Precision measurements in the DUNE Near Detector Complex

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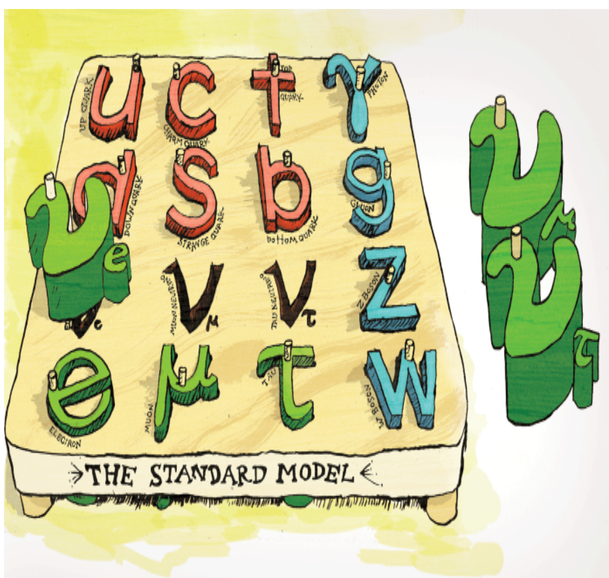
UNICAMP/Virginia Tech

31 January 2020

New Physics on the Low-Energy Precision Frontier
@CERN

Neutrinos in the SM

$$
\begin{aligned}
\mathcal{L} &= \sum_{\alpha=e,\mu,\tau} i\bar{\nu}_L^\alpha \partial\!\!\!/ \nu_L^\alpha && \text{(neutrino Kinetic term)} \\
&- \frac{g}{2\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_L^\alpha \gamma^\rho (1-\gamma^5) l_\alpha W_\rho + h.c. && \text{(Charged Current Interaction)} \\
&- \frac{g}{4\cos\theta_w} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_L^\alpha \gamma^\rho (1-\gamma^5) \nu_L^\alpha Z_\rho && \text{(Neutral Current Interaction)} \\
&- \sum_{\alpha=e,\mu,\tau} \bar{l}_L^\alpha M^l l_R^\alpha + h.c. && \text{(leptonic mass term)}
\end{aligned}
$$



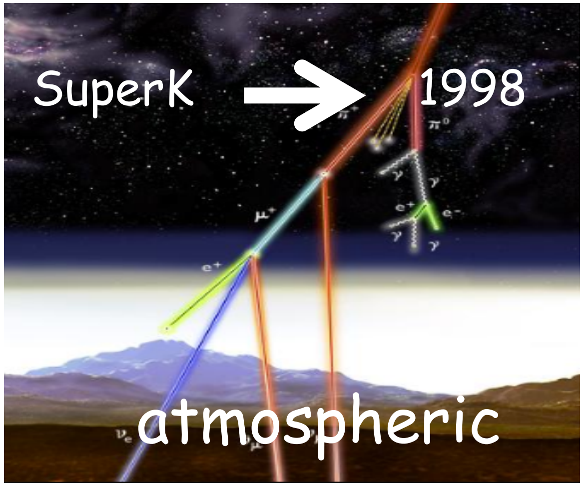
$$\mathbf{L_e} = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$$

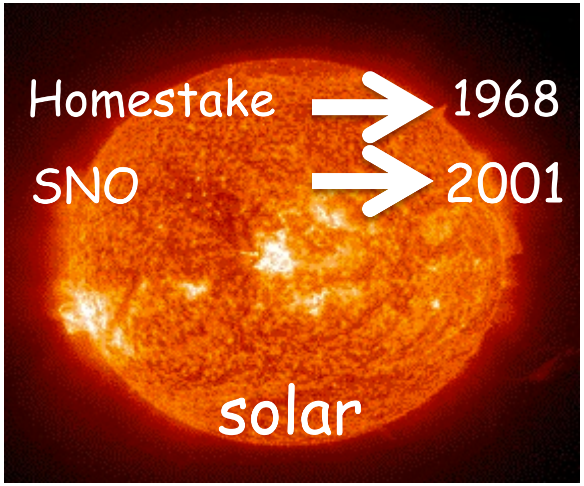
$$\mathbf{L}_\mu = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$$

$$\mathbf{L}_\tau = \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$$

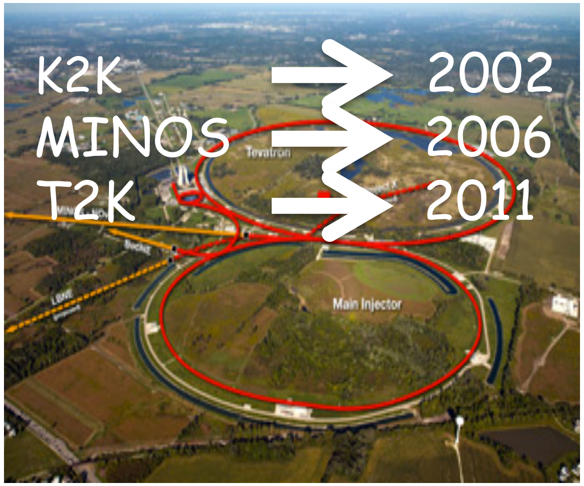
Neutrinos are massless in the SM!

However in nature...





Neutrino oscillation needs masses and mixing!



The mass and flavor eigenstates do not coincide!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The coefficient of the linear combination of neutrino mass eigenstates that couple to each flavor eigenstate!

Oscillation probability in vacuum:

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

Mass squared difference: $\Delta m^2_{ij} \equiv m^2_i - m^2_j$

Neutrinos energy: E

Baseline: L

What do we know?

I.Esteban, M.C. Gonzalez-Garcia, A.Hernandez-Cabezudo, M. Maltoni, T.Schwetz
JHEP 01 (2019) 106

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
$\delta_{CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

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.

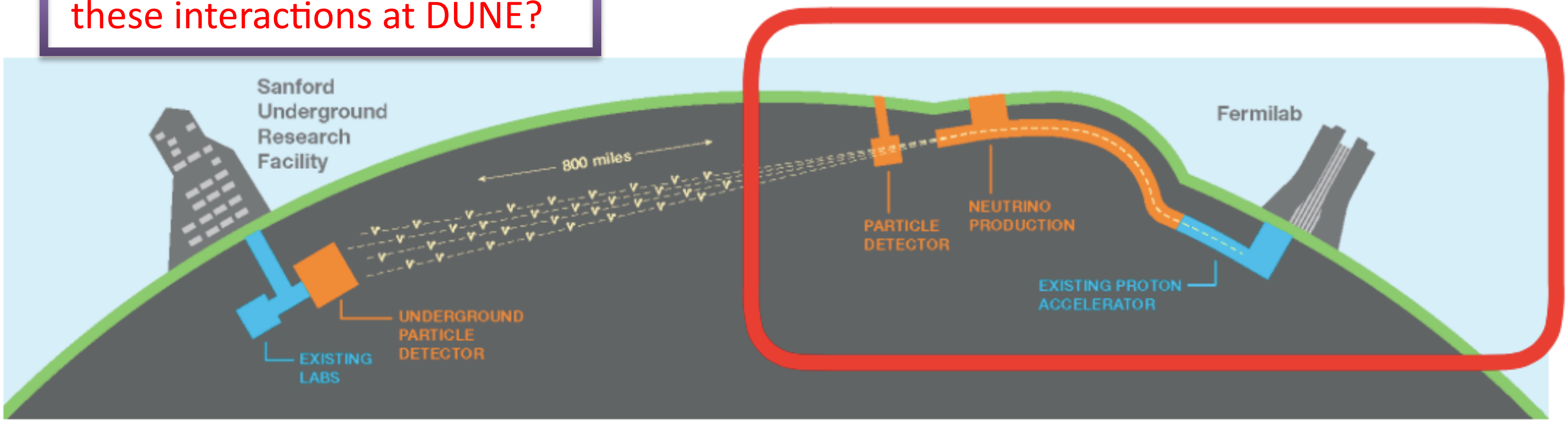
High beam luminosity + Large fiducial mass → Ideal to investigate (rare) neutrino interactions

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

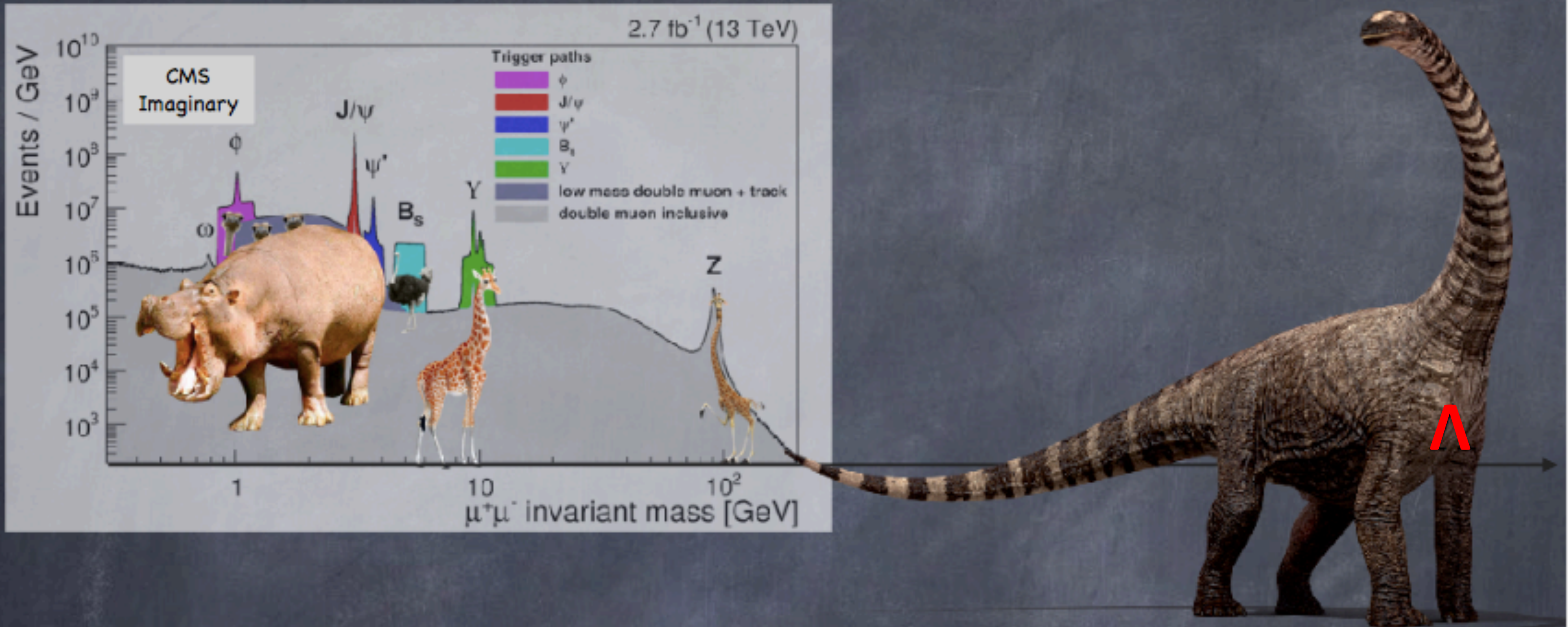
- neutrino-electron scattering
- neutrino trident production

- Test SM predictions
- Search for BSM physics

What can we learn from these interactions at DUNE?



Fantastic Beasts and Where To Find Them



x) It looks more and more likely that new degrees of freedom beyond the SM may not be directly available at the LHC or even at future colliders

x) However, even if it is not possible to see the head, it may be possible to see the tail…

A Falkowski, https://goo.gl/T8wUZV

Neutrino Trident Scattering at Near Detectors

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

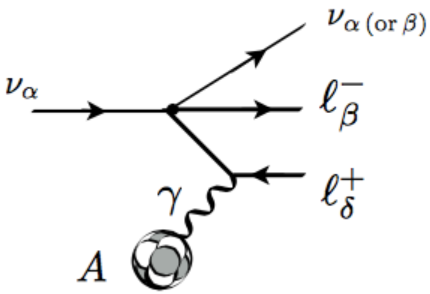
Neutrino Trident Scattering

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

Production of a **charged lepton pair**

in the scattering of a **neutrino**

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



First signal claimed at CHARM-II:

neutrinos with average energy $\sim$ 20

GeV on glass

Phys.Lett. B245, 271 (1990)

$$\sigma_{\text{CHARM II}}/\sigma_{\text{SM}} = 1.58 \pm 0.57$$

CCFR: neutrinos with average energy

$\sim$ 160 GeV on iron

Phys.Rev.Lett. 66, 3117 (1991)

$$\sigma_{\text{CCFR}}/\sigma_{\text{SM}} = 0.82 \pm 0.28$$

Neutrino Trident Scattering

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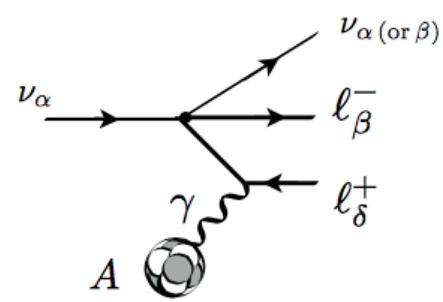


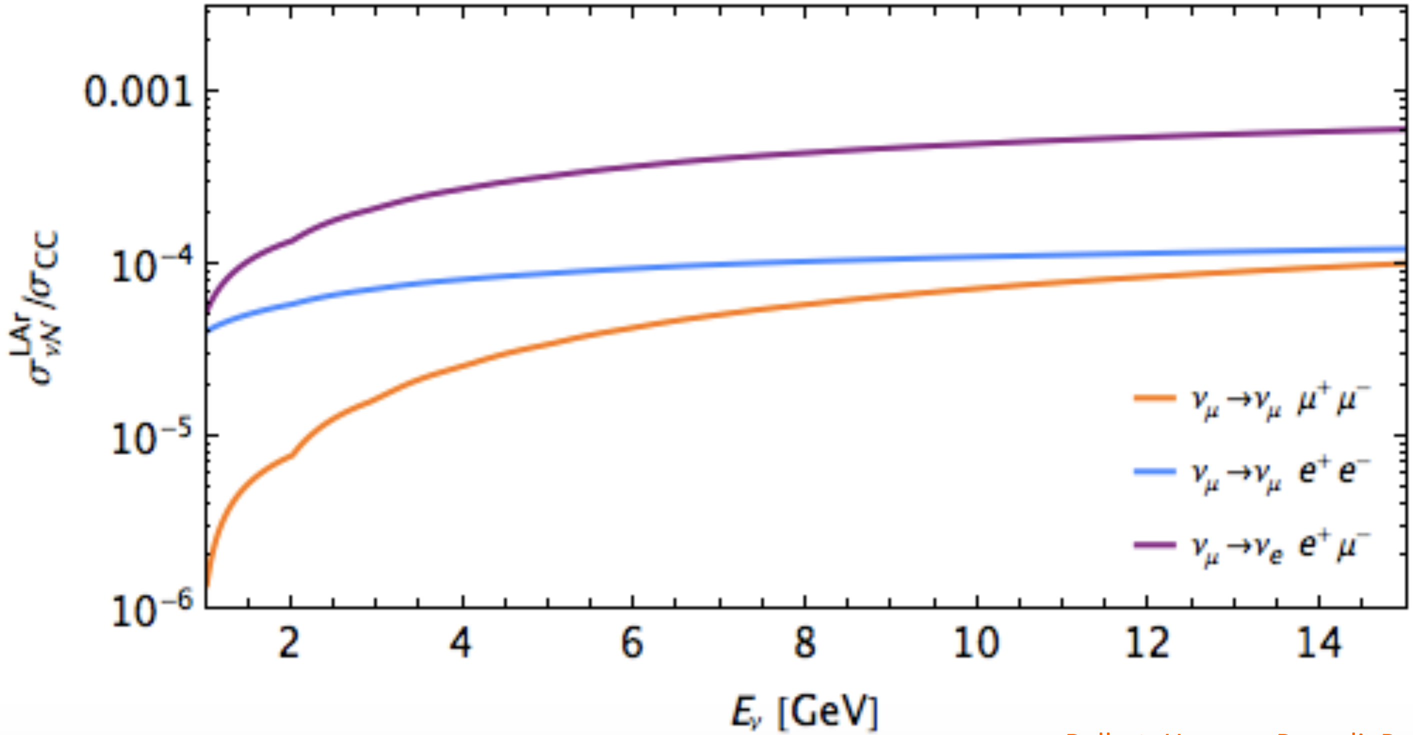
Neutrino	Antineutrino	SM Contributions
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	$\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^+ \mu^-$	CC, NC
$\nu_\mu \to \nu_e e^+ \mu^-$	$\bar{\nu}_\mu \to \bar{\nu}_e e^- \mu^+$	CC
$\nu_\mu \to \nu_\mu e^+ e^-$	$\bar{\nu}_\mu \to \bar{\nu}_\mu e^+ e^-$	NC
$\nu_e \to \nu_e e^+ e^-$	$\bar{\nu}_e \to \bar{\nu}_e e^+ e^-$	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
JHEP **1901**, 119 (2019)

Trident cross section:

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

hadronic tensor
(depends on scattering regime)

leptonic tensor

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

momentum transfer

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

Center-of-mass energy of the total system

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

We can separate photon contributions:

$$\frac{\mathrm{d}^2\sigma_{\nu \mathrm{X}}}{\mathrm{d}Q^2\mathrm{d}\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}\,Q^2}\left[h_{\mathrm{X}}^{\mathrm{T}}(Q^2,\hat{s})\,\sigma_{\nu\gamma}^{\mathrm{T}}(Q^2,\hat{s}) + h_{\mathrm{X}}^{\mathrm{L}}(Q^2,\hat{s})\,\sigma_{\nu\gamma}^{\mathrm{L}}(Q^2,\hat{s})\right]$$

Transversal — Longitudinal

Equivalent Photon Approximation (EPA) is widely used in the present literature.

