Applications of a Highly Granular Electromagnetic Calorimeter in the DUNE Experiment

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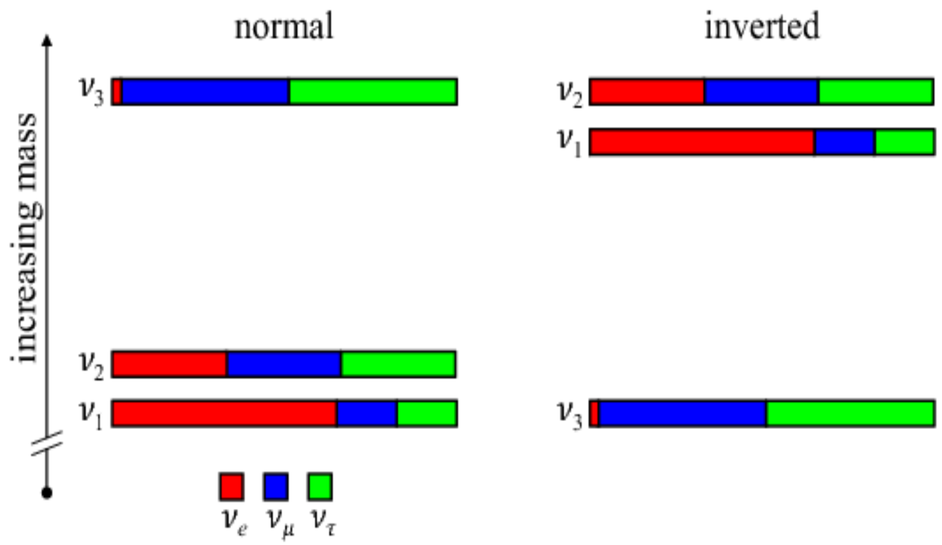
(Werner-Heisenberg-Institut)

Neutrino Oscillations

What do we know?



1. Neutrino flavour oscillation verified → Neutrinos are massive
2. Flavour eigenstates are a superposition of the mass eigenstates (predicted in 1957)
3. $m_2 > m_1$
4. All mixing angles are > 0

Neutrino Oscillations

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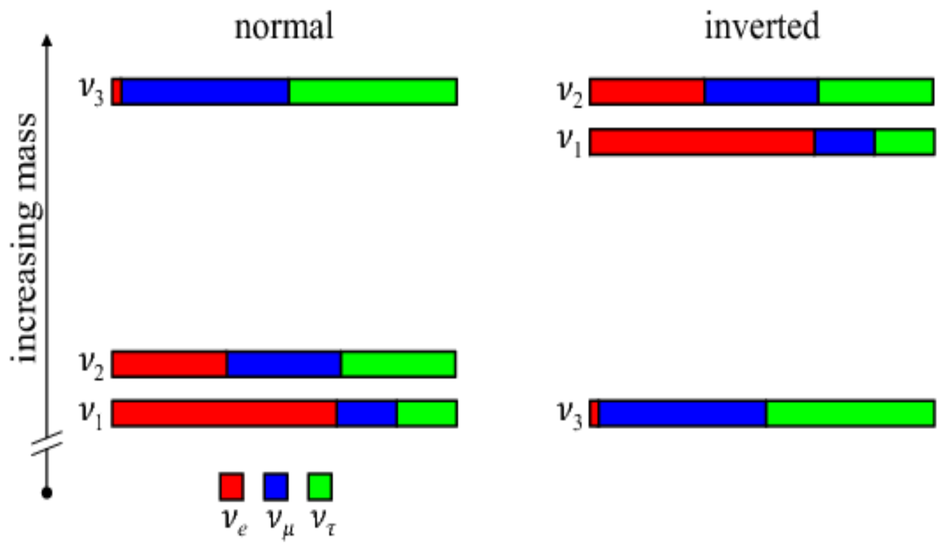

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4. All mixing angles are > 0

What we don't know:

1. Is $m_3 > m_1, m_2$ or $m_3 < m_1, m_2$?
2. Is CP violation also manifested in neutrino oscillations with θ_{13} being > 0? (T2K δ_{CP} best fit: ~ -1.7)

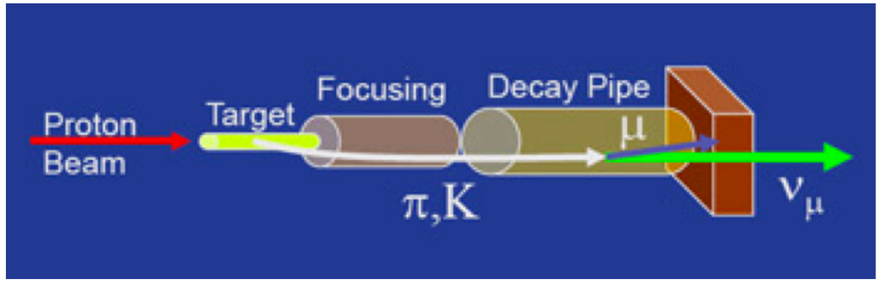
PMNS Matrix

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & \underline{s_{13}e^{-i\delta}} \\ -s_{12}c_{23} - c_{12}s_{23}\underline{s_{13}e^{i\delta}} & c_{12}c_{23} - s_{12}s_{23}\underline{s_{13}e^{i\delta}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}\underline{s_{13}e^{i\delta}} & -c_{12}s_{23} - s_{12}c_{23}\underline{s_{13}e^{i\delta}} & c_{23}c_{13} \end{pmatrix}$$

These questions are addressed by long baseline neutrino experiments

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



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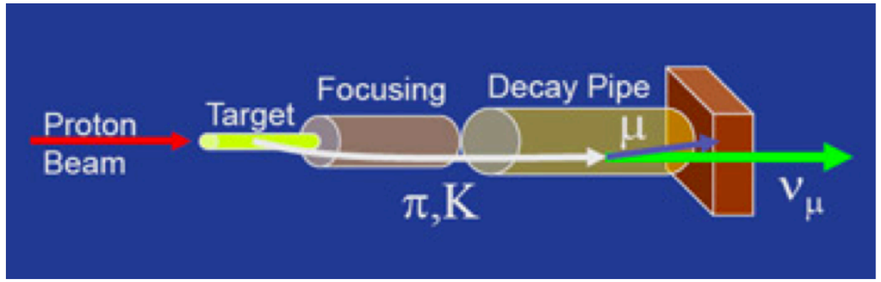
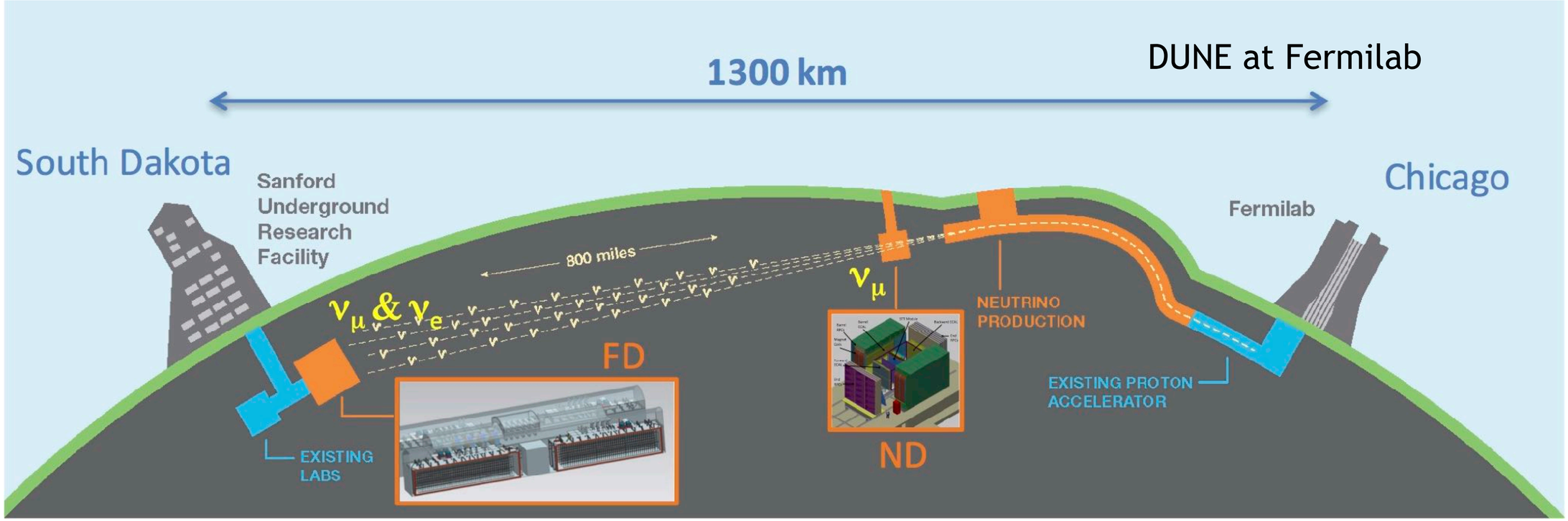


- It measures the ν_e appearance and ν_μ disappearance in the oscillated ν_μ beam
  - To determine the neutrino mass hierarchy
    - Effects of CP violation and neutrino mass hierarchy on the oscillation probability disentangle for long baselines
  - To search for CP-violation in differences of the ν_e/anti-ν_e appearance
    - $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if CP is conserved

DUNE Experiment

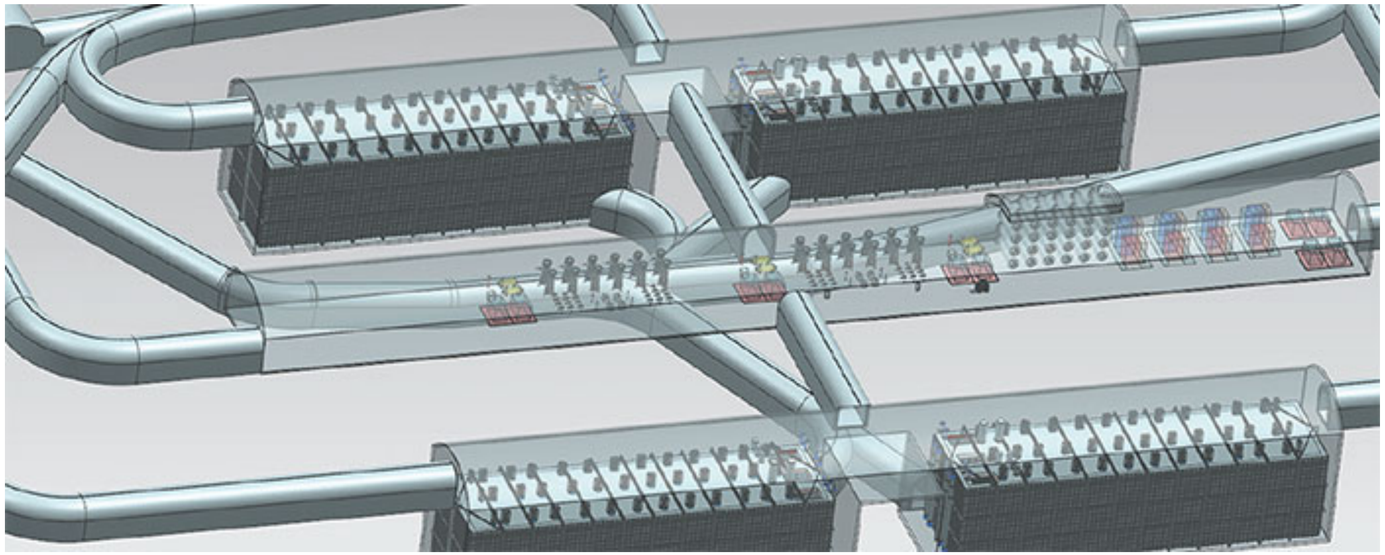
- The Long Baseline Neutrino Facility at Fermilab generates a high intensity, broadband ν_μ/anti-ν_μ beam within an energy range of 0.5 to 5 GeV



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

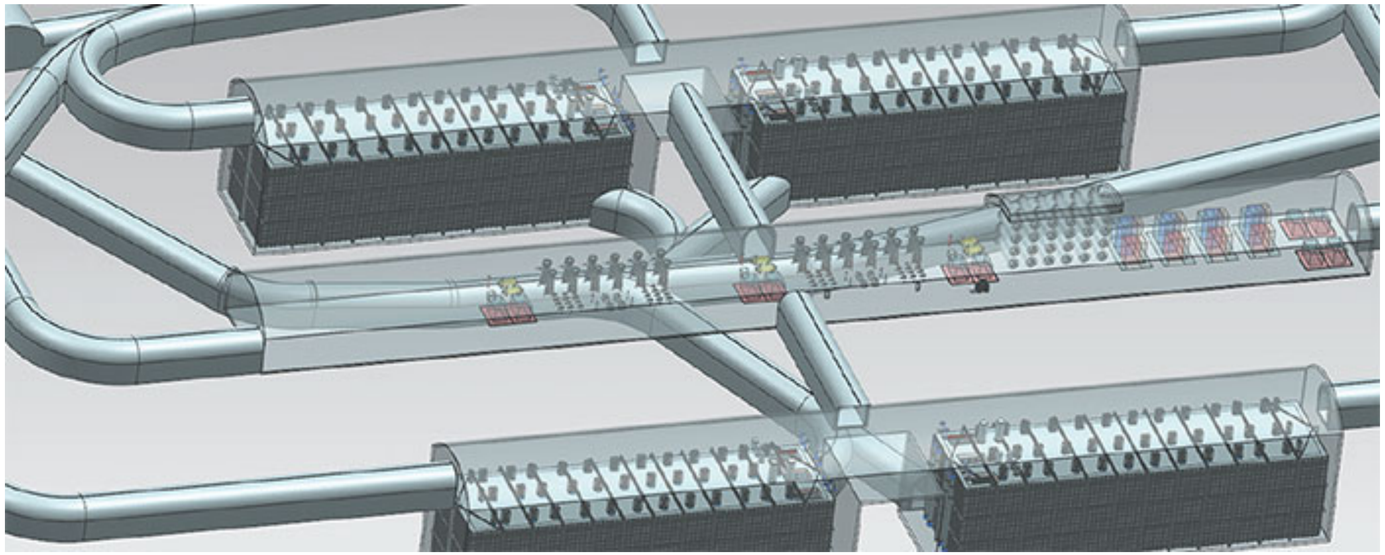
Near Detector: Measures beam before oscillation, required to understand initial flux and cross sections to understand FD signal

DUNE Far Detector



- ~1 mile underground
- 4 liquid argon TPCs with 10kt fiducial volume each
- High resolution 3D image of neutrino interactions to achieve good particle separation
- Current status: prototypes at CERN

DUNE Far Detector



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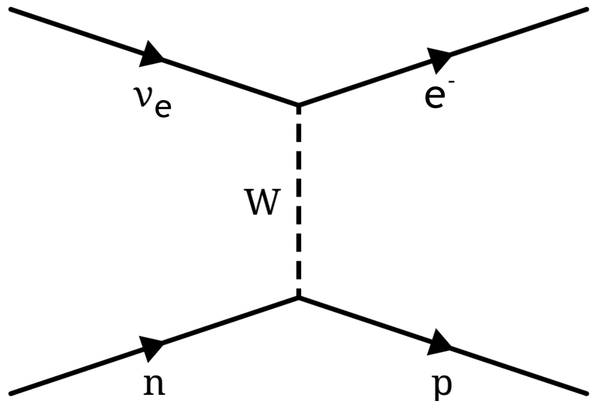
Main physics programme:
- Measure ν_e/anti-ν_e appearance via CC neutrino-nucleon interactions
  ➡Needs precise rate measurement from <u>near detector</u>

