

Constraining non-standard neutrino interactions with neutral current events at long-baseline oscillation experiments

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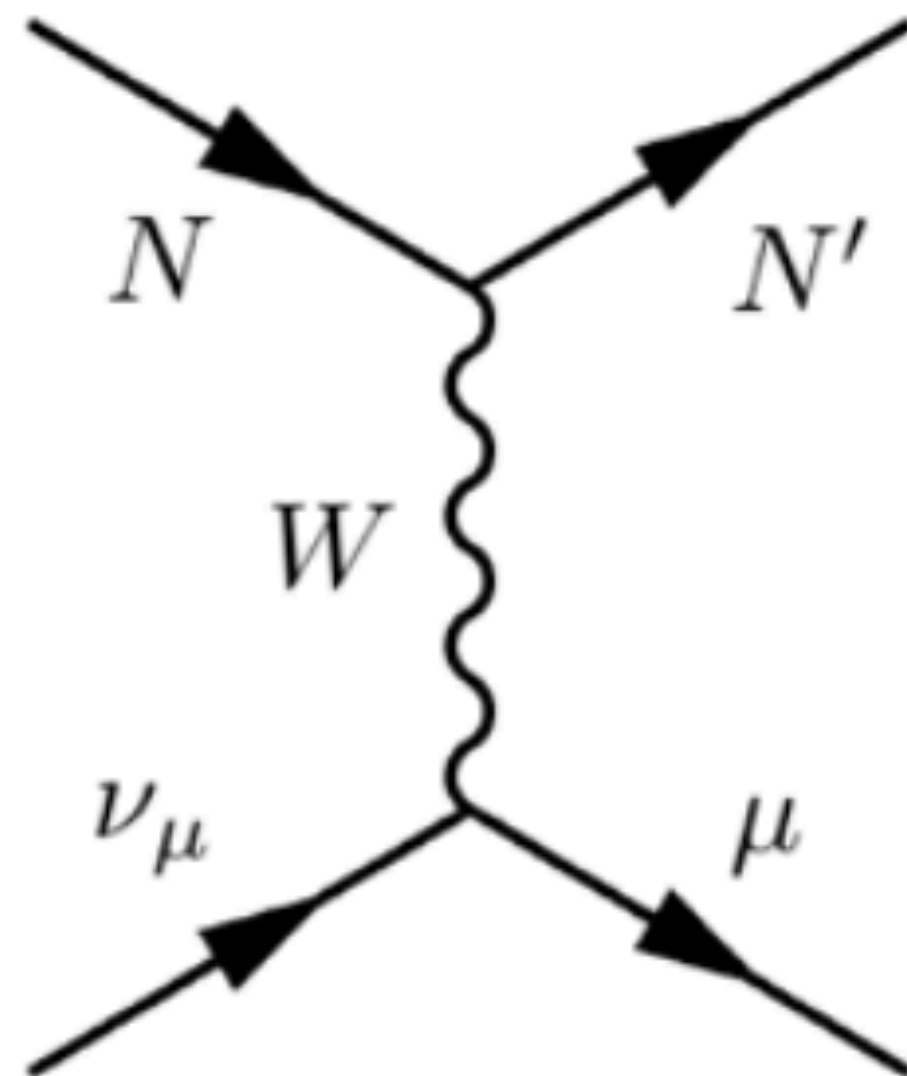


**COLORADO STATE
UNIVERSITY**

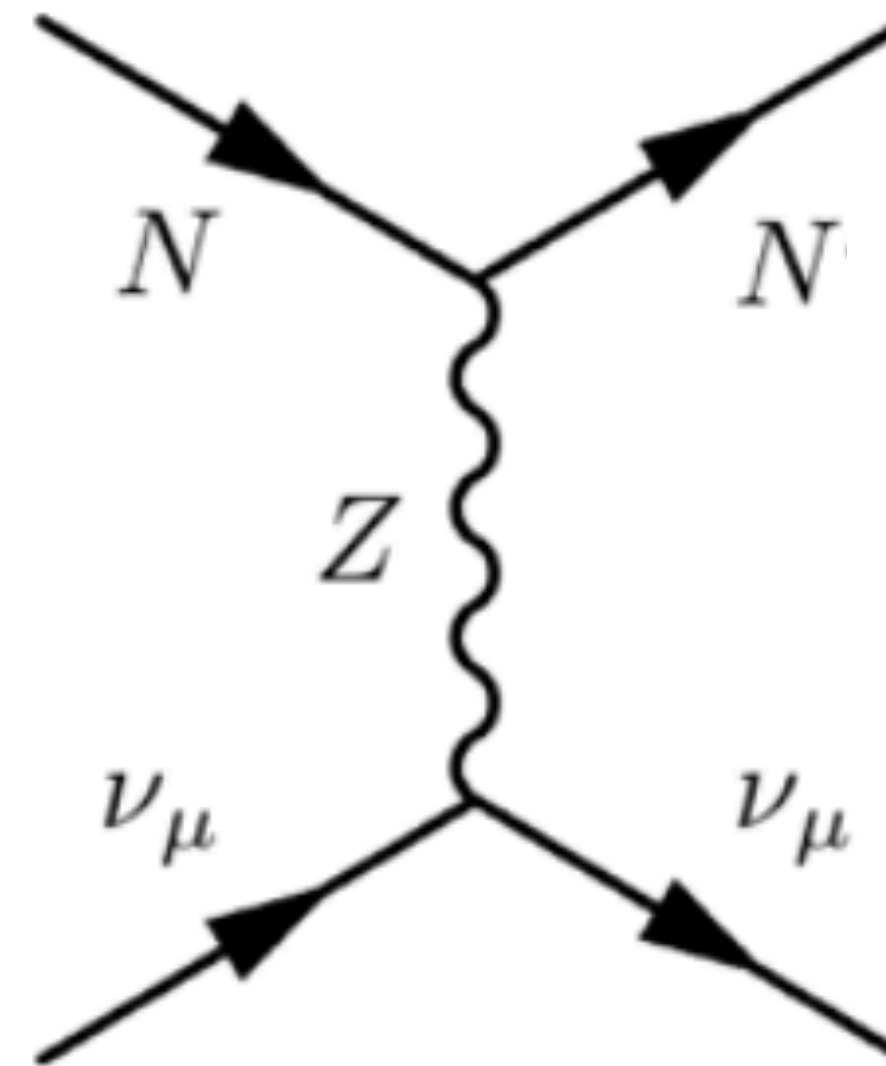
Neutrino interactions

Neutrino interactions in the SM

Charged Current (CC) interactions
via a W-boson



Neutral Current (NC) interactions
via a Z-boson



$$\propto G_F = \frac{\sqrt{2}}{8} \frac{g^2}{M_W^2}$$

Neutrino interactions

Neutrino interactions beyond the SM

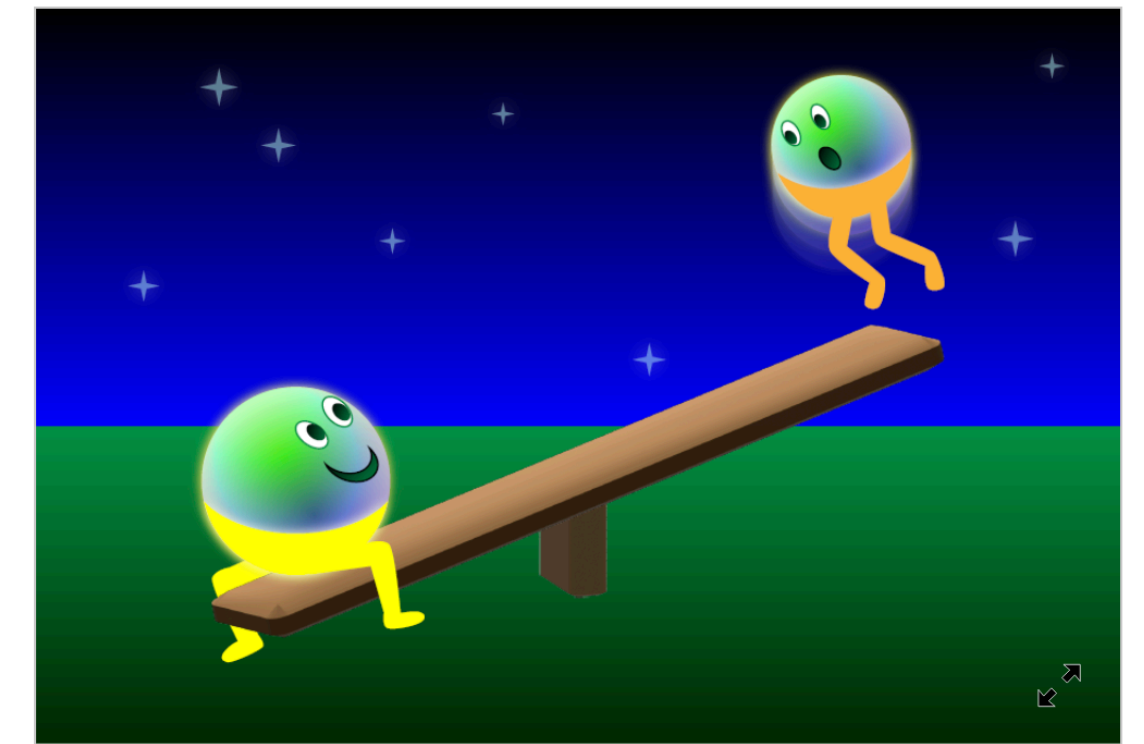
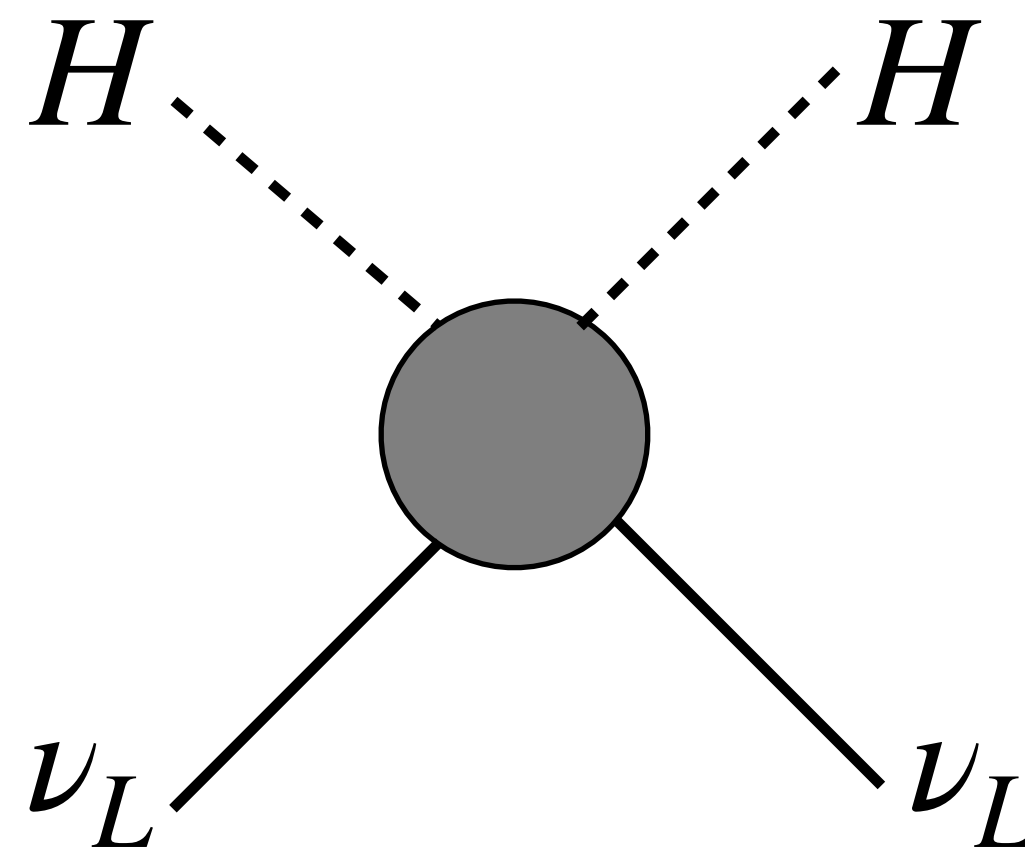
New terms in Lagrangian could appear as higher dimension operator

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \boxed{\frac{1}{\Lambda} \delta \mathcal{L}^{d=5}} + \frac{1}{\Lambda^2} \delta \mathcal{L}^{d=6} + \dots$$

Gives neutrino (Majorana) masses

$$\mathcal{L}_W = \frac{1}{\Lambda} (\bar{L}_L \tilde{H}) (\tilde{H}^T L_L^c)$$

[Weinberg, 1979]



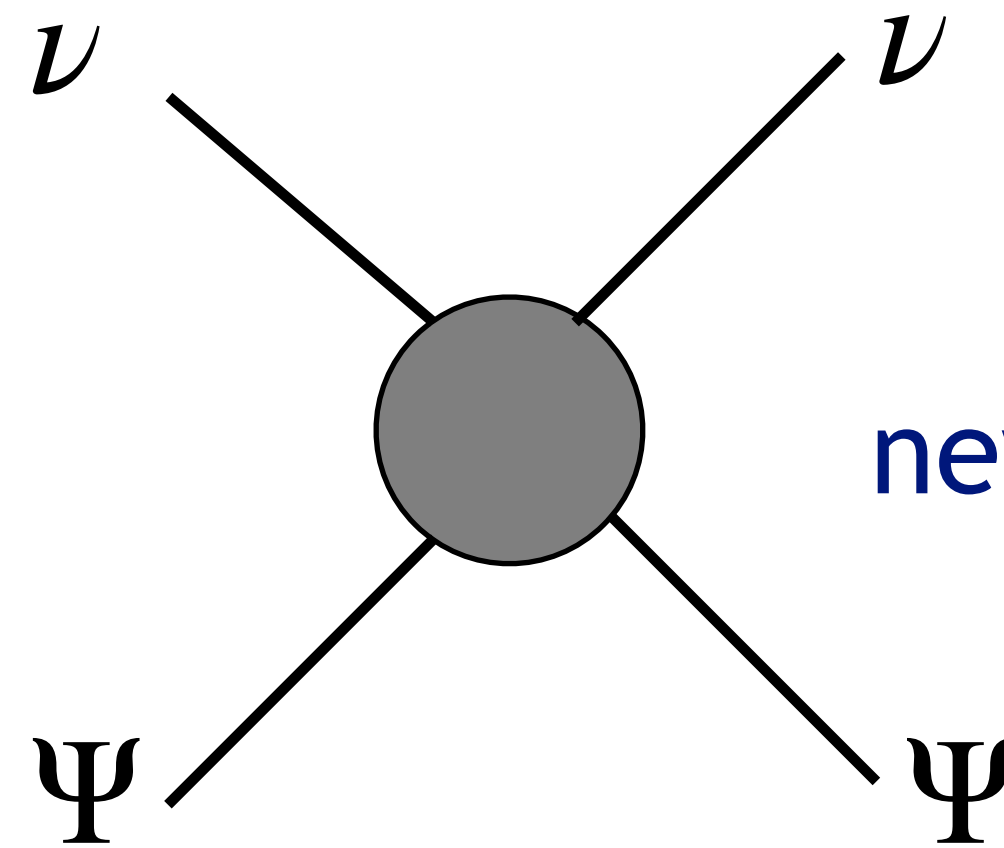
Neutrino interactions

Neutrino interactions beyond the SM

New terms in Lagrangian could appear as higher dimension operator

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \boxed{\frac{1}{\Lambda} \delta \mathcal{L}^{d=5}} + \boxed{\frac{1}{\Lambda^2} \delta \mathcal{L}^{d=6}} + \dots$$