Renewed interest, especially due to NP potential.	[W. Altmannshoffer et al, 2014]
Atmospheric trident production.	[SF Ge et al, 2017]
High rates for DUNE ND and SHiP for unobserved channels.	[G. MAGILL et al, 2016]
Charged scalars influence on CC channels.	[G. MAGILL et al, 2017]

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 ($\sigma^{\mathrm{T}}_{\nu\gamma}(q^2,\hat{s}) \approx \sigma^{\mathrm{T}}_{\nu\gamma}(0,\hat{s})$).

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

QED	Fermi Limit of the SM
$\sigma_\gamma^{\mathrm{QED}}(P_i + \gamma \to P_f; \hat{s}, 0) \propto \frac{1}{\hat{s}}$	$\sigma_\gamma^{\mathrm{FL}}(P_i + \gamma \to P_f; \hat{s}, 0) \propto G_{\mathrm{F}}^2\,\hat{s}$
Decreases with increasing transferred four-momentum	Increases with increasing transferred four-momentum
On-shell >> off-shell	On-shell << off-shell

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

How bad is it?

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

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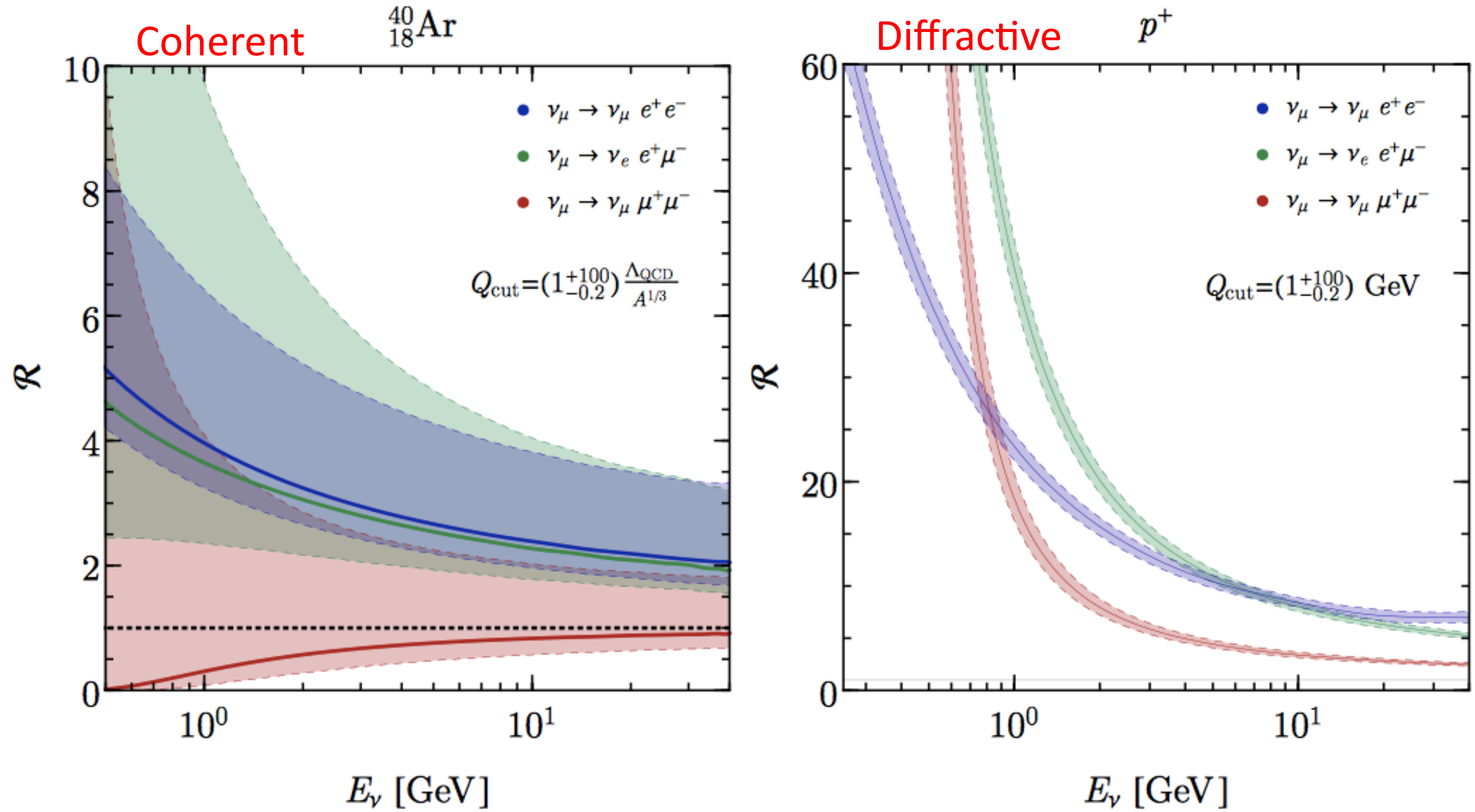


EPA approximation doesn't work. Full 4PS calculation must be done!!!

Trident rates at LAr Detectors

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

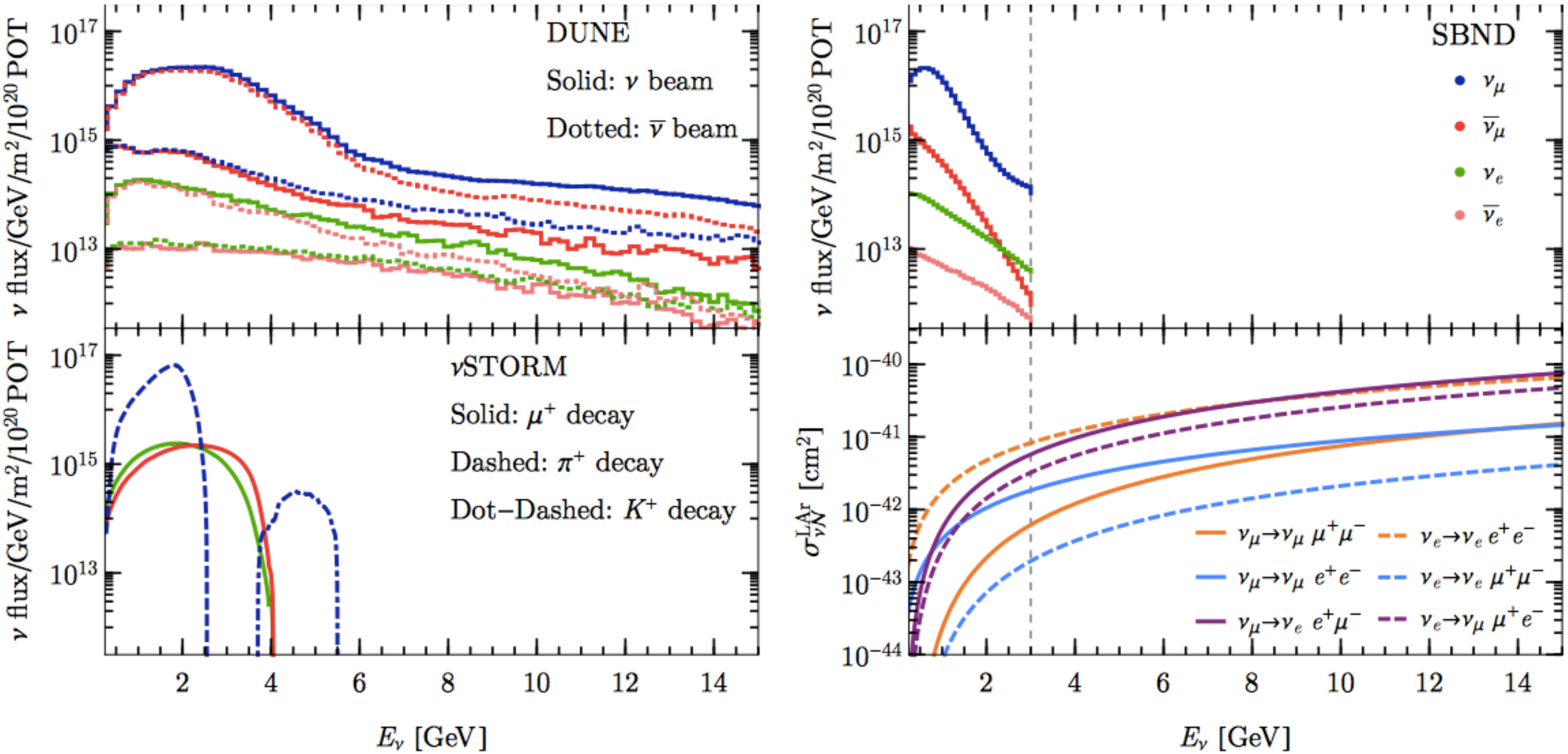
Channel	SBND	μBooNE	ICARUS	DUNE ND	νSTORM ND
Total $e^\pm \mu^\mp$	10	0.7	1	2993 (2307)	191
	2	0.1	0.2	692 (530)	41
Total $e^+ e^-$	6	0.4	0.7	1007 (800)	114
	0.7	0.0	0.1	143 (111)	14
Total $\mu^+ \mu^-$	0.4	0.0	0.0	286 (210)	11
	0.4	0.0	0.0	196 (147)	9

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

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

Trident rates at LAr Detectors

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



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

Trident background analysis

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

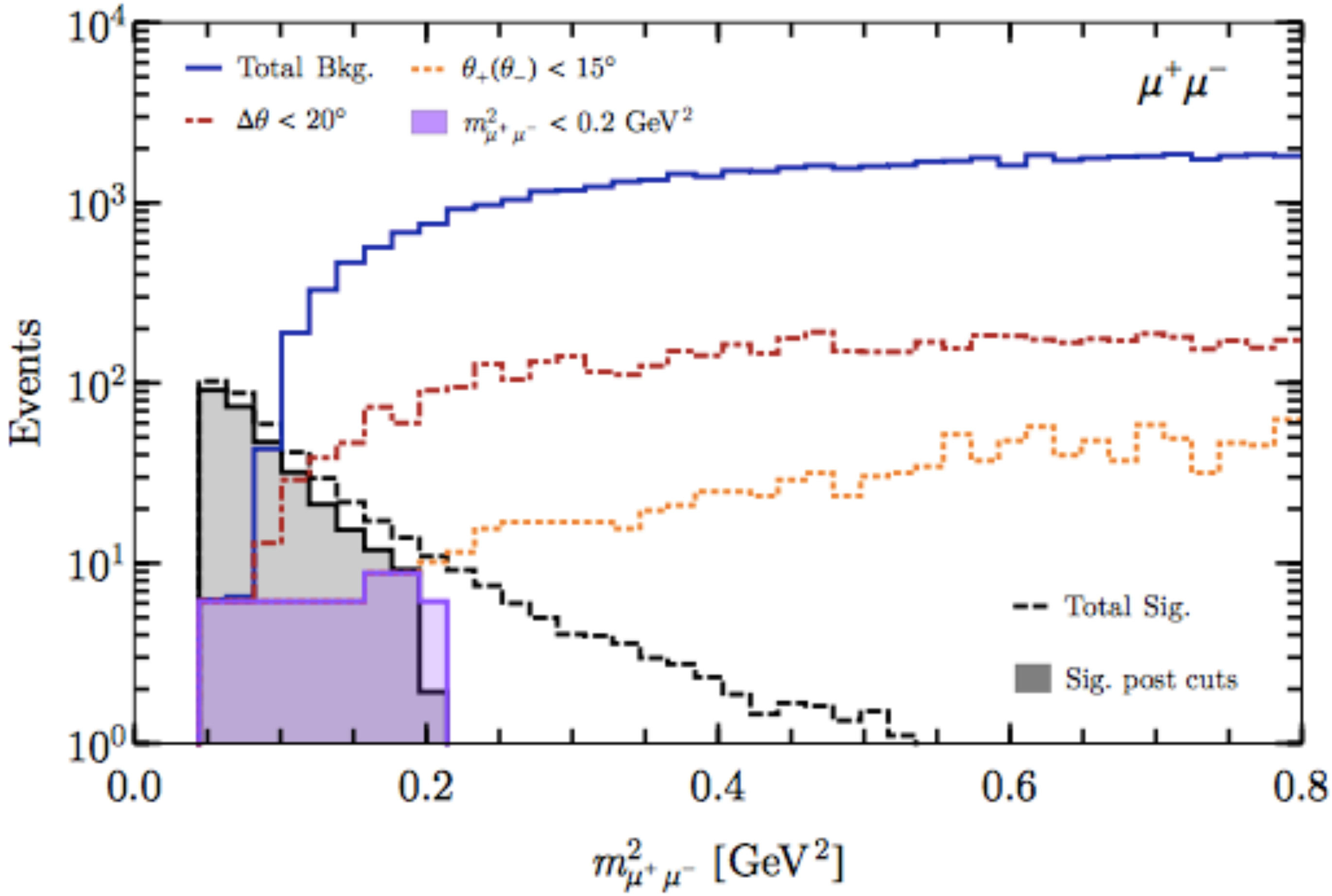
misID
γ as $e^{\pm}$
γ as e^+e^-
$\pi^{\pm}$ as $\mu^{\pm}$

Channel	$\mathbf{N_B^{misID}/N_{CC}}$	$\mathbf{N_B^{had}/N_{CC}}$	$\mathbf{N_B^{kin}/N_{CC}}$
$e^{\pm}\mu^{\mp}$	$1.67\ (1.62) \times 10^{-4}$	$2.68\ (4.31) \times 10^{-5}$	$4.40\ (3.17) \times 10^{-7}$
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
JHEP **1901**, 119 (2019)



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)

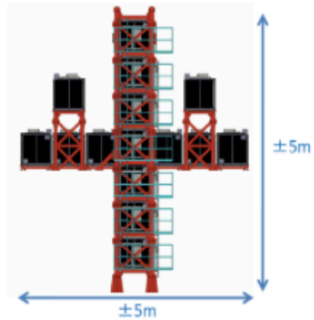
Trident rates at other Near Detectors

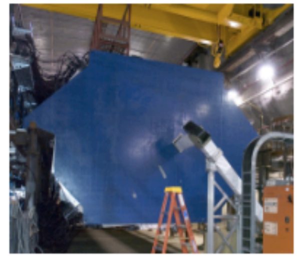
Experiment	**Material**	**Baseline (m)**	**Exposure (POT)**	**Fiducial Mass (t)**	**E_ν (GeV)**
INGRID	Fe	280	3.9×10^{21} [10^{22}] T2K-I [T2K-II]	99.4	$0 - 4$
MINOS[+]	Fe and C	1040	$10.56(3.36)[9.69] \times 10^{20}$	28.6	$0 - 20$
NOνA	C_2H_3Cl and CH_2	1000	$8.85(6.9)$ [$36(36)$] $\times 10^{20}$ [NOνA-II]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

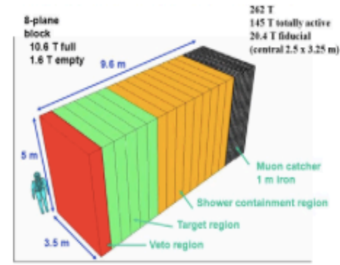
All have finished data taking or are still running

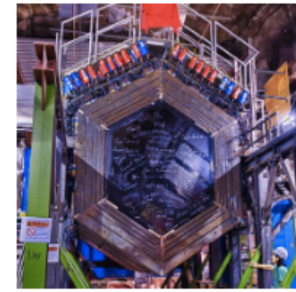
Trident rates at other Near Detectors

INGRID









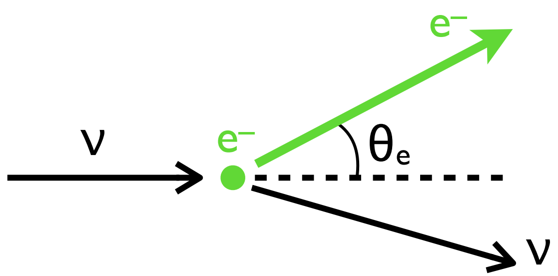
Channel	T2K-I	T2K-II	MINOS	MINOS+	NOνA-I	NOνA-II	MINERνA
Total $e^{\pm}\mu^{\mp}$	563	1444	222 (56)	730	83 (72)	340 (374)	149 (102)
	96	246	46 (11)	151	25 (22)	102 (114)	56 (39)
Total e^+e^-	277	711	61 (15)	62	29 (22)	119 (114)	39 (27)
	24	62	9 (2)	8	4 (4)	16 (21)	10 (7)
Total $\mu^+\mu^-$	30	76	26 (6)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

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

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.

