Constraining the X17 Boson: Neutrino Non-Standard Interactions and IceCube Data

Yaşar Hiçyılmaz

Balıkesir University

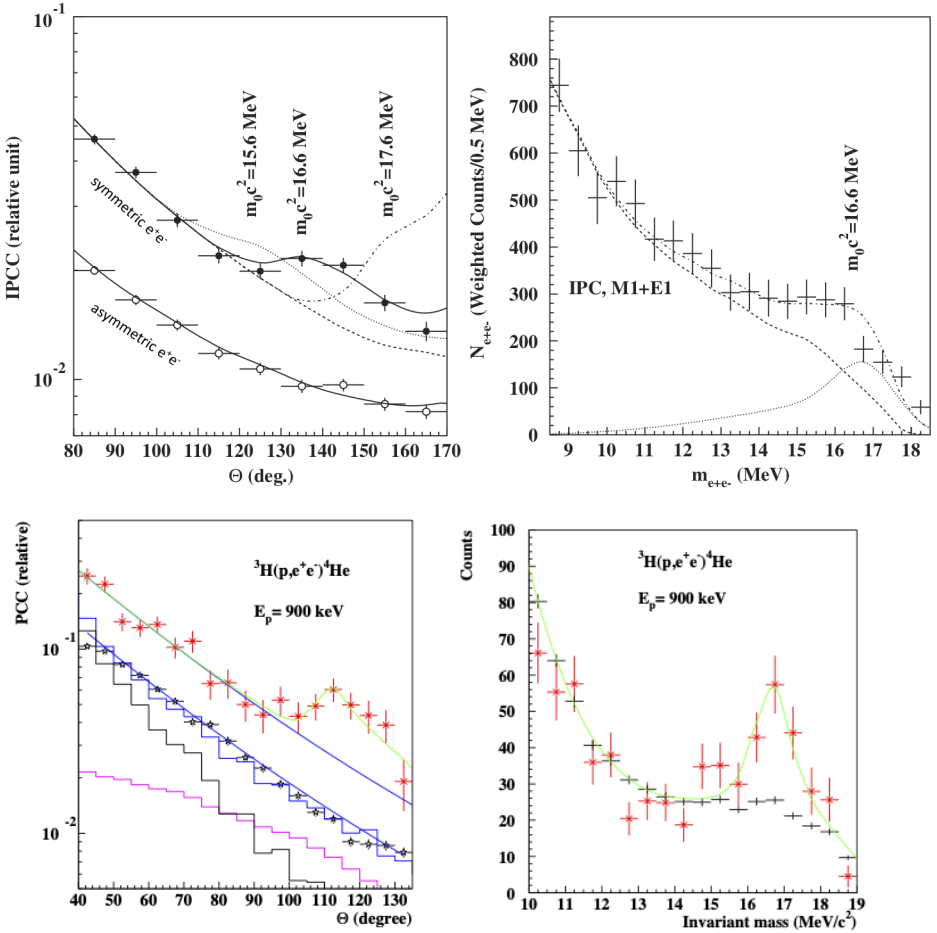
March 26, 2026

Joint work with Rikard Enberg, Stefano Moretti, Carlos Pérez de los Heros, and Harri Waltari
JHEP 06, 182 (2025)

The ATOMKI Anomalies

Key Results:

- ^{8}Be (2016):
  - 6.8σ excess in $^{8}\mathrm{Be}^{*} \rightarrow e^{+}e^{-}$
  - $m_{e^{+}e^{-}} \approx 17$ MeV
  - Angular distribution favors $J^{P} = 1^{+}$
  - Inconsistent with SM backgrounds
- ^{4}He (2019):
  - 7.2σ excess at $\sim$17 MeV
  - Confirms nuclear independence
- ^{12}C (2023):
  - 4.2σ excess at same mass
  - Strengthens case for new particle

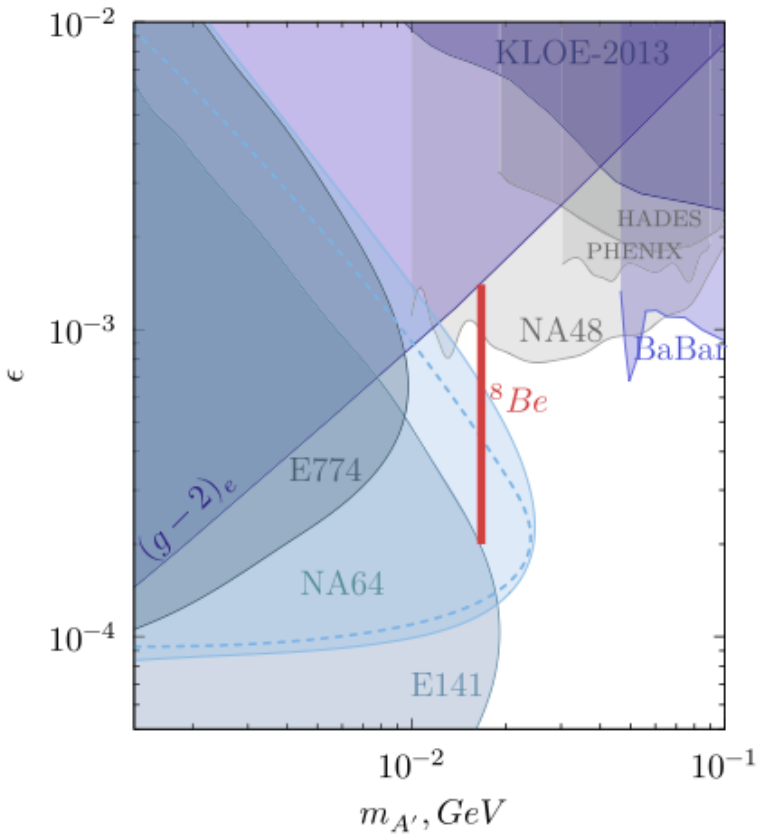


ATOMKI: Be (top), He (bottom)

Current Status

- Consistent mass across 3 nuclei $\Rightarrow$ not nuclear artifact
- Tension with PADME-2025 (1.8σ global at 16.90 MeV)

