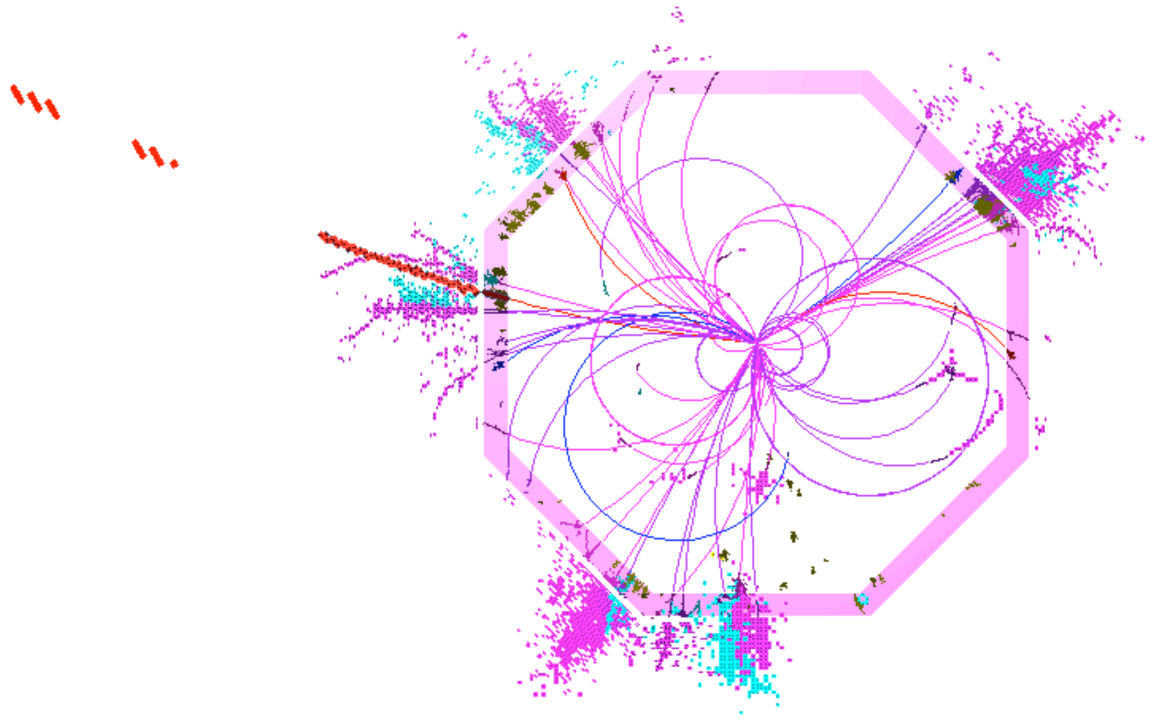

ECAL Simulation Studies

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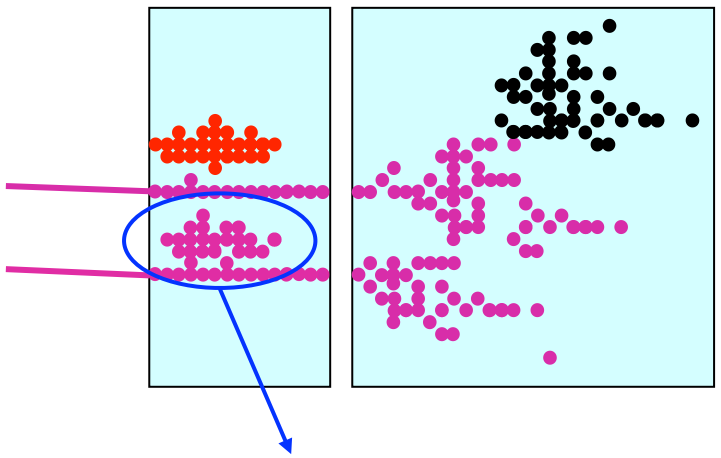
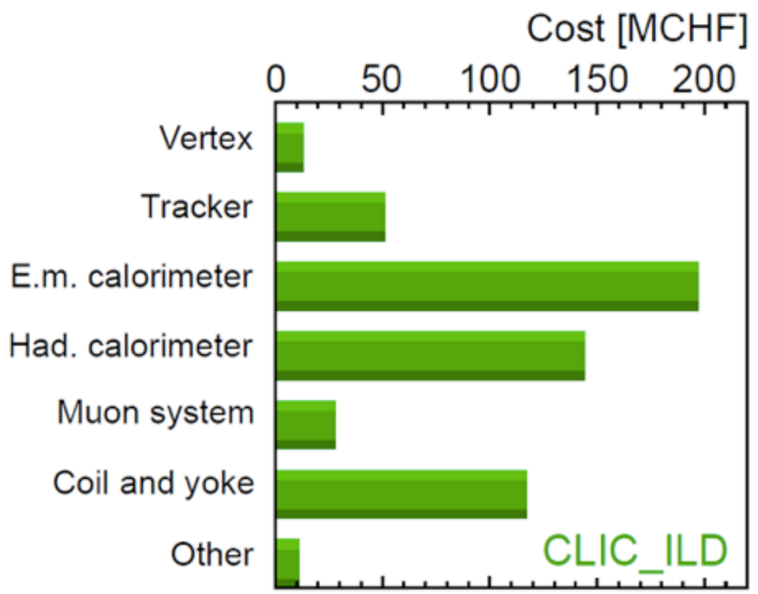
ILD Meeting, 25th September 2013

ECAL Simulation Studies

- Role of the ECAL is to measure energies of photons, and the early parts of hadronic showers, and to enable EM shower ID.
- In a particle flow approach, use pattern recognition algorithms to separate the energy deposits from different particles.
- Photons may be close together, or may overlap with charged hadrons, so require fine segmentation to allow separation.



- Granularity requirements and use of silicon as active material make the ECAL a very expensive component of the detector.
- This year, launched a new working group to develop a more cost-effective ECAL model for ILC and CLIC.
- Particle flow relies on both hardware and software: aim to develop full understanding of both to make recommendation.



New contributions welcome! Mailing list: lcd-ecal@cern.ch

Indico category: http://indico.cern.ch/categoryDisplay.py?categId=4379

ECAL Simulation Studies

- In this talk, will discuss results from a series of simulation studies, which focus on measuring and understanding jet energy resolutions. The starting point is the SiW ECAL in ILD_o1_v05:
  - 20 x 2.1mm + 9 x 4.1mm W absorber, representing $23X_0$ or $1\lambda_I$
  - 29 x 0.5mm Si active material, divided into $5.1 \times 5.1 mm^2$ pixels.
- Cheaper ECAL models could use Si for first few active layers, then move to scintillator (Sc) deeper in the calorimeter, using SiPM read-out. Sc cells sizes may then increase with depth.

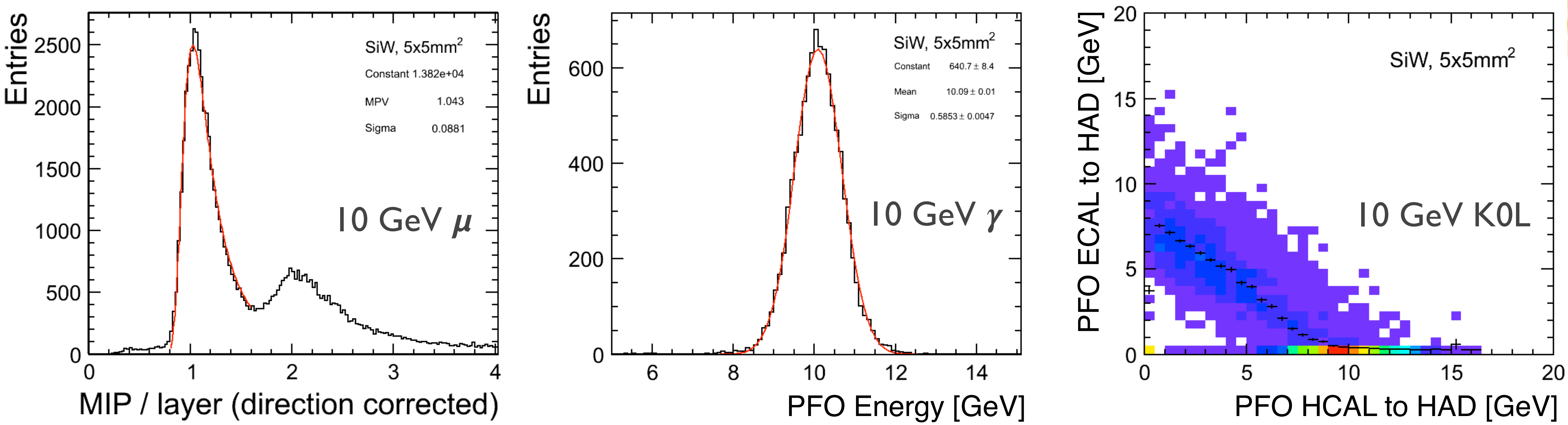
- Begin by comparing the performance of simple SiW and ScW ECALs. Then proceed to investigate the following parameters, building progressively more complex ECAL models:
  - Transverse granularity,
  - Regions of different transverse granularity,
  - Si/Sc hybrid models,
  - Number of ECAL layers.
- The particle flow approach means that the jet energy reconstruction performance will depend critically on the pattern recognition, not just the intrinsic calorimeter energy resolution.

To reproduce this work: use Mokka trunk rev. 445, with ILD_o1_v05 and SEcal05 driver; PandoraPFA trunk rev. 1402; IlcSoft v01-16-02 (GEANT4 9.5.p02) and QGSP_BERT physics list.

- For each ECAL model, determine calibration constants using 10 GeV γ, μ and K0L samples. Leave HCAL constants unchanged from DBD. For SiW expect entire calibration to remain unchanged.
  1. Set digitisation constant, "CalibrECAL", so sum of all hit energies peaks at 10GeV for γ.
  2. Set MIP constant so that direction corrected MIP/layer distribution peaks at 1.0 for μ.
  3. Run particle flow reconstruction for γ and K0L, with MIP cuts (0.5 for ECAL, 0.3 for HCAL).
  4. Examine distributions of PFO ECALToEM/HAD energy vs HCALToEM/HAD energy and set:

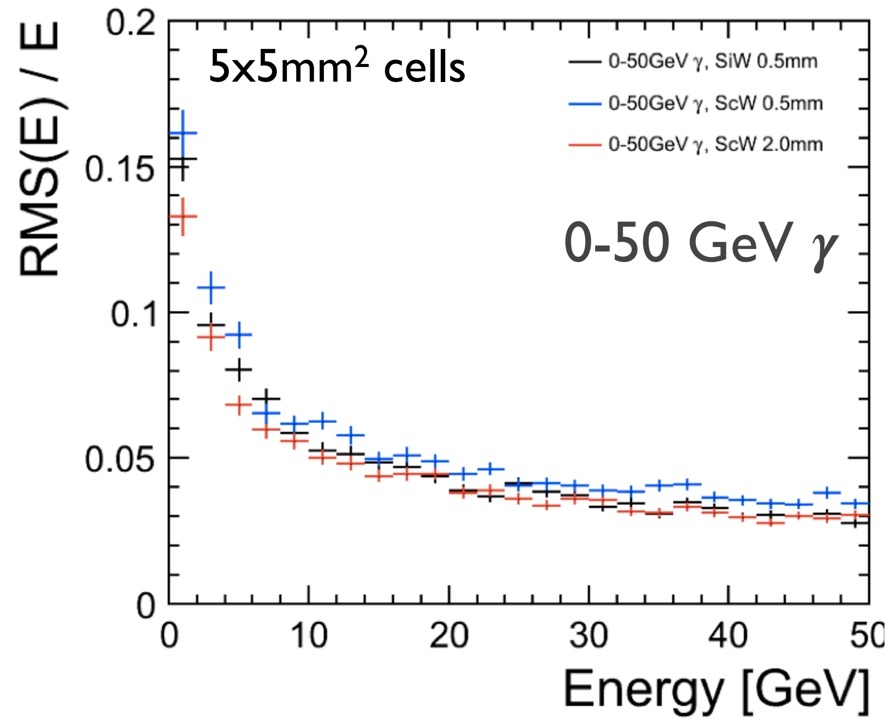
     ECALToEM: weight for ECAL energy deposits identified as part of EM showers

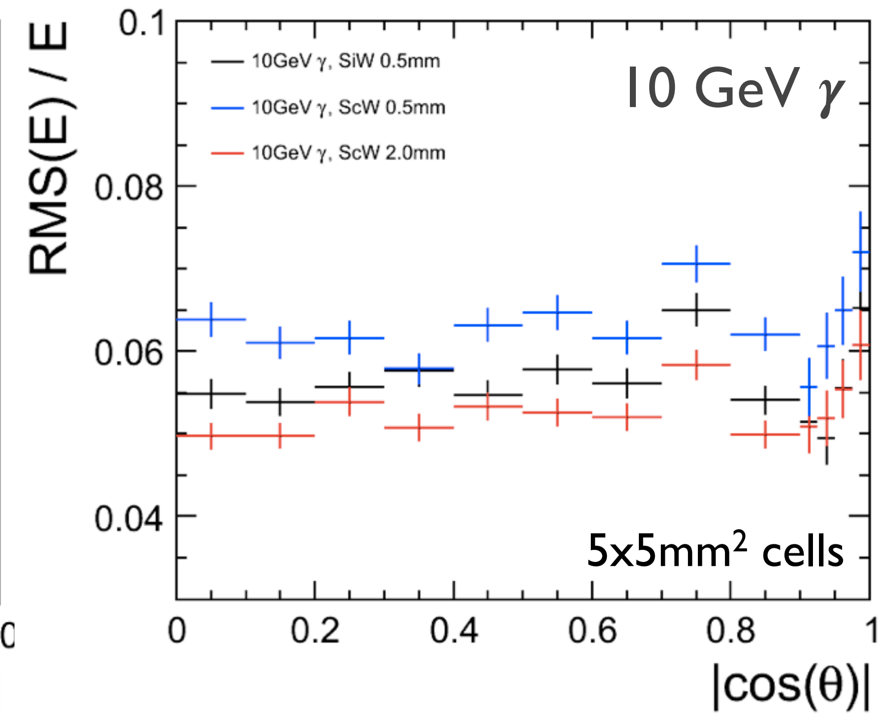
     ECALToHAD: weight for ECAL energy deposits identified as part of hadronic showers

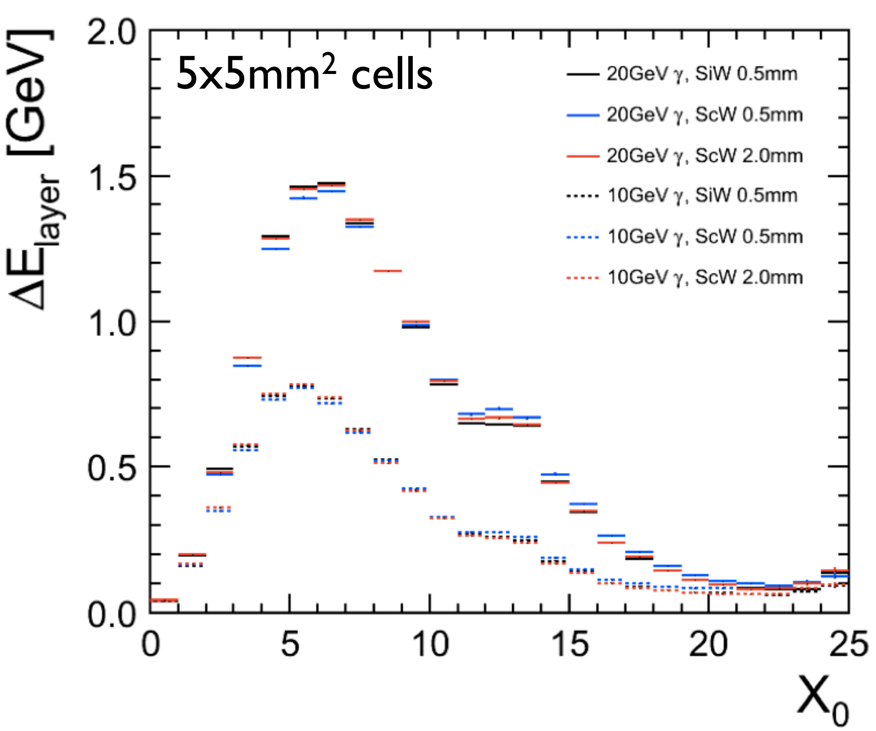


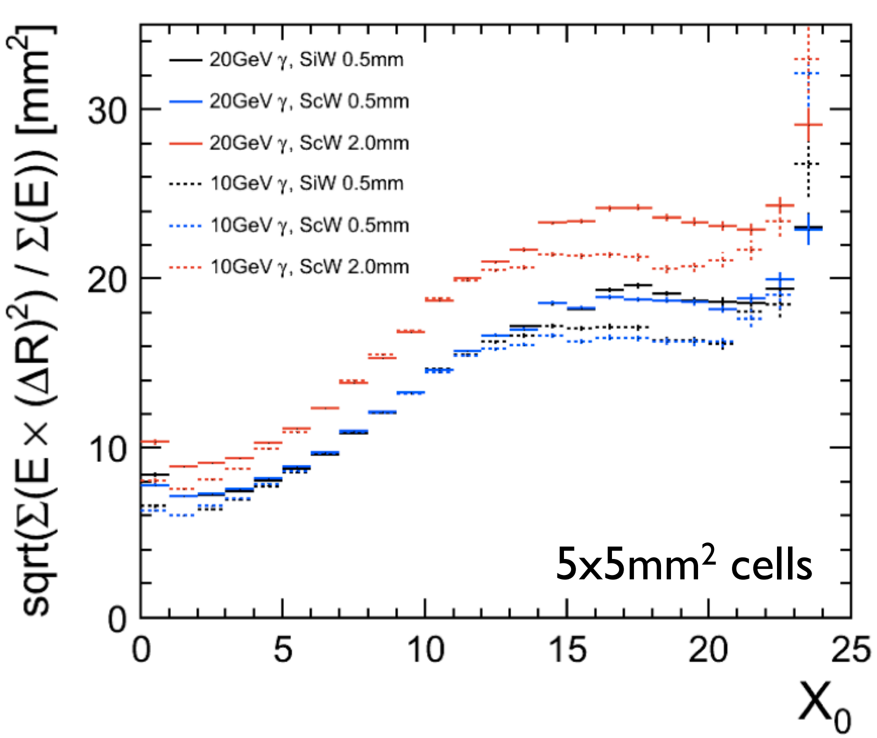
Single Particle Studies

- Compared to SiW ECAL, energy resolution:
  - Improves with 2.0mm Sc
  - Degrades with 0.5mm Sc
- Resolutions flat in barrel region for all models.
- For first studies, use a default Sc thickness of 2.0mm.









