# Highly Granular ECAL
## Studies in a HP-TPC Context

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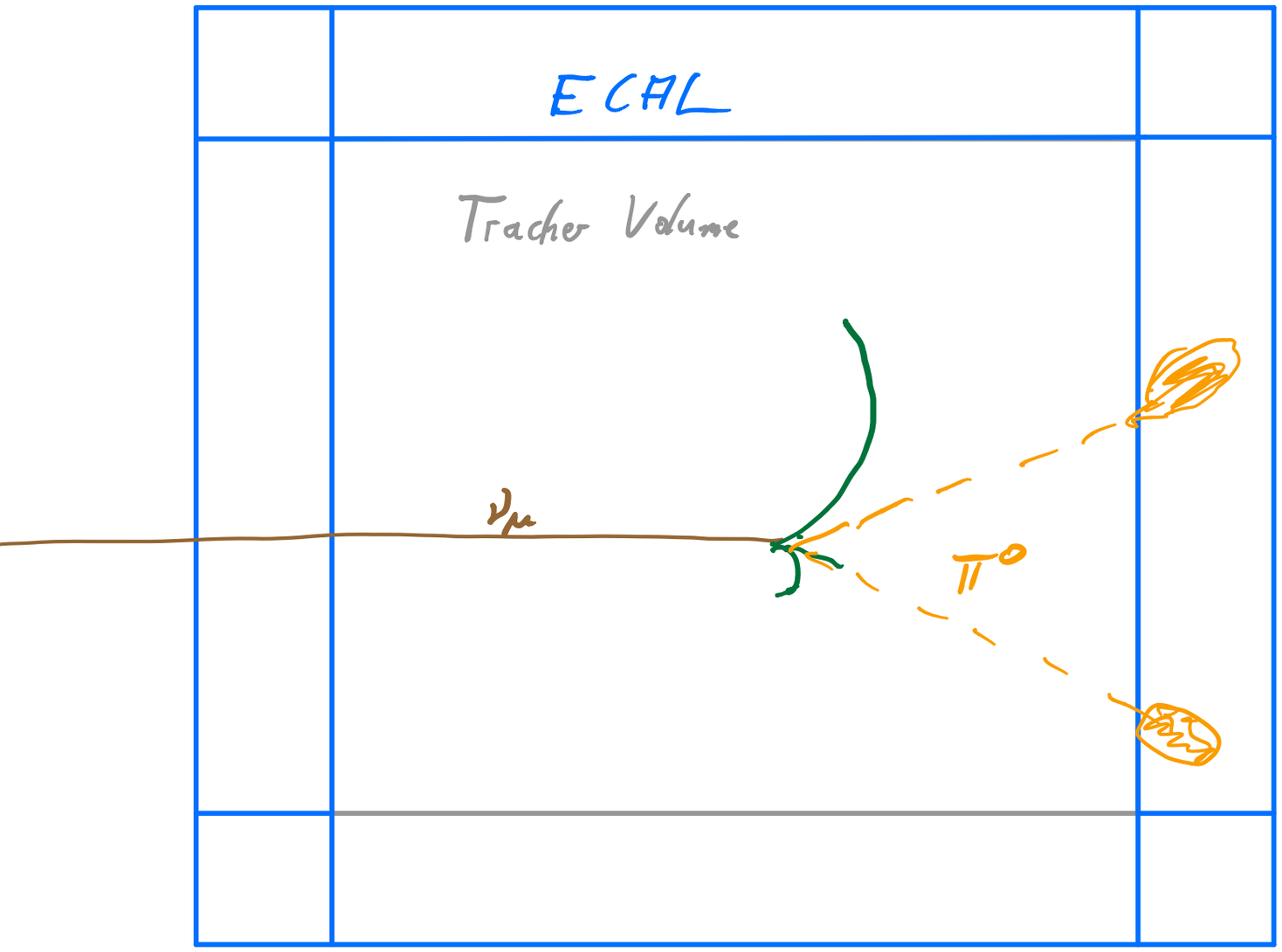
(Werner-Heisenberg-Institut)

# Outline

- A case for high granularity in the ECAL
- Straw man ECAL concept for a HP TPC
- Preliminary simulation results:
  - Energy resolution
  - Angular resolution
  - Scaling behavior with geometry changes
  - Neutral pions
- Real-world considerations: Channel count
- Possibilities: Timing

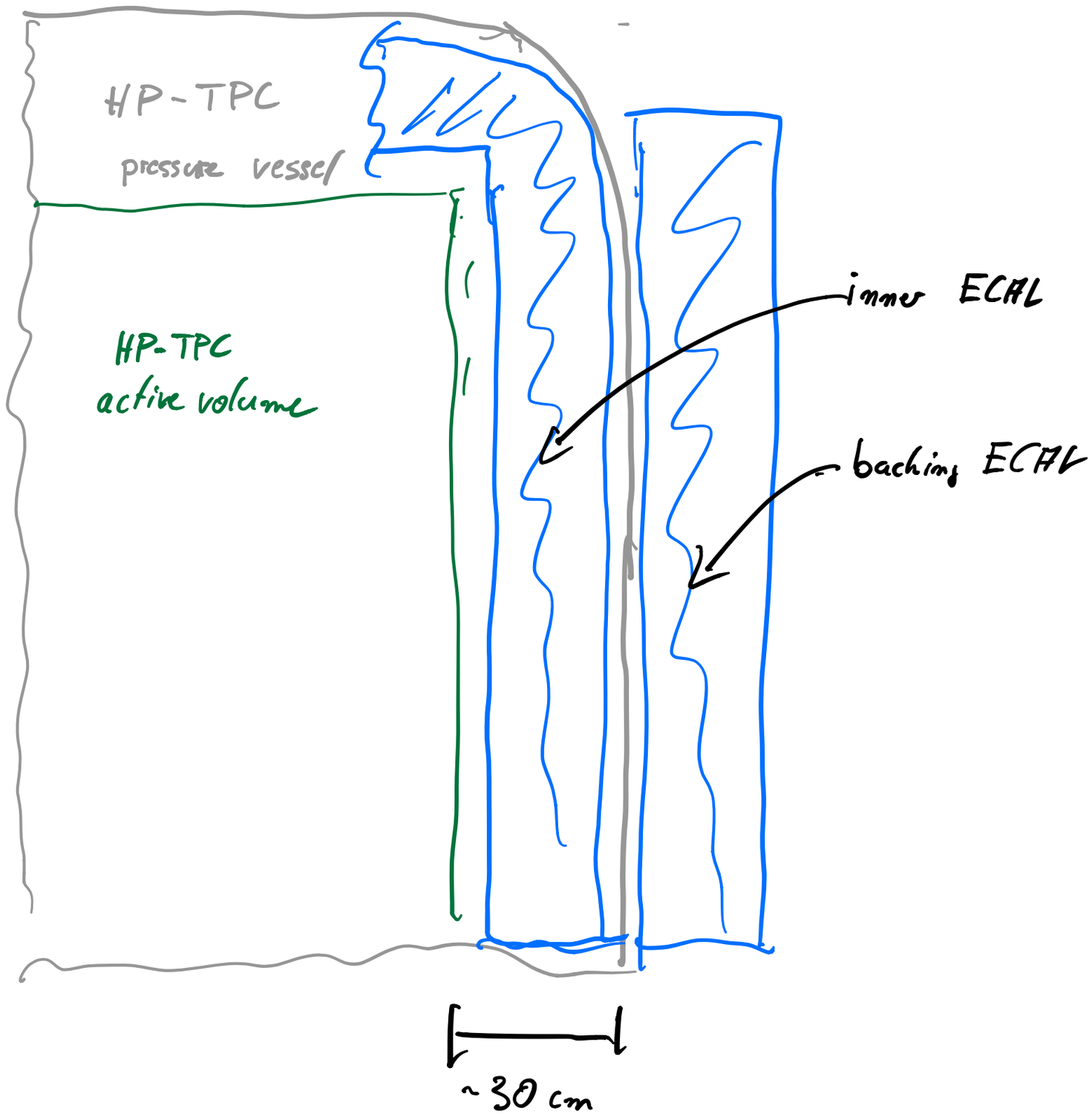
# A Case for Higher Granularity?

- An area where the ECAL can go beyond initial plans would be the capability to associated $\pi^0$s to neutrino interaction vertices in the tracking detector




- Generally useful - but particularly interesting in combination with a HP TPC, since the conversion probability in the TPC gas is too low to enable efficient $\pi^0$ reconstruction

# Straw Man Concept for HP TPC ECAL

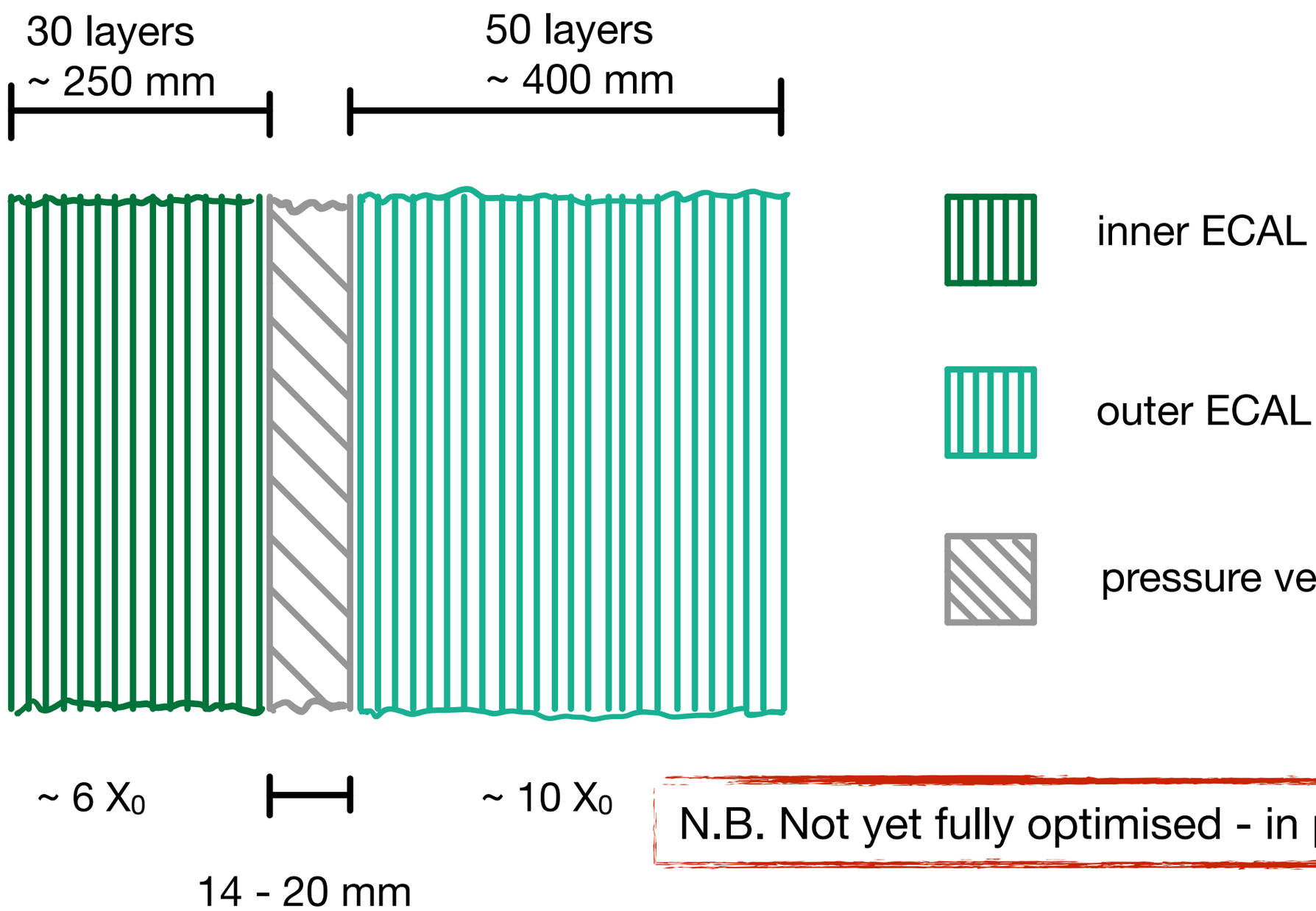



- Space inside pressure vessel is “premium real estate”

