A Highly Granular Calorimeter Concept for Long Baseline Near Detectors

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on behalf of the DUNE Collaboration

DEEP UNDERGROUND NEUTRINO EXPERIMENT

CALOR 2018, Eugene OR, USA, May 2018

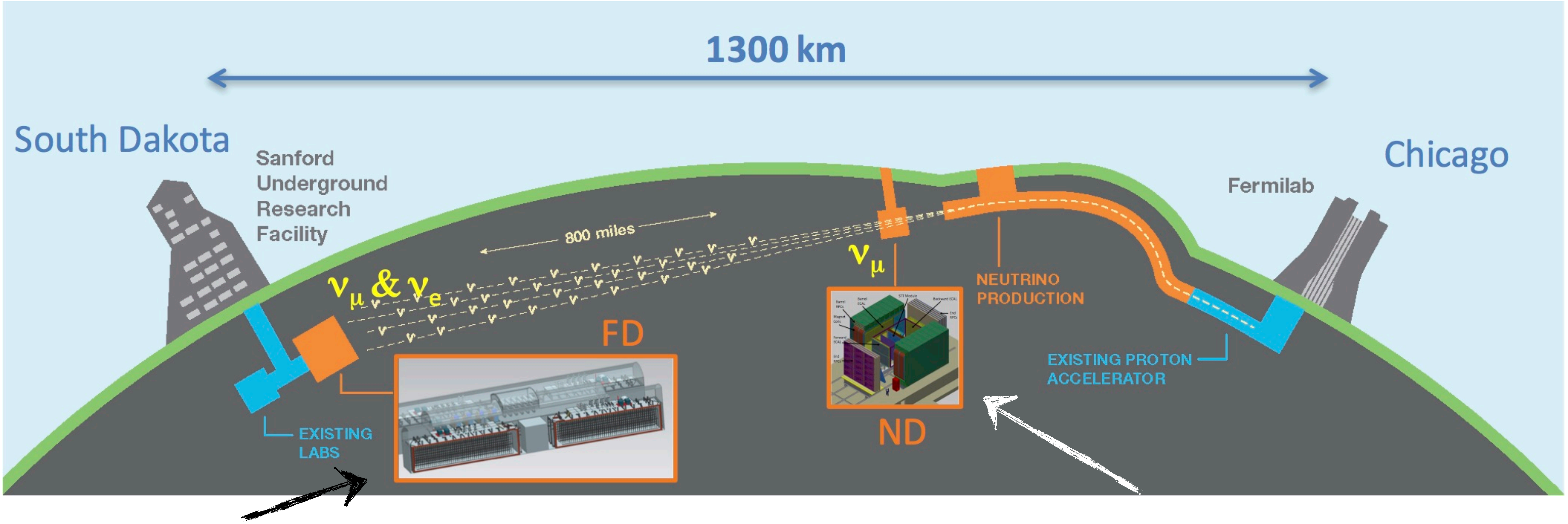
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Outline

- DUNE and the Near Detector
- A highly granular ECAL concept for the Near Detector
- Simulation studies
  - Energy resolution
  - Angular resolution
  - Neutron sensitivity
- Lessons Learned & Conclusions

Introduction

The DUNE Experiment



Primary physics goals:

- Observe and study leptonic CP violation
- Measure the mass ordering of neutrinos
- Measure supernova neutrinos
- Search for proton decay

Far detector to measure oscillated neutrinos in the beam physics program:

- 4 x 10 kT fiducial volume LAr TPC
- 1300 km baseline, covers 1st and 2nd oscillation max.

Near detector to constrain un-oscillated flux and to perform a rich, high statistics non-oscillation program

- Technologies and details of the detector concept currently under study

Construction has started in 2017 - Expect first physics in 2024, first beam in 2026

The DUNE Near Detector

Introduction

- The primary role:
  - provide strong constraints on the neutrino flux
  - improve understanding of cross-sections

needs to be capable of identifying and characterising neutrino interactions in Ar as well as in various other targets

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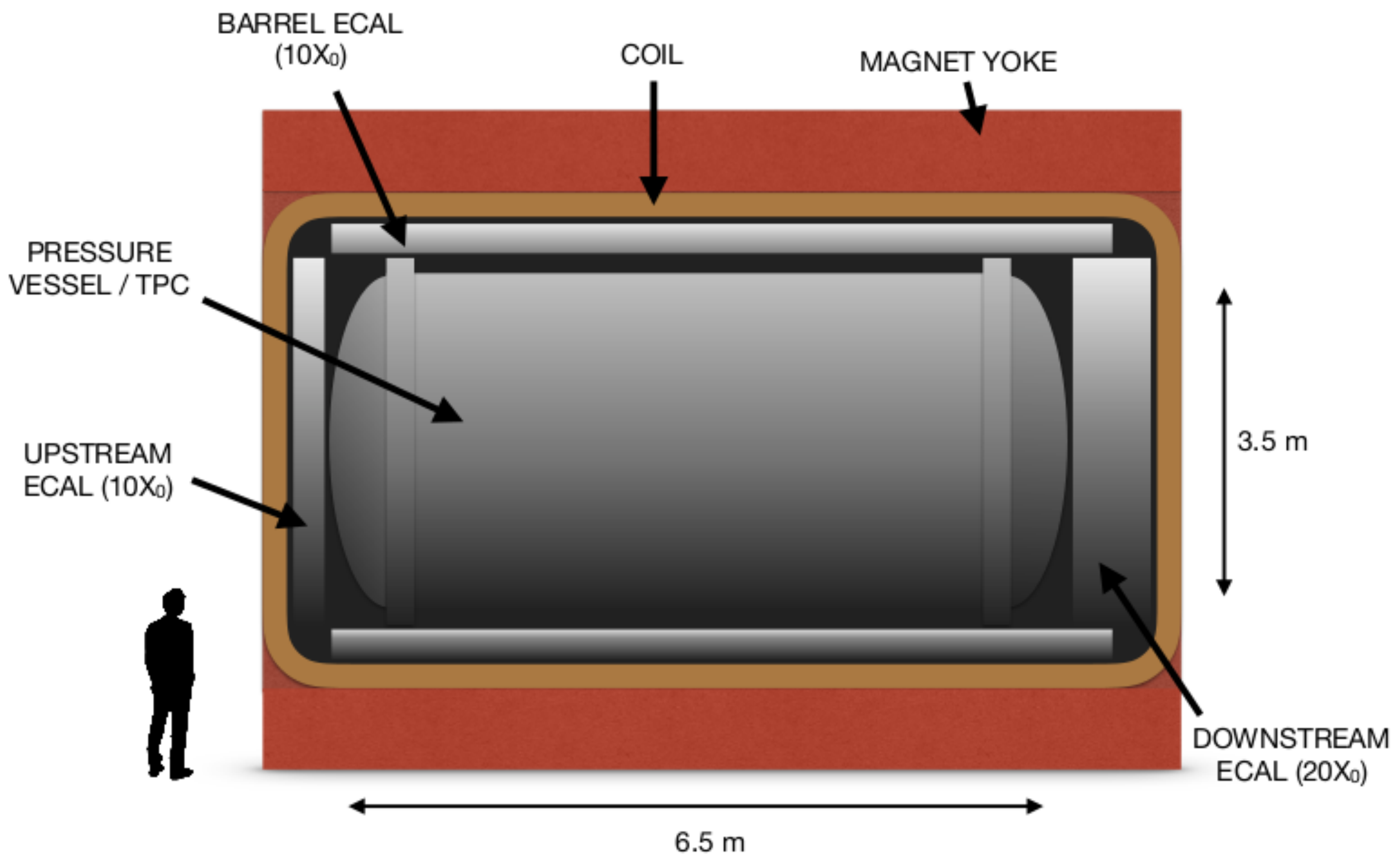
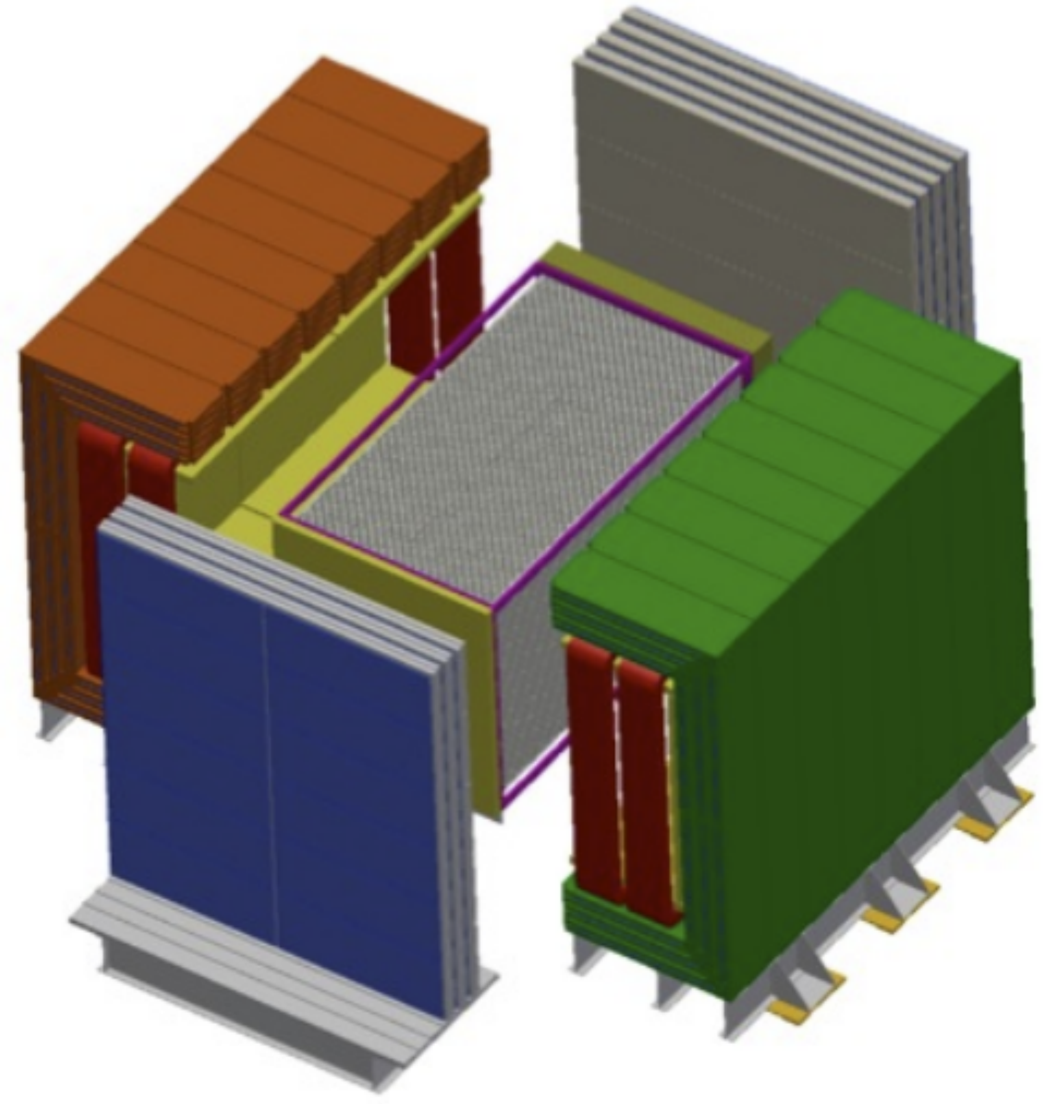
- Detailed layout and technological choices still open - the elements:
  - a non-magnetised LAr TPC
  - a multi-purpose detector with a capable tracking system that acts as a target, surrounded by EM calorimetry and muon detectors in a magnetic field
  - Additional technology and approach: 3D scintillator tracker, PRISM concept, …



High pressure TPC



Straw tube tracker

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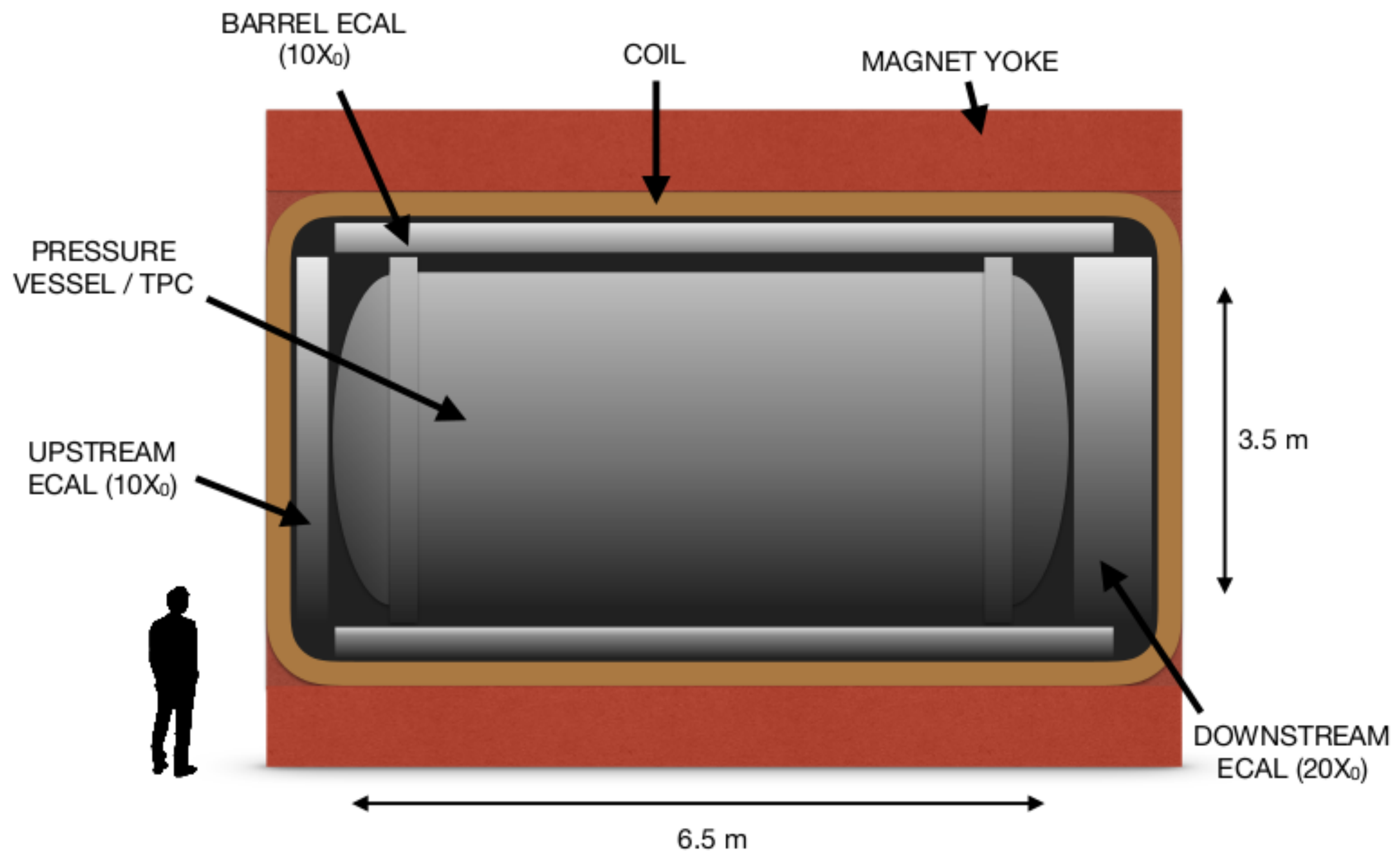

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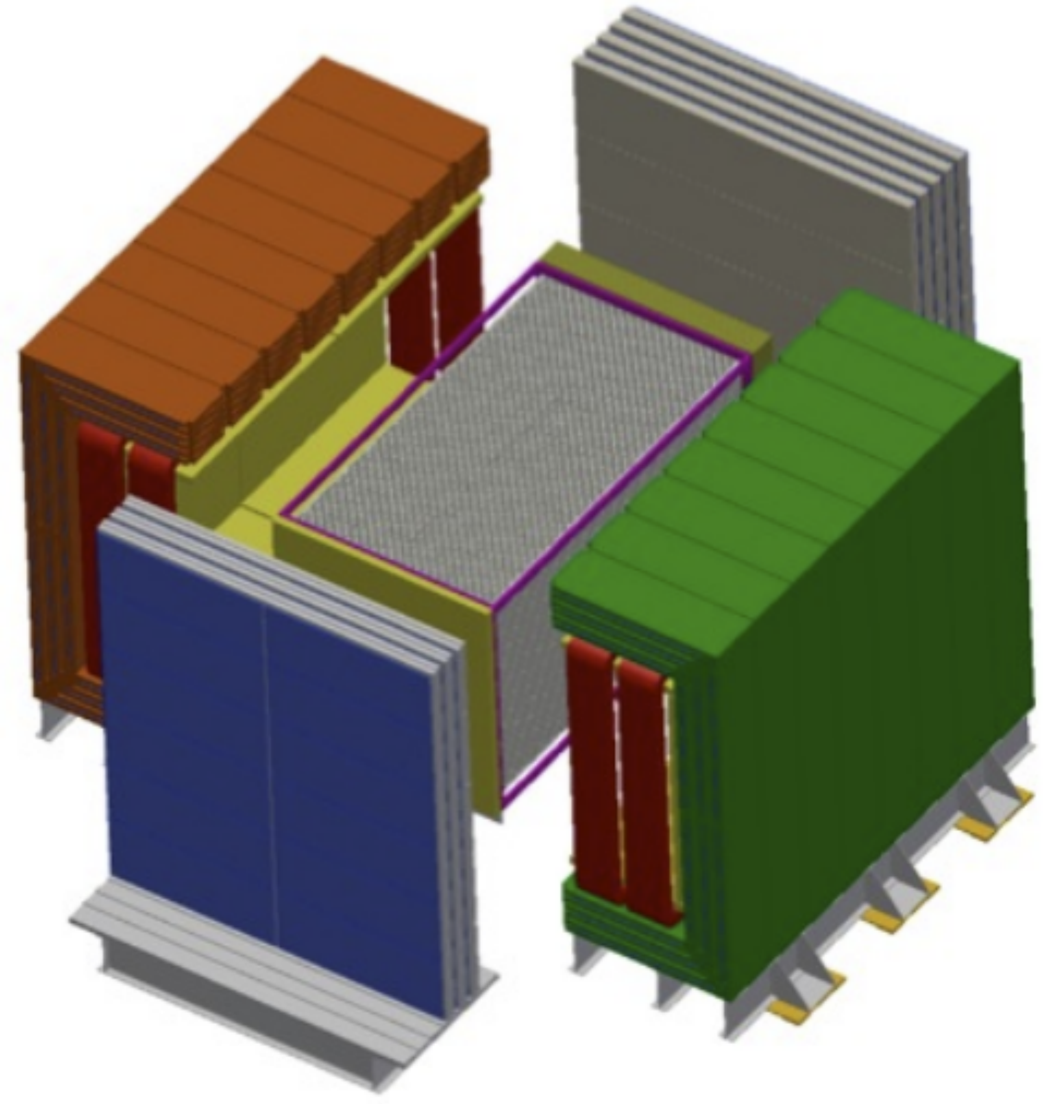


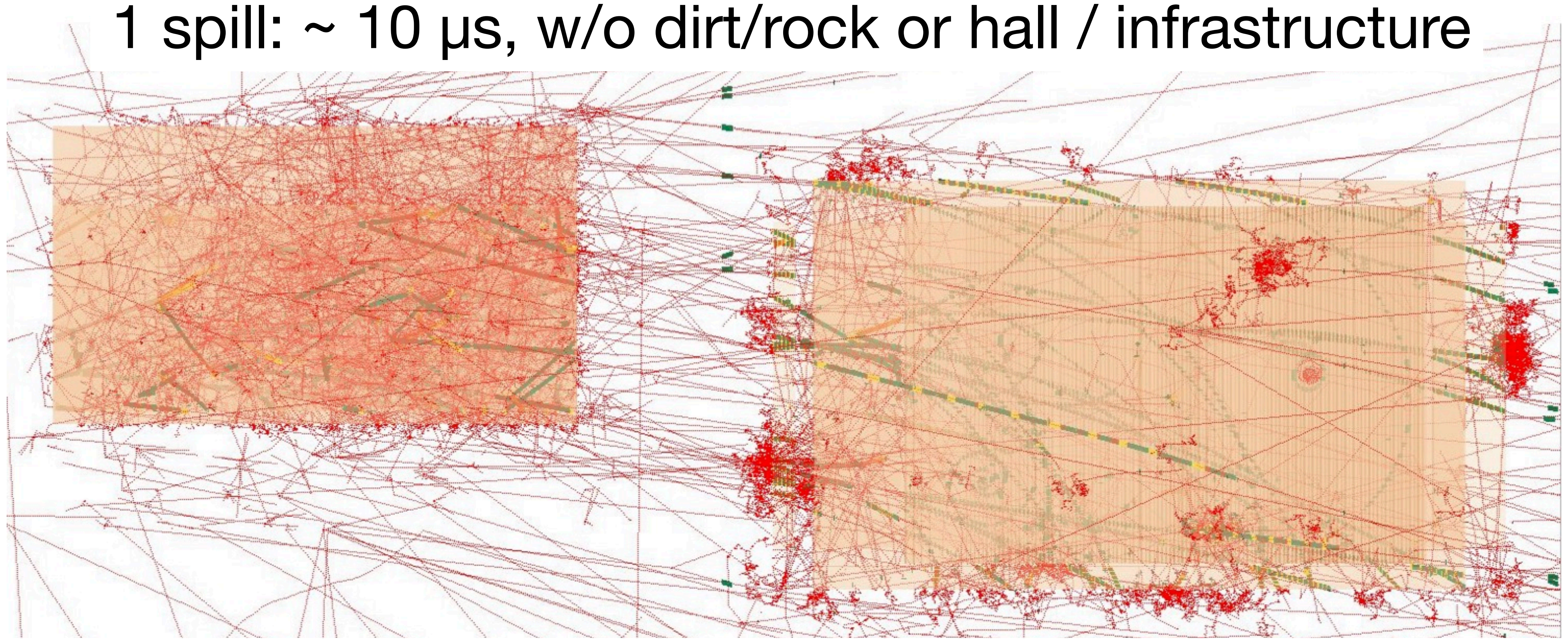
Straw tube tracker

The ECAL studies shown here are primarily performed in the context of a HP-TPC, but are also valid for other options

The DUNE Near Detector

Requirements for Calorimetry

1 spill: ~ 10 µs, w/o dirt/rock or hall / infrastructure



Here: DUNE ND with LAr TPCs, magnetised tracker + ECAL

- Overall conditions in the DUNE near detector:
  - pile-up: multiple interactions per spill
  - in contrast to collider detectors:
    - interactions happen everywhere
    - fixed-target geometry: higher-energy particles tend to go forward

