HCal Optimisation Studies for ILD

4.11.15

Steven Green

~~HCal Optimisation Studies for ILD~~

Approach to the HCal Optimisation Studies for ILD

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Aims

* The aim of this is to examine a number of changes to the simulation and reconstruction models since the time of the LoI/DBD, which have a significant effect on the detector performance.

* The changes, broadly speaking, fit into two categories:
  1. Pattern recognition changes;
  2. Energy metric changes.

* Once these changes are properly understood it will be possible to perform accurate detector optimisation studies.

* An extensive of detector optimisation studies have been performed and are included in the backup slides to this presentation. Parameters examined include: number of HCal layers, total interaction lengths in the HCal, sampling fraction the HCal, absorber material in the HCal, ECal inner radius and magnetic field.

Simulation and Reconstruction Evolution

Simulation and Reconstruction Evolution

- **Aim:** Show evolution of the detector performance from the DBD/LoI up to present day best estimates.

- This incorporates several significant changes such as:
  1. Initial Changes:
     - Updated detector model and reconstruction software (inc. PandoraPFA).
     - New calibration procedure as documented in PandoraAnalysis (v01-00-00).
     - New digitiser, ILDCaloDigi vs NewLDCCaloDigi
     - Realistic ECal and HCal simulations at the digitisation stage.
  2. Timing cuts applied to the simulation.
  3. HCal Hadronic Energy Cell truncation.

- This will be covered in three stages. Initial changes, timing cuts, hadronic energy cell truncation.

The changes, broadly speaking, fit into two categories:
1. Pattern recognition changes;
2. Energy metric changes.

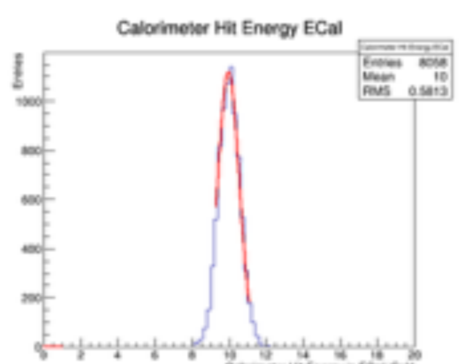
Details of Calibration Procedure

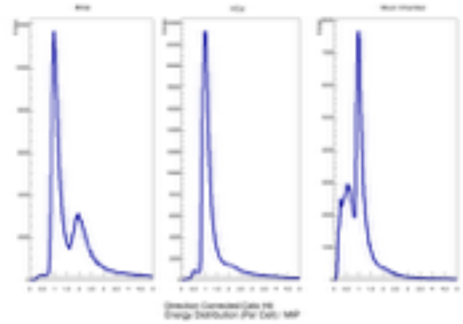
Simulation Output
Energy Deposited in Active Material of Calorimeters

Calorimeter Energy
Energy Deposited in the Total Calorimeter Volume

Reconstructed Particle Energy
Energy of Particle(s) Depositing Energy in Calorimeters

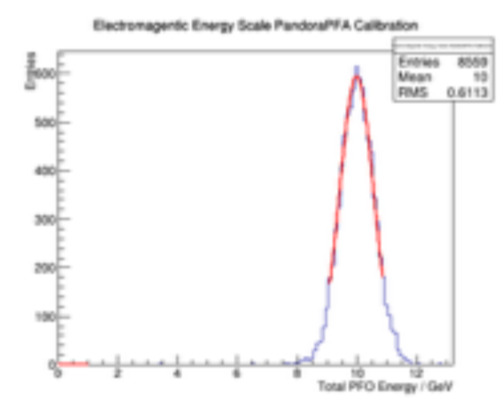
Digitisation
Set by looking at contained kaonL and ɣ events throughout the calorimeters.

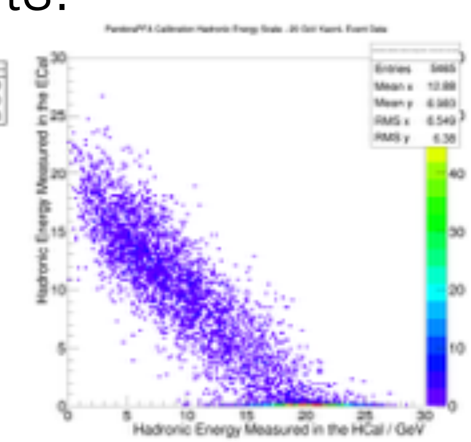




Minimum Ionising Particle (MIP) Detector Response
Determine the response of each part of the detector to a MIP, μ^- events. MIP scale used in PandoraPFA.

Electromagnetic and Hadronic Scale Setting
Electromagnetic/Hadronic scale set using PFO energy of contained ɣ and kaonL events.





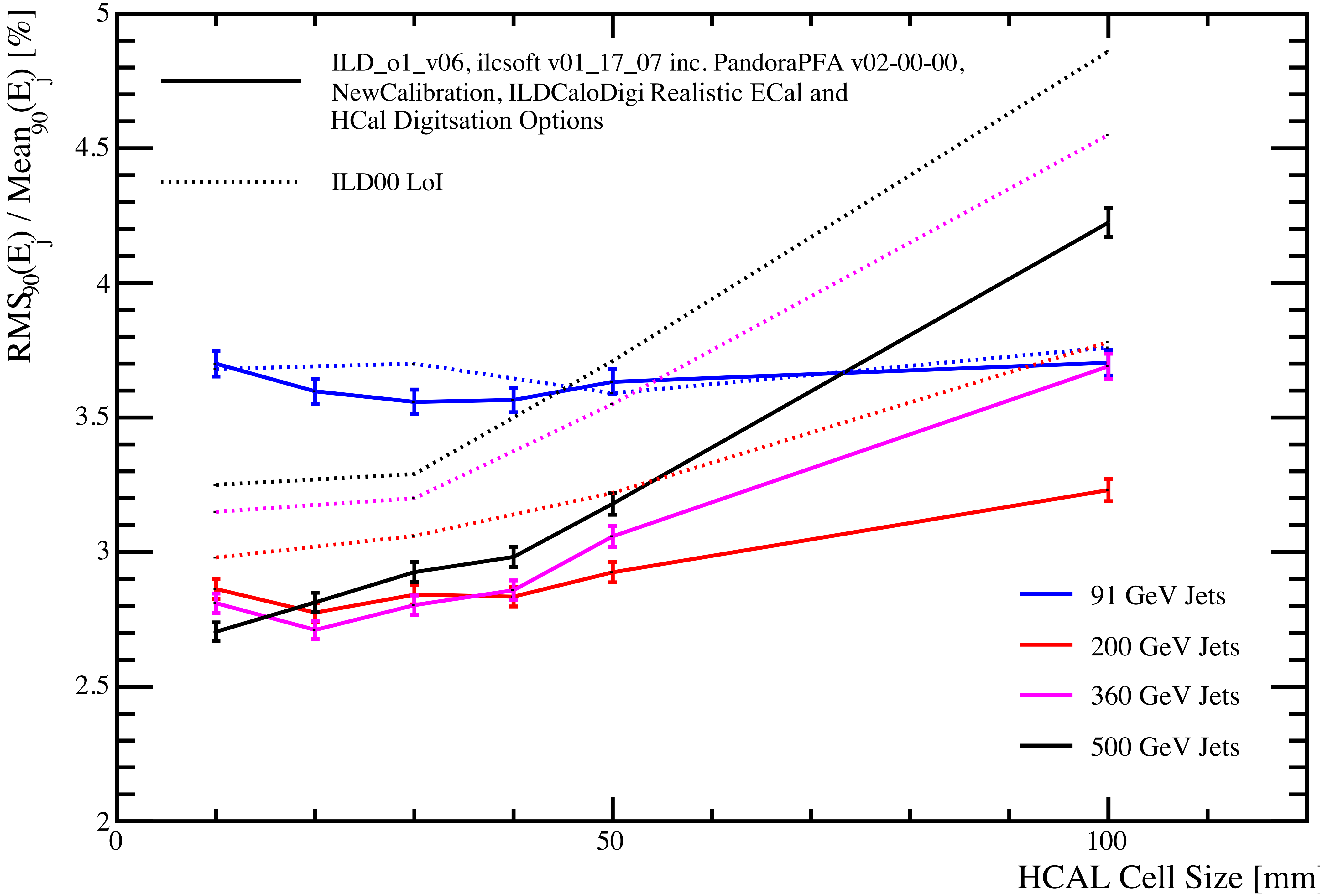
The PandoraAnalysis toolkit has several scripts designed for setting the digitisation and calibration constants. The user has to provide samples of kaonL, ɣ and μ^-.
These scripts make automation of this procedure possible.

Initial Changes

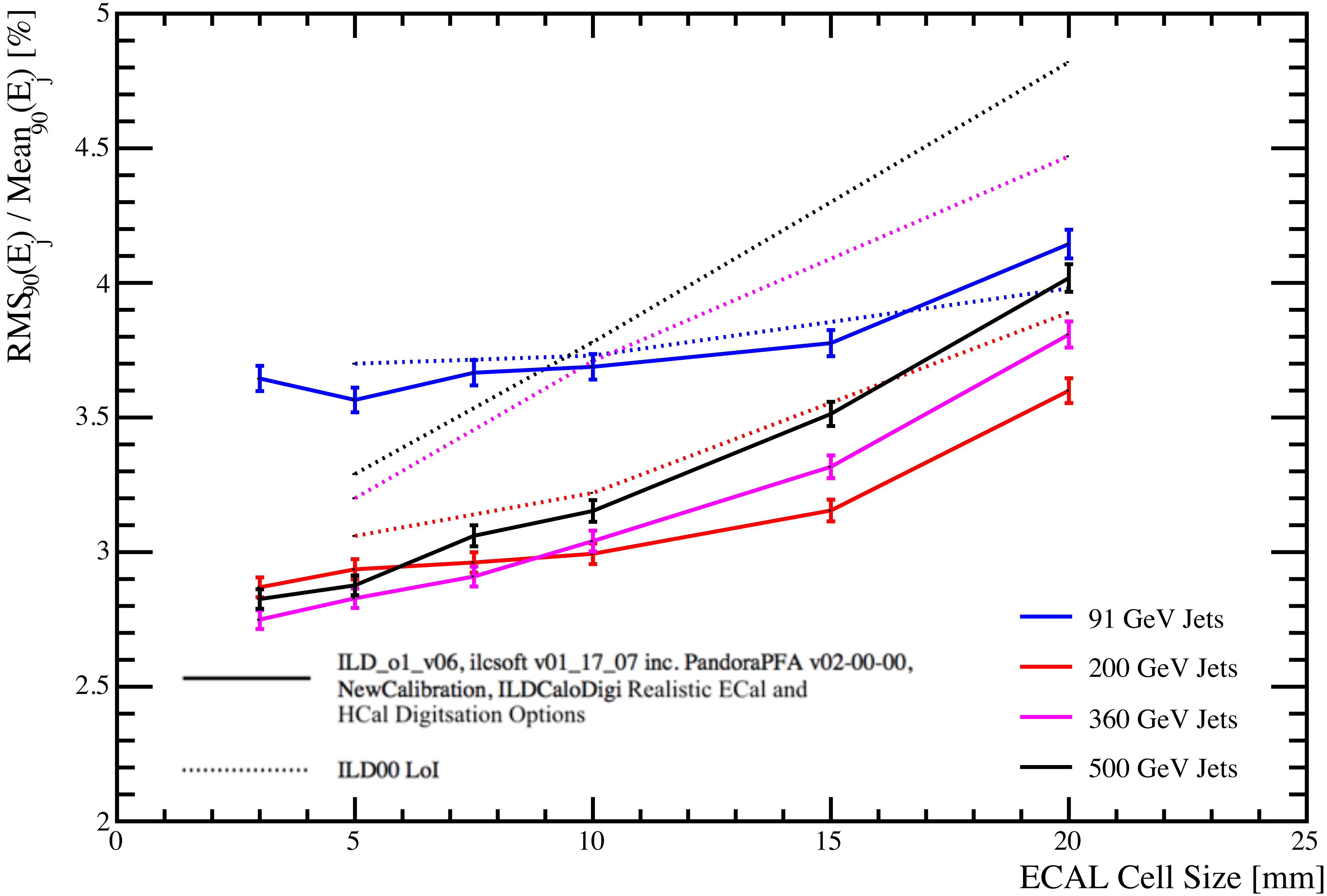
* Examine the change in detector performance when:
  - Updating the detector model from the time of the LoI, ILD00, to ILD_o1_v06.
  - Updating reconstruction software from that at the time of the LoI to version ilcsoft v01-17-07 including Pandora v02-00-00.
  - Changing the default calibration numbers used at the time of the DBD to applying the calibration procedure documented in the PandoraAnalysisi toolkit (v01-00-00 onwards).
  - Moving from the NewLDCCaloDigi digitiser to the ILDCaloDigi digitiser.
  - Moving from the default digitisation options in ILDCaloDigi to the realistic ECal and HCal options.

Disclaimer: These changes have been examined in a much more controlled manor and those results are shown in the backup slides.

Initial Changes

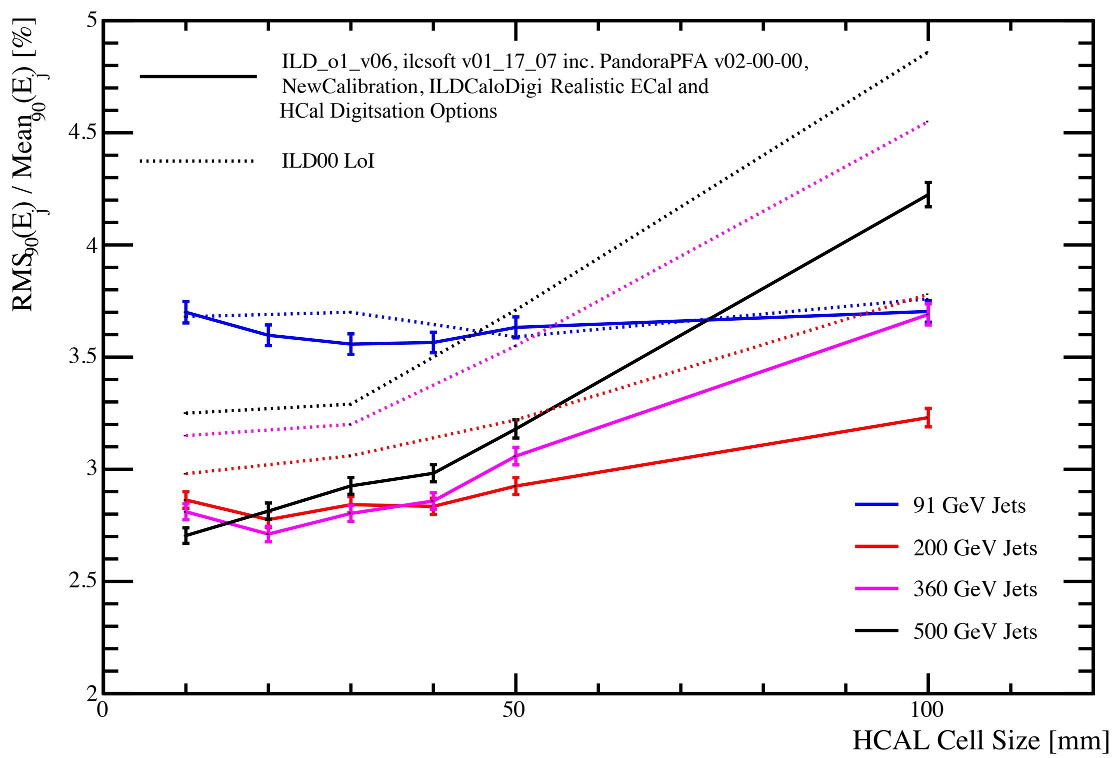


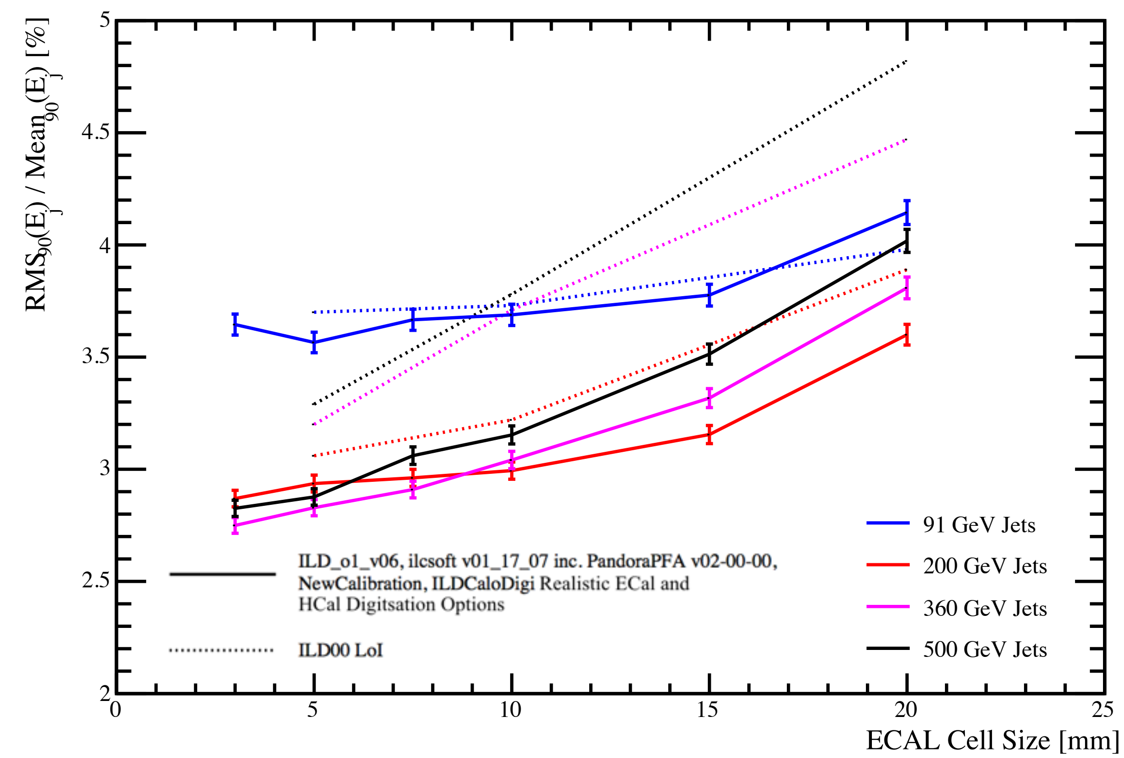
Initial Changes



Initial Changes - Conclusions

- We have already arrived the first important take home message:
  - ☑ Pattern recognition, which is only influenced by the change to Pandora, has improved significantly since the time of the LoI.
  - ☑ The improvements seen here are largely from the improvements in PandoraPFA.†





- For the following studies we will be using ILD_01_v06, ilcsoft_v01-17-07 (inc. PandoraPFA v02-00-00), the calibration procedure as described in the PandoraAnalysis toolkit (v01-00-00), the ILDCaloDigi digitiser with the realistic digitsation options enabled.

†Disclaimer: The backup slides show that the improvement in jet energy resolution shown here are largely down to improvements in PandoraPFA

Timing Cuts

* Now we look into the impact of applying timing cuts to the simulation.

* This will be the first study of this kind produced when we apply timing cuts to the simulation.

* The timing cuts applied to a simulation of a detector model have a significant effect on the performance and, as expected, they degrade performance, but we need to quantify this degradation.

* We will examine this degradation by looking at both single kaon0L and uds jets from the decay of off-shell mass Z bosons.

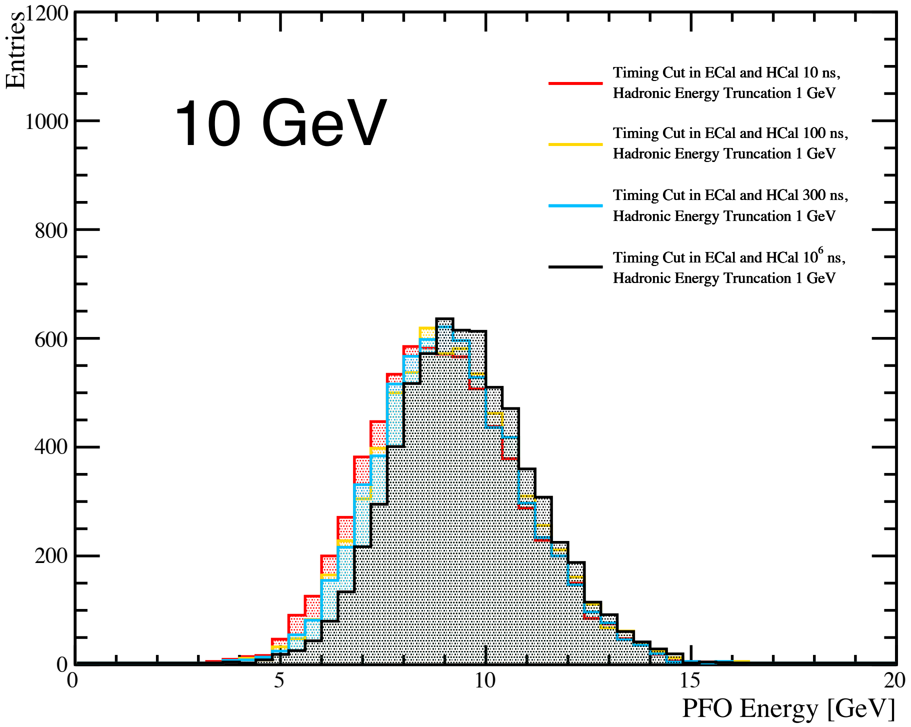
Single Particle Energy Analysis:

* Here we will look at:
  1. Raw reconstructed energy distributions;
  2. Mean reconstructed energy;
  3. Energy resolution.

Jet Energy Analysis:

* Here we will look at:
  1. Raw reconstructed energy distributions;
  2. Mean jet energies;
  3. Jet energy resolution.

Timing Cuts - Single Particle Energy Distributions

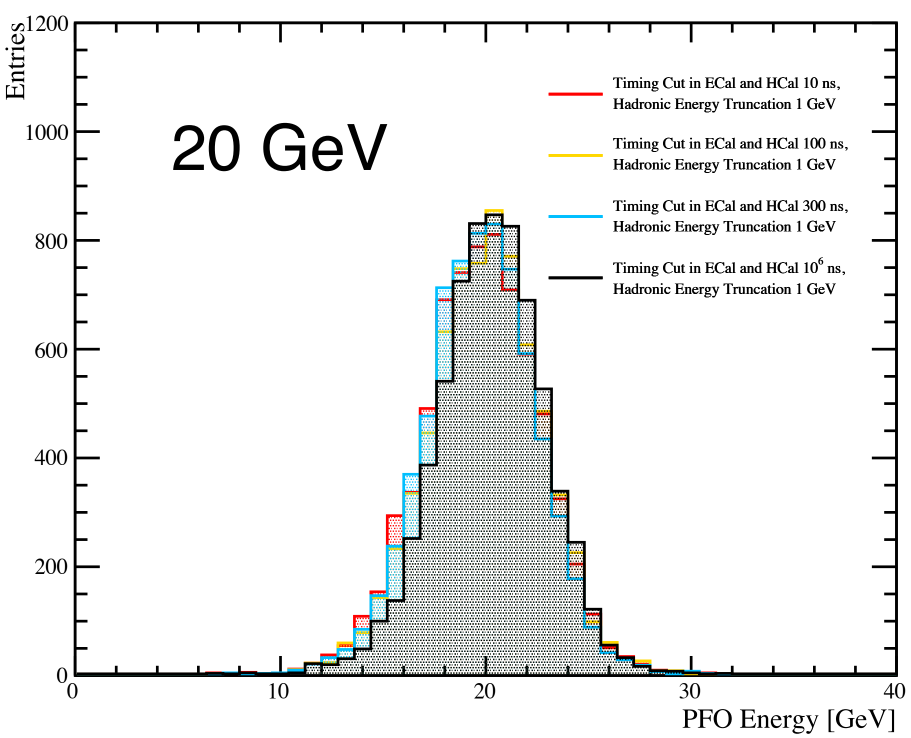


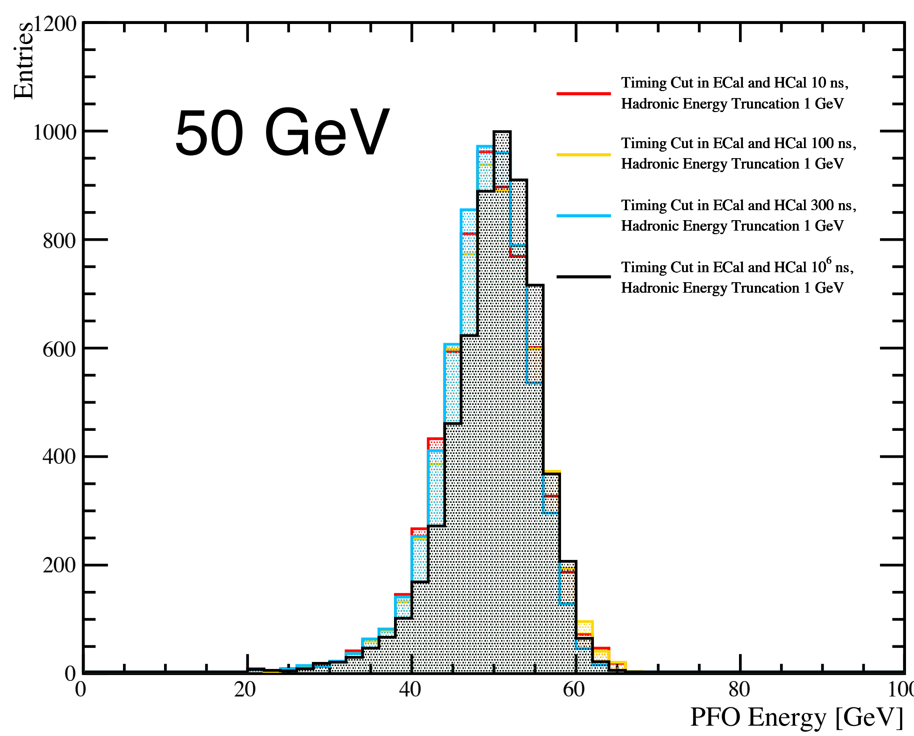
Timing Cut in ECal and HCal 10 ns, Hadronic Energy Truncation 1 GeV

