Probing generalized neutrino interactions with the DUNE Near Detector

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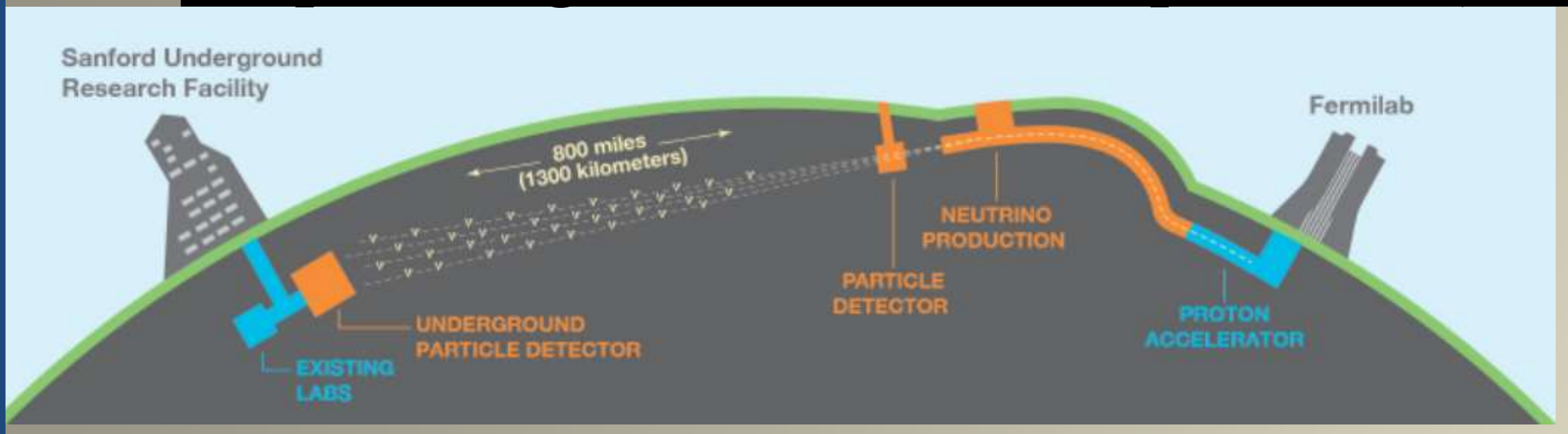
Deep Underground Neutrino Experiment (DUNE)



• The DUNE experiment is hosted by Fermi National Accelerator Laboratory at Chicago, IL, USA, the largest particle physics and accelerator laboratory in the United States.

• The DUNE experiment will send an intense neutrino beam 1300 kilometers through the earth from Fermilab to South Dakota. There, about 1.5 kilometers underground, a gigantic ~70 kT liquid-argon neutrino detector, will analyze how those neutrinos behave and interact.

• The DUNE experiment aims to explore and address fundamental questions such as [1] :

➢The neutrino mass ordering
➢CP violation in the ν-sector related with the matter-antimatter asymmetry in the universe
➢Proton decay

DUNE-ND

•The ND features a spectral beam monitor for timely detection of beam changes and uses beam models to extrapolate ND observations to expected FD signals.

•High statistics from the ND are crucial for tuning the neutrino interaction model, effectively reducing systematic errors in oscillation parameters.

•The ND can collect data at various off-axis beam positions, enabling DUNE to separate beam and cross-section models, improve the ND response matrix understanding, and create ND data sets with flux spectra similar to the oscillated FD fluxes, minimizing errors arising from the near-to-far flux difference