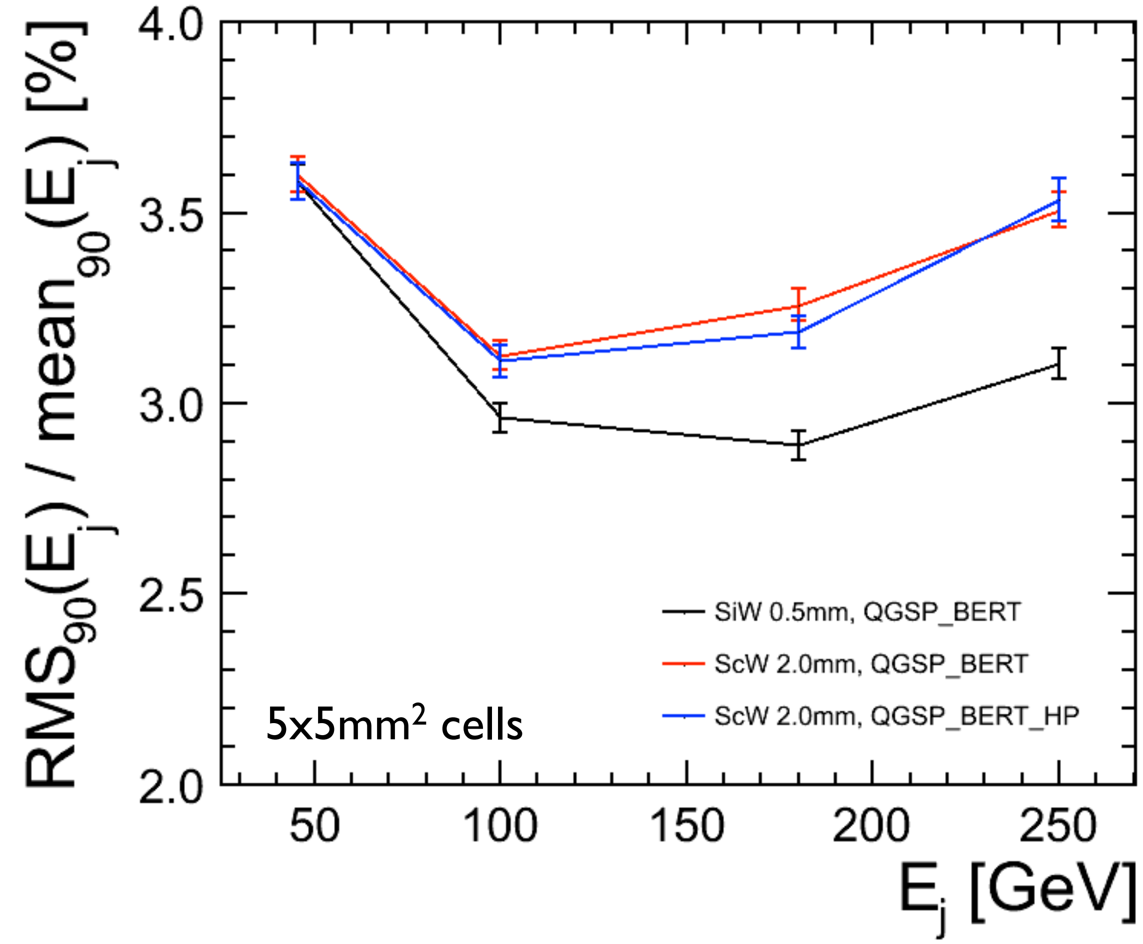
- Examine EM shower profiles:
- Longitudinal profiles same for SiW and ScW ECALs.
- EM showers noticeably wider with 2.0mm Sc thickness; may increase confusion for PFA.

Jet Energy Resolution Studies

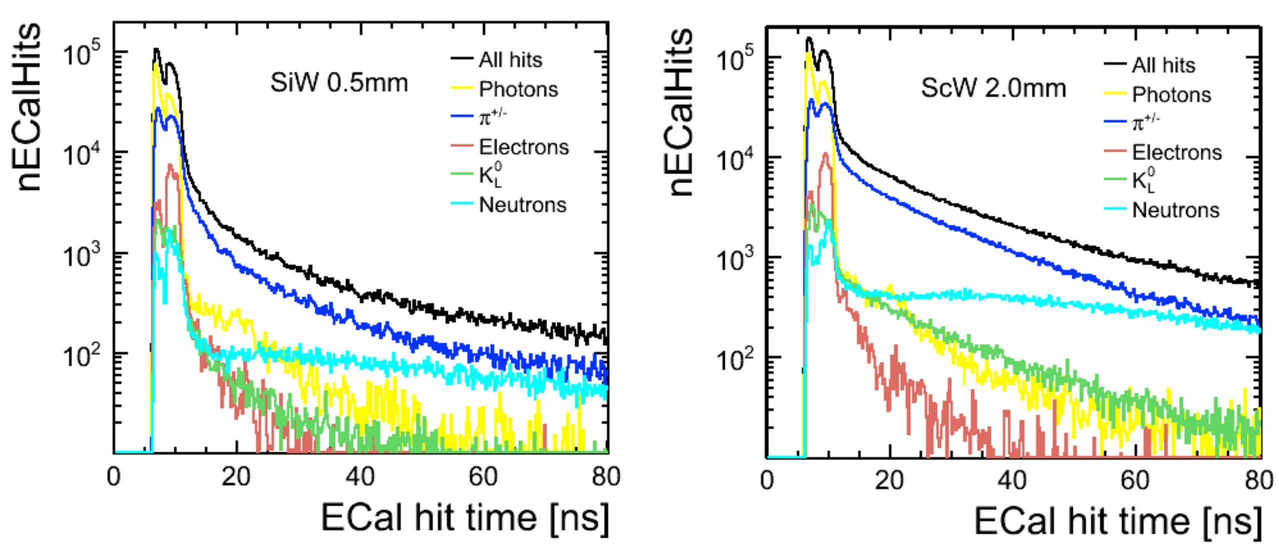
- Assess jet energy resolution using Zs at different E decaying at rest into light quarks.
- Produce two mono-energetic jets. Obtain jet energy resolution from total PFO energy:

$$\frac{RMS_{90}(E_j)}{mean_{90}(E_j)} = \frac{RMS_{90}(E_{jj})}{mean_{90}(E_{jj})}\sqrt{2}$$

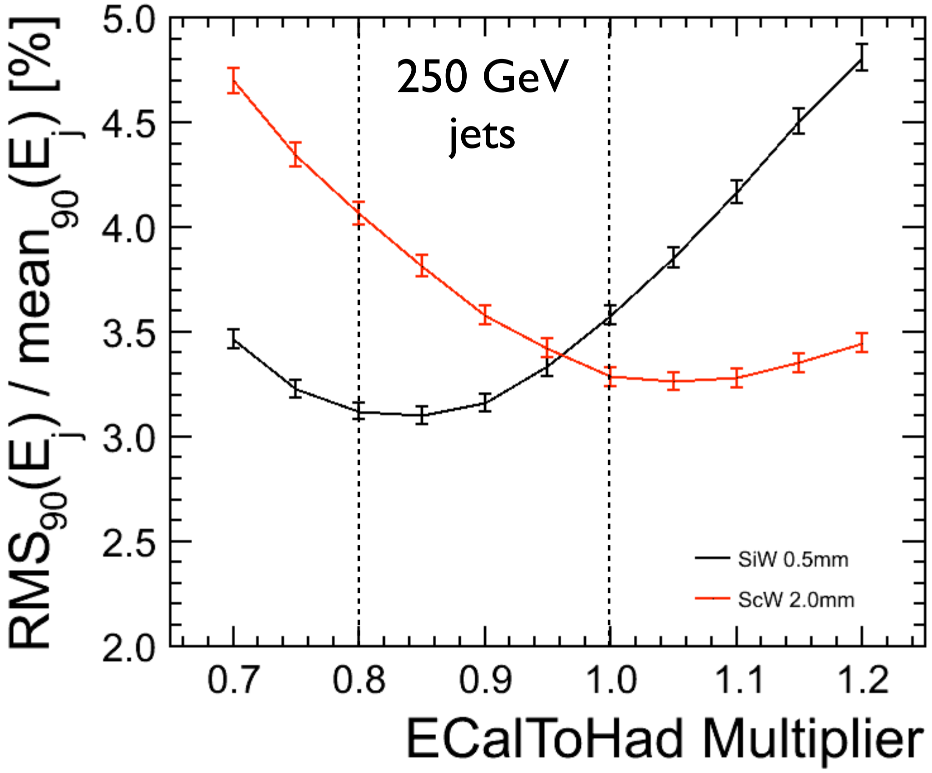
- Initial resolutions for 5x5mm² ScW rather poor above 45 GeV (compared to SiW).
- Used QGSP_BERT_HP to check problem wasn't due to (sensitivity to) poorly modelled neutron component.
- Decided to apply ECAL timing window of 20ns in digitisation (more realistic approach).
- During recalibration process, noticed that ECALToHAD constant is very important...

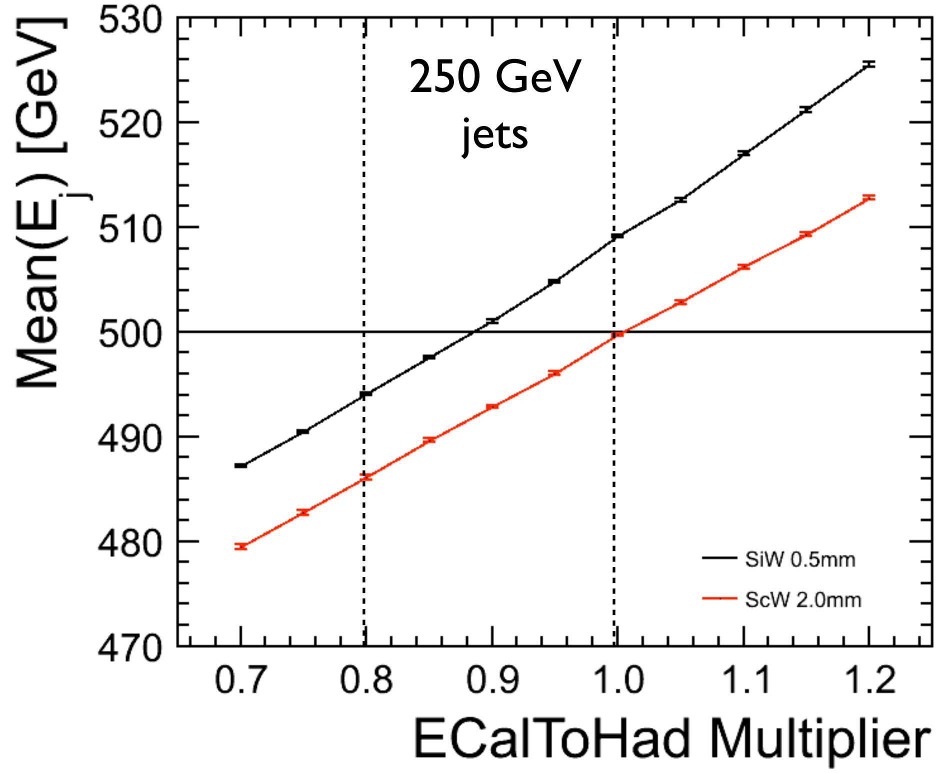


Component SimCalorimeterHits:

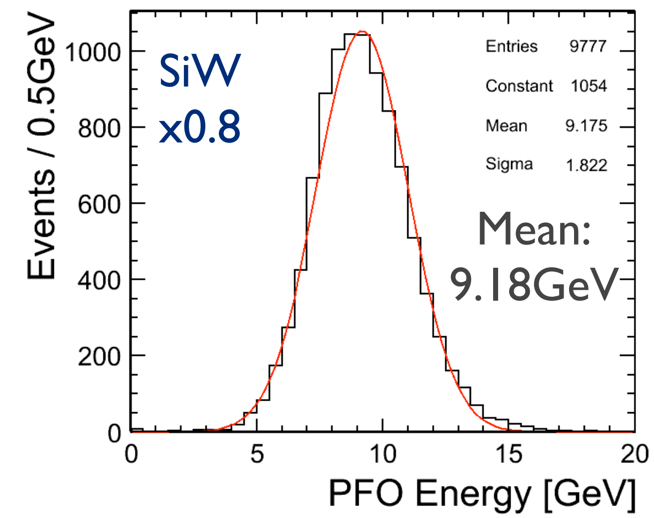


ECALToHAD Parameter Scan

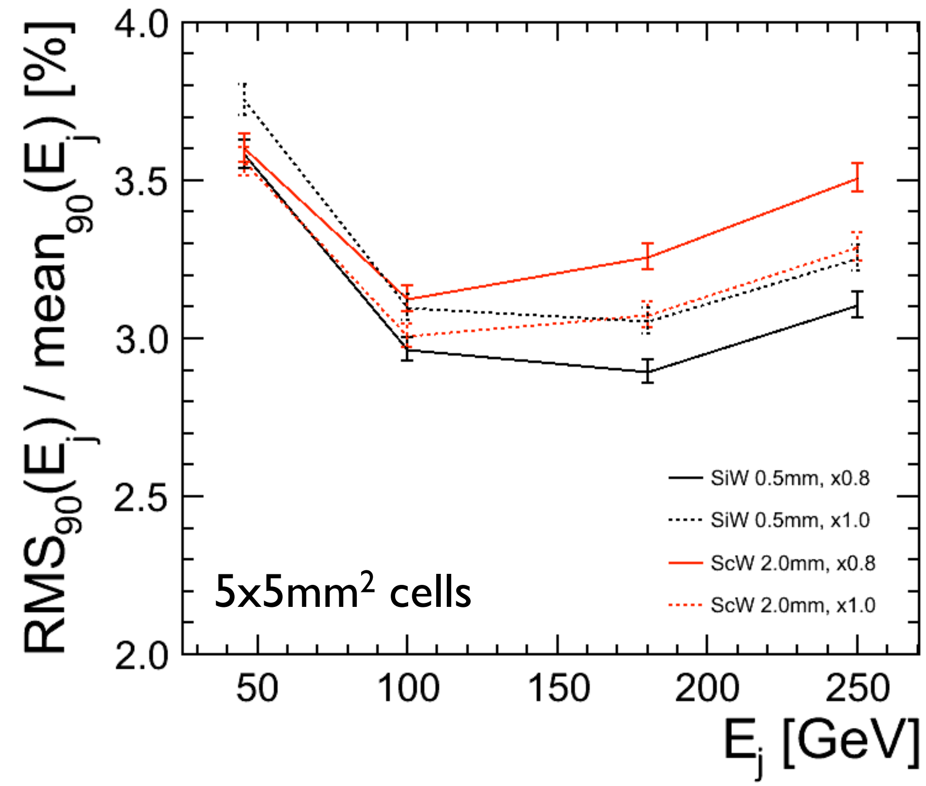




For 10 GeV K0L sample:



- Examine variation of jet energy resolution, for 250 GeV jets, in a sweep through a range of ECALToHAD values.
- Values centered around basic 10 GeV K0L calibration, x1.0. Observe different behaviour for SiW and ScW:
- For SiW, optimal jet energy resolution achieved if ECAL contribution to hadronic showers is deweighted: x0.8
- For ScW, optimal jet energy resolution is achieved with the calibration motivated by 10GeV K0L sample: x1.0

