Correcting for Leakage Energy in the SiD Silicon-Tungsten ECal

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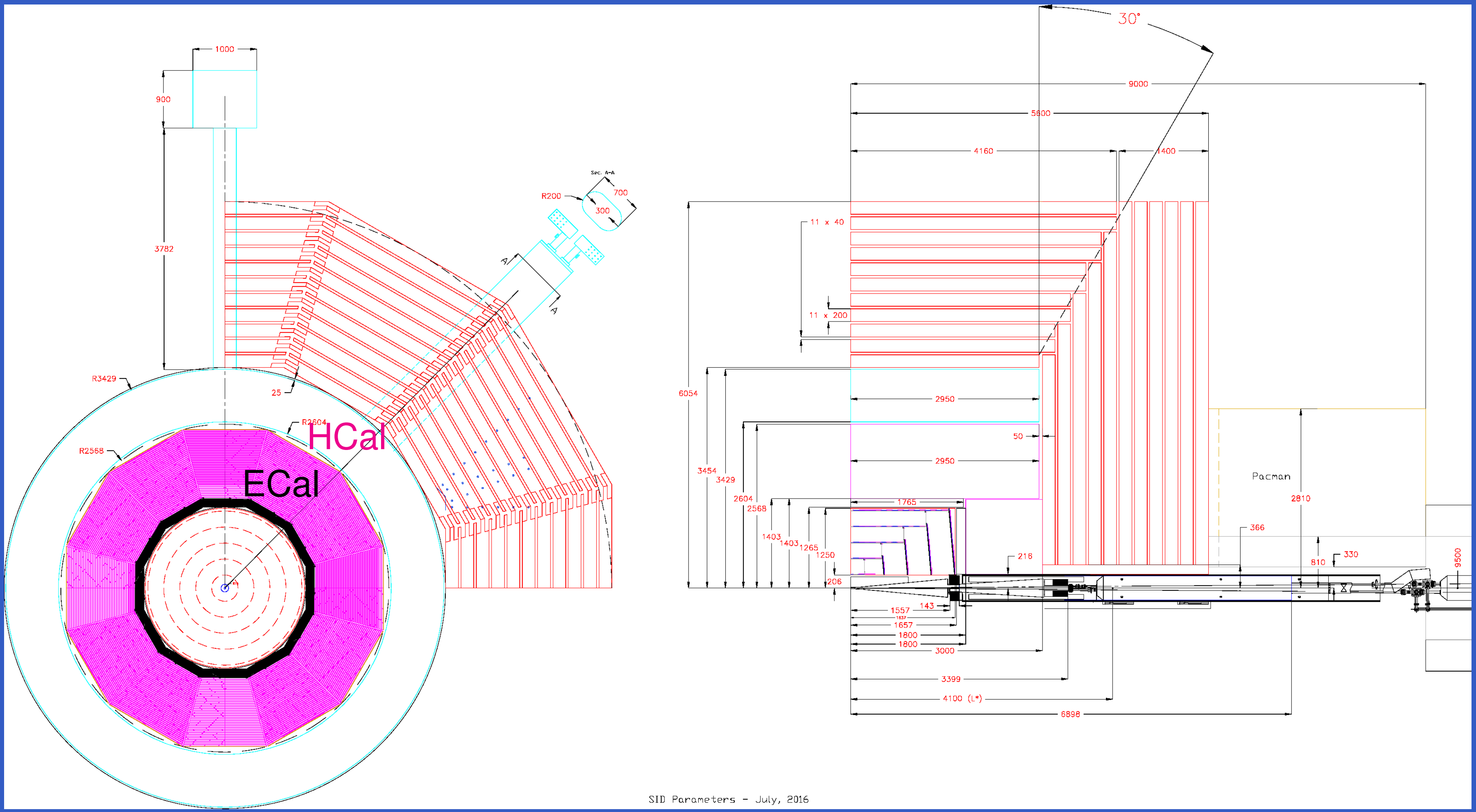
Abstract

A dominant contribution to ECal resolution at high energy (eg. 100 GeV) comes from leakage beyond the containment of the calorimeter. We have studied the leakage energy for the SiD silicon-tungsten ECal and developed a neural network algorithm for estimating the leakage energy and correcting the energy measurement. The SiD TDR design calls for 20 thin 2.5 mm tungsten layers followed by 10 thick 5.0 mm tungsten layers. We have investigated the impact on the leakage energy of a reduced number of layers, and the ability of an optimized neutral network analysis to correct for the leakage with a reduced number of layers, and reduced material thickness. Reducing layer numbers is motivated by cost containment.

See also "Application of the Machine Learning to the collider experiments", M. Iwasaki, Thursday Track 2 Session.

Nominal (TDR) SiD Design

ECal is black at left, HCal is magenta at left.

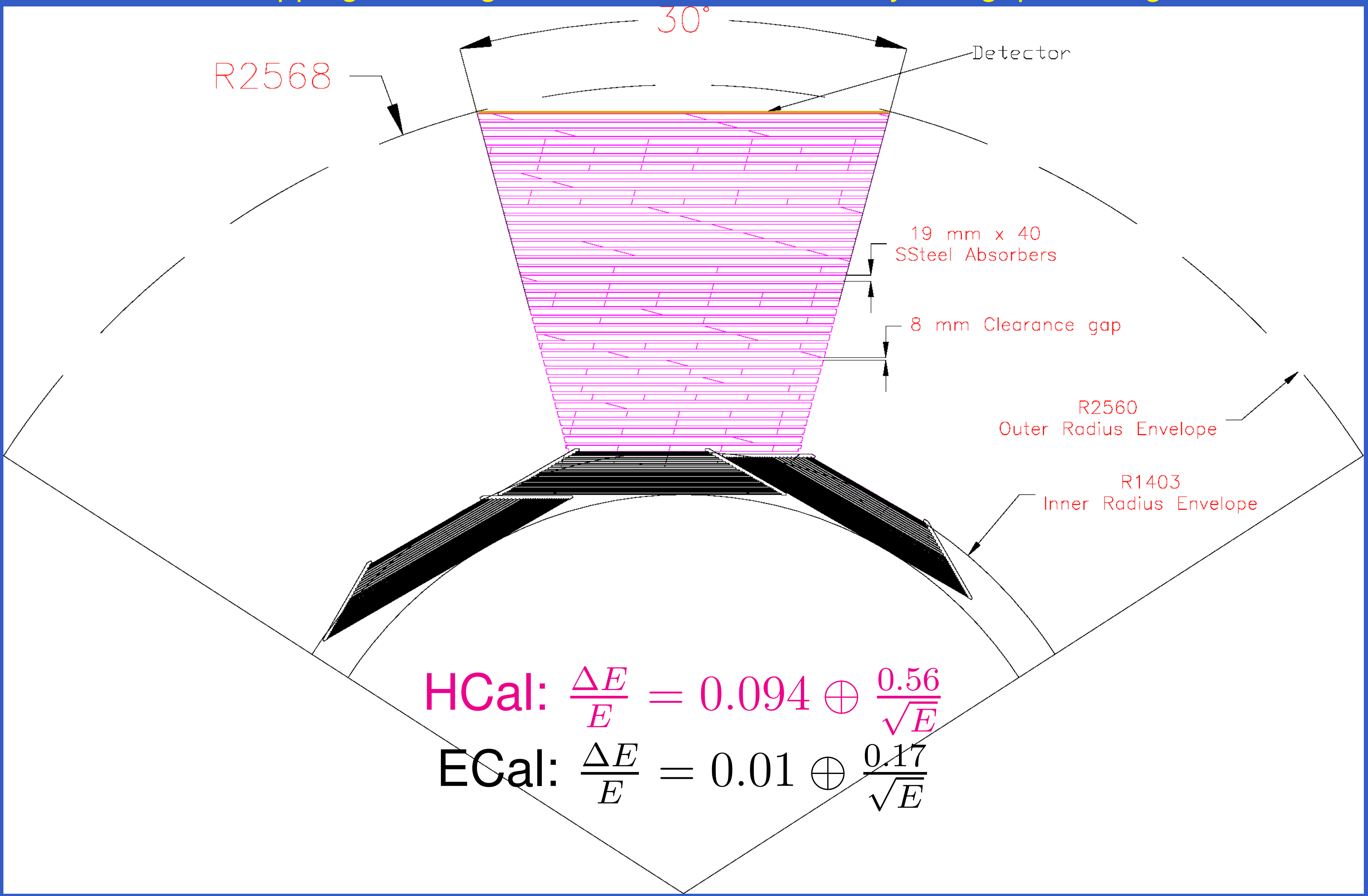


In the ECal, absorbing Tungsten layers alternate with sensitive Silicon layers for a total of $26X_0$

In the HCal, 40 absorbing Steel layers alternate with sensitive RPC layers for a total of 4.5λ

Nominal (TDR) SiD ECal/HCal Design

Overlapping ECal regions for mechanical stability and gap coverage.