Constraints on Light Z' Bosons



- Beam dump experiments (NA64,E774 and E141)
- Neutral pion decay (NA48)
  $\pi^0 \to Z'\gamma, Z' \to e^+e^-$
- Electron-positron colliders (KLOE2 and BABAR)
  $e^+e^- \to Z'\gamma, Z' \to e^+e^-$
- (g-2)$_e$ and (g-2)$_\mu$ results
- Electron-neutrino scattering (TEXONO)
- ^{8}Be Anomaly constraints on couplings and Z' lifetime

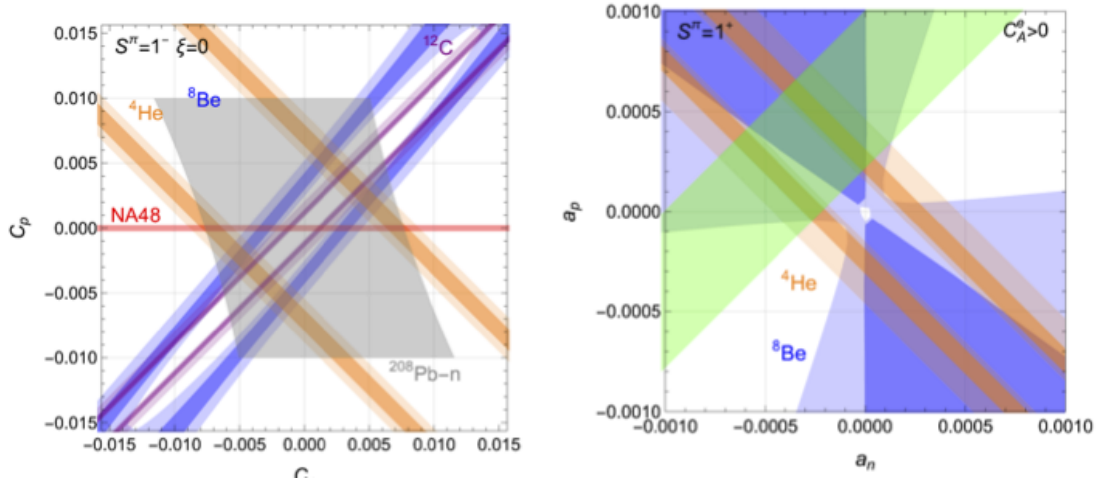
Constraints on Light Z' Bosons

Ruled out:

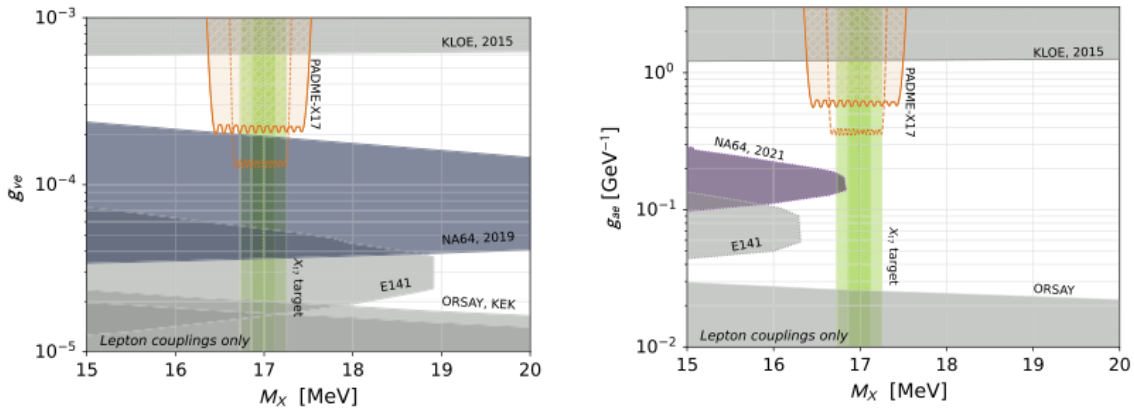
- Pure vector (NA48/2)

PADME-2023 Results:

- No signal in $e^+e^- \to \gamma + \text{inv}$ (2023)
- Excludes Z'-e coupling $\epsilon_e > 10^{-3}$ for $m_{Z'} \sim 17$ MeV



Barducci et al., JHEP02, 154 (2022)



PADME Collaboration, PRD 106, 115036 (2022)

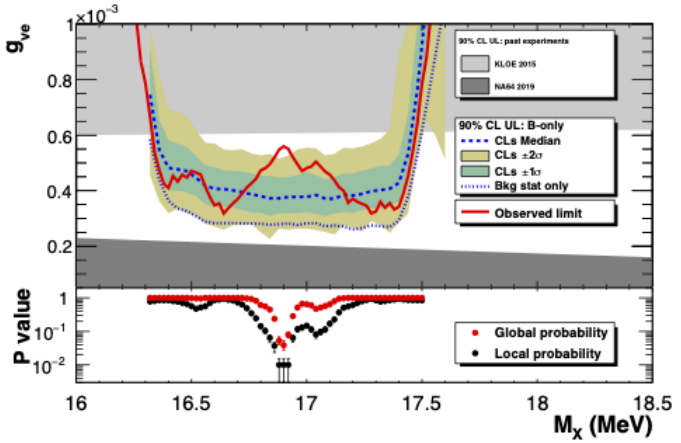
Survival Conditions

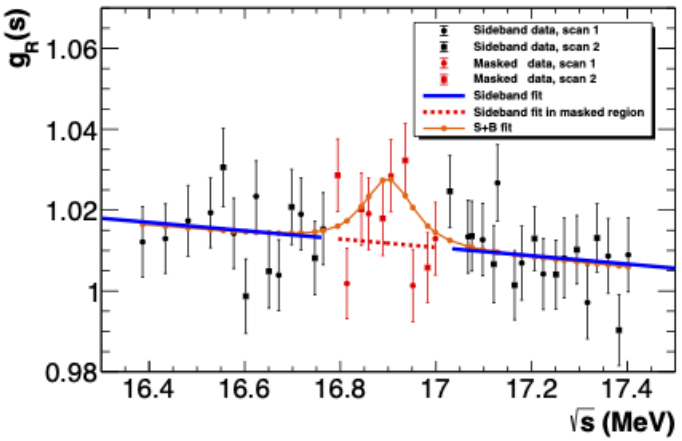
- Axial-vector dominated ($C_A^q \neq 0$)
- Suppressed Z'-e coupling ($C_V^e \lesssim 10^{-4}$)

