

# Constraining new neutrino interactions with neutral current events

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N3AS Seminar

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**COLORADO STATE  
UNIVERSITY**

# Neutrino interactions

Neutrino-fermion  
interactions

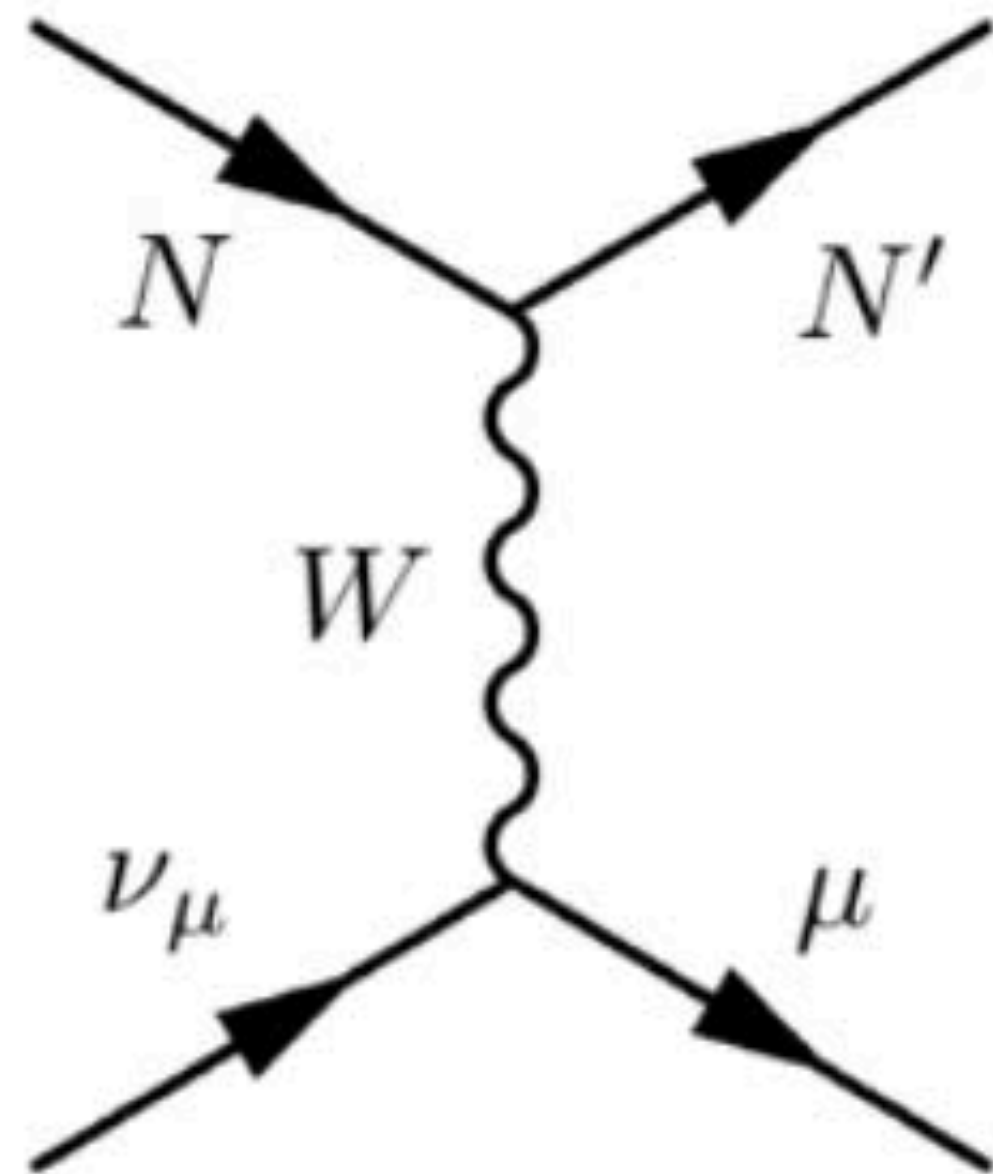
Neutrino-photon  
interactions

Neutrinos interact via the weak interactions  
Are there any other interactions of neutrinos?

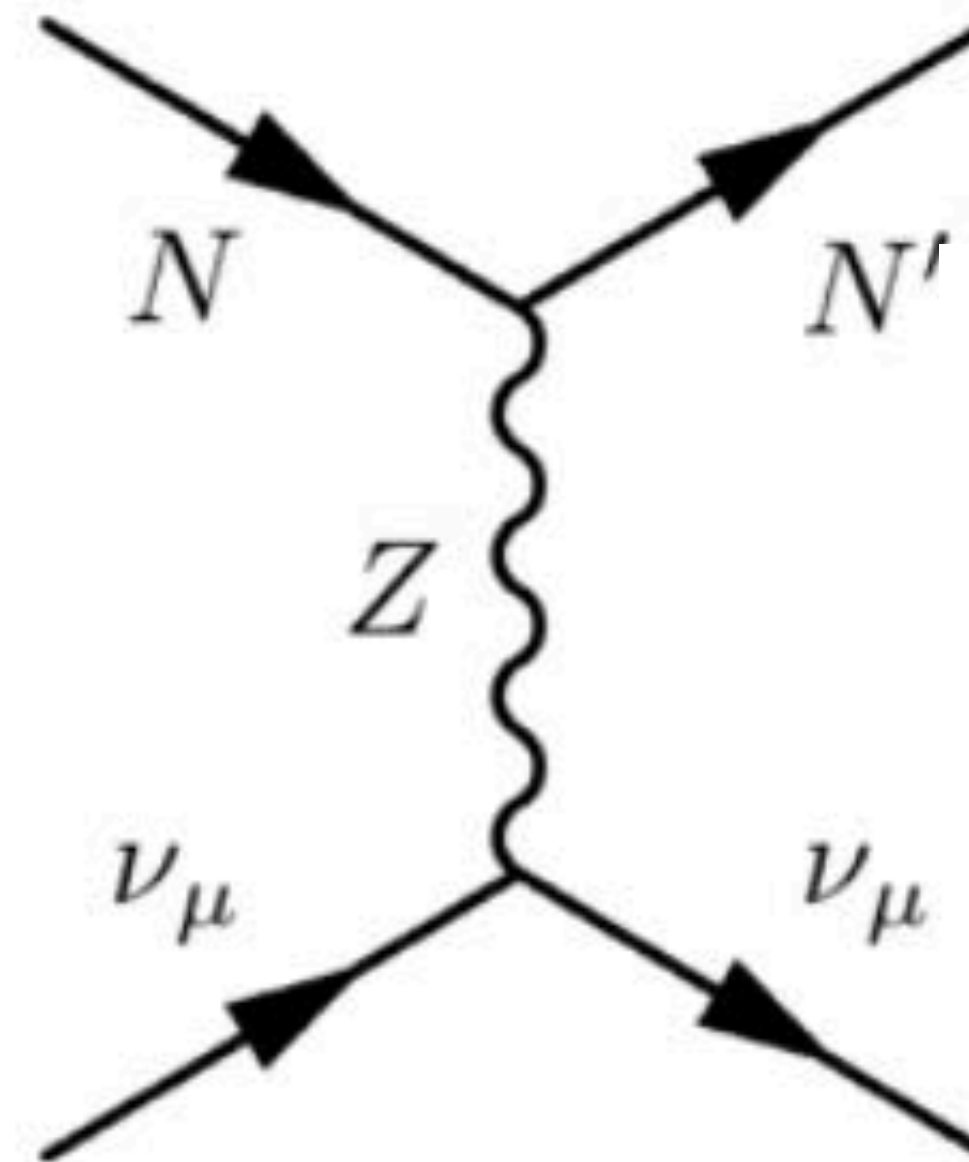
Current knowledge &  
New constraints

# 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 beyond the SM

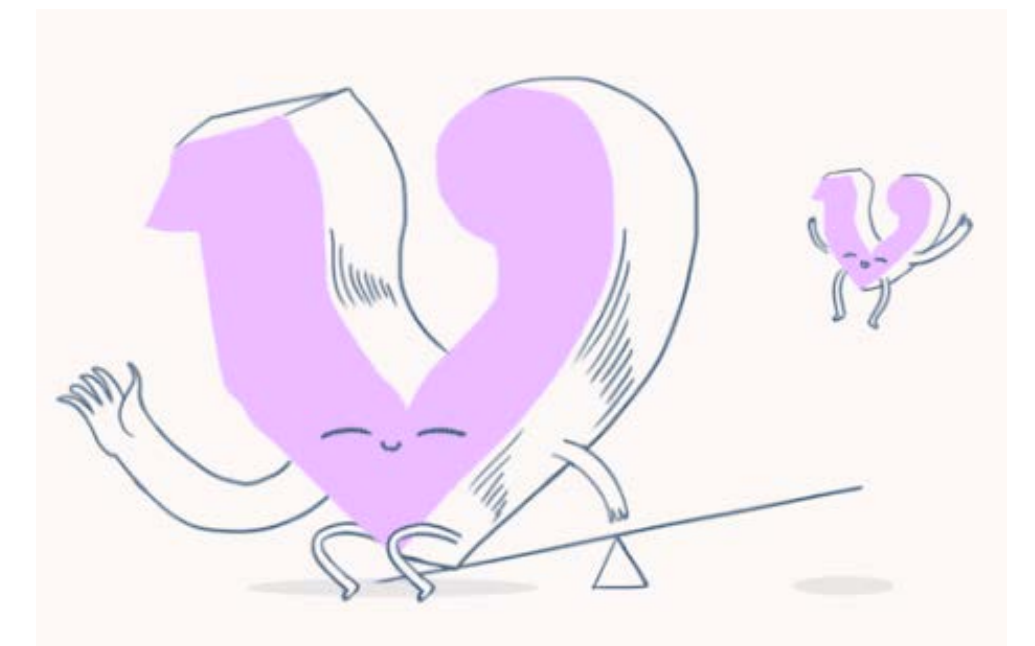
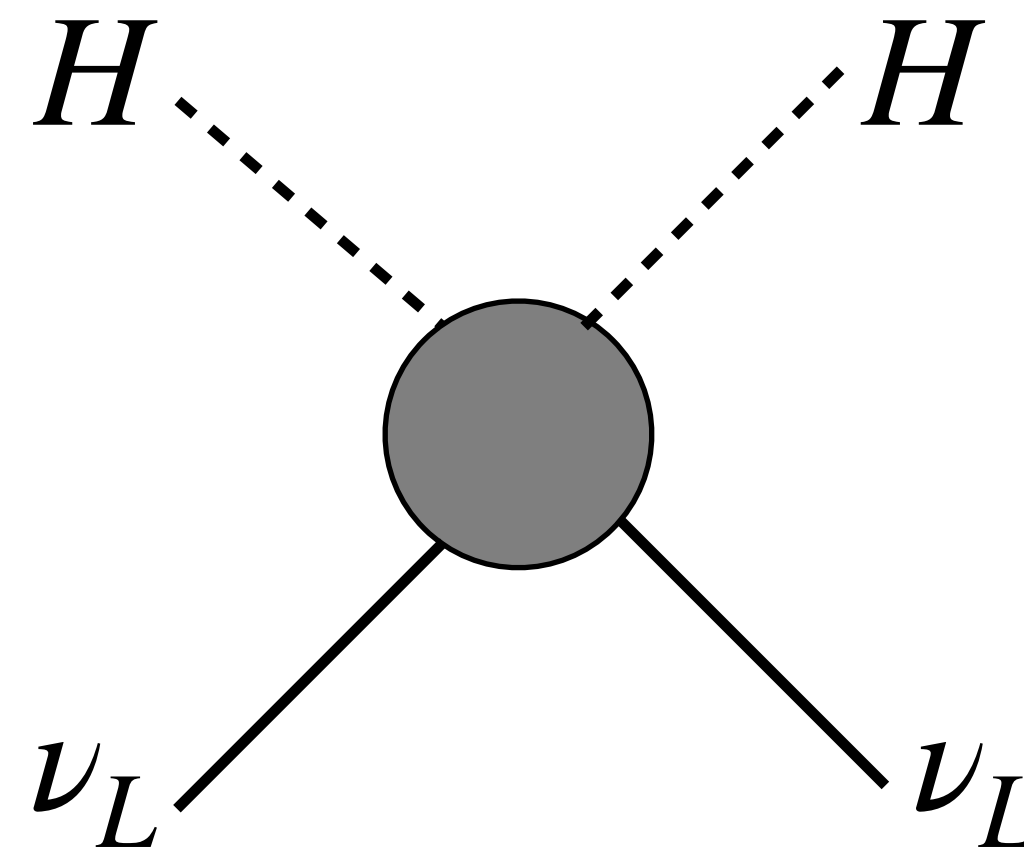
New terms in Lagrangian could appear as higher dimension operator

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

Gives neutrino (Majorana) masses

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

[Weinberg, 1979]

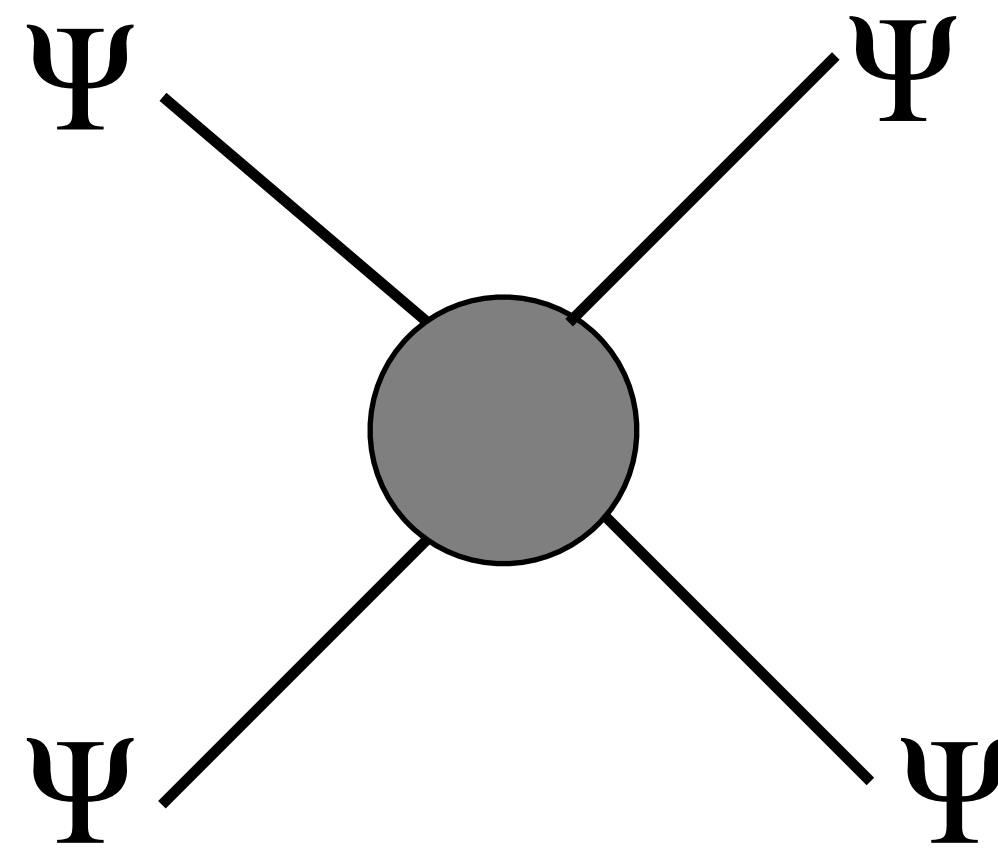


# Neutrino interactions beyond the SM

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Gives neutrino (Majorana) masses



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

# Neutrino non-standard interactions

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

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

NSI parameter  $\epsilon$ : 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?

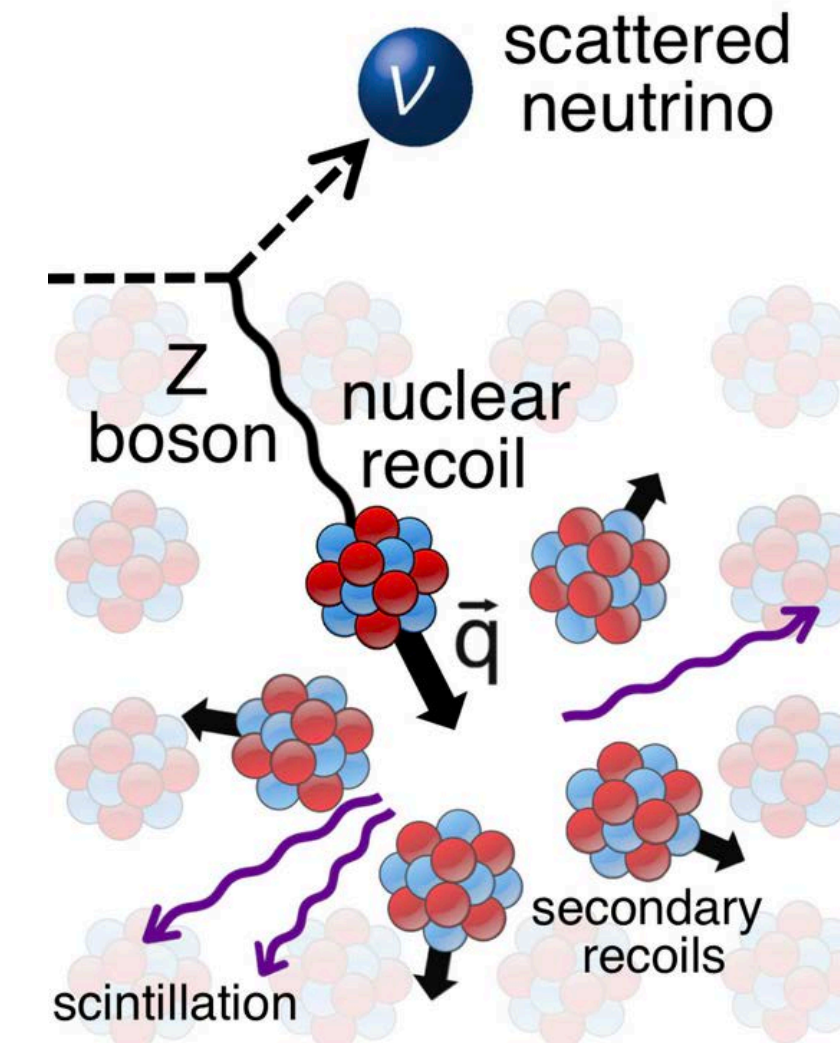
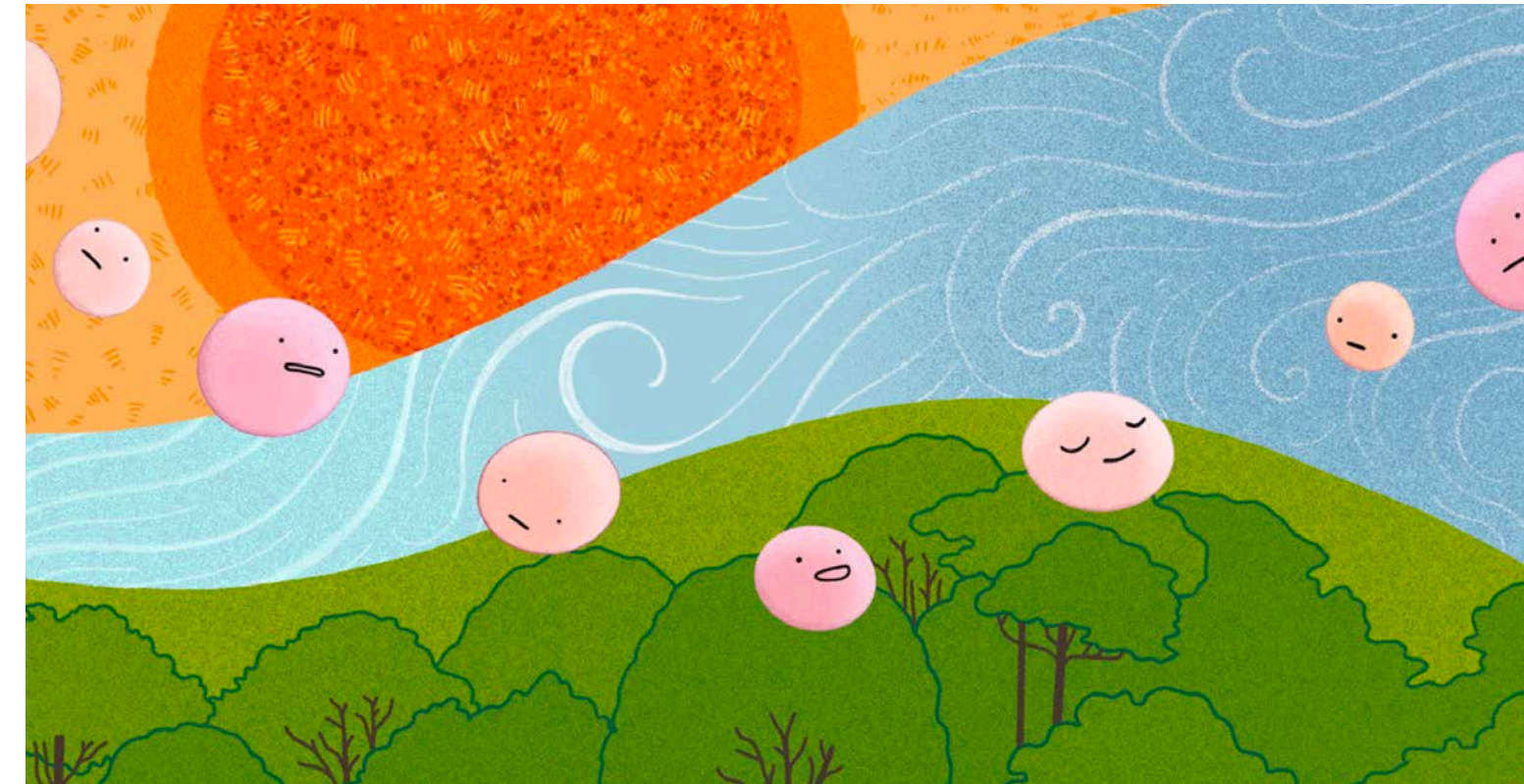
## Neutrino oscillations