HCal: $\frac{\Delta E}{E} = 0.094 \oplus \frac{0.56}{\sqrt{E}}$

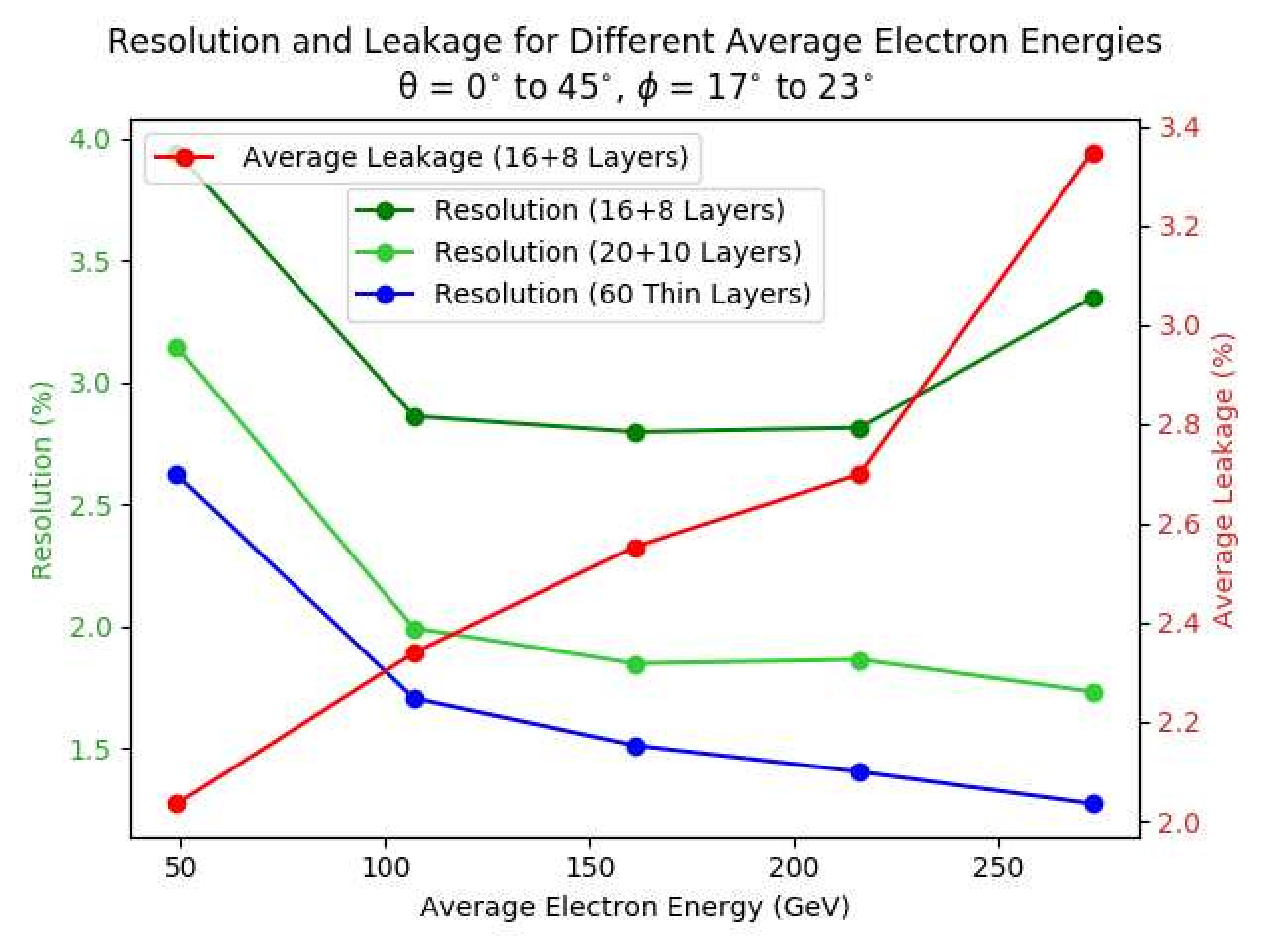
ECal: $\frac{\Delta E}{E} = 0.01 \oplus \frac{0.17}{\sqrt{E}}$

Nominal SiD ECal and HCal energy resolutions $\Delta E/E$ are from the ILC TDR.

Overview of Technical Details

- Nominal (TDR) SiD ECal Design (20+10):
  - Absorbing Tungsten layers alternate with sensitive Silicon layers ($26X_0$).
  - 20 thin (2.5mm) Tungsten layers followed by 10 thick (5.0mm) layers.
  - Energy resolution $\frac{\Delta E}{E} = 0.01 \oplus \frac{0.17}{\sqrt{E}}$.
  - Some showers develop late: ECal resolution is limited by energy leakage.
- Alternative SiD ECal Designs:
  - Reduced SiD ECal (16+8): 16 thin Tungsten layers followed by 8 thick layers.
  - Ideal SiD ECal: 60 thin Tungsten layers with no thick, for comparative purposes.
- Simulation models for Ideal SiD: simple G4 stack and full geometry simulation
  - Simple 16+8 standalone Geant4 stack of Silicon/Tungsten slabs, with SiD material.
  - ILCsoft v02-00-02 DD4hep/Geant4 simulation with compact 20+10 SiD description
- TensorFlow Neural Network: recovering leakage, thereby improving resolution
  - Inputs: energies by layer, total energy, hit multiplicity, incidence angle θ, azimuthal ϕ.
  - Multilayer perceptron with one hidden layer, simple topology.
  - One ouput: sum of energy deposited in leakage layers of ideal 60 layer SiD ECal

Motivation: Reduce Layers but Maintain Performance



Full ILCsoft simulation. Can the reduced (16+8) ECal performance approach the nominal (20+10) performance with a neural network trained on the 60 layer ECal?