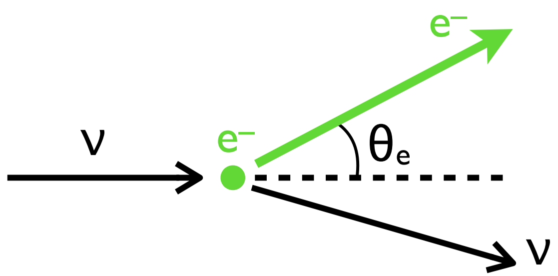
How many events at DUNE ND?

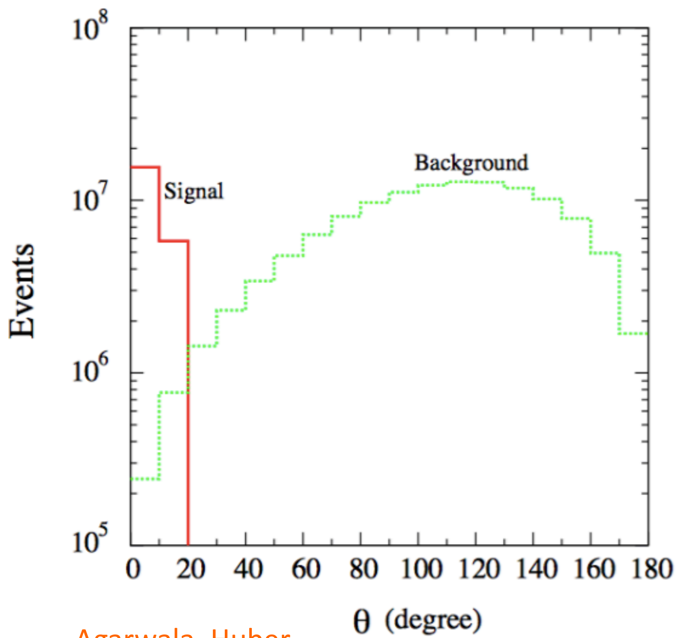
Approximately 60,000 nu-e events for 75 tonnes-7 years!

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

Neutrino-Electron Scattering

Signature: forward going electrons!





Agarwala, Huber,
JHEP 1108, 059 (2011)

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 (In press)

Measuring the Weak Mixing Angle at DUNE-PRISM

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

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

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:

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

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Gouvêa, Machado, Perez-Gonzalez and **ZT**
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$$\frac{d\sigma}{dE_R} \simeq 1.72 \times 10^{-41} \left\{ g_1^2 + g_2^2 \left(1 - \frac{E_R}{E_\nu}\right)^2 \right\} \frac{\text{cm}^2}{\text{GeV}}$$

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	$(g_V+g_A)/2$	$-1/2+s_W^2$

There is an exact degeneracy in the differential cross section for ν_μ – e scattering under the transformations:

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

There are half solutions for ν_e – e scattering:

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

Measuring the Weak Mixing Angle at DUNE-PRISM

We show the advantages of using the DUNE-PRISM concept: 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.

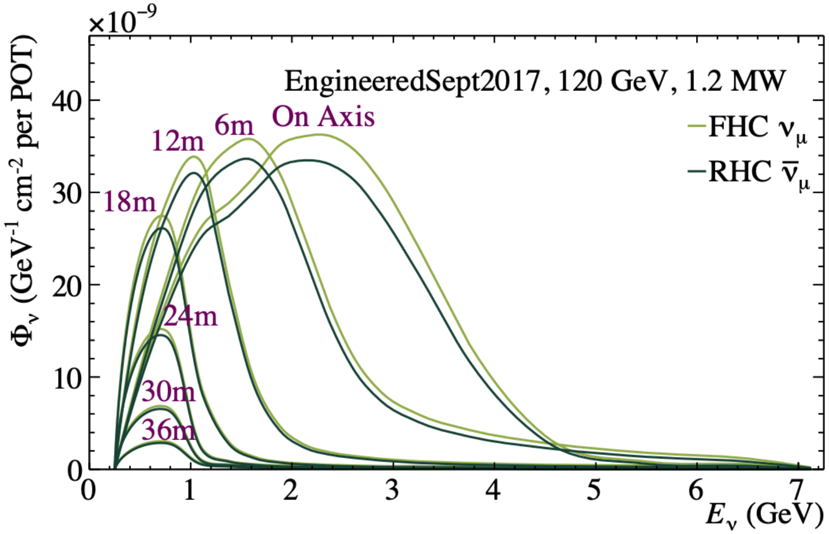


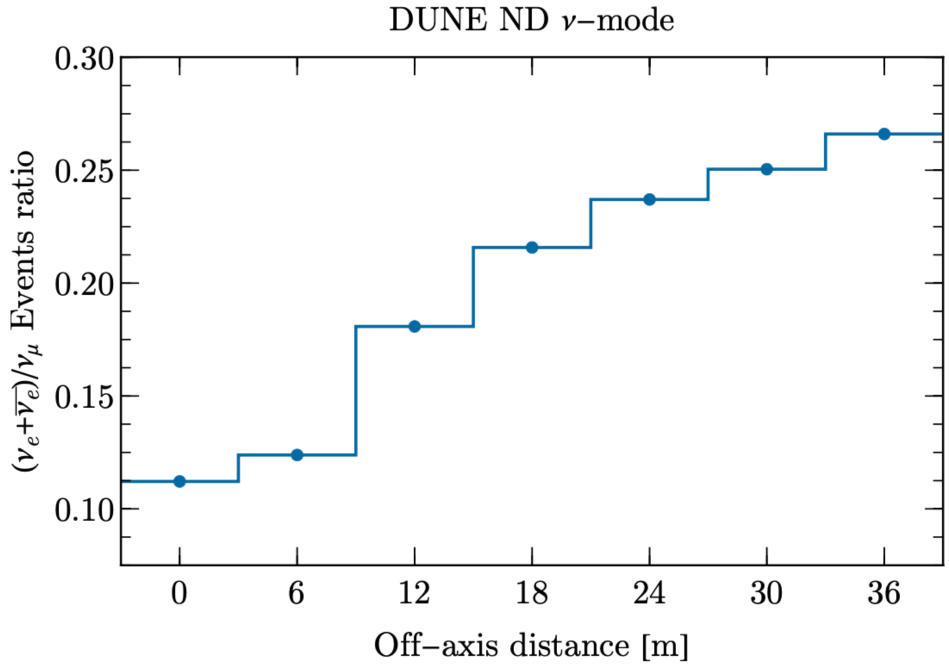
Figure from "The DUNE-PRISM Near Detector" T. Cai et al, 2018

Measuring the Weak Mixing Angle at DUNE-PRISM

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

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

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



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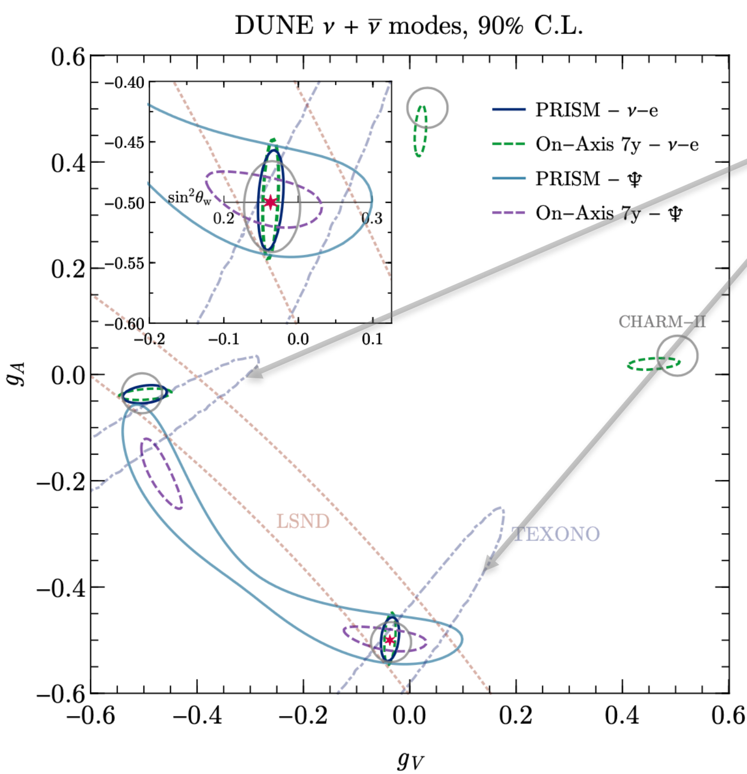

TEXONO measured electron recoils from electron anti-neutrinos in a nuclear reactor ($\bar{\nu}_e$–e).

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

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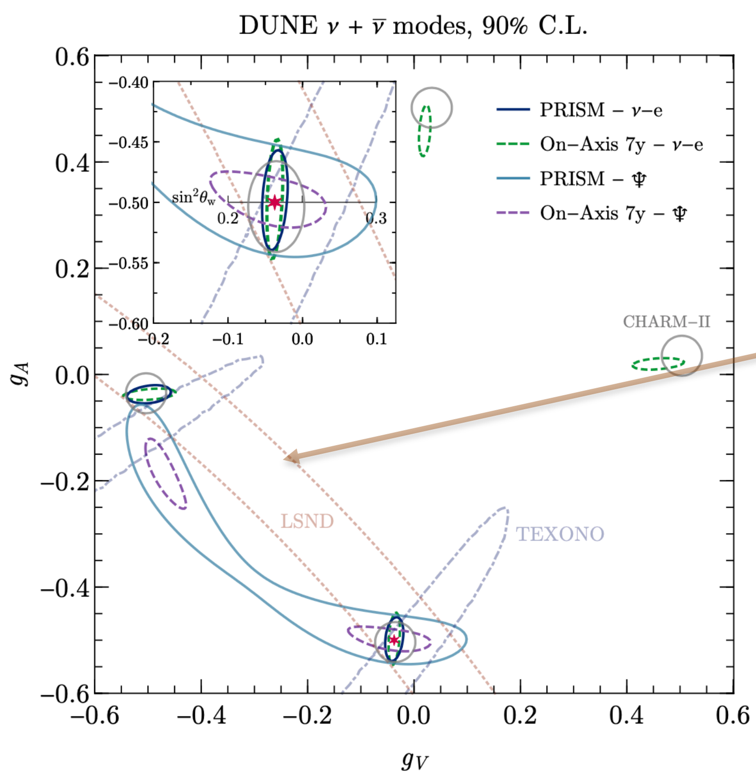

TEXONO measured electron recoils from electron anti-neutrinos in a nuclear reactor ($\bar{\nu}_e - e$).

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

LSND is similar, but with ($\nu_e - e$).

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

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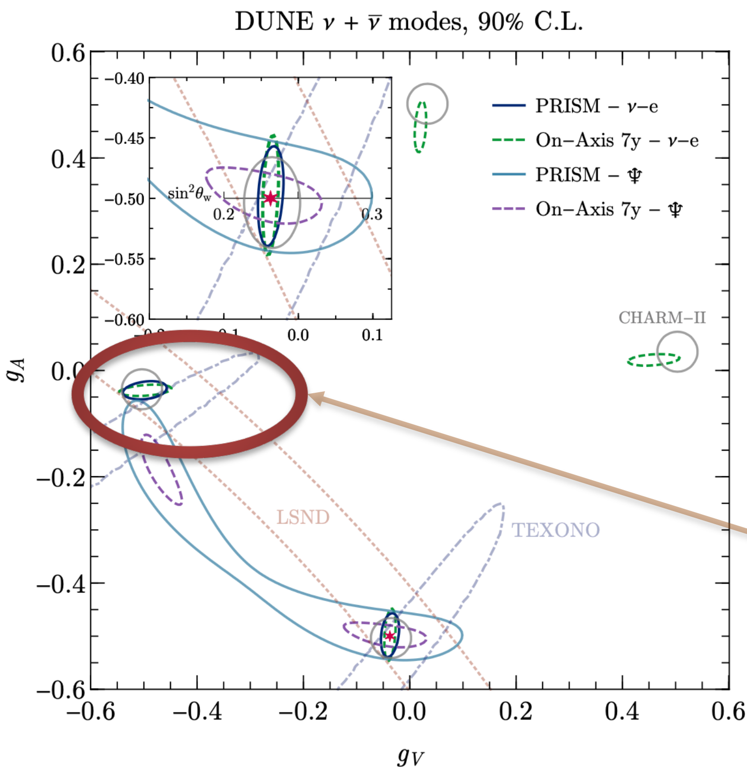

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LSND is similar, but with ($\nu_e - e$).

