Изучение энергетического отклика ближнего детектора SFGD

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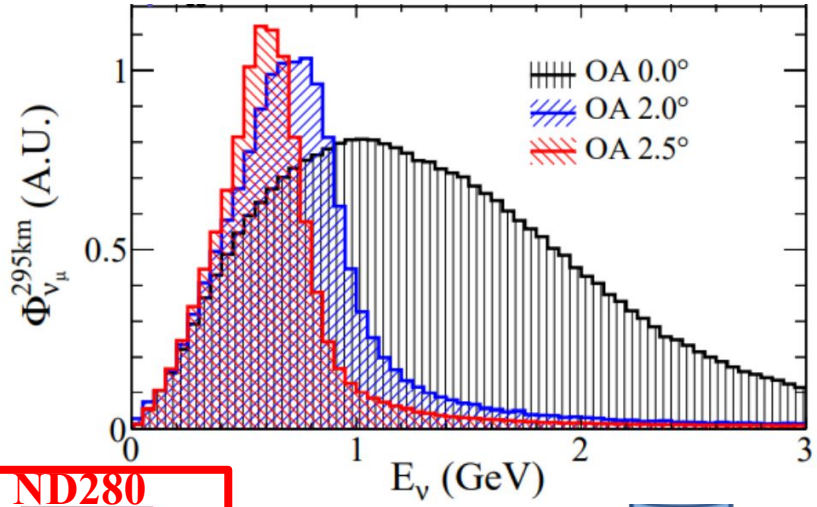
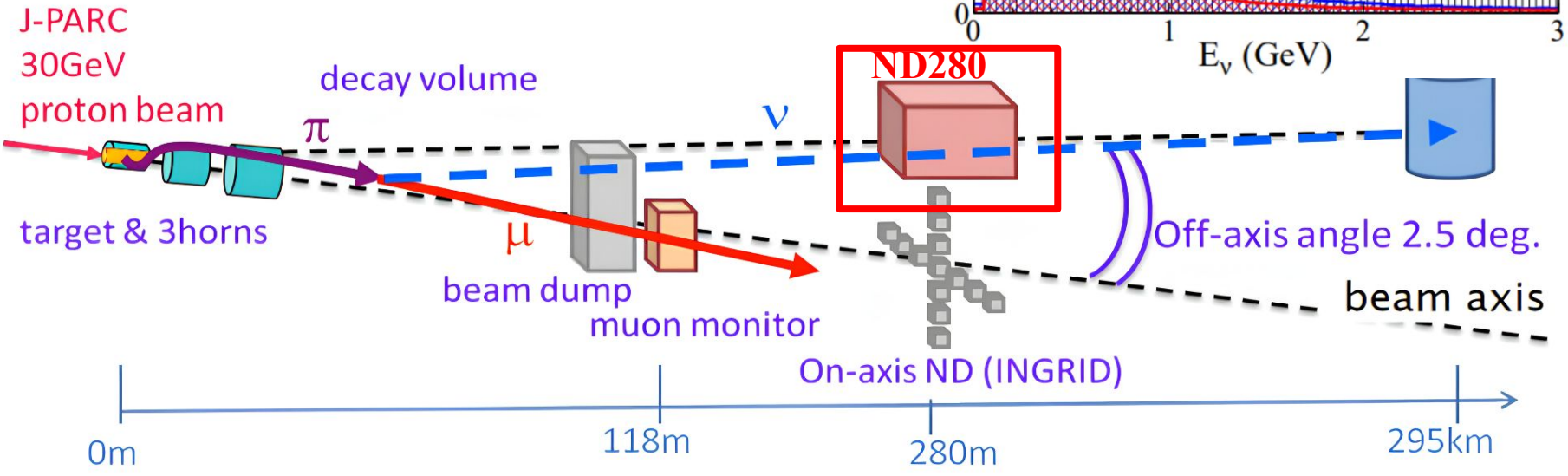
1 - МФТИ, 2 - ИЯИ РАН, 3 - ФИАН

The Tokai-to-Kamioka (T2K) experiment)

The T2K experiment is a long baseline neutrino oscillation experiment

- Discovery of $\sin^2\theta_{13} > 0$ with accelerator neutrinos
- Leading sensitivities to Δm^2_{23}, θ_{23}
- Rich variety of neutrino cross-section measurements
- Beyond the Standard Model studies