PADME-2025: X17 Search Results

Key Findings:

- Blind analysis of $e^+e^- \to e^+e^-/\gamma\gamma$ at $\sqrt{s} = 16.4$–17.4 MeV
- Excess at 16.90 MeV:
  - Local 2.5σ, global $1.77\sigma \pm 0.15$
  - Consistent with ATOMKI's m_{X17}
- Constraints:
  - $\epsilon_e < 10^{-4}$ (previously unexplored)
  - $\delta\sigma/\sigma < 1\%$ per energy point





PADME Collaboration (2025)

Implications

- Tension with ATOMKI $\sim 1.8\sigma$ global significance
- Our $U(1)'$ model survives if $C_V^e \lesssim 10^{-4}$

Experimental Landscape

ATOMKI (2016–2024):

- 6.8σ in $^8\mathrm{Be}^* \to e^+e^-$
- $m_{X17} = 17.01 \pm 0.16$ MeV

PADME (2025):

- 1.8σ excess at 16.90 MeV
- ϵ_e limits challenge vector models

Excluded:

- Pure vector (NA48/2)

Allowed:

- Axial-vector dominant
- Lepton non-universality

Resolution in Our Model

Axial C_A^q explains ATOMKI + small C_V^e evades PADME

Minimal U(1) Extension of SM

We focus on a semi-universal $U(1)'$ extension of the SM in which the kinetic term in the Lagrangian is given by

$$\mathcal{L}_{\rm kin} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \frac{1}{4}\hat{F}'_{\mu\nu}\hat{F}'^{\mu\nu} - \frac{\eta}{2}\hat{F}'_{\mu\nu}\hat{F}^{\mu\nu}, \tag{1}$$

where η quantifies the mixing between the SM $U(1)_Y$ and extra $U(1)'$. After the diagonalization of Eq. (1), the covariant derivative can be written as

$$\mathcal{D}_\mu = \partial_\mu + ... + ig_1 Y B_\mu + i(\tilde{g}Y + g'z)B'_\mu, \tag{2}$$

where z and g' are the $U(1)'$ charge and its gauge coupling. Further, $\tilde{g}$ is the mixed gauge coupling between the two groups.
g' and $\tilde{g}$ in terms of original diagonal gauge couplings and the kinetic mixing parameter η as

$$g' \equiv \frac{g_{U(1)'}}{\sqrt{1-\eta^2}}, \quad \tilde{g} \equiv -\frac{\eta g_1}{\sqrt{1-\eta^2}}. \tag{3}$$

Higgs Sector

The $U(1)'$ symmetry is broken by a new SM singlet scalar, χ, with $U(1)'$ charge z_χ and Vacuum Expectation Value (VEV) v'. The scalar potential for the Higgs fields can be written as

$$V(H,\chi) = -\mu^2|H|^2 + \lambda|H|^4 - \mu_\chi^2|\chi|^2 + \lambda_\chi|\chi|^4 + \kappa|\chi|^2|H|^2. \tag{4}$$

H is the SM Higgs doublet while κ is the mixing parameter which connects that SM and χ Higgs fields. After Electro-Weak Symmetry Breaking (EWSB), the Higgs mass matrix in the (h_2, h_1) basis can be written as

$$m^2_{h_2 h_1} = \begin{pmatrix} 2\lambda v^2 & \kappa v v' \\ \kappa v v' & 2\lambda_\chi v'^2 \end{pmatrix}, \tag{5}$$

where h_2 is dominantly the SM-like Higgs boson while the exotic state h_1 is dominantly the singlet Higgs (χ-like). In this work, we consider $m_{h_1} < m_{h_2}$.

Z' Interactions

The spontaneous breaking of the $U(1)'$ symmetry implies the existence of a mass term $m_{Z'} = g' z_\chi v'$. Thus, if $g' \sim \mathcal{O}(10^{-4} - 10^{-5})$, M'_Z would be of order $\mathcal{O}(10)$ MeV.

The Neutral Current (NC) interactions of this additional vector boson with the SM fermions are given as

$$\mathcal{L}^{Z'}_{\rm NC} = -\sum_f \bar{\psi}_f \gamma^\mu \left(C_{f,L} P_L + C_{f,R} P_R \right) \psi_f Z'_\mu, \tag{6}$$

where Left (L) and Right (R) handed coefficients are written as

$$\begin{aligned} C_{f,L} &= -g_Z \sin\theta' \left(T^3_f - \sin^2\theta_W Q_f \right) + (\tilde{g} Y_{f,L} + g' z_{f,L}) \cos\theta', \\ C_{f,R} &= g_Z \sin^2(\theta_W) \sin(\theta') Q_f + (\tilde{g} Y_{f,R} + g' z_{f,R}) \cos(\theta'). \end{aligned} \tag{7}$$

In the limit of small gauge coupling and mixing, $g', \tilde{g} \ll 1$, we can redefine the vector and axial couplings as

$$\begin{aligned} C_{f,V} &\approxeq \tilde{g} \cos^2(\theta_W) Q_f + g' [Q'_H (T^3_f - 2\sin^2(\theta_W) Q_f) + (Q'_{f,R} + Q'_{f,L})/2], \\ C_{f,A} &\approxeq g' [-Q'_H T^3_f + (Q'_{f,R} - Q'_{f,L})/2]. \end{aligned} \tag{8}$$

Yukawa Sector

SM Yukawa Lagrangian

$$-\mathcal{L}^{\mathrm{SM}}_{\mathrm{Yuk.}} = Y_u \bar{Q} \tilde{H} u_R + Y_d \bar{Q} H d_R + Y_e \bar{L} H e_R.$$

with the gauge invariance conditions of

$$-Q'_Q - Q'_H + Q'_u = -Q'_Q + Q'_H + Q'_d = -Q'_L + Q'_H + Q'_e = 0 \tag{10}$$

No axial-vector couplings to the Z' for quarks and leptons!!!

