# Leptonic Scalar at Colliders

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JHEP 07 (2020) 142 [arXiv:1910.01132]

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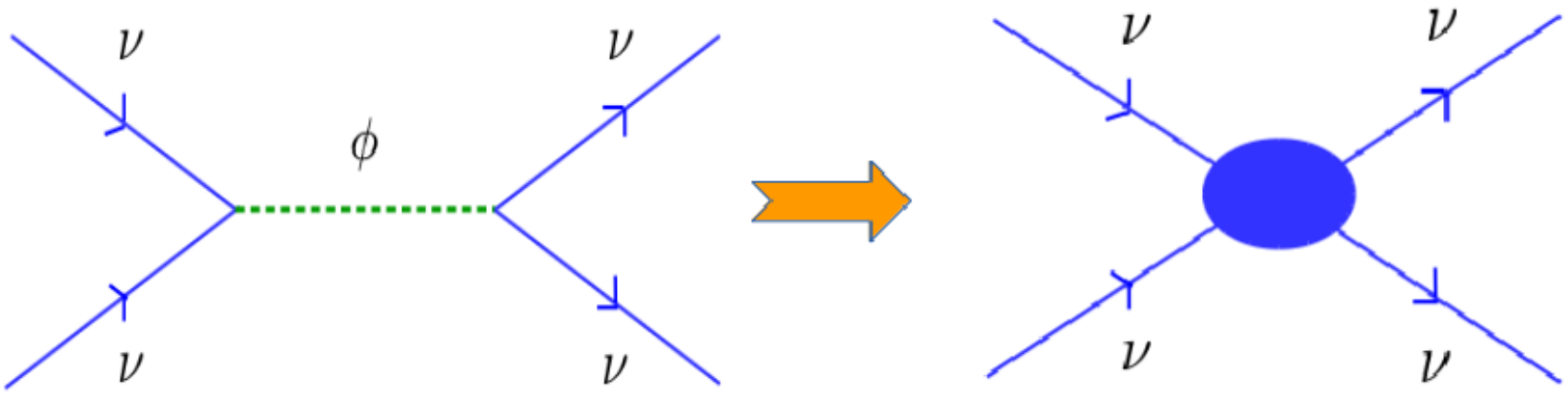



How to measure scalar-induced NSIs at colliders?

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

# Scalar $\phi$ with Lepton-number of $-2$

- Suppose we have a leptonic scalar $\phi$:
  - A singlet under SM gauge groups
  - Carries -2 ($+2$) units of $L\,(B-L)$ charge
  - Mass below EW scale (246 GeV)

- Effective coupling of $\phi$ to the active neutrinos ($\alpha, \beta = e, \mu, \tau$):

$$\mathcal{L}_\phi \supset \frac{1}{2}\,\lambda_{\alpha\beta}\,\nu_{L_\alpha}^T\,\mathcal{C}\,\nu_{L_\beta}\,\phi$$

- No lepton number violation in the interaction
- If $q^2 \ll m_\phi^2 \implies$ effective $(\nu\nu)(\nu\nu)$ self-interactions

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

Berryman, de Gouvêa, Kelly & Zhang, [1802.00009]; Lessa & Peres, [0701068]; Pasquini & Peres, [1511.01811]

As $\phi$ 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 $\nu_\alpha + p \to \ell^+_\beta + n + \phi$
- IceCube and CMB limits on NSIs

The LHC prospects are almost constants for $m_\phi \lesssim \mathcal{O}(10)$ 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 |
| $Z \to \mathrm{inv.}$ | $\Gamma^{\mathrm{inv}}_{\mathrm{obs}} = (499.0 \pm 1.5)$ MeV<br>$\Gamma^{\mathrm{inv}}_{\mathrm{SM}} = (501.44 \pm 0.04)$ MeV | $\sum_{\alpha,\beta} S_{\alpha\beta} \lvert\lambda_{\alpha\beta}\rvert^2$ | $m_\phi < 52.2$ 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 |
| $h \to \mathrm{inv.}$ | $\mathrm{BR} < 24\%\,(4.2\%)$ | $\sum_{\alpha,\beta} S_{\alpha\beta} \lvert\lambda_{\alpha\beta}\rvert^2$ | $m_\phi < 64.8\,(72.6)$ 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 |
| IceCube | see 1404.2279 | $\lvert\lambda_{\alpha\beta}\rvert$ | $m_\phi < 2.0\,(15.0)$ GeV |

# Production of $\phi$ at hadron colliders

Consider only the signals with $e$ and $\mu$ leptons

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

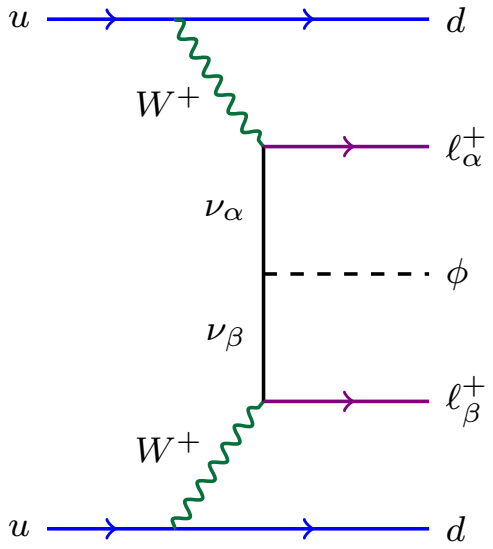
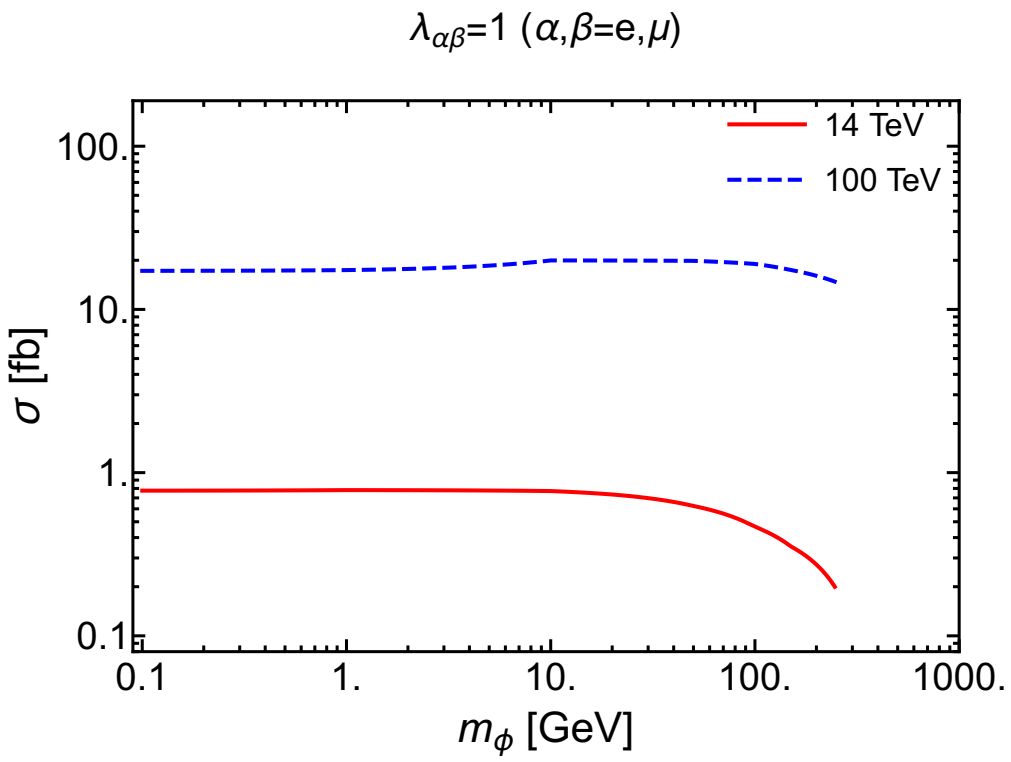



Figure: Representative Feynman diagram for the production of $\phi$ at the LHC.

