Analysis of anomalous tau neutrino appearance in the DUNE Near Detector

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Objectives

- Evaluate the eventual tau neutrinos that we may have in the DUNE Near Detector that come from short-baseline oscillations driven by sterile neutrino mixing with larger values of Δm^2 .Assuming a 3+1 model :

$$P(\nu_\mu \to \nu_\tau) \approx sin^2(2\theta_{\mu\tau}) sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

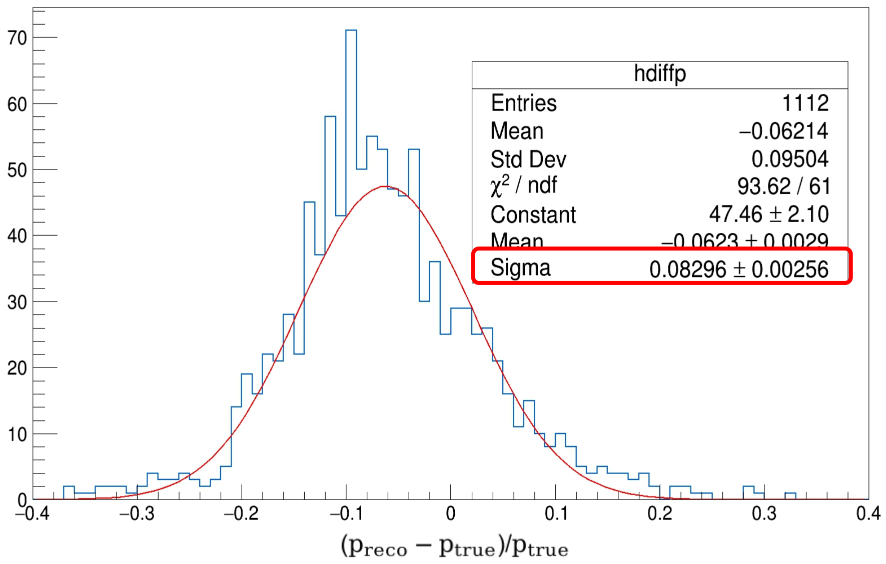
$$\begin{aligned} sin^2(2\theta_{\mu\tau}) &= 4|U_{\mu 4}|^2|U_{\tau 4}|^2 \\ &= cos^4\theta_{14} sin^2(2\theta_{24}) sin^2(\theta_{34}) \end{aligned}$$

- Specifically : Evaluate how using the ND-GAr-Lite, ND-GAr or TMS may impact the sensitivity of the DUNE ND to anomalous ν_τ CC appearance.

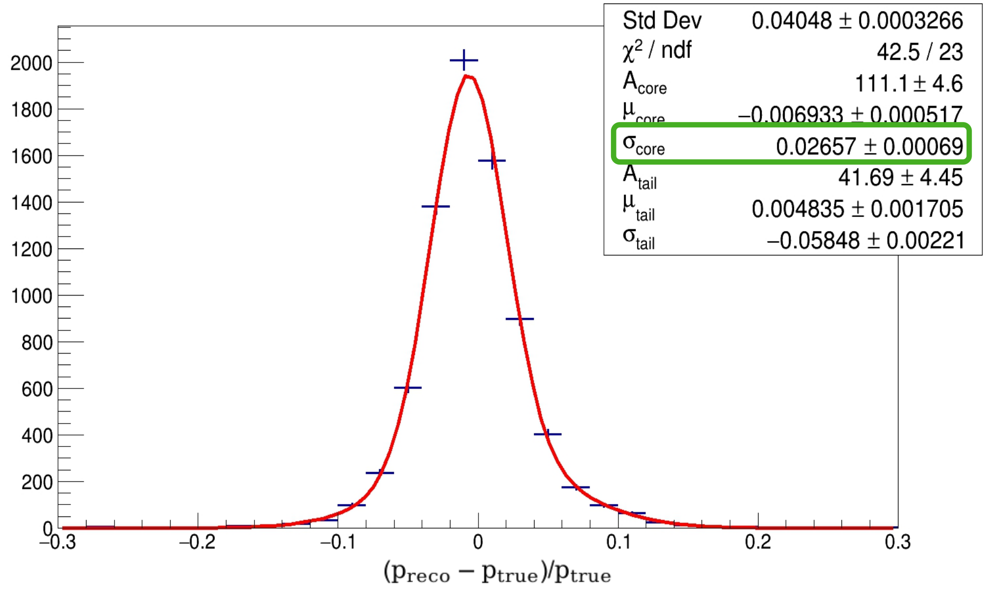
True vs Reco Energy 0 to 8 GeV for ND - GAr (Review)

- Changed and analyzed several reconstruction parameters in GArSoft with Tom Junk's advice
- Changes in Kalman gain parameters: parameters that go in the fitting process, it regulates how the fitted tracks closely follows the muon hits.
- The Kalman gain parameters were too high, the fitted tracks followed the hits too close and it caused problem at the end due to the scattering of the TPC Clusters.

