PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

Search for long-lived heavy neutrinos at the LHC with a VBF trigger

Joel Jones-Pérez
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Based on the following work:
A. Gago, P. Hernández, JJP, M. Losada, A. Moreno-Briceño (1505.05880)
JJP, J. Masias, J. D. Ruiz-Álvarez (1912.08206)

Type-I Seesaw

Type I Seesaw is probably most popular mechanism for neutrino masses

$$\mathcal{L} = \mathcal{L}_{\rm SM} + Y_\nu \left(\bar{\nu}_R \, L \cdot \tilde{H} \right) + \frac{1}{2} M_R \left(\bar{\nu}_R^c \, \nu_R \right) + {\rm h.c.}$$

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The Casas-Ibarra parametrisation for more than one heavy neutrino shows that the mixing does not have to be vanishingly small:

$$U_{a4} = \pm Z_a^{\rm NH} \sqrt{\frac{m_3}{M_4}} \cosh \gamma_{45} \, e^{\mp i\theta_{45}} \qquad U_{a5} = i \, Z_a^{\rm NH} \sqrt{\frac{m_3}{M_5}} \cosh \gamma_{45} \, e^{\mp i\theta_{45}}$$

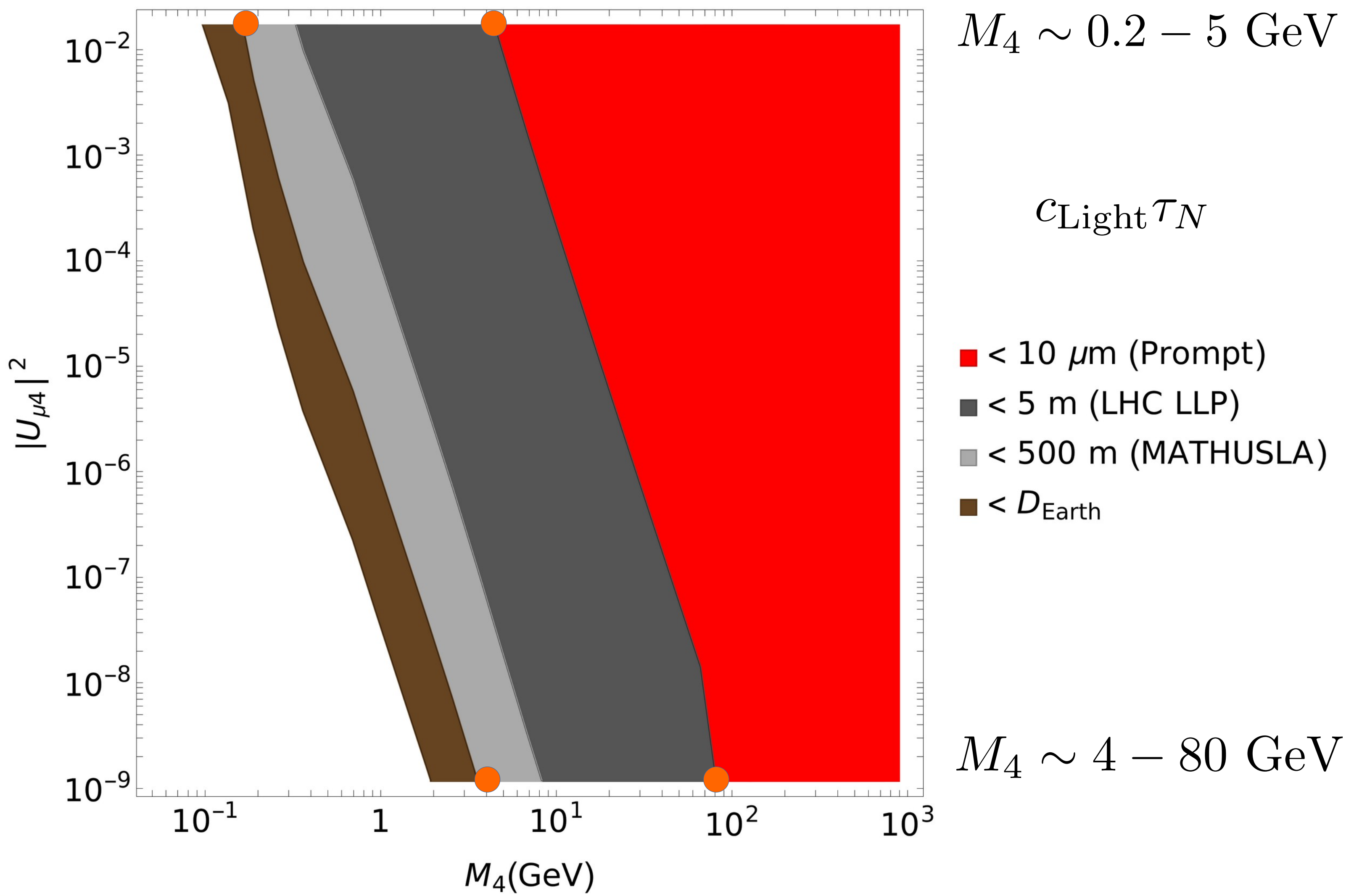
$$Z_a^{\rm NH} = \left(U_{\rm PMNS}\right)_{a3} \pm i \sqrt{\frac{m_2}{m_3}} \left(U_{\rm PMNS}\right)_{a2}$$

(Normal ordering)

Casas, Ibarra (hep-ph/0103065)

Small couplings, large decay lengths

The decays always involve active-heavy mixing, so decay width is small



Searching for Long Lived Heavy Neutrinos

Heavy Neutrino Trilepton Decay

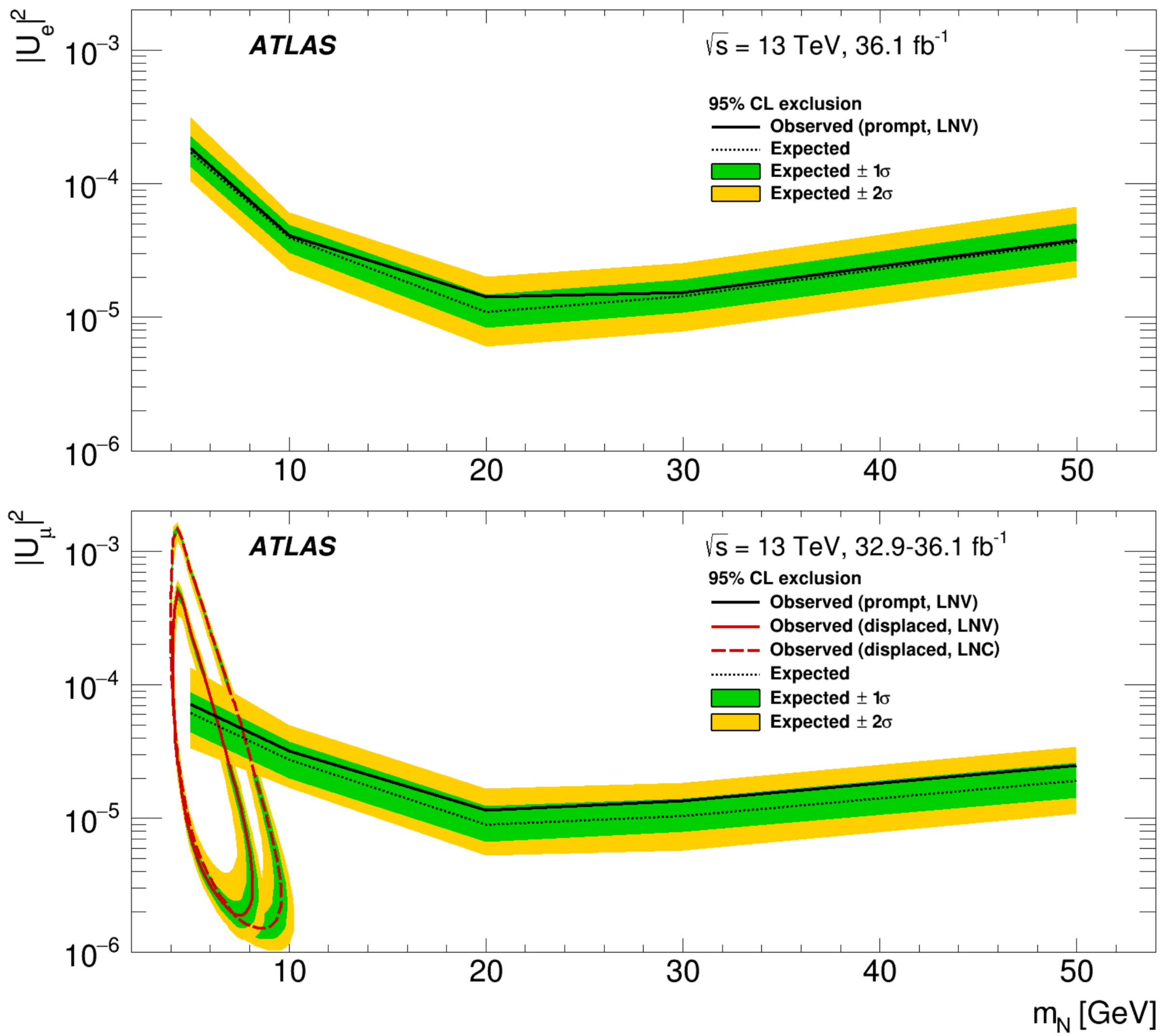
Constraints on displaced neutrinos already available!

$$W \to \mu\,\mu\,e\,\nu$$
$$W \to \mu\,e\,e\,\nu$$

ATLAS:

13 TeV

32.9 fb^{-1}



ATLAS: 1905.09787 [hep-ex]

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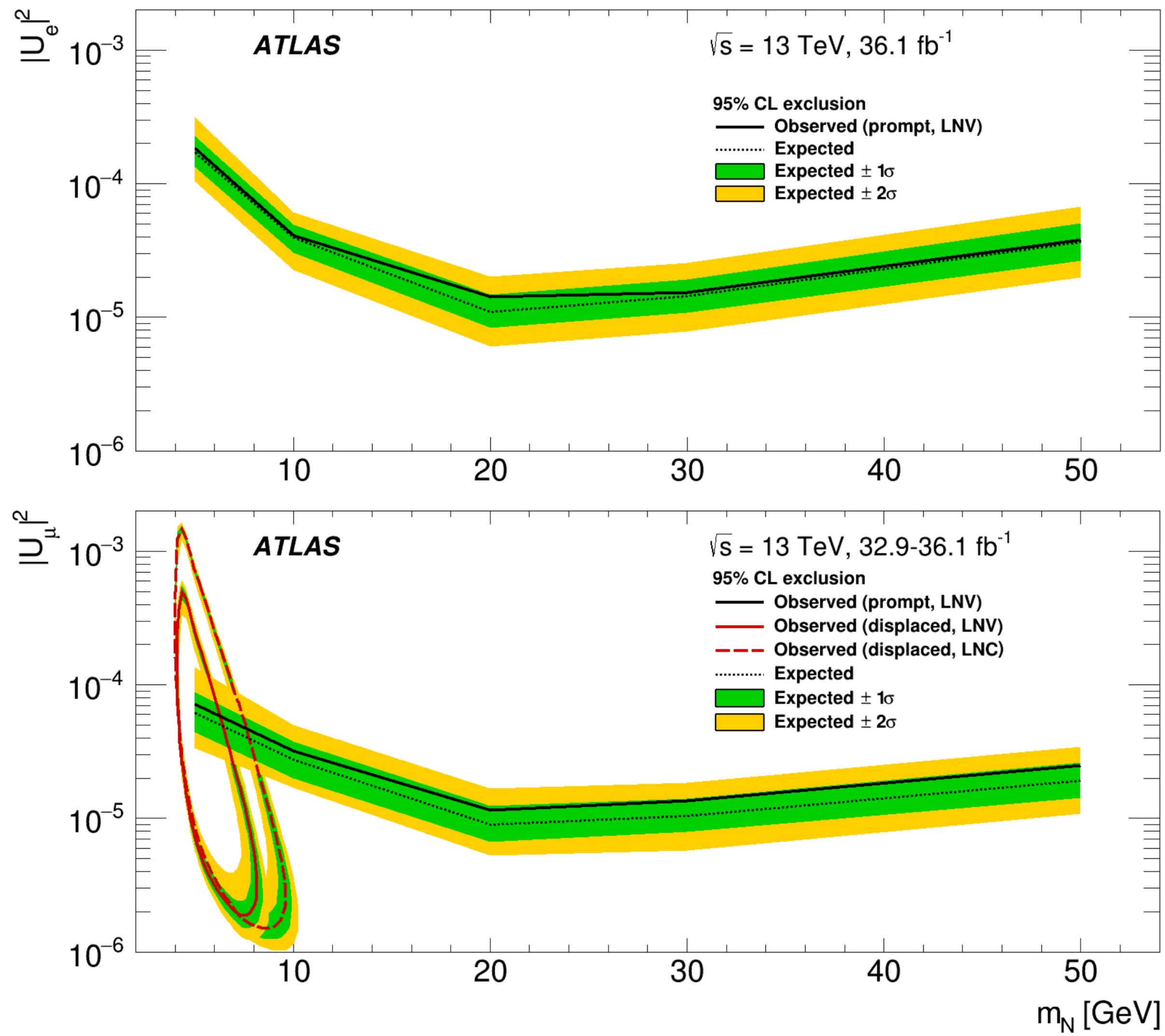