Produce neutrino of certain flavor  $\alpha$ ,  
detect neutrino of flavor  $\beta$  after a  
distance

→ extract oscillation probability  $P_{\alpha\beta}$

## Neutrino scatterings

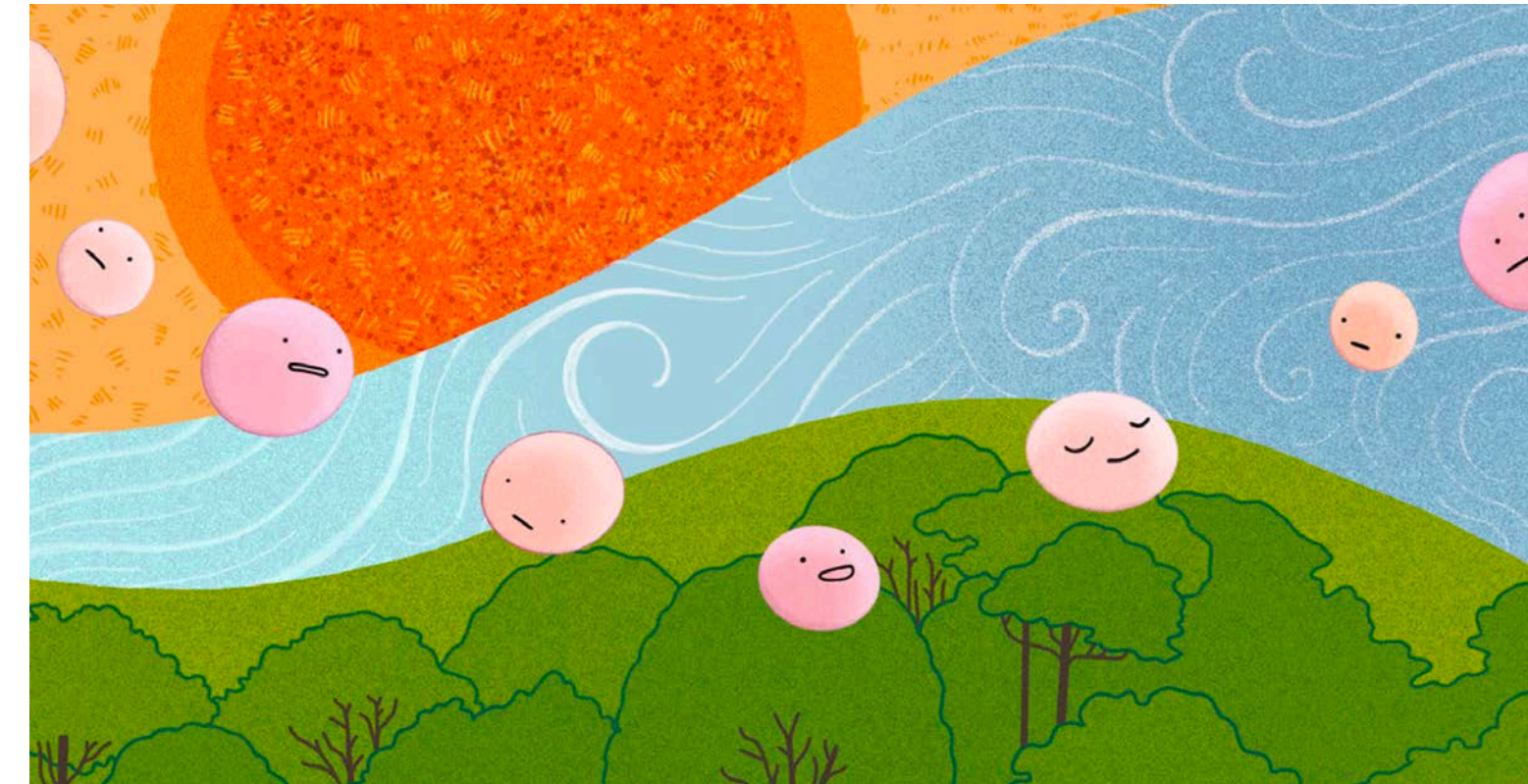
Produce and detect neutrino of certain  
flavor, typically without oscillation  
effects



# How to probe NSI?

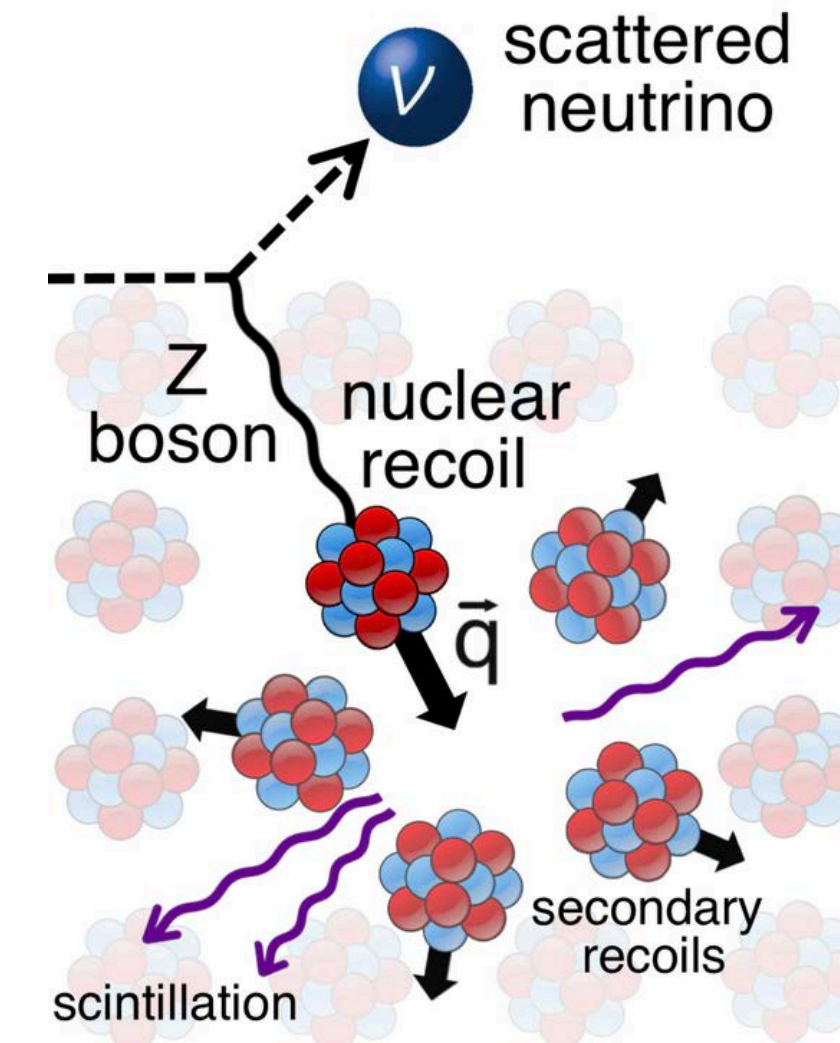
## Neutrino oscillations

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



## Neutrino scatterings

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



# How to probe NSI?

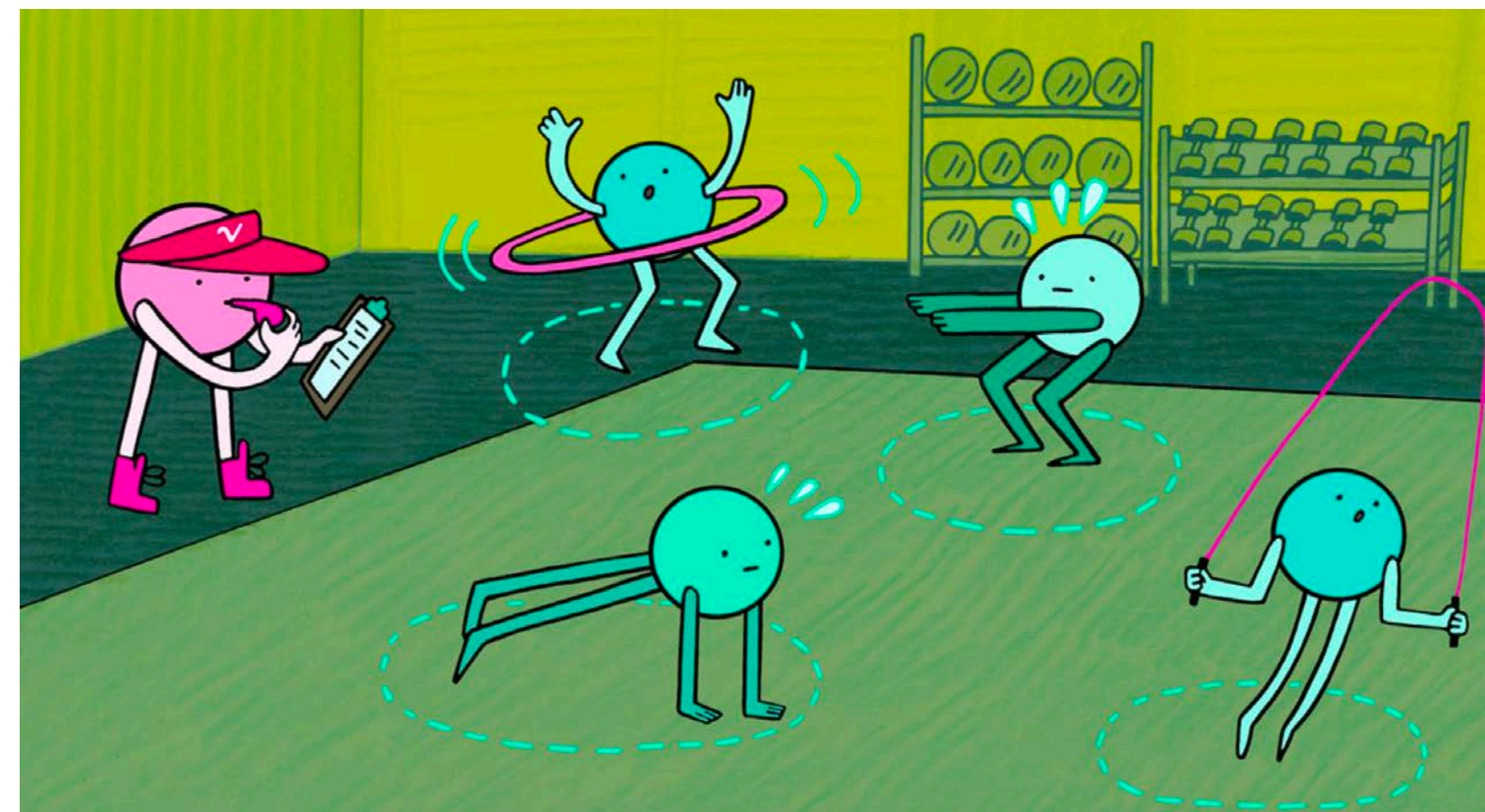
In neutrino oscillations:

**Scalar NSI:**

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

**Vector NSI:**

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



[Wolfenstein '78]

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Yukawa interaction term → induces mass  
depending on fermion density  
⇒ affects **masses** in Hamiltonian


$$H = \frac{1}{2E} \left[ U_{PMNS}^\dagger M^2 U_{PMNS} + V \right]$$

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$$M^2 \rightarrow (M + \delta M)(M + \delta M)^\dagger$$

$$\delta M \propto m_0 \epsilon$$

$$H = \frac{1}{2E} \left[ U_{PMNS}^\dagger M^2 U_{PMNS} + V \right]$$

[Ge, Parke [1812.08376](#)]

[Denton, Giarnetti, Meloni [2210.00109](#)]

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[Ge, Parke [1812.08376](#)]

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New forward scattering with matter  
 → Affect neutrino oscillations as a **new matter effect**

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New forward scattering with matter  
 $\rightarrow$  Affect neutrino oscillations as a **new matter effect**

$$V = a \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \rightarrow a \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

Matter potential  $a \propto G_F \rho E$

[Wolfenstein '78]

# How to probe NSI?

In neutrino oscillations:

Focus on **vector** NSI

New forward scattering with matter

[Wise, Zhang [1803.00591](#)]

→ independent of mass of new mediator! (unless  $m \sim d^{-1}$ )

Affect neutrino oscillations as a **new matter effect**

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

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# How to probe NSI?

In neutrino oscillations:

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  $\epsilon_{\alpha\beta} = \sum_f \epsilon_{\alpha\beta}^{f,V} \langle N_f(x) / N_e(x) \rangle$

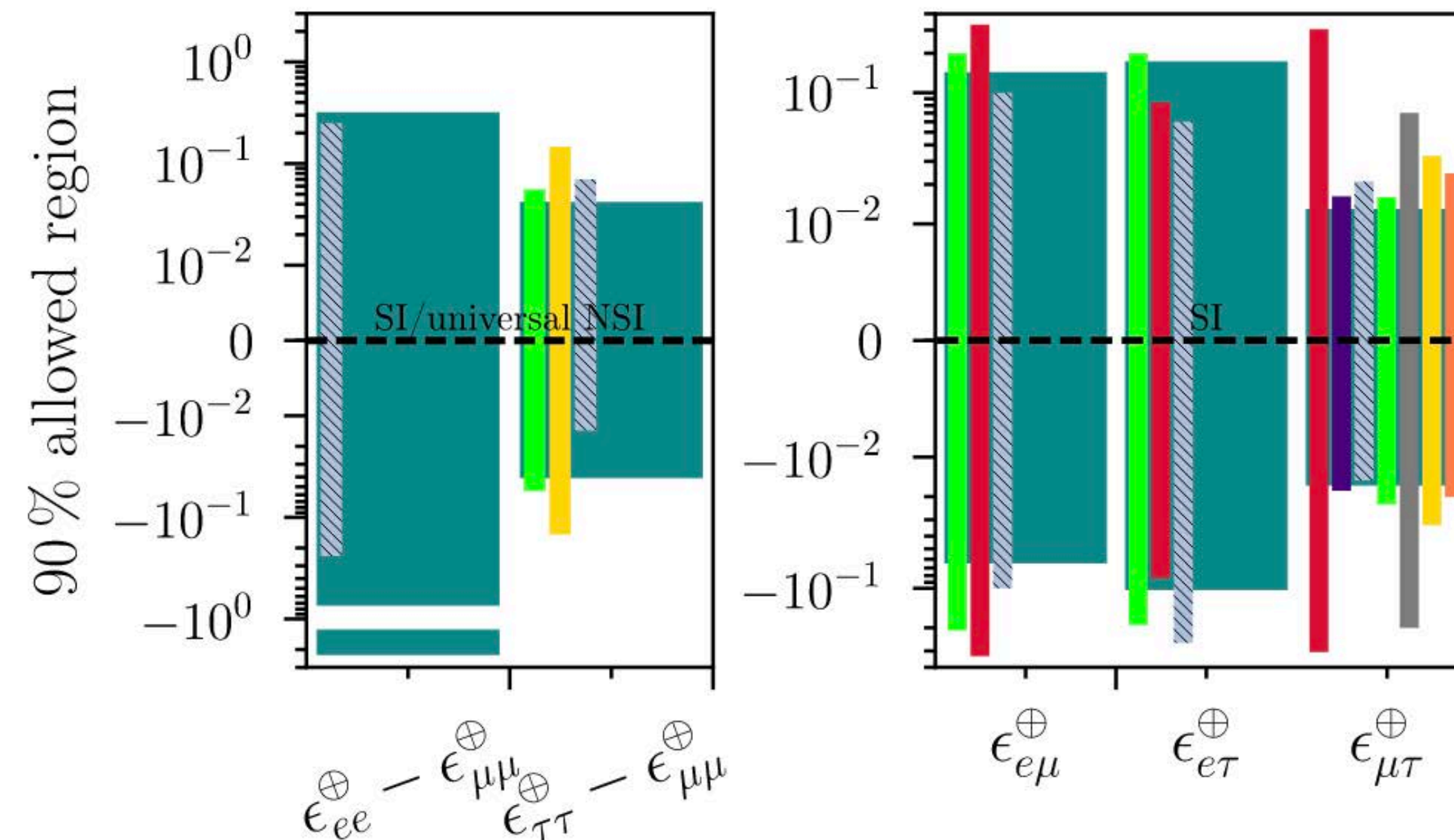
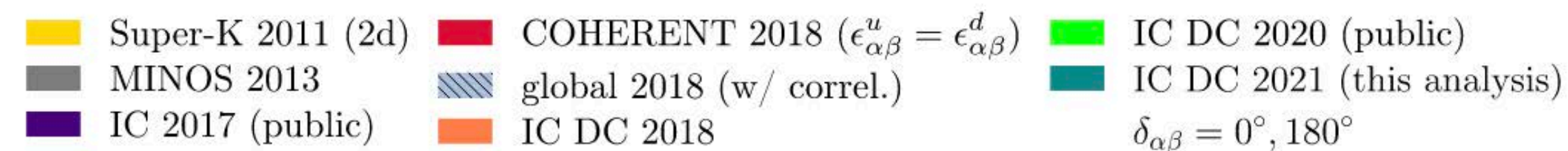
# How to probe NSI?

