Search for tau neutrino appearance in the DUNE Near Detector Complex

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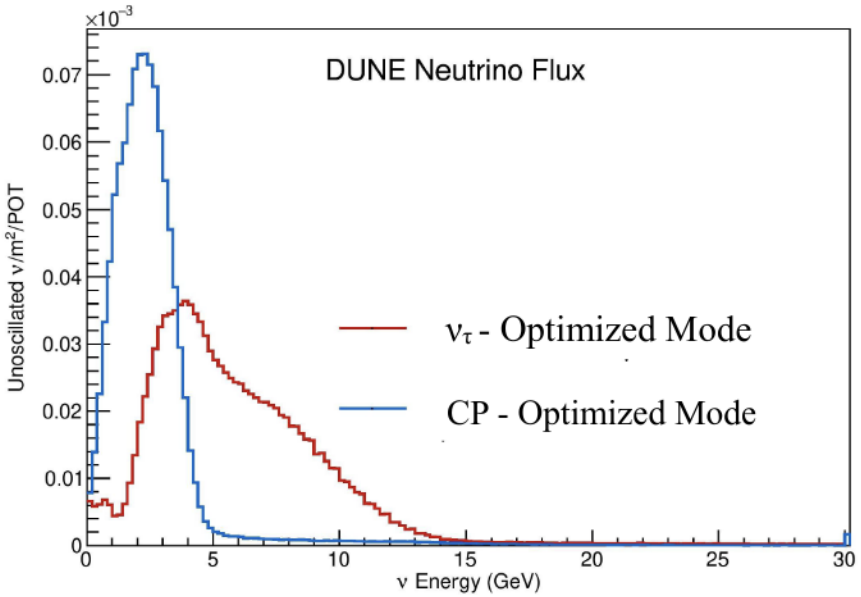
Objectives of the analysis

- ν_τ measurements are challenging due to the 3.5 GeV τ production threshold.
- **DUNE is in a unique position to probe the $\nu_\tau$sector:**
  - DUNE has a flexible beamline that can be optimized for higher energy flux for ν_τ studies.
  - 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 :

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

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

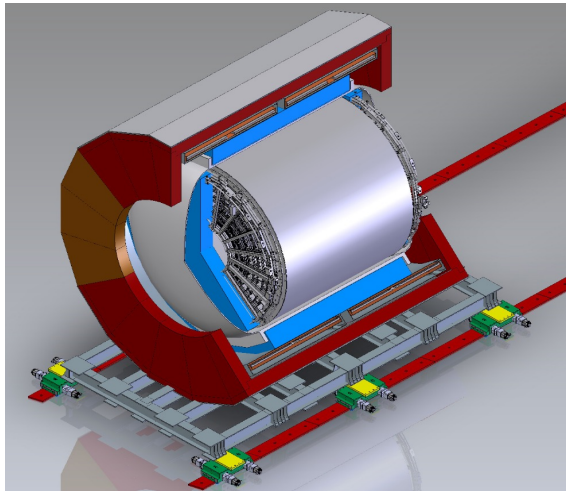
- Study tau neutrino interactions in the primary ND-LAr detector and evaluate how different secondary detector designs impact the sensitivity to tau neutrino appearance.
- Simulation: GENIE information was used.

Secondary detector in the Near Detector Complex

DUNE phase II :

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

Full scope DUNE Phase II



ND - GAr

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

- **HPgTPC** (high-pressure gaseous argon) :

☐ A TPC filled with gaseous argon; a possible component of the DUNE ND.

- **ECAL** (electromagnetic calorimeter) :

