New physics at LH-LHC with VBS signatures

VBS@Snowmass, Zoom State University

Richard Ruiz

Institute of Nuclear Physics – Polish Academy of Science (IFJ PAN)

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~~thank you for the invitation!~~

thank you for joining this week!

Acknowledgments, Apologies, and Disclaimers

finite time constraints $\Longrightarrow$ many omissions

- "BSM with VBS" is too rich for 25'+5'. okay, since many talks:

  EFTs (Ambrosio and Szleper); anomaly-hunting (Li); axions/ALPs (De Troconiz); Higgs couplings (Kotwal); new colliders (many); see also past VBSCan meetings

- Today's topic: "νBSM with VBS"

  Disclaimer: Snowmass RF4 topical group convener for LNV/LFV@colliders

- Focus on $\gamma\gamma$, $W^\pm\gamma$, $W^\pm Z$, and $W^\pm W^\pm$ scattering at the HL-LHC

  $\Longrightarrow$ $\sqrt{s} = 13 - 14$ TeV and $\mathcal{L} = 1 - 5$ ab^{-1}

source material:

1. Reviews on ν mass models at colliders

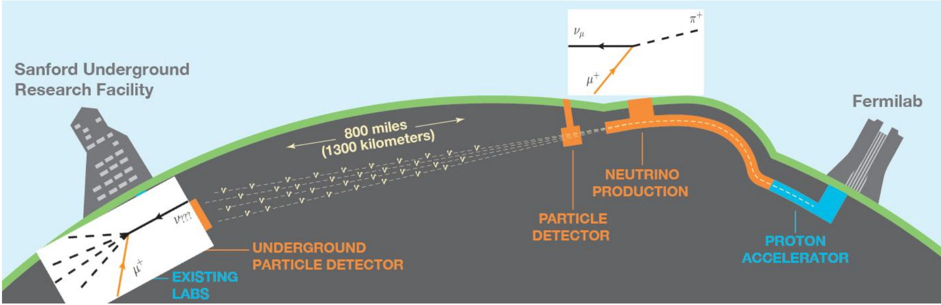
   w/ Y. Cai, T. Han, and T. Li [1711.02180]; w/ S. Pascoli and C. Wieland [1812.08750]

2. European Strategy Update 2019 chapter on ν mass models

   w/ T. Han, T. Li, X. Marcano, S. Pascoli, C. Weiland [1812.07831]

3. Input for 2021 Snowmass (link) and newer (pandemic-era) results

the big physics picture



ν oscillations $\Longrightarrow$ **evidence of ν masses!**

Nu Masses and New Particles

Nonzero neutrino masses  $\Longrightarrow$ new degrees of freedom exist: [Ma'98]

$$m_\nu \neq 0 + \text{left} - \text{handed (LH) Weak currents}$$

$(renormalizability)$

$$\text{LH Majorana Mass}: m_\nu^L \overline{\nu_L} \nu_L^c \qquad\qquad \text{Dirac Mass}: m_\nu^D \overline{\nu_L} \nu_R$$

$(gauge\ invariance)$

$$m_\nu^L = y\langle\Delta\rangle \text{ or new dynamics} \qquad\qquad m_\nu^D = y\langle\Phi_{\text{SM}}\rangle$$

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$m_\nu \neq 0$ **+ renormalizability + gauge inv.** $\implies$ **new particles!**

- New particles can be charged under new or old gauge interactions
- New particles must couple to h or L, often inducing processes that do not conserve lepton number (LNV) and/or lepton flavor (LFV)

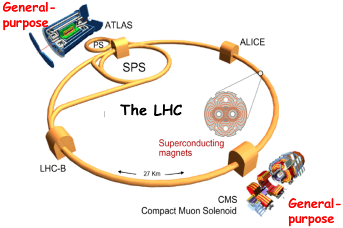
models that explain tiny neutrino masses (Seesaw models)

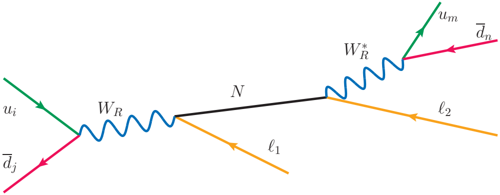
are testable

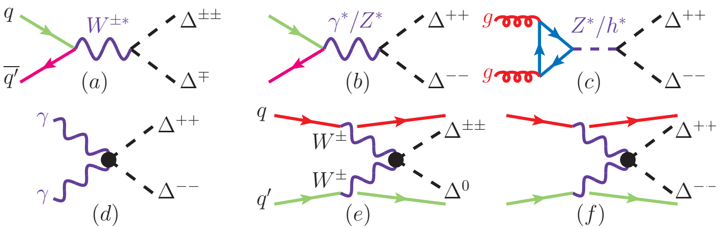
models that explain tiny neutrino masses (Seesaw models)

are testable, especially at colliders, through a variety of mechanism

for a review, see w/ Y. Cai, T. Li, and T. Han [1711.02180] as well as w/ Pascoli, et al [1812.08750]