Gives neutrino (Majorana) masses



Can lead to
new neutrino interactions!

$$\propto G_x \sim \frac{g_x^2}{\Lambda^2}$$

Neutrino non-standard interactions

New neutrino interactions with SM fermions:
neutrino non-standard interactions (NSI)

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \delta \mathcal{L}^{d=5} + \boxed{\frac{1}{\Lambda^2} \delta \mathcal{L}^{d=6}} + \dots$$



CC NSI: $\mathcal{L}_{NSI}^{CC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,f',P} \epsilon_{\alpha\beta}^{f,f'} (\bar{\nu}_\alpha P l_\beta) (\bar{f} P f')$

NC NSI: $\mathcal{L}_{NSI}^{NC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^f (\bar{\nu}_\alpha P \nu_\beta) (\bar{f} P f)$

With $\Lambda = \frac{1}{\sqrt{2\sqrt{2}\epsilon G_F}}$

Neutrino non-standard interactions

CC NSI: $\mathcal{L}_{NSI}^{CC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,f',P} \epsilon_{\alpha\beta}^{f,f'} (\bar{\nu}_\alpha P l_\beta) (\bar{f} P f')$

$P : S, P, V, A, T$

NC NSI: $\mathcal{L}_{NSI}^{NC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^f (\bar{\nu}_\alpha P \nu_\beta) (\bar{f} P f)$

NSI parameter ϵ : strength of new interaction
relative to weak interaction $\epsilon \sim \mathcal{O}(G_X/G_F)$

NSI can be flavor diagonal or off-diagonal

Neutrino non-standard interactions

Strong constraints on **CC** NSI!

⇒ Focus on **NC NSI** in the following

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^f (\bar{\nu}_\alpha P \nu_\beta) (\bar{f} P f)$$

$$P = S, P, V, A, T$$

$$P = 1, i\gamma_5, \gamma^\mu, \gamma^\mu\gamma_5, \sigma^{\mu\nu}, \sigma^{\mu\nu} = i/2[\gamma^\mu, \gamma^\nu]$$

Lots of possible NSI terms!

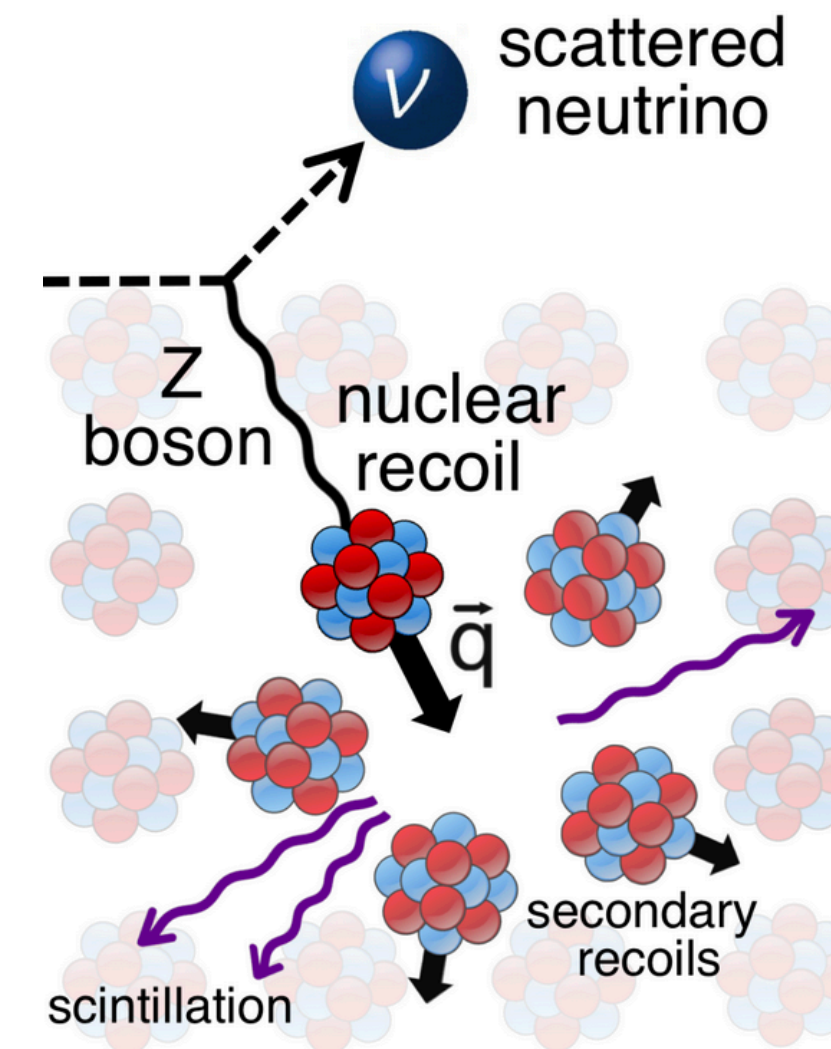
→ **a lot of new physics to discover!**

How to probe NSI?

Neutrino oscillations



Neutrino scatterings



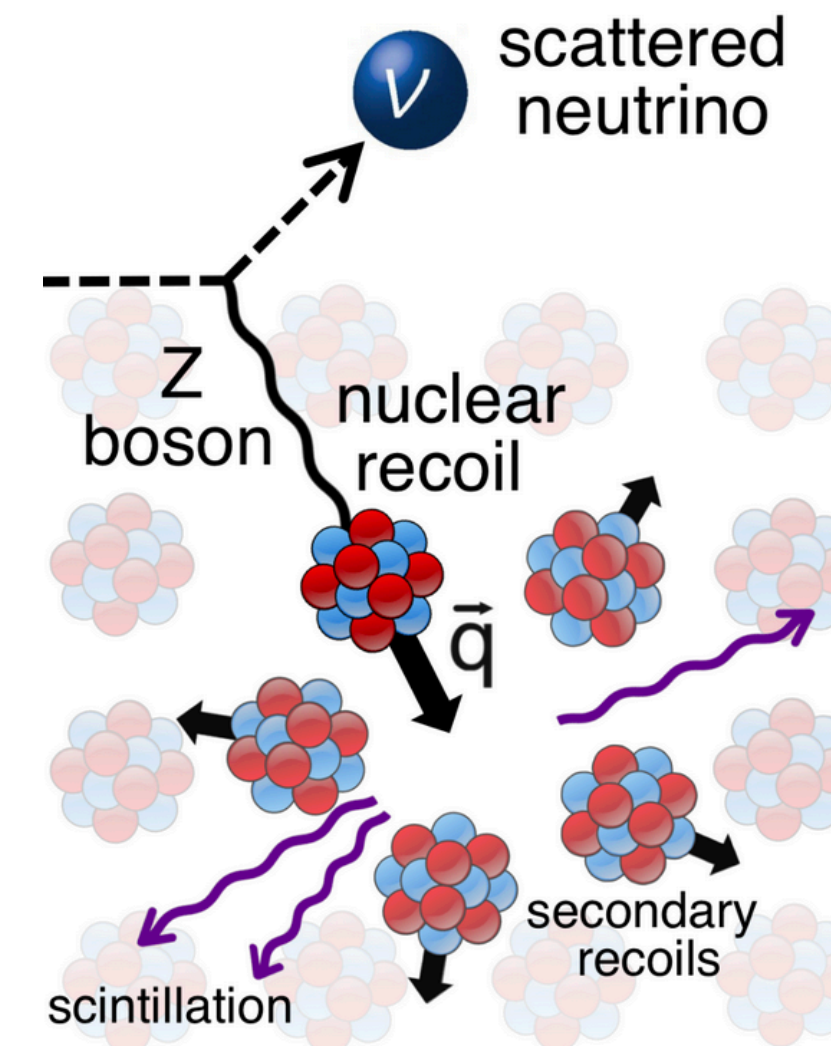
How to probe NSI?

Neutrino oscillations

- NC NSI in propagation (& detection)
(CC NSI in production/detection)
- No sensitivity to axial currents
- Independent of mediator mass
- no sensitivity to individual diagonal NSI parameters
- Degeneracies



Neutrino scatterings



How to probe NSI?

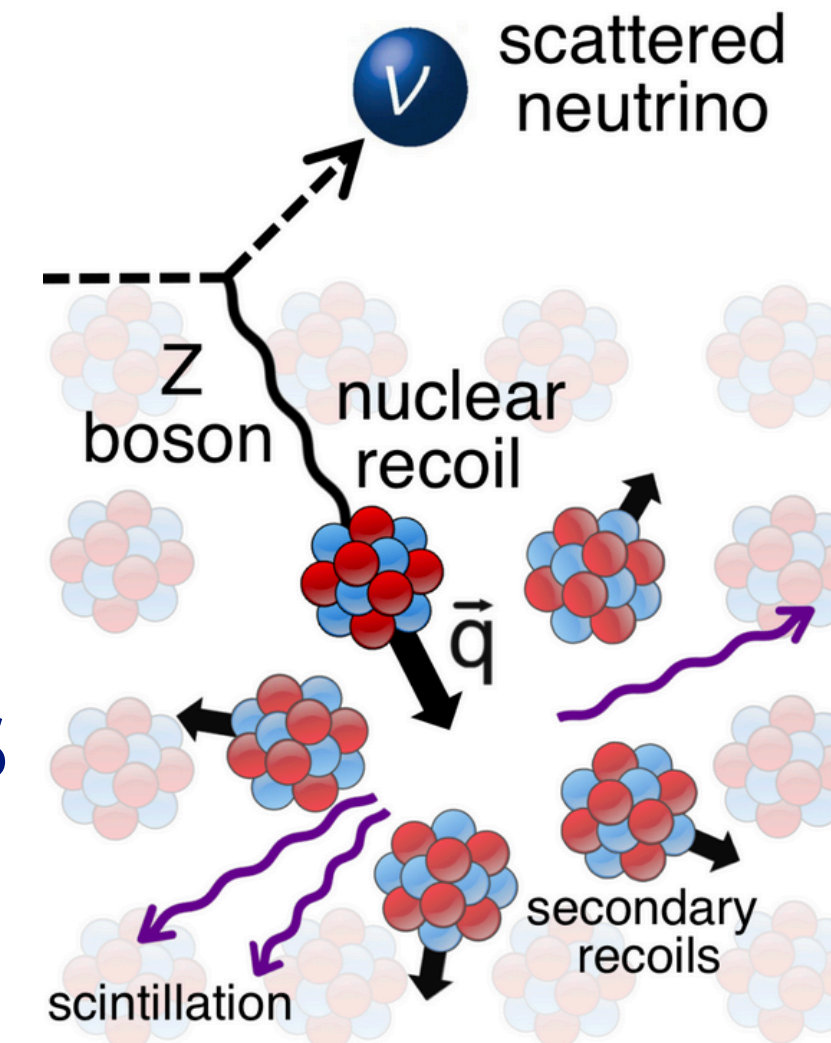
Neutrino oscillations

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- no sensitivity to individual diagonal NSI parameters
- Degeneracies



Neutrino scatterings

- Mediator mass dependence
- Need theoretically well understood process
- $\nu - e, \nu - N$ data
- Degeneracies



NC NSI events at LBL experiment

New idea:
combine both ways of testing NSI to break degeneracies
& derive new constraints

**Constraining non-standard neutrino interactions with
neutral current events at long-baseline oscillation
experiments**

**Complementarity Between Neutrino Neutral and Charged Current Events
in the Search for New Physics**

Julia Gehrlein,^{1,*} Jaime Hoefken Zink,^{2,†} Pedro A. N. Machado,^{3,‡} and João Paulo Pinheiro^{4,5,§}

Julia Gehrlein,^a Pedro A. N. Machado,^b and João Paulo Pinheiro^c

2412.08712

2604.16176

NC NSI events at LBL experiment

Current and future LBL experiments (will) have **large** NC data sets
(background to CC events)

→ analyze existing NOvA data & forecasted DUNE data

Without NSI: NC channel is flavor blind

With NSI: scattering cross section changes in flavor-dependent way



NC NSI events at LBL experiment

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With NSI: scattering cross section changes in flavor-
dependent way



Take effects of **propagation** and **scattering** into account using density matrix formalism

JG, Machado, Pinheiro, [2412.08712](#)

1. New constraints on isospin conserving vector and axial-vector NSI
2. Combination of CC and NC events → new constraints on isoscalar and isovector NSI

JG, Hoefken Zink, Machado, Pinheiro, [2604.16176](#)

NC NSI events at LBL experiment

Framework

JG, Machado, Pinheiro, [2412.08712](#)

Simplified framework:

Include NSI in NC cross section assuming *free nucleons*

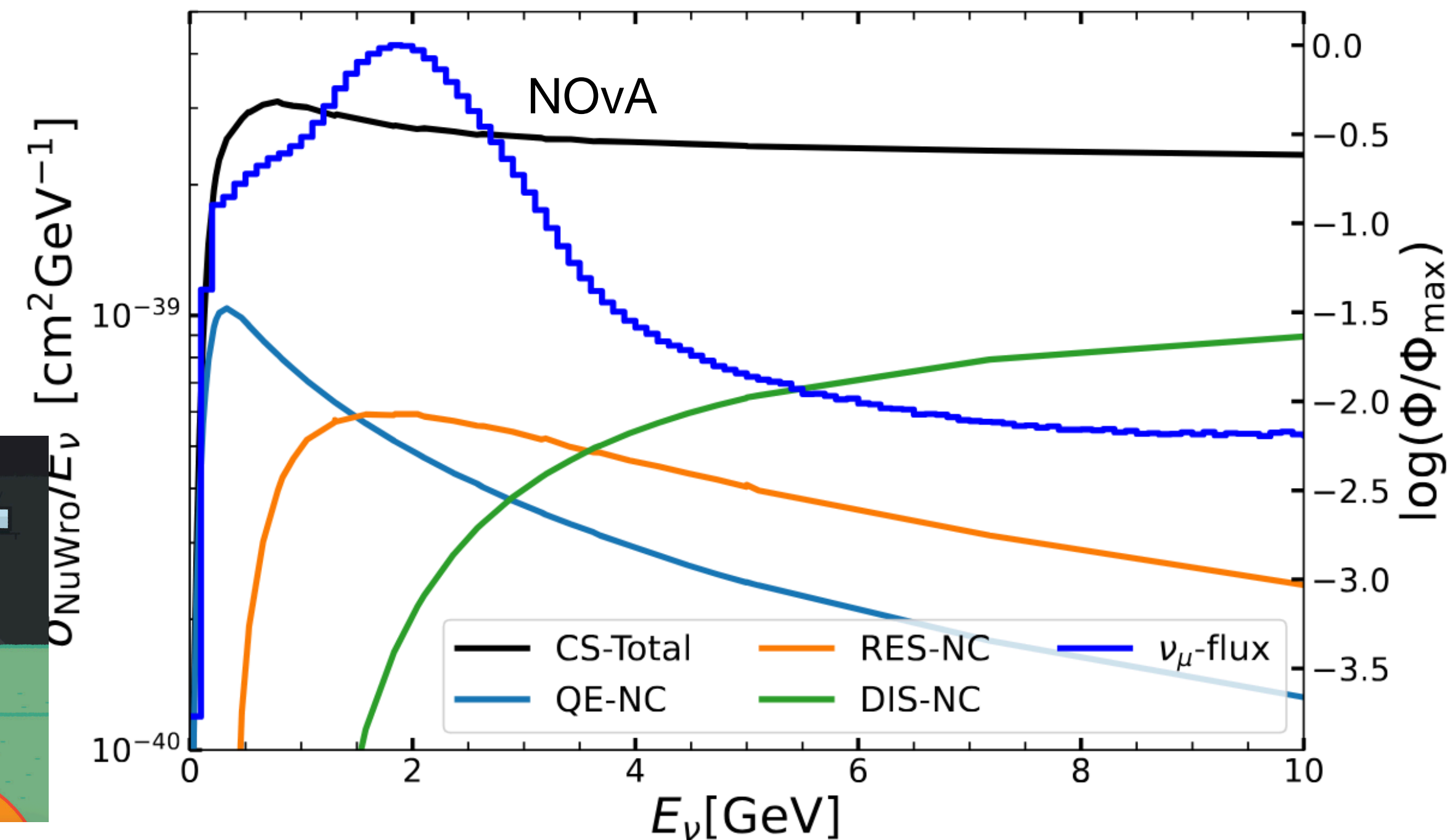
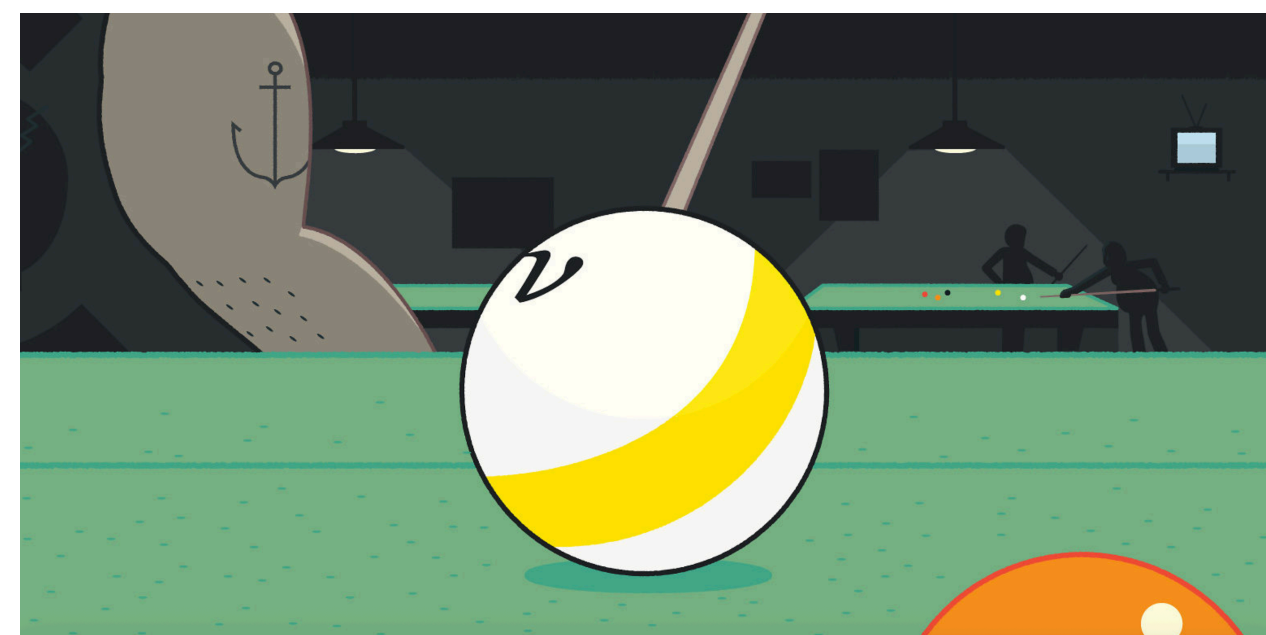
To model nuclear effects: multiply prefactor with nuWro result

$$N_{\text{ev}} \propto \frac{\sum_{\alpha\beta} N_p \rho_{\alpha\beta} \sigma_p^{\alpha\beta} + N_n \rho_{\alpha\beta} \sigma_n^{\alpha\beta}}{\sum_{\alpha} N_p \rho_{\alpha\alpha} (\sigma_p^{\alpha\alpha})_{\text{SM}} + N_n \rho_{\alpha\alpha} (\sigma_n^{\alpha\alpha})_{\text{SM}}} \sigma_{\text{NuWro}}$$

Assume isospin
conserving NSI

$$\epsilon^u = \epsilon^d$$

And no coupling to
electrons

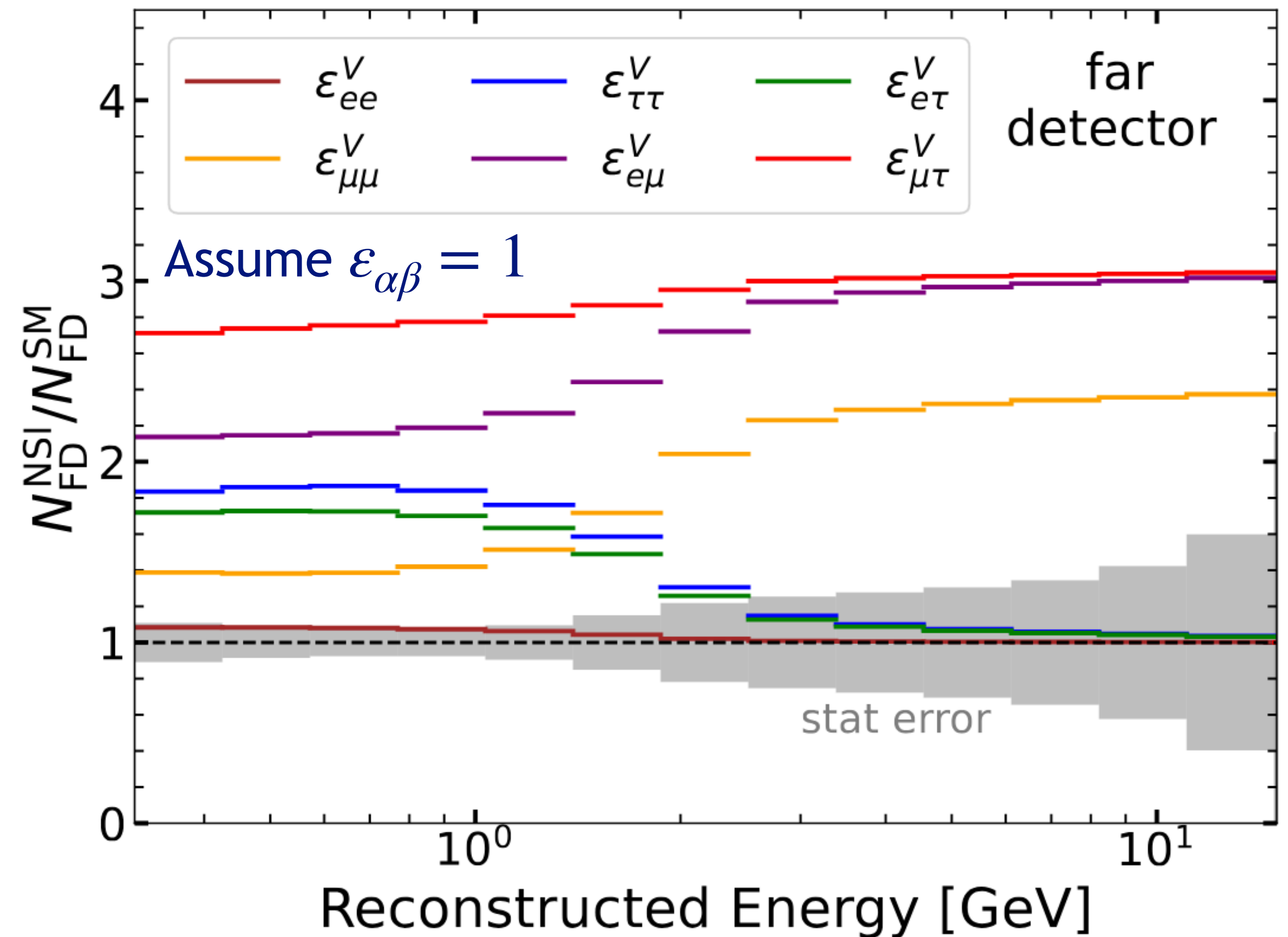


NC NSI events at LBL experiment

Effect of NSI

JG, Machado, Pinheiro, [2412.08712](#)

- Up to 2-3 times more events at the FD in the presence of NSI
- Take events at ND into account as well
- Results similar for axial-vector NSI since dominant effect at NOvA comes from scattering



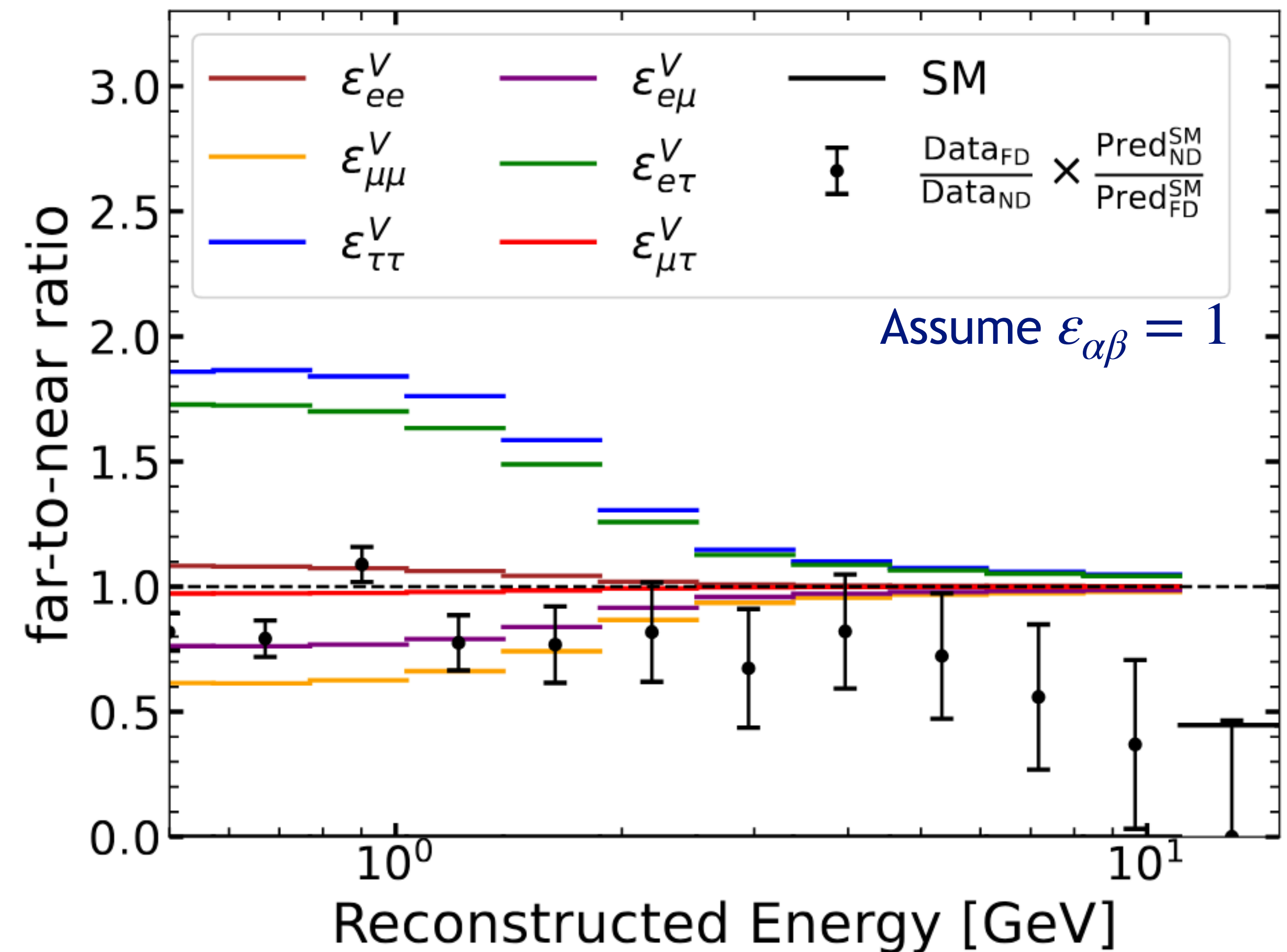
NC NSI events at LBL experiment

Effect of NSI

JG, Machado, Pinheiro, [2412.08712](#)

