Atmospheric ν Trident Production & Neutrino Collider

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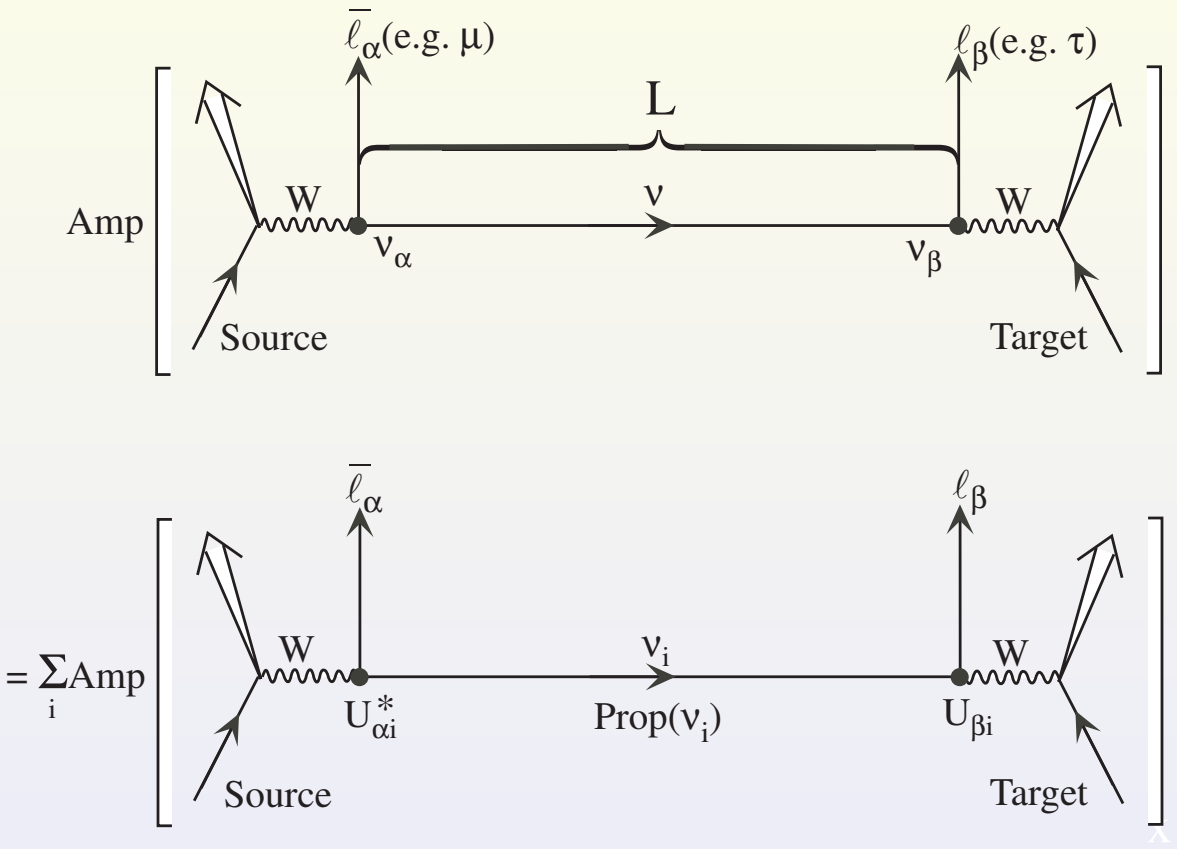
2018-2-13

SFG, Manfred Lindner, Werner Rodejohann, PLB **772** (2017) 164-168 [arXiv:1702.02617]
SFG, Duane A. Dicus, Wayne W. Repko, PLB **702**, 220 (2011) [arXiv:1104.0602]
SFG, Duane A. Dicus, Wayne W. Repko, PRL **108**, 041801 (2012) [arXiv:1108.0964]
Andrew D. Hanlon, **SFG**, Wayne W. Repko, PLB **729**, 185-191 (2014) [arXiv:1308.6522]
SFG [arXiv:1406.1985]

ν Oscillation



[Kayser, hep-ph/0506165]

$$\nu_\alpha = \sum_i V_{\alpha i}\nu_i \to \boxed{\sum_i V_{\alpha i} e^{i(E_i t - \vec{P}_i\cdot\vec{x})}\nu_i} = \boxed{\sum_i V_{\alpha i} e^{i\Phi_i} V^\dagger_{i\beta}\nu_\beta} \equiv \sum_\beta A_{\alpha\beta}\nu_\beta$$

ν Mass & Mixing

- **Mass & Mixing $\Rightarrow$ Oscillation:**

$$\nu_\alpha(t,L) = \sum_{i\beta} V_{\alpha i} e^{-i(E_i t - p_i L)} V^*_{\beta i} \nu_\beta \equiv \sum_\beta A_{\alpha\beta}\nu_\beta$$

$$P_{\alpha\beta}|_{\alpha\neq\beta} \equiv |A_{\alpha\beta}|^2 = \sin^2 2\theta \sin^2\left(\delta m^2 \frac{L}{4E}\right)$$

- **Flavor v.s. Mass** Eigenstates:

$$\nu_\alpha = \sum_i V_{\alpha i}\, \nu_i$$

$$V = \begin{pmatrix} c_s c_r & s_s c_r & s_r e^{-i\delta_D} \\ -s_s c_a - c_s s_a s_r e^{i\delta_D} & +c_s c_a - s_s s_a s_r e^{i\delta_D} & s_a c_r \\ +s_s s_a - c_s c_a s_r e^{i\delta_D} & -c_s s_a - s_s c_a s_r e^{i\delta_D} & c_a c_r \end{pmatrix}$$

[$(s,a,r) \equiv (12,23,13)$ for (**solar, atmospheric, reactor**) angles]

ν Oscillation Data

(for NH)	-1σ	Best Value	$+1\sigma$
$\Delta m^2_s \equiv \Delta m^2_{12}\,(10^{-5}\mathrm{eV}^2)$	7.37	**7.56**	7.75
$\lvert\Delta m^2_a \equiv \Delta m^2_{13}\rvert\ (10^{-3}\mathrm{eV}^2)$	2.51	**2.55**	2.59
$\sin^2\theta_s\ (\theta_s \equiv \theta_{12})$	0.305 (33.5°)	0.321 (**34.5°**)	0.339 (35.6°)
$\sin^2\theta_a\ (\theta_a \equiv \theta_{23})$	0.412 (39.9°)	0.430 (**41.0°**)	0.450 (42.1°)
$\sin^2\theta_r\ (\theta_r \equiv \theta_{13})$	0.02080 (8.29°)	0.02155 (**8.44°**)	0.02245 (8.62°)
δ_D		$\sim -90^\circ$	
δ_{Mi}	??	??	??

Salas, Forero, Ternes, Tortola & Valle, arXiv:1708.01186

Full v.s. Residual

[Lam, PRL**101**:121602(2008), PRD**78**:073015(2008)]

- **Full Symmetries:**

$\mathcal{H} \equiv \mathcal{G} \times \mathcal{F}$	$\mathcal{G}$	$\mathcal{F}$
S_4	$\mathbb{Z}_2^s \times \mathbb{Z}_2^{\mu\tau}$	$\mathbb{Z}_3 \equiv \{I, F, F^2\}$
$\{G_1, G_3, F\}$	$G_1(G_2), G_3$	$F \equiv \text{diag}\,(1, \omega, \omega^2)$

Bottom-Up $\Uparrow$ $\Downarrow$ **Top-Down**

See also Smirnov et. al., 1204.0445, 1212.2149, 1510.00344

- **Residual Symmetries:** $\mathbf{G_i = V d_i V^\dagger}$

$\nu_\mathbf{i}$: $\mathcal{G} \equiv \mathbb{Z}_2^s(\overline{\mathbb{Z}}_2^s) \times \mathbb{Z}_2^{\mu\tau}$ for $d_\nu^i = \text{diag}\,(\pm 1, \pm 1, \pm 1)$

$\ell_\mathbf{i}$: $\mathcal{F} \in U(1) \times U(1)$ for $d_\ell^i = \text{diag}\,(e^{i\beta_1}, e^{i\beta_2}, e^{i\beta_3})$

Partial Residual Symmetry $\mathbb{Z}_2^s$ or $\overline{\mathbb{Z}}_2^s$

- Although $\mathbb{Z}_2^{\mu\tau}$, represented by $\mathbf{G_3}$, is Broken!
- **No particular reason** for $\mathbb{Z}_2^s$ or $\overline{\mathbb{Z}}_2^s$ to be Broken!

$$\mathbb{Z}_2^s \quad : \quad \mathbf{G_1}(\mathbf{k}) = \frac{1}{2+k^2}\begin{pmatrix} 2-k^2 & 2k & 2k \\ & k^2 & -2 \\ & & k^2 \end{pmatrix},$$

$$\overline{\mathbb{Z}}_2^s \quad : \quad \mathbf{G_2}(\mathbf{k}) = \frac{1}{2+k^2}\begin{pmatrix} 2-k^2 & 2k & 2k \\ & -2 & k^2 \\ & & -2 \end{pmatrix}.$$

- $\mathbb{Z}_2^s$ & $\overline{\mathbb{Z}}_2^s$ are **Dependent**

$$\mathbf{G_1}(\mathbf{k}) = \mathbf{G_2}(\mathbf{k})\mathbf{G_3}$$

- **DIFFERENT Consequences!!!**

Correlation between Physical Observables

$$\mathbf{G}_\nu = \mathbf{V}_\nu \mathbf{d}_\nu \mathbf{V}_\nu^\dagger$$

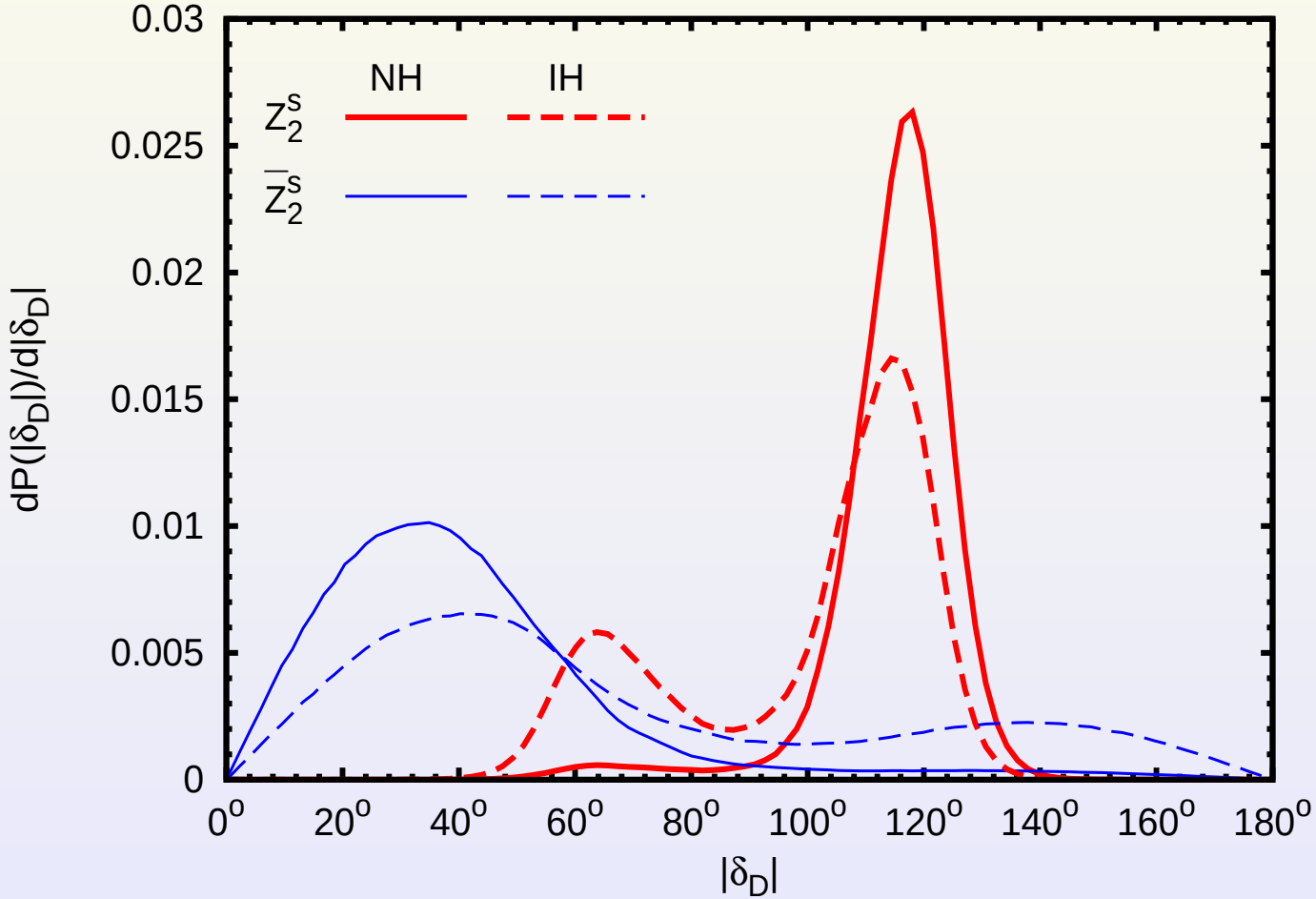
$\mathbb{Z}_2^{\mathbf{s}}$ (G_1)	$\overline{\mathbb{Z}}_2^{\mathbf{s}}$ (G_2)
$\cos\delta_{\mathbf{D}} = \dfrac{(s_s^2 - c_s^2 s_r^2)(\mathbf{c}_\mathbf{a}^2 - \mathbf{s}_\mathbf{a}^2)}{4 c_a s_a c_s s_s \mathbf{s}_\mathbf{r}}$	$\cos\delta_{\mathbf{D}} = \dfrac{(s_s^2 s_r^2 - c_s^2)(\mathbf{c}_\mathbf{a}^2 - \mathbf{s}_\mathbf{a}^2)}{4 c_a s_a c_s s_s \mathbf{s}_\mathbf{r}}$

