Probing (light) leptonic scalars at the LHC

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based on

A. de Gouvêa, P. S. Bhupal Dev, B. Dutta, T. Ghosh, T. Han, YCZ, 1910.01132

Open questions in the neutrino sector

- Only left-handed neutrinos in the SM (Parity Violation)
  - any right-handed neutrinos (RHNs)?
  - how heavy are the RHNs?
  - RHN mixings and CP violation?
- Neutrinos are electrically neutral
  - are they Majorana particles?
  - lepton number violation (in neutrinoless double beta decays)?
- Neutrino masses are much smaller than the electroweak scale: $0.1\text{eV}/100\,\text{GeV} \sim 10^{-12}$
  - how to generate such smaller masses? seesaw mechanism?
  - ultraviolet completion of seesaw models?
- Non-standard interactions (NSIs) of neutrinos?
  - how to measure the NSIs at colliders?
- ......

How to measure scalar-induced NSIs at colliders?

(How to produce a (light) scalar at colliders
if it couples only to neutrinos?)

Scalar ϕ with leptonic-number of -2

- Suppose we have a leptonic scalar ϕ:
  - a singlet under SM group;
  - carries -2 units of lepton-number charge;
  - mass below the electroweak scale (246 GeV).
- Effective couplings to active neutrinos (α, $\beta = e$, μ, τ)

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

- No lepton number violation in the interaction;
- Neutrinos are Dirac particles;
- Applicable if neutrinos are Majorana particles;
- If $q^2 \ll m_\phi^2 \Longrightarrow$ effective $(\nu\nu)(\nu\nu)$ interactions.

Low-energy limits on $\lambda_{\alpha\beta}$

Berryman, de Gouvêa, Kelly & Zhang, '18; Lessa & Peres, '07; Pasquini & Peres, '15

As ϕ couples exclusively to neutrinos, we have the limits for $m_\phi \gtrsim 100$ MeV:

- charged meson decay rates, e.g. $\pi^- \to \ell^- \nu \phi$
- charged lepton decay rates, e.g. $\tau^- \to \ell^- \nu \nu \phi$
- heavy neutrino searches in meson decay spectra, e.g. $\pi^- \to \ell^- N$ vs. $\pi^- \to \ell^- \nu \phi$
- W and Z decay rates: $Z \to \nu \nu \phi$, $W^- \to \ell^- \nu \phi$
- neutrino beam experiments, e.g. MINOS & DUNE $\nu_\alpha + p \to \ell_\beta^+ + n + \phi$
- light DM searches in NA64 and LDMX
- IceCube and CMB limits on NSIs

The LHC prospects are almost constants for $m_\phi \lesssim$ GeV.