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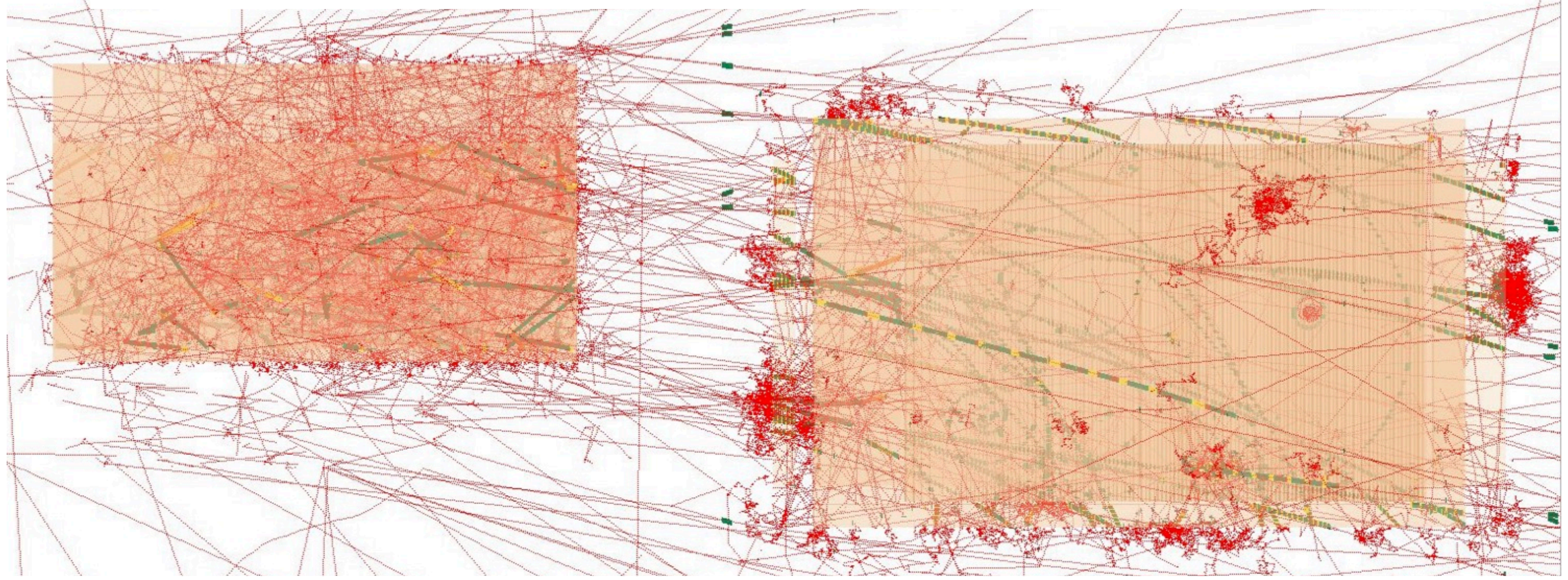

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The role of the ECAL:

- Detect π^0 produced in neutrino interactions
  - Important contribution to energy reconstruction
  - Understanding of ν_μ NC background to ν_e CC appearance signal
  - Detect photons and neutrons, track muons
  - Possibly provide event time stamps

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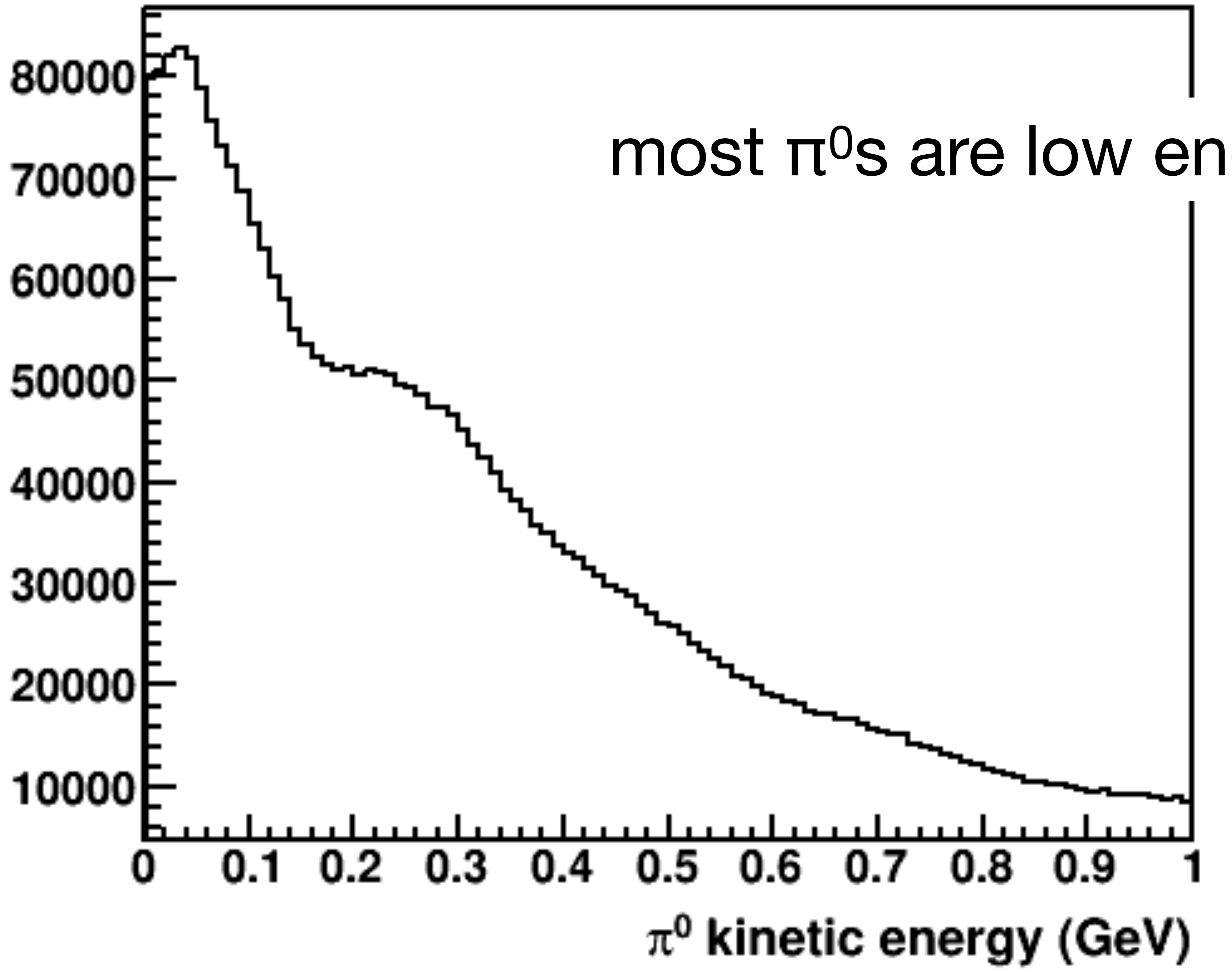
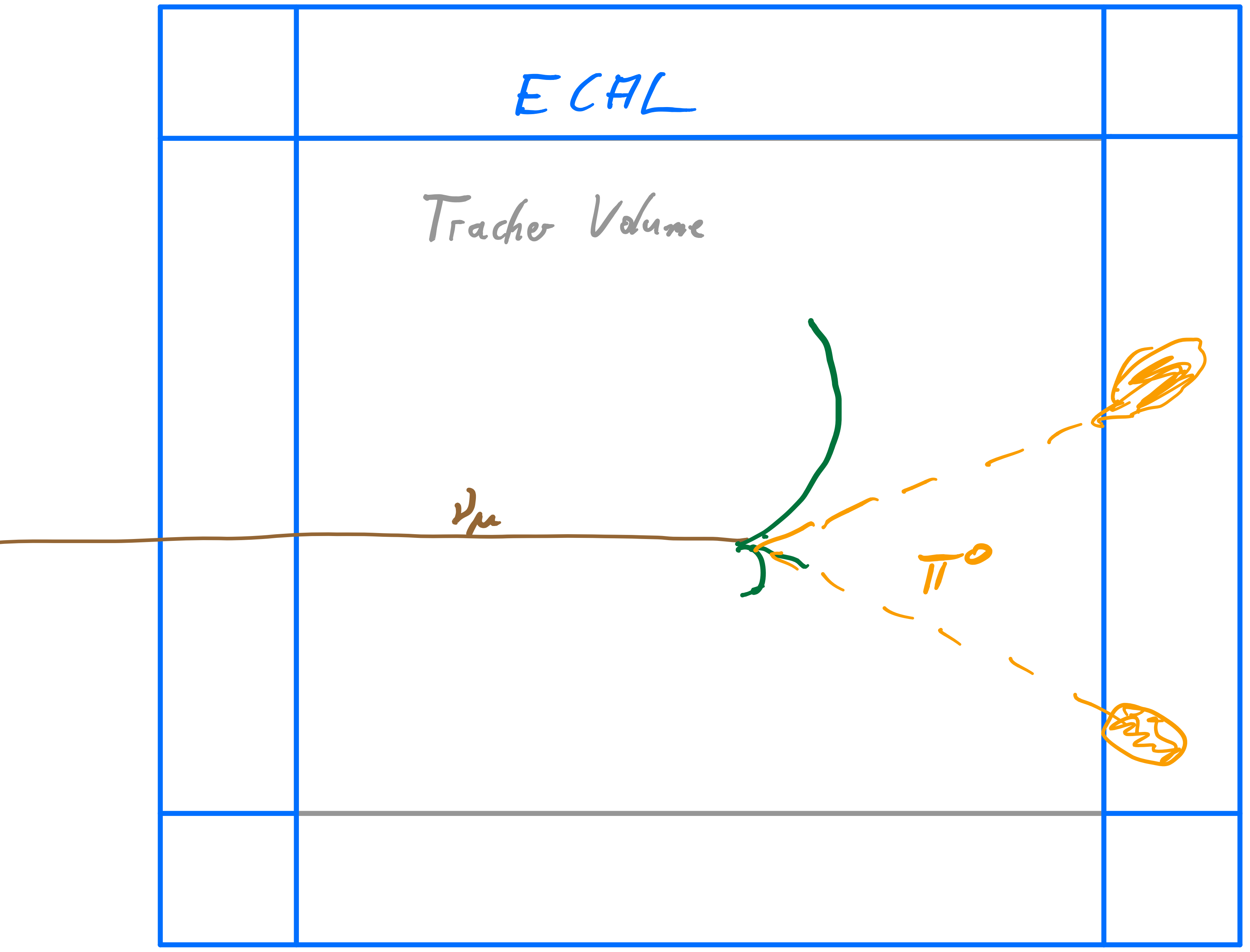


A highly granular Near Detector ECAL Concept

Benefits and general Idea



- The capability for (reasonably) accurate pointing of photon showers has the potential to substantially improve π^0 reconstruction
  - particularly important for low density trackers (such as HP-TPC), where conversion probability is low
- Granularity improves background rejection, and the identification of additional neutrino interactions in the ECAL volume
- Matching of particle tracks in tracker to calorimeter: Can be used to determine event time precisely

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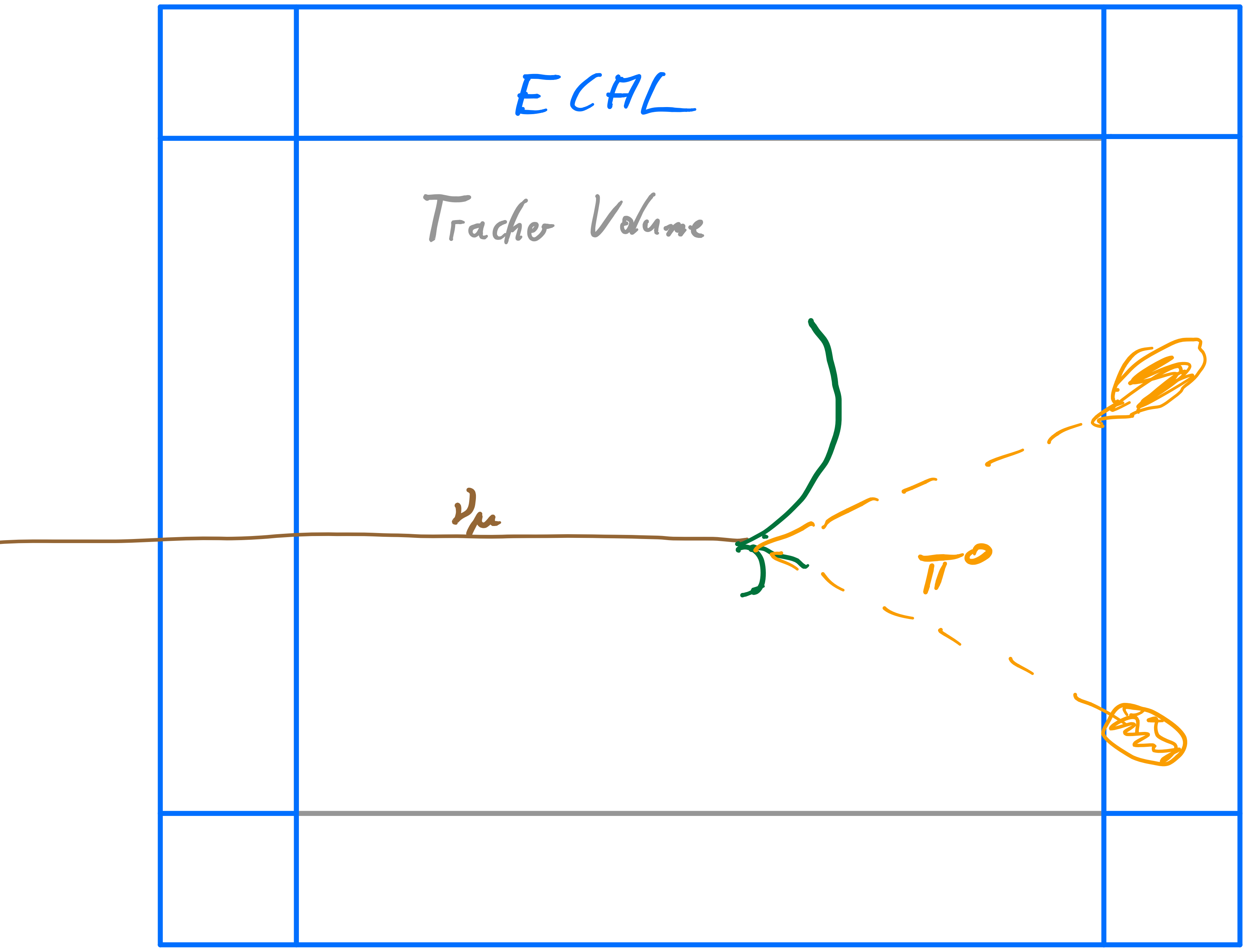

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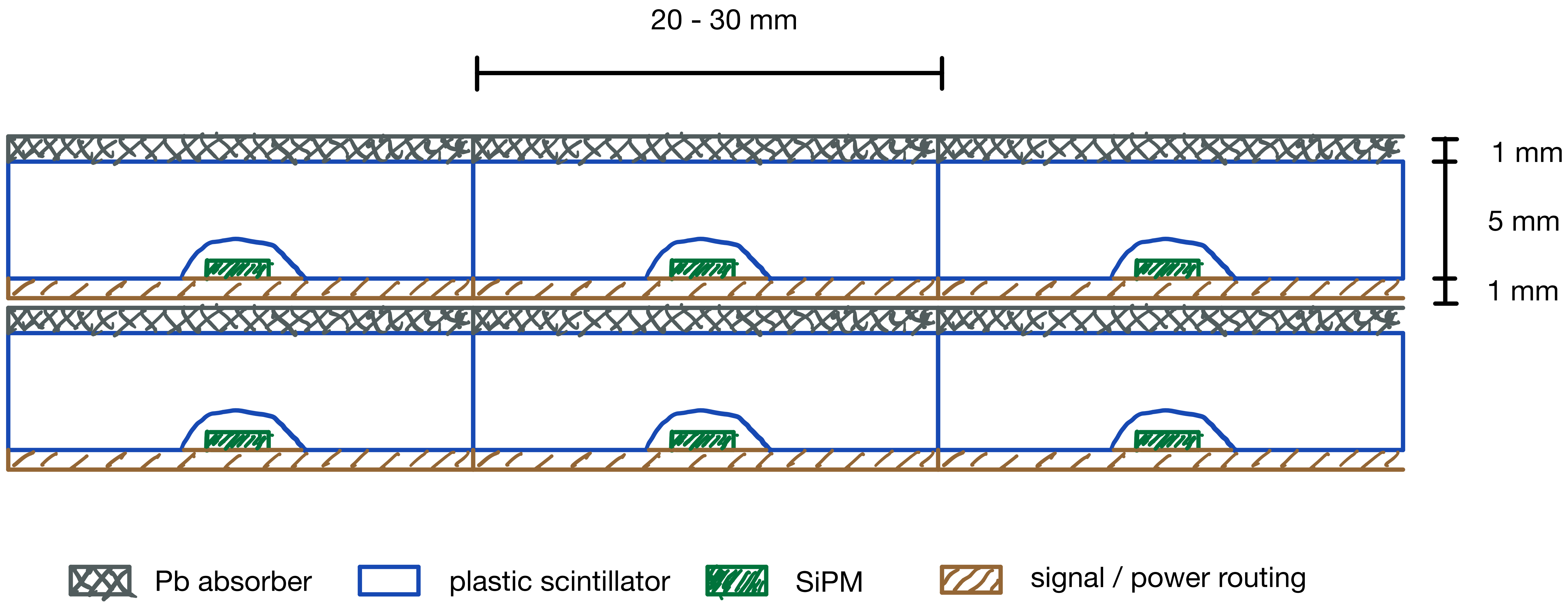
First naive concept: Scintillator tiles with SiPM readout

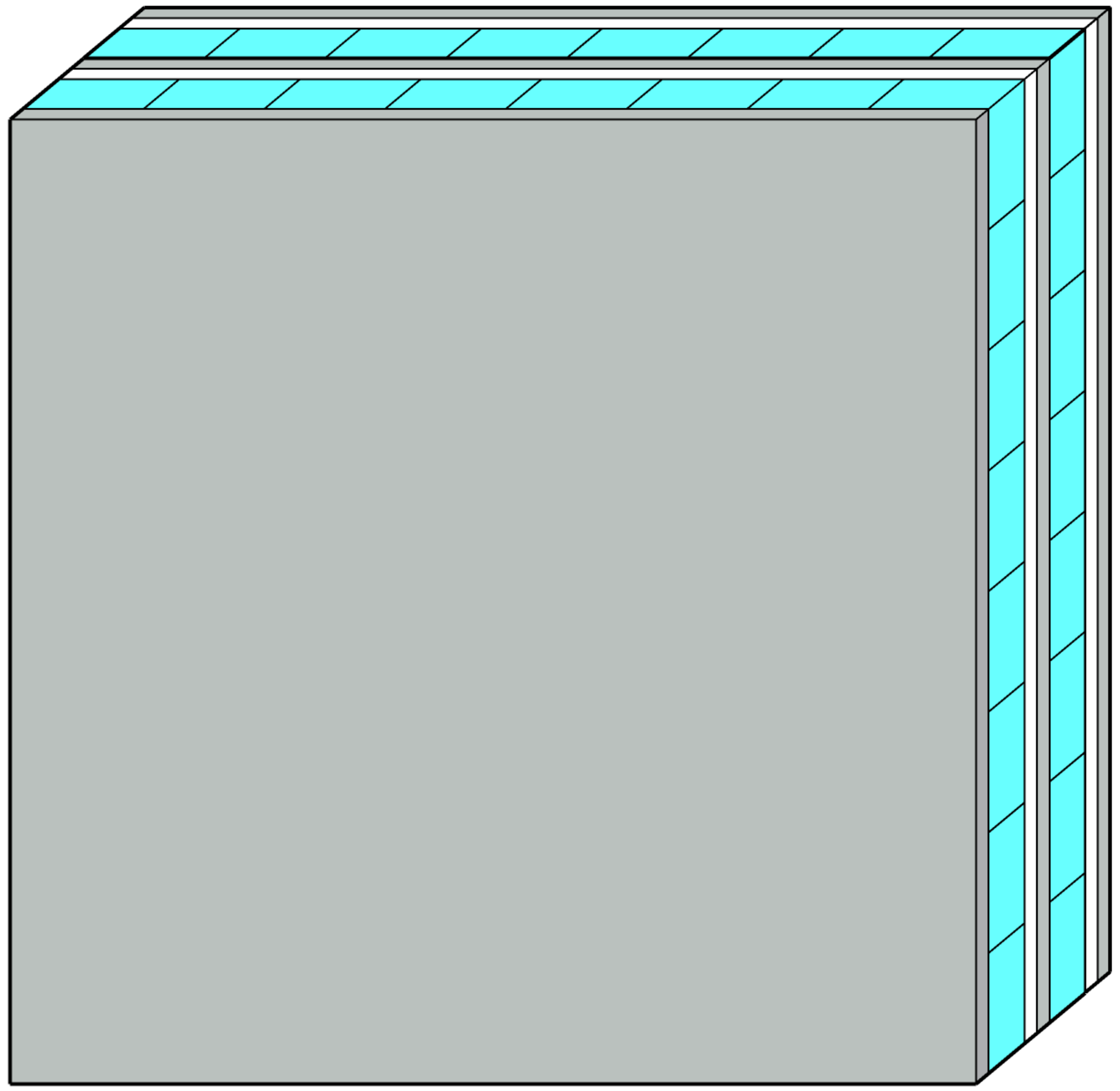
- Well-established technology for hadron calorimeters (22k channel CALICE prototype)

➩ Reduced absorber thickness and changed material, different electronics concept, more stringed uniformity requirements



Simulation Studies

Overview



- A simplified model of the calorimeter - implemented & simulated in GEANT4
- 1 layer implemented as
  - absorber plate: Pb or Cu, 1 mm or 2mm
  - 5 mm plastic scintillator - in software subdivided into cells with varying size
  - 1 mm air (assuming low-density layer for signal routing)
- Simplified digitization to model detector effects
  - amplitude smearing to account for electronic noise, photon statistics (~ 20% of a MIP signal as σ)
  - amplitude cut on each cell - 0.15 x MPV of a MIP
- The full detector: 80 layers (~ 16 X_0 when using 1mm Pb / 2 mm Cu)
  - Also considering scenarios with an ECAL split into two segments, with a HP TPC pressure vessel separating the two

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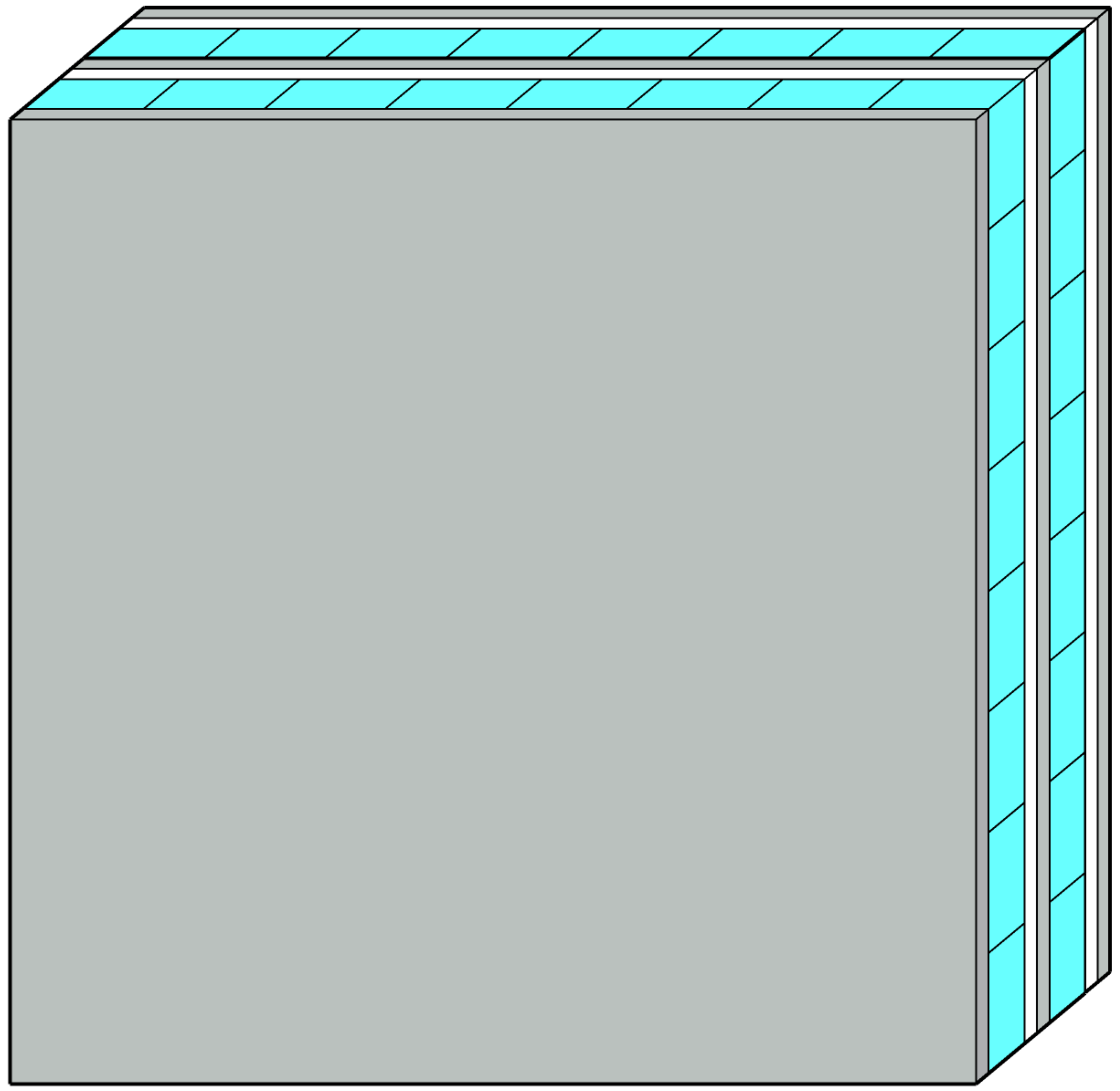

