Simulation Studies for a Highly Granular Calorimeter in DUNE.

CALICE Collaboration meeting Utrecht

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DESY
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DEEP UNDERGROUND NEUTRINO EXPERIMENT

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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Max-Planck-Institut für Physik
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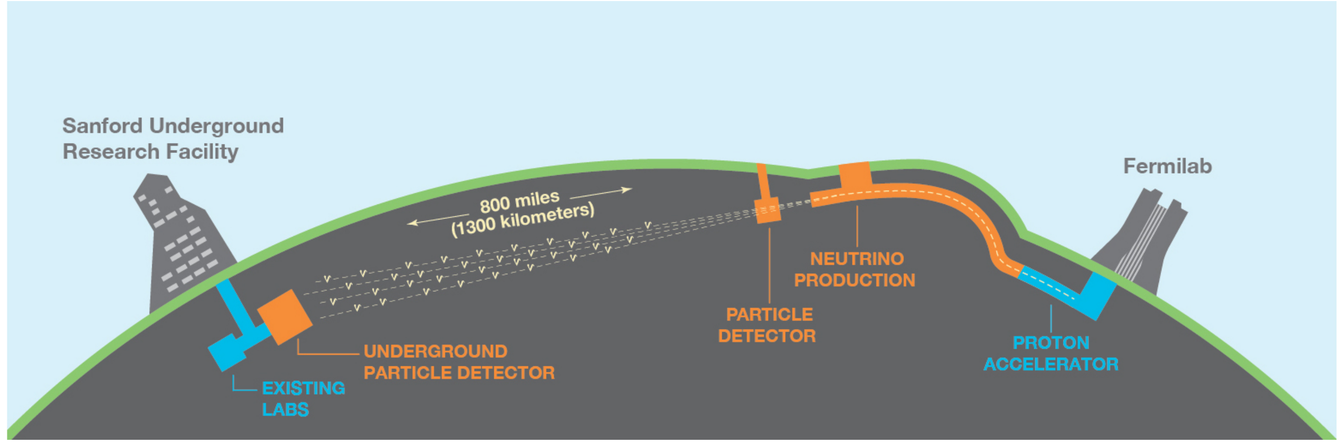
Outline.

1. The DUNE experiment
2. Optimisation studies
3. Neutron energy reconstruction
4. Outlook and Conclusion

The DUNE experiment.

A neutrino experiment

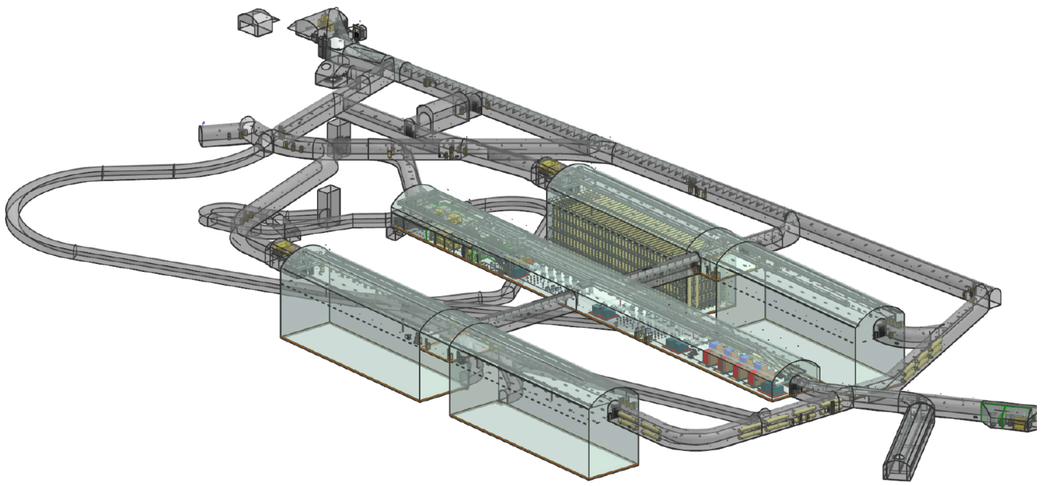


The experiment

- Observe and measure lepton CP violation
- Determine the neutrino mass hierarchy
- Study neutrinos from supernovas
- Search for proton decay

The detectors

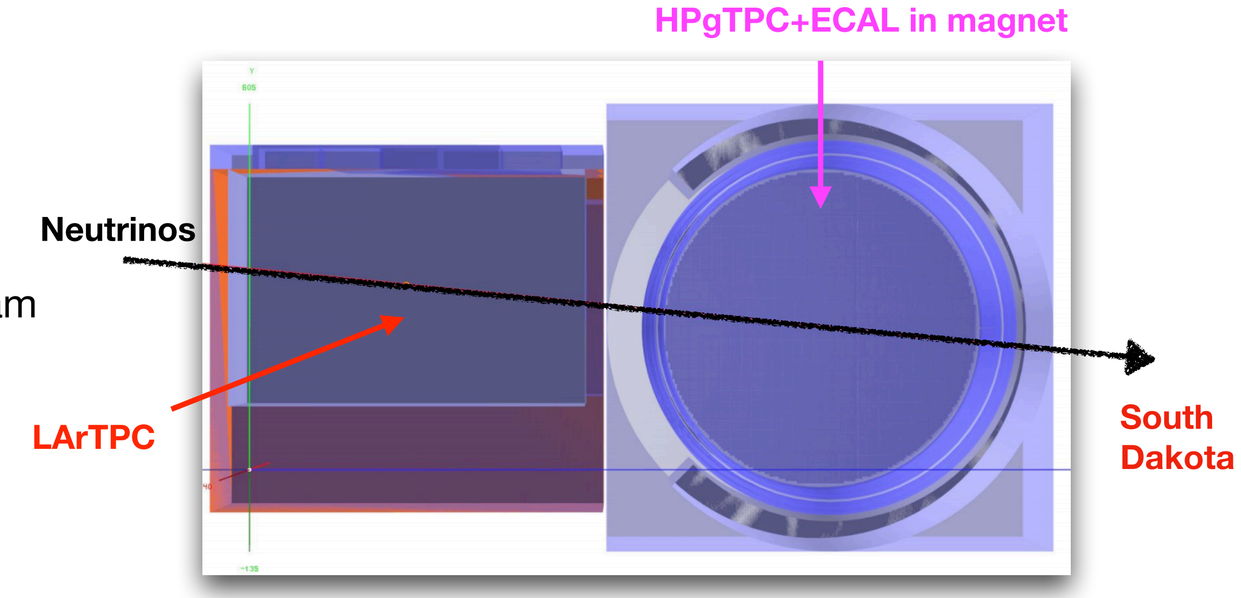
- Far detector (observe neutrino oscillations)
  - ~4 x 10 kT LAr TPC (single/dual phase)
  - ➠ Prototypes (ProtoDUNE) running at CERN
  - 1300 km baseline
- Near detector
  - LAr TPC + Magnetized multi-purpose detector (HPgTPC + ECAL)
  - Concept and technologies still under studies

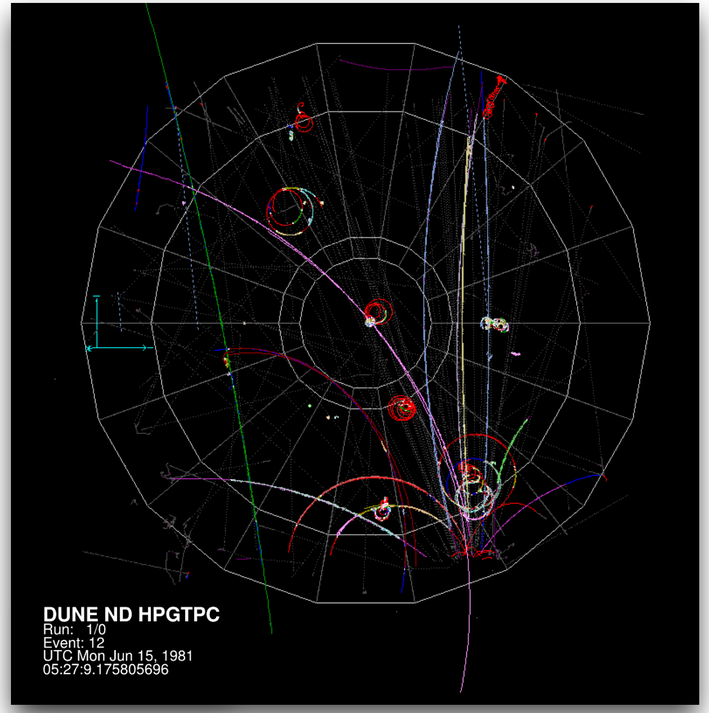


The goals for the ND ECAL.

Physics requirements

- **The role of the ND** is to provide constraints on systematics: beam energy spectrum, beam composition, model ν-Ar interactions…
  - ➠ Rich physics potential!
- **The role of the ECAL**
  - Primarily needed to reconstruct photons / electrons (identify neutral pions and electrons from NC, CC events)
    - ➠ Good ***energy resolution*** needed over a broad range of energies from few MeV to few GeV
  - Reconstruction of the π^0 energy and association to decay vertex
    - ➠ ***Angular resolution***
  - Identification of neutrons coming from ν-Ar interactions
    - ➠ ***Precise timing*** for ToF measurement
  - Help in **background rejection** (reject events outside the TPC/ coming from the ECAL)
  - Additional: Particle catcher + muon id/tracker for the LArTPC
- ➠ **A case for a highly granular ECAL!**





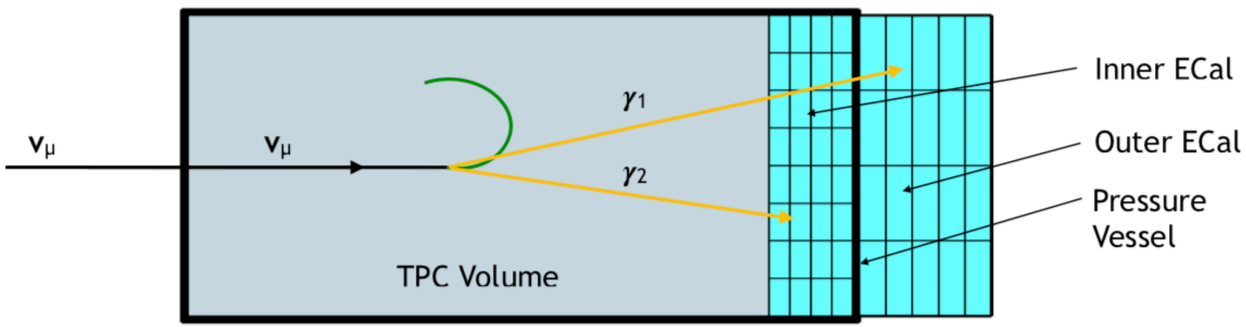
10 nu-interaction per spill (~x4 more than expected)

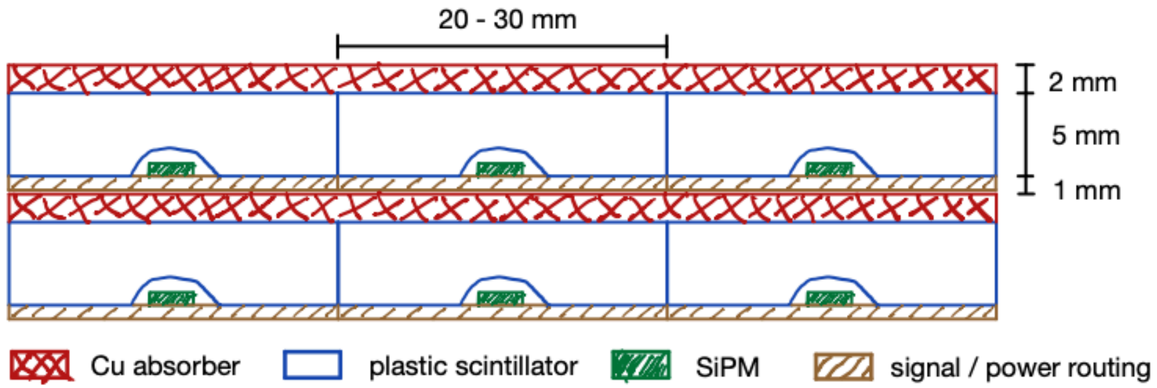
Optimisation studies.

