Hadron Energy Reconstruction with Barrel EMcal

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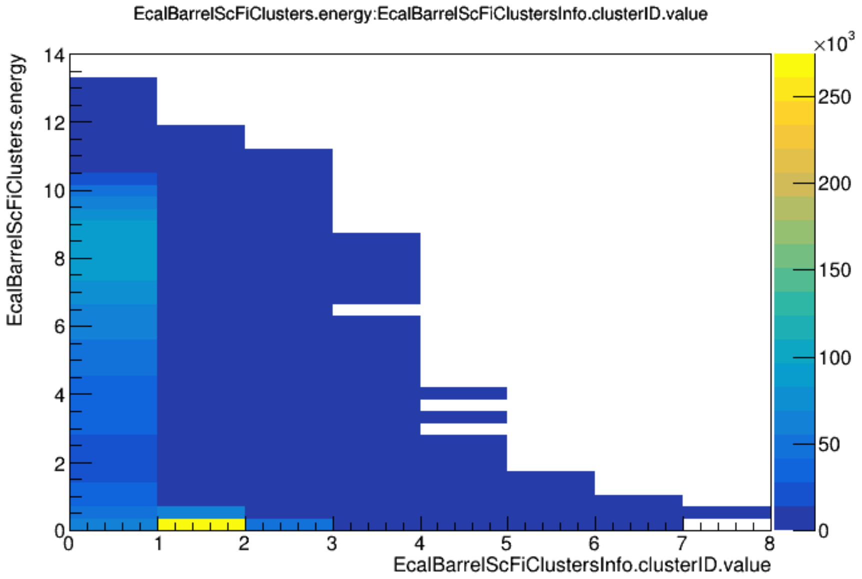
Summary from last time

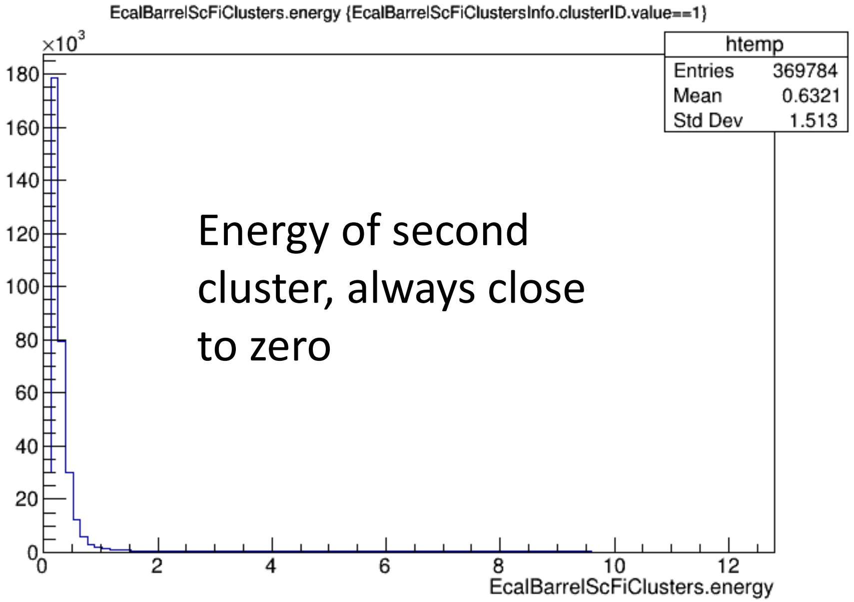
- A few options:
  - 1. Say that the EMCal is good enough for handling neutral hadrons, don't build BHCal
    - I have a set of slides on this, can present them now or just post to indico
  - 2. Reduce the material of the magnet, keep BHCal
    - A request: Could SWG do a quick run where they change SS in magnet to aluminum and shoot 10 GeV neutrons?
    - Should test if Al will make things alright, easiest change integration-wise
  - 3. Beef up the EMCal so that it has a better response to hadrons, don't build BHCal
    - Up to experts to decide how to do this, if it's possible
    - I'll be happy to analyze the DD4HEP data from another EMcal model

- HCal has poor efficiency for identifying/measuring energy of neutral hadrons due to large material in front
- This talk is meant to investigate option 1: Is the EMCal as currently implemented enough?
  - What kinds of cuts can we make to improve the situation?
- Grains of salt:
  - Clustering currently not optimized for neutral hadrons
  - Readout so far only in X-Y