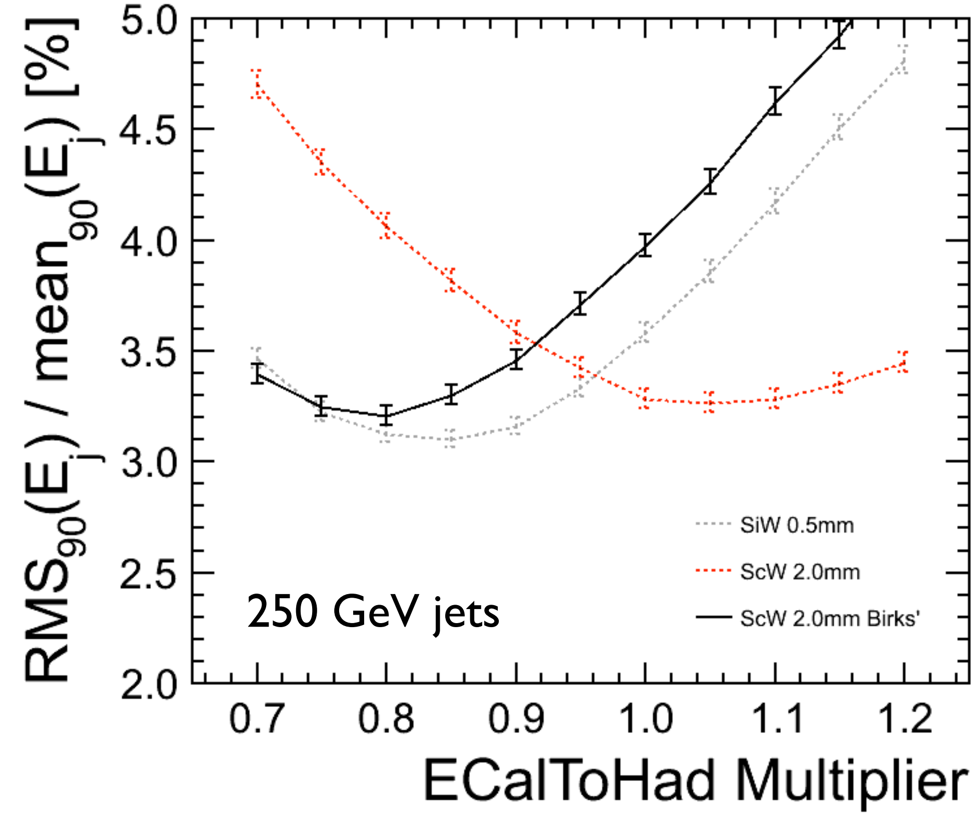


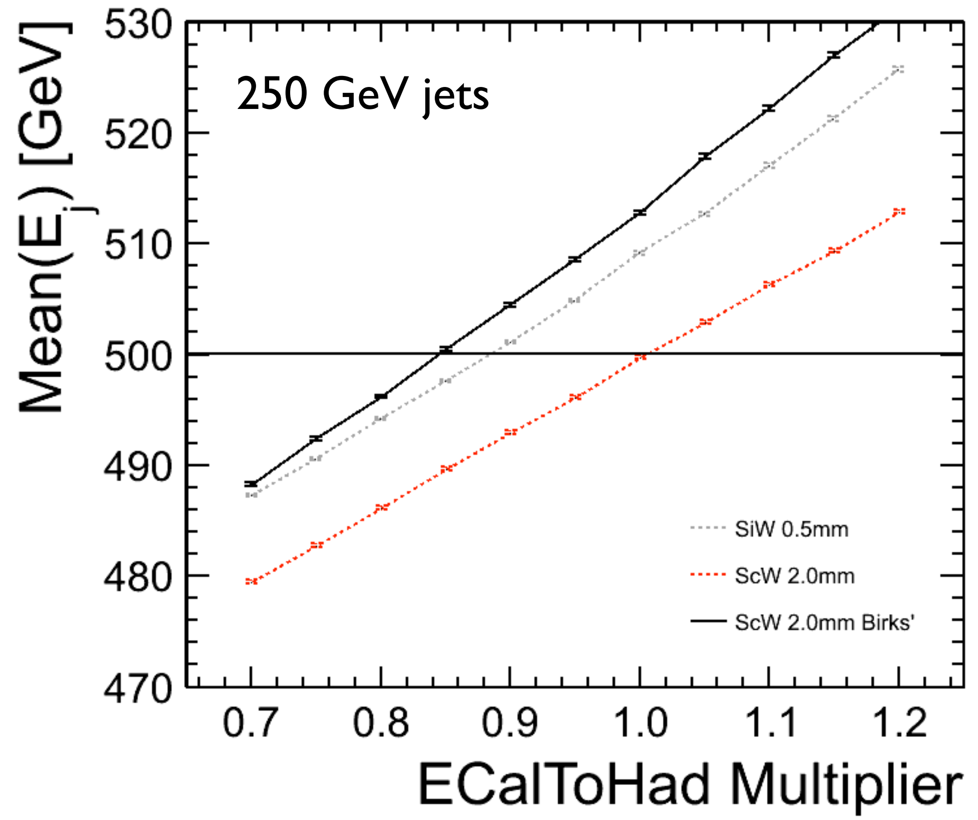
Birks' Law

- Must also remember that organic scintillator does not respond linearly to ionisation density.
- Dense ionisation columns emit less light than expected on the basis of dE/dx for MIP.
- Birks' Law gives empirical formula for light yield per path length and is included in Mokka SEcal05 driver:

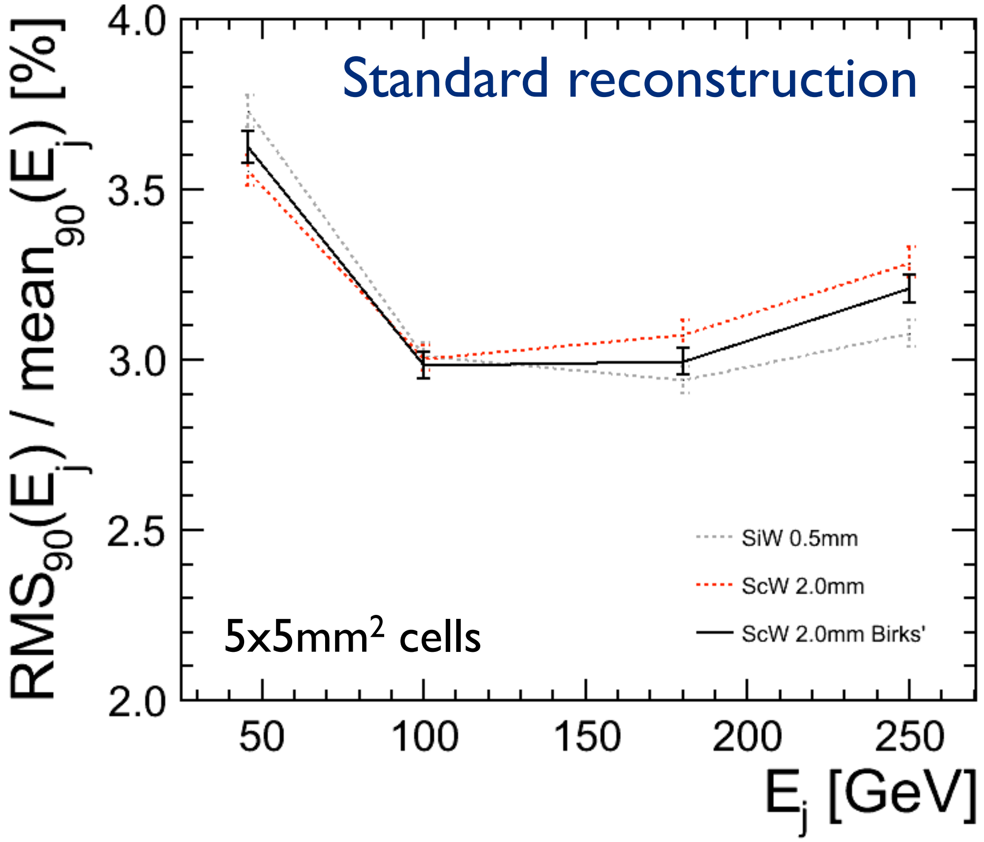
$$\frac{d\mathscr{L}}{dx} = \mathscr{L}_0 \frac{dE/dx}{1 + k_B\, dE/dx}$$

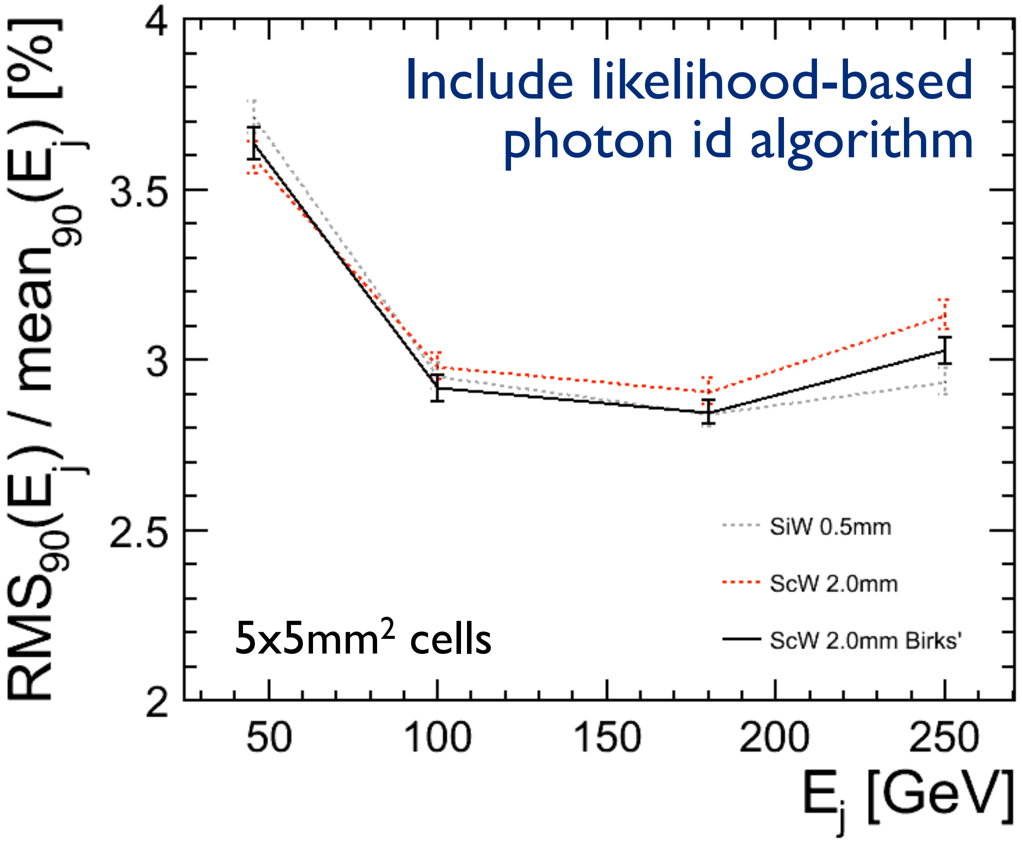
- Birks' Law has a significant impact on ScW ECAL:
  - As expected, CalibrECAL constant increases.
  - Dramatic change in response of jet energy resolution to variation of ECALToHAD constant.
  - Plots of jet energy resolution vs. ECALToHAD multiplier now very similar for ScW and SiW.
  - Adjusting ScW ECALToHAD value accordingly (x0.8), obtain improved jet energy resolutions.





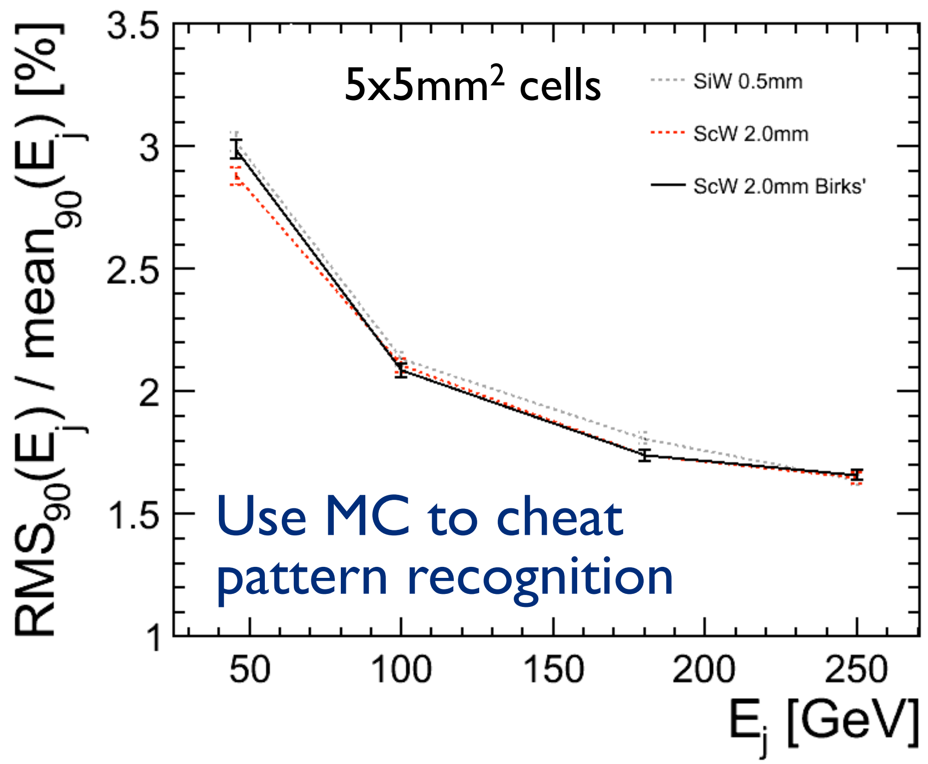
SiW vs. ScW, 5x5mm^2 Cells





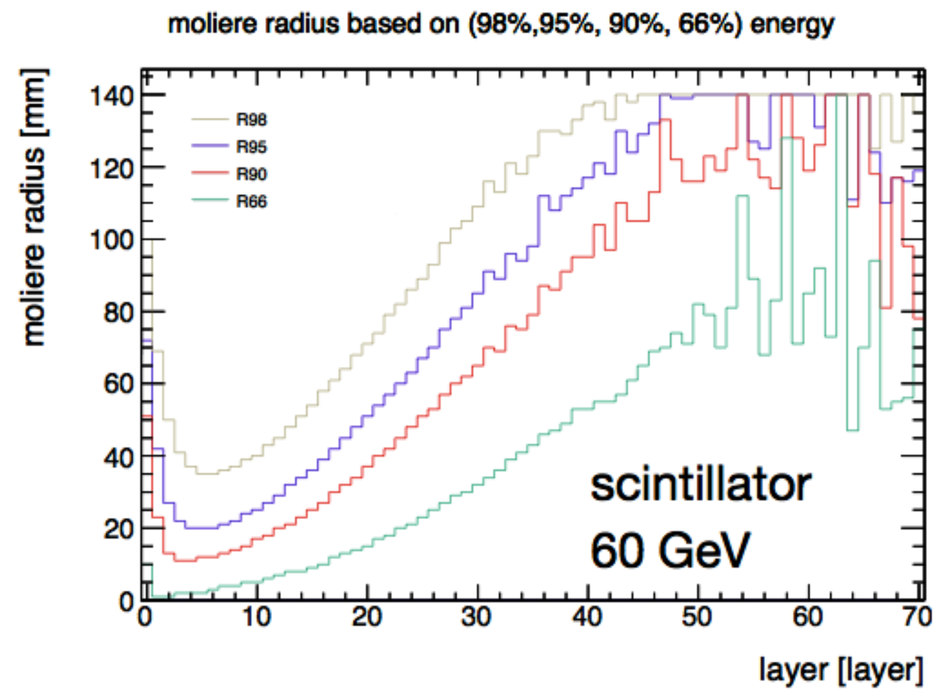
- With tuned ECALToHAD and inclusion of Birks' Law, obtain similar performance for SiW and ScW ECALs.
- Resolutions identical if cheat the pattern recognition.