Previous Studies.

First detector concept

- **First simulation studies** have been done at MPP/Mainz in the last years *(Lorenz Emberger/Jan Schaeffer)*
- First rough concept implemented in Geant4
  - Sampling calorimeter based:
    1.8 mm Pb absorber + 1 cm plastic scintillator
- Studies of calorimeter performance
  - **2D/3D segmentation** of the active material
    ➠ study of the benefits of granularity
  - **Influence of the absorber** material, thickness
  - **Influence of the pressure vessel**
  - **Neutral pion** identification and vertex reconstruction
  - **Neutron detection** efficiency
- Provided first **understanding** of the capabilities of such concept and dependency of the performance on some parameters
- -> See Lorenz's CALOR talk: https://indico.cern.ch/event/642256/contributions/2958338/attachments/1653183/2645330/DUNE_ECAL_CALOR.pdf

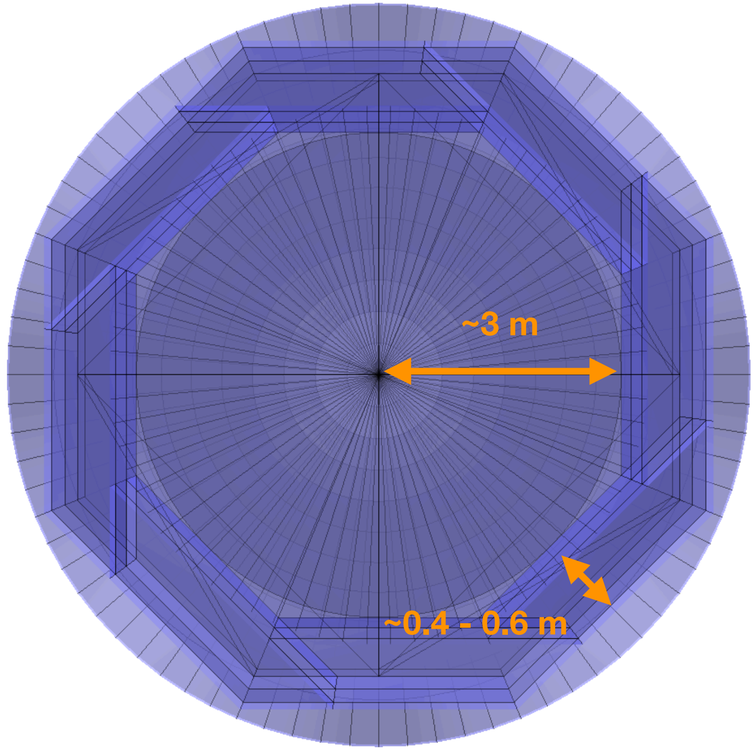


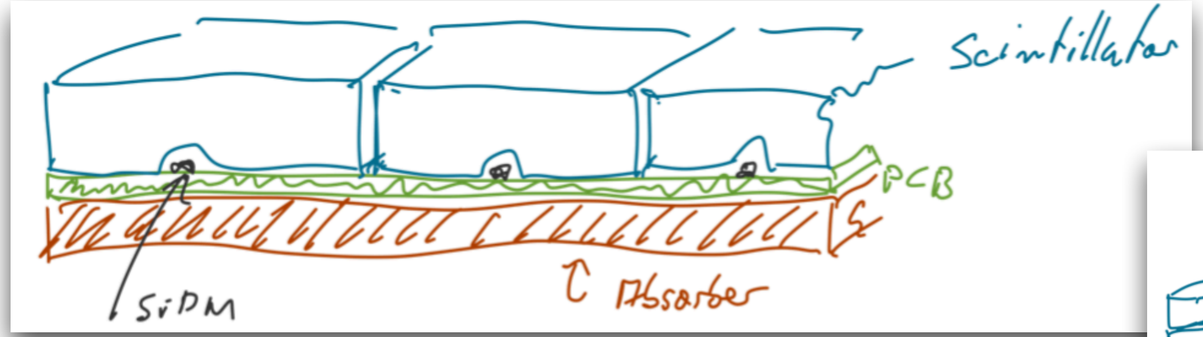


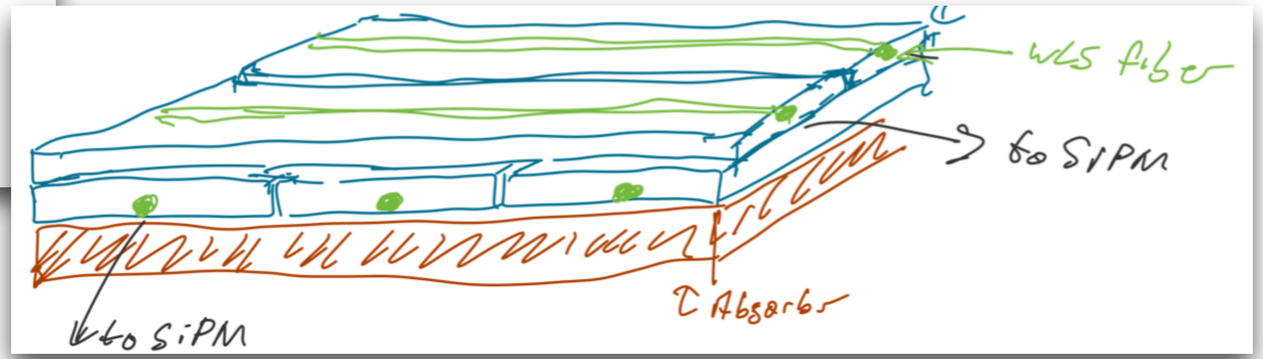
Towards a more realistic detector.

Geometry and integration with GArSoft

- Need to integrate into a **common software framework** ➠ GArSoft (software developed for HPgTPC based on LArTPC software)
- More *realistic ECAL* geometry (cubic ➠ octagonal)
- Full granularity ➠ *excessive channel count* ➠ not necessary (shown in former study)
    - **Combine** high granularity layers (HG) using SiPM-on-tile and low granularity layers with strips (LG) - crossed on same layer or every consecutive layer







Optimisation goals.

Taking into account the physics

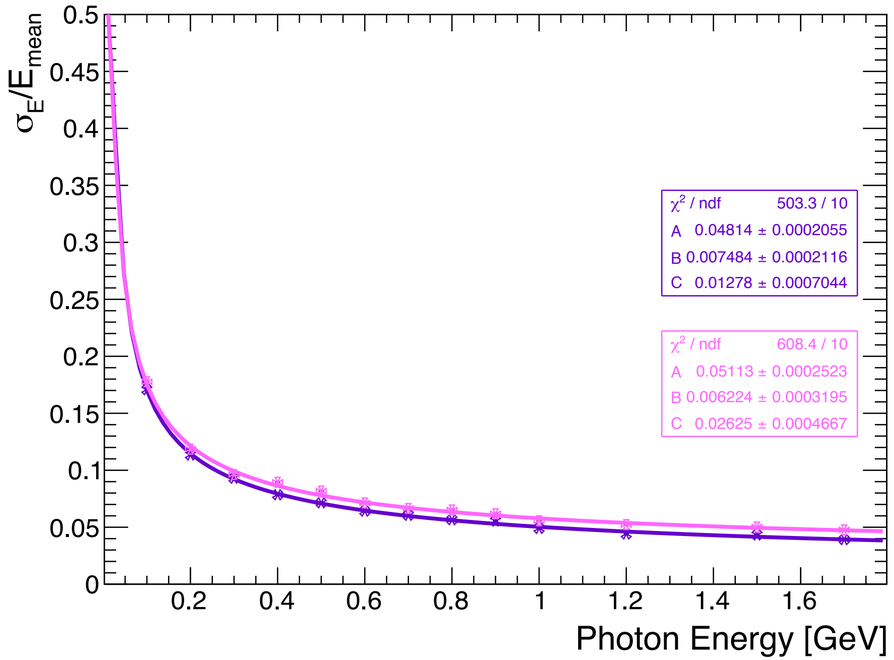
- **Goals**:
  - Optimisation of the overall design guided by former results
  - Optimisation of the **cost**: absorber/scintillator material, channel count.. etc…
  - Main design driver ➠ **calorimeter energy resolution**, **angular resolution, neutron detection!**
- **Design (inside pressure vessel)**:
  - **Setup A** (light pink) → 80 HG, 5 mm tile ➠ **sanity check with Lorenz Emberger's results (fully granular ECAL)**
  - **Setup B** (purple) → 8 HG, 5 mm tile + 97 LG, 2 mm Cu, cross-layers, 5 mm Sc ➠ **Granularity for the back layers**
  - **Setup C** (red) → 8 HG + 47 LG (HG: 2mm Cu/LG: 4 mm Cu), cross-strips, 10 mm Sc ➠ **Sc/absorber thickness**
  - **Setup D** (blue) → 8 HG + 12 LG, 2 mm Cu + 35 LG, 4 mm Cu, 10 mm Sc ➠ **thinner absorber in front layers**
  - **Setup E** (green) → 8 HG, 10 mm Sc + 92 LG, 2 mm Cu, cross-layers, 5 mm Sc ➠ **thinner absorber for LG layers**
  - **Setup F** (orange) → 8 HG, 3 mm tile + 100 LG, 2 mm Cu, cross-layers, 5 mm Sc ➠ **thinner HG tile**

Color index used as legend for the following plots

Simulation studies.

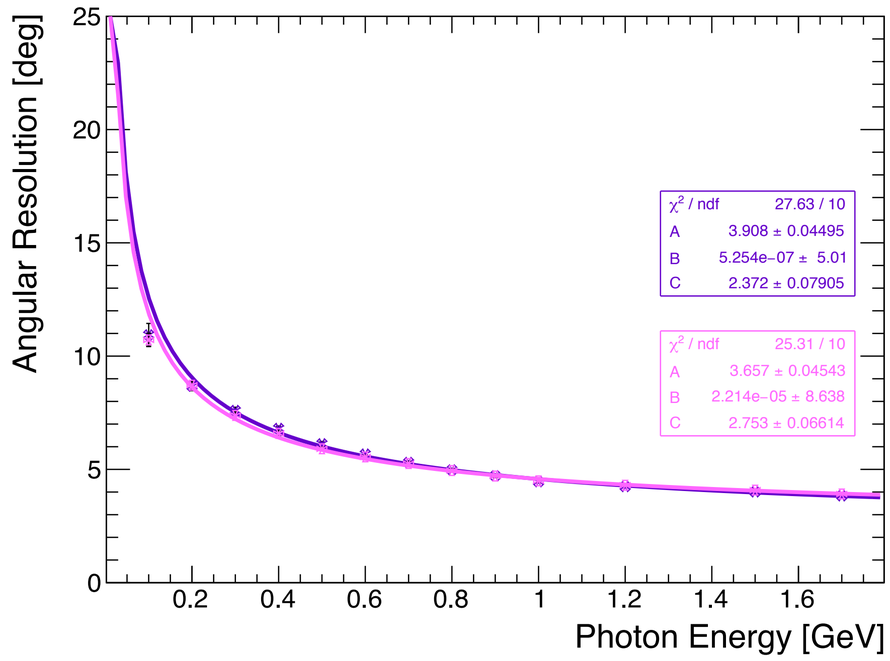
Influence of the granularity

- Change of the granularity of the back layers
- Using strips with WLS crossed perpendicularly between layers



Setup B (8 HG + 97 LG)

Setup A (full granularity)



Setup B (8 HG + 97 LG)

