Detectors for a Future Lepton Collider
Lecture 3: Calorimetry

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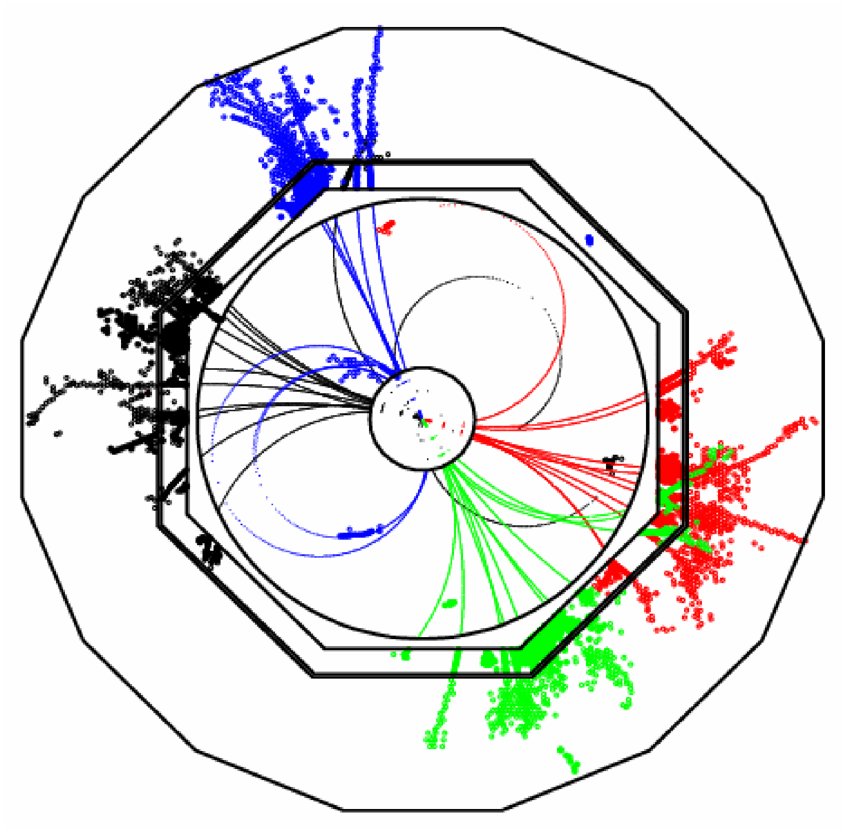
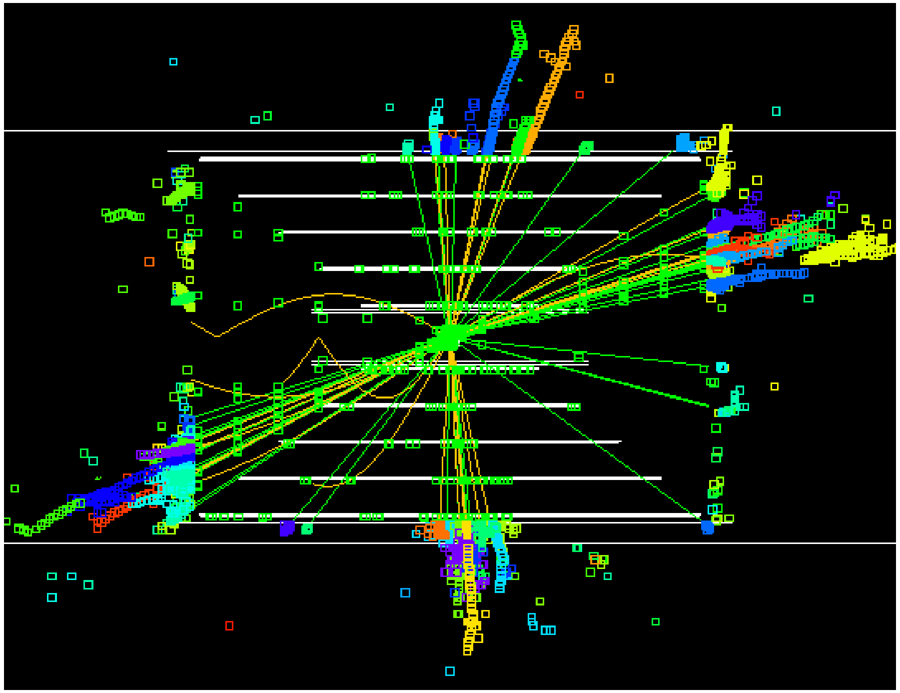




Today's Lecture

- ❶ e^+e^- Physics ↔ Calorimetry
- ❷ LC Jet Energy Requirements
- ❸ Particle Flow Calorimetry
- ❹ CALICE
- ❺ Realising Particle Flow Calorimetry
- ❻ Particle Flow Reconstruction
- ❼ Particle Flow Performance
- ❽ Summary

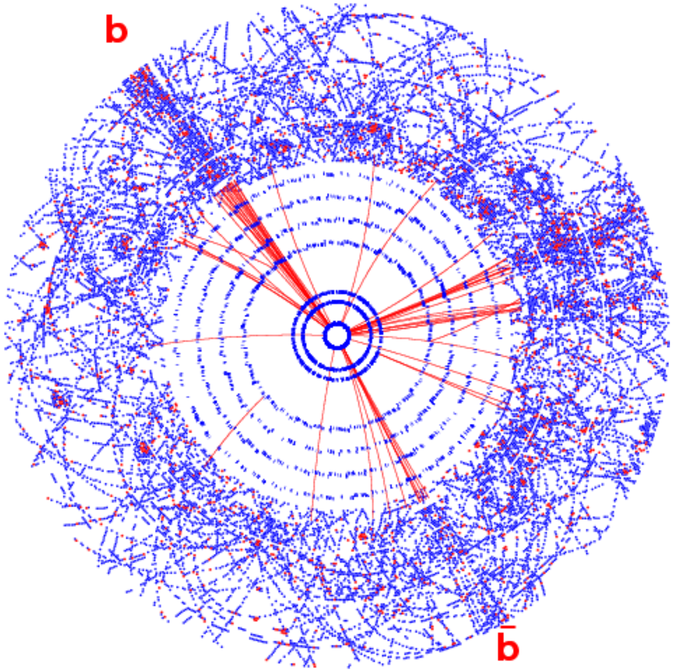
★ Concentrate on concepts rather than fine details of detector R&D

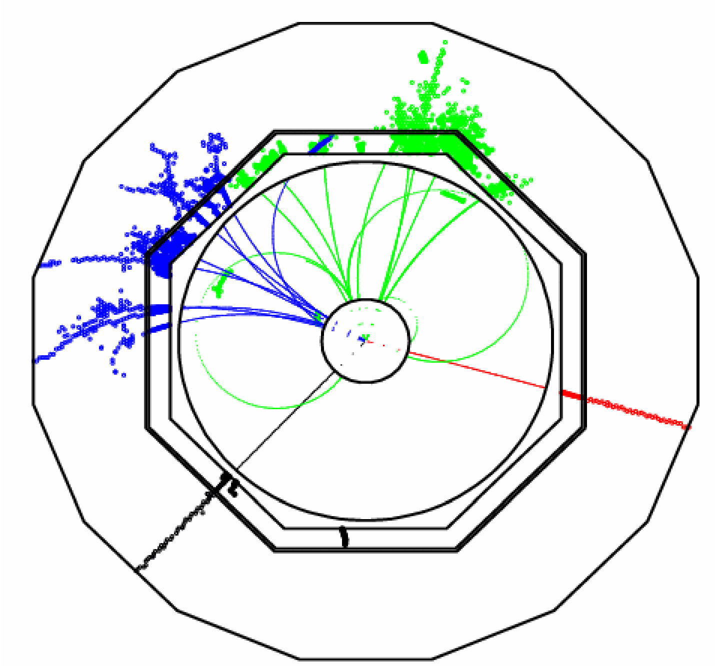
❶ e^+e^- Physics ↔ Calorimetry

- ★ Electron-positron colliders provide clean environment for precision physics

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

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





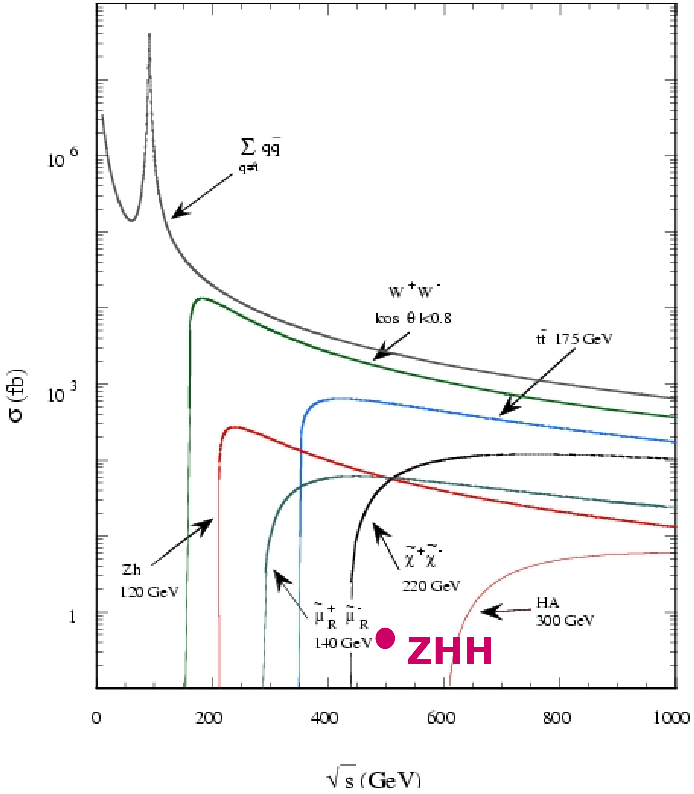
- ★ A detector at a future lepton collider (e.g. **ILC/CLiC**) will be designed to take full advantage of this clean environment
- ★ Very different detector design requirements c.f. **LHC**

e.g. ILC Physics

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.

$$\sigma(e^+e^- \to ZHH) = 0.3\,\mathrm{fb}$$

- ✸ Require High Luminosity – i.e. ILC/CLIC
- ✸ Detector optimized for precision measurements
  in difficult multi-jet environment

Compare with LEP

At LEP:

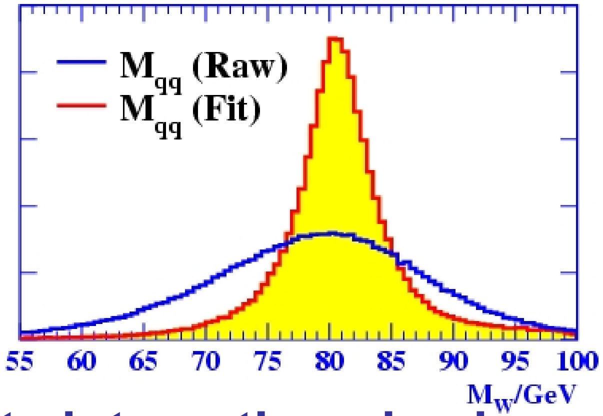
★ Signal dominates: $e^+e^- \rightarrow Z$ and $e^+e^- \rightarrow W^+W^-$
backgrounds not too problematic

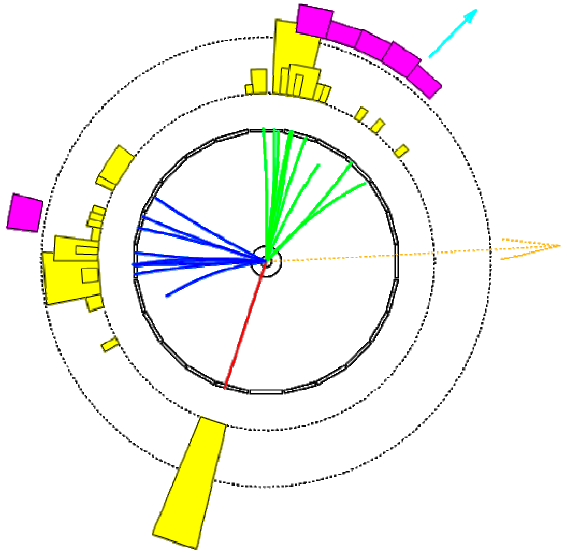
★ Even for W mass measurement, **jet energy resolution not too important**

Kinematic Fits

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

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





At the ILC:

