ν-e Scattering Radiative Corrections in Short Baseline Experiments

Omar Miranda, Guadalupe Moreno, Celio Moura

Presented by
Guadalupe Moreno

XXXV Anual Meeting DPYC
May 11, 2021

Outline

- Motivation
- Radiative corrections in the ν-e scattering
- Effective neutrino charge radius
- DUNE Near Detector sensitivity to radiative corrections, and effective neutrino charge radius
- Conclusions

This work is based on O. G. Miranda, G. Moreno-Granados and C. A. Moura, [arXiv:2102.01554 [hep-ph]].

Motivation
Neutrino electron scattering

The SM has been shown to be a fairly accurate theory. This theory has been verified in several physical observables by multiple experimental collaborations.

In the neutrino sector, the neutrino electron scattering has been proven to be a useful test tool,

- Its pure leptonic character has been helpful to provide clear signatures in different predictions of the SM, such as the existence of Neutral Currents (Gargamelle, CERN 1973).

- Another precision tests of the SM, with the neutrino electron scattering can be the precise measurements of the weak mixing angle .

Credit: Symmetry Magazine / Courtesy of CERN

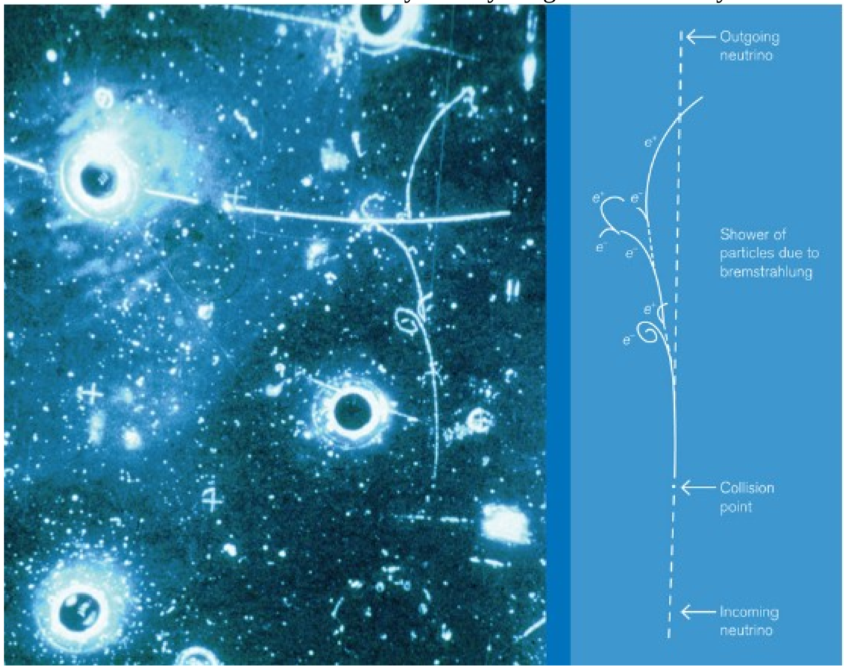


Fig. 1 Weak neutral current in Gargamelle 1973.

F. J. Hasert et al. [Gargamelle Neutrino], Phys. Lett. B 46 (1973)
S. L. Glashow, Nucl. Phys. 22, 579-588 (1961)
S. L. Glashow and S. Weinberg, Phys. Rev. D 15, 1958 (1977)
A. Salam, Conf. Proc. C 680519, 367-377 (1968)

Motivation
Future precision measurements

In the neutrino sector, the search for the existence of a CP-violating phase (and other neutrino oscillation properties, of which we know little), motivated the construction of long-baseline experiments, like DUNE at Fermilab.

Those long-baseline experiments predict intense neutrino beams, and the possibility to measure neutrino oscillation properties with unprecedented precision.

On the other hand, in the near detectors (ND) opens the possibility to measure the neutrino-electron scattering with high statistics, giving the chance for its precise measurement.