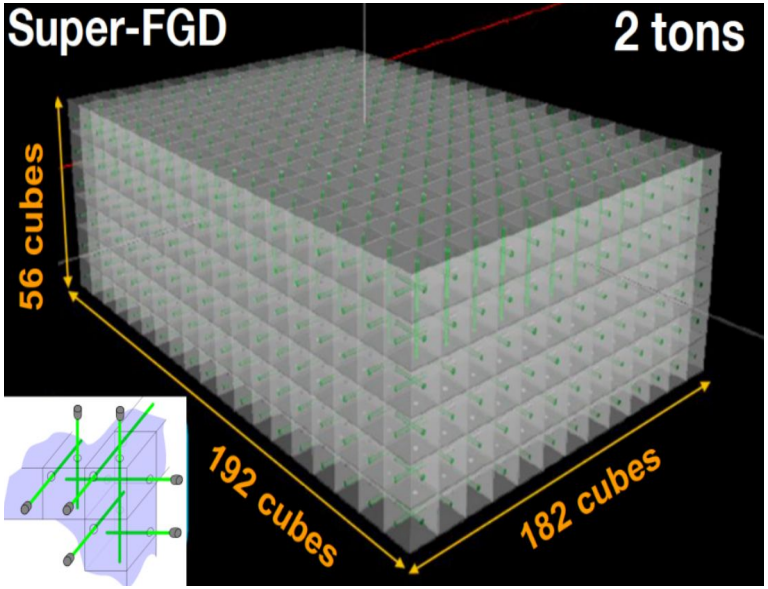


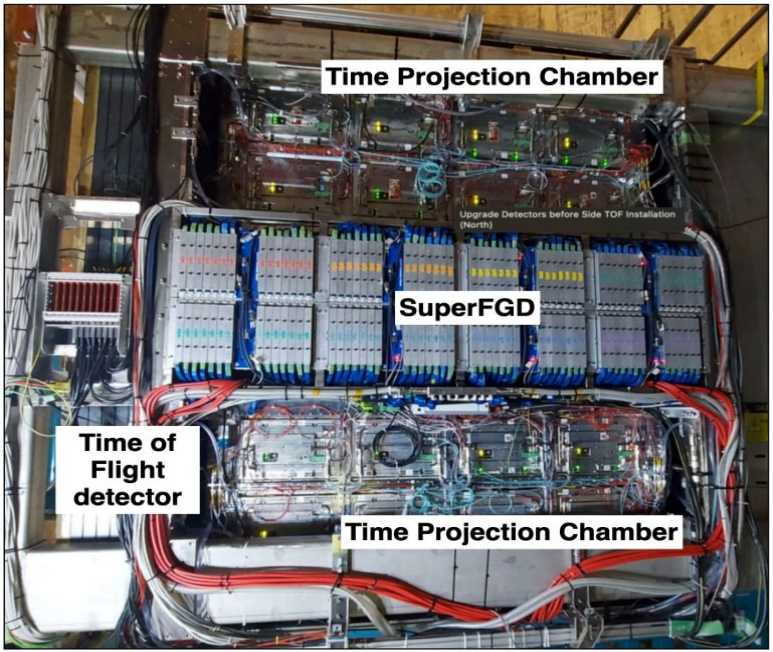


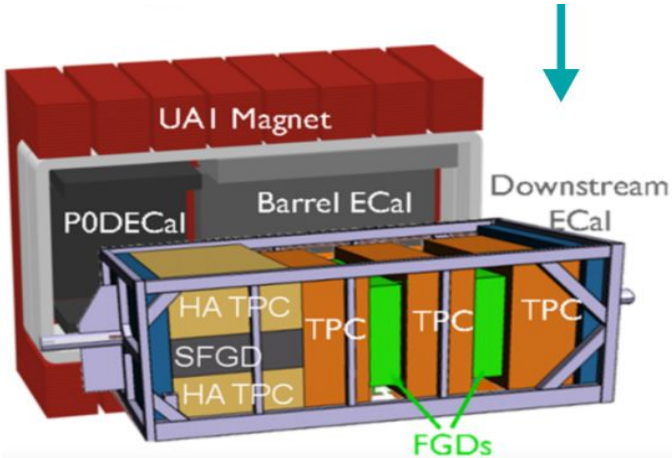
ND280: The SuperFGD detector

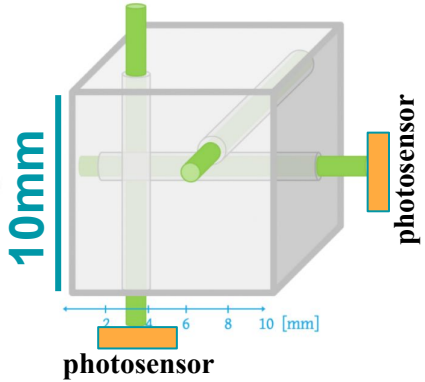
Fully active and highly granular 4π scintillator neutrino detector created to tune and constrain the flux and cross-section systematics model by selecting neutrino interactions before the oscillations:

- Total volume ~ 192 x 182 x 56 cm^3
- 3 projections per each cube via optical fibers ~ 60000 channels
- MPPC read-out









Motivation

Birks' law relates the detected light yield to the energy deposited in the scintillator, accounting for quenching effects. The main goal is to determine this relation for SFGD detector.

The observable is dE/dx, the energy deposition in the scintillator,

- k_B: Birks' constant, describing the scintillator quenching.
- k_E: Calibration coefficient (Data/MC ratio).
- k_{Ch}: Correction factor for Cherenkov light losses.

PID reconstruction analysis is based on particles Bragg peaks!

$$\frac{dL}{dx} = \frac{k_E \frac{dE}{dx}}{1 + k_B \frac{dE}{dx}} + \underbrace{k_{CH}\, e^2 \left(1 - \frac{E^2}{n^2\left(E^2 - m^2\right)}\right)}_{\text{Cherenkov contribution}}$$

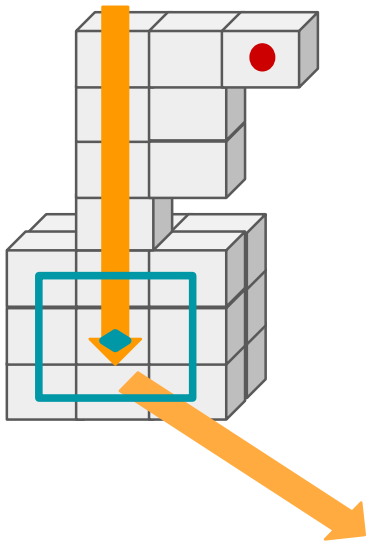
$$\chi^2(K_B, K_E, K_{Ch}) = \sum_{n=0}^{N_{layers}} \frac{\left(\frac{dE}{dx}_{n,MC} - \frac{dE}{dx}_{n,Data}\right)^2}{\sigma^2}$$

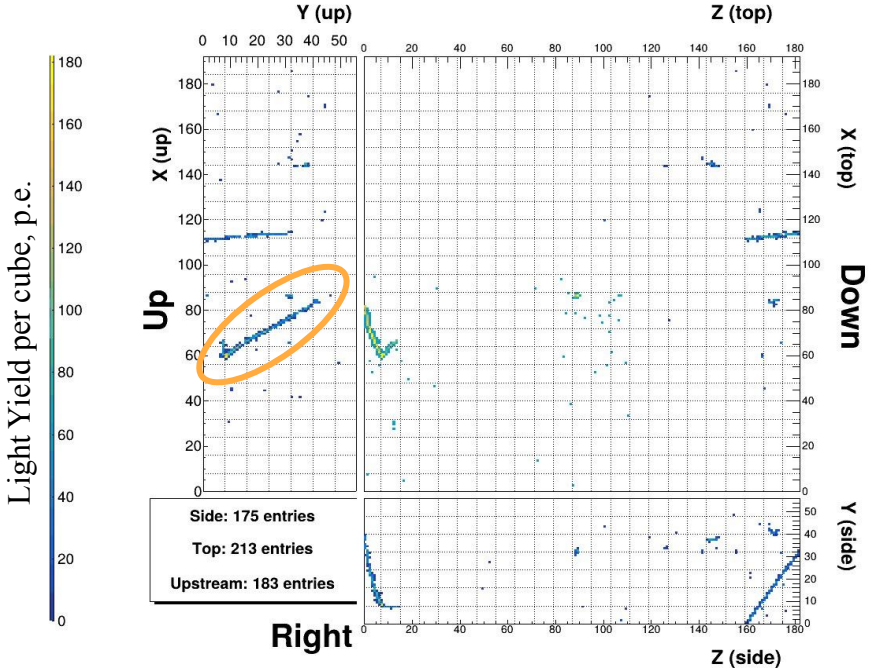
Cosmic Muon Stopping Sample: Selection

- An event is split into time clusters **(Δt >= 40 ns)**
- Each time cluster is divided into spatial clusters**(>= 15 cubes in cluster for primary)**
- Each spatial cluster in the first time cluster is checked to satisfy:

  1) **The cluster does not pass through the entire detector** (if y_max > 52 and y_min = 0, the track is discarded).

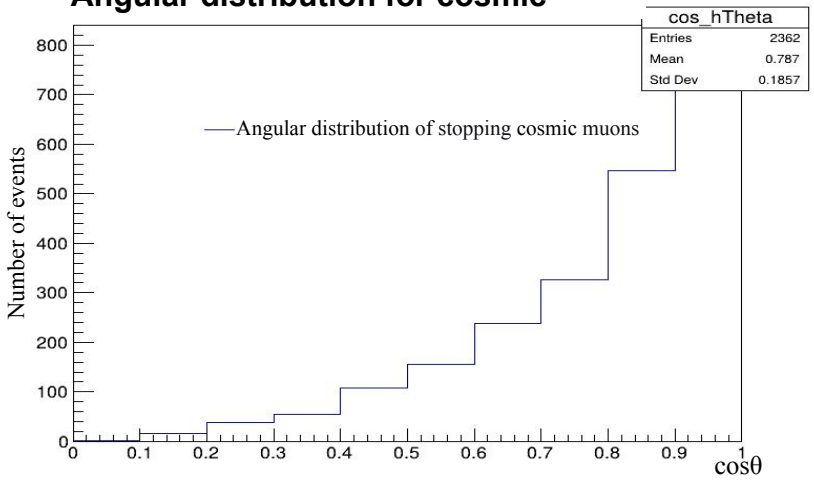
  2) **The cluster stops inside the FV** (3 < x_stop < 189 & 3 < z_stop < 179 & 3 < y_stop < 52).
- The spatial clusters in the second time clusters must have **>= 5 cubes**
- Each spatial track in the second time cluster is checked to start in the stop cube or in the neighbour to the stop cube





