Simulation and Hardware Studies on a Highly Granular Electromagnetic Calorimeter for the DUNE Near Detector

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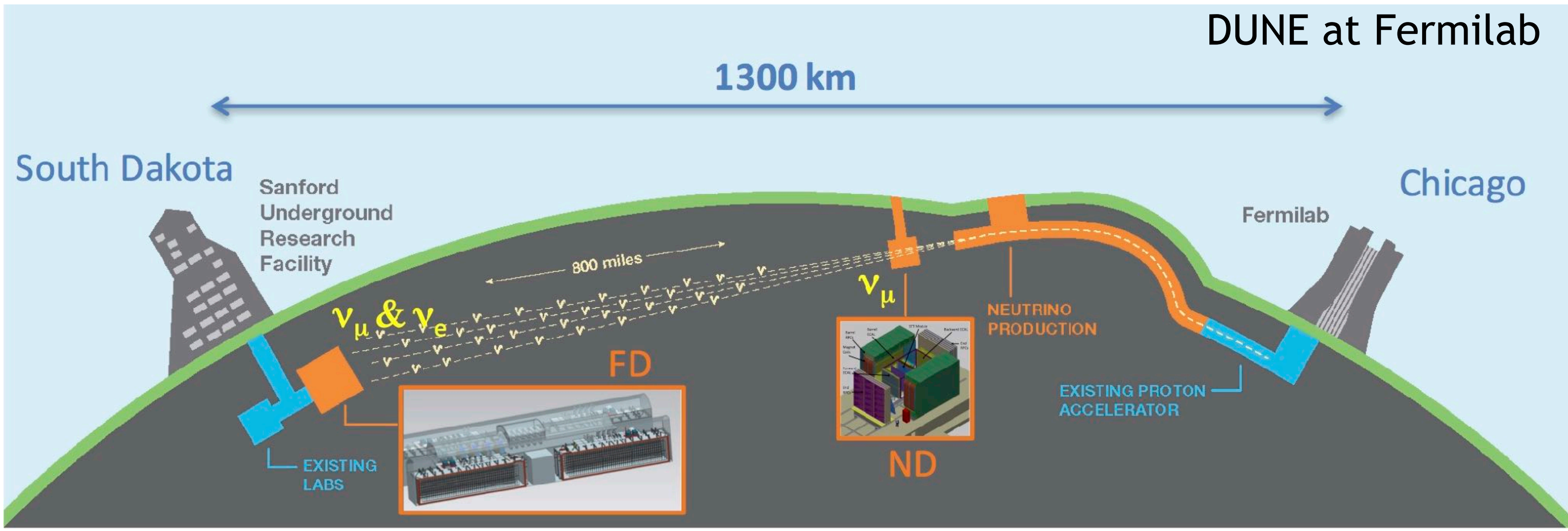
DUNE Experiment

- DUNE targets the precise study of neutrino mixing, including the potential discovery of CP violation

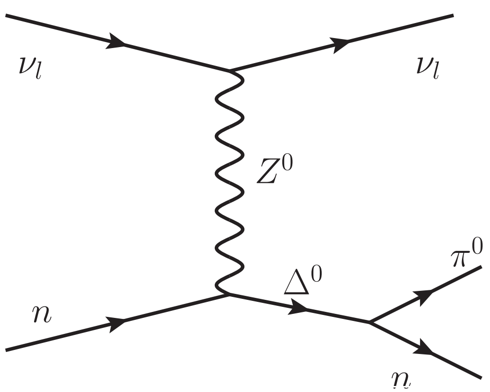


Far Detector: Liquid Argon TPC to measure oscillated spectrum - will see CP violation in ν_e/anti-ν_e appearance

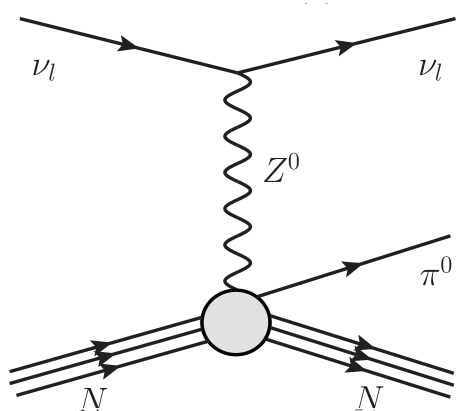
Near Detector: measures beam before oscillation, required to understand initial flux and cross sections to understand FD signal

Near Detector Tasks

- Measure the energy spectrum of the beam, background rates and contamination
  - Provide precise extrapolation of event rates in the far detector
- Largest errors arise from uncertainties in neutrino-nucleon scattering amplitudes
- Important for control of systematics: ν_μ-induced neutral current π^0 production



Resonant NC π^0 production

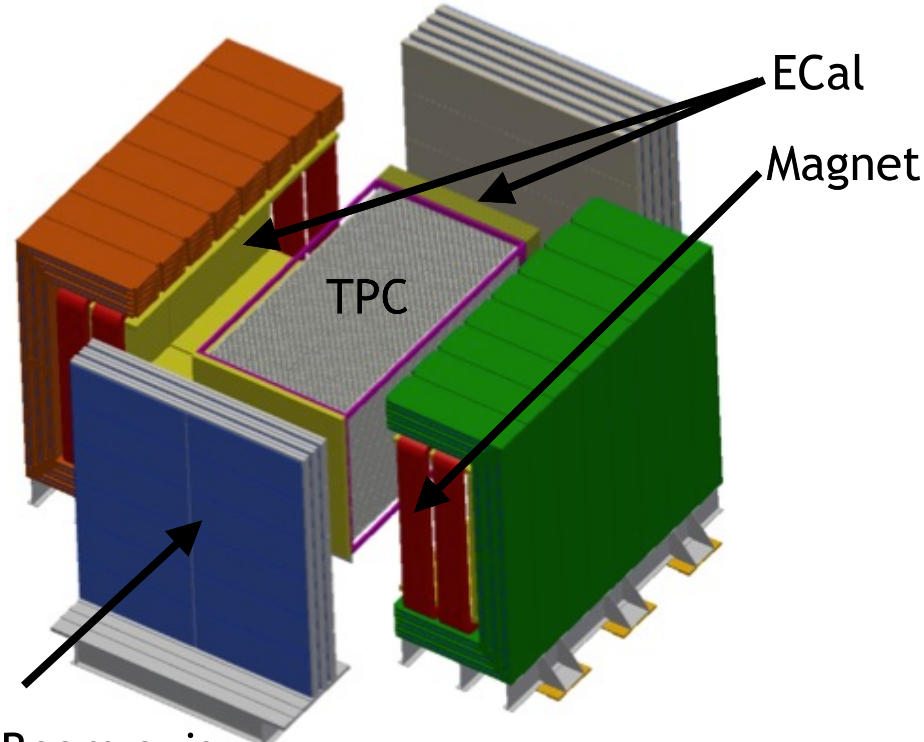


Coherent NC π^0 production

- $\pi^0 \rightarrow \gamma\gamma$ (R=98.8) events can mimic ν_e signals (electrons) in the far detector

Near Detector ECal

Possible layout: High Pressure Gaseous Argon TPC surrounded by an **electromagnetic calorimeter** and magnet



- Conversion probability for photons too low in TPC

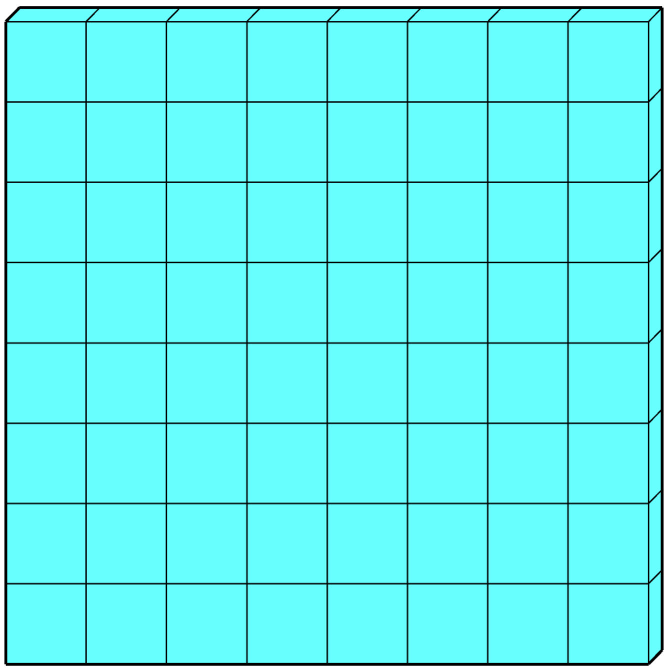
  → tracker based π^0 reconstruction not possible

- Our interest: Can high granularity help?
  - Try to reconstruct π^0 decay vertex

<u>The Challenge</u>: Typical π^0 energies ~100MeV → Photon energies ~50MeV

Detector Concept

Calorimeter design is inspired by CALICE Highly Granular Calorimeter

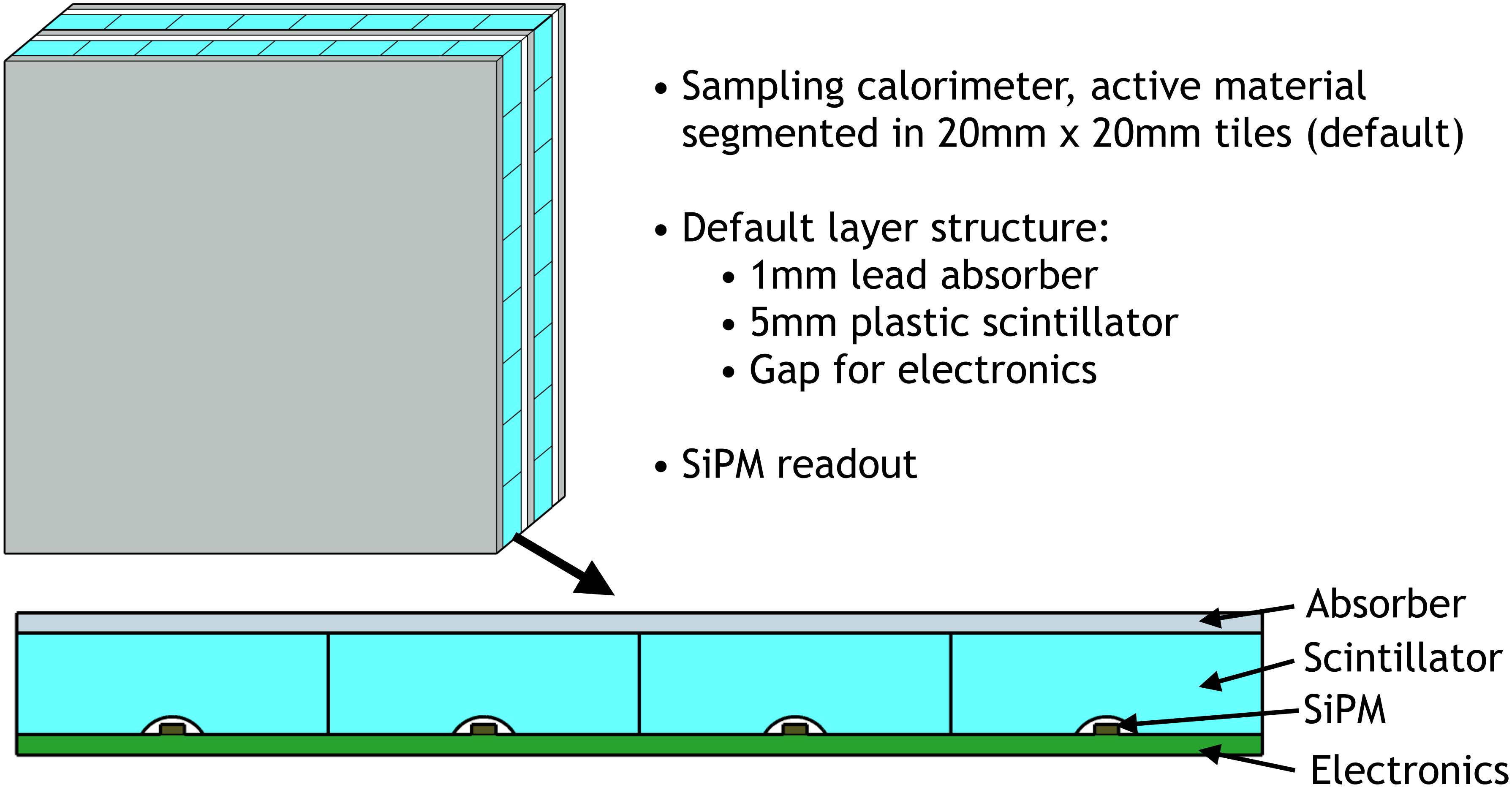


- Sampling calorimeter, active material segmented in 20mm x 20mm tiles (default)