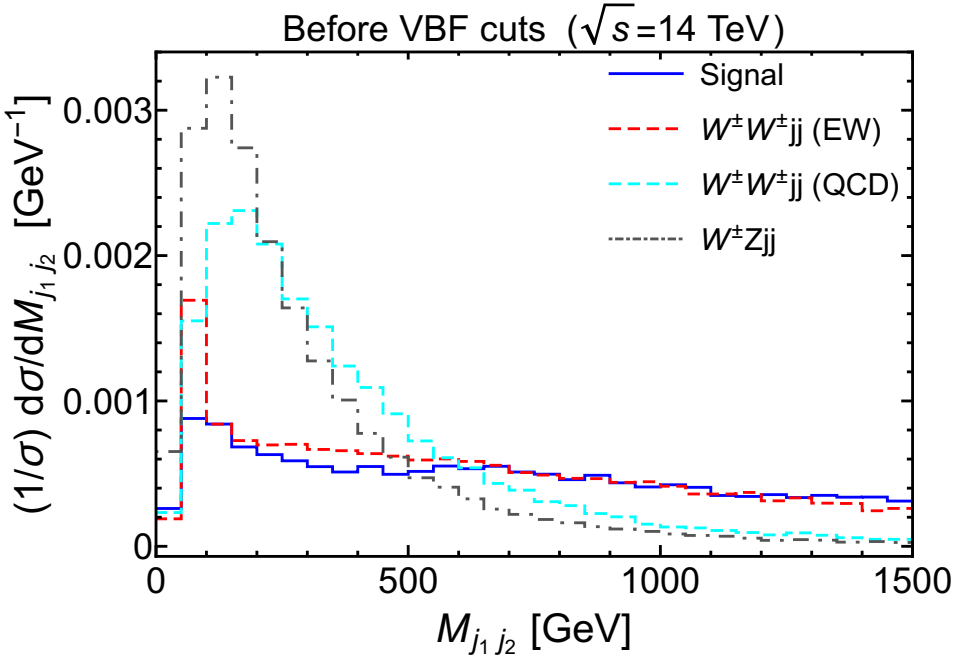
- Signal is clean: same-sign dilepton plus VBF jets plus MET;
- **NO lepton-number violation**;
- Similar processes mediated by $Z$ fusion: $uu \rightarrow uu\nu\nu\phi$

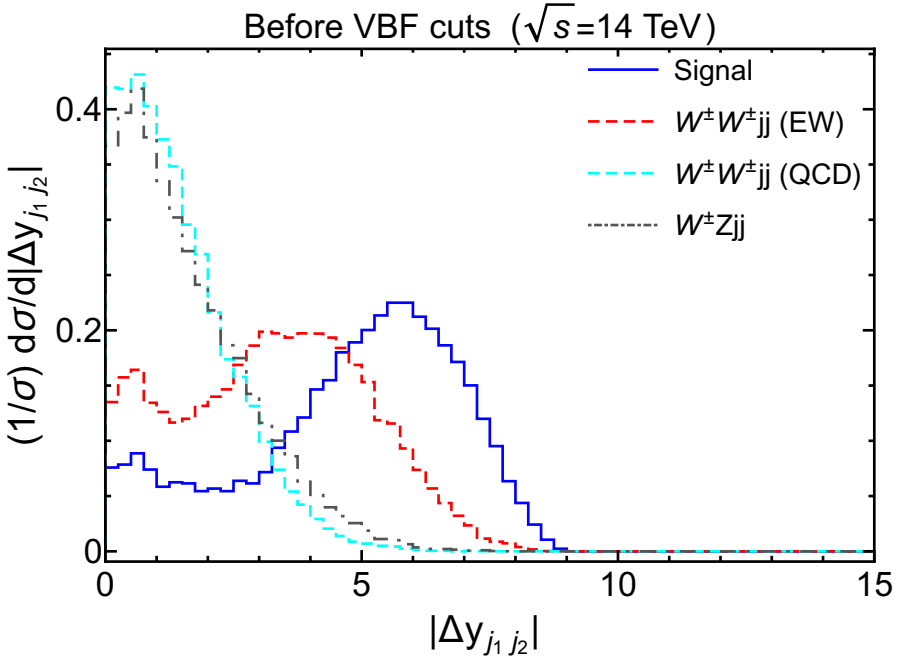
# Production cross section




- Collider prospects can be significantly improved at a future 100 TeV collider
- Dominant backgrounds: $pp \to W^\pm W^\pm jj \to jj\ell^\pm_\alpha \ell^\pm_\beta \nu\nu$, $pp \to W^\pm Zjj \to jj\ell^\pm_\alpha \ell^\pm_\beta \ell^\mp_\beta \nu$

# VBF kinematic distributions




Advantages of VBF search:

- VBF tagging jets – handle on trigger
- VBF jets are in forward-backward region
- Direct probing of EW sector

Characteristic kinematic cuts:

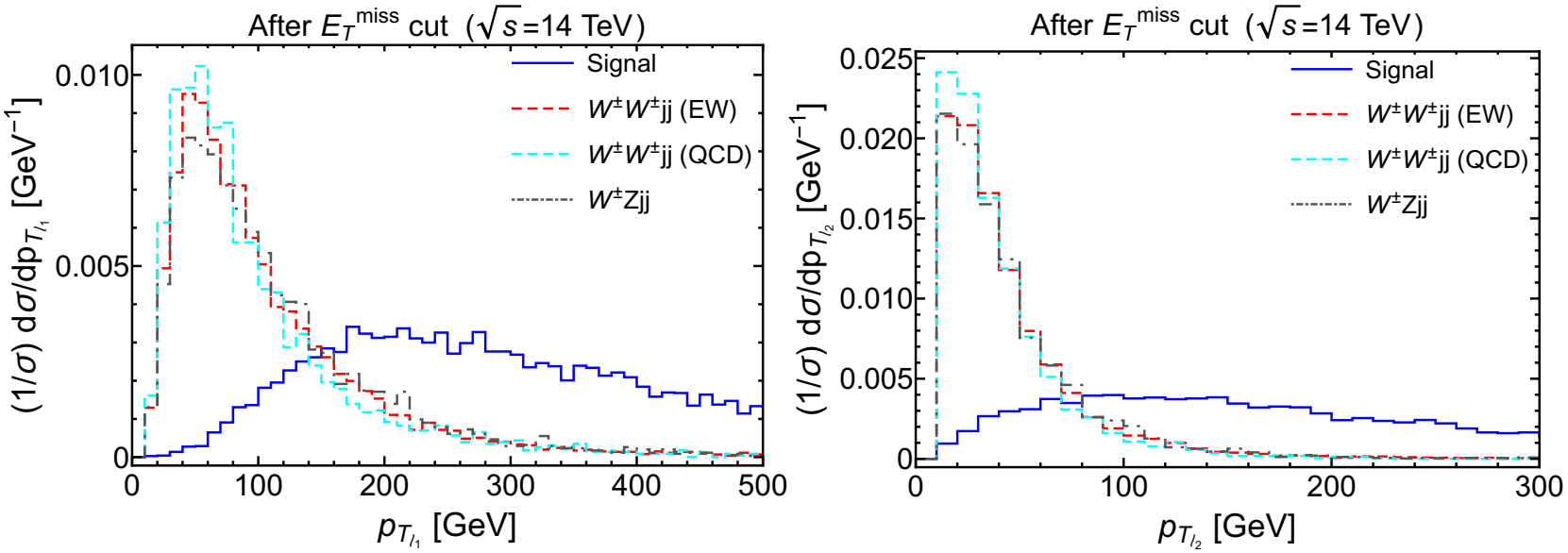
- Significant $p_T(j_1)\,, p_T(j_2)$ cuts
- Large $|\Delta\eta_{j_1 j_2}|$ separation
- $\eta_{j_1} * \eta_{j_2} < 0$
- Very large $M_{j_1 j_2}$

