Search for tau neutrino appearance in the DUNE Near Detector Complex

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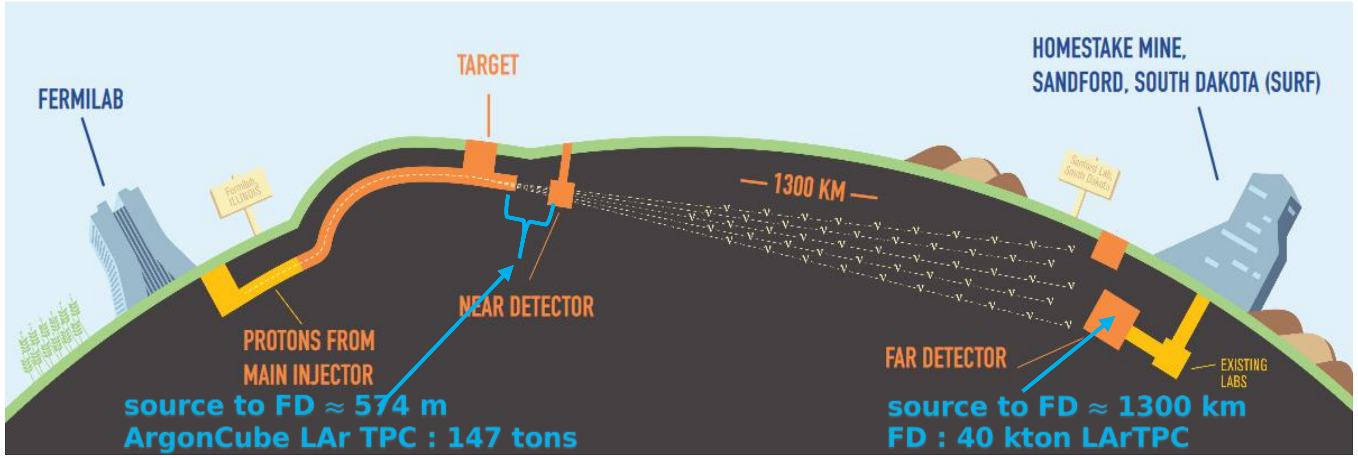
DUNE Experiment

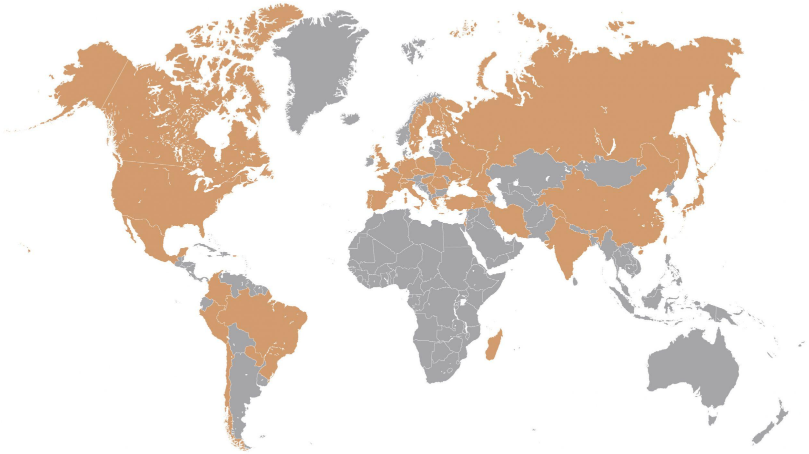
DEEP UNDERGROUND NEUTRINO EXPERIMENT

- LBL experiment with a baseline of 1300 km (Fermilab to South Dakota)
- Uses a ν_μ beam provided by the LBNF Facility (with a small ν_e contamination).



DUNE PRIMARY PHYSICS GOALS

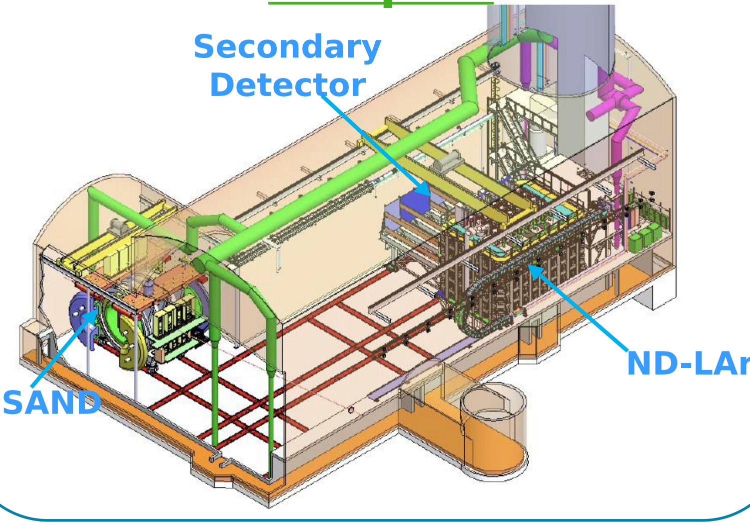
- Measurements of CP violation in the lepton sector.
- Resolving degeneracies by determining the neutrino mass ordering (the sign of $\Delta m^2_{31} \equiv m^2_3 - m^2_1$).
- Precise measurement of the mixing angle θ_{23} and determination of the octant in which it lies.
- Search for Physics Beyond the Standard Model.



- **~1300 Collaborators**
- **205 Institutions**
- **More than 30 countries**

DUNE Near Detector Complex

DUNE Near Detector complex

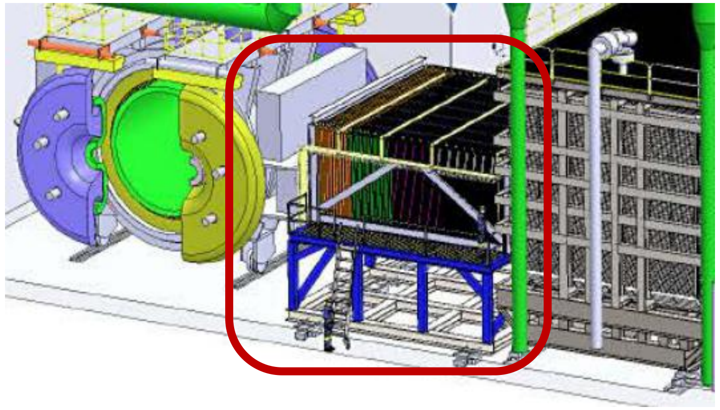


Phase I :

- Neutrino beam with 1.2 MW power
- Near detector: ND-LAr + TMS (PRISM)+ SAND
- 2 x 17kt Far Detector modules

DUNE Phase I Secondary Detector

TMS

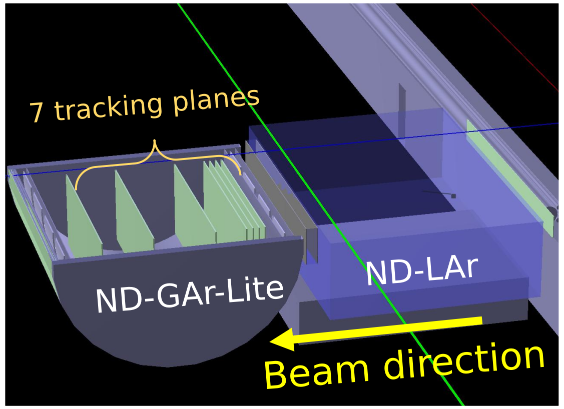


Temporary Muon Spectrometer

- Slice the steel block into planes and put detectors between each plane.
- Composed by 3 m of steel (thickness) divided into 100 layers spaced along 7 m longitudinally.
- First 40 (42) layers are 15 mm thick.
- Last 60 (58) layers are 40 mm thick.
- Detector design
  - MINOS/mu2e-like (co-extruded polystyrene).
  - Each plane (of 100) has four panels (192 channels).
  - Each panels are tilted ±3° in alternating layers.

ND - GArLite (alternative detector proposal)

Andrew Cudd



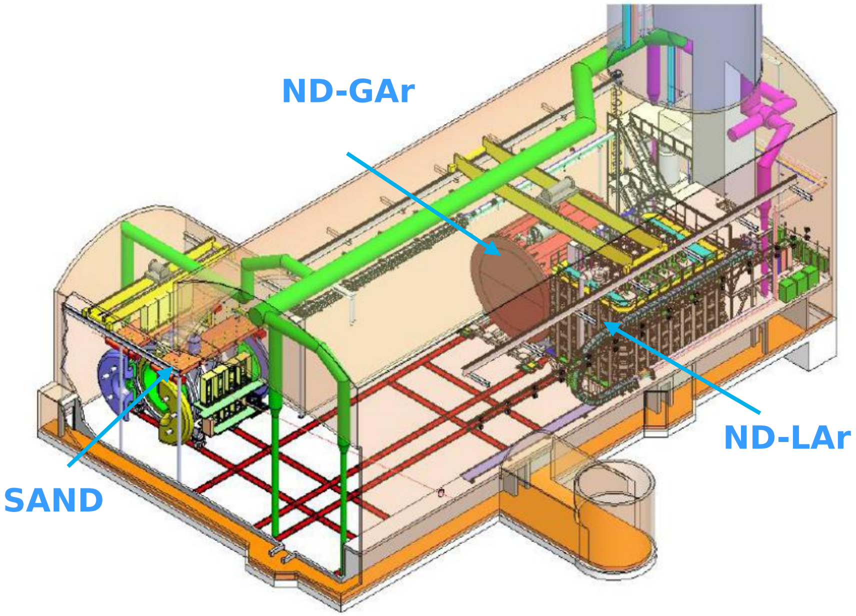
- Superconducting magnet + Scintillator tracking planes.
- Overall Detector Dimension: 8.4 m in diameter and 8.4 m in width.
- Superconducting magnet provides a nominal 0.51 T magnetic field.
- Scintillator tracking planes has a design of 7 tracking planes.