Neural Network: Simple Stack and Full SiD ECal Models

Low-Bias Correction Energy

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Simple Stack Setup

- Electrons fired perpendicular to calorimeter
- Data generated with 60 thin layers
- Model undersampling of deep layers by ignoring data from alternate silicon layers
  - Thin layer $\approx 0.64X_0$
  - Thick layer $\approx 1.28X_0$
- Correction methods here use only **16 thin layers and 8 thick layers** to measure energy and make correction
  - SiD uses 20 thin and 10 thick layers

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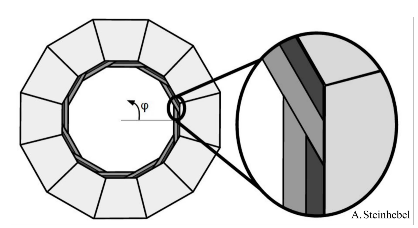
Neural Network using Only Discrete Particle Energies

- One hidden layer
- Batch size = 32
- Epochs = 1000
- Train on each data set separately
- Weight each fit based on how close a given particle's energy deposition is to the average deposited by each training set: $\frac{1}{(E_{avg} - E_{32})^{10}}$
  - E_{avg} is average energy deposited by each training set
  - E_{32} is the energy deposited for the event being corrected

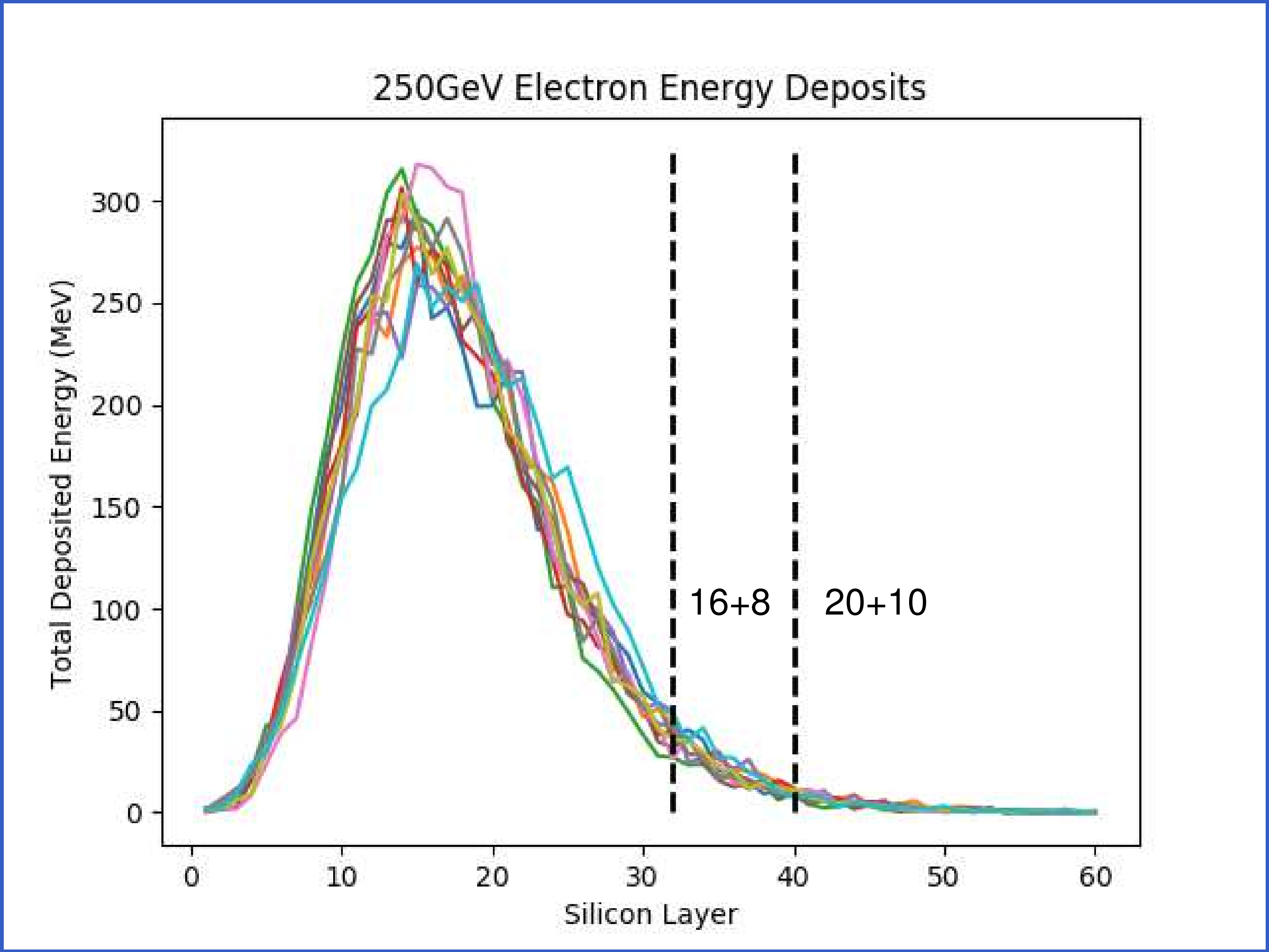
Full SiD Model

- More thorough geometry model
- Modified SiD specifications:
  - No solenoid, $B = 0$
  - No vertex detector, tracker, HCal, or muon system
  - Extended ECal to 60 layers
- Tested NN on distribution of energies (20-300GeV) and angles ($\theta \in (0°, 45°)$, $\phi \in (0°, 360°)$)



Typical Showers in Ideal/Nominal/Reduced SiD ECal

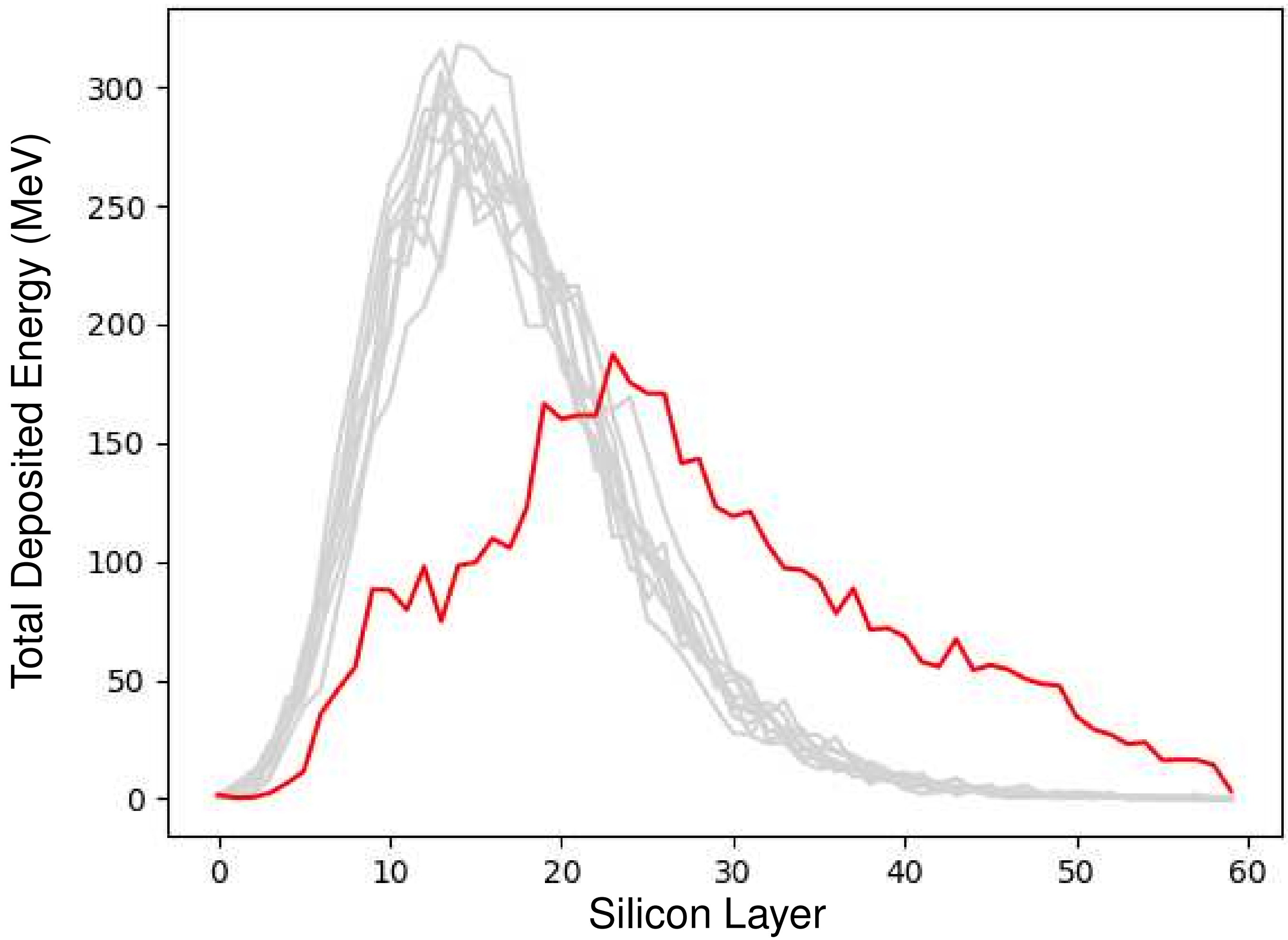
Energy deposition vs layer number in 60 layer simple stack.