$$\sin\theta_\mathbf{r} = \pm\left[\pm\sqrt{\mathbf{c}_\mathbf{D}^2 + \cot^2 2\theta_a} - \mathbf{c}_\mathbf{D}\right]\tan 2\theta_\mathbf{a}(\tan\theta_s)^{\pm 1}$$

$$\frac{\delta_\mathbf{r}}{\delta_\mathbf{a}} = -\frac{\tan\theta_s}{\cos\delta_\mathbf{D}} \qquad \frac{\delta_\mathbf{r}}{\delta_\mathbf{a}} = +\frac{\cot\theta_s}{\cos\delta_\mathbf{D}}$$

Prediction of Large δ_D from Residual $\mathbb{Z}_2^s/\overline{\mathbb{Z}}_2^s$

$$\cos\delta_D = \frac{(s_s^2 - c_s^2 s_r^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r} \qquad \cos\delta_D = \frac{(s_s^2 s_r^2 - c_s^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r}$$



SFG, Dicus, Repko, Hanlon: 1012.2571, 1104.0602, 1108.0964, 1308.6522

Residual Symmetry as Effective Theory

- **Full flavor symmetry HAS TO** be **Broken!**
  - Fermion needs to acquire mass.
  - Non-trivial mixing $\boxed{V_{\rm PMNS} = V_\ell^\dagger V_\nu}$ for $V_\nu \neq V_\ell$
- If mixing is **TRUELY determined by symmetry**, it has to be **residual symmetry**
  - VEVs
  - Yukawa couplings
- **Residual Symmetry** as **Custodial Symmetry**
  - **Gauge symmetry has to be broken**. Otherwise, no mixing.
  - **Weak mixing angle** is a function of gauge couplings, which **cannot be dictated by gauge symmetry** (and VEV).
  - **Weak mixing angle is related to** the physical observables, the **gauge boson masses**, by **custodial symmetry**.

Example Zee-A_4 Model

hep-ph/0508278

- **Lepton's Representation:**

$$\begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} \sim \mathbf{3}\,, \quad \begin{matrix} e_R \sim \mathbf{1} \\ \mu_R \sim \mathbf{1}'\,, \\ \tau_R \sim \mathbf{1}'' \end{matrix} \quad \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \end{pmatrix} \sim \mathbf{3}\,.$$

- A_4 **invariant Lagrangian:**

$$\begin{aligned} \mathcal{L}_\ell &= \mathbf{y_1}\overline{e}_R(\mathbf{1}\varphi_1^\dagger e_L + \mathbf{1}\varphi_2^\dagger \mu_L + \mathbf{1}\varphi_3^\dagger \tau_L) \\ &+ \mathbf{y_2}\overline{\mu}_R(\boldsymbol{\omega}\varphi_1^\dagger e_L + \mathbf{1}\varphi_2^\dagger \mu_L + \boldsymbol{\omega}^2\varphi_3^\dagger \tau_L) \\ &+ \mathbf{y_3}\overline{\tau}_R(\boldsymbol{\omega}^2\varphi_1^\dagger e_L + \mathbf{1}\varphi_2^\dagger \mu_L + \boldsymbol{\omega}\varphi_3^\dagger \tau_L)\,. \end{aligned}$$

- **Mass term** with $\langle \varphi_i \rangle = v_i$:

$$\mathcal{L}_\ell = \begin{pmatrix} \overline{e}_R & \overline{\mu}_R & \overline{\tau}_R \end{pmatrix} \begin{pmatrix} \mathbf{y_1} & & \\ & \mathbf{y_2} & \\ & & \mathbf{y_3} \end{pmatrix} \underbrace{\begin{pmatrix} \mathbf{1} & \mathbf{1} & \mathbf{1} \\ \boldsymbol{\omega} & \mathbf{1} & \boldsymbol{\omega}^2 \\ \boldsymbol{\omega}^2 & \mathbf{1} & \boldsymbol{\omega} \end{pmatrix}}_{\mathbf{U_{\ell,L}}(\boldsymbol{\omega})} \begin{pmatrix} \mathbf{v_1} & & \\ & \mathbf{v_2} & \\ & & \mathbf{v_3} \end{pmatrix} \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix}\,.$$

$$\mathbf{v_1} = \mathbf{v_2} = \mathbf{v_3} = \mathbf{v} \Rightarrow U_{\ell,R} = I,\ \mathbf{U_{\ell,L}}(\boldsymbol{\omega}),\ m_{\ell,i} = \mathbf{y_i v}.$$

$$\mathbf{y_1} = \mathbf{y_2} = \mathbf{y_3} = \mathbf{y} \Rightarrow U_{\ell,L} = I,\ \mathbf{U_{\ell,R}}(\boldsymbol{\omega}),\ m_{\ell,i} = \mathbf{y v_i}.$$

The Underlying Picture of Neutrino Mixing?

- **Neutrino Mass Itself is Effective Theory!**

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{ij} \frac{y_{ij} \sim \mathcal{O}(1)}{\Lambda \sim 10^{14}\mathrm{GeV}} (\overline{L}_i \tilde{H})(\tilde{H}^\dagger L_j)$$

- **What is the Underlying Picture?**
  - Full flavor symmetry has to be broken
  - Residual flavor symmetry
    - Not always testable
    - Sometimes no residual symmetry at all
  - How neutrinos obtain mass
  - The neutrino interactions
  - $\cdots$

Non-Standard Interaction

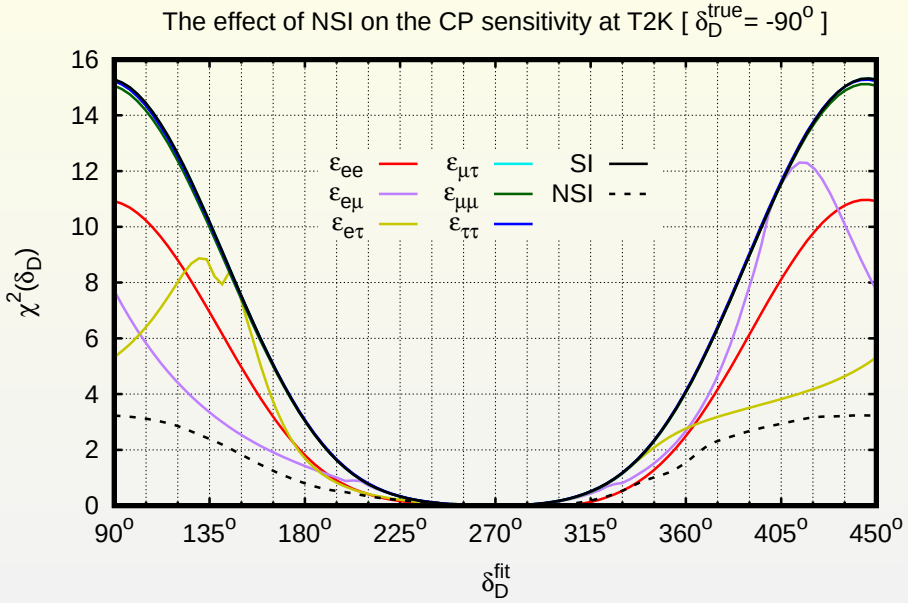
SFG & Smirnov [arXiv:1607.08513]

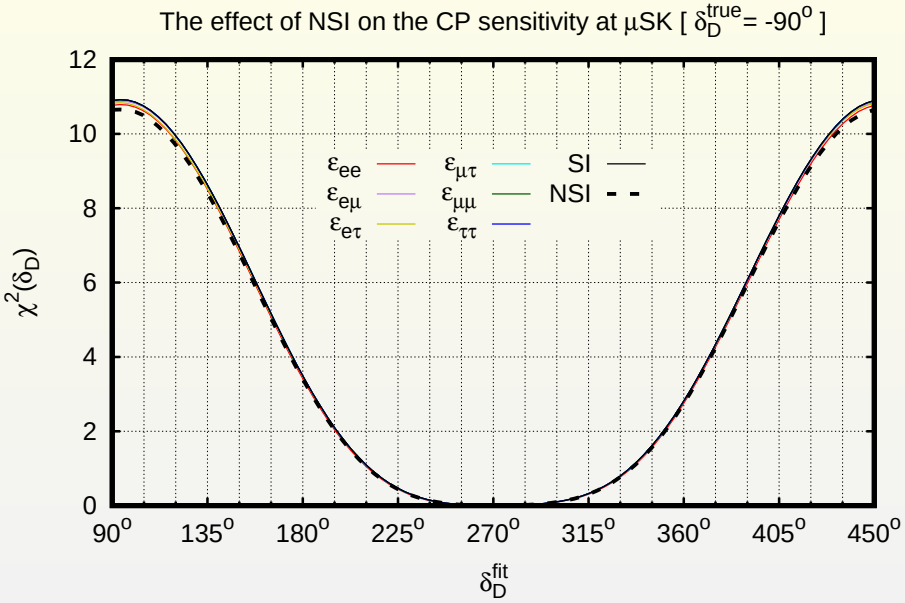
$$\mathcal{H} \equiv \frac{1}{2\mathbf{E}_\nu}\left\{ U_\nu \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U_\nu^\dagger + 2\mathbf{E}_\nu V_{cc} \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \right\}$$

