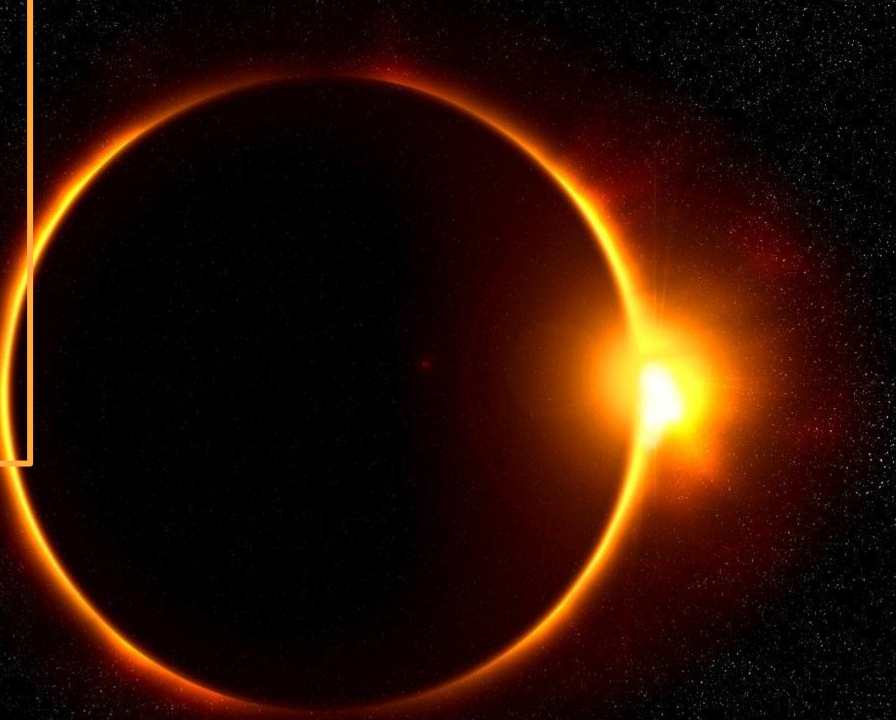
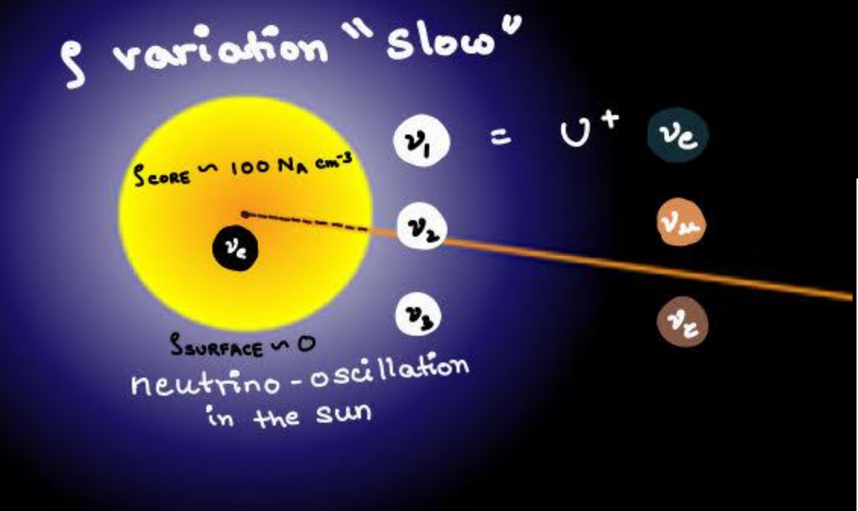
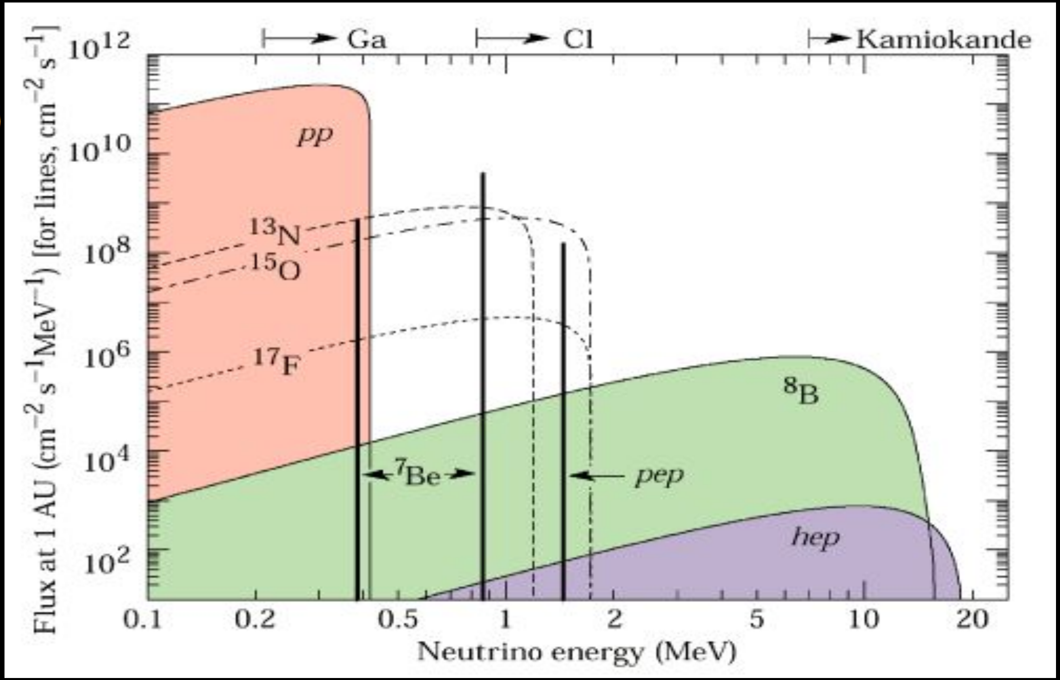
Looking at flavor composition of solar neutrinos.



Nityasa Mishra.

nityasa_mishra@tamu.edu
Texas A&M University



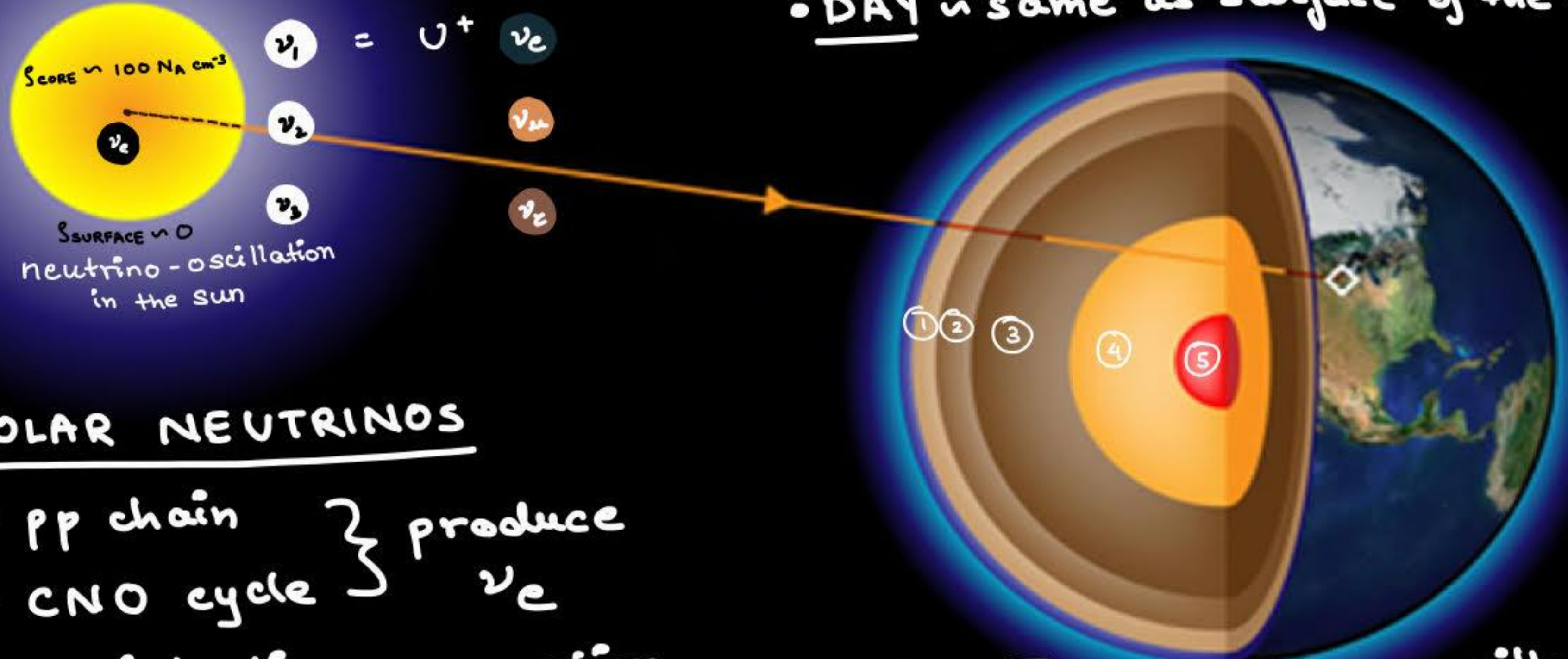


SOLAR NEUTRINOS

- pp chain
- CNO cycle } produce ν_e
- Adiabatic propagation
- $\nu_e \rightarrow \nu_1, \nu_2, \nu_3$

NEUTRINO PROPAGATION TROUGH EARTH

ρ variation "slow"

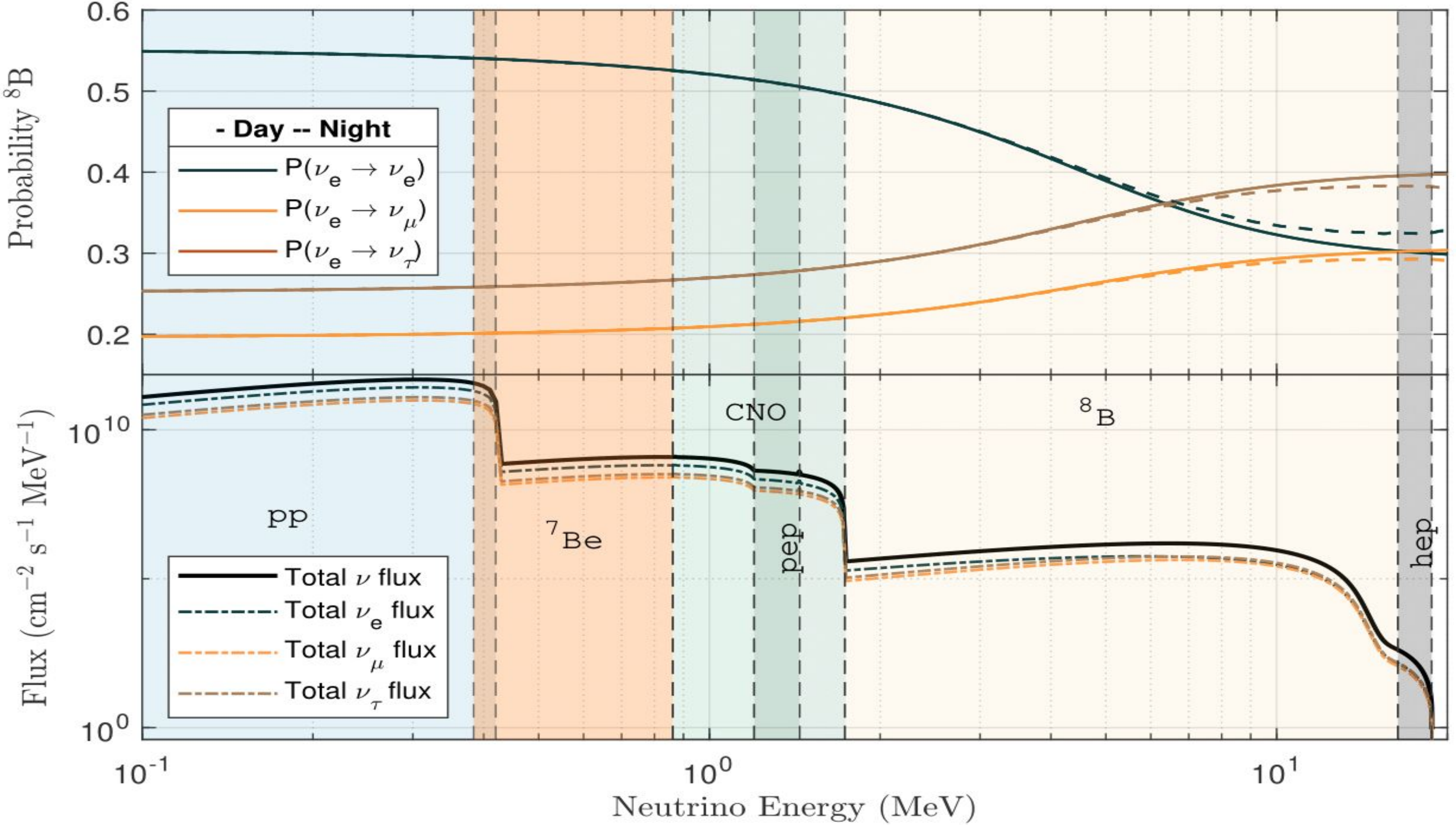


- **DAY** ~ same as surface of the sun

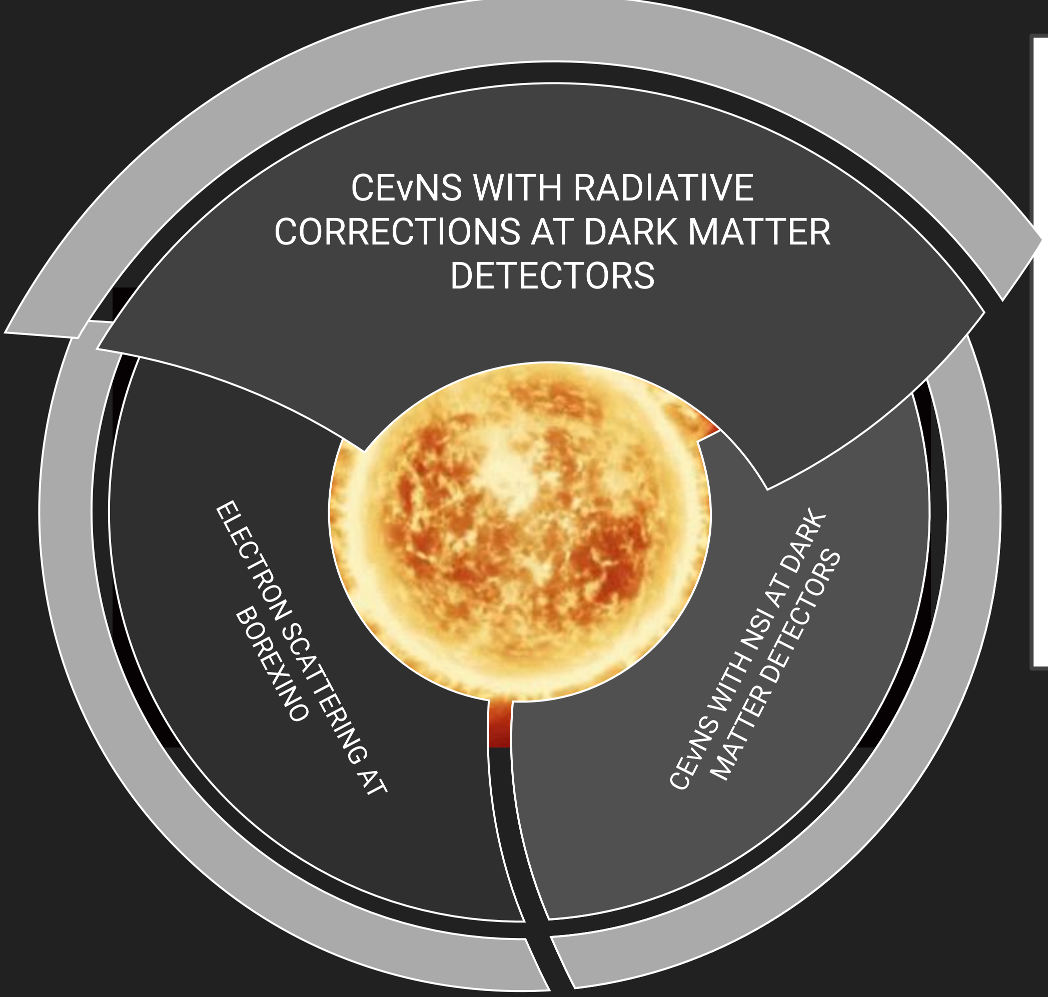
SOLAR NEUTRINOS

- pp chain } produce ν_e
- CNO cycle } produce ν_e
- Adiabatic propagation
- $\nu_e \rightarrow \nu_1, \nu_2, \nu_3$

- **NIGHT** ~ neutrinos oscillate through layers of Earth
  - Probability changes with Zenith angle

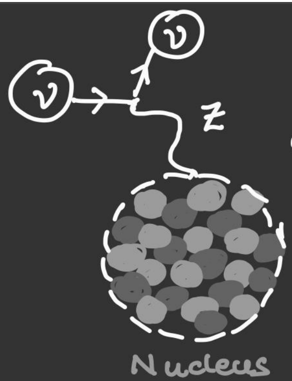


Probability ^{8}B
- Day -- Night
$P(\nu_e \to \nu_e)$
$P(\nu_e \to \nu_\mu)$
$P(\nu_e \to \nu_\tau)$
Flux ($cm^{-2}\,s^{-1}\,MeV^{-1}$)
CNO
^{8}B
pp
^{7}Be
pep
hep
Total ν flux
Total ν_e flux
Total ν_μ flux
Total ν_τ flux
Neutrino Energy (MeV)



SOLAR NEUTRINOS WITH CEνNS AND FLAVOR-DEPENDENT RADIATIVE CORRECTIONS

arxiv: **2305.17827**
10.1103/PhysRevD.108.063023
Nityasa Mishra, Louis E. Strigari