⇨ Cannot accommodate full calorimeter (depth ~ 80 cm) inside the vessel

⇨ Split the calorimeter into two sections, separated by the pressure vessel

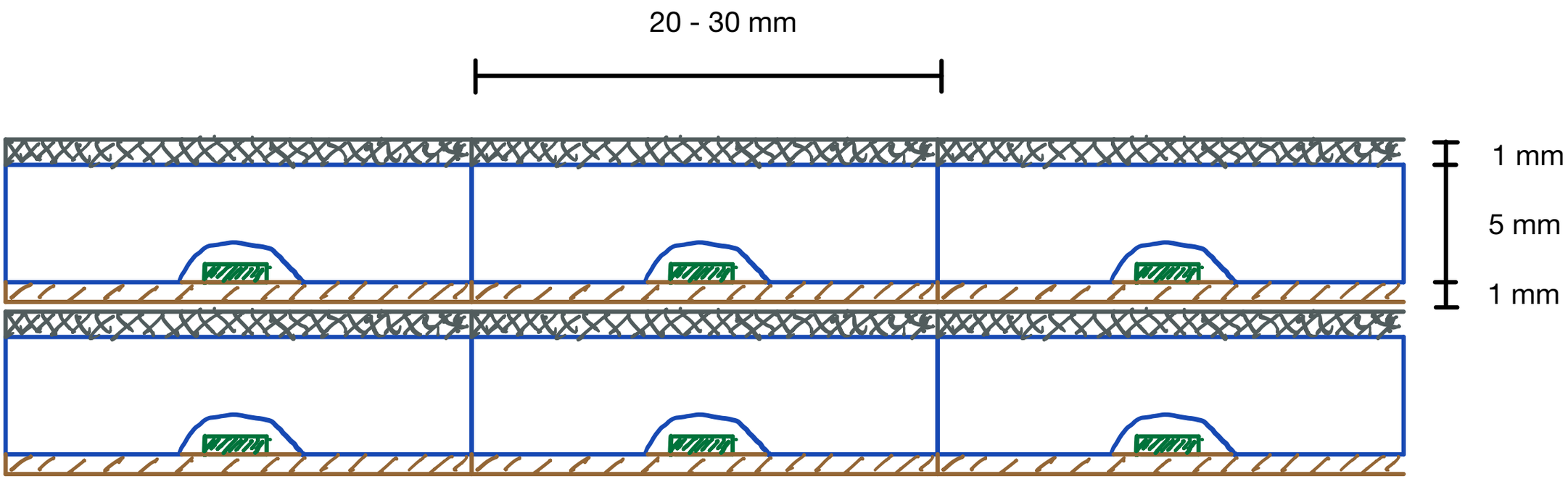
# Straw Man Concept for HP TPC ECAL



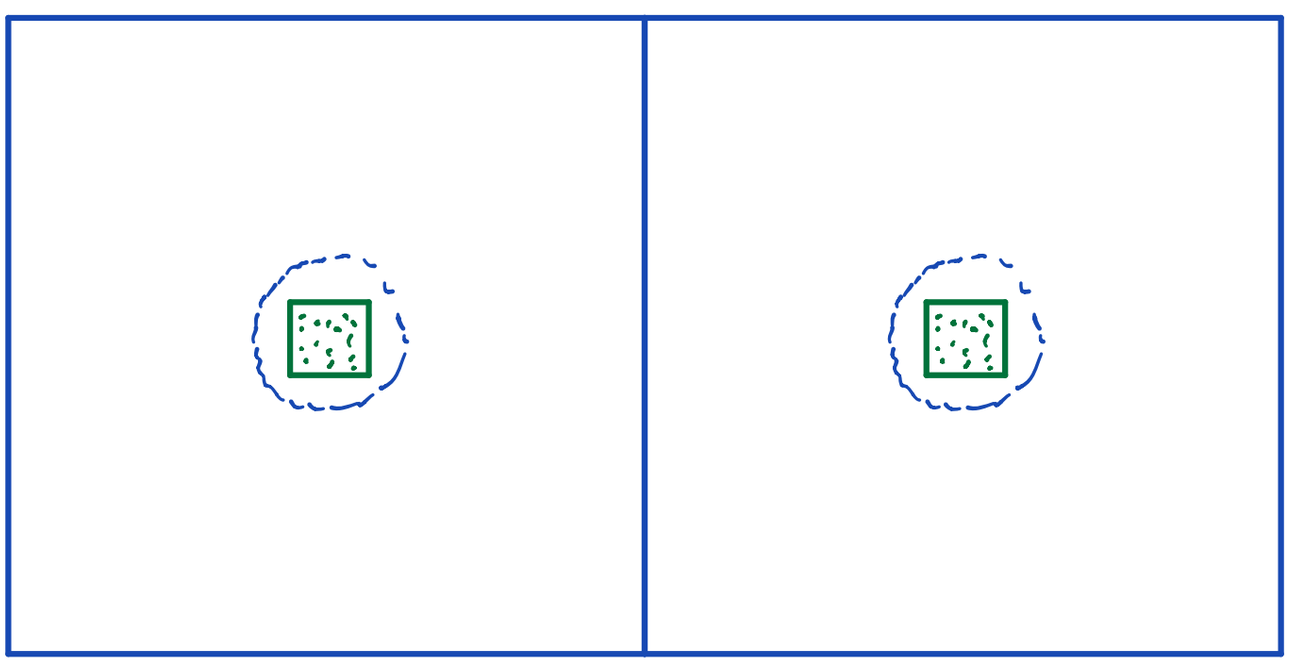

N.B. Not yet fully optimised - in particular outer segment!

- A two-component detector, separated by the pressure vessel
  - Default configuration: 1 mm Pb absorber, 5 mm plastic scintillator per layer
  - Other absorber configurations also studied

# Straw Man Concept for HP TPC ECAL




Pb absorber  plastic scintillator  SiPM  signal / power routing



- First design & simulations: assume a granularity of 20 x 20 - 30 x 30 mm$^2$

# Simulations - Present Status

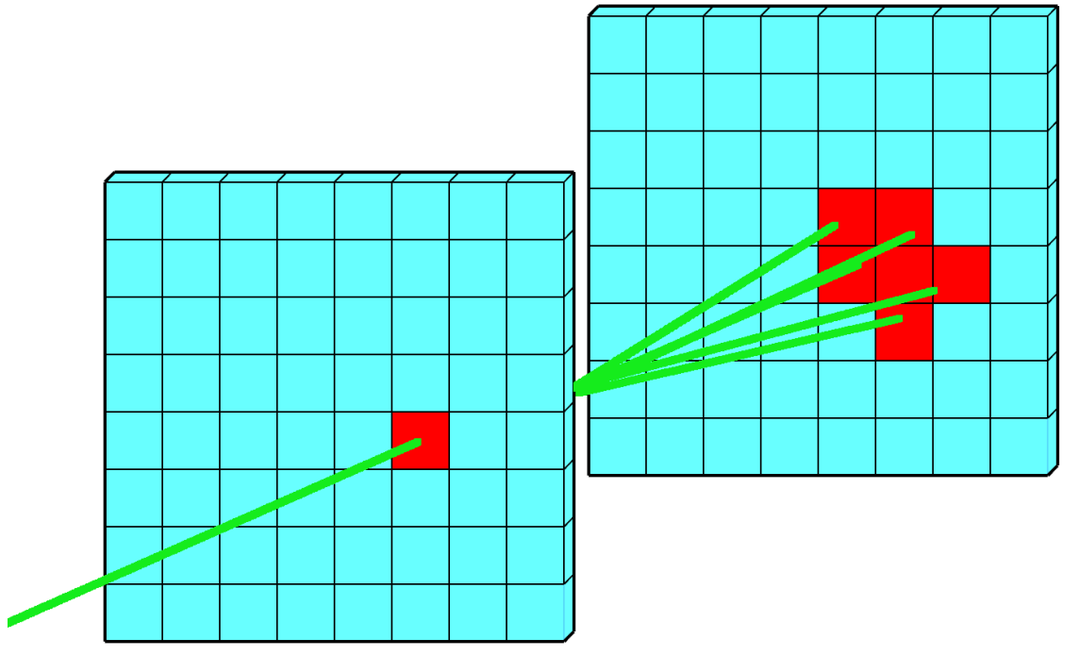
- GEANT4 - based detector simulations
- Default detector geometry: 1 layer implemented as
  - 1 mm lead
  - 5 mm plastic scintillator
  - 1 mm air (assuming low-density layer for signal routing - may be made more realistic)
  - Default granularity: 20 x 20 $mm^2$ inside pressure vessel, 40 x 40 $mm^2$ outside
- Simplified digitization
  - 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
- Still missing: Electronics at back end of inner ECAL: Will add material!

# Simulations: 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):

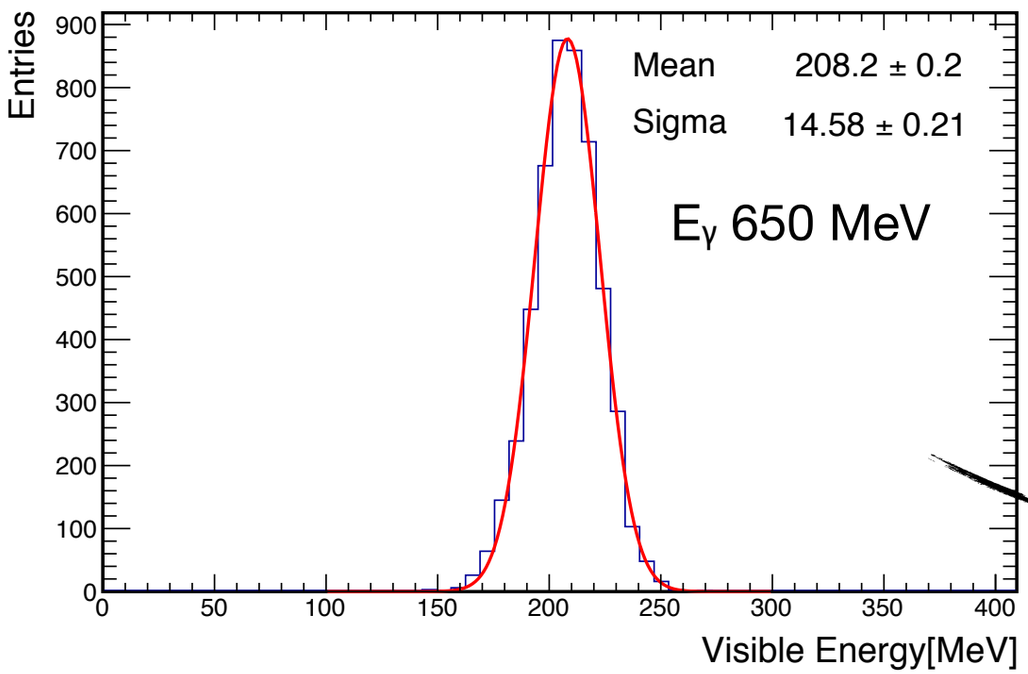
$$Resolution = \sqrt{\left(\frac{A}{\sqrt{E[MeV]}}\right)^2 + \left(\frac{B}{E[MeV]}\right)^2 + C^2}$$