Previous Plot



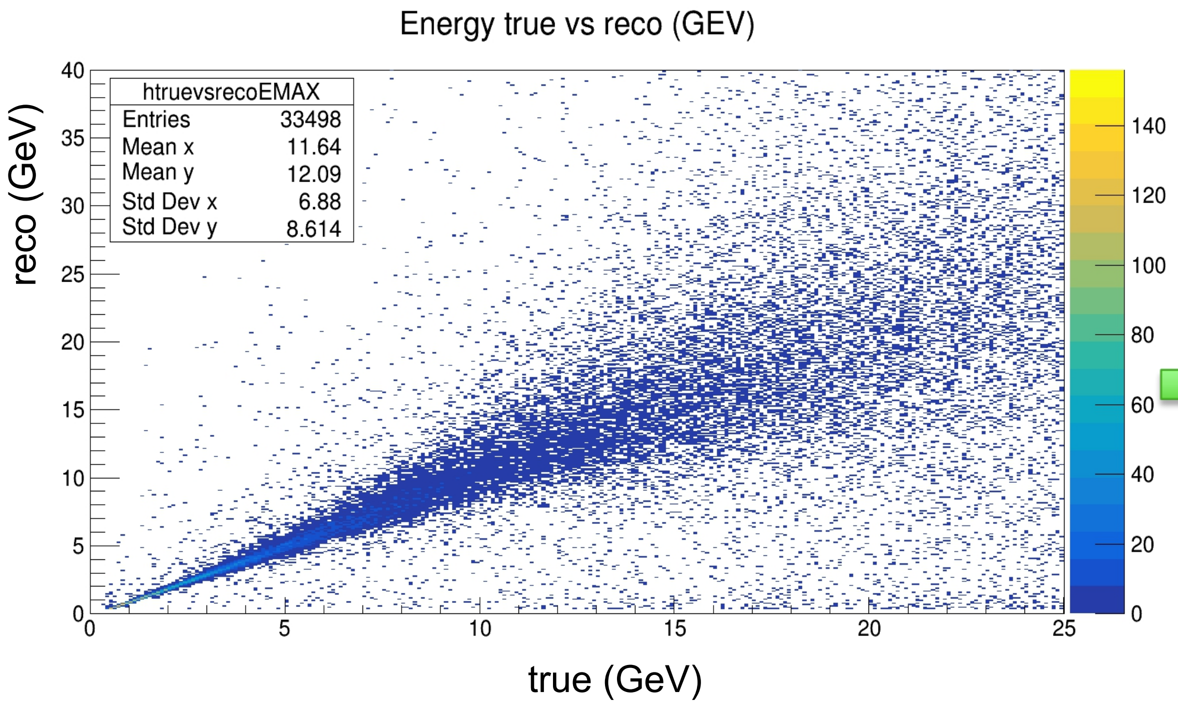
After Kalman Gain parameter change



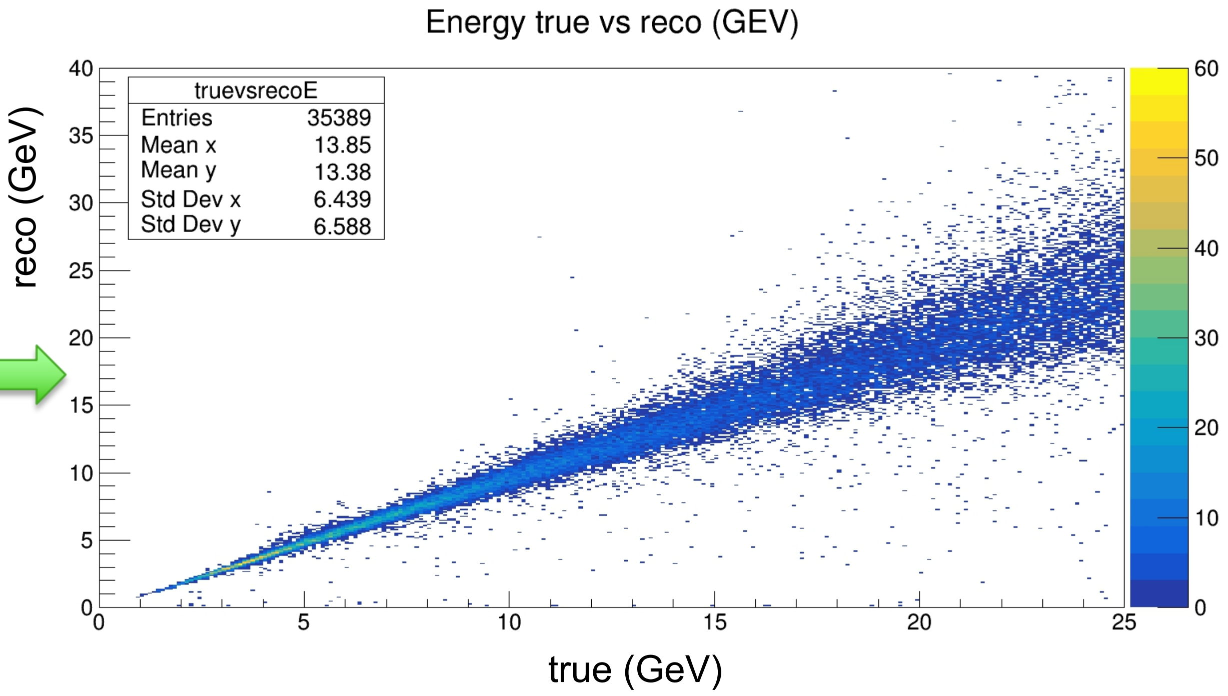
- Reduce the Kalman Gain parameters from 1e-8 to 1e-9.