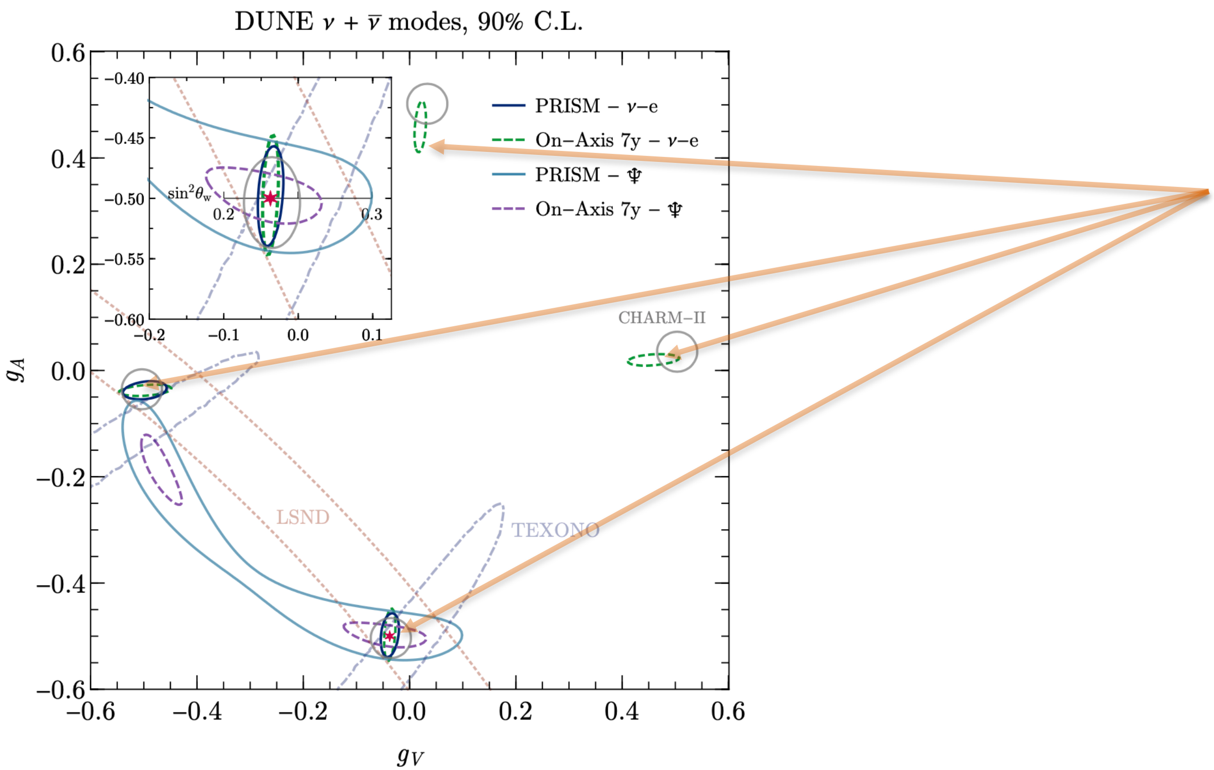
L. B. Auerbach et al. (LSND), Phys. Rev. **D63**, 112001 (2001)

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

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

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



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

Measuring the Weak Mixing Angle at DUNE-PRISM

Gouvêa, Machado, Perez-Gonzalez and **ZT**
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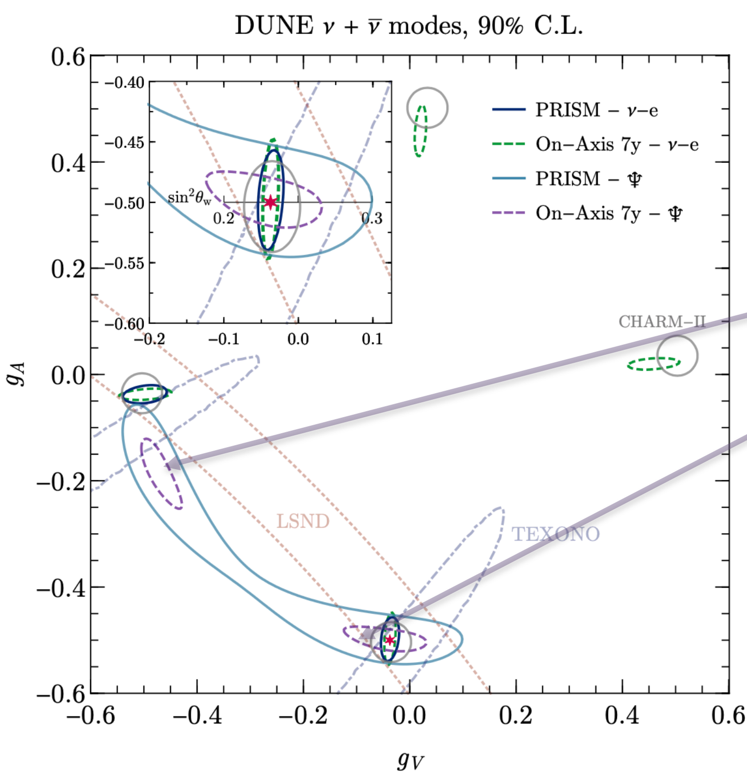

The trident cross section is more involved, in the limit where the muon mass vanishes, all cross sections are invariant under $g_V \leftrightarrow g_A$.

$C_V = g_V$	$C_A = g_A$	(e^+e^- trident)
$C_V = g_V + 1$	$C_A = g_A + 1$	($\mu^+\mu^-$ trident)

Measuring the Weak Mixing Angle at DUNE-PRISM

Gouvêa, Machado, Perez-Gonzalez and **ZT**
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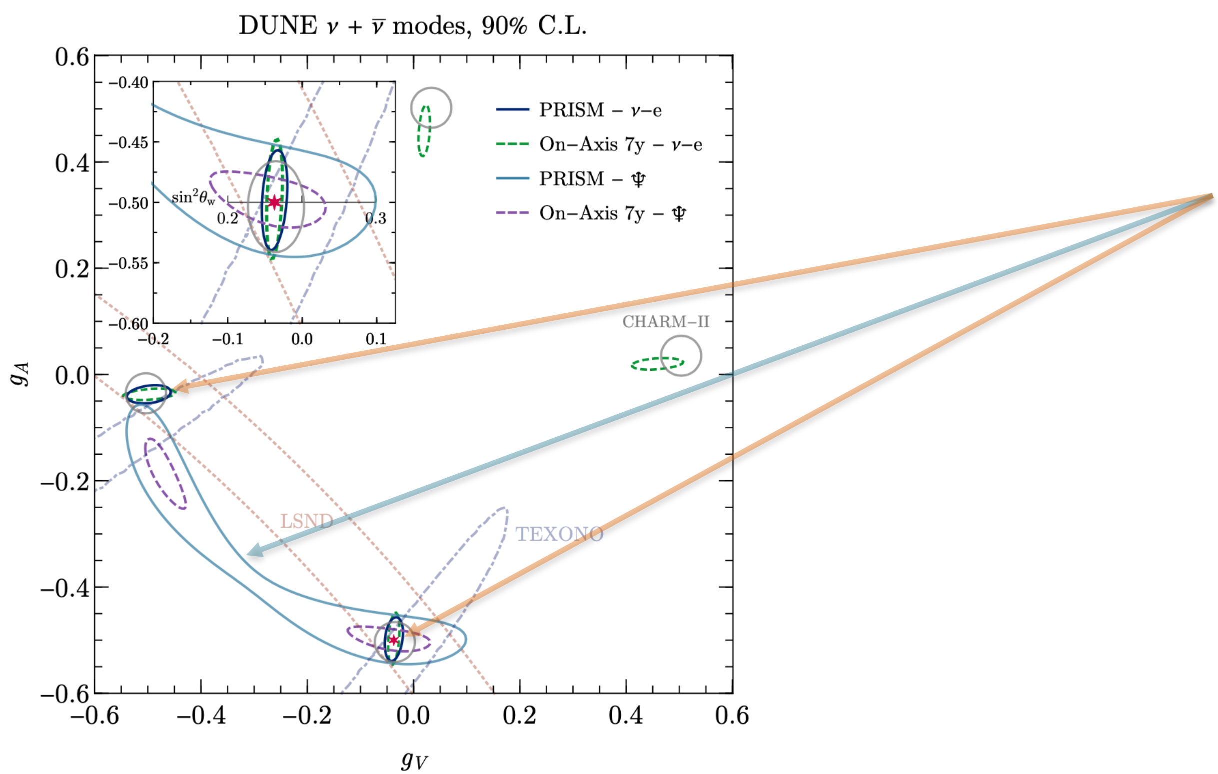


The sub-dominant ν_e beam component in DUNE-PRISM, as well as neutrino trident events, play an important role in resolving degeneracies currently present in the world data.

Measuring the Weak Mixing Angle at DUNE-PRISM

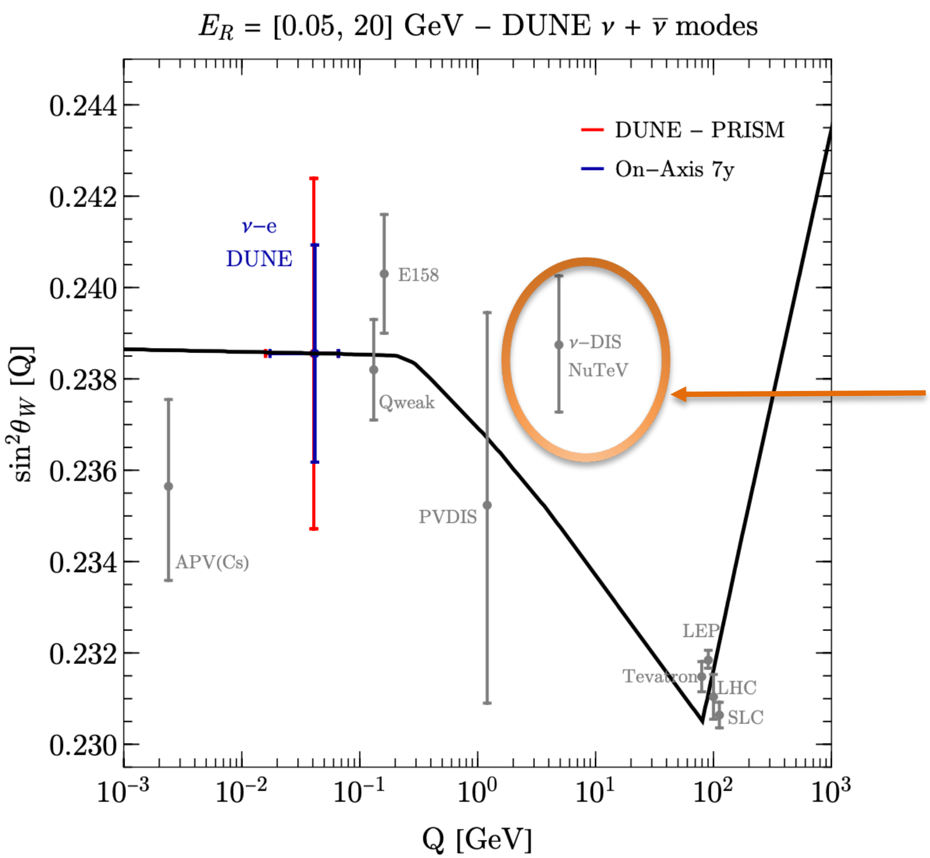
Gouvêa, Machado, Perez-Gonzalez and **ZT**
arXiv:1912.06658 (In press)

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

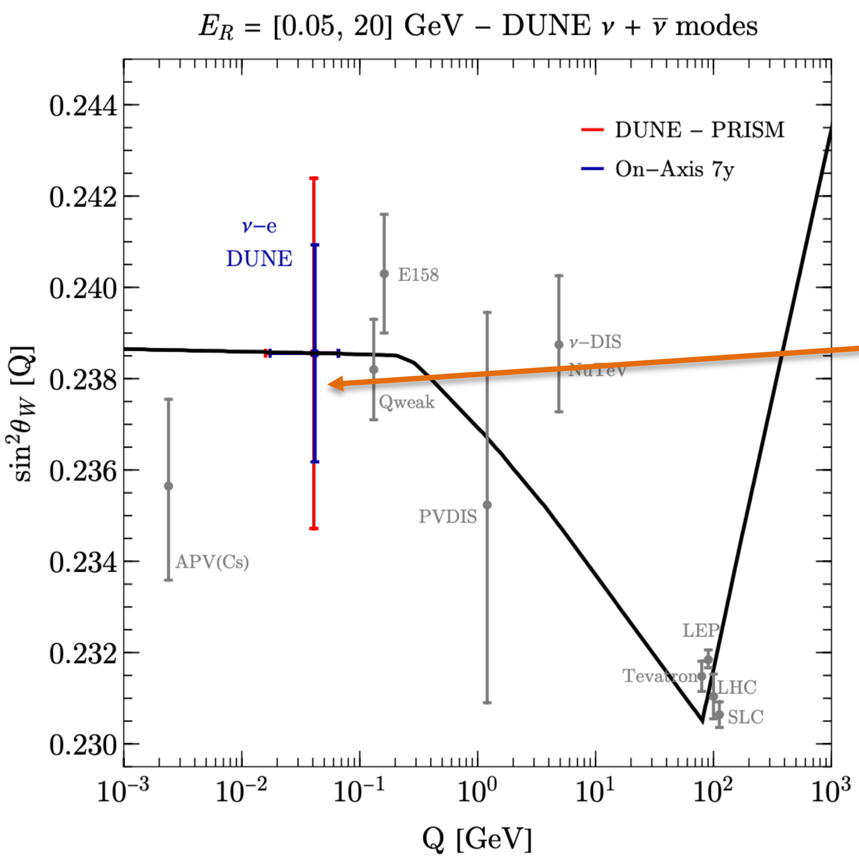


The most precise measurement of $\sin^2\theta_W$ using neutrino scattering, at $\langle Q \rangle \simeq 4.5$ GeV.

Deviates from the LEP measurement at 3σ level.

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

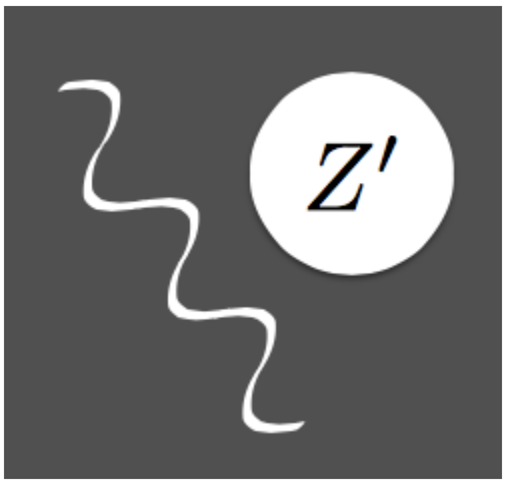
Measuring the Weak Mixing Angle at DUNE-PRISM



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

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

Z's in neutrino scattering at DUNE



Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012

- We study potential constraints which can be placed on a general set of leptophilic Z′ models in the two most likely channels for BSM scattering at the near detector of DUNE: neutrino-electron scattering and neutrino trident scattering.

$$\mathcal{L} \supset -g' Z'_\mu \left[Q^{\mathrm{L}}_\alpha \, \overline{L^\alpha_L} \gamma^\mu L^\alpha_L + Q^{\mathrm{R}}_\alpha \, \overline{\ell^\alpha_R} \gamma^\mu \ell^\alpha_R + \sum_{\mathrm{N}} Q_{\mathrm{N}} \, \overline{N_R} \gamma^\mu N_R \right]$$

- We focus on the anomaly free leptophilic extensions of the SM:

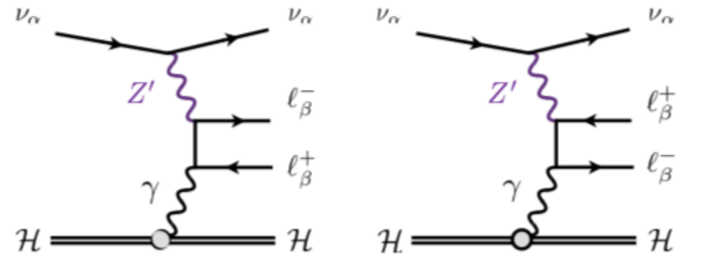
  $L_\alpha - L_\beta$, $\alpha,\beta = \{e,\mu,\tau\}$, $\alpha \neq \beta$.

