The ECAL in the DUNE ND MPD.

TPC Mini Workshop

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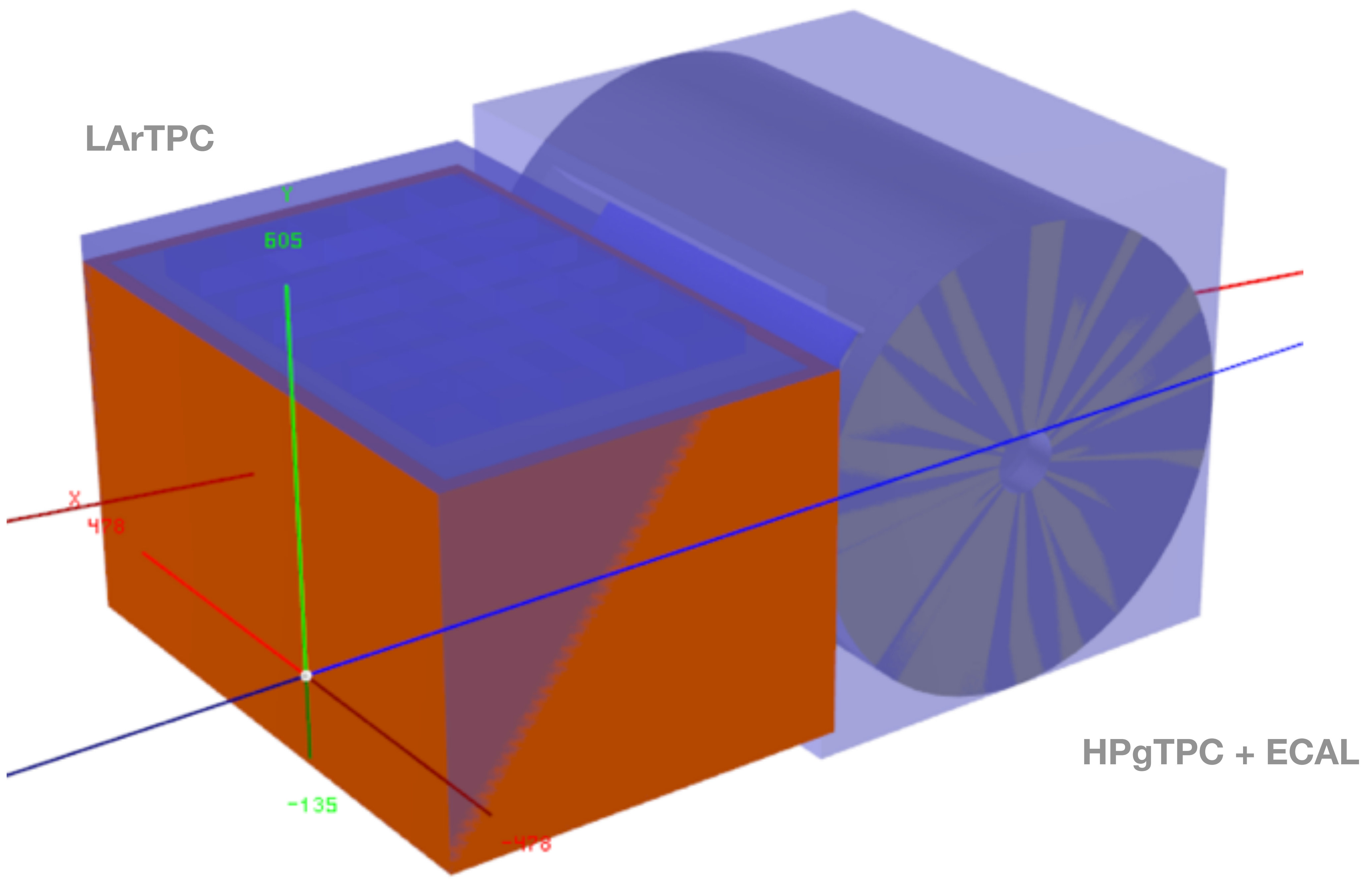
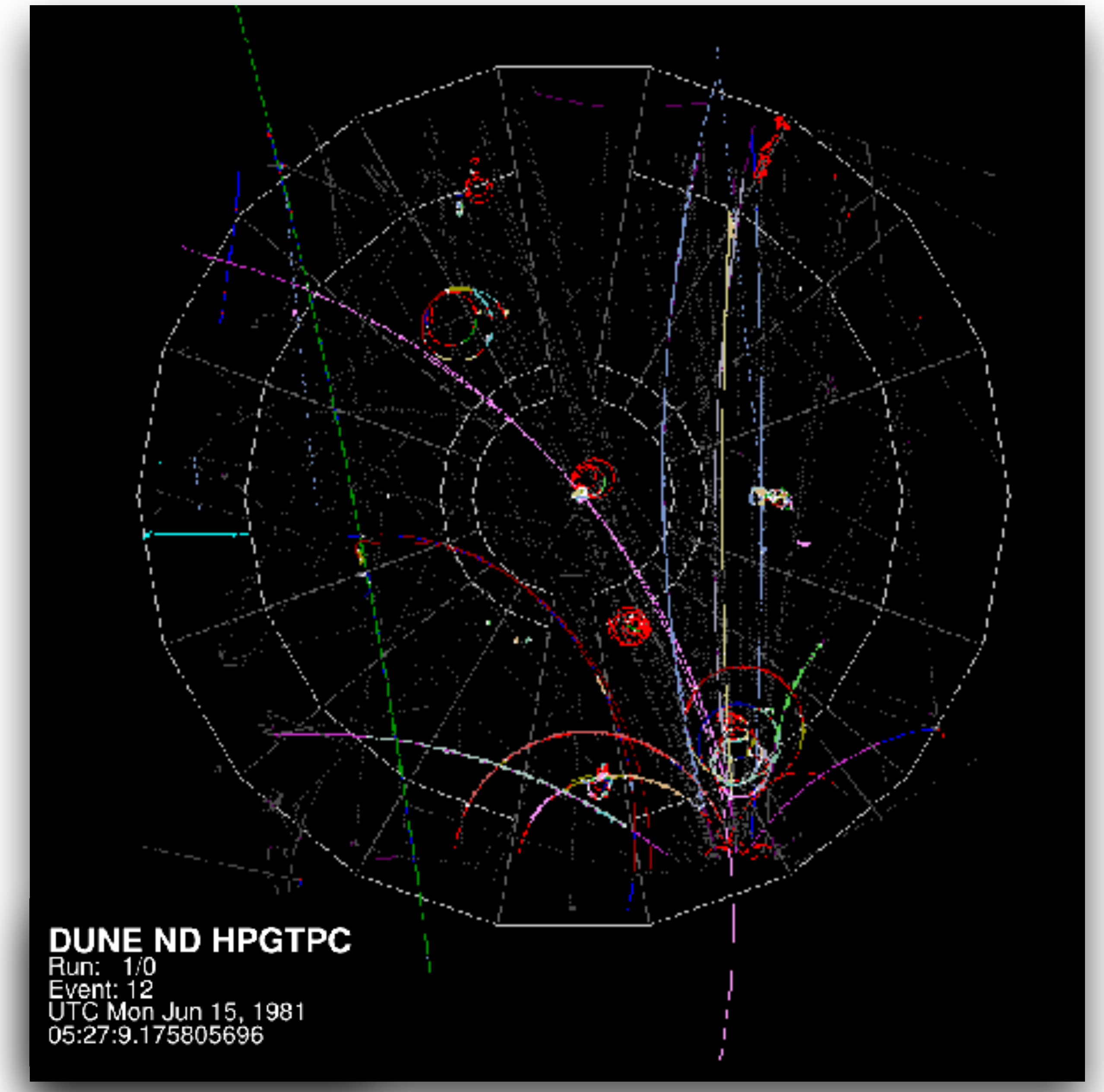
The Near Detector ECAL.

The goals

- The main **goals** of the ND ECAL surrounding the HPgTPC
  - Help in identifying **neutral pions** ➠ reject background π^0 s in ν_e interactions
  - Help in rejecting backgrounds / Provide an accurate **timestamp** of the event
  - Hadron containment, improve the **LAr acceptance** (HPgTPC + ECAL)
  - Help in **PID** with calorimetric variables / timing techniques
    - Separation mu/pi
    - Separation positron/proton > 1 GeV ➠ impossible with dE/dx
  - As a bonus
    - Possibly provide a handle on **neutron identification** and energy reconstruction
- The ND ECAL design needs to *take into account all these at the maximum*

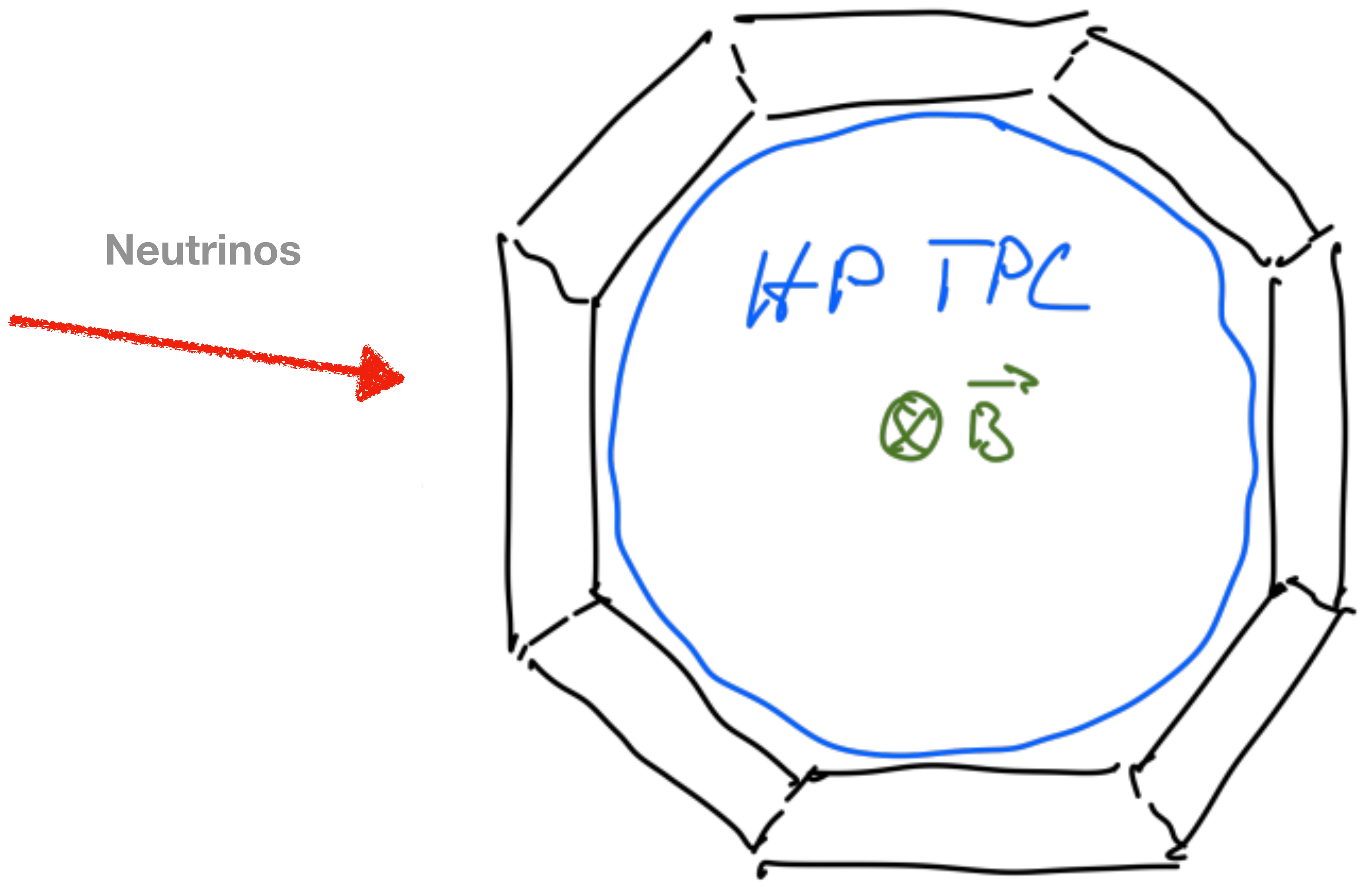


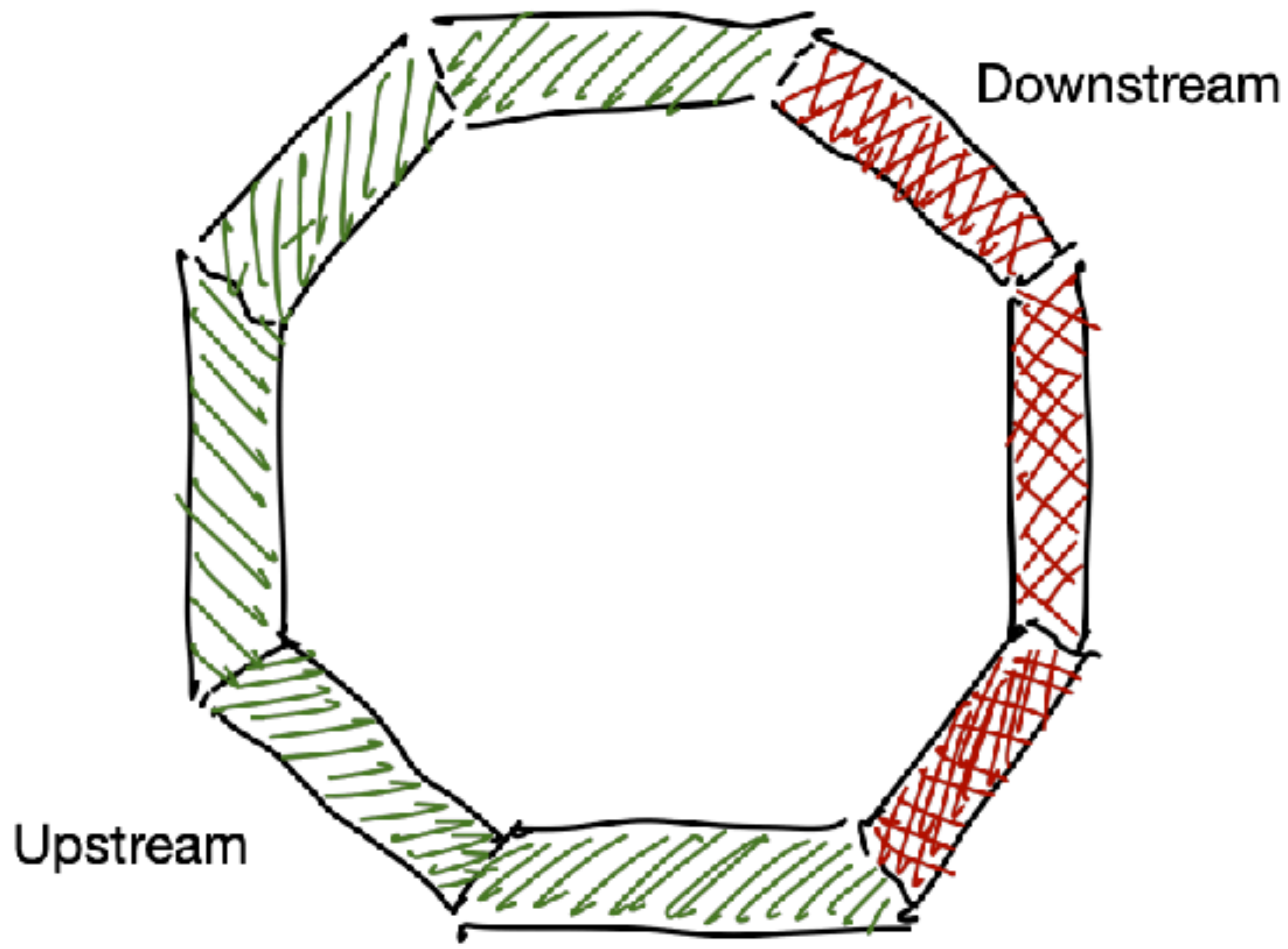


The ECAL concept.

Possible geometry design

- Global layout driven by the HPgTPC size
  - Radius ~2.7 m, Length ~5.5 m
- Need to fit the cylindrical geometry of the HP vessel and planar geometry of a granular calorimeter ➟ octagonal geometry
- Overall dimensions: Octogon side length ~ 2-3 m
  - Barrel surface ~ 150 m^2
  - Endcap surface ~ 70 m^2
- Due to the nature of the experiment ➟ granularity/depth/resolution does not need to be the same everywhere
  - Two regions: downstream and upstream
- Possible variable longitudinal segmentation
  - Thin layers in front (good EM res), thick layer in the back for containment

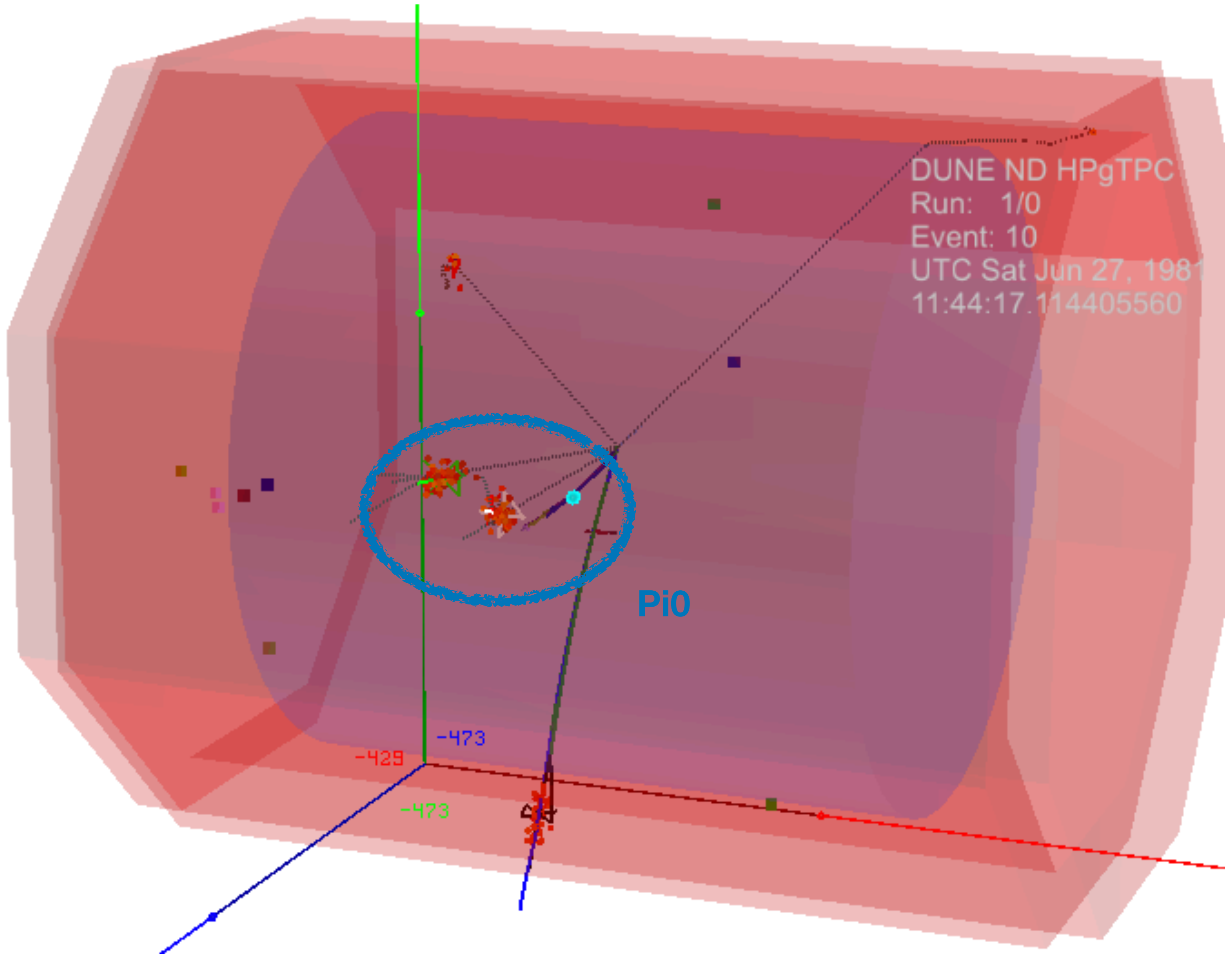


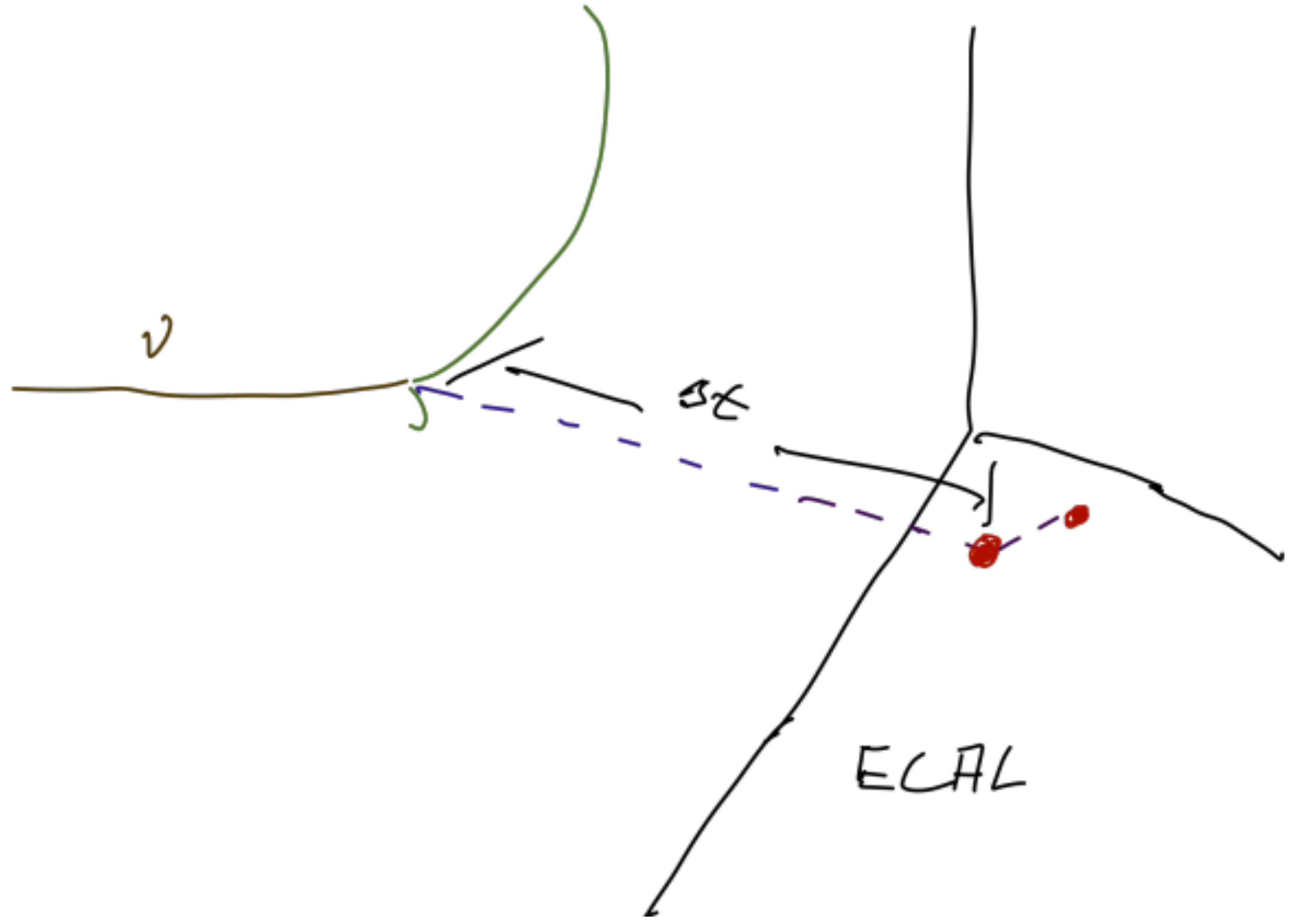


Performance goals.

Try to be based on physics

- Electromagnetic resolution ~ 5-10% / √E[GeV]
    - Drives the sampling structure design ➠ Thin absorbers
- π^0 reconstruction
    - Shower separation, position and angular resolution ➠ motivates a highly granular calorimeter
- Potential game changer ➠ Neutron identification and energy reconstruction (still needs to be well established)
    - Drives timing resolution to 100 ps level

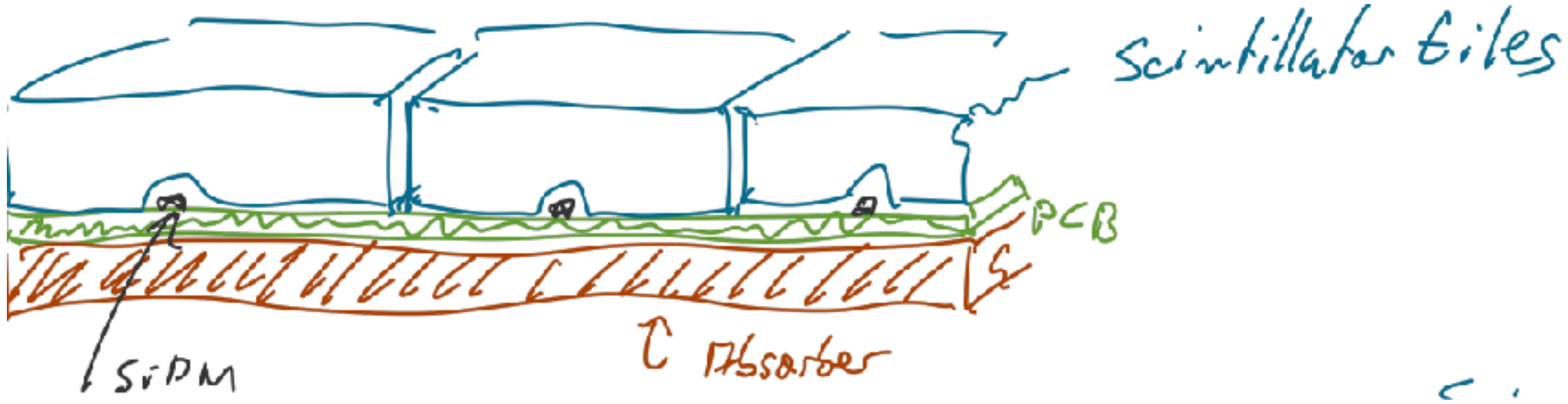


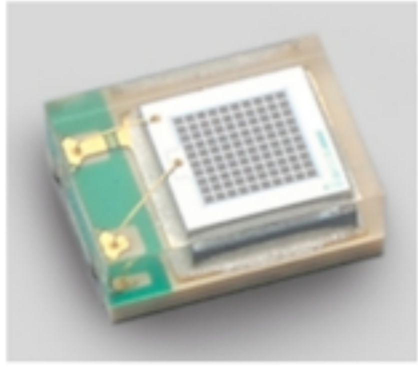


Technological choices.