★ Backgrounds dominate interesting physics

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

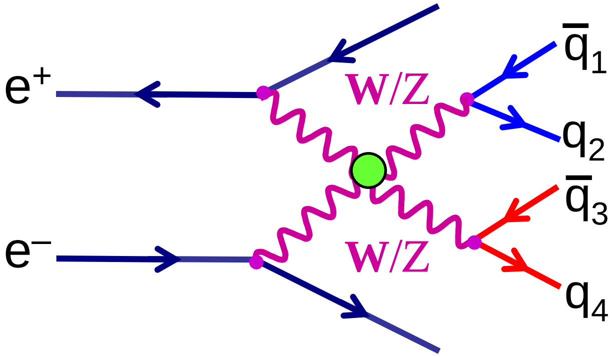
✸ Physics performance depends critically on the detector performance (not true at LEP)

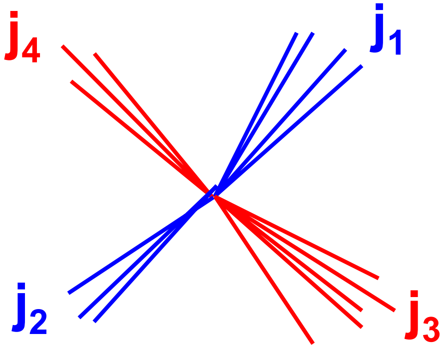
✸ Places stringent requirements on the ILC detector

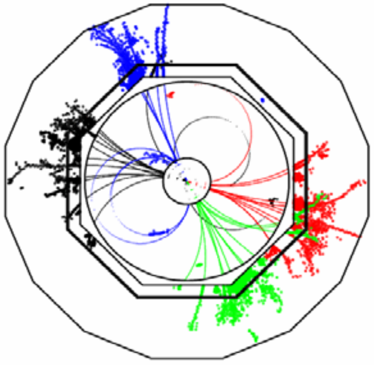
Linear Collider Calorimetry

★ **Any future collider experiment geared towards precise measurements requires very good jet energy resolution to maximise physics reach:**

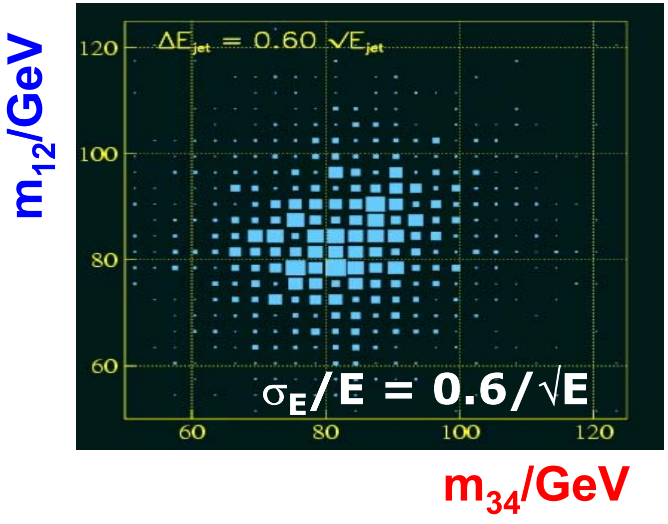
Often-quoted example at ILC: $e^+e^- \rightarrow \nu\bar{\nu}W^+W^-$ **vs.** $e^+e^- \rightarrow \nu\bar{\nu}ZZ$

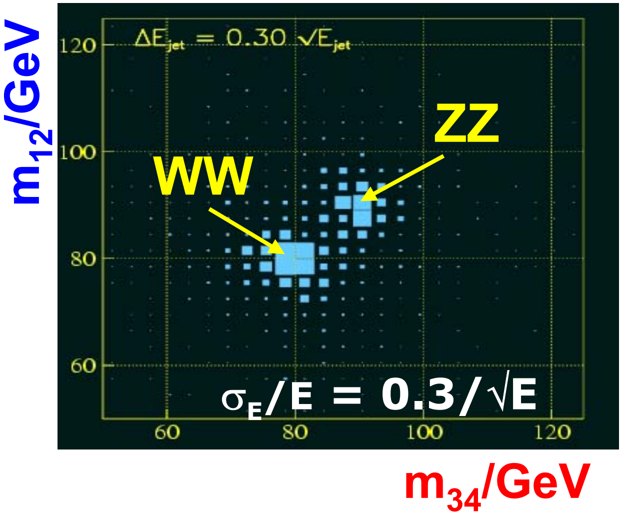






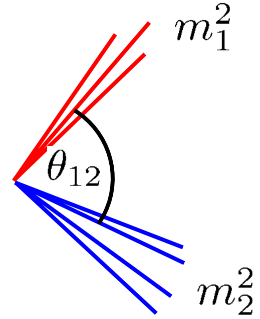
Reconstruction of two di-jet masses discriminates between WW and ZZ final states

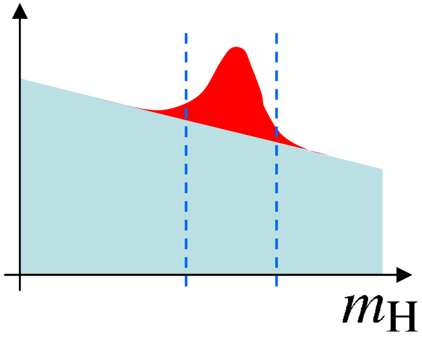




❷ LC Jet Energy Requirements

- ★ What are the jet energy requirements at a future LC ?
- ★ Probably not driven by single particle resolution
- ★ Primarily interested in di-jet mass resolution
  - For a narrow resonance, want best possible di-jet mass resolution

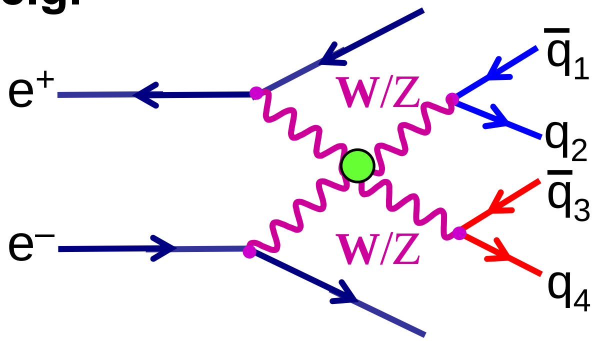


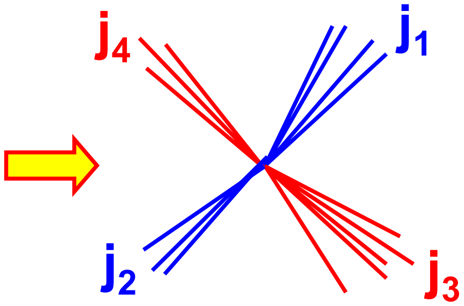


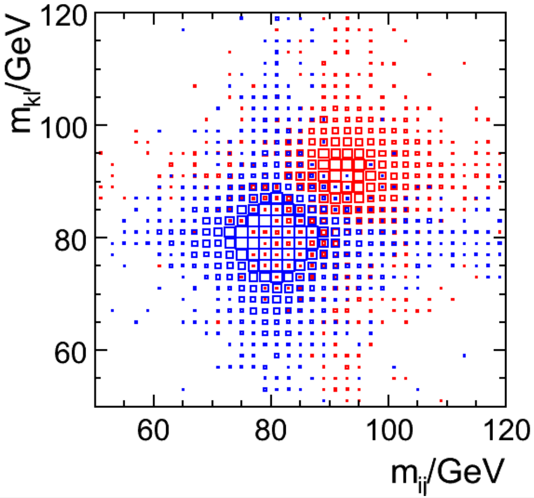
$$\text{signif.} \propto \frac{S}{\sqrt{B}} \propto (\text{resolution})^{-\frac{1}{2}}$$

  - At very least, need to separate W/Z hadronic decays

e.g.

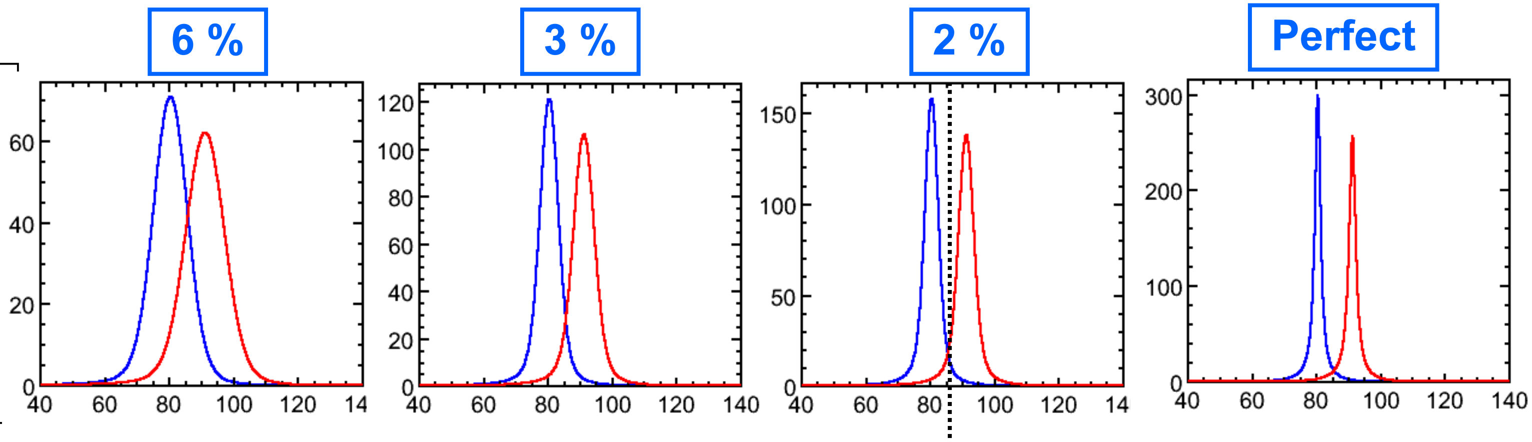






- **Gauge boson width sets "natural" goal for jet energy resolution**

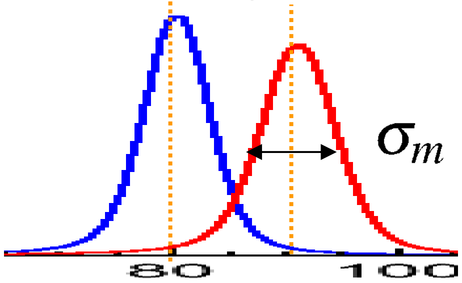
LEP-like



- **Quantify by effective W/Z separation**

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 level**
- **sets a reasonable choice for LC jet energy goal:**

$$\boxed{\sigma_E/E \sim 3.5\ \%}$$

Context: LC jet energies

- What jet energies are we likely to be interested in ?
- Determined by number of fermions in “interesting” final states
- Little need to reconstruct di-jet mass in $e^+e^- \rightarrow q\bar{q}$
- At 500 GeV primarily interested in 4-fermion/6-fermion final states
  - e.g. $e^+e^- \rightarrow ZH \rightarrow q\bar{q}b\bar{b}$ and $e^+e^- \rightarrow t\bar{t} \rightarrow bq\bar{q}\bar{b}q\bar{q}$
- For higher centre-of-mass energies, fermion multiplicities will tend to be higher, e.g. SUSY cascade decays
- Sets scale of typical jet energies:

$\sqrt{s}$	#fermions	Jet energy
250 GeV	4	~60 GeV
500 GeV	4 – 6	80 – 125 GeV
1 TeV	4 – 6	170 – 250 GeV
3 TeV	6 – 8	375 – 500 GeV