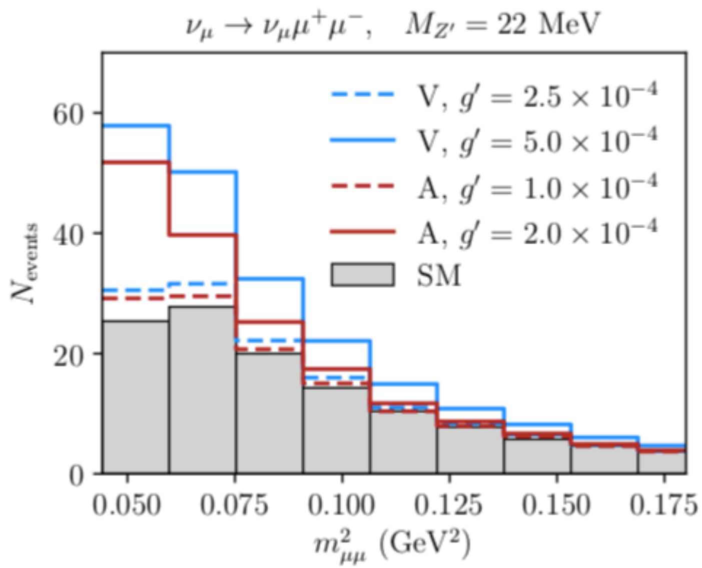
- Anomaly free conditions fix the charges

Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012

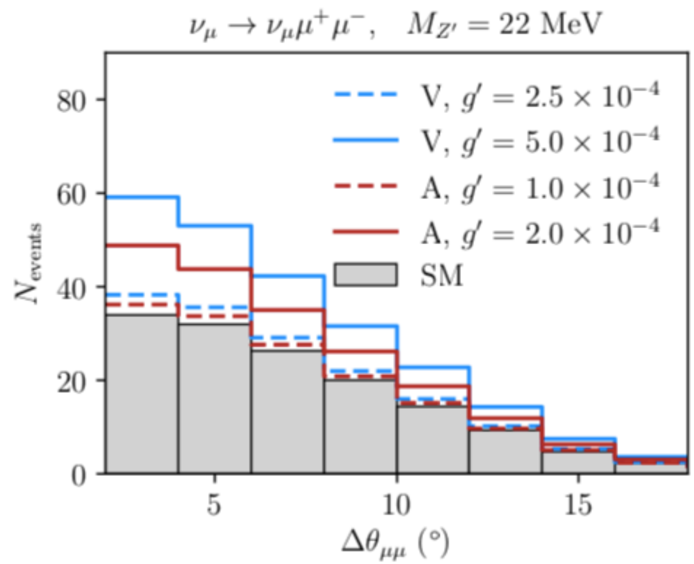
Trident kinematical distributions

$$\hat{V}_{\alpha\beta} = g_V^{\ell_\beta} + \delta_{\alpha\beta} + \frac{Q_\alpha^L Q_\beta^V}{2\sqrt{2}G_F}\frac{(g')^2}{K^2 + M_{Z'}^2}, \quad \hat{A}_{\alpha\beta} = g_A^{\ell_\beta} + \delta_{\alpha\beta} + \frac{Q_\alpha^L Q_\beta^A}{2\sqrt{2}G_F}\frac{(g')^2}{K^2 + M_{Z'}^2}$$





The invariant mass



Charged lepton separation angle

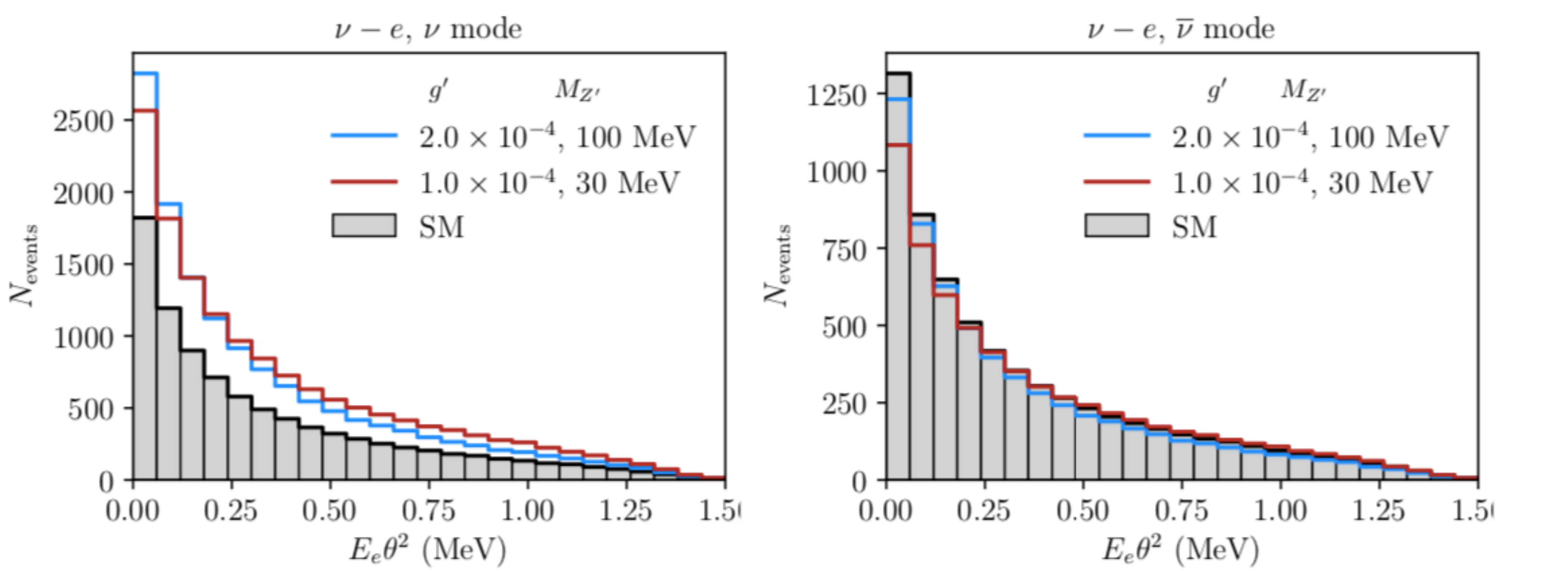
Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012

Neutrino-Electron scattering

The vector and axial couplings with Z':

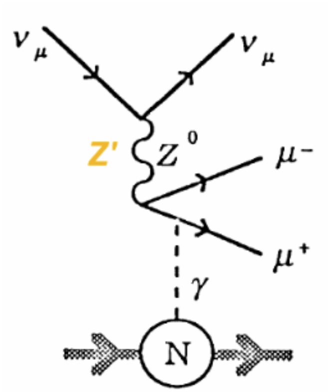
$$C_\alpha^{\rm V} = -\frac{1}{2} + 2s_{\rm W}^2 + \delta_{\alpha e} + \frac{Q_e^{\rm V} Q_\alpha^{\rm L}}{2\sqrt{2}G_F}\frac{(g')^2}{M_{Z'}^2 + 2m_e T_e},$$

$$C_\alpha^{\rm A} = -\frac{1}{2} + \delta_{\alpha e} + \frac{Q_e^{\rm A} Q_\alpha^{\rm L}}{2\sqrt{2}G_F}\frac{(g')^2}{M_{Z'}^2 + 2m_e T_e},$$

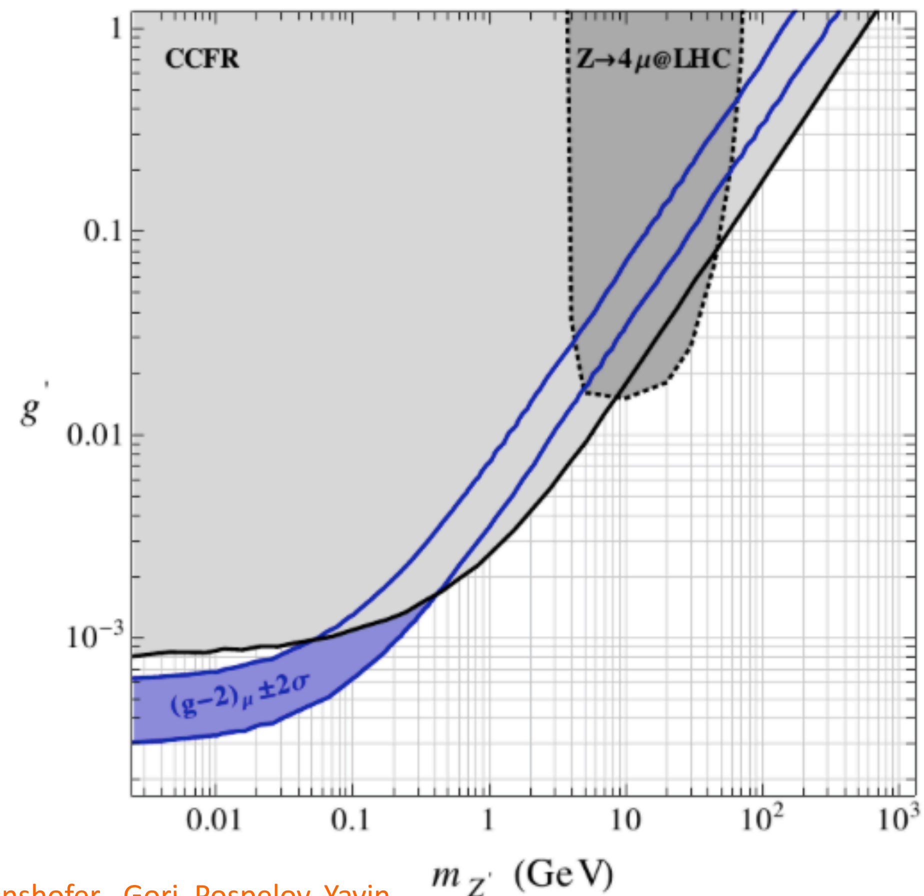


L_μ-L_τ Model:

Z′ bosons that couple vectorially to muons also couple to muon neutrinos, their contribution to neutrino trident production interferes constructively with the SM



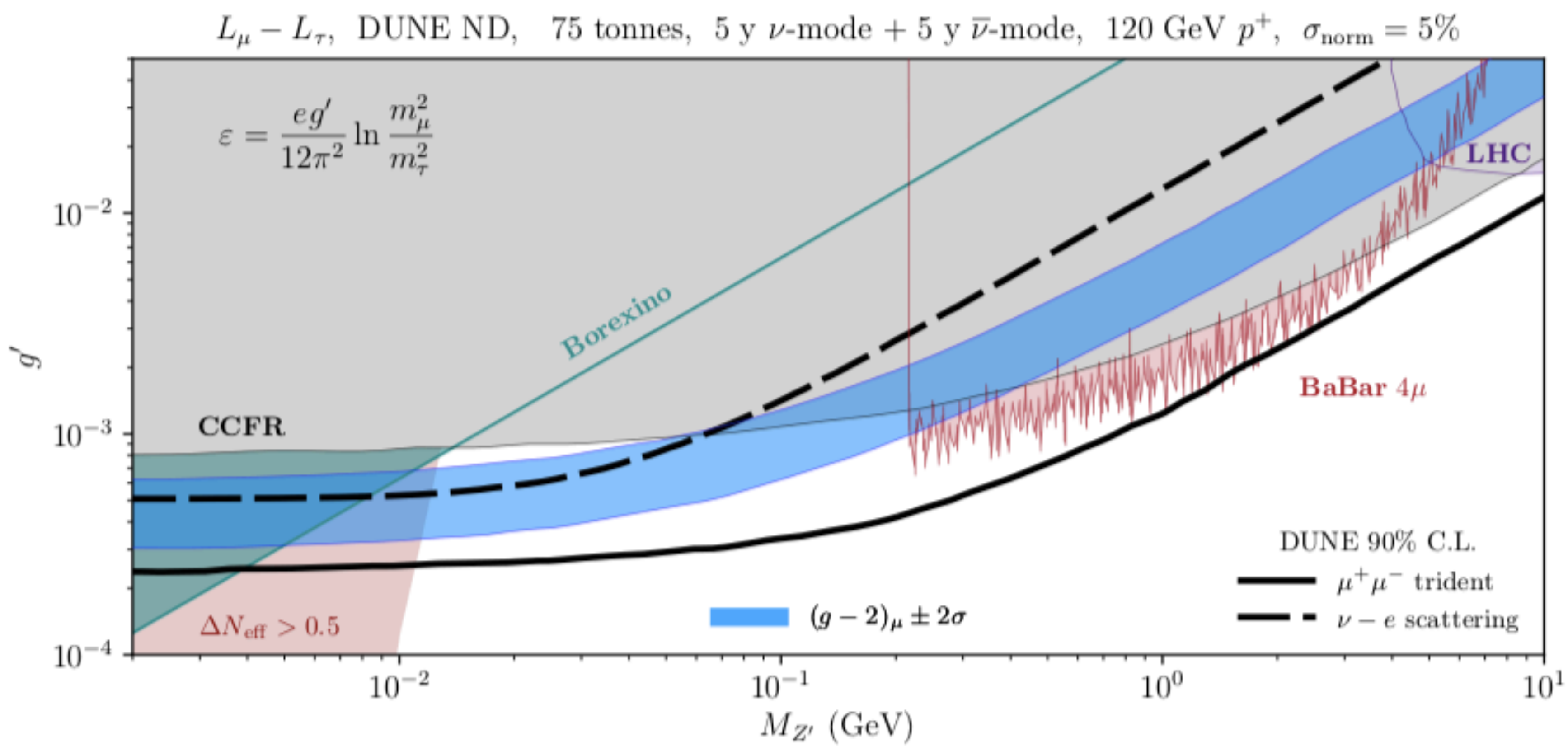
Z' based on $L_\mu - L_\tau$ can explain $(g-2)_\mu$ only if it is very light ($m_{Z'}$ < 400 MeV)



(Altmannshofer , Gori, Pospelov, Yavin, Phys.Rev.Lett. 113 (2014) 091801)

L_μ-L_τ Model at DUNE:

Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012



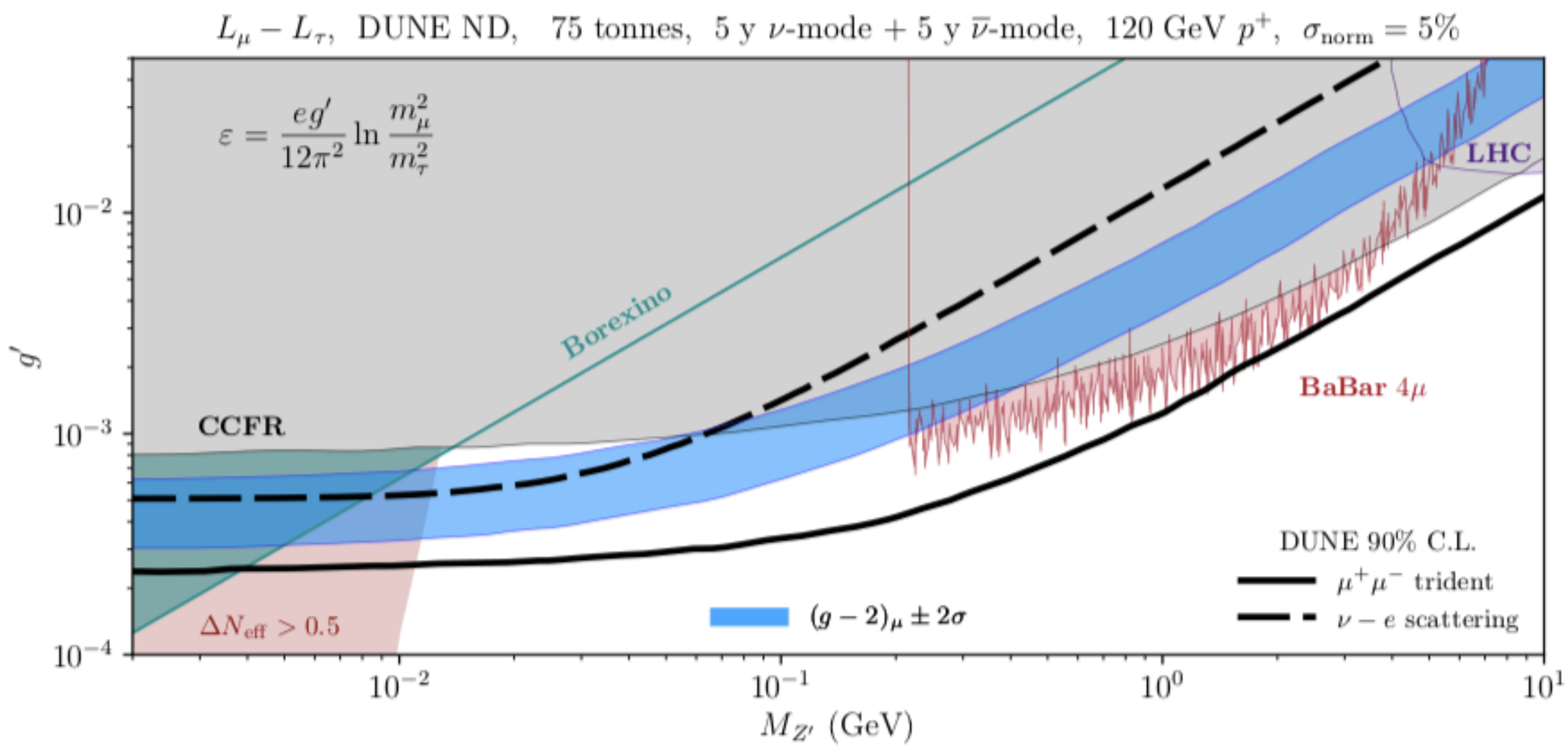
- The sensitive trident channel is:

  $\nu_\mu \rightarrow \nu_\mu \mu^+ \mu^-$ channel

- The loop-induced kinetic mixing also induces a neutrino-e mixing.