DUNE Near Detector Complex

Phase II :

- Fermilab proton beam upgrade to 2.4 MW
- Near detector: ND-LAr + MCND (ND-GAr) + SAND
- 4 x 17kt FD modules

DUNE Phase II ND



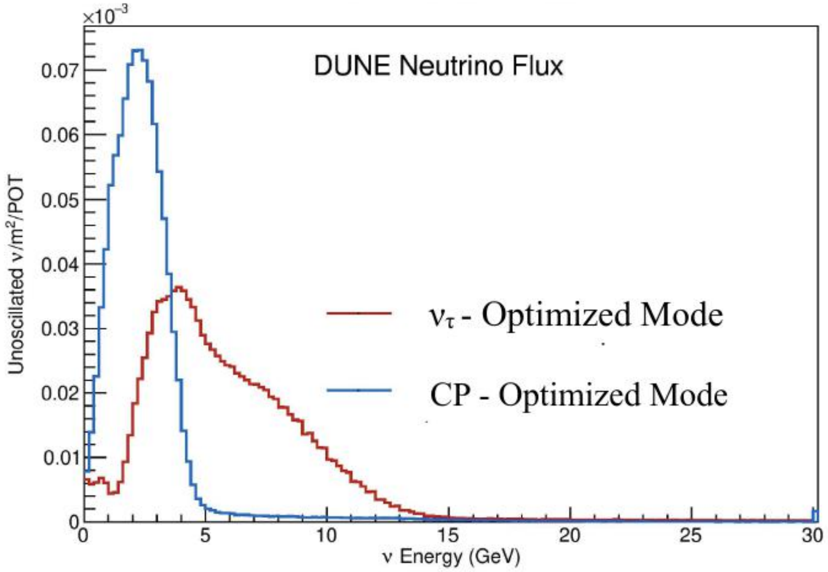
ND-GAr is a magnetized detector system consisting of a high-pressure gaseous argon TPC (HPgTPC) surrounded by an electromagnetic calorimeter (ECAL), in a 0.5T magnetic field.

- Can measure ν-Ar interactions with low thresholds to better understand hadronic system details and improve cross section uncertainties.
- Excellent spectrometer for tracks that exit ND-LAr: track sign and momentum from curvature in magnetic field

- The excellent resolution of the detectors**,** intense neutrino flux from LBNF and the short baseline of 574 m makes the DUNE ND ideal for a **sterile neutrino search**.

Objectives of the analysis

- ν_τ measurements are challenging due to the 3.5 GeV τ production threshold.
- **DUNE is in a unique position to probe the ν_τ sector:**
  - DUNE has a flexible beamline that can be optimized for higher energy flux for ν_τ studies.
  - DUNE can have a dedicated ν_τ optimized beam run during Phase II.



Beam configuration: higher energy neutrino beam optimized for ν_τ appearance.

Objectives

- Evaluate DUNE's ability to probe potential tau neutrino appearance in the ND from short-baseline oscillations driven by sterile neutrino mixing. Assuming a 3+1 model :

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

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

- Study tau neutrino interactions in the primary ND-LAr detector and evaluate how different secondary detector designs impact the sensitivity to tau neutrino appearance.

- Simulation: GENIE information was used.

Event display examples for ND-GAr

- Several τ decay channels were considered for the analysis and we focused particularly on the muon case.
- Only a small fraction of muons from tau decay will be contained in the ND-LAr, so secondary detectors like ND-GAr are needed to measure their momentum.
- ND-GAr reconstructs muon momentum from curvature.

ND-GAr
GArSoft event display

True energy = 1.408 GeV
Reco energy = 1.409 GeV

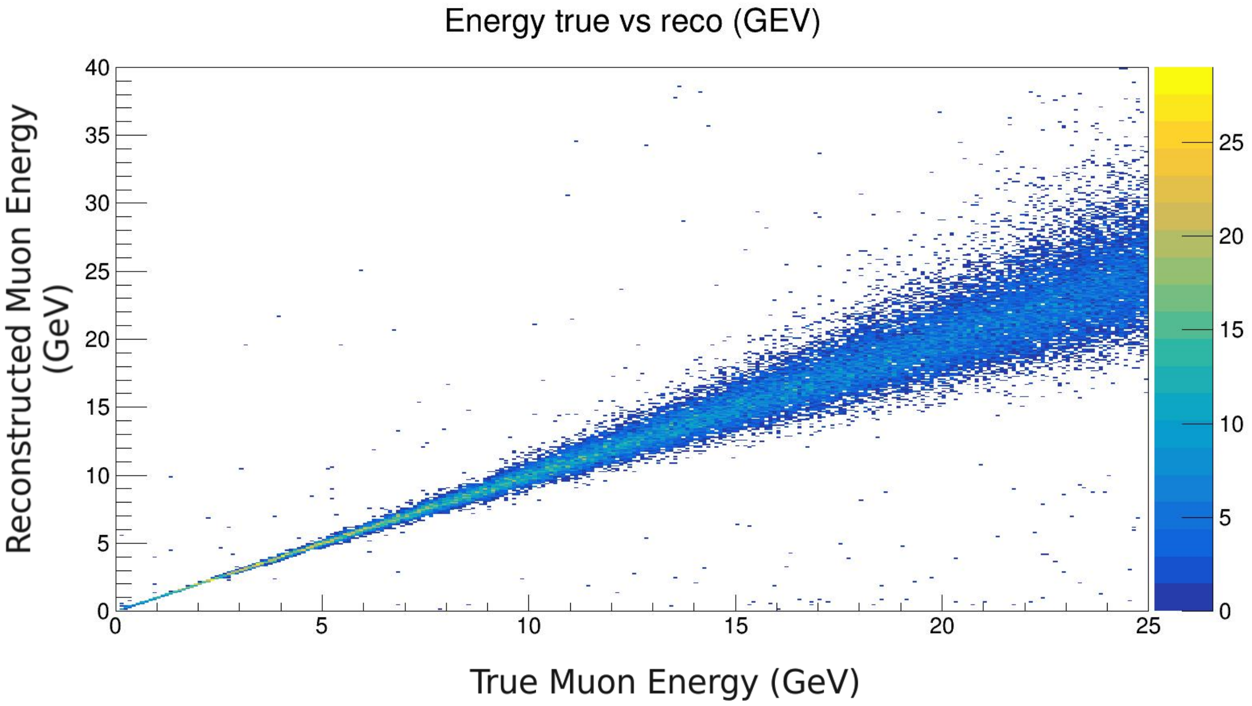
ND-GAr
GArSoft event display

True energy = 8.531 GeV
Reco energy = 8.578 GeV

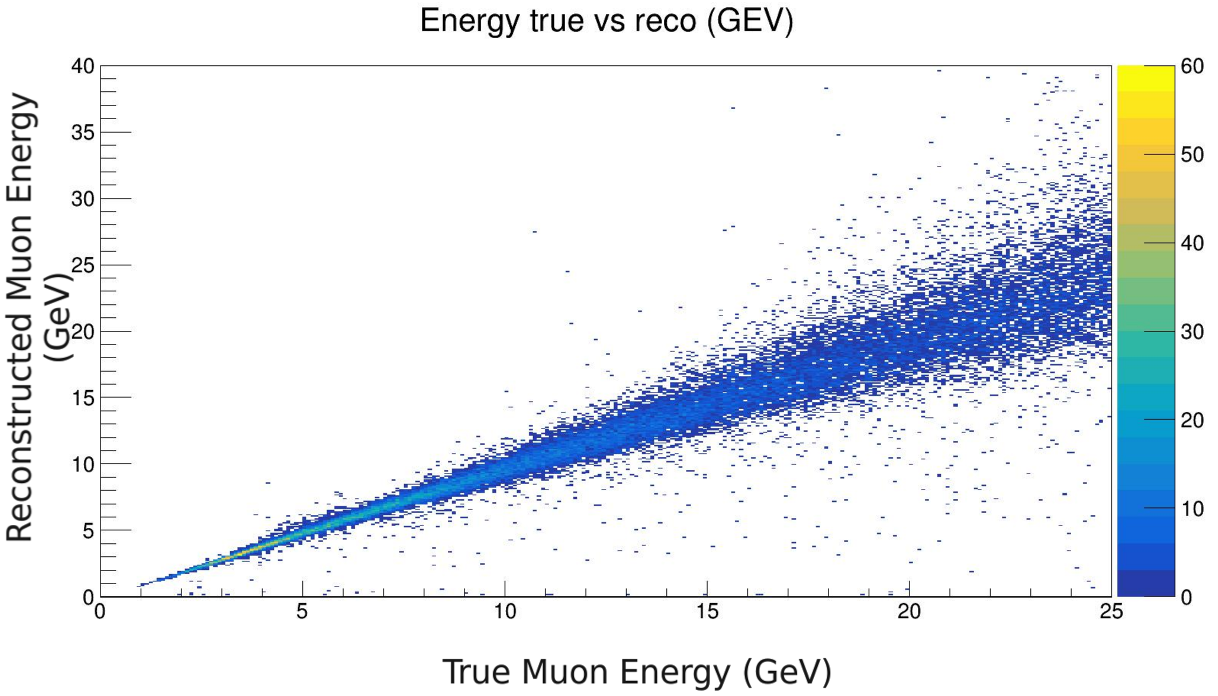
Muon energy reconstruction using ND GAr-Lite and ND GAr

- Several τ decay channels were considered for the analysis with a particular focus on the muon case.
- Only a small fraction of muons from tau decay will be contained in the ND-LAr.

