Sensitivity study within and beyond the SM

Pantelis Melas, Dimitris Papoulias

National and Kapodistrian University of Athens

H.F.R.I. Hellenic Foundation for Research & Innovation

DUNE

Outline

- Introduction to PMNS
- Non-unitary models
- Searches for violation of lepton unitarity
- Probing the weak mixing angle
- χ^2 analysis

Non-unitary models

One more question: Is PMNS unitary?

For the case **existence of a sterile neutrino** -> the PMNS matrix is non-unitary

The (3+1) model consist 3 original neutrino flavors + 1 sterile neutrino.

The neutrino mixing can be expressed by **a 4-generation PMNS matrix**:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Models like **type-I seesaw (linear or invert)** can accommodate several **new heavy neutral leptons**, leading to **violation of lepton unitarity**.

Non-unitary models

The New PMNS matrix for the type-I seesaw model

• Takes the form: **K = (N S),** where **N is a 3×3 matrix**, while **S is a 3× m matrix**, with m the number of fermionic singlets that mix with the active neutrinos.

• The small block **S ~ O (ε) is the seesaw expansion matrix**.

A systematic approach to **the (non-unitary) matrix N** can be derived from the seesaw expansion, as the lower triangular **parameterization**

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{31} & \alpha_{33} \end{pmatrix} \cdot U^{\,3\times 3}$$

,where $U^{\,3\times 3}$ is the PMNS

A viable way to study the non-unitarity is by using a combination of neutrino-electron elastic scattering (EνES) and inverse muon decay events.

DOI: 10.1103/PhysRevD.109.115007

DOI: 10.1103/PhysRevD.92.053009

DUNE Near Detector (ND)

- We are interested for events in the Lar-TPC. We **generated ND samples (on and off axis) using the code:**

/dune/app/users/pmelas/ND/ND_Production/scripts/ProcessND.py

- The code for the **parametric reconstruction** that is used is inspired by Chris Marshall https://github.com/DUNE/ND_CAFMaker/blob/nd-lar-analysis/makeCAF.cxx

- **The parametric reconstruction applies an energy/angle smearing:**

```
double ke = caf.LepE - mmu;
double reco_ke = rando->Gaus( ke, ke*par.LAr_muRes );
caf.Elep_reco = reco_ke + mmu;

double true_tx = 1000.*atan(caf.LepMomX / caf.LepMomZ);
double true_ty = 1000.*atan(caf.LepMomY / caf.LepMomZ);
double evalTsmear = tsmear->Eval(caf.Elep_reco - mmu);
if( evalTsmear < 0. ) evalTsmear = 0.;
double reco_tx = true_tx + rando->Gaus(0., evalTsmear/sqrt(2.));
double reco_ty = true_ty + rando->Gaus(0., evalTsmear/sqrt(2.));
caf.theta_reco = 0.001*sqrt( reco_tx*reco_tx + reco_ty*reco_ty );
```

tsmear ="0.162 + 3.407*pow(x,-1.) + 3.129*pow(x,-0.5)"

- **and it also apply some conditions for the misID of π0 to electrons like: the energy of the photon (from the pion) to be < 50 MeV or the angle between the photons should be less than 0.01 radians for the π^0 to be reconstructed as an electron**

- **The flux files that were used are located here:**

/cvmfs/dune.osgstorage.org/pnfs/fnal.gov/usr/dune/persistent/stash/Flux/g4lbne/v3r5p4/QGSP_BERT/OptimizedEngineeredNov2017/neutrino/flux/*dk2nu.root

DUNE Near Detector (ND)

Signal Selection

Elastic Scattering (Inverse muon decay) Criterion

Select events with only one reconstructed electron (muon) in the final state and no other activity (calorimetrically hadronic energy equals zero)

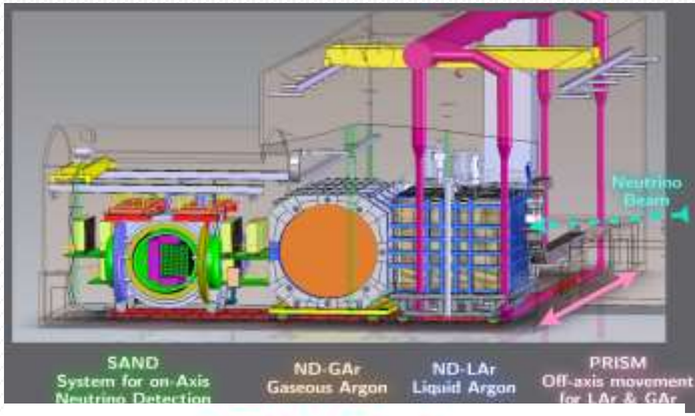
Reduction of the background

Angular Criterion:

Select electrons with **angle < 0.05 rad (angle < 0.01 rad),** the angle is between the incoming neutrino and the reconstructed electron**.**

Energy Criterion:

Select electrons with **energy greater than 300MeV (select muons greater than 10GeV)**



ND-LAr

- Same liquid argon target as the DUNE FD
- Modular design: 35 1×1×3 m^3 modules with two TPCs per module (50 cm drift)
- Charge: LArPix pixel readout for direct-to-3D charge information

χ^2 Analysis

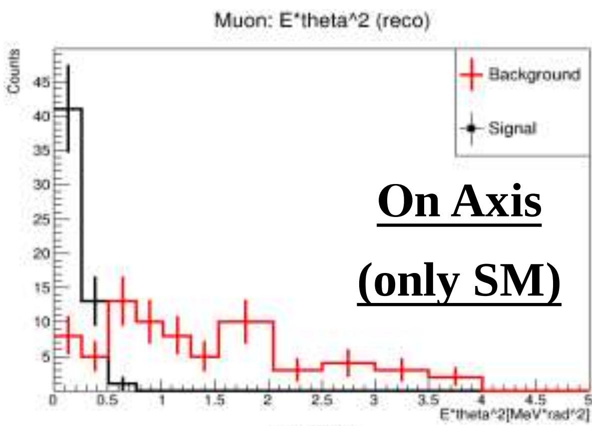
Under non-unitarity, the new EνES cross section can be expressed as

$$\left[\frac{d\sigma_{\nu_\ell}}{dT_e}\right]_{\mathrm{NU}} = (2a_{22}^2 - a_{11}^2)\left[\frac{d\sigma_{\nu_\ell}}{dT_e}\right]_{\mathrm{SM}} + \mathcal{O}(\varepsilon^4), \qquad \nu_\ell = \nu_\mu,\ \bar{\nu}_\mu \qquad \varepsilon \equiv \mathcal{O}(Yv/M)$$

As for the inverse muon decay cross section it takes the following form in the SM

$$\sigma^{(\mathrm{SM})} \approx \frac{G_F^2}{\pi}\left(2E_\nu m_e - m_\mu^2\right)$$

where it changes only by a factor of a_{22}^2 in the presence of NU



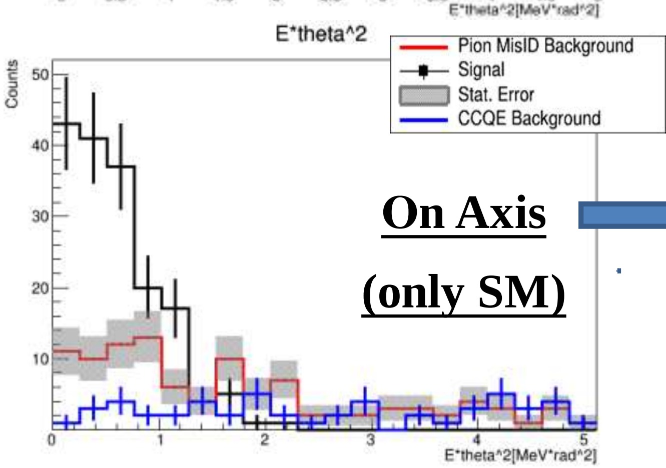
On Axis

(only SM)