Credit: Fermilab

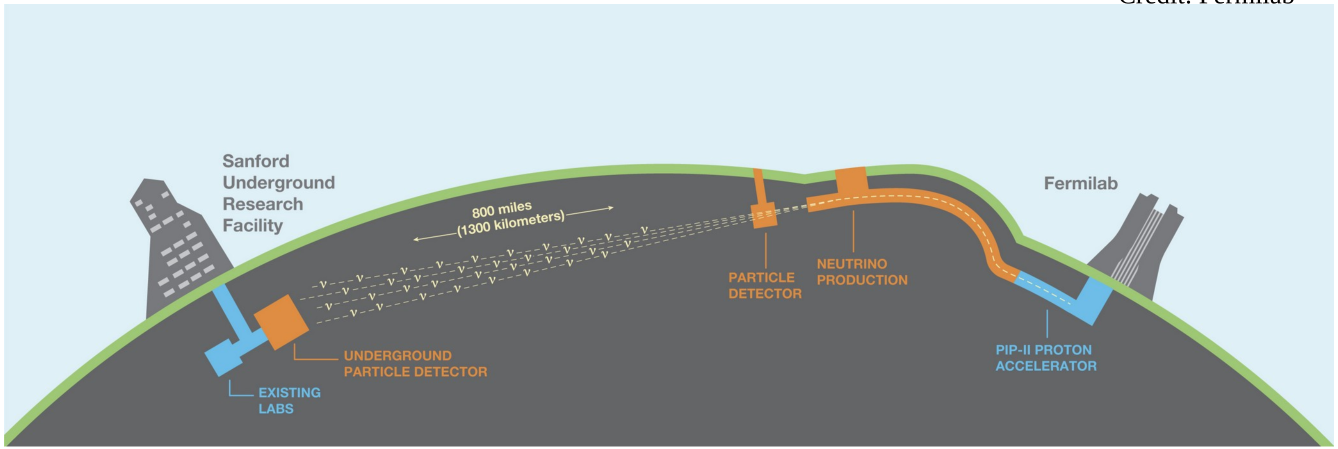


Fig. 2 DUNE will consist of two neutrino detectors. One detector near the source of the beam, at the Fermilab, and a second detector will be installed underground at the Sanford Underground Research Laboratory in SD 1,300 kilometers downstream of the source.

B. Abi, et al. [DUNE], [arXiv:1807.10334 [physics.ins-det]].

Radiative corrections
in ν-e scattering

The $\nu_\mu(\bar{\nu}_\mu)\, e^-$ is a neutral current Z-mediated process that involves only leptons. This process can provide a precise test of the SM at low energies, the consistency of the weak mixing angle and the possible existence of a neutrino charge radius (NCR).

The differential cross section for the $\nu_\mu e^-$ scattering at tree-level is:

$$\frac{d\sigma}{dT} = \frac{2m_e G_F^2}{\pi}\left\{ g_L^2 + g_R^2\left(1-\frac{T}{E_\nu}\right)^2 - g_R g_L m_e \frac{T}{E_\nu^2}\right\}$$

where m_e is the electron mass, G_F is the Fermi constant, T is the electron kinetic energy of recoil, and E_ν is the incoming neutrino energy. The coupling constants g_L and g_R are defined at tree-level, as

$$g_L = \frac{1}{2} - \sin^2\theta_W \qquad\qquad g_R = -\sin^2\theta_W$$

where θ_W is the weak mixing angle.

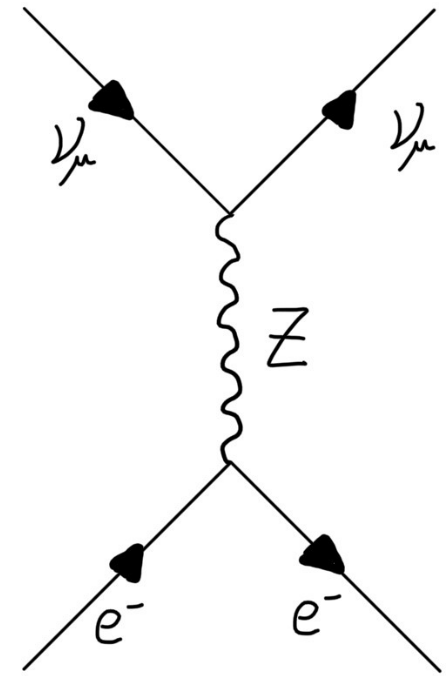


Fig. 3 Feynman diagram of $\nu_\mu e^-$ elastic scattering at tree-level.

Radiative corrections
in ν-e scattering

The radiative corrections in $\nu_\mu e^-$ scattering can be divided depending on their dynamic origin into:

(a) Quantum Electrodynamic (QED) corrections, that involve, e.g., the creation and absorption of photons in the electronic current.

(b) Electroweak (EW) corrections, due to the exchange of W and Z bosons.