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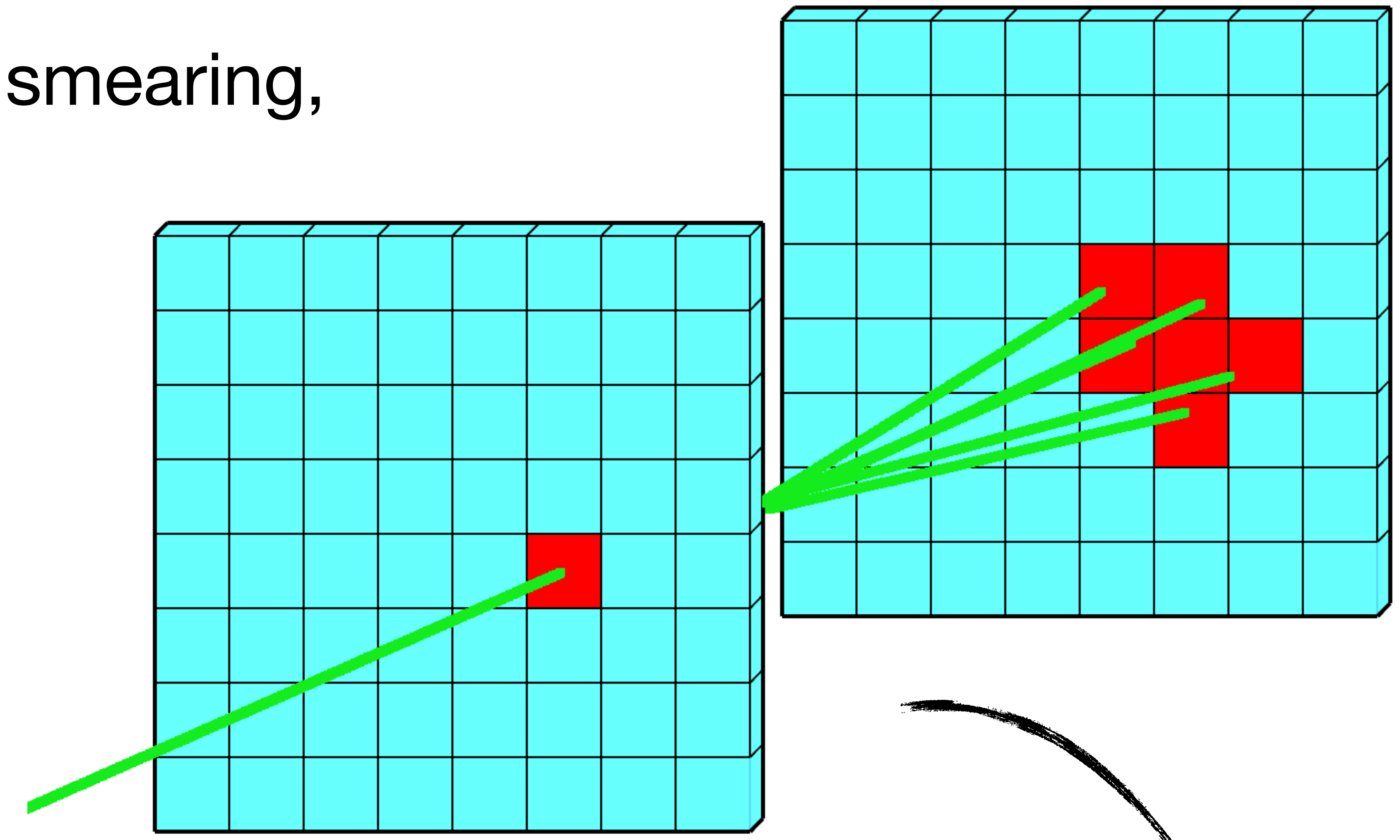
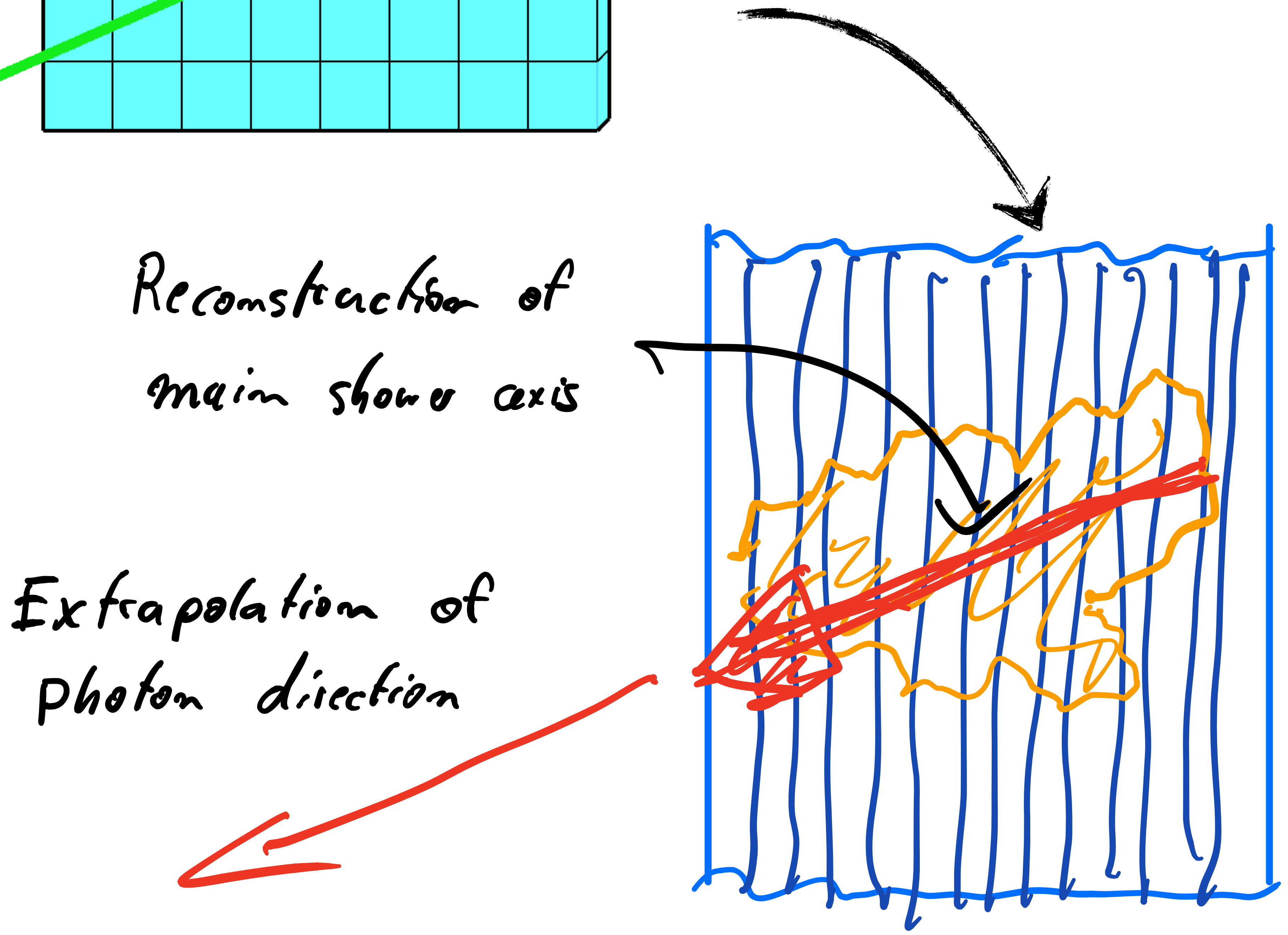
General remark: Dead material, detector effects only rudimentarily implemented, non-uniformities completely ignored: Projected performance, in particular on energy resolution, overly optimistic

Simulation Studies

Reconstruction

- For energy resolution: Take visible energy in calorimeter (with smearing, cell-level cuts applied); no clustering
- For direction of photons: A simple two-step approach:
  - principal component analysis of all detector hits to determine first estimate of shower axis
  - 3D line fit through layer-wise center of gravity using PCA as input to further improve estimate





Fits (energy & angular resolution):

$$Resolution = \sqrt{\left(\frac{A}{\sqrt{E[\,GeV\,]}}\right)^2 + \left(\frac{B}{E[\,GeV\,]}\right)^2 + C^2}$$

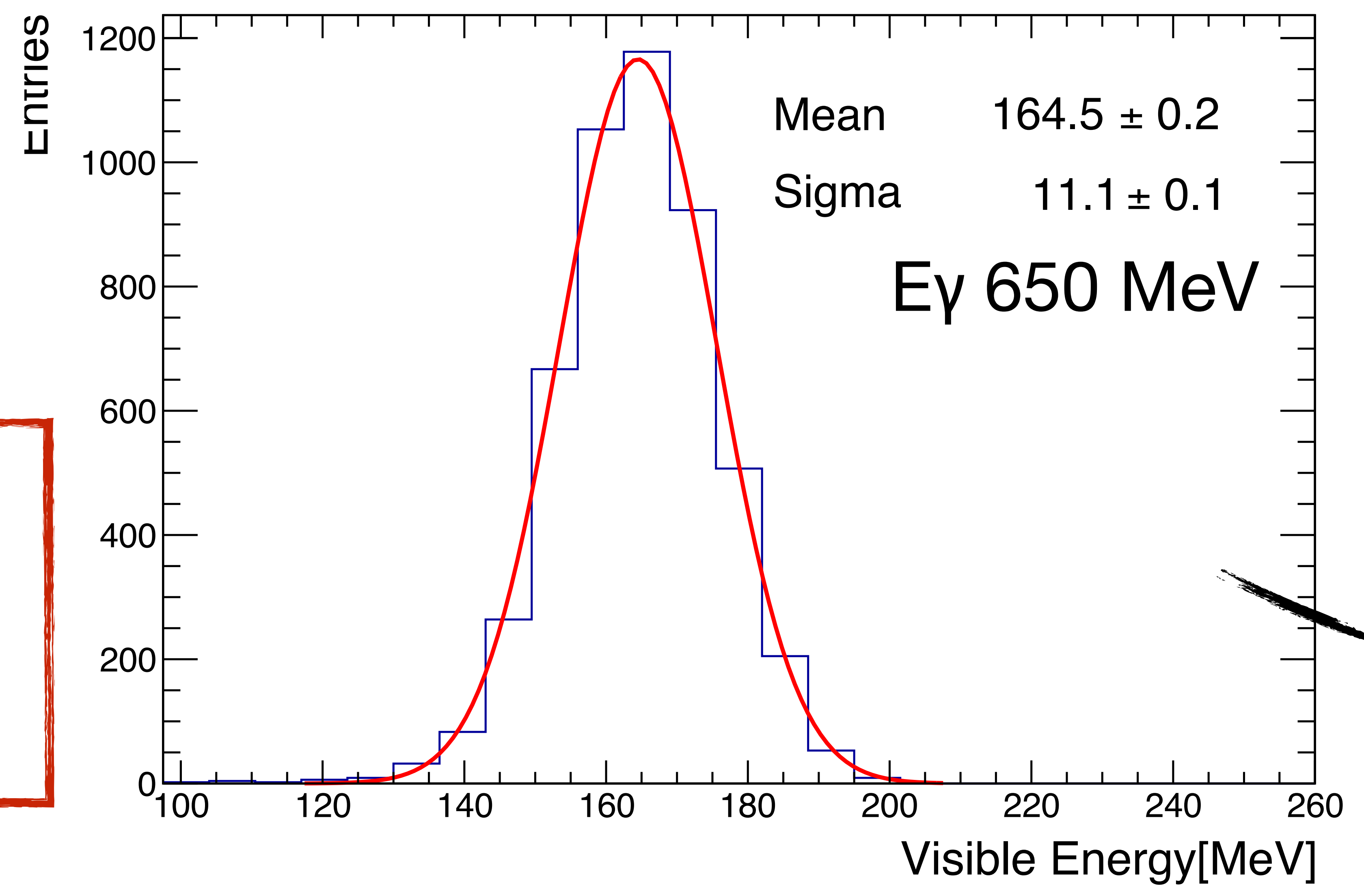
N.B.: Default detector geometry: 2 mm Cu / layer, 20 x 20 mm^2 granularity in first 30 layers, 40 x 40 mm^2 granularity outside

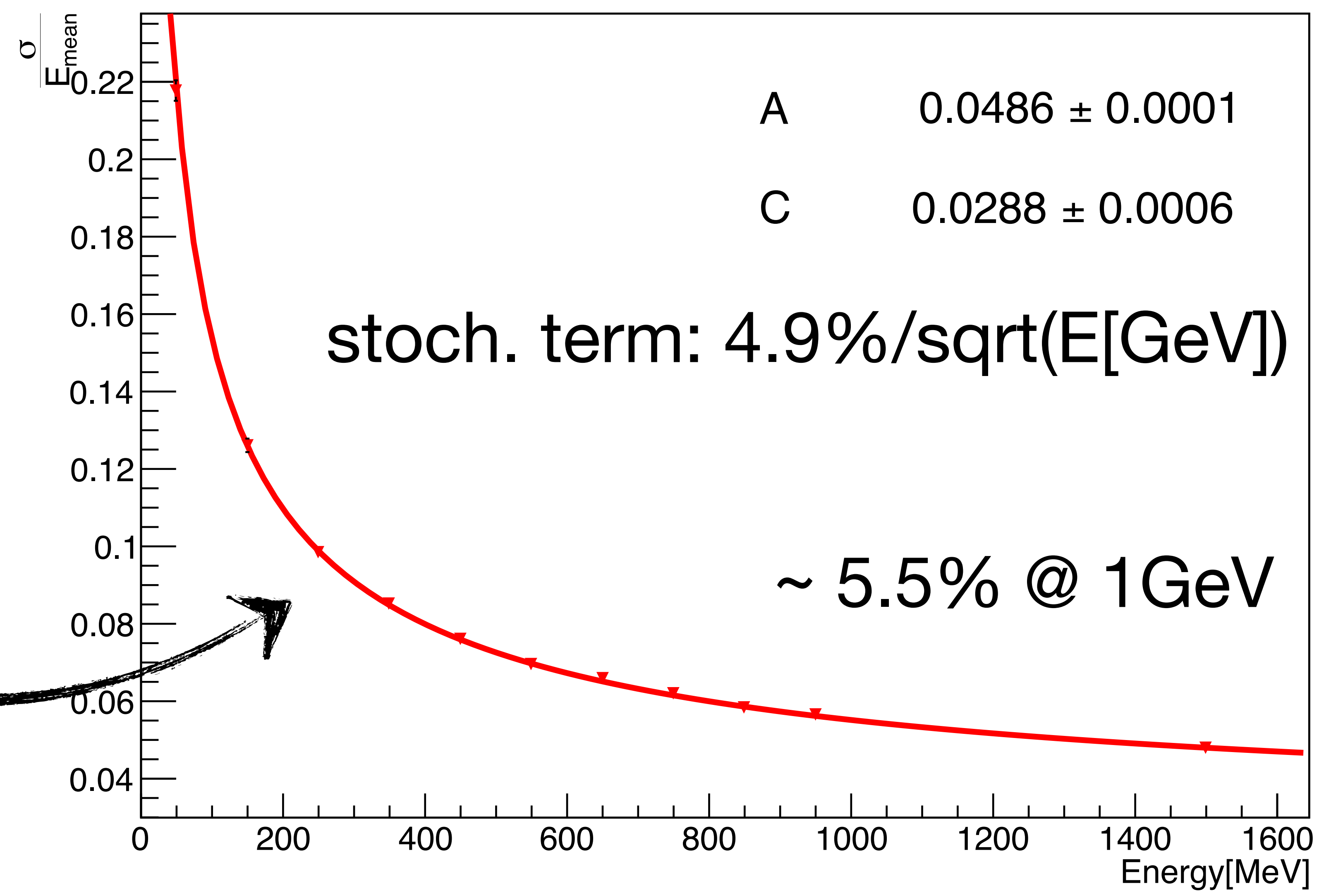
Single Photons

Performance Metrics -

- Energy resolution given by σ/mean

Note: Over-optimistic - not all detector effects simulated!