Leakage is energy above ideal layer $32 = 16 + 8 \times 2$ for the reduced ECal, or above $40 = 20 + 10 \times 2$ for the nominal ECal.

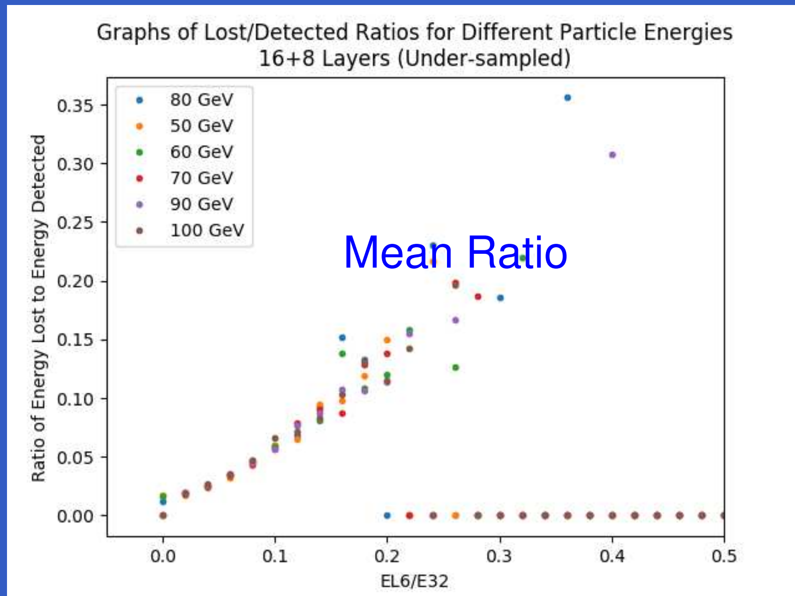
Pathological Shower in Ideal/Nominal/Reduced SiD ECal

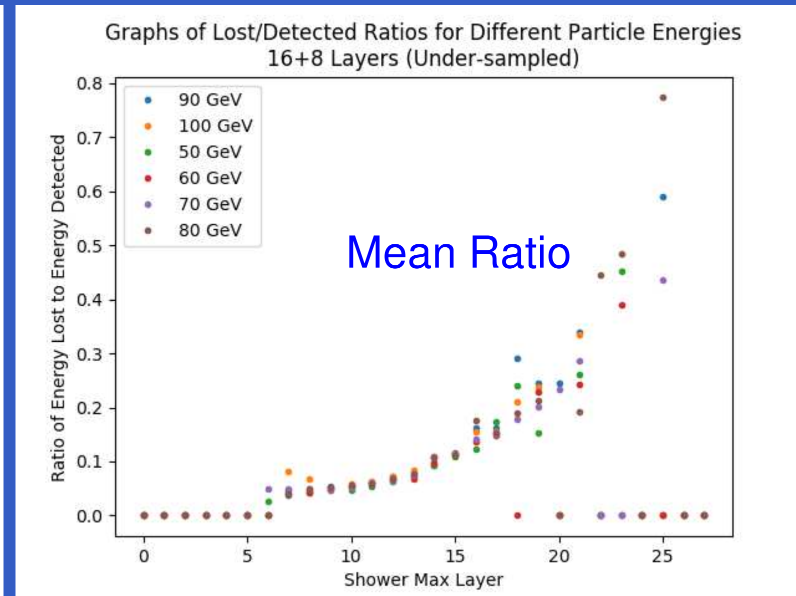
Energy deposition vs layer number in 60 layer simple stack.

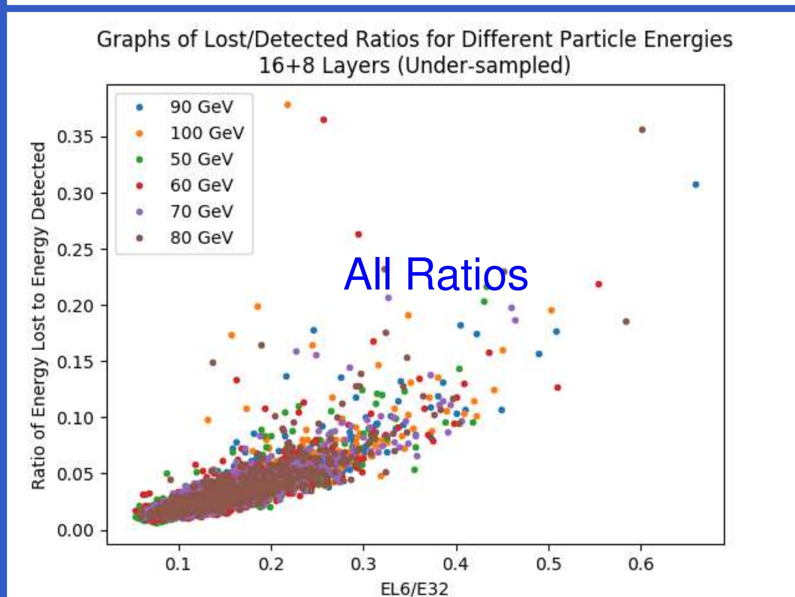


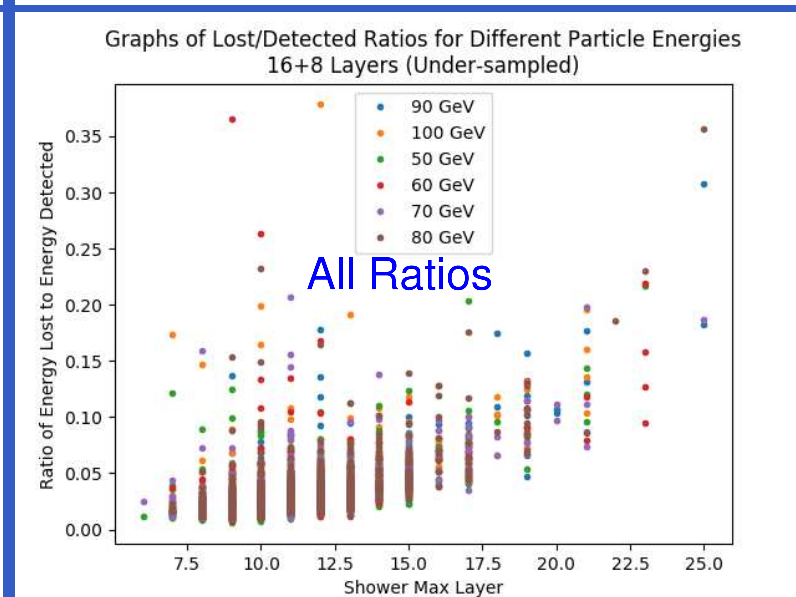
Typical showers (grey) and one pathological shower (red) with large leakage and irregular shape.