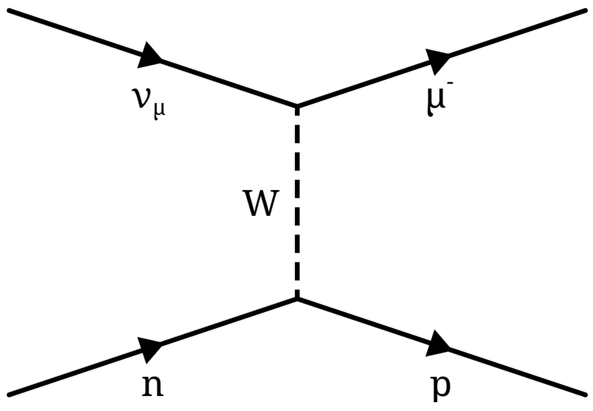


Ancillary programme:
- Search for proton decay: e.g. $P \rightarrow K^+\bar{\nu}$
- Detect neutrinos from e.g. core collapse supernova
- Additional…

DUNE Near Detector Tasks

- Measure the energy spectrum of the beam, background rates and contamination
  - Provide a precise extrapolation of event rates in the far detector
- Two different measurements:

Beam energy spectrum



CC inelastic scattering

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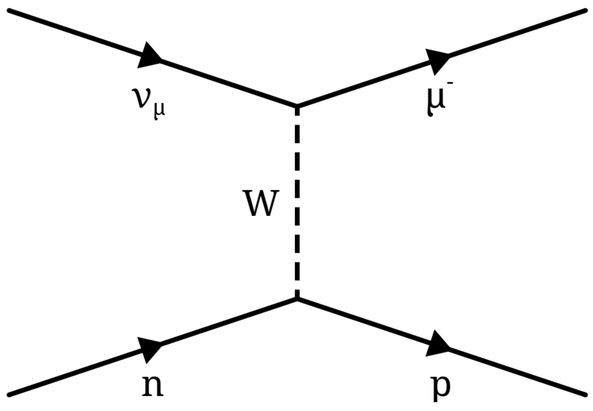
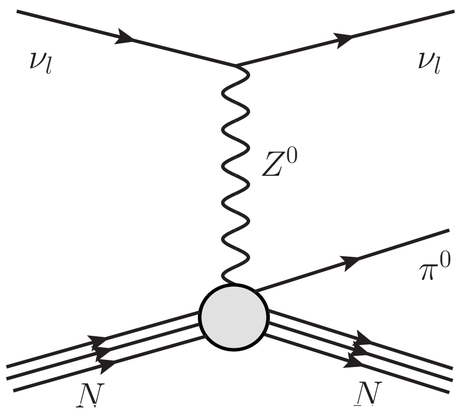
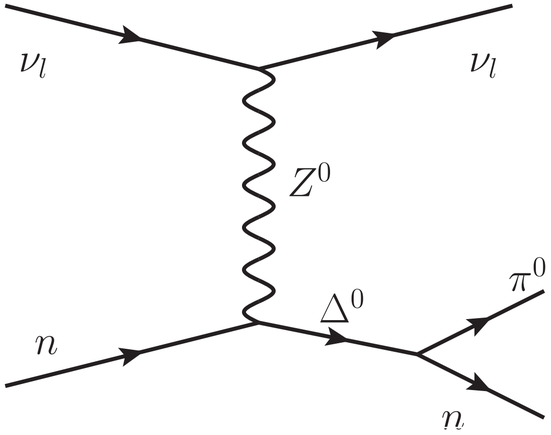


CC inelastic scattering

Cross sections



Coherent NC π^0 production

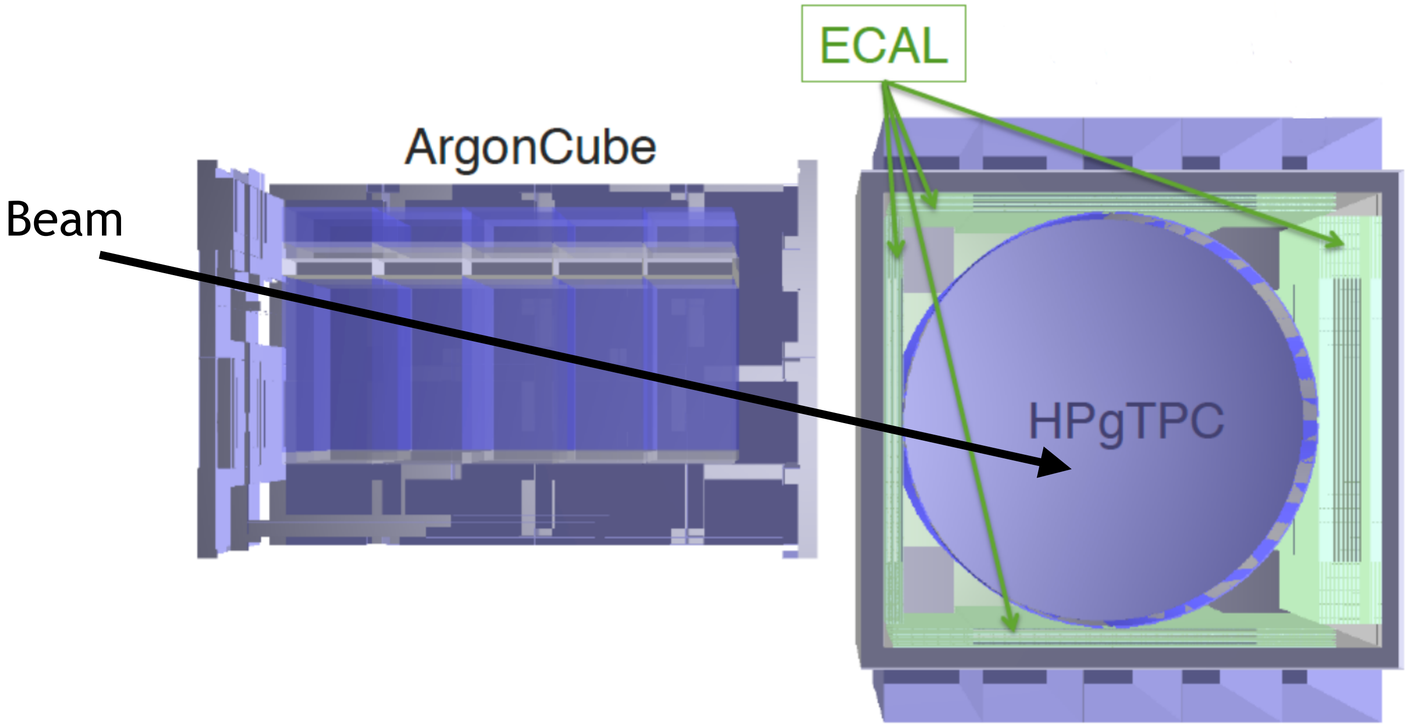


Resonant NC π^0 production

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

DUNE Near Detector

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



- ArgonCube mainly used to measure the energy spectrum of the beam
  →higher interaction rates because of higher argon density
- High pressure TPC also used to measure cross sections of rare interactions
  →lower detection threshold than liquid argon

Additional physics programme: Sterile neutrinos, structure of nucleons

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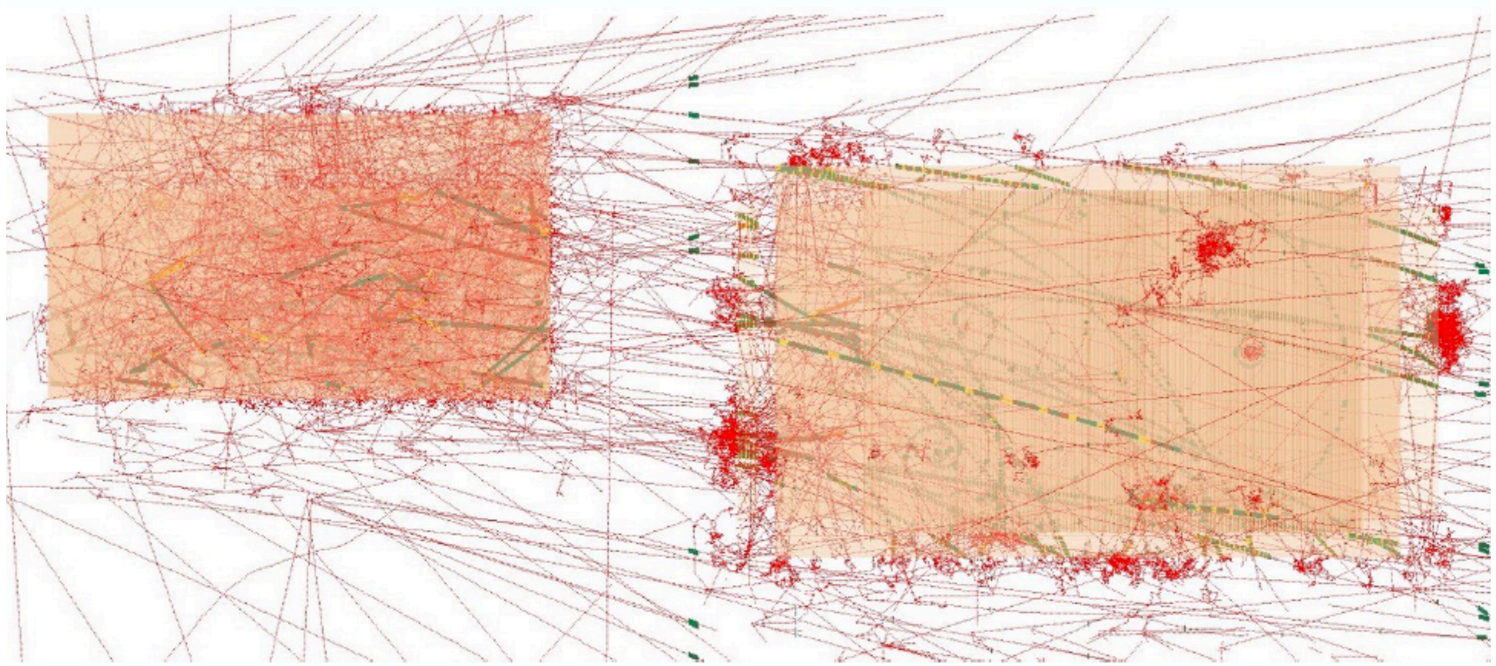

- Duration of one neutrino spill ~10μs

  →Pileup in slow detectors due to high beam intensity

- Many interactions inside ECal
- Majority of interactions in structures of surrounding hall (not shown)

  →Background source

  →No defined IP like in collider experiments

High timing resolution of the ECal is beneficial for disentangling the TPC image

→TPC has low efficiency for neutral particles (neutrons, photons,…)

ECal hits associated to TPC activity can provide T0 time for events

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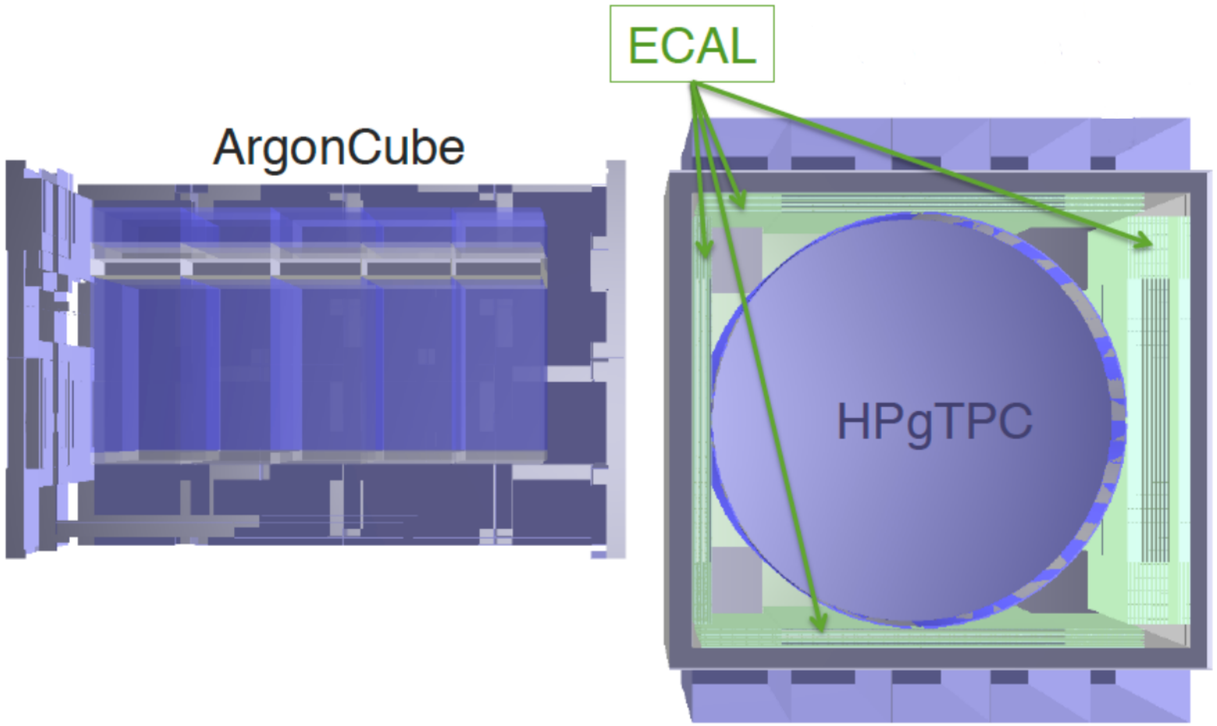

- Conversion probability for photons too low in TPC

  →tracker based π^0 reconstruction not possible

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

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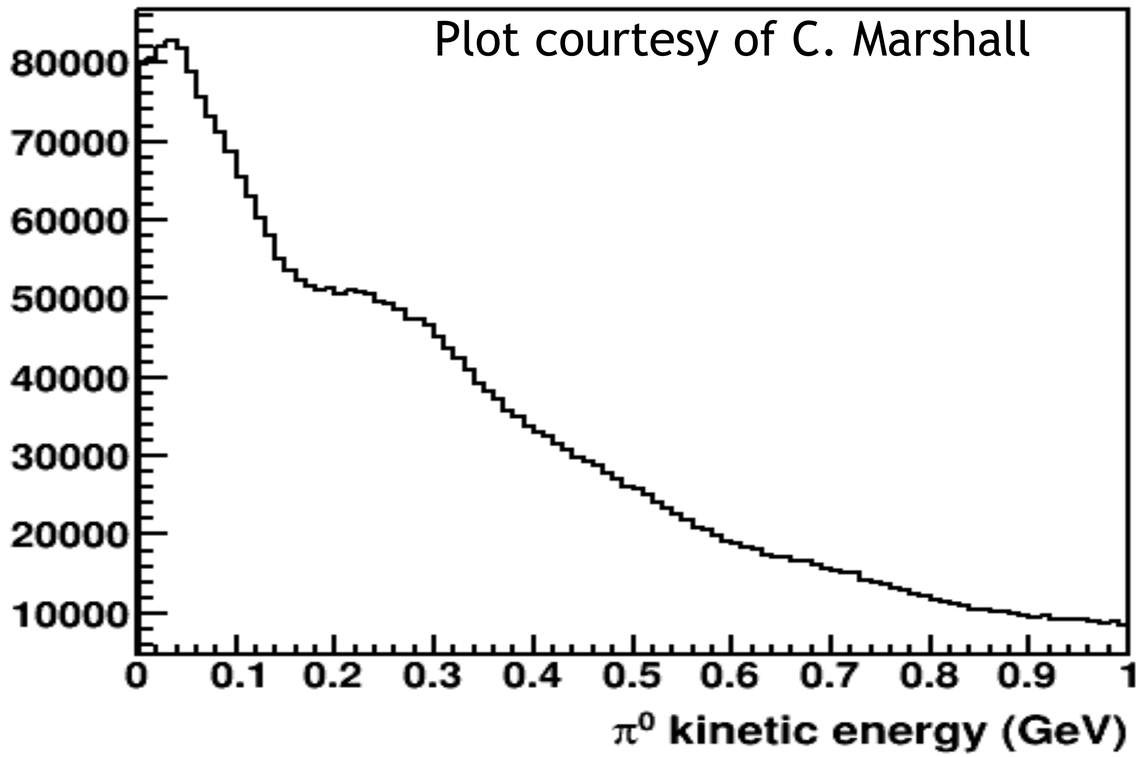