True vs Reco Energy 0 to 25 GeV

Before parameter change



After Kalman Gain parameter change

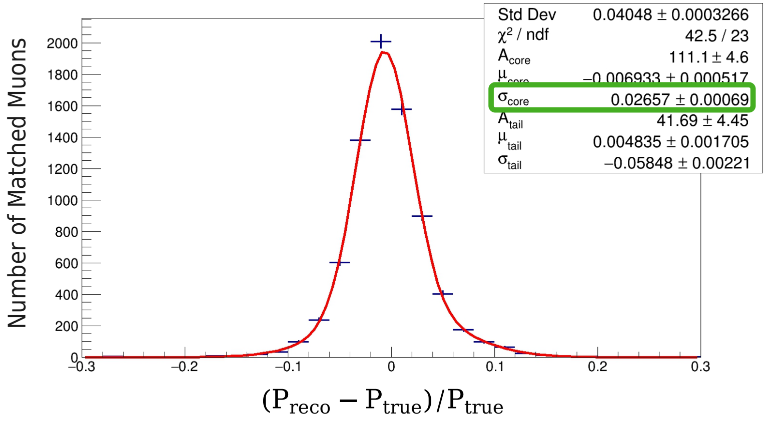


Muon momentum resolution using ND GAr

- The plots represent the muon momentum resolution at different energy range for ND GAr.
- Each plot shows the $\frac{P_{reco} - P_{true}}{P_{true}}$ distribution, which is fitted with a double gaussian.