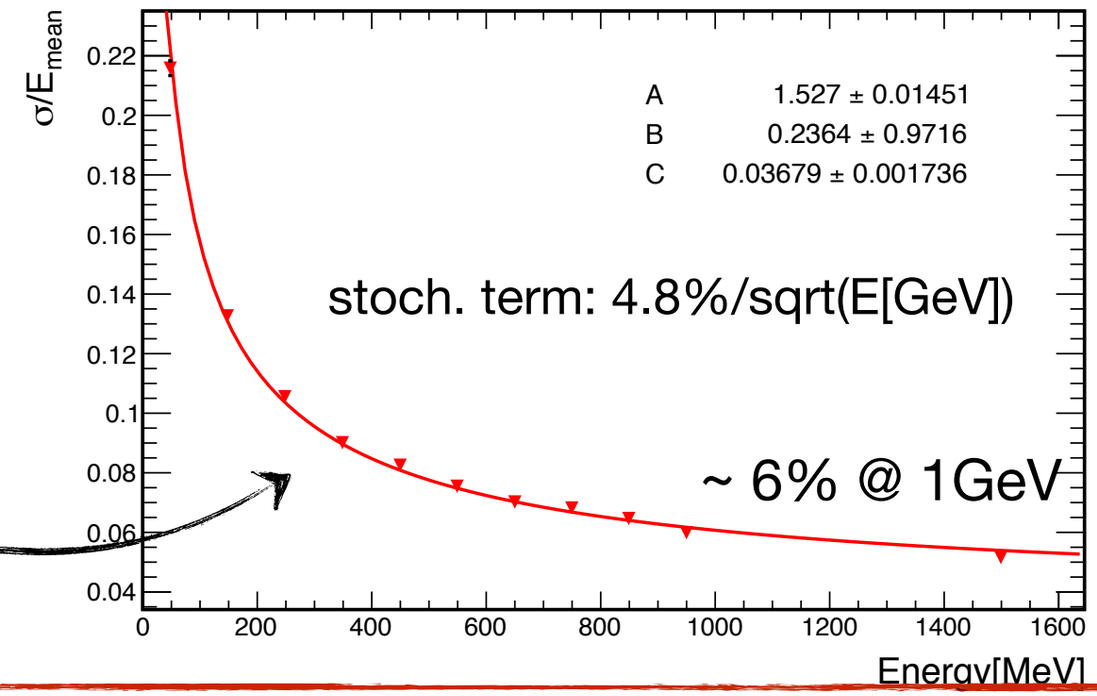


**N.B.:** to get stochastic term in units of 1/Sqrt(GeV) divide A by 32

# Single Photon Performance Metrics

- Energy resolution given by σ/mean




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

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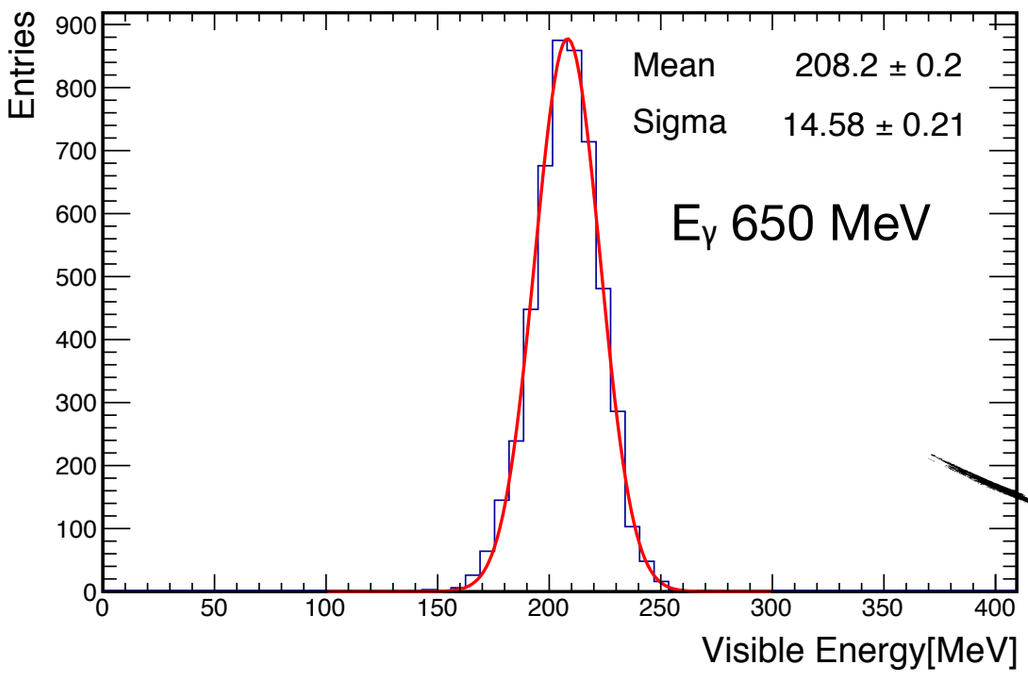
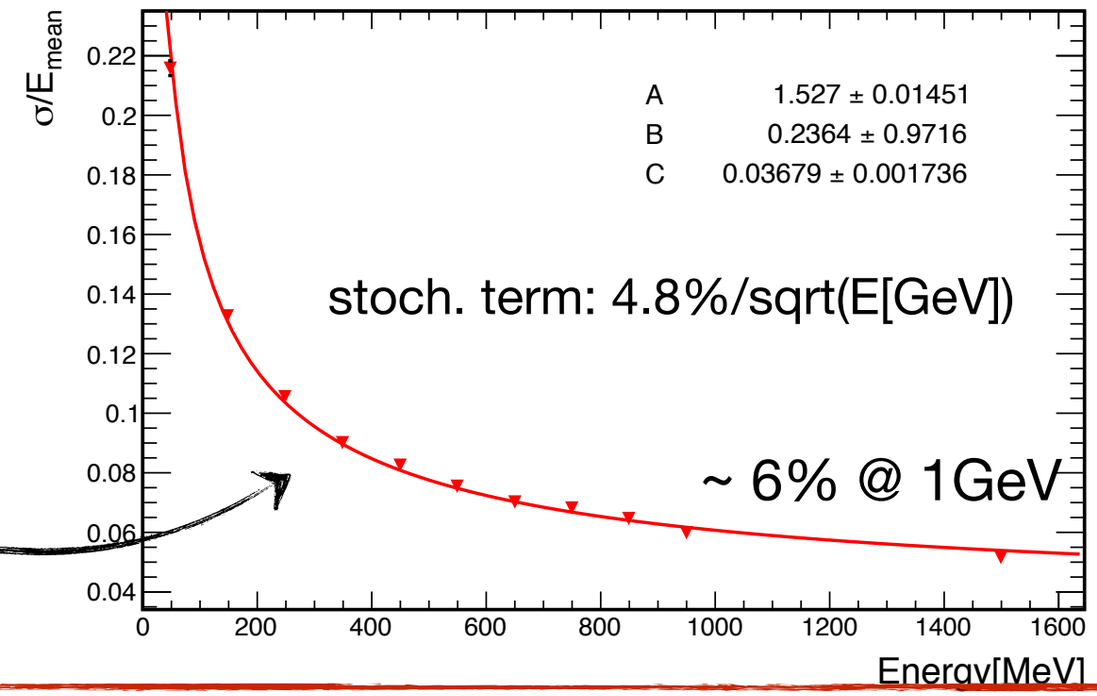
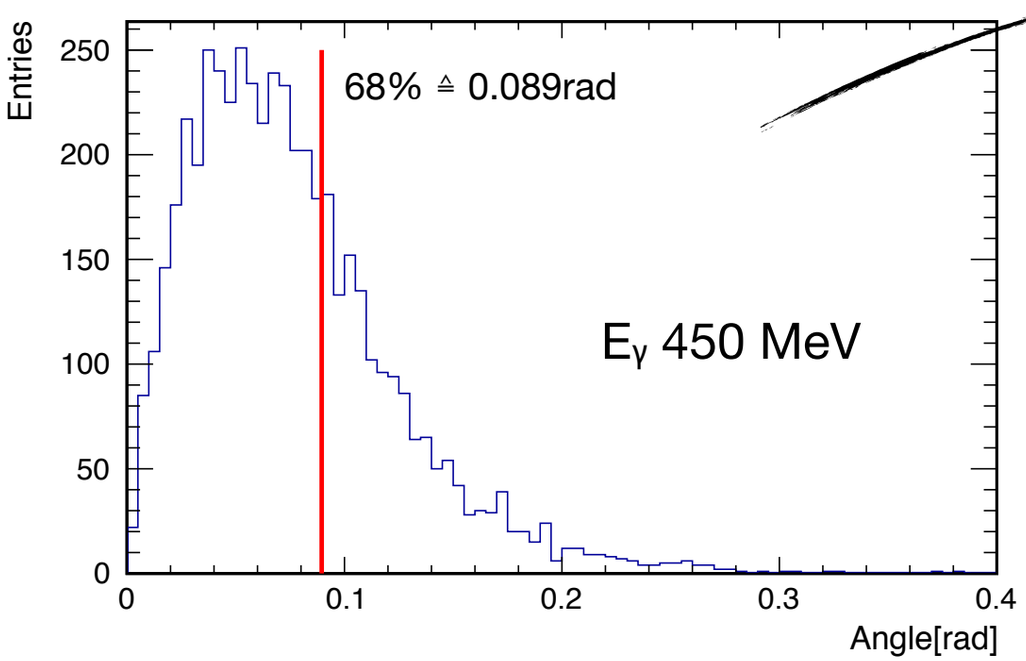
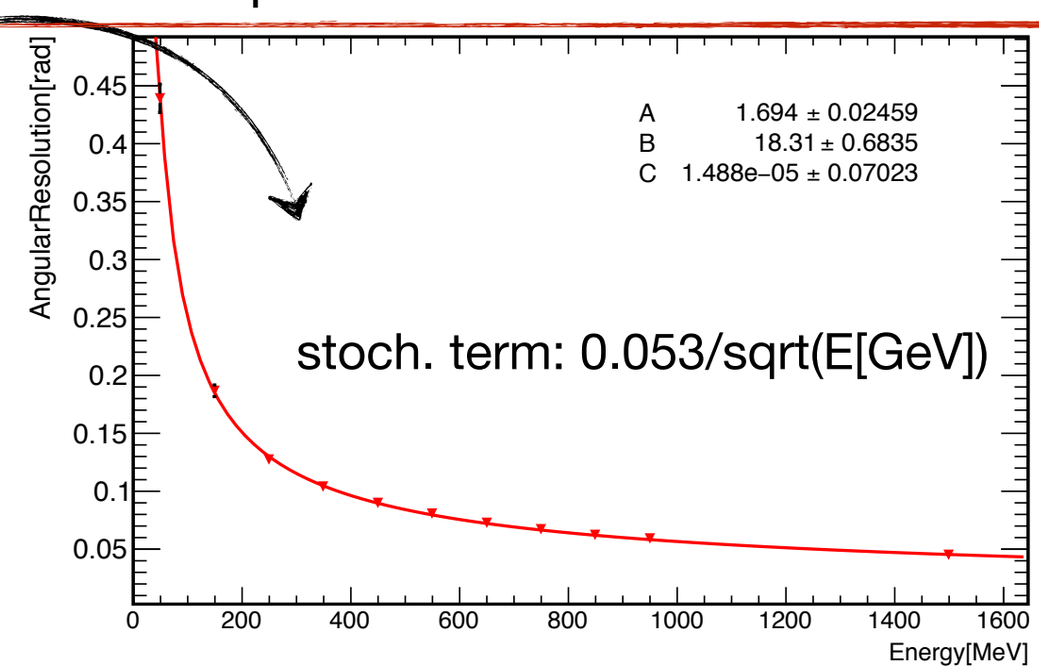


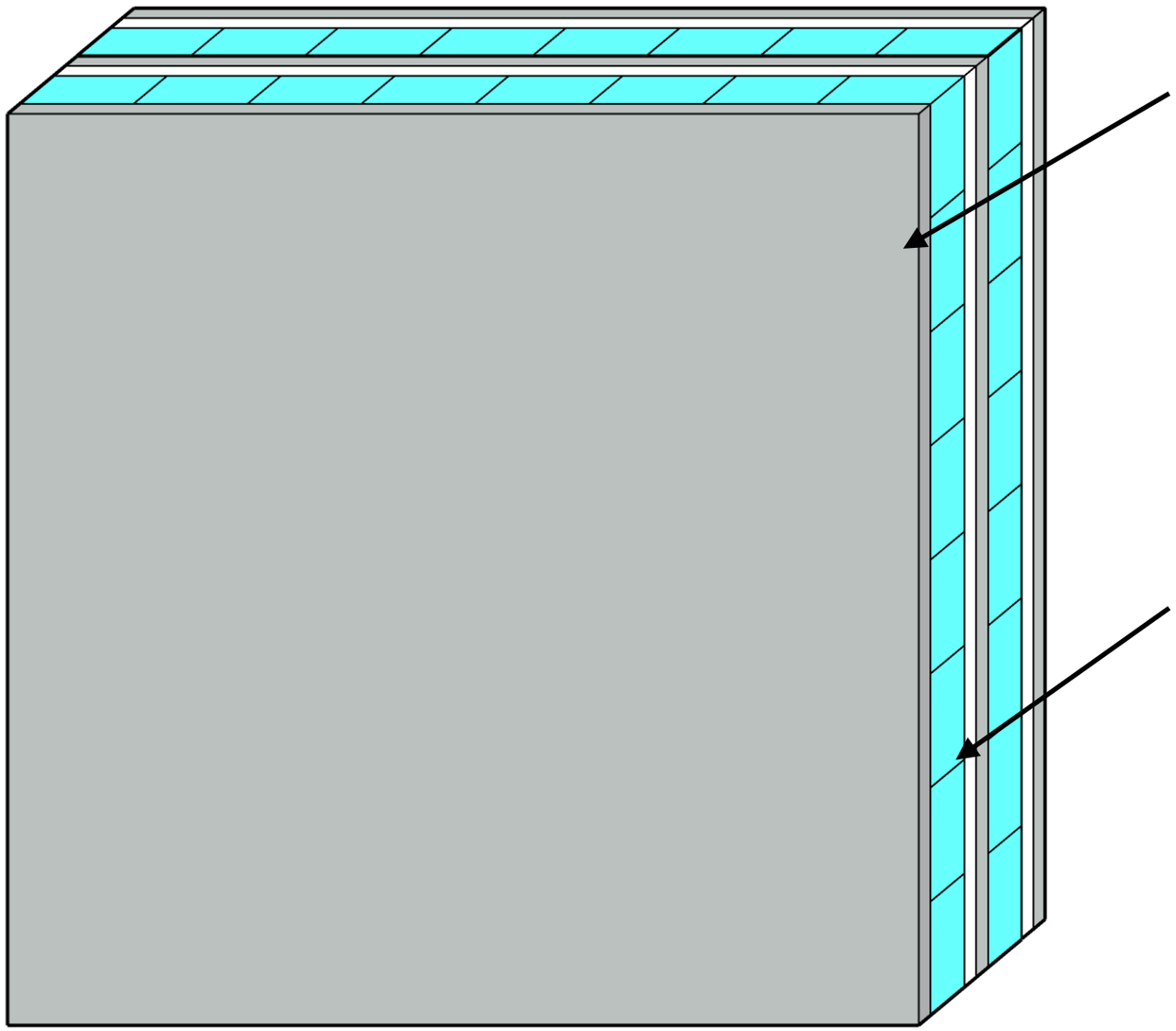

- Angular resolution given by 68%ile

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



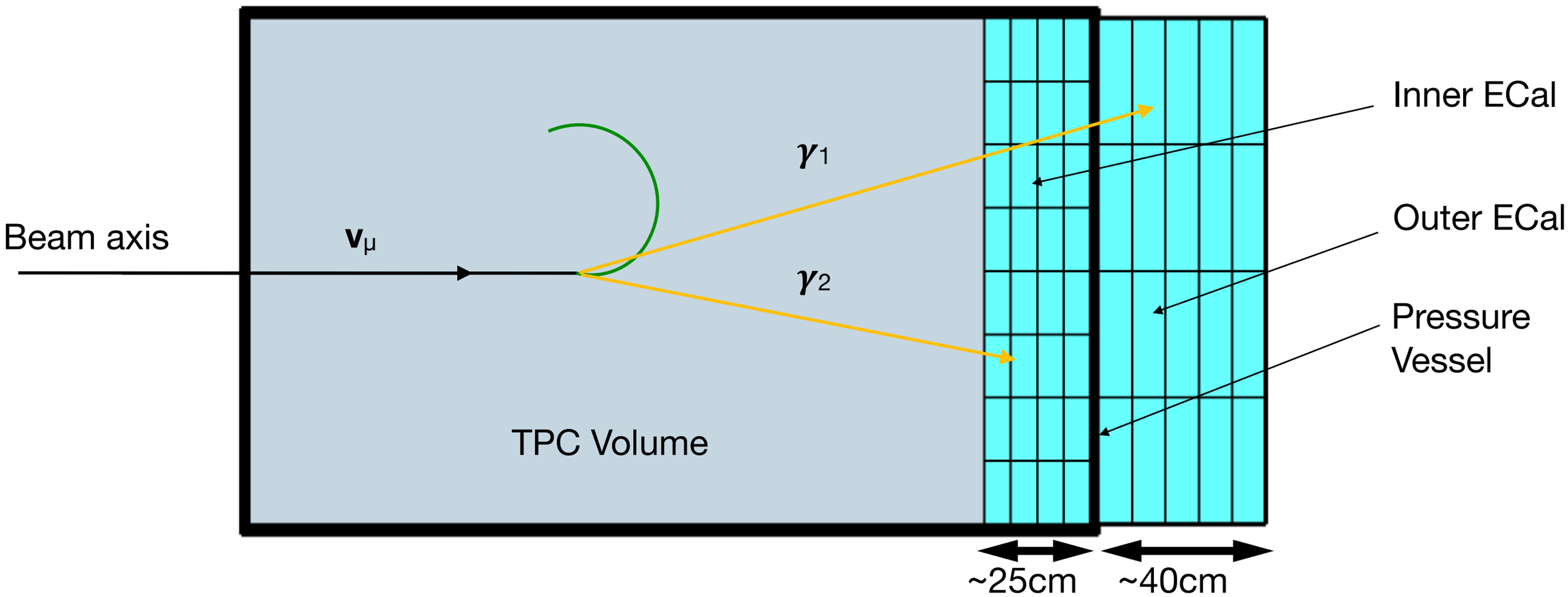
# The Parameter Studies



- 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

First goal: Understand scaling behavior of detector performance for configuration changes