Detector Concept

Calorimeter design is inspired by CALICE Highly Granular Calorimeter

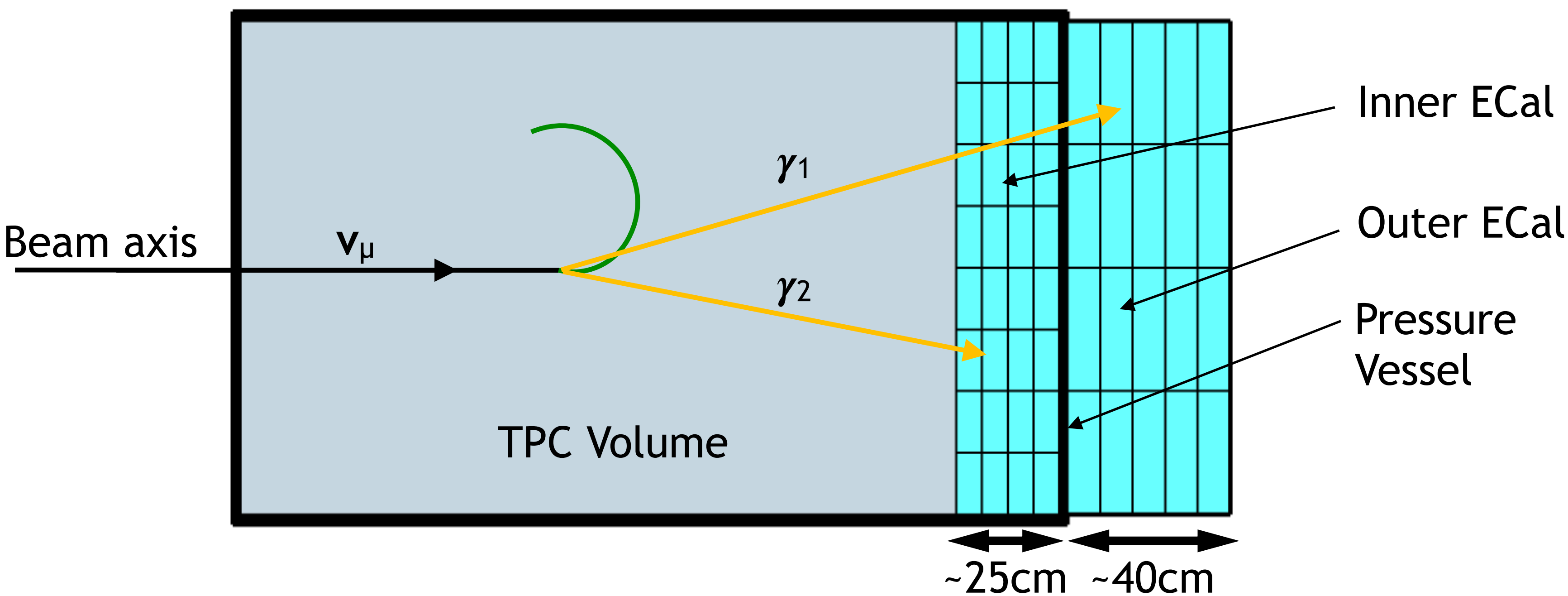
- Sampling calorimeter, active material segmented in 20mm x 20mm tiles (default)
- Default layer structure:
  - 1mm lead absorber
  - 5mm plastic scintillator
  - Gap for electronics
- SiPM readout



Detector Concept

Look at the scenario of a split ECal to instrument space in the TPC pressure vessel

Possible pressure vessel designs: 20mm Steel(~$1X_0$), 14mm Titan(~$0.4X_0$)



Inner ECal increases the chance to detect low energy photons

Simulation and Reconstruction

- Simulation is implemented in Geant 4.10.3

- Reconstruction:

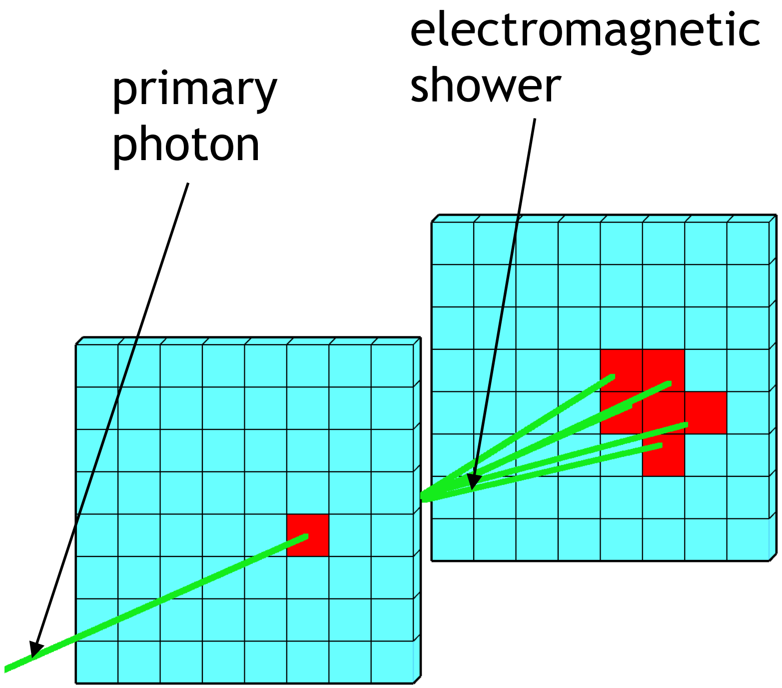
  1. Apply energy cut and amplitude smearing every channel

  2. Data preprocessing

  3. Calculate energy center of gravity in each layer

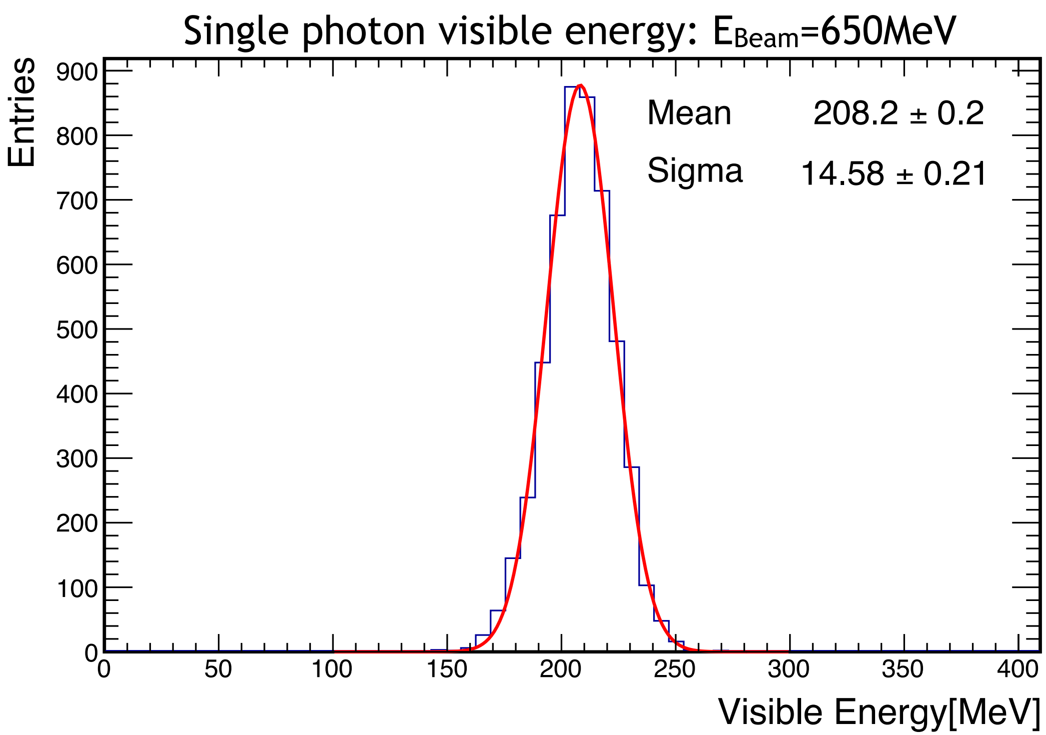
  4. Reconstruct direction with straight line fit of all centers of gravity

  5. Calculate angular and energy resolution



Energy Resolution

Energy resolution is an important parameter to compare different materials



1. Calculate energy sum over all channels per event
2. Plot sigma over mean for different energies

Energy Resolution

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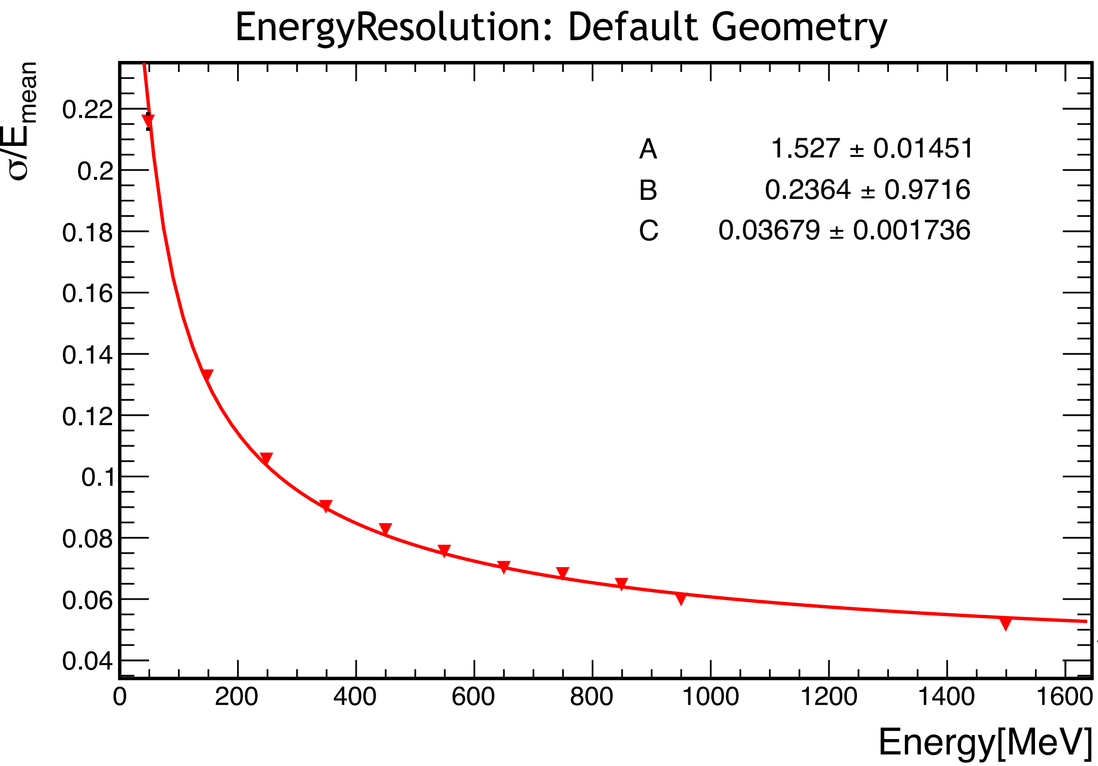


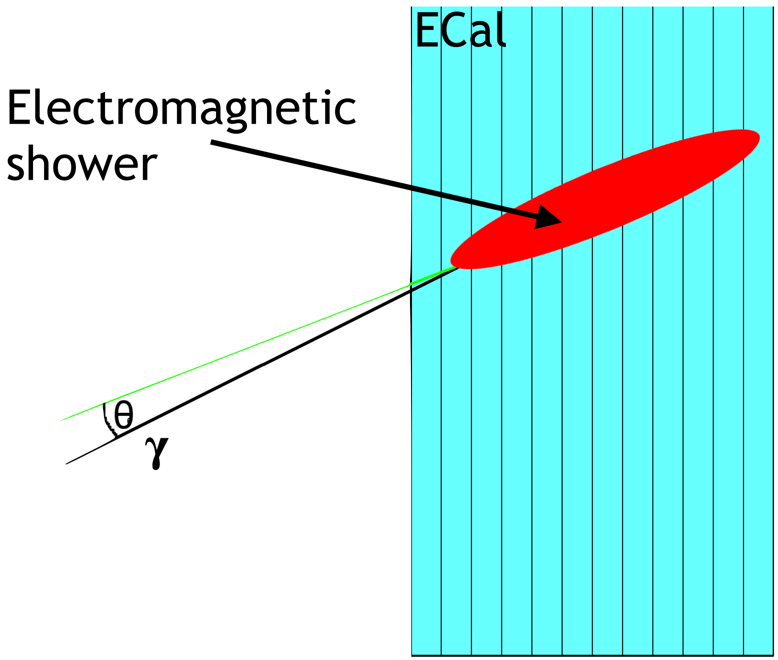
1. Calculate energy sum over all channels per event
2. Plot sigma over mean for different energies
3. Fit with

$$\frac{\sigma}{E_{mean}} = \sqrt{\left(\frac{A}{\sqrt{E[MeV]}}\right)^2 + \left(\frac{B}{E[MeV]}\right)^2 + C^2}$$

$\frac{4.8\%}{\sqrt{E[GeV]}}$ stochastic term, will get worse by simulating more electronics

