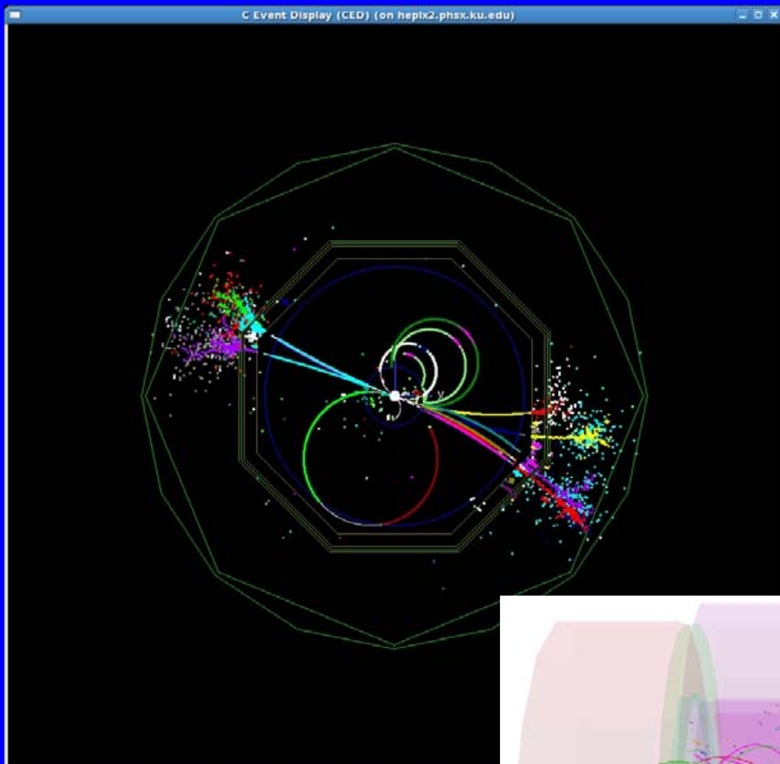
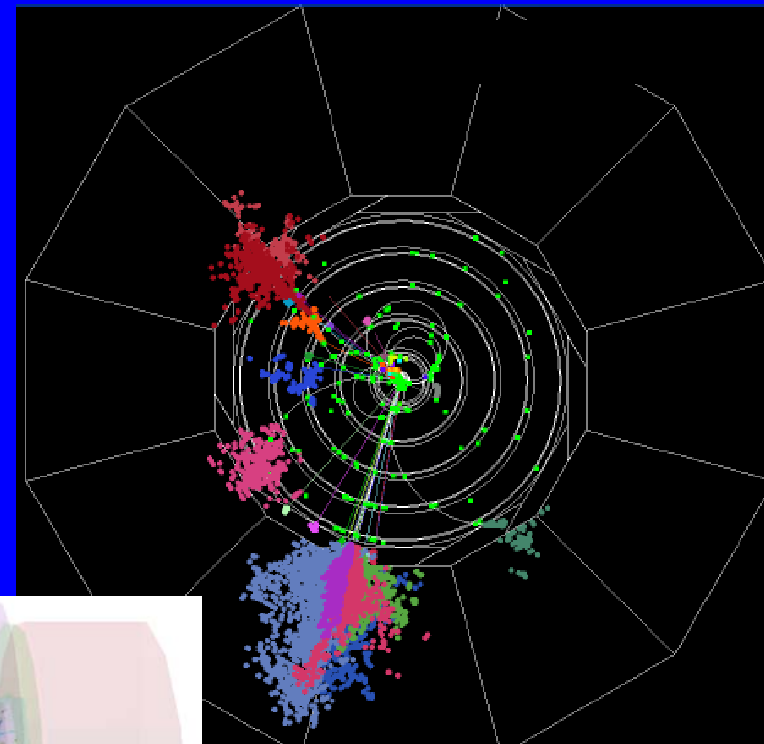
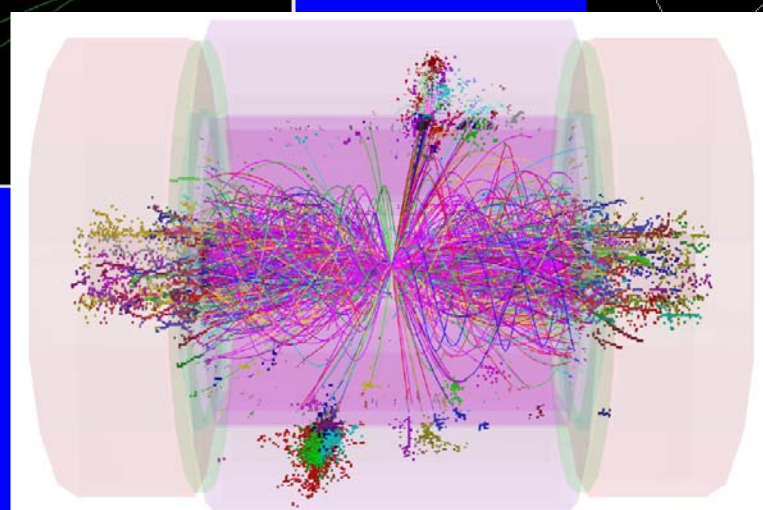
Particle Flow Calorimetry for Linear Collider Detectors







Graham W. Wilson, University of Kansas,
ALCPG11, Eugene, March 23rd 2011

Disclaimer

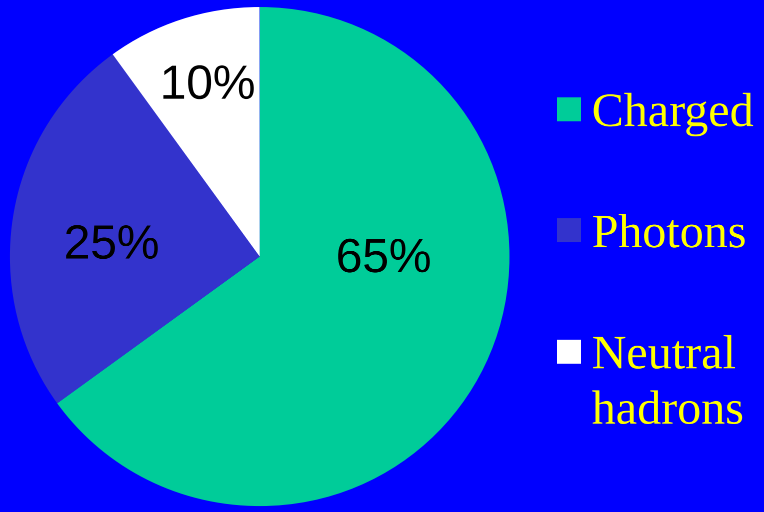
- This is not a summary talk.
- Many related issues have already been discussed in the Detector R&D, ILD, SiD, CLIC detector plenary talks and parallel sessions on calorimetry, simulation&reconstruction, tracking.

Particle-Flow in a Nut-Shell

E(jet) = E(charged) + E(photons) + E(neutral hadrons)

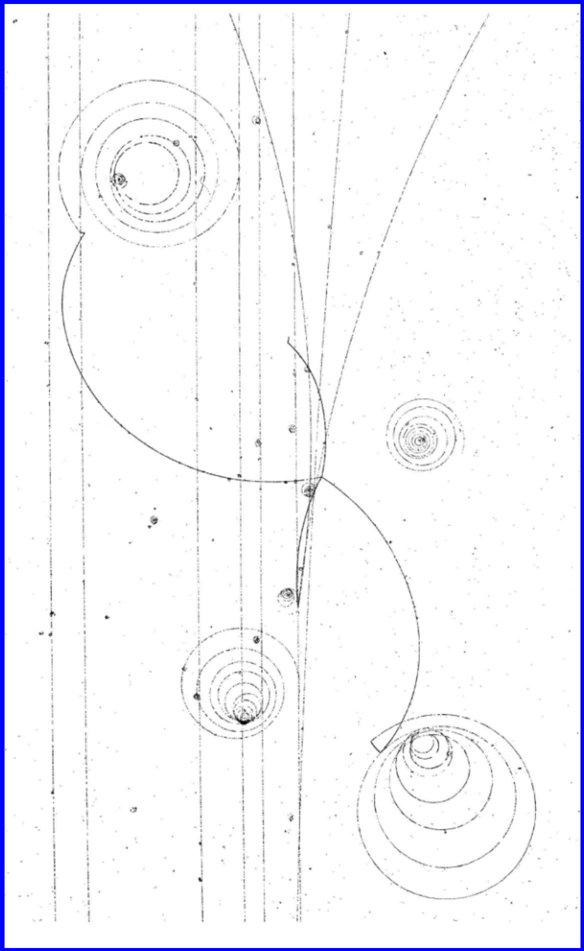
- Basics
  - Outsource **65%** of the event-energy measurement responsibility from the calorimeter to the tracker
    - Emphasize particle separability and tracking
    - Leading to better jet energy precision
  - Reduce importance of hadronic leakage
    - Now only 10% instead of 75% of the average jet energy is susceptible
    - Detector designs suited to wide energy range
  - Maximize event information
    - Aim for full reconstruction of each particle including V0s, kinks, π^0 etc.
    - Facilitates software compensation and application of multi-variate techniques