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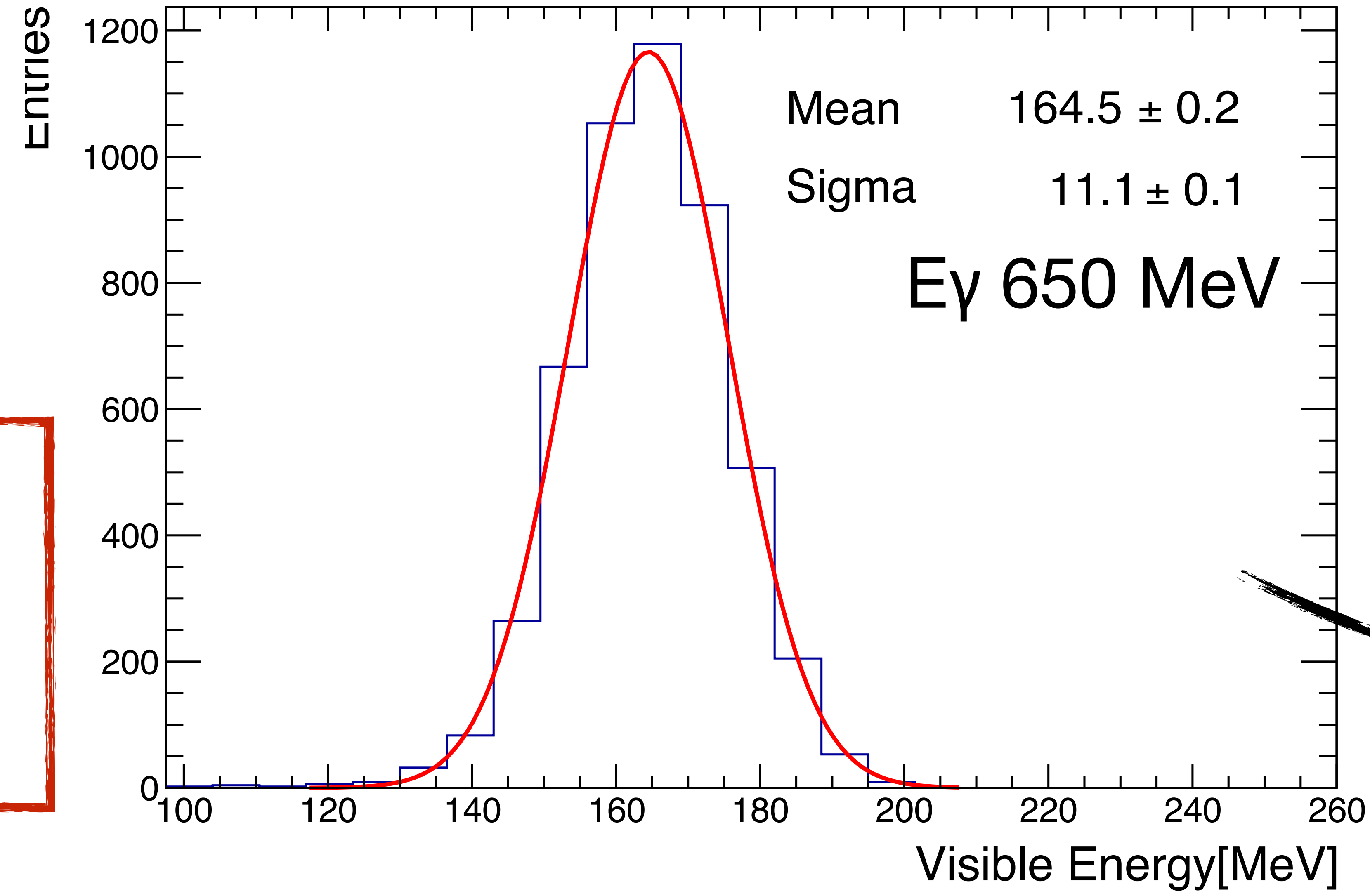
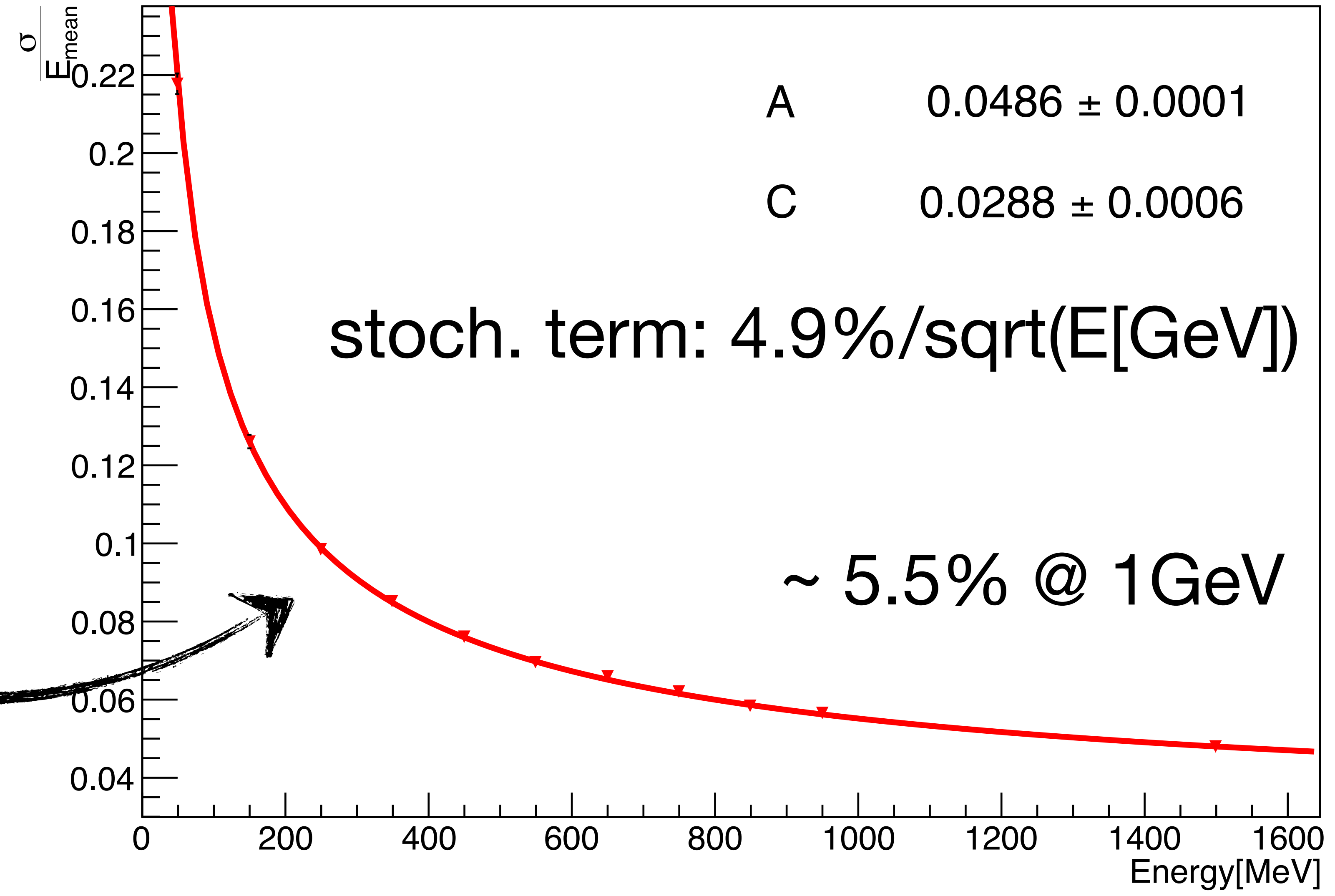
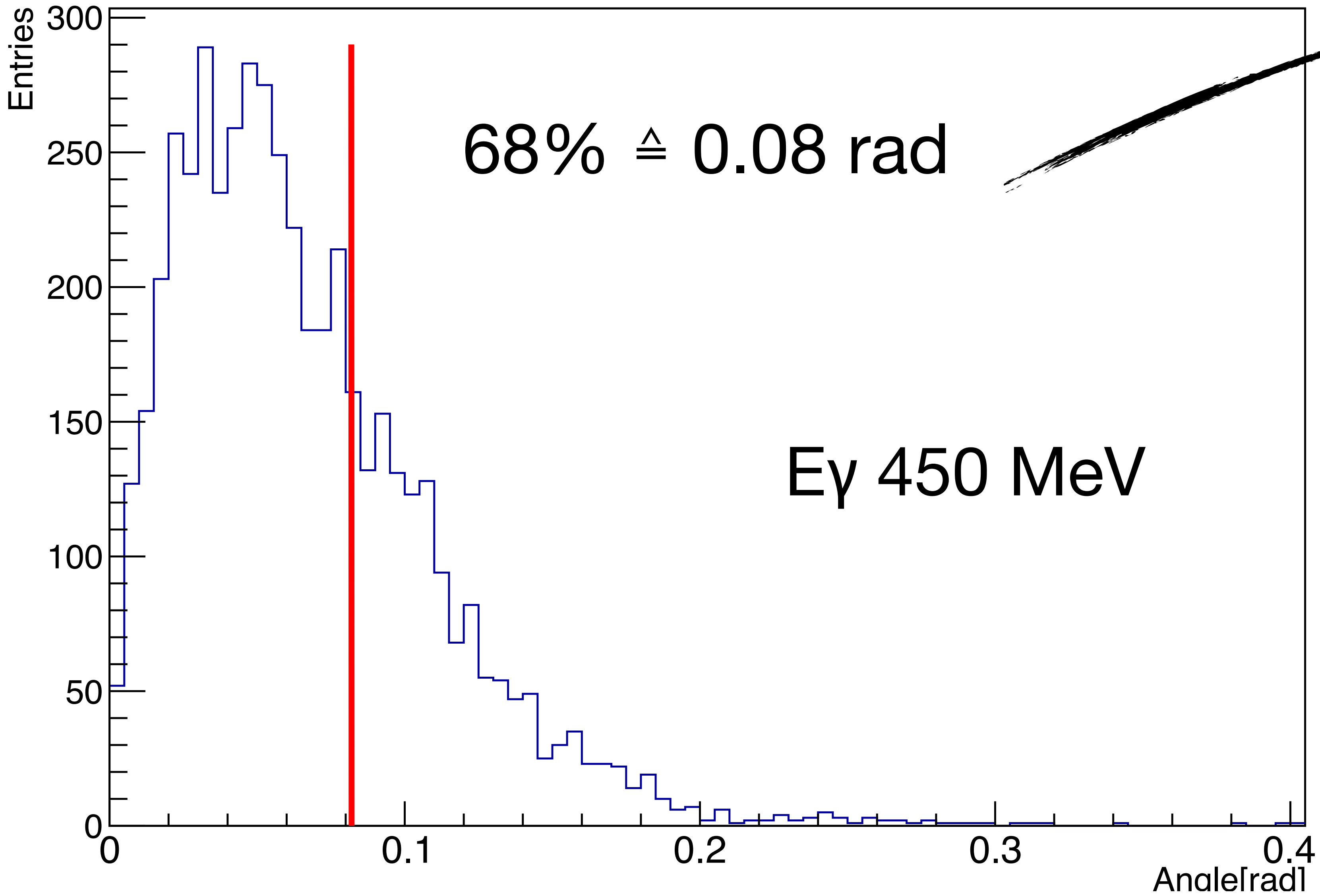
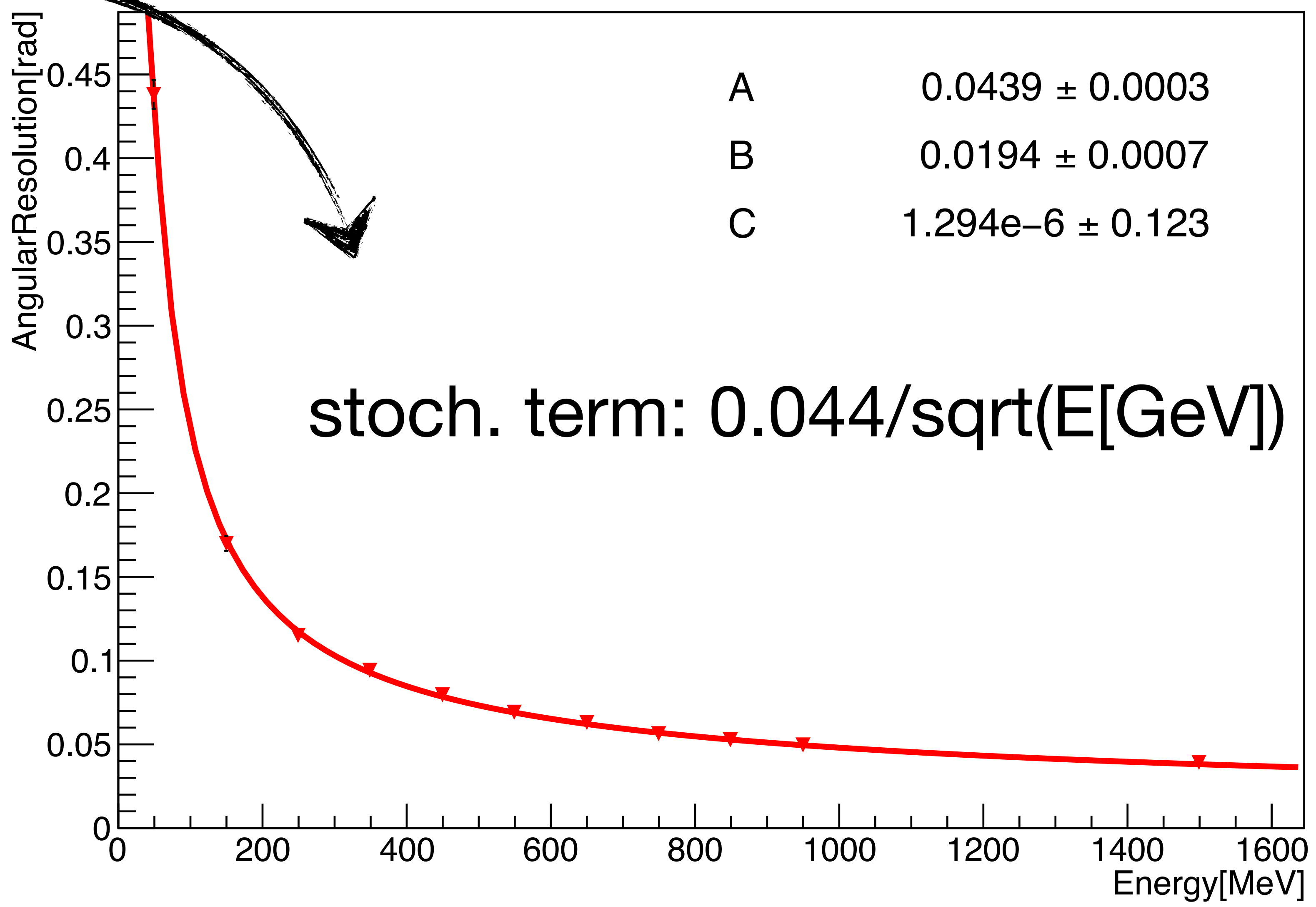




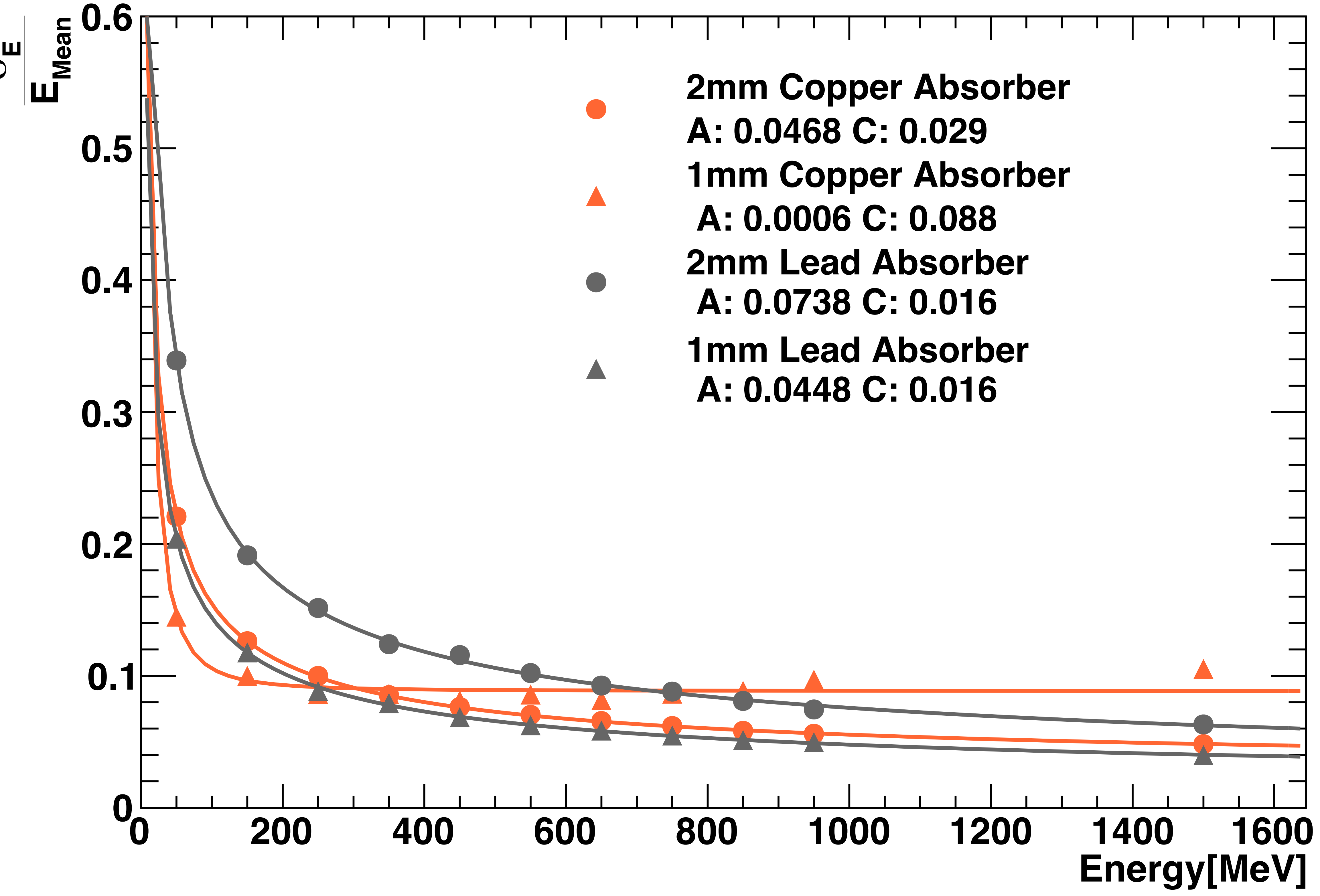




- Angular resolution given by 68%ile

Energy Resolution: Dependence on Absorber Material

Understanding Performance Drivers



- Choice of absorber material and thickness drives sampling fraction & overall depth of calorimeter
  - Low energies profit from thinnest possible absorbers
  - Acceptable performance beyond a few 100 MeV requires adequate thickness in X_0

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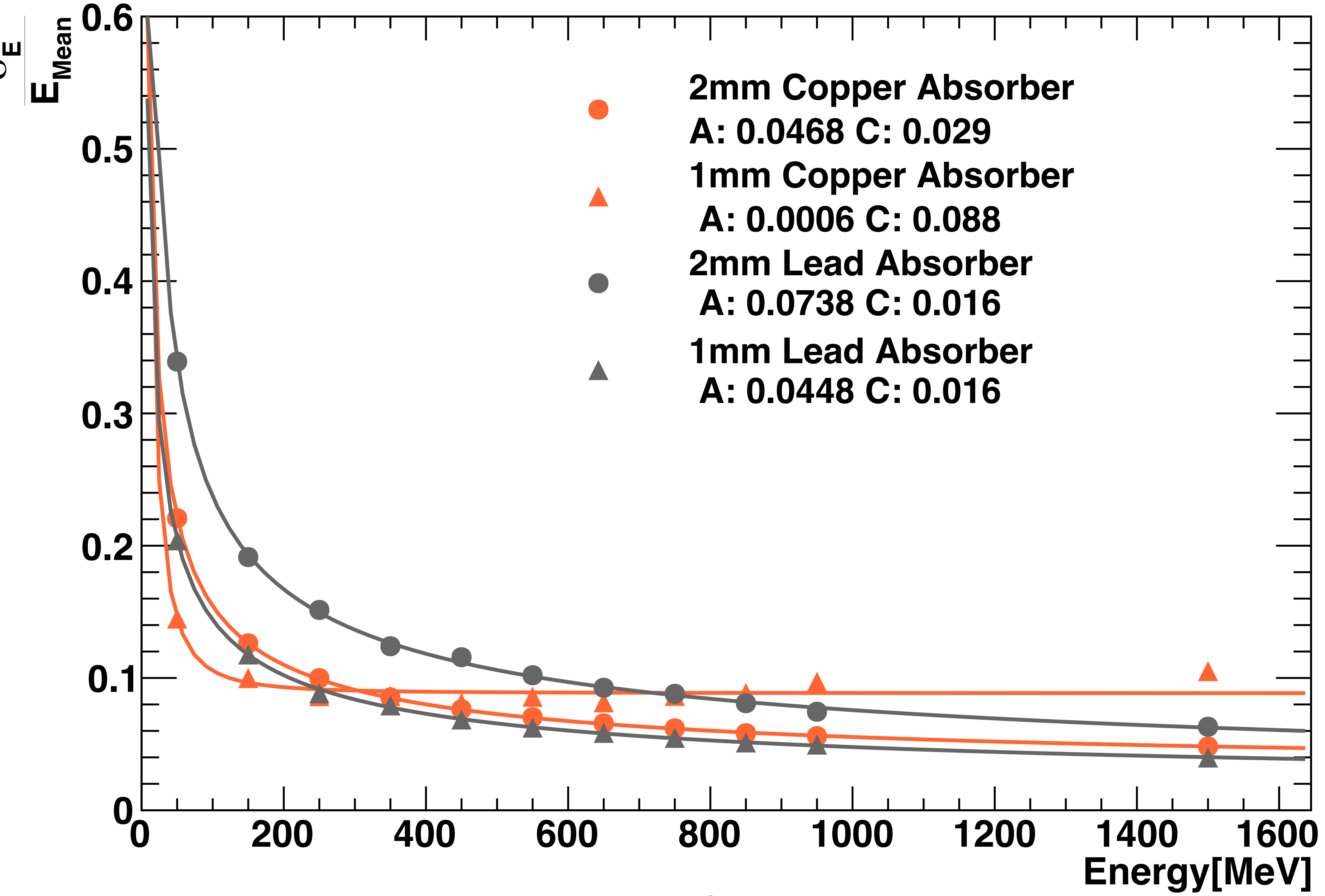

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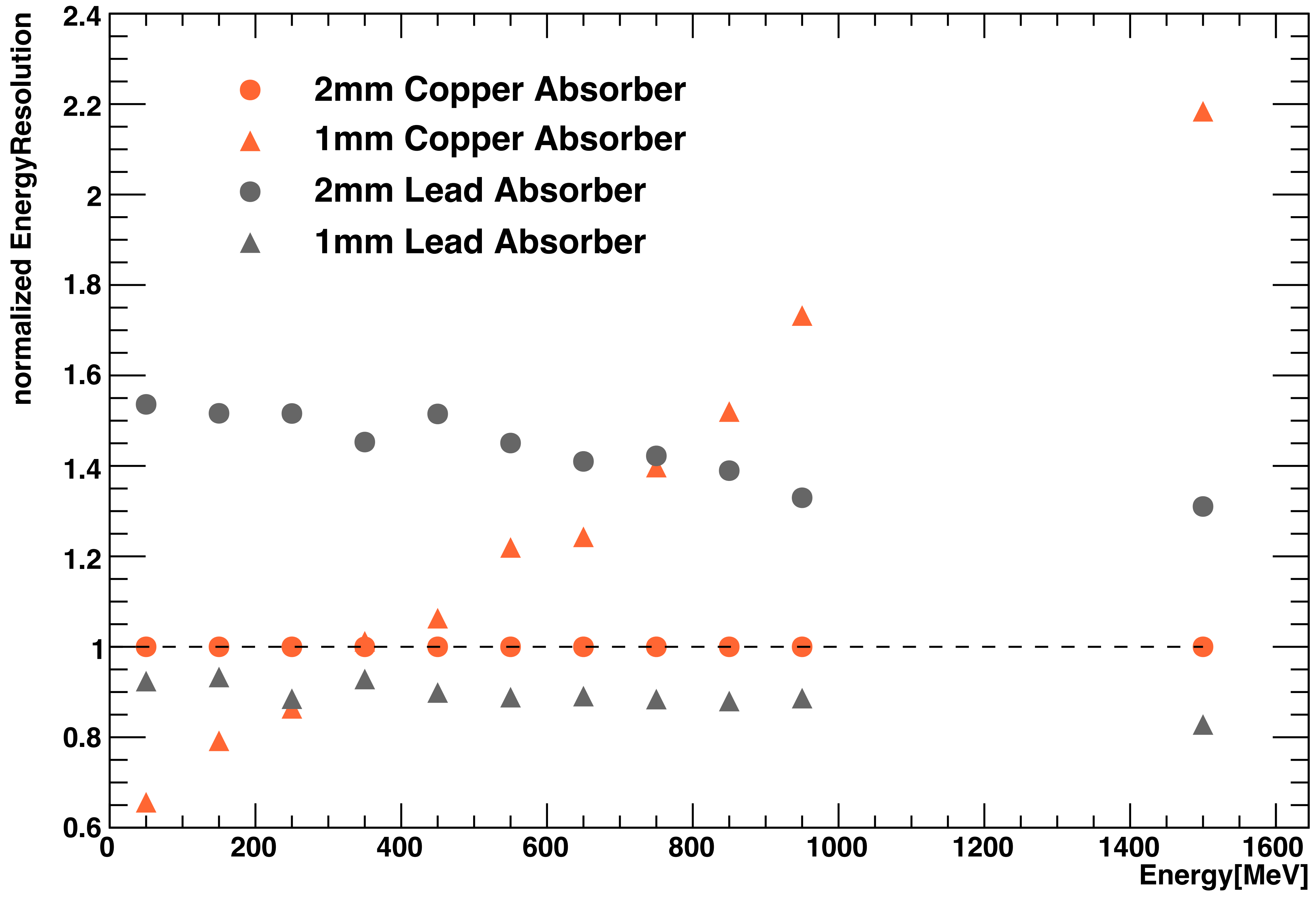
- Best energy resolution for 1 mm Pb, 2 mm Cu roughly 10% worse
  - 2 mm Pb absorber costly for low energies



NB: More realistic detector effects will deteriorate resolution (maybe a 20% - 30% effect): Washes out differences!

Pointing Resolution: Dependence on Absorber Material

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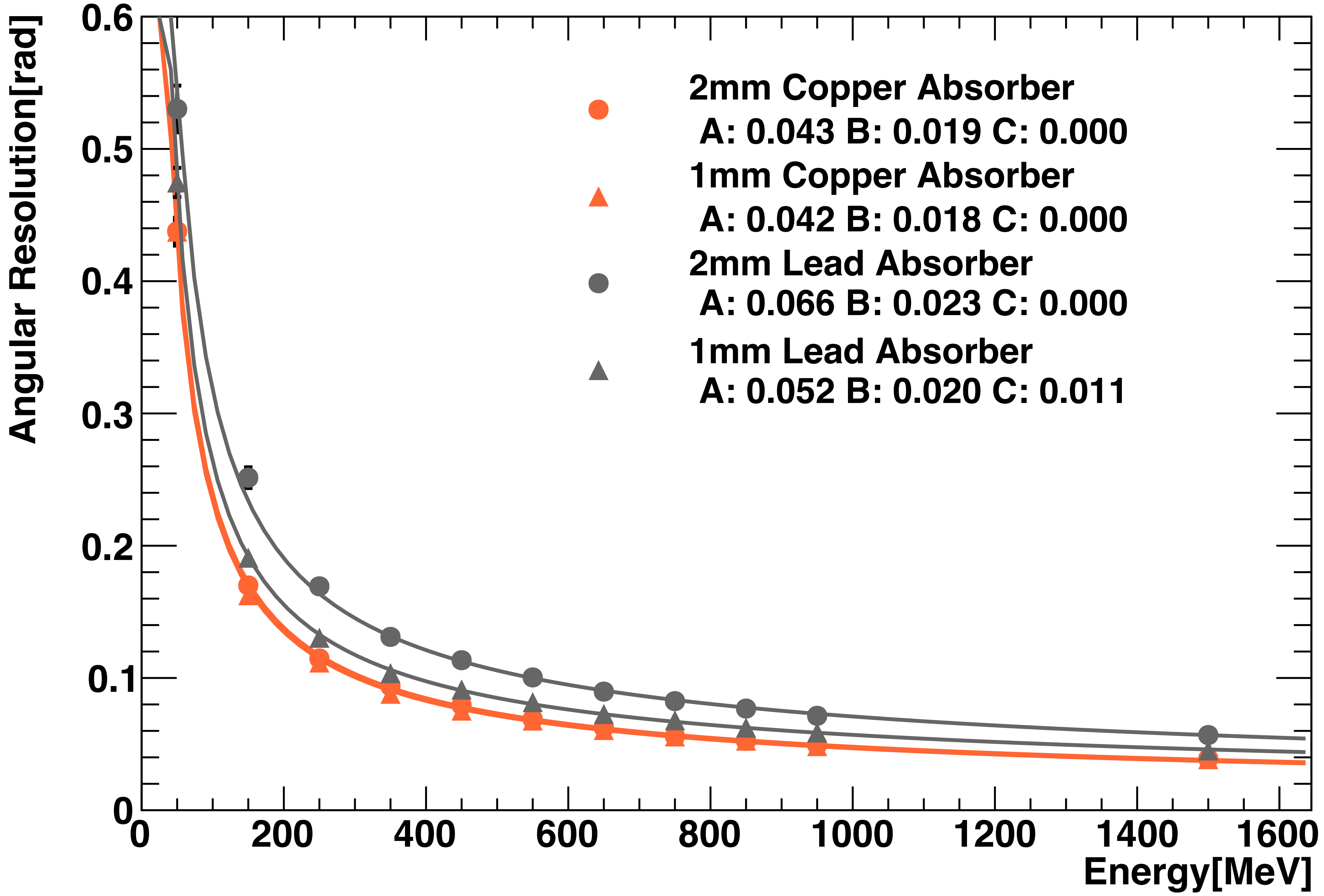

