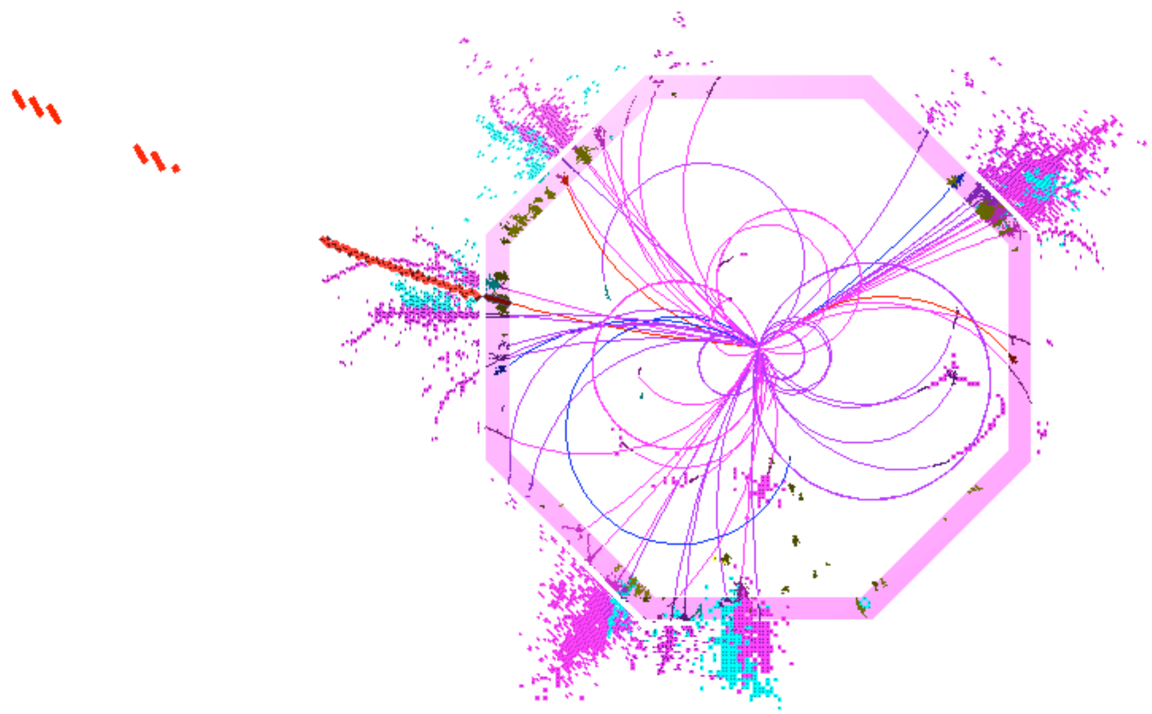

ECAL Optimisation Studies

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CLIC Workshop, 4th February 2014

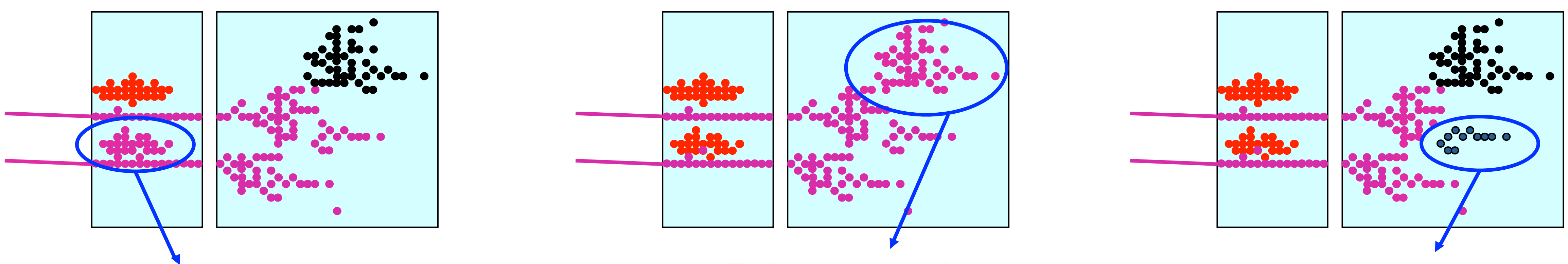
ECAL Optimisation Studies

- This talk will summarise 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 4.2mm 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.
- Alternative 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 models:
  - Transverse granularity,
  - Number of ECAL layers,
  - ECAL inner radius,
  - B-Field strength,
  - Sc thickness,
  - Regions of different transverse granularity and Si/Sc hybrids.
- 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.

Strategy

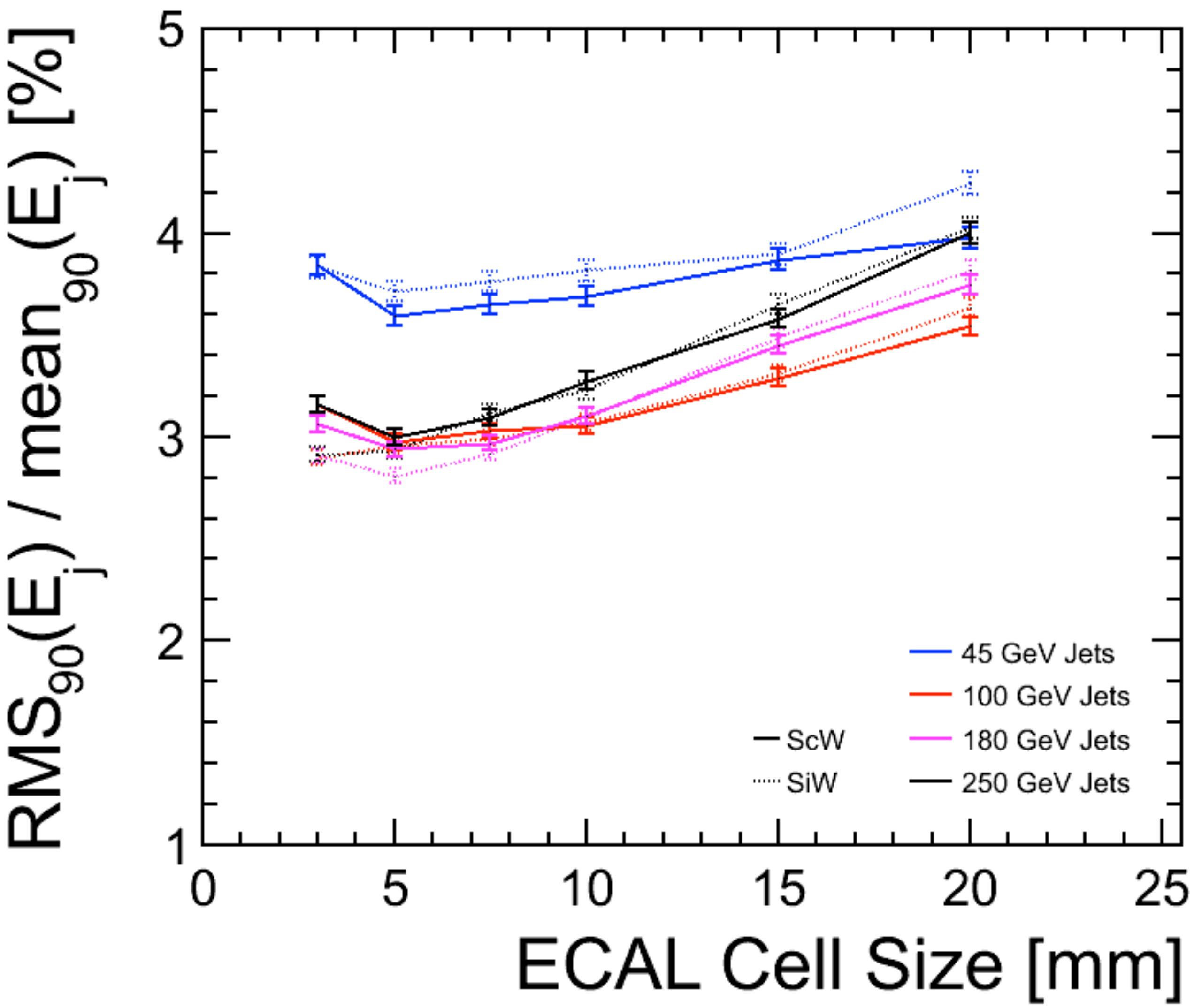
- Benchmark performance using Z decays to light quarks: produce two back-to-back mono-energetic jets, allowing jet energy resolution to be determined from total reconstructed energy.
- In order to truly understand resulting jet energy resolutions, want to investigate variation of each of the different contributing terms: ECAL energy resolution and three types of confusion.



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 and K0L pattern-recognition and id.
  - "Other" confusion: all other sources of confusion due to pattern-recognition and particle id.

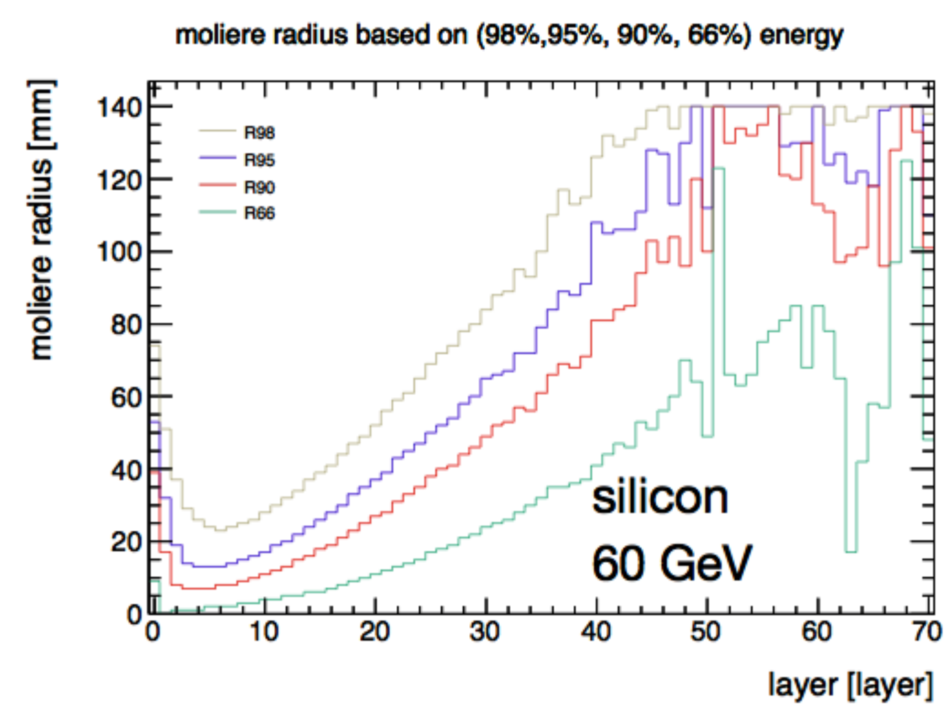
Transverse Granularity



Resolutions for 250 GeV jets:

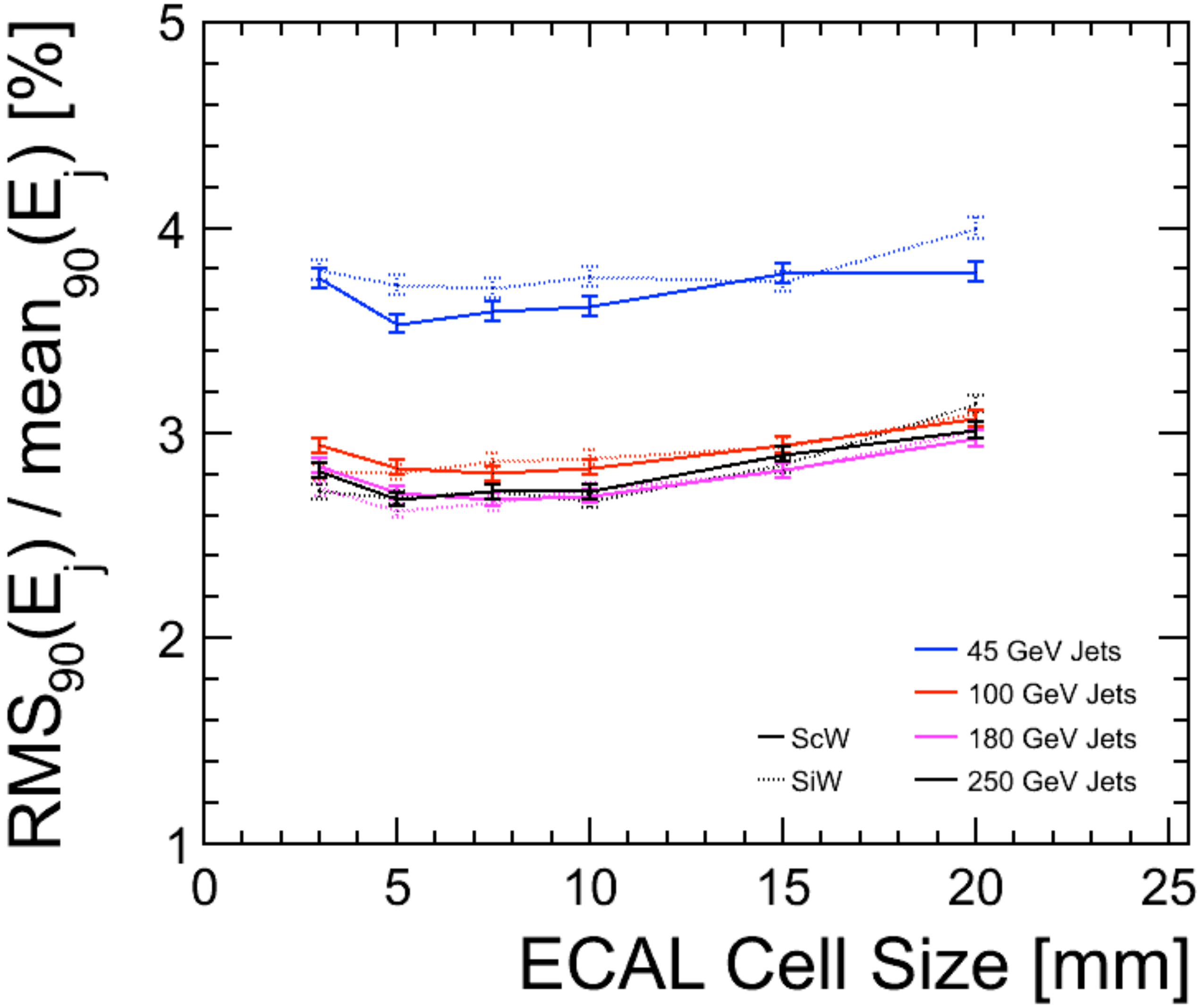
	3 mm	5 mm	7.5 mm	10 mm	15 mm	20 mm
SiW	2.91%	2.93%	3.12%	3.23%	3.65%	4.03%
ScW	3.16%	3%	3.09%	3.27%	3.58%	4%

- 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 function of depth. Sc cells 2.0mm thick.
- Default Pandora reconstruction now includes a dedicated photon algorithm, which runs early in the reconstruction.