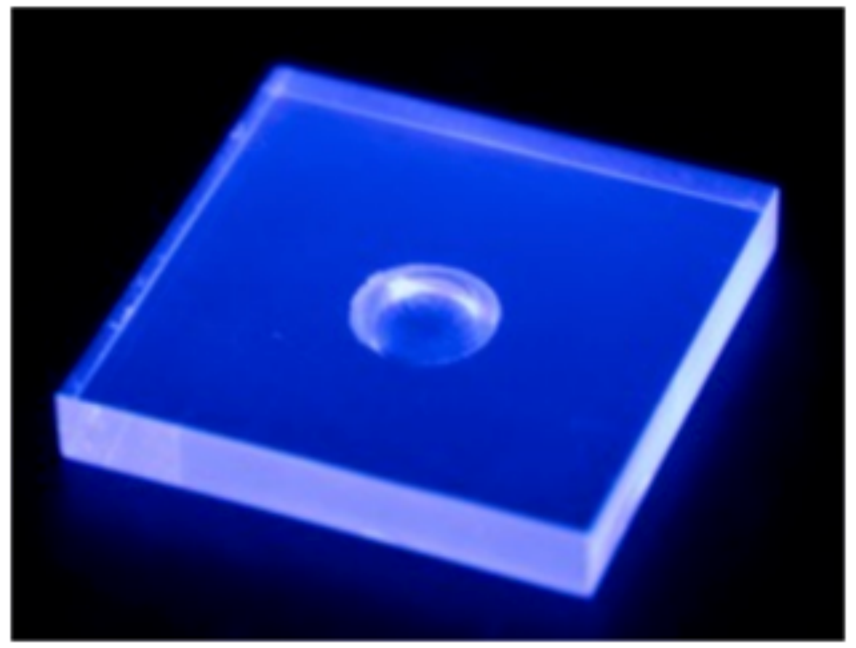
Based on acquired experience in CALICE

- Mix of high granular and low granular planes
  - High granular plane ➠ scintillator tiles with 1 SiPM per tile
  - Low granular plane ➠ crossed-scintillator strips readout on both sides





SMD SiPM



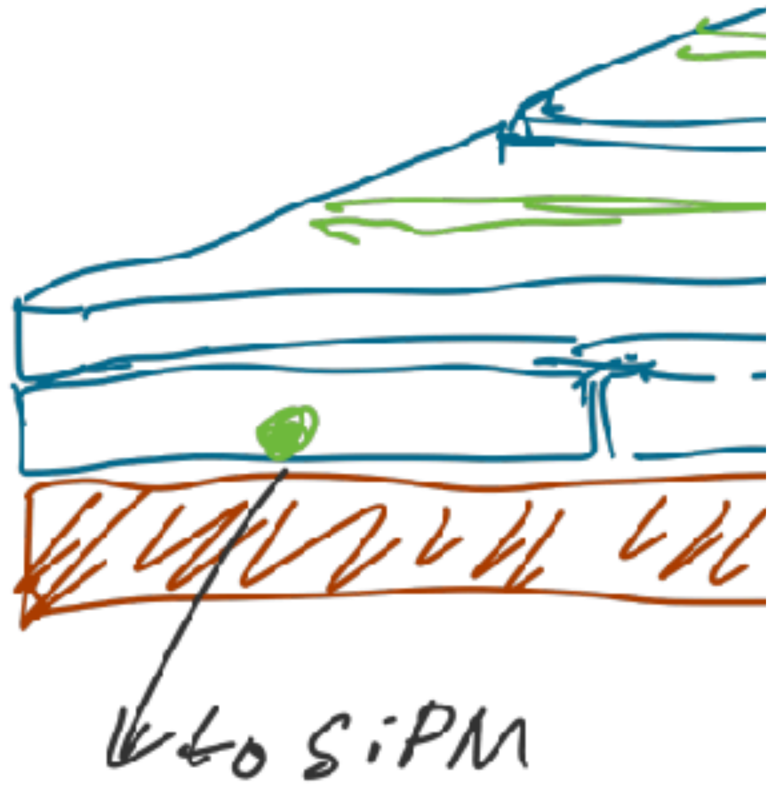
Direct coupling with dimple

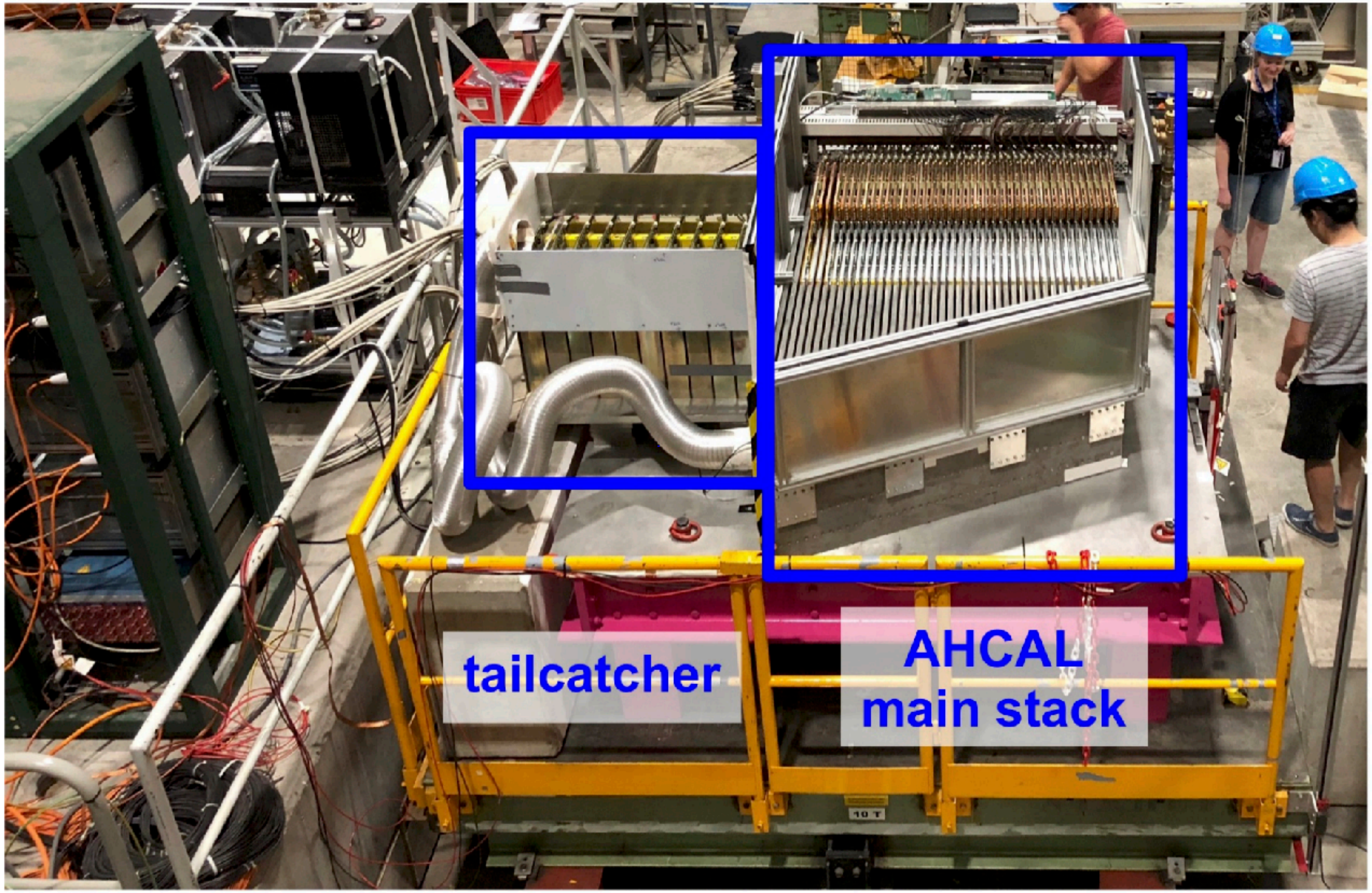
More details here: https://indico.fnal.gov/event/20425/session/5/contribution/10/material/slides/0.pdf

Technological choices.

Based on acquir

- Mix of high granul
  - HG -> scintillat
  - LG -> crossed





SMD SiPM

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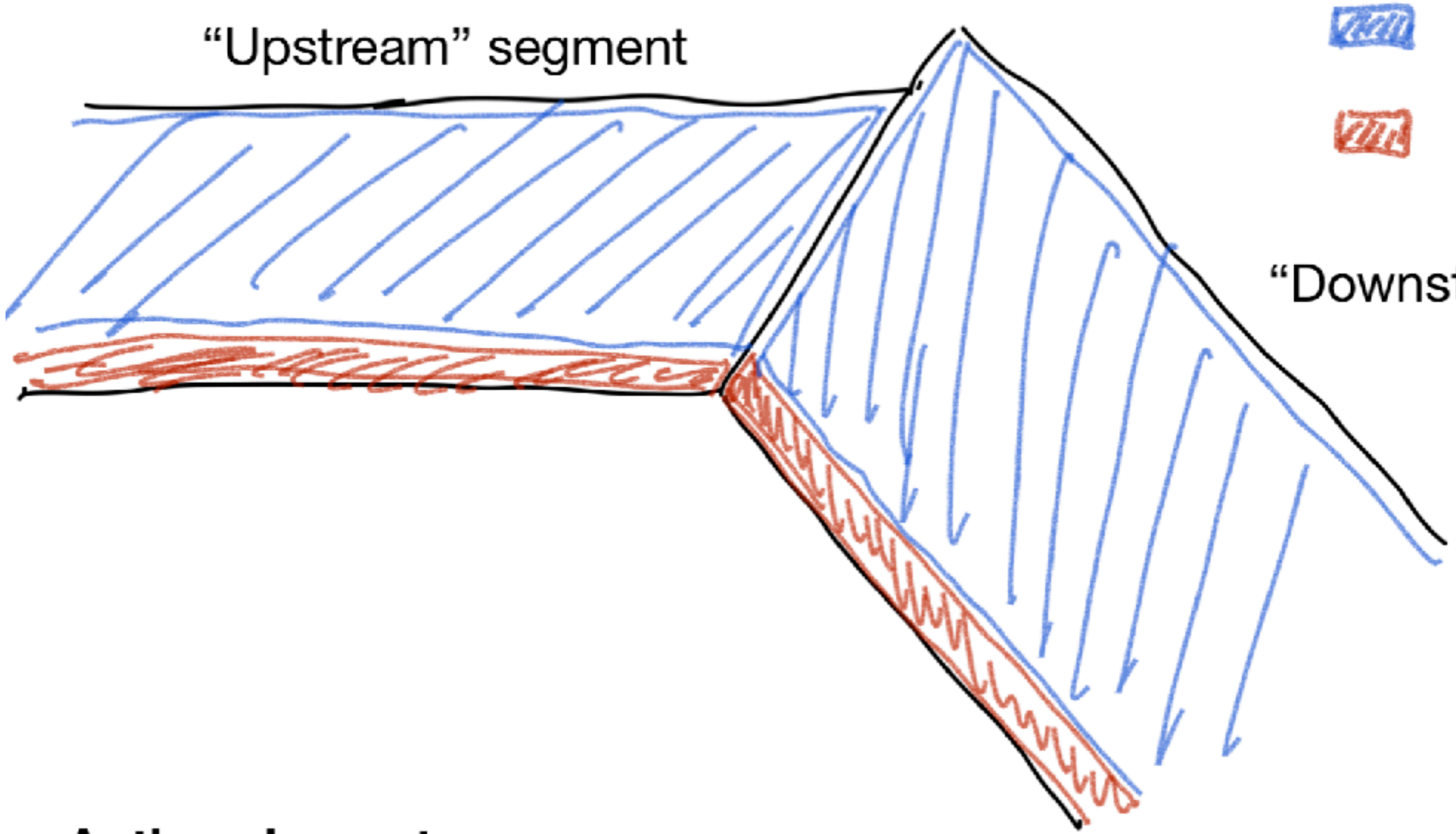
Well established technology
-> full prototype with ~22k channels

Current design overview.

Current status, not what will be built

Frank Simon's slide



low granularity layers: alternating orthogonal bars

high granularity layers: tiles

- Downstream layout [3 downstream octagon segments]:
  - 80 layers, first 8 high granularity
- Upstream layout [5 side and upstream segments, endcaps]:
  - 60 layers, first 6 high granularity

Active elements:

- *high granularity*: 25 x 25 mm² tiles, 5 mm thick
- *low granularity*: 40 mm wide, 5 mm thick bars over full module length, crossed in alternating layers

Optimisation goals.

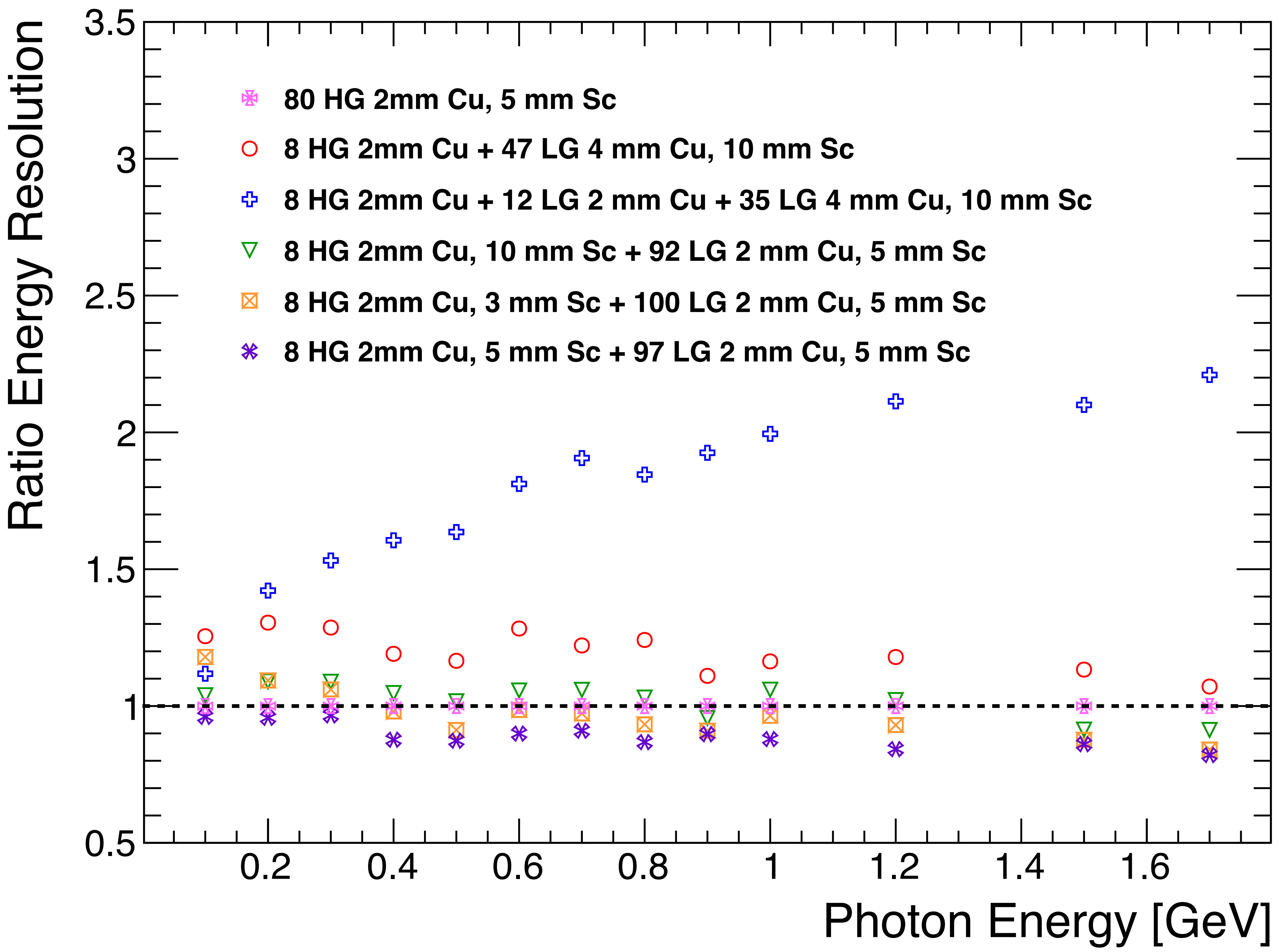
Study of several designs

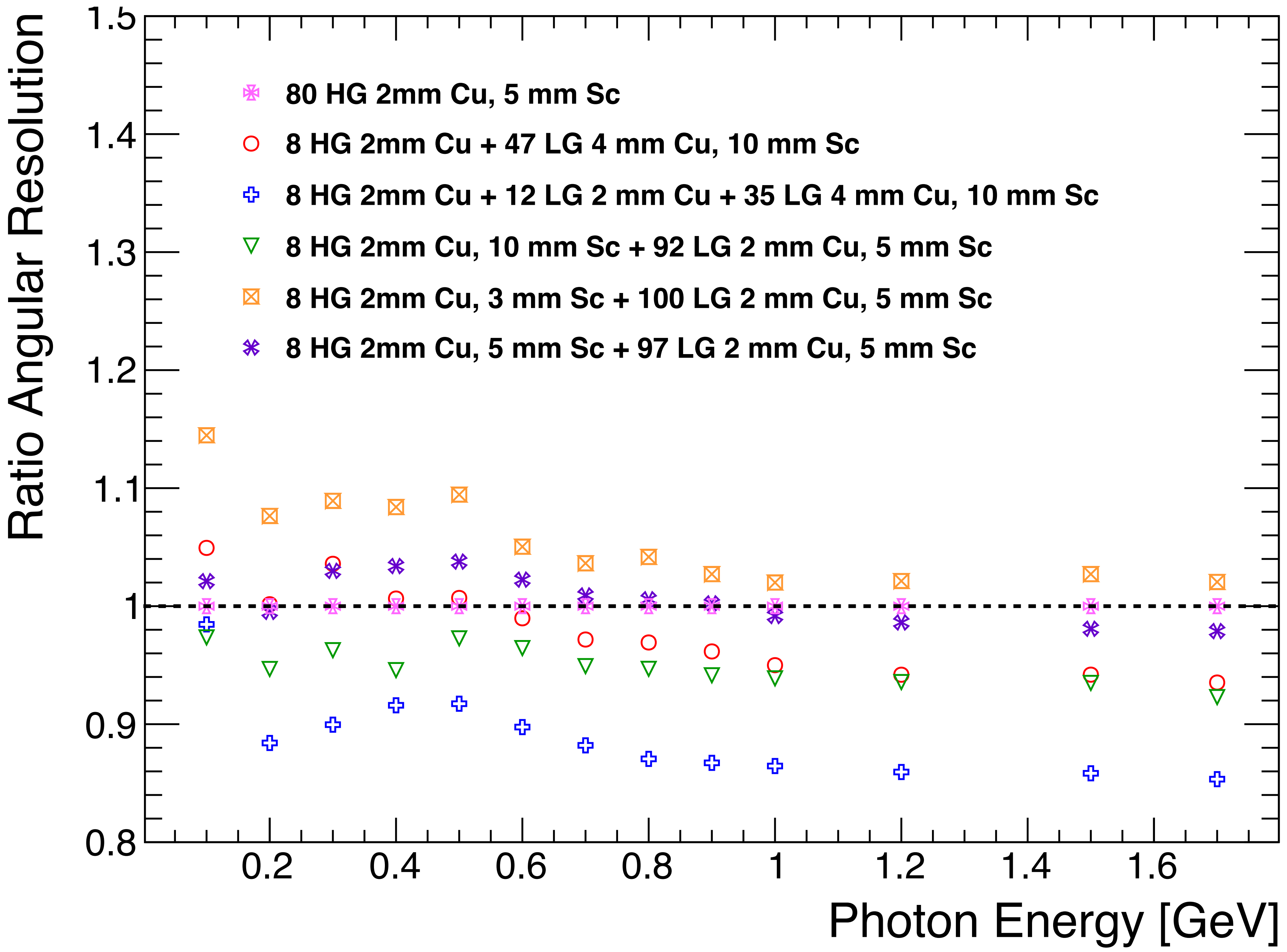
- **Goals**:
  - **Cost** drivers: Granularity, absorber material/thickness, number of layers (size)
  - Main design driver ➠ **calorimeter energy resolution**, **angular resolution, neutron detection…**
- Optimize by looking at the influence of
  - Granularity
  - **Absorber thickness**
  - **Scintillator thickness**
  - Pressure vessel

Simulation studies.

Full comparison

- A lot of models have been compared! (~12 models)
- **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
  - *Pressure vessel thickness* needs to be kept below 1 X_0 to keep energy resolution below 6%/√E ➠ ECAL can be put outside the PV

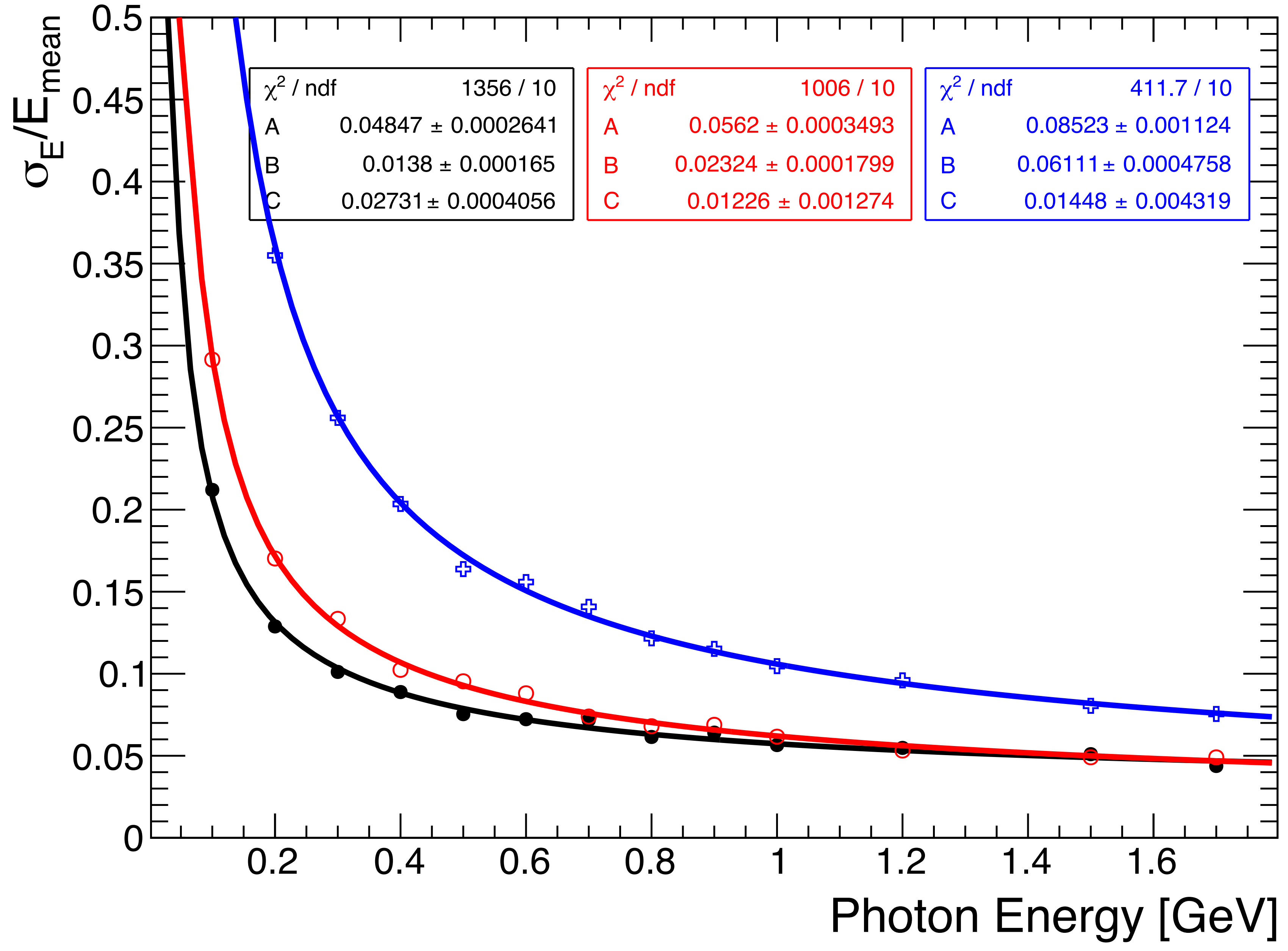


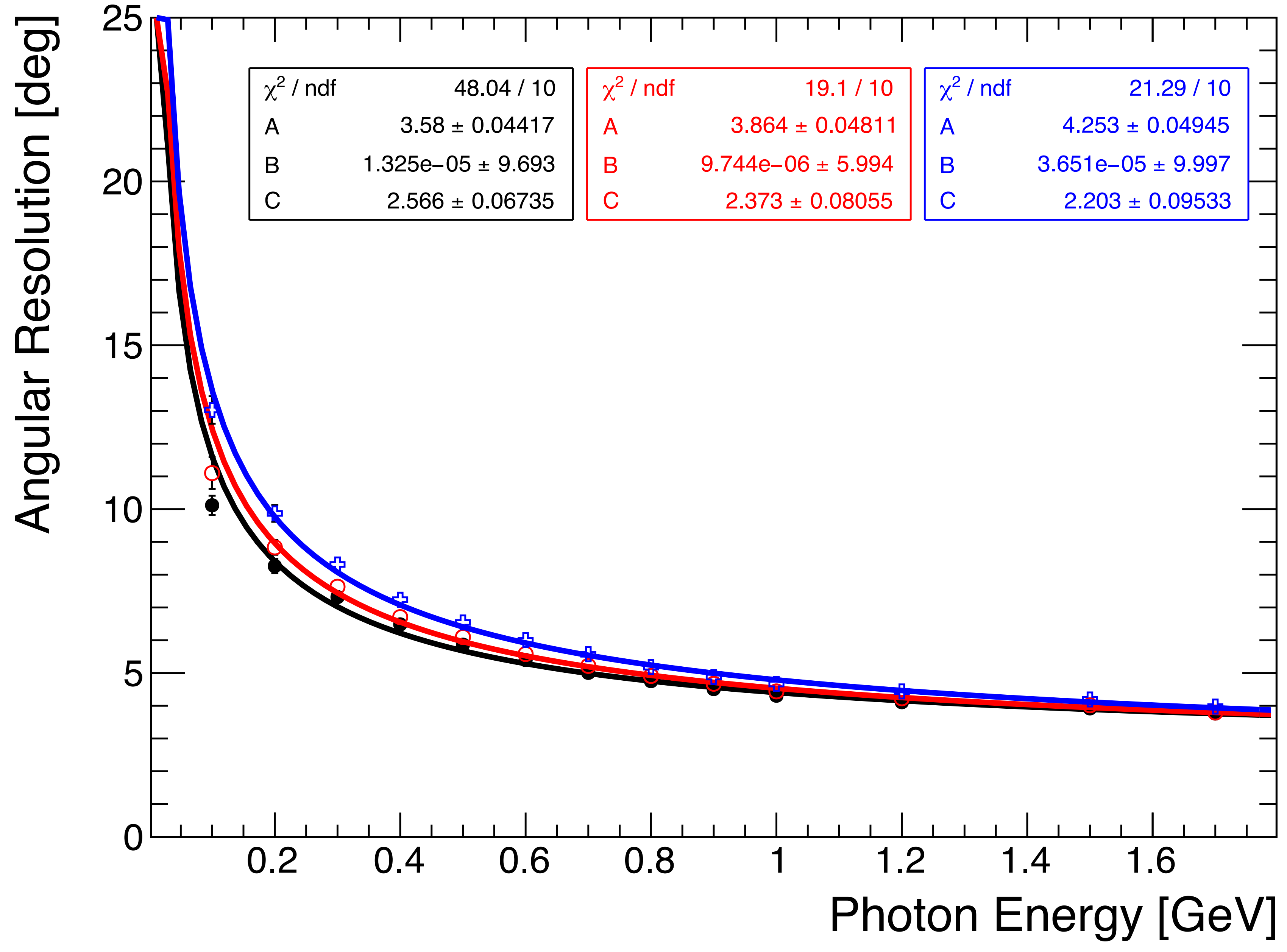


Simulation studies.