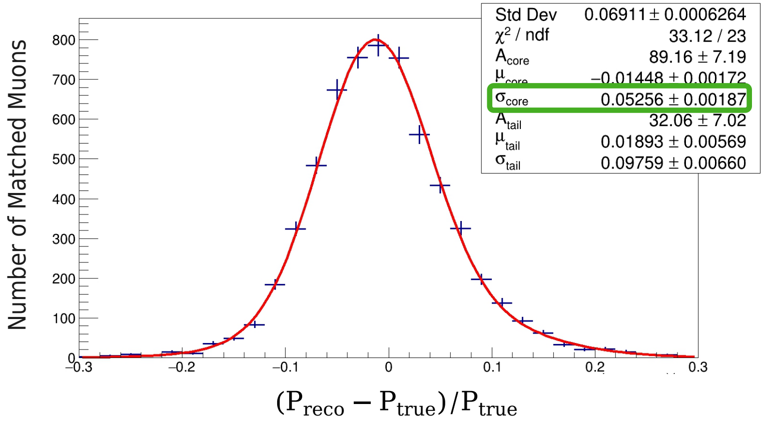
0 to 8 GeV

σ_{core} **= 0.027**



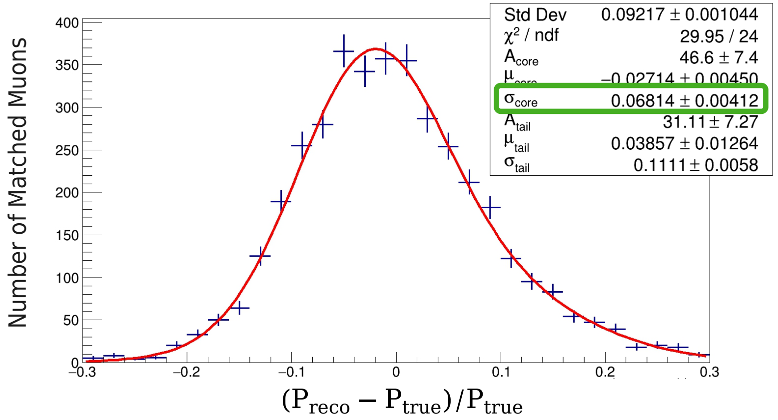
8 to 14 GeV

σ_{core} **= 0.052**



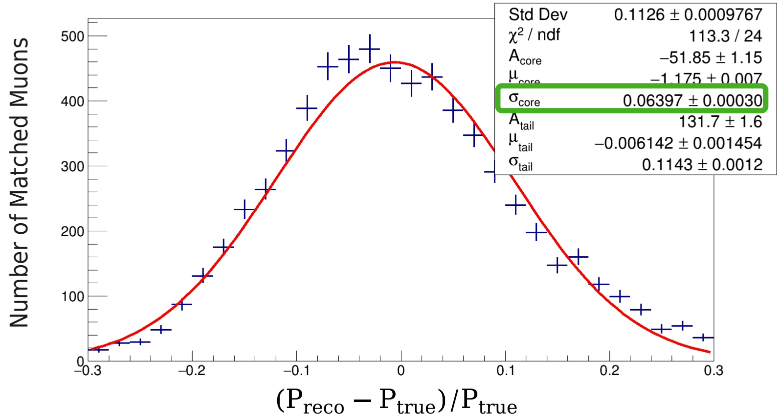
14 to 18 GeV

σ_{core} **= 0.063**



18 to 25 GeV

σ_{core} **= 0.068**

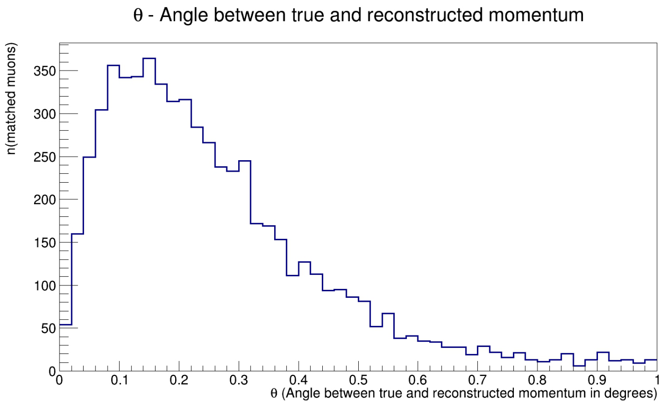


Muon angular resolution using ND GAr

- The plots represent the distributions of the angle between the true muon direction and the reconstructed muon direction for different energy ranges.

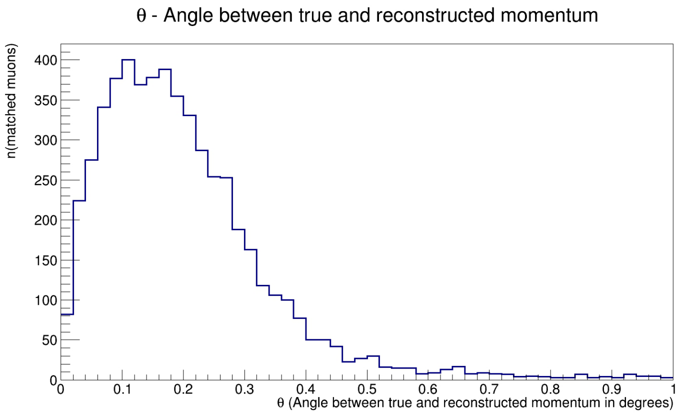
0 to 8 GeV

Angular resolution : 0.44 deg



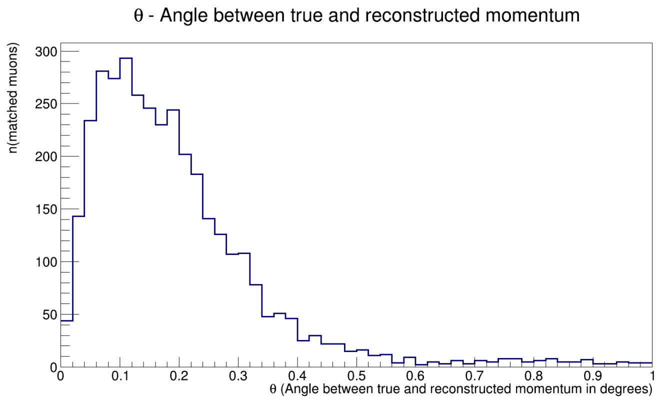
8 to 14 GeV

Angular resolution : 0.27 deg



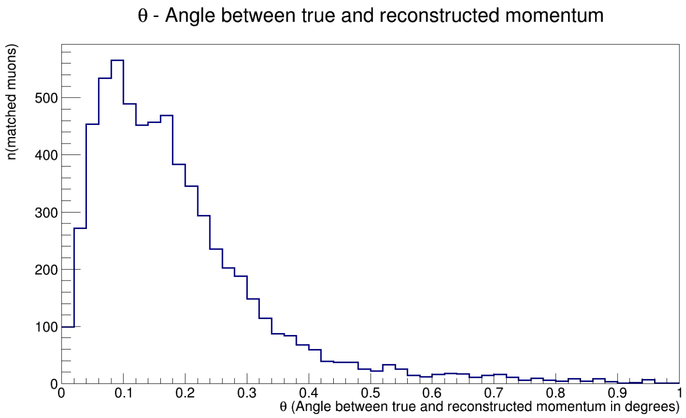
14 to 18 GeV

Angular resolution : 0.25 deg



18 to 25 GeV

Angular resolution : 0.24 deg

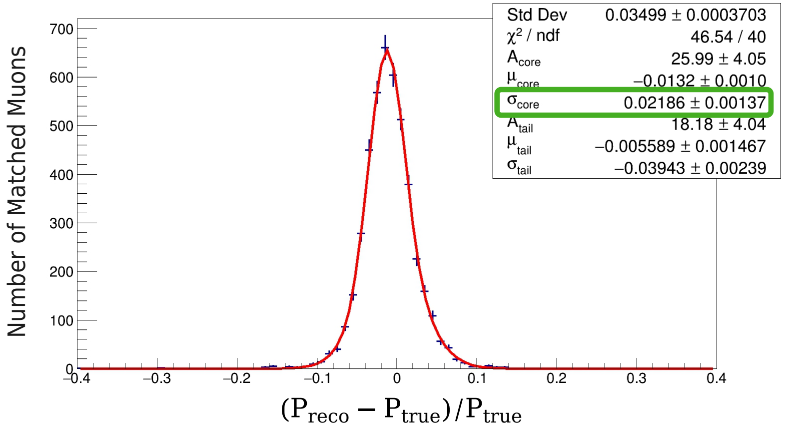


Muon momentum resolution using ND GAr-Lite

- The plots represent the muon momentum resolution at different energy range for ND GAr-Lite.
- Each plot shows the $\frac{P_{reco} - P_{true}}{P_{true}}$ distribution, which is fitted with a double gaussian.