L_μ-L_τ Model at DUNE:

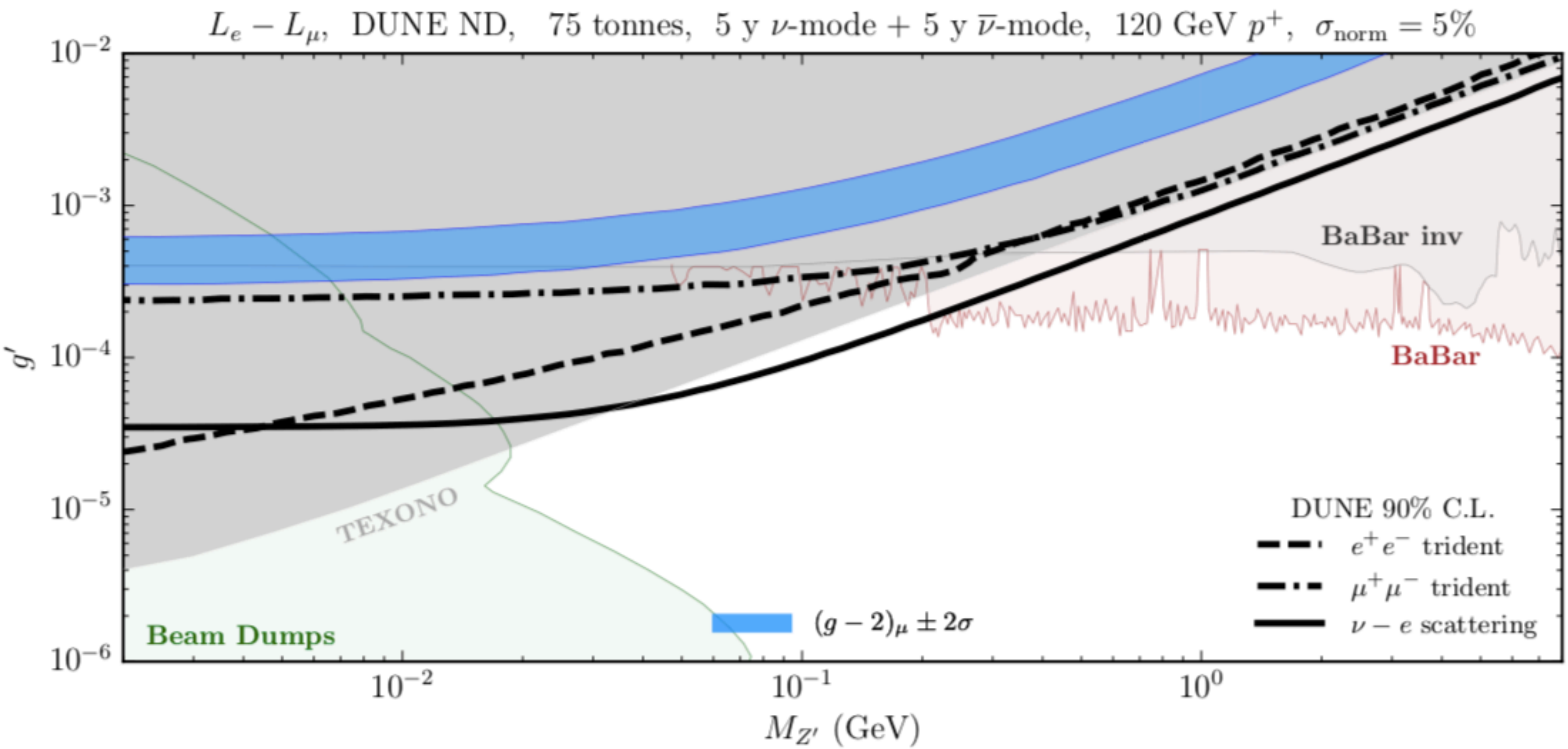
Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012



The whole g-2 region can be excluded by DUNE data!

L_e-L_μ Model at DUNE:

Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012

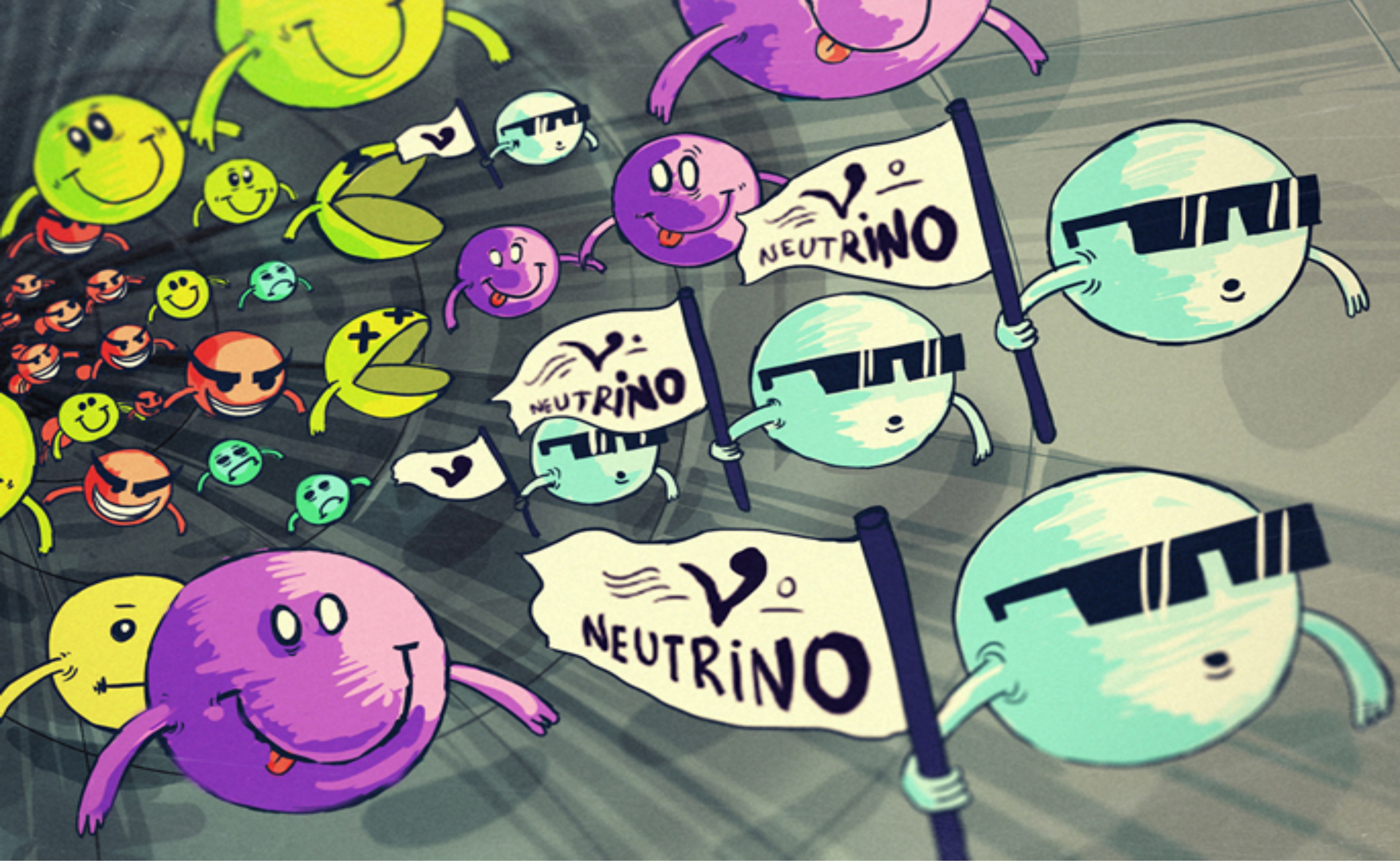


- The main constraint is from neutrino-electron scattering.
- The sensitive trident channels are:

  $\mu^+\mu^-$ and e^+e^-

Conclusion:

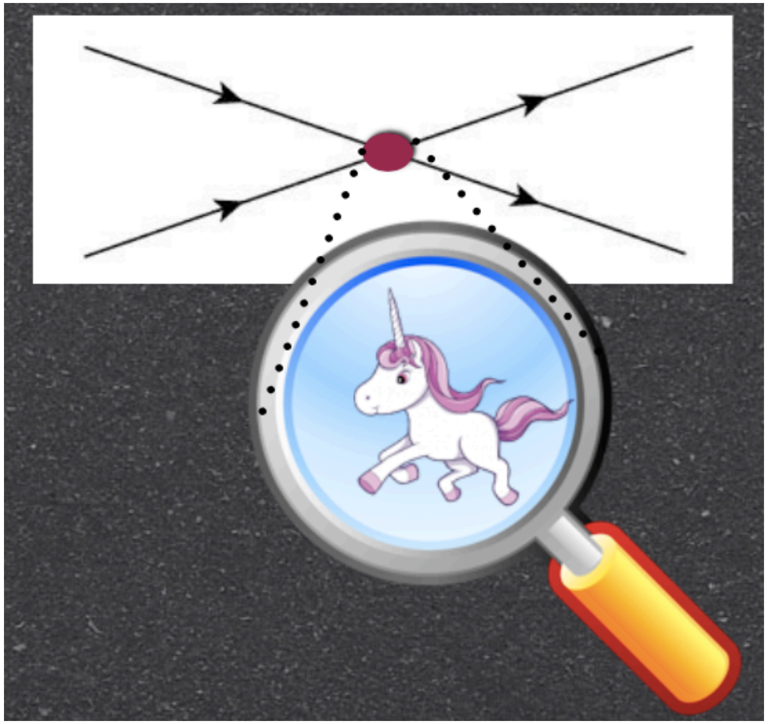
- The future DUNE experiment opens up the possibility to perform many measurements of rare neutrino processes at near detectors.
- We study Neutrino trident and Neutrino-Electron scattering at DUNE.
- We investigate the sensitivity of DUNE-PRISM, and find that it will qualitatively impact our ability to constrain the weak couplings of the electron.
- The DUNE near-detector can be used to measure $\sin^2\theta_W$ with better than 2% precision.
- We estimate the potential of the near detector of DUNE to probe anomaly-free leptophilic extensions of the SM.
- DUNE can fully exclude the (g-2) motivated parameter space when backgrounds are kept under control with kinematical considerations.



Thanks for your attention

Backup slides

Future DUNE constraints on EFT



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JHEP **1804** (2018) 101

Why EFT?

- Wealth of low-energy observables probing different aspects of particle interactions are described within one consistent framework.

- Constraints from different observables can be meaningfully compared.

- Results obtained in the language of EFT can be easily translated into constraints on any particular new physics model.

The point is that one can probe very heavy particles, often beyond the reach of present colliders, by precisely measuring low-energy observables.

Workflow

Constraints on BSM model #1

Constraints on BSM model #2

.....

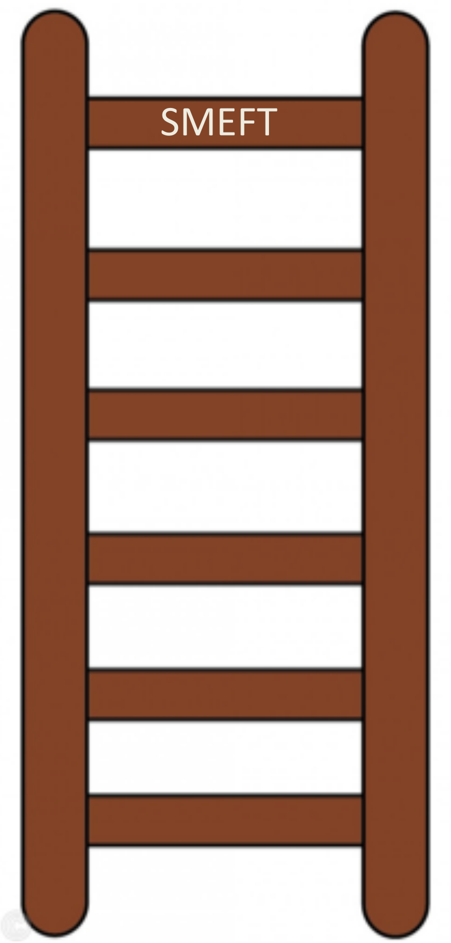
Constraints on SMEFT coefficients ($E>m_Z$)

low energy experiments ($E<<m_Z$)
Weak EFT
Energies relevant at reactor experiments

By measurements of WEFT parameters at $E<<m_Z$ we can drive constraints on higher dimensional SMEFT interactions.

EFT ladder

$E > m_Z$



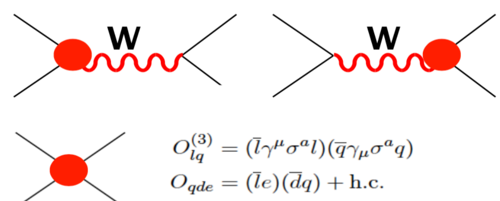
- If BSM particles are much heavier than the Z mass and the EWSB is linearly realized, then the relevant effective theory above the weak scale is the so-called SMEFT.

- It has the same particle content and local symmetry as the SM, but differs by the presence of higher-dimensional (non-renormalizable) interactions in the Lagrangian.

$$\mathcal{L}_{\text{SM EFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_L}\mathcal{L}^{D=5} + \boxed{\frac{1}{\Lambda^2}\mathcal{L}^{D=6}}$$

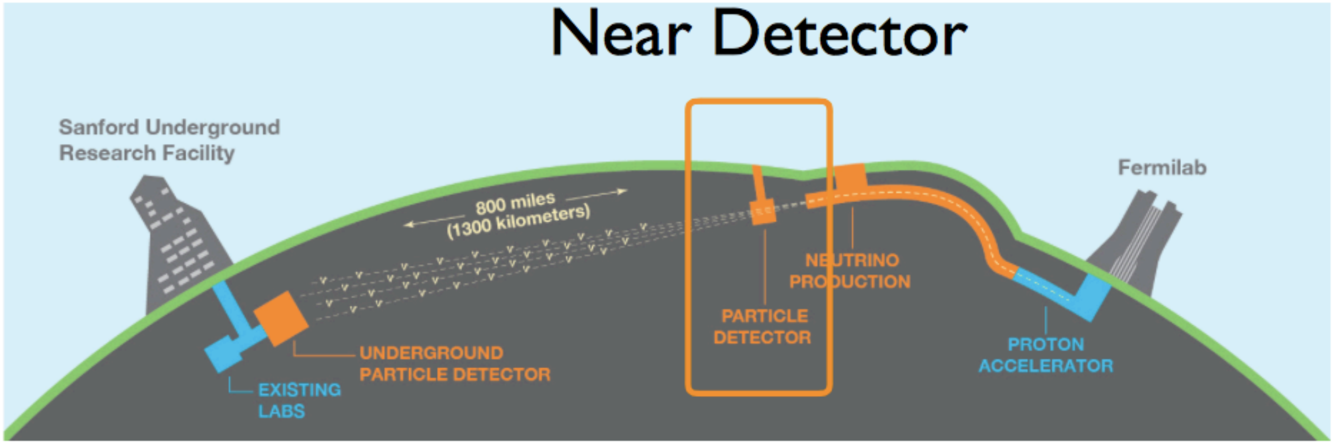
- The SMEFT framework allows one to describe effects of new physics beyond the SM in a model independent way

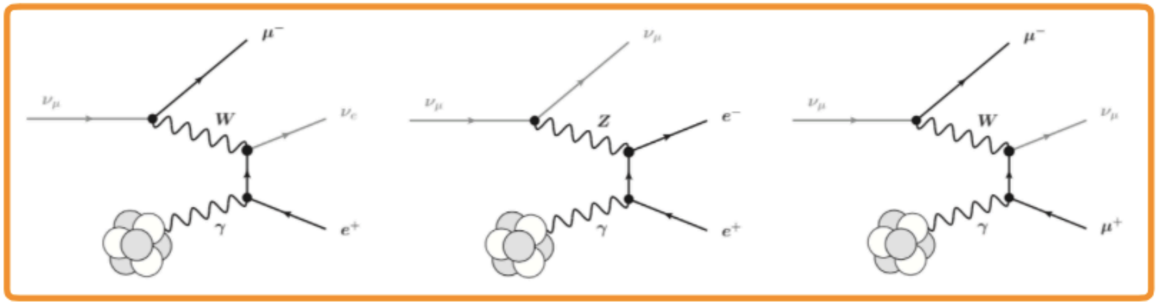
+

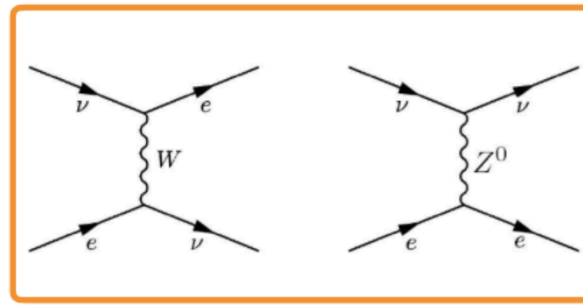


$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$$
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$
$$O_{lq}^t = (\bar{l}_a\sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu} u) + \text{h.c.}$$

How to study SMEFT at DUNE?