DOI: 10.1103/PhysRevD.92.053009

DOI: 10.1103/PhysRevD.109.115007

Thus we can rescale the spectra by a factor a_{22}^2



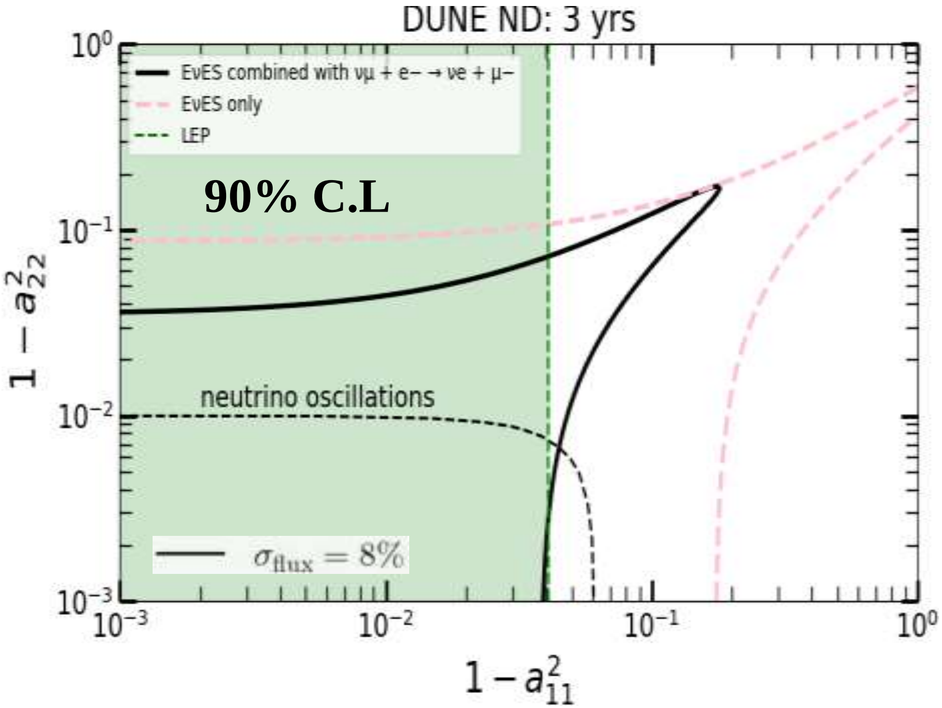
On Axis

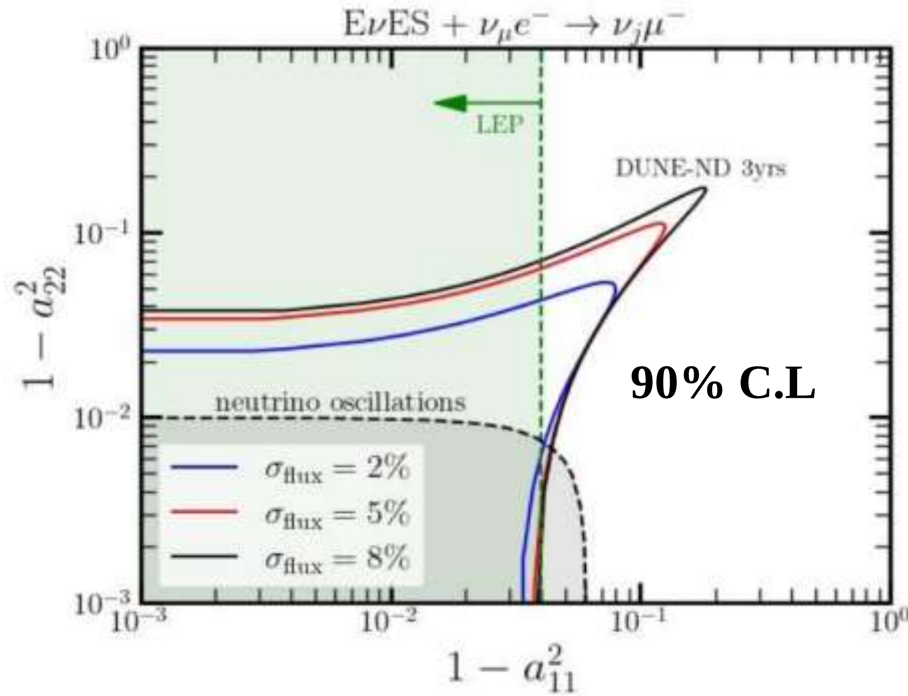
(only SM)

Thus we can rescale the EνES spectra by a factor $(2a_{22}^2 - a_{11}^2)$

https://doi.org/10.3390/ particles7030035

χ^2 Analysis





$$\chi^2 = 2\sum_{d=1}^{N_d}\sum_{i=1}^{20}\left[N^i_{\rm exp,d} - N^i_{\rm obs,d} + N^i_{\rm obs,d}\log\left(\frac{N^i_{\rm obs,d}}{N^i_{\rm exp,d}}\right)\right]$$
$$+\left(\frac{\alpha_1}{\sigma_{\alpha_1}}\right)^2 + \left(\frac{\alpha_2}{\sigma_{\alpha_2}}\right)^2$$

Where:

$$N_{\rm obs} = N_{\rm SM}(a_{11}, a_{22}) + N_{\rm bkg}$$
$$N_{\rm exp} = N_{\rm SM}\cdot(1+\alpha_1) + N_{\rm bkg}\cdot(1+\alpha_2)$$

- We consider two nuisance parameters α_1 and α_2 (which were minimized) with $\sigma_{\alpha 1}$=8% (5%, 2 %) and $\sigma_{\alpha 2}$ = 10% to account for the normalization uncertainties of the DUNE neutrino flux and background.
- We ignore the non-unitarity effects that are expected to affect the background rate; given the very low statistics of combined with the large assigned uncertainty of $\sigma_{\rm bkg}$ = 10%, we find this to be a valid assumption.
- The performed statistical analysis proceeds under the assumption that the EνES rate is induced by muon neutrinos only.

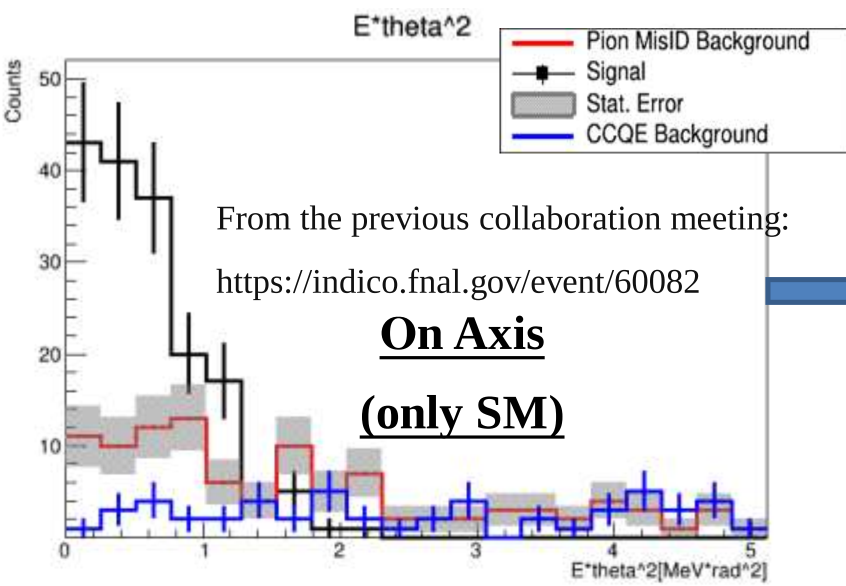
Probing the weak mixing angle

We now turn our attention on estimating the capabilities of DUNE-ND in probing the weak mixing angle within the SM via the exploitation of EνES events.

The EνES cross section for $E_\nu >> m_e$ can be expressed as

$$\sigma_{\nu_\ell - e^-}(E_\nu) \approx \frac{G_F^2 m_e E_\nu}{2\pi}\left(A + \frac{1}{3}B\right), \text{where } A = (g_V^{\nu_\ell} + g_A^{\nu_\ell})^2 \text{ and } B = (g_V^{\nu_\ell} - g_A^{\nu_\ell})^2$$

Assuming muon neutrinos, the couplings are $g_V^{\nu_\mu} = -\frac{1}{2} + 2\sin^2\theta_W$ and $g_A^{\nu_\mu} = -\frac{1}{2}$



From the previous collaboration meeting:

https://indico.fnal.gov/event/60082

On Axis

(only SM)

DOI: 10.1103/PhysRevLett.125.051803

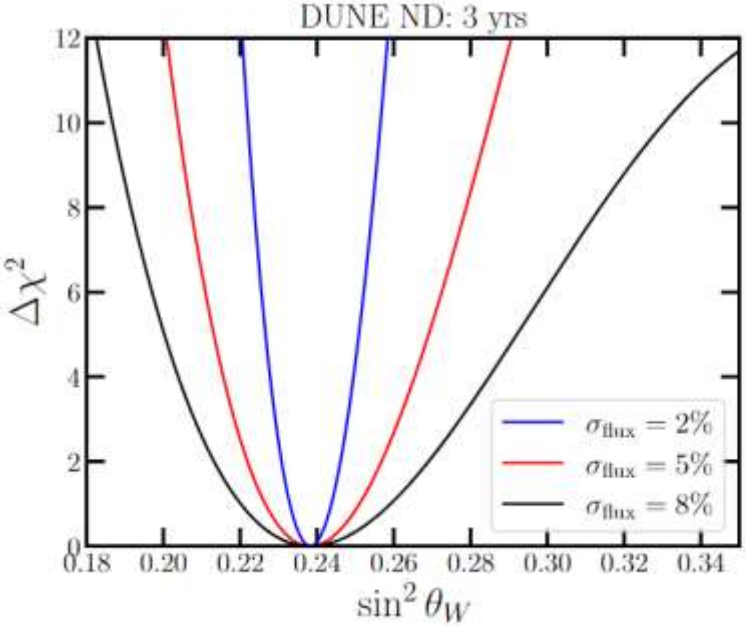
Thus we can rescale the EνES spectra by a factor

(A+(1/3)B) / (A′+(1/3)B′),

where A, B are allowed to vary with the weak mixing angle, while A′, B′ are fixed assuming

$\sin^2\theta_W = 0.2386$

χ^2 Analysis



$$\chi^2 = 2\sum_{i=1}^{20}\left[N_{\rm exp}^{ijk} - N_{\rm obs}^{ijk} + N_{\rm obs}^{ijk}\log\frac{N_{\rm obs}^{ijk}}{N_{\rm exp}^{ijk}}\right] + \left(\frac{\alpha_1}{\sigma_{\alpha_1}}\right)^2 + \left(\frac{\alpha_2}{\sigma_{\alpha_2}}\right)^2$$

