NSI in oscillation and scattering experiments

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Neutrinos as a portal to new physics and astrophysics

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New neutrino interactions (NSI)

- appear naturally in extensions of SM with new mediators [see Bhupal's talk]
- focus on NC NSI: general framework [Wolfenstein '78]

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon^f_{\alpha\beta}(\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

- diagonal $\epsilon_{\alpha\alpha}$ real, off-diagonal $\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$
- signature in **oscillation** and **scattering** experiments

NSI in oscillations

- framework

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f} \epsilon^f_{\alpha\beta}(\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

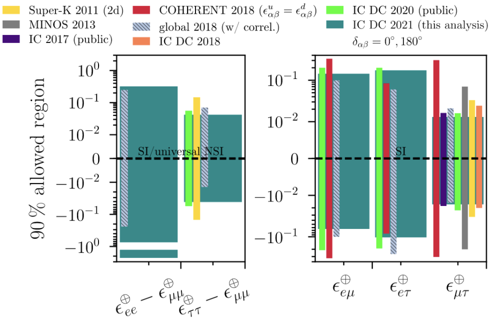
- affect oscillations via **new matter effect**

$$H = \frac{1}{2E}\left[U^\dagger M^2 U + a \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}\right]$$

  matter potential $a \propto G_F \rho E$
- can subtract one term on the diagonal $\Rightarrow$ **8 free** NSI parameter probed by oscillations $(|\epsilon_{\alpha\beta}|,\ \phi_{\alpha\beta}, \epsilon_{ee}-\epsilon_{\mu\mu}, \epsilon_{\tau\tau}-\epsilon_{\mu\mu})$
- parameters related to parameters in Hamiltonian by $\epsilon_{\alpha\beta} = \sum_f \epsilon^{f,V}_{\alpha\beta}\langle N_f(x)/N_e(x)\rangle$

How to measure ϵ with oscillations?

- effect of NSI scales with energy, baseline, and matter density $\Rightarrow$ use high-energy neutrino sources with long baselines $\rightarrow$ atmospheric neutrinos at IceCube



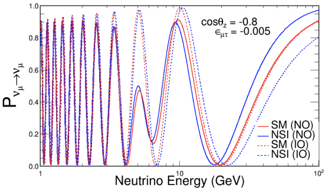
[IceCube '21]

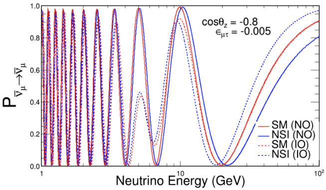
NSI in oscillations

How to measure ϵ with oscillations?

- $\epsilon_{\mu\tau}$:
  Do we need to observe tau neutrinos?

  long-baseline and atmospheric oscillations are dominated by ν_3 which contains ν_μ and ν_τ
  $\rightarrow$ use **muon neutrino disappearance** data from atmospheric neutrinos or long baseline experiments

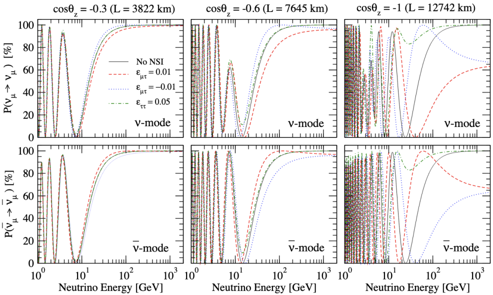




NSI in oscillations

How to measure ϵ with oscillations?

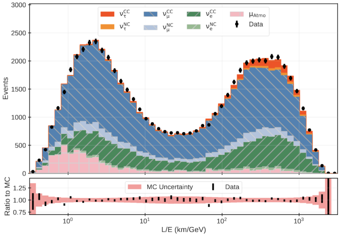
- $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$:
  diagonal NSI parameter $\rightarrow$ affects atmospheric mass splitting $\rightarrow$ compare results for Δm^2_{32} from **atmospheric muon neutrino disappearance** to measurements of Δm^2_{32} from reactor experiments in vacuum



[Miranda, Nunokawa '15]

How to measure ϵ with oscillations?

- $\epsilon_{e\mu}$:
  use **electron appearance from atmospheric muon neutrinos**
  cascade signature of ν_e, low ν_e yield
  use muon appearance from atmospheric ν_e: low atmospheric electron component
- $\epsilon_{e\tau}$: (no tau neutrinos required)
  use **electron appearance from atmospheric muon neutrinos**



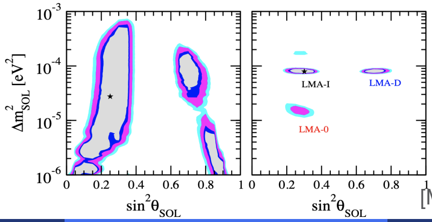
[IceCube '19]

How to measure ϵ with oscillations?