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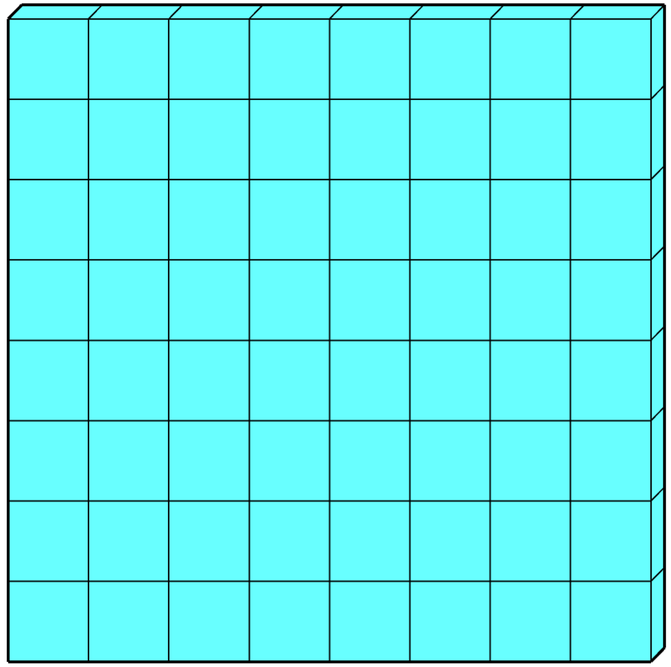
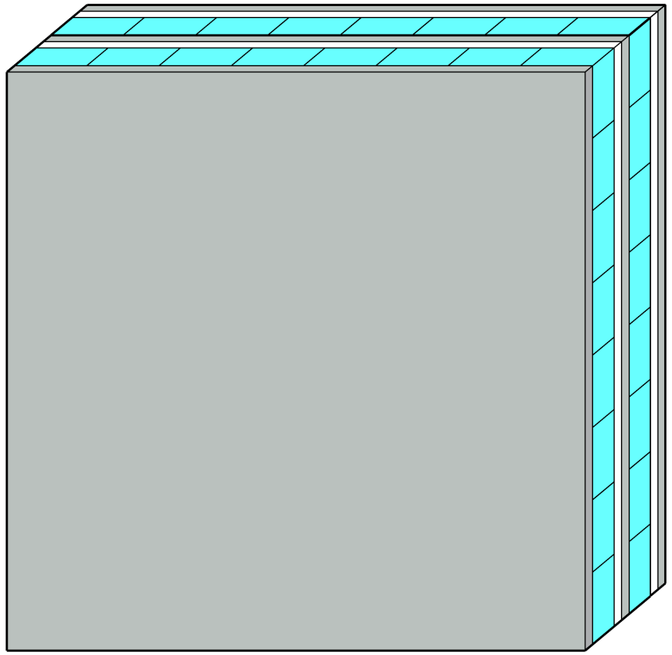
<u>Challenge</u>: Typical π^0 energies ~50 to ~400MeV → Photon energies often <50MeV
Noisy detector environment → problematic for slow detectors like TPCs

Detector Simulation



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

Detector Simulation



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

Default layer structure:

- 2mm copper absorber
- 5mm plastic scintillator
- Gap for electronics

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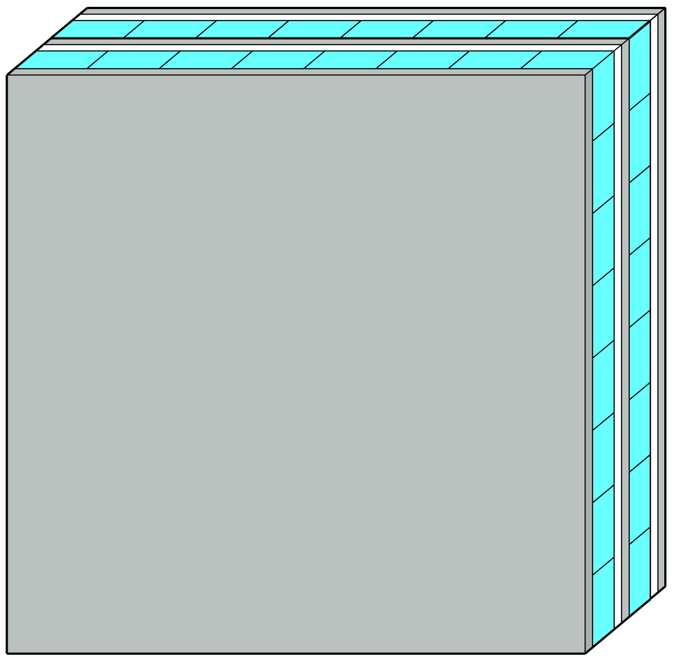

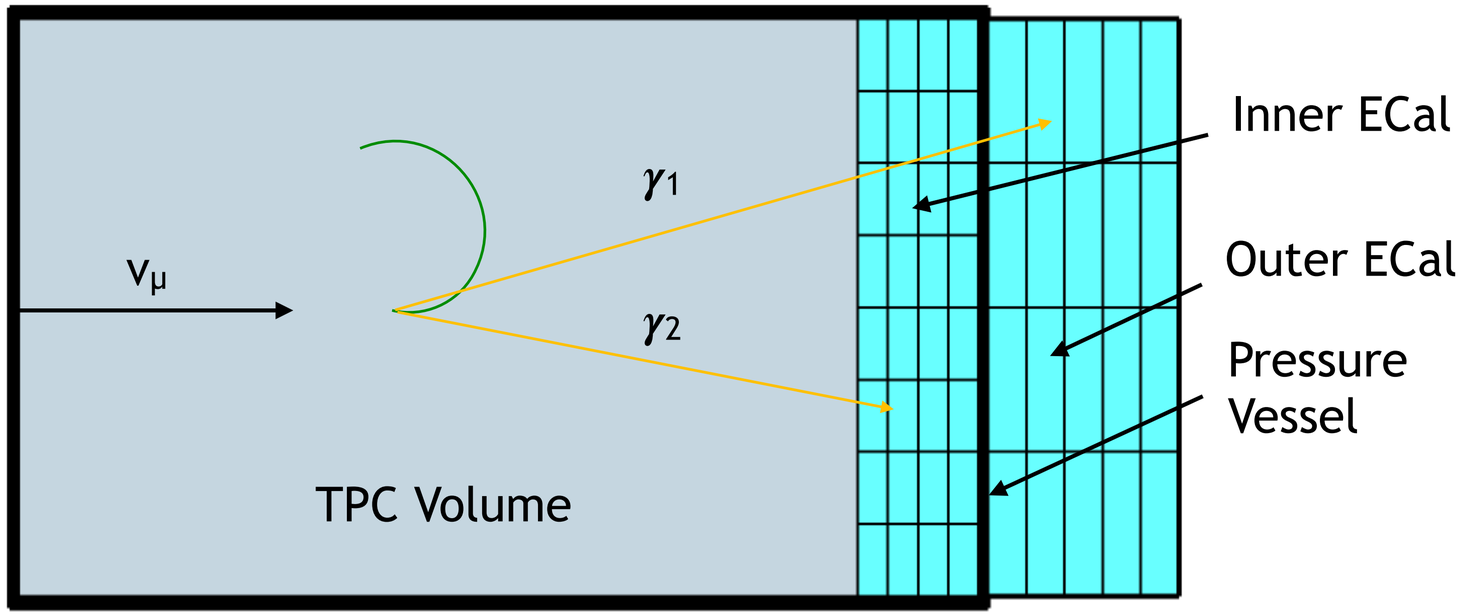

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Look at the scenario of incorporating (parts of) the ECal inside the TPC vessel

Inner ECal increases the chance to detect low energy photons

Goal of the Study

1. Proof of principle:
   - Is such a calorimeter capable of fulfilling the introduced tasks ?

2. Dependency on the detector configuration:
   - What are the performance driving parameters ?
   - ▸ Obtain plausible results to evaluate the impact of the detector configuration on the detectors performance

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<u>Studied scenarios:</u>

- Scaling of the single photon <u>energy and angular resolution</u> with
  1. the presence of a pressure vessel
  2. the granularity in inner and outer part of the calorimeter
  3. <u>the absorber material and thickness</u>

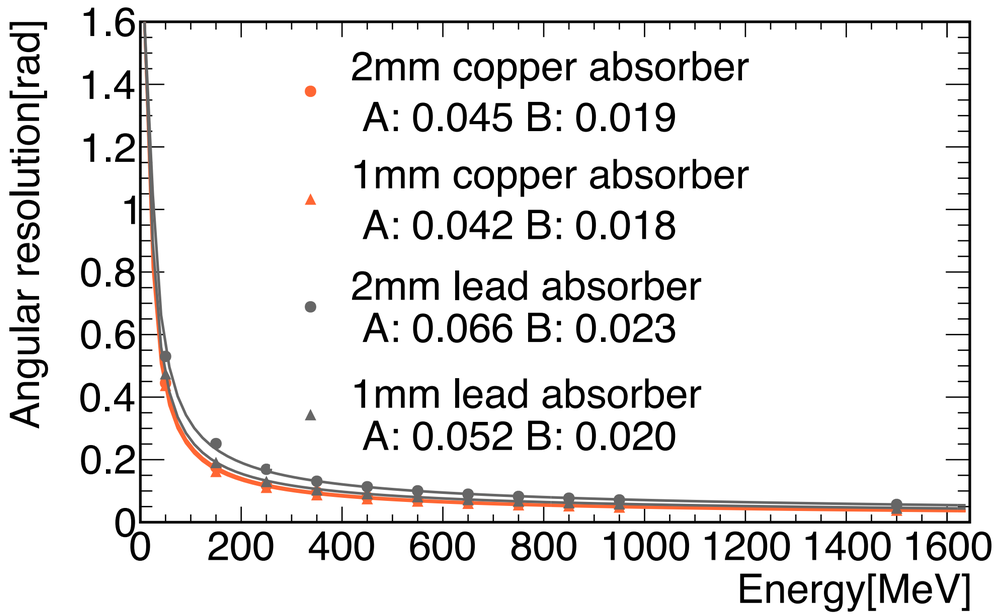
- <u>Precision of the vertex reconstruction of π^0 decays</u>

- Performance of identification and energy reconstruction of neutrons

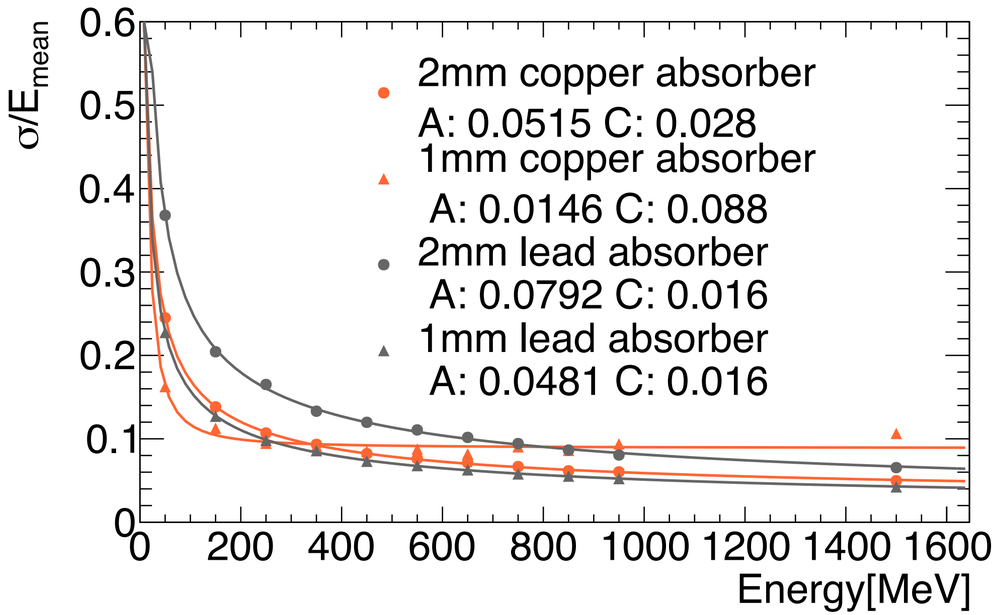
Influence of the Absorber

Granularity: 20mm, ECal inside TPC

Angular resolution



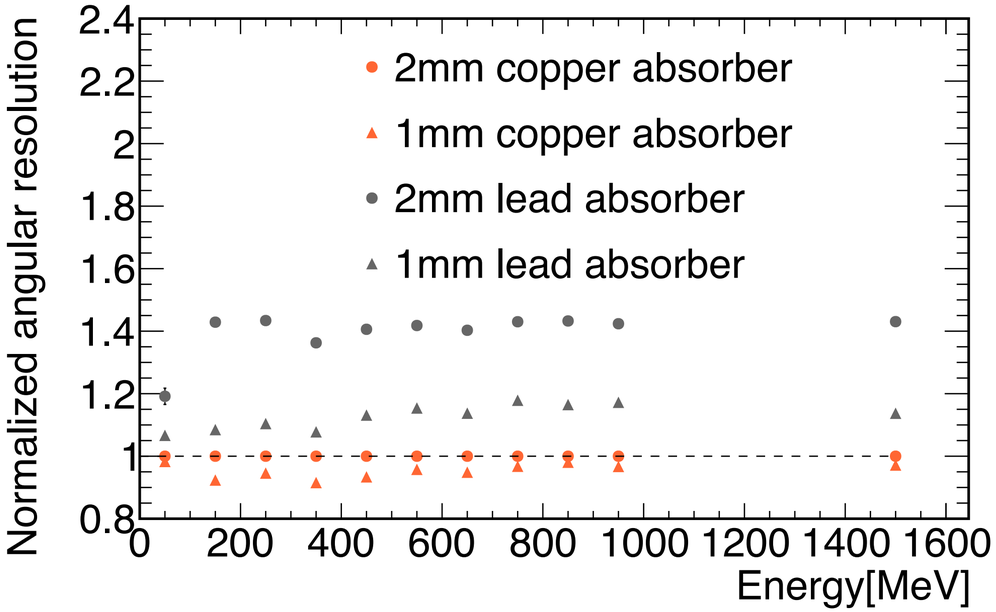
Energy resolution



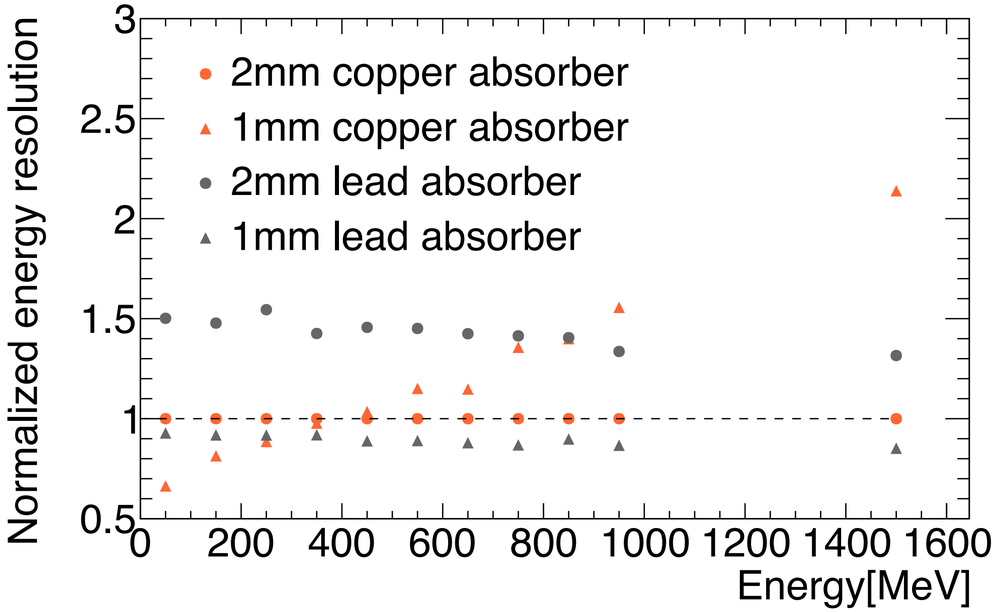
Influence of the Absorber

Granularity: 20mm, ECal inside TPC

Normalized angular resolution



Normalized energy resolution



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

Overview

	Angular Resolution	Energy Resolution
No vessel	Default	Default
Copper absorber	Default	Default
Titanium vessel	→	↘
Steel vessel	→	↘
Lead absorber	↘	↗
Higher granularity in inner calorimeter	↗	→
Higher granularity in outer calorimeter	→	→