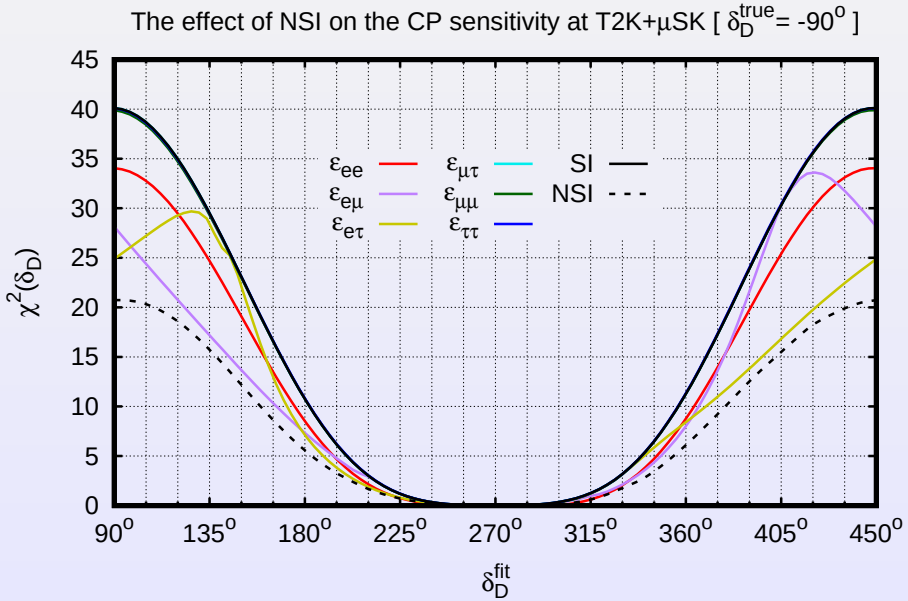
- Standard Interaction – V_{cc} (also V_{nc})
- Non-Standard Interaction – $\epsilon_{\alpha\beta}$
  - Diagonal $\epsilon_{\alpha\alpha}$ are real
  - Off-diagonal $\epsilon_{\alpha\neq\beta}$ are complex
  - Both can fake CP
- Z' in LMA-Dark model with $L_\mu - L_\tau$ gauged as $U(1)$
  - $M_{Z'} \sim \mathcal{O}(10)$MeV
  - $g_{Z'} \sim 10^{-5}$

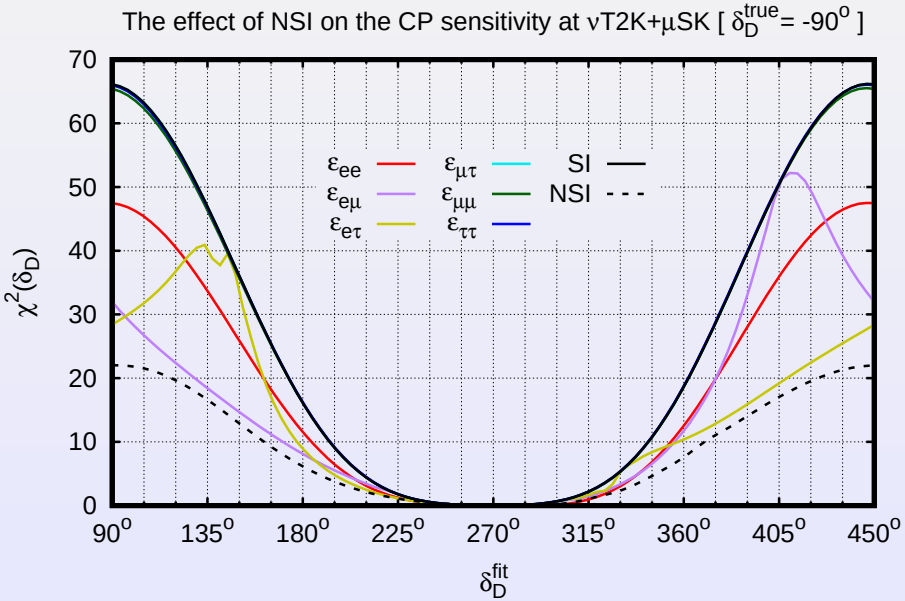
CP Sensitivity at T2K & μSK

SFG & Smirnov [arXiv:1607.08513]







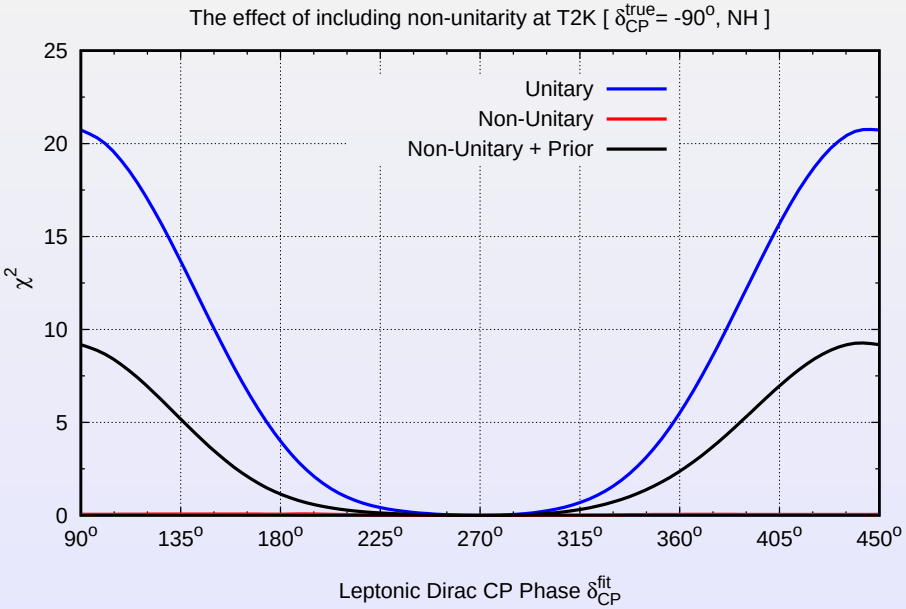


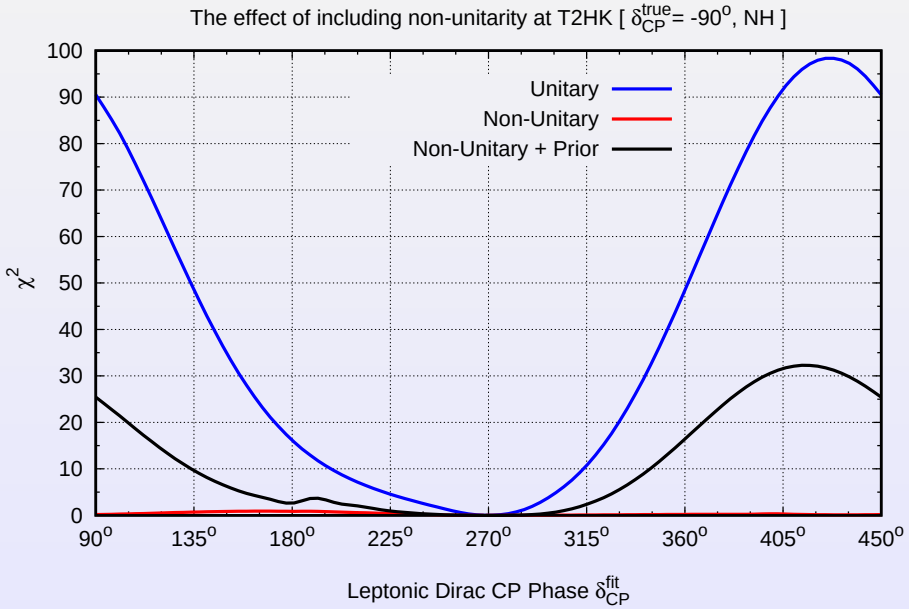
Non-Unitarity Mixing (NUM)

Ge, Pasquini, Tortola & Valle [1605.01670]

$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U \,.$$

$$P^{NP}_{\mu e} = \alpha_{11}^2 \left\{ \alpha_{22}^2 \left[c_a^2 |S'_{12}|^2 + s_a^2 |S'_{13}|^2 + 2 c_a s_a (\cos\delta_D \mathbb{R} - \sin\delta_D \mathbb{I})(S'_{12} S'^*_{13}) \right] + |\alpha_{21}|^2 P_{ee} \right.$$
$$\left. + 2\alpha_{22} |\alpha_{21}| \left[c_a \left(c_\phi \mathbb{R} - s_\phi \mathbb{I} \right) \left(S'_{11} S'^*_{12} \right) + s_a \left(c_{\phi+\delta_D} \mathbb{R} - s_{\phi+\delta_D} \mathbb{I} \right) \left(S'_{11} S'^*_{13} \right) \right] \right\} \,.$$

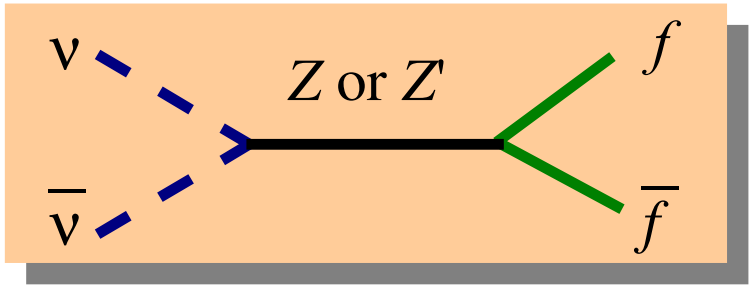




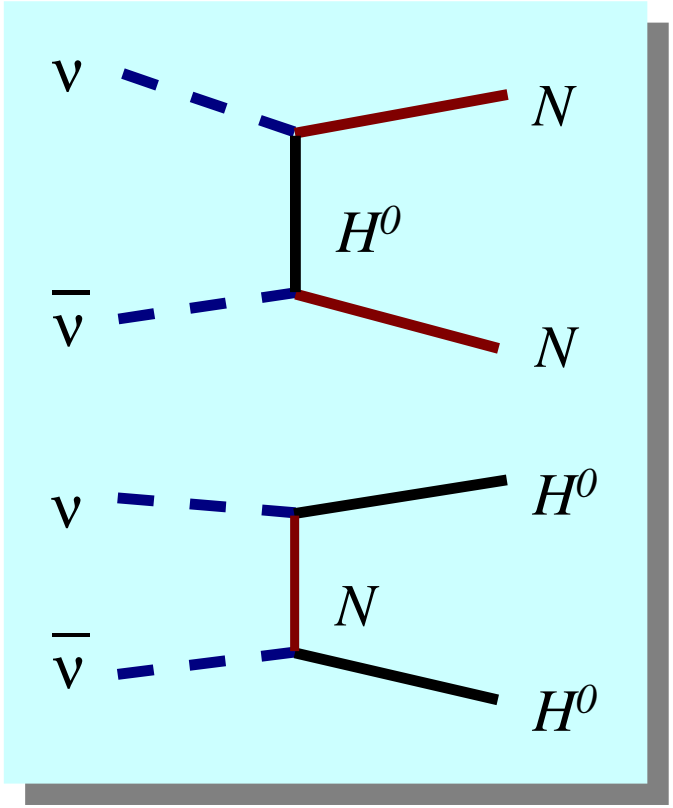
Neutrino Collider?

