms"
  - ★ i.e. serious reconstruction 10+ years before ILC turn-on
- ★ With PandoraPFA have reached the ILC "goal" (for $Z \rightarrow uds$ events)
- ★ More importantly, getting close to being able to address real issues:
  - ⊙ What is optimal detector size/B-field, etc.

FINAL COMMENT:

- ★ GLD, LDC, SiD calorimetry "designed" for PFA
  - ★ Needed to demonstrate this actually makes sense
    - ▪ until recently not completely proven !
  - ★ Now starting to study in the context of physics sensitivity

The End

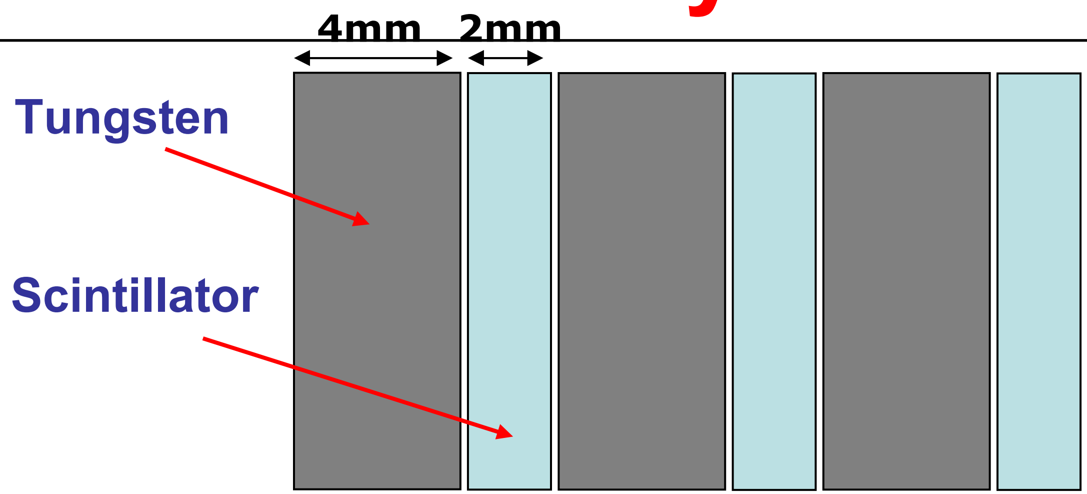
RESERVE SLIDES

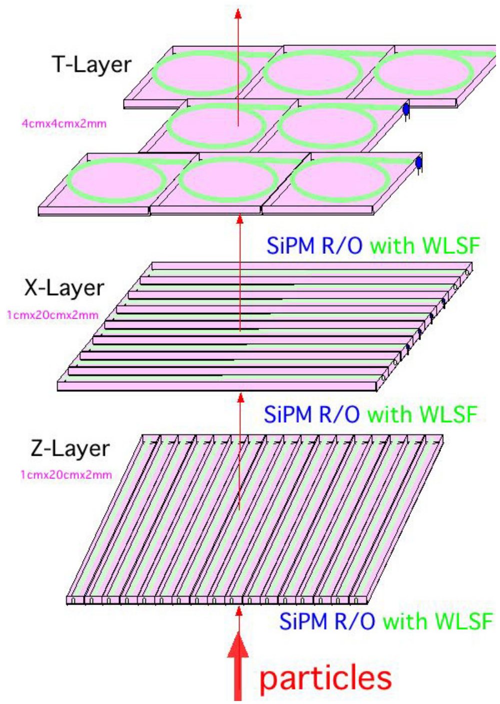
① GLD Calorimetry

★ ECAL and HCAL inside coil

★ W-Scintillator ECAL sampling calo.

★ Pb-Scintillator HCAL sampling calo.





