Non-Standard Neutrino Interactions: From Oscillations to Colliders

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Neutrinos: Cornerstone of the SM

At low energies, Fermi's contact interactions:

$$-\mathcal{L}^{cc}_{eff} = \frac{G_F}{\sqrt{2}} J^\mu_W J^\dagger_{W\mu}\,, \quad -\mathcal{L}^{NC}_{eff} = \frac{G_F}{\sqrt{2}} J^\mu_Z J_{Z\mu}\,, \quad \frac{G_F}{\sqrt{2}} \simeq \frac{g^2}{8M_W^2} = \frac{1}{2\nu^2}$$

$$J^{\mu\dagger}_W = (\bar\nu_e \bar\nu_\mu \bar\nu_\tau)\gamma^\mu(1-\gamma^5)V_\ell \overset{\text{PMNS}}{\begin{pmatrix} e^- \\ \mu^- \\ \tau^- \end{pmatrix}} + (\bar u\ \bar c\ \bar t)\gamma^\mu(1-\gamma^5)V_q \overset{\text{CKM}}{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}$$

$$J^\mu_Z = \sum_m \left[\bar u_{mL}\gamma^\mu u_{mL} - \bar d_{mL}\gamma^\mu d_{mL} + \bar\nu_{mL}\gamma^\mu \nu_{mL} - \bar e_{mL}\gamma^\mu e_{mL}\right]$$

At and above the EW scale:

$$\mathcal{L} = -\frac{g}{2\sqrt{2}}\left(J^\mu_W W^-_\mu + J^{\mu\dagger}_W W^+_\mu\right) - \frac{g}{2\cos\theta_W} J^\mu_Z Z_\mu$$

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Neutrinos Remain Most Elusive

Fundamental questions remain:

- Are neutrinos Dirac/Majorana? Leptogenesis?
- The three-mass ordering?
- How large is the CP phase?
- … … The next discovery (maybe)
- Are there "Non-Standard Interactions" (NSI)?

1. **NSI at the COHERENT & LHC #**
2. **NSI with a "Leptonic Scalar" ***

arXiv:1910.03272 [hep-ph] JHEP 1911 (2019), 028
TH, Hongkai Liu, Jiajun Liao, Danny Marfatia

* arXiv:1910.01132 [hep-ph]
Andre de Gouvea, Bhupal Dev, Bhaska Dutta, T. Ghosh, TH, Yongchao Zhang

1. "NSI": COHERENT & LHC

As originally formulated by Wolfenstein, NSI:

$$\mathscr{L}_{\mathrm{NSI}} = -2\sqrt{2}G_F \sum_{f,C,\alpha,\beta} \epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_C f)$$

$$= -\sqrt{2}G_F \epsilon^{fV}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu f) - \sqrt{2}G_F \epsilon^{fA}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu \gamma^5 f)$$

$$\epsilon^{fV}_{\alpha\beta} \equiv \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}\,, \quad \epsilon^{fA}_{\alpha\beta} \equiv \epsilon^{fR}_{\alpha\beta} - \epsilon^{fL}_{\alpha\beta}$$

- We will only consider the NC NSI.
- For a heavy mediator: $\boldsymbol{\varepsilon} \sim g'^2\, v_{EW}{}^2/M^2$.
- Interesting to consider UV formulation

L. Wolfenstein (1978);
T. Ohlsson arXiv:1209.2710;
Farzan & Tortola, arXiv:1710.09160.

Consider a UV-complete U(1)' model:

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} - \frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \frac{1}{2} M_{Z'}^2 Z'^{\mu} Z'_{\mu} + Z'_{\mu} J_X^{\mu}$$

$$J_X^{\mu} = g' \left[\sum_q Q'_q \bar{q} \gamma^{\mu} q + \sum_{L_\ell = \nu_{\ell L}, \ell} Q'_\ell \overline{L_\ell} \gamma^{\mu} L_\ell \right]$$

the quark charges $Q'_{1,2,3}$ and lepton charges $Q'_{e,\mu,\tau}$ satisfying the constraint

$$3(Q'_1 + Q'_2 + Q'_3) + Q'_e + Q'_\mu + Q'_\tau = 0\,.$$

$$Q'_1 = Q'_2 = Q'_3 = Q'_q$$

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Our representative choices for U(1)' charges:

(A) $Q'_q = 1/3, \underline{Q'_\mu = -3, Q'_e = Q'_\tau} = 0.$

(B) $Q'_q = 1/3, \underline{Q'_\mu = Q'_\tau = -3/2, Q'_e} = 0.$

(C) $Q'_q = 1/3, \underline{Q'_\tau = -3, Q'_e = Q'_\mu} = 0.$

- Electron flavor heavily constrained (beam-dump), not included here
- MZ' ~ 5 MeV – O(TeV)
  → heavy for oscillation expts, but suitable for LHC searches.

Neutrino oscillation experiments

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \delta m_{21}^2 & 0 \\ 0 & 0 & \delta m_{31}^2 \end{pmatrix} U^\dagger + V, \qquad V = \sqrt{2} G_F N_e \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

$\epsilon^u_{\alpha\alpha}$	Current data	DUNE+T2HK
ϵ^u_{ee}	$[-1.192, -0.802] \oplus [-0.020, +0.456]$	$[-0.407, -0.270] \oplus [-0.072, +0.064]$
$\epsilon^u_{\mu\mu}$	$[-0.130, 0.152]$	$[-0.019, +0.018]$
$\epsilon^u_{\tau\tau}$	$[-0.152, 0.130]$	$[-0.017, +0.017]$

I. Esteban et al., arXiv:1805.04530.

Table 1: 2σ allowed ranges for the diagonal NSI parameters from the global analysis of current oscillation data assuming both LMA and LMA-D [22] and from the simulation of next generation neutrino oscillation experiments DUNE and T2HK.

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In our Z' model: $M_{Z'} \sim 5$ MeV – 20 MeV

$$\mathscr{L}_{\rm eff} = \frac{(g')^2}{M^2_{Z'}} \left[\sum_q Q'_q \bar{q} \gamma^\mu q\right] \left[\sum_\alpha Q'_\alpha \bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha\right] \qquad \epsilon^{qV}_{\alpha\alpha} = -\frac{(g')^2 Q'_\alpha Q'_q}{\sqrt{2} G_F M^2_{Z'}}$$

$$\epsilon_{\alpha\beta} \equiv \sum_q \epsilon^{qV}_{\alpha\beta} \frac{N_q}{N_e}$$

CEvNS Constraints – COHERENT expt

$M_{Z'} \sim$ 10 MeV – 10 GeV

$$\pi^+ \to \mu^+ + \nu_\mu, \text{ and}$$
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e.$$

detector — PDF — SM

$$N_{th}(t, E_r, \epsilon) = \sum_\alpha \frac{m_{\rm det} N_A}{M} \int_{\Delta E_r} dE_r \int_{\Delta t} dt \rho_\alpha(t) \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} dE_\nu \, \phi_\alpha(E_\nu) \frac{d\sigma_\alpha(\epsilon)}{dE_r}$$

$$\phi_{\nu_\mu}(E_{\nu_\mu}) = \frac{2m_\pi}{m_\pi^2 - m_\mu^2} \delta\left(1 - \frac{2E_{\nu_\mu} m_\pi}{m_\pi^2 - m_\mu^2}\right)$$

$$\phi_{\nu_e}(E_{\nu_e}) = \frac{192}{m_\mu}\left(\frac{E_{\nu_e}}{m_\mu}\right)^2 \left(\frac{1}{2} - \frac{E_{\nu_e}}{m_\mu}\right),$$

$$\phi_{\bar{\nu}_\mu}(E_{\bar{\nu}_\mu}) = \frac{64}{m_\mu}\left(\frac{E_{\bar{\nu}_\mu}}{m_\mu}\right)^2 \left(\frac{3}{4} - \frac{E_{\bar{\nu}_\mu}}{m_\mu}\right),$$

$$\frac{d\sigma_\alpha(\epsilon)}{dE_r} = \frac{G_F^2}{2\pi} Q_\alpha^2 F^2(Q^2) M (2 - \frac{M E_r}{E_\nu^2}),$$

$$Q_\alpha^2 = [Z(g_p^V + 2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{dV}) + N(g_n^V + \epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{dV})]^2$$