# Other kinematic distributions

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

$\ell$s for the backgrounds are coming from $W, Z$ decay

For the signal most of the energy of the $WW$ system is carried by $\ell$s

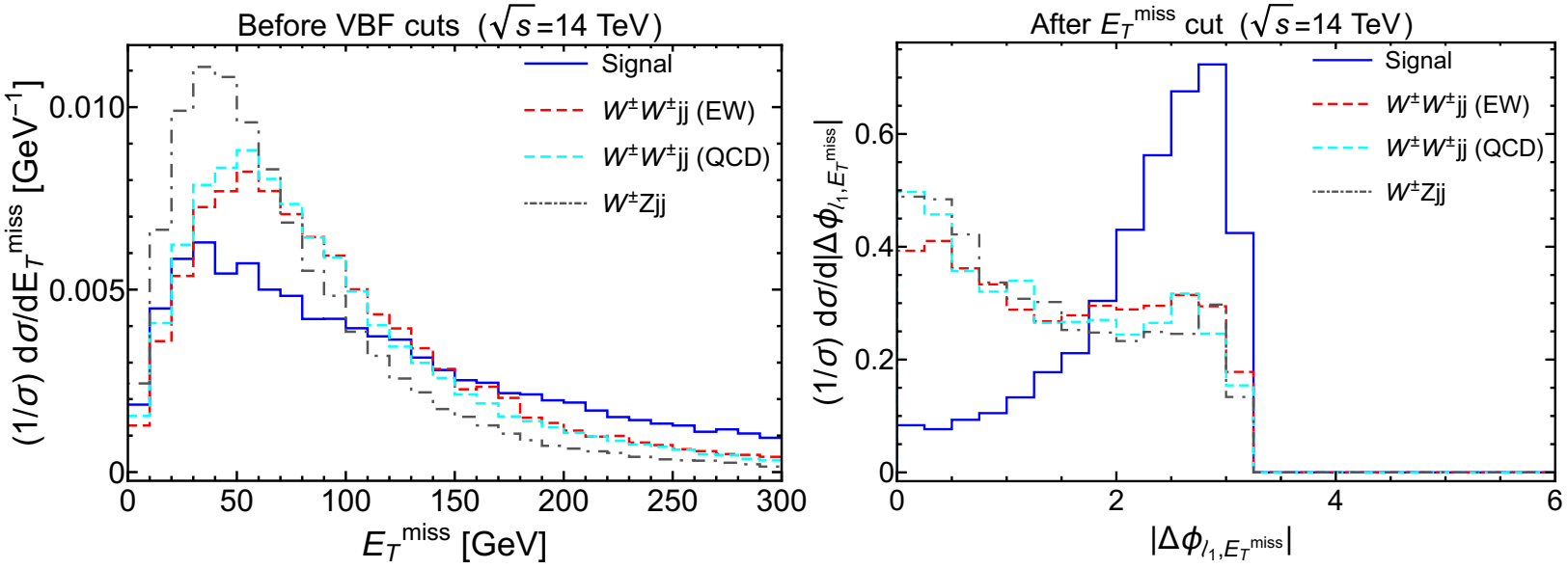


# Other kinematic distributions

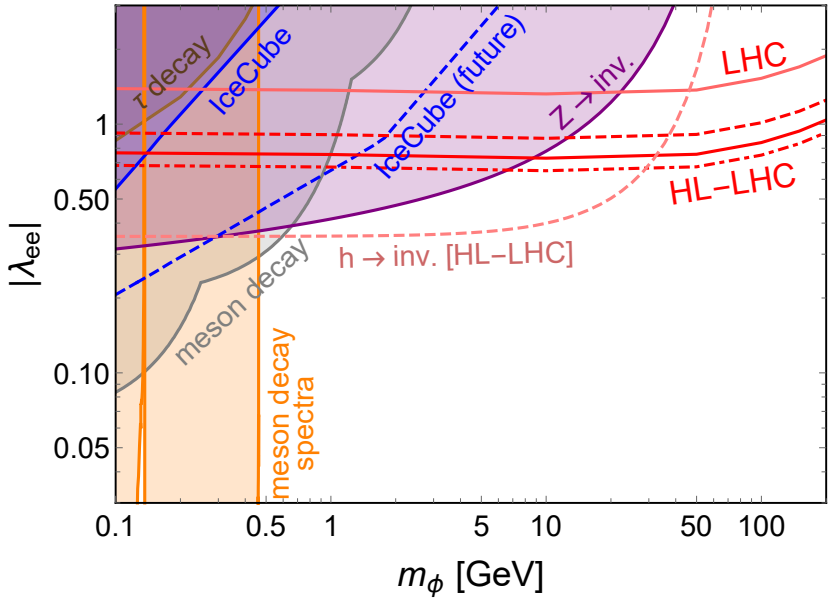
Most efficient cuts: $p_T(\ell_{1,2})$, $|\Delta\phi(\ell_1, E_T^{\rm miss})|$

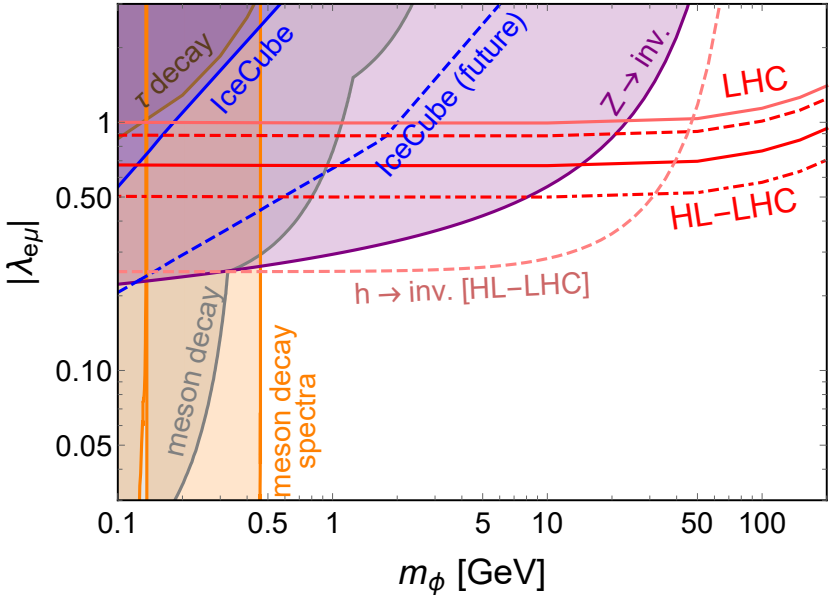
Origin of $E_T^{\rm miss}$ for the signal and backgrounds are different

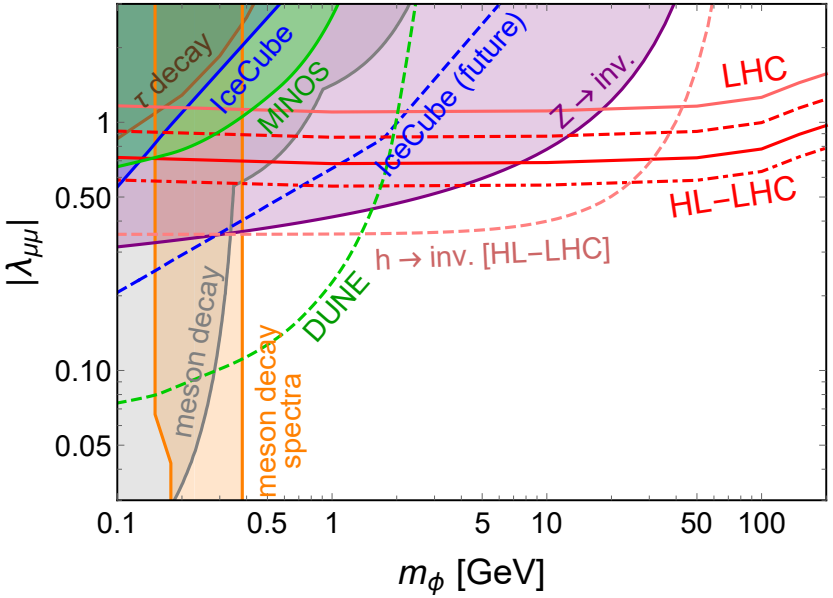
For the signal (background) $E_T^{\rm miss}$ is coming from $\phi\,(W)$ decay



# Prospects of $\lambda_{\alpha\beta}$ @ LHC & HL-LHC




(HL-)LHC sensitivities surpass all current existing limits if $m_\phi \gtrsim 20$ GeV.