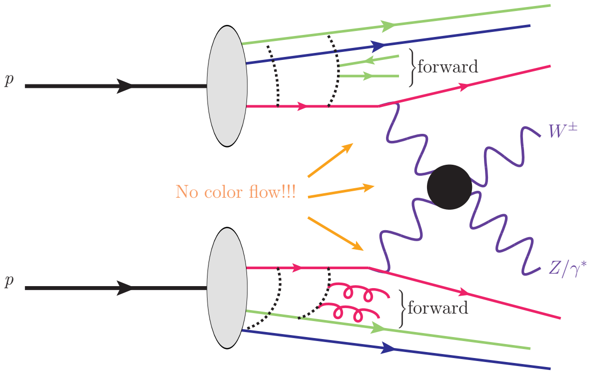






so why electroweak VBS/VBF?

EW boson scattering/fusion is special



Abscence of central color flow $\implies$ unusual topology for high-p_T physics

[Dokshitzer, Khoze et al ('86); Barger, Han, et al, PRD ('91) + PLB ('95); Bjorken, PRD ('94)]

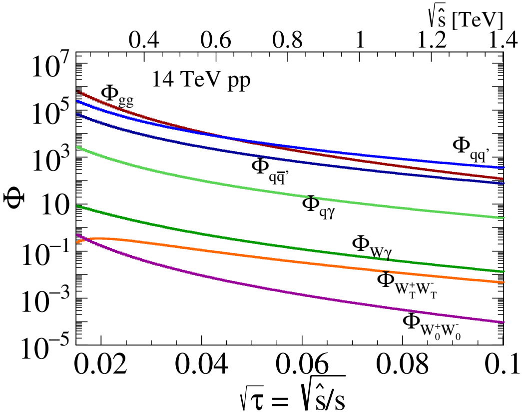
- E.g., forward jets, rapidity gap, high-scale invariants $m_{jj}, M_{VV} \gg M_V$
- Each is a powerful background discriminant

For new physics searches, VV' scattering gives access to spin, isospin, and QED configurations not accessible by, e.g., qq', $q\overline{q}$, and gg scattering

- Benefits compensated by a smaller VV' parton luminosity

See Xie's talk on EW boson PDFs!

$$\Phi_{ij}(\tau) = \int_\tau^1 \frac{d\xi}{\xi} f_i(\xi) f_j\left(\frac{\tau}{\xi}\right)$$

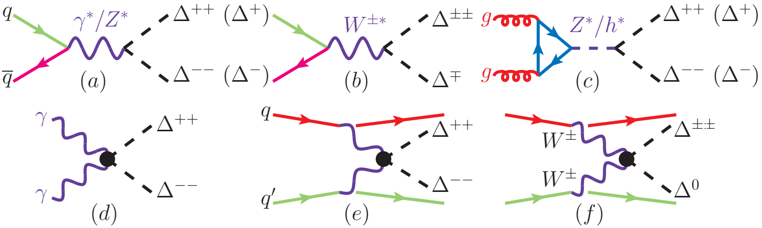


and now for a few results!

$\gamma\gamma$ and $W^\pm Z$ scattering

with exotically charged Higgs bosons $\Delta^{\pm\pm}, \Delta^{\pm}$

(Type II Seesaw)



The Type II Seesaw Mechanism generates neutrino masses ***without*** hypothesizing right-handed neutrinos

- Important example that $m_\nu \neq 0 \nRightarrow$ that ν_R exist

The Type II Seesaw Mechanism generates neutrino masses ***without*** hypothesizing right-handed neutrinos

- Important example that $m_\nu \neq 0 \not\Rightarrow$ that ν_R exist

Hypothesize a **scalar** $SU(2)_L$ triplet with **lepton number** $L = -2$

$$\hat{\Delta} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^+ & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^0 & -\Delta^+ \end{pmatrix}, \quad \text{with} \quad \mathcal{L}_{\Delta\Phi} \ni \mu_{h\Delta}\left(\Phi^\dagger \hat{\Delta} \cdot \Phi^\dagger + \text{H.c.}\right)$$

The mass scale $\mu_{h\Delta}$ breaks lepton number, and induces $\langle \Delta \rangle \neq 0$:

$$\sqrt{2}\langle\hat{\Delta}\rangle = v_\Delta \approx \frac{\mu_{h\Delta} v_{\rm EW}^2}{\sqrt{2} m_\Delta^2}$$

which leads to **left-handed Majorana masses** for neutrinos

$$\Delta\mathcal{L} = -\frac{y_\Delta^{ij}}{\sqrt{2}} \overline{L^c} \hat{\Delta} L = -\frac{y_\Delta^{ij}}{\sqrt{2}} \begin{pmatrix} \overline{\nu^{jc}} & \overline{\ell^{jc}} \end{pmatrix} \begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix} \begin{pmatrix} \nu^i \\ \ell^i \end{pmatrix}$$