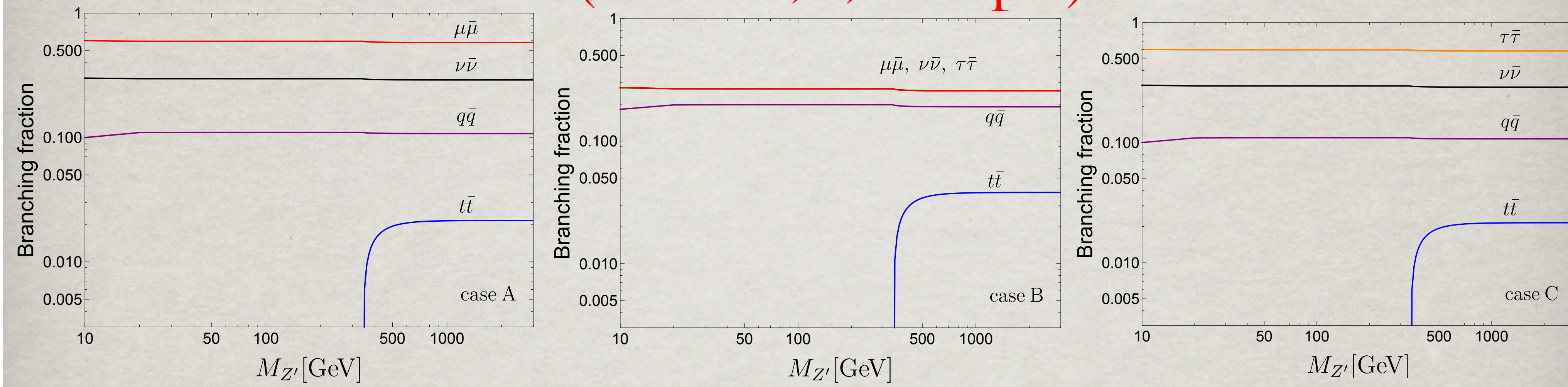
$$\frac{d\sigma_{\alpha,\rm CsI}}{dE_r} = \frac{d\sigma_{\alpha,\rm Cs}}{dE_r} + \frac{d\sigma_{\alpha,\rm I}}{dE_r}$$

$$\epsilon_{ee}^{uV} = \epsilon_{ee}^{dV} = \frac{g'^2 Q'_q Q'_e}{\sqrt{2} G_F (2 M E_r + M_{Z'}^2)}$$

$$\epsilon_{\mu\mu}^{uV} = \epsilon_{\mu\mu}^{dV} = \frac{g'^2 Q'_q Q'_\mu}{\sqrt{2} G_F (2 M E_r + M_{Z'}^2)}$$

$$\chi^2 = \sum_{i=4}^{15} \left[\frac{N_{\rm meas}^i - N_{\rm th}^i(1+\gamma) - B_{\rm on}(1+\beta)}{\sigma_{\rm stat}^i}\right]^2 + \left(\frac{\gamma}{\sigma_\gamma}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2$$

LHC Studies: $Z' \to l^+ l^-$
(Cases A,B,C on p.5)



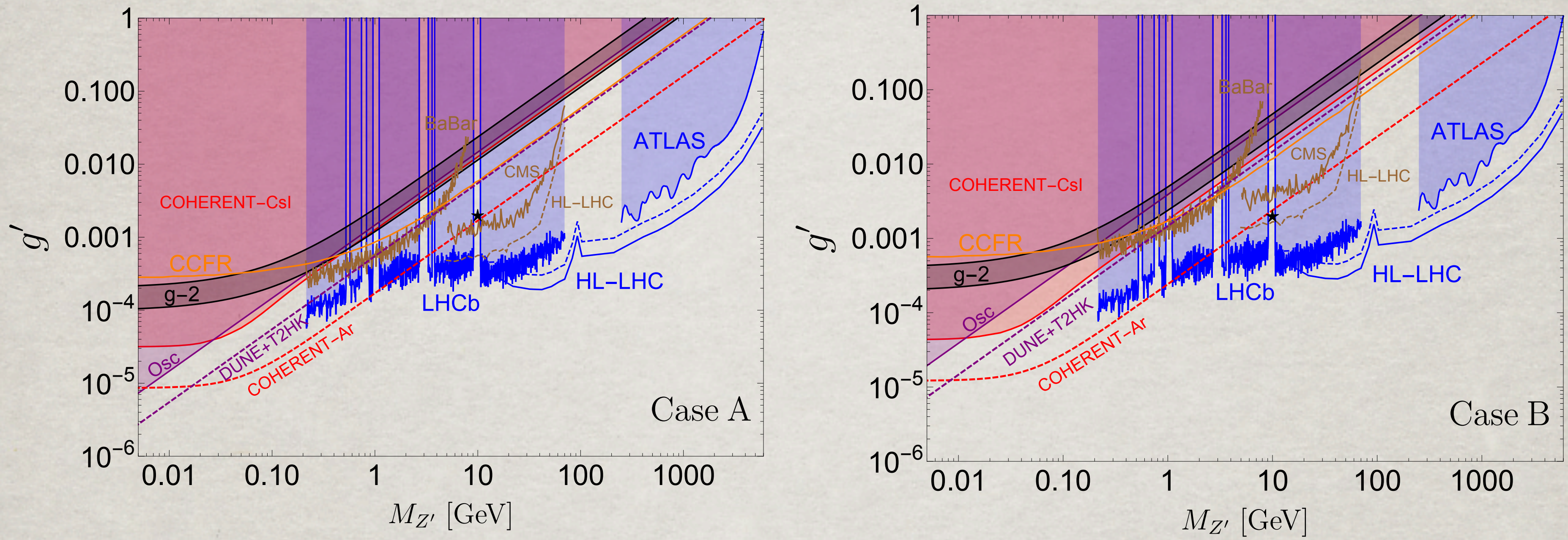
For $M_{Z'} < M_Z$ $\quad pp \to Z^*/\gamma^* \to \ell^+\ell^- + Z' \to \ell^+\ell^- + \ell^+\ell^- + X.$

- LHCb & CMS 4-lepton recast

For $M_{Z'} > M_Z$ $\quad pp \to Z' \to \ell^+\ell^- + X$

- ATLAS/CMS existing results recast
- HL-LHC new study

Everything together



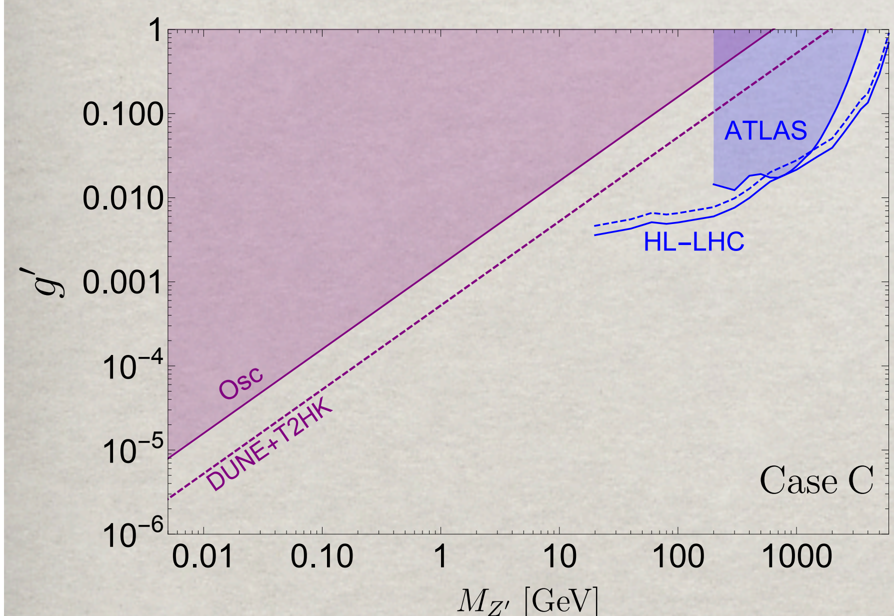
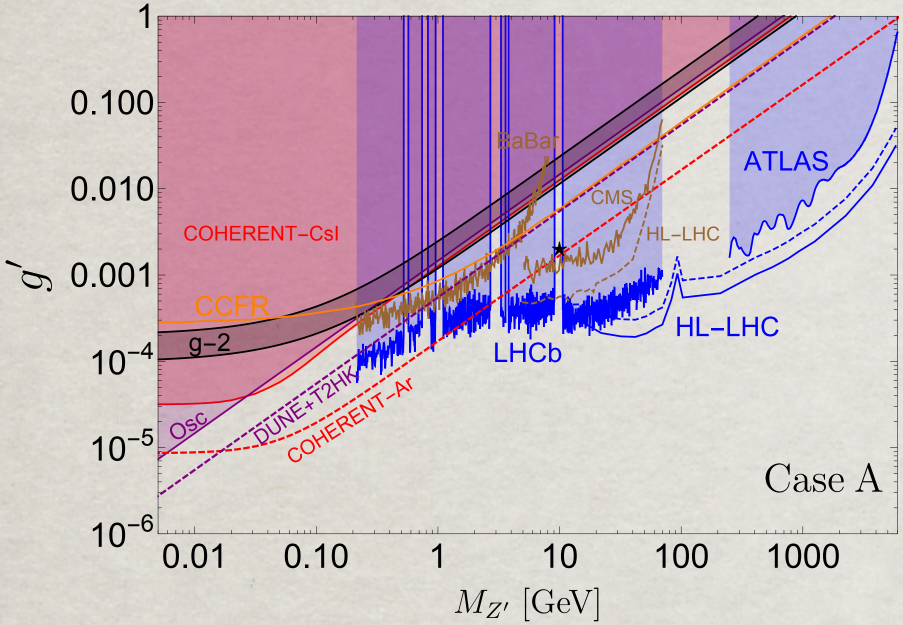
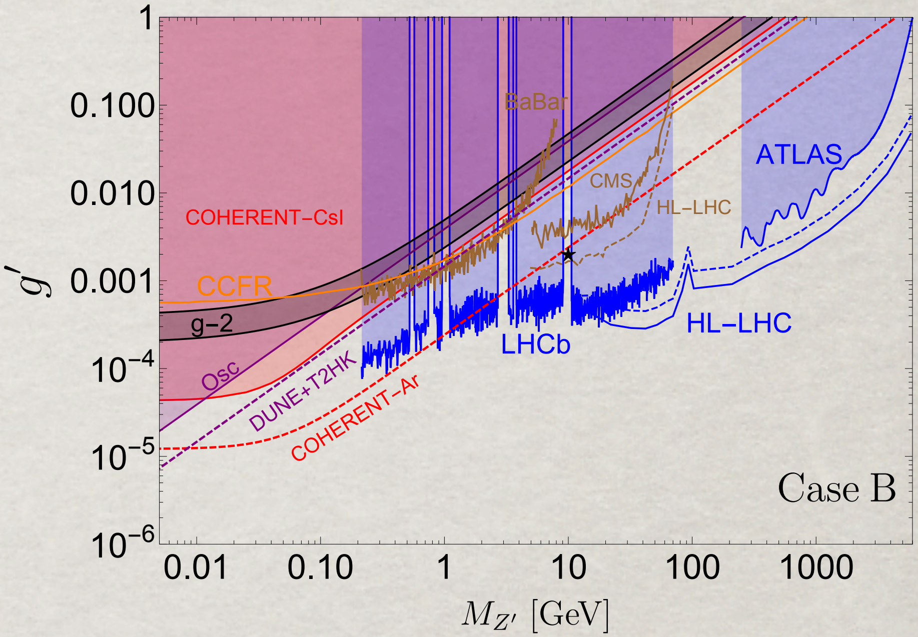
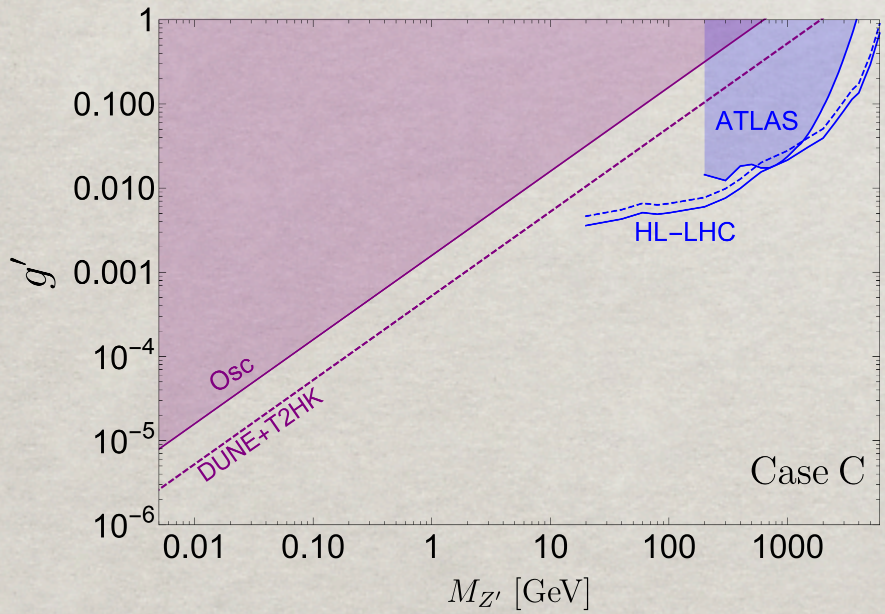


