Precision measurements in the DUNE Near Detector Complex

Zahra Tabrizi

Virginia Tech/CNP

Based on:

- Ballett, Hostert, Pascoli, Perez-Gonzalez, Tabrizi and Funchal, JHEP 1901, 119 (2019)
- de Gouvêa, Machado, Perez-Gonzalez and Tabrizi, arXiv:1912.06658

Brookhaven Neutrino Theory Virtual Seminars

April 20th 2020

Outline

- Neutrino Trident production
- Neutrino-Electron scattering
- Measuring the Weak Mixing Angle at DUNE
- Conclusion

Open Questions:

- What is the order of neutrino masses?
- What is the value of the CP phase?
- Is neutrino its own anti particle?
- What is the origin of neutrino mass?
- What is the absolute neutrino masses?
- Are there more than three neutrinos?

We need next generation long baseline neutrino experiments!

Physics goals of near detectors:

Primary role of the ND is to study the systematic uncertainties.

High beam luminosity + Large fiducial mass

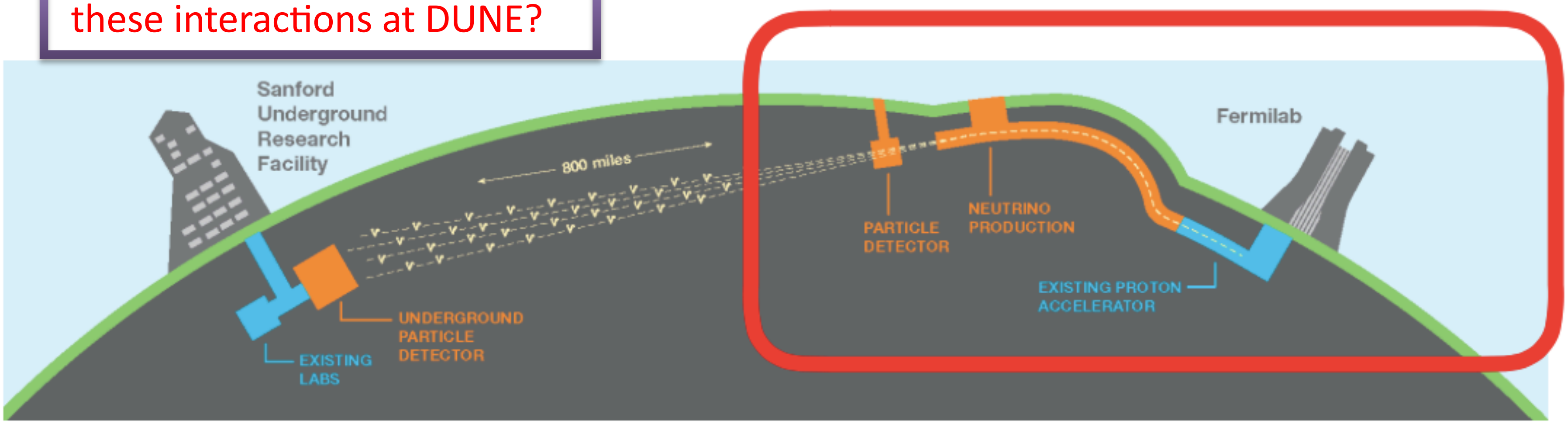
Ideal to investigate (rare) neutrino interactions

$\sigma < 10^{-44}$ cm^2

- neutrino-electron scattering
- neutrino trident production

- Test SM predictions
- Search for BSM physics

What can we learn from these interactions at DUNE?



Neutrino Trident Scattering at Near Detectors

Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)

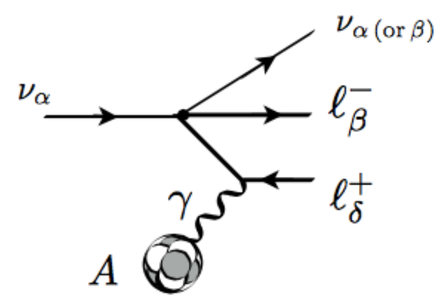
Neutrino Trident Scattering

$$\nu_\alpha + \mathcal{N} \to \nu_\beta + \ell^+_\gamma + \ell^-_\delta + \mathcal{N}$$

Production of a **charged lepton pair**

in the scattering of a **neutrino**

in the Coulomb field of a **heavy nucleus/nucleon**



CHARM II

PLB 245 (1990) 271

$$\frac{\sigma_{\mathrm{CHARM\ II}}}{\sigma_{\mathrm{SM}}} = 1.58 \pm 0.57$$

CCFR

PRL 66 (1991) 3117

$$\frac{\sigma_{\mathrm{CCFR}}}{\sigma_{\mathrm{SM}}} = 0.82 \pm 0.28$$

NuTeV

Vancouver 1998, High energy physics, vol. 1

$$\frac{\sigma_{\mathrm{NuTeV}}}{\sigma_{\mathrm{SM}}} = 0.67 \pm 0.27$$

Neutrino Trident Scattering

$$\nu_\alpha + \mathcal{N} \to \nu_\beta + \ell_\gamma^+ + \ell_\delta^- + \mathcal{N}$$

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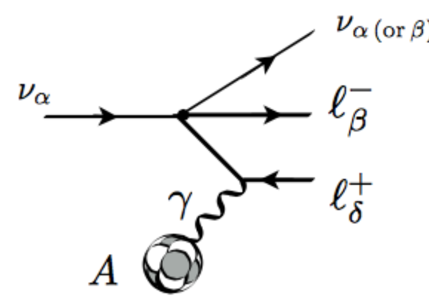


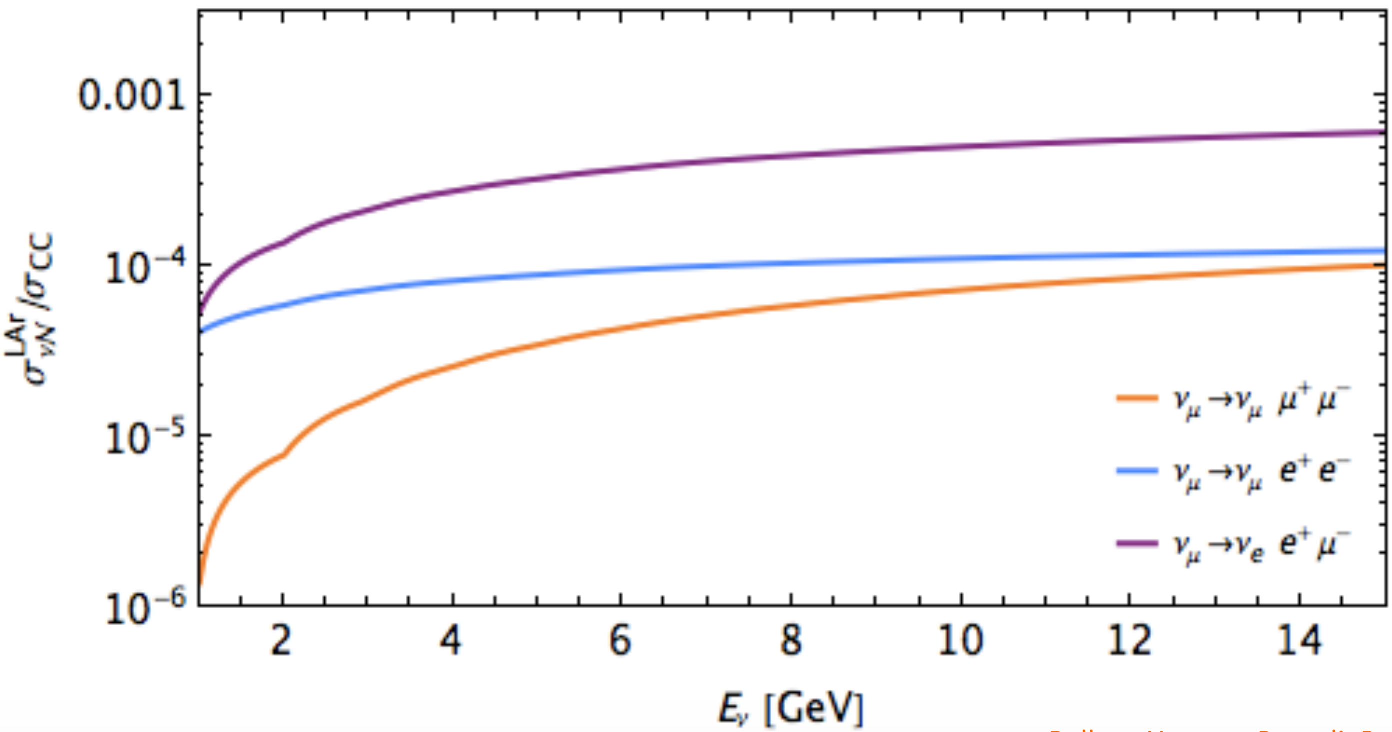
Neutrino	Antineutrino	SM Contributions
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	$\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^+ \mu^-$	CC, NC
$\nu_\mu \to \nu_e e^+ \mu^-$	$\bar{\nu}_\mu \to \bar{\nu}_e e^- \mu^+$	CC
$\nu_\mu \to \nu_\mu e^+ e^-$	$\bar{\nu}_\mu \to \bar{\nu}_\mu e^+ e^-$	NC
$\nu_e \to \nu_e e^+ e^-$	$\bar{\nu}_e \to \bar{\nu}_e e^+ e^-$	CC, NC
$\nu_e \to \nu_\mu \mu^+ e^-$	$\bar{\nu}_e \to \bar{\nu}_\mu e^+ \mu^-$	CC
$\nu_e \to \nu_e \mu^+ \mu^-$	$\bar{\nu}_e \to \bar{\nu}_e \mu^+ \mu^-$	NC

Observed

$$V_{\alpha\beta\kappa}(A_{\alpha\beta\kappa}) \equiv g_V^\beta (g_A^\beta) \delta_{\beta\kappa} + \delta_{\alpha\beta}$$

Measuring neutrino trident events give information on vector/axial couplings

How rare is it?



Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
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Trident cross section:

$$\nu_\alpha(p_1) + \mathscr{H}(P) \to \nu_{\alpha \,\mathrm{or}\, \kappa(\beta)}(p_2) + \ell^-_\beta(p_4) + \ell^+_\kappa(p_3) + \mathscr{H}(P')$$

hadronic tensor
(depends on scattering regime)

leptonic tensor

$$\frac{\mathrm{d}^2\sigma_{\nu \mathrm{X}}}{\mathrm{d}Q^2\mathrm{d}\hat{s}} = \frac{1}{32\pi^2(s-M^2_{\mathscr{H}})^2}\frac{\mathrm{H}^{\mu\nu}_{\mathrm{X}}\,\mathrm{L}_{\mu\nu}}{Q^4}$$

W. Czyz, G. C. Sheppey and J. D. Walecka, Nuovo Cim. 34 (1964) 404.

momentum transfer

Center-of-mass energy of the neutrino-photon system

Center-of-mass energy of the total system

Coherent Regime: The neutrino interacts with the whole nucleus

Diffractive Regime: The neutrino interacts with the individual nucleons

We can separate the phc

$$\frac{\mathrm{d}^2\sigma_{\nu \mathrm{X}}}{\mathrm{d}Q^2\mathrm{d}\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}\,Q^2}\Big[\underbrace{h^{\mathrm{T}}_{\mathrm{X}}(Q^2,\hat{s})\,\sigma^{\mathrm{T}}_{\nu\gamma}(Q^2,\hat{s})}_{\text{Transversal}} + \underbrace{h^{\mathrm{L}}_{\mathrm{X}}(Q^2,\hat{s})\,\sigma^{\mathrm{L}}_{\nu\gamma}(Q^2,\hat{s})}_{\text{Longitudinal}}\Big]$$

Equivalent Photon Approximation (EPA): The full cross section is related to the cross section of the neutrino scattering with a real photon, multiplied by the probability of creating a virtual photon.

EPA assumptions

1) Neglecting the L contribution ($h^{\mathrm{L}}(q^2,\hat{s})\,\sigma^{\mathrm{L}}_{\nu\gamma}(q^2,\hat{s}) \approx 0$).

2) Taking the T contribution of the cross section to be on-shell ($\sigma^{\mathrm{T}}_{\nu\gamma}(q^2,\hat{s}) \approx \sigma^{\mathrm{T}}_{\nu\gamma}(0,\hat{s})$).

$$\sigma_{\mathrm{t}}(P_i + C_s \to P_f + C_s) \approx \int dP(Q^2,\hat{s})\,\sigma_\gamma(P_i + \gamma \to P_f; \hat{s}, Q^2 = 0)$$

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QED

$$\sigma^{\mathrm{QED}}_\gamma(P_i + \gamma \to P_f; \hat{s},0) \propto \frac{1}{\hat{s}}$$

Decreases with increasing transferred four-momentum

On-shell >> off-shell

Fermi Limit of the SM

$$\sigma^{\mathrm{FL}}_\gamma(P_i + \gamma \to P_f; \hat{s},0) \propto G_{\mathrm{F}}^2\,\hat{s}$$

Increases with increasing transferred four-momentum

On-shell << off-shell

Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)

How bad is it?

$$\mathcal{R} = \frac{\sigma_{\mathrm{EPA}}(E_\nu)|_{Q_{\max}}}{\sigma_{\mathrm{4PS}}(E_\nu)}$$

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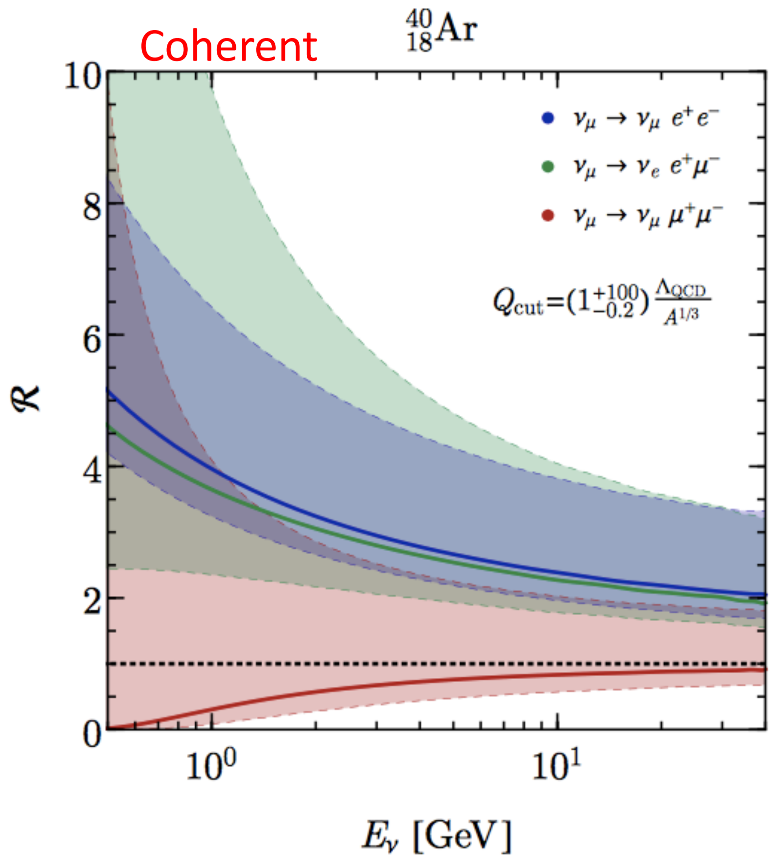
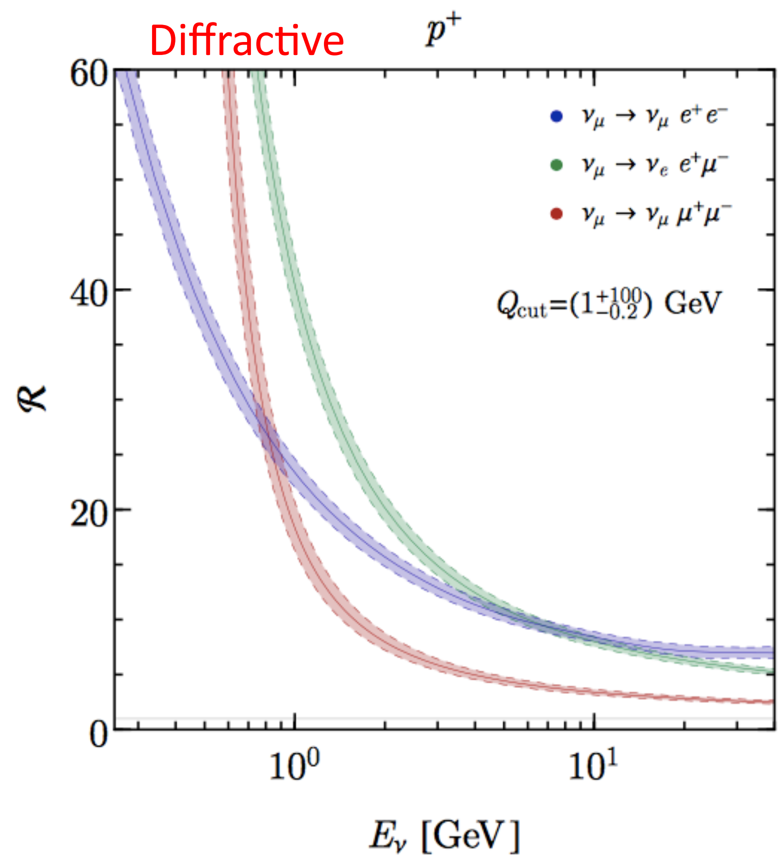
Coherent



Diffractive



EPA approximation doesn’t work. Full 4PS calculation must be done!!!

Trident rates at LAr Detectors

$$N = \text{time} \times \#\text{ of targets} \times \text{efficiency} \times \int_{E_i}^{E_f} dE_\nu \frac{d\phi(E_\nu)}{dE_\nu} \sigma(E_\nu)$$

Channel	SBND	μBooNE	ICARUS	DUNE ND	νSTORM ND
Total $e^{\pm}\mu^{\mp}$	10	0.7	1	2993 (2307)	191
	2	0.1	0.2	692 (530)	41
Total e^+e^-	6	0.4	0.7	1007 (800)	114
	0.7	0.0	0.1	143 (111)	14
Total $\mu^+\mu^-$	0.4	0.0	0.0	286 (210)	11
	0.4	0.0	0.0	196 (147)	9

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Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode.

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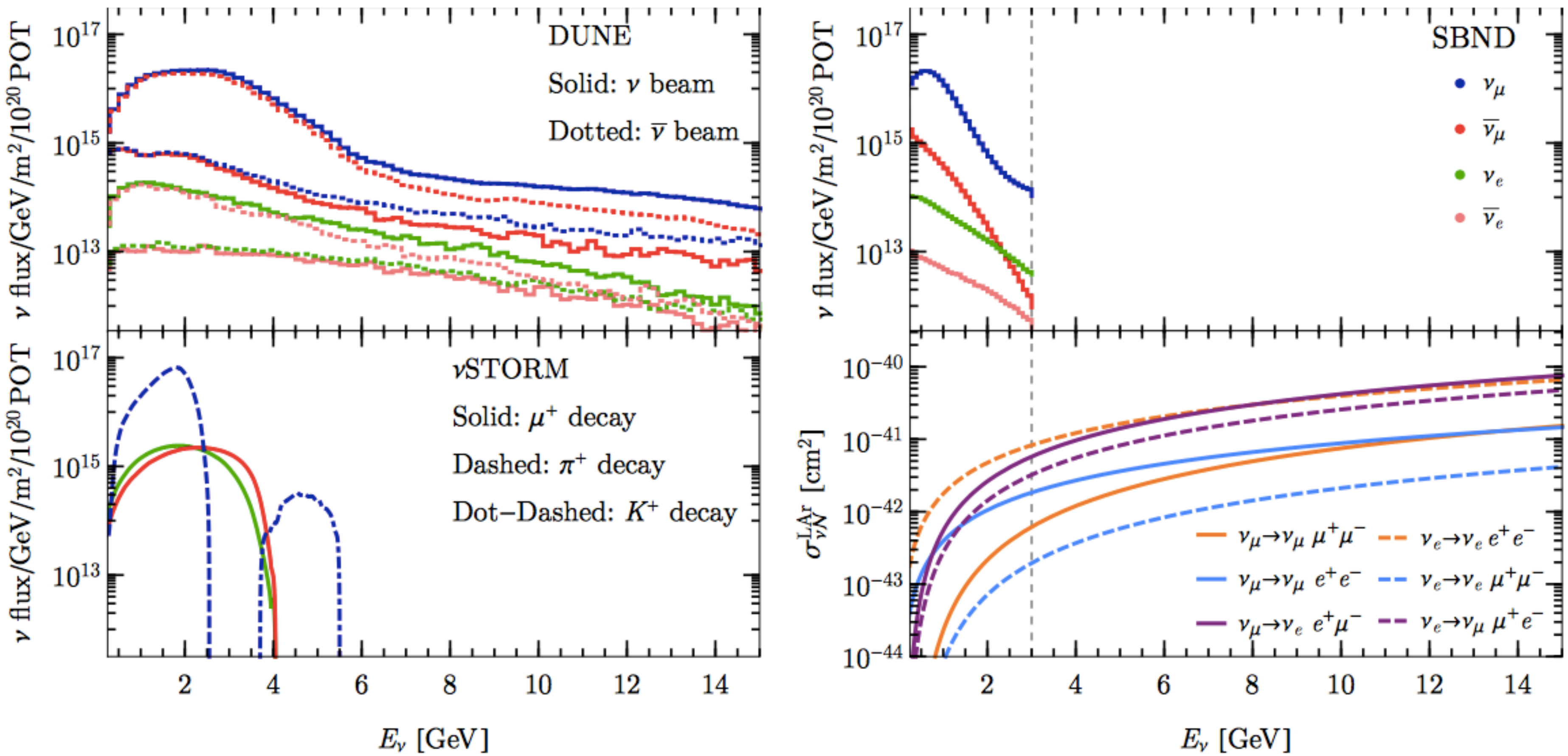

