A LEPTONIC SCALAR

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A. de Gouvea, B. Dev, B. Dutta, T. Ghosh, TH & Y. Zhang, 1910.01132;
TH, J. Liao, H. Liu & D. Marfatia, 1910.03272; 1912.01431

Non-Standard-neutrino Interactions

(NSI, or LEFT)

As originally formulated by Wolfenstein:

$$\mathcal{L}_{\rm NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} (\bar\nu_\alpha \gamma^\mu P_L \nu_\beta)(\bar f \gamma_\mu P f)\,,$$

$$\mathcal{L}_{\rm CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} (\bar\nu_\alpha \gamma^\mu P_L \ell_\beta)(\bar f \gamma_\mu P f')\,,$$

$$H = \frac{1}{2E}\left[U_{\rm PMNS}\begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix} U^\dagger_{\rm PMNS} + a\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$

For a heavy mediator: $\boldsymbol{\varepsilon} \sim g'^2\, v_{EW}^2/M^2$.

Already confirmed by oscillation experiments with matter effects; but measurements continue …

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

Further generalization

$$\mathscr{L}^{\rm NC}_{\rm LEFT} \supset -\frac{G_F}{\sqrt{2}} \sum_{j=1}^{10} (\overset{(\sim)}{\epsilon}_{j,f})^{\alpha\beta\gamma\delta} (\overline{\nu}_\alpha O_j \nu_\beta)(\overline{f}_\gamma O'_j f_\delta)\,,$$

$$\mathscr{L}^{\rm CC}_{\rm LEFT} \supset -\frac{G_F V^*_{\delta\gamma}}{\sqrt{2}} \sum_{j=1}^{10} (\overset{(\sim)}{\epsilon}_{j,du})^{\alpha\beta\gamma\delta} (\overline{\nu}_\alpha O_j \ell_\beta)(\overline{d}_\gamma O'_j u_\delta) + \text{h.c.}$$

j	$\overset{(\sim)}{\epsilon}_j$	O_j	O'_j
1	ϵ_L	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma_\mu(\mathbb{1}-\gamma^5)$
2	$\tilde{\epsilon}_L$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma_\mu(\mathbb{1}-\gamma^5)$
3	ϵ_R	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma_\mu(\mathbb{1}+\gamma^5)$
4	$\tilde{\epsilon}_R$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma_\mu(\mathbb{1}+\gamma^5)$
5	ϵ_S	$\mathbb{1}-\gamma^5$	$\mathbb{1}$
6	$\tilde{\epsilon}_S$	$\mathbb{1}+\gamma^5$	$\mathbb{1}$
7	$-\epsilon_P$	$\mathbb{1}-\gamma^5$	γ^5
8	$-\tilde{\epsilon}_P$	$\mathbb{1}+\gamma^5$	γ^5
9	ϵ_T	$\sigma_{\mu\nu}(\mathbb{1}-\gamma^5)$	$\sigma_{\mu\nu}(\mathbb{1}-\gamma^5)$
10	$\tilde{\epsilon}_T$	$\sigma_{\mu\nu}(\mathbb{1}+\gamma^5)$	$\sigma_{\mu\nu}(\mathbb{1}+\gamma^5)$

SMNEFT

Constraints/Collider searches from
meson decays, **β**-decay, CEνNS, DIS, LHC …
i.e. TH, J. Liao, H. Liu & D. Marfatia, 1912.01431:

What about ν-self interactions?

$$\mathcal{L}_{\rm eff} = G_{\rm eff}(\bar\nu\nu)(\bar\nu\nu)$$

← Important consequences, being actively explored.

Renewed interest to resolve the 4**σ** tension in the Hubble constant H_0 measurements:
CMB vs. Supernova

→ Need "strong interactions"
to slow down the **ν** free-streaming in the early universe,
thus increase $N_{\rm eff}$:

$$G_{\rm eff} = \begin{cases} (4.6 \pm 0.5\,\mathrm{MeV})^{-2} & (\mathrm{SI}\nu) \\ (90^{+170}_{-60}\,\mathrm{MeV})^{-2} & (\mathrm{MI}\nu) \end{cases}$$

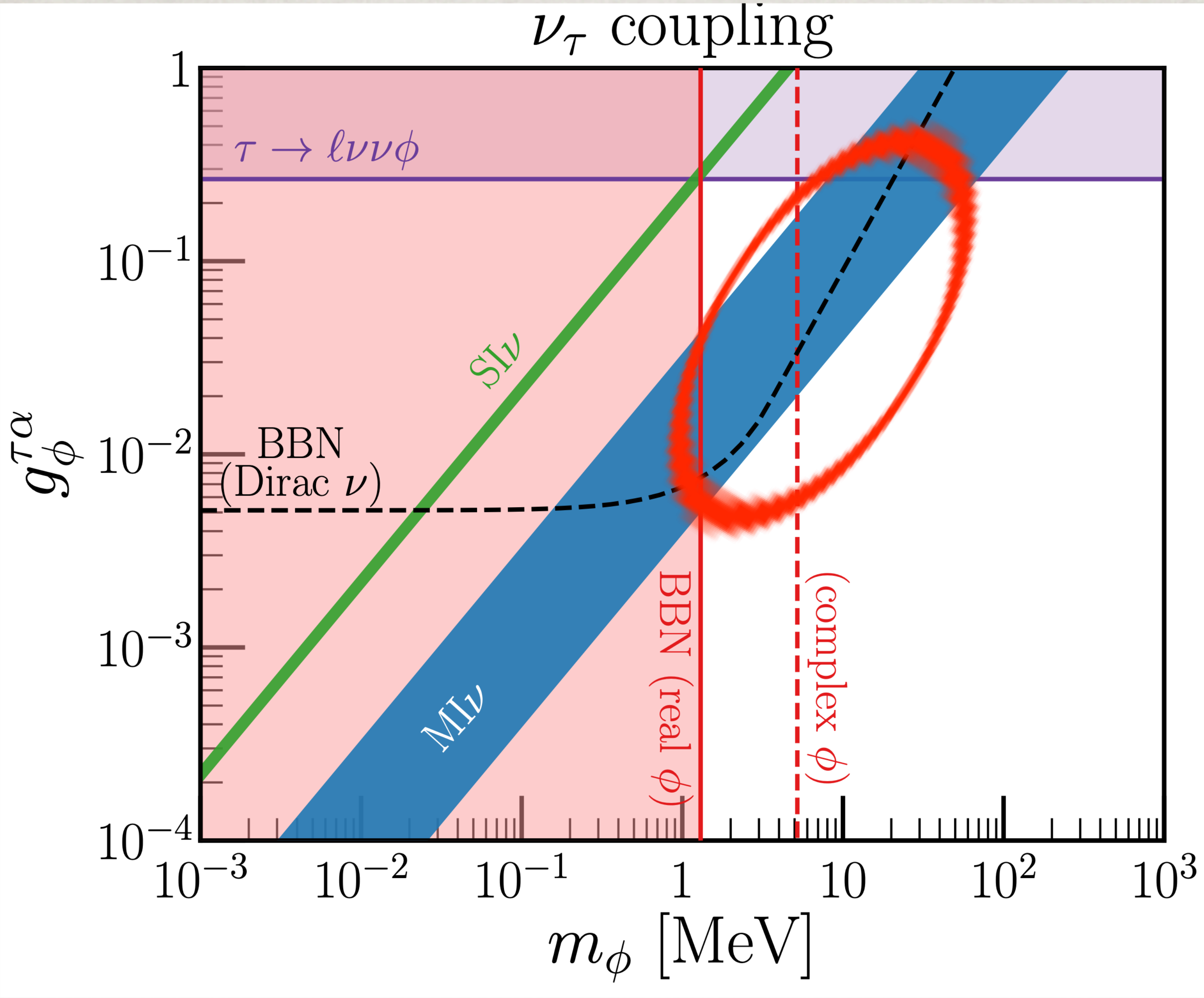
F.-Y. Cyr-Racine et al., 1306.1536; Oldengott et al., 1706.02123; …

A light force-mediator for the "strong interaction"

$$\mathcal{L}_{\rm phen} \supset -\frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}(g_\phi^{\alpha\beta}\nu_\alpha\nu_\beta\phi + \text{h.c.})$$

$$G_{\rm eff} \simeq \frac{g_\phi^2}{m_\phi^2} = (10\ \ \text{MeV})^{-2}\left(\frac{g_\phi}{10^{-1}}\right)^2\left(\frac{\text{MeV}}{m_\phi}\right)^2$$

Viable for the interpretation of H_0 discrepancy



Blinov et al., 1905.02727

A "Leptonic Scalar"

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, it may couple to $\nu_L\, \nu_L$:

  $(LH)(LH)\, \phi\, /\Lambda^2 \rightarrow \lambda_{\alpha\beta} \sim \kappa_1\, \kappa_2\, v_{EW}{}^2/M^2$

- Could be from a UV complete formulation

A Word of UV Completion

$\lambda_{\alpha\beta}\ \phi\ \nu_\alpha \nu_\beta \quad \leftarrow \quad (LH)(LH)\phi$

Type II Seesaw realization:

$\lambda_1 LL\Delta + \ \lambda_2 \phi H \Delta H$, where Δ is an $SU(2)_L$ scalar triplet

Similar embedding can be done
in Type I, III Seesaw models,
in fact, any other UV complete models.