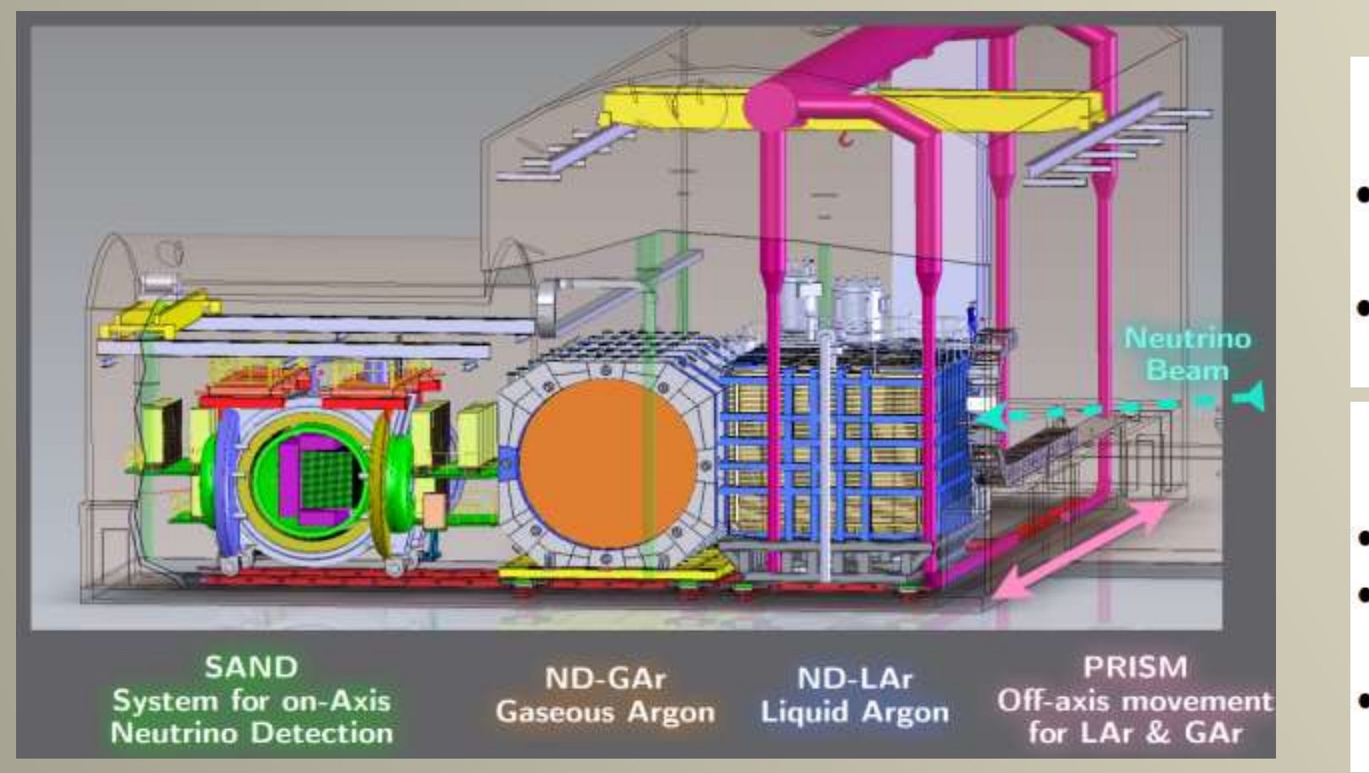
• The DUNE ND has three primary detector components and the capability for two of those components to move off the beam axis.

ND-GAr

- Same Ar nuclear target as the DUNE FD
- 10 atm Ar-CH$_4$ gas TPC, similar to ALICE (& reusing ALICE readout chambers)
- TPC surrounded by electromagnetic calorimeter and superconducting magnet

SAND

- Fixed on-axis position in DUNE ND hall
- LAr + tracker + ECAL in a solenoidal B field
- ECAL & magnet from the KLOE experiment
- Tracker technology is being finalized: Straw Tube Tracker (STT) or 3D scintillator (3DST) together with a gas TPC



PRISM

- System for moving ND-LAr and ND-GAr up to ~30 m transverse to the beam axis
- Enables scanning measurements as a function of off-axis angle