Cosmic Stopping Sample: MC

Angular distribution for cosmic

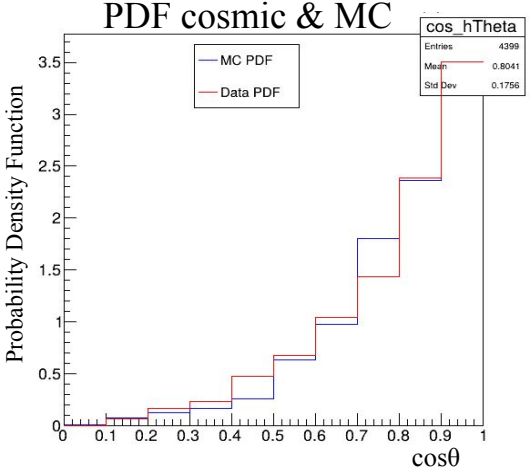


- **μ^+/μ^- proportion** in MC should be taken as expected in real data **(44.1 ± 0.3)%** of stopping muons are μ^- at sea level)

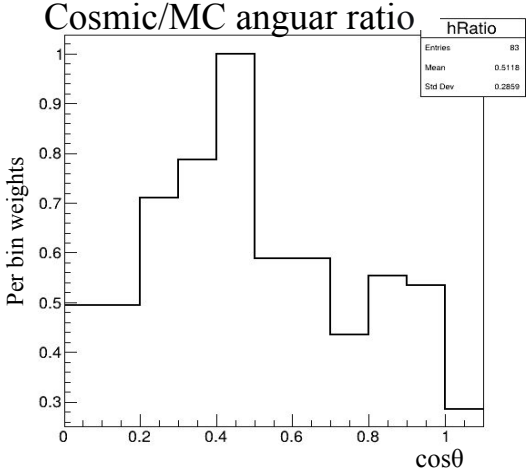
- **muon angular distribution in MC and data should match** in order to make an adequate Bragg curve comparison

1. The angular Probability Density Function (PDF) from data defines the required Monte Carlo (MC) statistics.
2. Normalization is conserved between data and simulation.
3. The known μ^+/μ^- ratio ((44.1 ± 0.3)% μ^-) is applied to the final angular distribution to estimate the number of μ^+ and μ^- events.

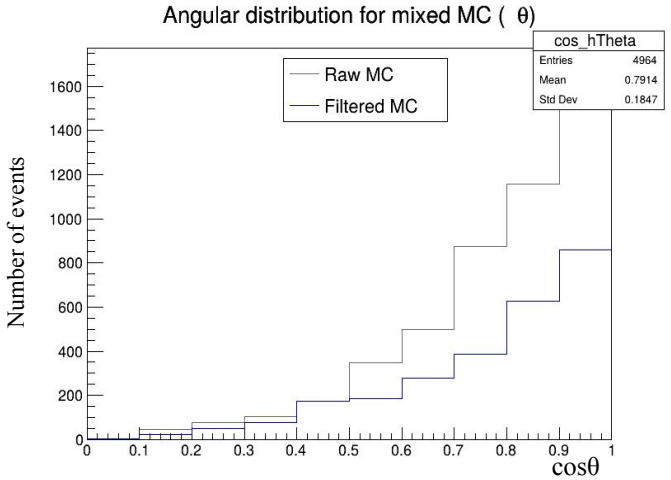
PDF cosmic & MC



Cosmic/MC anguar ratio



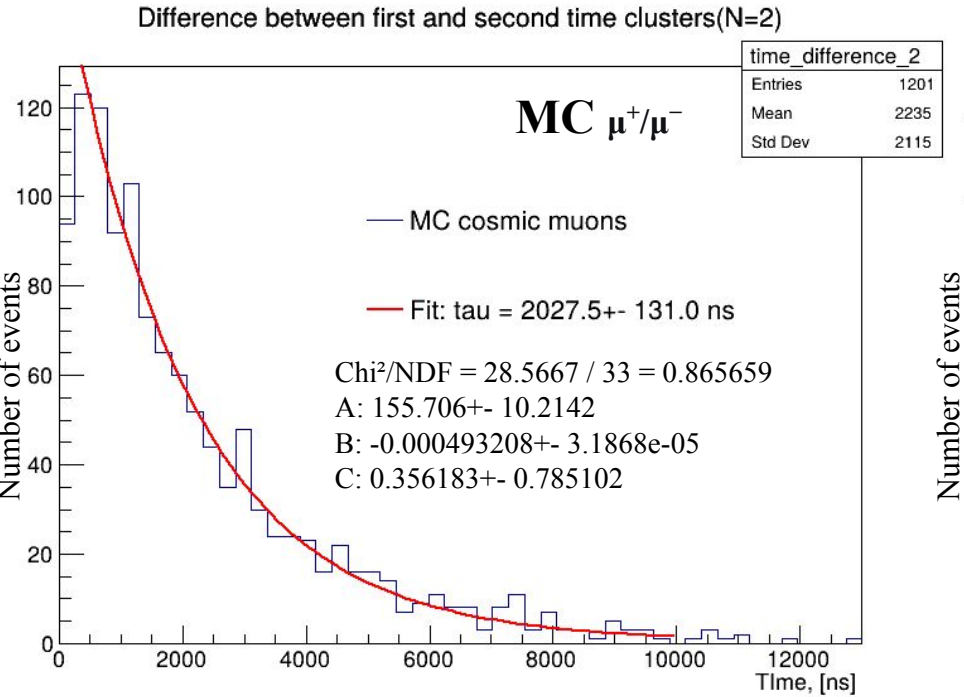
Angular distribution for mixed MC (θ)

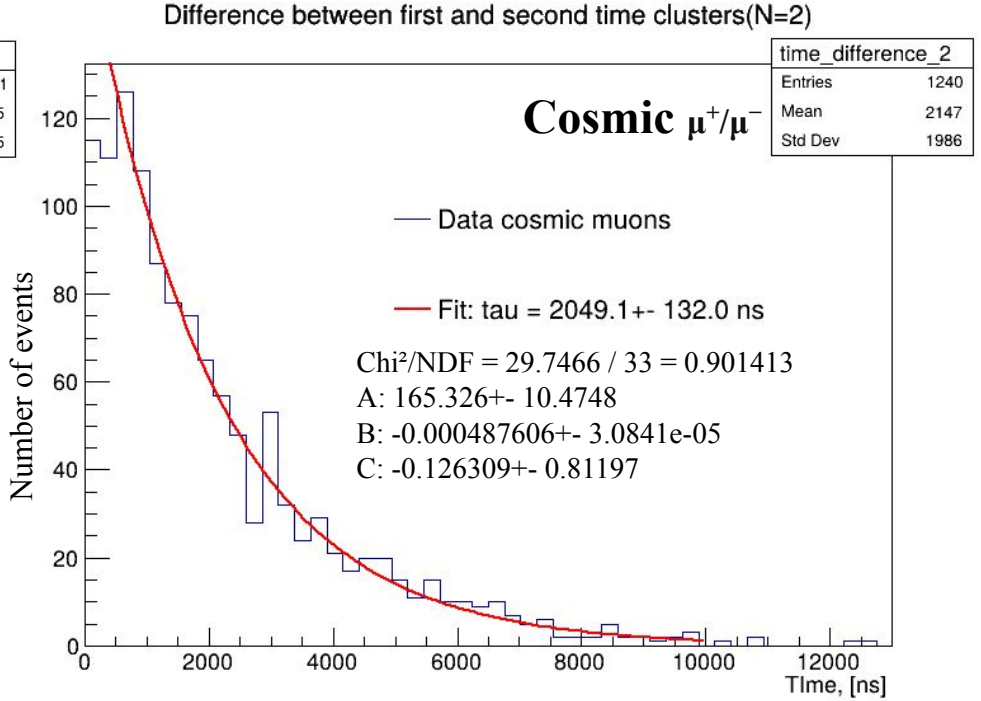


Cosmic Stopping Sample: Selection Validation

To validate the selection, reconstructed μ lifetime was compared with the expected value.