Layer Correlation: Reduced ECal (16+8), Simple Stack



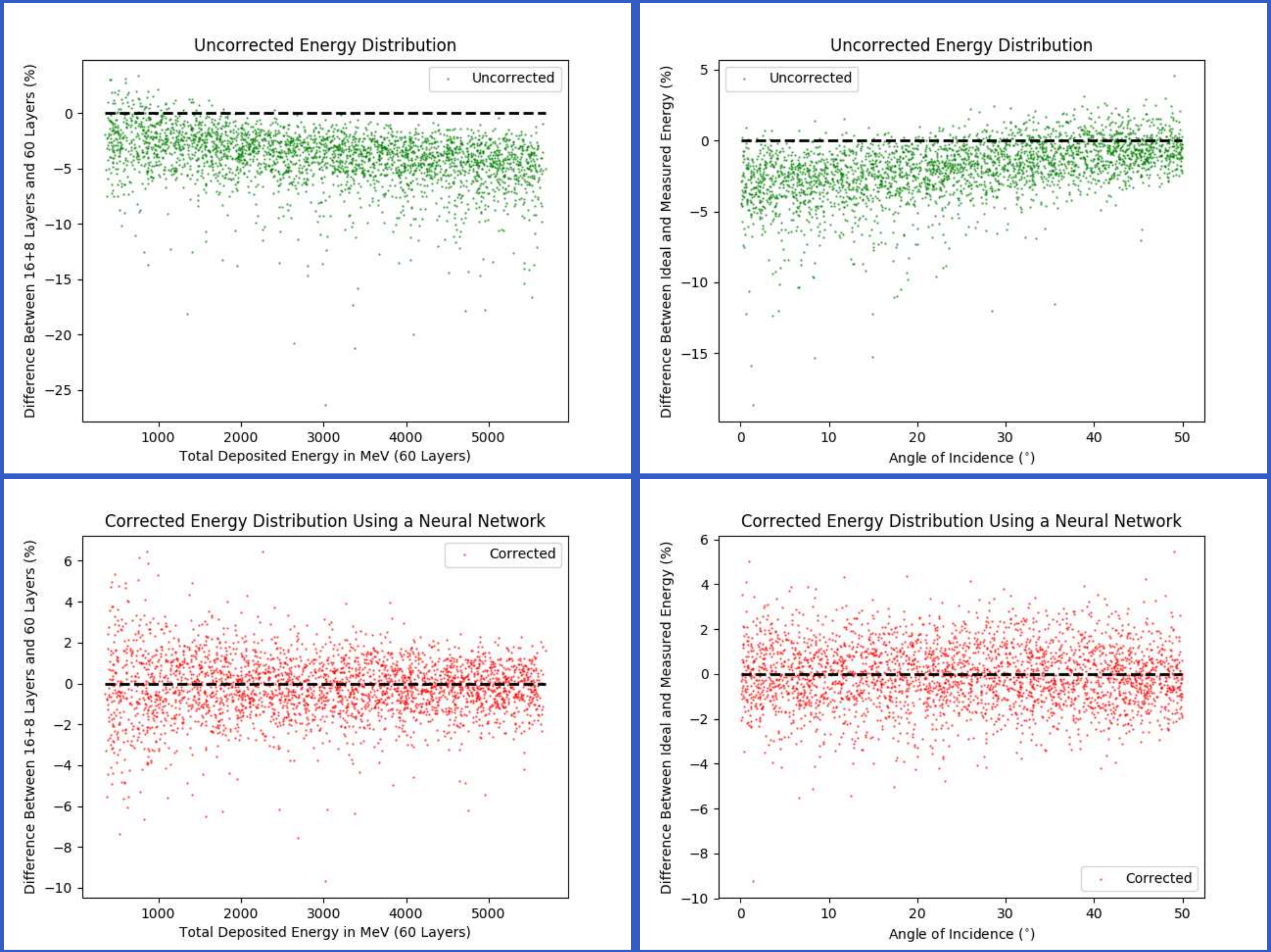






Uniformity of shower profiles yield correlations between energy deposits in layers. EL6 is energy in last 6 layers, E32 is energy in first 32 layers.

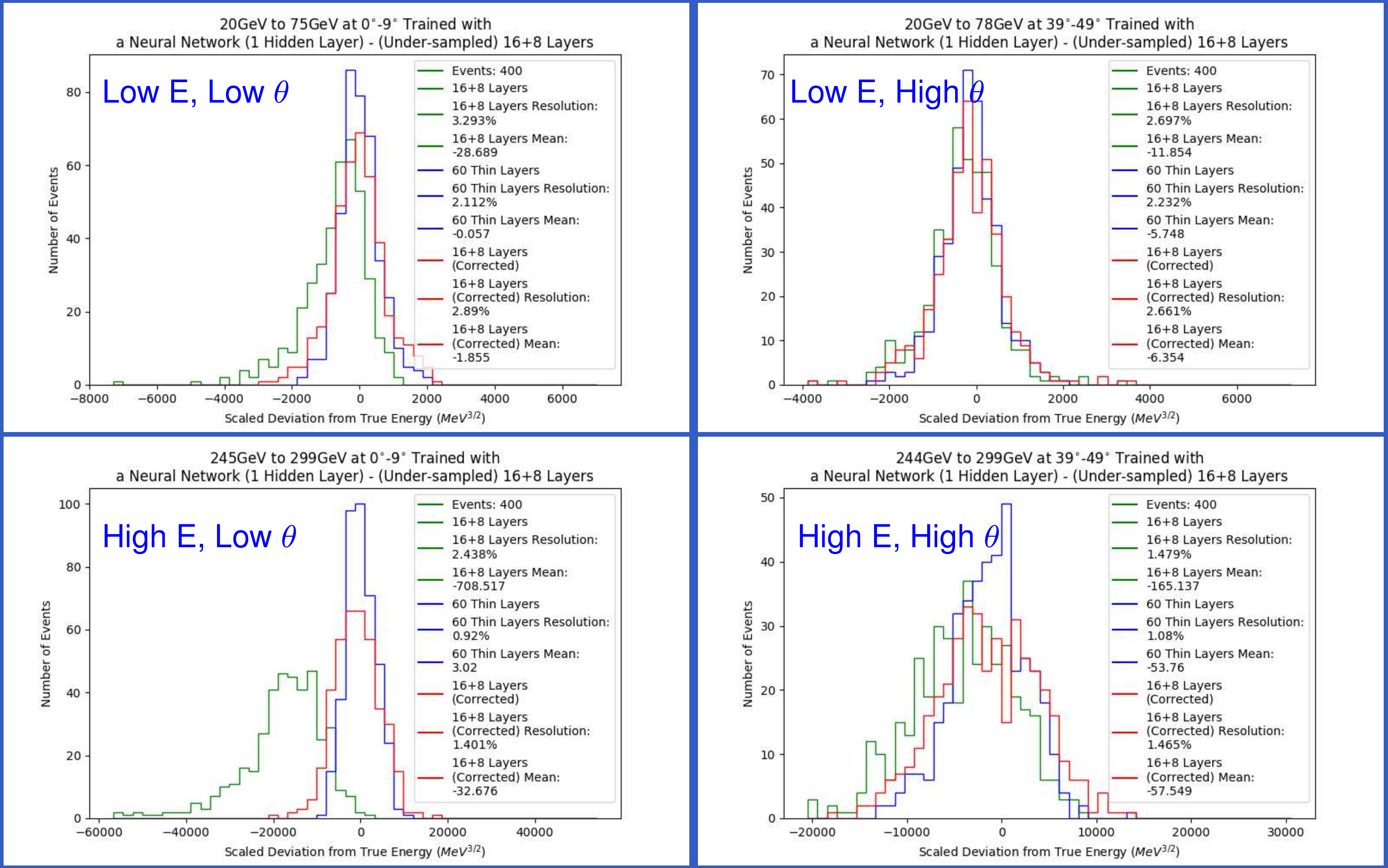
Electron E and θ: Reduced ECal (16+8), Simple Stack



Large leakage at high energy and low θ (angle of incidence) can be corrected using a Neural Network prediction of leakage.