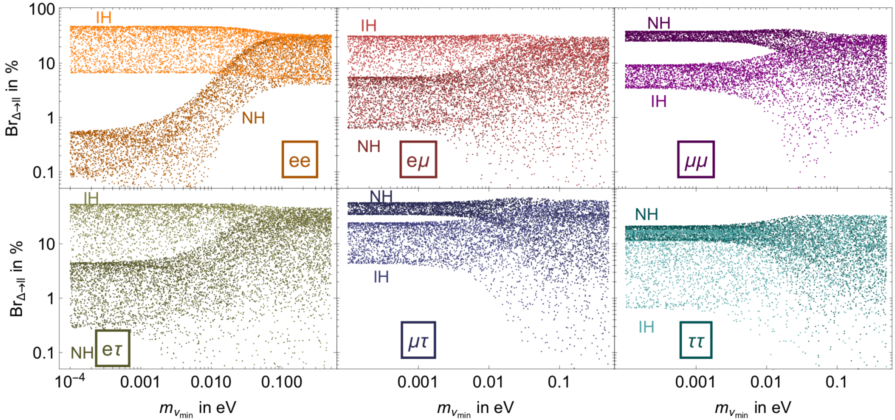
$$\ni -\frac{1}{2} \underbrace{\left(\sqrt{2} y_\Delta^{ij} v_\Delta\right)}_{= m_\nu^{ij}} \overline{\nu^{jc}} \nu^i$$

Fewer free parameters $\Longrightarrow$ richer experimental predictions

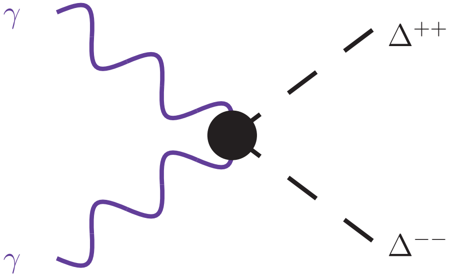
Fileviez Perez, Han, Li, et al, [0805.3536], Crivellin, et al [1807.10224], Fuks, Nemevšek, RR [1912.08975] + others

- E.g., $\Delta^{\pm}, \Delta^{\pm\pm}$ branching rates encode inverse (IH) vs normal (NH) ordering of light neutrino masses

$$\text{BR}(\Delta^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \sim y_{\Delta}^{ij} \sim (U_{\rm PMNS}^{*}\tilde{m}_{\nu}^{\rm diag}U_{\rm PMNS}^{\dagger})_{ij}$$



photon fusion



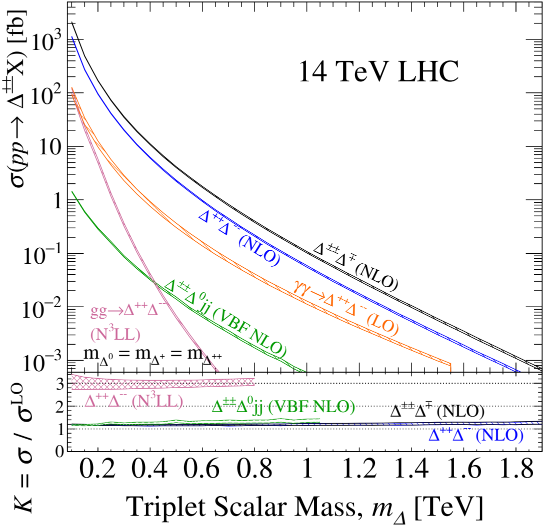
$\gamma\gamma \to \Delta^{++}\Delta^{--}$ is wickedly cool!

- **Elastic+inelastic terms**: as $p_T^{j_F}/E^{j_F} \to 0$, recover diffractive limit $j_F + X_B \to p$

- **Subleading** but ultra peripheral collisions have *tiny* backgrounds

- LO+Pythia8* can match γ to $q \to \gamma q$ splitting, i.e., match to forward jets

- Many modern γ PDFs on the market these days. (See backup for comparison.)

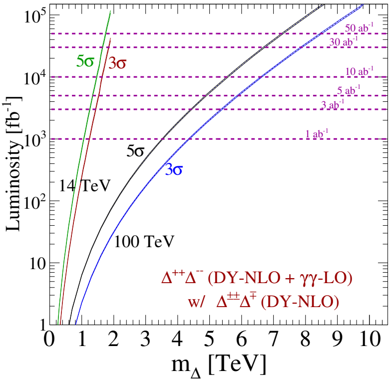


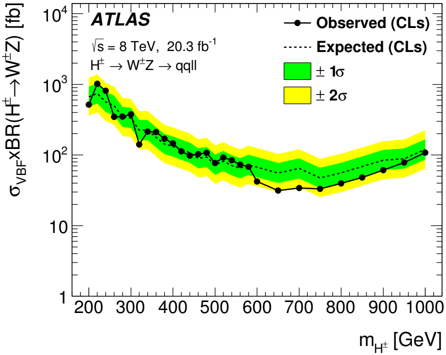
*For details, see home.thep.lu.se/ torbjorn/pythia81html/SpacelikeShowers.html