- Choice of absorber material influences shower size (laterally and longitudinally)
  - Pointing accuracy profits from narrow and long showers (and frequent sampling)

always 20 x 20 mm^2 granularity in first 30 layers

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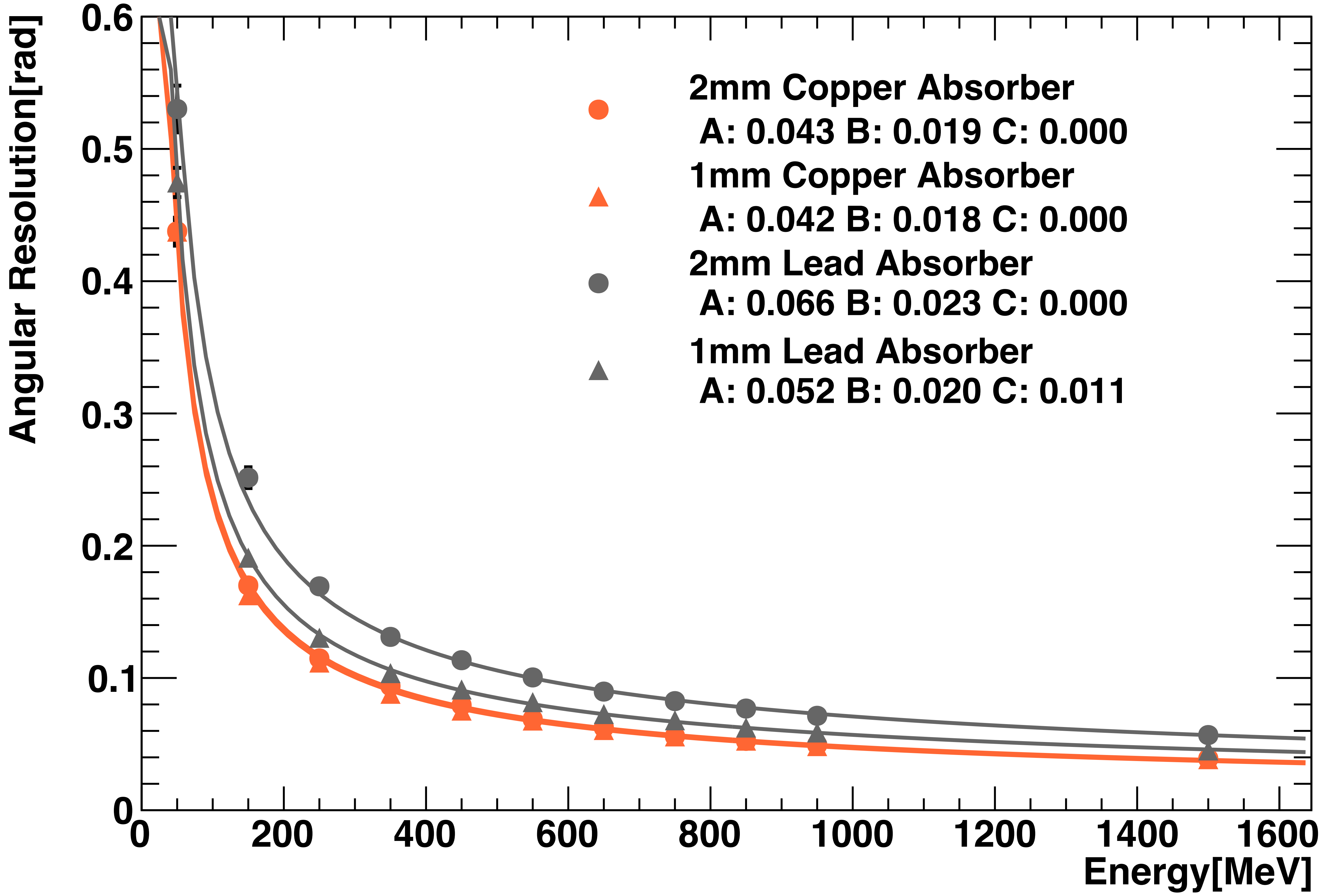

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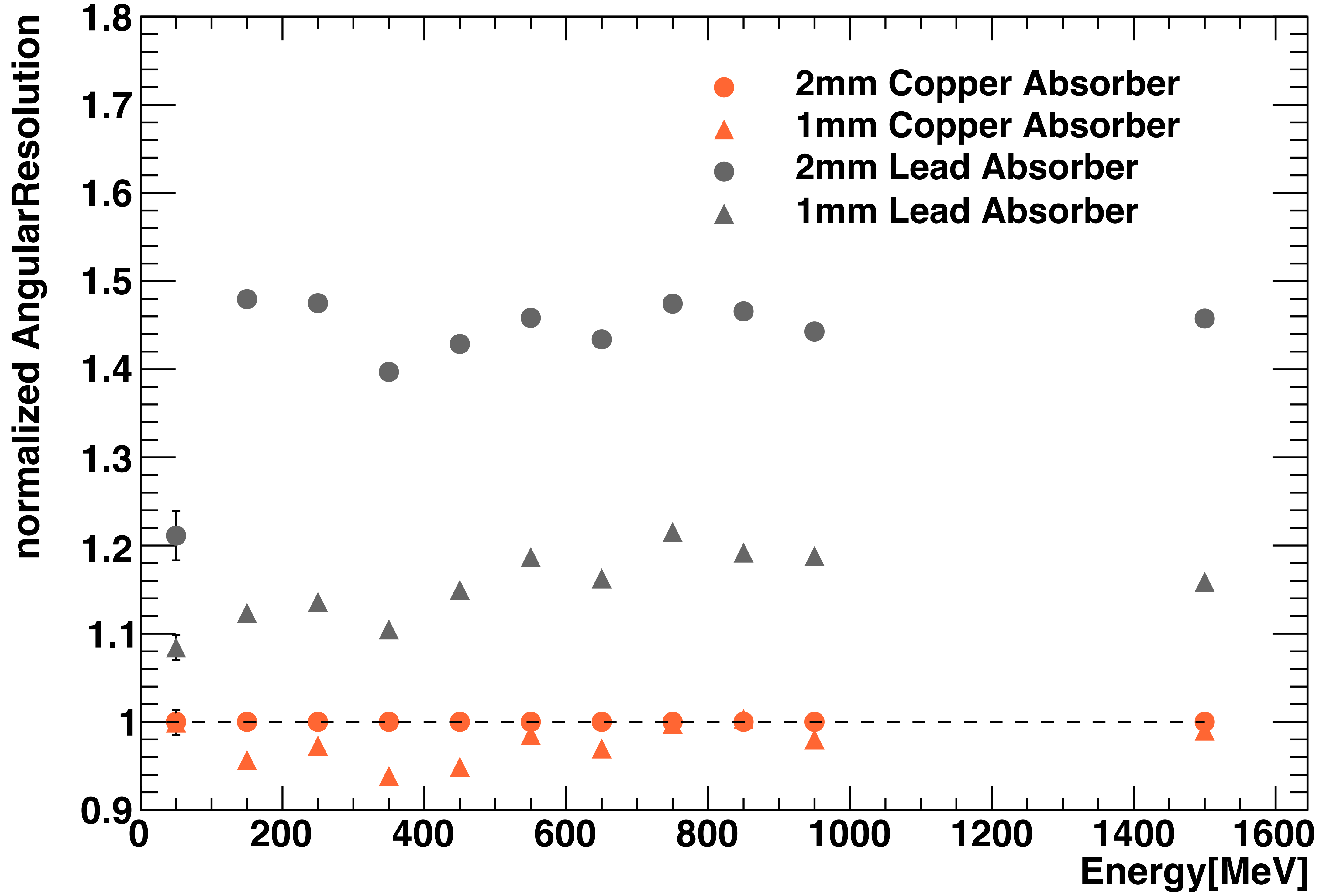

- Best pointing accuracy for Cu absorber - very little benefit when going from 2 mm to 1 mm thickness

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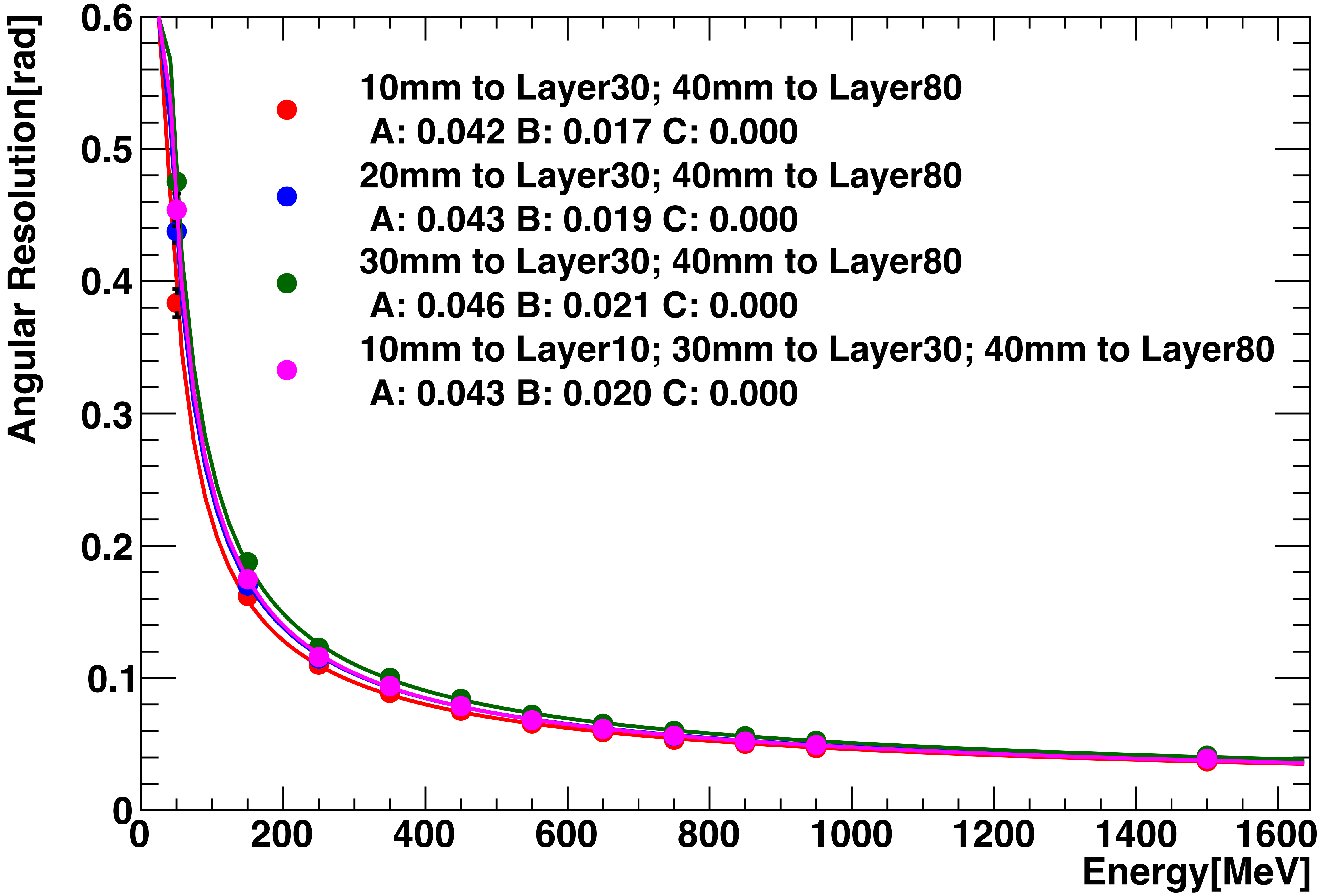
Pointing Resolution: Dependence on Granularity

Understanding Performance Drivers



- Granularity influences angular resolution: Better spacial reconstruction of shower for finer granularity

always 2 mm Cu absorber

Pointing Resolution: Dependence on Granularity

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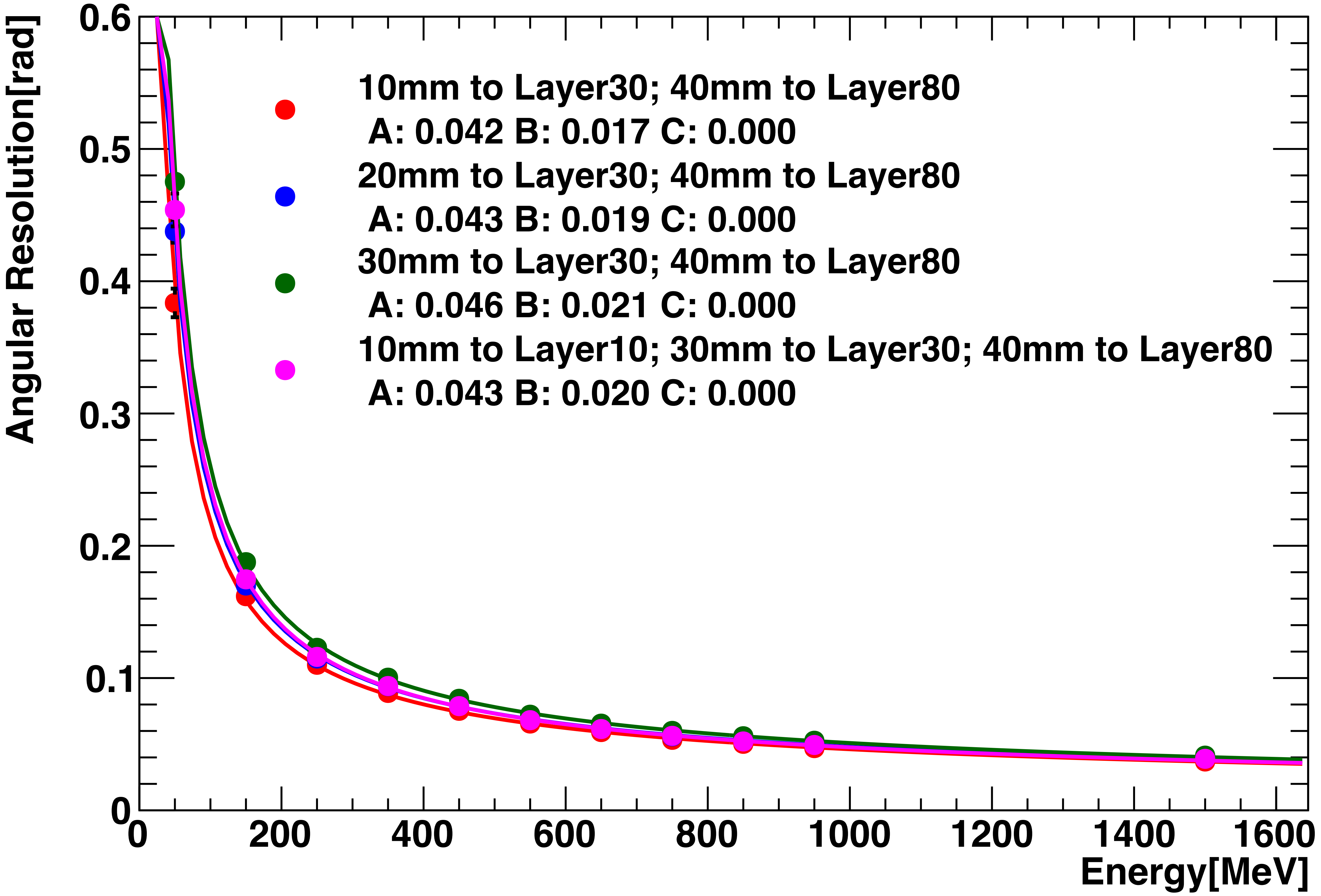

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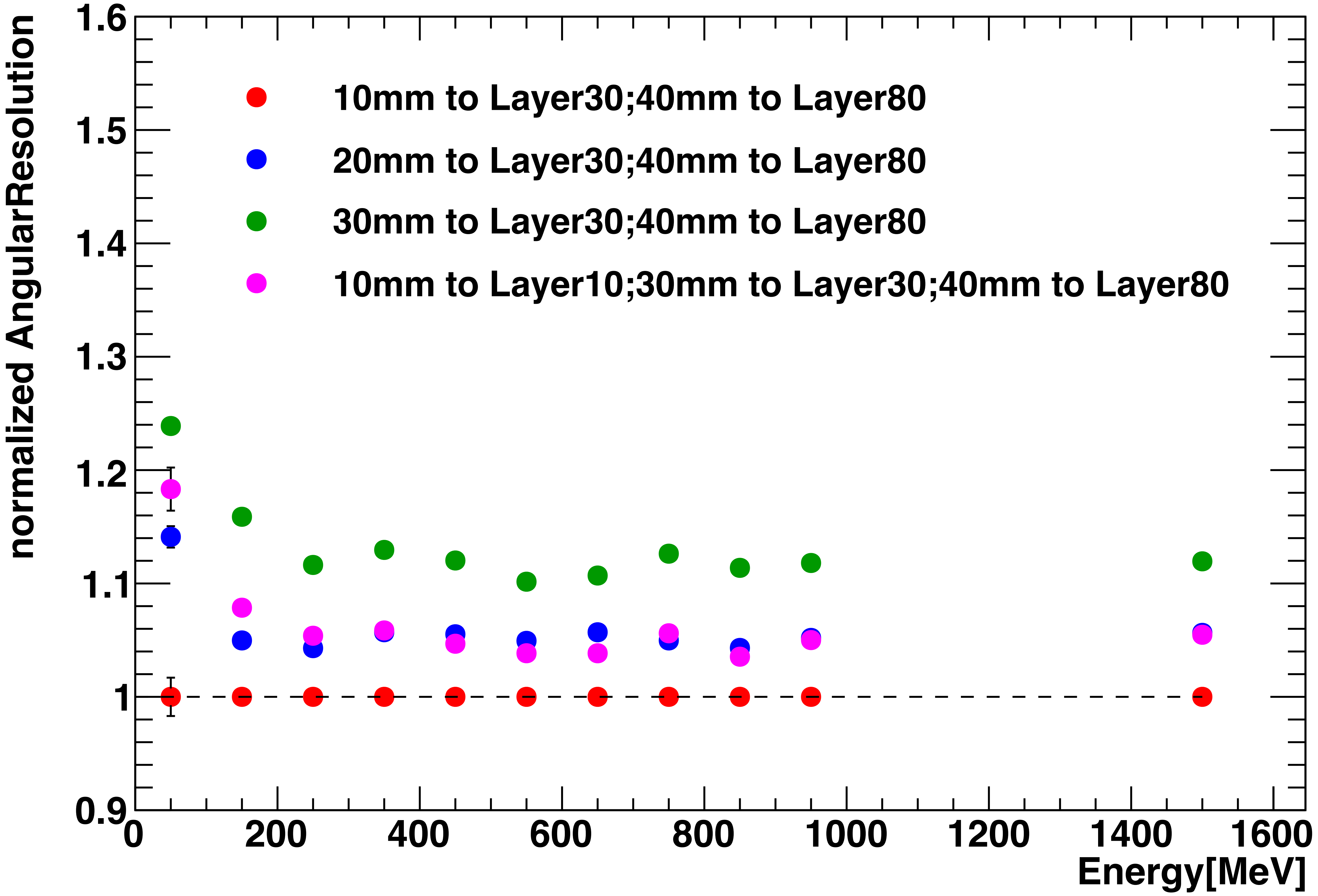


- Granularity particularly beneficial in first layers - gain starts to diminish below 20 x 20 mm^2 at higher energy

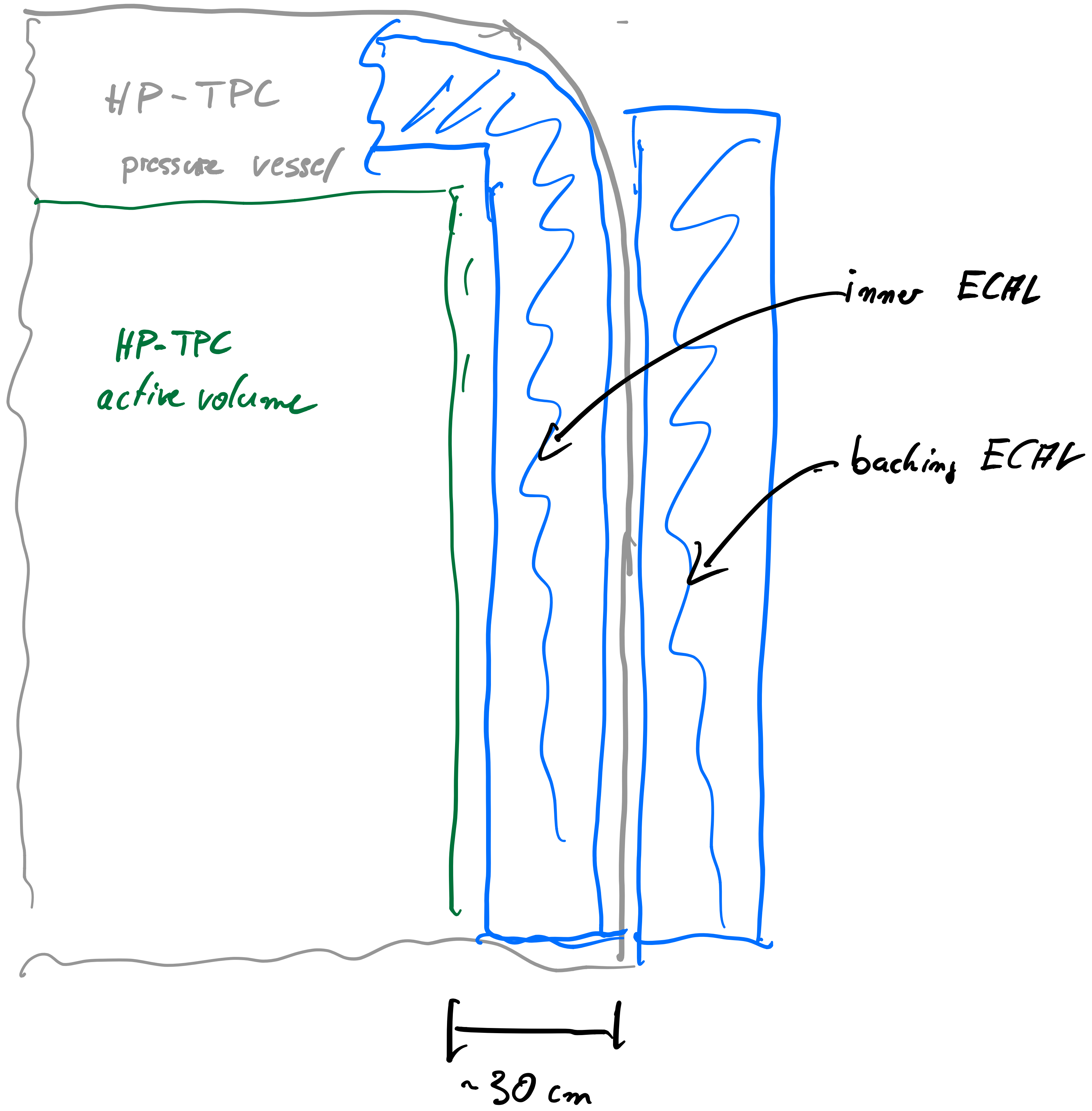
always 2 mm Cu absorber

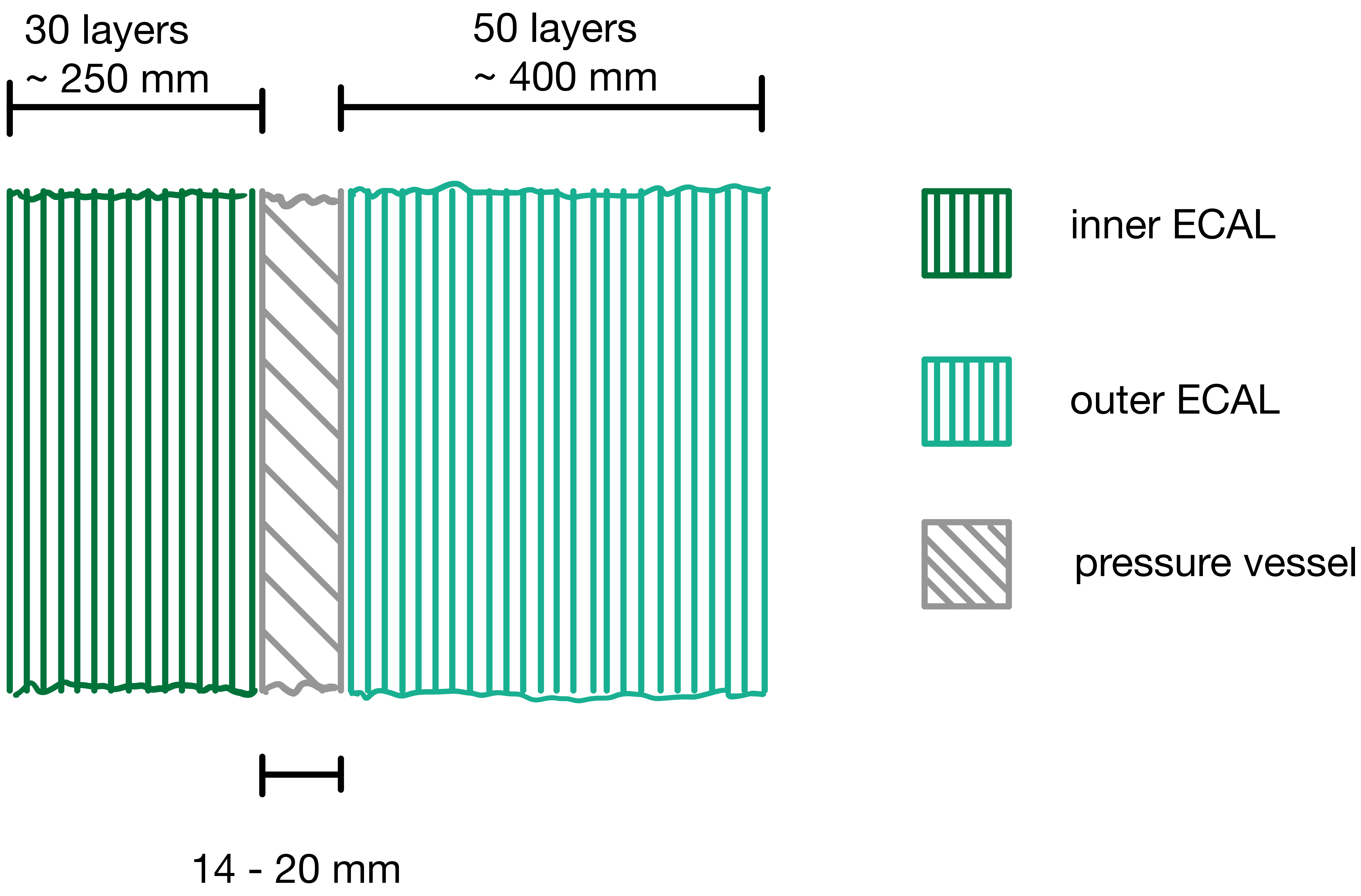
- 20 x 20 mm^2 granularity and 1 mm Pb absorber comparable to 30 x 30 mm^2 with 2 mm Cu absorber