First Attempts at Energy Reconstruction

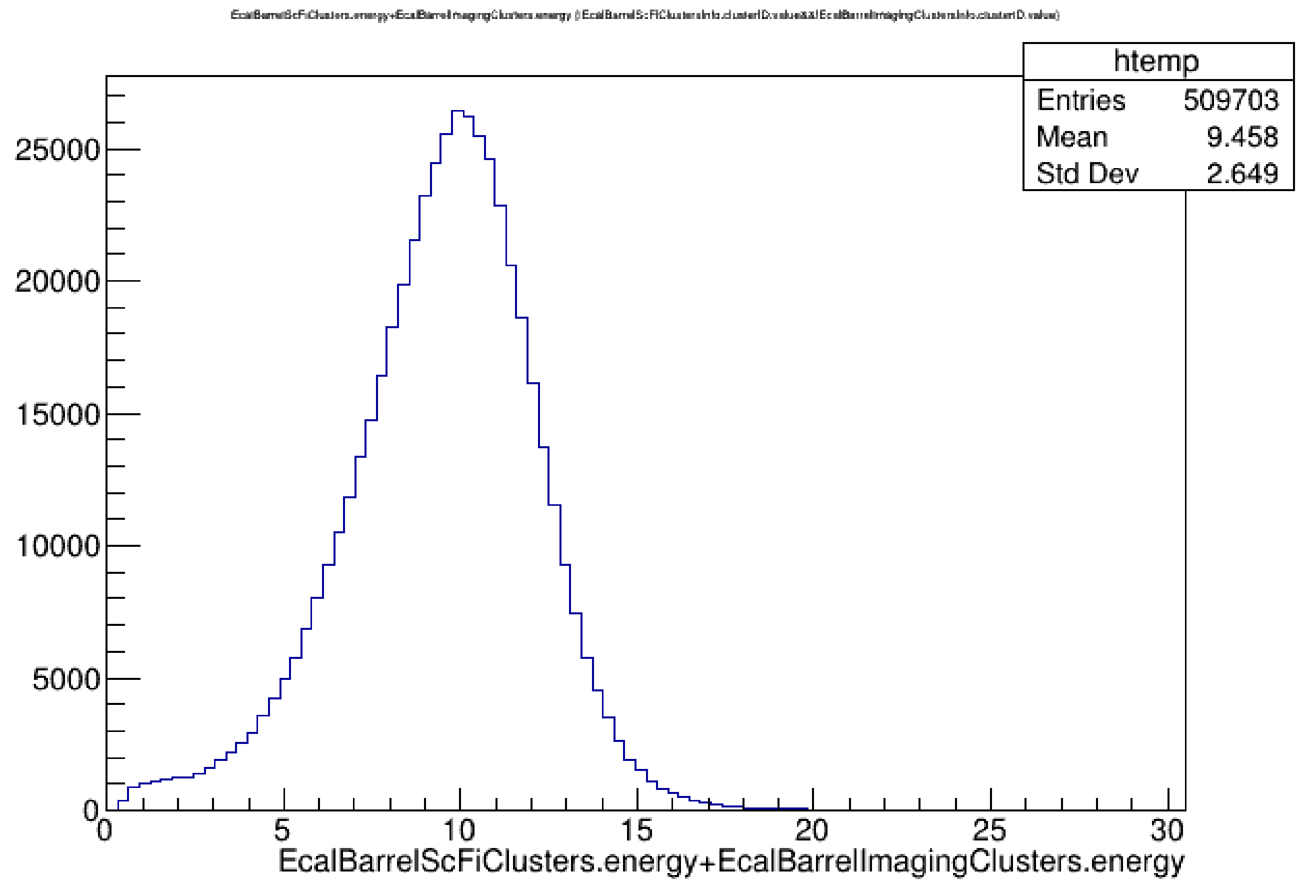
- 10 GeV neutrons
  - Lower energy seems to have issues with clustering
- Take most energetic cluster as the particle's reconstructed energy
  - For energetic neutral hadrons, not such a bad assumption
  - In 2M events: 1.6M have one cluster, 370k have two clusters, 74k have three+
- Will use first cluster as a proxy for reconstructed energy moving forward