☐ A detector component that measures energy deposition of traversing particles

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

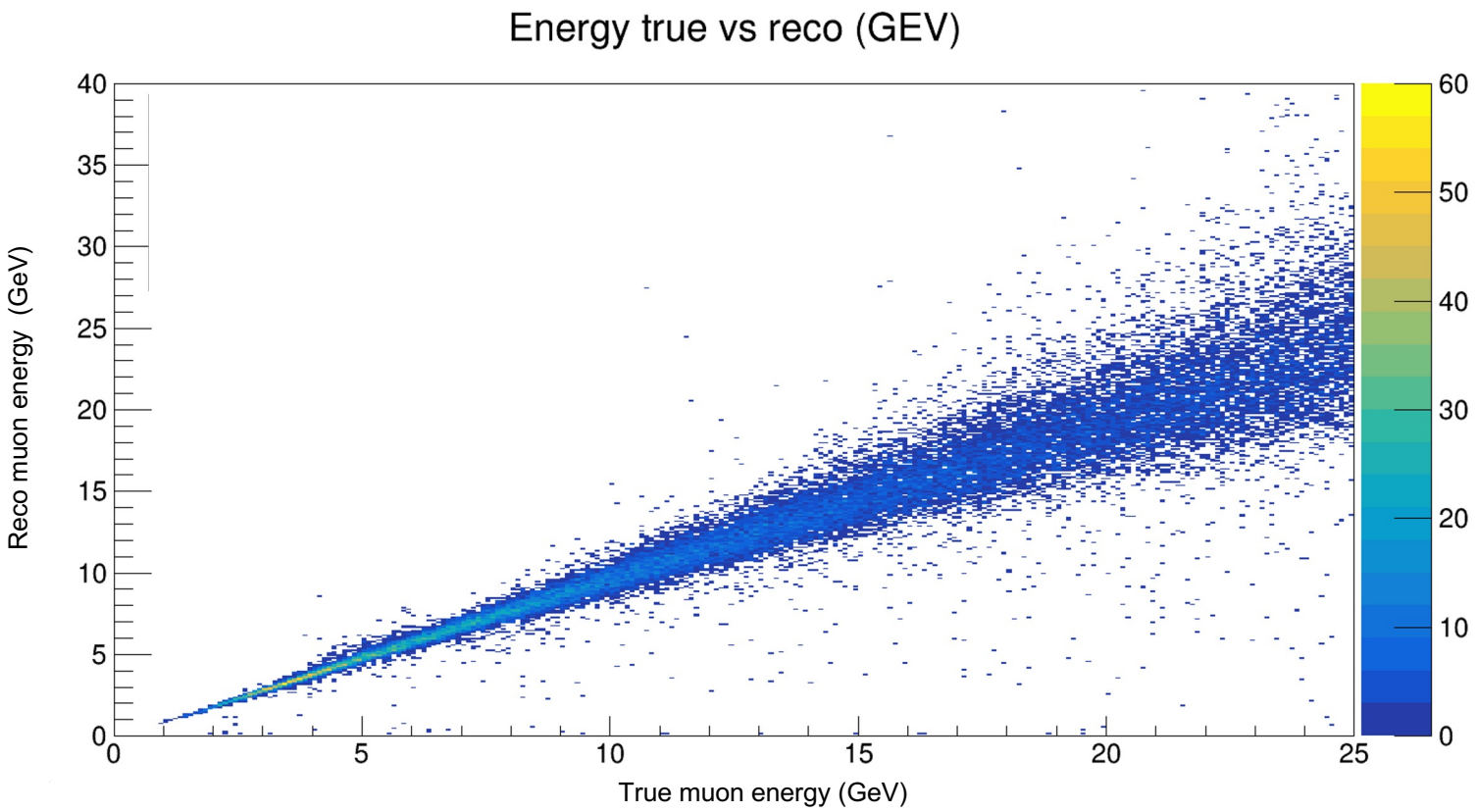
Muon energy reconstruction using ND-GAr

- 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

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

ND-GAr

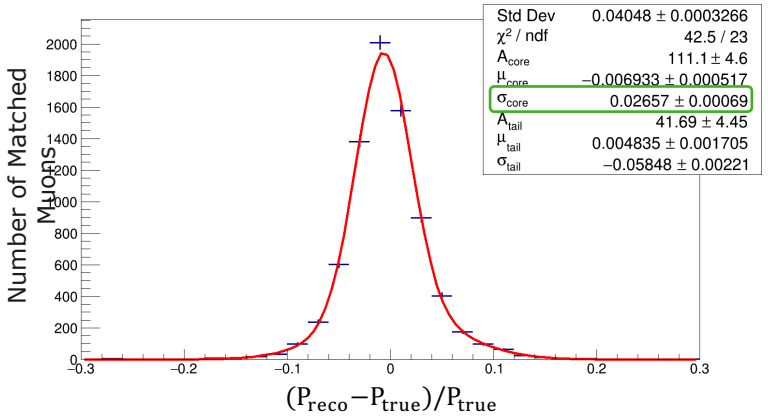


Muon momentum resolution using ND-GAr

- 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.