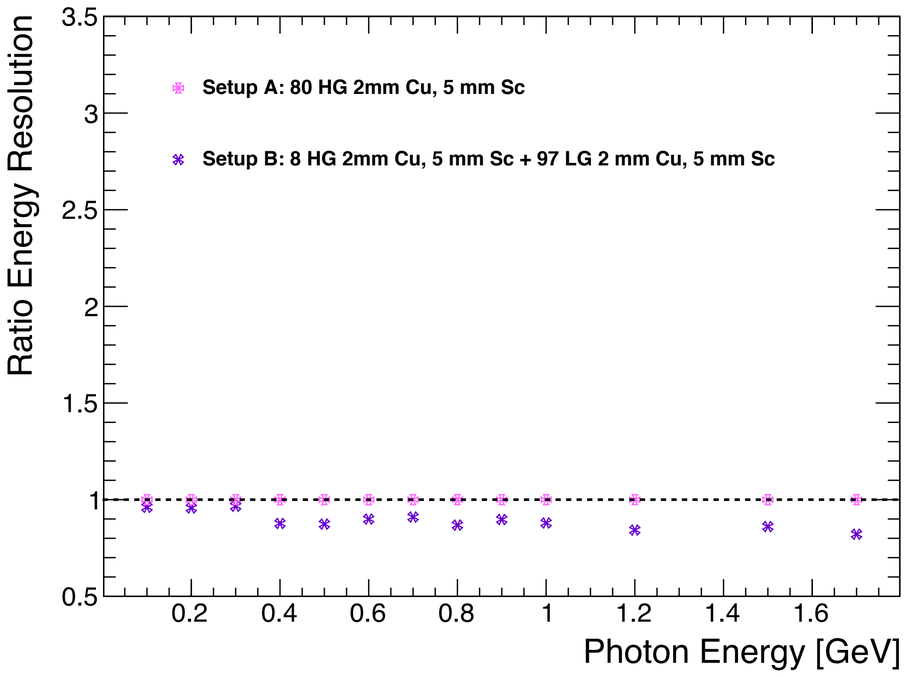
Setup A (full granularity)

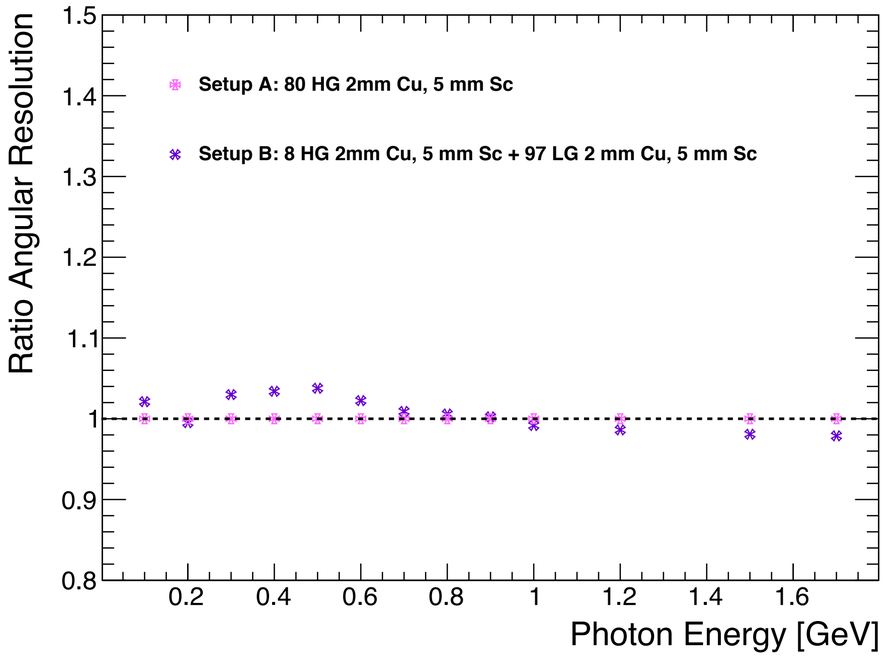
Simulation studies.

Influence of the granularity

- Change of the granularity of the back layers
- Using strips with WLS crossed perpendicularly between layers

- Slight improvement of the energy resolution ~5-10% → more layers → less leakage
- Angular resolution not much affected (~2%) by using strips instead of tiles ➠ viable option to reduce channel count!

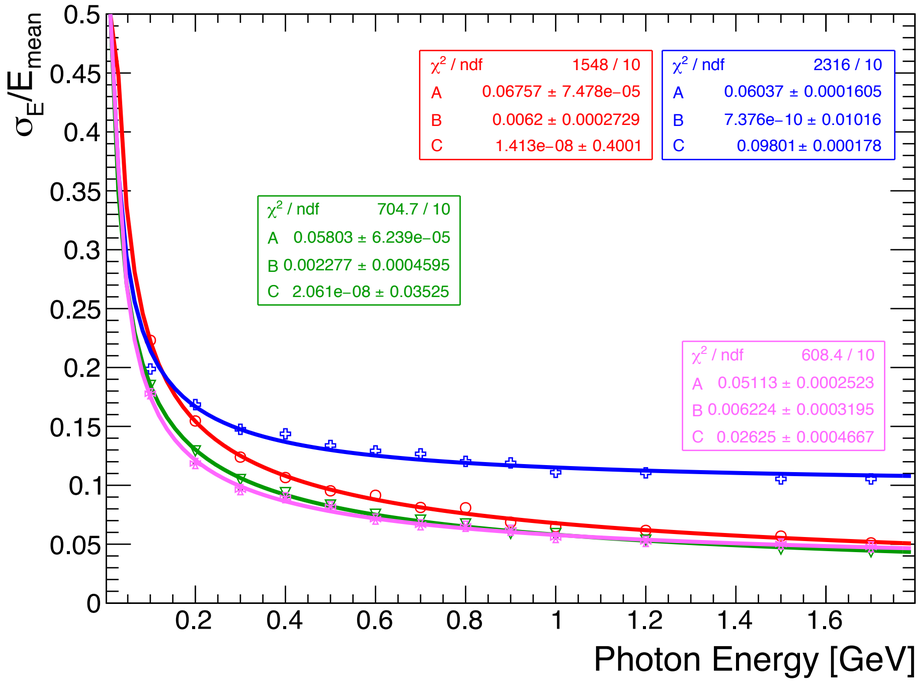




Simulation studies.

Influence of the absorber thickness

- Change of the absorber thickness
  - 2 mm Cu for HG layers
  - 2/4 mm Cu for LG layers

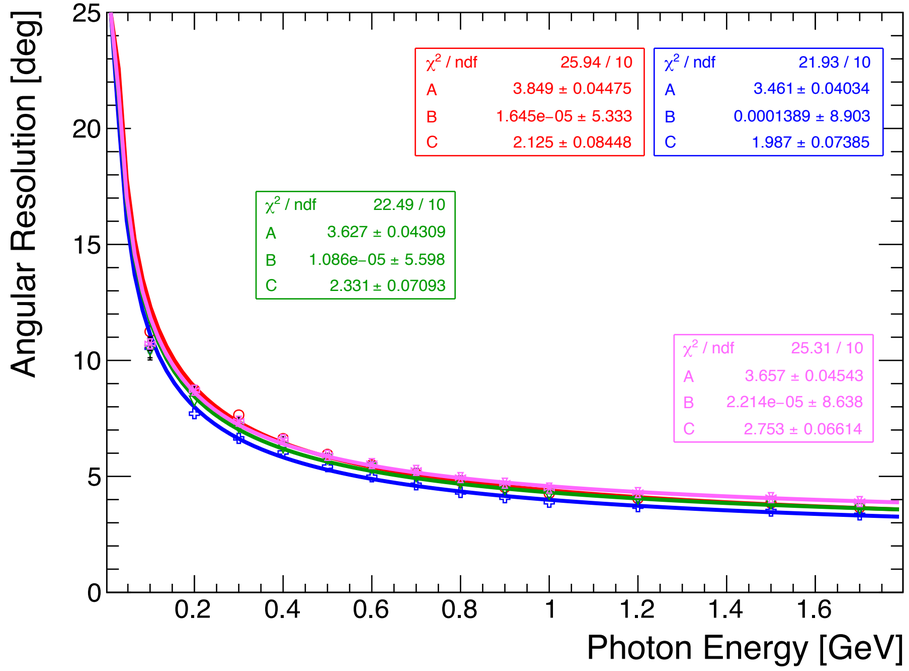


Setup A (2 mm Cu)

Setup C (2 + 4 mm Cu)

Setup D (2 + 4 mm Cu)

Setup E (2 mm Cu)



Setup A (2 mm Cu)

Setup C (2 + 4 mm Cu)

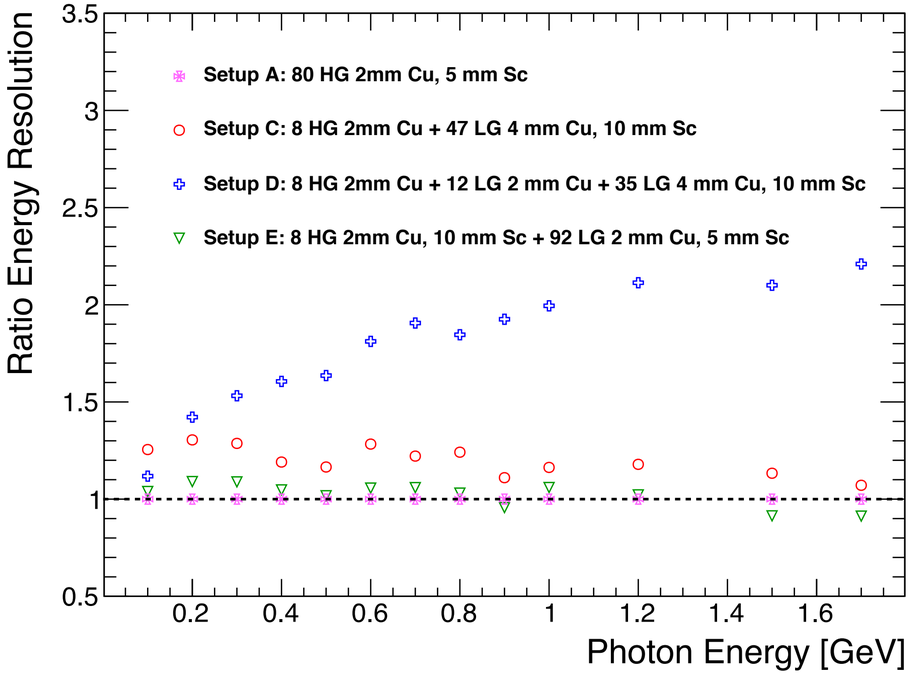
Setup D (2 + 4 mm Cu)

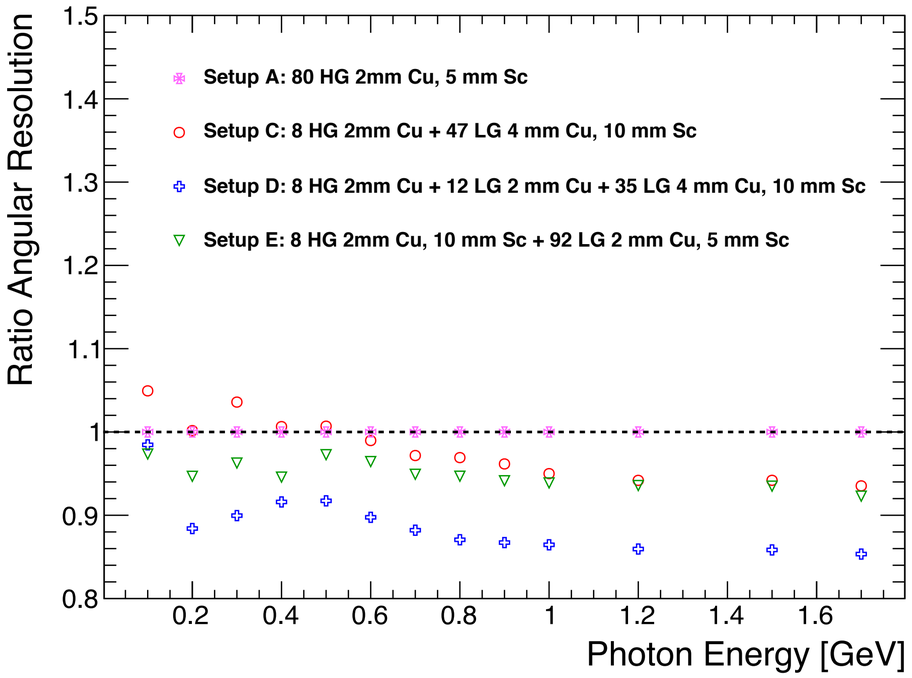
Setup E (2 mm Cu)

Simulation studies.