→ Negative

→ Positive

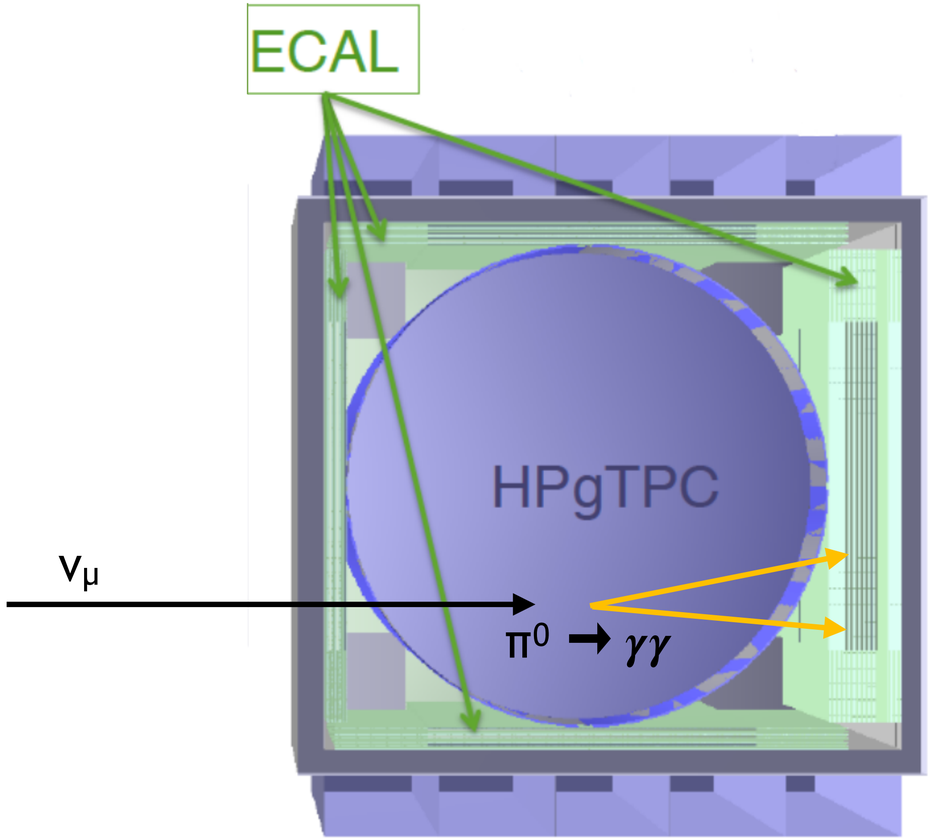
→ Neutral

Pitch: severity of effect

Default: Used for the reconstruction of neutral Pions

Pion Reconstruction

Detect pions with 6 calorimeter segments enclosing a 3x3x3m^3 volume



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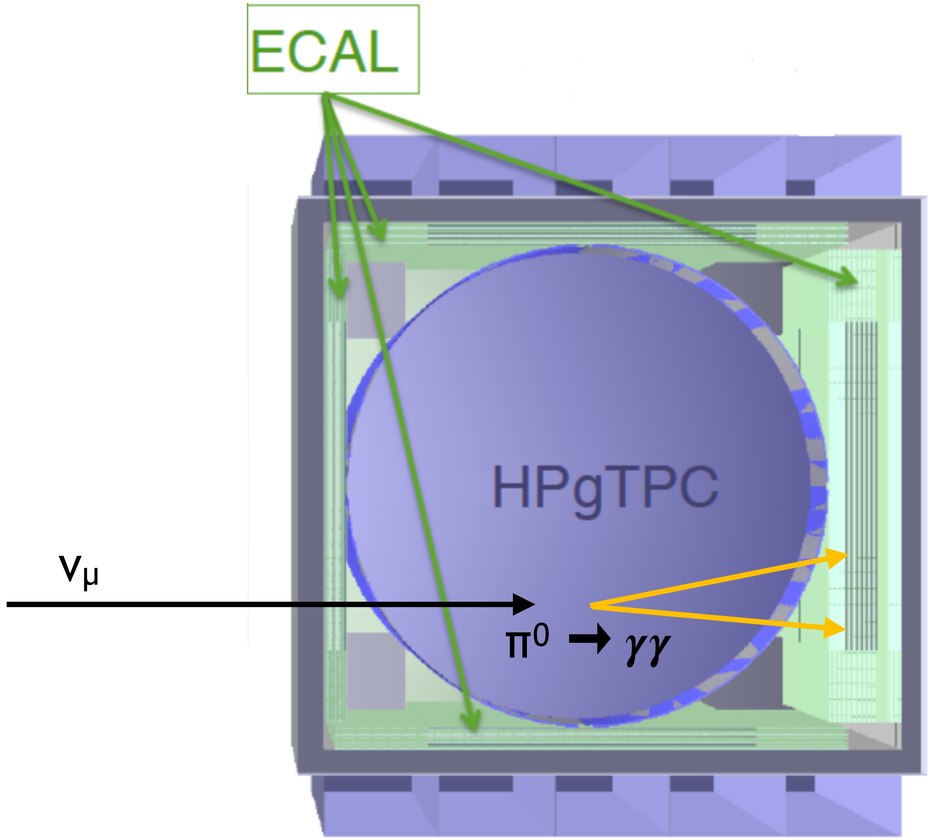
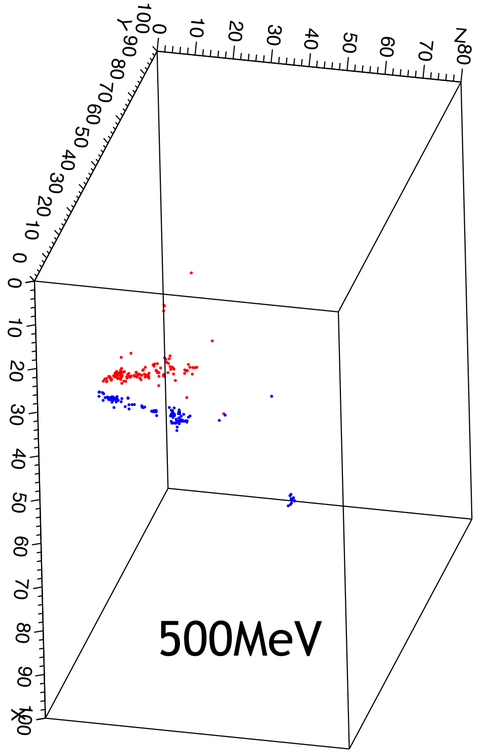


Event display



- Distinguish photon1 from photon2 by MC truth
- Reconstruct the directions of both photons separately

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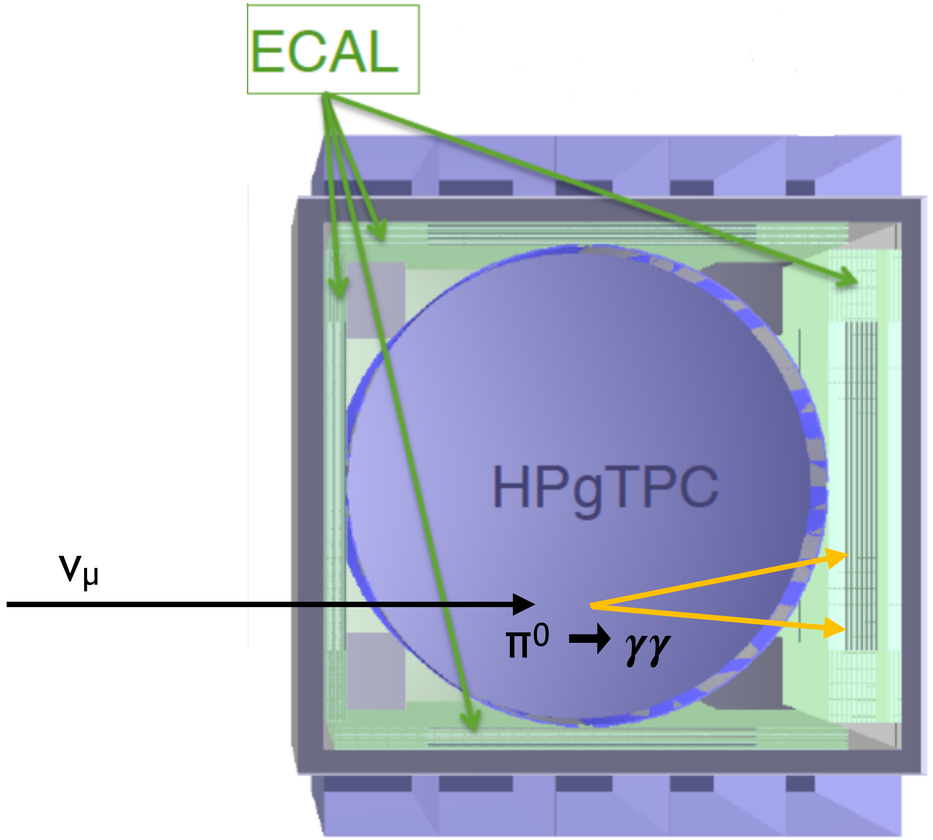

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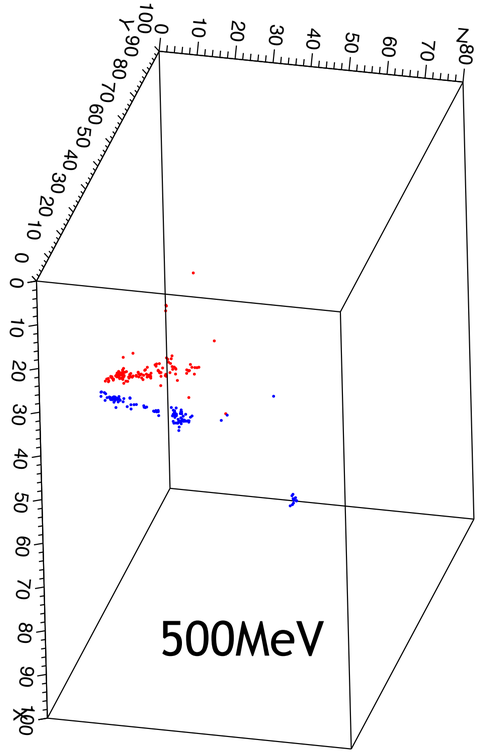

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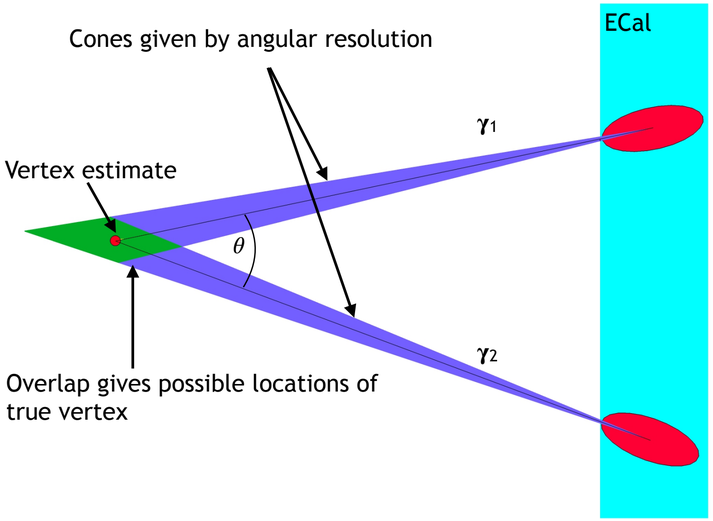
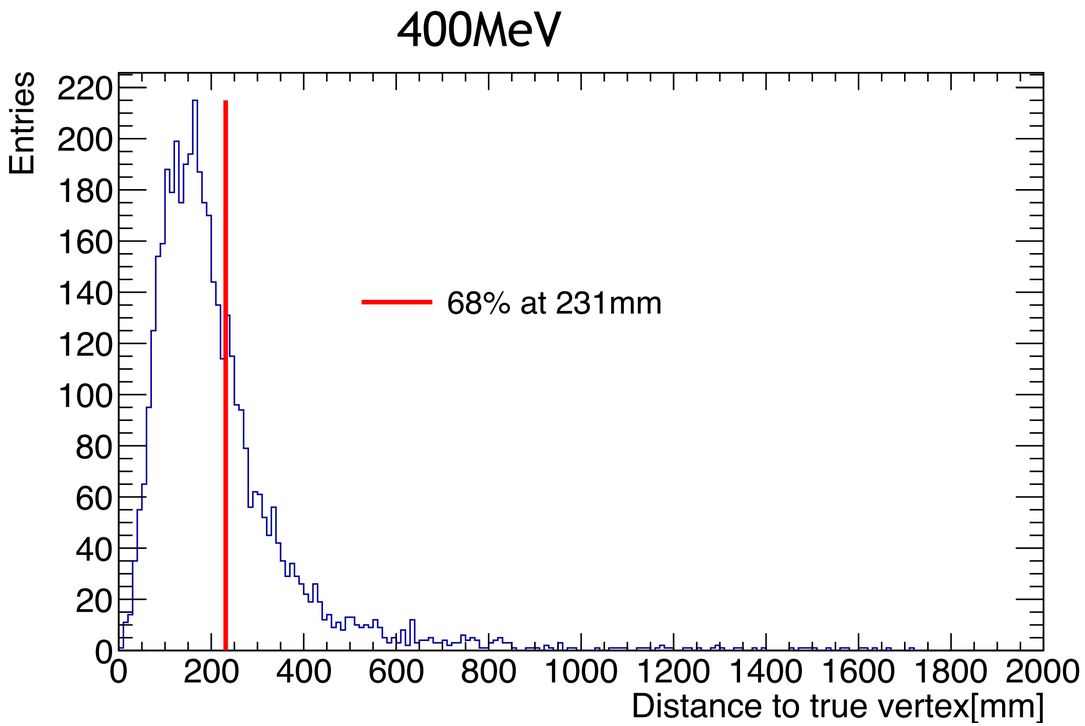


- Take point of closest approach of the reconstructed directions as an estimate of the decay vertex → Improve with χ^2-minimization

Pion Reconstruction

Pions decay in the center of the TPC volume
➡ Distance to forward calorimeter: 1.5m