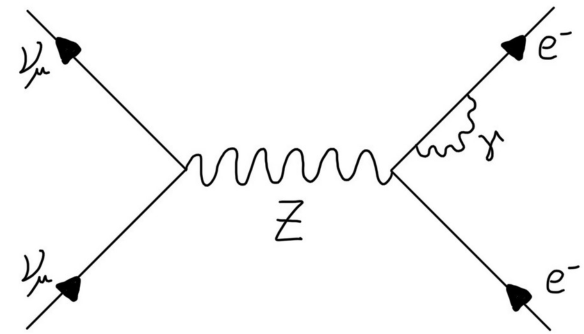
The expression considering QED and EW radiative corrections for the $\nu_\mu e^-$ differential cross section is:

$$\frac{d\sigma'}{dT} = \frac{2m_e G_F^2}{\pi}\left\{ g_L'^2(T)\left[1+\frac{\alpha}{\pi}f_-(z)\right] + g_R'^2(T)\left(1-\frac{T}{E_\nu}\right)^2\left[1+\frac{\alpha}{\pi}f_+(z)\right] - g_R'(T)g_L'(T)m_e\frac{T}{E_\nu^2}\left[1+\frac{\alpha}{\pi}f_{+-}(z)\right]\right\}$$

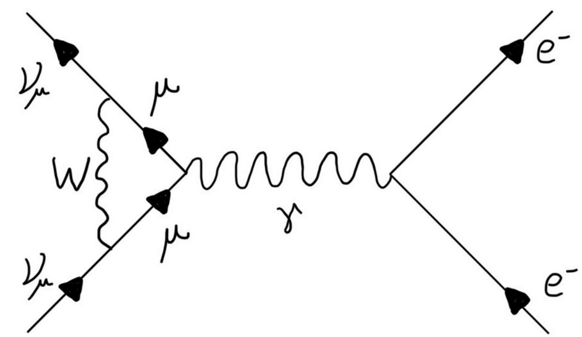
where the functions $f_+(z)$, $f_-(z)$, and $f_{+-}(z)$ account for the QED corrections. The coupling constants include the EW corrections:

$$g_L'(T) = \rho_{\rm NC}\left[\frac{1}{2} - \kappa_{\nu_l}(T)\sin^2\theta_W^{(m_Z)}\right] \qquad g_R'(T) = -\rho_{\rm NC}\kappa_{\nu_l}(T)\sin^2\theta_W^{(m_Z)}$$

J. N. Bahcall, M. Kamionkowski and A. Sirlin, Phys. Rev. D 51, 6146-6158 (1995)



(a) QED, eye vertexes



(b) EW, μW ν_μ vertexes

Fig. 4 Feynman diagrams representing radiative corrections

Radiative corrections
in ν-e scattering

where $\sin^2\theta_W^{(mZ)}$ is $\sin^2\theta_W$ calculated at the m_Z scale, the factor ρ_{NC} has the numerical value 1.014 and the factor $\kappa_{\nu l}(T)$ is defined as:

$$\kappa_{\nu_l}(q^2) = 1 - \frac{\alpha}{2\pi\hat{s}^2}\left[\sum_i \left(C_{3i}Q_i - 4\hat{s}^2 Q_i^2\right) J_i(q^2) - 2J_l(q^2) + \ln c\left(\frac{1}{2} - 7\hat{c}^2\right) + \frac{\hat{c}^2}{3} + \frac{1}{2} + \frac{\hat{c}_\gamma}{\hat{c}^2}\right]$$

where $q^2 = -2m_eT$ is the squared 4-momentum transfer, and

$$J_i(q^2) = \int_0^1 dx x(1-x)\ln\left(\frac{m_i^2 - q^2x(1-x)}{m_Z^2}\right)$$

The flavor dependence of the incident neutrino is contained in the $2J_l(q^2)$ term.

A. Sirlin and A. Ferroglia, Rev. Mod. Phys. 85, no.1, 263-297 (2013)
A. Ferroglia, G. Ossola and A. Sirlin, Eur. Phys. J. C 34, 165-171 (2004)
M. Passera, Phys. Rev. D 64, 113002 (2001)
J. Erler and R. Ferro-Hernández, JHEP 03 196 (2018)

Neutrino charge radius

The radiative corrections to $\nu_\mu e^-$ scattering have flavor-dependent contributions that is referred to as the neutrino charge radius (NCR).