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

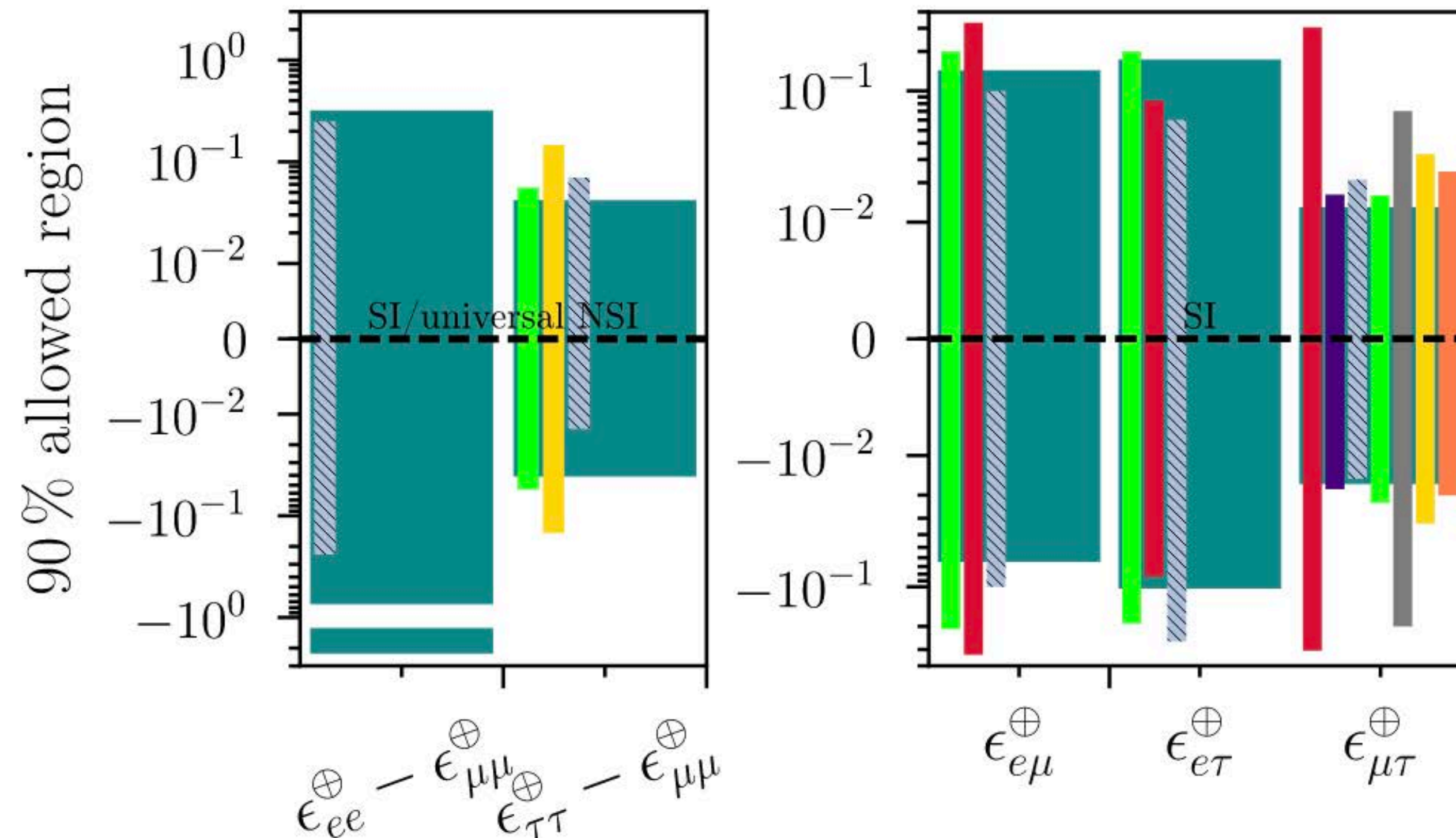
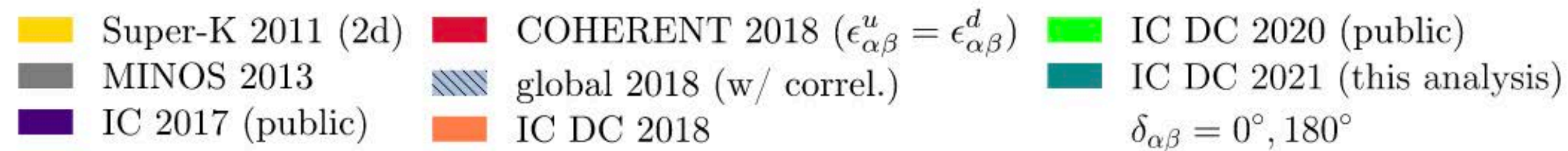


[IceCube 2106.07755]

# How to probe NSI?

In neutrino oscillations:

## Constraints on NSI



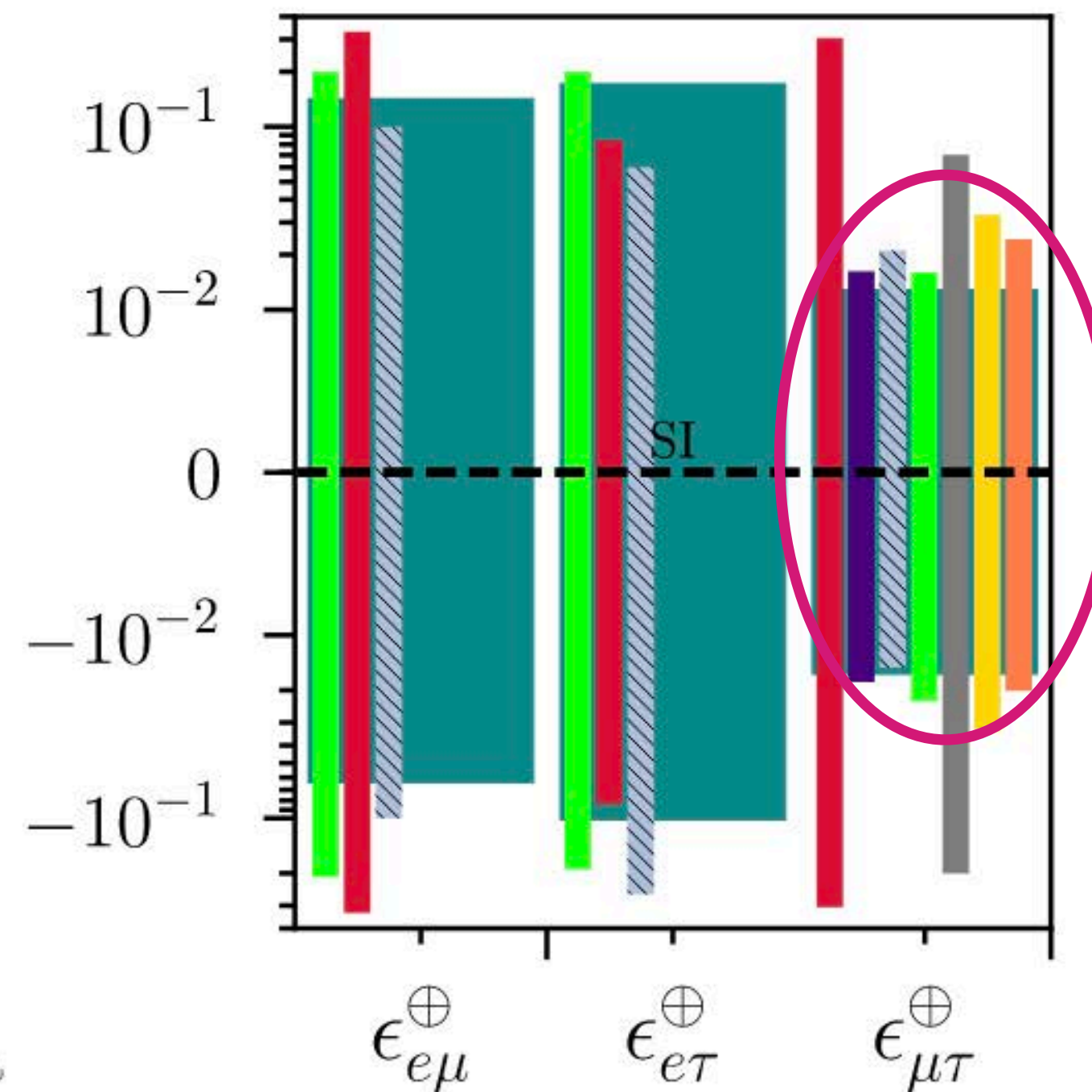
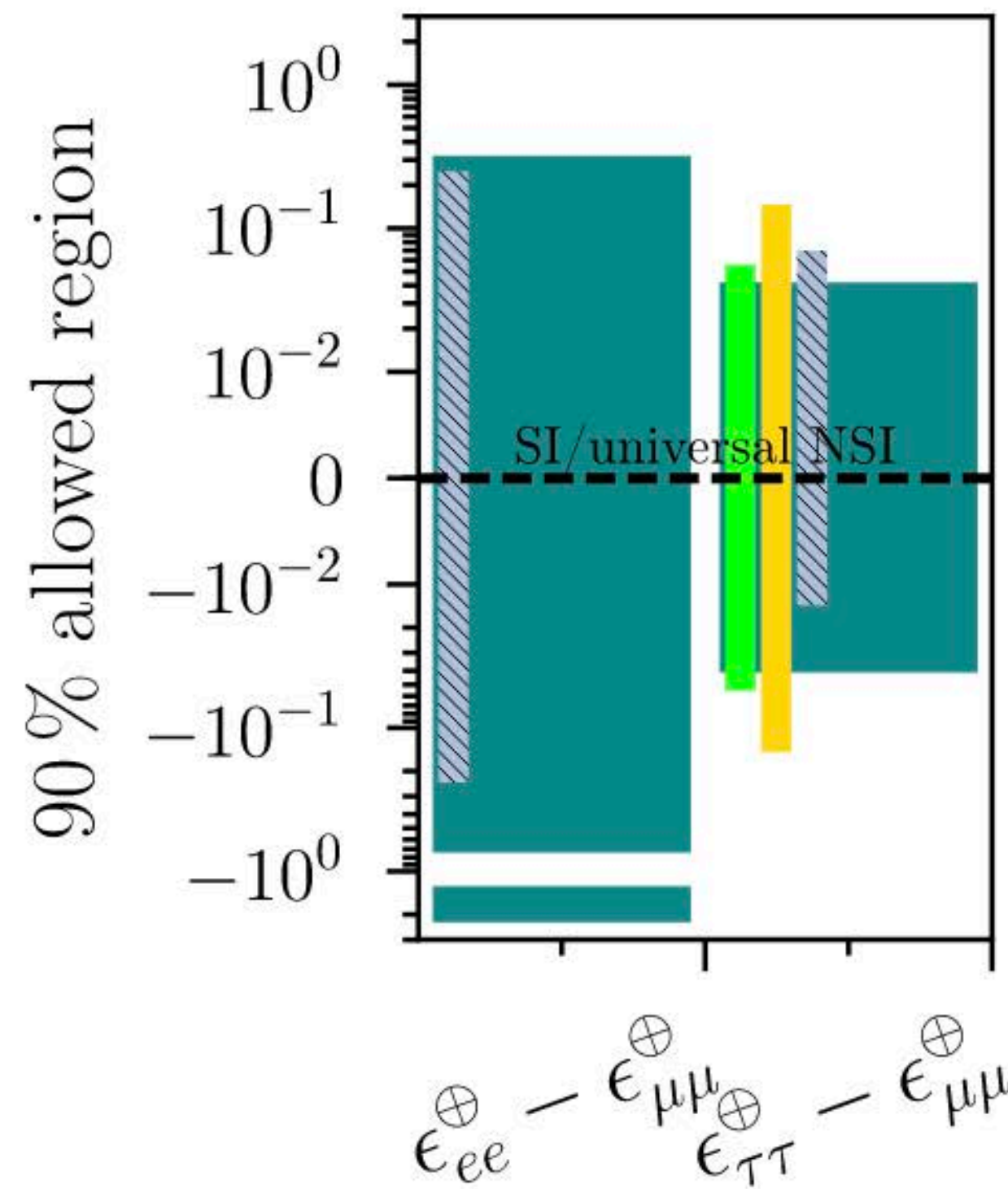
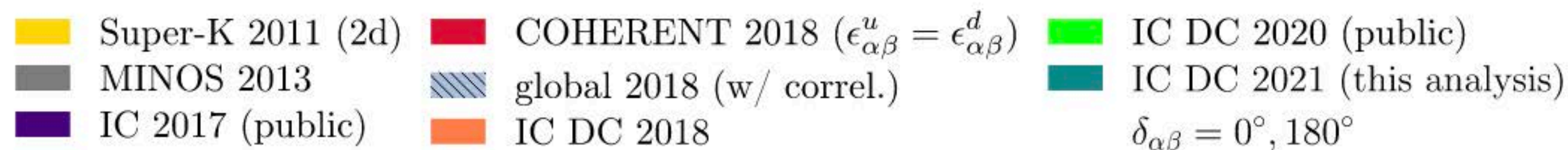
$\mathcal{O}(0.1 \times G_F)$  NSI  
allowed!

[IceCube 2106.07755]

# How to probe NSI?

In neutrino oscillations:

## Constraints on NSI



Don't need to observe tau neutrinos:  
 Atmospheric neutrinos propagate as  $\nu_3$  which is composed of mostly  $\nu_\mu$  and  $\nu_\tau$

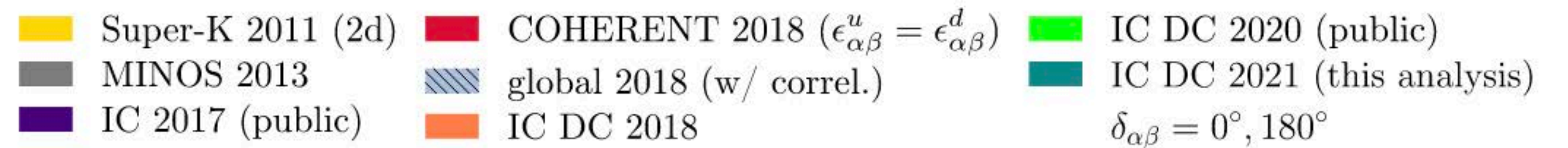


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# How to probe NSI?

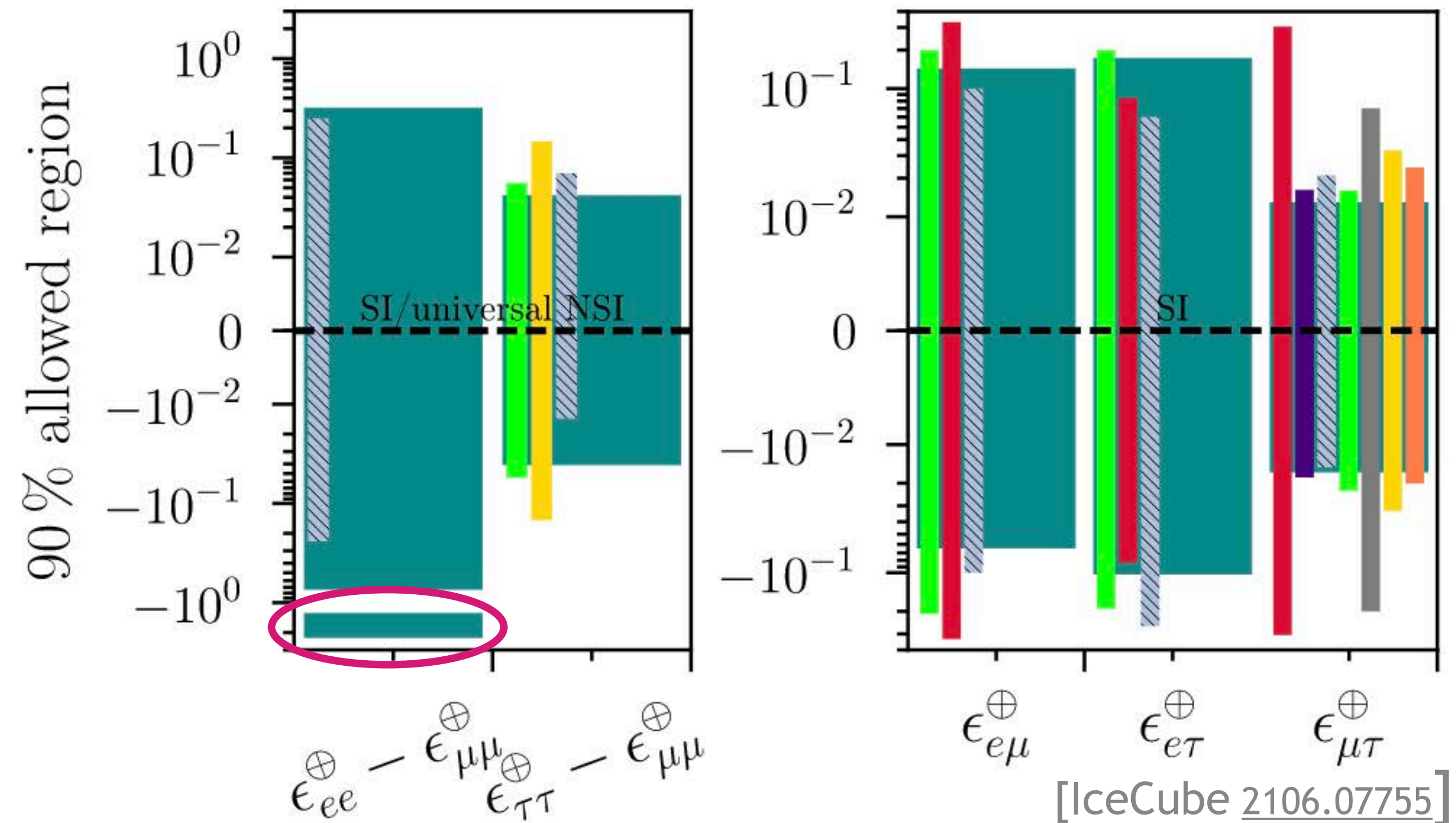
In neutrino oscillations:

## Constraints on NSI



Effects of  $\epsilon_{ee} - \epsilon_{\mu\mu}$  of  $\mathcal{O}(1 \times G_F)$  allowed at the same C.L. as the SM!

LMA-D degeneracy



# LMA-D degeneracy

## Target NSI parameter space

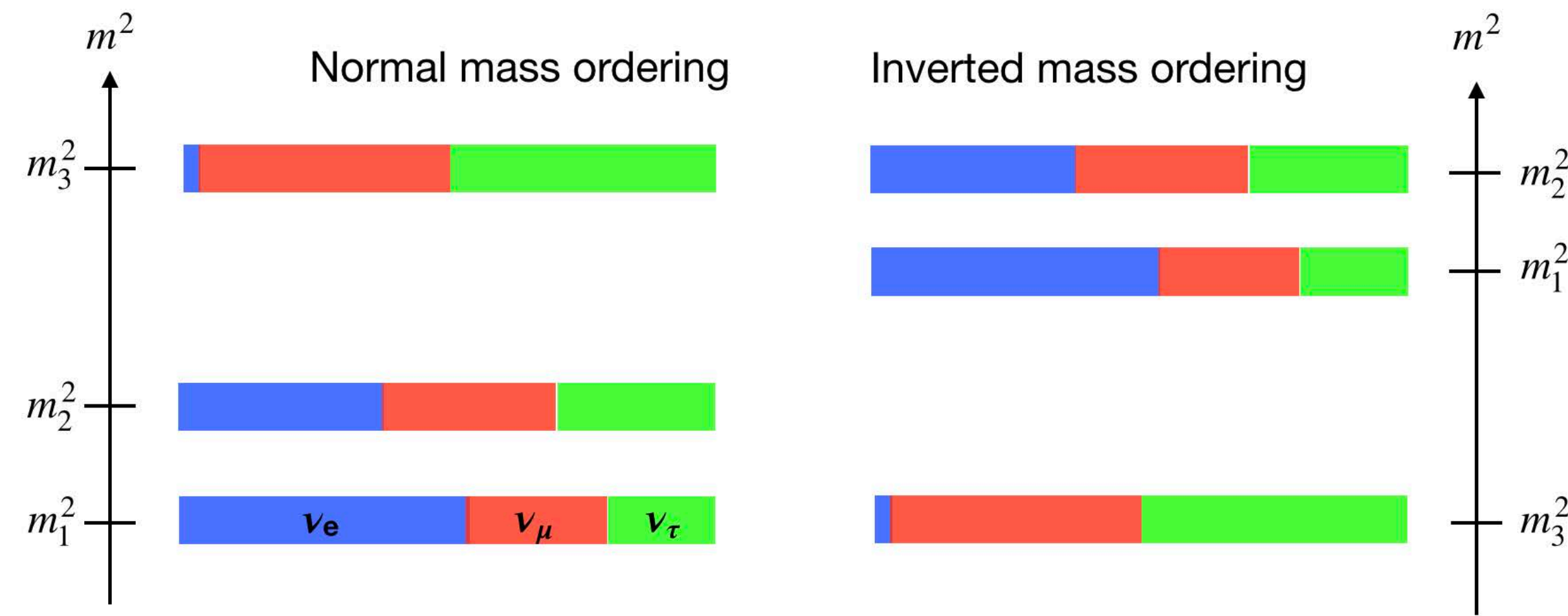
**LMA-D degeneracy:** Neutrino oscillations exhibit a degeneracy in the presence of NSI which makes it **impossible** to determine the **neutrino mass ordering!**

If  $\epsilon_{ee} = -2$ , all other NSI parameters zero

$$P_{\alpha\beta}(\text{NO}, L, E, \rho, \epsilon = 0) = P_{\alpha\beta}(\text{IO}, L, E, \rho, \epsilon = -2)$$

$$P_{\alpha\beta}(\text{IO}, L, E, \rho, \epsilon = 0) = P_{\alpha\beta}(\text{NO}, L, E, \rho, \epsilon = -2)$$

In **all** oscillation channels!

