New Physics at Neutrino Detectors

Salvador Urrea

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IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

cnrs

OUTLINE OF THE TALK

INTRODUCTION

OPEN PROBLEMS

PORTALS

NEUTRINO EXPERIMENTS

LIGHT SCALE PHYSICS

NEW PHYSICS IN OSCILLATIONS

STERILE NEUTRINOS

NON-UNITARITY

NSI

SEARCHING FOR FIPS AT NEUTRINO EXPERIMENTS

PROTODUNE AND HNLS

DUNE AND ALPS

MICROBOONE AND ALPS

Open problems in particle physics

Origin of neutrino masses

Baryon asymmetry of the Universe

Nature of dark matter

Hierarchy problem

Strong CP problem

Flavor puzzle

Call for new physics

What if the new physics is heavy?

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \ldots$$

$$\delta\mathcal{L}^{d} \equiv \sum_k \frac{c_k \mathcal{O}_k^{(d)}}{\Lambda^{d-4}}$$

Weinberg operator

$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\frac{\kappa_{\alpha\beta}^{(5)}}{\Lambda}\left(\overline{L_{L\alpha}^{C}}\tilde{\phi}^{*}\right)\left(\tilde{\phi}^{\dagger}L_{L\beta}\right) + \text{ h.c.}$$

Neutrino Masses

Weinberg, S. 1979

What if the new physics is heavy?

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \ldots$$

$$\delta\mathcal{L}^{d} \equiv \sum_k \frac{c_k \mathcal{O}_k^{(d)}}{\Lambda^{d-4}}$$

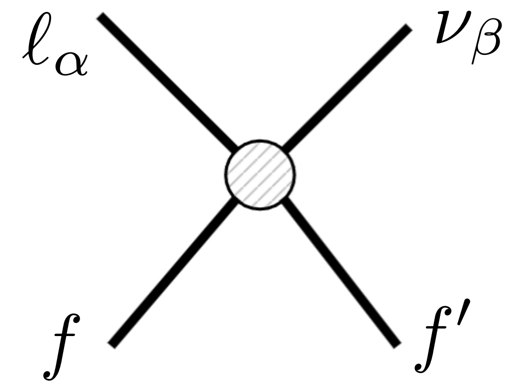
Operators affecting neutrinos oscillations

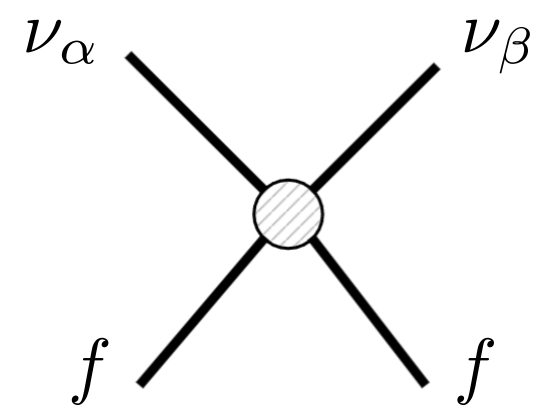
$$\delta\mathcal{L}^{d=6} = \mathrm{NSI} + \ldots$$

ν Production

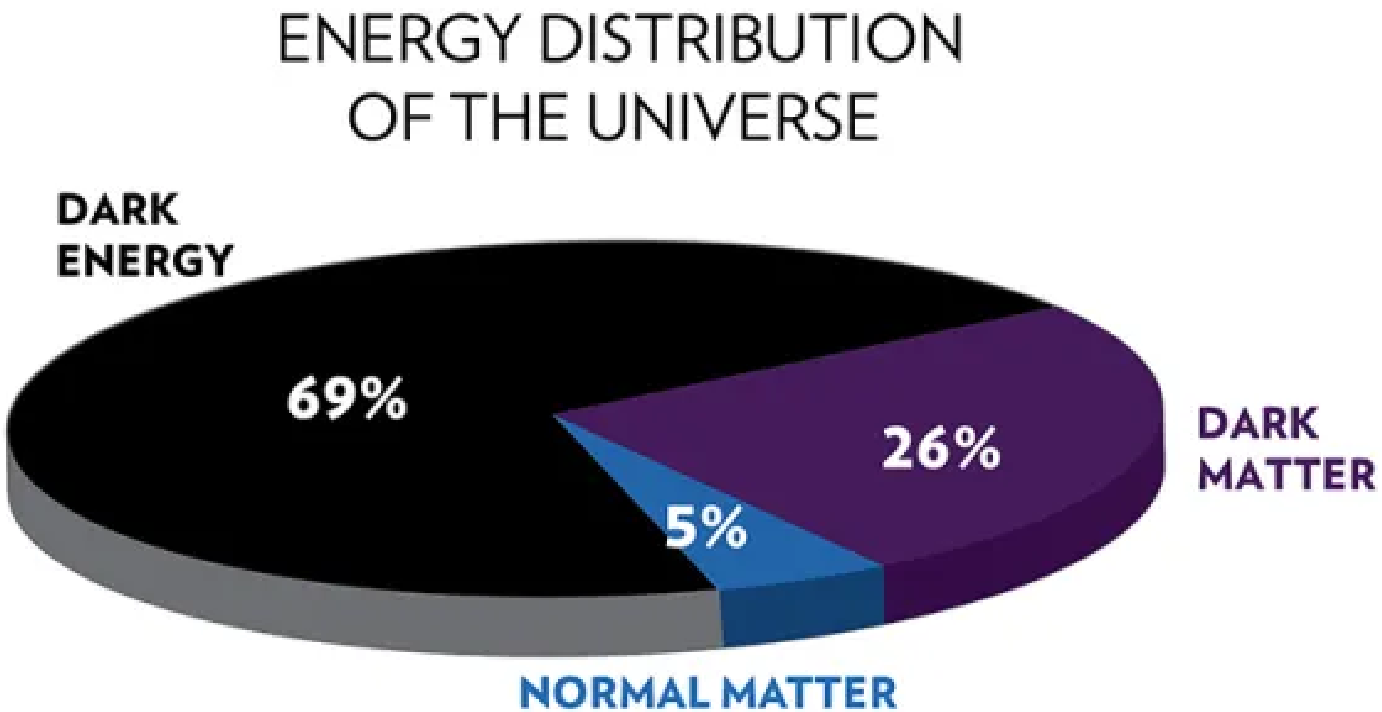
ν Propagation

ν Detection





Origin of Dark Matter

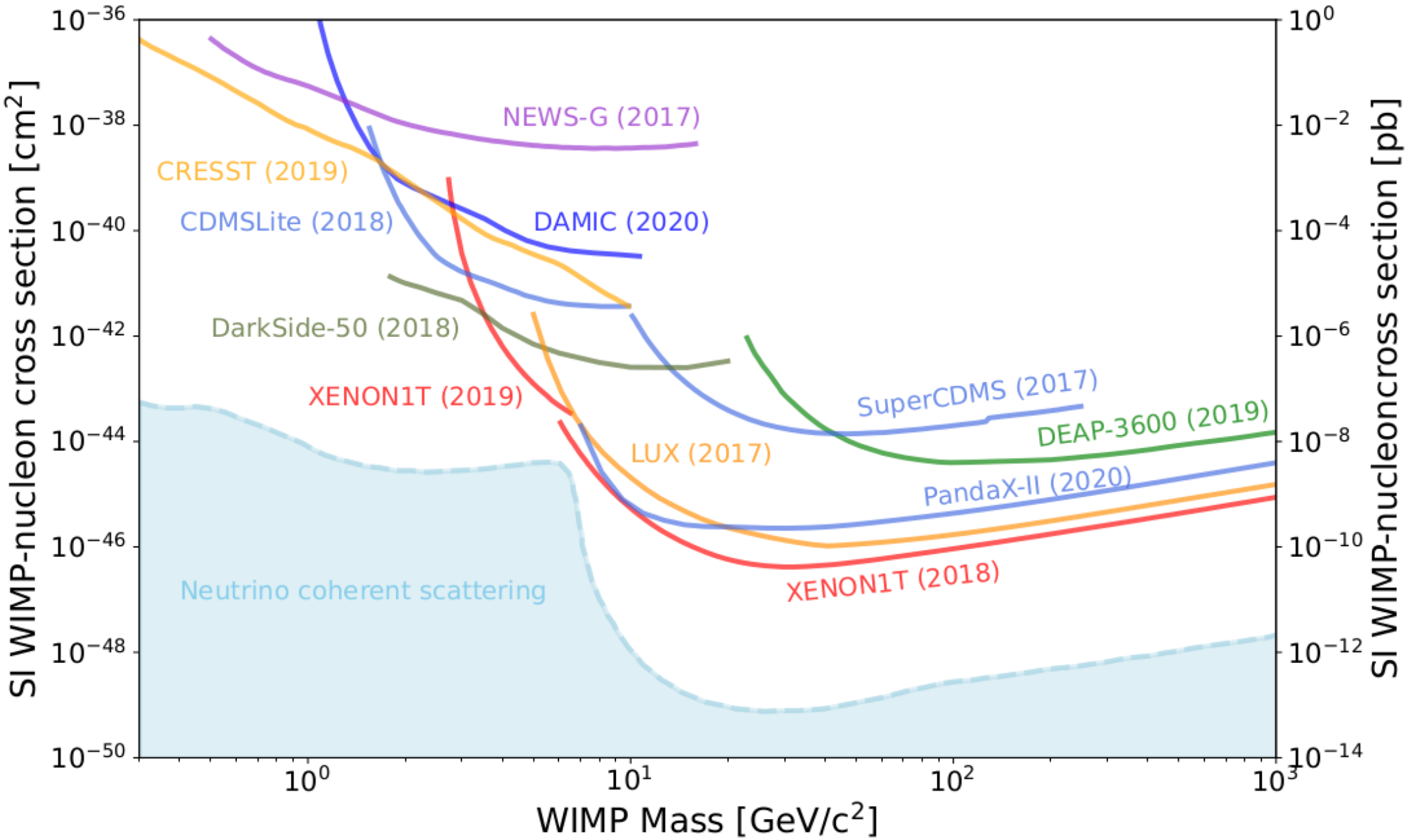


Many pieces of evidence

- Gravitational lensing
- Rotational curves
- CMB anisotropies
- BBN constraints

Origin of Dark Matter

The WIMP window is closing *No Luck @ LHC !*



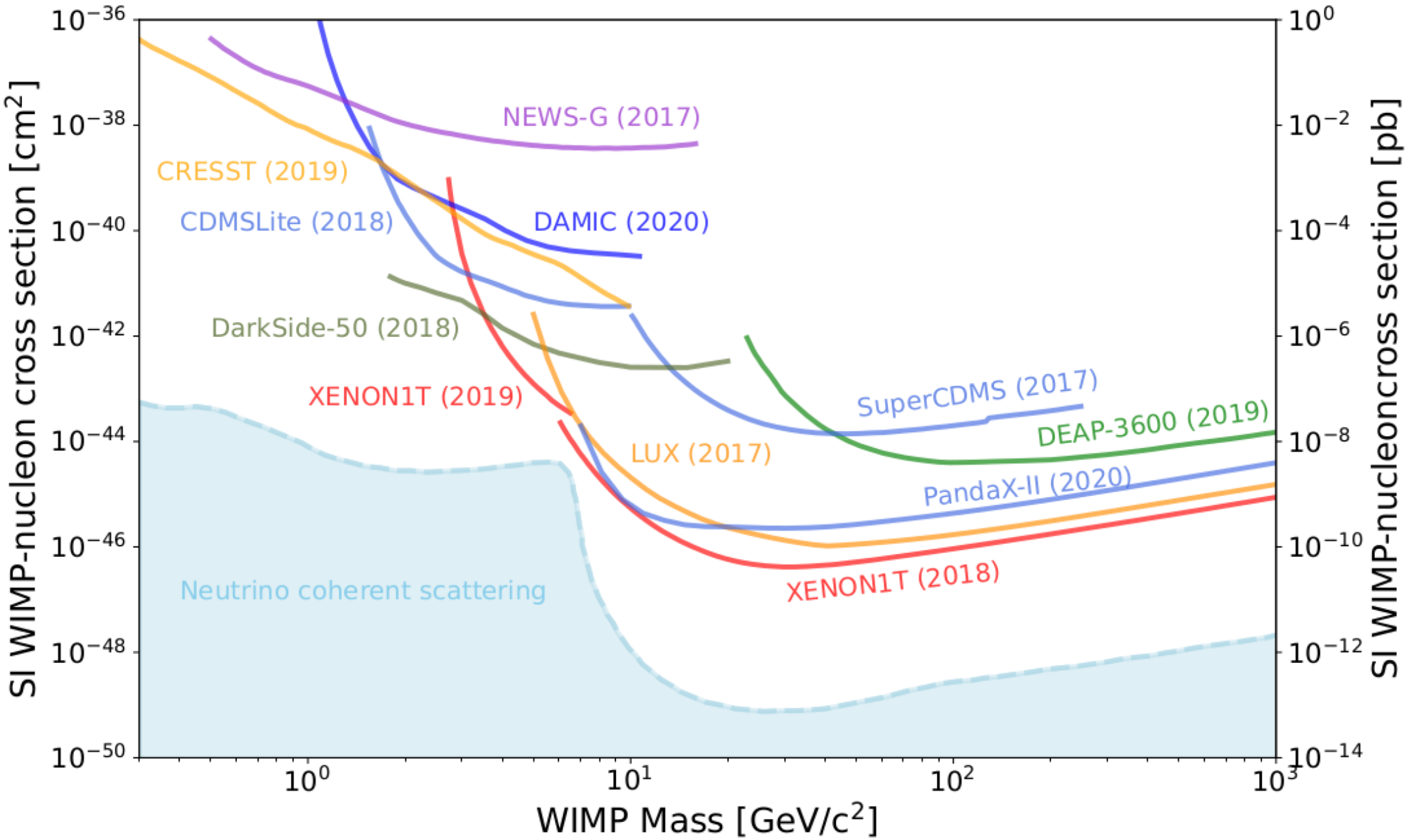
Misiaszek, M., & Rossi, N. 2024

Maybe the WIMP is heavier than anticipated

Other mechanisms, possible lighter scale particles

Origin of Dark Matter

The WIMP window is closing *No Luck @ LHC !*



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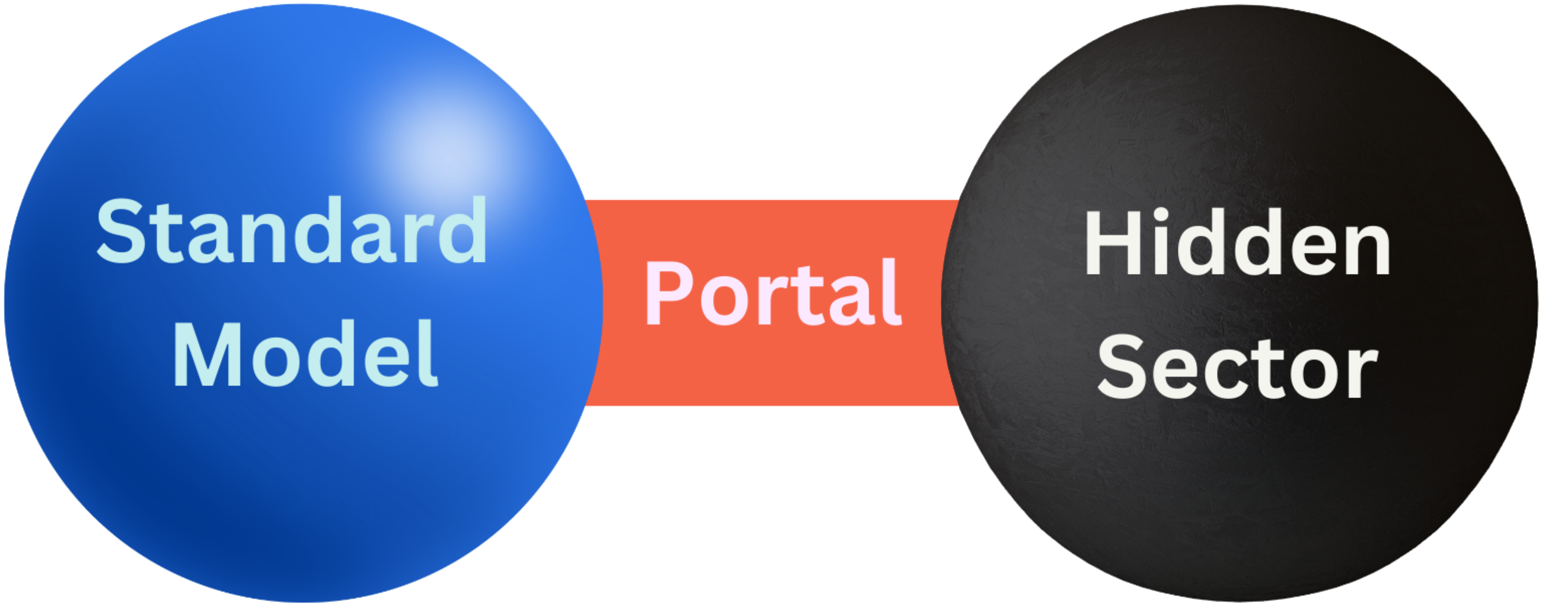
Portals



Scalar (Dark Higgs)

$$\left(\mu S + \lambda S^2\right) H^\dagger H$$

Pseudoscalar (Axions, ALPs)

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \; \frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}, \; \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

Vector (Dark Photon)

$$\frac{\epsilon'}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$$

Neutrino (HNLs)

$$Y_{i\alpha} \overline{N_i} \tilde{H}^\dagger L_\alpha$$

Holdom 1986; Batell, Pospelov, Ritz 2009;
Patt, Wilczek 2006; FIPs 2022 report.

FIPs

Vector Portal: Dark Photon

$$G_{\mathrm{SM}} \times U(1)_{Z'}$$

$$\mathcal{L}_V = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\varepsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu} - \frac{M^2_{Z'}}{2} Z'_\mu Z'^\mu$$

Vector Portal

Dark current $\Rightarrow$ **Millicharged particles**

$$\frac{\varepsilon g_{Z'}}{\cos\theta_W} \sum_\chi q^\chi_{Z'} \bar{\chi} \gamma_\mu \chi Z'^\mu .$$

$$i\bar{\chi}\left(\gamma^\mu \partial_\mu + m_\chi\right)\chi - \varepsilon e \bar{\chi}\gamma_\mu \chi A^\mu$$

Holdom 1986; Stueckelberg 1938;

Okun 1982;

Neutrino Portal

- Simplest extension of SM able to account for **neutrino masses**. Consists in the addition of fermion singlets (N_i) to the SM field content:

Neutrino Portal

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\mathcal{K}} - \frac{1}{2}\overline{N_i^c} M_{ij} N_j - Y_{i\alpha}\overline{N_i}\widetilde{H}^{\dagger} L_\alpha + \text{ h.c.}$$

New Scale

Lepton Number Violation

Fukugita, Yanagida 1986

Leptogenesis

Baryon Asymmetry

How do we give mass to neutrinos?

ΔL conserved

Higgs mechanism

$$m_\nu \sim y_\nu \frac{v}{\sqrt{2}}$$

$y_\nu < 6.5 \cdot 10^{-13}$

Why so small?

ΔL largely violated

High scale See-saw

$$m_\nu \sim \frac{y_\nu^2 v^2}{M}$$

If $y_\nu^2 \sim O(1) \rightarrow M \sim 10^{11}\text{GeV},$

If $y_\nu^2 \sim O(y_e^2) \rightarrow M \sim 1\text{GeV},$

Schechter and Valle 1980; Mohapatra and Senjanovic 1979; Minkowski 1977; Gell-Mann, Ramond and Slansky 1979; Yanagida 1980

ΔL approximately conserved

Low scale see-saw

$$m_\nu \sim \frac{v^2}{M^2}\mu$$

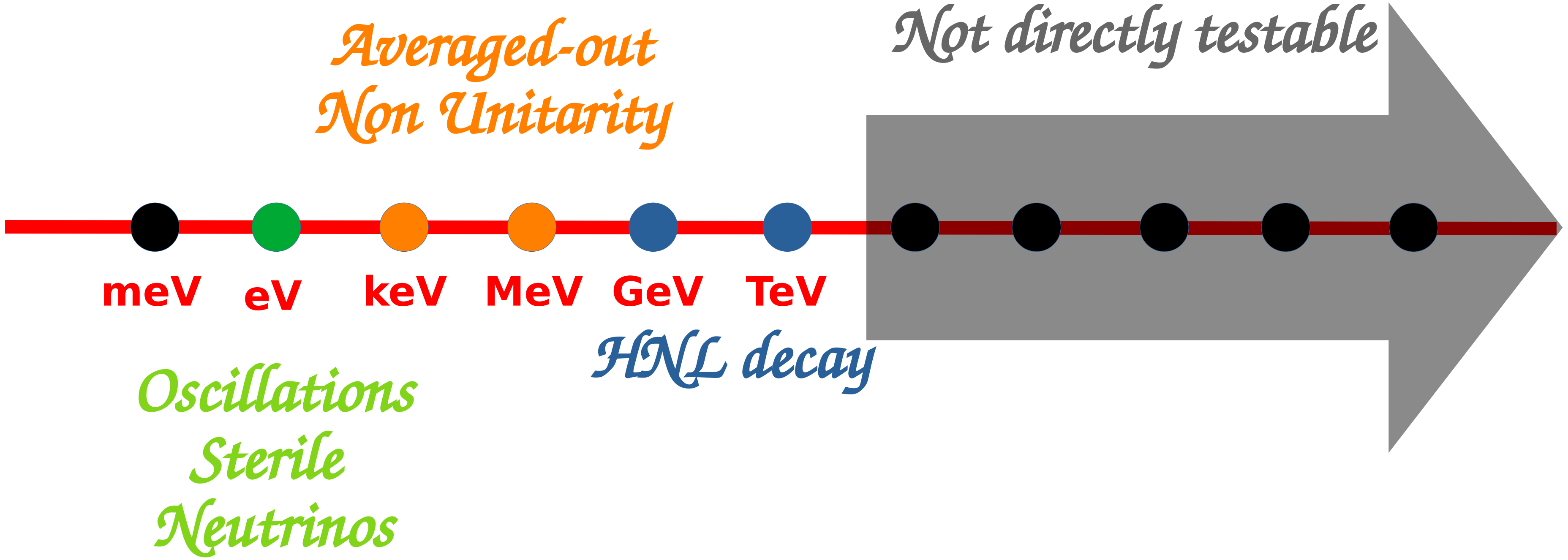
$\mu \ll 1$

Symmetry protected scenarios

Mohapatra, & Valle 1986 ; Akhmedov, Lindner, Schnapka, and Valle 1996; Gonzalez-Garcia and Valle 1989; Gavela, Hambye, Hernandez 2009; Bernabéu, Santamaria, Vidal, Mendez, and Valle 1987; Mohapatra 1986

How do we give mass to neutrinos?

New Physics scale M



Pseudoscalar Portal: ALPs

Appear in many new Physics models

Warm dark matter

QCD Axion solution and Strong CP problem

$$\mathcal{L}_{\text{QCD}} + \frac{\theta g_s^2}{32\pi^2}\epsilon_{\mu\nu\alpha\beta}G_a^{\mu\nu}G^{\alpha\beta}$$

Neutron electric dipole moment

$$d_n = \left(5.2 \times 10^{-16} e \cdot \text{cm}\right)\theta.$$

Why so small?

$$\theta < 10^{-10}$$

Abel, C., & Others. (2020). Measurement of the Permanent Electric Dipole Moment of the Neutron. Phys. Rev. Lett.

$$\frac{a g_s^2}{32\pi^2}\epsilon_{\mu\nu\alpha\beta}G_a^{\mu\nu}G_a^{\alpha\beta}$$

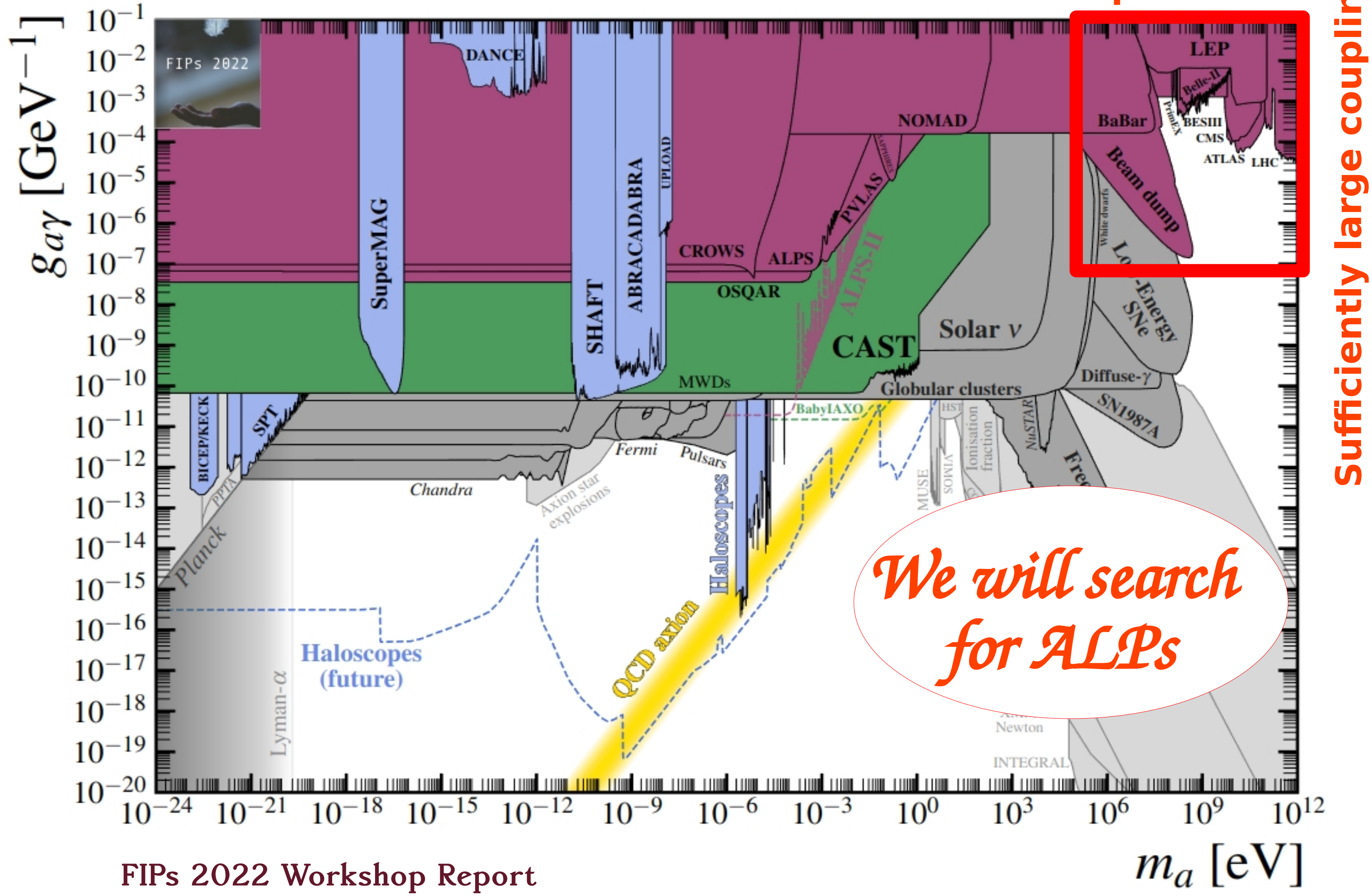
Solves dynamically the Strong CP problem

Peccei, Quinn 1977

Weinberg 1978

How do we search for ALPs?

Neutrino Detectors

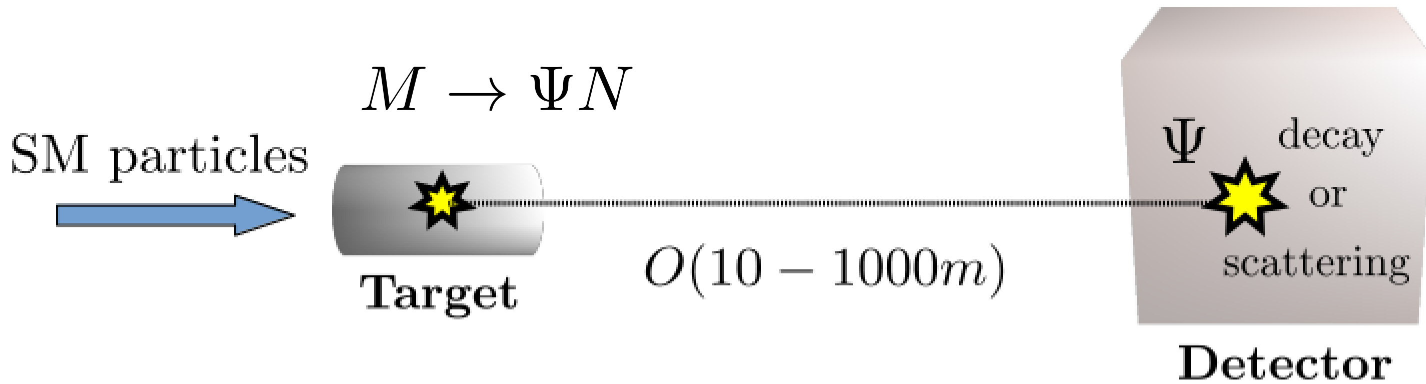


FIPs 2022 Workshop Report

Similarly for other types of FIPs

How do we search for FIPs?

New particles produced in meson decays



Long-lived	Very long-lived (Stable)
(HNL, ALPs, dark photon,...)	(Millicharged particles,...)
Decay in flight inside the detector	Scattering signals

Searching for New Physics at Neutrino detectors

Part I

Affecting the 3 neutrino oscillation picture

Non-unitarity

Sterile neutrinos

NSI

Neutrino Experiments

- Accelerator-based experiments

Searching for New Physics at Neutrino detectors

Part I

Affecting the 3 neutrino oscillation picture

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NSI

Neutrino Experiments

- Accelerator-based experiments
- Reactor Neutrinos
- Solar Neutrinos
- Atmospheric Neutrinos
- CEvNS

Searching for New Physics at Neutrino detectors

Neutrino Experiments

- Accelerator-based experiments

Part II

Non-oscillation New Physics

Millicharged particles

ALPs

Dark Photon

HNLs

Light mediators

Articles

Part I

- **P. Coloma, J. López-Pavón, S. Rosauro-Alcaraz, and S. Urrea, New physics from oscillations at the DUNE near detector, and the role of systematic uncertainties, JHEP 08 (2021) 065.**

- P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni, J. P. Pinheiro, and S. Urrea, Constraining new physics with borexino phase-ii spectral data, JHEP 2022 (July, 2022) .

- **P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni, J. a. P. Pinheiro, and S. Urrea, Global constraints on non-standard neutrino interactions with quarks and electrons, JHEP 0 8 (2023) 032.**

Part II

- P. Coloma, P. Hernández, and S. Urrea, New bounds on axion-like particles from MicroBooNE, JHEP 08 (2022) 025.

- **P. Coloma, J. López-Pavón, L. Molina-Bueno, and S. Urrea, New physics searches using ProtoDUNE and the CERN SPS accelerator, JHEP 01 (2024) 134.**

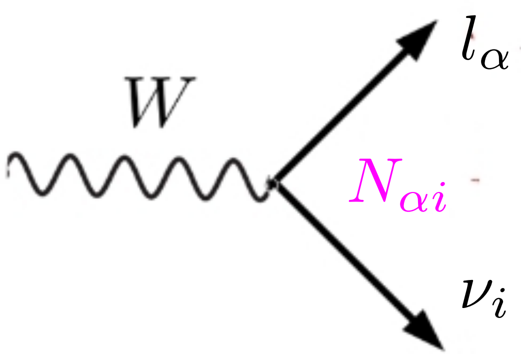
- **P. Coloma, J. Martín-Albo, and S. Urrea, Discovering long-lived particles at DUNE, Phys. Rev. D 109 (2024), no. 3 035013**

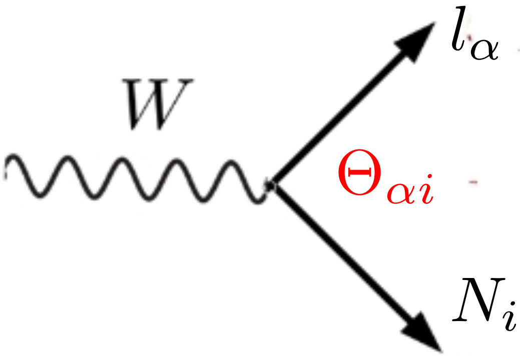
Part I: New Physics in Neutrino Oscillations

Non-unitarity and sterile neutrinos

$$\begin{pmatrix} \text{3 flavour neutrinos} \\ n-3 \text{ sterile neutrinos} \end{pmatrix} = \mathcal{U} \begin{pmatrix} \text{3 light neutrinos } \nu_i \\ n-3 \text{ heavy neutrinos } N_i \end{pmatrix}$$

$$\mathcal{U} = \begin{pmatrix} N_{3\times 3} & \Theta_{3\times(n-3)} \\ R_{(n-3)\times 3} & S_{(n-3)\times(n-3)} \end{pmatrix}$$



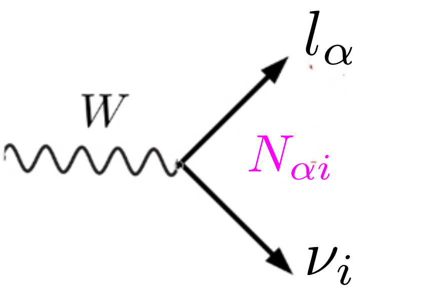


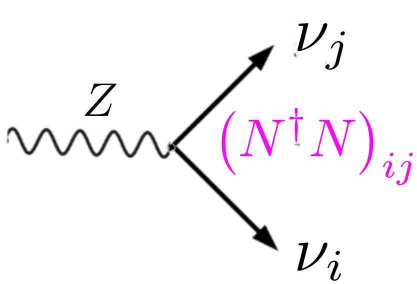
Non-unitarity

$$m > \mathrm{EW}$$

- Strong constraints from EW and flavour precision data

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\left(W_\mu^- \bar{l}_{L\alpha}\gamma_\mu N_{\alpha i}\nu_{Li} + \mathrm{h.c.}\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{\nu}_{Li}\gamma^\mu \left(N^\dagger N\right)_{ij}\nu_{Lj} + \mathrm{h.c.}\right)$$





Examples of observables constraining Non-unitarity

$$\Gamma_{\mu\to\nu_\mu e\bar{\nu}_e} = \frac{m_\mu^5 G_F^2}{192\pi^3}\sum_i |N_{\mu i}|^2 \sum_j |N_{ej}|^2 \qquad G_F = \frac{G_F^{\mathrm{PDG}}}{\sqrt{\sum_j |N_{ej}|^2 \sum_i |N_{\mu i}|^2}}.$$

Lepton flavour universality

$$\frac{\Gamma(P\to\mu\nu)}{\Gamma(P\to e\nu)} = \frac{\Gamma\left(P\to\mu\nu_\mu\right)^{\mathrm{SM}}}{\Gamma\left(P\to e\nu_e\right)^{\mathrm{SM}}}\frac{\sum_{i=1}^3 |N_{\mu i}|^2}{\sum_{i=1}^3 |N_{ei}|^2} \qquad P = \pi, K$$

Invisible decay width of Z $\quad (NN^\dagger)_{ij} = \delta_{ij} + O(10^{-3})$

Blennow, Fernández-Martínez, Hernández-García, López-Pavón, Marcano, Naredo-Tuero 2023

Antusch, Biggio, Fernández-Martínez, Gavela, López-Pavón 2006

- Heavy neutrinos are not kinematically accessible in neutrino experiments

Non-unitarity at near detector

Non-unitary mixing matrix

$$P_{\alpha\beta} = \left|\left(NS^0N^\dagger\right)_{\beta\alpha}\right|^2, \; S^0 = \exp(-iHL)$$

Common parametrization of N

$$\mathbf{N} = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ -\alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ -\alpha_{\tau e} & -\alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix} U_{\text{PMNS}}$$

Xing 2007; Xing 2011; Escrihuela, Forero, Miranda, Tórtola, Valle 2015

$\mathcal{L} = 0$

Standard unitary case

$$\mathrm{P}^{\text{Standard}}_{\gamma\beta} = \left|\left(UU^\dagger\right)_{\beta\gamma}\right|^2 = \delta_{\gamma\beta}$$

Non-unitarity appearance

$$\gamma \neq \beta$$

$$P^{\text{Non-unitarity}}_{\gamma\beta} = \left|\left(NN^\dagger\right)_{\beta\gamma}\right|^2 = |\alpha_{\gamma\beta}|^2$$

Non-unitarity disappearance

$$\gamma = \beta$$

$$P^{\text{Non-unitarity}}_{\beta\beta} = \left|\left(NN^\dagger\right)_{\beta\beta}\right|^2 = 1 - 4\alpha_{\beta\beta}$$

Stronger constraints from EW data

Sterile Neutrinos

$$m \lesssim O(1\mathrm{KeV})$$

- All massive neutrinos are now accessible at EW processes and the strong bounds disappear

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\left(W_\mu^- \bar{l}_{L\alpha}\gamma_\mu \mathcal{U}_{\alpha i}\nu_{Li} + \text{h.c.}\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{\nu}_{Li}\gamma^\mu (\overbrace{\mathcal{U}^\dagger \mathcal{U}}^{I})_{ij}\nu_{Lj} + \text{h.c.}\right)$$

$$\Gamma_{\mu\to\nu_\mu e\bar{\nu}_e} = \frac{m_\mu^5 G_F^2}{192\pi^3}\overbrace{\sum_i |\mathcal{U}_{\mu i}|^2}^{1}\overbrace{\sum_j |\mathcal{U}_{ej}|^2}^{1} = \frac{m_\mu^5 G_F^2}{192\pi^3}$$

- Produced in beams like DUNE and bounds from oscillation experiments

- Anomalies in short-baseline experiments like LSND and MiniBooNE suggest the presence of an extra neutrino around 1 eV.