- neutrino-electron scattering
- neutrino trident production
- neutrino-nuclei scattering

We use these to study SMEFT!

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$$\mathcal{L}_{\rm wEFT} \supset -\frac{2}{v^2}(\bar\nu_a\bar\sigma_\mu\nu_b)\left[g_{LL}^{abcd}(\bar e_c\bar\sigma_\mu e_d) + g_{LR}^{abcd}(e_c^c\sigma_\mu\bar e_d^c)\right]$$

Neutrino-electron scattering in EFT:

g=g_{SM}+δg

$$\sigma_{\nu_\mu e} = \frac{s}{2\pi v^4}\left[(g_{LL}^{2211})^2 + \frac{1}{3}(g_{LR}^{2211})^2\right] \approx \frac{m_e E_\nu}{\pi v^4}\left[(g_{LL}^{2211})^2 + \frac{1}{3}(g_{LR}^{2211})^2\right]$$
$$\sigma_{\bar\nu_\mu e} = \frac{s}{2\pi v^4}\left[(g_{LR}^{2211})^2 + \frac{1}{3}(g_{LL}^{2211})^2\right] \approx \frac{m_e E_\nu}{\pi v^4}\left[(g_{LR}^{2211})^2 + \frac{1}{3}(g_{LL}^{2211})^2\right]$$

- We define the following ratios and its deviation from 1:

$$R_{\nu e}^i \equiv \frac{x_i\sigma_{\nu_\mu e} + \bar x_i\sigma_{\bar\nu_\mu e}}{x_i\sigma_{\nu_\mu e}^{\rm SM} + \bar x_i\sigma_{\bar\nu_\mu e}^{\rm SM}}$$

$$\begin{cases} x_\nu = 0.9 \\ x_{\bar\nu} = 0.1 \\ \bar x_i = 1 - x_i \end{cases}$$

$$\delta R_{\nu e}^i = 2\frac{(1+2x_i)\,\delta g_{LL}^{2211} g_{LL,\rm SM}^{2211} + (3-2x_i)\,\delta g_{LR}^{2211} g_{LR,\rm SM}^{2211}}{(1+2x_i)\,(g_{LL,\rm SM}^{2211})^2 + (3-2x_i)\,(g_{LR,\rm SM}^{2211})^2}$$

- Using DUNE we get:

$$-8.0\times10^{-4} < \delta R_{\nu e}^{\nu} < 8.0\times10^{-4}, \qquad -9.1\times10^{-4} < \delta R_{\nu e}^{\bar\nu} < 9.1\times10^{-4}$$

- Neutrino-electron scattering in EFT:

projected 95% CL constraints on the wEFT parameters

Dashed: 1% systematic error on the $R_{\nu e}$ measurements

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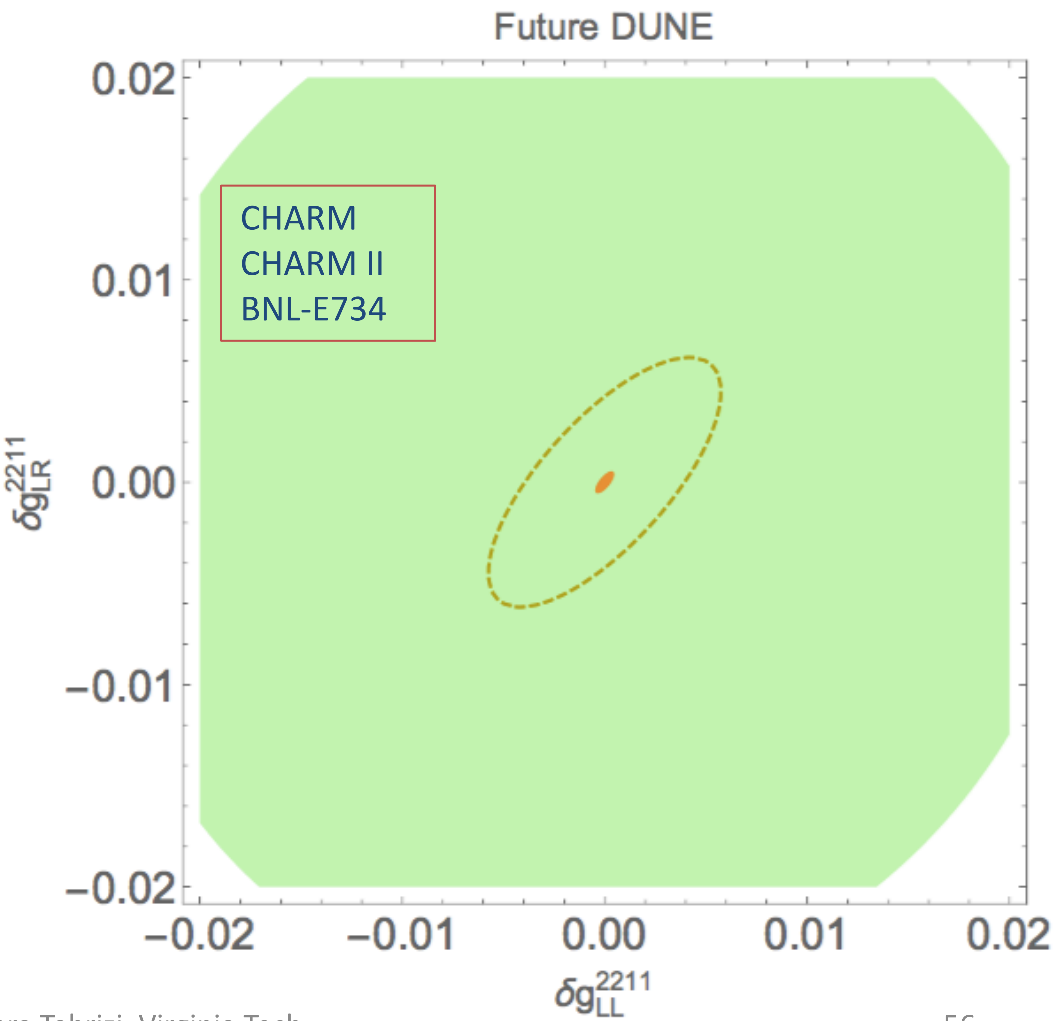

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Neutrino scattering off nuclei in EFT:

- We define the following ratios and its deviation:

$$R_{\nu_a N} \equiv \frac{x\sigma_{\nu_a N \to \nu_a N} + \overline{x}\sigma_{\overline{\nu}_a N \to \overline{\nu}_a N}}{\overline{x}\sigma_{\nu_a N \to e_a^- N} + x\sigma_{\overline{\nu}_a N \to e_a^+ N}}$$

$$\delta R^i_{\nu_\mu N} \simeq 2\frac{g^{\nu}_{L,\mathrm{SM}}\delta g^{\nu_\mu}_L + r_i^{-1} g^{\nu}_{R,\mathrm{SM}}\delta g^{\nu_\mu}_R}{(g^{\nu}_{L,\mathrm{SM}})^2 + r_i^{-1}(g^{\nu}_{R,\mathrm{SM}})^2}$$

- Using DUNE we get:

$$-9.5 \times 10^{-5} < \delta R^{\nu}_{\nu_\mu N} < 9.5 \times 10^{-5}, \qquad -1.4 \times 10^{-4} < \delta R^{\overline{\nu}}_{\nu_\mu N} < 1.4 \times 10^{-4}$$

$$\mathcal{L}_{\mathrm{wEFT}} \supset -\frac{2V_{ud}}{v^2}(1+\epsilon_L^{de_a})(\overline{e}_a\overline{\sigma}_\mu\nu_a)(\overline{u}\,\overline{\sigma}^\mu d) - \frac{2}{v^2}(\overline{\nu}_a\overline{\sigma}_\mu\nu_a)\sum_{q=u,d}[g_{LL}^{\nu_a q}\,\overline{q}\,\overline{\sigma}^\mu q + g_{LR}^{\nu_a q}(q^c\sigma^\mu\overline{q}^c)]$$

- Neutrino scattering off nuclei in EFT:

projected 95% CL constraints on the wEFT parameters

Dashed: 1% systematic error on the $R_{\nu N}$ measurements

Adam Falkowski, Giovanni Grilli di Cortona and **ZT**
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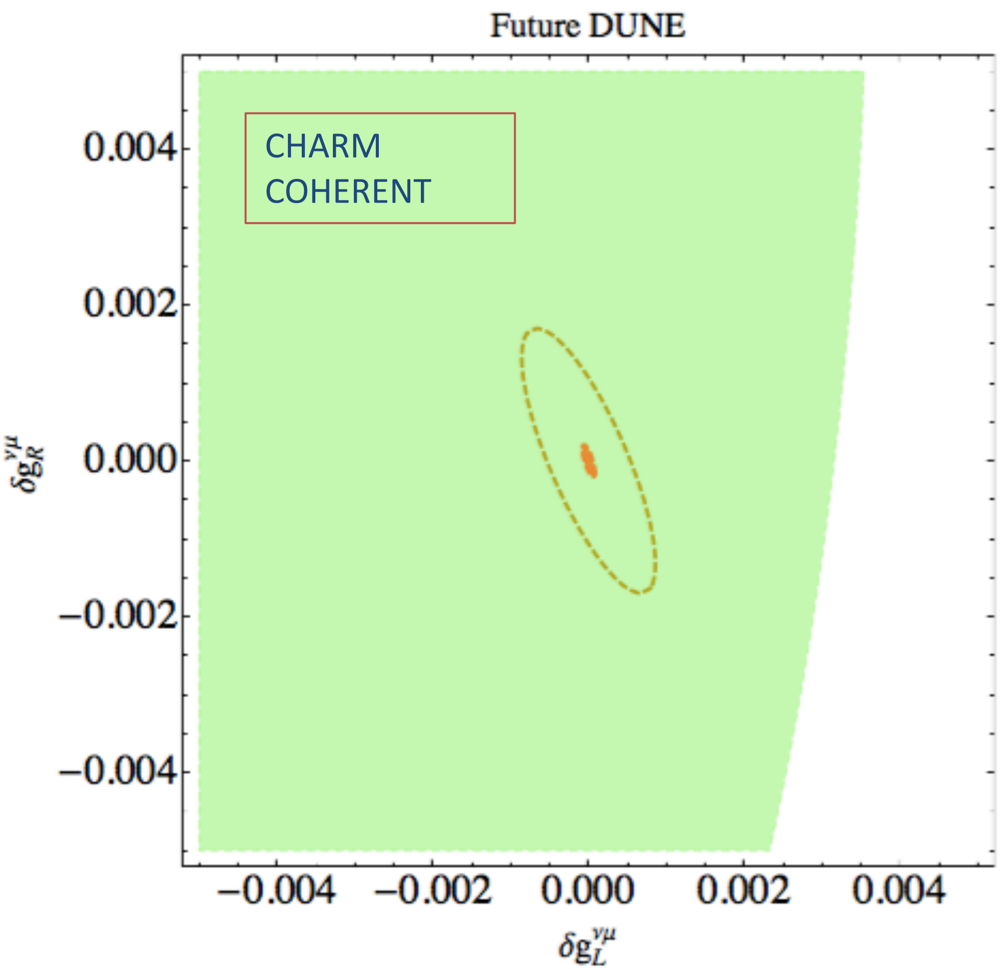


$$\mathcal{L}_{\rm wEFT} \supset -\frac{2}{v^2}(\overline{\nu}_a\overline{\sigma}_\mu\nu_b)\left[g^{abcd}_{LL}(\overline{e}_c\overline{\sigma}_\mu e_d) + g^{abcd}_{LR}(e^c_c\sigma_\mu\overline{e}^c_d)\right]$$

Trident production in EFT:

$$\frac{\sigma(\nu_b\gamma^* \to \nu_a\ell_c^-\ell_d^+)}{\sigma_{\rm SM}(\nu_b\gamma^* \to \nu_a\ell_c^-\ell_d^+)} = \frac{\sigma(\overline{\nu}_a\gamma^* \to \nu_b\ell_c^-\ell_d^+)}{\sigma_{\rm SM}(\overline{\nu}_a\gamma^* \to \nu_b\ell_c^-\ell_d^+)} \approx 1 + 2\frac{g^{abcd}_{LL,\rm SM}\delta g^{abcd}_{LL} + g^{abcd}_{LR,\rm SM}\delta g^{abcd}_{LR}}{(g^{abcd}_{LL,\rm SM})^2 + (g^{abcd}_{LR,\rm SM})^2}$$

- We define the following ratios:

$$R_e \equiv \frac{\sigma(\nu_\mu \to \nu_\mu e^- e^+) + \sigma(\overline{\nu}_\mu \to \overline{\nu}_\mu e^- e^+)}{\sigma(\nu_\mu \to \nu_\mu e^- e^+)_{\rm SM} + \sigma(\overline{\nu}_\mu \to \overline{\nu}_\mu e^- e^+)_{\rm SM}},$$
$$R_\mu \equiv \frac{\sigma(\nu_\mu \to \nu_\mu \mu^- \mu^+) + \sigma(\overline{\nu}_\mu \to \overline{\nu}_\mu \mu^- \mu^+)}{\sigma(\nu_\mu \to \nu_\mu \mu^- \mu^+)_{\rm SM} + \sigma(\overline{\nu}_\mu \to \overline{\nu}_\mu \mu^- \mu^+)_{\rm SM}}.$$

- Using DUNE we get:

$$R_e = 1 \pm 0.024, \qquad R_\mu = 1 \pm 0.039$$

$$-0.024 < 2\frac{g^{2211}_{LL,\rm SM}\delta g^{2211}_{LL} + g^{2211}_{LR,\rm SM}\delta g^{2211}_{LR}}{(g^{2211}_{LL,\rm SM})^2 + (g^{2211}_{LR,\rm SM})^2} < 0.024$$
$$-0.039 < 2\frac{g^{2222}_{LL,\rm SM}\delta g^{2222}_{LL} + g^{2222}_{LR,\rm SM}\delta g^{2222}_{LR}}{(g^{2222}_{LL,\rm SM})^2 + (g^{2222}_{LR,\rm SM})^2} < 0.039$$

Other relevant experiments:

- Parity-violating Møller scattering probes the electron's axial self-coupling

$$\frac{1}{2v^2} g_{AV}^{ee} \left[-(\overline{e}\overline{\sigma}_\mu e)(\overline{e}\overline{\sigma}_\mu e) + (e^c \sigma_\mu \overline{e}^c)(e^c \sigma_\mu \overline{e}^c) \right]$$

- The MOLLER collaboration in JLAB will significantly reduce the error by a factor of 5

$$g_{AV}^{ee} = 0.0225 \pm 0.0006$$

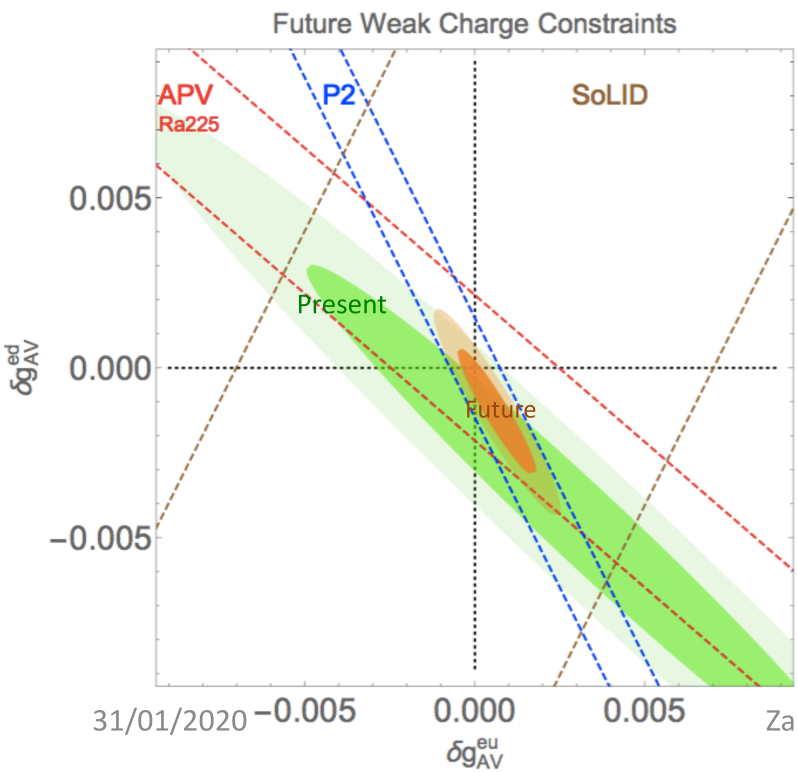
Moller collaboration, 1411.4088

Atomic Parity violation (APV):