Current & future data on $\lambda_{\alpha\beta}$ limits

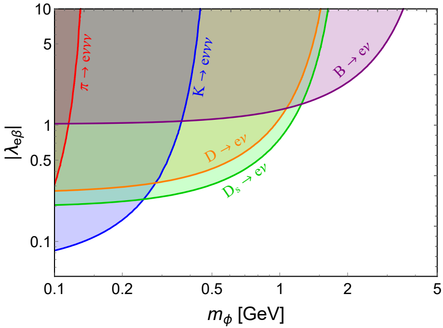
Process	Data	Couplings	Mass range
$\pi^- \to e^- \bar{\nu}_e \nu \bar{\nu}$	$\mathrm{BR} < 5 \times 10^{-6}$	$\sum_\beta \lvert\lambda_{e\beta}\rvert^2$	$m_\phi < 131$ MeV
$K^- \to e^- \bar{\nu}_e \nu \bar{\nu}$	$\mathrm{BR} < 6 \times 10^{-5}$	$\sum_\beta \lvert\lambda_{e\beta}\rvert^2$	$m_\phi < 444$ MeV
$K^- \to \mu^- \bar{\nu}_\mu \nu \bar{\nu}$	$\mathrm{BR} < 2.4 \times 10^{-6}$	$\sum_\beta \lvert\lambda_{\mu\beta}\rvert^2$	$m_\phi < 386$ MeV
$D^- \to e^- \bar{\nu}_e$	$\mathrm{BR} < 8.8 \times 10^{-6}$	$\sum_\beta \lvert\lambda_{e\beta}\rvert^2$	$m_\phi < 1.52$ GeV
$D^- \to \mu^- \bar{\nu}_\mu$	$\mathrm{BR} < 3.4 \times 10^{-5}$	$\sum_\beta \lvert\lambda_{\mu\beta}\rvert^2$	$m_\phi < 1.39$ GeV
$D_s^- \to e^- \bar{\nu}_e$	$\mathrm{BR} < 8.3 \times 10^{-5}$	$\sum_\beta \lvert\lambda_{e\beta}\rvert^2$	$m_\phi < 1.64$ GeV
$D_s^- \to \mu^- \bar{\nu}_\mu$	$\mathrm{BR} = (5.50 \pm 0.23) \times 10^{-3}$	$\sum_\beta \lvert\lambda_{\mu\beta}\rvert^2$	$m_\phi < 1.50$ GeV
$B^- \to e^- \bar{\nu}_e$	$\mathrm{BR} < 9.8 \times 10^{-7}$	$\sum_\beta \lvert\lambda_{e\beta}\rvert^2$	$m_\phi < 3.54$ GeV
$B^- \to \mu^- \bar{\nu}_\mu$	$\mathrm{BR} = (2.90 - 10.7) \times 10^{-7}$	$\sum_\beta \lvert\lambda_{\mu\beta}\rvert^2$	$m_\phi < 3.50$ GeV
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	$\mathrm{BR} = (17.82 \pm 0.04)\%$	$\sum_\beta \lvert\lambda_{e\beta}\rvert^2$	$m_\phi < 741$ MeV
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	$\mathrm{BR} = (17.39 \pm 0.04)\%$	$\sum_\beta \lvert\lambda_{\mu\beta}\rvert^2$	$m_\phi < 741$ MeV
$P^- \to e^- N$	see 1712.00297	$\sum_\beta \lvert\lambda_{e\beta}\rvert^2$	$3.3\,\mathrm{MeV} < m_\phi < 448$ MeV
$P^- \to \mu^- N$	see 1712.00297	$\sum_\beta \lvert\lambda_{\mu\beta}\rvert^2$	$87\,\mathrm{MeV} < m_\phi < 379$ MeV
$Z \to \mathrm{inv.}$	$\mathrm{BR} = (20.0 \pm 0.055)\%$	$\sum_{\alpha,\beta} S_{\alpha\beta}\lvert\lambda_{\alpha\beta}\rvert^2$	$m_\phi < 52.2$ GeV
$W \to e\nu$	$\mathrm{BR} = (10.71 \pm 0.16)\%$	$\sum_\beta \lvert\lambda_{e\beta}\rvert^2$	$m_\phi < 38.8$ GeV
$W \to \mu\nu$	$\mathrm{BR} = (10.63 \pm 0.15)\%$	$\sum_\beta \lvert\lambda_{\mu\beta}\rvert^2$	$m_\phi < 39.3$ GeV
MINOS	see 1802.00009	$\lvert\lambda_{\mu\mu}\rvert$	$m_\phi < 1.67$ GeV
DUNE	see 1802.00009	$\lvert\lambda_{\mu\mu}\rvert$	$m_\phi < 3.00$ GeV
NA64	see 1906.00176	$\sum_{\alpha,\beta} S_{\alpha\beta}\lvert\lambda_{\alpha\beta}\rvert^2$	$m_\phi < 948$ MeV
LDMX	see 1808.05219	$\sum_{\alpha,\beta} S_{\alpha\beta}\lvert\lambda_{\alpha\beta}\rvert^2$	$m_\phi < 1.50$ GeV
IceCube	see p1404.2279	$\lvert\lambda_{\alpha\beta}\rvert$	$m_\phi < 2.0\,(15.0)$ GeV

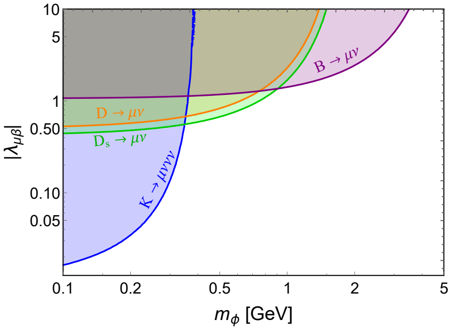
Limits from charged meson decay rates

Lessa & Peres, '07; Pasquini & Peres, '15

meson decays involving ϕ:

$$P^- \to \ell_\alpha^- \nu \phi \,, \quad P^- = \pi^-, K^-, D^-, D_S^-, B^- \,, \quad \ell = e, \mu$$





