ILD Calorimeter Granularities

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Overview/Aims

This primary aim of this talk is to summarise studies relating to the granularities of the ILD.

- For both the electromagnetic (ECal) and hadronic (HCal) calorimeters this includes studies relating to:
  - Transverse granularity studies. i.e. cell size optimisation.
  - Longitudinal granularity studies. i.e. optimisation of number of layers.
- For the ECal there is also a series of studies being summarised relating to novel granularity models e.g. combining multiple granularities in the ECal.

This talk will also touch upon other important results from recent studies including:

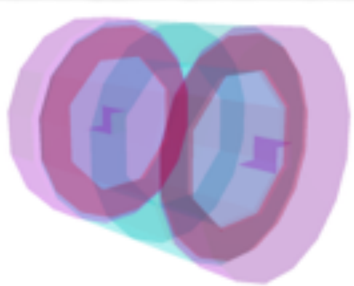
- For the ECal this includes studies relating to:
  - Sc/Si active material choice.
- For the HCal this includes studies relating to:
  - Absorber material choice;
  - Total depth of HCal;
  - Sampling fraction.
- A number of complementary studies are summarised relating to general optimisation of the calorimeters.

ECal and HCal Default Models

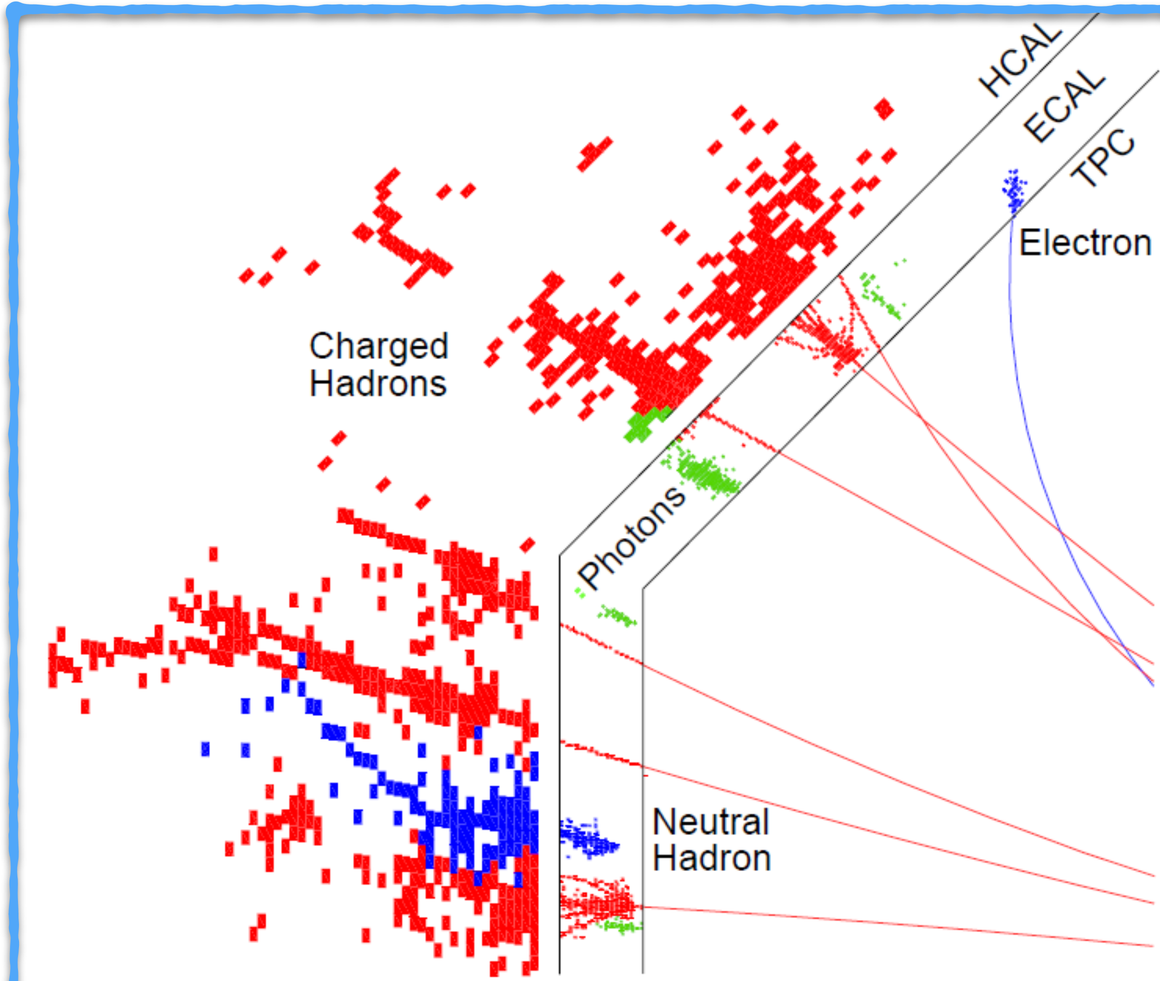
ECal

- Default ECal is a SiW model with:
  - 20 x 2.1mm + 9 x 4.2mm W absorber, representing 23 X_0 or 1λ_I
  - 29 x 0.5mm Si active material, divided into 5.1 x 5.1 mm² pixels.

HCal



- Default HCal is a Si-Steel model with:
  - 48 x 20mm steel absorber, representing 6λ_I
  - 48 x 3mm Si active material, divided into 30 x 30 mm² pixels.

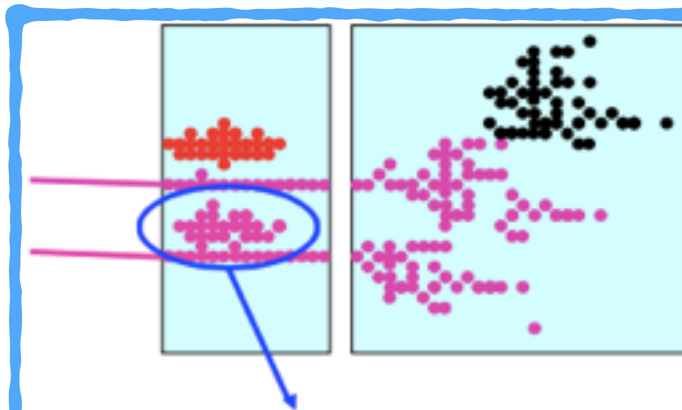


Typical event topologies used in reconstruction

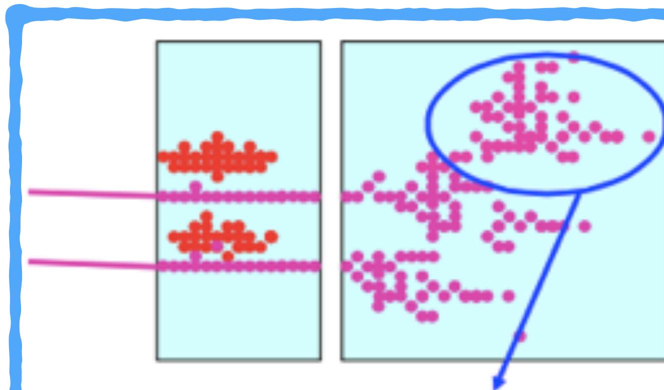
- The particle flow approach means that the jet energy reconstruction performance will **depend critically on the pattern recognition**, not just the intrinsic calorimeter energy resolution.

Detector Performance Studies using PandoraPFA

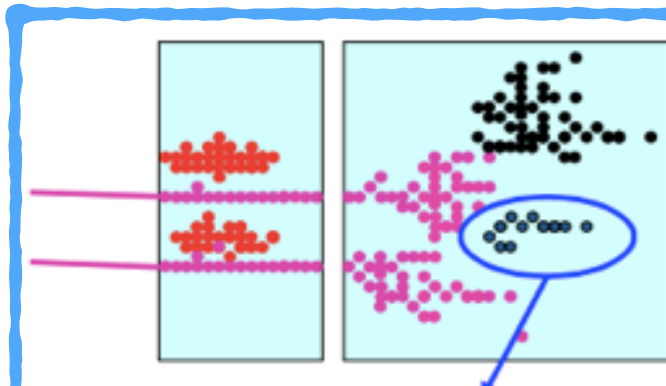
- **Benchmark performance using Z decays to light quarks**: produce two back-to-back mono-energetic jets, allowing jet energy resolution to be determined from total reconstructed energy.
- In order to truly understand resulting jet energy resolutions, want to investigate variation of each of the different contributing terms: **Intrinsic detector energy resolution and three types of confusion**.
- It should also be noted that for every detector model simulated in these studies a **careful recalibration procedure** was applied to ensure the accuracy of the results. This procedure considers both digitisation and PandoraPFA calibration.



Failure to resolve photons



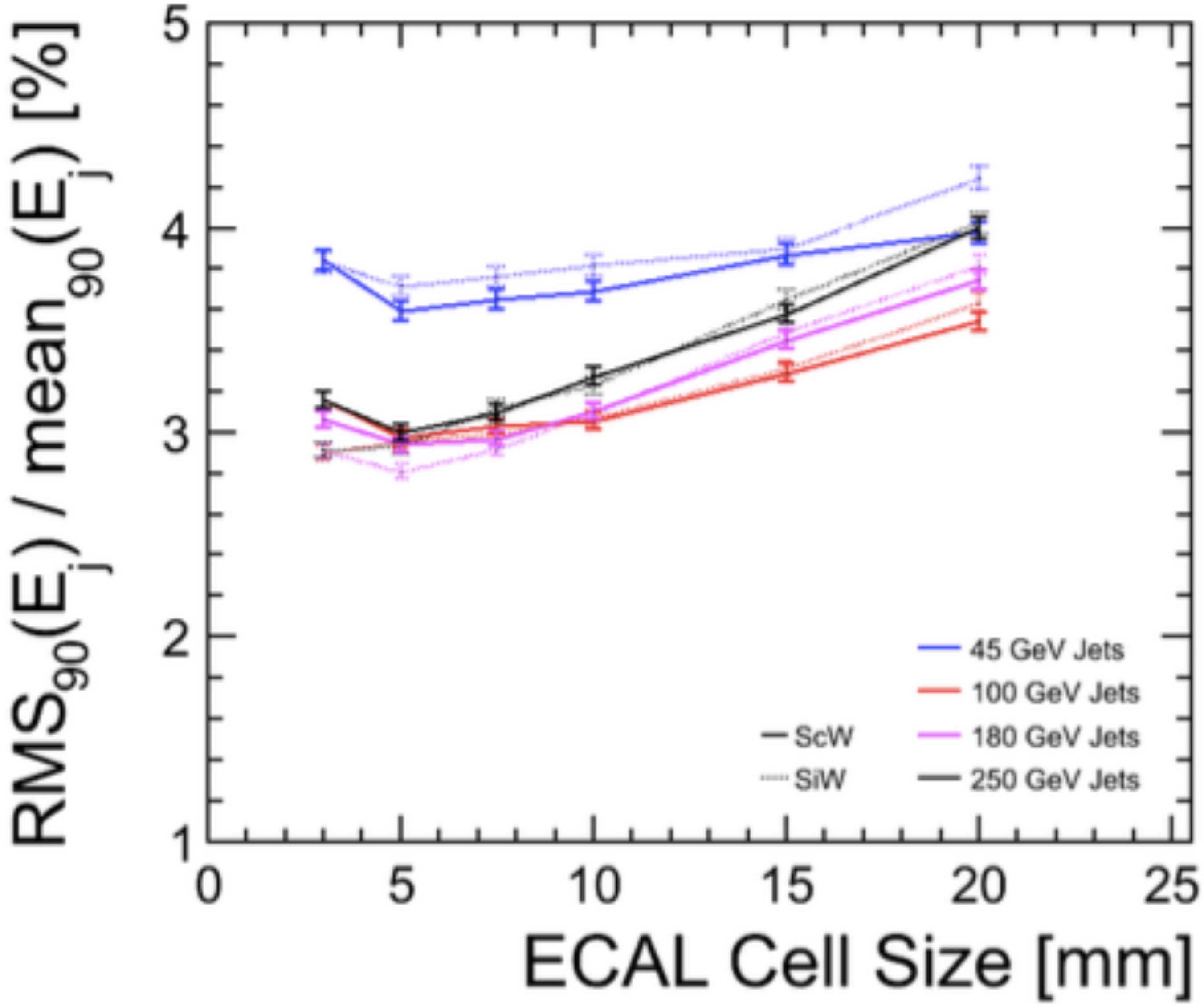
Failure to resolve neutral hadrons



Reconstruct fragments as separate neutral hadrons

- In order to extract the confusion terms, try gradually swapping Pandora algorithms with MC "cheating" versions. With currently available algorithms can obtain the following terms:
  - **Photon confusion**: contribution due to incorrect photon pattern-recognition and id.
  - **Neutral hadron confusion**: contribution due to incorrect n, K0L, etc pattern-recognition and id.
  - **"Other" confusion**: all other sources of confusion due to pattern-recognition and particle id.