Sterile Neutrinos 3+1

4×4 unitary matrix

$$\mathcal{U} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} = \begin{pmatrix} N_{3\times 3} & \Theta_{3\times 1} \\ R_{1\times 3} & S_{1\times 1} \end{pmatrix}$$

4×4 unitary matrix

$$P_{\alpha\beta}^{\text{Steriles}} = \left| \left(\mathcal{U}\mathcal{S}\mathcal{U}^{\dagger} \right)_{\beta\alpha} \right|^2, \mathcal{S} = \text{diag}\left(\exp\left(-i\Delta m_{j1}^2 L/2E \right) \right)$$

Sterile neutrino appearance

$$\mathbf{P}_{\alpha\beta}^{\text{SBL}} = 4\,|U_{\alpha 4}|^2\,|U_{\beta 4}|^2 \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

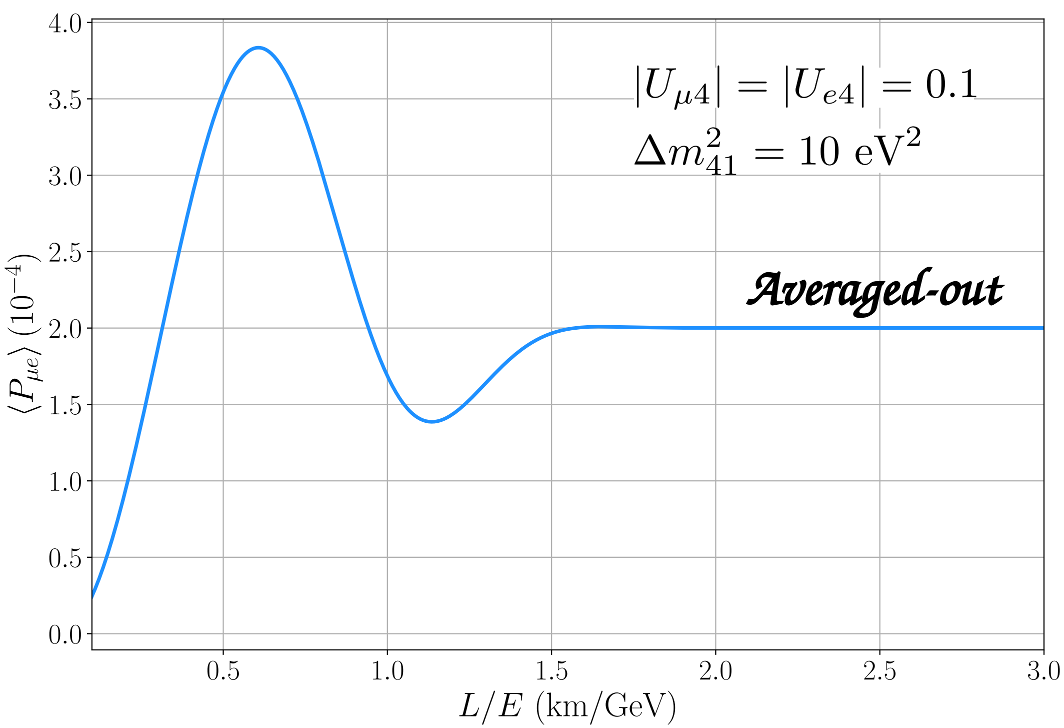
Sterile neutrino disappearance

$$\mathbf{P}_{\beta\beta}^{\text{SBL}} = 1 - 4\,|U_{\beta 4}|^2\left(1 - |U_{\beta 4}|^2\right)\sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

Averaged-out limit $\frac{\Delta m_{14}^2 L}{4E} \gg 1$

$$\left\langle \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)\right\rangle = \frac{1}{2}$$

$$\left\langle \mathbf{P}_{\alpha\beta}^{\text{SBL}}\right\rangle = 2\,|U_{\alpha 4}|^2\,|U_{\beta 4}|^2, \qquad \left\langle \mathbf{P}_{\beta\beta}^{\text{SBL}}\right\rangle = 1 - 2\,|U_{\beta 4}|^2\left(1 - |U_{\beta 4}|^2\right)$$



$2\,|U_{\mu 4}|^2\,|U_{e4}|^2$

Sterile neutrino 3+1 averaged-out limit vs non-unitarity

Mapping

$$\begin{pmatrix} |\alpha_{ee}| & 0 & 0 \\ |\alpha_{\mu e}| & |\alpha_{\mu\mu}| & 0 \\ |\alpha_{\tau e}| & |\alpha_{\tau\mu}| & |\alpha_{\tau\tau}| \end{pmatrix} = \begin{pmatrix} \frac{1}{2}\left|U_{e4}\right|^2 & 0 & 0 \\ \left|U_{\mu 4}\right|\left|U_{e4}\right| & \frac{1}{2}\left|U_{\mu 4}\right|^2 & 0 \\ \left|U_{\tau 4}\right|\left|U_{e4}\right| & \left|U_{\tau 4}\right|\left|U_{\mu 4}\right| & \frac{1}{2}\left|U_{\tau 4}\right|^2 \end{pmatrix}$$

Non-unitarity $m >$ EW

$$P^{\text{App}}_{\gamma\beta} = \left|\alpha_{\gamma\beta}\right|^2$$

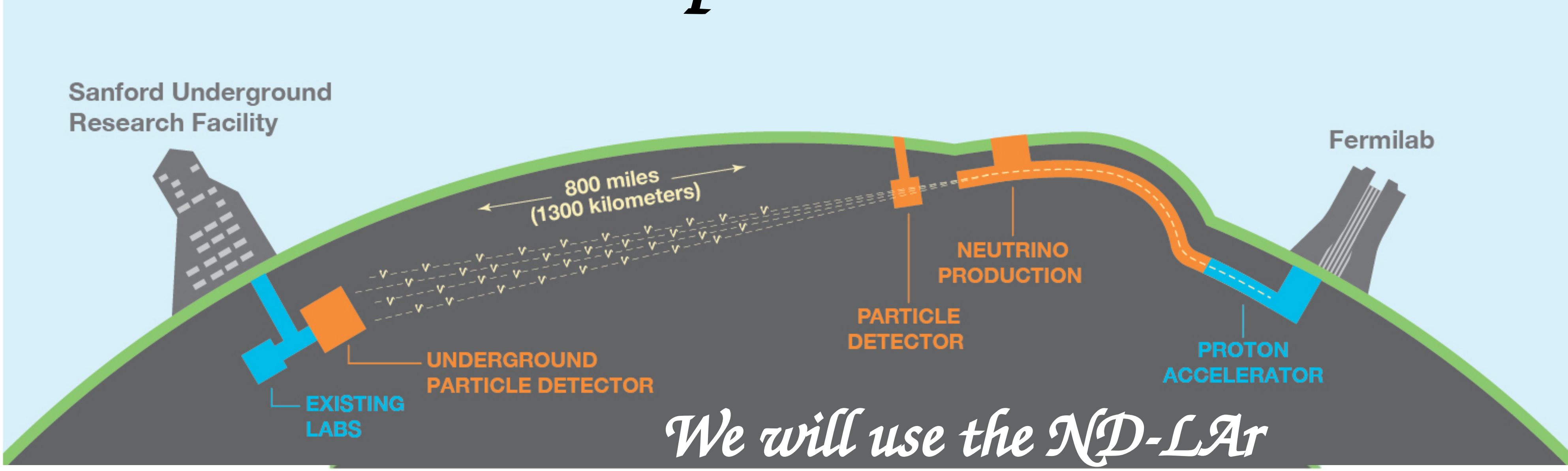
$$P^{\text{Dis}}_{\beta\beta} = 1 - 4\alpha_{\beta\beta}$$

Averaged-out limit $EW \gg \Delta m^2 \geq 100\text{eV}^2$

$$P^{\text{App}}_{\gamma\beta} = 2\left|\alpha_{\gamma\beta}\right|^2$$

$$P^{\text{Dis}}_{\beta\beta} = 1 - 4\alpha_{\beta\beta}$$

DUNE will test the robustness of the three-neutrino picture



We will use the ND-LAr

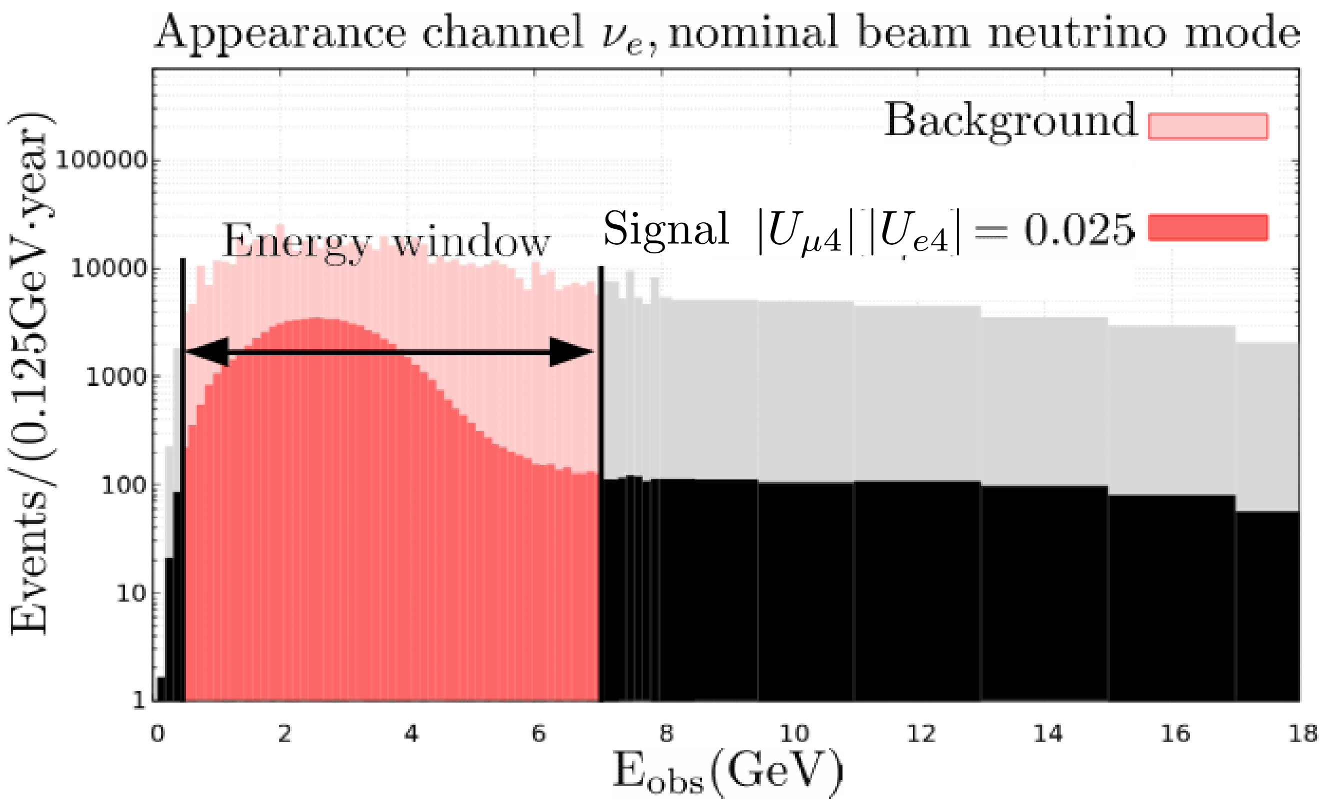
Sources of systematics

- Cross sections
- ν flux

Far detector vs near detector

- Near detector measurements reduce the far detector systematic uncertainties.
- New physics at the near detector (heavily affected by systematics)

Why is the shape uncertainty very important for the near detector?



Type of systematics

- Global normalization error. Marginal impact on the sensitivity.
- **Shape uncertainty**: a normalization error in each energy beam. High impact on the sensitivity.

The sensitivity comes from the spectral information

Coloma, P., López-Pavón, J., Rosauro-Alcaraz, S., & Urrea, S. (2021). New physics from oscillations at the DUNE near detector, and the role of systematic uncertainties. JHEP, 08, 065

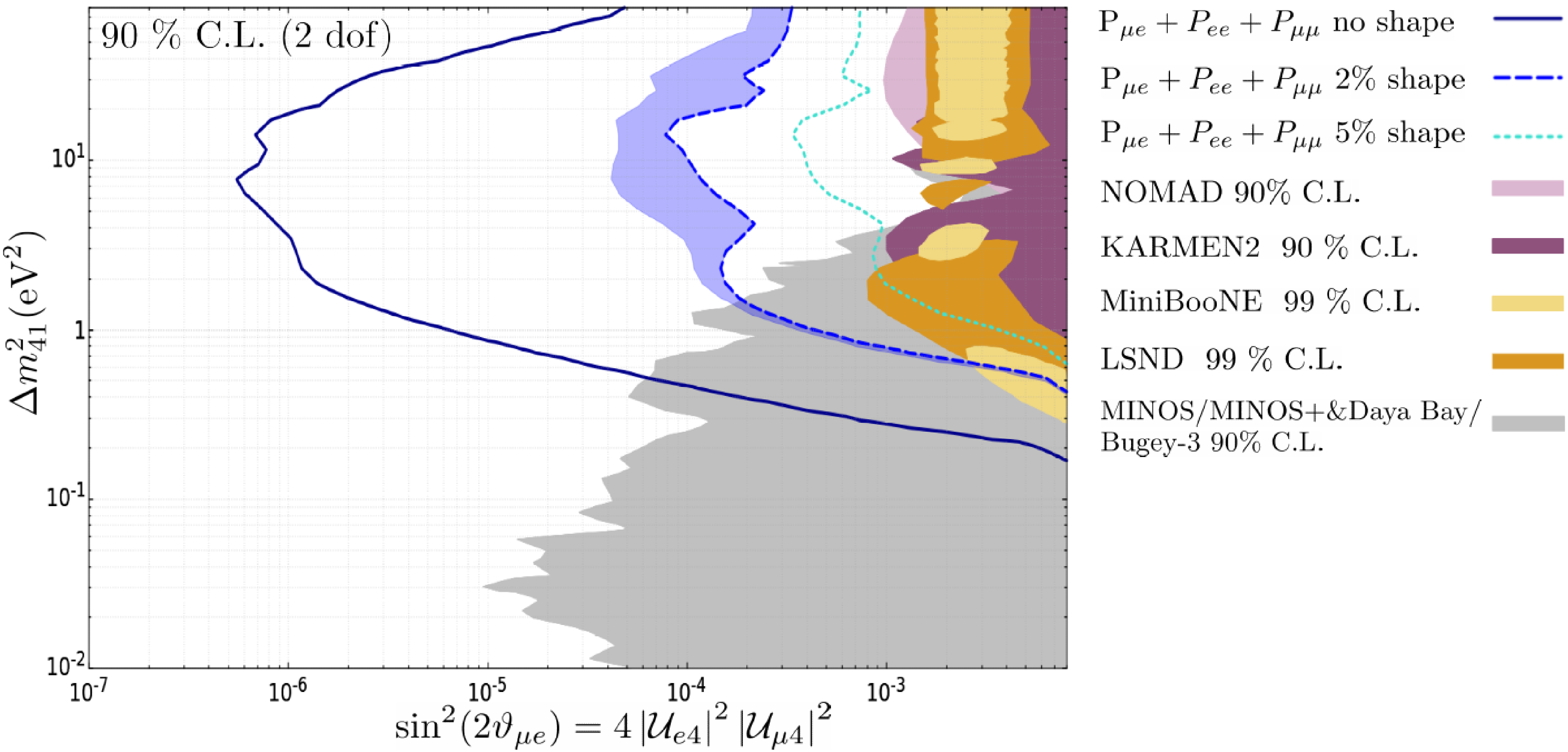
See also: Miranda, Pasquini, Tórtola, Valle 2018

Results at DUNE ND

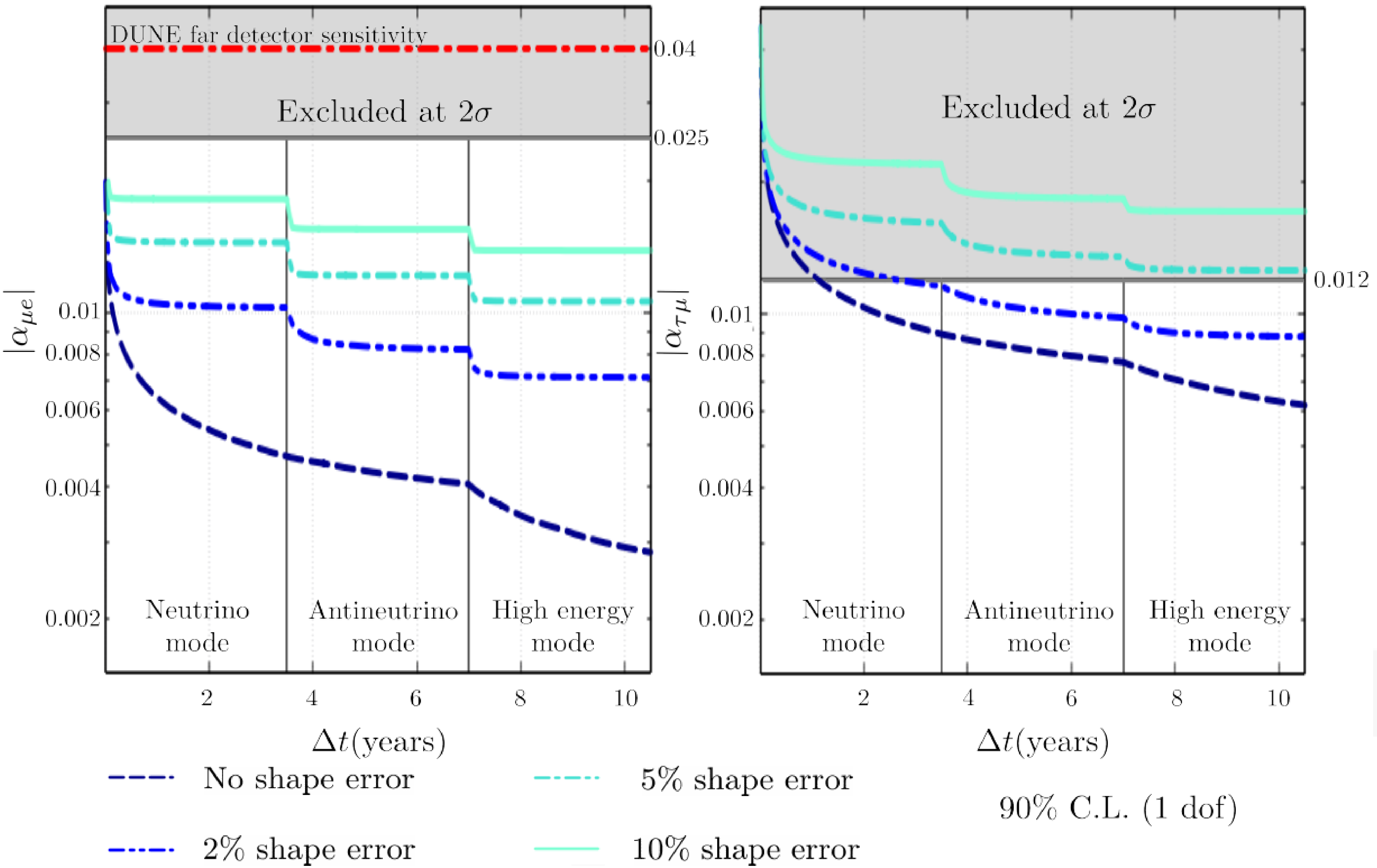
Coloma, P., López-Pavón, J., Rosauro-Alcaraz, S., & Urrea, S. (2021). **New physics from oscillations at the DUNE near detector, and the role of systematic uncertainties.** JHEP, 08, 065

Sterile neutrinos analysis

$$\mathrm{P}_{\mu e} + P_{ee} + P_{\mu\mu}$$



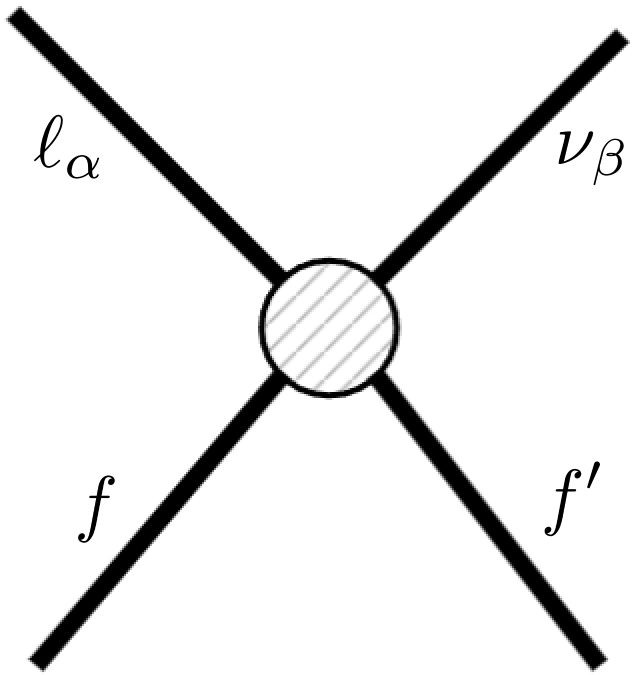
Appearance averaged-out results



Non-standard neutrino interactions (NSI)

Charged current (CC) NSI

$$\mathcal{L}_{\text{NSI,CC}} = -2\sqrt{2}G_F \sum_{f,f',\alpha,\beta} \varepsilon_{\alpha\beta}^{ff',P} \left(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta\right) \left(\bar{f}\gamma^\mu P f'\right) + \text{ h.c.}$$



- Affect detection and production.
- **Strongly constrained** by other observables like meson and lepton decays.
- **We do not include them.**

Biggio, Blennow, Fernández-Martínez 2019

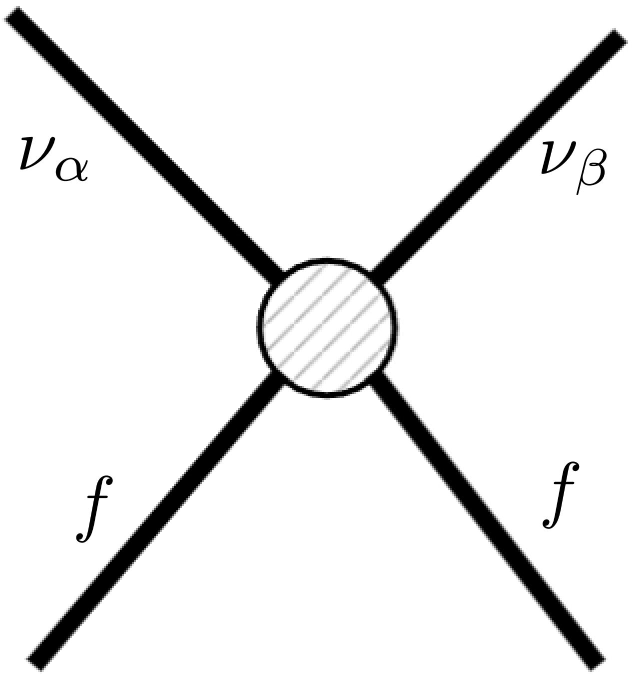
Neutral current (NC) NSI

$$P = P_L, P_R$$

$$\mathcal{L}_{\text{NSI,NC}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f}\gamma_\mu P f\right).$$

$$\varepsilon_{\alpha\beta}^{f,V} \equiv \varepsilon_{\alpha\beta}^{f,L} + \varepsilon_{\alpha\beta}^{f,R} \qquad \varepsilon_{\alpha\beta}^{f,A} \equiv \varepsilon_{\alpha\beta}^{f,L} - \varepsilon_{\alpha\beta}^{f,R}$$

Propagation Detection | **Detection**



- Much more difficult to probe, main bounds from oscillation data.
- We do include them. Including for the **first time NSI with e** as well as quarks.

Simplifications

$$\varepsilon_{\alpha\beta}^{f,P} \equiv \varepsilon_{\alpha\beta}\xi^f \chi^P \qquad \varepsilon_{\alpha\beta}^{f,P} \in \mathbb{R}, \text{CP conserving}$$

Experiments included in the Global fit

NSI

Propagation

(only vector NSI)

Detection cross sections

(Both vector and axial NSI)

- Elastic scattering with electrons (ES)
- NC on deuterium (Axial)
- CEvNS(Vector)

Our analysis includes data from:

- **Solar:** (Chlorine, Gallex/GNO, SAGE, SNO, SK[1-4], the first two phases of Borexino);
- **Atmospheric:** (SK[1-4], Deepcore, IceCUBE)
- **Reactor**: (KamLAND, Double-Chooz, Daya-Bay, RENO)
- **Accelerator:** (Minos, T2K, NovA)
- **CEvNS**: Dresden II, both the Ar target and the CsI target configurations of COHERENT.

Neutrino Propagation

$$H^{\nu} = H_{\text{vac}} + H_{\text{mat}}$$

$$\mathrm{H}_{\text{mat}} = \sqrt{2} G_F N_e(x) \begin{pmatrix} 1+\mathcal{E}_{ee}(x) & \mathcal{E}_{e\mu}(x) & \mathcal{E}_{e\tau}(x) \\ \mathcal{E}^*_{e\mu}(x) & \mathcal{E}_{\mu\mu}(x) & \mathcal{E}_{\mu\tau}(x) \\ \mathcal{E}^*_{e\tau}(x) & \mathcal{E}^*_{\mu\tau}(x) & \mathcal{E}_{\tau\tau}(x) \end{pmatrix} \qquad \mathcal{E}_{\alpha\beta}(x) = \sum_{f=e,u,d} \frac{N_f(x)}{N_e(x)} \varepsilon^{f,V}_{\alpha\beta}$$

$$\mathcal{E}_{\alpha\beta}(x) = \left(\varepsilon^{e,V}_{\alpha\beta} + \varepsilon^{p,V}_{\alpha\beta}\right) + Y_n(x)\varepsilon^{n,V}_{\alpha\beta} \quad \text{with} \quad Y_n(x) \equiv \frac{N_n(x)}{N_e(x)}$$

Solar Neutrinos and KamLand

$\Delta m^2_{31} \to \infty$ Effective 2 families approximation

$$\varepsilon_D = f(\vartheta_{13}, \vartheta_{23}, \varepsilon_{e\mu}, \varepsilon_{e\tau}, \varepsilon_{\mu\tau}, \varepsilon_{ee}, \varepsilon_{\mu\mu}, \varepsilon_{\tau\tau}),$$
$$\varepsilon_N = g(\vartheta_{13}, \vartheta_{23}, \varepsilon_{e\mu}, \varepsilon_{e\tau}, \varepsilon_{\mu\tau}, \varepsilon_{\mu\mu}, \varepsilon_{\tau\tau}).$$

2 degrees of freedom

Atmospheric and LBL

$$\varepsilon^{\oplus}_{\alpha\beta} = \left(\varepsilon^{e,V}_{\alpha\beta} + \varepsilon^{p,V}_{\alpha\beta}\right) + Y^{\oplus}_n \varepsilon^{n,V}_{\alpha\beta},$$

$$Y^{\oplus}_n = \frac{N^{\oplus}_n}{N^{\oplus}_e} \simeq 1.051$$ **(Average in Earth)**

We derive bounds $\varepsilon^{\oplus}_{\alpha\beta} \sim O(0.01 - 0.1)$

Coloma, P., Gonzalez-Garcia, M. C., Maltoni, M., Pinheiro, J. P., & Urrea, S. (2023). Global constraints on non-standard neutrino interactions with quarks and electrons. JHEP, 08, 032.

Neutrino Propagation and LMA-Dark solution

$$H^{\nu} = H_{\rm vac} + H_{\rm mat}$$

Generalized mass-ordering degeneracy

$$\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21} = -\Delta m^2_{32},$$

$$\theta_{12} \to \pi/2 - \theta_{12}$$

$$\delta_{\rm CP} \to \pi - \delta_{\rm CP}$$

Miranda, Tortola, Valle, 2006

MCGG, Maltoni, Salvado 2011

Coloma, Schwetz, 2016

Farzan, 2015

$$H^{\nu}_{\rm vac} \to -(H^{\nu}_{\rm vac})^*$$

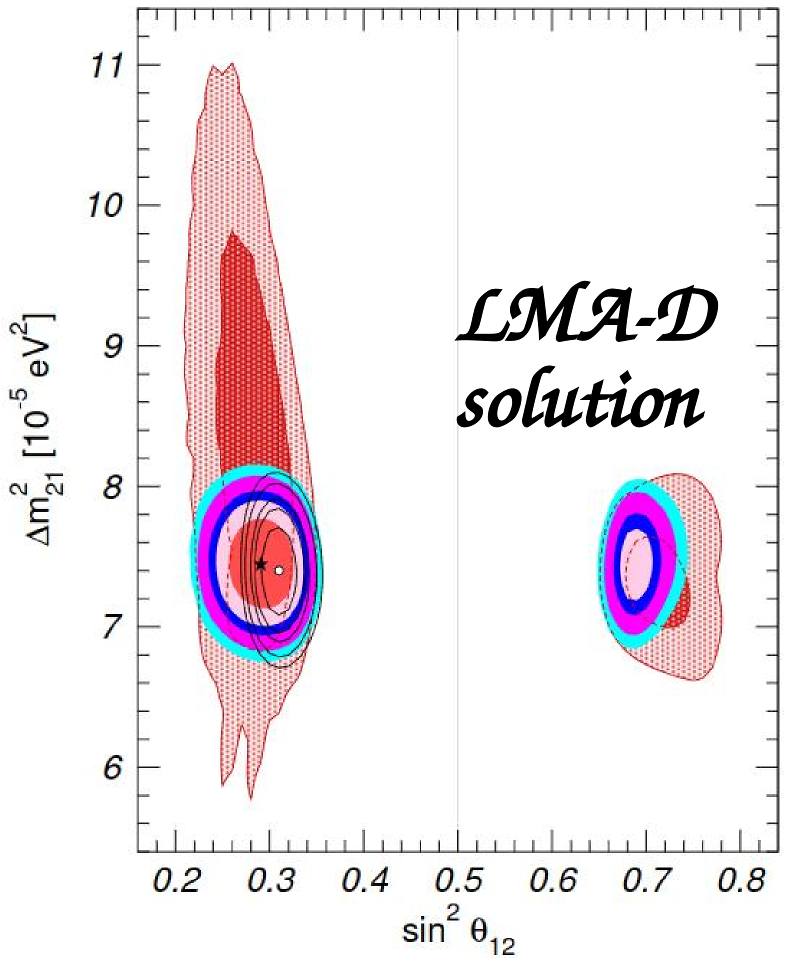
$$\mathcal{E}_{\alpha\beta}(x) = \sum_{f=e,u,d} \frac{N_f(x)}{N_e(x)} \varepsilon^{f,V}_{\alpha\beta}$$

$$[\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] - 2,$$

$$[\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)]$$

$$\mathcal{E}_{\alpha\beta}(x) \to -\mathcal{E}^*_{\alpha\beta}(x) \quad (\alpha \neq \beta),$$

$$H^{\nu}_{\rm mat} \to -(H^{\nu}_{\rm mat})^*$$



Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler & Salvado 2018.

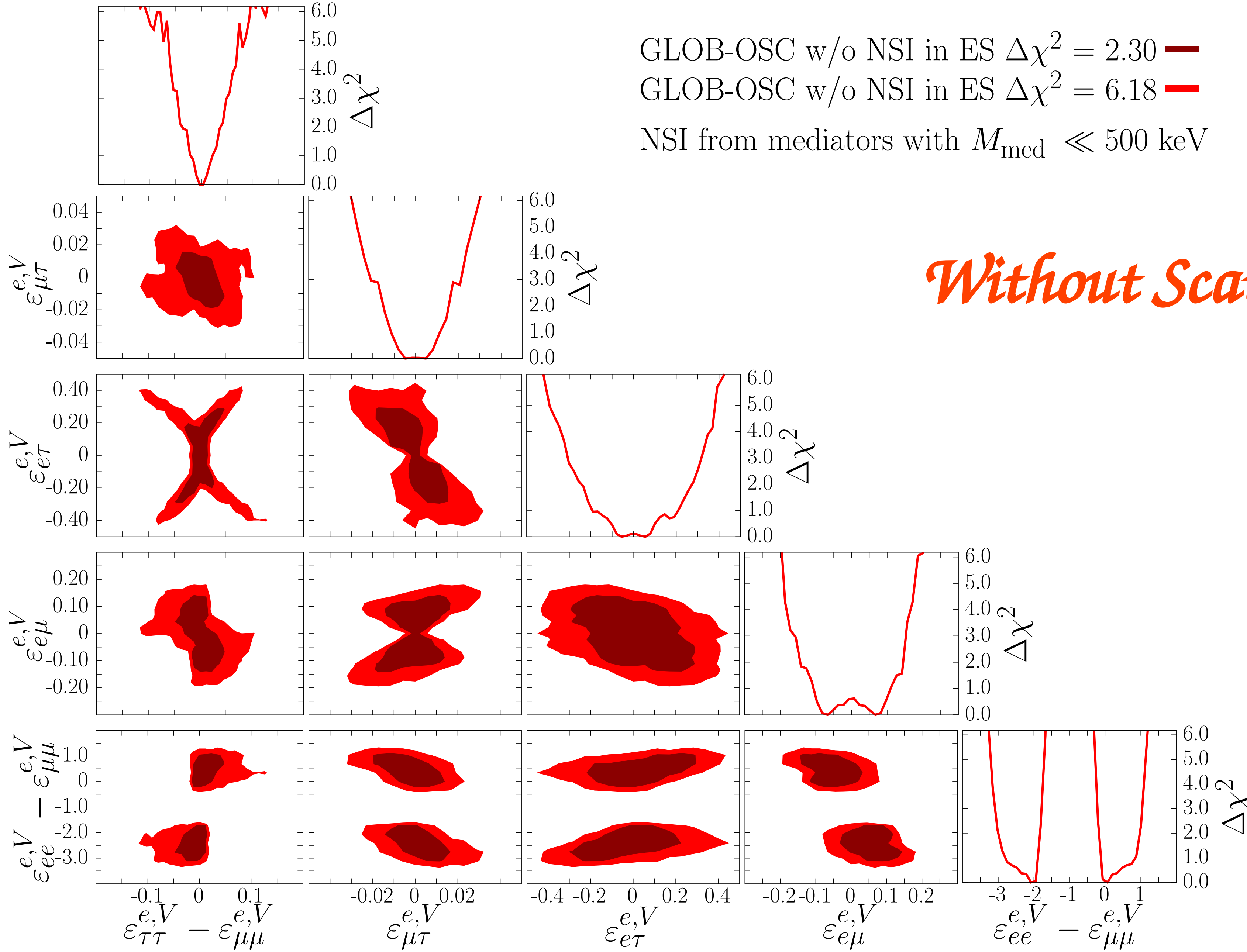
Can the mass ordering determination be spoiled?

Results Global fit NSI

Coloma, P., Gonzalez-Garcia, M. C., Maltoni, M., Pinheiro, J. P., & Urrea, S. (2023). **Global constraints on non-standard neutrino interactions with quarks and electrons.** JHEP, 08, 032.

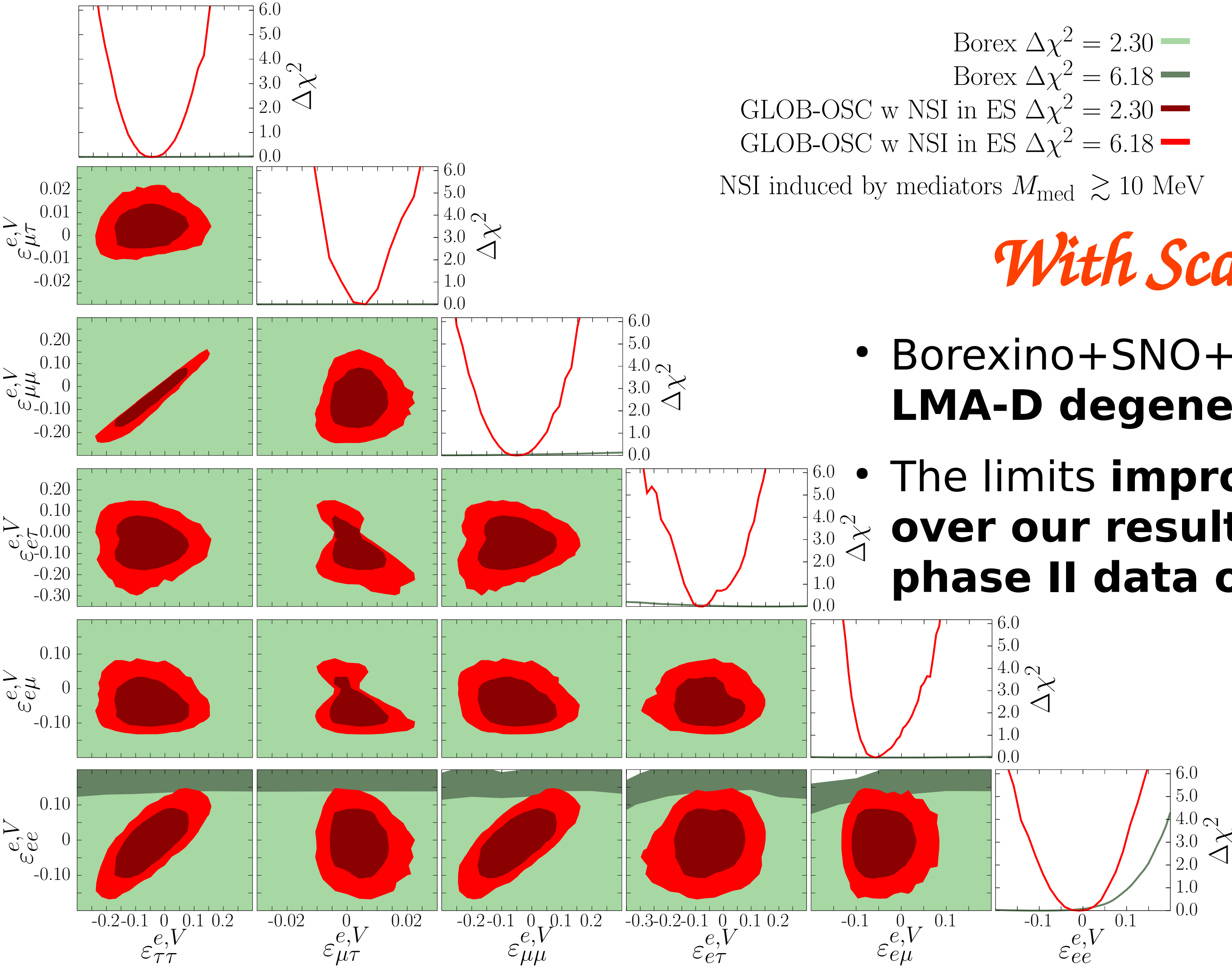
Coloma, P. Gonzalez-Garcia, M. C., Maltoni, M.,Joao P. Urrea, S. (2022). **Constraining new physics with Borexino Phase-II spectral data.** JHEP, 07, 138

Vector NSI with electrons and LMA-D solution



Without Scattering

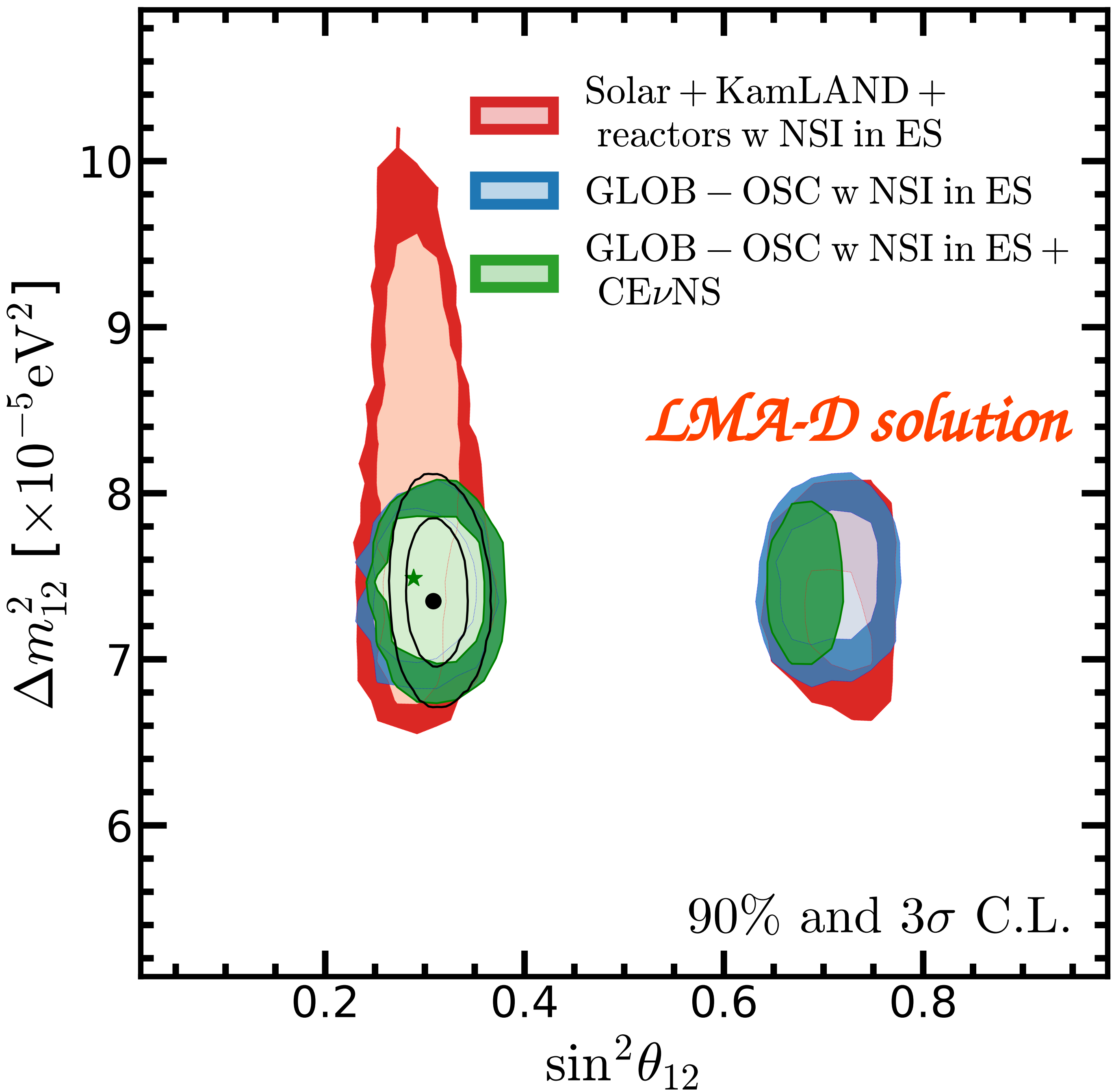
Vector NSI with electrons and LMA-D solution



With Scattering

- Borexino+SNO+SK **break the LMA-D degeneracy through ES**.
- The limits **improve 4-200 times over our results of Borexino phase II data only**