ND GAr-Lite



ND - GAr

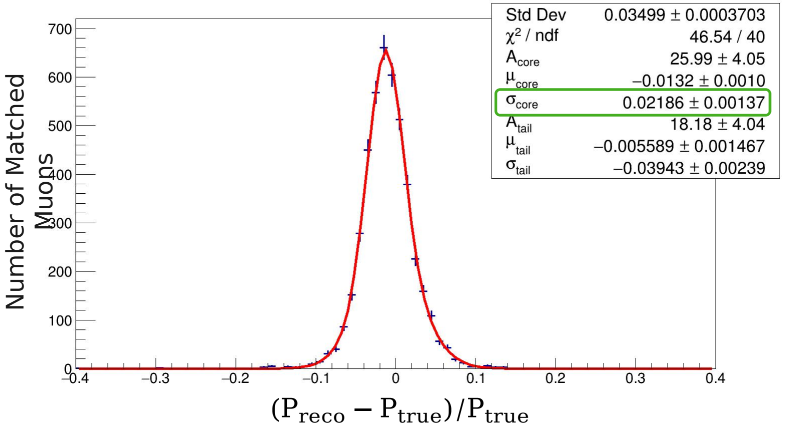


Muon momentum resolution using ND GAr-Lite

- 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.

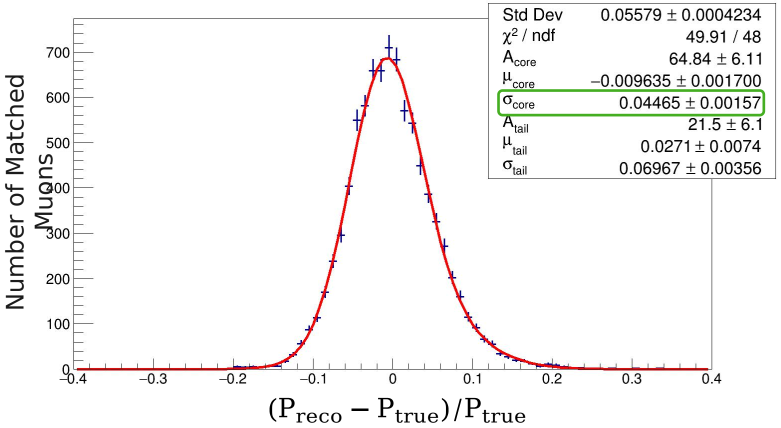
0 to 8 GeV

σ_{core} **= 0.022**



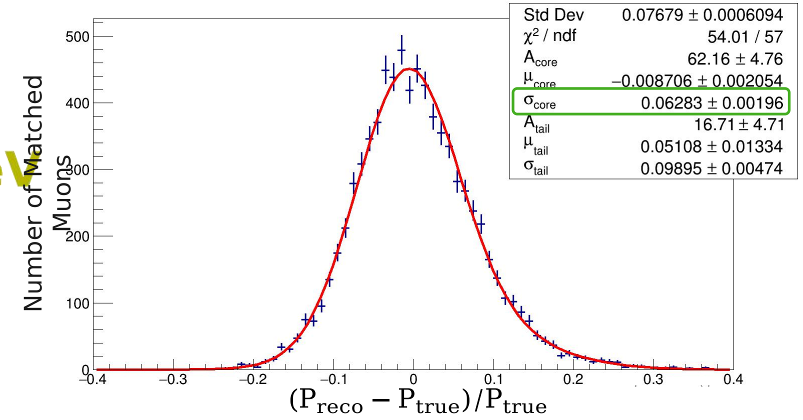
8 to 14 GeV

σ_{core} **= 0.045**



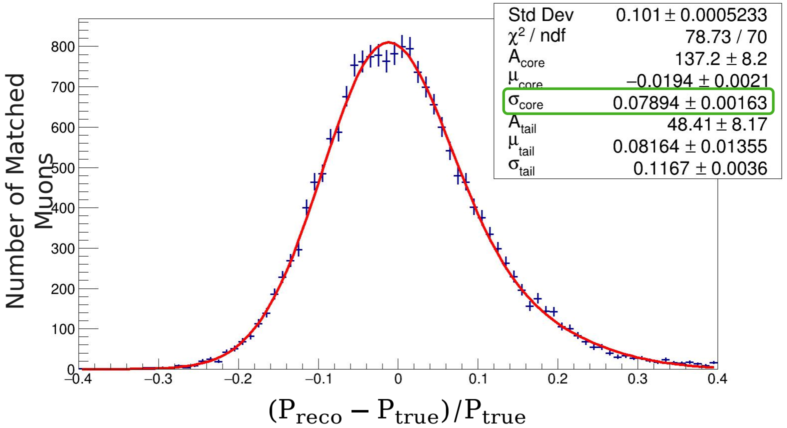
14 to 18 GeV

σ_{core} **= 0.063**



18 to 25 GeV

σ_{core} **= 0.079**

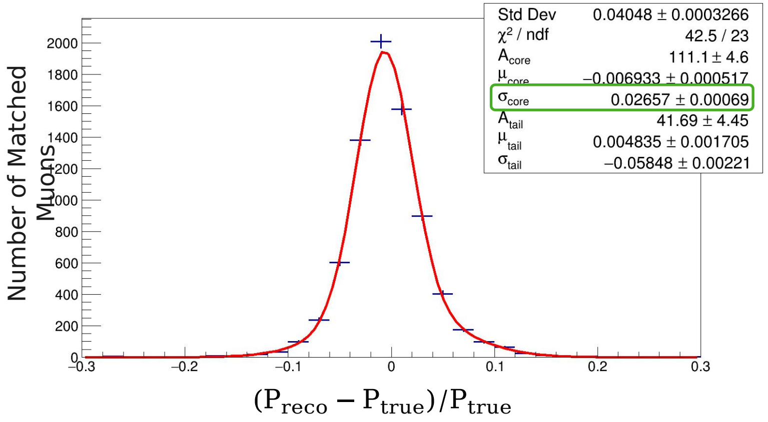


Muon momentum resolution using ND GAr

- 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.

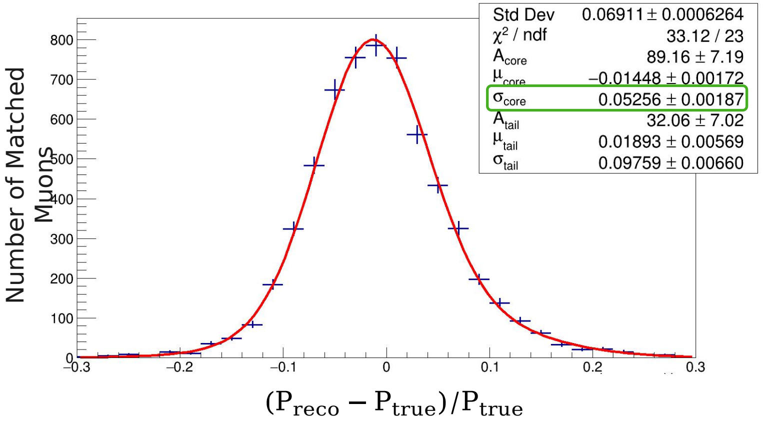
0 to 8 GeV

σ_{core} = 0.027



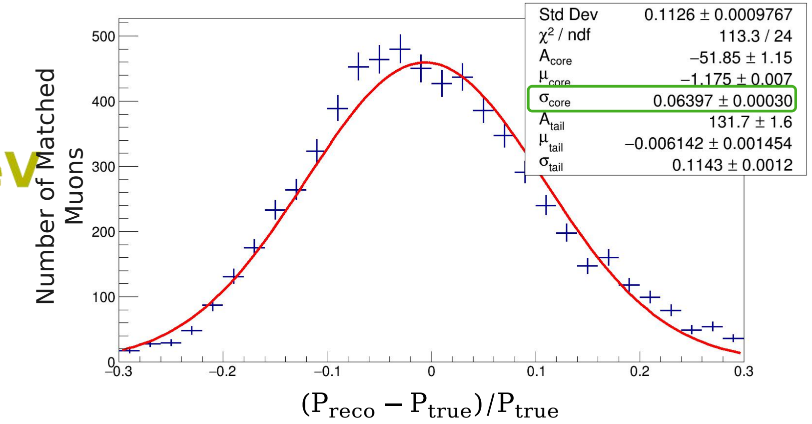
8 to 14 GeV

σ_{core} = 0.052



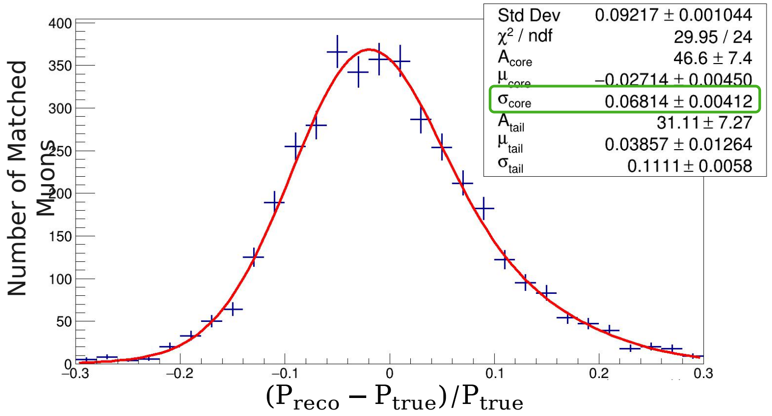
14 to 18 GeV

σ_{core} = 0.063



18 to 25 GeV

σ_{core} = 0.068



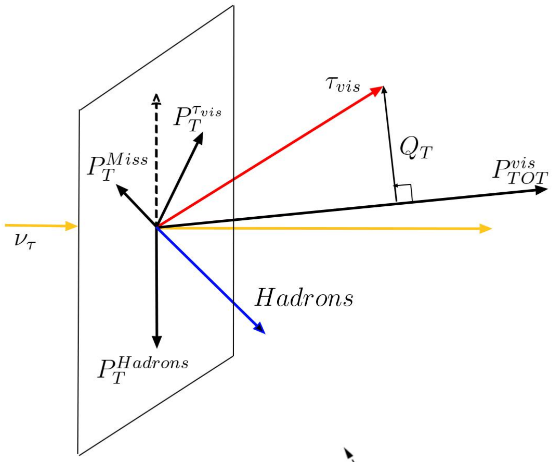
ND GArLite vs ND GAr

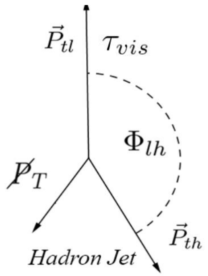
- Comparison of the muon momentum and angular resolution for ND-GAr and ND-GAr-Lite

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 °

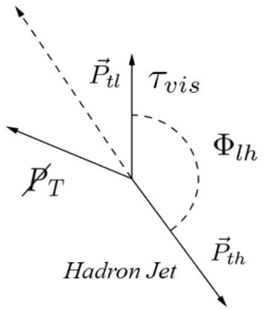
ν_τ signal and background separation

The signal and background separation is based on kinematic differences. Used a total of 18 variables.