Observationally:

- ϕ can be radiated off any neutrino and thus could effect many processes:
  - astrophysical, cosmological constraints
  - double-beta decay
  - meson decays; tau decay; W/Z decays
  - light DM searches; IceCube, …
  - collider experiments

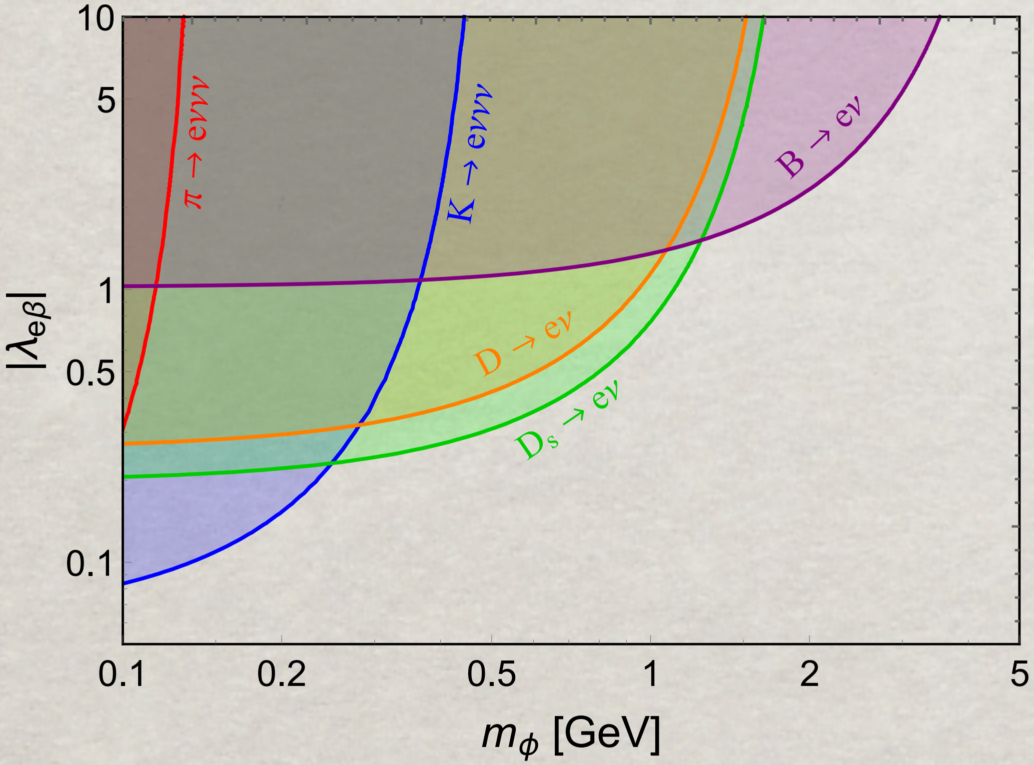
A. de Gouvea, B. Dev, B. Dutta, T. Ghosh, TH & Y. Zhang, 1910.01132; Kreisch et al., 1902.00534; Blinov et al. 1905.02727; Deppisch et al. 2020…; Bradar et al., 2003.05339.

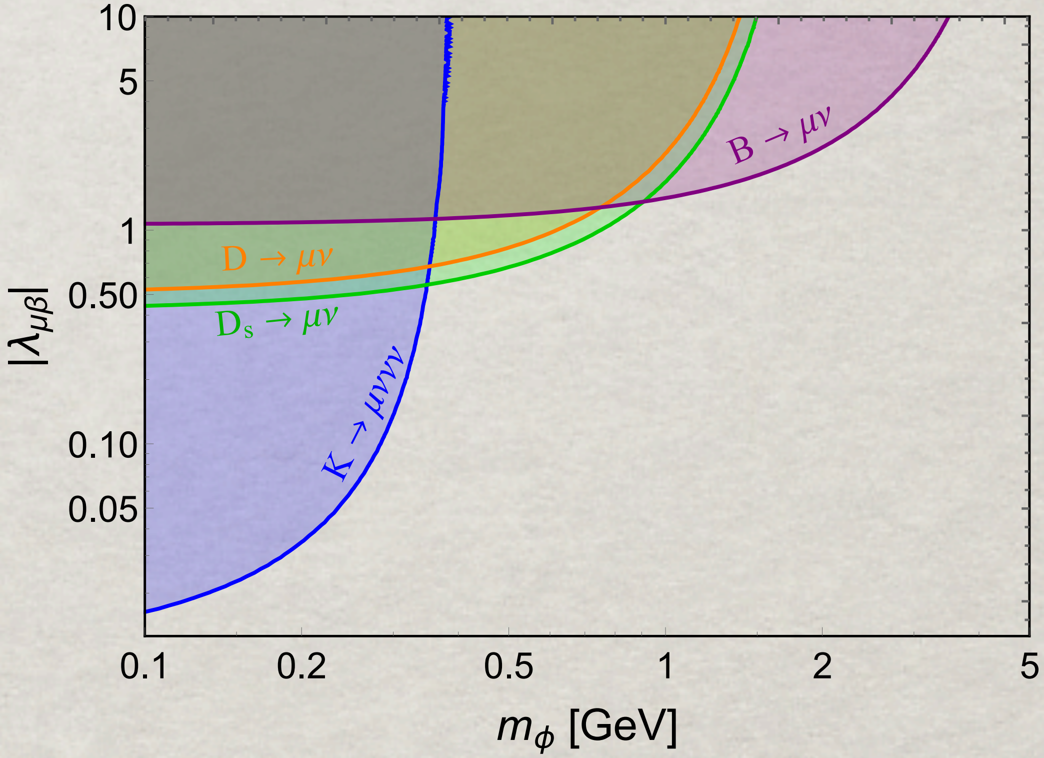
Low-energy constraints: Meson decay rates

$P^- \to \ell^- \bar{\nu}$ with $P^- = \pi^-, K^-, D^-, D_S^-, B^-$

$$\Gamma(P^- \to \ell_\alpha^- \bar{\nu}\phi) = \frac{G_F^2 |V_{qq'}|^2 m_P^3 f_P^2 \sum_\beta |\lambda_{\alpha\beta}|^2}{256\pi^3}$$

$$\times \int_{x_\phi}^{(1-\sqrt{x_\ell})^2} \mathrm{d}x \frac{\left((x+x_\ell)-(x-x_\ell)^2\right)(x-x_\phi)^2}{x^3} \lambda^{1/2}(1,\, x,\, x_\ell)$$





Low-energy constraints: Meson decay spectrum

2-body decay vs. 3-body decay:

$$\frac{\mathrm{d}}{\mathrm{d}p_\ell}\Gamma(P^- \to \ell^- N) \simeq \rho\Gamma_0(P^- \to \ell^-\bar{\nu})|U_{\ell N}|^2\delta(p_{\rm peak} - p_\ell)$$

$$\frac{\mathrm{d}}{\mathrm{d}p_\ell}\Gamma(P^- \to \ell_\alpha^-\nu\phi) = \frac{G_F^2|V_{qq'}|^2 m_P^3 f_P^2|\lambda_{\alpha\beta}|^2}{128\pi^3}\left[(x+x_\ell)-(x-x_\ell)^2\right] \times \frac{(x-x_\phi)^2}{x^3\sqrt{x_\ell^2+p_\ell^2/m_P^2}}\frac{p_\ell}{m_P^2}\lambda^{1/2}(1,x,x_\ell)\,,$$

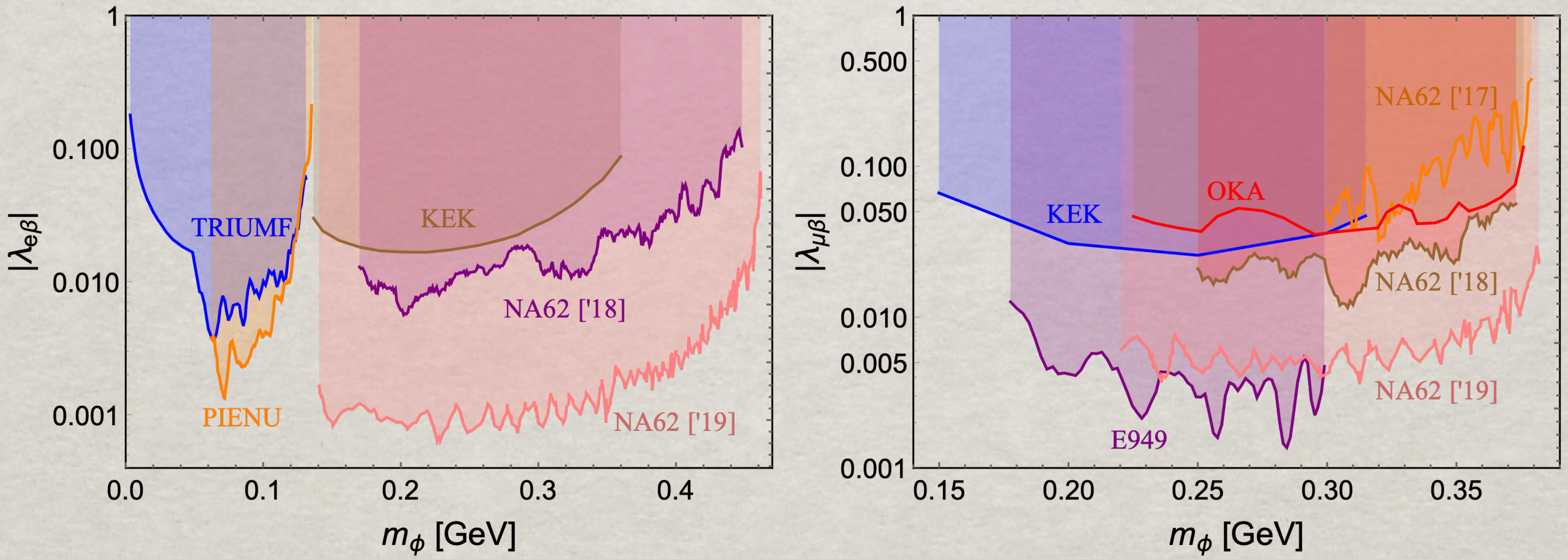
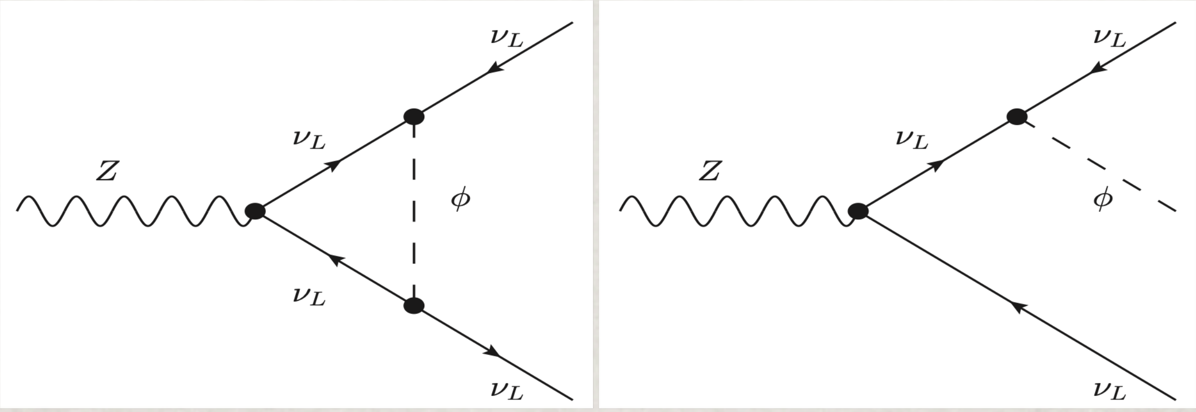
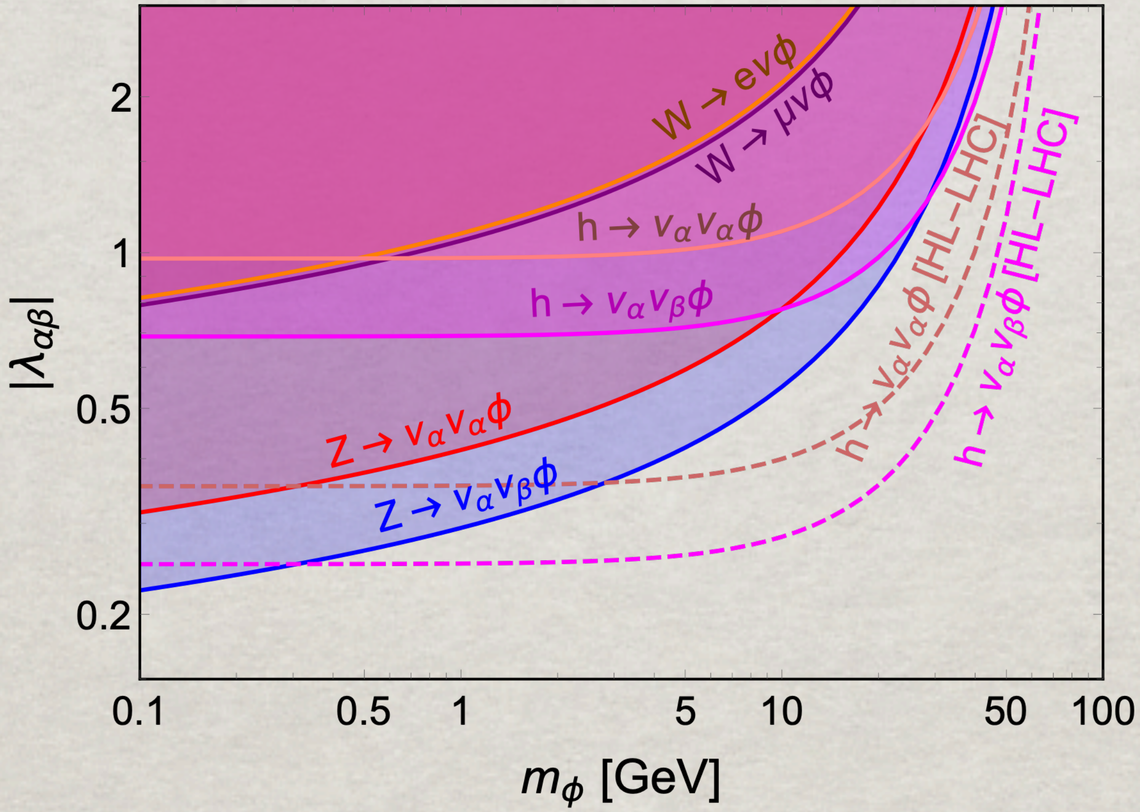