Consider: $R = (N_{NSI}^{FD}/N_{NSI}^{ND})/(N_{SM}^{FD}/N_{SM}^{ND})$

- $R < 1$ for $\varepsilon_{e\mu}, \varepsilon_{\mu\mu}$: at ND only ν_μ but at FD most of the ν_μ have oscillated away
- $R > 1$ for $\varepsilon_{e\tau}, \varepsilon_{\tau\tau}$: at ND no ν_τ , at FD ν_τ appear (sensitivity to NSI in tau sector!)
- $R \approx 1$ for $\varepsilon_{ee}, \varepsilon_{\mu\tau}$: small ν_e flux at ND and FD, ν_μ appear as either ν_τ or stay ν_μ



NC NSI events at LBL experiment

Effect of NSI

JG, Machado, Pinheiro, [2412.08712](#)

Consider: $R = (N_{NSI}^{FD}/N_{NSI}^{ND})/(N_{SM}^{FD}/N_{SM}^{ND})$
at $E_\nu = 2$ GeV

Degeneracies for two non-zero NSI parameters
(in effective 2-flavor scenario)

$$\varepsilon_{\tau\tau}^V = \varepsilon_{\mu\mu}^V$$

and

$$\varepsilon_{\tau\tau}^A = \varepsilon_{\mu\mu}^A$$

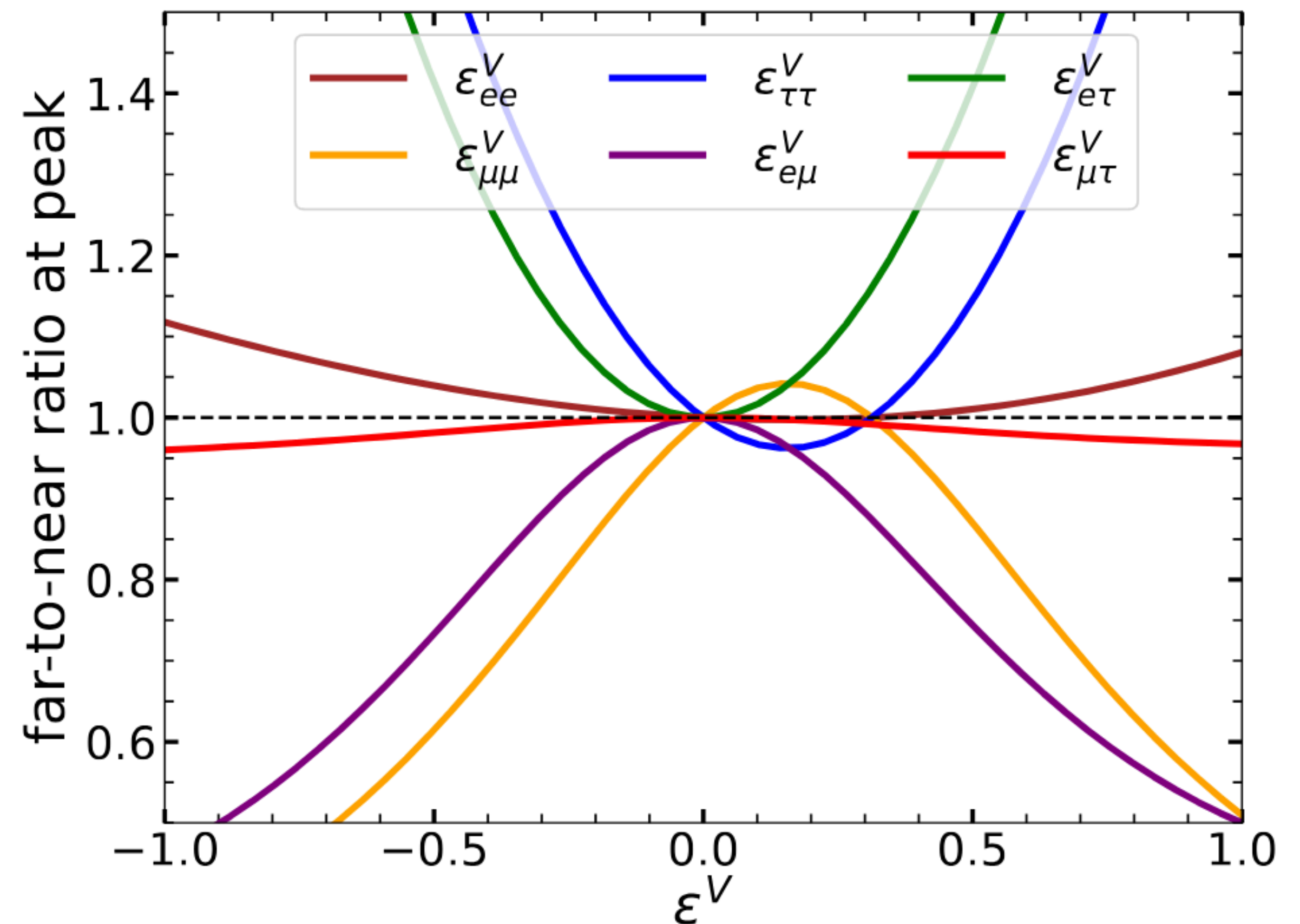
and

$$\varepsilon_{\tau\tau}^V = \frac{1}{4} - \varepsilon_{\mu\mu}^V$$

$$\varepsilon_{\tau\tau}^A = -\varepsilon_{\mu\mu}^A$$

Specific to NC cross section with free nucleons

Changing cross section for all flavors doesn't change R



NC NSI events at LBL experiment

Results

JG, Machado, Pinheiro, [2412.08712](#)

- Analyze 13.6×10^{20} POT from NOvA at ND and FD [NOvA, 2409.04553](#)
- theory prediction suffers from uncertainties on cross section, flux, etc
- Fit ND and FD data and use bin-by-bin fully correlated pull-parameters

$$\chi^2 = \sum_i^{\text{bins}} \left[\frac{D_i^{\text{ND}} - (1 + \gamma_i)T_i^{\text{ND}}}{\sqrt{D_i^{\text{ND}}}} \right]^2 + \sum_i^{\text{bins}} \left[\frac{D_i^{\text{FD}} - (1 + \alpha + \gamma_i)T_i^{\text{FD}}}{\sqrt{D_i^{\text{FD}}}} \right]^2 + \left(\frac{\alpha}{\sigma_\alpha} \right)^2$$

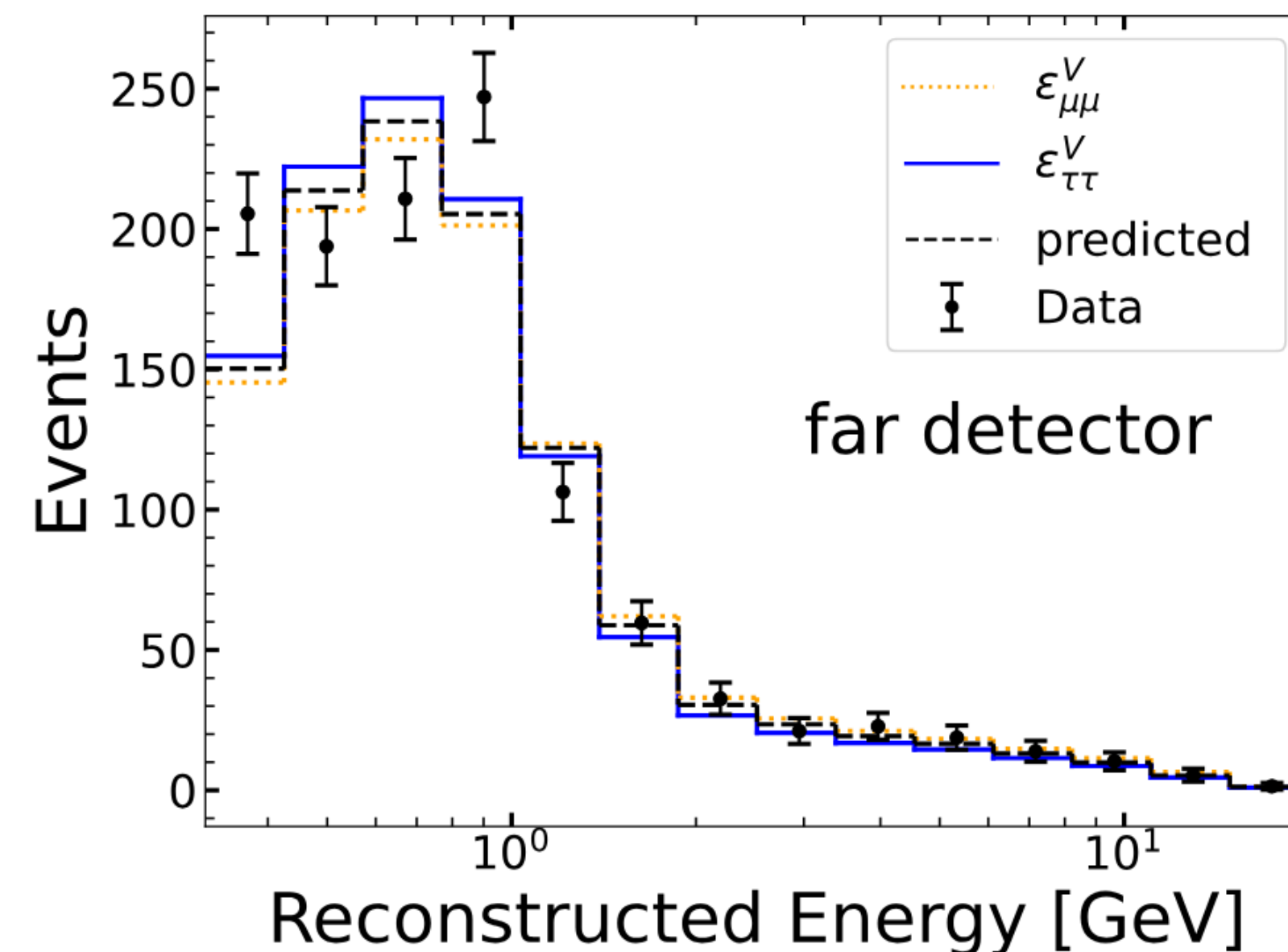
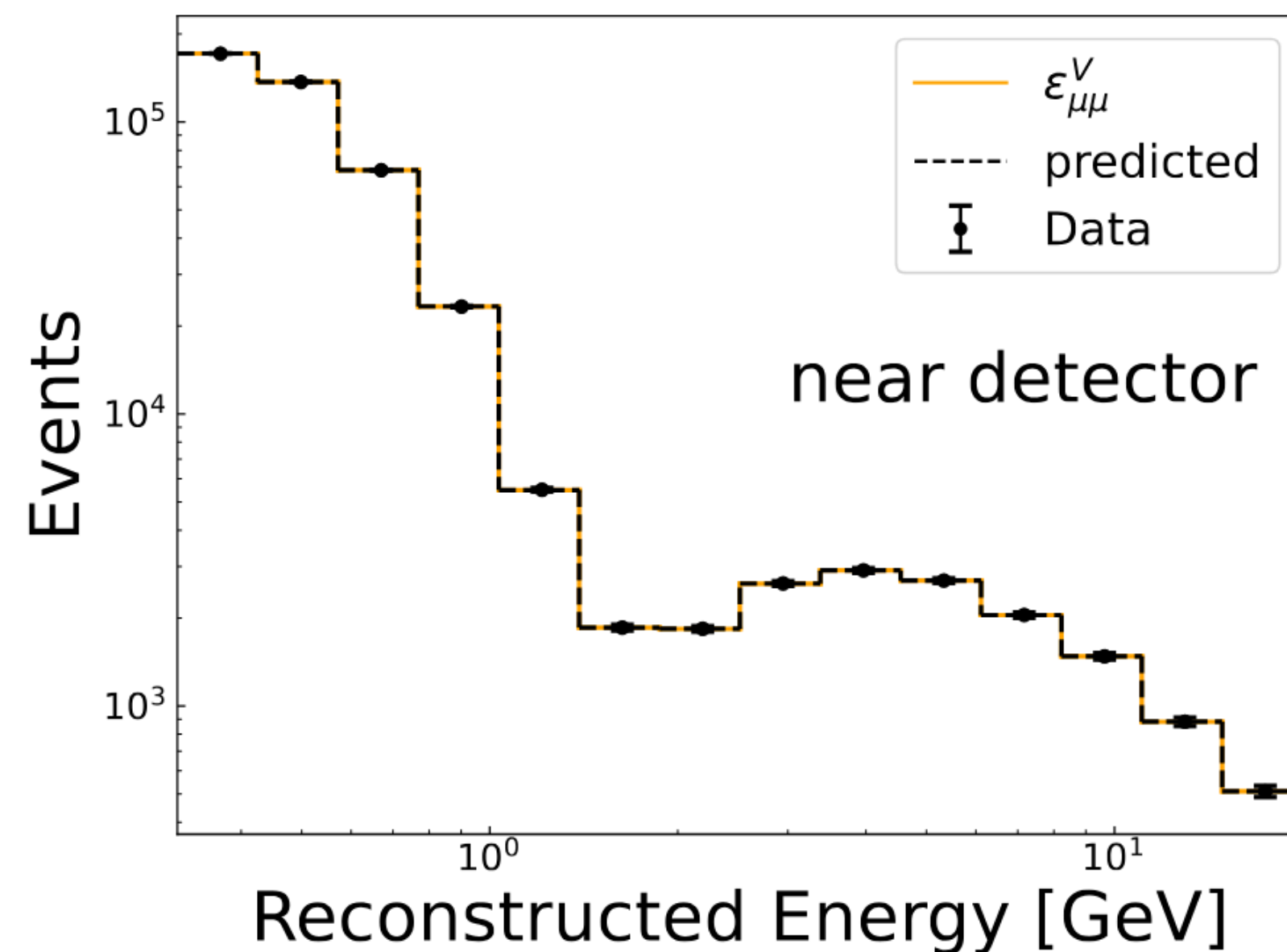
$\sigma_\alpha = 0.15$

NC NSI events at LBL experiment

Results

JG, Machado, Pinheiro, [2412.08712](#)