- One can generate $\nu\nu\phi$ in $B-L$ extensions of the SM
- A single $\phi$ can couple to $q_{B-L} = +2$ gauge-invariant odd-dimensional SM operators:

$$\mathcal{L}_\phi \supset \frac{1}{2}\,\tilde{\lambda}_{ij}\,\nu_{R_i}^T\,\mathcal{C}\,\nu_{R_j}\,\phi \;+\; \frac{(L_\alpha^T\, i\sigma_2 H)\,\mathcal{C}\,(H^T i\sigma_2\, L_\beta)}{\Lambda_{\alpha\beta}^2}\,\phi \;+\; h.c$$

- After EWSB effective coupling of $\phi$ to the active neutrinos $(\alpha, \beta = e, \mu, \tau)$ are generated:

$$\mathcal{L}_\phi \supset \frac{1}{2}\,\lambda_{\alpha\beta}\,\nu_{L_\alpha}^T\,\mathcal{C}\,\nu_{L_\beta}\,\phi$$

- However, for $\lambda \sim \mathcal{O}(1),\ \Lambda \sim v \implies \Lambda$ can not be integrated out at the LHC

# Possible UV completion

- Introduce a scalar $\Delta$, a triplet under $SU(2)_L$ with hypercharge $+1$ and $B-L$ charge $+2$

$$
\begin{aligned}
V(H,\Delta,\phi) = & -m_H^2 + \frac{\lambda}{4}(H^\dagger H)^2 + M_\Delta^2 Tr\Delta^\dagger\Delta + M_\phi^2\phi^\dagger\phi \\
& + \lambda_1(H^\dagger H)Tr\Delta^\dagger\Delta + \lambda_2(Tr\Delta^\dagger\Delta)^2 + \lambda_3 Tr(\Delta^\dagger\Delta)^2 + \lambda_4 H^\dagger\Delta\Delta^\dagger H \\
& + \lambda_5(\phi^\dagger\phi)^2 + \lambda_6(\phi^\dagger\phi)(H^\dagger H) + \lambda_7(\phi^\dagger\phi)Tr\Delta^\dagger\Delta + \lambda_8(i\phi H^T\sigma_2\Delta^\dagger H + h.c.).
\end{aligned}
$$

- $\phi$ can mix with $\Delta^0$ with $\mathcal{O}(1)$ mixing to generate $\lambda_{\alpha\beta} \sim 1$
- One can search for $\Delta$s directly at the LHC
- We are studying the prospect of discovering $\phi$ in $\Delta^{++} \to \phi W^+ W^+$ and $\Delta^+ \to \phi W^+$ decays

Dev, Dutta, TG, Han, Qin, Zhang, [In preparation]

# 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.

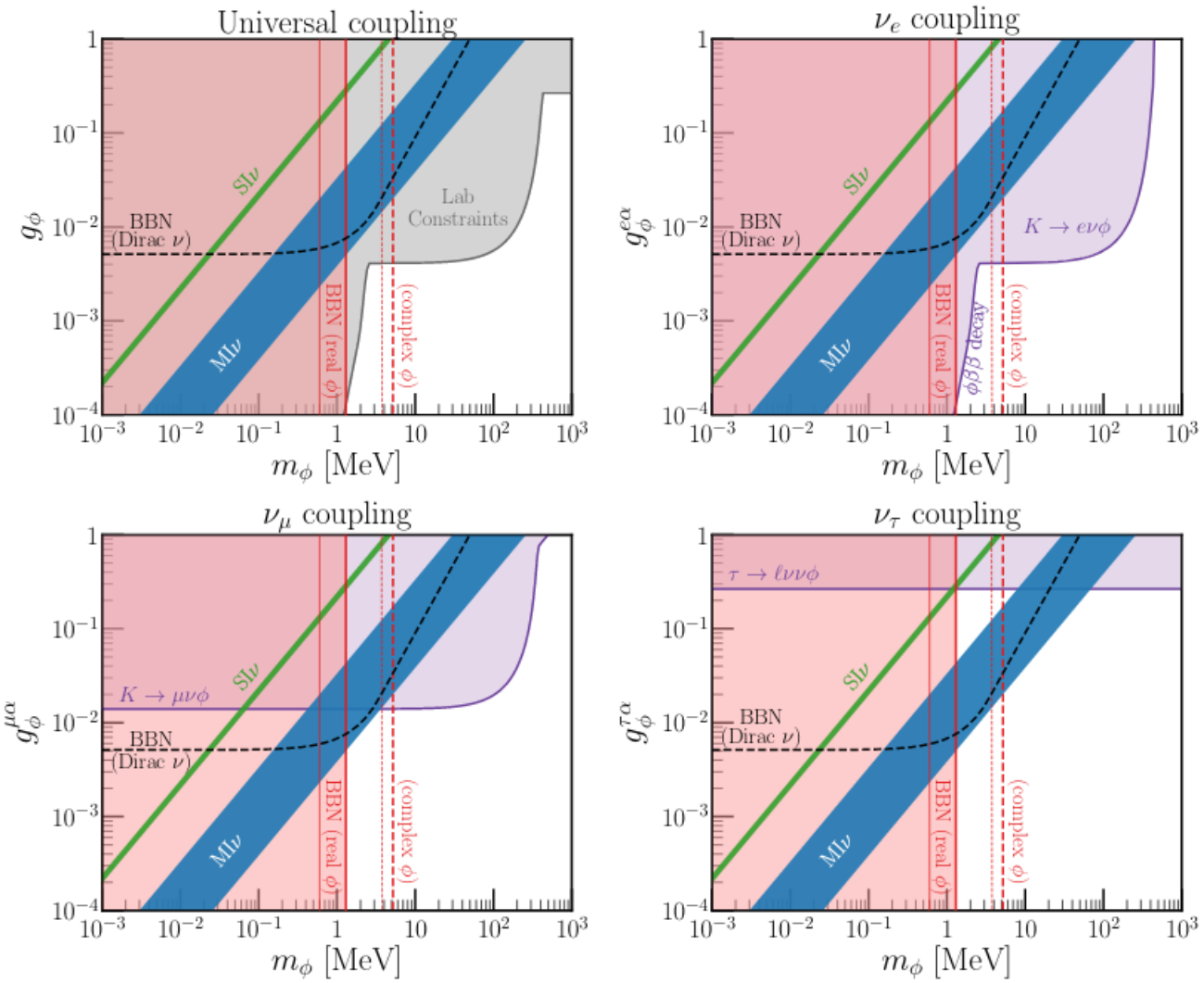
$$pp \to \ell^{\pm}_{\alpha}\ell^{\pm}_{\beta}jj + \mathrm{MET}$$

- When the scalar mass $m_\phi \lesssim$ GeV, we have stringent limits from meson decays, charged lepton decays, meson decay spectra, $W$ & $Z(h)$ boson decays, neutrino beam experiments (MINOS), astrophysical/cosmological limits on NSIs (IceCube) and other limits.
- The HL-LHC prospects can go down to 0.51 (0.3) using our VBF analysis ($h \to inv$), depending on the charged lepton flavors, and surpass all current existing limits if $m_\phi \gtrsim 20(1)$ GeV.
- A 100 TeV collider can improve the bounds by a factor of $\sim 5$ assuming the same luminosity

# The End

# Backup

# Hubble constant anomaly




Blinov, Kelly, Krnjaic, McDermott [arXiv:1905.02727]

# Summary of what we know now

- Convincing evidence of neutrino oscillations obtained in:
  - SK, SNO, KamLAND
  - Other solar and atmospheric neutrino experiments
  - Accelerator K2K experiment
- Neutrino oscillations are direct consequence of small neutrino masses and mixings

MIXINGS Defined as:

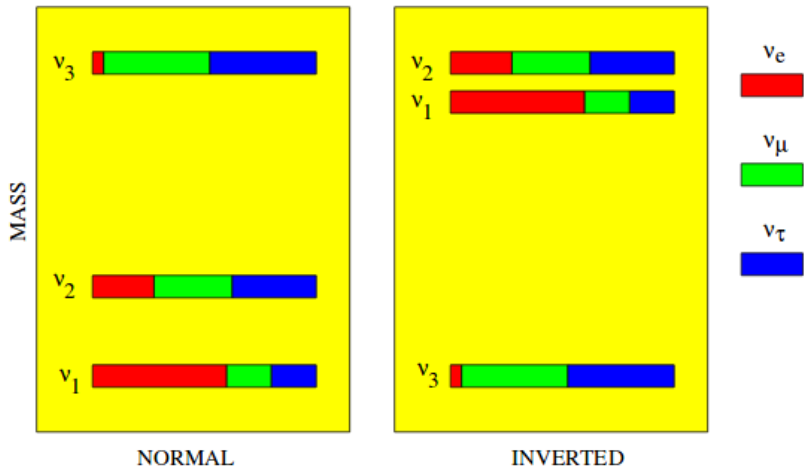
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\alpha i} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad c_{ij} = \cos\theta_{ij} \qquad s_{ij} = \sin\theta_{ij}$$

$$P = \mathrm{diag}\{1, 1, e^{i\alpha}\}$$

$$U = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -c_{23}\, s_{12} - s_{23}\, s_{13}\, c_{12}\, e^{i\delta} & c_{23}\, c_{12} - s_{23}\, s_{13}\, s_{12}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{23}\, s_{12} - c_{23}\, s_{13}\, c_{12}\, e^{i\delta} & -s_{23}\, c_{12} - c_{23}\, s_{13}\, s_{12}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix} P$$