Figure 2: Bounds on g' for Cases A (upper left panel), B (upper right panel) and C (lower panel). The red shaded areas correspond to the 2σ exclusion regions by using the energy spectrum from the COHERENT CsI detector [9]. The red dashed lines show the expected 2σ limit from COHERENT with a 750 kg LAr detector [22] and a 4-year exposure using both energy and time information. The purple areas correspond to the 2σ bounds from a global fit to neutrino oscillation data [21]. The dashed purple lines show the expected 2σ exclusion limit from DUNE and T2HK combined. Regions above the brown curves are excluded by CMS [23] and BaBar [24] at 2σ and 90% CL, respectively, using $pp/e^+e^- \to \mu^+\mu^- Z'$ searches. The brown dashed curves are the 2σ expected sensitivities from HL-LHC, with an integrated luminosity of 3000 fb^{-1}, in the $\mu^+\mu^- Z'$ channel, and the blue solid (dashed) curves correspond to the expected 2σ (5σ) limit using di-muon searches for Cases A and B, and di-tau searches for Case C. In the upper panels, the blue shaded regions are excluded at 90% CL by the LHCb dark photon searches [25] and at 2σ by the ATLAS di-muon searches [26] with 139 fb^{-1}. In the lower panel, the blue area is excluded at 2σ by the ATLAS di-tau searches [27] with 36.1 fb^{-1}. The 2σ limit from CCFR [28, 29] is given by the orange curves. The 2σ allowed regions that explain the discrepancy in the anomalous magnetic moment of the muon ($\Delta a_\mu = (29 \pm 9) \times 10^{-10}$ [30]) are indicated by the black band. The black stars mark the benchmark points we consider in Section 5.

Everything together





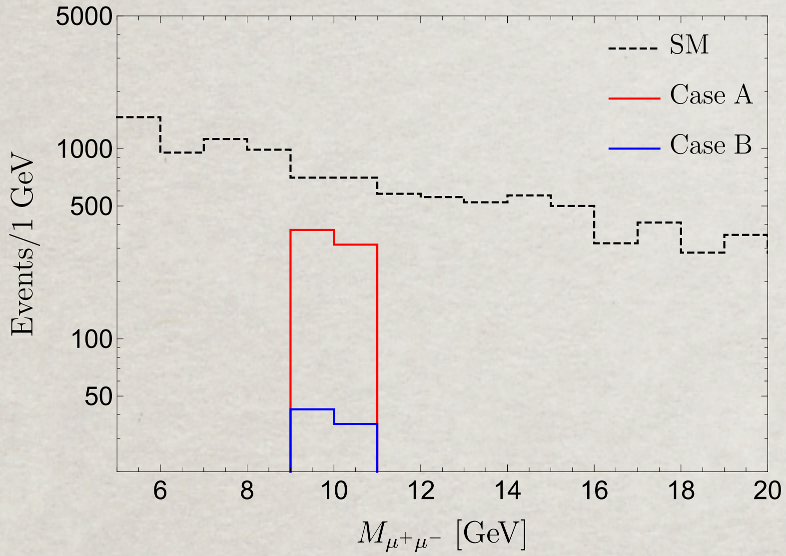


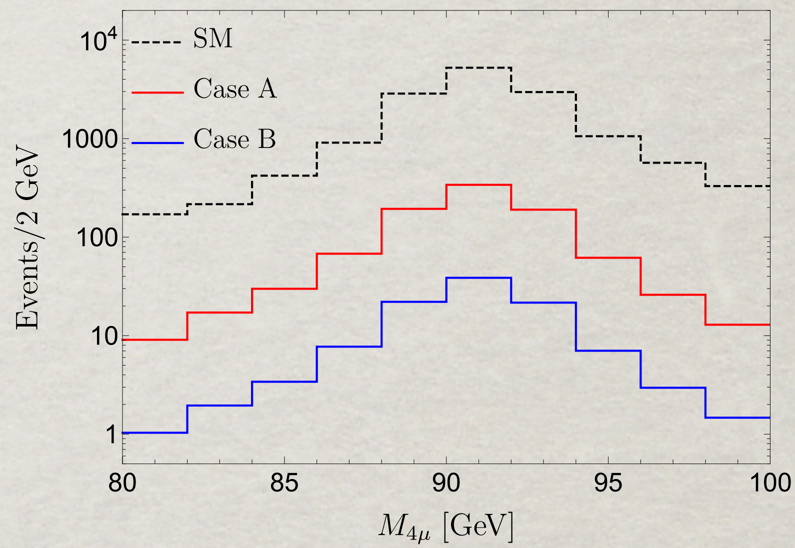
- $M_{Z'} \sim$ 5 MeV – 20 MeV: DUNE+T2HK
- $M_{Z'} \sim$ 20 MeV – 1 GeV: COHERENT Lar
- $M_{Z'} \sim$ 1 GeV – 20 GeV: LHCb, CMS 4-leptons
- $M_{Z'} \sim$ 20 GeV – 4 TeV: HL-LHC 2-leptons