250 GeV	SiW 0.5mm	ScW 2.0mm	ScW + Birks'
Standard	3.08%	3.28%	3.21%
Photon alg.	2.94%	3.13%	3.02%
Perfect PFA	1.64%	1.64%	1.66%

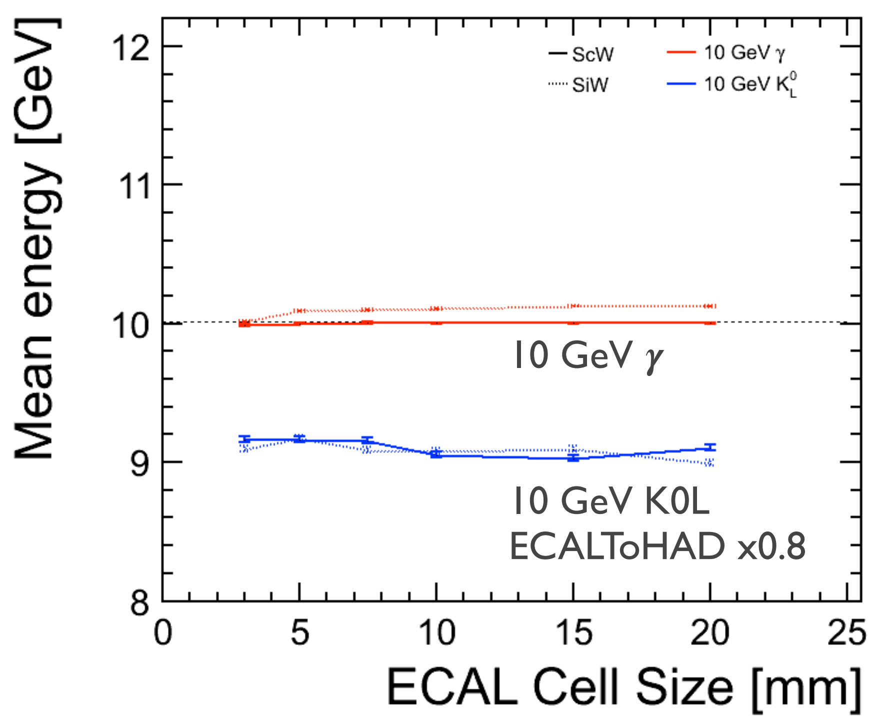


Transverse Granularity Study

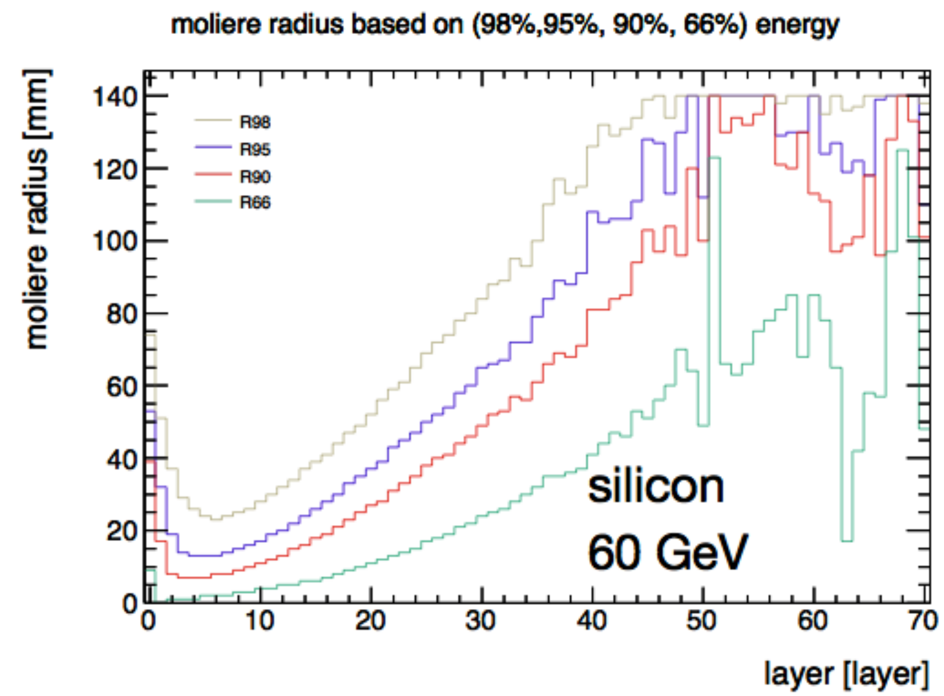
- Study SiW/ScW performance with range of different cell sizes. Keep cells square to reduce algorithm tuning:
  - $3x3$ mm^2, $5x5$ mm^2, $7.5x7.5$ mm^2, $10x10$ mm^2, $15x15$ mm^2 and $20x20$ mm^2
- This range of cell dimensions was motivated by studies of transverse shower size as function of depth.
- Aim to understand how contributions to jet energy resolution vary with cell size, so try gradually swapping Pandora algorithms with MC "cheating" versions.



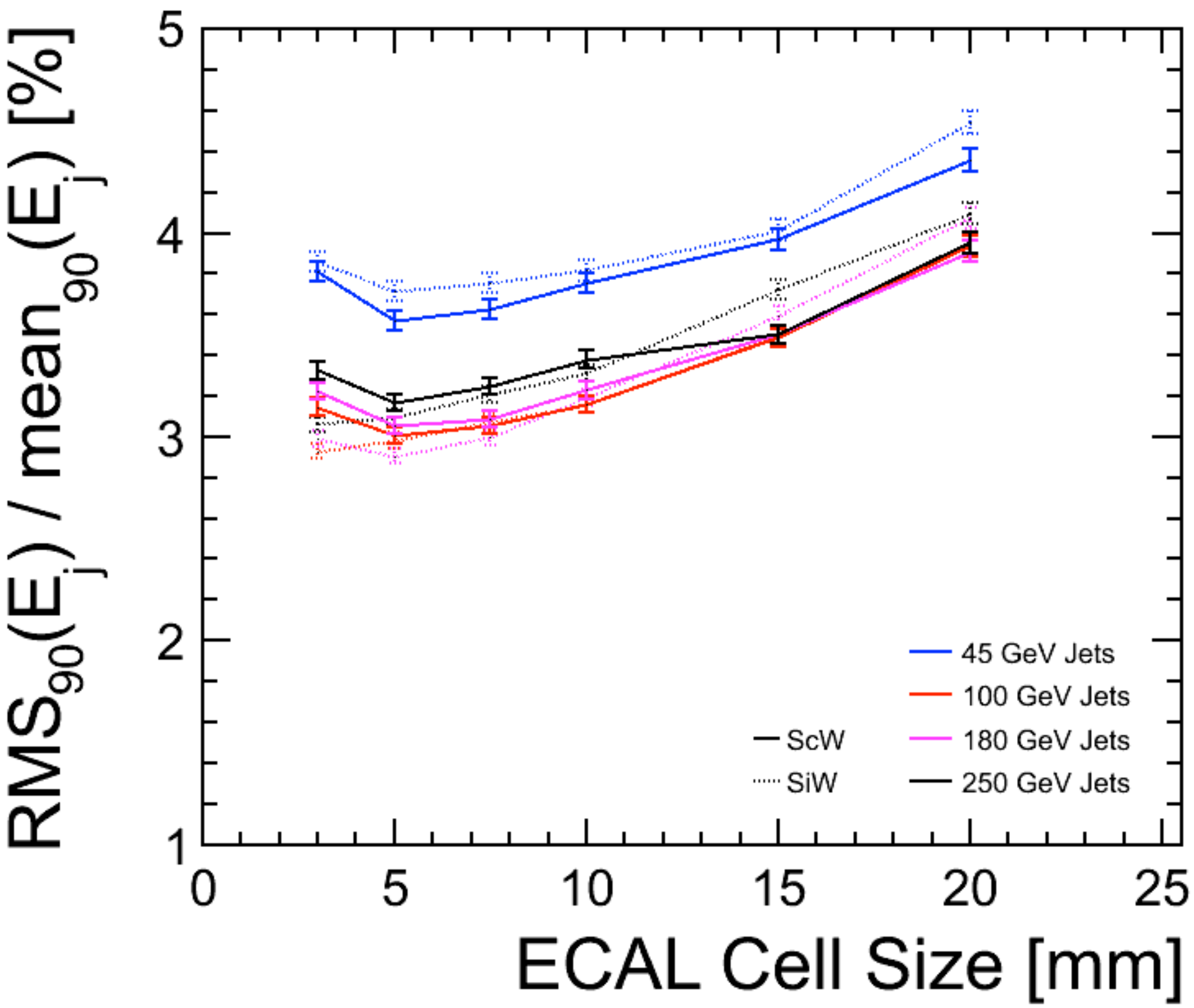
D. Schoke, F. Simon
ECAL Meeting 15.04.2013



- Check calibration with different cell sizes:
- SiW: same calibration works for all samples.
- ScW: necessary to recalibrate for each scintillator tile size.



Standard Pandora PFA

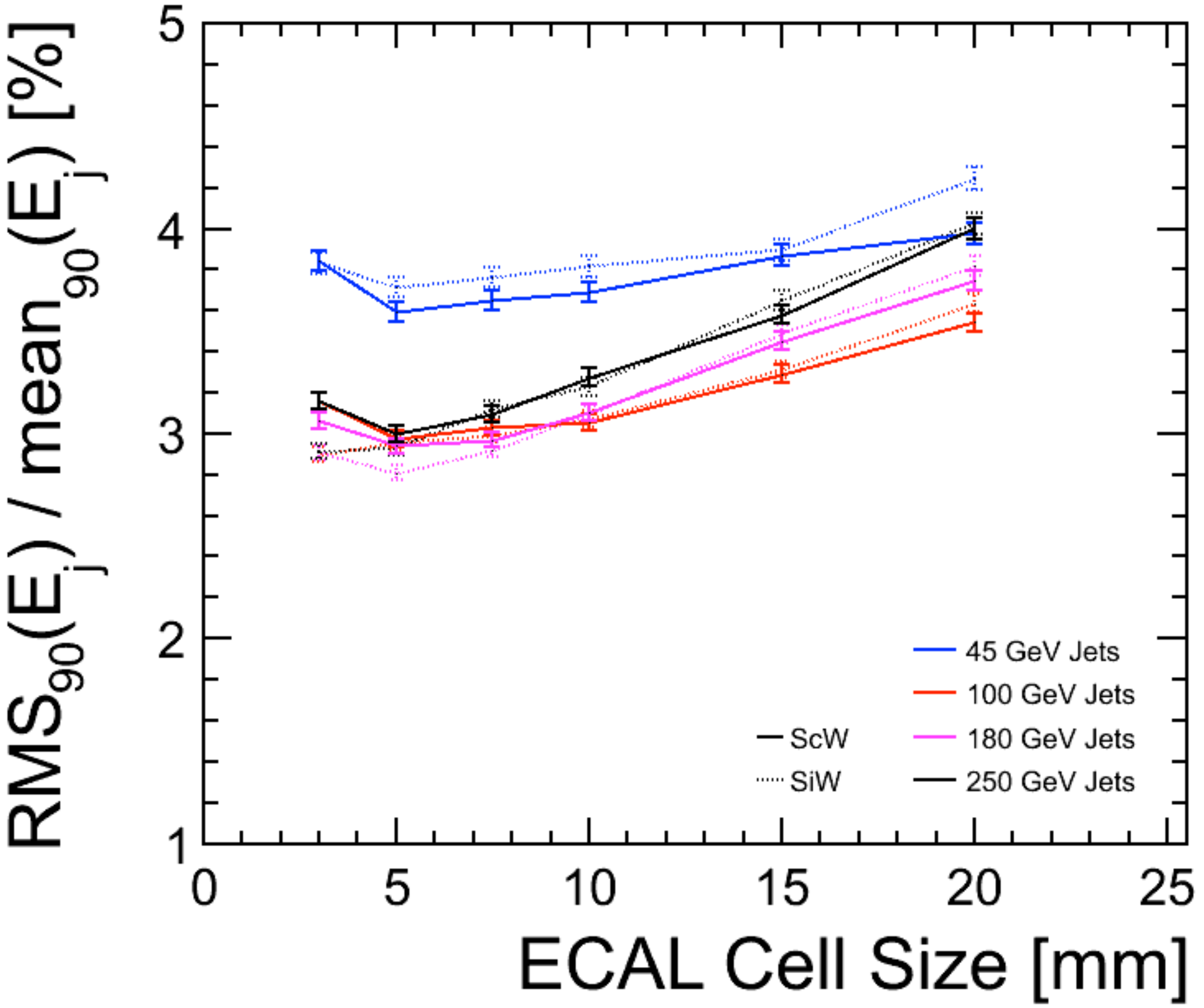


Resolutions for 250 GeV jets:

	3 mm	5 mm	7.5 mm	10 mm	15 mm	20 mm
SiW	3.06%	3.10%	3.21%	3.31%	3.72%	4.09%
ScW	3.33%	3.17%	3.25%	3.38%	3.51%	3.95%

- Begin by examining jet energy resolutions achieved using standard Pandora algs.
- Recall that these algs only optimised for $5x5mm^2$ cells; improvements possible.
- However, achieve 3.5% resolution goal, for 100-250GeV jets, up to ~$15x15mm^2$.
- SiW/ScW performance similar, except at high jet energies with $3x3mm^2$ cells.
- Now vary choice of Pandora algs...

Standalone Photon Algorithm

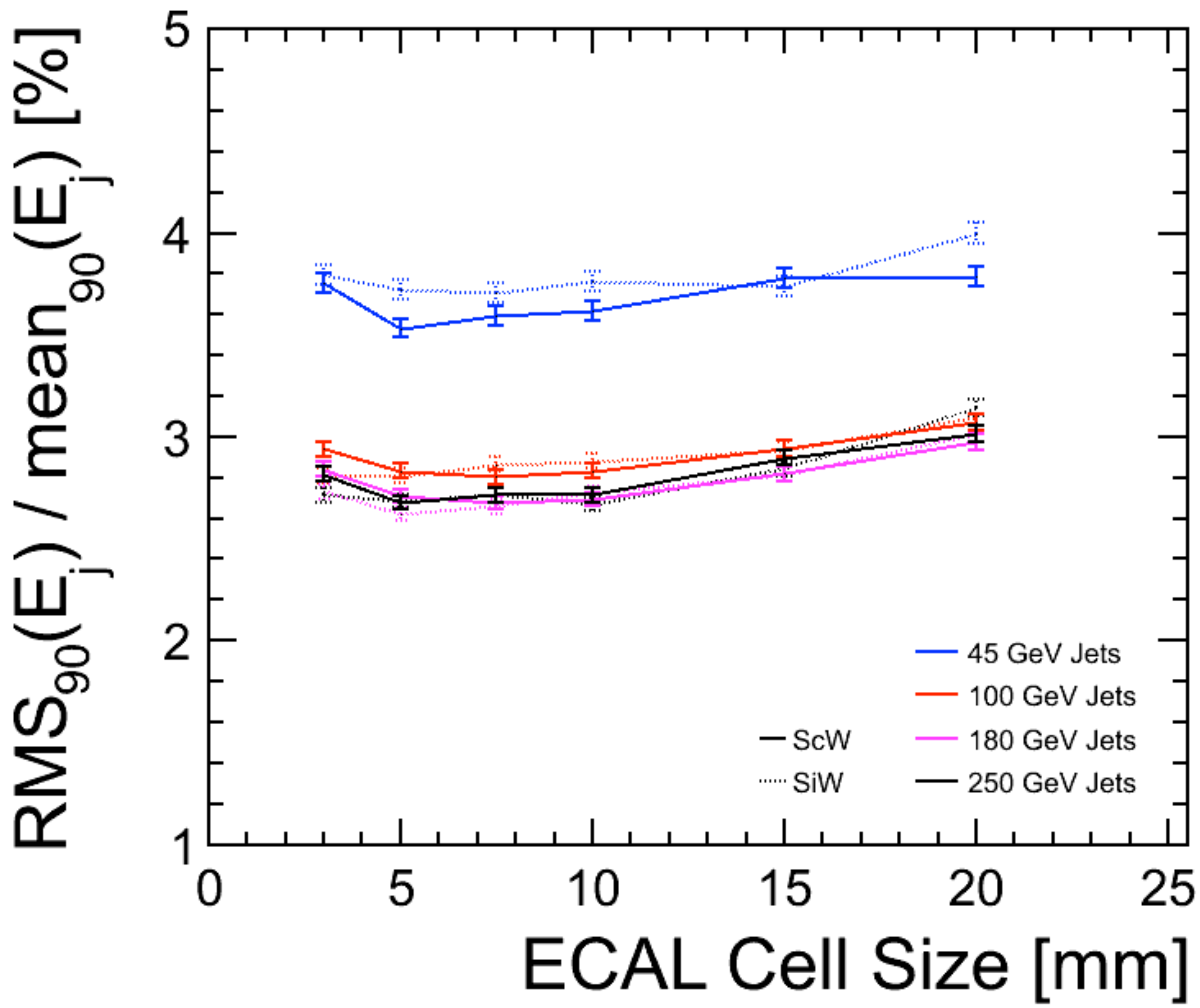


Resolutions for 250 GeV jets:

	3 mm	5 mm	7.5 mm	10 mm	15 mm	20 mm
SiW	2.91%	2.93%	3.12%	3.23%	3.65%	4.03%
ScW	3.16%	3.00%	3.09%	3.27%	3.58%	4.00%

- Concentrate photon reconstruction into single Pandora algorithm, which runs early in reconstruction.
- Examine ECAL hits in transverse plane, look for peaks in energy deposition, try to separate peaks from nearby tracks.
- Use likelihood technique to finalise photon identification. Photon clusters then removed until PFO construction.
- Likelihood PDFs must be recreated for each detector configuration.
- Algorithm consistently improves resolution, but doesn't really reduce sensitivity to granularity changes.