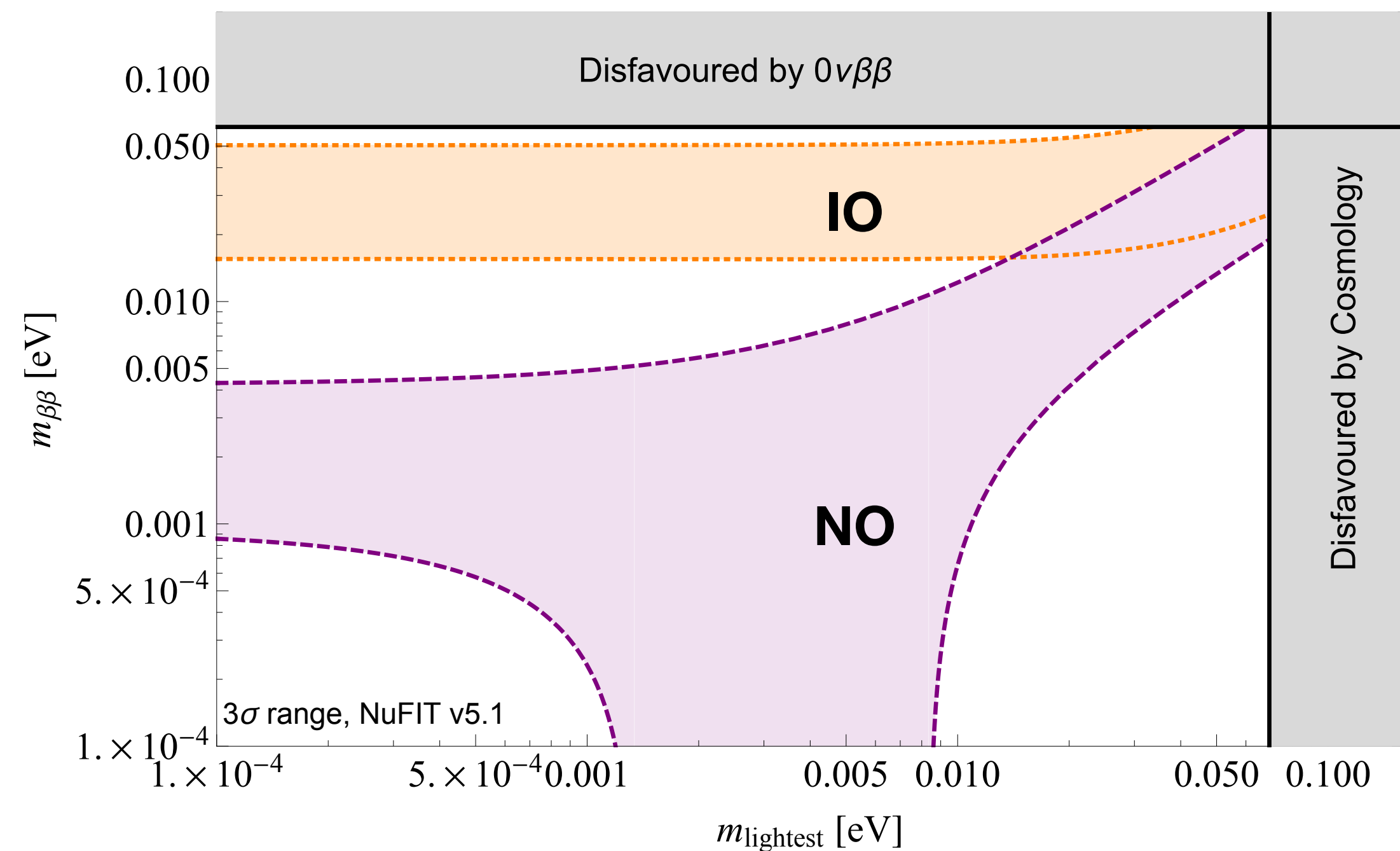


# Neutrino mass ordering

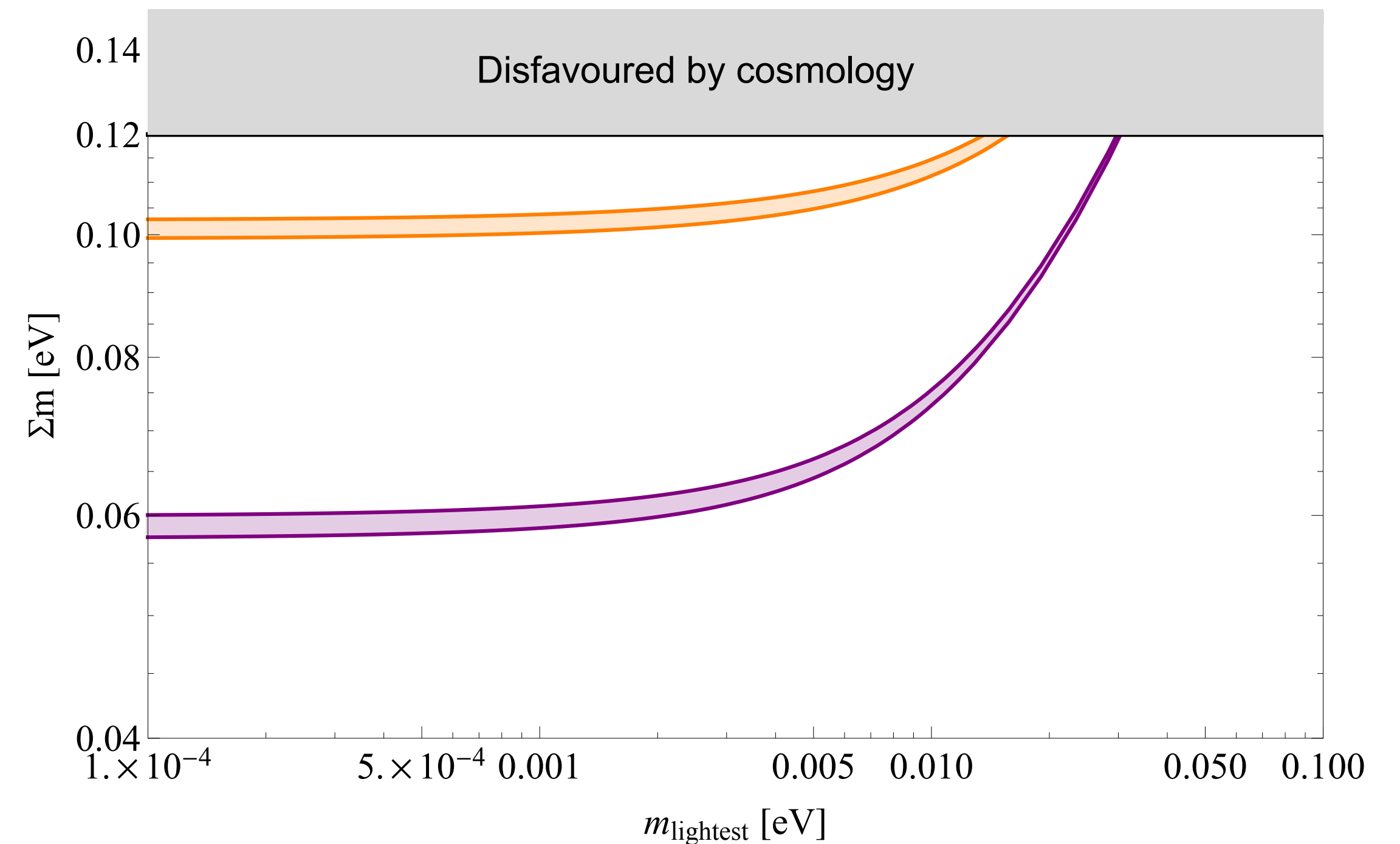
Neutrino mass ordering has **important** implications for observables

Are neutrinos normal?

Neutrinoless double beta decay



Sum of neutrino masses,  
beta decay endpoint spectrum  
Cosmic neutrino background observation



# LMA-D degeneracy

LMA-D degeneracy present in **all** oscillation channels (degeneracy of the Hamiltonian in matter)

⇒ use **neutrino scattering** data to probe NSI parameter space



# LMA-D degeneracy

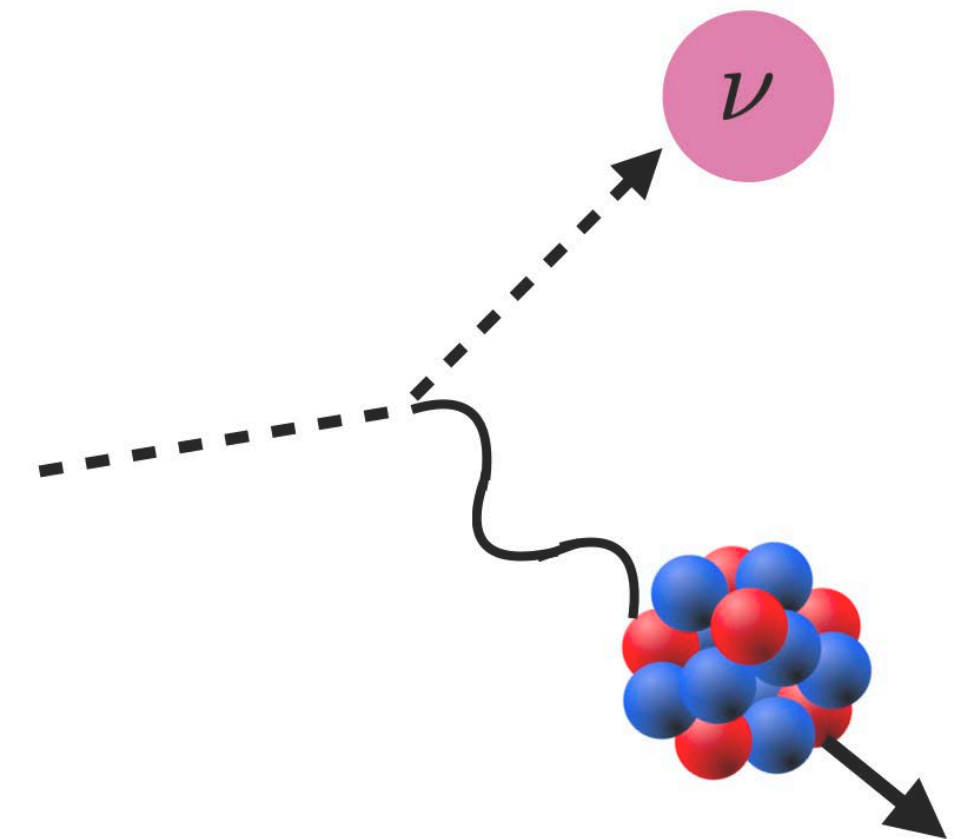
neutrino scattering data to probe LMA-D parameter space

NSI in scattering depends on mediator mass  
→ lower bound on mediator mass which can be probed

NuTeV and CHARM rule out LMA-D for  $M_{Z'} \gtrsim 10$  GeV

[Coloma et al [1701.04828](#)]

Need process with lower momentum transfer  
to probe lighter mediators!



# LMA-D degeneracy

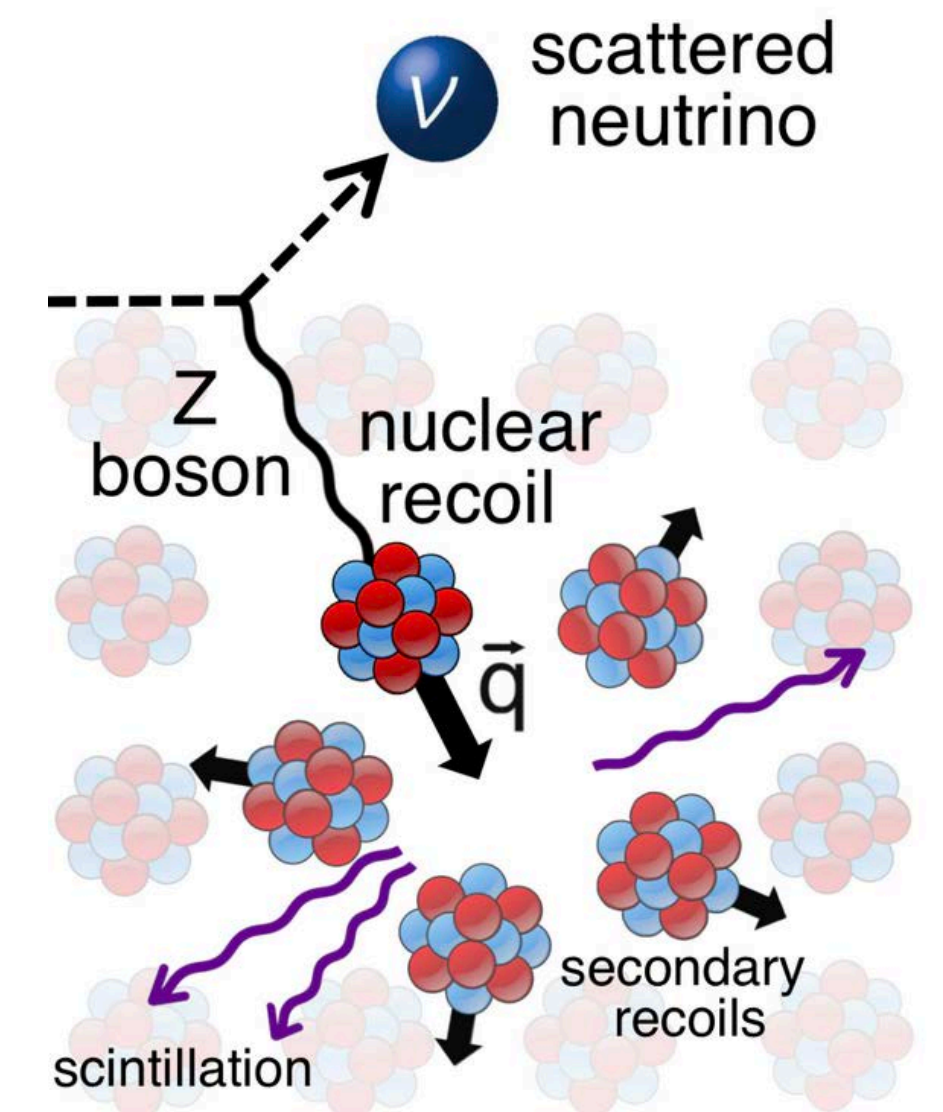
Scattering with low momentum transfer:  
**CEvNS** (coherent elastic neutrino nucleus scattering)

Recently observed for the first time:  
**COHERENT** (piDAR neutrinos):  
rules out LMA-D for  $M_{Z'} > 50 \text{ MeV}$

[Denton et al [1804.03660](#)]

Need experiment with lower neutrino energy  
and low threshold to probe **lighter** mediators!

⇒ reactor neutrino CEvNS experiments



# LMA-D degeneracy

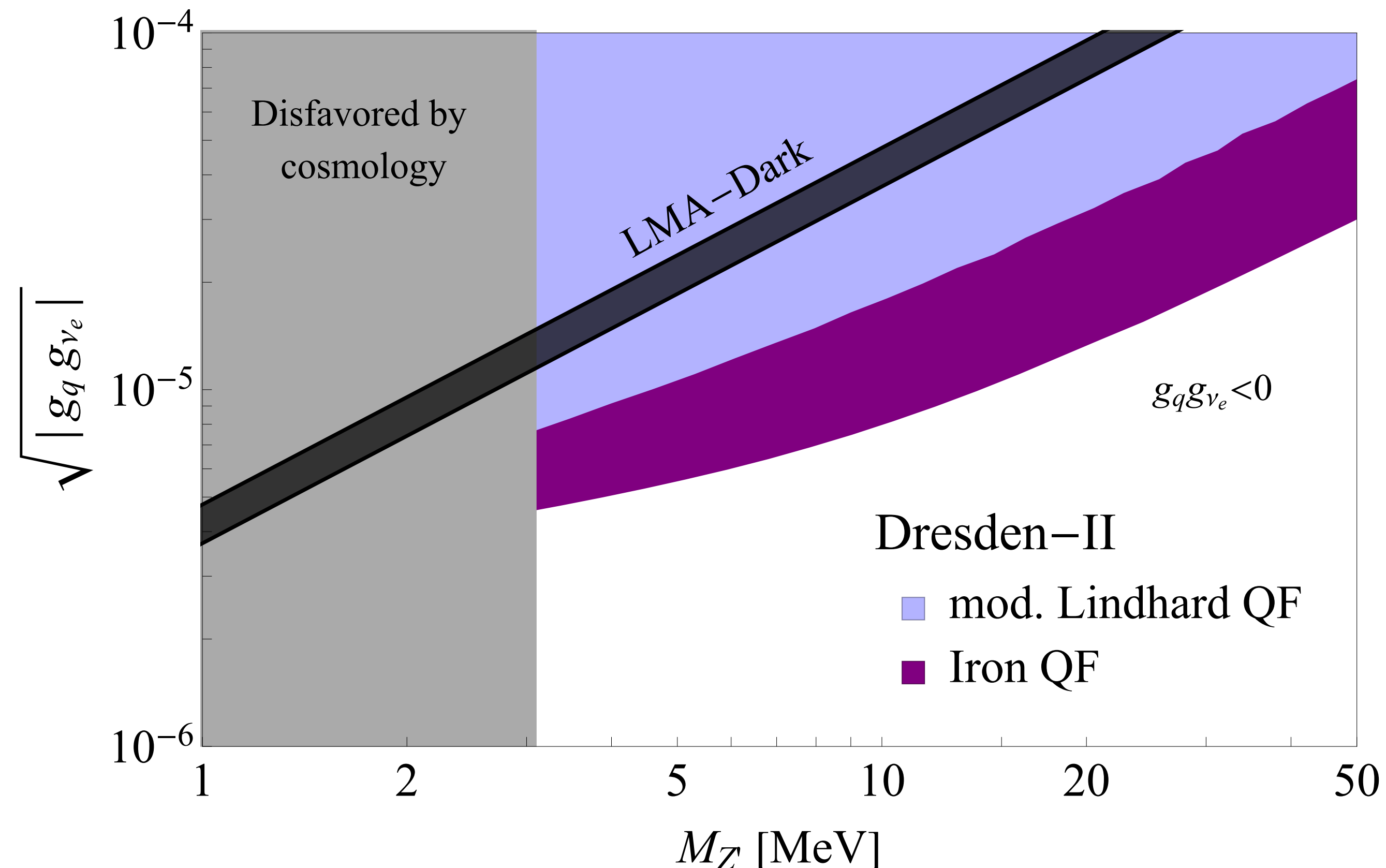
Reactor neutrino experiment Dresden-II observed CEvNS

[Colaesi et al [2202.09672](#)]

data rules out remaining parameter space of LMA-D!

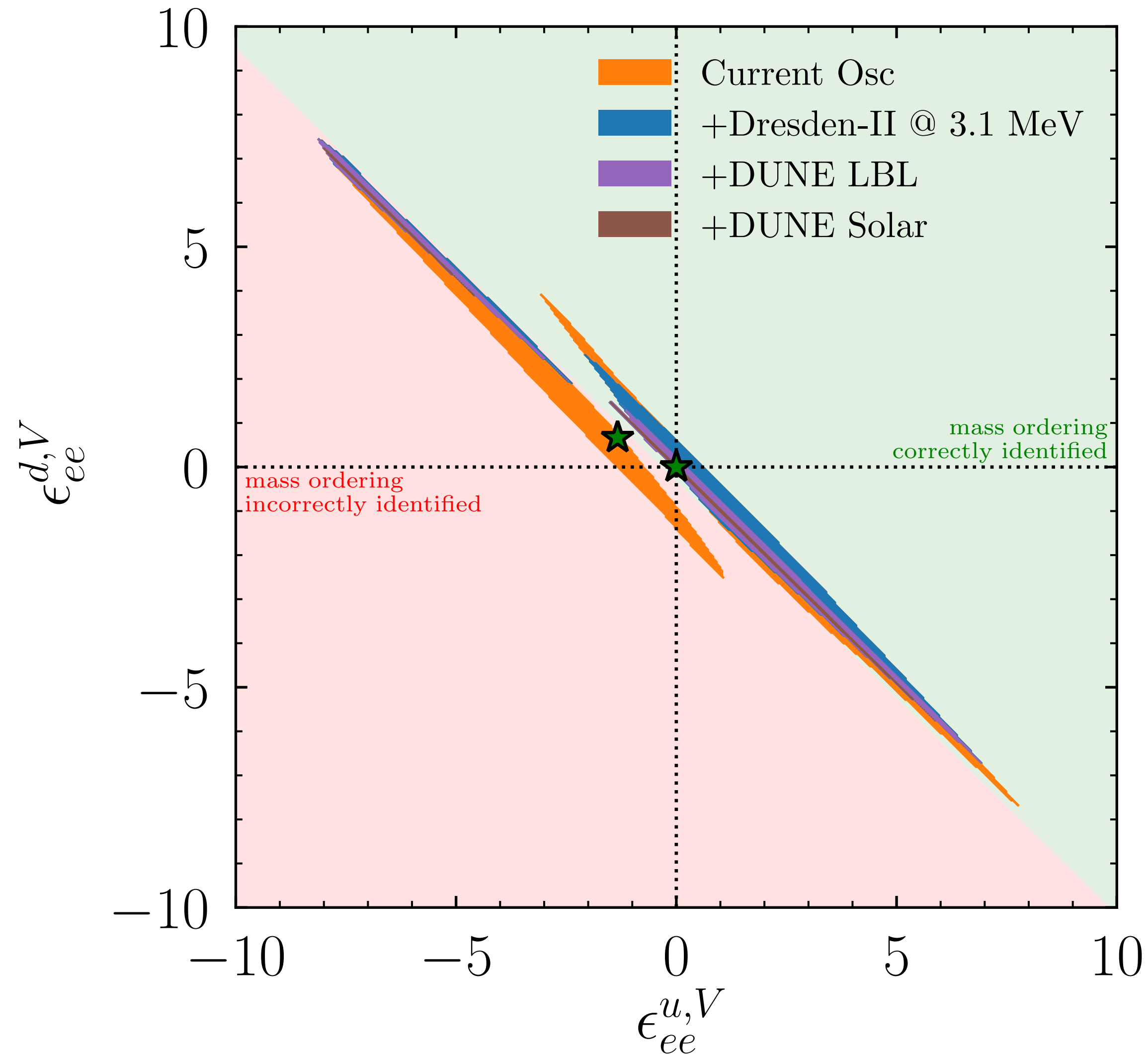
→ **Degeneracy broken** if LMA-D in electron sector!