D. Schoke, F. Simon

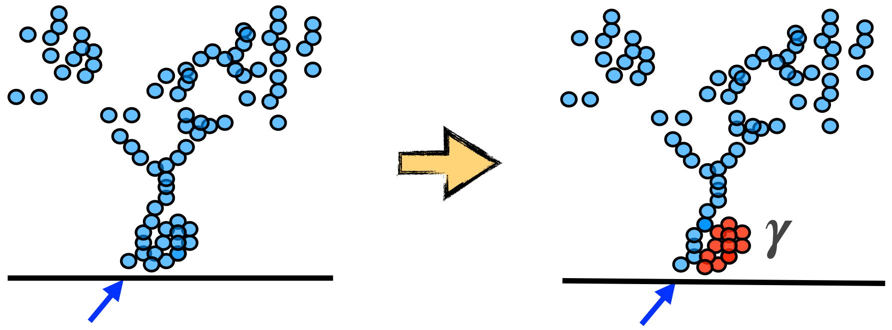
Cheat Photon Clustering



Resolutions for 250 GeV jets:

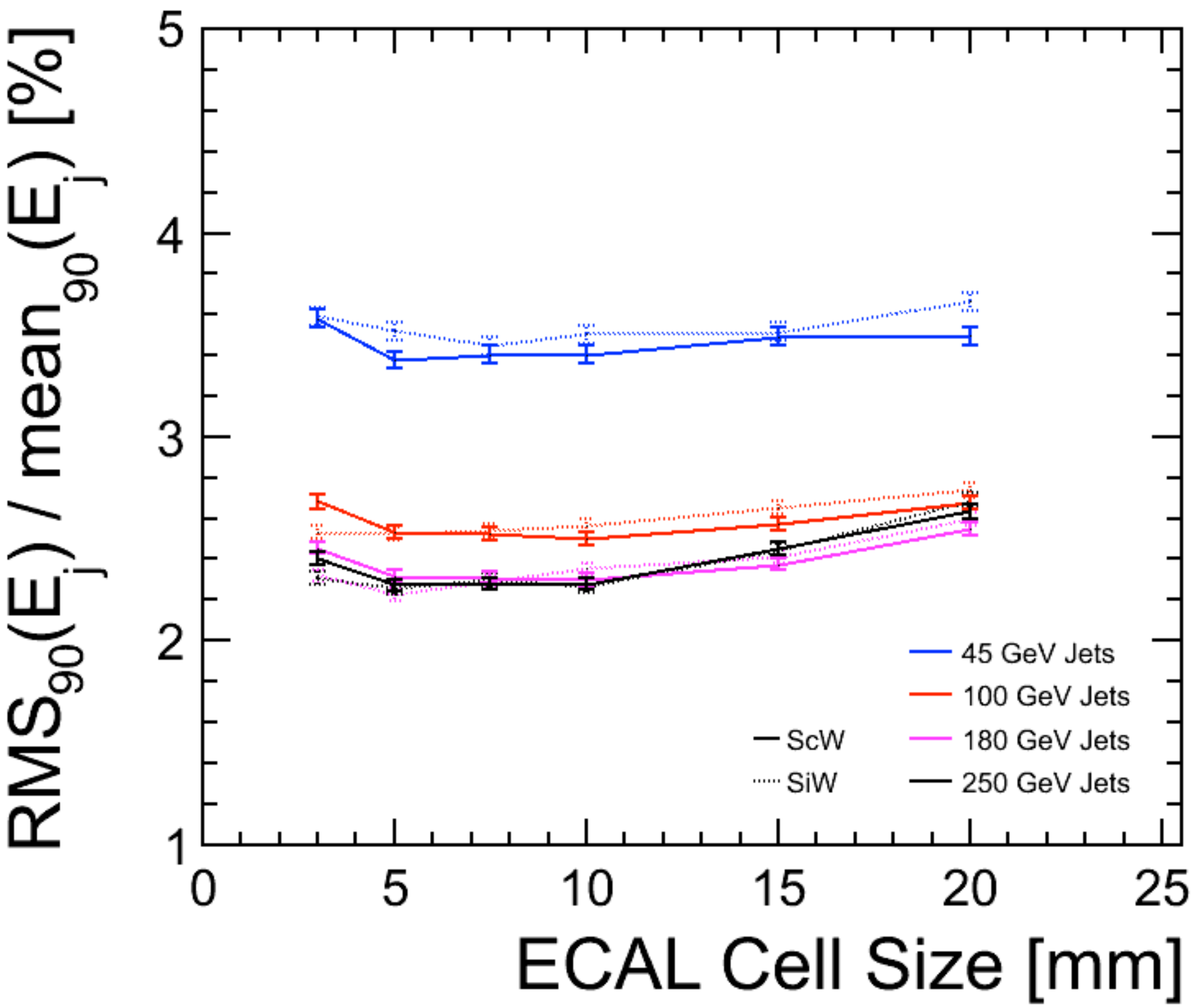
	3 mm	5 mm	7.5 mm	10 mm	15 mm	20 mm
SiW	2.72%	2.69%	2.71%	2.67%	2.84%	3.14%
ScW	2.82%	2.68%	2.71%	2.72%	2.9%	3.02%

- Replace Pandora 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.

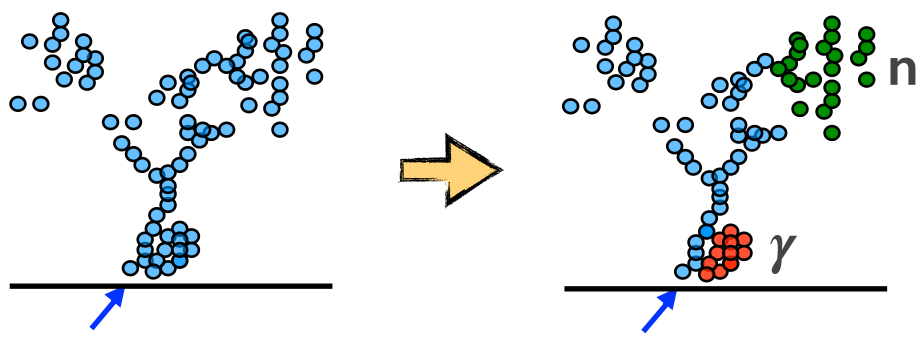
Cheat Photons & Neutral Hadrons



Resolutions for 250 GeV jets:

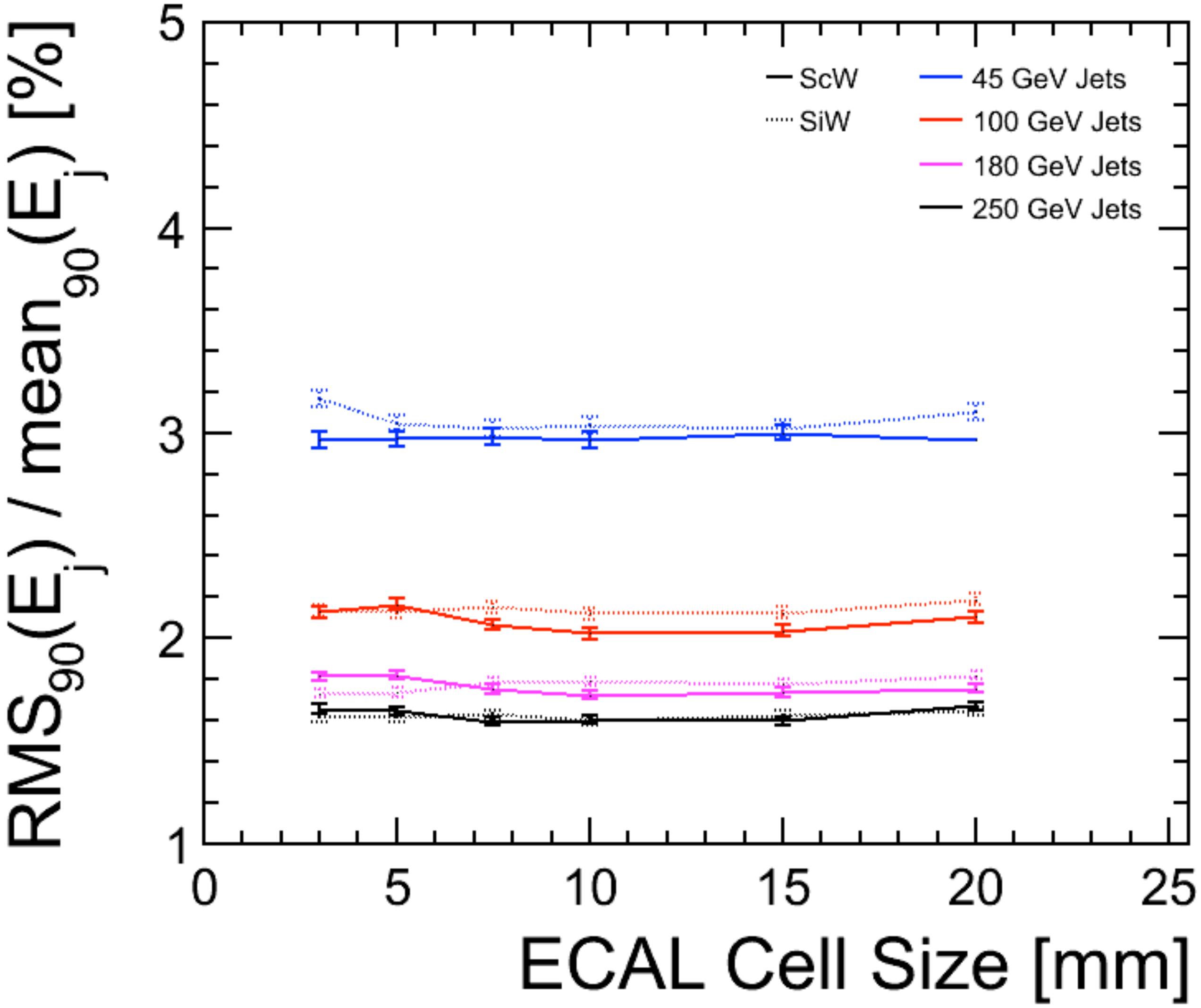
	3 mm	5 mm	7.5 mm	10 mm	15 mm	20 mm
SiW	2.31%	2.26%	2.3%	2.27%	2.45%	2.69%
ScW	2.4%	2.27%	2.28%	2.28%	2.46%	2.63%

- 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

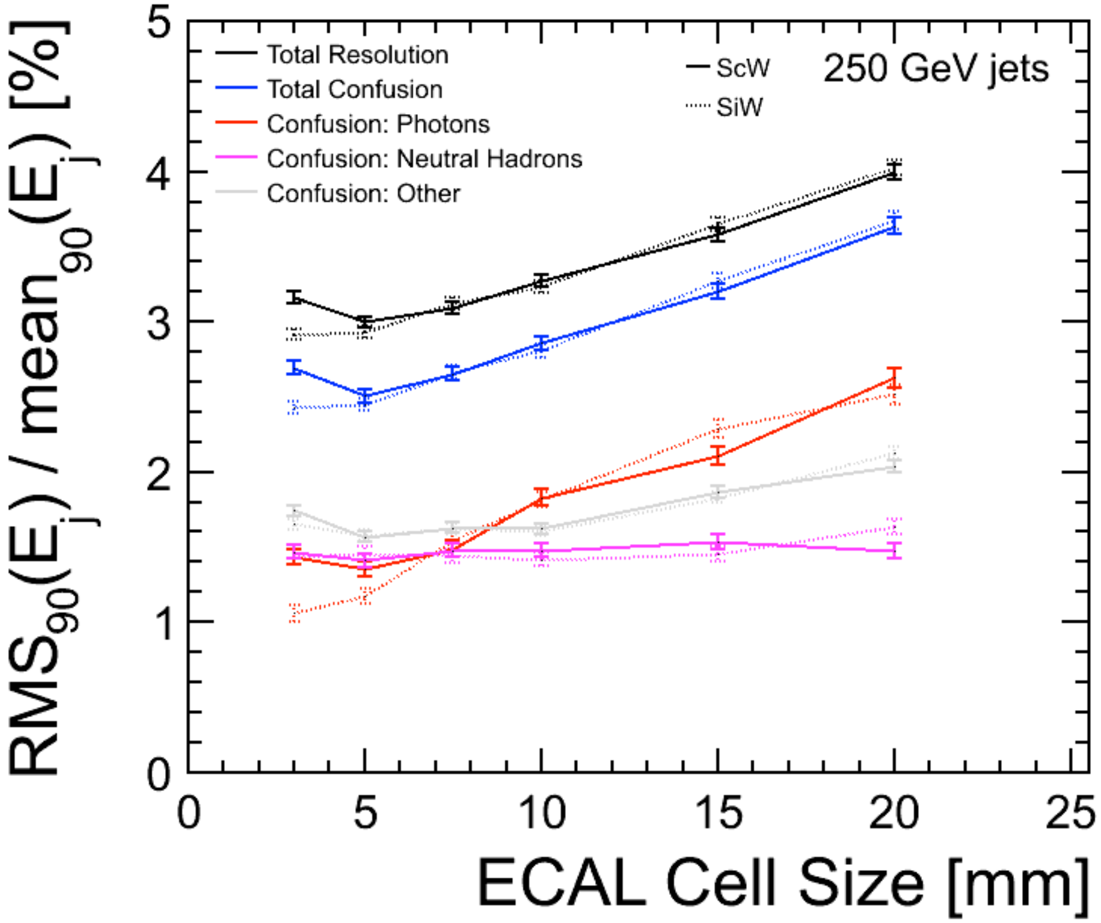


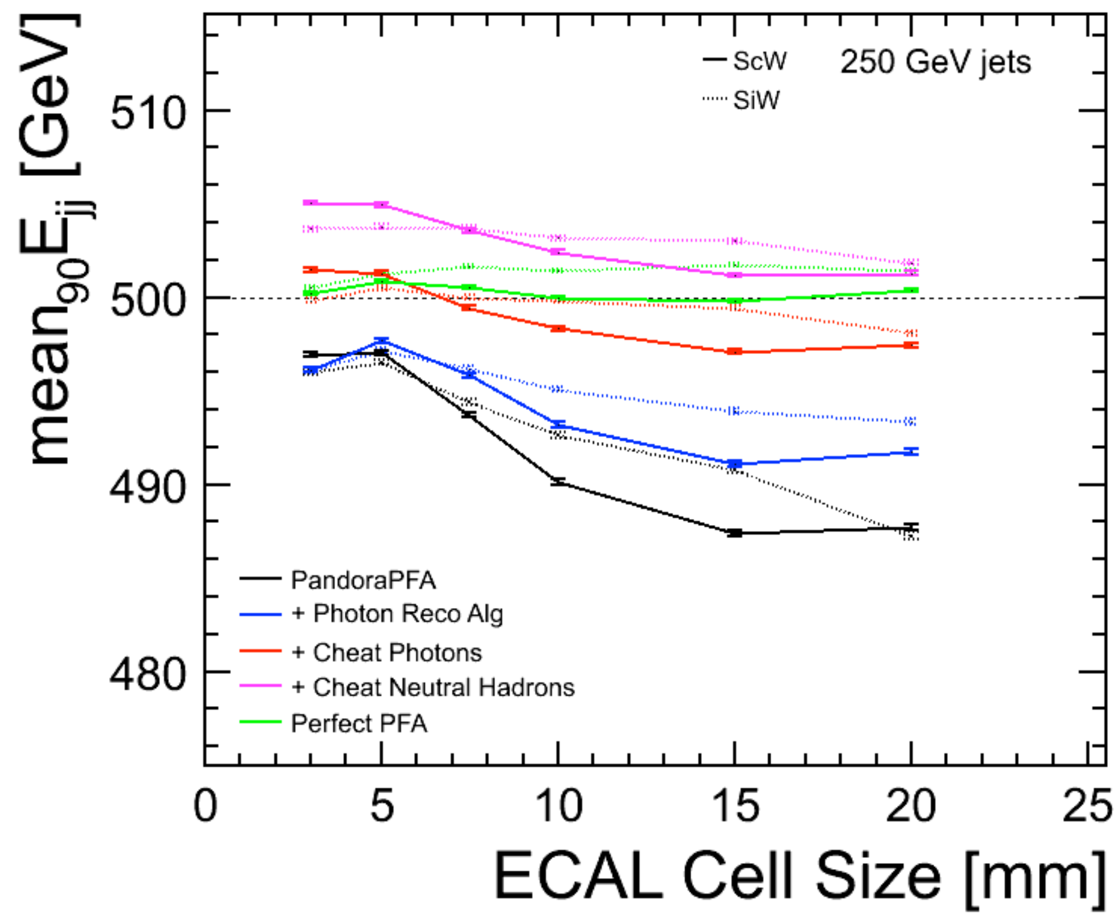
Resolutions for 250 GeV jets:

	3 mm	5 mm	7.5 mm	10 mm	15 mm	20 mm
SiW	1.61%	1.61%	1.63%	1.6%	1.62%	1.65%
ScW	1.66%	1.64%	1.59%	1.6%	1.6%	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.