Initial GLD ECAL concept:

★ Achieve effective ~1cm x 1cm segmentation using strip/tile arrangement

★ Strips : 1cm x 20cm x 2mm

★ Tiles : 4cm x 4cm x 2mm

Big question of pattern recognition in dense environment

SiD/LDC/GLD : Basic design = sampling calorimeter

③ PerfectPFA

- ★ **Recently added PerfectPFA option in Pandora (not yet in CVS)**
  - <parameter name="PerfectPFA" type="int"> 1 </parameter>
- ★ **Uses MC information to create the ProtoClusters**
- ★ **The rest of the algorithm is the same**
- ★ **Although very fresh, can already learn something…**
- ★ **Process same events/same analysis and compare PFA to perfect PFA**
  - **Note in these studies the tracks are the same "TrackCheater"**

i) How close to being "Perfect" is PandoraPFA?

E_{JET}	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$ $\lvert\cos\theta\rvert<0.7$	
	PerfectPandora	PandoraPFA
100 GeV	0.220	0.305
180 GeV	0.305	0.418

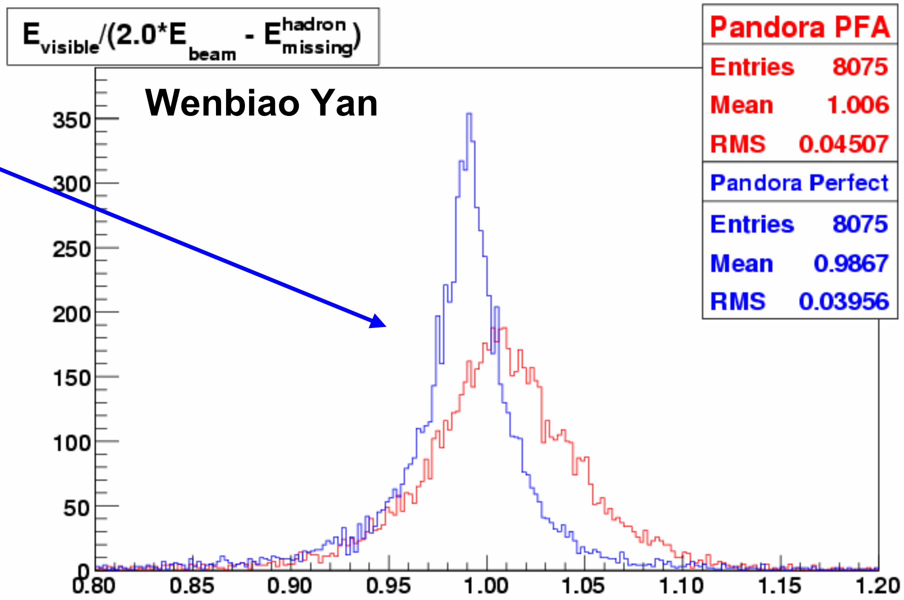
Still someway to go even for low energy jets – needs study

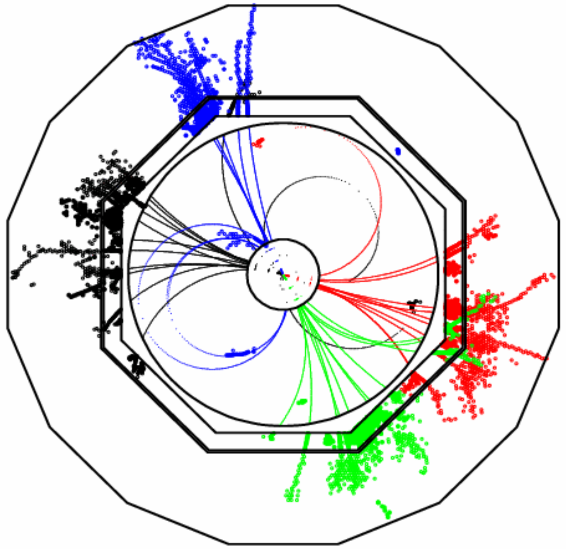
ii) PFA impact in a real physics process

e.g. $e^+e^- \rightarrow \nu\bar{\nu}W^+W^- \rightarrow \nu\bar{\nu}qqqq$ $\sqrt{s} = 800\,\mathrm{GeV}$