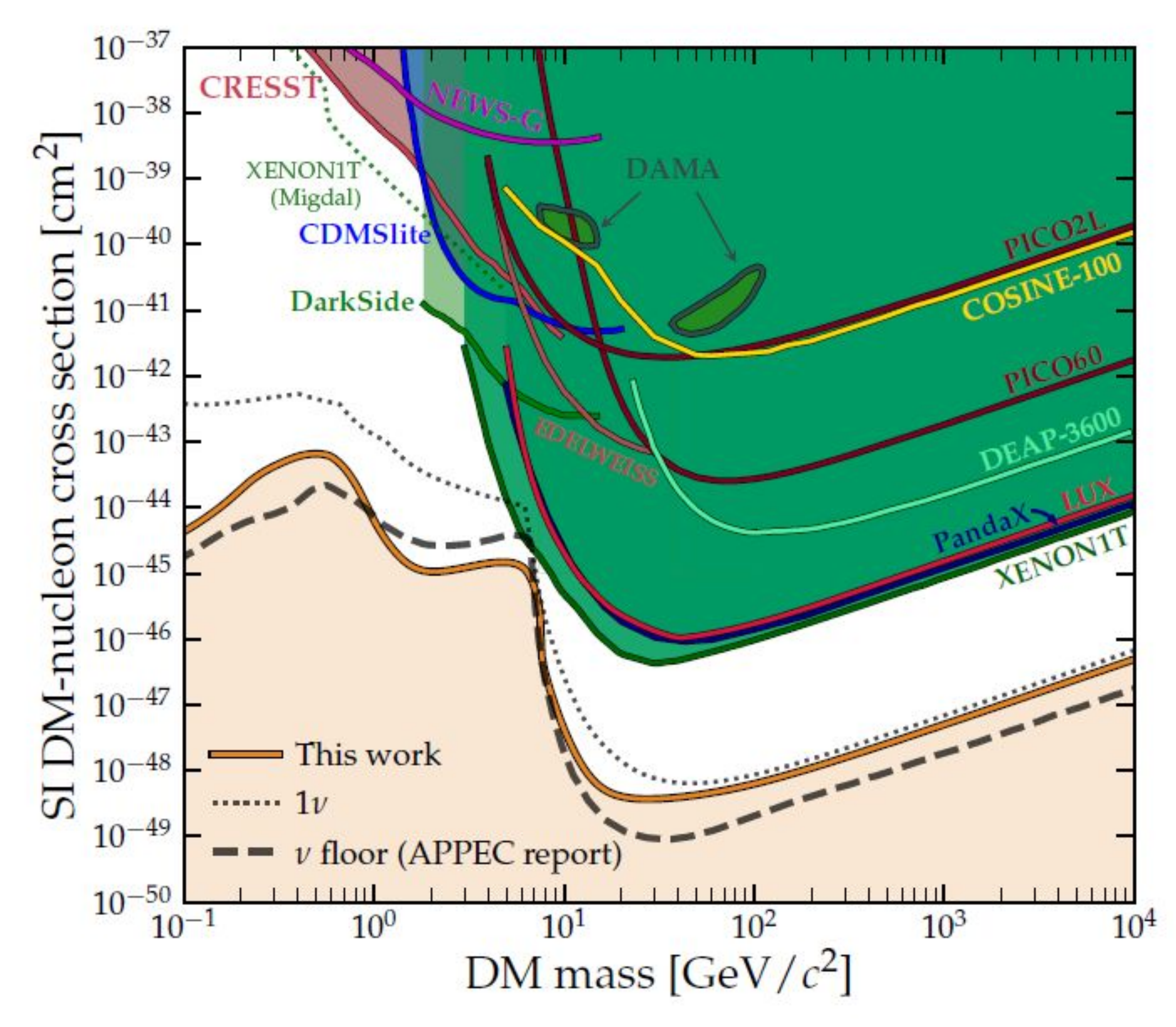


$qR \lesssim 1$

$\sigma \sim N^2$

Coherent
Elastic
Neutrino (**ν**)
Nucleus
Scattering

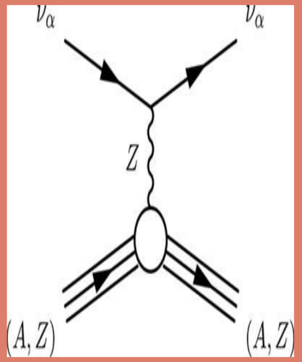
NEUTRINO FLOOR



Plot credit:
arXiv: 2109.03116v2
Ciaran A. J. O'Hare

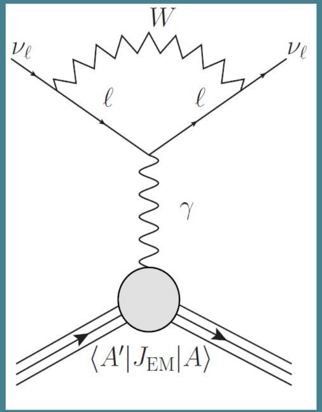
- arXiv:1712.06522
  David G. Cerdeno, Jonathan H. Davis, Malcolm Fairbairn, Aaron C. Vincent
- arXiv:1910.12437
  D. Aristizabal Sierra, Bhaskar Dutta, Shu Liao, Louis E. Strigari

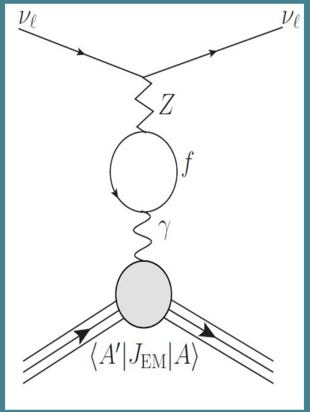
TREE-LEVEL



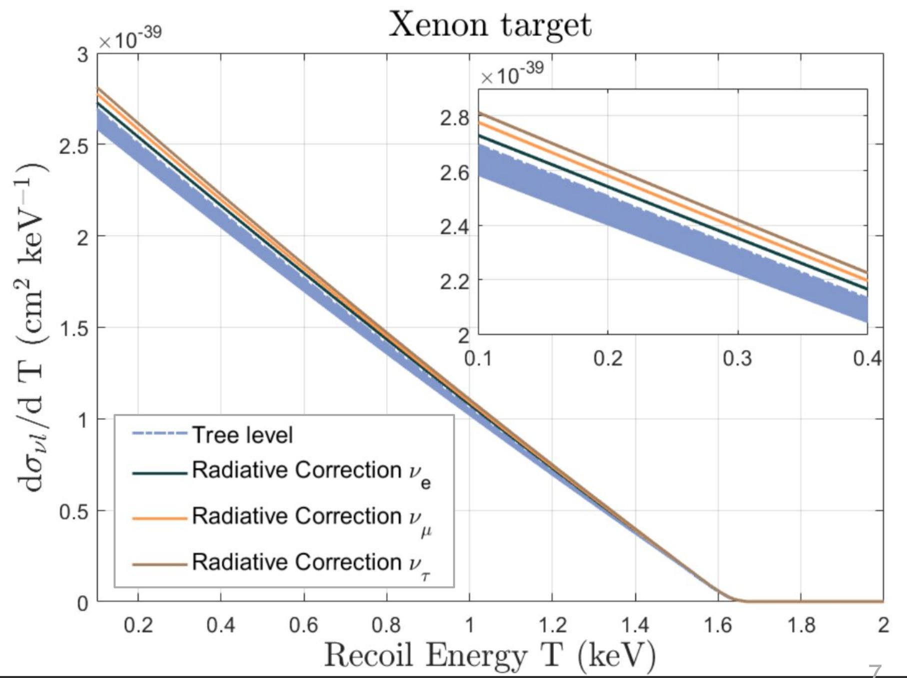
WITH RADIATIVE CORRECTION

arXiv:2011.05960 : Tomalak et al

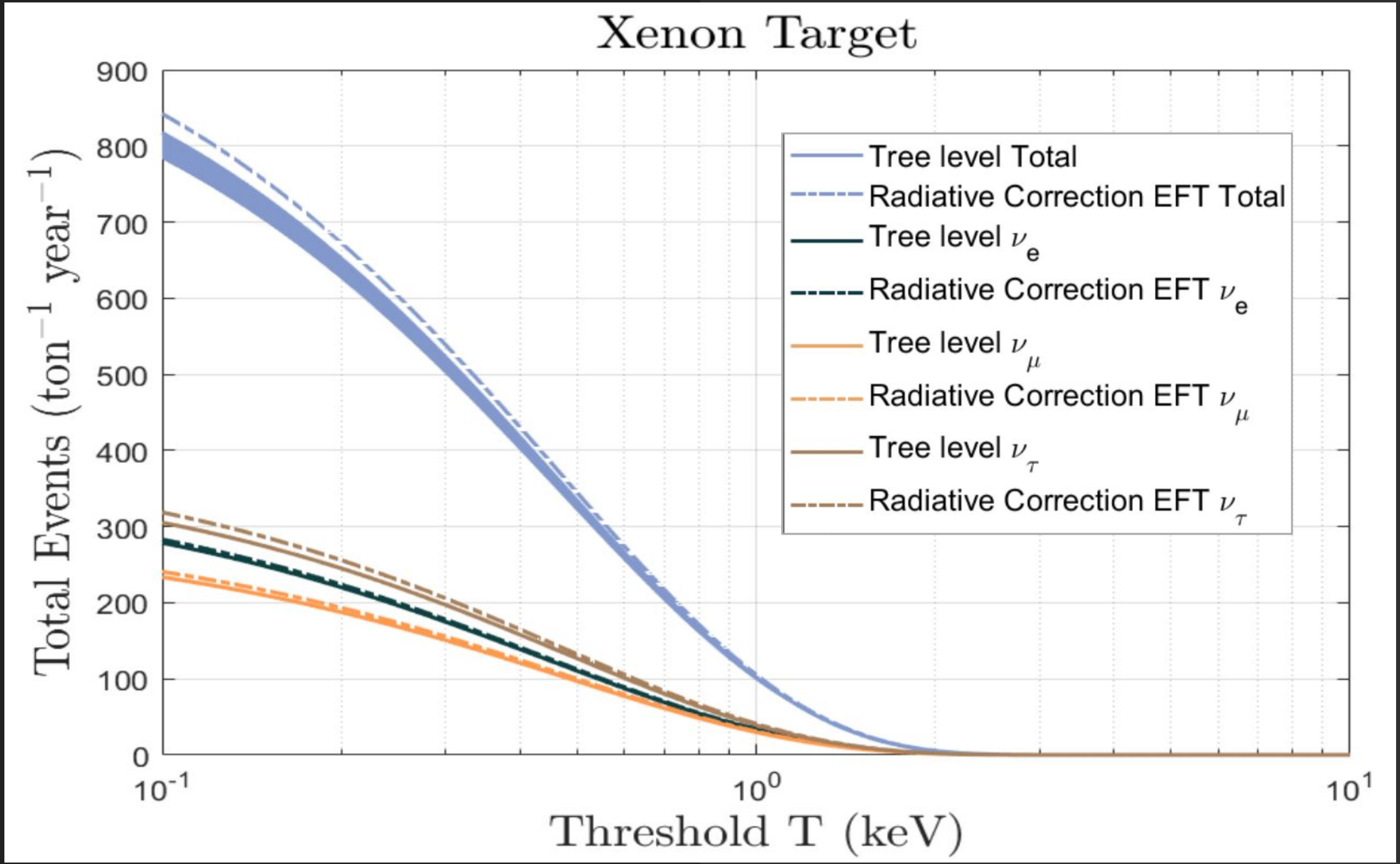




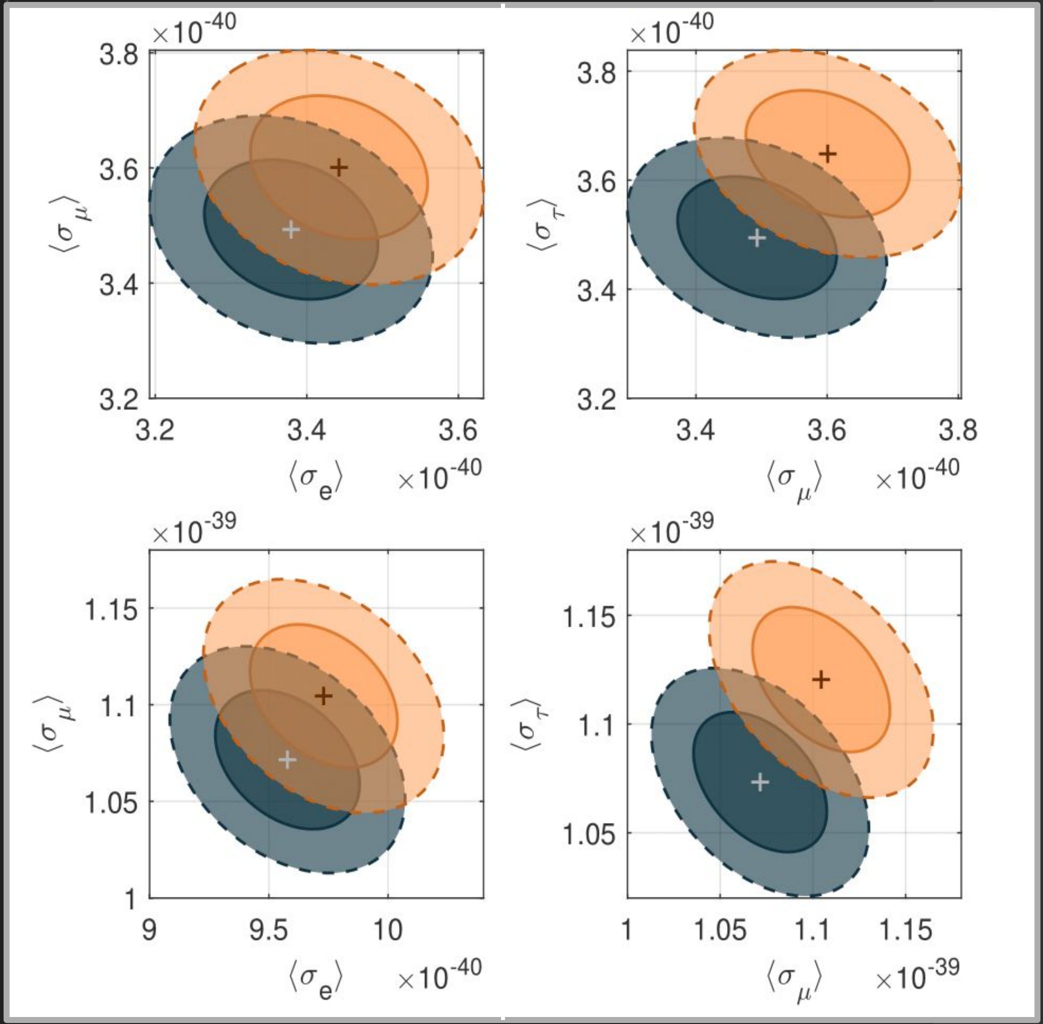
$$\sigma_{\text{radiative corrections}}(\nu_\tau > \nu_\mu > \nu_e) > \sigma_{\text{tree-level}}(\nu_\tau = \nu_\mu = \nu_e)$$



TOTAL EVENTS VS THRESHOLD



XENON TARGET
ERROR ELLIPSES



$$\mu_i = \sum_\alpha f_\alpha \mu_{i\alpha} = f_e \mu_{ie} + f_\mu \mu_{i\mu} + f_\tau \mu_{i\tau}$$