Particle AVERAGEs

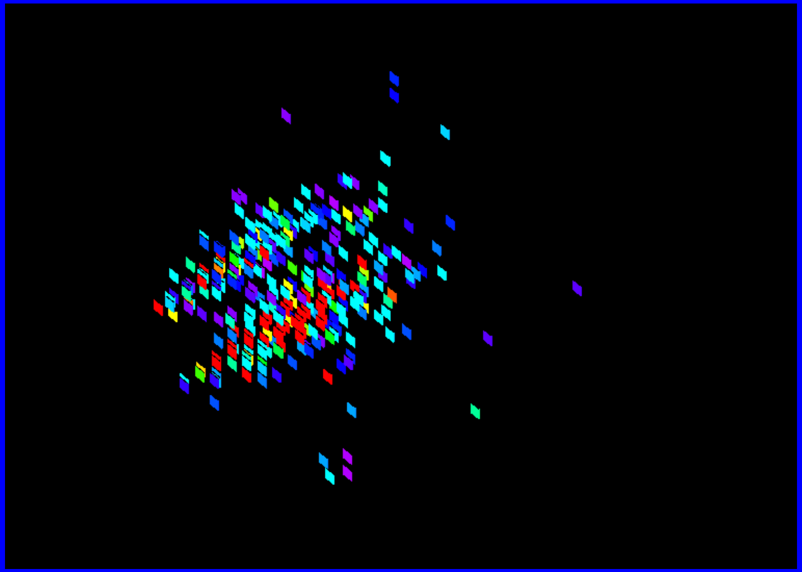


Bubble Chamber

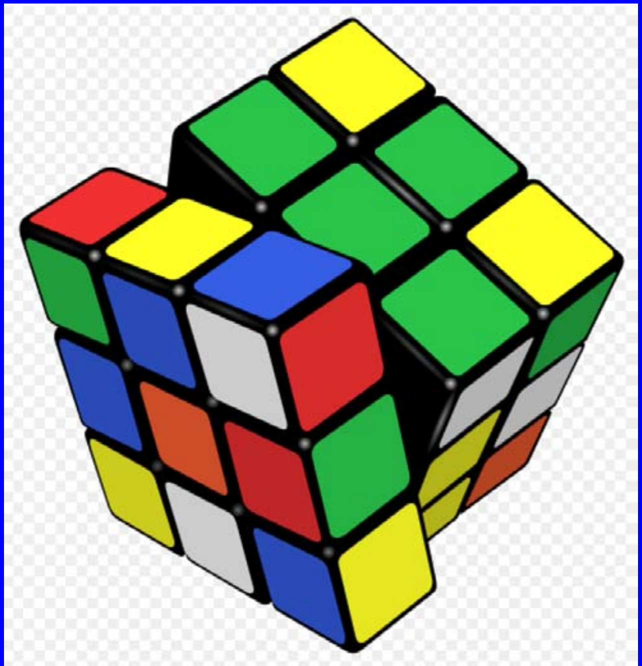
- The vision is to do the best possible physics at the linear collider, by reconstructing as far as possible every single piece of each event.
- Very much in the spirit of bubble chamber reconstruction – but with full efficiency for photons and neutral hadrons, and in a high multiplicity environment at high luminosity.



Imaging Calorimeters



- Standard cell-sizes under discussion
- ECAL : 5mm X 5mm X 30 layers
  - 10,000 more channels than OPAL
- HCAL : 10 mm X 10 mm X 50 layers
- Immense amount of information.
- Potentially (E, time) for each volume pixel.



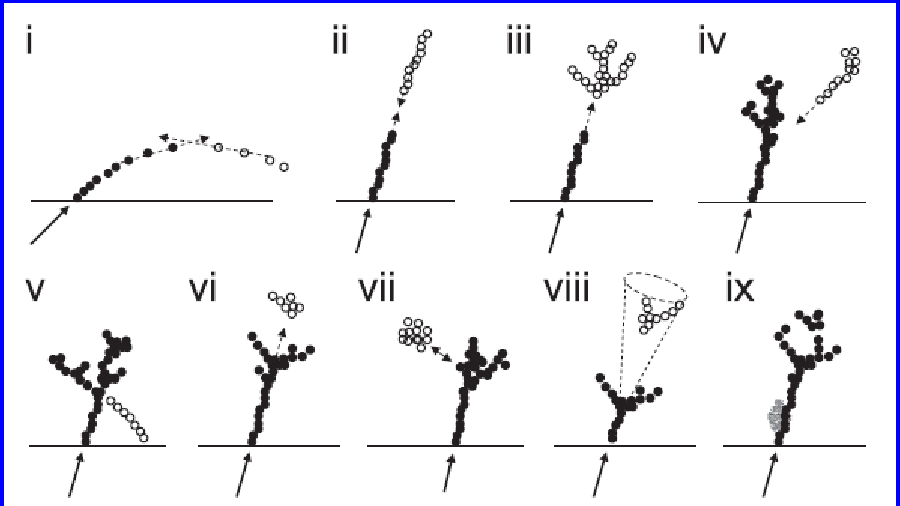
Particle Flow Detector Recipe

- Sufficient calorimetry inside solenoid
- Large radius calorimeter
- Robust track reconstruction
- High granularity calorimeters for particle separation
- Hermetic design
- Integrated detector concept – minimize material
- High B-field - helps separate charged particles
- Good resolution and linear response for neutral hadrons (leading intrinsic resolution component)

Particle Flow Algorithms

- Highly non-trivial.
  - Many groups have worked in this area
  - To date, PandoraPFA developed primarily by M. Thomson for ILD and using the Mokka/Marlin framework and now rewritten by J. Marshall has set the performance bar.
  - At this meeting progress was reported on UIPFA applied to SiD (R. Zaidan, R. Cassell) and PandoraPFANew applied to SiD and CLIC_SiD (N. Graf)

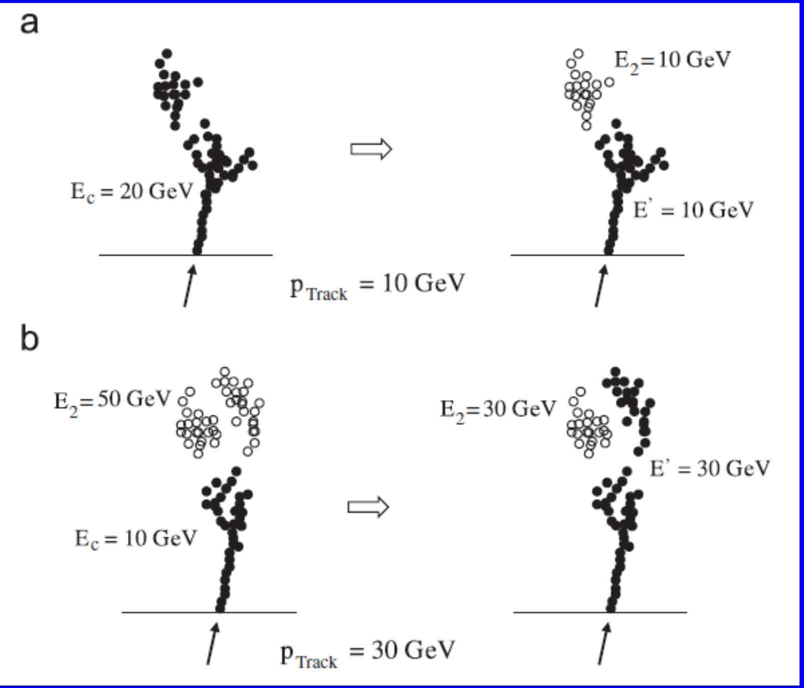
Depends at basic level on calorimeter clustering.