Yukawa Lagrangian with higher order terms only for first two fermion generations

$$-\mathcal{L}_{\mathrm{Yuk.}} = \Gamma^u \frac{\chi^{n_{ij}}}{M^{n_{ij}}} \overline{Q}_{L,i} \tilde{H} u_{R,j} + \Gamma^d \frac{\chi^{l_{ij}}}{M^{l_{ij}}} \overline{Q}_{L,i} H d_{R,j} = \Gamma^e \frac{\chi^{m_{ij}}}{M^{m_{ij}}} \overline{L}_i H e_{R,j} + h.c.,$$

with

$$-Q'_{Q_{1,2}} - Q'_H + Q'_{u_{1,2}} \neq 0$$
$$-Q'_{Q_{1,2}} + Q'_H + Q'_{d_{1,2}} \neq 0.$$

where M is the non-renormalisable scale .

Delle Rose, Khalil, King, Moretti and Thabt, , Phys. Rev. D 99, no.5, 055022 (2019)

Possible axial-vector couplings to the Z' for quarks and leptons!!!

Anomaly Cancellation

Conditions

$$\sum_{i=1}^{3}(2Q'_{Q_i} - Q'_{u_i} - Q'_{d_i}) = 0\,,$$

$$\sum_{i=1}^{3}(3Q'_{Q_i} + Q'_{L_i}) = 0\,,$$

$$\sum_{i=1}^{3}\left(\frac{Q'_{Q_i}}{6} - \frac{4}{3}Q'_{u_i} - \frac{Q'_{d_i}}{3} + \frac{Q'_{L_i}}{2} - Q'_{e_i}\right) = 0\,,$$

$$\sum_{i=1}^{3}\left(Q'^{2}_{Q_i} - 2Q'^{2}_{u_i} + Q'^{2}_{d_i} - Q'^{2}_{L_i} + Q'^{2}_{e_i}\right) = 0\,,$$

$$\sum_{i=1}^{3}\left(6Q'^{3}_{Q_i} - 3Q'^{3}_{u_i} - 3Q'^{3}_{d_i} + 2Q'^{3}_{L_i} - Q'^{3}_{e_i}\right) + \sum_{i=1}^{3}Q'^{3}_{\nu_i} = 0\,,$$

$$\sum_{i=1}^{3}\left(6Q'_{Q_i} - 3Q'_{u_i} - 3Q'_{d_i} + 2Q'_{L_i} - Q'_{e_i}\right) + \sum_{i=1}^{3}Q'_{\nu_i} = 0.$$

Example Solution

Field	Q'_1	Q'_2	Q'_3
L_i	-1.6	-1.4	-0.9
e_i	-2.9	-3.1	-2.2

Neutrino Non-Standard Interactions

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{fX}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_X f)$$

- Z' mediates matter NSIs:

$$\epsilon^{fV}_{\alpha\beta} = \frac{C_L^{\alpha\beta}C_V^{ff}}{2\sqrt{2}G_F m^2_{Z'}}$$

$$\varepsilon^{fX}_{\alpha\beta} \propto \frac{1}{q^2 - M^2}$$

- IceCube probes via atmospheric ν:
  - 5.6-100 GeV energy range
  - Earth matter effects (upgoing ν)

Hamiltonian in Matter:

$$H_{\text{eff}} = H_{\text{vac}} + \sqrt{2}G_F N_e \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

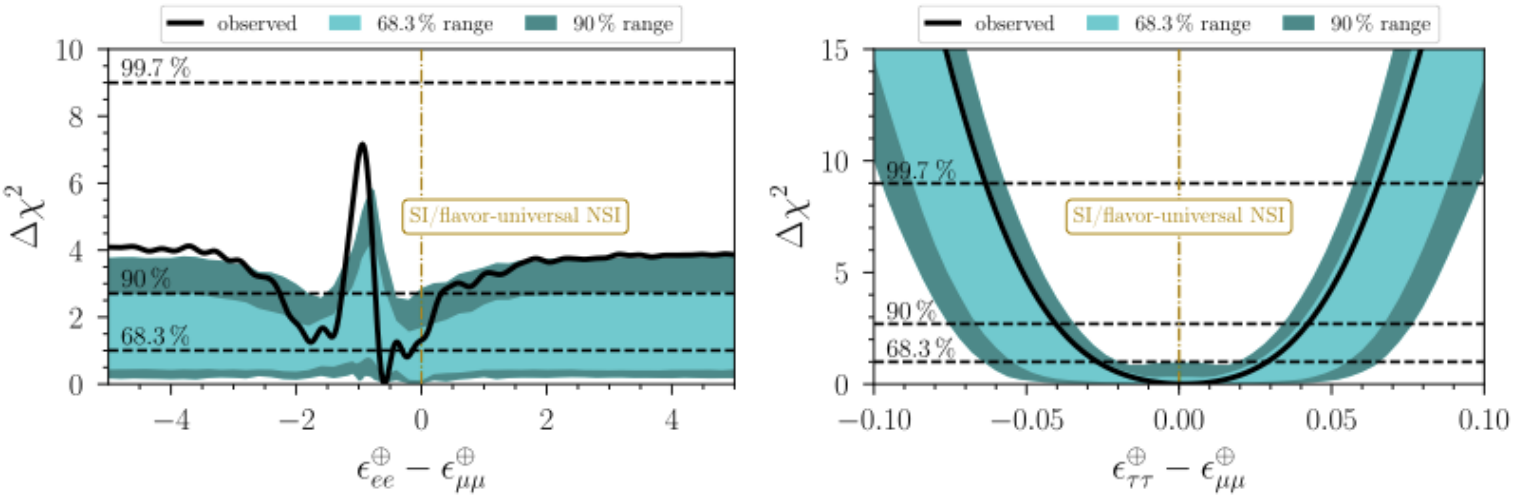
IceCube Sensitivity:

- ν_μ disappearance $\propto |\epsilon_{\mu\tau}|$
- Earth matter effects enhance $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$

IceCube Constraints

$$\begin{pmatrix} \epsilon_{ee} - \epsilon_{\mu\mu} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & 0 & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} - \epsilon_{\mu\mu} \end{pmatrix}$$

IceCube Constraints



R. Abbasi et al.(IceCube Collaboration), Phys. Rev. D 104 (2021) no.7, 072006

IceCube Results

$$\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu} \in [-0.041, 0.042] \quad (90\%\ \text{CL})$$