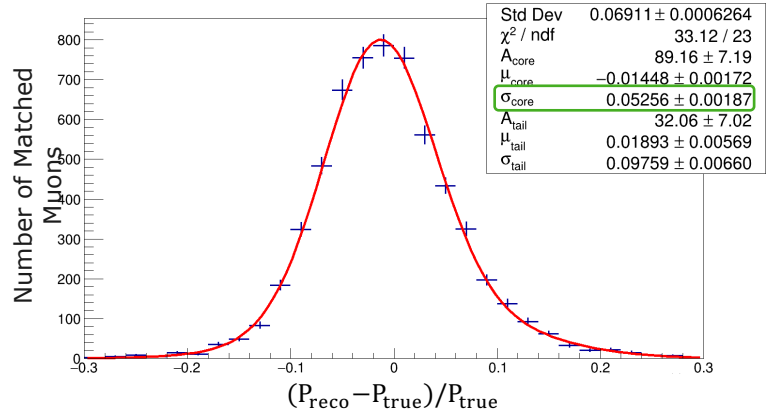
0 to 8 GeV

σ_{core} = 0.027



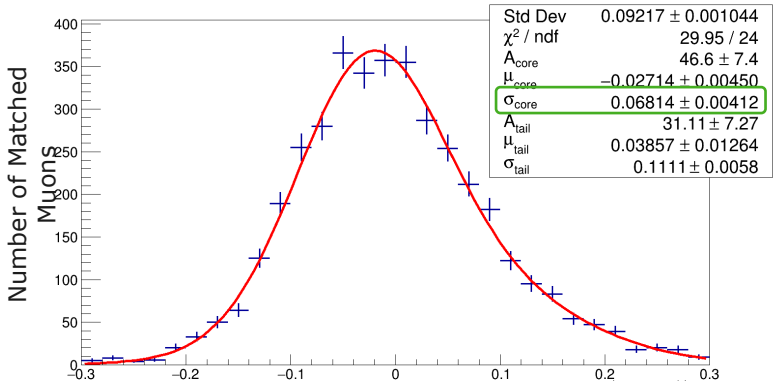
8 to 14 GeV

σ_{core} = 0.052



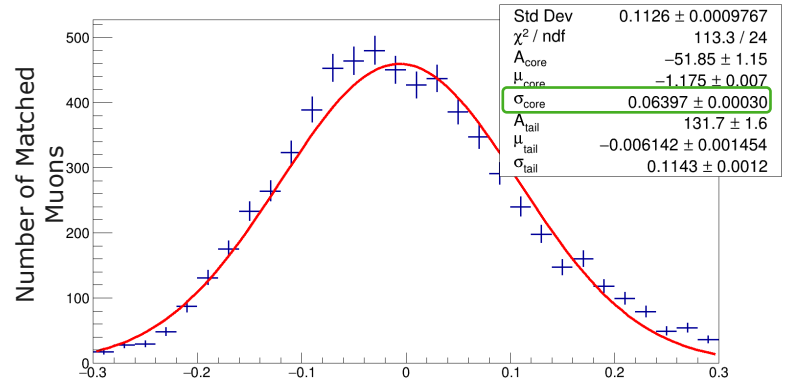
14 to 18 GeV

σ_{core} = 0.068



18 to 25 GeV

σ_{core} = 0.063



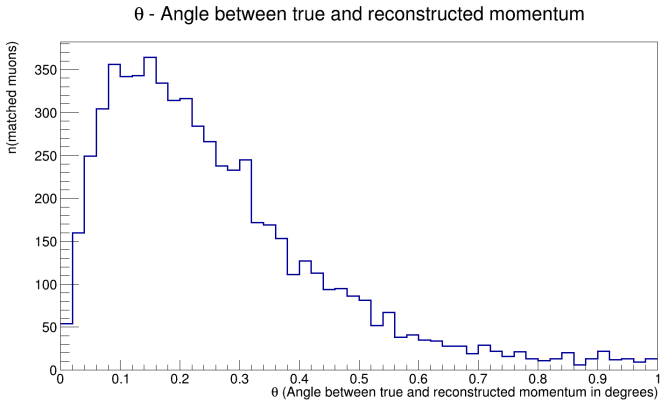
➤ TMS is limited to μ energy less than 6GeV because of μ containment

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.