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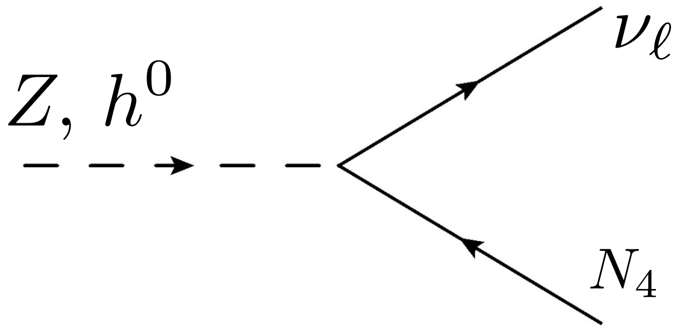
Measuring Neutral Current Production

Neutral current: Z- or Higgs-mediated: No prompt charged lepton!



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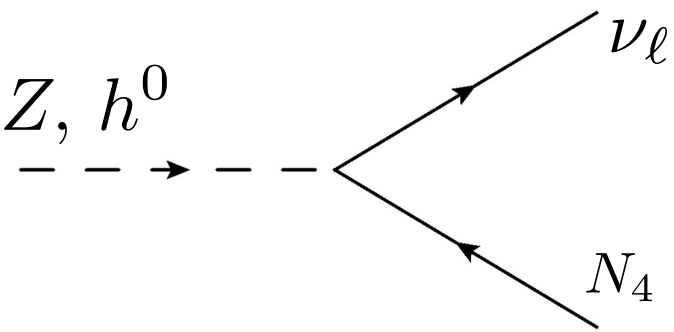
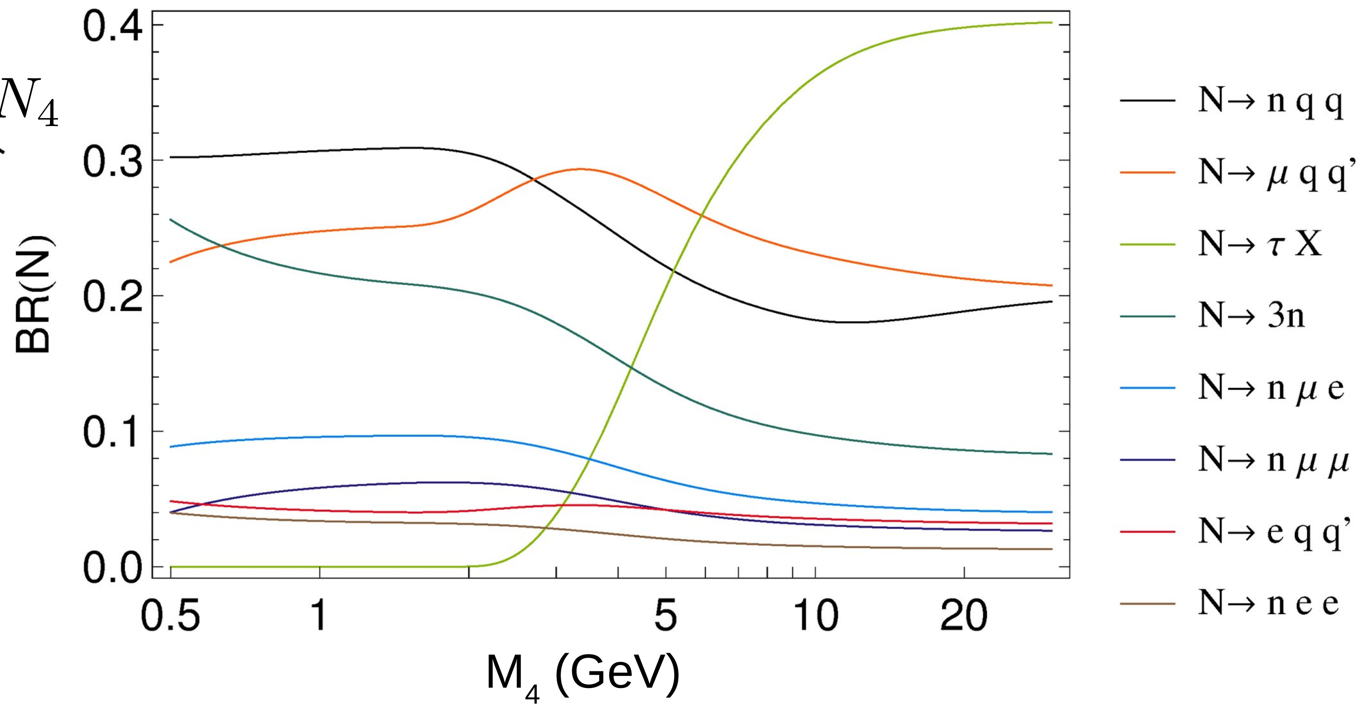


Trigger for gluon fusion?

Need to use N_4 decay products!



Atre, Han, Pascoli, Zhang (0901.3589 [hep-ph])
Kovalenko, Lu, Schmidt (0907.2533 [hep-ph])

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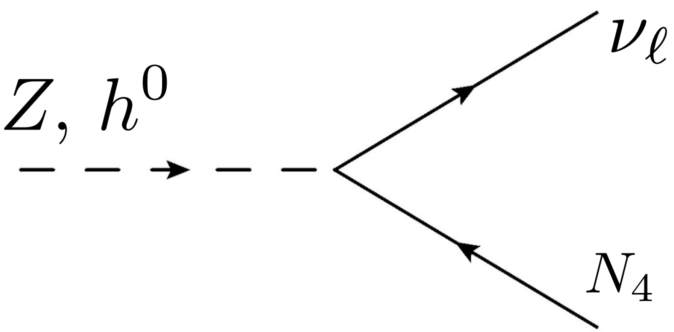

Trigger for gluon fusion?

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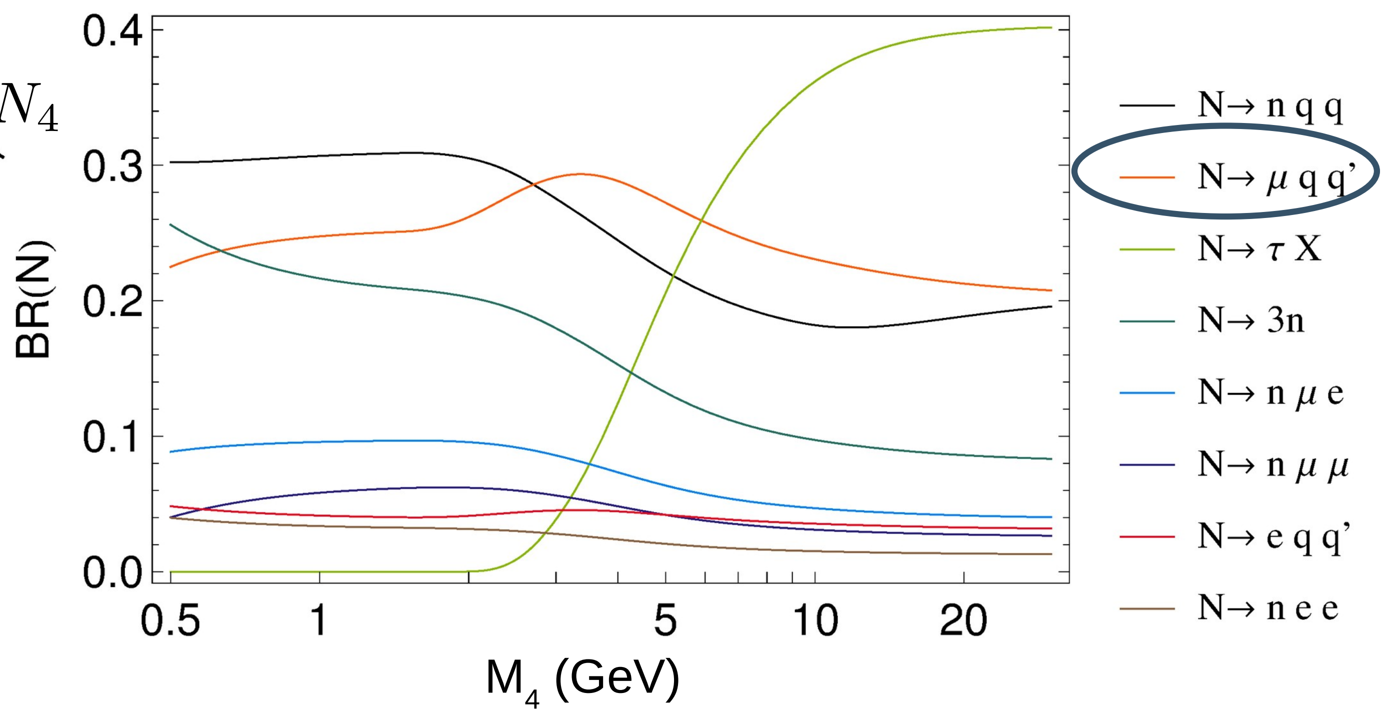
With this channel, you get

~ 20 – 30% of events.