Topological clustering

M. Thomson, NIM A611 (2009) 25.

Reclustering



Use track-momentum – cluster-energy consistency to drive re-partitioning of energy.

Current state-of-the-art performance

M. Thomson

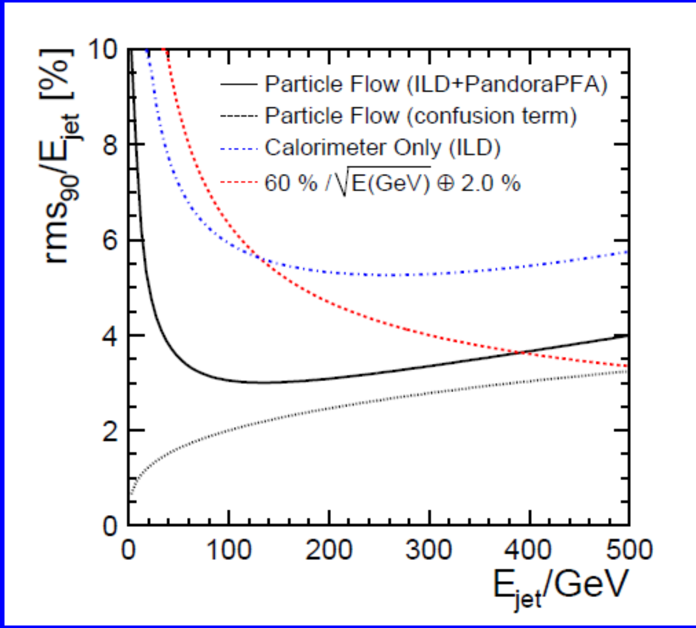
ILD00

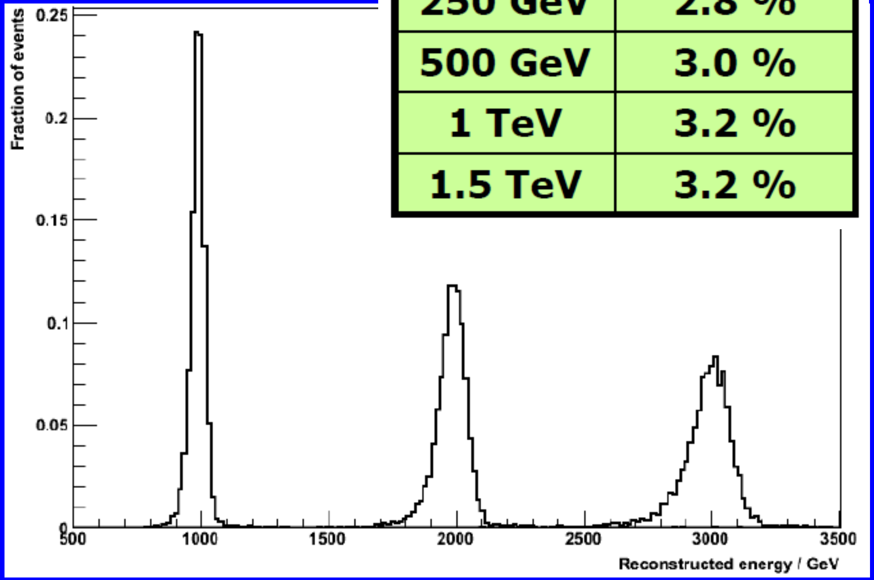
E_{JET}	RMS_{90}/E_J
45 GeV	3.6 %
100 GeV	3.1 %
180 GeV	3.0 %
250 GeV	3.3 %

Adjusted ILD detector for high energies – retains good PFA performance in terms of energy measurement at much higher energy.

CLIC_ILD no overlay

E_{JET}	RMS_{90}/E_J
45 GeV	3.6 %
100 GeV	2.9 %
250 GeV	2.8 %
500 GeV	3.0 %
1 TeV	3.2 %
1.5 TeV	3.2 %