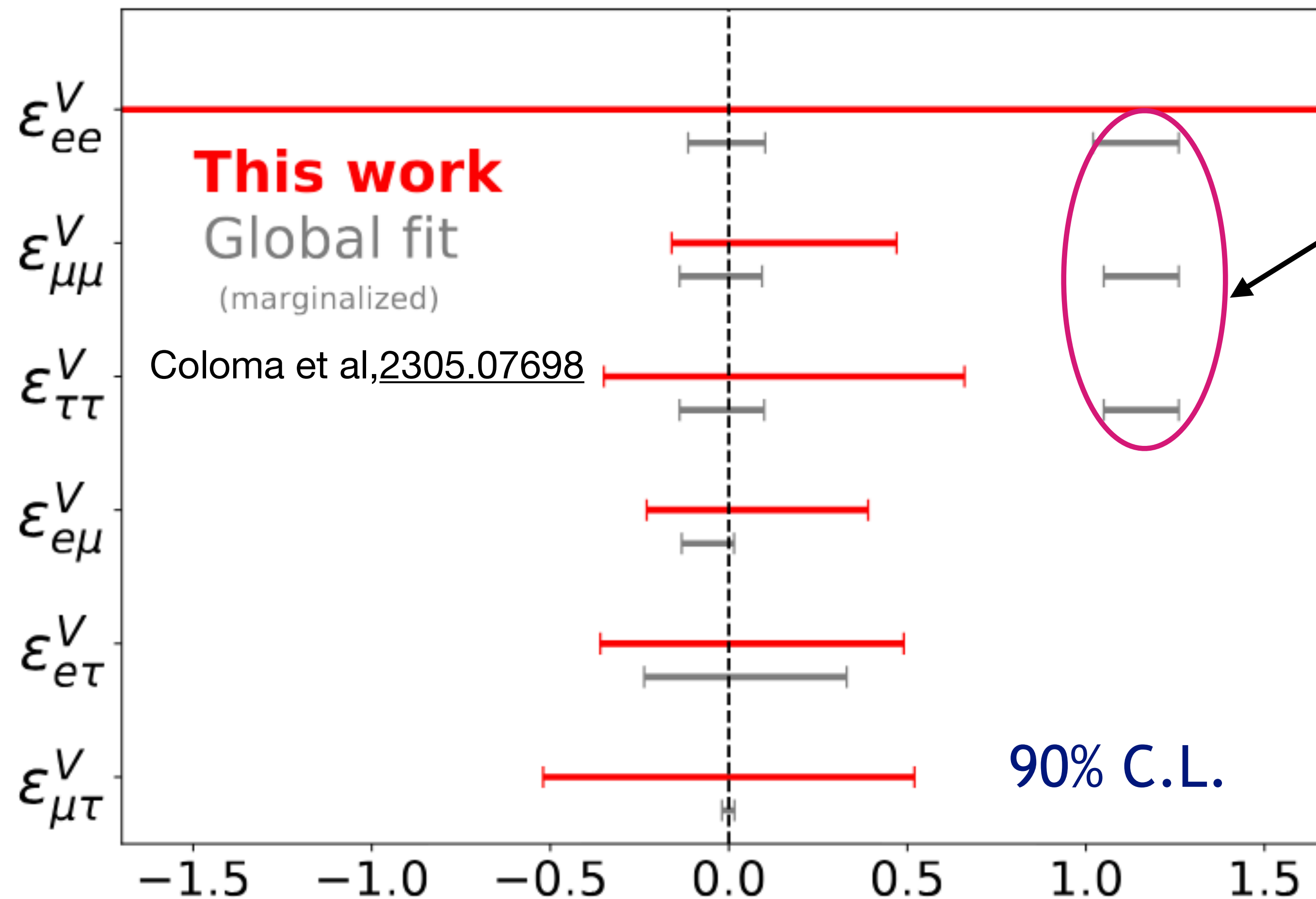
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NC NSI events at LBL experiment

Results: Vector NSI

JG, Machado, Pinheiro, [2412.08712](#)



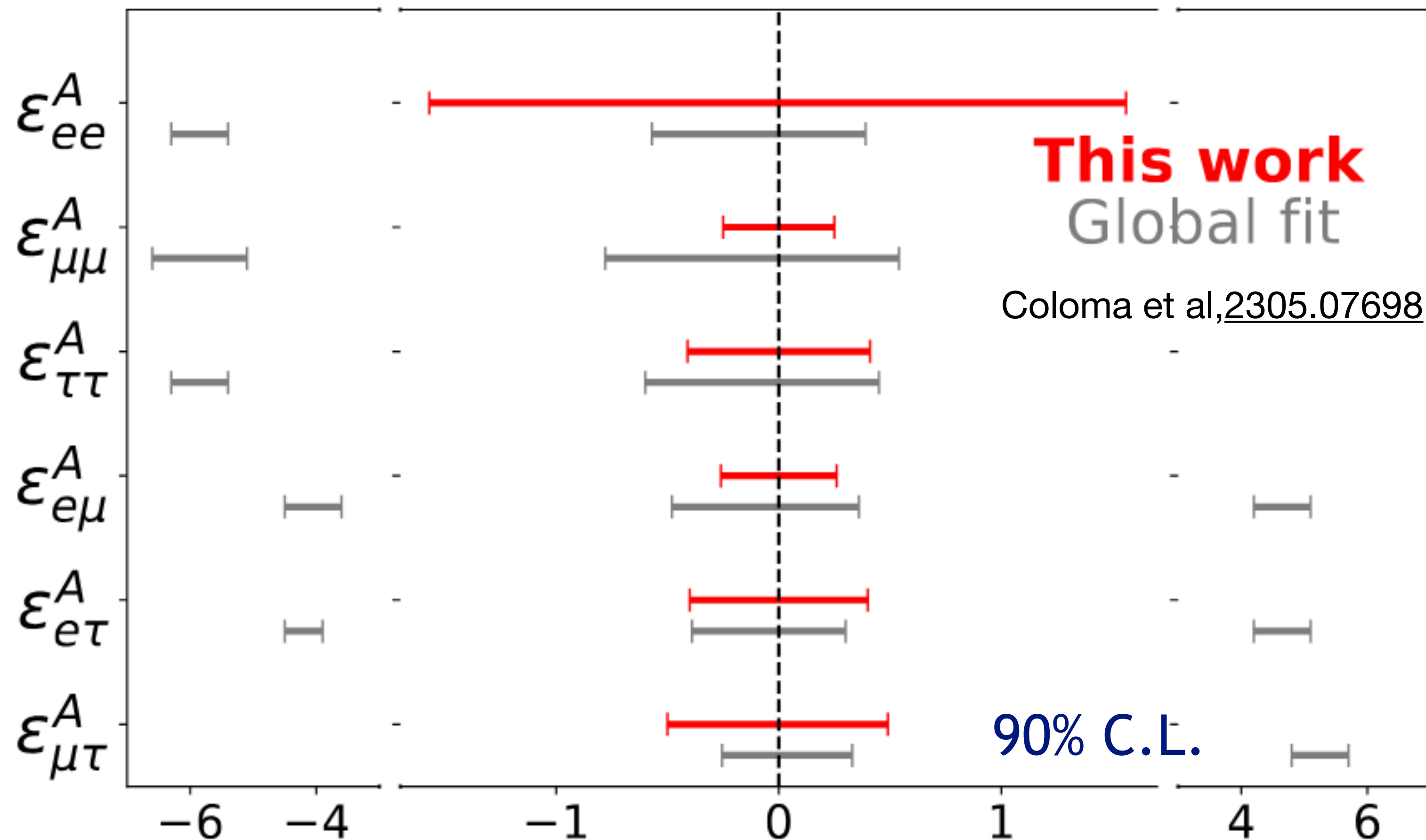
LMA-Dark:
Exact degeneracy in
oscillations

- degeneracy **broken** in scattering processes
- **Complementary** constraints from CC channel
- **Little** sensitivity to phase of off-diagonal NSI

NC NSI events at LBL experiment

Results: Axial-vector NSI

JG, Machado, Pinheiro, [2412.08712](#)



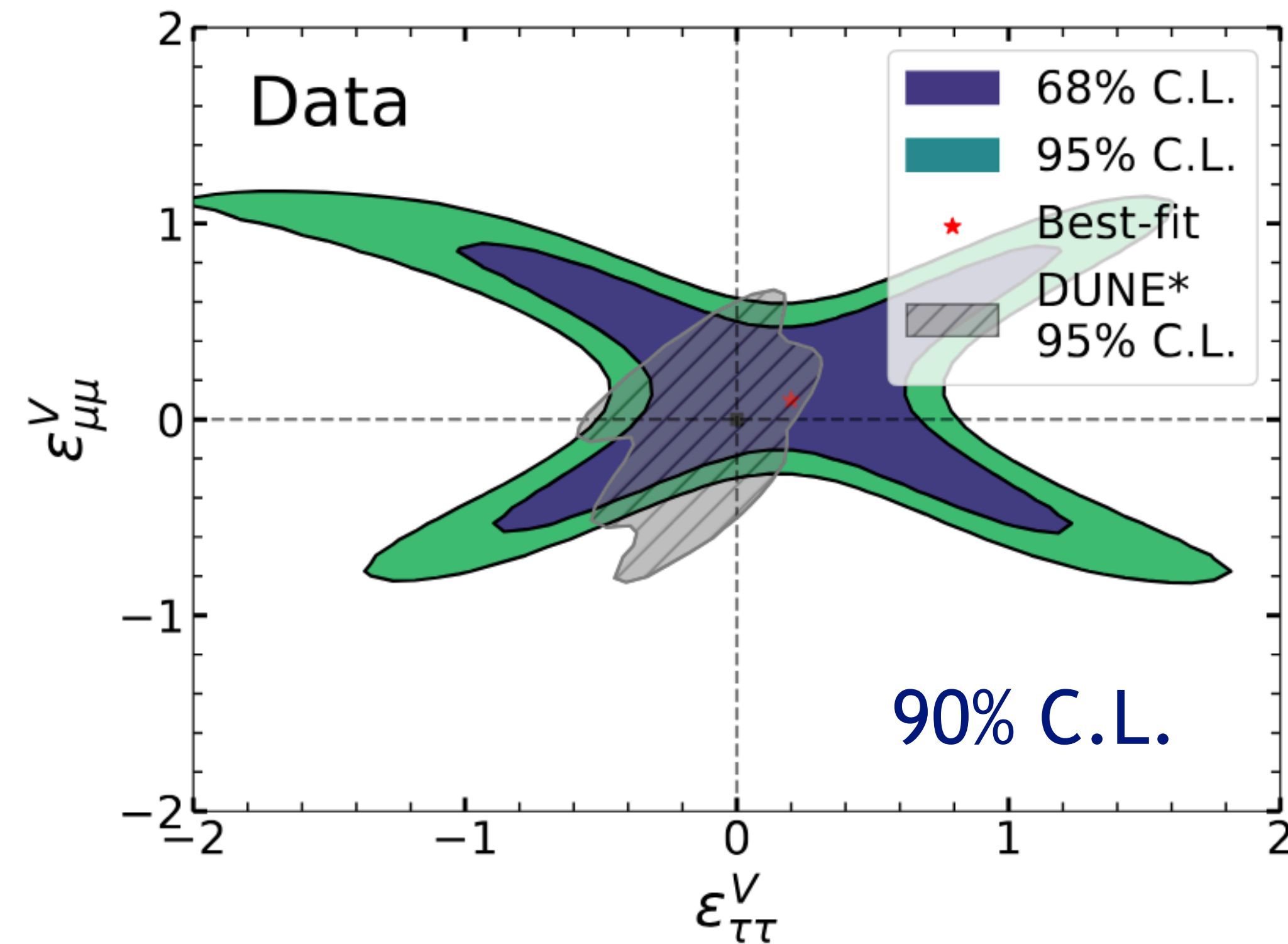
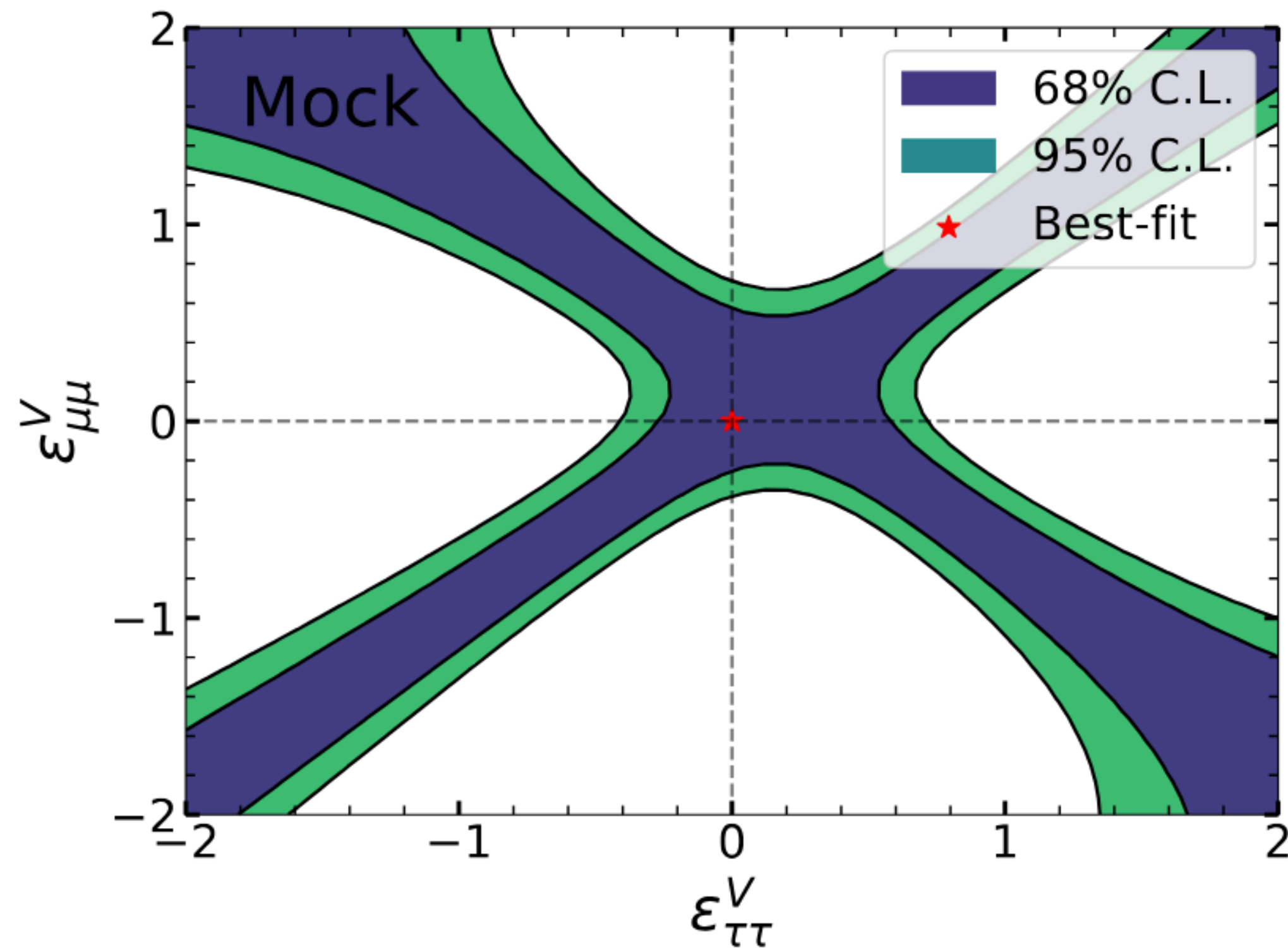
See [Abbaslu, Dehpour, Farzan, Safari '23](#), [Abbaslu, Farzan '25](#) for studies at axial vector NSI from NC events at DUNE and MINOS (+)