★ First compare visible energy from PFA with expected (i.e. after removing neutrinos/forward tracks+clusters)

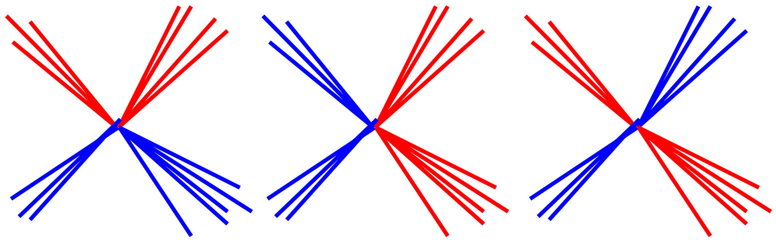
- ♦ PerfectPFA gives better energy resolution than PandoraPFA (as expected)



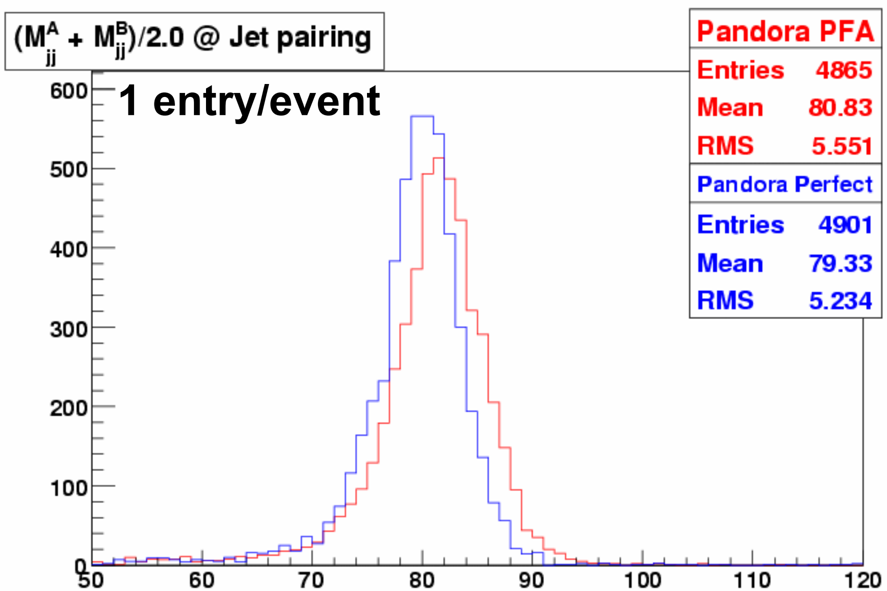


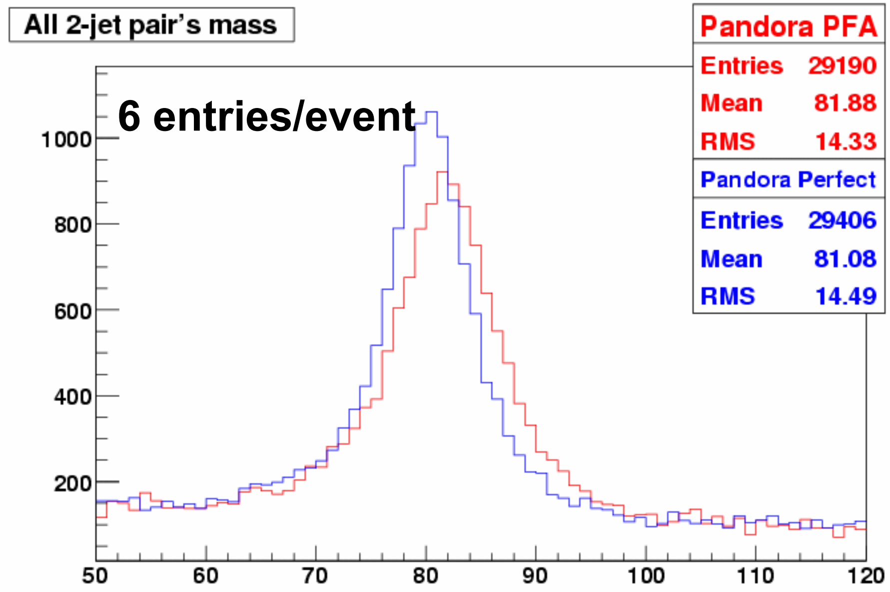
★ Does this difference make it through to a physics analysis (i.e. after jet finding/ jet pairing) ?