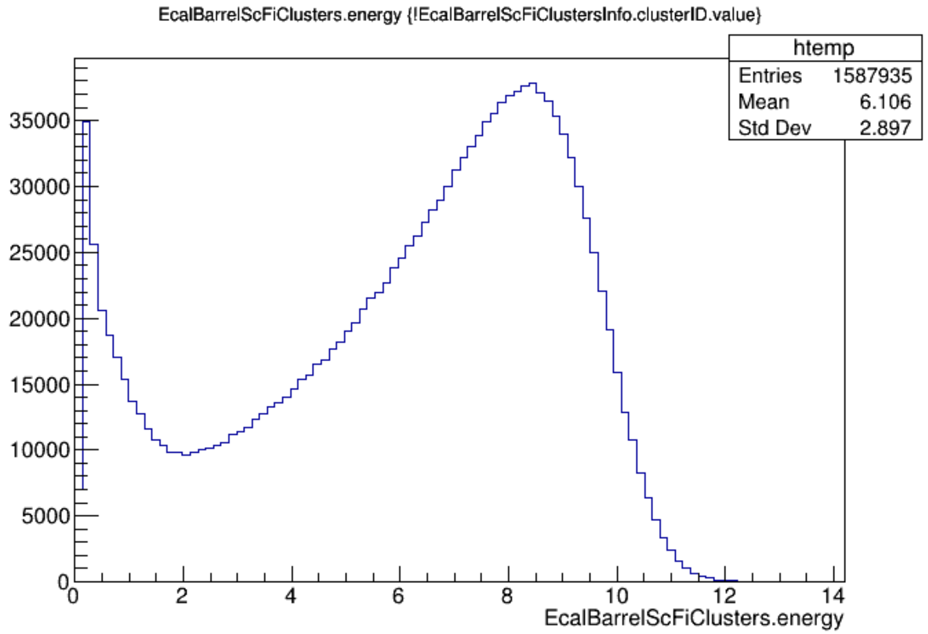
Resolution doesn't tell the whole story

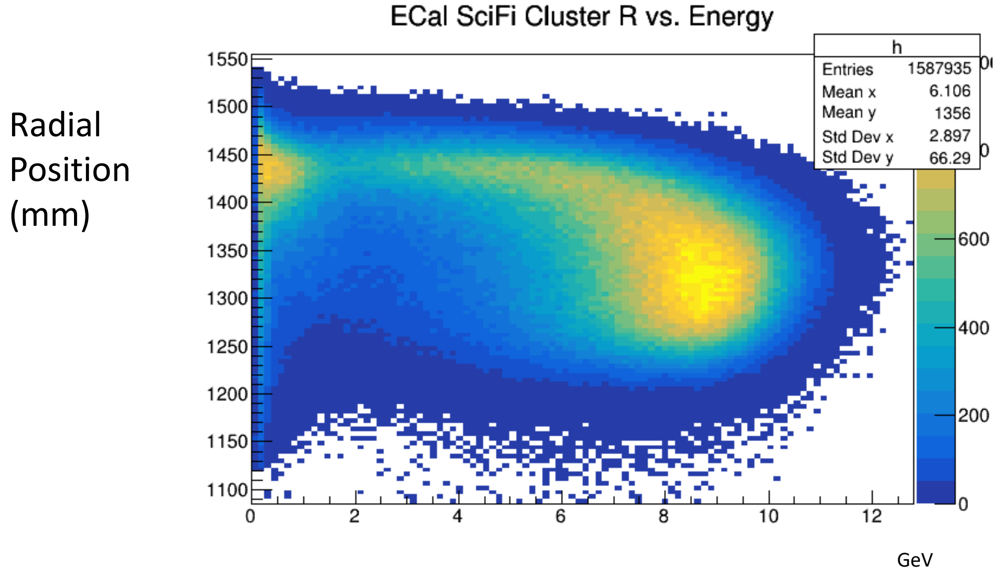
- 10 GeV neutrons
  - Requiring at least one cluster in both SciFi and imaging
    - Proxy for early shower, well contained
- Relatively gaussian, 28% sigma
  - ~Matches previous studies for Ecal hadronic resolution
- However, only ~25% of thrown particles pass this imaging+SciFi cluster criteria at 10 GeV
  - 0.07% at 1 GeV, 10% at 5 GeV



Resolution doesn't tell the whole story

- 10 GeV n (pi+/- similar)
- Here only a cluster in the SciFi is required
  - Shower no longer constrained to be early
- Standard deviation is similar to previous case, but highly non-gaussian
  - $\frac{\sigma}{Mean}$ is not too bad, but this is misleading
- Large number of events where energy is missing
  - To be expected from leakage
- Still, ~20% of events leave no cluster in either Ecal section
  - 16% leave no cluster in any calorimeter
- Could also be an issue with the current clustering, but results are ~consistent with expectations
  - See CALICE plot in backup