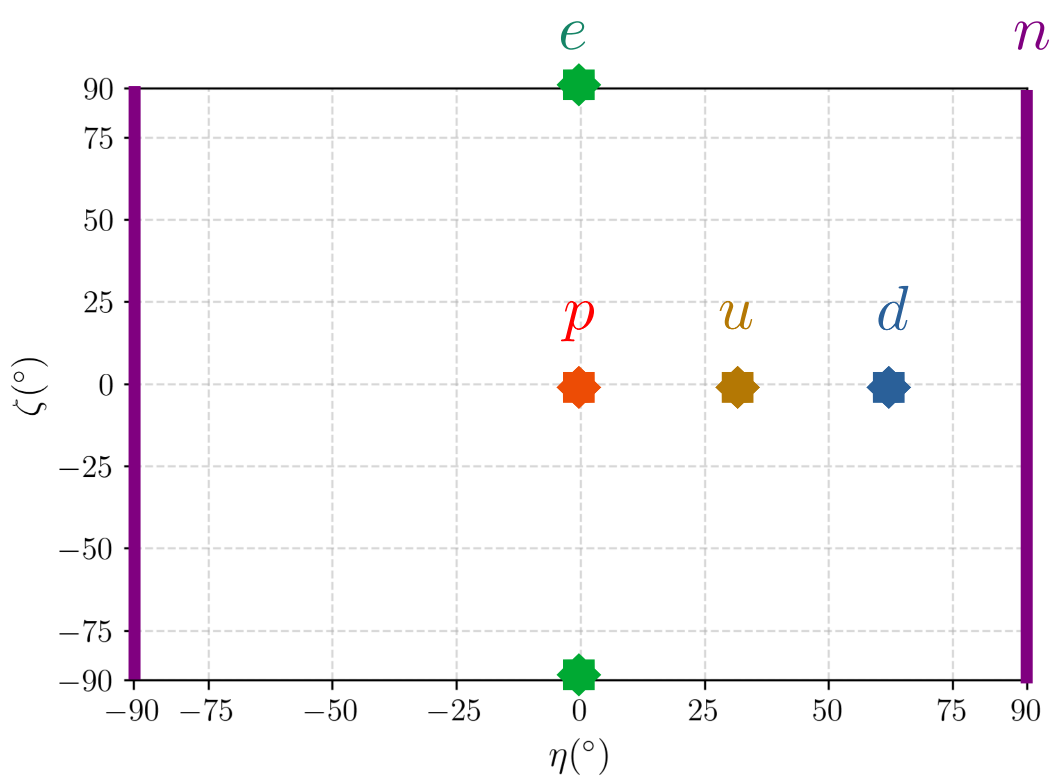
Neutrino Propagation and LMA-Dark solution



LMA-D solution general status

Remember

$$\xi^e = \sqrt{5}\cos\eta\sin\zeta, \quad \xi^p = \sqrt{5}\cos\eta\cos\zeta, \quad \xi^n = \sqrt{5}\sin\eta \qquad \varepsilon^{f,P}_{\alpha\beta} \equiv \varepsilon_{\alpha\beta}\xi^f\chi^P$$

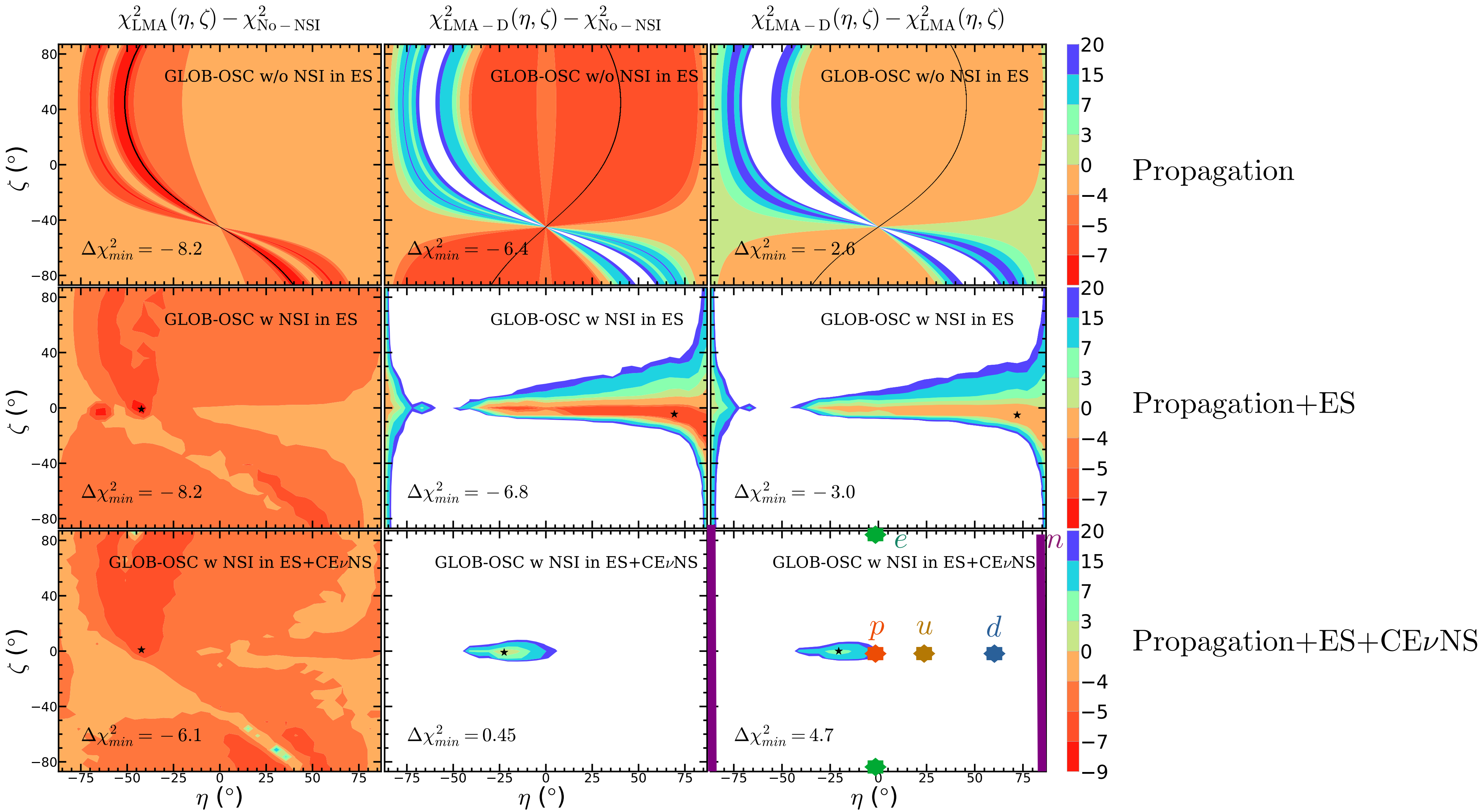


LMA-D solution general status

Remember

$$\xi^e = \sqrt{5}\cos\eta\sin\zeta, \quad \xi^p = \sqrt{5}\cos\eta\cos\zeta, \quad \xi^n = \sqrt{5}\sin\eta$$

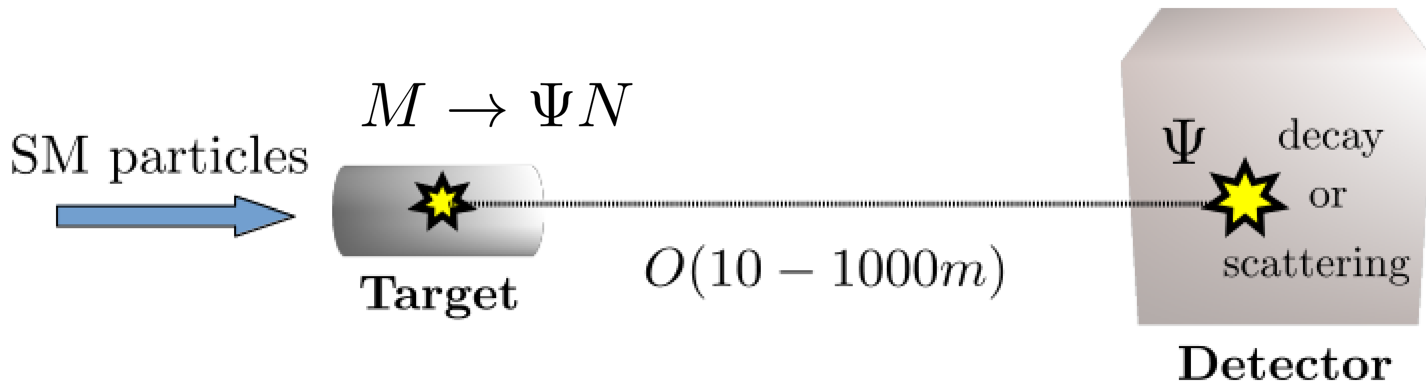
$$\varepsilon_{\alpha\beta}^{f,P} \equiv \varepsilon_{\alpha\beta}\xi^f\chi^P$$



Part II: Neutrino detectors searching for FIPs

Types of FIPs searches in neutrino detectors

New particles produced in meson decays



Long-lived

(HNL, ALPs, dark photon,...)

Decay in flight inside the detector

Very long-lived (Stable)

(Millicharged particles,...)

Scattering signals

See our paper **New physics searches using ProtoDUNE and the CERN SPS accelerator** where we study these searches in ProtoDUNE

Neutrino experiments we used to look for FIPs

- MicroBooNE
- ProtoDUNE
- DUNE-ND

Neutrino experiments we used to look for FIPs

- MicroBooNE
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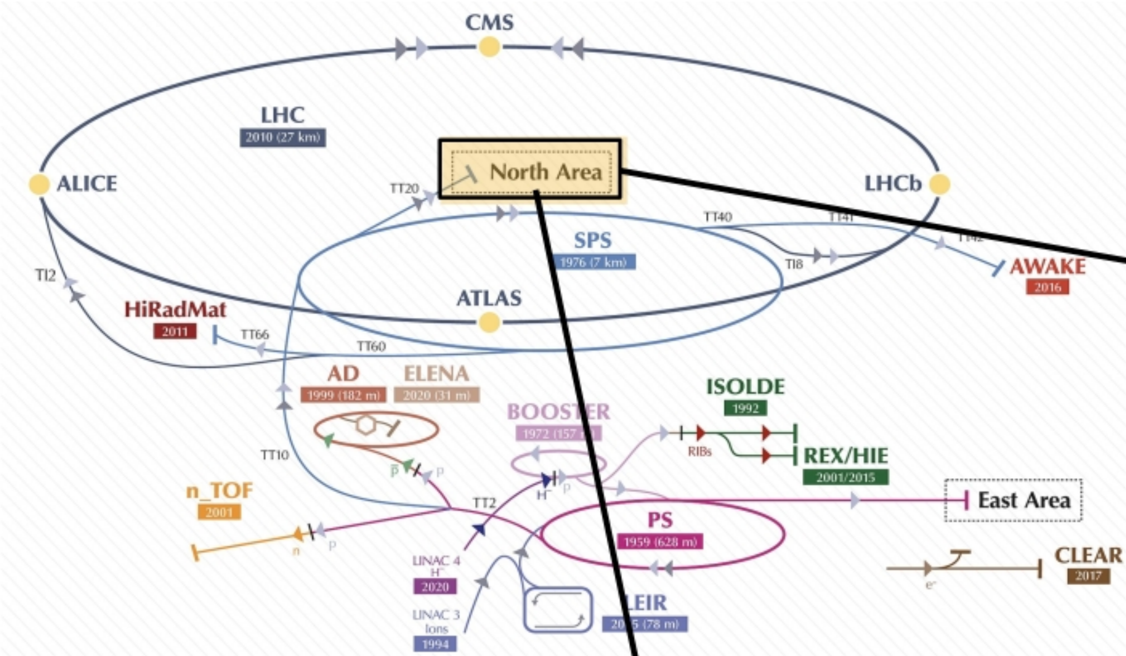
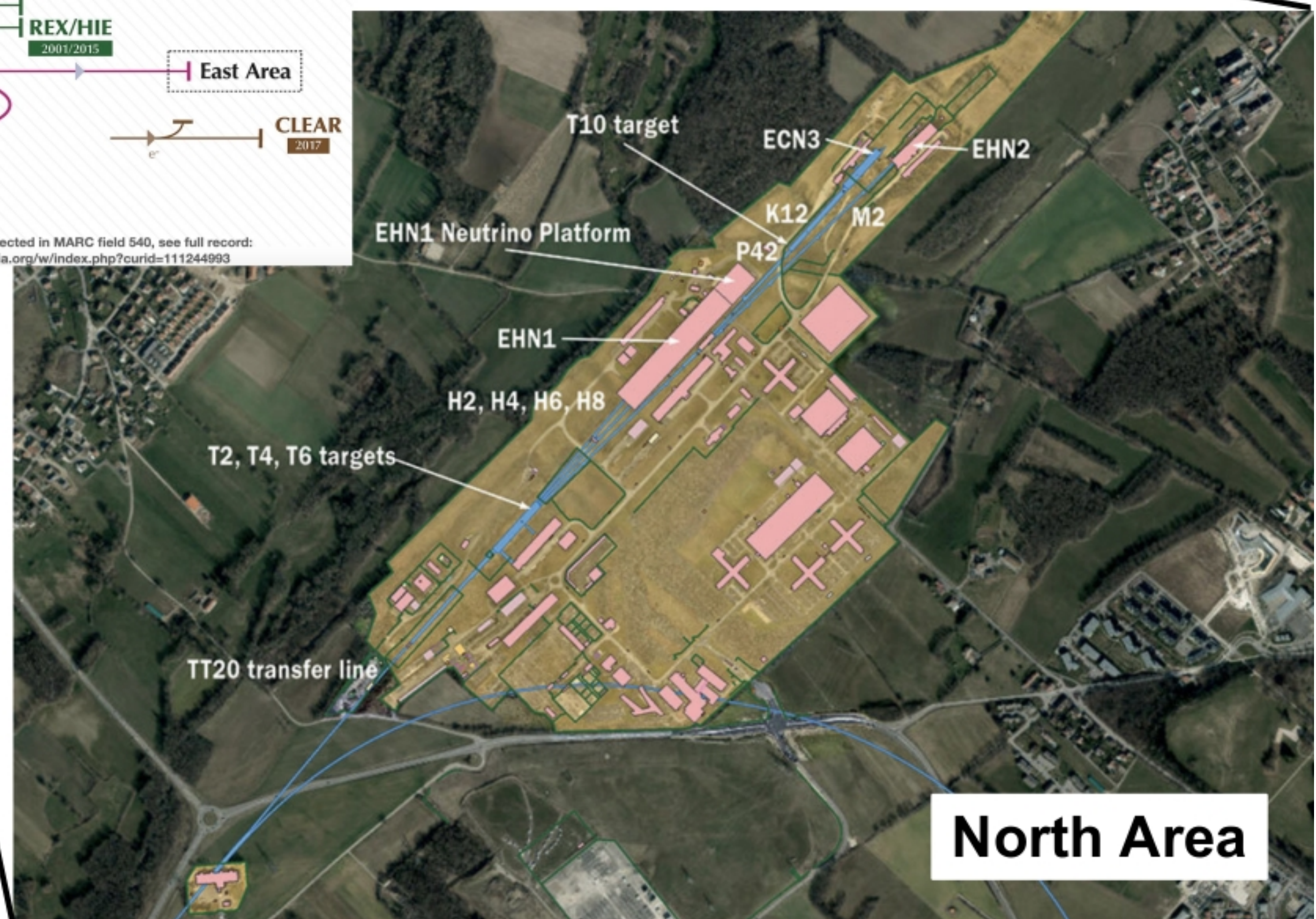
- DUNE-ND

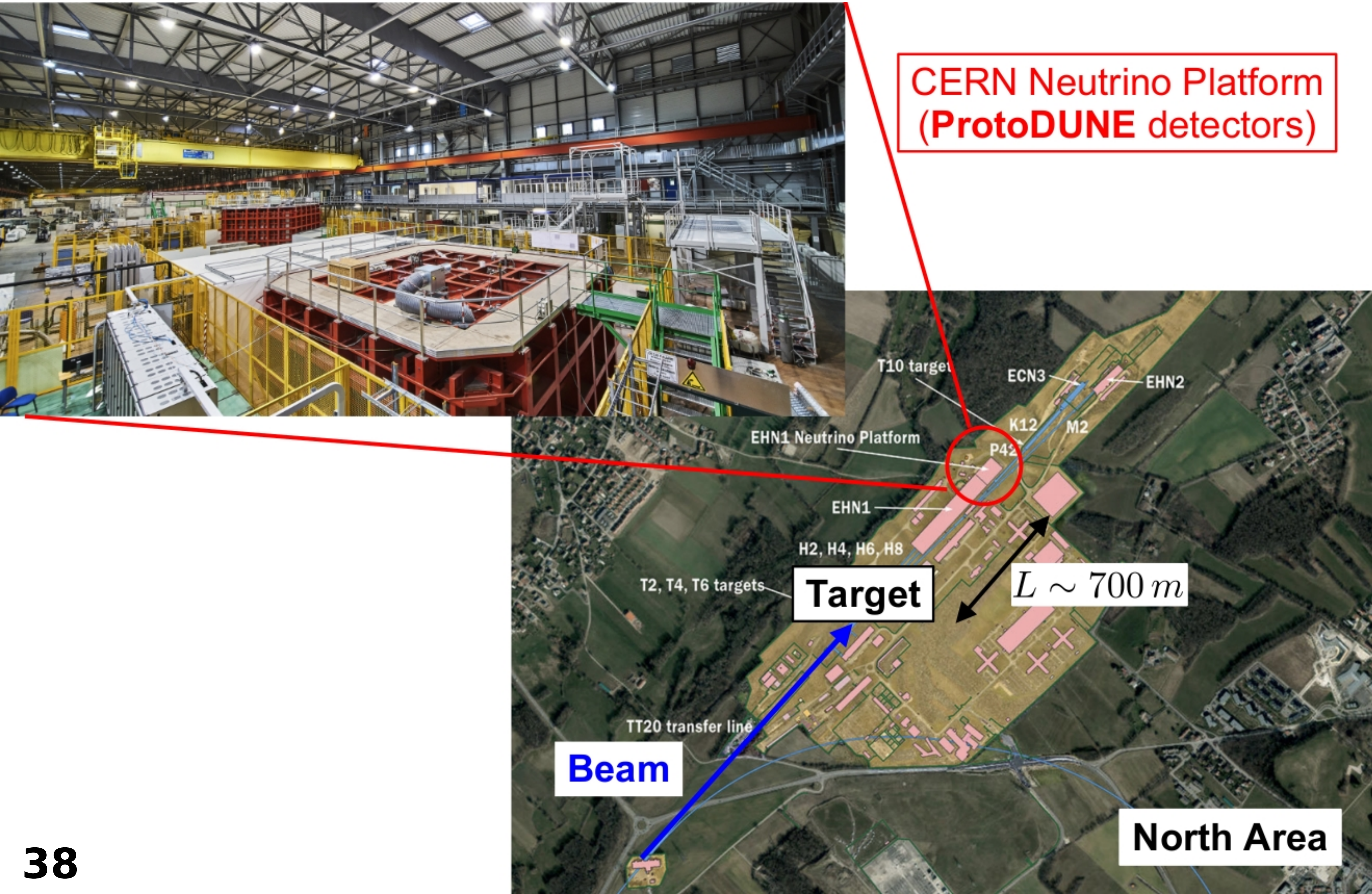
Experimental set-up ProtoDUNE

ProtoDUNE: Extracted beam lines



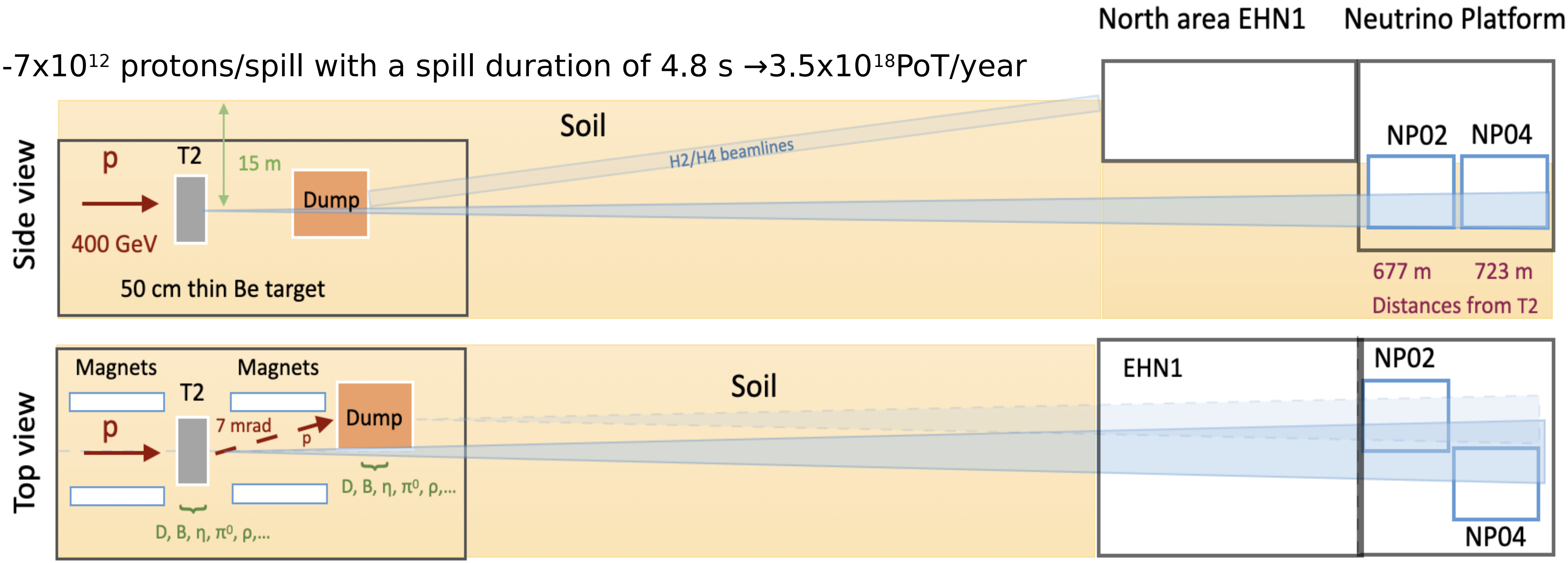


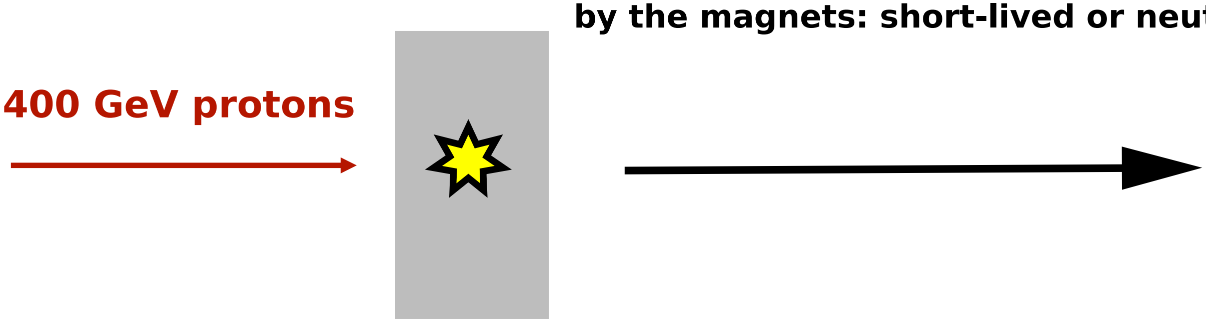
ProtoDUNE: Extracted beam lines



ProtoDUNE: T2 target

~5-7x10^{12} protons/spill with a spill duration of 4.8 s →3.5x10^{18}PoT/year





We are only interested in mesons not affected by the magnets: short-lived or neutral

Meson production yield Y_M (normalised per PoT)

π^0	η	η'	D	D_s	τ
4.03	0.46	0.05	$4.8 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$	$7.4 \cdot 10^{-6}$
ρ	ω	ϕ	J/ψ	B	Υ
0.54	0.53	0.019	$4.4 \cdot 10^{-5}$	$1.2 \cdot 10^{-7}$	$2.3 \cdot 10^{-8}$

Distributions obtained from *Pythia*

Less background from neutrinos due to the magnets

A working group has been formed

HNLs

HNL: Production

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}} \left(W_\mu^- \bar{l}_{L\alpha} \gamma_\mu U_{\alpha 4} N + \text{h.c.} \right) - \frac{g}{\cos\theta_W} \left(Z_\mu \bar{N} \gamma^\mu U_{\alpha 4}^* \nu_{L\alpha} + \text{h.c.} \right)$$

We consider the simplified phenomenological benchmarks of one HNL mixing with one SM neutrino of a given flavour

U_{e4} $U_{\mu 4}$ $U_{\tau 4}$

We don't have pions and kaons in ProtoDUNE

Parent	2-body decay	3-body decay
$\pi^+ \to$	$e^+ N_4$	—
	$\mu^+ N_4$	
$K^+ \to$	$e^+ N_4$	$\pi^0 e^+ N_4$
	$\mu^+ N_4$	$\pi^0 \mu^+ N_4$
$\tau^- \to$	$\pi^- N_4$	$e^- \overline{\nu} N_4$
	$\rho^- N_4$	$\mu^- \overline{\nu} N_4$

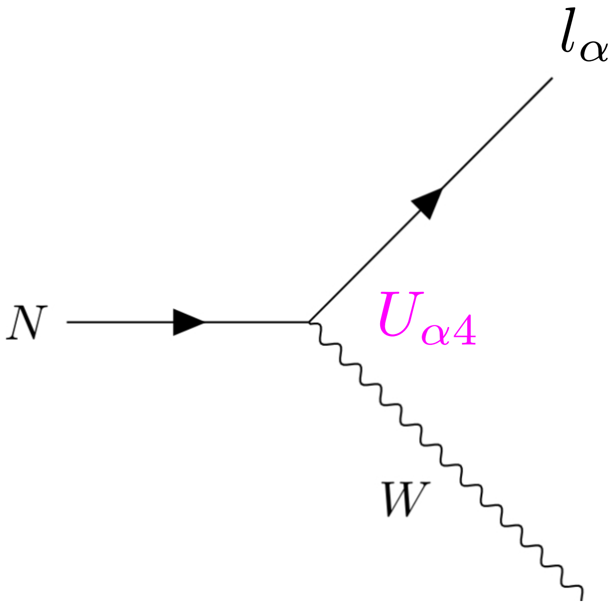
Parent	2-body decay	3-body decay
$D^+ \to$	$e^+ N_4$	$e^+ \overline{K^0} N_4$
	$\mu^+ N_4$	$\mu^+ \overline{K^0} N_4$
	$\tau^+ N_4$	
$D_s^+ \to$	$e^+ N_4$	—
	$\mu^+ N_4$	
	$\tau^+ N_4$	

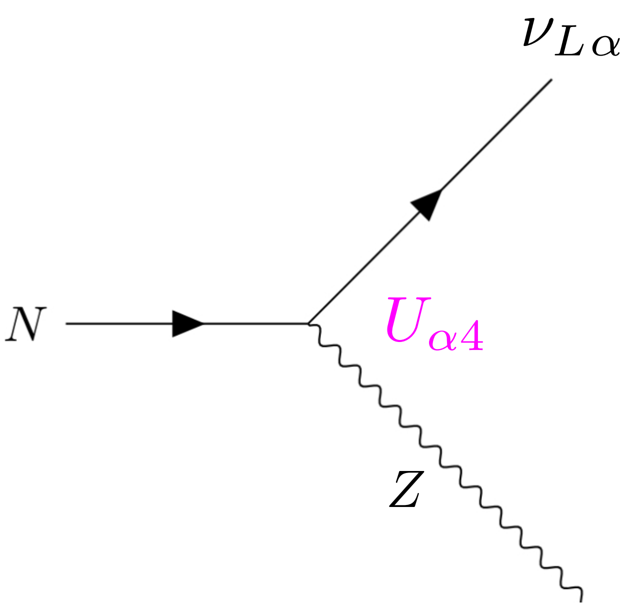
HNL: Detection

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\left(W_\mu^- \bar{l}_{L\alpha}\gamma_\mu U_{\alpha 4} N + \mathrm{h.c.}\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{N}\gamma^\mu U^*_{\alpha 4}\nu_{L\alpha} + \mathrm{h.c.}\right)$$

We consider the simplified phenomenological benchmarks of one HNL mixing with one SM neutrino of a given flavour

U_{e4} $\quad$ $U_{\mu 4}$ $\quad$ $U_{\tau 4}$





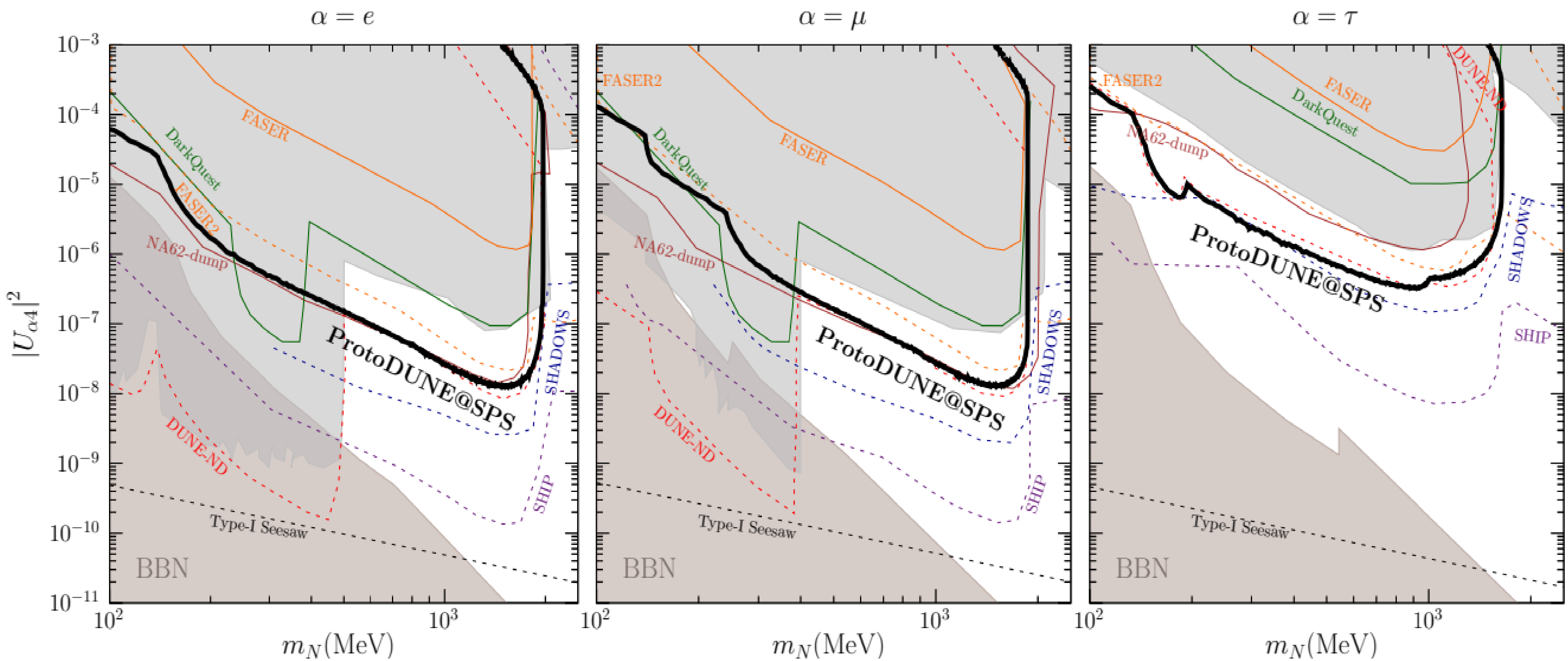
$N \to \nu e\mu, l\pi, \ldots$ $\quad$ $N \to \nu l^+ l^-, \nu\pi^0, \ldots$

Results HNLs ProtoDUNE

Coloma, P., López-Pavón, J., Molina-Bueno, L., & Urrea, S. (2024). **New physics searches using ProtoDUNE and the CERN SPS accelerator.** JHEP, 01, 134.

HNL: Decays into visible channels (combination)

We consider the following channels $N \to \nu ee, \nu\mu\mu, \nu e\mu, e\pi, \mu\pi$ and $\nu\pi^0$



Sensitivity for 5 years

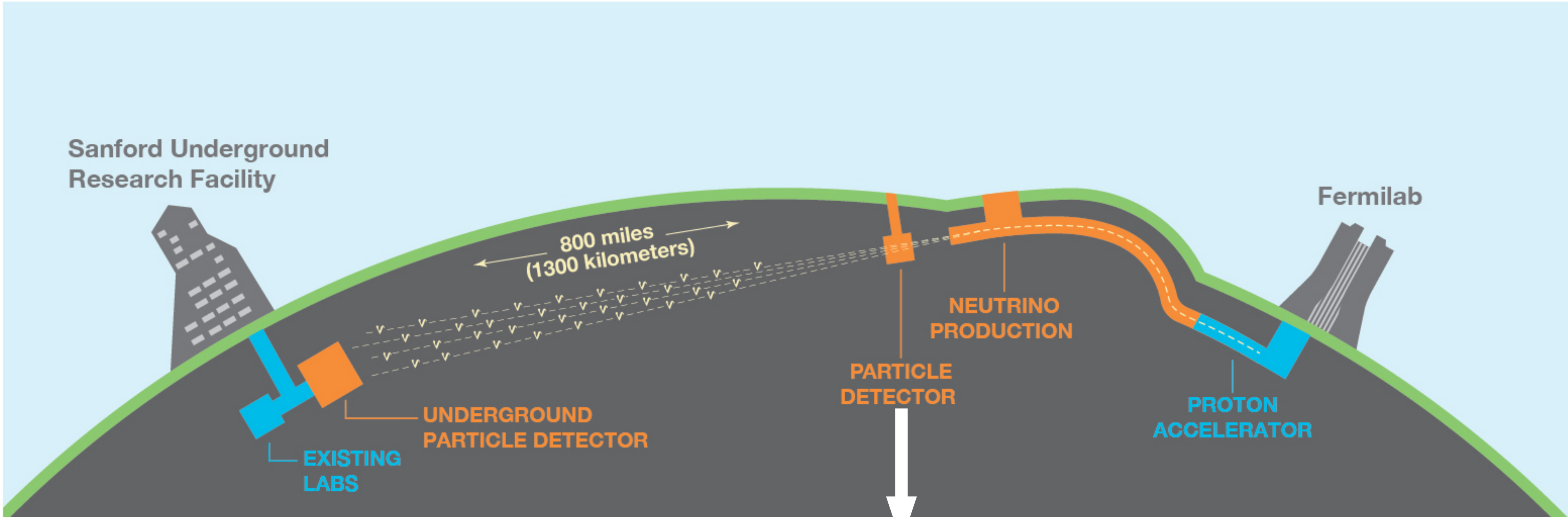
D	D_s	τ
$4.8 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$	$7.4 \cdot 10^{-6}$

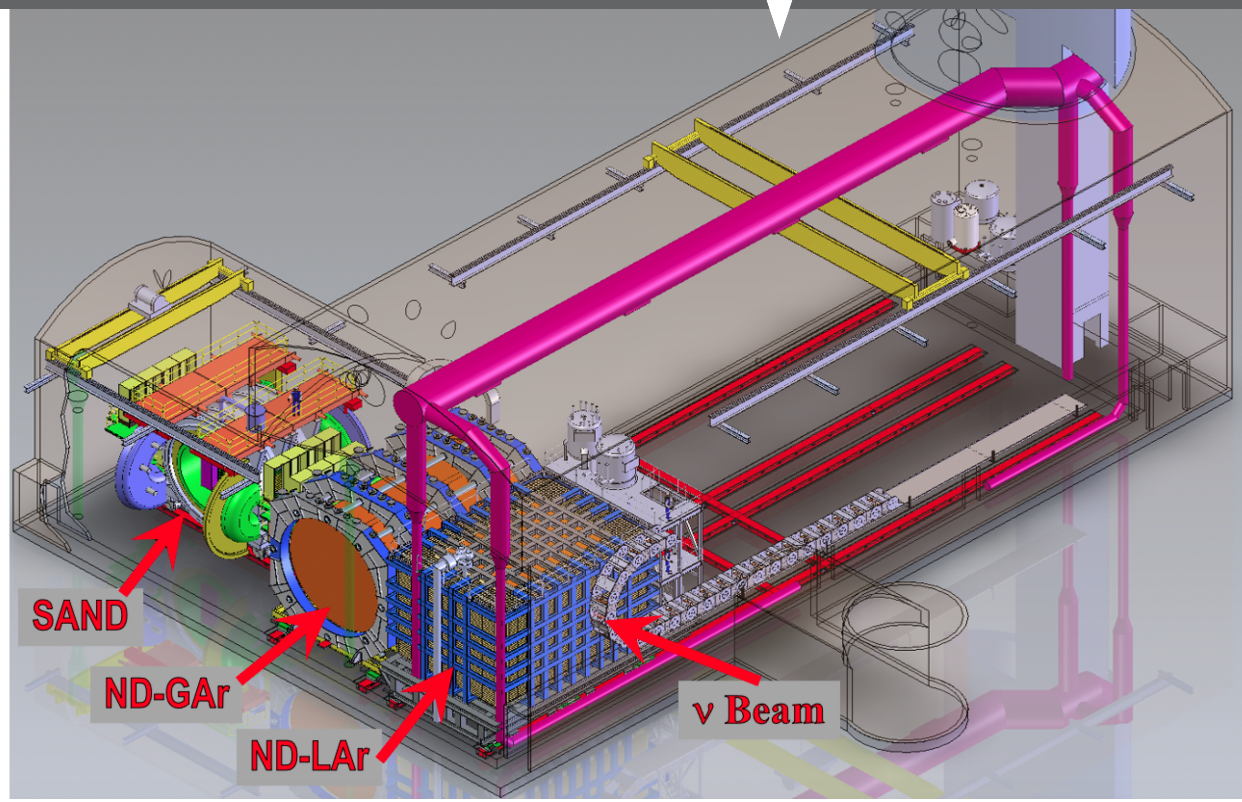
$Br(D_s^- \to \tau^- \overline{\nu}_\tau) = 5.43\%$

(normalised per PoT)

Experimental set-up
DUNE-ND

DUNE-ND complex





ALPs

Electroweak ALPs

$$\delta\mathcal{L}_{\rm EW} = c_\phi \mathcal{O}_\phi + c_B \mathcal{O}_B + c_W \mathcal{O}_W$$

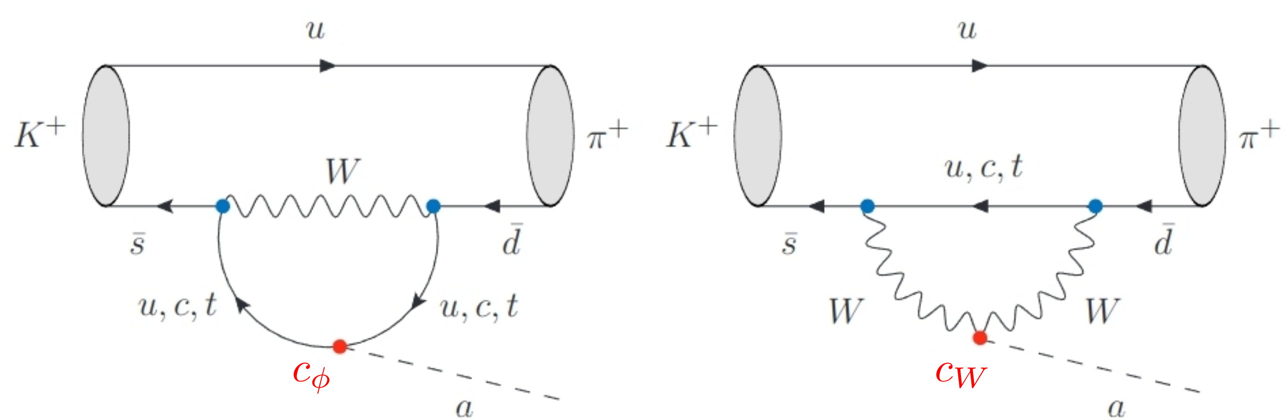
$$\Lambda \propto f_a = 1\text{TeV}$$

where c_i stand for the Wilson coefficients of each operator:

$$\mathcal{O}_\phi = i\frac{\partial^\mu a}{f_a}\phi^\dagger \overleftrightarrow{D}_\mu \phi \xrightarrow{\text{Hypercharge rotation}} \frac{\partial_\mu a(x)}{f_a}\sum_F \bar{\Psi}_F \gamma^\mu \Psi_F$$

$$\mathcal{O}_B = -\frac{a}{f_a} B_{\mu\nu}\widetilde{B}_{\mu\nu}$$

$$\mathcal{O}_W = -\frac{a}{f_a} W^a_{\mu\nu}\widetilde{W}^a_{\mu\nu}$$



Georgi, Kaplan, Randall 1986

Gavela, Houtz, Quilez Del Rey, Sumensari 2019.

Electroweak ALPs: Production

Energy

TeV Our effective Lagrangian

RG equations

Coloma, P., Hernández, P., & Urrea, S. (2022). **New bounds on axion-like particles from MicroBooNE.** JHEP, 08, 025.