- $\epsilon_{ee} - \epsilon_{\mu\mu}$:
  no source of high energy ν_e!
  LMA Dark solution: transformation

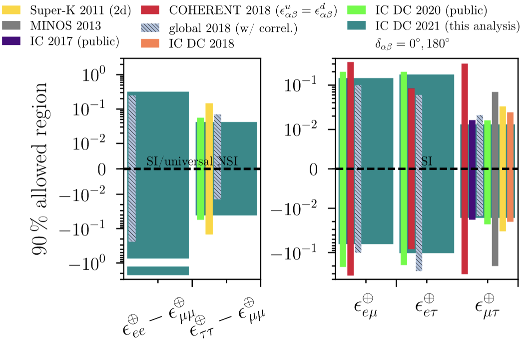
$$\sin\theta_{12} \to \cos\theta_{12},\ \Delta m^2_{31} \to -\Delta m^2_{32}, \delta \to \pi - \delta,$$
$$(\epsilon_{ee} - \epsilon_{\mu\mu}) \to (\epsilon_{ee} - \epsilon_{\mu\mu}) - 2, (\epsilon_{\tau\tau} - \epsilon_{\mu\mu}) \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu}),$$
$$\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta}$$

leaves neutrino evolution invariant [Miranda, Tortola, Valle '04, Coloma, Schwetz '16]



[Miranda, Tortola, Valle '04]

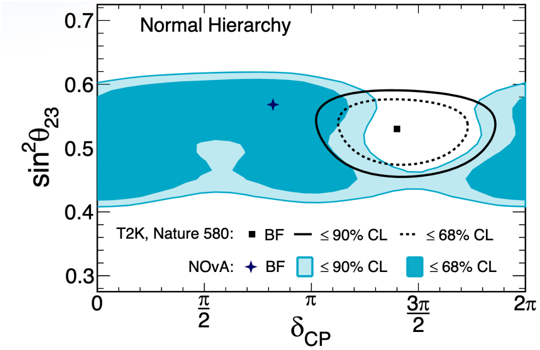
How to measure ϵ with oscillations?



[IceCube '21]

NSI in oscillations

Hint for non-zero ϵ?



[Himmel '20]

$\rightarrow$ **disagreement** at $\sim 2\sigma$!

NSI at NOvA & T2K [Denton, JG, Pestes '20]

- difference between NOvA and T2K are baselines and matter densities $\rightarrow$ neutrinos at NOvA experience stronger **matter effects**

$\Rightarrow$ Can NSI resolve this tension?

CP-Violating Neutrino Non-Standard Interactions in Long-Baseline-Accelerator Data

Peter B. Denton,[1,*] Julia Gehrlein,[1,†] and Rebekah Pestes[1,2,‡]

[arxiv: 2008.01110, Phys. Rev. Lett. 126 (2021) no.5, 051801]

NSI at NOvA & T2K [Denton, JG, Pestes '20]

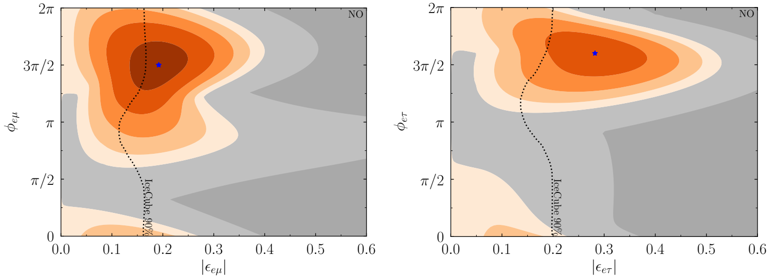
- focus on off-diagonal NSI parameters
- derived analytical and numerical results

$$|\epsilon_{e\beta}| \approx \frac{s_{12}c_{12}c_{23}\pi\Delta m^2_{21}}{2s_{23}w_\beta}\left|\frac{\sin\delta_{\text{T2K}} - \sin\delta_{\text{NOvA}}}{a_{\text{NOvA}} - a_{\text{T2K}}}\right| \approx \begin{cases} 0.22 & \text{for } \beta = \mu \\ 0.24 & \text{for } \beta = \tau \end{cases},$$

with $w_\beta = \sin\theta_{23}(\cos\theta_{23})$

- used disappearance, appearance data from NOvA and T2K, information from vacuum experiments for $\theta_{13}, |\Delta m^2_{32}|, \theta_{12}, \Delta m^2_{21}$

NSI at NOvA & T2K [Denton, JG, Pestes '20]



orange preferred over SM at integer values of $\Delta\chi^2$, dark gray disfavored at $\Delta\chi^2 = 4.61$ [see also Chatterjee, Palazzo '20]

- complex NSI with $|\epsilon| \approx 0.2,\ \phi \approx 3\pi/2,\ \delta \approx 3\pi/2$, NO can fully resolve tension
- change in MO from NO to IO: improvement of $\Delta\chi^2 = 2.3$ [Kelly et al '20; Esteban et al '20]

NSI in scattering

- framework

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f} \epsilon^f_{\alpha\beta} (\overline{\nu}_\alpha \gamma^\mu \nu_\beta)(\bar{f}\gamma_\mu P f)$$

$\rightarrow$ NSI affect neutrino-SM scattering experiments like CEvNS (coherent elastic neutrino nucleus scattering)