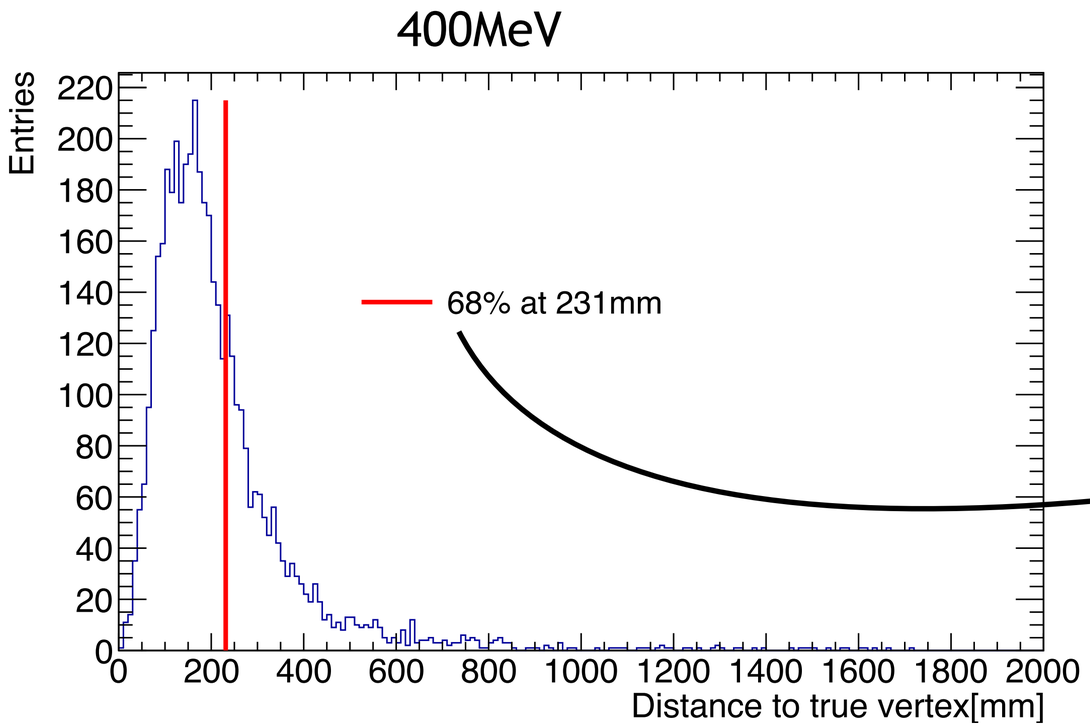


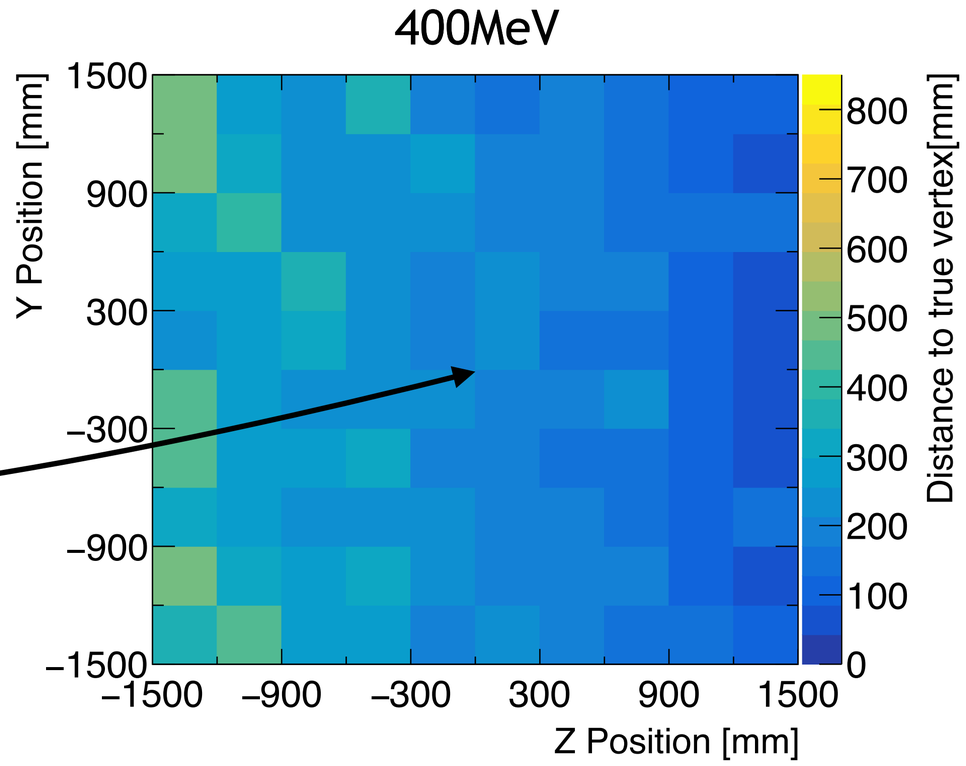
Pion Reconstruction

Pions decay in the center of the TPC volume
➡ Distance to forward calorimeter: 1.5m

Divide cross section plane (0,Y,Z) of the TPC in 30x30cm² pixel

Simulate 5000 Pion events with momentum along (0,0,Z) in the center of each pixel





Summary and Outlook

Implemented simulation study is capable of

- determining the scaling of the performance with different configurations (Absorber, Granularity, …)
- proving the concept of a calorimeter aided π^0 reconstruction

Reconstruction of π^0:

- Developed a technique to reconstruct vertex
- Vertex reconstruction within 20cm to 40cm at higher energies
- Reconstruction of the invariant mass is possible with π^0 at rest

Next Steps:

- Implementation of a full detector simulation including TPC
- Optimization of the channel count (~1.000.000) to reduce the cost and develop a concrete design

Backup

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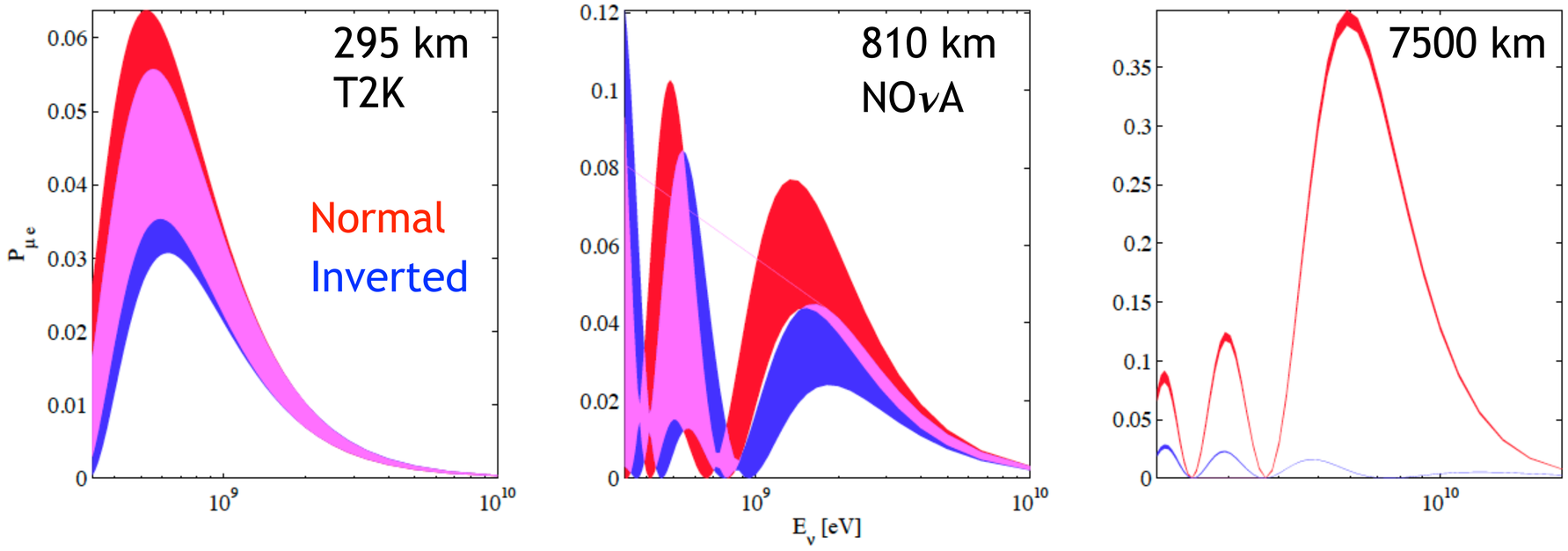
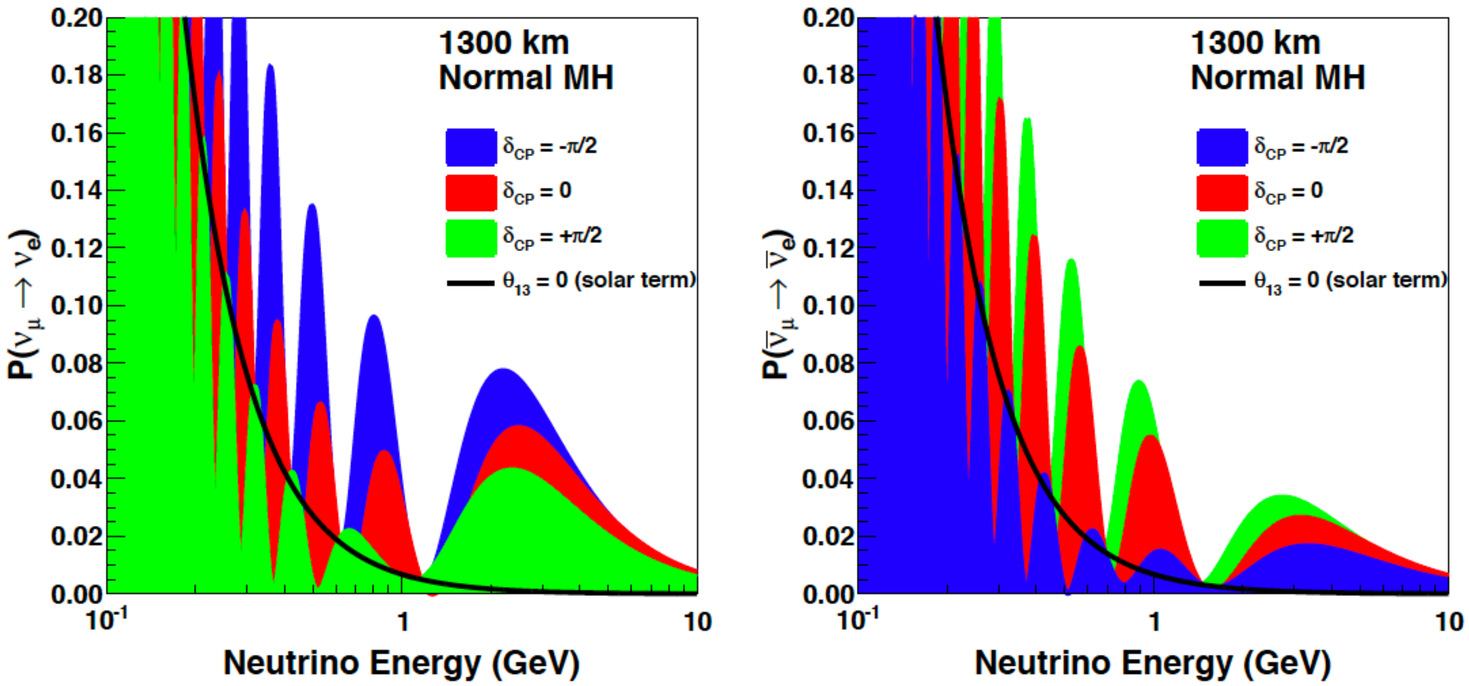
Long Baseline Neutrino Physics

- <u>Goal:</u> Determination of the neutrino mass hierarchy
  - Effects of CP violation and neutrino mass hierarchy on the oscillation probability disentangle for long baselines



Long Baseline Neutrino Physics

- <u>Goal:</u> Potential discovery of leptonic CP violation
  - Probability $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if CP is conserved



CP and T Violation

PMNS-Matrix:

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Transition probability:

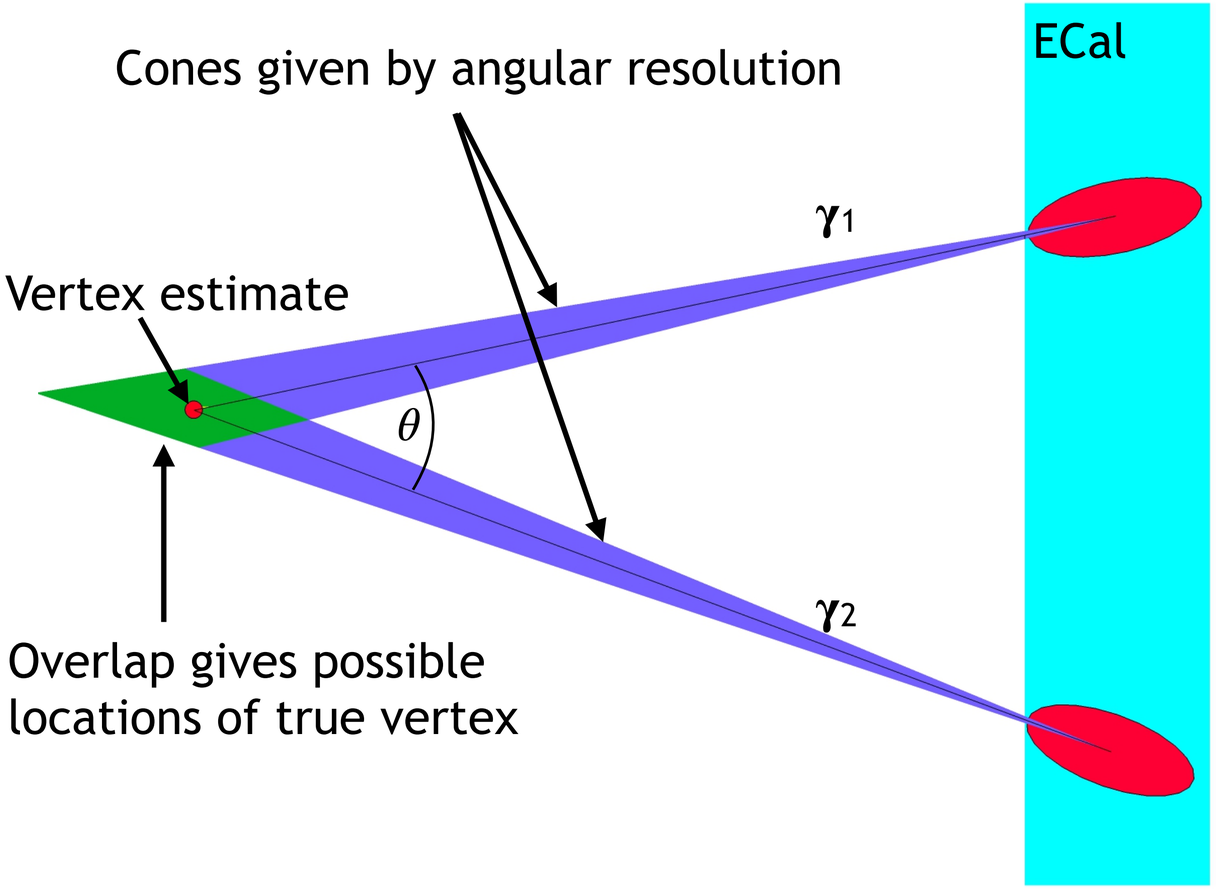
$$P_{\nu_\mu \to \nu_e} \simeq -4 \sum_{k>j} \Re \left[U^*_{\mu k} U_{ek} U_{\mu j} U^*_{ej} \right] \sin^2 \left(\frac{\Delta m^2_{kj} L}{4E_\nu} \right)$$
$$+2 \sum_{k>j} \Im \left[U^*_{\mu k} U_{ek} U_{\mu j} U^*_{ej} \right] \sin^2 \left(\frac{\Delta m^2_{kj} L}{2E_\nu} \right)$$

Neutrino Oscillation in Matter

$$P_{\nu_\mu \to \nu_e} \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\frac{\sin^2(\Delta(1-x))}{(1-x)^2}$$
$$+\alpha J \cos(\Delta \pm \delta)\frac{\sin(\Delta x)\sin(\Delta(1-x))}{x(1-x)}$$
$$+\alpha^2 \cos^2(\theta_{23})\sin^2(2\theta_{12})\frac{\sin^2(\Delta x)}{x^2}$$