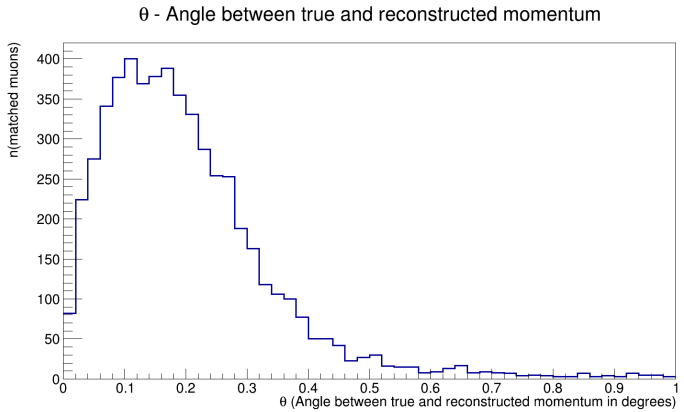
0 to 8 GeV

Angular resolution : 0.4392



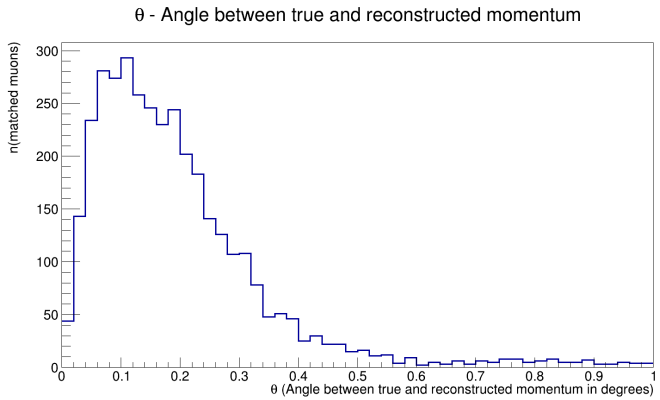
8 to 14 GeV

Angular resolution : 0.268



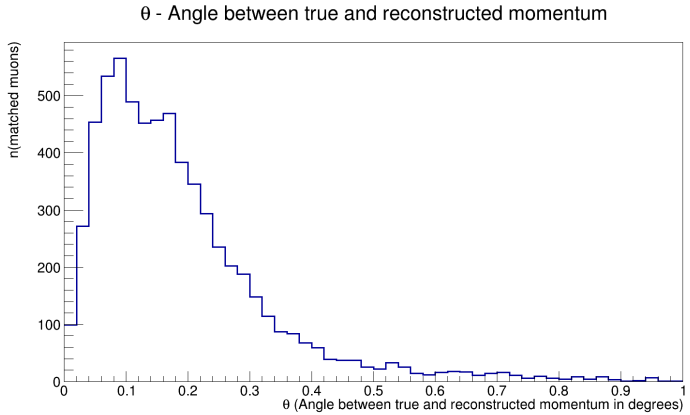
14 to 18 GeV

Angular resolution : 0.251



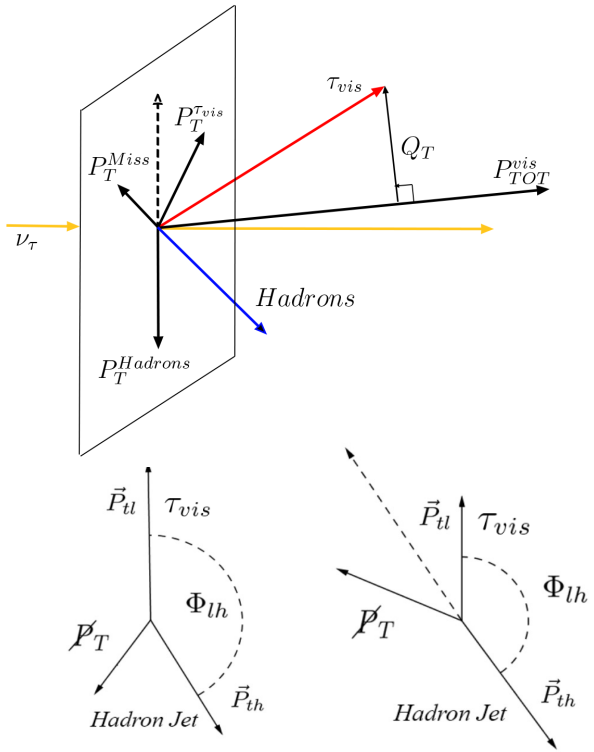
18 to 25 GeV

Angular resolution : 0.235



ν_τ signal and background separation

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

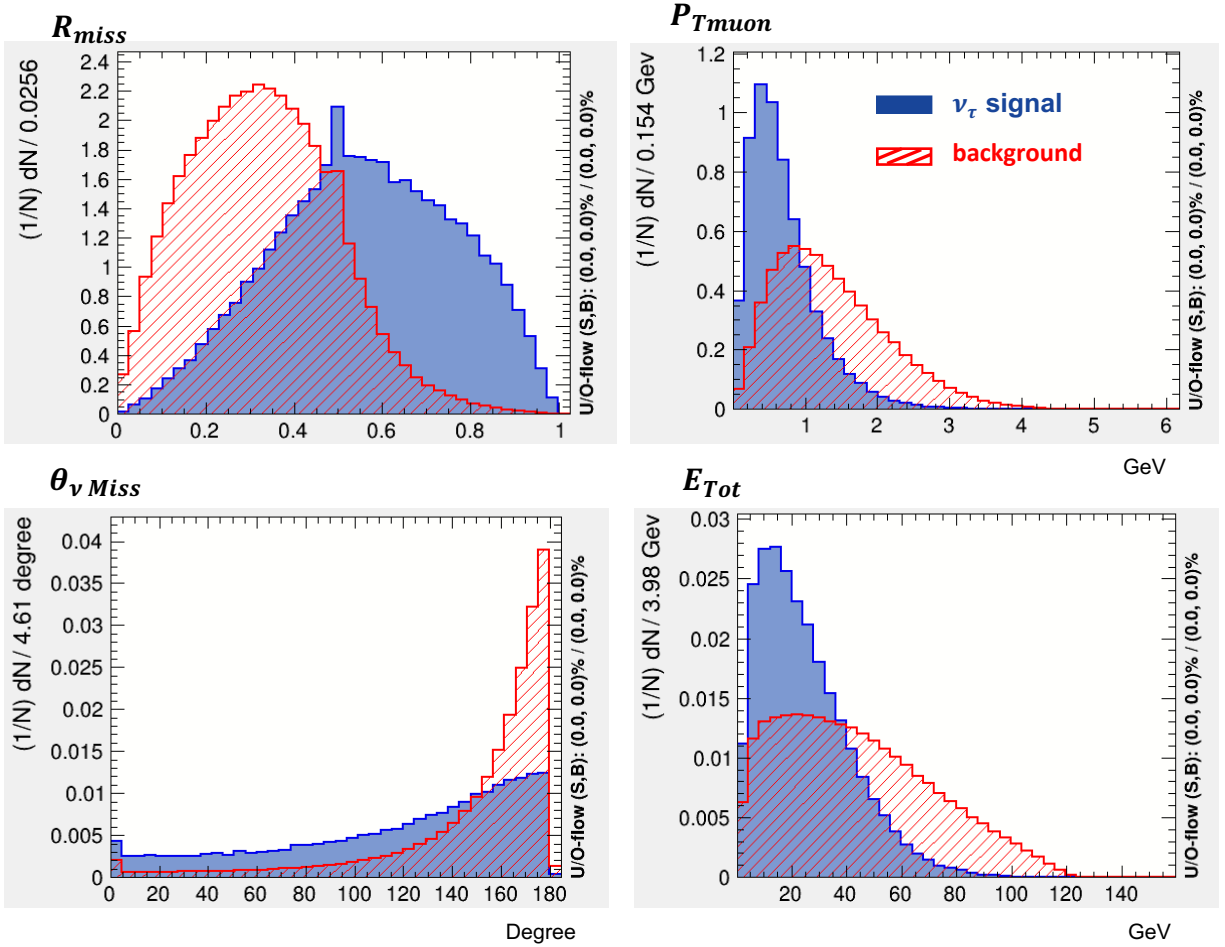


Background interaction products in the transverse plane

ν_τ CC interaction products in the transverse plane

Table shows 6 variables providing highest signal/bg separation

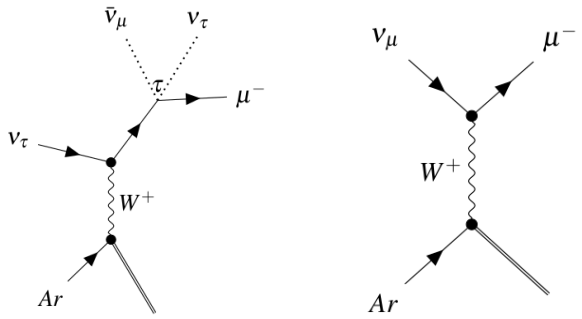
Ranking	Kinematic varialbles
1	$R_{miss} = \frac{P_{TMiss}}{P_{TMiss} + P_{Tmuon}}$
2	P_{Tmuon}: transverse lepton momentum
3	$\theta_{\nu\ Miss}$: angle between beam direction and missing transverse momentum
4	E_{Tot}: total visible energy
5	$\Phi_{muon\ hadron}$: angle between transverse muon and hadron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