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



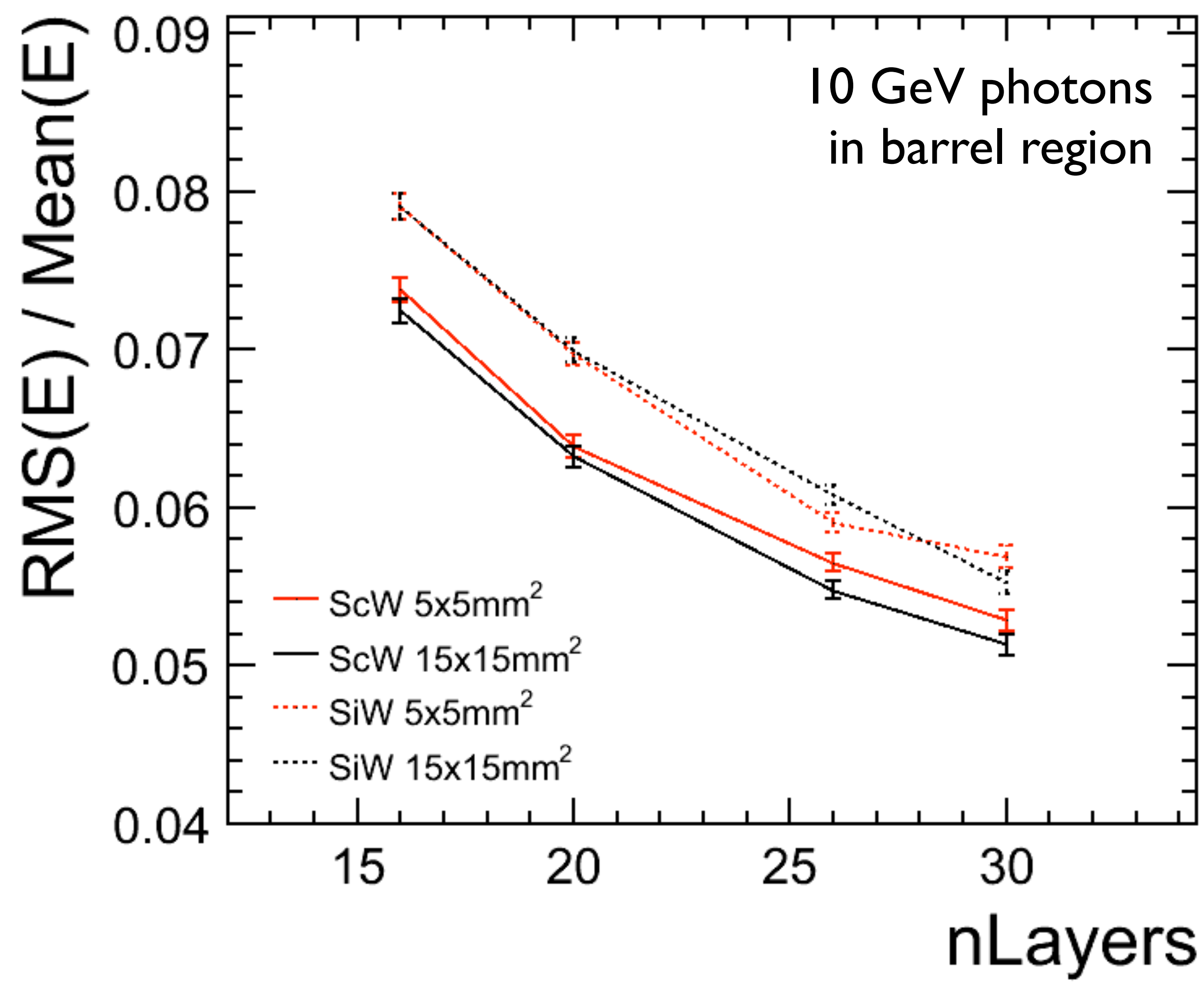


- Total confusion represents difference between reconstructed resolution and perfect PFA; it comprises neutral hadron confusion, photon confusion and all "other" remaining contributions.
- As could infer from earlier plots, neutral hadron confusion contribution is essentially flat with respect to ECAL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

Number of ECAL Layers

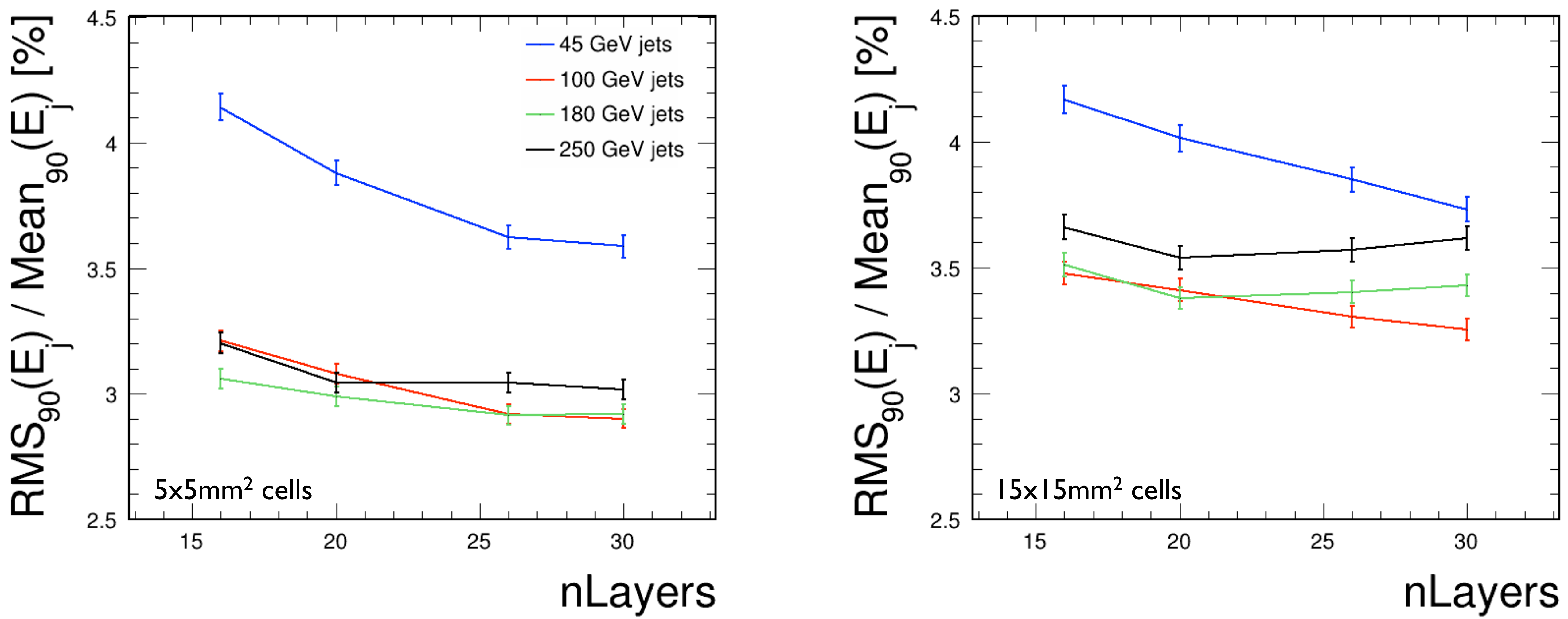
- Next, investigate impact on jet energy resolution of reducing number of layers.
- Look to reduce the number of absorber and active layers whilst maintaining a constant depth of $23X_0$.
- Extend and complement results obtained by T. H. Tran to include both SiW and ScW ECALs, with two different granularities.
- 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

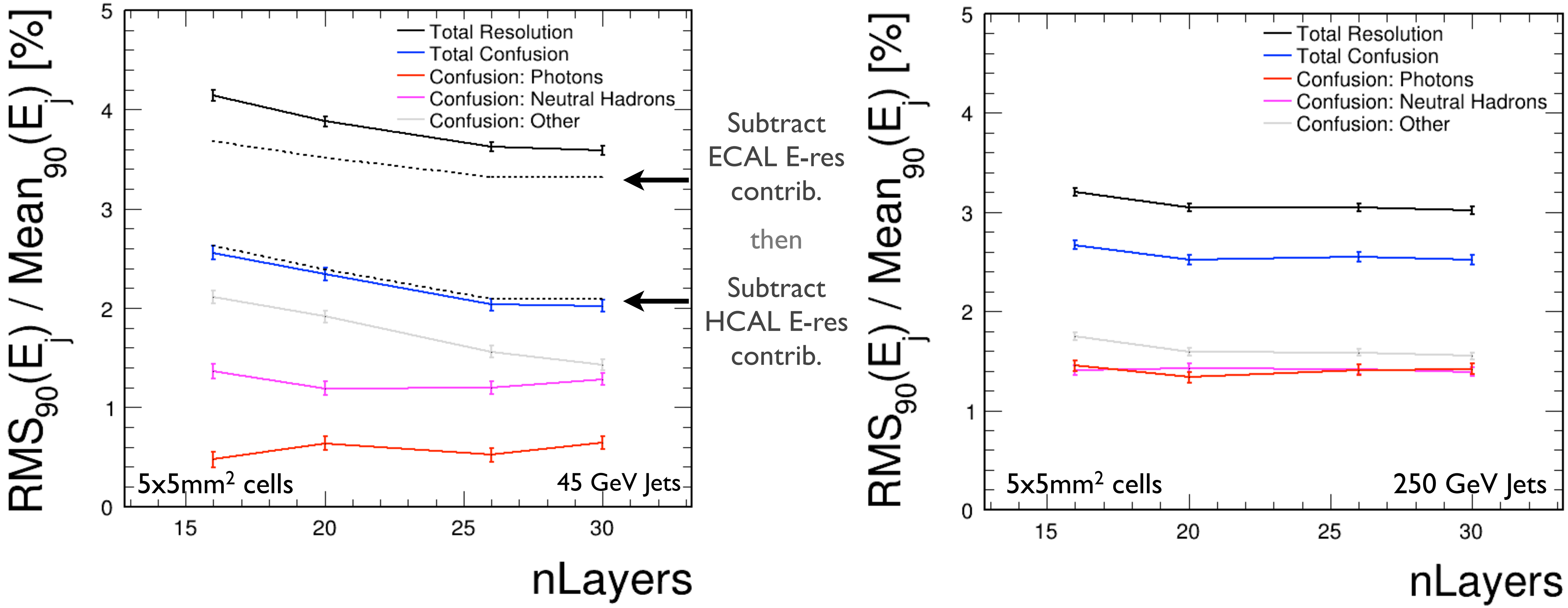


- Following calibration (for jet E), examine E resolution for 10GeV photons in the barrel.
- As expected, 2.0mm thick Sc offers better energy resolution than 0.5mm thick Si.
- Sc resolution varies with cell size (MPPC "dark" area), whilst Si resolution unaffected.

Number of ECAL Layers



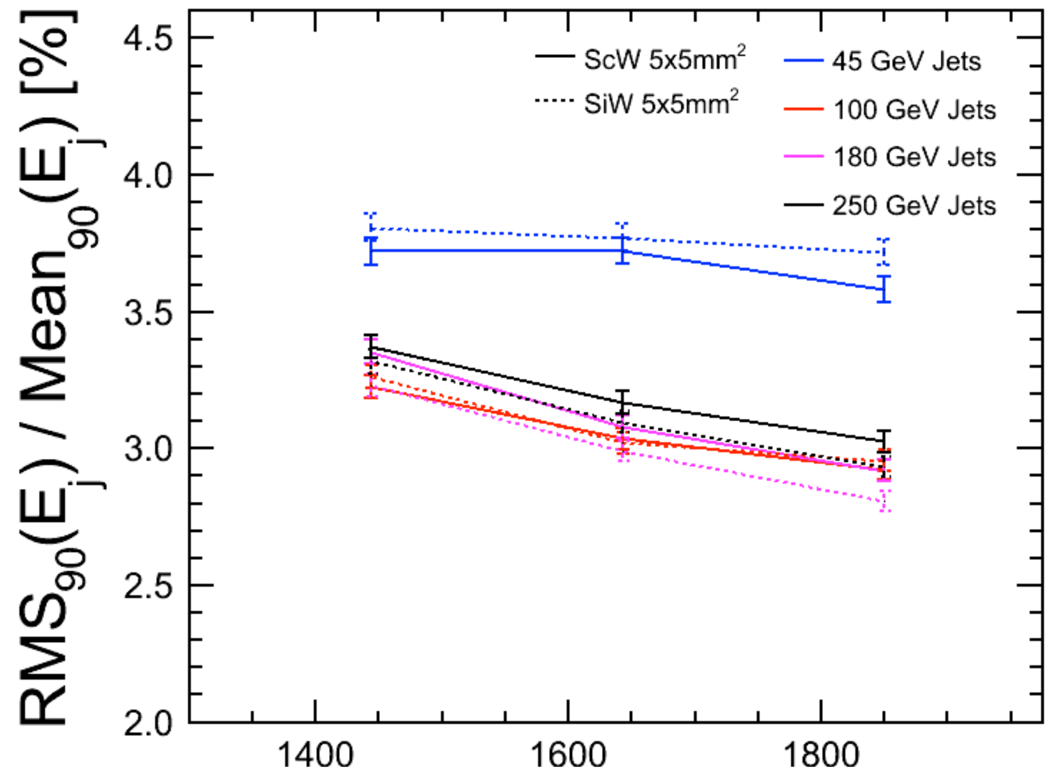
- Examine jet energy vs. number of ECAL layers for the two transverse granularities. Note that resolutions are shown only for ScW ECAL models, for the sake of clarity. Differences between SiW and ScW results were small and consistent with previous findings.
- Some variation of resolution with #layers 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.