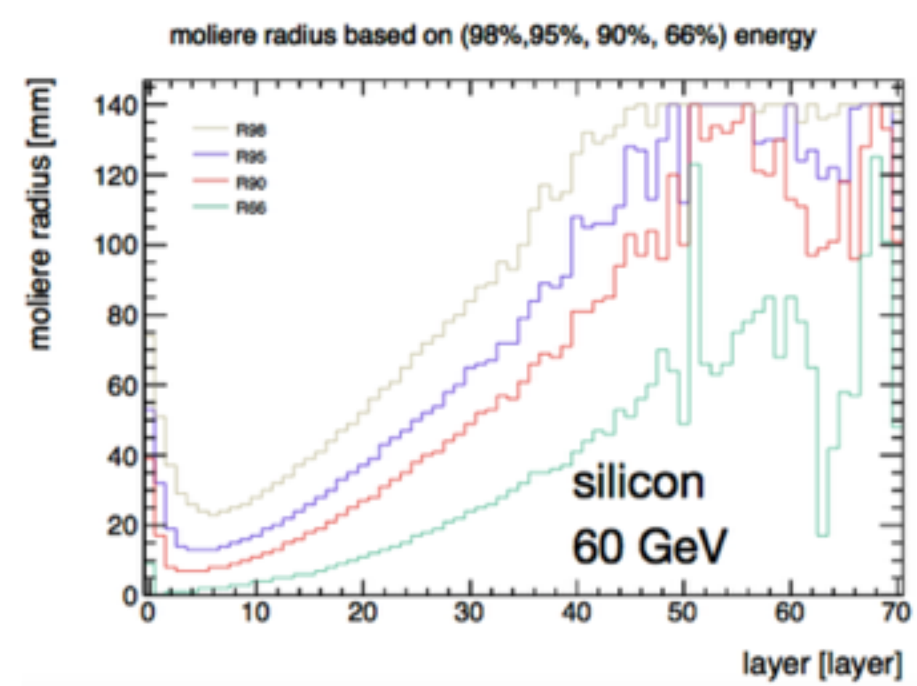
ECal Transverse Granularity



Resolution for 250 GeV jet:

	3mm	5mm	7.5mm	10mm	15mm	20mm
SiW	3.06%	3.1%	3.21%	3.31%	3.72%	4.09%
ScW	3.33%	3.17%	3.25%	3.38%	3.51%	3.95%

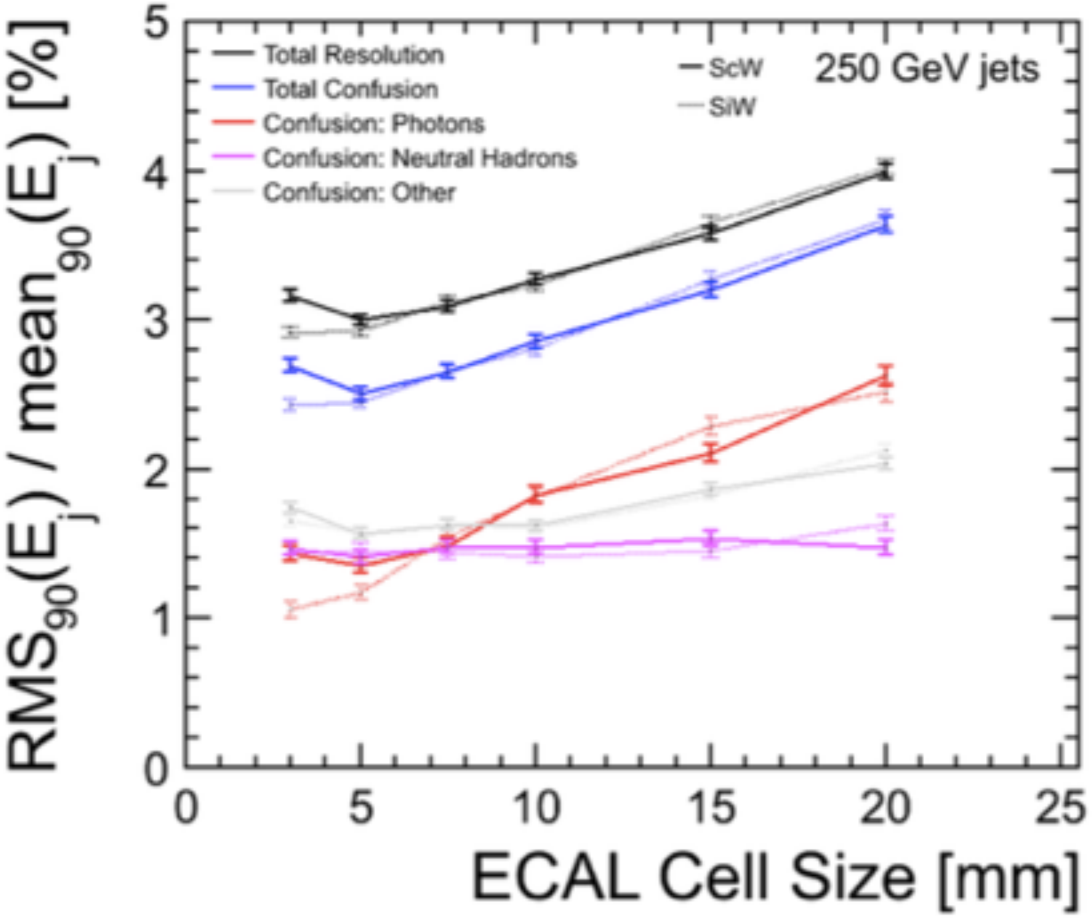
- Study **SiW/ScW performance with range of different cell sizes**. Keep cells square to reduce algorithm tuning:
- Range of cell dimensions was motivated by studies of transverse shower size as a function of depth. Sc cells 2.0mm thick.
- We can apply the MC “cheating” algorithms to analyse these results.

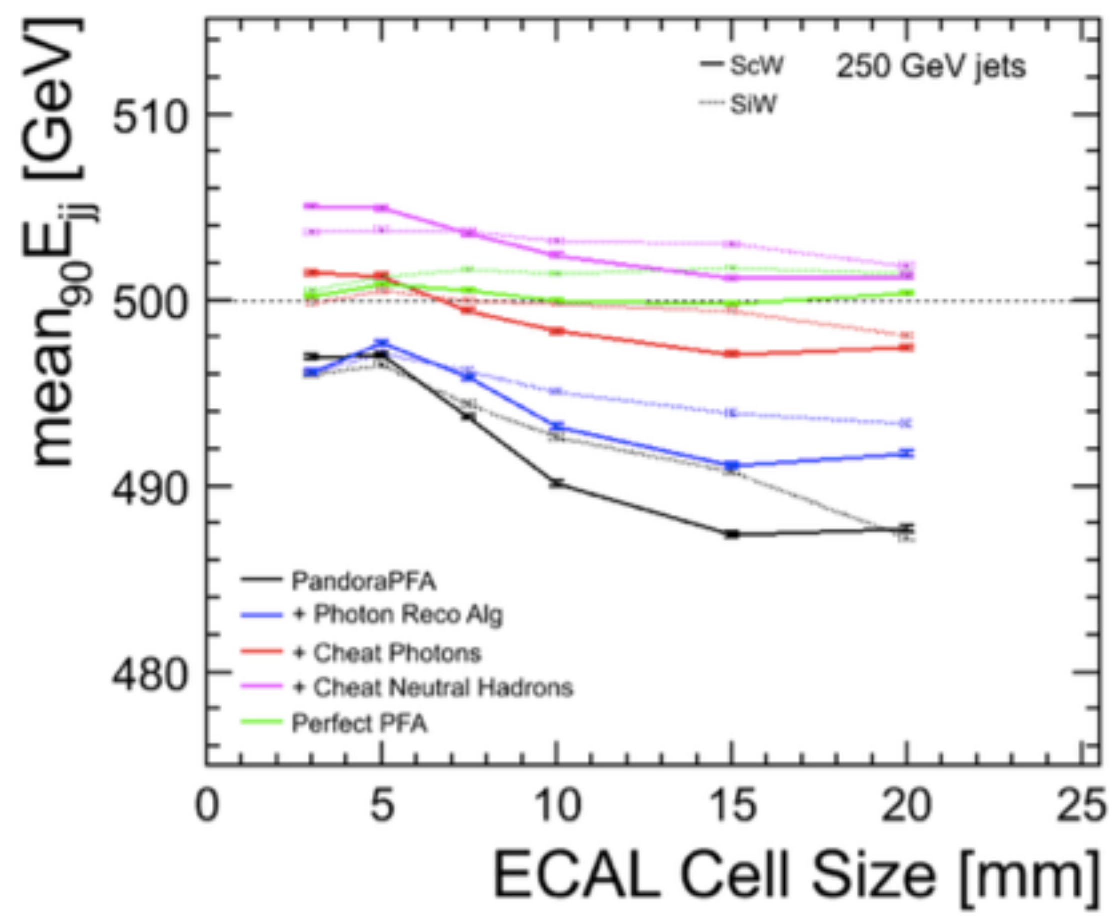


D. Schoke, F. Simon

ECal Transverse Granularity

- Can examine changes in performance between different algorithm configurations to explicitly determine **confusion contributions**. Contributions to overall resolution enter in quadrature.