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Trident background analysis

Genuine dilepton production is rare, but misID of particles is the problem.

misID
γ as $e^{\pm}$
γ as e^+e^-
$\pi^{\pm}$ as $\mu^{\pm}$

Channel	$\mathbf{N}_{\mathrm{B}}^{\mathrm{misID}}/\mathbf{N}_{\mathrm{CC}}$	$\mathbf{N}_{\mathrm{B}}^{\mathrm{had}}/\mathbf{N}_{\mathrm{CC}}$	$\mathbf{N}_{\mathrm{B}}^{\mathrm{kin}}/\mathbf{N}_{\mathrm{CC}}$
$e^{\pm}\mu^{\mp}$	$1.67\ (1.62) \times 10^{-4}$	$2.68\ (4.31) \times 10^{-5}$	$4.40\ (3.17) \times 10^{-7}$
e^+e^-	$2.83\ (4.19) \times 10^{-4}$	$1.30\ (2.41) \times 10^{-4}$	$6.54\ (14.1) \times 10^{-6}$
$\mu^+\mu^-$	$2.66\ (2.73) \times 10^{-3}$	$10.4\ (9.75) \times 10^{-4}$	$3.36\ (3.10) \times 10^{-8}$

	N_{tot}^{CC}	$r_{\nu_\mu}^{CC}$	$r_{\overline{\nu}_\mu}^{CC}$	$r_{\nu_e}^{CC}$	$r_{\overline{\nu}_e}^{CC}$
ν-mode	4.25×10^8	0.964	0.028	0.007	0.001
$\overline{\nu}$-mode	1.74×10^8	0.201	0.790	0.004	0.005
	N_{tot}^{NC}	$r_{\nu_\mu}^{NC}$	$r_{\overline{\nu}_\mu}^{NC}$	$r_{\nu_e}^{NC}$	$r_{\overline{\nu}_e}^{NC}$
ν-mode	1.48×10^8	0.956	0.037	0.006	0.001
$\overline{\nu}$-mode	7.58×10^7	0.157	0.835	0.003	0.005

Reaching background rates of O(10^{-6}–10^{-5}) times the CC rate is necessary to observe trident events at DUNE ND, which is an attainable goal in a LAr detectors.

Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
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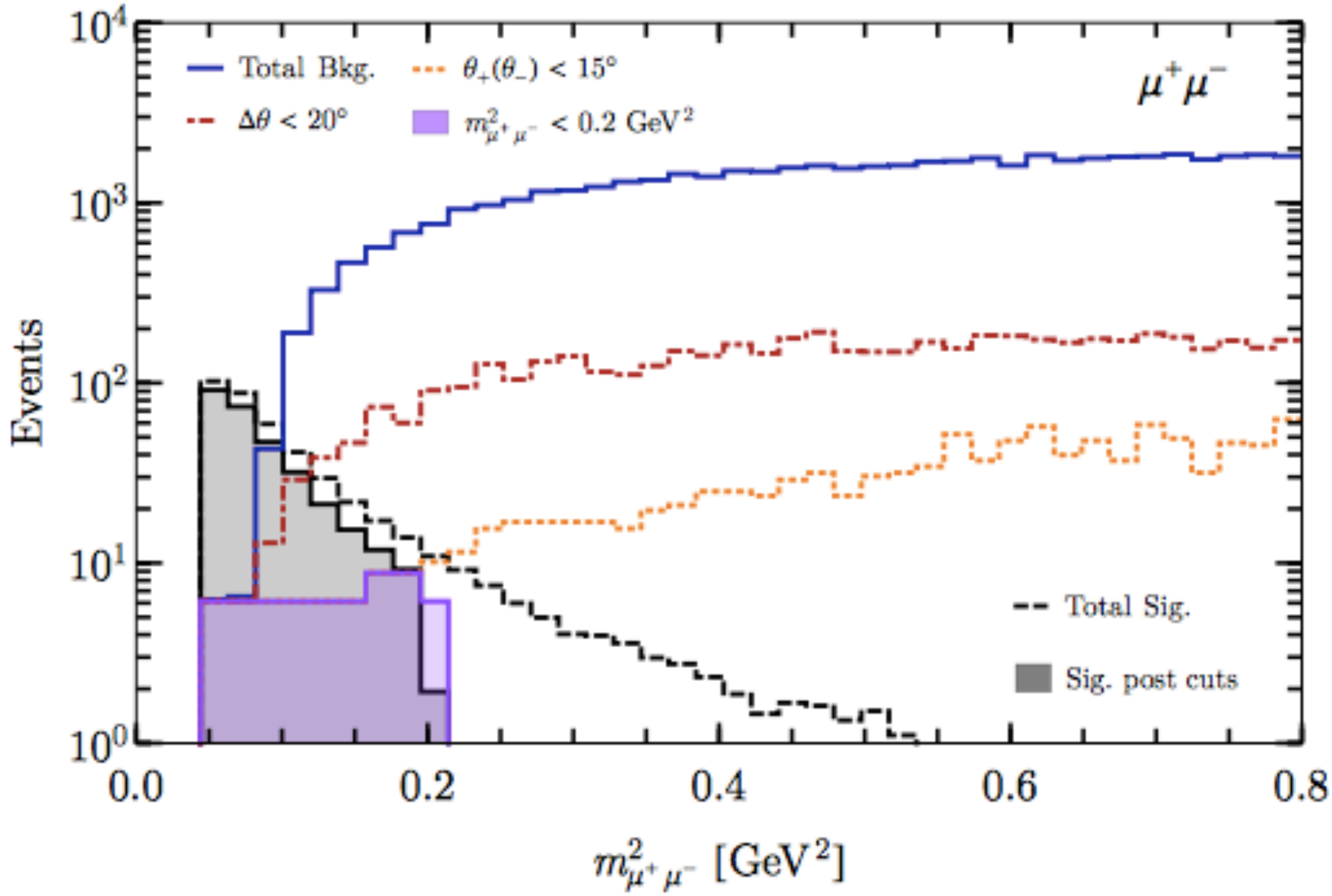


We apply consecutive cuts on the background, starting with cuts on the separation angle $\Delta\theta$ (red), both charged lepton angles to the beamline (θ_+ and θ_-) (orange) and the invariant mass.

Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)

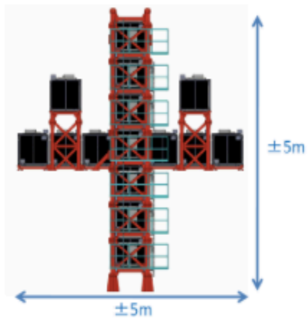
Trident rates at other Near Detectors

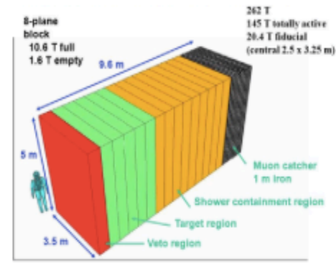
Experiment	Material	Baseline (m)	Exposure (POT)	Fiducial Mass (t)	E_ν (GeV)
INGRID	Fe	280	3.9×10^{21} $[10^{22}]$ T2K-I [T2K-II]	99.4	$0-4$
MINOS[+]	Fe and C	1040	$10.56(3.36)[9.69] \times 10^{20}$	28.6	$0-20$
NOνA	C_2H_3Cl and CH_2	1000	$8.85(6.9)$ $[36(36)] \times 10^{20}$ [NOνA-II]	231	$0-20$
MINERνA	CH, H_2O, Fe, Pb, C	1035	$12(12) \times 10^{20}$	7.98	$0-20$

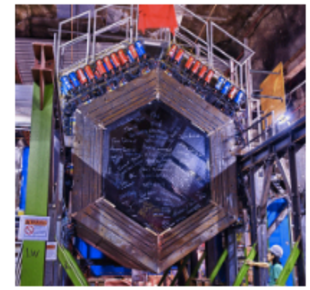
All have finished data taking or are still running

Trident rates at other Near Detectors

INGRID







Channel	T2K-I	T2K-II	MINOS	MINOS+	NOνA-I	NOνA-II	MINERνA
Total $e^{\pm}\mu^{\mp}$	563	1444	222 (56)	730	83 (72)	340 (374)	149 (102)
	96	246	46 (11)	151	25 (22)	102 (114)	56 (39)
Total e^+e^-	277	711	61 (15)	62	29 (22)	119 (114)	39 (27)
	24	62	9 (2)	8	4 (4)	16 (21)	10 (7)
Total $\mu^+\mu^-$	30	76	26 (6)	86	9 (9)	37 (47)	18 (13)
	21	54	15 (3)	49	8 (8)	34 (36)	18 (13)

Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode.