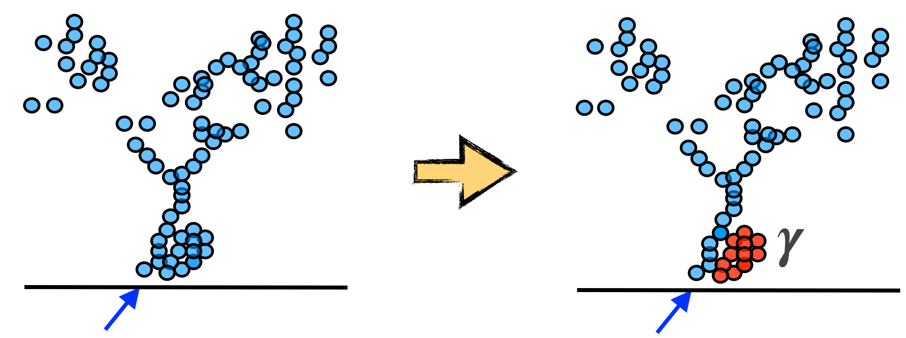
Cheat Photon Clustering



Resolutions for 250 GeV jets:

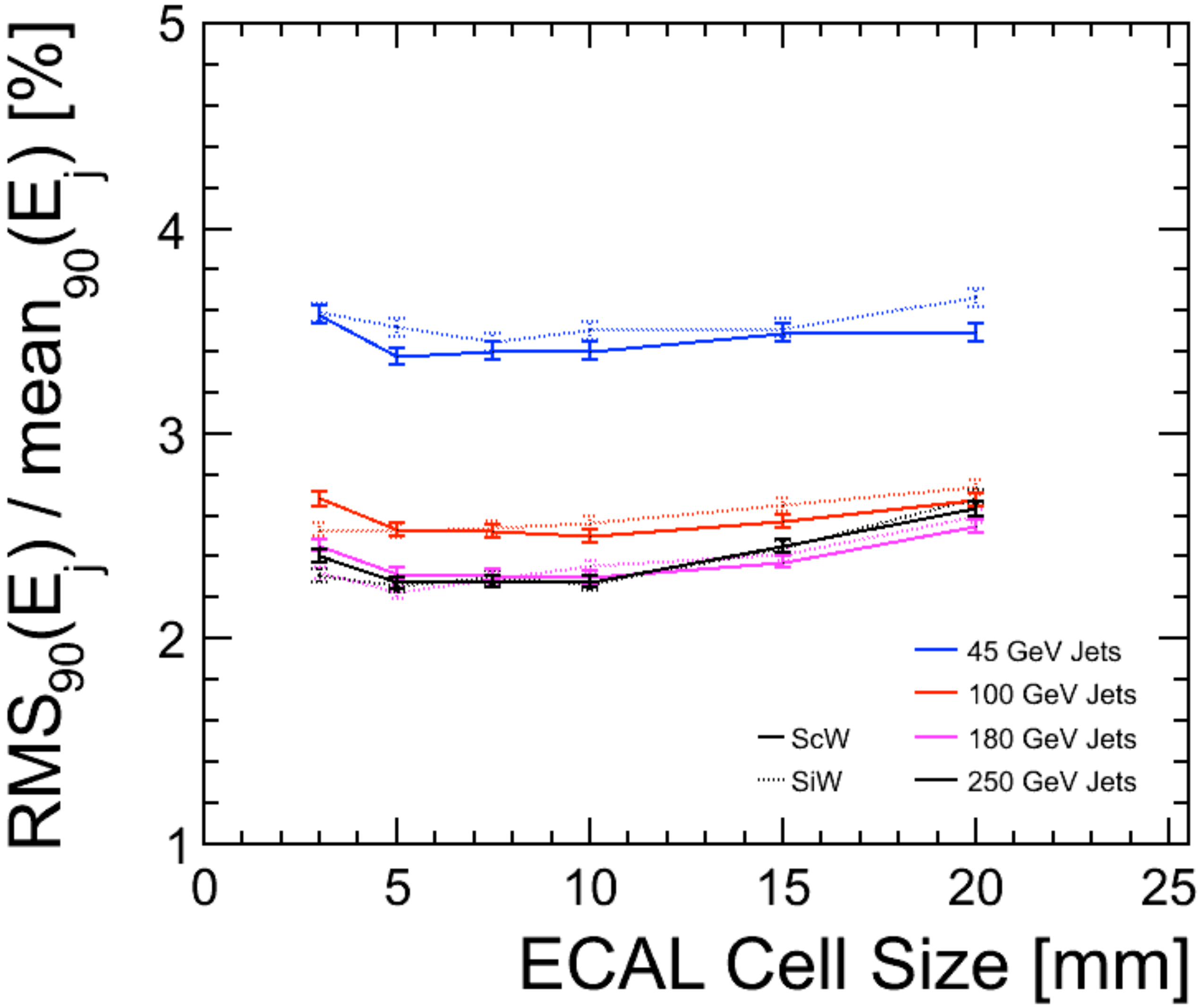
	3 mm	5 mm	7.5 mm	10 mm	15 mm	20 mm
SiW	2.72%	2.69%	2.71%	2.67%	2.84%	3.14%
ScW	2.82%	2.68%	2.71%	2.72%	2.90%	3.02%

- Switch standalone photon reconstruction with an algorithm that uses MC info to cheat the photon clustering:



- True photon energy deposits then removed from Pandora reconstruction and are guaranteed to form photon PFOs.
- Calorimeter energies still used to calculate final photon energies; MC info used only for pattern recognition.
- Additional fake photons could still be formed by standard Pandora algorithms.
- As expected, see dramatically reduced sensitivity to ECAL granularity changes.

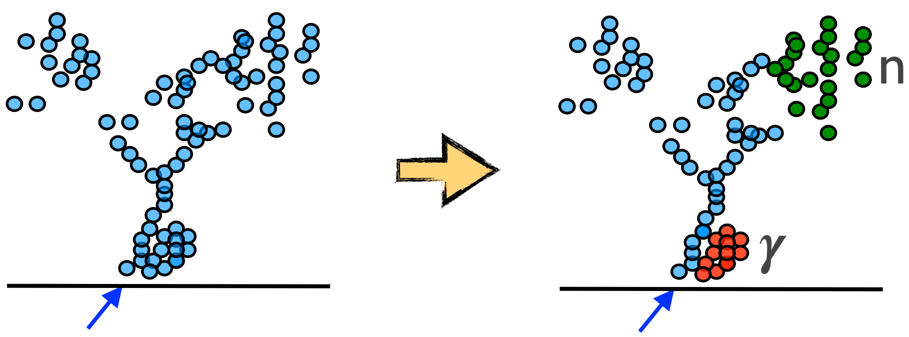
Cheat Photons & Neutral Hadrons



Resolutions for 250 GeV jets:

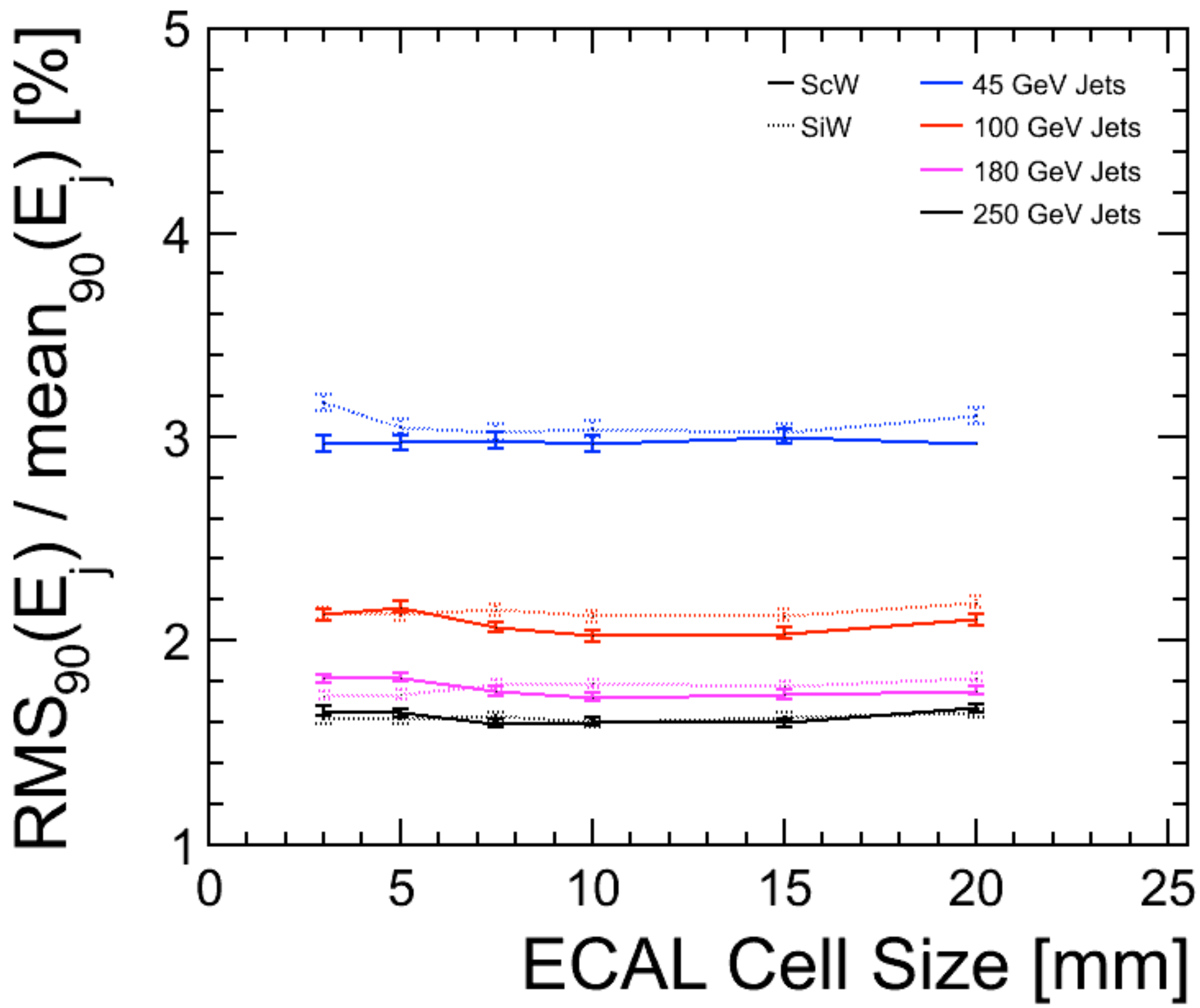
	3 mm	5 mm	7.5 mm	10 mm	15 mm	20 mm
SiW	2.31%	2.26%	2.30%	2.27%	2.45%	2.69%
ScW	2.40%	2.27%	2.28%	2.28%	2.46%	2.63%

- Extend cheated pattern recognition to also include neutrons and K0L:



- Once removed from reconstruction, cheated clusters are only used to collect "isolated hits" and to form PFOs.
- Neutral hadron confusion very important for jet energy reconstruction, but, as expected, its impact is independent of ECAL granularity.

Perfect PFA



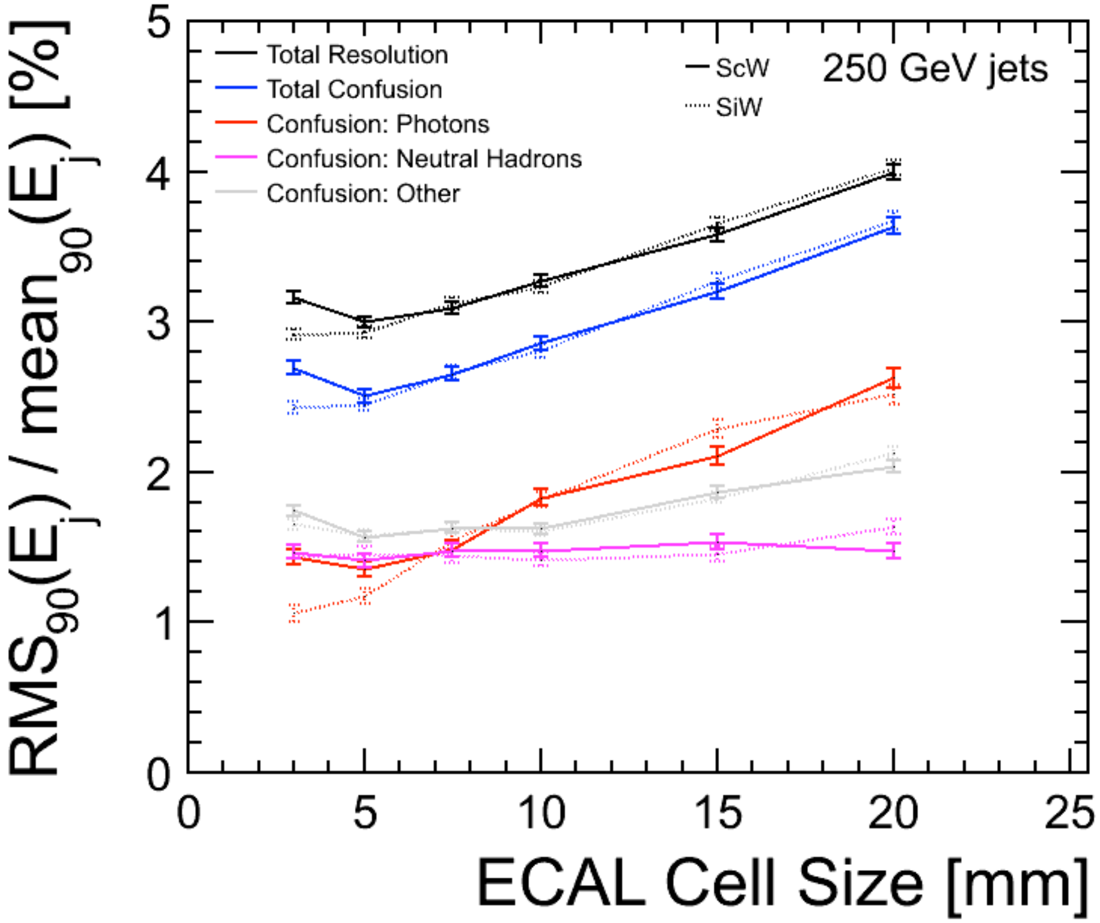
Resolutions for 250 GeV jets:

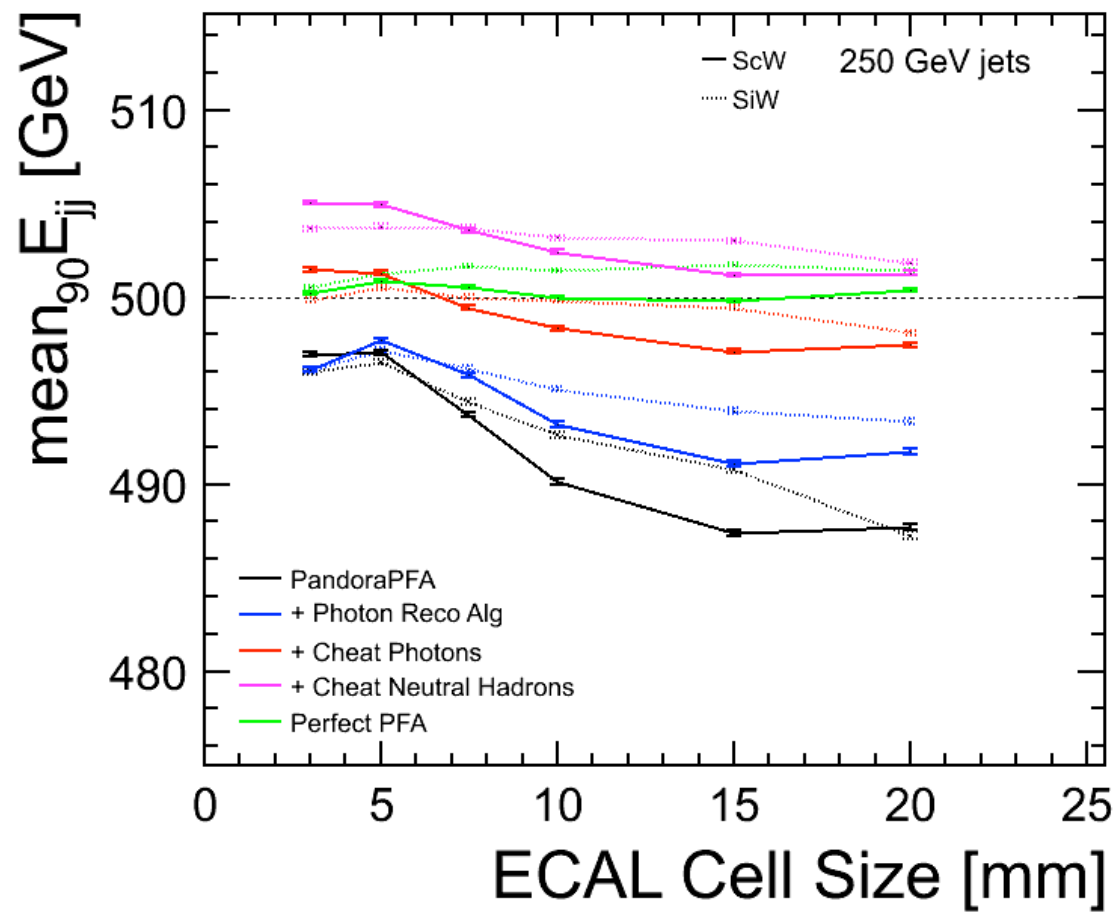
	3 mm	5 mm	7.5 mm	10 mm	15 mm	20 mm
SiW	1.61%	1.61%	1.63%	1.60%	1.62%	1.65%
ScW	1.66%	1.64%	1.59%	1.60%	1.60%	1.67%

- Collect together hits and tracks associated with each MC PFO target (MC particle with vtx radius < 500mm and endpoint radius > 500mm).
- Still use reconstructed hit/track properties to calculate PFO energies, but remove (nearly) all aspects of calorimeter pattern recognition.
- Granularity now only important because associate just one MC particle (that depositing most energy) to each cell.
- Perfect pattern recognition means that resolutions are flat for ECAL cell dimensions in range 3-20mm.
- Important check of robustness of simulation.