- ★ Force event into 4 jets (Durham)
- ★ Plot masses of the 2 Ws formed from the 3 possible jet-pairings



HERE: PandoraPFA ~ PerfectPFA





- ★ Choose pairing with smallest mass difference
- ★ Plot average mass of the 2 Ws

HERE: PandoraPFA ~ PerfectPFA

⇨ "Physics Ready PFA"

Not The End

- What jet energy resolution is really needed at the ILC ?
  - NOT 30%/√E
  - Ideally reach point where dominated by Z/W width
  - NOT the same as

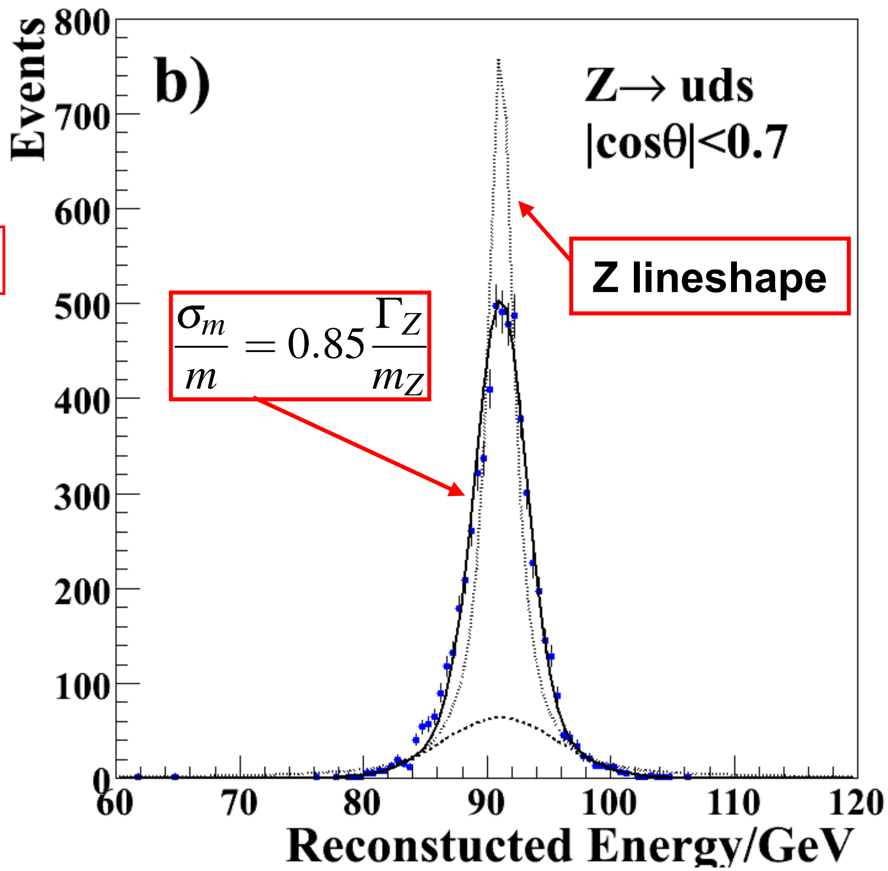
$$\frac{\sigma_m}{m} \sim \frac{\Gamma_Z}{m_Z}$$

FWHM

  - Suggests

$$\frac{\sigma_m}{m} < \frac{\Gamma_Z}{m_Z}$$

  - Significant advantages in further improvements ?



- Ultimate criterion – "physics performance"