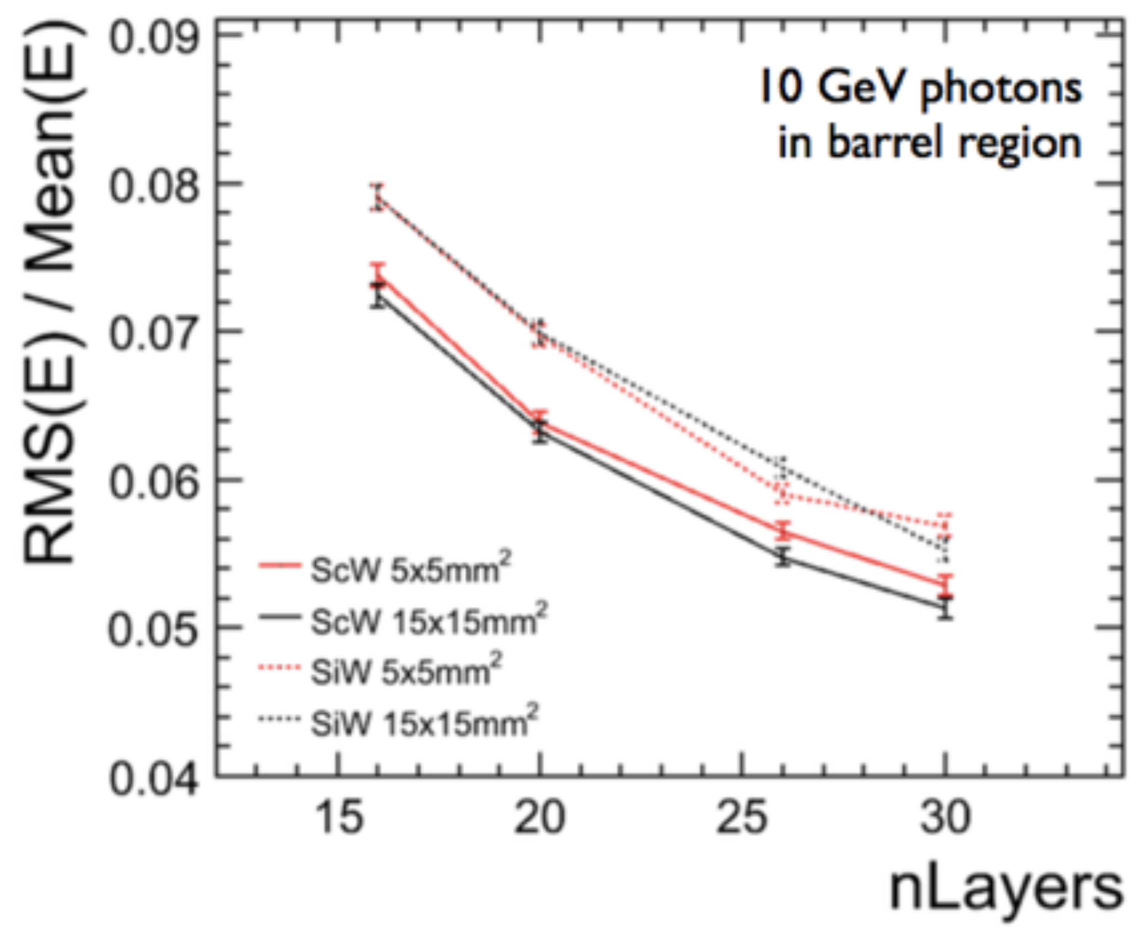


- Total confusion represents difference between best reconstructed resolution and perfectPFA; it comprises **neutral hadron confusion**, **photon confusion** and all "**other**" remaining contributions.
- **Neutral hadron confusion** contribution is essentially **flat with respect to ECal cell size**, whilst photon confusion increases significantly with increasing ECal cell size.
- Loss of photons also clearly evident in plot of mean di-jet energies vs. ECal cell size.

ECal Longitudinal Granularity

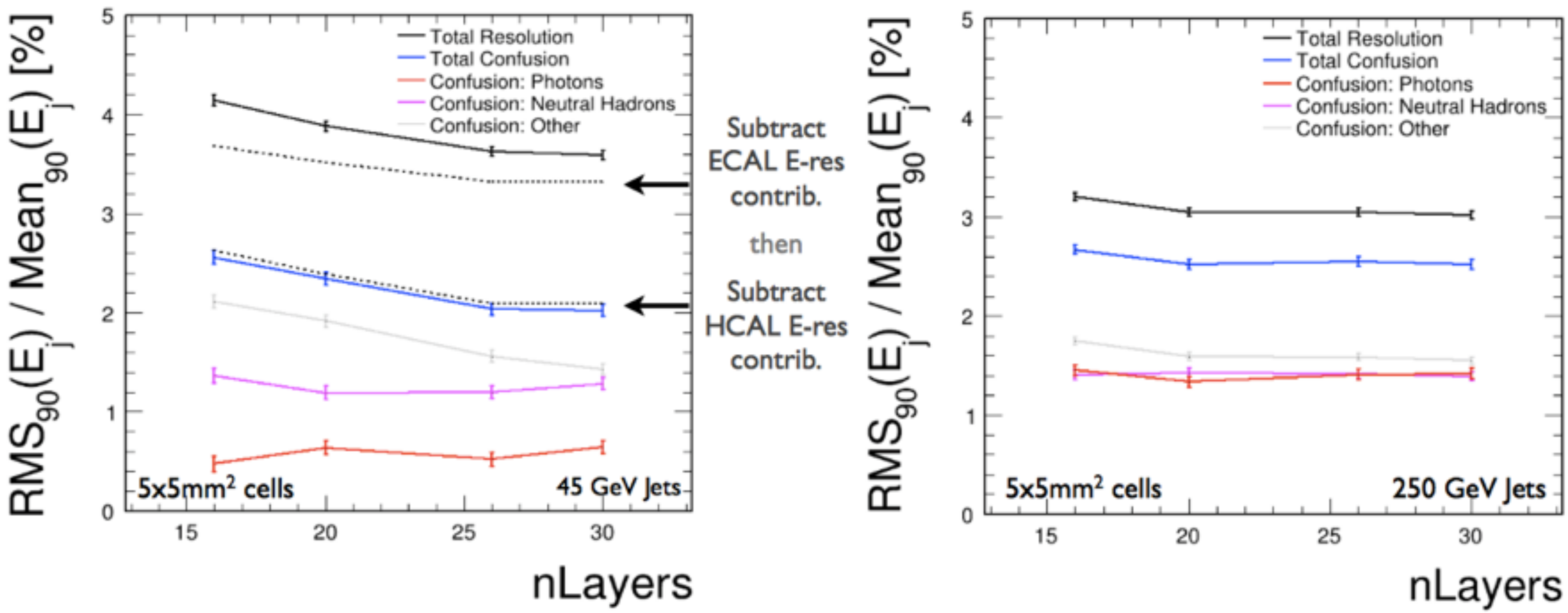
- Next, investigate impact on jet energy resolution of **reducing number of layers in the ECal**.
- Look to reduce the number of absorber and active layers in some of the ECal models considered so far.
- Extend and complement results obtained by T.H.Tran to include both SiW and ScW ECals, with two different granularities.
- SiW and ScW; 5x5mm^2 and 15x15mm^2; use each of the layer configurations below:

ECal Model	W Layers	Layer Thickness[mm]
30 Layers	20,9	2.1, 4.2
26 Layers	17,8	2.4, 4.8
20 Layers	13,6	3.15, 6.3
16 Layers	10,5	4.0, 8.0



- Examine the energy resolution for 10 GeV photons in the barrel.
- As expected, the 2.0mm thick Sc offers better energy resolution than 0.5mm thick Si.
- Sc resolution varies with cell size (MPPC “dark” area), whilst Si resolution unaffected.

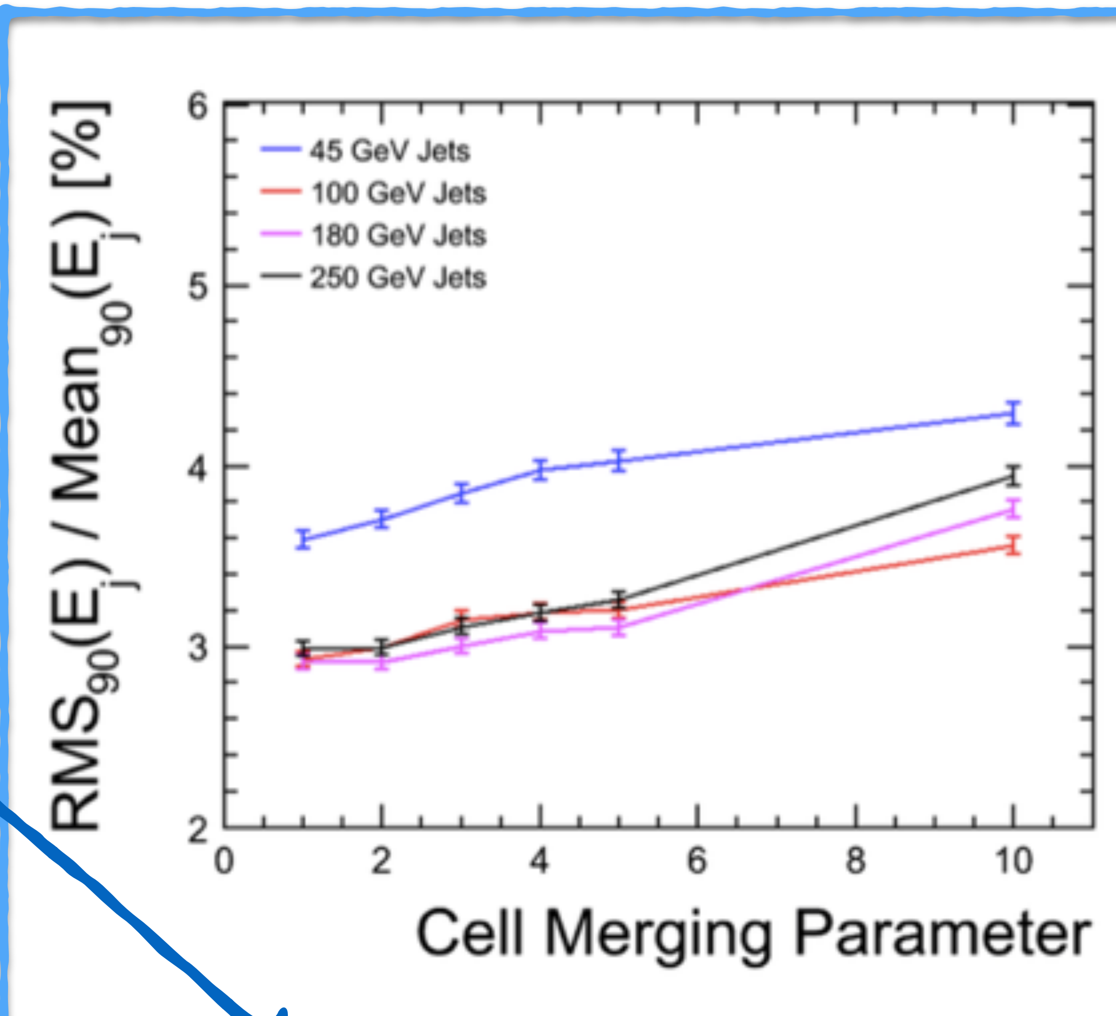
ECal Longitudinal Granularity



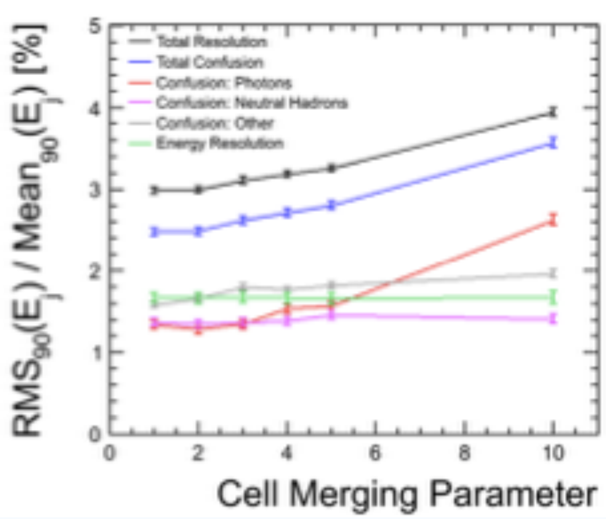
- For 250 GeV jets, resolution does not vary with #layers. For 45 GeV jets, there is some variation. To assess how much is due to energy resolution, use 10 GeV photon resolution plot from slide 6 to subtract ECal energy resolution component (assume 30% energy measured in ECal).
- Following this subtraction, the resolution curve is flatter; but still displays some variation. This is due to the "other" confusion component which encompasses many issues and is difficult to address in alg. improvements: charged hadron problems, MC matching issues, fake particles, etc.