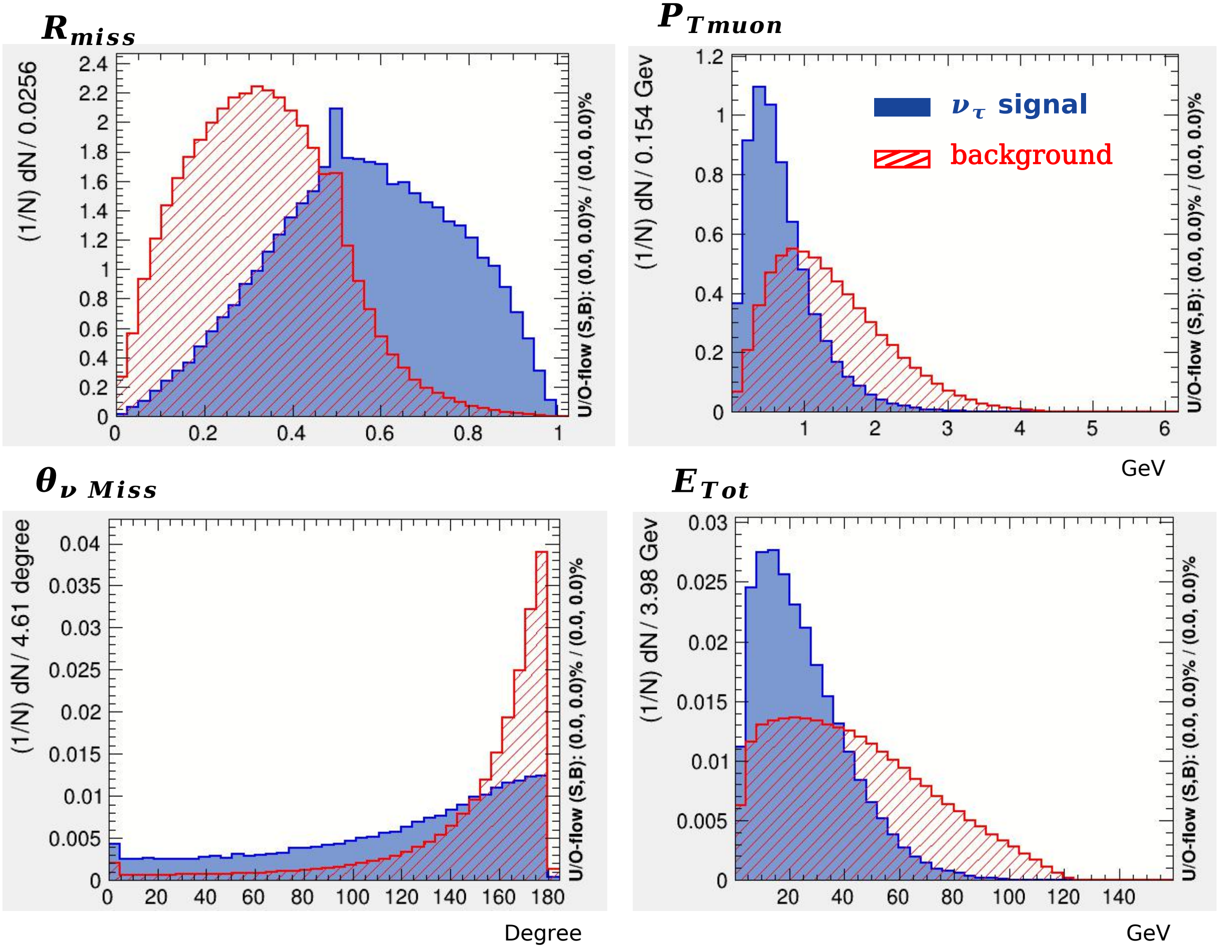
Background interaction
products in the transverse plane



ν_τ CC interaction
products in the transverse plane

Table shows 6 variables providing highest signal/bg separation

Ranking	Kinematic varialbles
1	$R_{miss} = \frac{P_{T\,Miss}}{P_{T\,Miss} + P_{T\,muon}}$
2	$P_{T\,muon}$: transverse lepton momentum
3	$\theta_{\nu\ Miss}$: angle between beam direction and missing transverse momentum
4	E_{Tot}: total visible energy
5	$\Phi_{muon\ hadron}$: angle between transverse muon and hadron momentum
6	P_{Tot}: total transverse momentum



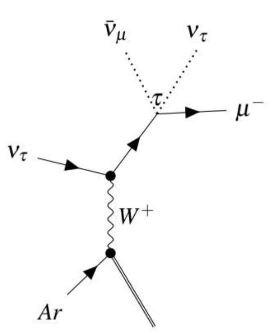
Examples of ν_τ signal (blue) and background (red) kinematic variables distribution.

ν_τ signal and background separation

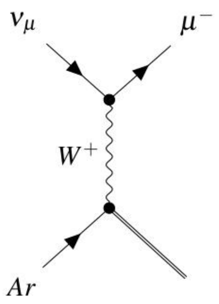
τ decay modes

Decay mode	Branching ratio (%)
$\pi^- \pi^0 \nu_\tau$	25.49
$e^- \bar{\nu}_e \nu_\tau$	17.82
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.39
$\pi^- \nu_\tau$	10.82
$\pi^- 2\pi^0 \nu_\tau$	9.26

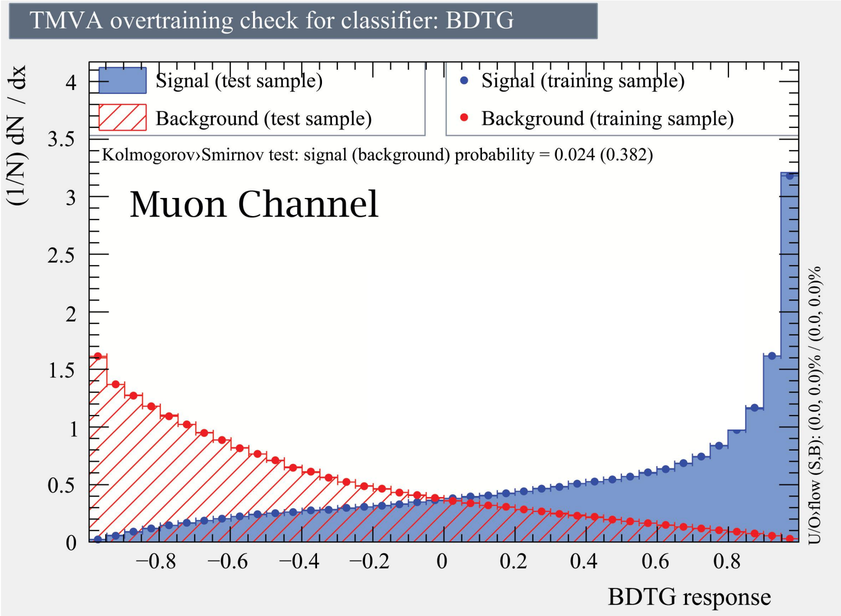
A Boosted Decision Tree classifier was used with the kinematic variables for the signal and background separation. The BDT was trained and tested with flat energy ν_τ and ν_μ events.