Figure 3. Limits on $|\lambda_{e\beta}|$ (left panel) and $|\lambda_{\mu\beta}|$ (right panel) with $\beta = e, \mu, \tau$ from heavy neutrino searches in meson decays in TRIUMF [39], PIENU [40], KEK [41], E949 [42], OKA [43], NA62 ['17] [44], NA62 ['18] [31] and NA62 ['19] [45]. The shaded regions are excluded.

Low-energy constraints: Invisible decays



Representative Feynman diagrams contributing to invisible Z decays.



$$\mathcal{L}_{\text{int}} \supset \frac{\lambda_{\alpha\beta}}{v} h\phi\nu_\alpha\nu_\beta$$

Figure 4. Limits on $|\lambda_{\alpha\beta}|$ (with α, $\beta = e$, μ) from invisible Z decay $Z \to \nu_\alpha\nu_\alpha\phi$ (red), $\nu_\alpha\nu_\beta\phi$ with $\alpha \neq \beta$ (blue), the decay $W \to e\nu\phi$ (orange), $\mu\nu\phi$ (purple) and invisible decay of the SM Higgs $h \to \nu_\alpha\nu_\alpha\phi$ (pink), $\nu_\alpha\nu_\beta\phi$ with $\alpha \neq \beta$ (magenta). The data can be found in Table 1, and all the shaded regions are excluded. The dashed pink and magenta lines denote the limits from the prospects of invisible decay of the SM Higgs at the HL-LHC.

Low-energy constraints: beam-dump experiments & perspectives

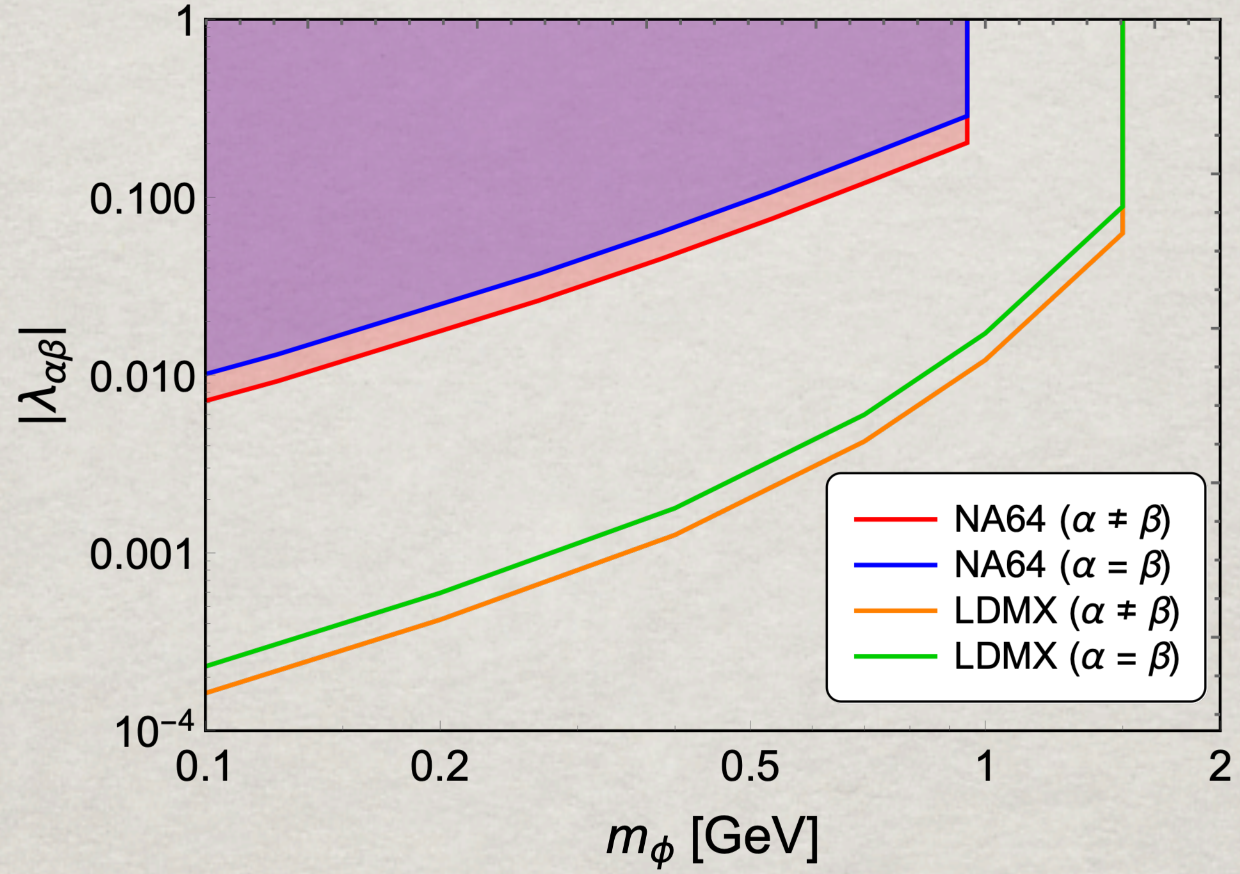


Figure 5. Limits on $|\lambda_{\alpha\beta}|$ from light DM searches in NA64 [26], and the prospects at LDMX [27]. The shaded regions are excluded.

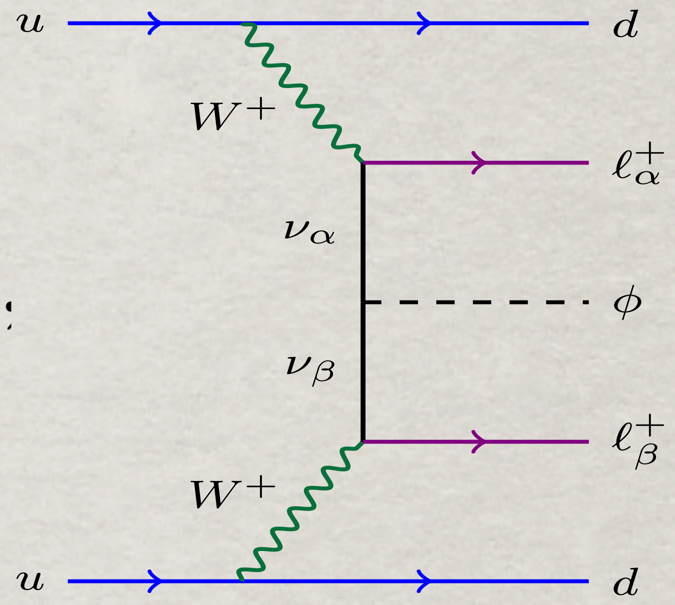
Low-energy constraints on ϕ radiation:

Decay rates of mesons / τ /W,Z

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

LHC searches:

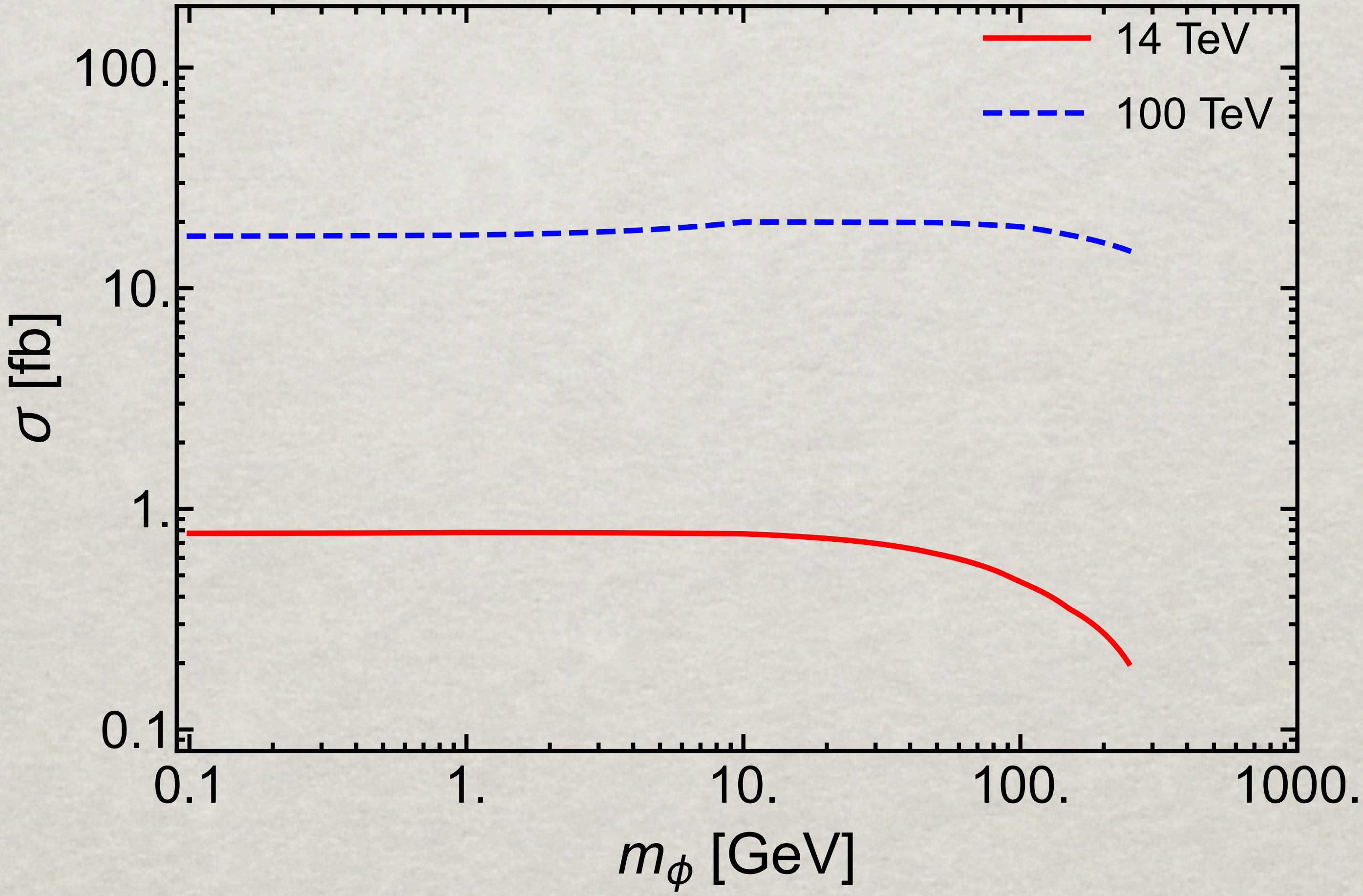
A unique, clean channel



VBF processes $W^\pm W^\pm \to \ell^\pm \ell^\pm \phi$

$$pp \;\to\; \ell^\pm_\alpha \ell^\pm_\beta \; \phi \; jj$$

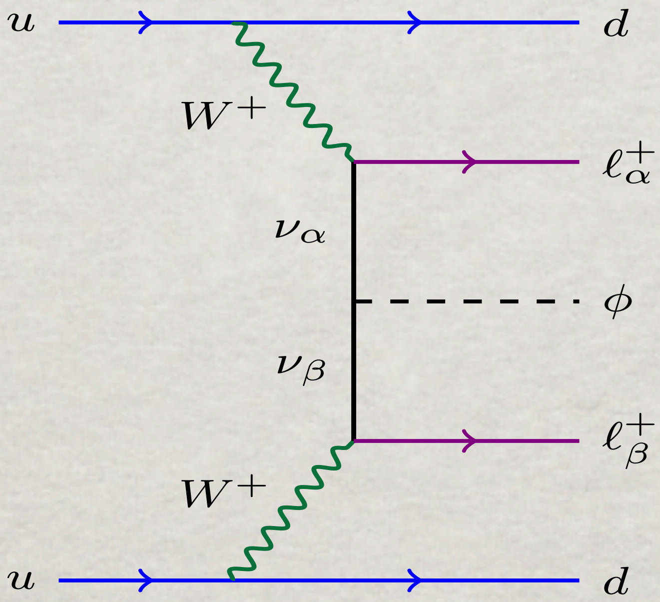
$\lambda_{\alpha\beta}=1$ $(\alpha,\beta=e,\mu)$

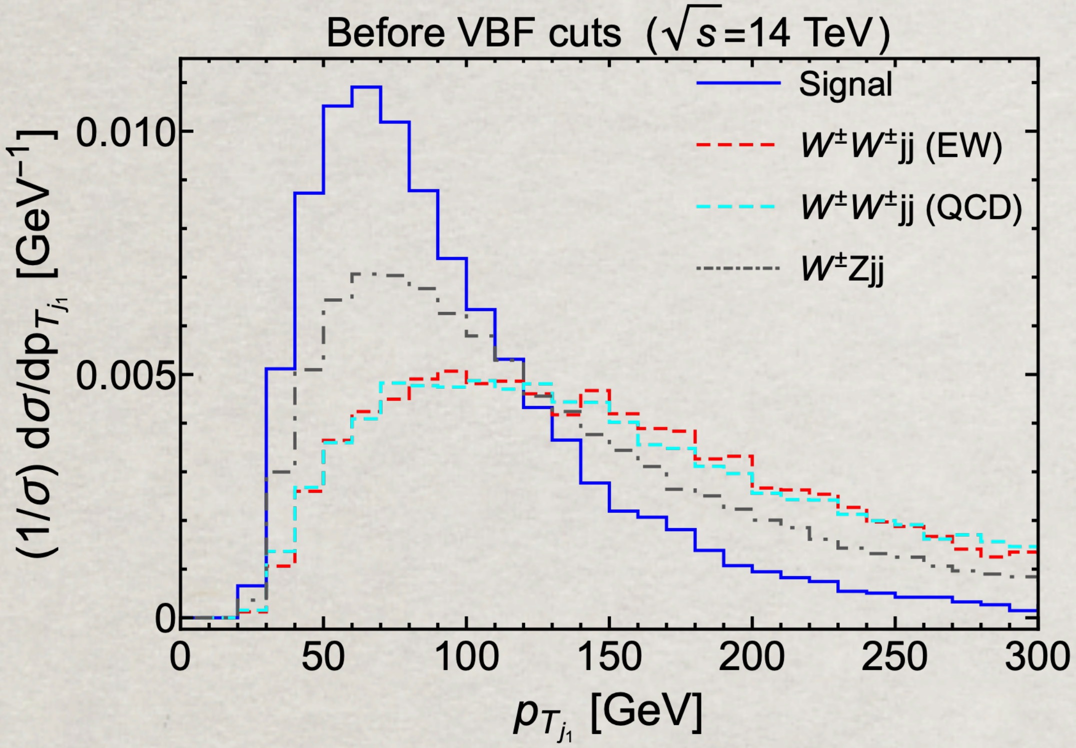


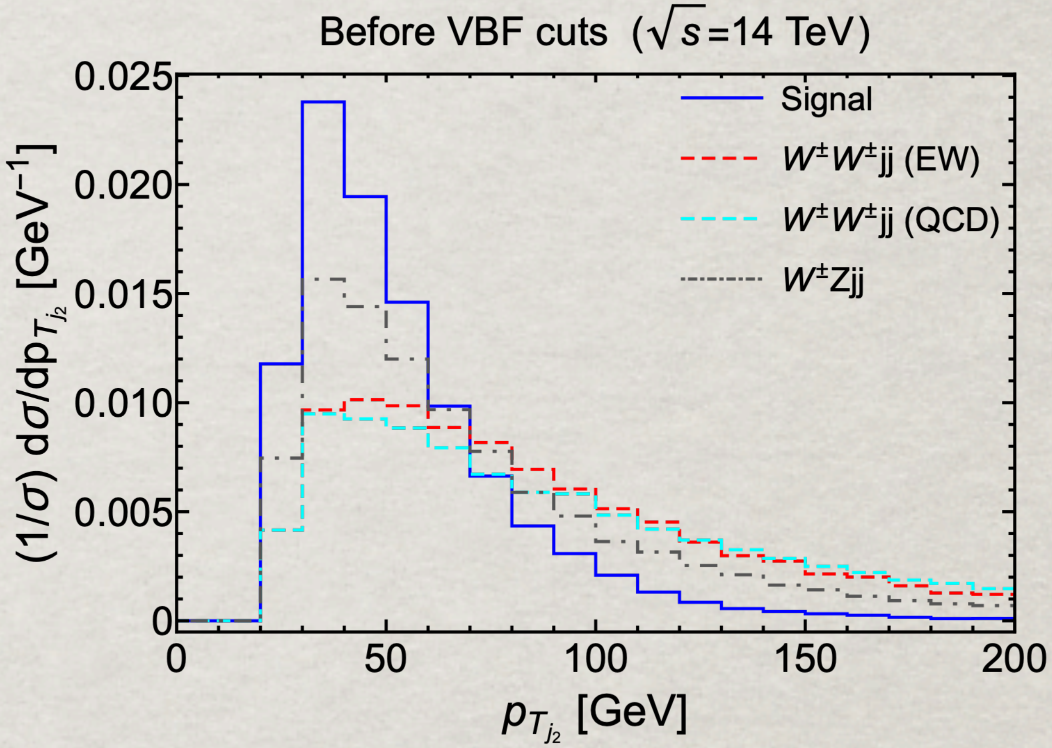
(m_ϕ not to exceed the EW scale)