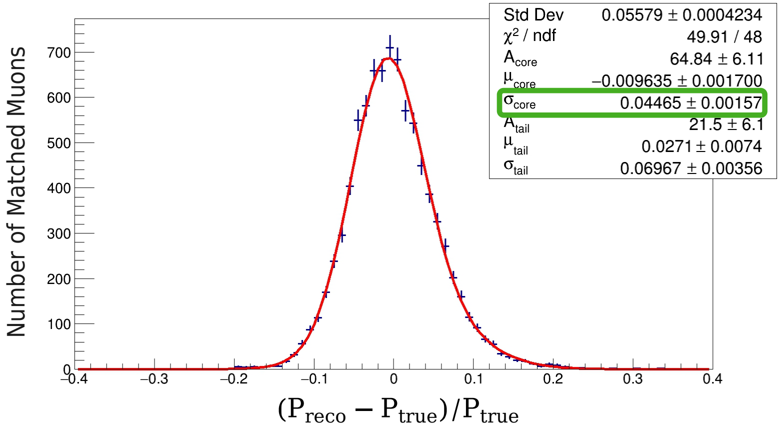
0 to 8 GeV

σ_{core} = 0.022



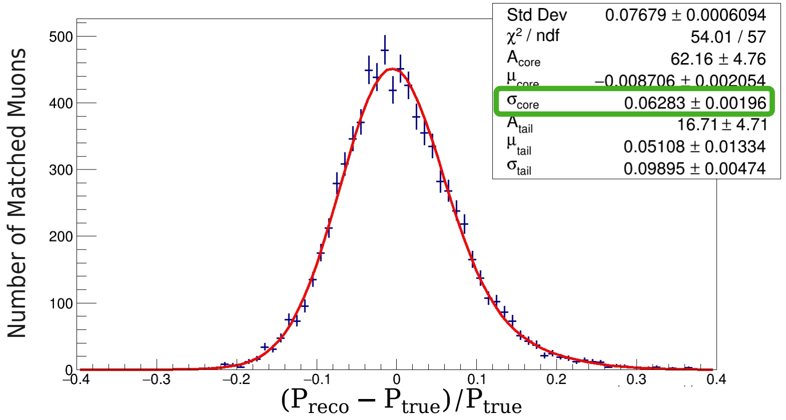
8 to 14 GeV

σ_{core} = 0.045



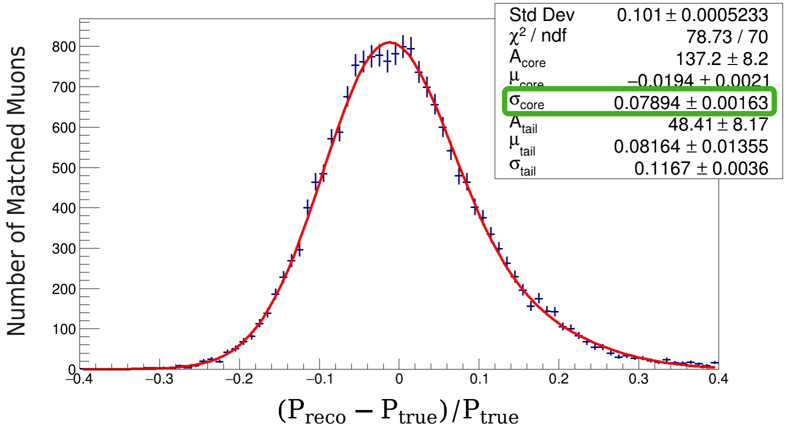
14 to 18 GeV

σ_{core} = 0.063



18 to 25 GeV

σ_{core} = 0.079

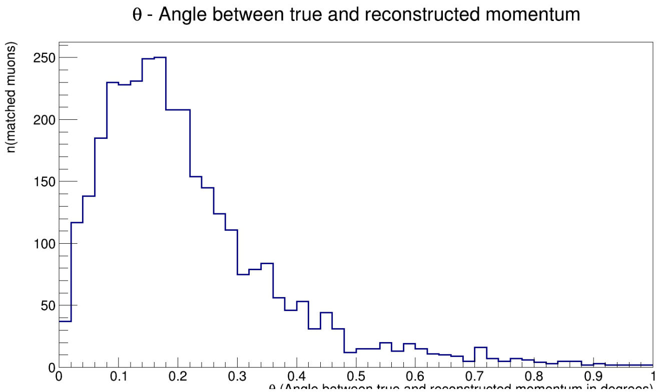


Muon angular resolution using ND GAr-Lite

- The plots represent the distributions of the angle between the true muon direction and the reconstructed muon direction for different energy ranges.