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)

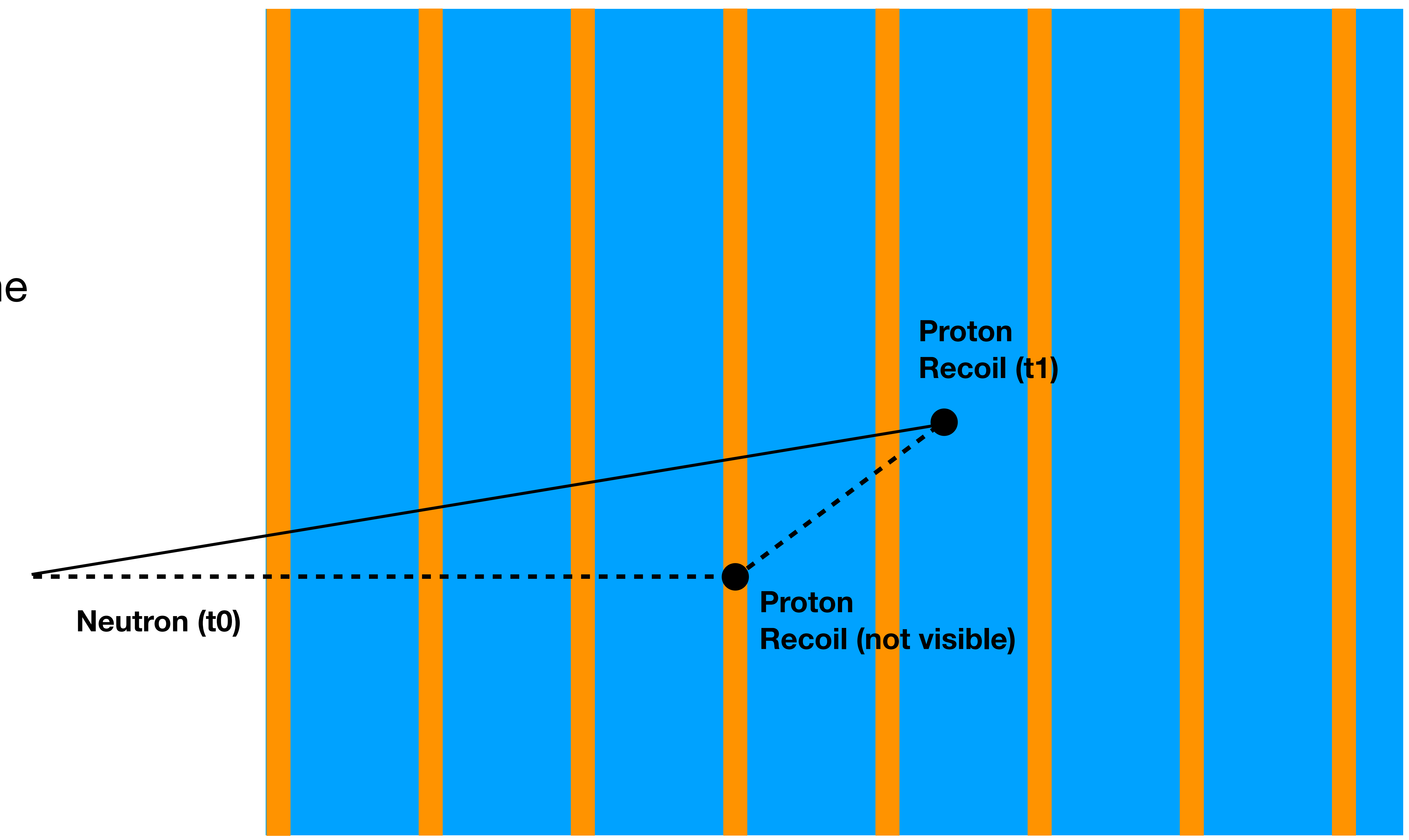




Neutron reconstruction.

ToF technique

- Typical proton recoil energies: few MeVs - however depends on the simulation model used
- **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



Neutron reconstruction.

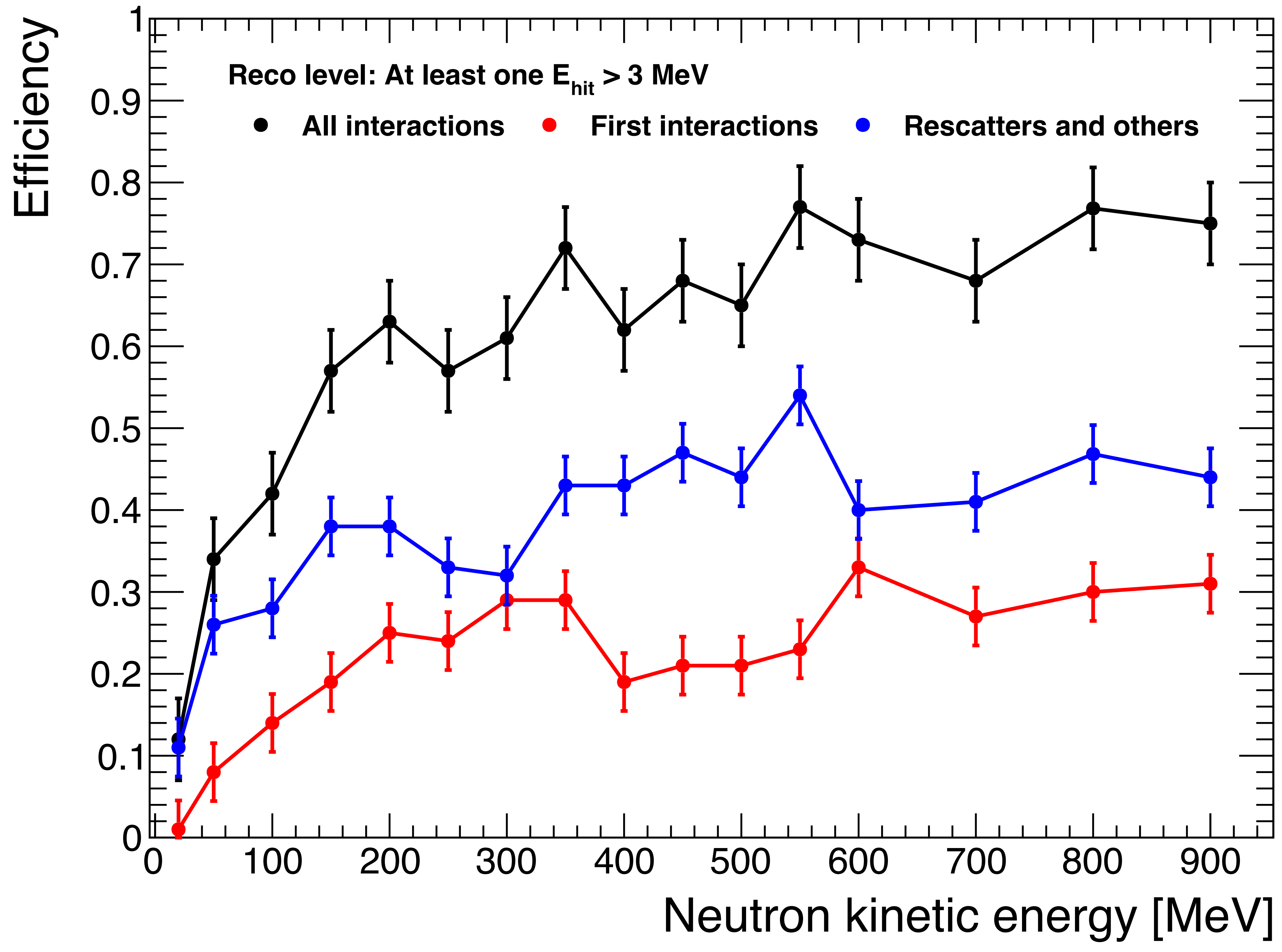
Baseline design

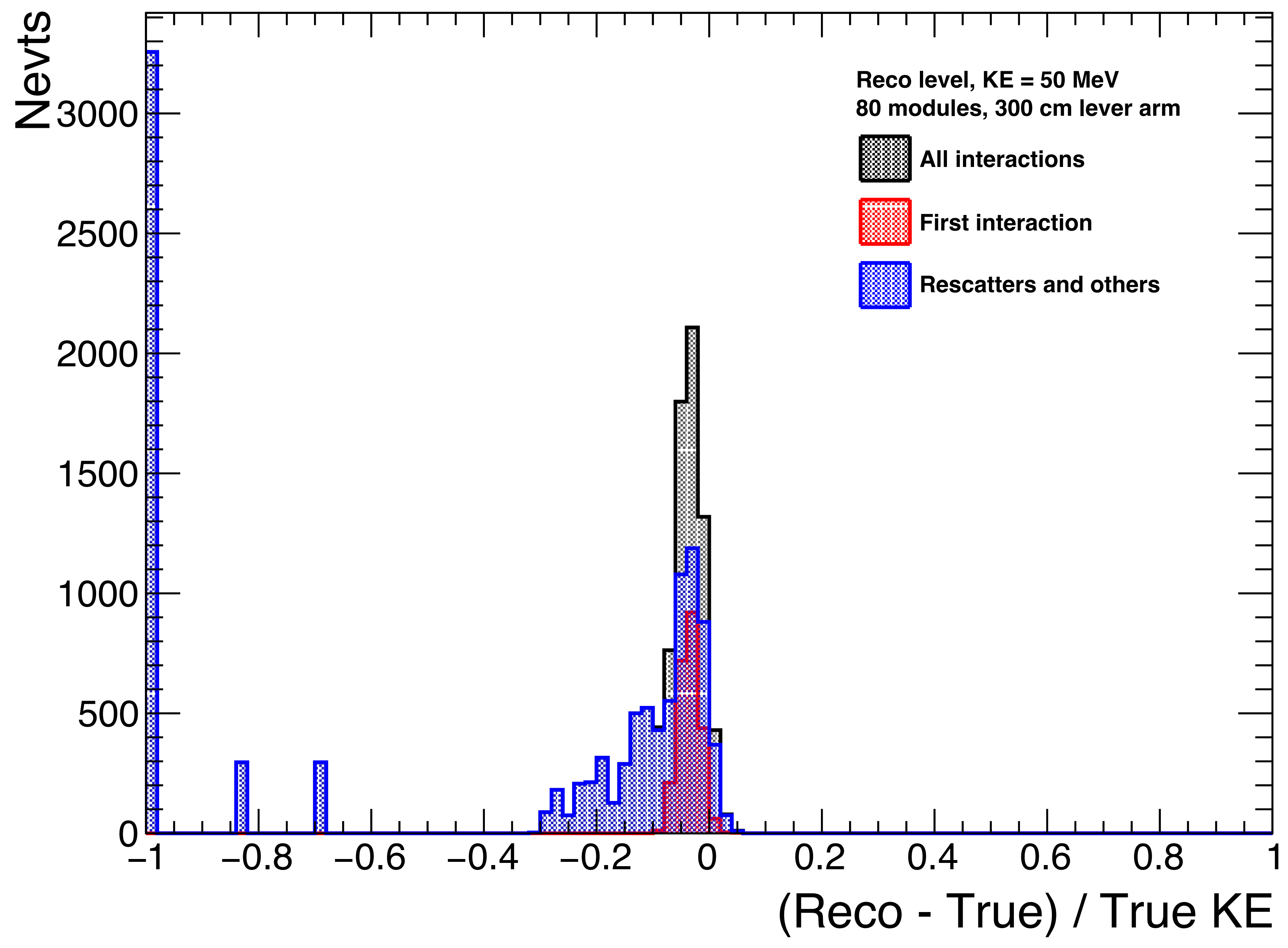
Configuration

- 2 mm Cu + 5 mm Sc (80 layers)
- Particle gun between 20 and 900 MeV
- Assumes **250 ps time resolution**
- Requirements:
  - First hit in time with **at least 3 MeV** of deposited energy

Observations

- Overall efficiency of above **50-60%**
  - Mostly **dominated** by rescatters





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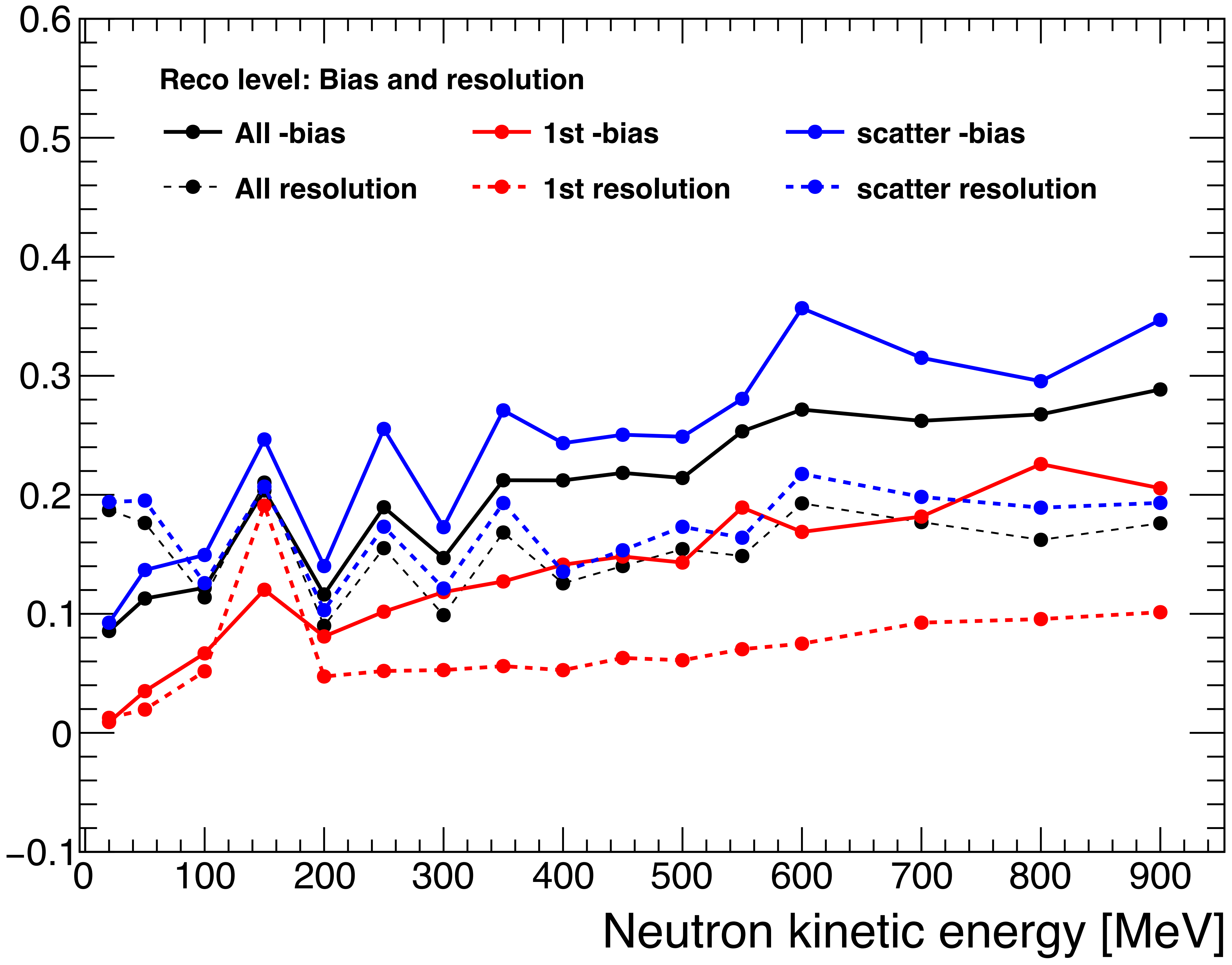
Observations

- Overall efficiency of above **50-60%**
    - Mostly **dominated** by rescatters
- Rescatters degrade the energy resolution and introduce a bias! ➠ can be limited by cutting on the layer

Improvements

- Still needs to be established in a real environment
- Scintillator doping / impact on background

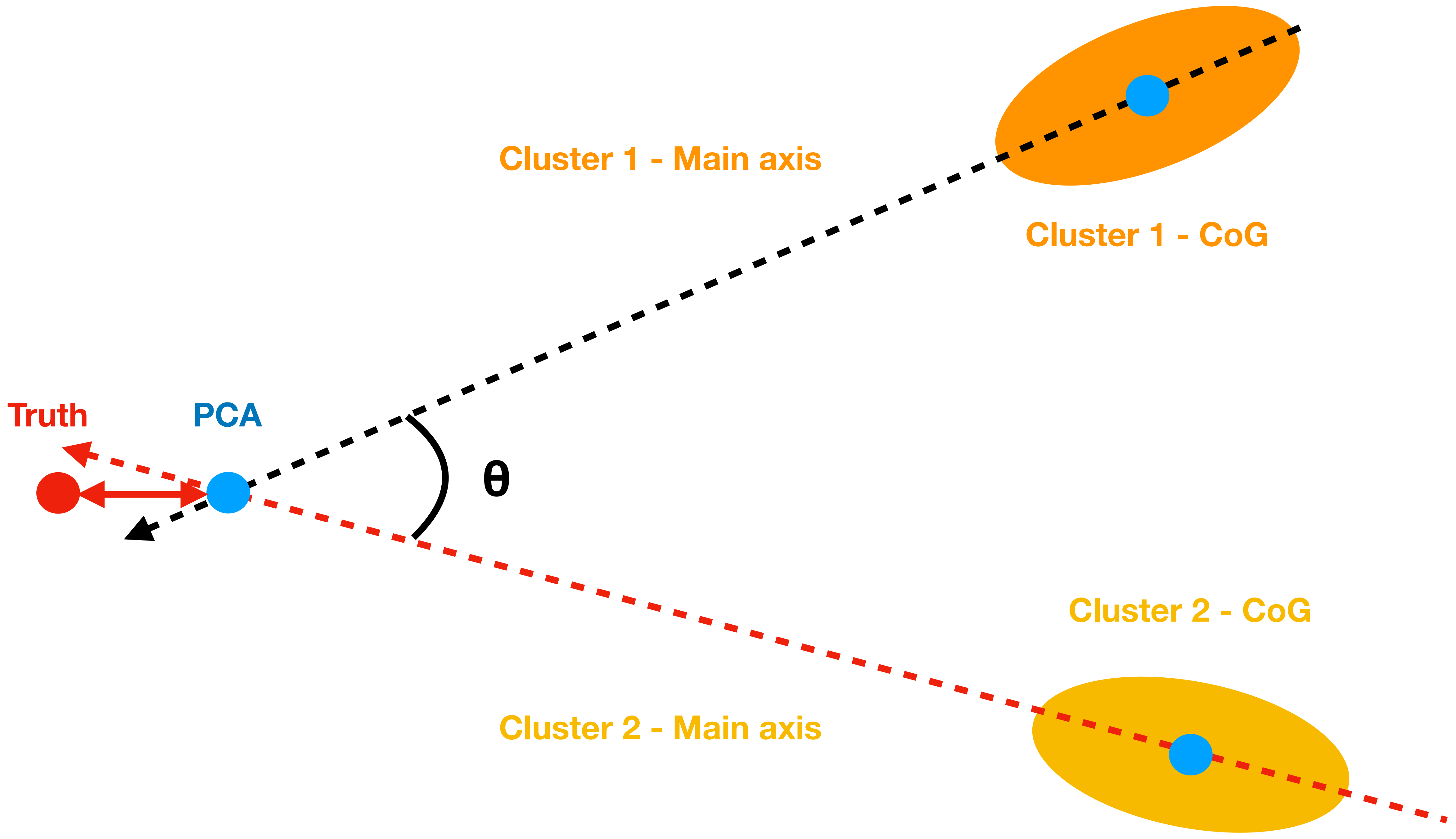


If demonstrated to be possible -> Bonus point for the ECAL

Neutral pion reconstruction.

Setup and method

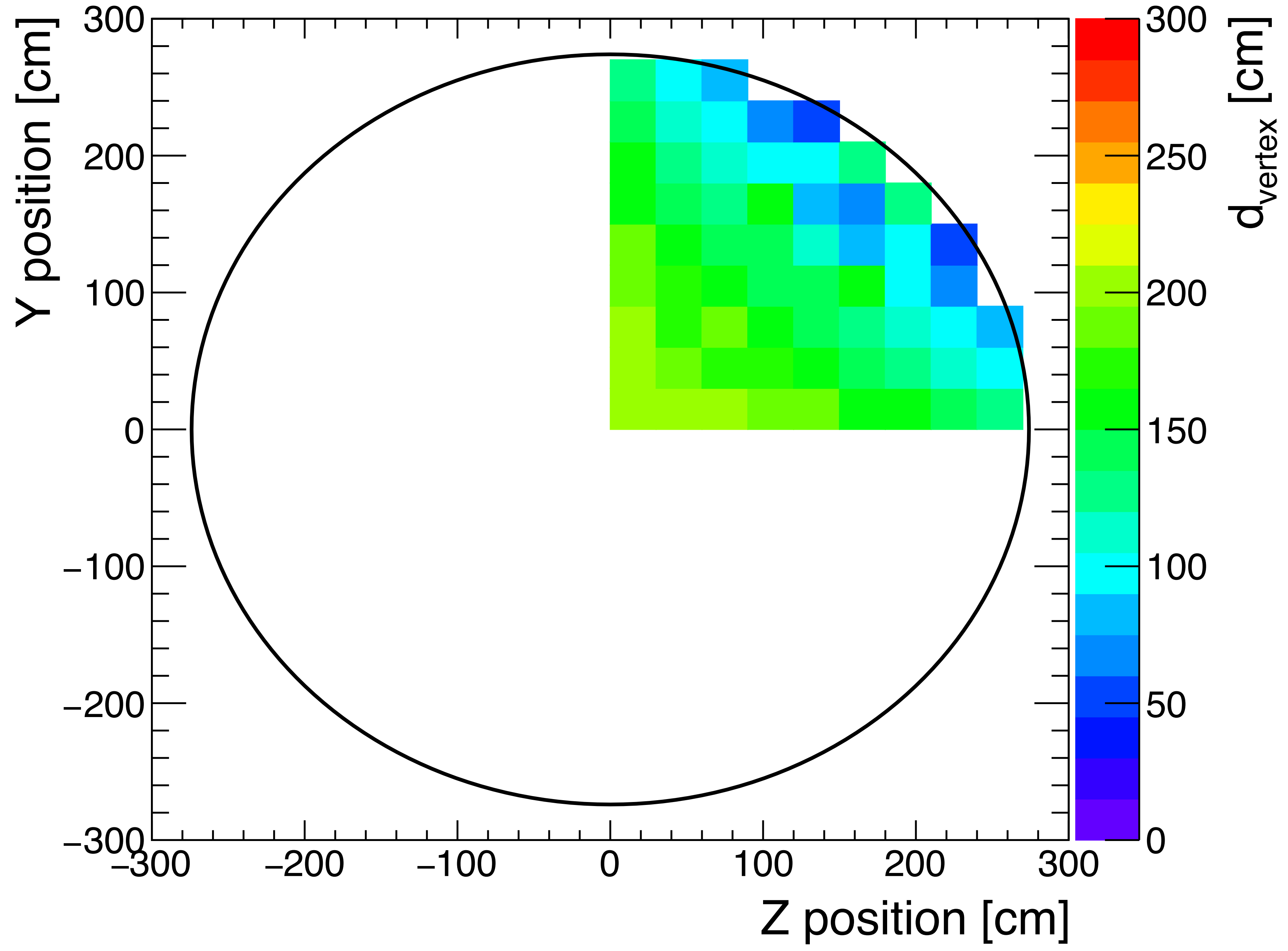
- Shooting π^0 s in the z direction between 0 and the TPC radius at intervals of 15 cm (x position fixed)
- **Simple Method** (no MC info used):
  - Take the *two most energetic clusters* (some case have more than two clusters)
  - Take the direction from the cluster main axis and calculate the PCA between the two cluster axis
  - Calculate the angle between the two cluster axis and reconstruct the π^0 mass
  - Calculate the 3D distance between the true vertex and the geometrical determined one
  - χ^2 minimization can be done after using the energy and geometrical information combined (not yet included)
- Work in progress

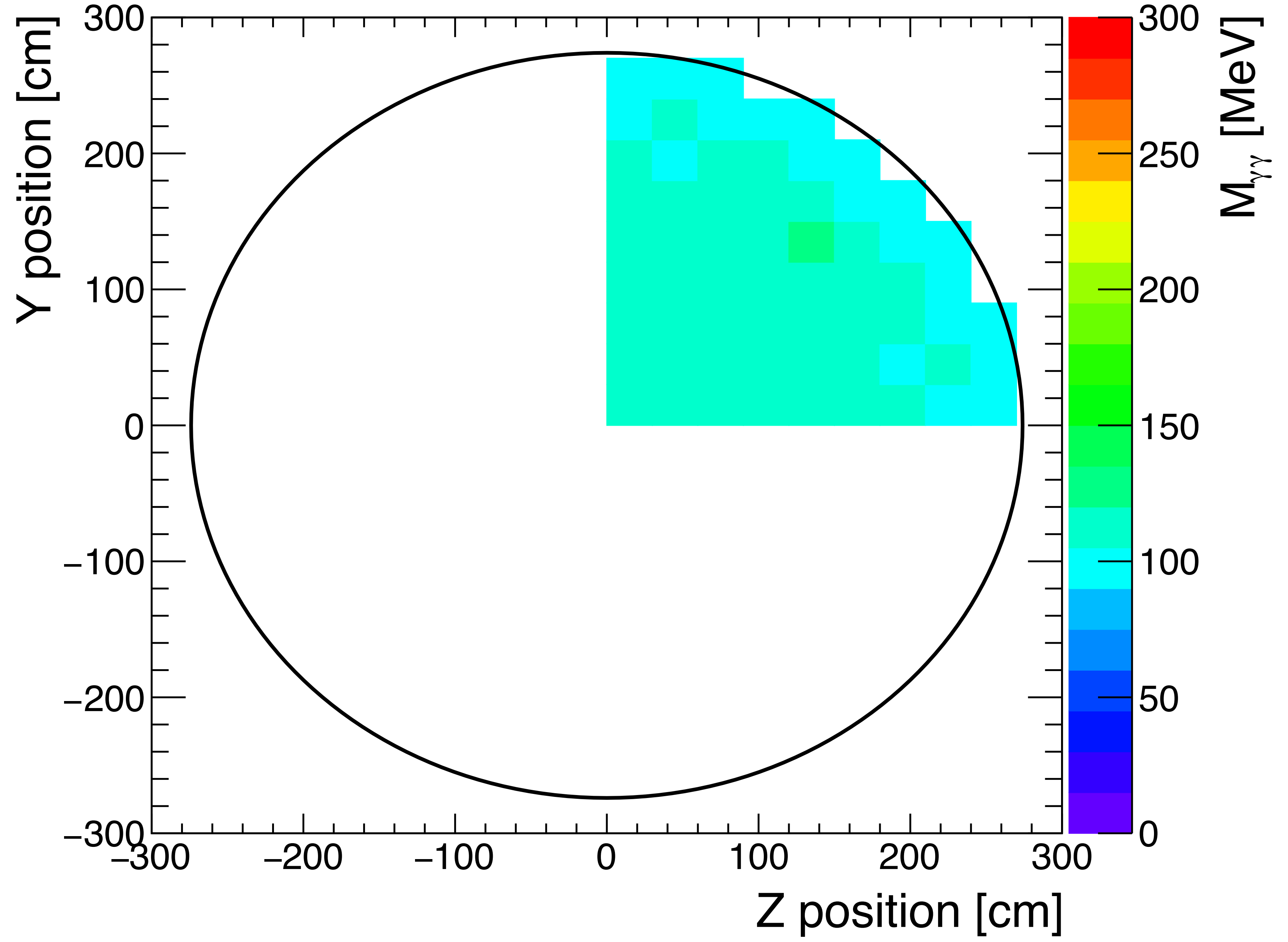


Neutral pion reconstruction.