Number of Cells per SiPM

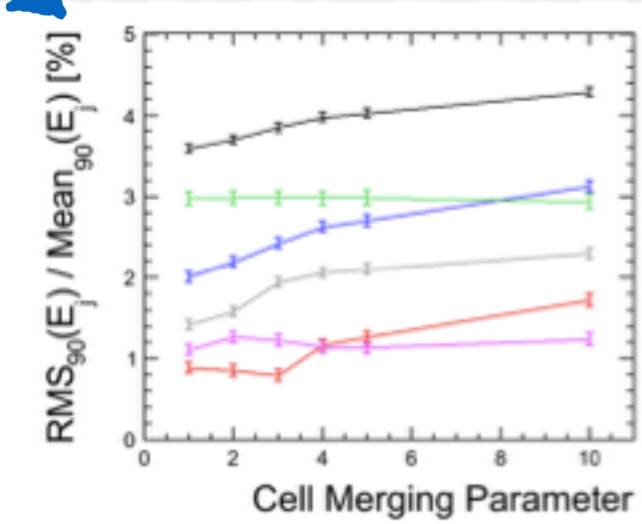
- Now we consider **increasing the number of cells which are read out by individual silicon photomultipliers**.
- The cell merging parameter is the number of cells grouped together in the readout.
- Detector performance is degraded as the cell merging parameter increases.
- Confusion plots tell us this primarily down to **photon confusion** for high energy jets and a combination of **photon** and **other confusion** for low energy jets.
- **Key point**: Here we are **able to reduce the number of layers in the ECal whilst leaving the intrinsic energy resolution completely unchanged**. The normal method for layer reduction also reduces intrinsic energy resolution.



250 GeV Jets

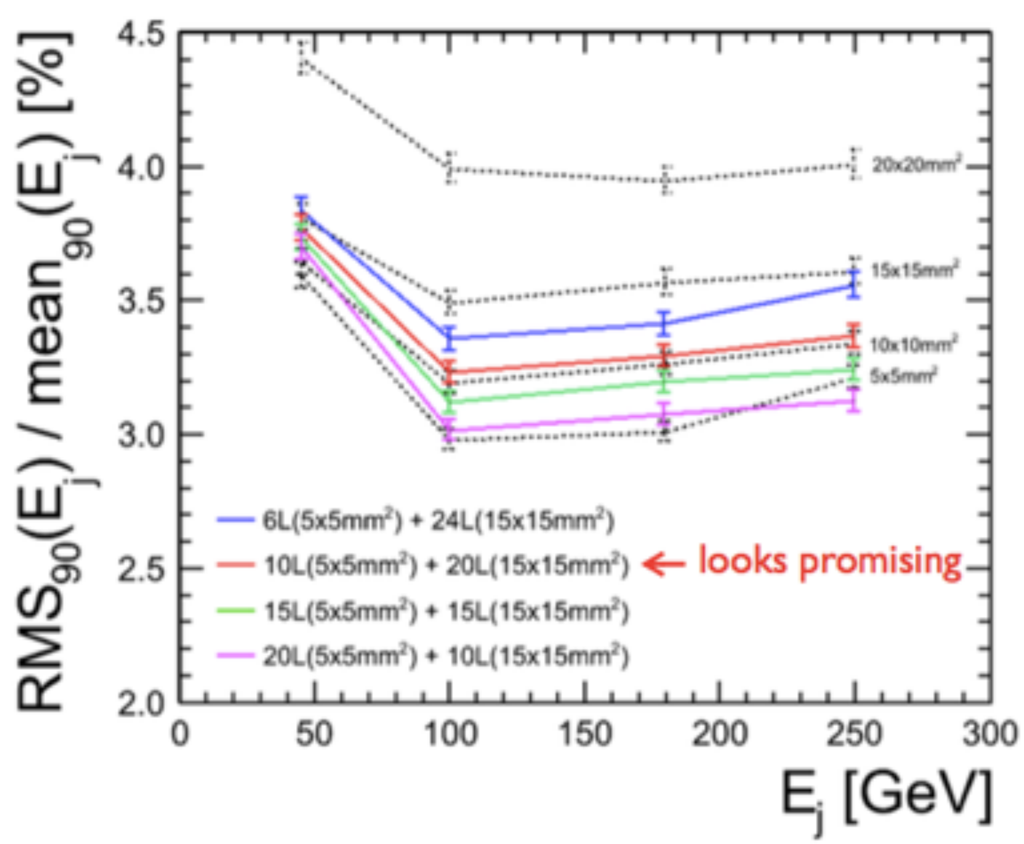


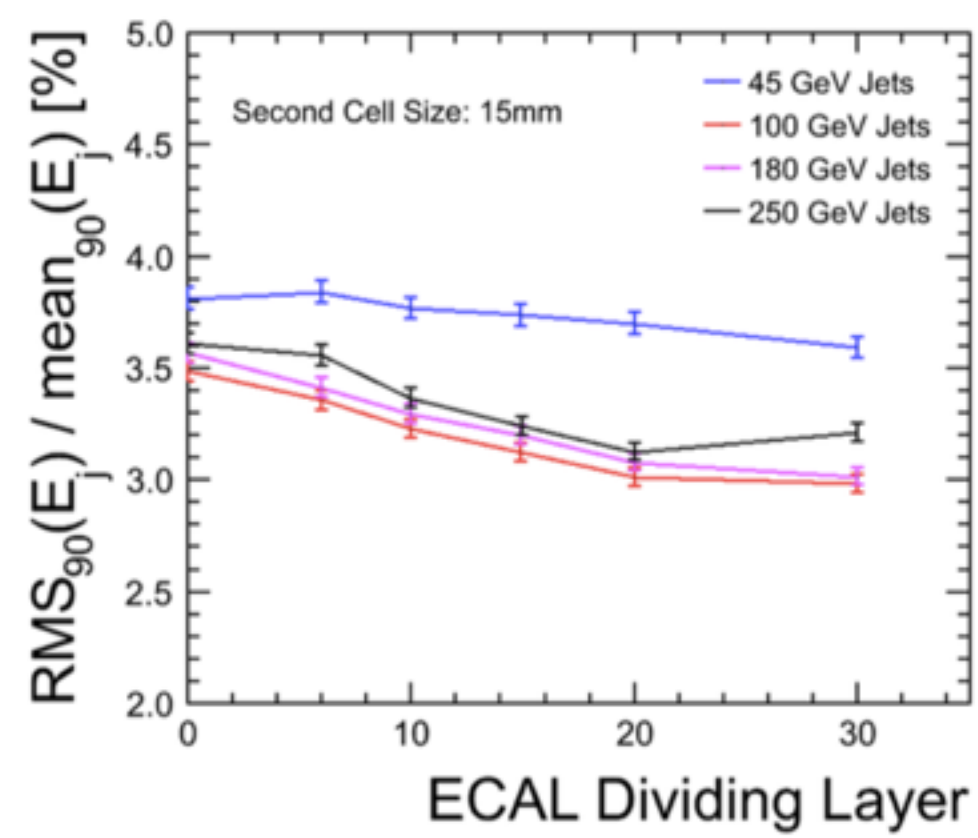
45 GeV Jets



ECal Two Granularity Regions

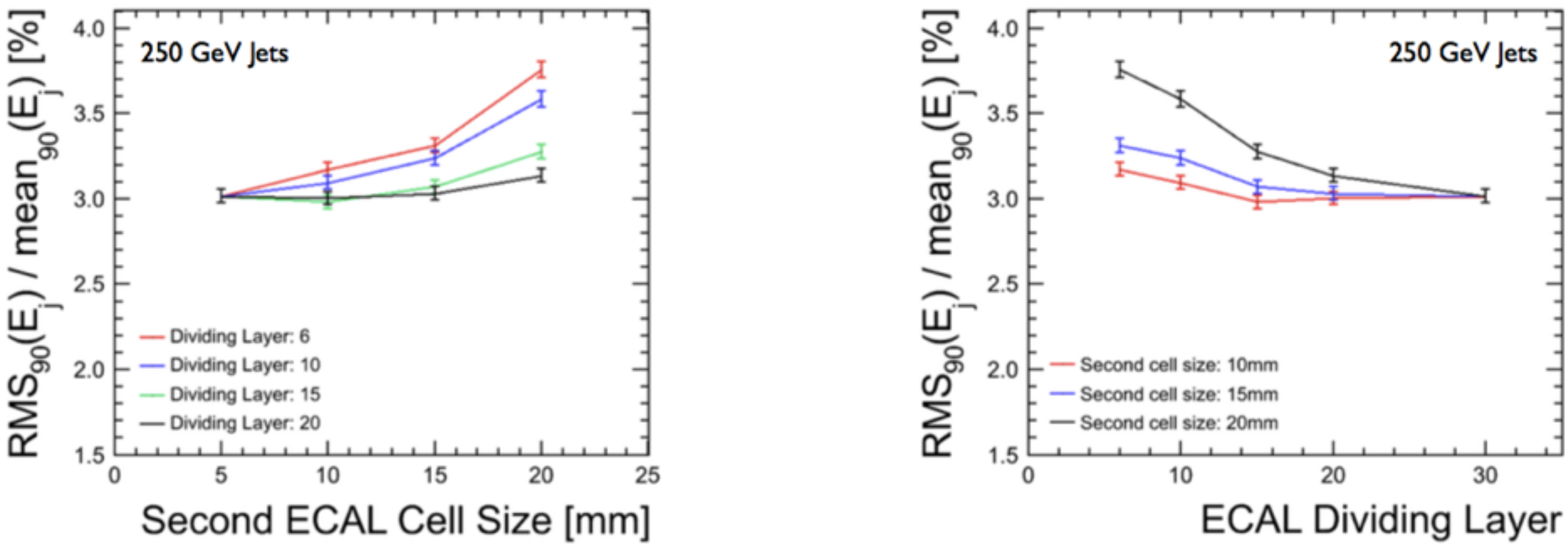
- Now investigate performance of novel ECal models with **two transverse segmentations**. Use ScW ECal models and assume first region comprises 5x5mm² cells (Sc thickness remains 2.0mm and the W absorber thicknesses are unchanged), so study parameters are:
  - The **size of squared Sc cells used in second region**;
  - The "**dividing layer**", i.e. the ECal layer at which the Sc cell size changes.





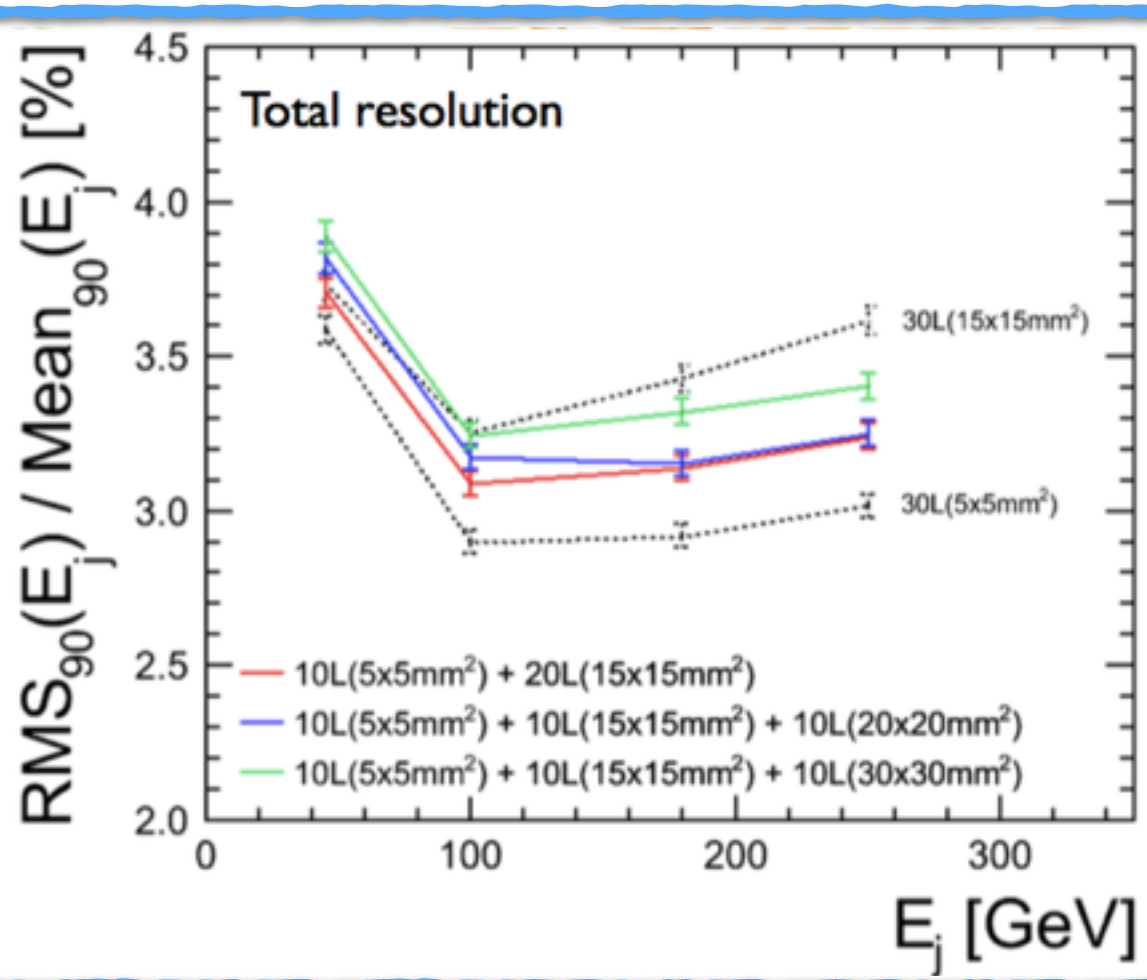
- Very **promising configuration** of 10 layers of 5x5mm² and 20 layers of 15x15mm² achieves performance comparable to uniform10x10mm² cells.