Angular Resolution

Angular resolution has direct impact on photon pointing

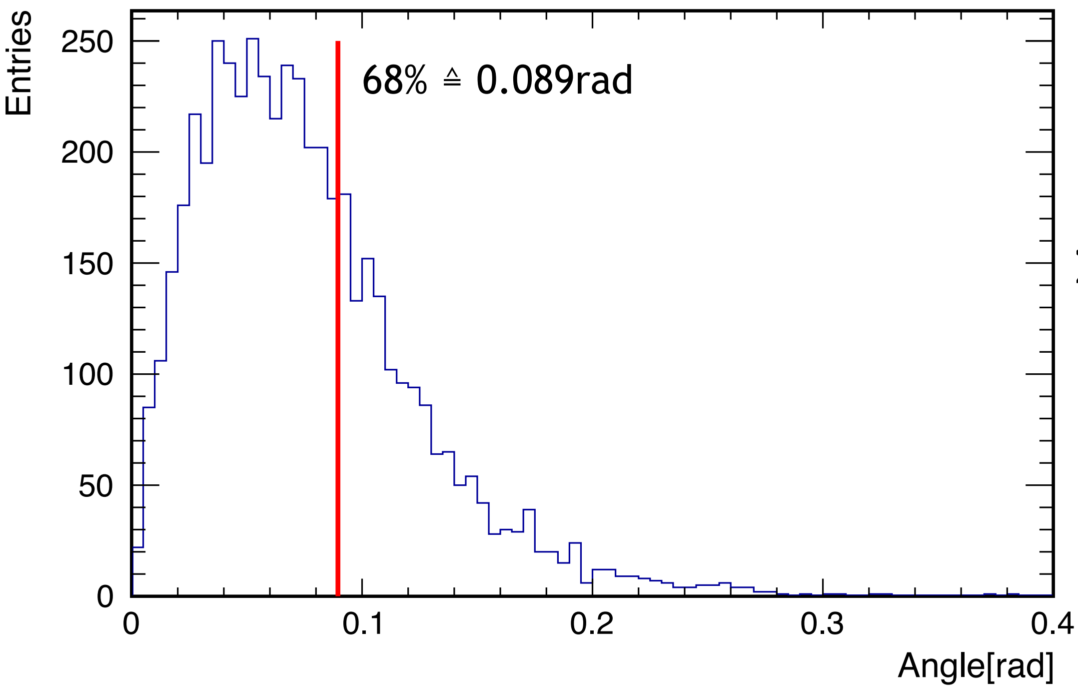


1. Find the distribution of the angle between true and reconstructed direction for every energy

Angular Resolution

Angular resolution has direct impact on photon pointing

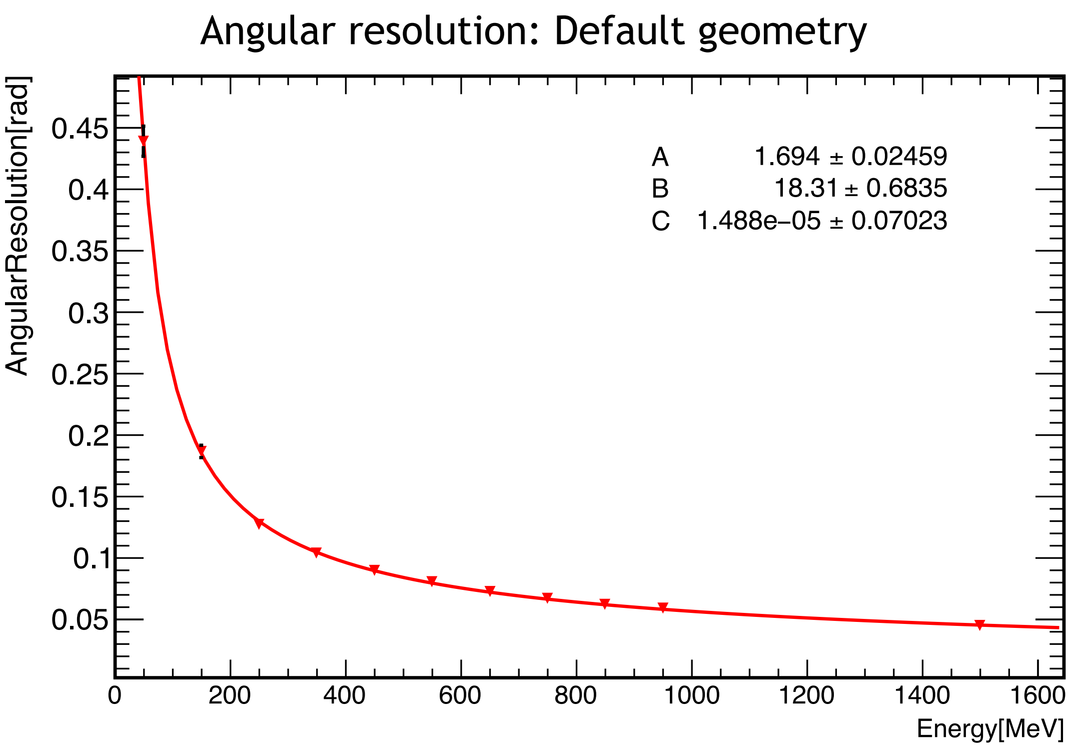
Single photon angle distribution: E_{Beam}=450MeV



1. Find the distribution of the angle between true and reconstructed direction for every energy
2. Plot 68% integral for every energy

Angular Resolution

Angular resolution has direct impact on error of photon direction reconstruction

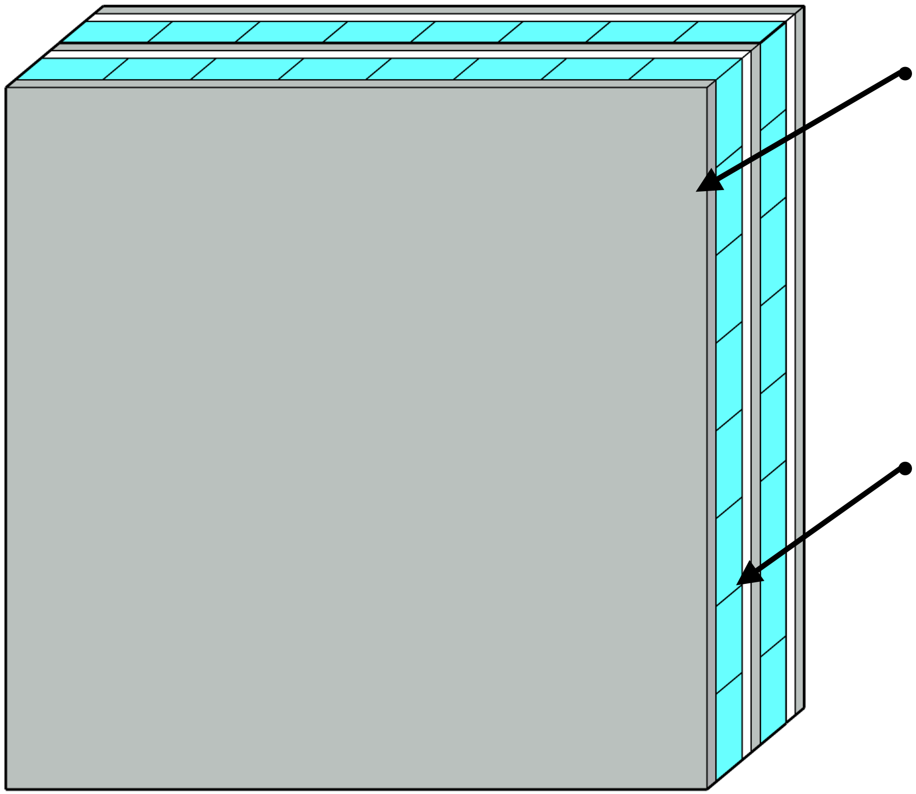


1. Find the distribution of the angle between true and reconstructed direction for every energy
2. Plot 68% integral for every energy
3. Fit with

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

Both resolutions are used to evaluate the performance of the calorimeter

Study of Detector Parameters



- Absorber:
  - different thickness: 1mm, 2mm
  - different materials: lead, copper

  →Changes sampling fraction and Moliere radius (size of shower)
- Active elements:
  - different cell sizes: 5mm - 40mm

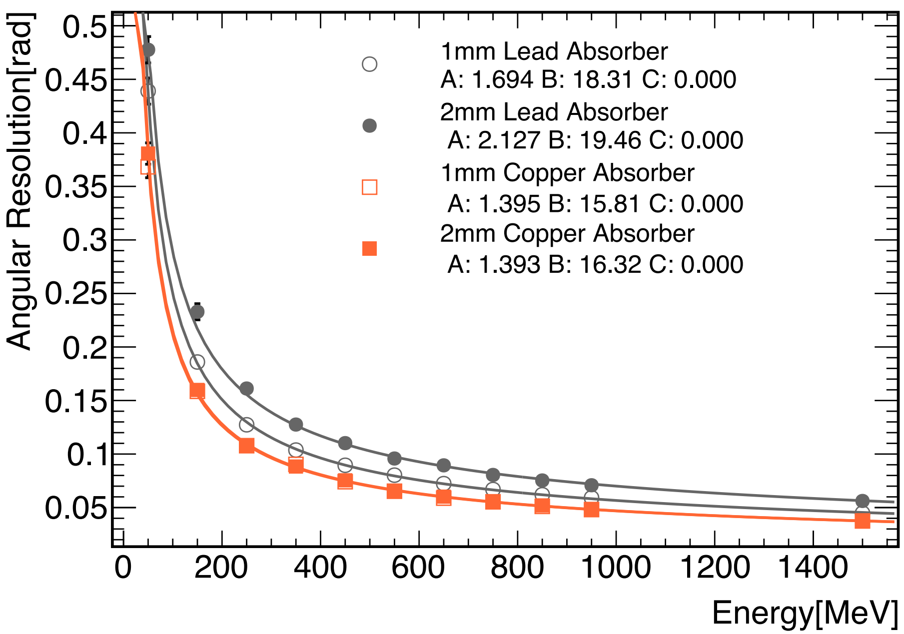
  →Changes "image resolution" and channel count

Goal: understand scaling behaviour of detector response with geometrical parameters

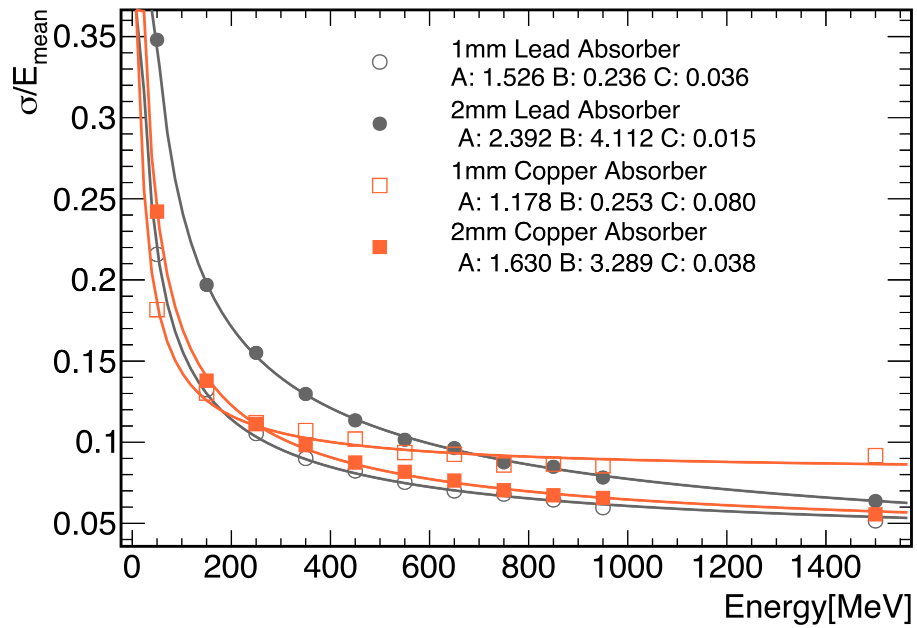
Influence of the Absorber

Inner granularity: 20mm, Outer granularity: 40mm, 14mm titanium vessel

Angular resolution



Energy resolution



Conclusion: Copper yields better angular resolution, but 1mm copper is leaking very much energy

Overview

	Angular Resolution	Energy Resolution
Titanium Vessel	Default	Default
Lead Absorber	Default	Default
NO Vessel	→	↗
Steel Vessel	↘	↘
Copper Absorber	↗	↘
Higher granularity in inner calorimeter	↗	→
High granularity in outer calorimeter	→	→