Influence of the absorber thickness

- Change of the absorber thickness
  - 2 mm Cu for HG layers
  - 2/4 mm Cu for LG layers
- Energy resolution mostly affected by
  - change in ratio scintillator thickness / absorber thickness ➠ sampling fraction
  - Leakage
- Angular resolution is slightly affected depending on the configuration
  - Mainly dominated by front layers
  - → thinner absorber in the front layers ➠ shower evolves deeper in the calorimeter, gives better lever arm on the direction

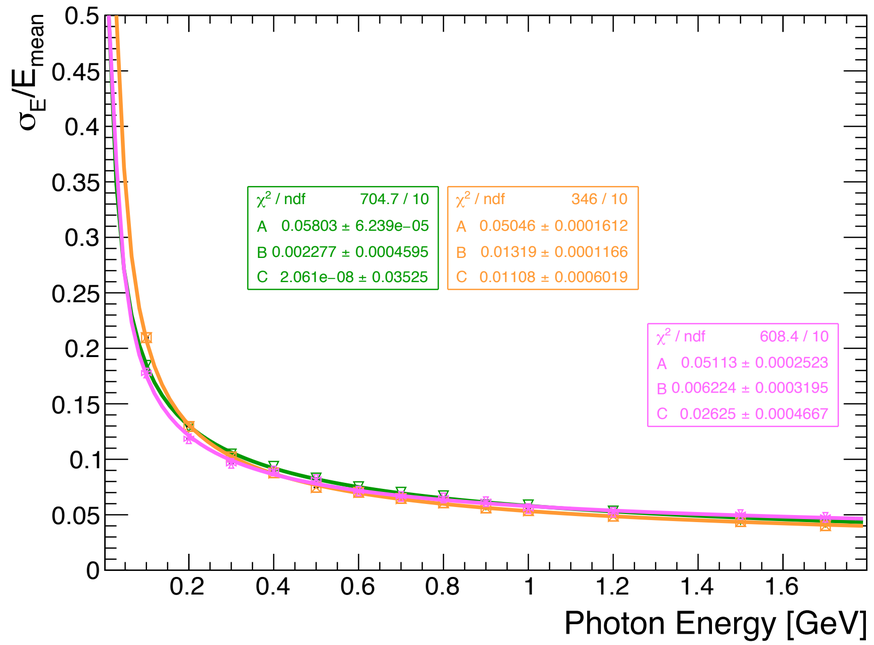




Simulation studies.

Influence of the scintillator thickness

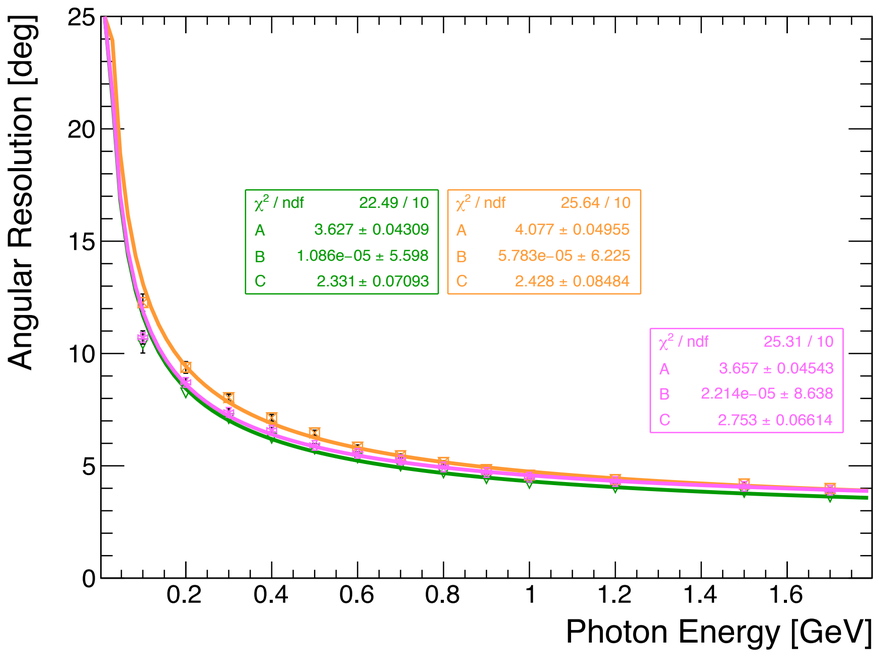
- Change in scintillator thickness for the front layers
  - 3, 5 and 10 mm
- Overall, not much change except at low energies



Setup A (5 mm Sc)

Setup E (10 mm Sc)

Setup F (3 mm Sc)



Setup A (5 mm Sc)

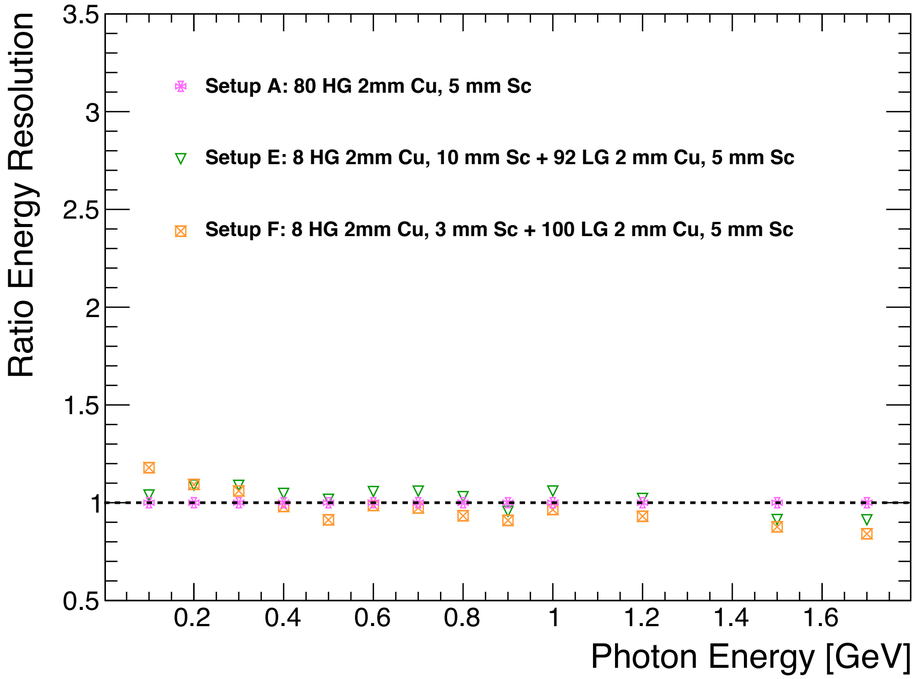
Setup E (10 mm Sc)

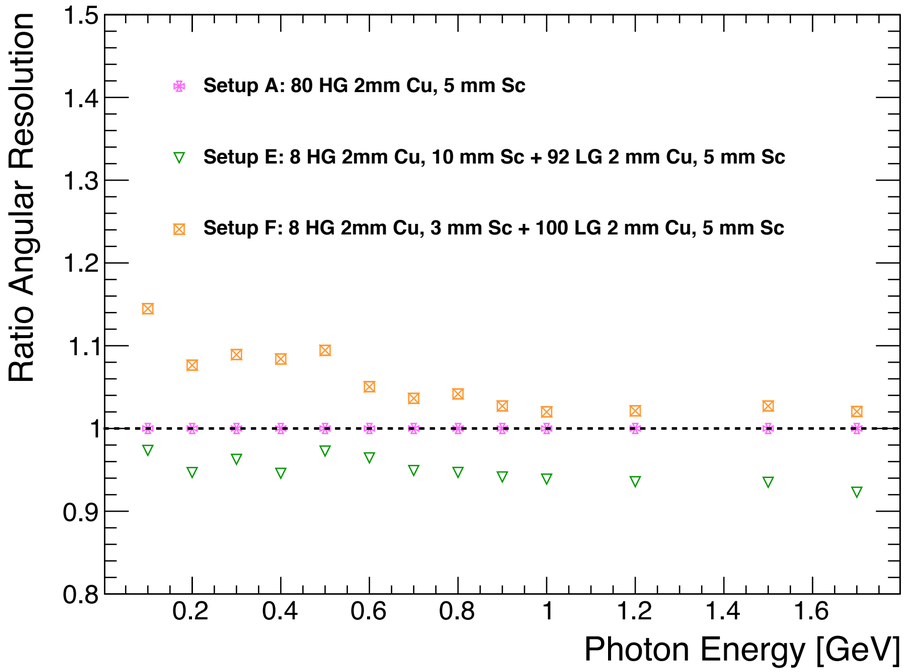
Setup F (3 mm Sc)

Simulation studies.

Influence of the scintillator thickness

- Change in scintillator thickness for the front layers
  - 3, 5 and 10 mm
- Overall, not much change except at low energies
- Change most significant for 3 mm tiles especially at low energies ➠ effect of the threshold
- Better angular resolution for thicker tiles
  - → Mostly due to the PCA that favours large energy deposits

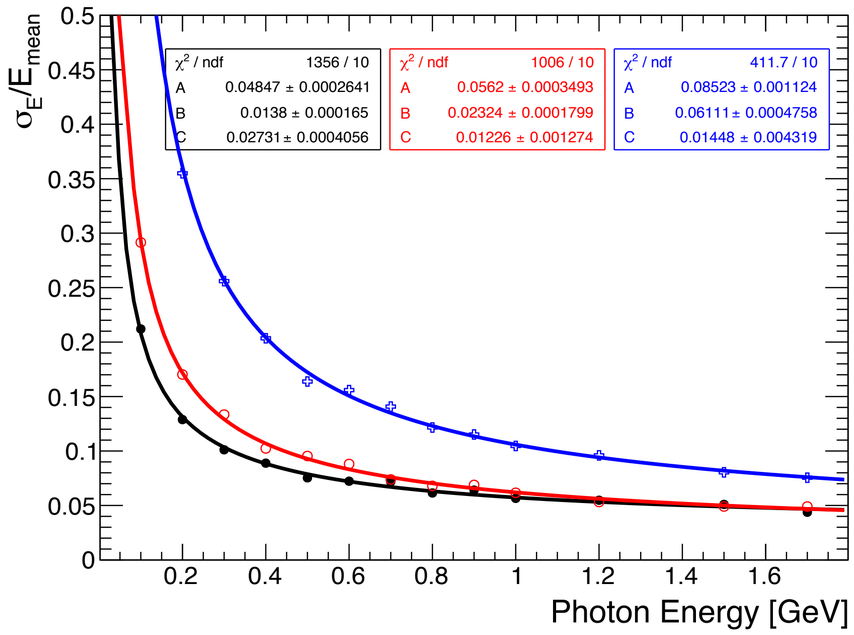


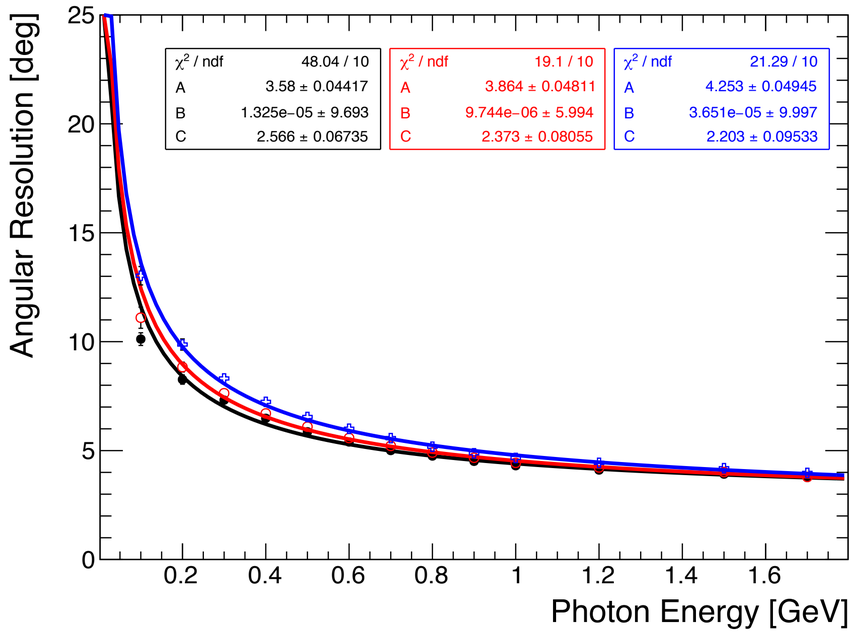


Simulation studies.