1.6 GeV Chiral Lagrangian

$$K^+ \to \pi^+ a$$

Computation

Bauer, Neubert, Renner, Schnubel, Thamm 2020
Bauer, Neubert, Renner, Schnubel, Thamm 2021

Production

$$\Gamma\left(K^+ \to \pi^+ a\right) \propto (coupling)^2$$

c_B dominated | c_W dominated | c_ϕ dominated

$$\Gamma\left(K^+ \to \pi^+ a\right) \ll \Gamma\left(K^+ \to \pi^+ a\right) \approx \Gamma\left(K^+ \to \pi^+ a\right)$$

Detection

$$\Gamma\left(a \to XY\right) \propto (coupling)^2$$

c_W dominated

$\mathrm{a} \to \gamma\gamma$

c_ϕ dominated

$\mathrm{a} \to e^+e^-$

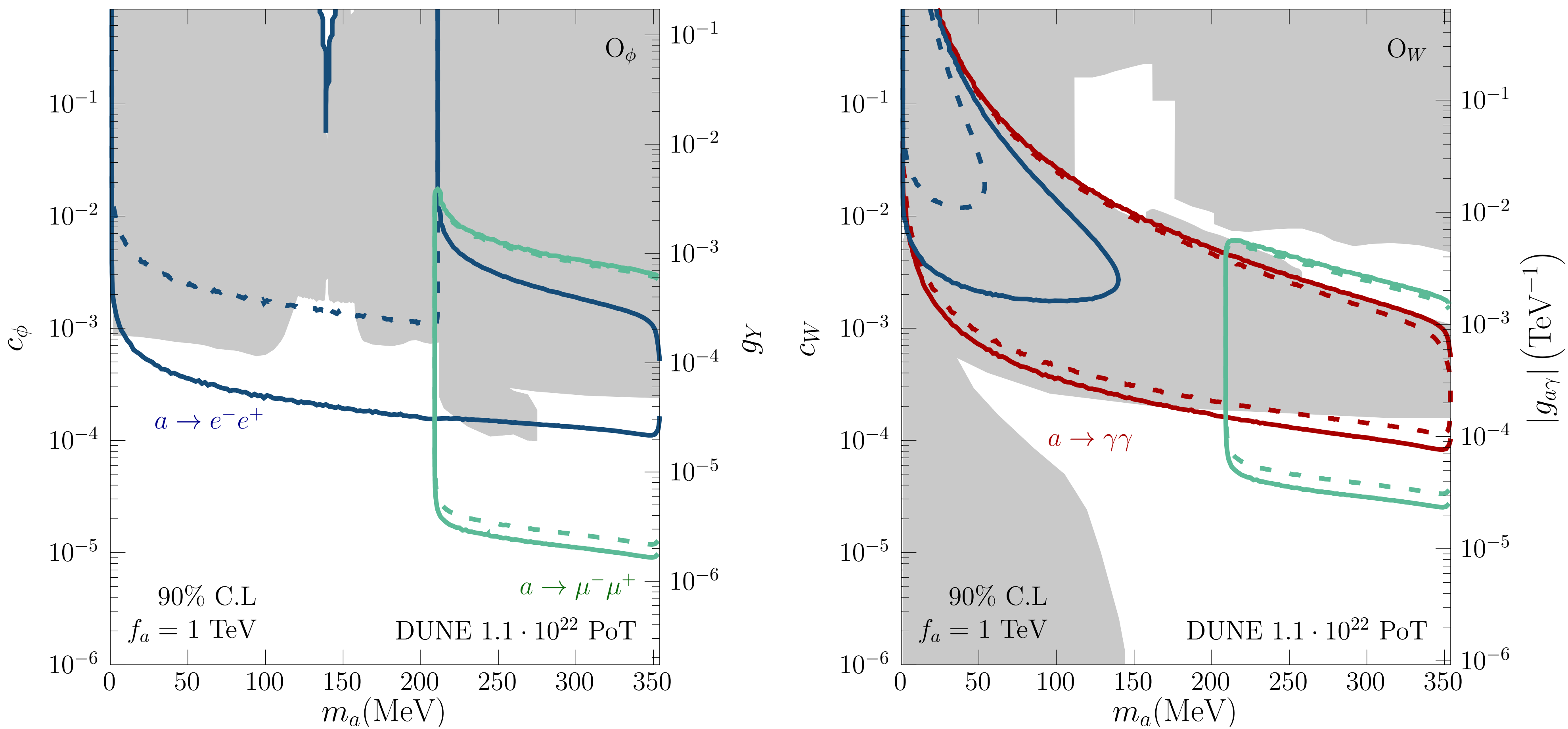
$\mathrm{a} \to \mu^+\mu^-$

Results ALPs DUNE-ND

Coloma, P., Martín-Albo, J., & Urrea, S. (2024). **Discovering long-lived particles at DUNE.** Phys. Rev. D, 109(3), 035013.

Electroweak ALPs at DUNE ND

BKG included



—— ND-GAr

- - - ND-LAr

Conclusions

- **Light New Physics is interesting since it can provide solutions to some of the SM open problems and might be accessible in laboratory experiments.**

- **Neutrino detectors offer a magnificent complementarity in the search of this light sectors.**

- **Future neutrino experiments are expected to push the boundary further and constraint and hopefully have hints of the existence of these new physics scenarios.**

Thank you

Back-up

Extra Information
Motivation

INVERSE SEESAW

$$\mathcal{L} = y\bar{L}NH + M\bar{N}S + \frac{1}{2}\mu\overline{S^c}S + \text{ h.c.}$$

$$\mathrm{M}=\left(\begin{array}{ccc} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{array}\right)$$

$$\mu \ll m_D \ll M$$

$N, S:$ fermion singlets $\quad m_\nu = m_D\left(M^T\right)^{-1}\mu M^{-1}m_D^T \sim \frac{v^2}{M^2}\mu$

Solar ALPs

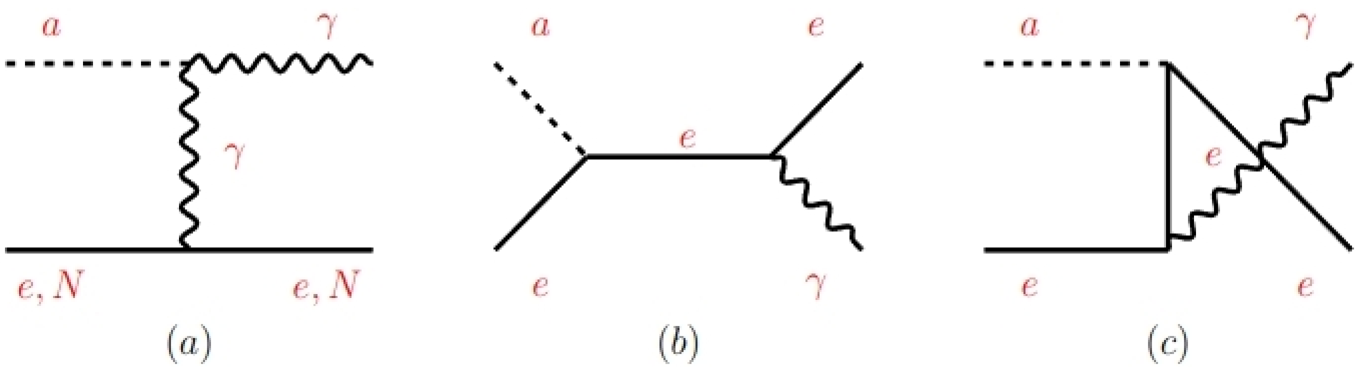
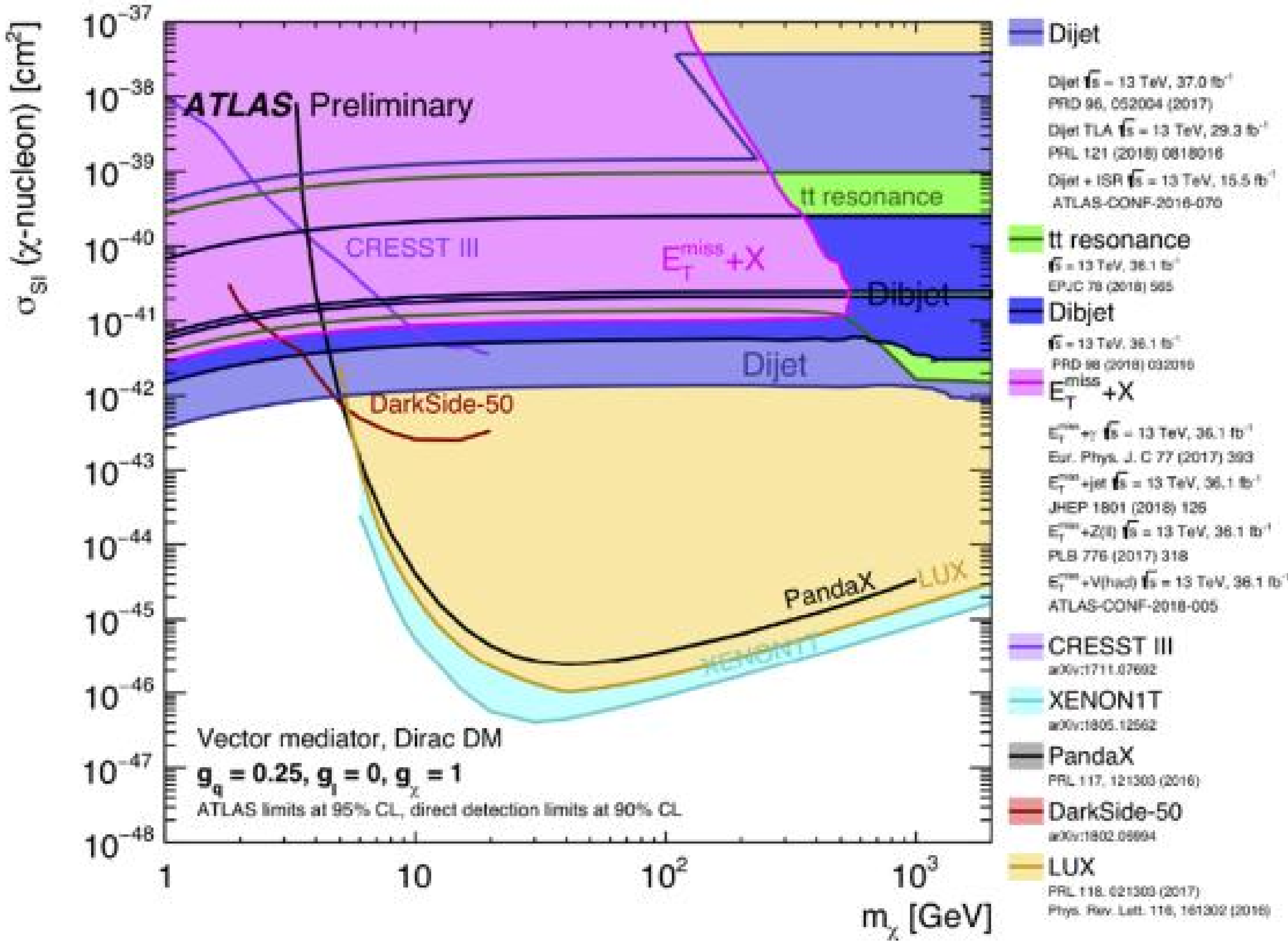


FIG. 1: Tree-level Feynman diagrams illustrating (a) the inverse Primakoff process and (b), (c) the inverse Compton process.

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

Bound coming from SNO



ATLAS Preliminary
σ_{SI} (χ-nucleon) [cm^2]
m_χ [GeV]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
1
10
10^2
10^3
CRESST III
E_T^{miss}+X
tt resonance
Dibjet
Dijet
DarkSide-50
PandaX
LUX
XENON1T
Vector mediator, Dirac DM
$g_q = 0.25$, $g_l = 0$, $g_\chi = 1$
ATLAS limits at 95% CL, direct detection limits at 90% CL
Dijet
Dijet $\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}
PRD 96, 052004 (2017)
Dijet TLA $\sqrt{s}$ = 13 TeV, 29.3 fb^{-1}
PRL 121 (2018) 0818016
Dijet + ISR $\sqrt{s}$ = 13 TeV, 15.5 fb^{-1}
ATLAS-CONF-2016-070
tt resonance
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
EPJC 78 (2018) 565
Dibjet
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
PRD 98 (2018) 032016
E_T^{miss}+X
$E_T^{miss}+\gamma$ $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
JHEP 1801 (2018) 126
E_T^{miss}+Z(ll) $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
PLB 776 (2017) 318
E_T^{miss}+V(had) $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2018-005
CRESST III
arXiv:1711.07692
XENON1T
arXiv:1805.12562
PandaX
PRL 117, 121303 (2016)
DarkSide-50
arXiv:1802.06994
LUX
PRL 118, 021303 (2017)
Phys. Rev. Lett. 116, 161302 (2016)

Strong CP problem

$$\mathcal{L}_{\mathrm{QCD}} + \frac{\theta g_s^2}{32\pi^2}\epsilon_{\mu\nu\alpha\beta}G_a^{\mu\nu}G^{\alpha\beta}$$

- This term is a total derivative and its presence does **not affect perturbation theory.**
- Due the existence of instantons related to the non-trivial nature of the QCD vacuum, the term **will contribute to QCD non-perturbative predictions.**

The mass matrices M^X are general complex matrices.

The general eigenvalues are $\mathrm{m}_i e^{i\alpha_i}$

$$q_L^i \to e^{i\frac{1}{2}\alpha_i} q_L^i \quad q_R^i \to e^{-i\frac{1}{2}\alpha_i} q_R^i,$$

Phases removed by chiral transformations

Strong CP problem

$$S \longrightarrow S - i\sum_i \alpha_i \int d^4x \frac{g_s^2}{32\pi^2}\epsilon_{\mu\nu\alpha\beta}G_a^{\mu\nu}G^{\alpha\beta} + \text{ extra terms}$$

$$\theta \to \theta - \sum_i \alpha_i \equiv \bar{\theta}$$

Neutron electric dipole moment

$$d_n = \left(5.2 \times 10^{-16} e \cdot \mathrm{cm}\right)\bar{\theta}.$$

Why so small?

$$\bar{\theta} < 10^{-10}$$

Axion solution

Imagine a theory with a dynamical θ term

Axion $\Rightarrow$ $$\frac{\theta(x) g_s^2}{32\pi^2}\epsilon_{\mu\nu\alpha\beta}G_a^{\mu\nu}G_a^{\alpha\beta}$$

$\Downarrow$ **Vafa-Witten theorem**

When QCD confines it will generate a potential for $\theta(x)$ which will have a minima around $\langle\theta(x)\rangle = 0$ relaxing the effective value of $\bar{\theta}$ to 0

Also they can be good warm dark matter candidates via the misalignment mechanism

Hierarchy Problem

$\delta m_{\text{fermion}} \sim m_{\text{fermion}} \log\left(\Lambda/m_{\text{fermion}}\right)$ **Chiral symmetry**

$\delta m_{\text{Gauge}} \sim m_{\text{Gauge}} \log\left(\Lambda/m_{\text{Gauge}}\right)$ **Gauge symmetry**

$\delta m_{\text{Scalar}} \sim \Lambda$ **Like SM Higgs** $\Lambda = \text{new Physics scale}$

Planck Scale

Fine tuning

Light New Physics do not worsen the HP

Beware of new scalars

Extra Results Part I Dune

High scale non-unitarity

$$\|I-\alpha\| = \begin{pmatrix} [0.081, 1.4]\cdot 10^{-3} & 0 & 0 \\ < 2.4\cdot 10^{-5} & < 1.4\cdot 10^{-4} & 0 \\ < 1.8\cdot 10^{-3} & < 3.6\cdot 10^{-4} & < 8.9\cdot 10^{-4} \end{pmatrix}$$

Blennow, Fernández-Martínez, Hernández-García, López-Pavón, Marcano, Naredo-Tuero 2023

Low scale non-unitarity

	"flavor+electroweak" $m >$ EW (2σ limit)	"Averaged-out oscillations" $\Delta m^2 \gtrsim 0.1$ eV^2 (90% CL)
α_{ee}	$1.3\cdot 10^{-3}$ [36]	$8.4\cdot 10^{-3}$ [55]
$\alpha_{\mu\mu}$	$2.2\cdot 10^{-4}$ [36]	$5.0\cdot 10^{-3}$ [15]
$\alpha_{\tau\tau}$	$2.8\cdot 10^{-3}$ [36]	$6.5\cdot 10^{-2}$ [56]
$\|\alpha_{\mu e}\|$	$6.8\cdot 10^{-4}$ ($2.4\cdot 10^{-5}$) [36]	$9.2\cdot 10^{-3}$
$\|\alpha_{\tau e}\|$	$2.7\cdot 10^{-3}$ [36]	$1.4\cdot 10^{-2}$
$\|\alpha_{\tau\mu}\|$	$1.2\cdot 10^{-3}$ [36]	$1.1\cdot 10^{-2}$

Snowmass 2021

- Four determinations of the W-boson mass: M_W^{LEP}, M_W^{Tev}, M_W^{LHCb}, M_W^{ATLAS}.
- Two determinations of the effective weak angle: ${s_{\mathrm{eff}}^2}^{\mathrm{LHC}}$ and ${s_{\mathrm{eff}}^2}^{\mathrm{Tev}}$.
- Five LEP observables measured at the Z-pole, plus a determination of the Z invisible width from CMS: Γ_Z, σ_{had}^0, R_e, R_μ, R_τ, $\Gamma_{\mathrm{inv}}^{\mathrm{LHC}}$.
- Five weak decay ratios constraining lepton flavor universality: $R_{\mu e}^\pi$, $R_{\tau\mu}^\pi$, $R_{\mu e}^K$, $R_{\mu e}^\tau$, $R_{\tau\mu}^\tau$.
- Ten weak decays constraining CKM unitarity.
- cLFV observables.

Blennow, Fernández-Martínez, Hernández-García, López-Pavón,
Marcano, Naredo-Tuero 2023

$$N = (I - T)U$$

$$\mathrm{T}{=}\begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

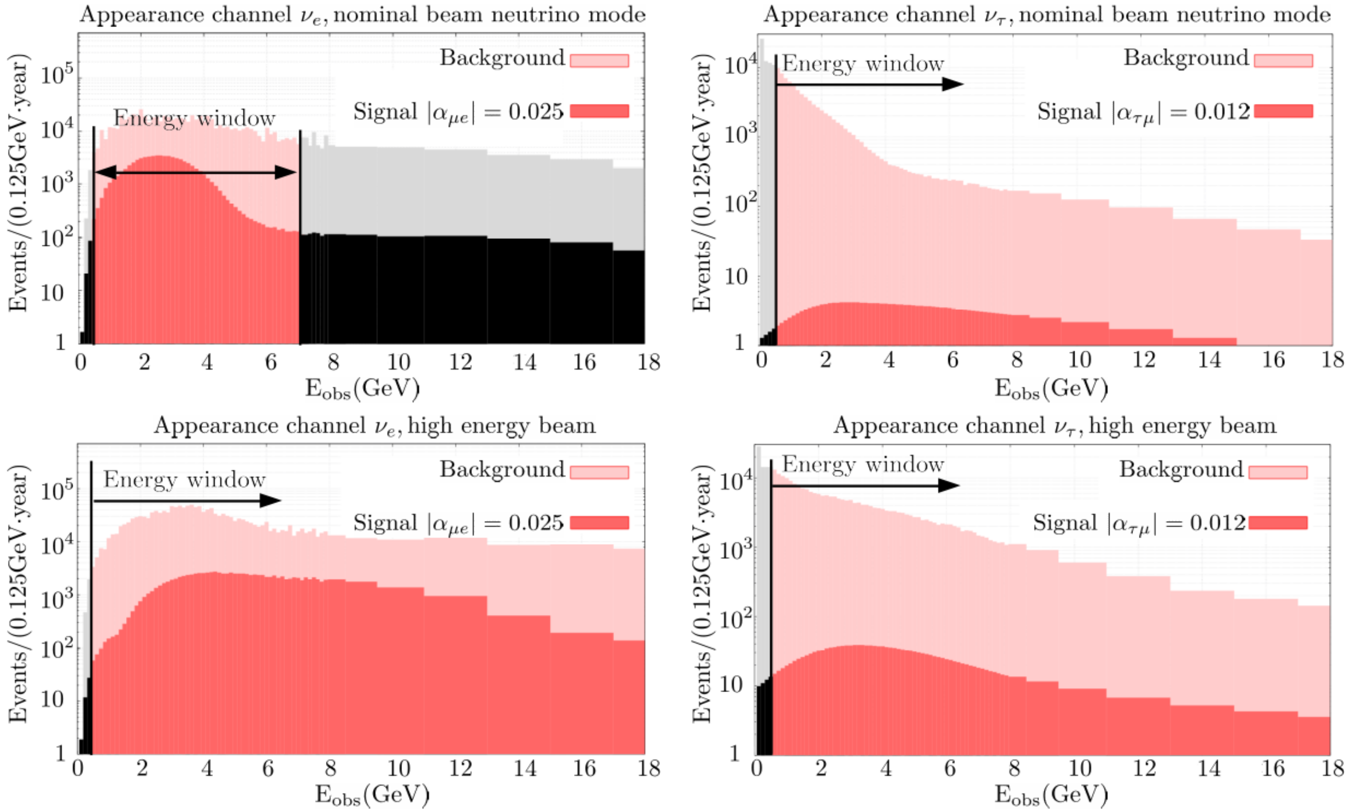
$$NN^\dagger + \Theta\Theta^\dagger = I = I - T - T^\dagger + \Theta\Theta^\dagger + \mathcal{O}\left(\alpha^2\right)$$

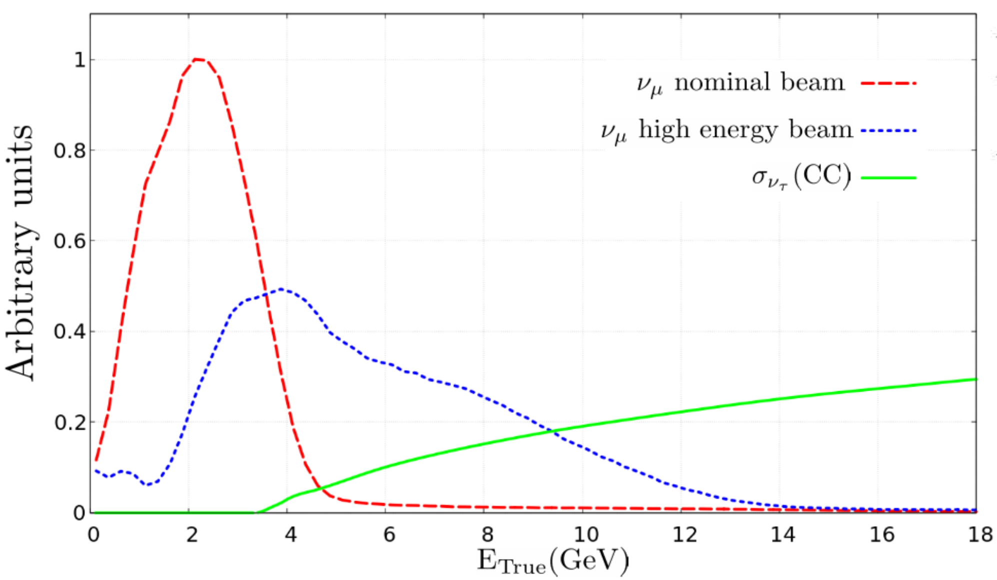
$$\alpha_{\beta\beta} = \frac{1}{2}\left(\Theta\Theta^\dagger\right)_{\beta\beta} = \frac{1}{2}\sum_{i=4}^{n} |\mathcal{U}_{\beta i}|^2$$

$$\alpha_{\gamma\beta} = \left(\Theta\Theta^\dagger\right)_{\gamma\beta} = \sum_{i=4}^{n} \mathcal{U}_{\gamma i}\mathcal{U}^*_{\beta i}.$$

Mapping

$$\begin{pmatrix} |\alpha_{ee}| & 0 & 0 \\ |\alpha_{\mu e}| & |\alpha_{\mu\mu}| & 0 \\ |\alpha_{\tau e}| & |\alpha_{\tau\mu}| & |\alpha_{\tau\tau}| \end{pmatrix} = \begin{pmatrix} \frac{1}{2}\left|U_{e4}\right|^2 & 0 & 0 \\ \left|U_{\mu 4}\right|\left|U_{e4}\right| & \frac{1}{2}\left|U_{\mu 4}\right|^2 & 0 \\ \left|U_{\tau 4}\right|\left|U_{e4}\right| & \left|U_{\tau 4}\right|\left|U_{\mu 4}\right| & \frac{1}{2}\left|U_{\tau 4}\right|^2 \end{pmatrix}$$





Beam configuration	Power	E_p	PoT/yr	t_ν (yr)	$t_{\bar{\nu}}$ (yr)	$M_{\rm det}$
Nominal	1.2 MW	120 GeV	1.1×10^{21}	3.5	3.5	67.2 tons
High-Energy	1.2 MW	120 GeV	1.1×10^{21}	3.5	–	67.2 tons

Running mode	Sample	Contribution	Event rates ($\times 10^5$)	$E_{\rm obs}^{\rm max}$ (GeV)
ν mode (nominal)	ν_e-like	Intrinsic cont.	20.18	7.125
		Flavor mis-ID	4.61	
		NC	6.77	
	ν_μ-like	$\nu_\mu, \bar{\nu}_\mu$ CC ($P_{\mu\mu} = 1$)	2,235.72	7.125
		NC	17.35	
	ν_τ-like	$\nu_\tau, \bar{\nu}_\tau$ CC ($P_{\mu\tau} = 1$)	39.33	18
		NC	3.23	
$\bar{\nu}$ mode (nominal)	$\bar{\nu}_e$-like	Intrinsic cont.	11.18	7.125
		Flavor mis-ID	1.07	
		NC	3.89	
	$\bar{\nu}_\mu$-like	$\nu_\mu, \bar{\nu}_\mu$ CC ($P_{\mu\mu} = 1$)	1,013.42	7.125
		NC	9.76	
	$\bar{\nu}_\tau$-like	$\nu_\tau, \bar{\nu}_\tau$ CC ($P_{\mu\tau} = 1$)	27.75	18
		NC	1.80	
ν mode (HE)	ν_e-like	Intrinsic cont.	38.10	18
		Flavor mis-ID	12.98	
		NC	30.51	
	ν_μ-like	$\nu_\mu, \bar{\nu}_\mu$ CC ($P_{\mu\mu} = 1$)	5,784.30	18
		NC	72.15	
	ν_τ-like	$\nu_\tau, \bar{\nu}_\tau$ CC ($P_{\mu\tau} = 1$)	259.67	18
		NC	9.42	

Event sample	Contribution	Benchmark 1		Benchmark 2		Benchmark 3	
		σ_{norm}	σ_{shape}	σ_{norm}	σ_{shape}	σ_{norm}	σ_{shape}
ν_e-like	Signal	5%	–	5%	–	5%	–
	Intrinsic cont.	10%	–	10%	2%	10%	5%
	Flavor mis-ID	5%	–	5%	2%	5%	5%
	NC	10%	–	10%	2%	10%	5%
ν_μ-like	$\nu_\mu, \bar{\nu}_\mu$ CC (signal)	10%	–	10%	2%	10%	5%
	NC	10%	–	10%	2%	10%	5%
ν_τ-like	Signal	20%	–	20%	–	20%	–
	NC	10%	–	10%	2%	10%	5%

τ^- Decay Mode	Branching Ratio
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.4%
$e^- \bar{\nu}_e \nu_\tau$	17.8%
$\pi^- \nu_\tau$	10.8%
$\pi^- \pi^0 \nu_\tau$	25.5%
$\pi^- 2\pi^0 \nu_\tau$	9.3%
$2\pi^- \pi^0 \nu_\tau$	9.3%
$2\pi^- \pi^+ \pi^0 \nu_\tau$	4.6%

- 30% signal 0.5% NC background

$$\chi^2_{\min}(\{\Theta\}) = \min_{\{\xi,\zeta\}} \left[\chi^2_{\text{stat}} \left(\{\Theta, \xi, \zeta\}\right) + \sum_s \left(\frac{\zeta_s}{\sigma_{\text{norm }, s}} \right)^2 + \sum_b \left(\frac{\zeta_b}{\sigma_{\text{norm }, b}} \right)^2 + \sum_i \left(\frac{\xi_i^{\text{sig}}}{\sigma_{\text{shape }, \text{sig}}} \right)^2 + \sum_i \left(\frac{\xi_i^{\text{bg}}}{\sigma_{\text{shape }, \text{bg}}} \right)^2 \right]$$

$$\chi^2_{\mathrm{stat}}\left(\{\Theta,\xi,\zeta\}\right) = \sum_i 2\left(N_i(\{\Theta,\xi,\zeta\}) - O_i + O_i \ln \frac{O_i}{N_i(\{\Theta,\xi,\zeta\})}\right),$$

$$N_i(\{\Theta,\xi,\zeta\}) = \sum_s \left(1+\xi_i^{\mathrm{sig}}+\zeta_s\right) s_i(\{\Theta\}) + \sum_b \left(1+\xi_i^{\mathrm{bg}}+\zeta_b\right) b_i(\{\Theta\})$$

$$\chi^2_{\min}(\{\Theta\}) = \min_{\{\xi,\zeta\}}\left[\chi^2_{\mathrm{stat}}\left(\{\Theta,\xi,\zeta\}\right) + \sum_s \left(\frac{\zeta_s}{\sigma_{\mathrm{norm}\ ,s}}\right)^2 + \sum_b \left(\frac{\zeta_b}{\sigma_{\mathrm{norm}\ ,b}}\right)^2 \right.$$
$$\left. + \sum_i \left(\frac{\xi_i^{\mathrm{sig}}}{\sigma_{\mathrm{shape}\ ,\mathrm{sig}}}\right)^2 + \sum_i \left(\frac{\xi_i^{\mathrm{bg}}}{\sigma_{\mathrm{shape}\ ,\mathrm{bg}}}\right)^2\right]$$

$$f_{L/E_i}\left(\frac{L}{E}\right) \approx \frac{1}{\sigma_{L/E_i}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{L/E - L/E_i^c}{\sigma_{L/E_i}}\right)^2}, \text{ with } \sigma_{L/E_i} = L\frac{\Delta E_i}{\left(E_i^c\right)^2}$$

$$\langle P_{\alpha\beta}\left(L/E_i\right)\rangle = \int_0^\infty P_{\alpha\beta}\left(L/E_i\right) f_{L/E_i}\left(\frac{L}{E}\right) d\frac{L}{E}.$$

$$\langle P_{\alpha\beta}\left(L/E_i\right)\rangle = \delta_{\alpha\beta} - 4\left|\mathcal{U}_{\alpha 4}\right|^2 \left(\delta_{\alpha\beta} - \left|\mathcal{U}_{\beta 4}\right|^2\right) \left[\frac{1}{2} - \frac{1}{2}\cos\left(\frac{\Delta m_{41}^2 L}{2E_i^c}\right)\exp\left\{-\frac{1}{2}\left(\frac{\Delta m_{41}^2 \sigma_{L/E_i}}{2}\right)^2\right\}\right]$$

ν_e appearance

$$P_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

ν_τ appearance

$$P_{\mu\tau} = 4|U_{\tau 4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

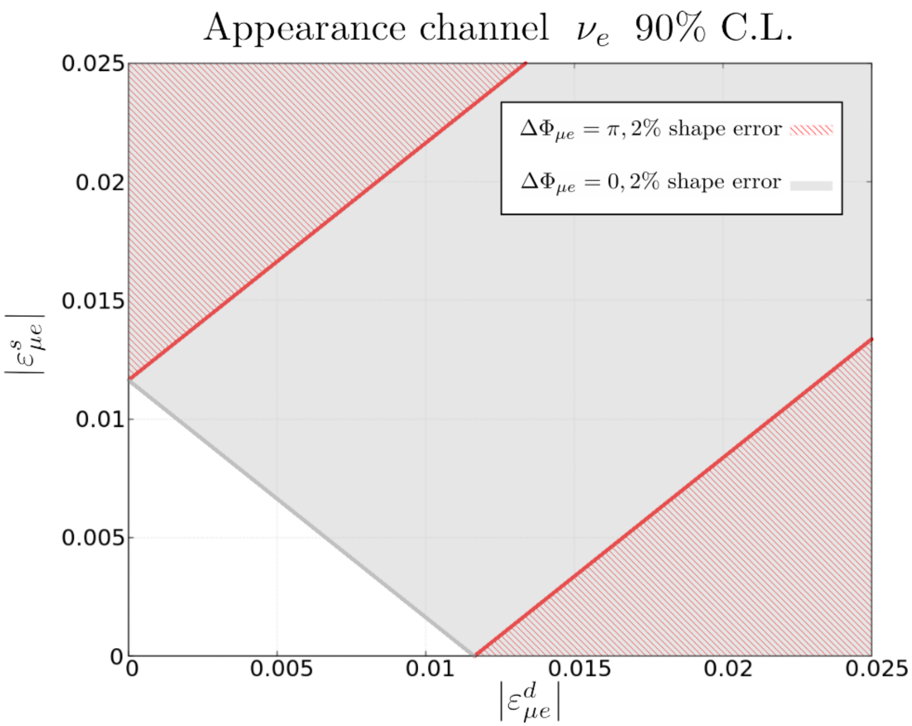
ν_e disappearance

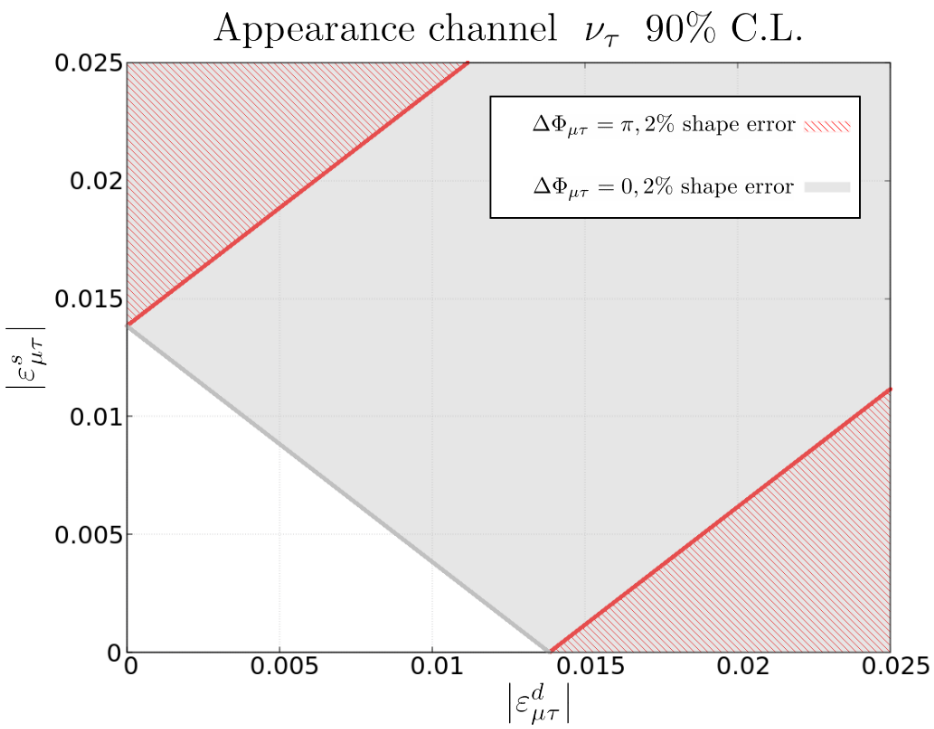
$$P_{ee} = 1 - 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right) \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

ν_μ disappearance

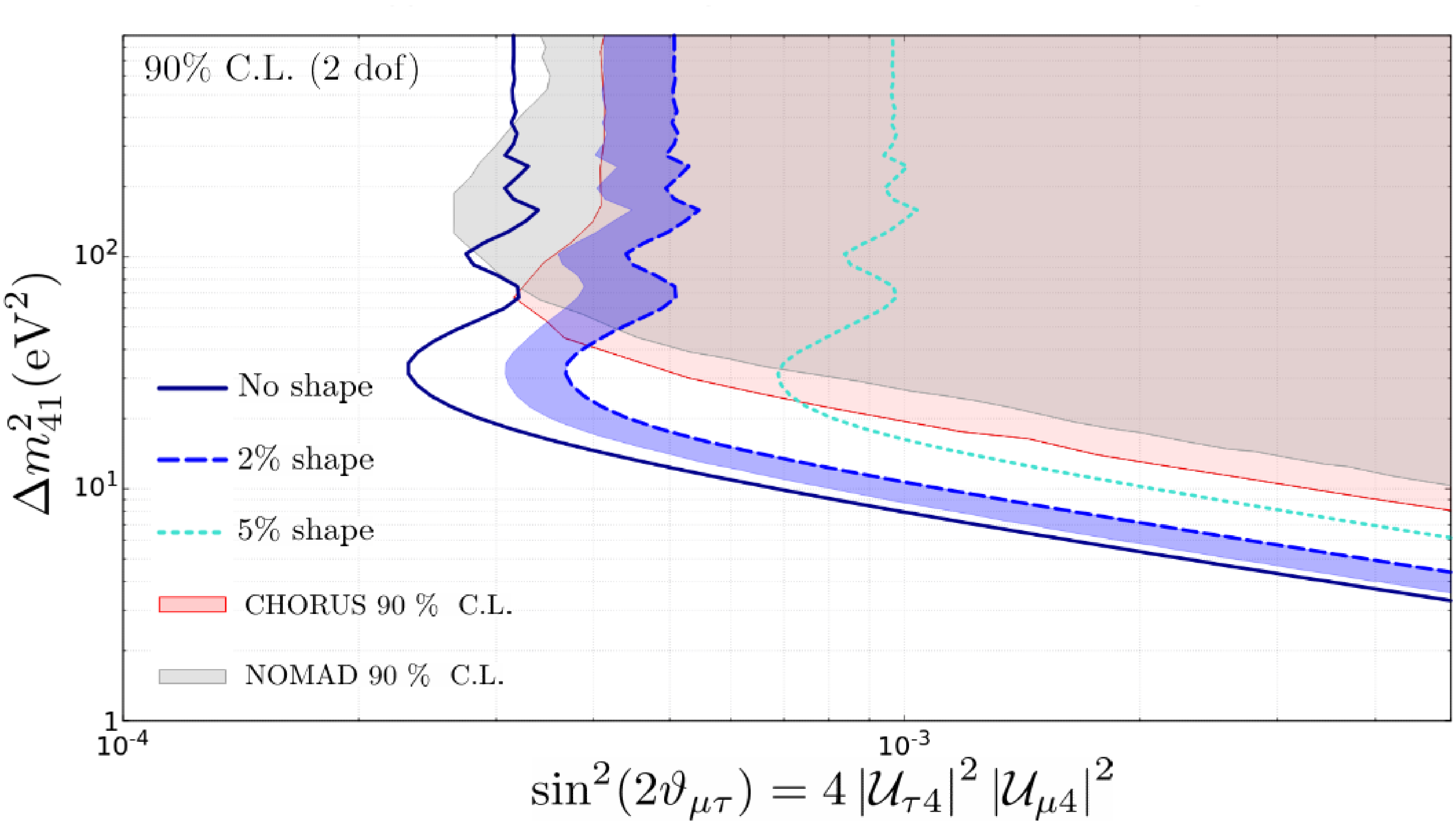
$$P_{\mu\mu} = 1 - 4|U_{\mu 4}|^2\left(1 - |U_{\mu 4}|^2\right) \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

$$P_{\gamma\beta}(L=0) = \left| \left[\left(I + \epsilon^d \right) \left(I + \epsilon^s \right) \right]_{\beta\gamma} \right|^2 = \left| \epsilon^d_{\beta\gamma} \right|^2 + \left| \epsilon^s_{\beta\gamma} \right|^2 + 2 \left| \epsilon^d_{\beta\gamma} \right| \left| \epsilon^s_{\beta\gamma} \right| \cos \left(\Phi^s_{\beta\gamma} - \Phi^d_{\beta\gamma} \right) ,$$