Timing Cut in ECal and HCal 100 ns, Hadronic Energy Truncation 1 GeV

Timing Cut in ECal and HCal 300 ns, Hadronic Energy Truncation 1 GeV

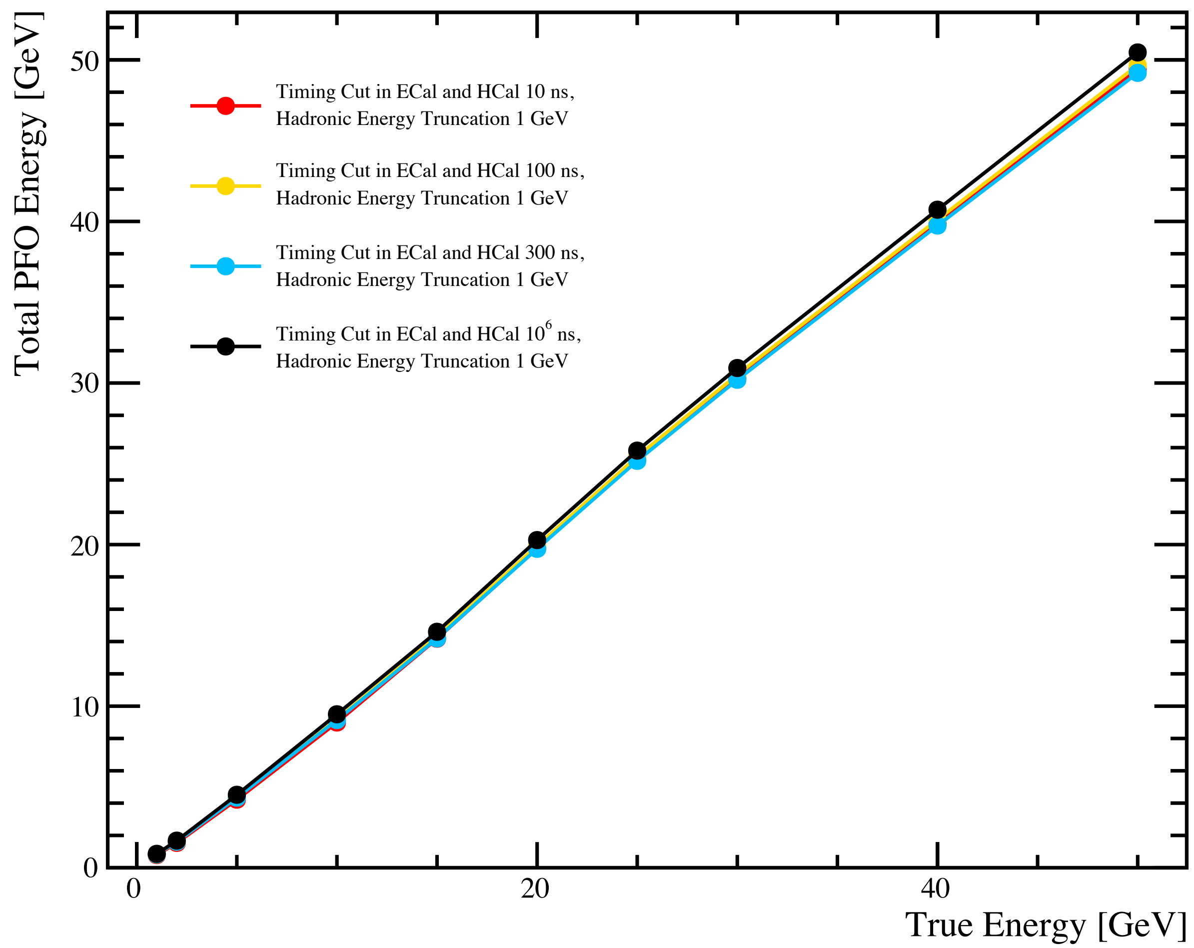
Timing Cut in ECal and HCal 10^6 ns, Hadronic Energy Truncation 1 GeV

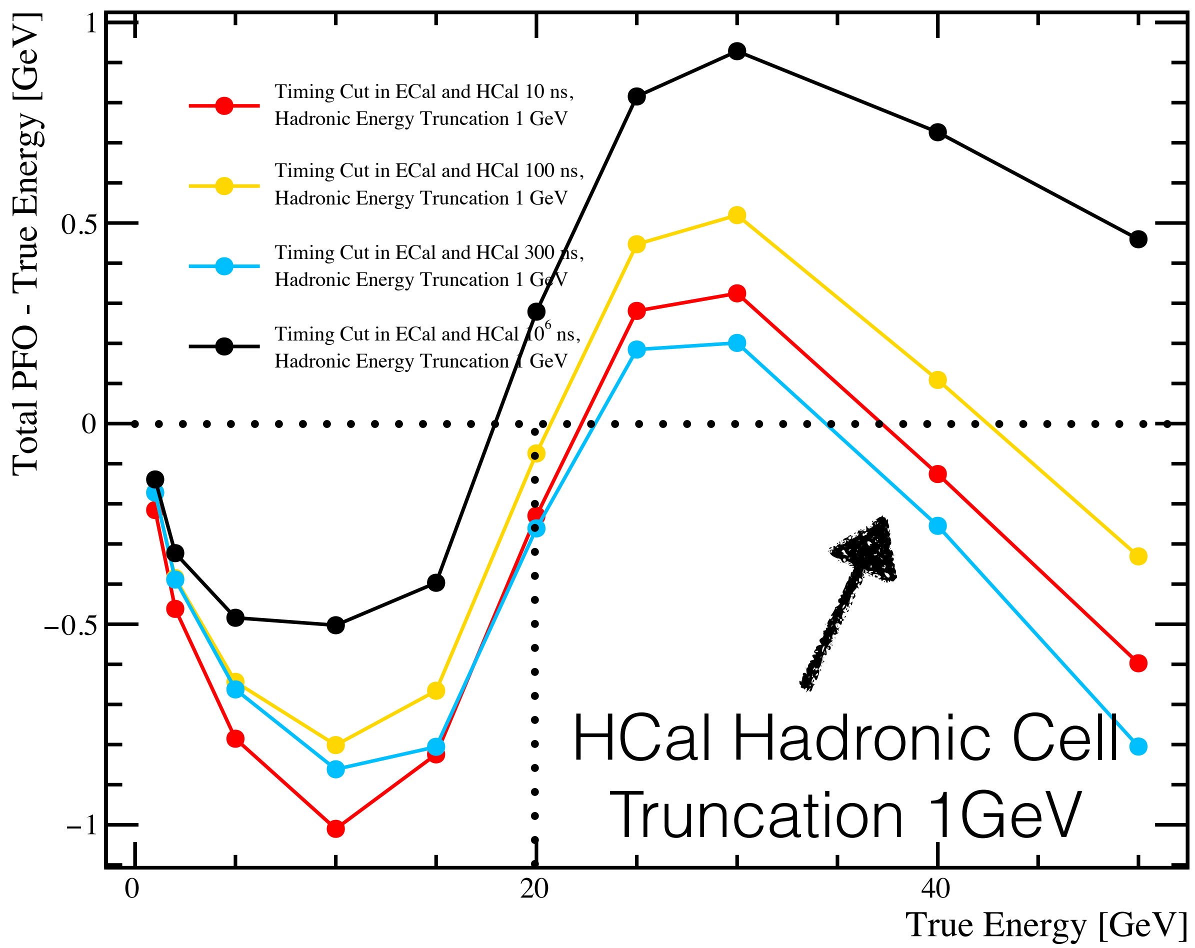




* Histograms of the reconstructed energy for single Kaon0L events of fixed energy.
* Distributions have largely the same shape.
* Calibration fixes the mean of the 20 GeV distributions to be close to 20 GeV.

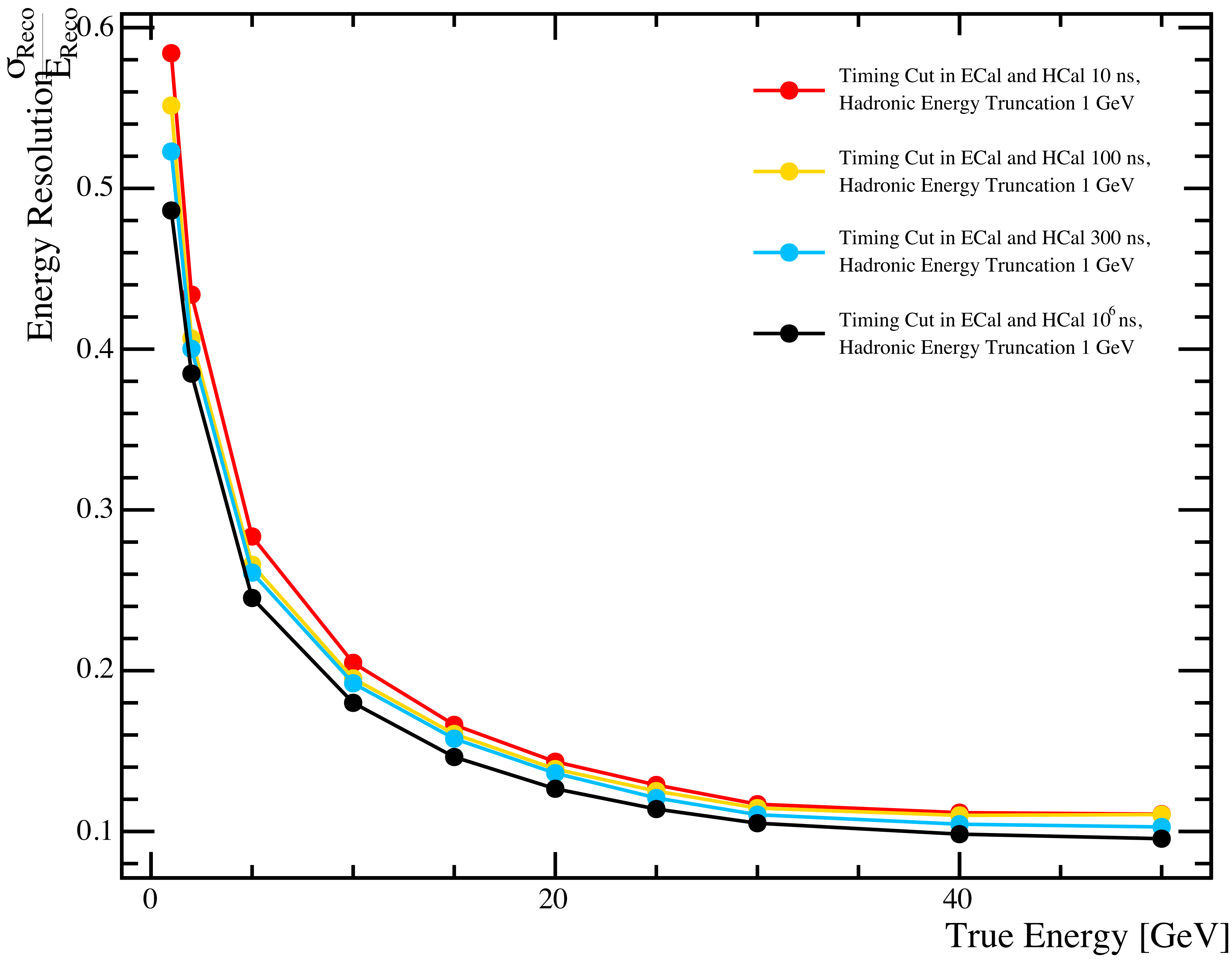
Timing Cuts - Single Particle Mean Energy





- For particle of energy less that 10 GeV the distributions aren’t Gaussian so the points for energy less that 10 GeV don’t properly represent the data.
- Timing cuts effect the total amount of reconstructed energy, but the trend is unchanged.
- In general larger timing cuts means larger reconstructed energy as expected, but varying the timing cut from 10 to 300ns, doesn’t change these results significantly.

Timing Cuts - Single Particle Energy Resolutions



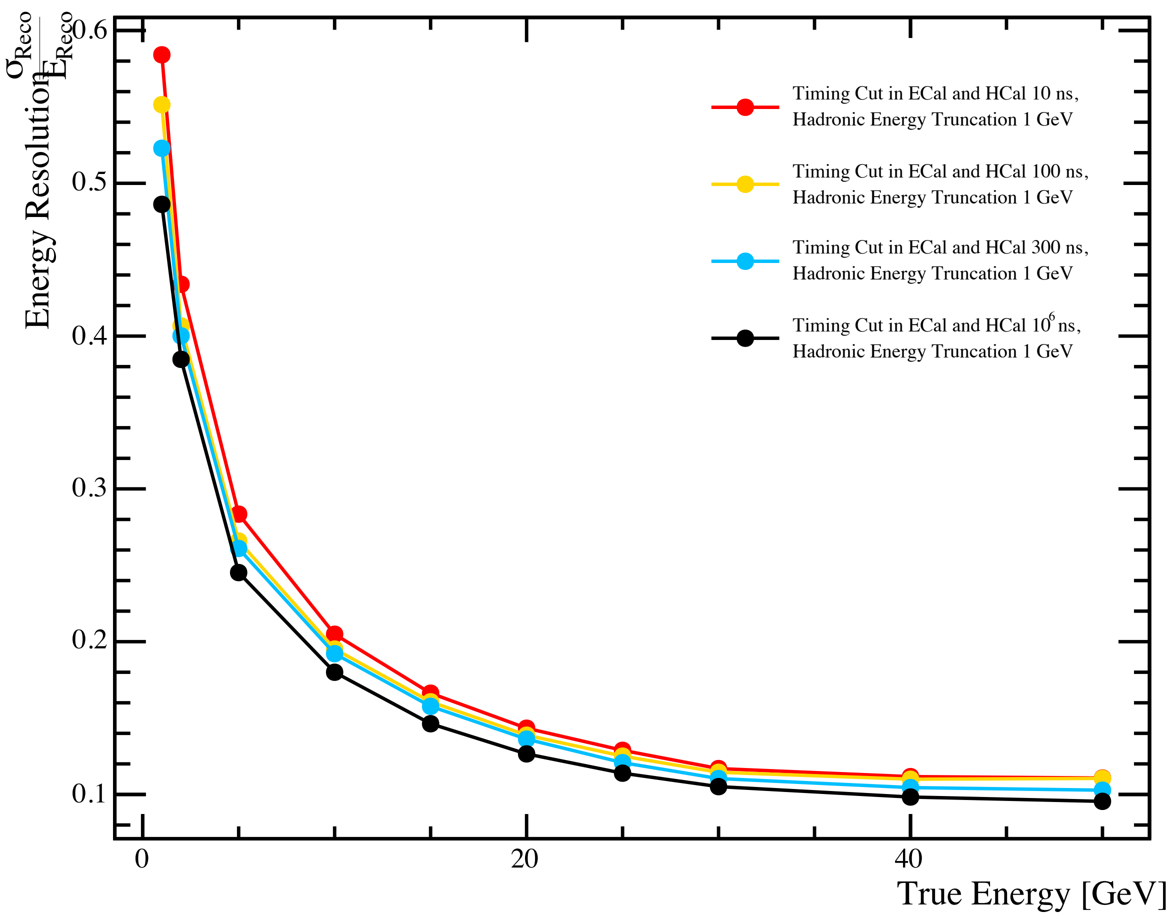
- Plot of energy resolution vs true energy for single Kaon0L events of fixed energy.
- The energy resolution here is defined as:

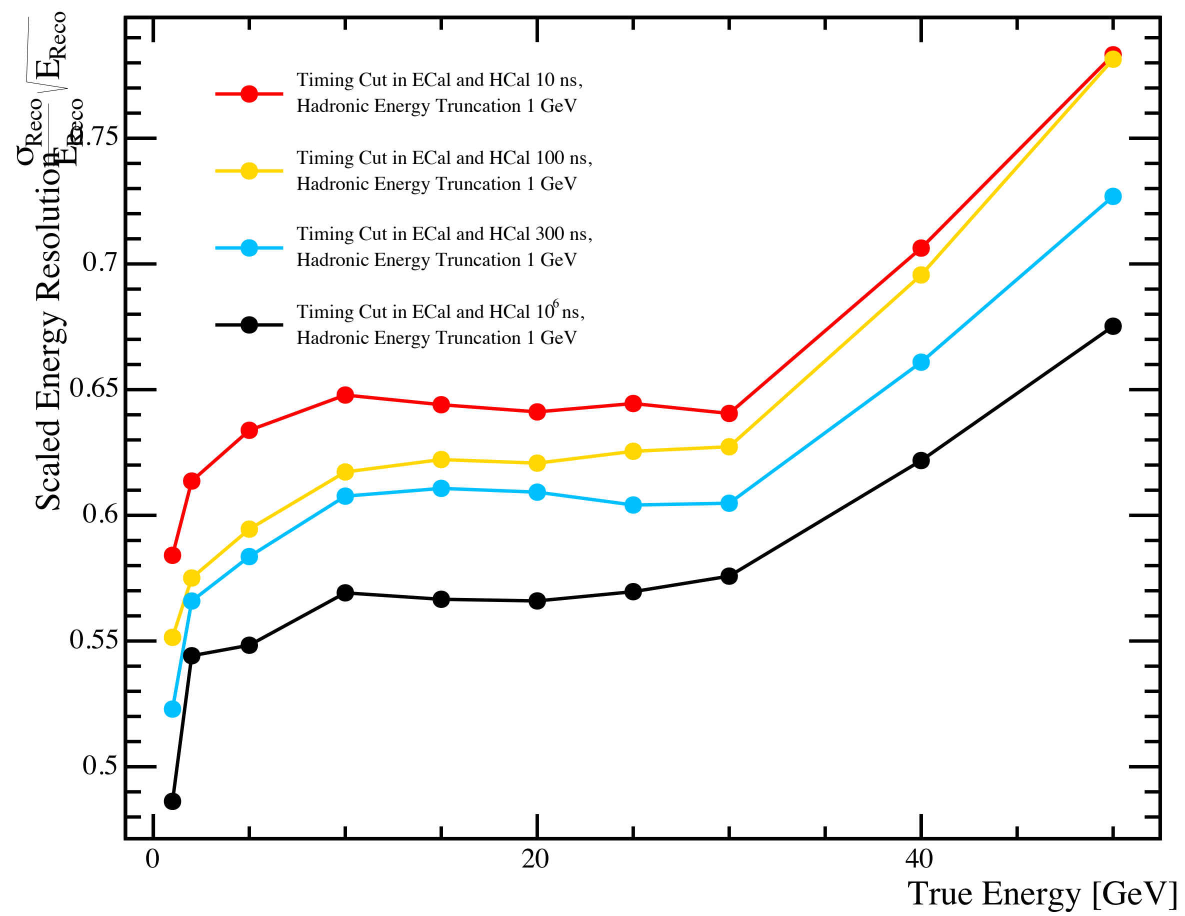
Resolution = σ_E / E

Where both σ_E and E are the standard deviation and mean of a Gaussian fit to the reconstructed energy distribution respectively.

- Energy resolution degrades with decreasing timing cuts.

Timing Cuts - Single Particle Energy Resolutions Scaled





- Quickly look at the scaled energy resolution, which is $\sqrt{E} \times \sigma_E / E$.
- Useful to compare to the generally accepted results that the energy resolution for the HCal is $0.55 / \sqrt{E}$.
- As you increase the timing cut the resolution gets better.

Timing Cuts - Jet Reconstructed Energy Distributions

* Histograms of the reconstructed jet energy for Z_uds jet events of fixed energy.

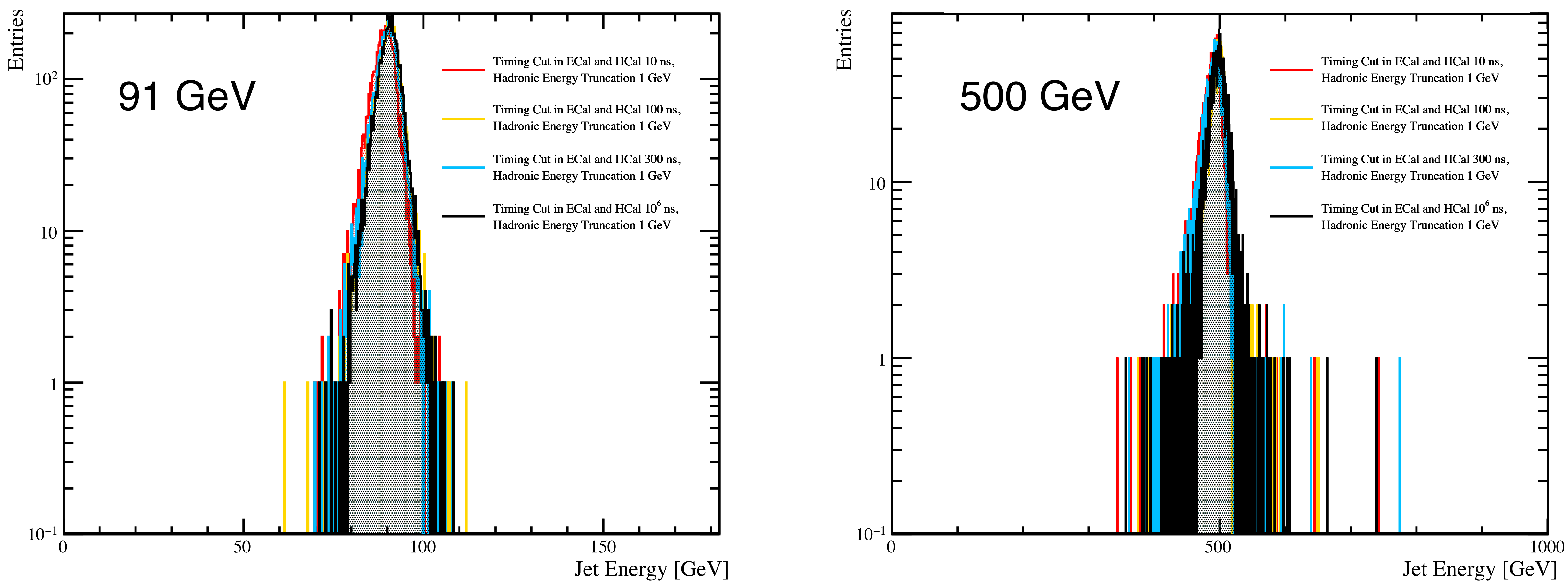
* Distributions look similar when varying the timing cuts.