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

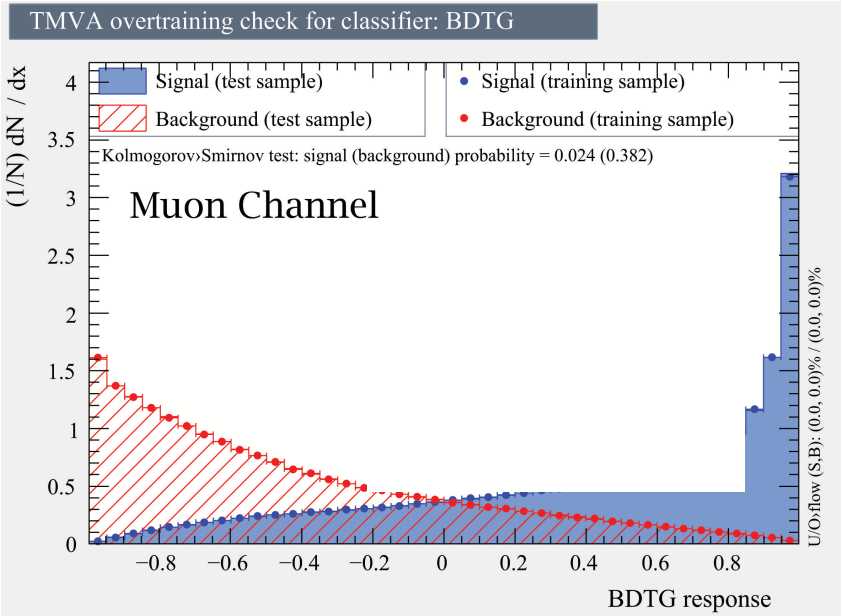
ν_τ signal and background separation

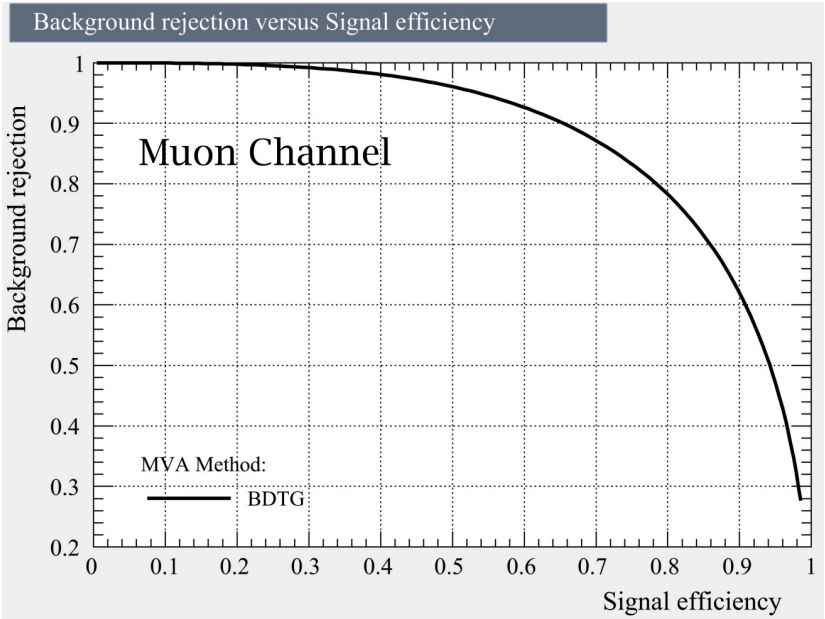
- A Boosted Decision Tree classifier was used with the kinematic variables for the signal and background separation. The BDT was trained and tested with flat energy ν_τ and ν_μ events.



ν_τ CC ($\tau \to \mu^-$)