Work in progress

- Case shown: 400 MeV neutral pion
- Look at the distance to the true vertex and reconstructed invariant mass as function of the vertex position
- π^0 s reconstructed between 100-150 MeV ➟ clustering effect
- Distance to the truth vertex around 150 - 200 cm ➟ mostly the z-coordinate is badly reconstructed
- Factor ~x5 worse than more complete studies
  - Not yet using the χ^2 minimization ➟ *important for the position resolution*
  - Clustering *not optimized*



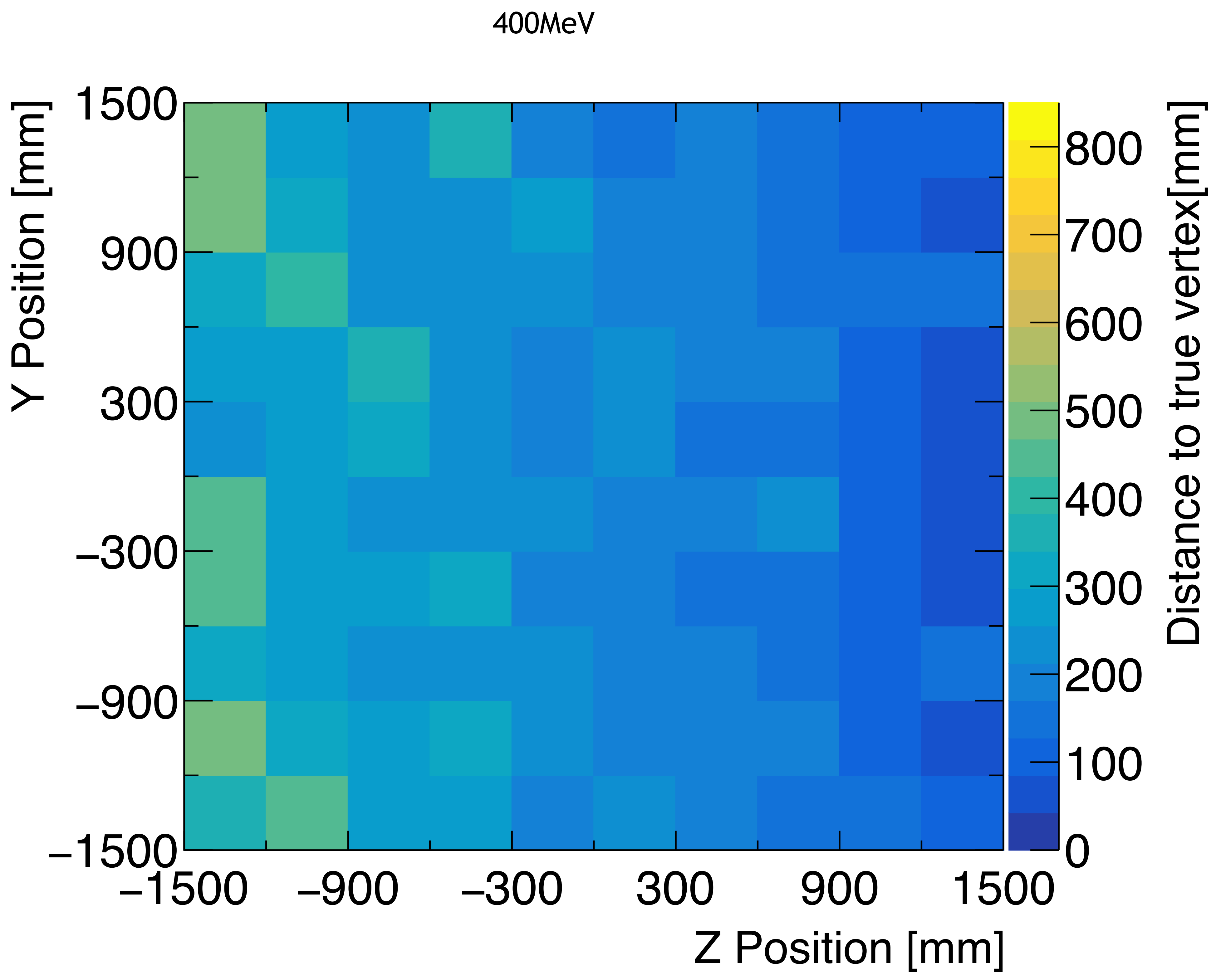


Neutral pion reconstruction.

Work in progress

Previous study at MPP

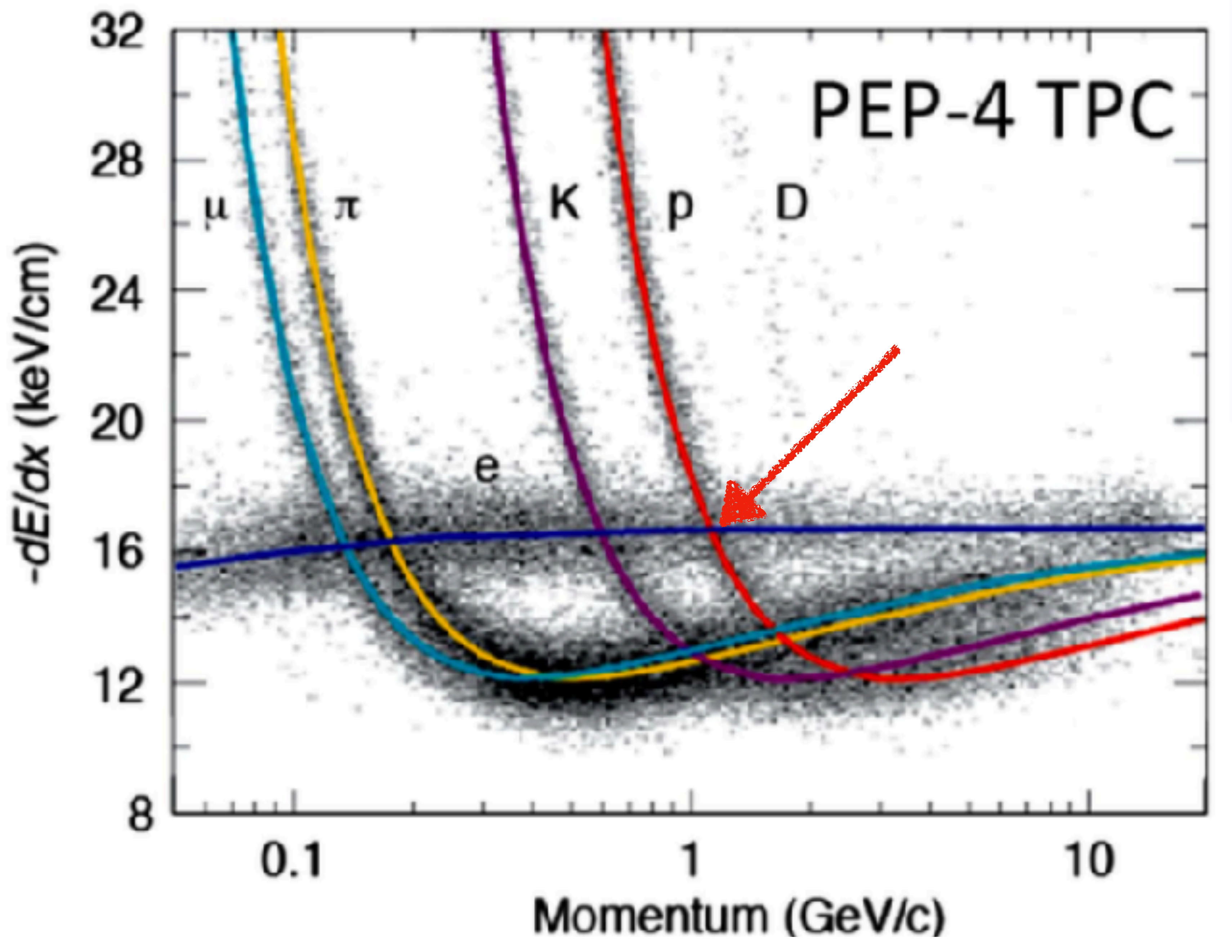
- Photon energy resolution and angular resolution very similar to previous studies ➠ similar results as previous study should be achievable
- Clustering degrades significantly the reconstructed π^0 mass ➠ was avoided before by truth clustering
- Possible improvements:
  - Better clustering algorithm
  - χ^2 minimisation using the mass information in order to improve the vertex reconstruction (previous studies showed a distance around 20-30 cm depending on the distance from the ECAL)
  - The use of timing/additional tracks could help in constraining the angle between the clusters and the location of the vertex
  - Improve the method by using the most energetic photon direction and timing to give a better estimate of the vertex



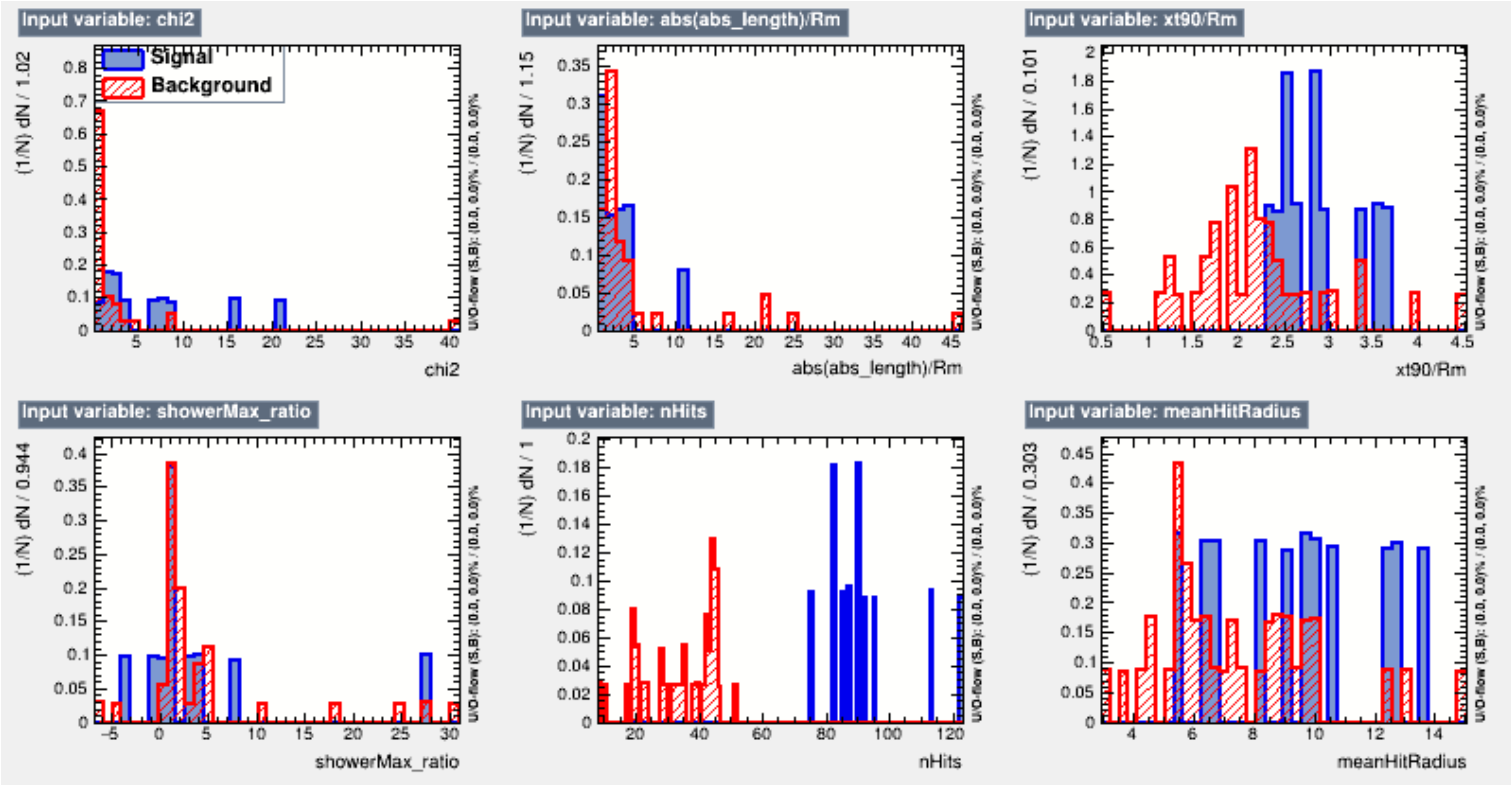
Particle identification.

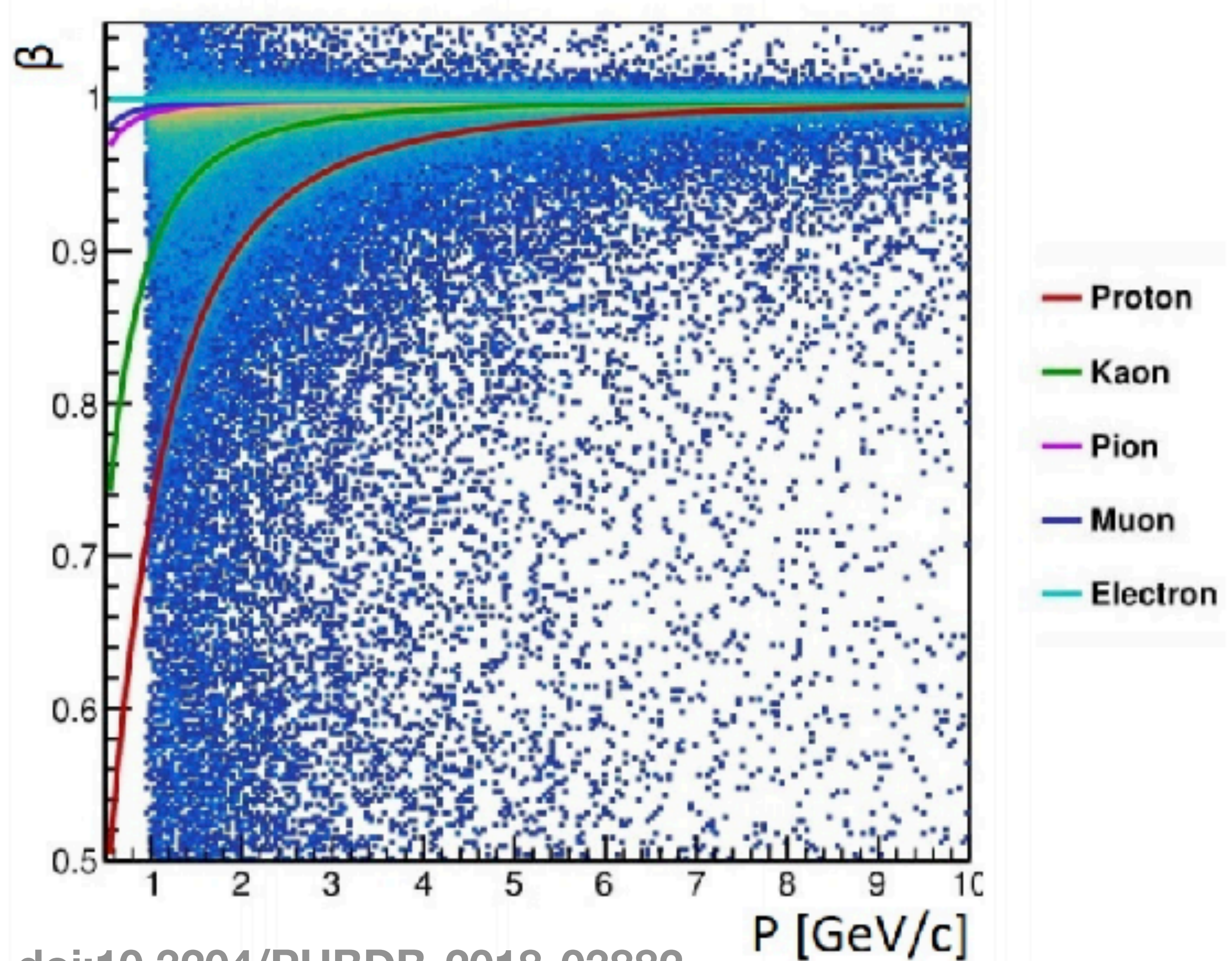
Work in progress

- ECAL needs to be complementary to the HPgTPC
- Example
  - Separation muon / pion
  - Separation proton / positron around 1 GeV
- Use of shower shape variables: shower start, number of hits, shower size … combined with TMVA techniques (Likelihood, BDT…)
- Alternatively, time of flight technique could be used combined with dE/dx



Work in progress



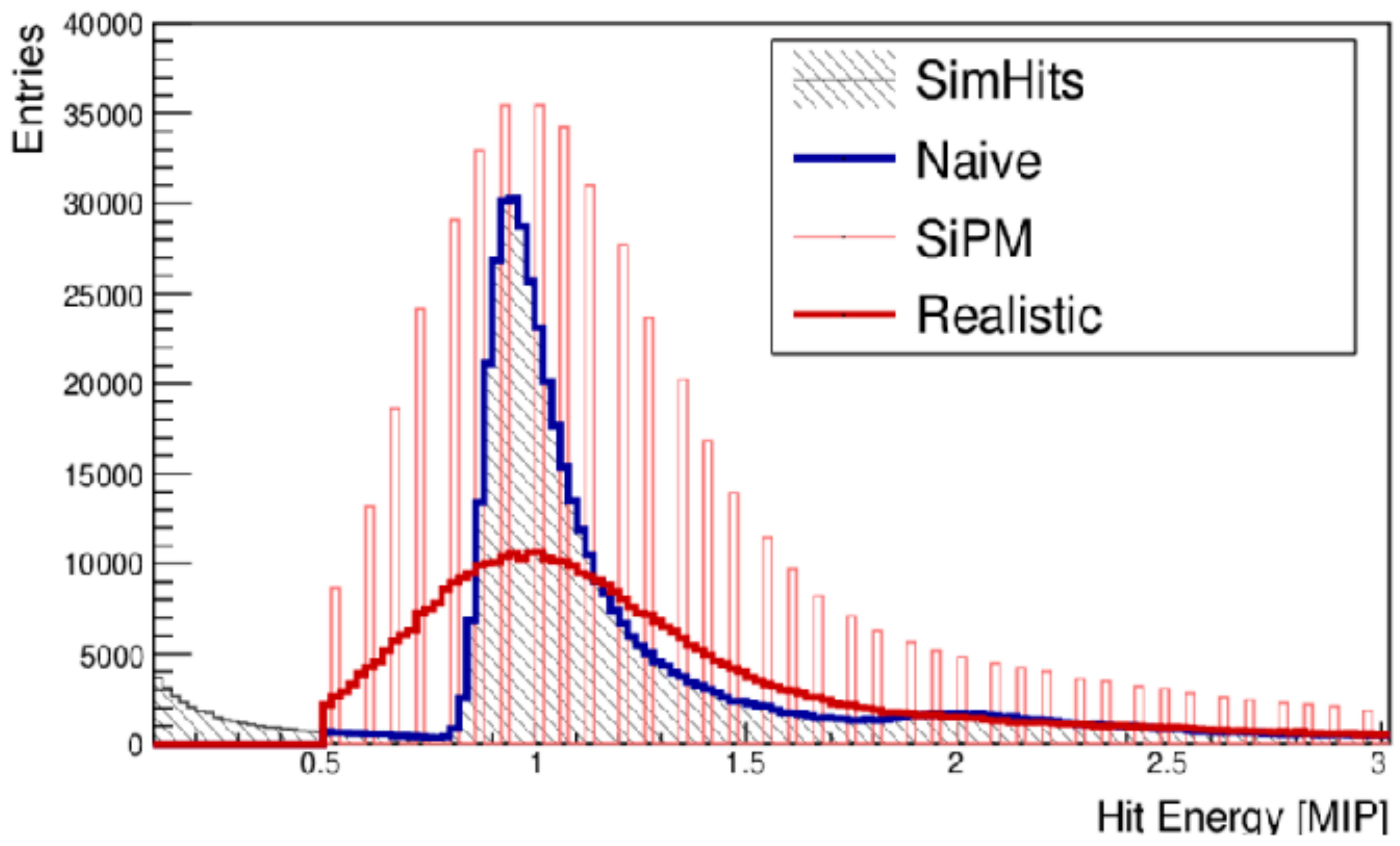


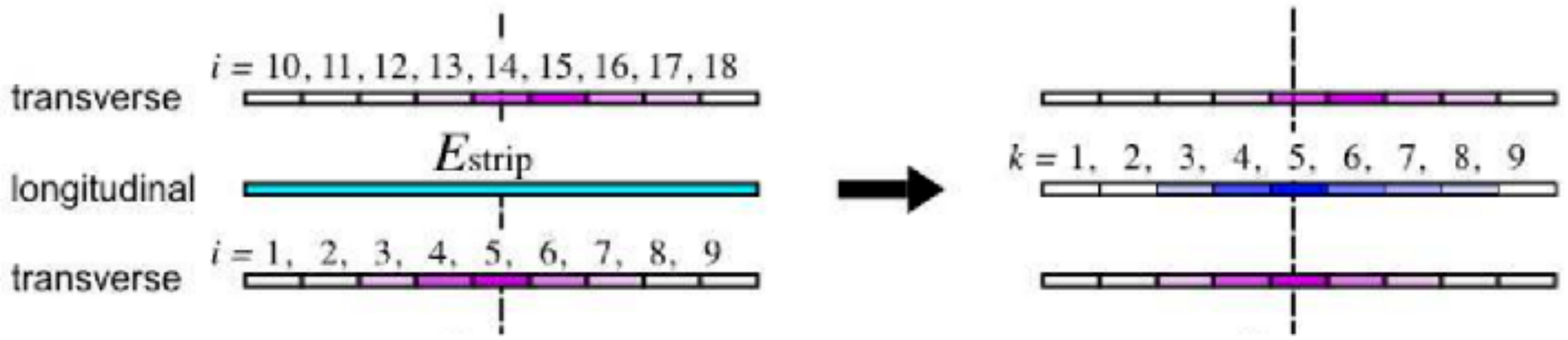
doi:10.3204/PUBDB-2018-03882

Software: ECAL Reconstruction.

Work in progress

- Developed in parallel to the HPgTPC reconstruction (see Tom's talk) and integrated into GArSoft
- SiPM digitisation ➠ Saturation + SiPM binomial smearing as used in CALICE
- Hit reconstruction
  - Tiles straight forward (threshold check - still need proper electronic response)
  - Cross-strips
    - ➠ strip-splitting algorithm (1405.4456v2) in development
    - ➠ use timing to reconstruct hit along the strip (250 ps ~ 7 cm)
- Clustering algorithm
  - Simple NN algorithm
- Integration issues
  - Unified software framework for the ND complex ➠ task force starting





Software: To do list.

Open-ended list

- ECAL specific
  - More realistic electronic response
  - Improvement of clustering and possible Pandora integration
  - SSA to be finalised
  - Association TPC tracks to ECAL clusters
  - Implement particle identification / π^0 reconstruction / neutron reconstruction techniques
  - Full energy reconstruction (only visible energy so far)
- General
  - Full event reconstruction
- **Ideas and help are welcomed!**

Conclusions and Outlook.