Confusion vs. Cell Size

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

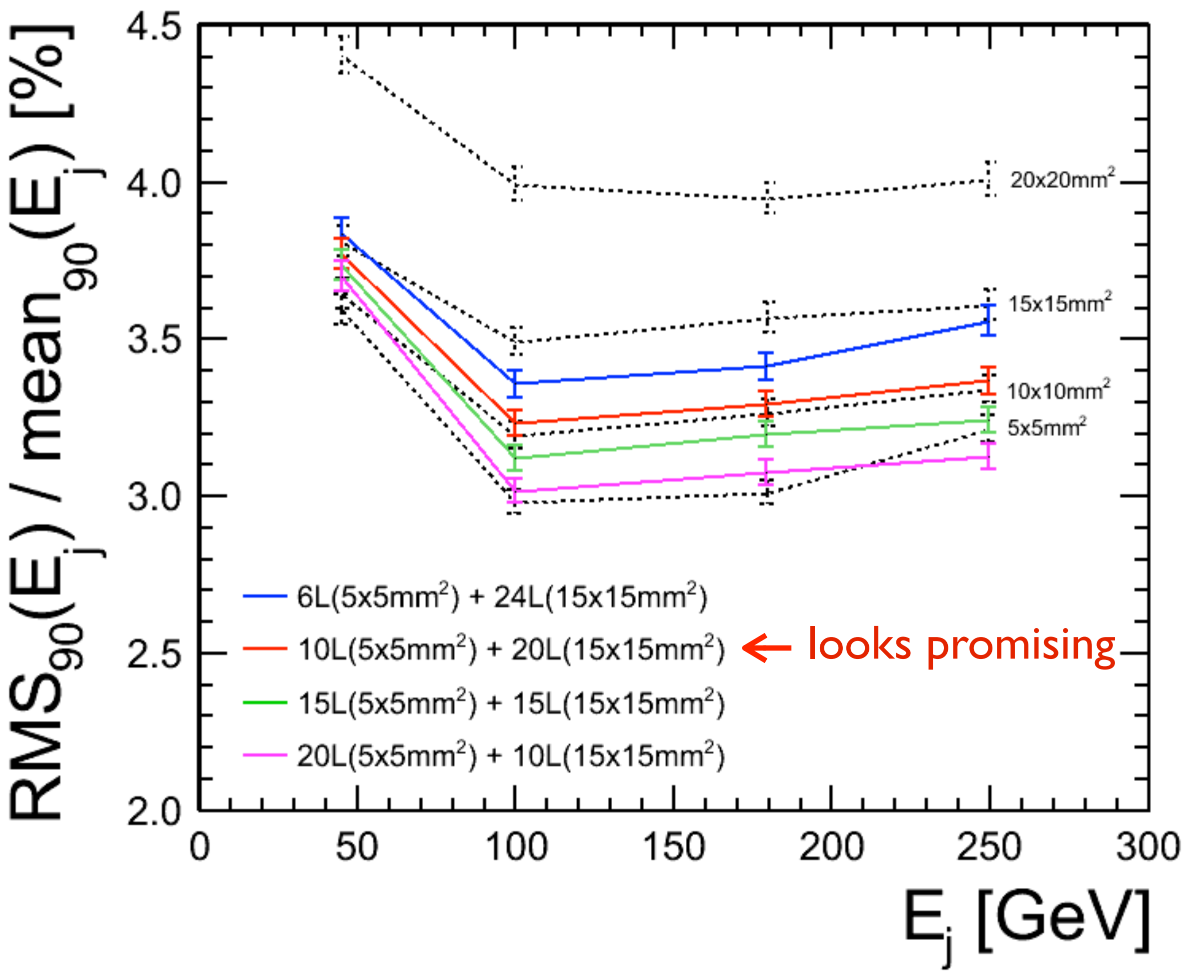


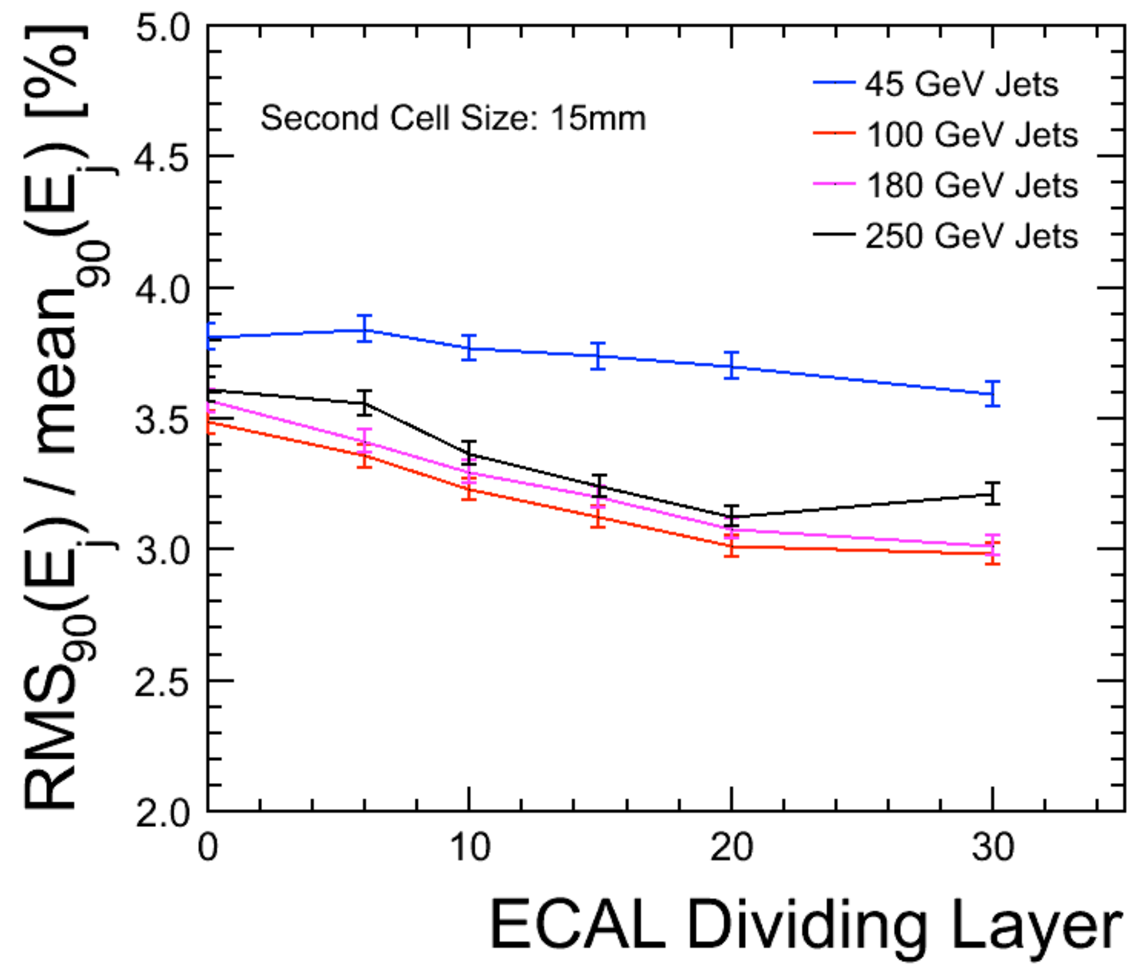


- Total confusion represents difference between best reconstructed resolution and perfect PFA; it comprises neutral hadron confusion, photon confusion and all "other" remaining contributions.
- As could infer from earlier plots, neutral hadron confusion contribution is essentially flat with respect to ECAL cell size, whilst photon confusion increases significantly.
- Loss of photons also clearly evident in plot of mean di-jet energies vs. ECAL cell size.

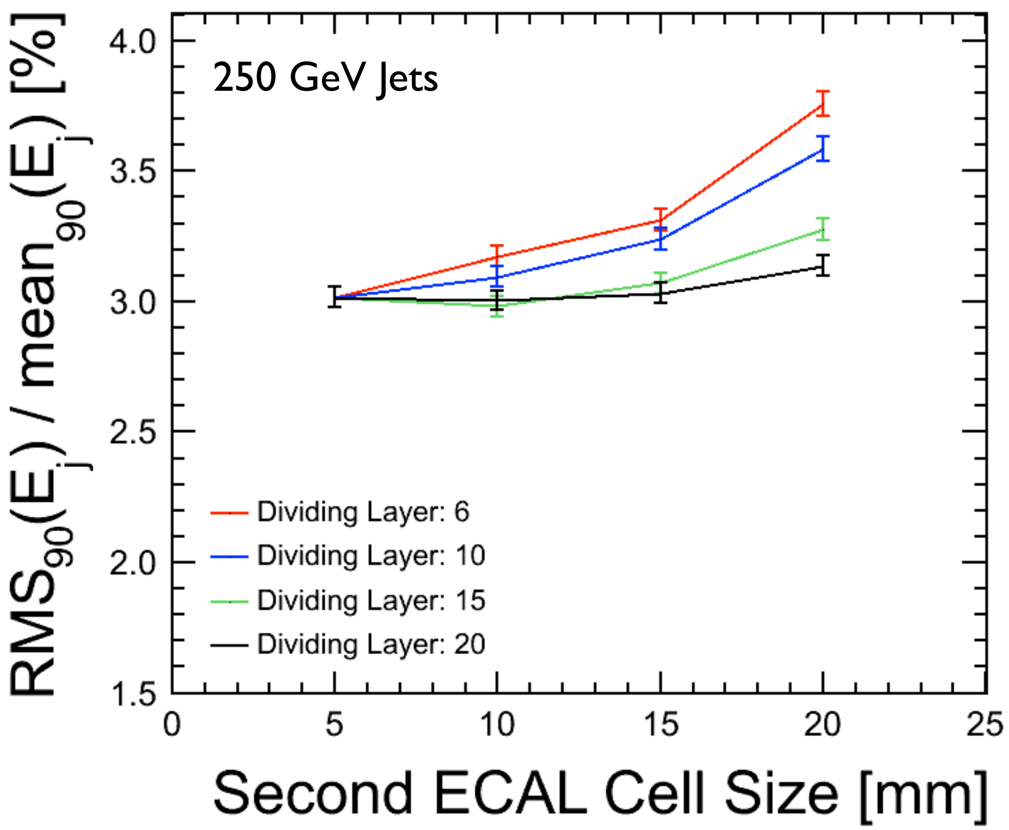
Two Granularity Regions

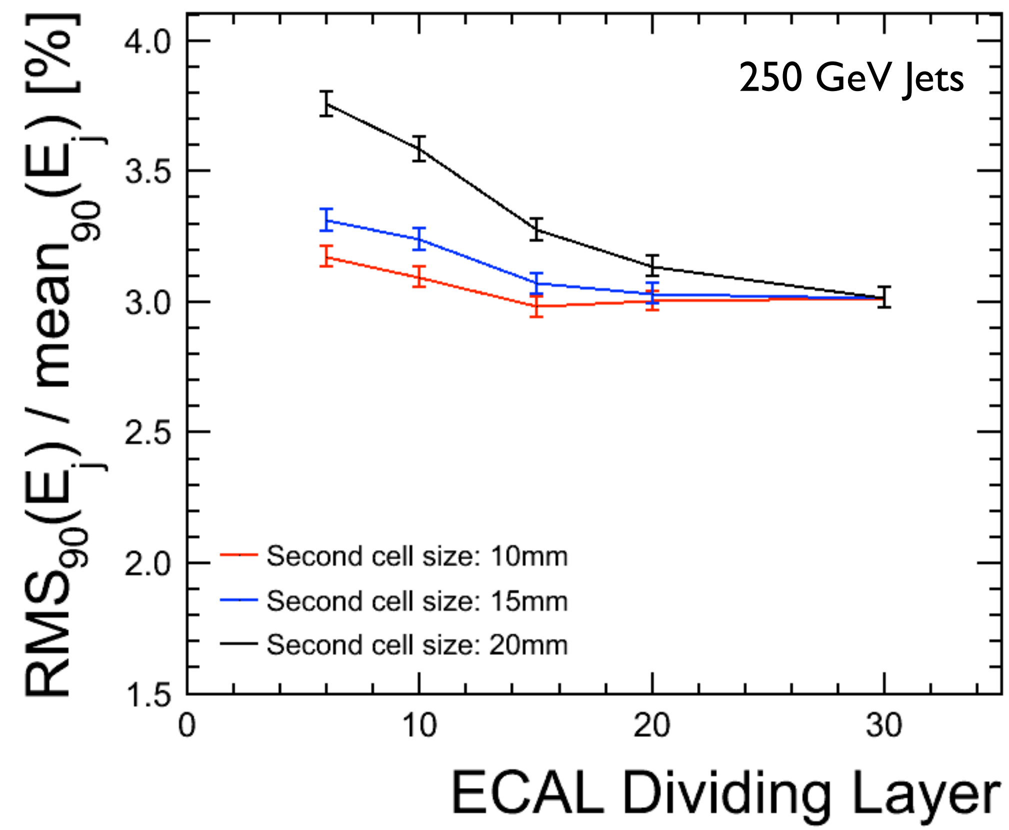
- Next, investigate performance of ECAL models with two transverse segmentations. Use ScW ECAL models and assume first region comprises $5 \times 5 mm^2$ cells, so the study parameters are:
  - The size of square Sc cells used in second region;
  - The "dividing layer", i.e. the ECAL layer at which the Sc cell size changes.
- The Sc thickness remains 2.0mm and the W absorber thicknesses are unchanged. Note that the nominal ECAL consists of 30 layers, but first layer is a pre-sampler and is not used in PFA.