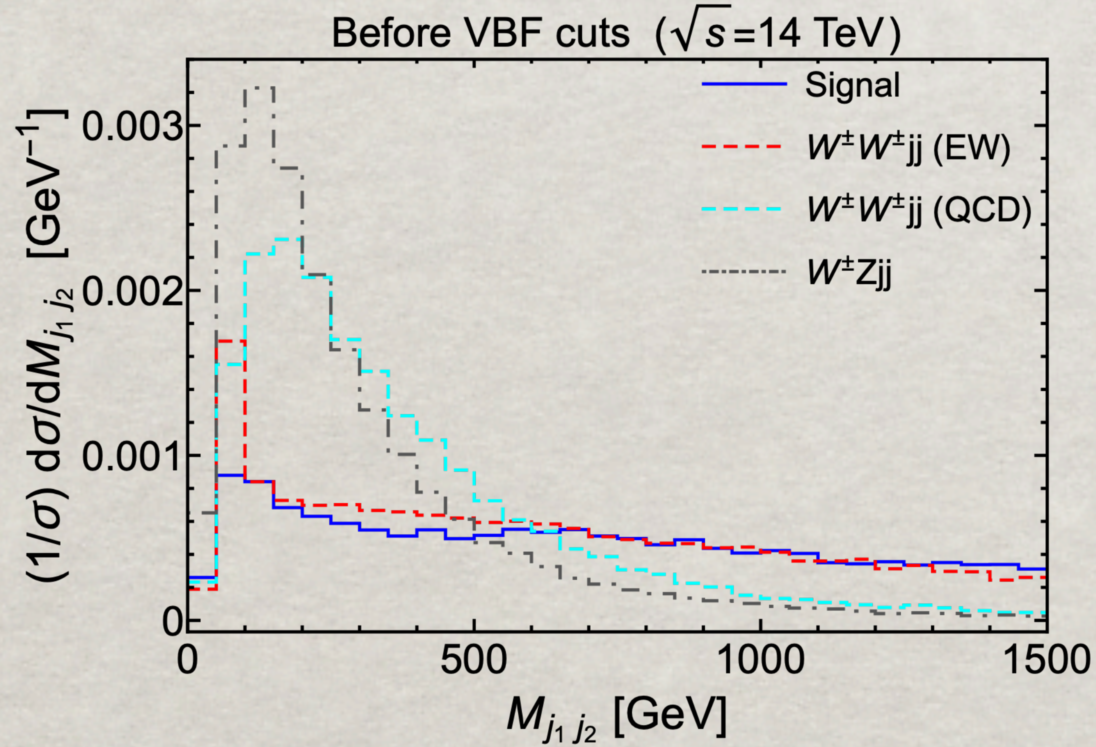
Signal & Backgrounds:

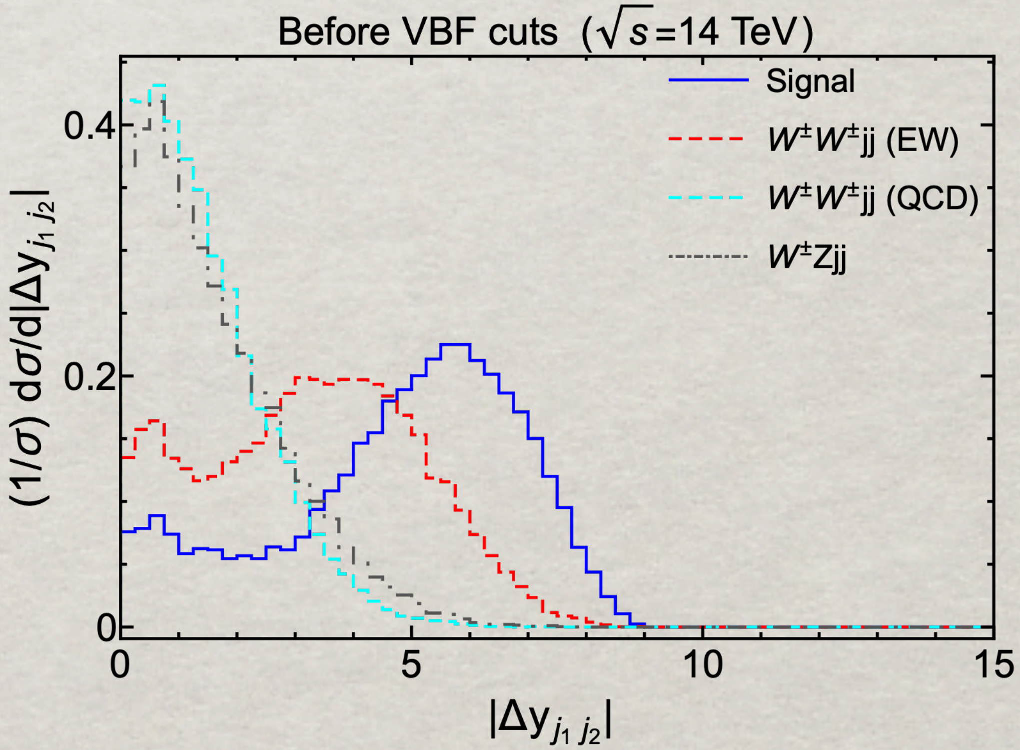
- the EW process $pp \to W^{\pm}W^{\pm}jj \to jj\ell_{\alpha}^{\pm}\ell_{\beta}^{\pm}\nu\nu$,
- the QCD process $pp \to W^{\pm}W^{\pm}jj \to jj\ell_{\alpha}^{\pm}\ell_{\beta}^{\pm}\nu\nu$
- $pp \to W^{\pm}Zjj \to jj\ell_{\alpha}^{\pm}\ell_{\beta}^{\pm}\ell_{\beta}^{\mp}\nu$,

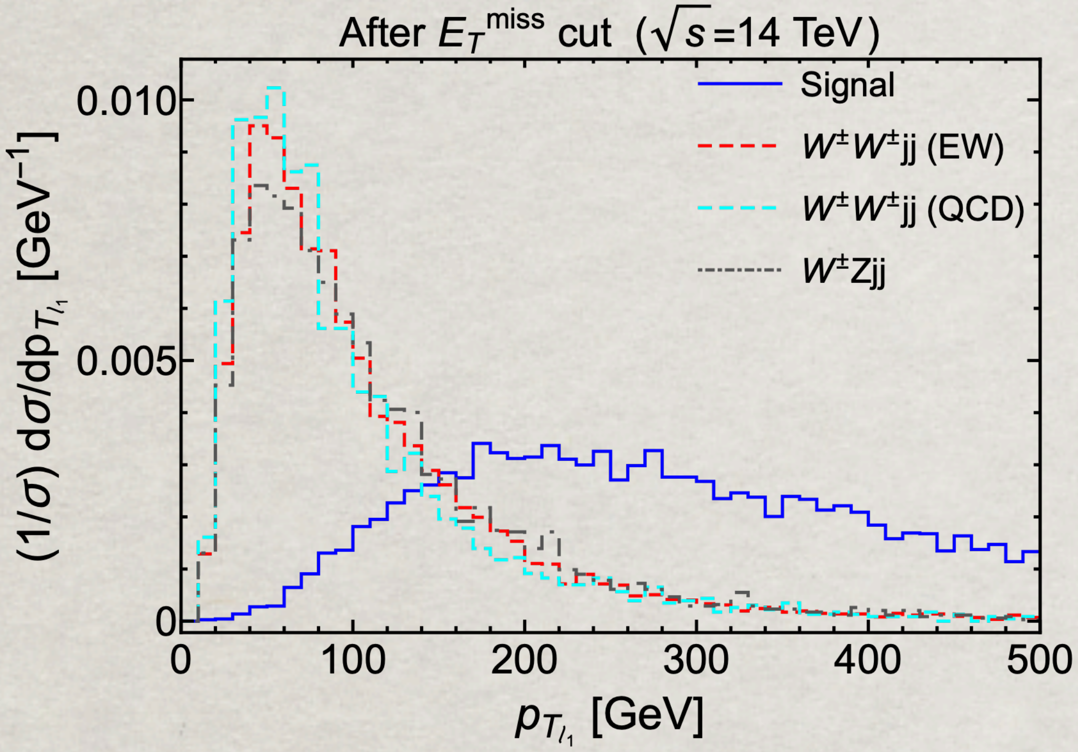



Before VBF cuts ($\sqrt{s}$=14 TeV)

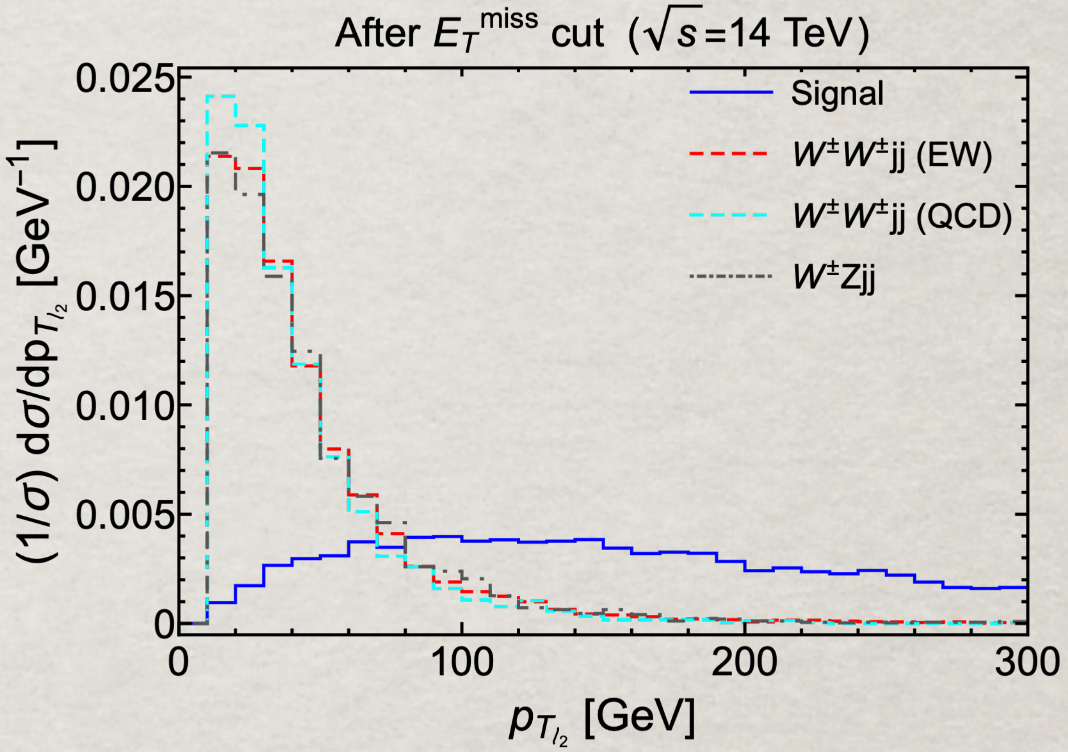

Before VBF cuts ($\sqrt{s}$=14 TeV)