$$\kappa_{\nu_l}(q^2) = 1 - \frac{\alpha}{2\pi\hat{s}^2}\left[\sum_i \left(C_{3i}Q_i - 4\hat{s}^2 Q_i^2\right) J_i(q^2) \boxed{- 2J_l(q^2)} + \ln c\left(\frac{1}{2} - 7\hat{c}^2\right) + \frac{\hat{c}^2}{3} \boxed{+ \frac{1}{2}} + \frac{\hat{c}_\gamma}{\hat{c}^2}\right]$$

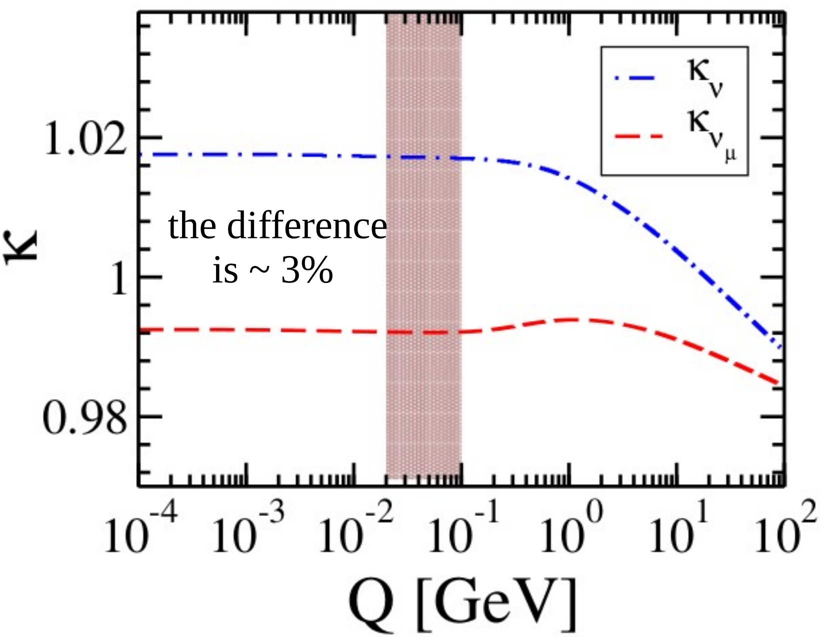


Fig. 5 κ_ν and $\kappa_{\nu\mu}$ as functions of $Q \equiv -q^2$

If we turn our attention to $-2J_l(q^2) + 1/2$, from $\kappa_{\nu l}(q^2)$ evaluated in q=0, this quantity is usually associated with the NCR and becomes:

$$\boxed{-2J_l(0) + \frac{1}{2} = \frac{1}{6}\left[3 - 2\ln\left(\frac{m_l^2}{m_Z^2}\right)\right]} \Rightarrow \left\langle r_{\nu_l}^2 \right\rangle = \frac{G_F}{4\sqrt{2}\pi^2}\left[3 - 2\ln\left(\frac{m_l^2}{m_W^2}\right)\right]$$

Considering that $\kappa_\nu(q^2)$, is a common contribution for all the neutrino flavors:

$$\kappa_\nu(q^2) = 1 - \frac{\alpha}{2\pi\hat{s}^2}\left[\sum_i \left(C_{3i}Q_i - 4\hat{s}^2 Q_i^2\right) J_i(q^2) + \ln c\left(\frac{1}{2} - 7\hat{c}^2\right) + \frac{\hat{c}^2}{3} + \frac{\hat{c}_\gamma}{\hat{c}^2}\right]$$

C. Giunti and A. Studenikin, Rev. Mod. Phys. 87 (2015)
J. Papavassiliou, J. Bernabeu, D. Binosi and J. Vidal, Eur. Phys. J. C 33, S865-S867 (2004)

DUNE-PRISM

DUNE-PRISM is a ND design option, which uses the same technology LarTPC as the DUNE FD.
One of the most important features of PRISM is that is a movable ND, that allows collecting data at several off-axis angles up to a maximum of 3.6°, exposing the ND to different fluxes and spectra.
PRISM expects to have 75 t of LAr, and we conduct our analysis for a 3.5 years period in the neutrino mode and the same period in the antineutrino mode.