$$= f_e N_{ie} + f_\mu N_{i\mu} + f_\tau N_{i\tau}$$

$$f_\alpha = \frac{(\phi_\alpha)}{(\phi_\alpha)_{SSM}}.$$

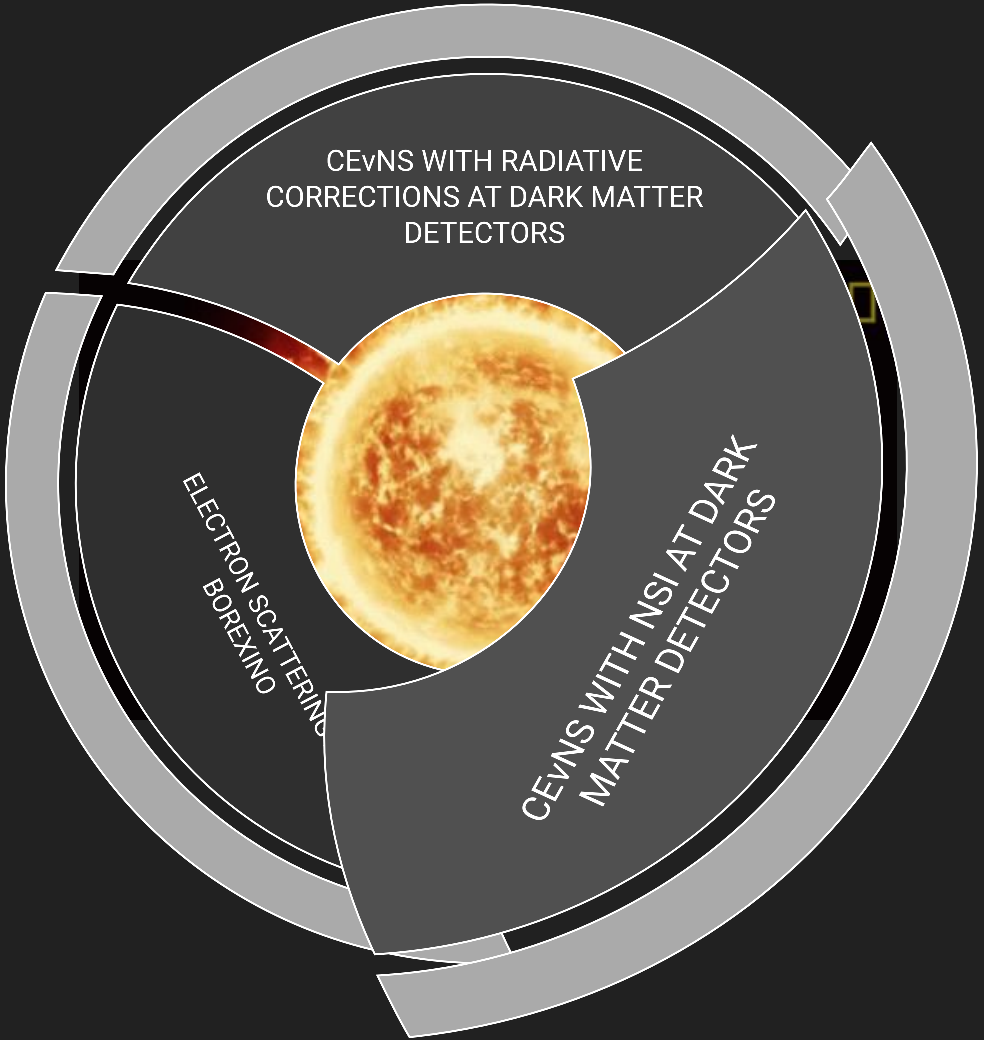
$$\phi_\alpha \sim (\phi P_{e\alpha})$$

$\sin^2 \theta_w = 0.2385$

flux prior:2.5%
Exp:100 ton-yr

top: Threshold = 1 keV
bottom: Threshold = 0.1 keV

- 1 sigma - - 2 sigma
Tree Level Radiative Corrections



IMPLICATIONS OF FIRST NEUTRINO-INDUCED NUCLEAR RECOIL MEASUREMENTS IN DIRECT DETECTION EXPERIMENTS

arxiv: **2409.02003**

D. Aristizabal Sierra, N. Mishra, L. Strigari

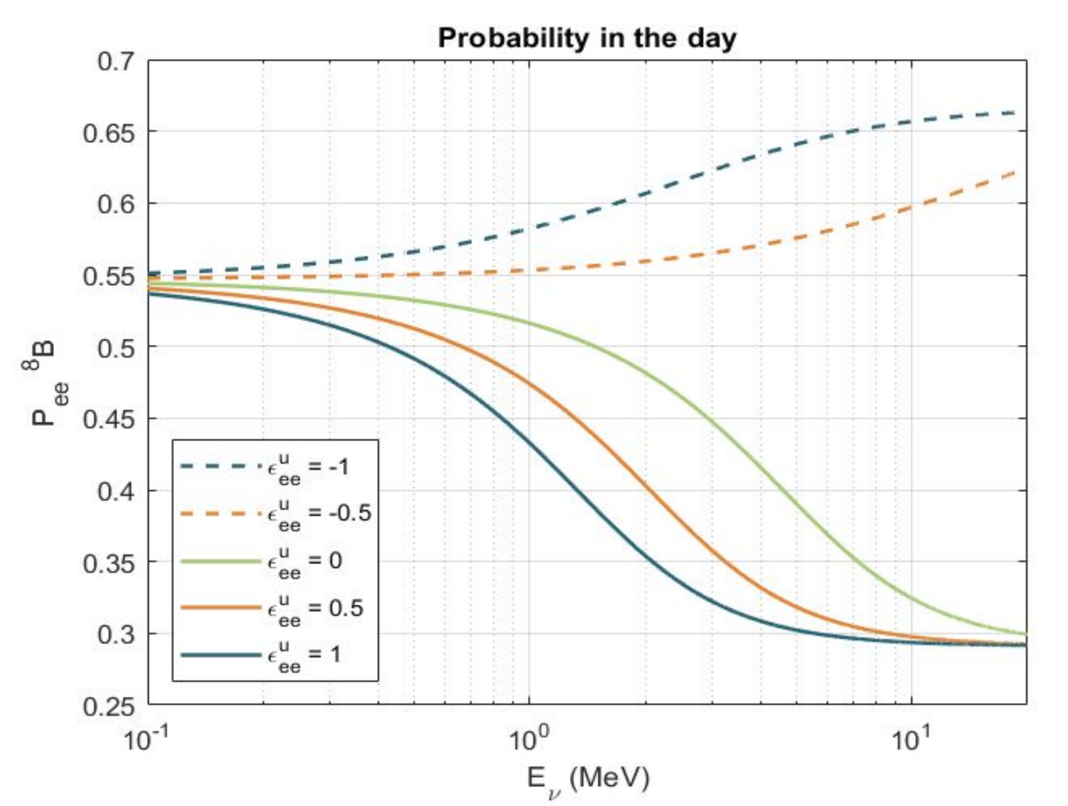
PandaX-4T	• Paired data • US2	2.64 σ
XENON-nT	• Paired only	2.73 σ

$$\mathcal{L}_{NSI} = -\sqrt{2}\, G_F \sum_{\substack{\alpha,\beta = e,\mu,\tau \\ q = u,d}} \varepsilon^{q,V}_{\alpha\beta} \left[\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta\right]\left[\bar{q} \gamma^\mu q\right]$$

$$\varepsilon^f = \begin{pmatrix} \varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau} \\ \varepsilon^f_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau} \\ \varepsilon^f_{e\tau} & \varepsilon^f_{\mu\tau} & \varepsilon^f_{\tau\tau} \end{pmatrix}$$

$$C^n_V \equiv g^n_V \delta_{\alpha\beta} + \varepsilon^{u,V}_{\alpha\beta} + 2\,\varepsilon^{d,V}_{\alpha\beta}$$

$$C^p_V \equiv g^p_V \delta_{\alpha\beta} + 2\,\varepsilon^{u,V}_{\alpha\beta} + \varepsilon^{d,V}_{\alpha\beta}$$



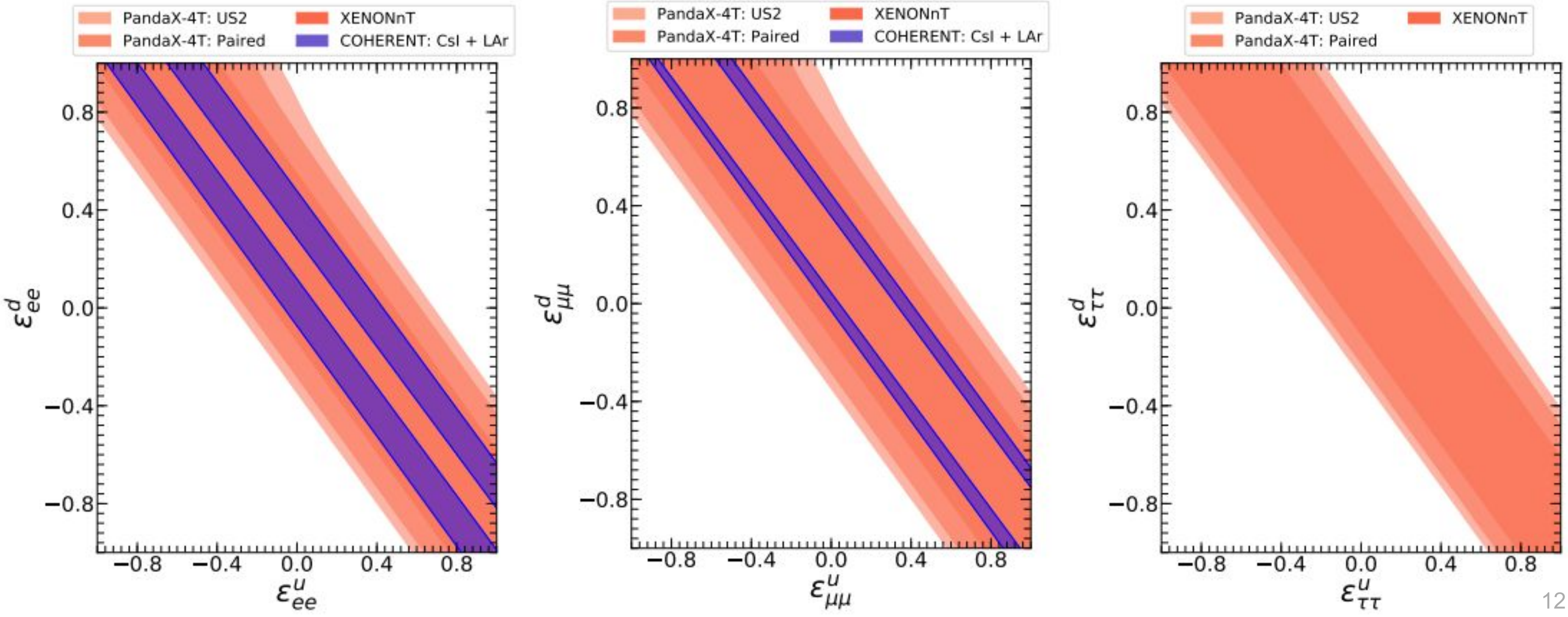
PROBING NON-STANDARD INTERACTION PARAMETERS AT DARK MATTER DETECTORS

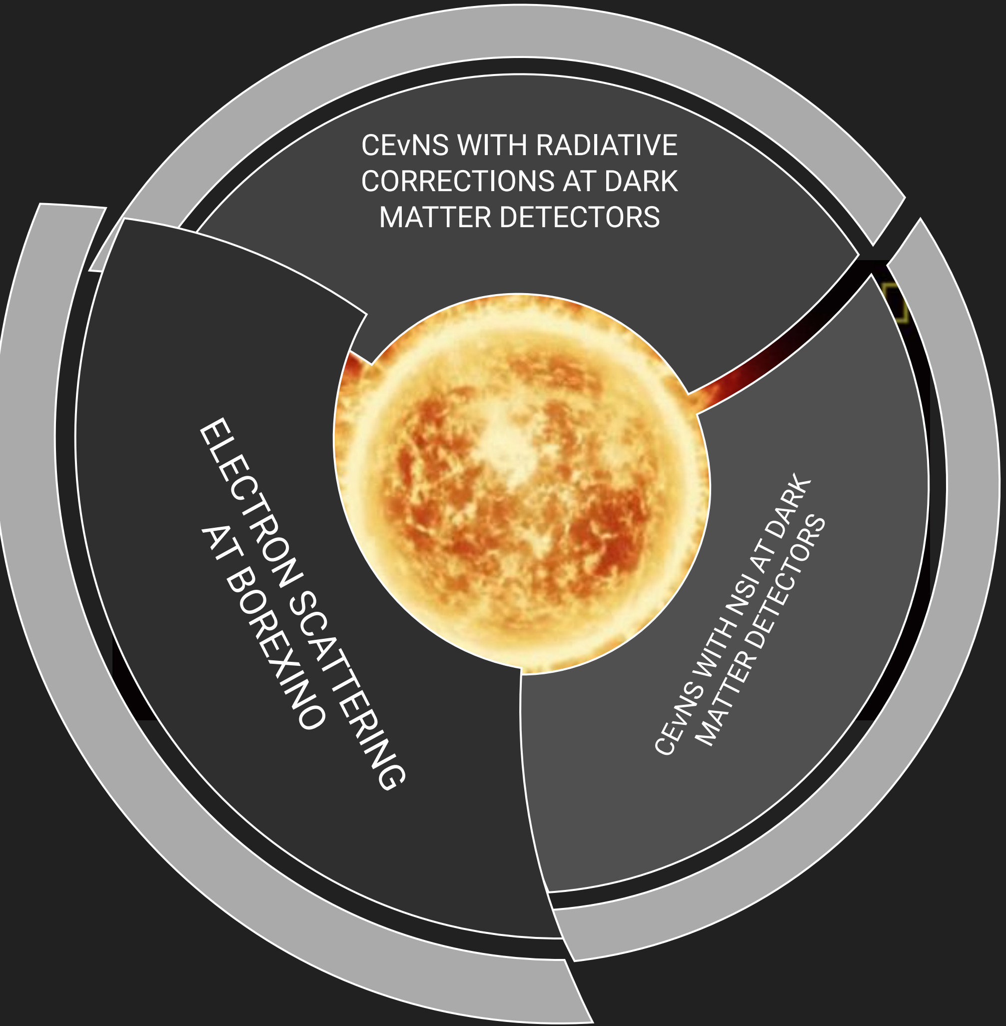
πDAR source - flux of ν_μ & ν_e

$\varepsilon_{\alpha,\beta}$; α,β = {μ,e}

Solar neutrino - flux of ν_e ,ν_μ & ν_τ

$\varepsilon_{\alpha,\beta}$; α,β = {e,μ,τ}





ν_μ AND ν_τ ELASTIC SCATTERING IN BOREXINO

arxiv: **2407.03174**

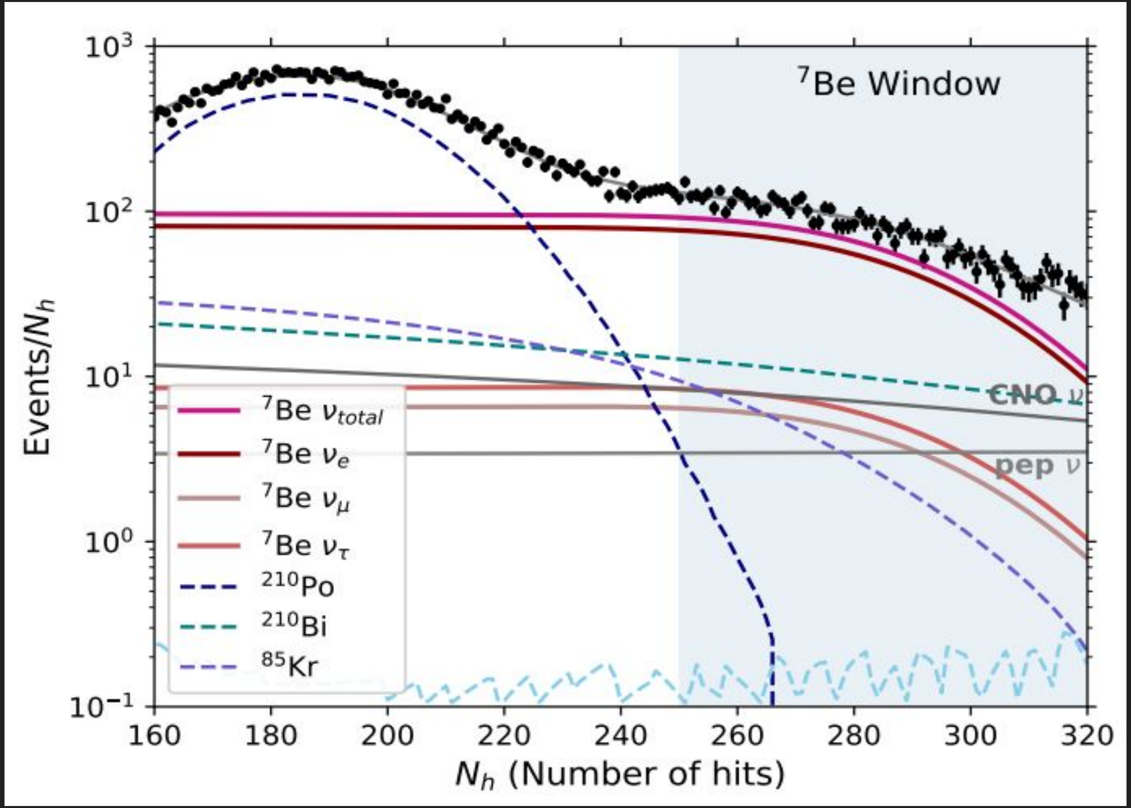
Kevin J Kelly, Nityasa Mishra, Mudit Rai, Louis E. Strigari

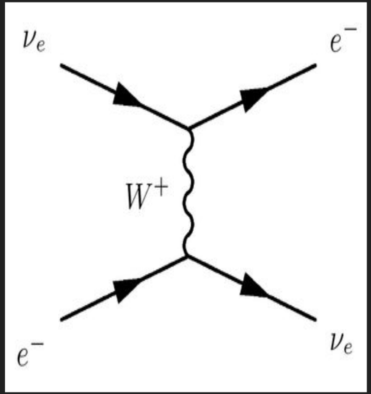
BOREXINO : 278-ton ultra-pure organic liquid scintillator

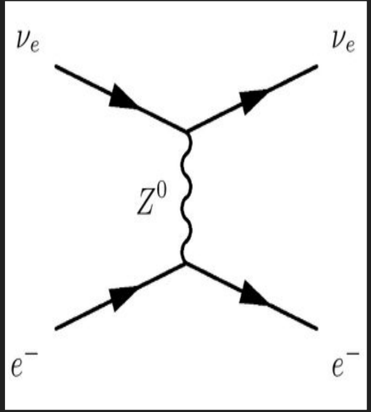
DETECTION : Elastic Electron scattering

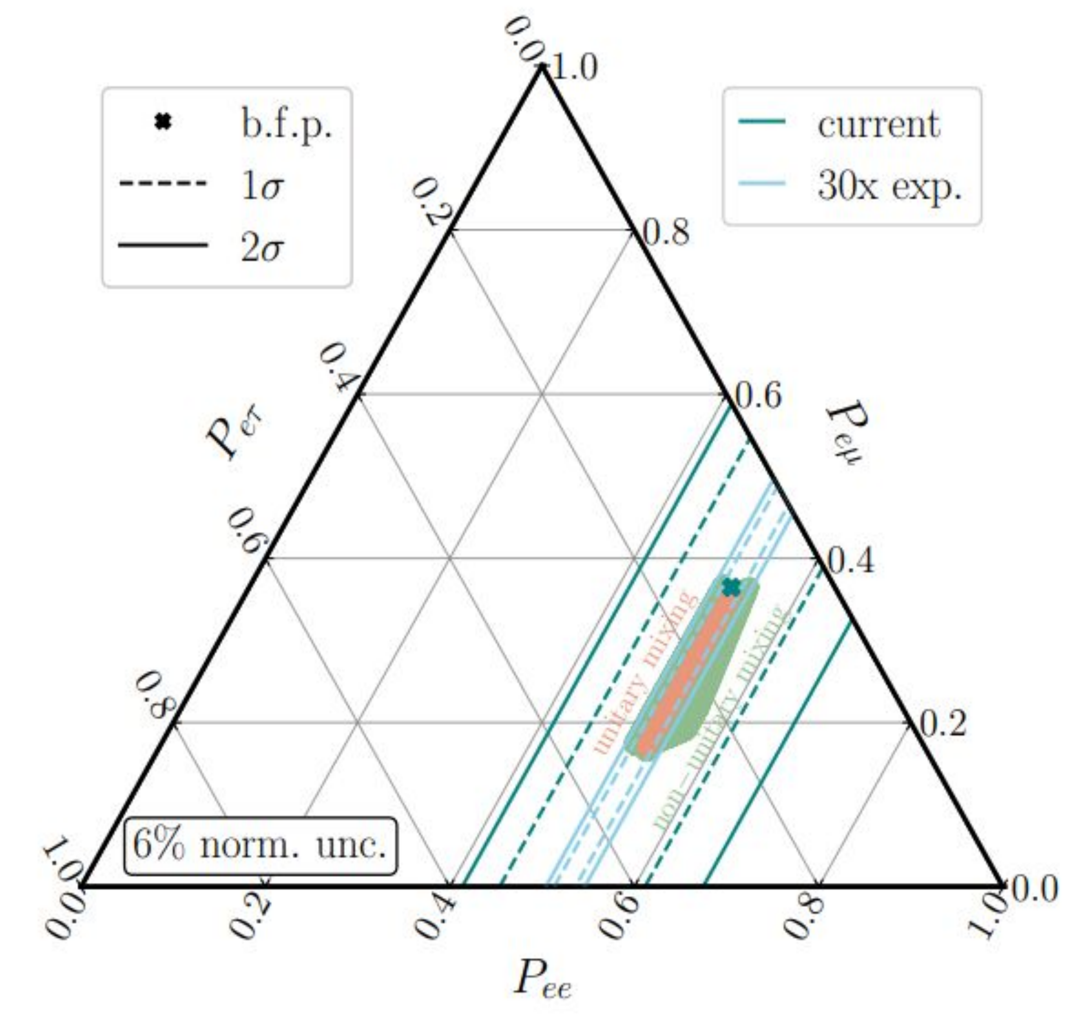
DATA : Phase III data set

^{7}Be SIGNAL AT BOREXINO AND ITS FLAVOR COMPOSITION









3-flv Analysis

$$S_i \equiv n \sum_{\alpha=e,\mu\tau} S_{\alpha i}, \quad S_{\alpha i} \equiv \frac{f_\alpha}{P_{e\alpha}^{\mathrm{BF}}} N_{\alpha i}^{\mathrm{BF}},$$