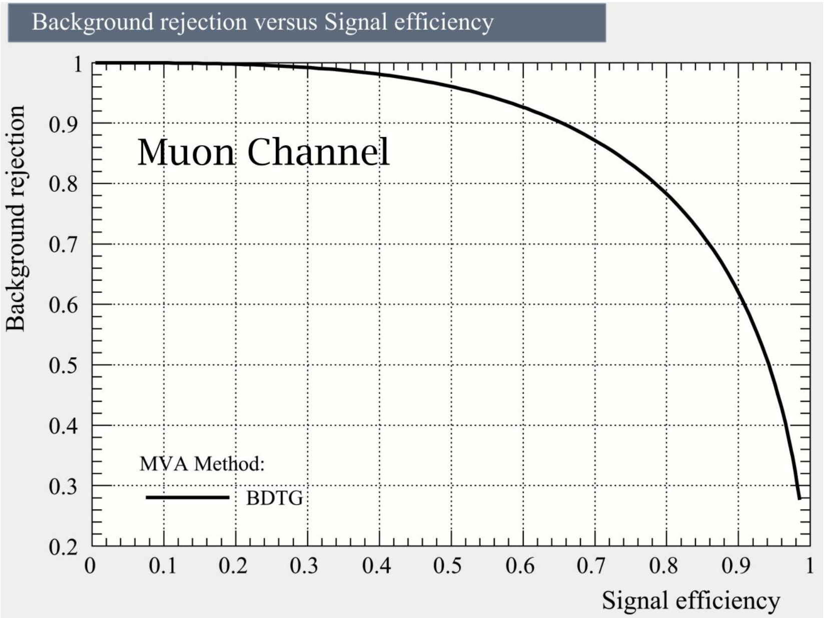


ν_τ CC
($\tau \rightarrow \mu^-$)



ν_μ CC

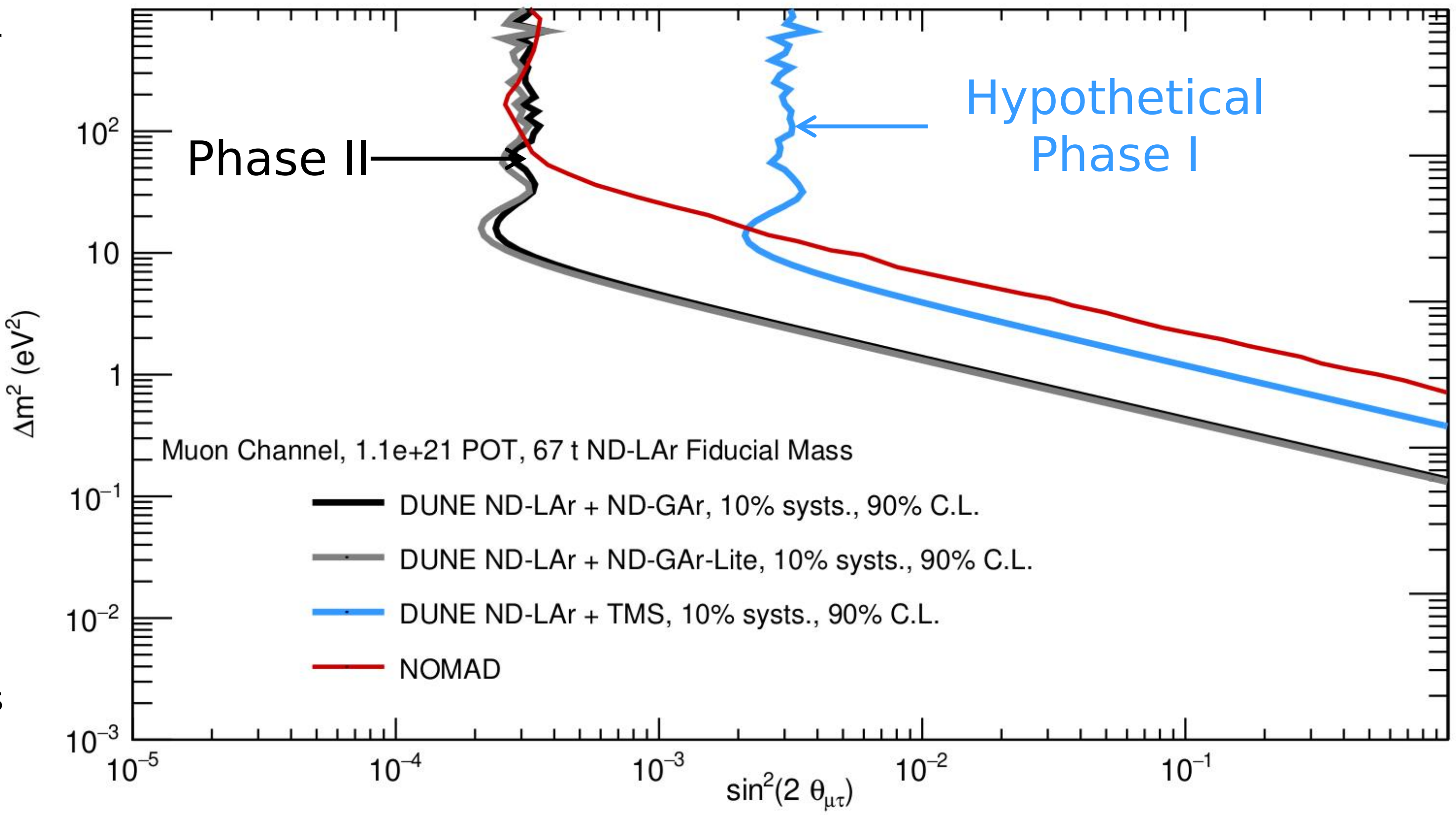




- Reasonable separation of the ν_τ CC from their main backgrounds.

Sensitivity to ν_τ appearance Muon channel only

- Sensitivity determination based on event counting. Using **1 year of running in DUNE ν_τ optimized mode** and 67t fiducial mass for ND-Lar (beam power assumed to be 1.2 MW). 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.
- Phase I TMS sensitivity includes neutrino interactions contained inside ND-LAr+TMS, corresponding to muon energies below 6 GeV.
  - Shown for comparison, as no nutau-optimized running is projected for Phase I

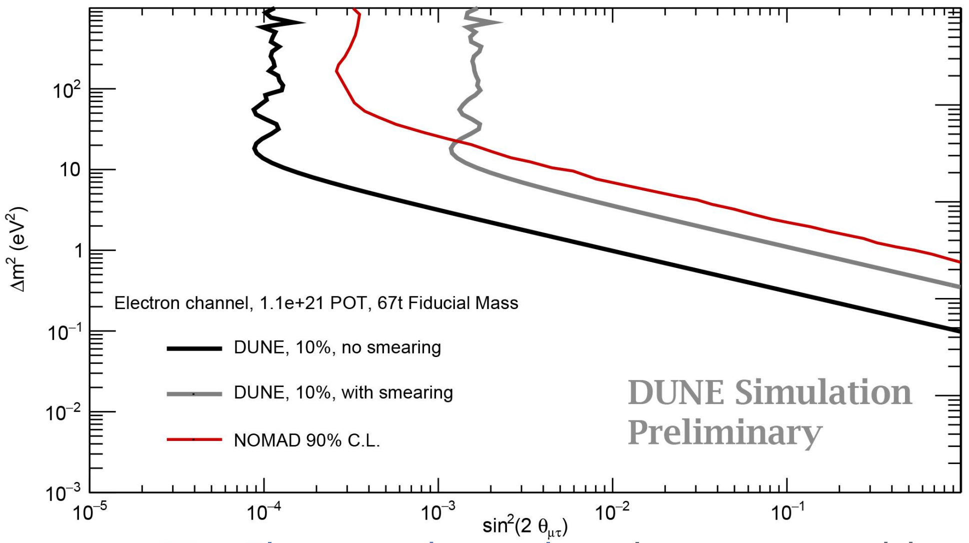


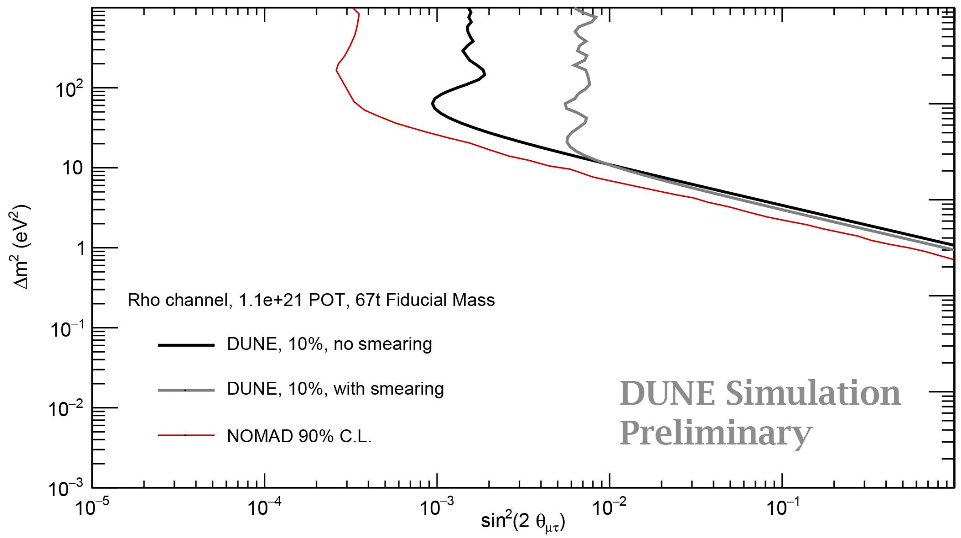
Sensitivity to ν_τ appearance
Electron and rho channel

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

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

- For the electron and rho channel, the particles from interaction were supposed to be contained in the ND-LAr and the ND-LAr resolution was used to smear the momentum.
  - Grey contours : sensitivity considering the ND-LAr smearing values.