COHERENT & LHC: Correlated Studies

- Generate events for SM+Z’
- Scan & search for the signal

$$\chi^2 = \sum_i \frac{N_{S,i}^2}{N_{B,i} + (\sigma_B N_{B,i})^2}$$





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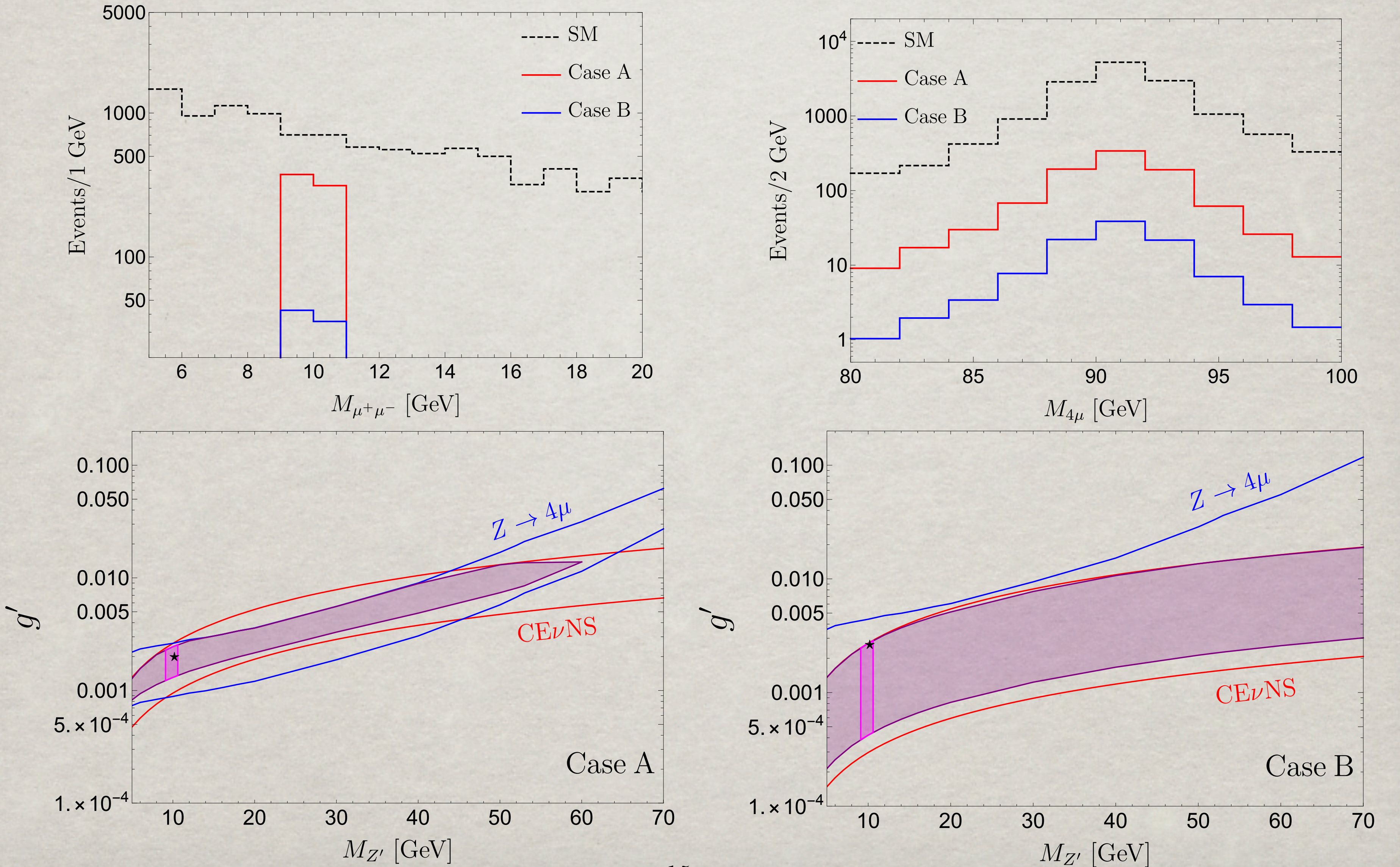

2. NSI with a "Leptonic Scalar"

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Tree-level "seesaw mechanism"

The dim-5 Weinberg operator:

$$\frac{1}{\Lambda}\,(y_\nu L H)(y_\nu L H) + h.c. \quad \Rightarrow \quad \frac{y_\nu^2 v^2}{\Lambda}\,\overline{\nu_L}\,\nu_R^c.$$

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Type-I: Add N_R's $\quad \left(\overline{\nu_L} \quad \overline{N^c}_L\right) \begin{pmatrix} 0_{3\times3} & D^\nu_{3\times n} \\ D^{\nu T}_{n\times 3} & M_{n\times n} \end{pmatrix} \begin{pmatrix} \nu^c{}_R \\ N_R \end{pmatrix}$

(along with W_R)

Minkowski (1976); Yanagita (1979); Glashow (1980); Mohapatra, Senjanovic (1980); Magg, Wetterich (1980); Lasarides, Shafi (1981); Mohapatra, Senjanovic (1981); Foot, Lew, He, Joshi (1989); G. Senjanovic (1981)

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(along with W_R)

Type-II: Add a scalar triplet $\Phi\ (Y=2):\ \phi^{\pm\pm}, \phi^{\pm}, \phi^0$ (along with W_R)

$$Y_{ij} L_i^T C (i\sigma_2) \Phi L_j + h.c. \quad \mu H^T (i\sigma_2) \Phi^\dagger H + h.c.$$

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Type-III: Add a fermionic triplet $T\ (Y=0):\ T^+\ T^0\ T^-$

$$-M_T(T^+T^- + T^0T^0/2) + y_T^i H^T i\sigma_2 T L_i + h.c.$$

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2. NSI with a "Leptonic Scalar"

Neutrinos are elusive, and could couple to new particles, and thus modify their behaviors. Consider:

$$\mathcal{L} \supset \frac{1}{2}\lambda_{\alpha\beta}\, \phi\, \nu_\alpha \nu_\beta$$

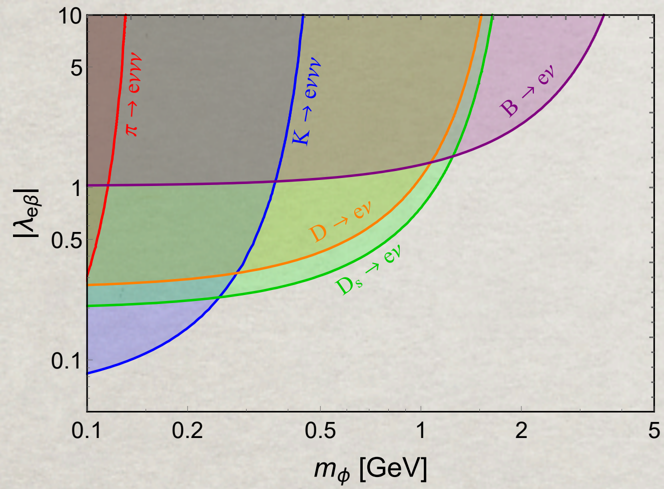
- ϕ carries lepton-number L = -2
- At renormalizable level: $\phi\, \nu_R\, \nu_R$
- At dim-6: $\lambda_{\alpha\beta} \sim \kappa_1\, \kappa_2\, v_{EW}^2/M^2$
- Could be from a UV complete formulation

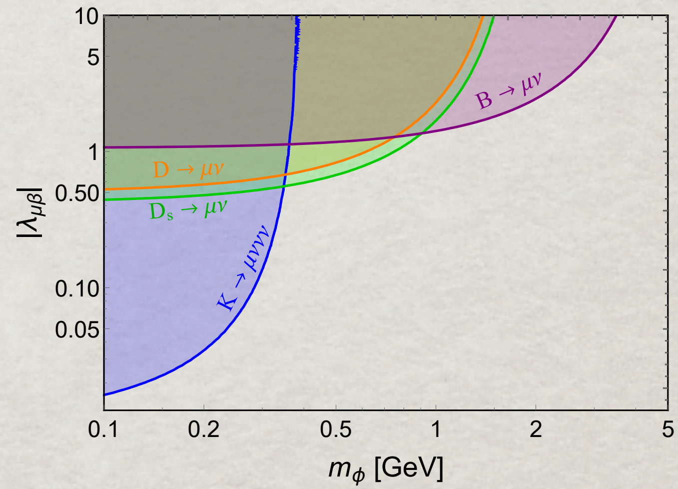
- It can radiate off any neutrino and thus could effect many processes:
  - meson decays; W/Z decays
  - light DM searches; IceCube
  - collider experiments

Low energy bounds: Meson decays

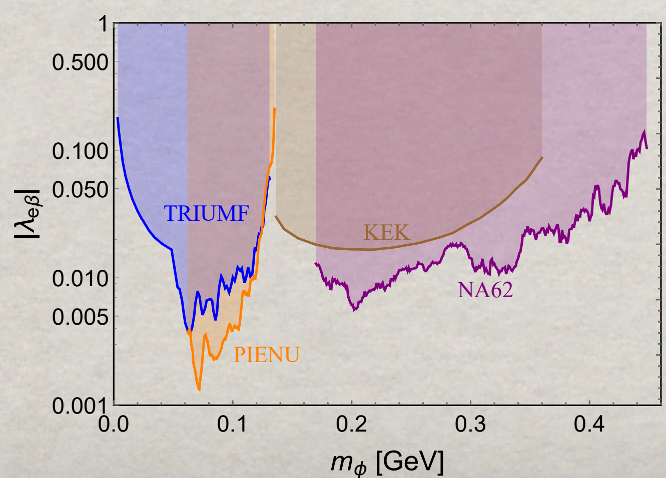
For leptonic decays of charged mesons $P^- \to \ell^- \bar{\nu}$ with $P^- = \pi^-, K^-, D^-, D_S^-, B^-$:

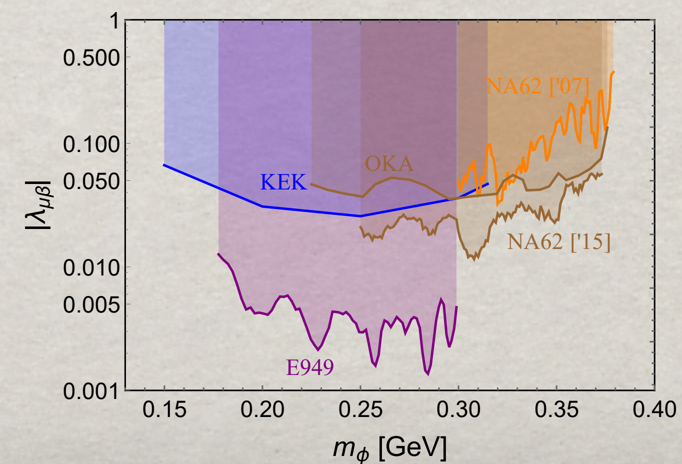
$$\Gamma(P^- \to \ell_\alpha^- \bar{\nu}\phi) = \frac{G_F^2 |V_{qq'}|^2 m_P^3 f_P^2 \sum_\beta |\lambda_{\alpha\beta}|^2}{256\pi^3} \times \int_{x_\phi}^{(1-\sqrt{x_\ell})^2} dx \frac{\left((x + x_\ell) - (x - x_\ell)^2\right)(x - x_\phi)^2}{x^3} \lambda^{1/2}(1, x, x_\ell)$$



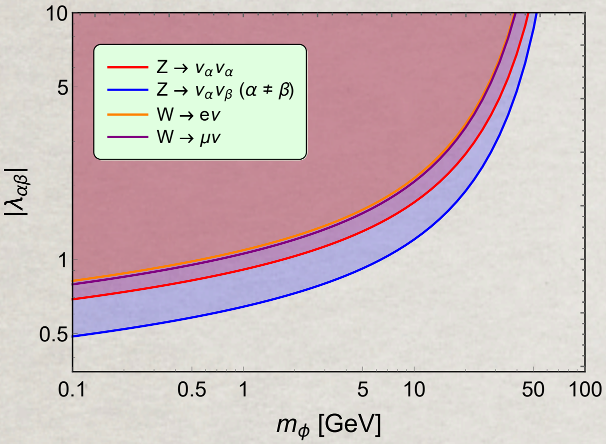


Heavy neutrino searches in meson decay spectra

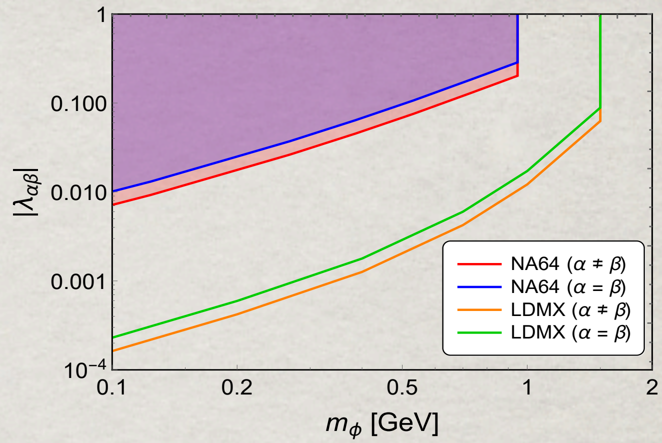




W/Z decays:



Dark photon/DM searches:



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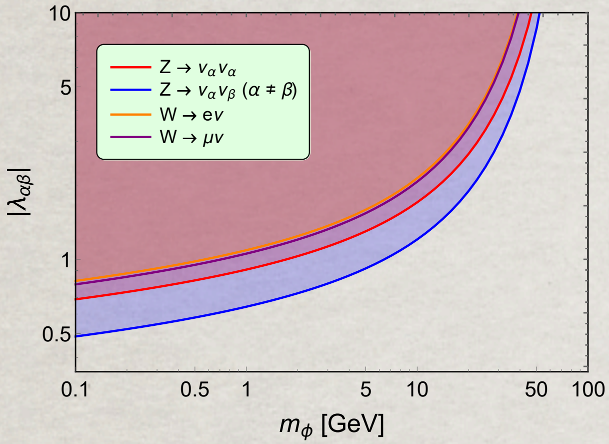

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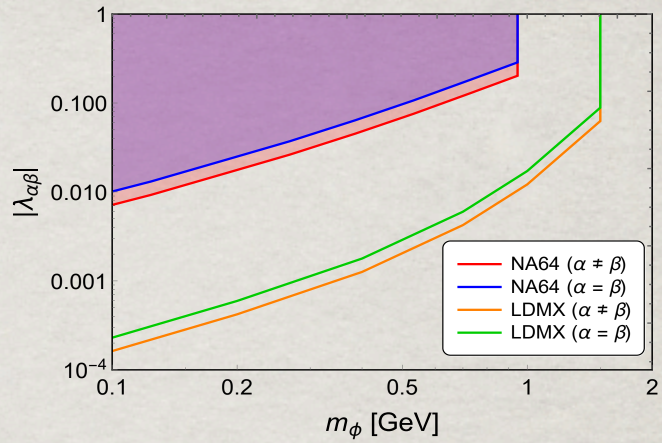


Ref.	Process	Data	Couplings	Mass range
[1, 2]	$\pi^- \to e^- \bar{\nu}_e \nu \bar{\nu}$	BR $< 5 \times 10^{-6}$	$\sum_\beta |\lambda_{e\beta}|^2$	$m_\phi < 131$ MeV
[1, 2]	$K^- \to e^- \bar{\nu}_e \nu \bar{\nu}$	BR $< 6 \times 10^{-5}$	$\sum_\beta |\lambda_{e\beta}|^2$	$m_\phi < 444$ MeV
[1, 2]	$K^- \to \mu^- \bar{\nu}_\mu \nu \bar{\nu}$	BR $< 2.4 \times 10^{-6}$	$\sum_\beta |\lambda_{\mu\beta}|^2$	$m_\phi < 386$ MeV
[1, 2]	$D^- \to e^- \bar{\nu}_e$	BR $< 8.8 \times 10^{-6}$	$\sum_\beta |\lambda_{e\beta}|^2$	$m_\phi < 1.52$ GeV
[1, 2]	$D^- \to \mu^- \bar{\nu}_\mu$	BR $< 3.4 \times 10^{-5}$	$\sum_\beta |\lambda_{\mu\beta}|^2$	$m_\phi < 1.39$ GeV
[1, 21]	$D_s^- \to e^- \bar{\nu}_e$	BR $< 8.3 \times 10^{-5}$	$\sum_\beta |\lambda_{e\beta}|^2$	$m_\phi < 1.64$ GeV
[1, 21]	$D_s^- \to \mu^- \bar{\nu}_\mu$	BR $= (5.50 \pm 0.23) \times 10^{-3}$	$\sum_\beta |\lambda_{\mu\beta}|^2$	$m_\phi < 1.50$ GeV
[1, 21]	$B^- \to e^- \bar{\nu}_e$	BR $< 9.8 \times 10^{-7}$	$\sum_\beta |\lambda_{e\beta}|^2$	$m_\phi < 3.54$ GeV
[1, 21]	$B^- \to \mu^- \bar{\nu}_\mu$	BR $= (2.90 - 10.7) \times 10^{-7}$	$\sum_\beta |\lambda_{e\beta}|^2$	$m_\phi < 3.50$ GeV
[1, 20]	$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	BR $= (17.82 \pm 0.04)\%$	$\sum_\beta |\lambda_{e\beta}|^2$	$m_\phi < 741$ MeV
[1, 20]	$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	BR $= (17.39 \pm 0.04)\%$	$\sum_\beta |\lambda_{\mu\beta}|^2$	$m_\phi < 741$ MeV
[1, 21]	$P^- \to e^- N$	see Ref. [25]	$\sum_\beta |\lambda_{e\beta}|^2$	$3.3\,\text{MeV} < m_\phi < 448$ MeV
[1, 21]	$P^- \to \mu^- N$	see Ref. [25]	$\sum_\beta |\lambda_{\mu\beta}|^2$	$87\,\text{MeV} < m_\phi < 379$ MeV
[1]	$Z \to$ inv.	BR $= (20.0 \pm 0.055)\%$	$\sum_{\alpha,\beta} S_{\alpha\beta} |\lambda_{\alpha\beta}|^2$	$m_\phi < 52.2$ GeV
[1]	$W \to e\nu$	BR $= (10.71 \pm 0.16)\%$	$\sum_\beta |\lambda_{e\beta}|^2$	$m_\phi < 38.8$ GeV
[1]	$W \to \mu\nu$	BR $= (10.63 \pm 0.15)\%$	$\sum_\beta |\lambda_{\mu\beta}|^2$	$m_\phi < 39.3$ GeV
[2]	MINOS	see Ref. [2]	$|\lambda_{\mu\mu}|$	$m_\phi < 1.67$ GeV
[2]	DUNE	see Ref. [2]	$|\lambda_{\mu\mu}|$	$m_\phi < 3.00$ GeV
[26]	NA64	see Ref. [26]	$\sum_{\alpha,\beta} S_{\alpha\beta} |\lambda_{\alpha\beta}|^2$	$m_\phi < 948$ MeV
[27]	LDMX	see Ref. [27]	$\sum_{\alpha,\beta} S_{\alpha\beta} |\lambda_{\alpha\beta}|^2$	$m_\phi < 1.50$ GeV
[28, 29]	IceCube	see Ref. [28]	$|\lambda_{\alpha\beta}|$	$m_\phi < 2.0\,(15.0)$ GeV

Some other constraints:

- *Muon decay*: As discussed in Section 2.4, ϕ can be emitted from tree-level decay $\mu \to e\nu\nu\phi$. As a result of the precise μ decay data, for sufficiently light ϕ, the limits from μ decay are expected to be much more stringent than those from τ decays. In addition, the electron [98, 99] and neutrino [100, 101] spectra could be altered in presence of ϕ, which can also be used to set limits on $\lambda_{\alpha\beta}$.