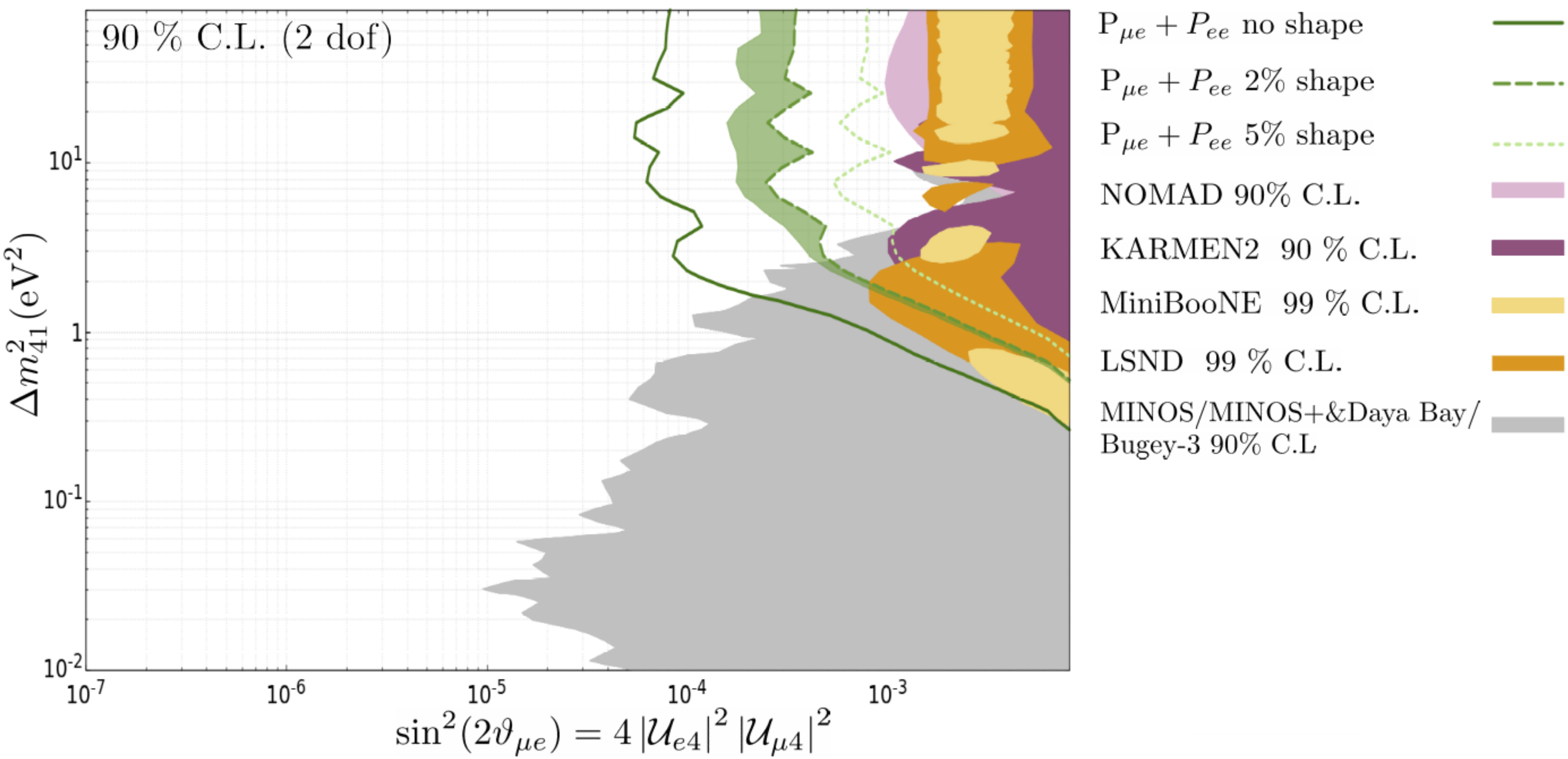




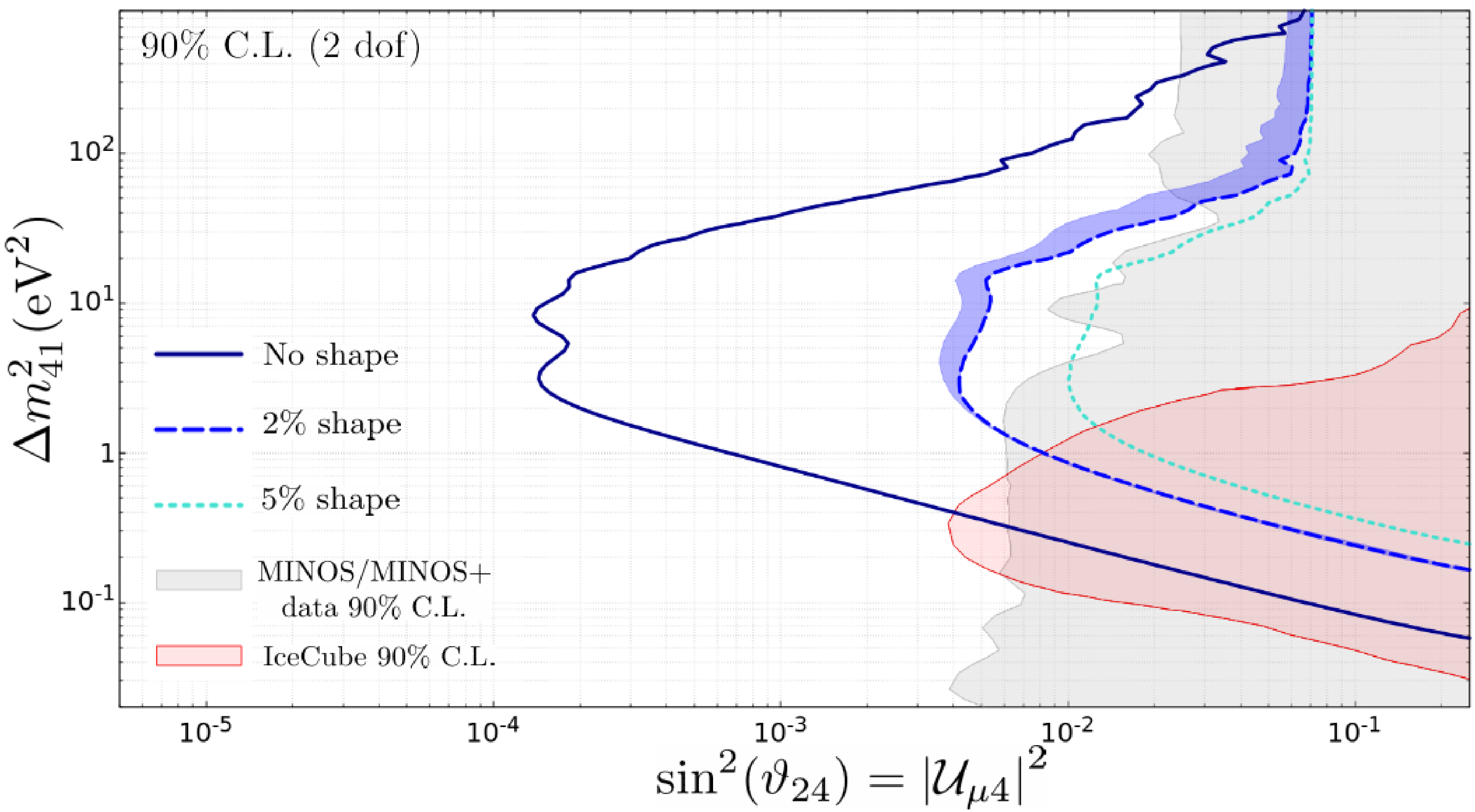
ν_τ appearance



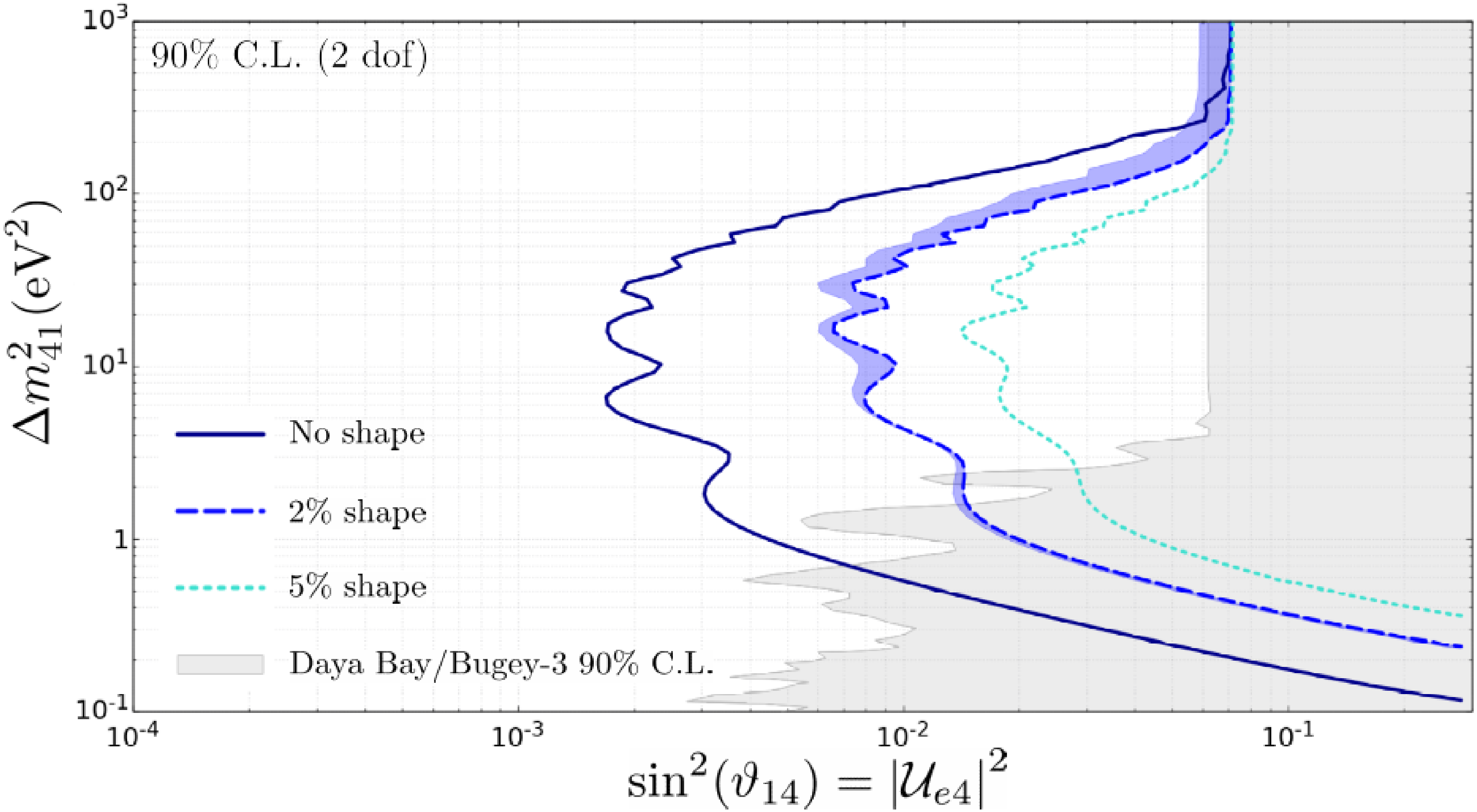
ν_e appearance

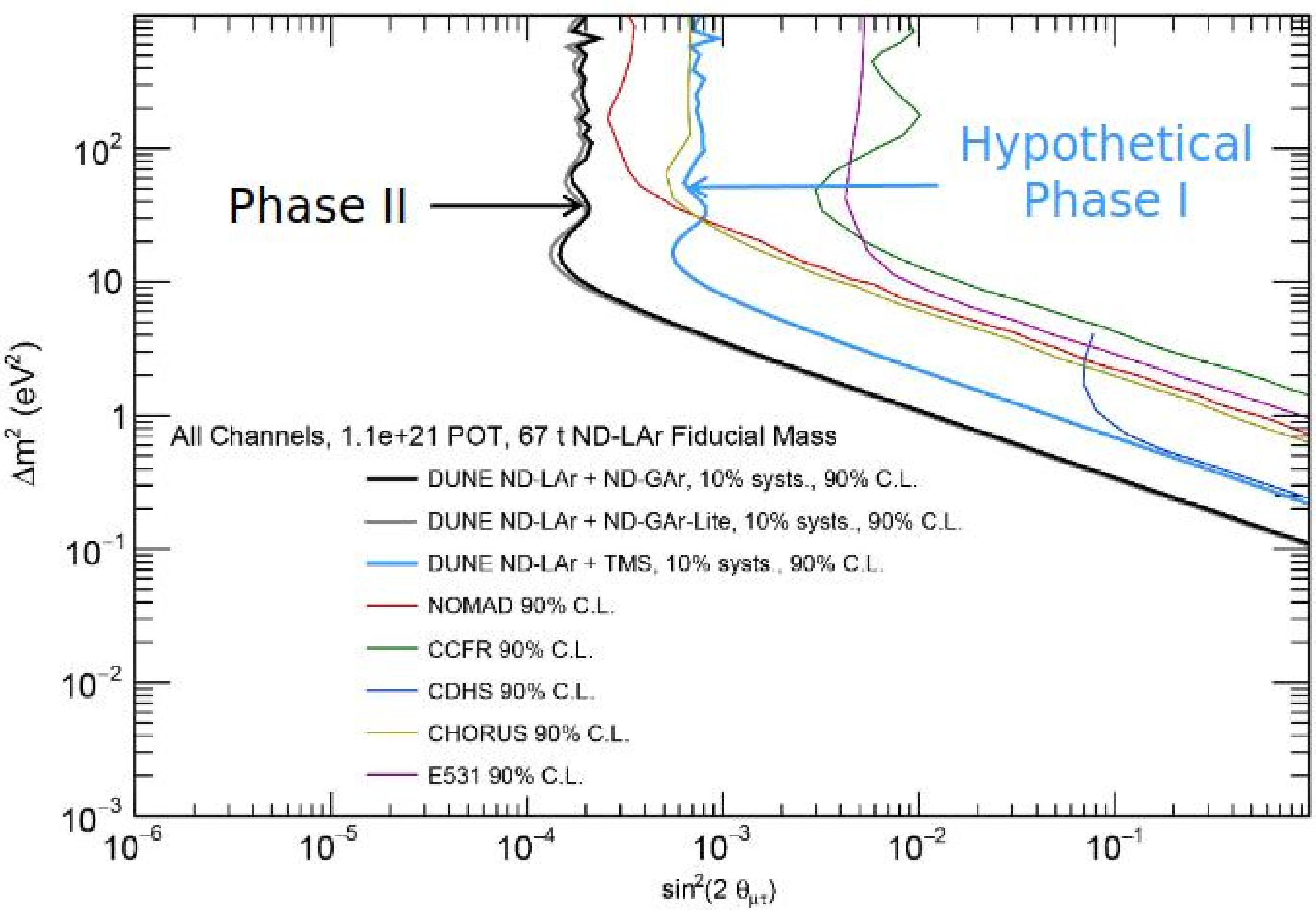


ν_μ disappearance



ν_e disappearance





Hypothetical
Phase I
Phase II
All Channels, 1.1e+21 POT, 67 t ND-LAr Fiducial Mass
DUNE ND-LAr + ND-GAr, 10% systs., 90% C.L.
DUNE ND-LAr + ND-GAr-Lite, 10% systs., 90% C.L.
DUNE ND-LAr + TMS, 10% systs., 90% C.L.
NOMAD 90% C.L.
CCFR 90% C.L.
CDHS 90% C.L.
CHORUS 90% C.L.
E531 90% C.L.
Δm^2 (eV^2)
$\sin^2(2\,\theta_{\mu\tau})$

Extra Results Part I NSI Global fit

One of the most paradigmatic models that give rise to NSI are light mediators.

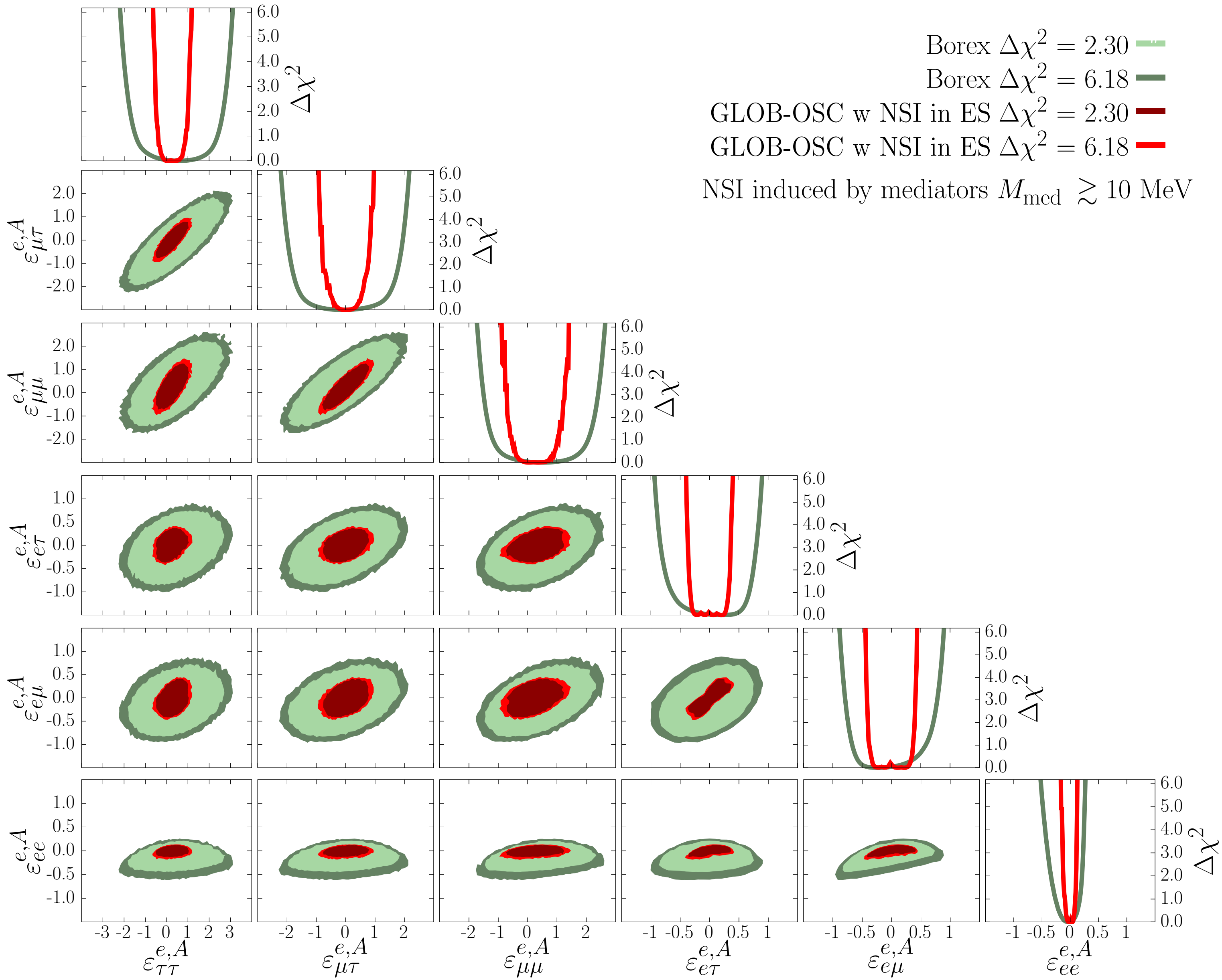
To put a concrete example, let us consider models with a vector mediator coupling to electrons and neutrinos.

$$\mathcal{L}_V = g_{Z'} Z'_\mu \left(q^e_{Z'} \bar{e} \gamma^\mu e + \sum_\alpha q^{\nu_\alpha}_{Z'} \bar{\nu}_{\alpha,L} \gamma^\mu \nu_{\alpha,L} \right) + \frac{1}{2} M^2_{Z'} Z'^\mu Z'_\mu,$$

Model	q^e	q^{ν_e}	q^{ν_μ}	q^{ν_τ}
Universal/leptonic scalar (or pseudoscalar)	1	1	1	1
$B-L$ vector	-1	-1	-1	-1
$L_e - L_\mu$ vector	1	1	-1	0
$L_e - L_\tau$ vector	1	1	0	-1

The oscillation data can be used to constraint very light mediators but for scattering the mass of the mediator must be larger than the momentum transfer (q) of the neutrinos interacting $M_{\rm med} \gtrsim q$

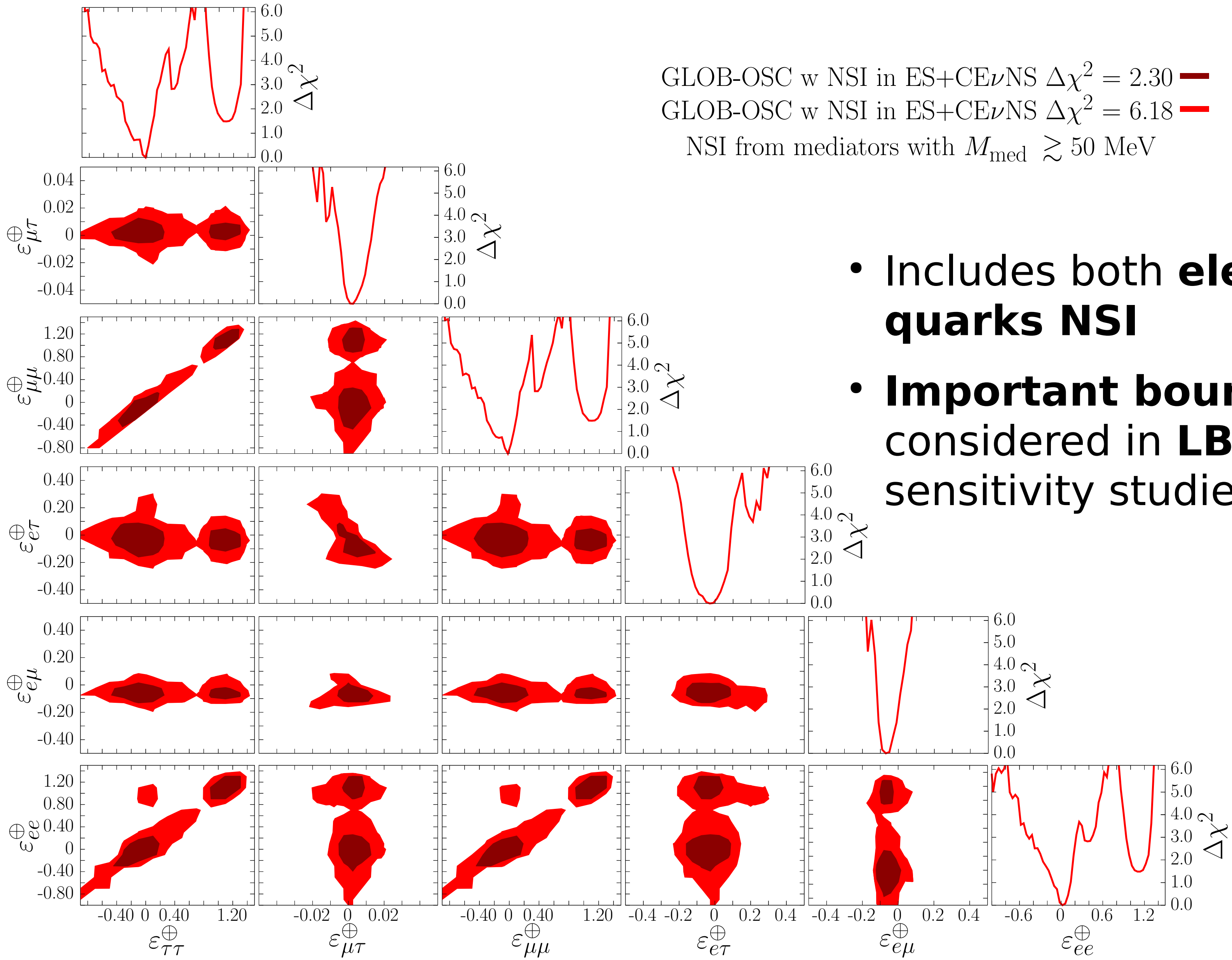
- Borexino scattering: $q \sim \mathcal{O}(500 \text{ keV}),$
- SNO and SuperK: $q \sim \mathcal{O}(5-10 \text{ MeV})$
- CEvNS: COHERENT $q \sim 30-50 \text{ MeV}$ Dresden II $q \sim 5 \text{ MeV}$



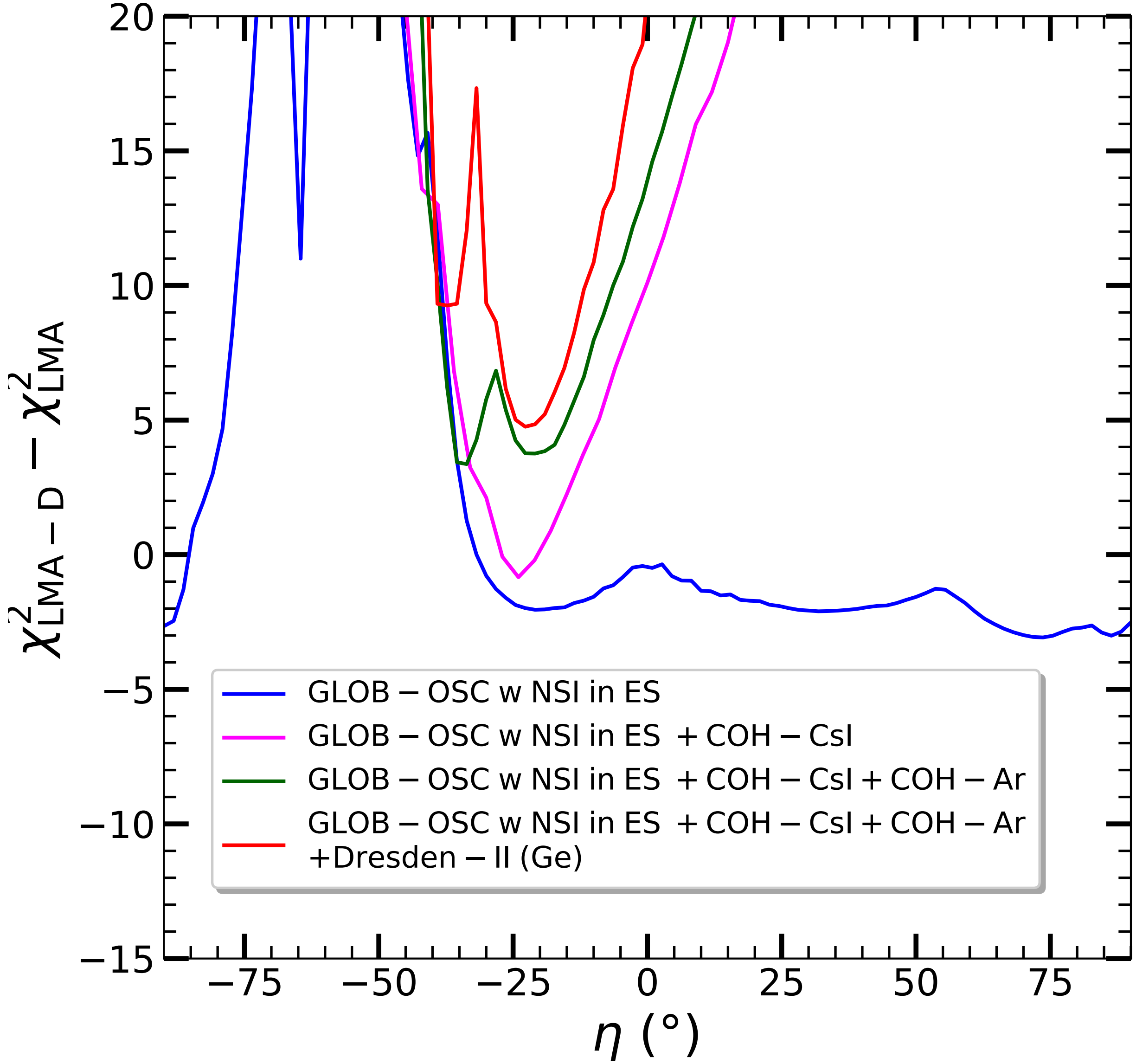
Borex $\Delta\chi^2 = 2.30$
Borex $\Delta\chi^2 = 6.18$
GLOB-OSC w NSI in ES $\Delta\chi^2 = 2.30$
GLOB-OSC w NSI in ES $\Delta\chi^2 = 6.18$
NSI induced by mediators $M_{\rm med} \gtrsim 10$ MeV
$\Delta\chi^2$
$\varepsilon^{e,A}_{\tau\tau}$
$\varepsilon^{e,A}_{\mu\tau}$
$\varepsilon^{e,A}_{\mu\mu}$
$\varepsilon^{e,A}_{e\tau}$
$\varepsilon^{e,A}_{e\mu}$
$\varepsilon^{e,A}_{ee}$

General NSI with e, p and n

$$\varepsilon^{\oplus}_{\alpha\beta} = \left(\varepsilon^{e,V}_{\alpha\beta} + \varepsilon^{p,V}_{\alpha\beta}\right) + Y^{\oplus}_{n}\varepsilon^{n,V}_{\alpha\beta}\,,$$



- Includes both **electron and quarks NSI**
- **Important bounds** to be considered in **LBL experiments** sensitivity studies



20
15
10
5
0
−5
−10
−15
−75
−50
−25
0
25
50
75
$\chi^2_{\rm LMA-D} - \chi^2_{\rm LMA}$
η (°)
GLOB − OSC w NSI in ES
GLOB − OSC w NSI in ES + COH − CsI
GLOB − OSC w NSI in ES + COH − CsI + COH − Ar
GLOB − OSC w NSI in ES + COH − CsI + COH − Ar +Dresden − II (Ge)

$$\frac{\mathrm{d}\sigma^{\mathrm{coh}}\left(E_R, E_\nu\right)}{\mathrm{d}E_R} = \frac{G_F^2}{2\pi}\mathcal{Q}^2 F^2\left(q^2\right) m_A\left(2 - \frac{m_A E_R}{E_\nu^2}\right)$$

$$\mathcal{Q}_{\alpha\beta} = Z\left(g_p^V \delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{p,V}\right) + N\left(g_n^V \delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{n,V}\right)$$

where $g_v^V = 1/2 - 2\sin^2\theta_w$ and $g_n^V = -1/2$

$$\mathcal{Q}_{\alpha\beta} = Z\left[\left(g_p^V + Y_n^{\mathrm{coh}} g_n^V\right)\delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{\mathrm{coh}}\right] \quad \text{with} \quad \varepsilon_{\alpha\beta}^{\mathrm{coh}} \equiv \varepsilon_{\alpha\beta}^{p,V} + Y_n^{\mathrm{coh}}\varepsilon_{\alpha\beta}^{n,V}$$

$$\varepsilon_{\alpha\beta}^{\mathrm{coh}} = \varepsilon_{\alpha\beta}\left(\xi^p + Y_n^{\mathrm{coh}}\xi^n\right)\left(\chi^L + \chi^R\right) = \sqrt{5}\left[\cos\eta\cos\zeta + Y_n^{\mathrm{coh}}\sin\eta\right]\left(\chi^L + \chi^R\right)\varepsilon_{\alpha\beta}.$$

$$i\frac{\mathrm{d}}{\mathrm{d}x}\begin{pmatrix}\tilde{\nu}_1\\ \tilde{\nu}_2\end{pmatrix}=\begin{pmatrix}-\Delta_m(x) & -i\theta'_m(x)\\ i\theta'_m(x) & \Delta_m(x)\end{pmatrix}\begin{pmatrix}\tilde{\nu}_1\\ \tilde{\nu}_2\end{pmatrix}$$

$$\theta_m(x)\equiv\frac{1}{2}\arctan\left[H^{\mathrm{eff}}_{12}(x)/H^{\mathrm{eff}}_{22}(x)\right]\qquad\qquad \Delta_m(x)\equiv\sqrt{\left[H^{\mathrm{eff}}_{12}(x)\right]^2+\left[H^{\mathrm{eff}}_{22}(x)\right]^2}$$

In most of the literature to simplify the computation the so-called adiabatic approximation is assumed

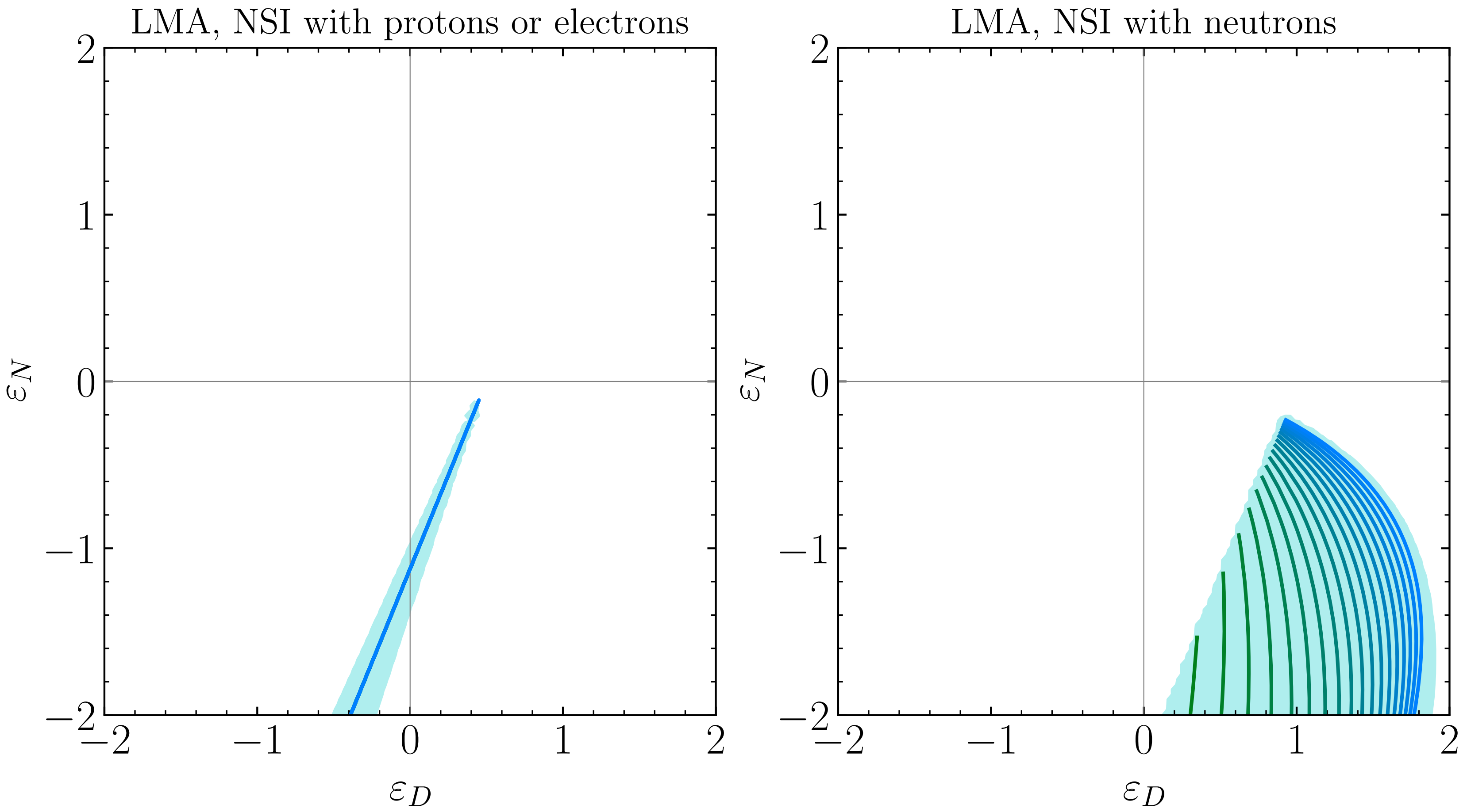
$$\gamma^{-1}(x)\equiv\left|\frac{\theta'_m(x)}{\Delta_m(x)}\right|\ll 1$$

However in the presence of NSI, we can have the case in which $\Delta_m(x)\to 0$, this is realized when:

$$\left[\xi^e+\xi^p+Y_n(x)\xi^n\right]\left(\chi^L+\chi^R\right)\varepsilon_D\to-\frac{\Delta m^2_{12}\cos 2\theta_{12}}{4E_\nu V(x)}+\frac{c^2_{13}}{2}$$

$$\left[\xi^e+\xi^p+Y_n(x)\xi^n\right]\left(\chi^L+\chi^R\right)\varepsilon_N\to-\frac{\Delta m^2_{12}\sin 2\theta_{12}}{4E_\nu V(x)}$$

Results: Adiabaticity

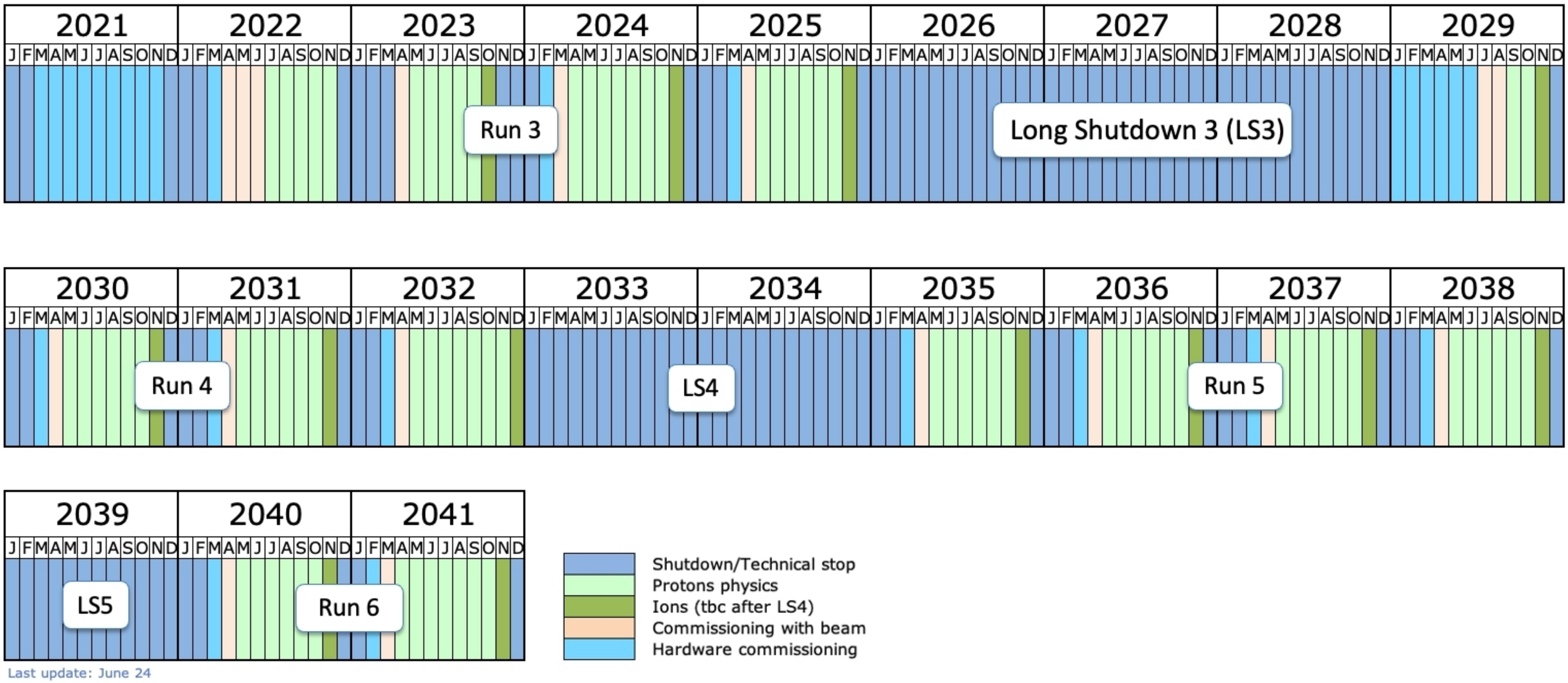


- A good fit can be fake if we use the adiabatic approximation for non adiabatic points.
- If we throw away the non adiabatic points we recover the correct sensitivity

Extra Results Part II
ProtoDUNE

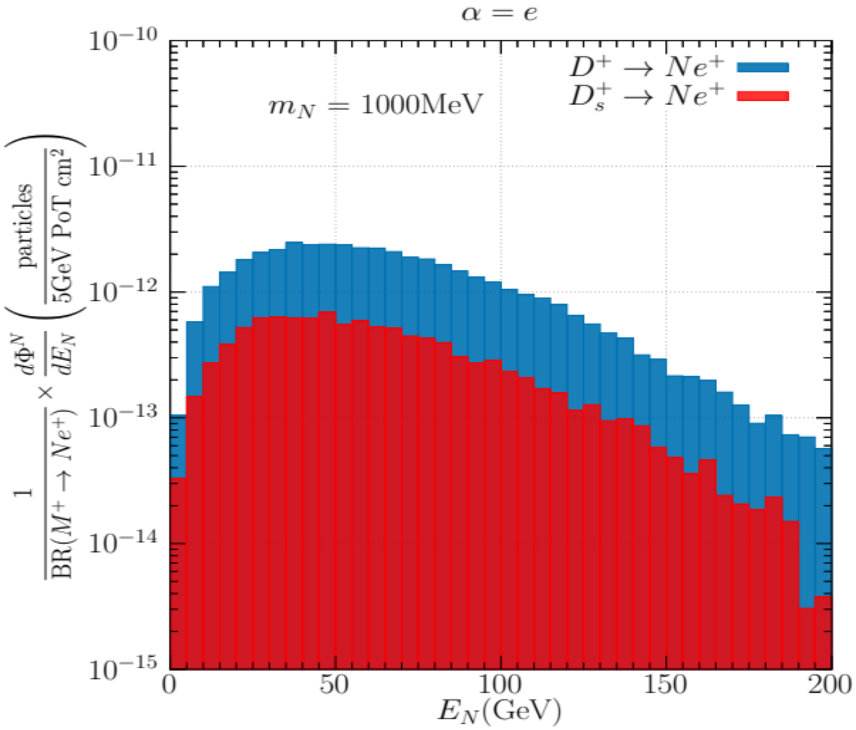
Longer term LHC schedule

In January 2022, the schedule was updated with long shutdown 3 (LS3) to start in 2026 and to last for 3 years. HL-LHC operations now foreseen out to end 2041.