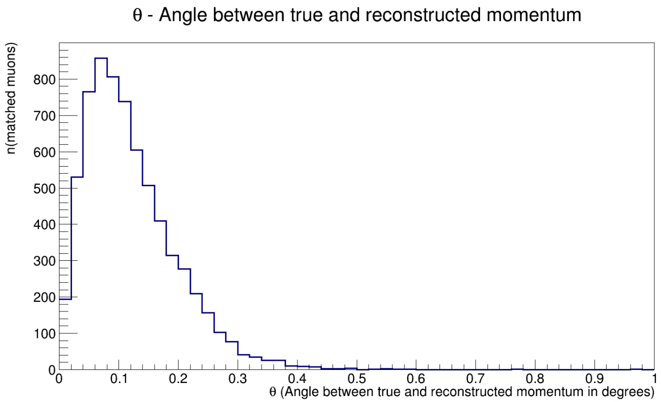
0 to 8 GeV

Angular resolution :0.45 deg



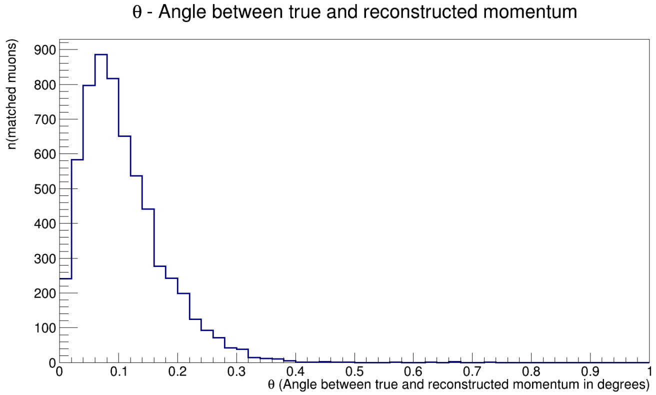
8 to 14 GeV

Angular resolution : 0.21 deg



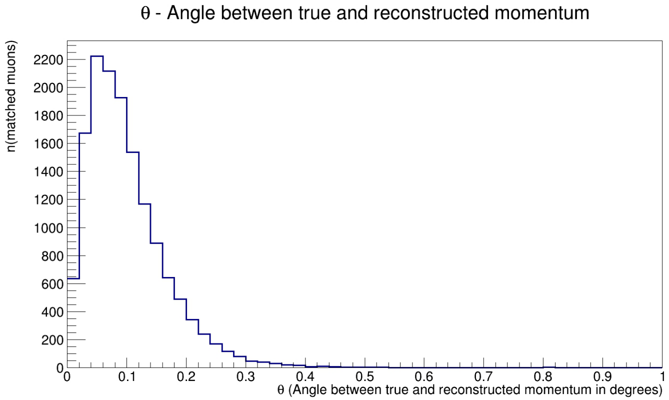
14 to 18 GeV

Angular resolution : 0.19 deg



18 to 25 GeV

Angular resolution : 0.18 deg



ND GArLite vs ND GAr

Energy (GeV)	ND GAr-Lite		ND GAr	
Resolution	Momentum	Angular	Momentum	Angular
0 - 8	2.186 %	0.452147 °	2.657 %	0.439295 °
8 - 14	4.465 %	0.213239 °	5.256 %	0.268346 °
14 - 18	6.283 %	0.194204 °	6.397 %	0.250816 °
18 - 25	7.894 %	0.178582 °	6.814 %	0.235035 °

Sensitivity to ν_τ appearance Muon channel only

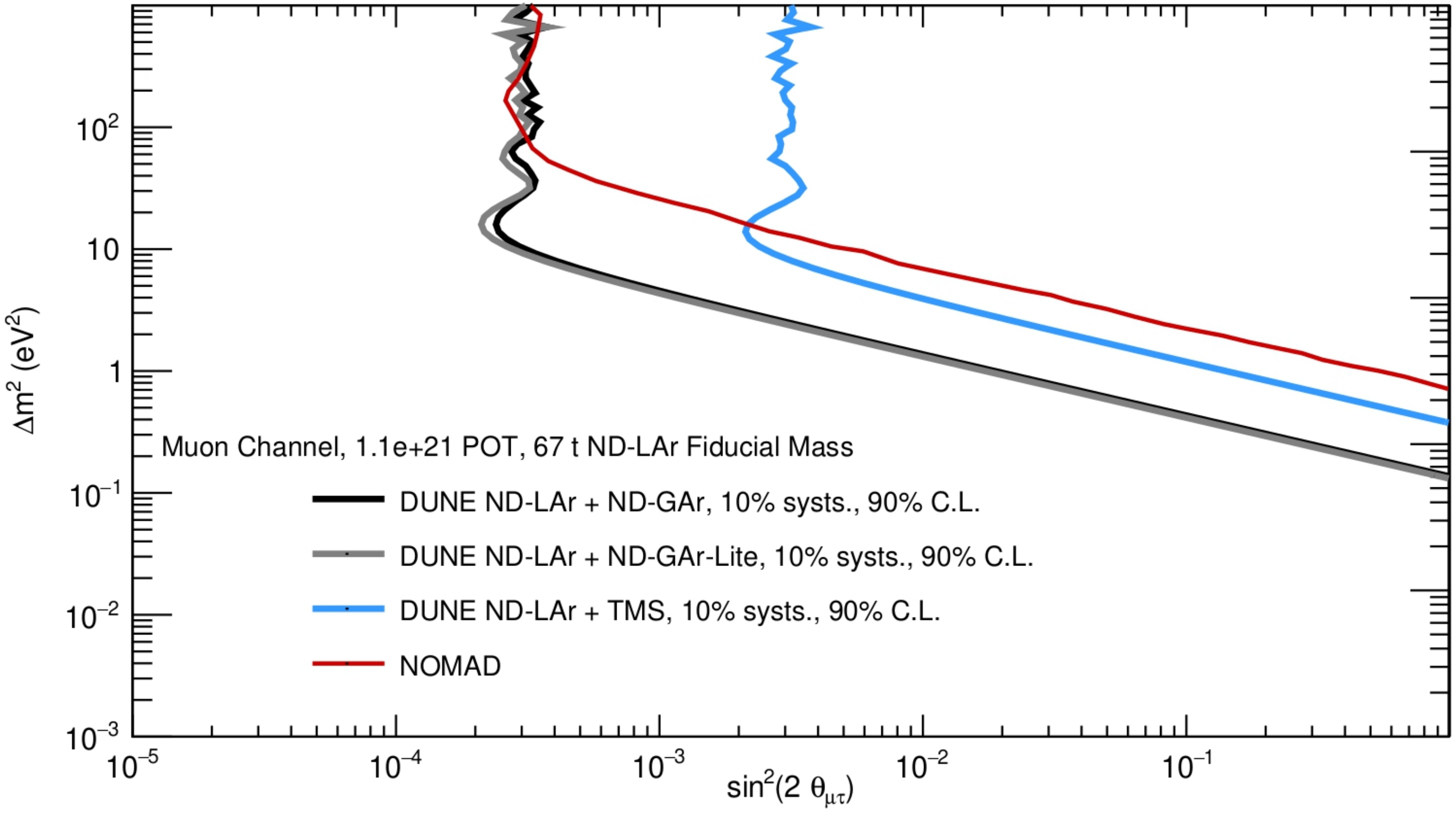
- Using the DUNE tau optimized flux for a year of running and 67t fiducial mass for ND-LAr. The kinematic information from GENIE was used.