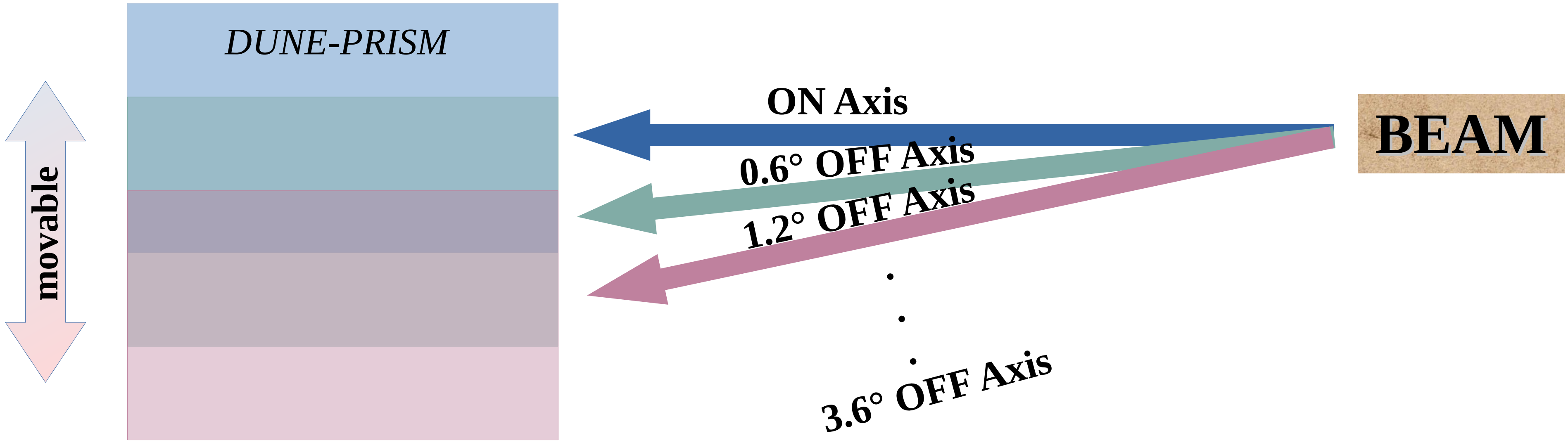


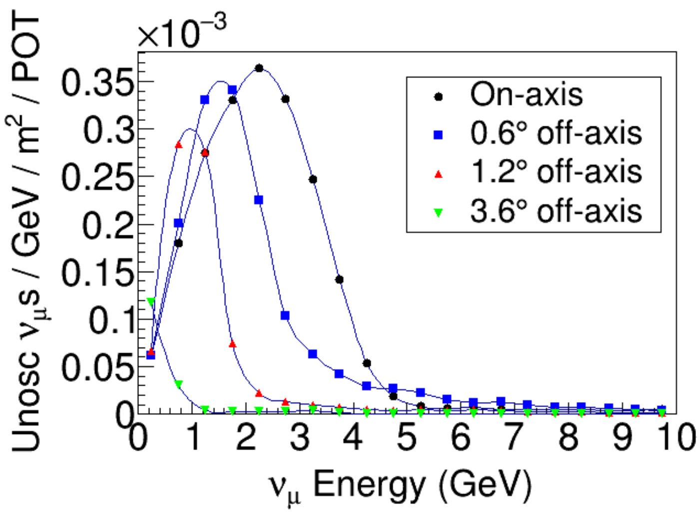
Fig. 6 DUNE-PRISM cartoon, illustrating their mobility to several OFF axis locations.

D. Hongyue [DUNE], PoS NuFact2017, 058 (2018)

V. De Romeri, K. J. Kelly and P. A. N. Machado, Phys. Rev. D 100, no.9, 095010 (2019)
C. Vilela, (2018), presented at Physics Opportunities in the Near DUNE Detector hall (PONDD 2018)