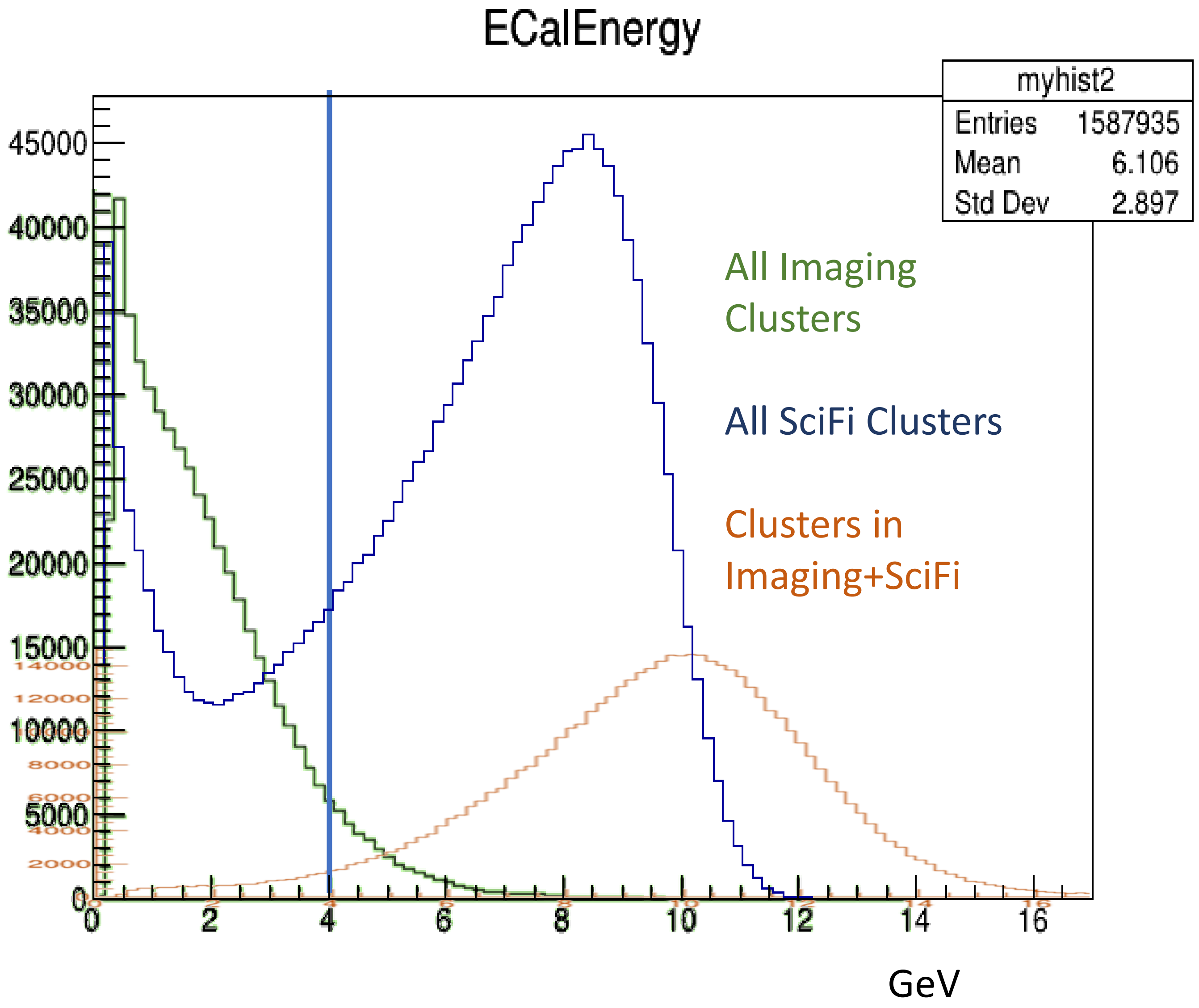


- Peak at 0 in SciFi isn't from energy lost to imaging
  - Imaging absorbs very little energy overall
  - ~20% of SciFi clusters < 4 GeV
  - ~11% < 2 GeV

- If orange condition is met, one can measure energy for sure
  - Otherwise, energy response will be very non-linear

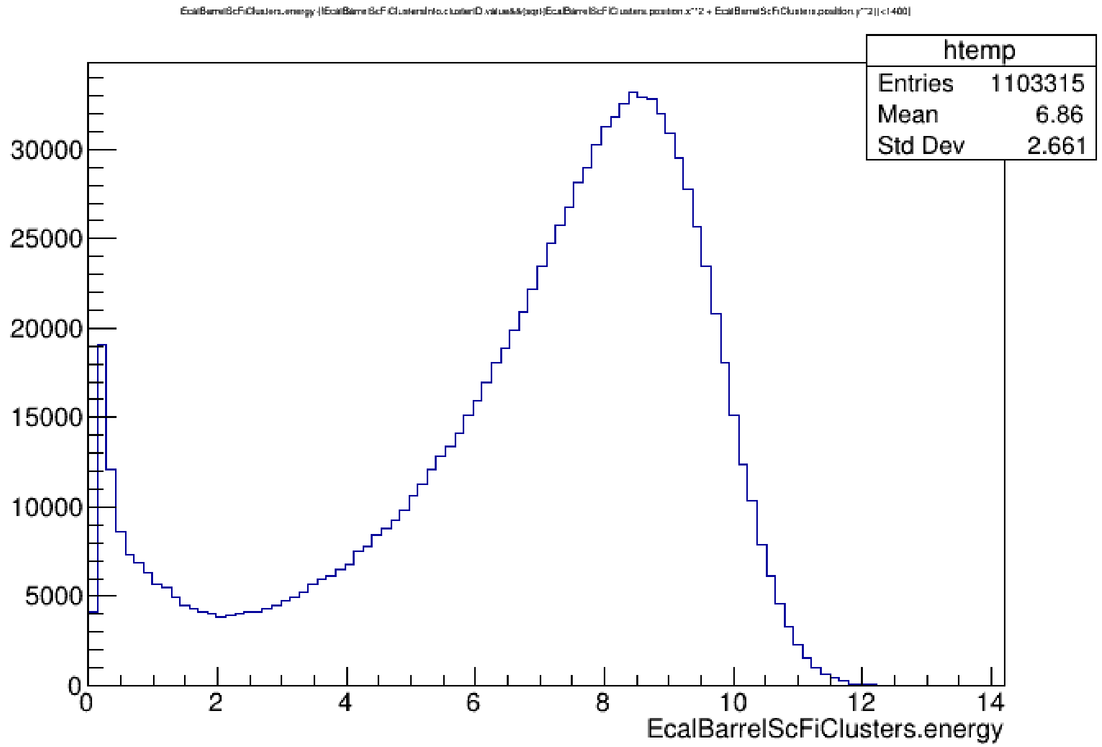
- Can maybe still provide neutral-ID with only one cluster
  - Will need in-depth study with DIS sample, timing implemented

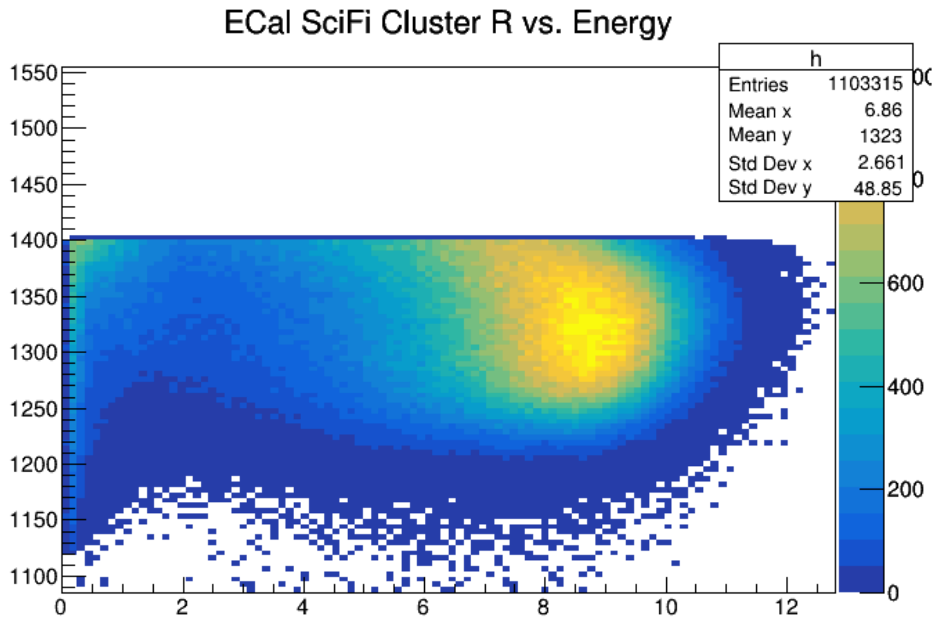
- Aside: EMcal cracks can be problematic, magnet will absorb channeled hadrons, electrons, photons before HCal