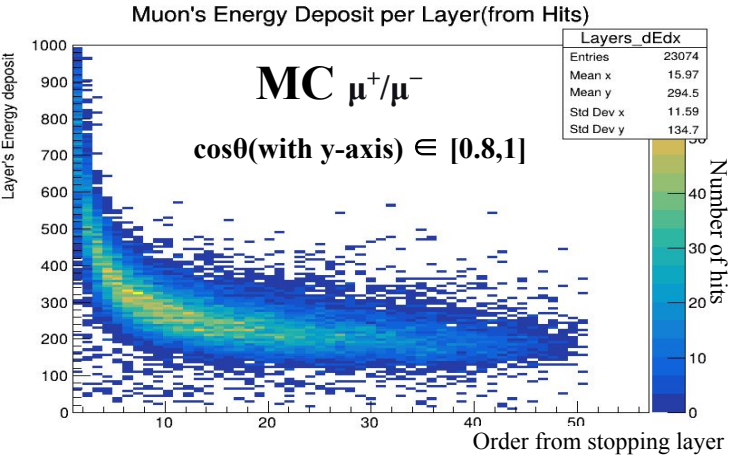
- Parameters fit A*exp(B*T)+C

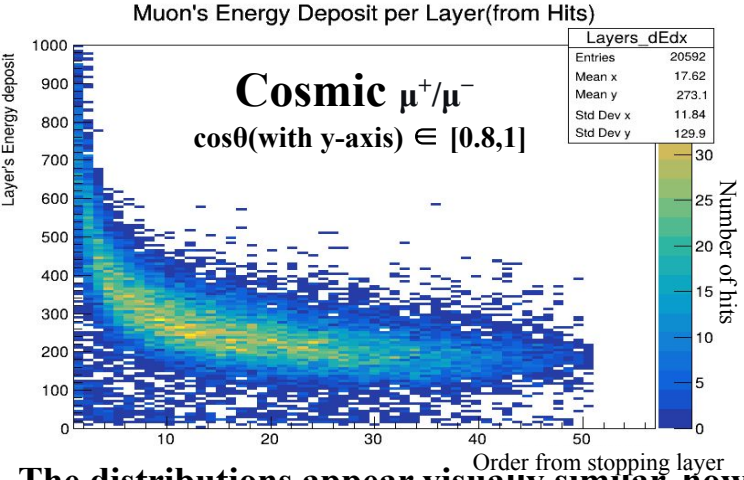




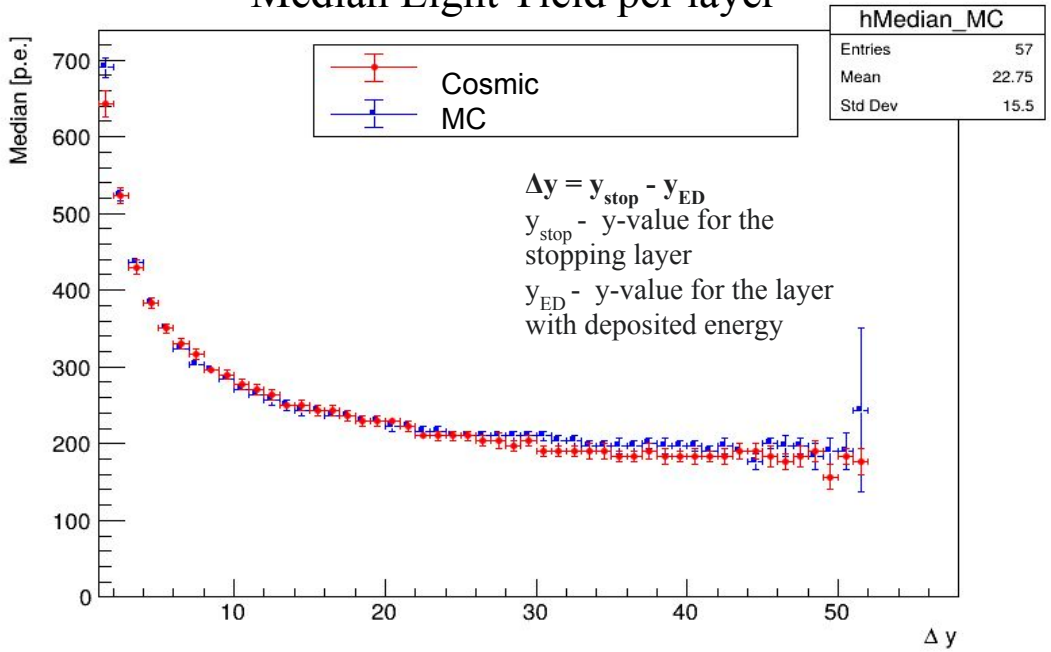
The mixed MC dataset yielded results compatible with the data within errors. However, a difference in the shapes of the distributions is observed, which requires further study.

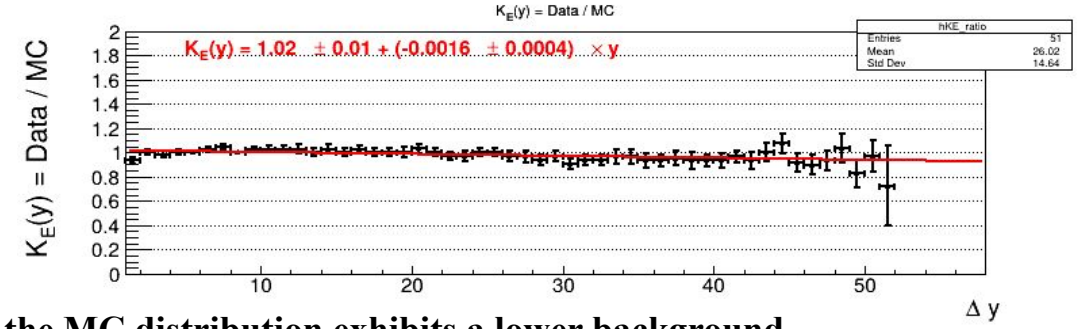
Cosmic Stopping Sample





Median Light Yield per layer

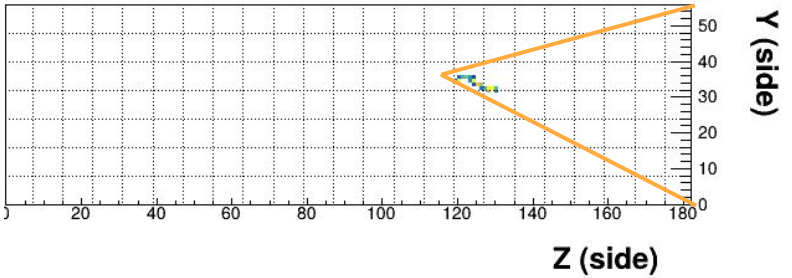


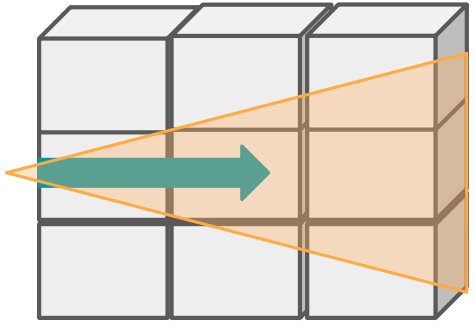


The distributions appear visually similar, however, the MC distribution exhibits a lower background.