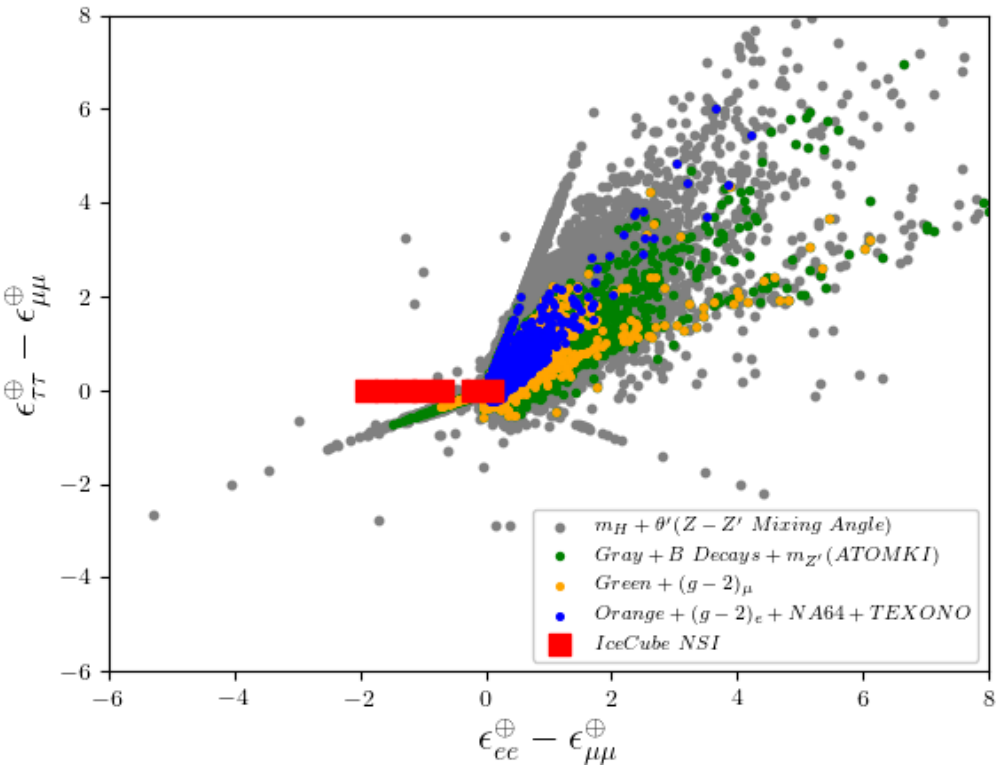
$\Rightarrow$ Enforces $|C_{\nu_\mu} / C_{\nu_\tau}| \approx 1$

$$\epsilon_{ee} - \epsilon_{\mu\mu} \in [-2.26, 0.32] \quad (90\%\ \text{CL})$$

Implications:

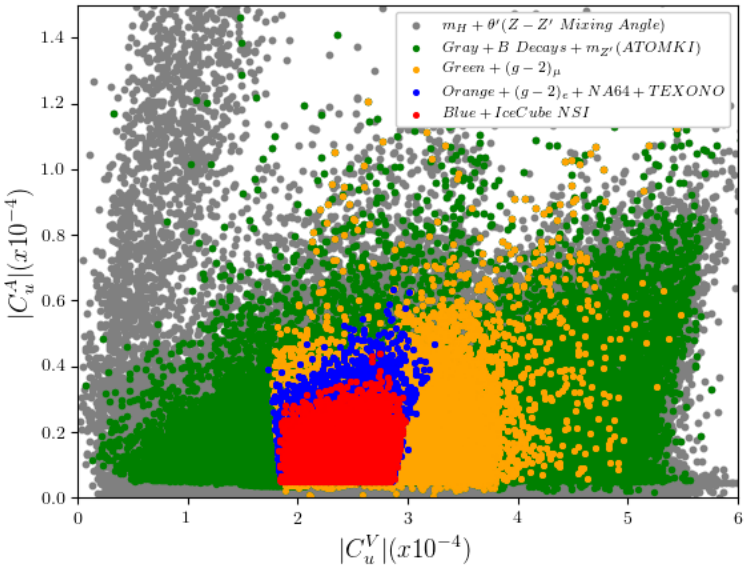
- Requires $C_V^\mu \approx C_V^\tau$
- Allows $C_A^\mu \neq C_A^\tau$

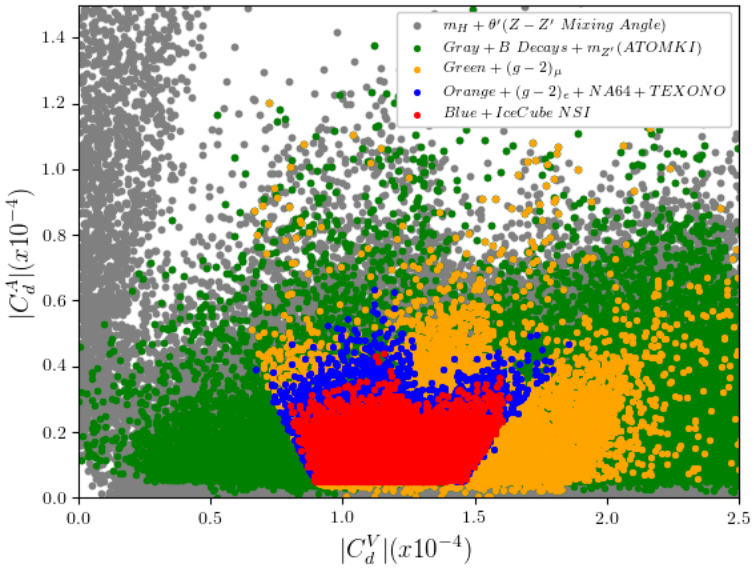
Results: The distribution of diagonal NSI parameters