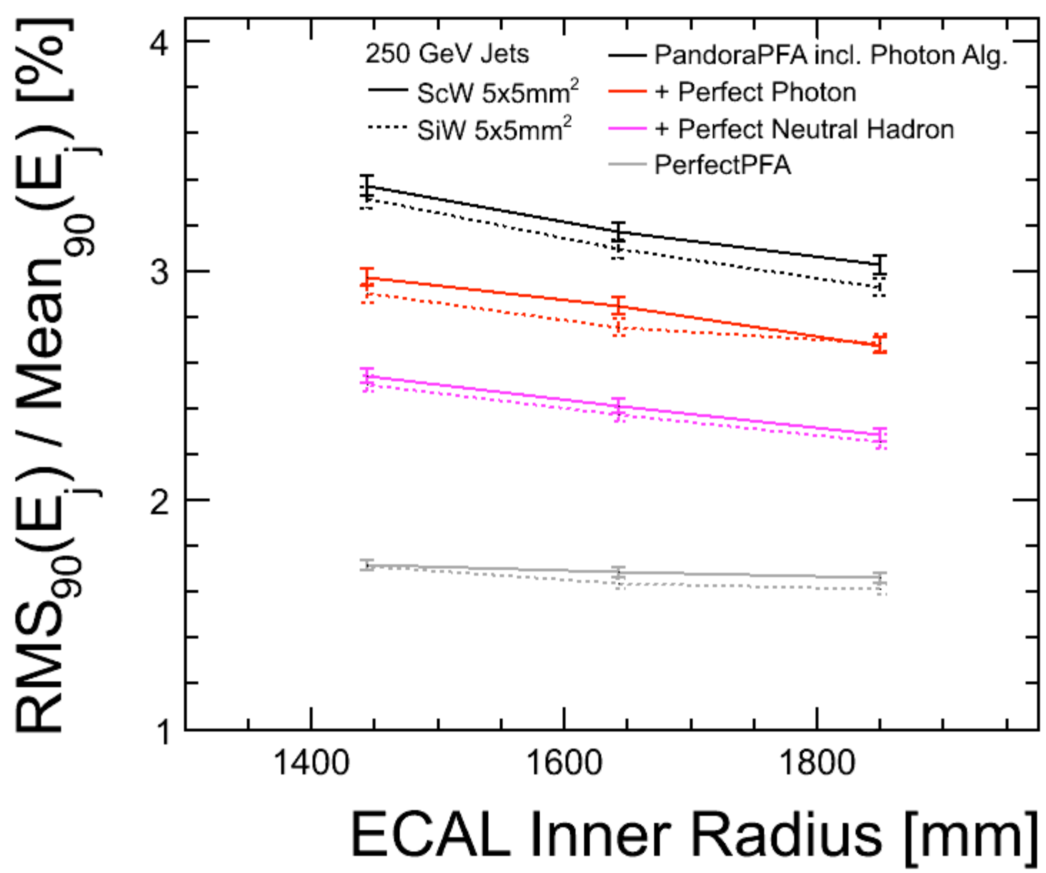


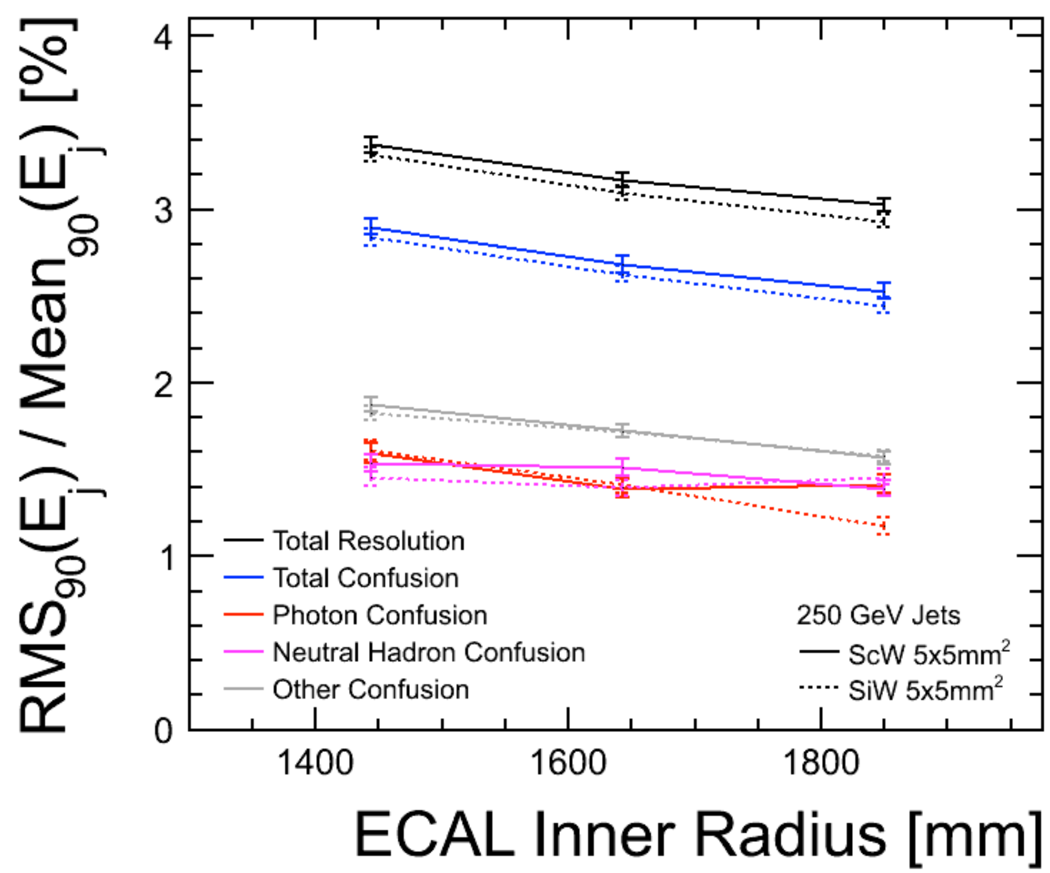
- For 250GeV jets, resolution does not vary with #layers. For 45GeV jets, there is some variation. To assess how much is due to energy resolution, use 10GeV photon resolution plot from slide 9 to subtract ECAL energy resolution component (assume 30% energy measured in ECAL).
- Following this subtraction, 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.

ECAL Inner Radius

- Move on to investigate impact of varying ECAL inner radius. Specify TPC outer radii of 1400, 1600 and (default) ~1800mm to obtain ECAL inner radii of 1443, 1643 and 1850mm.
- Mostly "other" confusion term that accounts for the improvement in jet energy resolution with ECAL inner radius: Likely due to reduced numbers of fake (neutral hadrons) fragments.

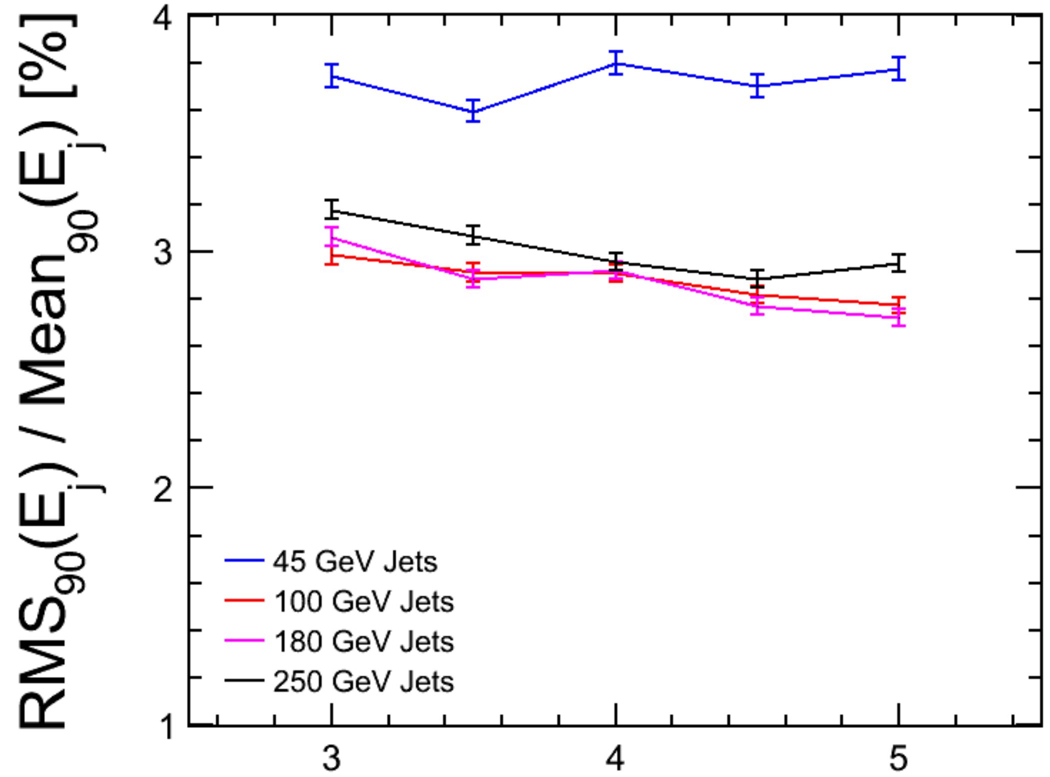


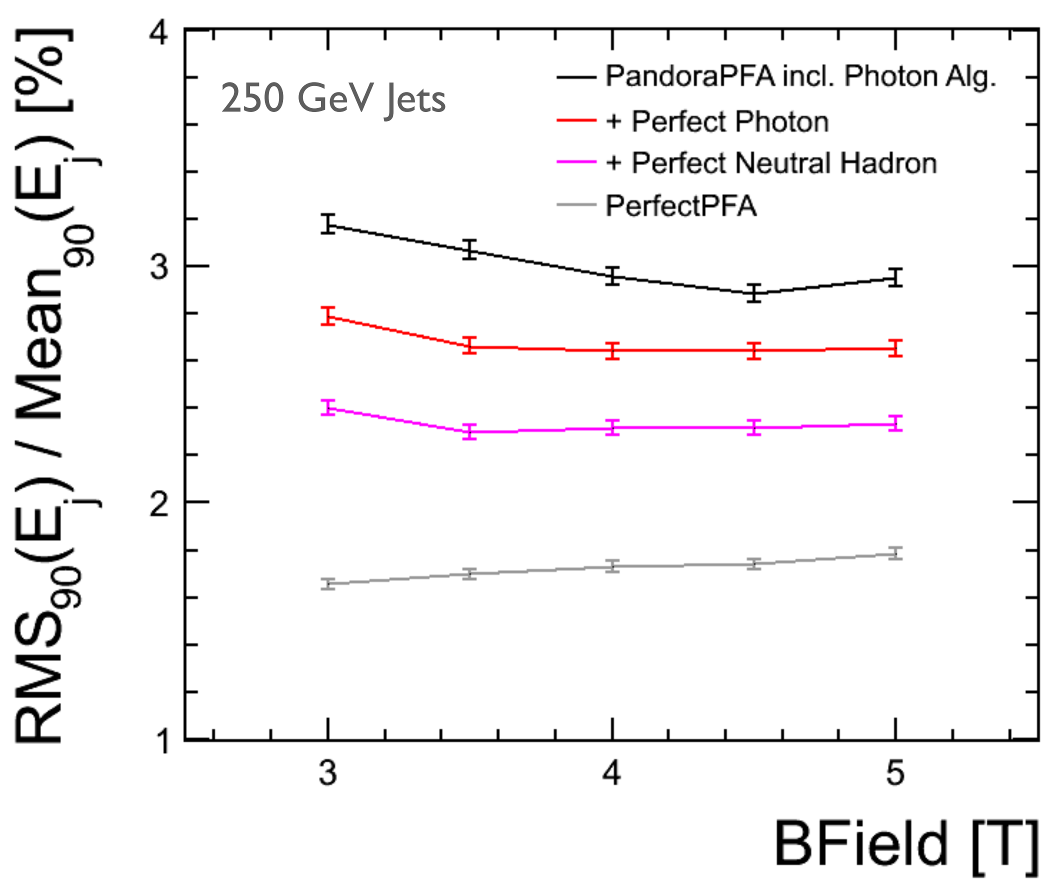


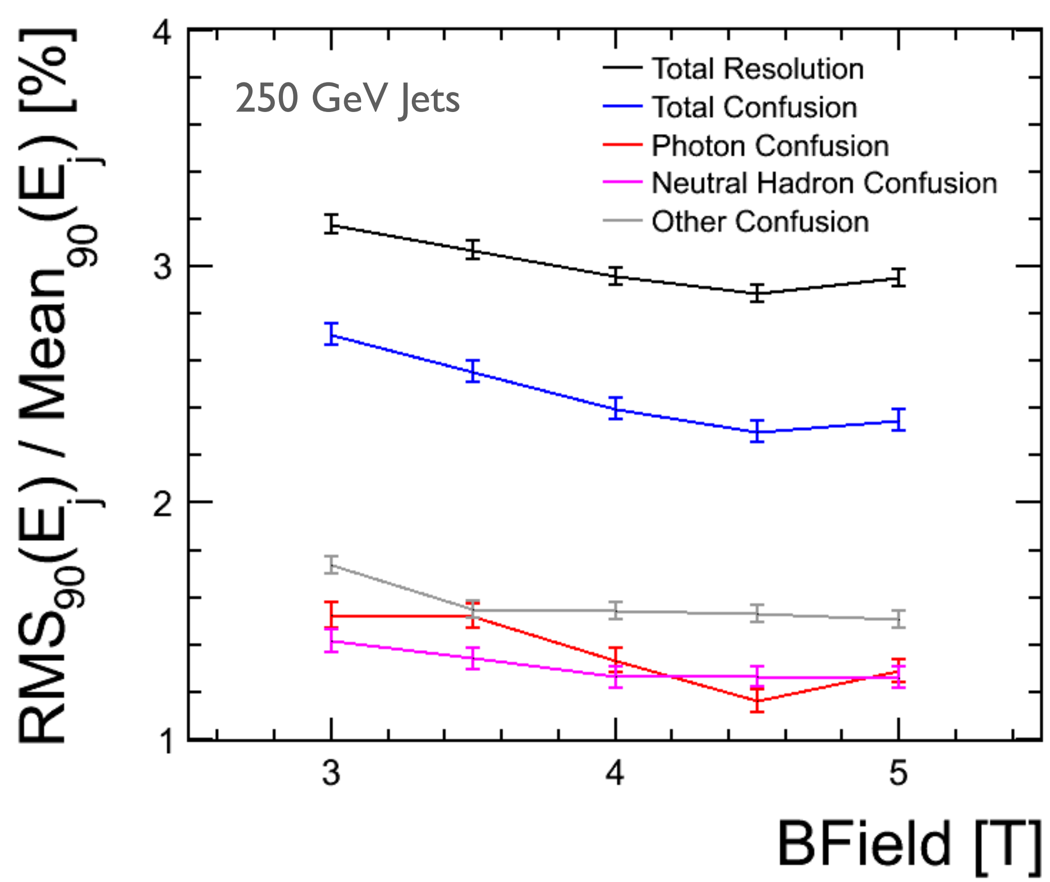


B-Field Strength

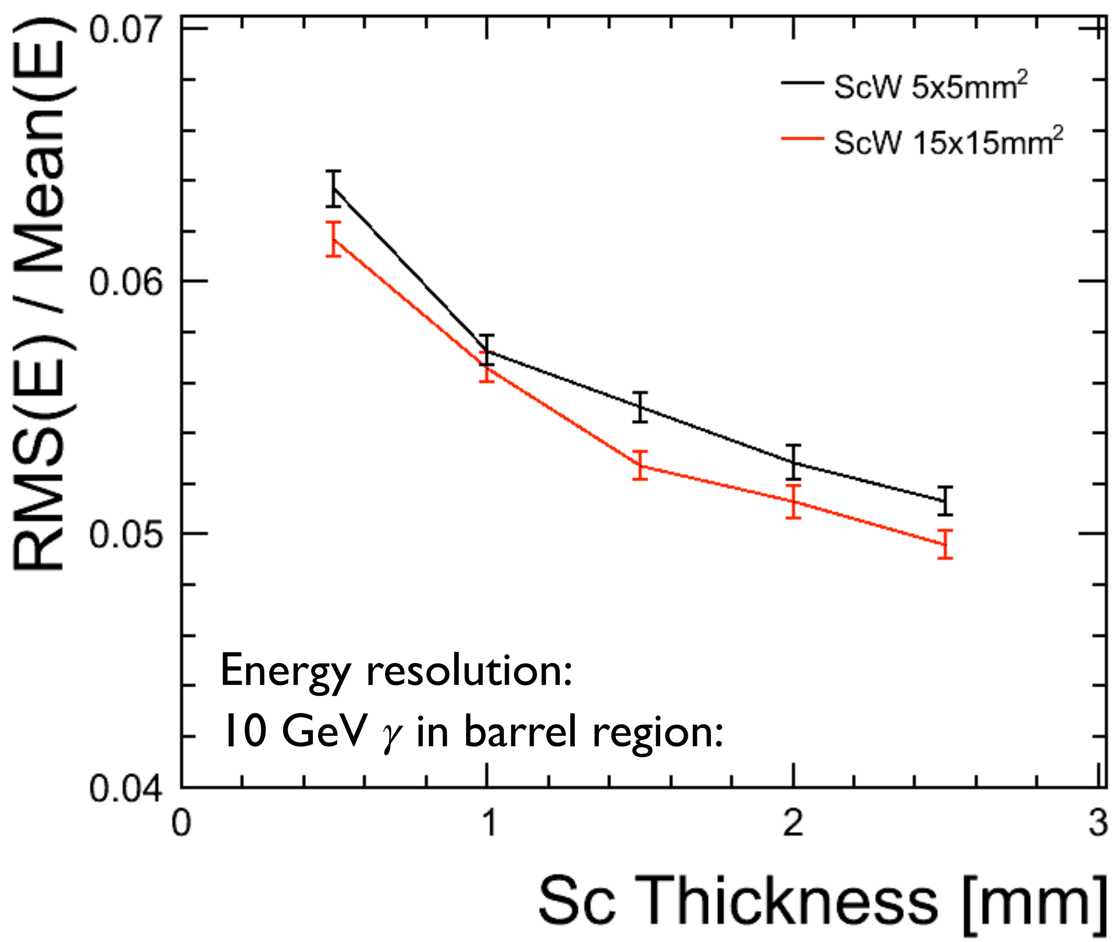
- Examine a range of different B-Field strengths: 3-5 T in 0.5 T steps (3.5 T is nominal ILD value). Here look at results for ScW ECAL with 30 layers, 5x5x2mm^3 cells and R=1850mm.
- Perfect PFA resolutions degrade as field strength increases, presumably as more charged particles are directed towards forward region. Confusion terms all decrease with B.