[Denton, **JG** [2204.09060](#)]



# LMA-D degeneracy

[Denton, [JG 2204.09060](#)]



Only **small** region in LMA-D parameter space with electron neutrinos with different couplings of electron neutrinos to up-and down-quarks allowed

# LMA-D degeneracy

[JG, Kushwaha 2508.14166]

Diagonal **degeneracy** of Hamiltonian: can subtract an overall term from diagonal

$$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (x - 2, x, x)$$

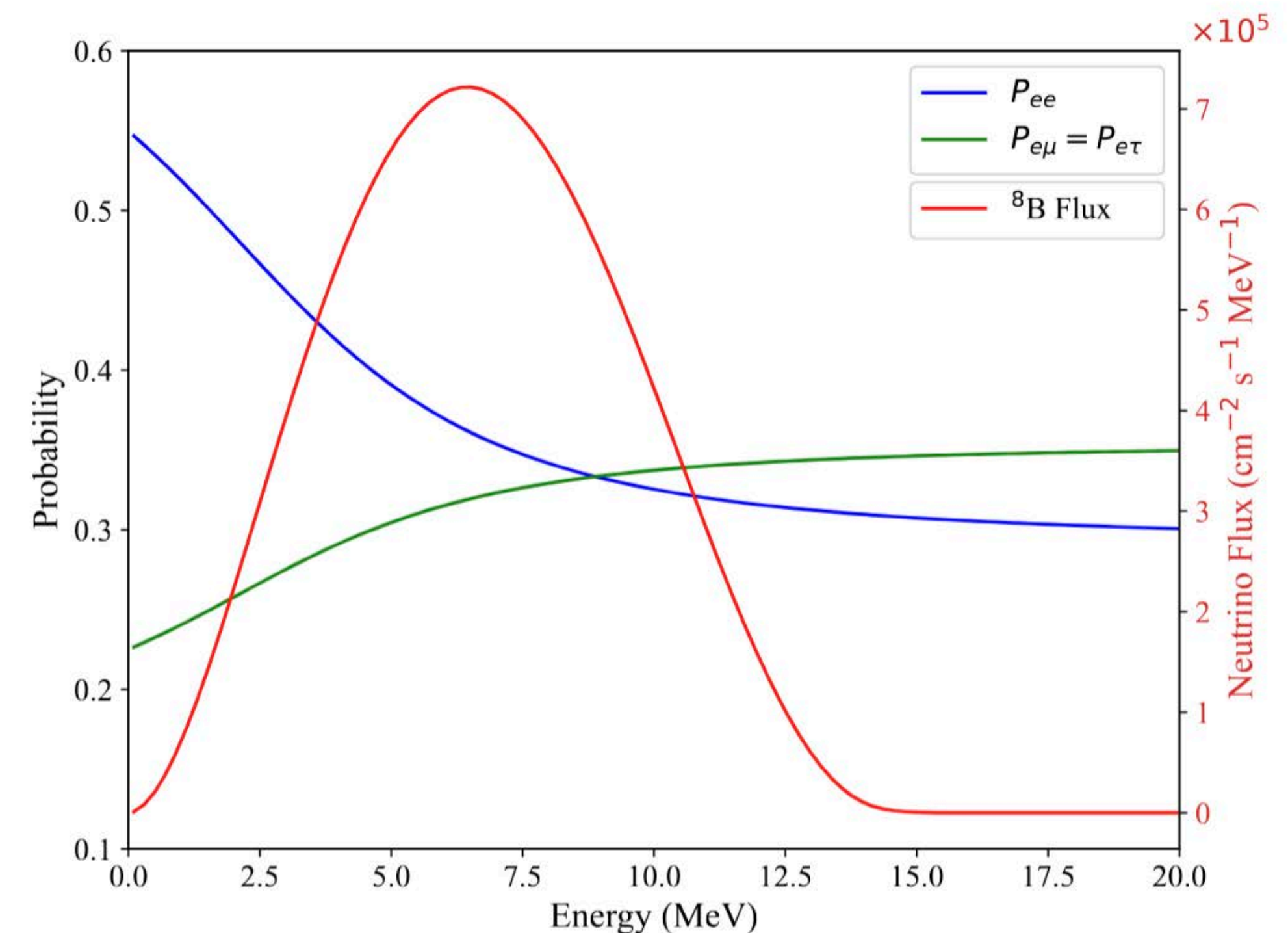
→ Move LMA-D into muon and tau sector

$$\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$$

→ need low energy source of tau neutrinos

$^8\text{B}$  solar neutrinos arrive as three flavors at the Earth

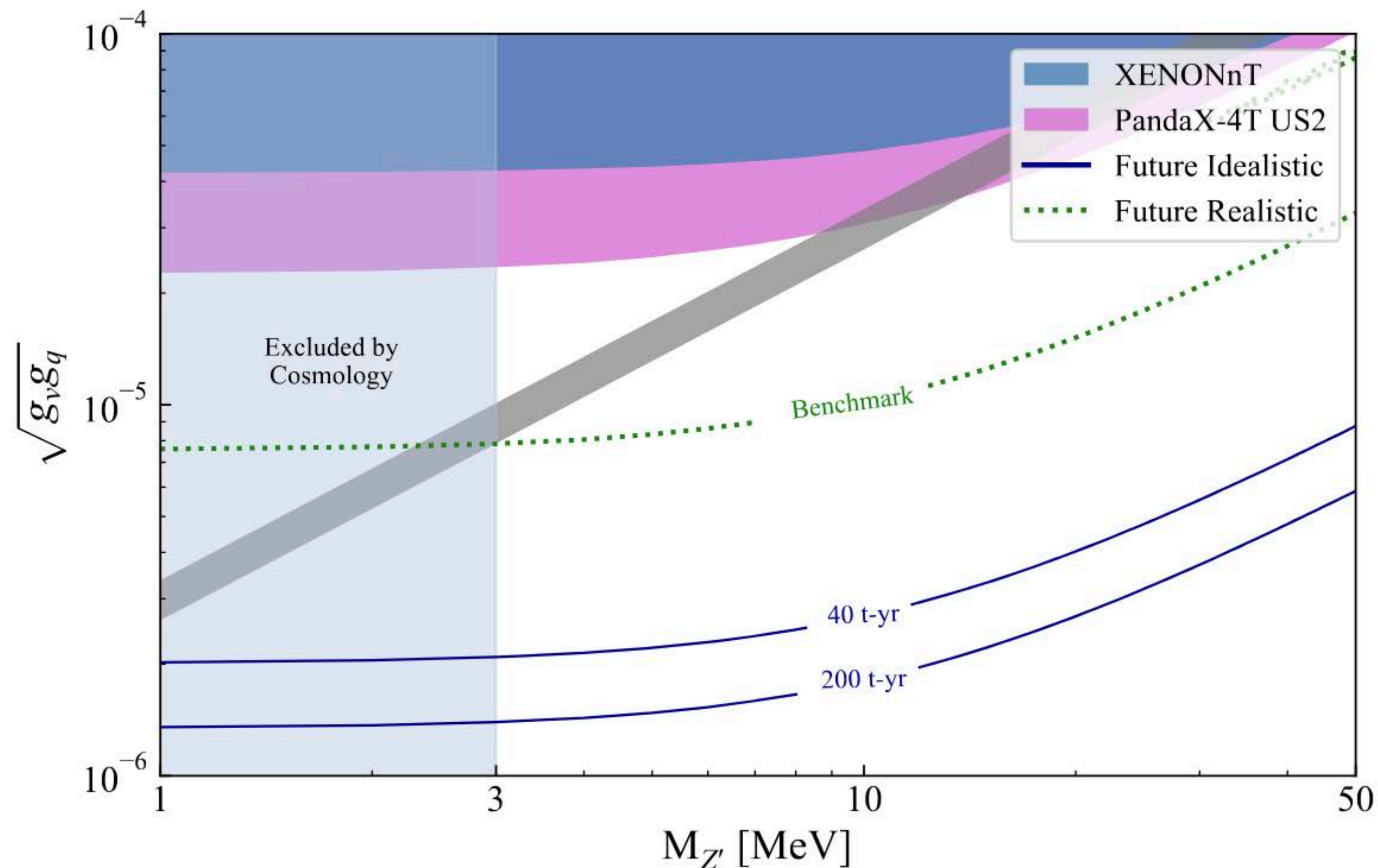
Observe CEvNS with solar neutrinos:  
Background at DM direct detection experiments



# LMA-D degeneracy

[JG, Kushwaha 2508.14166]

First observed last Summer at XENONnT and PandaX ( $\sim 2.5\sigma$ )



Current data does **not fully exclude** LMA-D in the muon and tau sector yet

125 t-yr of exposure required assuming current systematics

(Current exposure: 1.04 t-yr for PandaX, 3.51 t-yr for XENONnT)

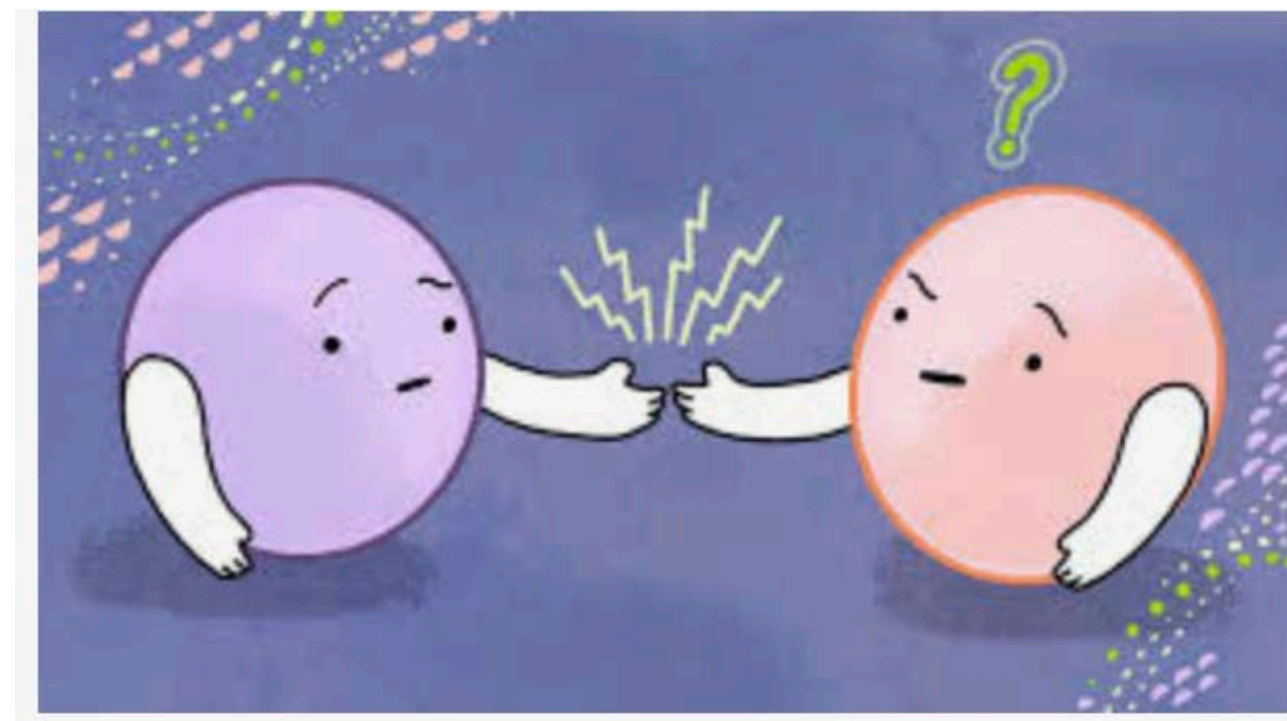
DM experiments are now neutrino experiments!

# NC NSI events at LBL experiment

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

Can we use them to obtain new constraints on NSI?

Yes!

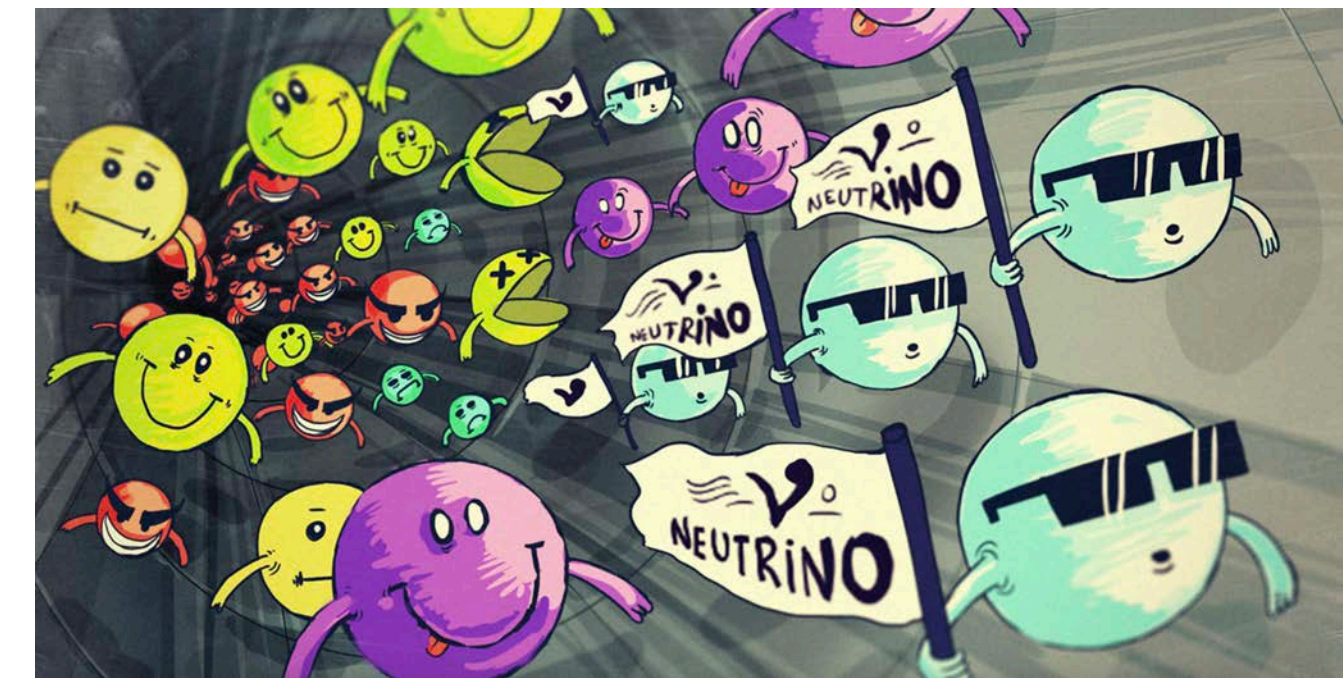


[JG, Machado, Pinheiro, [2412.08712](#)]

# NC NSI events at LBL experiment

Focus on NOvA data as concrete example

*Without NSI:* NC channel is flavor blind  
*With NSI:* scattering cross section changes in flavor-dependent way



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

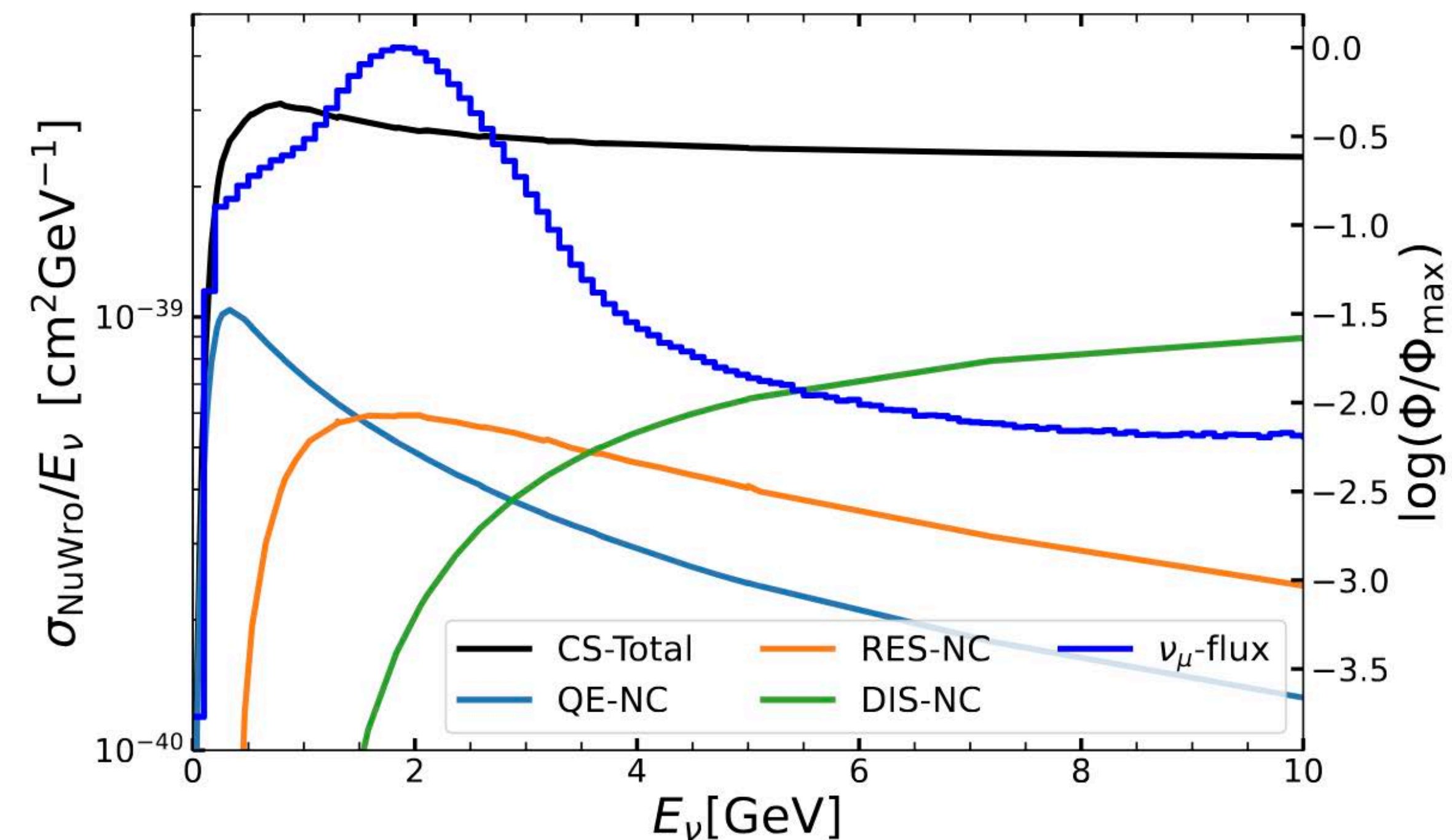
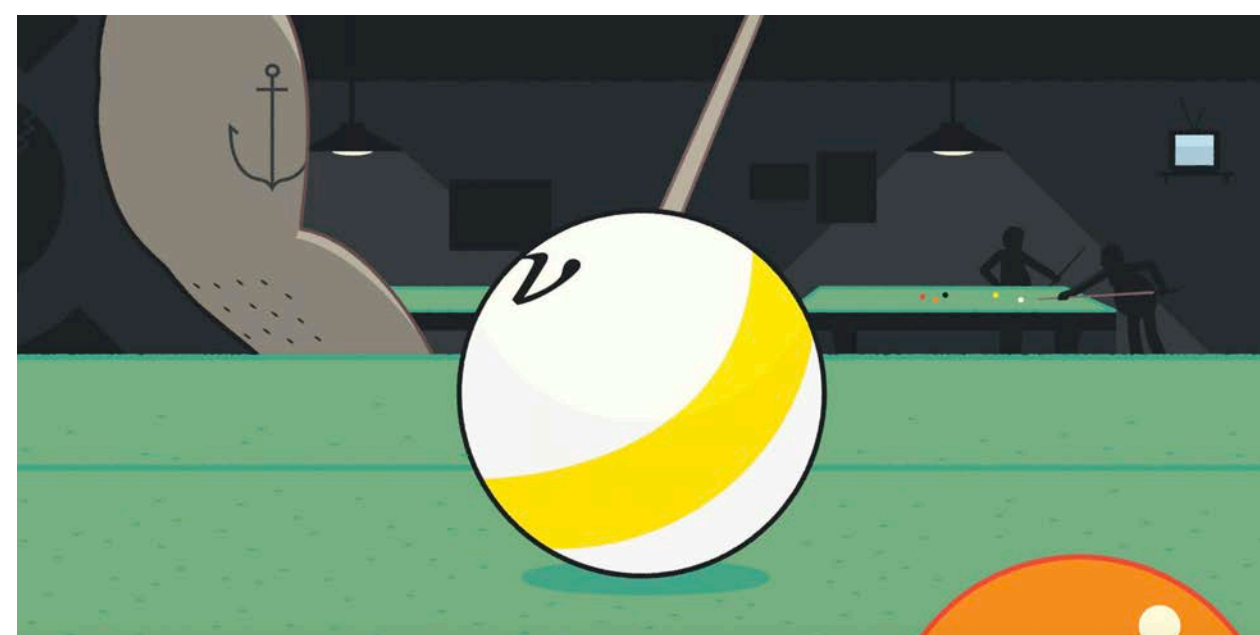
Focus on vector and axial-vector NSI