Impact of a TPC Pressure Vessel in ECAL Volume

Understanding Performance Drivers

- Space inside pressure vessel is “premium real estate”
- In case it is not possible to accommodate the full calorimeter (depth ~ 80 cm) inside the vessel: Split the calorimeter into two sections





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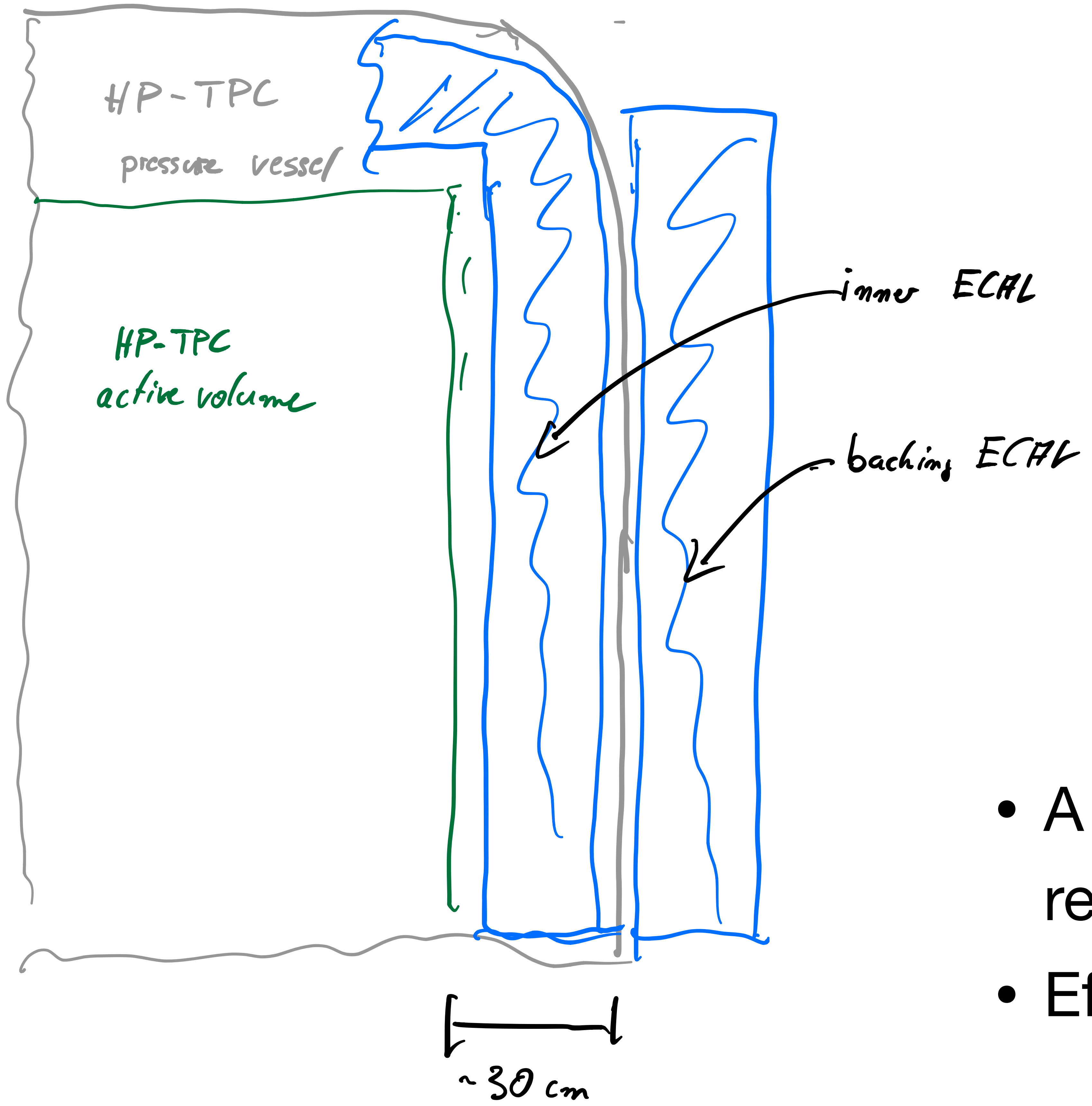
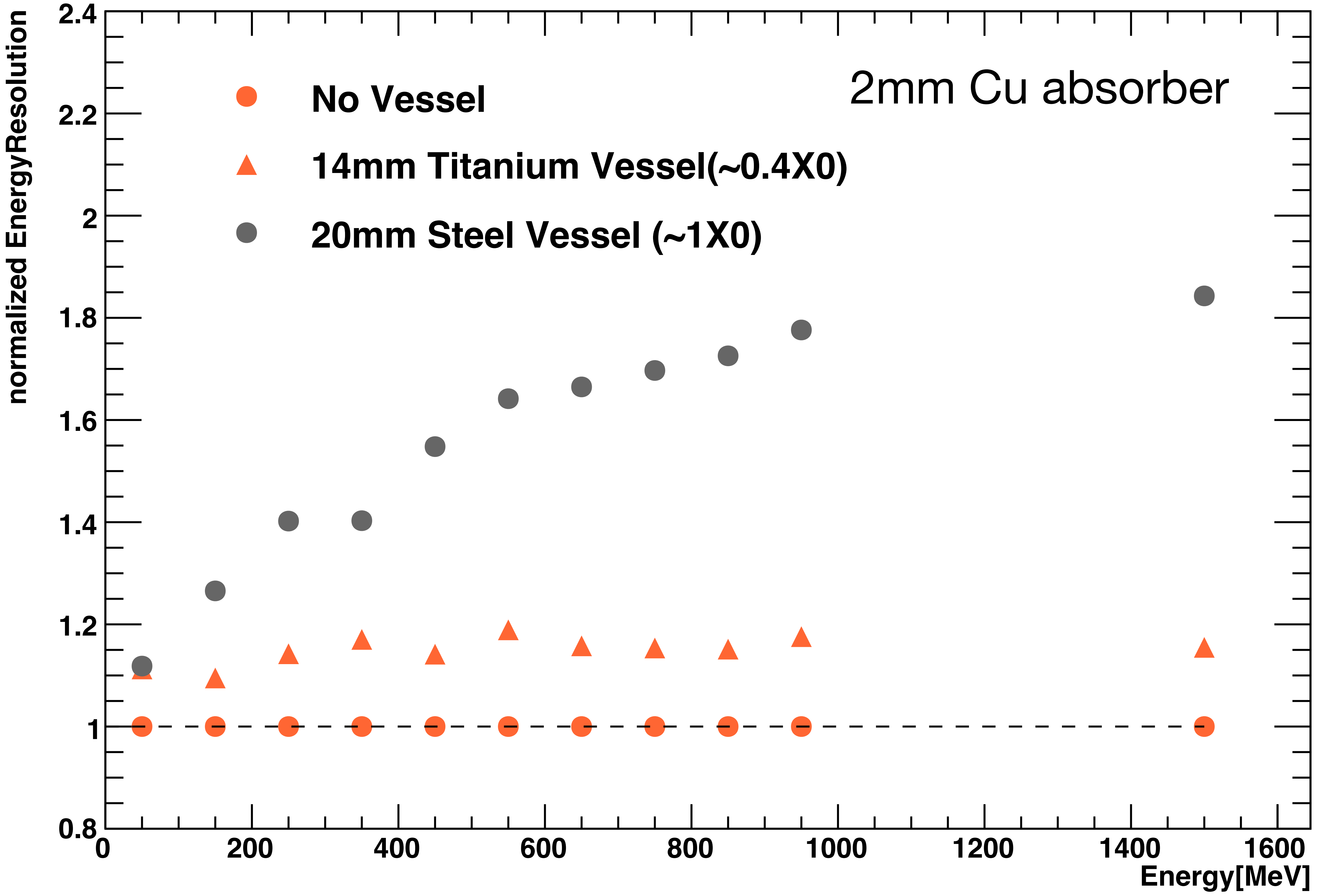




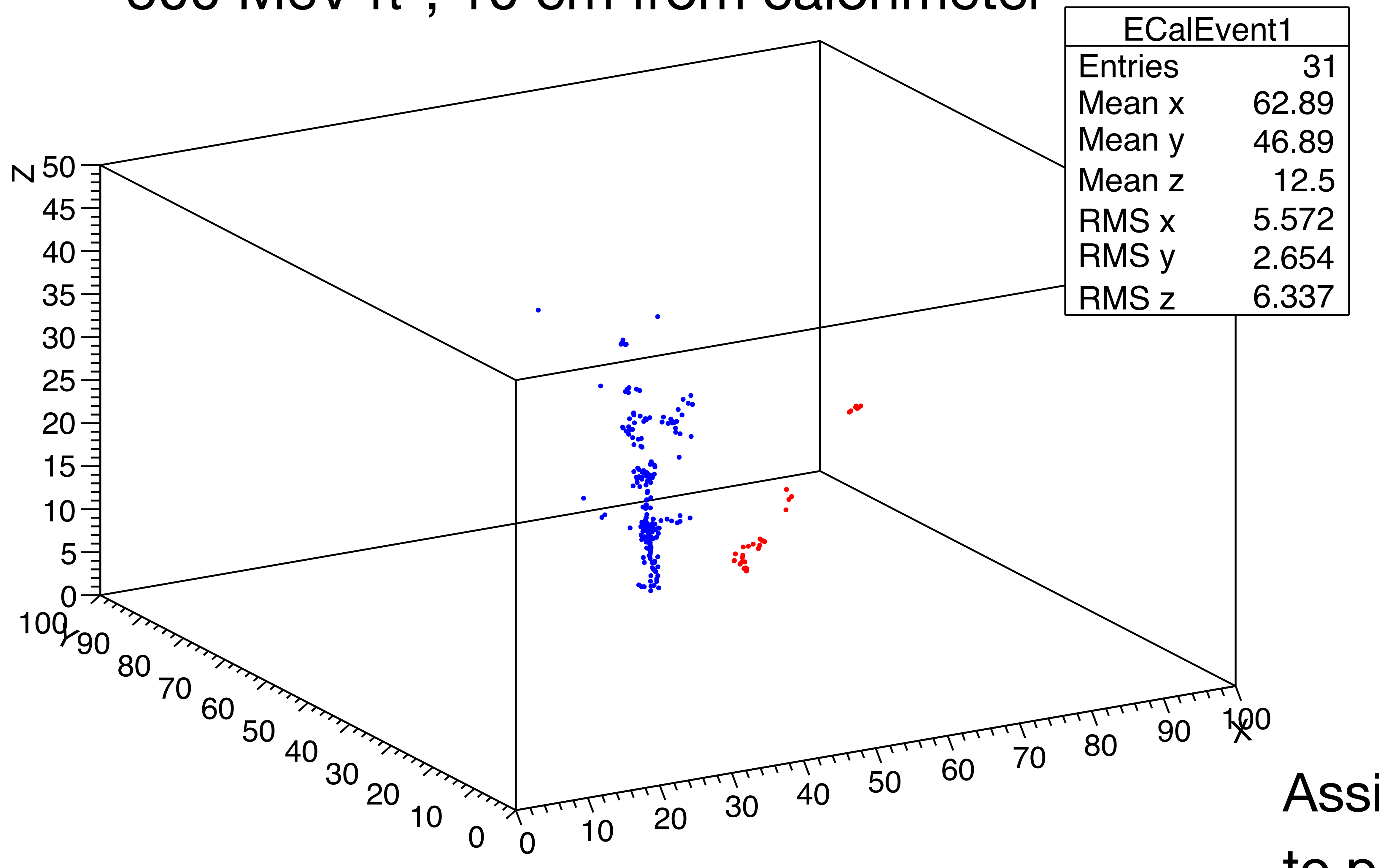
- A 1 X_0 thick stainless steel pressure vessel has a sizeable impact on energy resolution - use of Titanium would substantially mitigate that
- Effect on angular resolution is negligible: driven by first 30 layers

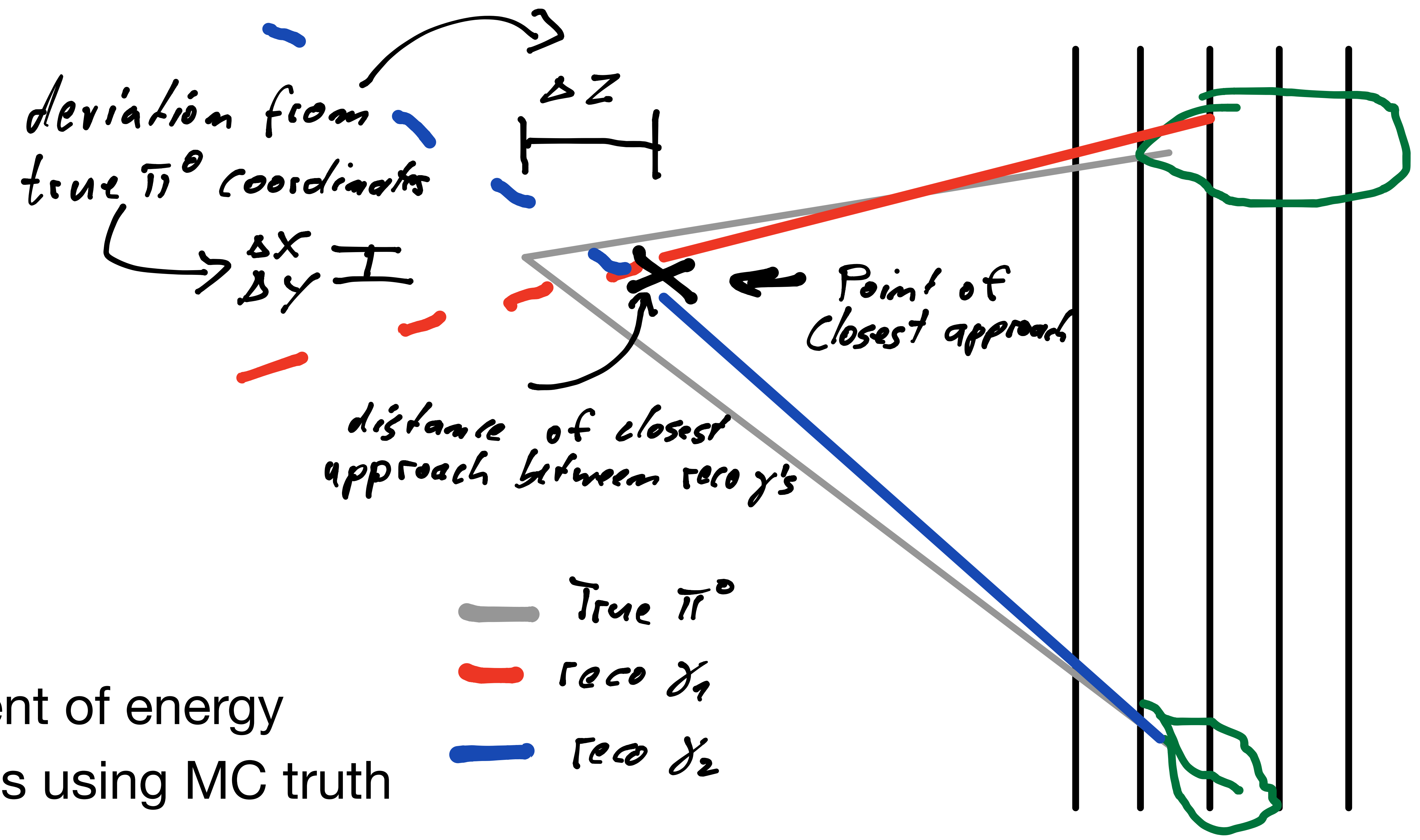
A First Look at π⁰s

Going beyond single particles

- Still in an early stage - clustering algorithms to identify photons based on energy deposit not yet implemented - will need somewhat more sophisticated simulations for a full study
  - Also: Results still need to be fully understood and QAed - bugs not unlikely!

500 MeV π^0, 10 cm from calorimeter





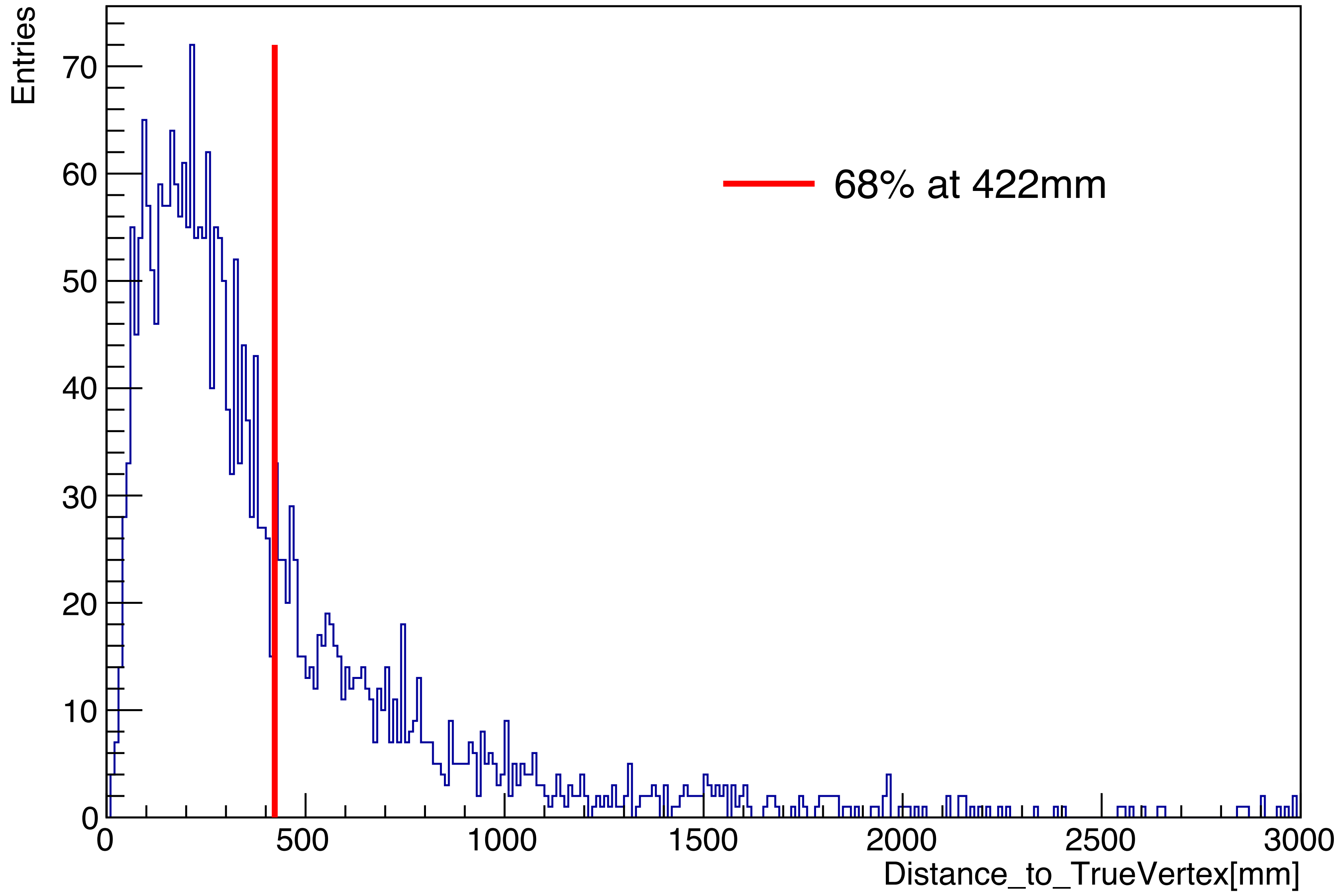
Assignment of energy to photons using MC truth information