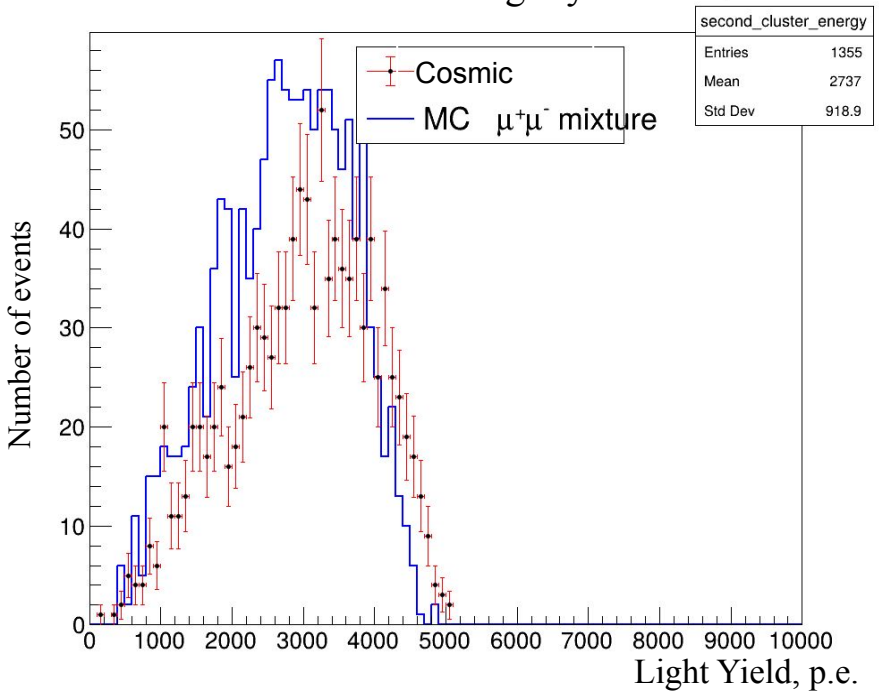
Reco info: Michel electron

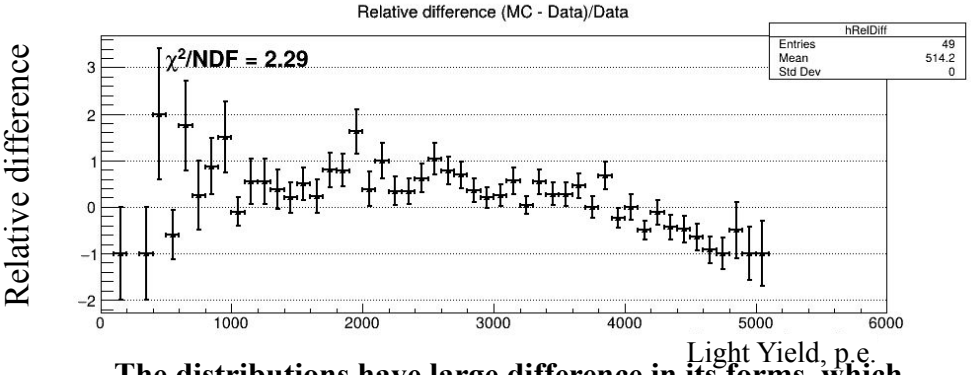
Michel electron spectrum is reconstructed by summing the 3D read-out light yield from the electron track and the electromagnetic showers within a selected cone.





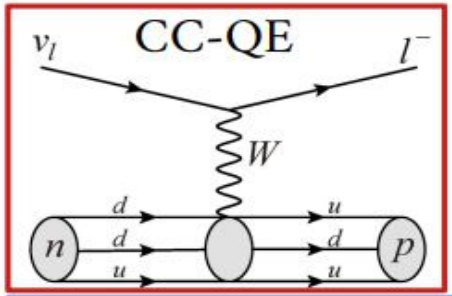
Michel electron total light yield





The distributions have large difference in its forms, which points to further investigation.

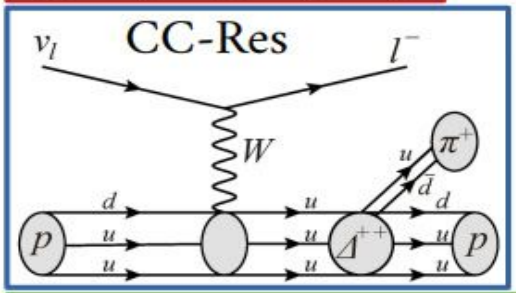
Neutrino Interaction Modes



Charged-current quasi elastic (CCQE) - muon and proton at the final state:

$$\nu_\mu + n \rightarrow \mu^- + p$$
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

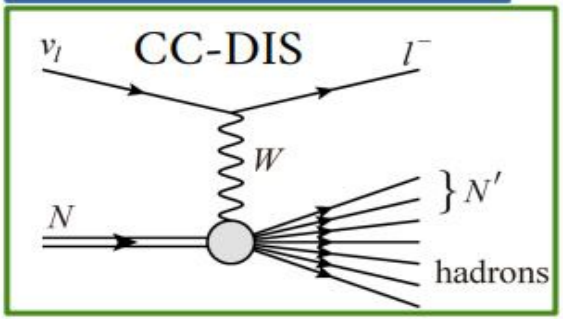
100MeV < E_ν< 1GeV



Resonance Production (CCRES) - muon and proton at the final state:

$$\nu_\mu + N \rightarrow \mu^- + \Delta^{++} \rightarrow \mu^- + p + \pi^+$$
$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \Delta^- \rightarrow \mu^+ + n + \pi^-$$

400MeV < E_ν<5GeV



Deep Inelastic Scattering (CCDIS) - muon and proton at the final state:

$$\nu_\mu + N \rightarrow \mu^- + X$$
$$\bar{\nu}_\mu + N \rightarrow \mu^+ + X$$

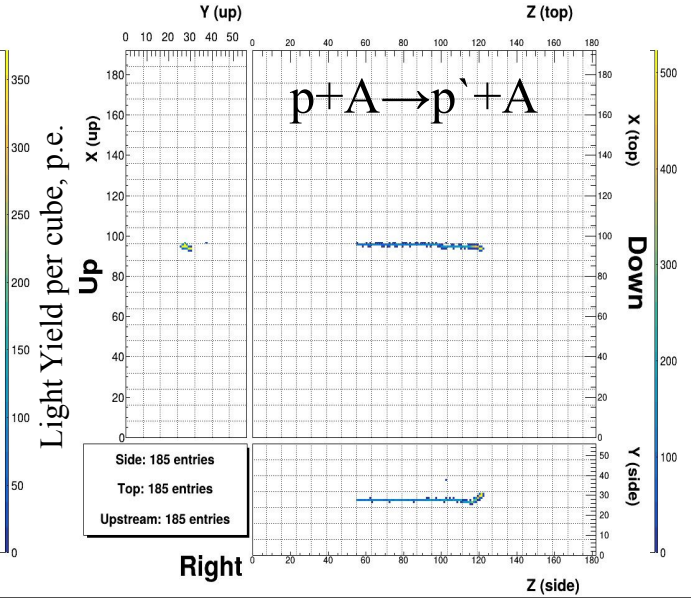
E_ν>5GeV

Proton Stopping Sample: MC true

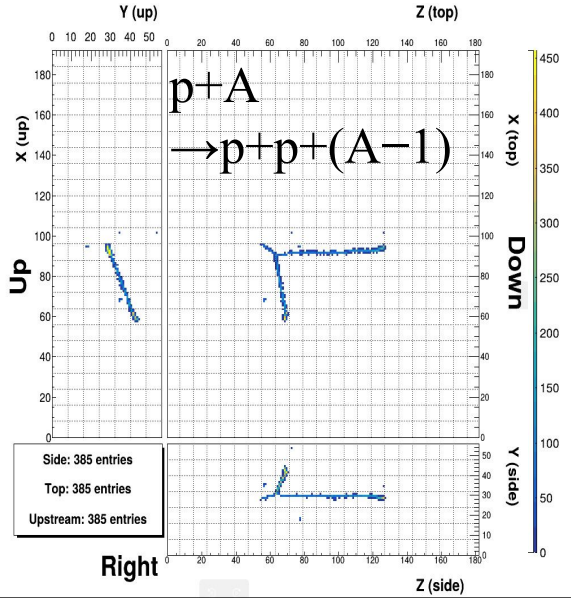
Type	100 MeV	200 MeV	400 MeV
Events total	5000	5000	5000
Elastic	96	672	1875
Inelastic	1	26	582
Stopped	4902	4270	2323
Divided	1	0	0
Escaped	0	32	220

- Protons are generated along the Z-axis with an angular distribution. Particles start in the SFGD. Every MC set has fixed energy ranging from 30 to 600 MeV.