DUNE-PRISM
Fluxes

Neutrino beam mode



Antineutrino beam mode

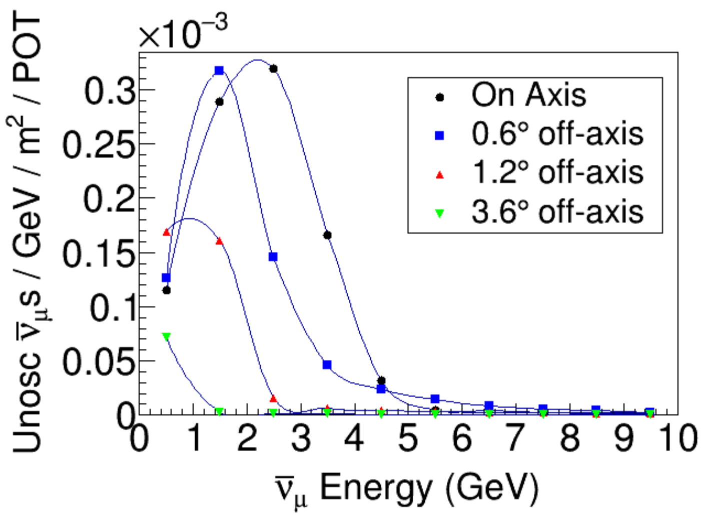
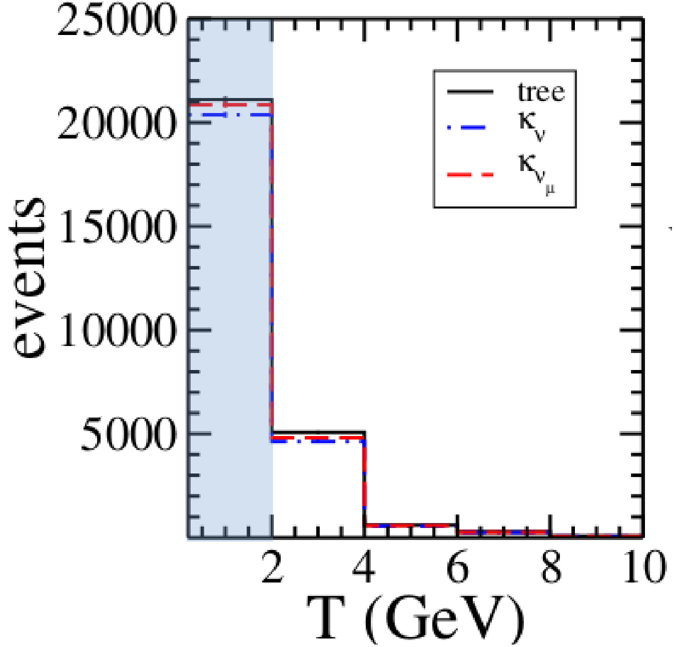


Fig. 7 Fluxes at several off-axis locations. Neutrino mode, on the left side, and antineutrino mode, on the right side.

L. Fields, ***https://home.fnal.gov/~ljf26/DUNEFluxes/***

DUNE-PRISM (On-axis)
Radiative Corrections, and NCR

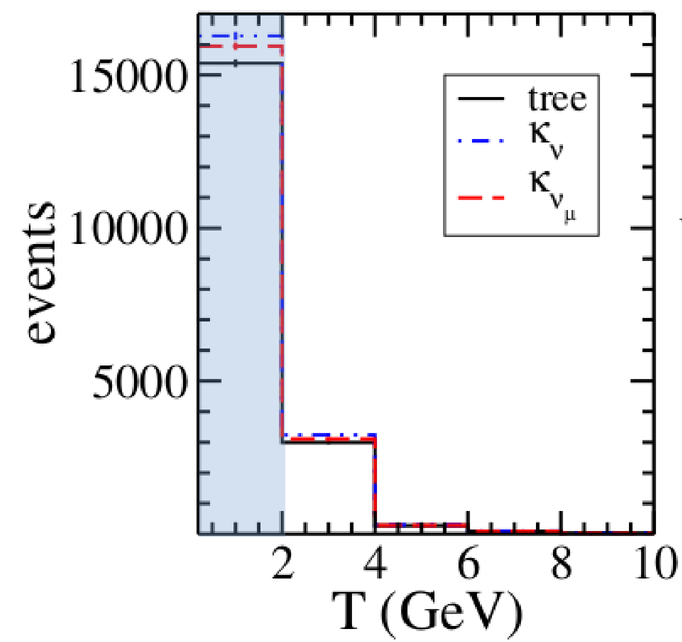
Neutrino beam mode



Number of ν_μ Events					
		Without NCR		With NCR	
Tree-level	σ_{stat}	EW+QED	Δ	EW+QED	Δ
27134	165	25859	-1275	26567	-567

Table 1. The total number of events from $\nu_\mu e^-$ scattering for an energy range of 0.2 to 10 GeV.

Antineutrino beam mode



Number of $\bar{\nu}_\mu$ Events					
		Without NCR		With NCR	
Tree-level	σ_{stat}	EW+QED	Δ	EW+QED	Δ
18775	137	19931	1156	19447	672

Table 2. The total number of events from $\bar{\nu}_\mu e^-$ scattering for an energy range of 0.2 to 10 GeV.

Conclusions

We have studied the sensitivity of future near detectors (the case of DUNE-PRISM as a example), to radiative corrections in neutrino-electron scattering.

- For a ν_μ beam mode, due to its higher statistics, will allow a better determination of the radiative corrections and possibly the NCR, if the systematic uncertainties are under control (should be ~3%).