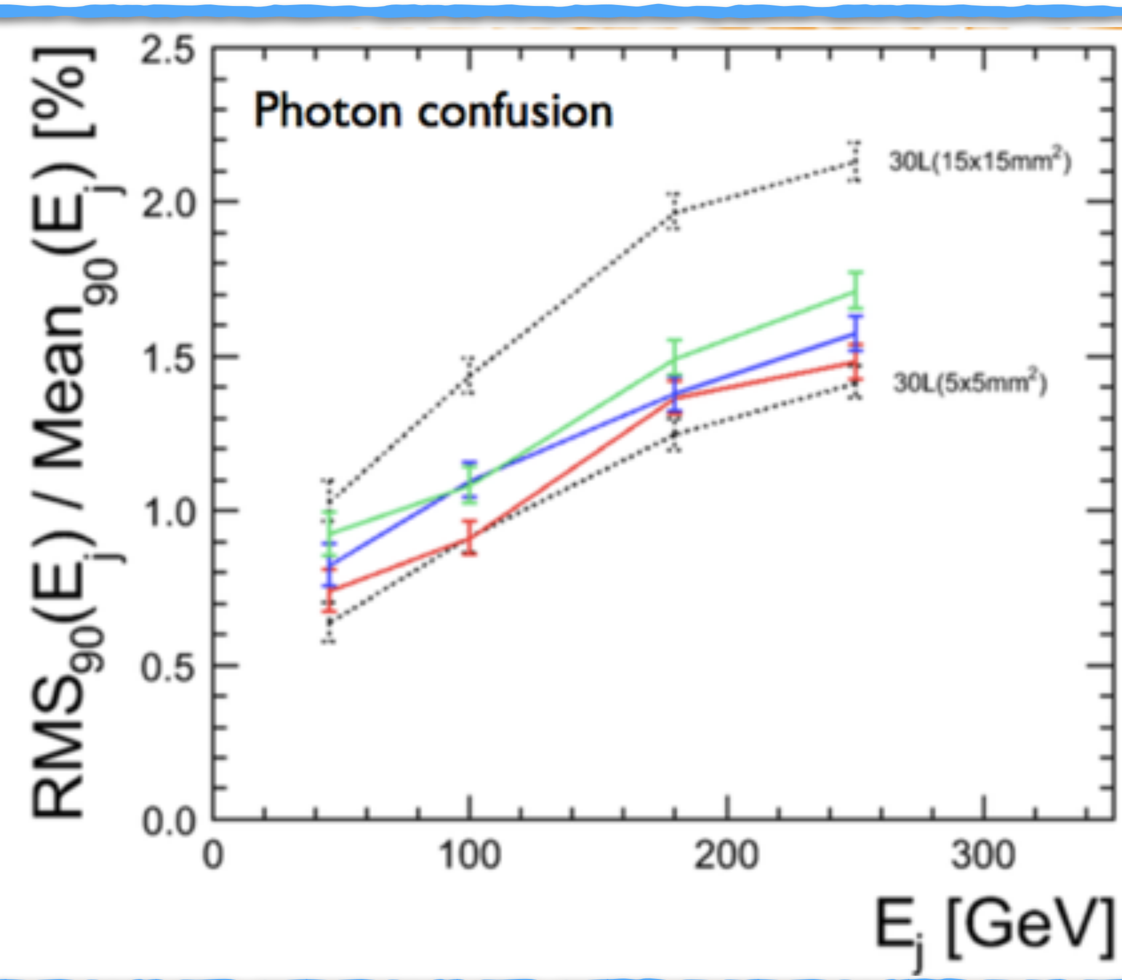
ECal Two Granularity Regions



- **Plot resolution vs. second cell size and vs. dividing layer**. Note: second cell size of 5mm and dividing layer of 30 both correspond to a uniform 5x5mm^2 ECal.
- **Key point: Fine granularity at the front of the ECal and coarse granularity from then on can produce high performance**.

ECal Three Granularity Regions



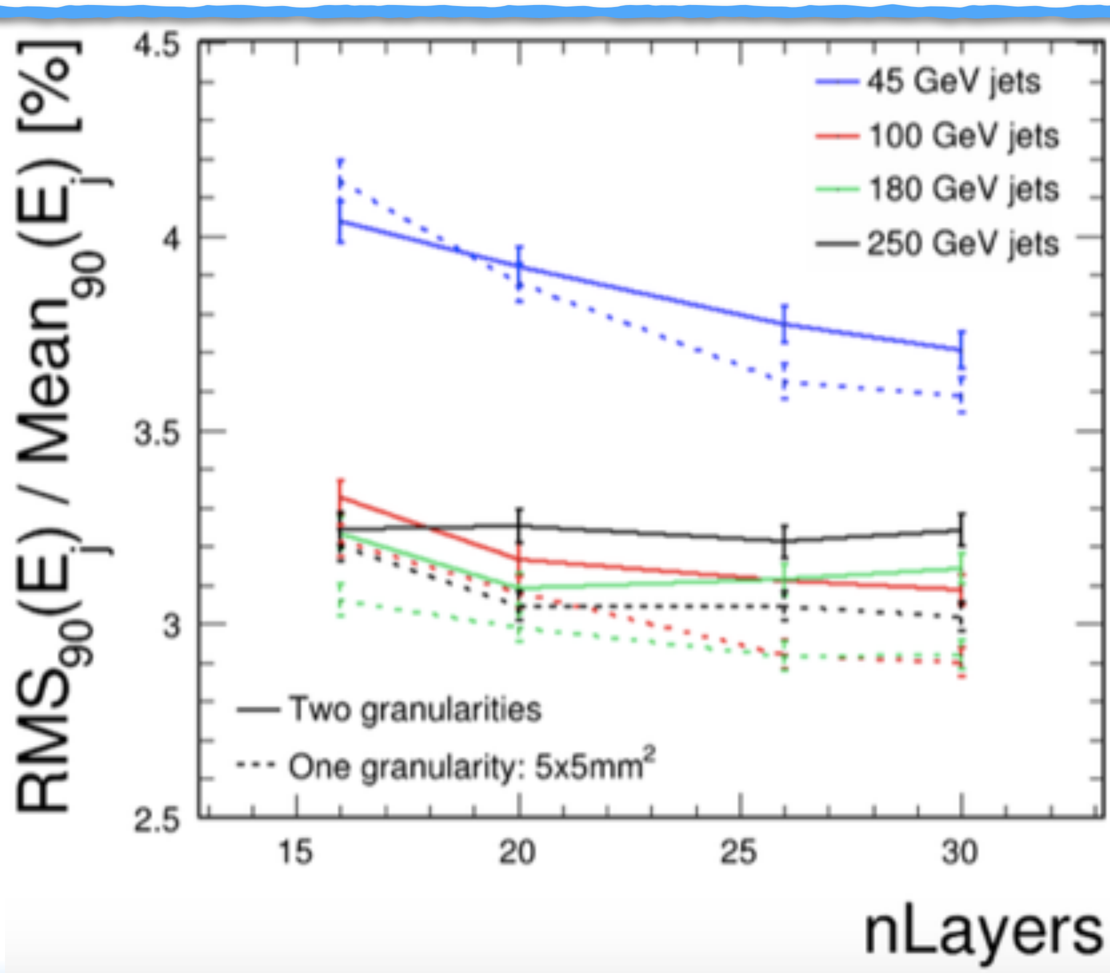


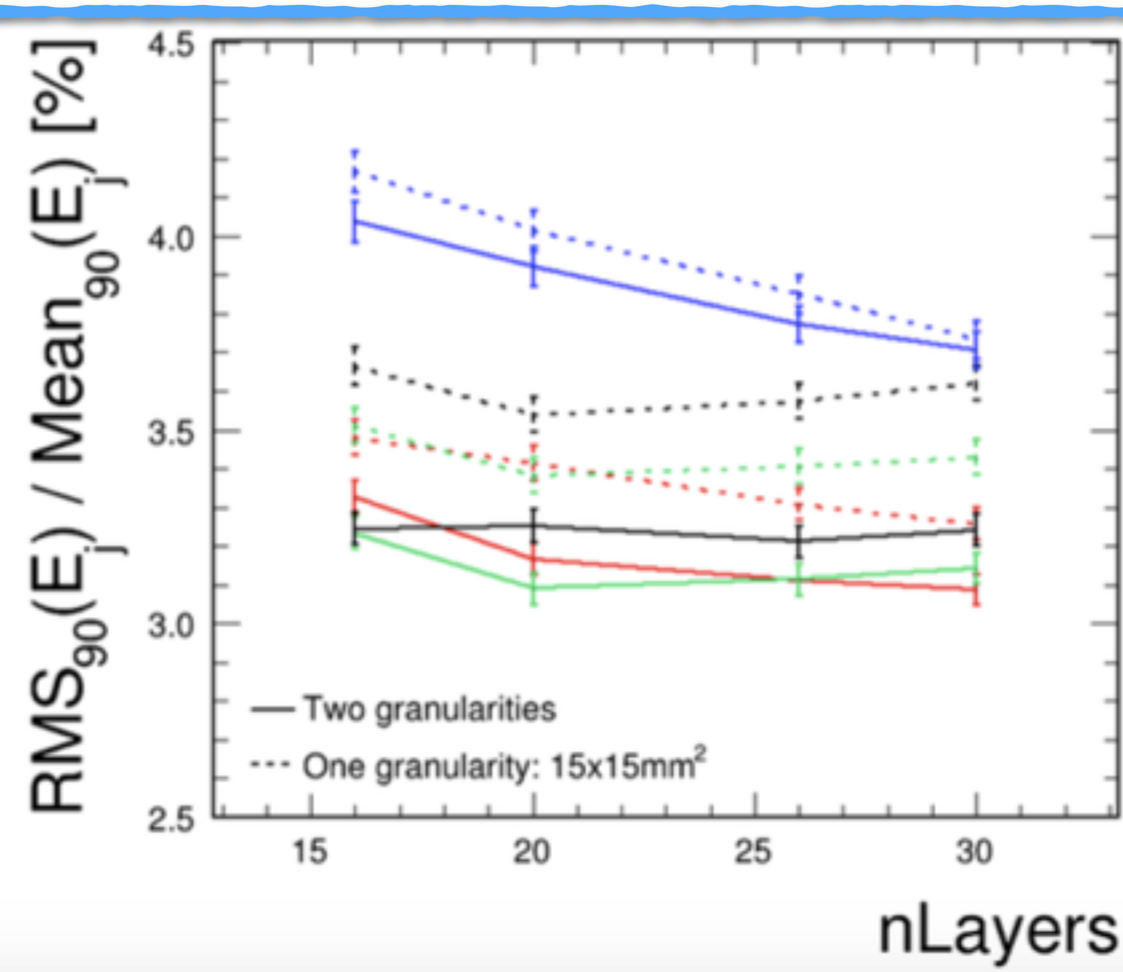
- **Extend study to examine ScW ECals with three granularity regions**. Compare resolutions with those for constant granularity and best two granularity model. Also examine photon confusion.
- Very Little degradation in jet energy resolution when changing last 10 layers from 15x15mm^2 to 20x20mm^2. Larger impact for 30x30mm^2, but resolution still better than constant 15x15mm^2.
- Support for hypothesis that **very fine granularity is only needed early in the calorimeter** and evidence that **Pandora algorithms can handle multiple discontinuities in cell sizes without issue**.