# The Parameter Studies

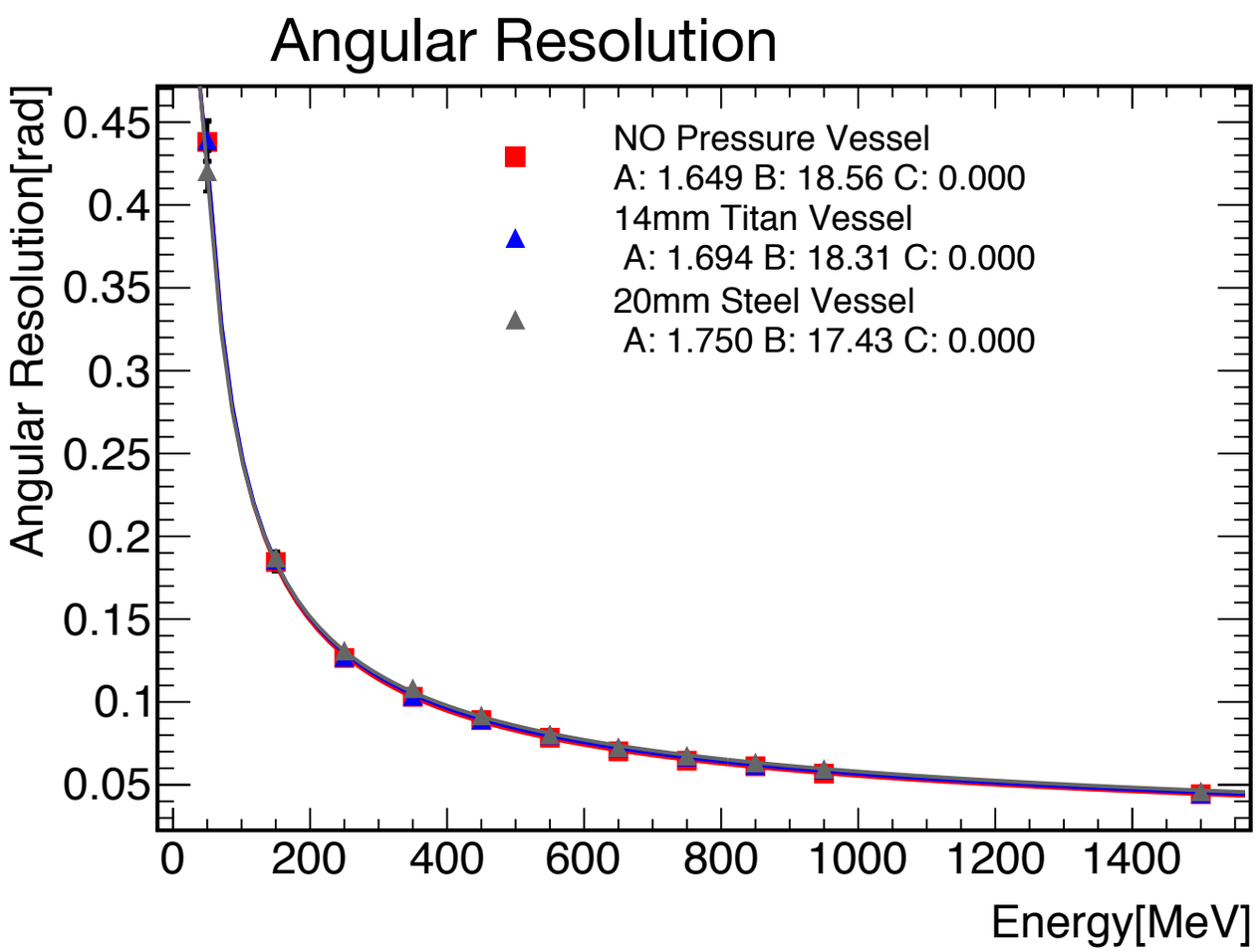


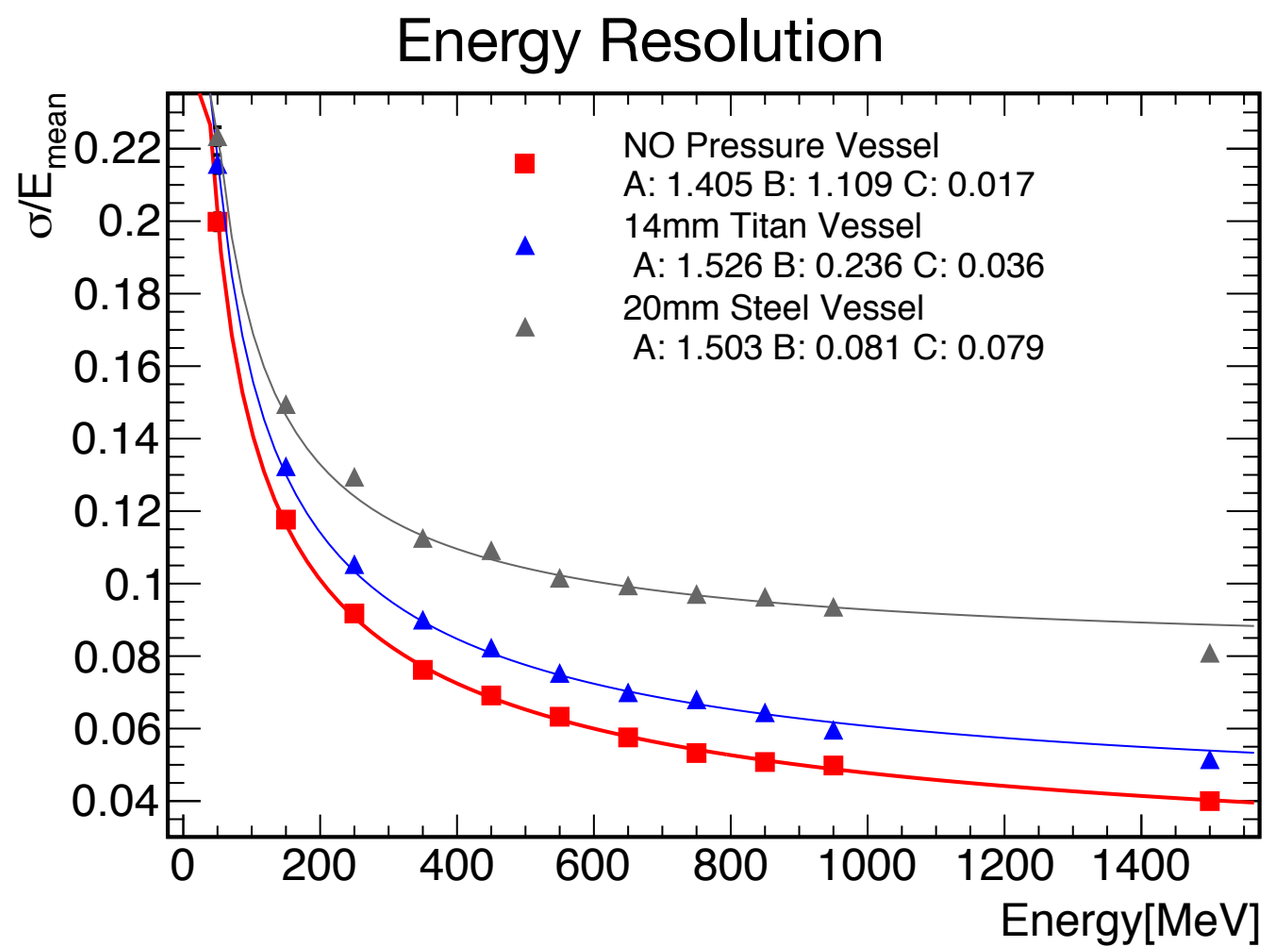

- Considering different granularities in different ECAL sections
  - Also: changing granularity in inner ECAL [not shown…]

First goal: Understand scaling behavior of detector performance for configuration changes

# Single Photons: Impact of Pressure Vessel

- ECAL configuration: 1 mm Pb, inner granularity 20 mm, outer granularity 40 mm



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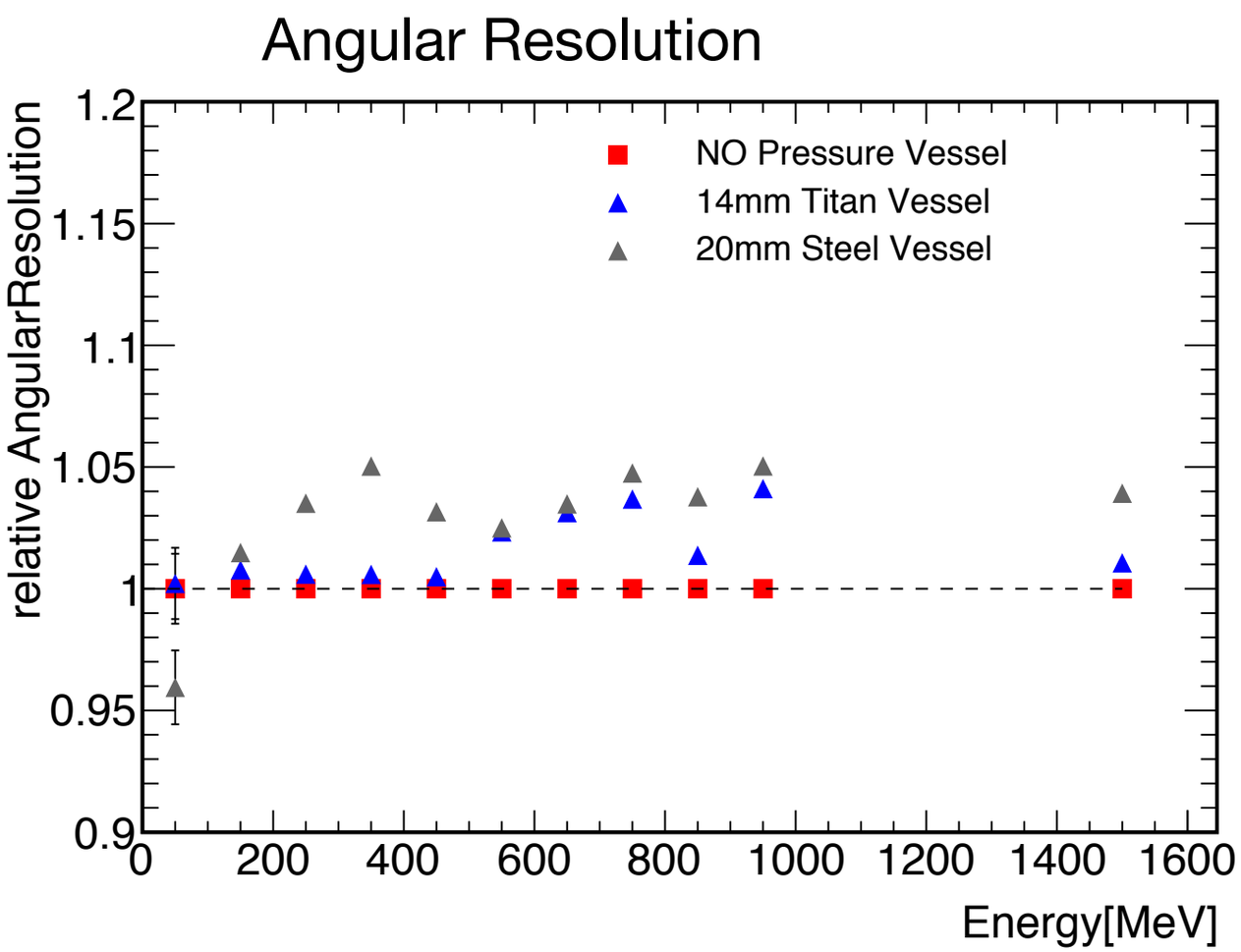
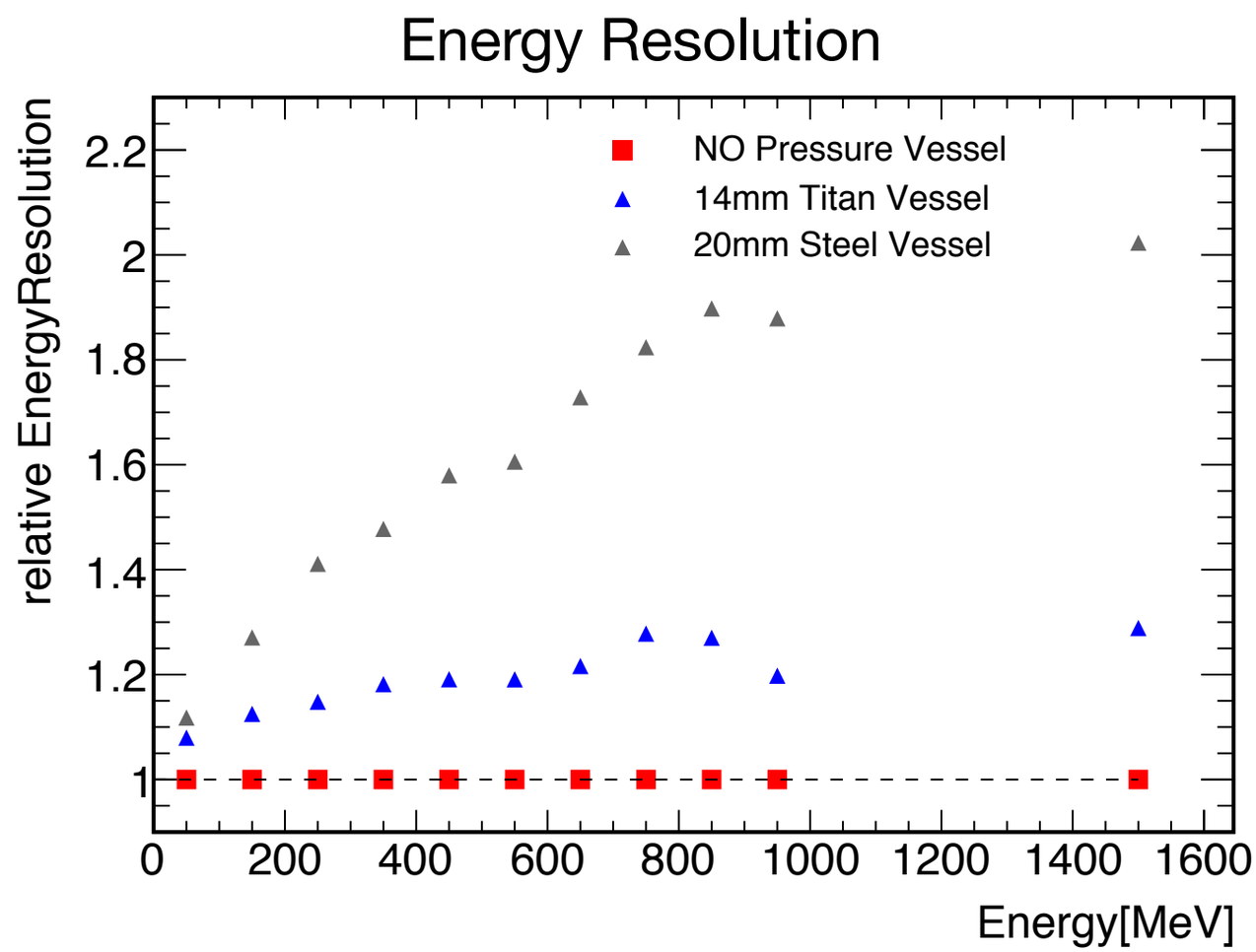


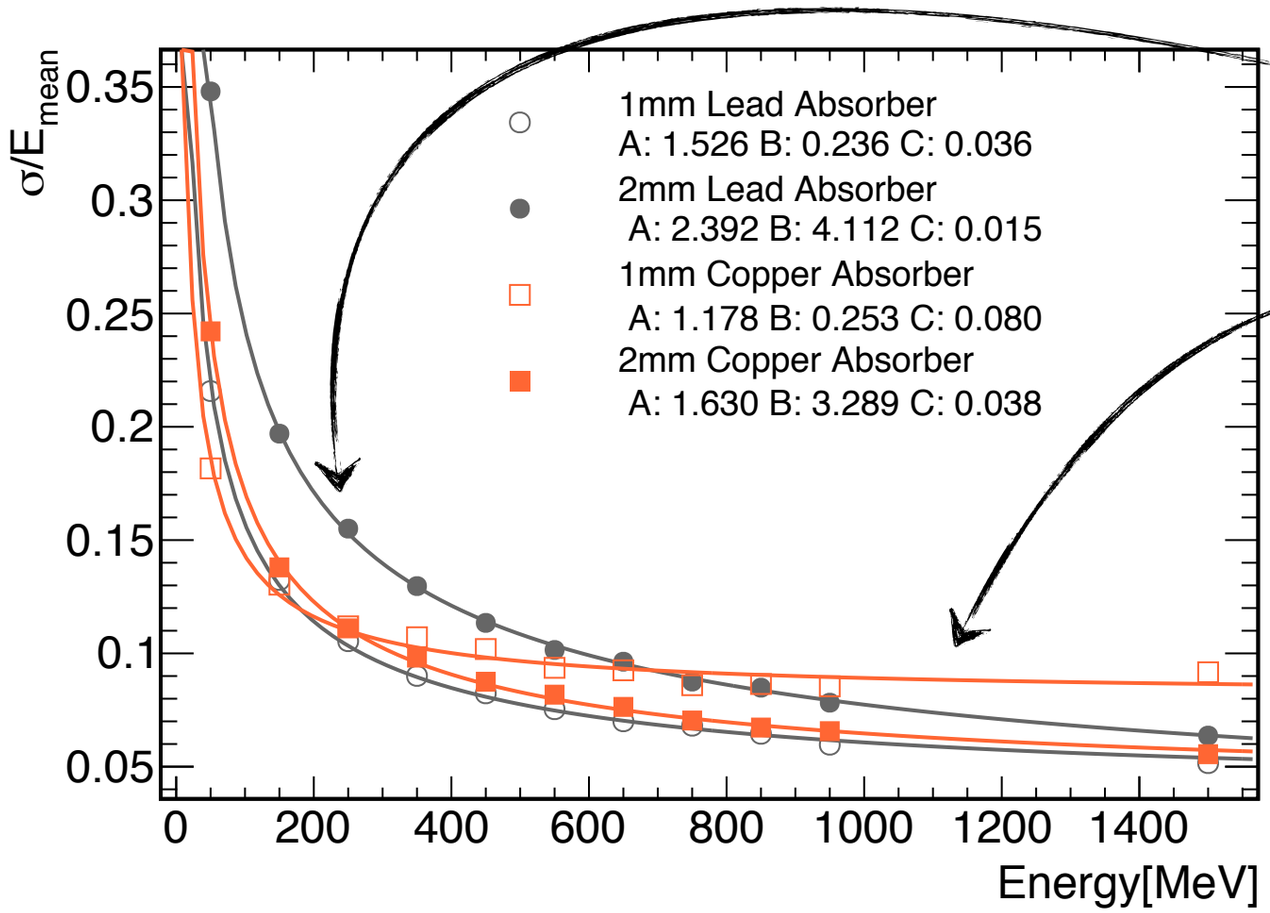

➪ Very mild impact on angular resolution: few %

➪ Substantial impact on energy resolution - thick steel vessel up to x2 deterioration, with titanium only ~ 30% loss compared to no vessel