Neutrino-neutrino collisions

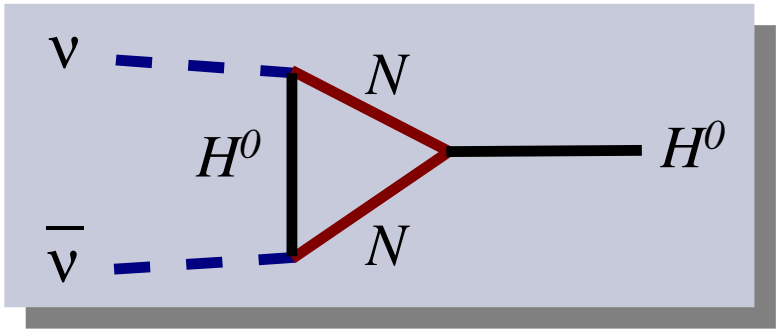
- SM: Z-boson production
- New heavy boson Z'



- Pair-production of right-handed heavy neutrinos N
  - or neutrino-Higgs H^0

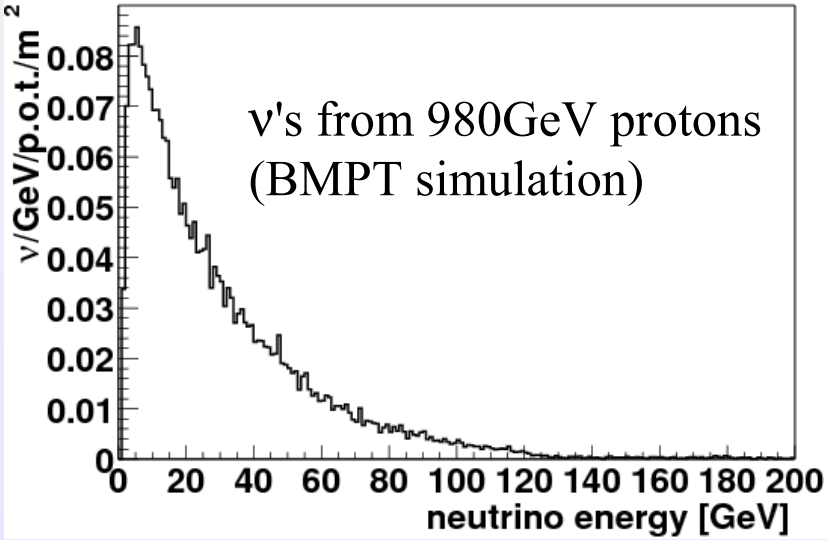


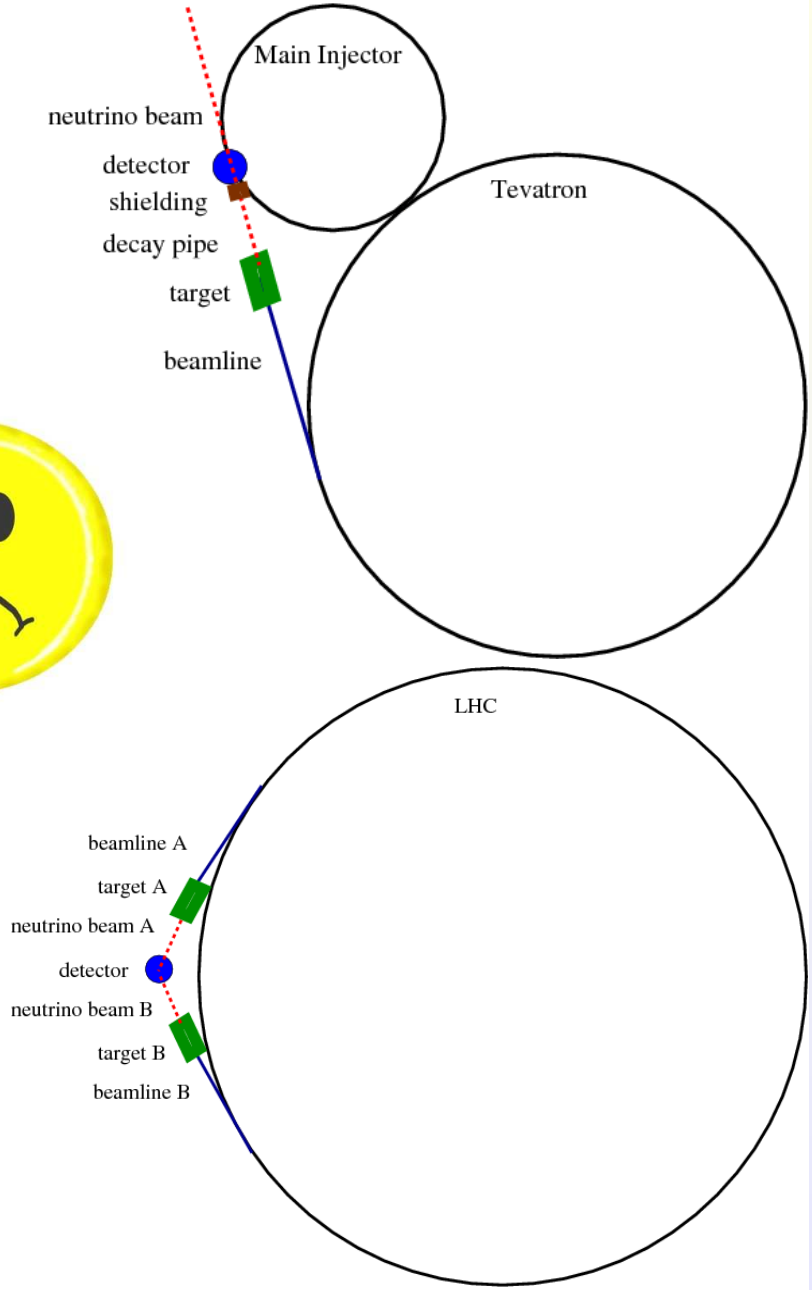
- Neutrino-Higgs production via Majorana neutrinos



Neutrino colliders based on proton machines

- Assume Project X proton intensity
- Protons from Tevatron or LHC incident on production target
  - Tevatron: Neutrino-proton luminosity of 0.02 nb^{-1} per year
    - Need factor ~100 more to get few SM events per year
  - LHC: Neutrino-neutrino luminosity of 20 μb-1 per year
    - Need factor ~100 more to ge few SM *Z*'s per year



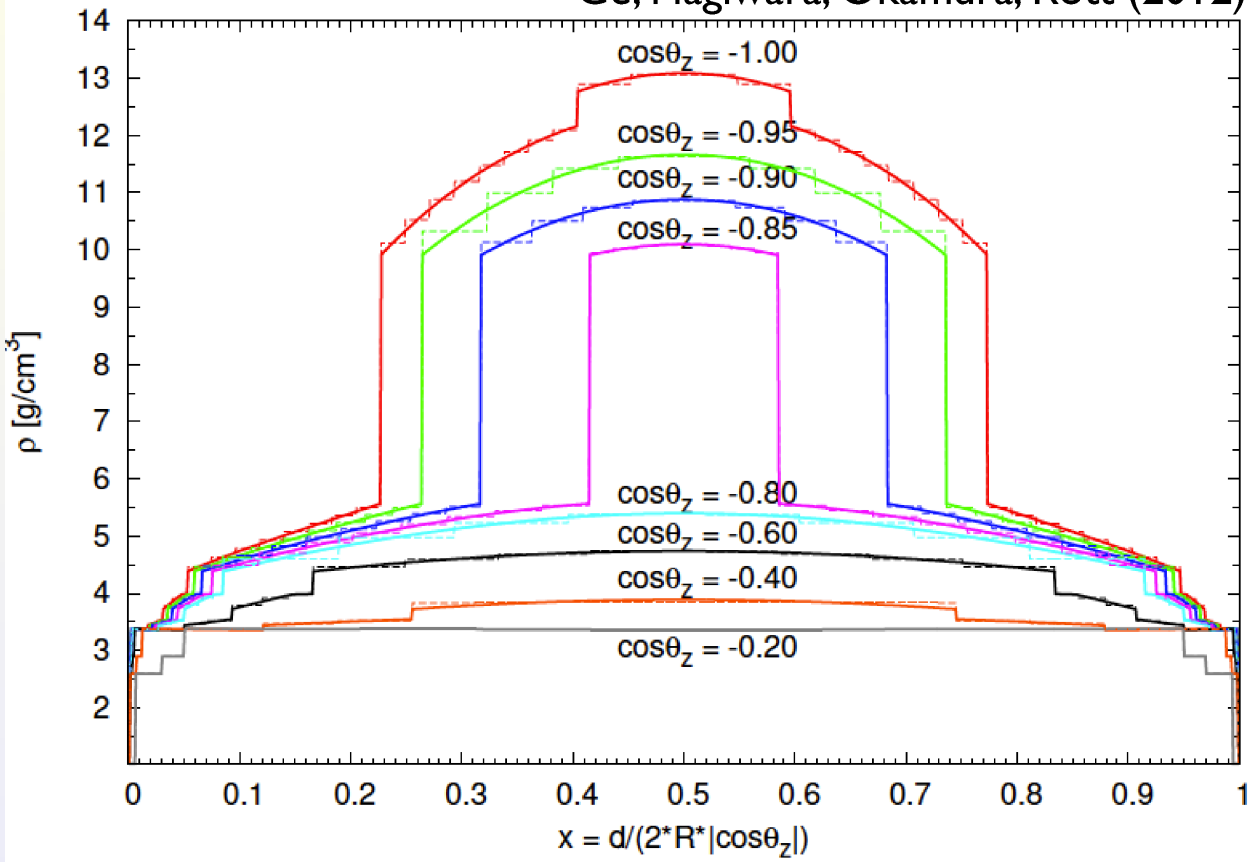


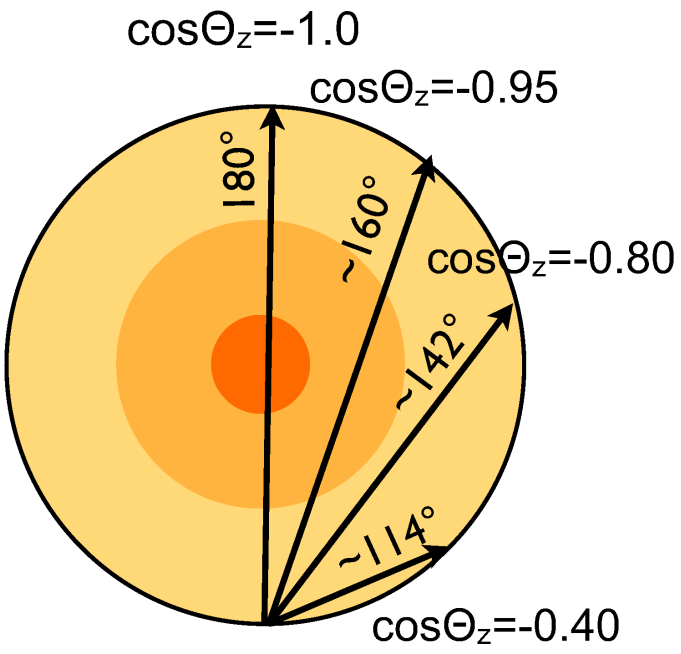
Atmospheric Neutrino Trident Production

SFG, Manfred Lindner, Werner Rodejohann, Phys.Lett. **B772** (2017) 164-168 [arXiv:1702.02617]