ILC - like

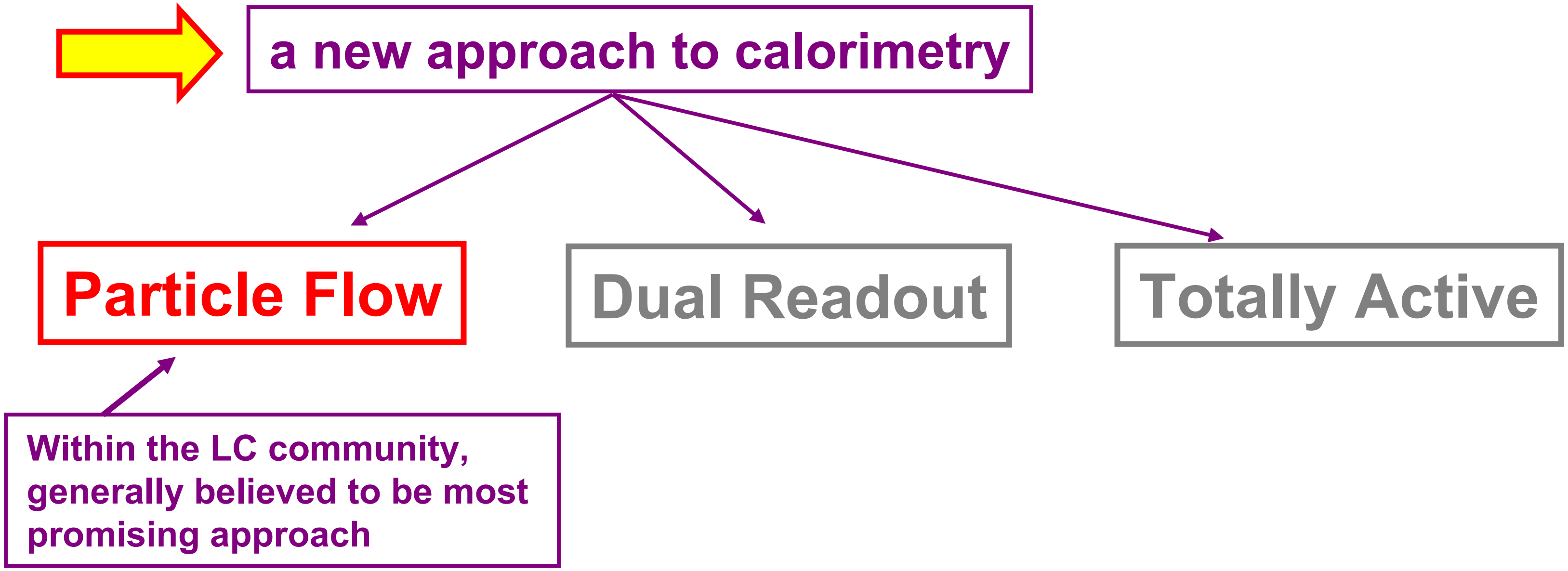
CLIC - like

LC Calorimetry Goal: ~3.5 % jet energy resolution for 50 – 500 GeV jets

★ **Want** $\boxed{\sigma_E/E < 3.5\%}$

★ **Very hard (probably not possible) to achieve this with a traditional approach to calorimetry**

Limited by typical HCAL resolution of > 60 %/√E(GeV) + constant



a new approach to calorimetry

Particle Flow

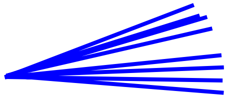
Dual Readout

Totally Active

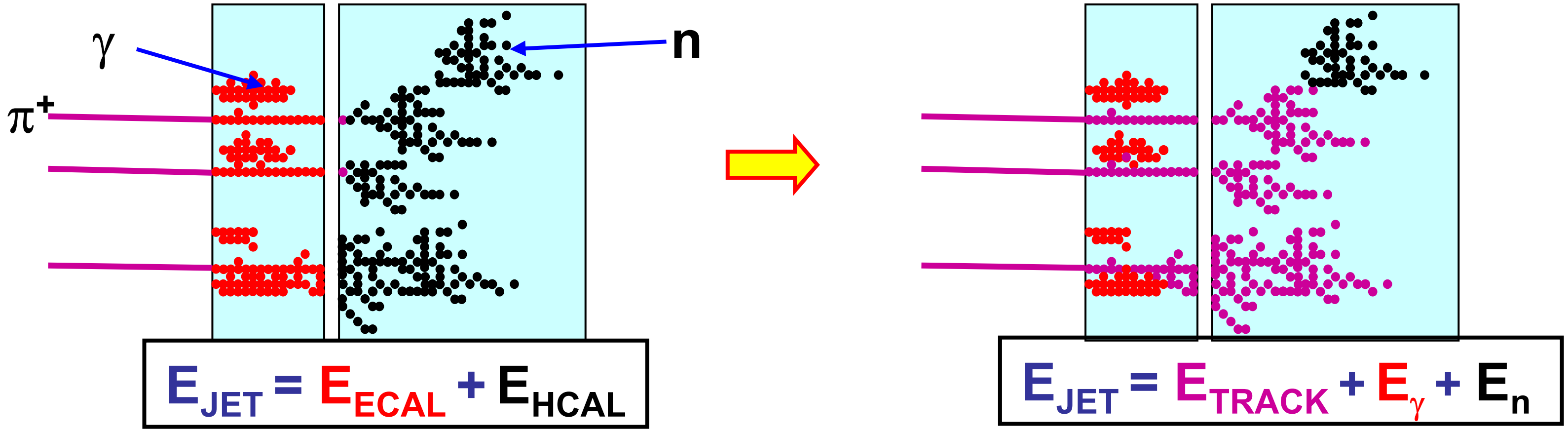
Within the LC community, generally believed to be most promising approach

❸ Particle Flow Calorimetry

- **In a typical jet :**
  - 60 % of jet energy in charged hadrons
  - 30 % in photons (mainly from $\pi^0 \to \gamma\gamma$)
  - 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



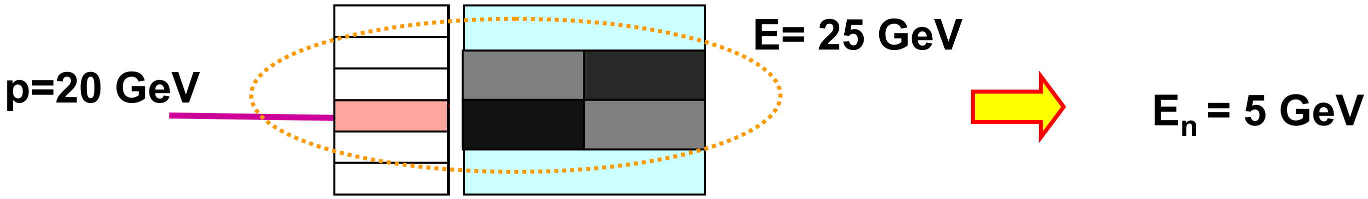
$E_{JET} = E_{ECAL} + E_{HCAL}$

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

- **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

"Energy Flow" → "Particle 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 CAL 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

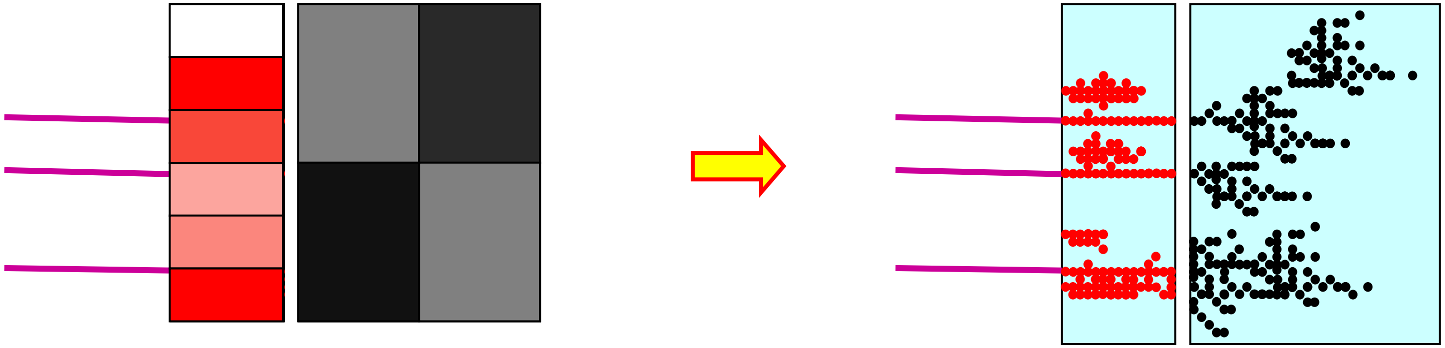
- Similar approach used by a number of other collider experiments, e.g CMS
- "PARTICLE FLOW" significantly extends this approach to a high granularity calorimeter
  - Now directly reconstruct neutral hadrons
  - Potentially much better performance
  - but need highly granular calorimeter + sophisticated "particle flow algorithm"

Particle Flow Calorimetry

Hardware:

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

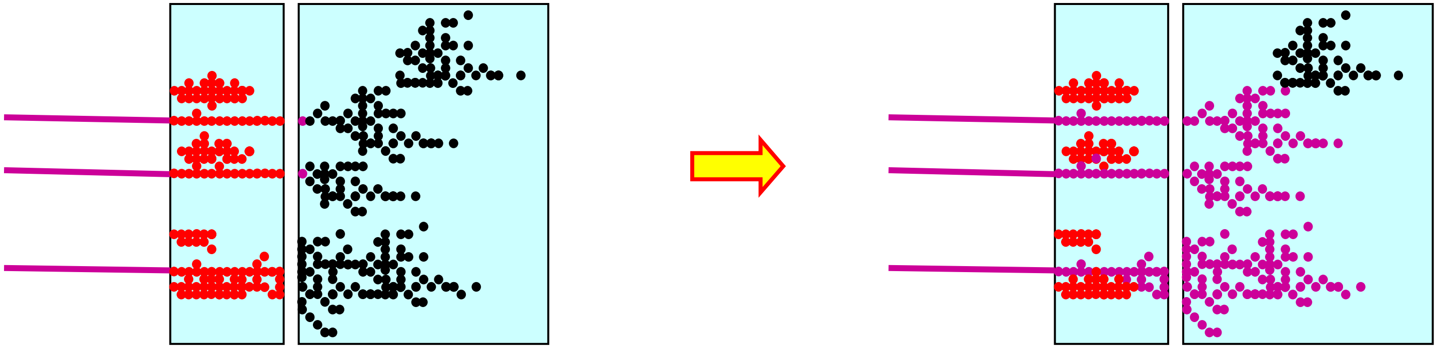
→ Highly granular detectors (as studied in CALICE)



Software:

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

→ Sophisticated reconstruction software



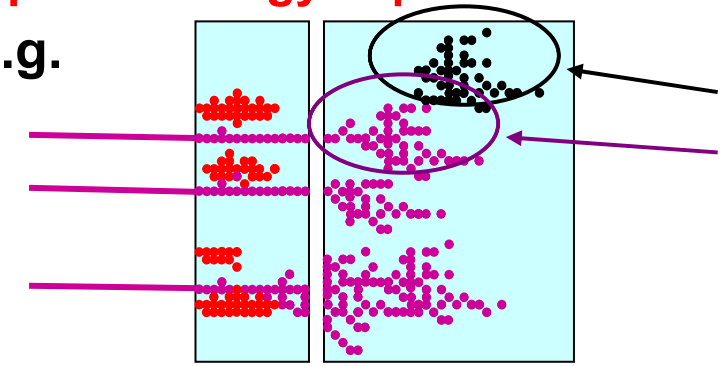
★ **Particle Flow Calorimetry = HARDWARE + SOFTWARE**

Particle Flow Algorithms (PFA)

Reconstruction of a Particle Flow Calorimeter:

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

e.g.