In the following: Always assume titanium vessel

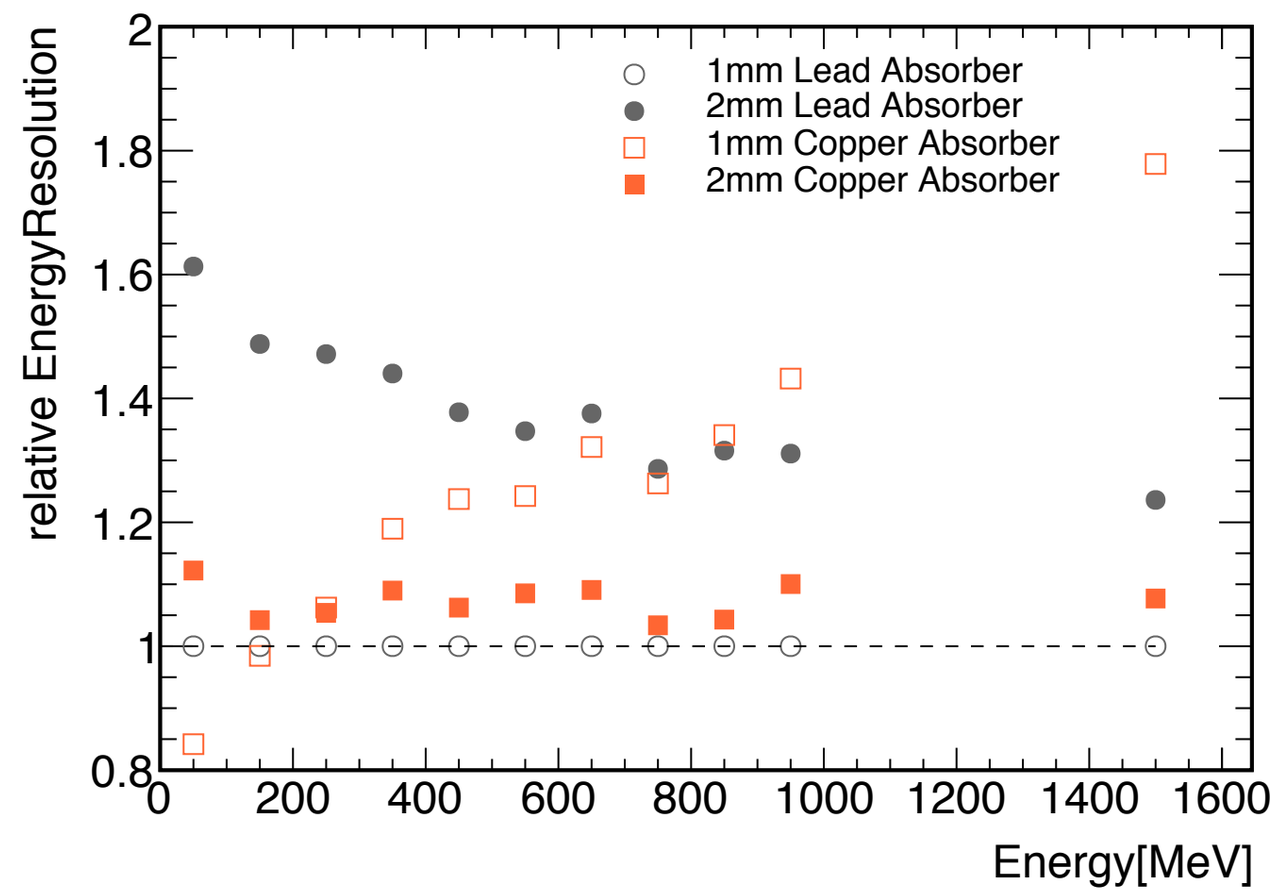
# Scaling of Energy Resolution with Absorber

- Looking at four scenarios: 1 mm & 2 mm absorber plates, Pb & Cu
  - always: Ti pressure vessel




smaller sampling fraction for 2 mm Pb: larger stochastic term

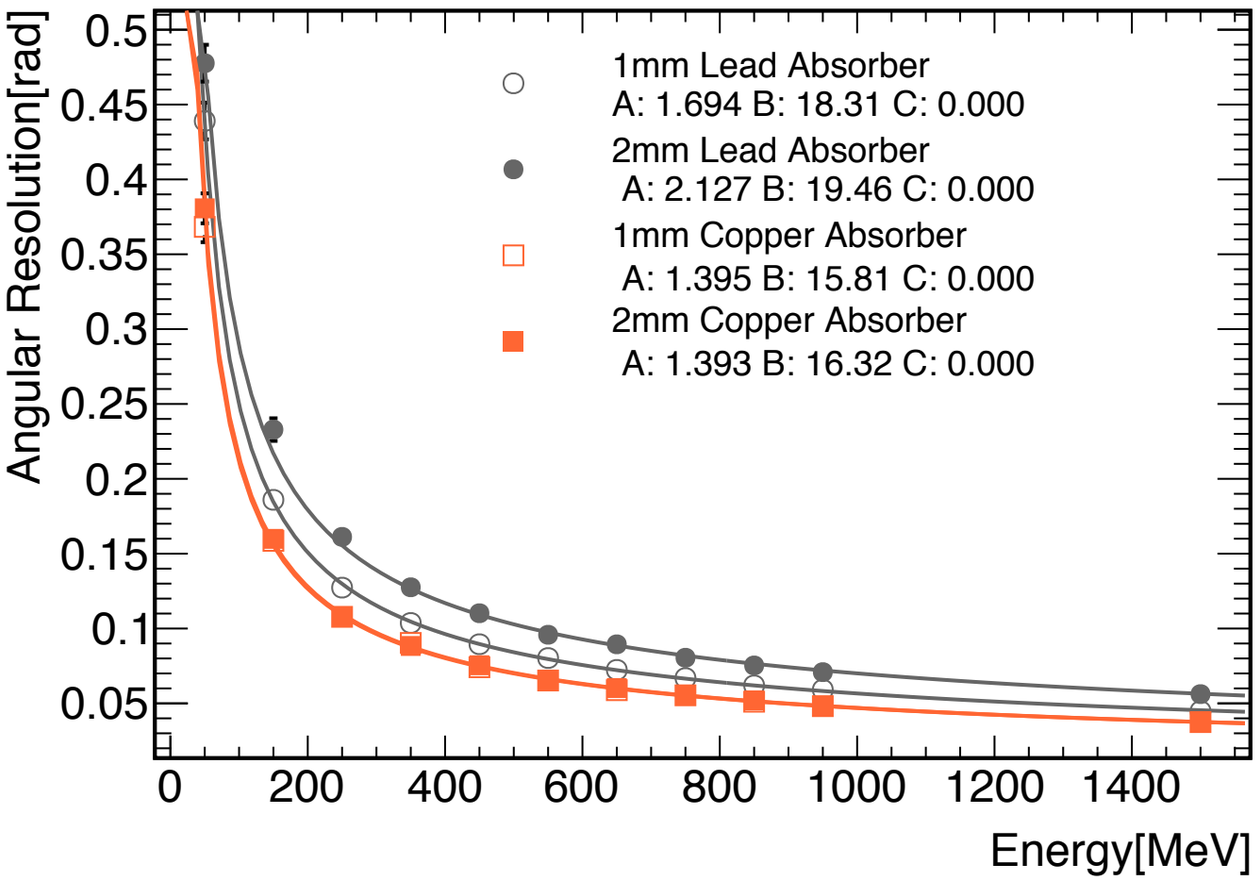
substantial energy leakage for 1 mm Cu: not enough $X_0$ in calorimeter!

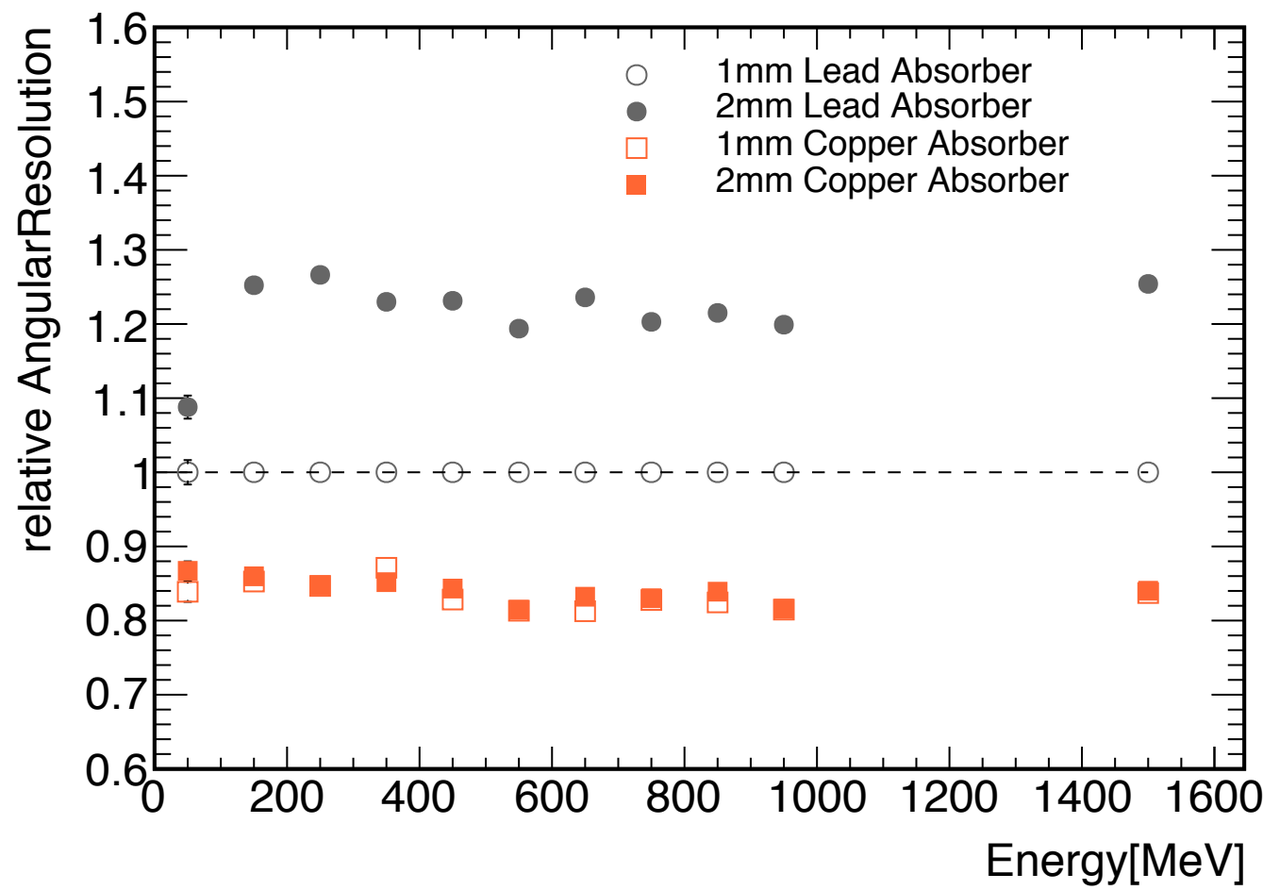



- Best performance for 1 mm Pb, only slight performance loss when using 2 mm Cu

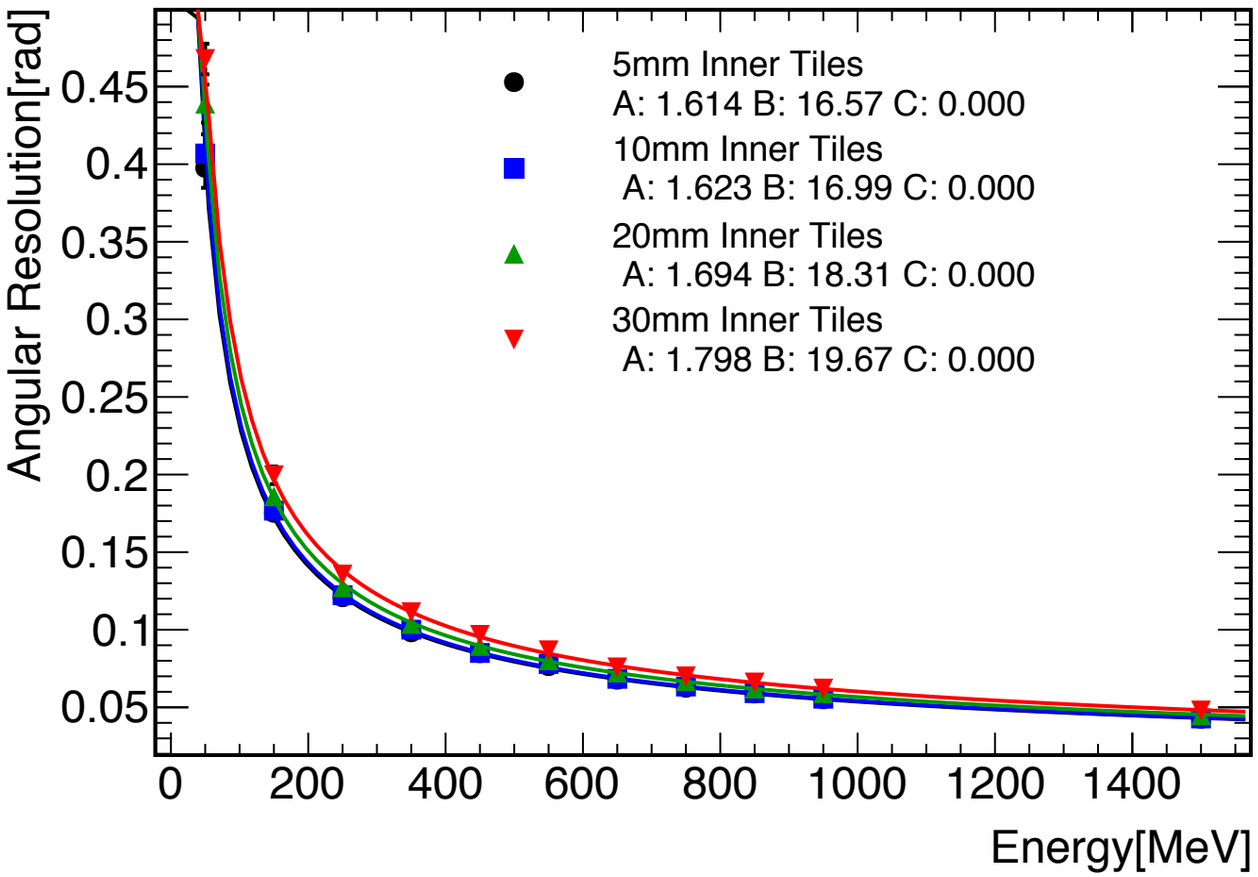
# Scaling of Angular Resolution with Absorber