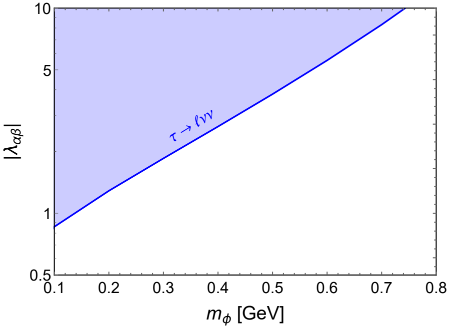
Limits from τ^- decay rates

Lessa & Peres, '07; Pasquini & Peres, '15

τ^- decays involving ϕ:

$$\tau^- \to \ell^- \nu\nu\phi\,, \quad \ell = e,\, \mu$$

ϕ can be emitted from the ν_ℓ or ν_τ line, therefore all the six flavor combinations of $\lambda_{\alpha\beta}$ $(\alpha, \beta = e, \mu, \tau)$ are constrained.



Heavy neutrino searches in meson decay spectra

Lessa & Peres, '07; Pasquini & Peres, '15

- Heavy neutrinos N from two-body meson decays (peak searches in charged lepton energy spectra), e.g.

$$\pi^- \to e^- N\,, \quad K^- \to \ell^- N \;\; (\ell = e,\, \mu)$$

- This can be used to set limits on lepton spectra of three-body decays $P^- \to \ell \nu \phi$

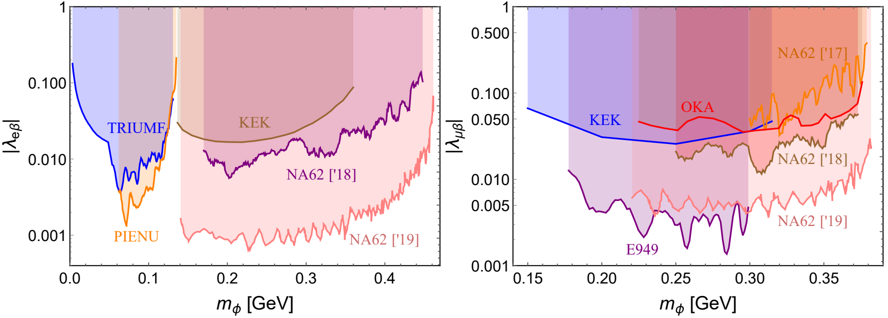


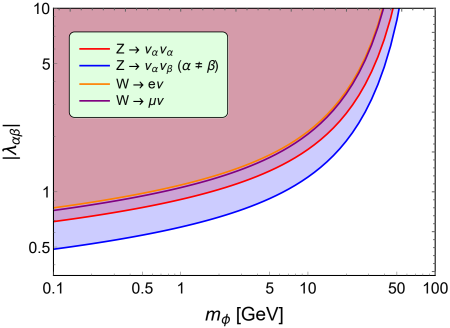
Figure: Limits from heavy neutrino searches in meson decays in TRIUMF '92, PIENU '17, KEK '84, E949 '14, OKA '17, NA62 '17, '18, '19.

Limits from W and Z decay rates

Berryman, de Gouvêa, Kelly & Zhang, '18

W and Z decays involving ϕ:

$$Z \to \nu\nu\phi\,, \quad W \to \ell\nu\phi$$



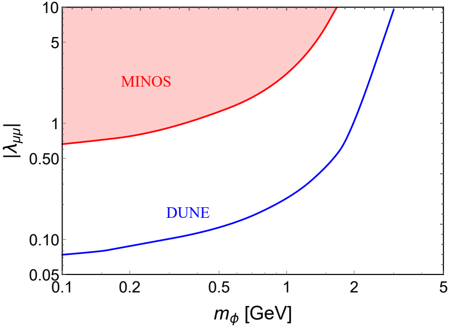
Limits from neutrino beam experiments (MINOS and DUNE)

Berryman, de Gouvêa, Kelly & Zhang, '18

Neutrino-matter scattering involving ϕ:

$$\nu_\alpha + p \to \ell_\beta^+ + n + \phi$$

- affect the charged lepton momentum distributions;
- charged leptons have the "wrong" sign, due to emission of lepton-number-charged ϕ.