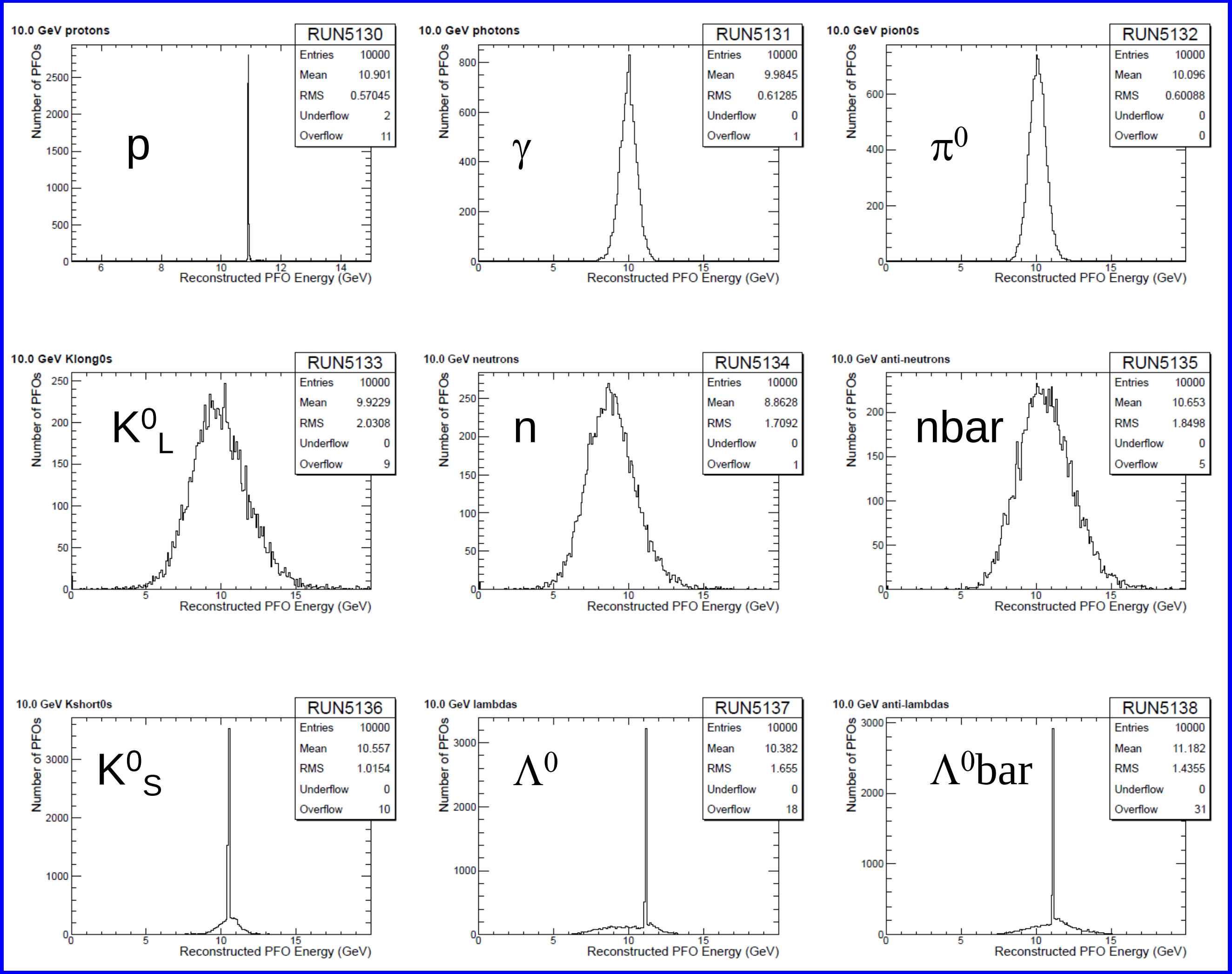


Single Particle Response

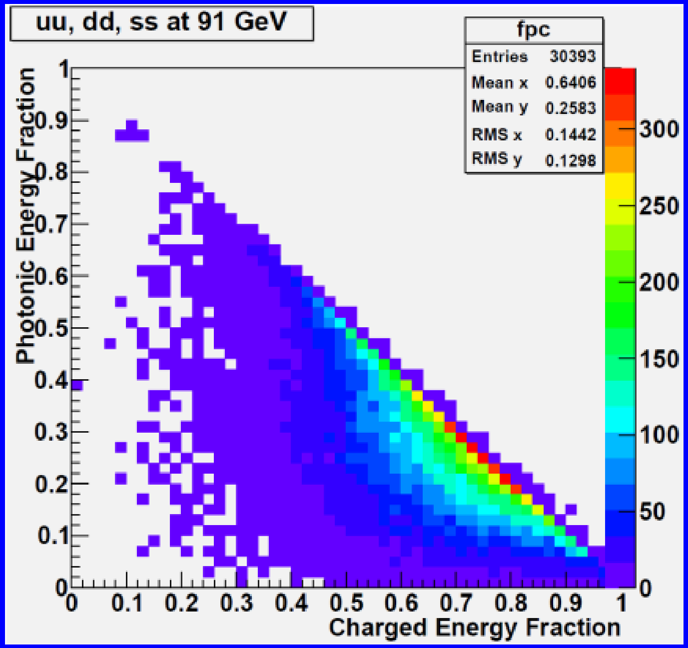
M. Carrasco

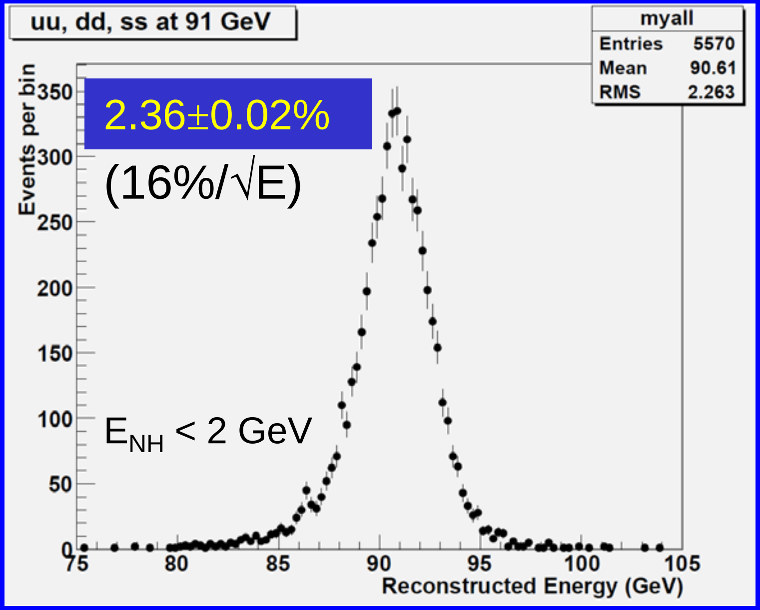
10 GeV kinetic energy particles in barrel region using ILD and PandoraPFANew

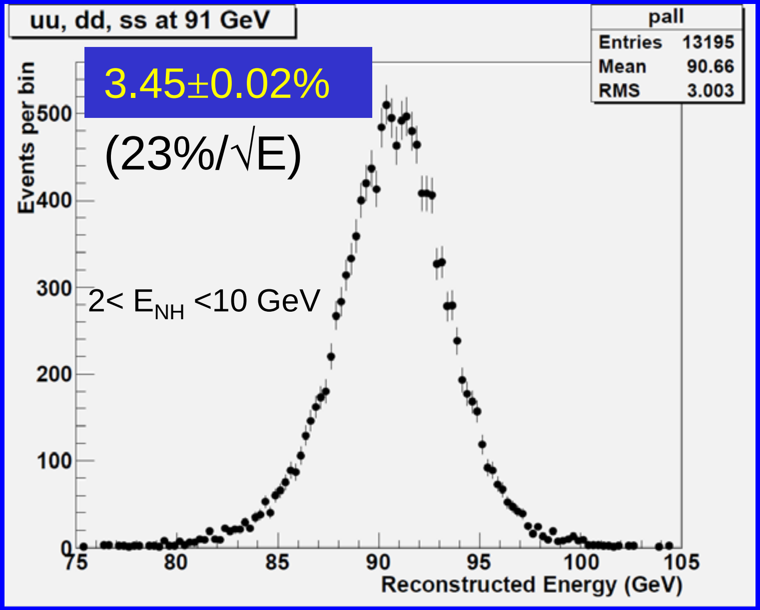
IF everything is reconstructed OK, neutral hadrons typically dominate the intrinsic resolution, followed by photons.