- *Tritium decay*: If the scalar mass $m_\phi \lesssim \mathcal{O}(10\,\text{eV})$, it can be produced from tritium decay in the process $^3\text{H} \to {}^3\text{He}^+ + e^- + \nu + \phi$ [102], and this process can be probed in the KATRIN experiment [103, 104].

- *$0\nu\beta\beta$ decay*: The coupling of ϕ to electron neutrinos contributes to $0\nu\beta\beta$ decays via the process $(Z, A) \to (Z+2, A)e^-e^-\phi$ if the mass $m_\phi \lesssim \mathcal{O}(\text{MeV})$ – the typical Q-value for the relevant nuclei. This is strongly constrained by the searches of Majoron emission in $0\nu\beta\beta$ decay experiments like NEMO-3 using ^{100}Mo [6, 7, 11] and ^{150}Nd [9] nuclei, as well as KamLAND-Zen [12] and EXO-200 [13] using ^{136}Xe. Somewhat weaker limits were also obtained by NEMO-3 using ^{48}Ca [8] and ^{82}Se [10], as well as by GERDA using ^{76}Ge [14].

- *Supernovae*: A light ϕ can be produced abundantly in the supernova core if its mass $m_\phi \lesssim \mathcal{O}(30\,\text{MeV})$ – the typical core temperature of supernovae. The couplings $|\lambda_{\alpha\beta}|$ can be constrained from both the luminosity and deleptonization arguments [105–107].

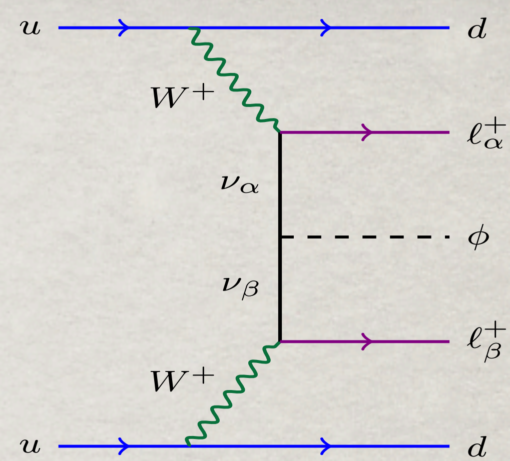
- *CMB and BBN*: As a light particle, ϕ itself contributes to the relativistic degrees of freedom N_{eff} if the mass $m_\phi \lesssim 100$ keV [108]. The current precision cosmological data $\Delta N_{\text{eff}} = 0.18$ at 1σ C.L. [109] has excluded a large parameter space for such light leptonic scalar mass m_ϕ and the couplings $|\lambda_{\alpha\beta}|$. Similarly, the big-bang-nucleosynthesis (BBN) constraints rule out $m_\phi \lesssim 0.2$ MeV for sizable couplings $\lambda_{\alpha\beta}$, as long as they allow ϕ particles to thermalize at BBN temperature [110].

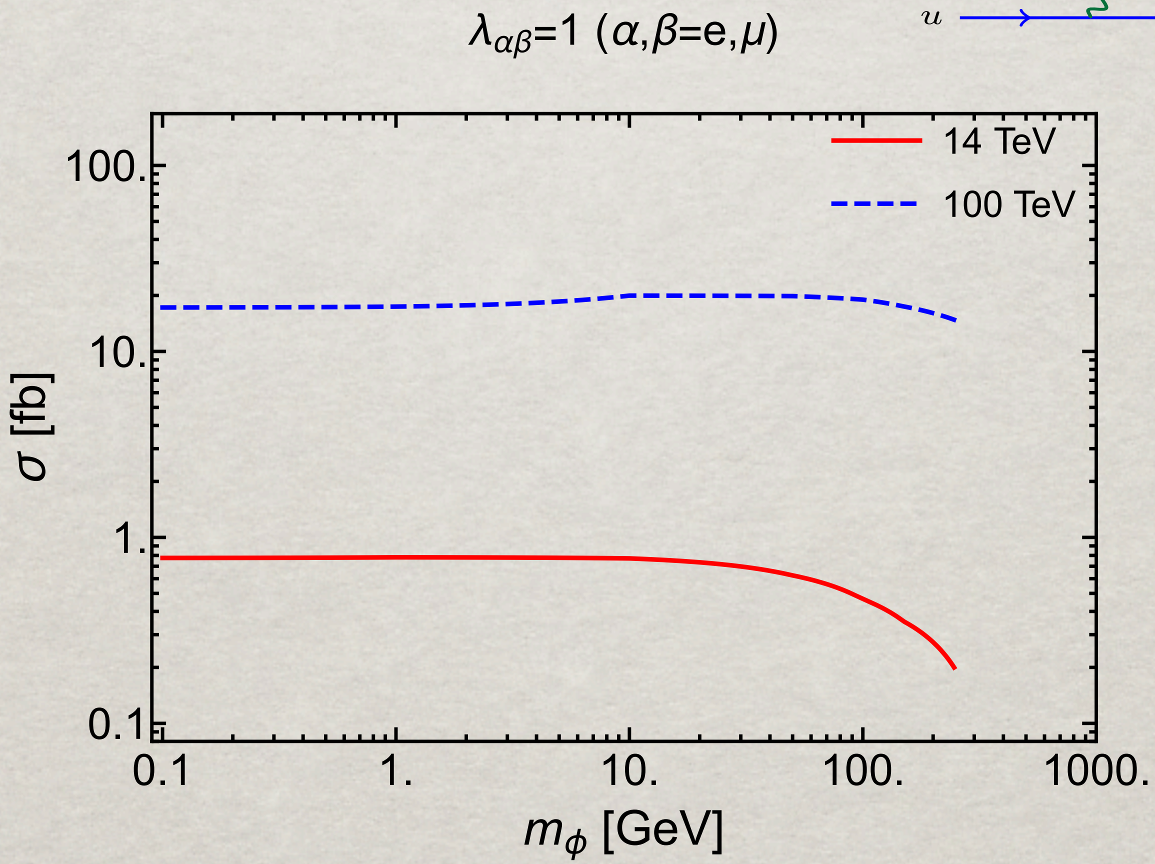
- *Neutrino decay*: For sufficiently light ϕ, the heavier neutrinos might decay via $\nu_j \to \nu_i + \phi$ with the mass indices $i, j = 1, 2, 3$ and $i < j$. Therefore we can impose stringent bounds on the leptonic scalar mass m_ϕ and the λ_{ij} couplings from the solar neutrino data [111–115]. There are also constraints from atmospheric and long baseline experiments [116–118]. The CMB limits on neutrino free streaming could also set limits on neutrino decays, as long as the mediator is lighter than neutrino mass and the non-diagonal couplings λ_{ij} are non-vanishing [93, 94, 119].