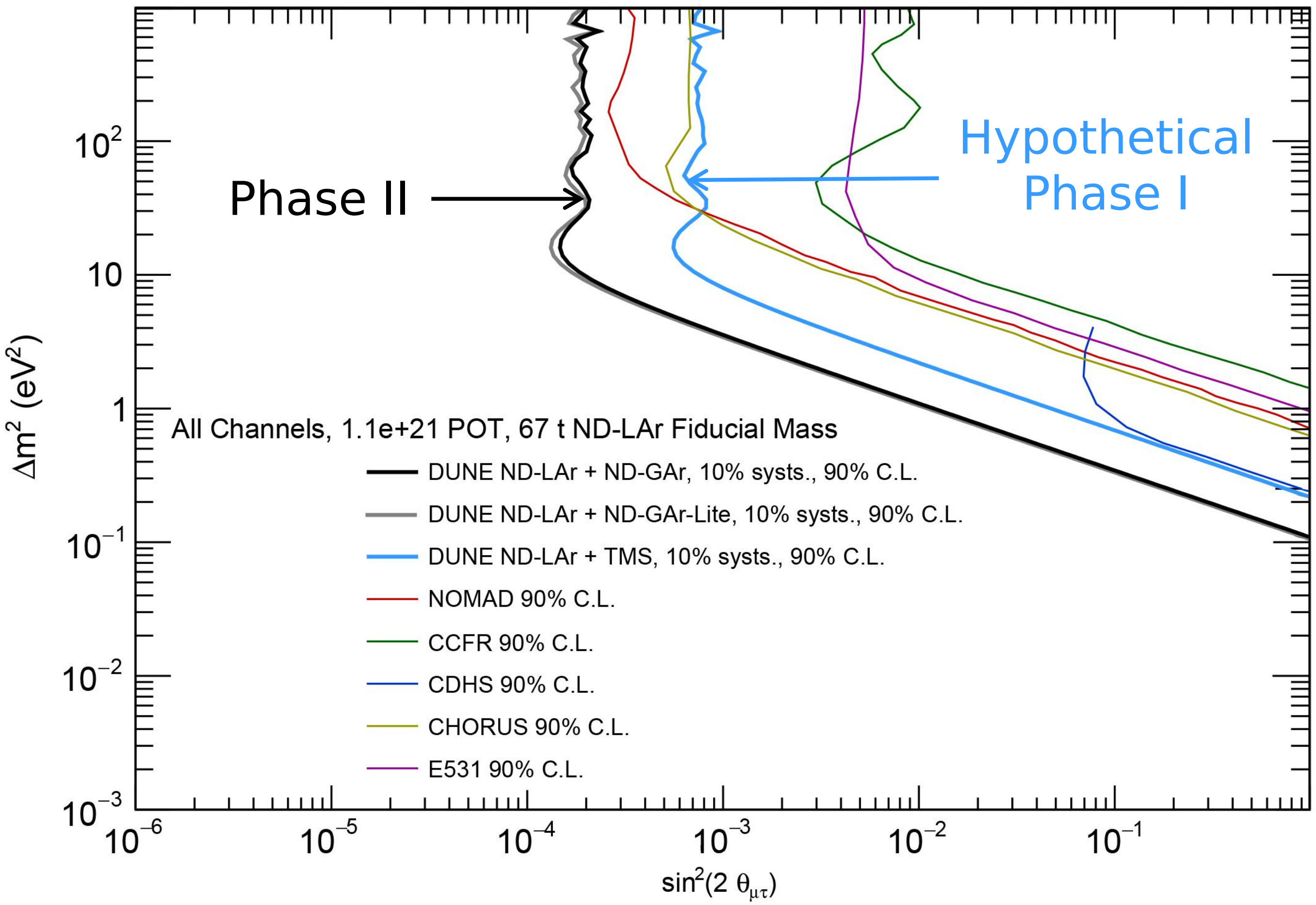


- Electron channel : select events with ν_τ BDTG score > 0.995
- Rho channel : select events with ν_τ BDTG score > 0.99

(*Miriama Rajaoalisoa - APS 2021*)

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.



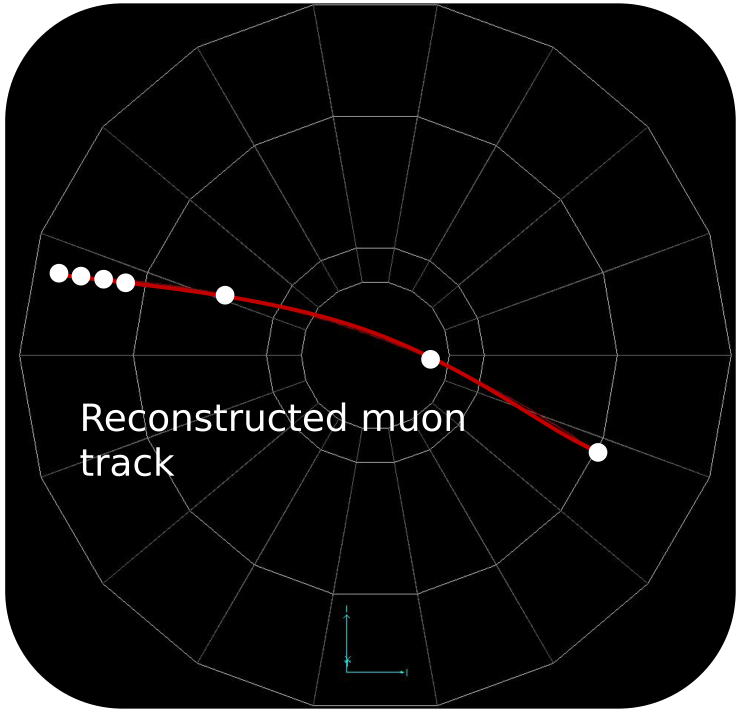
DUNE ND offers the possibility of a competitive sensitivity to anomalous nutau appearance compared to other experiments with ND GAr or ND GAr Lite.

Summary

- The DUNE ND complex offers a great setup for probing anomalous tau neutrino appearance.
- Specifically, the ND GAr and ND GAr Lite allow the possibility of reconstructing a very wide range of muon momenta with excellent resolution.
- With high BDTG score cuts (region with almost no background) and nutau-optimized beam configuration, DUNE will potentially have 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. The effect of the DUNE PRISM in the sensitivity will also be analyzed.

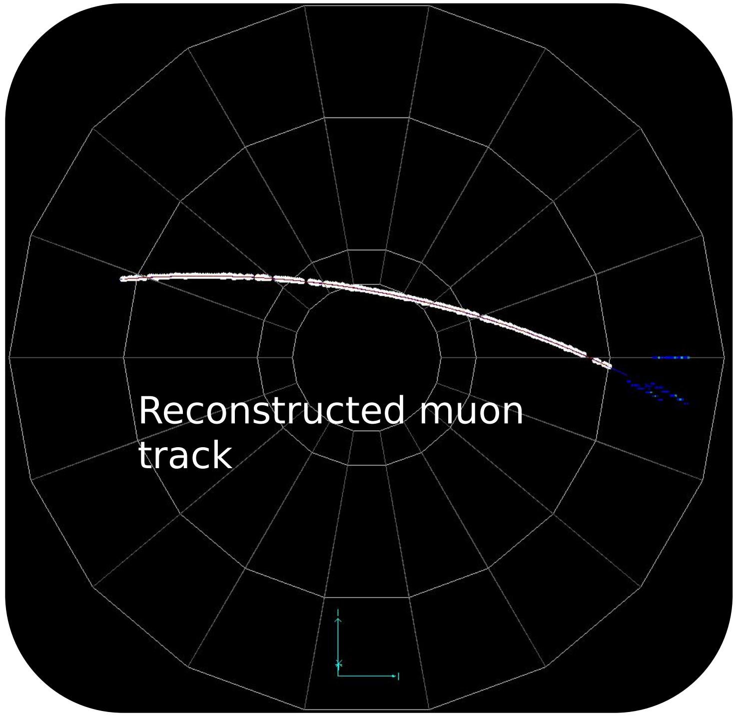
BACKUP SLIDES

Event display examples for ND-GAr-Lite and ND-GAr



ND GAr-Lite GArSoft event display

True energy = 1.446 GeV
Reco energy = 1.435 GeV



ND GAr GArSoft event display

True energy = 1.408 GeV
Reco energy = 1.409 GeV

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 °
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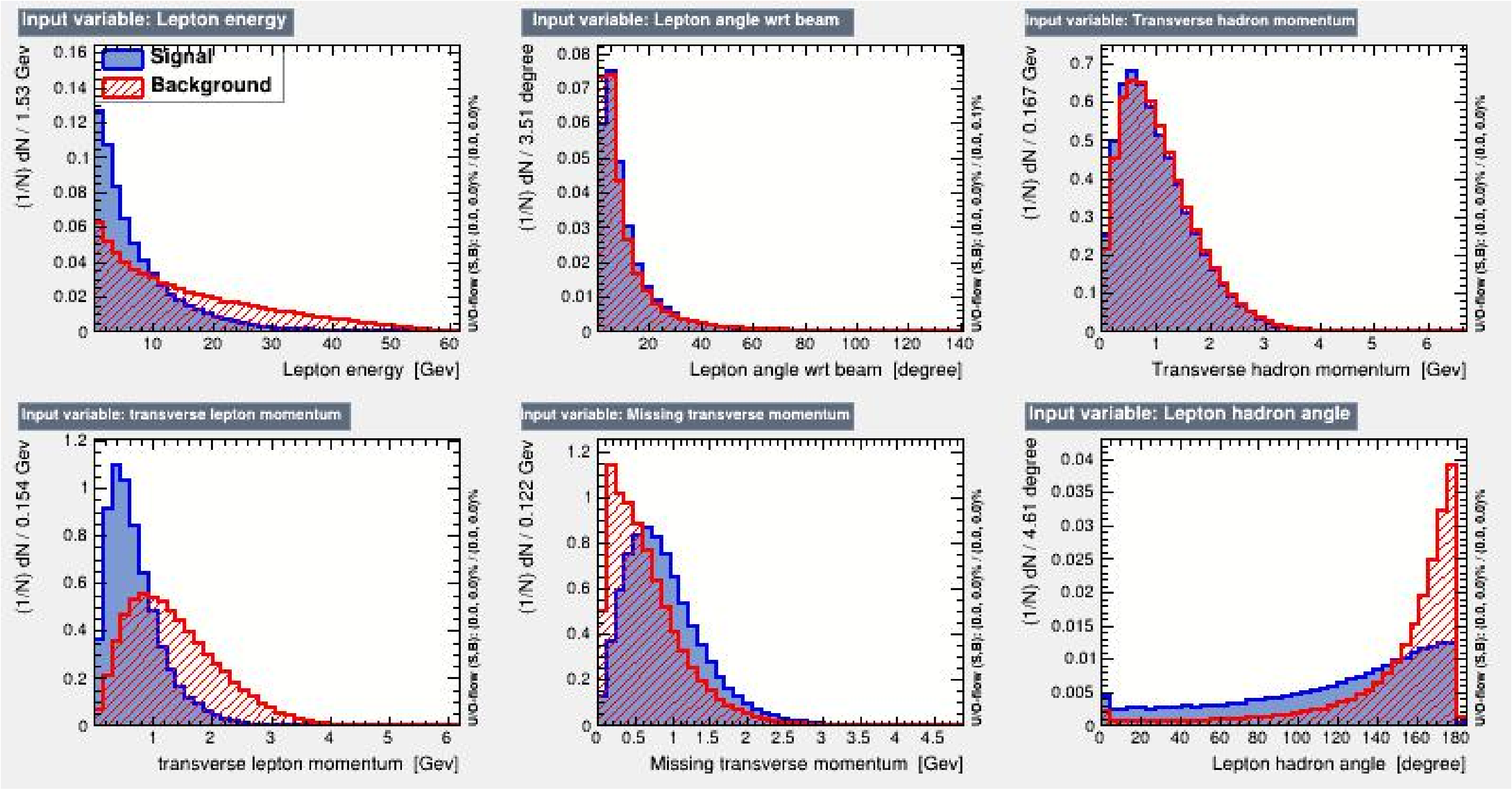
Kinematic variables used for signal and background separation using GENIE information for ND-LAr
(Trained with flat energy events)