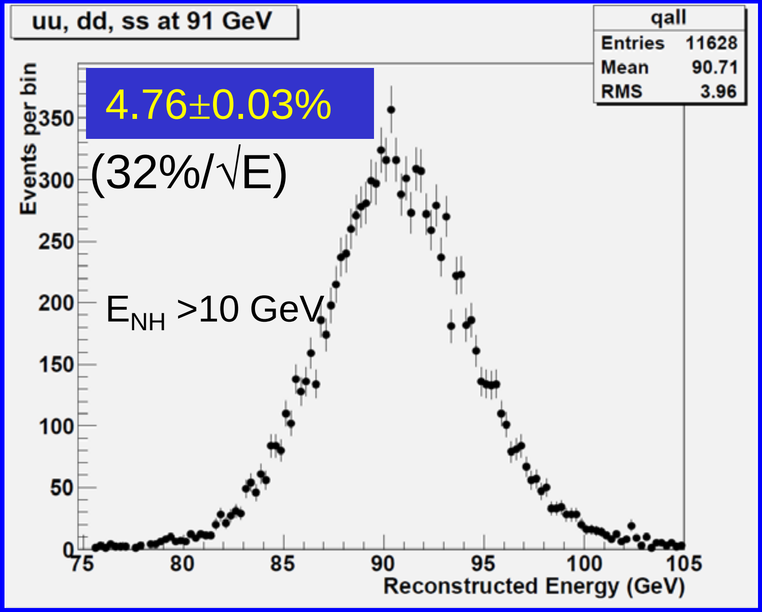


Event-Specific Resolution

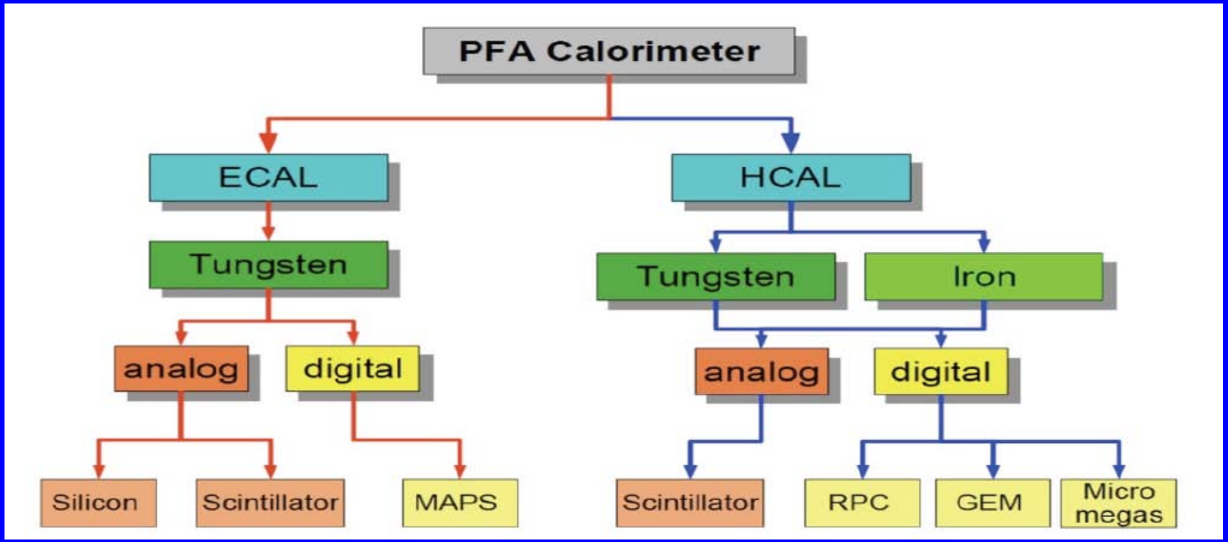








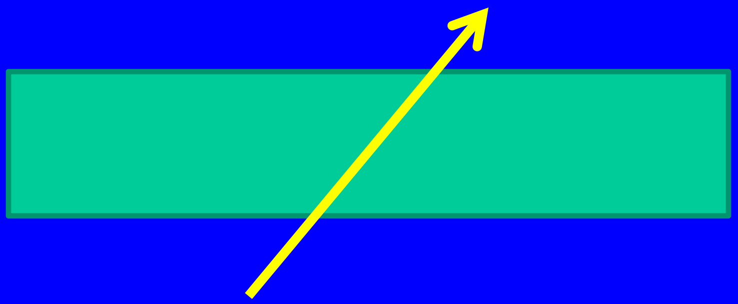
Calorimeter Technology Tree



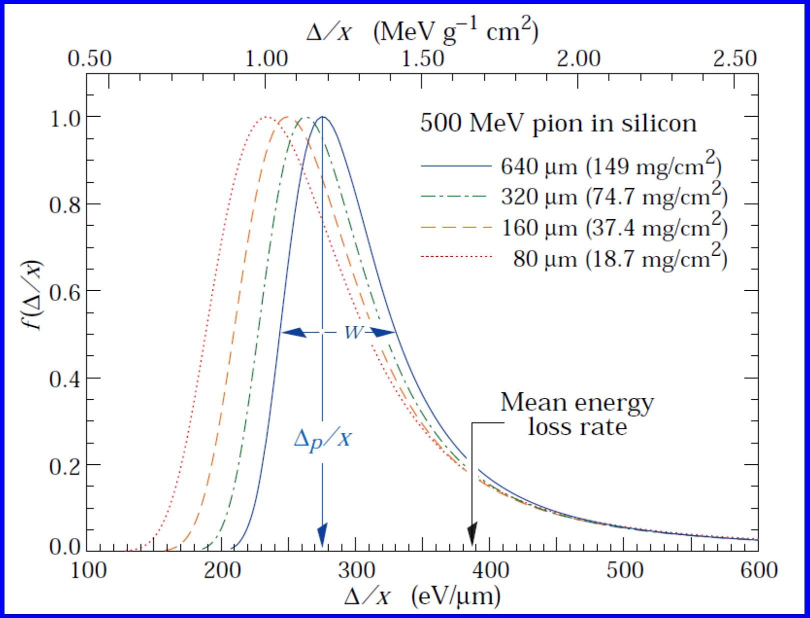
- Several options under study
- Defined by absorber material, active medium, sensor, granularity, readout mode.
- What is refreshing, is that the established rules of calorimetry are being re-written !

Why Digital ?

- Energy-loss fluctuations and angle-of-incidence effects lead to broadening of the analog response of sampling calorimeters.
- In the low energy or ultra-high granularity regime, hit counting can lead to better resolution.
  - Digital ECAL possibility
  - Digital HCAL studies

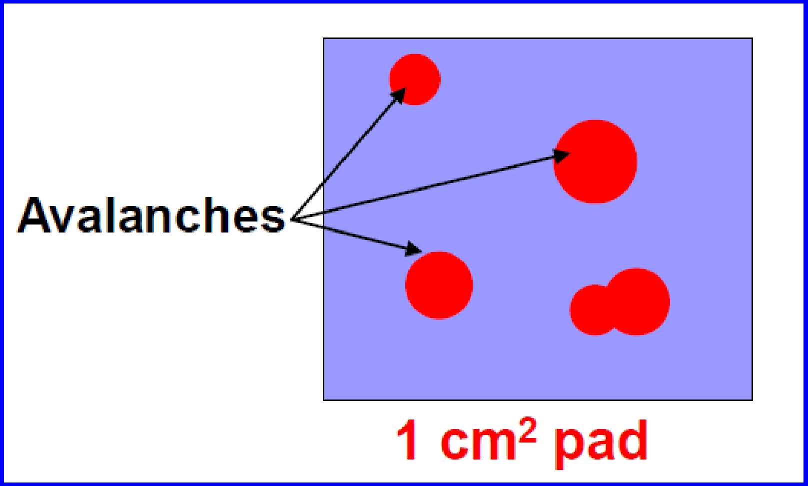


PDG



Why Analog ?

- Pure digital approach does not detect multiple particles incident on a single sensitive volume.
- Problem is acute for the core of electro-magnetic showers and becomes more important at high energy.
  - Can be mitigated somewhat with 2-bit readout (semi-digital)
  - Or by going to smaller cell size.



Electromagnetic Calorimetry

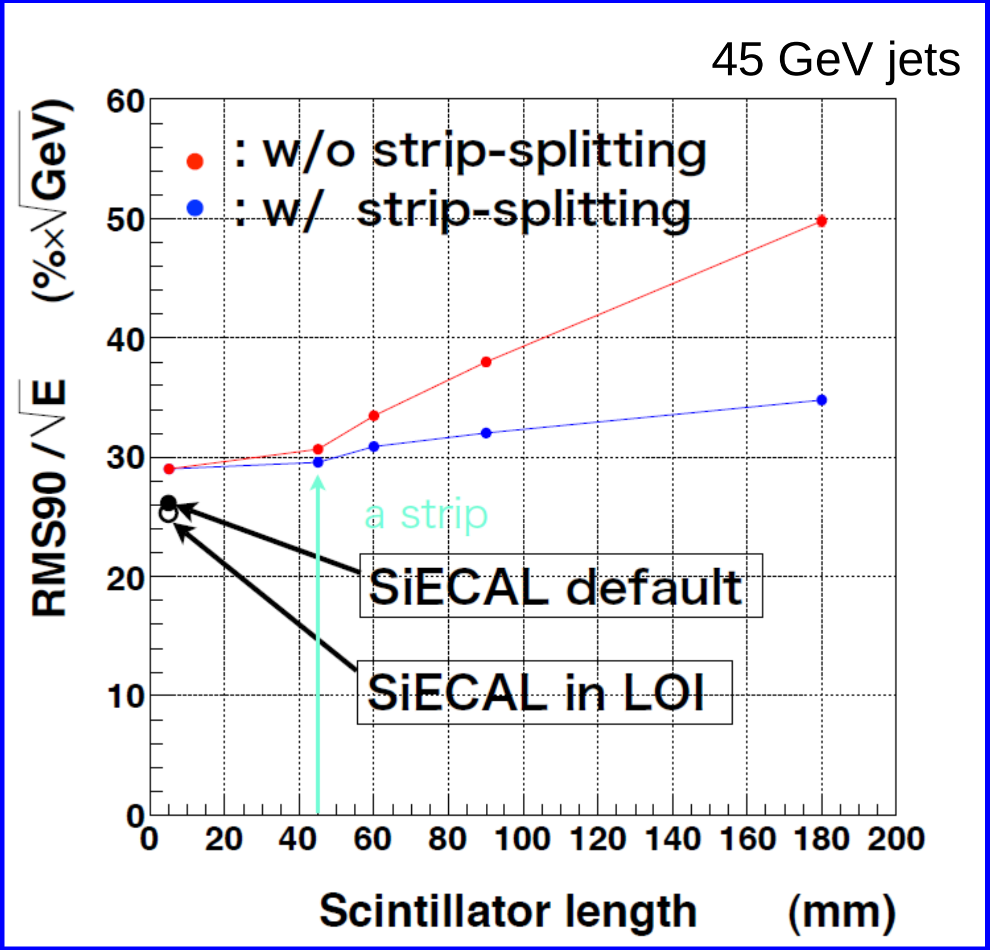
- Basic physics of EM showers well understood – but envisaged technologies have unprecedented granularity.
- Challenges – cost, low energy photons, taus, π^0s
- Two main approaches
  - Si-W.
  - Scintillator-W.
  - Or mix of the two.
- Geometry in principle open.
  - Current R&D focus in ECAL context is on Si-pads and scintillator strips.

Scintillator-strip ECAL

K. Kotera & T. Takeshita

Starts to be competitive with Si-W ECAL in overall jet energy resolution performance using PandoraPFA – tuning just started.