Some work and more to come…

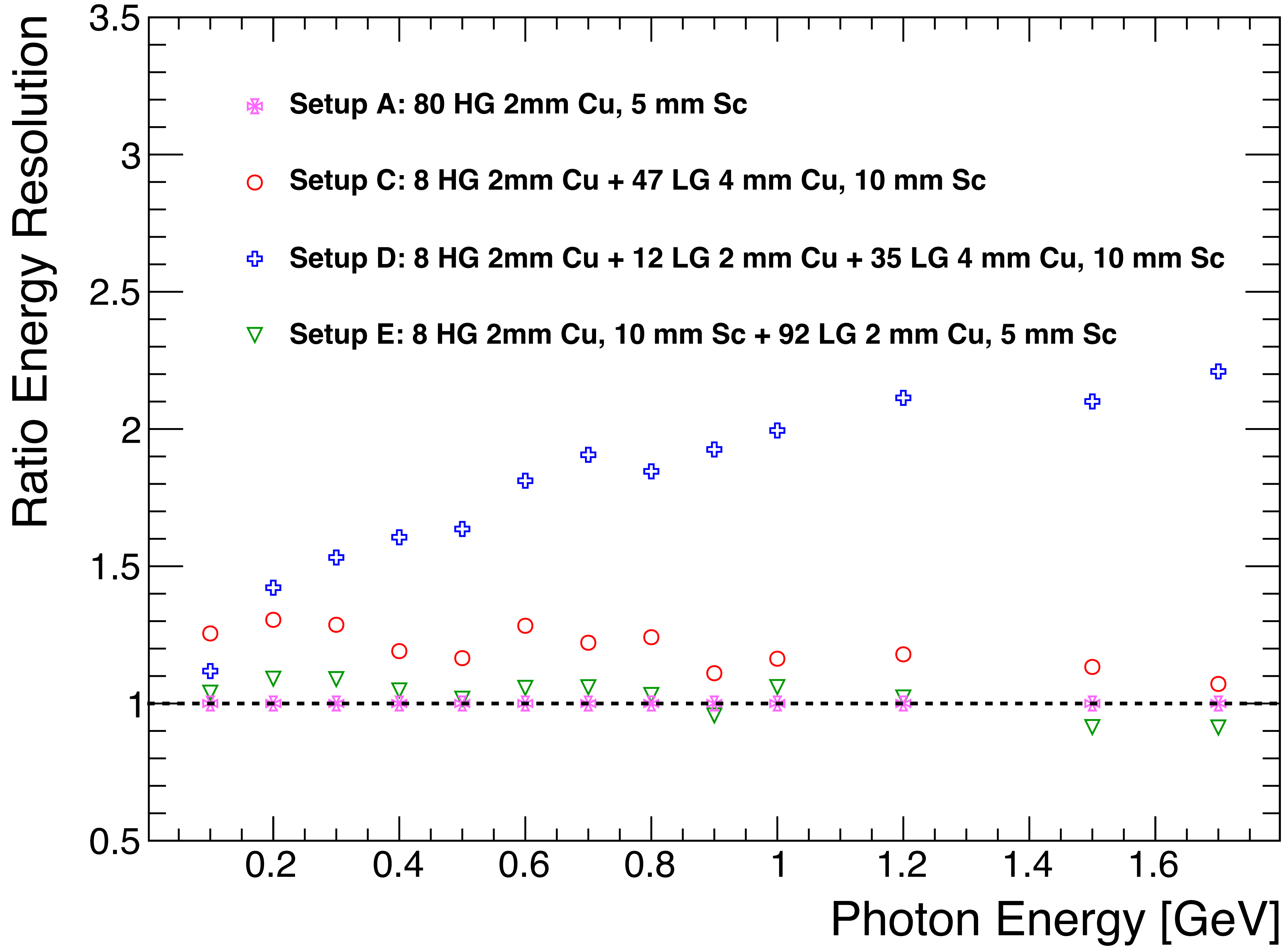
- An ECAL design is on its way
- Detailed optimisation studies are starting
  - EM **energy resolution and angular resolution** investigated for several models to understand the impact of each parameters
    - **Best achieved**: ~5%/√E + 1% - ~3.5°/√E + 2°
  - The ECAL may **have potential in neutron energy reconstruction** with ToF
    - Energy resolution below 20% for a large range of neutron KE - however bias in the reconstruction
    - Improvements possible
  - **Neutral pion reconstruction/Particle identification** is work in progress, still place for improvements
- Software:
  - Much progress been done in the last few months
  - Integration into a common ND framework started
  - Long to do list
  - Need to identify few key benchmark analyses

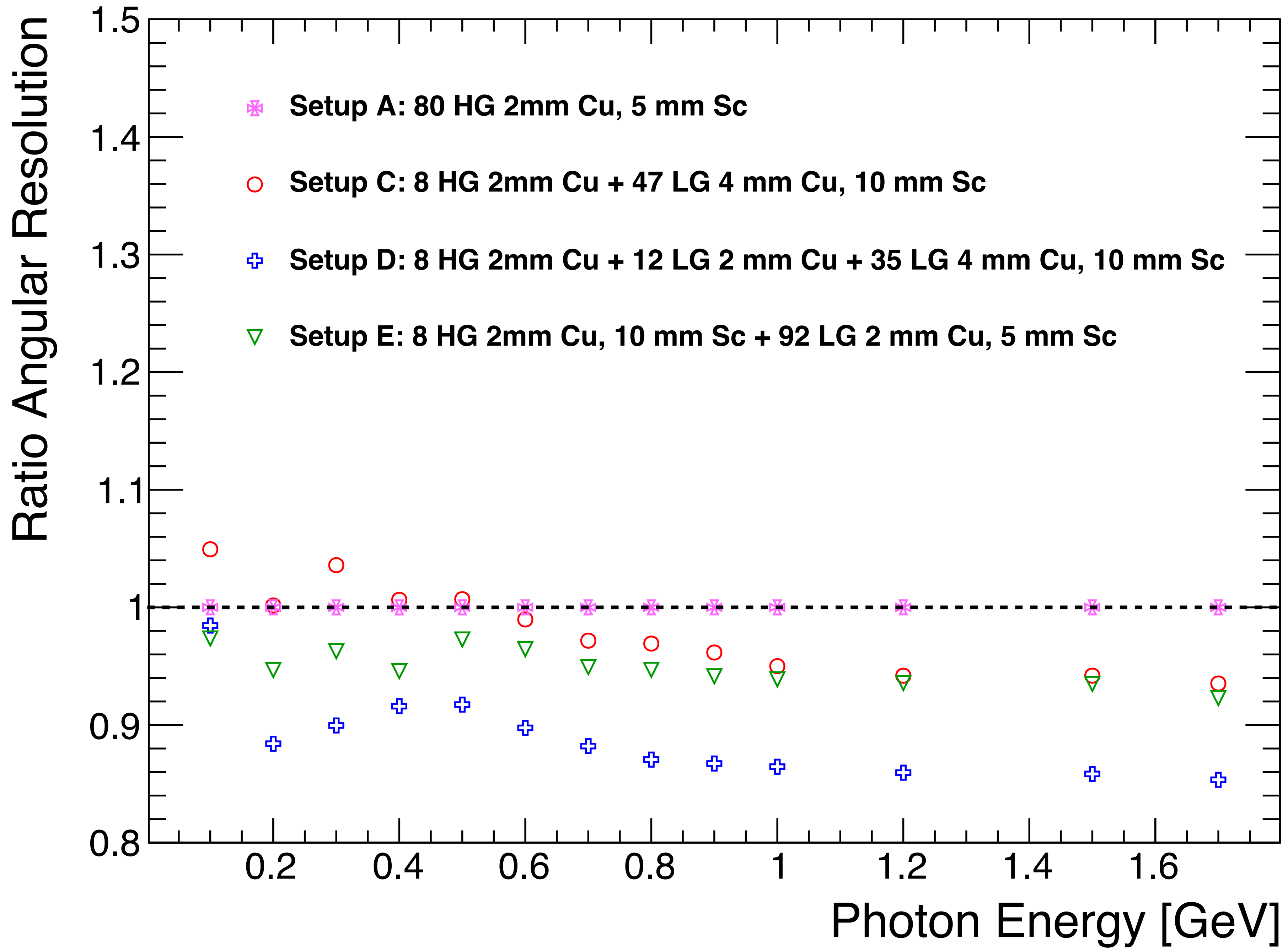
Backup Slides.

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

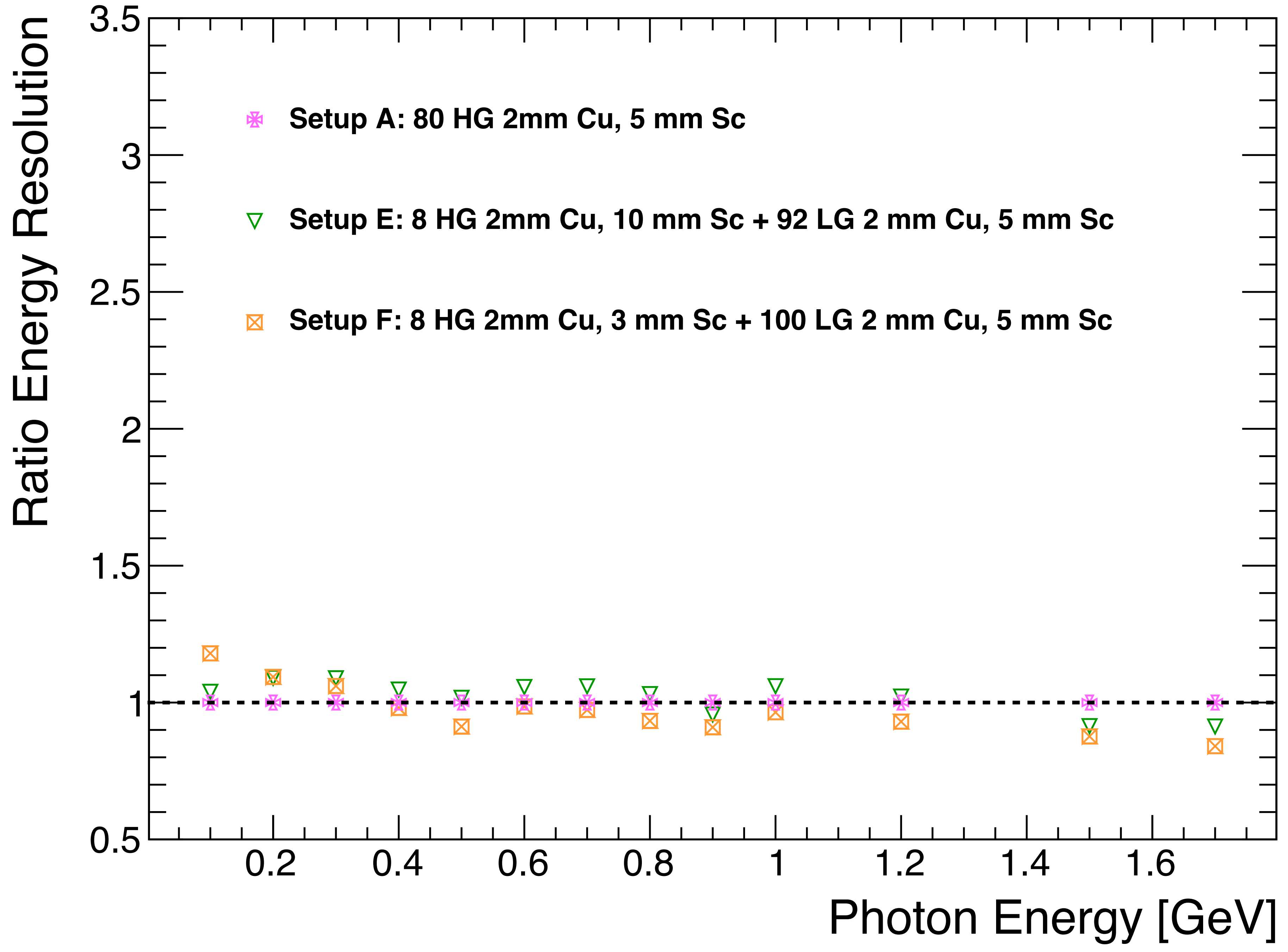


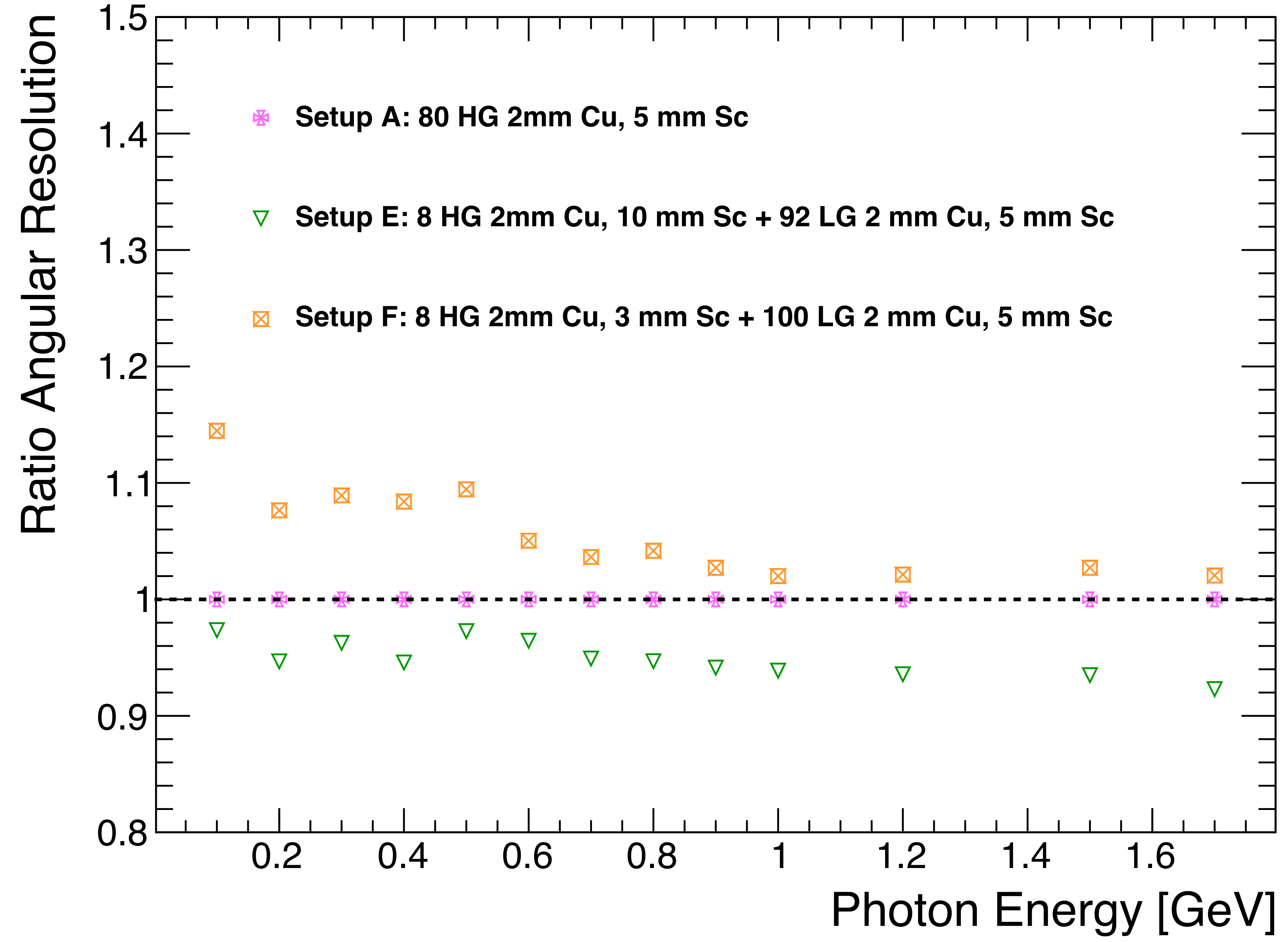


Simulation studies.

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
- 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





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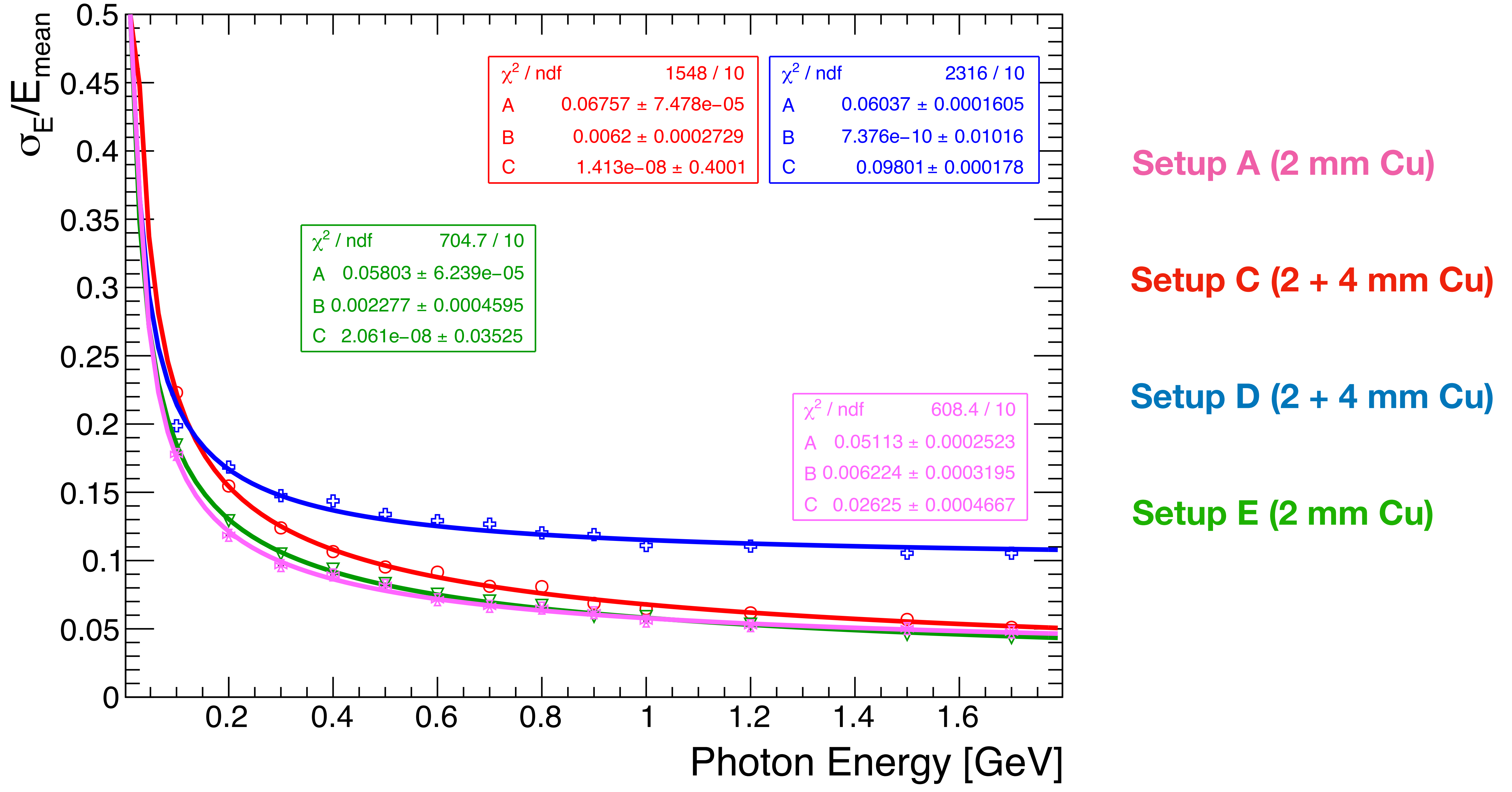