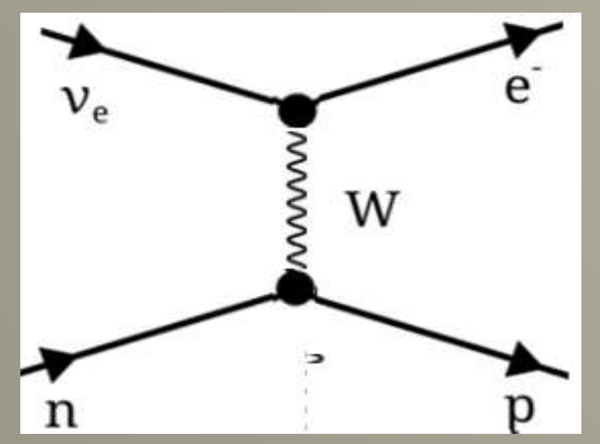
ND-LAr

- 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

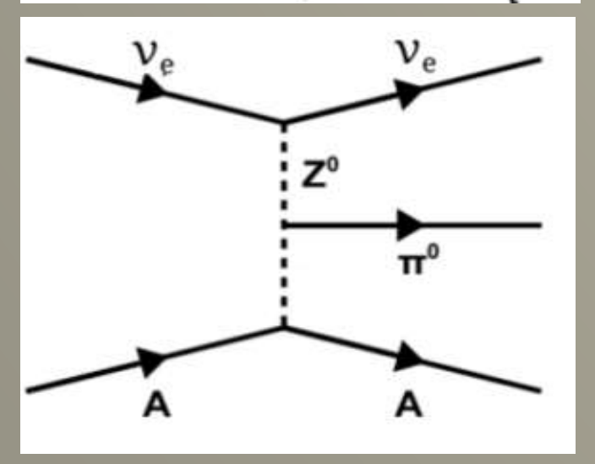
Signal and Background

Backgrounds

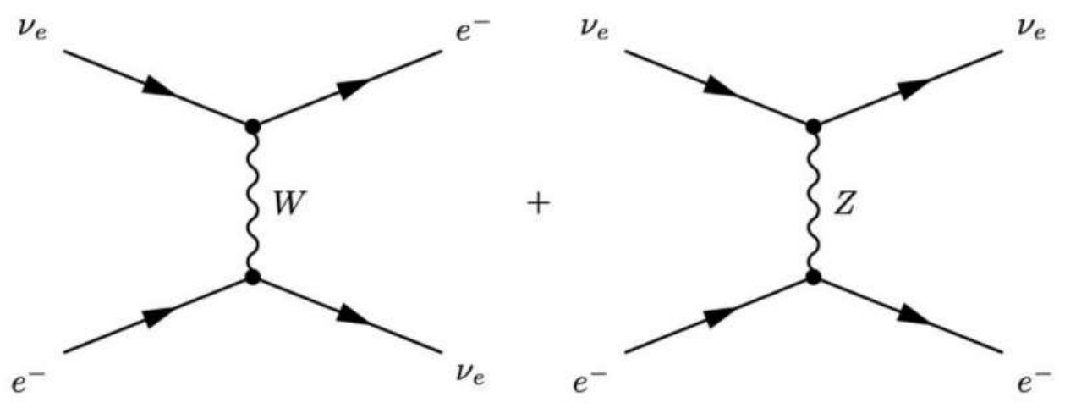
Charged Current Quasi Elastic interaction, where the nucleon is invisible either for being below threshold or reabsorbed
(reducible background)

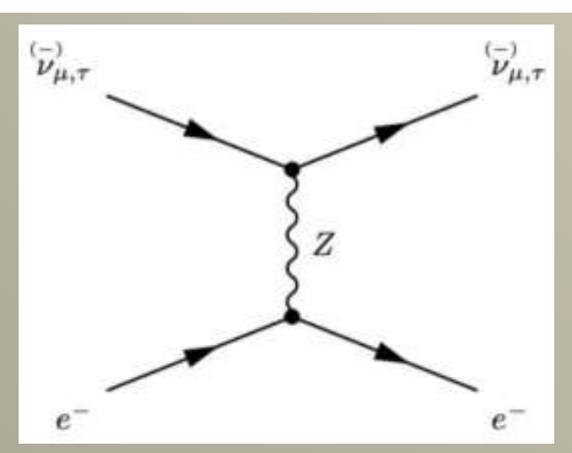


Neutral Current π^0 production, where the π^0 is misidentified as an electron, because one of the photons escapes detection
(reducible background)



Signal: SM ν-e





NGI Differential Cross Sections

- Neutrino generalized interactions (NGIs) constitute a **useful model-independent** probe that can accommodate several attractive BSM scenarios. New physics could come from all possible Lorentz invariant structures.