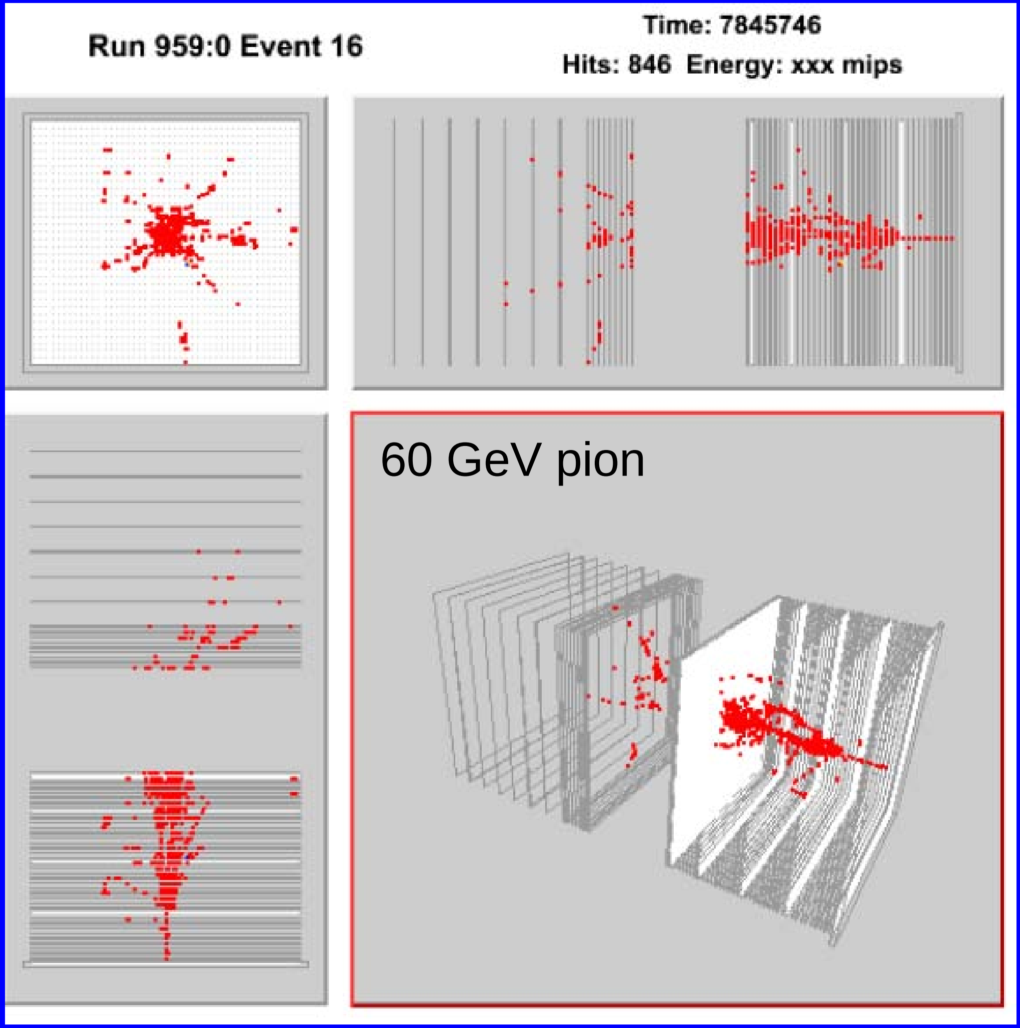
Encouragingly small dependence on strip length.

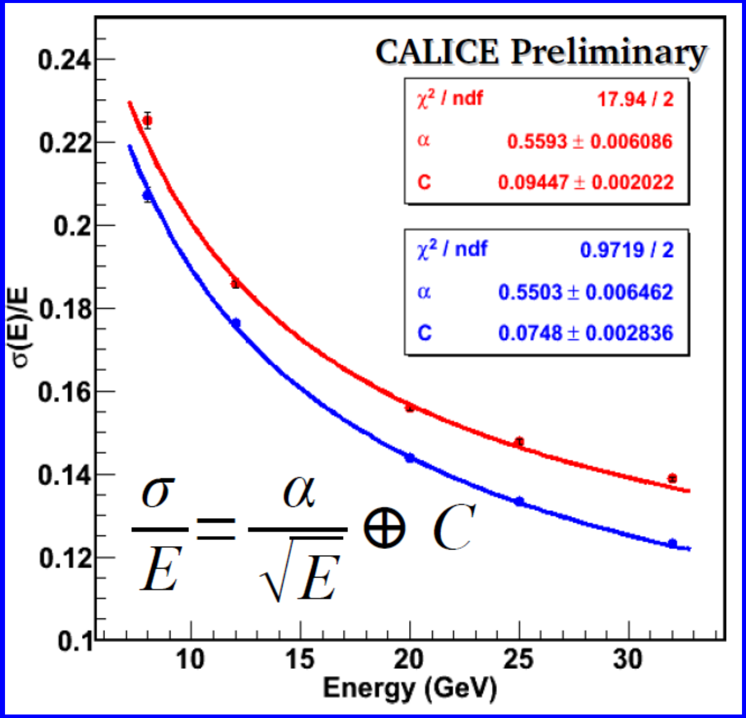


Digital HCAL

Impressive progress with DHCAL.
Data from Fermilab test-beam.

B. Bilki



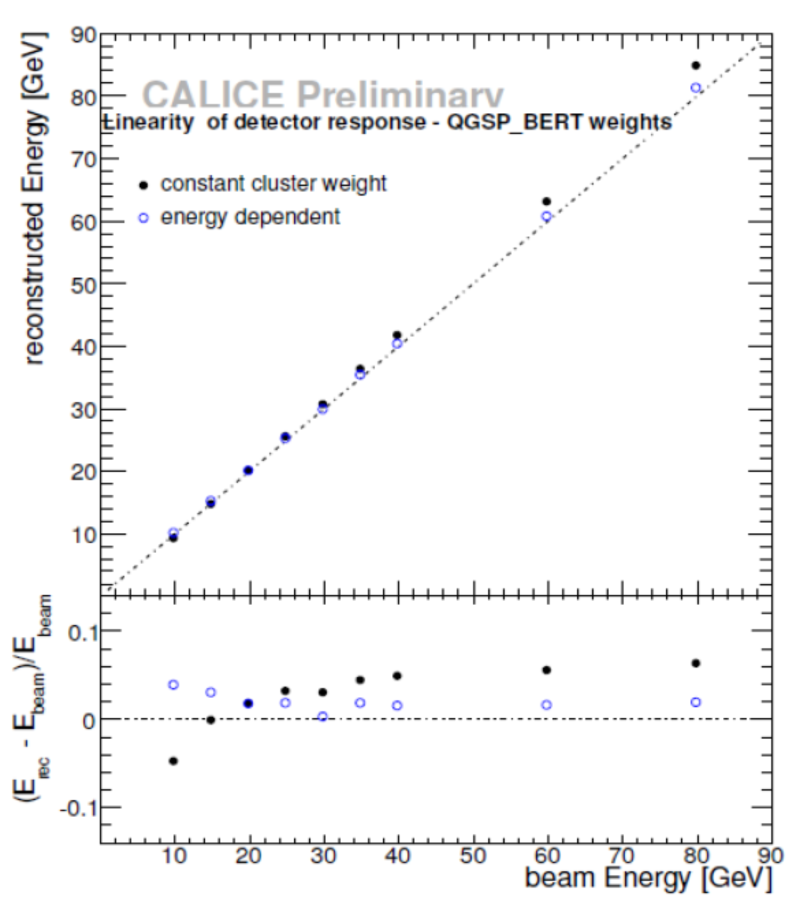


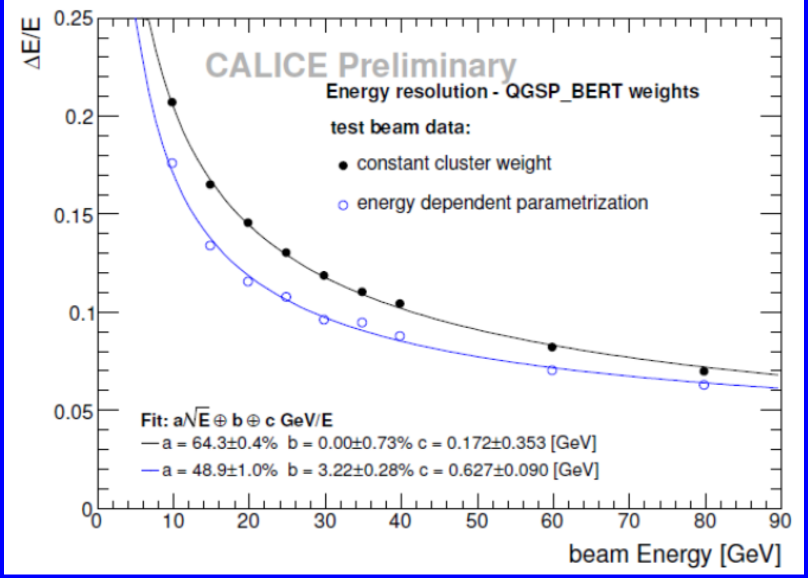
Early days. Expect further improvement.
Likely need to leverage the imaging capabilities for software compensation.