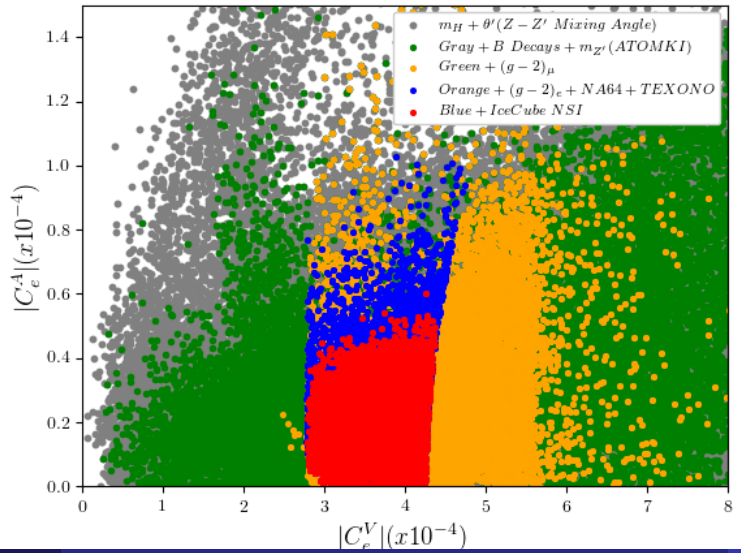


- Gray: Allowed by $m_H + Z - Z'$ mixing
- Green: Allowed by Gray + B-decays and m'_Z (ATOMKI)
- Yellow: Allowed by Green + $(g-2)_\mu$
- Blue: Allowed by Yellow + $(g-2)_e$ + NA64 + TEXONO
- Red: Allowed by Blue + IceCube NSI

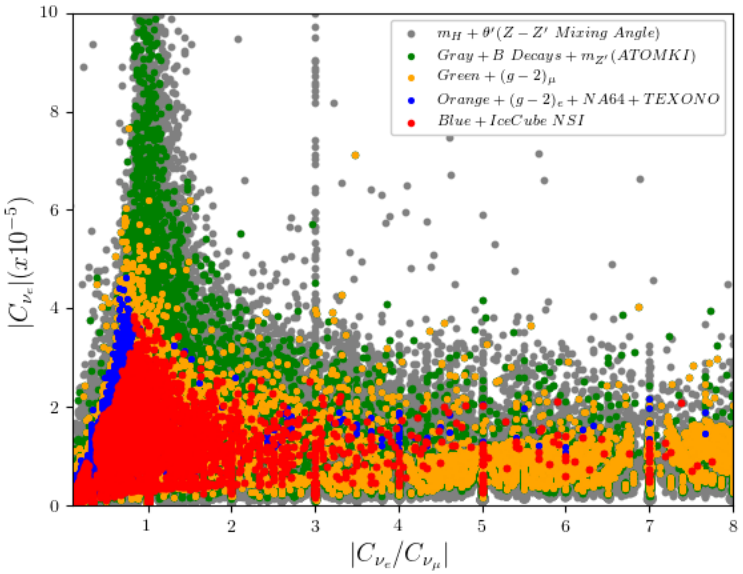
Global Constraints: Vector&Axial-Vector Couplings