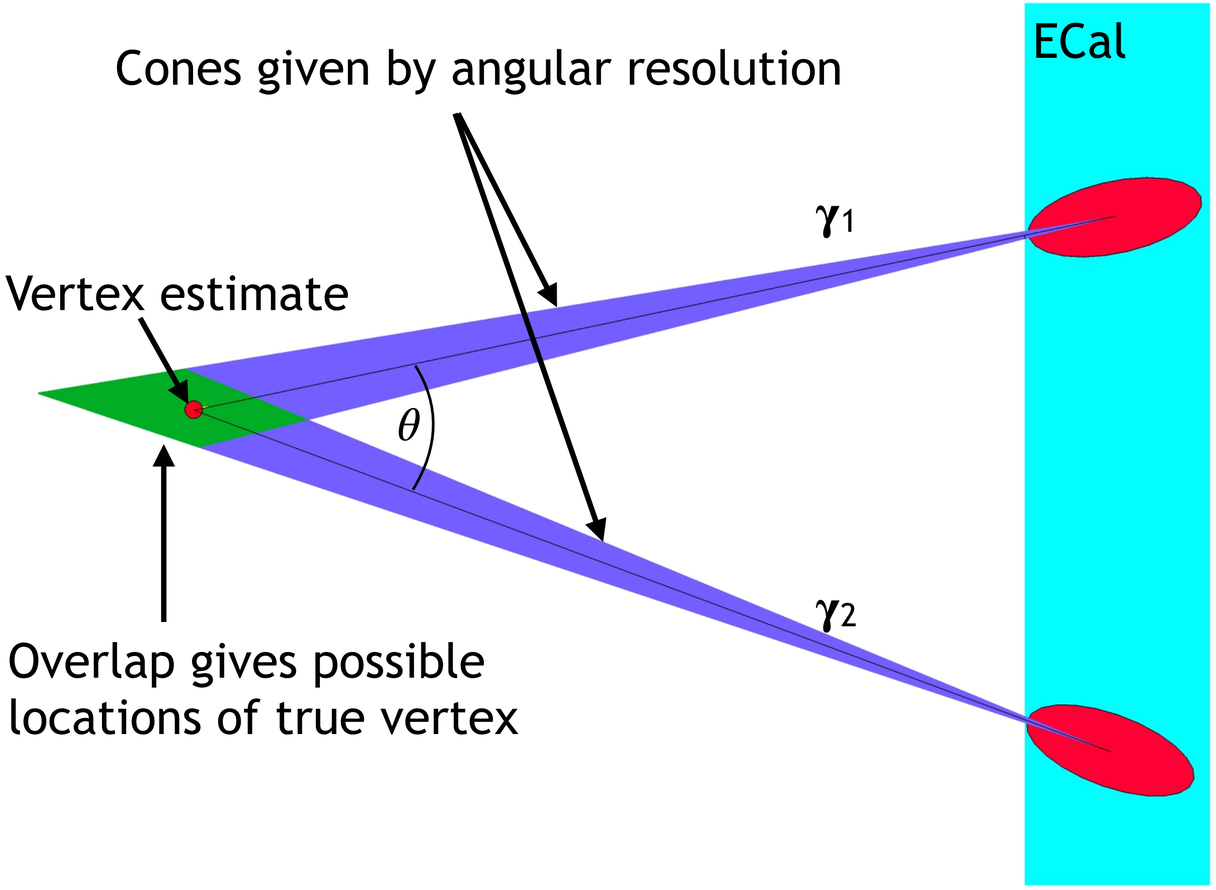
$$\Delta = \Delta m^2_{23} L/4E_\nu$$
$$x = \pm 2\sqrt{2} G_F N_e E_\nu / \Delta m^2_{23}$$

Pion - Vertex Reconstruction



Purely geometric reconstruction
→ using Calorimeter information exclusively

Pion - Vertex Reconstruction



Purely geometric reconstruction
→ using Calorimeter information exclusively

Add kinematical information
→ invariant mass

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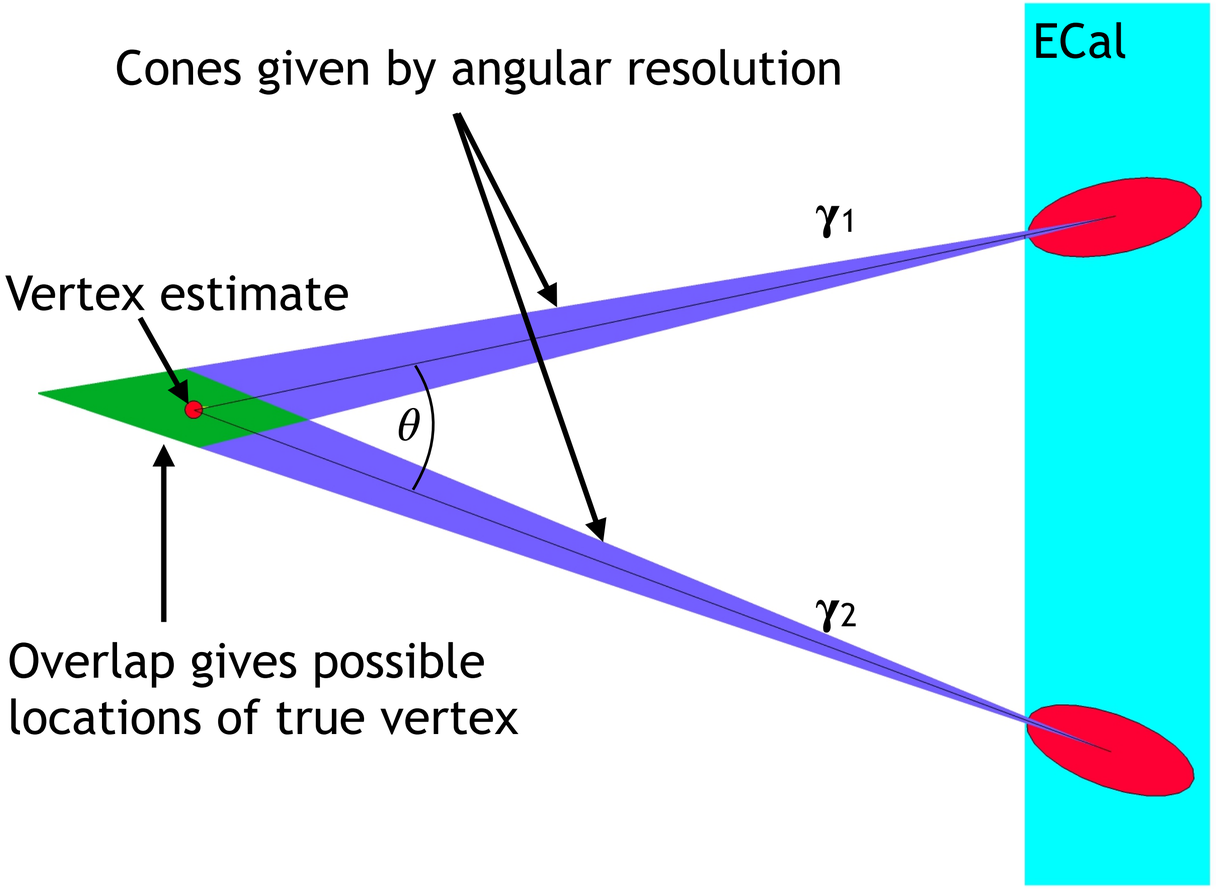
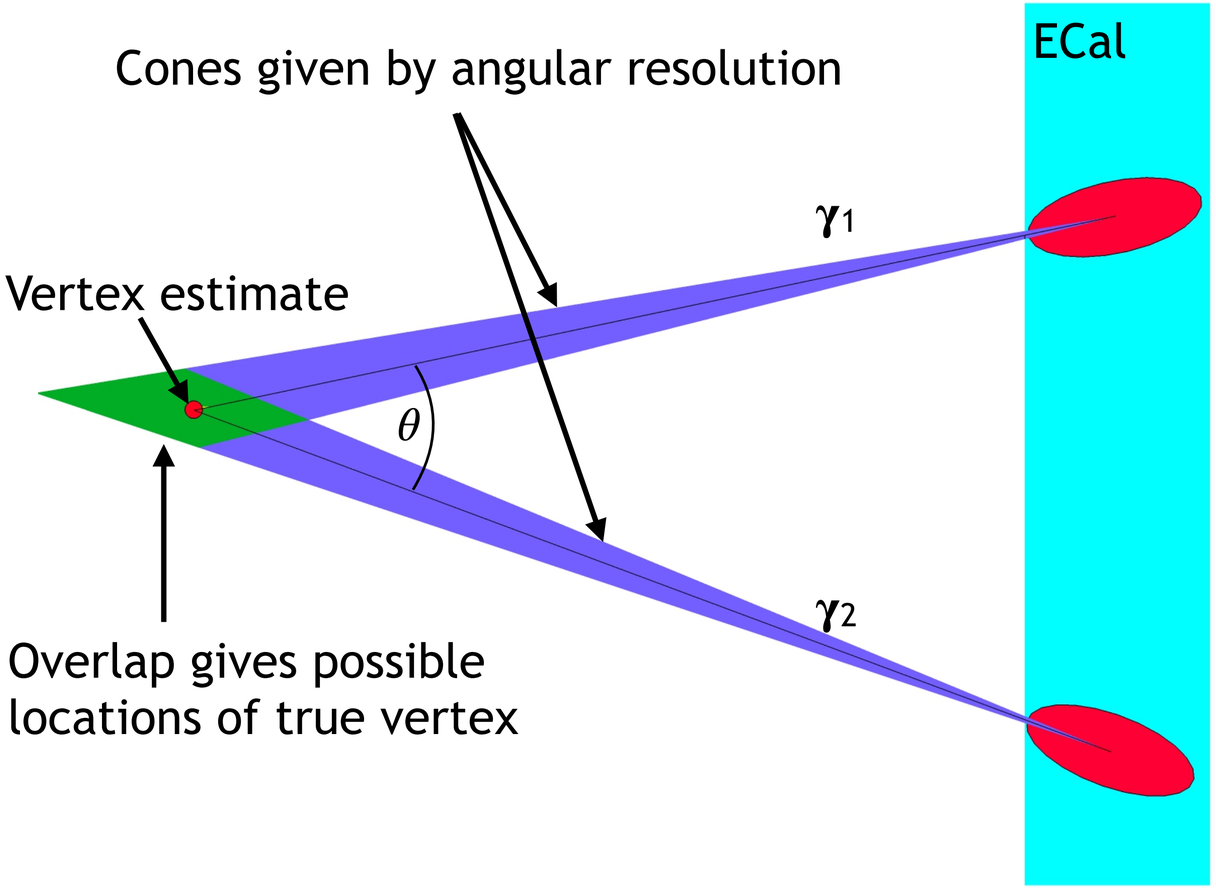


Purely geometric reconstruction
→ using Calorimeter information exclusively

Add kinematical information
→ invariant mass

- Require the optimization to be consistent with known π^0 mass
- Require the optimization to be consistent with the energy dependent angular resolution

Pion -Minimization



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Add kinematical information
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$$\chi^2 = \frac{(M_{pion} - M_{reco})^2}{\sigma^2_{mass}}$$

, with $M_{reco} = \sqrt{2E_{ph1}E_{ph2}(1 - \cos\theta)}$

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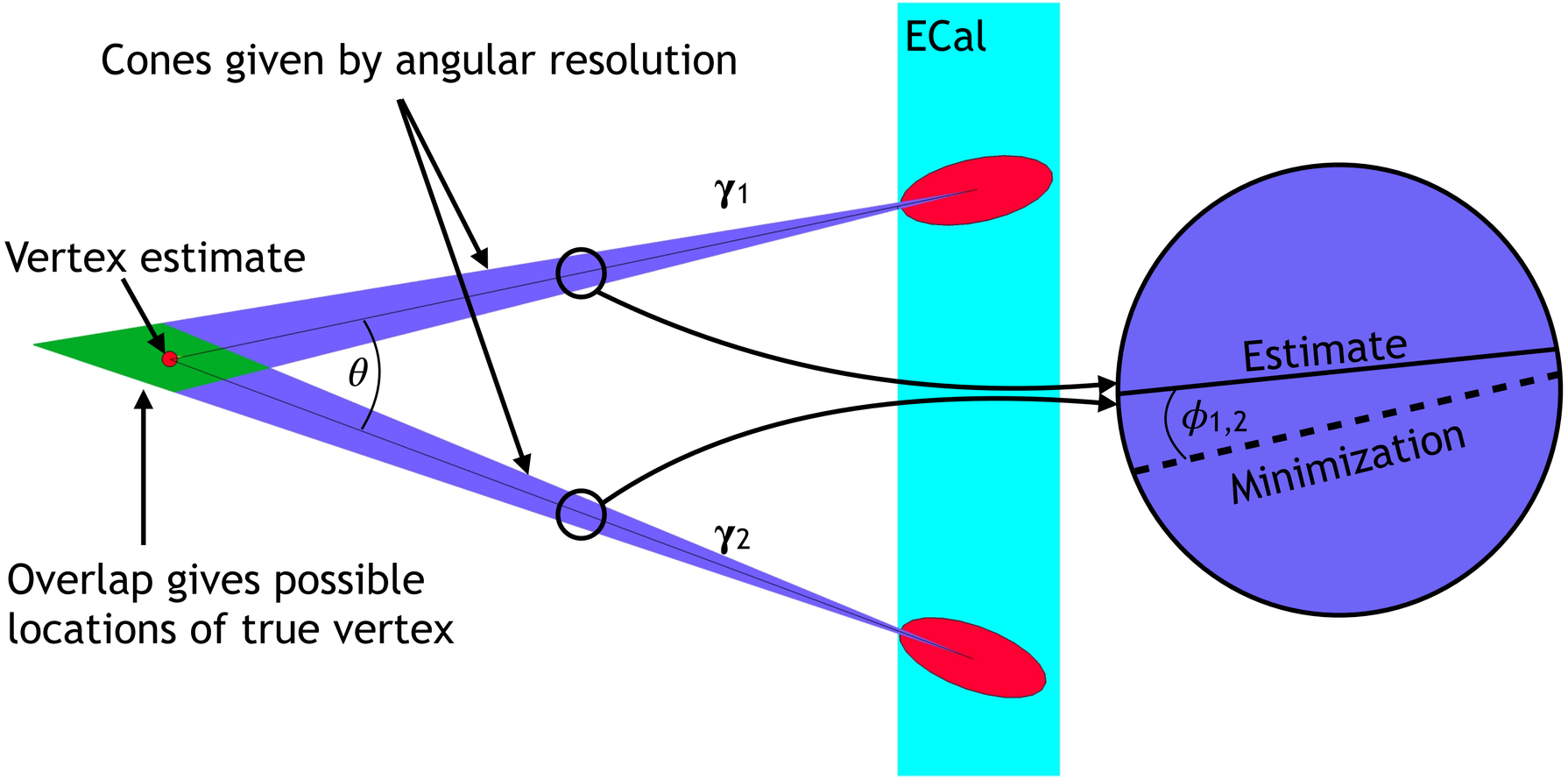
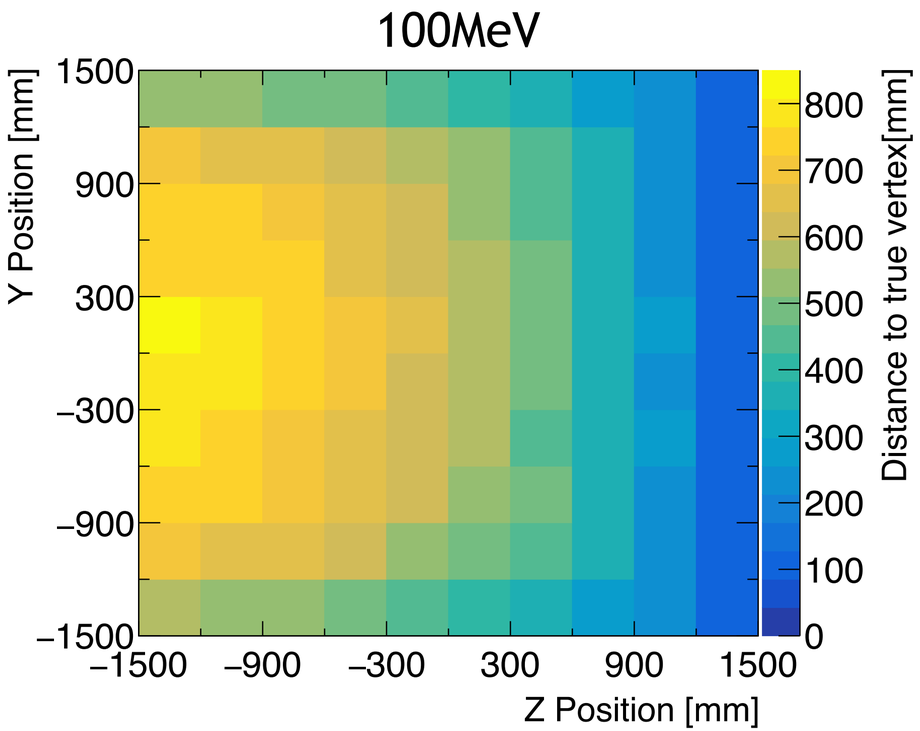


$$\chi^2 = \frac{(M_{pion} - M_{reco})^2}{\sigma^2_{mass}} + a\left[\frac{\phi_1^2}{\sigma^2_{photon1}} + \frac{\phi_2^2}{\sigma^2_{photon2}}\right], \text{ with } M_{reco} = \sqrt{2E_{ph1}E_{ph2}(1-\cos\theta)}$$