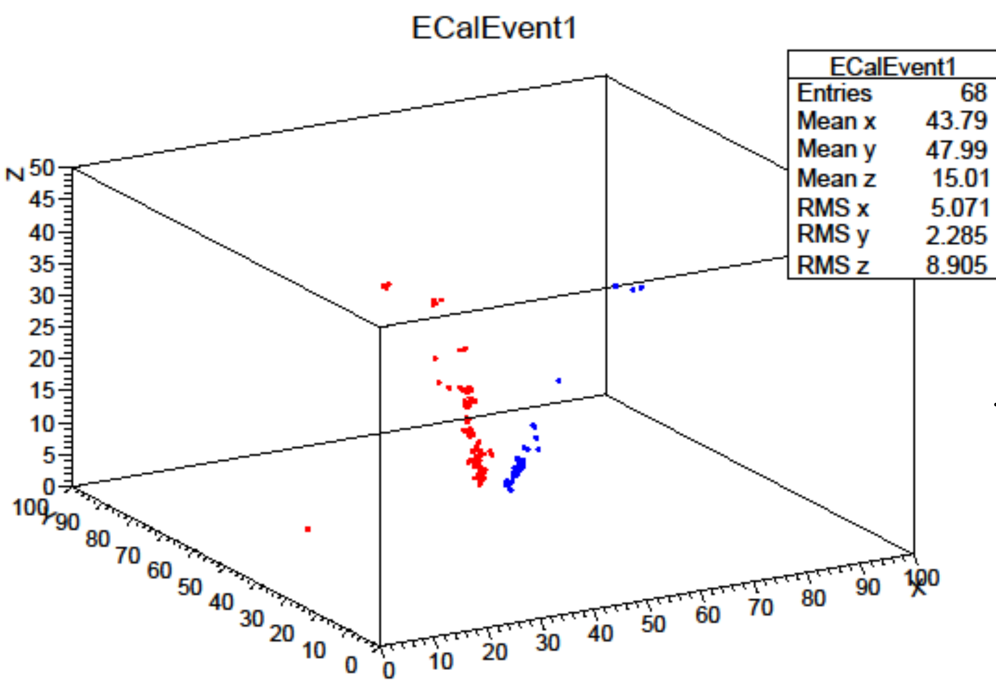
→ Negative

→ Positive

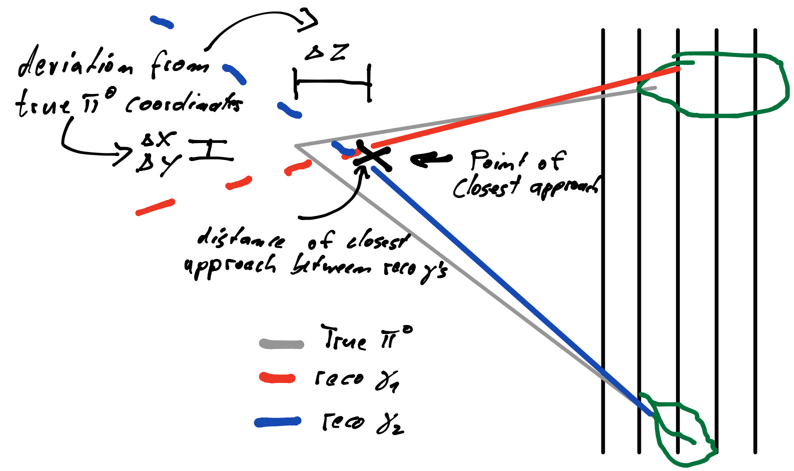
→ Neutral

Pitch: severity of effect

Pion Reconstruction

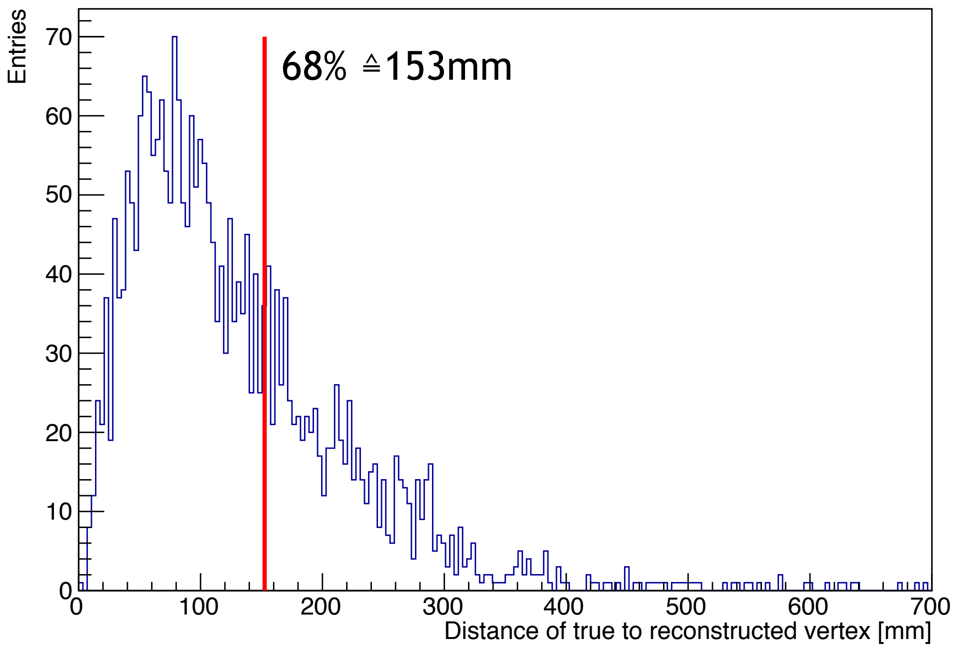


- Distinguish photon1 from photon2 by Monte Carlo truth



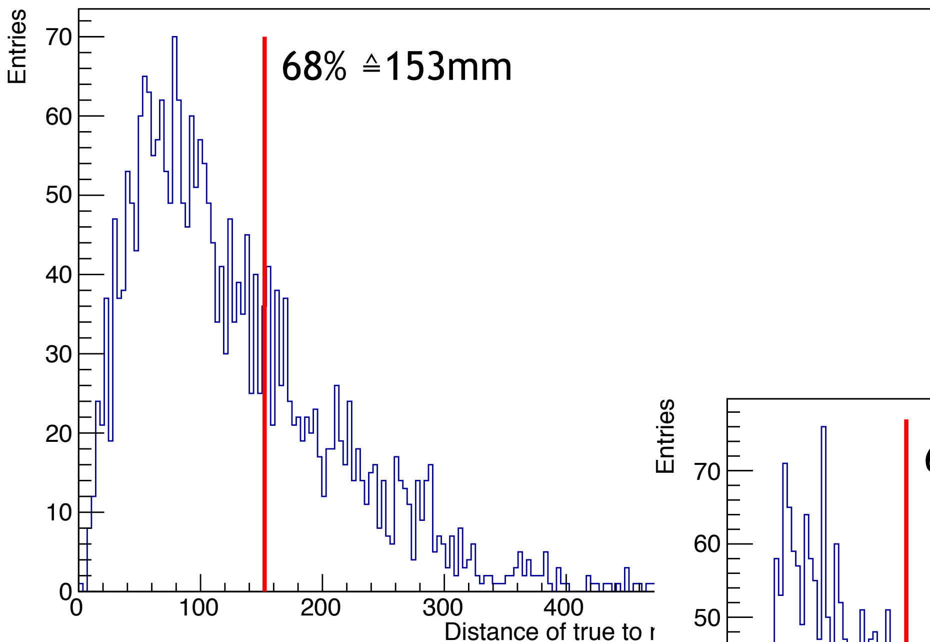
- Take point of closest approach of the reconstructed tracks as decay vertex
- Look at uncertainty of reconstructed vertex in 3D: $\Delta d = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$

Pion Reconstruction



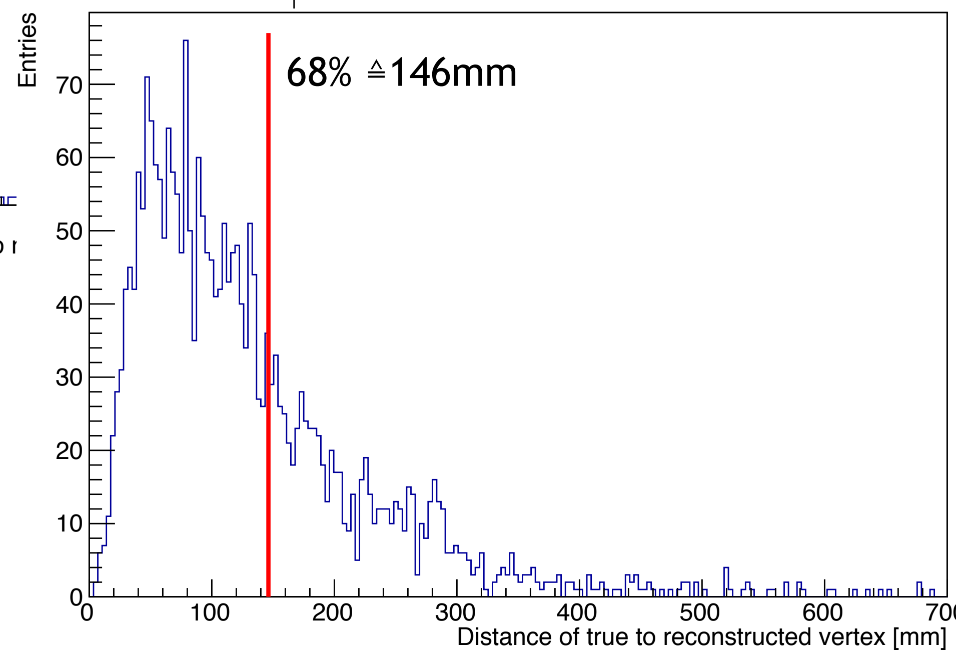
- 450MeV
- 1mm lead absorber
- Inner granularity 20mm, outer granularity 40mm

Pion Reconstruction



- 450MeV
- 1mm lead absorber
- Inner granularity 20mm, outer granularity 40mm

- 450MeV
- 2mm copper absorber
- Inner granularity 30mm, outer granularity 40mm



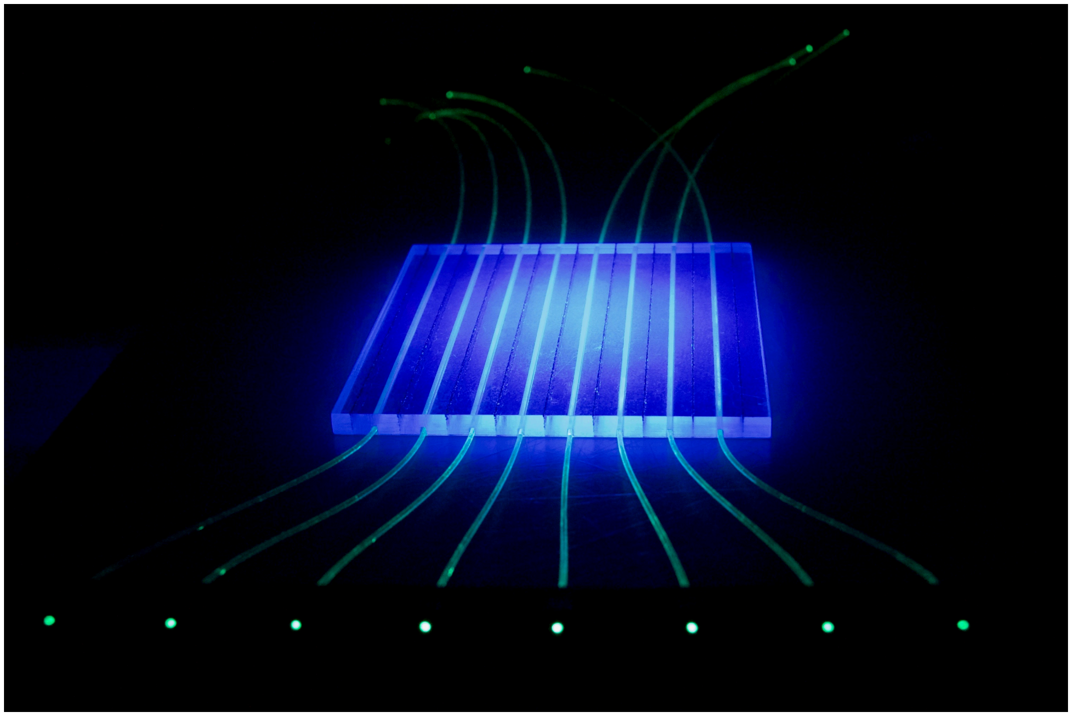
Hardware Studies

- Readout of individual scintillator tiles is a well established technology:
    - CALICE, BEAST/CLAWS
- Study possibilities to achieve high effective granularity with smaller channel count

→Several tiles with projective fiber readout ready/in production at the MPP

Hardware Studies

Several tiles with projective fiber readout ready/in production at the MPP



- 90x90x5mm scintillator tile
- 8 fibers separated by 10mm
- Sub surface laser engraved optical barriers to separate channels
- SiPM readout for every fiber

Try to achieve higher granularity with crossed strip geometry
➞Use two tiles with orthogonally aligned strips

Summary and Outlook

- Pressure vessel worsens energy resolution in general
  - 14mm Titanium has less negative impact than 20mm Steel

- Absorber material influences angular and energy resolution
  - Copper is better than lead

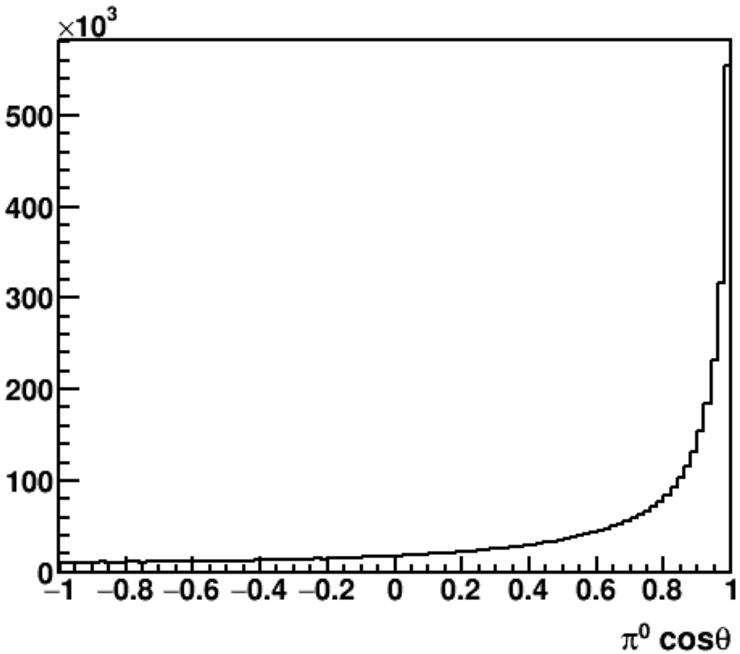
- Granularity in first few X_0 influences overall angular resolution

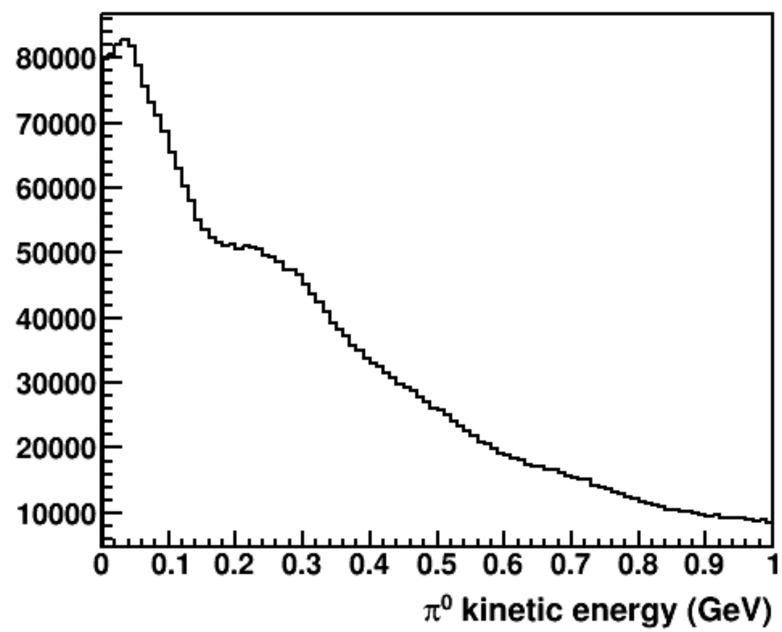
→Pion reconstruction can be improved with information on angular and energy resolution