# NC NSI events at LBL experiment

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

Include NSI in NC cross section assuming *free nucleons*  
 To model nuclear effects: multiply prefactor with nuWro result

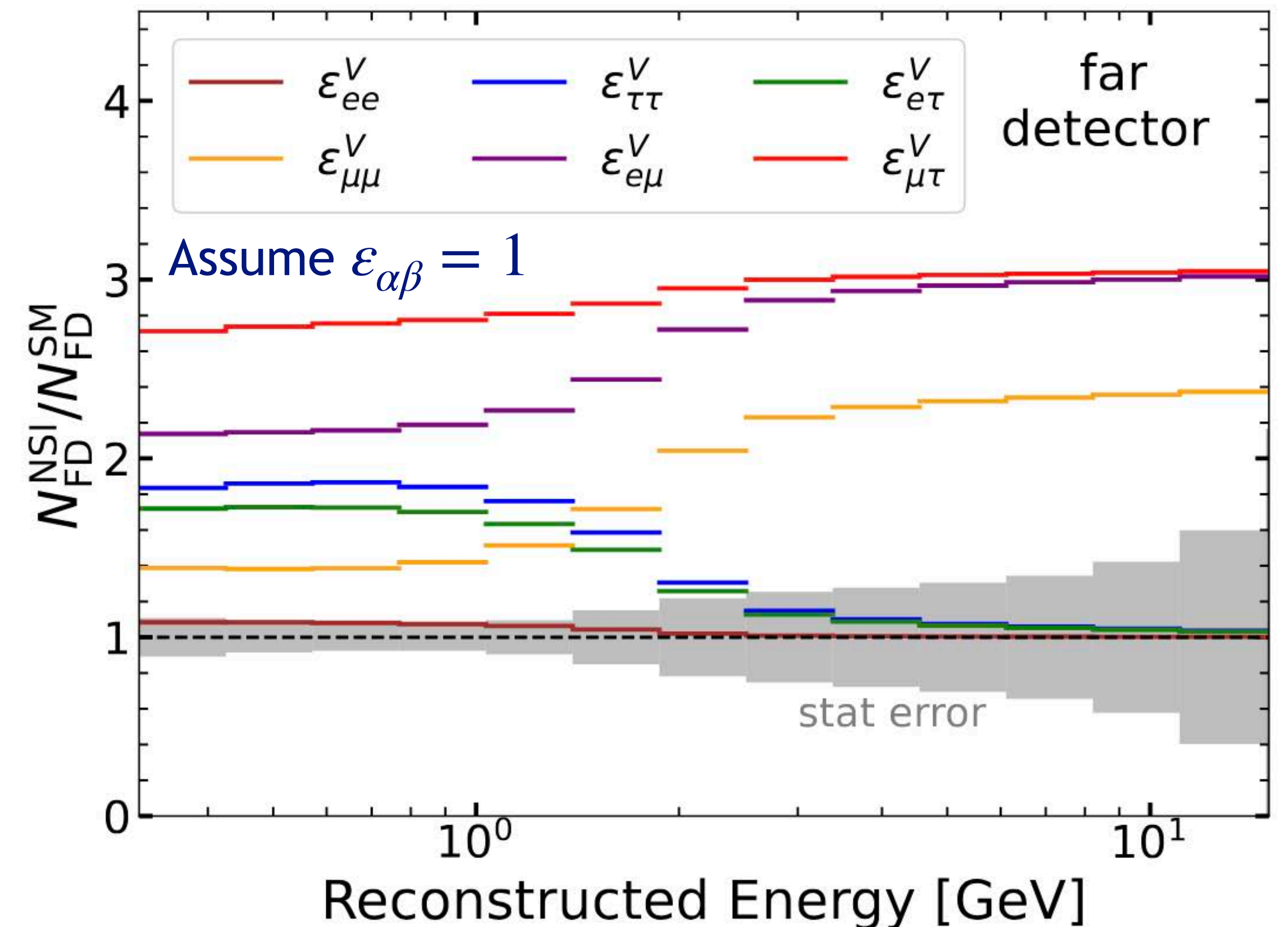
$$N_{\text{ev}} \propto \frac{\sum_{\alpha\beta} N_p \rho_{\alpha\beta} \sigma_p^{\alpha\beta} + N_n \rho_{\alpha\beta} \sigma_n^{\alpha\beta}}{\sum_{\alpha} N_p \rho_{\alpha\alpha} (\sigma_p^{\alpha\alpha})_{\text{SM}} + N_n \rho_{\alpha\alpha} (\sigma_n^{\alpha\alpha})_{\text{SM}}} \sigma_{\text{NuWro}}$$



# NC NSI events at LBL experiment

[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

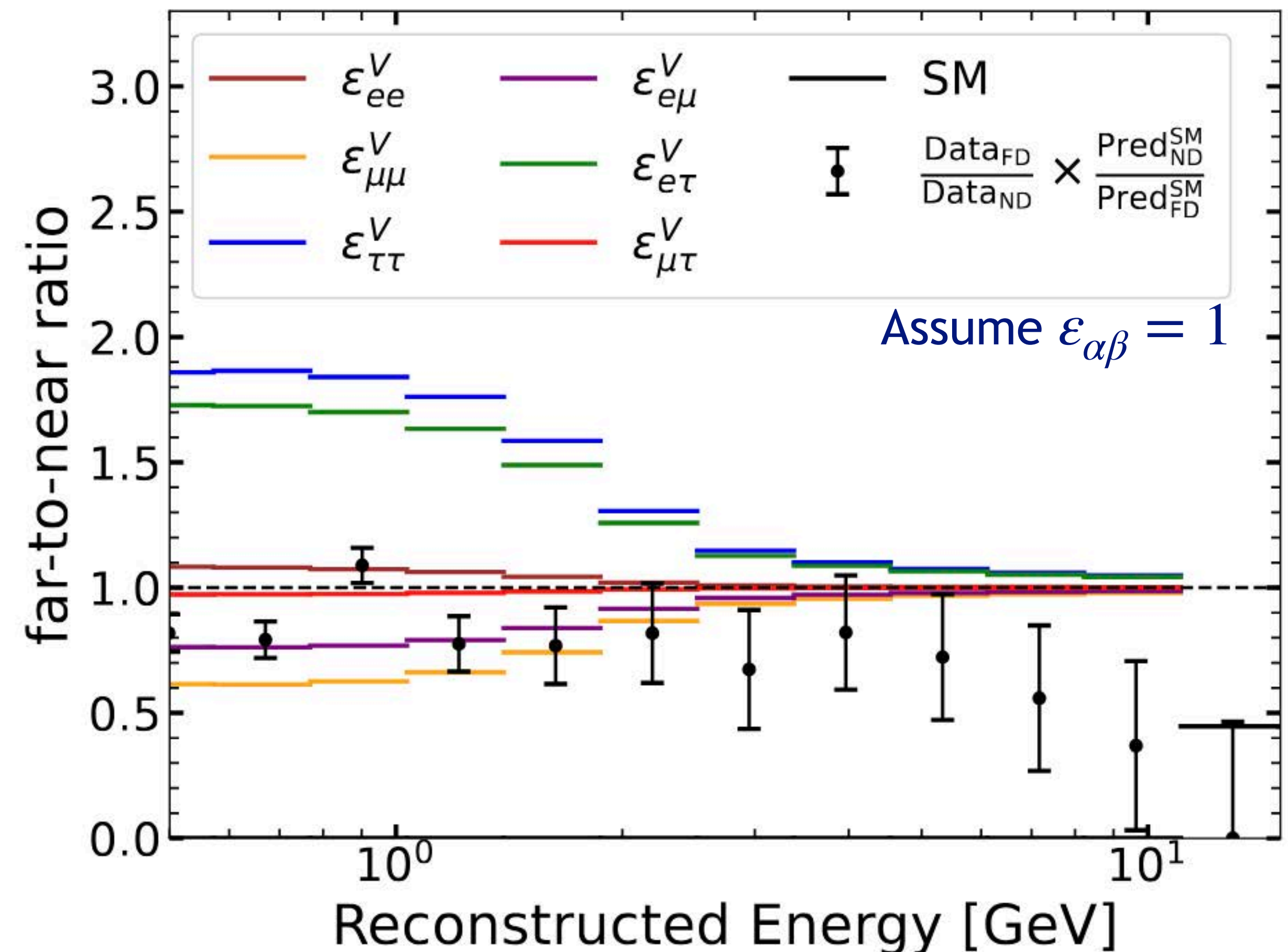


# NC NSI events at LBL experiment

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



# NC NSI events at LBL experiment

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

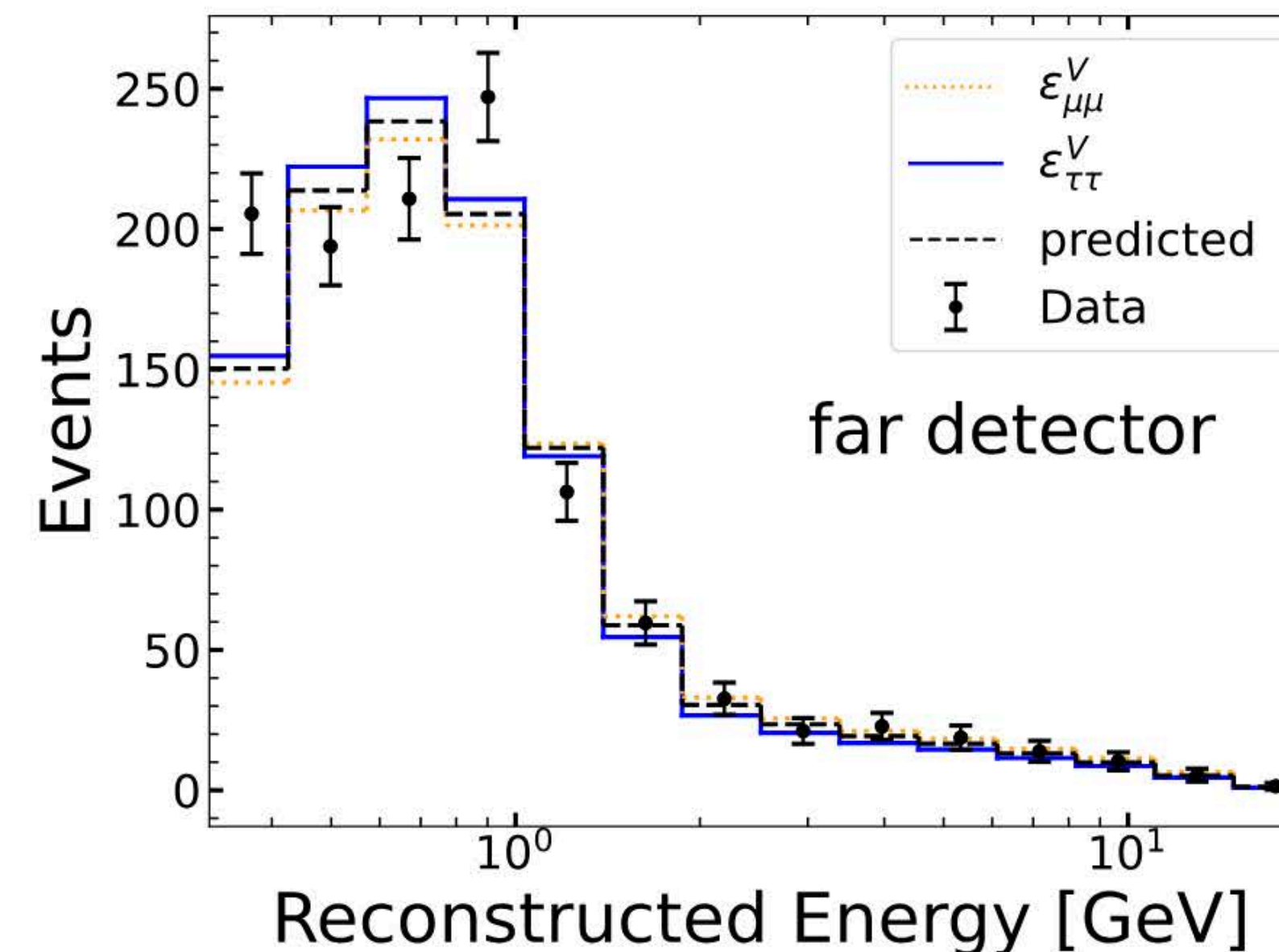
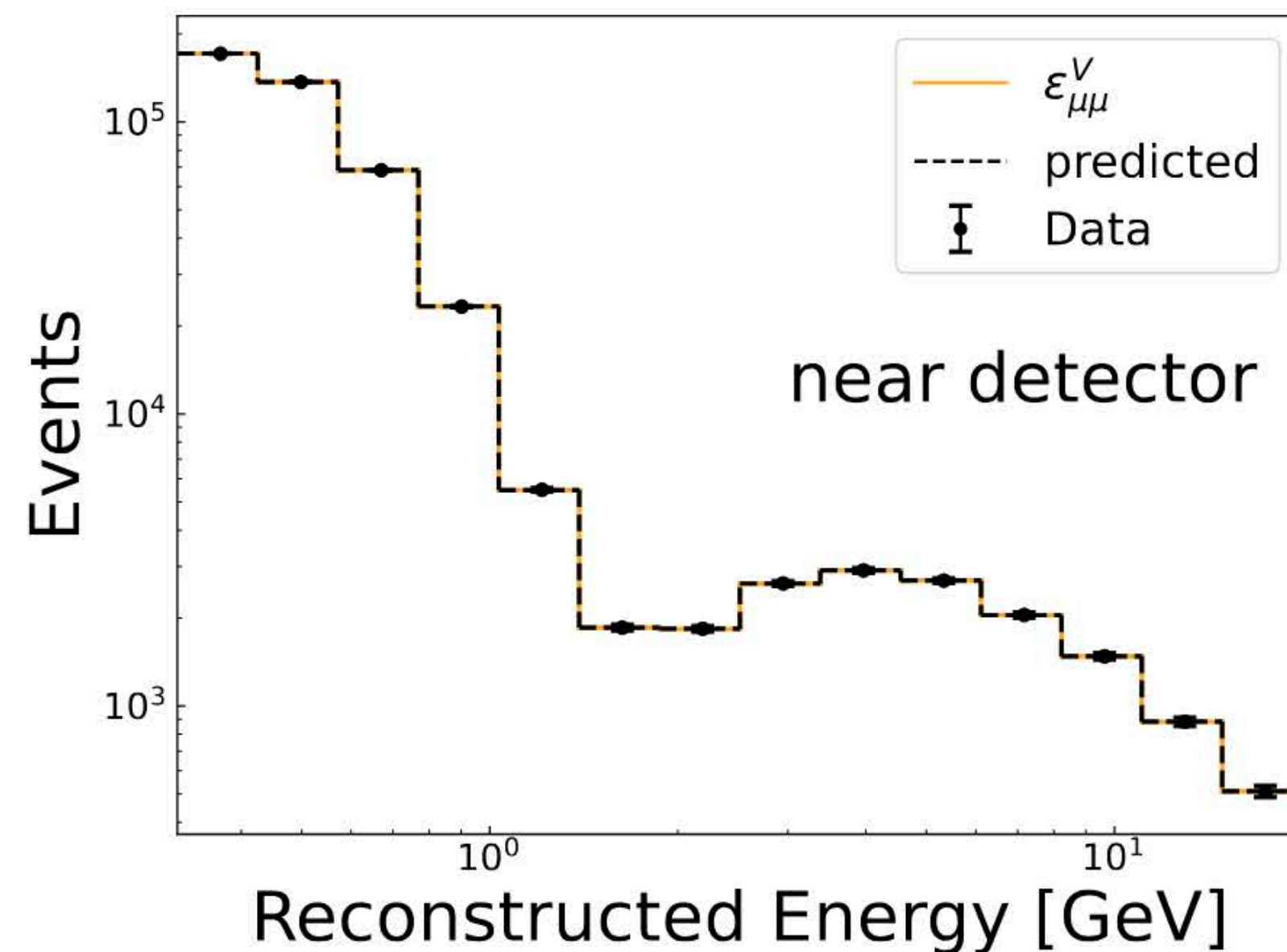
- Analyze  $13.6 \times 10^{20}$  POT from NOvA at ND and FD NOvA, [2409.04553](#)
- theory prediction suffers from uncertainties on cross section, flux, etc
- Fit ND and FD data and use bin-by-bin fully correlated pull-parameters

$$\chi^2 = \sum_i^{\text{bins}} \left[ \frac{D_i^{\text{ND}} - (1 + \gamma_i)T_i^{\text{ND}}}{\sqrt{D_i^{\text{ND}}}} \right]^2 + \sum_i^{\text{bins}} \left[ \frac{D_i^{\text{FD}} - (1 + \alpha + \gamma_i)T_i^{\text{FD}}}{\sqrt{D_i^{\text{FD}}}} \right]^2 + \left( \frac{\alpha}{\sigma_\alpha} \right)^2 \quad \sigma_\alpha = 0.15$$