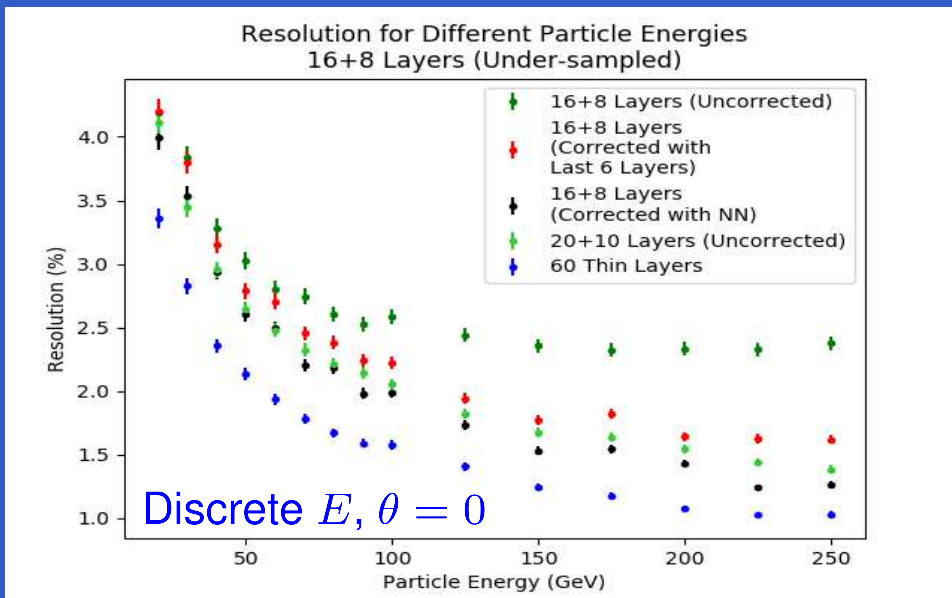
Results: Reduced ECal (16+8), Simple Stack

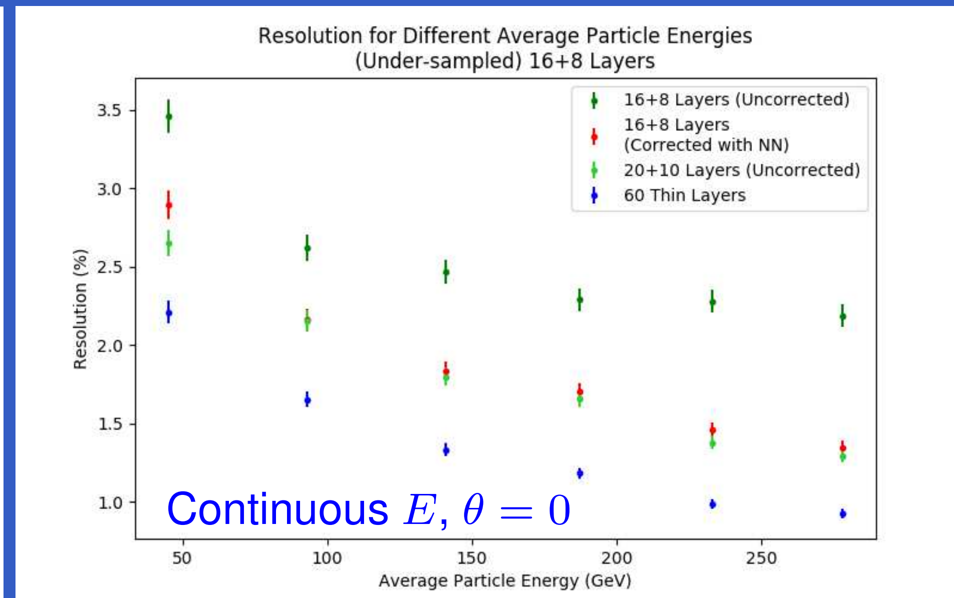
Measured (16 thin + 8 thick layers)/Neural Network Corrected/Ideal (60 thin layers)

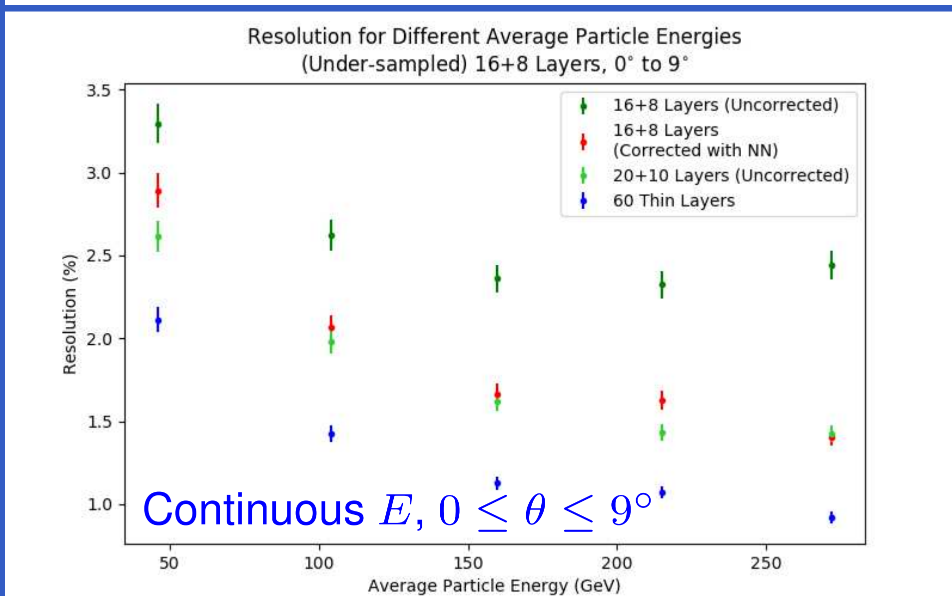


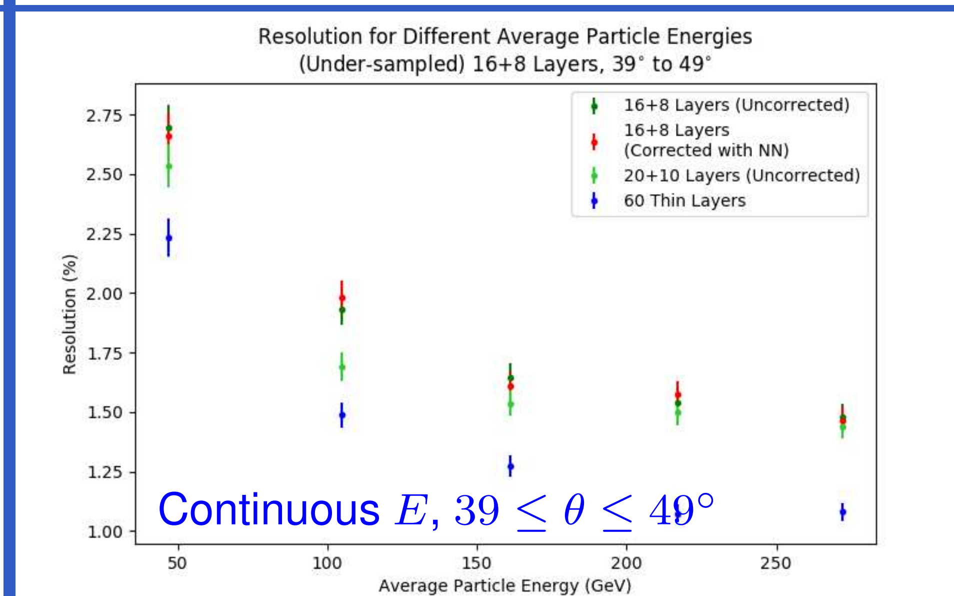
Resolution: Reduced/Corrected/Nominal, Simple Stack

Measured (16 thin + 8 thick layers)/Neural Network Corrected/Ideal (60 thin layers)









Full ECal Geometry: Overlap Regions at $\phi \approx 10^\circ + n \times 30^\circ$