Radial Cuts

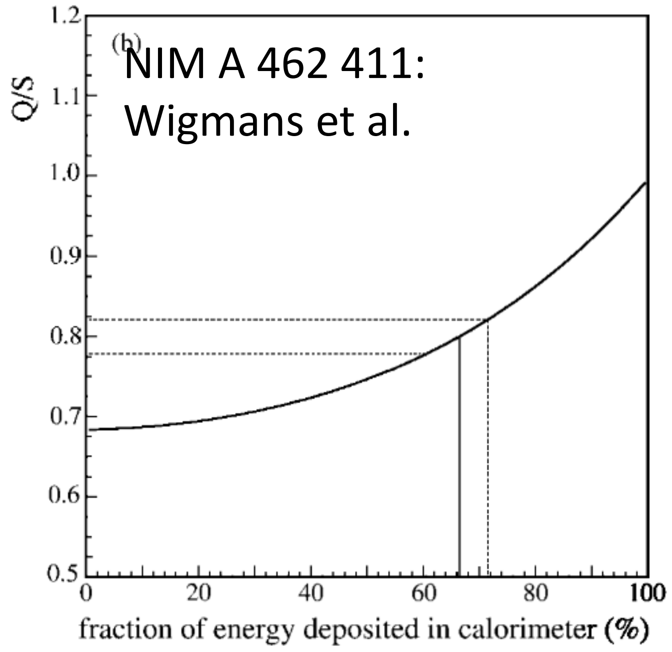
- Can define some fiducial volume, where clusters beyond a certain R aren't considered as having energy measured properly due to anticipated leakage
  - Response is still somewhat non-linear, but looks better
- Cut removes ~30% of clusters
  - Brings fraction of single-particles with an associated cluster passing cuts to 55%
- What else can we do?





Dual-readout Benefits

- Detect Cherenkov and scintillation light
  - Quartz/plastic + Scintillator
- Hadrons that interact early or have a large EM fraction can also be relatively well measured in EMcal
  - Dual-readout gives additional information about the degree of leakage
    - Q/S is proportional to fraction of energy deposited
- Can more accurately cut away badly measured hadrons to improve energy resolution
  - Not ideal from inclusive physics standpoint, but better than nothing
  - Charge ID should still be possible for those cut away



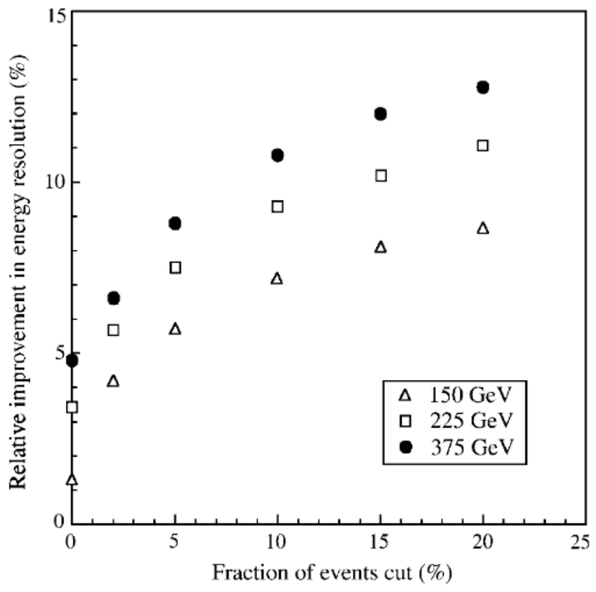
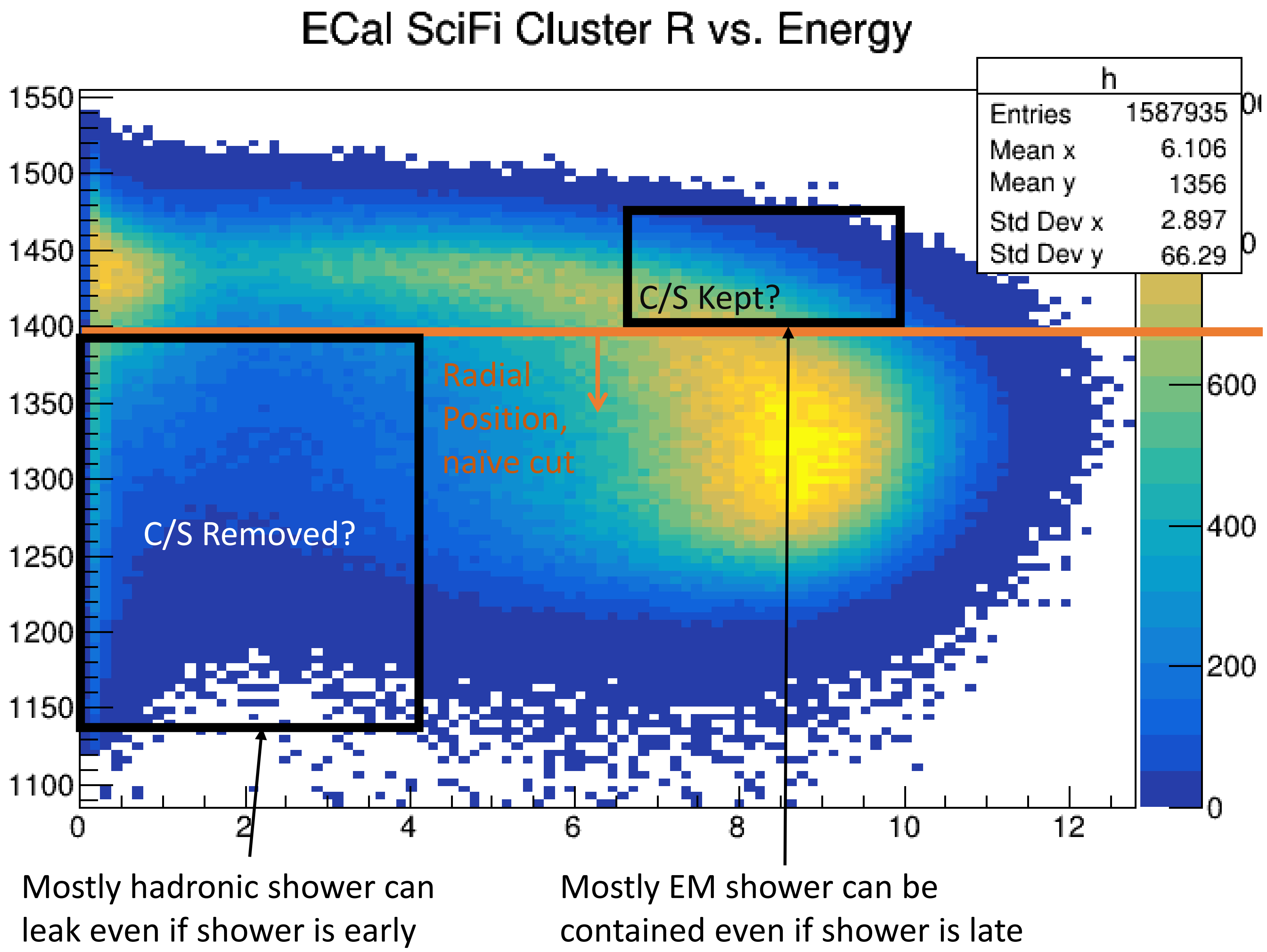