Before VBF cuts ($\sqrt{s}$=14 TeV)

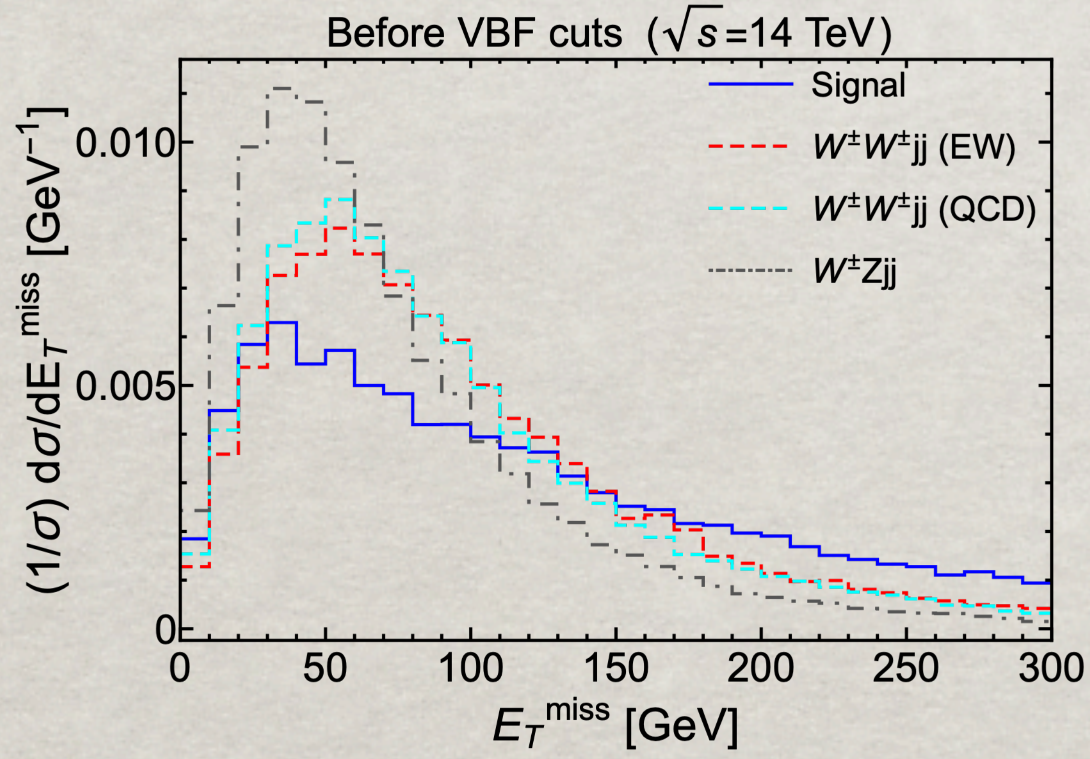

Before VBF cuts ($\sqrt{s}$=14 TeV)



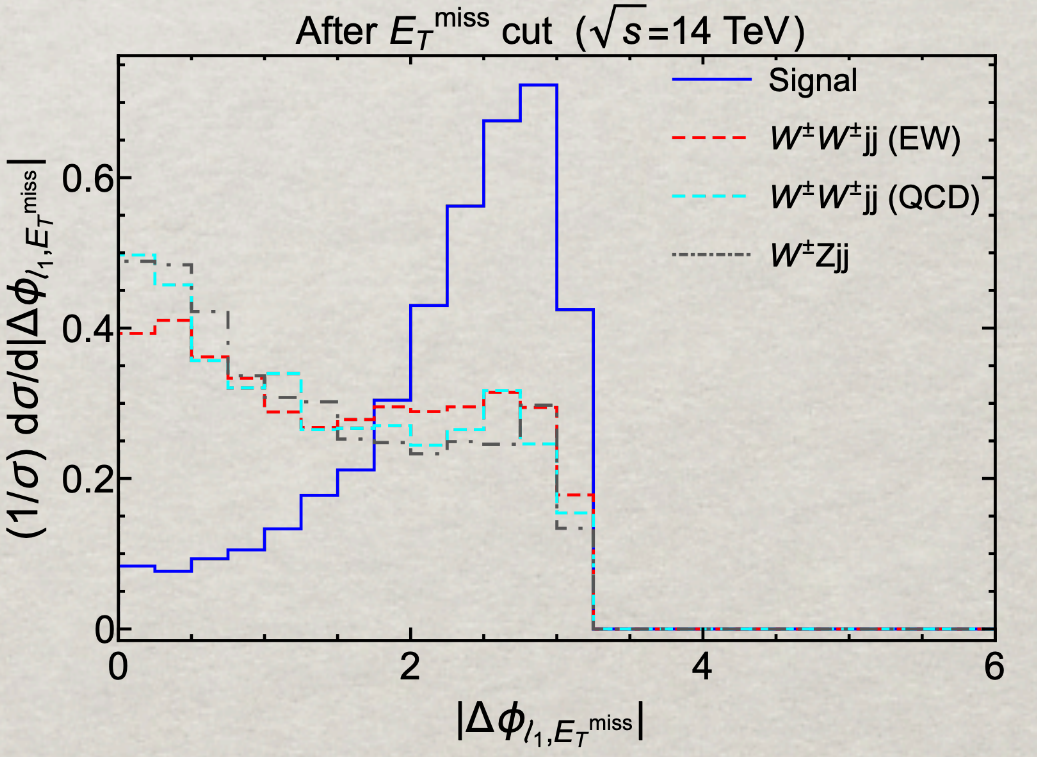
After E_T^{miss} cut ($\sqrt{s}$=14 TeV)



After E_T^{miss} cut ($\sqrt{s}$=14 TeV)

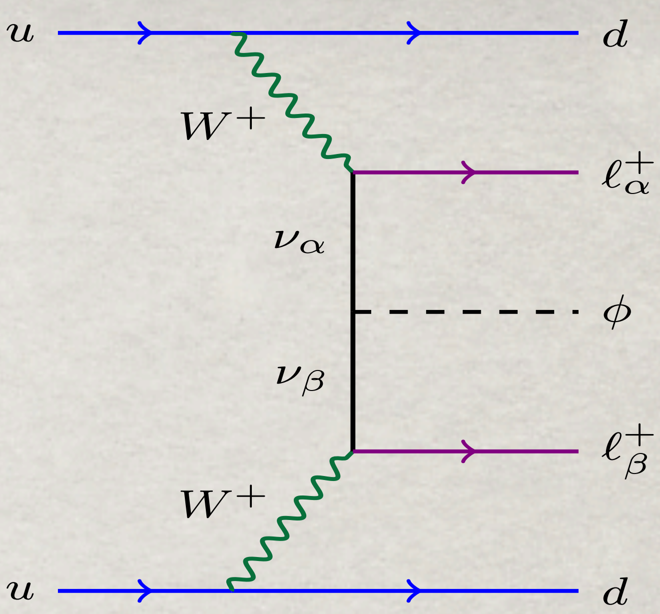


Before VBF cuts ($\sqrt{s}$=14 TeV)



After E_T^{miss} cut ($\sqrt{s}$=14 TeV)

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

Table 2. Cut-flow table of the signal, with $m_\phi = 1$ GeV, and SM backgrounds $W^\pm W^\pm jj$ (EW), $W^\pm W^\pm jj$ (QCD) and $W^\pm Zjj$ at 14 TeV LHC. We decay $W^\pm\,(Z)$ boson to $\ell^\pm\nu\,(\ell^+\ell^-)$, where $\ell = e, \mu, \tau$ during generation. In contrast, for the signal only $\ell = e, \mu$ are considered. The couplings $|\lambda_{\alpha,\beta}|\,(\alpha, \beta = e, \mu)$ are set to be 1. Note that the particular cuts in the last two rows can suppress very effectively the SM backgrounds.

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

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

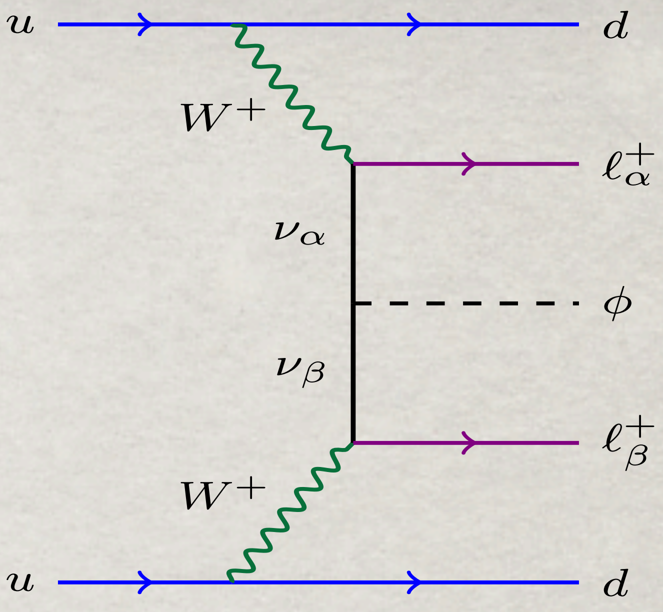


Table 3. Event yields in different lepton flavor combination channels $e^\pm e^\pm$, $e^\pm \mu^\pm$ and $\mu^\pm \mu^\pm$ for both the signal and SM backgrounds at 14 TeV LHC with 3 ab^{-1} of integrated luminosity. For the signal we set $m_\phi = 1$ GeV and $|\lambda_{\alpha,\beta}| = 1$ (with $\alpha, \beta = e, \mu$). We consider systematic errors of 0% and 10% on the background events only.