Correction Energy with Modified SiD Model

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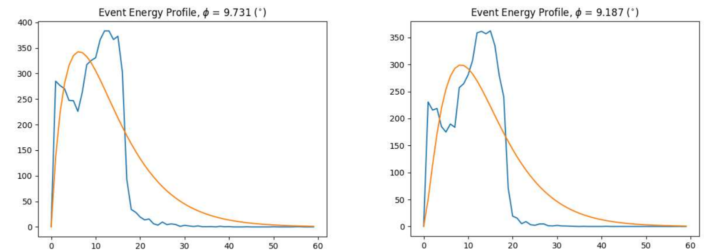
Energy-per-Layer Problem

- In overlapping region, treating layer numbers the same as in non-overlapping regions distorts shower profiles
- Prevents standard best-fit method from working



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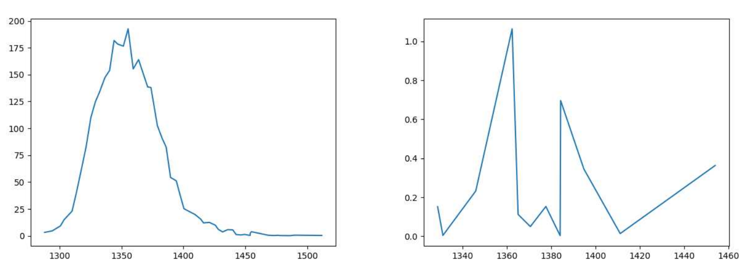
Plotting Profiles for Each Module Separately

- Allows for profile analysis without ignoring low-deposit layers
- Low-deposit layers inconsistent in deposition trend
- Deposits in low-deposit layers are low enough that best-fit correction is not as important

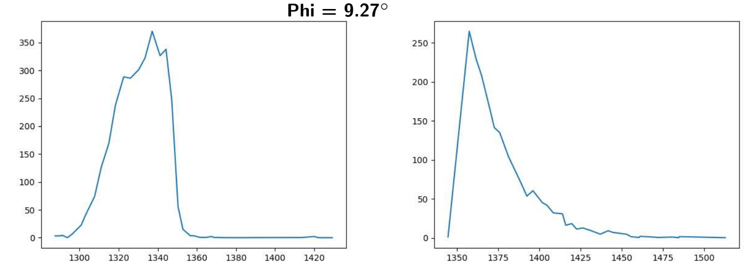
Phi = 17.38°



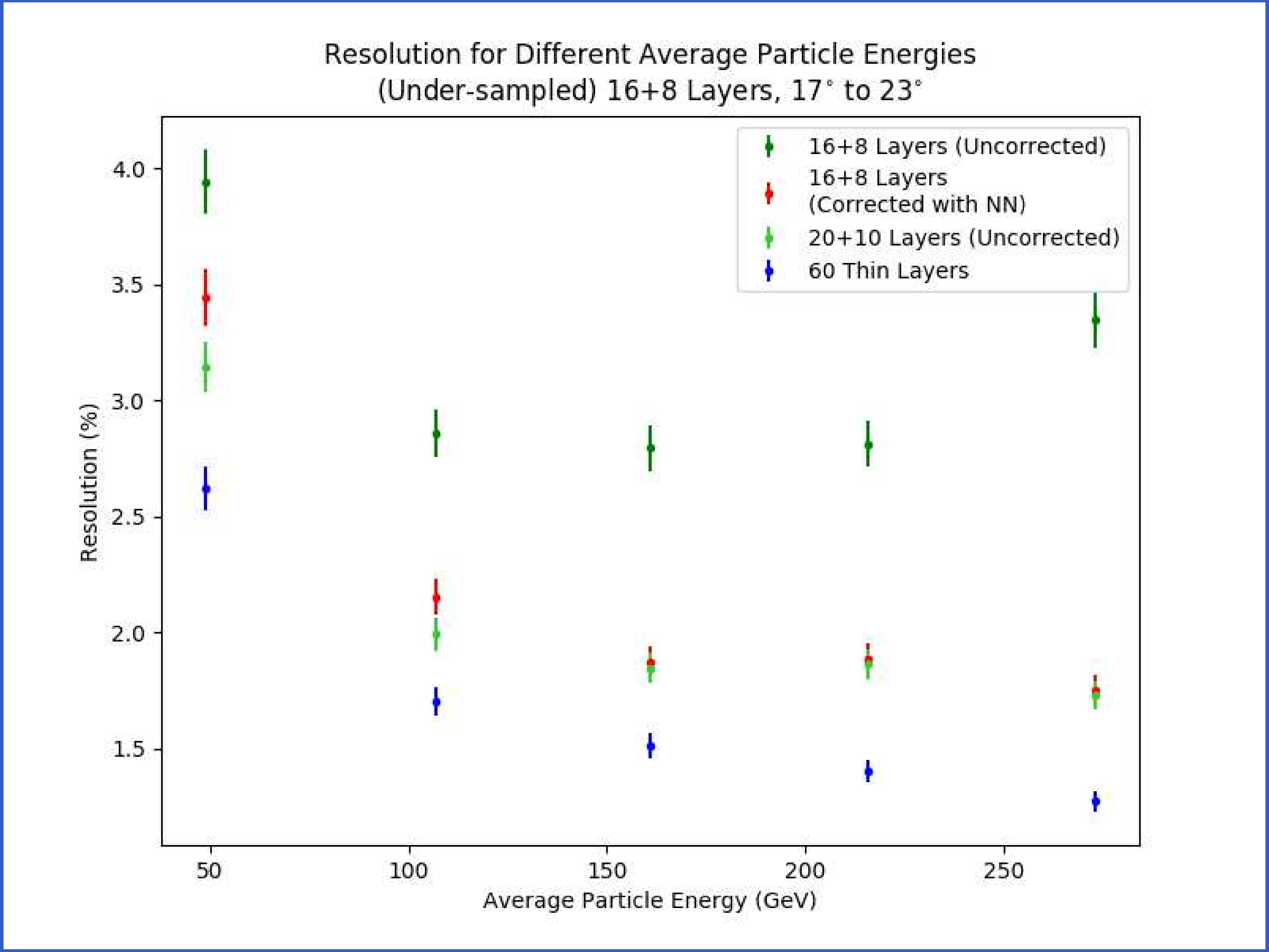
Plotting Profiles for Each Module Separately

- Some events have large deposits in both modules
- In this case, energy deposit trends are consistent enough to apply a best fit