Timing Cut in ECal and HCal 10 ns, Hadronic Energy Truncation 1 GeV

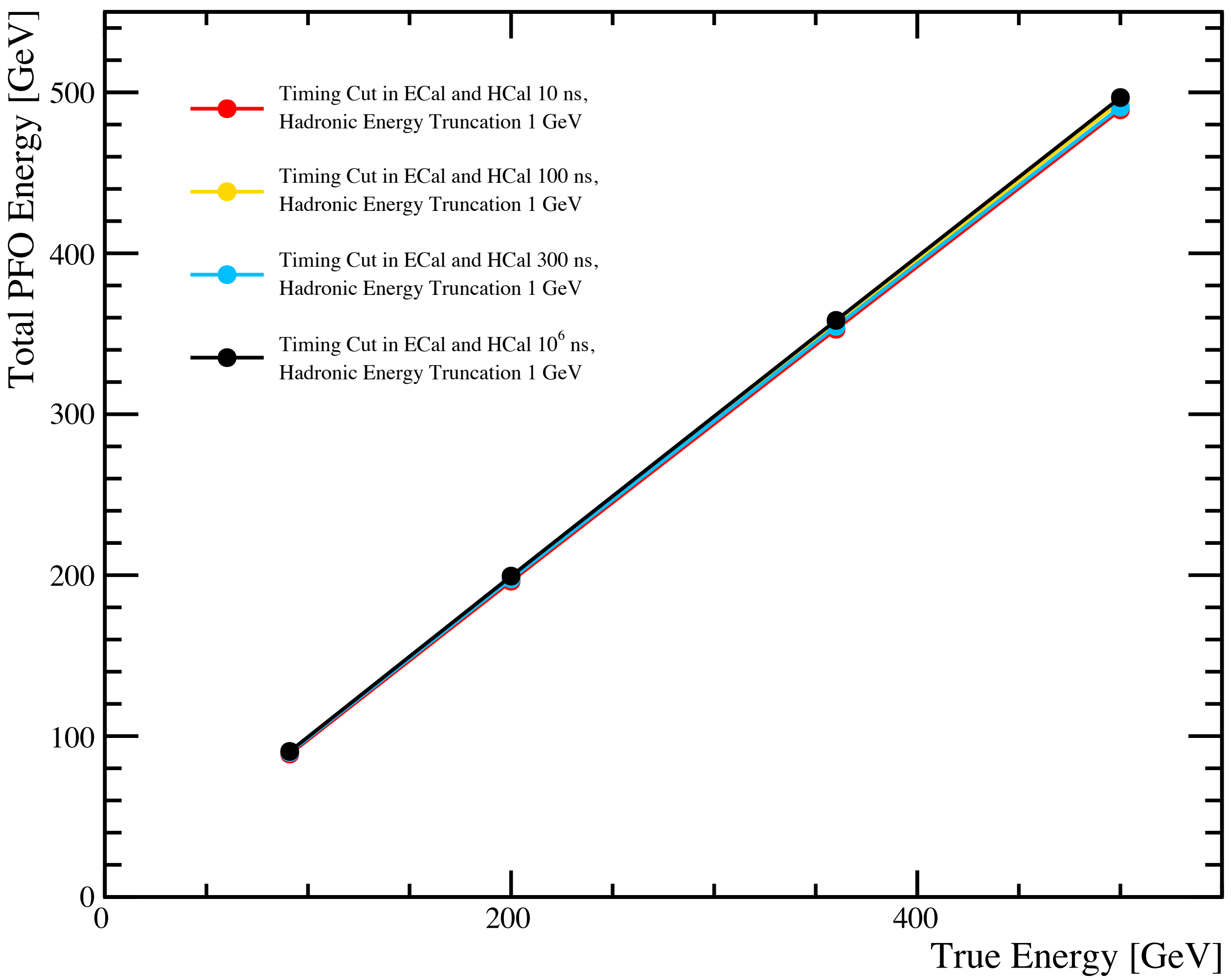
Timing Cut in ECal and HCal 100 ns, Hadronic Energy Truncation 1 GeV

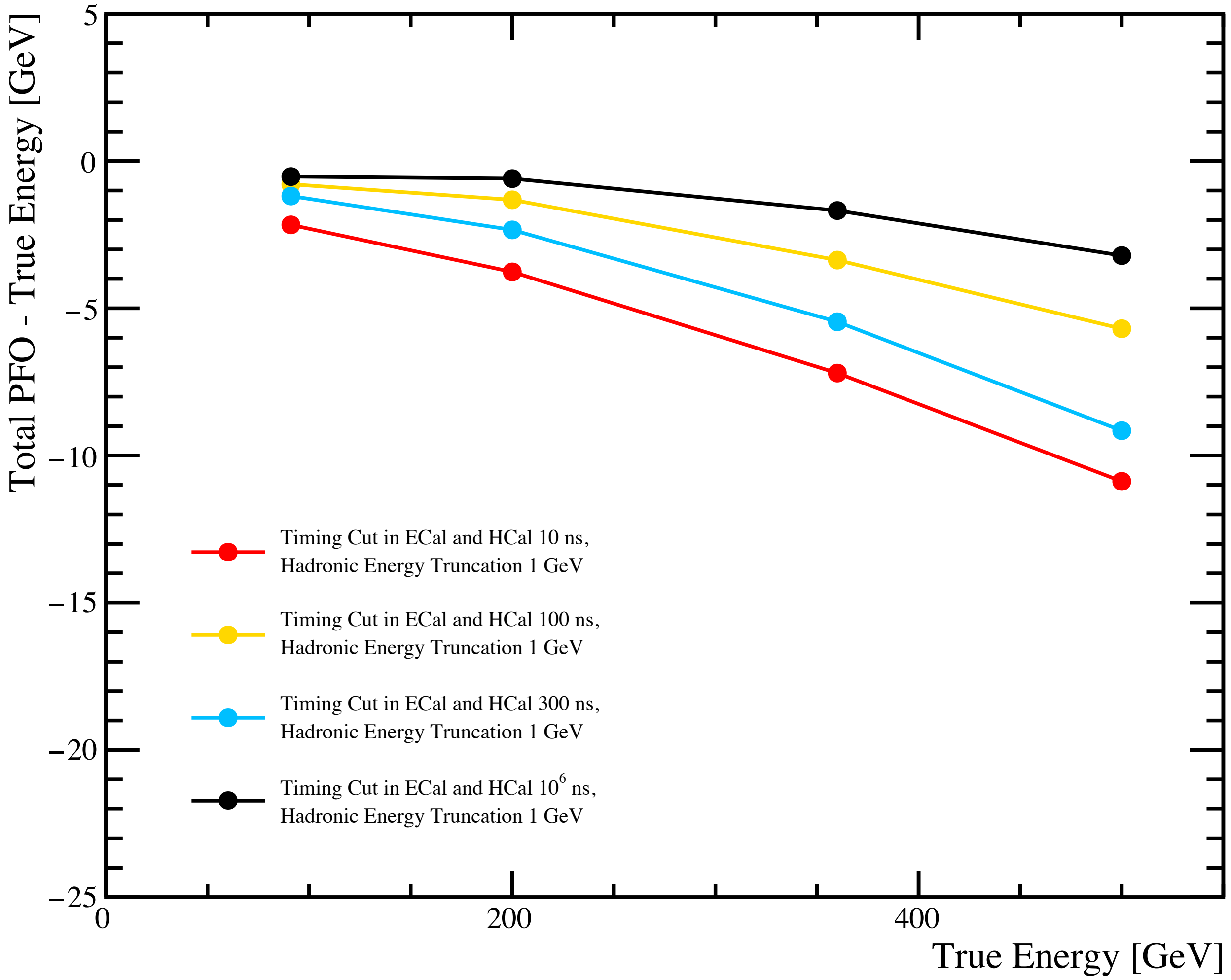
Timing Cut in ECal and HCal 300 ns, Hadronic Energy Truncation 1 GeV

Timing Cut in ECal and HCal 10^6 ns, Hadronic Energy Truncation 1 GeV



Timing Cuts - Jet Mean Energy

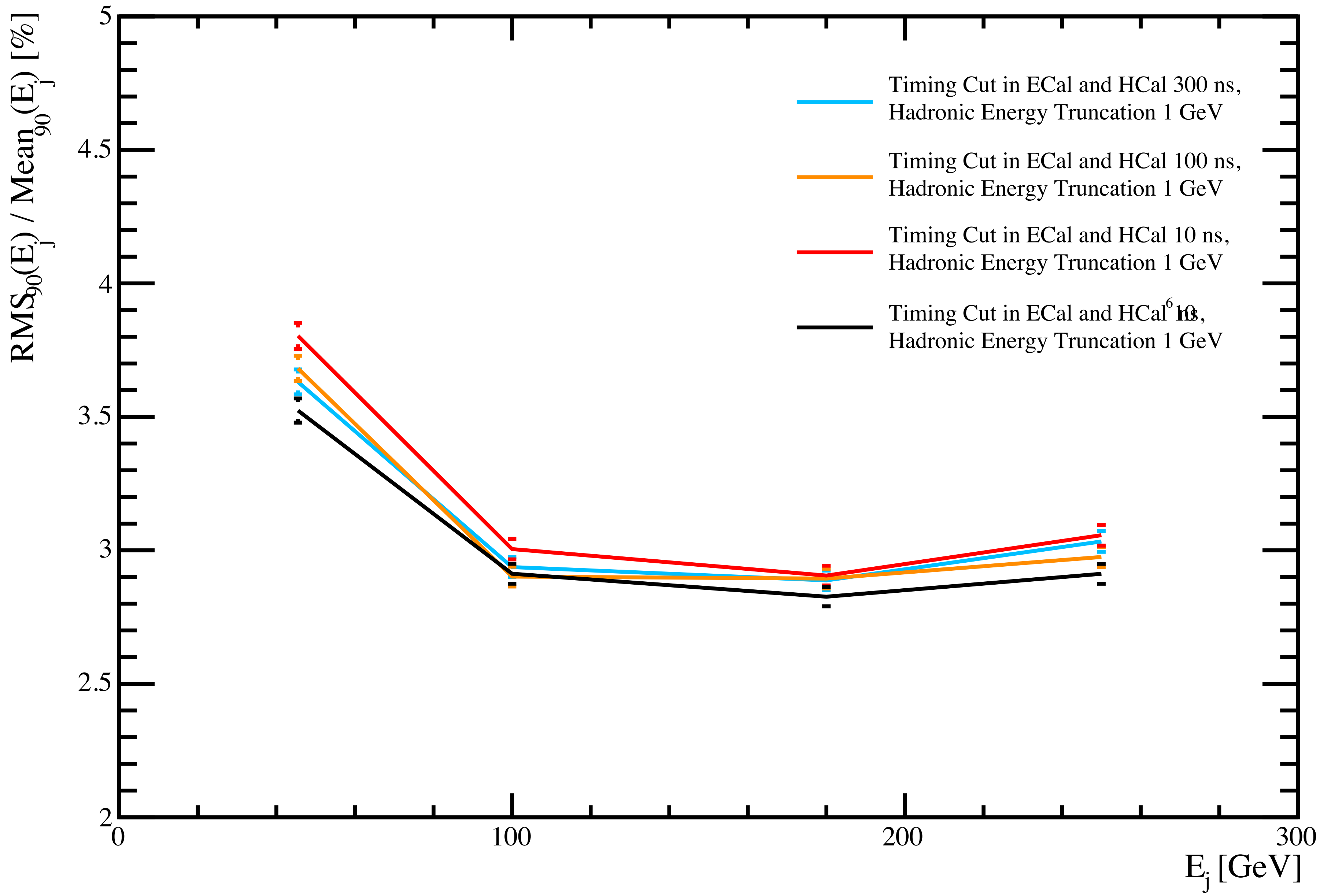




* As expected the mean jet energy decreases with increasing energy due to the HCal cell hadronic energy truncation of 1GeV.

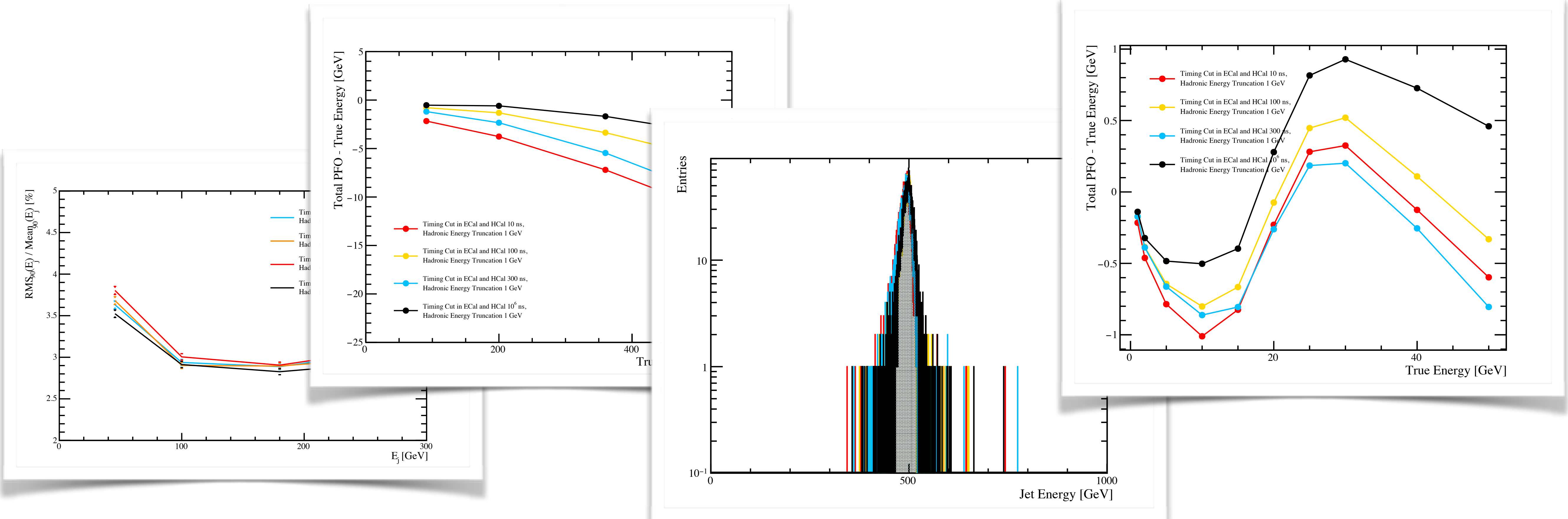
* Also as expected with larger the timing cuts you record more energy.

Timing Cuts - Jet Energy Resolutions



- Plot of jet energy resolution vs true jet energy for Z_uds jets of fixed energy.
- Some variation in performance, but relatively small.

Timing Cuts - Conclusions



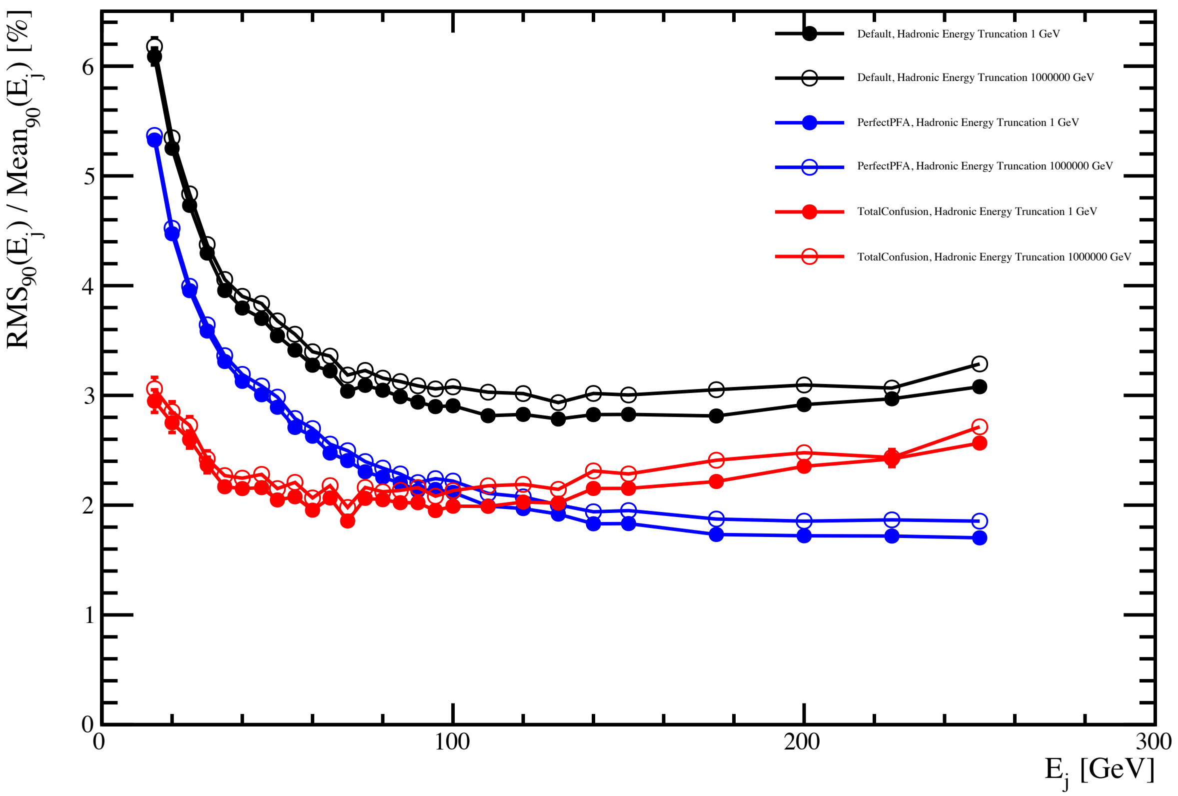
- Timing cuts are important.
- They do, as expected degrade performance.
- There is relatively little difference when applying realistic timing cuts. By realistic we mean anywhere between 10ns and 300ns.
- For future studies we will be applying a default timing cut of 100 ns.

HCal Hadronic Energy Truncation

- Within PandoraPFA a hadronic energy truncation can be applied, which aids the reconstruction in both intrinsic energy resolution and pattern recognition, by improving the energy estimator for the calorimeter hits.

- The exact value of this truncation significantly impact the energy resolution.

- Here we aim to show the extent of this impact.



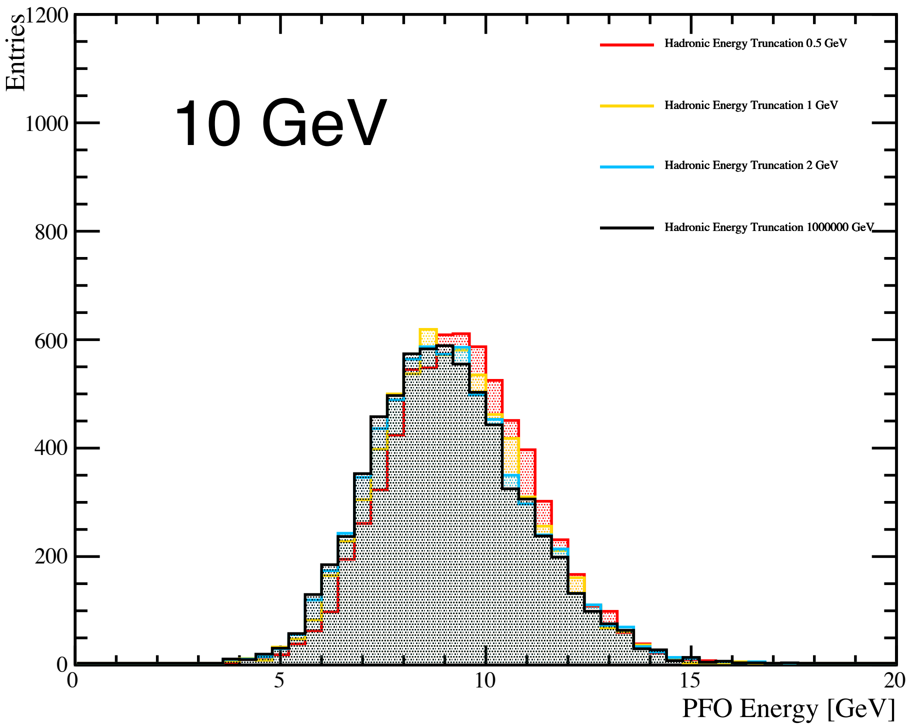
Single Particle Energy Analysis:

- Here we will look at:
  1. Raw reconstructed energy distributions;
  2. Mean reconstructed energy;
  3. Energy resolution.

Jet Energy Analysis:

- Here we will look at:
  1. Raw reconstructed energy distributions;
  2. Mean jet energies;
  3. Jet energy resolution.

HCal Hadronic Energy Truncation - Single Particle Energy Distributions

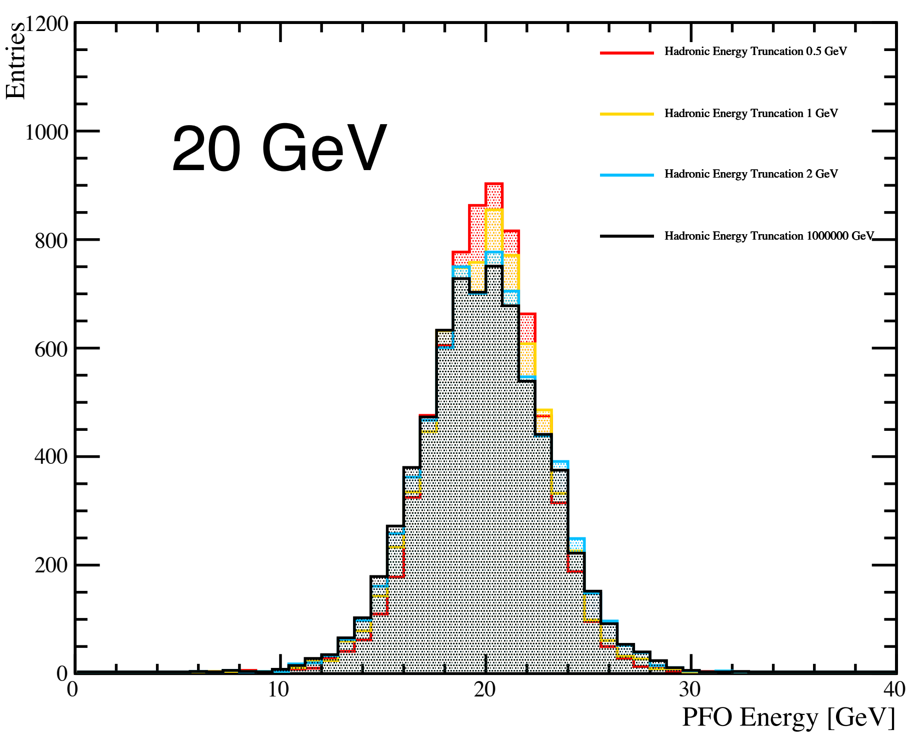


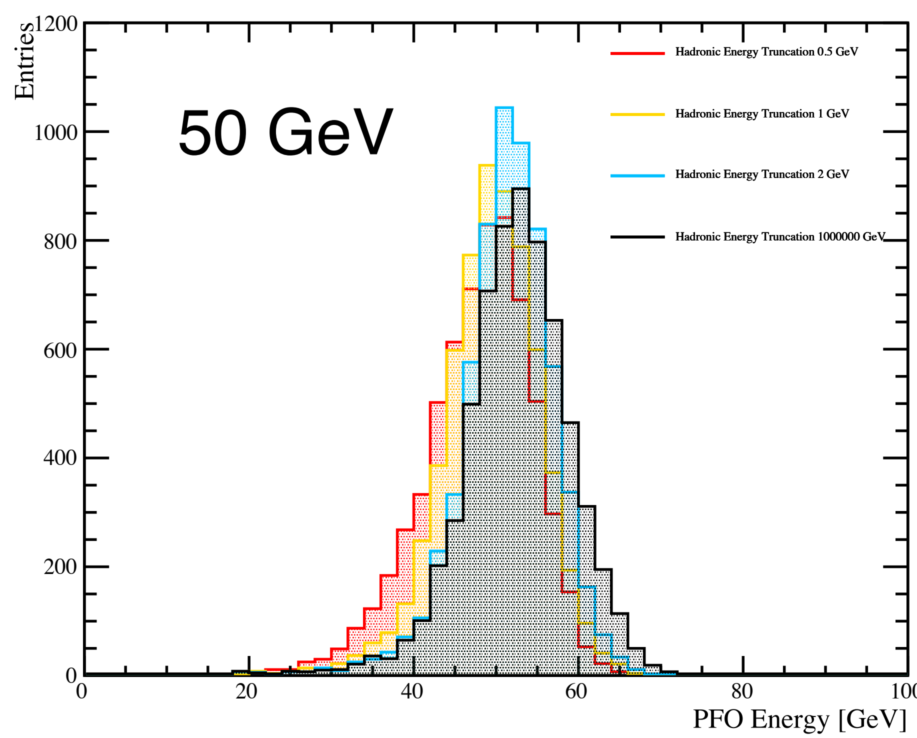
Hadronic Energy Truncations 0.5 GeV

Hadronic Energy Truncations 1 GeV

Hadronic Energy Truncations 2 GeV

Hadronic Energy Truncations 10^6 GeV





- Histograms of the reconstructed energy for single Kaon0L events of fixed energy.

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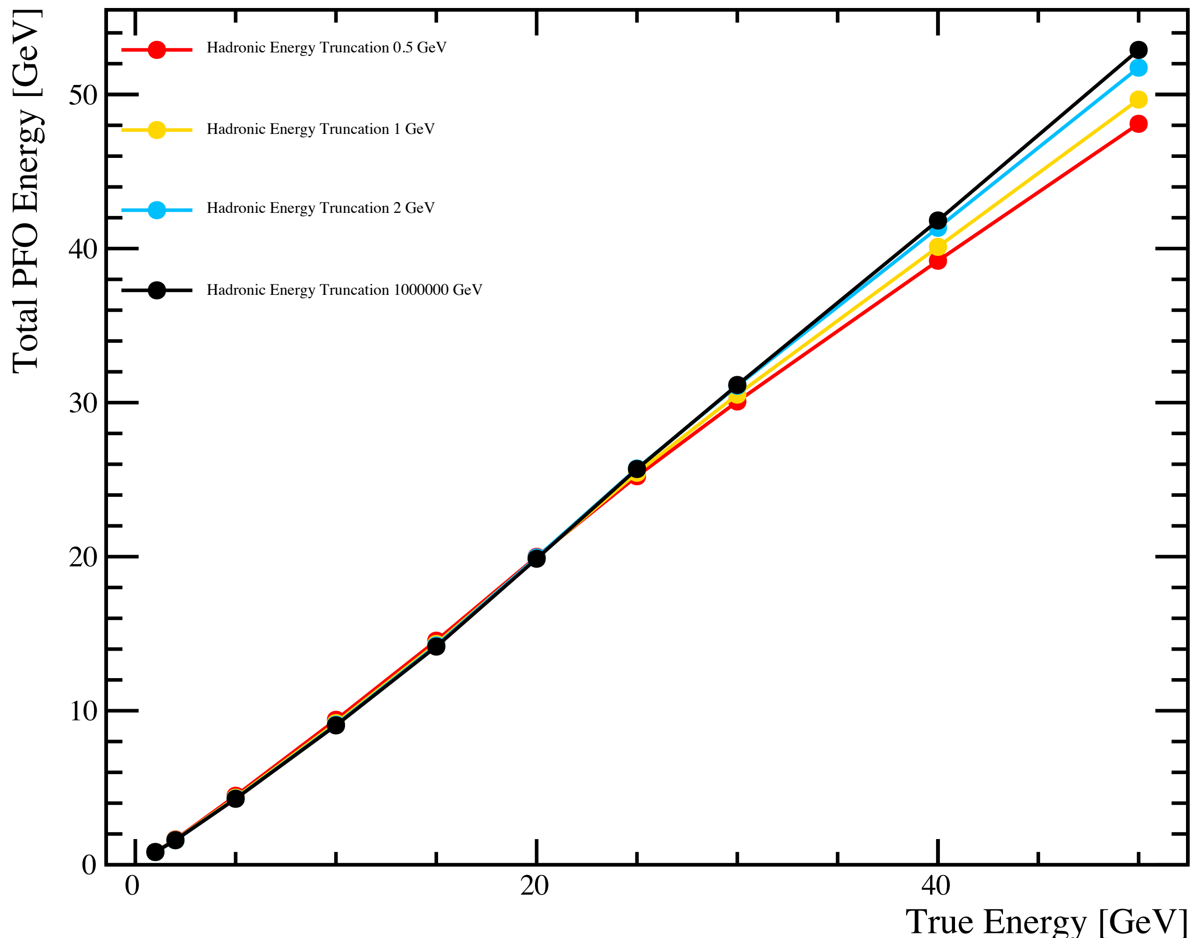
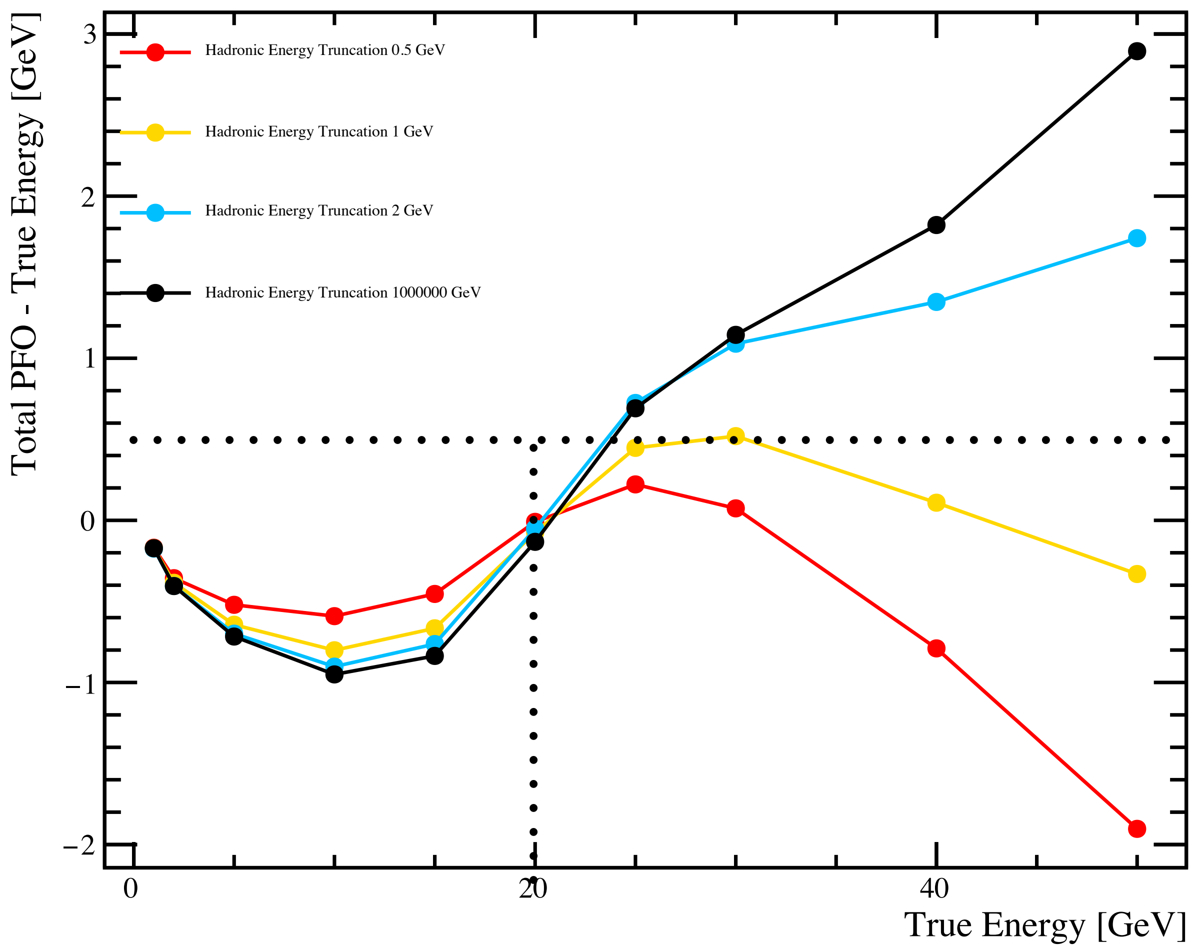
- Distributions have largely the same shape at low energy, <= 20GeV.
- Very big difference in distribution at large energies when several cells will have their energy truncated.
- Calibration fixes the mean of the 20 GeV distributions to be close to 20 GeV.