- For the $\bar{\nu}_\mu$ beam mode, despite the lower statistics, compared to the neutrino mode, our analysis shows a good possibility of measuring the radiative corrections and even the NCR with the lower energy bin.

Thank you!

Credit: Symmetry Magazine / Sandbox Studio, Chicago

Work supported by CONACYT-Mexico grant A1-S-23238

Backup

Neutrino oscillation

The neutrino oscillation from the active flavors neutrinos explain the Solar and Atmospheric neutrino fluxes problem.

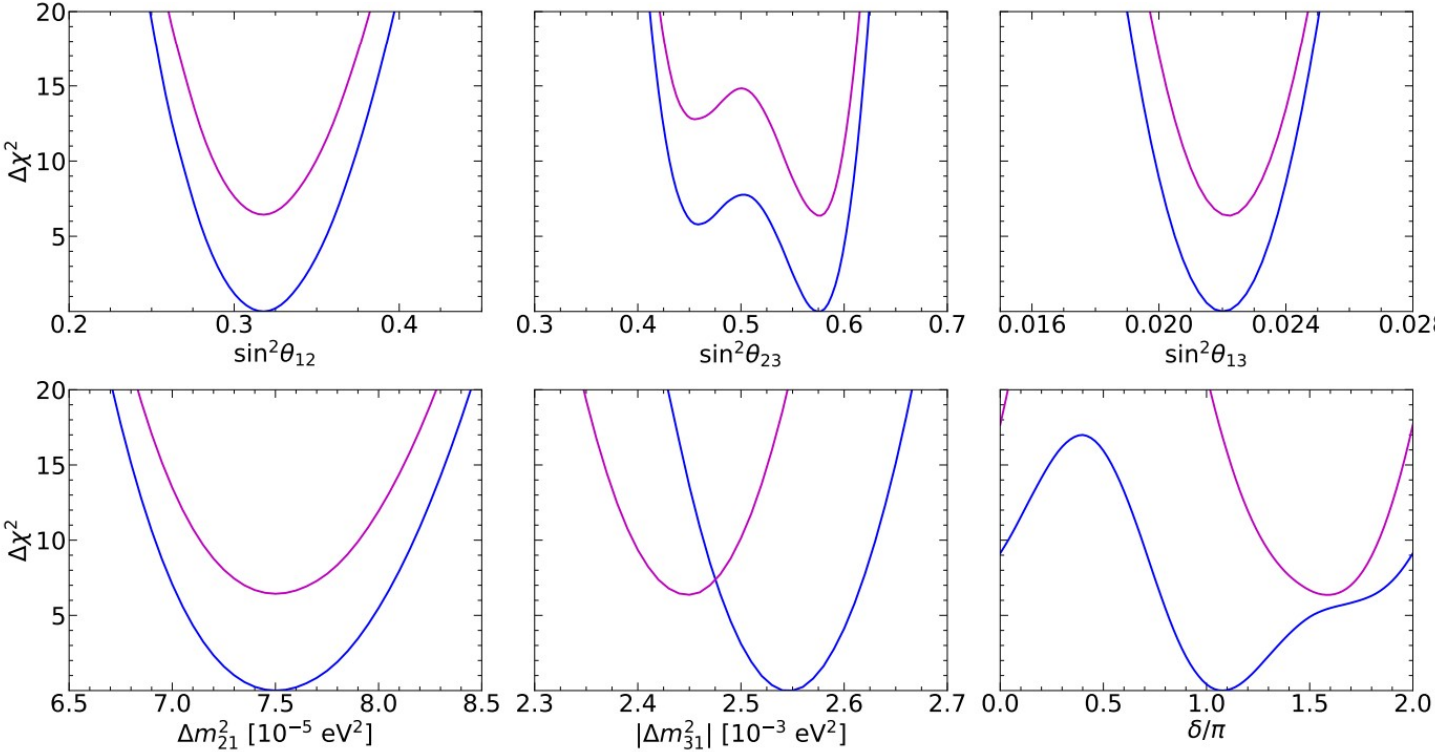
$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4\sum_{k>j} \Re\mathfrak{e}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) + 2\sum_{k>j} \Im\mathfrak{m}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