Fig. 10. Improvement in the energy resolution for 150, 225 and 375 GeV π^- as a function of the fraction of events cut from the tails of the Q/S distributions.

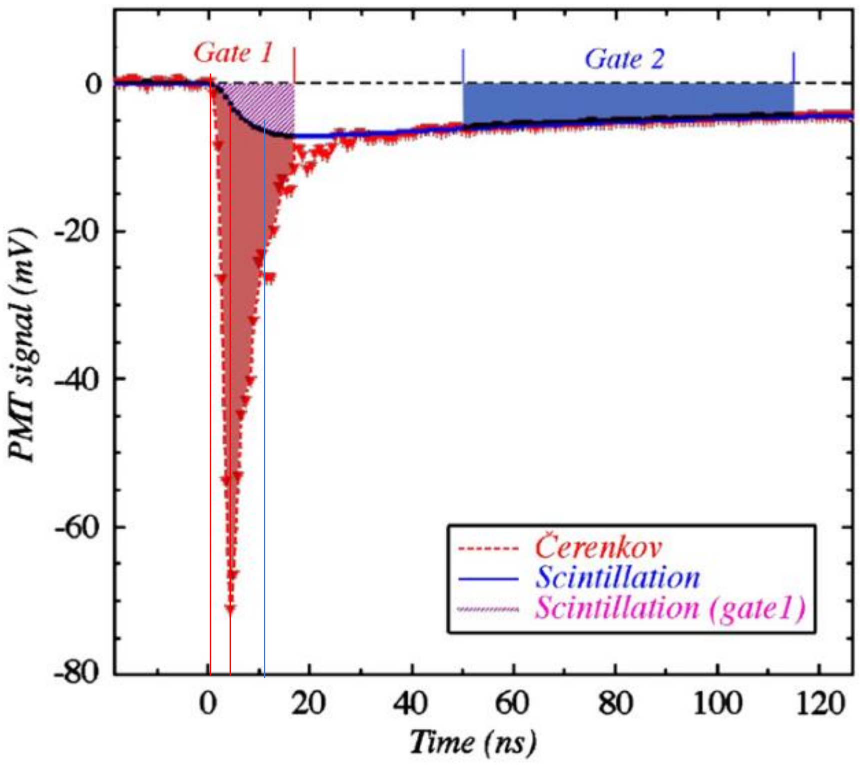
Clearly cut on radial position can be imposed here to improve energy resolution

C/S gives another axis to use in cutting, can be used to save events that otherwise may have been cut, or cut events that would have been saved