Backup

Backup

Pi0 Distribution





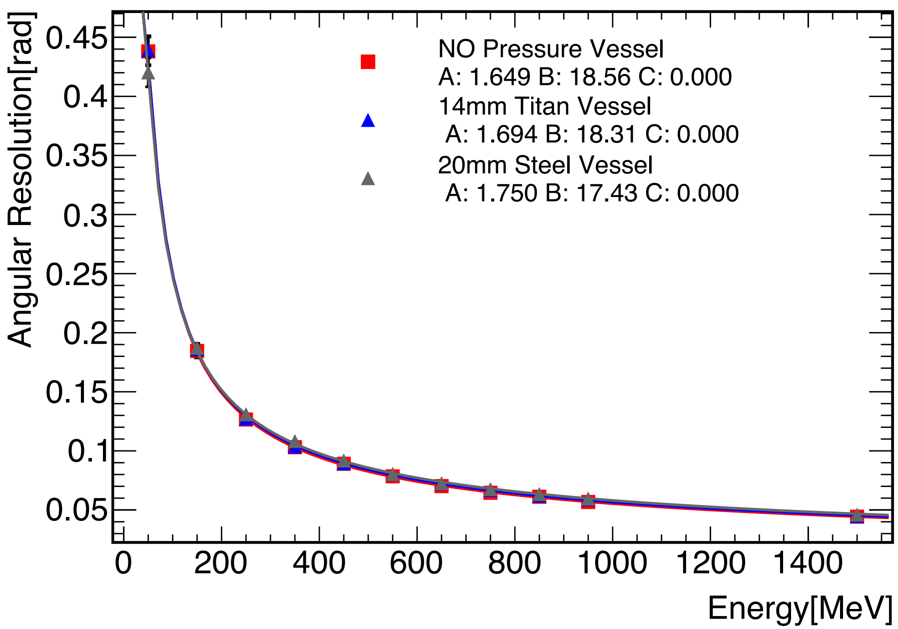
DUNE Physics Program

- DUNE is a Long Baseline Neutrino Experiment using a broad-band ν_μ beam produced with an accelerator
- It consists of two different detectors, separated by 1300 km
- It measures the ν_e appearance and ν_μ disappearance in the oscillated ν_μ beam,
  - To determine the neutrino mass hierarchy
    - Effects of CP violation and neutrino mass hierarchy on the oscillation probability disentangle for long baselines
  - To search for CP-violation in differences of the ν_e/anti-ν_e appearance
    - $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if CP is conserved

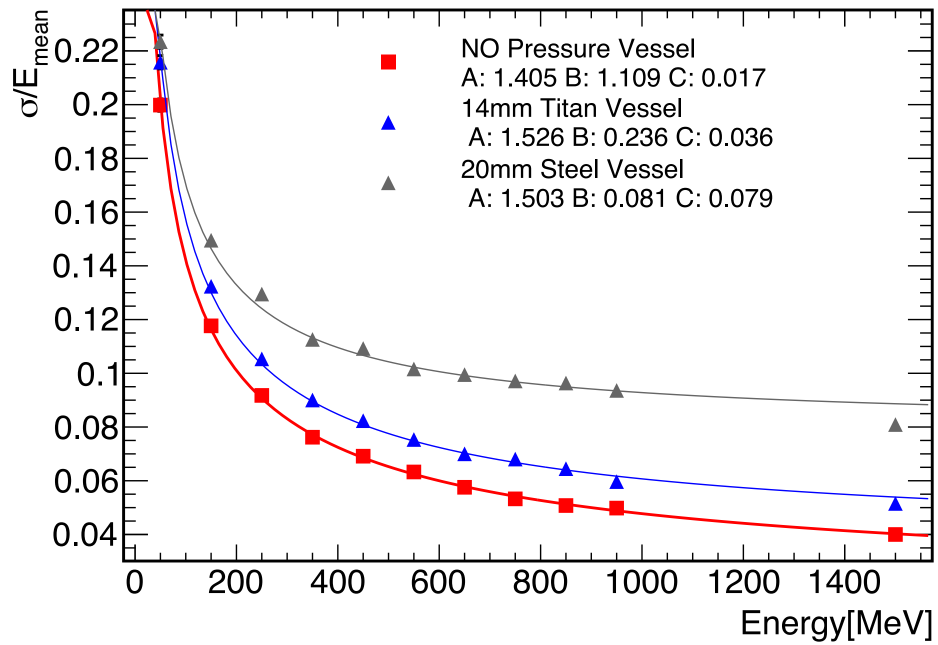
Influence of the Pressure Vessel

1mm lead absorber, Inner granularity: 20mm, Outer granularity: 40mm

Angular resolution



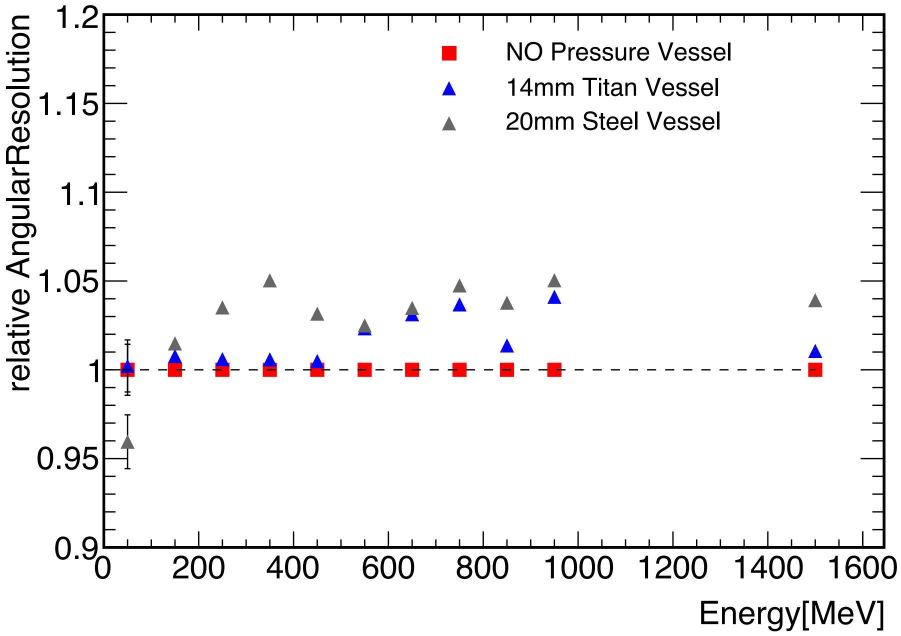
Energy resolution



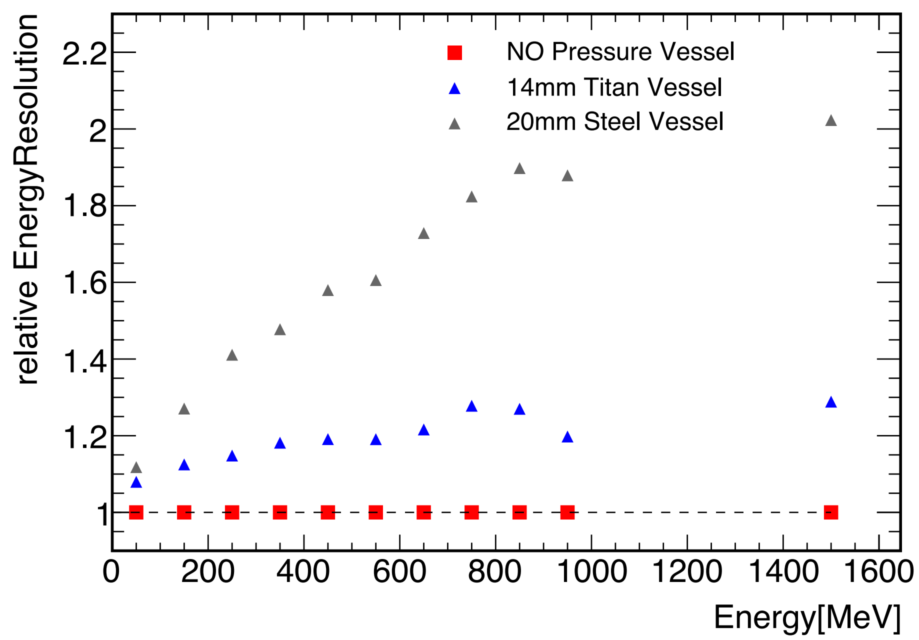
Influence of the Pressure Vessel

1mm Lead absorber, Inner granularity: 20mm, Outer granularity: 40mm

Relative angular resolution



Relative energy resolution

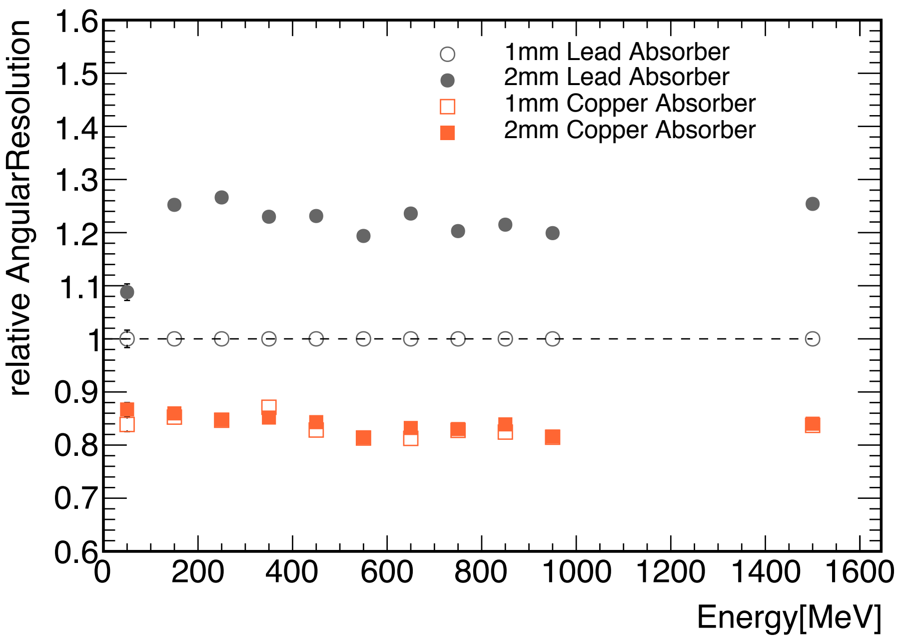


Conclusion: Thin titanium pressure vessel yields better results

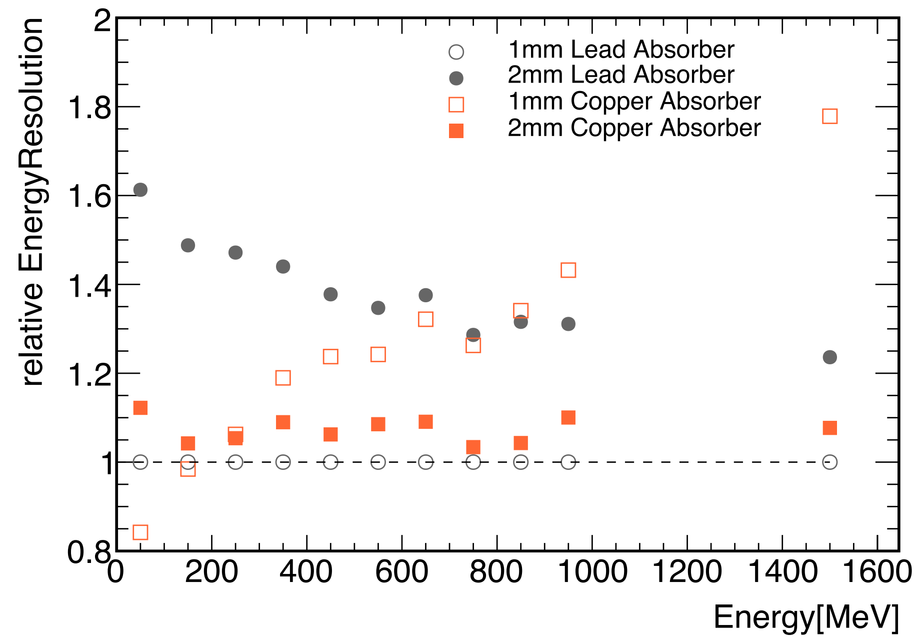
Influence of the Absorber

Inner granularity: 20mm, Outer granularity: 40mm, 14mm titanium vessel

Relative angular resolution



Relative energy resolution

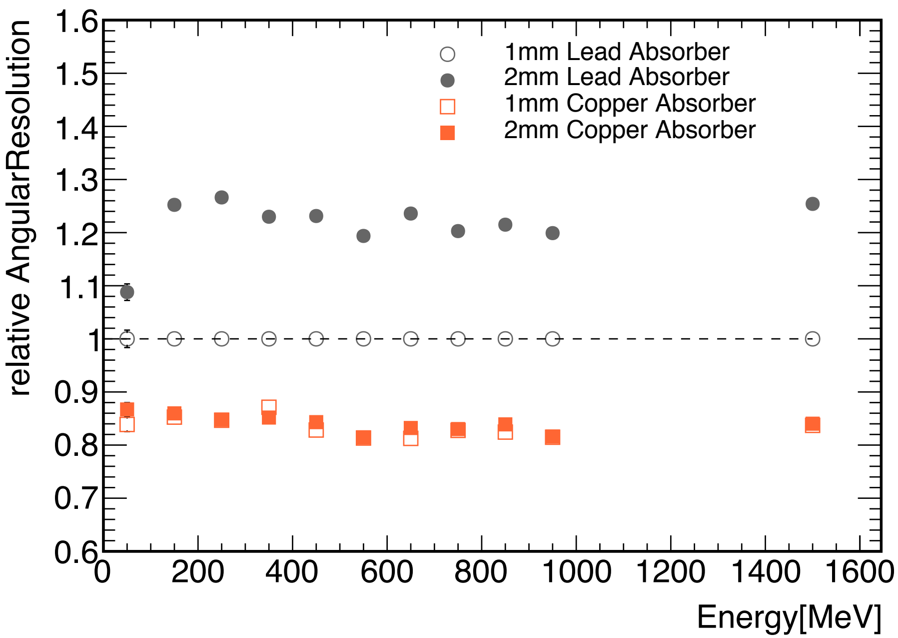


$$RelativeAngularResolution = \frac{AngularResolution[rad]}{DefaultAngularResolution[rad]}$$