LHC searches:

A unique, clean channel

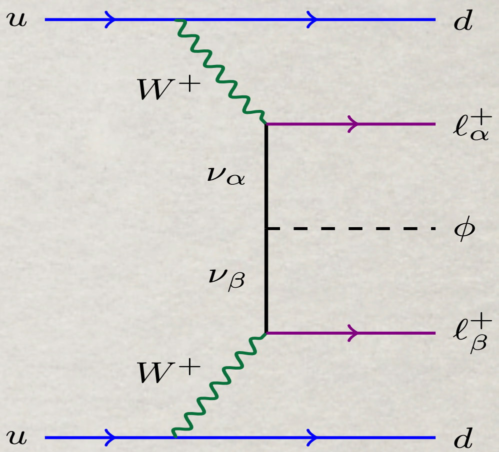
$$pp \;\to\; \ell^{\pm}_{\alpha}\ell^{\pm}_{\beta}\;\phi\;jj$$





(m_ϕ not to exceed the EW scale)

Signal & Backgrounds:



- the EW process $pp \to W^\pm W^\pm jj \to jj\ell_\alpha^\pm \ell_\beta^\pm \nu\nu$,
- the QCD process $pp \to W^\pm W^\pm jj \to jj\ell_\alpha^\pm \ell_\beta^\pm \nu\nu$
- $pp \to W^\pm Zjj \to jj\ell_\alpha^\pm \ell_\beta^\pm \ell_\beta^\mp \nu$,

Channels		$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	**Total**
Signal		40	129	84	253
$W^\pm W^\pm jj$ (EW)		37	137	89	263
$W^\pm W^\pm jj$ (QCD)		2	9	2	13
$W^\pm Zjj$		29	94	54	177
Total background		68	240	145	453
Significance	syst. error 0%	3.87	6.73	5.53	9.53
	syst. error 10%	3.24	4.21	4.00	4.83

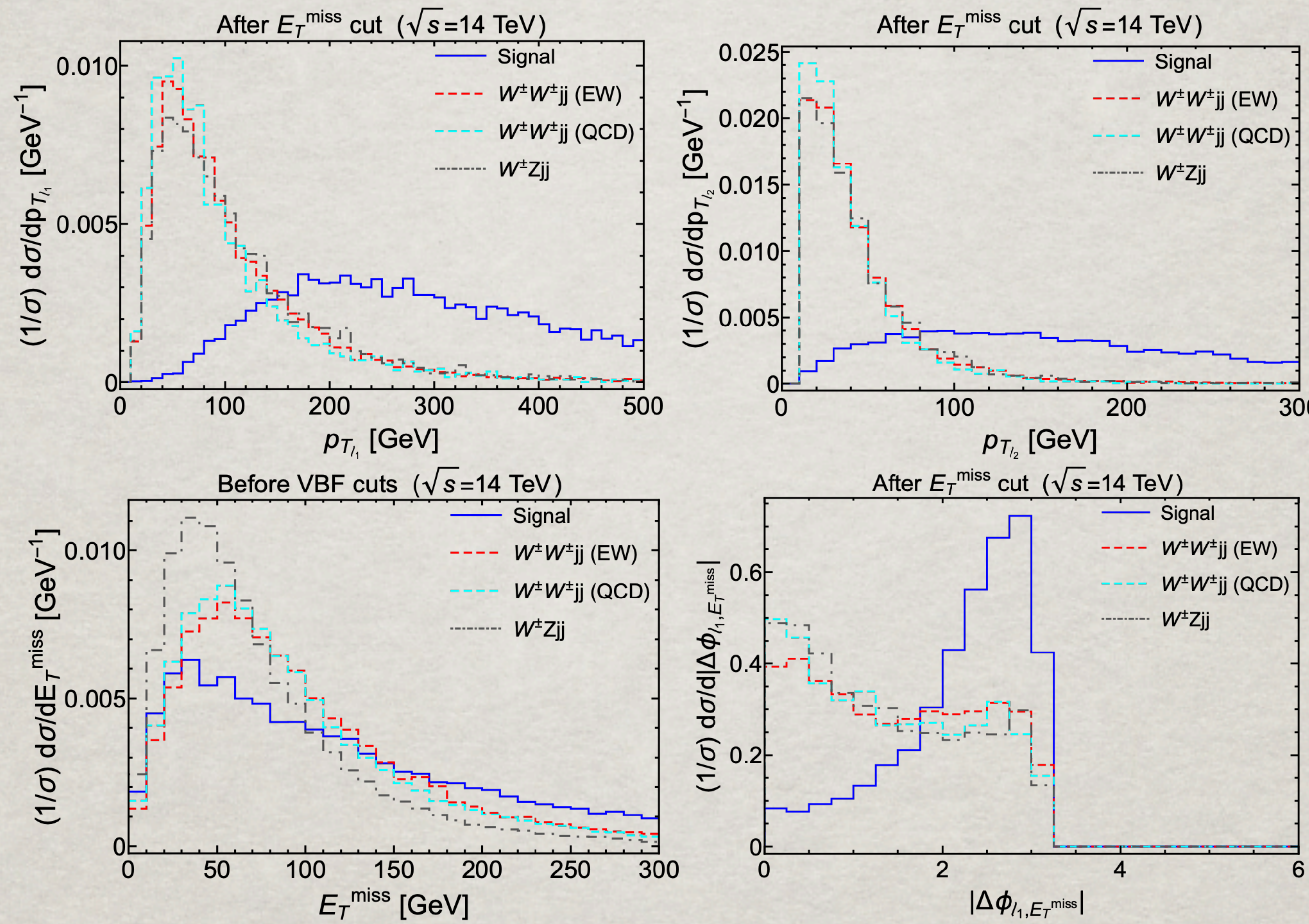


Figure 8. Kinematic distributions of the signal and SM backgrounds $W^{\pm}W^{\pm}jj$ (EW), $W^{\pm}W^{\pm}jj$ (QCD) and $W^{\pm}Zjj$ after the $E_T^{\rm miss}$ cut. The top left and right panels are respectively for the p_T distributions of the leading lepton ℓ_1 and the sub-leading lepton ℓ_2, and the lower left and right panels respectively for the missing transverse energy $E_T^{\rm miss}$ and the angular separation $|\Delta\phi_{\ell_1 E_T^{\rm miss}}|$. Only the $E_T^{\rm miss}$ distribution is shown before VBF cuts.

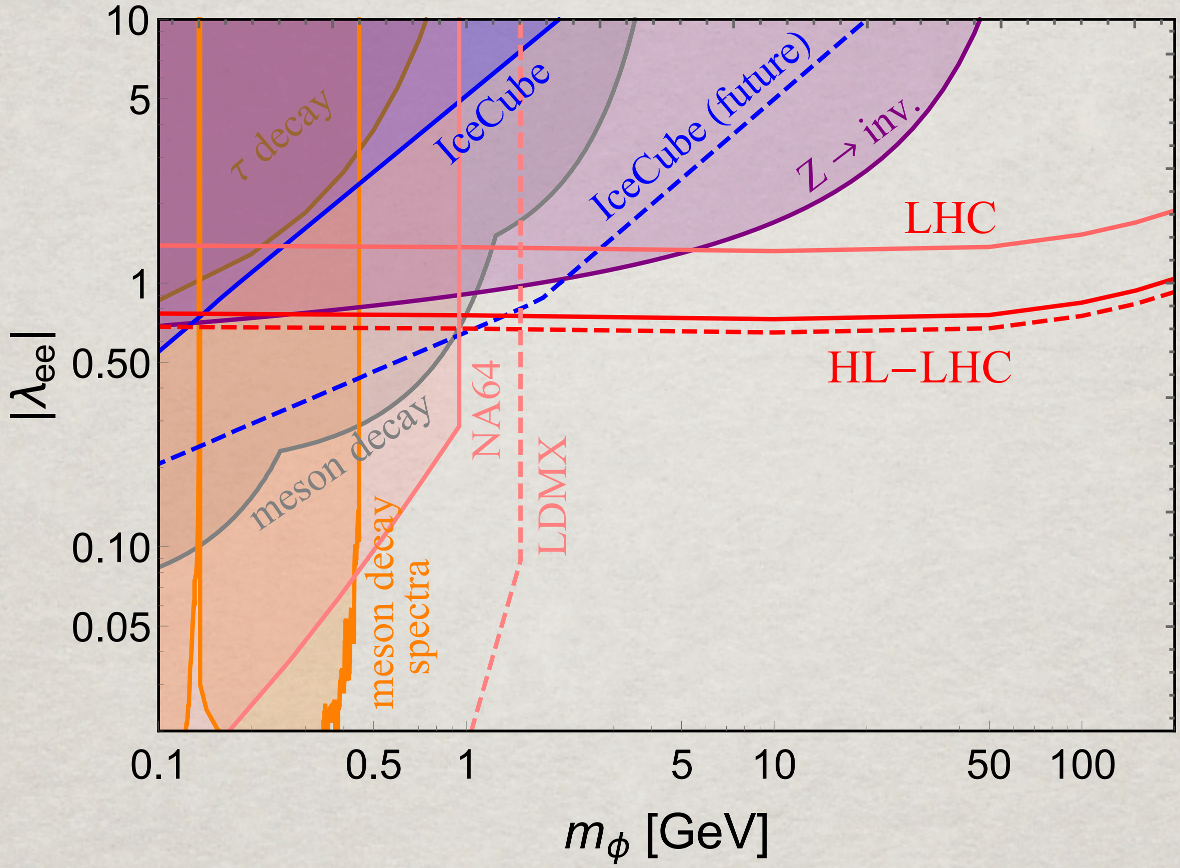
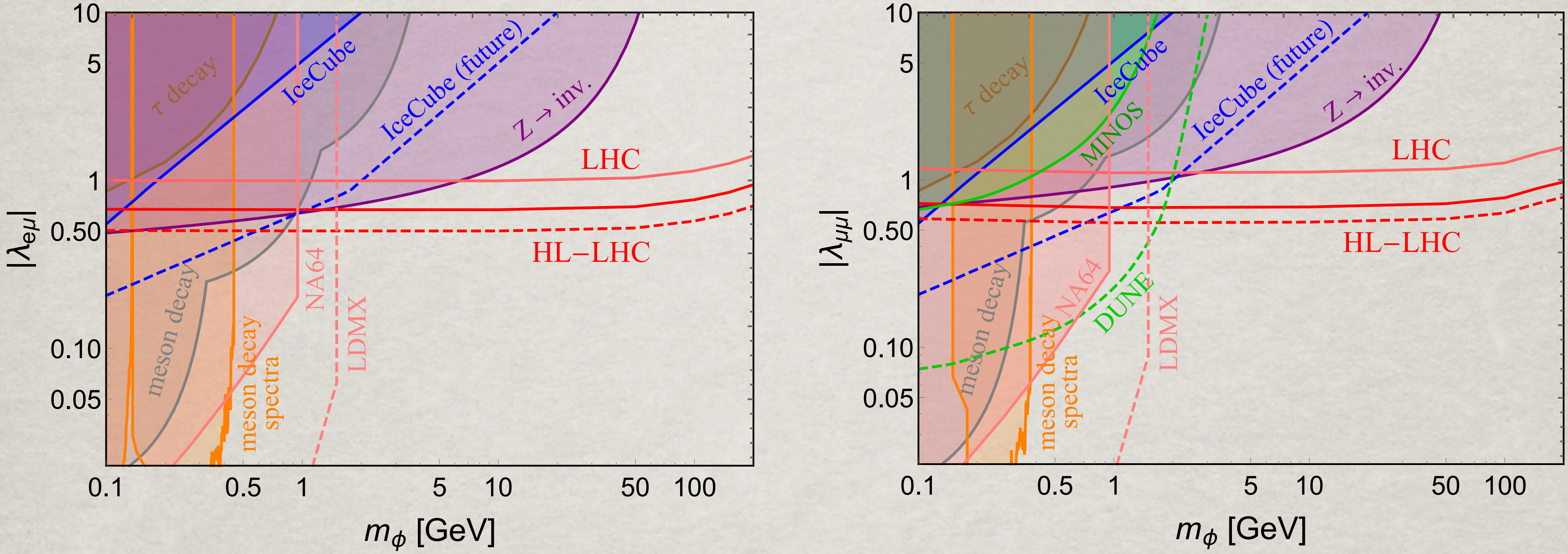