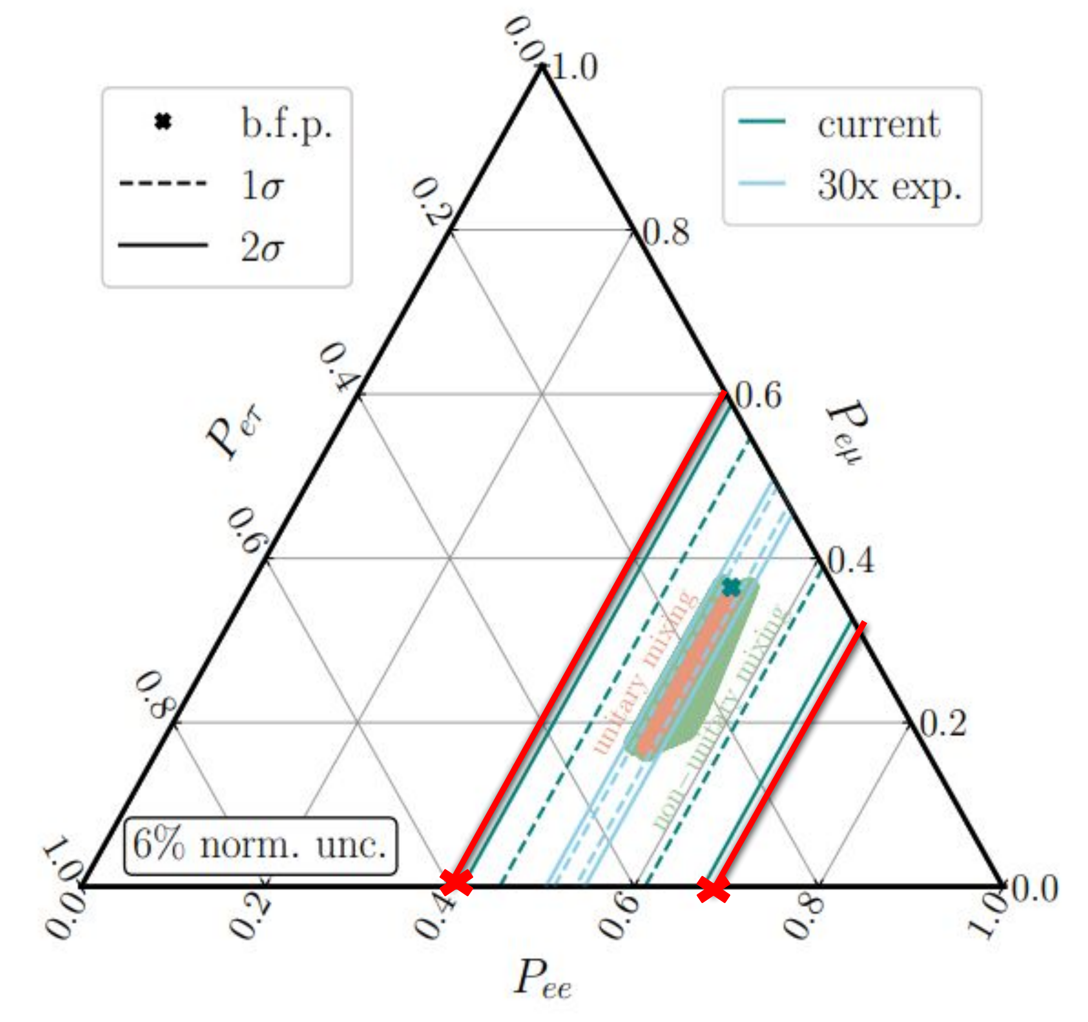
Constraint : $f_e + f_\mu + f_\tau = 1$

Non-Unitary Mixing

$$N = \alpha U = \begin{bmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{bmatrix} U^{3\times3}$$

Unitary Mixing

Vary θ_{23} & δ_{CP}



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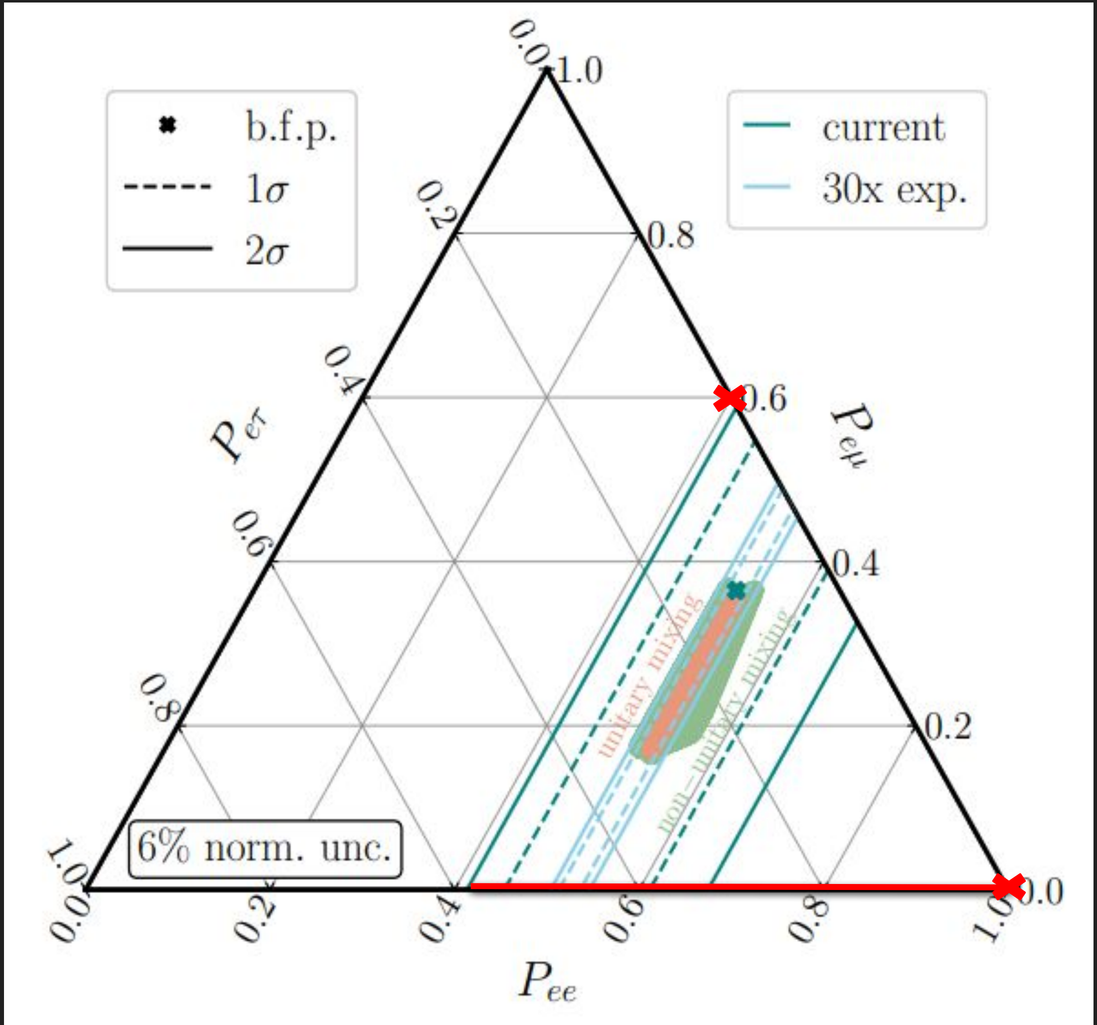

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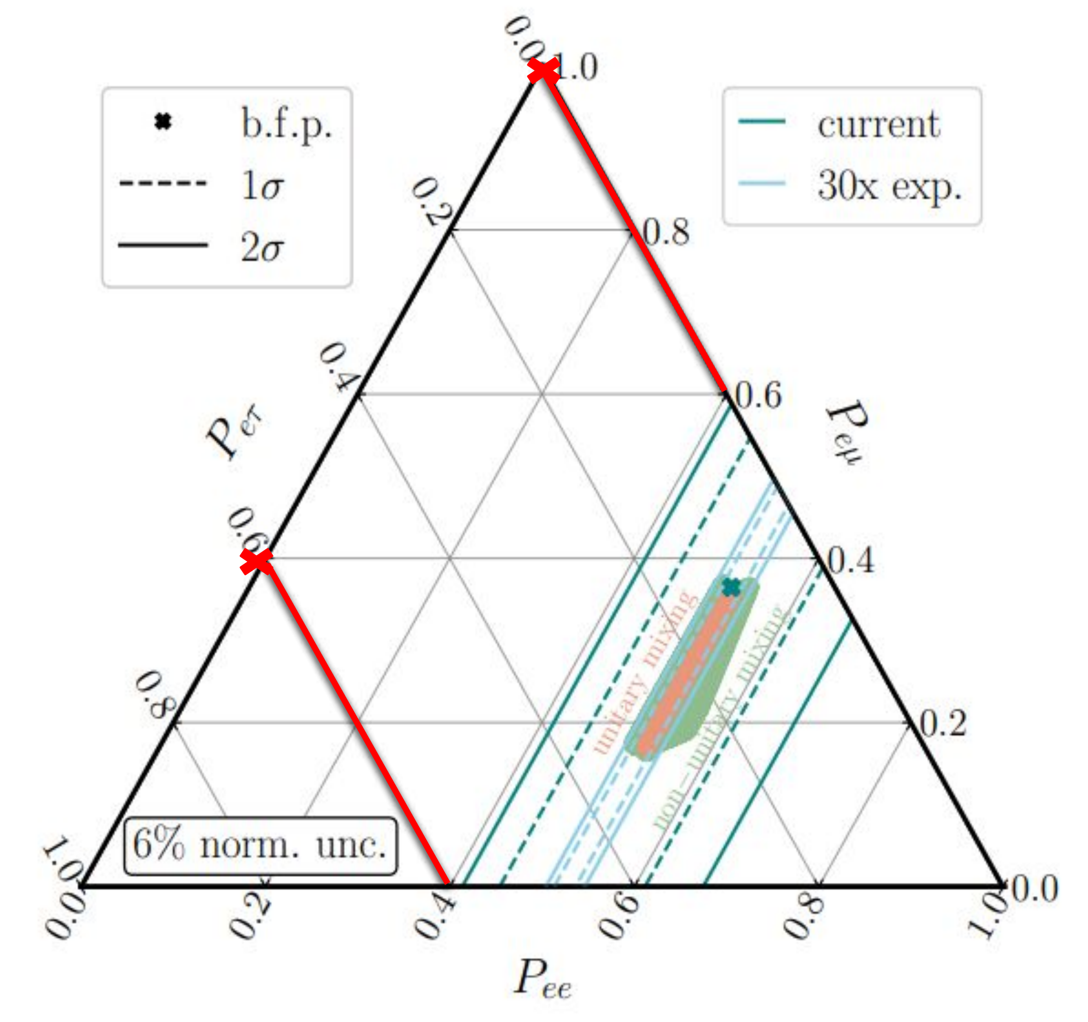

3-flv Analysis

$$S_i \equiv n \sum_{\alpha=e,\mu\tau} S_{\alpha i}, \quad S_{\alpha i} \equiv \frac{f_\alpha}{P^{\mathrm{BF}}_{e\alpha}} N^{\mathrm{BF}}_{\alpha i},$$

Constraint : $f_e + f_\mu + f_\tau = 1$

Non-Unitary Mixing

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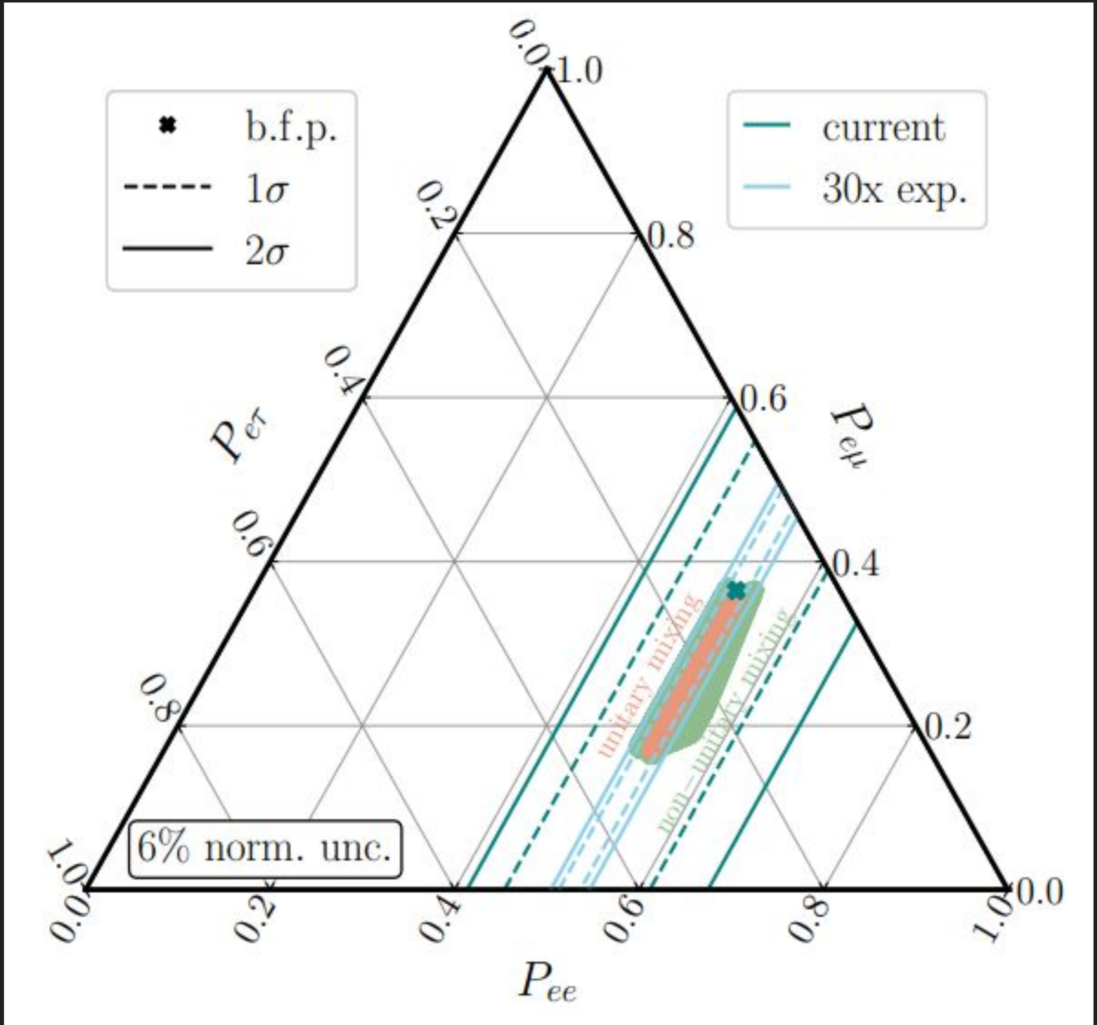
Unitary Mixing

Vary θ_{23} & δ_{CP}



3-flv Analysis

$$S_i \equiv n \sum_{\alpha=e,\mu\tau} S_{\alpha i}, \quad S_{\alpha i} \equiv \frac{f_\alpha}{P^{\rm BF}_{e\alpha}} N^{\rm BF}_{\alpha i},$$

Constraint : $f_e + f_\mu + f_\tau = 1$

Non-Unitary Mixing

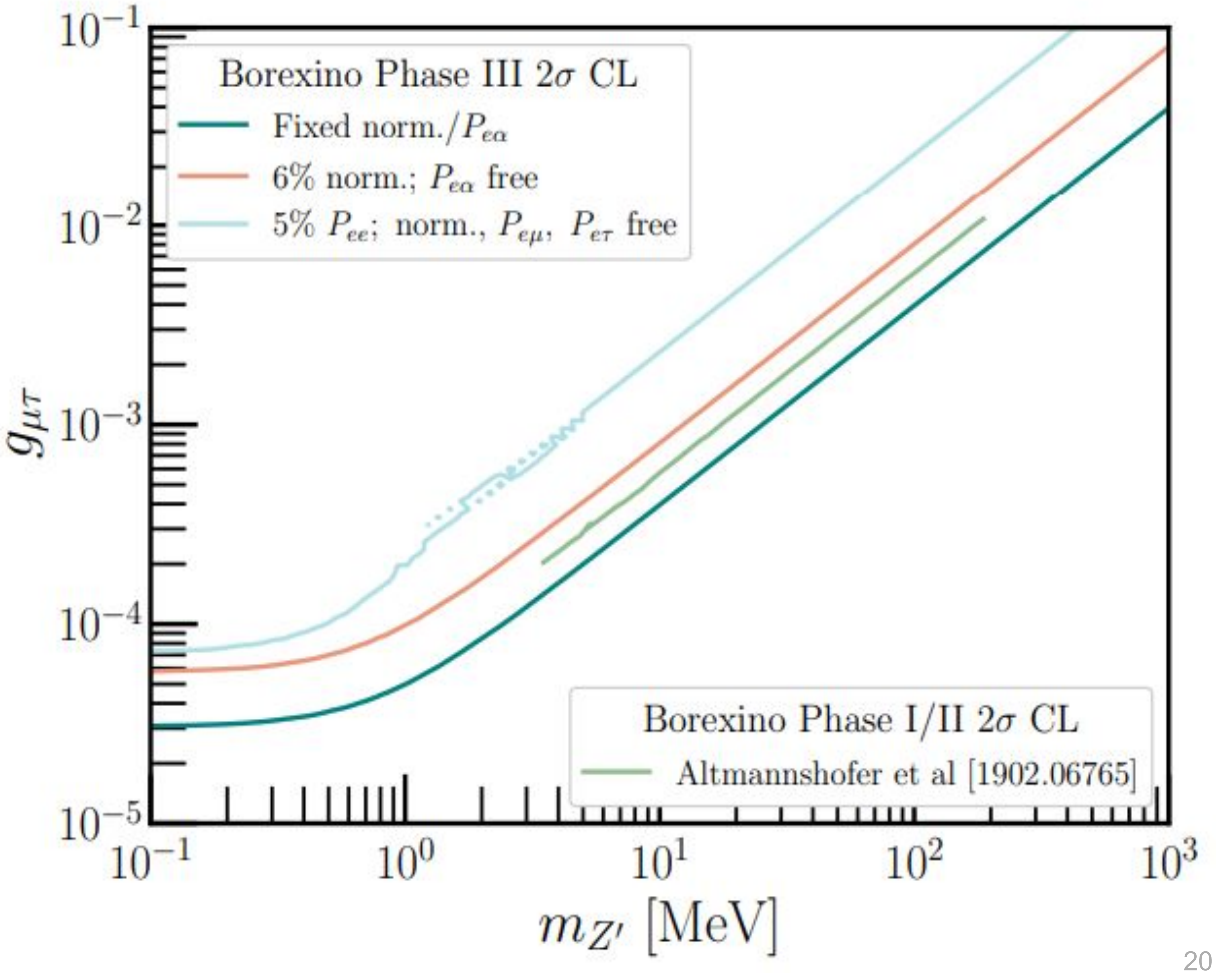
$$N = \alpha U = \begin{bmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{bmatrix} U^{3\times 3}$$