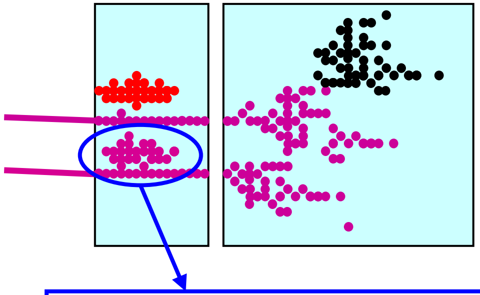


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution
not the intrinsic calorimetric performance of ECAL/HCAL

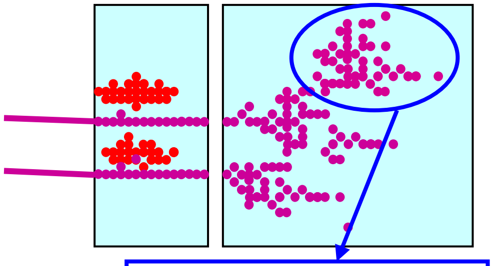
Three types of confusion:

i) Photons



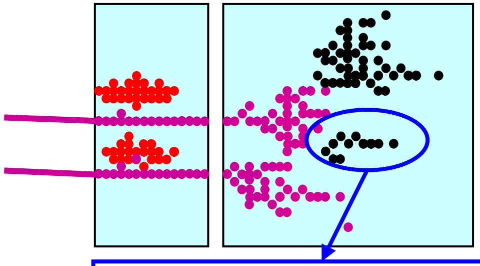
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

iii) Fragments



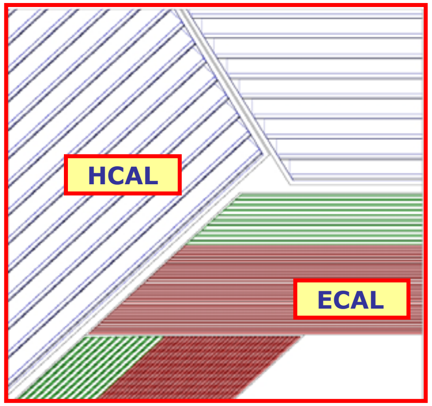
Reconstruct fragment as separate neutral hadron

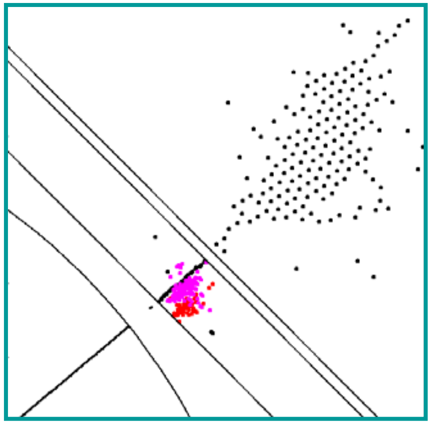
Particle Flow ECAL considerations

★ **Require: high longitudinal and transverse segmentation**

★ **ECAL:**

- **minimise transverse spread of EM showers**
  - ⇨ **small Moliere radius**
- **high transverse granularity ~ Moliere radius**
- **longitudinally separate EM and Hadronic showers**
  - ⇨ **large ratio of λ_I/X_0**
- **longitudinal segmentation to cleanly ID EM showers**

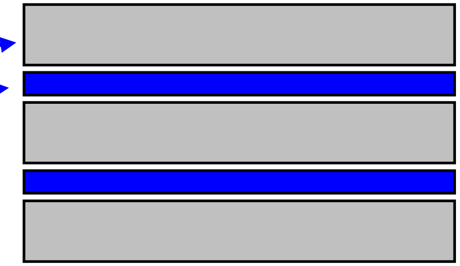




Material	X_0/cm	ρ_M/cm	λ_I/cm	X_0/λ_I
Fe	1.76	1.69	16.8	9.5
Cu	1.43	1.52	15.1	10.6
W	0.35	0.93	9.6	27.4
Pb	0.56	1.00	17.1	30.5

★ **Favoured option : Tungsten absorber**

- ♦ **need to keep sensitive material "thin" to maintain small ρ_M**

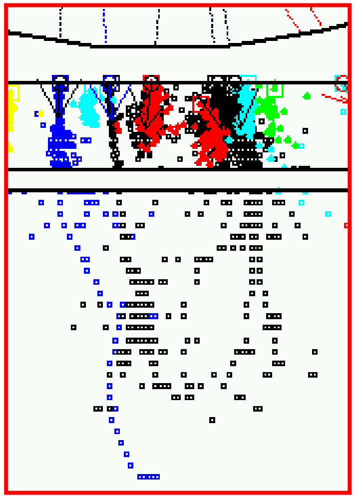


Particle Flow HCAL considerations

★ Require: high longitudinal and transverse segmentation

★ HCAL:

- resolve structure in hadronic showers
  - ⇨ longitudinal and transverse segmentation
- contain hadronic showers
  - ⇨ small λ_I
- HCAL will be large: absorber cost & structural properties will be important



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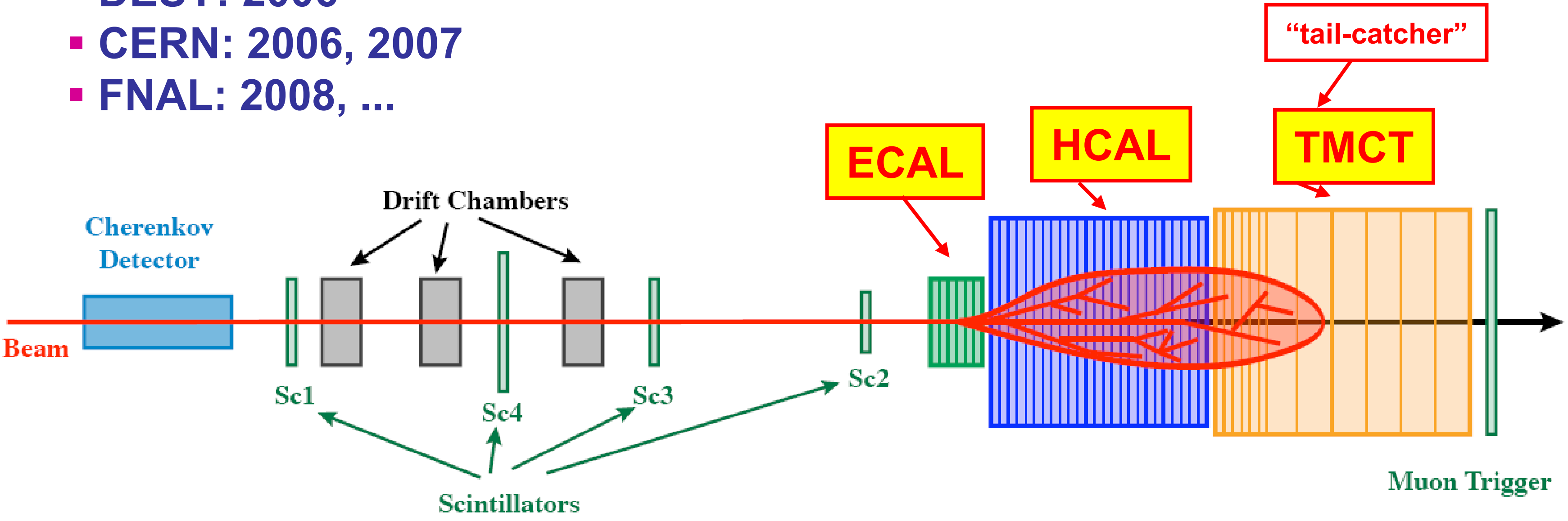
?

★ A number of technological option being studied, e.g. by the CALICE collab: CAlorimetry for the LInear Collider Experiment

❹ CALICE

- Umbrella for LC PFlow Calorimeter R&D
  - in addition US effort focussed on SiD ECAL concept (also SiW)
- Approximately 330 scientists and engineers from 57 institutes in 17 countries (Africa, Americas, Asia, Europe)

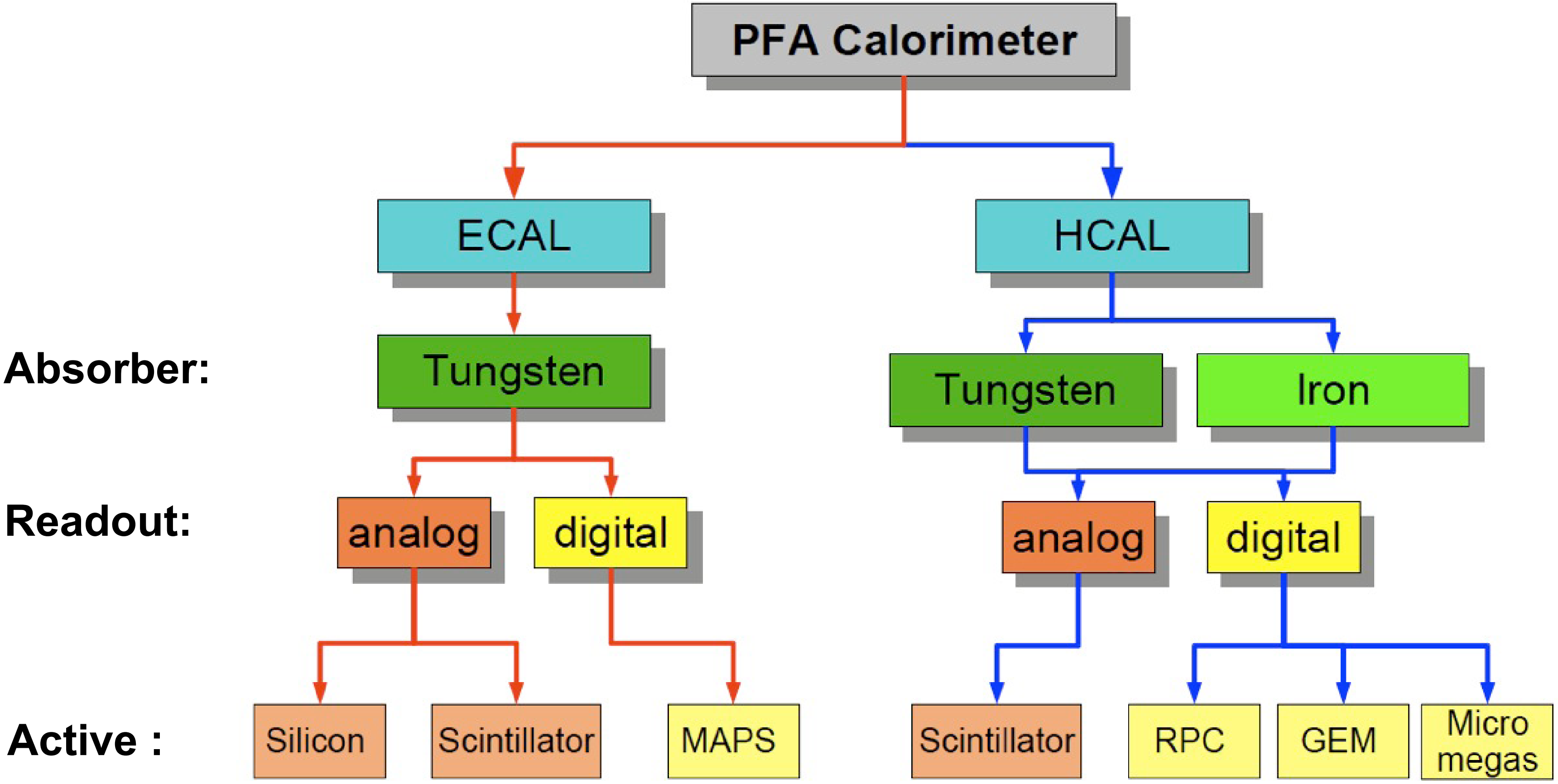
- Extensive test beam campaign
  - DESY: 2006
  - CERN: 2006, 2007
  - FNAL: 2008, ...



- Wide variety of beam energies and particle species
  - 2 GeV to 80 GeV
  - muons, $e^{\pm}$, $\pi^{\pm}$, unseparated hadrons
- Different technologies (to date 1 HCAL, 1 TCMT, 2 ECAL)

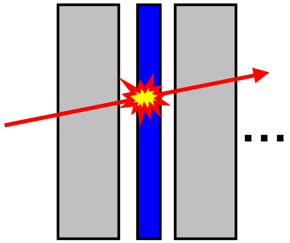
LC PFlow Calorimetry options

★ **Various options for high granularity sampling calorimeters…**

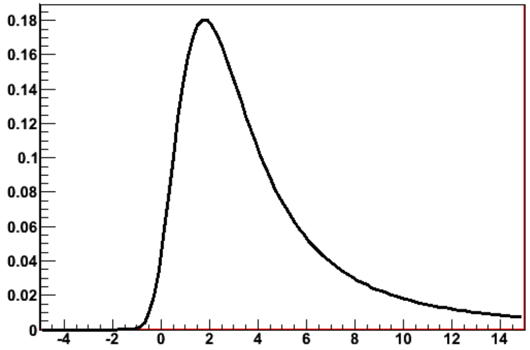


★ **A number of interesting issues…**

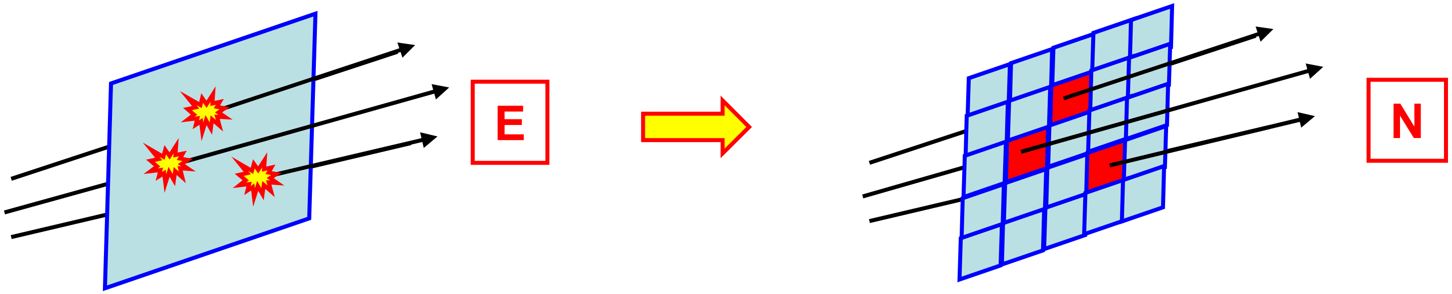
Analogue vs Digital Readout



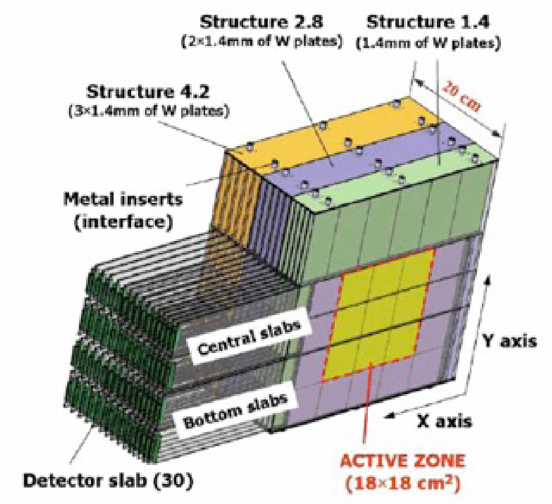
- ★ Energy deposited by a **charged particle** in the active material of a sampling calorimeter follows a **Landau distribution**