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

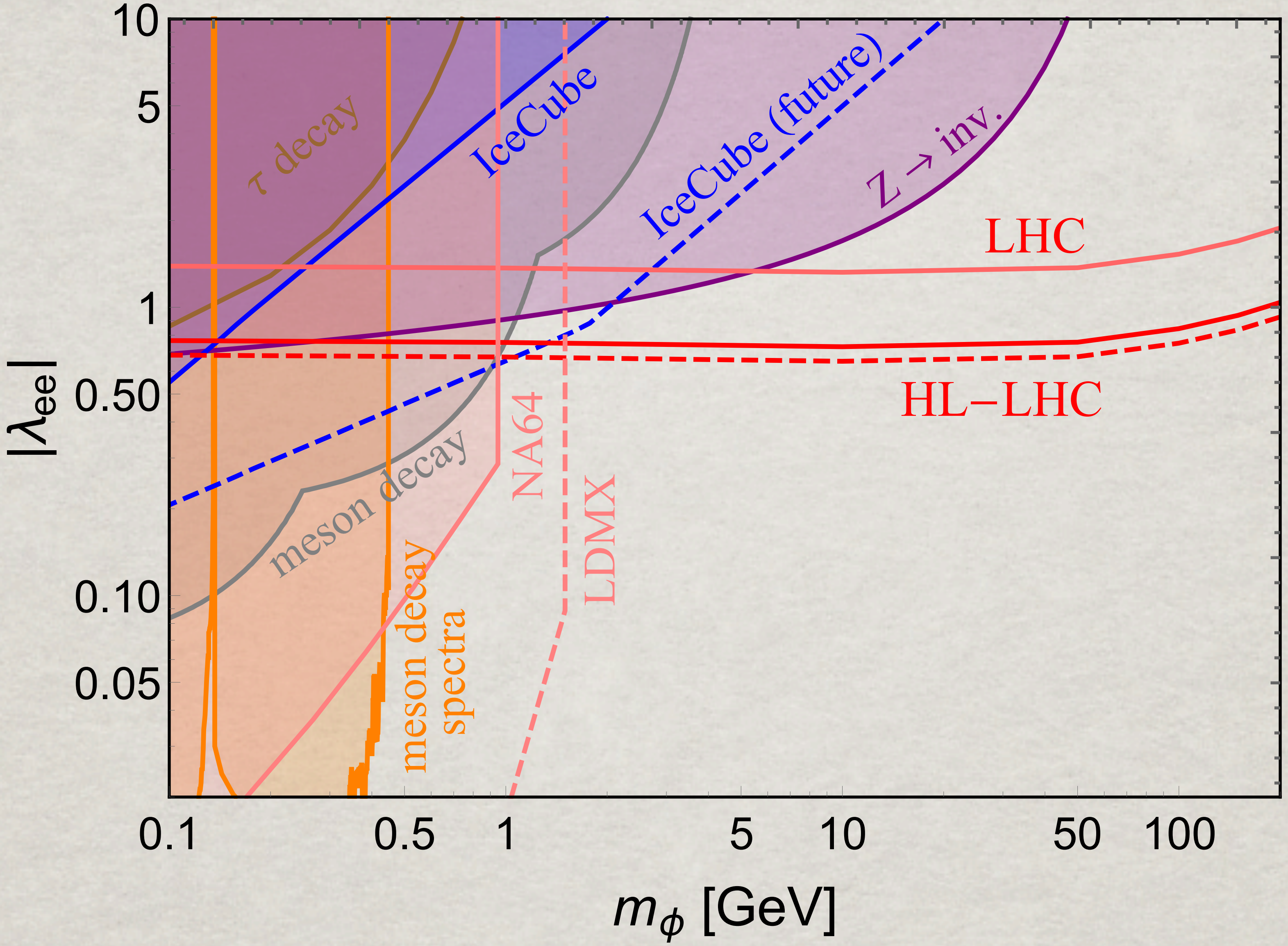
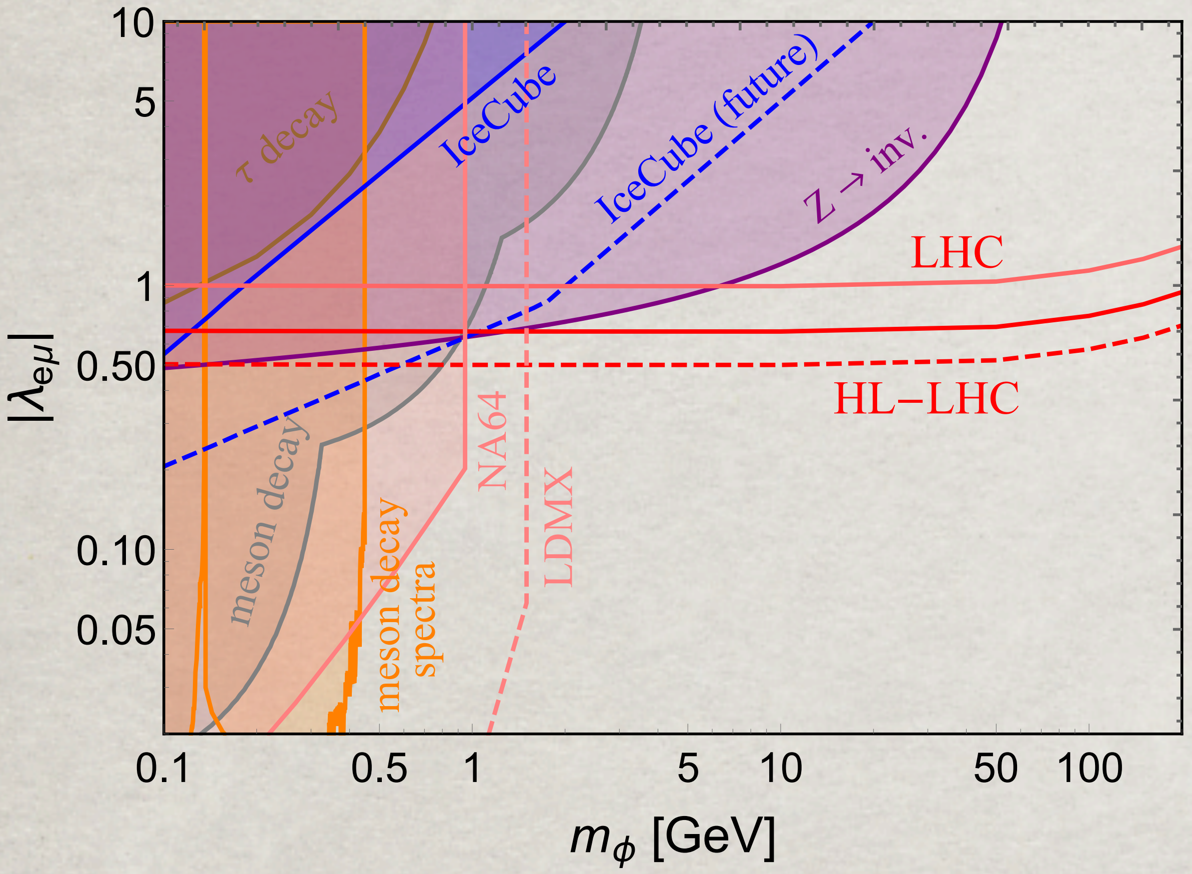
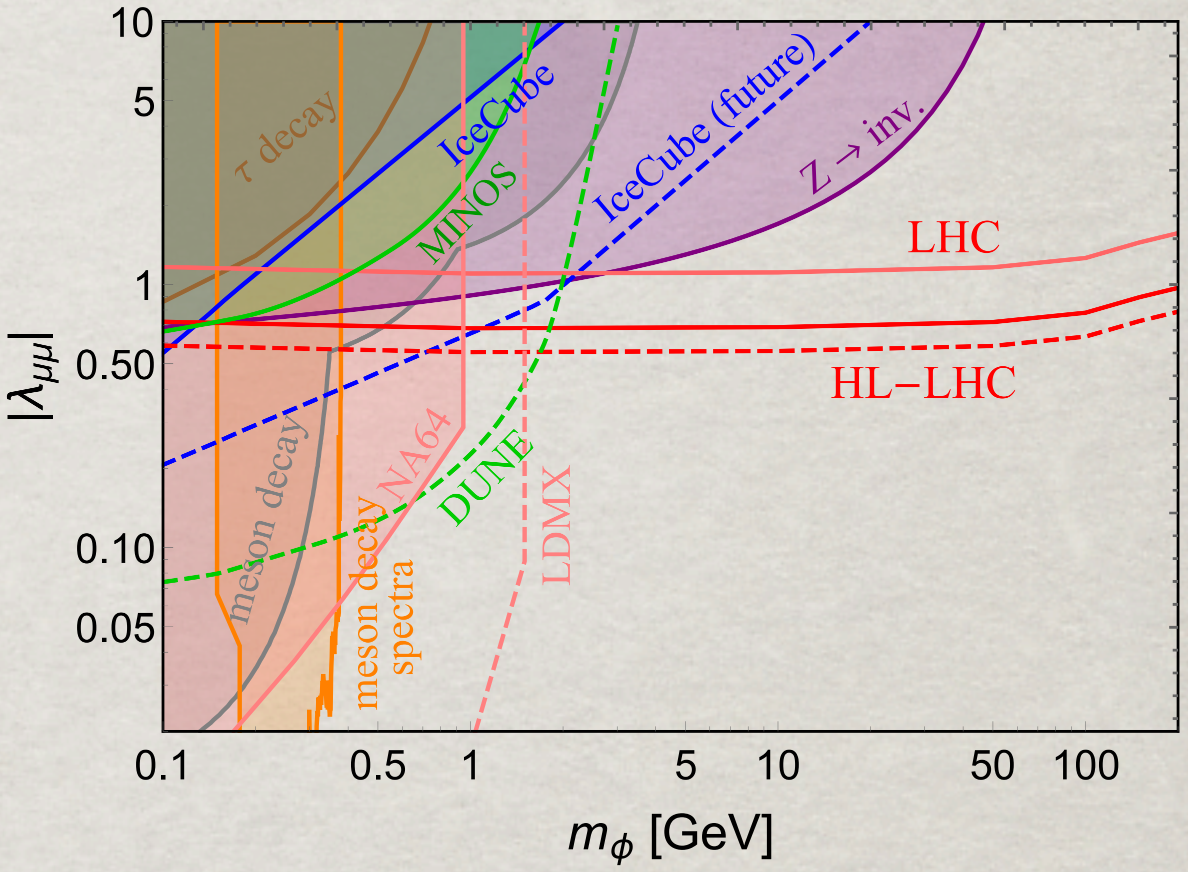
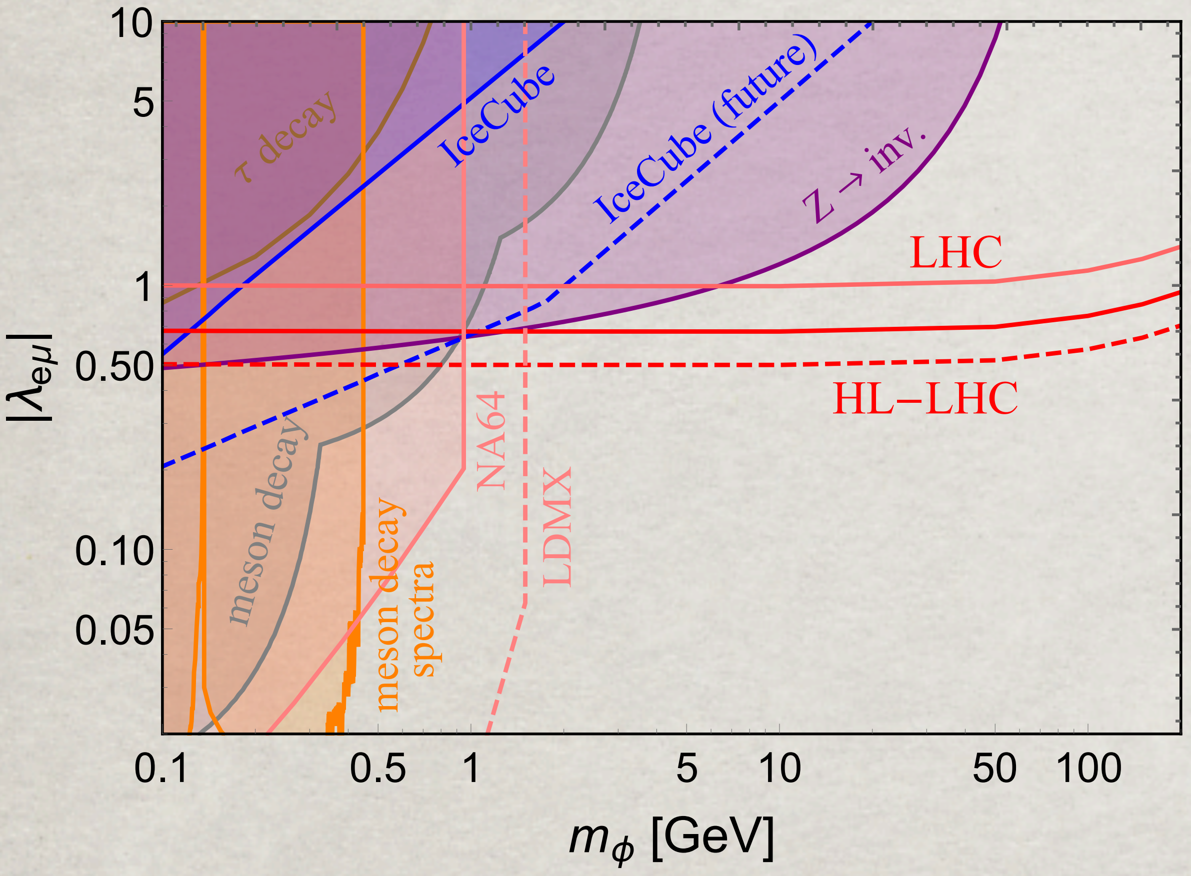
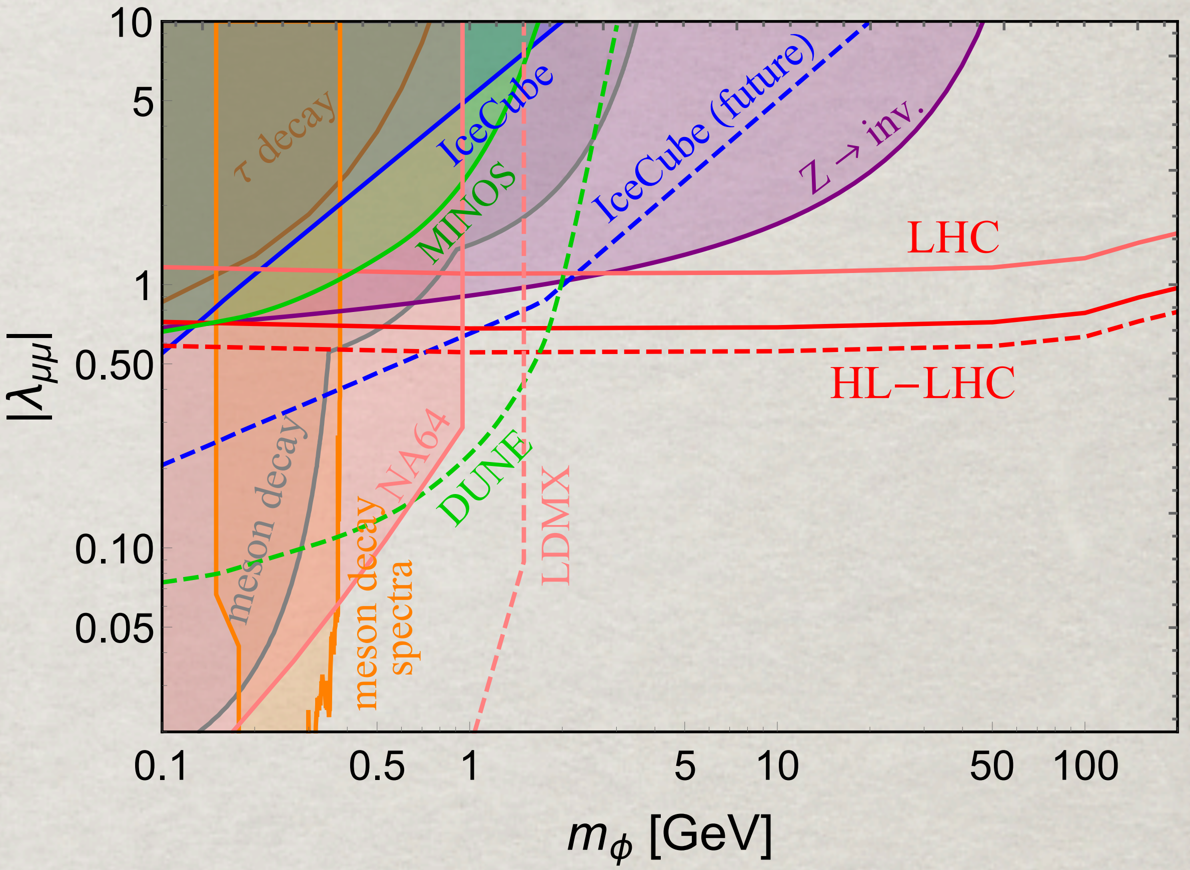