PREM

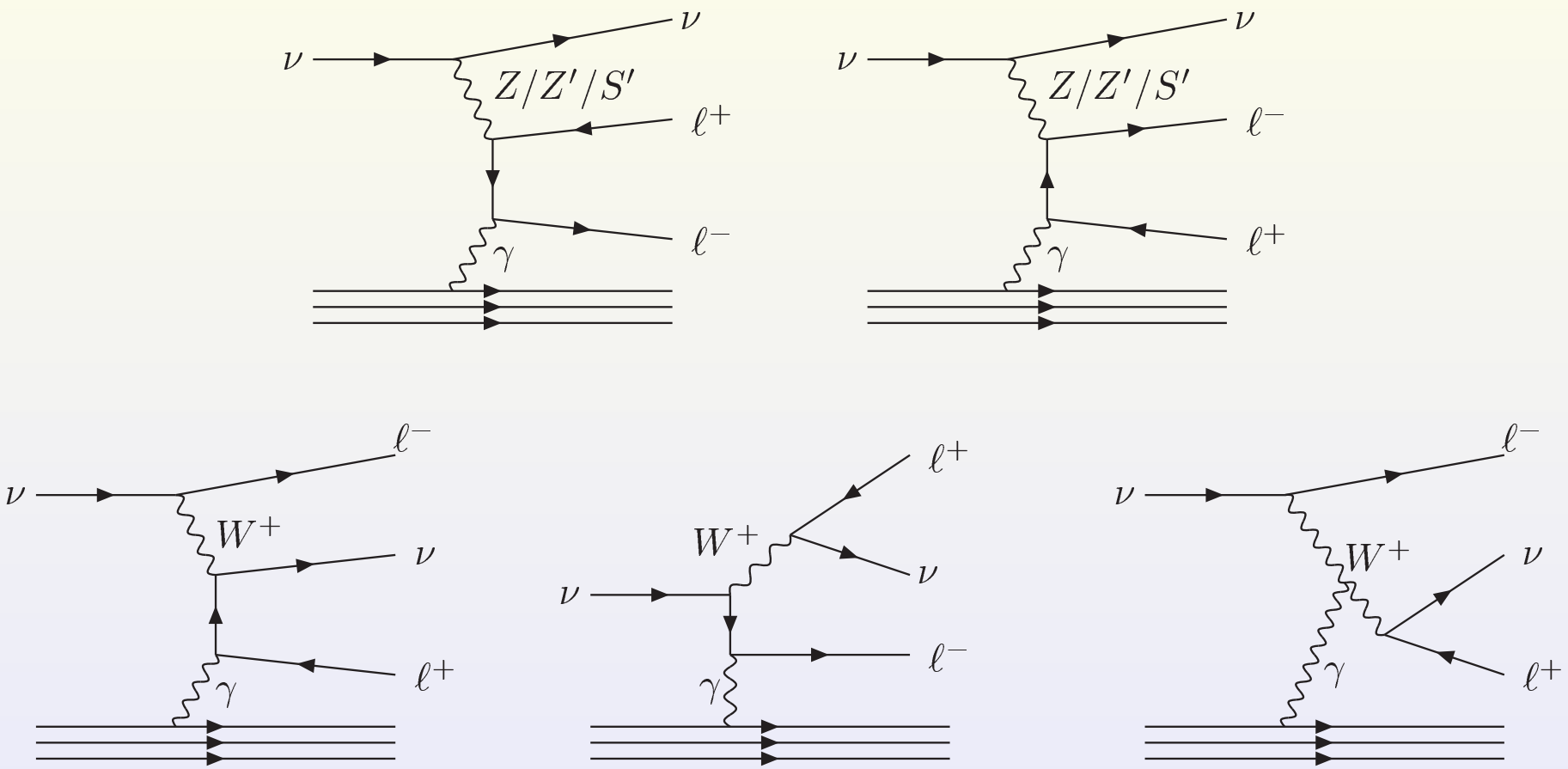
Ge, Hagiwara, Okamura, Rott (2012)





- The PREM - Preliminary Reference Earth Model is based on a paper by Dziewonski and Anderson in 1981. It still still represents the standard framework for interpretation of seismological data

Neutrino Trident Production

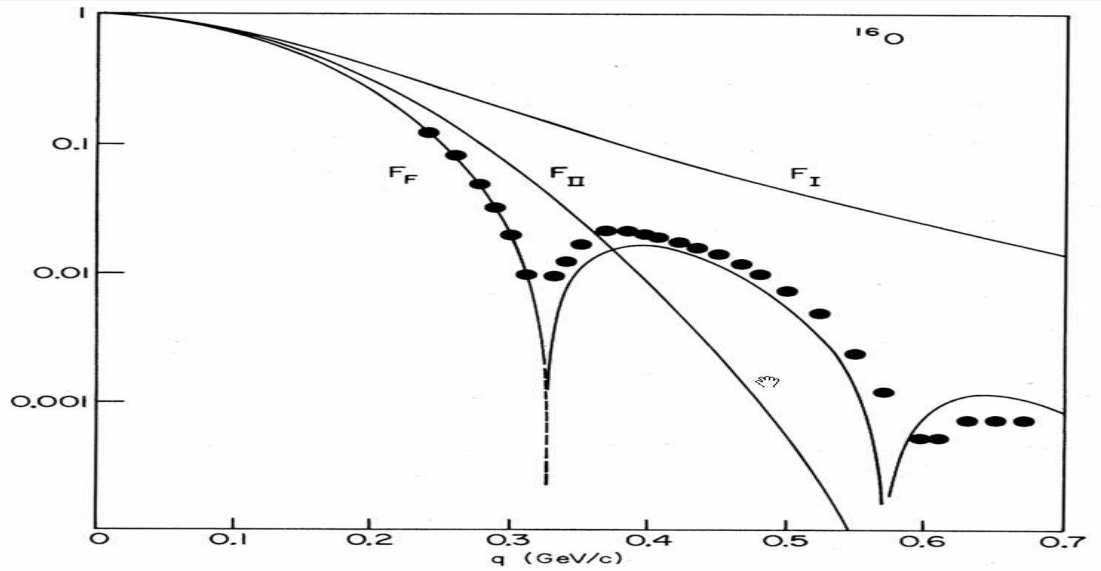


- Produce particles ($\mathbf{Z}/\mathbf{Z}'/\mathbf{S}'$) in t channel.

Suppressed Momentum Transfer

- Coherent Region (EPA): $Q < R_A^{-1} \sim A^{-\frac{1}{3}}\,\mathrm{fm}^{-1}$

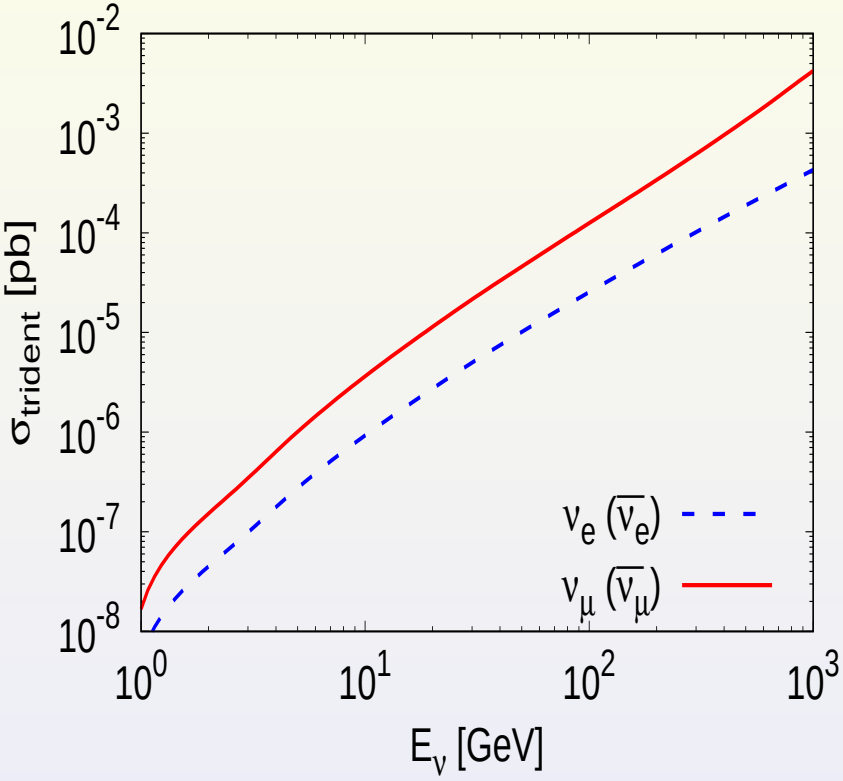
$$\sigma(\nu N \to \nu \ell^+ \ell^-) = \int \sigma(\nu \gamma \to \nu \ell^+ \ell^-) \frac{Z^2 \alpha}{\pi} \frac{ds}{s} \frac{dq^2}{q^2} F^2(q^2)\,.$$

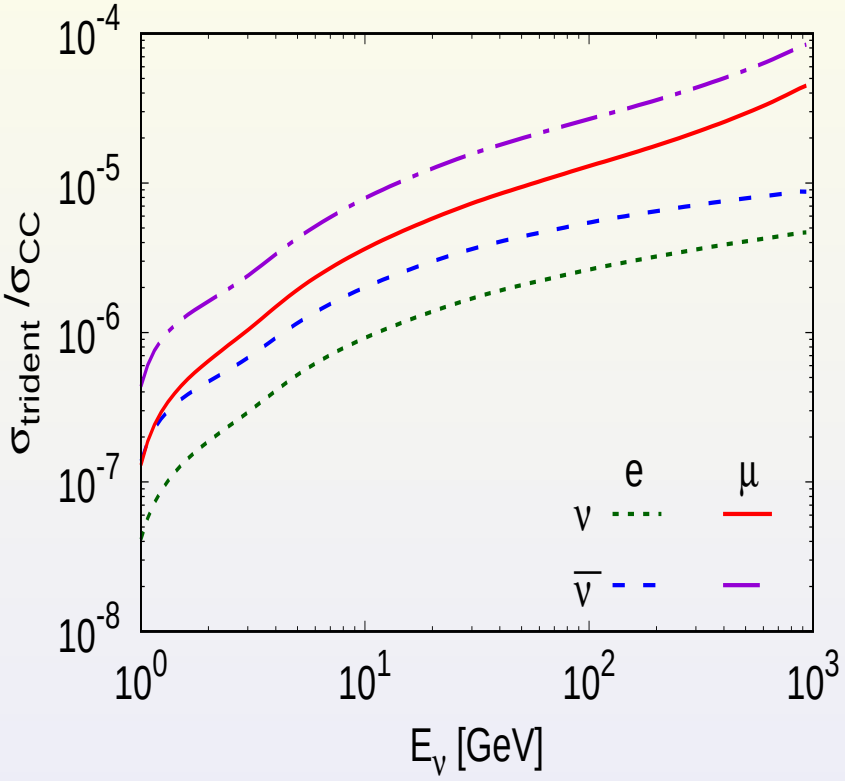


- Diffractive Region: $R_A^{-1} < Q < 1\mathrm{GeV}$

$$\sigma(\nu N \to \nu \ell^+ \ell^-) = \int \sigma(\nu \gamma \to \nu \ell^+ \ell^-) \frac{Z \alpha}{\pi} \frac{ds}{s} \frac{dq^2}{q^2} F_{dip}^2(q^2)\,.$$

Neutrino Trident Production

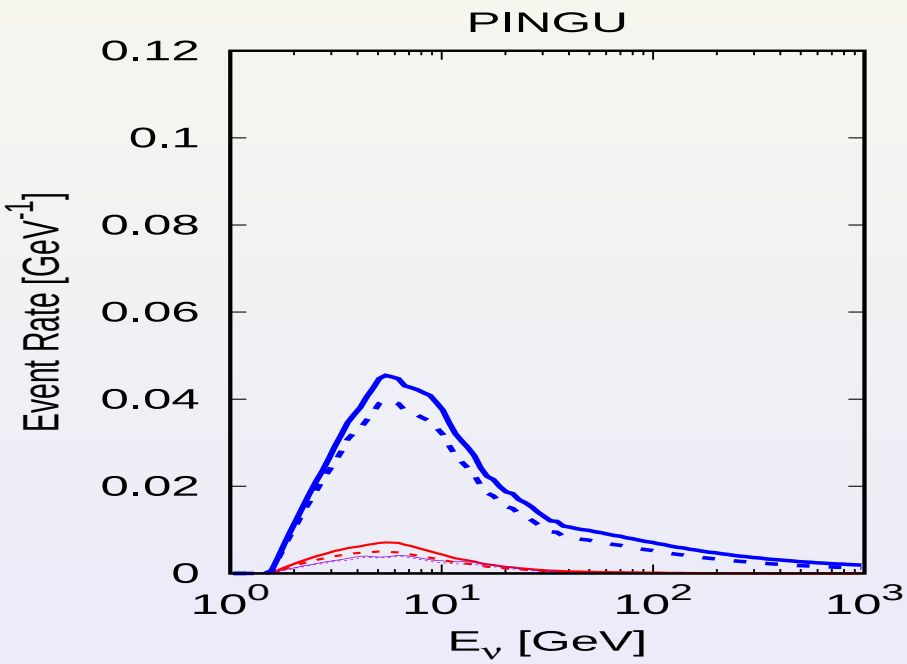


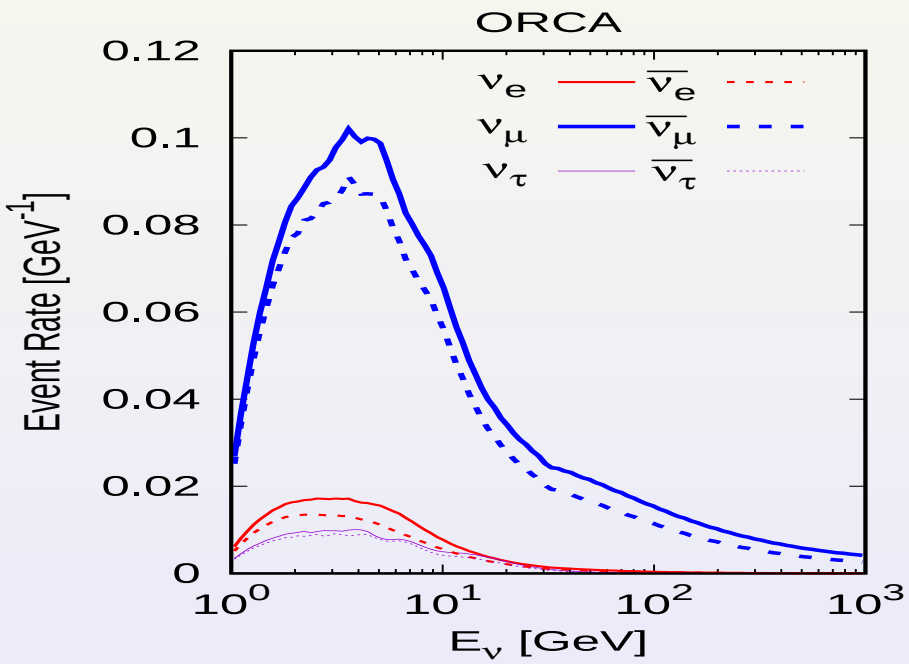


- Typically $\sigma_{\rm trident} \sim (10^{-6} \sim 10^{-5})\sigma_{\rm CC}$.
- To collect a handful of events, at least 10^6 CC events.
- **ARCA+ORCA** & **IceCube+DeepCore+PINGU** are perfect candidate experiments.