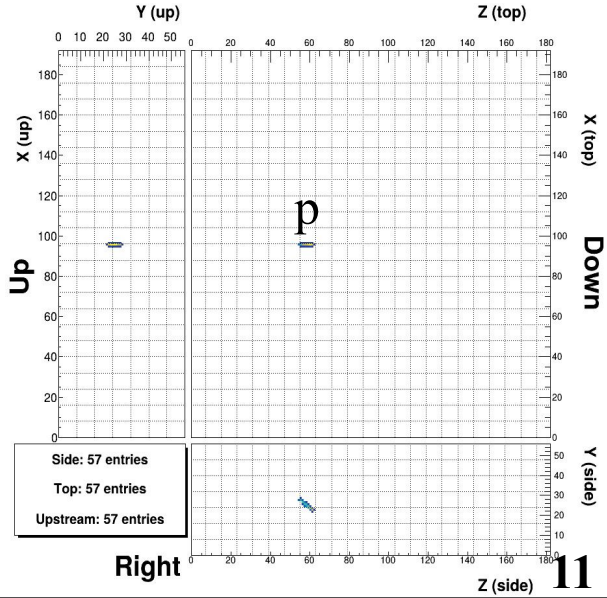
Elastic



InElastic

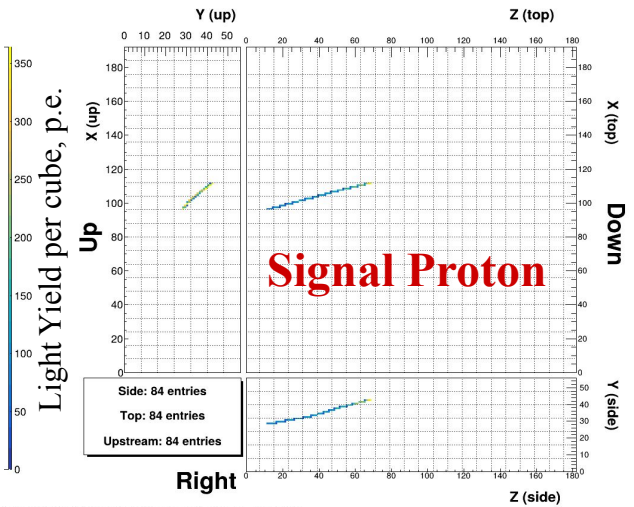


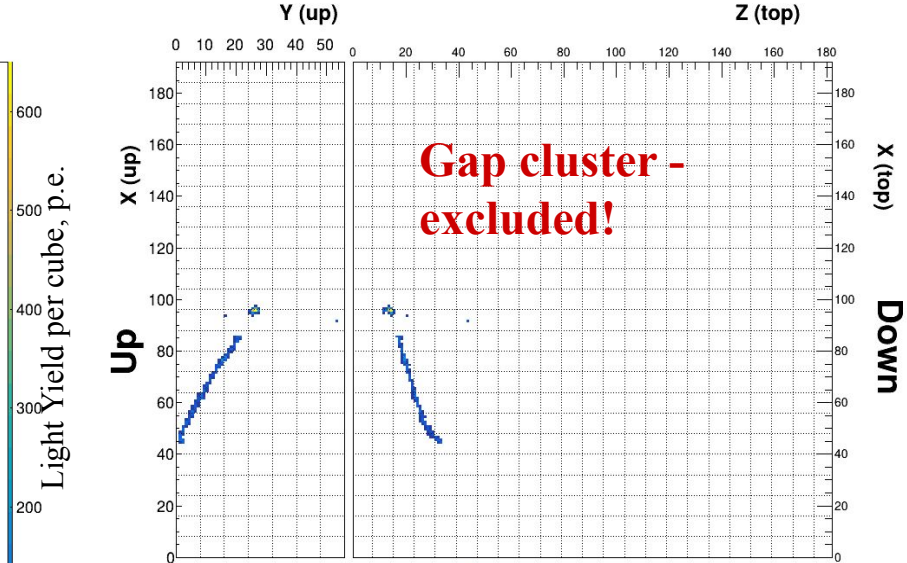
Stopped

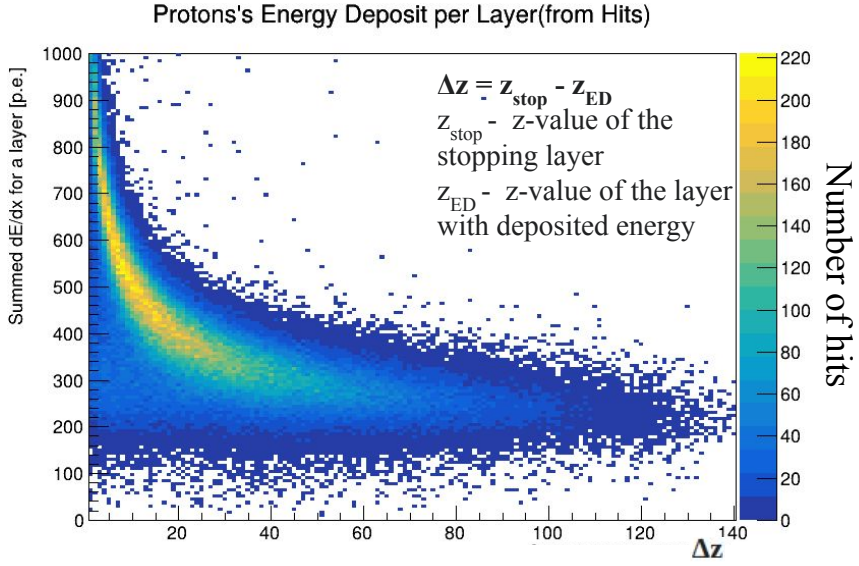


Proton Stopping Sample: Hits info MC

- Only unique hits are used
- Hits within an event are sorted by Z and grouped into spatial clusters
- Isolated clusters are selected (no common vertices within 2 cubes of track start/end)
- **Clusters with gaps are rejected (direction and alignment cut)**
- Clusters must be straight (χ^2 cut)
- Isolated clusters must stop inside the fiducial volume (FV)
- Clusters with fewer than 6 cubes are excluded
- Clusters in all directions are used
- Stopping cube layer is excluded from distribution







Summary

- **Lifetime Measurement & Bragg Peak Analysis:**

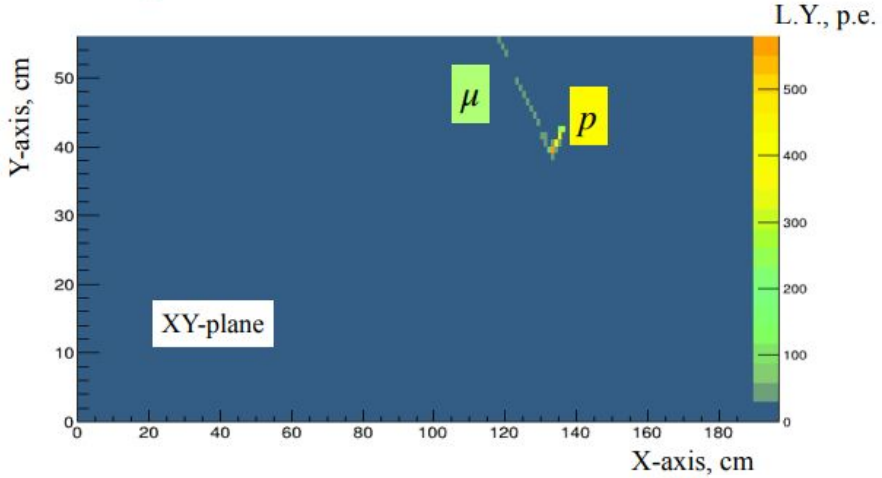
  - Muon Selection: The selection of stopped muons has been validated. The reconstructed muon lifetime of 2049.1 ± 132 ns is in good agreement with the PDG world average 2196.9811 ± 0.0022 ns