Kinematic variables used for signal and background separation using GENIE information for ND-LAr
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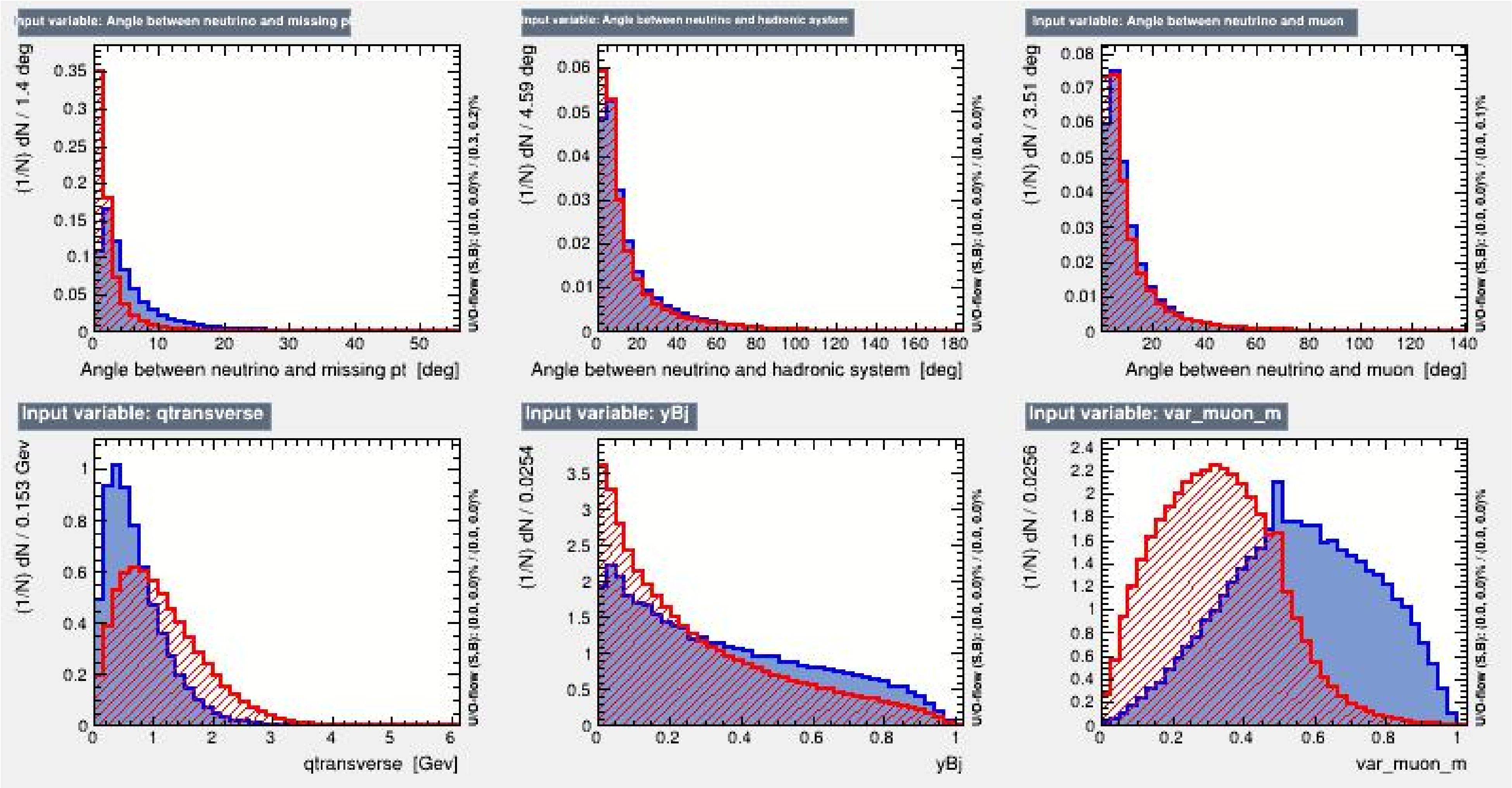
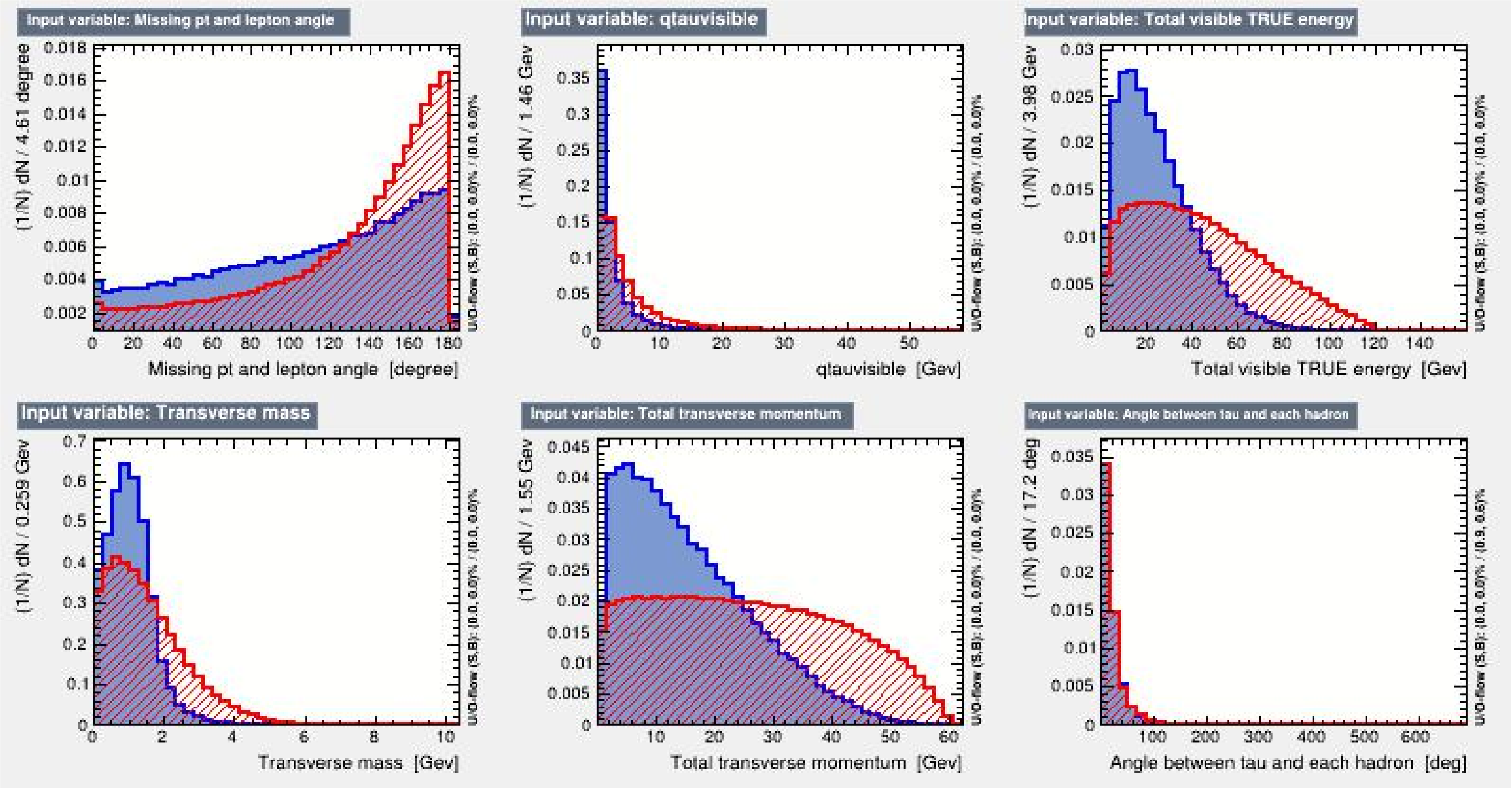


Kinematic variables used for signal and background separation using GENIE information for ND-LAr
(Trained with flat energy events)