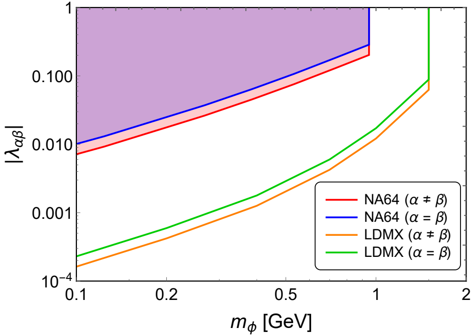
Light Dark matter searches (NA64 & LDMX)

Dark photon A' searches in NA64 [1906.00176] via the electron-nuclei scattering, with A' decaying into a pair of DM χ ($2 \to 3$ process, further improvement in LDMX 1808.05219):

$$e\mathcal{N} \;\to\; e\mathcal{N}A', \quad A' \;\to\; \chi\chi\,,$$

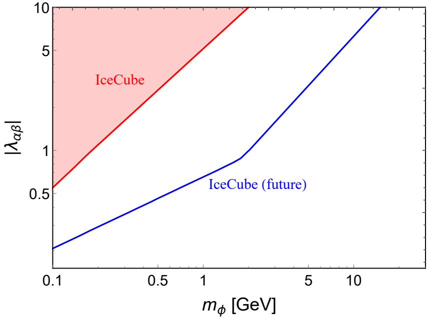
ϕ can induce the process via Z fusion, with the same final states ($2 \to 5$ process)

$$e\mathcal{N} \;\to\; e\mathcal{N}\nu\nu + \phi\,,$$



IceCube & CMB limits on NSIs

- PeV neutrino events could in principle set (flavor-universal) limits on neutrino–neutrino interactions in the early universe, which is effectively $|\lambda_{\alpha\beta}|^2/m_\phi^2$ here [Ioka & K. Murase '14; Ng & Beacom '14].
- Neutrino free streaming will alter the CMB temperature power spectrum. Current precision cosmological data have excluded the effective coupling $G_{\rm eff} \simeq |\lambda_{\alpha\beta}|^2/m_\phi^2 \gtrsim 2.5 \times 10^7\, G_F$ [Cyr-Racine & K. Sigurdson '13; Basboll, Bjaelde, Hannestad & Raffelt '08; Archidiacono & Hannestad '13; Lancaster, Cyr-Racine, Knox & Pan '17; Oldengott, Tram, Rampf & Wong '17; Kreisch, Cyr-Racine & Dor '19]



Limits for lighter ϕ ($m_\phi \lesssim 100$ MeV)

- muon decay (for $m_\phi \lesssim 100$ MeV): $\mu \to e\nu\nu\phi$;
- Tritium decay (for $m_\phi \lesssim 10$ keV): ${}^3\mathrm{H} \to {}^3\mathrm{He}^+ + e^- + \nu + \phi$ [Arcadi, Heeck, Heizmann, Mertens, Queiroz, Rodejohann, Slezk and Valerius '18];
- $0\nu\beta\beta$ decays (for $m_\phi \lesssim$ MeV): $(Z, A) \to (Z+2, A)e^- e^- \phi$, constrained by searches of Majoron emission in $0\nu\beta\beta$ experiments NEMO-3, KamLAND-Zen, EXO-200, GERDA.
- supernova (for $m_\phi \lesssim 30$ MeV) [Choi, Kim, Kim & Lam '88 Farzan '02; Heurtier & YCZ '16];
- $\Delta N_{\rm eff}$ (for $m_\phi \lesssim 100$ keV) [Planck, 1807.06209] & BBN (for $m_\phi \lesssim 200$ keV) [Ahlgren, Ohlsson & Zhou '13];
- neutrino decay (for $m_\phi \lesssim 0.05$ eV): $\nu_j \to \nu_i + \phi$ including solar, atmospheric & long baseline neutrino experiments