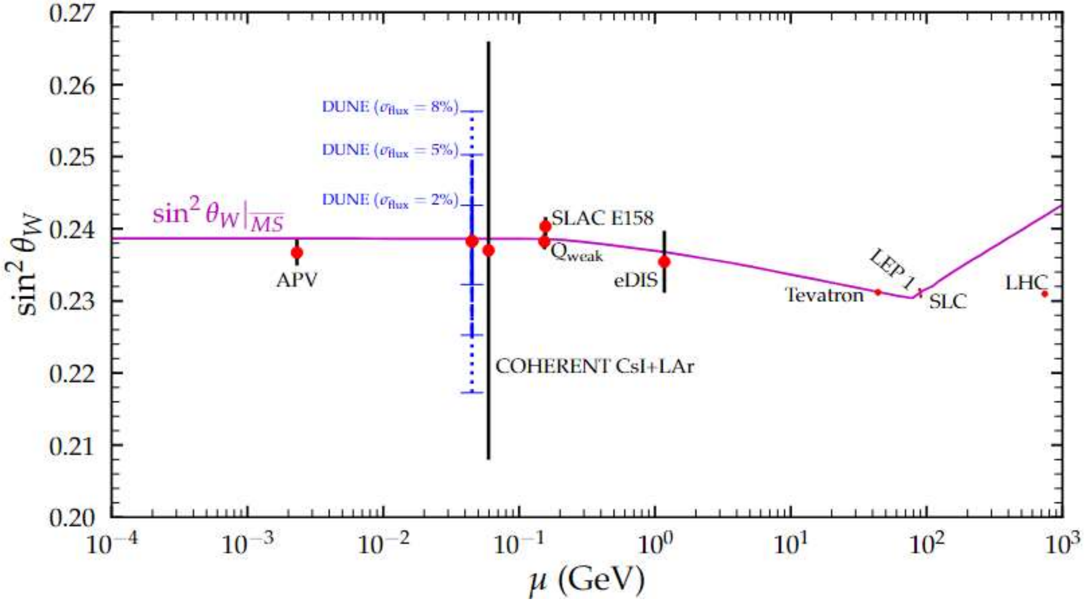
$$N_{obs} = N_{SM}(\sin^2\theta_W) + N_{bkg}$$

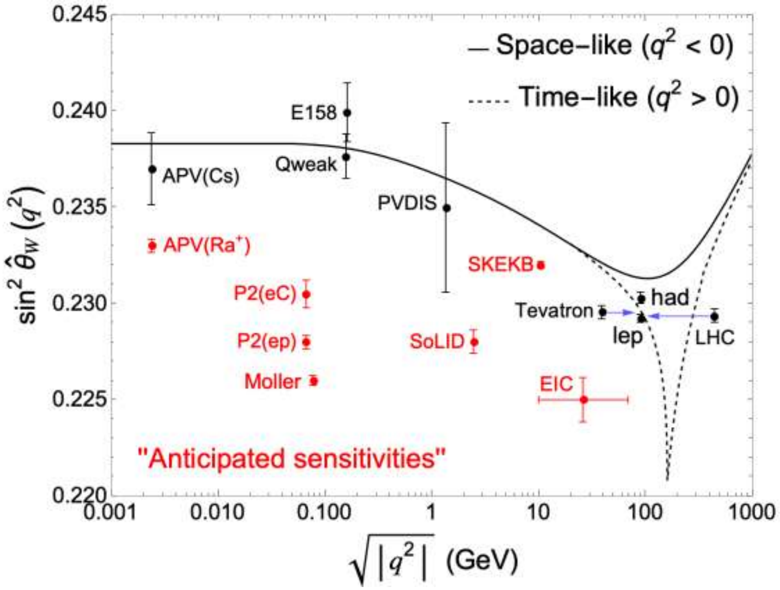
$$N_{exp} = N_{SM}\cdot(1+\alpha_1) + N_{bkg}\cdot(1+\alpha_2)$$

$$N_{\rm bkg} = N_{\pi^0}^{\rm missID} + N_{\rm CCQE}$$

- We consider two nuisance parameters α_1 and α_2 (which were minimized) with $\sigma_{\alpha 1}$=8% (5%, 2%) and $\sigma_{\alpha 2}$ = 10% to account for the normalization uncertainties of the DUNE neutrino flux and background.
- We ignore the effects that are expected to affect the CCQE background rate; given the very low statistics of CCQE combined with the large assigned uncertainty of σ_{bkg} = 10%, we find this to be a valid assumption.
- The performed statistical analysis proceeds under the assumption that the EνES rate is induced by muon neutrinos only.

Probing the weak mixing angle





EνES measurements at DUNE-ND can place competitive constraints in the low-energy regime and complementary to existing results from the analysis of COHERENT experiment

The black points are existing experimental data, and the red points are future anticipated sensitivities.

Summary – Publication Plans

- We have explored the utility of elastic neutrino-electron scattering (EνES) events within and beyond the Standard Model (BSM) searches.

- The analysis is based of EνES and relevant background events using parameterized reconstruction techniques.

- We are considering publishing this with the full DUNE-ND event reconstruction

Thank you for your kind attention

National and Kapodistrian University of Athens

The research project was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "3rd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers" (Project Number: 7036)

BACK-UP

Signal Selection

Inverse muon decay criterion:

Select events with only one reconstructed muon in the final state and no other activity (calorimetrically hadronic energy equals zero)

Removal of DIS interactions with one muon in the final state:

Angular Criterion:

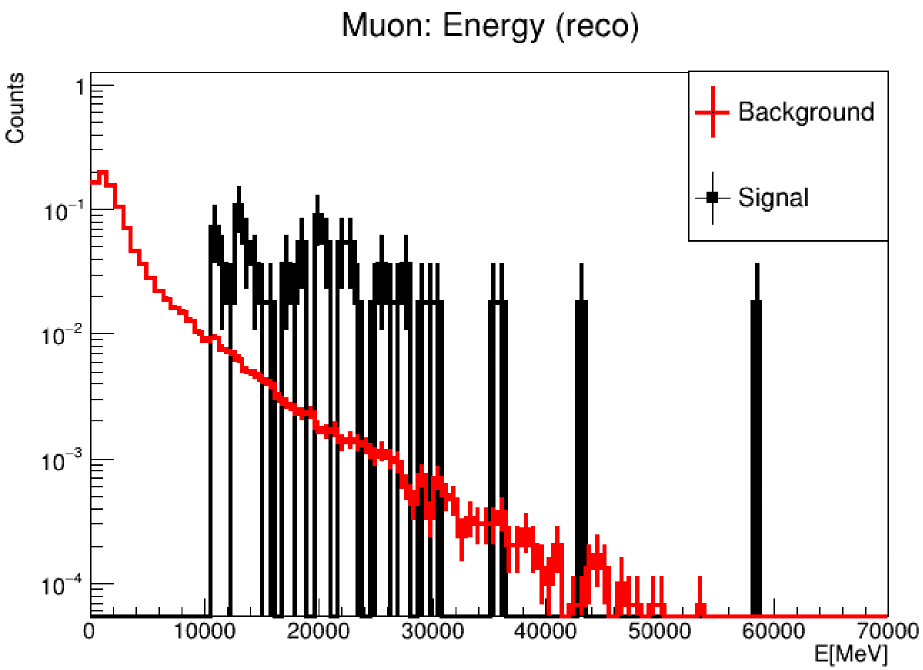
Select muons with **angle < 0.01 rad (**the angle is between the incoming neutrino and the reconstructed muon**)**

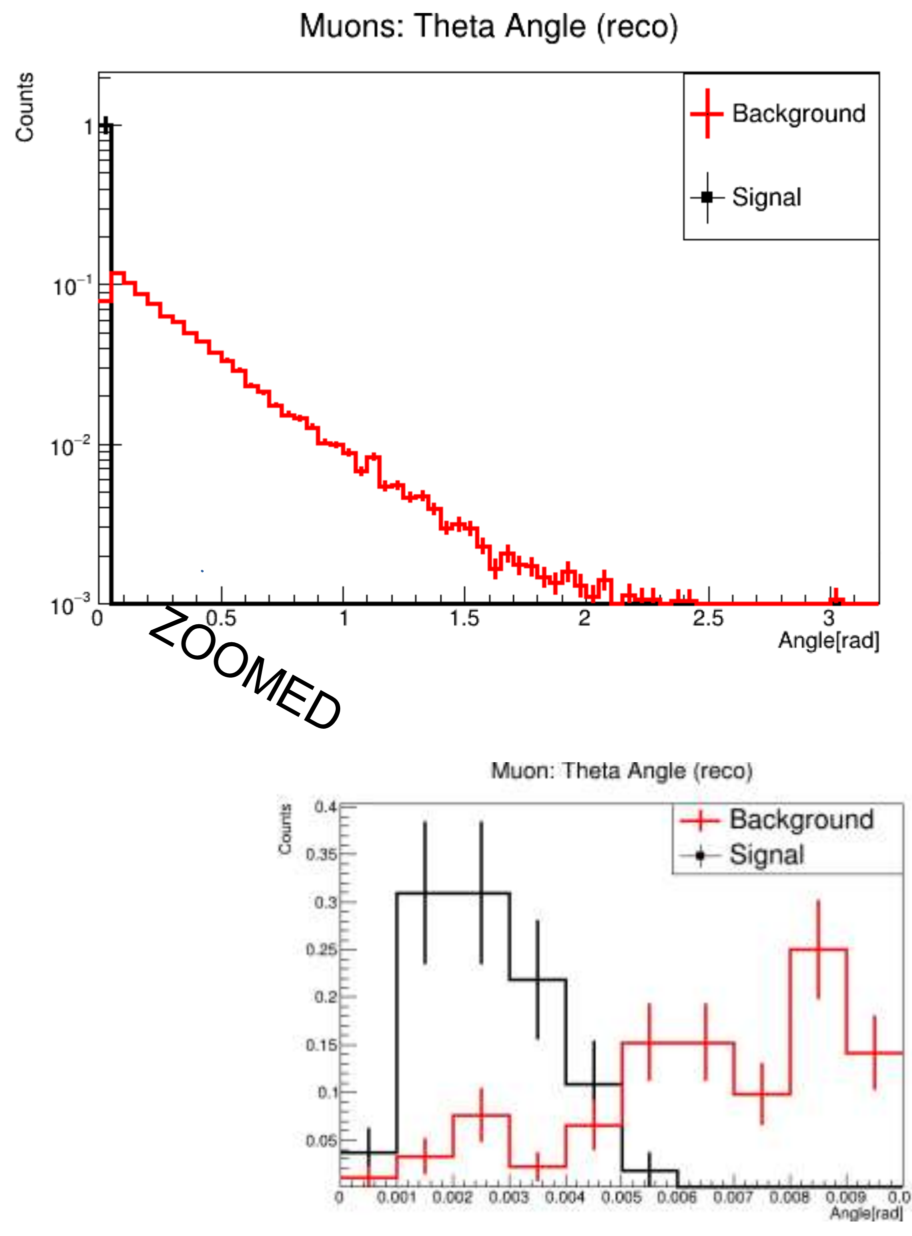
Energy Criterion:

Select electrons with **energy greater than 10GeV.**

10^{19}POT	Background			Signal		
Selection Criteria	Counts	Absolute Efficiency	Relative Efficiency	Counts	Absolute Efficiency	Relative Efficiency
All	3149249			55		
No Baryons/mesons	29602	0.94%	0.94%	55	100,00%	100,00%
No electrons	29555	0.94%	99.84%	55	100,00%	100,00%
Only 1 muon	29555	0.94%	100,00%	55	100,00%	100,00%
Muon energy >10GeV	2680	0.09%	9.07%	55	100,00%	100,00%
Muon angle <0.01 rad	71	0.00226%	2.65%	55	100,00%	100,00%

Muon's Distributions





Muon distributions prior to the application of **angular or energy cuts**

Selection criteria for v-e elastic scattering events

Elastic Scattering Criterion : We select events wi**th only 1 reconstructed electron** in the final state and **no other activity (calorimetrically hadronic energy equals zero)**

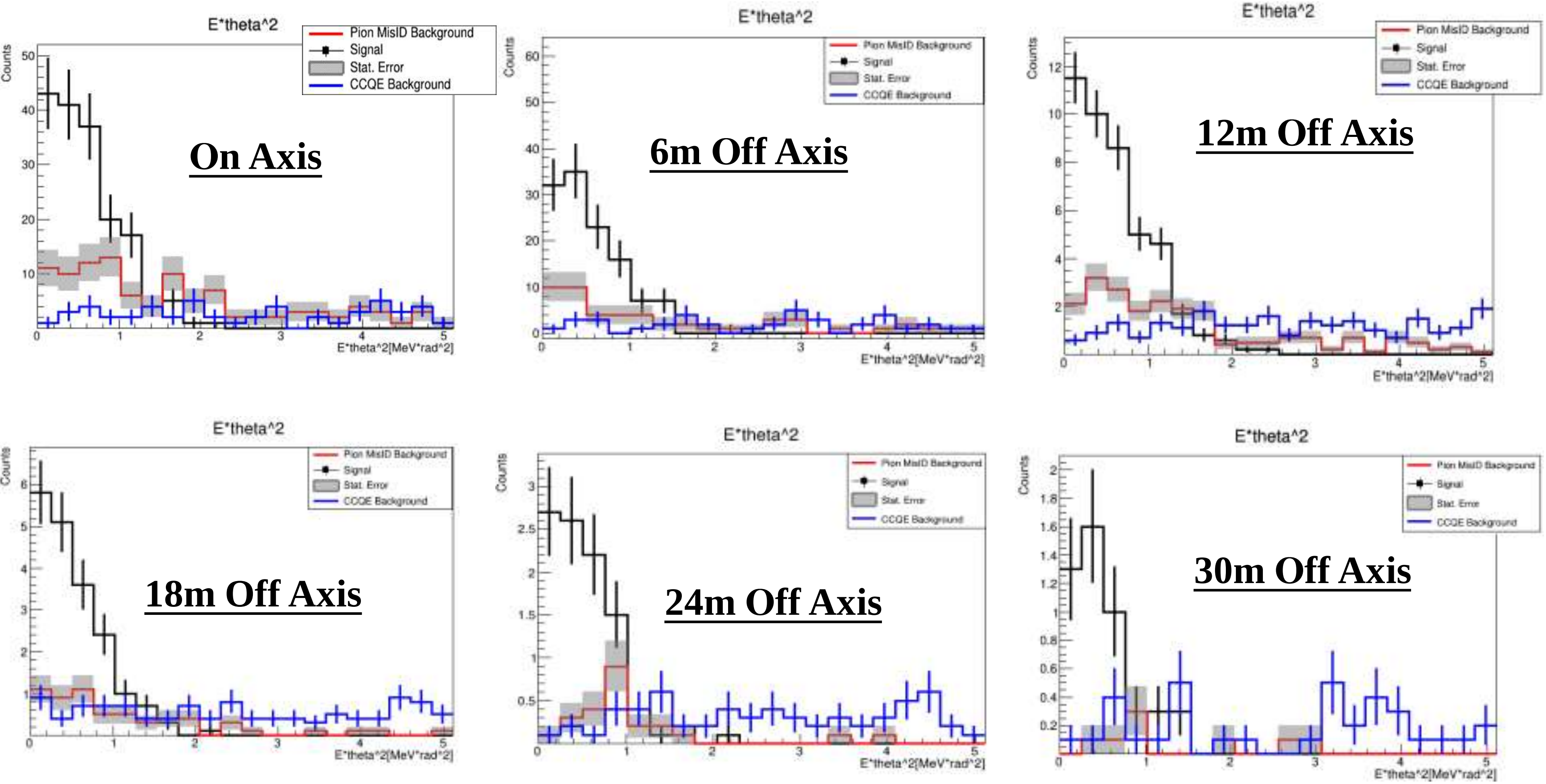
Energy Criterion: We keep final state **reconstructed electrons** with **reconstructed energy greater than 300MeV.**

Angular Criterion: Keep **final state reconstructed electrons** with reconstructed **angle < 0.04 rad (**the angle is between the incoming neutrino and the reconstructed electron**)**

Best observable for the analysis : Both the **energy** and **angular distributions** of signal background events are very different (see next slides), so one **of the best observables** is **E*θ^2**

	Signal (Reco)			Background (Reco)		
Criterion	**# Particles**	**Relative(%)**	**Absolute(%)**	**# Particles**	**Relative(%)**	**Absolute(%)**
Elastic Scattering	**179**	**-**	**-**	**12518**	**-**	**-**
Energy	**179**	**100 .0**	**100**	**12515**	**99.9**	**99.9**
Angular	**169**	**94.4**	**94.4**	**303**	**2.4**	**2.4**

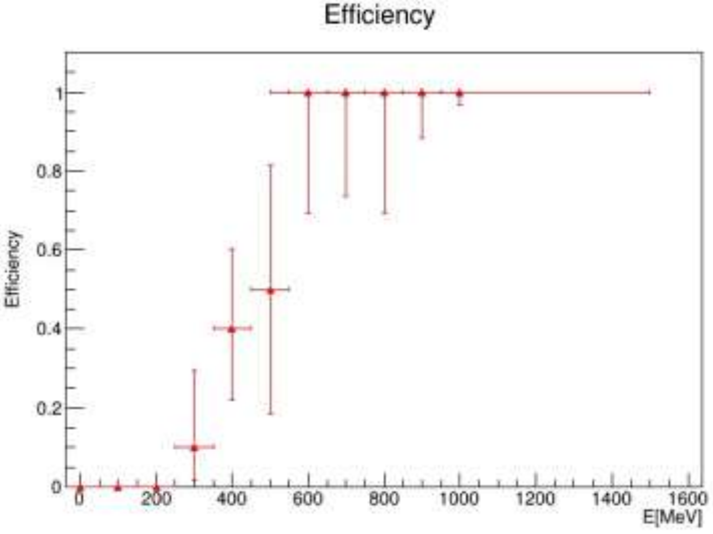
$E\theta^2$ for off-Axis locations for 10^{19} POT

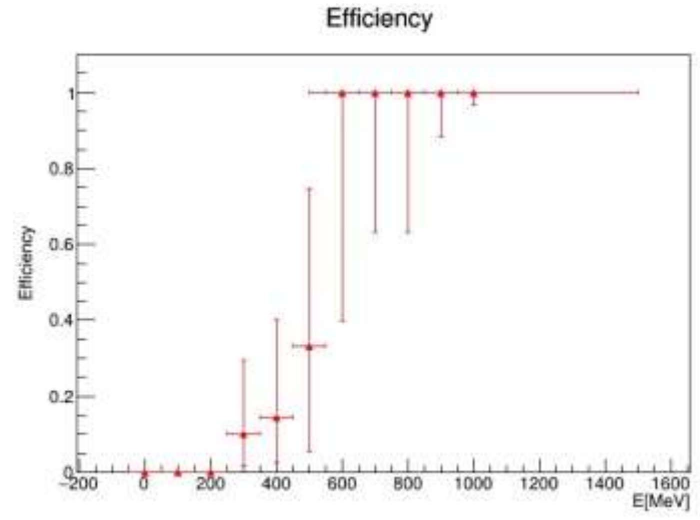


- **Very clear signal-background separation, very low background remaining.**

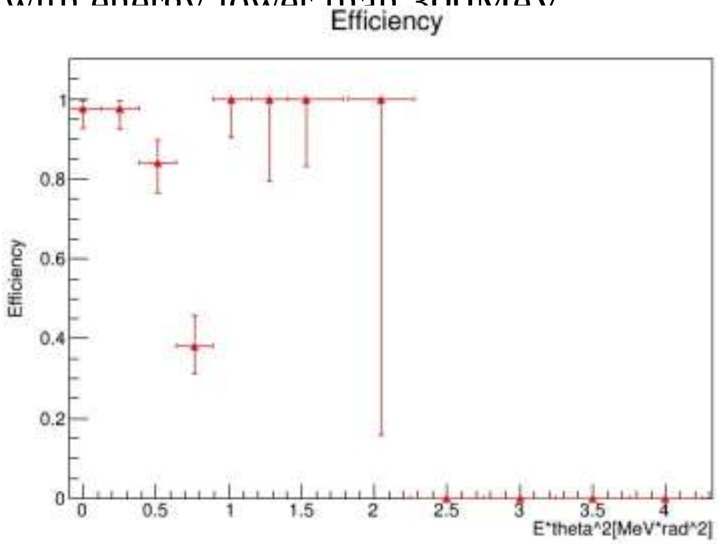
Differential Signal Selection Efficiency