Trident Production Event @ PINGU/ORCA

- $\nu + N \to \mu^+\mu^-\nu' N^*$
- **Double muon tracks simultaneously produced at the same vertex!**





- **South Pole** (PINGU+DeepCore+IceCube) - **87** events
- **Mediterranean** (ORCA+ARCA) - **39** events

Backgrounds to Trident Production

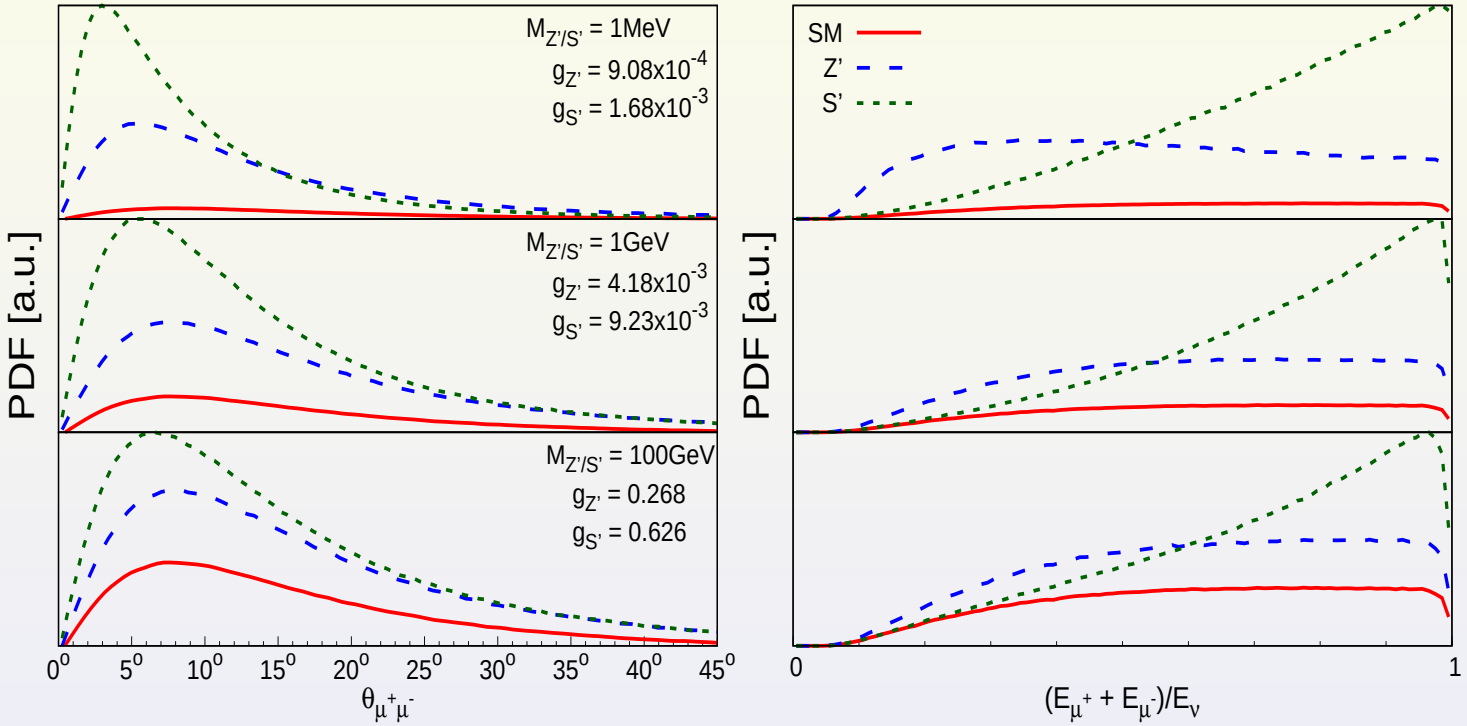
- **Coincident Double CC muons**
  - Using only **time-window cut**
    - $N_{CC} \sim 10^5$ per year ($T = 3 \times 10^7 s$)
    - Rate of coincidence within time-window Δt

$$C_{N_{CC}}^2 (\Delta t / T)^2 \lesssim 1 \quad \Rightarrow \quad \Delta t \approx \frac{\sqrt{2}T}{N_{CC}} \approx 500s\,.$$

    - Large enough to cut off all coincident background!
  - **Vertex cut**

- **High-p_T pion**
  - $\nu + N \to \ell + \pi^\pm + X \to \ell + \mu^\pm + X'$
  - The muon from pion decay tends to be soft.
  - Momentum transfer to N is highly suppressed in trident production.
  - Much cleaner hadronic shower in trident event.

Event Reconstruction

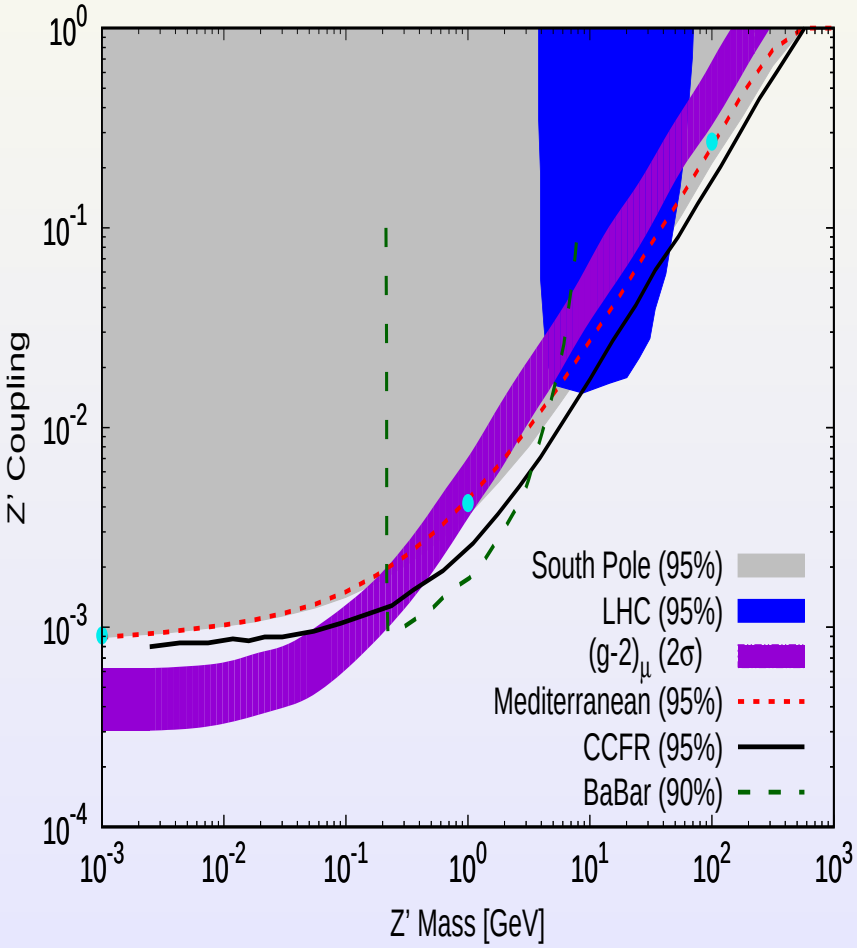


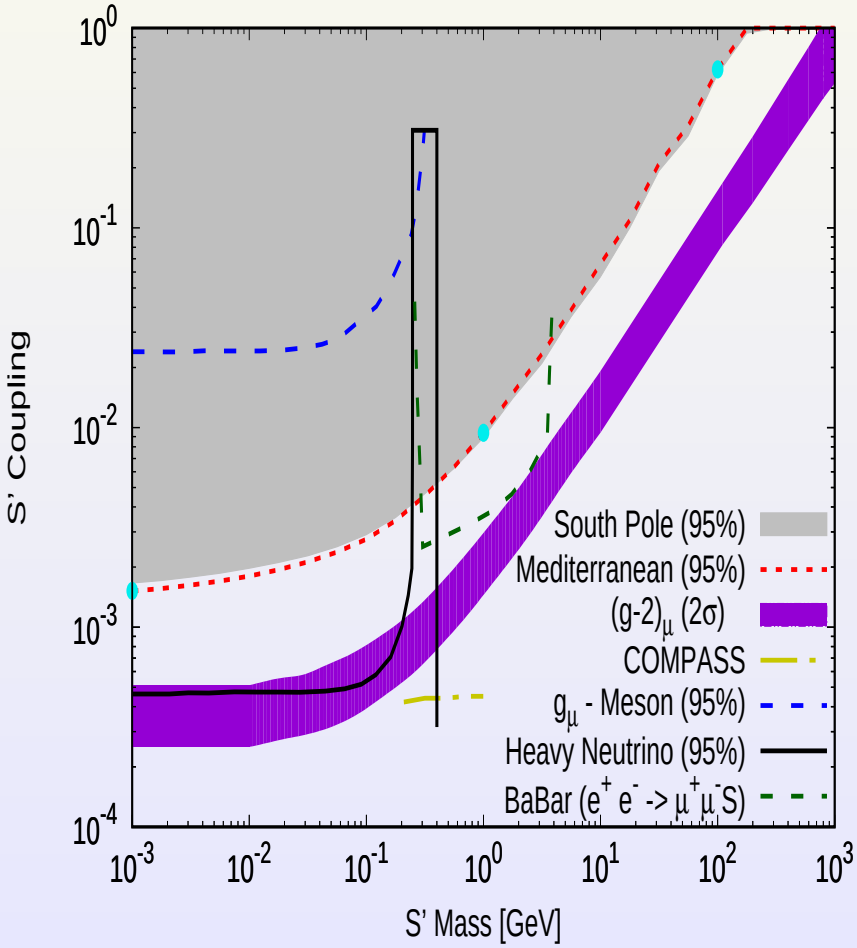
- **Angular opening is not necessary** for recognizing double muon!
  - **Edepillim** can reconstruct energy from **radiation rate**
  - **Track length** can also tell the muon energy.
  - **Mismatch** between the two estimations for overlapping double muon.