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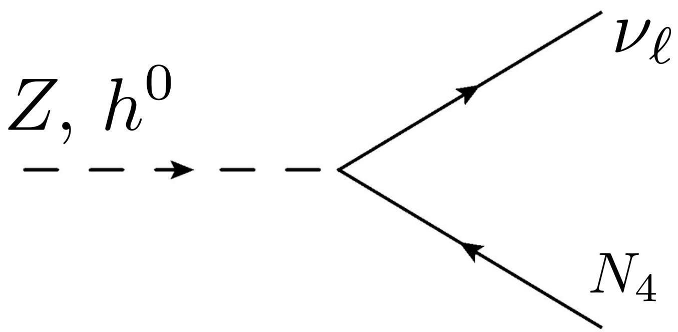
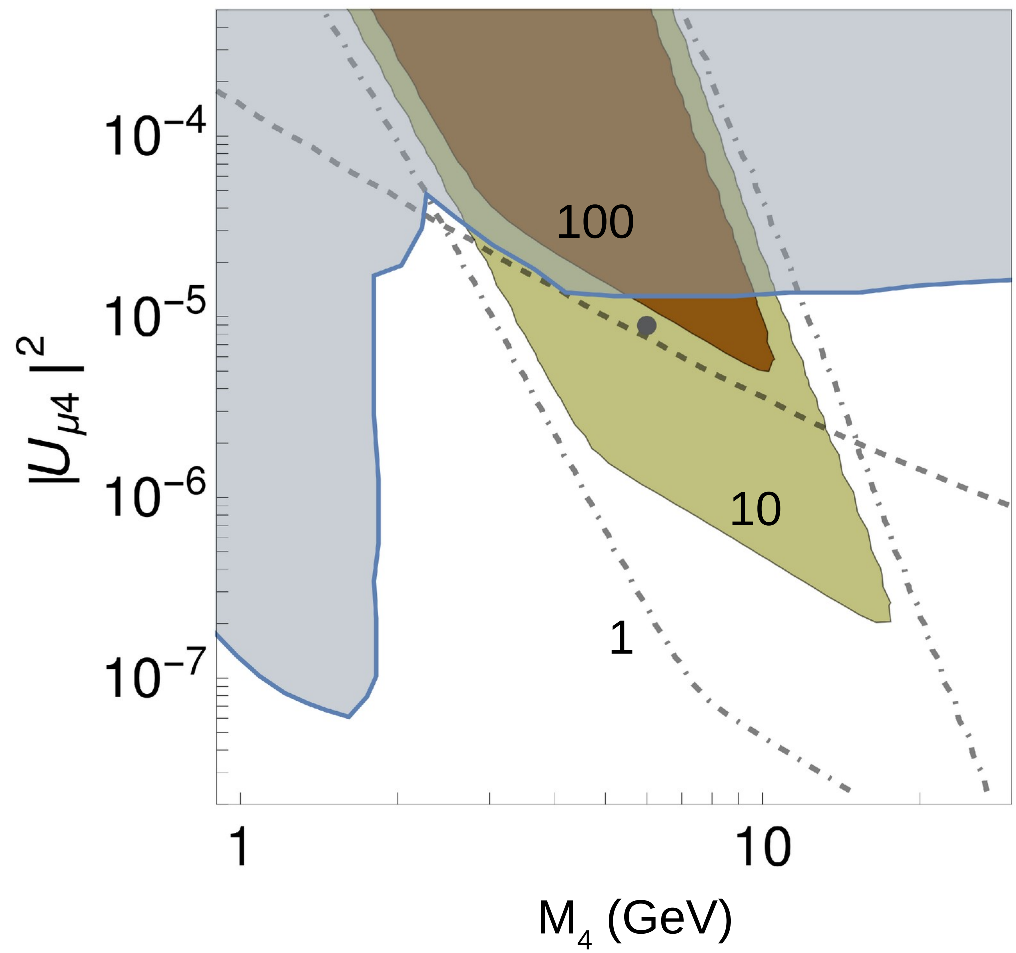
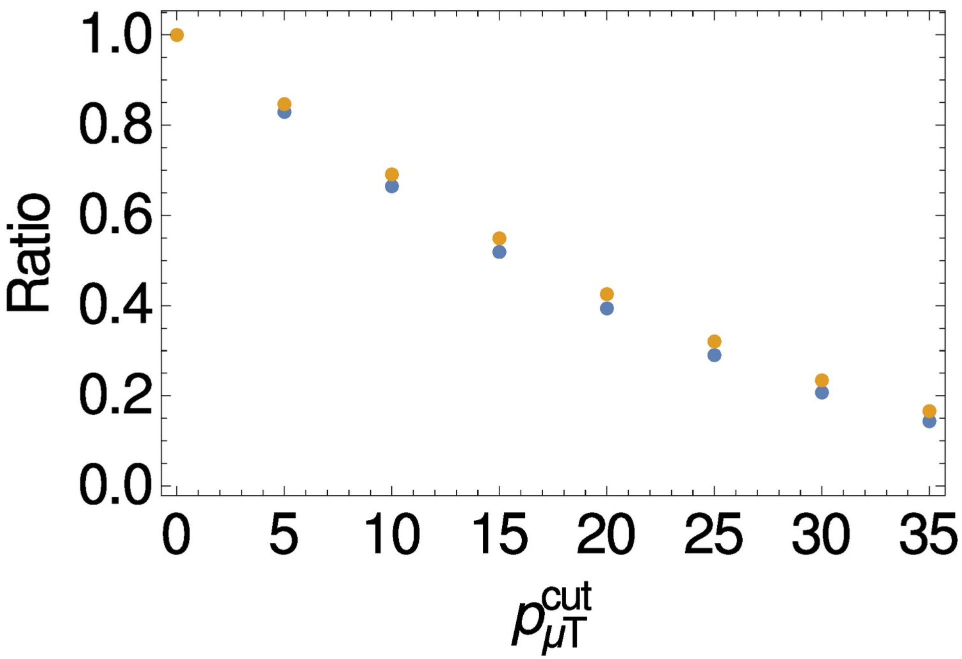
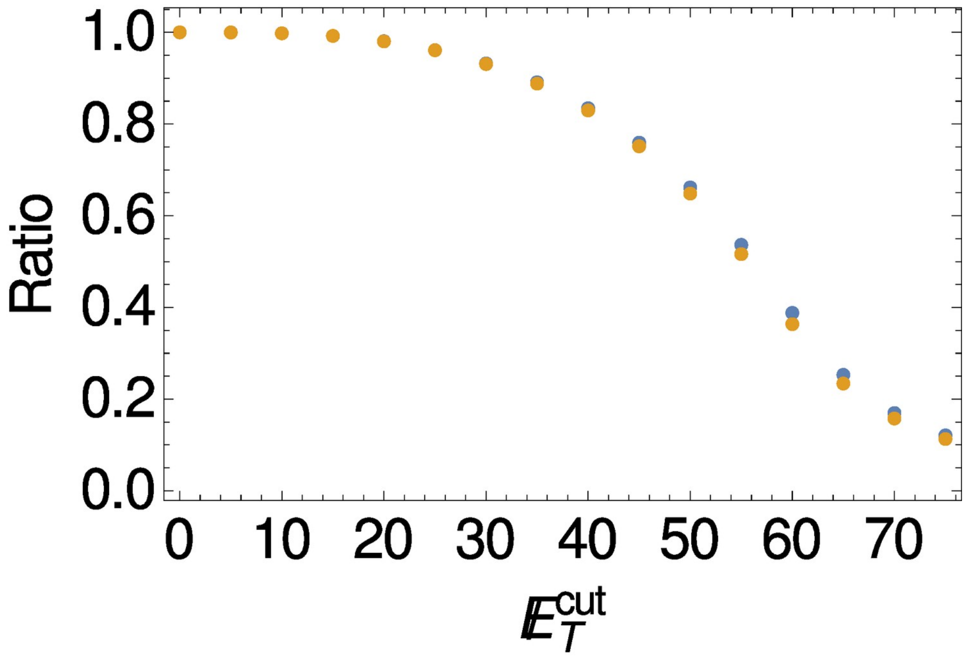


$$\left[N(pp \to h^0 \to \nu_\ell N_{4,5}) \times BR(N_4 \to \mu qq)\right]_{\text{Contained}}$$



Higgs decays: the problem with triggering using decay products





Standard triggering would strongly restrict total number of events!

Situation gets more complicated with increase in luminosity, as triggers can get more stringent.

Trying again with VBF

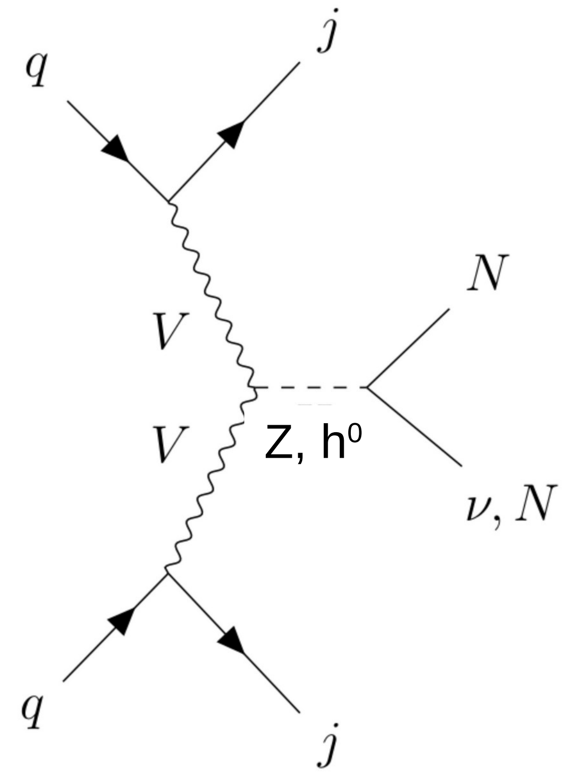
Vector Boson Fusion: Triggering independent of decay products

Minimal model: $$\mathcal{L} = \mathcal{L}_{\rm SM} + Y_\nu \left(\bar{\nu}_R\, L \cdot \tilde{H}\right) + \frac{1}{2} M_R \left(\bar{\nu}_R^c\, \nu_R\right) + \text{h.c.}$$

Extended model: $$-\frac{\lambda_{st}}{\Lambda}\, \bar{\nu}^c_{R_s}\, \nu_{R_t}\, \phi^\dagger\, \phi + \text{h.c.}$$

$$\downarrow$$

$$-(\alpha_{NH})_{st}\, \bar{\nu}^c_{R_s}\, \nu_{R_t}\, h^0 + \text{h.c.}$$



Vector Boson Fusion: Triggering independent of decay products

$p_T(j_1)$	> 30 GeV	$\eta(j_1)\cdot\eta(j_2)$	< 0
$\|\eta(j_1)\|$	< 5.0	$\|\Delta\eta(j_1, j_2)\|$	> 4.2
$p_T(j_2)$	> 30 GeV	$m_{j_1 j_2}$	> 750 GeV
$\|\eta(j_2)\|$	< 5.0	$\sum_j p_T$	> 200 GeV

CMS (1506.01010 [hep-ph])
ATLAS (ATL-DAQ-PUB-2019-001 [hep-ph])