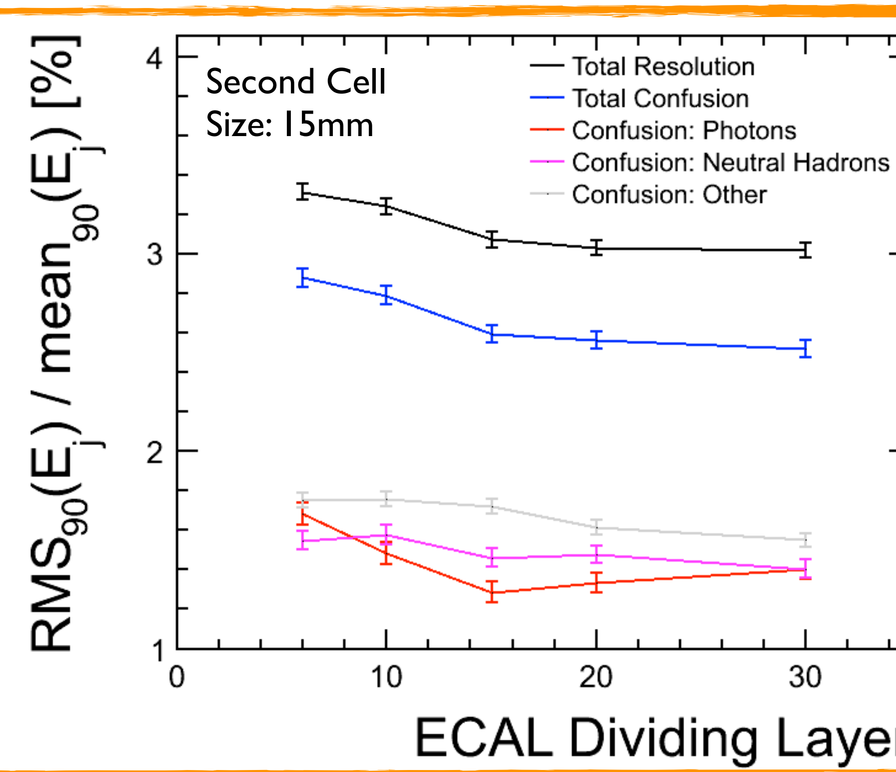


Two Granularity Regions

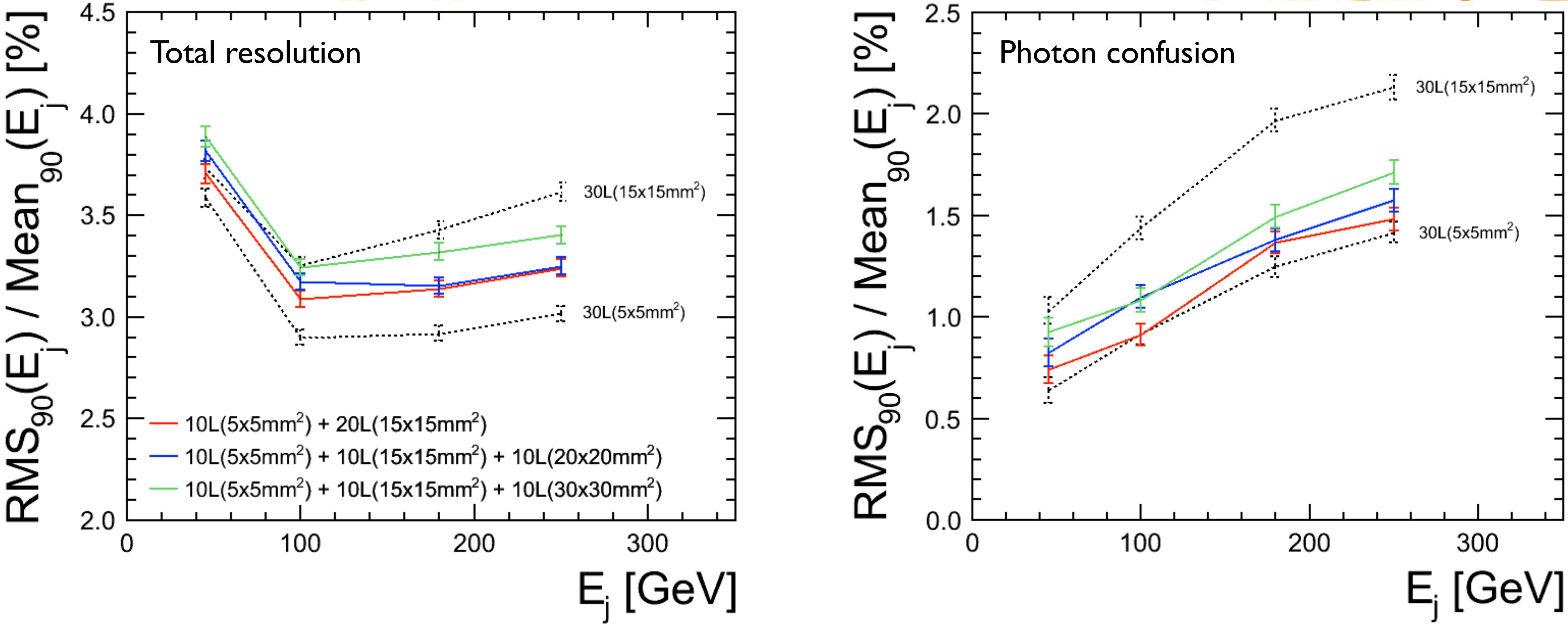




- Fix jet energy at 250 GeV and examine resolutions obtained with newly-trained standalone photon alg.
- Plot resolution vs. second cell size and vs. dividing layer. Note: second cell size of 5mm and dividing layer of 30 both correspond to a uniform 5x5mm^2 ECAL.
- Second cell size of 15mm and dividing layer of 10 is most aggressive configuration for which photon confusion remains less than neutral hadron confusion.



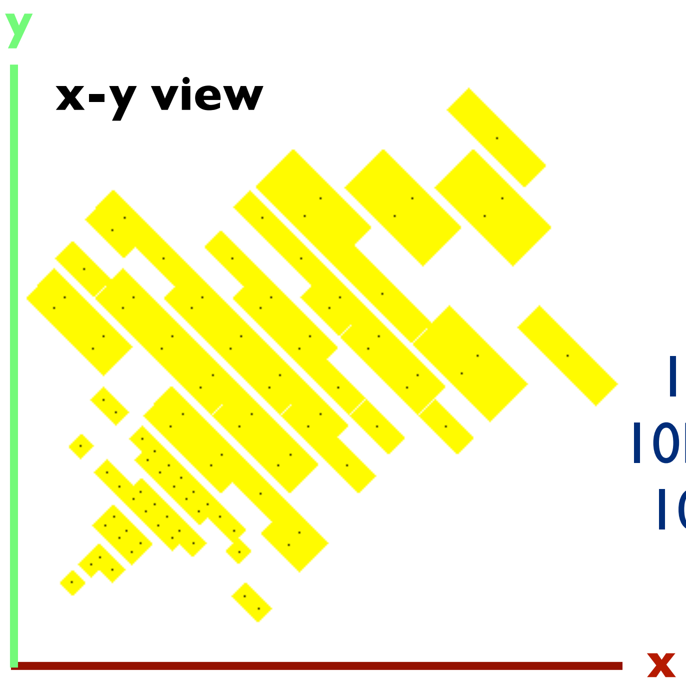
Three Granularity Regions



- 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 for 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.

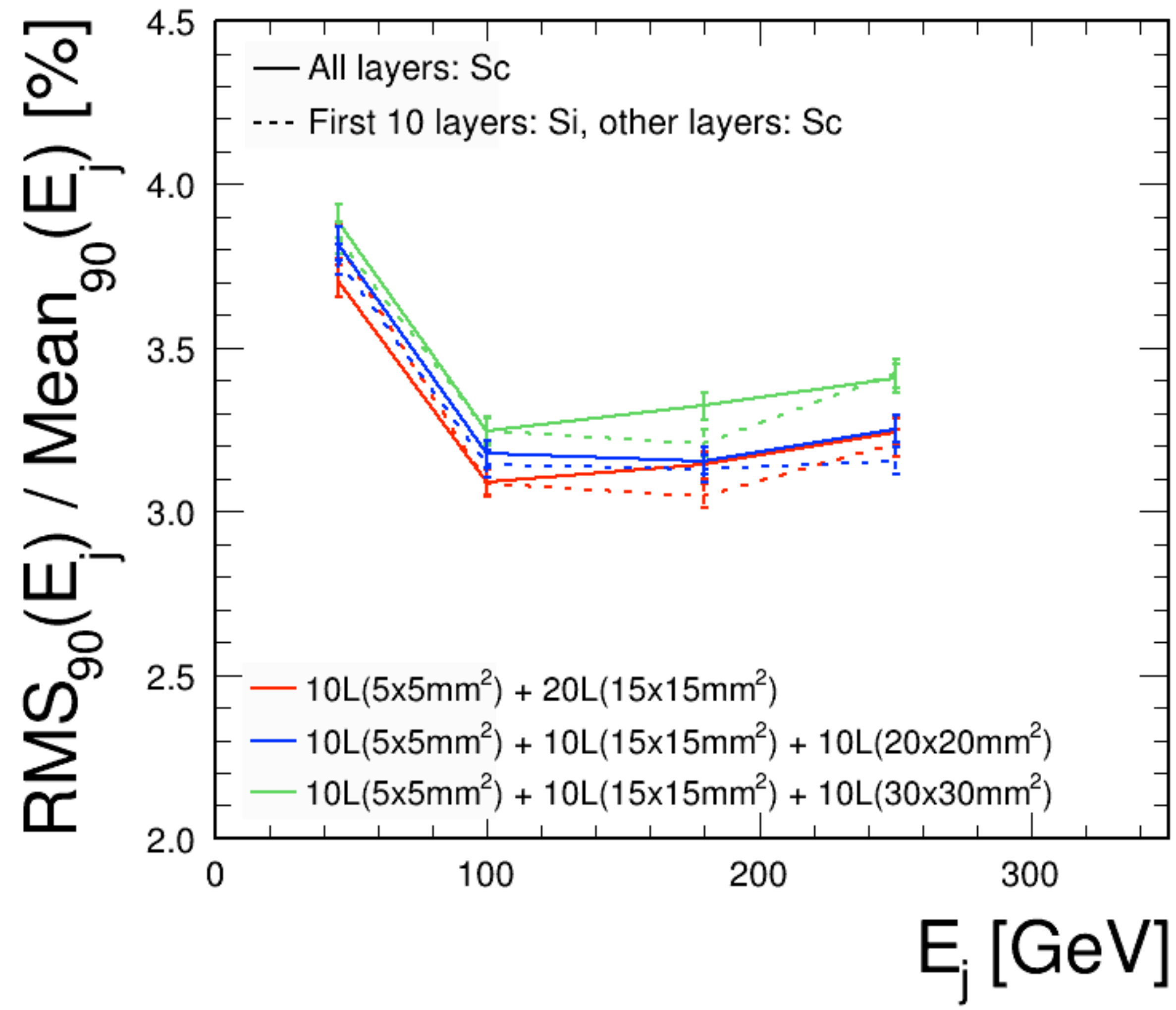
First Granularity Region: Si or Sc?

- Unlikely that 5x5mm^2 region of the ECAL would consist of Sc tiles; Si more likely.
- Therefore want to answer a question: How does performance change if we switch the first detector region to Si?
- Si only 0.5mm thick, whilst Sc is 2.0mm thick, so there is an expected discontinuity in the typical shower width.
- First hybrid models examined so far: care required with digitisation and calibration.



Typical 10GeV photon display:

10L(5x5mm^2 Si) + 10L(15x15mm^2 Sc) + 10L(30x30mm^2 Sc)

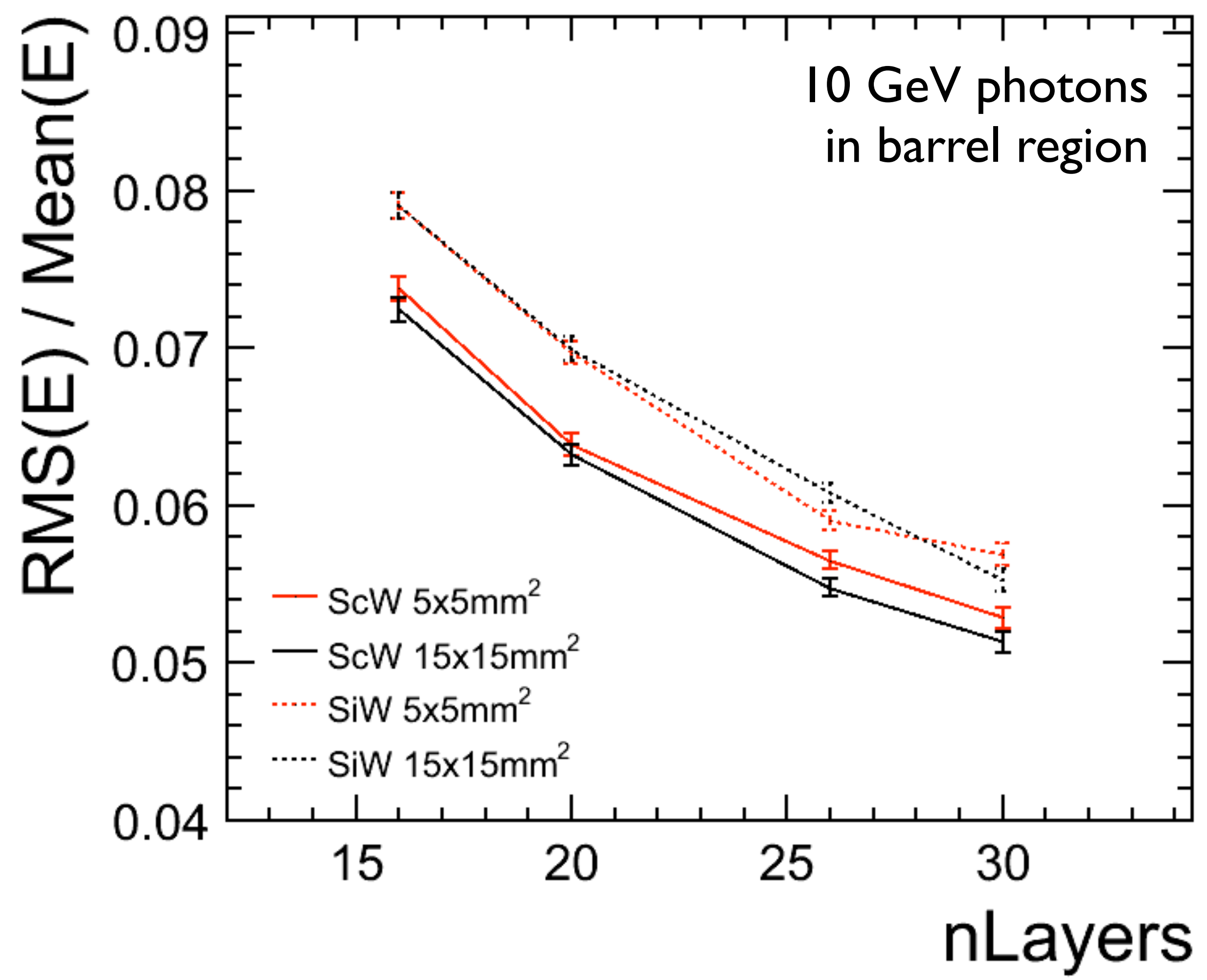


- Compare jet energy resolutions obtained using full Sc models with those for models using Si in the first 10 layers.
- Performance very similar; no evidence of problems. Some sign of improvements, maybe due to reduced shower widths.

Layer Reduction Studies

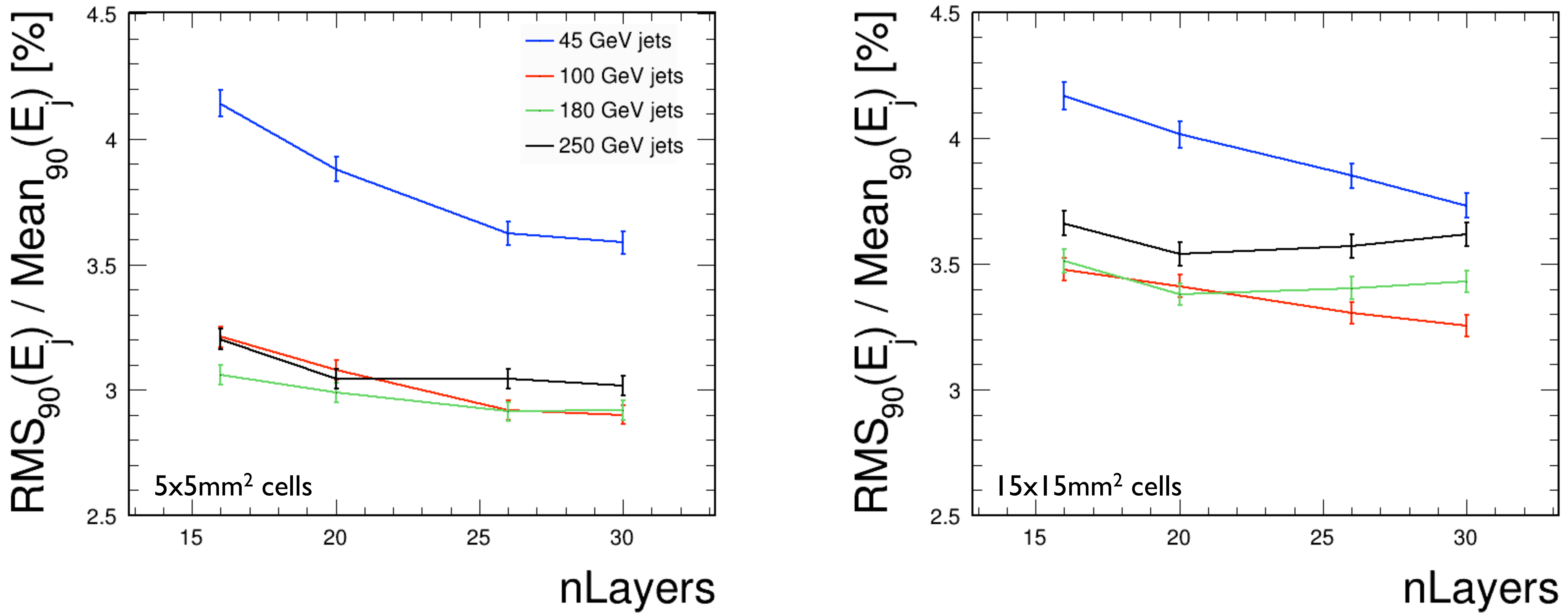
- Next, investigate impact on jet energy resolution of reducing number of layers.
- Look to reduce the number of absorber and active layers in some of the ECAL models considered so far.
- Extend and complement results obtained by T. H. Tran to include both SiW and ScW ECALs, with two different granularities.
- 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