Z'/S' Sensitivities

$$\mathcal{L}_{Z'} \equiv g_{Z'} Q_{\alpha\beta} \left[\overline{L}_\alpha \gamma^\mu L_\beta + \overline{\ell}_{R\alpha} \gamma^\mu \ell_{R\beta}\right] \mathbf{Z'_\mu} + h.c.$$

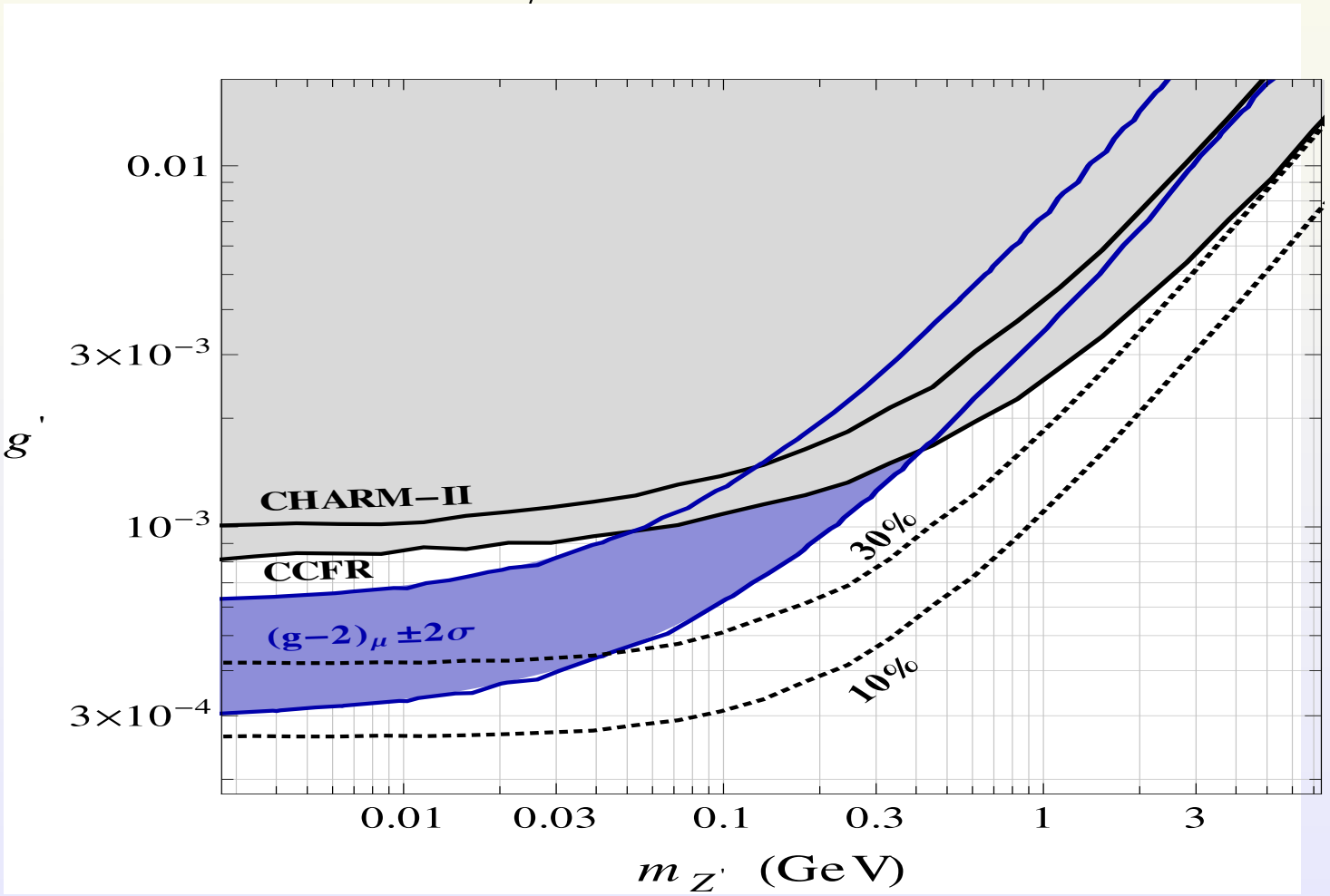
$$\mathcal{L}_{S'} \equiv g_{S'} Q_{\alpha\beta} \left[\overline{\ell_{R\alpha}} \ell_{L\beta} + \overline{\nu^c_{L\alpha}} \nu_{L\beta}\right] \mathbf{S'} + h.c.$$





Existing Constraints

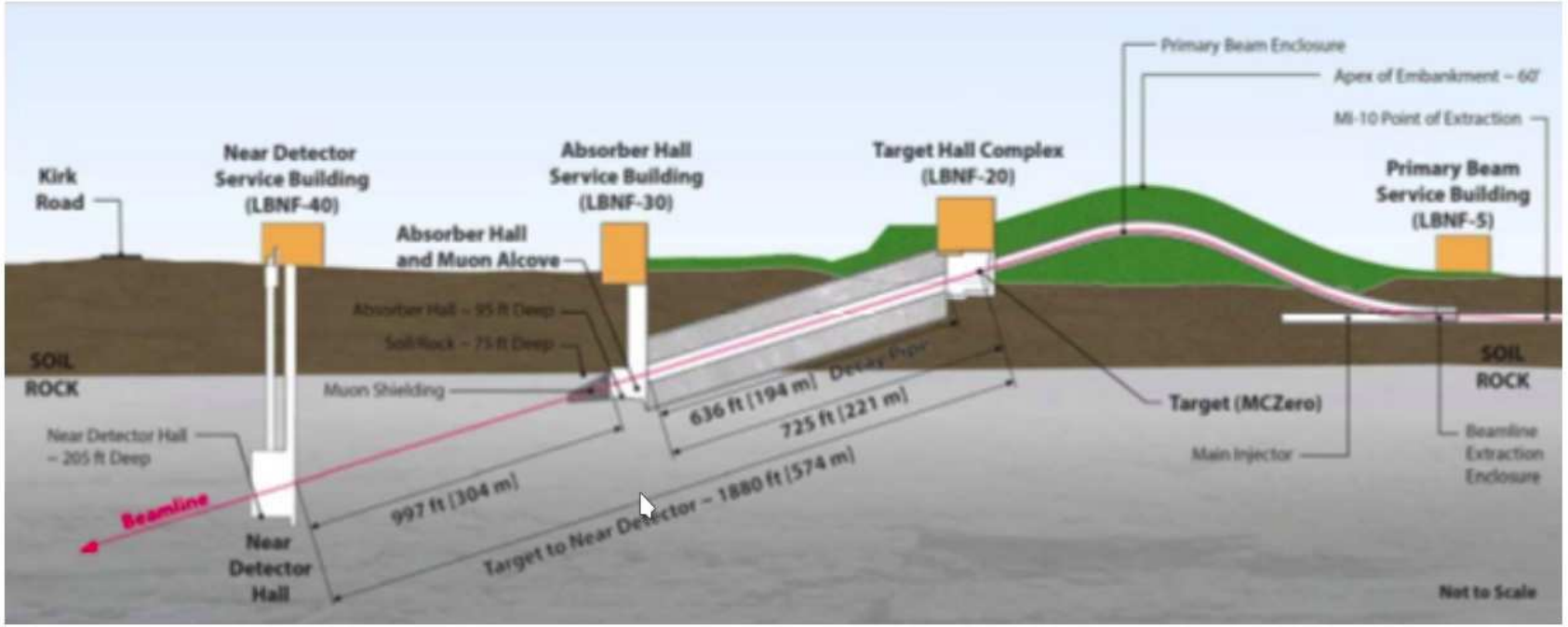
$$\sigma_{\rm CHARM-II}/\sigma_{\rm SM} = 1.58 \pm 0.57$$
$$\sigma_{\rm CCFR}/\sigma_{\rm SM} = 0.82 \pm 0.28$$



Altmannshofer, Gori, Pospelov & Yavin [arXiv:1406.2332]

Neutrino Collider @ Intensity Frontier

LBNF Near Site Facility



- Distance to near detector: >210 m needed for muon range-out for 120 GeV protons
- Distance Target-Near detection Location: 574 m
- Depth of the Near Detector : 60 m deep
- Option to be considered after CD-1 Refresh: Excavate ~x2 larger underground cavern to provide future facility for additional neutrino detector / experiment

Mixed-Flavor Trident Production

ν Process	$\overline{\nu}$ Process	V_{ijk}	A_{ijk}	Mediator
$\nu_e \to \nu_e e^+ e^-$	$\overline{\nu}_e \to \overline{\nu}_e e^+ e^-$	$\frac{1}{2} + 2\sin^2\theta_w$	$\frac{1}{2}$	W,Z
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	$\overline{\nu}_\mu \to \overline{\nu}_\mu \mu^+ \mu^-$	$\frac{1}{2} + 2\sin^2\theta_w$	$\frac{1}{2}$	W,Z
$\nu_e \to \nu_\mu \mu^+ e^-$	$\overline{\nu}_e \to \overline{\nu}_\mu e^+ \mu^-$	1	1	W
$\nu_\mu \to \nu_e e^+ \mu^-$	$\overline{\nu}_\mu \to \overline{\nu}_e \mu^+ e^-$	1	1	W
$\nu_e \to \nu_e \mu^+ \mu^-$	$\overline{\nu}_e \to \overline{\nu}_e \mu^+ \mu^-$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z
$\nu_\mu \to \nu_\mu e^+ e^-$	$\overline{\nu}_\mu \to \overline{\nu}_\mu e^+ e^-$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z
$\nu_\mu \to \nu_\mu \tau^+ \tau^-$	$\overline{\nu}_\mu \to \overline{\nu}_\mu \tau^- \tau^+$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z
$\nu_\mu \to \nu_\tau \mu^- \tau^+$	$\overline{\nu}_\mu \to \overline{\nu}_\tau \mu^+ \tau^-$	1	1	W
$\nu_\tau \to \nu_\mu \tau^- \mu^+$	$\overline{\nu}_\tau \to \overline{\nu}_\mu \tau^+ \mu^-$	1	1	W
$\nu_\tau \to \nu_\tau \mu^+ \mu^-$	$\overline{\nu}_\tau \to \overline{\nu}_\tau \mu^- \mu^+$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z
$\nu_\tau \to \nu_\tau e^+ e^-$	$\overline{\nu}_\tau \to \overline{\nu}_\tau e^- e^+$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z

Table: Modified vector and axial coupling constants for different combinations of incident neutrino flavours and final states

Magill & Plestid [arXiv:1612.05642]