Influence of the pressure vessel

- Look at the influence of the pressure vessel
  - Case if the ECAL is fully outside the PV → easier from the engineering side
- Different thicknesses
  - **0.5**, **1** and **2** X_0 of steel
- Until when the pressure vessel becomes a significant problem?
- Angular resolution get slightly affected over $1X_0$
- Energy resolution gets heavily affected ➠ pressure vessel should stay below 1 X_0 to keep energy resolution below 6% / Sqrt(E)

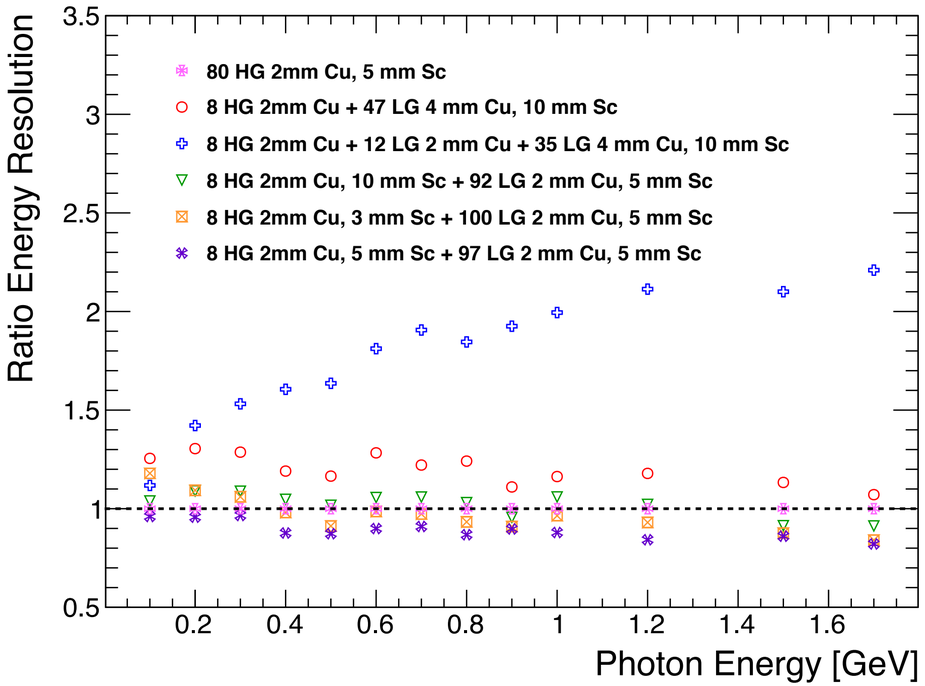


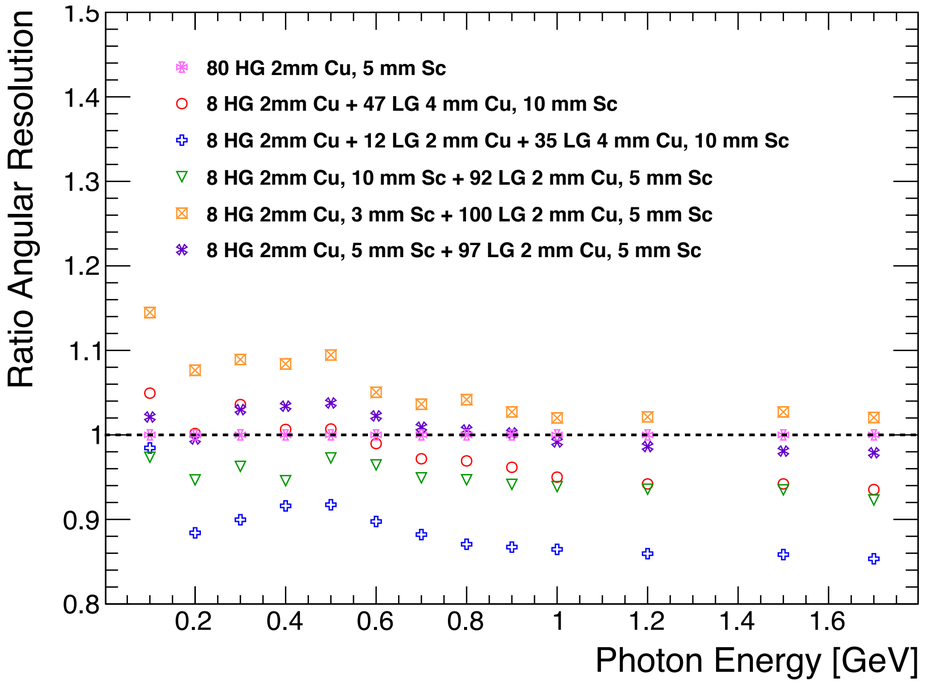


Simulation studies.

Full comparison

- Full comparison between the setups
- To take away
  - Angular resolution dominated by front layers → granularity in the back layers does not matter much ➠ strips can be used
  - Thinner absorber with small Molière radius in the front is preferred for angular resolution
  - Shower containment is important for high energies ➠ more layers or thicker absorber in the back
  - Thicker scintillator in the front helps in the angular resolution

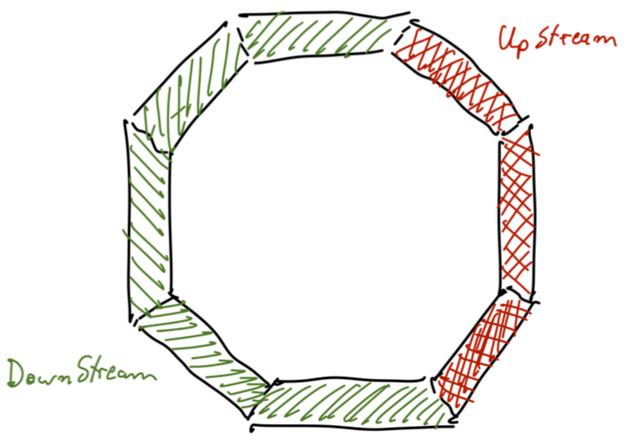




Real considerations.

Trade between performance, cost, feasibility..

- Limited space: place inside the pressure vessel? Mechanically possible?
- Cost: scales with size of the TPC, number of layers and granularity
- Fixed-target style ➠ different ECAL modules upstream/downstream



	DS Segments (3)	US Segments / Endcap (7)
HG Layers (0.5 cm of Sc)	8	6
HG Tile size	2.5 x 2.5 cm^2	2.5 x 2.5 cm^2
HG Absorber thickness (Cu)	2 mm	2 mm
LG Layers	72	54
LG strip width (0.5 cm of Sc, crossed)	4 cm	4 cm
LG Absorber thickness (Cu)	2 mm	2 mm
Total thickness	11 X_0	9 X_0
Number of channels	~ 2.8 - 3 M	
Copper volume	~ 31.8 m^3	
Sc volume	7 m^3 (tiles) - 63 m^3 (strips)	
Fiber length	~ 320 km	

Neutron energy reconstruction.

Motivation.

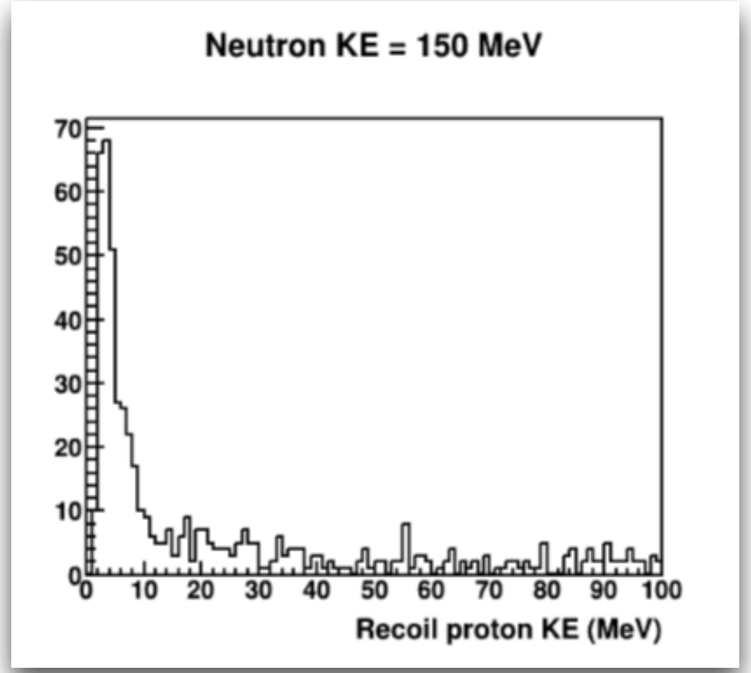
Pushing the limits

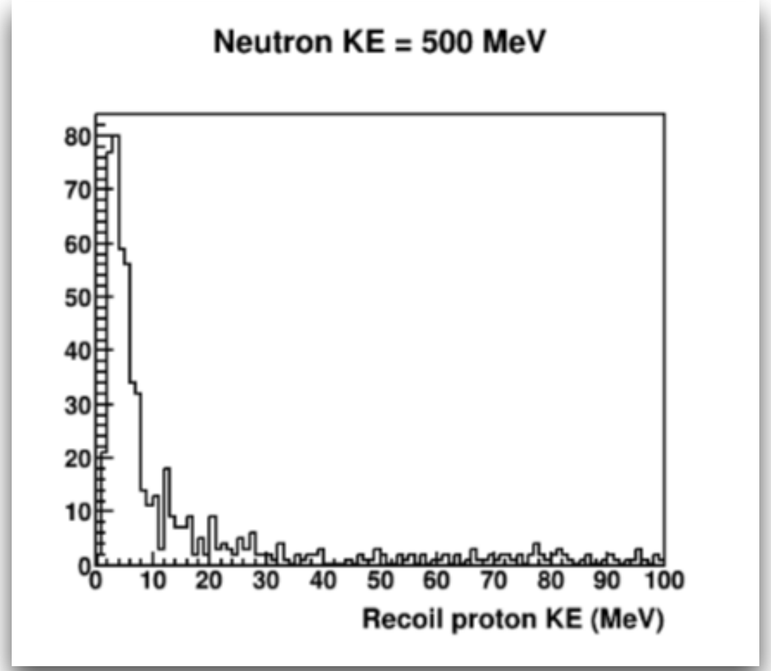
- **Neutron production** for anti/neutrinos on Ar target is highly uncertain
- Moreover, neutron energy is a source of ***neutrino energy mis-reconstruction***
- Neutron energy measurement:
  - **Time of flight** (ToF) by measuring the time between the production vertex and the located hit
  - Technique demonstrated in simulation with the 3DST (full scintillator-based detector)
  - Technique can be used with the ECAL
    - Need for ***precise time measurement*** (sub-ns)
    - **Advantage** ➠ long lever arm with the ECAL (~3 m from TPC center)
    - **Challenge** ➠ need to identify hits that belong to a neutron!

How to identify neutron hits?