# Masses

- We only know two mass difference squares:
  - Atmospheric: $\Delta m^2_{31}$
  - Solar: $\Delta m^2_{21}$
  - Mass pattern still unknown
- Possibilities:
  - Normal: $m_1 \ll m_2 \ll m_3$
  - Inverted: $m_1 \simeq m_2 \gg m_3$



# What do we notknow about the three-flavor paradigm?

| | | Normal Ordering (best fit) | | Inverted Ordering ($\Delta\chi^2 = 9.3$) | |
|---|---|---|---|---|---|
| | | bfp $\pm 1\sigma$ | $3\sigma$ range | bfp $\pm 1\sigma$ | $3\sigma$ range |
| with SK-atm | $\sin^2\theta_{12}$ | $0.310^{+0.013}_{-0.012}$ | $0.275 \to 0.350$ | $0.310^{+0.013}_{-0.012}$ | $0.275 \to 0.350$ |
| | $\theta_{12}/^\circ$ | $33.82^{+0.78}_{-0.76}$ | $31.61 \to 36.27$ | $33.82^{+0.78}_{-0.75}$ | $31.62 \to 36.27$ |
| | $\sin^2\theta_{23}$ | $0.582^{+0.015}_{-0.019}$ | $0.428 \to 0.624$ | $0.582^{+0.015}_{-0.018}$ | $0.433 \to 0.623$ |
| | $\theta_{23}/^\circ$ | $49.7^{+0.9}_{-1.1}$ | $40.9 \to 52.2$ | $49.7^{+0.9}_{-1.0}$ | $41.2 \to 52.1$ |
| | $\sin^2\theta_{13}$ | $0.02240^{+0.00065}_{-0.00066}$ | $0.02044 \to 0.02437$ | $0.02263^{+0.00065}_{-0.00066}$ | $0.02067 \to 0.02461$ |
| | $\theta_{13}/^\circ$ | $8.61^{+0.12}_{-0.13}$ | $8.22 \to 8.98$ | $8.65^{+0.12}_{-0.13}$ | $8.27 \to 9.03$ |
| | $\delta_{CP}/^\circ$ | $217^{+40}_{-28}$ | $135 \to 366$ | $280^{+25}_{-28}$ | $196 \to 351$ |
| | $\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$ | $7.39^{+0.21}_{-0.20}$ | $6.79 \to 8.01$ | $7.39^{+0.21}_{-0.20}$ | $6.79 \to 8.01$ |
| | $\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$ | $+2.525^{+0.033}_{-0.031}$ | $+2.431 \to +2.622$ | $-2.512^{+0.034}_{-0.031}$ | $-2.606 \to -2.413$ |

$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0$ for NO and $\Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0$ for IO.

Is $\theta_{23}$ non-negligibly greater or smaller than 45 deg?

poor knowledge

sign of $\Delta m^2$ unknown (ordering of masses)

Esteban, I., Gonzalez-Garcia, M.C., Hernandez-Cabezudo, A. et al. J. High Energ. Phys. (2019) 2019: 106. https://doi.org/10.1007/JHEP01(2019)106

Slide credit: Kate Scholberg

# Open questions in the neutrino sector

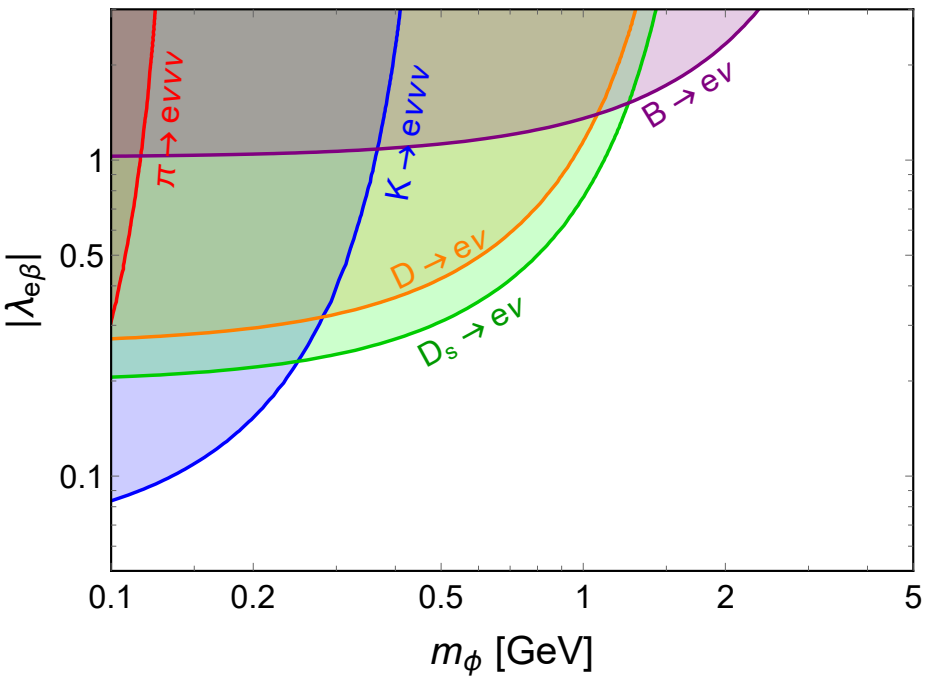
- Only left-handed neutrinos in the SM (Parity Violation)
  - Any right-handed neutrinos (RHNs)?
  - How heavy are the RHNs?
  - RHN mixings and CP violation?
- Neutrinos are electrically neutral
  - Are they Majorana particles?
  - Lepton number violation (in neutrinoless double beta decays)?
- Neutrino masses are much smaller than the electroweak scale: $0.1\mathrm{eV}/100\,\mathrm{GeV} \sim 10^{-12}$
  - How to generate such smaller masses? See-saw mechanism?
  - Ultraviolet completion of see-saw models?
- Non-standard interactions (NSIs) of neutrinos?
  - Can colliders play any role to measure the NSIs?
- .....

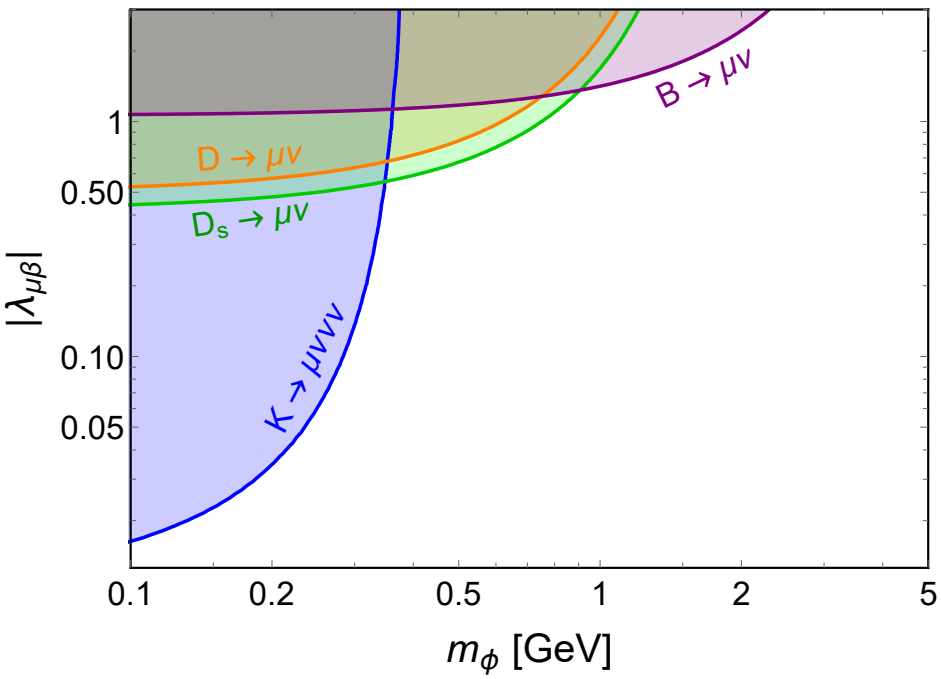
# Limits from charged meson decay rates

Lessa & Peres, [0701068]; Pasquini & Peres, [1511.01811]

meson decays involving $\phi$:

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



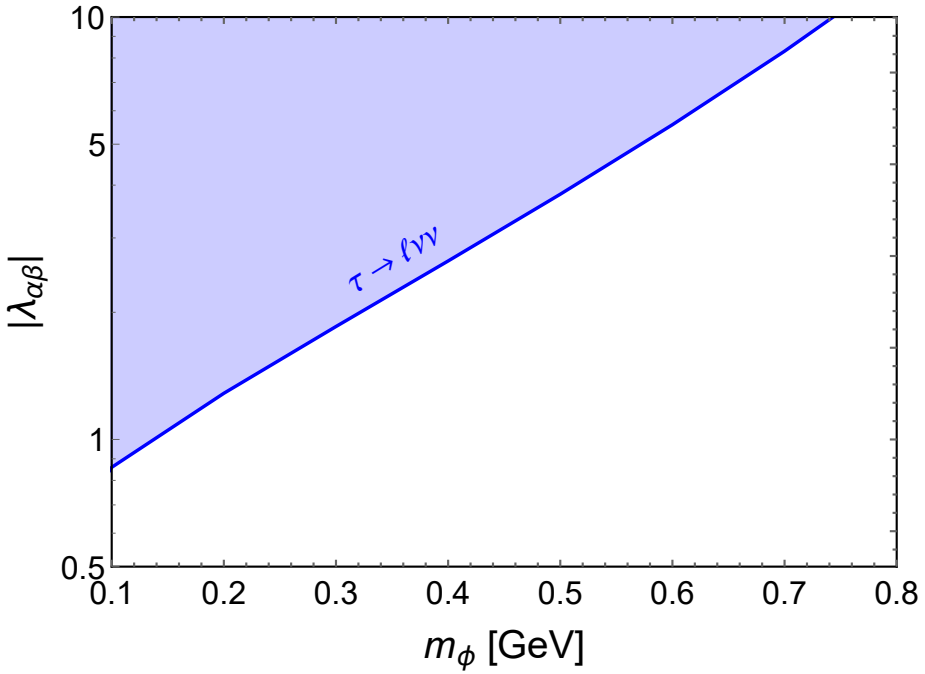
# Limits from $\tau^-$ decay rates

Lessa & Peres, [0701068]; Pasquini & Peres, [1511.01811]

$\tau^-$ decays involving $\phi$:

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

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



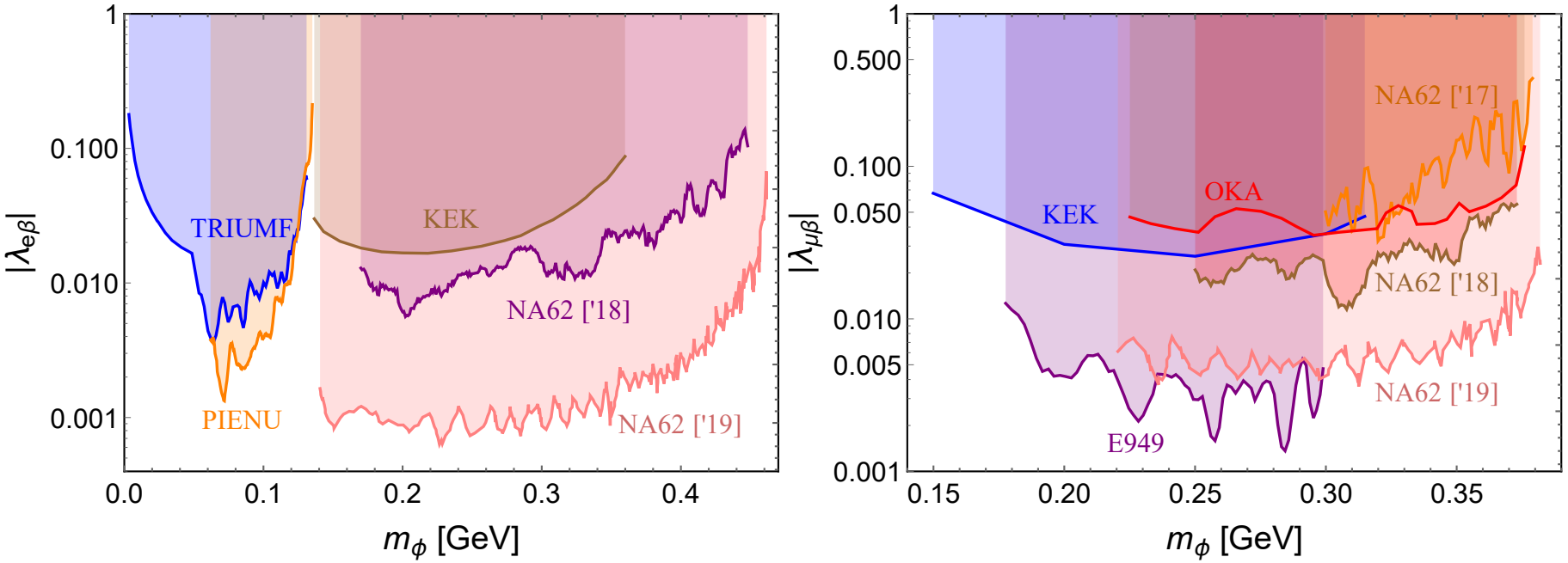
# Heavy neutrino searches in meson decay spectra

Lessa & Peres, [0701068]; Pasquini & Peres, [1511.01811]

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

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

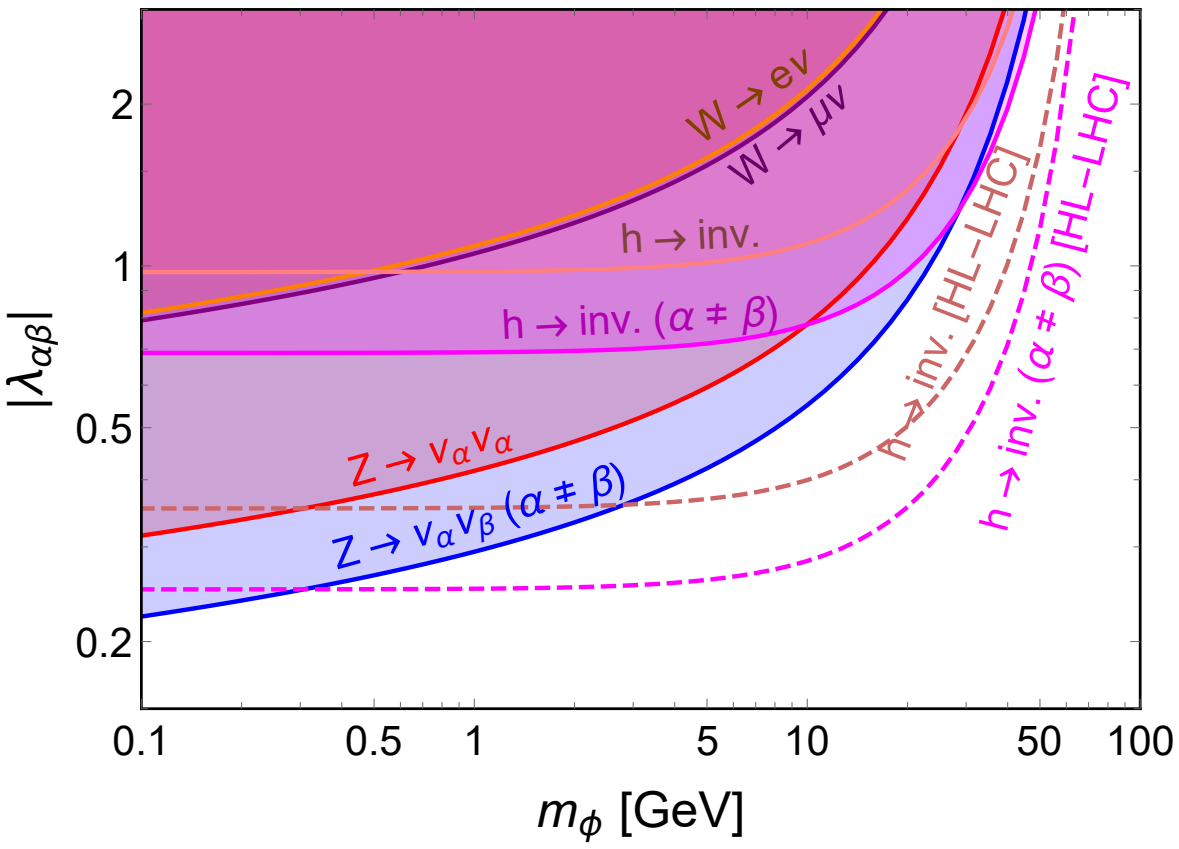
- This can be used to set limits on lepton spectra of three-body decays $P^- \to \ell \nu \phi$