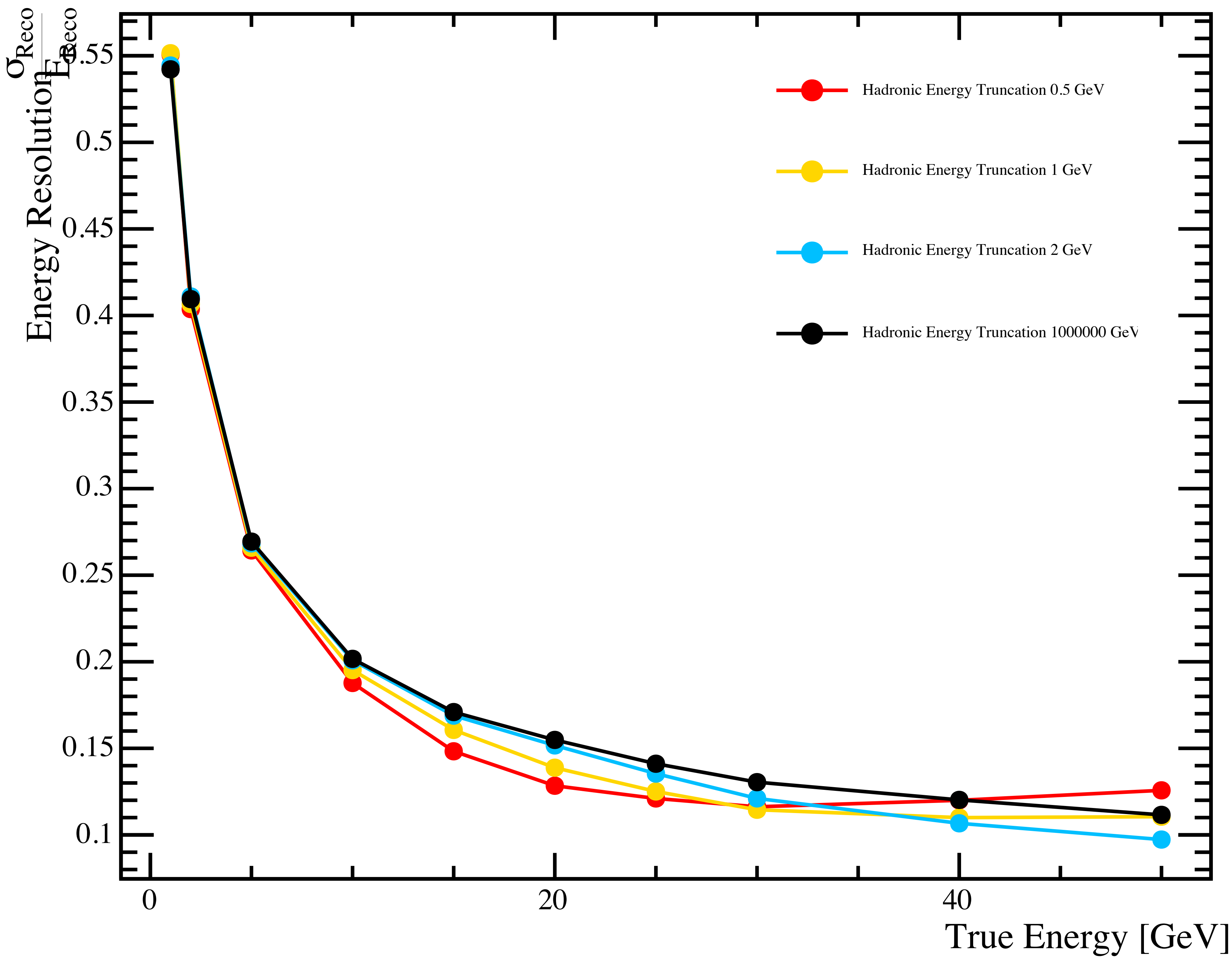
HCal Hadronic Energy Truncation - Single Particle Mean Energy





- For particle of energy less that 10 GeV the distributions aren't Gaussian so the points for energy less that 10 GeV don't properly represent the data.
- The trend at high energy clearly shows that the hadronic energy truncation is dictating the reconstructed energy.
- Applying too small a cut for a given cell size causes bad degradation in the reconstructed energy,

HCal Hadronic Energy Truncation - Single Particle Energy Resolutions



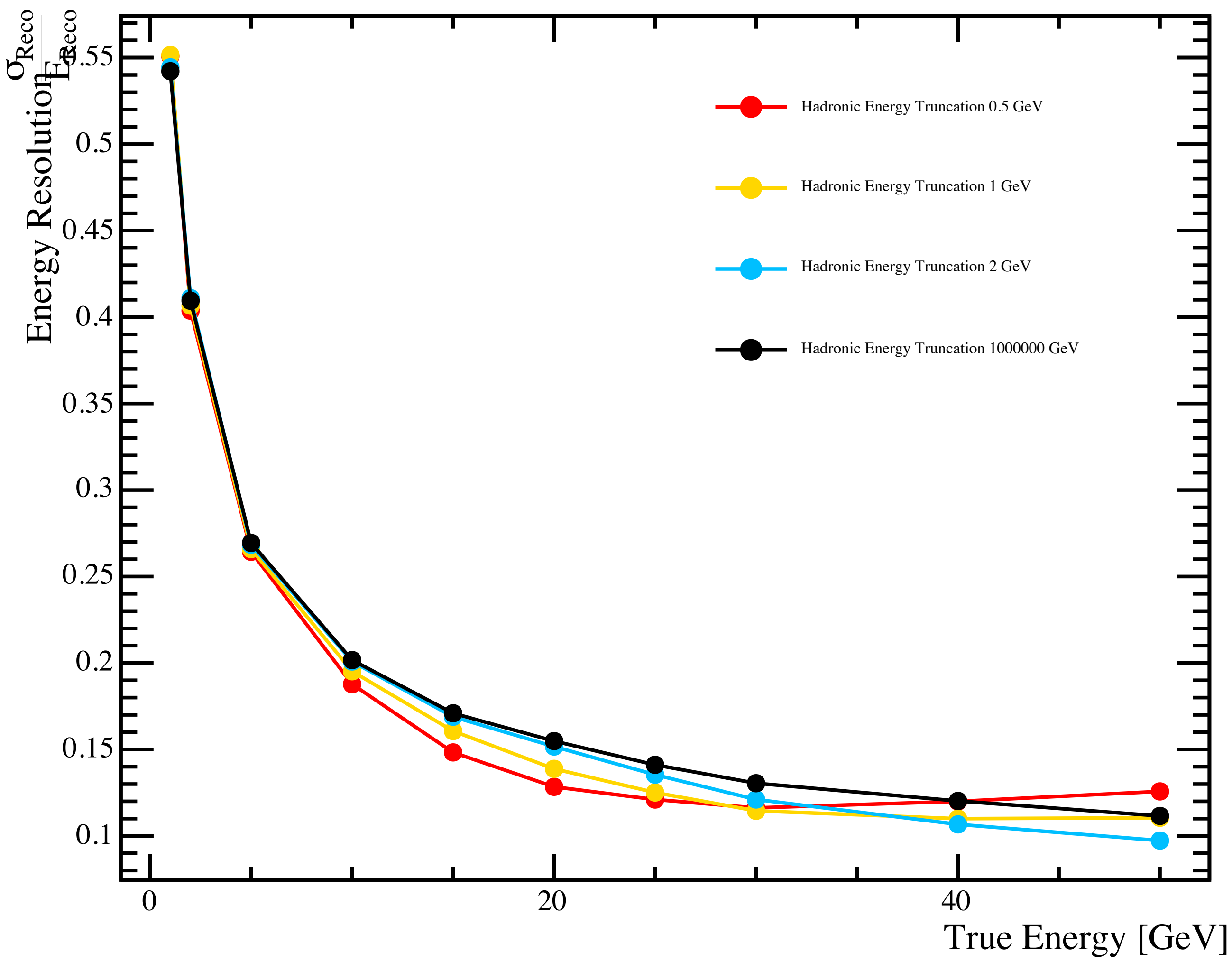
- Plot of energy resolution vs true energy for single Kaon0L events of fixed energy.
- The energy resolution here is defined as:

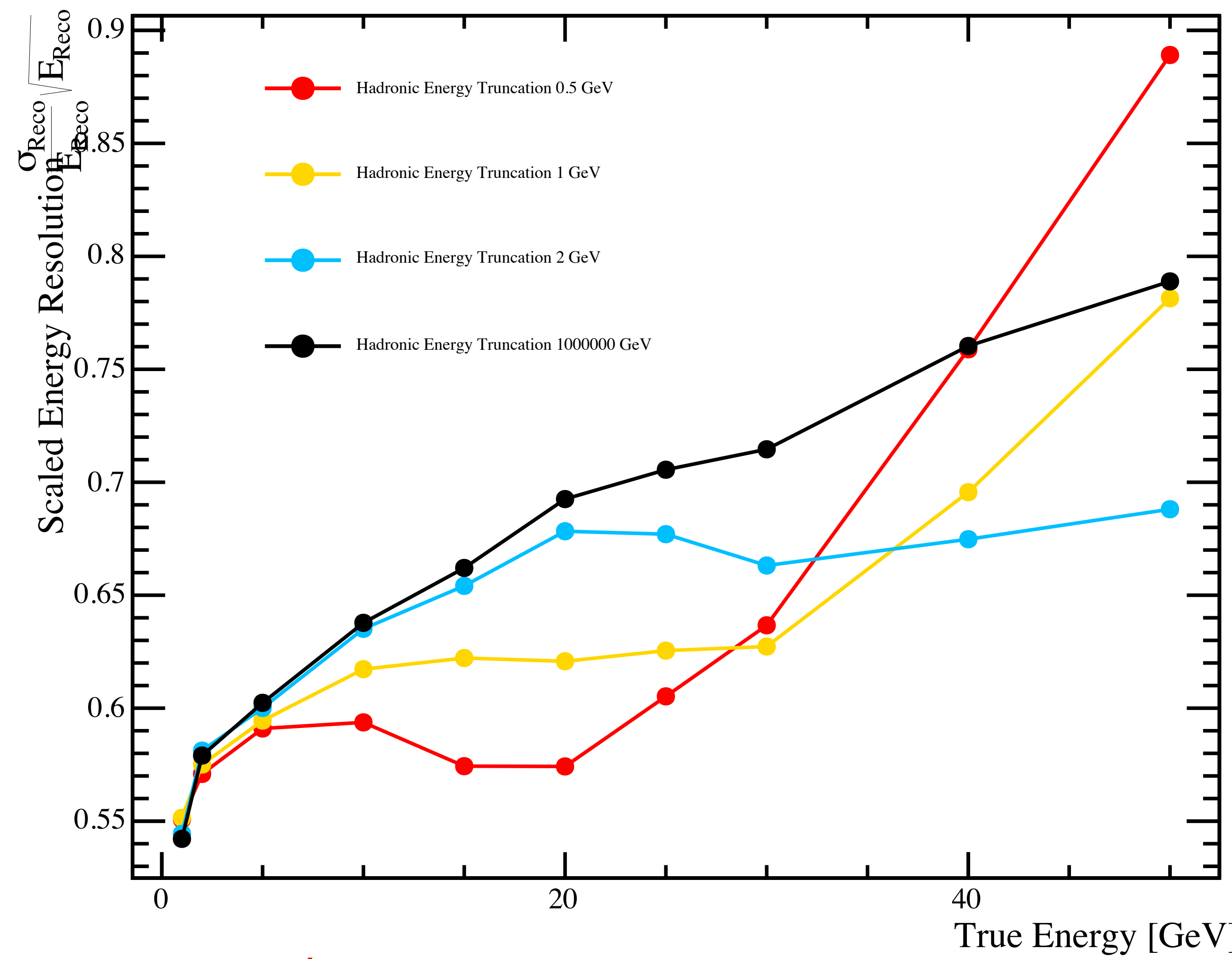
Resolution = σ_E / E

Where both σ_E and E are the standard deviation and mean of a Gaussian fit to the reconstructed energy distribution respectively.

- Energy resolution is largely unaffected by the hadronic energy truncation at these enegies.

HCal Hadronic Energy Truncation - Single Particle Energy Resolutions Scaled





- Quickly look at the scaled energy resolution, which is $\sqrt{E} \times \sigma_E / E$.
- Useful to compare to the generally accepted results that the energy resolution for the HCal is $0.55 / \sqrt{E}$.
- The optimal energy resolution occurs for different energy truncations at different single kaon0L energy samples.

HCal Hadronic Energy Truncation - Jet Reconstructed Energy Distributions

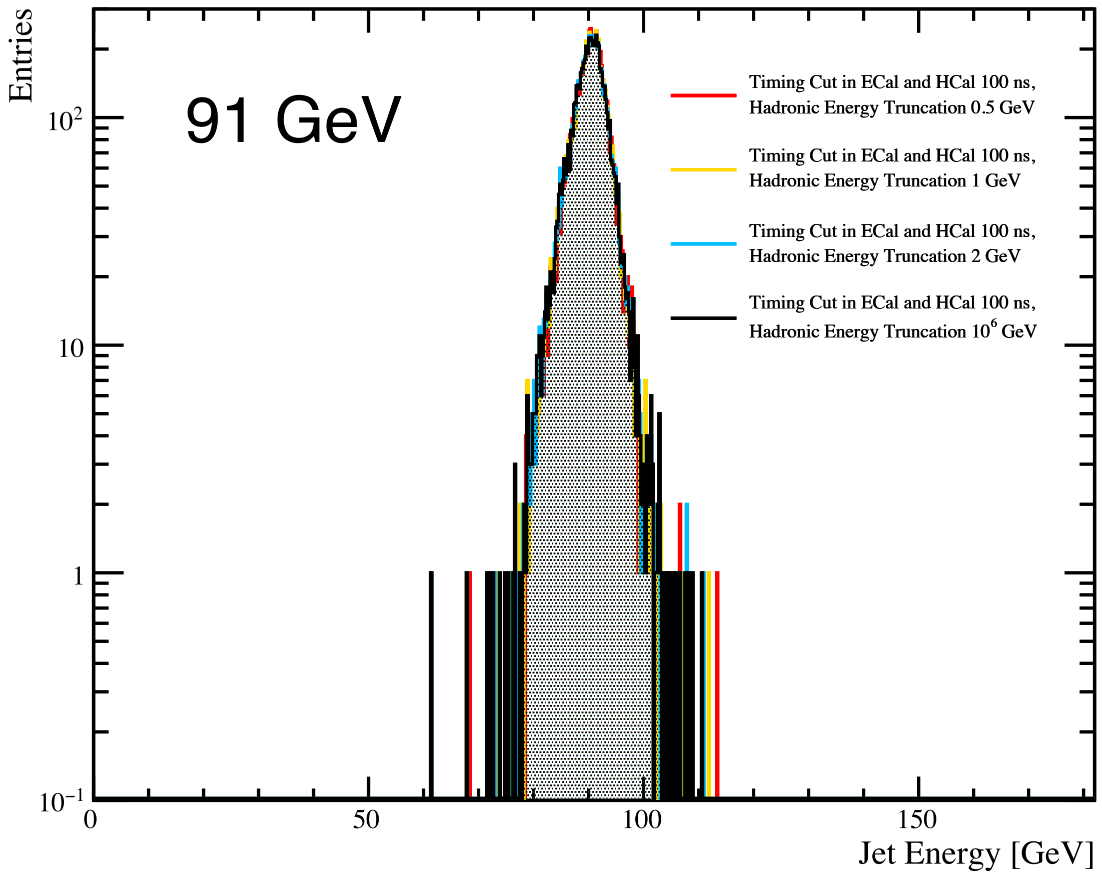
* Histograms of the reconstructed jet energy for Z_uds jet events of fixed energy.
* Distributions look similar at low jet energy where the truncation doesn't impact many cells, but at high energy a clear impact is observed. varying the timing cuts.