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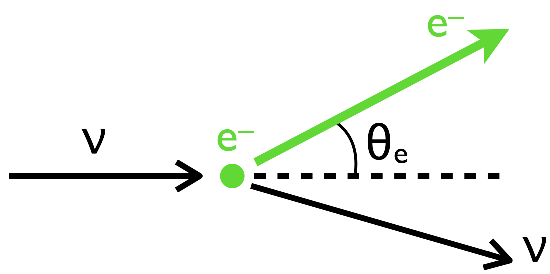
Neutrino-Electron Scattering

$$\frac{d\sigma}{dE_R} = \frac{2G_F^2 m_e}{\pi}\left\{g_1^2 + g_2^2\left(1-\frac{E_R}{E_\nu}\right)^2 - g_1 g_2\frac{m_e E_R}{E_\nu^2}\right\}$$
$$\simeq 1.72\times 10^{-41}\left\{g_1^2 + g_2^2\left(1-\frac{E_R}{E_\nu}\right)^2\right\}\frac{\mathrm{cm}^2}{\mathrm{GeV}}$$

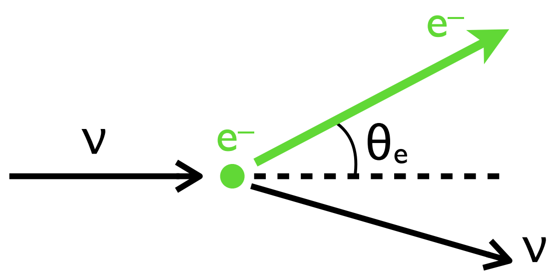


ν_α	g_1	g_1(SM)	g_2	g_2(SM)
ν_e	$1+(g_V+g_A)/2$	$1/2+s_W^2$	$(g_V-g_A)/2$	s_W^2
$\nu_{\mu,\tau}$	$(g_V+g_A)/2$	$-1/2+s_W^2$	$(g_V-g_A)/2$	s_W^2
$\bar\nu_e$	$(g_V-g_A)/2$	s_W^2	$1+(g_V+g_A)/2$	$1/2+s_W^2$
$\bar\nu_{\mu,\tau}$	$(g_V-g_A)/2$	s_W^2	$(g_V+g_A)/2$	$-1/2+s_W^2$

We translate neutrino–electron scattering measurements into a determination of the weak mixing angle at low scales.

Neutrino-Electron Scattering

Process	Total cross-section
$\nu_e + e^-$	$(G_F^2\, s/4\,\pi)\left[(1+2\,\sin^2\vartheta_W)^2 + \frac{4}{3}\,\sin^4\vartheta_W\right] \simeq 93\, s/\mathrm{MeV}^2$
$\bar{\nu}_e + e^-$	$(G_F^2\, s/4\,\pi)\left[\frac{1}{3}\,(1+2\,\sin^2\vartheta_W)^2 + 4\,\sin^4\vartheta_W\right] \simeq 39\, s/\mathrm{MeV}^2$
$\nu_{\mu,\tau} + e^-$	$(G_F^2\, s/4\,\pi)\left[(1-2\,\sin^2\vartheta_W)^2 + \frac{4}{3}\,\sin^4\vartheta_W\right] \simeq 15\, s/\mathrm{MeV}^2$
$\bar{\nu}_{\mu,\tau} + e^-$	$(G_F^2\, s/4\,\pi)\left[\frac{1}{3}\,(1-2\,\sin^2\vartheta_W)^2 + 4\,\sin^4\vartheta_W\right] \simeq 13\, s/\mathrm{MeV}^2$



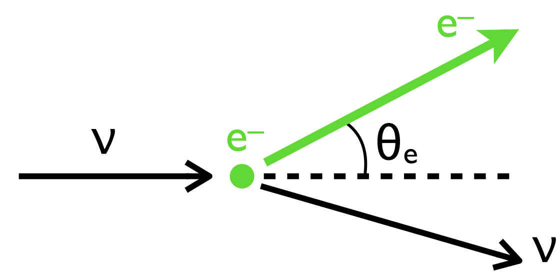
$$\boxed{s = 2\,m_e\,E_\nu}$$

The approximate ratios of the four cross-sections:

$$\boxed{\sigma_{\nu_e} : \sigma_{\bar{\nu}_e} : \sigma_{\nu_{\mu,\tau}} : \sigma_{\bar{\nu}_{\mu,\tau}} \simeq 1 : 0.42 : 0.16 : 0.14}$$

Neutrino-Electron Scattering

How many events at DUNE ND?

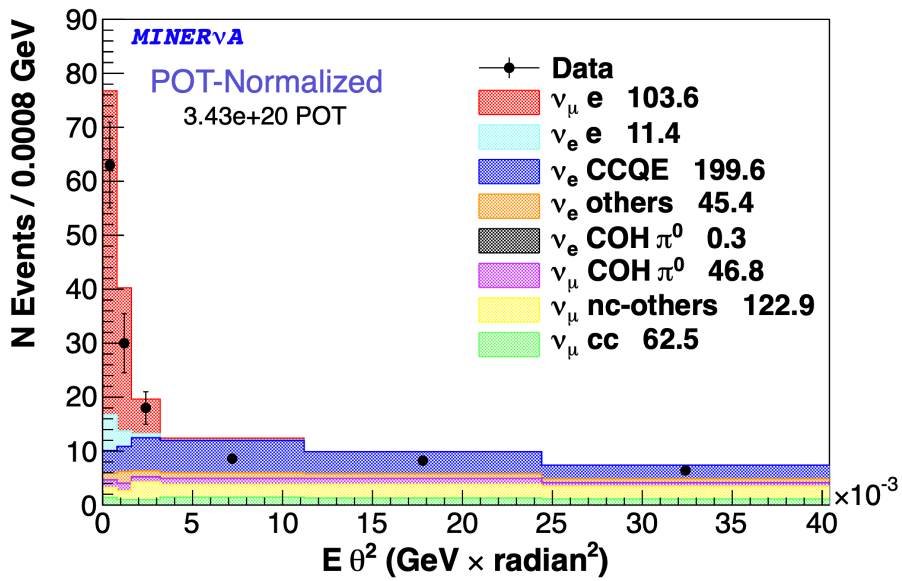


Channel	On axis	
$\nu_\mu e \to \nu_\mu e$	$27,705$	neutrino beam
	$2,888$	anti-neutrino beam
$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	$2,066$	
	$21,926$	
$\nu_e e \to \nu_e e$	$2,234$	
	782	
$\bar{\nu}_e e \to \bar{\nu}_e e$	226	
	705	

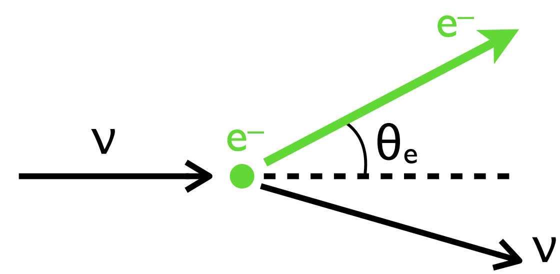
Approximately 60,000 nu-e events for 75 tonnes-7 years!

Neutrino-Electron Scattering

Signature: forward going electrons!



Jaewon Park, PhD thesis



The main source of background is CC quasi-elastic (CCQE) ν_e scattering.

A cut on the angular distribution can suppress the background!

Measuring the Weak Mixing Angle at DUNE-PRISM

Gouvêa, Machado, Perez-Gonzalez and **ZT**
arXiv:1912.06658

Measuring the Weak Mixing Angle at DUNE-PRISM

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$$\boxed{\frac{d\sigma}{dE_R} \simeq 1.72 \times 10^{-41} \left\{ g_1^2 + g_2^2 \left(1 - \frac{E_R}{E_\nu}\right)^2 \right\} \frac{\mathrm{cm}^2}{\mathrm{GeV}}}$$

ν_α	g_1	$g_1(\mathrm{SM})$	g_2	$g_2(\mathrm{SM})$
ν_e	$1+(g_V+g_A)/2$	$1/2+s_W^2$	$(g_V-g_A)/2$	s_W^2
$\nu_{\mu,\tau}$	$(g_V+g_A)/2$	$-1/2+s_W^2$	$(g_V-g_A)/2$	s_W^2
$\bar{\nu}_e$	$(g_V-g_A)/2$	s_W^2	$1+(g_V+g_A)/2$	$1/2+s_W^2$
$\bar{\nu}_{\mu,\tau}$	$(g_V-g_A)/2$	s_W^2	$(g_V+g_A)/2$	$-1/2+s_W^2$

There is an exact degeneracy in the differential cross section for $\nu_\mu - e$ scattering under the transformations:

$$(g_V, g_A) \to (g_A, g_V) \quad \text{and} \quad (g_V, g_A) \to (-g_V, -g_A)$$

Measuring the Weak Mixing Angle at DUNE-PRISM

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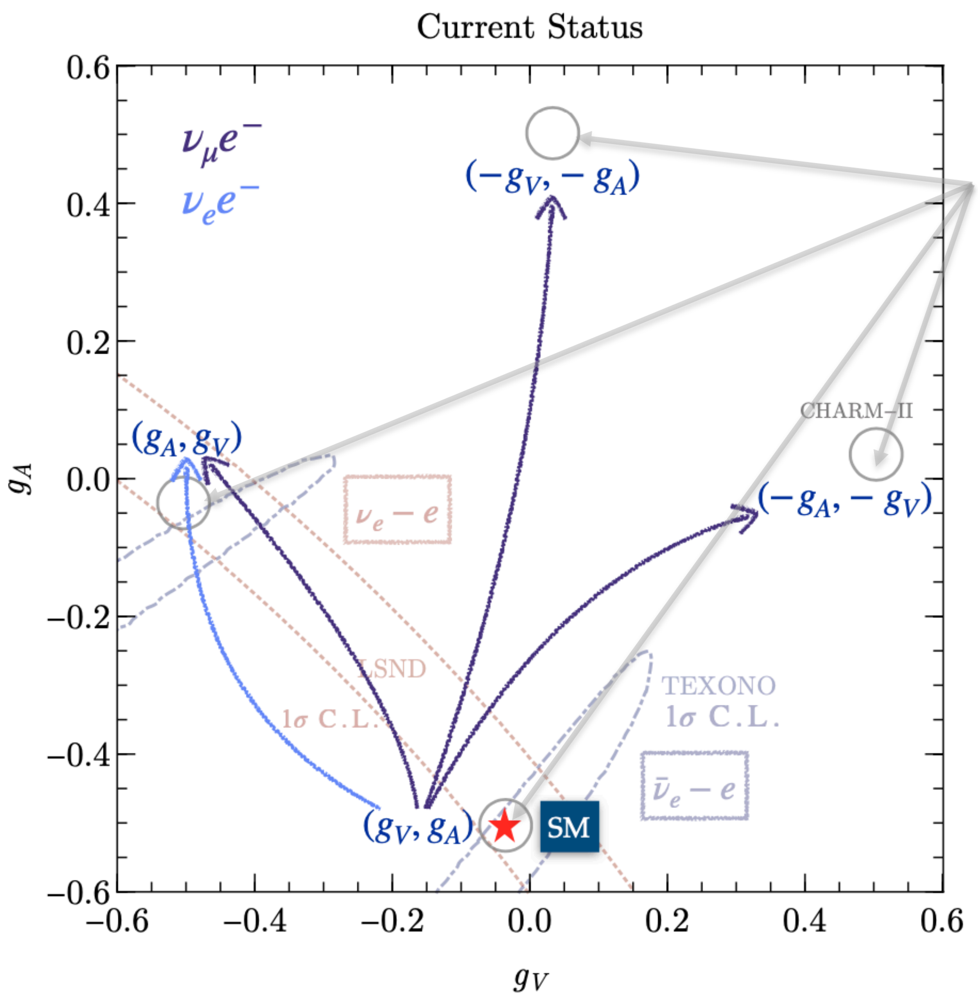
$$(g_V, g_A) \to (g_A, g_V) \quad \text{and} \quad (g_V, g_A) \to (-g_V, -g_A)$$