(L) Projections for $q\overline{q} + \gamma\gamma$ at $\sqrt{s} = 14$ TeV and 100 TeV!

w / Fuks and Nemevšek [1912.08975] ATLAS [1503.04233]

(R) Limits at $\sqrt{s} = 8$ TeV for $W^\pm Z \to \Delta^\pm \to W^\pm Z$





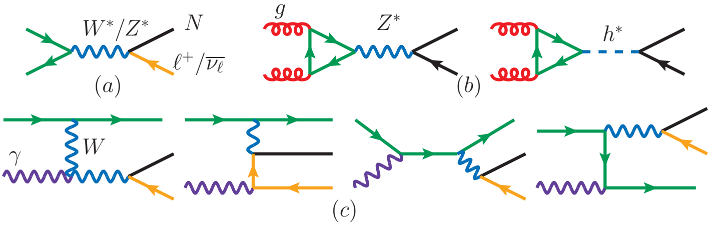
- At LHC with $\mathcal{L} = 5$ ab^{-1}, 3σ sensitivity up to $m_\Delta \sim 1.5$ TeV
- **Warning**: projections can be improve for specific parameter spaces

a Snowmass task if anyone is interested!

$W^{\pm}\gamma$ and $W^{\pm}W^{\pm}$ scattering

with heavy Dirac and Majorana neutrinos N

(Low-scale Type I Seesaw)



Heavy neutrino mixing for non-experts

The Type I Seesaw Mechanisms generate neutrino masses by hypothesizing a few right-handed neutrinos ν_R

depending on assuptions, $m_\nu \sim \Lambda_{LNV}$ or v^2/Λ_{LNV}. details are not so important right now.

After EWSB, ν_ℓ and ν_R have same quantum numbers $\implies$ mixing!

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Example: In a two-state system, mixing between chiral eigenstates and mass eigenstates is given by unitary transformation/rotation

$$\underbrace{\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}}_{\text{chiral basis}} = \underbrace{\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}}_{\text{mixing}} \underbrace{\begin{pmatrix} \nu_1 \\ N_2 \end{pmatrix}}_{\text{mass basis}}$$

Decompose chiral/interaction states into mass states using:

$$\underbrace{|\nu_L\rangle}_{\text{interaction basis}} = \cos\theta \underbrace{|\nu_1\rangle}_{\textit{light}} + \sin\theta \underbrace{|N_2\rangle}_{\textit{heavy}}$$

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$$\underbrace{|\nu_L\rangle}_{\text{interaction basis}} = \cos\theta\underbrace{|\nu_1\rangle}_{light} + \sin\theta\underbrace{|N_2\rangle}_{heavy} \overset{\theta\ll 1}{\approx} (1-\tfrac{1}{2}\theta^2)|\nu_1\rangle + \theta|N_2\rangle$$

In practice?

For **discovery purposes**, no need to complicate life. Take agnostic/pheno. approach with generic $V_{\ell N}$ parametrization and one N mass eigenstate

Atre, Han, Pascoli, Zhang [0901.3589]

$$\underbrace{\nu_{\ell L}}_{\text{flavor basis}} \approx \underbrace{\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell m'=4} N_{m'=4}}_{\text{mass basis}}$$

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The SM W chiral coupling to **leptons** in **flavor basis** is

$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \nu_\ell\right] + \text{H.c.}, \qquad \text{where } P_L = \frac{1}{2}(1-\gamma^5)$$

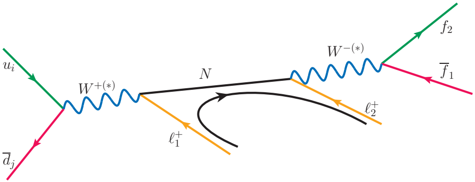
$\implies$ SM W coupling to N and charged **leptons** in the **mass basis is**

$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \left(\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell N} N\right)\right] + \text{H.c.}$$

$\implies$ N is **accessible through** SM currents

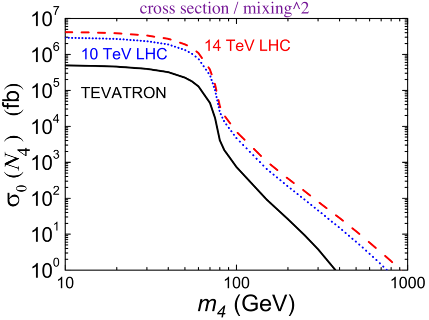
Historically, searches for N with $m_N > M_W$ relied on $(q\overline{q})$ annihilation