ν_μ CC

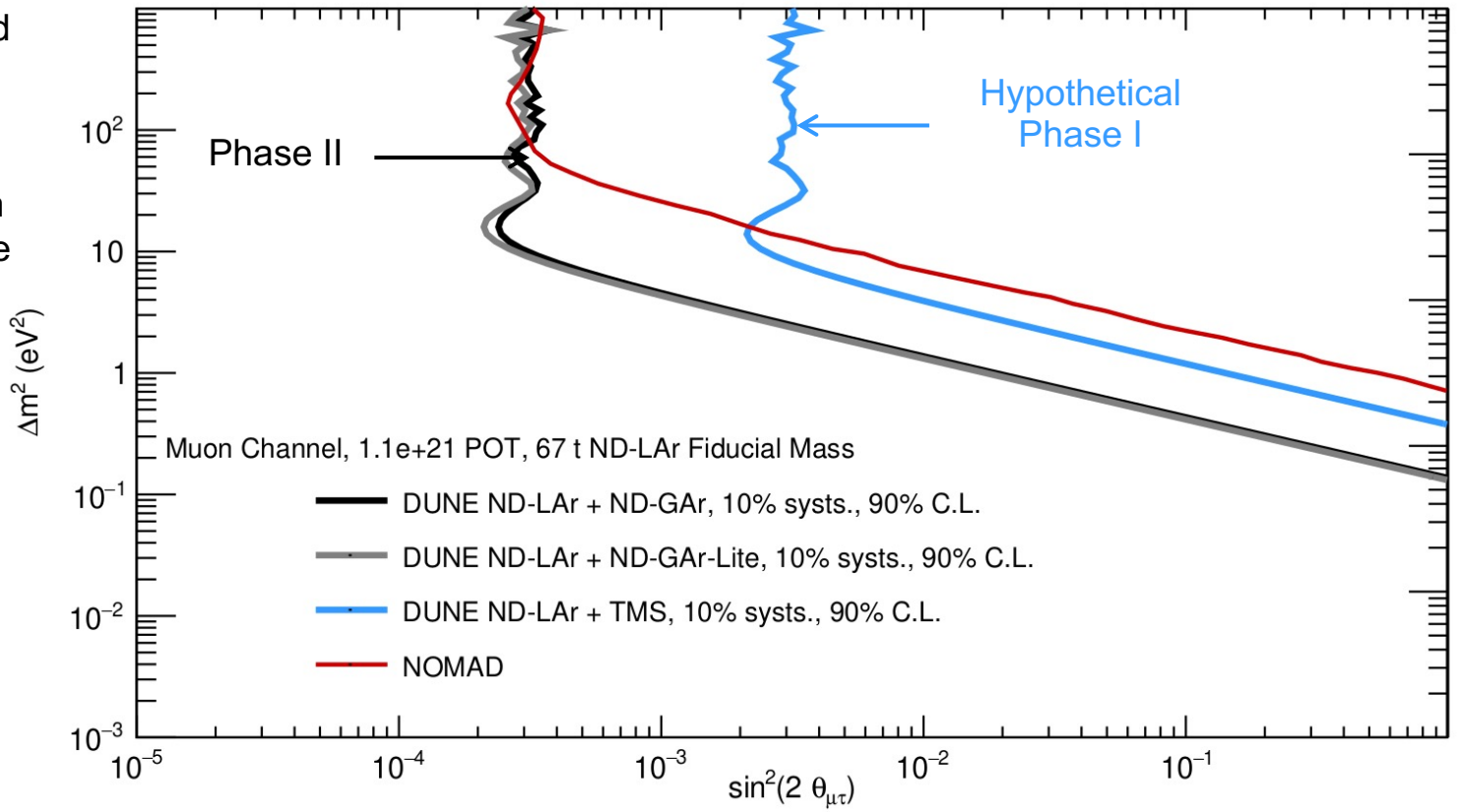




- Reasonable separation of the ν_τ CC from their main backgrounds.

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 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 ND-GAr (BDTG score > 0.9965) 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 ν_τ -optimized running is projected for Phase I

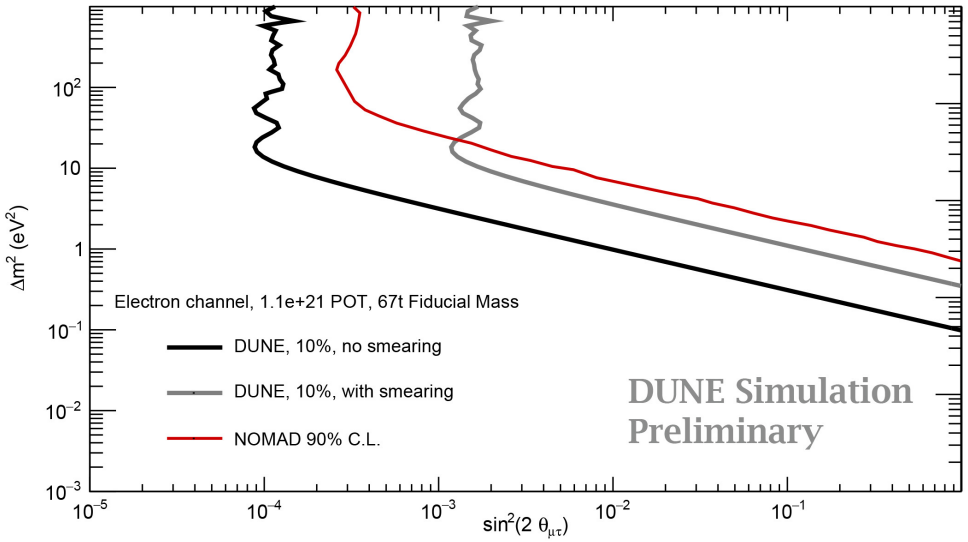


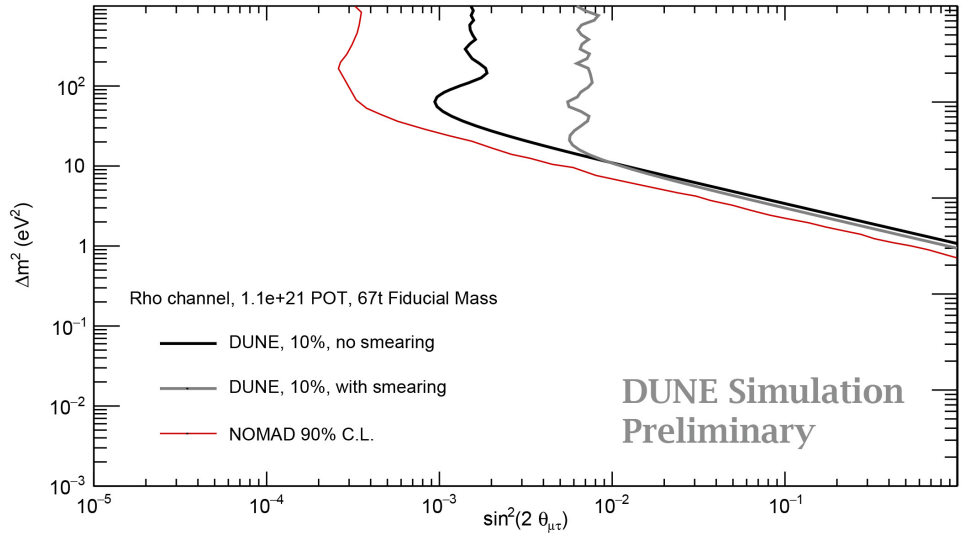
Sensitivity to ν_τ appearance Electron and rho channel

- 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.