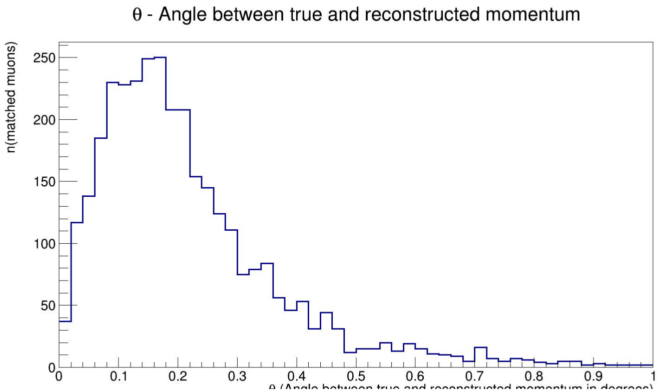


Muon angular resolution using ND GAr-Lite

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

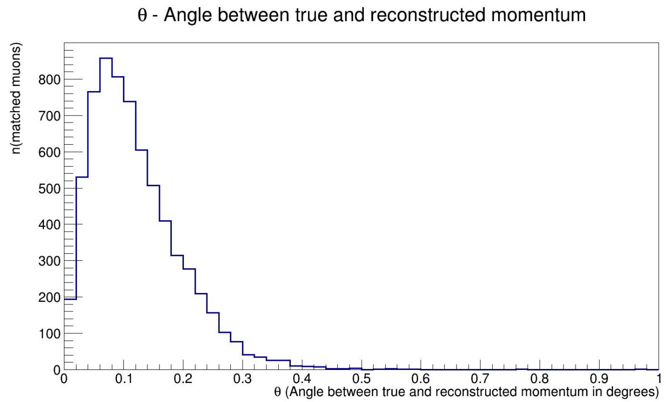
0 to 8 GeV

Angular resolution :0.452 deg



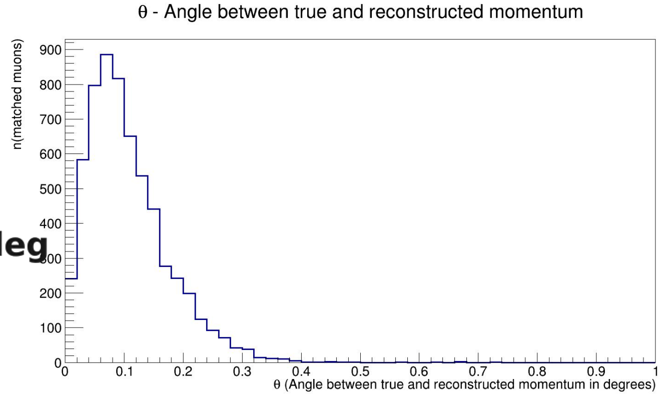
8 to 14 GeV

Angular resolution : 0.213 d



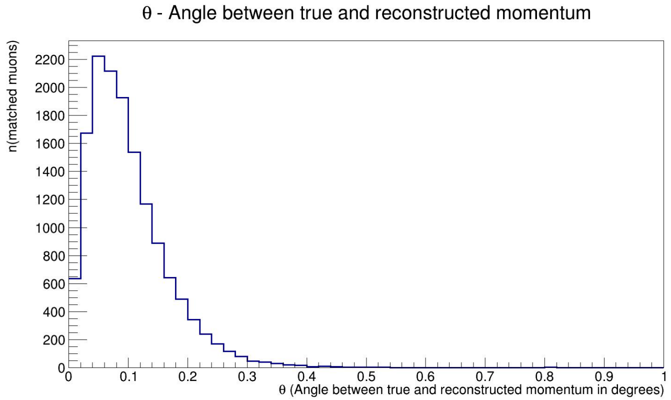
14 to 18 GeV

Angular resolution : 0.194 deg



18 to 25 GeV

Angular resolution : 0.179 d

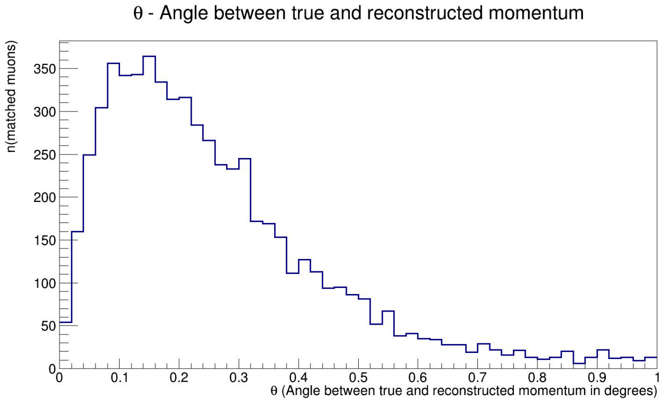


Muon angular resolution using ND GAr

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

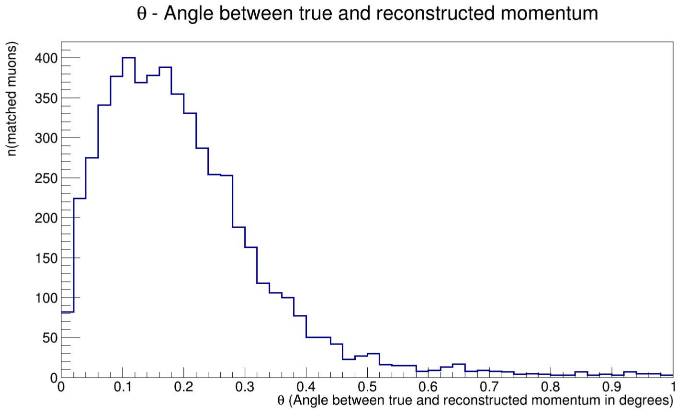
0 to 8 GeV

Angular resolution : 0.4392



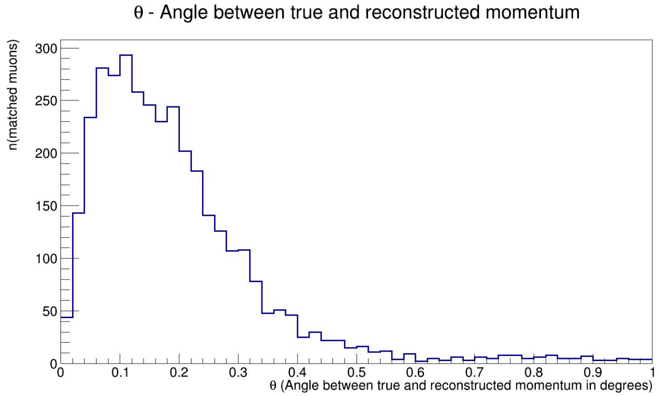
8 to 14 GeV

Angular resolution : 0.268



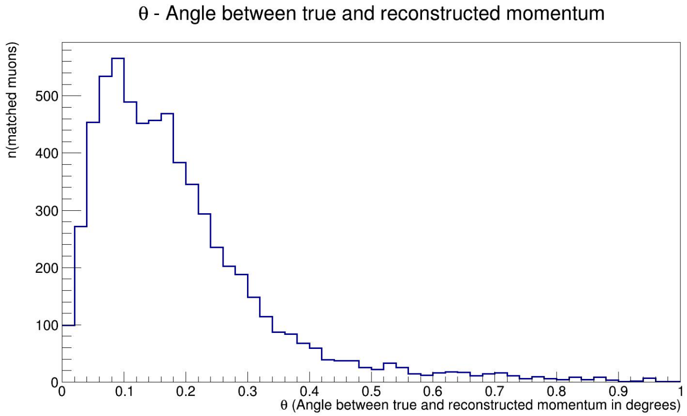
14 to 18 GeV

Angular resolution : 0.251

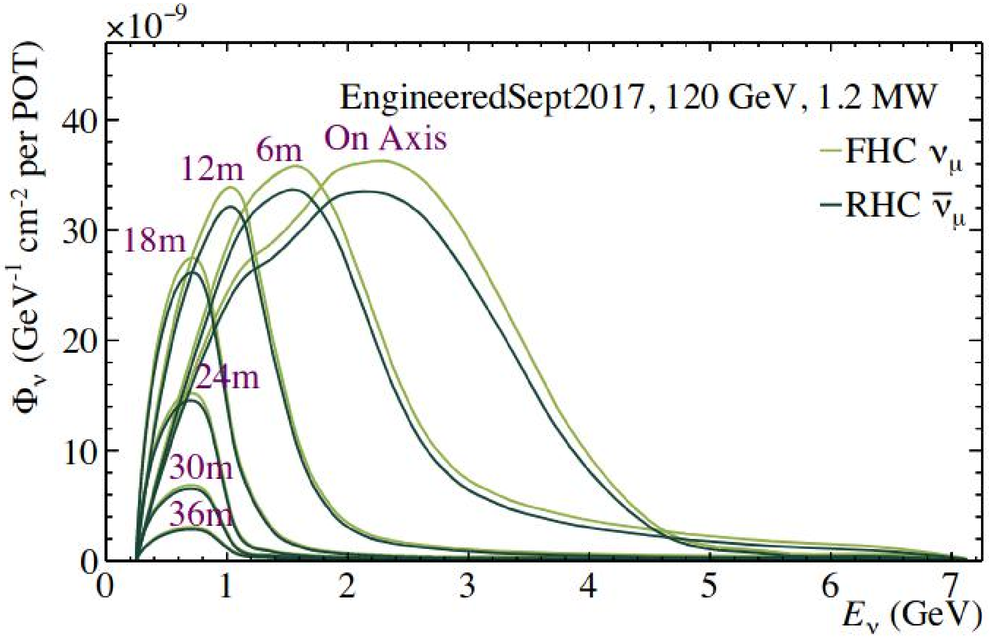


18 to 25 GeV

Angular resolution : 0.235



DUNE PRISM



- Neutrino flux varies as one moves "off-axis" from the center of the beam
- Observing neutrino interactions observed at different off-axis angles provides an independent handle on the neutrino energy
- Determining the relation between the incident and reconstructed neutrino energies is a (the?) key measurement in the near detector

(H.A.TANAKA)
(The DUNE-PRISM Near Detector Program)