Mixed-Flavor Trident Production

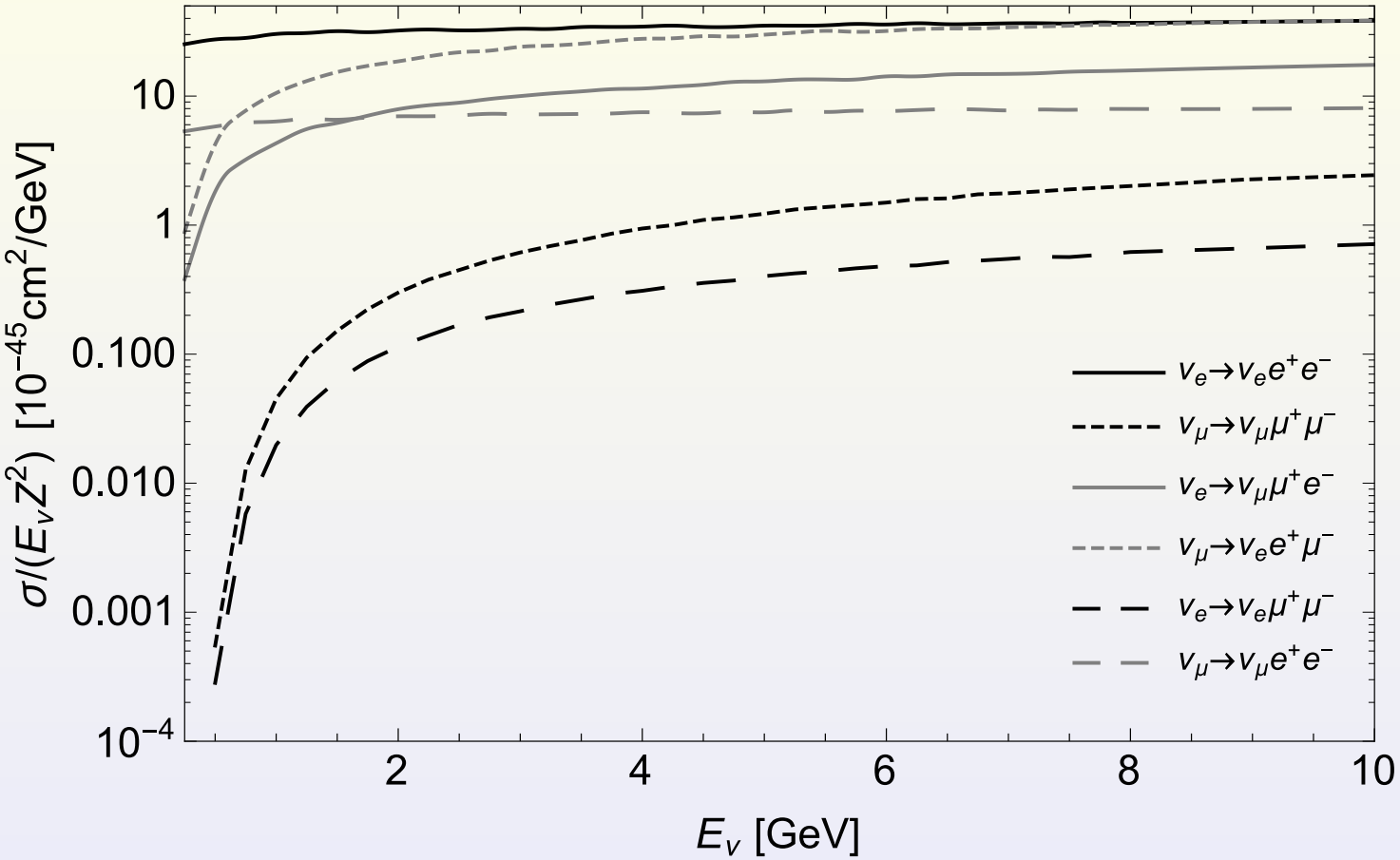


Figure: σ/E_ν trident cross sections normalized by Z^2 for various SM flavours as a function of the incoming neutrino energy on an argon target (DUNE).

Magill & Plestid [arXiv:1612.05642]

Mixed-Flavor Trident Production

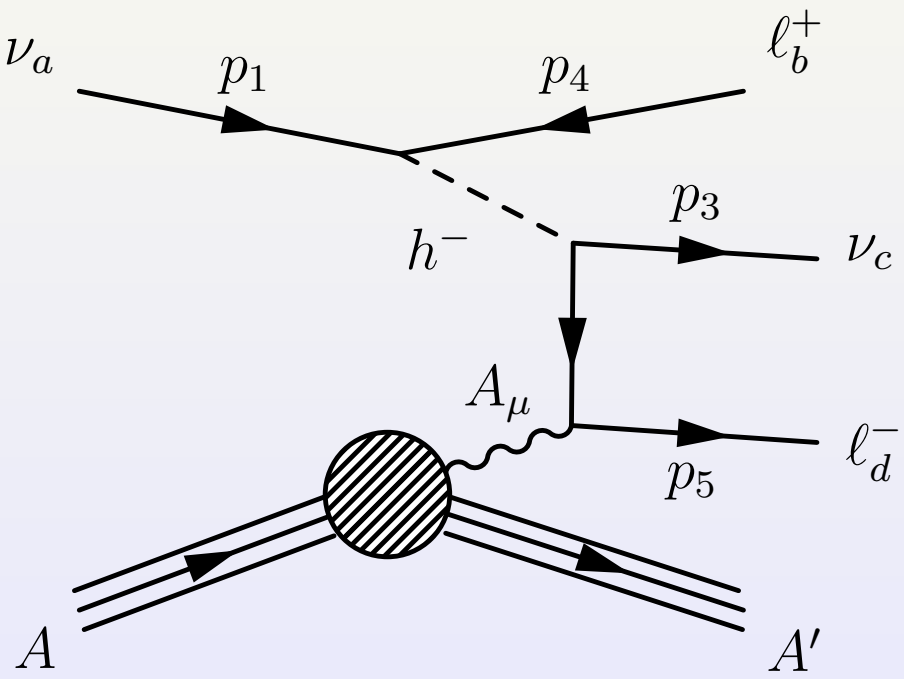
Neutrino Beam			Anti-Neutrino Beam		
Process	Coh	Diff	Process	Coh	Diff
$\nu_\mu \to \nu_e e^+ \mu^-$	73.98	53.15	$\bar{\nu}_\mu \to \bar{\nu}_e e^- \mu^+$	25.23	18.7
$\nu_\mu \to \nu_\mu e^+ e^-$	23.03	9.64	$\bar{\nu}_\mu \to \bar{\nu}_\mu e^+ e^-$	16.45	6.79
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	2.03	5.28	$\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^+ \mu^-$	2.16	4.3
$\nu_e \to \nu_e e^+ e^-$	0.7	0.29	$\bar{\nu}_e \to \bar{\nu}_e e^+ e^-$	0.54	0.22
$\nu_e \to \nu_\mu \mu^+ e^-$	0.21	0.17	$\bar{\nu}_e \to \bar{\nu}_\mu \mu^- e^+$	0.4	0.27
$\nu_e \to \nu_e \mu^+ \mu^-$	0.01	0.01	$\bar{\nu}_e \to \bar{\nu}_e \mu^+ \mu^-$	0.	0.01
Total	99.96	68.54		44.78	30.29

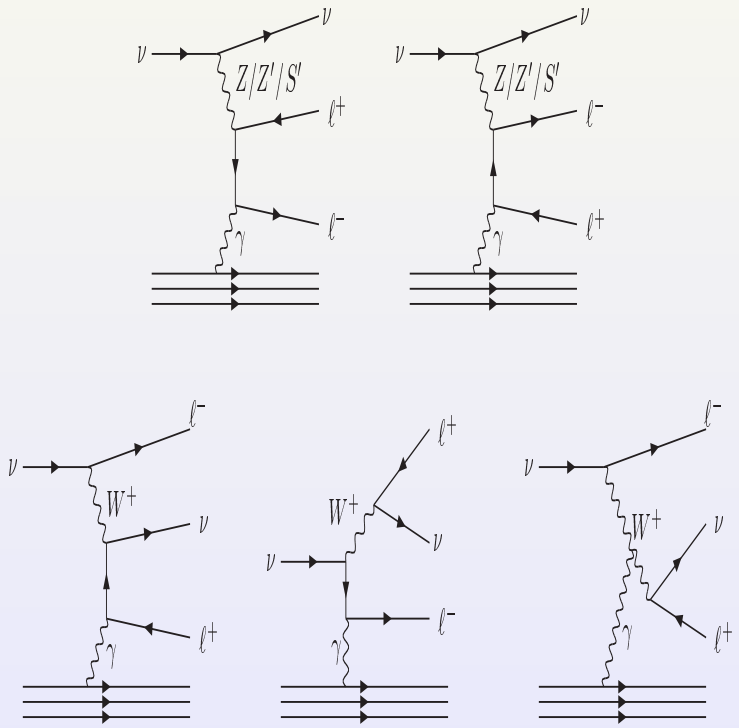
Table: Number of expected trident events for coherent (Coh) and diffractive (Diff) scattering, using the EPA, in the lifetime of the **DUNE near** detector assuming $\sim 3 \times 10^{22}$ POT (equivalently, an 850 kt-MW-yr exposure at the far detector).

Magill & Plestid [arXiv:1612.05642]

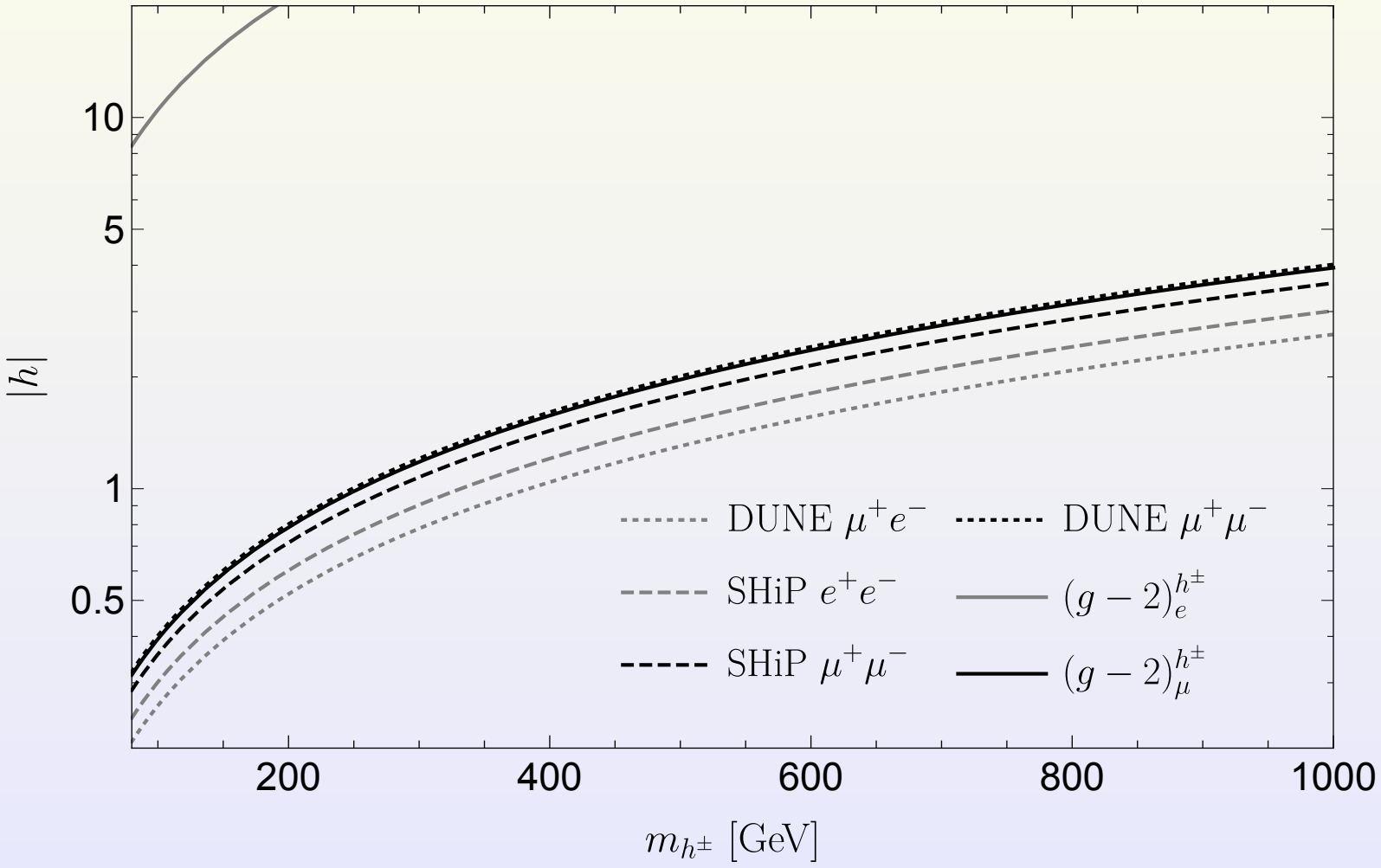
Charged Scalar Search

$$\mathcal{L} = |\partial_\mu h|^2 - m_h^2 |h|^2 + \sqrt{2} h_{ab} \nu^a \ell^b h + \cdots$$





Charged Scalar Search



Probing New Physics @ Neutrino Collider

- Trident event can produce **new particles** as **intermediate state**.
- This provides an opportunity to *directly* probe **new physics beyond the SM**.
- It essentially turns **neutrino oscillation experiment** to **neutrino collider**.
- **Neutrino oscillation experiments** reconstruct the intial state:
  - **Momentum**
  - **Flavor**
- **Neutrino collider** reconstructs NP with final-state particles.

Thank You!