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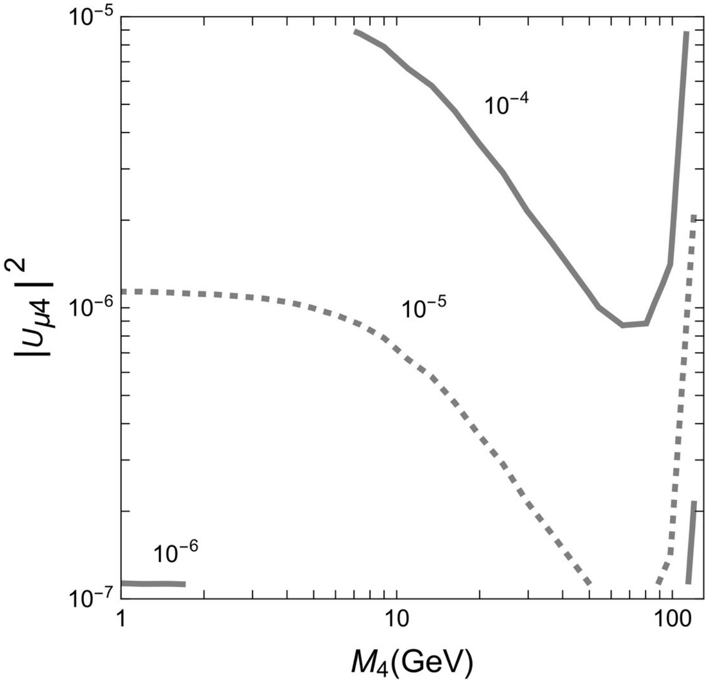
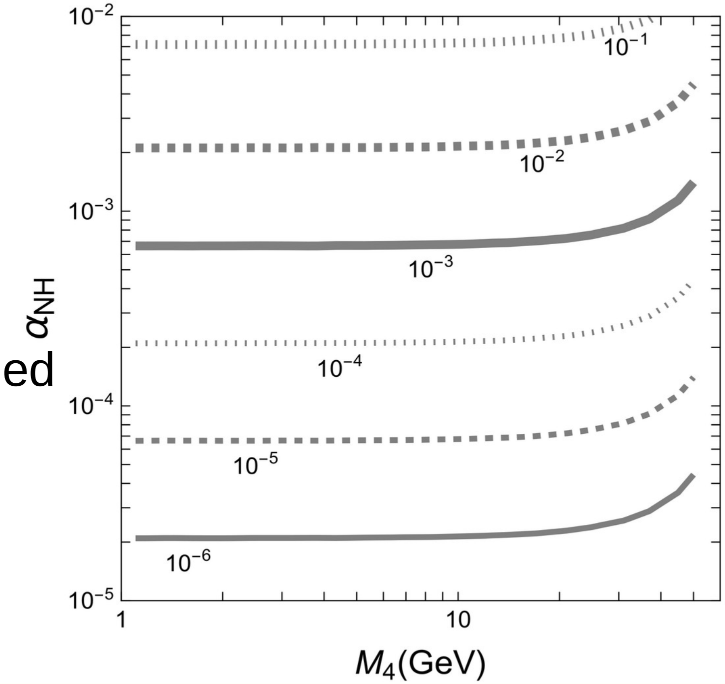


Heavy neutrino production (in pb)

Minimal

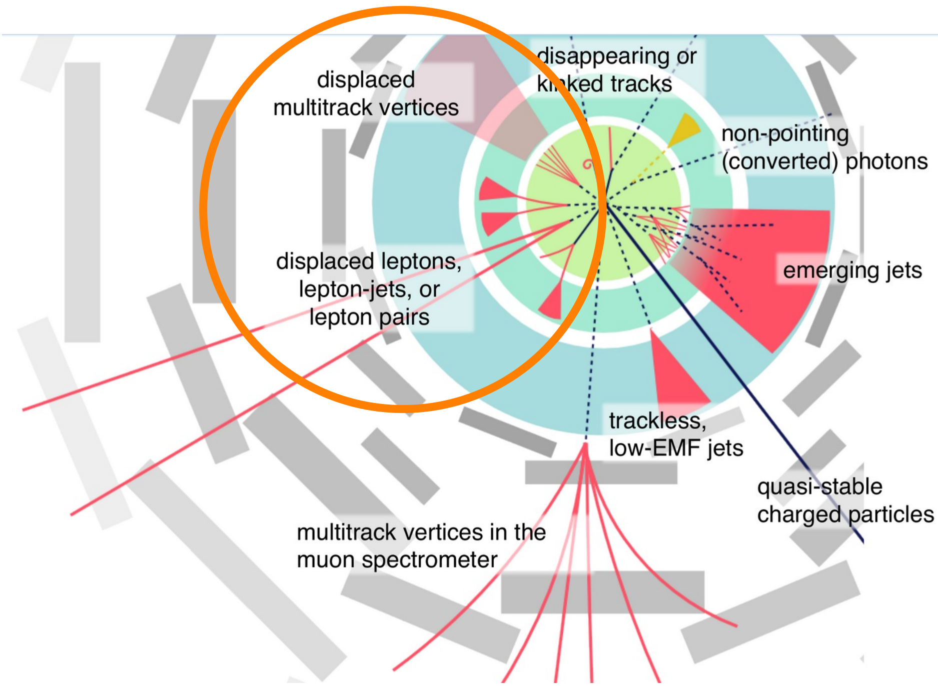
Extended



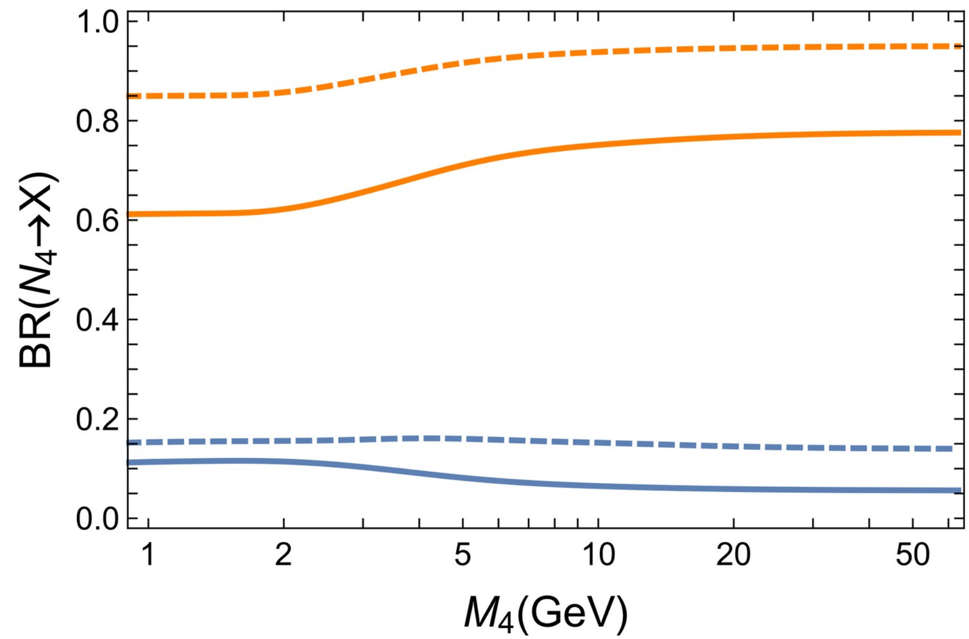
Joel Jones-Pérez

CMS (1506.01010 [hep-ph])
ATLAS (ATL-DAQ-PUB-2019-001 [hep-ph])

Final state: displaced dileptons vs displaced jets



(From H. Russel)



Branching ratios into final states contributing to displaced dileptons (blue) and displaced jets (red).

Solid (dashed) lines refer to minimal (extended) model.

Dileptons (CMS): CMS-PAS-EXO-16-022
Jets (ATLAS): 1710.04901

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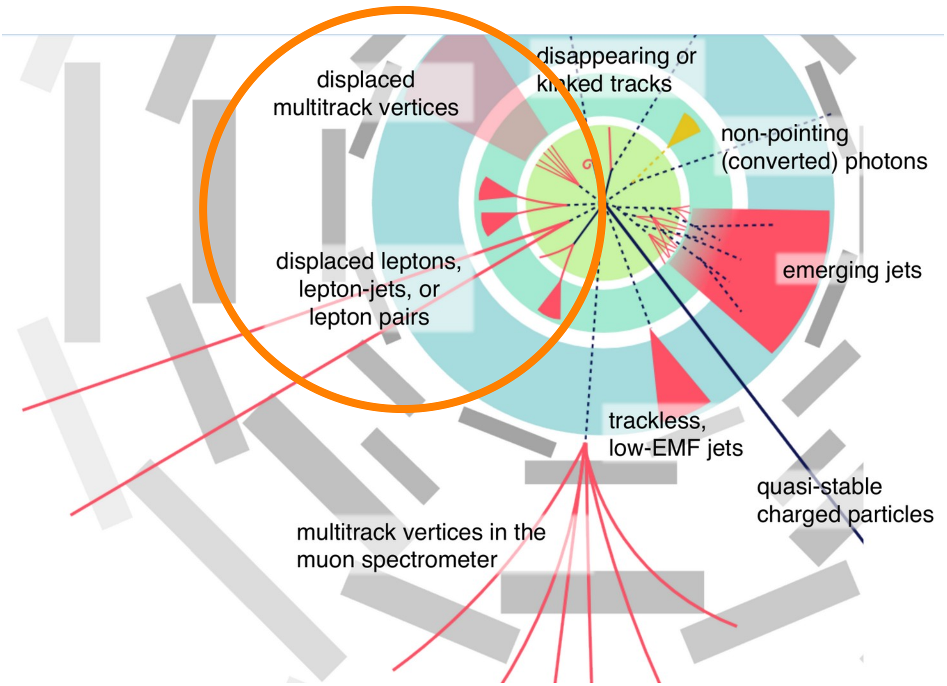

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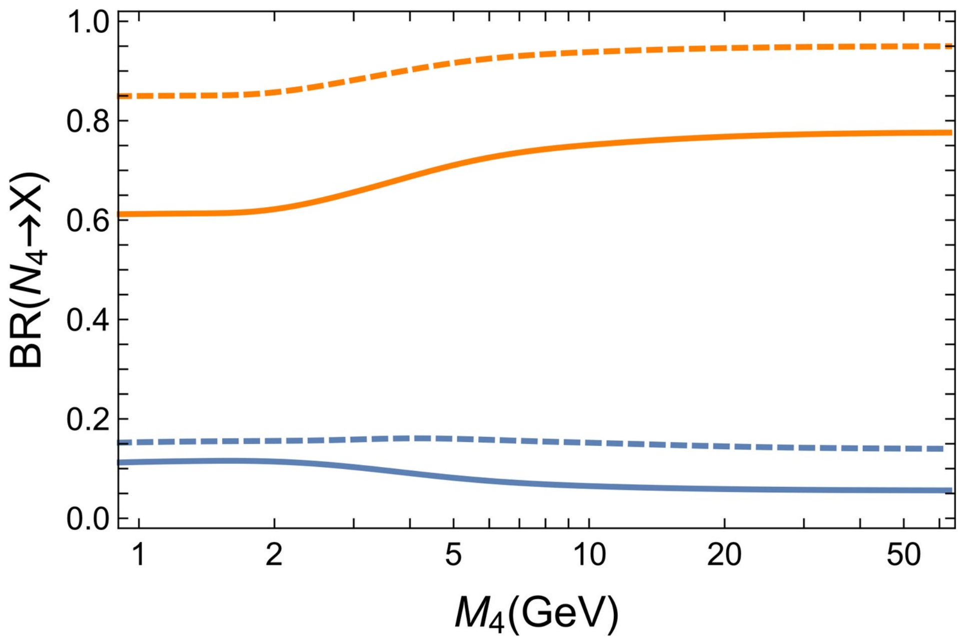

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See also talks by:
A.R. Sahasransu (displaced dilepons)
J. Liu, P. Tunney (displaced jets)

Dileptons (CMS): CMS-PAS-EXO-16-022
Jets (ATLAS): 1710.04901

Displaced dileptons

Final state: one displaced electron, one displaced muon, with opposite charge

Original trigger: p_T larger than 42 (40) GeV for electron (muon)

Proposal: Use VBF, relax p_T requirements.

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Proposal: Use VBF, relax p_T requirements.