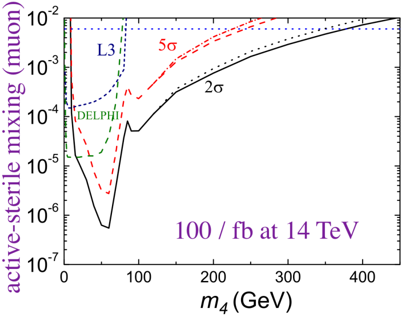
Keung & Senjanovic (PRL'83)



At the LHC, a canonical signature for N: $pp \to \ell_i^\pm \ell_j^\pm + nj +$ no MET

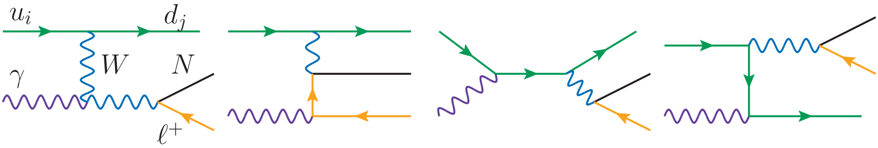
based on seminal works by K&S, del Aguila & Aguilar-Saavedra [0808.2468], and Atre, et al [0901.3589]





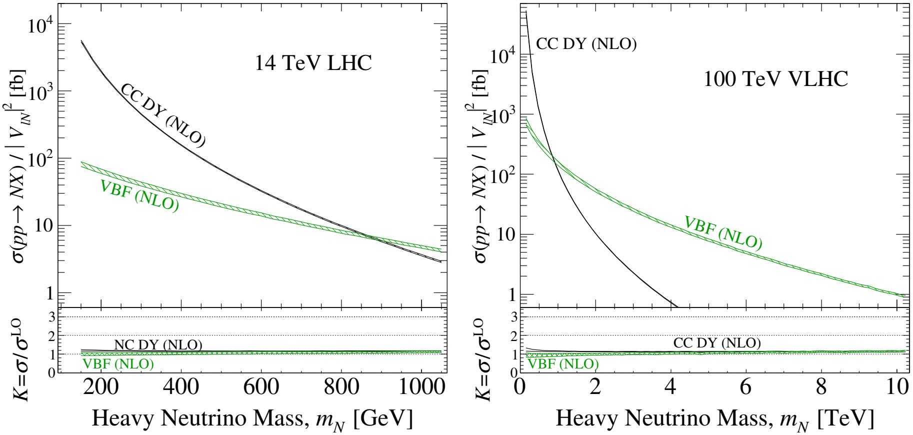
How heavy can we go?

high-mass production mechanisms: $W\gamma$ fusion



$W\gamma \to N\ell^\pm$ is powerful but subtle due to QED singularities and γ PDF

Dev, et al [1308.2209], w/ Alva, Han [1411.7305], w/ Degrande, Mattelaer, Turner [1602.06957]



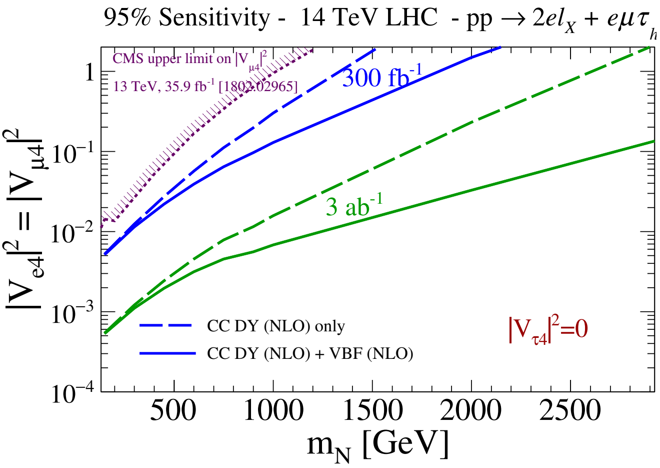
w/ Pascoli, Weiland [1812.08750]

Again, be careful when choosing γ PDF

for up-to-date comparison see study w/ Fuks, Nemevšek [1912.08975]

How important is $W\gamma$ fusion?

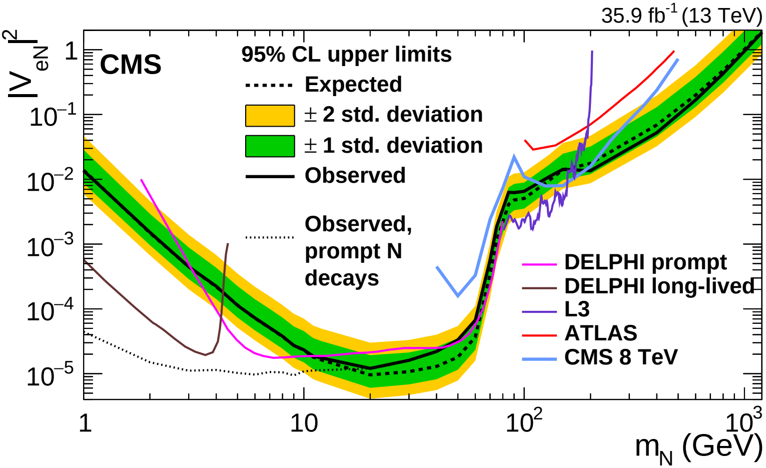
Plotted: LHC 14 sensitivity to active-sterile neutrino mixing (coupling) vs heavy neutrino mass (m_N) in search for $pp \to \mu^\pm e^\mp \ell_X \quad (\ell_X = e, \mu, \tau_h)$