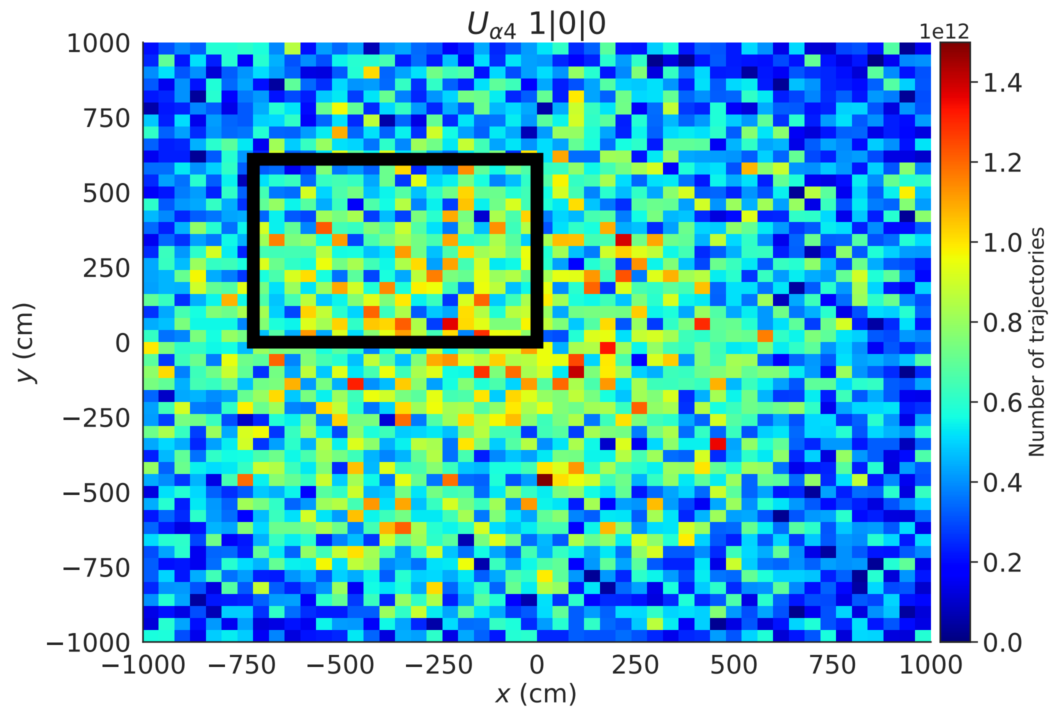
HNL: Fluxes

HNL intersecting the detector



- **Quite energetic HNL beam**

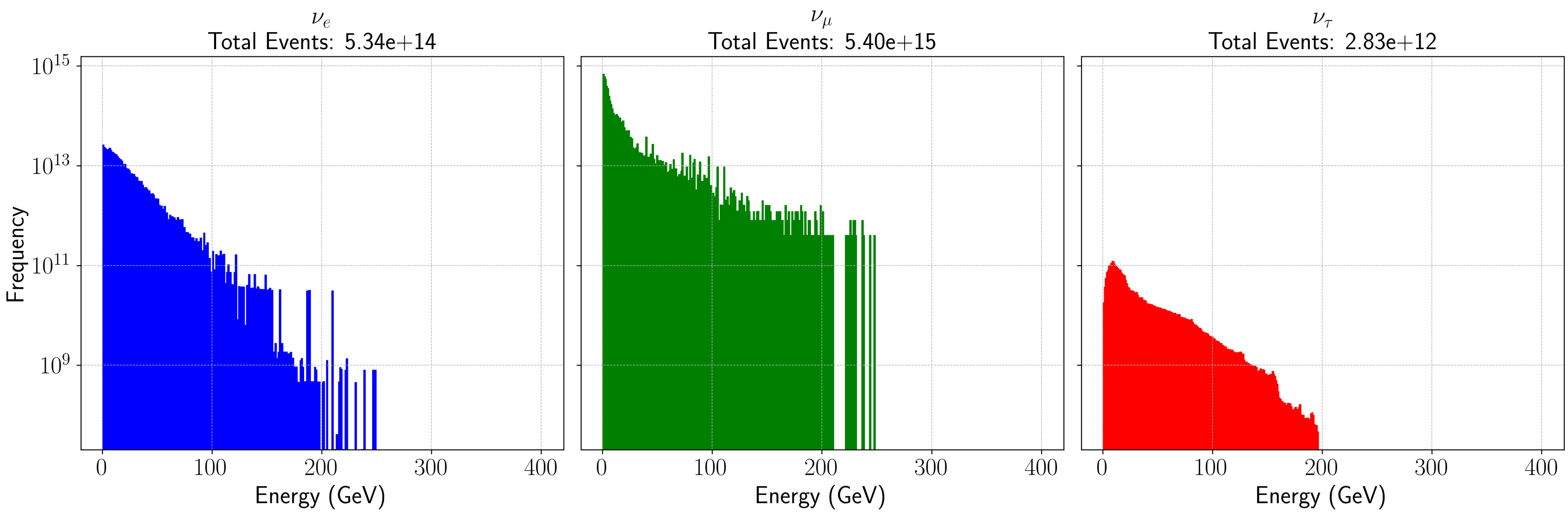
HNL at z = 677 m

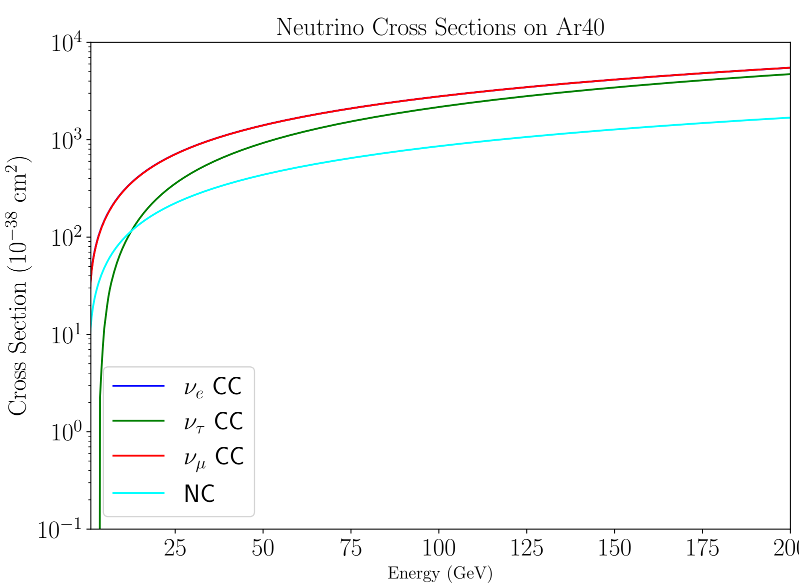


- **Wide HNL beam**
- **Small changes in the geometry will not significantly change the results**
- **Any of the two ProtoDUNE detectors can be used**

Neutrinos entering the detector

These neutrino fluxes are based on the meson simulation done with Geant4





Neutrinos interacting in the detector

Interaction Type	Number of neutrino events
ν_e CC	86217 (55156)
ν_e NC	27144 (17390)
ν_μ CC	305577 (28389)
ν_μ NC	96151 (9020)
ν_τ CC	146
ν_τ NC	76

1.75×10^{19}PoT in 5 years

 Simulated with GENIE

$\pi^{\pm}\mu^{\mp}$ or $\mu^{\pm}\mu^{\mp}$

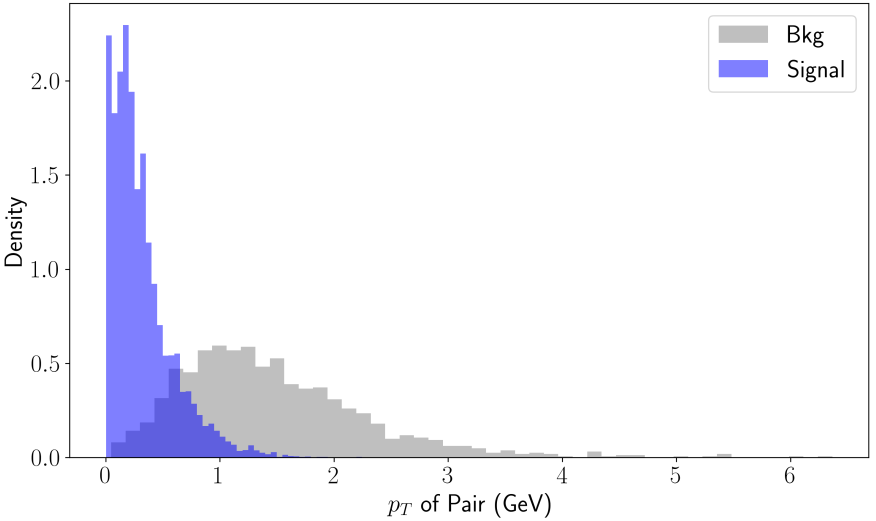
We have 1278 background events with the following cuts:

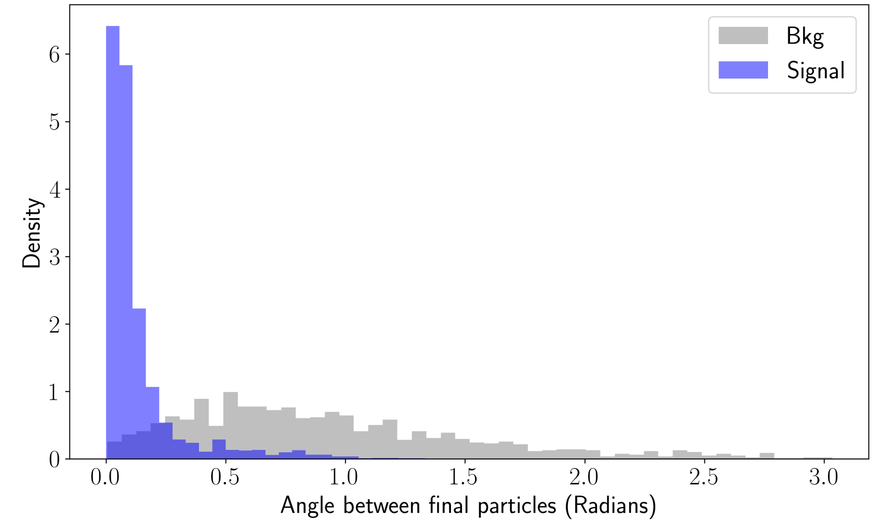
- We keep events with only two μ-like ($\pi^{\pm}$, $\mu^{\pm}$) particles, above an energy threshold of 30 MeV.
- We reject events with other detectable particles in the final state.

We can reduce the events to **15** events with the following kinematical cuts:

- $p_T < 0.35$ GeV.
- $\theta_{\mu\pi} < 0.18$ rad.

These 15 events of background are $\mu^{\pm}\pi^{\mp}$, for the channel $\mu^{+}\mu^{-}$, we could reduce this background further by noting that pions are more likely to interact in the TPC, producing noticeable differences in their tracks with respect to the muons.





Simulated with GENIE

$e^{\pm}\mu^{\mp}$ or $e^{\pm}\pi^{\mp}$

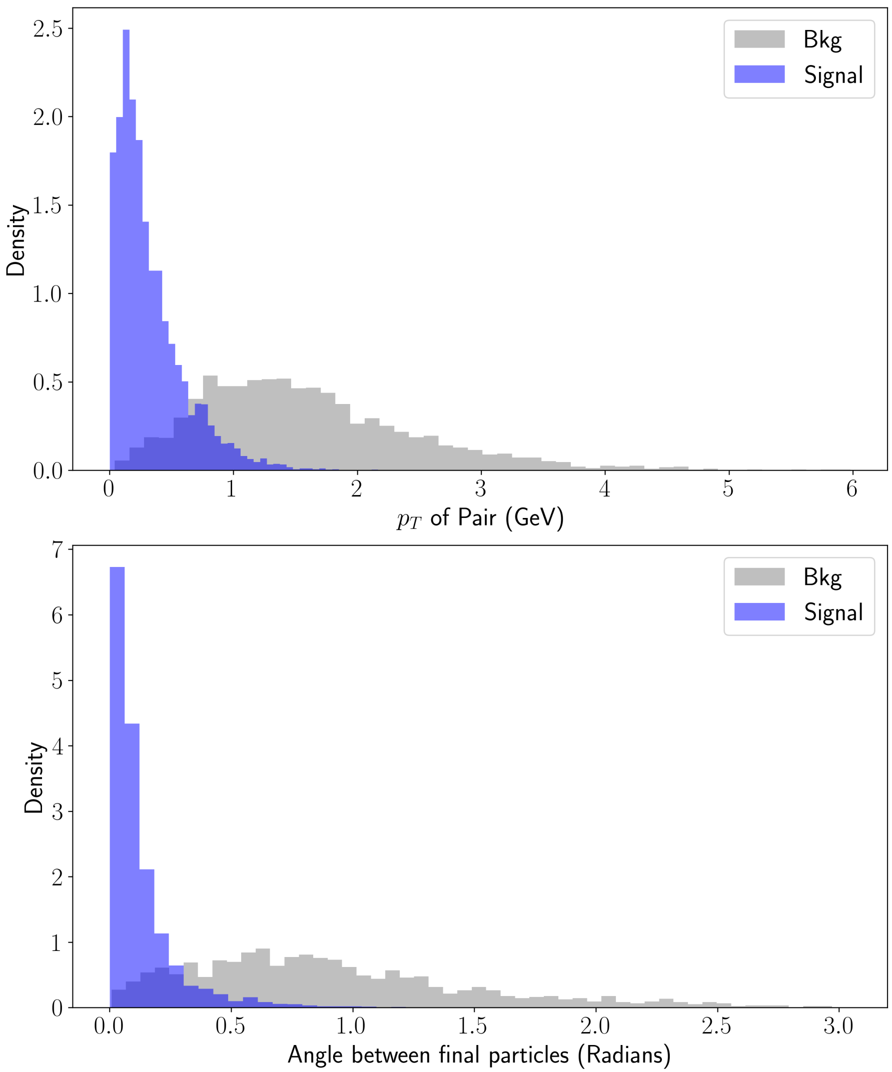
We have 1982 background events with the following cuts:

- We keep events with only one μ-like ($\pi^{\pm}$, $\mu^{\pm}$) particle and one ($e^{\pm}$), above an energy threshold of 30 MeV.
- We reject events with other detectable particles in the final state.

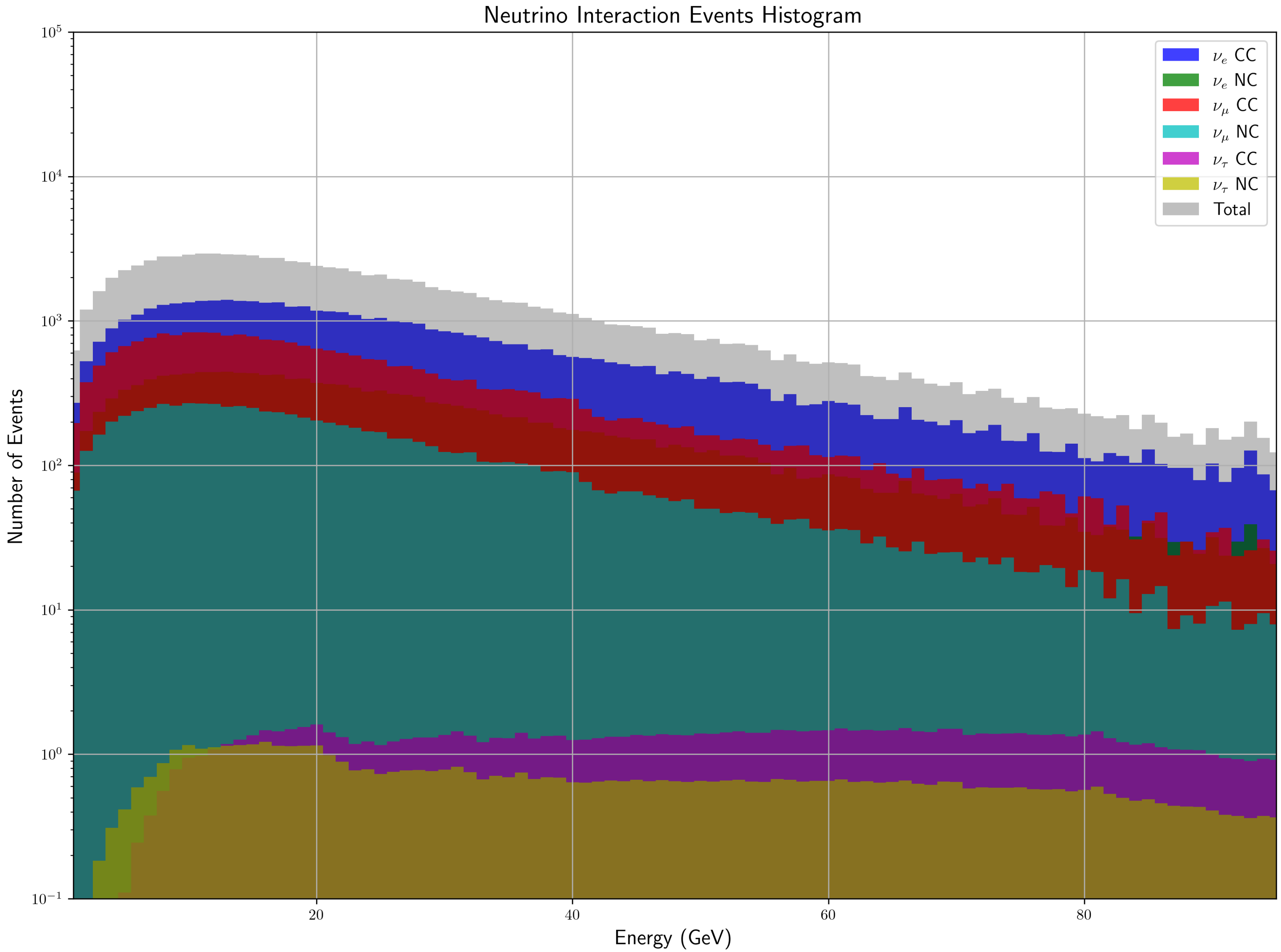
We can reduce the events to **24** events with the following kinematical cuts:

- $p_T < 0.35$ GeV.
- $\theta_{e\mu} < 0.180$ rad.

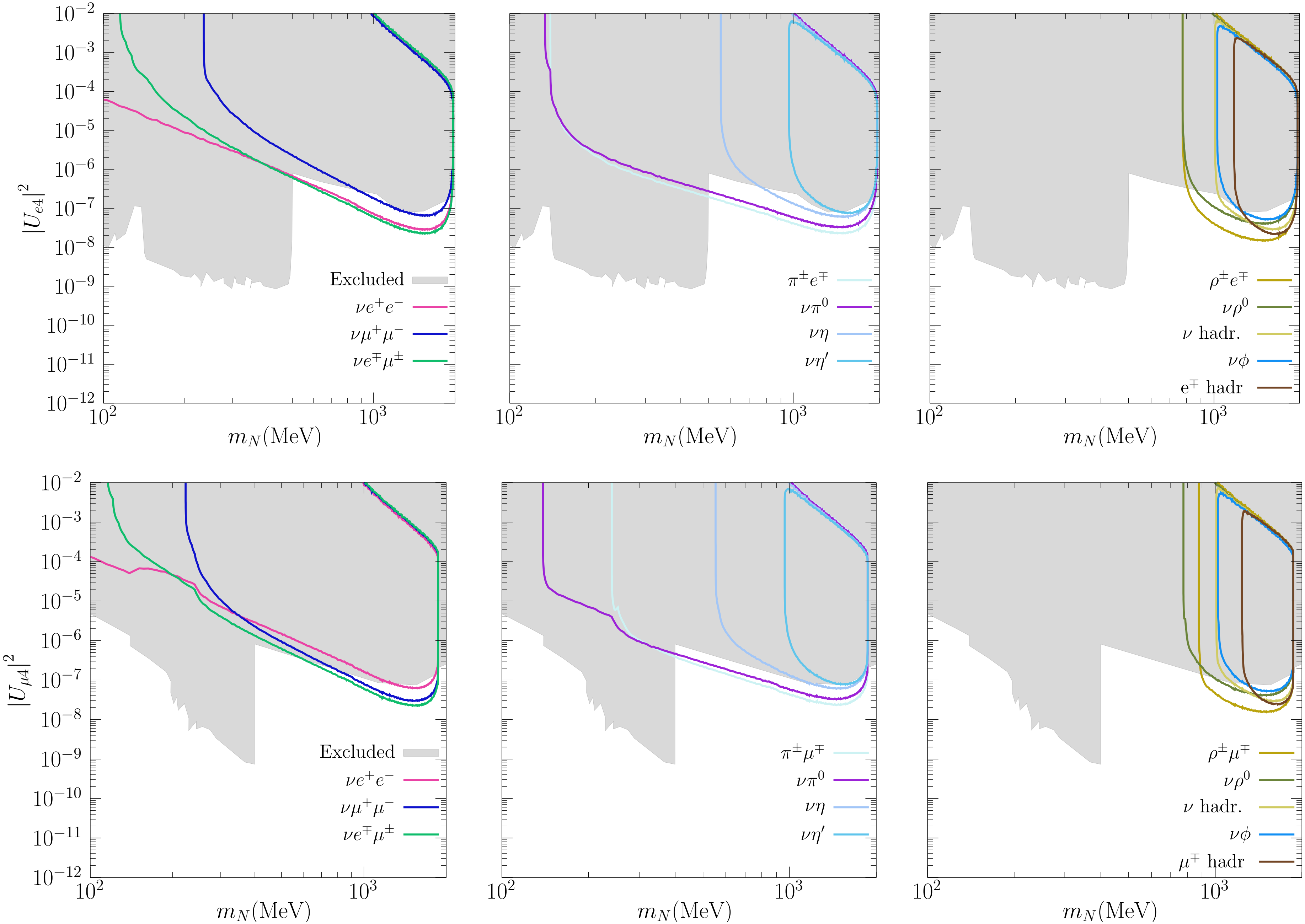
These 24 events of background are $e^{\pm}\pi^{\mp}$, for the channel $e^{-}\mu^{+}$, we could reduce this background further by noting that pions are more likely to interact in the TPC, producing noticeable differences in their tracks with respect to the muons.

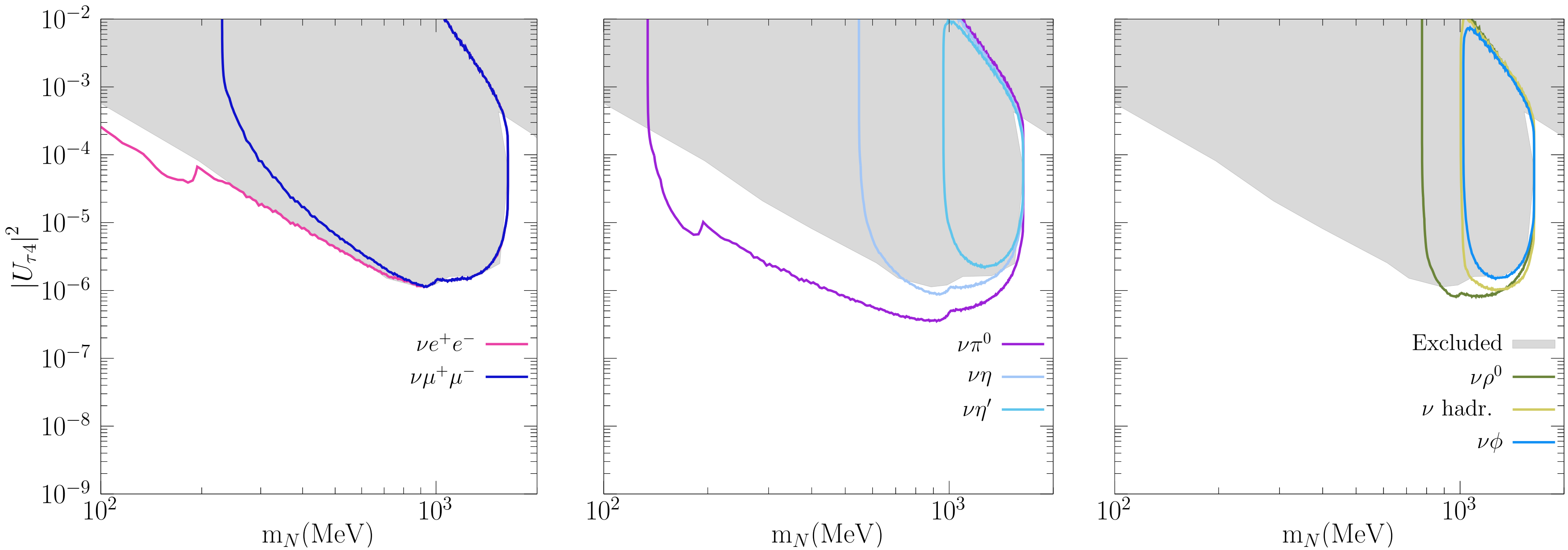


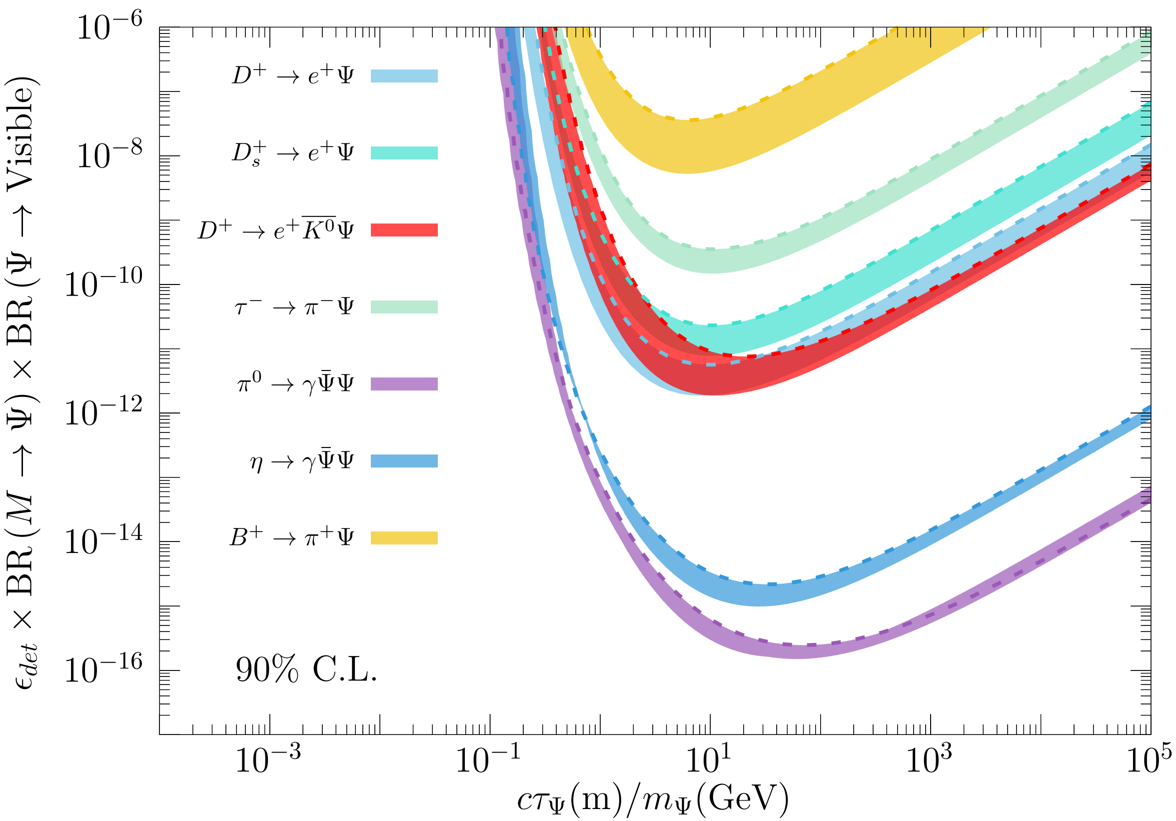
Simulated with GENIE



Neutrino Interaction Events Histogram
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
Number of Events
20
40
60
80
Energy (GeV)
ν_e CC
ν_e NC
ν_μ CC
ν_μ NC
ν_τ CC
ν_τ NC
Total


$|U_{e4}|^2$
m_N(MeV)
Excluded
νe^+e^-
$\nu\mu^+\mu^-$
$\nu e^\mp\mu^\pm$
$\pi^\pm e^\mp$
$\nu\pi^0$
$\nu\eta$
$\nu\eta'$
$\rho^\pm e^\mp$
$\nu\rho^0$
ν hadr.
$\nu\phi$
e$^\mp$ hadr
$|U_{\mu4}|^2$
$\pi^\pm\mu^\mp$
$\rho^\pm\mu^\mp$
$\mu^\mp$ hadr

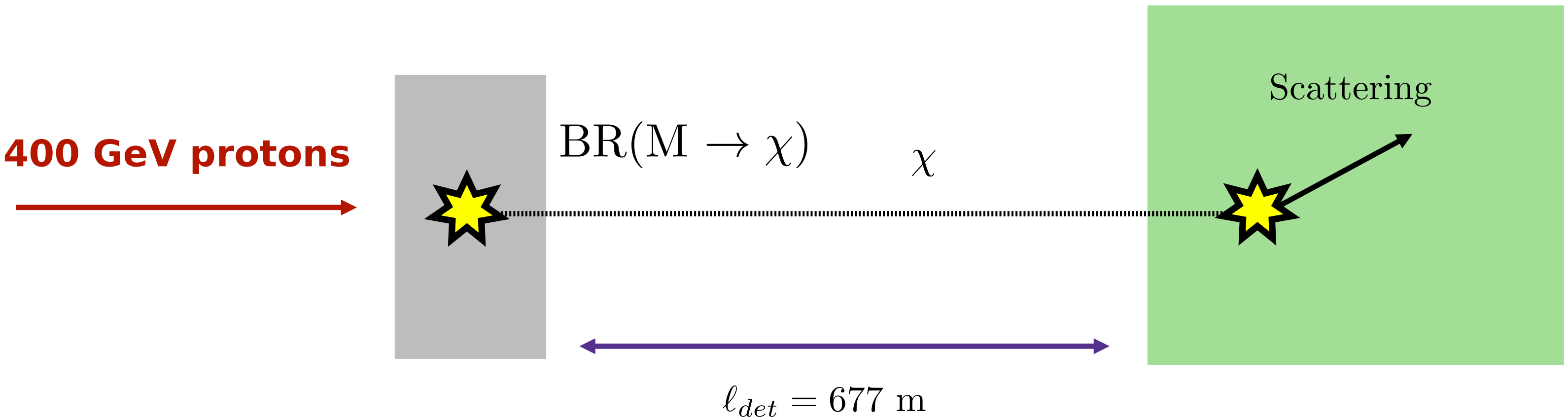




$$\mathcal{P} = e^{\frac{-\ell_{\text{det}}}{L_\Psi}}\left(1 - e^{\frac{-\Delta\ell_{\text{det}}}{L_\Psi}}\right)$$

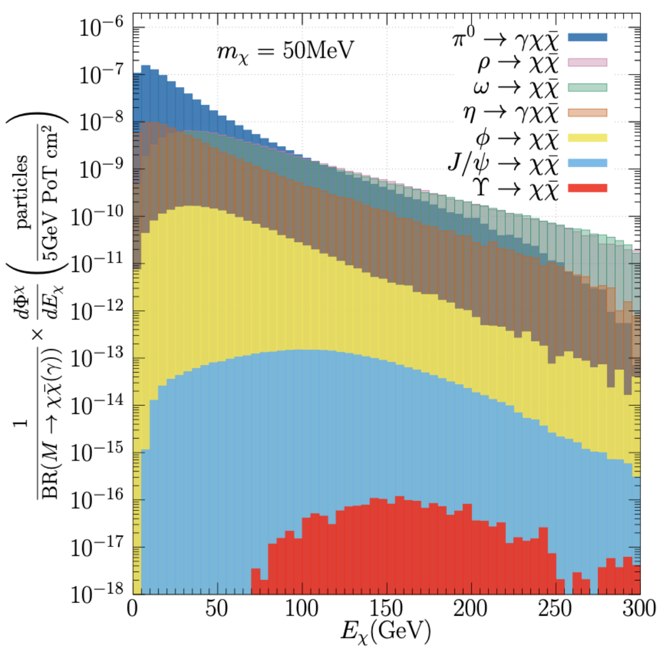
New Physics: stable particles

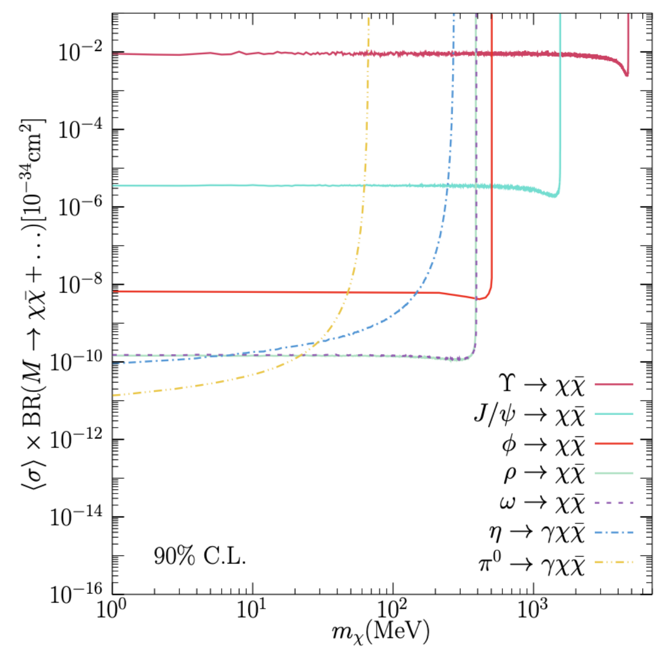
Detector(NP02) Liquid Argon TPC



$$\langle\sigma\rangle = \frac{1}{\Phi^\chi}\int_0^\infty \int_{T^{\min}}^{T^{\max}} \frac{d\sigma}{dT}\left(E_\chi, \{X\}\right) \frac{d\Phi^\chi}{dE_\chi} dT dE_\chi$$

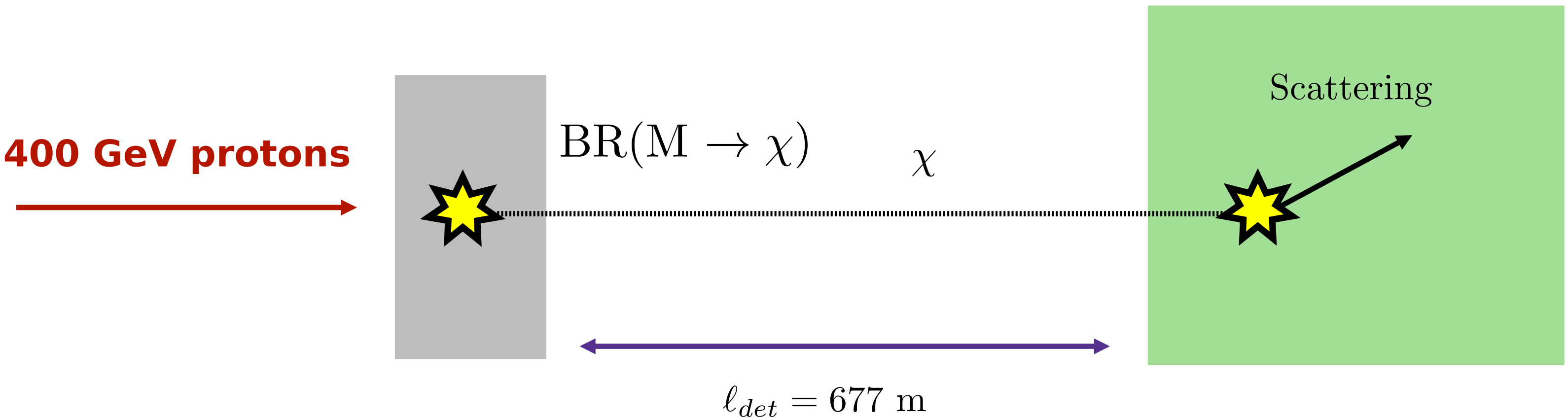
$$\mathrm{N}_{ev} = \epsilon_{\rm det}\, N_{trg} \langle\sigma\rangle \Phi^\chi N_{\rm PoT},$$

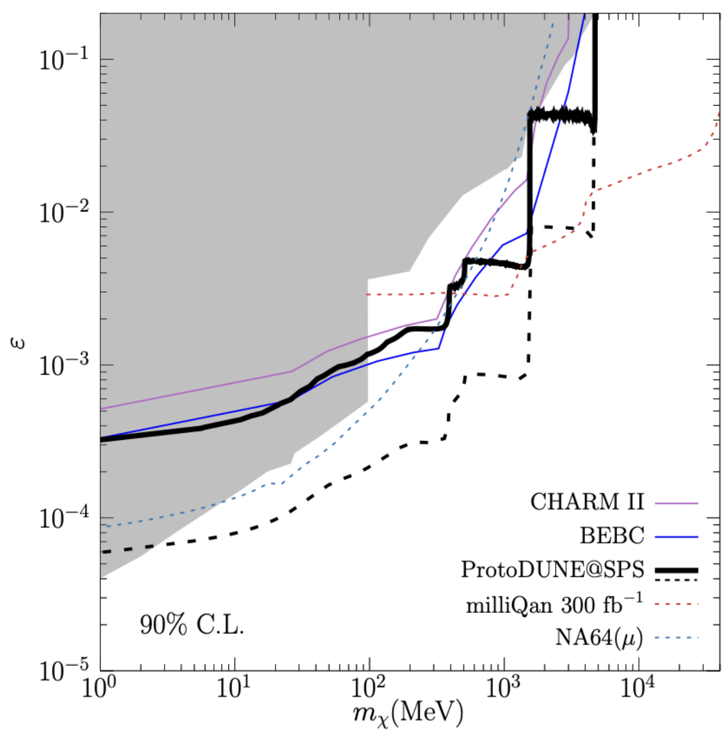




Millicharged particles

Detector(NP02) Liquid Argon TPC





$$N_{ev} = \epsilon_{\rm det}\, N_{trg} \langle\sigma\rangle \Phi^{\chi} N_{\rm PoT},$$

$$\sigma \sim \varepsilon^2 \left(\frac{30\mathrm{MeV}}{T_{\rm min}}\right) 10^{-26}\ \mathrm{cm}^{-2},$$

Extra Results Part II
DUNE-ND

DUNE Timeline and Phasing

DUNE phase-I:

- LBNF completed
  - PIP-II and neutrino beamline by 2031
  - full near detector site and facilities by 2028
  - far site with facilities and caverns for 2 modules – total of 70kt FD complete by the end of 2024
- Two FD modules – 17kt LArTPC each of HD and VD
  - HD starts installation in 2026, complete and commissioned by 2028
  - VD starts installation in 2029
- LAr-ND w/ TMS and on-axis SAND by 2031

TMS: Three-Dimensional Muon Spectrometer, **SAND:** System for on-Axis Neutrino Detection

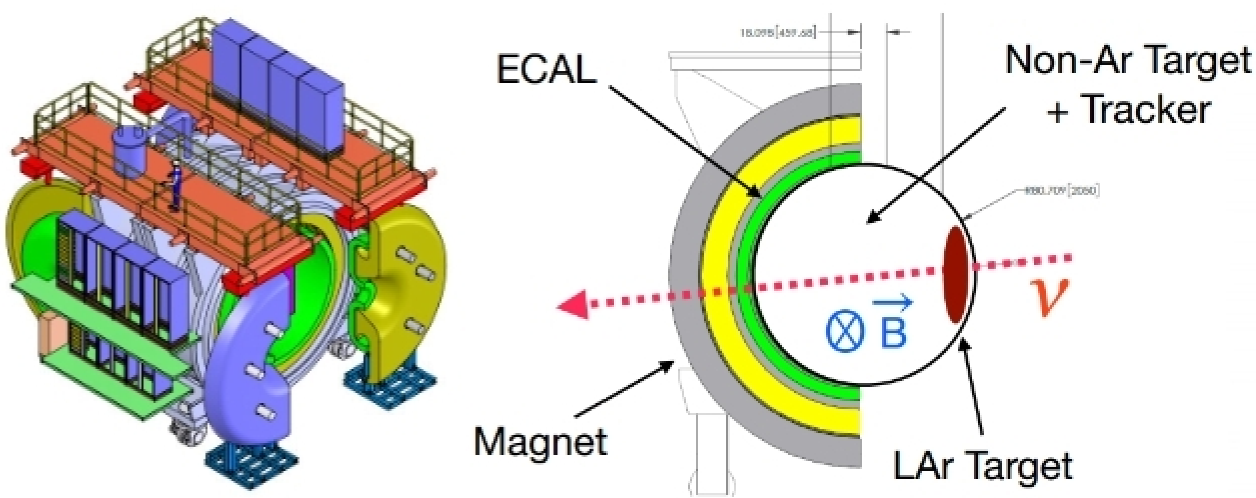
PIP: Proton improvement plan

DUNE phase-II:

- Fermilab beamline: Booster and other upgrade allowing for 2.1MW
- ND – additional sub-detectors – ND-Gar, calorimeter
- FD – FD3 and FD4 – technology TBD.