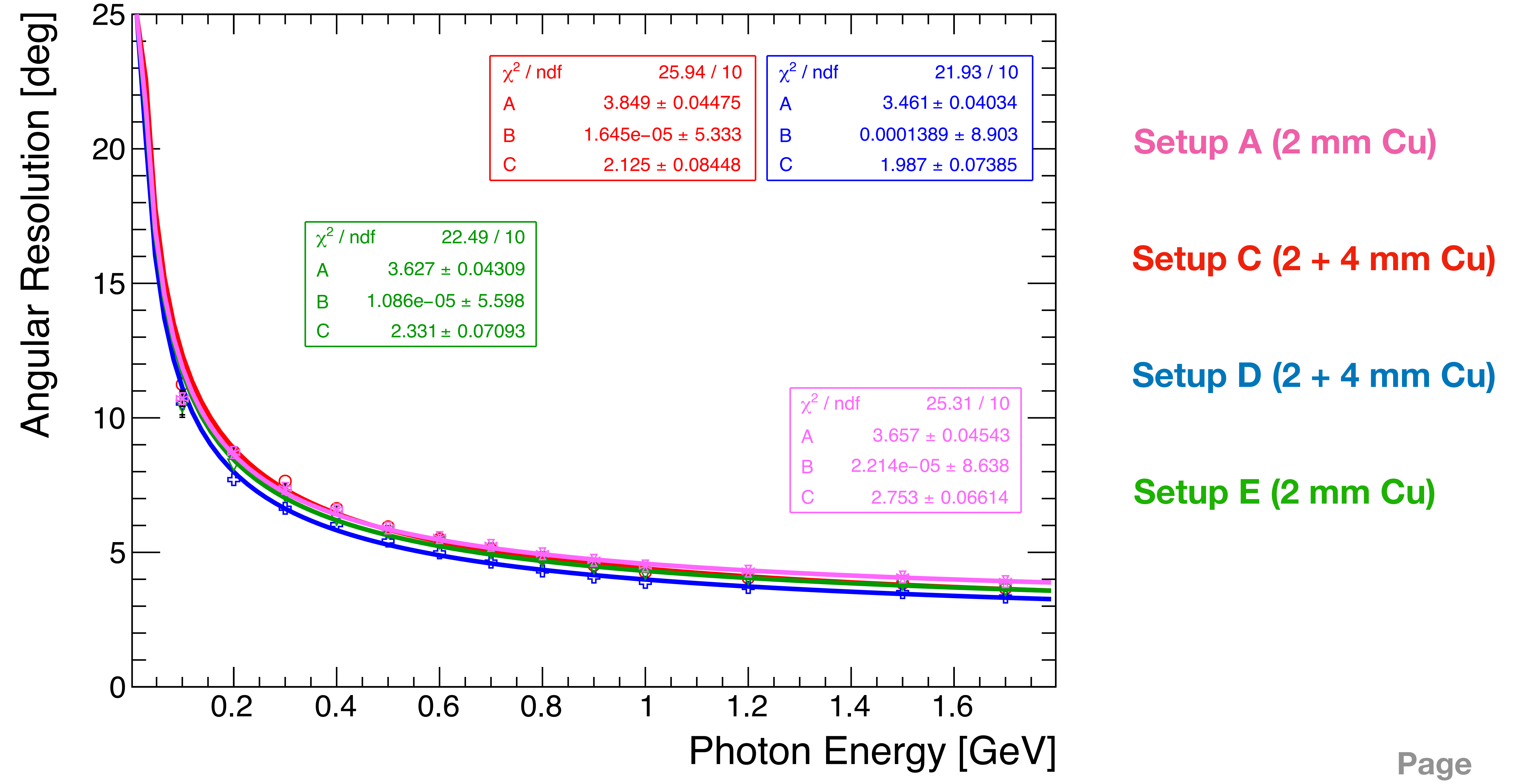

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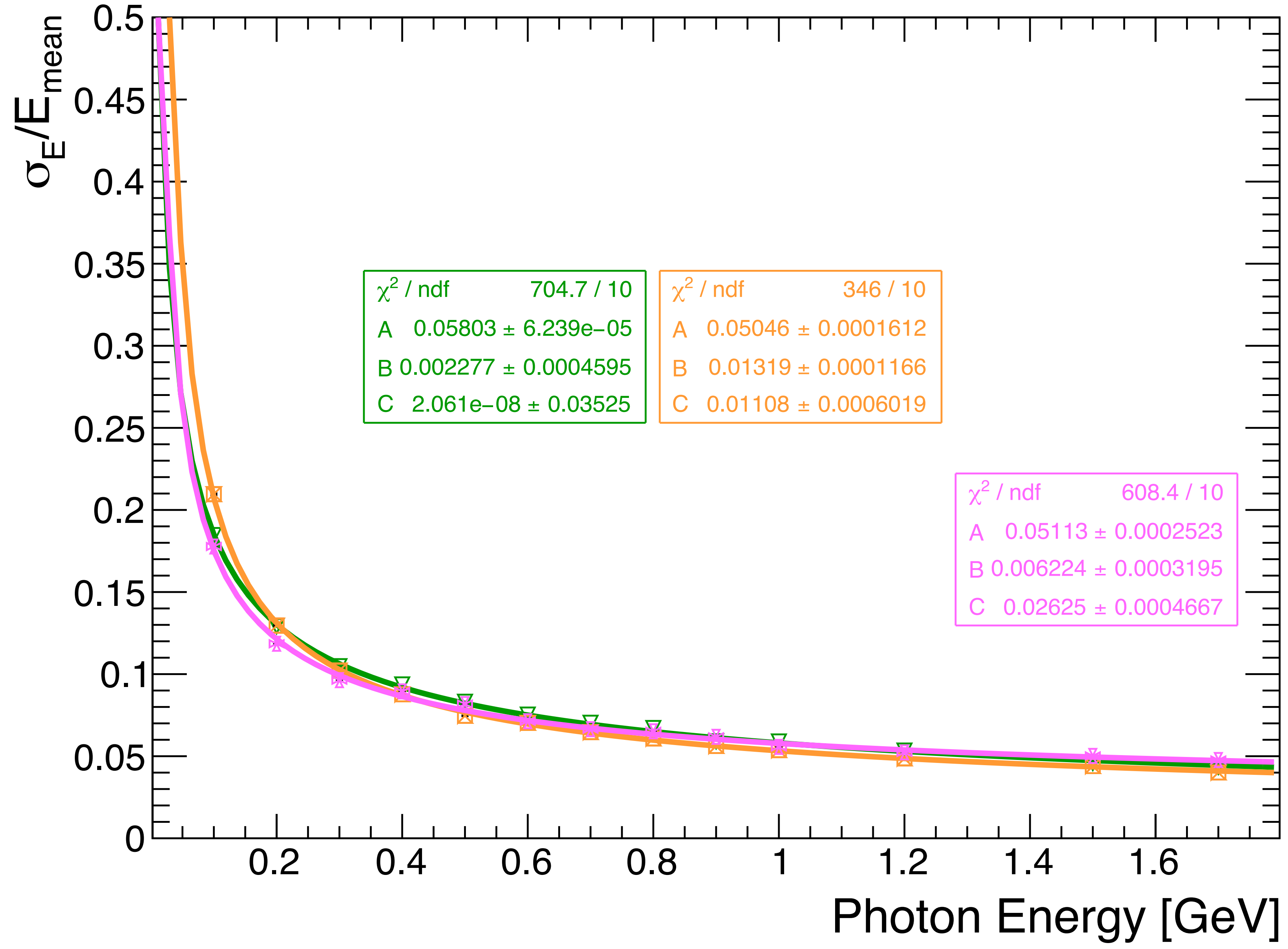
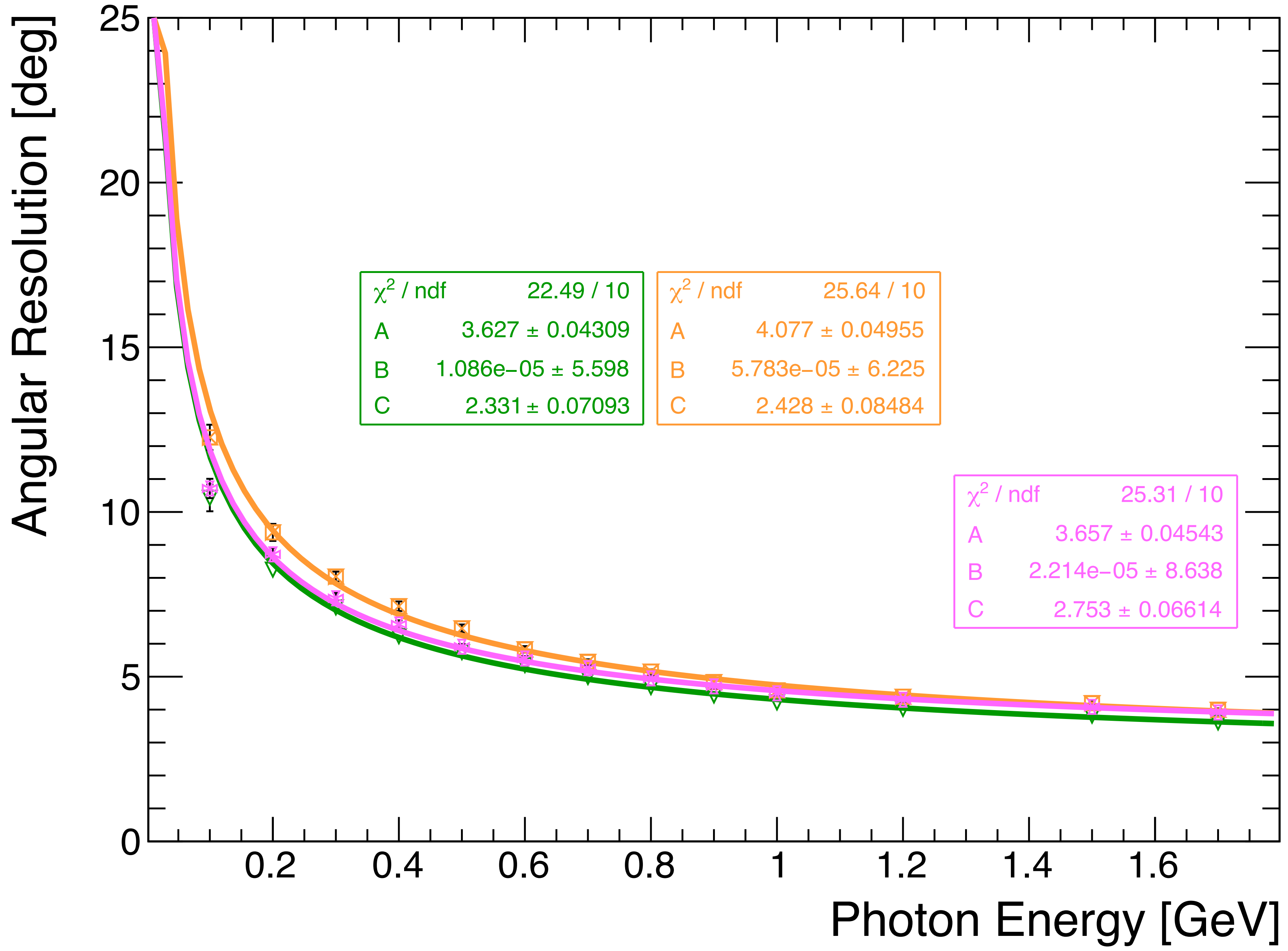


Setup A (5 mm Sc)

Setup E (10 mm Sc)

Setup F (3 mm Sc)



Setup A (5 mm Sc)

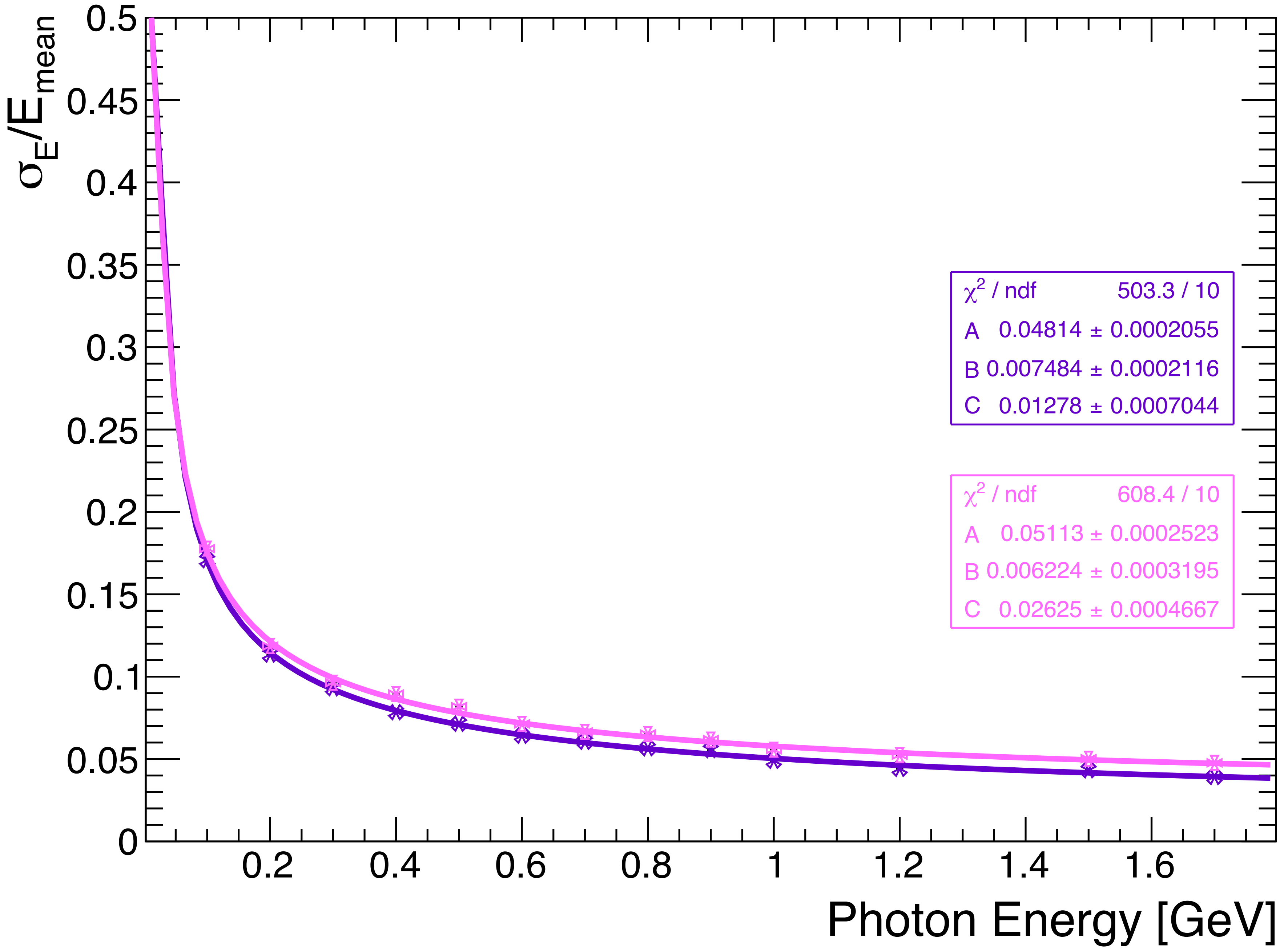
Setup E (10 mm Sc)

Setup F (3 mm Sc)

Simulation studies.

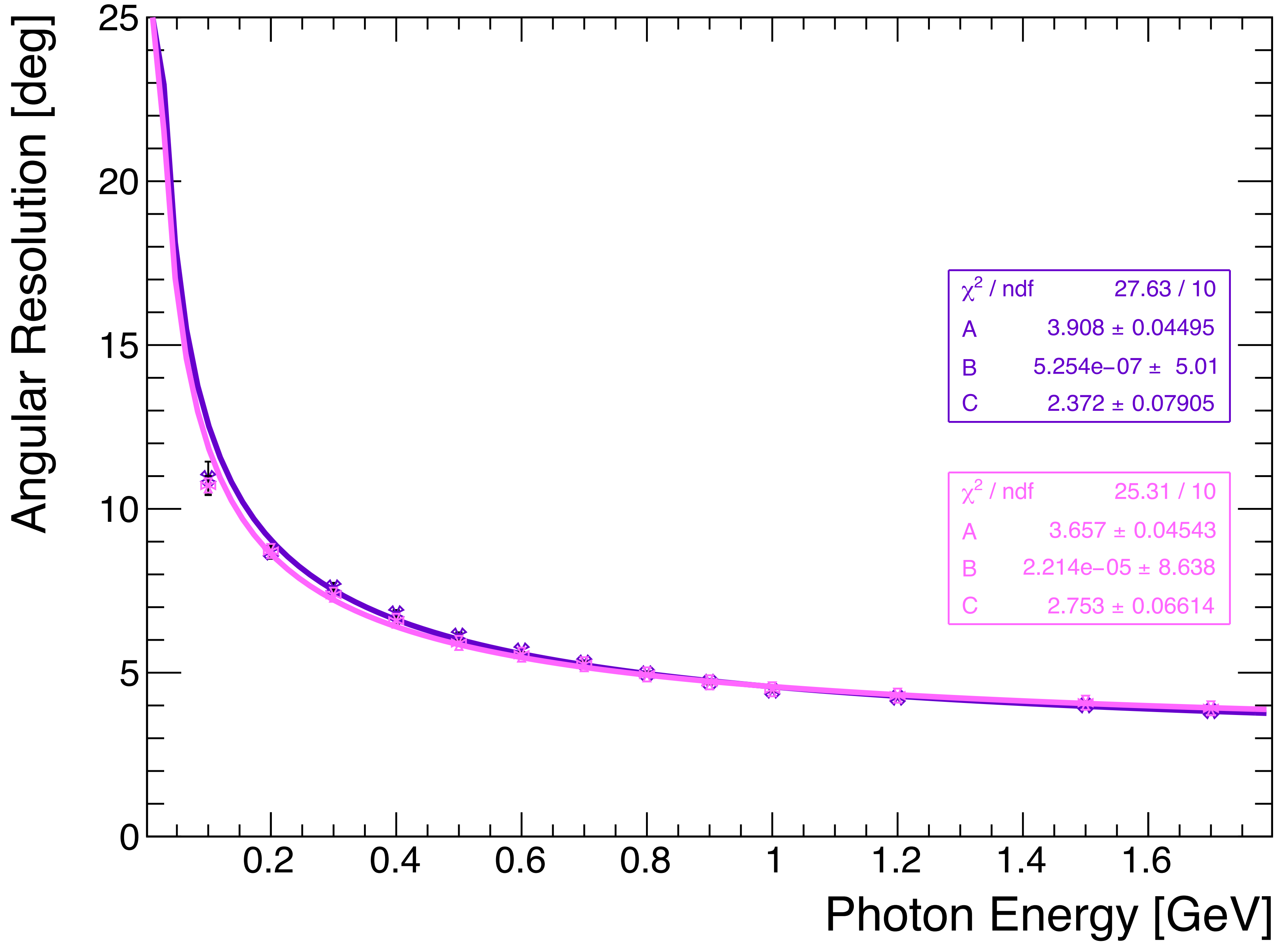
Influence of the granularity

- 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)

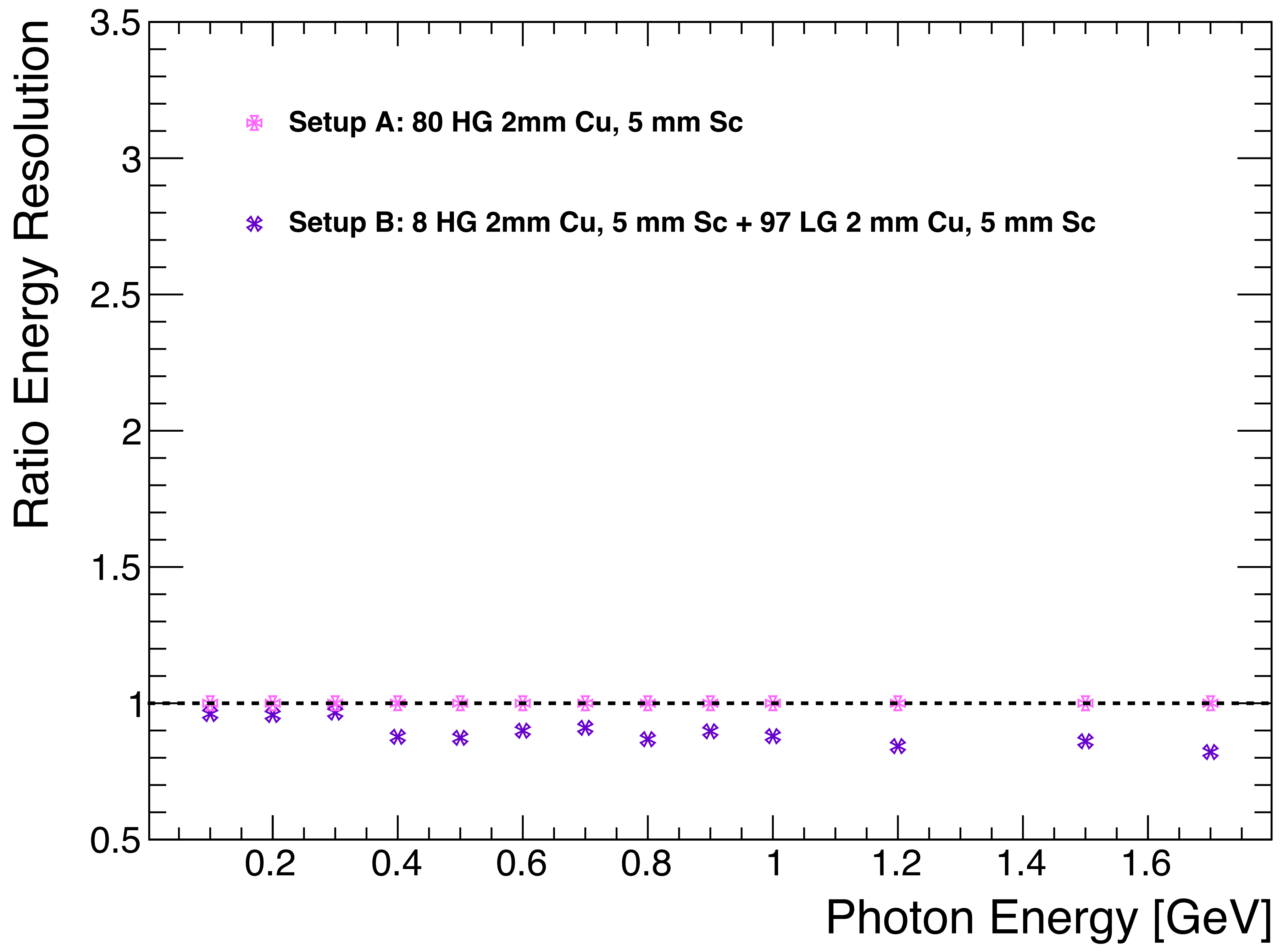
Setup A (full granularity)

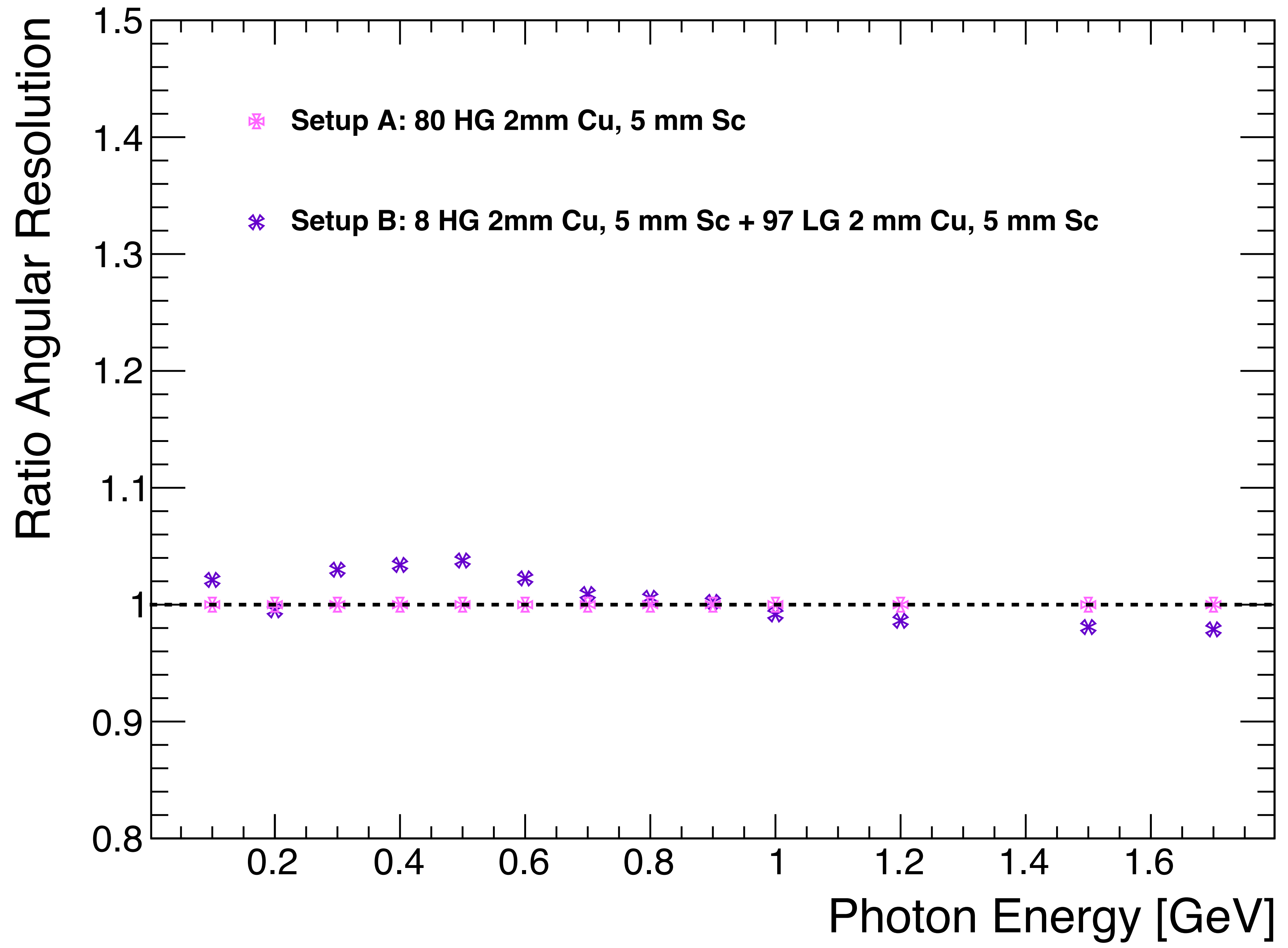
Simulation studies.

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!





Motivation.

Pushing the limits

- **Neutron production** for anti/neutrinos on Ar target is highly uncertain
    - 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!

Parameters for this preliminary study.

Setup

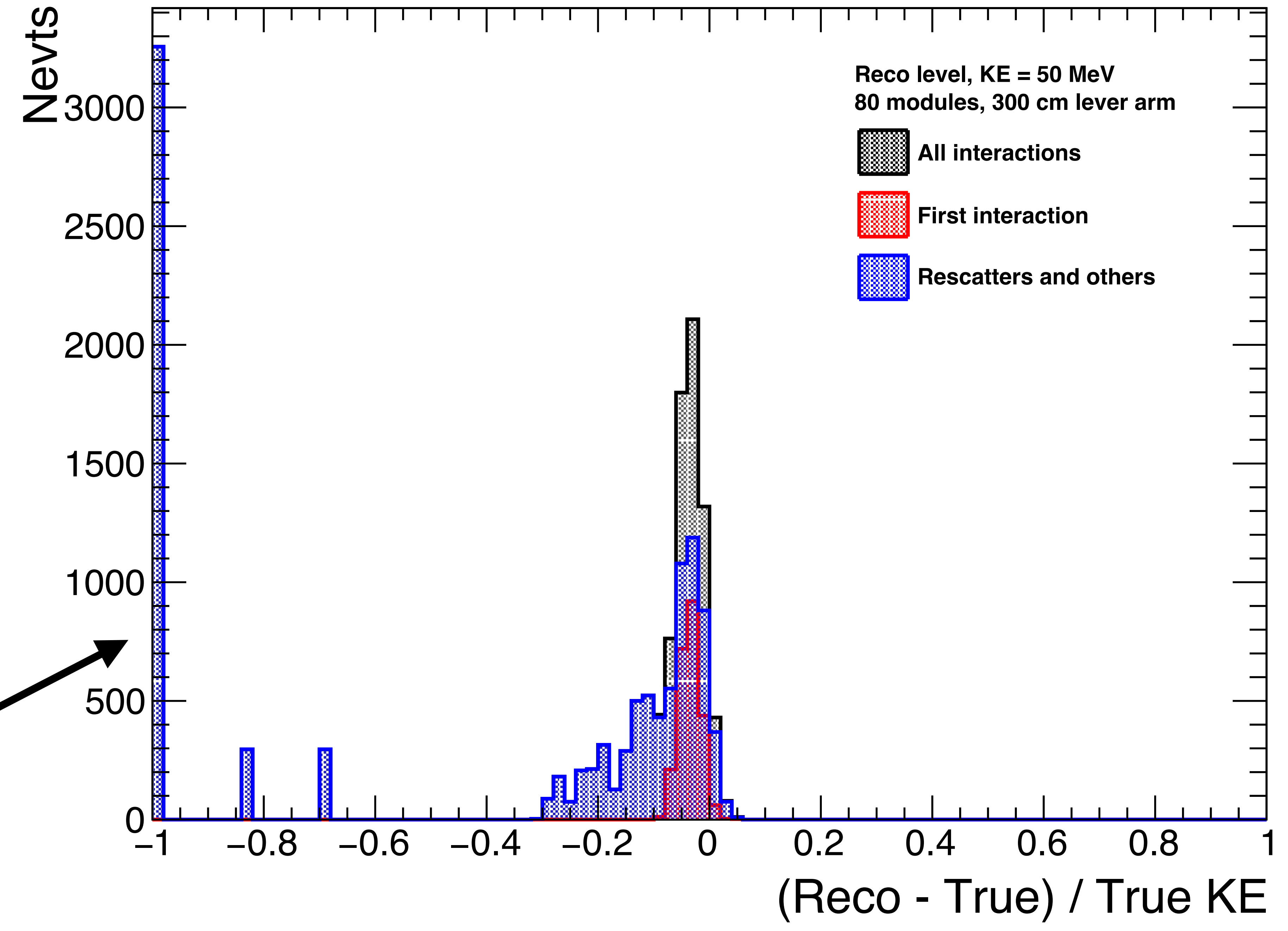
- Single neutron gun placed at ~3m or ~1m from the ECAL front face
- Comparison of *3 ECAL models (third one in backup)*
  - Outside the pressure vessel (0.5 X_0 of Al)
  - 80 / 45 layers
  - 5 mm Sc (+ Boron loaded), 10 mm Sc
- Two levels
  - **Simulation level** ➠ Geant4 step
  - **Reconstruction level** ➠ reconstructed calorimeter hit
- Assumes **250 ps time resolution**
- Requirements:
  - First hit in time with **at least 3 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)

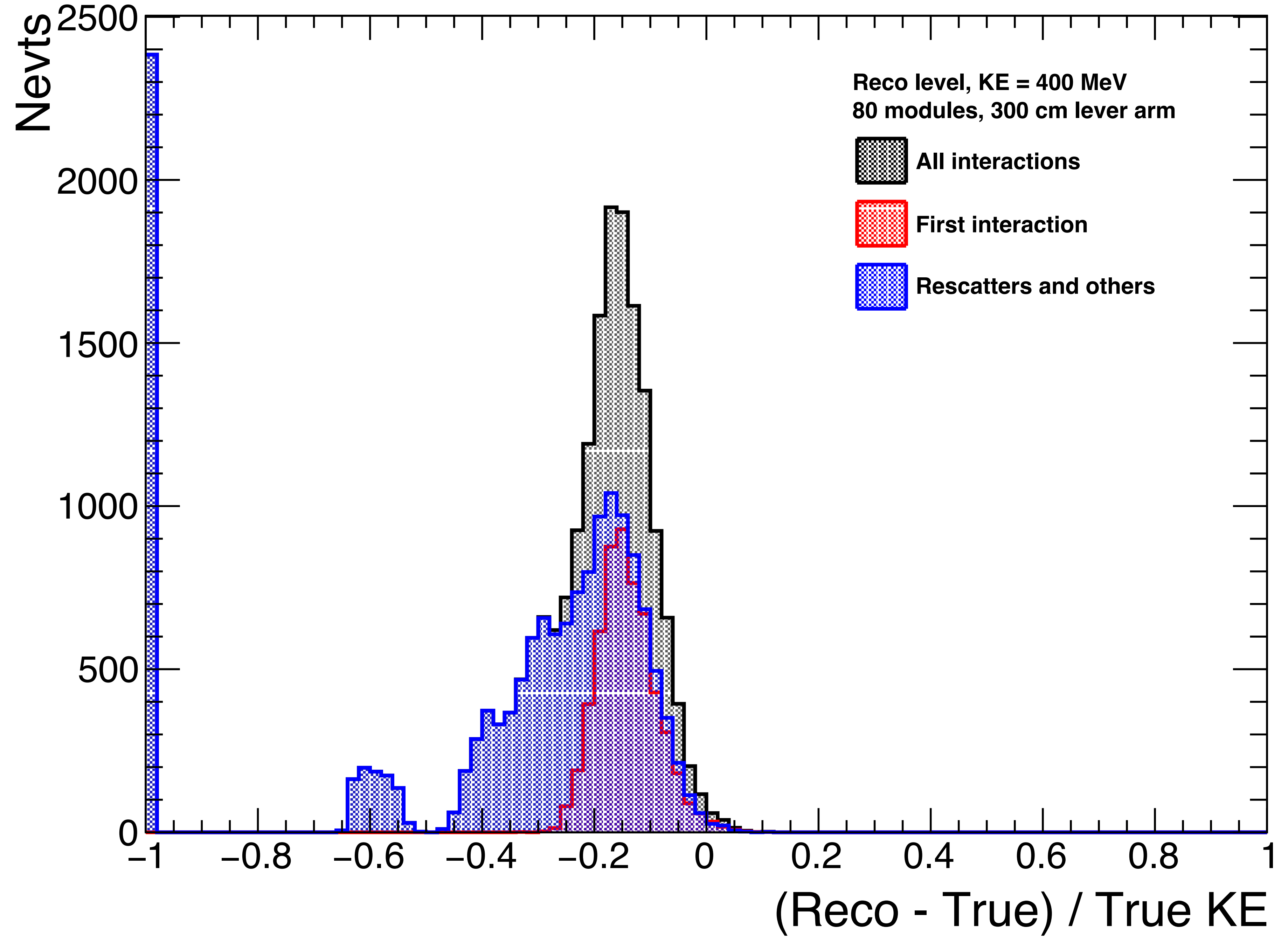
Neutron energy reconstruction.