[1812.08750]

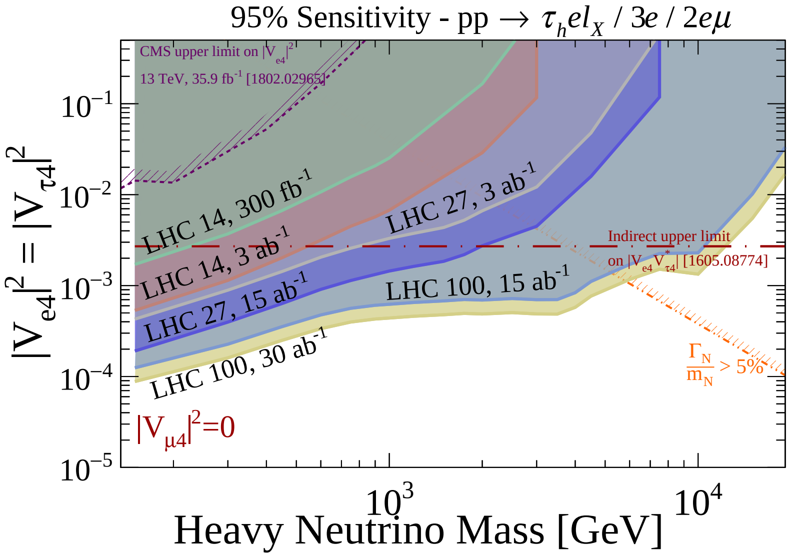
- Dash = CMS-inspired trilepton analysis with only $q\overline{q'}$ annihilation
- Solid = $+W\gamma$ fusion $\implies$ $W\gamma$ drives high-mass sensitivity!

Plotted: LHC 13 limits in search for $pp \to 3\ell + MET \quad (\ell_X = e, \mu)$



- $W\gamma$ included in CMS trilepton [1802.02965] and dilepton [1806.10905] searches
- ATLAS does not include $W\gamma \implies$ lower high-mass sensitivity [1905.09787]

A peak at the future.



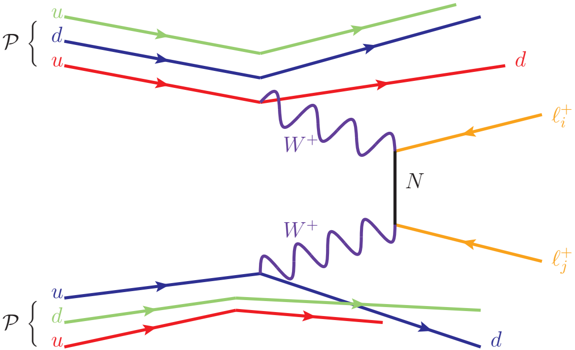
Improved analysis + $W\gamma \implies$ competitive sensitivity to cLFV at LHC[1]

- **Specific coupling reach is model-dependent**

[1] Only a few results now. See "big" paper for various flavor, Dirac vs Majorana, and $\sqrt{s}$ permutations [1812.08750]

How heavy can we go?

N from $W^{\pm}W^{\pm}$ scattering



$W^\pm W^\pm \to \ell_i^\pm \ell_j^\pm$ is high-energy version of $0\nu\beta\beta$ decay with $\ell = e, \mu, \tau$

Dicus, et al (PRD'91)

Plotted: Normalized production rate ($\sigma/|V|^{2\ (4)}$) vs mass (m_N)

w/ Fuks, Neundorf, Peters, Saimpert [2011.02547;2012.09882]

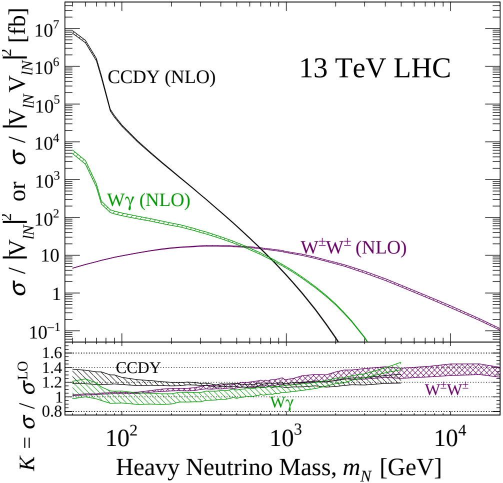
Driven by $W_0^+ W_0^+$ scattering

"Low-mass" limit ($M_{WW} \gg m_N$):

$$\hat{\sigma}(W^+W^+ \to \ell^+\ell^+) \sim g_W^4 |V_{\ell N}|^4 \frac{m_N^2}{m_W^4}$$