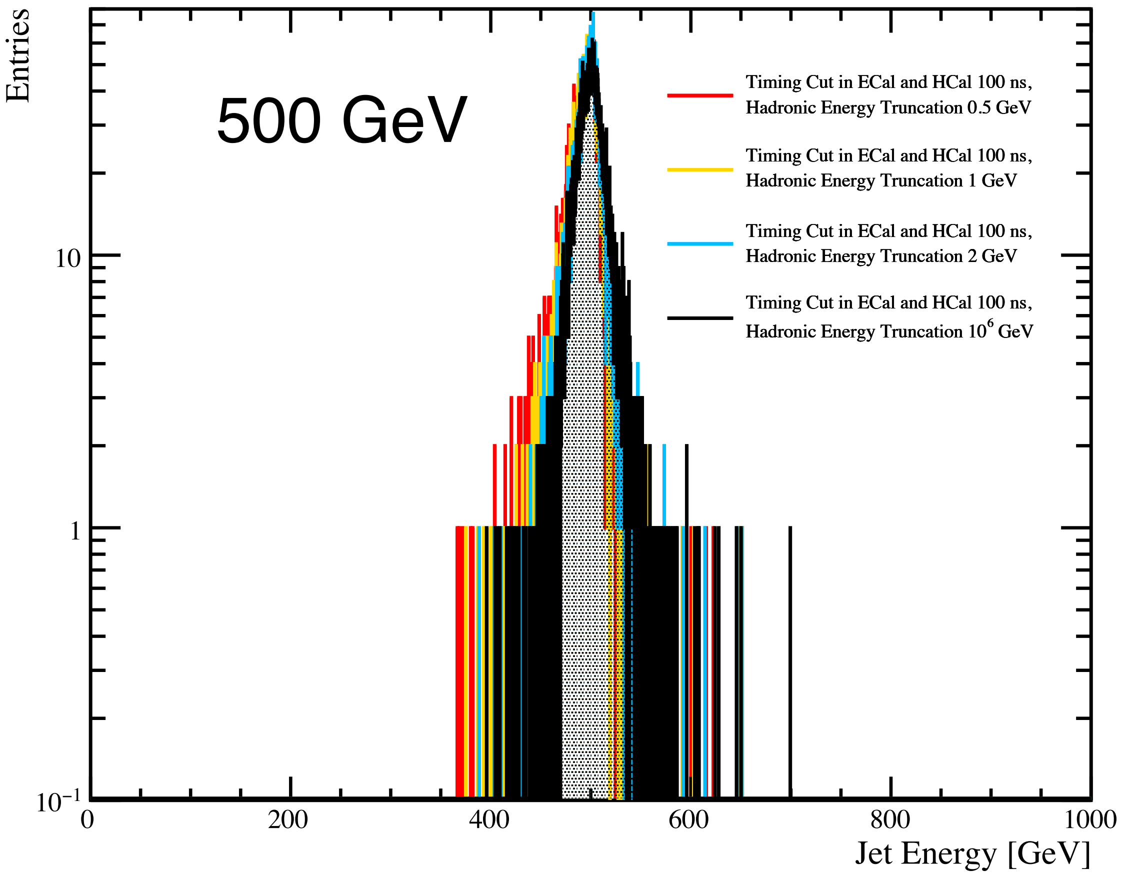
Hadronic Energy Truncations 0.5 GeV

Hadronic Energy Truncations 1 GeV

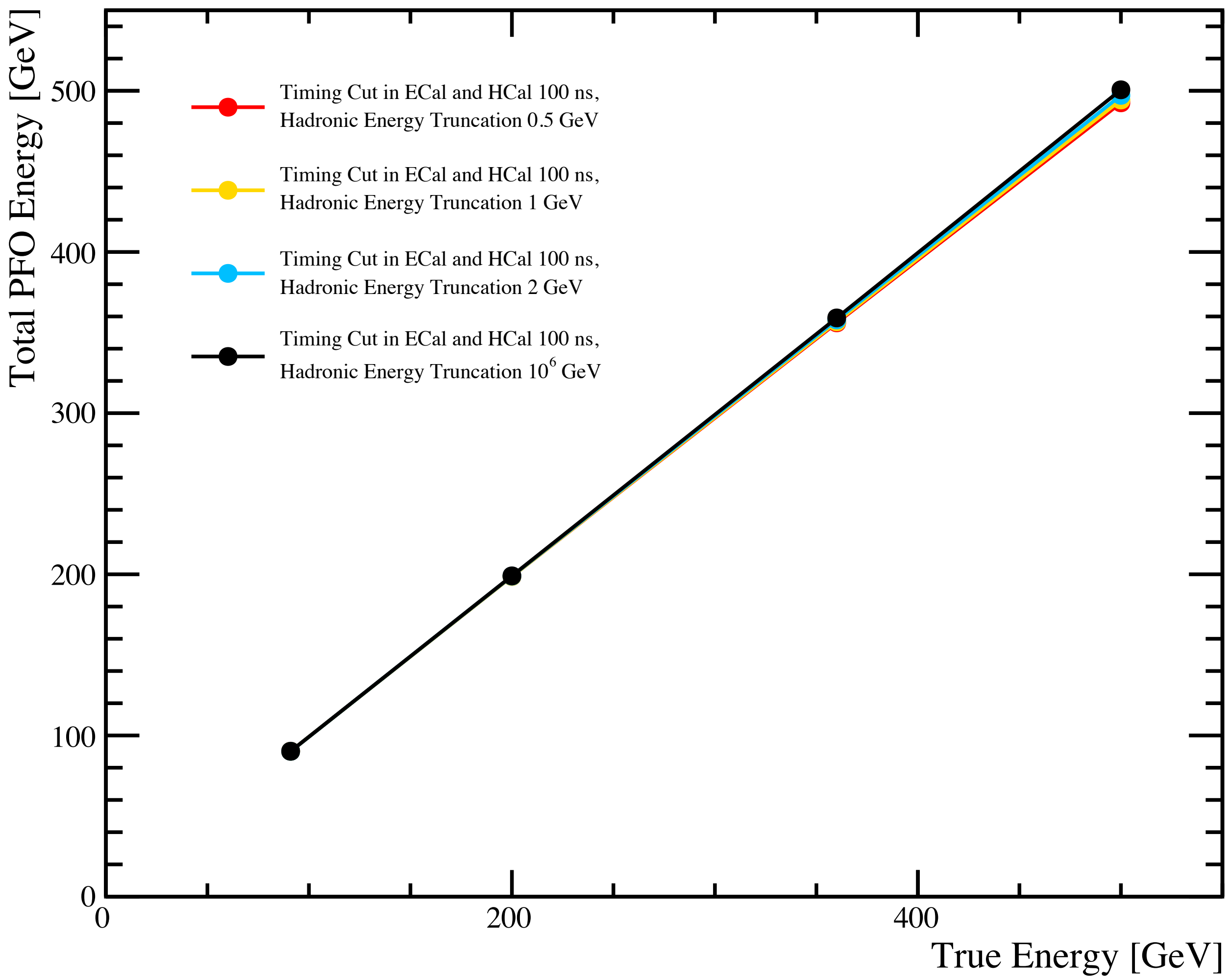
Hadronic Energy Truncations 2 GeV

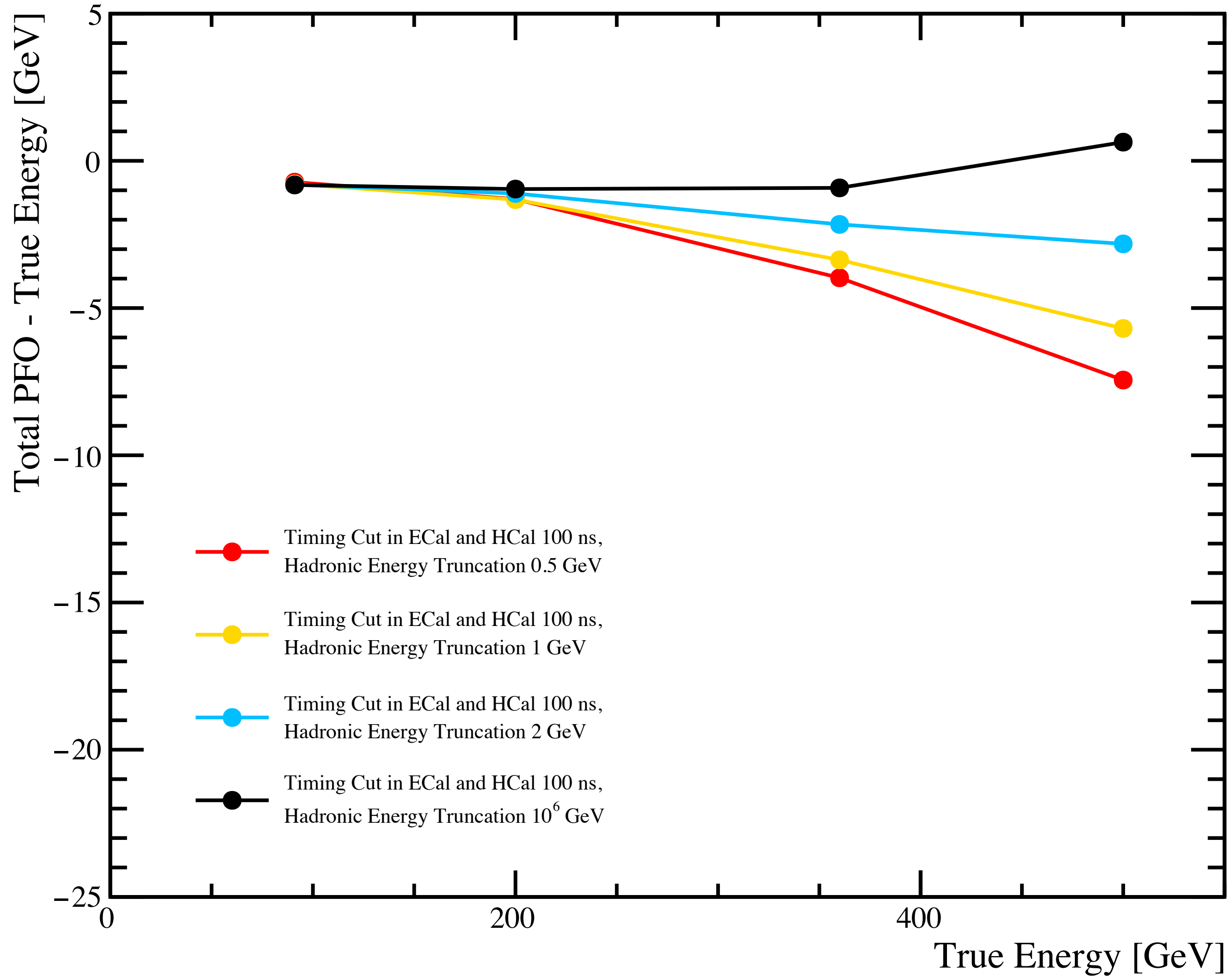
Hadronic Energy Truncations 10^6 GeV





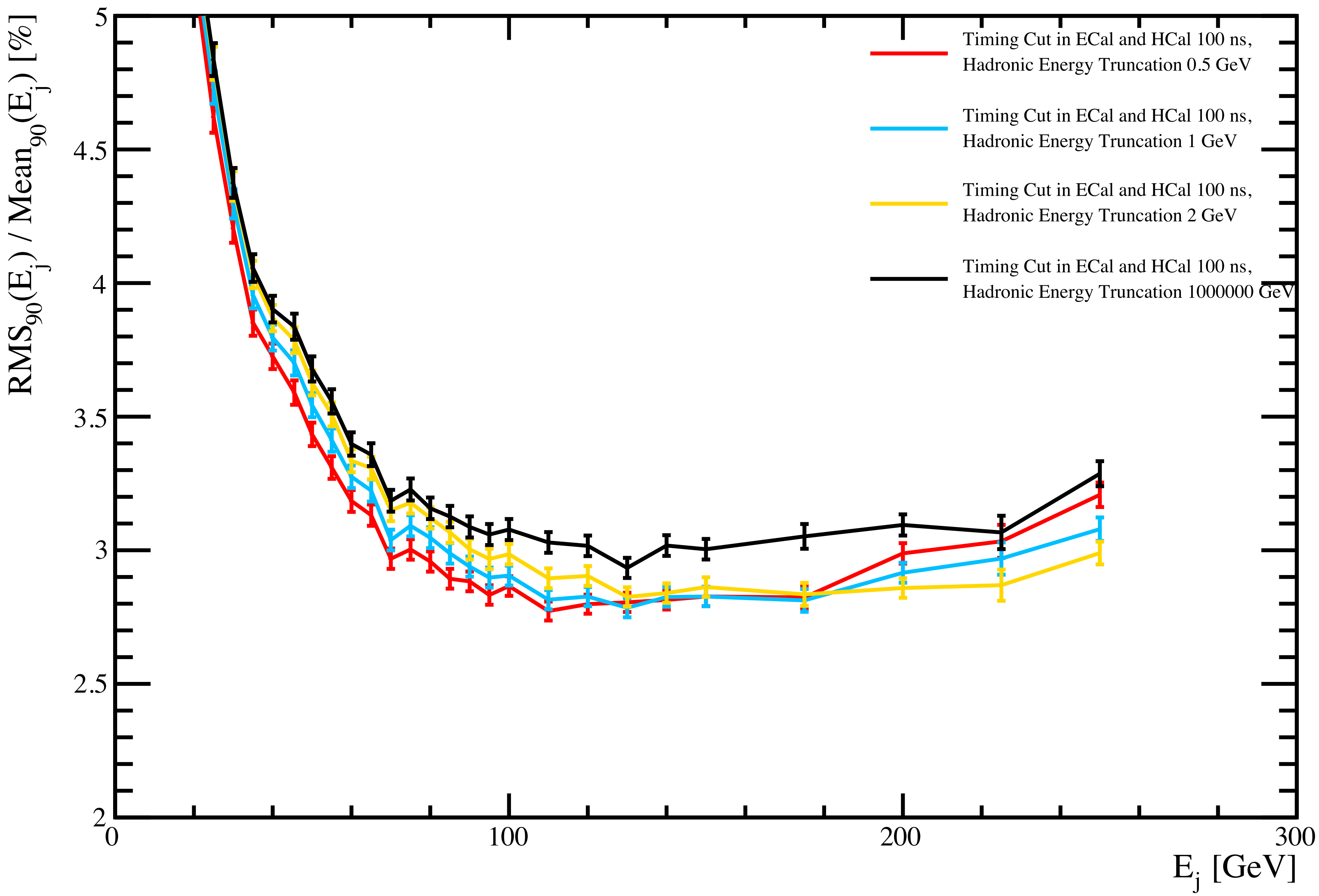
HCal Hadronic Energy Truncation - Jet Mean Energy





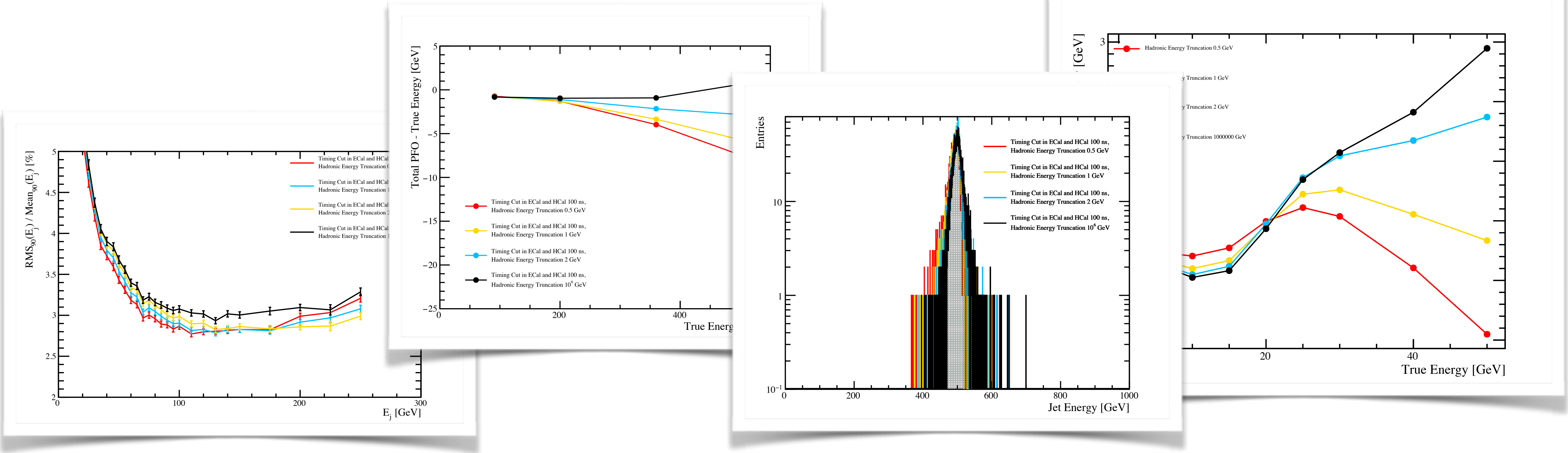
* As expected the mean jet energy decreases with increasing energy when a small HCal hadronic energy truncation is applied, but without this truncation the mean reconstructed energy approaches the expected value.

HCal Hadronic Energy Truncation - Jet Energy Resolutions



- Plot of jet energy resolution vs true jet energy for Z_uds jets of fixed energy.
- Significant variation.
- The best energy truncation varies as a function of energy.

HCal Hadronic Energy Truncation - Conclusions



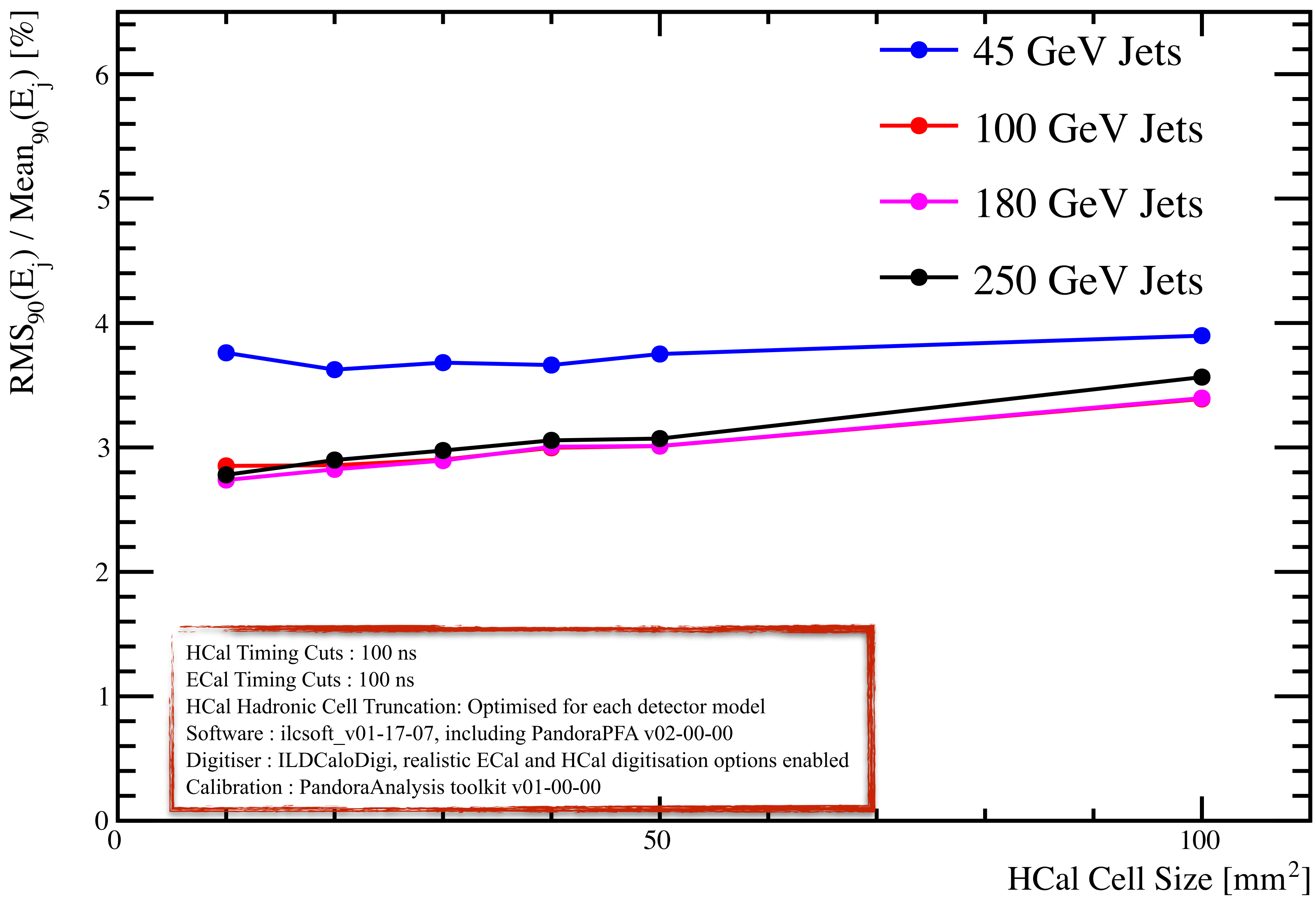
* The HCal hadronic energy truncation is very important for detector performance.
* It improves both the intrinsic energy resolution as well as reducing confusion in pattern recognition (as the energy estimators are more accurate).
* The optimal energy truncation must be specified for a given detector.
* For future studies we will optimise this truncation as a function of energy.

Optimisation of HCal

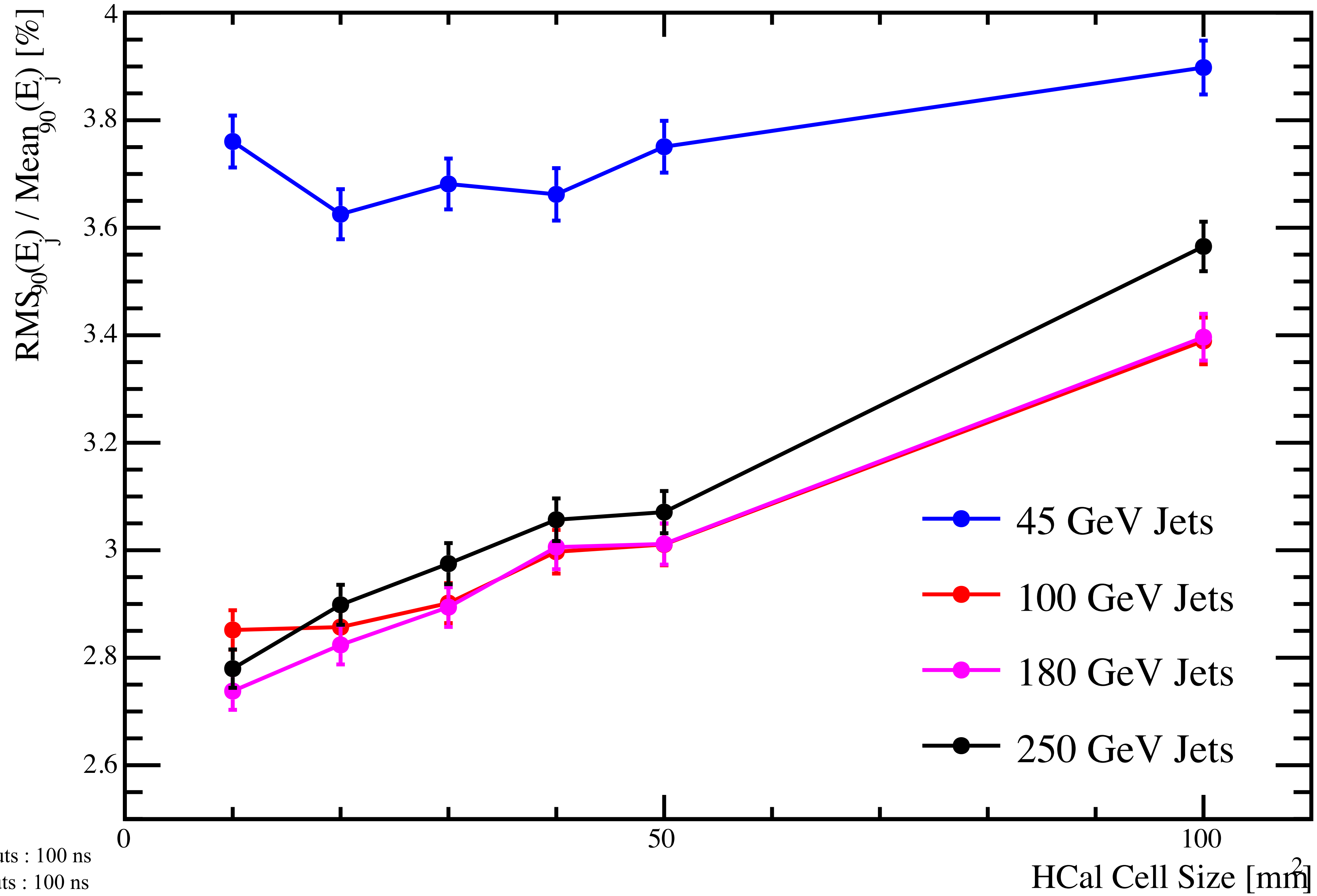
HCal Cell Size

HCal Timing Cuts : 100 ns
ECal Timing Cuts : 100 ns
HCal Hadronic Cell Truncation : Optimised for each detector model
Software : ilcsoft_v01-17-07, including PandoraPFA v02-00-00
Digitiser : ILDCaloDigi, realistic ECal and HCal digitisation options enabled
Calibration : PandoraAnalysis toolkit v01-00-00

HCal Cell Size



HCal Cell Size



HCal Timing Cuts : 100 ns
ECal Timing Cuts : 100 ns
HCal Hadronic Cell Truncation: Optimised for each detector model
Software : ilcsoft_v01-17-07, including PandoraPFA v02-00-00
Digitiser : ILDCaloDigi, realistic ECal and HCal digitisation options enabled
Calibration : PandoraAnalysis toolkit v01-00-00

Conclusions

1. *Initial Changes:*
    - *Updated detector model and reconstruction software (inc. PandoraPFA).*
    - *New calibration procedure.*
    - *New digitiser, ILDCaloDigi vs NewLDCCaloDigi*
    - *Realistic ECal and HCal simulations at the digitisation stage.*

There were significant improvements in detector performance when we (considered as a whole) moved from:

☑ Detector Model : ILD00 -> ILD_01_v06

☑ Reconstruction Software : From that used for the LoI -> ilcsoft_v01-17-07 (including **PandoraPFA_v02-00-00**)

☑ Digitiser : NewLDCCaloDigi -> ILDCaloDigi (+Realistic Digitsation Options)

☑ Calibration: Default LoI Numbers -> PandoraAnalysis toolkit (v01-00-00)

Conclusions

2. Timing cuts applied to the simulation.

- Timing cuts play a very large role in detector performance. As expected they degrade performance, but we now know the exact extent of the degradation.
- When applying physical timing cuts, there is relatively little difference in detector performance.

3. HCal Hadronic Energy Cell truncation.

- The HCal hadronic energy cell truncation is extremely important in determining the detector performance.
- It must be optimised for each detector model to get accurate results for optimisation studies.

BackUp

Realistic ECal Digitiser Settings

```
<!-- Realistic ECal -->
<parameter name="ECAL_apply_realistic_digi" type="int">1</parameter>
<parameter name="CalibECALMIP" type="float">0.0001475</parameter>
<parameter name="ECAL_maxDynamicRange_MIP" type="float">2500</parameter>
<parameter name="ECAL_elec_noise_mips" type="float">0.07</parameter>
<parameter name="ECAL_deadCellRate" type="float">0</parameter>
<parameter name="ECAL_miscalibration_uncorrel" type="float">0</parameter>
<parameter name="ECAL_miscalibration_uncorrel_memorise" type="bool">false</parameter>
<parameter name="ECAL_miscalibration_correl" type="float">0</parameter>
<parameter name="energyPerEHpair" type="float">3.6</parameter>
```

* **CalibrECalMIP** sets MIP scale in digitiser.
* **ECAL_maxDynamicRange_MIP** sets the dynamic range of the electronics readout in units of MIPs.
* **ECAL_elec_noisemips** is the standard deviation of a Gaussian with mean 0. A random number with this distribution is added to the energy measure to simulate electrical noise.
* **energyPerEHpair** sets the energy required to produce and electron hole pair. Energies are converted to numbers of electrons hole pairs. A smearing of the energy distribution is applied by exchanging the number of electron hole pairs (n) produced by a randomly drawn number from a Poisson distribution, which has mean n.
* No dead cells or mis-calibration simulated.

Realistic HCal Digitiser Settings

```
<!-- Realistic HCal -->
 <parameter name="HCAL_apply_realistic_digi" type="int">1</parameter>
 <parameter name="HCALThresholdUnit" type="string">MIP</parameter>
 <parameter name="CalibHCALMIP" type="float">0.0004925</parameter>
 <parameter name="HCAL_maxDynamicRange_MIP" type="float">99999999</parameter>
 <parameter name="HCAL_elec_noise_mips" type="float">0.06</parameter>
 <parameter name="HCAL_deadCellRate" type="float">0</parameter>
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 <parameter name="HCAL_PPD_PE_per_MIP" type="float">15</parameter>
 <parameter name="HCAL_pixel_spread" type="float">0.05</parameter>
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 <parameter name="HCAL_miscalibration_correl" type="float">0</parameter>
```

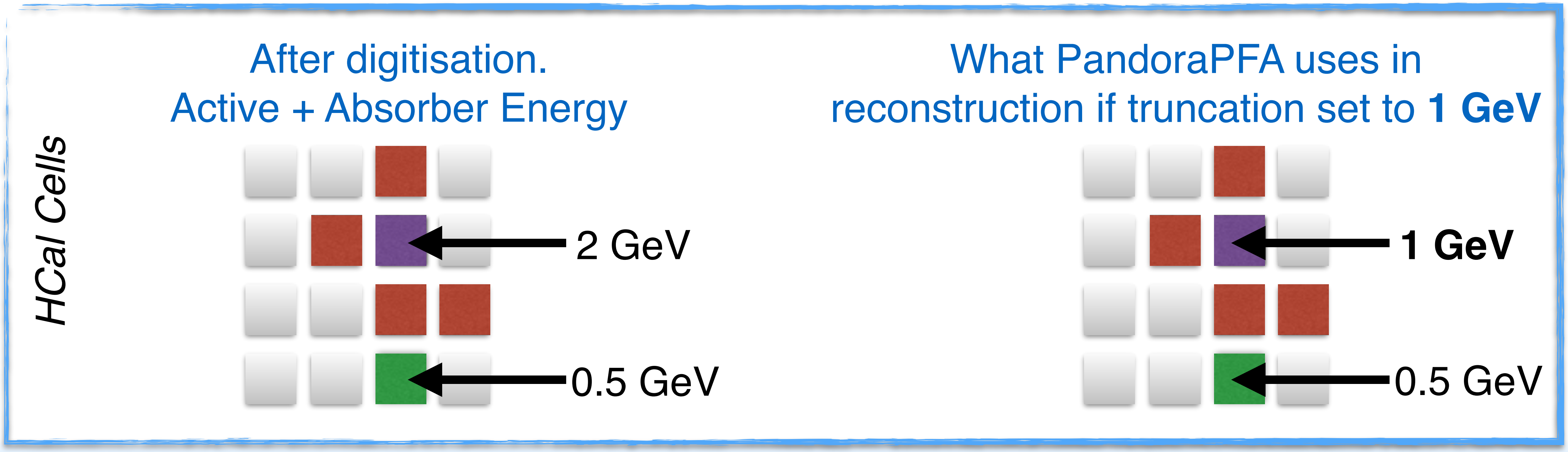
* **CalibrHCalMIP** sets MIP scale in digitiser.
* HCAL_maxDynamicRange_MIP sets the dynamic range of the electronics readout in units of MIPs.
* **HCAL_elec_noise_mips** sets the electrical noise. HCAL_elec_noise_mips is the standard deviation of a Gaussian with mean 0. A random number with this distribution is added to the energy measure to simulate electrical noise.
* **HCAL_PPD_N_Pixels** sets the number of pixels which are fired for a given number of photo electrons produced.
* **HCAL_PPD_PE_per_MIP** sets the number of photo electrons produced by one MIP in the pixelated photo detectors.
* **HCAL_pixel_spread** sets variations in pixel response (e.g. from different capacitances).
* No dead cells or mis-calibration simulated.

$$n_{pix}^{sig} = n_{pix} \times \texttt{RandGauss}(1, \S\texttt{CAL\_pixel\_spread}/\sqrt{(}n_{pix}))$$