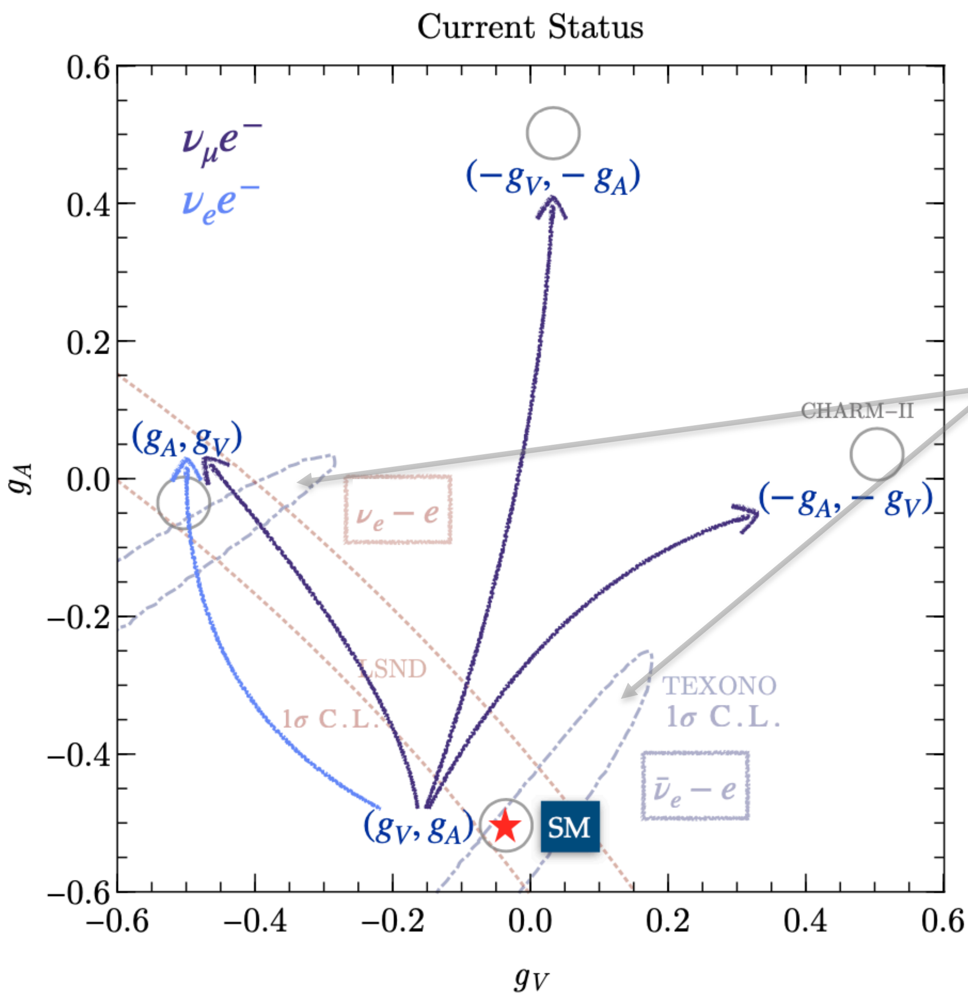
There are half solutions for ν_e – e scattering:

$$(g_V, g_A) \to (g_A, g_V)$$



CHARM-II measured the couplings from the scattering of muon-neutrinos on electrons

P. Vilain et al. (CHARM-II),
Phys. Lett. B335, 246 (1994).



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TEXONO measured electron recoils from electron anti-neutrinos in a nuclear reactor.

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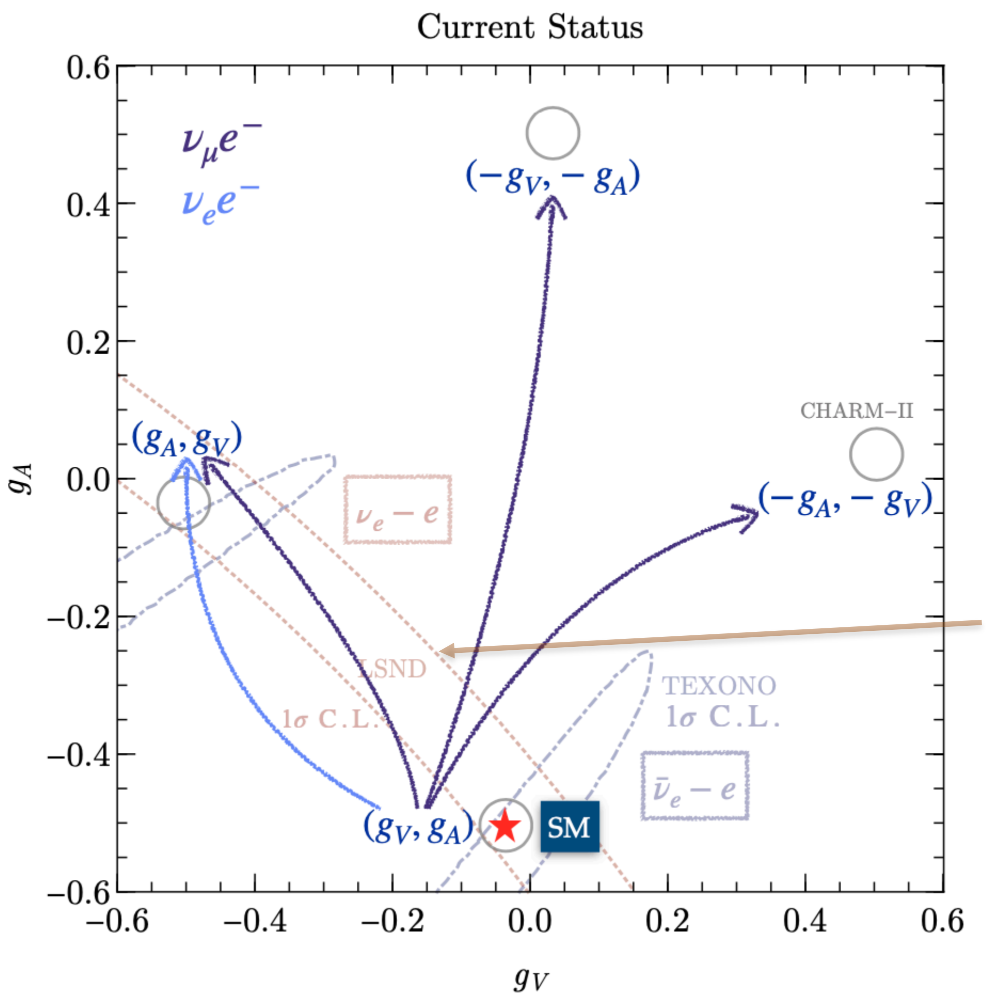

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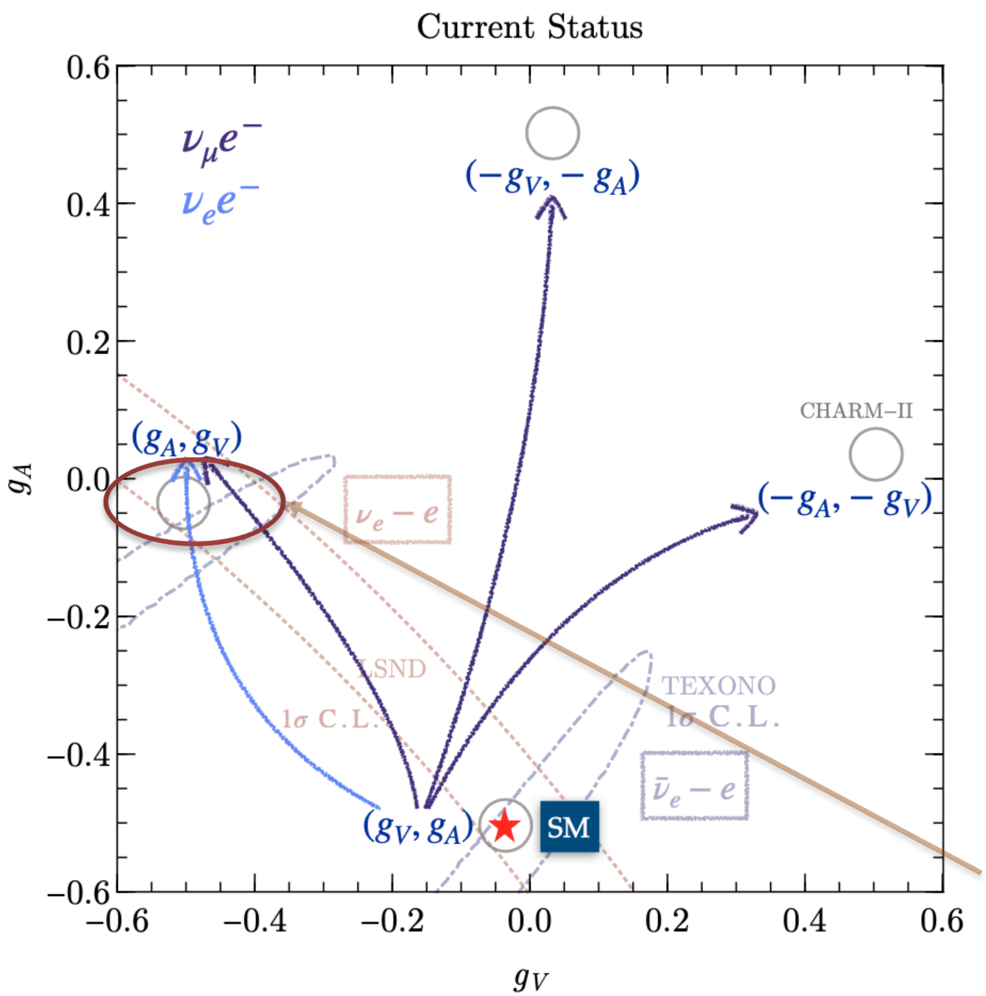
LSND is similar, but with electron-neutrinos.