# Limits from $h$, $Z$ and $W$ decay rates

Berryman, de Gouvêa, Kelly & Zhang, [1802.00009]

$W$ and $Z$ decays involving $\phi$: $Z \to \nu\nu\phi$ , $W \to \ell\nu\phi$
$h \to \nu\nu\phi$ arises if $\nu\nu\phi$ coupling develops from $LHLH\phi/\Lambda$



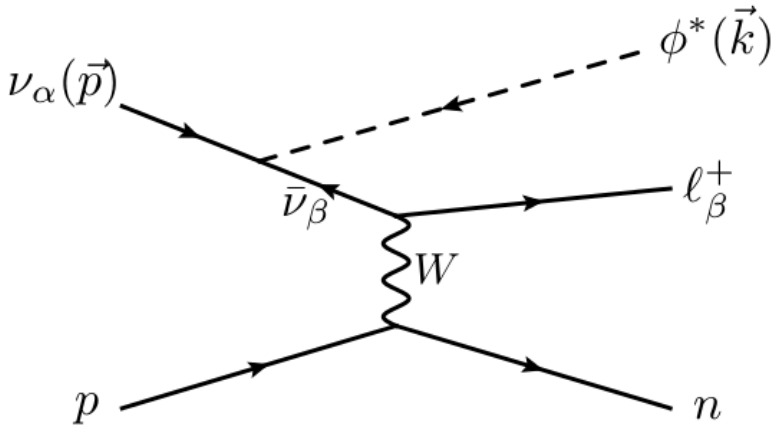
# Limits from neutrino beam experiments (MINOS and DUNE)

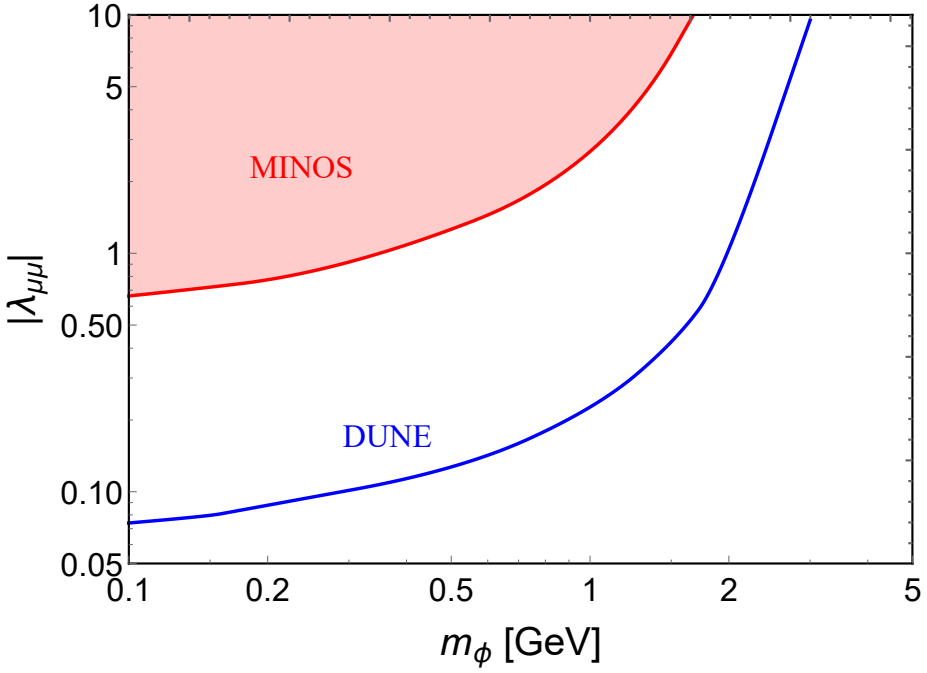
Berryman, de Gouvêa, Kelly & Zhang, [1802.00009]

Neutrino-matter scattering involving $\phi$:

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

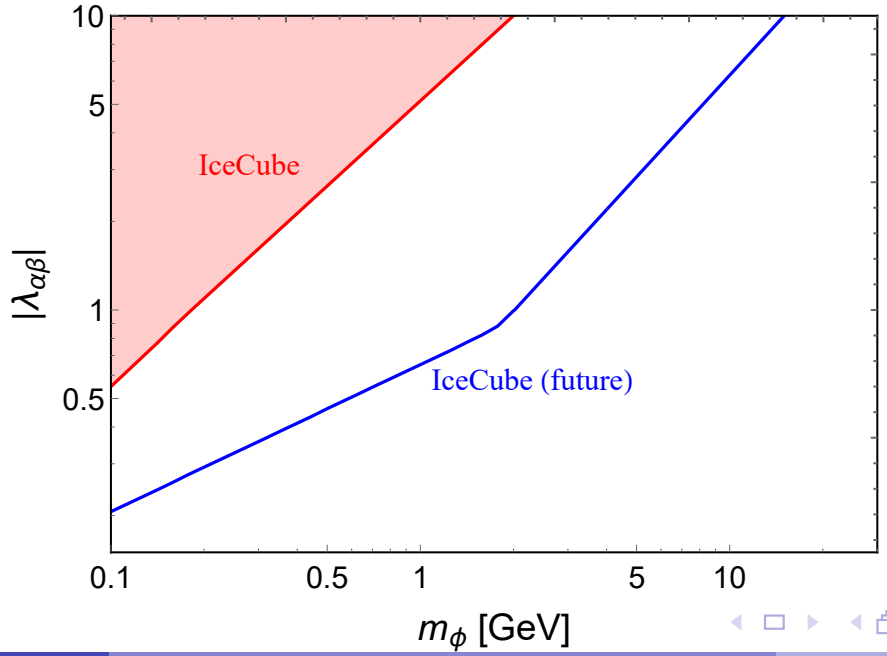
- affect the charged lepton momentum distributions;
- charged leptons have the "wrong" sign, due to emission of lepton-number-charged $\phi$.



# 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 [1404.2279]; Ng & Beacom [1404.2288]
- Effect on neutrino free streaming will 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 [1306.1536]; Basboll, Bjaelde, Hannestad, Raffelt [0806.1735]; Archidiacono, Hannestad [1311.3873]; Lancaster, Cyr-Racine, Knox, Pan [1704.06657]; Oldengott, Tram, Rampf, Wong [1706.02123]; Kreisch, Cyr-Racine, Dor [1902.00534]



# Other constraints

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

- $pp \to W \to \ell\nu$ data @ LHC: emission of $\phi$ ($m_\phi < M_W$) will affect the distributions of $p_T$ of charged lepton, missing energy and the transverse mass of $W$ boson ... bounds are weaker than LEP $Z \to inv$ limits ATLAS[1701.07240]
- $pp \to W^* \to \ell\nu$ @ HL-LHC: For $m_\phi > M_W$, $1\ell + E_T^{miss}$ final state search will have $S/B \sim 10^{-3}$, no bounds with realistic systematics
- $e^+e^- \to W^+W^- \to q\bar{q}\ell\nu$ @ LEP: the uncertainties of distributions are too large OPAL [0708.131]
- $pp \to t\bar{t}$ @ LHC: cross section small compared to $pp \to W$ and backgrounds are complicated