➠ Proton recoil

- In order to get a good energy measurement
  - Need to identify the first neutron interaction from a **proton recoil**
- Study by Chris Marshall (Berkeley) of typical **proton recoil** kinetic energies
  - ➠ between 2-10 MeV
  - ➠ seem *independent* to the incoming neutron energy
  - ➠ dependent of the simulation model… Geant4/MARS give different results - being investigated
- In general ➠ need to be ***sensitive to isolated hits of few MeV***

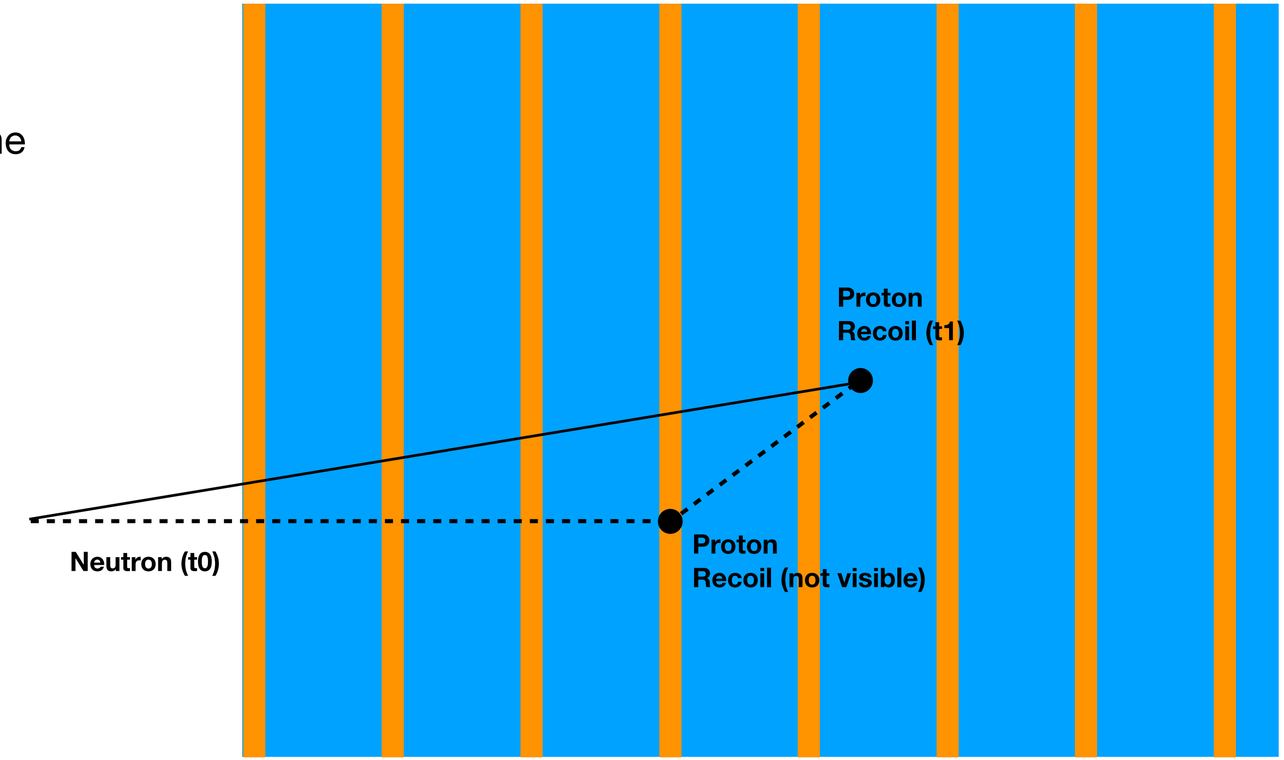




Neutron energy reconstruction.

ToF technique

- **First interaction** missed ➠ travel distance under-estimated
- **Scattered neutron** is slower ➠ ToF is over-estimating the initial neutron kinetic energy
- In the ECAL case:
  - Due to passive absorber ➠ more chance to have *scattered neutrons*
  - ➠ Expect low left tail in the energy reconstruction
- Sensitive parameters:
  - **Amount of H** ➠ thickness active material
  - **Absorber** ➠ thickness / material Z



Parameters for this preliminary study.

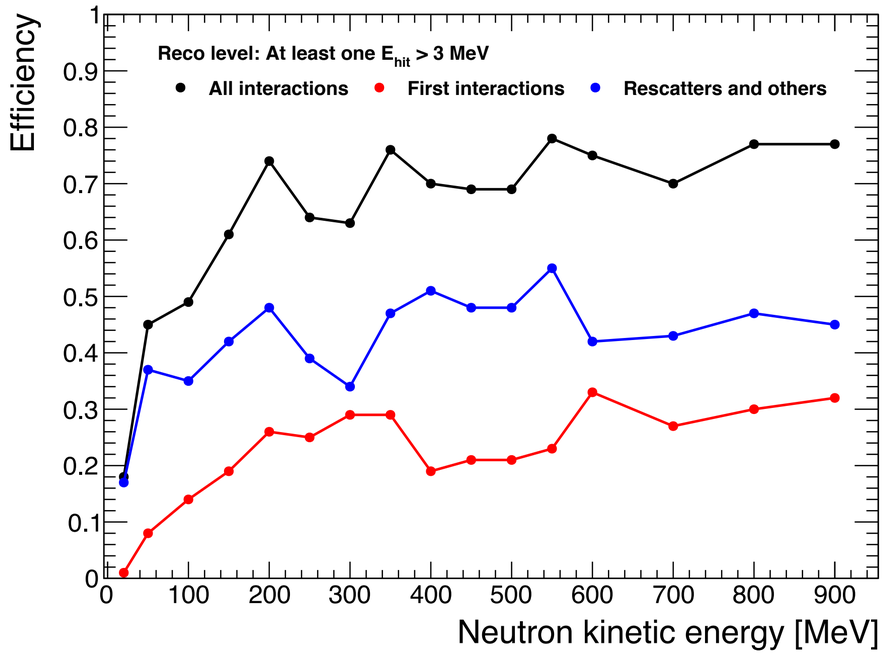
Setup

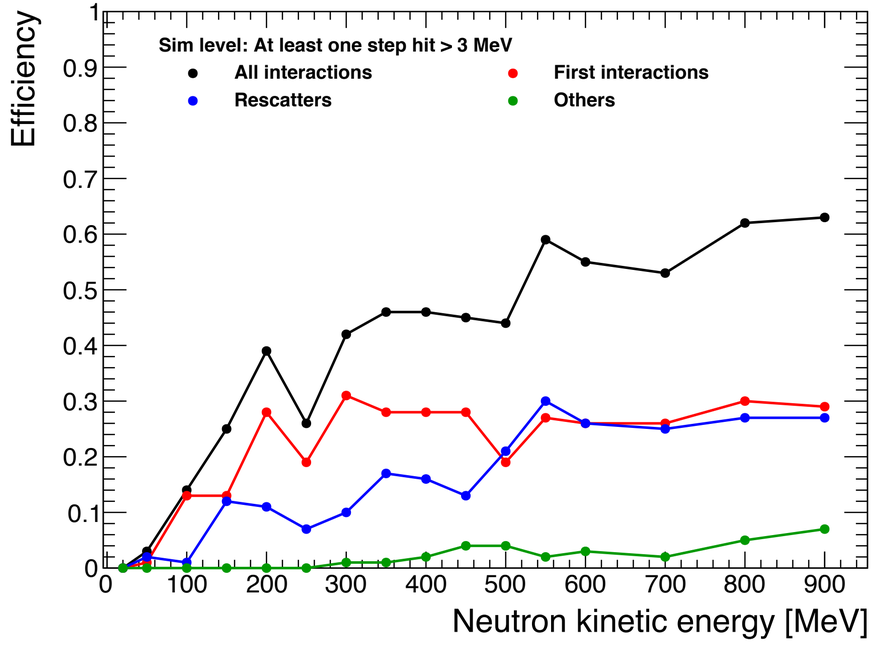
- Single neutron gun placed at ~3m or ~1m from the ECAL front face
- ECAL model
  - Outside the pressure vessel (0.5 X_0 of Al)
  - 80 layers: 8 HG layers with 2 mm Cu + 5 mm Sc + 1 mm FR4, 72 LG layers with 2 mm Cu + 5 mm Sc
- Looking at two levels
  - **Simulation level** ➠ geant4 step
  - **Reconstruction level** ➠ reconstructed calorimeter hit
- Assumes 250 ps time resolution (KLOE-like)
- Requirements:
  - First hit in time with **at least 2 MeV** of deposited energy
- Classified as **first interaction** / **scatter** based:
  - On the distance between the primary neutron endpoint and the reconstructed hit (d < 6 cm ~ 2-3 tiles)
  - On the true MC information (trackID - daughter/mother relationship)

Efficiency versus kinetic energy.

How good can we detect a neutron hit

- Efficiency for 80 layers
- Top: Reco-Level - Bottom: Sim-level
- Discrepancy between sim and reco efficiency
  - ➠ due to hits from gammas due to nuclear de-excitations (prompt and delayed)
  - still need to be worked out
- In principle, thicker scintillator would improve the efficiency - especially the first interaction

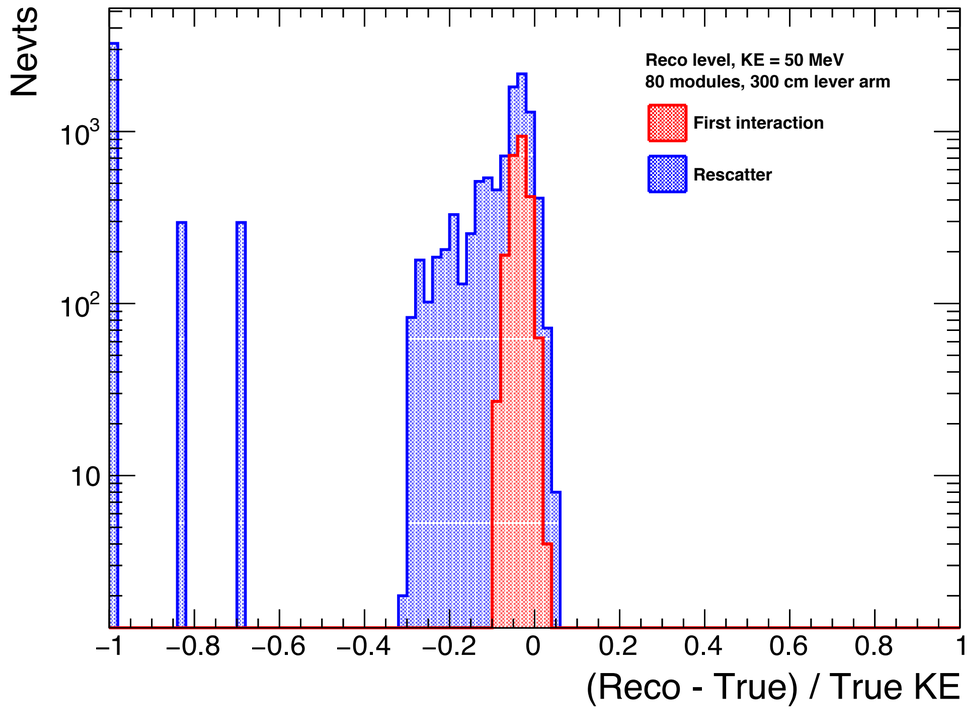


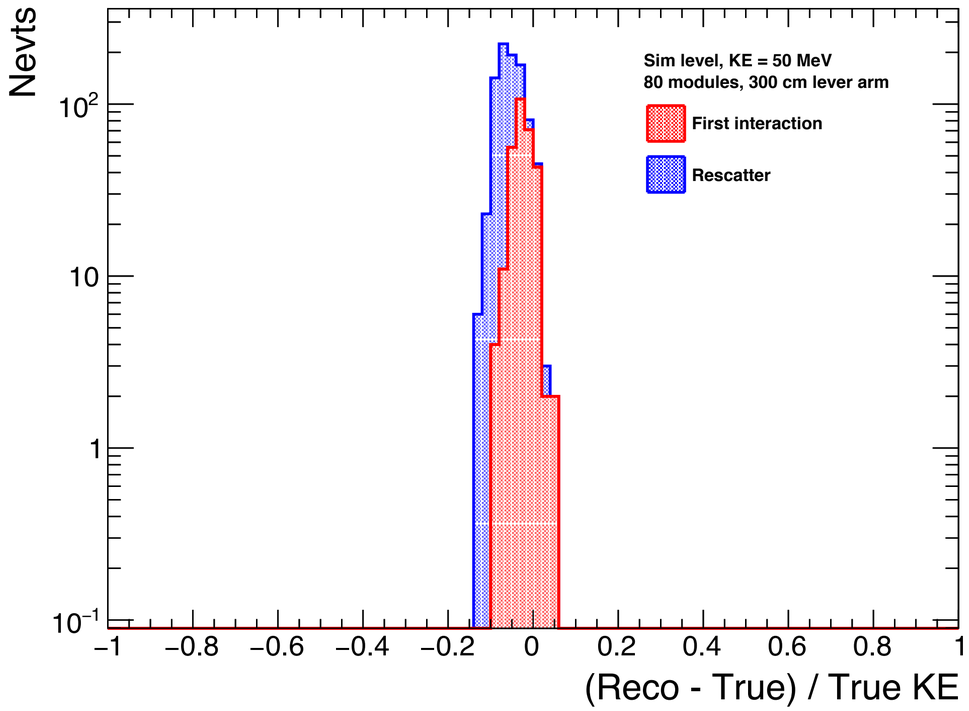


Energy residuals.