ECal Two Granularity and Layer Reduction

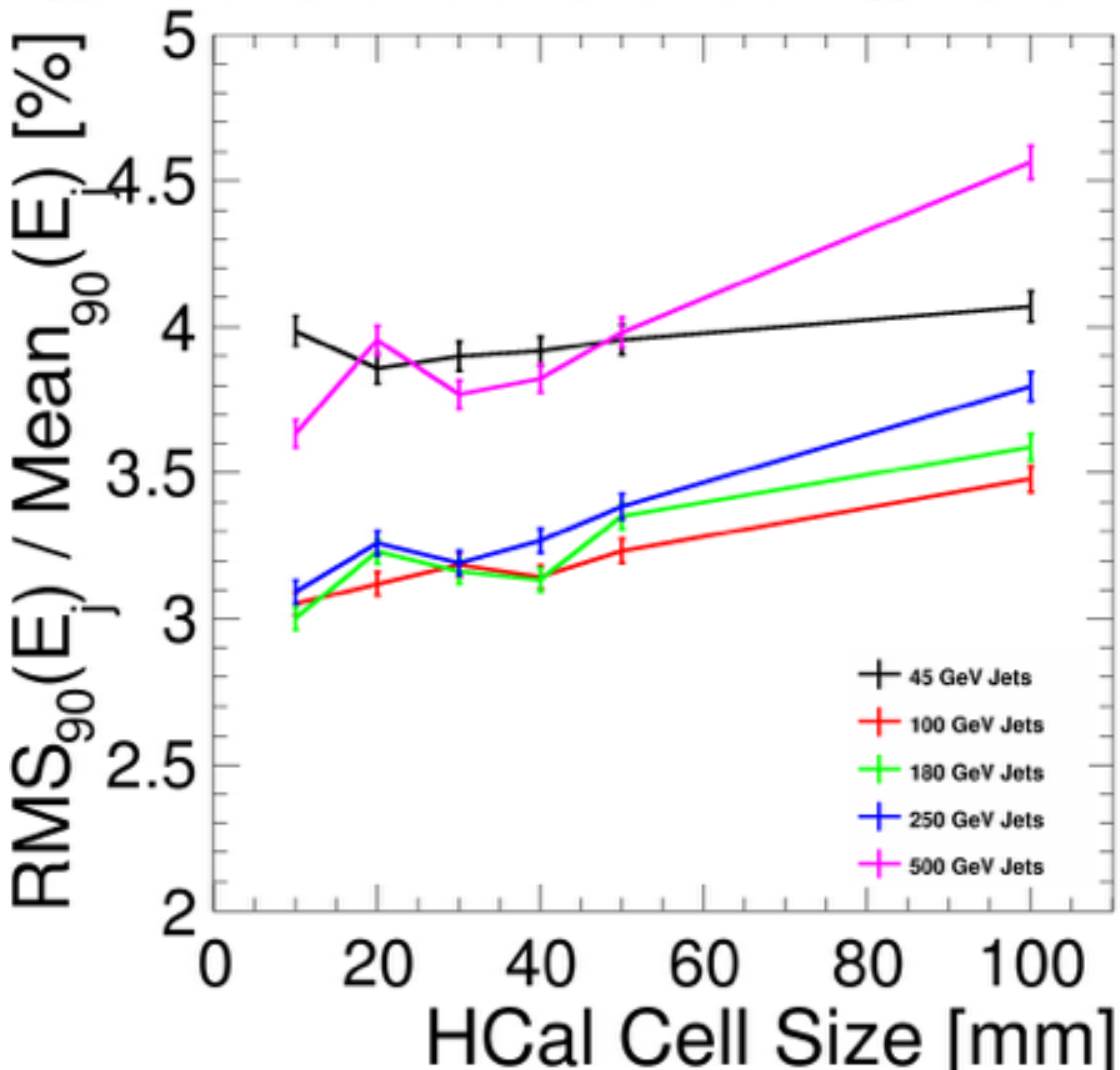
- Finally, study **ECal layer reduction in the context of a two granularity model**. The W absorber thicknesses remain as described on slide 7, but the transverse granularities are:
- Maintain roughly constant fraction of total layers with 5x5mm^2 granularity.
- As expected, resolutions flat wrt layer number at high E_j; performance closer to constant 5x5mm^2 than 15x15mm^2.

30 Layers	10L(5x5mm^2) + 20L(15x15mm^2)
26 Layers	9L(5x5mm^2) + 17L(15x15mm^2)
20 Layers	7L(5x5mm^2) + 13L(15x15mm^2)
16 Layers	6L(5x5mm^2) + 10L(15x15mm^2)





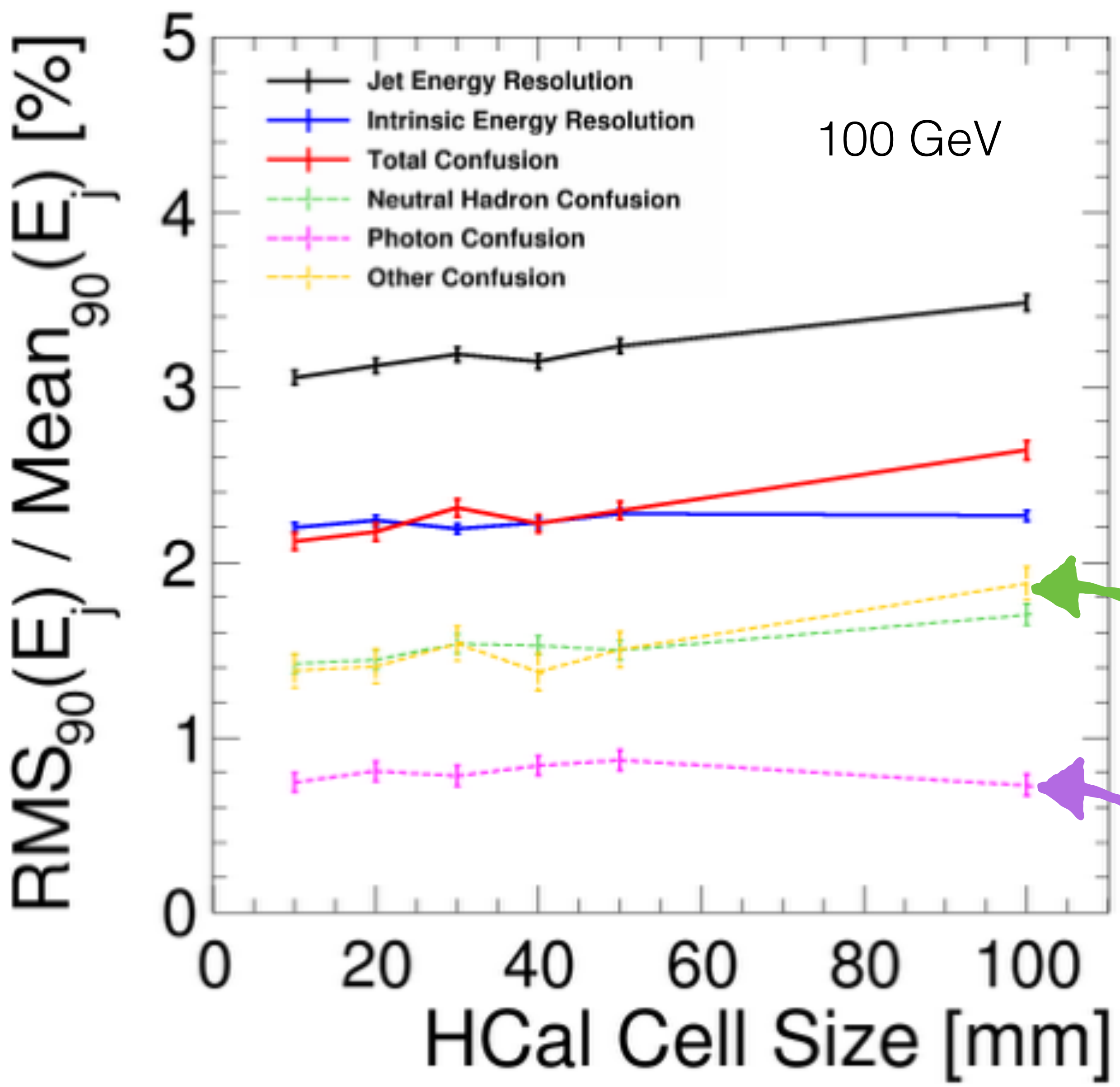
HCal Transverse Granularity



- Study the performance for a range of **different HCal cell sizes** (square cells).
- The range of HCal cell sizes used in this study was chosen by expanding around the default cell size of 30x30mm^2. A 100x100mm^2 data point was added to examine coarse transverse granularity in the HCal.
- Analogously to the ECal studies, we can **break down the jet energy resolution into the various confusion terms** by applying the MC "cheated" algorithms.
- A constant timing cut of 10 ns in the HCal was applied in these studies. These results were comparable to those using a semi-infinite (10^6 ns) timing cut.

- For the **45 GeV jets, the jet energy resolution is essentially flat wrt HCal cell size variations**. At this energy the jet energy resolution is dominated by intrinsic energy resolution.
- For **higher energy jets the jet energy resolution deteriorates with increasing HCal cell size**.