Analog HCAL

Several techniques under study for software compensation.
EM fraction of hadronic showers increases with energy – exacerbating inequalities in the electron/pion response.

M. Terwort

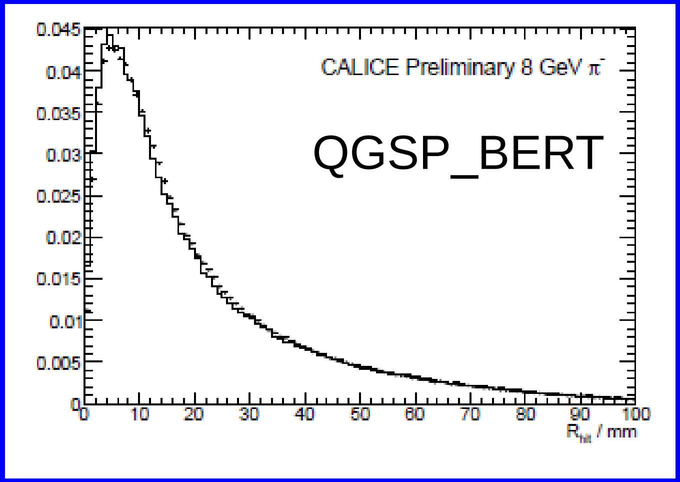


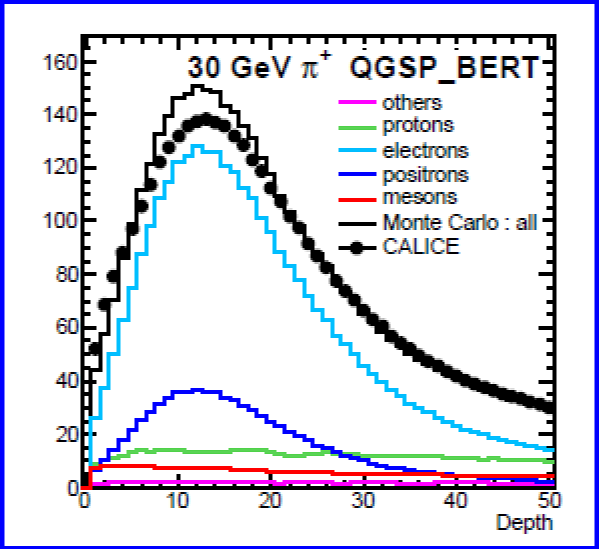


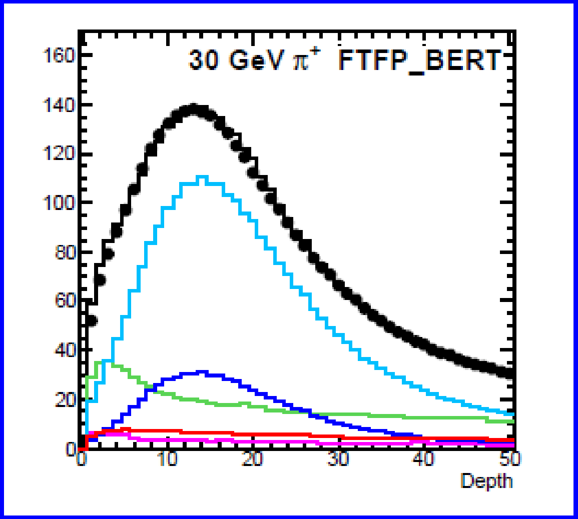
The claim is that the e/π ratio being close to 1 is no longer a strong constraint.
But frankly – if it doesn't compromise the design – why not go in the direction of e/π ≈1.

Particle Separability I

- Electro-magnetic and hadronic shower radial and longitudinal profiles are well known – and give high confidence that particle-flow calorimetry is conceptually sound.
- Nevertheless, recent measurements with pions in the CALICE Si-W ECAL help constrain further the various hadronic shower models in GEANT4.