Details of Simulation and Reconstruction Evolution

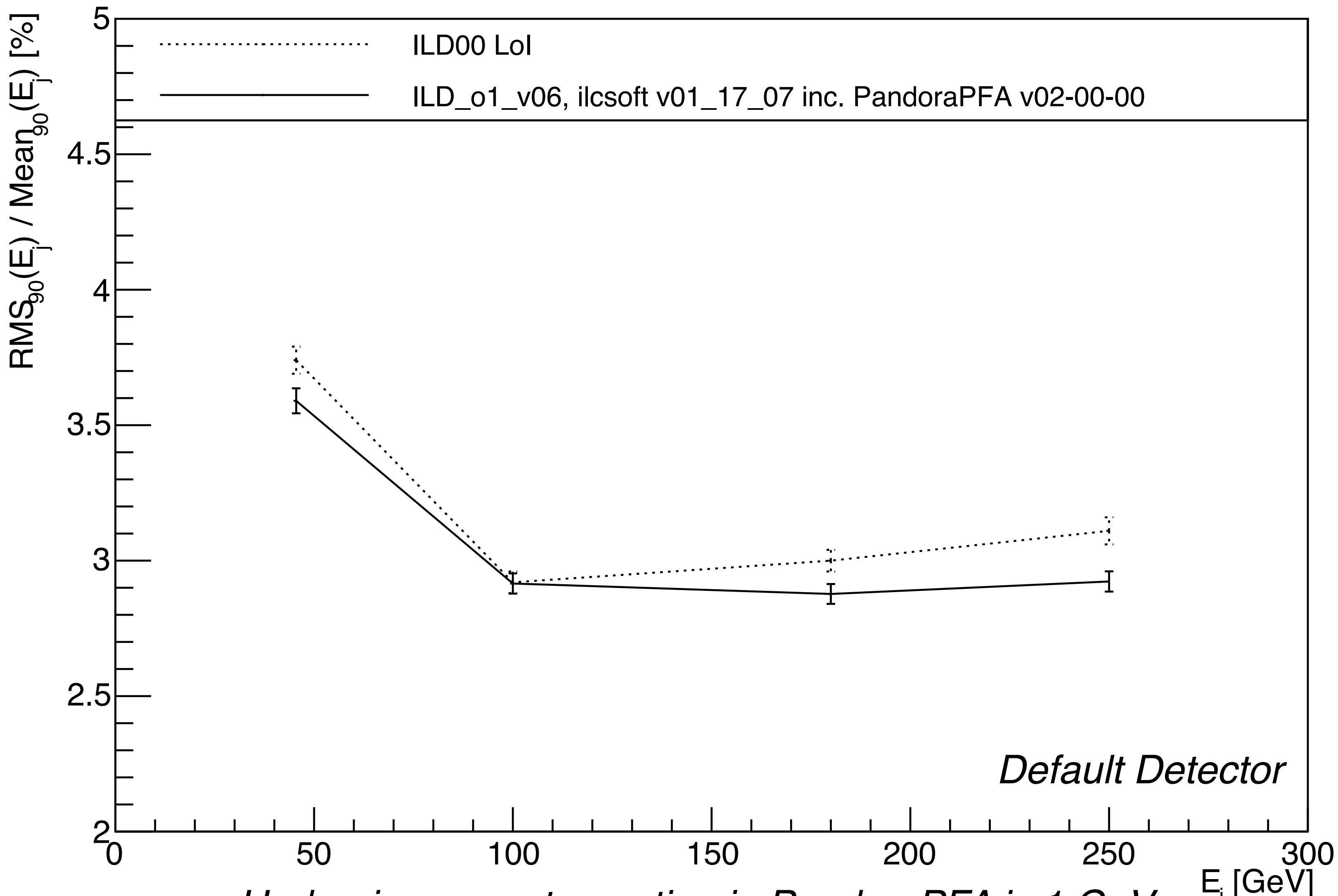
Hadronic Energy Truncation in PandoraPFA

- A variable of key significance in these studies is the hadronic energy truncation applied in the HCal in PandoraPFA.
- Within PandoraPFA, the HCal cells contain an estimate of the energy deposited in both the active and absorber material.
- The cut limits/truncates the amount of hadronic energy that can be measured in an individual HCal cell.
- It's purpose is to act as naive software compensation, which improves the hadronic energy estimator.



LoI vs PandoraPFANew v02-00-00

- Examine the change in detector performance when:
  - Updating the detector model from the time of the LoI to ILD_o1_v06.
  - Updating reconstruction software from that at the time of the LoI to version ilcsoft v01-17-07 including Pandora v02-00-00.

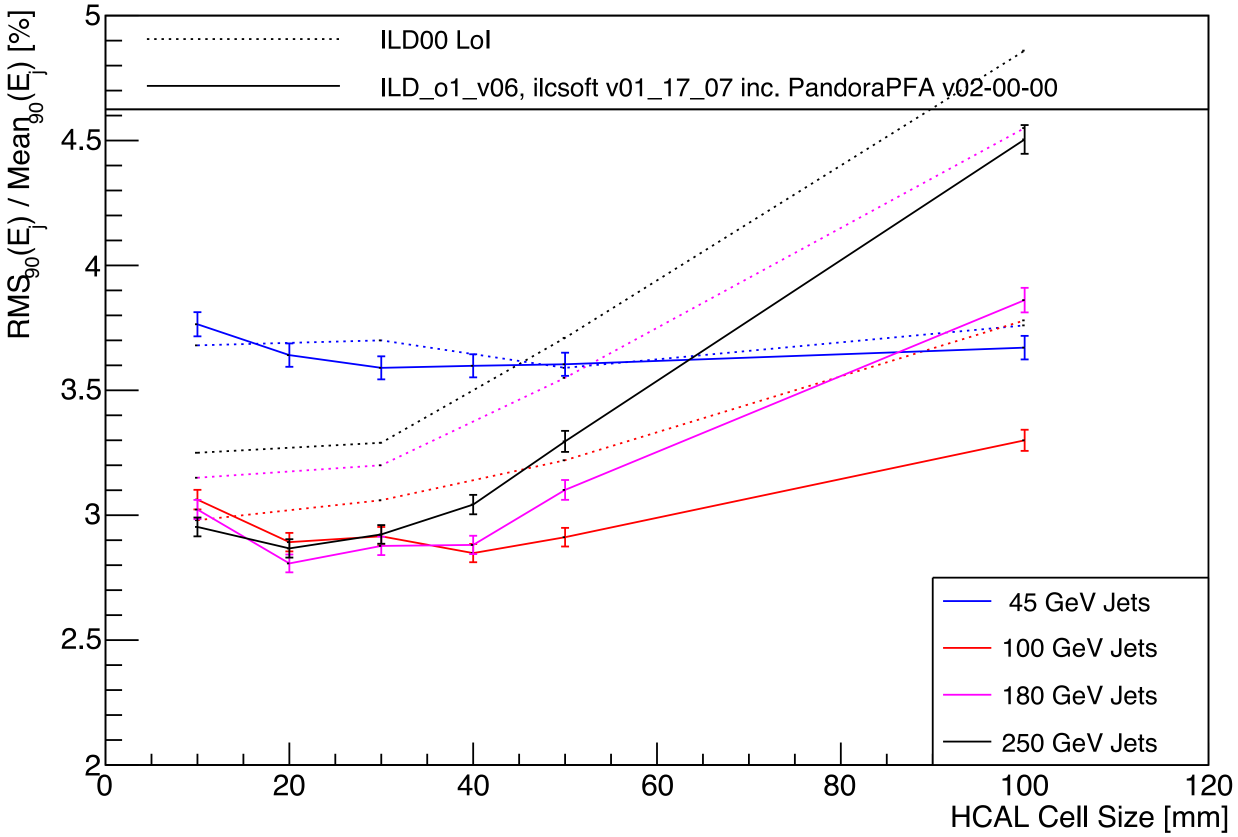


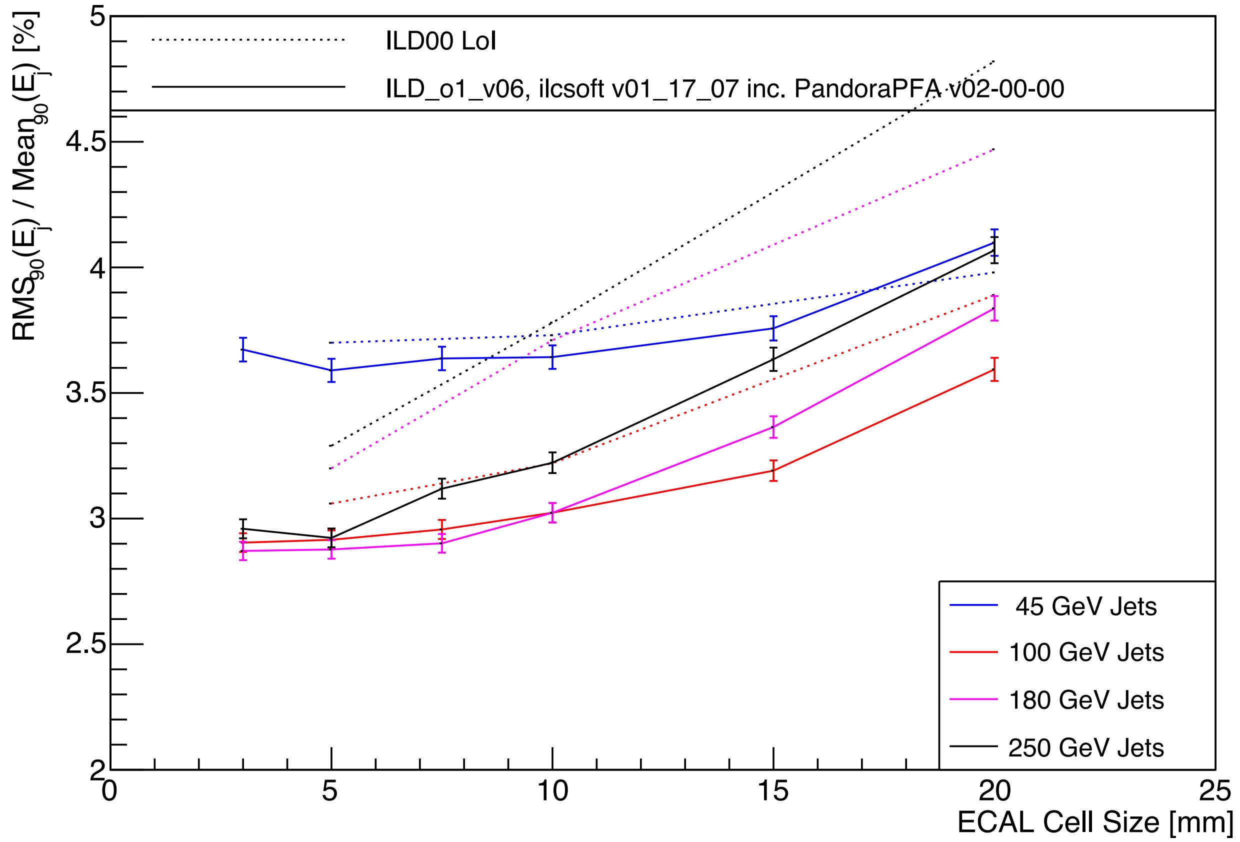
Hadronic energy truncation in PandoraPFA is 1 GeV.

- All input variables to the simulation and reconstruction are unchanged.
- Improvements seen across the energy range considered for the default detector.

LoI vs PandoraPFANew v02-00-00

Look at the non default detector models…





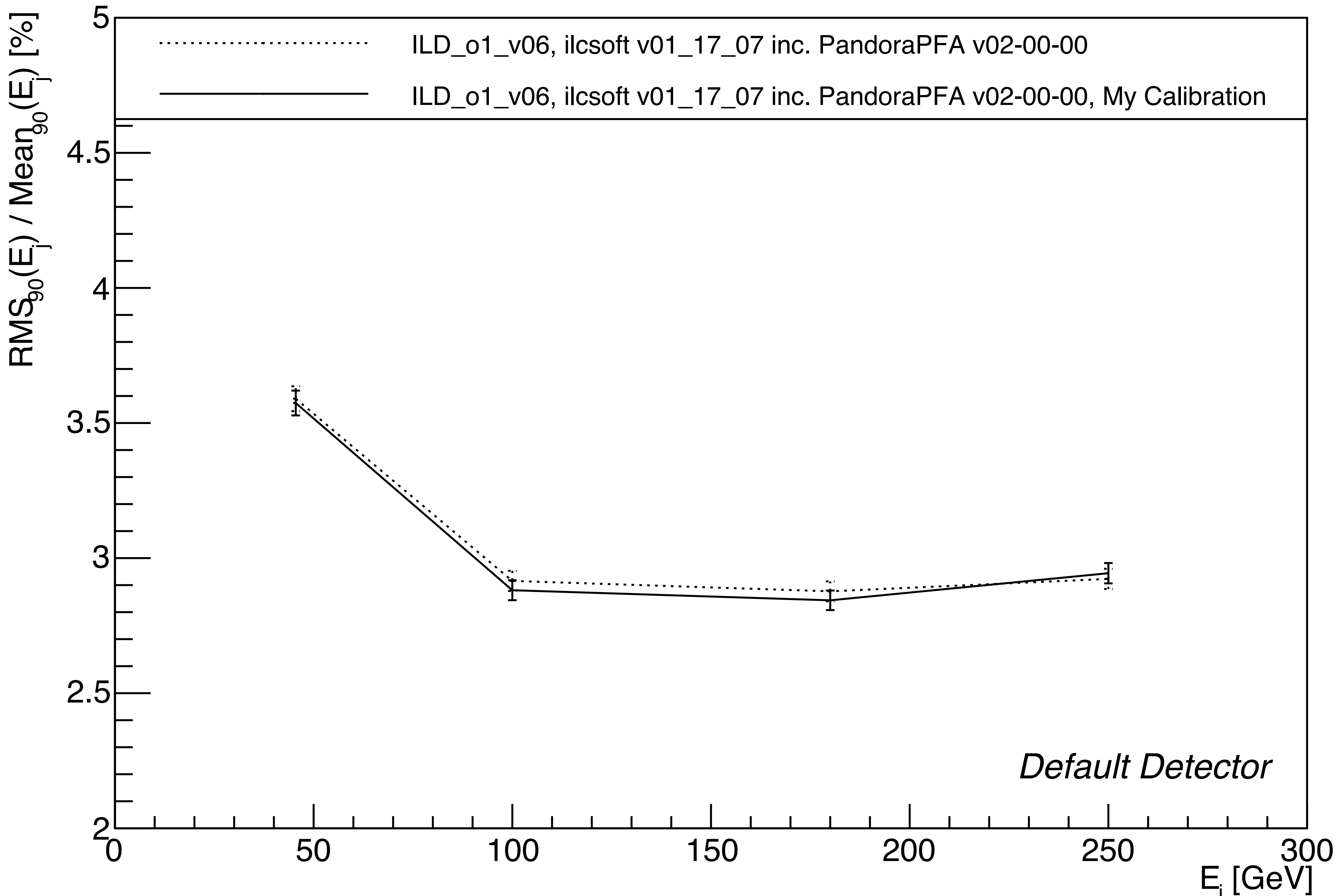
Hadronic energy truncation in PandoraPFA is 1 GeV.

* Improvements seen when we vary the ECal and HCal cell sizes (otherwise detector is default ILD_o1_v06).

☑ Changes to the detector model and reconstruction software since the time of the LoI have improved the detector performance.

DBD vs New Calibration

- Examine the change in detector performance when going from the default calibration numbers used for the DBD to the newly developed calibration procedure (see back up slides for further detail).



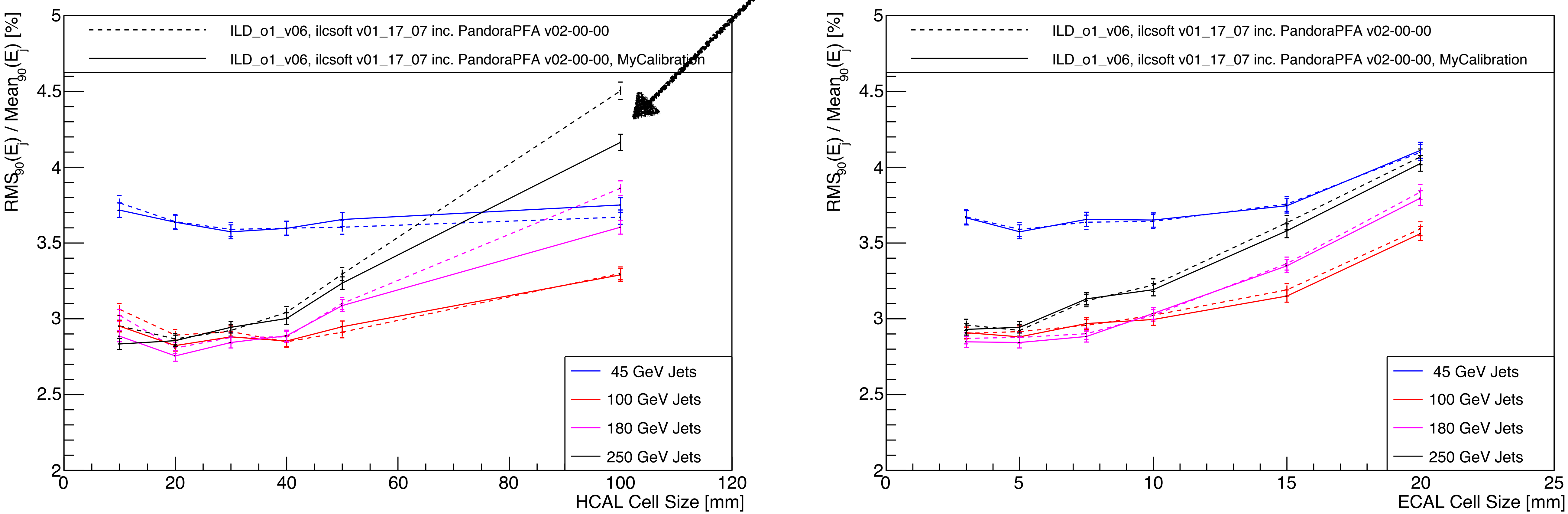
Hadronic energy truncation in PandoraPFA is 1 GeV.

- New calibration procedure is documented in the PandoraAnalysis toolkit (cf. pdf in doc folder).
- No difference in performance.

DBD vs New Calibration

Look at the non default detector models…

Calibration compensates for lost energy due to truncation at large HCal cell sizes.



Hadronic energy truncation in PandoraPFA is 1 GeV.

- New calibration procedure either reproduced the DBD calibration or improves it for large HCal cell sizes and high energy jets.

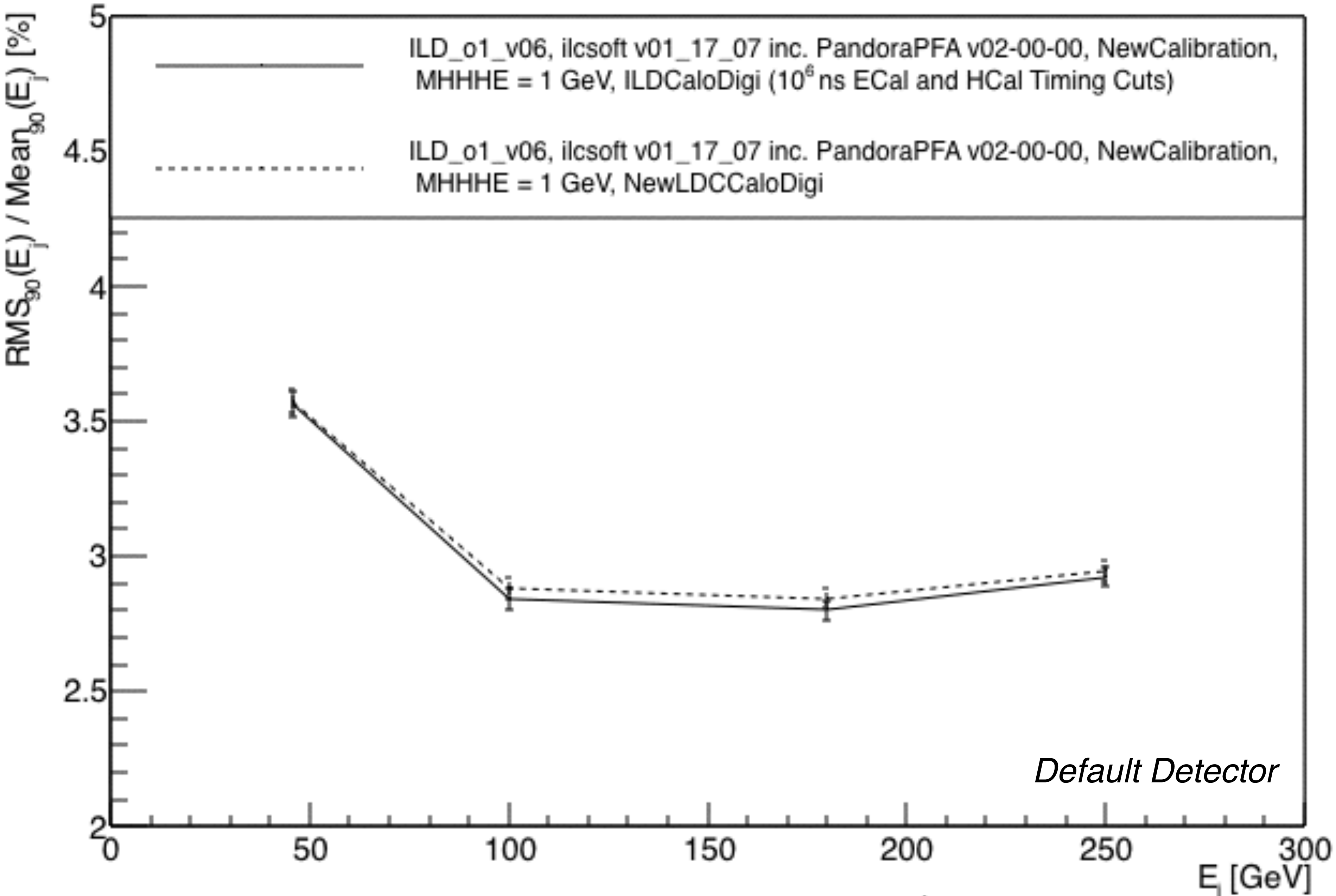
☑ New calibration procedure produces consistent results, is physically justifiable and so should be used for future studies.

NewLDCCaloDigi vs ILDCaloDigi

* There are two different digitisation options available to us:
  * **NewLDCCaloDigi**. This is what was used for the LoI and DBD.
  * **ILDCaloDigi**. This is a modified version of NewLDCCaloDigi, which has features such as timing cuts and realistic options (details in later slide), both of which we would like to study further.
* There is a subtle difference in the grouping of SimCalorimeterHits into CalorimeterHits between these two digitisers (details in back up slide). Could be significant as thresholds are place on CalorimeterHits once they are in PandoraPFA.
* NewLDCCaloDigi places no timing cuts and so in the following comparisons, unless explicitly stated, we set the timing cut in ILDCaloDigi to be a very large value 10^6ns.

NewLDCCaloDigi vs ILDCaloDigi

* Examine the change in detector performance when going from the NewLDCCaloDigi digitiser to the ILDCaloDigi digitiser.