- Within the framework of the **SM, the differential cross section** with respect to the electron recoil energy Te, corresponding to the process **ν_e+e$^-$ -> ν_e+e$^-$**, reads

$$\left[\frac{d\sigma_{\nu_\alpha}}{dT_e}\right]_{SM} = \frac{G_F^2 m_e}{2\pi}\left[(g_V+g_A)^2 + (g_V-g_A)^2\left(1-\frac{T_e}{E_\nu}\right)^2 - (g_V^2-g_A^2)\frac{m_e T_e}{E_\nu^2}\right]$$

$$g_V = -\frac{1}{2} + 2\sin^2\theta_W + \delta_{\alpha e}, \qquad g_A = -\frac{1}{2} + \delta_{\alpha e}$$

- For **light vector and axial vector** novel mediators, the total differential cross sections can be achieved by replacing g_V and g_A from the SM cross section as

$$g'_{V/A} = g_{V/A} + \frac{g_{\nu V/A}\cdot g_{eV/A}}{\sqrt{2}G_F(2m_eT_e + m_{V/A}^2)}$$

- For the case of **scalar, pseudoscalar and tensor mediator,** the cross sections contributions can be added **incoherently** to the SM cross section

$$\left[\frac{d\sigma_{\nu_\alpha}}{dT_e}\right]_S = \left[\frac{g_{\nu S}^2\cdot g_{eS}^2}{4\pi(2m_eT_e+m_S^2)^2}\right]\frac{m_e^2T_e}{E_\nu^2}\left(1+\frac{T_e}{2m_e}\right)$$

$$\left[\frac{d\sigma_{\nu_\alpha}}{dT_e}\right]_P = \left[\frac{g_{\nu P}^2\cdot g_{eP}^2}{8\pi(2m_eT_e+m_P^2)^2}\right]\frac{m_eT_e^2}{E_\nu^2}$$

$$\left[\frac{d\sigma_{\nu_\alpha}}{dT_e}\right]_T = \frac{m_e\cdot g_{\nu T}^2\cdot g_{eT}^2}{2\pi(2m_eT_e+m_T^2)^2}\cdot\left[1+2\left(1-\frac{T_e}{E_\nu}\right)+\left(1-\frac{T_e}{E_\nu}\right)^2-\frac{m_eT_e}{E_\nu^2}\right]$$

Left-Right Symmetric Models

- In **Left-Right (LR) Symmetric Models**, the premise is that the fundamental weak interaction Lagrangian is **invariant under parity symmetry** at high energy scales.

- At these energy scales, the LRMS predicts that the weak force should be described by a theory with a gauge group that is the semi-direct product of the SU(2)$_L$ and SU(2)$_R$, which results in **a left-right symmetry of the interactions**.

- The **couplings for the neutrino-electron** scattering are:

$$f_L^{LR} = \mathcal{A}g_L + \mathcal{B}g_R$$
$$f_R^{LR} = \mathcal{A}g_R + \mathcal{B}g_L$$

$$\mathcal{A} = 1 + \frac{\hat{s}_Z^4}{1-2\hat{s}_Z^2}\gamma\,, \qquad \mathcal{B} = \frac{\hat{s}_Z^2\left(1-\hat{s}_Z^2\right)}{1-2\hat{s}_Z^2}\gamma$$

$$\gamma = (M_Z/M_{Z'})^2$$

The abbreviations s_z is the sin(θ_W), where θ_W is the Weinberg angle

- The left- and right-handed SM **couplings g_L and g_R** are related to the **vector and axial vector** couplings according to

$$g_L = \frac{g_V+g_A}{2} \qquad g_R = \frac{g_V-g_A}{2}$$

E6 Gauge Symmetry Models

- **E6 Gauge Symmetry Models** are a class of grand unified theories (GUTs) in particle physics that **are based on the E6 Lie group**.