Dual-readout Benefits

- Cherenkov light emitted immediately and in smaller area, better to localize shower
  - Shower neutron detection + scintillation decay spreads over a few tens of ns and tens of cm
    - This time is still << time between collisions, no problem with event overlap
  - $\frac{2\ meters}{.66*c} \sim 10$ ns is lower limit for light emitted at midrapidity to get to readout
    - To localize shower to within 20 cm at midrapidity, Δt_{Start} will need to be known to ~2 ns
    - Realistically (in a sensor with noise) this is easier to do with a quickly rising signal
  - SiPMs can have O(100 ps) time resolution
    - Limiting factor will not be the sensor but the signal itself
- Better precision in shower localization will improve neutral ID in jets
  - EM-core detected by Cherenkov fibers provides a better shower position than full hadronic shower in SciFi's
- Dual-readout + imaging will provide a wealth of information for ML optimization



Illustrative timing example (BGO)

SciFi can have much shorter scintillation decay time than shown here, O(3 ns)

Note sharpness of Cherenkov rise time compared to Scintillation

Conclusions

- Current ECal sees clusters from ~80% of high energy neutral hadrons
  - Can measure energy relatively well if shower is in imaging layers (~25% of the time)
  - Poorer energy measurement if only SciFi has clusters
  - Dual-readout has benefits for energy measurement
- Efficiency of ECal is significantly worse for low energy neutral hadrons (e.g 1 GeV neutrons)
  - 10 GeV should be harder than 1 GeV
  - Clustering issue? Threshold? Dynamic Range? Below Noise?
    - Is there enough dynamic range in the readout to measure 20 GeV electrons and 500 MeV neutrons? Can ranges be set different in “early” SciFi’s and “Late” SciFi’s?
- Extending/Increasing density of ECal should improve efficiency and gaussianity of energy response to hadrons
  - Current end of ECal is near to shower max

Backup

“Efficiency” (Fraction with > 0 Clusters)

- Neutron efficiency even lower than K_L except at 20 GeV
  - Less likely to interact in the Ecal at lower energies
  - K_L Decays easier to detect

- Sanity Check: $e^{-4} \sim .02$, $e^{-2} \sim .14$
  - Showers in magnet can still leave energy in Hcal
  - If a shower can longitudinally extend by 2 λ_0, then results are sensible
  - Would naively expect even less coming out of magnet than seen here

Species	Hcal	Ecal SciFi	Ecal Imaging	Hcal+SciFi	SciFi+ Imaging	Total fraction with > 0 clusters
500 MeV neutron	0.00001	0.14	0.0004	0	0.000006	0.140394
1 GeV neutron	0.0016	0.393	0.001229	0.00001	0.000678	0.395141
5 GeV neutron	0.028	0.76	0.1	0.078	0.1	0.71
10 GeV neutron	0.08	0.79	0.25	0.031	0.25	0.839
20 GeV neutron	0.175	0.81	0.31	0.087	0.31	0.898

Low energy hadrons are surprising

SLD used an extended Ecal of 3 int. lengths + tail catcher WIC due to .5 int length magnet

2.2. Hadronic section

The requirement of very good hadron calorimetry then posed a possible problem. The presence of a large coil (about 0.5 nuclear-interaction lengths thick) following 22 radiation lengths would place this unsampled material in the vicinity of the maximum energy deposition in hadron showers, resulting in large fluctuations in the sampled energy. At the same time, the total calorimeter thickness must be at least six interaction lengths for good hadron shower containment and muon filtering. Placing such a large device entirely inside the magnet coil was judged too expensive.

The chosen solution may be termed a "hybrid" hadron calorimeter. First, the liquid-argon calorimeter (LAC) inside the coil is extended to a thickness of about three interaction lengths, using coarser sampling after the electromagnetic section. The LAC will then contain, on average, more than 85% of the-shower energy for most hadrons encountered in SLC events, so that most of the hadronic energy is sampled in a high-quality liquid-argon device. The coil is placed out in the shower tails where the unsampled energy will be small. The coil is then surrounded by an iron-plate calorimeter sampled with plastic streamer tubes (called the WIC, for Warm Iron Calorimeter), which also serves

Shower Shapes

- CALICE found that a simple λ parameterization works well for 10 GeV pi⁻
- Largest portion of showers occur in 1st λ