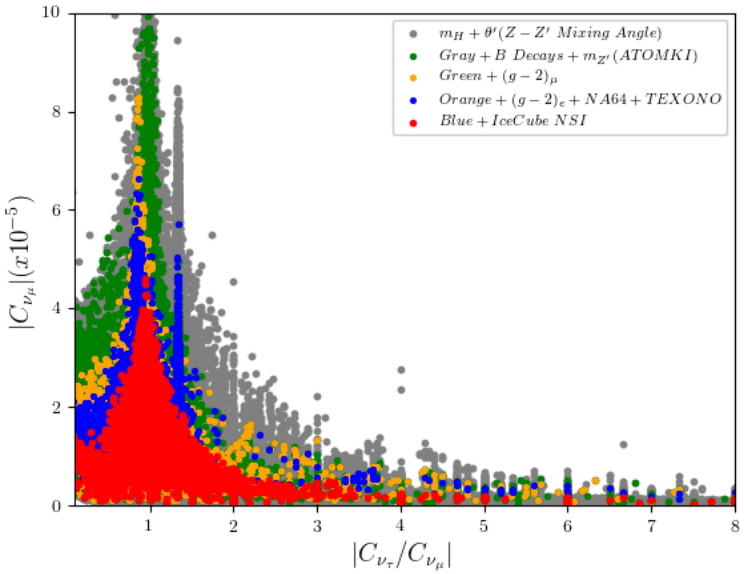


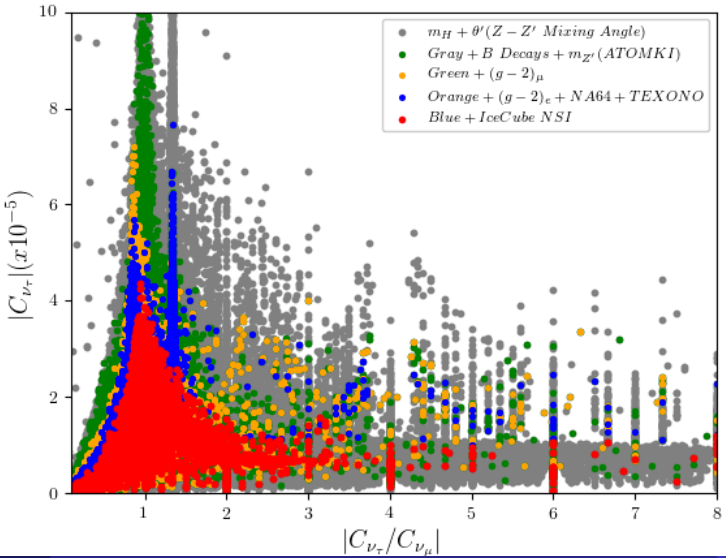




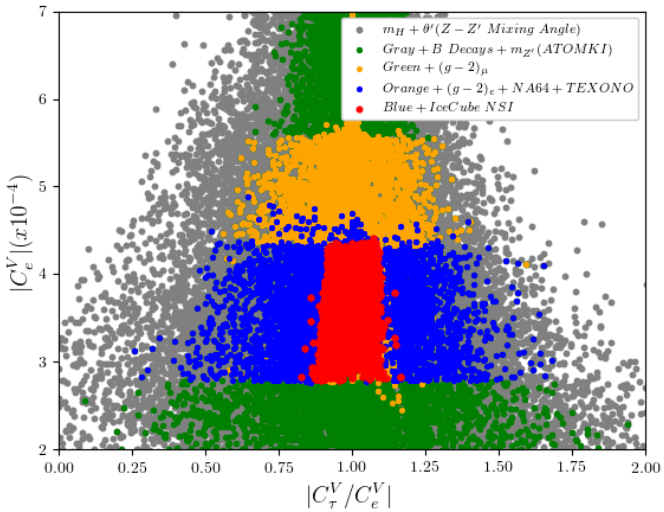
Global Constraints: Neutrino Couplings

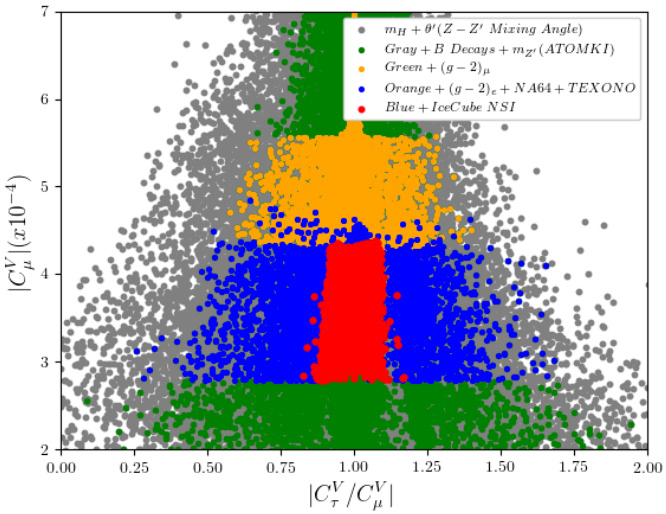


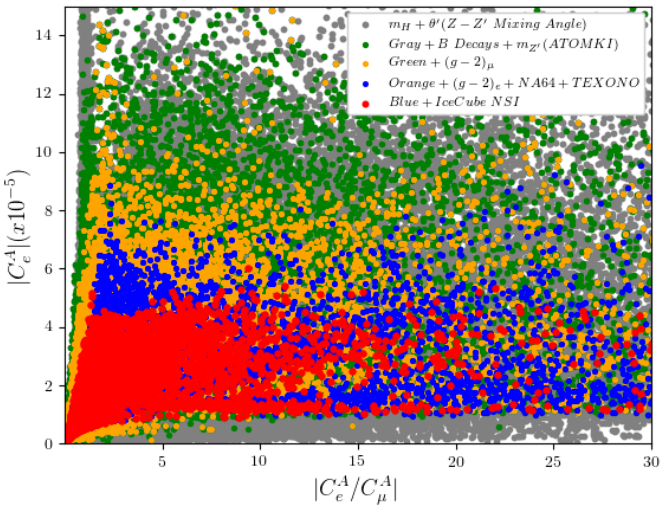


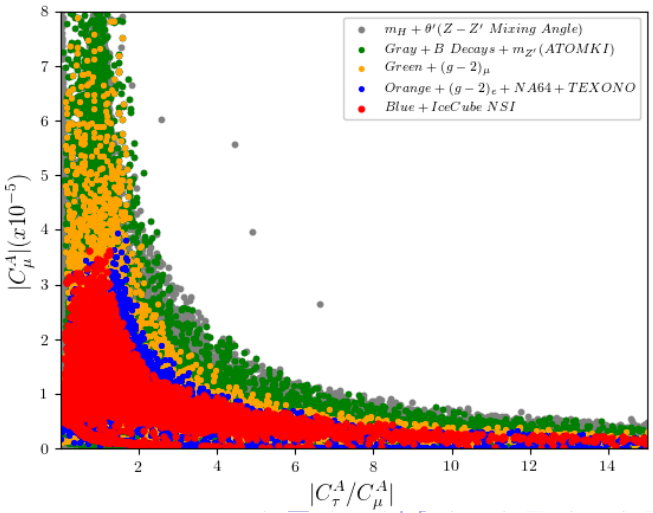


Global Constraints: Vector&Axial-Vector Couplings (Leptons)