Parameter	Phase I	Phase II
FD mass	2 FD modules (20 kt fiducial)	4 FD modules (40 kt fiducial LAr equivalent)
Beam power	1.2 MW	Up to 2.3 MW
ND configuration	ND-LAr+TMS, SAND	ND-LAr, ND-GAr, SAND

What is SAND?



(a) SAND engineering model

(b) Sketch of SAND vertical cross-section

Figure 1: Drawings of the current SAND design.

Always on axis,

Monitors the beam,

Interactions with different nuclei.

$$(\mathrm{Ar}, \mathrm{CH_2}, \mathrm{C})$$

SAND primary goals

- On-axis ν-spectrum monitor to detect any potential changes in the beam over time on a weekly basis that can affect the FD oscillation analysis
- Provide an independent in-situ measurements of ν_μ, anti- ν_μ, ν_e, anti- ν_e fluxes and energy spectra
- Constrains systematics from nuclear effects by measuring the ν and anti-ν cross sections on nuclei other than argon (carbon and hydrocarbons)
- Exploit the unprecedented high statistics to perform a rich physics program besides the oscillation program

	Selection cut	Signal efficiency		Background rate	
		ND-LAr	ND-GAr	ND-LAr	ND-GAr
$\mu^+\mu^-$	Two μ-like tracks only	1.00	1.00	3545674	70656
	PID μ and opposite charge sign	0.40	1.00	6226	124
	Transverse momentum < 0.125 GeV/c	0.40	0.99	99	2
	Angle between muons < 0.7 rad	0.40	0.94	0	0
e^+e^-	Two e-like tracks/showers	0.10	1.00	9432	145
	Reconstructed ALP direction	**0.10**	0.99	180	15
$\gamma\gamma$	Two γ showers only	0.05	0.79	36276	14222
	Reconstructed ALP direction	0.05	0.79	6938	**7923**
	Angle between γ showers	**0.05**	—	**1367**	—
$\pi^+\pi^-\pi^0$	Two μ-like tracks, two γ showers	0.04	0.81	2030490	40462
	PID $\pi^\pm$ and charge sign	0.04	0.81	431035	8589
	Transverse momentum < 0.2 GeV/c	0.04	0.79	17182	342
	Angle between pions < 0.15 rad	**0.04**	0.69	**946**	19

UV completions

$$\delta\mathcal{L}_{\mathrm{EW}} = c_\phi \mathcal{O}_\phi + c_B \mathcal{O}_B + c_W \mathcal{O}_W$$

$$\Lambda \propto f_a = 1\mathrm{TeV}$$

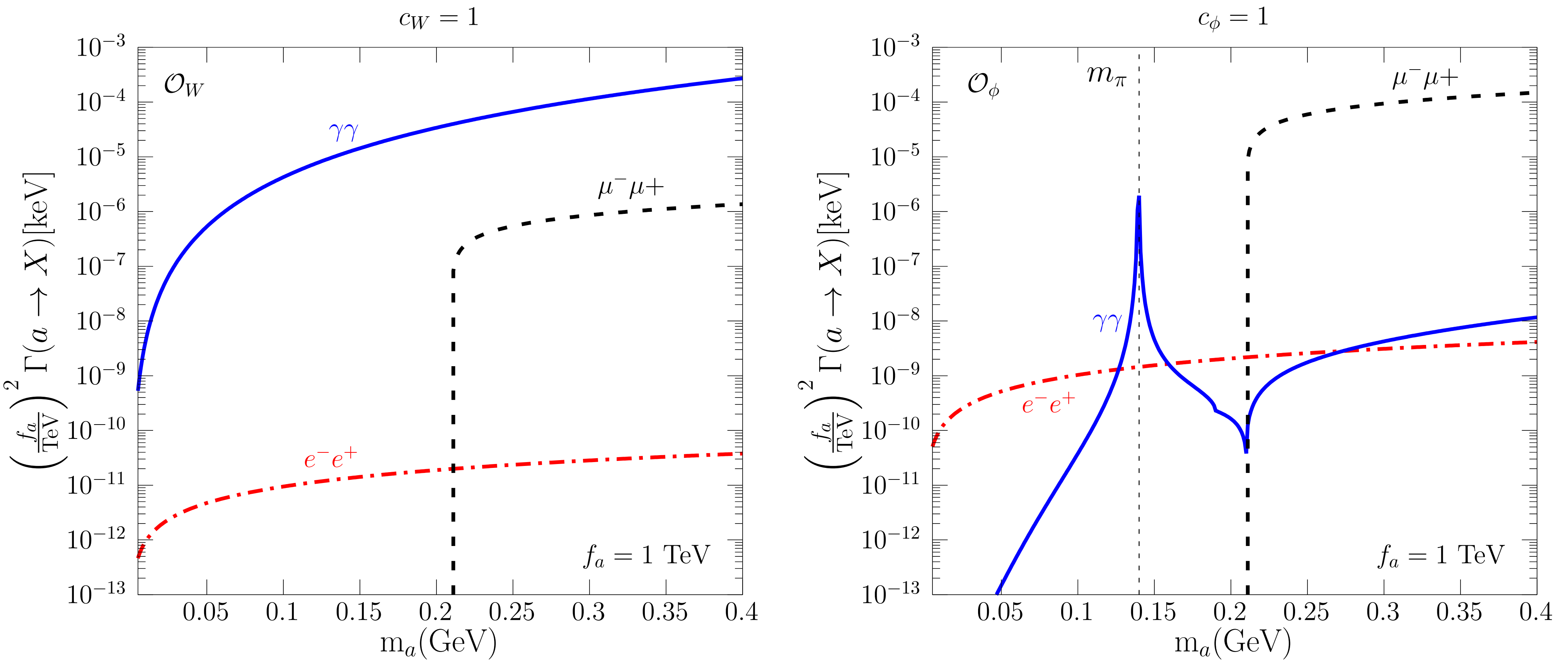
where c_i stand for the Wilson coefficients of each operator:

$$\mathcal{O}_\phi = i\frac{\partial^\mu a}{f_a}\phi^\dagger \overleftrightarrow{D}_\mu \phi \quad \xrightarrow{\text{Hypercharge rotation}} \quad \frac{\partial_\mu a(x)}{f_a}\sum_F \bar{\Psi}_F \gamma^\mu \Psi_F$$

$$\mathcal{O}_B = -\frac{a}{f_a} B_{\mu\nu}\widetilde{B}_{\mu\nu}$$

$$\mathcal{O}_W = -\frac{a}{f_a} W^a_{\mu\nu}\widetilde{W}^a_{\mu\nu}$$

Bonnefoy, Q., Di Luzio, L., Grojean, C., Paul, A., & Rossia, A. N. (2021). **The anomalous case of axion EFTs and massive chiral gauge fields.** Journal of High Energy Physics, 2021(7).



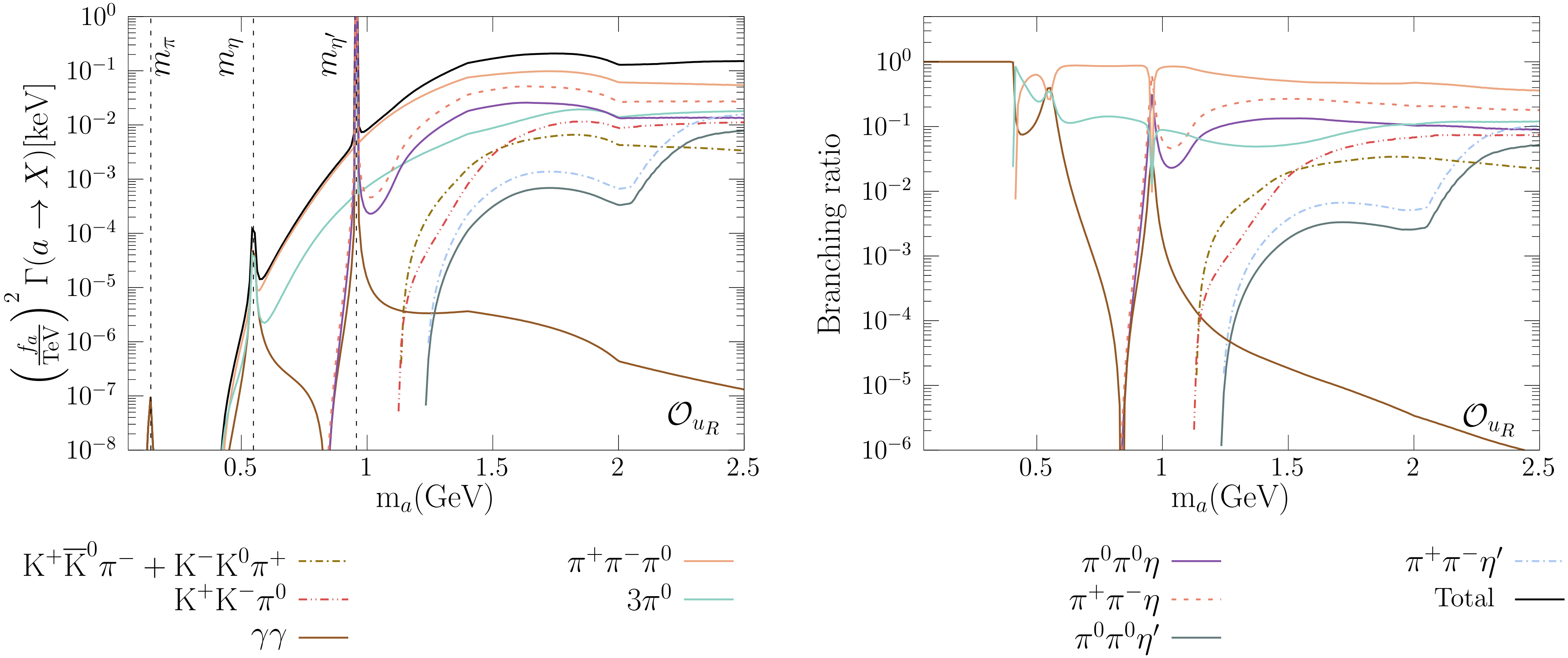
$c_W = 1$
$\mathcal{O}_W$
$\gamma\gamma$
$\mu^-\mu+$
e^-e^+
$f_a = 1$ TeV
$\left(\frac{f_a}{\text{TeV}}\right)^2 \Gamma(a \to X)[\text{keV}]$
$\text{m}_a(\text{GeV})$
$c_\phi = 1$
$\mathcal{O}_\phi$
m_π
$\mu^-\mu+$
$\gamma\gamma$
e^-e^+
$f_a = 1$ TeV
$\left(\frac{f_a}{\text{TeV}}\right)^2 \Gamma(a \to X)[\text{keV}]$
$\text{m}_a(\text{GeV})$

$$\delta\mathcal{L}_{a,int} = c_{u_R}\mathcal{O}_{u_R} = \sum_{i,j}\frac{\partial_\mu a}{f_a}\left(c_{u_R}\right)_{ij}\bar{u}_{Ri}\gamma^\mu u_{Rj}$$

$$\Gamma\left(D^+ \to \pi^+ a\right) \underset{\text{to}}{=} \frac{m_D^3\,\left|[c_{u_R}]_{12}\right|^2}{64\pi f_a^2}\left[f_0^{D\pi}\left(m_a^2\right)\right]^2\lambda^{1/2}\left(1, m_a^2/m_D^2, m_\pi^2/m_D^2\right)\left(1-\frac{m_\pi^2}{m_D^2}\right)^2$$

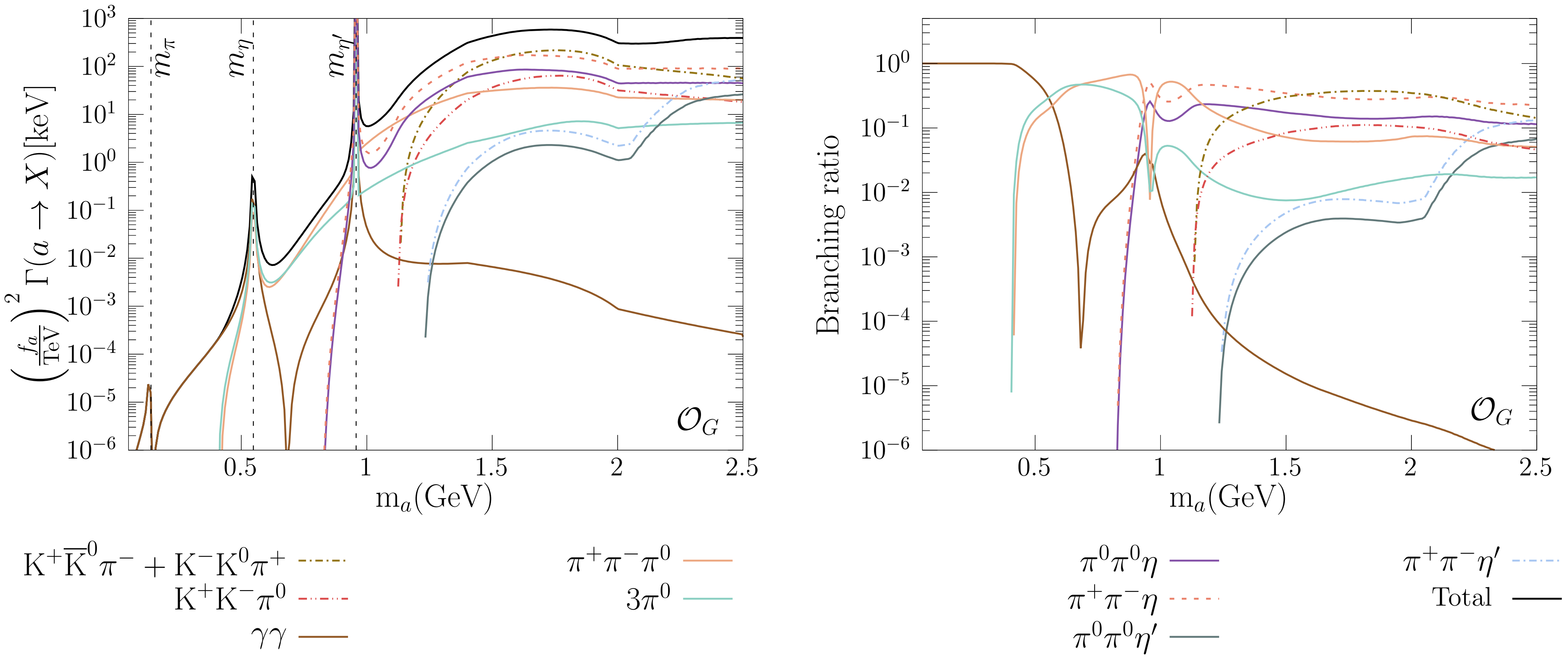
$$c_{u_R}^{\mathrm{FN}} = \begin{pmatrix} 2 & 3\epsilon & 3\epsilon^2 \\ 3\epsilon & 1 & \epsilon \\ 3\epsilon^2 & \epsilon & \epsilon^2 \end{pmatrix}$$

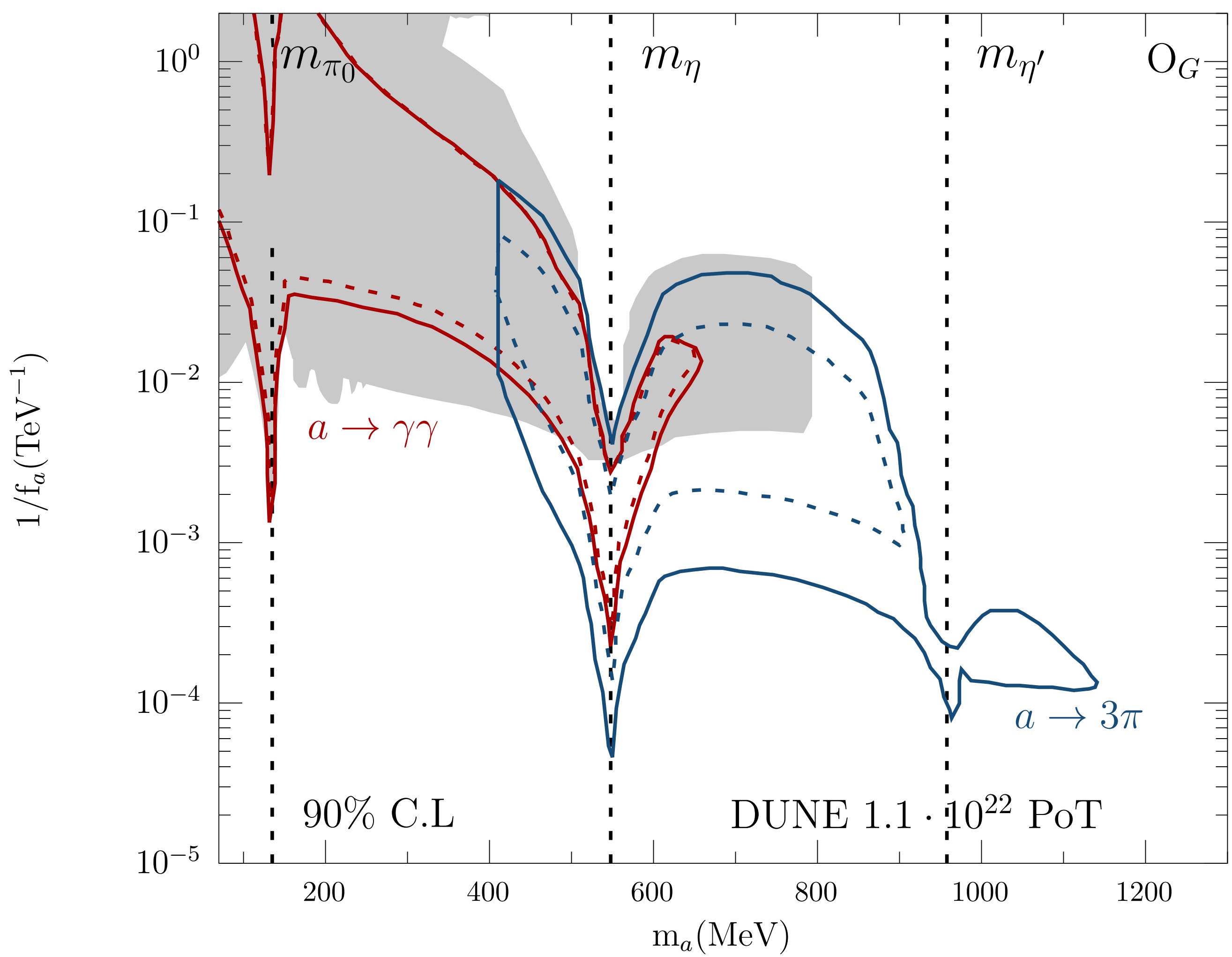
where off-diagonal entries are controlled by $\epsilon = f_a/\Lambda \sim m_c/m_t$.



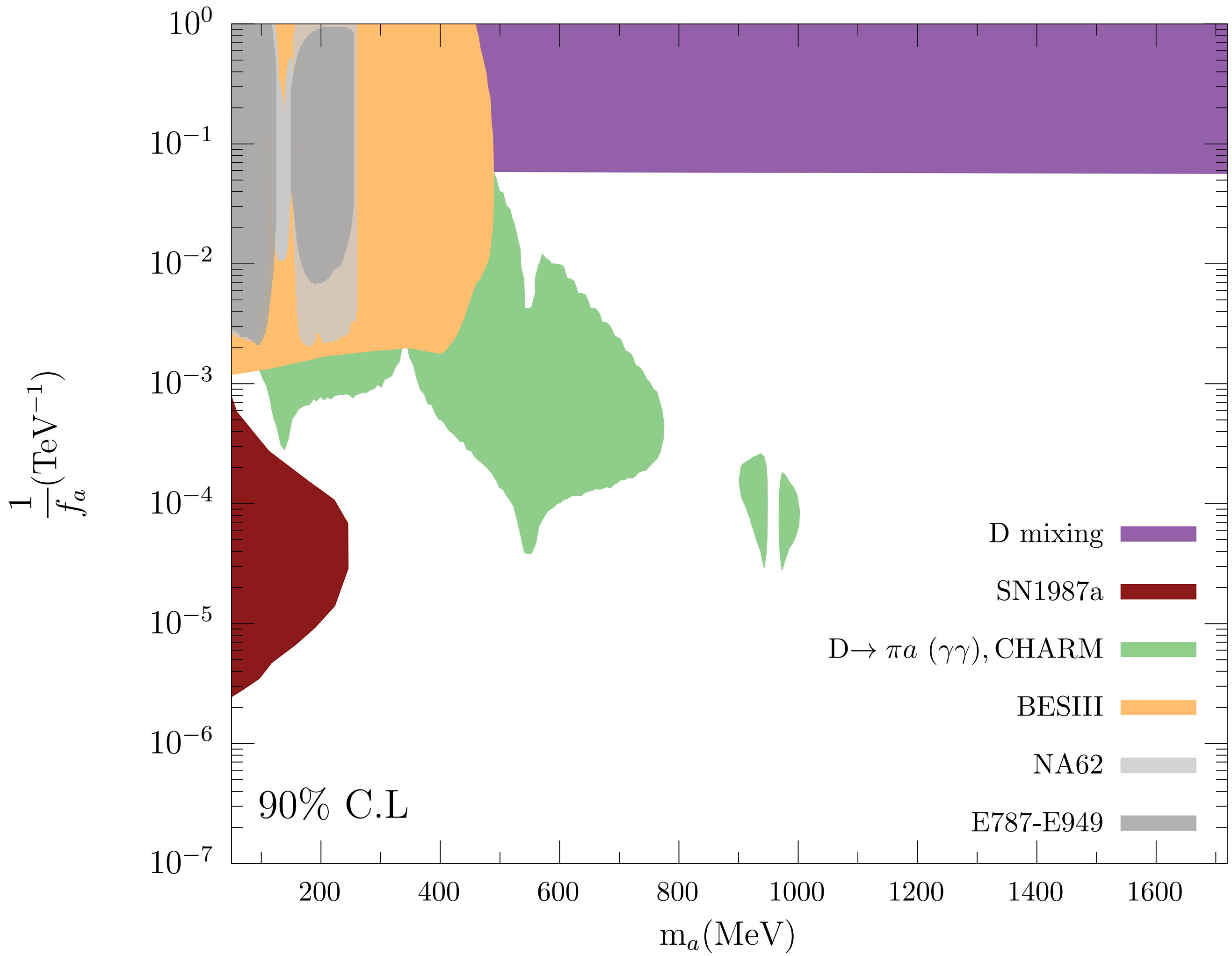
$$\delta\mathcal{L}_{a,\ \mathrm{int}} = c_G \mathcal{O}_G = \frac{\alpha_s}{8\pi f_a} a G^b_{\mu\nu} \widetilde{G}^{b\mu\nu}$$

where $G^b_{\mu\nu}$ is the gluon field strength, $\widetilde{G}^{b\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} G_{b\rho\sigma}$, with $\epsilon^{0123} = 1$. Also, $\alpha_s \equiv g_s^2/(4\pi)$, and g_s stands for the strong coupling constant.

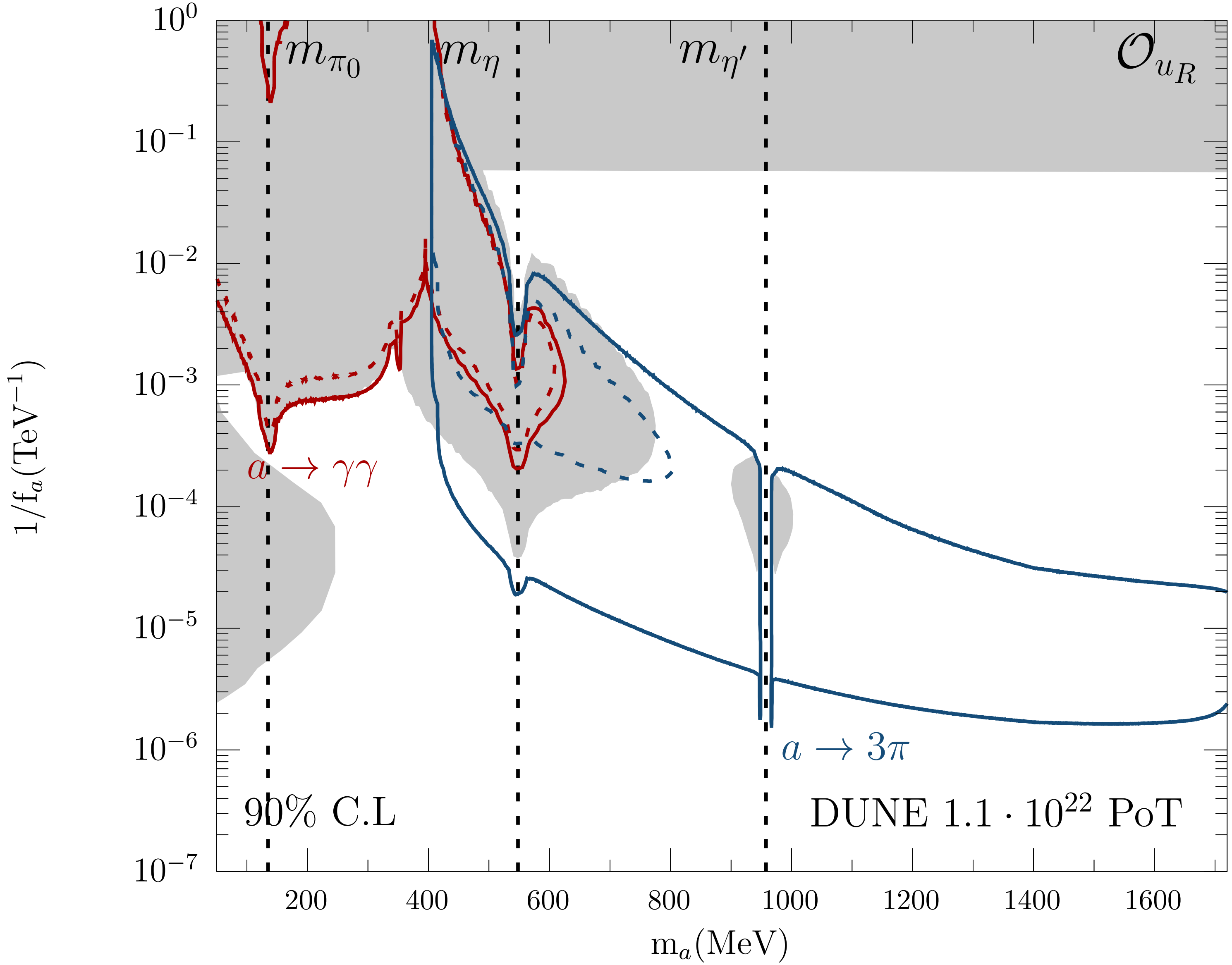




m_{π_0}
m_η
$m_{\eta'}$
O_G
$a \to \gamma\gamma$
$a \to 3\pi$
90% C.L
DUNE $1.1 \cdot 10^{22}$ PoT
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
200
400
600
800
1000
1200
m_a(MeV)
$1/f_a(\mathrm{TeV}^{-1})$



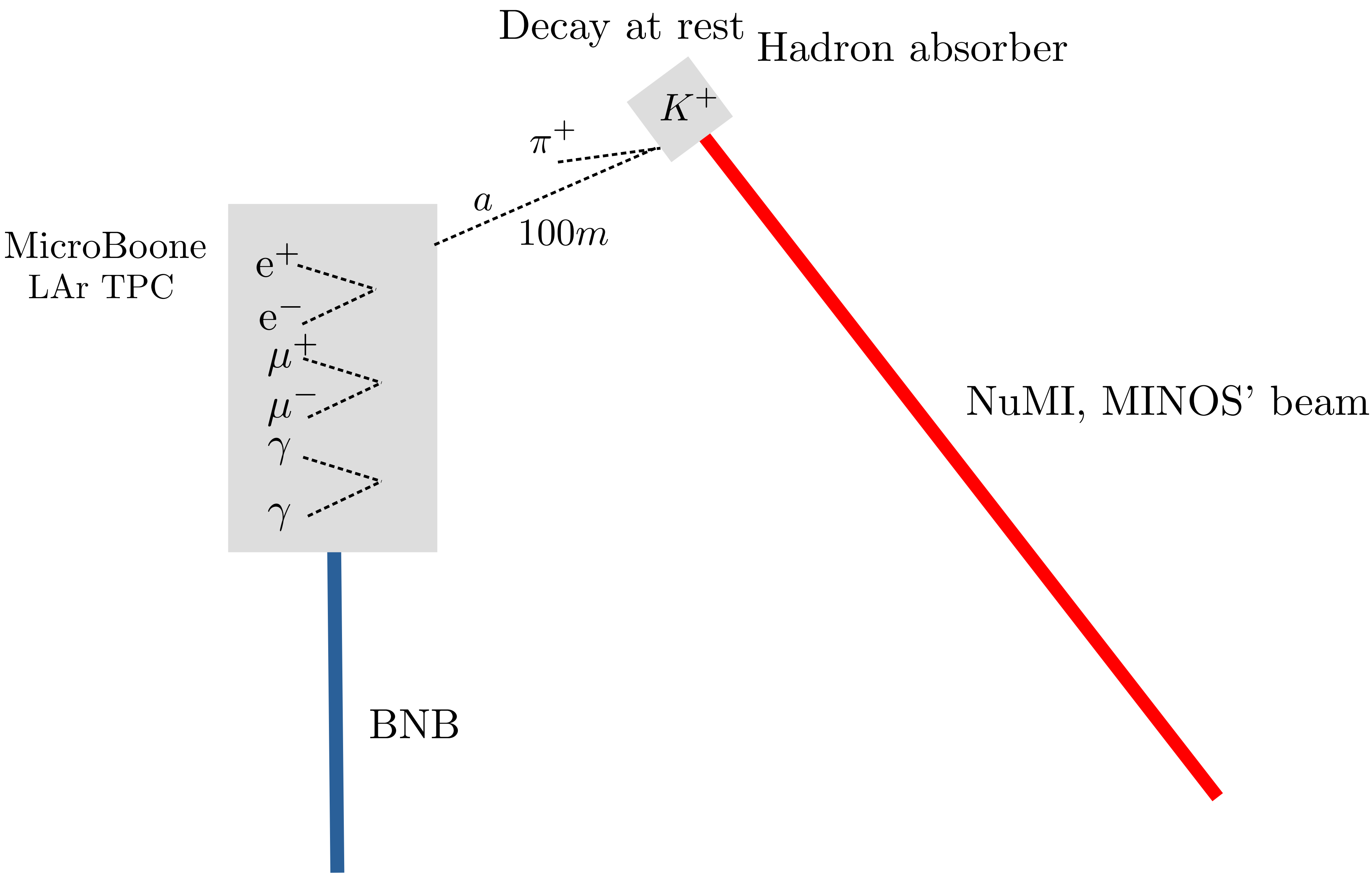
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\frac{1}{f_a}(\mathrm{TeV}^{-1})$
200
400
600
800
1000
1200
1400
1600
$\mathrm{m}_a(\mathrm{MeV})$
90% C.L
D mixing
SN1987a
D$\rightarrow \pi a\ (\gamma\gamma)$, CHARM
BESIII
NA62
E787-E949



m_{π_0}
m_η
$m_{\eta'}$
$\mathcal{O}_{u_R}$
$a \to \gamma\gamma$
$a \to 3\pi$
90% C.L
DUNE $1.1 \cdot 10^{22}$ PoT
$1/\mathrm{f}_a(\mathrm{TeV}^{-1})$
$\mathrm{m}_a(\mathrm{MeV})$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
200
400
600
800
1000
1200
1400
1600

Extra Results Part II
MicroBooNE

Experimental set-up MicroBooNE



MicroBooNE. Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector. Physical Review Letters, 127(15).

ALPs Production

$$\Gamma\left(K^{+} \rightarrow \pi^{+} a\right)=\frac{m_{K}^{3}\left|\left[k_{Q}\left(\mu_{w}\right)\right]_{s d}\right|^{2}}{64 \pi} \lambda_{\pi a}^{1 / 2}\left(1-\frac{m_{\pi}^{2}}{m_{K}^{2}}\right)^{2}$$

$$\lambda_{\pi a} \equiv \lambda\left(1, m_{a}^{2} / m_{K}^{2}, m_{\pi}^{2} / m_{K}^{2}\right)$$

$$\lambda(a, b, c)=a^{2}+b^{2}+c^{2}-2 a b-2 a c-2 b c$$

$$\left.\frac{\left[k_{Q}\left(\mu_{w}\right)\right]_{d s}}{V_{t d}^{*} V_{t s}}\right|_{\Lambda=1 \mathrm{TeV}} \simeq-9.7 \times 10^{-3} c_{W}(\Lambda)+8.2 \times 10^{-3} c_{\phi}(\Lambda)-3.5 \times 10^{-5} c_{B}(\Lambda)$$

Detection: ALPs decays

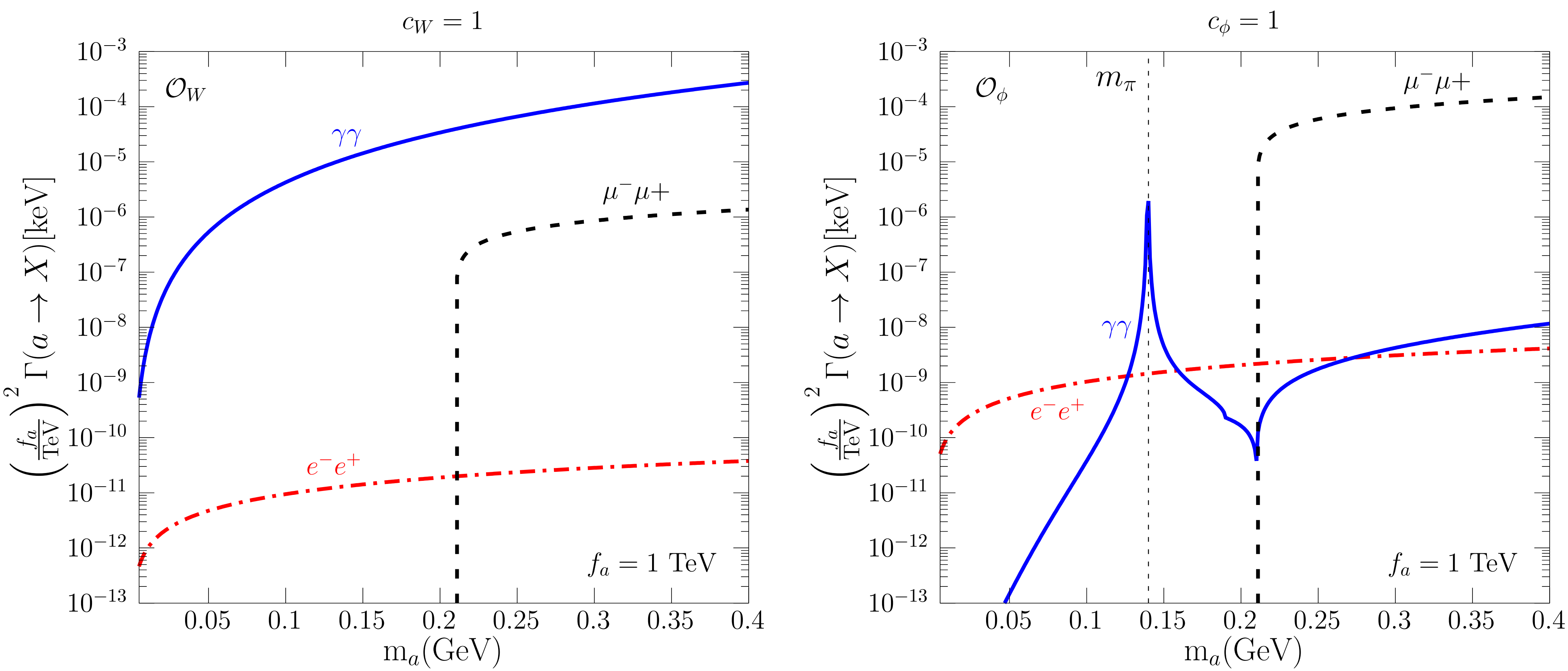
$$\Gamma\left(a \to \ell^+\ell^-\right) = |c_{\ell\ell}|^2 \, \frac{m_a m_\ell^2}{8\pi f_a^2}\sqrt{1 - \frac{4m_\ell^2}{m_a^2}}$$

$$c_{\ell\ell} = c_\phi + \frac{3\alpha}{4\pi}\left(\frac{3c_W}{s_w^2} + \frac{5c_B}{c_w^2}\right)\log\frac{f_a}{m_W} + \frac{6\alpha}{\pi}\left(c_B c_w^2 + c_W s_w^2\right)\log\frac{m_W}{m_\ell}$$

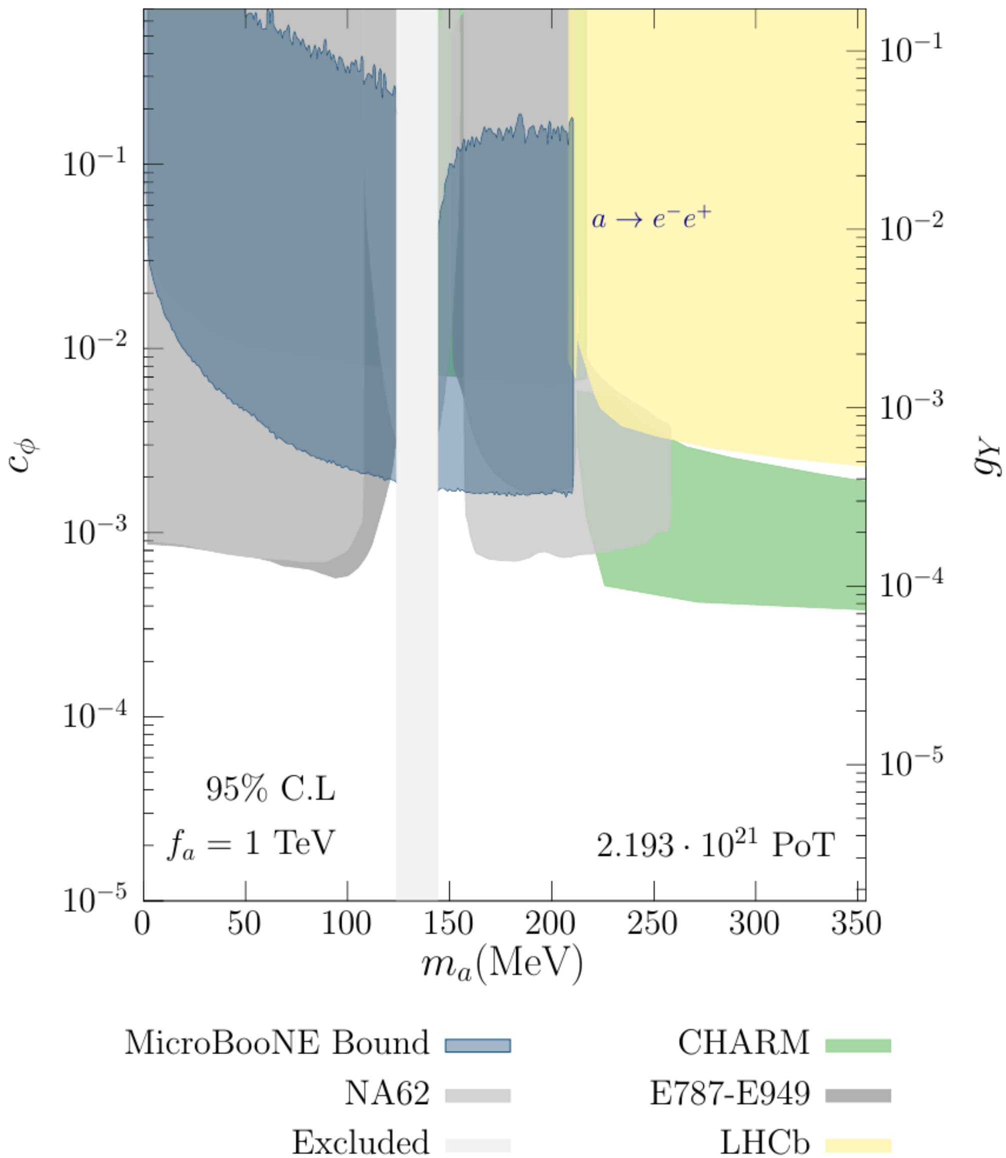
$$\Gamma(a \to \gamma\gamma) = |c_{\gamma\gamma}|^2 \, \frac{m_a^3}{4\pi f_a^2}$$

$$c_{\gamma\gamma} = c_W\left[s_w^2 + \frac{2\alpha}{\pi}B_2\left(\tau_W\right)\right] + c_B c_w^2 - c_\phi\frac{\alpha}{4\pi}\left(B_0 - \frac{m_a^2}{m_\pi^2 - m_a^2}\right)$$