First Setup

First Setup

- 2 mm Cu + 5 mm Sc (80 layers)
- Overall efficiency of above **50-60%**
  - Mostly **dominated** by rescatters
- Energy reconstruction
  - @ 50 MeV: large fraction at -1 (very delayed events due to *nucleus de-excitations*)
  - @ 400 MeV: Rescatter get more pronounced
  - Rescatter more pronounced at higher KE energies



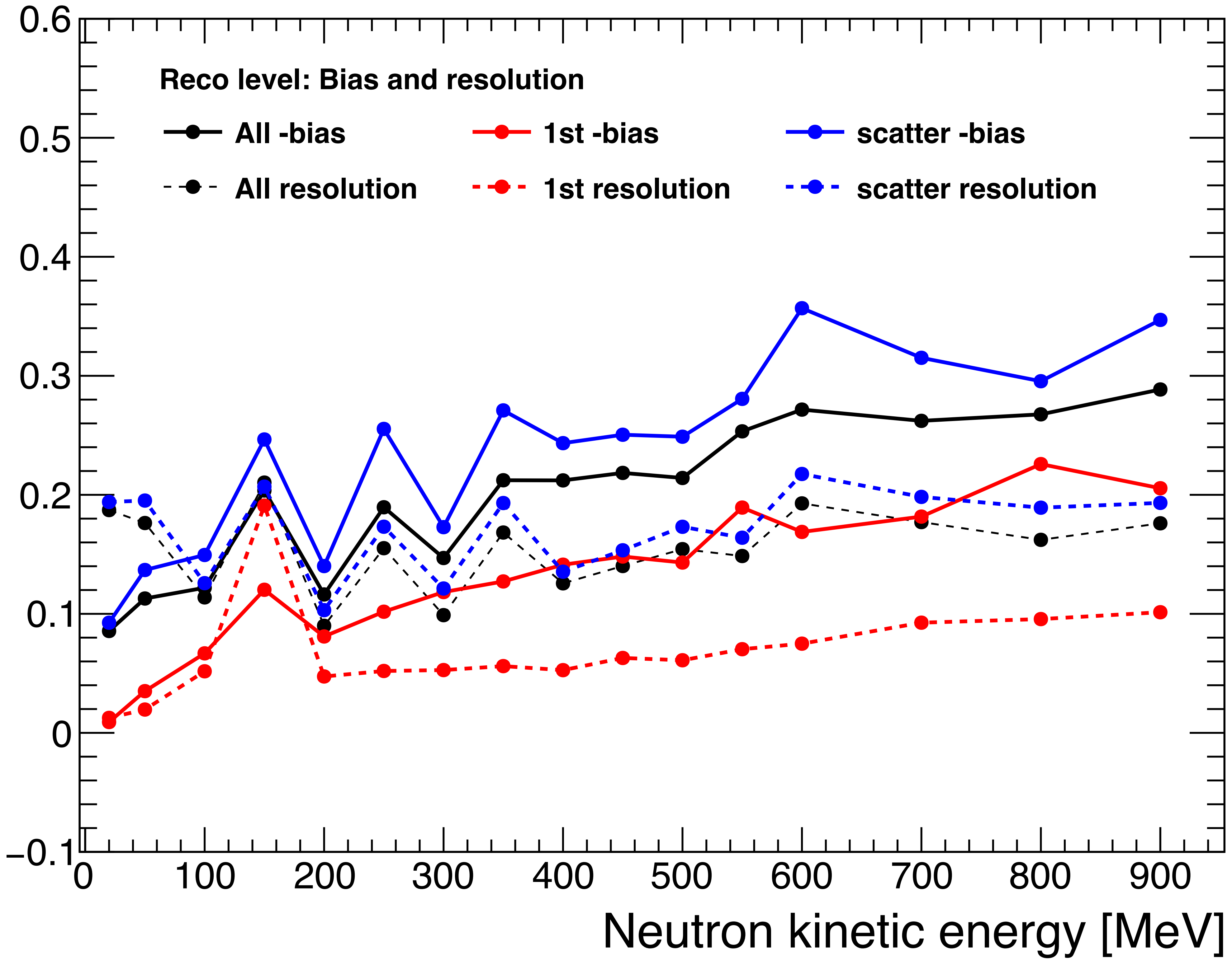


Neutron energy reconstruction.

First Setup

First Setup

- 2 mm Cu + 5 mm Sc (80 layers)
- Overall efficiency of above **50-60%**
  - Mostly **dominated** by rescatters
- Energy reconstruction
  - @ 50 MeV: large fraction at -1 (very delayed events due to nucleus de-excitations)
  - @ 400 MeV: Rescatter get more pronounced
  - Rescatter more pronounced at higher KE energies
- **Overall picture**
  - Bias increases with KE - RMS slightly increases
  - Adding rescatters worsen the bias and resolution

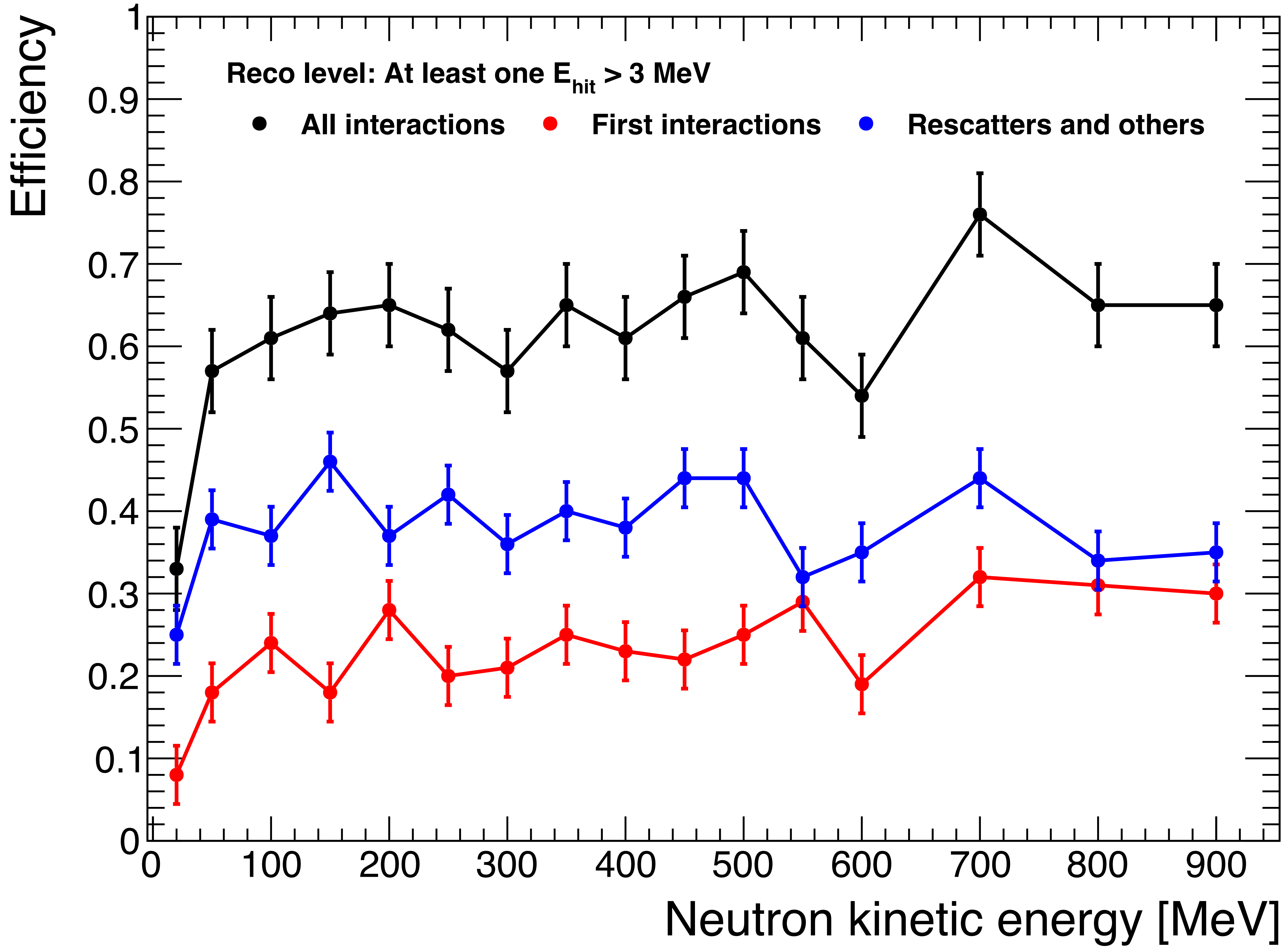


Neutron energy reconstruction.

Second Setup

Second Setup

- 2 mm Cu + 5 mm Sc with 5% natural B (1% B^{10}) in weight (80 layers)
- Overall efficiency of above **50-60%**
  - Mostly **dominated** by rescatters
  - Slight **improvement below 200 MeV** ➠ mostly due to gamma from neutron capture with the B^{10}

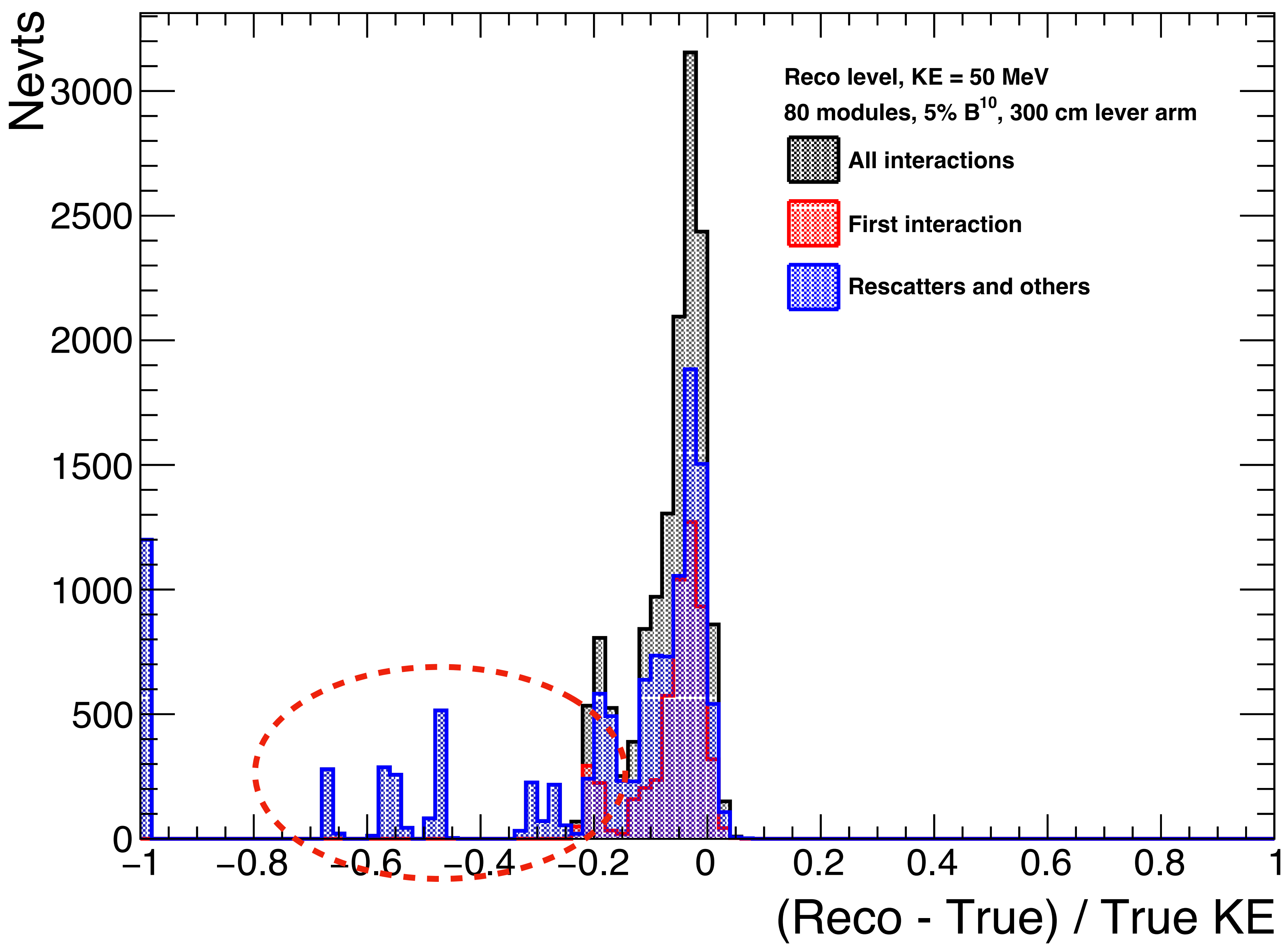


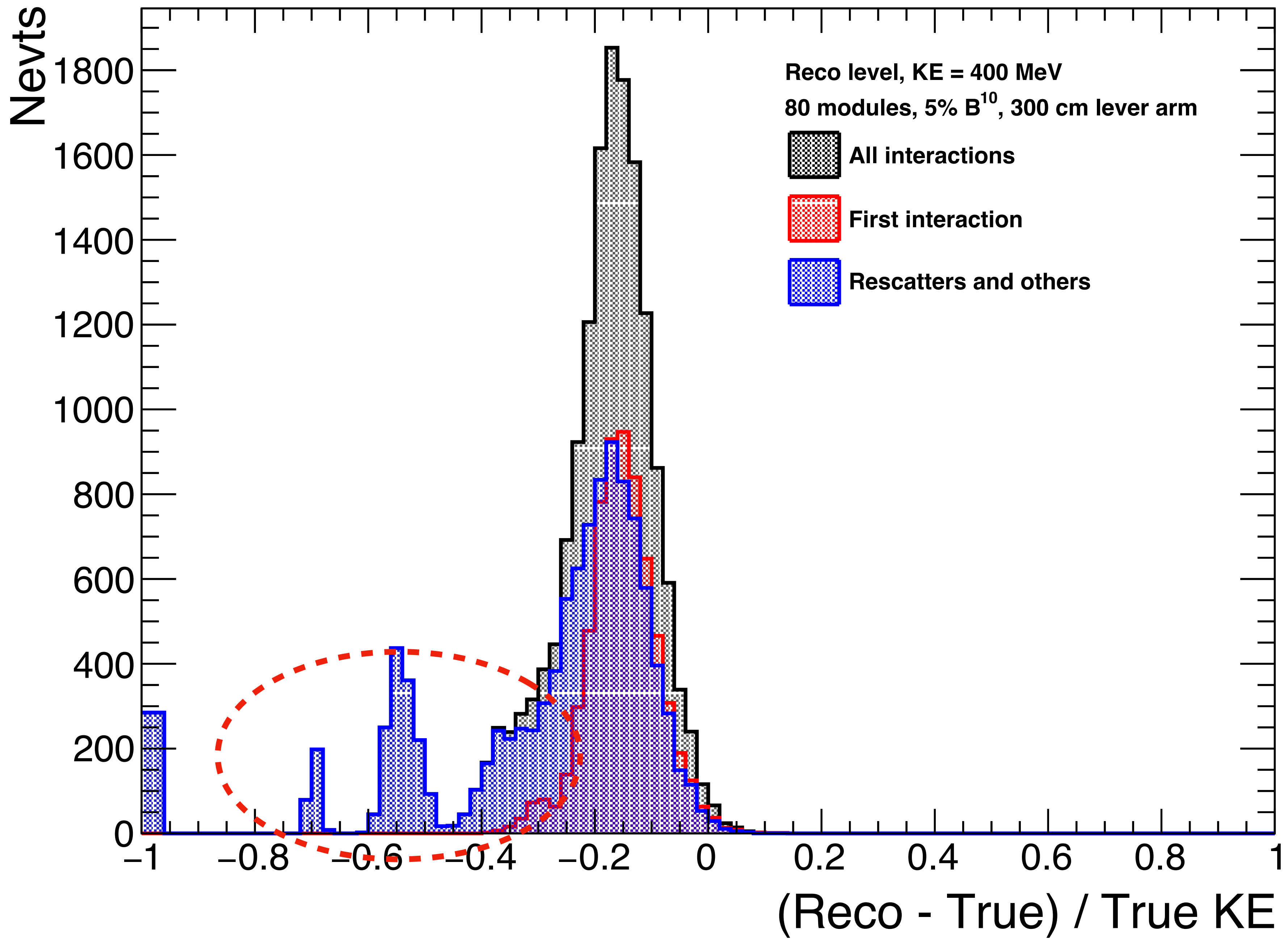
Neutron energy reconstruction.

Second Setup

Second Setup

- 2 mm Cu + 5 mm Sc with 5% B^{10} in weight (80 layers)
- Overall efficiency of above **50-60%**
  - Mostly **dominated** by rescatters
  - Slight **improvement below 200 MeV** ➠ mostly due to gamma from neutron capture with the B^{10}
- Energy reconstruction
  - @ 50 MeV: smaller fraction at -1
  - @ 400 MeV: Rescatter get more pronounced
  - Visible peak around -0.5 ➠ may be due to delayed neutron capture in B^{10}



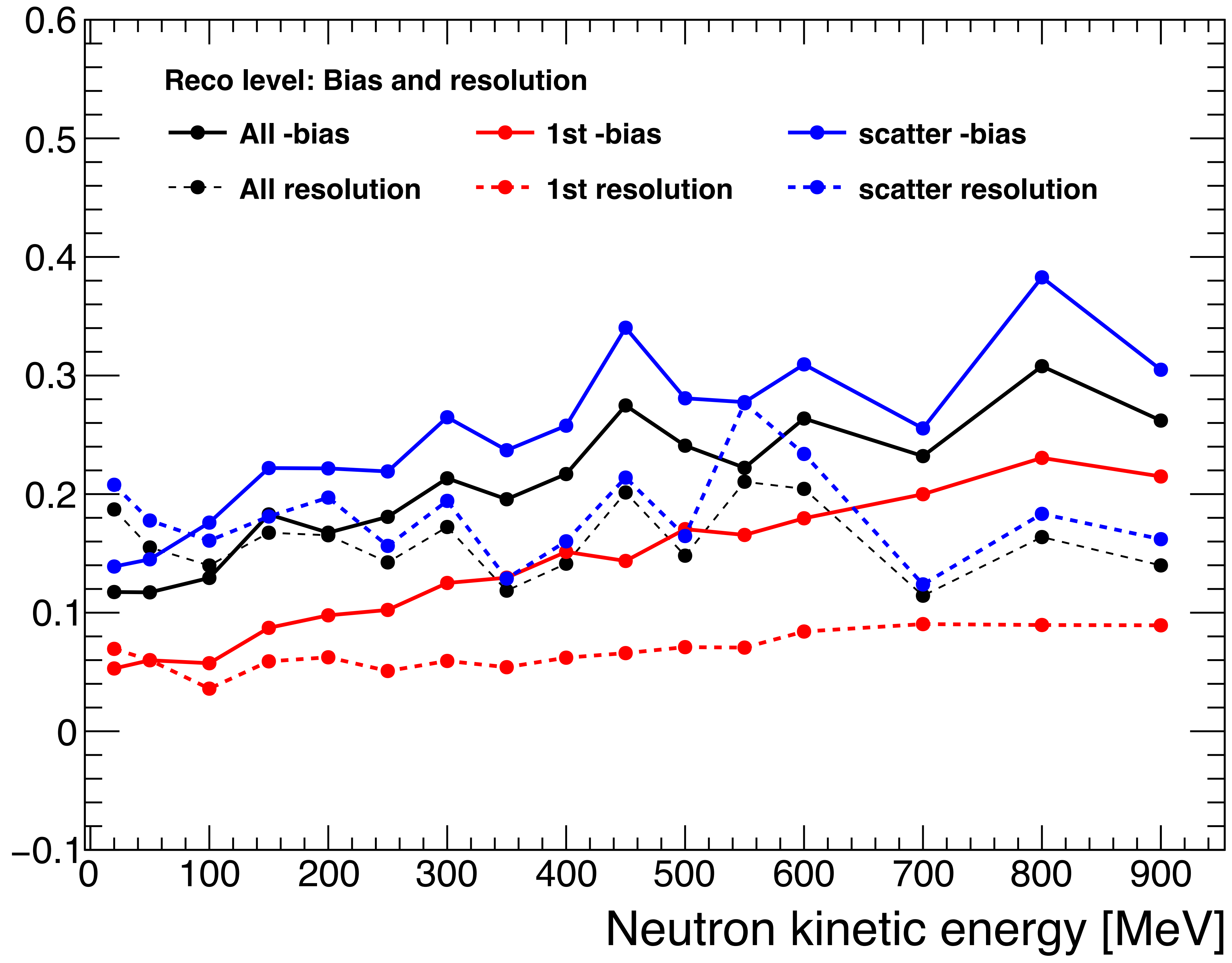


Neutron energy reconstruction.

Second Setup

Second Setup

- 2 mm Cu + 5 mm Sc with 5% B^{10} in weight (80 layers)
- Overall efficiency of above **50-60%**
  - Mostly **dominated** by rescatters
  - Slight **improvement below 200 MeV** ➠ mostly due to gamma from neutron capture with the B^{10}
- Energy reconstruction
  - @ 50 MeV: smaller fraction at -1
  - @ 400 MeV: Rescatter get more pronounced
  - Visible peak around -0.5 ➠ may be due to delayed neutron capture in B^{10} (need to check)
- **Overall picture**
  - 1st interaction resolution more flat
  - Very similar to 5 mm Sc w/o B^{10}

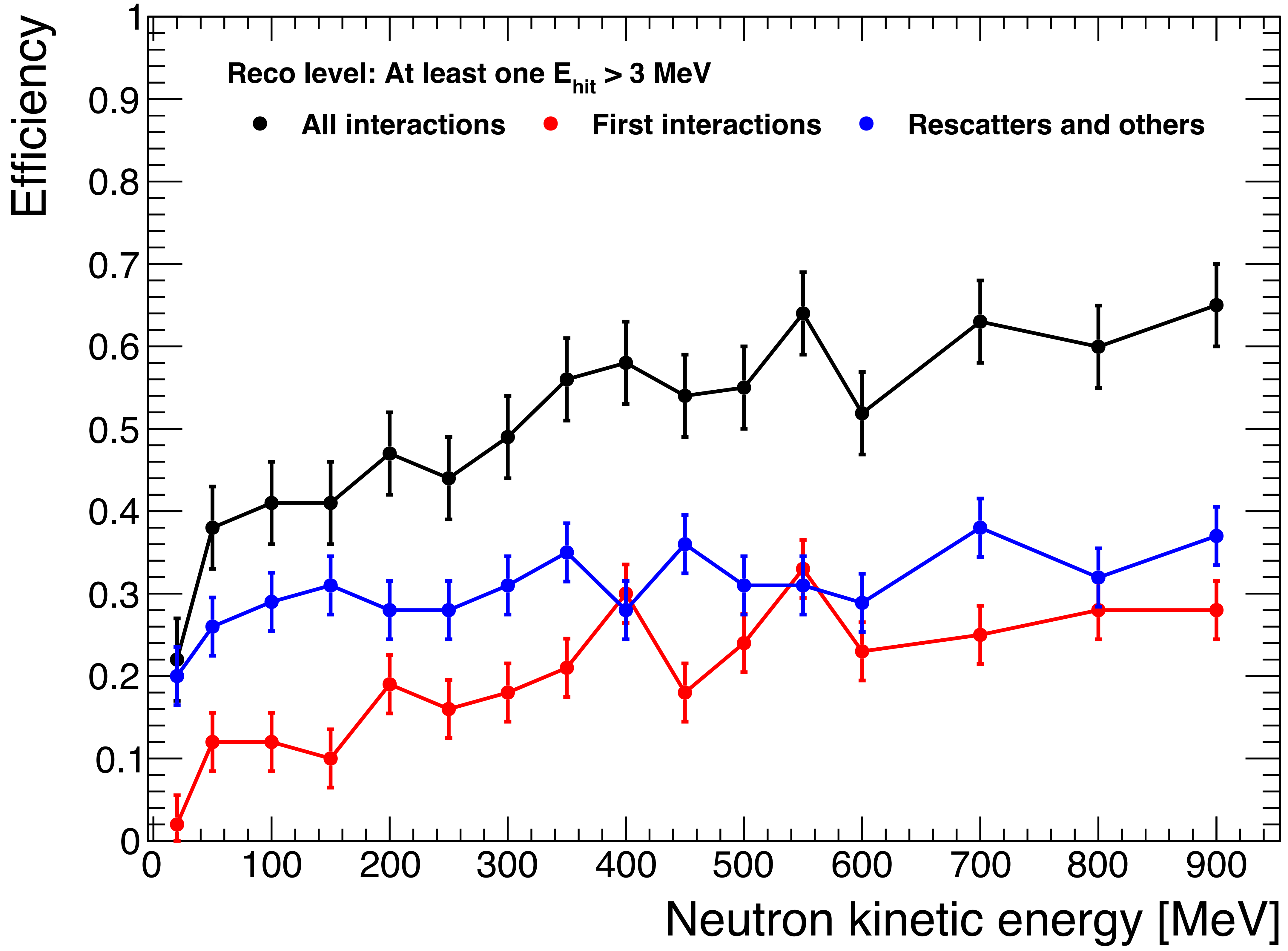


Neutron energy reconstruction.