$p_T(e)$	> 10 GeV	$\Delta R(\mu, e)$	> 0.5
$p_T(\mu)$	> 8 GeV	$\sqrt{L_x^2 + L_y^2}$	$< 40\,\text{mm}$
$\lvert\eta(\ell)\rvert$	< 2.4	L_z	$< 300\,\text{mm}$

- **SR III**: $|d_0|_{e,\mu} > 1000\,\mu\text{m}$
- **SR II**: $|d_0|_{e,\mu} > 500\,\mu\text{m}$
- **SR I**: $|d_0|_{e,\mu} > 200\,\mu\text{m}$

$$d_0 = \frac{|p_x^\ell L_y - p_y^\ell L_x|}{p_T^\ell}$$

Displaced dileptons

Extended model: generate 100 000 VBF events

Criterion	$\|U_{\mu 4}\|^2 = 10^{-7}$ $M_4 = 14\text{GeV}$	$\|U_{\mu 4}\|^2 = 10^{-9}$ $M_4 = 25\text{GeV}$	$\|U_{\mu 4}\|^2 = 10^{-11}$ $M_4 = 50\text{GeV}$
VBF	12643	12769	12621
Contained	11444	7539	6803
$\|\eta(e,\mu)\| < 2.4$	10240	6501	5890
$\Delta R(\mu, e) > 0.5$	8843	5633	5256
SR1+p_T	1211/606/125	573/177/103	279/53/39
SR2+p_T	617/226/100	482/144/73	562/126/53
SR3+p_T	525/110/40	1106/217/66	2611/781/215
LHC events ($\alpha_{NH} = 10^{-3}$)	2/1/0	2/1/0	2/1/0
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VBF: 13 % efficiency

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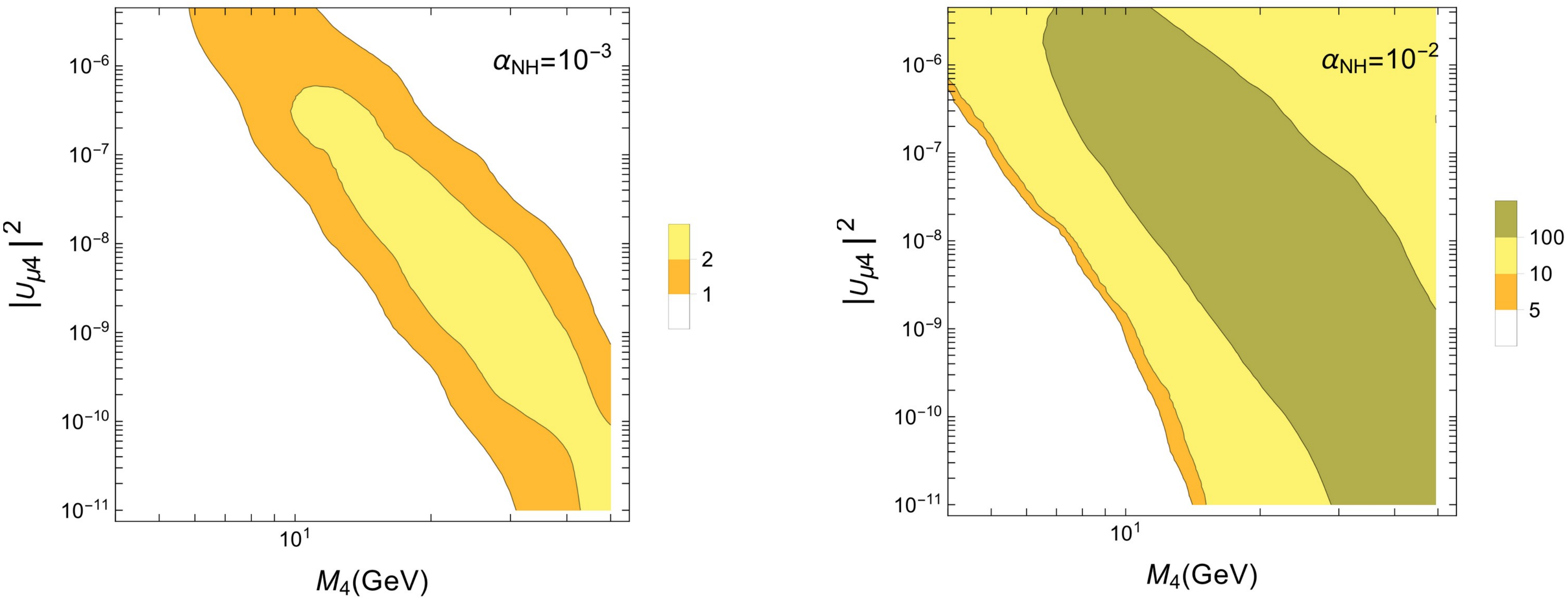
Leptons are still too soft...

… but may leave a signal at the LHC!

Displaced dileptons

Number of signal events at the LHC:



Caveat: instrumental background, no way to estimate it. Thus, no detector simulation

Displaced jets

Final state: displaced multitrack jets

Original trigger: E_T^{miss} larger than 200 GeV

Proposal: Use VBF, remove E_T^{miss} requirements.

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$p_T(j_1,\, j_2)$	$> (70,\, 0)\,\text{GeV} \vee > (25,\, 25)\,\text{GeV}$	$\lvert d_0 \rvert$	$> 2\,\text{mm}$
$\lvert \eta(j_i) \rvert$	< 4.9	$\left(\sqrt{L_x^2 + L_y^2}\right)_{\text{min}}$	4 mm.
# of tracks	≥ 5	$\left(\sqrt{L_x^2 + L_y^2}\right)_{\text{max}}$	300 mm.
m_{DV}	$> 10\,\text{GeV}$	$\lvert L_z \rvert$	$< 300\,\text{mm}.$

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VBF	22669	22318	22422
Trackless Jets	22651	22308	22411
Contained	22525	21368	21255
Displaced tracks	1446	5995	9853
$m_{DV} > 10\,\text{GeV}$	72	3795	8802
DV efficiency	24	1016	3657
LHC events ($\alpha_{NH} = 10^{-3}$)	<1	6	5
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Displaced jets

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Observable at the LHC!

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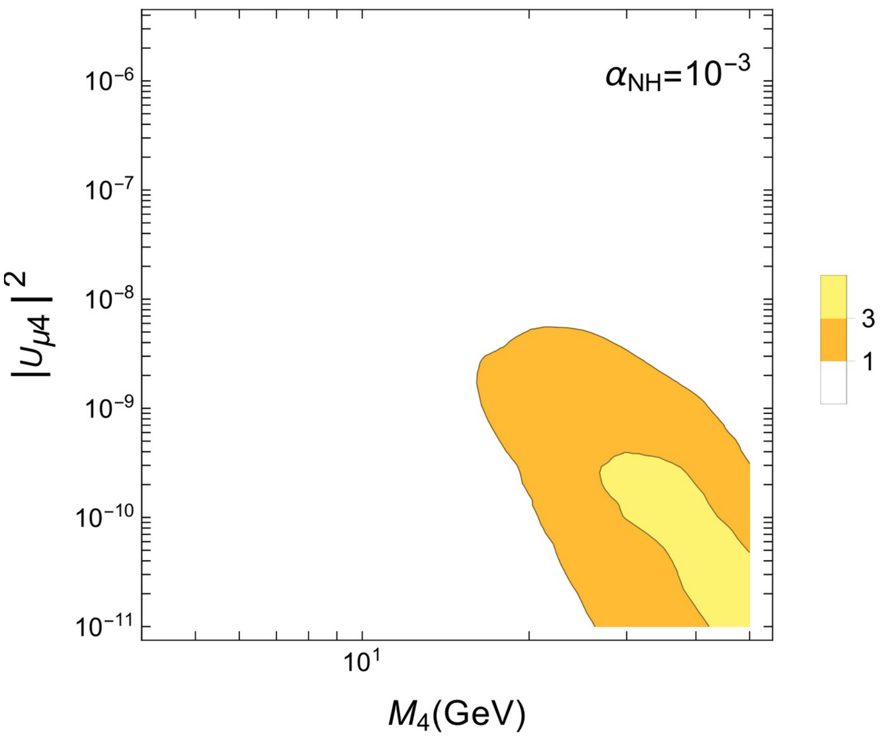
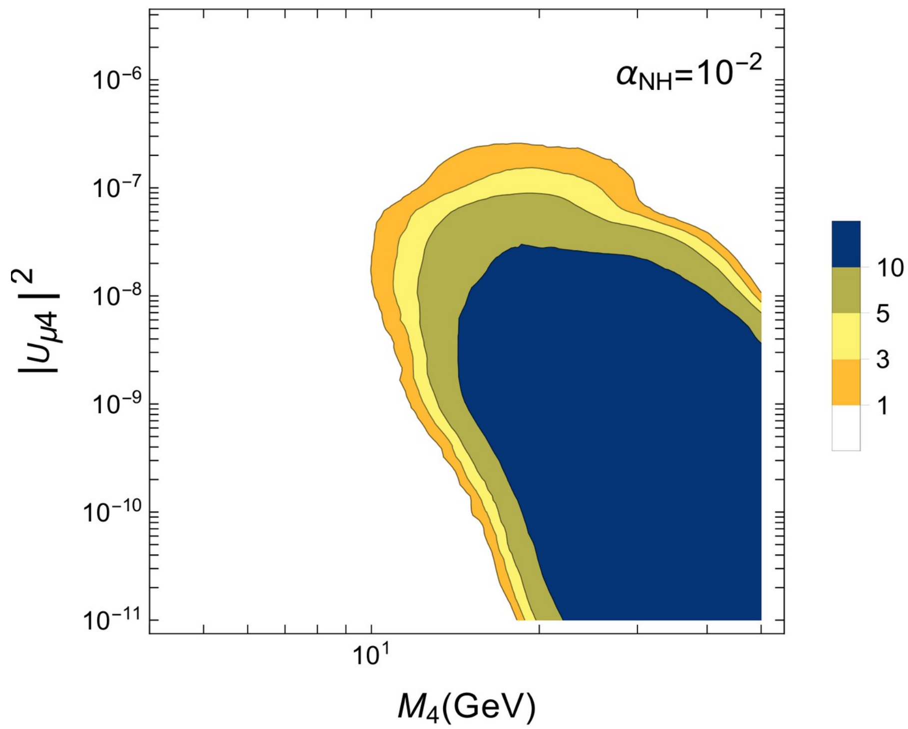
m_{DV} favours heavier neutrinos

Displaced jets

Sensitivity at LHC:





Note: background taken from original work, without E_T^{miss} cut, adding VBF efficiency

(Recasting Codes for Displaced Vertex Repository) Brooijmans *et al*: 1803.10379
Allanach, Badziak, Cottin, Desai, Hugonie, Ziegler: 1606.03099

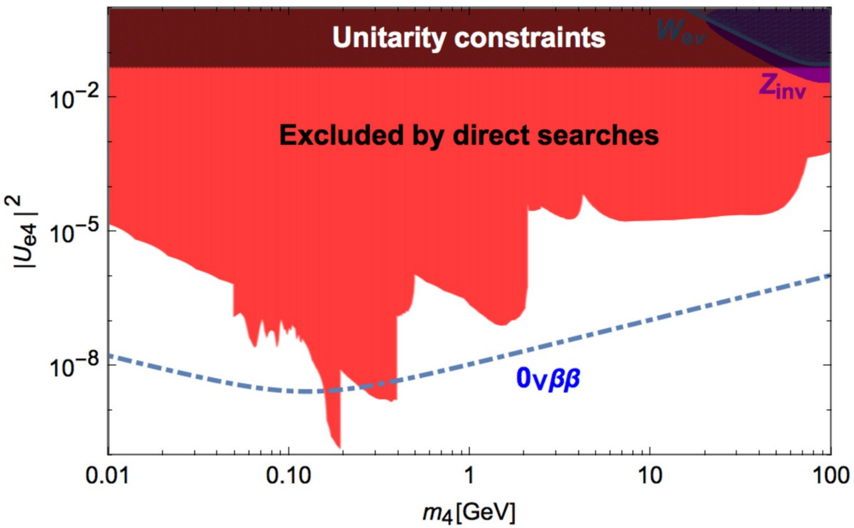
Conclusions

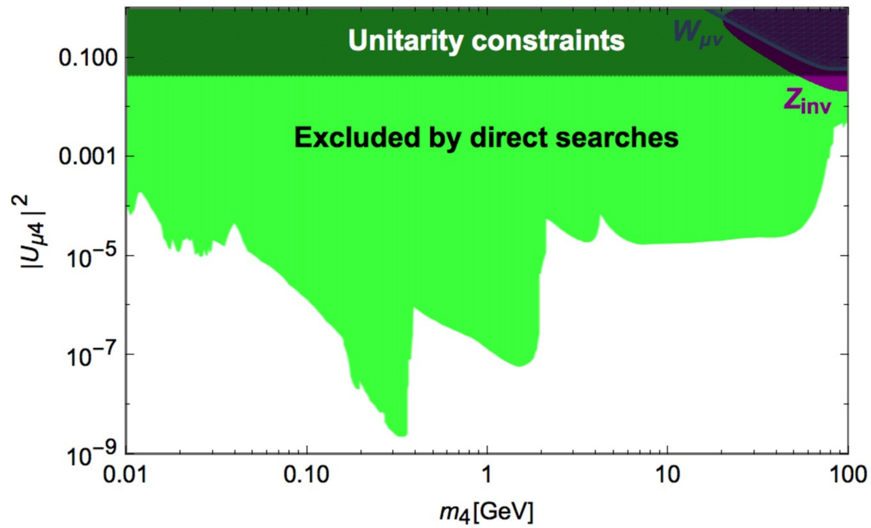
- Using a VBF trigger is a reasonable alternative if you are dealing with long-lived particles produced through neutral current interactions.
- Unfortunately not efficient for the minimal type-I seesaw. Extended models that decouple production and decays processes have better results.
- For heavy neutrinos above 10 GeV, VBF + displaced multitrack jets is promising.
- For lighter neutrinos, VBF + displaced dileptons can provide a signal, but a calculation of the background is essential.