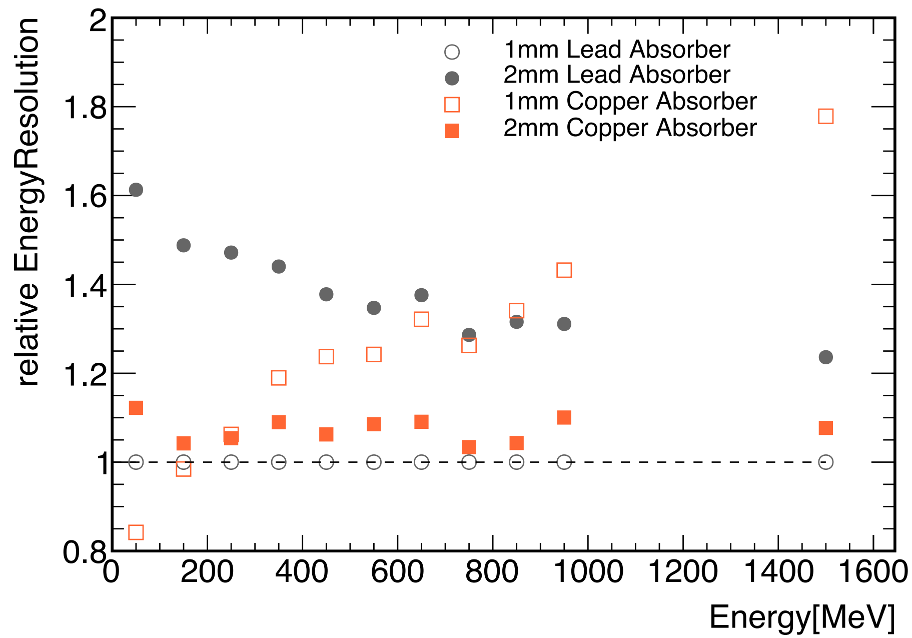
Influence of the Absorber

Inner granularity: 20mm, Outer granularity: 40mm, 14mm titanium vessel

Relative angular resolution



Relative energy resolution

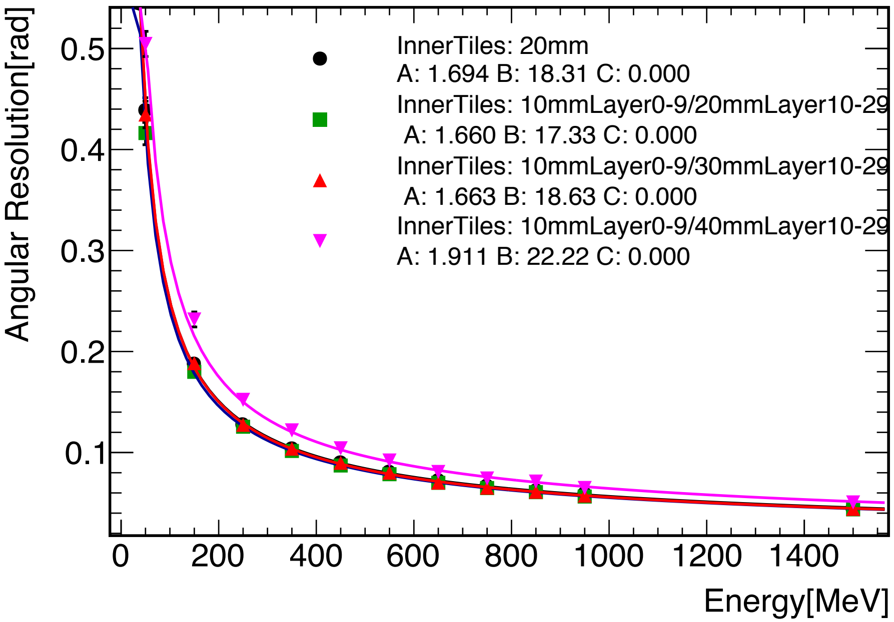


Conclusion: Copper yields better angular resolution,
but 1mm copper is leaking very much energy

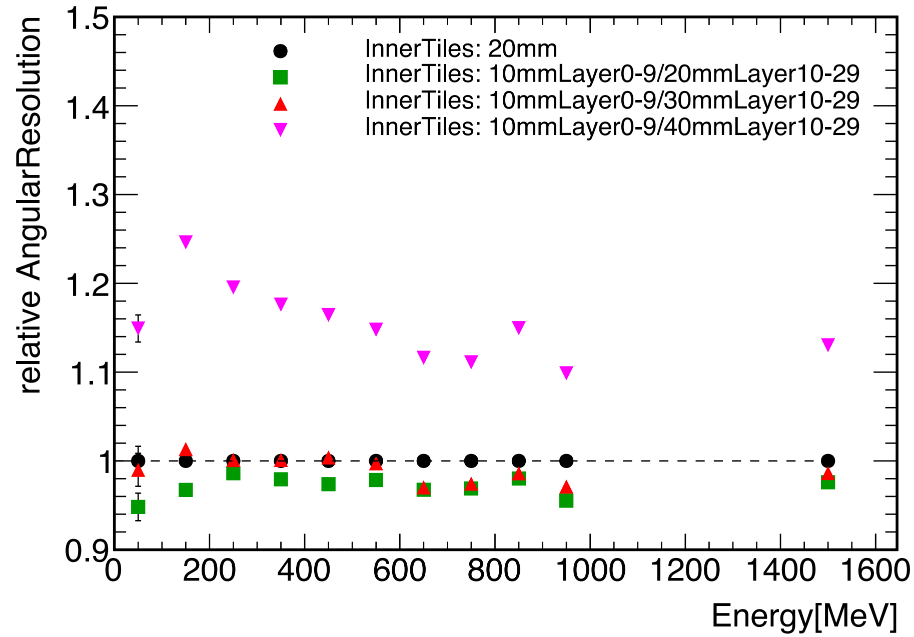
Influence of Inner Granularity

1mm Lead absorber, Outer Granularity: 40mm, 14mm Titanium vessel

Angular resolution



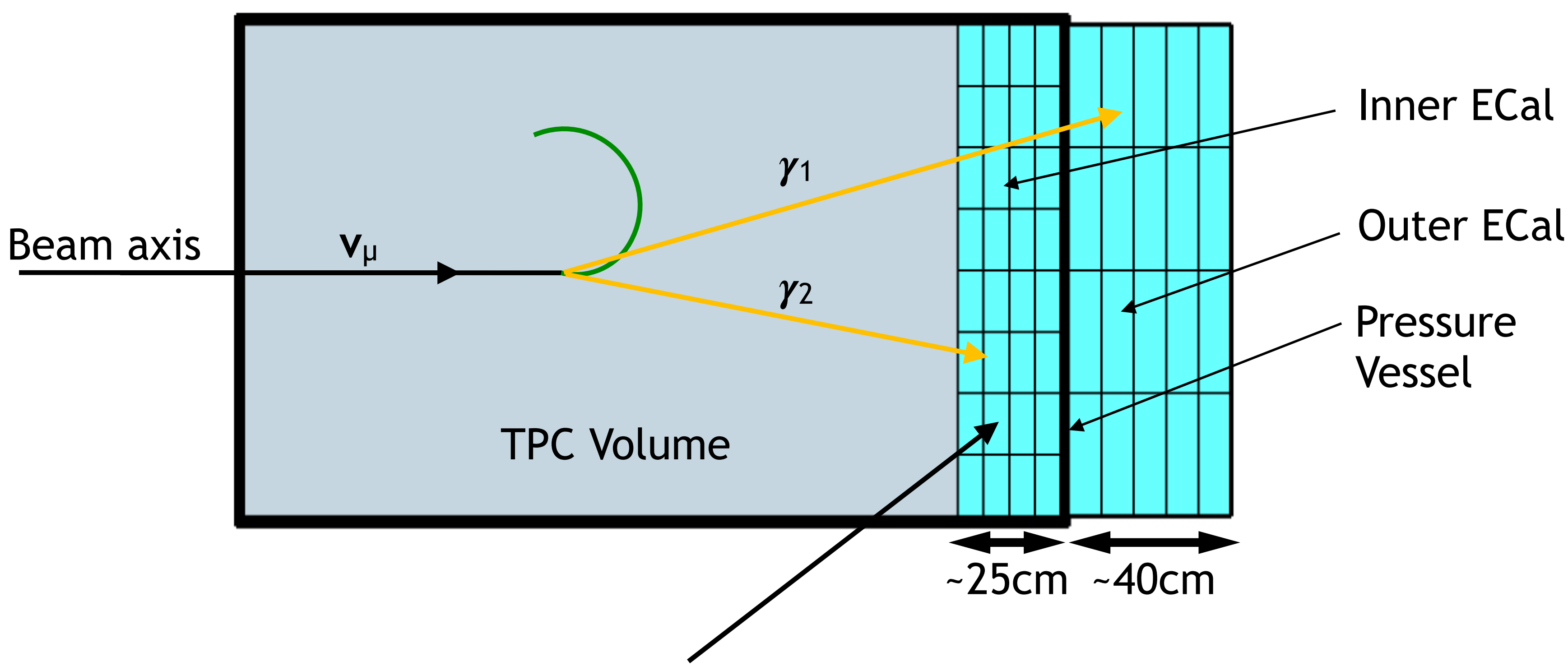
Relative angular resolution



Conclusion: Granularity in first few X_0 has a major influence on overall angular resolution

Influence of Inner Granularity

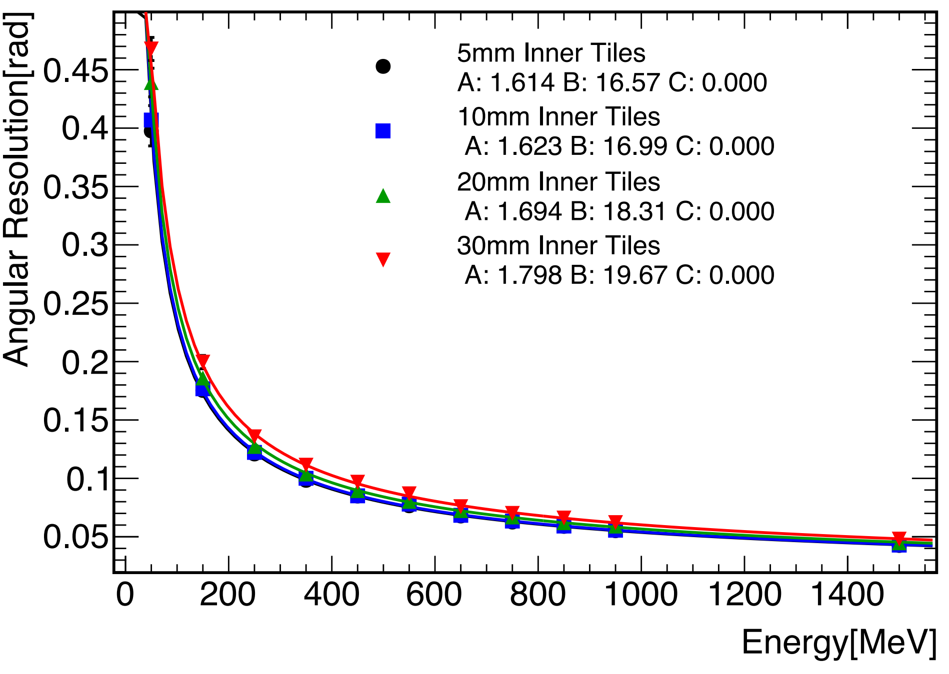
Reminder: ECal is split into inner and outer part by the pressure vessel
→ Look at impact of inner cell size on angular resolution