Phi = 9.27°

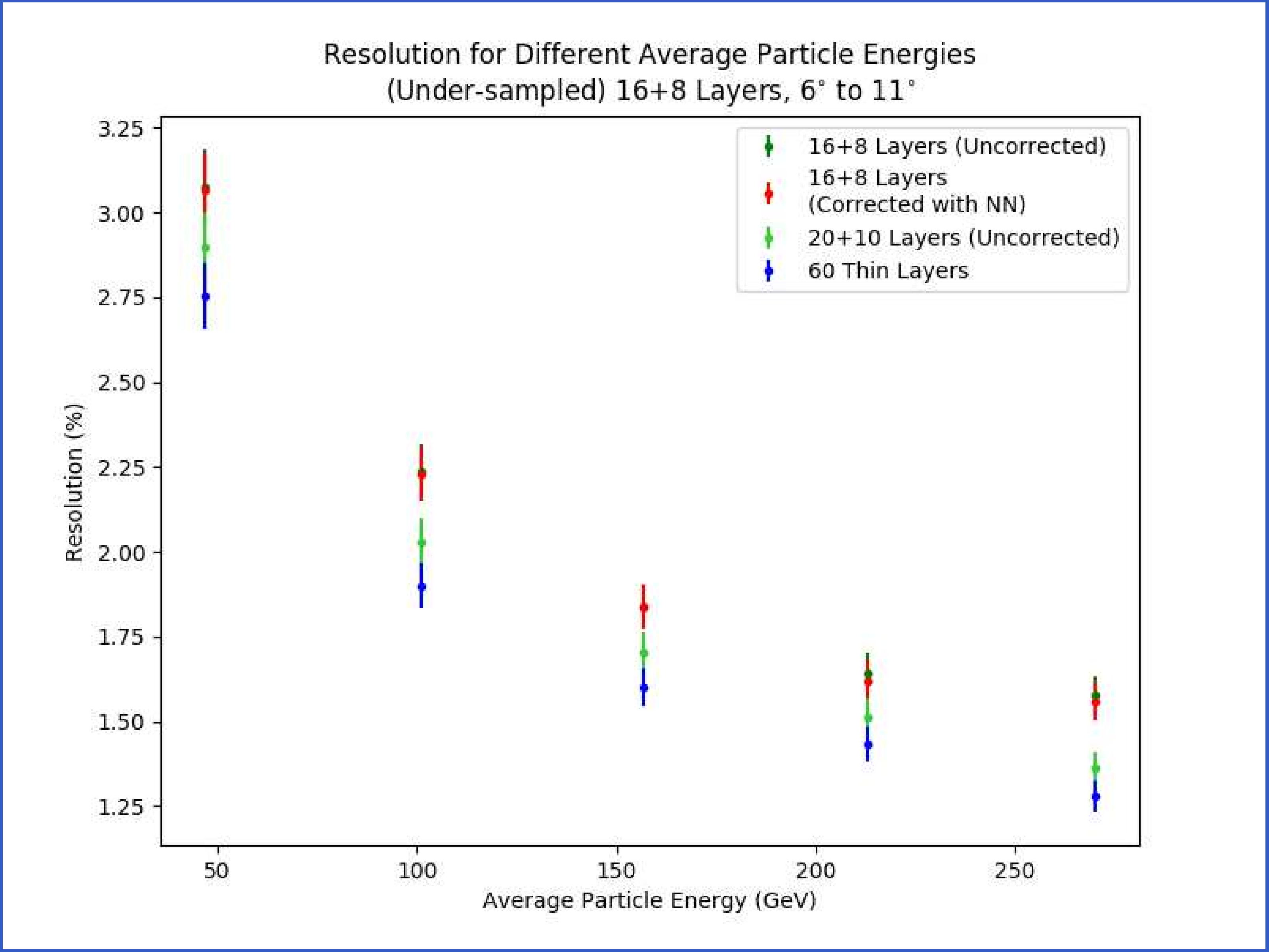


SiD ECal Geometries (TDR/Reduced) for Non-Overlap Regi



Improvement in resolution similar to simple stack. The reduced SiD ECal performance is comparable to the nominal performance with leakage corrections.

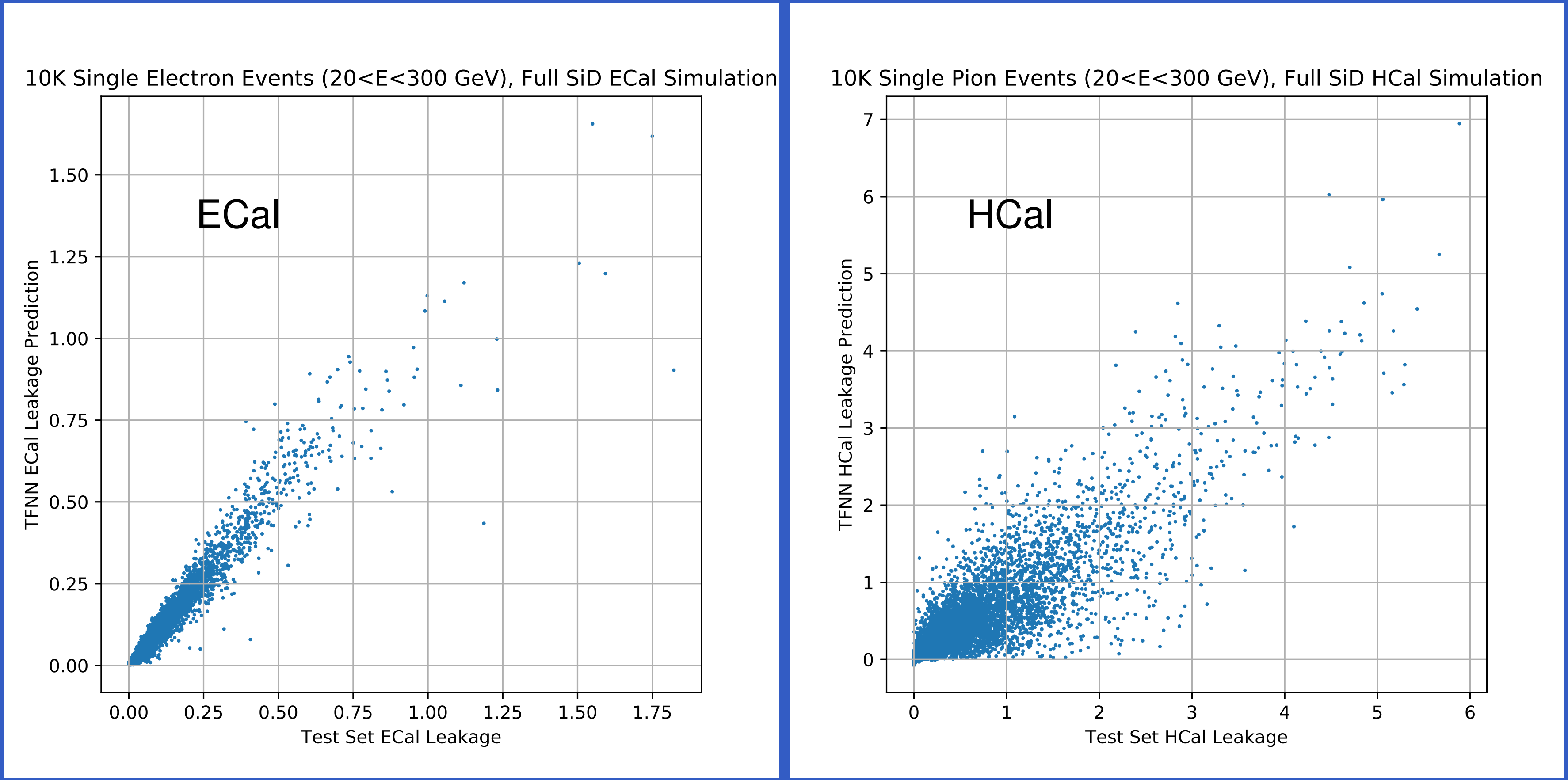
SiD ECal Geometries (TDR/Reduced) for Overlap Regions



No improvement in resolution due to layer geometry in overlap regions, as expected, since the resolution as already good since leakage is minimal.

Preliminary Application to SiD HCal Leakage

Predicted vs actual leakage in the ECal (left) and HCal (right).



- Nominal SiD HCal uses 40 layers of absorbing Steel alternating with sensitive layers.
- Ideal SiD HCal uses 80 layers, for use in training Neural Network to predict leakage
- Including intervening ECal layers ($\approx 1\lambda$), unused in right plot, should improve the correlation.

Conclusions

- SiD ECal exhibits correlations between Silicon/Tungsten layer energy depositions.
- Such correlations can be exploited using a Neural Network to predict energy leakage.
- Correcting ECal measurements with predicted leakage yields improved energy resolution.
- Specifically, the Reduced SiD ECal (16+8) performance can match the Nominal SiD ECal (20+10) by correcting measurements with Neural Network predicted leakage.
- Nominal ECal performance can be maintained with fewer layers, and therefore lower cost.
- While ECal leakage can also be measured in the HCal, we expect that the Silicon based prediction will be more precise than the HCal based measurement.
- We reach no conclusions about the application to HCal leakage, studies are ongoing.