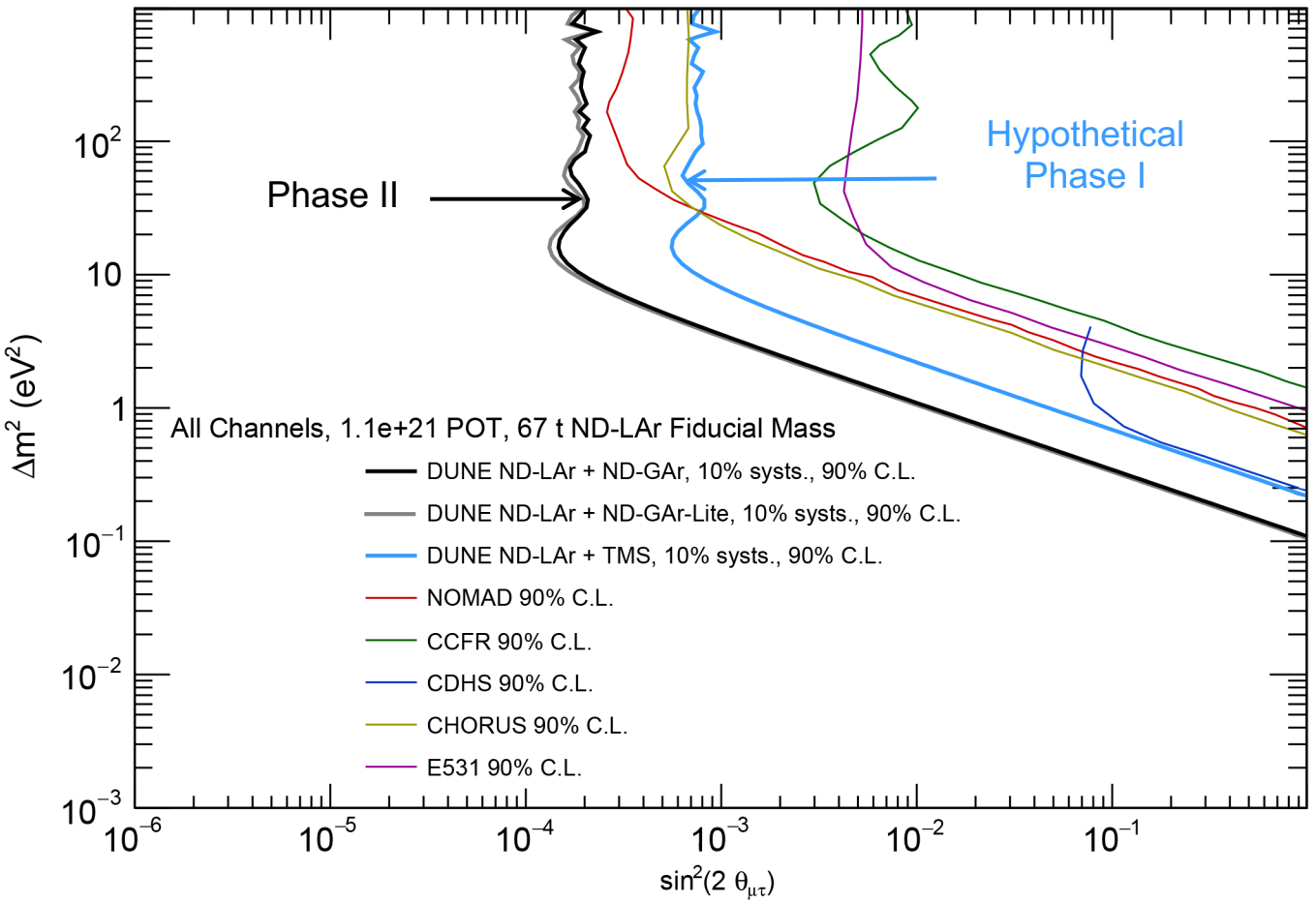
- Electron channel : select events with ν_τ BDTG score > 0.995
- Rho channel : select events with ν_τ BDTG score > 0.99

([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 ν_τ appearance compared to other experiments with ND-GAr.



Next step in the analysis

- Analysis of the BDT cut robustness:
  - High BDTG cuts were applied for event selection (ex: BDTG score > 0.9965 used for the muon channel) corresponding to regions with almost no backgrounds.
  - The model used in the analysis might influence the BDT cut due to changes in the hadronic system.
  - Test how robust the chosen cuts are if we were to use a different model.
  - This will be done by using a different GENIE Comprehensive Model Configuration (GENIE CMC).
  - Current work: deeper analysis of the backgrounds to understand what alternative CMC might be relevant to the considered kinematic regime.

Summary

- The DUNE ND complex offers a great setup for probing anomalous tau neutrino appearance.
- ND-GAr's ability to measure muon momentum from range with excellent resolution, due to its magnetic field, is essential to maximize sensitivity of this analysis
- With high BDTG score cuts (region with almost no background) and ν_τ-optimized beam configuration, DUNE will potentially have leading sensitivity to anomalous short-baseline ν_τ appearance.