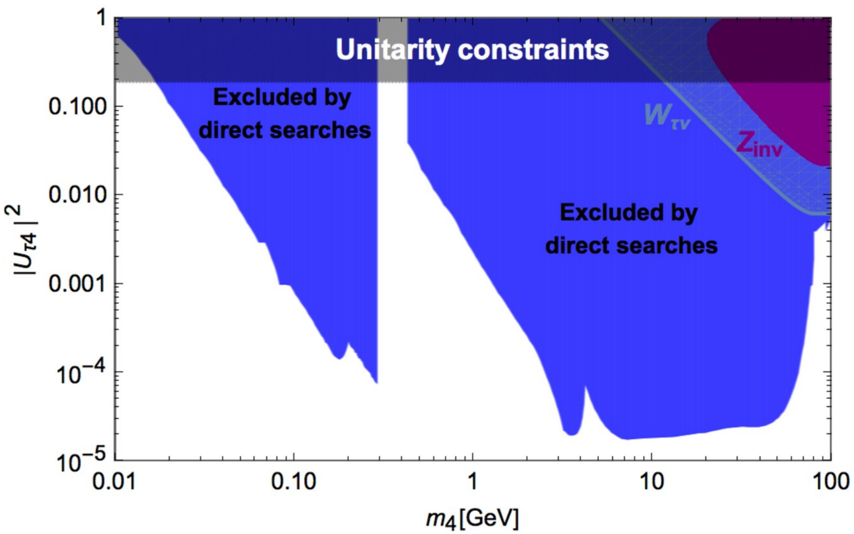
Thanks!

Backup

Direct Searches (pre LHC)



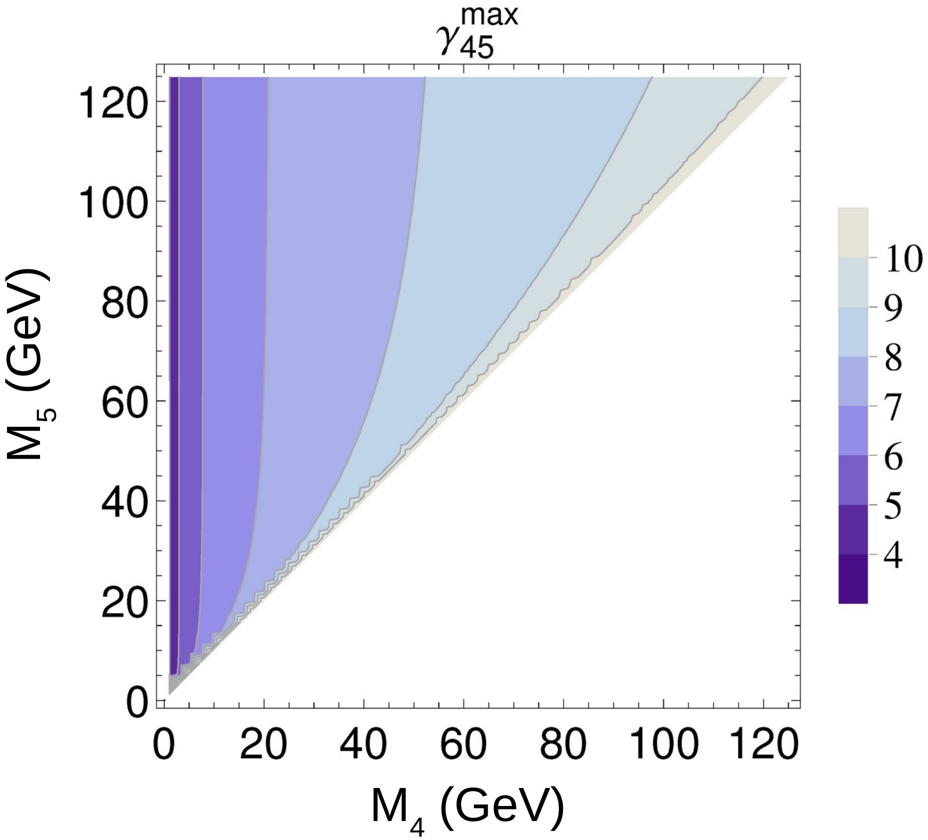




Notice these bounds are on only one heavy neutrino!

Abada, De Romeri, Lucente, Teixeira, Toma: 1712.03984 [hep-ph]

Neutrinoless Double Beta Decay and Loop Corrections



Gago, Hernandez, JJP, Losada, Moreno-Briceño: 1505.05880 [hep-ph]
Hernandez, JJP, Suarez: 1810.07210 [hep-ph]

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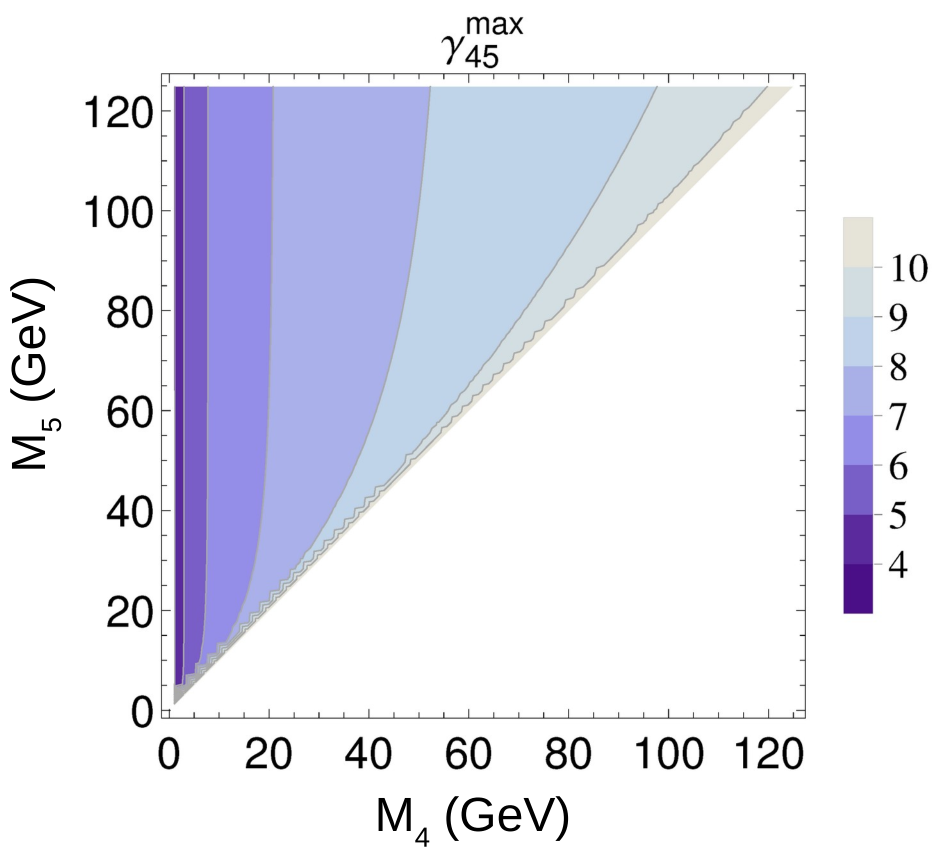