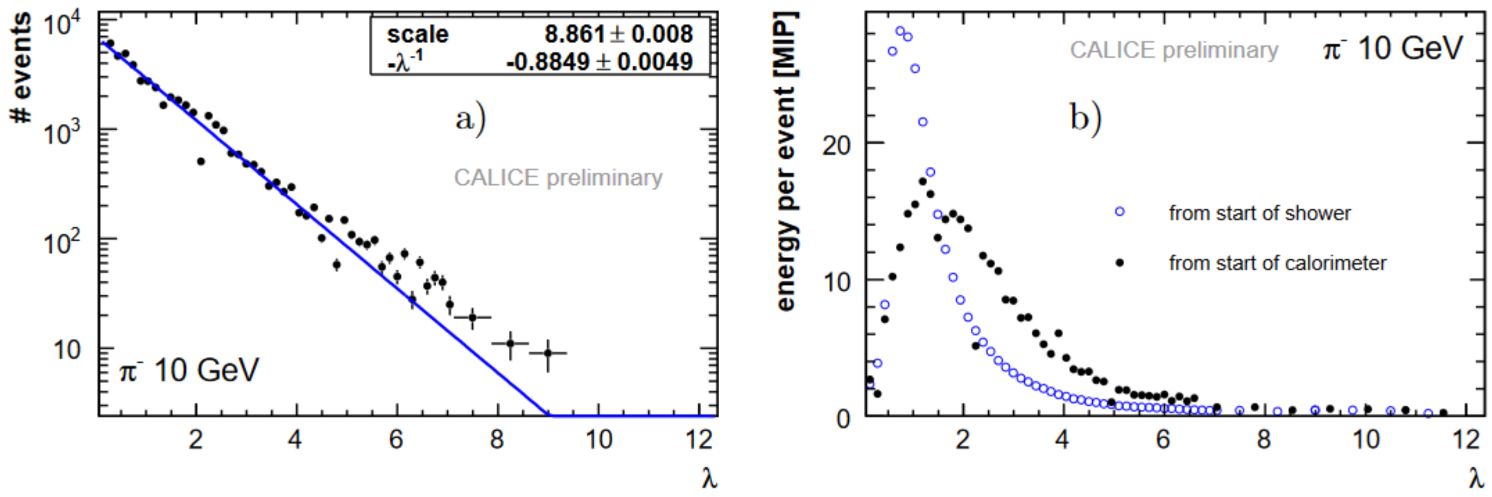
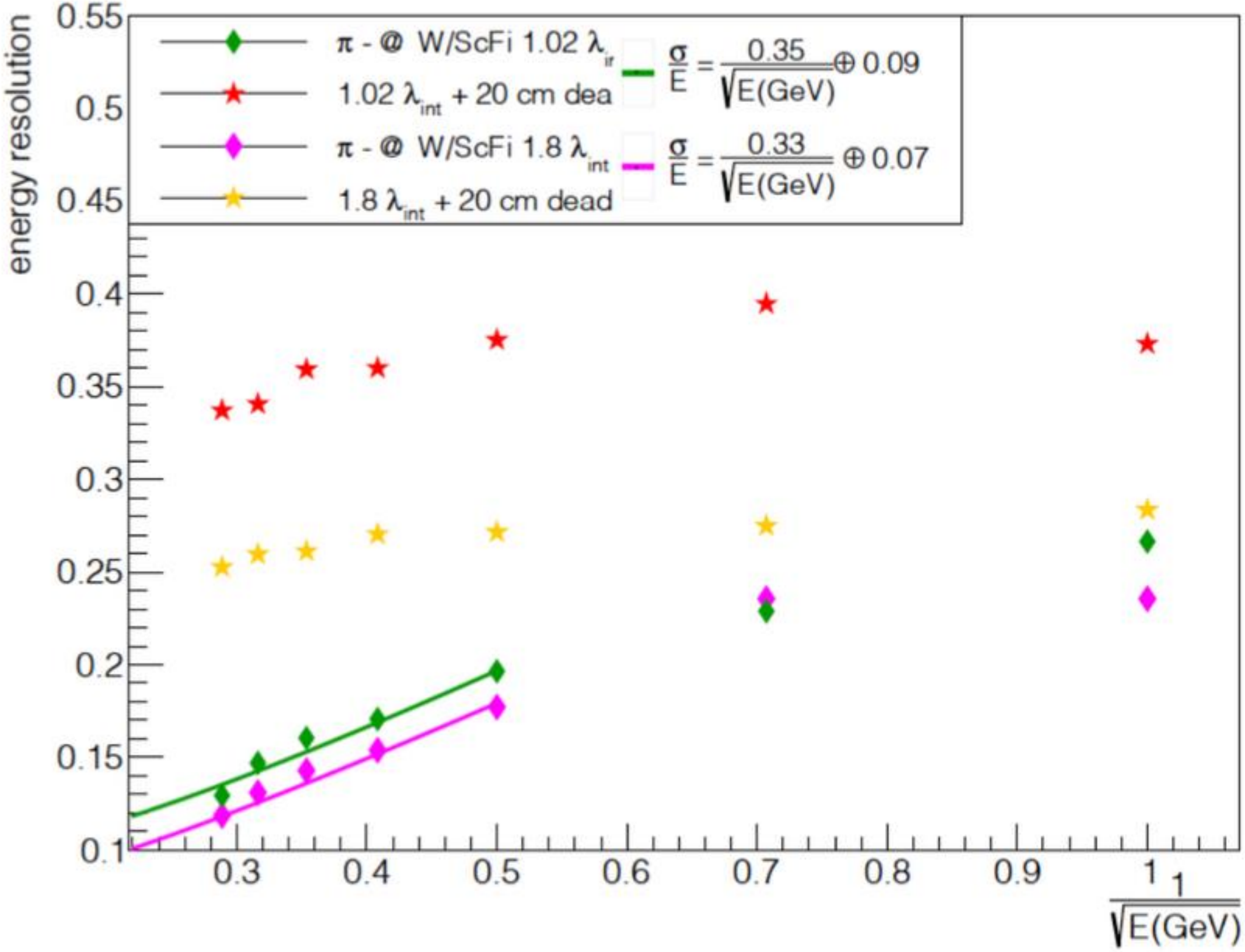


Figure 7. *a) Position of shower start in the calorimeter as a function of the number of interaction lengths. b) Longitudinal shower profile in the calorimeter determined before and after the shift, event by event, to the shower starting point, for 10 GeV pion showers.*



energy resolution
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\frac{1}{\sqrt{E(GeV)}}$
π - @ W/ScFi 1.02 λ_{ir}
1.02 λ_{int} + 20 cm dea
π - @ W/ScFi 1.8 λ_{int}
1.8 λ_{int} + 20 cm dead
$\frac{\sigma}{E} = \frac{0.35}{\sqrt{E(GeV)}} \oplus 0.09$
$\frac{\sigma}{E} = \frac{0.33}{\sqrt{E(GeV)}} \oplus 0.07$