Compare angular resolution for different cell sizes

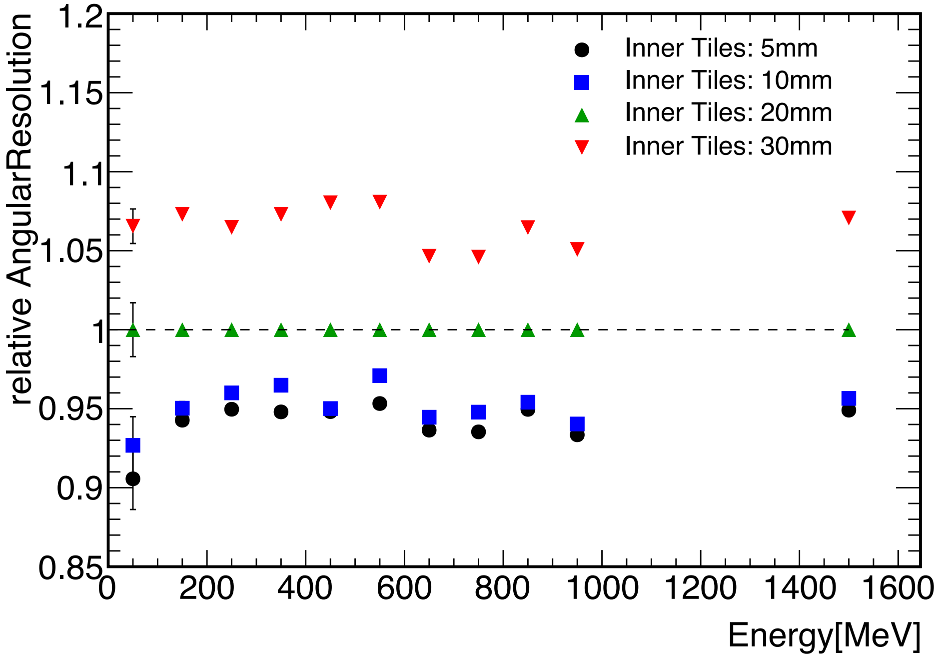
Influence of Inner Granularity

Angular resolution



Influence of Inner Granularity

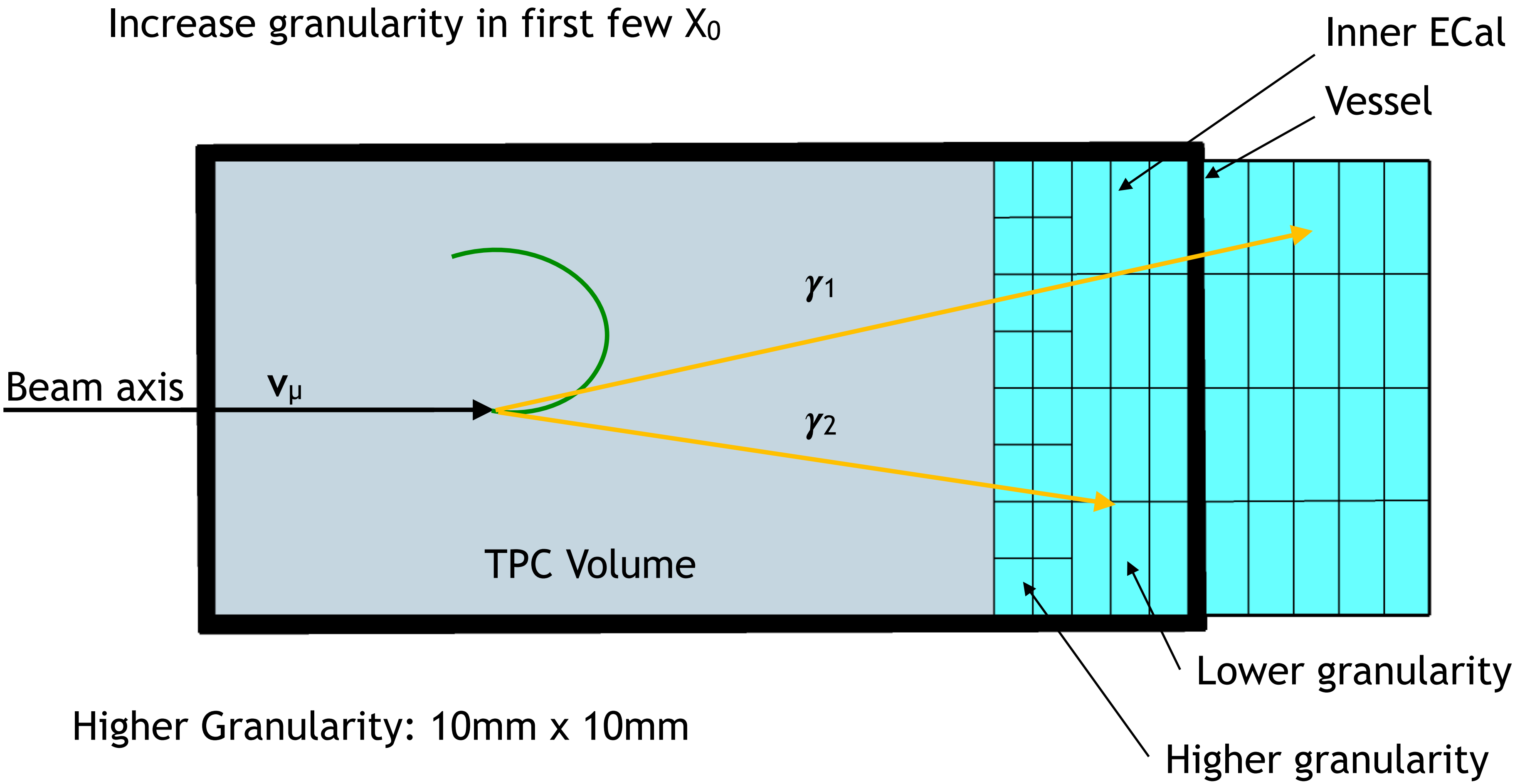
Relative angular resolution



$$RelativeAngularResolution = \frac{AngularResolution[rad]}{DefaultAngularResolution[rad]}$$

Influence of Mixed Granularity

Increase granularity in first few X_0

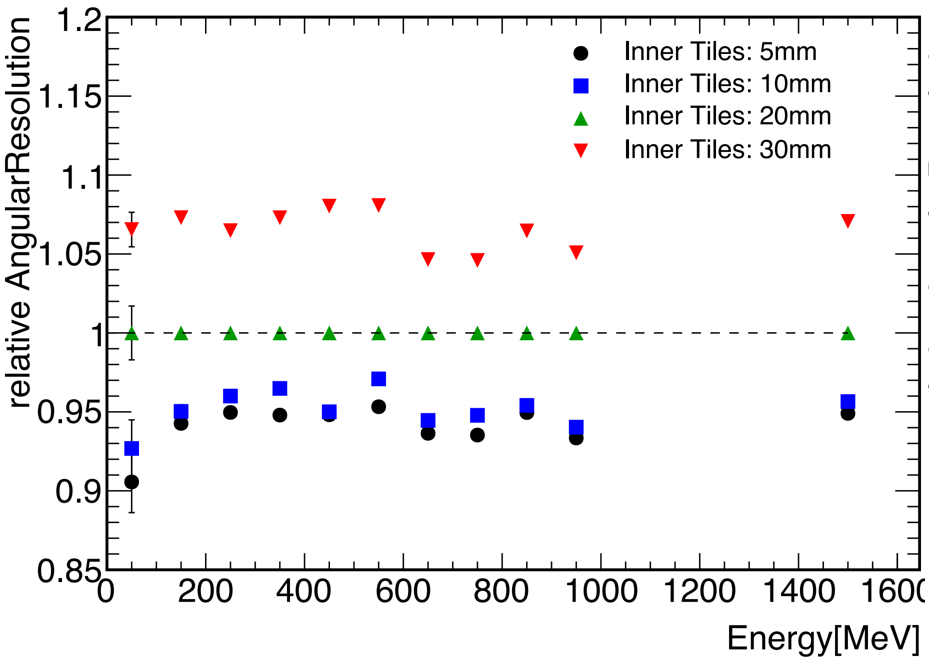


Higher Granularity: 10mm x 10mm

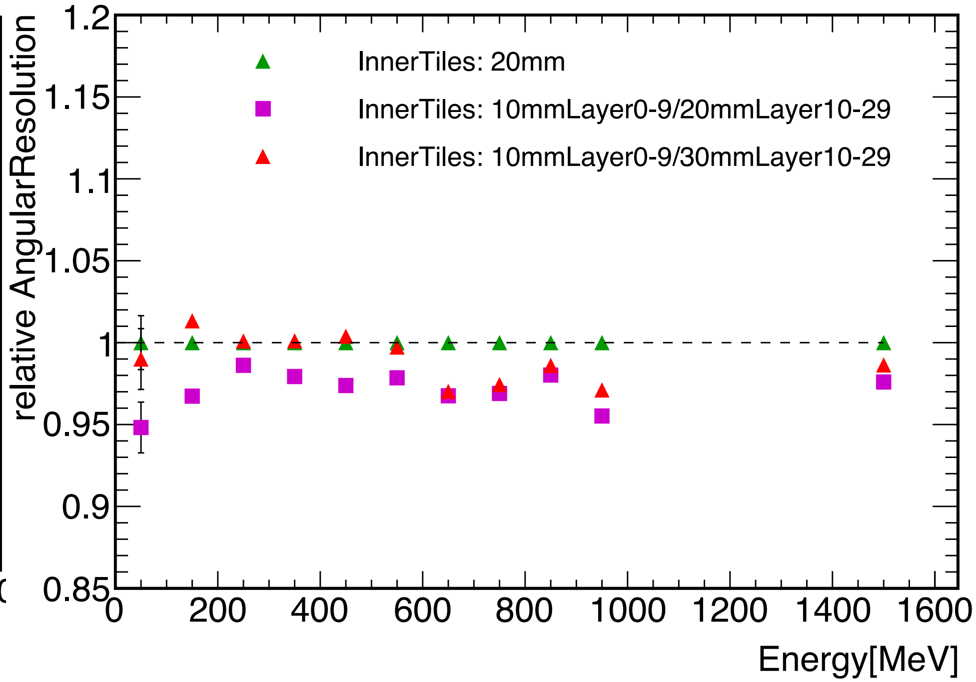
Lower Granularity: 20mm x 20mm, 30mm x 30mm

Influence of Mixed Granularity

Relative angular resolution
Homogeneous granularity

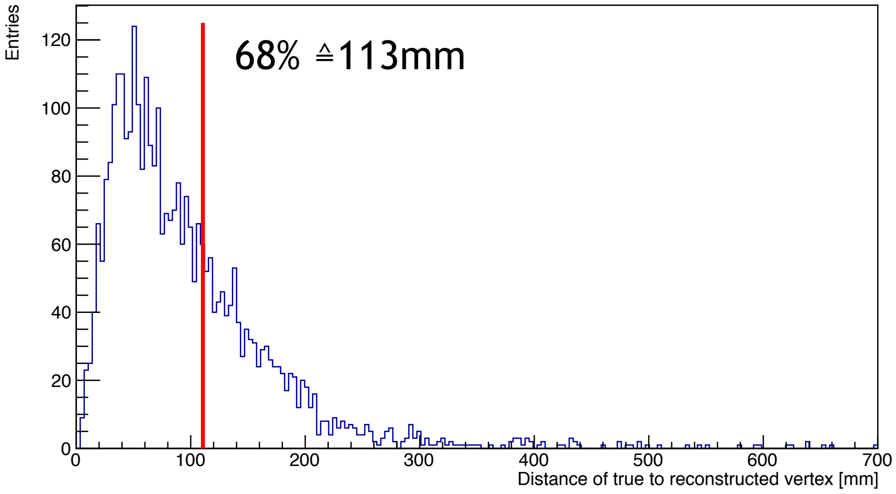


Relative angular resolution
Mixed granularity



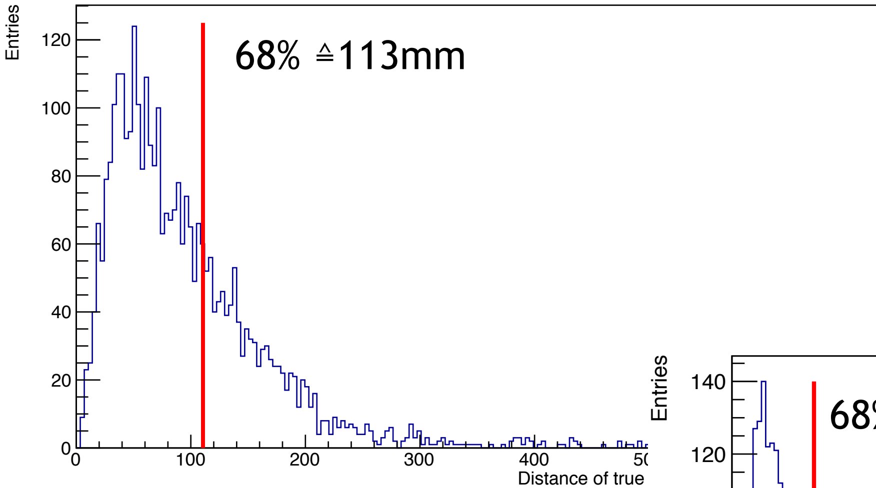
Conclusion: Granularity in first few X_0 has a major influence on overall angular resolution

Pion Reconstruction



- 450MeV
- 1mm lead absorber
- Inner granularity 20mm, outer granularity 40mm

Pion Reconstruction



- 450MeV
- 1mm lead absorber
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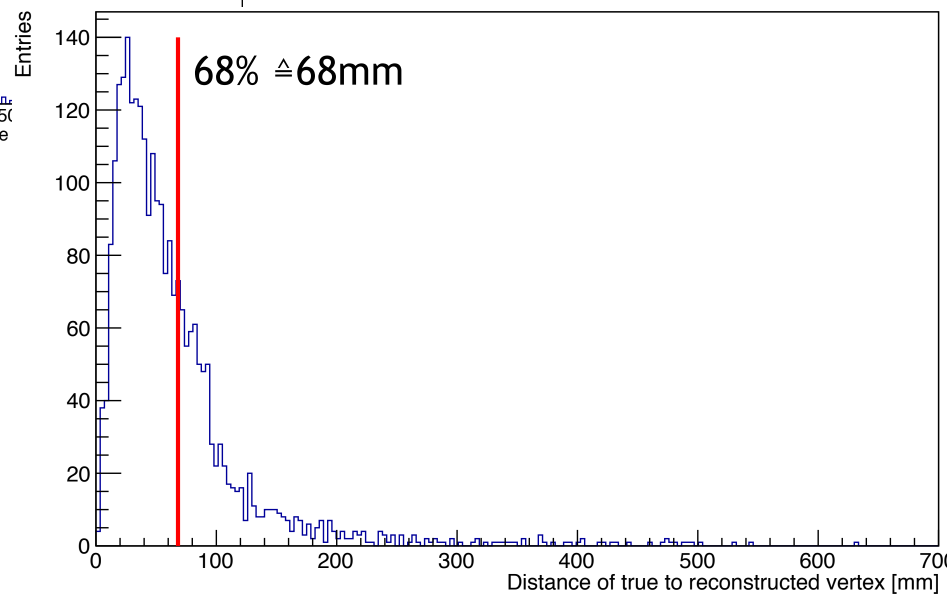
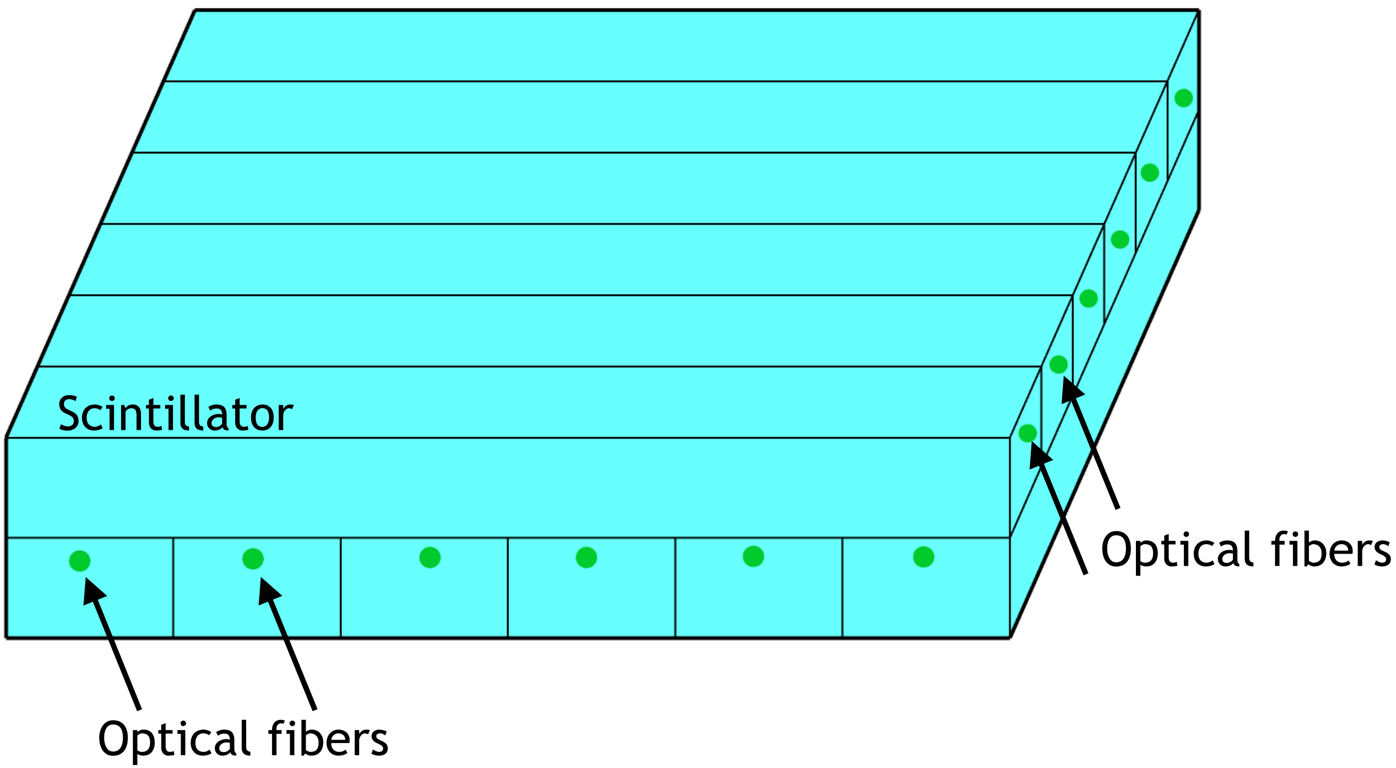