Pion - Vertex Reconstruction

- Divide cross section plane (0,Y,Z) of the TPC in 30x30cm^2 pixel
- Simulate 5000 Pion events with momentum along (0,0,Z) in the center of each pixel



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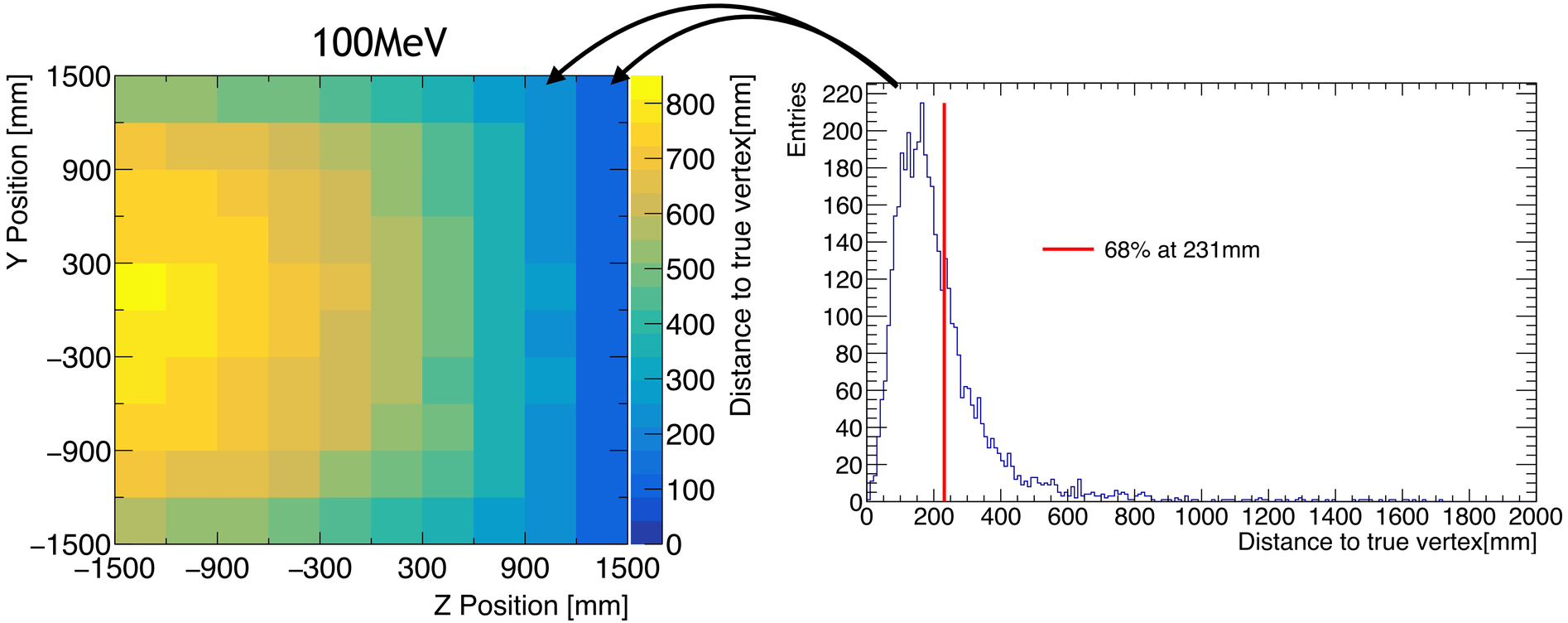

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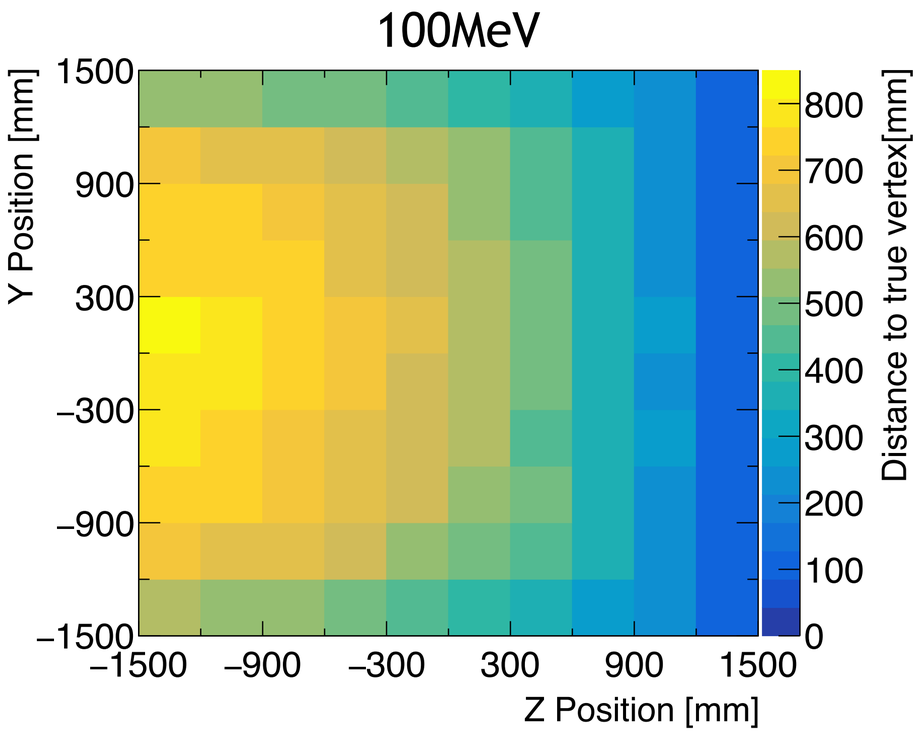

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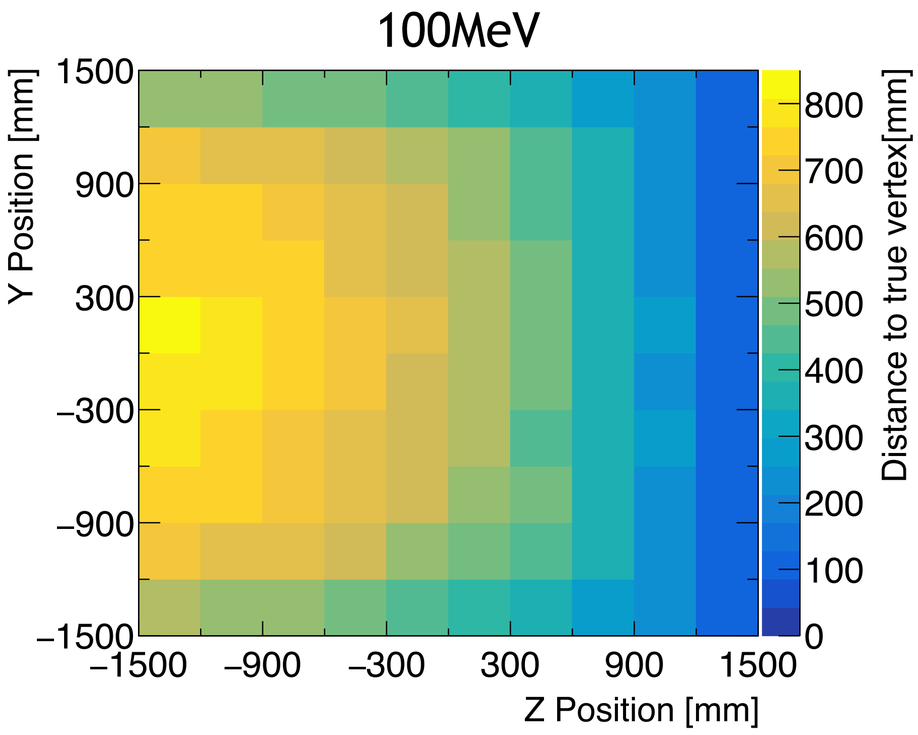
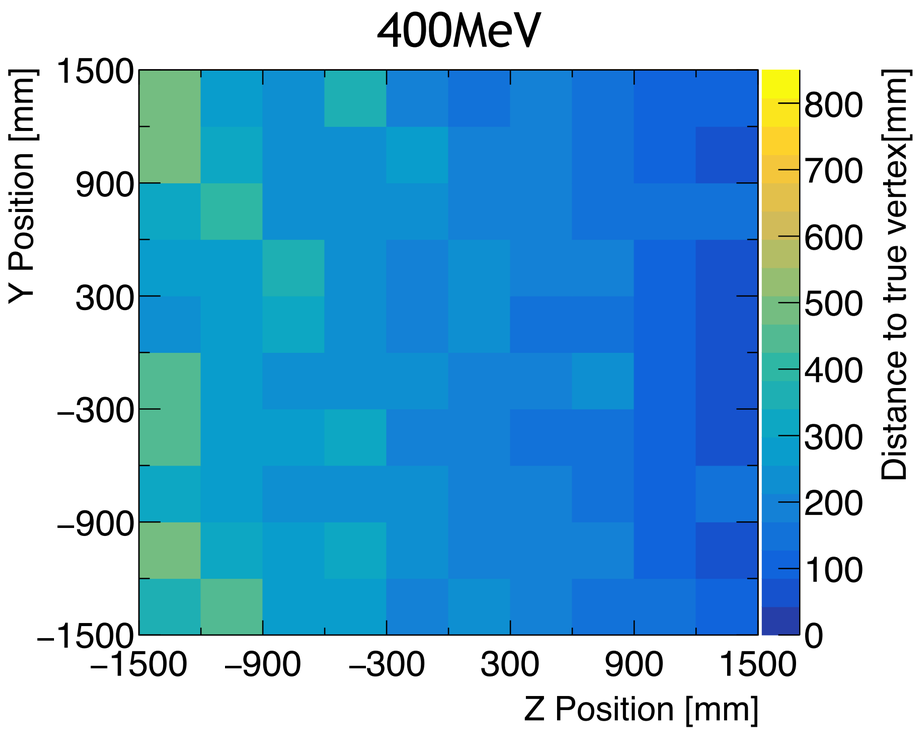


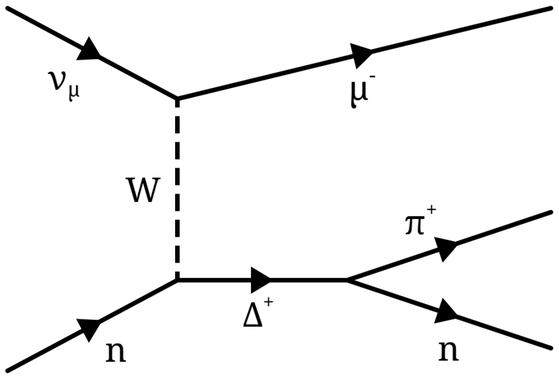


Neutron Performance

Neutrons are generated in neutrino interactions with the argon nucleons

The detection and energy measurement is vital for:

- The determination of the energy spectrum of the neutrino beam
- The reduction of systematic errors in the energy spectrum
- The determination of cross-sections of neutrino-nucleus interactions



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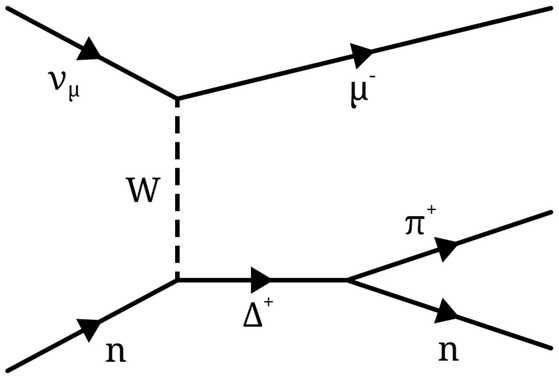

<u>Challenge:</u> Neutron energies of a few 100MeV

→Study detection efficiency and hadronic energy resolution in this region

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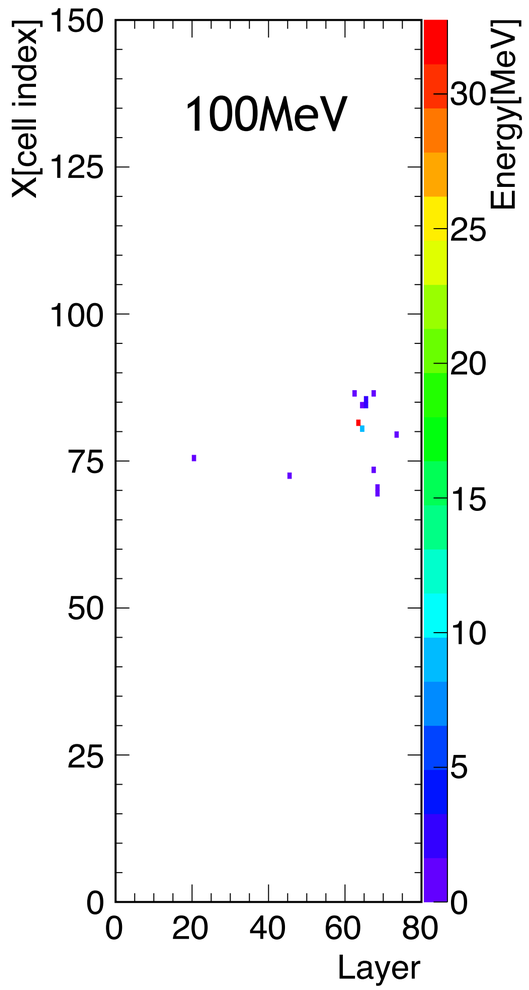

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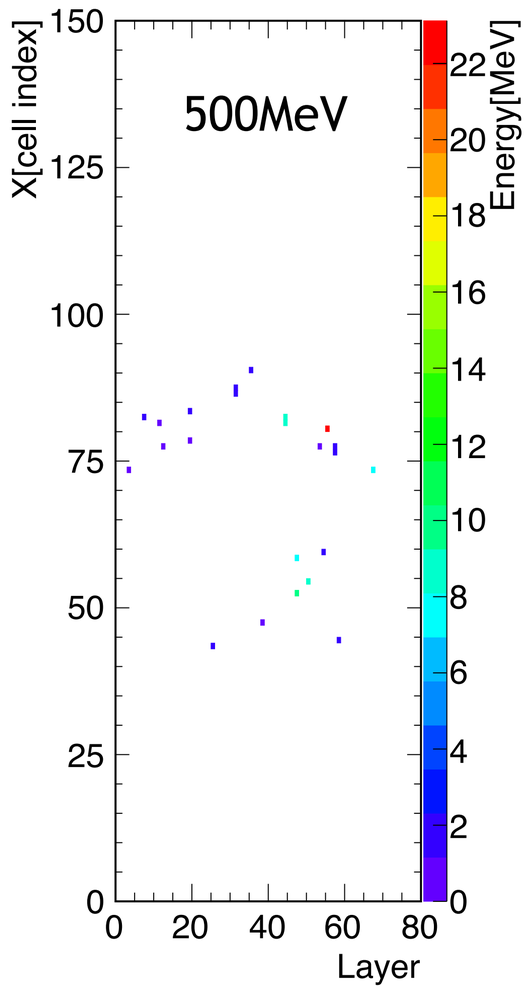