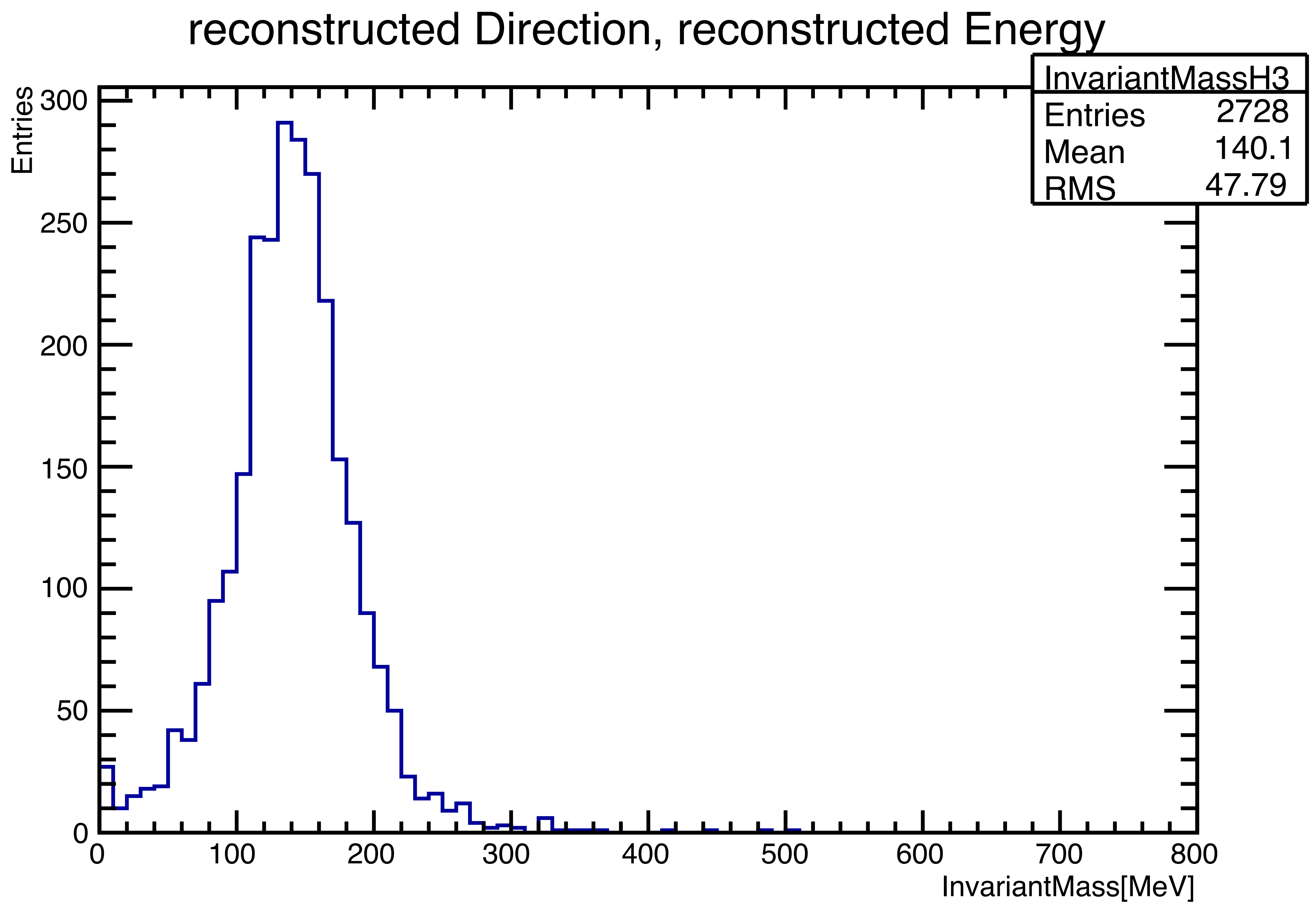
Reconstructing π^0s

Determination of origin

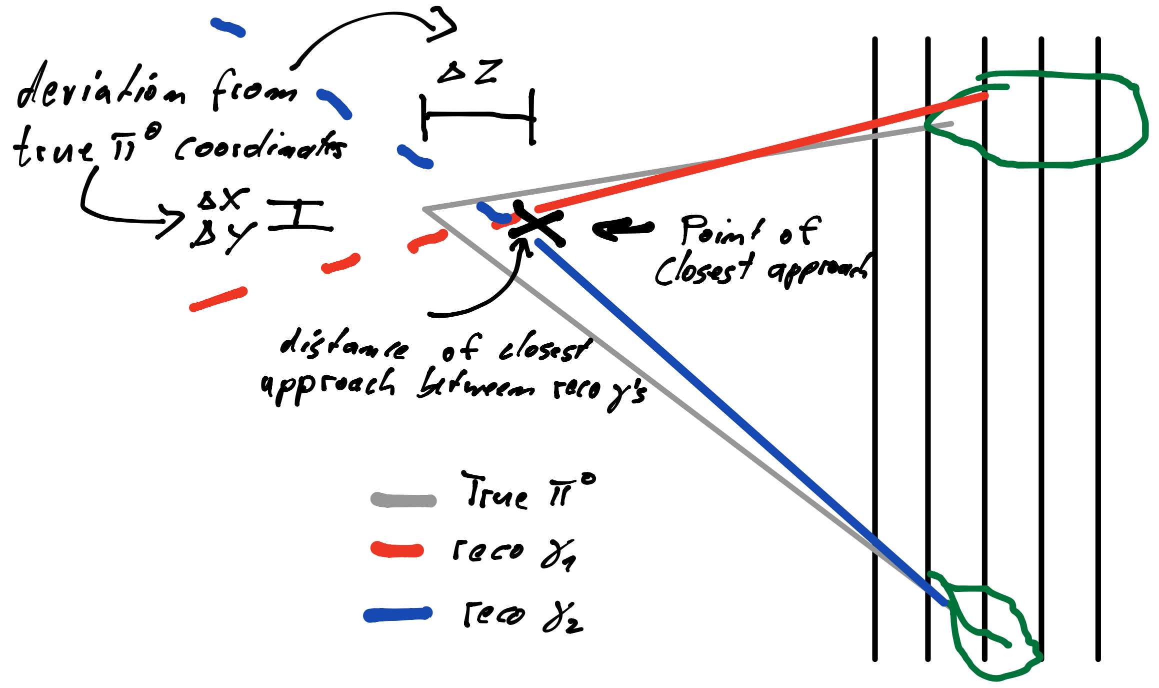
- Most π^0s at low kinetic energy (a few 100 MeV): Low photon energy, with rather poor pointing precision: Use a two-step procedure
    - Candidate identification based on vertex, invariant mass

coordinate in flight direction particularly uncertain - angular resolution introduces a systematic bias





400 MeV E_{kin}, 1 m from forward calorimeter



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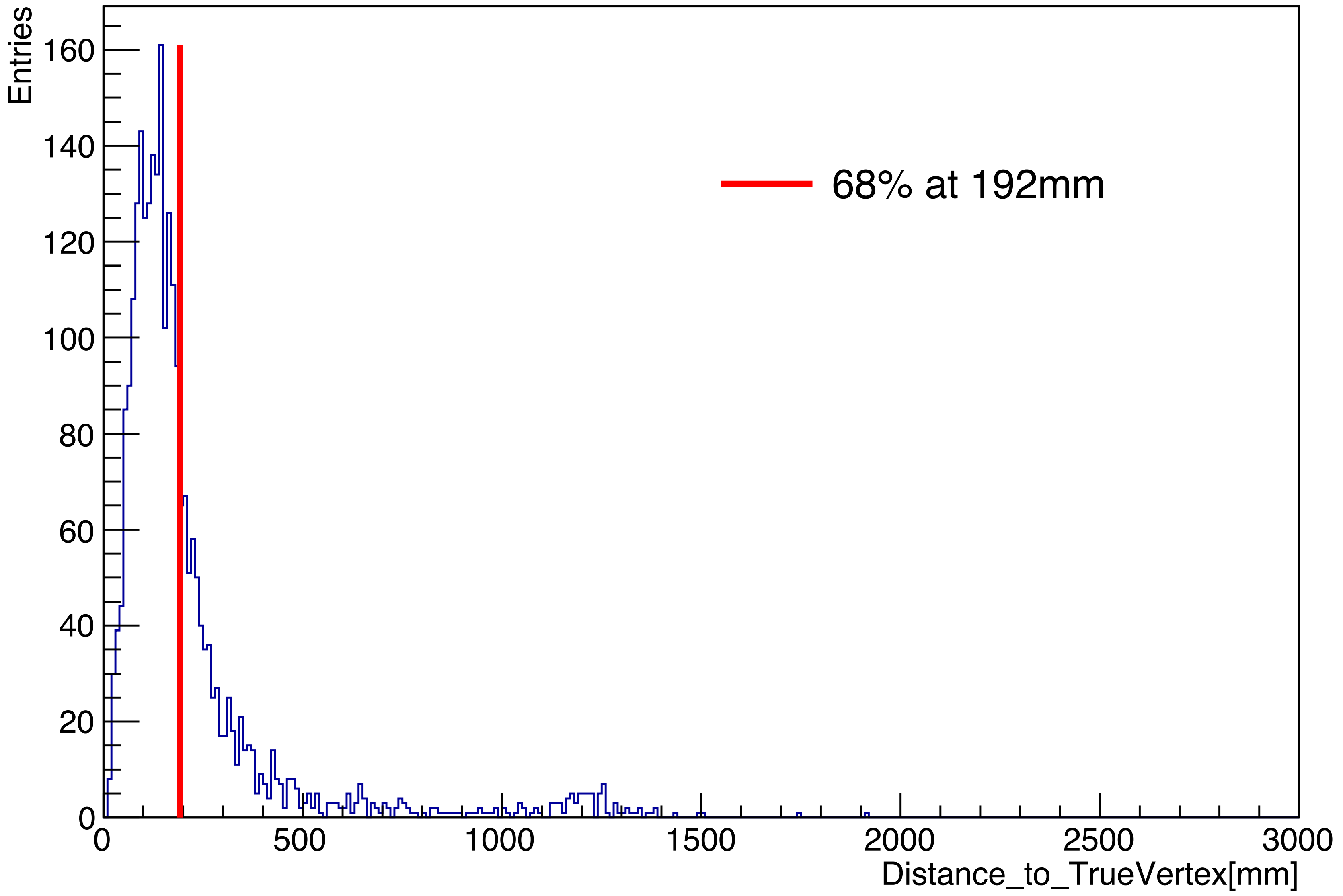
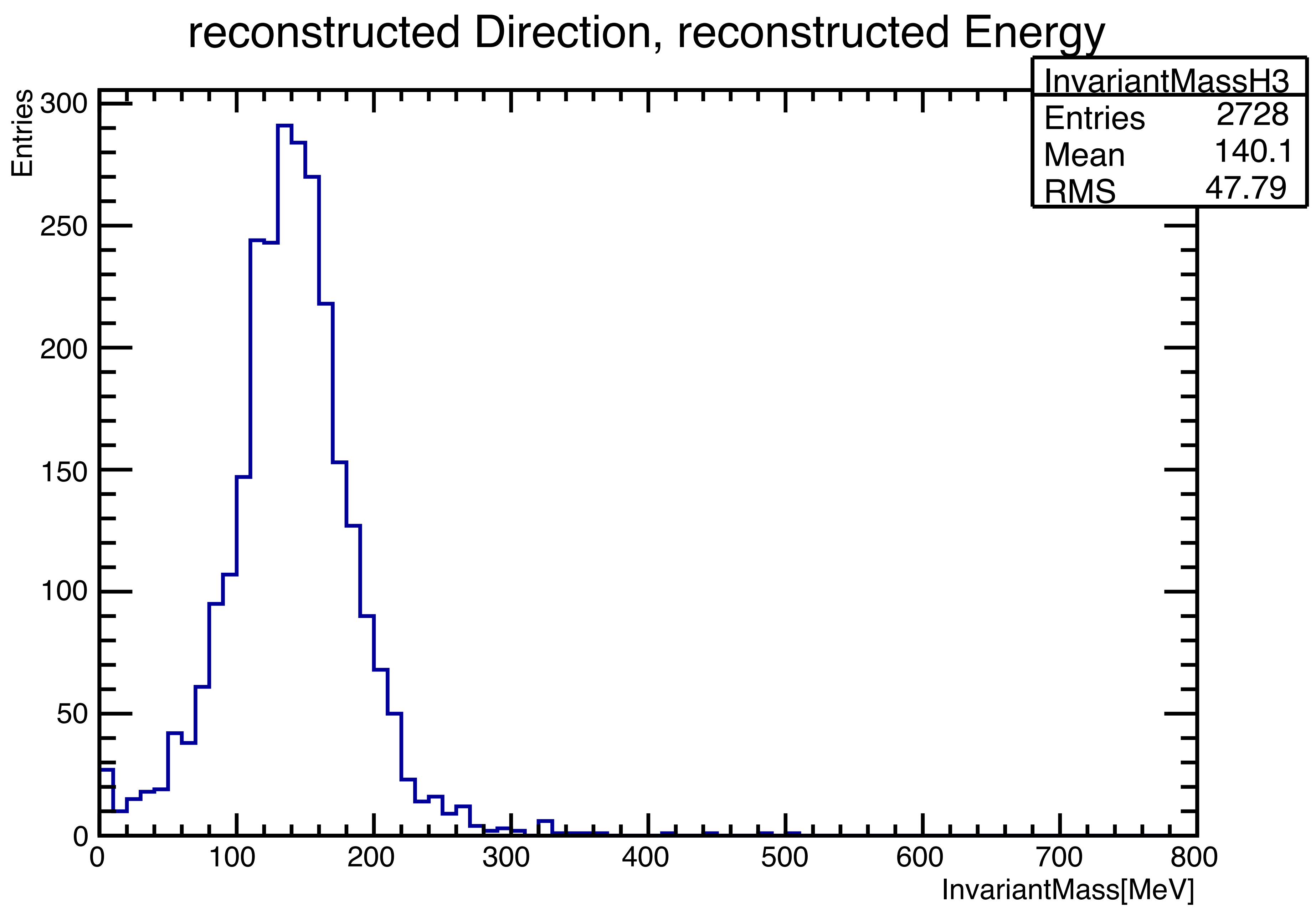
adding mass improves all coordinates - largest uncertainty still in flight direction





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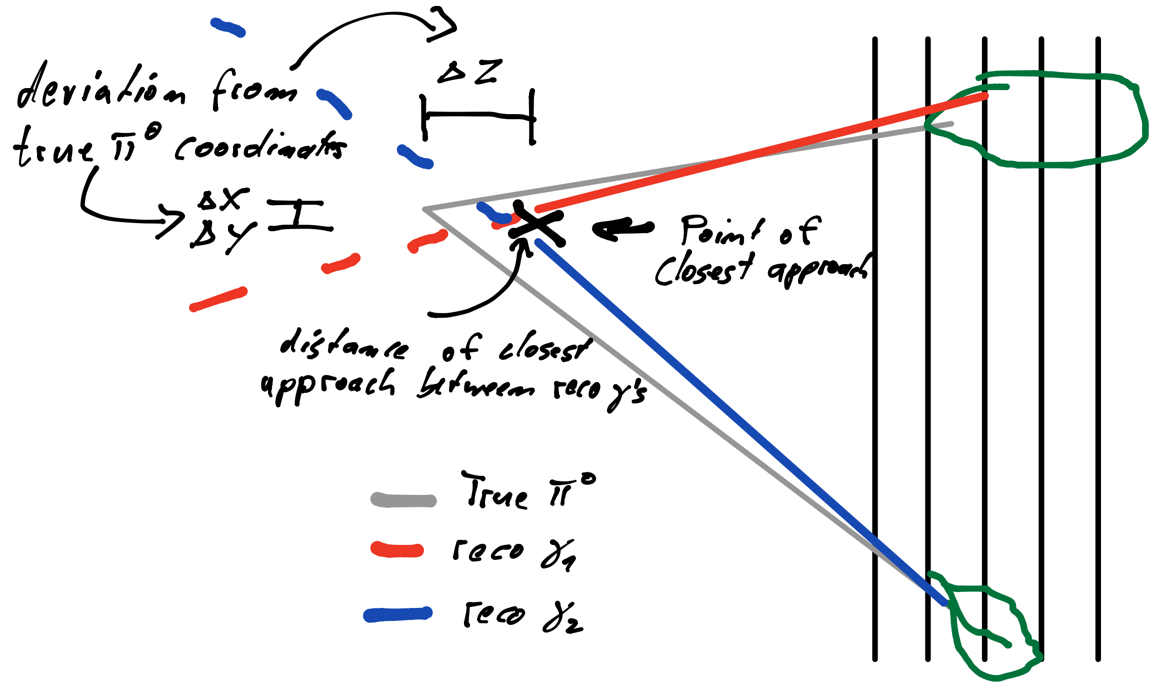

- Substantially improved location accuracy when adding π^0 mass constraint to the fit: fitting location, using m_{inv}, photon position, direction, energy

Neutrons

Looking beyond Photons

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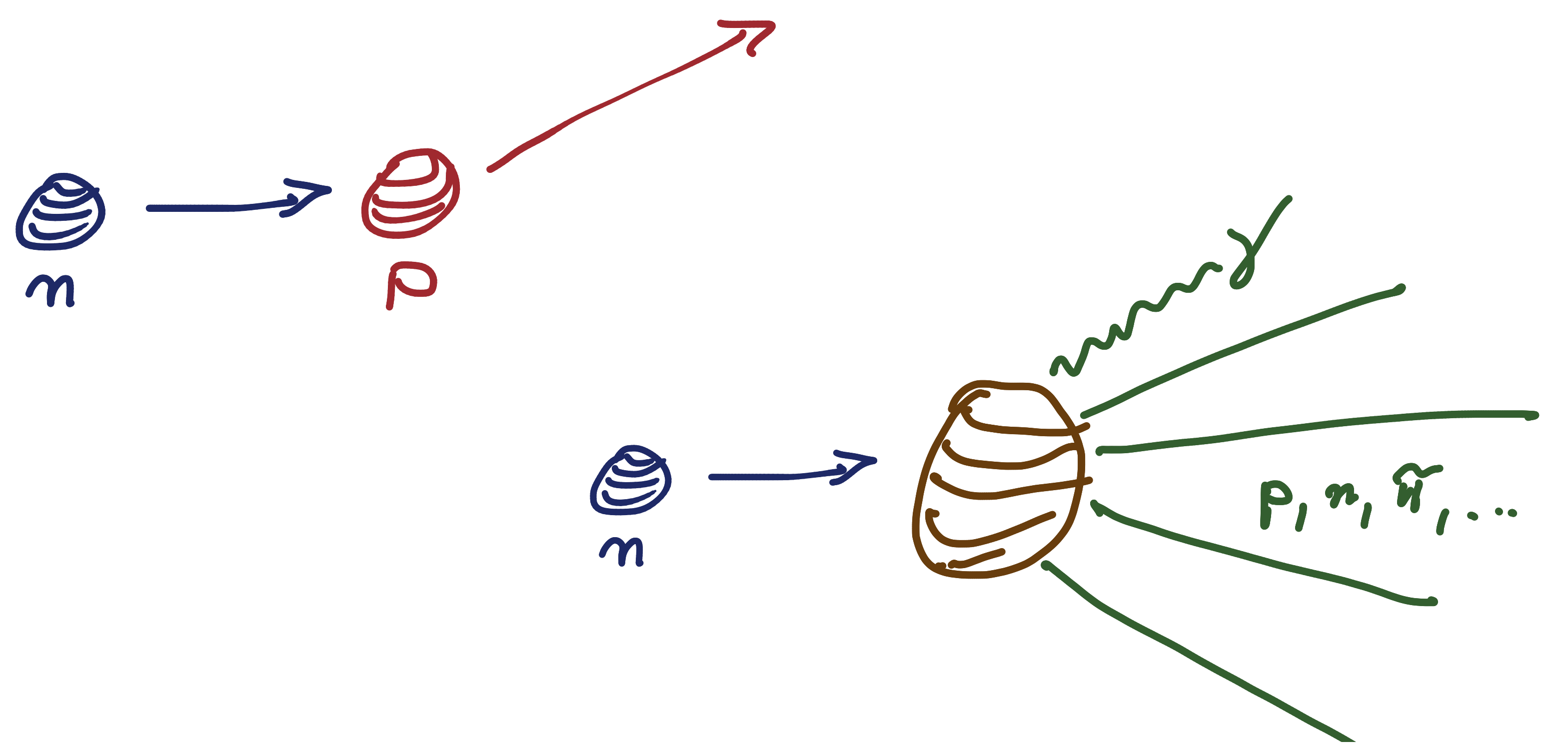
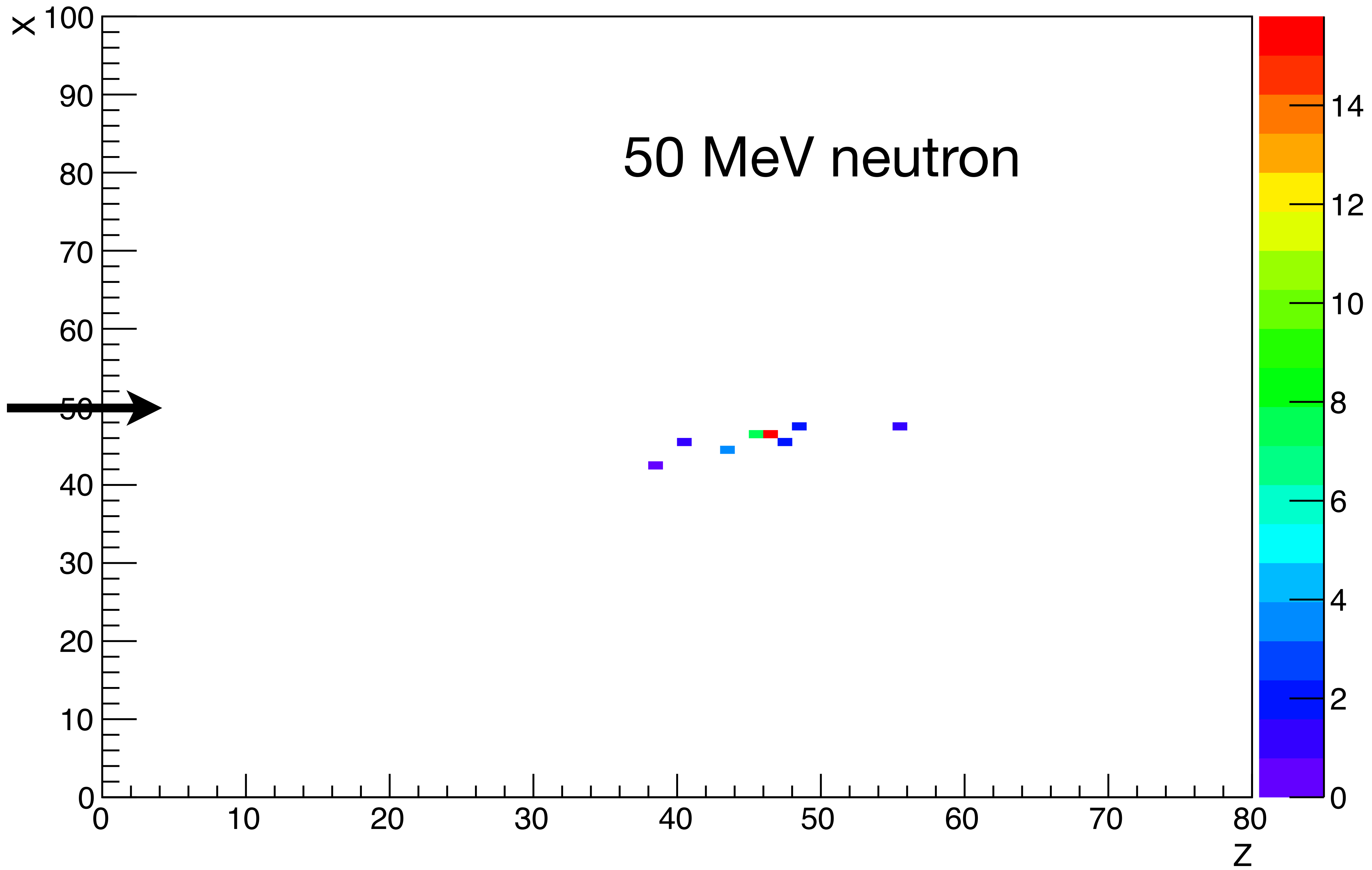
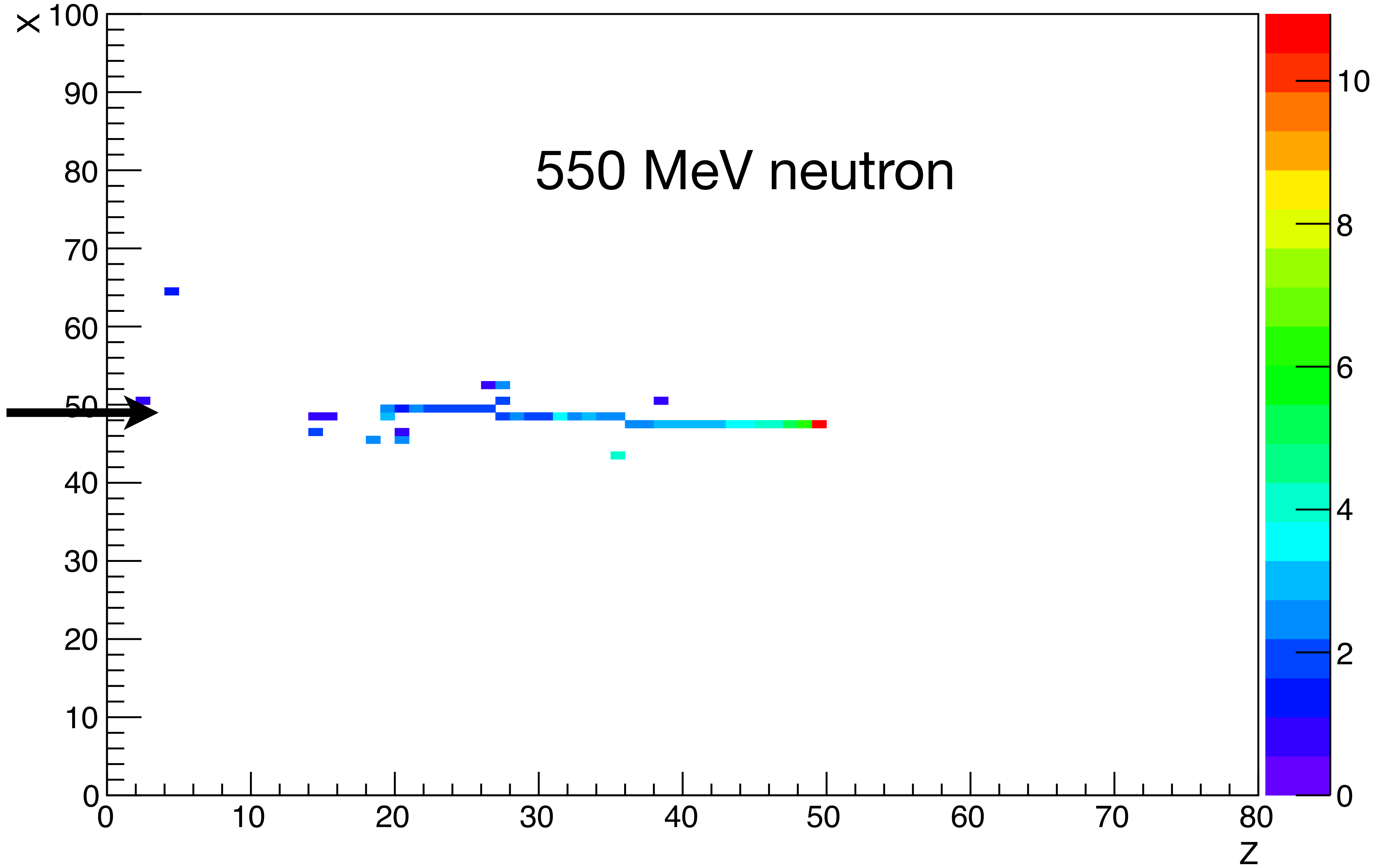
  - important for the reconstruction of the total event energy
  - not straight-forward to detect, hard to associate to an event