HCal Transverse Granularity

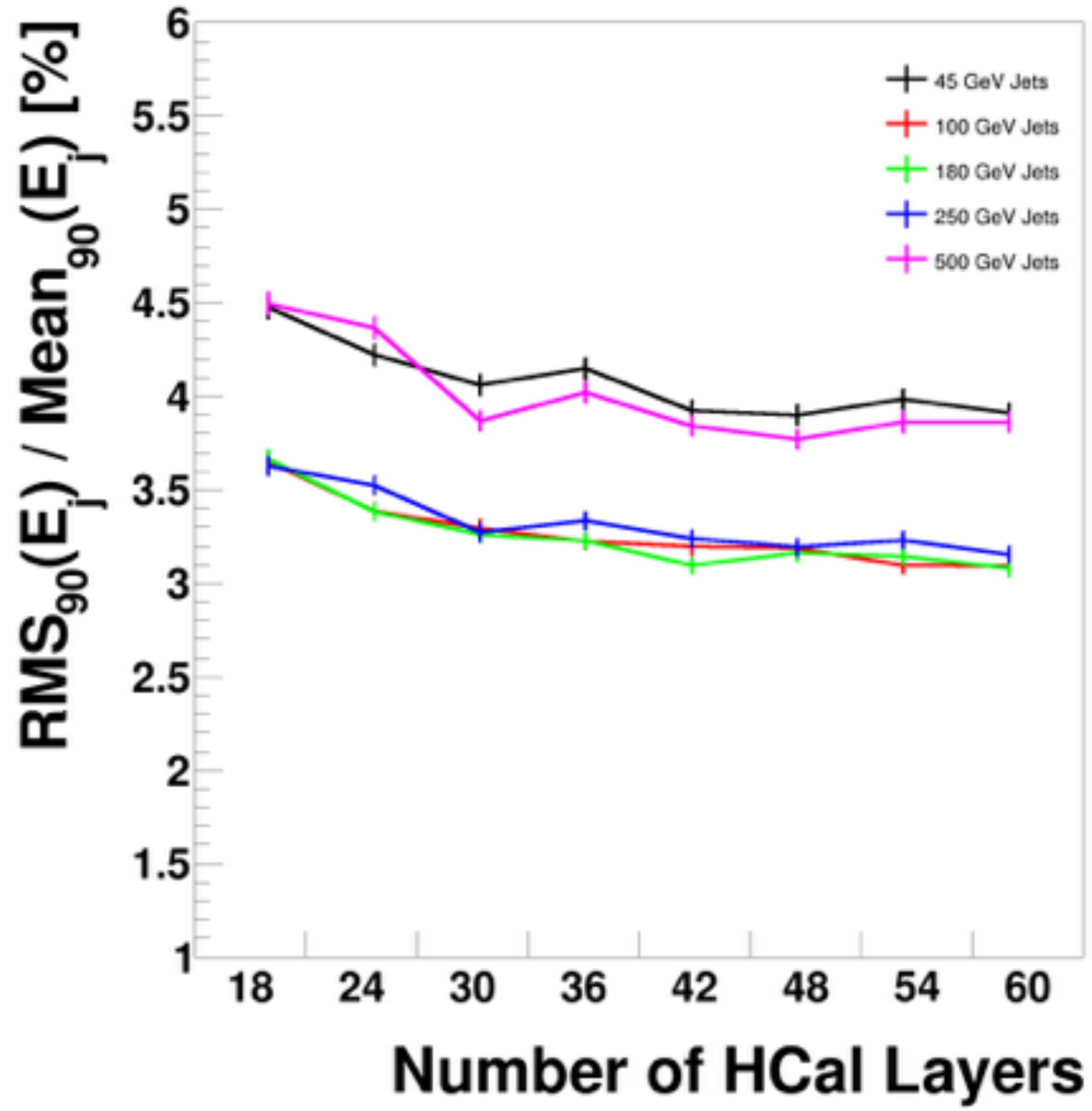


- As with the ECal studies, we can examine changes in performance between different algorithm configurations to explicitly determine confusion contributions. Contributions to overall resolution enter in quadrature.
- As expected, the **intrinsic energy resolution is flat with respect to changes in the HCal cell size**.
- Total confusion represents the difference between the best reconstructed resolution and perfect PFA; it comprises **neutral hadron confusion, photon confusion** and all "**other**" remaining contributions.

Neutral hadron and "other" confusion increase with increasing HCal cell size.

Photon confusion contribution is essentially flat with respect to HCal cell size.

HCal Longitudinal Granularity

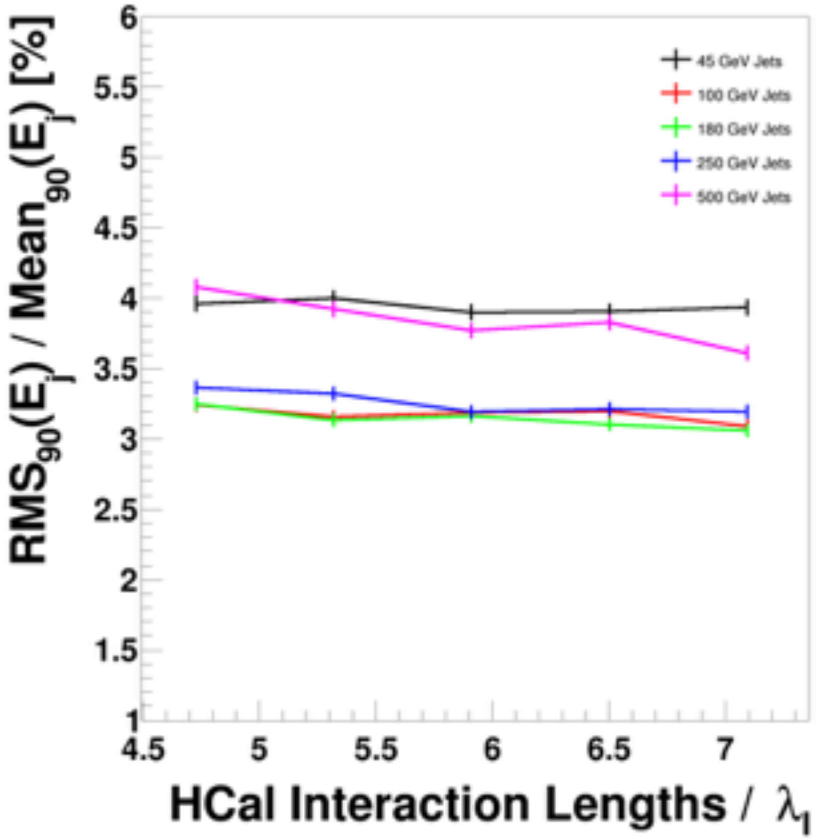


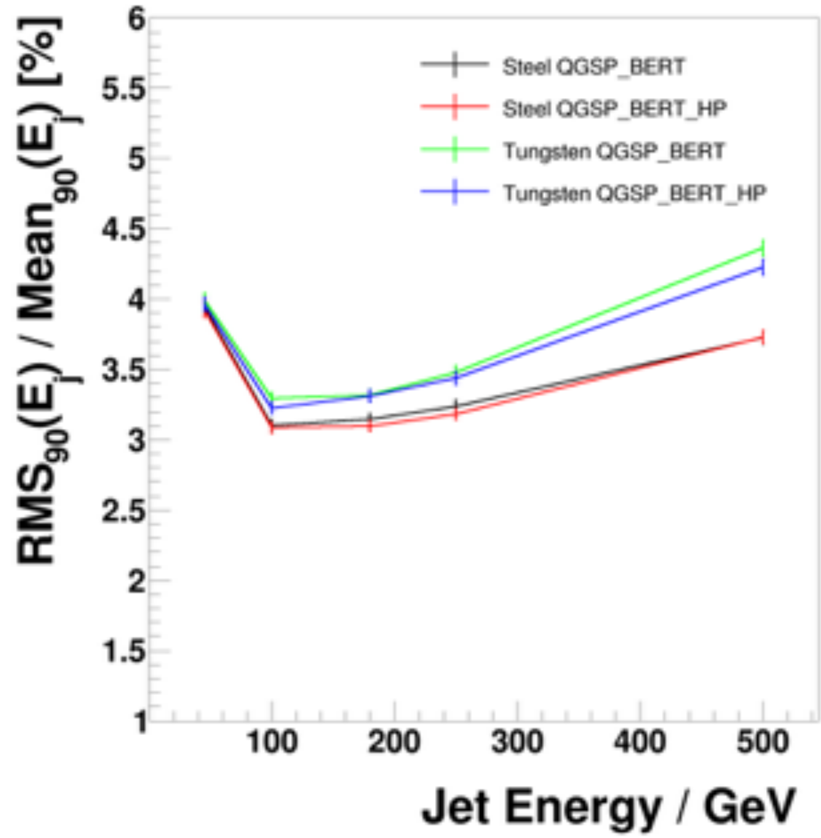
- This study examines the effect of **variations to the longitudinal granularity, or total number of layers contained within the HCal**.
- The range of longitudinal granularities used in this study was chosen by expanding around the default number of HCal layers (48). The expansion was extended towards lower number of HCal layers given the relatively flat distributions observed.
- The absorber and scintillator thicknesses were scaled such that the HCal in each detector model contained the same number of nuclear interaction lengths.

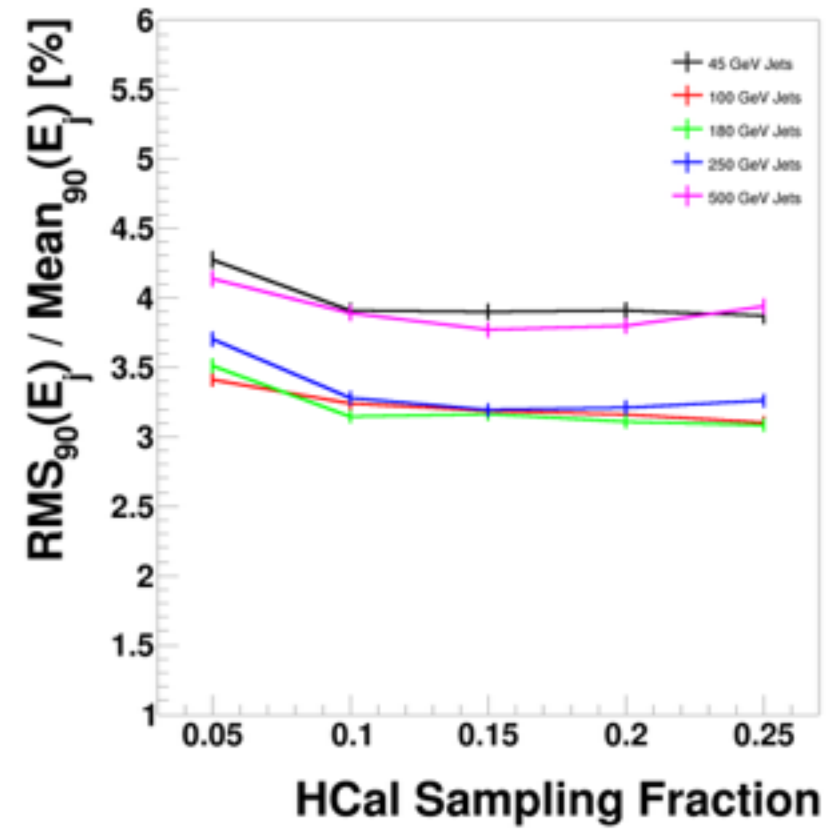
- **Finer longitudinal granularity in the HCal improves the jet energy resolution**. Benefit to jet energy with finer longitudinal granularity is comparable across all jet energies considered.
- **Relatively flat trends observed around the default number of HCal layers.**

Other HCal Optimisation Studies

- A number of other HCal related optimisation studies have been performed including optimisation of **absorber material, sampling fraction and total number of nuclear interaction lengths** in the HCal.



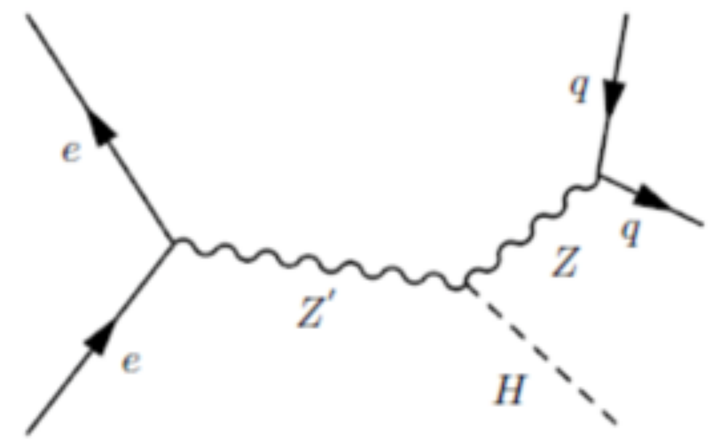




- **The jet energy resolution is invariant to chances in the number of nuclear interaction lengths in the HCal except for high energy** (greater than 250 GeV) jets.
- **Steel outperformed tungsten** as an absorber material.
- **Changes to sampling fraction do not change the jet energy resolution** given sufficient sampling of the shower (i.e, sampling fraction > 0.05)

ECal Granularity - Physics Study

- An **invisible Higgs study** was performed in which a direct comparison between jet energy resolution and physics performance could be examined.
- **Increasing the ECal cell size**, which degrades the jet energy resolution, **causes worse selection of invisible Higgs events**.