- **Stronger** constraints than global fit for many parameter
- Dominant experiment: SNO (ν –deuterium scattering) **only** sensitive to isospin violating axial NSI ($\varepsilon^u - \varepsilon^d$)
- Degeneracies **broken** by addition of NOvA
- **Novel** constraints on isospin conserving axial NSI

NC NSI events at LBL experiment

Results: 2D vector NSI

JG, Machado, Pinheiro, [2412.08712](#)

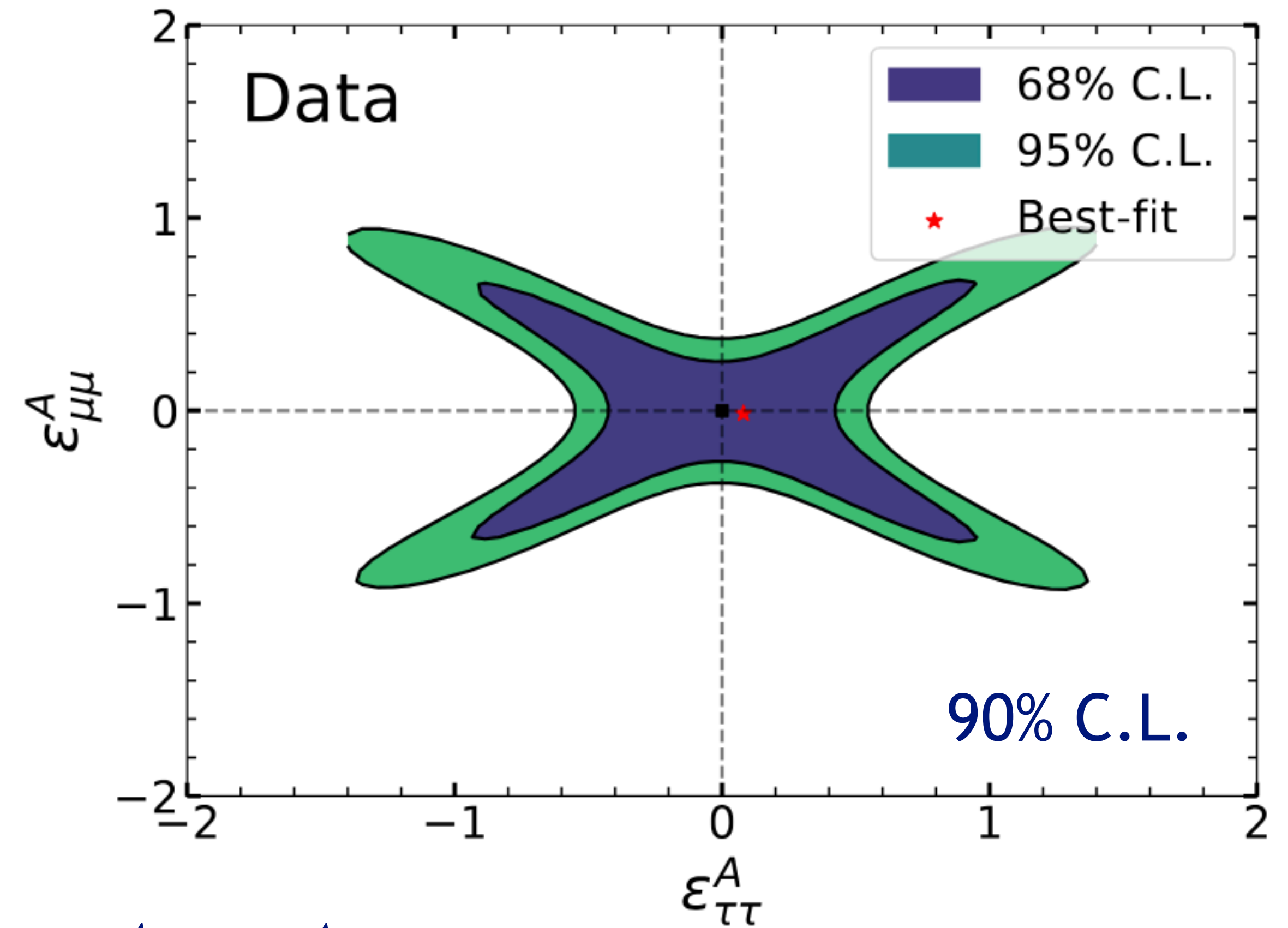
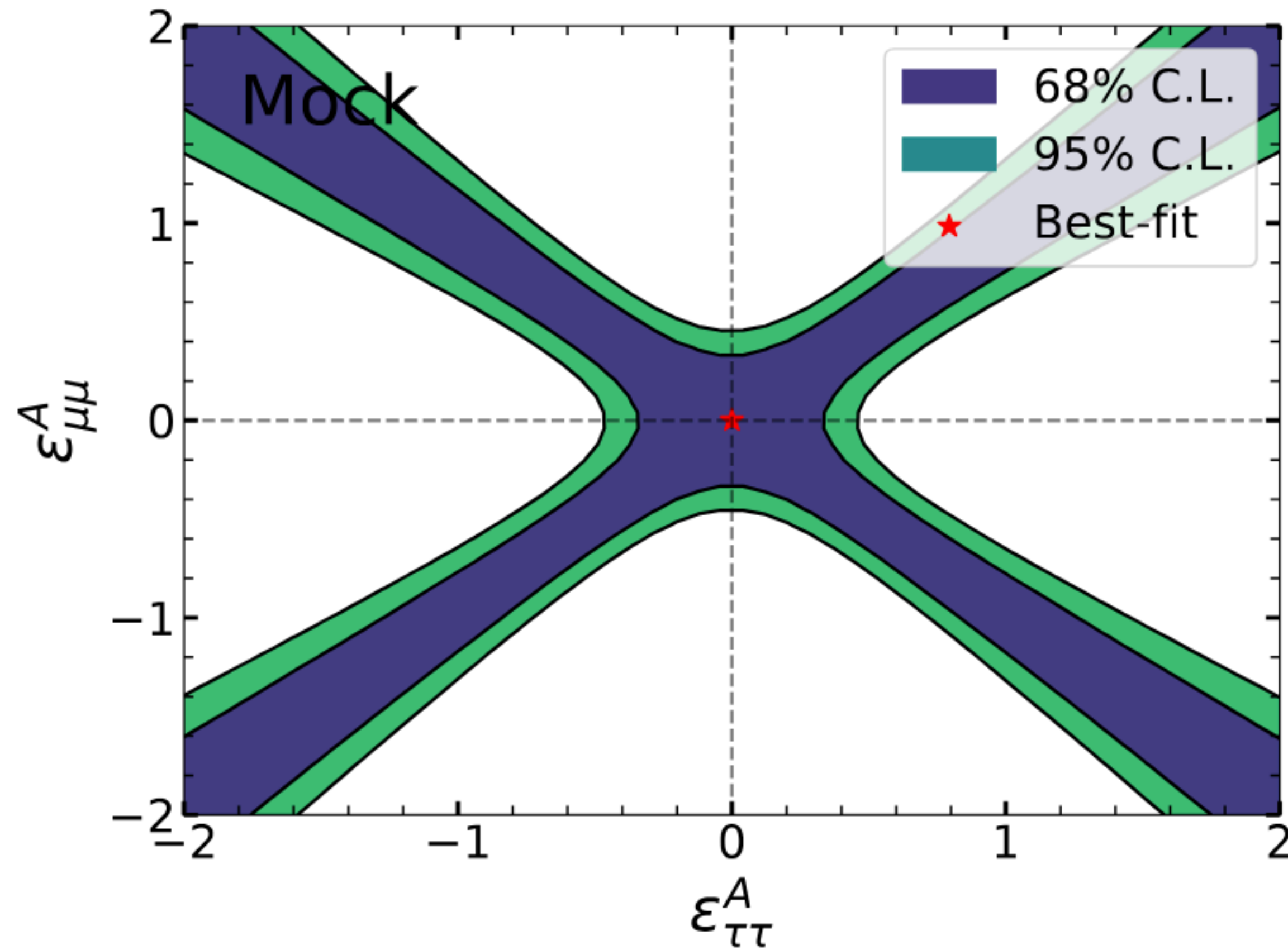


Degeneracy between $\epsilon_{\mu\mu}^V - \epsilon_{\tau\tau}^V$,
different from degeneracy in the CC channel

NC NSI events at LBL experiment

Results: 2D axial-vector NSI

JG, Machado, Pinheiro, [2412.08712](#)



Degeneracy between $\varepsilon_{\mu\mu}^A - \varepsilon_{\tau\tau}^A$

90% C.L.

NC NSI events at LBL experiment

Complementary with CC channel

Results show **complementary constraints** on *isospin conserving* NC vector NSI from NC & CC detection

Can we learn something about the case $\epsilon^u \neq \epsilon^d$?



NC NSI events at LBL experiment

Complementary with CC channel

Results show **complementary constraints** on *isospin conserving* NC vector NSI
from NC & CC detection

Can we learn something about the case $\epsilon^u \neq \epsilon^d$?

Yes, but not in the CC channel!
→ need NC channel

NC NSI events at LBL experiment

Effect of NSI in CC channel: **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 $a \propto G_F \rho E$

Effective NSI parameters are sum of contributions from electrons, up- and down quarks

$$\epsilon_{\alpha\beta} = \epsilon_{\alpha\beta}^{eV} + (2 + Y_n) \epsilon_{\alpha\beta}^{uV} + (1 + 2Y_n) \epsilon_{\alpha\beta}^{dV}$$

NC NSI events at LBL experiment

Effect of NSI in CC channel: new matter effect

JG, Hoefken Zink, Machado, Pinheiro, [2604.16176](#)

Effective NSI parameters are sum of contributions from up- and down quarks (assuming no coupling to electrons)

$$\epsilon_{\alpha\beta} = \epsilon_{\alpha\beta}^{eV} + (2 + Y_n)\epsilon_{\alpha\beta}^{uV} + (1 + 2Y_n)\epsilon_{\alpha\beta}^{dV}$$

neutron to electron ratio $Y_n \approx 1.05$ in the Earth

Assuming no coupling to electrons and with the isospin decomposition

$$\epsilon_{\alpha\beta}^{\text{iS}(V,A)} \equiv \epsilon_{\alpha\beta}^{uV,A} + \epsilon_{\alpha\beta}^{dV,A} \quad (\text{isoscalar}) ,$$

$$\epsilon_{\alpha\beta}^{\text{iV}(V,A)} \equiv \epsilon_{\alpha\beta}^{uV,A} - \epsilon_{\alpha\beta}^{dV,A} \quad (\text{isovector})$$

NC NSI events at LBL experiment

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$$\begin{aligned} \epsilon_{\alpha\beta}^{\text{iS}(V,A)} &\equiv \epsilon_{\alpha\beta}^{uV,A} + \epsilon_{\alpha\beta}^{dV,A} && \text{(isoscalar)} , \\ \epsilon_{\alpha\beta}^{\text{iV}(V,A)} &\equiv \epsilon_{\alpha\beta}^{uV,A} - \epsilon_{\alpha\beta}^{dV,A} && \text{(isovector)} \end{aligned} \quad \Rightarrow \quad \epsilon_{\alpha\alpha}^{\oplus} \approx 3.08 \epsilon_{\alpha\alpha}^{\text{iS}} - 0.025 \epsilon_{\alpha\alpha}^{\text{iV}}$$