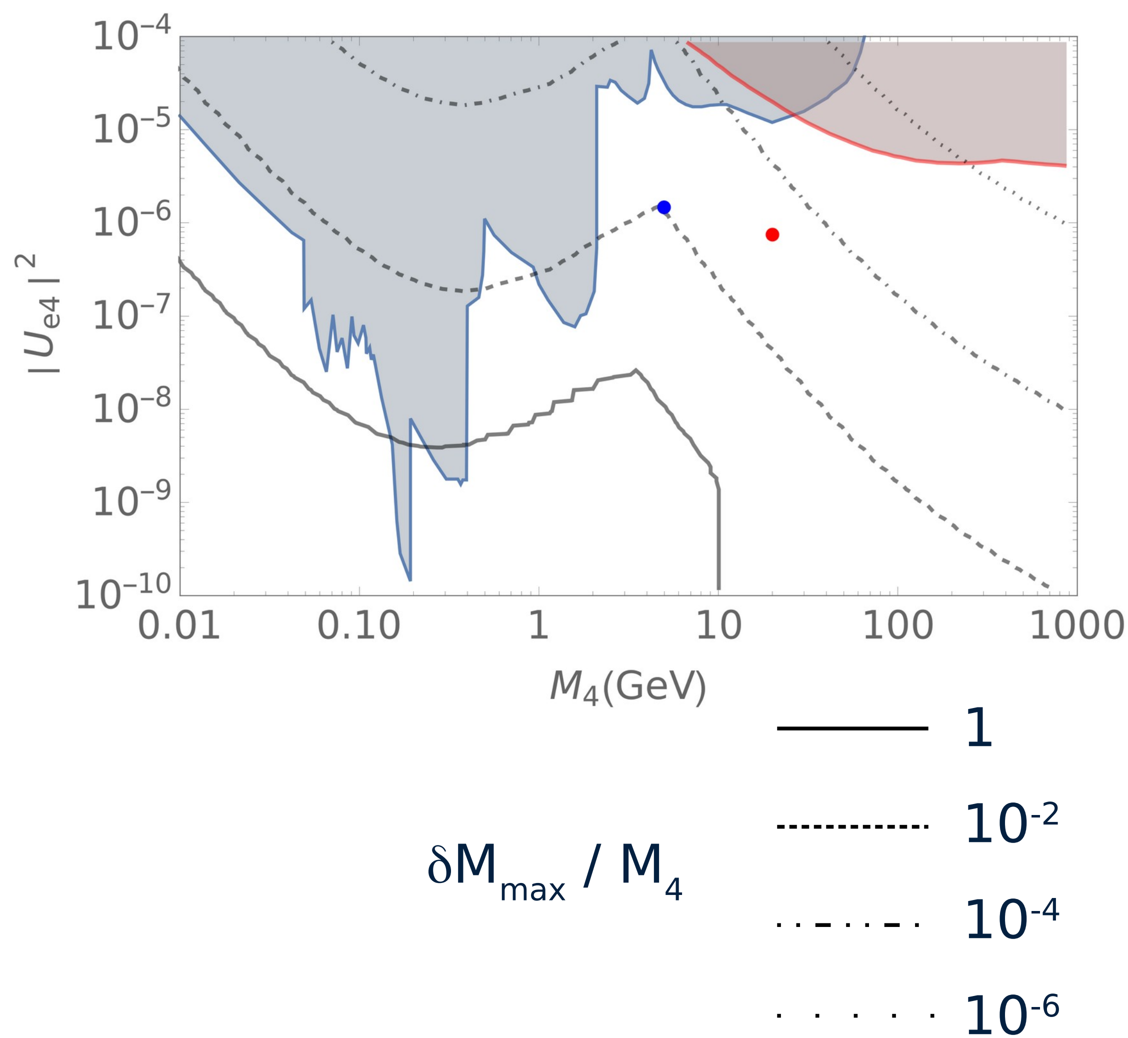

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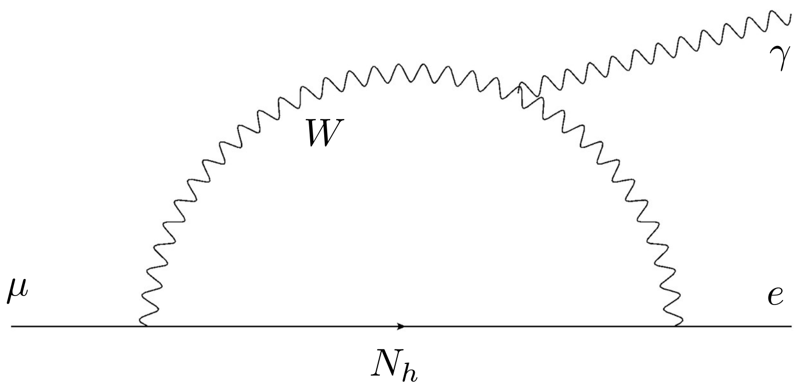
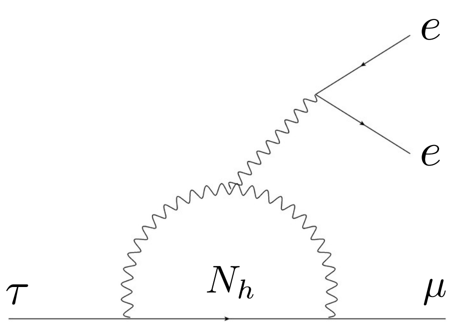
Lepton Flavour Violation

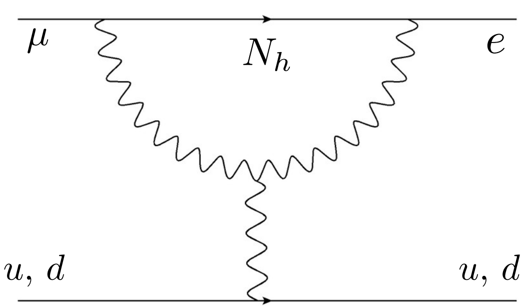
Heavy neutrinos can contribute to LFV decays via loops

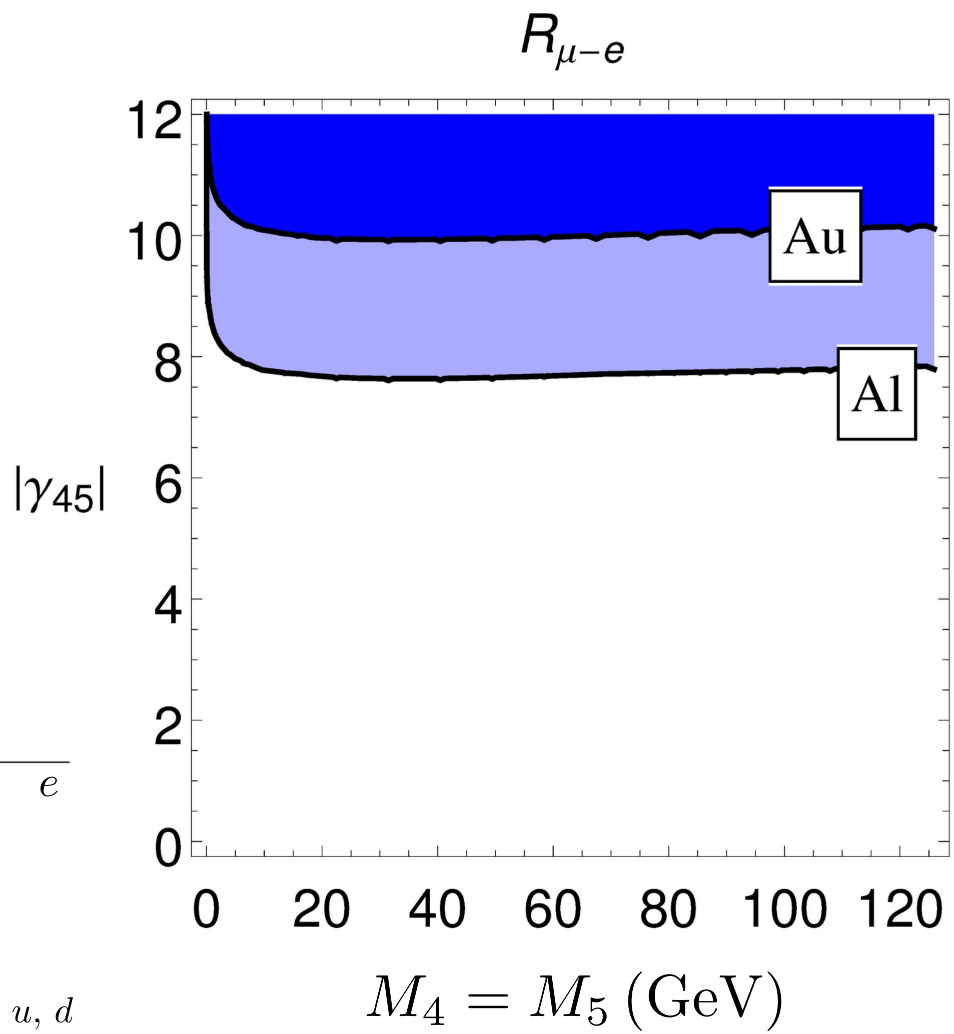


$\ell'' \to \ell' \ell \ell$



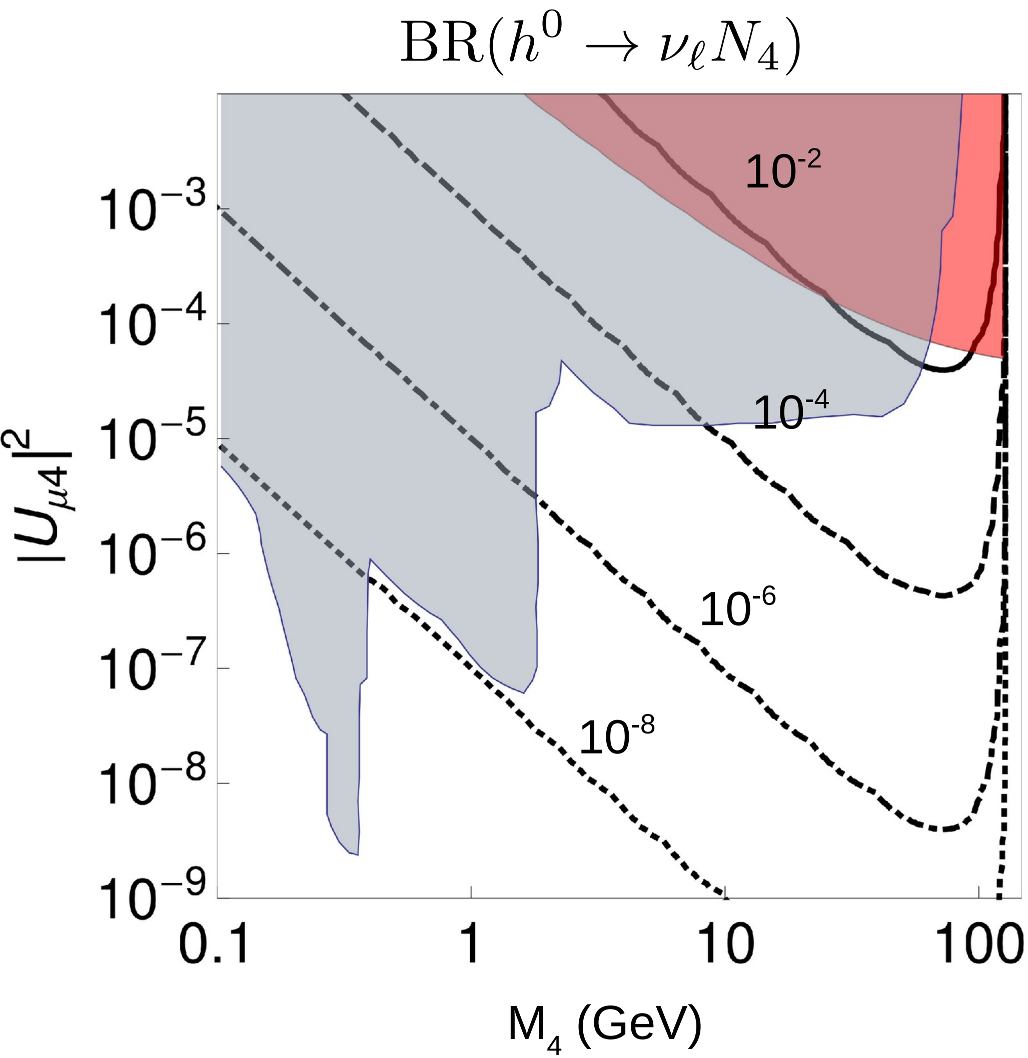
$\mu\,\mathrm{Nuc.} \to e\,\mathrm{Nuc.}$

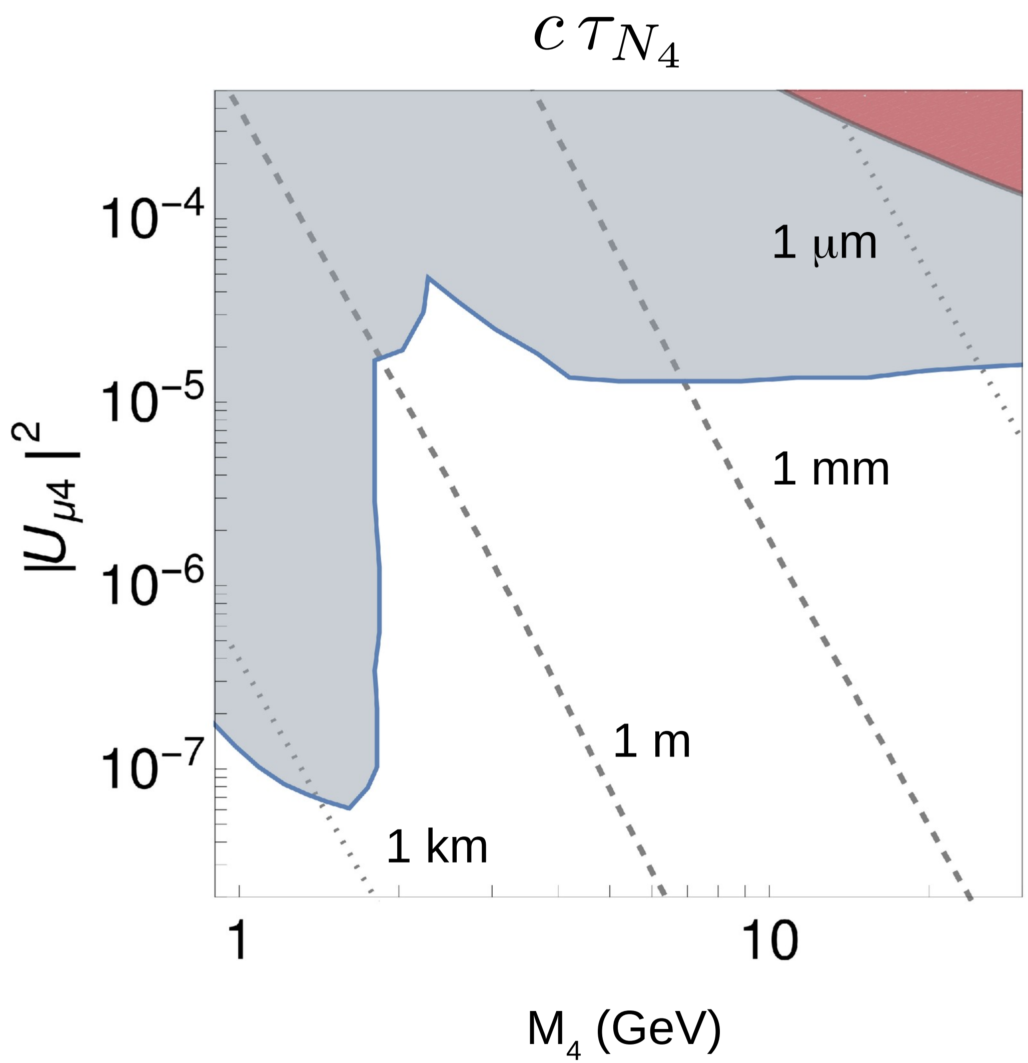




Alonso, Dhen, Gavela, Hambye: 1209.2679 [hep-ph]