L. B. Auerbach et al. (LSND),
Phys. Rev. **D63**, 112001 (2001)



CHARM-II measured the couplings from the scattering of muon-neutrinos on electrons

P. Vilain et al. (CHARM-II), Phys. Lett. B335, 246 (1994).

TEXONO measured electron recoils from electron anti-neutrinos in a nuclear reactor.

M. Deniz et al. (TEXONO), Phys. Rev. **D81**, 072001 (2010)

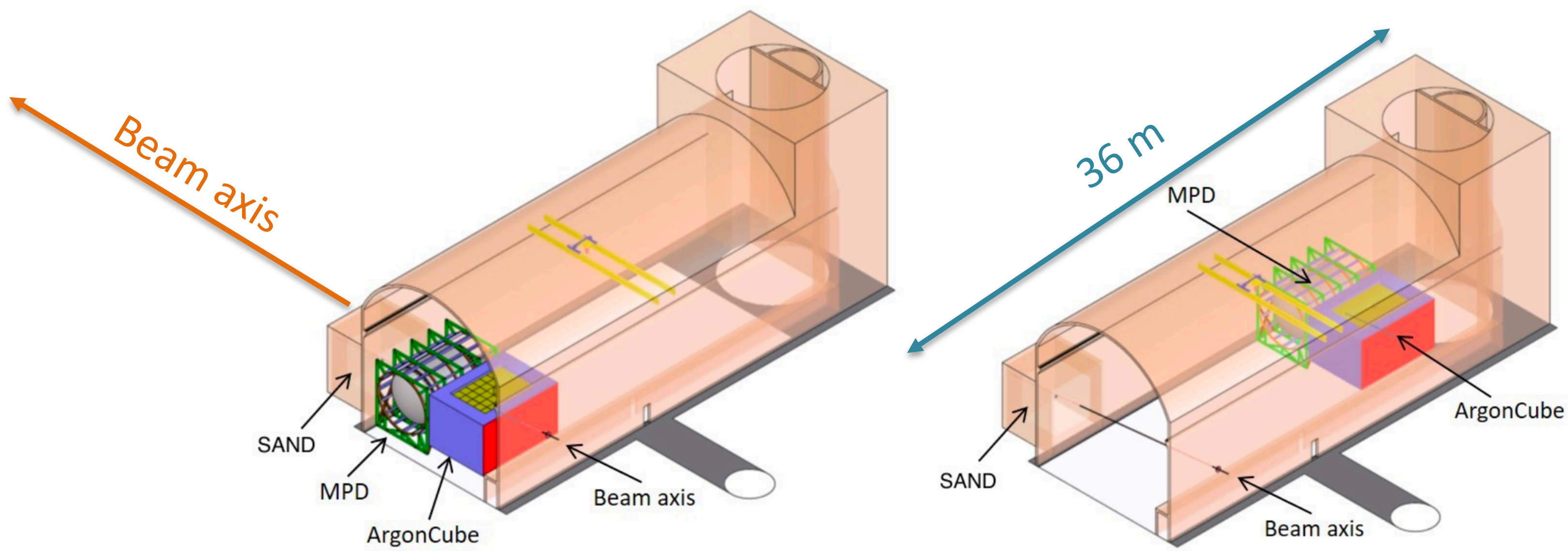
LSND is similar, but with electron-neutrinos.

L. B. Auerbach et al. (LSND), Phys. Rev. **D63**, 112001 (2001)

Current data are not able to rule out very small g_A and $g_V \sim -0.5$.

Measuring the Weak Mixing Angle at DUNE-PRISM

DUNE-PRISM: a near detector that is capable of moving in the direction perpendicular to the neutrino-beam axis.

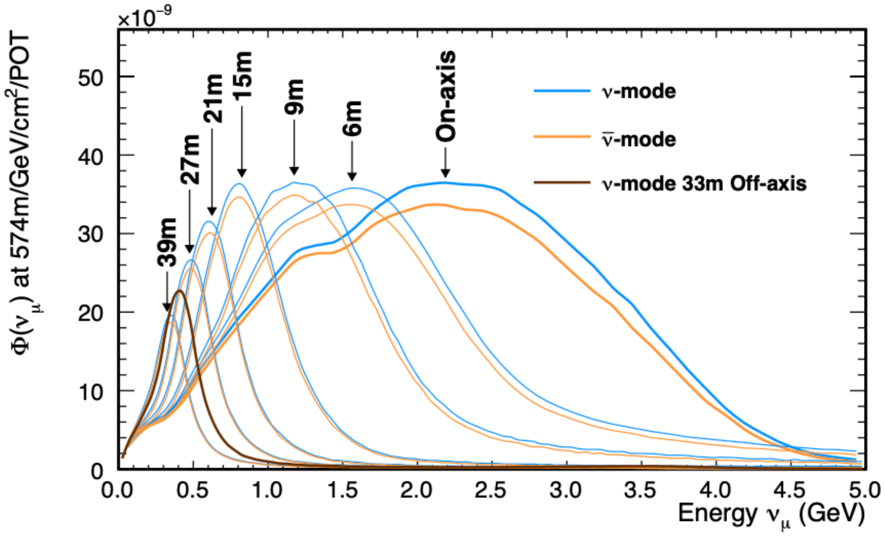


DUNE TDR, arXiv: 2002.03005

Measuring the Weak Mixing Angle at DUNE-PRISM

DUNE-PRISM: a near detector that is capable of moving in the direction perpendicular to the neutrino-beam axis.

Although the neutrino flux has prohibitively large uncertainties, the ratios of on-axis to off-axis fluxes are dictated only by meson-decay kinematics and thus are much better understood.



DUNE TDR, arXiv: 2002.03005

Measuring the Weak Mixing Angle at DUNE-PRISM

de Gouvêa, Machado, Perez-Gonzalez and **ZT**
arXiv:1912.06658 (In press)

Less statistics in the off-axis locations:

Channel	**0 m**	**6 m**	**12 m**	**18 m**	**24 m**	**30 m**	**36 m**
$\nu_\mu e \to \nu_\mu e$	3,958	2,671	882	398	213	127	83
	413	352	170	96	60	43	31
$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	295	232	114	64	40	26	20
	3,132	2,068	679	284	151	90	59
$\nu_e e \to \nu_e e$	319	226	132	76	45	29	19
	112	88	63	38	24	17	13
$\bar{\nu}_e e \to \bar{\nu}_e e$	32	31	20	13	9	6	4
	101	78	41	24	14	9	6

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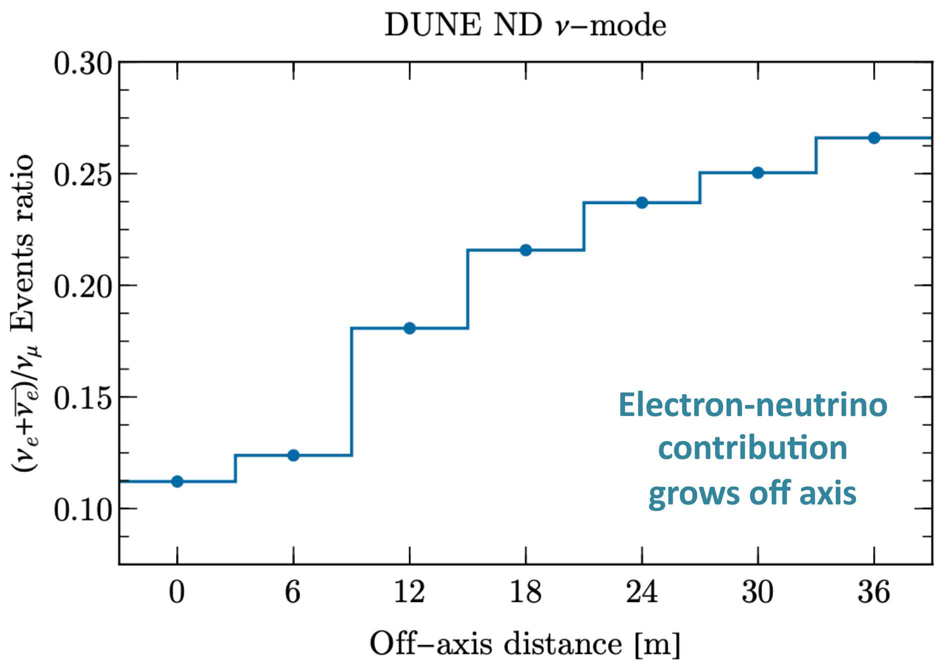
The relevance of the ν_e events grows significantly with the off-axis angle.



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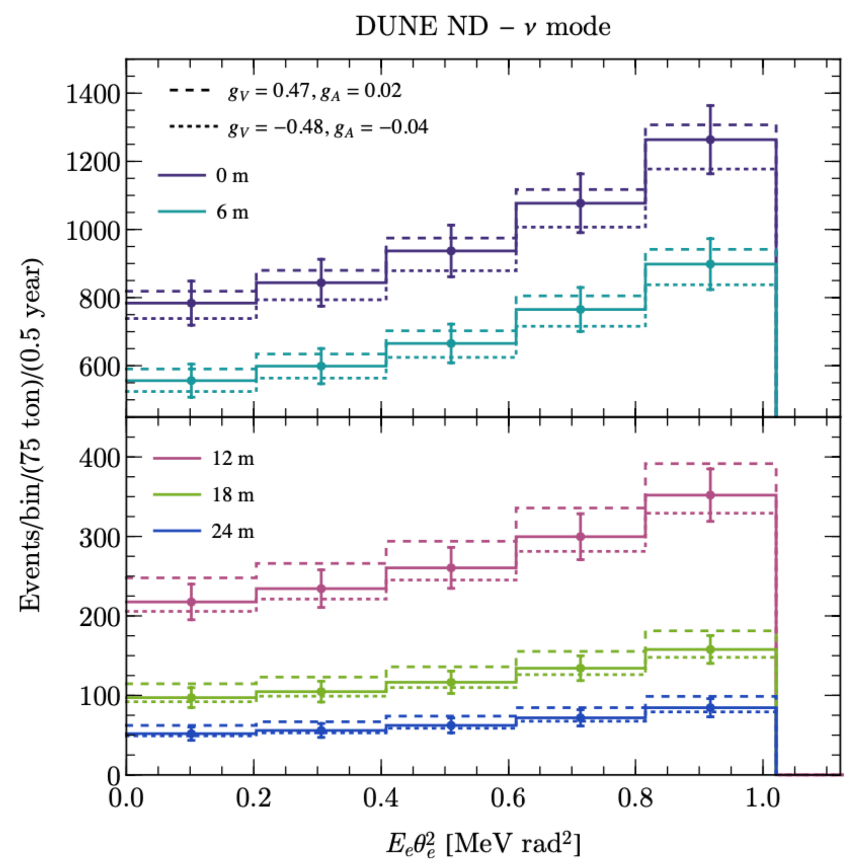
Error bars illustrating the statistical and systematic errors, are included for the SM case.