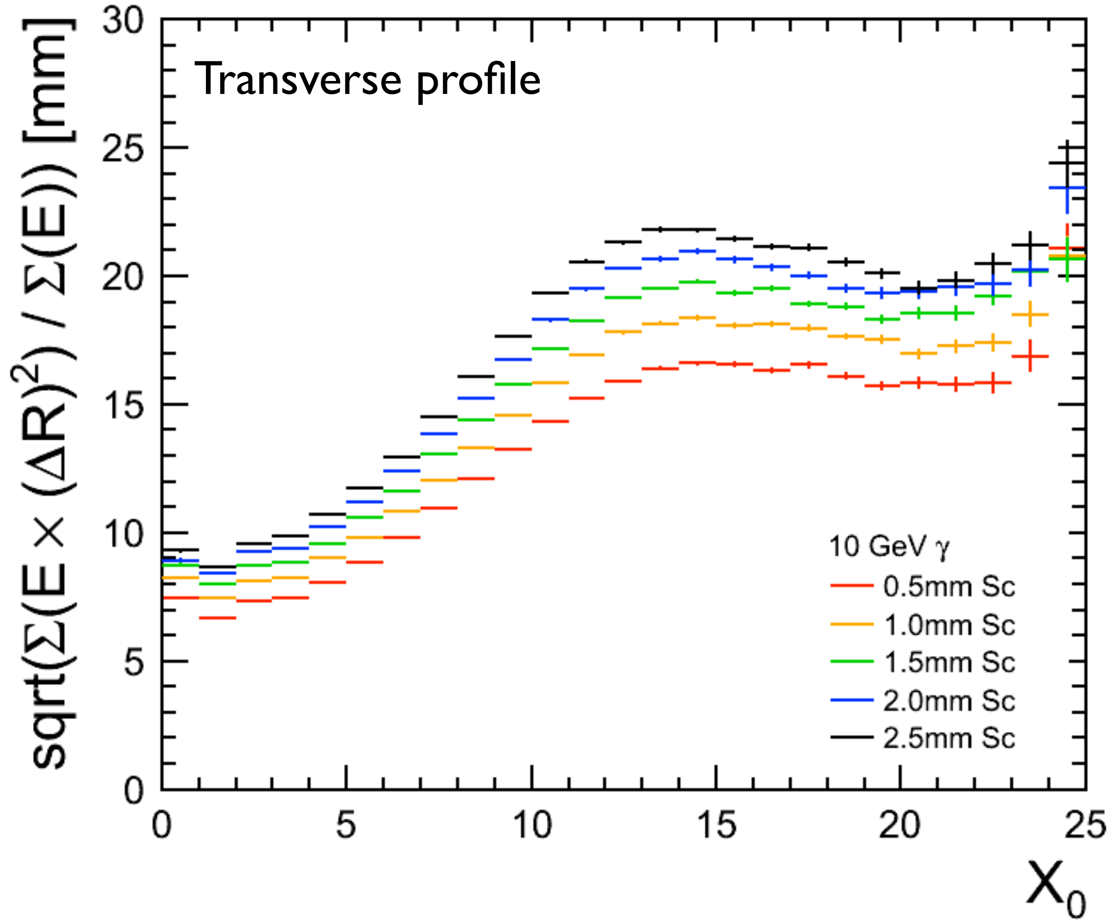






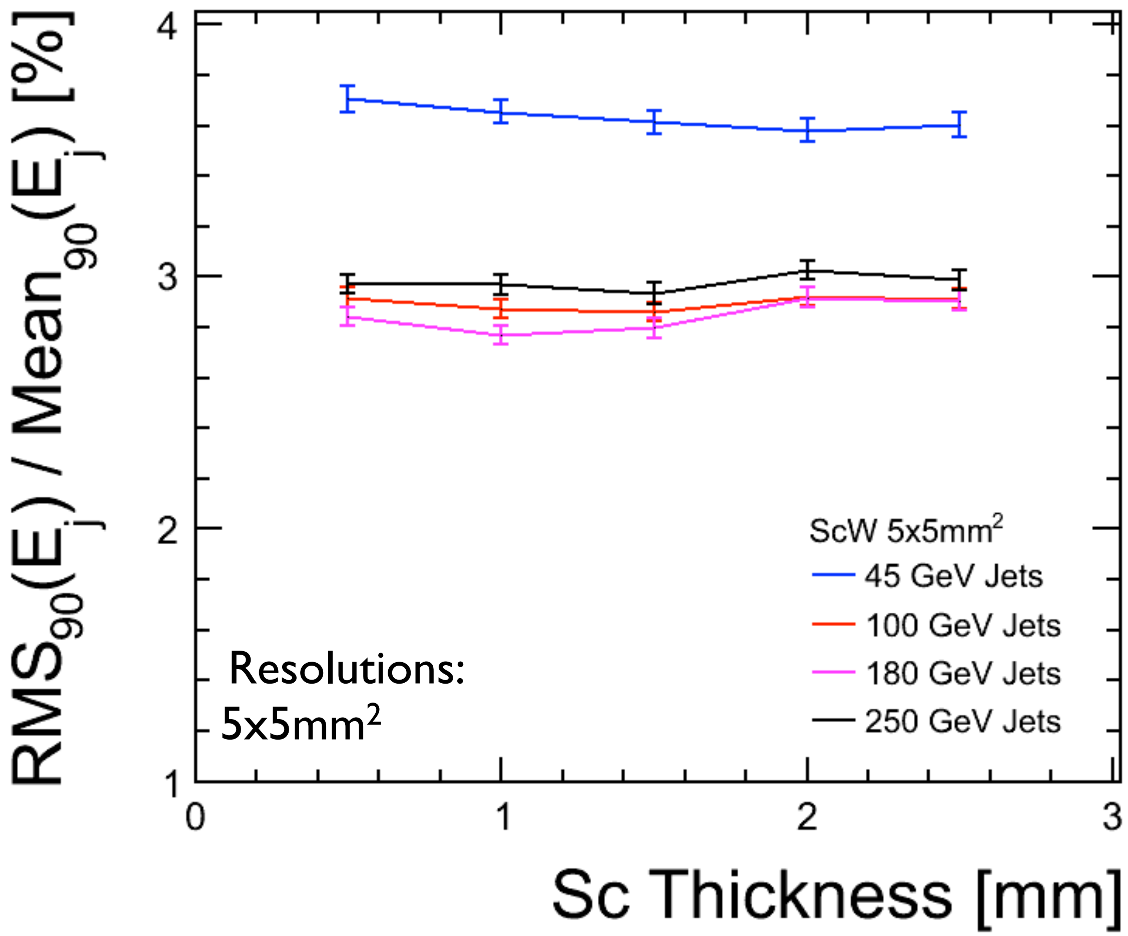
Scintillator Thickness

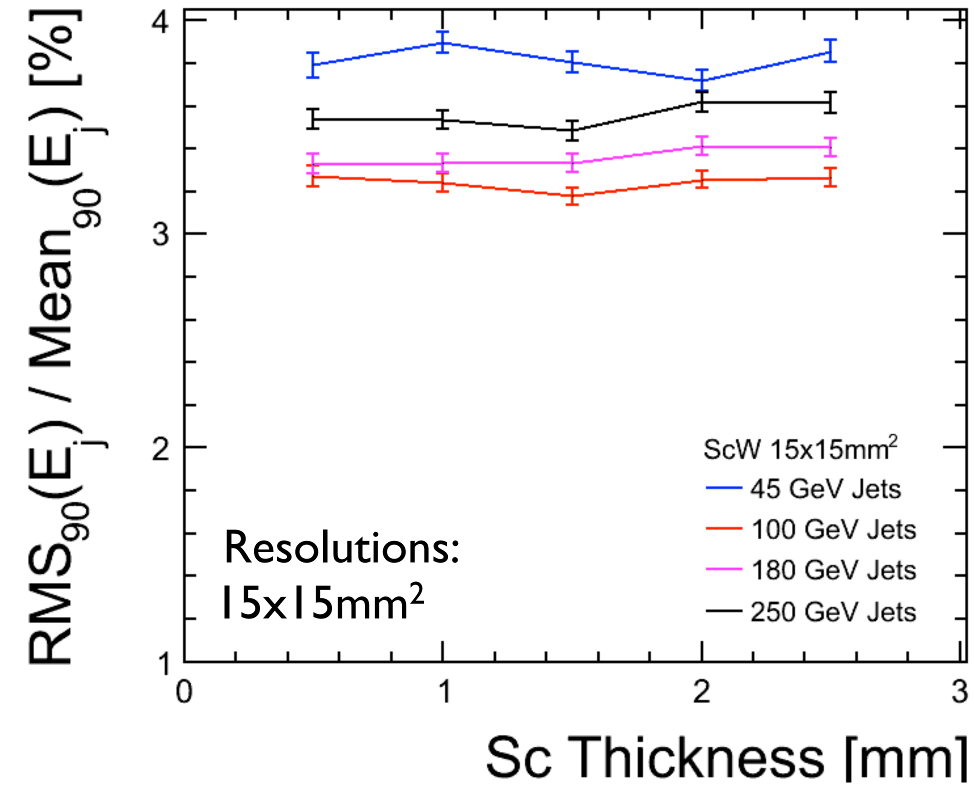


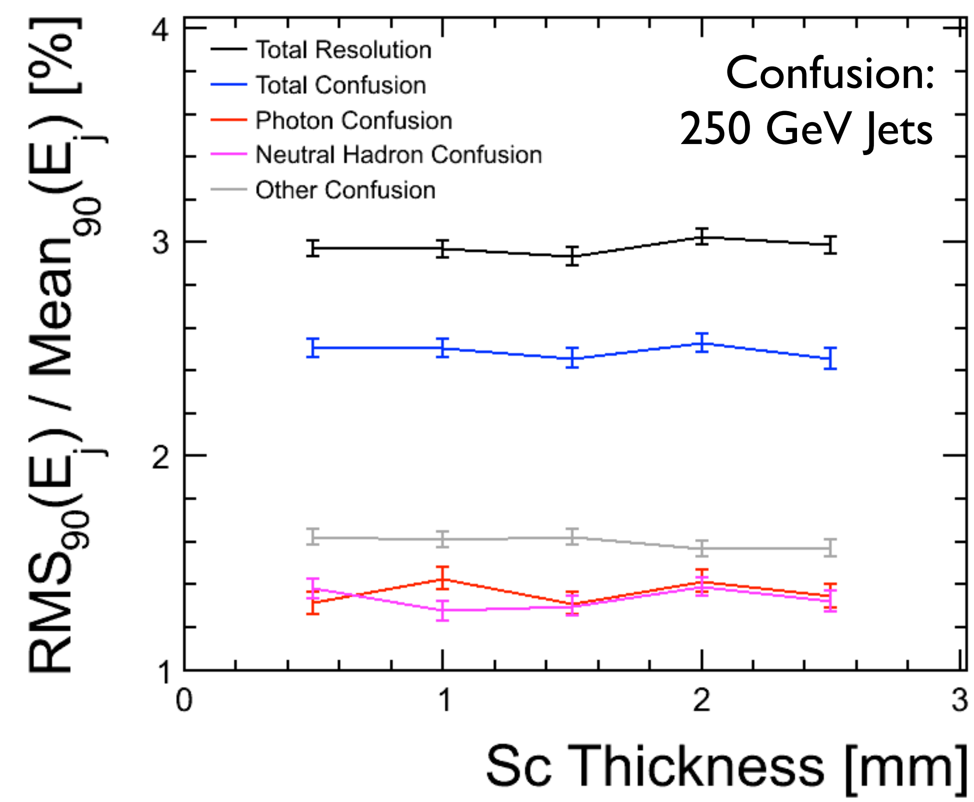


- Use standard 30 layer ScW ECAL with Sc thicknesses in the range 0.5-2.5mm. Examine performance with two transverse granularities: 5x5mm^2 and 15x15mm^2 cells.
- For 5x5mm^2 Sc cells, energy resolution varies from16%/$\sqrt{E}$ (2.5mm) to 20%/$\sqrt{E}$ (0.5mm). For 15x15mm^2 Sc cells, resolution is a little better, due to reduced MPPC "dark" area.
- Examine transverse profile, via energy-weighed mean hit displacement from the cluster axis. Notice significant broadening of showers with Sc thickness, as showers "spread out" in Sc.

Scintillator Thickness

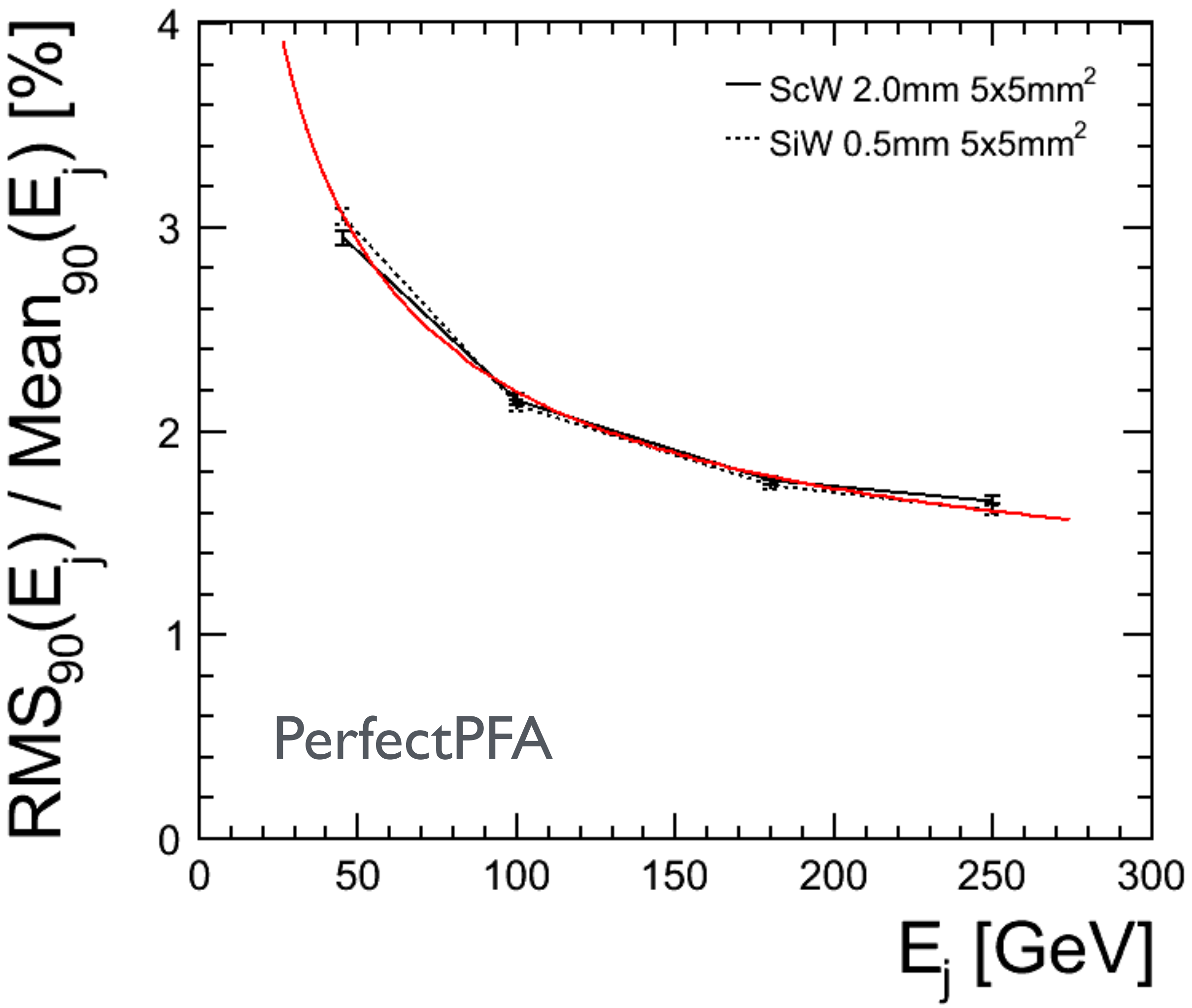






- Jet energy resolutions will depend on intrinsic energy resolution and the pattern recognition.
- Thicker Sc offers improved energy resolution, but may make pattern recognition more difficult...
- Turns out that jet energy resolutions, and all the confusion terms, are rather flat wrt Sc thickness.