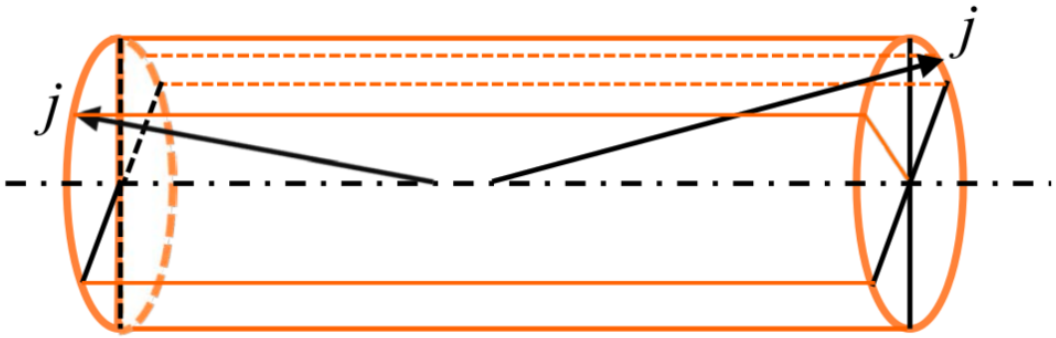
# Limits for lighter $\phi$ ($m_\phi \lesssim 100$ MeV)

- 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 et. al. [1811.03530]
- $0\nu\beta\beta$ 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 [Phys. Rev. D37, 3225 (1988)]; Farzan [0211375]]; Heurtier, Zhang [1609.05882]
- $\Delta N_{\mathrm{eff}}$ (for $m_\phi \lesssim 100$ keV) from CMB [Planck Collaboration [1807.06209] & BBN (for $m_\phi \lesssim 200$ keV) [Ahlgren, Ohlsson, Zhou [1309.0991];
- neutrino decay (for $m_\phi \lesssim 0.05$ eV): $\nu_j \to \nu_i + \phi$ including solar, atmospheric & long baseline neutrino experiments

# Vector Boson Fusion Topology




VBF tagged jets (2 energetic jets: large $m_{jj}$, forward region, opposite hemispheres)

Fig. credit: Kechen Wang

Advantages of VBF search:

- VBF tagging jets – handle on trigger
- VBF jets are in forward-backward region
- Direct probing of EW sector – agnostic about color sector

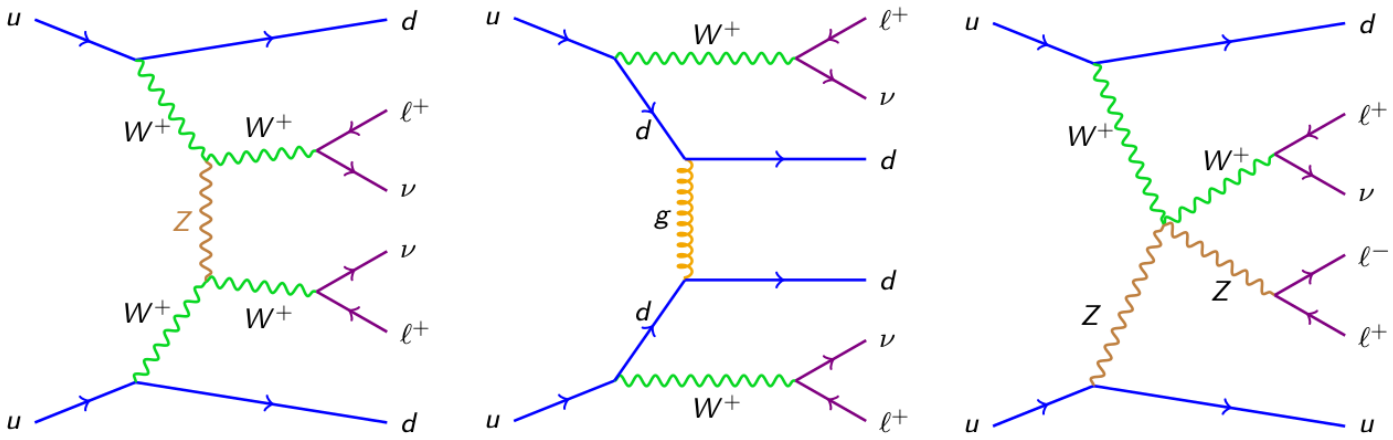
Characteristic kinematic cuts:

- Significant $p_T(j_1)$, $p_T(j_2)$ cuts
- Large $|\Delta\eta_{j_1 j_2}|$ separation
- $\eta_{j_1} * \eta_{j_2} < 0$
- Very large $M_{j_1 j_2}$
- No central jet-activity

# Dominant backgrounds

ATLAS collaboration [1906.03203]; CMS collaboration [1709.05822]

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



# 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 $2\ell$: $p_{T_{\ell_{1,2}}} > 10$ 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 |
| $\geq 2$ 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 |

- There are also some sub-leading backgrounds -
  - Charged leptons from heavy-flavor hadron decays
  - Jets misidentified as leptons
  - Backgrounds coming from lepton charge misidentification
  - the $V\gamma$ production with photon misidentified as electron
- They can contribute at 20% level after VBF cuts
- $ZZ, VVV, ttV(V = W, Z)$ contribute $< 2\%$ after VBF cuts
- If we switch on couplings involving $\tau$ leptons as well we can get $\sim 15\%$ enhancement on the signal yield.
- Electrons are required to be outside the calorimeter transition region $(1.37 < |\eta_e| < 1.52)$
- To avoid additional background contributions from electron charge mis-reconstruction in di-electron events, we restrict electrons within $|\eta_e| < 1.37$ for such events, and discard events with $|m_{e_1 e_2} - m_Z| < 15$ GeV

# 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 |
| | syst. error 20% | 2.35 | 2.50 | 2.56 | 2.68 |

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 |
| | syst. error 20% | 1.42 | 1.09 | 1.19 |
| HL-LHC | syst. error 0% | 0.68 | 0.51 | 0.57 |
| | syst. error 10% | 0.76 | 0.68 | 0.70 |
| | syst. error 20% | 0.91 | 0.88 | 0.87 |

# Possible origin of $\nu\nu\phi$ interaction

- One can generate $\nu\nu\phi$ in $U(1)_{B-L}$ extensions of the SM
- Adding three $\nu_R$s to the SM $\implies$ one can gauge $B-L$ symmetry and $U(1)_{B-L}$ can be a fundamental symmetry of nature
- Neutrinos are Dirac fermions

$$\mathcal{L}_{Yuk} \supset y_\nu \bar{L} \tilde{H} \nu_R + \text{h.c}$$

- Interesting phenomenological consequences of $Z'$ J. Heeck [1408.6845]
- Gauge-invariance and Lorentz-invariance ensures that for any operator, consisting of SM($+\ \nu_R$) fields only, and of mass-dimension $d$, and $B-L$ charge $q_{B-L}$, are constrained by:

$$(-1)^d = (-1)^{q_{B-L}/2}$$

A. Kobach [1604.05726]

# $U(1)_{B-L}$ symmetry of nature?

- Baryon number ($B$) and lepton number ($L$) are exact accidental global symmetries of the SM Lagrangian
- Both turn out to be anomalous and hence violated at the quantum level
- Adding three $\nu^C$ to the SM $\implies$ one can gauge $B-L$ symmetry and $U(1)_{B-L}$ can be a fundamental symmetry of nature
- $\nu^C$ carry $L=-1$ and $B-L$ charge $+1$
- Conserved $U(1)_{B-L}$ $\implies$ neutrinos are Dirac fermions

$$\mathcal{L}_{Yuk} \supset y_\nu L H \nu^C + \text{h.c}$$

- Interesting phenomenological consequences

J. Heeck [1408.6845]

# $U(1)_{B-L}$ invariant operators

- We assume $U(1)_{B-L}$ is conserved even if higher-dimensional operators are allowed

- We are interested in the consequences of allowing for the existence of new degrees of freedom charged under $U(1)_{B-L}$
- Gauge-invariance and Lorentz-invariance ensures that for any operator of mass-dimension $d$ and $B-L$ charge $q_{B-L}$

$$(-1)^d = (-1)^{q_{B-L}/2}$$

A. Kobach [1604.05726]

- Odd dimensional operators will have $B-L$ charge $4n+2$
- Even dimensional operators will have $B-L$ charge $4n$
- $L$ charged scalars $\implies$ $(B-L)$ charged scalars $\implies$ Leptonic Scalars
- All $L$ charged species with odd $B-L$ charge can only couple to the SM fields in pairs $\implies$ DM candidate

Berryman, de Gouvea, Kelly, Zhang [1802.00009], Kelly, Zhang [1901.01259]

# VBF kinematic distributions