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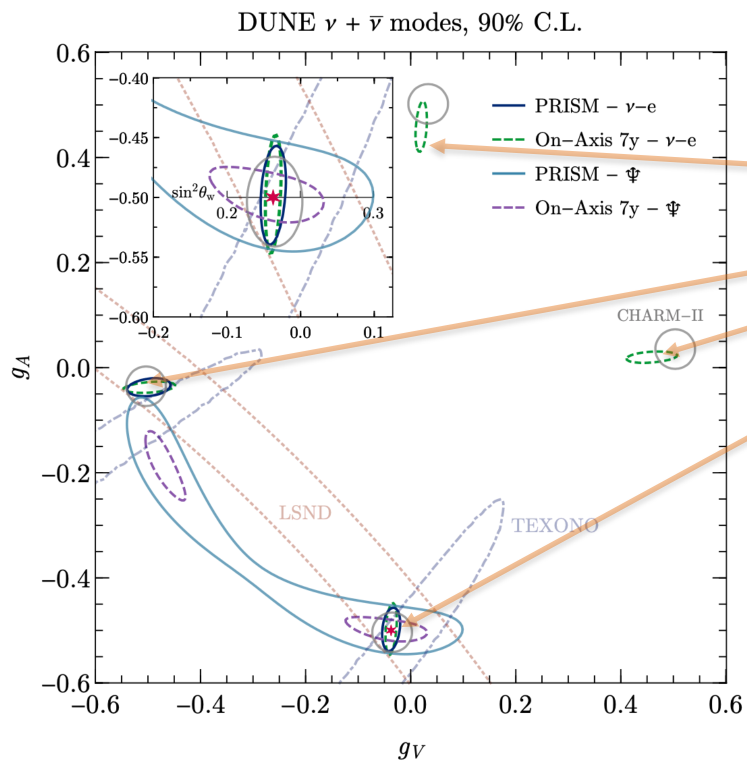

Both DUNE on-axis and CHARM-II have almost pure ν_μ flux and suffer from a four-fold degeneracy.

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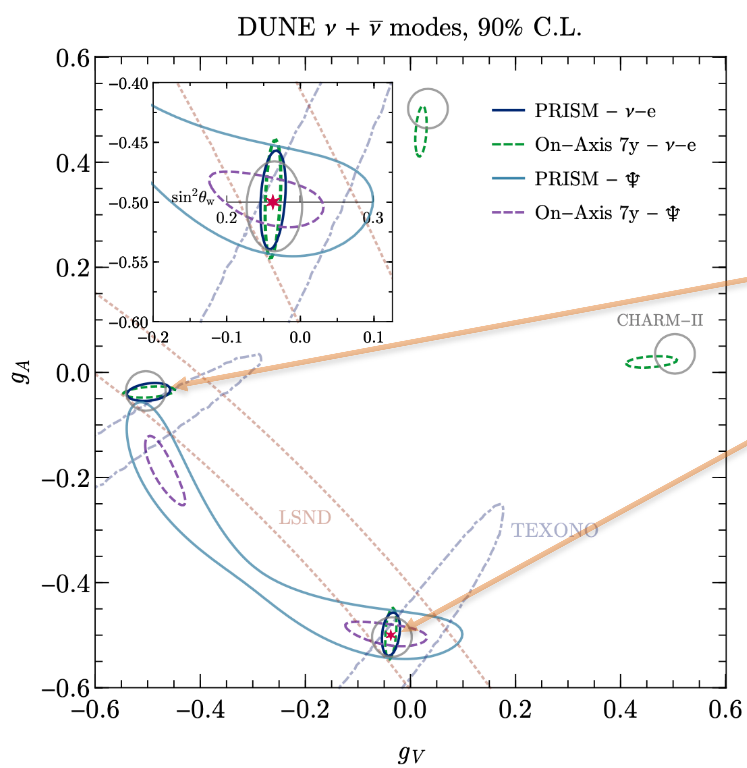

The sub-dominant ν_e beam component in DUNE-PRISM can break half the degeneracy!

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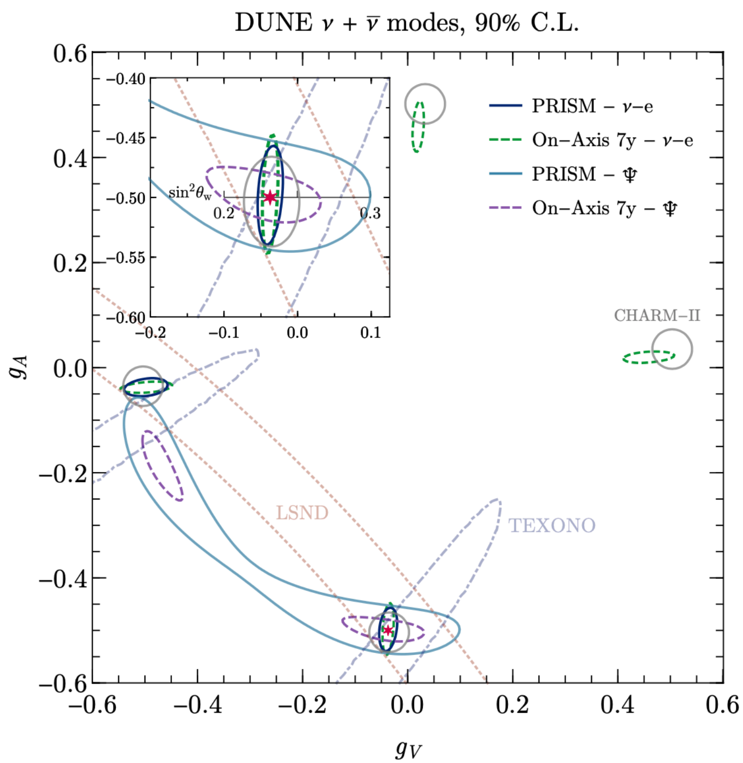

The trident cross section is more involved, in the limit where the muon mass vanishes, all cross sections are invariant under $g_V \leftrightarrow g_A$.

$m_e, m_\mu \to 0$

$$\sigma \sim g_V^2 + g_A^2 \qquad (\nu_\mu\, e^+ e^-)$$

$$\sigma \sim (g_V + 1)^2 + (g_A + 1)^2 \qquad (\nu_\mu\, \mu^+ \mu^-)$$

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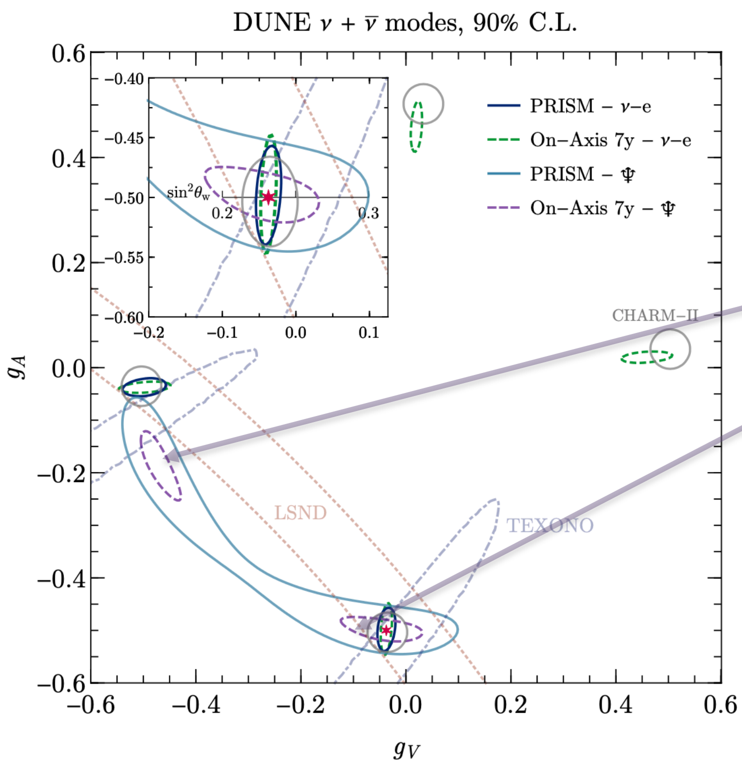

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Lepton masses break the final degeneracy!

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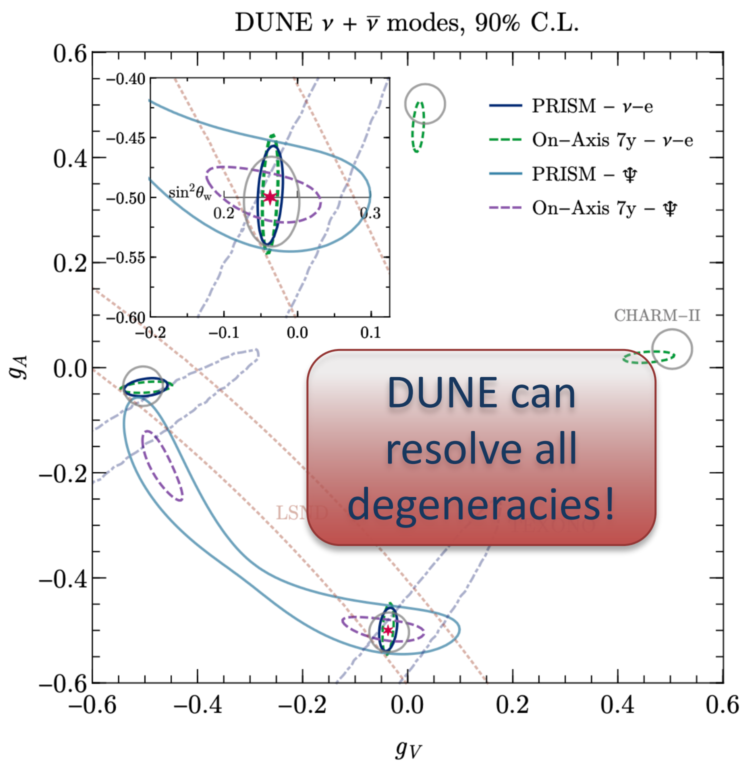

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Lepton masses break the final degeneracy!