Isovector contribution is **suppressed** by a factor ~ 100 in the CC channel

→ CC channel is **only** sensitive to isoscalar NSI

NC NSI events at LBL experiment

Effect of NSI in CC channel: new matter effect

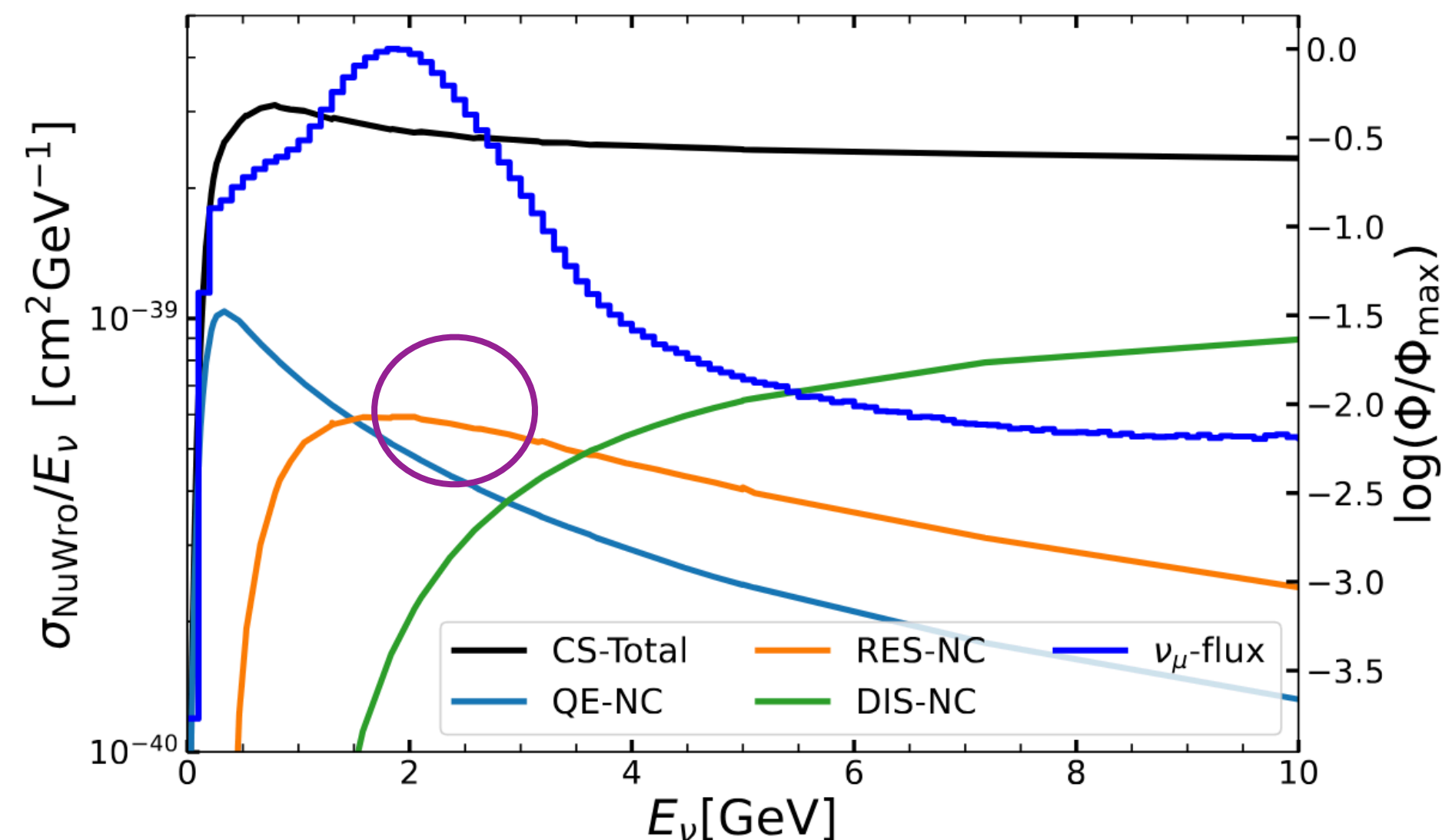
JG, Hoefken Zink, Machado, Pinheiro, [2604.16176](#)

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Effect of NSI in NC channel: new contribution to cross section

Isovector and isoscalar enter the cross section with comparable weights



Isovector NSI enters pion-production transition amplitude for the $\Delta(1232)$ and $N(1520)$ resonances which dominates resonance scattering

→ experiments with sizable neutrino flux at $E_\nu \approx 2.5$ GeV will test isovector NSI

NC NSI events at LBL experiment

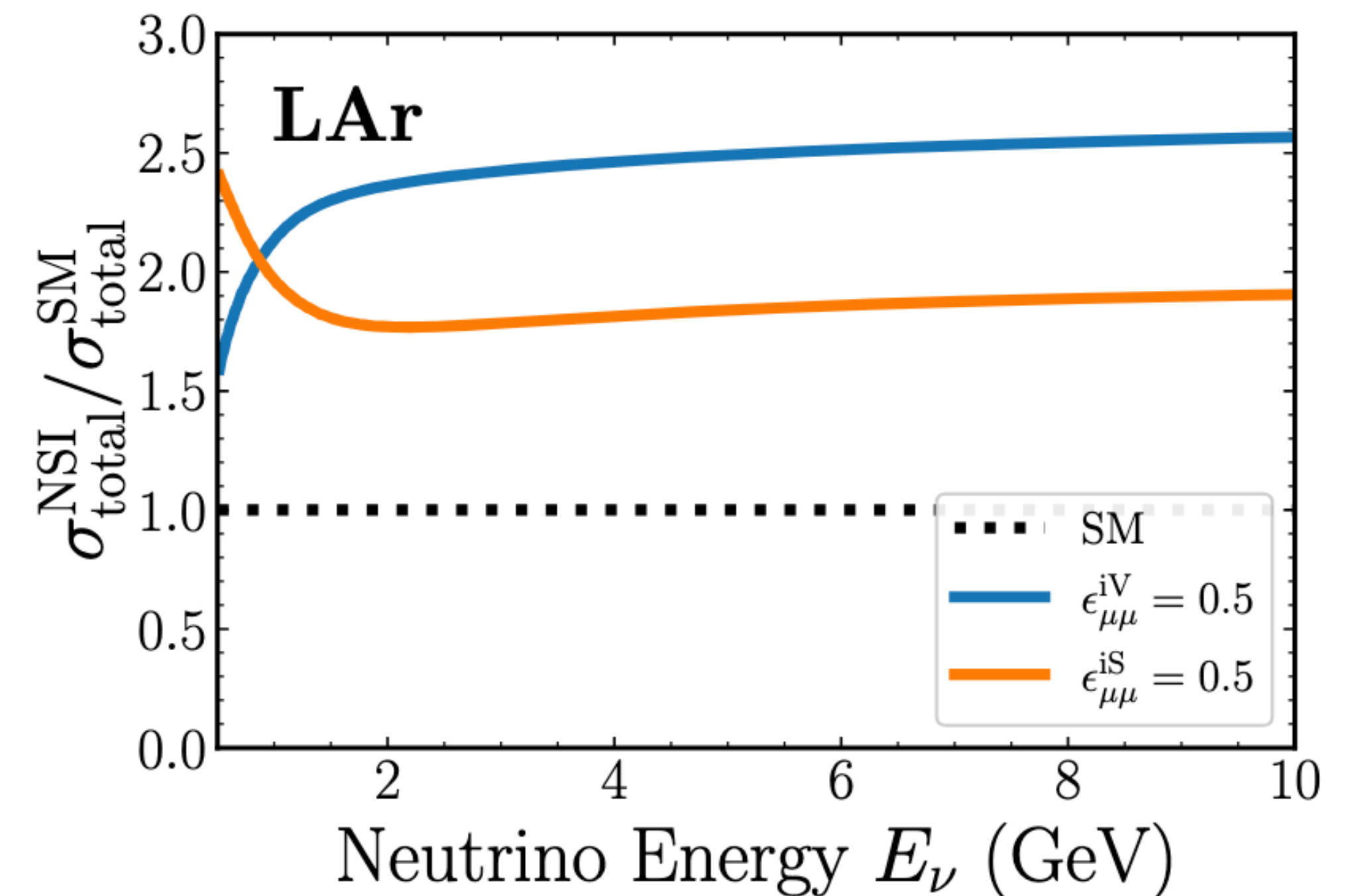
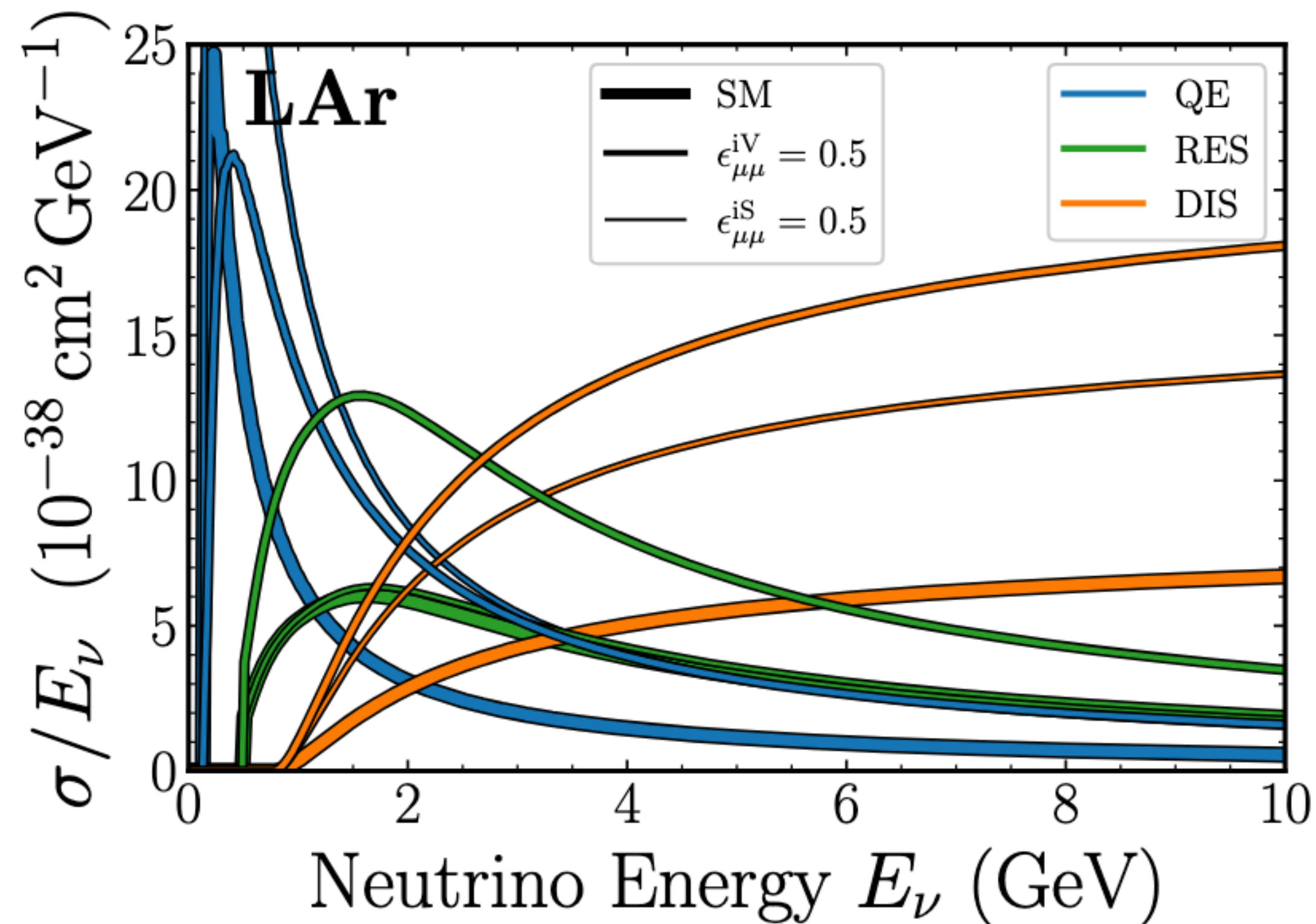
Results: complementary with CC channel

JG, Hoefken Zink, Machado, Pinheiro, 2604.16176

Implementation of QE, RES, DIS cross section with NSI

JG, Hoefken Zink, Machado, Pinheiro, 2606.xxx

Effects at LAr detector

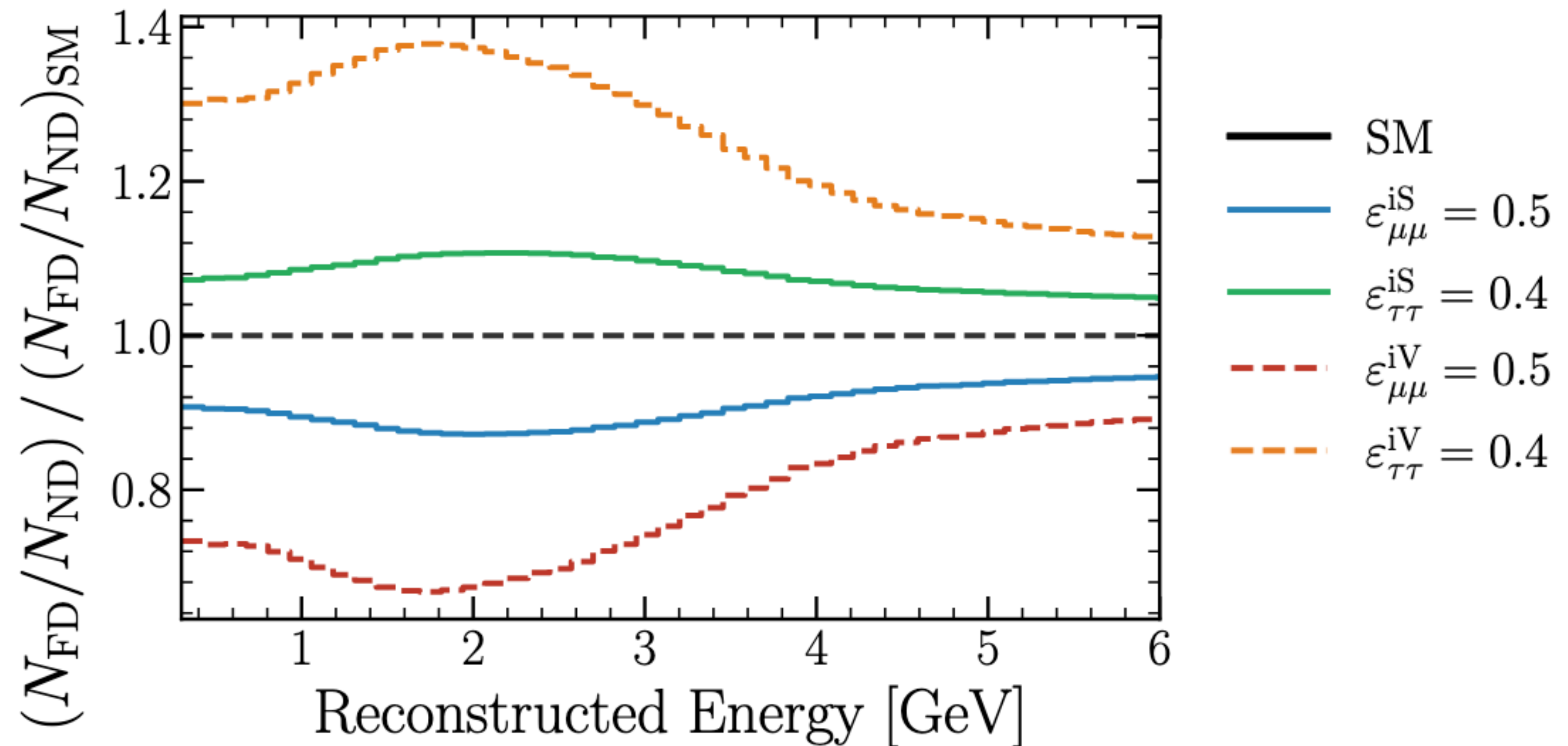


NC NSI events at LBL experiment

Results: complementary with CC channel

JG, Hoefken Zink, Machado, Pinheiro, [2604.16176](#)