- 450MeV
- 2mm copper absorber
- Inner granularity 20mm, outer granularity 40mm

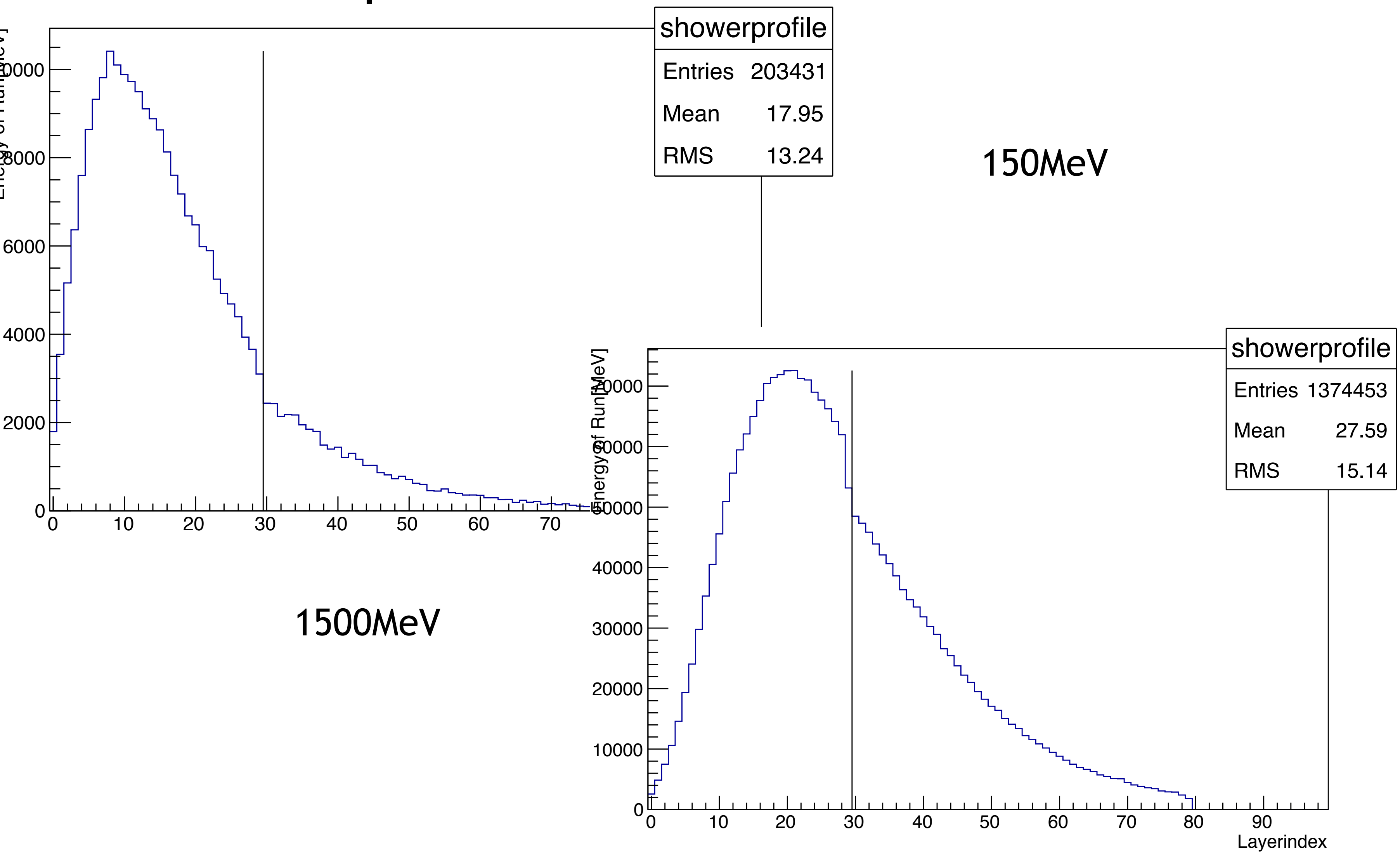
Hardware Studies

Several tiles with projective fiber readout ready/in production at the MPP

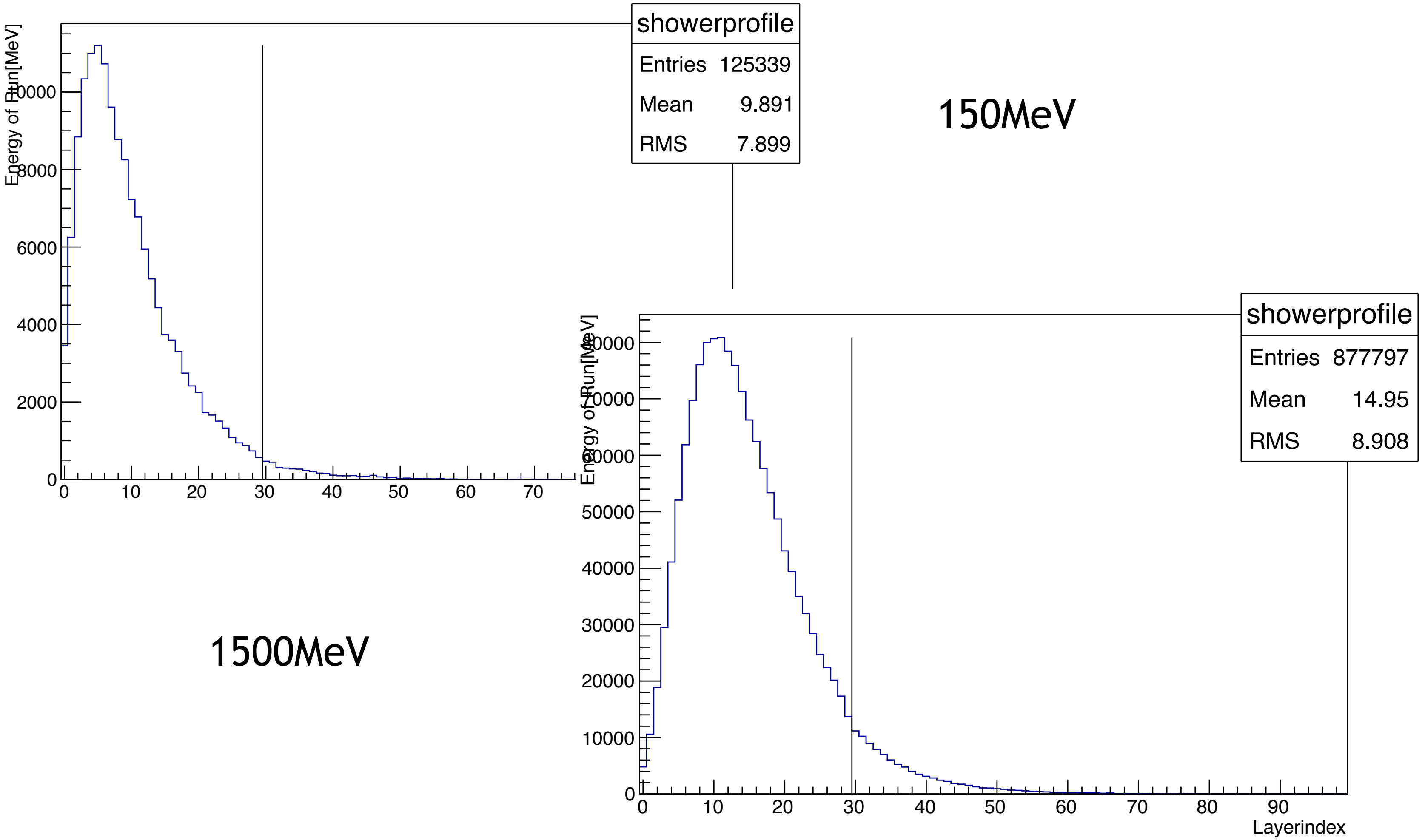


Try to achieve higher granularity with crossed strip geometry

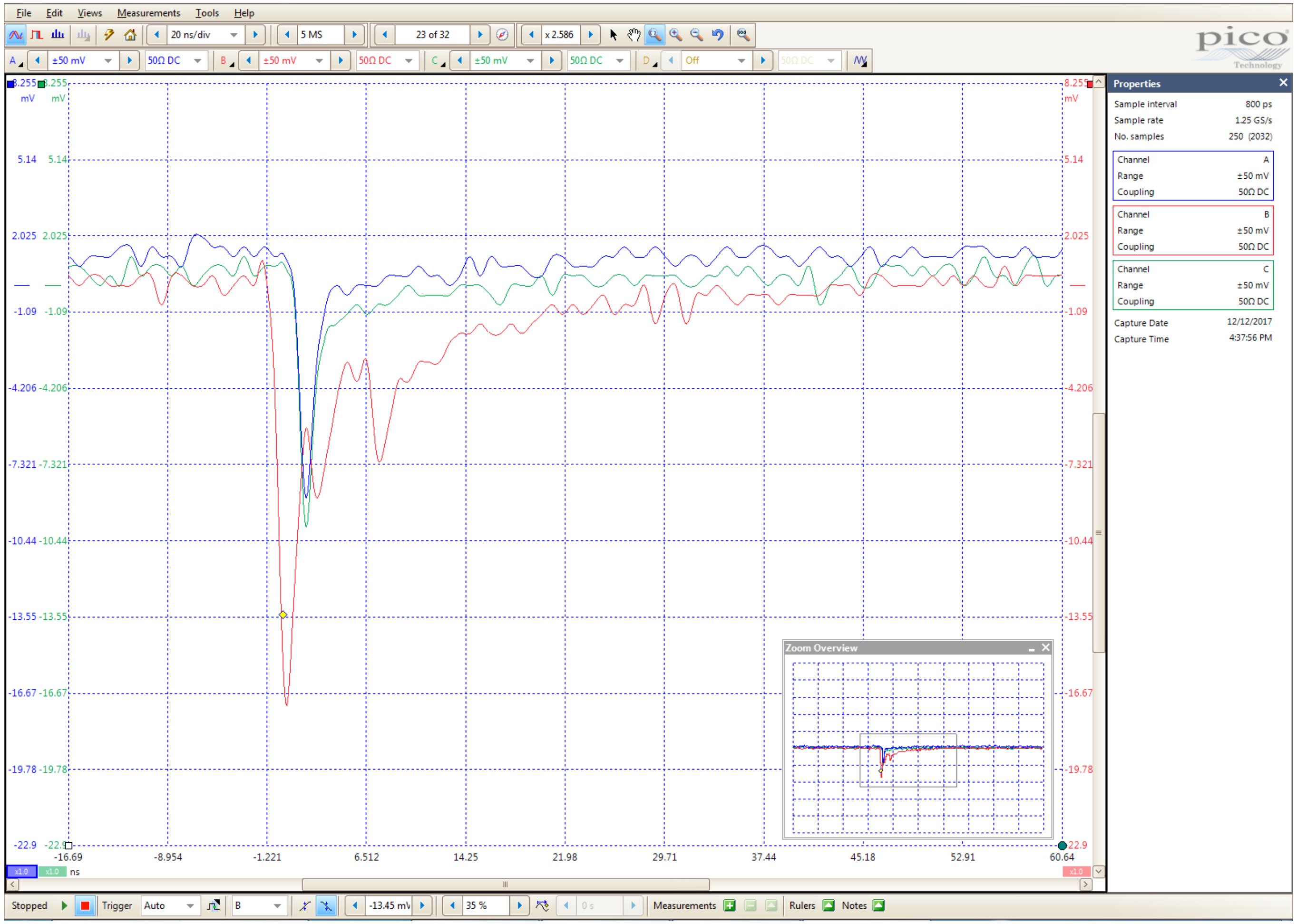
Showerprofile 1mmLead



Showerprofile 2mmLead



Hardware Studies



- Source on top of Channel 2
- Direct neighbours:
  - Channel 1
  - Channel 3

Fiber Readout