Unitary Mixing

Vary θ_{23} & δ_{CP}

Constraints on $L_\mu - L_\tau$ by Borexino Phase III data

- New U(1) gauge boson Z '
- Couples to only ν_μ & ν_τ (and corresponding charged leptons)



SOLAR ν - SENSITIVE TO ALL FLAVORS

- ELECTRON SCATTERING
  - current state of exp - not completely sensitive to all flavors
  - future exp - sensitive with greater exposure - Eg. JUNO - 2306.03160
- CEνNS
  - Dark matter detectors - improve measurements of ν in future
  - can get interesting results even with such measurements - 2409.04385, 2409.04703

BACK UP

NEUTRINO OSCILLATIONS:

WEAK | **MASS**

$\nu_e \leftrightarrow \nu_1$

$\nu_\mu \leftrightarrow \nu_2$

$\nu_\tau \leftrightarrow \nu_3$

U_{PMNS}

$$i\frac{d}{dt}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = H\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

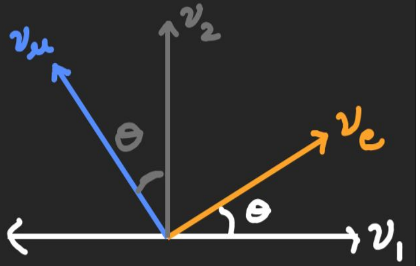
$$|\nu_i\rangle = e^{-iHt}|\nu_i(0)\rangle$$

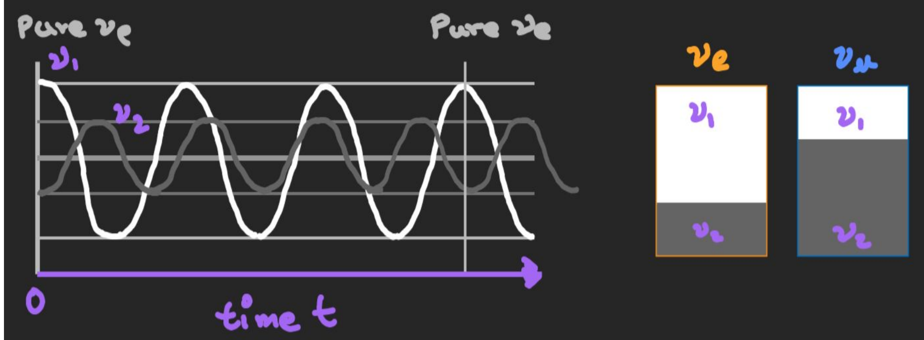
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H_{fl}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$|\nu_\alpha\rangle = e^{-iH_{fl}}|\nu_\alpha(0)\rangle$$

Weak State | Mass states

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$





$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

VACUUM

$$H_{fl} = U H U^{\dagger}$$

$$H = \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix}$$

MATTER EFFECT

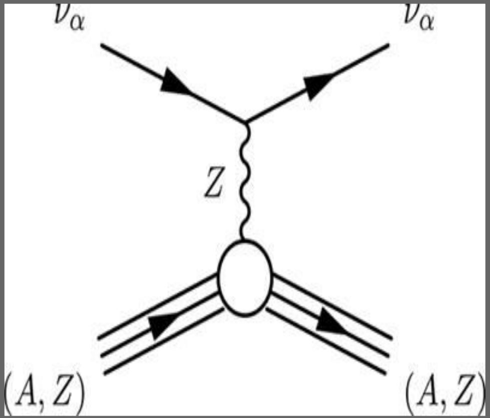
$$V_{cc} = \sqrt{2}G_F N_e$$

$$H_{fl} = U H U^{\dagger} + V$$

$$V = \begin{pmatrix} V_{cc} & 0 \\ 0 & 0 \end{pmatrix}$$

CEνNS

Coherent Elastic Neutrino Nucleus Scattering



PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

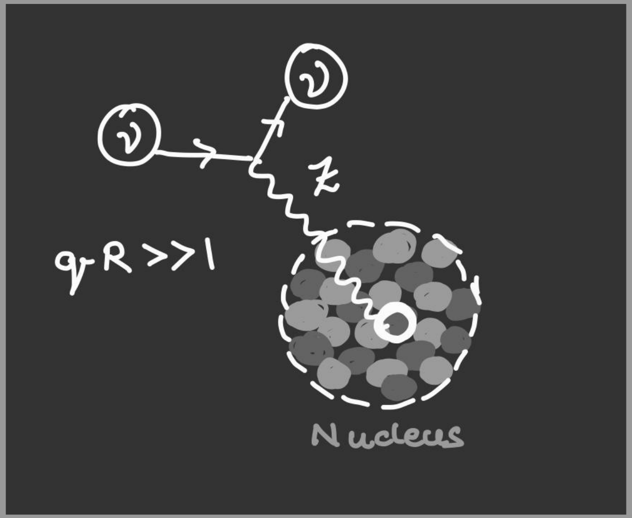
Coherent effects of a weak neutral current

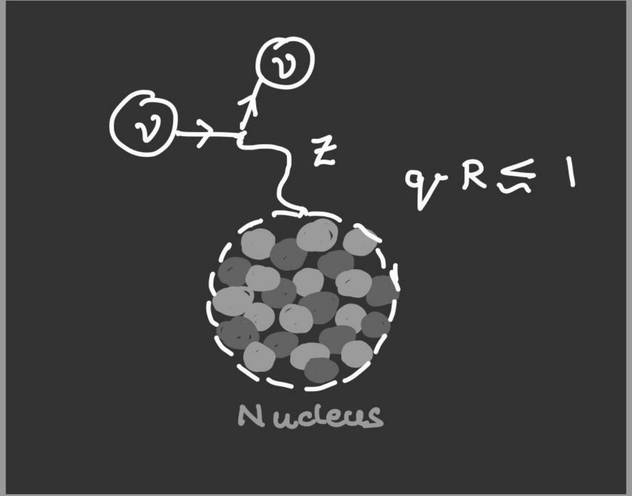
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

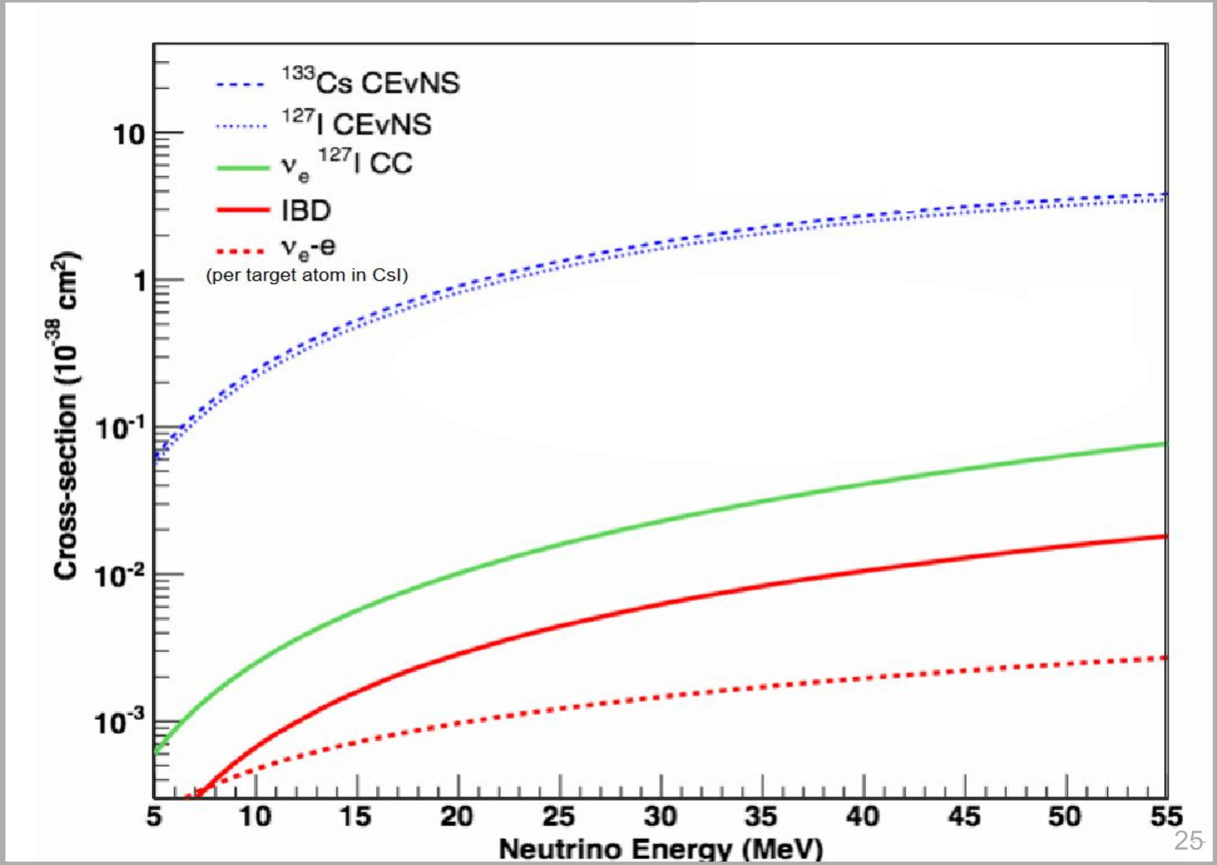
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

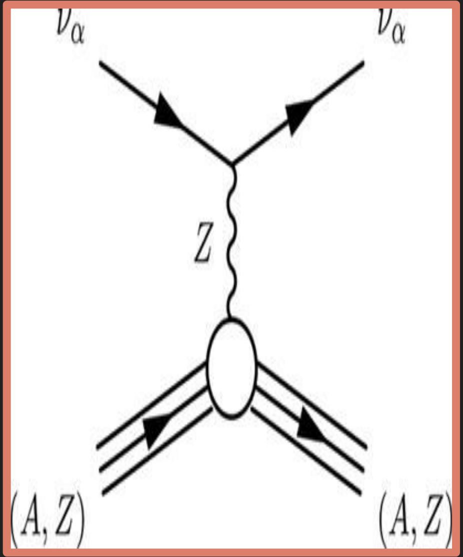
CEνNS → coherent enhancement ⟶ $\sigma \sim N^2$



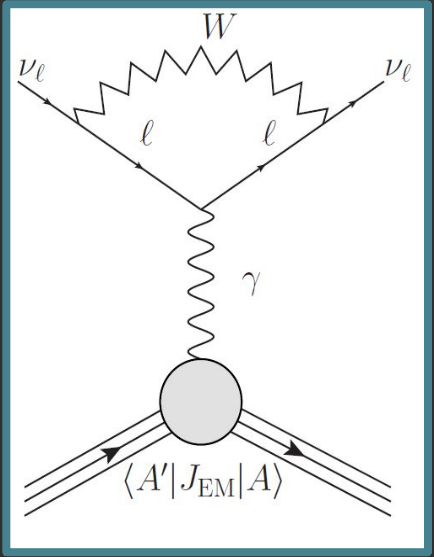


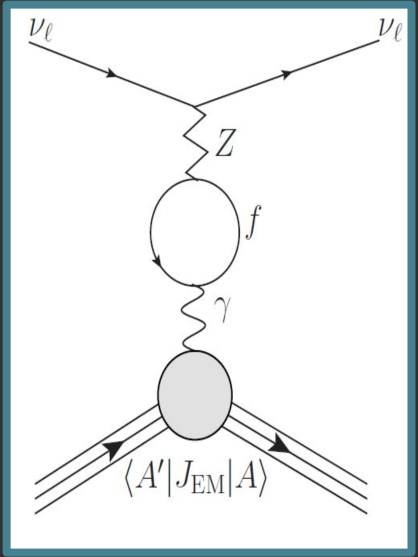


TREE-LEVEL



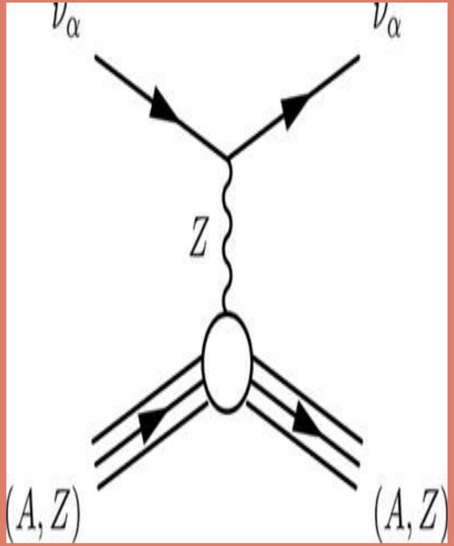
WITH RADIATIVE CORRECTION





arXiv:2011.05960 :
Oleksandr Tomalak, Pedro Machado,
Vishvas Pandey, Ryan Plestid

TREE-LEVEL

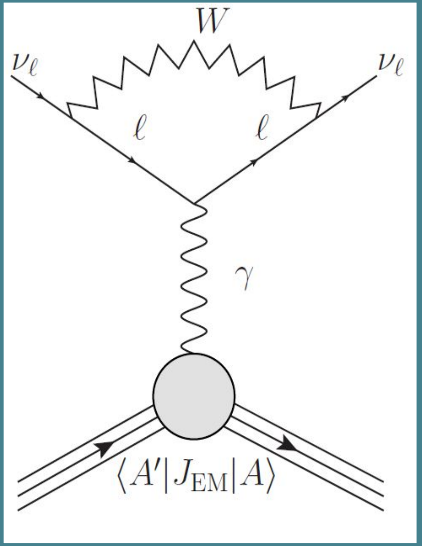


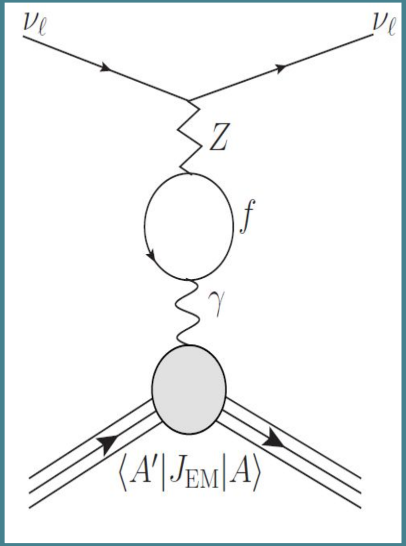
$$\frac{d\sigma_\nu}{dT} = \frac{G_F^2 M_A}{4\pi}\left(1 - \frac{T}{E_\nu} - \frac{M_A T}{2E_\nu^2}\right) Q_W^2 F_W^2(Q^2)$$

Weak charge:

$$Q_W = N - (1 - 4\sin^2\theta_w)Z$$

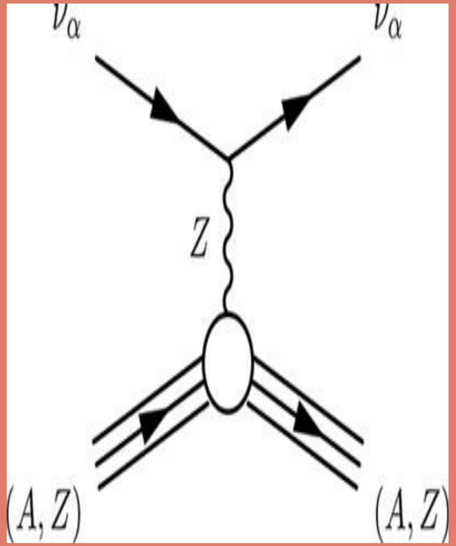
WITH RADIATIVE CORRECTION





arXiv:2011.05960 :
Oleksandr Tomalak, Pedro Machado, Vishvas Pandey, Ryan Plestid

TREE-LEVEL



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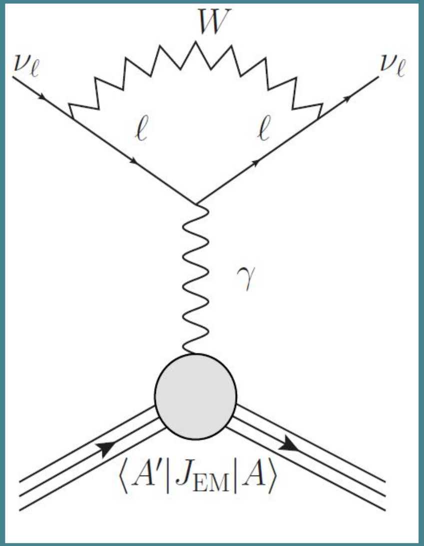
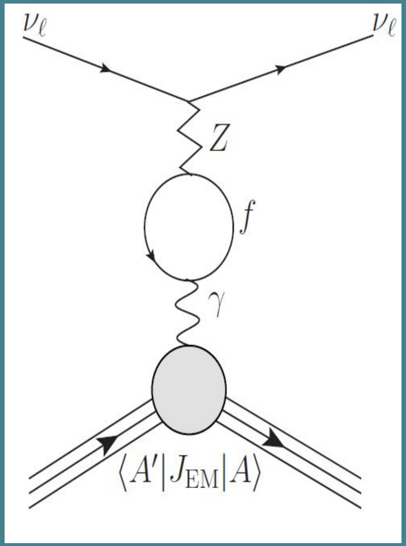
Weak Form Factor:

$$F_W = \frac{1}{Q_W}[N F_n(Q^2) - (1 - 4\sin^2\theta_w) Z F_p(Q^2)]$$

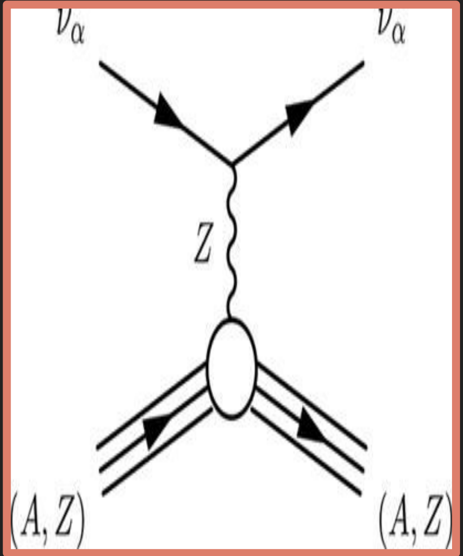
WITH RADIATIVE CORRECTION





$$\frac{d\sigma_{\nu l}}{dT} = \frac{G_F^2 M_A}{4\pi}\left(1 - \frac{T}{E_\nu} - \frac{M_A T}{2E_\nu^2}\right) \mathcal{F}_{\nu l}^2(Q^2)$$