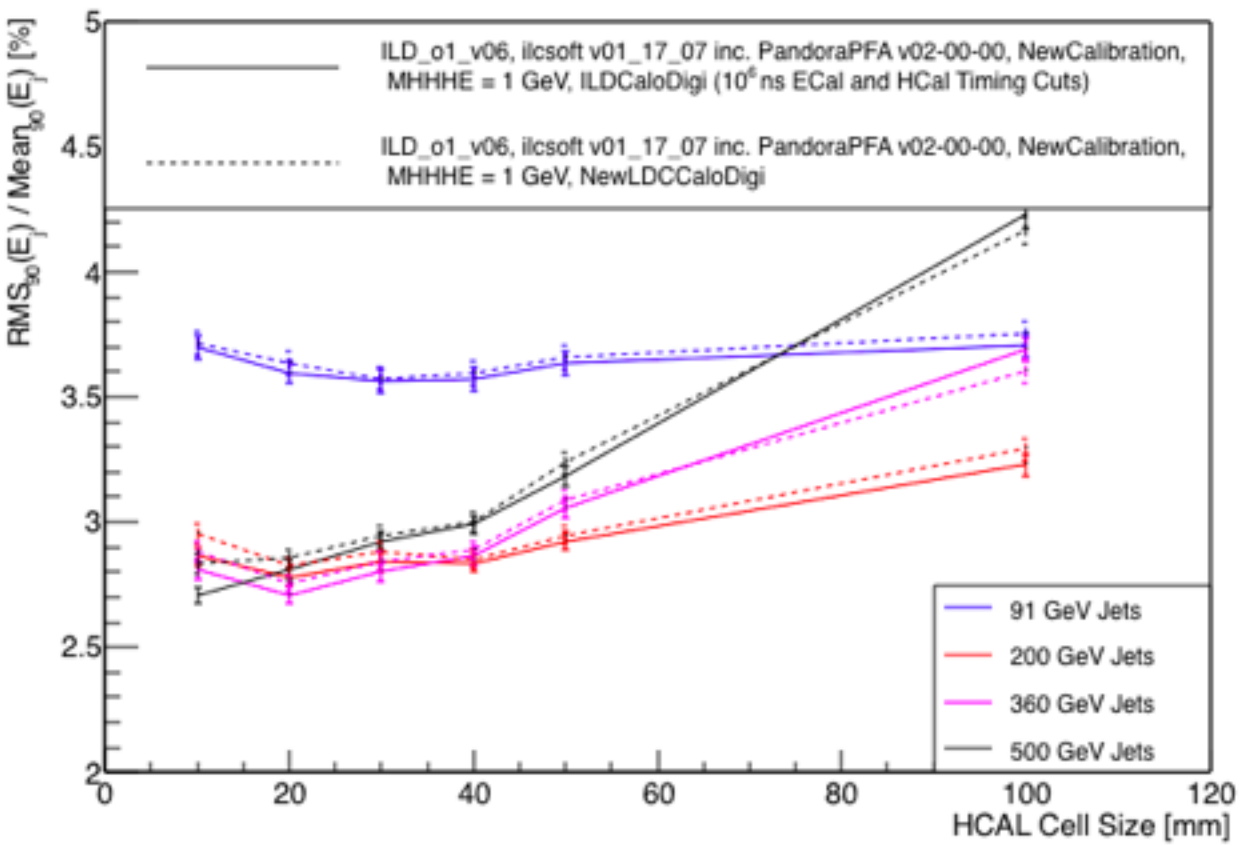


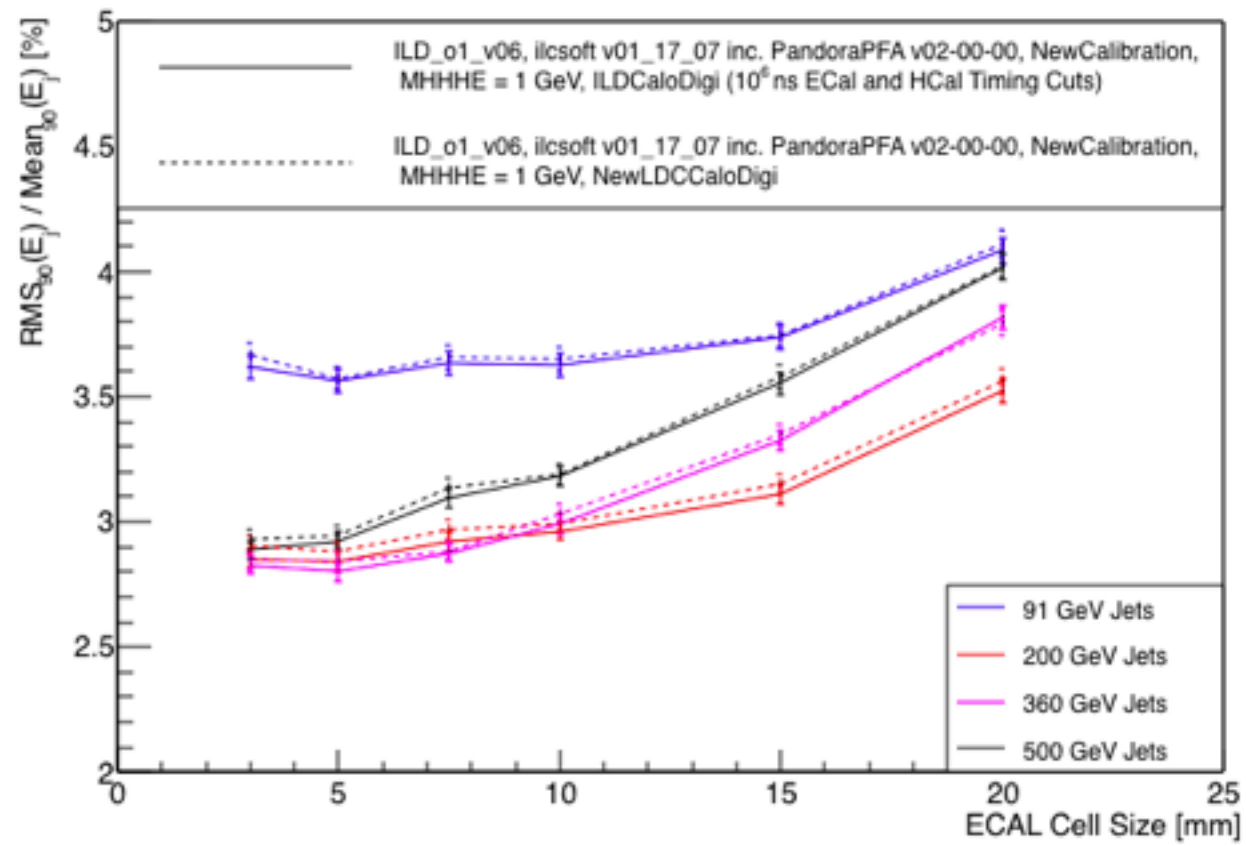
Hadronic energy truncation in PandoraPFA is 1 GeV.

* Slight performance difference. Most likely from grouping of SimCalorimeterHits differences.
* ILDCaloDigi performs slightly better than NewLDCCaloDigi.

NewLDCCaloDigi vs ILDCaloDigi

Look at the non default detector models…





Hadronic energy truncation in PandoraPFA is 1 GeV.

- No significant changes when moving from NewLDCCaloDigi to ILDCaloDigi.

- ☑ Should use ILDCaloDigi in latest studies as it has more added functionality e.g. timing cuts can be applied.

Realistic Digitisation in ILDCaloDigi

* Thanks to the efforts of Daniel Jeans, Oskar Hartbrich and Katsu Coterra et al. the ILDCaloDigi processor has a number of realistic options.

* The realistic digitisation of the calorimeters allows for simulation of mis-calibration, limited dynamic ranges in readout technology and signal fluctuations.

* The effects that we were advised to simulate were the electronics read out range and the electrical noise. The read out range is determined in MIP units this required modification of the calibration procedure.

* The realistic digitisation of the ECal was applied to the silicon ECal we have been using in the studies, however, there is also a realistic ECal scintillator option that can be used.

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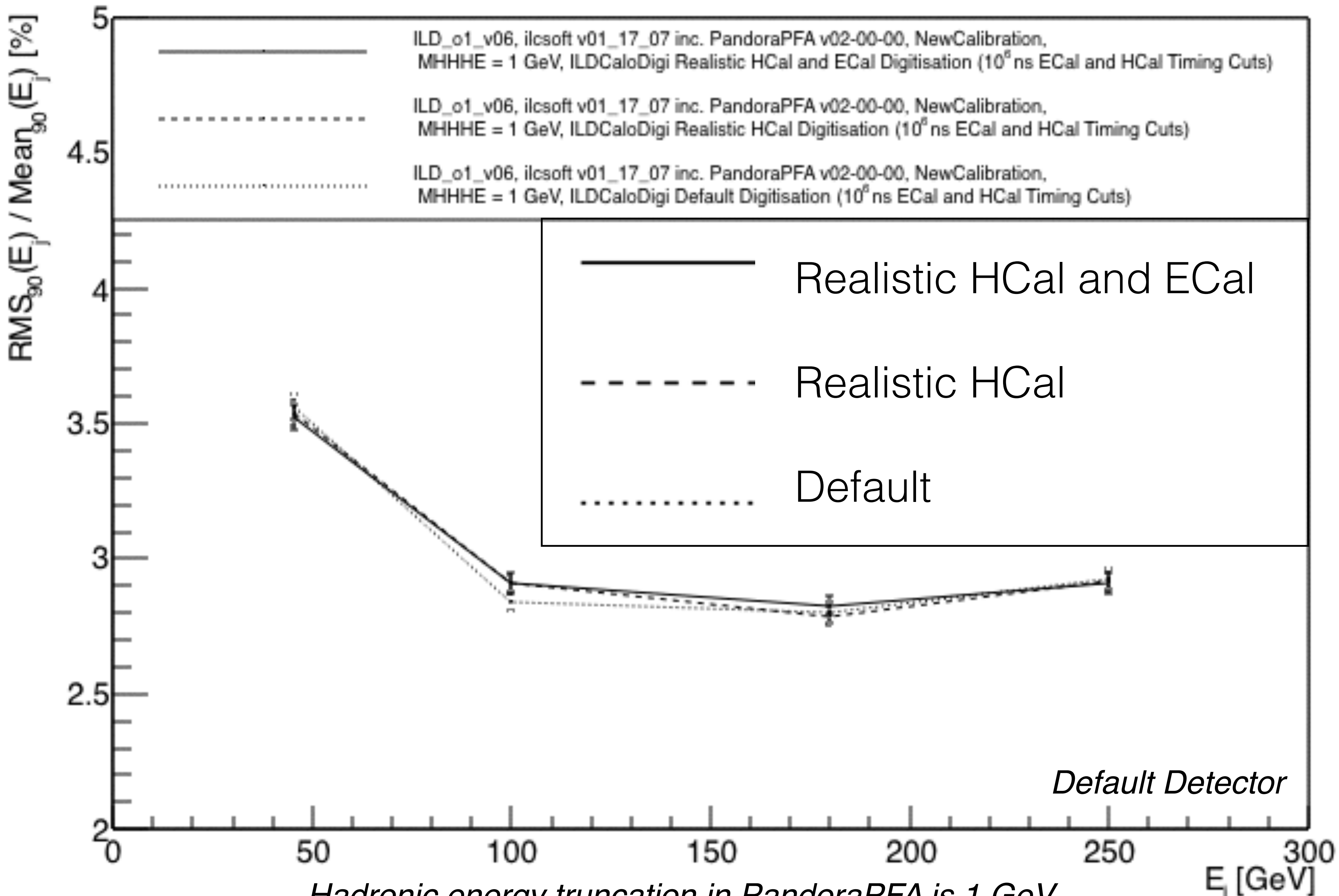
Realistic Digitisation in ILDCaloDigi

- Comparing the default digitisation in ILDCaloDigi with the realistic HCal option and the realistic ECal and HCal option.



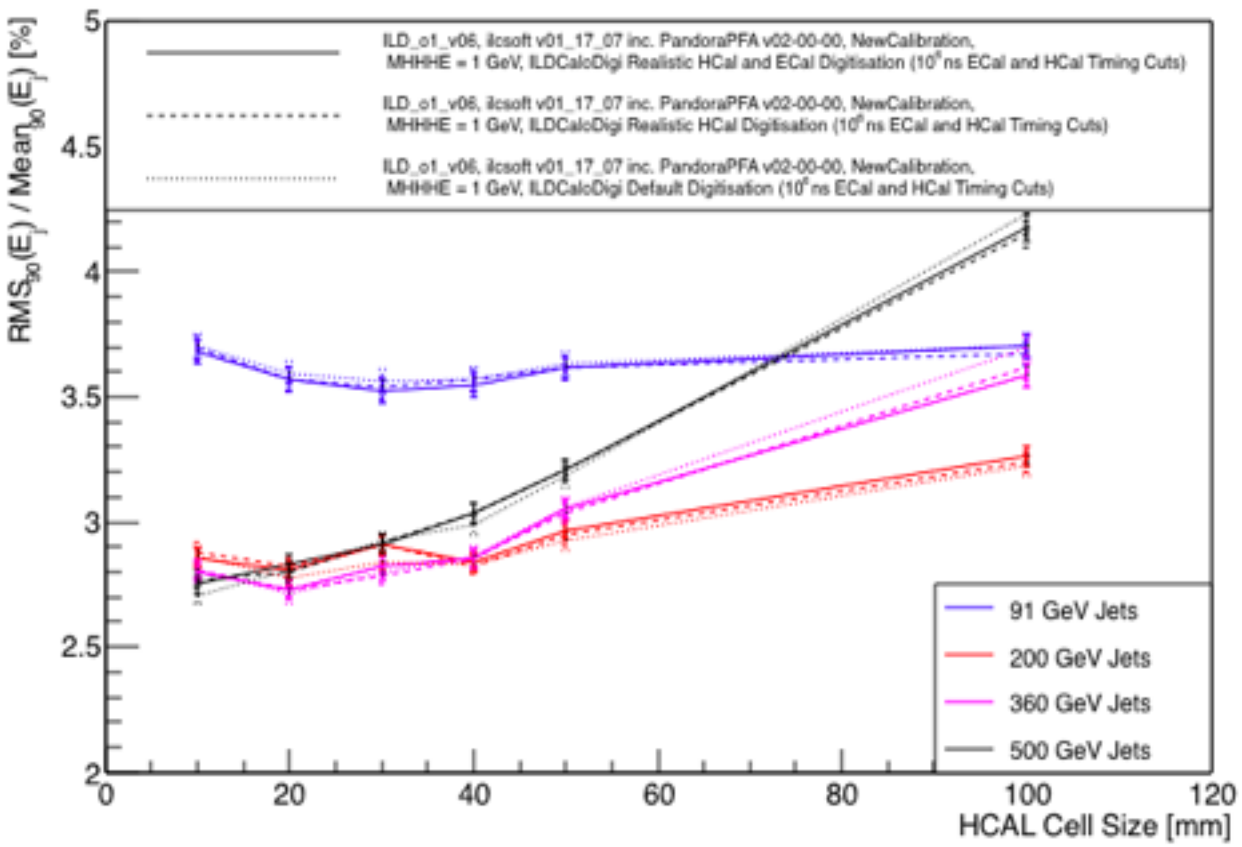
Hadronic energy truncation in PandoraPFA is 1 GeV.

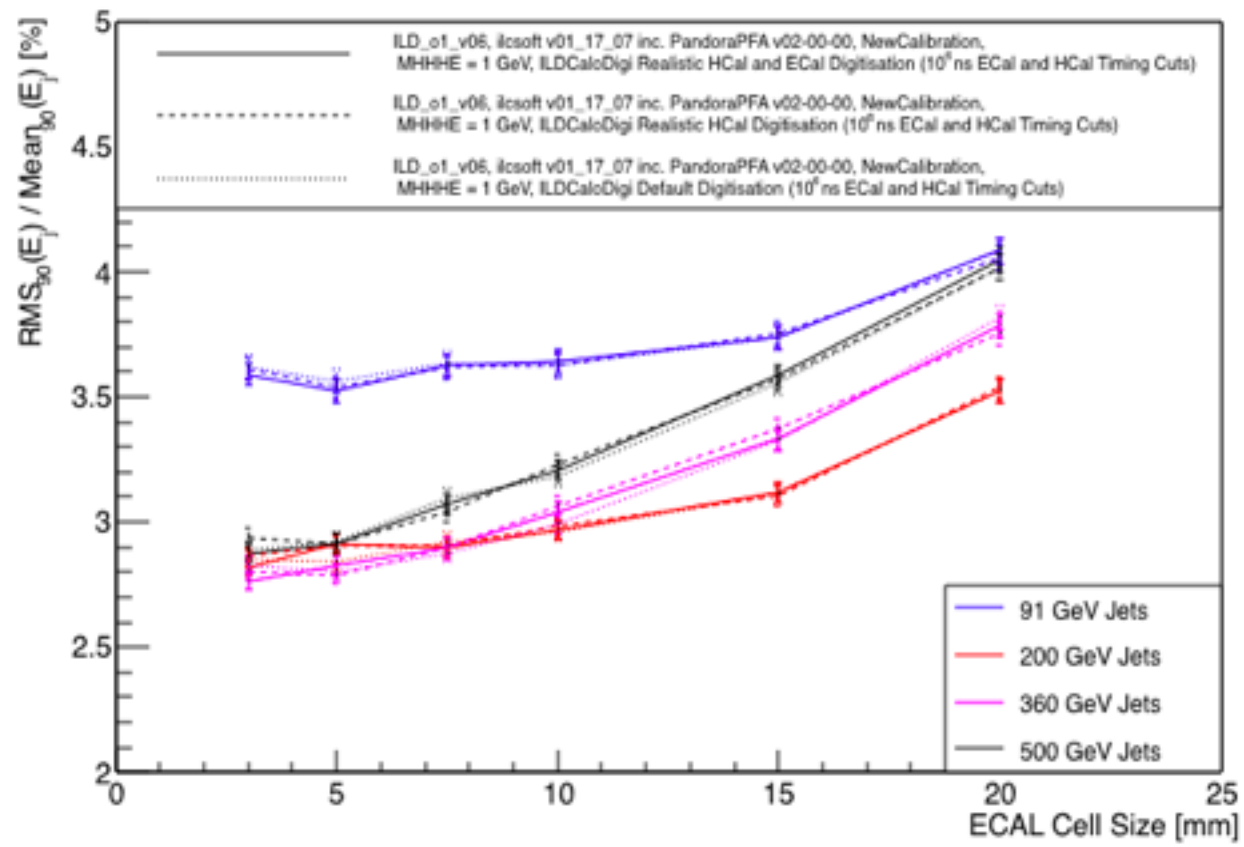
- Consistent performance between all digitisation options.

Thanks to D. Jeans, O. Hartbrich and K. Coterra et al

Realistic Digitisation in ILDCaloDigi

Look at the non default detector models…





Hadronic energy truncation in PandoraPFA is 1 GeV.

- We find consistent performance between ILDCaloDigi digitisation options for this energy truncation also.

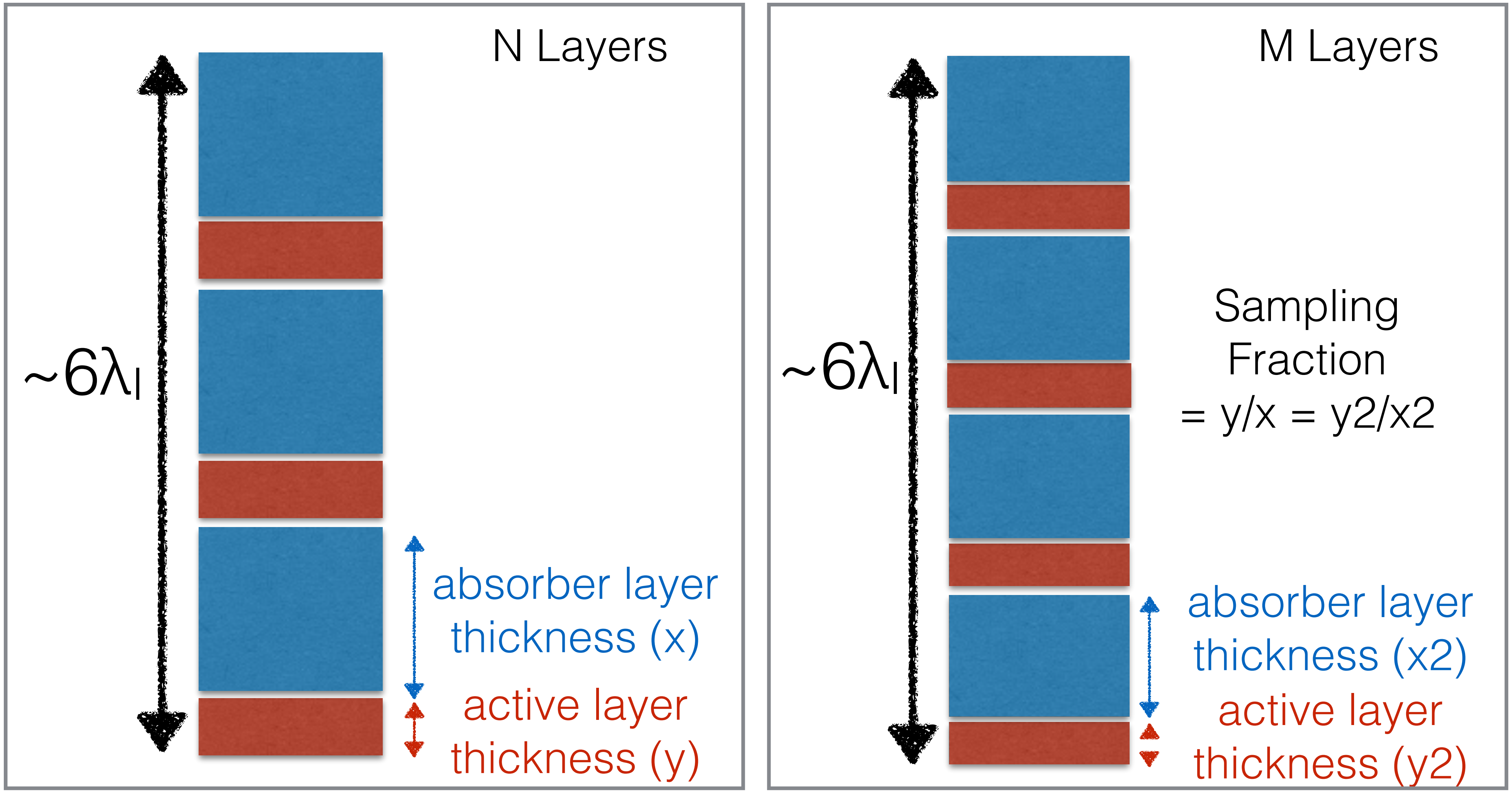
☑ Evidence to suggest we should be using the realistic ECal and HCal options for further studies.

———	Realistic HCal and ECal
- - - - - -	Realistic HCal
··········	Default

Optimisation of HCal

Number of HCal Layers

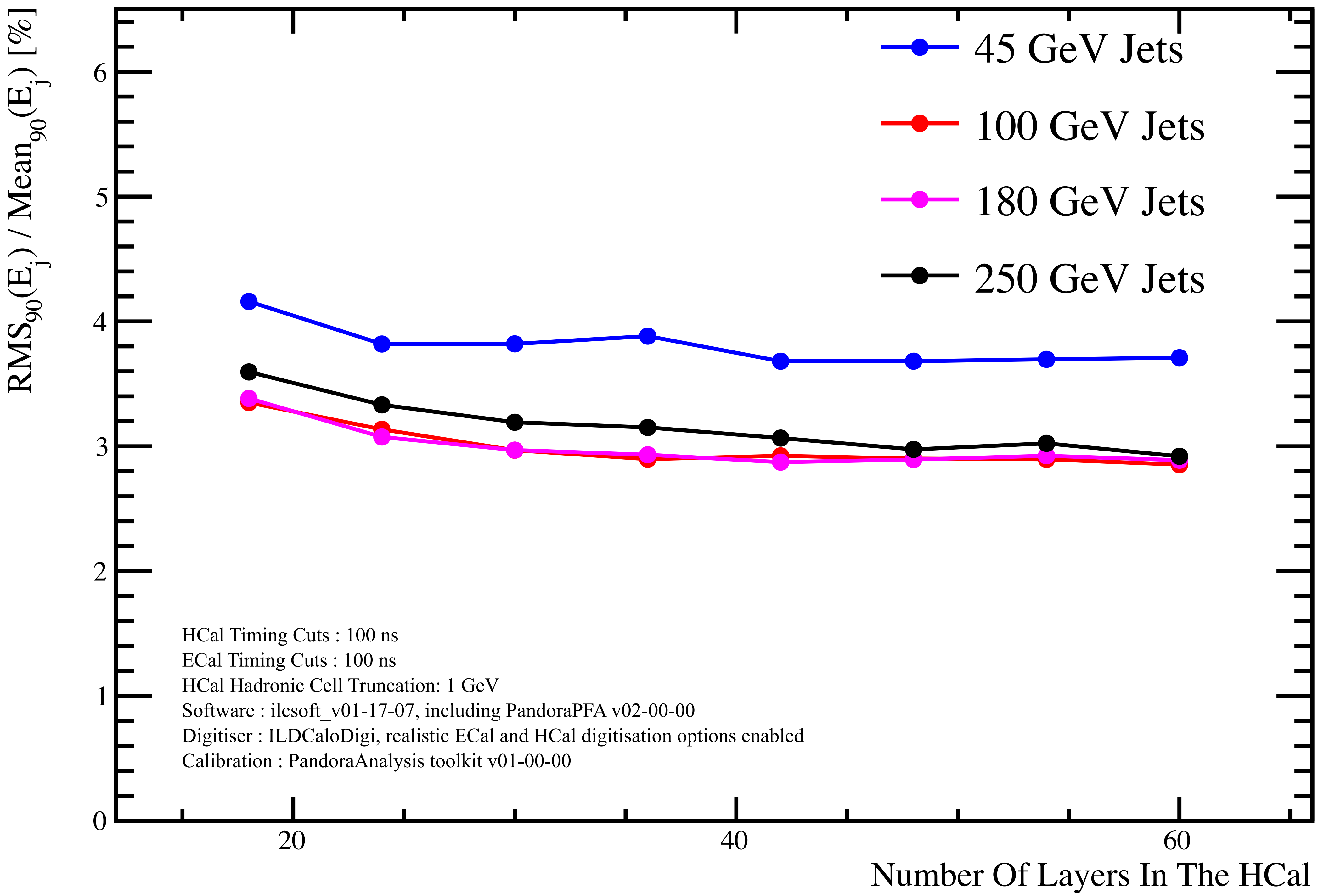
- Here we wish to consider varying the total number of layers in the HCal.
- However, we do not want to implicitly vary either the total number of interaction lengths or the sample fraction when varying this study:



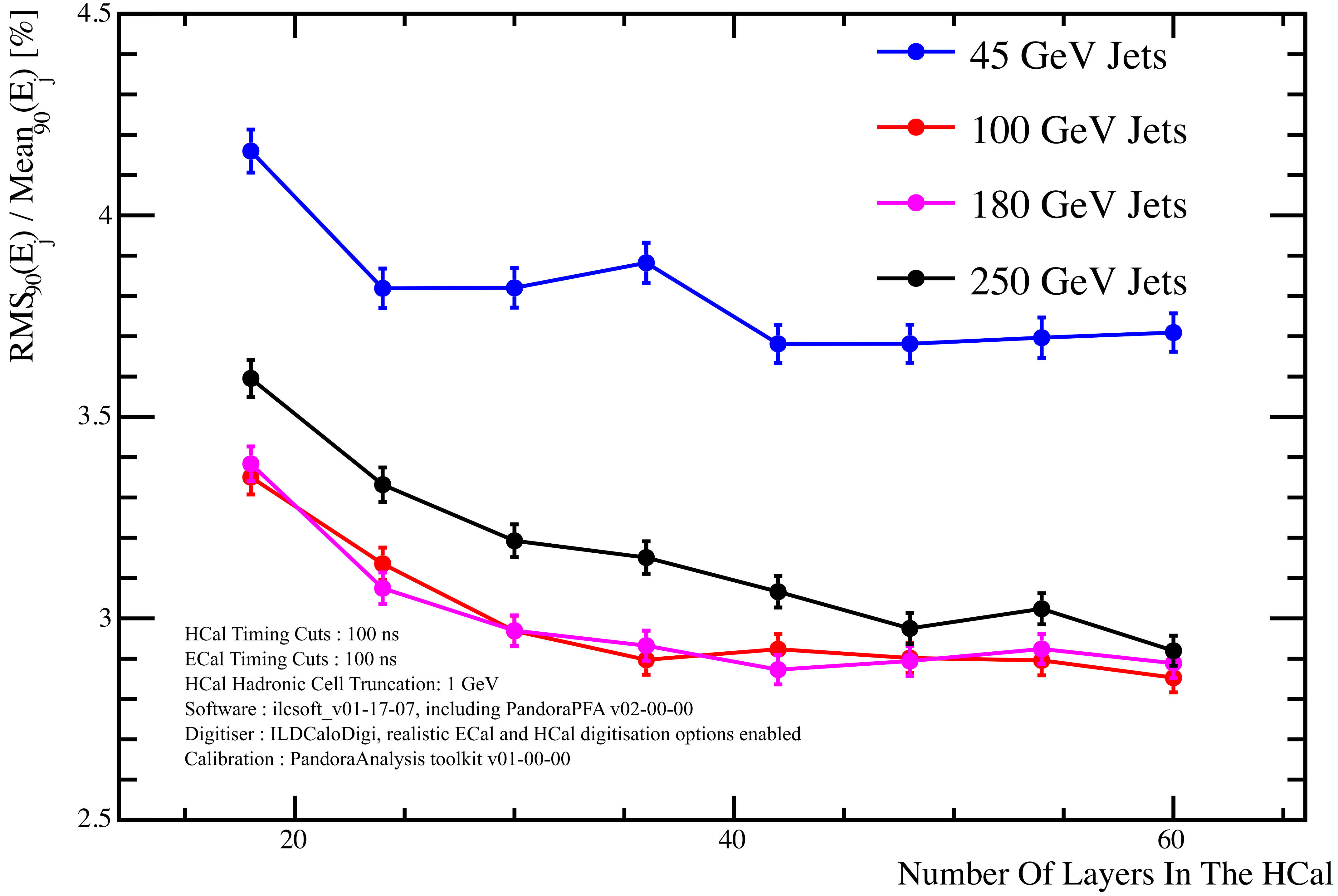
Cartoon showing effect of changing number of HCal layers

- The number of nuclear interaction lengths and the ratio of the absorber layers thicknesses to the active layer thicknesses is **unchanged** in this study.