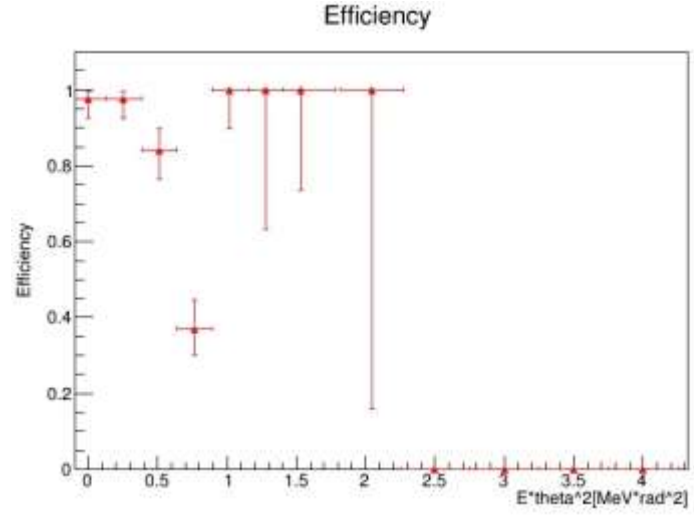
Before the selection criteria | **After the selection criteria**





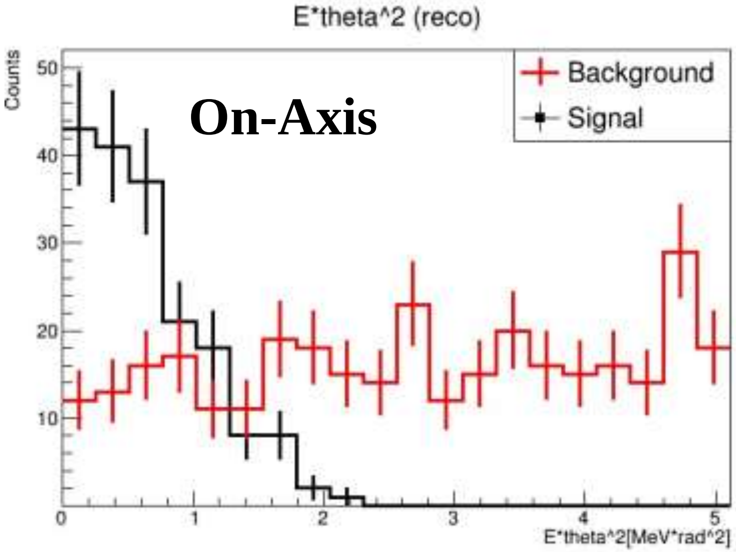
- Due to our **parametric reconstruction** the **electron identification/reconstruction starts from 300 MeV.**
- There is a **significant efficiency drop** in the region close to **E*θ^2 =1 MeV*rad^2** , caused by reco electrons with energy lower than 300MeV.

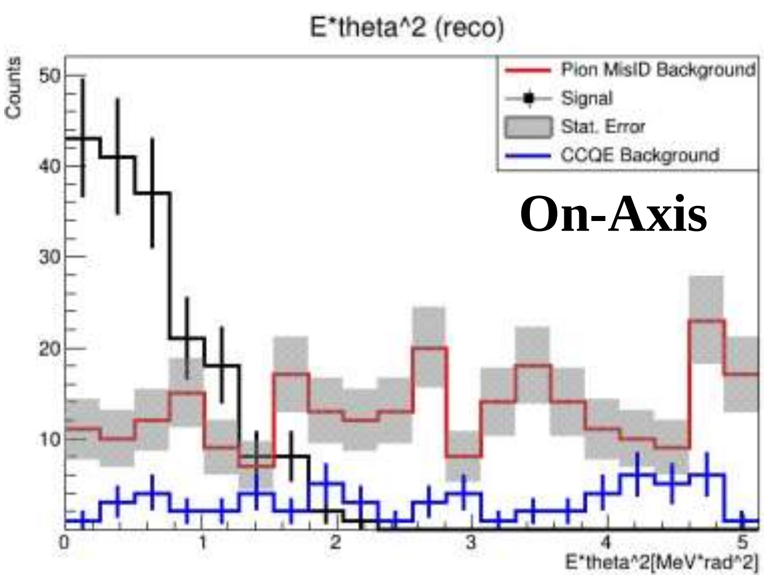




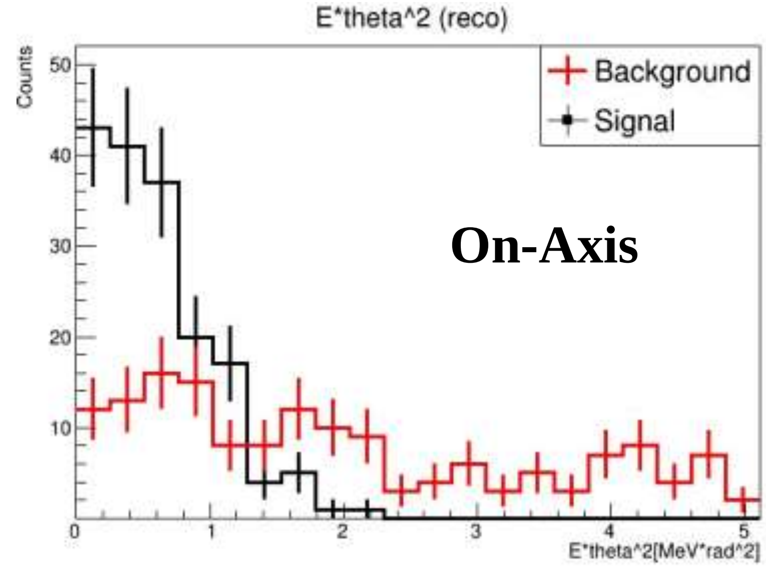
Signal/Background distributions

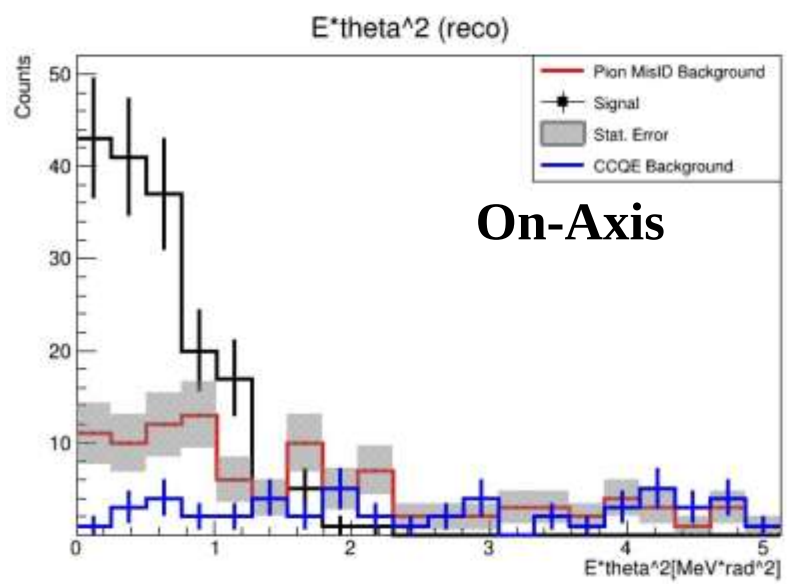
Before the selection criteria





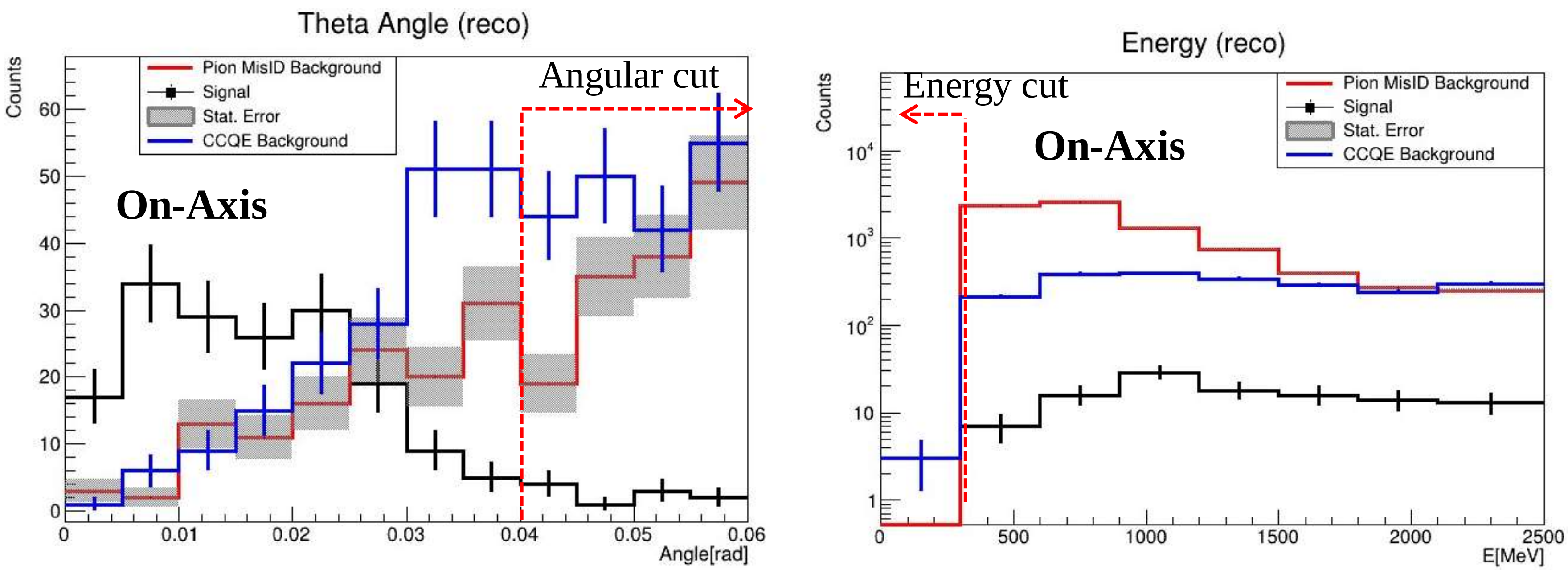
After the selection criteria





- The **background is significantly reduced** with the selection criteria, **more so for higher $E\theta^2$**