Production of ϕ at hadron colliders

Consider only the signals with e and μ leptons

$$uu \;\rightarrow\; dd\;\ell_\alpha^+\ell_\beta^+\;\phi$$

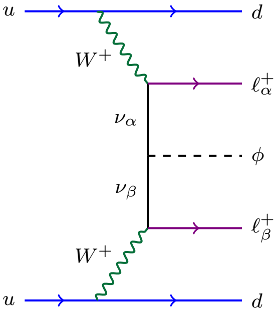
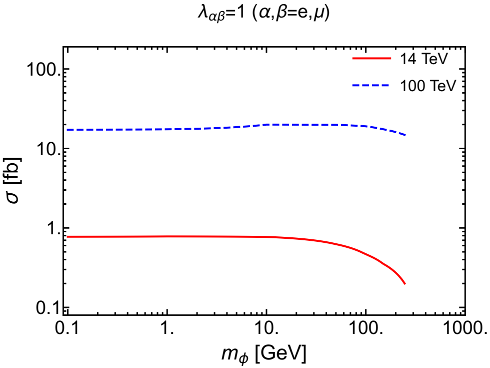


Figure: Representative Feynman diagram for the production of ϕ at the LHC.

- Signal is clean: same-sign dilepton plus VBF jets plus MET;
- **NO lepton-number violation**;
- Similar processes mediated by Z fusion: $uu \rightarrow uu\nu\nu\phi$

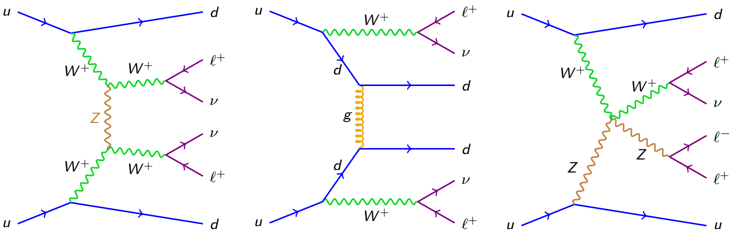
Production cross section



- We stop at $m_\phi = v_{\rm EW}$ beyond which ϕ might couple also to charged leptons.
- The LHC prospects can be significantly improved at future 100 TeV colliders.

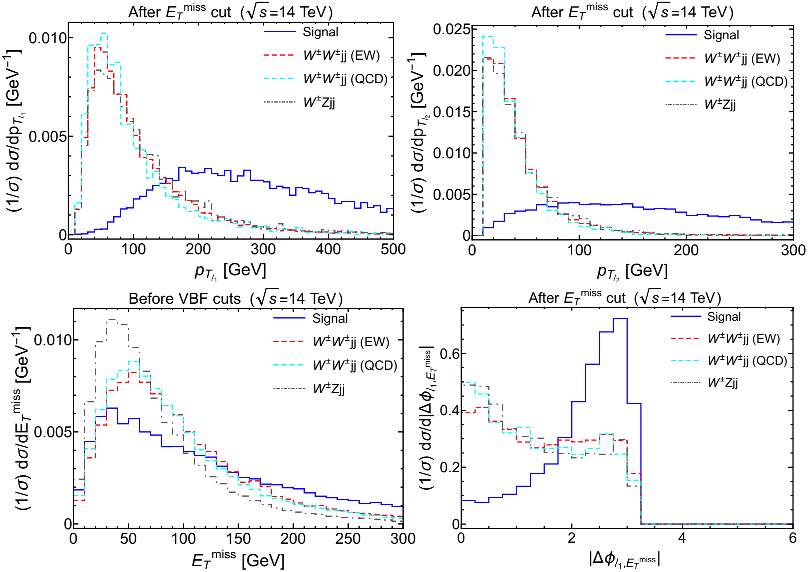
ATLAS 1906.03203; CMS 1709.05822

- EW process $pp \to W^\pm W^\pm jj \to jj\ell_\alpha^\pm \ell_\beta^\pm \nu\nu$,
  the final states are the same as signal, with the LHC cross section comparable for $\lambda_{\alpha\beta} = 1$;
- QCD process $pp \to W^\pm W^\pm jj \to jj\ell_\alpha^\pm \ell_\beta^\pm \nu\nu$,
  mediated by a t-channel gluon, can be effectively suppressed by the VBF cuts;
- $pp \to W^\pm Zjj \to jj\ell_\alpha^\pm \ell_\beta^\pm \ell_\beta^\mp \nu$,
  one of the charged leptons from Z decay missed by detector, and the LHC cross section comparable for $\lambda_{\alpha\beta} = 1$.