- NSI effect on weak charge

$$Q^2_{w\alpha} \propto \left[N(g^V_n + \epsilon^V_{\alpha\alpha})\right]^2 + \sum_{\beta\neq\alpha}\left[\epsilon^V_{\alpha\beta}(Z+N)\right]^2$$

$\rightarrow$ no sensitivity to complex NSI phase

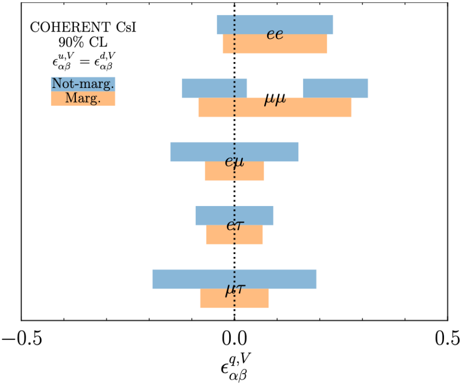
- sensitivity to 5 NSI parameters (not sensitive to $\epsilon_{\tau\tau}$)

NSI in scattering

- NSI in oscillations:
  forward scattering interactions $\rightarrow$ constraints **independent of mediator masses** (unless $m \sim d_{max}^{-1}$ [Wise, Zhang '18])
- NSI in scattering:
  dependence on mediator mass
  - heavy mediator regime ($m^2 > q^2 \sim (10\ \text{MeV})^2$): $\epsilon \propto g_x^2/m^2$
  - light mediator regime $\epsilon \propto g_X^2/(q^2 + m^2)$

NSI in scattering: heavy mediators

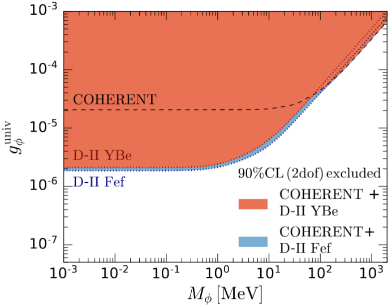
- CEvNS detected for the first time in 2016 by COHERENT
- NSI constraints apply to mediators $m > 10$ MeV
- constraints derived in [Denton, JG '20] using Feldman-Cousins framework



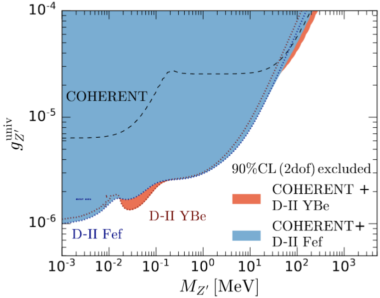
NSI in scattering: light mediators

use CEvNS at low energy accelerator and reactor CEvNS

scalar mediator



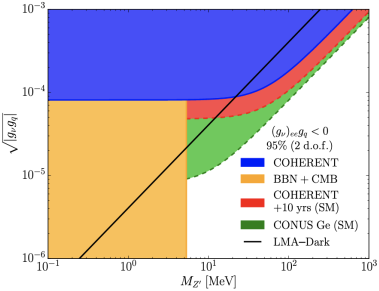
vector mediator

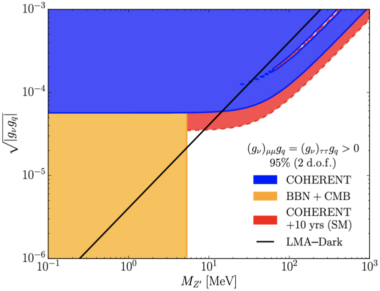


[Coloma et al ’22]

NSI in scattering: light mediators

connection to oscillation phenomenology

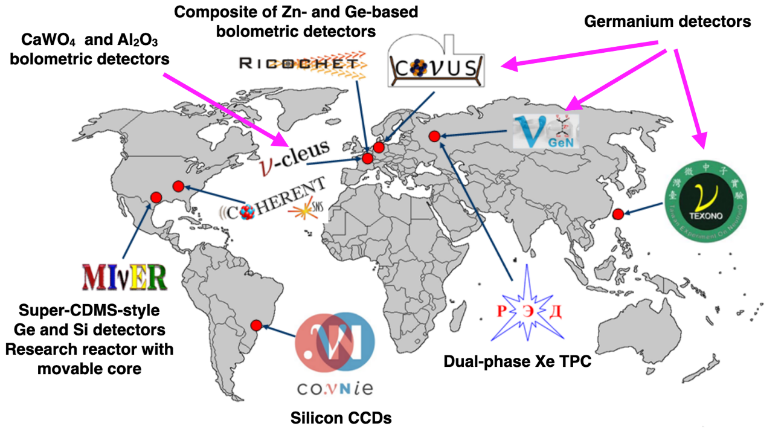




[Denton, Shoemaker, Farzan '18]

⇒ scattering experiments can probe degeneracies in oscillation parameters in presence of NSI

NSI in scattering: future



Summary & Conclusions

- NSI can be tested in oscillation experiments and scattering experiments $\rightarrow$ complementarity between different probes
- currently weak hint for non-zero NSI from oscillations
- future atmospheric and long baseline experiments as well as scattering experiments will probe NSI further

Thank you for your attention!