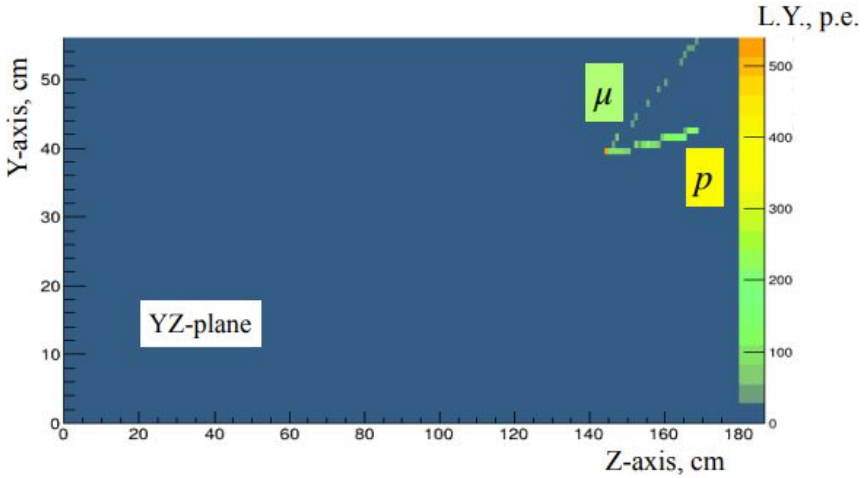
  - Bragg Curve Agreement: The Bragg curves show good agreement between data and Monte Carlo simulation, produced specially for SFGD. Further refinement of the Birks' constant is expected to improve this agreement.

  - Michel electron spectra: Recondstructed spectra significantly differs for data/MC, which requires further studies**.**

BACK UP

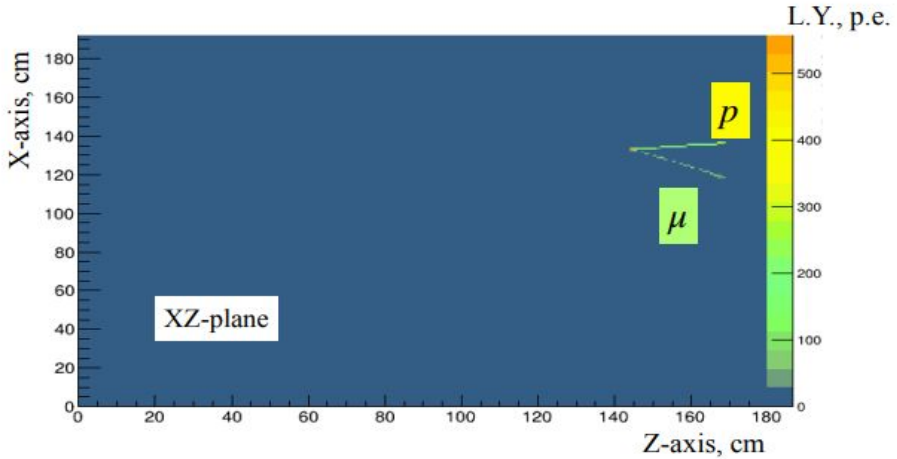
SFGD current status - neutrino event display





Charged-current quasi elastic (CCQE) scattering of ν_μ on CH gives muon and proton at the final state:

$$\nu_\mu + n \rightarrow \mu^- + p$$



SuperFGD test beams - 2019/2020

<u>2019-2020:</u> 2 Super-FGD prototypes have been exposed to a neutron beam in Los Alamos

– Important measurement to demonstrate neutron detection capability
– First measurement of neutron cross-section in scintillator
– Achieved time resolution for neutrons is 0.5 ns

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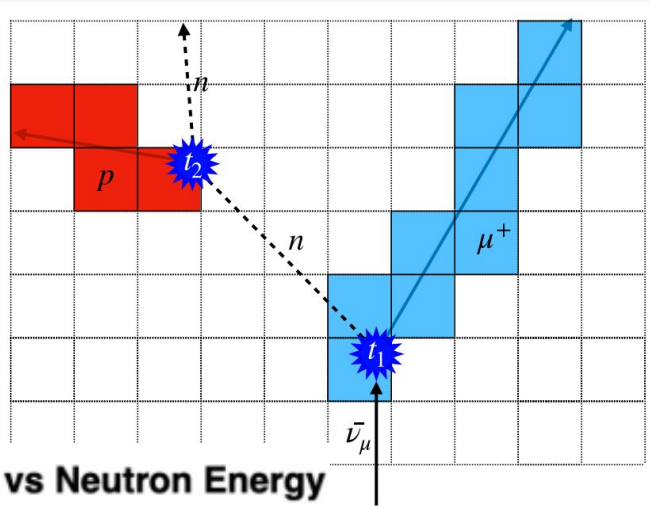
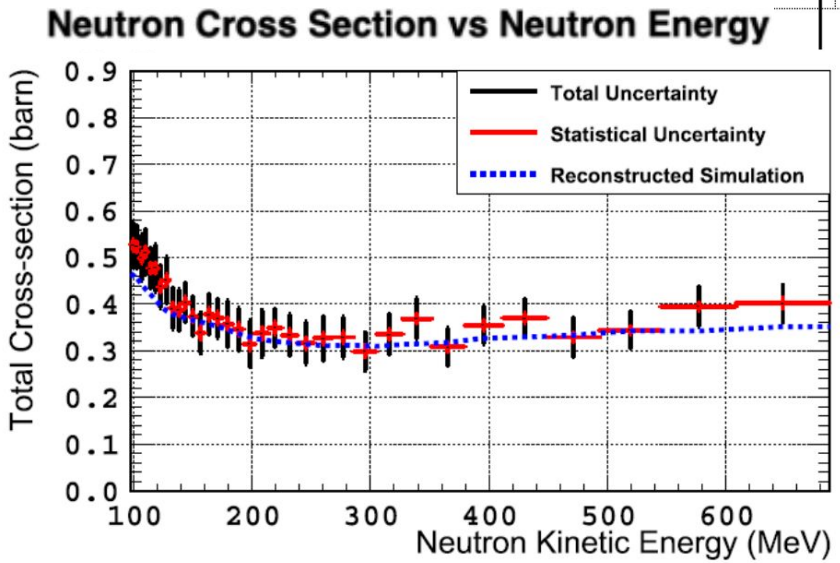
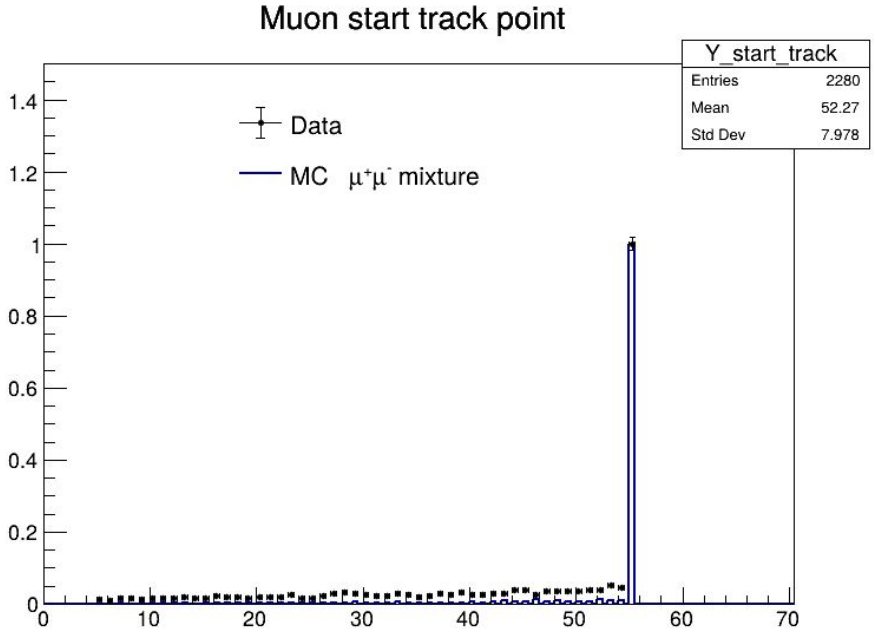
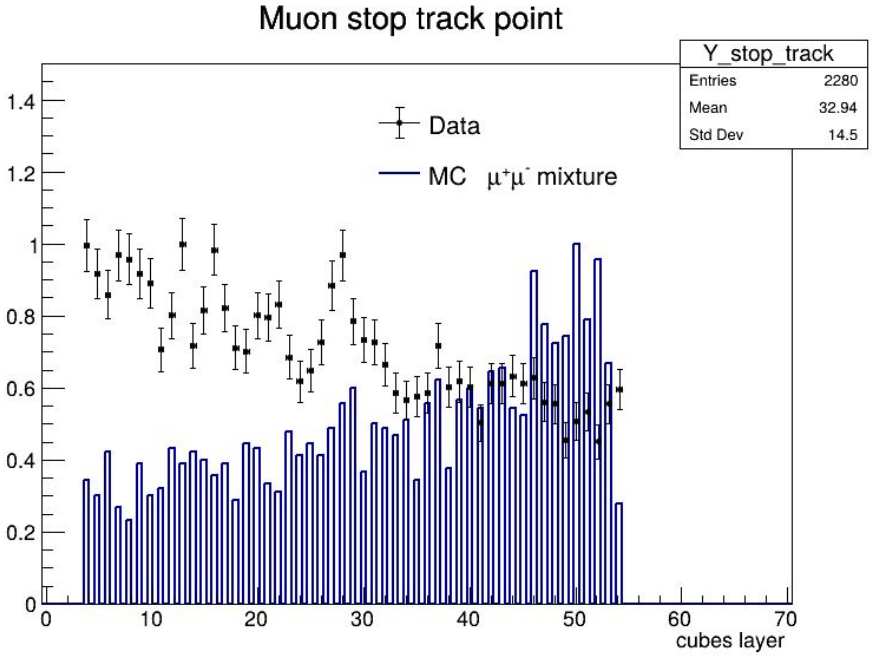