Kinematic distributions

most efficient cuts: $p_T(\ell_{1,2})$, $|\Delta\phi(\ell_1, E_T^{\text{miss}})|$



Event yields and sensitivities

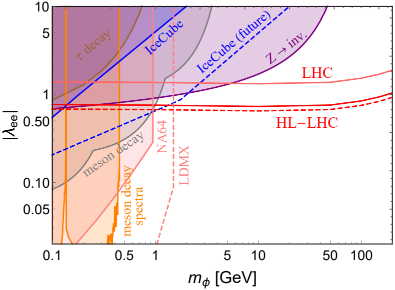
We have set $m_\phi = 1$ GeV and $\lambda_{\alpha\beta} = 1$ in the first table (14 TeV, 3000 fb^{-1})

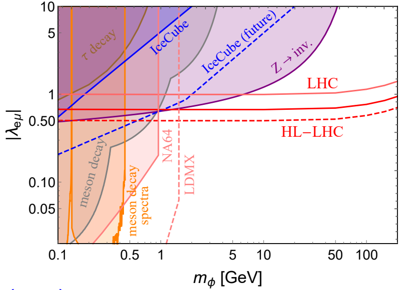
Channels		$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	**Total**
Signal		40	129	84	253
$W^\pm W^\pm jj$ (EW)		37	137	89	263
$W^\pm W^\pm jj$ (QCD)		2	9	2	13
$W^\pm Zjj$		29	94	54	177
Total background		68	240	145	453
Significance	syst. error 0%	3.87	6.73	5.53	9.53
	syst. error 10%	3.24	4.21	4.00	4.83

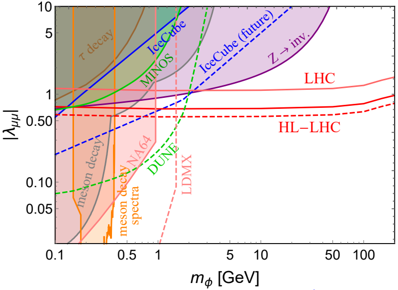
LHC (HL-LHC): 14 TeV, $\mathcal{L} = 300\,(3000)\,\mathrm{fb}^{-1}$

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

Prospects of λ_{ee} @ LHC & HL-LHC







(HL-)LHC sensitivities suppress all current existing limits if $m_\phi \gtrsim$ GeV.

Conclusion

- If a scalar couples only to neutrinos, it can be produced at LHC (and future high-energy hadron colliders) from W fusion.
- The signal is very clean, i.e. same-sign dilepton plus VBF jets plus missing energy, i.e.

$$pp \to \ell_\alpha^\pm \ell_\beta^\pm jj + \mathrm{MET}$$

- When the scalar mass $m_\phi \lesssim$ GeV, we have stringent limits from meson decays, charged lepton decays, meson decay spectra, W & Z boson decays, neutrino beam experiments (MINOS), light DM searches (NA64), astrophysical/cosmological limits on NSIs (IceCube) and other limits.
- The LHC prospects can go up to 0.51, depending on the charged lepton flavors, and surpass all current existing limits if $m_\phi \gtrsim$ GeV.

Thank you very much!

backup slides

UV completion

- At dimension-4 level, ϕ couples only to right-handed neutrinos (if there is any)

$$\mathcal{L}_y \supset y\, \phi^* \, \nu^c \nu^c$$

- At dimension-6 level, ϕ can couple to active neutrinos:

$$\frac{1}{\Lambda^2}(LH)(LH)\phi \quad \Longrightarrow \quad \frac{v_{\rm EW}^2}{\Lambda^2}\phi\,\nu\nu$$

- A realistic UV-complete model: introducing a triplet scalar Δ:
  [Dey, Lahiri & Mukhopadhyaya '18]

$$\mathcal{L} \supset \lambda_1 LL\Delta + \lambda_2 \phi H \Delta H \,,$$

Integrating out Δ:

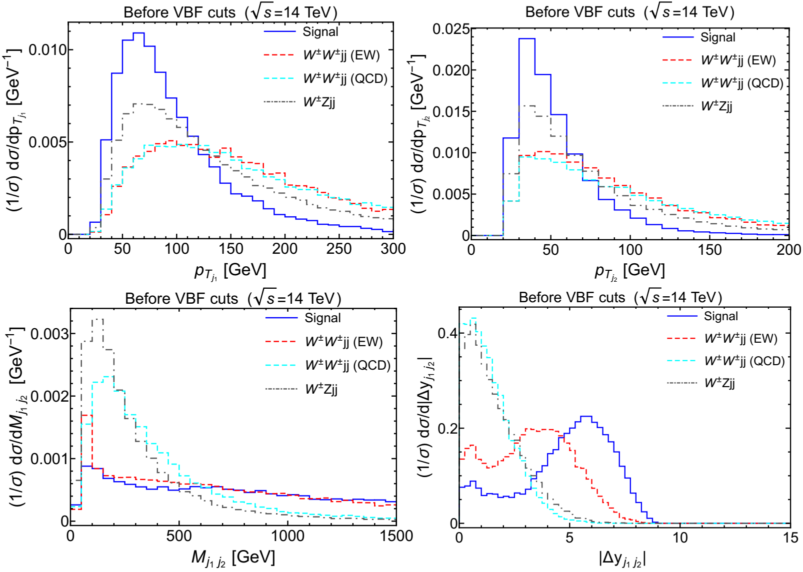
$$\mathcal{L} \sim \lambda_{\rm eff} \phi \nu\nu \,, \quad \lambda_{\rm eff} \sim \left(\frac{v_{\rm EW}^2}{M_\Delta^2} \right) \lambda_1 \lambda_2$$

More (weaker) limits from W data

More limits from LEP and LHC data involving W boson which are weaker:

- $pp \to W \to \ell\nu$ data @ LHC: emission of ϕ will affect the distributions of p_T of charged lepton, missing energy and the transverse mass of W boson [ATLAS, 1701.07240].
- $e^+e^- \to W^+W^- \to q\bar{q}\ell\nu$ @ LEP: the uncertainties of distributions are too large (limited by luminosity) [OPAL, 0708.131].
- $e-\mu$ universality in W decay @ LHC: current experimental uncertainties $\sim 1\%$, larger than 0.05% from Z decay [ATLAS, 1612.03016].
- $pp \to t\bar{t}$ @ LHC: cross section small and backgrounds complicated.

Kinematic distributions



Cut-flow table

The last two rows are the most efficient cuts.

Cut selection	**Signal** [fb]	$W^\pm W^\pm jj$ (EW) [fb]	$W^\pm W^\pm jj$ (QCD) [fb]	$W^\pm Zjj$ [fb]
Production	0.782	39.0	34.5	594
exactly 2ℓ: $p_{T_{\ell_{1,2}}} > 10$ GeV, $\lvert\eta_{\ell_{1,2}}\rvert < 2.5$, $m_{\ell_1\ell_2} > 20$ GeV, $\Delta R_{\ell_1\ell_2} > 0.3$	0.530	9.26	5.65	177
same-sign dilepton	0.529	9.26	5.65	44.5
for di-electron events: $\lvert\eta_{e_1,e_2}\rvert > 1.37$, $\lvert m_{e_1e_2} - m_Z\rvert < 15$ GeV vetoed	0.476	7.90	4.71	36.5
≥ 2 jets: $p_{T_{j_{1,2}}} > 20$ GeV, $\lvert\eta(j_{1,2})\rvert < 4.5$	0.397	7.46	4.51	33.7
VBF cuts: $p_{T_{j_1}} > 65$ GeV, $p_{T_{j_2}} > 35$ GeV, $m_{j_1j_2} > 500$ GeV, $\lvert\Delta y_{j_1j_2}\rvert > 2$	0.165	4.08	0.502	3.42
b-jet veto	0.158	3.77	0.441	3.03
$E_T^{\text{miss}} > 30$ GeV	0.143	3.41	0.399	2.58
$p_{T_{\ell_1}} > 150$ GeV, $p_{T_{\ell_2}} > 90$ GeV	0.108	0.217	0.017	0.176
$\lvert\Delta\phi_{\ell_1,E_T^{\text{miss}}}\rvert > 1.8$	0.084	0.088	0.004	0.059