- In these models, the standard model gauge group is **embedded in the larger E6 group**, which unifies all of the known forces of nature

- At low energy scale, this E6 gauge symmetry yields a U(1) symmetry which can be written as a combination of the symmetries U(1)χ and U(1)ψ

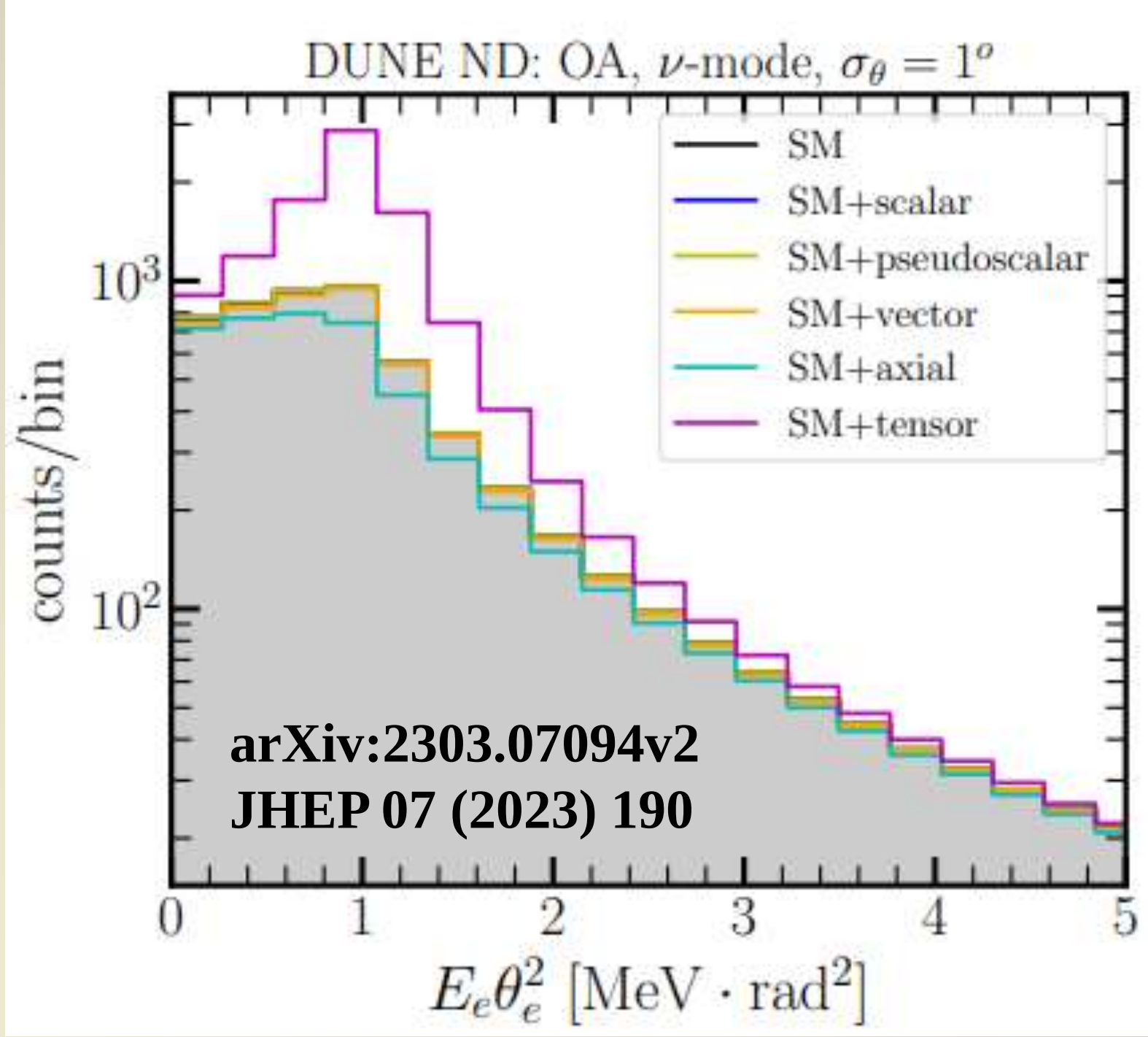
- The couplings for these models are:

$$f_R = g_R + 2\gamma\sin^2\theta_W\left(\frac{c_\beta}{2\sqrt{6}} - \frac{s_\beta}{3}\sqrt{\frac{5}{8}}\right)\left(\frac{3c_\beta}{2\sqrt{6}} + \frac{s_\beta}{3}\sqrt{\frac{5}{8}}\right)$$

$$f_L = g_L + 2\gamma\sin^2\theta_W\left(\frac{3c_\beta}{2\sqrt{6}} + \frac{s_\beta}{3}\sqrt{\frac{5}{8}}\right)^2$$