Figure 9. Prospects of the coupling $|\lambda_{ee}|$ as a function of the scalar mass m_ϕ at 14 TeV LHC with luminosity of 300 fb^{-1} (solid thin red line) and HL-LHC with 3 ab^{-1} and with systematic errors of 10% (solid thick red line) and 0% (dashed thick red line). Also shown are the low-energy limits (cf. Table 1) from meson decay (gray), τ decay (brown), heavy neutrino searches in meson decay spectra (orange), invisible Z decay (purple), light DM searches in NA64 (pink) and the prospects at LDMX (dashed pink), the current IceCube limits on neutrino–neutrino interactions (blue) and prospects (dashed blue). All the shaded regions are excluded.



Collider		$\lvert\lambda_{ee}\rvert$	$\lvert\lambda_{e\mu}\rvert$	$\lvert\lambda_{\mu\mu}\rvert$
LHC	syst. error 0%	1.35	0.95	1.07
	syst. error 10%	1.38	1.00	1.13
HL-LHC	syst. error 0%	0.68	0.51	0.57
	syst. error 10%	0.76	0.68	0.70

Summary

- NSI's obvious targets to scrutinize.
- Example 1: a UV complete model Z'
  - $M_{Z'}$ ~ 5 MeV – 20 MeV: DUNE+T2HK
  - $M_{Z'}$ ~ 20 MeV – 1 GeV: COHERENT Lar
  - $M_{Z'}$ ~ 1 GeV – 20 GeV: LHCb, CMS 4-leptons
  - $M_{Z'}$ ~ 20 GeV – 4 TeV: HL-LHC 2-leptons
  - There are parameter regions for correlated studies

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  Meson decays: 0.01; NA64: 0.02; DUNE: 0.08;
  IceCube: 0.3; Z-decay: 0.6; LHC: 1; HL-LHC: 0.5

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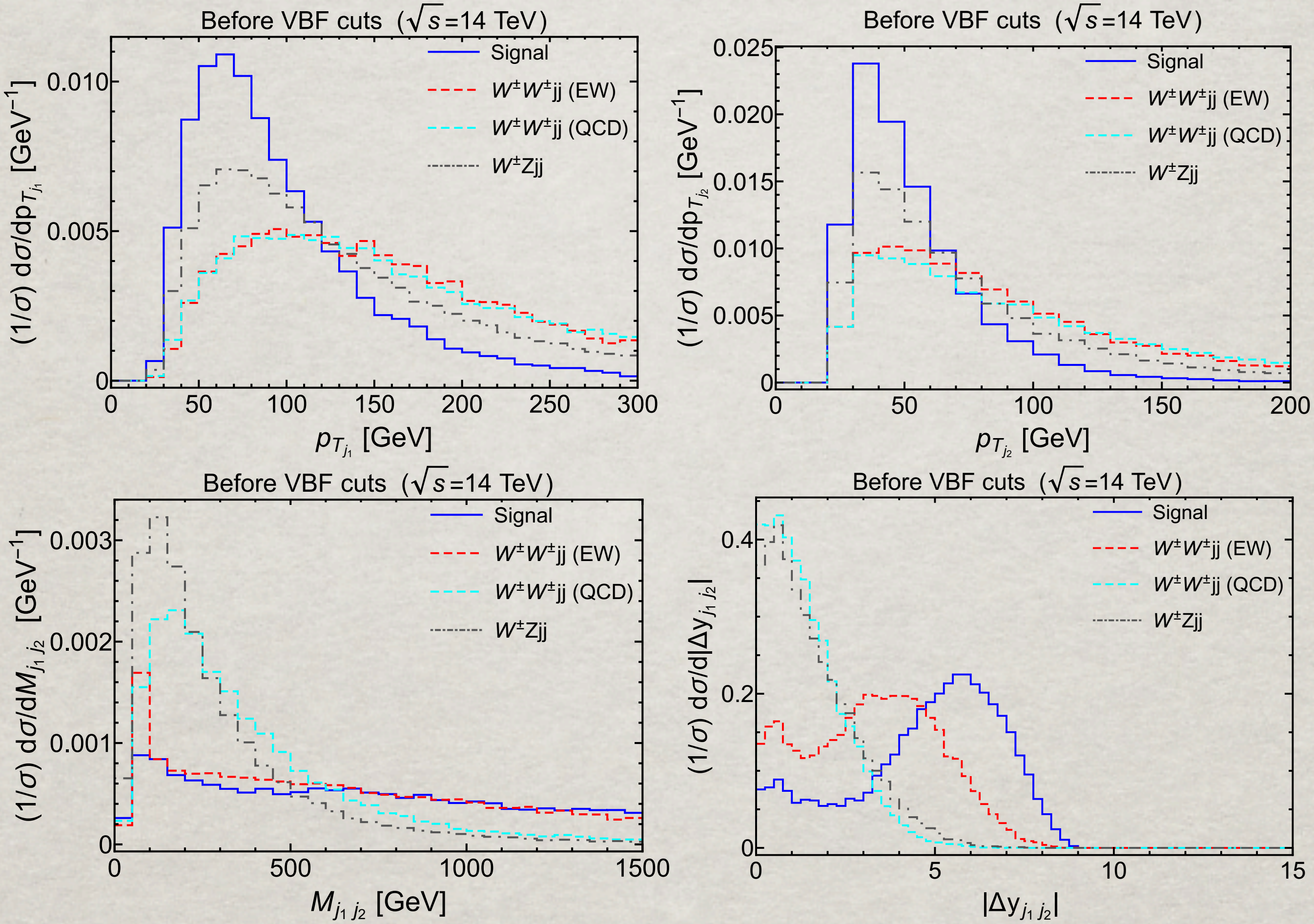
Low-energy expts <-> LHC complementary!



Before VBF cuts ($\sqrt{s}$=14 TeV)
Signal
$W^\pm W^\pm jj$ (EW)
$W^\pm W^\pm jj$ (QCD)
$W^\pm Zjj$
$(1/\sigma)\, d\sigma/dp_{T_{j_1}}$ [GeV^{-1}]
$p_{T_{j_1}}$ [GeV]
Before VBF cuts ($\sqrt{s}$=14 TeV)
Signal
$W^\pm W^\pm jj$ (EW)
$W^\pm W^\pm jj$ (QCD)
$W^\pm Zjj$
$(1/\sigma)\, d\sigma/dp_{T_{j_2}}$ [GeV^{-1}]
$p_{T_{j_2}}$ [GeV]
Before VBF cuts ($\sqrt{s}$=14 TeV)
Signal
$W^\pm W^\pm jj$ (EW)
$W^\pm W^\pm jj$ (QCD)
$W^\pm Zjj$
$(1/\sigma)\, d\sigma/dM_{j_1 j_2}$ [GeV^{-1}]
$M_{j_1 j_2}$ [GeV]
Before VBF cuts ($\sqrt{s}$=14 TeV)
Signal
$W^\pm W^\pm jj$ (EW)
$W^\pm W^\pm jj$ (QCD)
$W^\pm Zjj$
$(1/\sigma)\, d\sigma/d|\Delta y_{j_1 j_2}|$
$|\Delta y_{j_1 j_2}|$