- Aim to complete study by providing basic parameterisation of jet energy resolution.
- Start by parameterising ECAL E-resolution, then the PerfectPFA jet energy resolutions.
- Estimate HCAL E-resolution and assume 30% jet E measured in ECAL, 10% in HCAL.
- Fit an additional term proportional to E, to account for leakage and tracking failures.
- Can then proceed to parameterise each of the confusion terms separately.



ScW ECAL Energy Resolution

$$\left(\frac{\sigma_E}{E}\right) = \left(\frac{100\%}{E}\right)\left(\left(0.30E\left(\frac{0.154}{\sqrt{0.30E/\mathrm{GeV}}} \oplus 0.0200\right)\left(\frac{t}{2\,\mathrm{mm}}\right)^{-0.14}\left(\frac{L}{30\mathrm{lyr}}\right)^{-0.50}\right) \oplus \left(0.10E\left(\frac{0.55}{\sqrt{0.10E/\mathrm{GeV}}}\right)\right) \oplus (0.0086E)\right)$$

HCAL Energy Resolution

Leakage/Tracking

Parameterised Resolution

ECAL Energy Resolution — HCAL Energy Resolution — Leakage/Tracking

$$\left(\frac{\sigma_E}{E}\right) =$$

$$\left(\frac{100\%}{E}\right)\left(\left(\left(0.30E\left(\frac{0.154}{\sqrt{0.30E/\mathrm{GeV}}}\oplus 0.0200\right)\left(\frac{t}{2\,\mathrm{mm}}\right)^{-0.14}\left(\frac{L}{30\mathrm{lyr}}\right)^{-0.50}\right)\oplus\left(0.10E\left(\frac{0.55}{\sqrt{0.10E/\mathrm{GeV}}}\right)\right)\right)\oplus(0.0086E)\right)\oplus$$

$$\left(0.90\left(\frac{E}{100\mathrm{GeV}}\right)^{0.50}\left(\frac{R}{1853\mathrm{mm}}\right)^{-0.40}\left(\frac{C}{5\mathrm{mm}}\right)^{0.40}\left(\frac{B}{3.5\mathrm{T}}\right)^{-0.40}\right)\oplus$$ ← Photon Confusion

$$\left(1.25\left(\frac{E}{100\mathrm{GeV}}\right)^{0.15}\left(\frac{R}{1853\mathrm{mm}}\right)^{-0.30}\left(\frac{B}{3.5\mathrm{T}}\right)^{-0.20}\right)\oplus$$ ← Neutral Hadron Confusion

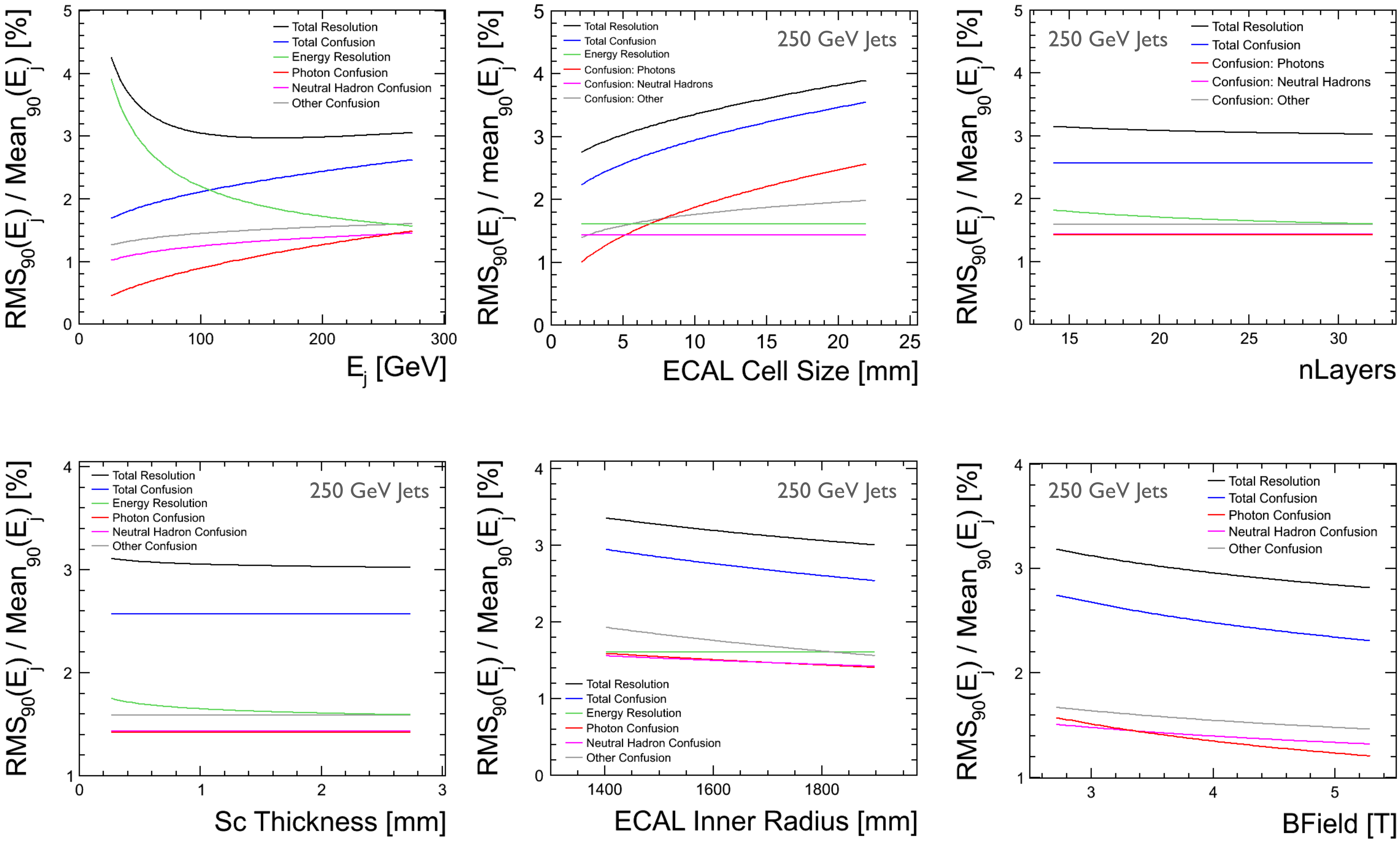
$$\left(1.45\left(\frac{E}{100\mathrm{GeV}}\right)^{0.10}\left(\frac{R}{1853\mathrm{mm}}\right)^{-0.70}\left(\frac{C}{5\mathrm{mm}}\right)^{0.15}\left(\frac{B}{3.5\mathrm{T}}\right)^{-0.20}\right)$$ ← Other Confusion

$$\left(2.11\left(\frac{E}{100\mathrm{GeV}}\right)^{0.20}\left(\frac{R}{1853\mathrm{mm}}\right)^{-0.50}\left(\frac{C}{5\mathrm{mm}}\right)^{0.20}\left(\frac{B}{3.5\mathrm{T}}\right)^{-0.25}\right)$$

Alternative Combined Confusion Term

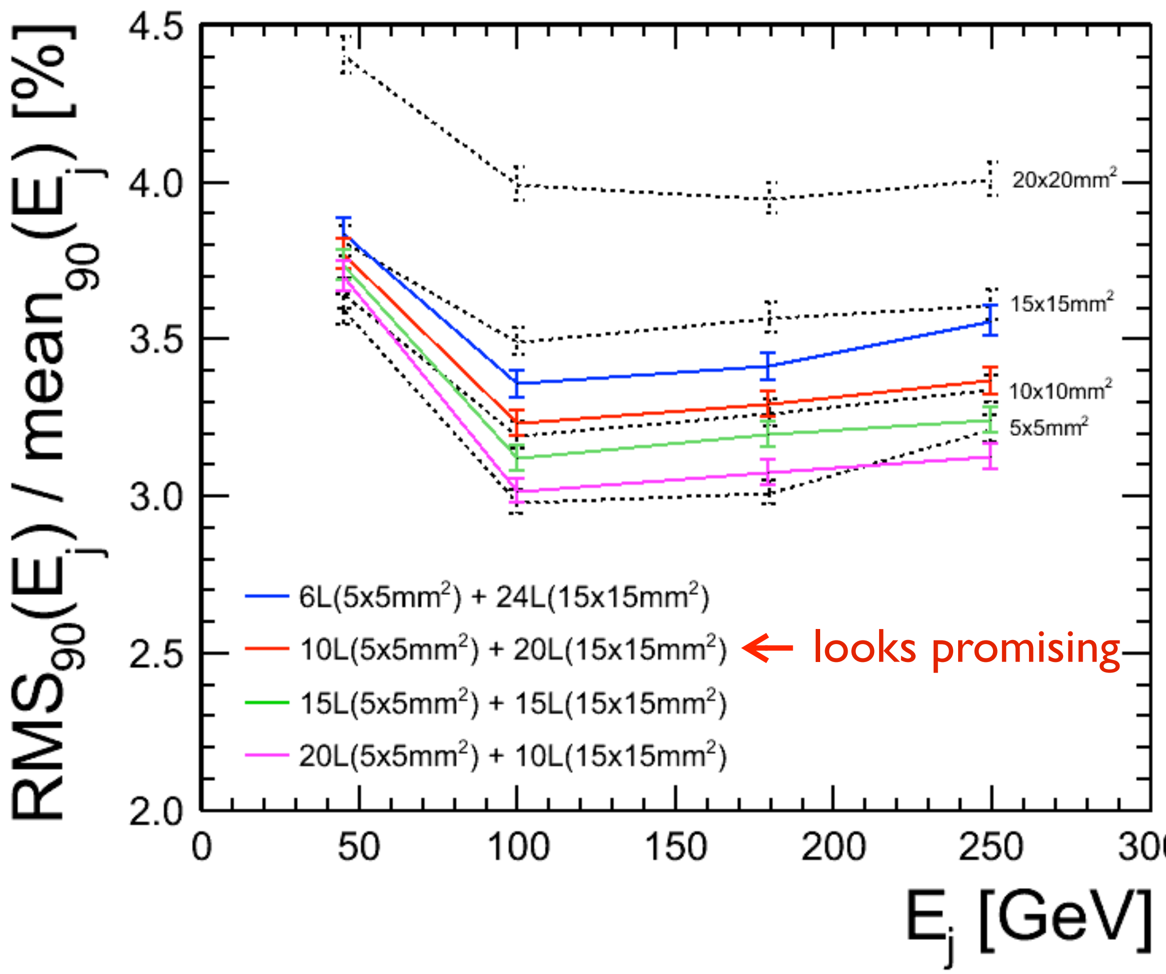
Parameterisation can be used for a ScW or SiW ECAL. To use with SiW ECAL, remove references to cell thickness variation and alter basic ECAL energy resolution.