- Looking at four scenarios: 1 mm & 2 mm absorber plates, Pb & Cu
  - always: Ti pressure vessel, 20 x 20 mm$^2$ scintillator tiles in inner ECAL

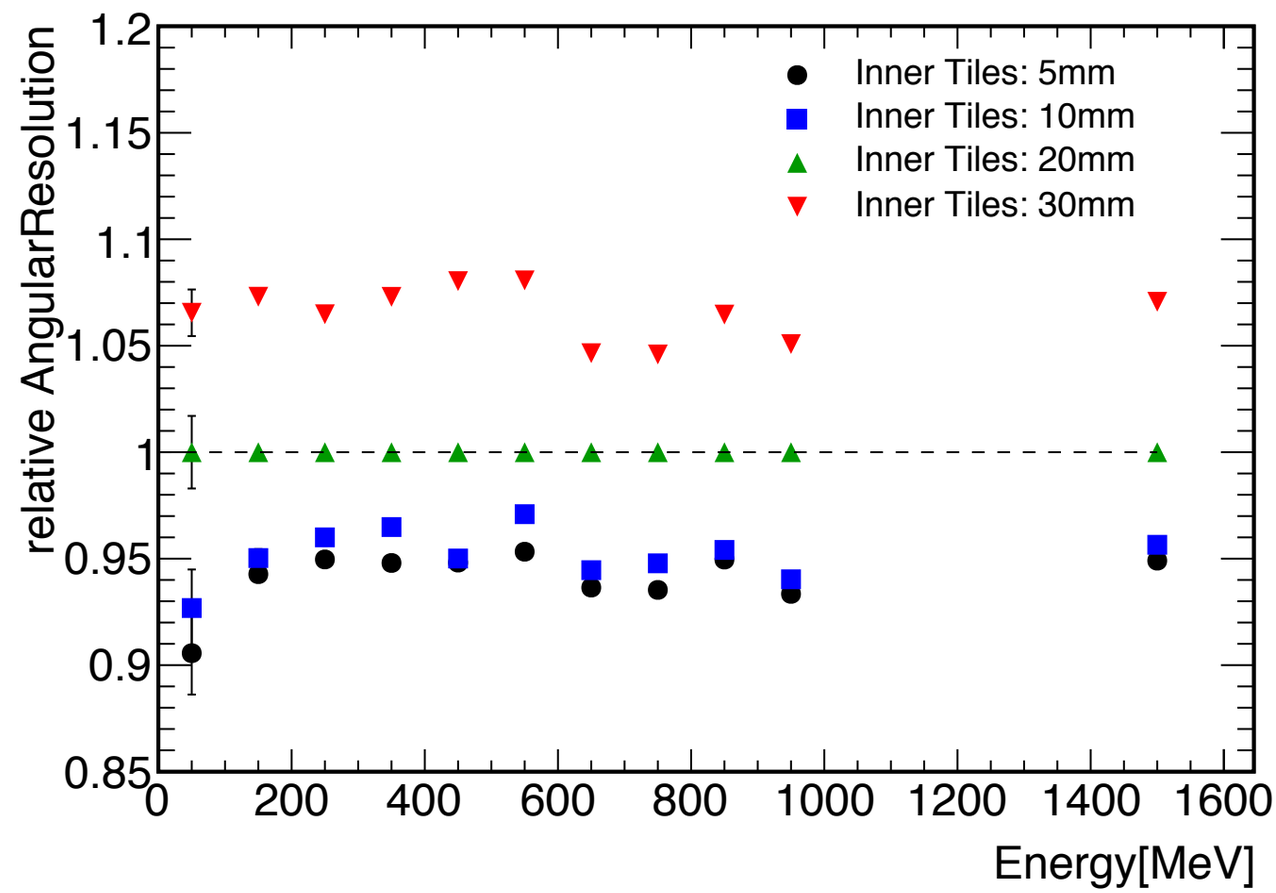


# Scaling of Angular Resolution with Granularity




- Varying the size of the scintillator tiles in the inner ECAL for 1 mm Pb absorber




- Saturation of improvement for smaller tiles at 10 x 10 mm$^2$
- Not shown: For Cu 2 mm the performance for 30 x 30 mm$^2$ is slightly better than for Pb 20 x 20 mm$^2$: Wider showers

# Scaling of Detector Performance - Summary

- Indicative performance impact of detector layout changes

| | 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

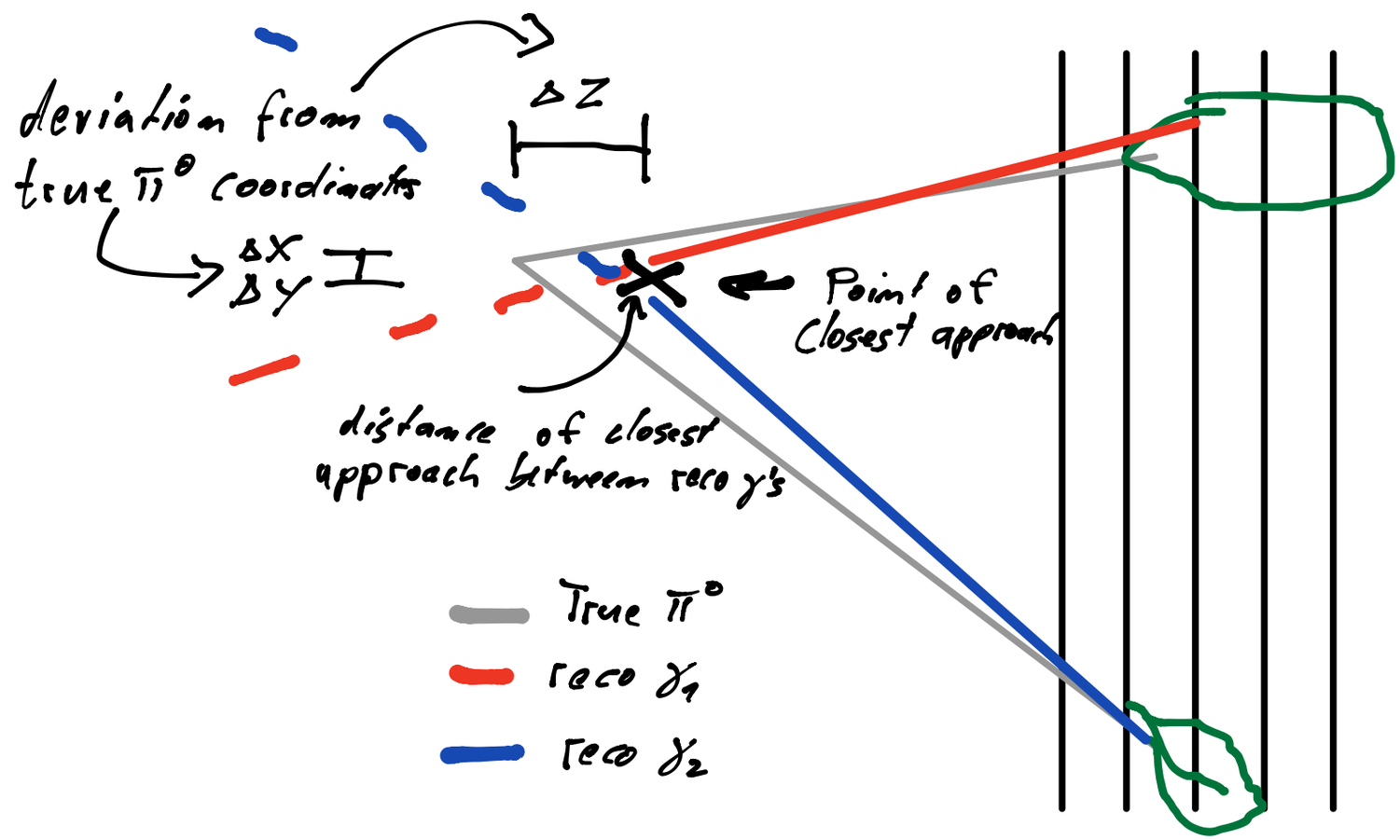
→ Neutral

Arrow slope:
strength of effect

# Naive Look at Pi0s

- Still in an early stage - also hampered by the current limitation of a single box-like detector - will need somewhat more sophisticated simulations for a full study
  - Also: Results still need to be fully understood and QAed - bugs not unlikely!
  - In addition: Issues when dealing with very low-energy photons - at present no algorithm for stable estimate of direction below ~ 70 MeV: For now a cut-off is applied

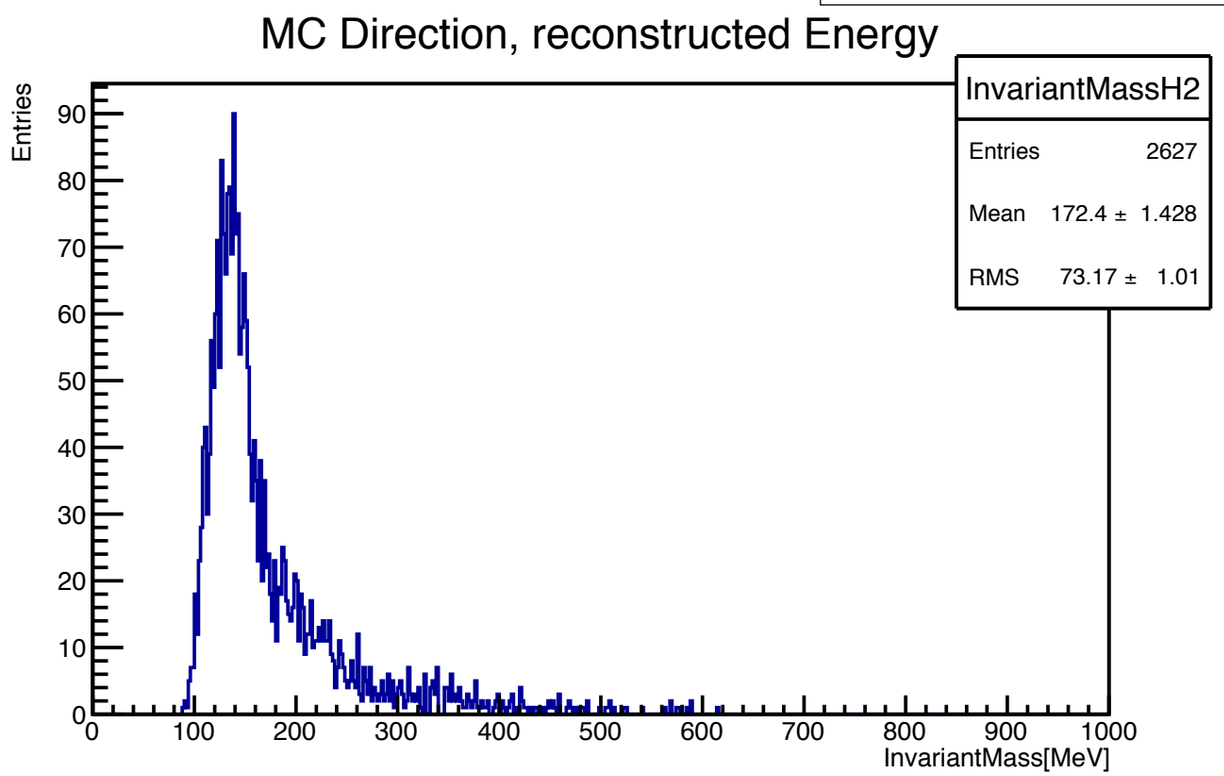
Assignment of energy to photons using MC truth information

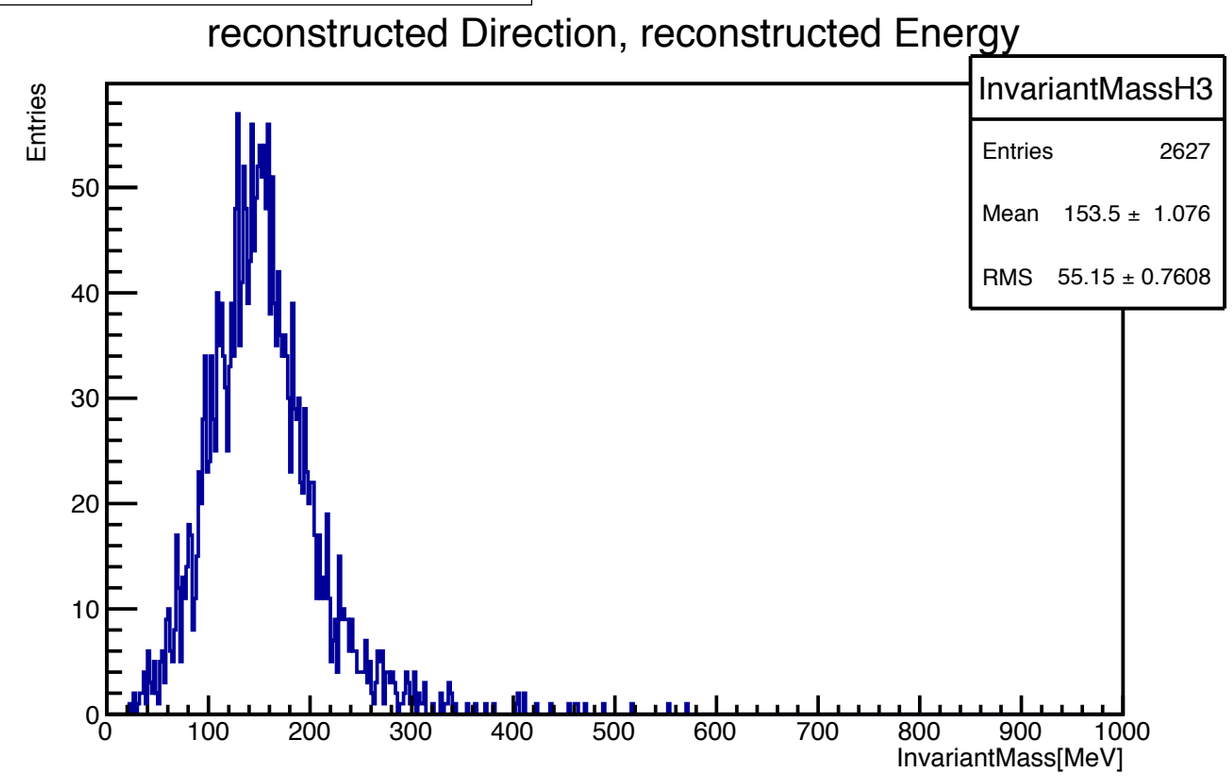


# Naive Look at Pi0s

- Work still in progress (understanding, in particular) on spatial resolution for $\pi^0$
- First indications: Location accuracy of $\pi^0$ on the 10 - 15 cm level - uncertainties in coordinate perpendicular to ECAL front face largest (e.g., reconstruction of distance from ECAL), better in other two coordinates
  - Cu absorber with 30 x 30 $mm^2$ granularity very slightly better than Pb absorber with 20 x 20 $mm^2$ granularity