Measuring the Weak Mixing Angle at DUNE-PRISM

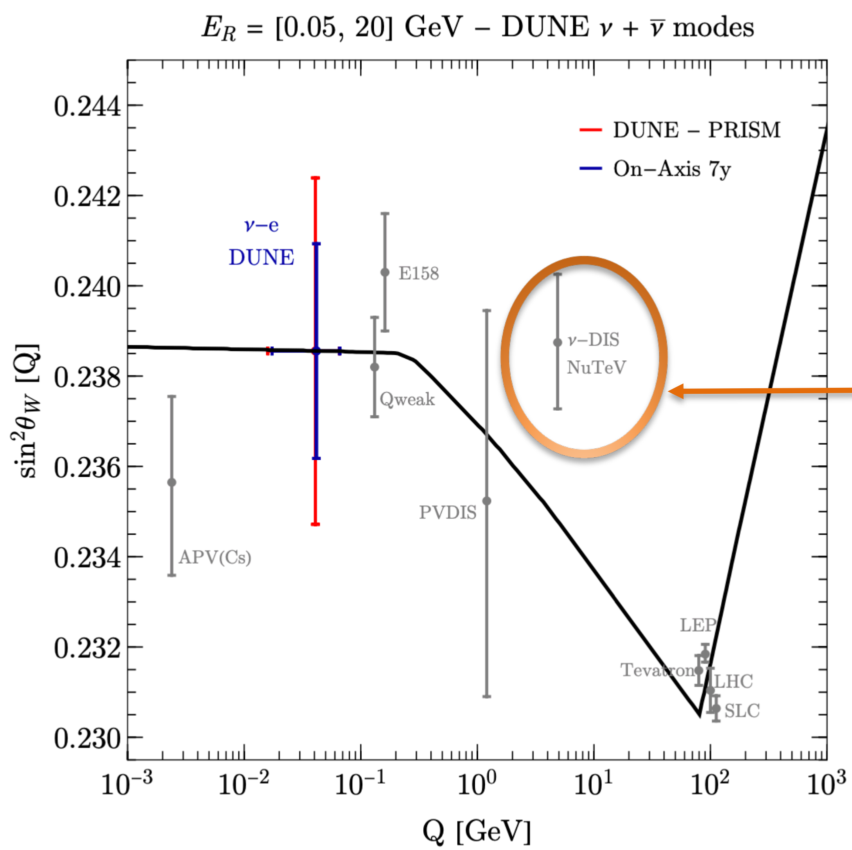
de Gouvêa, Machado, Perez-Gonzalez and **ZT**
arXiv:1912.06658

We translate the neutrino–electron and trident scattering measurements into a determination of the vector and axial couplings of the electron to the Z-boson and the weak mixing angle at low scales.

in the modified minimal subtraction scheme:

$$\sin^2\theta_W(\mu) \equiv \frac{g'^2(\mu)}{g^2(\mu)+g'^2(\mu)}$$

Measuring the Weak Mixing Angle at DUNE-PRISM



The most precise measurement of $\sin^2\theta_W$ using neutrino scattering, at $\langle Q \rangle \simeq 4.5$ GeV.

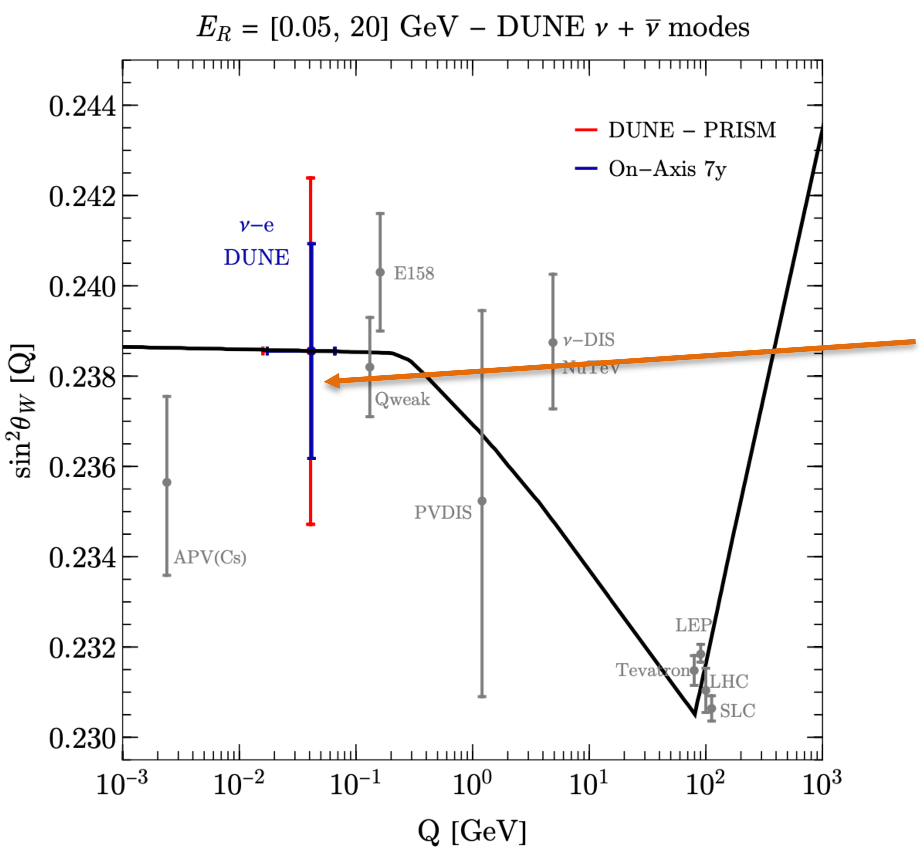
Deviates from the LEP measurement at 3σ level.

$$R^{\nu(\bar{\nu})} = \frac{\sigma(\nu(\bar{\nu})N \to \nu(\bar{\nu})X)}{\sigma(\nu(\bar{\nu})N \to \ell^{-(+)}X)} \approx g_L^2 + 2g_R^2$$

$$\sin^2\theta_W(\langle Q^2 \rangle = 20\ \text{GeV}^2) = 0.2277 \pm 0.0013 \pm 0.0009$$

G. P. Zeller et al. (NuTeV),
Phys. Rev. Lett. **88**, 091802 (2002)

Measuring the Weak Mixing Angle at DUNE-PRISM

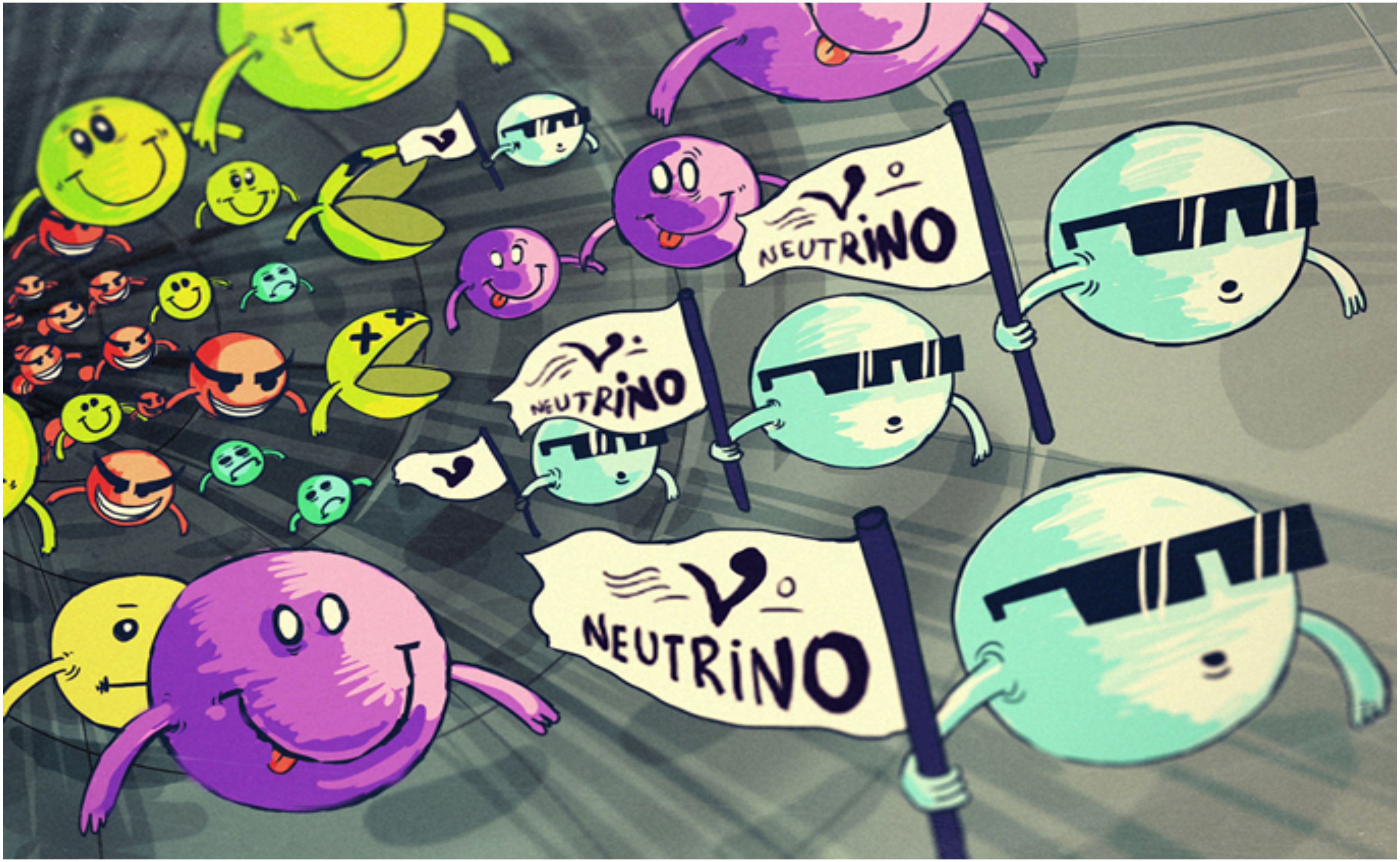


DUNE-ND can be used to measure $\sin^2\theta_W$ with better than 2% precision, at $\langle Q^2 \rangle = (40\ \mathrm{MeV})^2$

de Gouvêa, Machado, Perez-Gonzalez and **ZT**
arXiv:1912.06658 (In press)

Conclusion:

- The future DUNE experiment opens up the possibility to perform many measurements of rare neutrino processes at near detectors.
- We study Neutrino trident and Neutrino-Electron scatterings at DUNE.
- We investigate the sensitivity of DUNE-PRISM, and find that it will qualitatively impact our ability to constrain the weak couplings of the electron.
- Trident measurements could contribute to break the final degeneracy.
- DUNE can achieve competitive measurements and test (g_V, g_A) without the aid of external data.
- The DUNE near-detector can be used to measure $\sin^2\theta_W$ with better than 2% precision.



Thanks for your attention