TREE-LEVEL

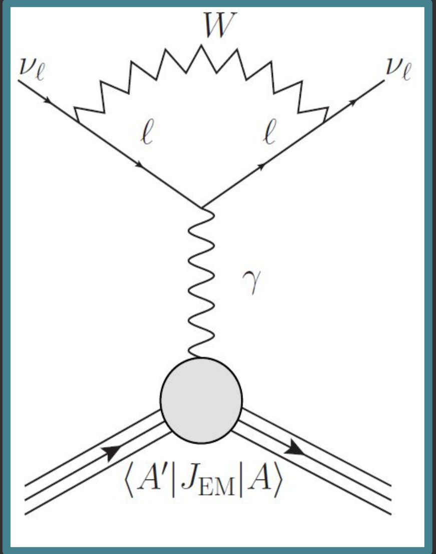


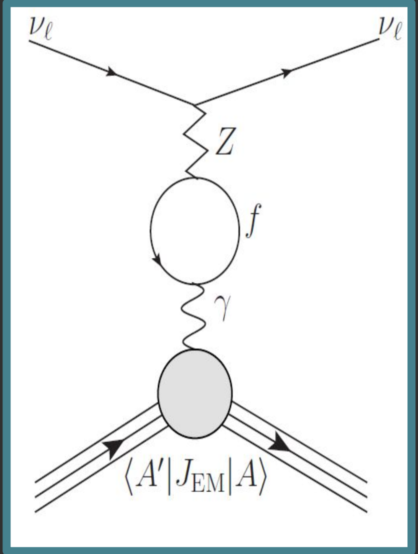
$$\frac{d\sigma_\nu}{dT} = \frac{G_F^2 M_A}{4\pi}\left(1 - \frac{T}{E_\nu} - \frac{M_A T}{2E_\nu^2}\right) Q_W^2 F_W^2(Q^2)$$

Weak Form Factor:

$$F_W = \frac{1}{Q_W}[N F_n(Q^2) - (1 - 4\sin^2\theta_w) Z F_p(Q^2)]$$

WITH RADIATIVE CORRECTION

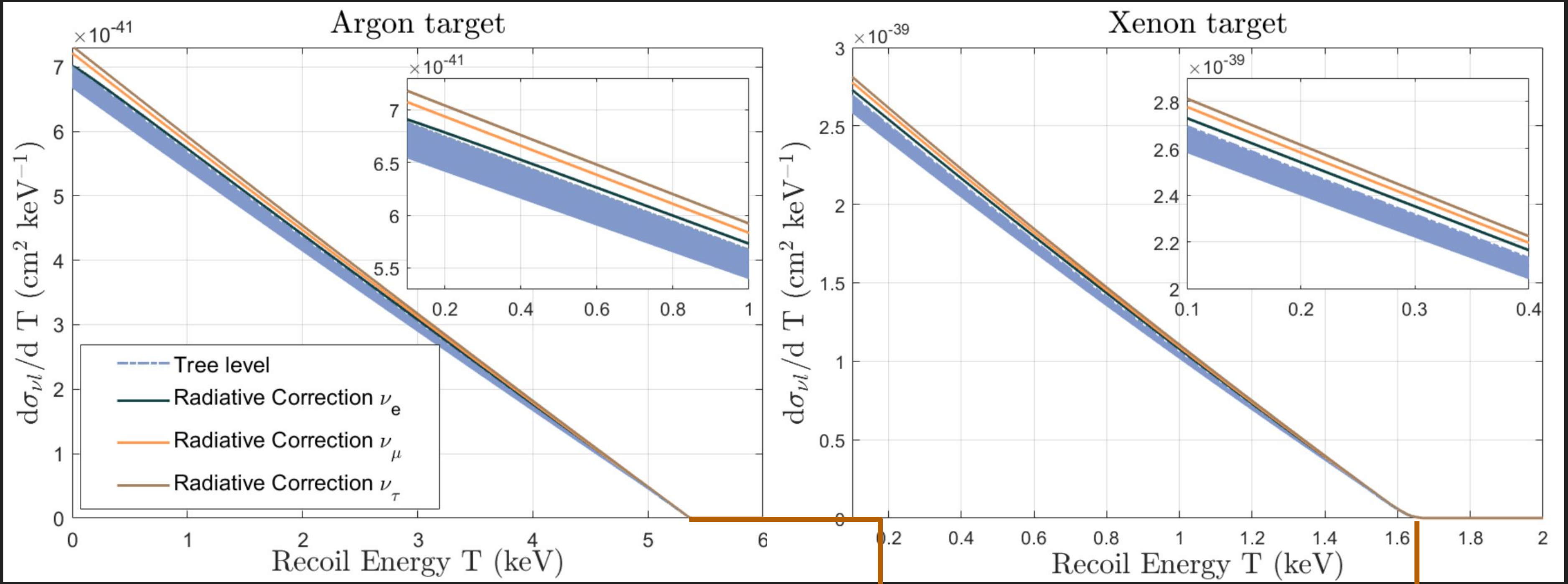




$$\frac{d\sigma_{\nu l}}{dT} = \frac{G_F^2 M_A}{4\pi}\left(1 - \frac{T}{E_\nu} - \frac{M_A T}{2E_\nu^2}\right) \mathcal{F}_{\nu l}^2(Q^2)$$

$$\mathcal{F}_{\nu l}(Q^2) = (\mathcal{F}_W(Q^2) + \frac{\alpha}{\pi}[\delta^{\nu l} + \delta^{QCD}]\mathcal{F}_{ch}(Q^2))$$

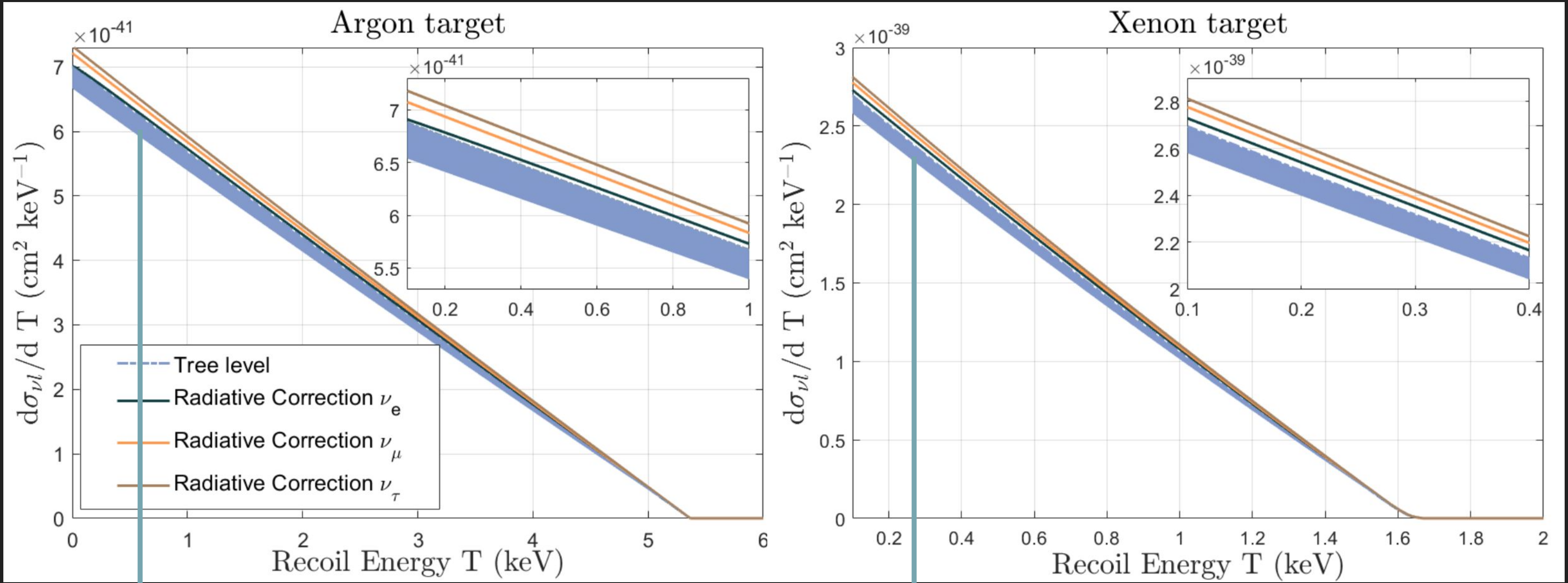
CEνNS DIFFERENTIAL CROSS-SECTION



$$F_W = \frac{1}{Q_W}[NF_n(Q^2) - (1 - 4\sin^2\theta_w)ZF_p(Q^2)]$$

$$T_{max} = \frac{2E_\nu^2}{M_A + 2E_\nu}.$$

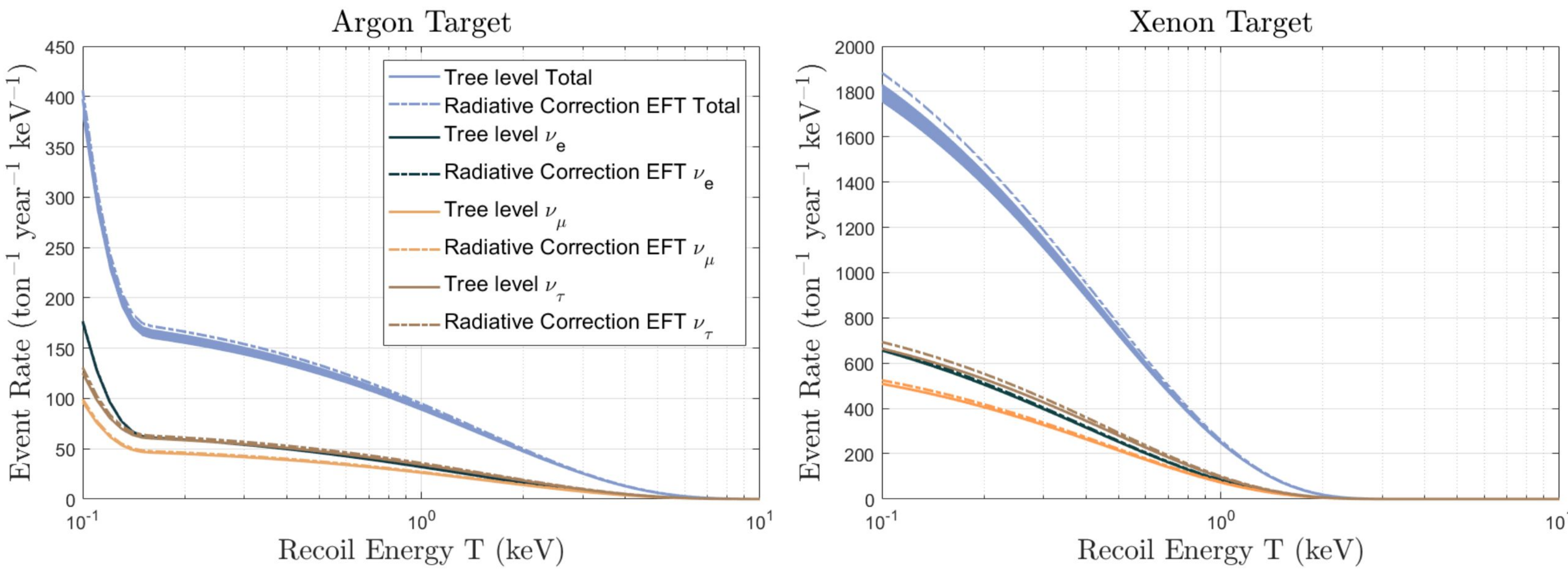
Cross-section for $\nu_\tau > \nu_\mu > \nu_e$ radiative corrections > Cross-section for tree-level ($\nu_\tau = \nu_\mu = \nu_e$)



$$F_W = \frac{1}{Q_W}\left[NF_n(Q^2) - (1 - 4\sin^2\theta_w)ZF_p(Q^2)\right]$$

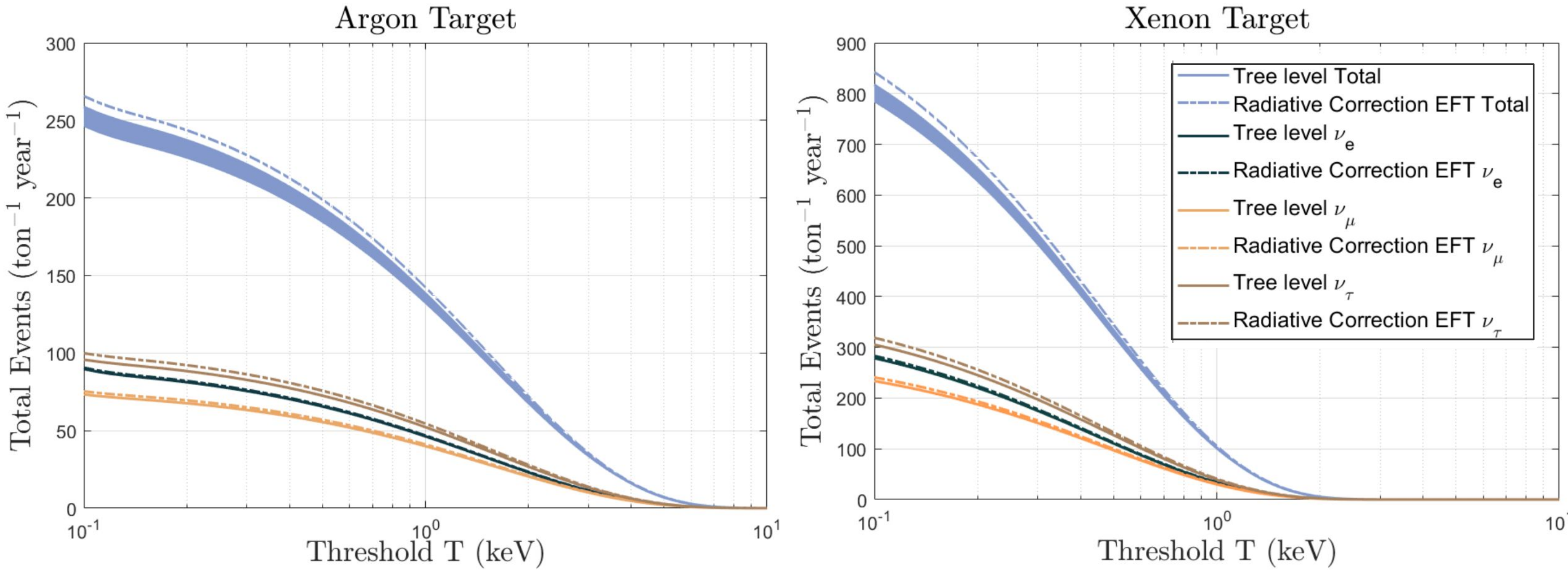
$$T_{max} = \frac{2E_\nu^2}{M_A + 2E_\nu}.$$

EVENT RATE:



$$\frac{dN_\alpha}{dT} = \int_{E_{\nu,min}} \frac{d\phi(E_\nu)}{dE_\nu} \frac{d\sigma_\alpha(E_\nu, T)}{dT} P(\nu_e \to \nu_\alpha) dE_\nu$$

EVENTS:



$$N_\alpha = \int_{T_{th}} \frac{dN_\alpha}{dT} dT.$$

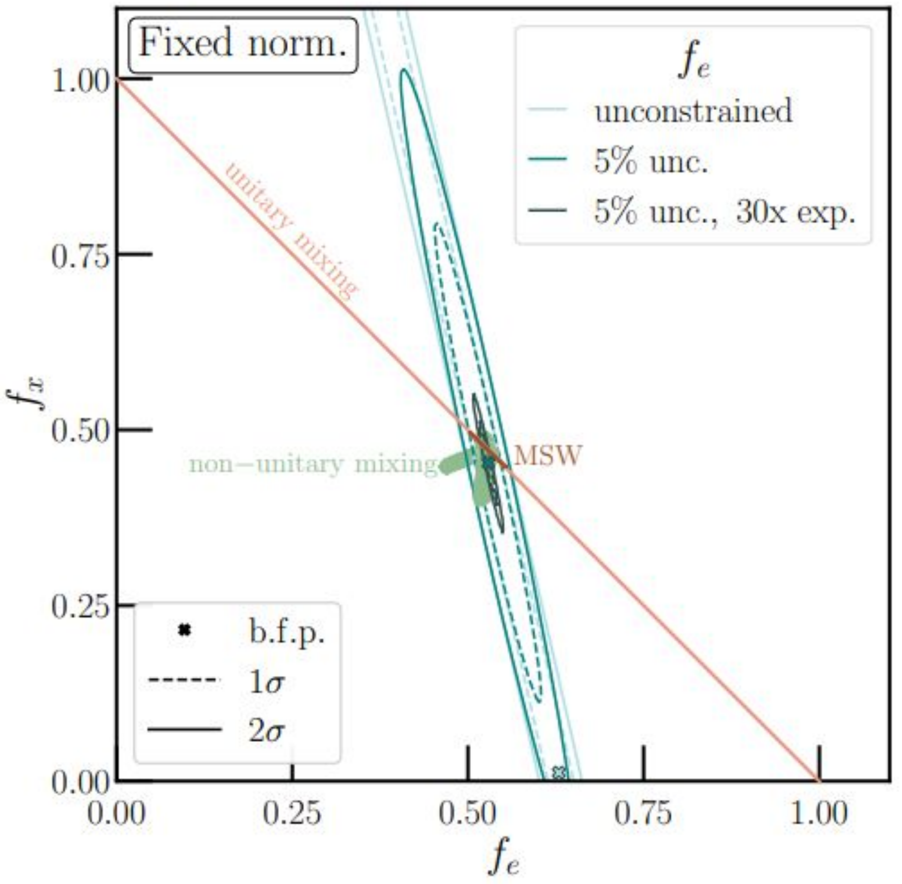
CONCLUSION:

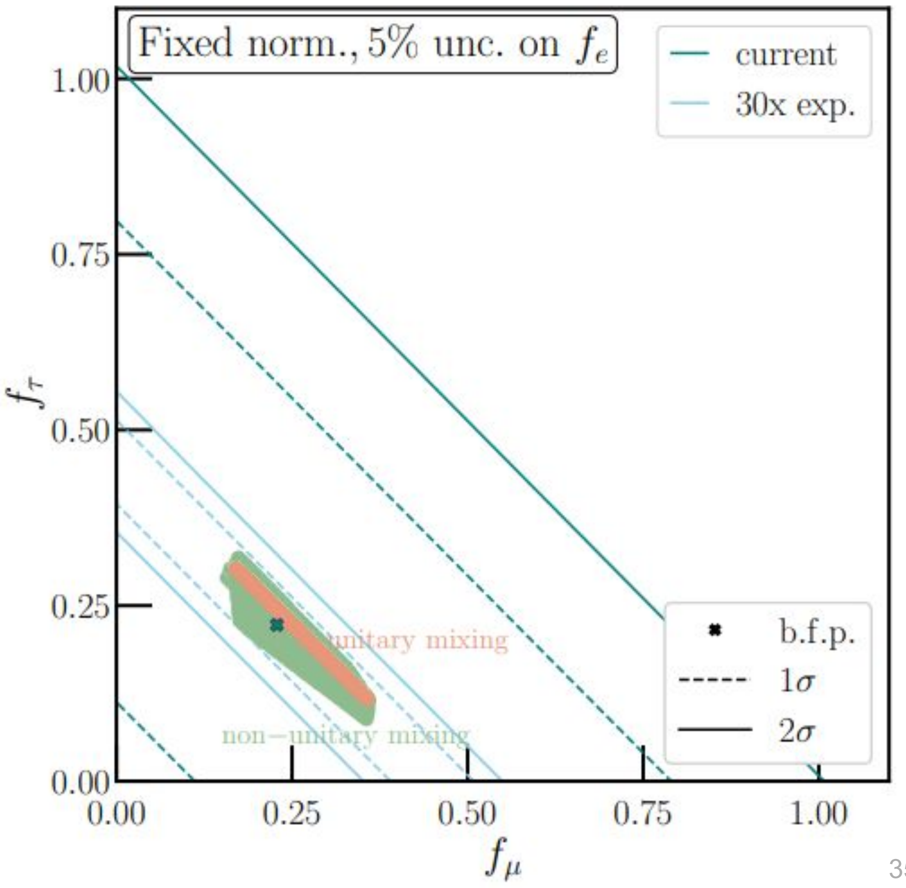
Within the context of a full three-flavor analysis that includes the
effects of matter oscillations in the Sun and the Earth, we find that detectors with exposure ~ 100 ton-year would be able to
measure a cross section value that deviates from the tree-level prediction.

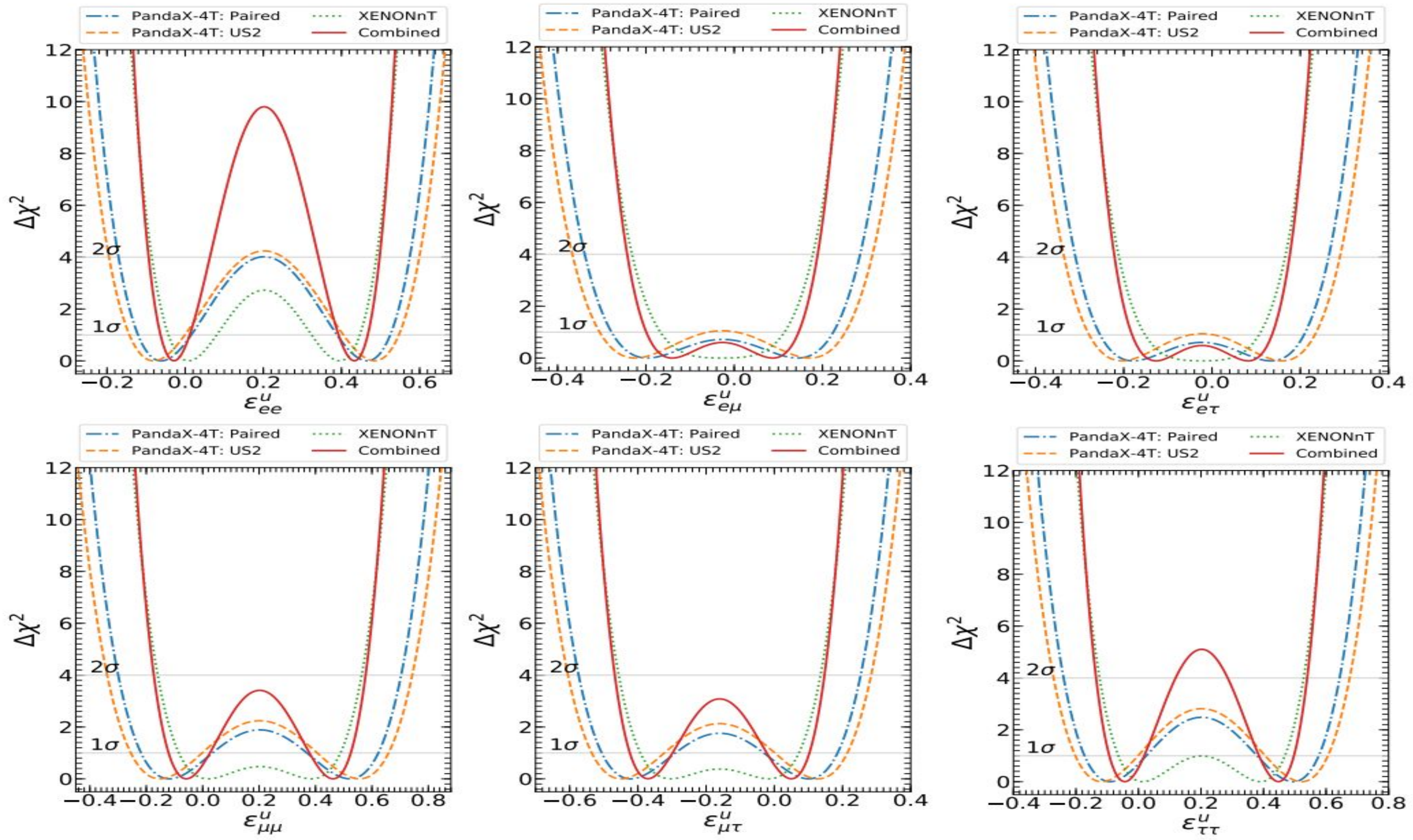
FUTURE ASPECTS

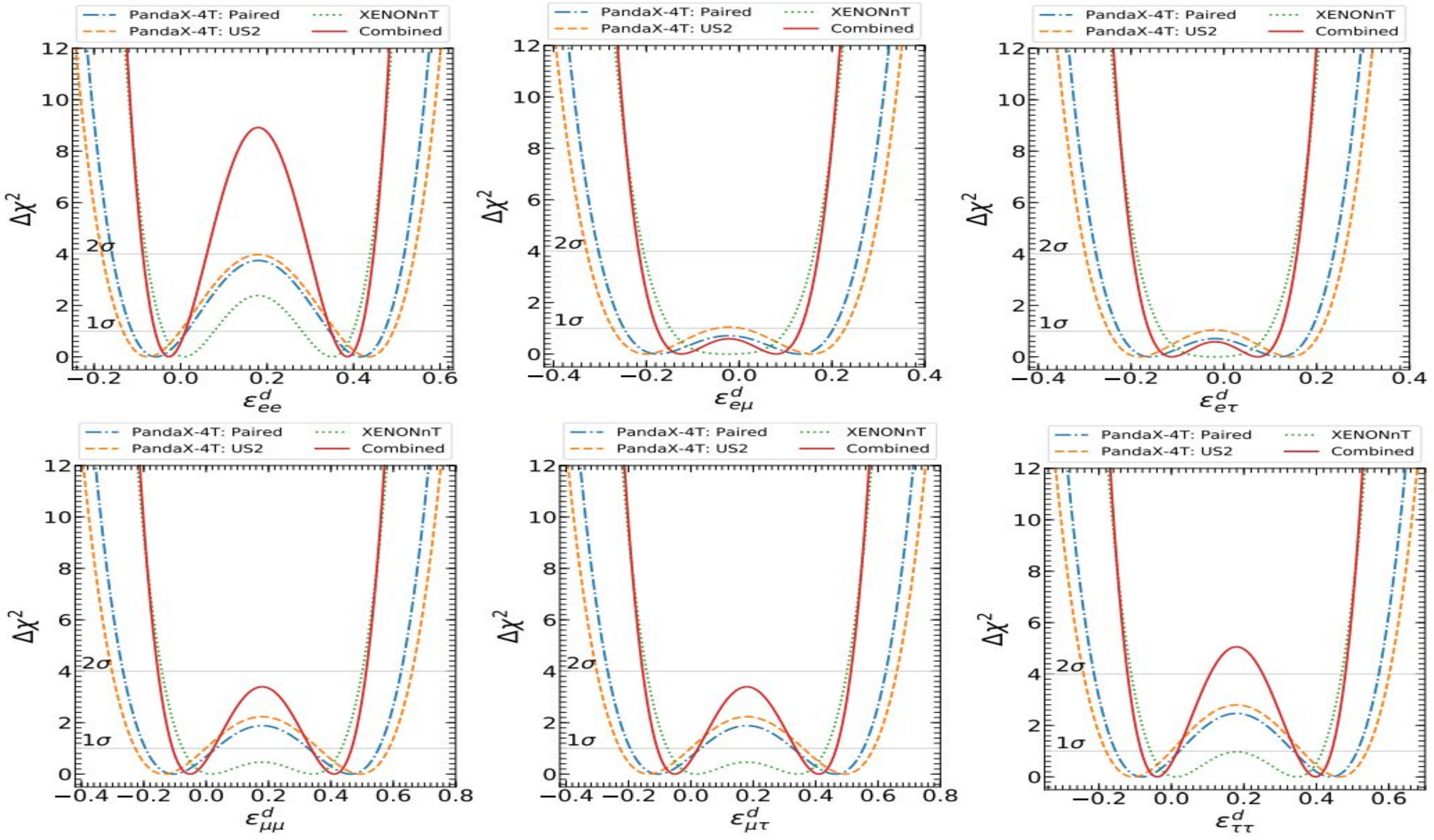
- Rigorous monte-carlo based simulation analysis with backgrounds
- Analysis with other neutral current channels arXiv:2306.03160 Vedran Brdar, Xun-Jie Xu
- BSM physics

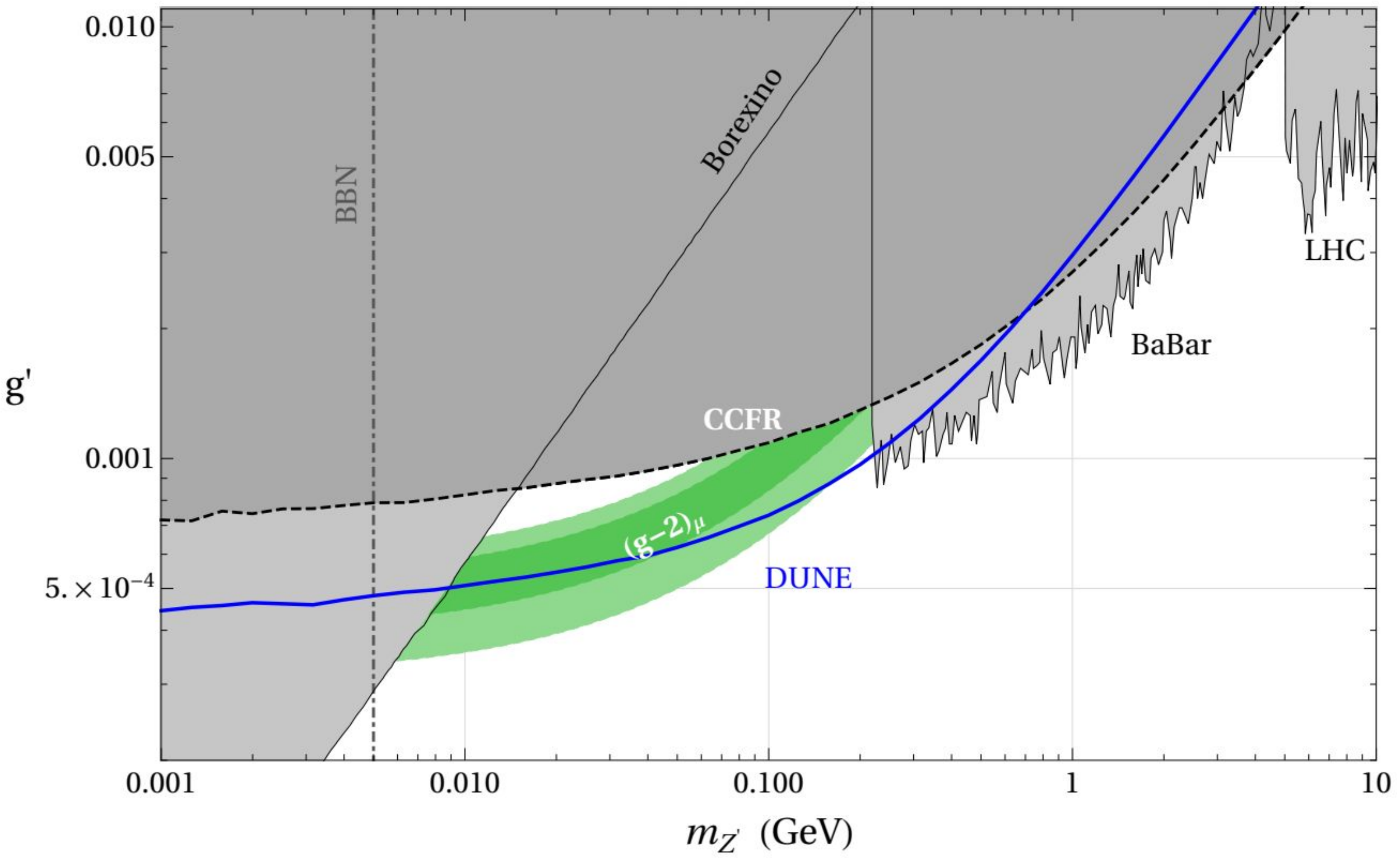
2-flv Analysis	3-flv Analysis



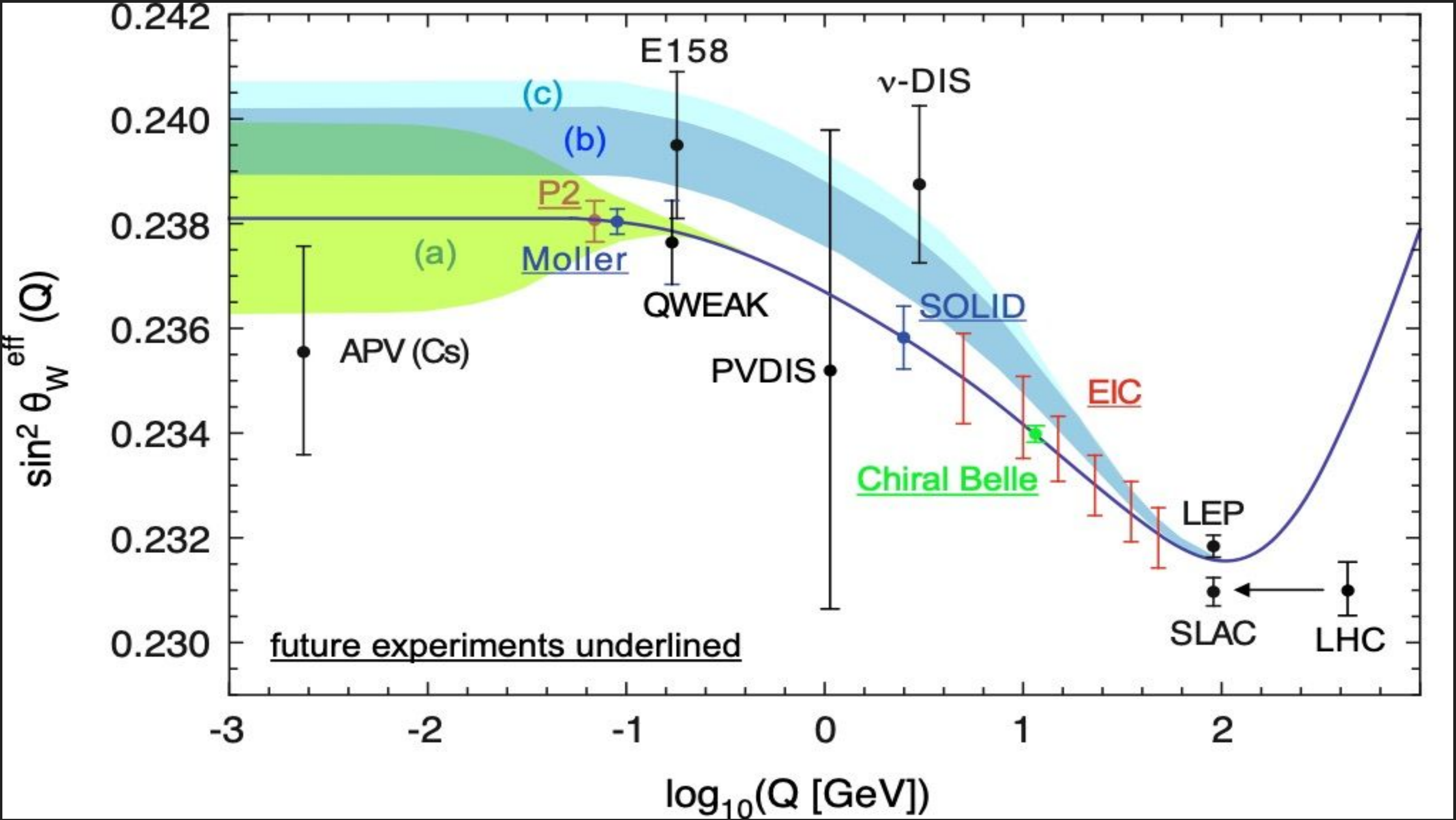



PandaX-4T: Paired
PandaX-4T: US2
XENONnT
Combined
$\Delta\chi^2$
2σ
1σ
ε^u_{ee}
$\varepsilon^u_{e\mu}$
$\varepsilon^u_{e\tau}$
$\varepsilon^u_{\mu\mu}$
$\varepsilon^u_{\mu\tau}$
$\varepsilon^u_{\tau\tau}$