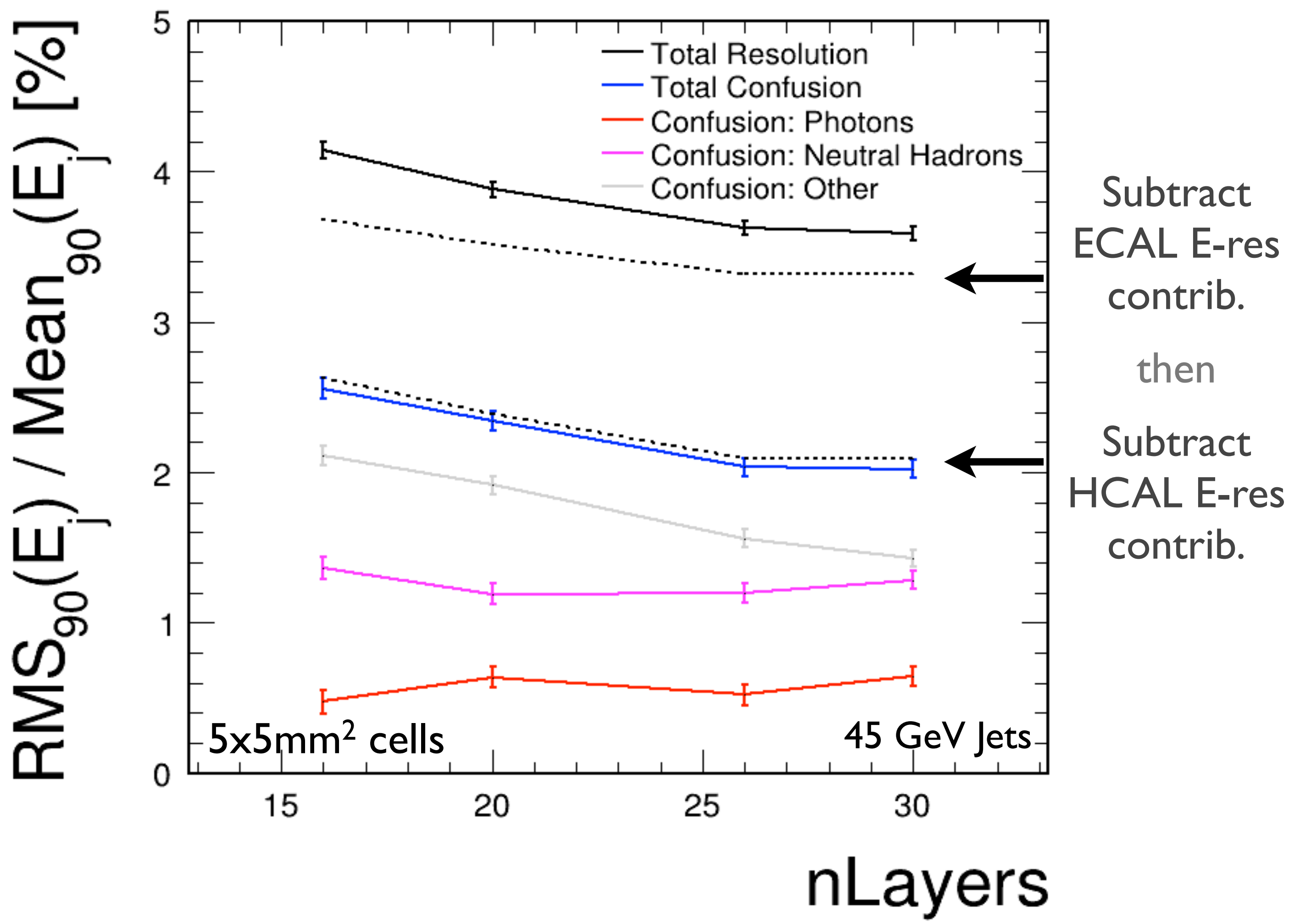
- Following calibration (for jet E), examine E resolution for 10GeV photons in the barrel.
- As expected, 2.0mm thick Sc offers better energy resolution than 0.5mm thick Si.
- Sc resolution varies with cell size (MPPC "dark" area), whilst Si resolution unaffected.

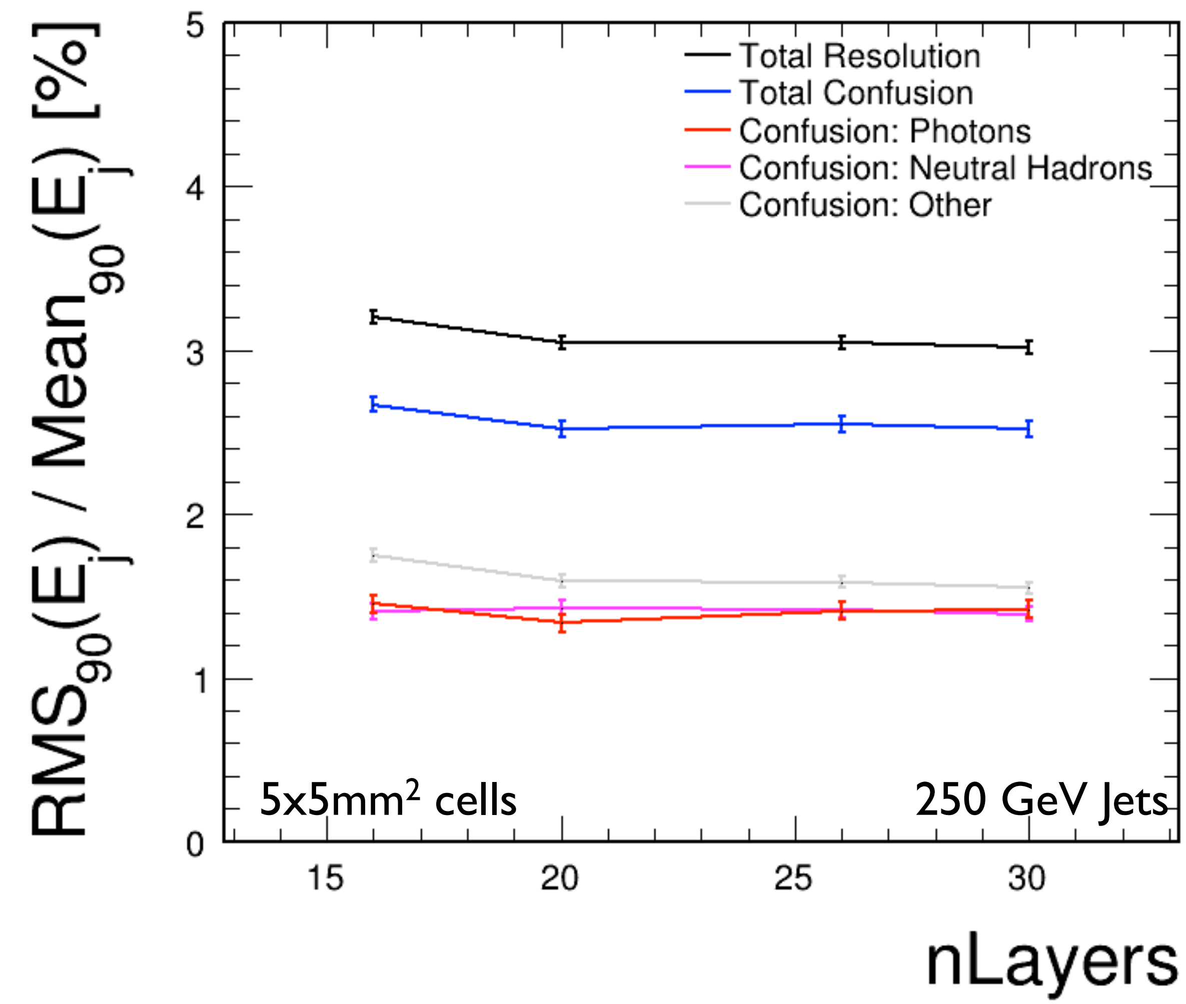
Layer Reduction Studies



- Examine jet energy vs. number of ECAL layers for the two transverse granularities. Note that resolutions are shown only for ScW ECAL models, for the sake of clarity. Differences between SiW and ScW results were small and consistent with previous findings.
- Some variation of resolution with #layers seen for lowest energy jets (mostly due to energy resolution?), but distributions for high energy jets are surprisingly flat. For 100-250GeV jets, can reduce the number of layers from 30 to 20 without harm.

Confusion vs. nLayers



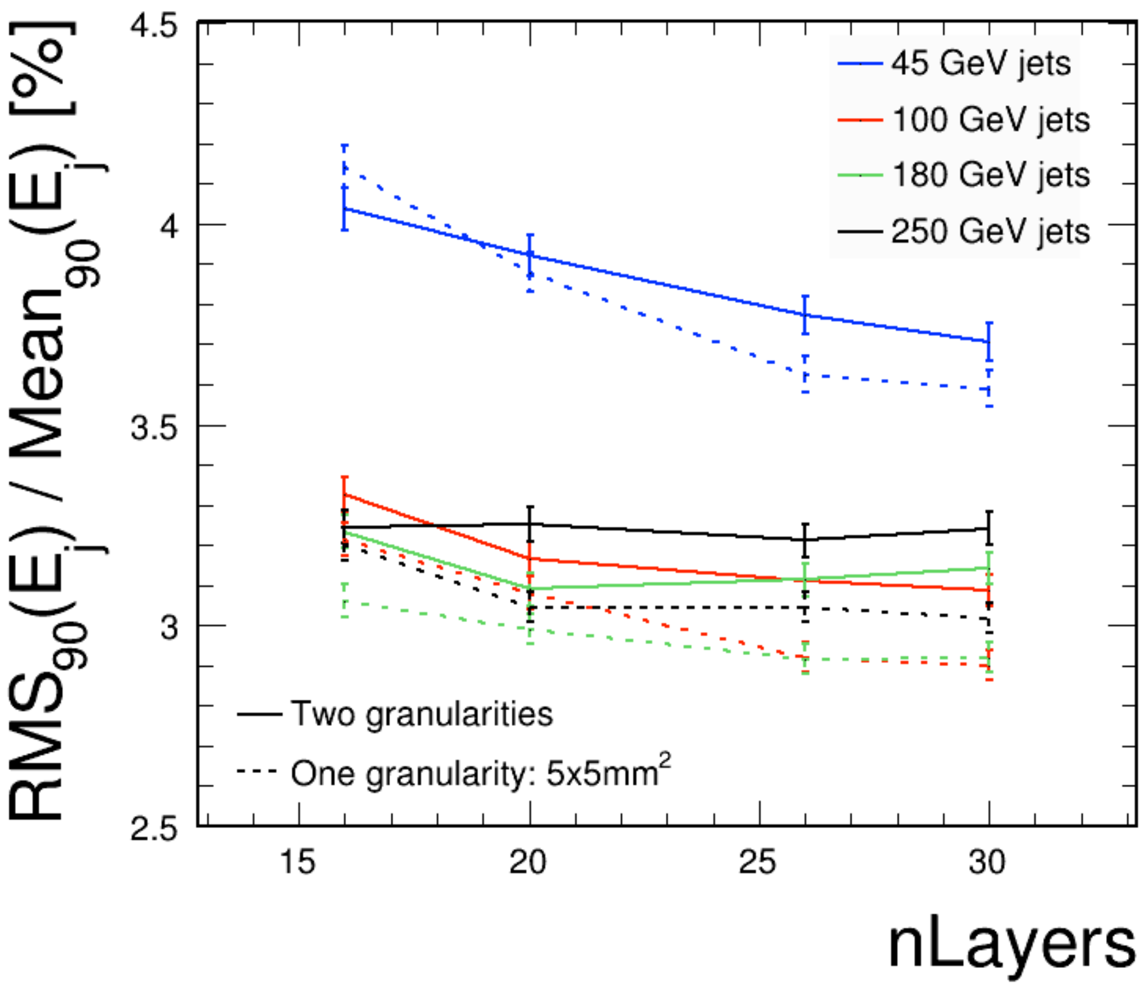


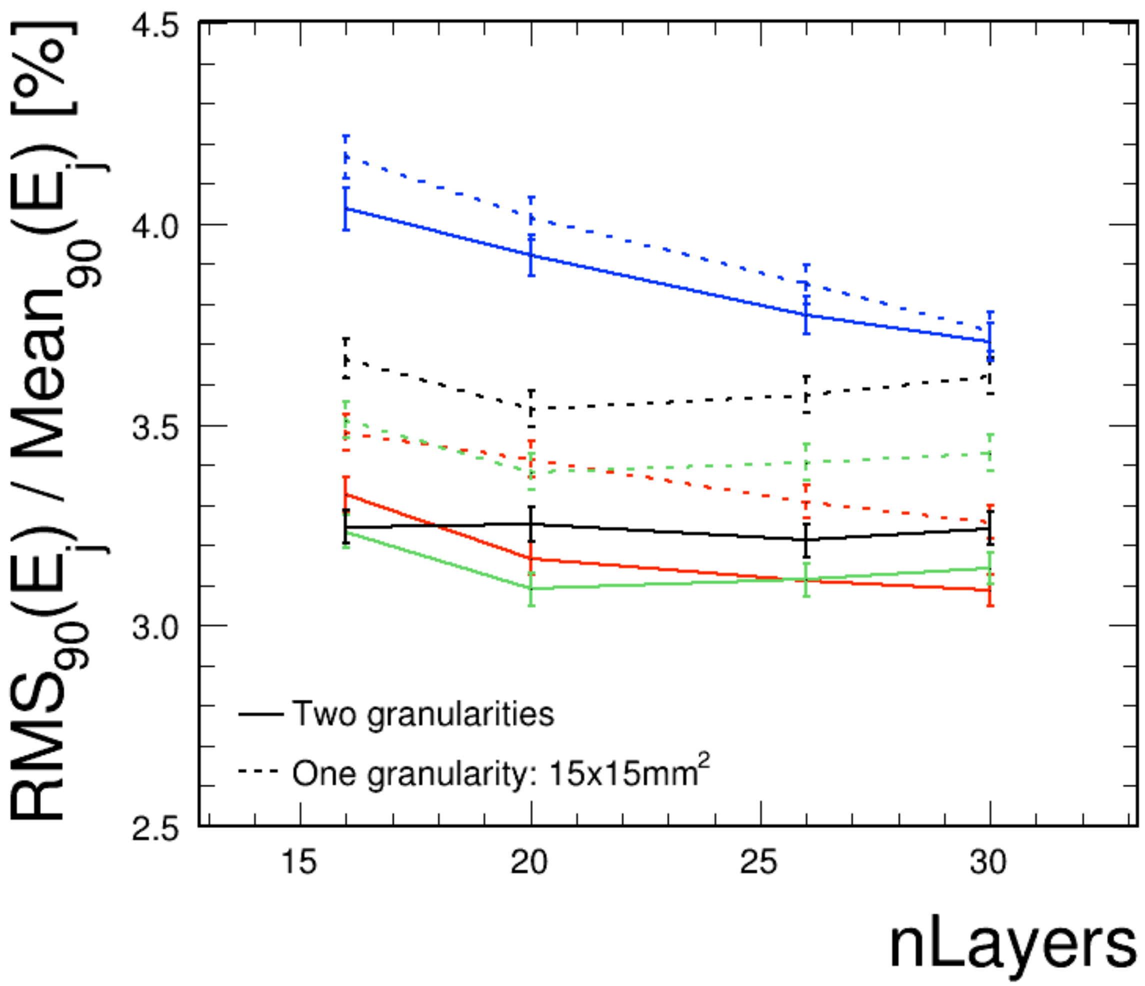
- For 250GeV jets, resolution does not vary with #layers. For 45GeV jets, there is some variation. To assess how much is due to energy resolution, use 10GeV photon resolution plot from slide 21 to subtract ECAL energy resolution component (assume 30% energy measured in ECAL).
- Following this subtraction, 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.

Two Granularity & Layer Reduction

- Finally, study ECAL layer reduction in the context of a two granularity model. The W absorber thicknesses remain as described on slide 21, 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	$6L(5x5mm^2) + 10L(15x15mm^2)$





Summary

- A new study is underway to investigate options for a cost-effective ECAL for ILD. Aim to fully understand behaviour of particle flow reconstruction with different ECAL models.
- Following inclusion of Birks' Law and adjustment of calibration procedure, observed similar jet energy resolutions for SiW/ScW ECALs with for square cells of size 5-20mm.
- Jet energy resolutions degrade with increasing cell size and this is almost entirely due to the reduced ability to separate photons from charged hadrons.
- Examining ScW ECAL models with multiple transverse segmentations suggests that fine granularity is only required in the first layers; cell sizes can be rather large in final layers.
- There is no dramatic change in jet energy resolutions when the first layers of a two or three granularity ScW ECAL are modified and instrumented with Si.
- For jet energies of 100-250GeV, the jet energy resolutions stay more or less constant for ECALs of thickness $23X_0$, having between 20 and 30 active layers.