"High-mass" limit ($M_{WW} \ll m_N$):

$$\hat{\sigma}(W^+W^+ \to \ell^+\ell^+) \sim g_W^4 \frac{|V_{\ell N}|^4}{m_N^2} \frac{M_{WW}^4}{m_W^4}$$



Lots of rich phenomenology

The collider signature exhibits both LNV and VBS/F characteristics

$$pp \to \mu^\pm \mu^\pm jj + X$$

- same-sign, high-p_T charged leptons without MET and back-to-back
- forward, high-p_T with rapidity gap
- See backup slides for kinematic distributions at NLO+PS

Built simplified analysis for expedience:

TABLE III. Pre-selection and signal region cuts.

Pre-selection Cuts
$p_T^{\mu_1\ (\mu_2)} > 27\ (10)$ GeV, $\lvert\eta^\mu\rvert < 2.7$, $n_\mu = 2$,
$p_T^j > 25$ GeV, $\lvert\eta^j\rvert < 4.5$, $n_j \geq 2$,
$Q_{\mu_1} \times Q_{\mu_2} = 1$, $M(j_1, j_2) > 700$ GeV
Signal Region Cuts
$p_T^{\mu_1}$, $p_T^{\mu_2} > 300$ GeV

TABLE I. Generator-level cross sections [fb] and cuts, μ_f, μ_r scale uncertainty [%], PDF uncertainties [%], and perturbative order for leading backgrounds at $\sqrt{s} = 13$ TeV.

Process	Order	Cuts	$\sigma^{\text{Gen.}}$ [fb]	$\pm\delta_{\mu_f,\mu_r}$	$\pm\delta_{\text{PDF}}$
$W^\pm W^\pm jj$ (QCD)	NLO in QCD	Eq. (4.2)	385	$^{+10\%}_{-10\%}$	$^{+1\%}_{-1\%}$
$W^\pm W^\pm jj$ (EW)	NLO in QCD	Eq. (4.2) + diagram removal	254	$^{+1\%}_{-1\%}$	$^{+1\%}_{-1\%}$
Inclusive $W^\pm V$ $(3\ell\nu)$	FxFx (1j)	Eqs. (4.3), (4.4)	2,520	$^{+5\%}_{-6\%}$	$^{+1\%}_{-1\%}$

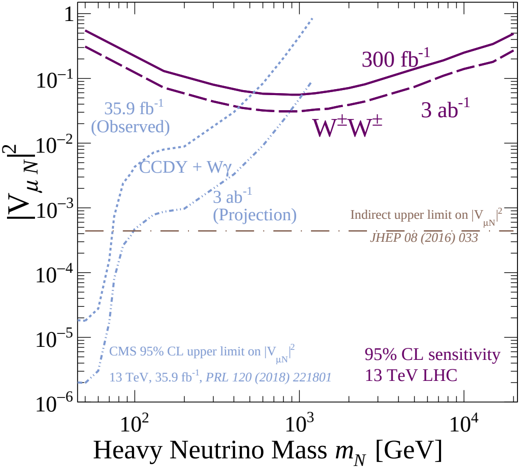
TABLE IV. Visible signal cross sections (and efficiencies) after applying different selections to the simulated events.

m_N	$\sigma^{\text{Gen.}}$ [fb]	$\sigma^{\text{Pre.}}$ [fb]	$(\mathcal{A})$	σ^{SR} [fb]	(ε)
150 GeV	13.3	3.7	(28%)	0.5	(14%)
1.5 TeV	8.45	3.18	(38%)	1.9	(63%)
5 TeV	1.52	0.58	(38%)	0.46	(79%)
15 TeV	0.190	0.072	(38%)	0.056	(78%)

TABLE V. Expected number of SM background events in the Signal Region at the (HL-)LHC with $\mathcal{L} = 300$ fb^{-1} (3 ab^{-1}).

Collider	QCD $W^\pm W^\pm jj$	EW $W^\pm W^\pm jj$	$W^\pm V(3\ell\nu)$	Total
LHC	0.05	0.52	0.14	0.71
HL-LHC	0.49	5.17	1.40	7.10

Plotted: LHC 13 sensitivity to active-sterile neutrino mixing (coupling) vs heavy neutrino mass (m_N)

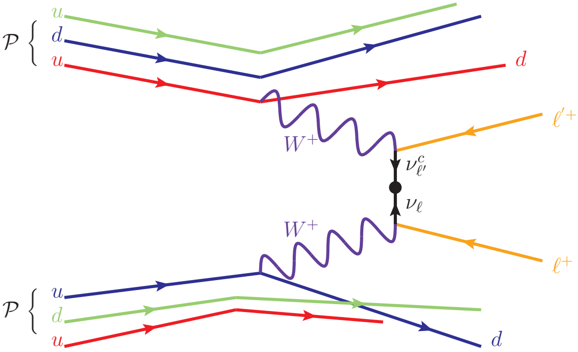


$W^\pm W^\pm \to \ell_i^\pm \ell_j^\pm$ allows direct probe $m_N \sim 1 - 10$ TeV at $|V|^2 \lesssim 0.1$

- Simplified analysis = room for improvement!