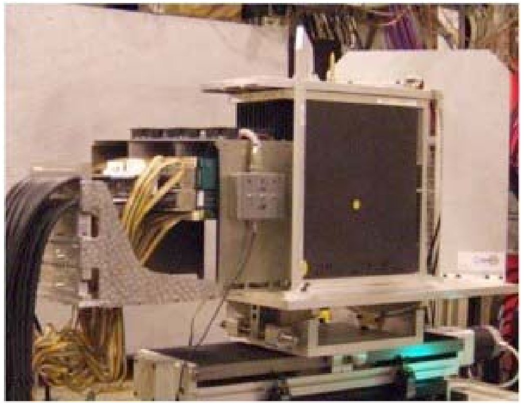


  - Long-tail
  - Therefore large fluctuations in energy deposition for a single particle
- ★ In previous collider experiments typically have multiple particles crossing each calorimeter cell
  - analogue readout – including Landau fluctuations
- ★ In a **sufficiently high granularity** calorimeter may only have a single particle crossing each calorimeter cell
  - **possibility of digital readout**
  - **i.e. count charged particles – insensitive to Landau fluctuations**



ECAL: Silicon-Tungsten (Analogue)





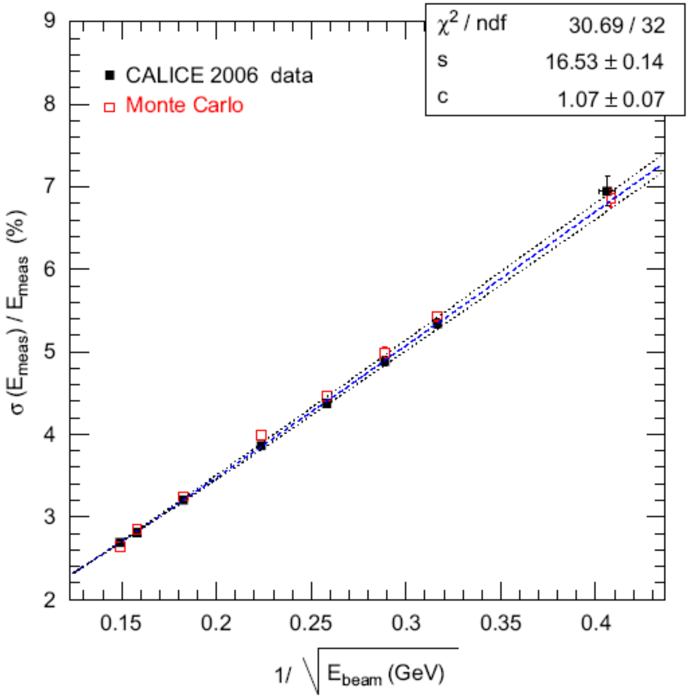
Absorber
- ♦30 layers W
- ♦Total 24 X_0

Active Material
- ♦High resistivity 525 μm Si
- ♦10×10 mm² segmentation

- ★ Operation demonstrated in test beam
- ★ Performance consistent with expectation

$$\frac{\sigma_E}{E} = \frac{16.5\,\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1\,\%$$

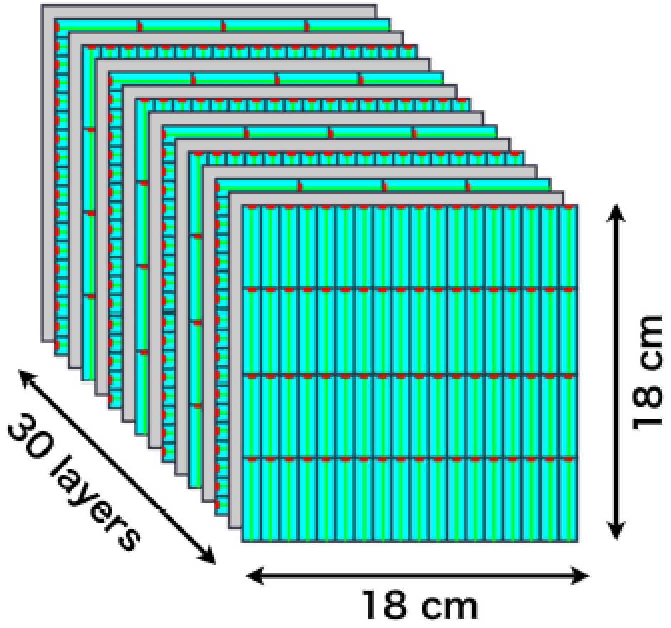
- ★ Remember, aim for granularity/PFlow rather than single particle energy resolution



Pros/Cons:

- ✓ Technology demonstrated
- ✗ Cost

ECAL: Scintillator-Tungsten



Active Material/Readout

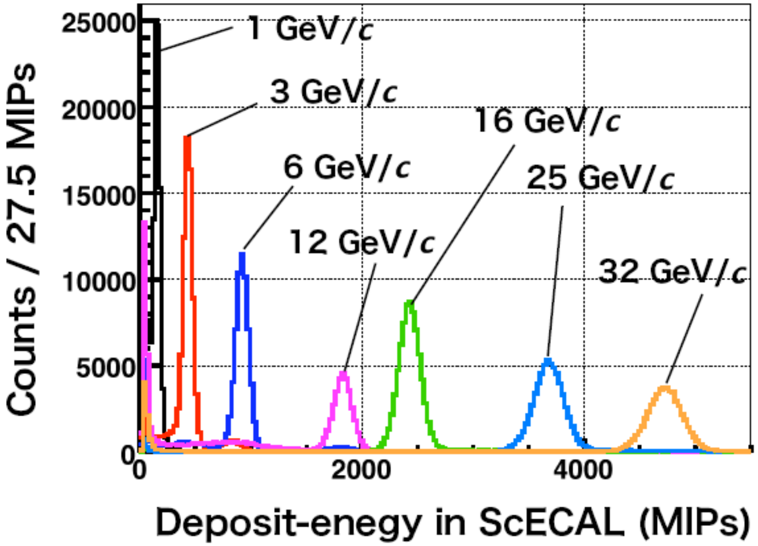
- Scintillator strips 1 cm x 4.5 cm
- Alternating “x” and “y” layers
- Read out via WLS fibres and multi-pixel photon counters (MPPCs) aka SiPMs

★ Operation demonstrated in test beam

★ Linear response

★ Energy resolution

$$\frac{\sigma_E}{E} = \frac{15\,\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1\,\%$$



Pros/Cons:

✓ Technology demonstrated (scintillator + WLS + SiPMs)

✗ Strips may cause problems for pattern recognition in PFlow

ECAL: Digital MAPS-Tungsten

★ Charged particle densities in EM showers very high – **100 particles mm^{-2}**

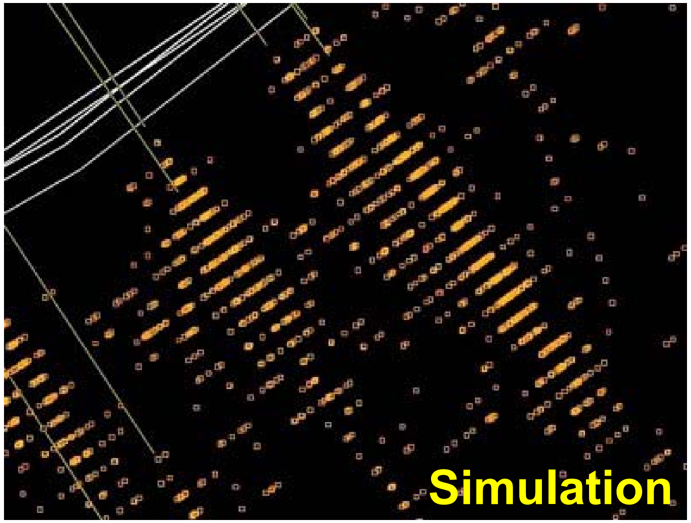
★ For digital calorimetry require **0** or **1** particles per pixel

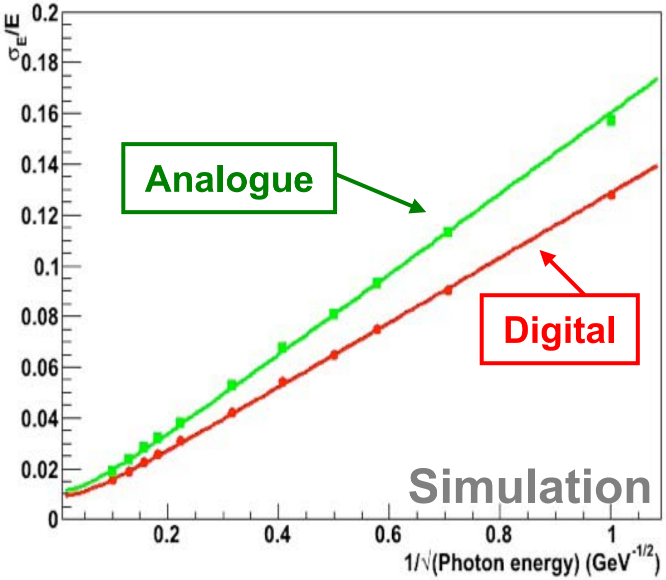
⇨ ~ **50×50 μm^2** pixel size **!**

★ The technology exists: **m**onolithic **a**ctive **p**ixel **s**ensors - **MAPS**

★ Standard **CMOS** product

★ Highly detailed images of EM showers





Pros/Cons:

✓ Some gain in resolution (Landau tails)

✓ Cost – potentially cheaper than high resistivity Si

✗ Novel: Very early stage of R&D – single sensor tests only

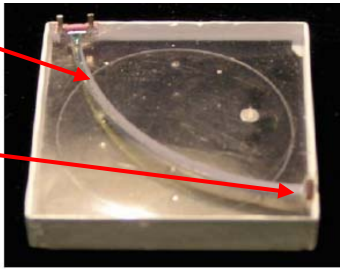
HCAL: Steel-Scintillator

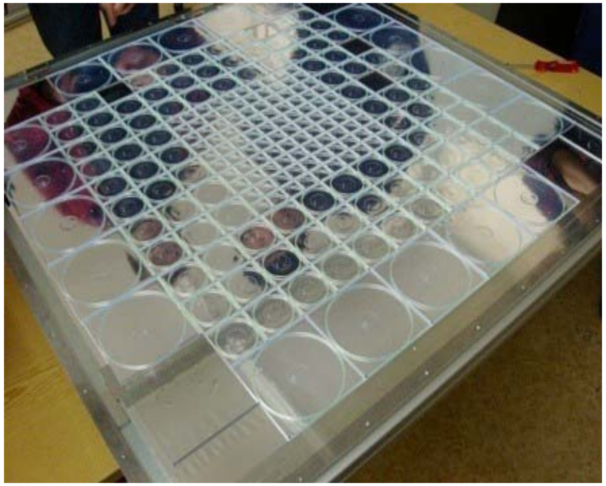
Absorber

- 38 layers 2cm steel
- Total 4.5 λ_I

Active Material/Readout

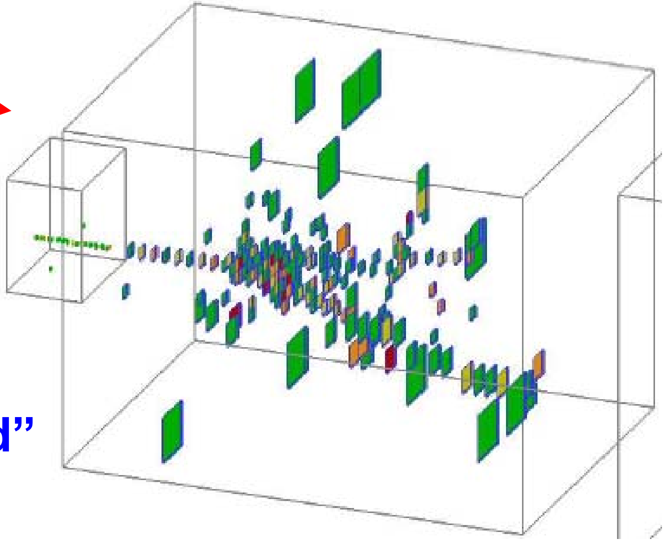
- Scintillator tiles 3×3 cm^2, 6×6 cm^2, …
- Light collection via WLS fibres
- Readout using Multi-pixel silicon Photomultipliers (SiPMs)