# NC NSI events at LBL experiment

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

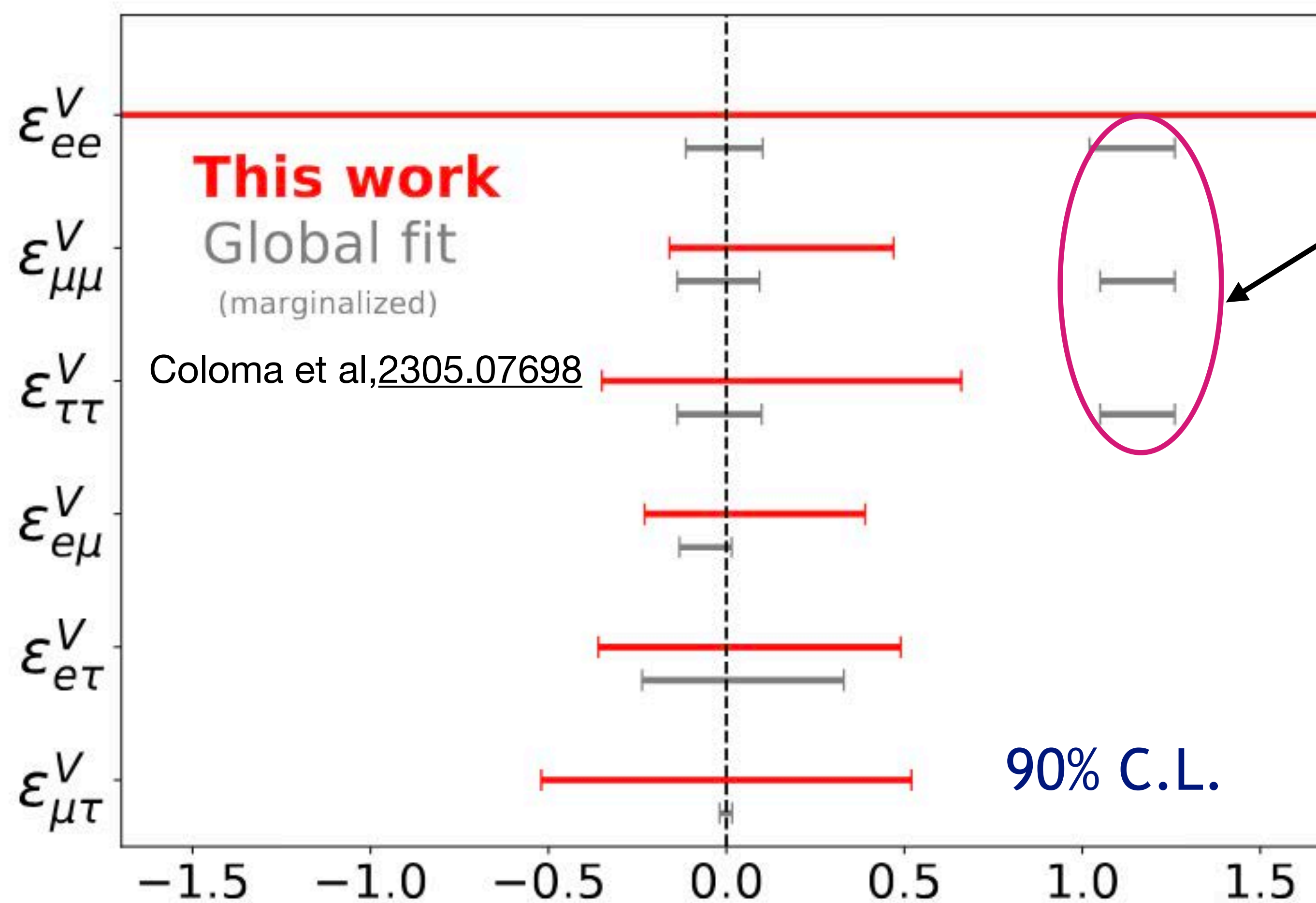
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# NC NSI events at LBL experiment

## Results: Vector NSI

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



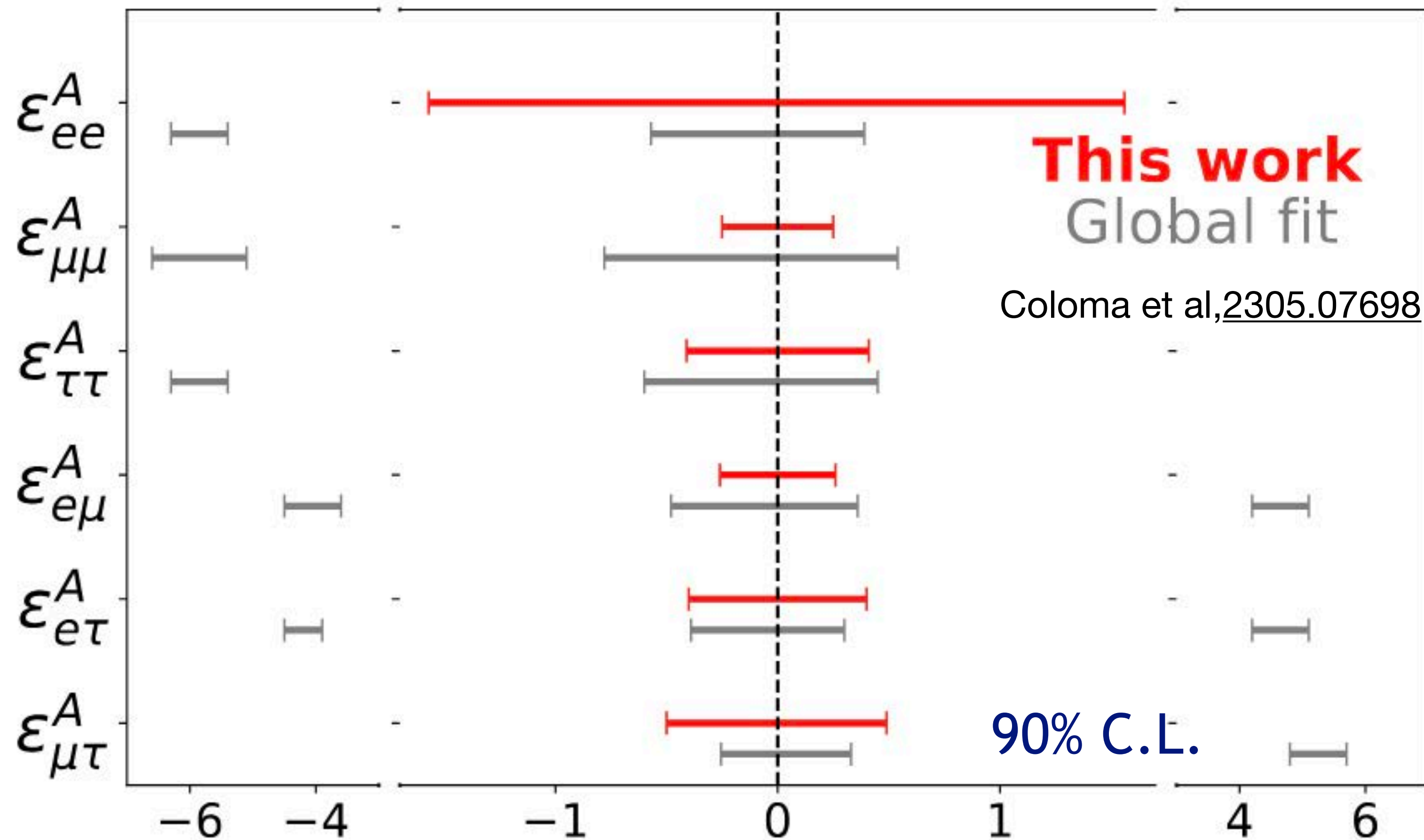
### LMA-Dark

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

# NC NSI events at LBL experiment

## Results: Axial-vector NSI

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

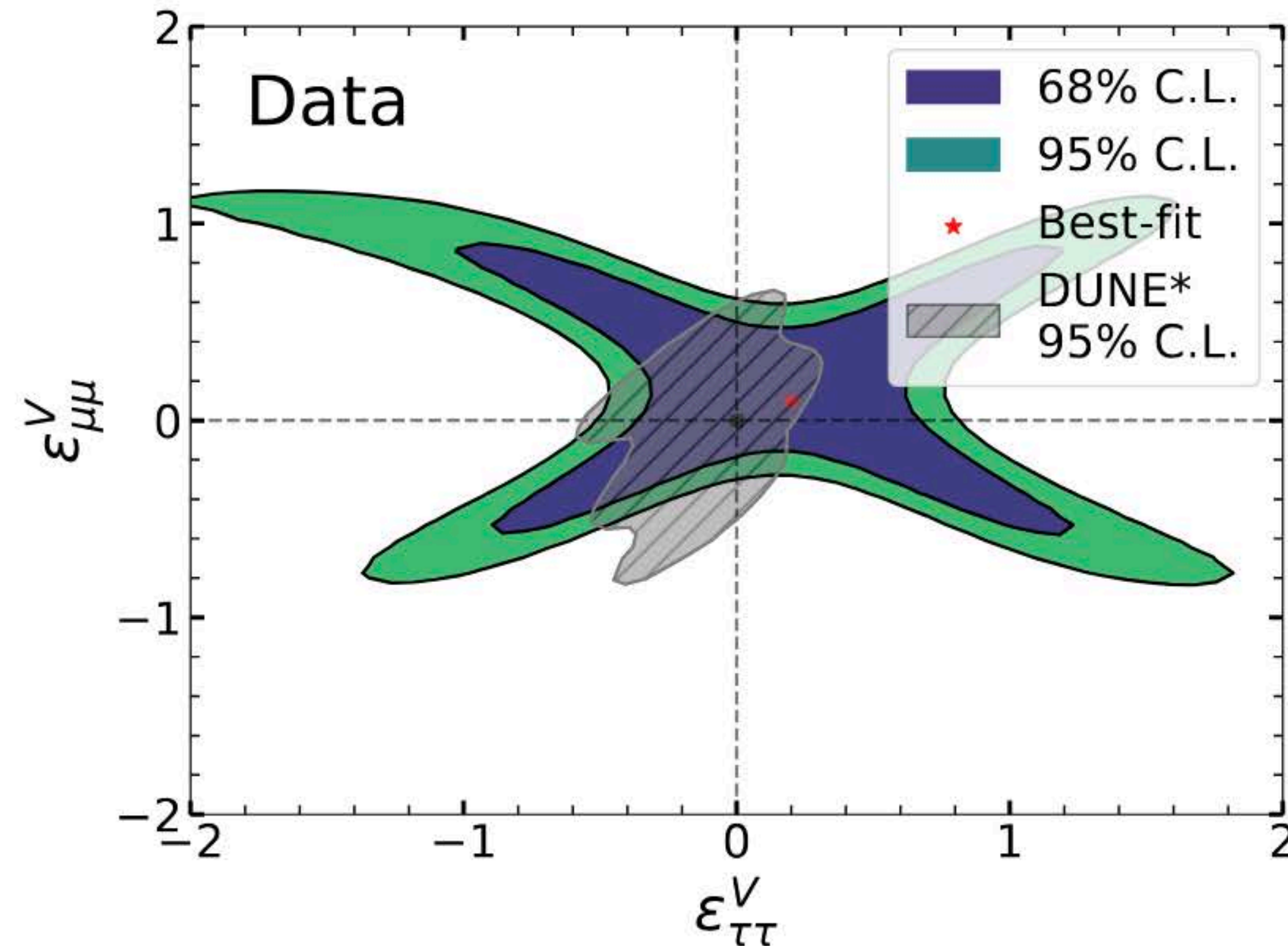
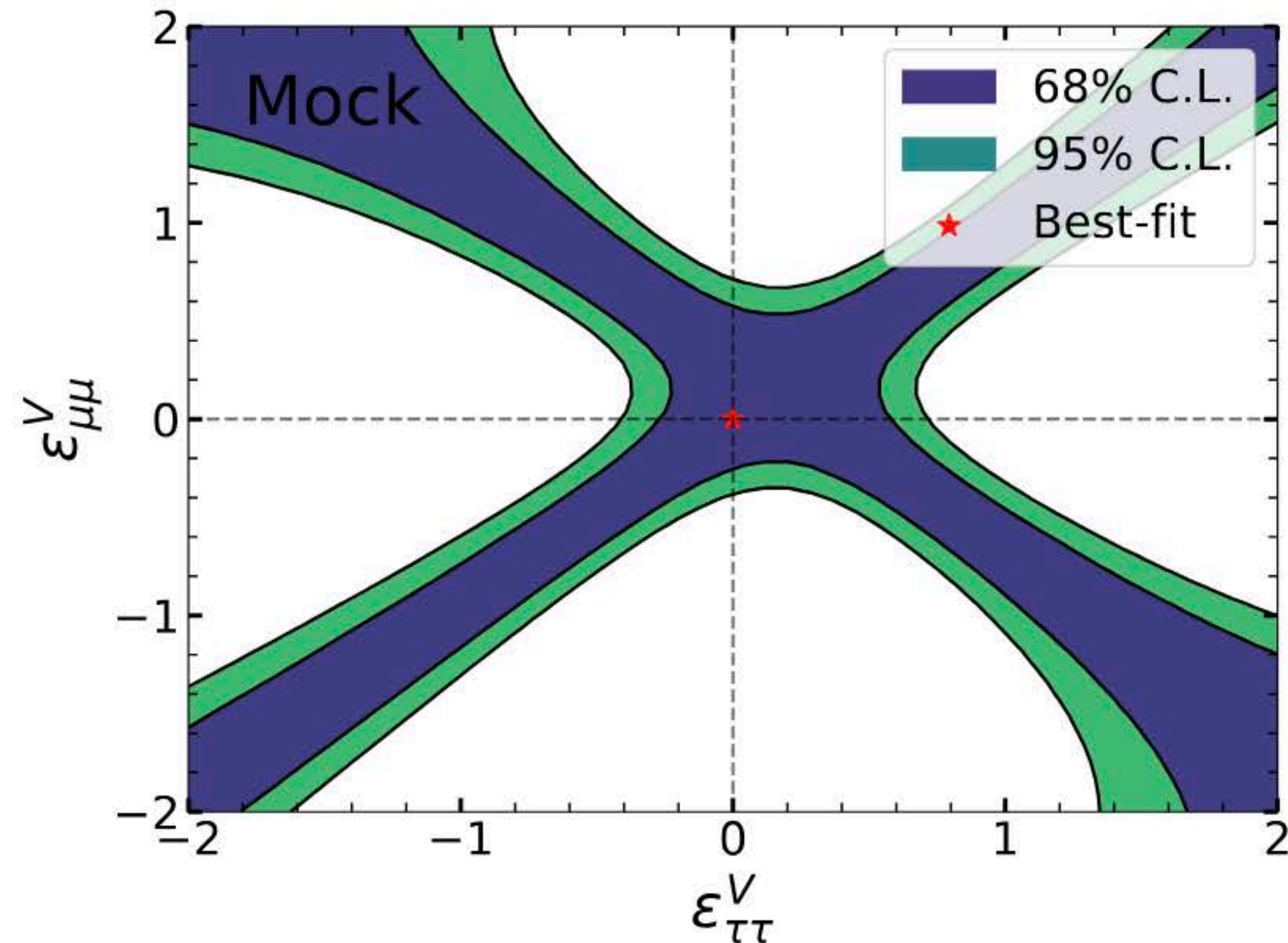


- **Stronger** constraints than global fit for many parameter
- Dominant experiment: SNO ( $\nu$ -deuterium scattering) **only** sensitive to isospin violating axial NSI ( $\epsilon^u - \epsilon^d$ )
- Degeneracies **broken** by addition of NOvA
- **Novel** constraints on isospin conserving axial NSI

# NC NSI events at LBL experiment

## Results: 2D vector NSI

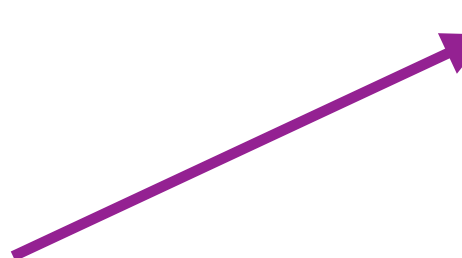
[JG, Machado, Pinheiro, [2412.08712](#)]



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

# Neutrino interactions beyond the SM

New terms in Lagrangian could appear as higher dimension operator

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \delta \mathcal{L}^{d=5} + \frac{1}{\Lambda^2} \delta \mathcal{L}^{d=6} + \boxed{\frac{1}{\Lambda^3} \delta \mathcal{L}^{d=7}} + \dots$$


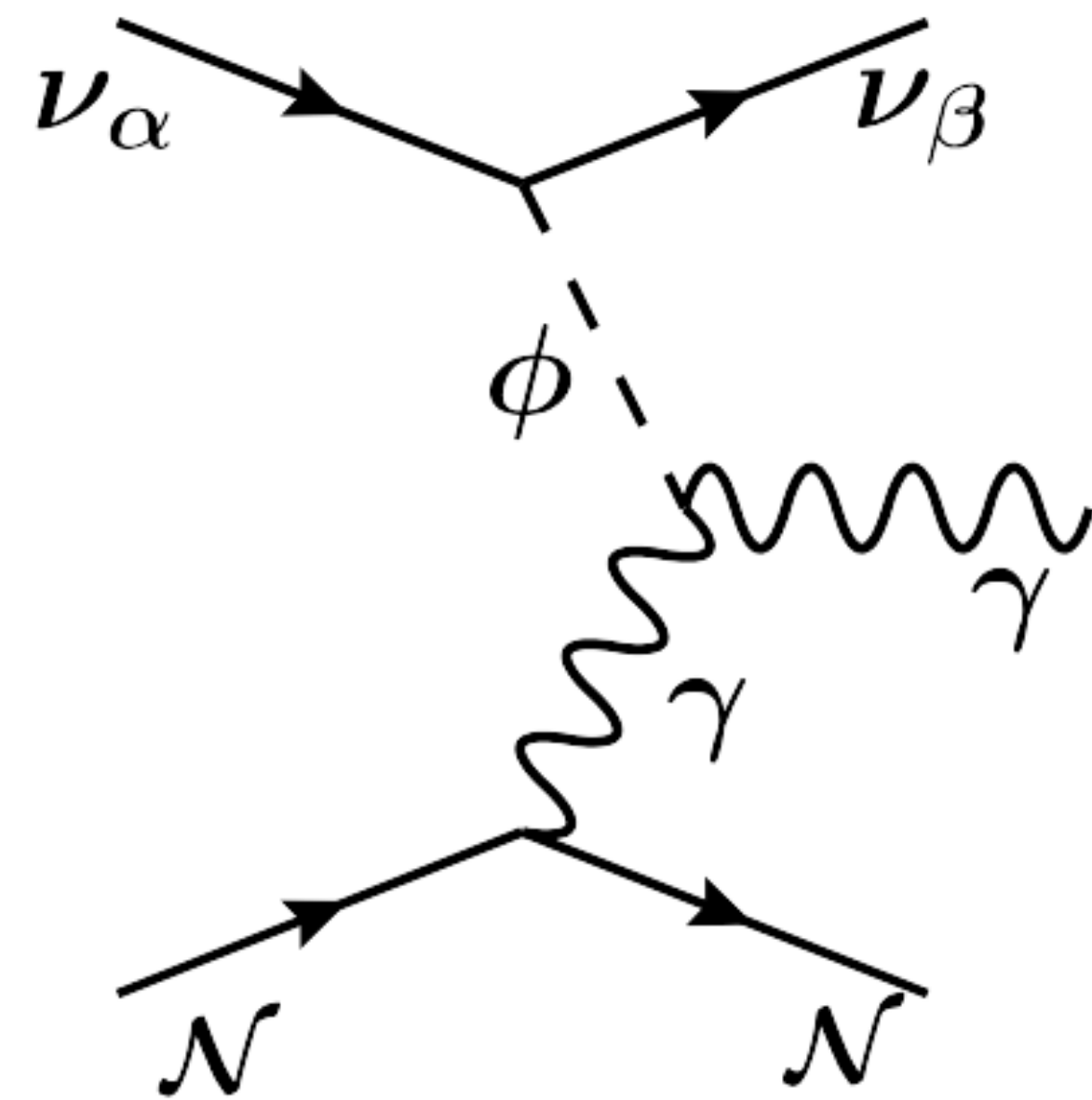
Coupling of fermions to **gauge boson** field

strength tensors:  $\bar{\nu} \nu F_{\mu\nu} F^{\mu\nu}$

→ new neutrino interactions not captured in  
NSI framework

# Neutrino-photon coupling

Example: Effective two neutrino-two photons vertex [JG, Shoemaker, Thapa '25]



Neutrino **polarizability** operator:

$$\frac{C_{ij}^7}{\Lambda^3} (\bar{\nu}_i P_L \nu_j) F^{\mu\nu} \widetilde{F}_{\mu\nu}$$

[Bansal, Paz, Petrov, Tammaro, Zupan '22]

Realized via light pseudoscalar  $\phi$  with derivative couplings to photons and neutrinos