- The effective couplings of electrons to quarks can be accessed by atomic parity violation (APV)

$$Q_W(Z,N) = -2[(2Z+N)g_{AV}^{eu} + (Z+2N)g_{AV}^{ed}] = Z(1-4s_W^2) - N$$

$$-\frac{1}{2v^2} g_{AV}^{eq} (\bar{e}\,\bar{\sigma}_\rho e - e^c \sigma_\rho \bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q + q^c \sigma^\rho \bar{q}^c)$$



Experiment	Year	$\Delta \sin^2(\theta_W)$
JLab-Qweak (final)		0.0008
JLab-SoLID	2022	0.00057
JLab-MOLLER	2020	0.00026
Mainz-P2	2018	0.0003
APV(^{225}Ra$^+$)		0.0018
APV(^{213}Ra$^+$/^{225}Ra$^+$)		0.0037
PVES (^{12}C)		0.0007

Erler, Horowitz, Mantry, Souder,
Ann. Rev. Nucl. Part. Sci. 64 (2014) 269–298

Future Now

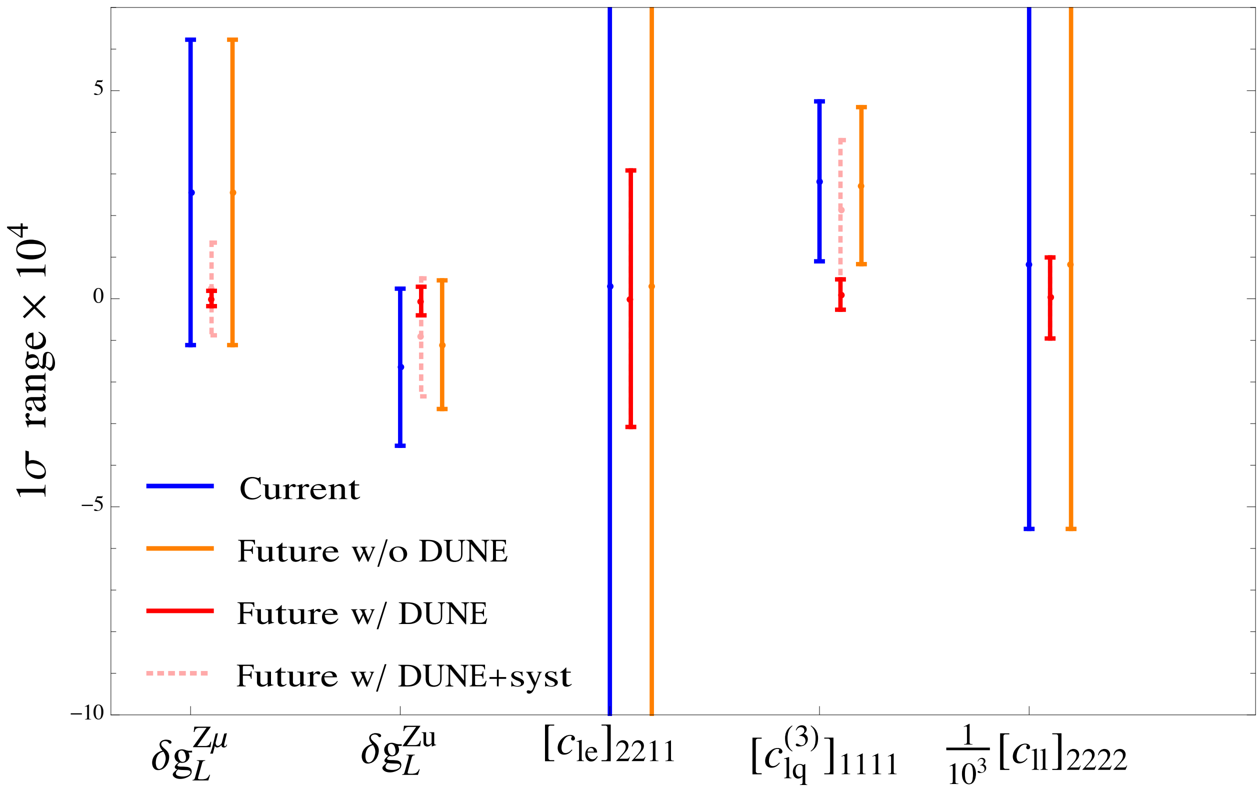
Comparing current and future results of EFT parameters

- Current:

Falkowski, González-Alonso, Mimouni
JHEP08(2017)123

- Future w/o DUNE:

Mainz P2, Qweak, SoLID, ^{225}Ra+ APV, Moller



Adam Falkowski, Giovanni Grilli di Cortona and **ZT**
JHEP **1804** (2018) 101

DUNE will potentially have a dramatic impact on constraining the SMEFT parameter space.

Future Now

1σ uncertainty Δ in units of 10^{-4} on selected SMEFT Wilson coefficient from current and future low-energy precision measurements, assuming only one Wilson coefficient at a time.

Wilson coefficient	Δ(current)	Δ (future)	Δ (future+syst.)	Δ (future w/o DUNE)
δg_L^{We}	3.5	0.37	2.5	3.5
$\delta g_L^{Z\mu}$	3.7	0.18	1.1	3.7
δg_L^{Zu}	1.9	0.34	1.4	1.5
δg_R^{Zu}	9.5	0.58	2.3	2.6
δg_L^{Zd}	1.9	0.28	1.5	1.7
δg_R^{Zd}	9.7	1.1	3.9	4.2
$\delta g_R^{Wq_1}$	2.0	0.36	1.7	2.0
$[c_{\ell\ell}]_{1122}$	28	2.6	2.6	28
$[c_{\ell e}]_{2211}$	45	3.1	3.1	45
$[c_{\ell\ell}]_{2222}$	2100	310	310	2100
$[c_{\ell e}]_{2222}$	6300	970	970	6300
$[c_{\ell q}^{(3)}]_{1111}$	1.9	0.36	1.7	1.9
$[c_{\ell q}^{(3)}]_{2211}$	12	1.8	10	12
$[c_{\ell q}]_{2211}$	210	3.0	30	210
$[c_{\ell u}]_{2211}$	190	1.2	9.5	190
$[c_{\ell d}]_{2211}$	370	2.4	19	370

- Current:

Falkowski, González-Alonso, Mimouni JHEP08(2017)123

- Future w/o DUNE: Mainz P2, Qweak, SoLID, ^{225}Ra+ APV, Moller

Equivalent Photon Approximation (EPA) is widely used in the present literature.

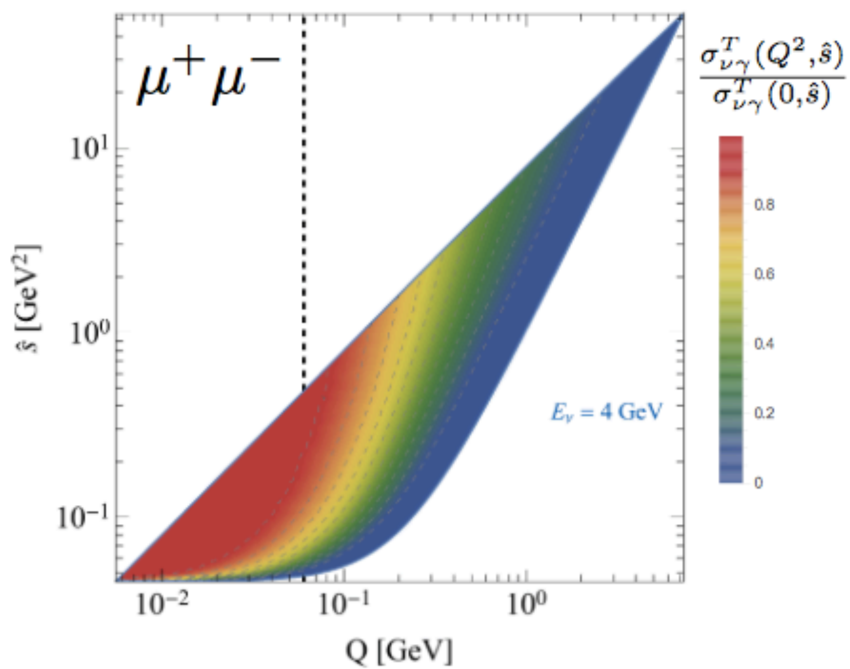
Renewed interest, especially due to NP potential.	[W. Altmannshoffer et al, 2014]
Atmospheric trident production.	[SF Ge et al, 2017]
High rates for DUNE ND and SHiP for unobserved channels.	[G. MAGILL et al, 2016]
Charged scalars influence on CC channels.	[G. MAGILL et al, 2017]

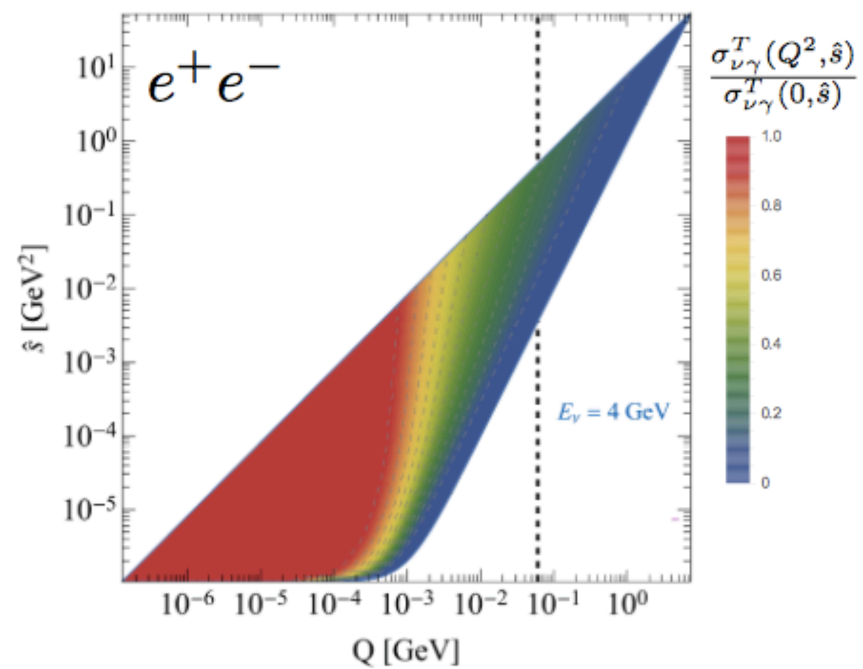
EPA: The full cross section is related to the cross section of the neutrino scattering with a real photon, multiplied by the probability of creating a virtual photon.

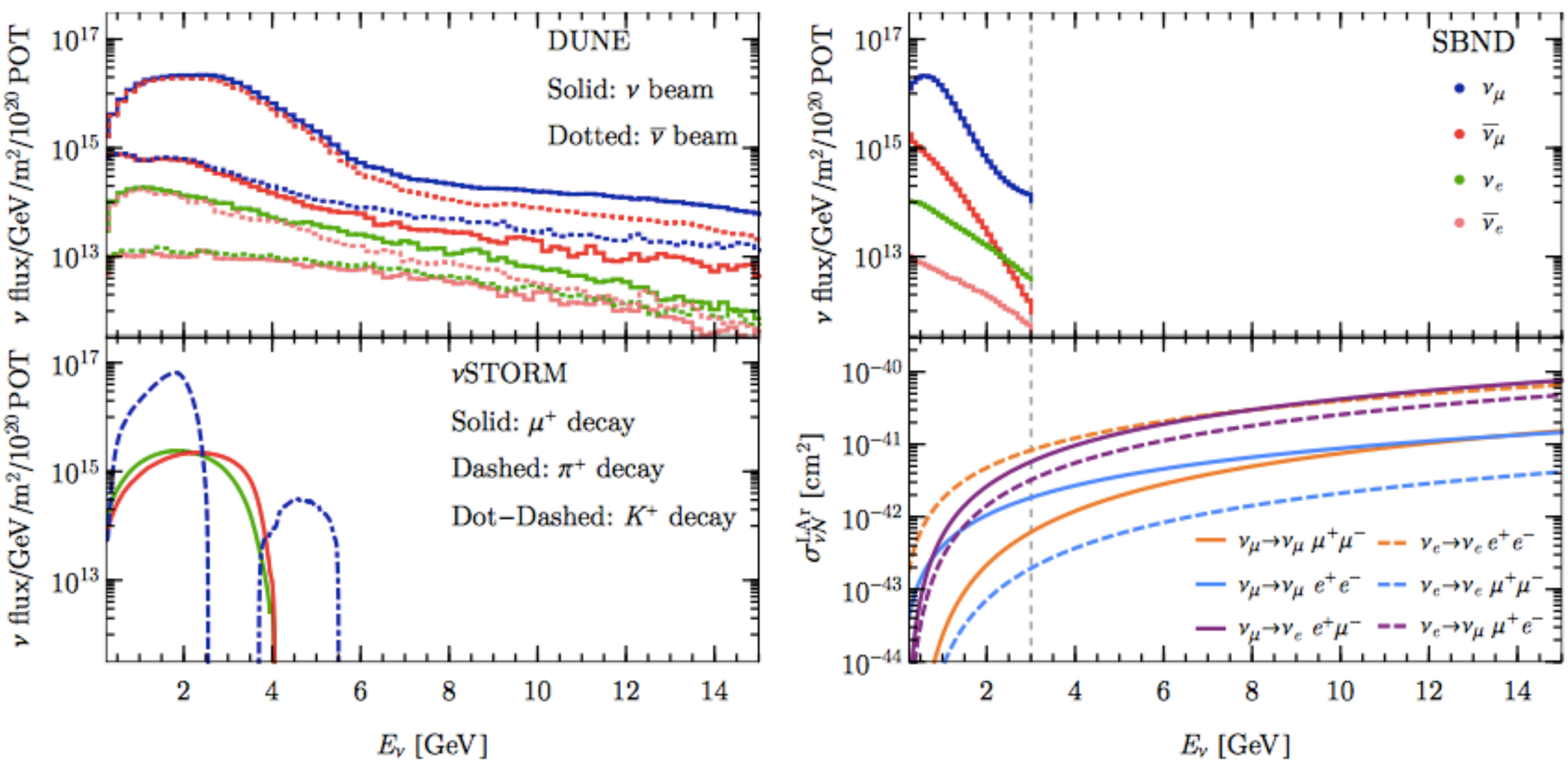
EPA assumptions

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 ($\sigma^{\mathrm{T}}_{\nu\gamma}(q^2,\hat{s}) \approx \sigma^{\mathrm{T}}_{\nu\gamma}(0,\hat{s})$).







DUNE
Solid: ν beam
Dotted: ν̄ beam
νSTORM
Solid: μ⁺ decay
Dashed: π⁺ decay
Dot−Dashed: K⁺ decay
SBND
ν flux/GeV/m²/10²⁰ POT
$\sigma_{\nu N}^{\rm LAr}$ [cm²]
E_ν [GeV]
$\nu_\mu \to \nu_\mu\ \mu^+\mu^-$
$\nu_\mu \to \nu_\mu\ e^+e^-$
$\nu_\mu \to \nu_e\ e^+\mu^-$
$\nu_e \to \nu_e\ e^+e^-$
$\nu_e \to \nu_e\ \mu^+\mu^-$
$\nu_e \to \nu_\mu\ \mu^+e^-$