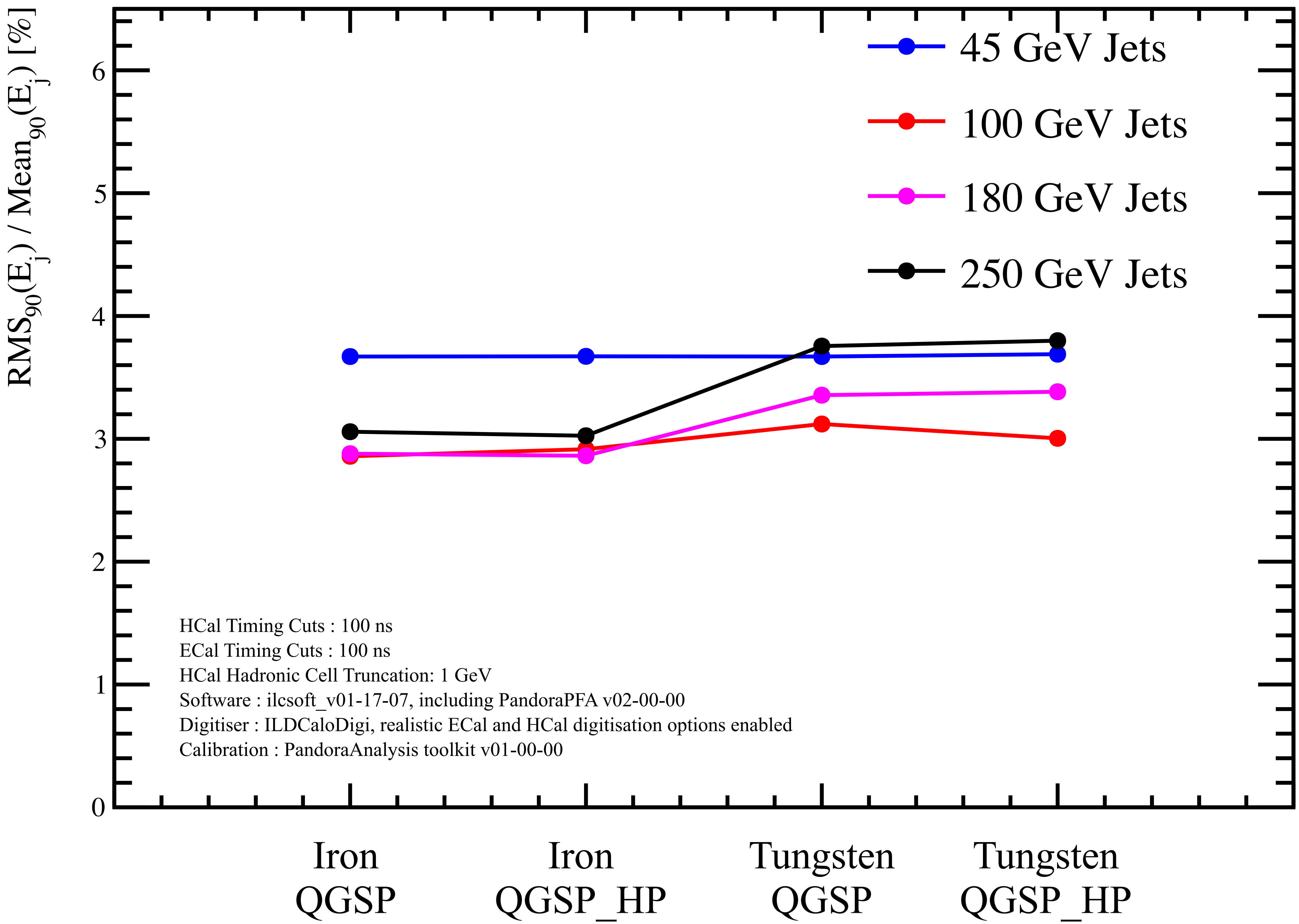
Number of HCal Layers



Number of HCal Layers

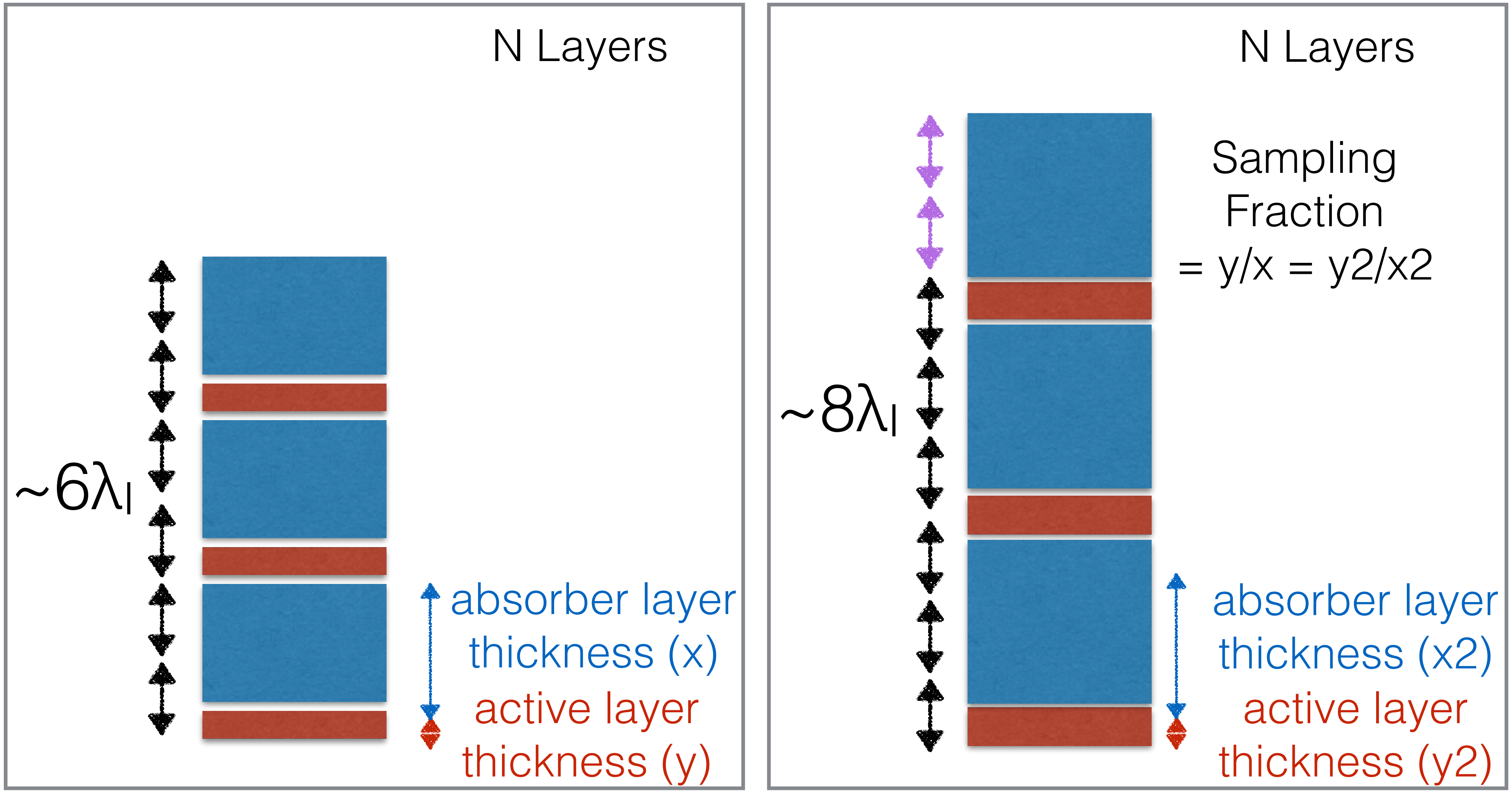


HCal Absorber Material



Number of Interaction Lengths in the HCal

* Here we wish to consider varying the total number of nuclear interaction in the HCal.
* However, we do not want to implicitly vary either the number of layers in the HCal or the sample fraction when varying this study:



* The number of nuclear interaction lengths and the ratio of the absorber layers thicknesses to the active layer thicknesses is **unchanged** in this study.

Cartoon showing effect of changing number of nuclear interaction lengths in the HCal

Number of Interaction Lengths in the HCal

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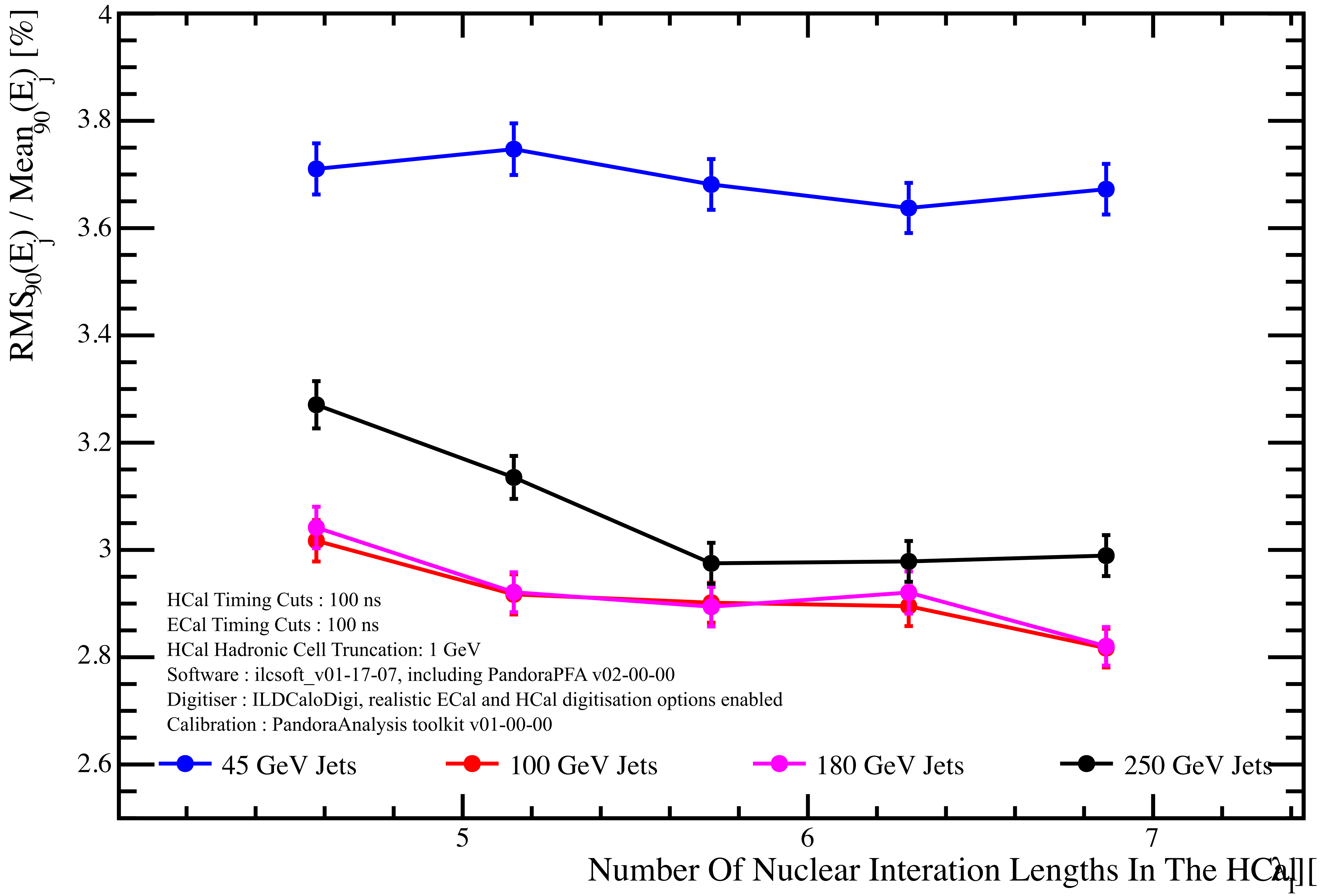
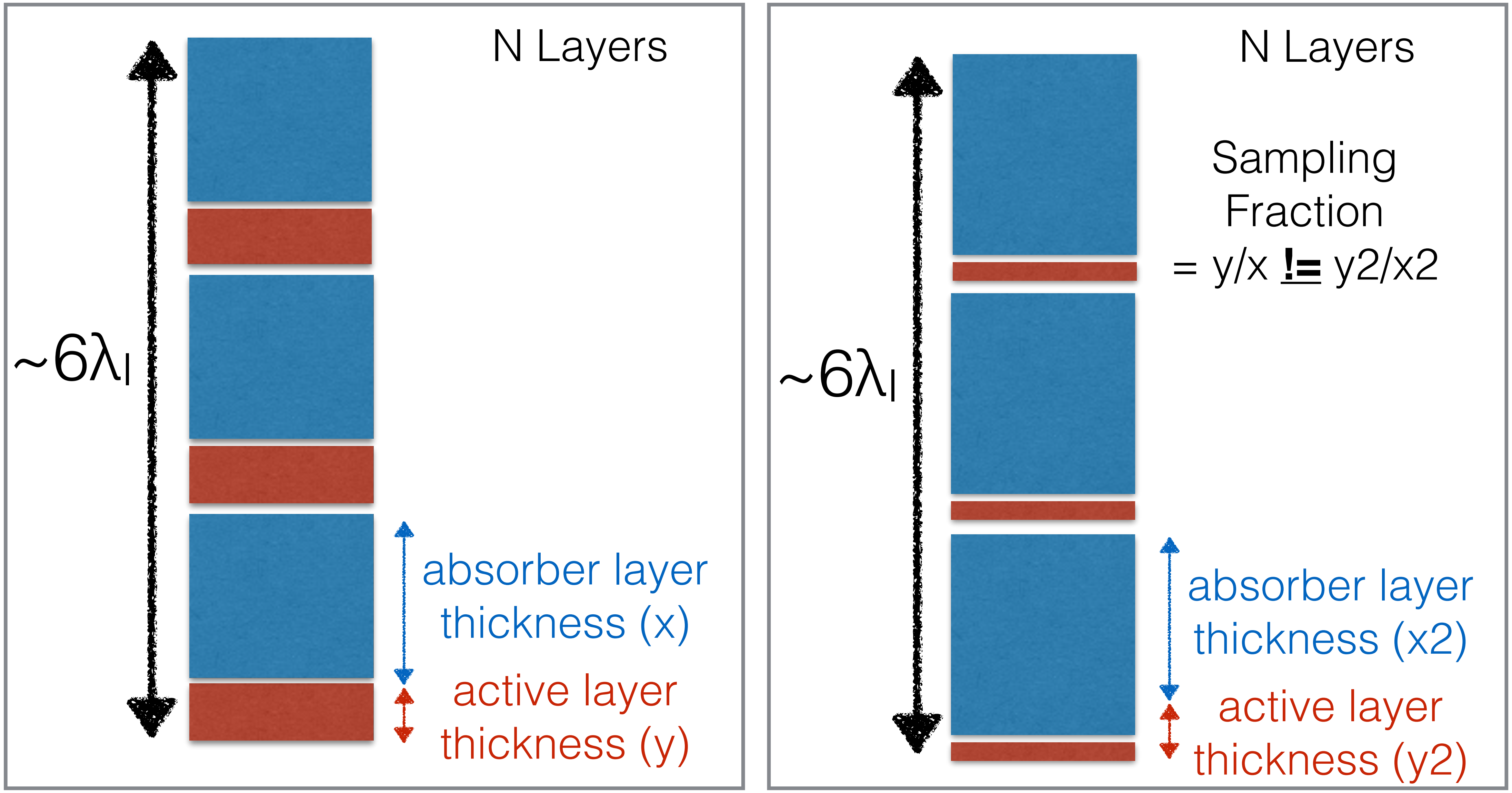


Sampling Fraction in the HCal

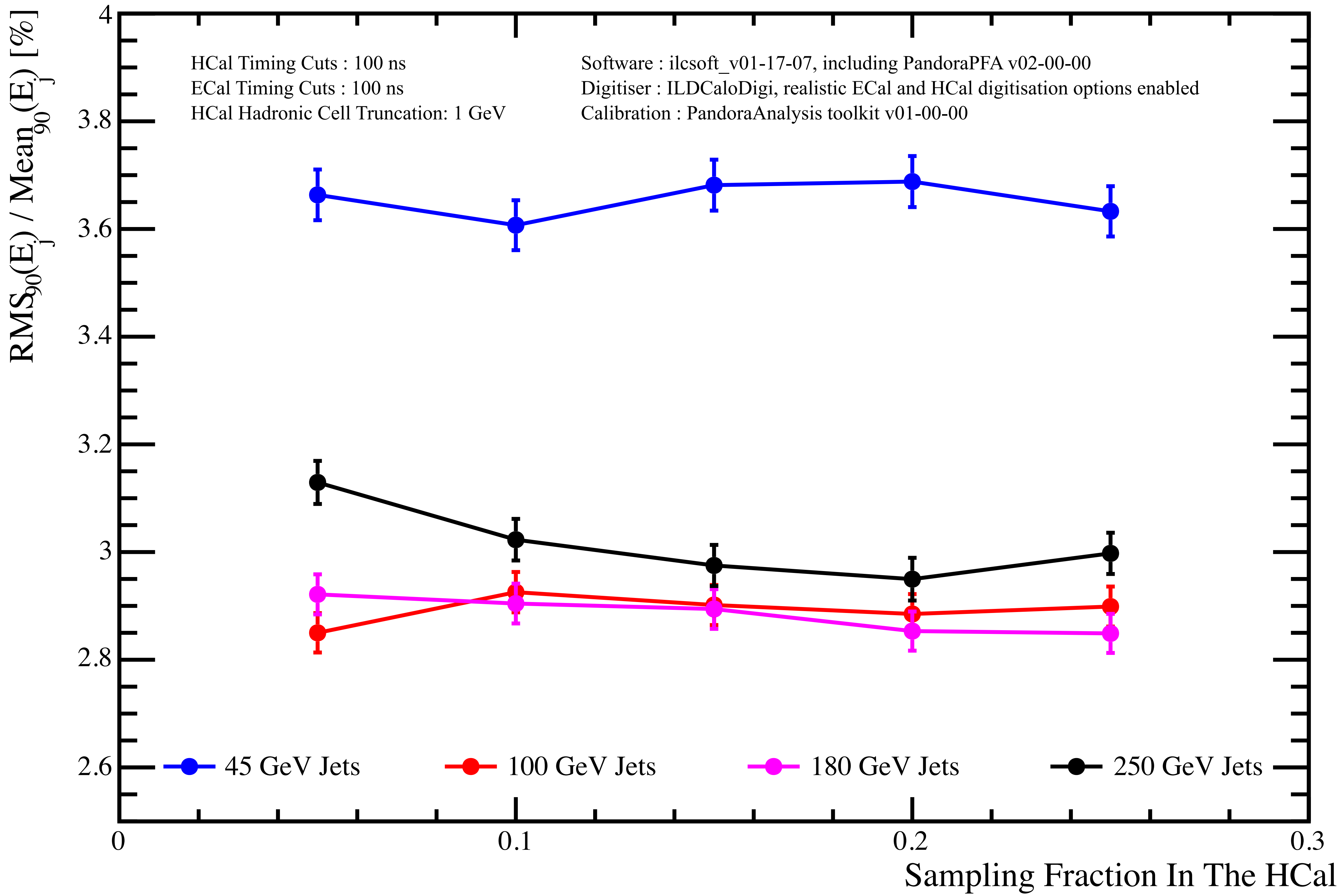
- Here we wish to consider varying the sampling fraction in the HCal.
- However, we do not want to implicitly vary either the number of layers or the number of nuclear interaction lengths in the HCal this study:



Cartoon showing effect of changing number of nuclear interaction lengths in the HCal

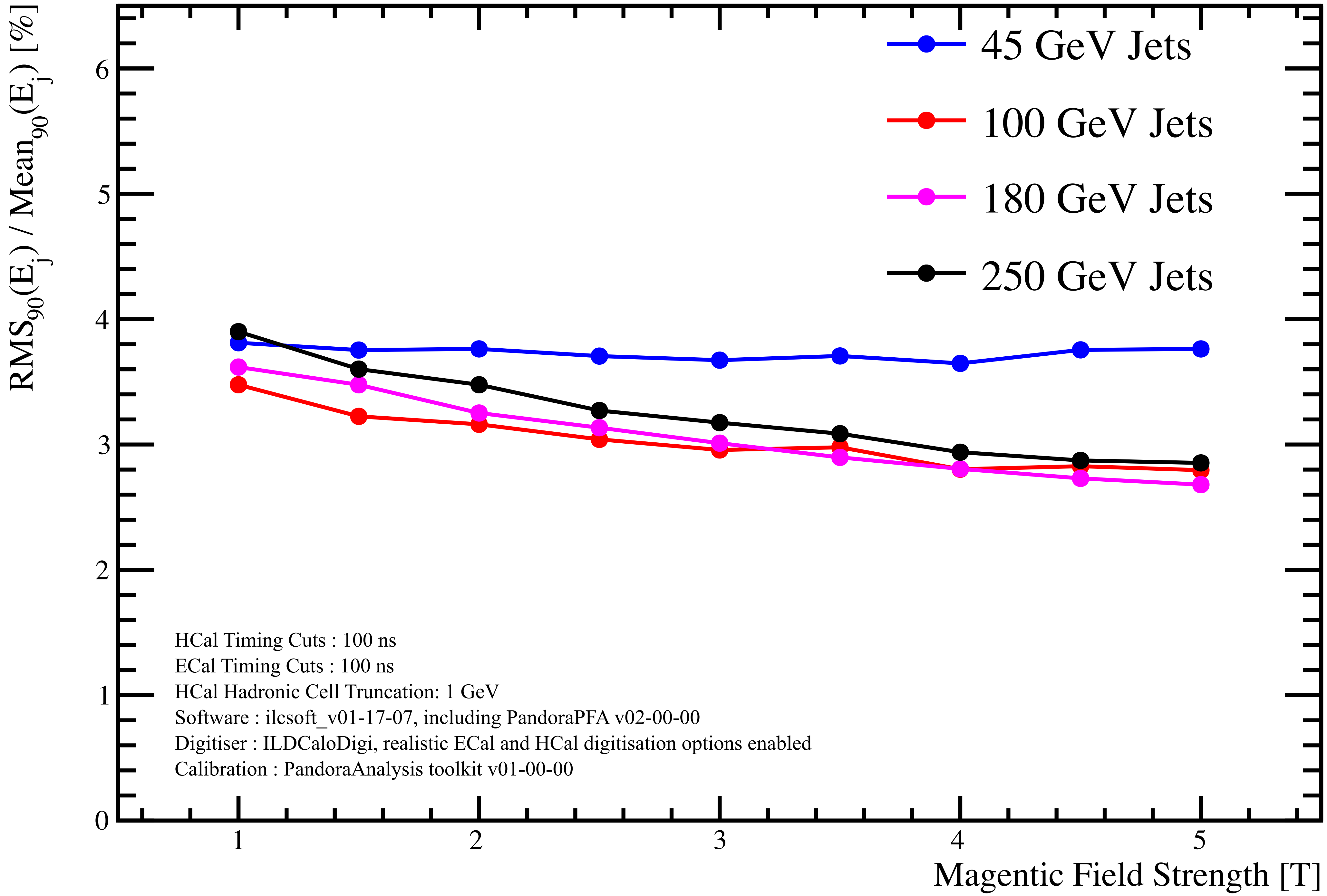
- The number of nuclear interaction lengths and the ratio of the absorber layers thicknesses to the active layer thicknesses is **unchanged** in this study.

Sampling Fraction in the HCal



Optimisation of Global Parameters

B Field



45 GeV Jets
100 GeV Jets
180 GeV Jets
250 GeV Jets
HCal Timing Cuts : 100 ns
ECal Timing Cuts : 100 ns
HCal Hadronic Cell Truncation: 1 GeV
Software : ilcsoft_v01-17-07, including PandoraPFA v02-00-00
Digitiser : ILDCaloDigi, realistic ECal and HCal digitisation options enabled
Calibration : PandoraAnalysis toolkit v01-00-00
RMS90(Ej) / Mean90(Ej) [%]
Magentic Field Strength [T]

ECal Inner Radius