- Three different E6 models can be considered : the **(χ, ψ, η) model** with cos β = (1,0, √3/8)
 and the abbreviations c_β = cos β, s_β = sin β

χ^2 Analysis



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

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

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

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

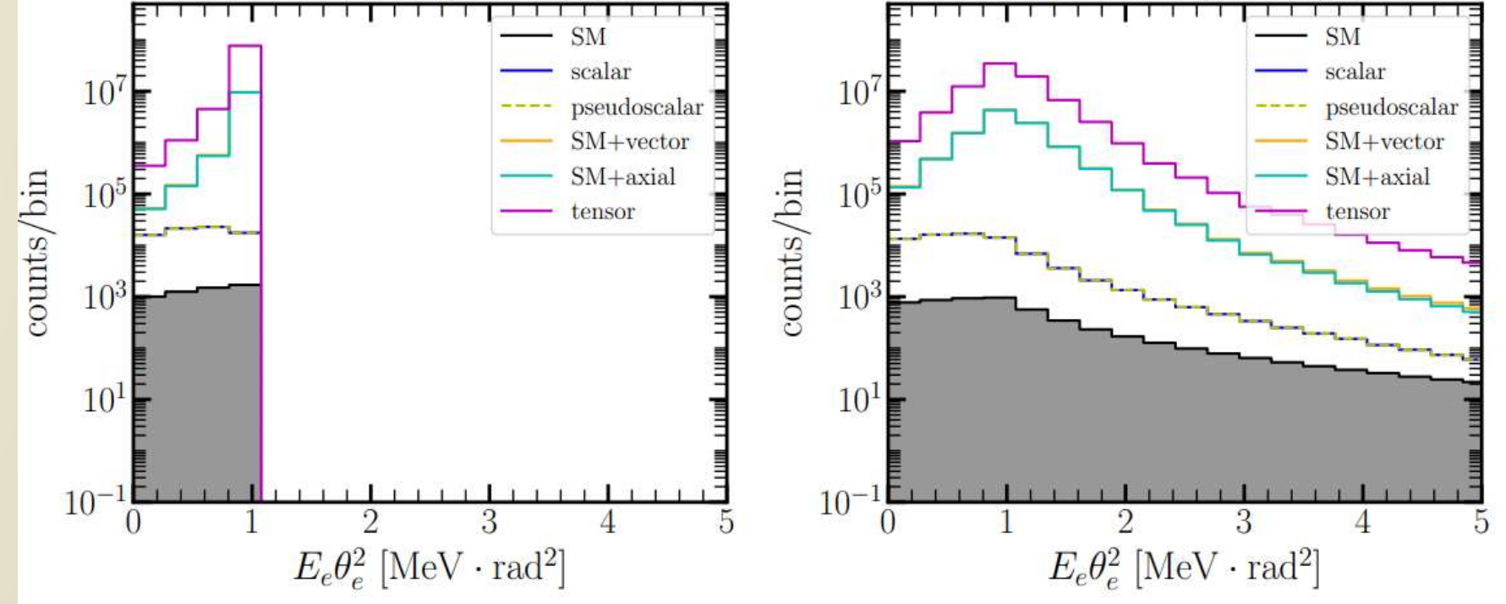
- **Eθ^2** distributions for **angular resolution 1^0** in different **on-axis locations**, where **E** and **θ** is the **energy** and **angle** of the **outgoing electron**

- We consider two nuisance parameters α_1 and α_2 with $\sigma_{\alpha1}$=5% and $\sigma_{\alpha2}$ = 10% to account for the normalization uncertainties of the DUNE neutrino flux and background.