450 MeV $\pi^0$, 30 cm away from ECAL



# Real-world Considerations: Channel Count

- High granularity means high channel count…
- With 2 x 2 $cm^2$ individual tiles:
  - 2500 cells / $m^2$ / layer: 75k channels / $m^2$ of inner ECAL
- With 3 x 3 $cm^2$ individual tiles:
  - 1100 cells / $m^2$ / layer: 33k channels / $m^2$ of inner ECAL
- With 4 x 4 $cm^2$ individual tiles:
  - 625 cells / $m^2$ / layer: 19k channels / $m^2$ of inner ECAL

➪ Need to fully understand granularity requirements to optimise detector layout

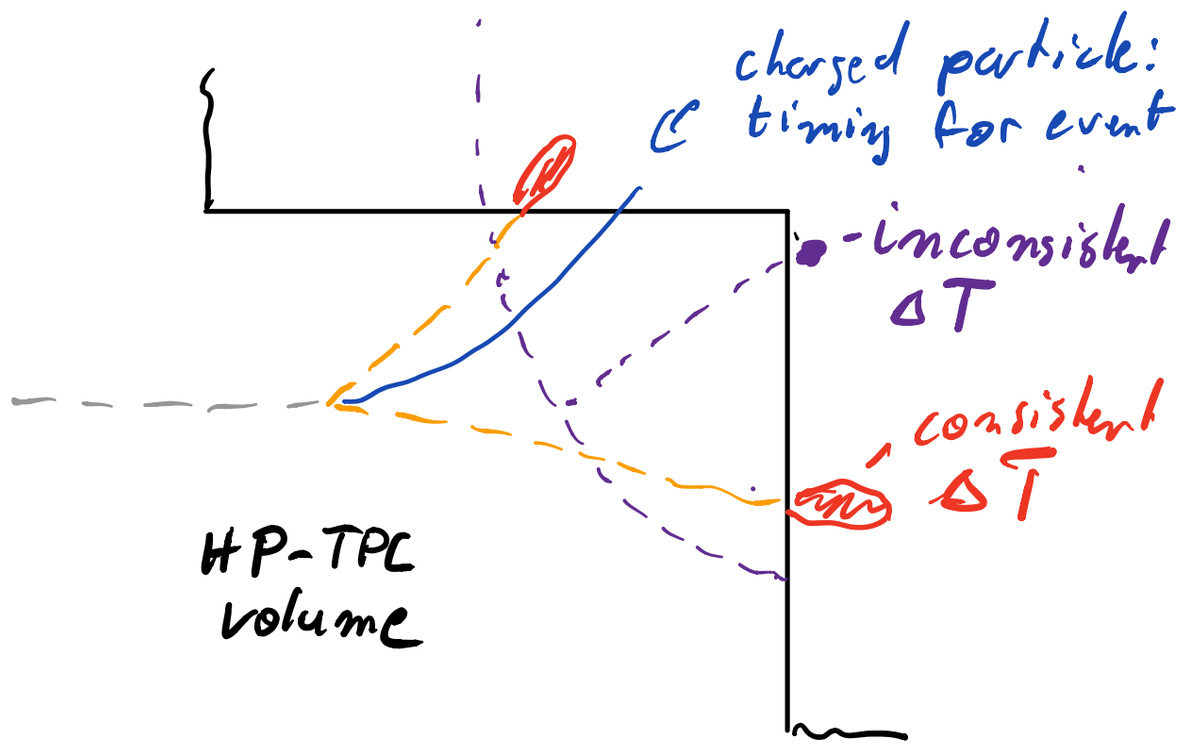
➪ Develop solutions to achieve high effective granularity with reduced channel count - may be a viable options in some areas of the detector

# Additional Possibilities: Timing

- In principle the technology considered supports sub-ns timing per cell (better for showers)
  - Obviously there is a cost and complexity impact on the front-end electronics…

Lets speculate a bit:

- We are lacking an absolute time reference, but relative timing could also be useful: measure relative distance of two photons from calorimeter to ~ 30 cm or better
  - ➪ Could be used to improve assignment of low-energy photons with very poor pointing accuracy to interactions and $\pi^0$ candidates



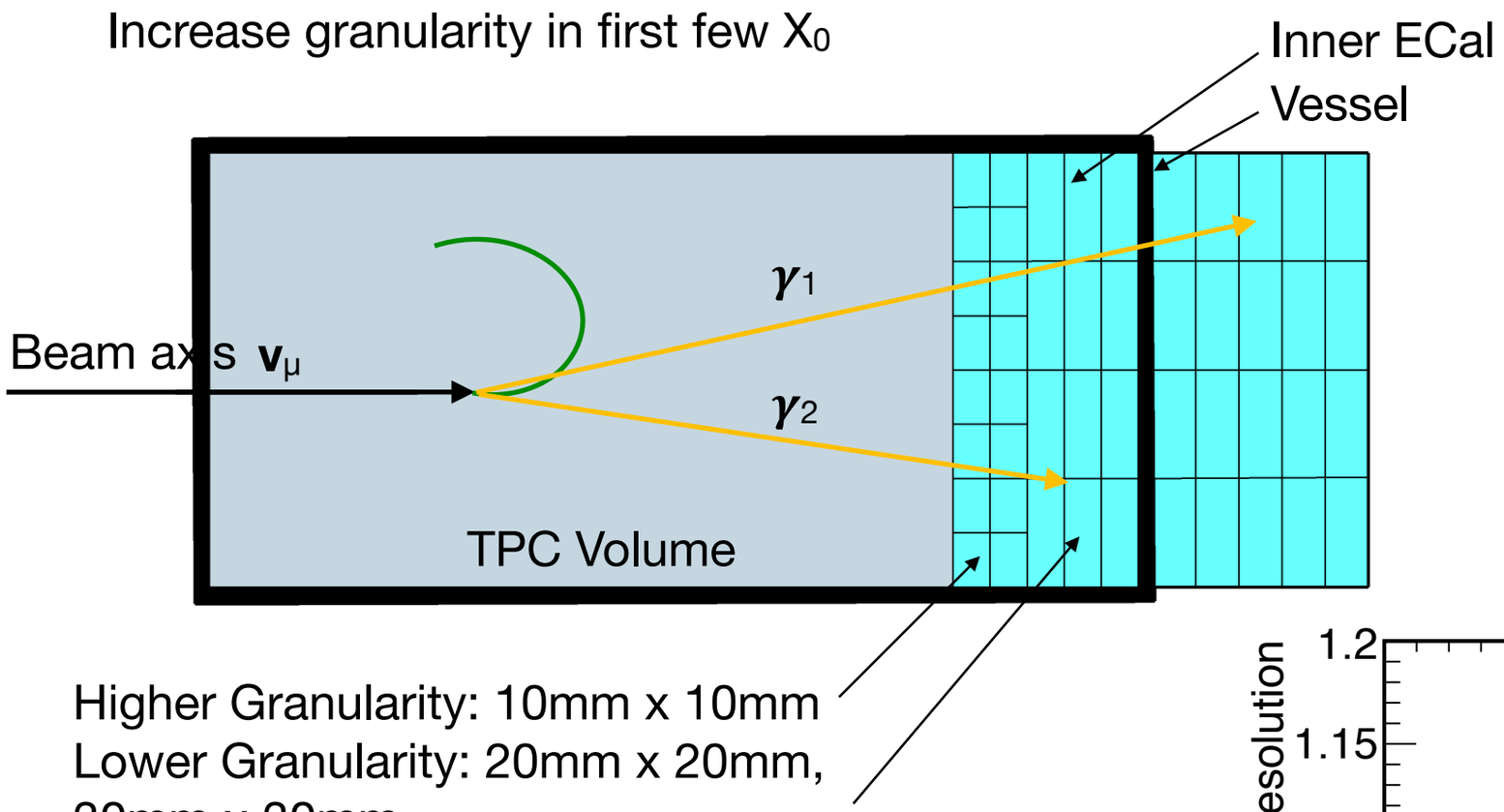
# Summary

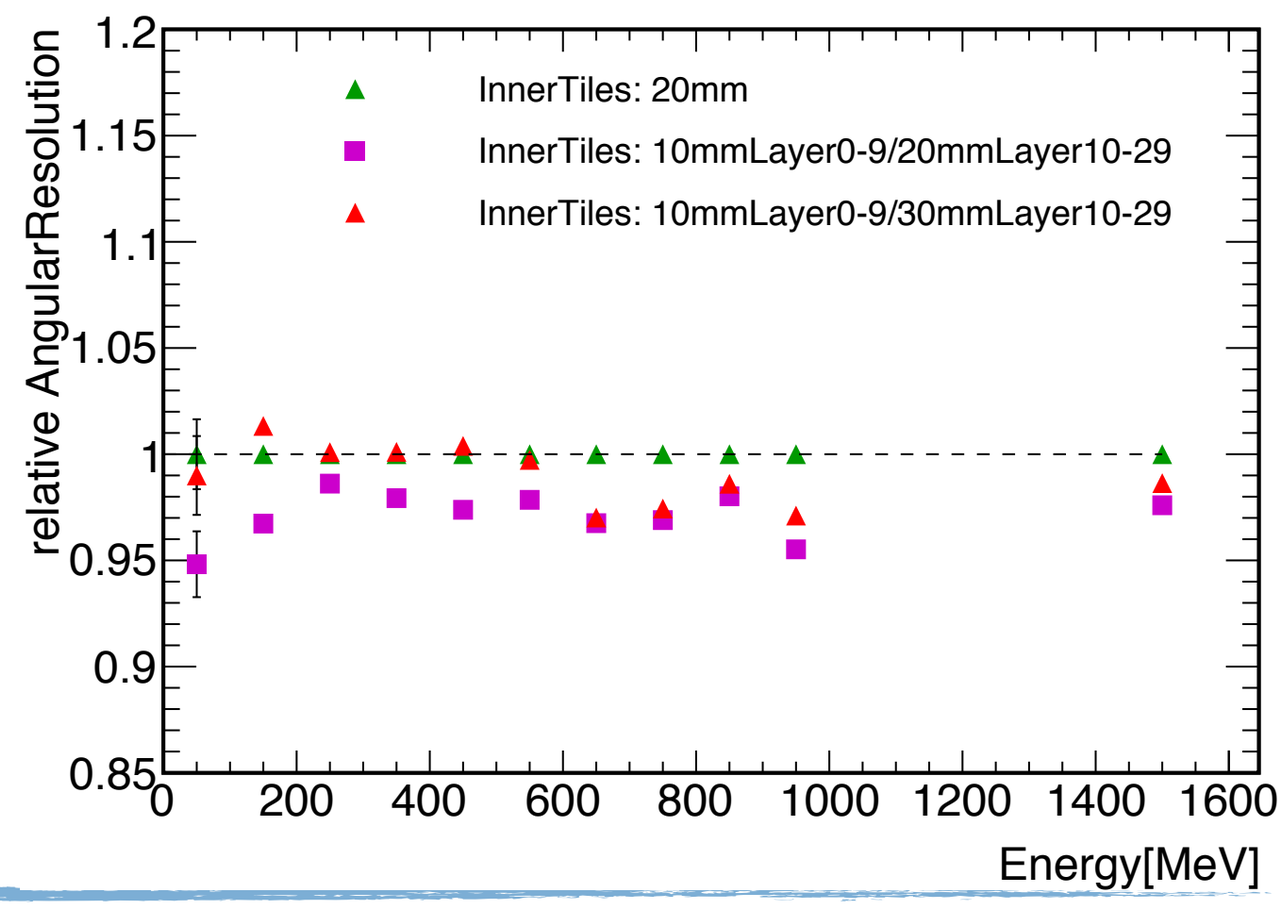
- The ECAL for a HP-TPC is an interesting challenge
  - High granularity may be crucial to achieve good photon pointing, and with this the capability to locate $\pi^0$s with few cm accuracy
- Constraints imposed by pressure vessel of HP TPC lead to a two-segment ECAL:
  - inner ECAL (~ $6X_0$) with high granularity to provide angular resolution
  - outer ECAL (~10 $X_0$) to achieve good energy resolution
- Simulation studies ongoing - observed trends:
  - Angular resolution improves with granularity up to a tile size of 1 x 1 $cm^2$ -
  - Energy resolution improves for thinner pressure vessel - substantial advantage for Titanium over stainless steel for energies of 1 GeV and higher
  - Using 2 mm Cu instead of 1 mm Pb per layer improves angular resolution
    - 30 x 30 $mm^2$ granularity with Cu absorbers slightly better angular resolution than 20 x 20 $mm^2$ with Pb absorbers