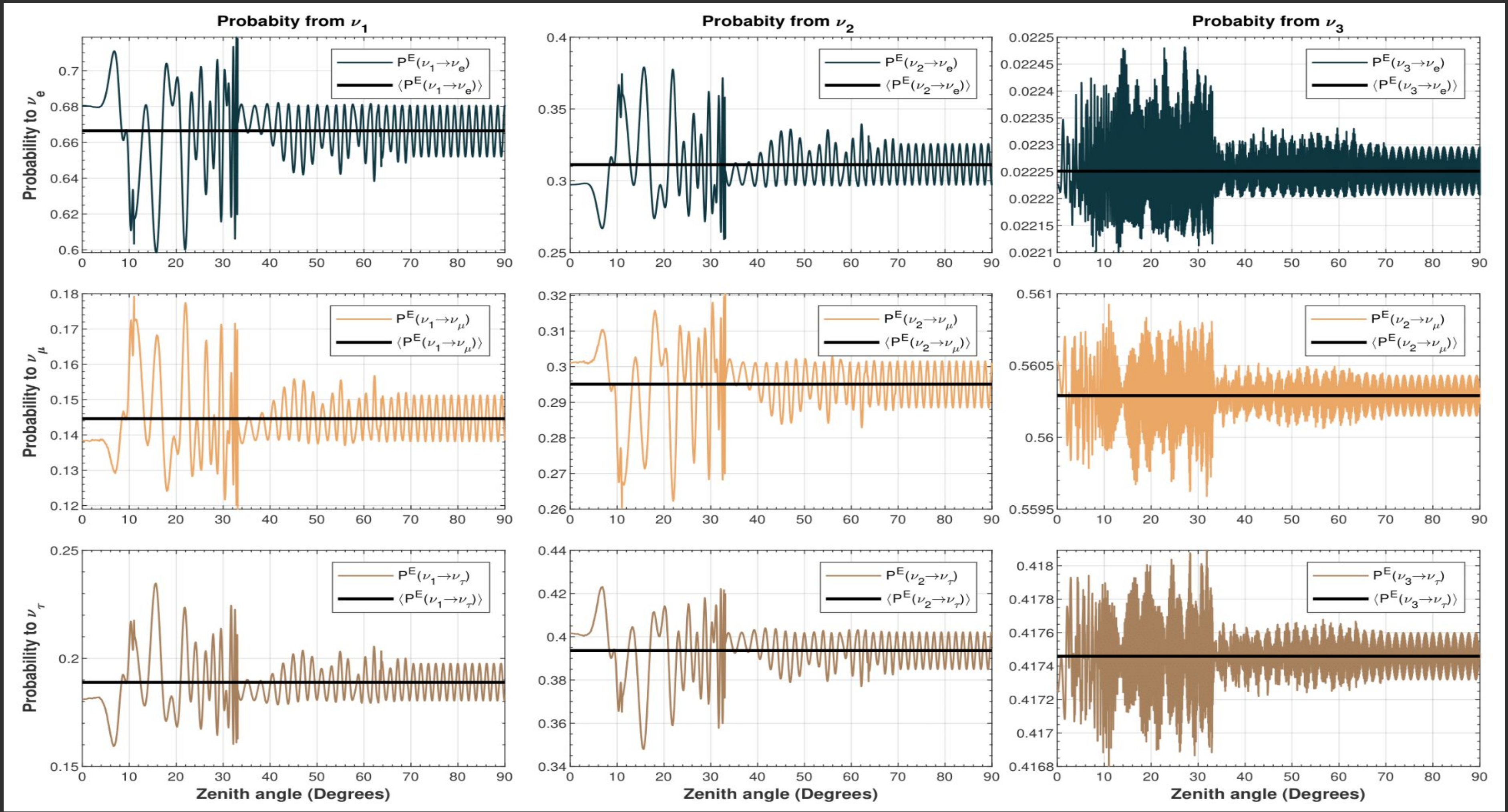

PandaX-4T: Paired
PandaX-4T: US2
XENONnT
Combined
$\Delta\chi^2$
2σ
1σ
ε^d_{ee}
$\varepsilon^d_{e\mu}$
$\varepsilon^d_{e\tau}$
$\varepsilon^d_{\mu\mu}$
$\varepsilon^d_{\mu\tau}$
$\varepsilon^d_{\tau\tau}$



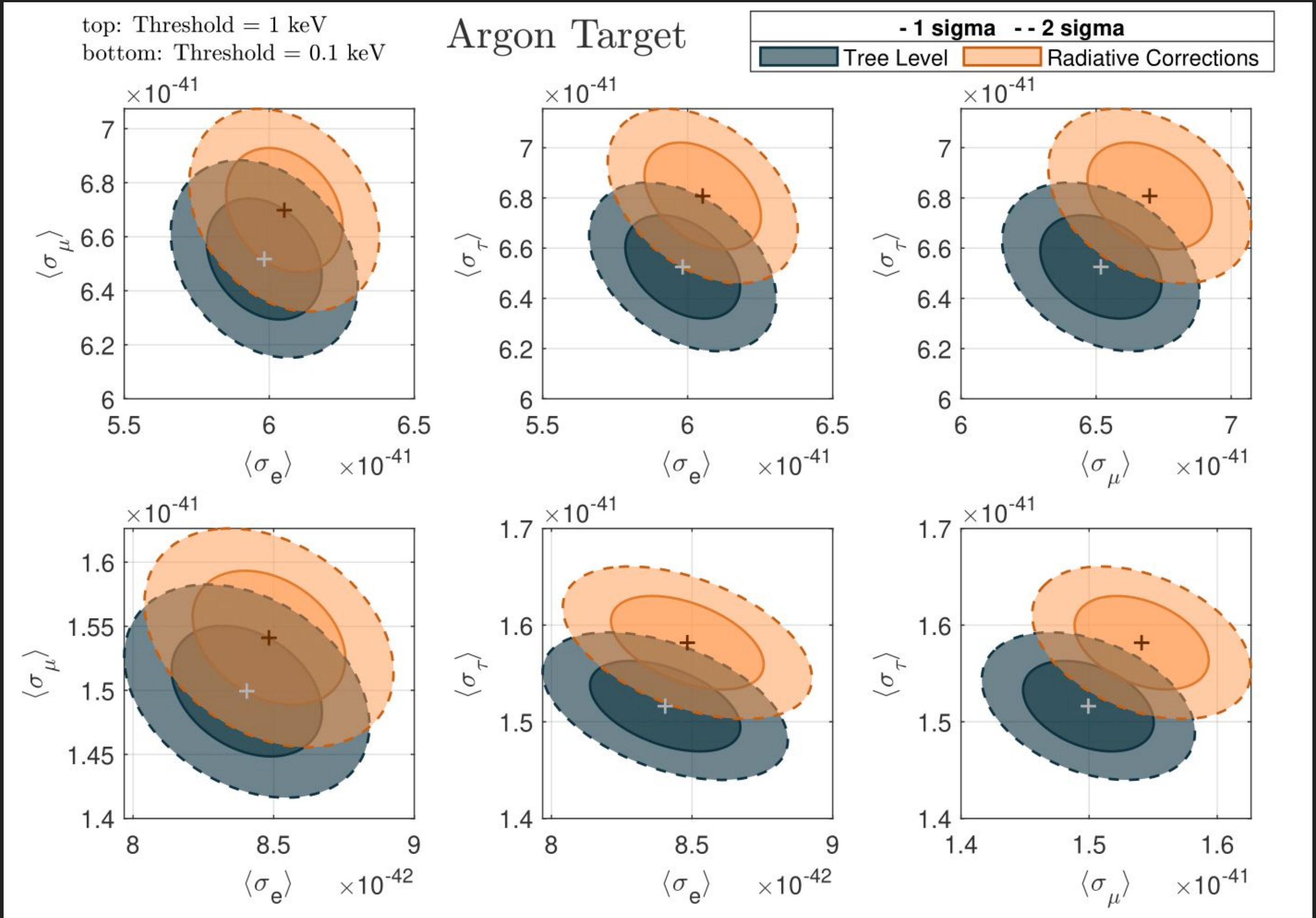
0.010
0.005
0.001
$5.\times10^{-4}$
g'
BBN
Borexino
LHC
BaBar
CCFR
$(g-2)_\mu$
DUNE
0.001
0.010
0.100
1
10
$m_{Z'}$ (GeV)



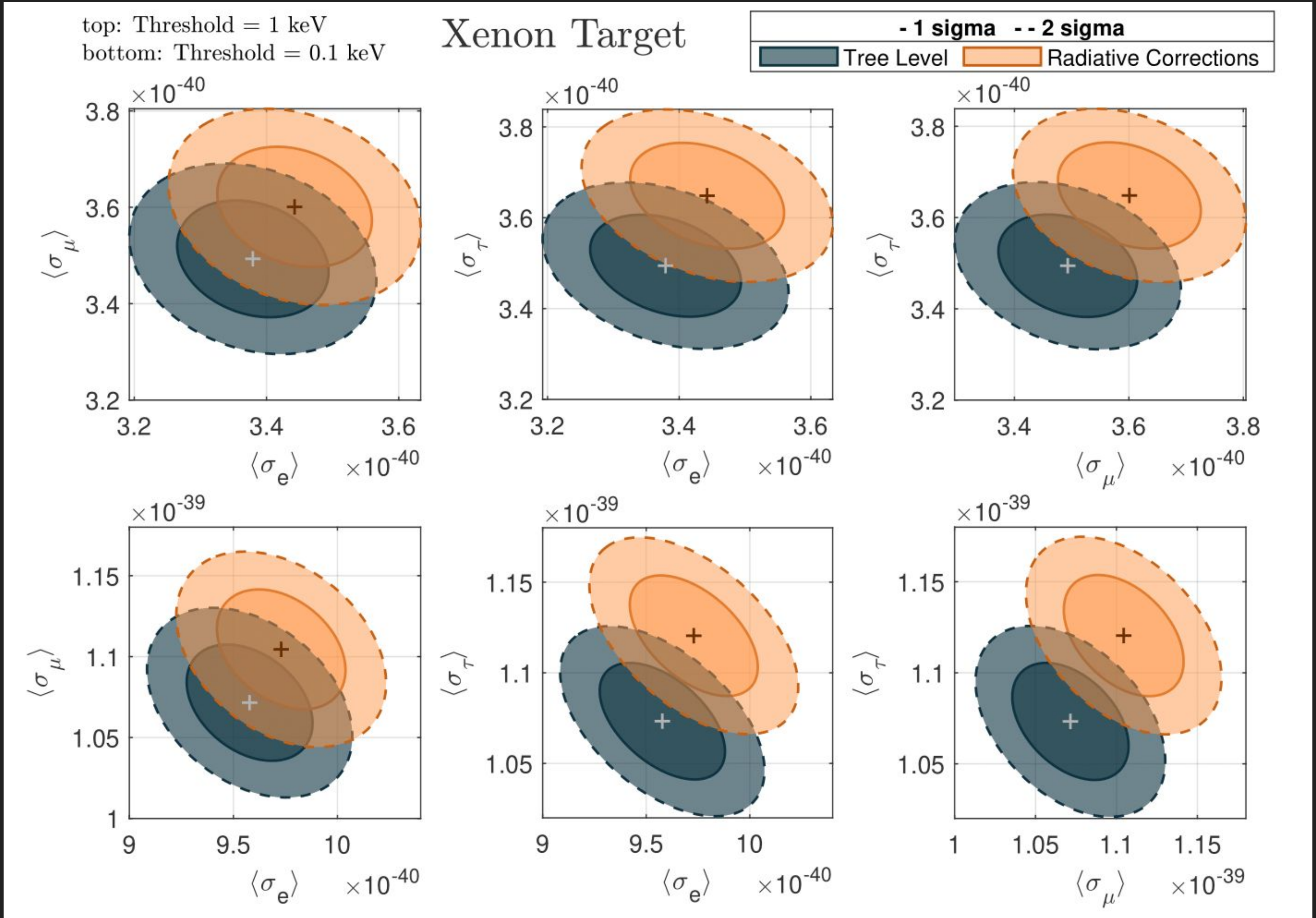
E158
ν-DIS
(c)
(b)
P2
(a)
Moller
QWEAK
SOLID
APV (Cs)
PVDIS
EIC
Chiral Belle
LEP
SLAC
LHC
future experiments underlined
0.242
0.240
0.238
0.236
0.234
0.232
0.230
-3
-2
-1
0
1
2
$\sin^2 \theta_W^{eff}$ (Q)
$\log_{10}$(Q [GeV])



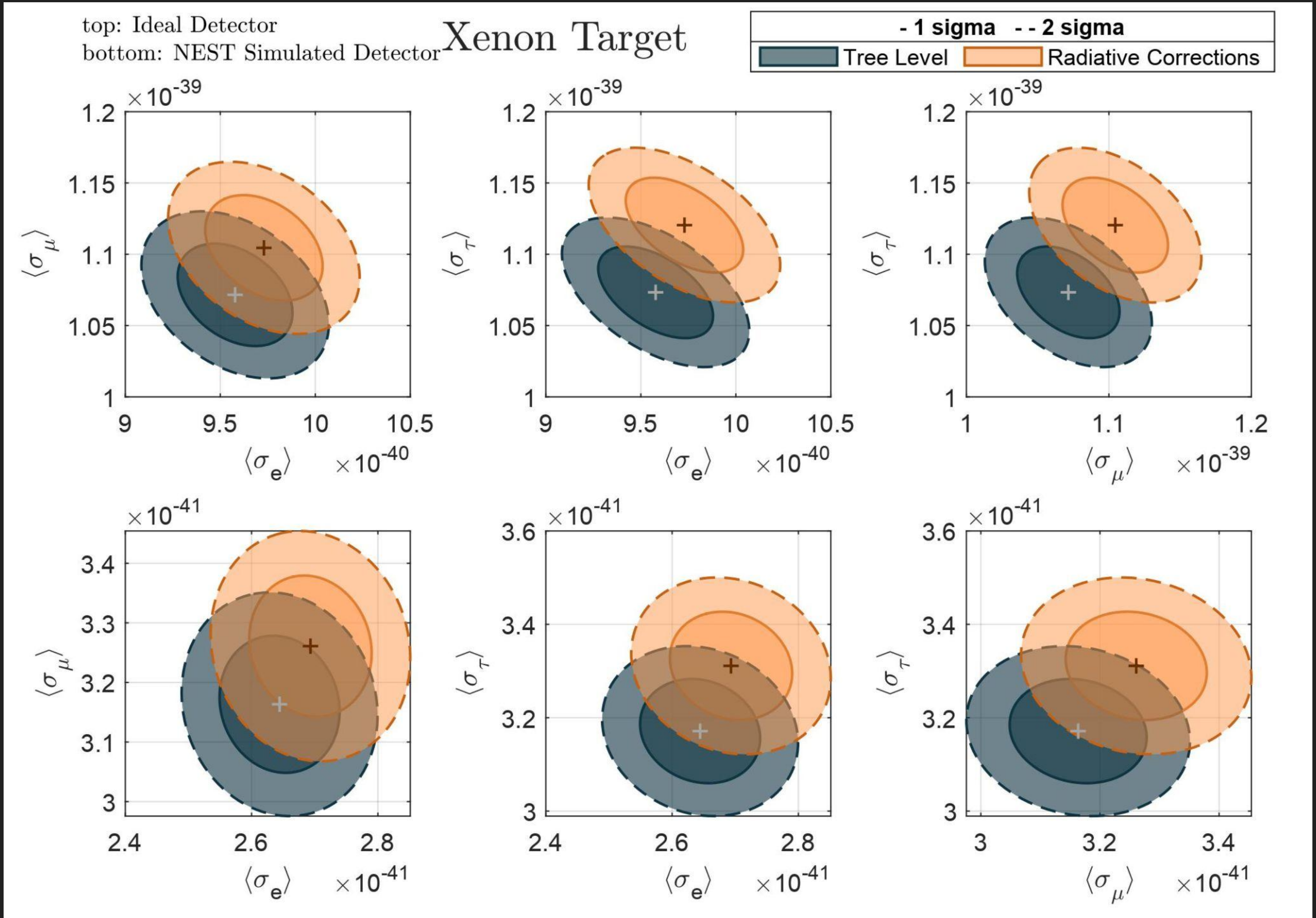
Probabity from ν1
Probabity from ν2
Probabity from ν3
Probability to νe
Probability to νμ
Probability to ντ
P^E(ν1→νe)
⟨P^E(ν1→νe)⟩
P^E(ν2→νe)
⟨P^E(ν2→νe)⟩
P^E(ν3→νe)
⟨P^E(ν3→νe)⟩
P^E(ν1→νμ)
⟨P^E(ν1→νμ)⟩
P^E(ν2→νμ)
⟨P^E(ν2→νμ)⟩
P^E(ν2→νμ)
⟨P^E(ν2→νμ)⟩
P^E(ν1→ντ)
⟨P^E(ν1→ντ)⟩
P^E(ν2→ντ)
⟨P^E(ν2→ντ)⟩
P^E(ν3→ντ)
⟨P^E(ν3→ντ)⟩
Zenith angle (Degrees)
Zenith angle (Degrees)
Zenith angle (Degrees)



top: Threshold = 1 keV
bottom: Threshold = 0.1 keV
Argon Target
- 1 sigma - - 2 sigma
Tree Level
Radiative Corrections
⟨σ_e⟩ ×10^-41
⟨σ_μ⟩ ×10^-41
⟨σ_τ⟩ ×10^-41
⟨σ_e⟩ ×10^-42



top: Threshold = 1 keV
bottom: Threshold = 0.1 keV
Xenon Target
- 1 sigma - - 2 sigma
Tree Level
Radiative Corrections
$\langle\sigma_\mu\rangle$
$\langle\sigma_\tau\rangle$
$\langle\sigma_e\rangle$
$\times 10^{-40}$
$\times 10^{-39}$


top: Ideal Detector
bottom: NEST Simulated Detector
Xenon Target
- 1 sigma - - 2 sigma
Tree Level
Radiative Corrections
×10^-39
×10^-40
×10^-41
⟨σ_e⟩
⟨σ_μ⟩
⟨σ_τ⟩