For 50 MeV neutrons at 300 cm

- Unphysical events at -1 ➠ very late depositions (nuclear de-excitations) or reconstructed super-luminal
- Scatter more pronounced in the reconstructed case

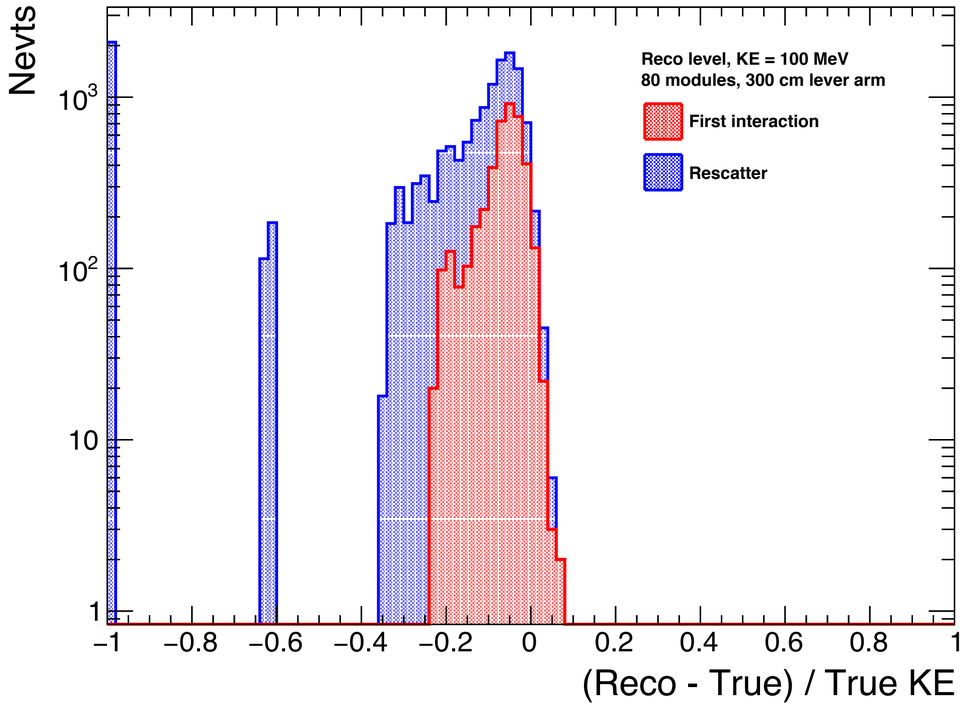


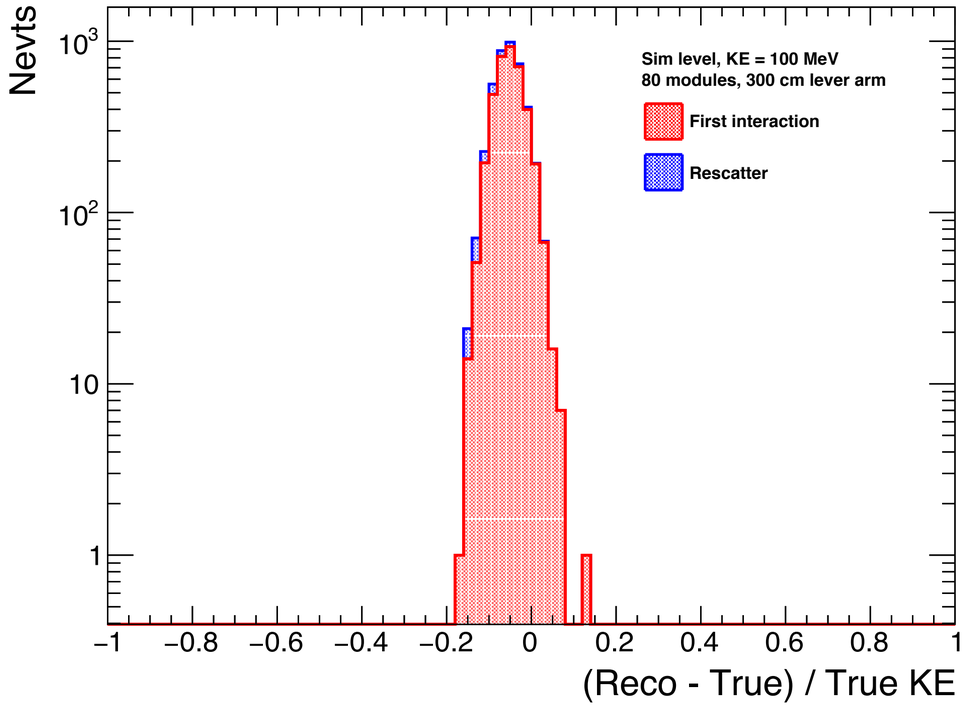


Energy residuals.

For 100 MeV neutrons at 300 cm

- Increase of the width of the residuals
- Increase of the scatters in the reconstructed case

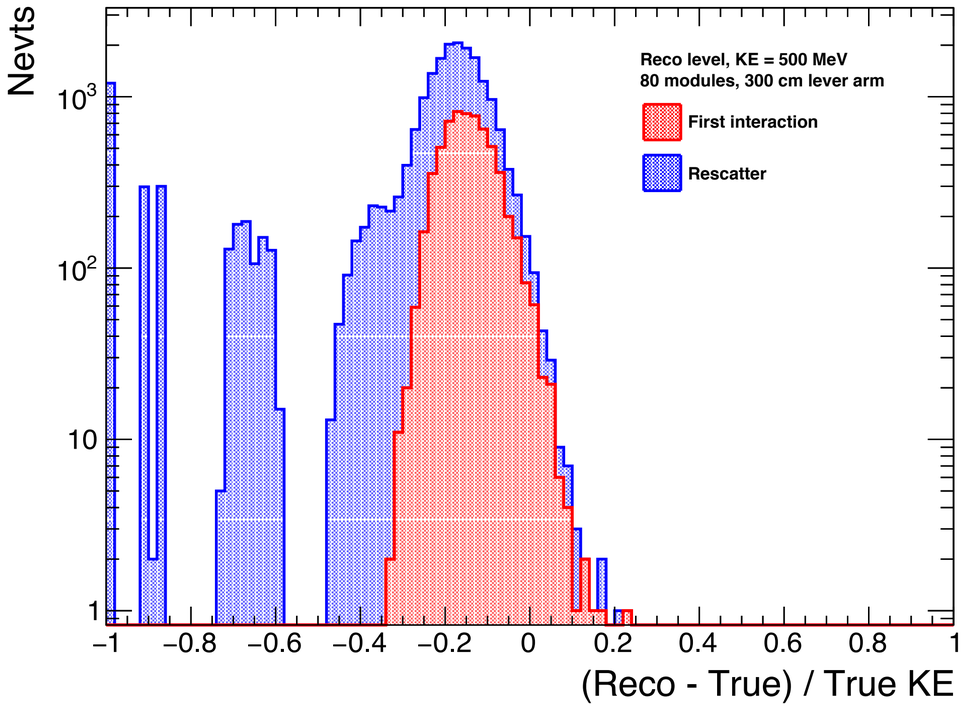


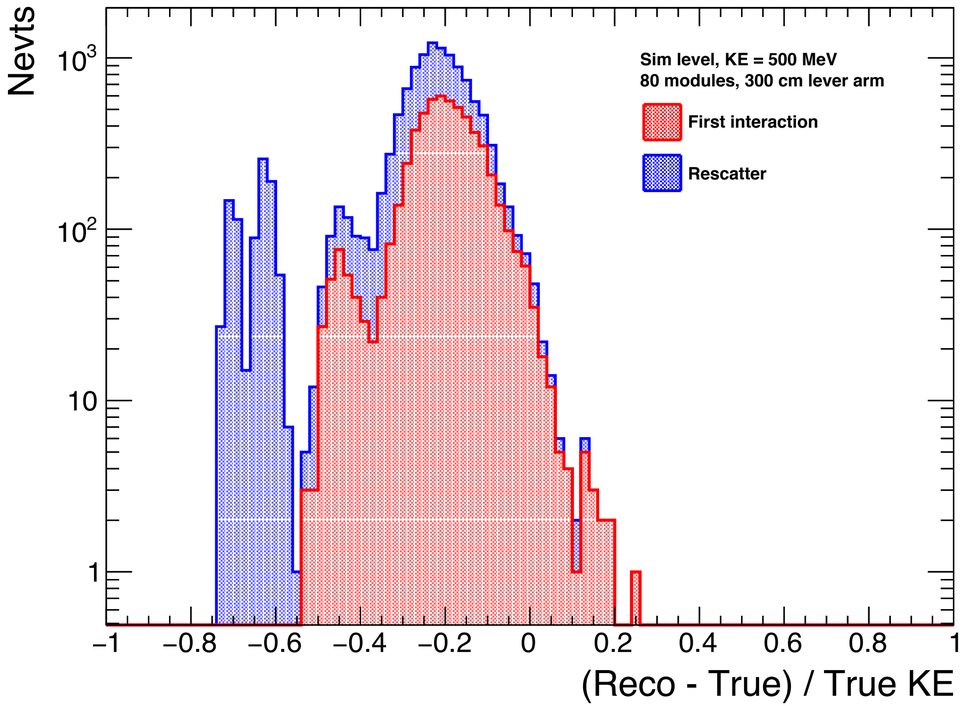


Energy residuals.

For 500 MeV neutrons at 300 cm

- Scatter case becomes much more pronounced
- Increase of the resolution and bias in the energy reconstruction

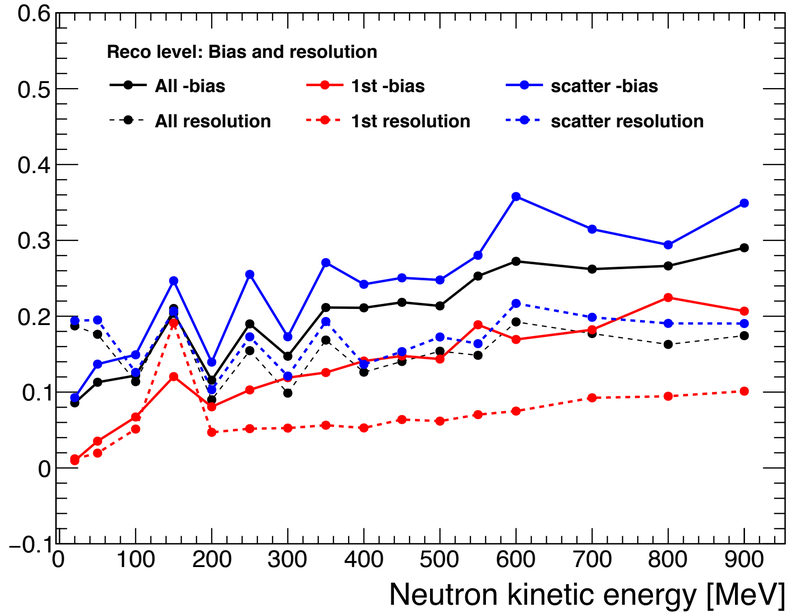


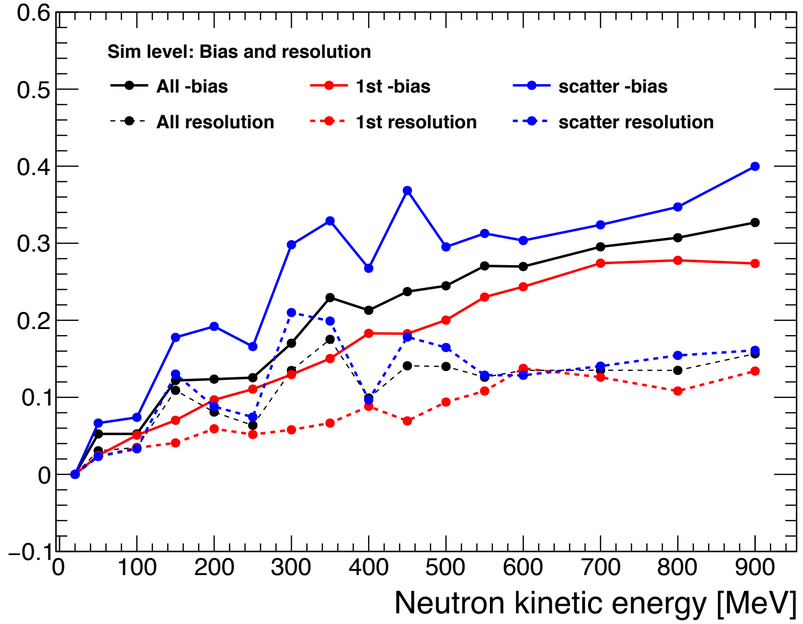


Look at the resolution and bias versus energy.