Effects at DUNE

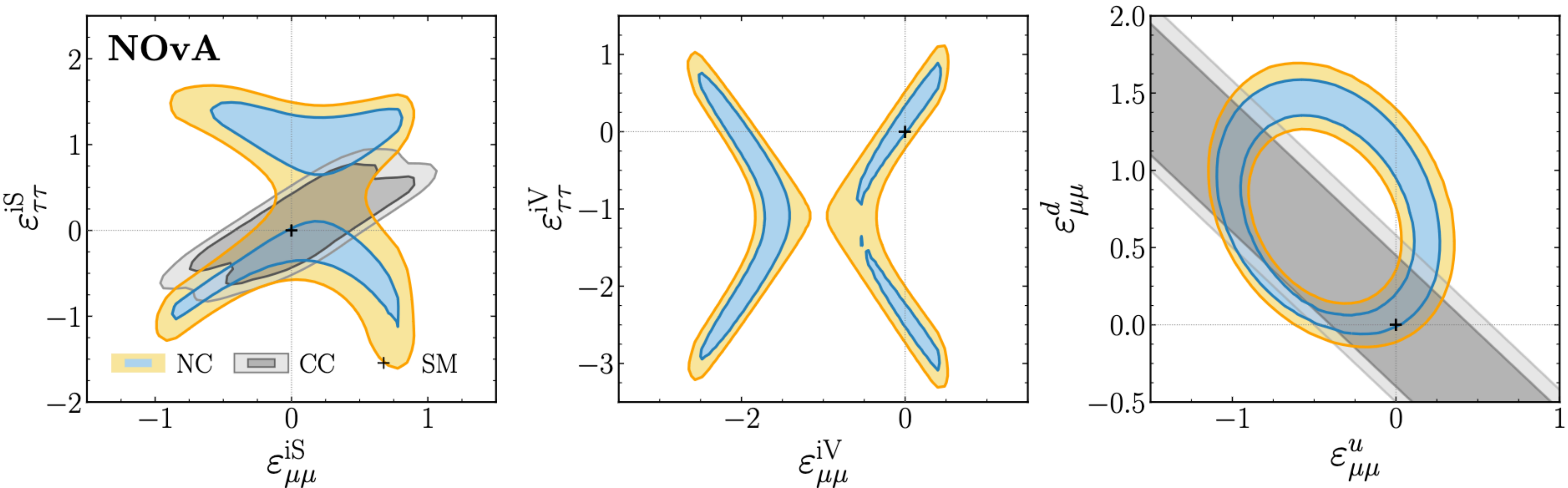


NC NSI events at LBL experiment

Results: complementary with CC channel

JG, Hoefken Zink, Machado, Pinheiro, [2604.16176](#)

Real NOvA data



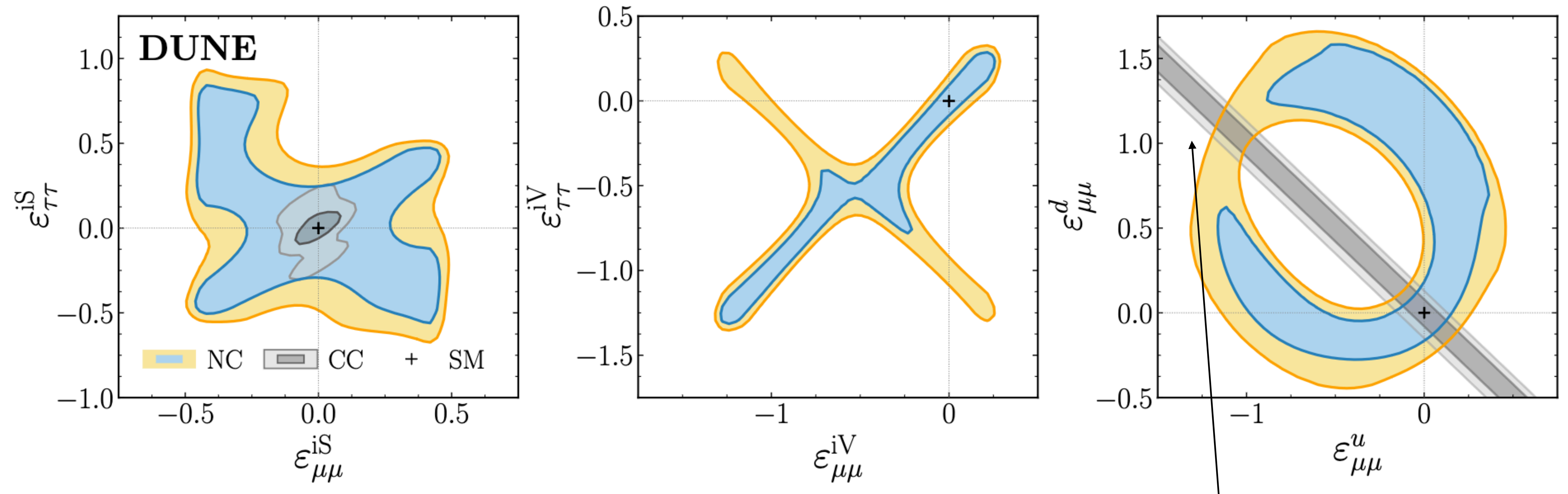
NC NSI events at LBL experiment

Results: complementary with CC channel

JG, Hoefken Zink, Machado, Pinheiro, [2604.16176](#)

Forecasted DUNE data

Generally stronger constraints than NOvA due to longer baseline, larger matter effects



CC constraints are stronger than NC ones

No CC constraints

isoscalar direction: $\epsilon^u + \epsilon^d$

NC NSI events at LBL experiment

Conclusions

- Introduced a **new** way to probe NSI using NC events at LBL experiments
- Constraints on **individual** vector NSI parameters → complementary to CC detection results
- **New, strong** constraints on axial vector NSI → isospin conserving constraints
- Constraints on NSI in tau sector → **complementary** to CEvNS experiments
- NC events **break degeneracy** between $\epsilon_{\mu\mu}^{dV} - \epsilon_{\mu\mu}^{uV}$ which cannot be resolved in the CC channel
- Derived **first constraints** using NC events at NOvA, DUNE will **improve** constraints by a factor of 2-3
- Upcoming paper about implementation of NSI in cross section

Thanks for your attention!



Appendix: How to probe NSI?

In neutrino oscillations:

Vector NSI affect neutrino oscillations as a new matter effect

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

- Real diagonal NSI parameters $\epsilon_{\alpha\alpha}$,
complex off-diagonal parameters $\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}| e^{i\phi_{\alpha\beta}}$
- Can subtract one term on the diagonal $\Rightarrow$ **8 free parameters** 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 as $\epsilon_{\alpha\beta} = \sum_f \epsilon_{\alpha\beta}^{f,V} \langle N_f(x)/N_e(x) \rangle$

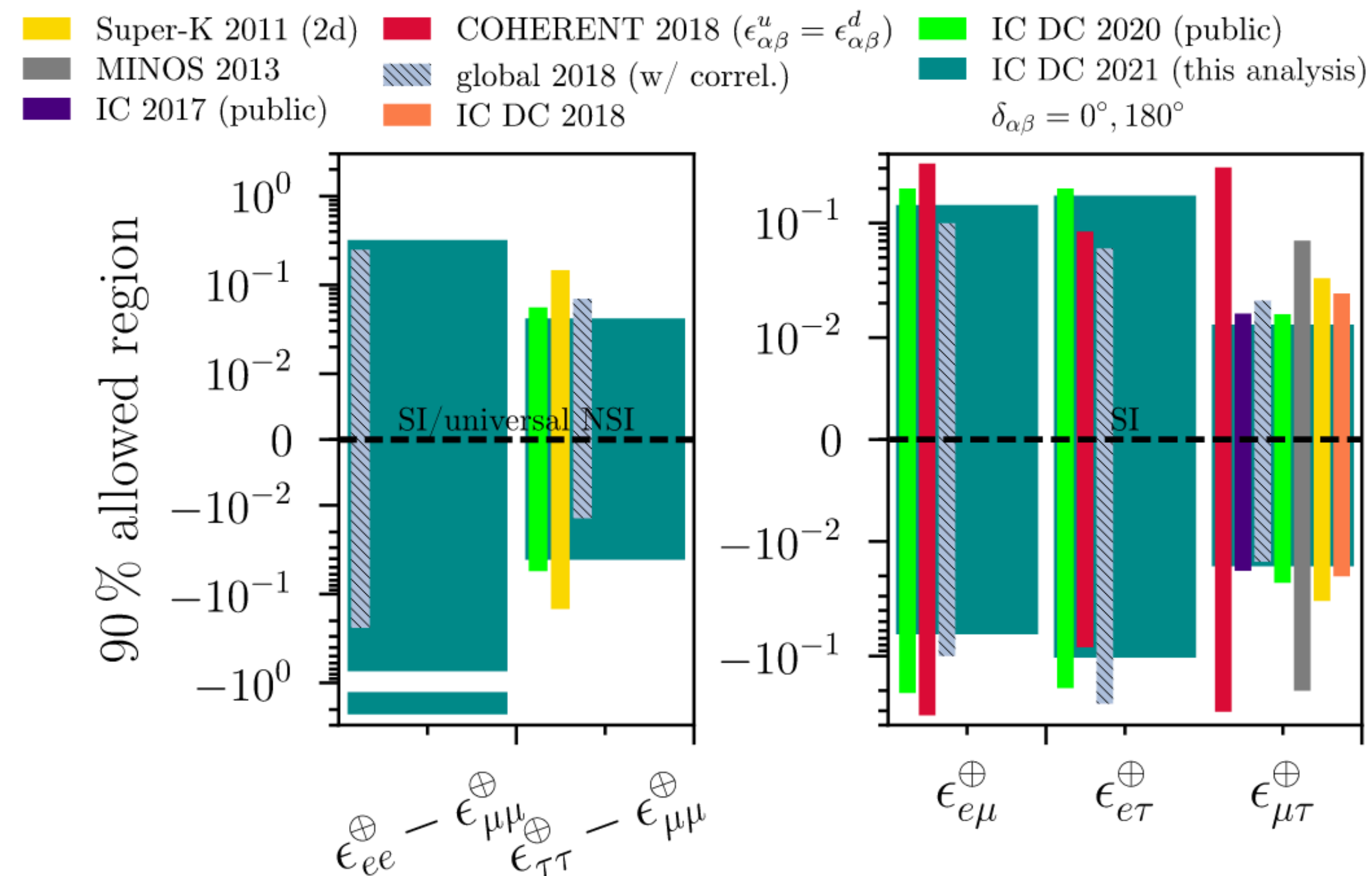
Appendix: How to probe NSI?

In neutrino oscillations:

effect of NSI scales with **energy**, **baseline**, and **matter density**

⇒ use high-energy neutrino sources with long baselines

→ atmospheric neutrinos at IceCube



[IceCube '21]

Appendix: NC NSI events at LBL experiment

Effect of NSI in CC channel: new matter effect

$$\epsilon_{\alpha\beta} = \epsilon_{\alpha\beta}^{eV} + (2 + Y_n)\epsilon_{\alpha\beta}^{uV} + (1 + 2Y_n)\epsilon_{\alpha\beta}^{dV}$$

neutron to electron ratio $Y_n \in [0.14, 0.5]$ in the Sun

→ no $Y_n \approx 1$ suppression but only sensitivity to difference in diagonal NSI

Appendix: NC NSI events at LBL experiment

Effect of NSI in NC channel: new contribution to cross section

CEvNS

$$\text{Weak charge: } Q_{w\alpha} = Zg_V^p + Ng_V^n + \frac{3(Z+N)}{2}\epsilon_{\alpha\alpha}^{\text{iS}} + \frac{Z-N}{2}\epsilon_{\alpha\alpha}^{\text{iV}}$$

For targets with $Z \approx N$ the isovector component is suppressed
Using detectors with different Z/N ratios could probe the isovector component with improved precision

Appendix: How to probe NSI?

In neutrino scattering:

Use NC scattering processes to probe NC NSI

$\nu - N$ scattering: NuTeV, CHARM, CEvNS

$\nu - e$ scattering: Borexino, GEMMA, TEXONO

App: NC NSI events at LBL experiment

JG, Machado, Pinheiro, [2412.08712](#)

Results

vector NSI	constraint at 90%C.L.	axial-vector NSI	constraint at 90%C.L.
ε_{ee}^V	$[-6.4, 1.7]$	ε_{ee}^A	$[-1.6, 1.6]$
$\varepsilon_{\mu\mu}^V$	$[-0.16, 0.47]$	$\varepsilon_{\mu\mu}^A$	$[-0.25, 0.25]$
$\varepsilon_{\tau\tau}^V$	$[-0.35, 0.66]$	$\varepsilon_{\tau\tau}^A$	$[-0.41, 0.41]$
$\varepsilon_{e\mu}^V$	$[-0.23, 0.39]$	$\varepsilon_{e\mu}^A$	$[-0.26, 0.26]$
$\varepsilon_{e\tau}^V$	$[-0.36, 0.49]$	$\varepsilon_{e\tau}^A$	$[-0.40, 0.40]$
$\varepsilon_{\mu\tau}^V$	$[-0.52, 0.52]$	$\varepsilon_{\mu\tau}^A$	$[-0.49, 0.49]$

App: NC NSI events at LBL experiment

JG, Hoefken Zink, Machado, Pinheiro, [2604.16176](#)

Results

NSI	NOvA	DUNE
$\varepsilon_{\tau\tau}^{uV}$	$(-0.22, 0.21)$ $[-0.25, 0.25]$	$(-0.063, 0.054)$ $[-0.080, 0.066]$
$\varepsilon_{\tau\tau}^{dV}$	$(-0.17, 0.13)$ $[-0.21, 0.19]$	$(-0.064, 0.056)$ $[-0.080, 0.070]$
$\varepsilon_{\mu\mu}^{uV}$	$(-0.18, 0.10)$ $[-0.25, 0.14]$	$(-0.060, 0.069)$ $[-0.074, 0.090]$
$\varepsilon_{\mu\mu}^{dV}$	$(-0.10, 0.17)$ $[-0.14, 0.21]$	$(-0.059, 0.072)$ $[-0.073, 0.099]$