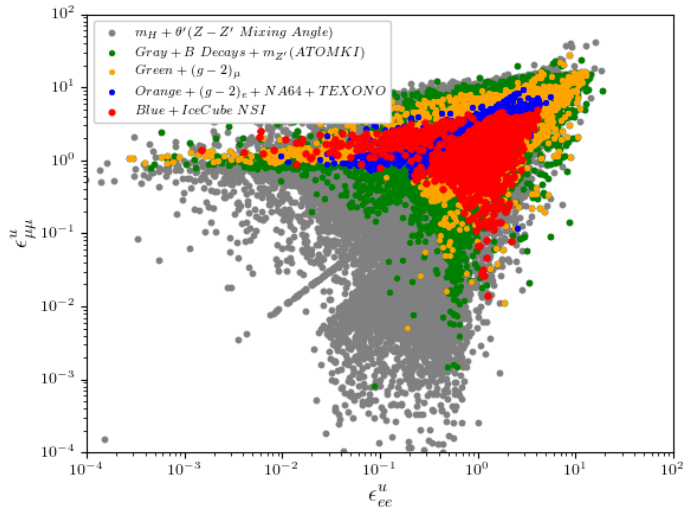


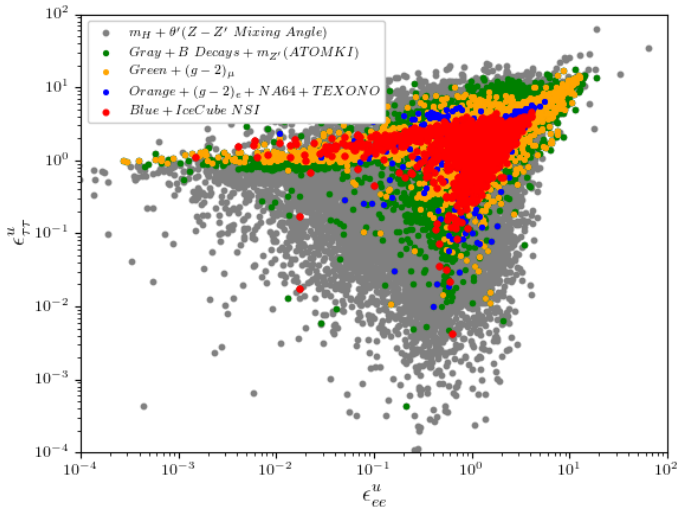


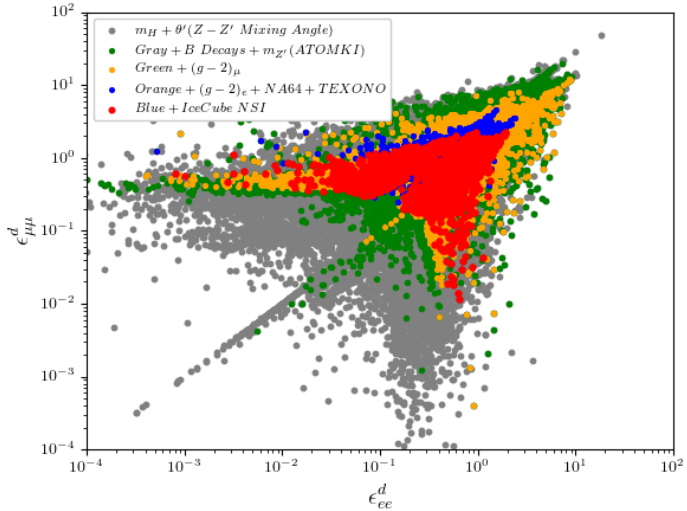


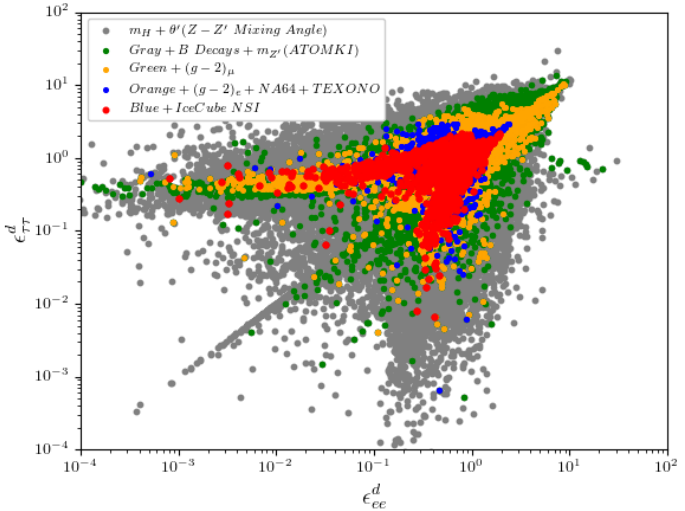


Global Constraints: NSI effective couplings of neutrinos with up&down quarks via Z' mediation

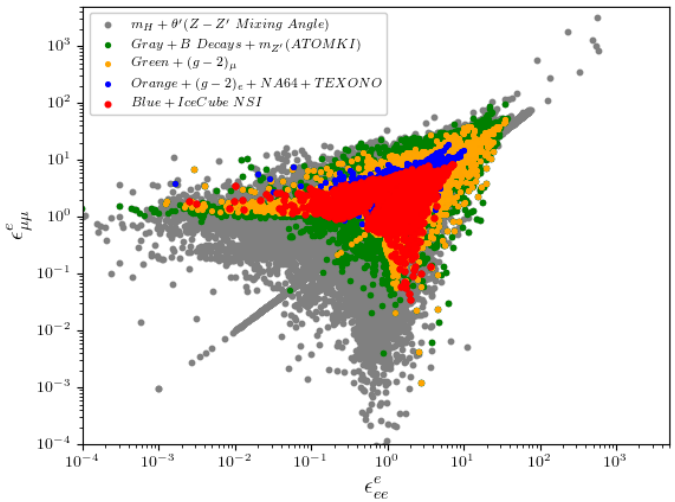


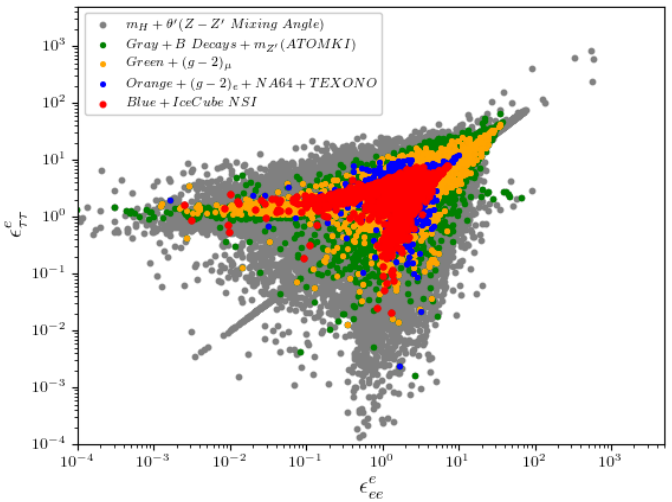






Global Constraints: NSI effective couplings of neutrinos with electrons via Z' mediation





Benchmark Points

- Vector couplings $\sim \mathcal{O}(10^{-4})$
- Axial couplings $\sim \mathcal{O}(10^{-5})$
- IceCube excludes most non-universal scenarios:
  - $|C_{\nu_\mu}/C_{\nu_\tau}| \approx 1$
  - $|C_e^V/C_\mu^V| \approx 1$

BP	g'	v' (GeV)	C_A^q	C_V^e
1	1.2×10^{-5}	746	1.4×10^{-5}	3.6×10^{-4}
2	1.5×10^{-5}	588	-1.3×10^{-5}	3.8×10^{-4}

BP1 Properties:

- Explains ATOMKI at 1σ
- $\Delta a_e = 0.8 \times 10^{-13}$

BP2 Properties:

- Better IceCube fit
- LFV testable

Summary

- Key achievement: Viable $X17$ solution compatible with:
  - ATOMKI anomaly (Z' axial couplings)
  - $(g-2)_{e,\mu}$ and beam dump constraints
  - IceCube NSI limits

Experiment	Sensitivity to Our Model	Result
ATOMKI	C_A^q	✓
PADME	C_V^e	Excluded $\epsilon_e > 10^{-3}$
IceCube	C_V^ν	✓

- Critical constraints:
  - IceCube enforces ν_μ-ν_τ universality
  - TEXONO bounds $\sqrt{\epsilon_e \epsilon_\nu} < 3 \times 10^{-4}$
- Outlook:
  - DUNE (NSI sensitivity)
  - NA64 upgrades ($Z' \to e^+e^-$)
  - LFV searches probe axial couplings

Thank you!