- 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.**

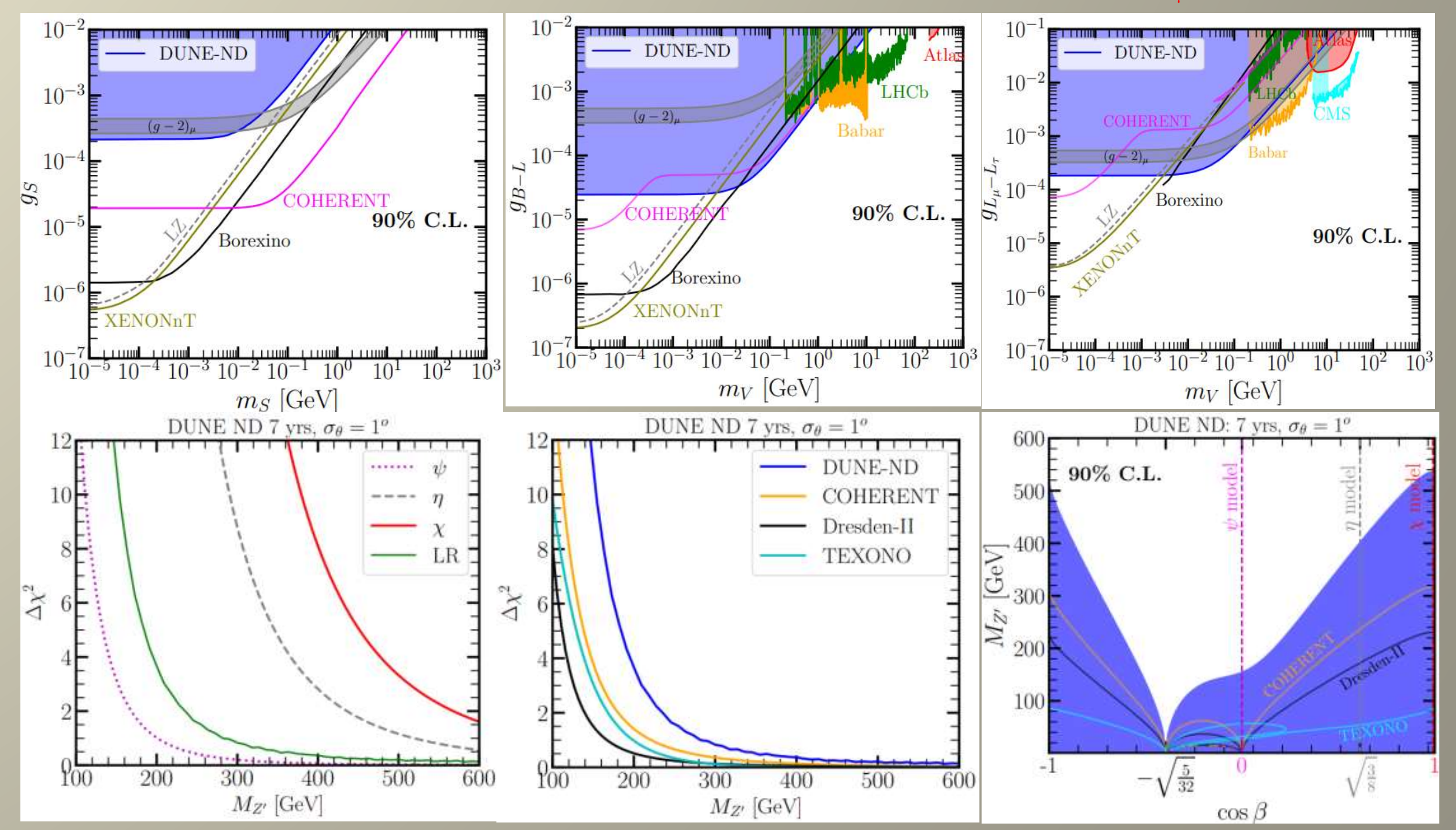


Assuming 3.5 yr (neutrino) + 3.5 yr (antineutrino) mode at the DUNE-ND.
The left (**mid**) panel shows the results assuming perfect (**σ(θ) = 1º**) angular resolution

•. The NGI spectra are calculated for $g_X = 5.7\cdot10^{-5}$ and m_X = 10 MeV
•The scalar and pseudoscalar are exactly the same

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**

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