- Muon smearing based on the ND GAr and ND GAr-Lite energy resolution was applied to the GENIE kinematic information. For the hadronic system, ND LAr expected resolutions were used.

- Considered an overall 10% systematic uncertainty.

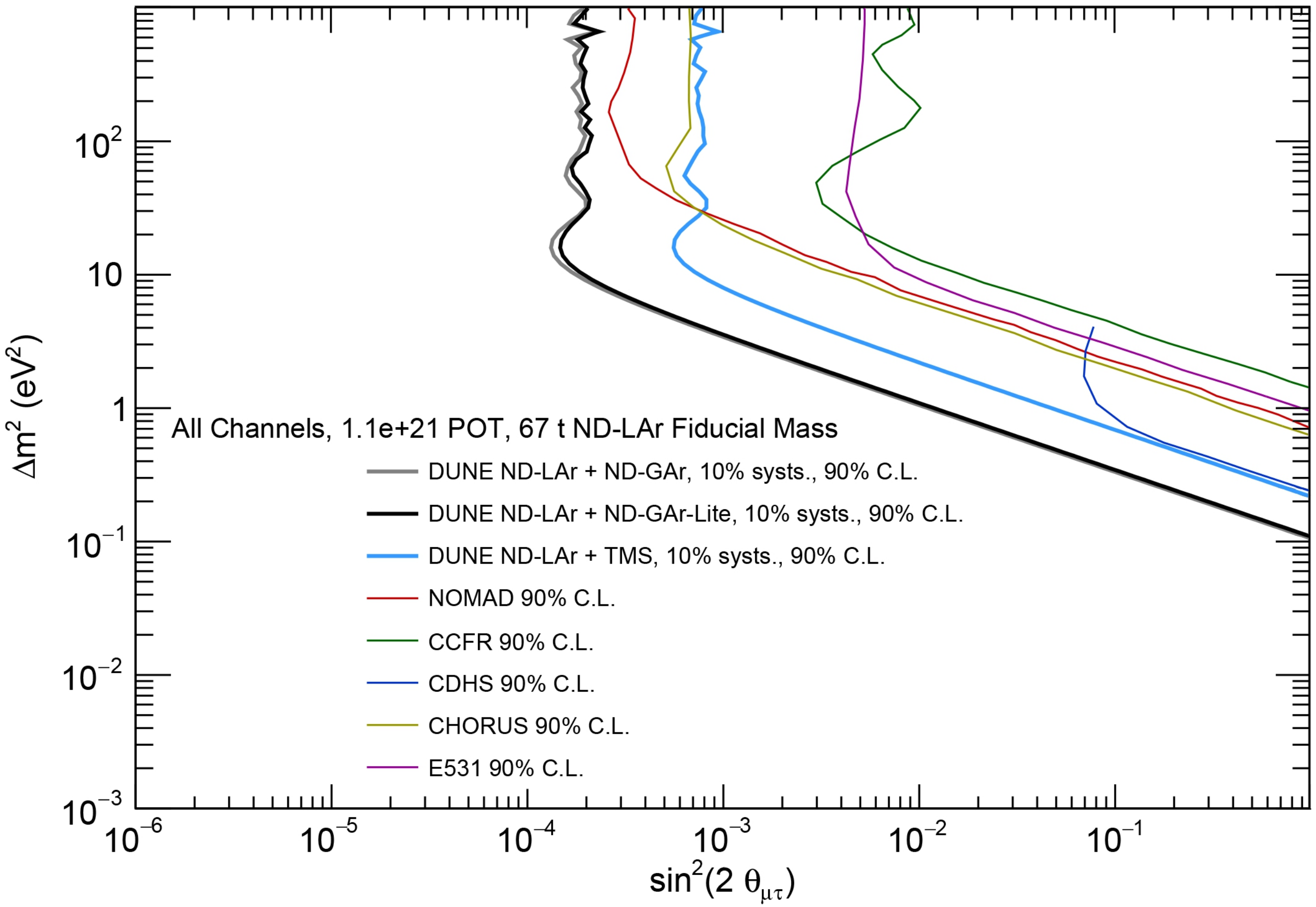
- High BDTG cuts were applied to both ND GAr (BDTG score > 0.9965) and ND GAr-Lite (BDTG score > 0.9969) corresponding to regions with almost no backgrounds.