Figure 9. Prospects of the coupling $|\lambda_{ee}|$ as a function of the scalar mass m_ϕ at 14 TeV LHC with luminosity of 300 fb^{-1} (solid thin red line) and HL-LHC with 3 ab^{-1} and with systematic errors of 10% (solid thick red line) and 0% (dashed thick red line). Also shown are the low-energy 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.


τ decay
IceCube
IceCube (future)
Z → inv.
LHC
HL−LHC
meson decay
meson decay spectra
NA64
LDMX
$|\lambda_{e\mu}|$
m_ϕ [GeV]
10
5
1
0.50
0.10
0.05
0.1
0.5
1
5
10
50
100


τ decay
IceCube
MINOS
IceCube (future)
Z → inv.
LHC
HL−LHC
meson decay
meson decay spectra
NA64
DUNE
LDMX
$|\lambda_{\mu\mu}|$
m_ϕ [GeV]
10
5
1
0.50
0.10
0.05
0.1
0.5
1
5
10
50
100





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 target to scrutinize.
- Neutrino self-interaction

  → important consequences

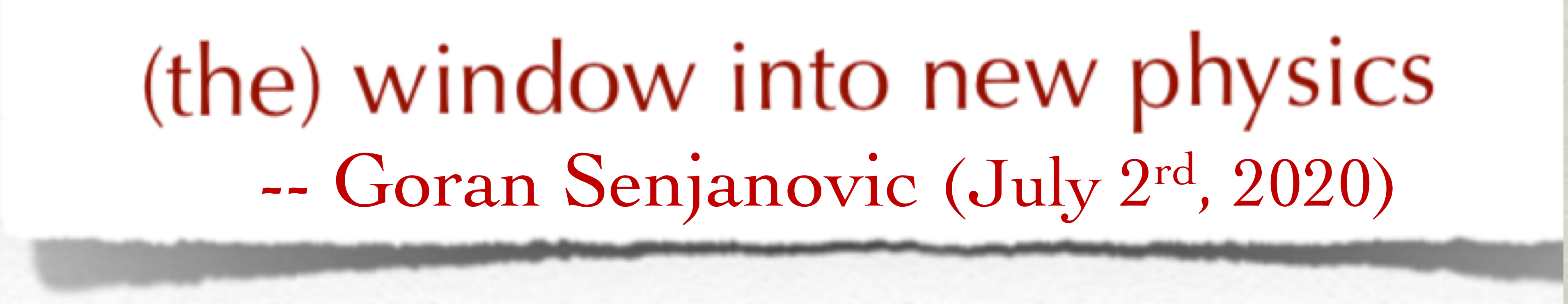
- A "leptonic scalar"$\boldsymbol{\phi}$ $\lambda_{\alpha\beta}\ \phi\ \nu_\alpha \nu_\beta$

  radiated off neutrinos, carrying away missing energy & lepton-number. Sensitivity on $\lambda_{\alpha\beta}$:

  Meson decays: 0.01; NA64: 0.02; DUNE: 0.08;

  IceCube: 0.3; Z-decay: 0.6; LHC: 1; HL-LHC: 0.5

Low-energy expts <-> LHC complementary!



(the) window into new physics

-- Goran Senjanovic (July 2nd, 2020)