Signal and Background distributions

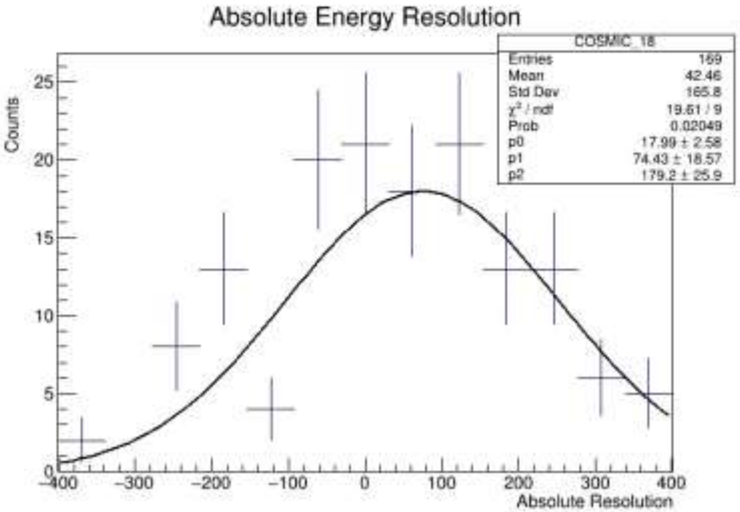


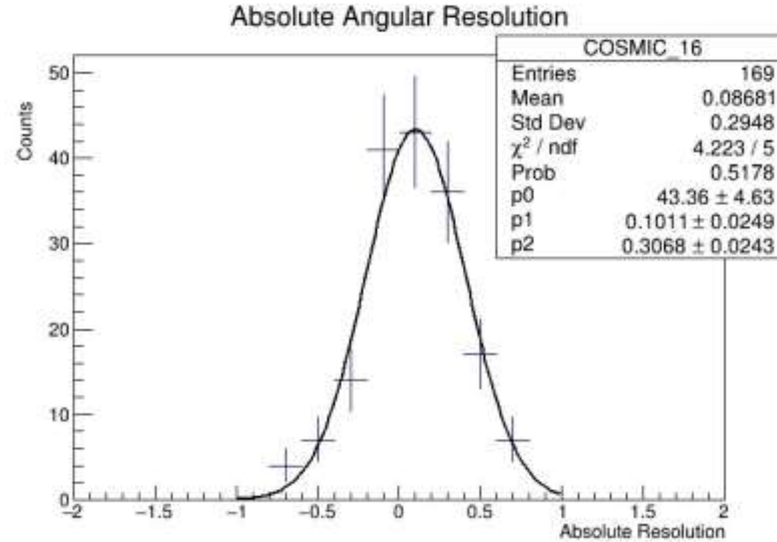
- The **π0** that are **reconstructed as electrons (background)** have **significantly larger scattering angle** compared to that of the **true electrons (signal)**

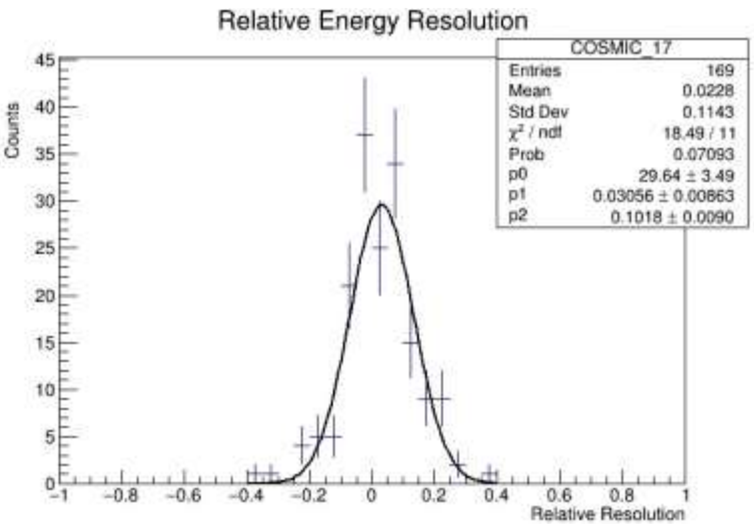
- We remove reconstructed electrons with angle greater than **0.04 rad.** (see slide 30)

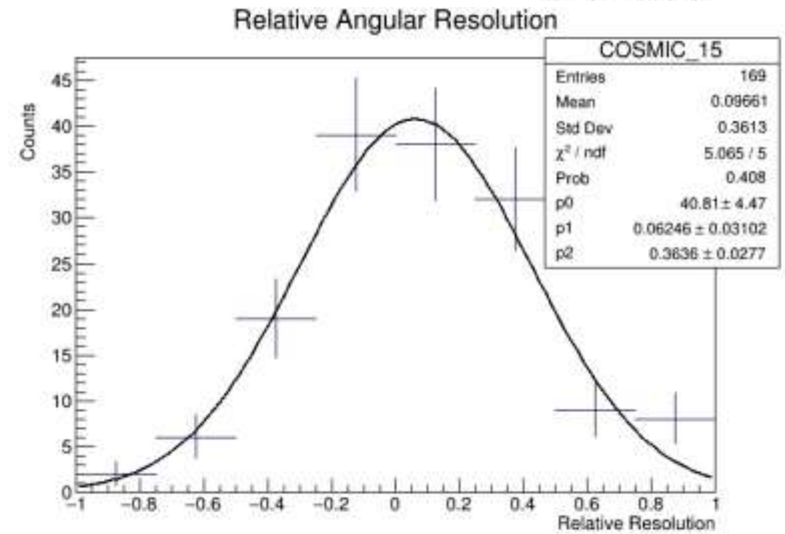
- We apply an energy cut **at 300MeV** in order to remove a small portion of the background

Energy and angular resolution : Signal









- Relative **angular resolution** for the signal to be 36+/-3% and the relative **energy resolution** 10.2% +/-0.9%

Significance for the Off-Axis locations

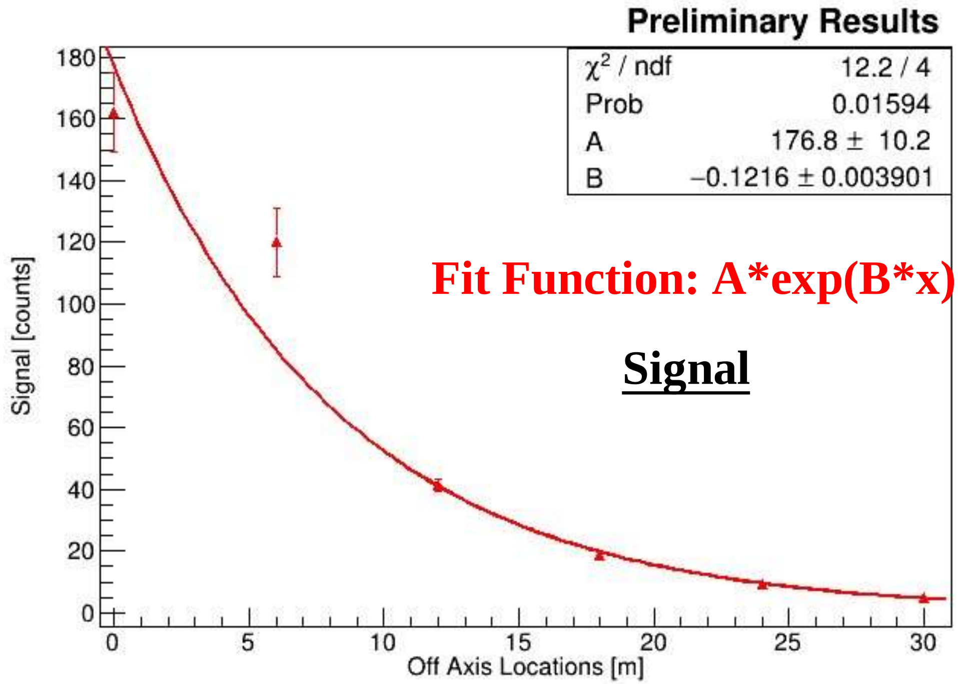
3yrs exposure	10^{19} POT		10^{20} POT(Scaled down)			
Off-Axis (m)	**0**	**6**	**12**	**18**	**24**	**30**
Signal(reco)	**169**	**121**	**43.2**	**19.0**	**9.8**	**4.8**
Background (reco)	**303**	**204**	**85.3**	**28.4**	**12.1**	**5.2**
Signal for E*theta^2< 1.5 (reco)	161	121	41.4	19	9.8	4.8
Background for E*theta^2< 1.5 (reco)	71	44	19.5	8.0	3.8	1.8
Significance (normalization)	**19.1**	**18.2**	**9.4**	**6.7**	**5.0**	**3.6**
Shape Significance	**20.8**	**18.4**	**10.1**	**7.0**	**7.3**	**5.4**