- TMS sensitivity includes neutrino interactions contained inside ND-LAr+TMS, corresponding to muon energies below 6 GeV.



Sensitivity to ν_τ appearance
Muon + Electron + Rho decay channels

- Apart from the muon channel, the electron and rho τ decay channels were also considered (for the electron and rho channel, only the ND-LAr was considered).
- Considered an overall 10% systematic uncertainty.
- Smearing according to each detector's expected resolution was applied.



Summary

- ND GAr and ND GAr-Lite offers comparable muon momentum and angular resolution with the ND GAr-Lite having slightly better resolution.

- They both allow the possibility of reconstructing charged muon momentum with great resolution.

- With high BDTG score cuts (region with almost no background) and high-energy beam configuration, DUNE offers the possibility of leading sensitivity to anomalous short-baseline nutau appearance.

- Next steps in this analysis include adding the SAND detector, and considering additional hadronic decay channels, like the single pion channel, to further improve the sensitivity.

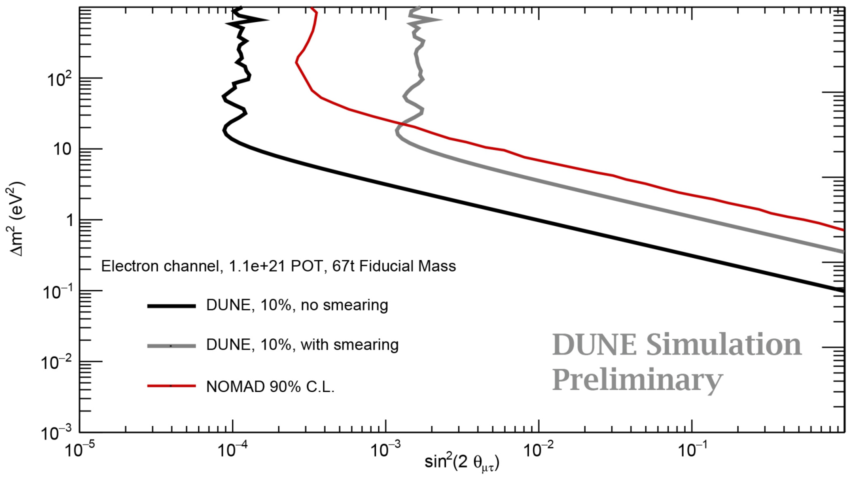
BACKUP

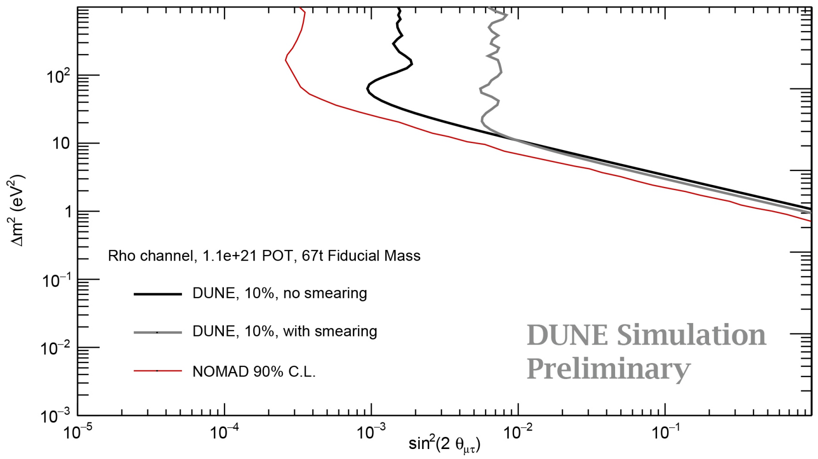
Sensitivity

- Sensitivity : based on event counting. All events were normalized such that they would correspond to **1.1e21 P.O.T.** and **67t** fiducial mass.

$$FOM_{stats} = \frac{signal}{\sqrt{signal + background}} \qquad FOM_{systs} = \frac{s}{\sqrt{(s+b) + (\mathbf{0.1}*(s+b))^2}}$$

- Event cuts : region with almost no backgrounds, events scoring a very high BDTG score were selected.
  - advantage : improvement of sensitivity for the non smeared case
  - disadvantage : harsher cuts for the case with smearing due to the BDTG Classifier's reduced performance in selecting smeared events → ongoing work : use Deep Neural Network instead of BDTG as it is more robust against smearing.





- Electron channel : select events with ν_τ BDTG score > 0.995
- Rho channel : select events with ν_τ BDTG score > 0.99