<u>Challenge:</u> Neutron energies of a few 100MeV

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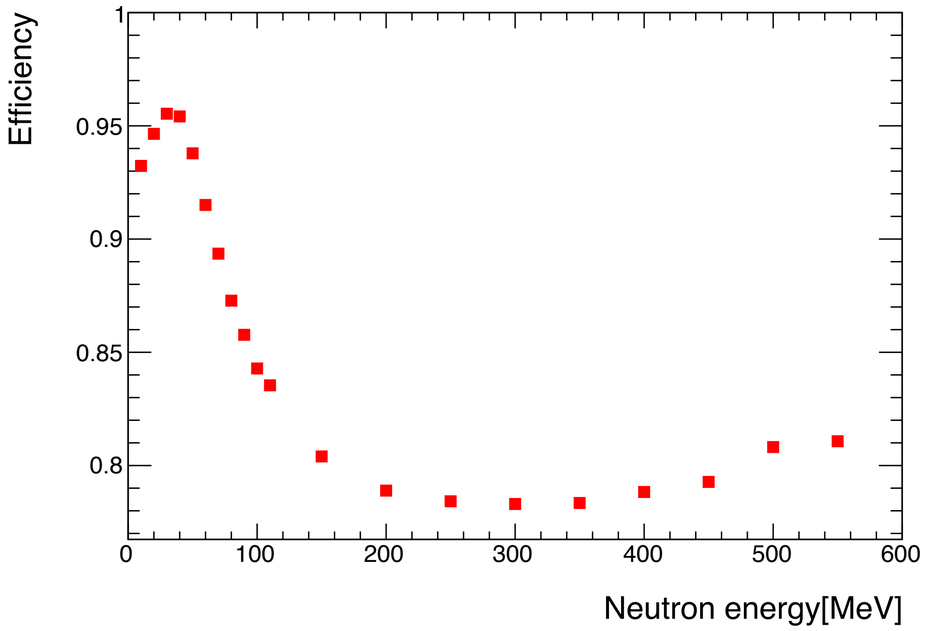
Neutron Detection Efficiency

Apply requirements on the recorded event to estimate detection efficiency

- 20000 neutron events per energy



Requirement:

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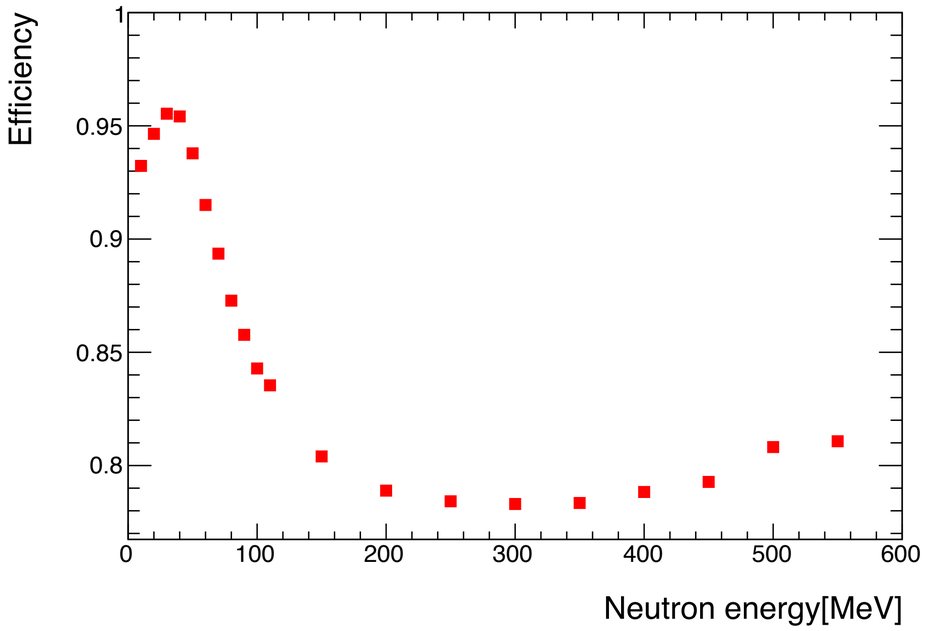
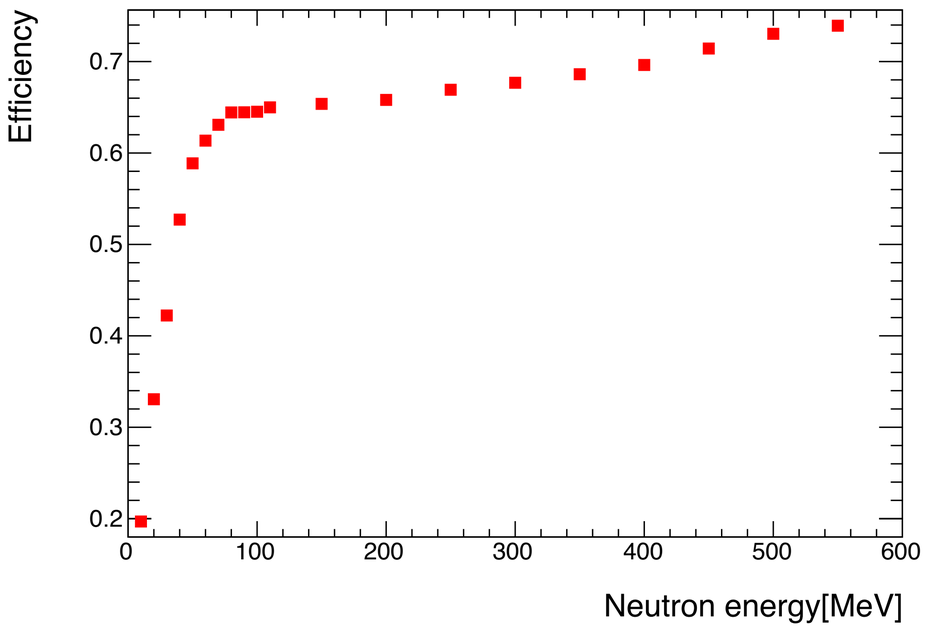


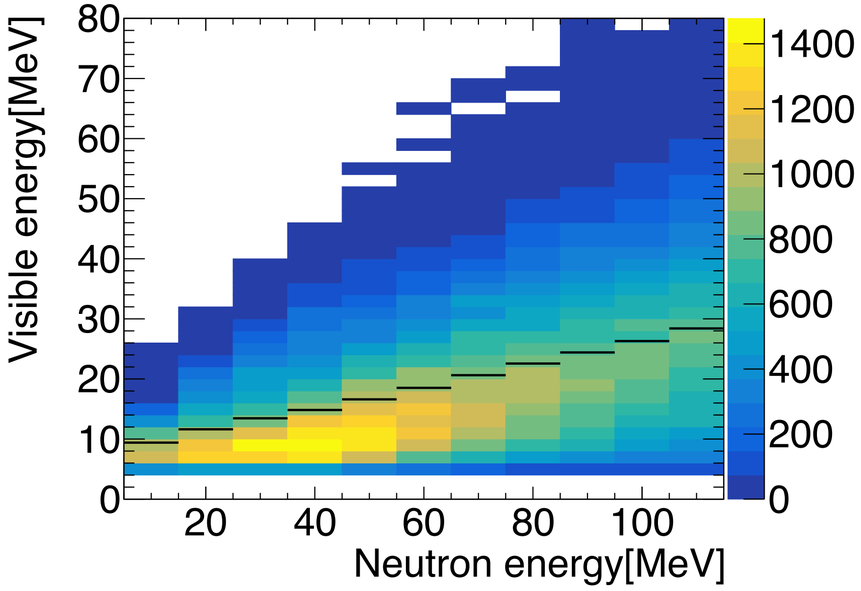


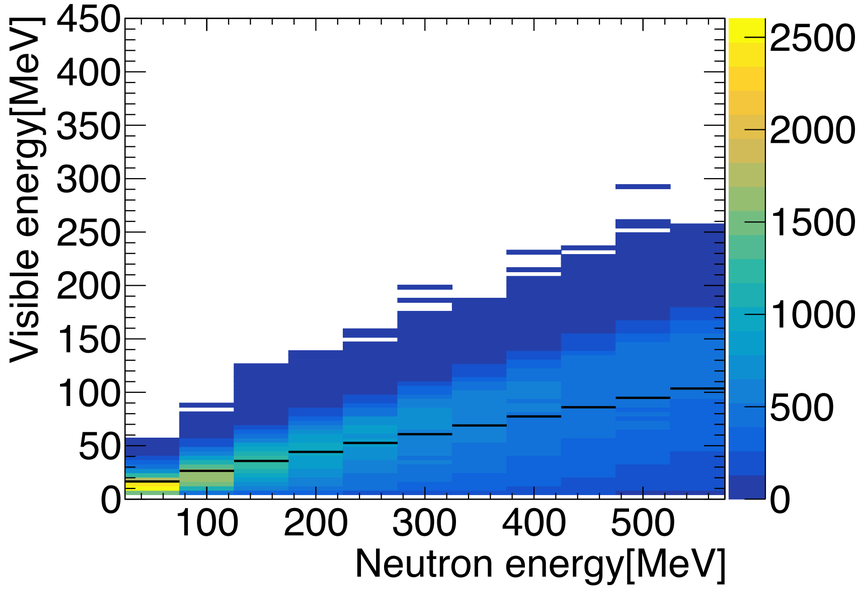
Requirement:
- One channel with E_{Dep} > 0.5MeV

Requirement:
- Five channels with E_{Dep} > 0.5MeV
- E_{Vis} > 5MeV

Visible Neutron Energy

- Obtain ratio of mean visible energy to true energy





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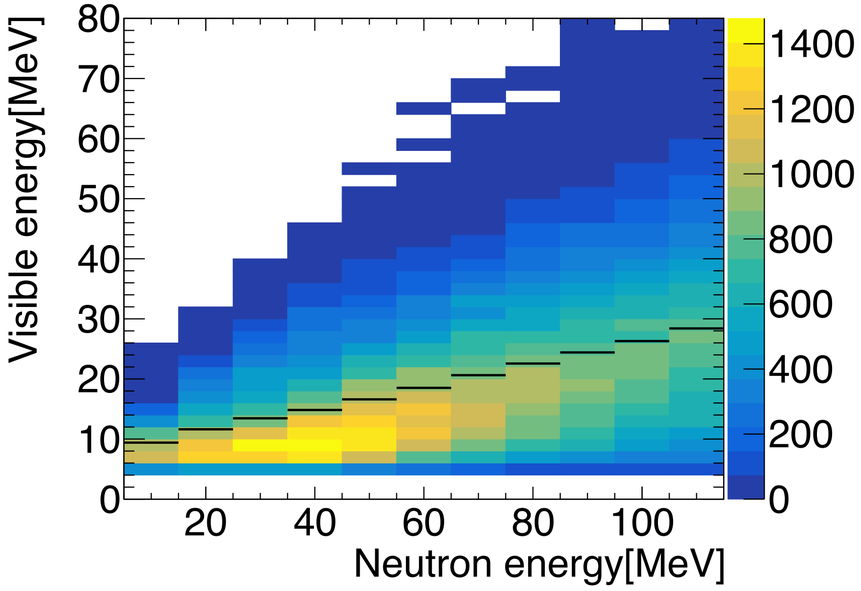
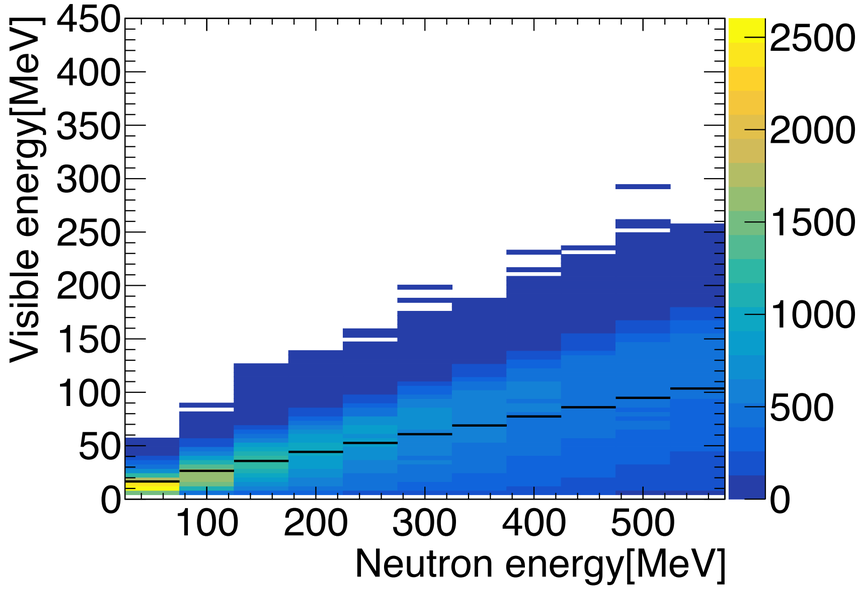
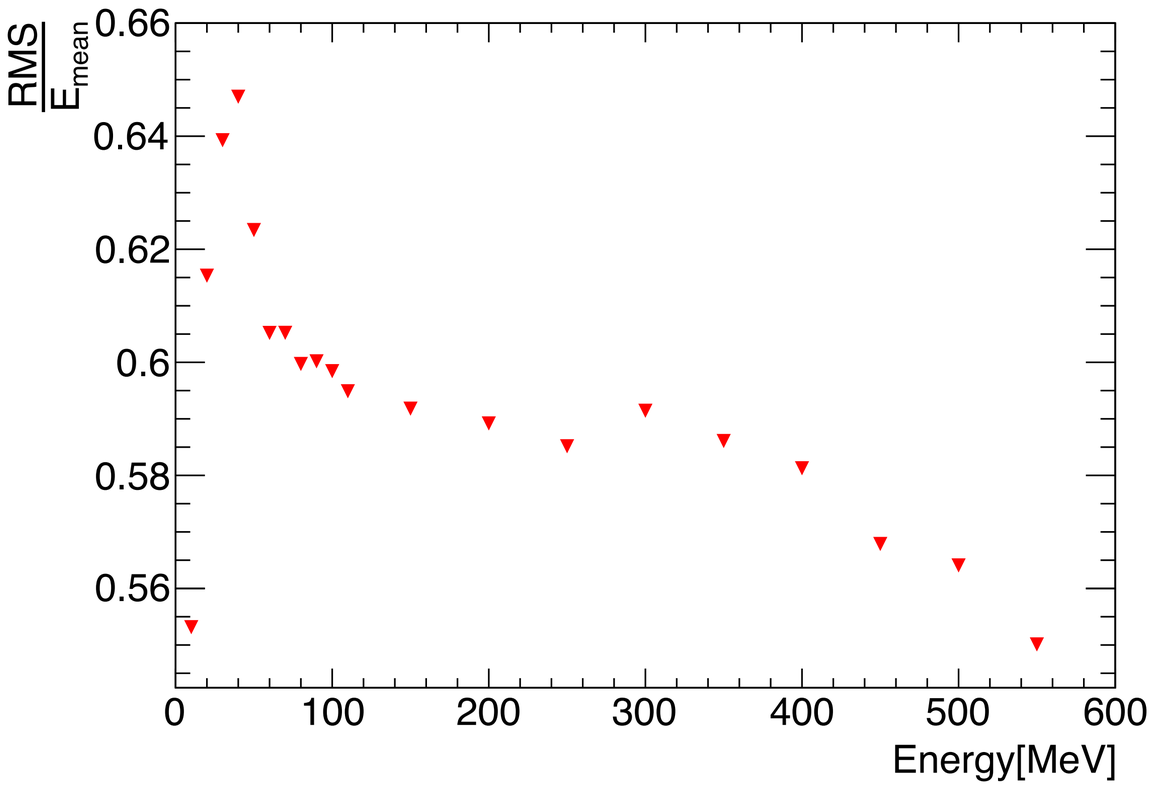




- Ratio of mean visible energy to true energy is about 0.2 for energies above 100MeV

- Distributions are not gaussian → use mean and RMS of binned distribution to obtain energy resolution

Neutron Energy Resolution



- Resolution follows no obvious law
  → $1/\sqrt{E}$ only applicable for higher energies

- Neutron energy resolution at about 58% over the full simulated energy range