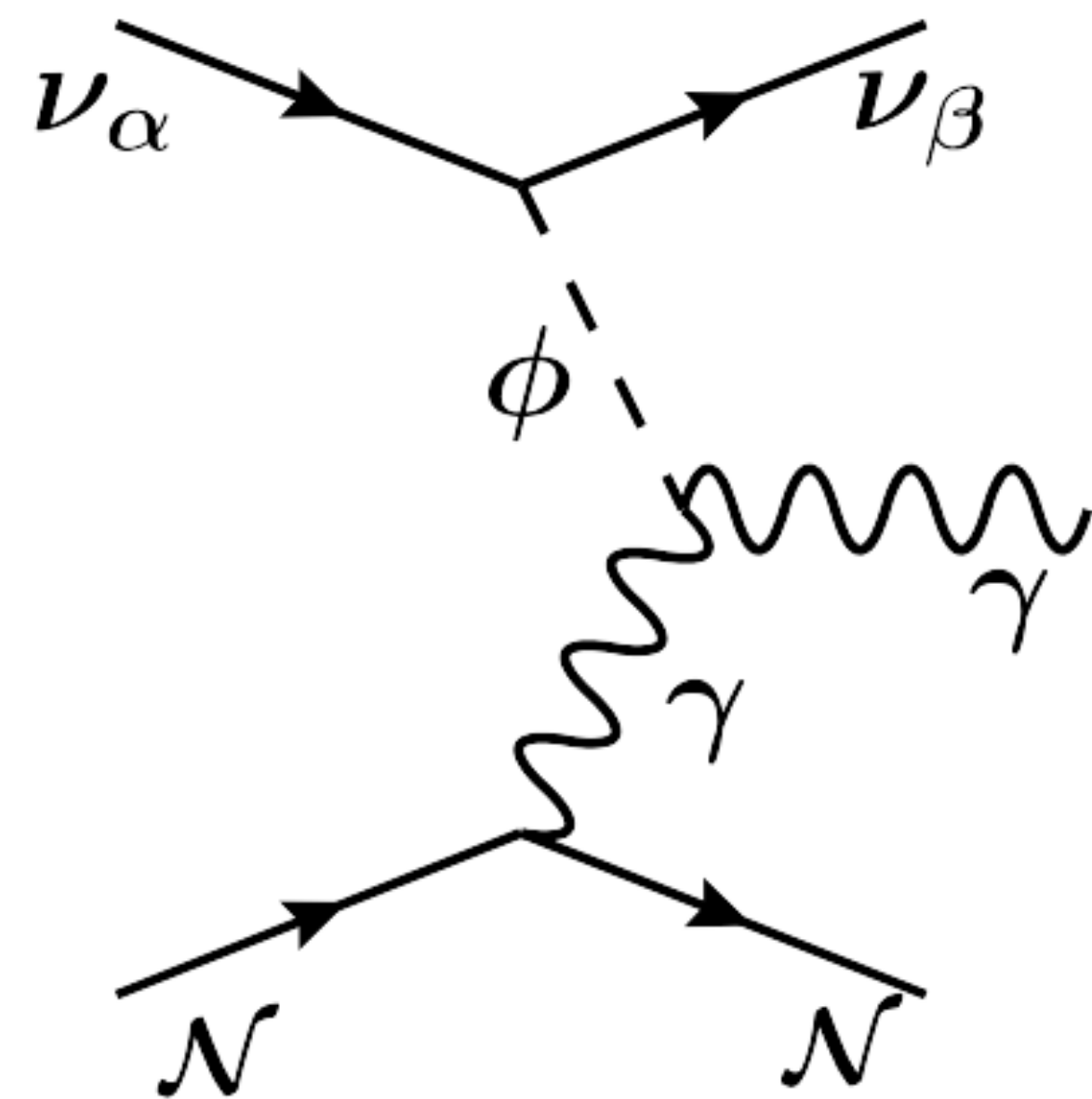
$$\mathcal{L} \supset \frac{\alpha}{8\pi} \frac{c'_\gamma}{f_\phi} \phi F^{\mu\nu} \widetilde{F}_{\mu\nu} + \frac{1}{2} c_\nu^{ij} (\bar{\nu}_i P_L \nu_j) \phi + \text{h.c.},$$

# Neutrino-photon coupling

[JG, Shoemaker, Thapa '25]

Predict **new NC scattering** signal:

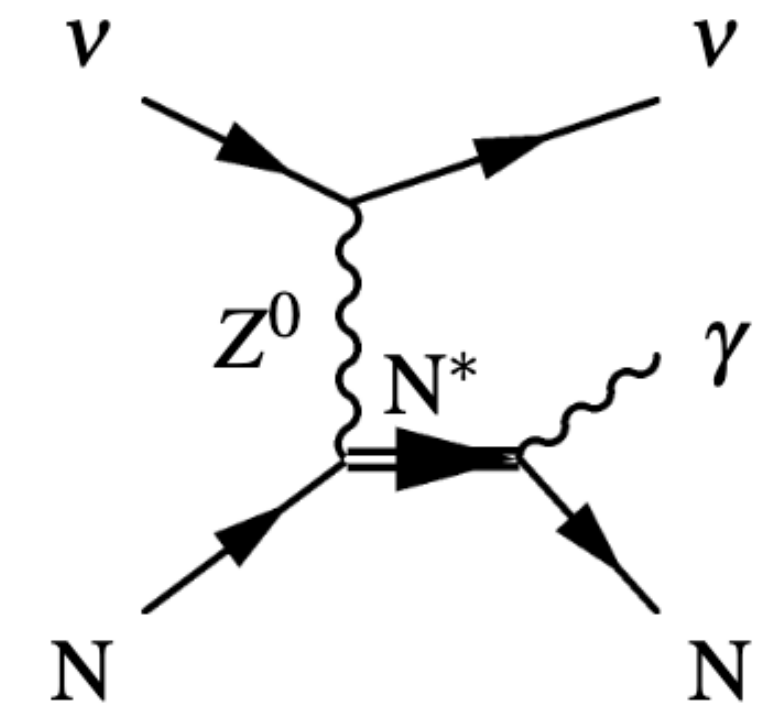
$$\nu N \rightarrow \nu N \gamma$$



Energy of photon depends on mass of mediator

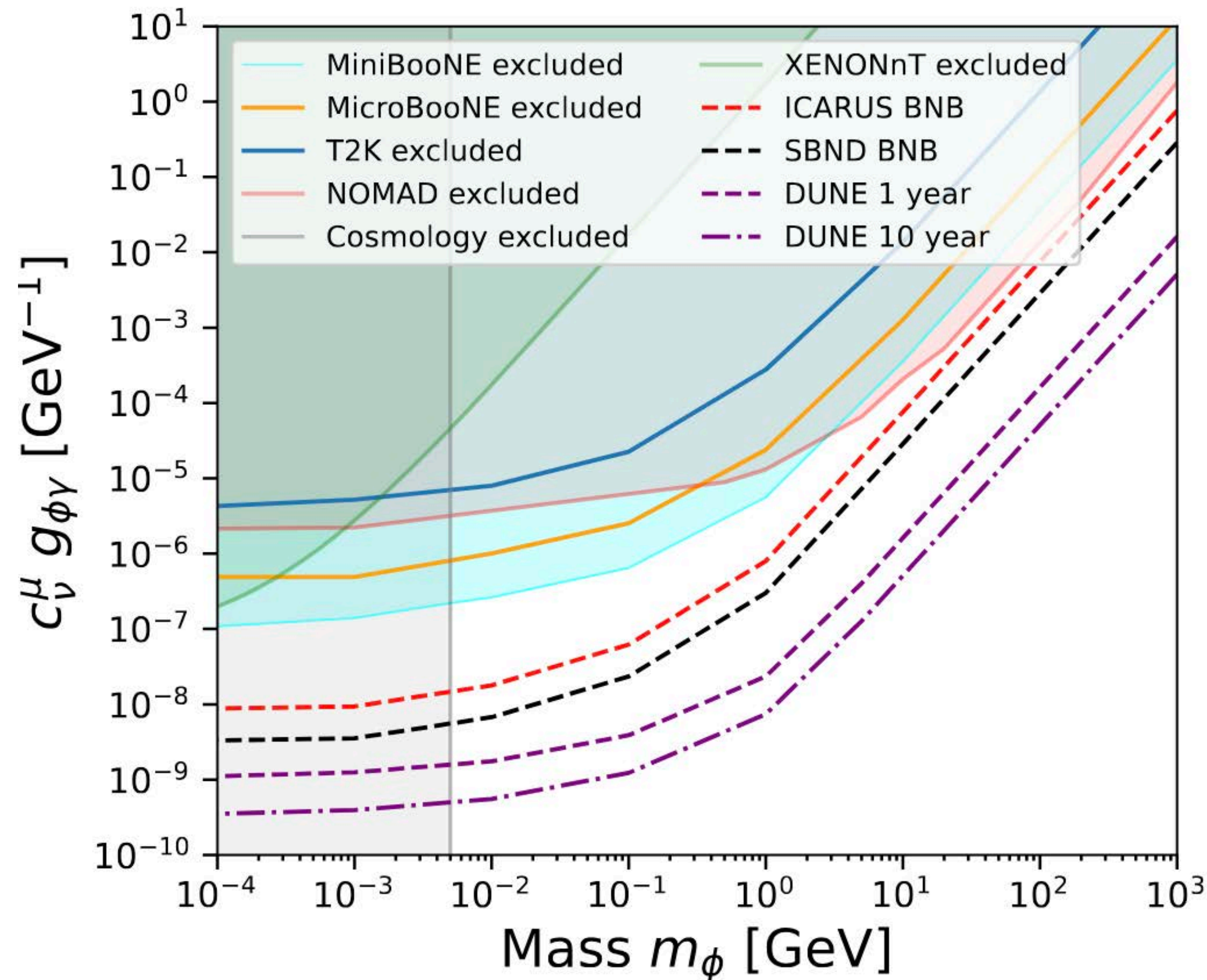
Dedicated searches for mono-photons at neutrino experiments

Final state predicted in SM: coherent process, baryonic resonance, ...



# Neutrino-photon coupling

[JG, Shoemaker, Thapa '25]



LAr technology (MicroBooNE, DUNE)  
has good sensitivity to single photons  
Strongest current constraints:  
MiniBooNE, NOMAD

Constraints on model will improve  
with future experiments

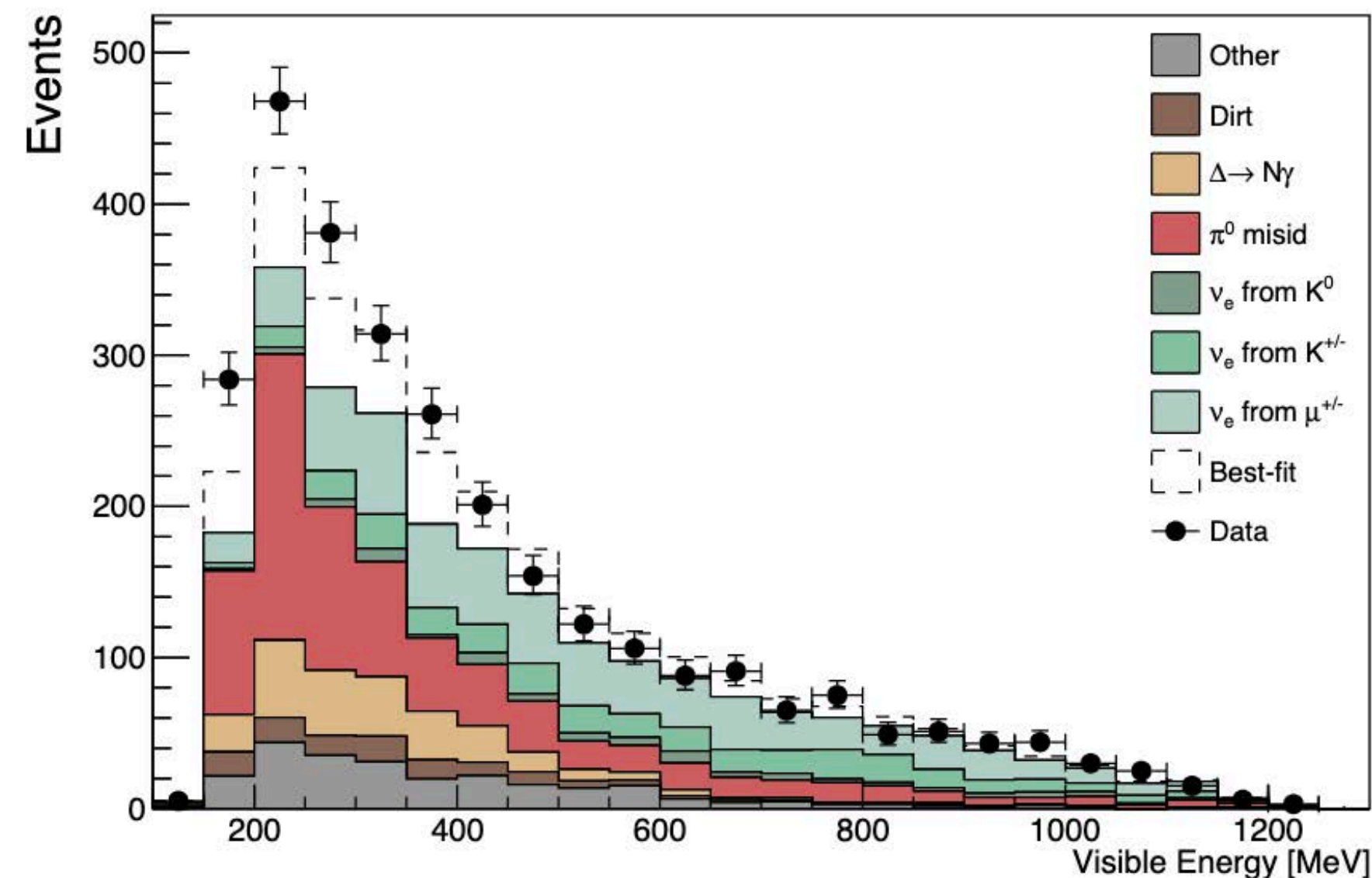
See also [Carey, Machado, Petrov,  
Sousa, Tammara, Zupan '25]

# Neutrino-photon coupling

Have we already seen hints for anomalous neutrino-photon couplings?

MiniBooNE low energy excess:

Could be due to anomalous appearance of electrons or photons, correlated with neutrino beam



eV-scale vanilla sterile neutrino explanation **not** a good global fit!

So far **no convincing SM explanation** either

[MiniBooNE '20]

# Neutrino-photon coupling

Have we already seen hints for anomalous neutrino-photon couplings?

[JG, Thapa, Thompson soon]

Polarizability with active neutrinos is not a good fit to the MiniBooNE data  
Enhanced neutrino polarizability with a sterile neutrino

$$\frac{C_{ij}^7}{\Lambda^3} (\bar{\nu}_{Ri} P_L \nu_{Lj}) F^{\mu\nu} \widetilde{F}_{\mu\nu}$$

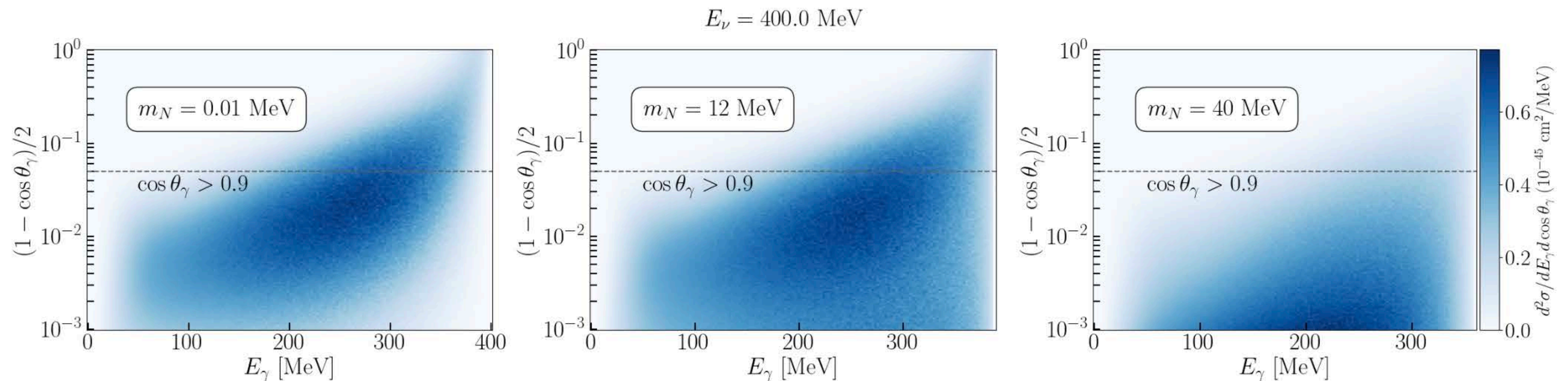
→ changes photon energy spectrum

# Neutrino-photon coupling

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Enhanced neutrino polarizability with a sterile neutrino

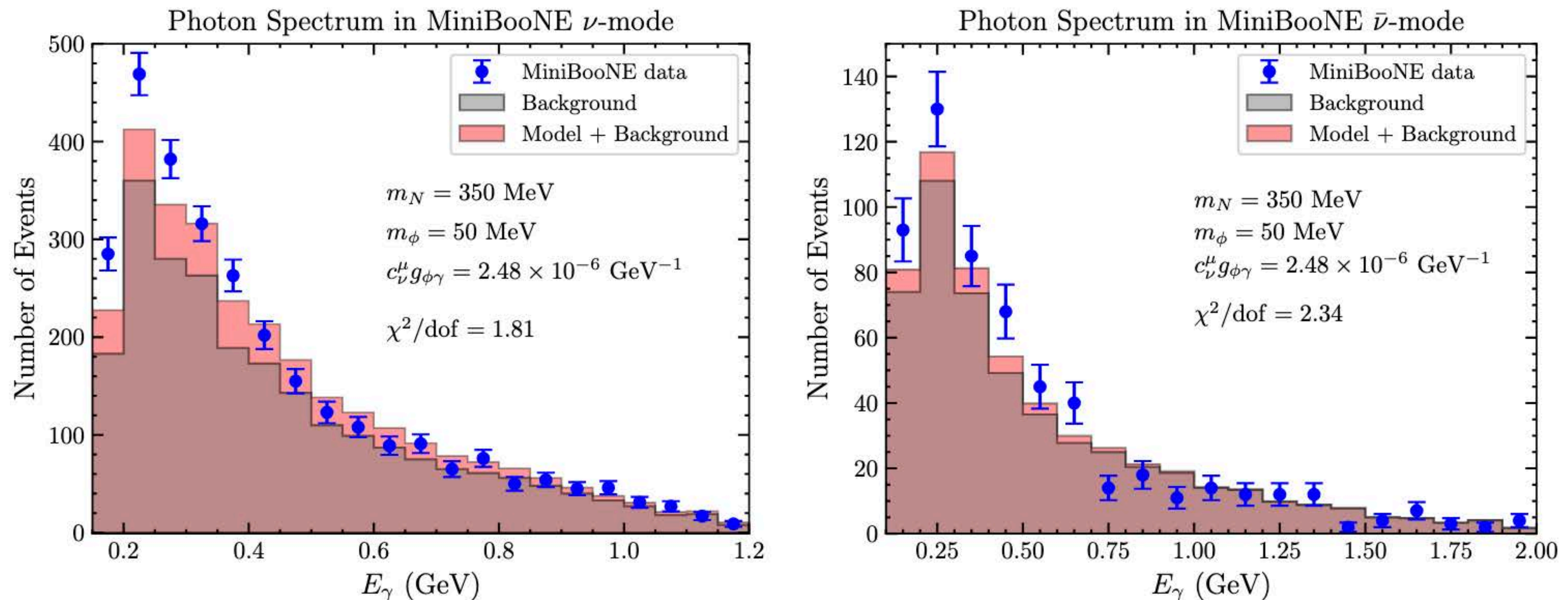


Sterile mass  $\longrightarrow$

# Neutrino-photon coupling

Have we already seen hints for anomalous neutrino-photon couplings?

[JG, Thapa, Thompson soon]



Model is better fit than background only, scenario can be tested at current SBN experiments and DUNE

# New neutrino interactions

## Summary & Conclusion

- New neutrino interactions **appear naturally** in extensions of SM with new mediators
- Test of NSI in **oscillation** experiments and **scattering** experiments → **complementarity** between probes but also **degeneracies**
- **New** idea to test NC NSI using NC events at oscillation experiments → new constraints on isospin conserving axial-vector NSI
- **New** constraints on neutrino interactions with photons
- Future experiments will continue to probe new neutrino interactions
- **Theory effort** needed to build consistent models

# Thank you for your attention!