- ★ Operation demonstrated in test beam
  - high granularity imaging HCAL
- ★ Good hadronic resolution

$$\frac{\sigma_E}{E} = \frac{60\,\%}{\sqrt{E/\mathrm{GeV}}} \oplus 2.5\,\%$$



Pros/Cons:

- ✓ Technology demonstrated + fairly “standard”
- × Cost probably limits cell size to 3x3 cm^2

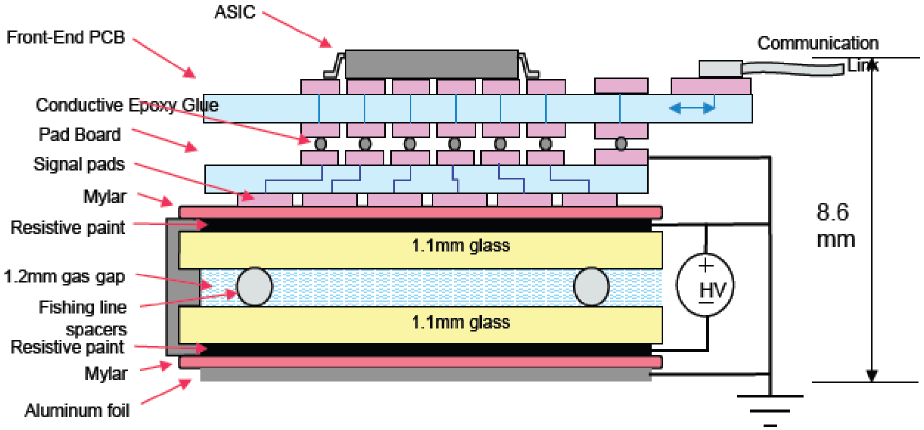
Digital HCAL: Steel-RPC

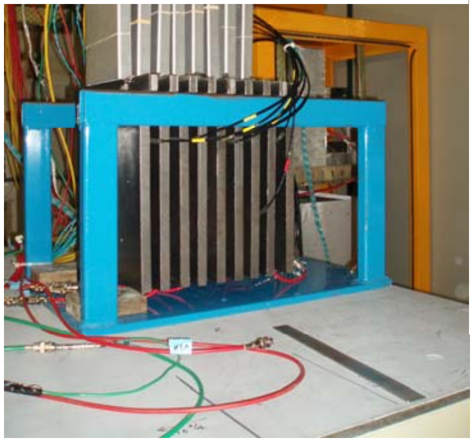
Active Material

- ♦ Resistive plate chambers (RPC)
- ♦ 1.2 mm gas gap

(Semi-) Digital Readout

- ♦ 1×1 cm² readout pads
- ♦ 1 bit readout
- ♦ semi-digital readout (3 bit) also being developed
- ♦ GEMs/MicroMegas being studied





- ★ Small prototype in Fermilab test beam
- ★ Response close to that expected from simulation
- ★ 1m³ physics prototype integrated into CALICE test-beam in **2010**

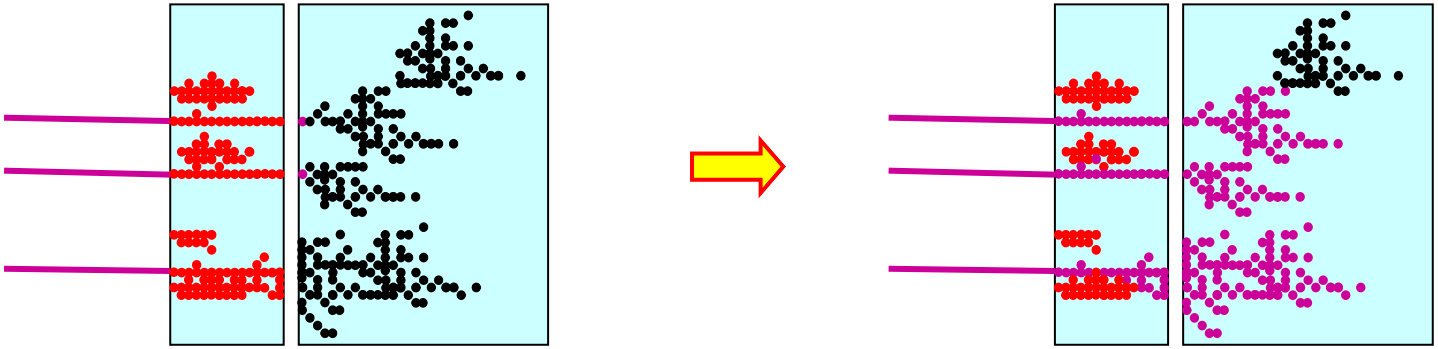
Pros/Cons:

- ✓ Small cell sizes achievable – “baseline” is 1×1 cm²
- ✓ Insensitivity to low energy neutrons
- ✗ Possible saturation effects in dense jets (semi-digital approach should help)
- ✗ Digital approach needs to be validated in test-beam

❺ Realising Particle Flow Calorimetry

- ★ CALICE studying a number of technological options for a high granularity ECAL/HCAL
- ★ No obvious show-stoppers…
- ★ Only makes sense in the context of Particle Flow Calorimetry
- ★ **Particle Flow Calorimetry = HARDWARE + SOFTWARE**

➡ Need sophisticated PFlow reconstruction software

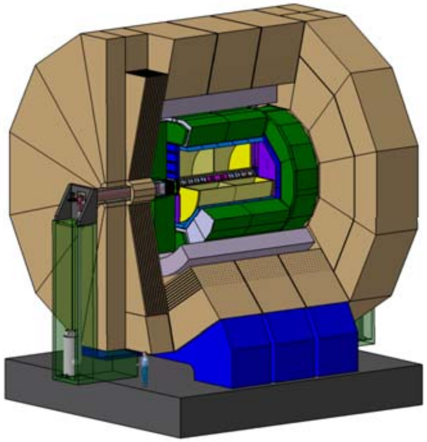


- ★ In addition, Particle Flow Calorimetry is more than just the **ECAL** and **HCAL**
- ★ It needs to be studied in the context of the whole detector
  - ♦ tracking is central to jet energy reconstruction
- ★ Need detailed GEANT 4 simulations of potential detector designs…

ILC Detector Concepts

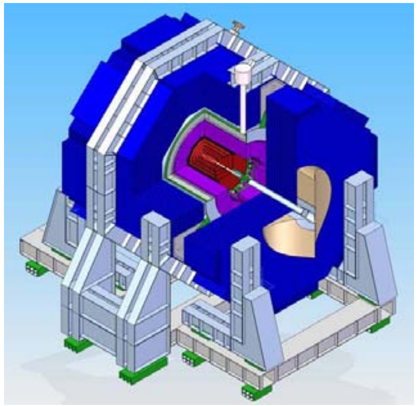
- ★ Particle Flow needs to be studied in the context of the **whole detector**
  - ♦ tracking is central to jet energy reconstruction
- ★ Need detailed GEANT 4 simulations of potential detector designs, e.g. the ILC detector concepts

ILD: International Large Detector



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

SiD: Silicon Detector



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

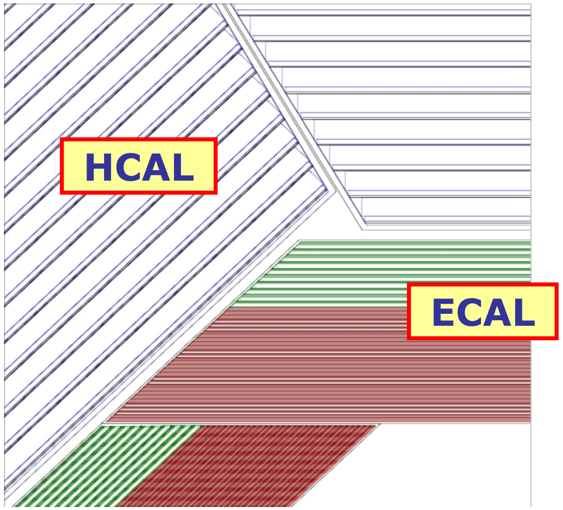
Calorimetry in the ILC Detector Concepts

- ★ **ILD** and **SiD** concepts designed for **particle flow calorimetry**, e.g. ILD*
- ★ The most detailed Particle Flow studies have been performed in the context of the ILD concept

- ★ **ILD calorimetry in simulation baseline:**

ECAL:

- SiW sampling calorimeter
- longitudinal segmentation: **30 layers**
- transverse segmentation: **5x5 mm^2** pixels

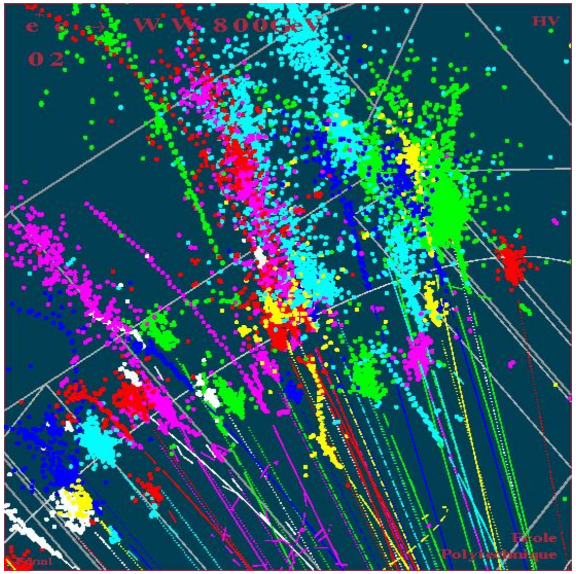


HCAL:

- Steel-Scintillator sampling calorimeter
- longitudinal segmentation: **48 layers** (6 interaction lengths)
- transverse segmentation: **3x3 cm^2** scintillator tiles

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 Algorithms (PFA)

- ★ Particle flow performance will depend on algorithm sophistication
- ★ To assess full potential of Particle Flow need a “realistic” algorithm
  - Full detector reconstruction (no use of Monte Carlo information) many years before project is approved !
- ★ Development of particle flow reconstruction algorithms is a hot topic in Linear Collider detector development
- ★ Most sophisticated and best performing Particle Flow Algorithm (PFA) is “**PandoraPFA**”

MT, NIM 611 (2009) 24-40

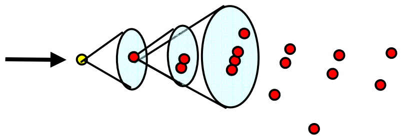
- ★ Used to demonstrate the potential of high granularity Particle Flow Calorimetry

❻ Particle Flow Reconstruction

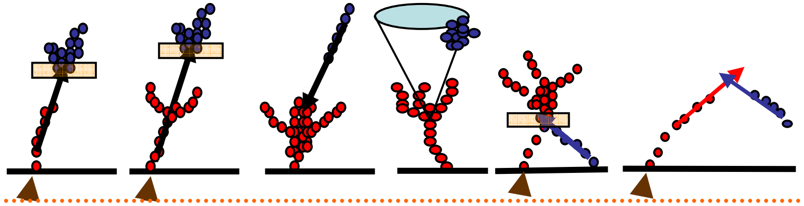
★ **Highly non-trivial - a new type of calorimeter system**

e.g. **PandoraPFA** consists of a number complex steps (not all shown)