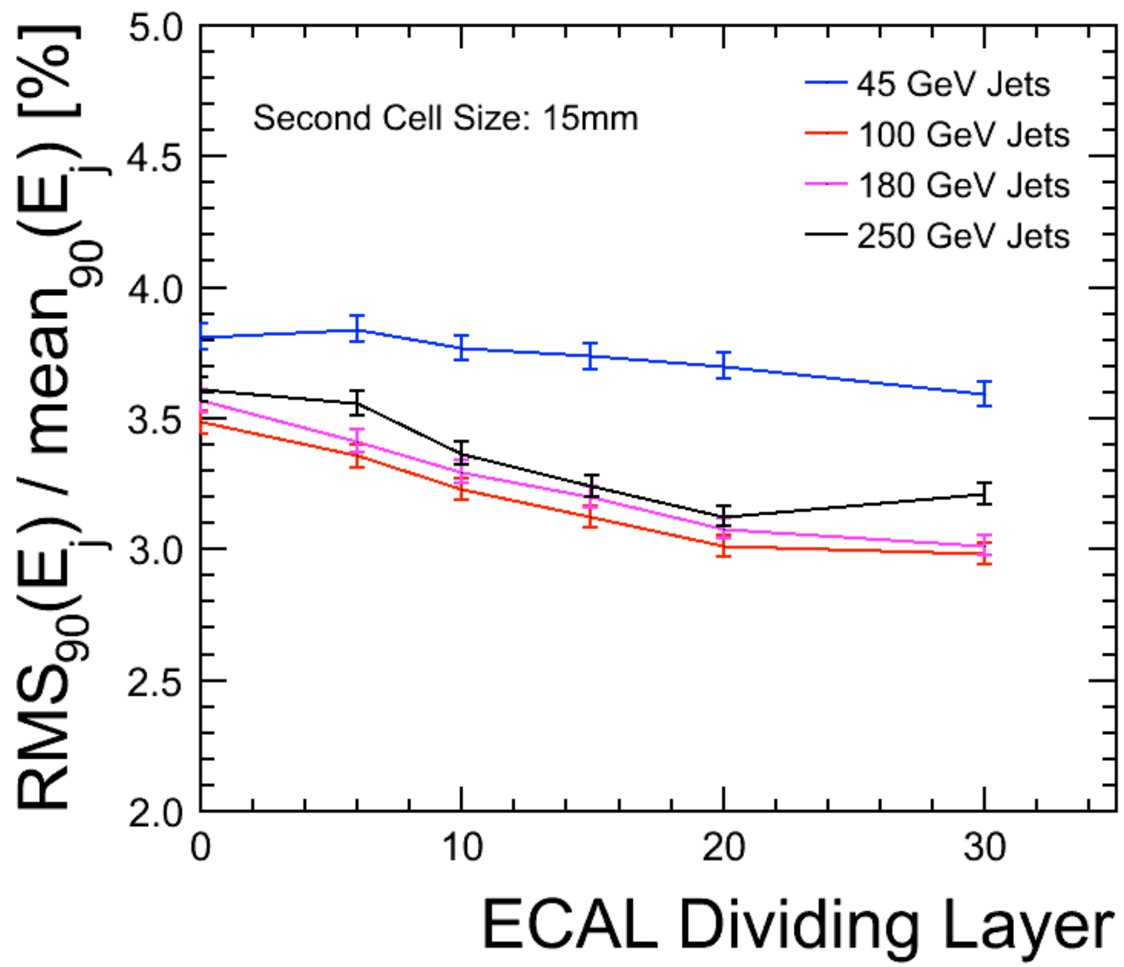
Parameterised Resolution



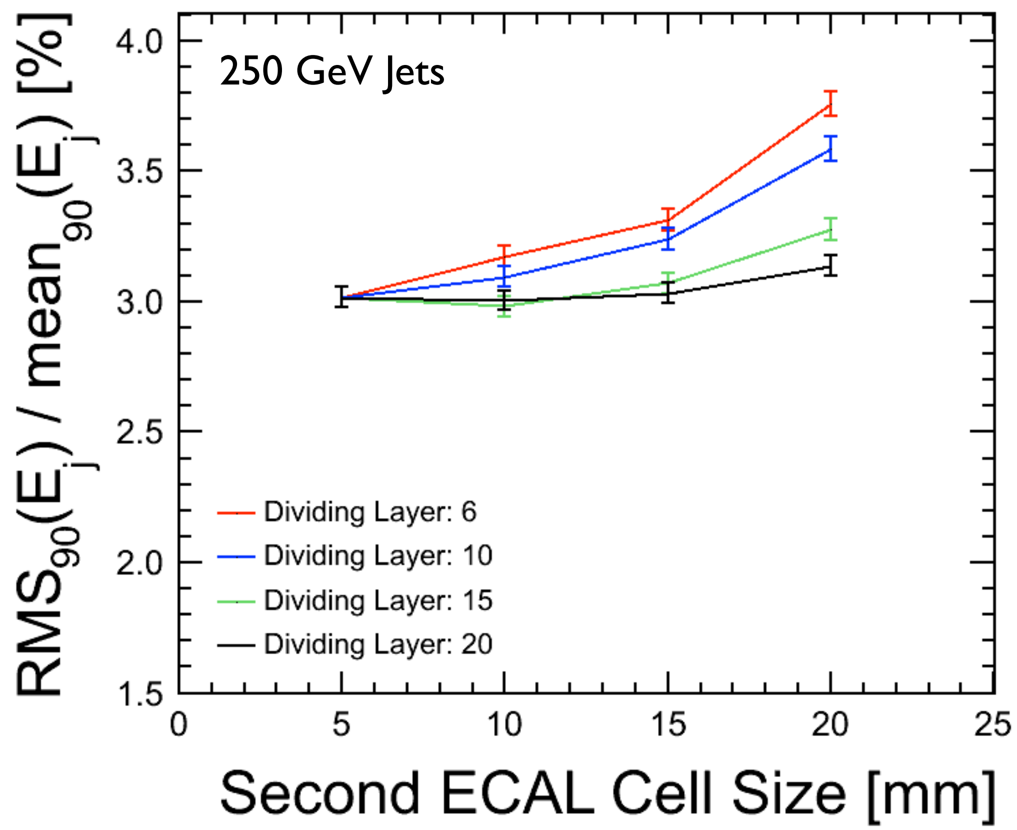
Two Granularity Regions

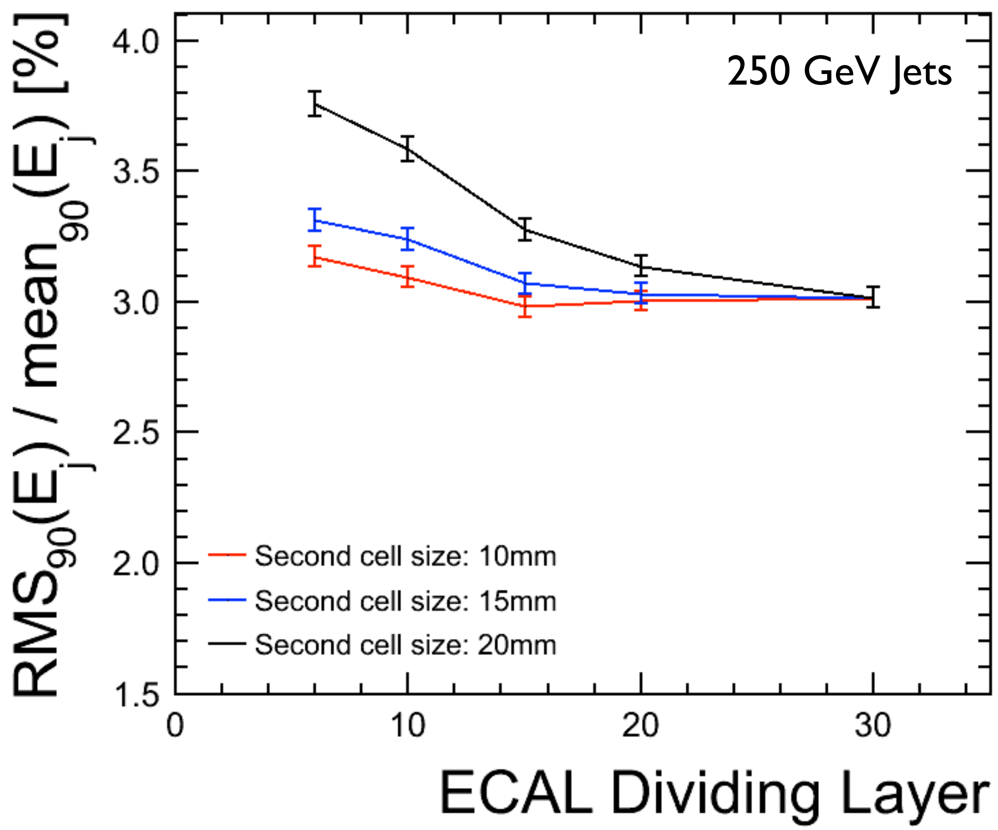
- Now investigate performance of novel ECAL models with two transverse segmentations. Use ScW ECAL models and assume first region comprises 5x5mm² cells, so study parameters are:
  - The size of the square Sc cells used in second region;
  - The "dividing layer", i.e. the ECAL layer at which the Sc cell 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.



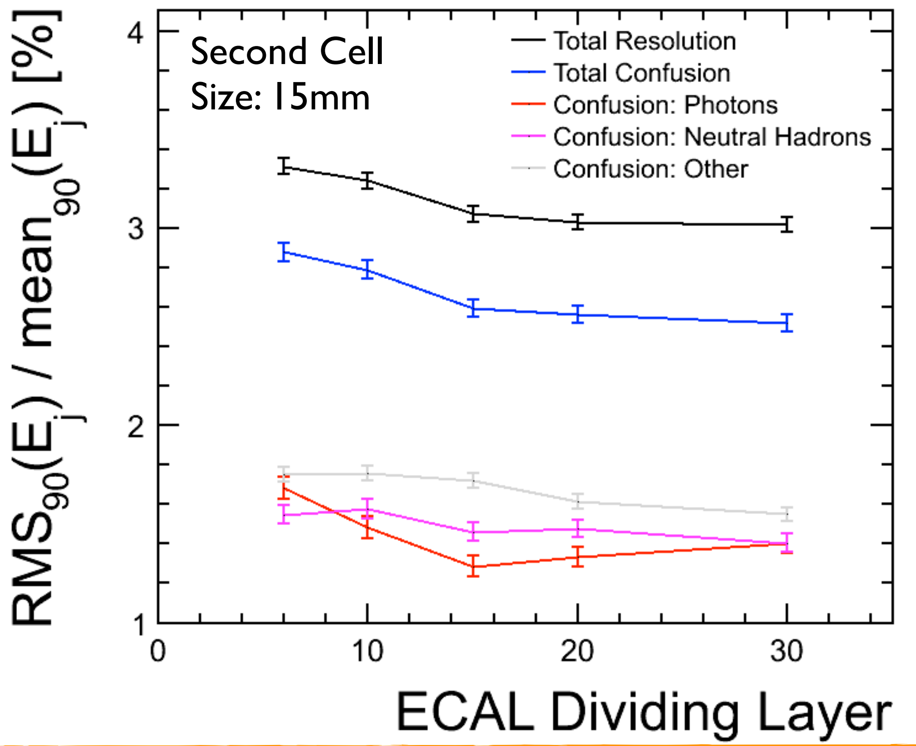


Two Granularity Regions

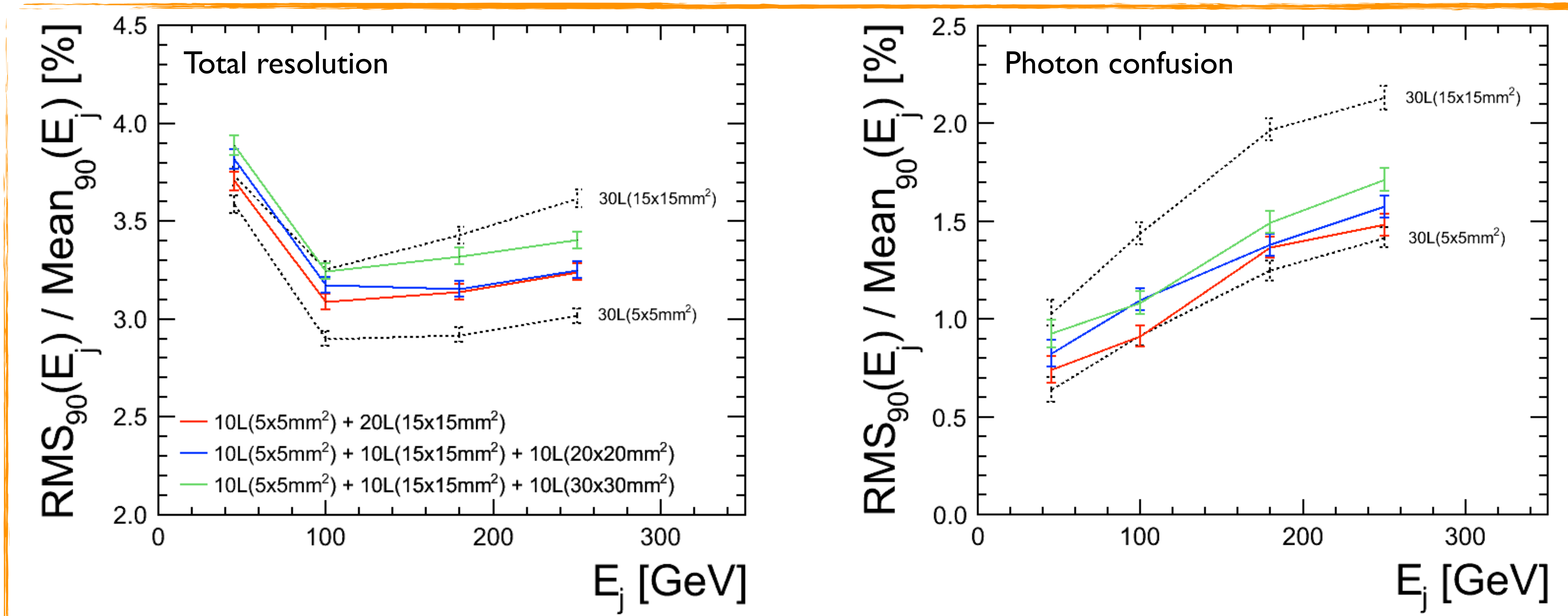




- For 250GeV jets, plot resolution vs. second cell size and vs. dividing layer. Note: second cell size of 5mm and dividing layer of 30 both correspond to a uniform 5x5mm^2 ECAL.
- Second cell size of 15mm and dividing layer of 10 is most aggressive configuration for which photon confusion remains less than neutral hadron confusion.



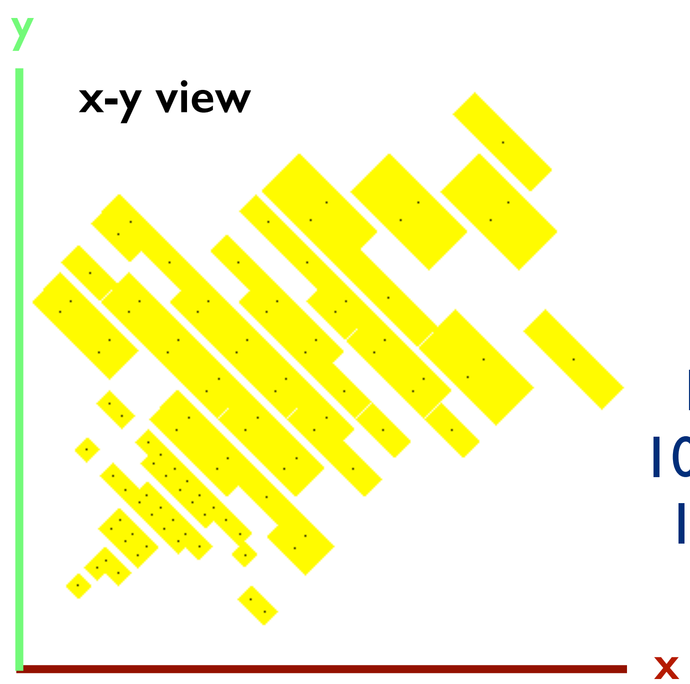
Three Granularity Regions



- 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.

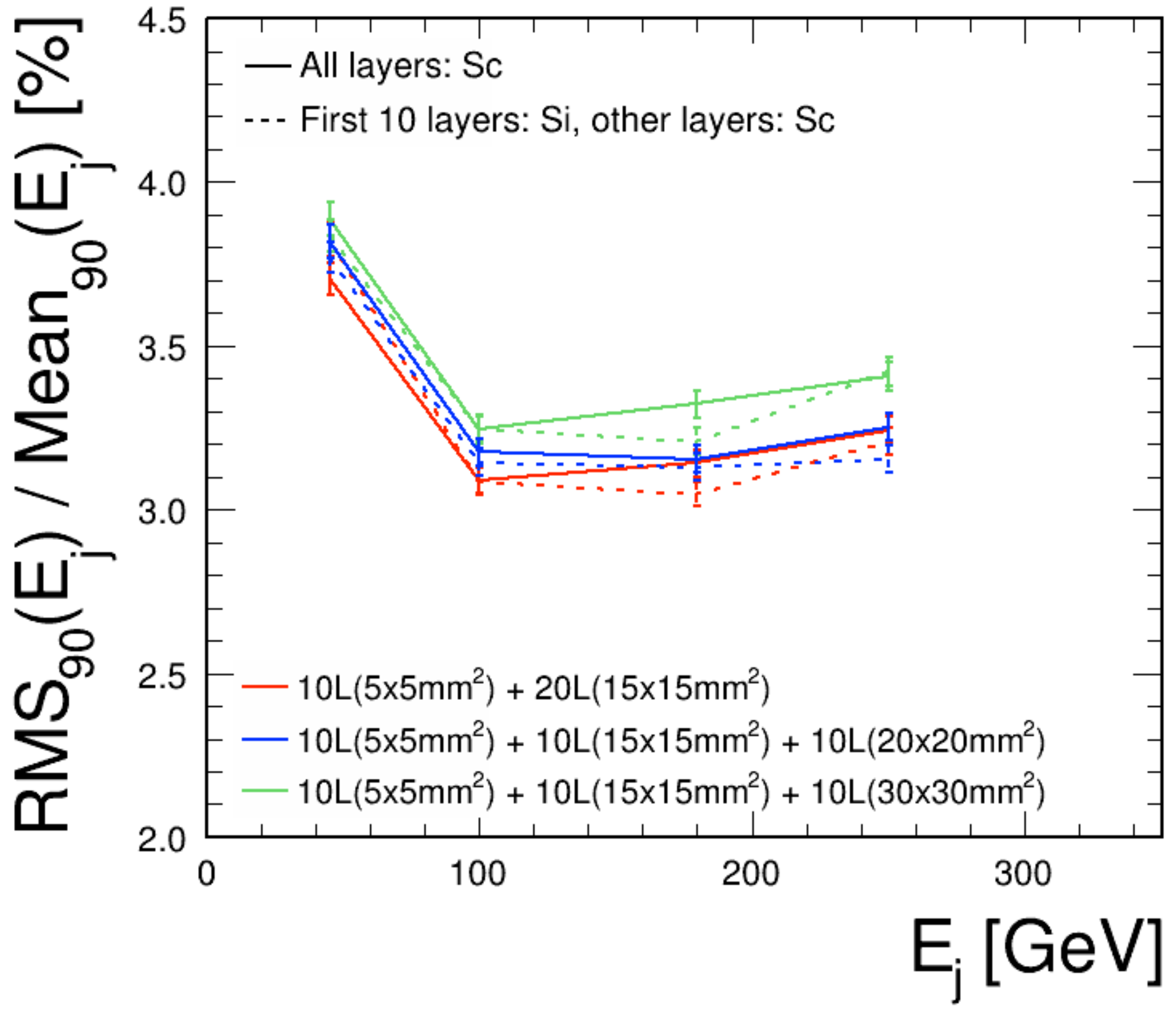
Si/Sc Hybrid ECAL

- Appealing prospect is to use Si for first layers, then move to Sc deeper in ECAL. Need to confirm this is a viable approach.
- Si 0.5mm thick, whilst Sc is 2.0mm thick, so there is an expected discontinuity in the typical shower width.
- Note: care is required with digitisation and calibration for Si/Sc hybrid models.



Typical 10GeV photon display:

10L(5x5mm² Si) + 10L(15x15mm² Sc) + 10L(30x30mm² Sc)



- Compare performance for full Sc models and for hybrids using Si for first 10 layers.
- Performance maybe a bit better for hybrids, due to reduced shower width early in ECAL.