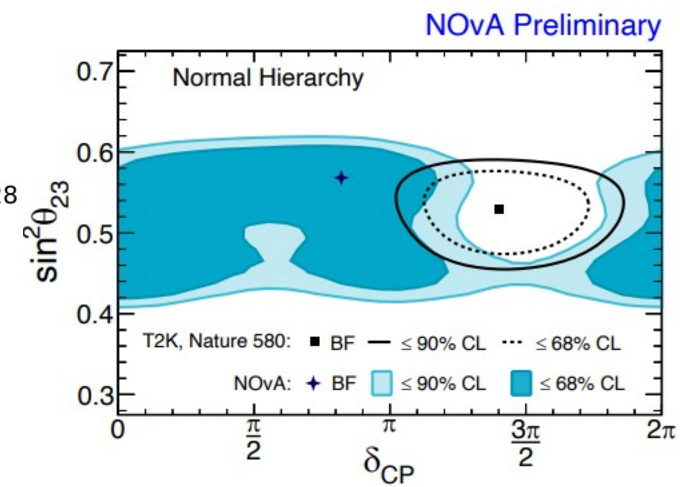
Where the U (PMNS matrix) is usually expressed by 3 rotation matrices, in terms of three mixing angles, θ_{12} , θ_{23} and θ_{13} and a single complex phase δ_{CP}

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -sin\theta_{13} e^{i\delta_{CP}} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric and Accelerator **Reactor and Accelerator** **Solar and Reactor**

Neutrino oscillation





P.de Salas, D.V. Forero, S.Gariazzo, P.Martínez-Miravé, O.Mena, C. A.Ternes, M.Tórtola and J.W.F.Valle, JHEP 02, 071 (2021)

Erika Cataño-Mur, 5th ComHEP, December 1st, 2020

Ratio of radiative corrections
for neutrino and antineutrino

The deviation from the tree-level differential cross section is defined as the ratio

$$R_X := \frac{\frac{d\sigma'_X}{dT} - \frac{d\sigma}{dT}}{\frac{d\sigma}{dT}}$$

where X denotes EW, QED, or the addition of both. Although the behavior of this ratio was calculated for a fixed neutrino energy, the qualitative behavior persists for the neutrino beam spectrum.

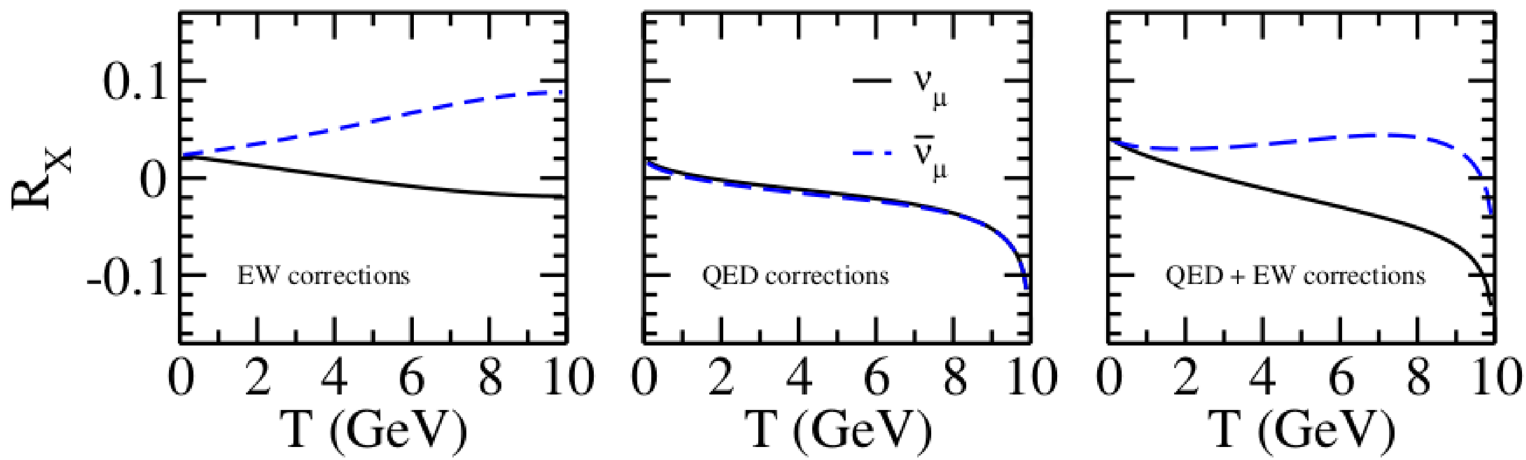


Fig. 5 Comparison of the ratio of radiative corrections for neutrino and antineutrino beam modes, for a fixed neutrino energy of 10 GeV.