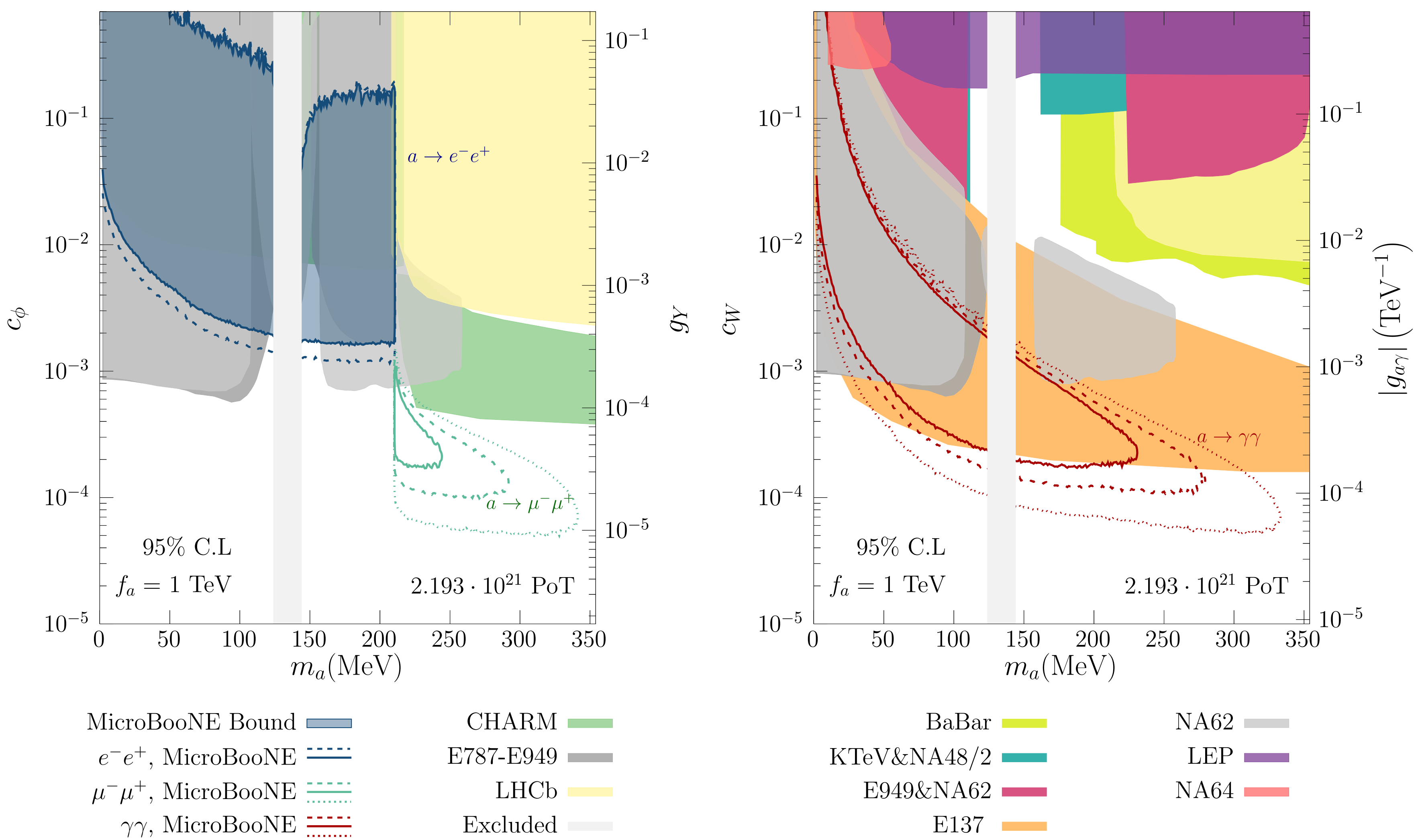
Electroweak ALPs: Detection



Bound using MicroBoone data

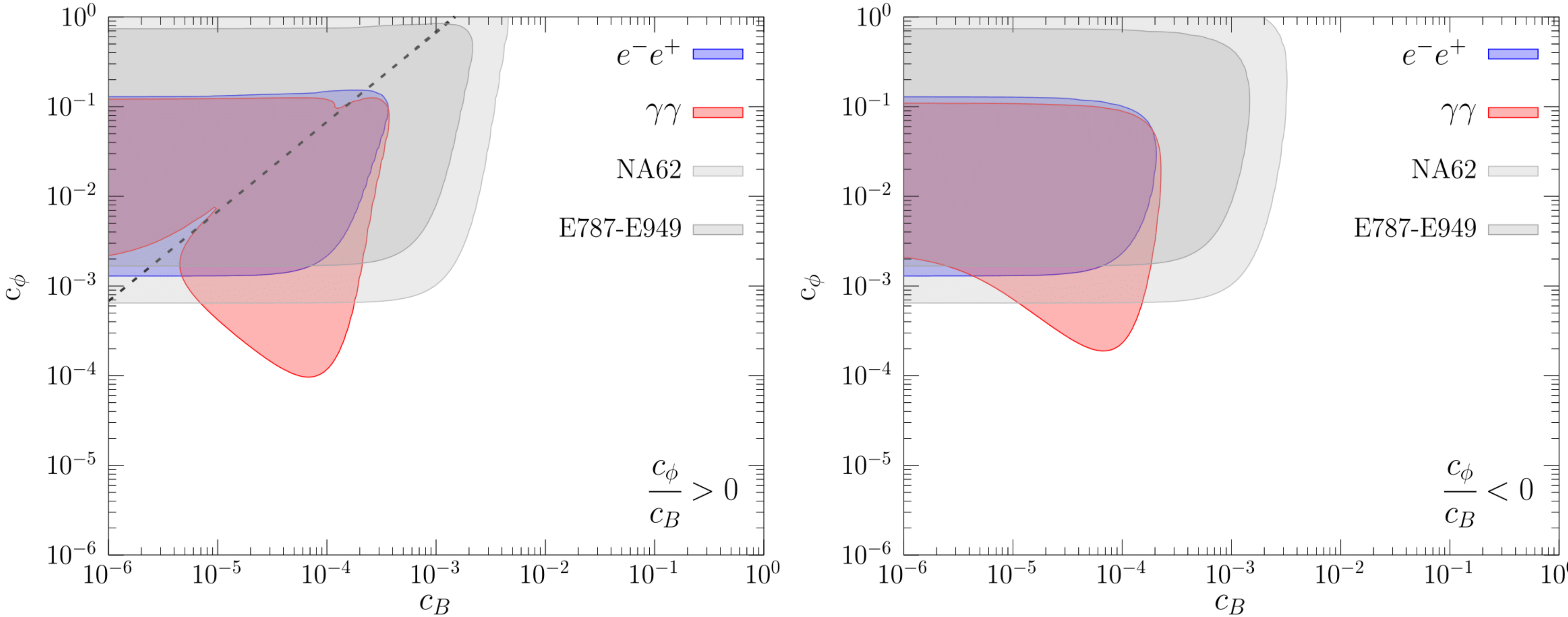


P. Coloma, P. Hernández, S. Urrea. arXiv:2202.03447



c_ϕ
g_Y
$a \to e^-e^+$
$a \to \mu^-\mu^+$
95% C.L
$f_a = 1$ TeV
$2.193 \cdot 10^{21}$ PoT
m_a(MeV)
c_W
$|g_{a\gamma}|$ (TeV^{-1})
$a \to \gamma\gamma$
95% C.L
$f_a = 1$ TeV
$2.193 \cdot 10^{21}$ PoT
m_a(MeV)
MicroBooNE Bound
e^-e^+, MicroBooNE
$\mu^-\mu^+$, MicroBooNE
$\gamma\gamma$, MicroBooNE
CHARM
E787-E949
LHCb
Excluded
BaBar
KTeV&NA48/2
E949&NA62
E137
NA62
LEP
NA64

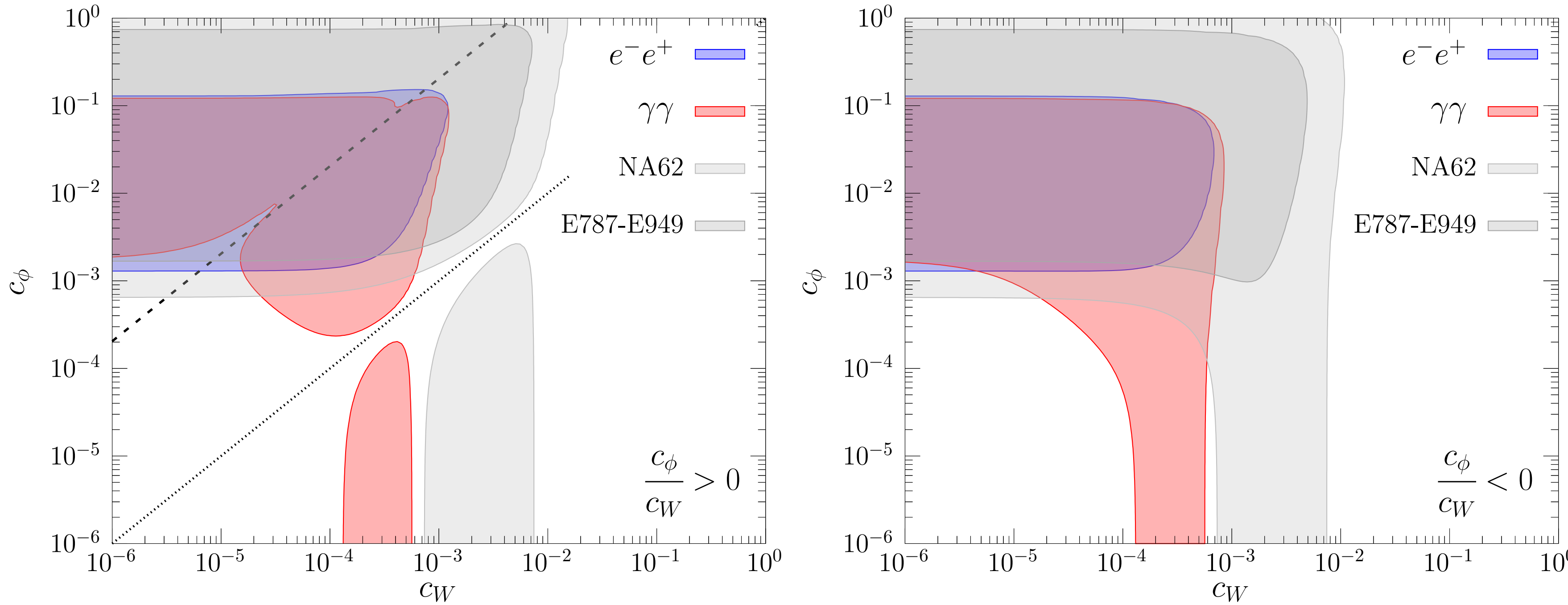
More results



Dashed line cancellation in detection

$$c_B \sim m_a^2/\left(m_a^2 - m_\pi^2\right) c_\phi \alpha/\left(4c_w^2\pi\right)$$

More results

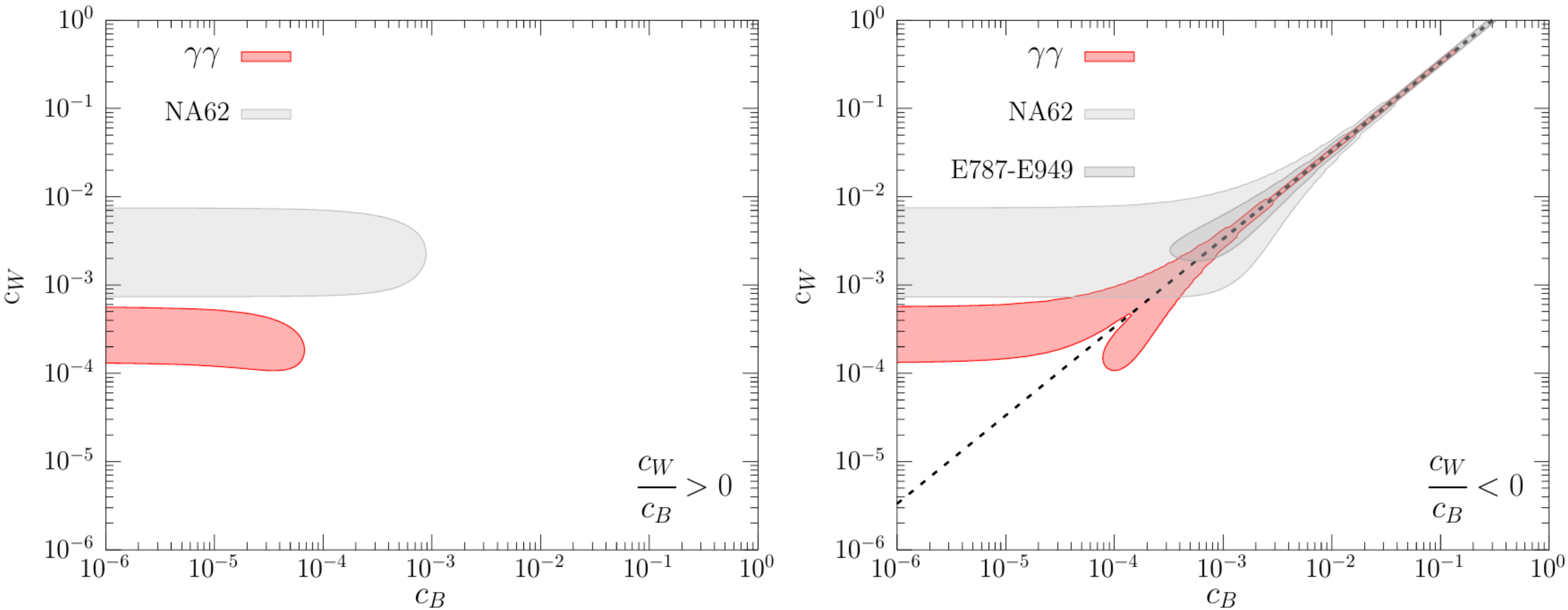


Dotted line cancellation in production

Dashed line cancellation in detection

$$c_W \sim m_a^2 / \left(m_a^2 - m_\pi^2\right) c_\phi \alpha / \left(4 s_w^2 \pi\right)$$

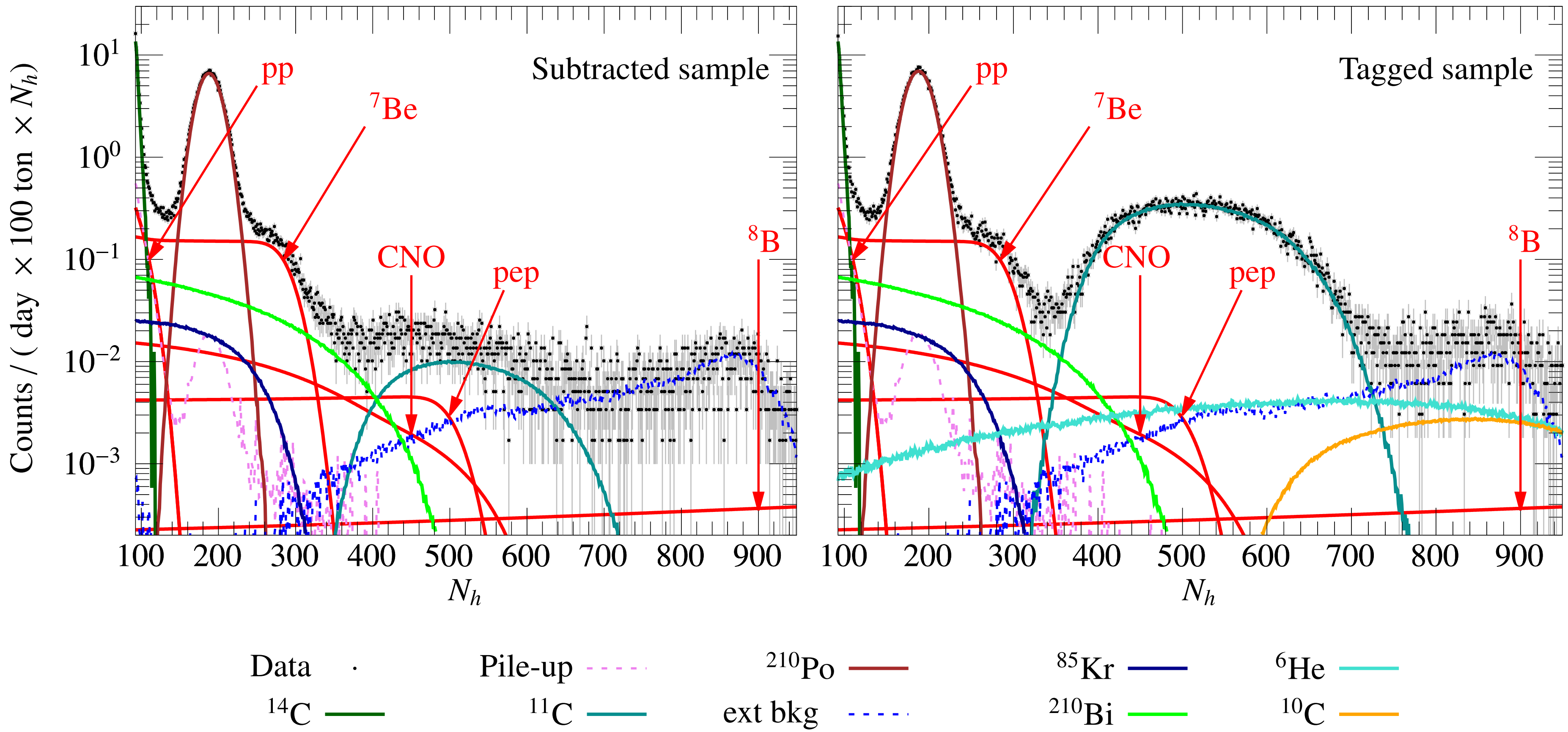
More results



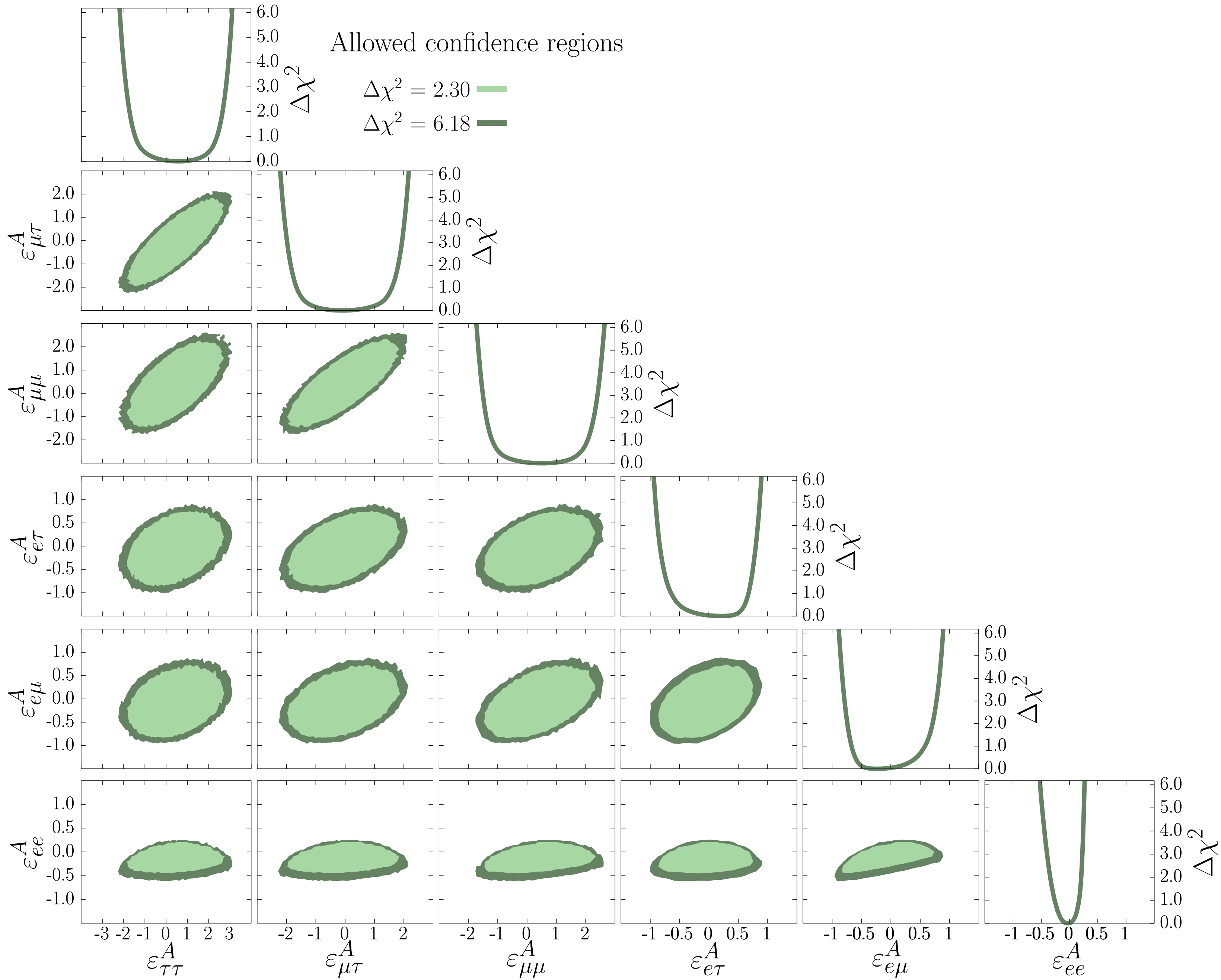
Possible sensitivity in the line where a cancellation of diphoton channel give you larger lifetimes

$$c_W s_w^2 \sim c_B c_w^2$$

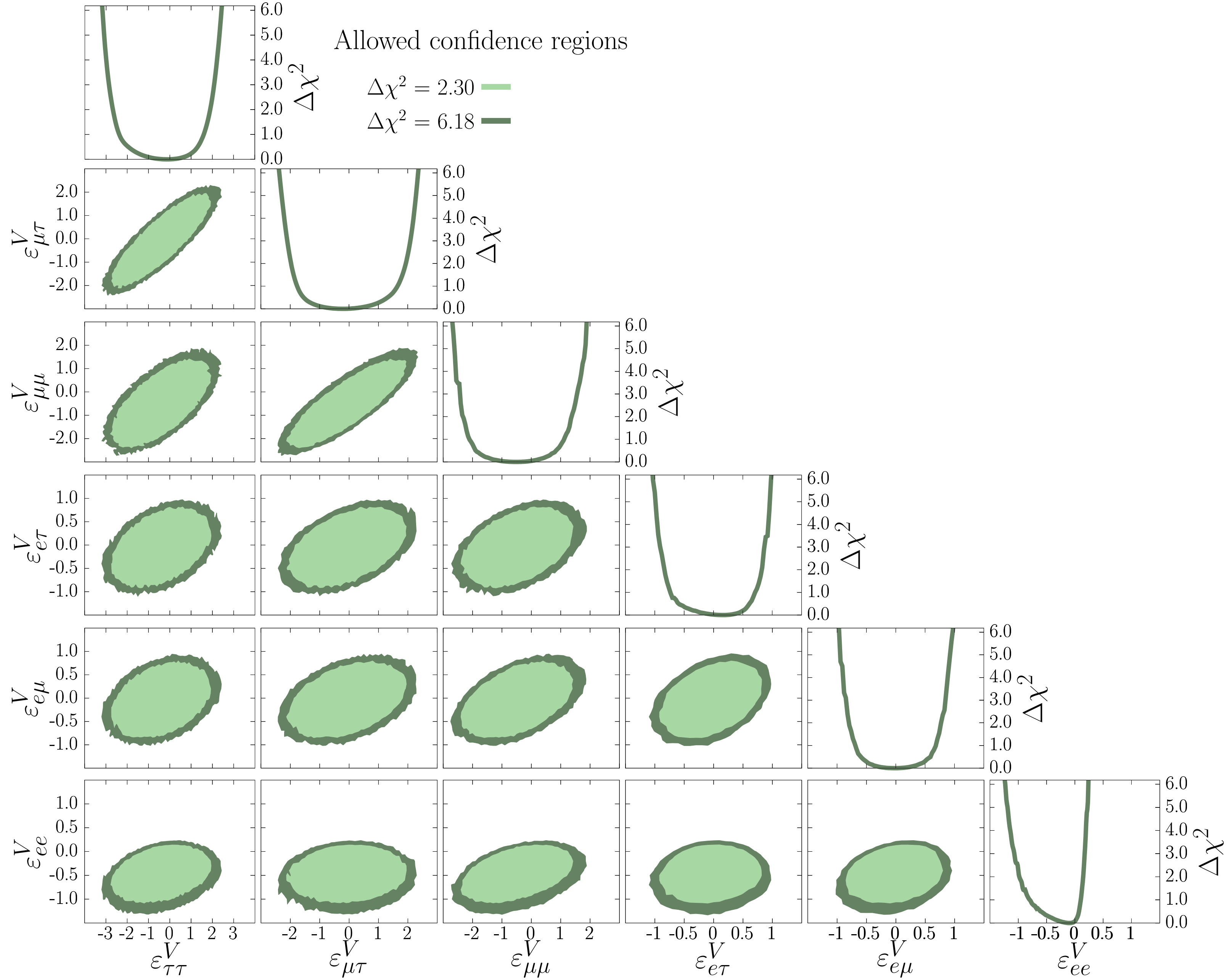
Extra Results Part I Borexino



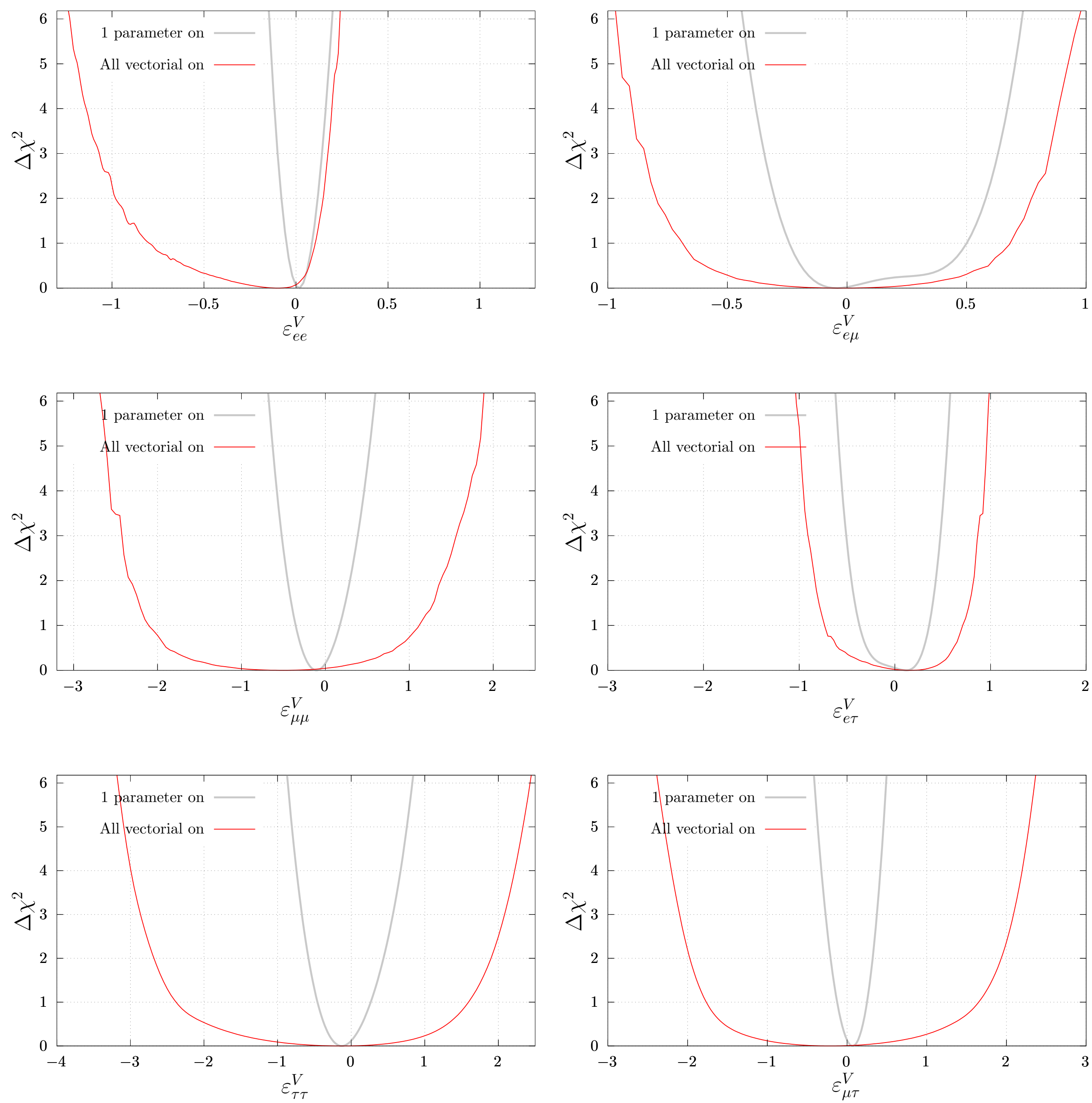
Subtracted sample
Tagged sample
pp
7Be
CNO
pep
8B
Counts / (day × 100 ton × N_h)
N_h
Data
Pile-up
210Po
85Kr
6He
14C
11C
ext bkg
210Bi
10C



Allowed confidence regions
$\Delta\chi^2 = 2.30$
$\Delta\chi^2 = 6.18$
$\Delta\chi^2$
$\varepsilon^A_{\tau\tau}$
$\varepsilon^A_{\mu\tau}$
$\varepsilon^A_{\mu\mu}$
$\varepsilon^A_{e\tau}$
$\varepsilon^A_{e\mu}$
ε^A_{ee}

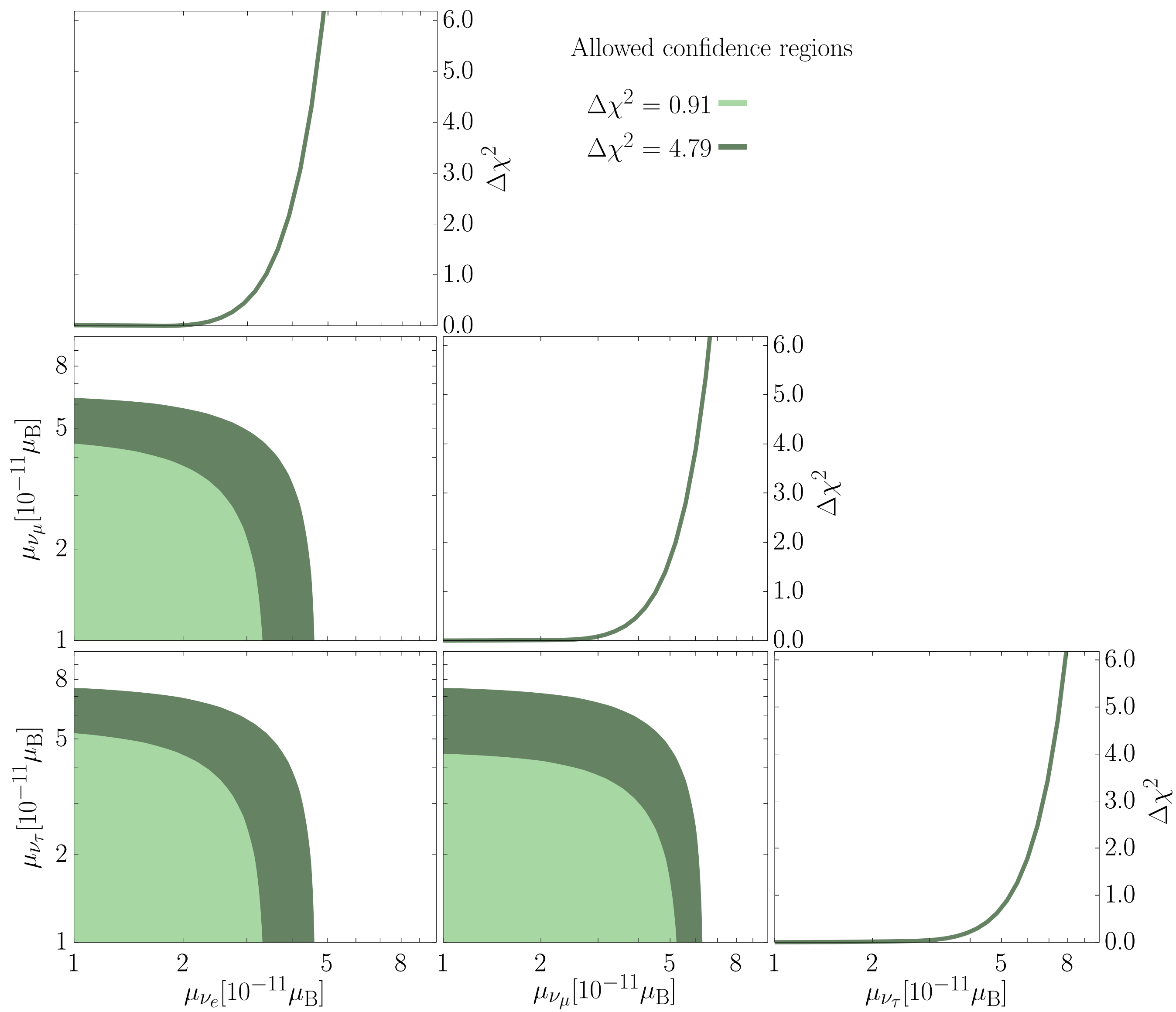


Allowed confidence regions
$\Delta\chi^2 = 2.30$
$\Delta\chi^2 = 6.18$
$\Delta\chi^2$
$\varepsilon^V_{\tau\tau}$
$\varepsilon^V_{\mu\tau}$
$\varepsilon^V_{\mu\mu}$
$\varepsilon^V_{e\tau}$
$\varepsilon^V_{e\mu}$
ε^V_{ee}



1 parameter on
All vectorial on
$\Delta\chi^2$
ε^V_{ee}
$\varepsilon^V_{e\mu}$
$\varepsilon^V_{\mu\mu}$
$\varepsilon^V_{e\tau}$
$\varepsilon^V_{\tau\tau}$
$\varepsilon^V_{\mu\tau}$

$$\frac{\mathrm{d}\sigma_\beta^{\mu_\nu}}{\mathrm{d}T_e} = \frac{\mathrm{d}\sigma_\beta^{\mathrm{SM}}}{\mathrm{d}T_e} + \left(\frac{\mu_{\nu_\beta}}{\mu_B}\right)^2 \frac{\alpha^2\pi}{m_e^2}\left[\frac{1}{T_e} - \frac{1}{E_\nu}\right]$$



One of the most paradigmatic models that give rise to NSI are light mediators.

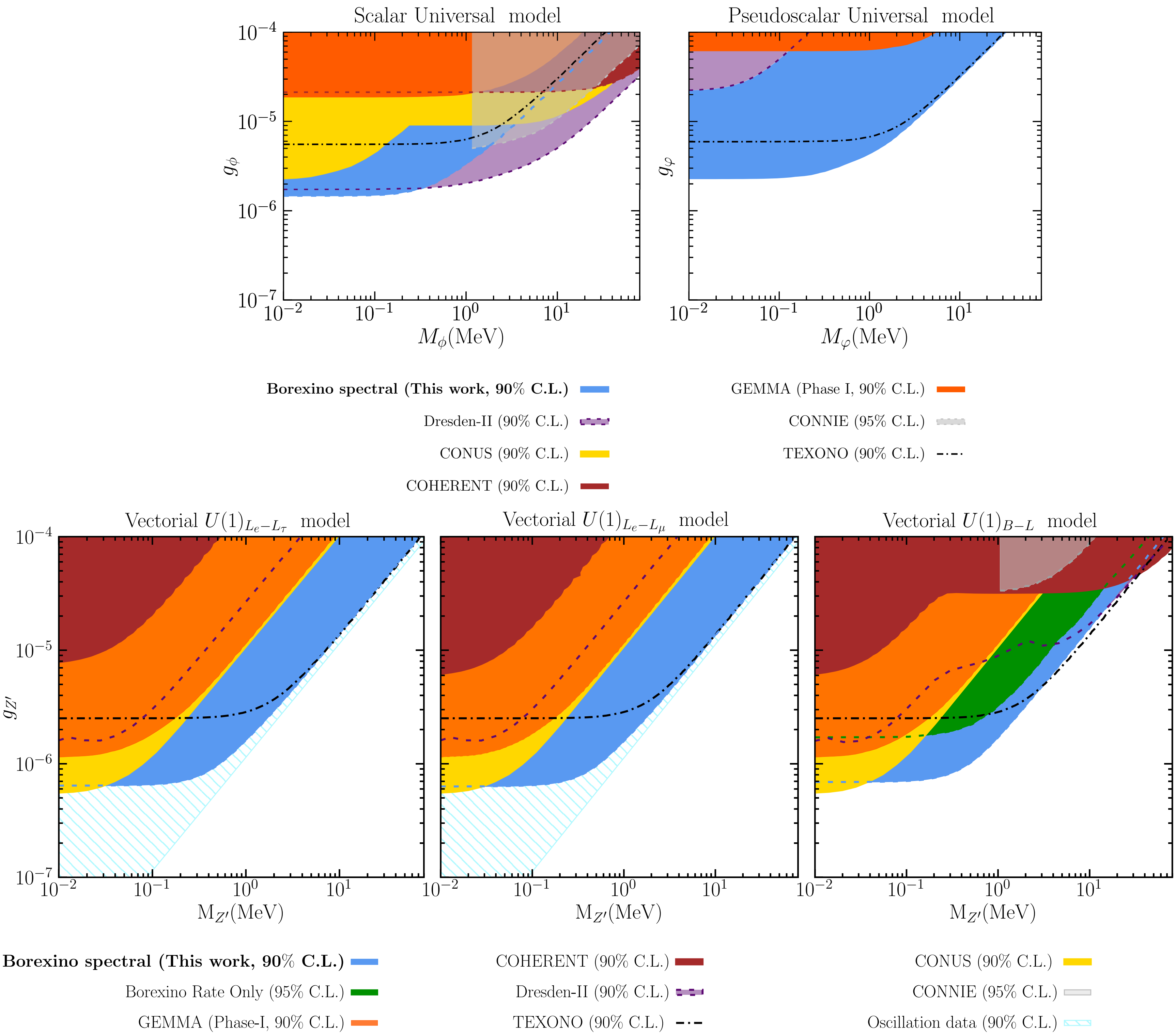
To put a concrete example, let us consider models with a vector mediator coupling to electrons and neutrinos.

$$\mathcal{L}_V = g_{Z'} Z'_\mu \left(q^e_{Z'} \bar{e}\gamma^\mu e + \sum_\alpha q^{\nu_\alpha}_{Z'} \bar{\nu}_{\alpha,L}\gamma^\mu \nu_{\alpha,L} \right) + \frac{1}{2} M^2_{Z'} Z'^\mu Z'_\mu,$$

Model	q^e	q^{ν_e}	q^{ν_μ}	q^{ν_τ}
Universal/leptonic scalar (or pseudoscalar)	1	1	1	1
$B-L$ vector	-1	-1	-1	-1
$L_e - L_\mu$ vector	1	1	-1	0
$L_e - L_\tau$ vector	1	1	0	-1

The oscillation data can be used to constraint very light mediators but for scattering the mass of the mediator must be larger than the momentum transfer (q) of the neutrinos interacting $M_{\rm med} \gtrsim q$

- Borexino scattering: $q \sim \mathcal{O}(500 \text{ keV}),$
- SNO and SuperK: $q \sim \mathcal{O}(5-10 \text{ MeV})$
- CEvNS: COHERENT $q \sim 30-50 \text{ MeV}$ Dresden II $q \sim 5 \text{ MeV}$


Scalar Universal model
Pseudoscalar Universal model
g_ϕ
g_φ
M_ϕ(MeV)
M_φ(MeV)
Borexino spectral (This work, 90% C.L.)
Dresden-II (90% C.L.)
CONUS (90% C.L.)
COHERENT (90% C.L.)
GEMMA (Phase I, 90% C.L.)
CONNIE (95% C.L.)
TEXONO (90% C.L.)
Vectorial $U(1)_{L_e-L_\tau}$ model
Vectorial $U(1)_{L_e-L_\mu}$ model
Vectorial $U(1)_{B-L}$ model
$g_{Z'}$
$\mathrm{M}_{Z'}$(MeV)
Borexino spectral (This work, 90% C.L.)
Borexino Rate Only (95% C.L.)
GEMMA (Phase-I, 90% C.L.)
COHERENT (90% C.L.)
Dresden-II (90% C.L.)
TEXONO (90% C.L.)
CONUS (90% C.L.)
CONNIE (95% C.L.)
Oscillation data (90% C.L.)