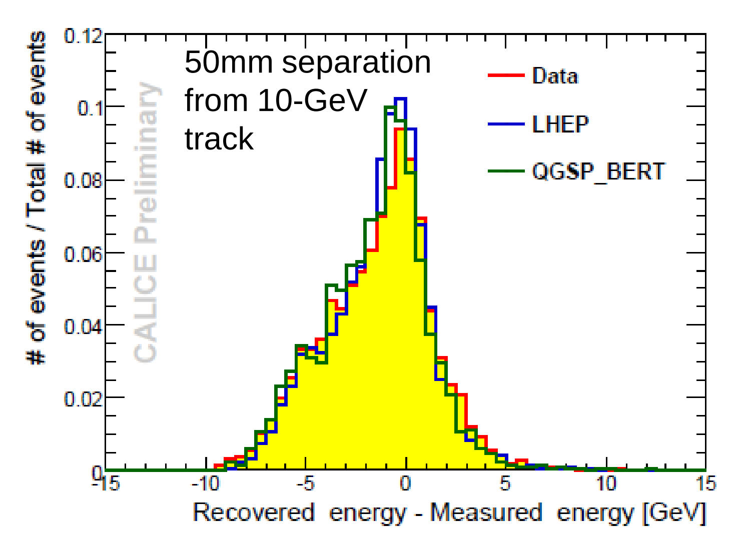


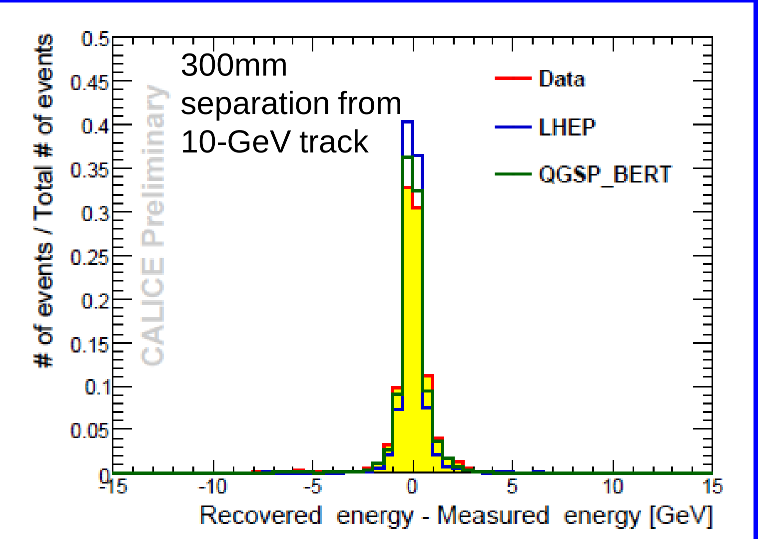


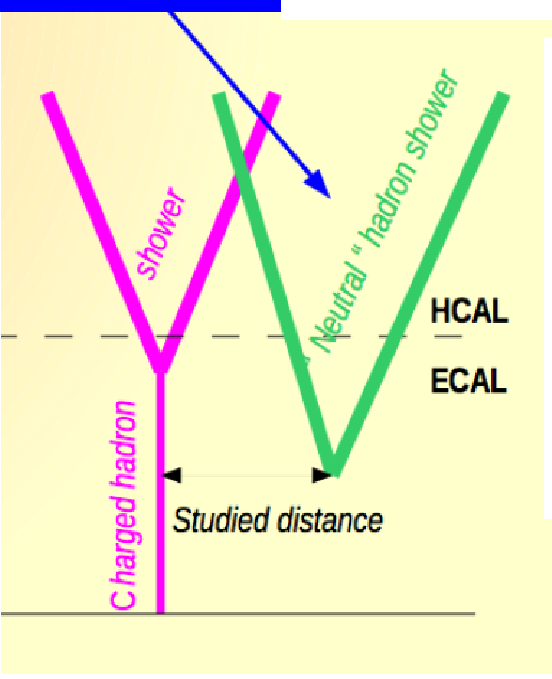


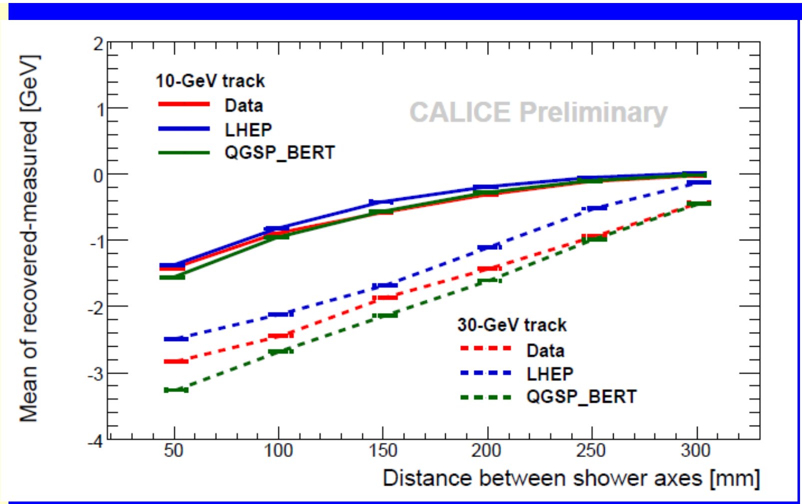
Particle Separability II

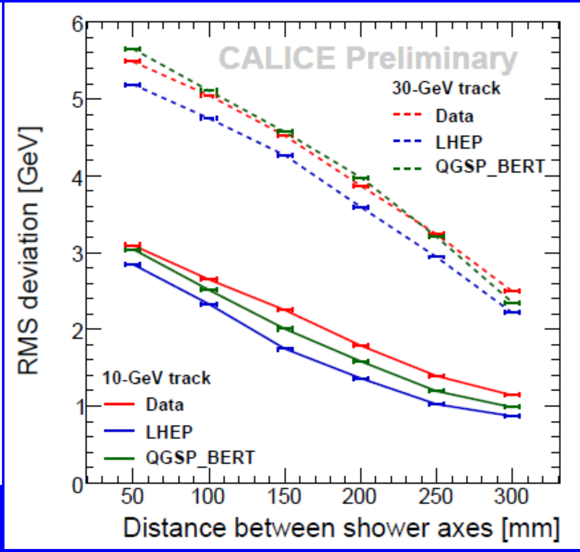
Overlay test-beam charged-pion events to assess ability to measure 10 GeV neutral hadron in the vicinity of a charged hadron.





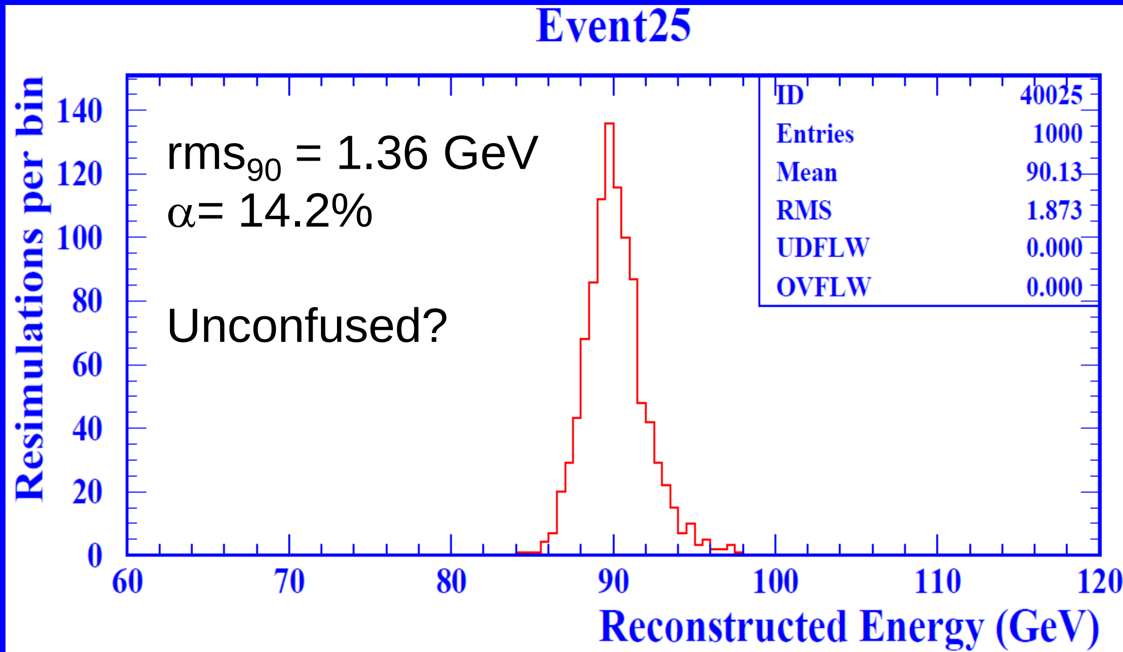


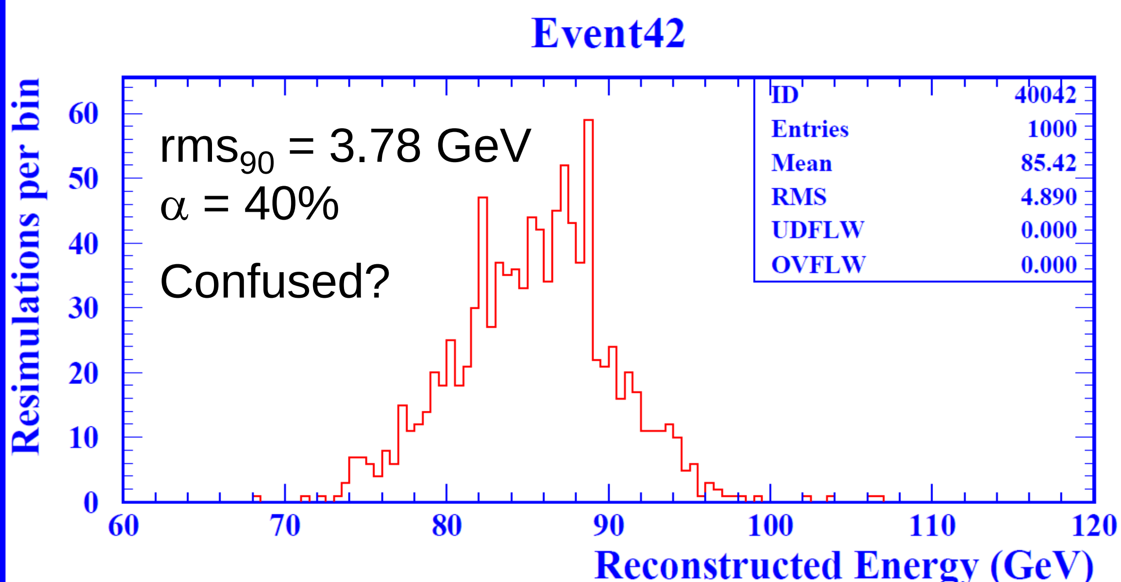




Conclusion: “Confusion” in data is in the expected range.

Energy Biases and Uncertainties





Measurements using current algorithms of the event-specific bias and event-specific resolution suggest that there may be scope to improve further the effective resolution by up to a factor of 0.76 (if one can calibrate out event-to-event systematics and understand uncertainties.)

We also care about systematic errors on jet energy scale – here again neutral hadrons are likely to be the big issue.

Higher Energy Remarks

- Occupancy/BX from $\gamma\gamma \rightarrow$hadrons increases as ln(s) for both ILC and CLIC.
- At the same $\sqrt{s}$, ILC is experimentally much easier than CLIC:
  - 337 ns / BX cf to 0.5 ns / BX
  - σz = 300 μm cf 44 μm
- This background is easily resolved between BXs at ILC, and may also be resolved spatially using bunch length
- For CLIC, precise time-stamping mandatory.
  - An interesting challenge for a 4π calorimeter.

Summary

- Particle flow calorimetry can reach the 3-4% basic goal for linear collider jet energy measurement motivated by W, Z separation over an energy range from 45 GeV to 1.5 TeV
  - Improvements beyond this baseline performance are anticipated as we learn how best to exploit the unprecedented imaging capabilities of particle-flow calorimeters.