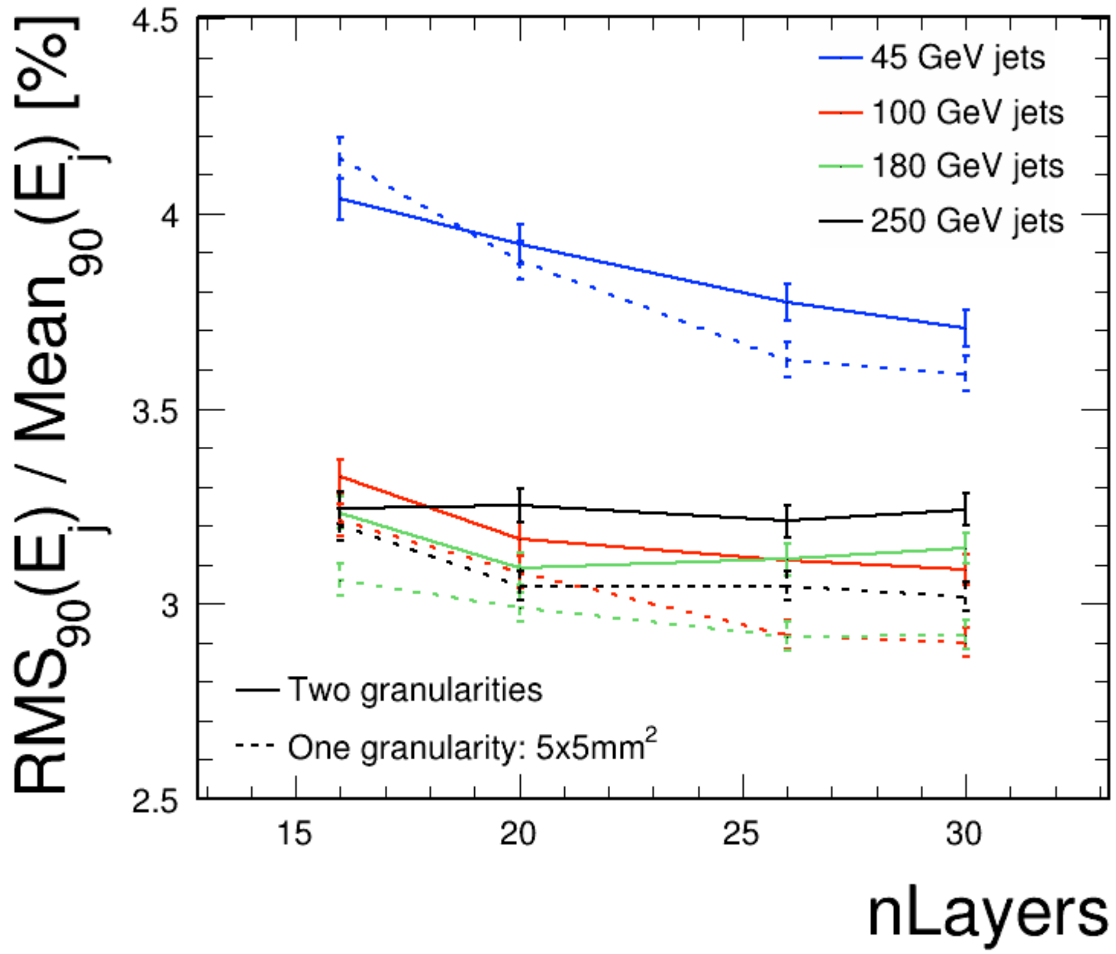
Two Granularities & Layer Reduction

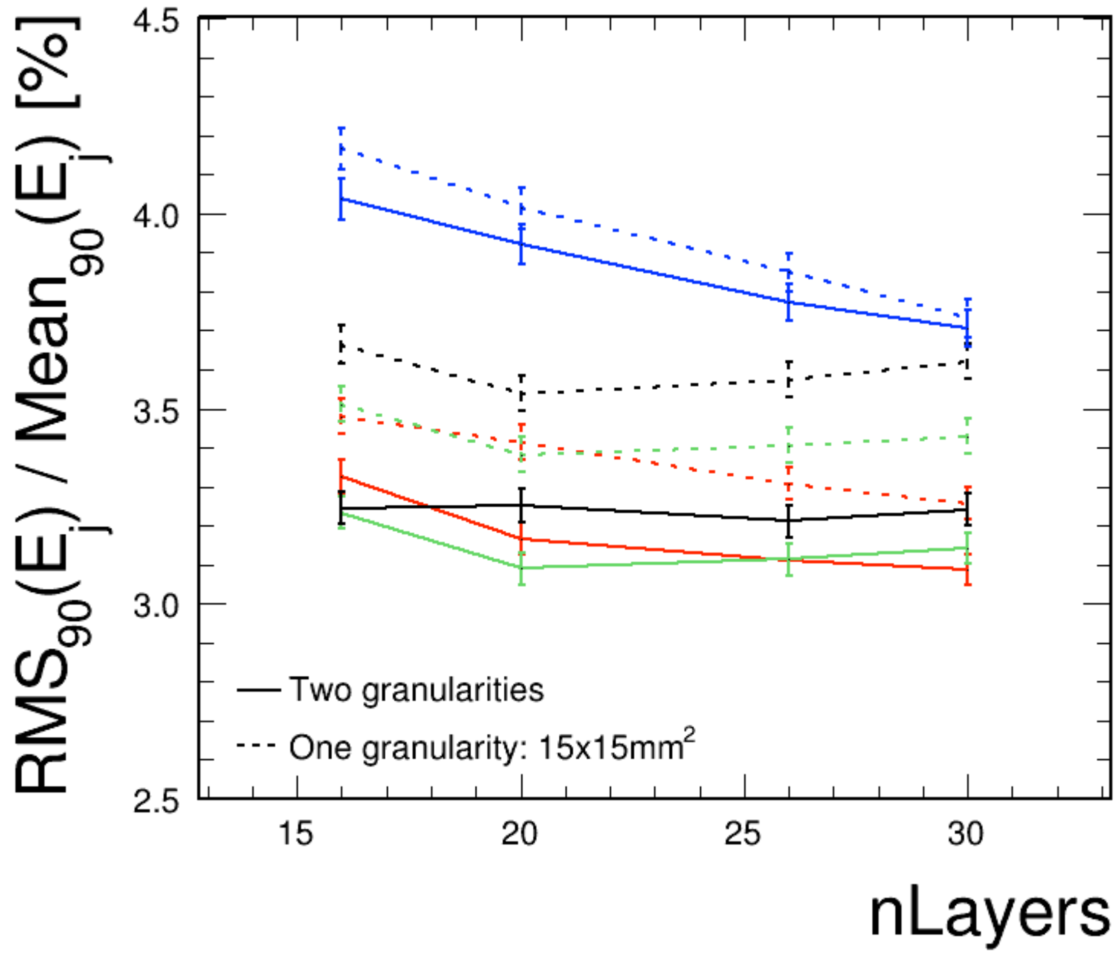
- Study ECAL layer reduction in the context of a two granularity model. The W absorber thicknesses remain as described on slide 9, but the transverse granularities are:

- Maintain roughly constant fraction of total layers with 5x5mm^2 granularity.

- Able to closely predict outcome using results from earlier separate studies.

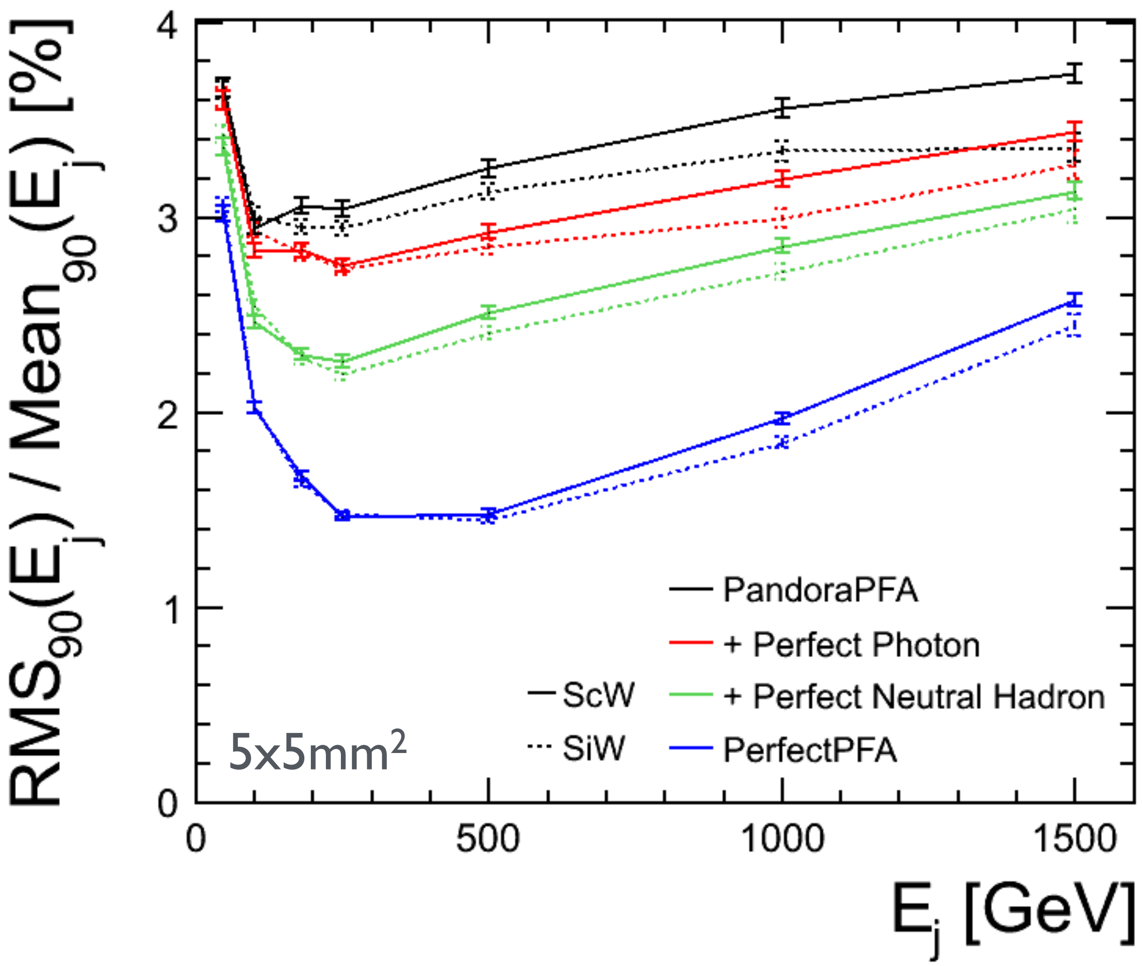
30 layers	10L(5x5mm2) + 20L(15x15mm2)
26 layers	9L(5x5mm2) + 17L(15x15mm2)
20 layers	7L(5x5mm2) + 13L(15x15mm2)
16 layers	6L(5x5mm2) + 10L(15x15mm2)

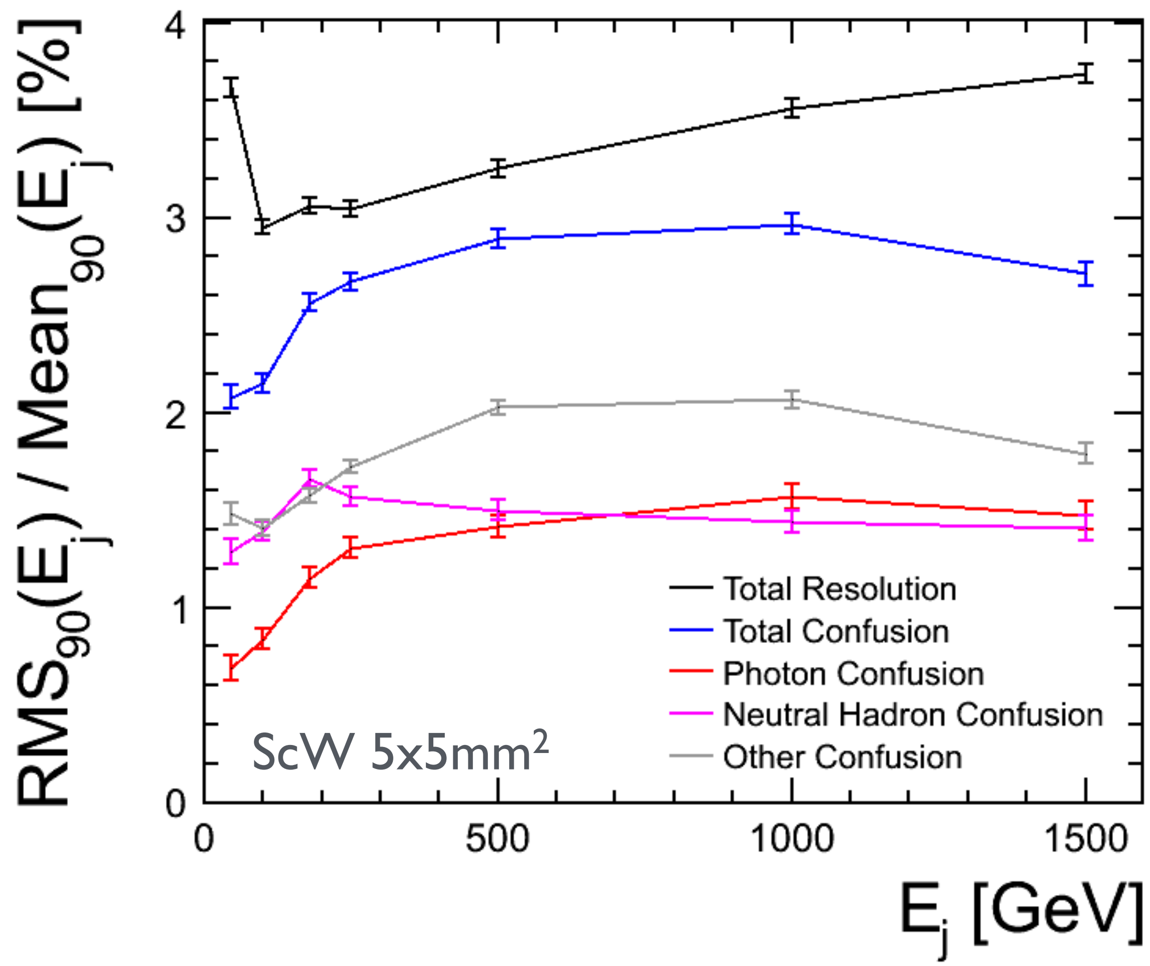




Higher Energy Jets

- Finish by looking at performance for high energy jets in ILD_o1_v06, with a 60 layer HCAL. Performance is better at highest energies with 5x5mm^2 SiW ECAL than with 5x5mm^2 ScW. Difference shrinks as progressively cheat aspects of the pattern recognition.
- Difference between total resolution and total confusion represents basic energy resolution and leakage. Confusion terms remain constant or even fall at high E, maybe associated with increased reclustering activity and the potential transition to energy flow calorimetry.





Summary

- Series of full simulation studies performed, examining variation of jet energy resolutions (including confusion terms) in context of ILD_o1_v05.
- Studies performed very carefully with re-calibration and re-tuning for each detector configuration. Simulation and reconstruction behave as would be expected.
- Results enable construction of simple power-law parameterisation as a function of the different ECAL parameters, displaying key trends.
- Have also looked at some novel ECAL models with multiple regions of different transverse granularity and SiW/ScW hybrid detectors.
- Now intend to document these studies and submit to NIMA for publication.

A Few Remarks

- Information provided by this study should aid the design of a more cost-effective ECAL.
- Results presented are all in the form of jet energy resolutions. Would like to see some similar studies in the context of one or more physics analyses.
- Also need to fully understand behaviour of readout for a Sc ECAL, taking the SiPM response/saturation curves into account in the digitisation.
- Finally, need to develop an ECAL cost model, so that each change in jet energy resolution can be accompanied by an increase or decrease in financial terms.

- However, given the information we have, it seems that a Sc-based ECAL (or Si/Sc hybrid) for which the Sc cell size increases with depth would be a sensible option.
- The (10Lx5x5mm^2 + 10Lx15x15mm^2 + 10Lx20x20mm^2) ScW ECAL was very nearly as performant as a uniform 30Lx10x10mm^2 SiW or ScW ECAL.
- Having selected an active layer technology and transverse granularity scheme, could then look at cost vs. performance balance for number of layers, B-Field strength, radius, etc.

Other interpretations of the presented results would be most welcome.