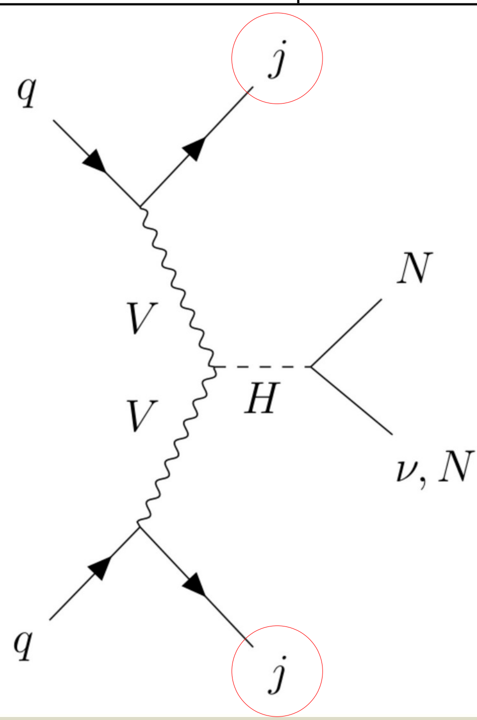
Higgs decays

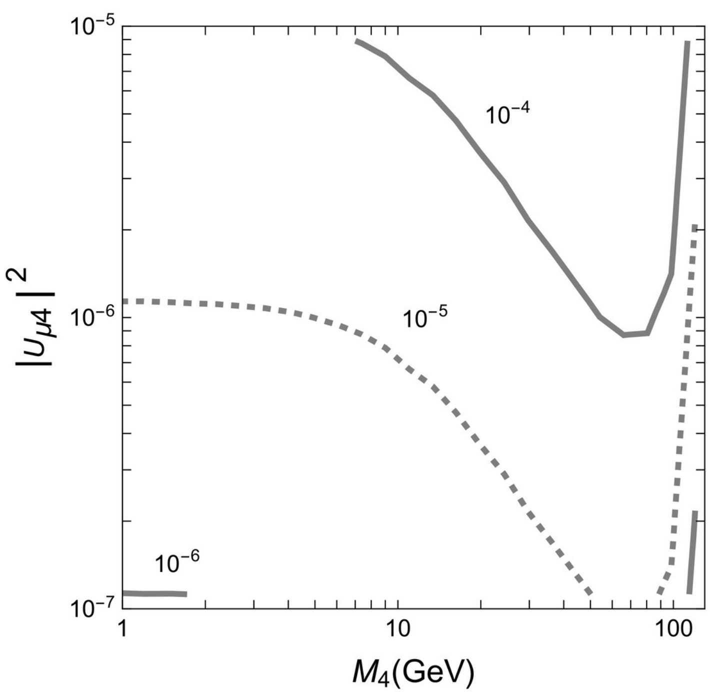




Vector Boson Fusion: Triggering independent of decay products

$p_T(j_1)$	> 30 GeV	$\eta(j_1)\cdot\eta(j_2)$	< 0
$\lvert\,\eta(j_1)\,\rvert$	< 5.0	$\lvert\,\Delta\eta(j_1, j_2)\,\rvert$	> 4.2
$p_T(j_2)$	> 30 GeV	$m_{j_1 j_2}$	> 750 GeV
$\lvert\,\eta(j_2)\,\rvert$	< 5.0	$\sum_j p_T$	> 200 GeV





Minimal

$$\sigma(pp \to h^0 jj) \times \mathrm{BR}(h^0 \to \nu_\ell N_{4,5}) + \sigma(pp \to Zjj) \times \mathrm{BR}(Z \to \nu_\ell N_{4,5})$$

(pb)

CMS (1506.01010 [hep-ph])
ATLAS (ATL-DAQ-PUB 2019-001 [hep-ph])

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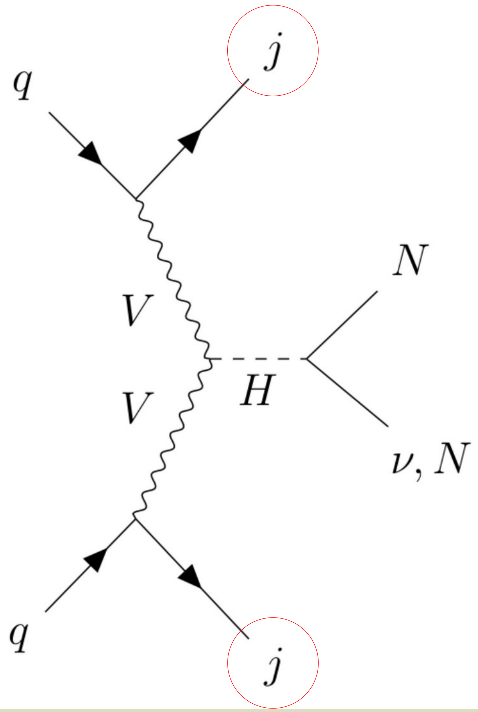

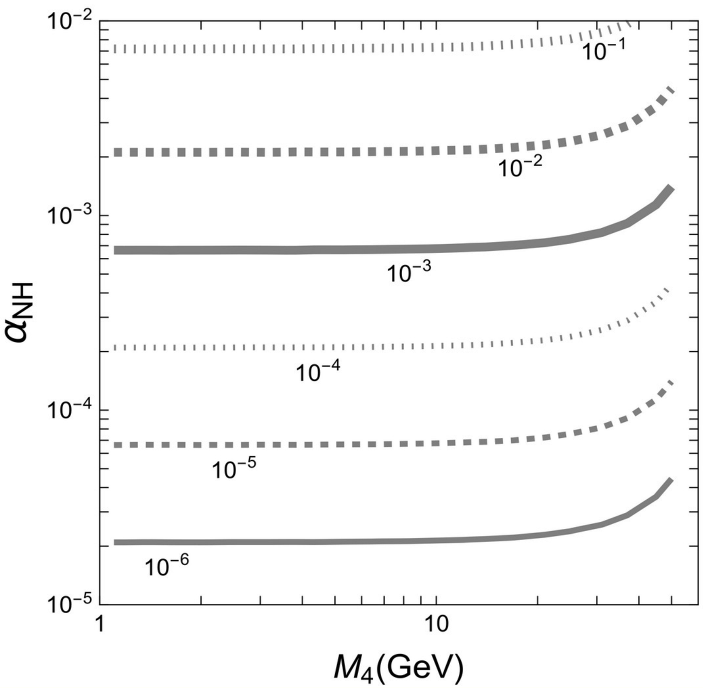

Extended

$$\sigma(pp \to h^0 jj) \times \mathrm{BR}(h^0 \to N_4 N_4)$$

(pb)

CMS (1506.01010 [hep-ph])
ATLAS (ATL-DAQ-PUB 2019-001 [hep-ph])

Displaced jets

Minimal model: generate 100 000 VBF events

Criterion	$\lvert U_{\mu 4}\rvert^2 = 10^{-6}$ $M_4 = 14\text{GeV}$	$\lvert U_{\mu 4}\rvert^2 = 10^{-7}$ $M_4 = 14\text{GeV}$	$\lvert U_{\mu 4}\rvert^2 = 10^{-7}$ $M_4 = 50\text{GeV}$
VBF	21462	21494	20506
Trackless Jets	21442	21469	20499
Contained	21440	21315	20499
Displaced tracks	28	1021	0
$m_{DV} > 10\,\text{GeV}$	5	85	0
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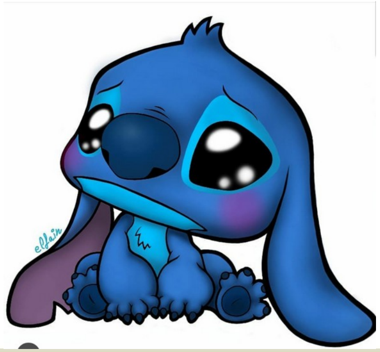
m_{DV} ends up killing most events



Enhancing the mixing

$$M_\nu = \left(\begin{array}{c|cc} 0 & m_D & \varepsilon\, m'_D \\ \hline m_D^T & \mu' & M \\ \varepsilon\, m'^T_D & M & \mu \end{array}\right)$$

If μ' is small, the mass splitting and LNV processes should vanish. The heavy neutrinos are called **Pseudo-Dirac.**

If μ' is large, there can exist significant LNV effects, linked to mass splitting. Heavy neutrinos are called **Majorana.**

Avoiding Backgrounds

Probability heavy neutrino will decay between x_1 and x_2:

$$P(x_1,\, x_2) = \int_{t_1}^{t_2} \frac{1}{\tau^{\rm lab}} \exp\left[-\frac{t}{\tau^{\rm lab}}\right] dt$$

$$\tau^{\rm lab} = \frac{E_N}{M_N}\tau$$

$$t_i = \frac{x_i}{|\vec{v}_N|} \qquad |\vec{v}_N| = \frac{|\vec{p}_N|}{E_N}$$

Parameter region where this is feasible at the ILC is restricted:

$$10\ \mu{\rm m} < L_{xy} < 2.49\ {\rm m}$$

$$L_z < 3\ {\rm m}$$

Charged lepton impact parameter:

$$d_\ell \equiv \frac{L_x\, p_y^\ell - L_y\, p_x^\ell}{p_T^\ell} > 6\ \mu{\rm m}$$

Antusch, Cazzato, Fischer: 1604.02420 [hep-ph]

Small couplings, large decay lengths

Probability of decay if produced within detector of size *d*:

$$P^{\rm det} = 1 - \exp\left(-\frac{M_4}{|\vec{p}_N|}\frac{d}{\tau^{\rm rest}}\right)$$

Probability of decay at far detector, distance *L*:

$$P^{\rm det} = \exp\left(-\frac{M_4}{|\vec{p}_N|}\frac{L}{\tau^{\rm rest}}\right)\left[1 - \exp\left(-\frac{M_4}{|\vec{p}_N|}\frac{d}{\tau^{\rm rest}}\right)\right]$$

One needs:

$$L \ll \frac{|\vec{p}_N|}{M_4}\tau^{\rm rest} \ll d$$

It is usually the other way around! Experiments need $L \sim d$.