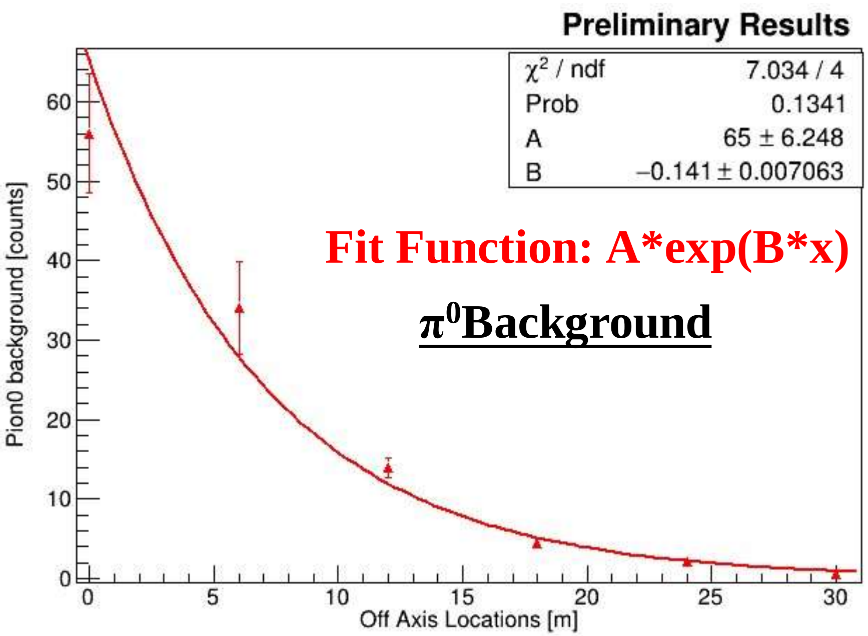
- The **significance** is **lower** as we move to **further off axis** locations due to **lower statistics.**

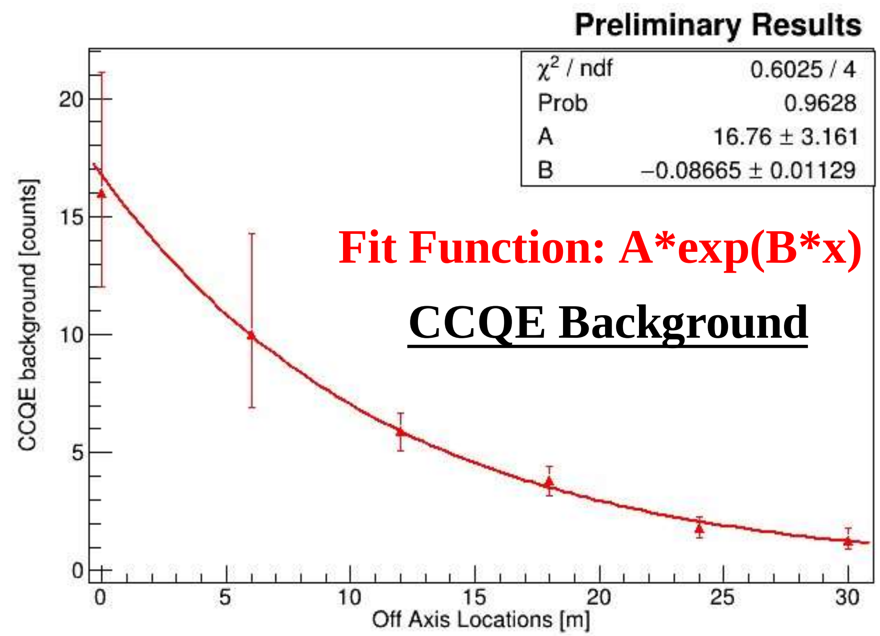
- **Still of-axis locations do contribute to the overall sensitivity.**

Signal and Background in off-Axis locations

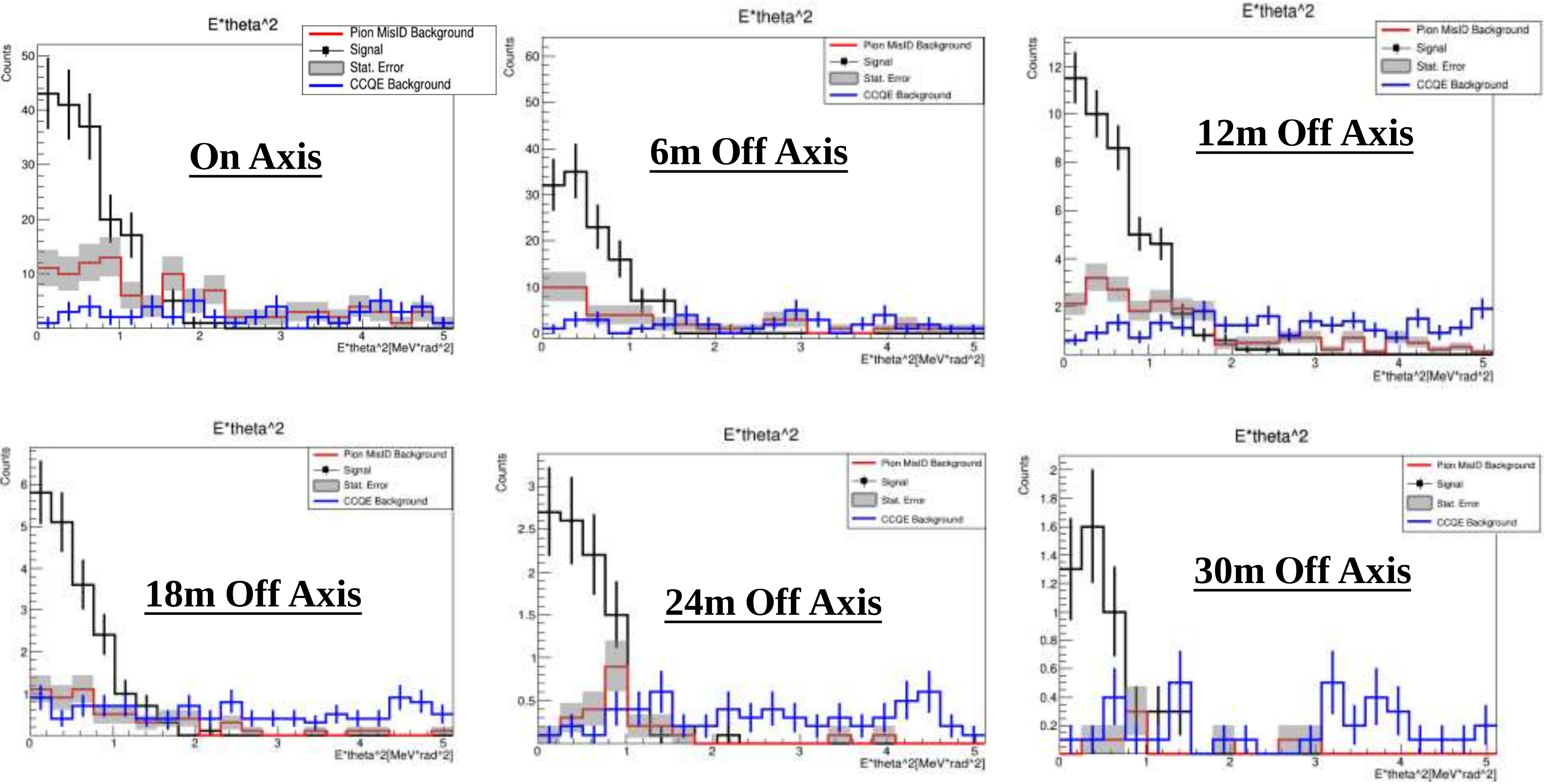
The π^0 background reduces faster than the signal





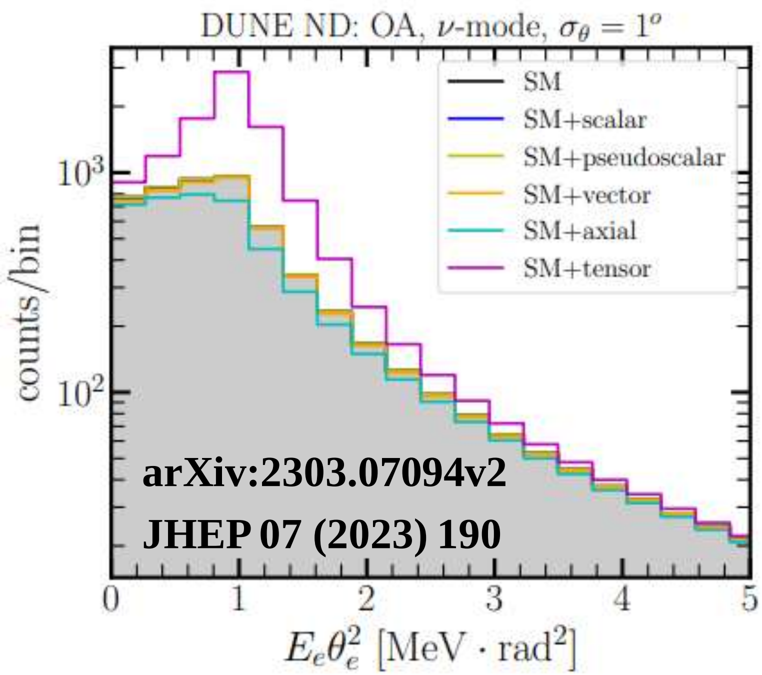


Eθ^2 for off-Axis locations for 10^{19} POT



- **Very clear signal-background separation, very low background remaining.**

χ^2 Analysis



$$\chi^2 = 2\sum_{k=\nu/\bar{\nu}}\sum_{j=\mathrm{loc}}\sum_{i=1}^{20}\left[N_{\mathrm{exp}}^{ijk} - N_{\mathrm{obs}}^{ijk} + N_{\mathrm{obs}}^{ijk}\log\frac{N_{\mathrm{obs}}^{ijk}}{N_{\mathrm{exp}}^{ijk}}\right] + \left(\frac{\alpha_1}{\sigma_{\alpha_1}}\right)^2 + \left(\frac{\alpha_2}{\sigma_{\alpha_2}}\right)^2$$

$$N_{obs} = N_{SM} + N_{bkg} + N_X(g_X, m_X)$$

$$N_{exp} = N_{SM}\cdot(1+\alpha_1) + N_{bkg}\cdot(1+\alpha_2)$$

$$N_{bkg} = N_{\pi^0}^{\mathrm{missID}} + N_{\mathrm{CCQE}}$$

- We consider two nuisance parameters α_1 and α_2 with $\sigma_{\alpha 1}$=5% and $\sigma_{\alpha 2}$ = 10% to account for the normalization uncertainties of the DUNE neutrino flux and background.