- Singal: Higgsstrahlung events with final state of two jets + missing energy
- Background:
  - Other HZ events (WW, ZZ, ɣɣ, $\tau\tau$)
  - 4 jet and 2 jet SM events

ECal Cell Size	5x5mm² SiW	15x15mm² SiW	Ratio
Δσ(H→inv)	0.430%	0.447%	+3.9%
Jet Energy Resolution	2.96	3.31	+11.8%

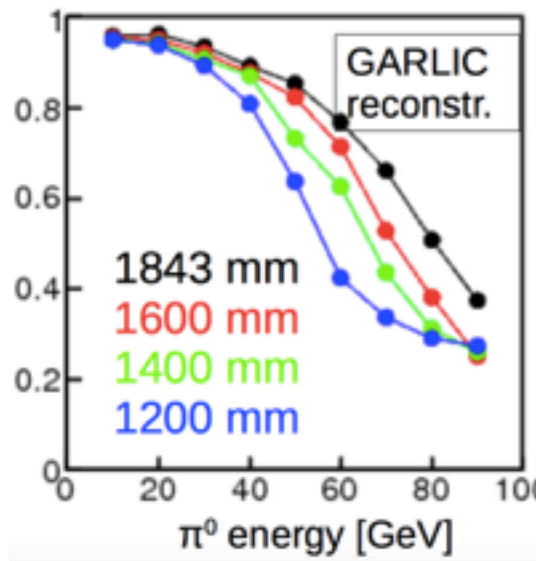
K.Mei

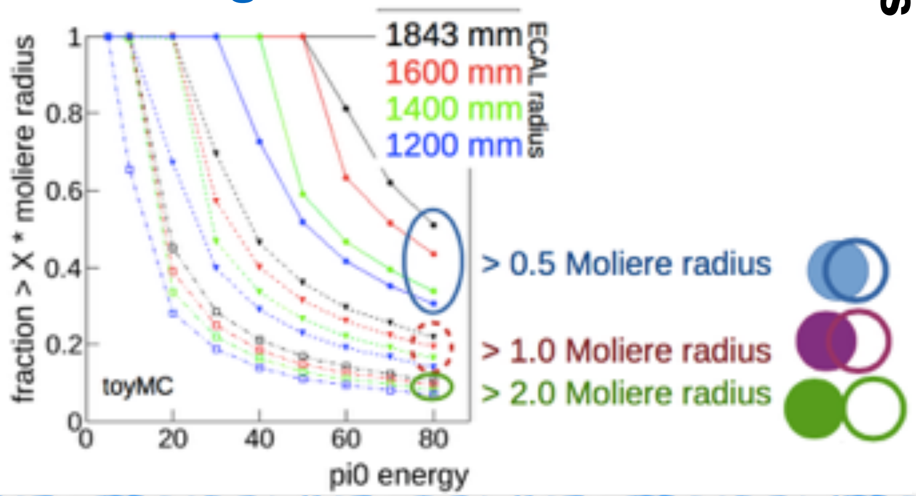
$$\Delta\sigma = \frac{\sqrt{N_{back}}}{N_{sig,100\%}}$$

Complementary Studies

There are a large number of other interesting studies based on the ILD calorimeters, which have not been covered in depth. Here are a few selected studies:

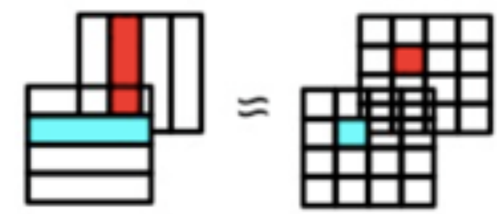
- **π^0 reconstruction efficiency as a function of inner ECal radius** using GARLIC instead of PandoraPFA.
- It was found that **reduction of the ECal radii causes a reduction in the π^0 reconstruction efficiency**.
- This will be due to the **reduction in the photon separation at the calorimeters with decreasing ECal inner radius**.



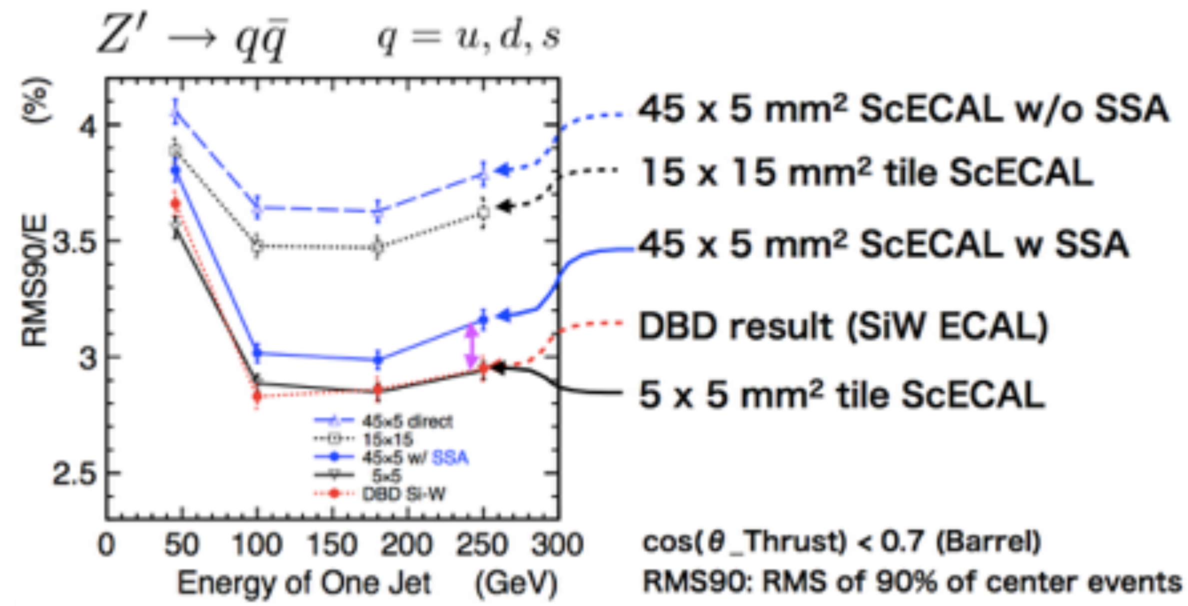


D. Jeans

- **Strip segmentation of active material in ECal** used to reduce the number of read out channels from ~10^8 to ~10^7.



- Strip splitting algorithm developed to read out the strip active elements and convert these into virtual square cells.



K. Kotera

- **Very encouraging jet energy resolution achieved using the strip splitting algorithm.**
- For further details see: doi:10.1016/j.nima.2015.04.001

Semi-Digital HCal

- An ongoing study is being performed comparing the **performance of a semi-digital HCal** (SDHCal) and the default analogue HCal.
- SDHCal has three threshold levels; triggered based on the amount of charge deposited in a calorimeter cell.
- An **energy correction plugin** has been implemented in Pandora, which returns an accurate energy measurement for a cluster of calorimeter hits, based on the number of hits passing the various thresholds.
- Latest work is determining calibration of the SDHCal.

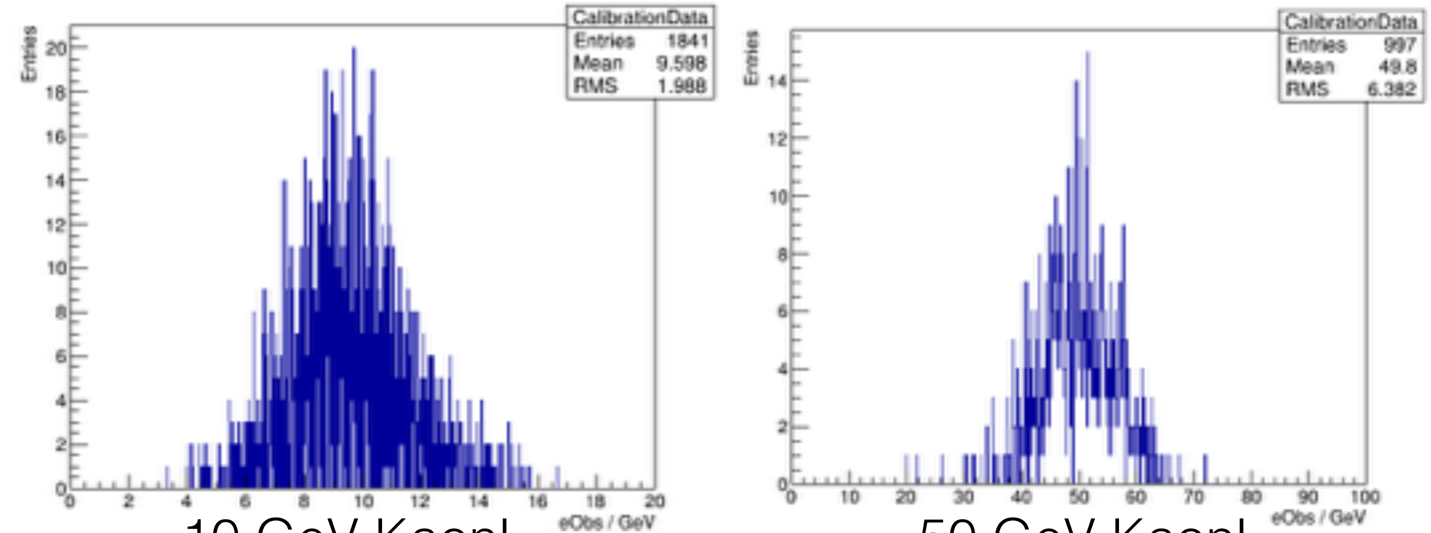
This is a joint study between the University of Cambridge and CALICE (collaborating with University of Lyon).

Digitisation

Hadronic energy estimator:

Cluster Energy = a * N1 + b * N2 + c *N3

a, b and c digitisation constants



10 GeV KaonL

50 GeV KaonL

PandoraPFA Calibration

Corrected hadronic energy estimator:

$$\text{Cluster Energy} = \alpha * N1 + \beta * N2 + \gamma * N3$$

$$\alpha = C1 + C2 * N + C3 * N^2$$

$$\beta = C4 + C5 * N + C6 * N^2$$

$$\gamma = C7 + C8 * N + C9 * N^2$$

N is total number of hits. N1, N2, N3 are number of hits passing various thresholds. C1 to C9 are constants.

Conclusions

- A **great deal of information** relating to calorimeter granularities has been produced in the studies summarised here, which will be of **great benefit when considering the optimisation** of the calorimeters.
- The results produced, ranging from a physics study to reconstruction efficiency plots and the jet energy resolution studies, show a **crucial dependance on the granularity** of the calorimeters.
- In summary we have found that **finer granularity will benefit detector performance** in both the ECal and the HCal, but that the magnitude of the benefit depends crucially on the granularity in question and in the ECal very good performance can be achieved by using novel granularity models.
- It is important to have fine transverse granularity early on in the calorimeters to aid pattern recognition in the particle flow paradigm.
- High quality performance can be achieved using fine transverse granularity early on in the ECal despite having coarse granularity towards the back of the ECal.
- Detector performance is relatively insensitive to the HCal transverse granularity for all but the largest cell sizes, ~50x50mm^2 and greater.
- The detector performance is also relatively insensitive to variations in the longitudinal granularity of the calorimeters. Any sensitivity to longitudinal granularity observed is dominated by the intrinsic energy resolution.

ECal Studies summary slides (J. Marshall): http://www.hep.phy.cam.ac.uk/~marshall/ECAL_marshall_plot_selection.pdf
HCal Studies summary slides (S.Green): https://indico.cern.ch/event/384099/contribution/2/material/slides/0.pdf

Thank you for your attention!