Third Setup

Third Setup

- 2 mm Cu + 10 mm Sc (45 layers)
- Overall efficiency of above **50-60%**
  - Still **dominated** by rescatters but smaller contribution ➠ mainly due to less layers, however *degrades heavily the EM resolution*
  - Slight improvement at low KE for first interactions?

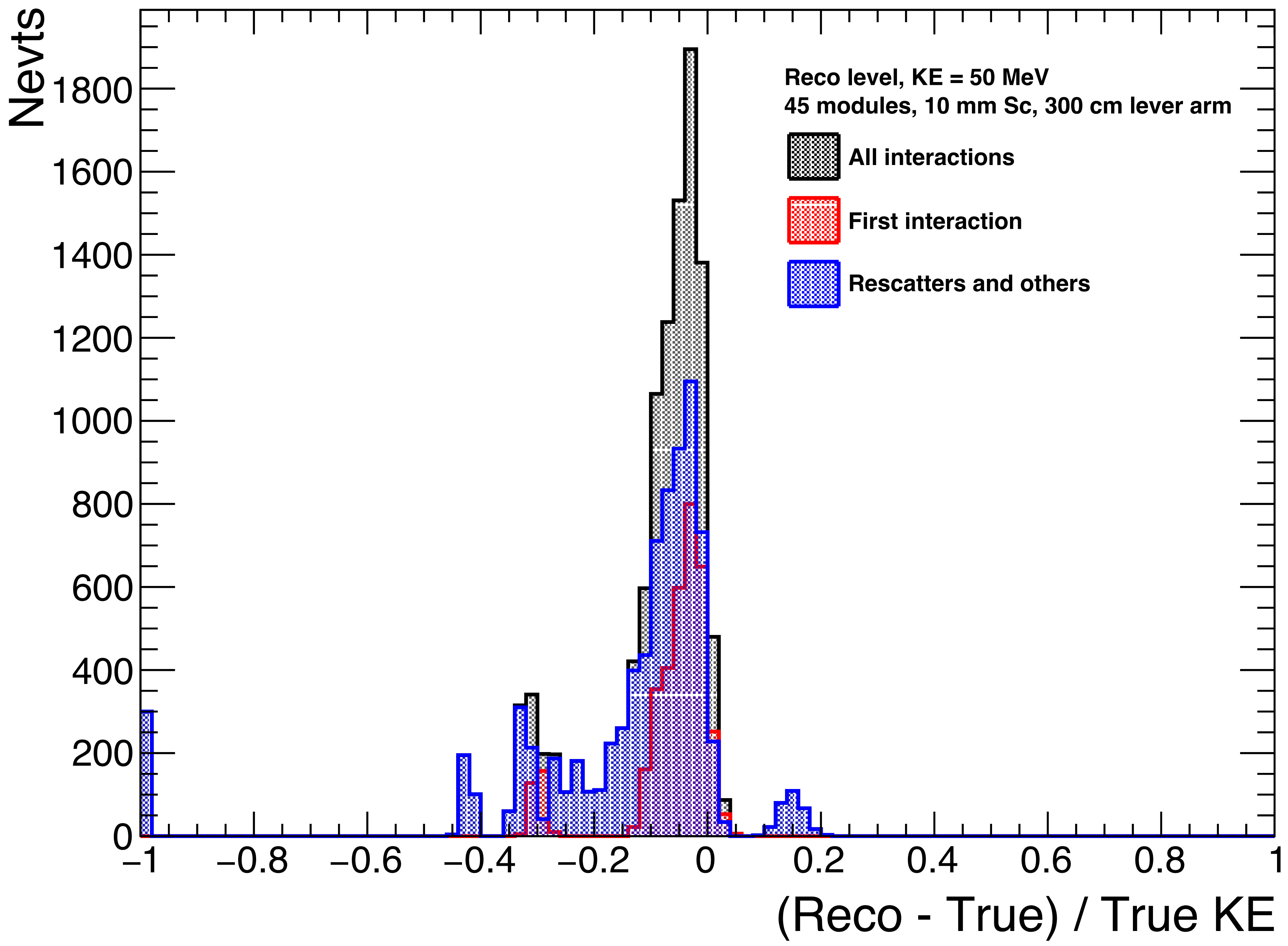


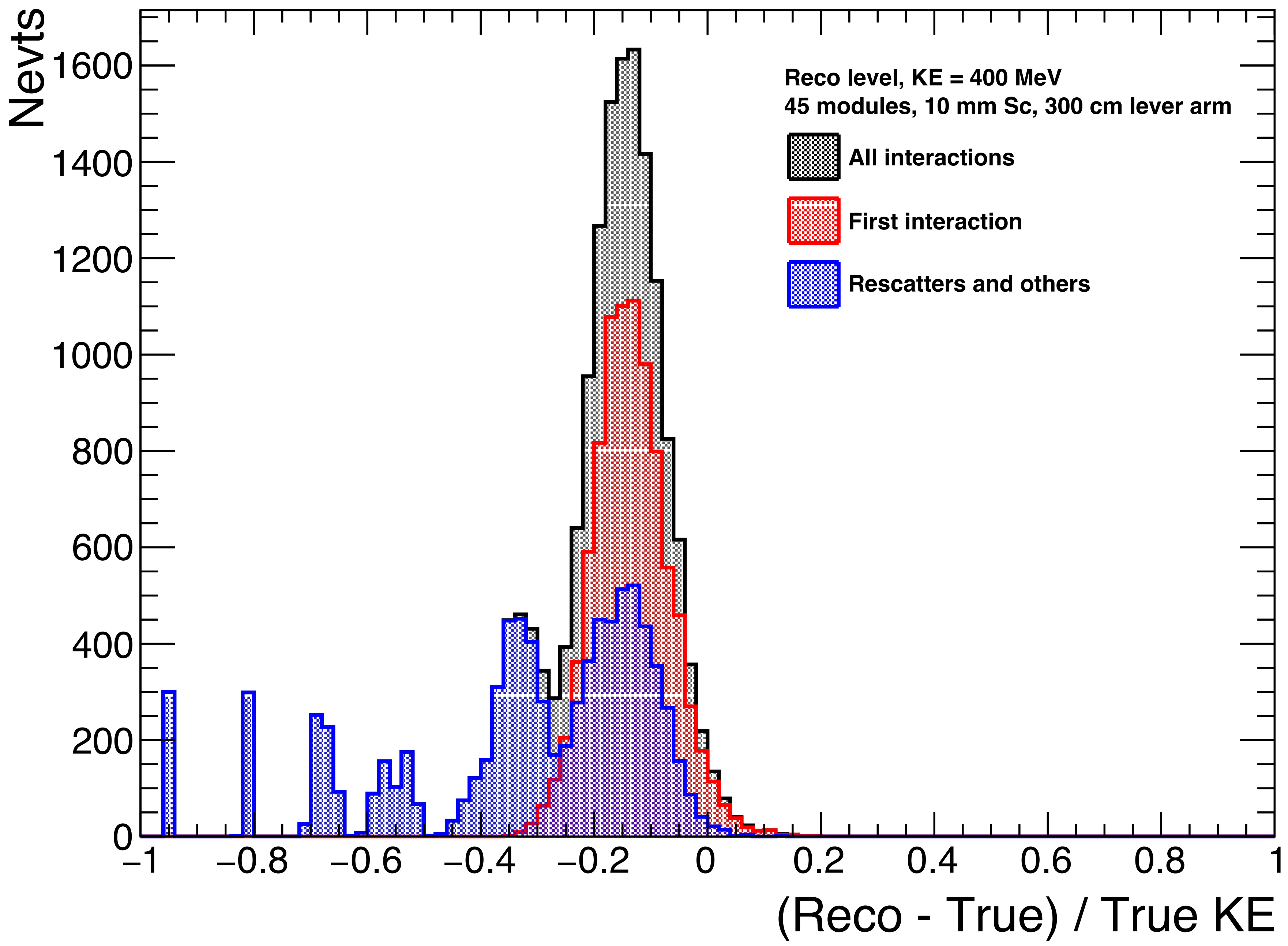
Neutron energy reconstruction.

Third Setup

Third Setup

- 2 mm Cu + 10 mm Sc (45 layers)
- Overall efficiency of above **50-60%**
  - Still **dominated** by rescatters but smaller contribution ➟ mainly due to less layers, however *degrades heavily the EM resolution*
  - Slight improvement at low KE for first interactions?
- Energy reconstruction
  - @ 50 MeV: smaller fraction at -1 - sharper peak
  - @ 400 MeV: Rescatter get more pronounced
  - Multiple peaks ➟ needs investigations





Neutron energy reconstruction.

Third Setup

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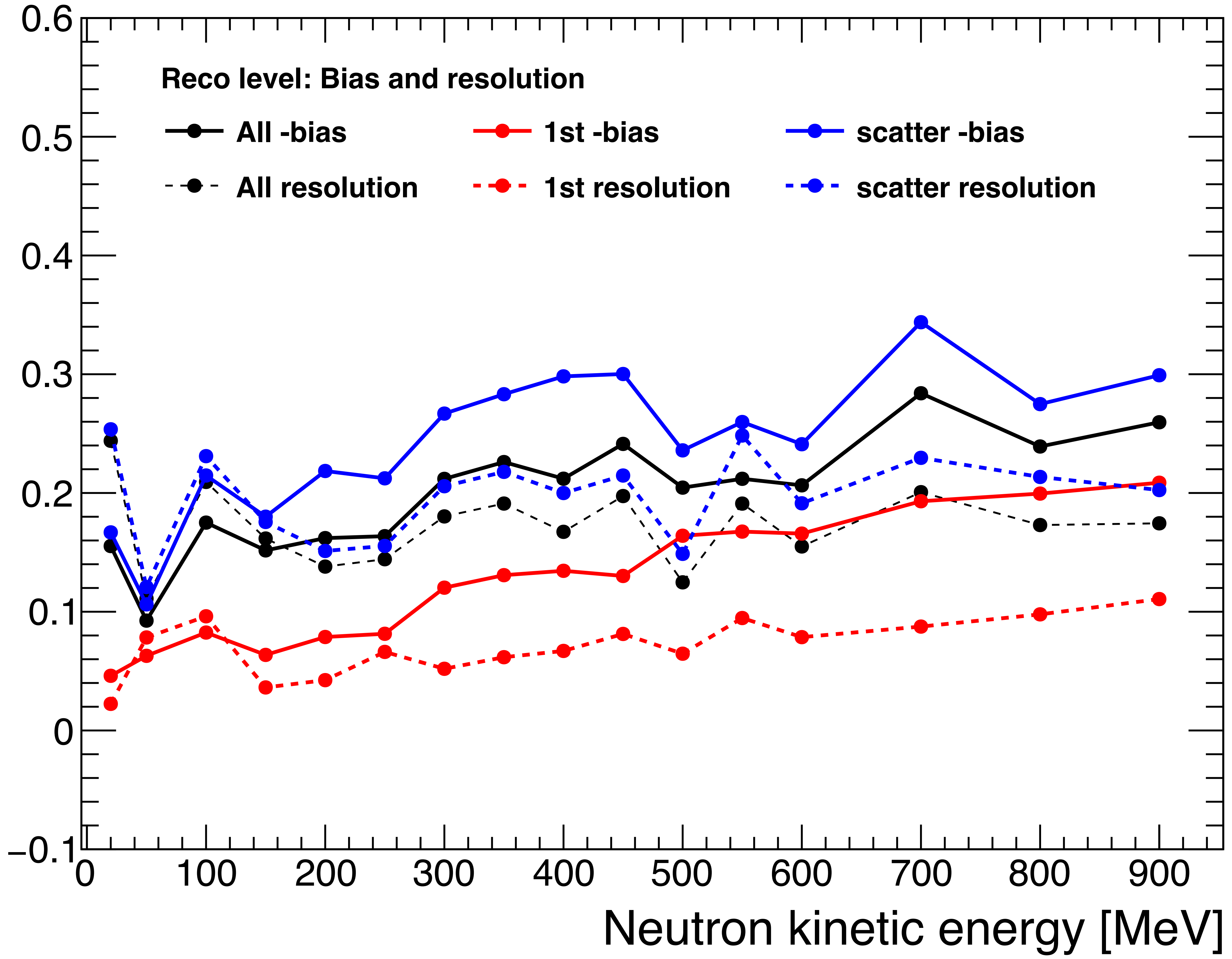
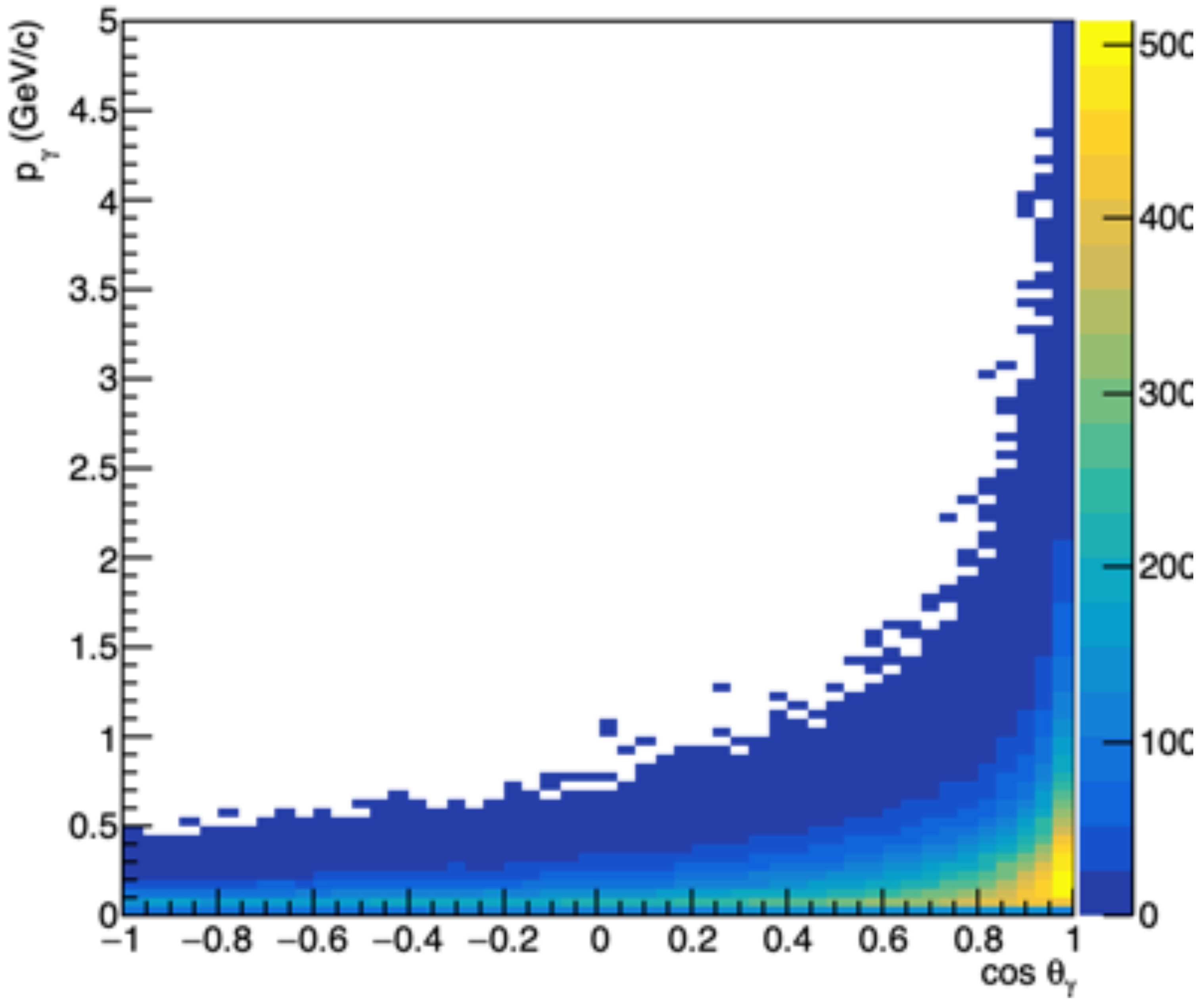
- Overall efficiency of above **50-60%**
  - Still **dominated** by rescatters but smaller contribution ➠ mainly due to less layers, however *degrades heavily the EM resolution*
  - Slight improvement at low KE for first interactions?
- Energy reconstruction
  - @ 50 MeV: smaller fraction at -1 - sharper peak
  - @ 400 MeV: Rescatter get more pronounced
  - Multiple peaks ➠ needs investigations
- **Overall picture**
  - Similar conclusions as 5 mm Sc
  - Bias and resolution slightly more flat

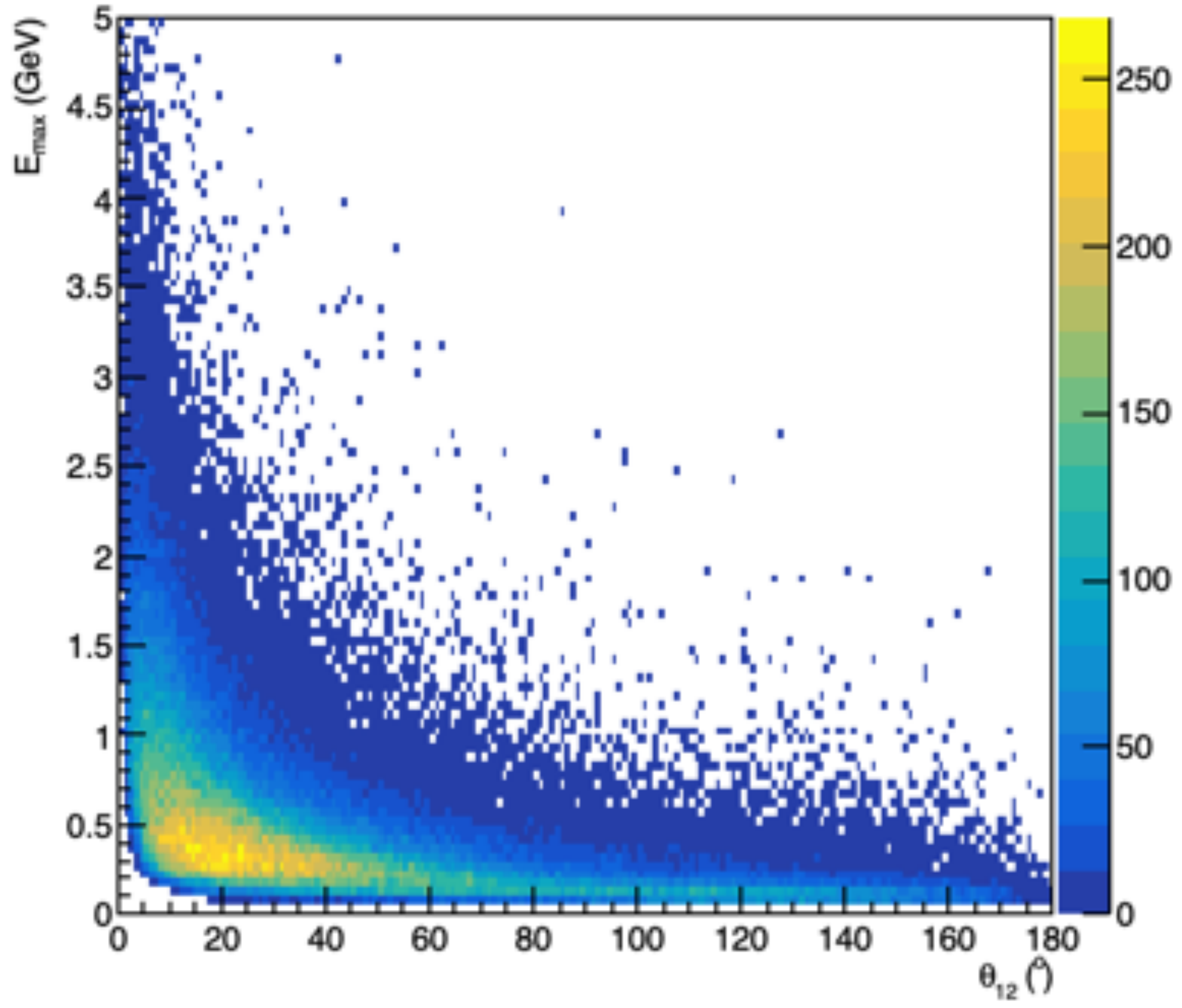


Where to optimise?.

Guided by the physics

- Preliminary studies done by Hiro
- **Understand** π^0 production in DUNE to help in ECAL design considerations
- Momentum of π^0 ➠ guide the *dynamic range* needed and the needed *granularity* (angular separation)
- Kinematics:
  - π^0 s up to 5 GeV/c
  - π^0 s below 1 GeV/c ➠ large angle between the photons
- Angular distribution:
  - High energy photon lead to very small angular separation
  - Low energy photons ➠ angular separation typically around 20 degrees and above
    - Contains most of the events - 2.5 cm granularity ➠ few degrees





Conclusions for neutron studies.

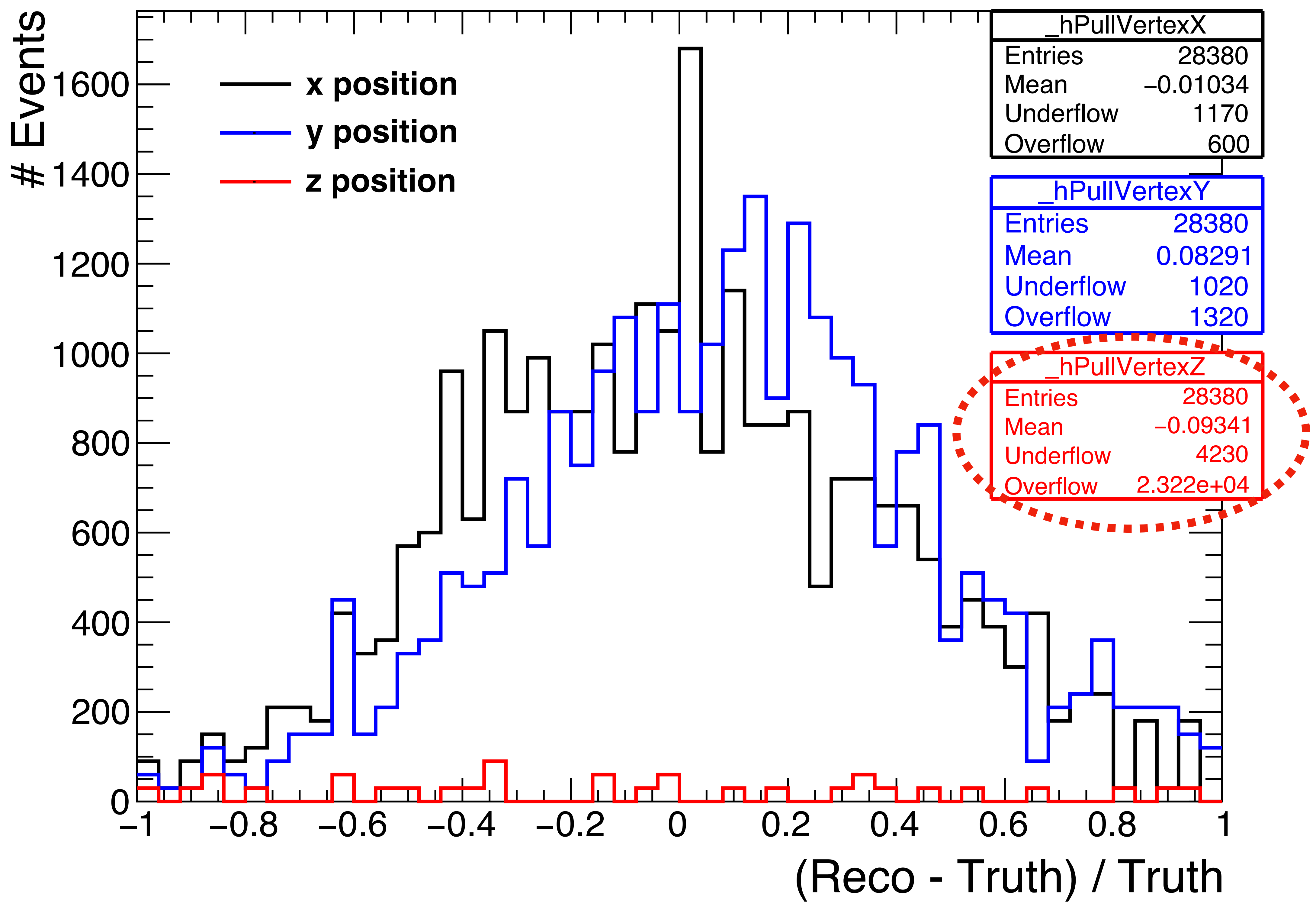
To take away

- Neutron energy reconstruction is **challenging** but would be a plus for the near detector
  - Increase of **scintillator thickness** may improve the efficiency at lower neutron KE
  - **Number of layer** will influence the number of rescatters ➠ less would improve the energy resolution / however would impact the EM resolution
  - **Loaded-boron Sc** ➠ may be a very nice solution to improve efficiency at low neutron KE + Can we differentiate proton recoil from gamma emissions by timing?
- Next steps:
  - Looking at MC in more details to get a better understanding
  - Investigate efficiency and purity in *background environment*
  - Investigate Gadolinium coating (would not change optical properties of the Sc) and Lead absorber (high Z material)
  - Understand timing of doped Sc ➠ does it affect the *background rate*?

Neutral pion reconstruction.

Work in progress

- 400 MeV neutral pion
- Look at the distance to the true vertex and reconstructed invariant mass
- π^0 s reconstructed between 100-150 MeV (due to clustering effects)
- Distance to the truth vertex around 150 - 200 cm ➠ mostly the z-coordinate is badly reconstructed
- Factor ~x5 worse than more complete studies
  - Not yet using the Chi2 minimization ➠ important for the position resolution
  - Clustering not optimized



Neutral pion reconstruction.

Work in progress

- 400 MeV neutral pion at 15/15 cm vertex
- Distance between the true vertex and the PCA from the line determined from the highest energy cluster ➠ better angular resolution!
- Very promising method to be used for better constrain on the vertex location