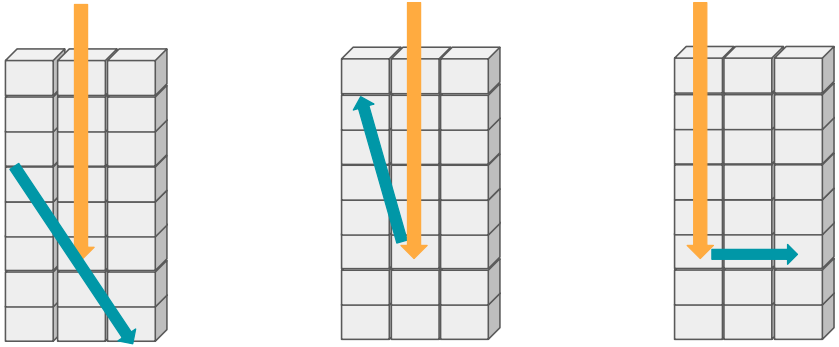


Muon Stopping Sample: MC sample issues



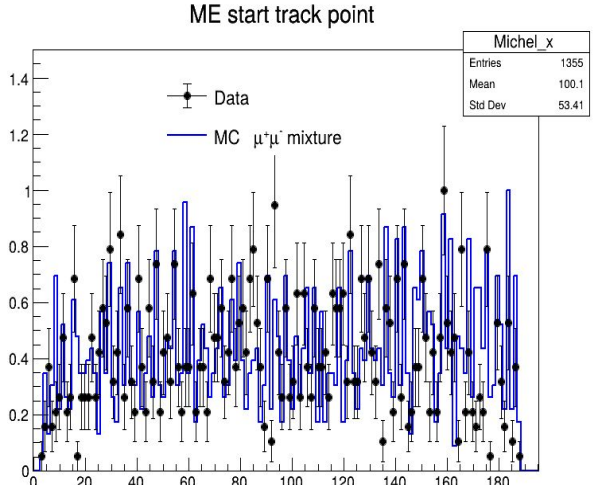


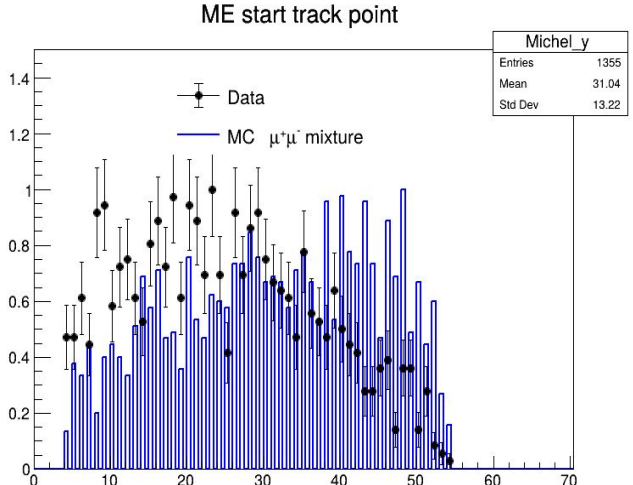
Reco info: Secondary

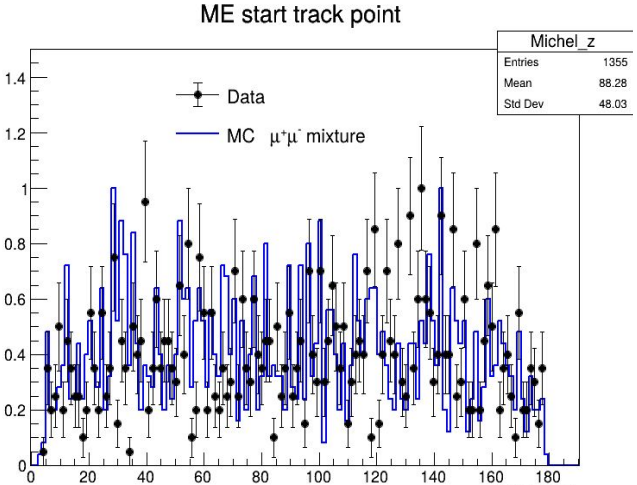


Evaluation of the Distance to the Stopping Point:

1) The **track's axis** is defined by the highest **Δ**.
2) Distances from both ends of the track to the muon stop point are calculated.
3) **The end with the shorter distance is defined as the start of the secondary track.**
4) **This starting point is checked if it lies within the muon stop cube or its neighbors.**







Reco info: ME

For pairs of muon+ME selected via previous analysis the difference in muon stopping point and ME starting point was evaluated.

- **Distribution of the distance between the ME and muon for MC and Data have different shapes, which also points to the MC/DATA inconsistency.**