How good?

- Non-physical events are ignored
- Case 3m lever arm
- Resolution ➠ RMS of the residuals
- Bias ➠ Mean of the residuals (negated to be on the same scale)
- Bias and resolution increase with kinetic energy
- Adding scatters worsen the bias and resolution





Conclusion and Outlook.

Summary

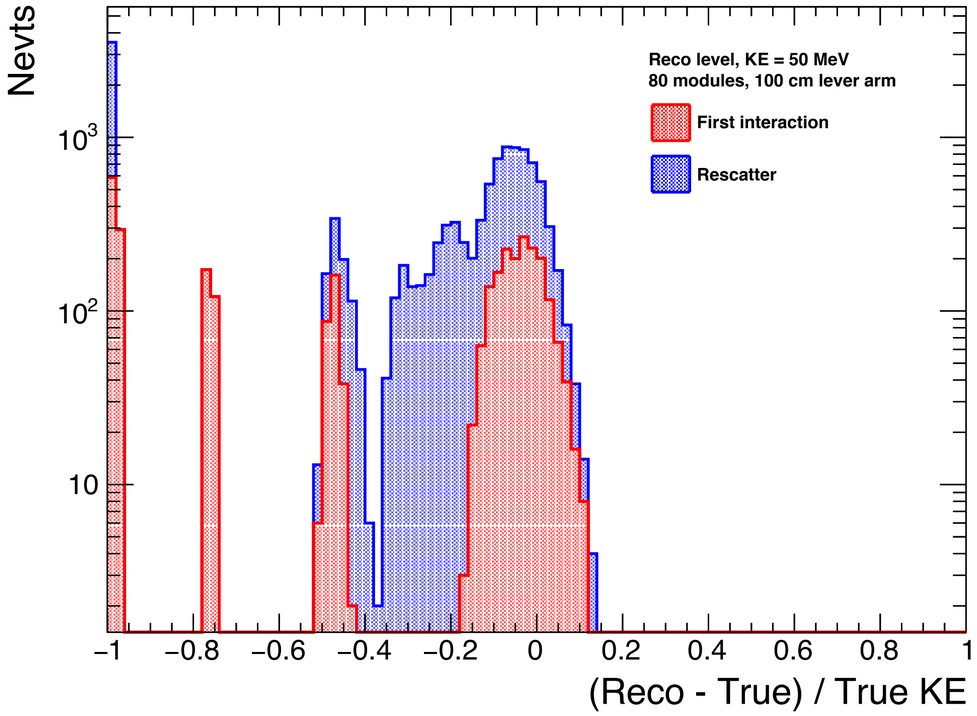
- CALICE calorimeters are ***good candidates for a DUNE*** Near detector ECAL
- Obvious modifications:
  - Absorber type/thickness, granularity, timing, electronics…
- **Optimization studies** of the ECAL design are ongoing
  - Reduce channel count / cost - Keep/Improve energy, angular and neutron performance
  - → Understand the details of the calorimeter implementation on low/mid-level performance parameters
- However, still to be done - understand the **impact of performance** on oscillation analysis → study to be done
- First look (promising) into **neutron energy reconstruction** with ToF technique
  - Overall good efficiency (> 50-70%) and good energy resolution (10-20%) between 50 to 900 MeV
  - However, significant bias (10-30%) in the energy reconstruction to higher kinetic energies
- Still few things to work out
  - Re-run the study for different configurations (Sc thickness / Abs material)
  - Perform the study in a pile-up environment - study purity

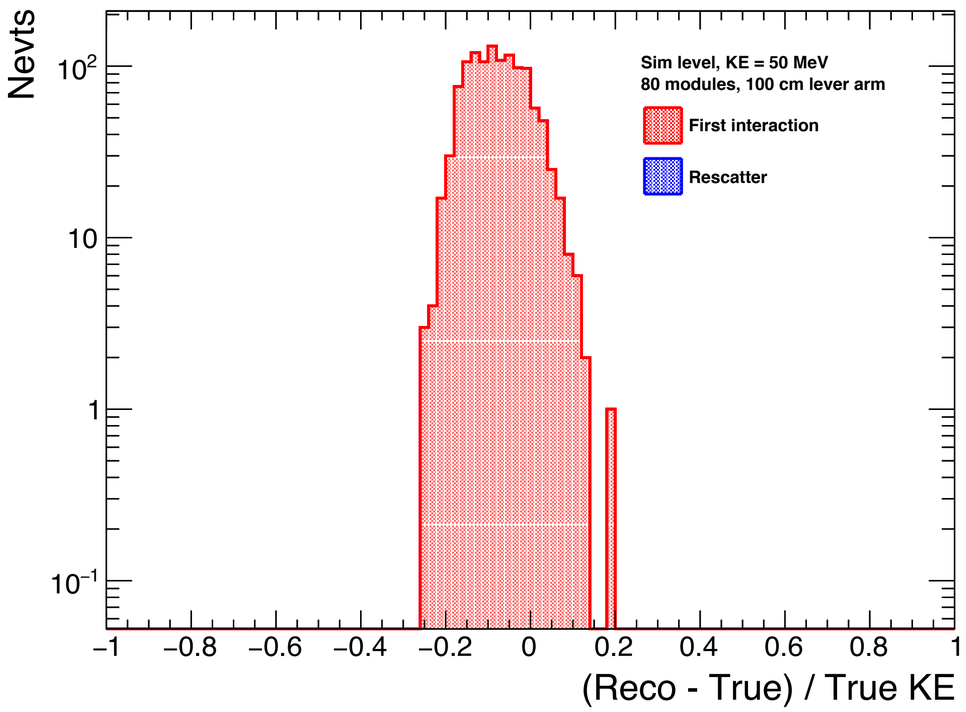
Backup Slides.

Energy residuals.

For 50 MeV neutrons at 100 cm

- Unphysical events at -1 ➠ very late depositions (nuclear de-excitations) or reconstructed super-luminal
- Scatter more pronounced in the reconstructed case

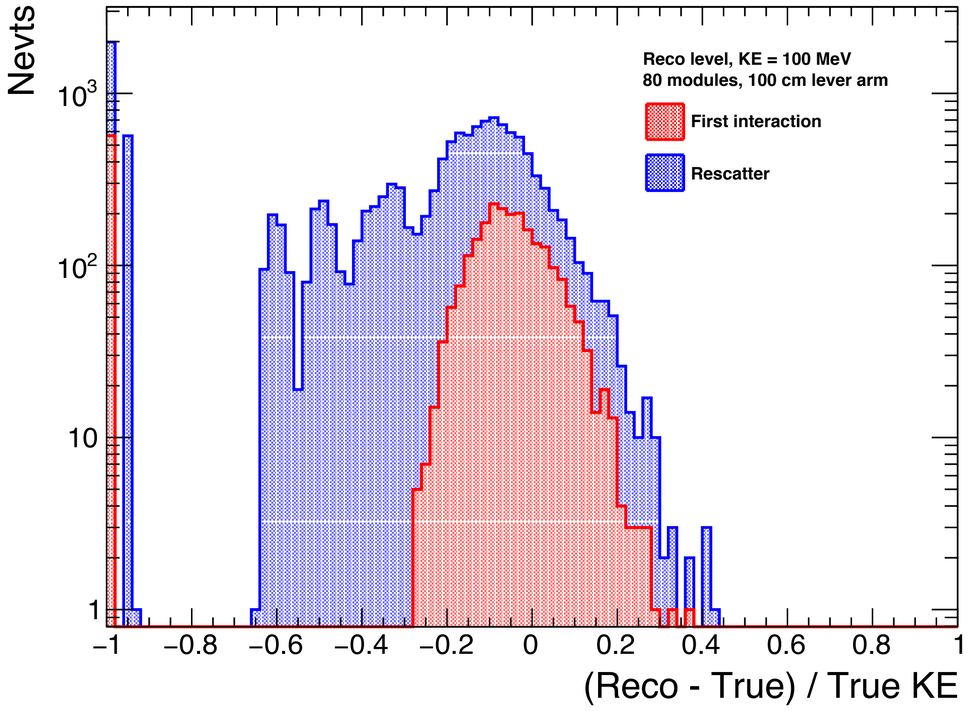


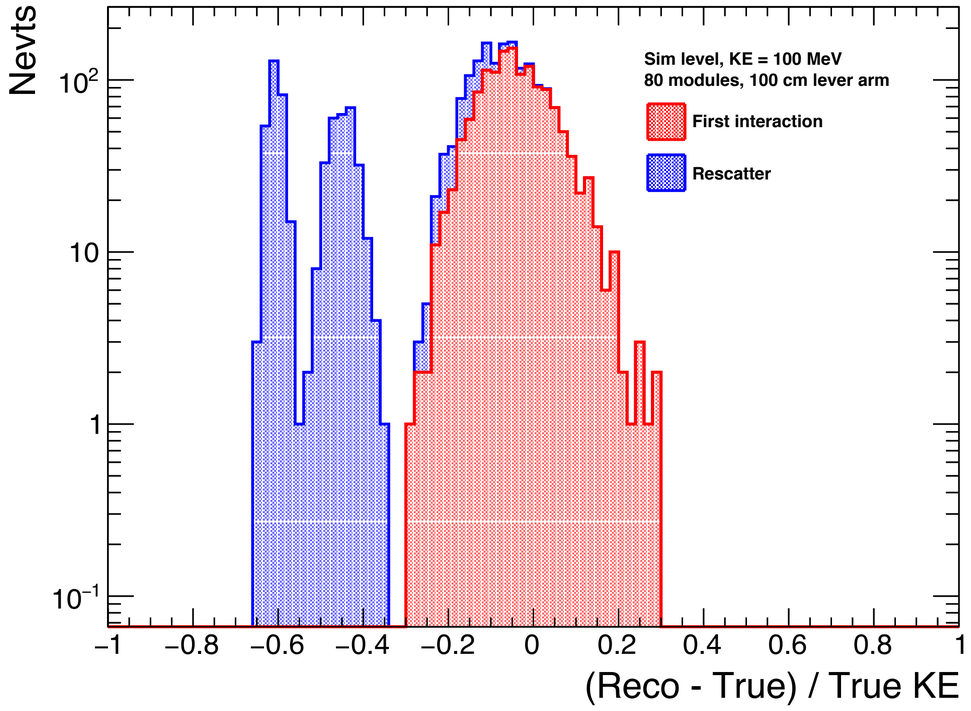


Energy residuals.

For 100 MeV neutrons at 100 cm

- Increase of the width of the residuals
- Increase of the scatters in the reconstructed case





Energy residuals.

For 500 MeV neutrons at 100 cm

- Scatter case becomes much more pronounced
- Increase of the resolution and bias in the energy reconstruction