# Extras

# Granularity: Changes within Inner ECAL

Increase granularity in first few $X_0$



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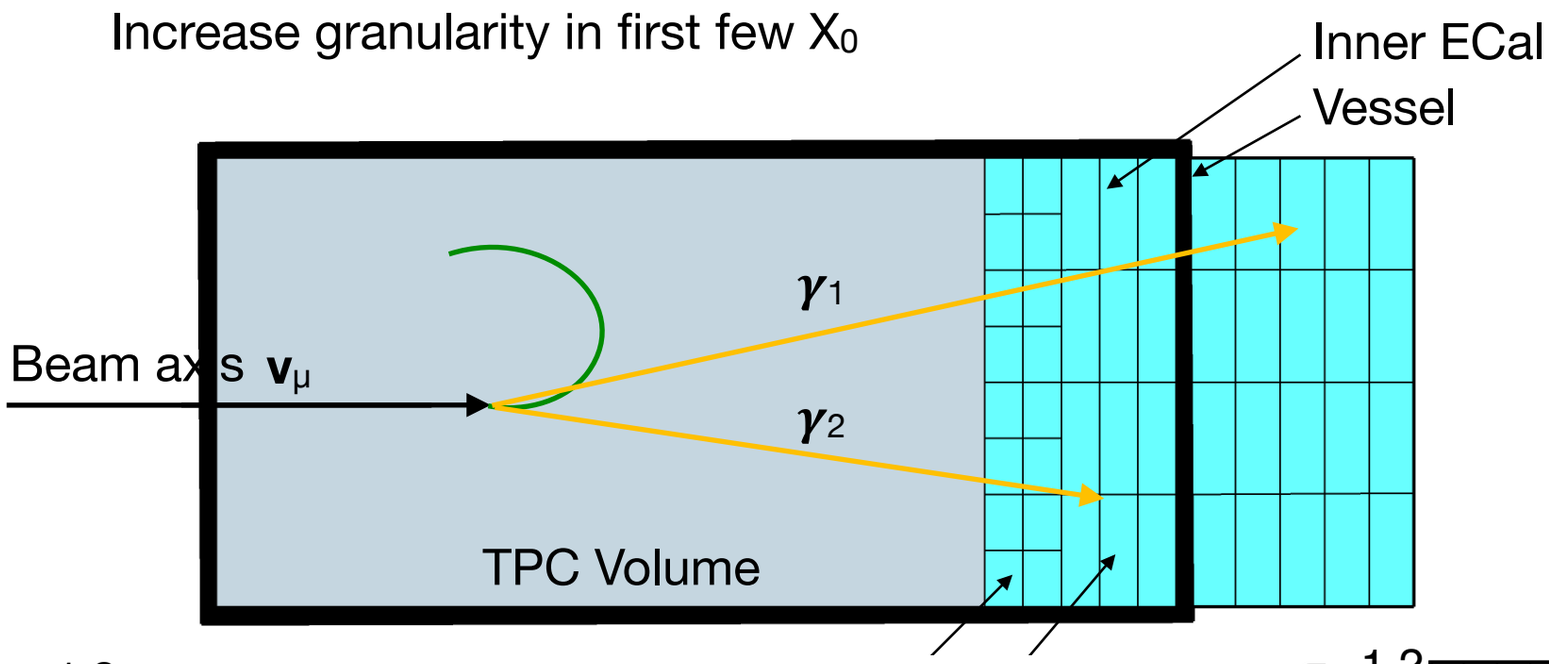
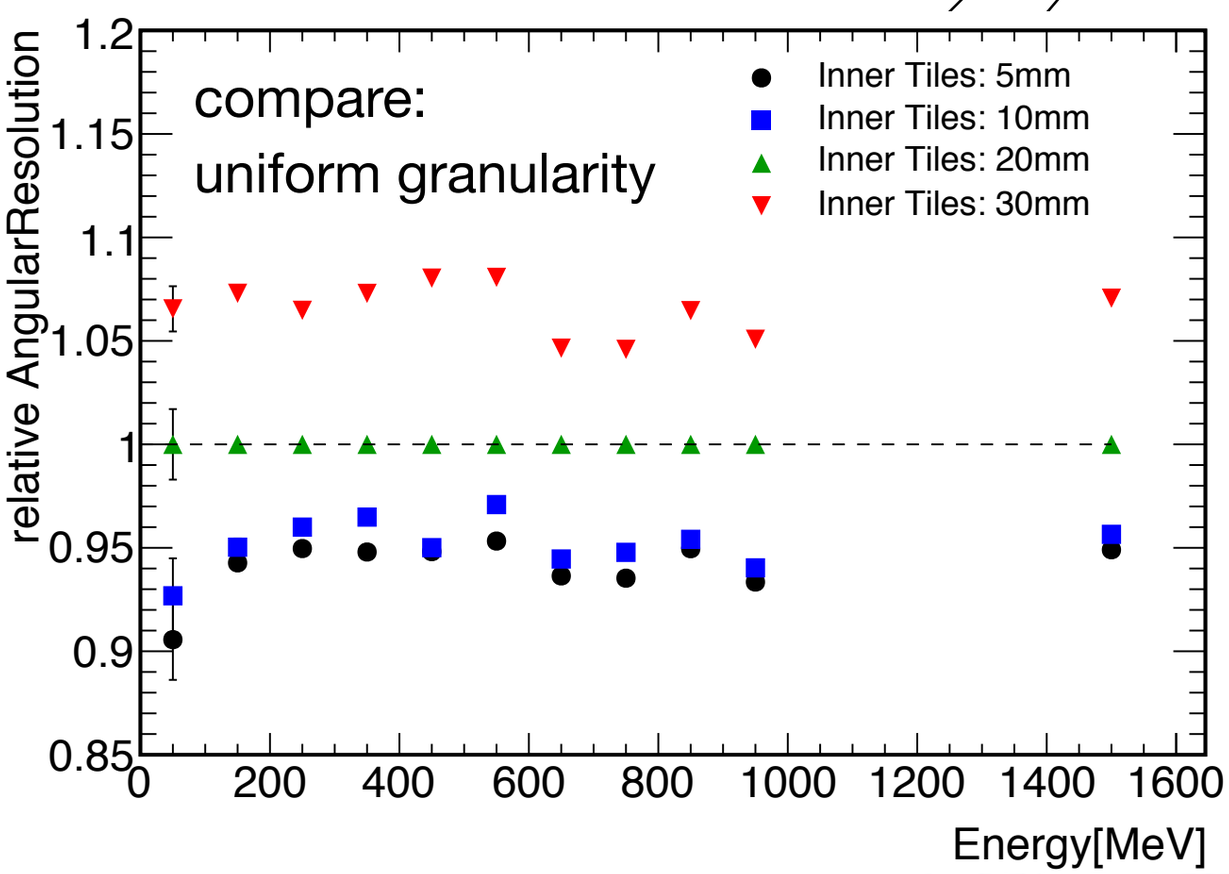
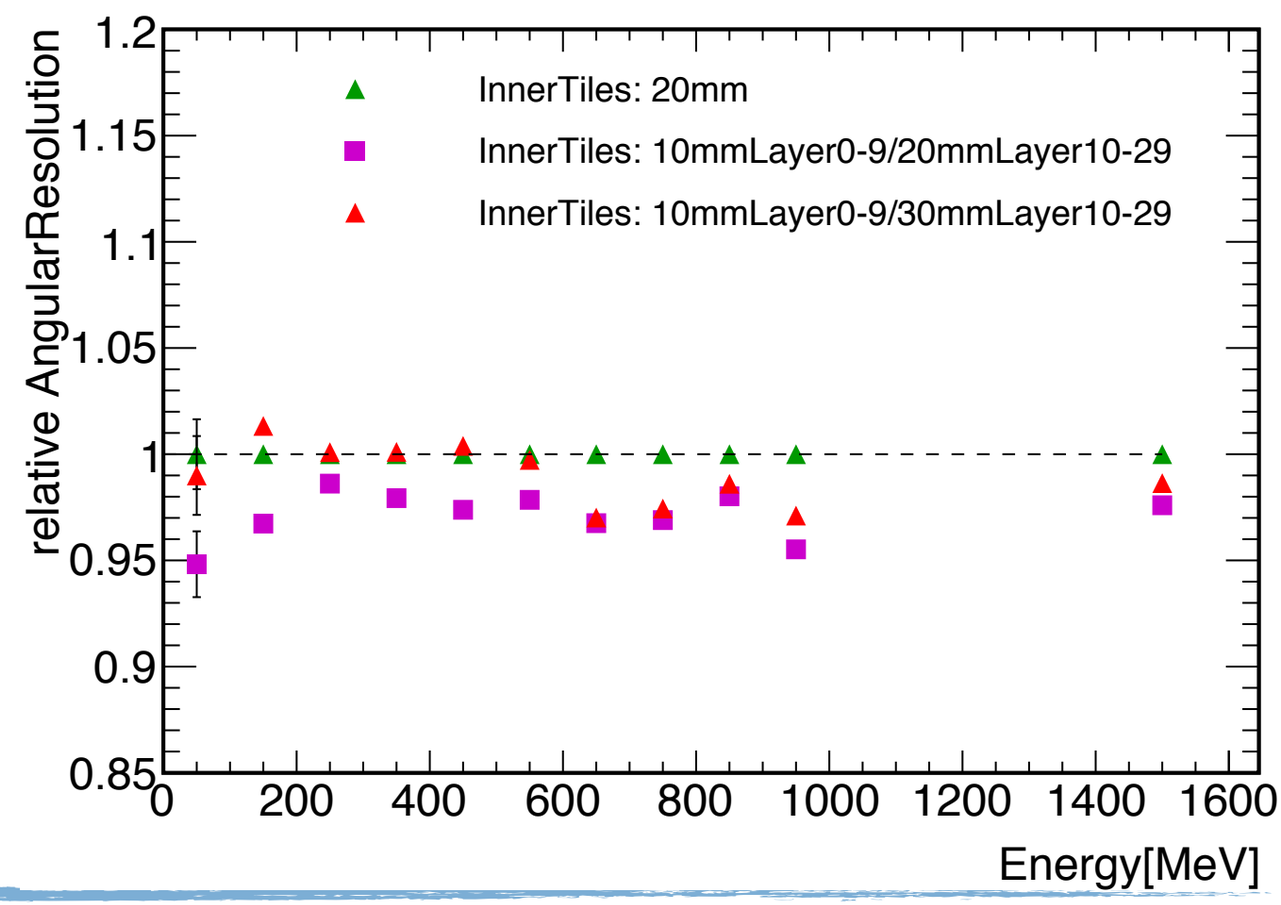
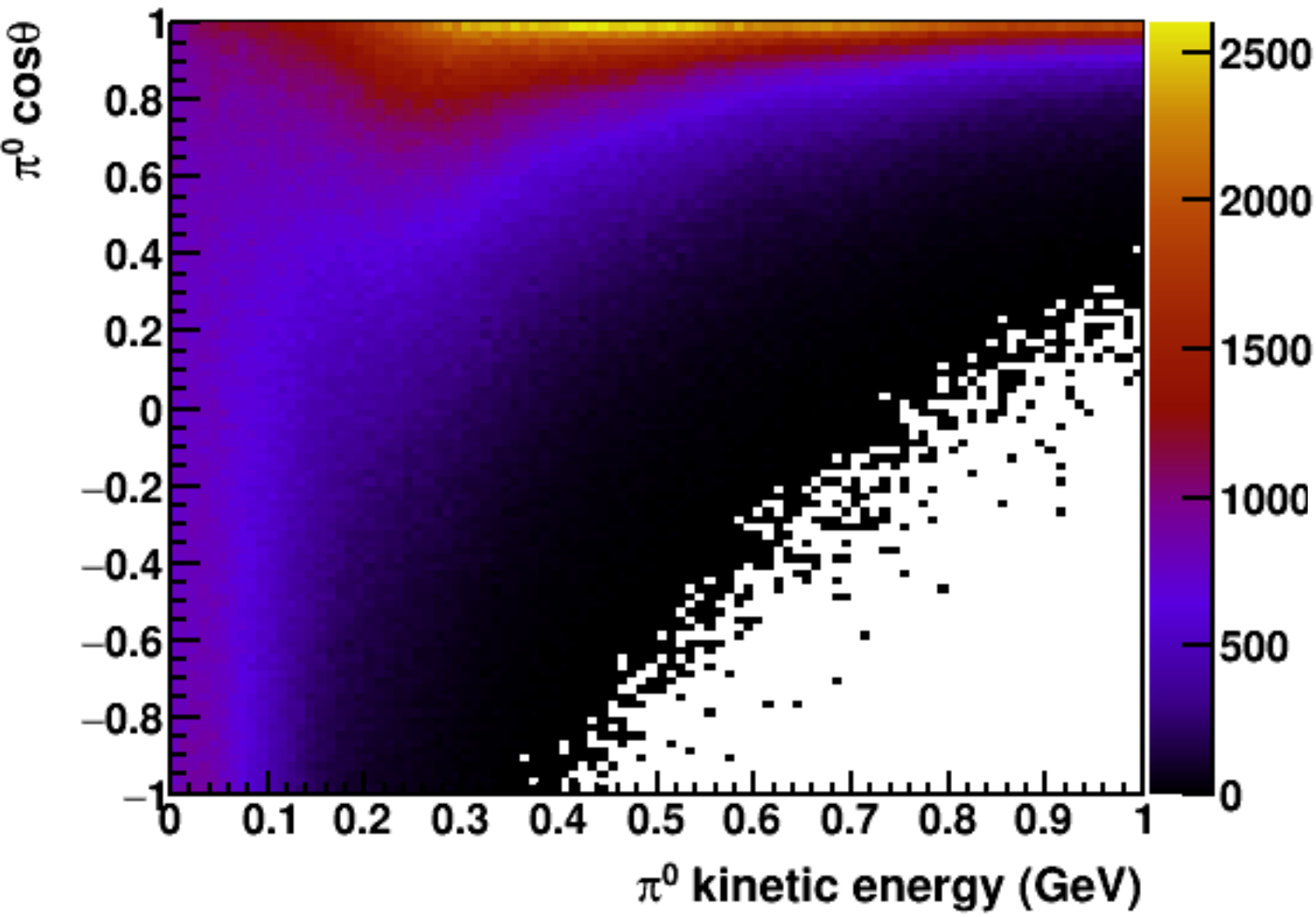


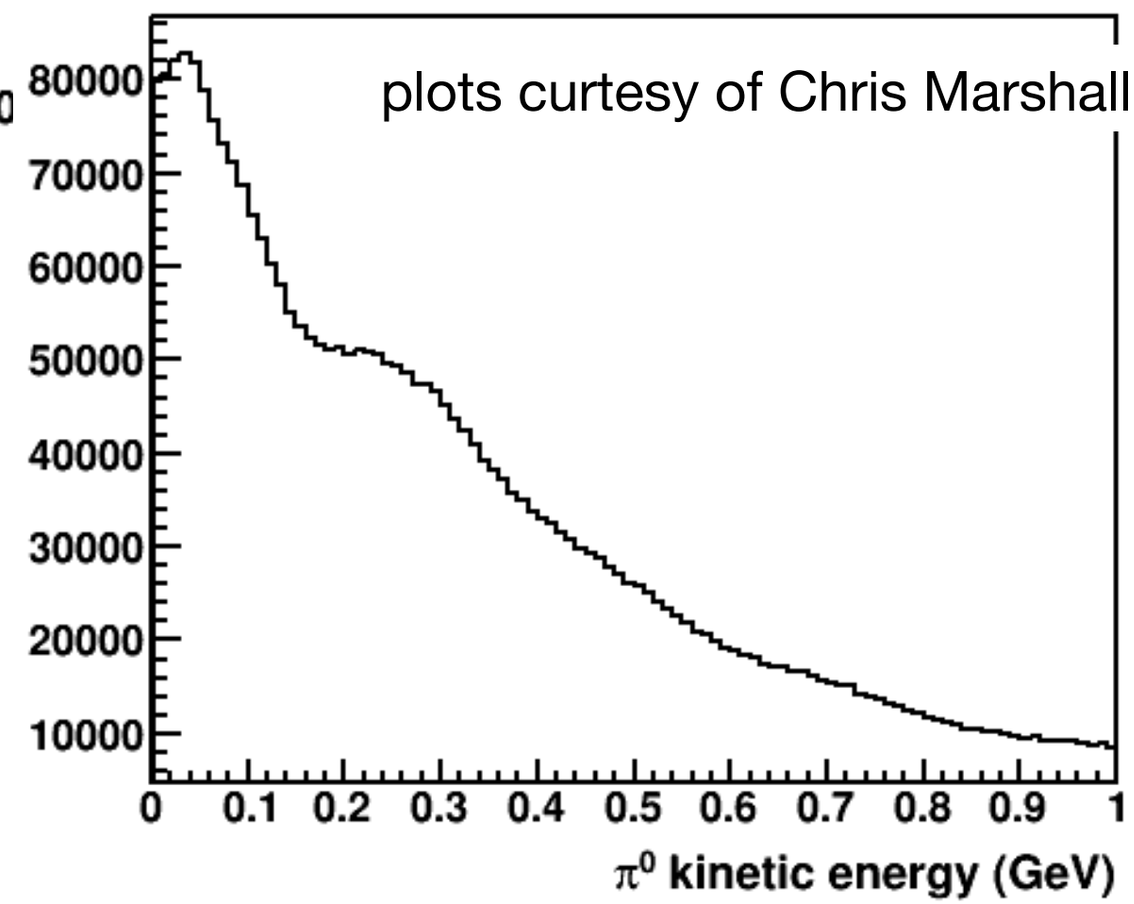



# The Particles we are after

- One of the primary goal of the ND ECAL is the measurement of neutral pions in ν interactions




- Typical $\pi^0$ energy low - most produced essentially at rest of from resonance decays with 200 - 300 MeV
  - ➪ Need to reconstruct few 100 MeV γ




NB: Also multi-GeV $\pi^0$s are relevant: Those can fake oscillation signals in the far detector