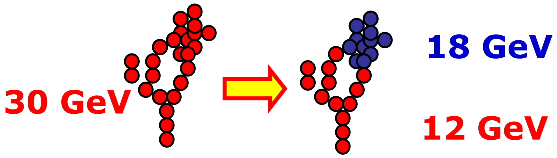
Clustering



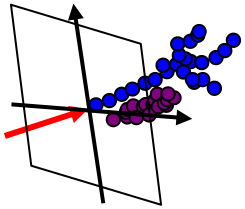
Topological Association



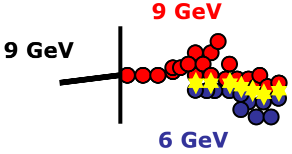
Iterative Reclustering

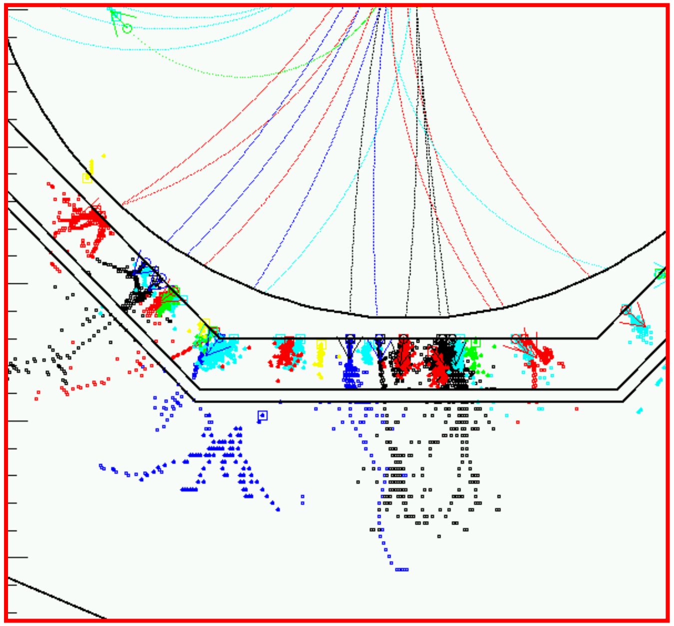


Photon ID



Fragment ID





PFA : Basic issues

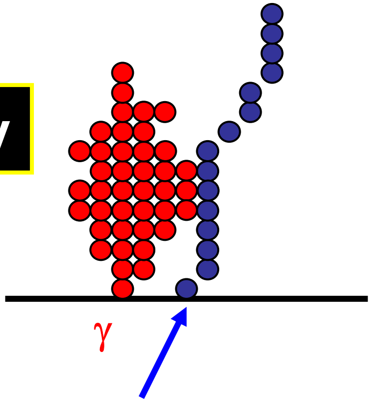
- Separate energy deposits from different particles
- Avoid double counting of energy from same particle
- Mistakes drive particle flow jet energy resolution

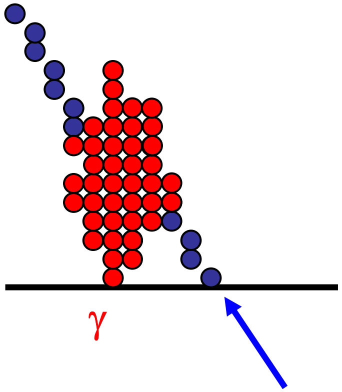
e.g.

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

hardware

granularity

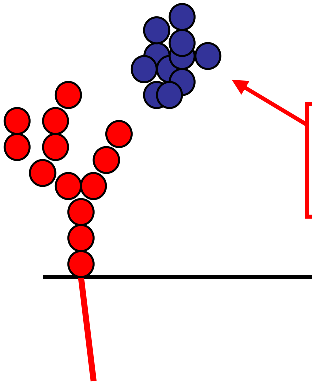




software

PFlow Algorithm

- Need to separate neutral hadrons from charged hadrons



Isolated neutral hadron or fragment from shower ?

PandoraPFA Overview

- ★ ECAL/HCAL reconstruction and PFA performed in a single algorithm
- ★ Applicable to multiple detector concepts
  - ♦ Used to study conceptual designs
- ★ Use tracking information to help ECAL/HCAL clustering

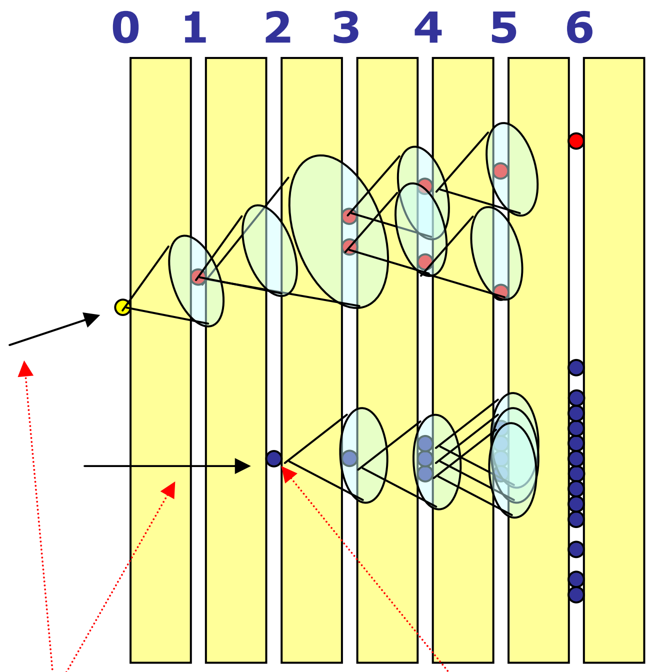
Eight Main Stages:

i. Track classification/extrapolation
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)

- ★ Here focus on main reconstruction concepts

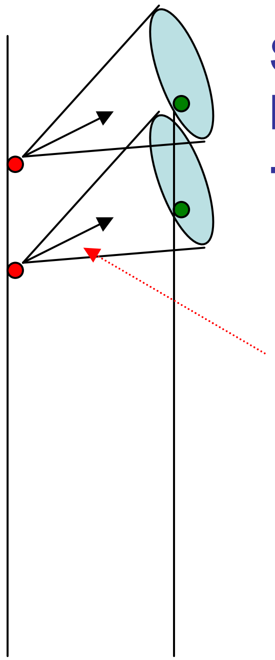
ii) ECAL/HCAL Clustering

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



Initial cluster direction

Unmatched hits seeds new cluster



Simple cone algorithm based on current direction + additional N pixels

Cones based on either:
initial PC direction or
current PC direction

Parameters:
- cone angle
- additional pixels

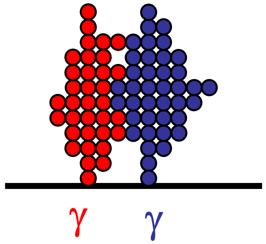
iii) Topological Cluster Association

- 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

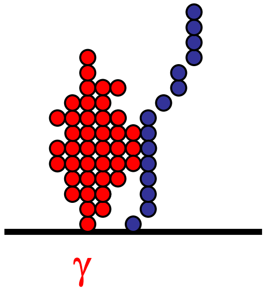
Photon ID

- 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

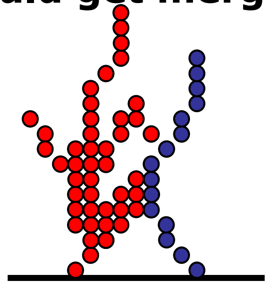
Won't merge



Won't merge



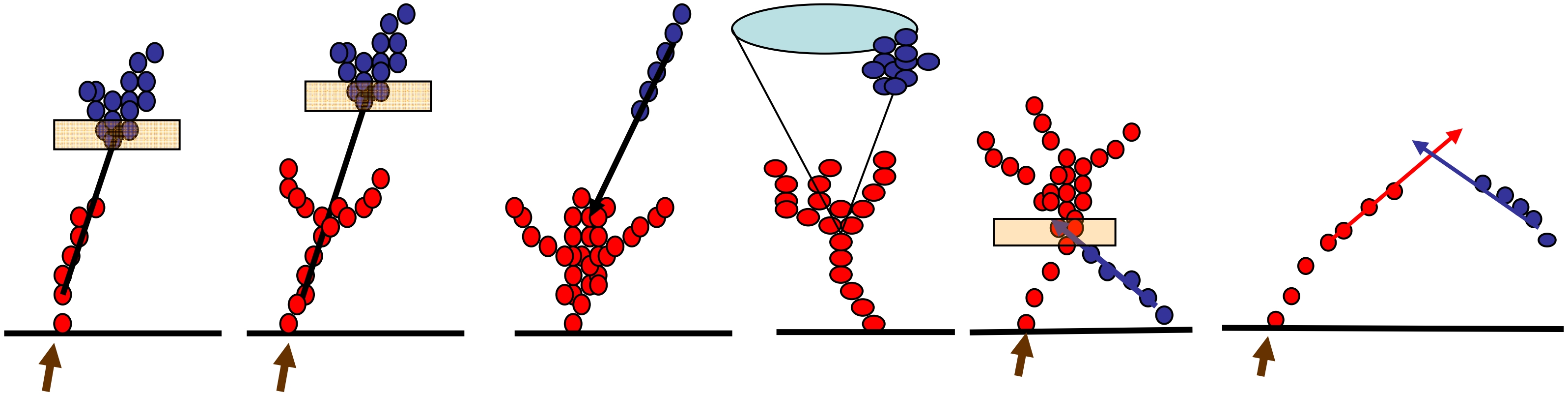
Could get merged



★ Clusters associated using a number of topological rules

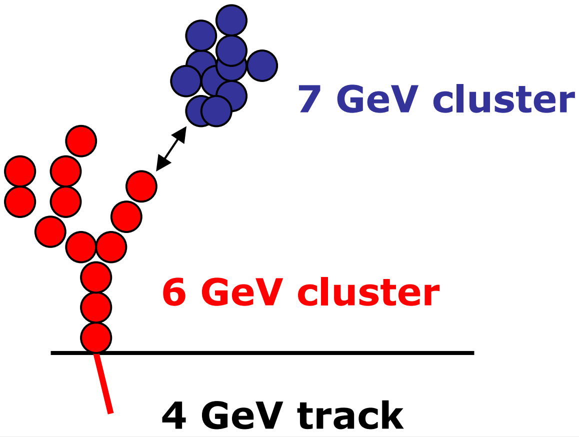
Clear Associations:

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



Less clear associations:

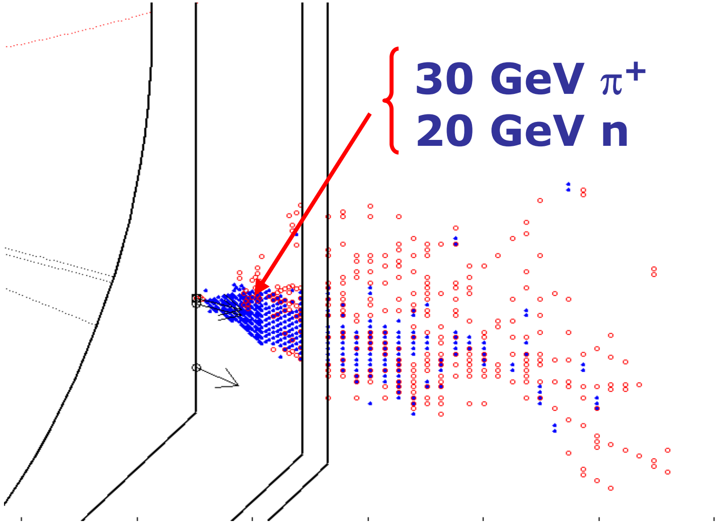
e.g. Proximity



Use E/p consistency to veto clear mistakes

v) Iterative Reclustering

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

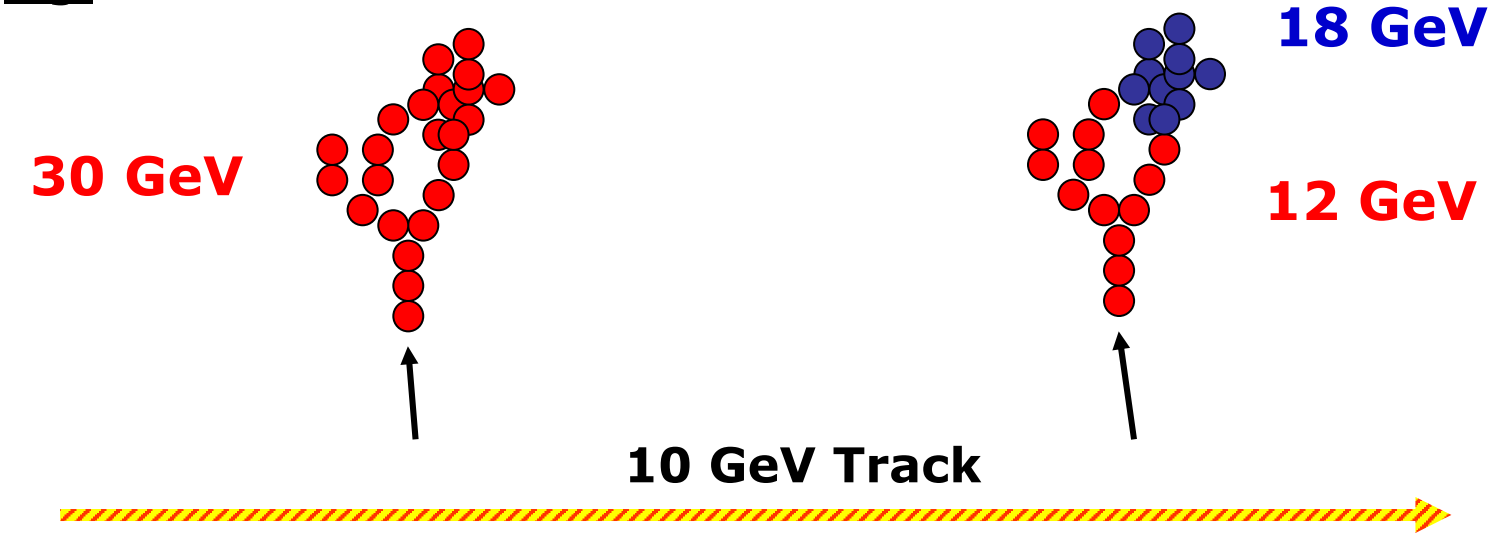


30 GeV π^+
20 GeV n

Address this "statistically" → e.g. if have 30 GeV track pointing to 50 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:

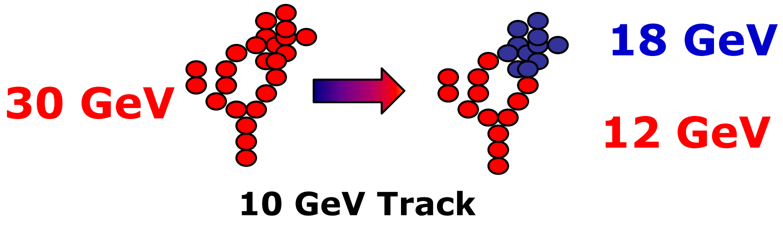
- clustering guided by track momentum
- more powerful than subtraction (Energy Flow)

This is very important for higher energy jets

Iterative Reclustering Strategies

① Cluster splitting

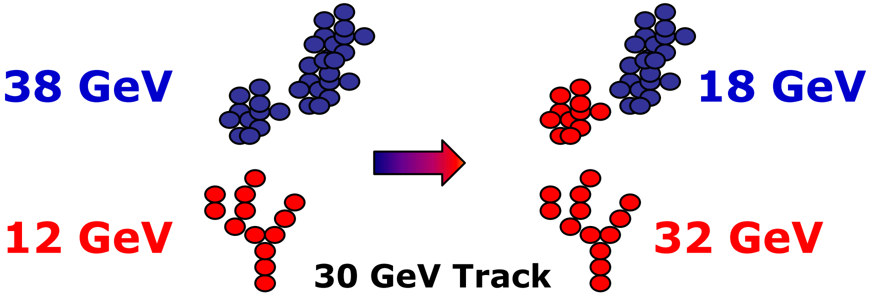
Reapply entire clustering algorithm to hits in “dubious” cluster. Iteratively reduce cone angle until cluster splits to give acceptable energy match to track



★ + plug in alternative clustering algorithms

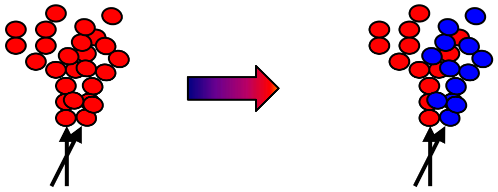
② Cluster merging with splitting

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

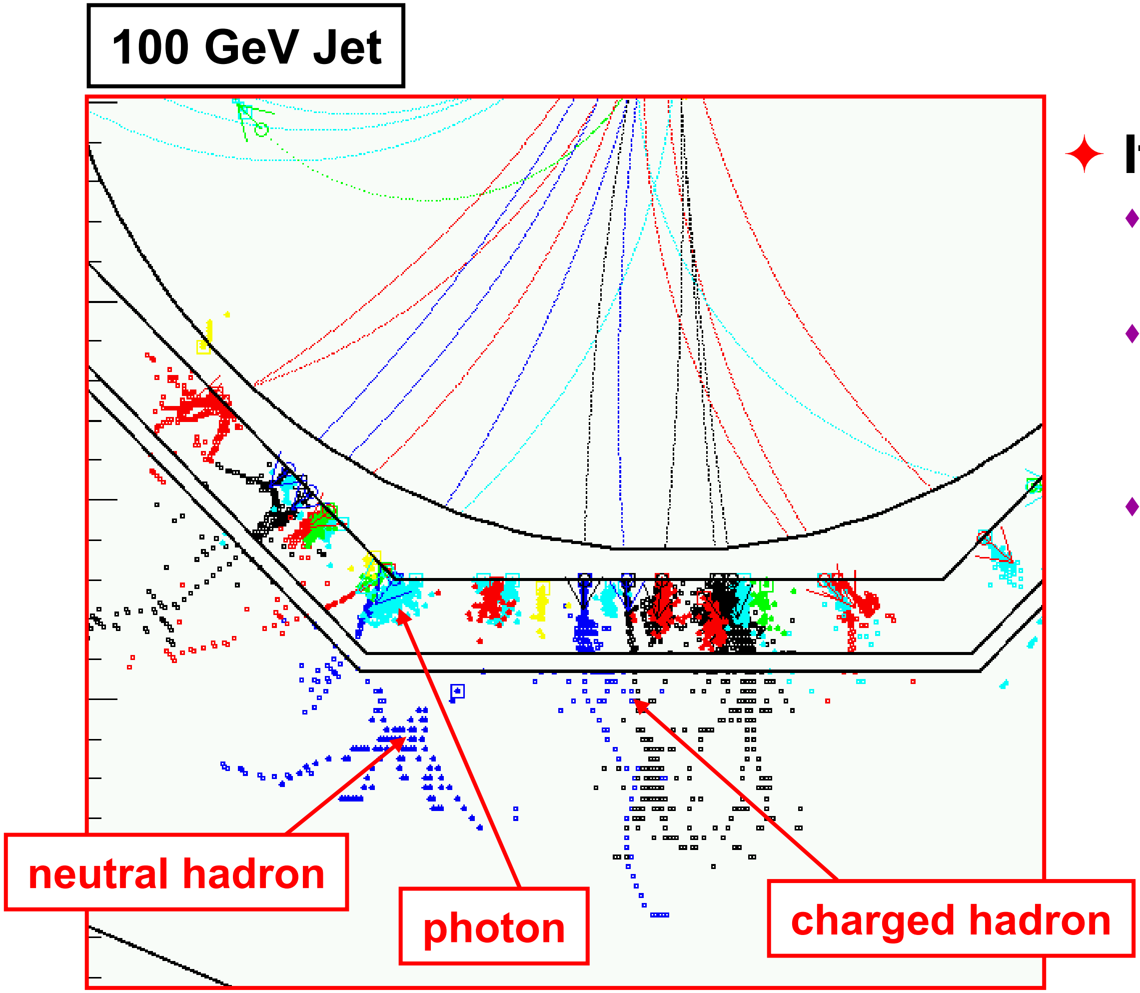


③ Track association ambiguities

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



Putting it all together…



- **If it all works…**
  - **Reconstruct the individual particles in the event.**
  - **Calorimeter energy resolution not critical: most energy in form of tracks.**
  - **Level of mistakes in associating hits with particles, dominates jet energy resolution.**

★ **Can now start to understand performance of a Particle Flow detector…**

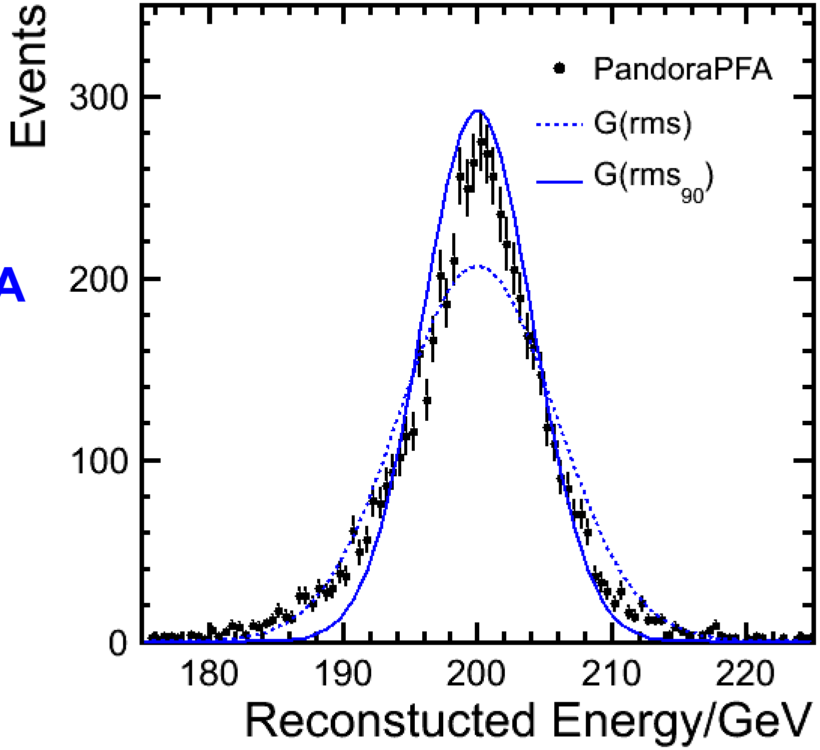
❼ Particle Flow Performance

- ★ Particle Flow Reconstruction is inherently non-Gaussian
- ★ PFA resolution presented in terms of **rms_{90}**
  - defined as **"rms in smallest region containing 90 % of events"**
  - introduced to reduce sensitivity to tails in a well defined manner
- ★ How to interpret **rms_{90}** ? With care…
  - how to compare 4 GeV PFA rms90 with 5 GeV Gaussian resolution ?
- ★ For a true Gaussian distribution
  - **$\mathrm{rms}_{90} = 0.79\,\sigma$**
- ★ Highly misleading…
  - distributions almost always have tails: Gaussian usually = fit to some region
  - **rms_{90}** larger than central peak from PFA
  - e.g. for 200 GeV di-jets (from rest):

rms(E) = 5.8 GeV
rms_{90}(E) = 4.1 GeV
fit to 196-205 GeV : 3.8 GeV

- ★ MC studies to determine equivalent statistical power show

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



Jet Energy Resolution

★ Motivation for high granularity Particle Flow Calorimetry was the desire for a jet energy resolution: $\boxed{\sigma_E/E < 3.5\%}$

★ Can particle flow deliver ?

- Simplest metric, jet energy resolution in $Z \to q\bar{q}, \quad q = u, d, s$ decays at rest (i.e. two back to back jets)

★ With PandoraPFA and ILD simulation obtain:

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	29.2 %	2.9 %
180 GeV	40.3 %	3.0 %
250 GeV	49.3 %	3.1 %

× 3 better than best at LEP

× 2 better than conventional approach

★ For ILC energies*, PFlow Calorimetry has potential to deliver unprecedented jet energy resolution !

★ I believe that the principle of high granularity Particle Flow Calorimetry has been demonstrated; it can deliver at ILC energies*

*Will discuss CLIC energies in next lecture

❽ Summary

Summary of today's lecture

- ★ The next linear collider will place unprecedented demands on calorimetry; jet energy requirements are more than a factor two-three better than achieved at LEP
- ★ Requires a new approach
- ★ High granularity Particle Flow Calorimetry is the most favoured approach
- ★ It is technologically reasonable – actively studied by CALICE
  - ▪ a number of technology options
- ★ For particle flow calorimetry, performance = hardware + software
- ★ Now have sophisticated (realistic?) reconstruction tools…
- ★ MC proof of principle that Particle Flow Calorimetry can deliver required performance

In tomorrow's lecture I will discuss:

- ♦ alternatives to Particle Flow
- ♦ understanding particle flow in more depth
- ♦ the issues related to building a Particle Flow detector and limitations
- ♦ Particle Flow performance at higher energies
- ♦ the overall design issues for a linear collider detector where calorimetry
- ♦ the status of the detector concept performance studies