- The ECAL can play a key role: Plastic scintillator sensitive also to low-energy neutrons





2 mm Cu absorber, 80 layers

Neutrons

First estimates for detection efficiency

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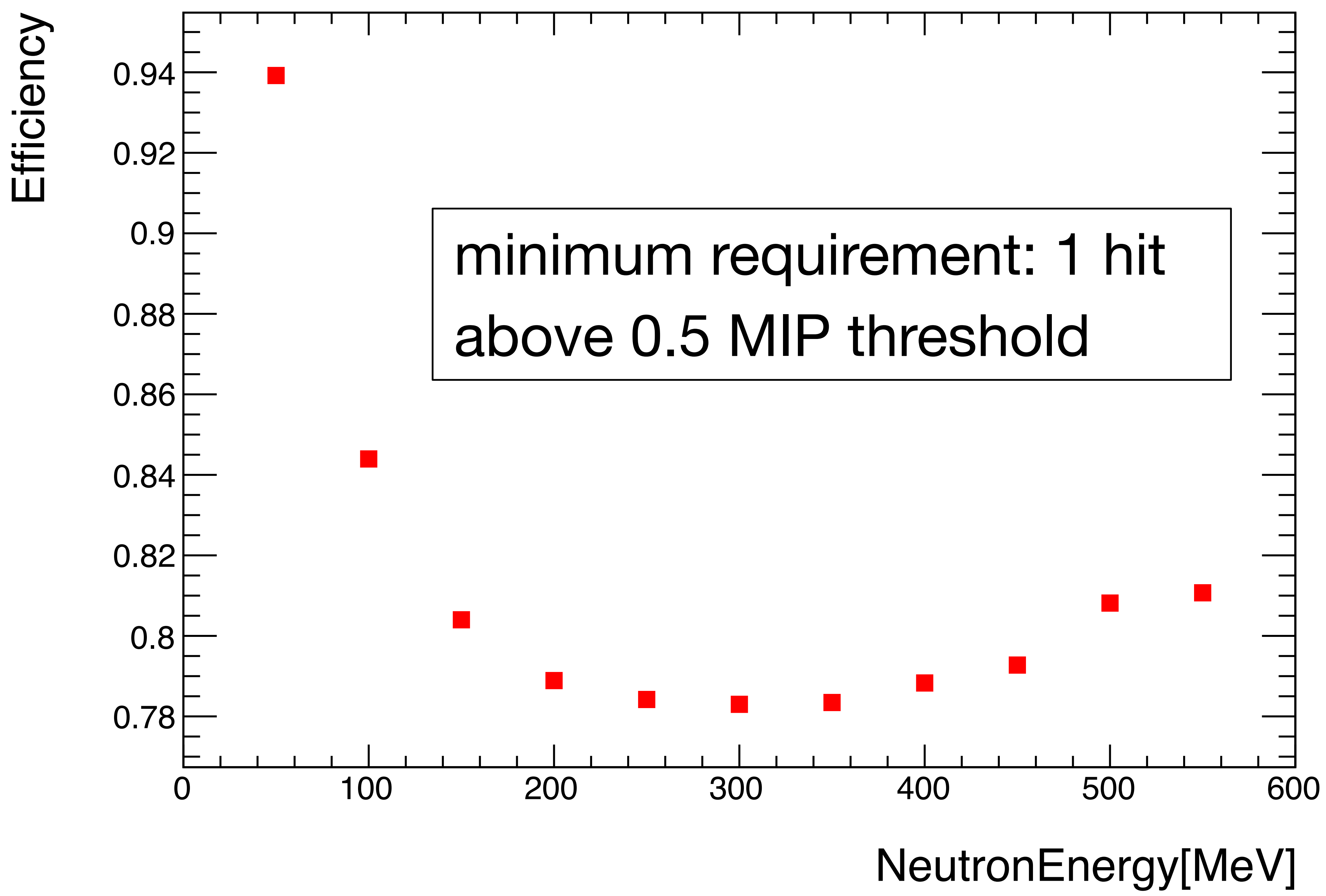

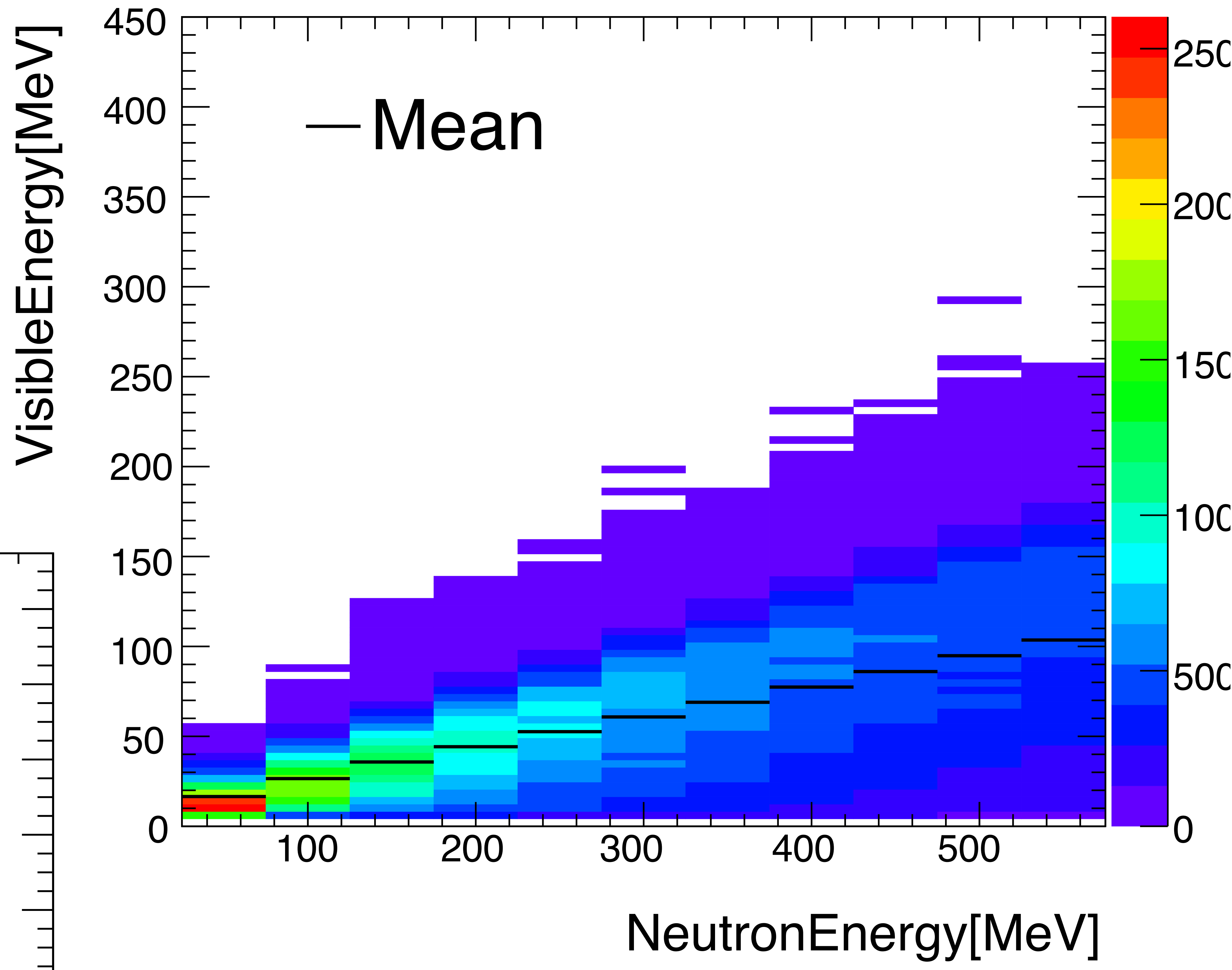

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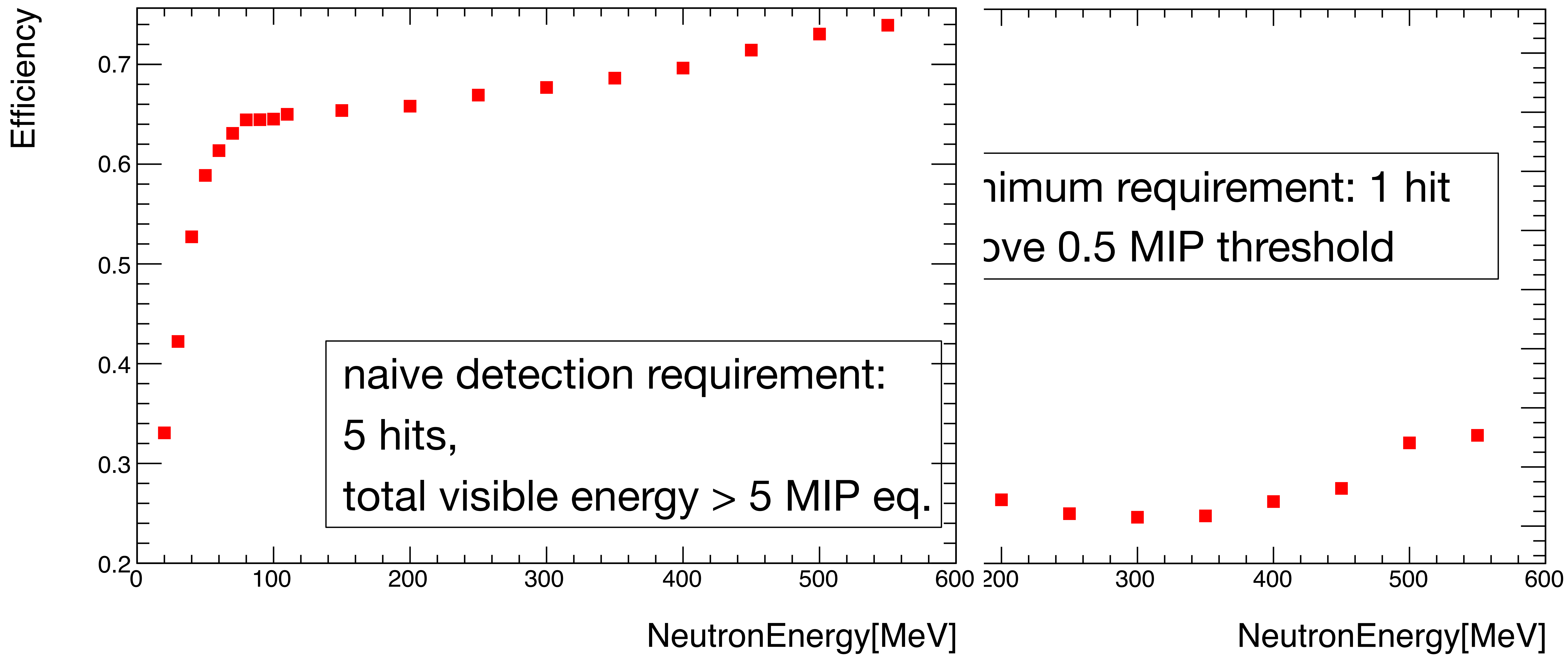
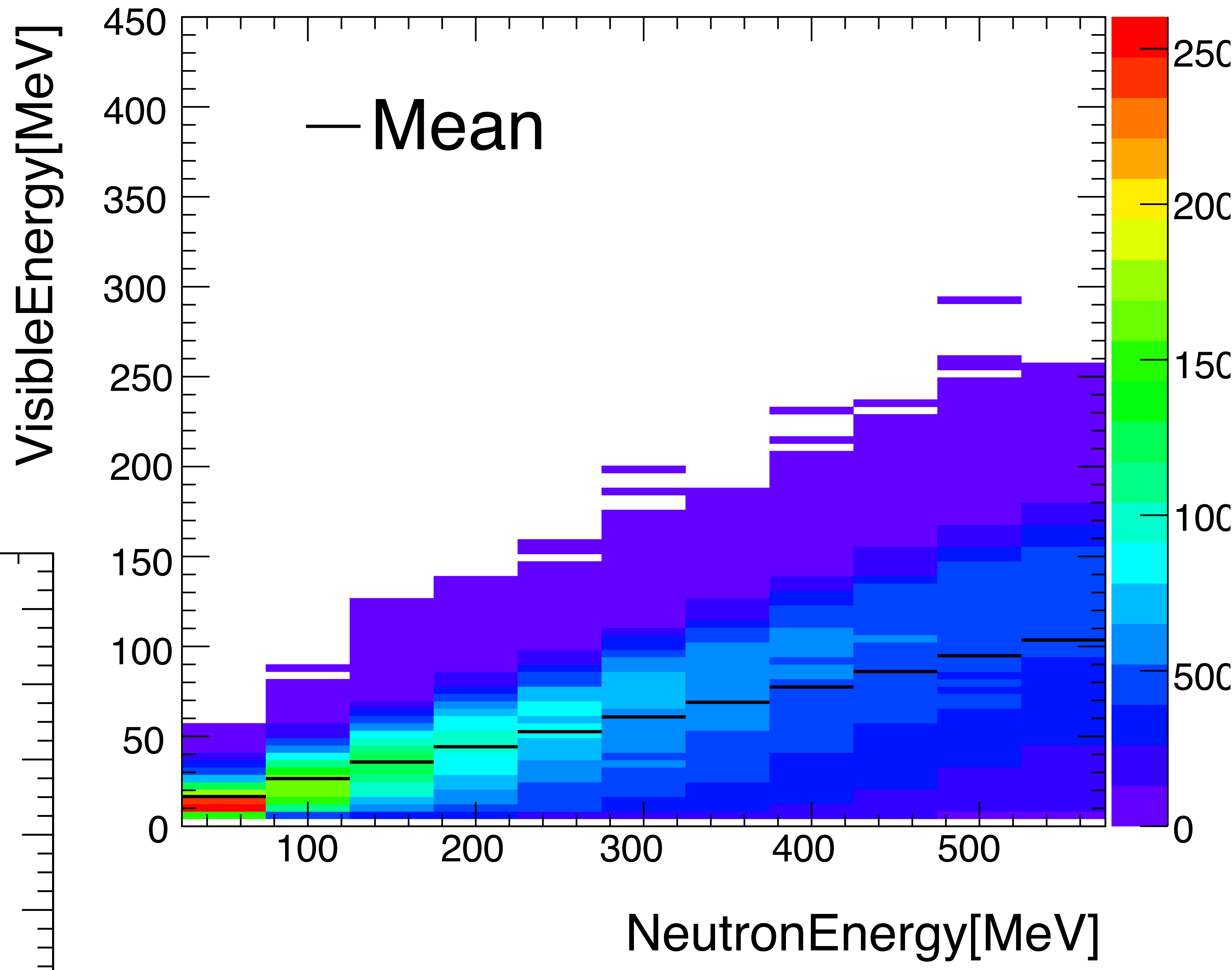
- The ECAL can play a key role: Plastic scintillator sensitive also to low-energy neutrons





2 mm Cu absorber, 80 layers

Lessons Learned

Towards a Detector Concept

- Absorber: Copper provides an advantage for the angular resolution, a slight deterioration of the energy resolution wrt lead
- Granularity: Finer granularity in the inner ~ 30 layers is highly beneficial for angular resolution, later layers do not have a large impact
- Pressure vessel: Deteriorates energy resolution, Ti better than Fe

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Real-world considerations:

- With 2 x 2 cm2 individual tiles:
  - 2500 cells / m2 / layer: 75k channels / m2 of inner ECAL (30 layers)
- With 3 x 3 cm2 individual tiles:
  - 1100 cells / m2 / layer: 33k channels / m2 of inner ECAL
- With 4 x 4 cm2 individual tiles:
  - 625 cells / m2 / layer: 19k channels / m2 of inner ECAL

Downstream ECAL ~ 9 m^2, total ECAL area ~ 50 m^2 (still in flux…)

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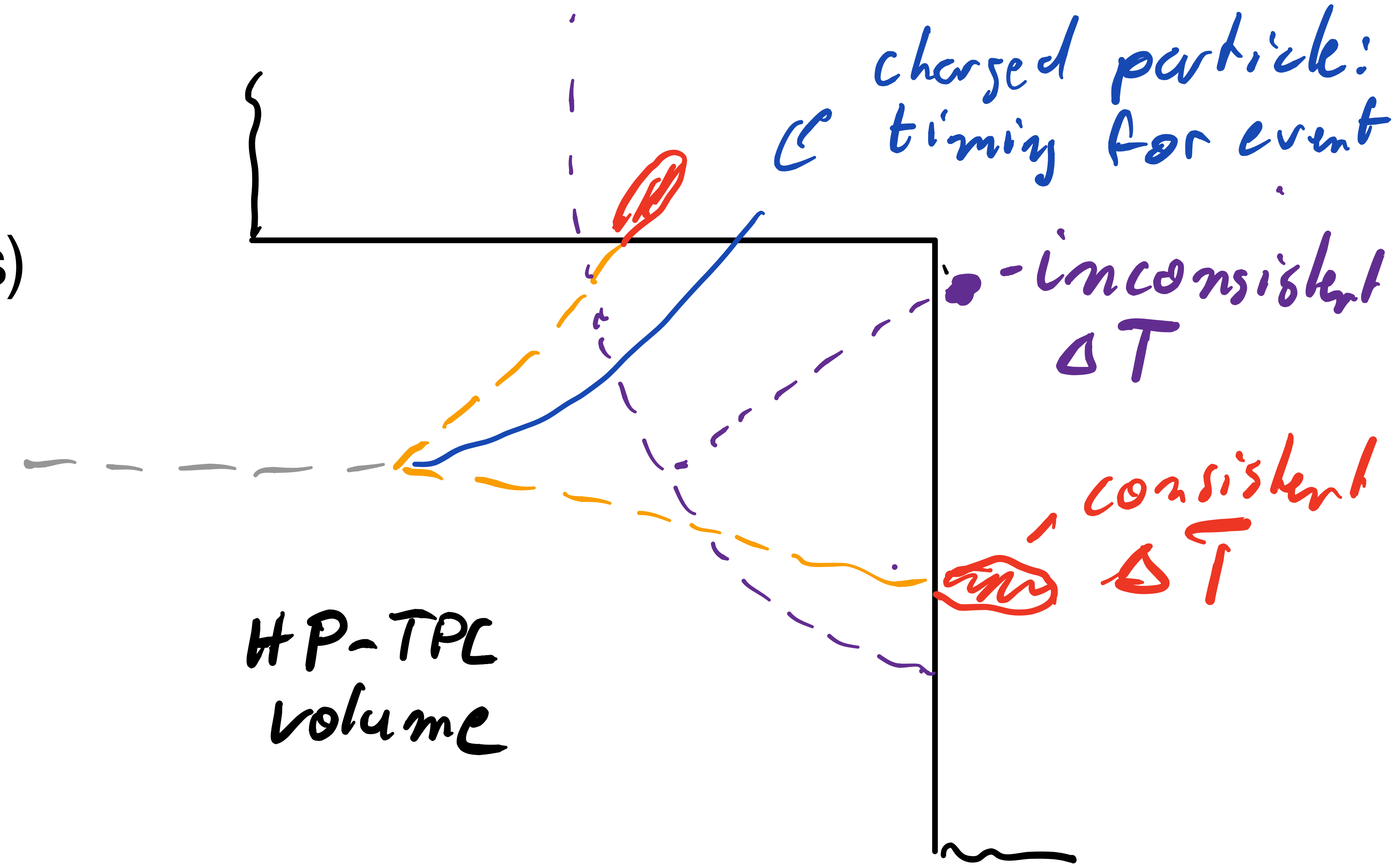
- Beyond energy:
  The Tile - on - SiPM technology can provide sub-ns time resolution:
  - Could be used to improve assignment of low-energy photons with very poor pointing accuracy to interactions and π^0 candidates



Conclusions

- A highly granular electromagnetic calorimeter, based on plastic scintillator tiles with SiPM readout, is an interesting option for Near Detectors at future long baseline neutrino experiments
  - Capable of providing the location of π^0s with ~ 20 cm accuracy using photon shower direction and energy: Effectively subdivides the tracker volume into a few 1000 voxels for the association of π^0s to vertices
  - Can provide a reasonable efficiency for neutrons in the few 10 to few 100 MeV range
  - ➾ Particularly relevant when combined with a low-density tracker, such as a HP-TPC
  - If needed, the pressure vessel of a HP-TPC can be accommodated by splitting the ECAL into two segments - angular resolution can be preserved with 30 layers (6 X_0) inside of the vessel

- Such a detector provides interesting technological challenges:
  - Signal routing & electronics
  - Uniformity of scintillator response
  - Uniform distribution of non-absorber material
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Still a lot to study, optimise and develop!