- Also, the study of neutrino-electron elastic scattering could help minimize the uncertainty on the flux even more (**arXiv:1910.10996v2 Phys. Rev. D 101, 032002 (2020)**).

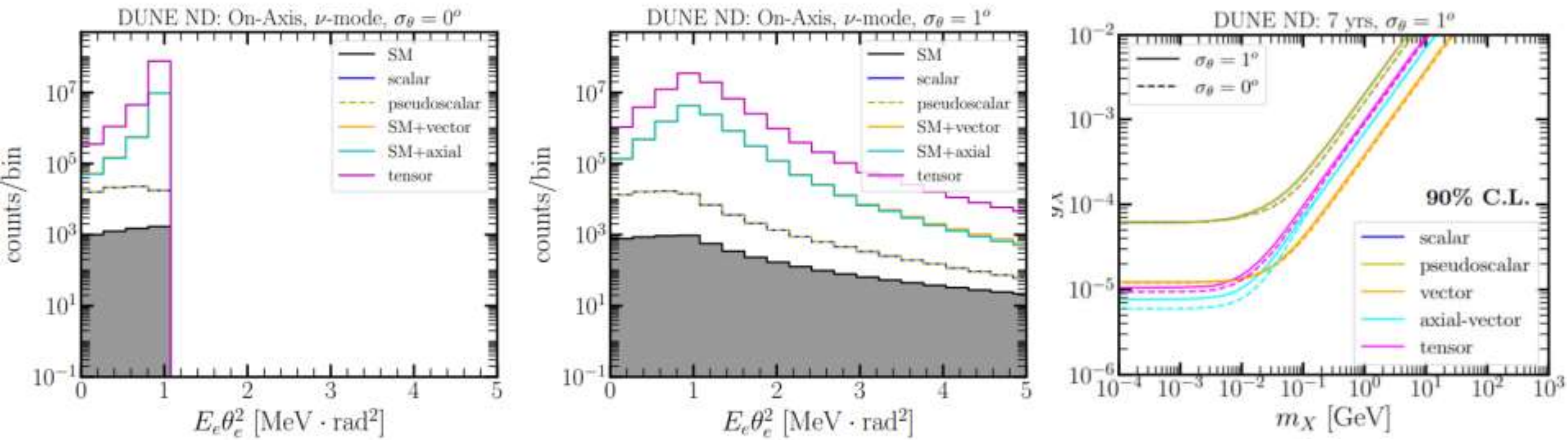
- A simultaneous fit was applied after adding the individual χ^2 per location and per neutrino mode

Sensitivities

- **New physics** could come from **all possible Lorentz invariant structures** that **alter the expected number of neutrino-electron scattering events and spectral shape in the Near Detector.**

Assuming 3.5 yr (neutrino) + 3.5 yr (antineutrino) mode at the DUNE-ND.

The left (**mid**) panel shows the results assuming perfect (**$\sigma(\theta) = 1^o$**) angular resolution



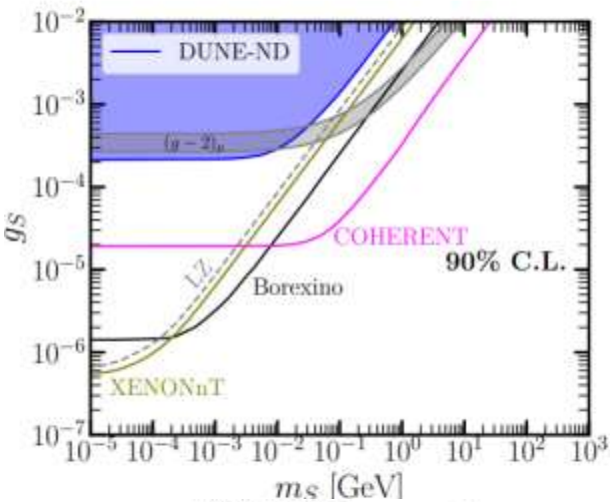
- **The NGI spectra are calculated for $g_X = 5.7 \cdot 10^{-5}$ and $m_X = 10$ MeV.**

- **The scalar and pseudoscalar are exactly the same**

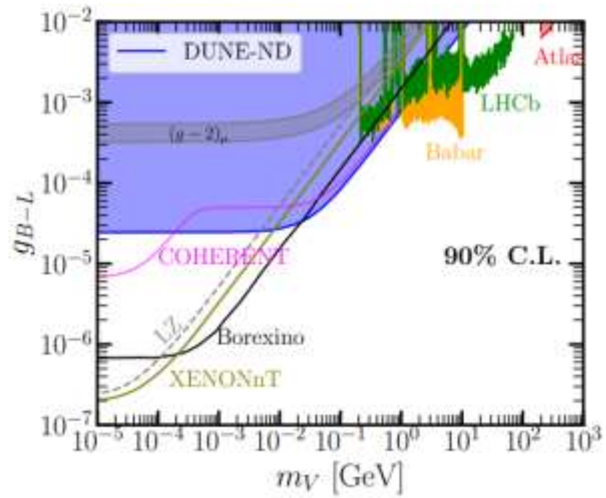
arXiv:2303.07094v2 JHEP 07 (2023) 190

BSM (NGI, LR, E6) Sensitivities

For scalar mediators

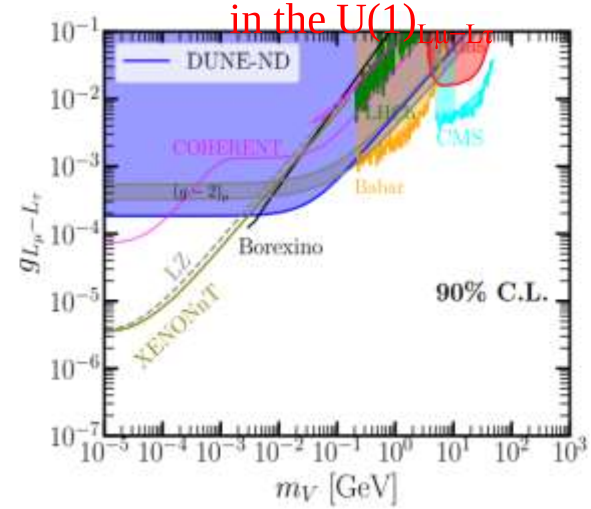


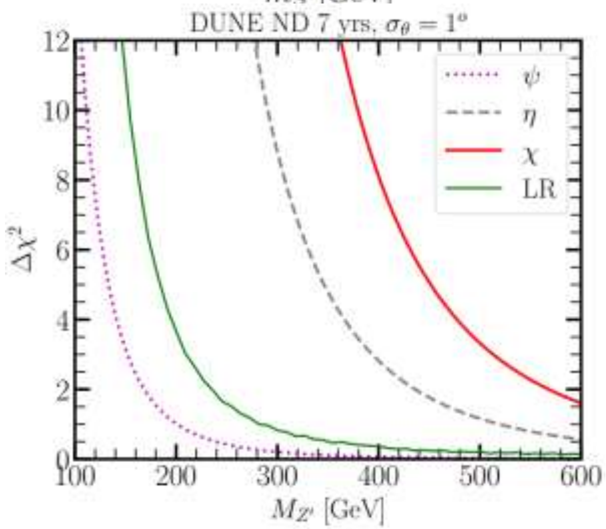
For vector mediators

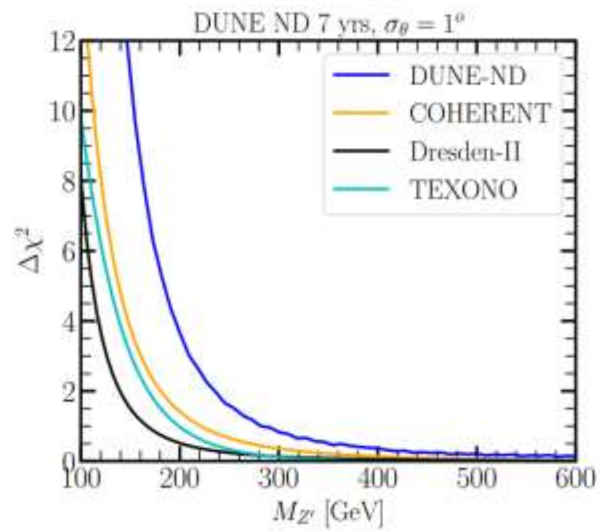


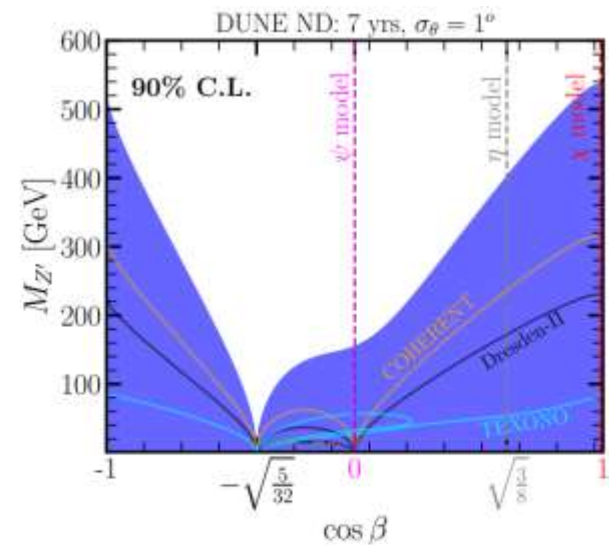
For vector mediators

in the $U(1)_{L\mu-L\tau}$









- **Sensitivities** of **DUNE-ND** are **competitive and complementary** to the ones from **other experiments**

arXiv:2303.07094v2 JHEP 07 (2023) 190