NEW: $W^{\pm}W^{\pm}$ scattering at dimension five

(Weinberg Operator)



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Dicus, et al (PRD'91)

Plotted: Normalized production rate ($C_5 = 1$) vs scale (Λ)

w/ Fuks, Neundorf, Peters, Saimpert [2011.02547;2012.09882]

Weinberg operator only SMEFT operator at $d = 5$:

$$\mathcal{L} = \frac{C_5^{\ell\ell'}}{\Lambda}[\Phi \cdot \overline{L}_\ell^c][L_{\ell'} \cdot \Phi]$$

generates/corrects ν mass matrix:

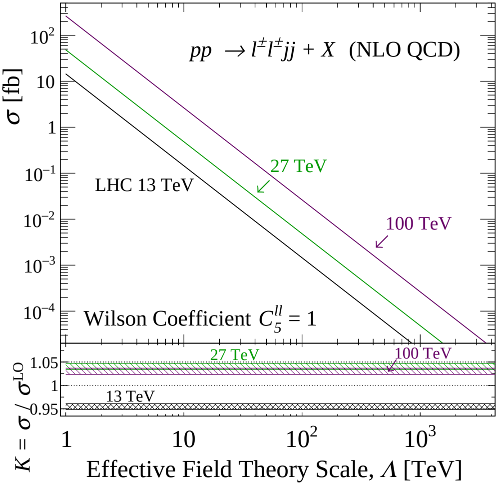
$$m_{\ell\ell'} = C_5^{\ell\ell'}\langle\Phi\rangle^2/2\Lambda$$

C_5^{ee}/Λ is constrainted by $0\nu\beta\beta$.

What about the other $C_5^{\ell\ell'}$?

Driven by $W_0^+ W_0^+$ scattering

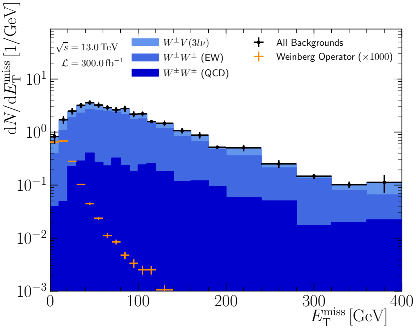
$$\hat{\sigma}(W^+W^+ \to \ell^+\ell^+) \sim g_W^4 \frac{|C_5^{\ell\ell}|^2}{18\pi\Lambda^2}$$

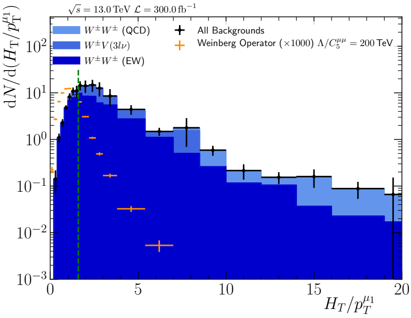


The collider signature exhibits both LNV and VBS/F characteristics

$$pp \to \mu^{\pm}\mu^{\pm}jj + X$$

(L) $E_T^{\rm miss}$ (R) $H_T/p_T^{\mu_1}$

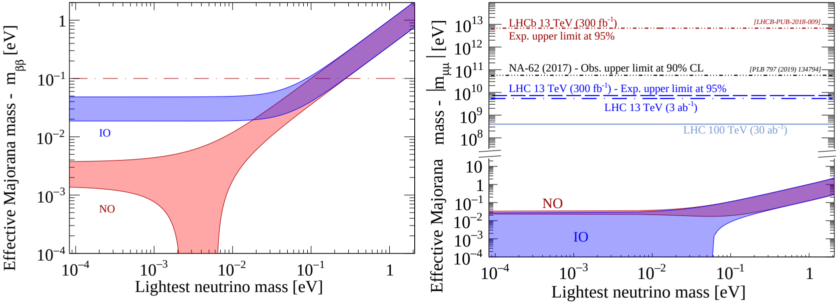




the big picture

Plotted: Allowed and projected reach of $|m_{\mu\mu}|$ vs lights ν mass

$$|C_5^{\ell\ell'}|\frac{\langle\Phi\rangle^2}{2\Lambda} = |m_{\ell\ell'}| = |\sum_{k=1}^{3} U_{\ell k} m_{\nu_k} U_{\ell' k}|$$



With a minimal cuts (= can be improved) $\mathcal{L} = 300\ (3000)\ \mathbf{fb}^{-1}$

$$\Lambda/|C_5^{\mu\mu}| \lesssim 8.3\ (13)\ \text{TeV}$$

$\Longrightarrow$ "light Majorana mass scales" (in flavor space) as small as

$$|m_{\mu\mu}| \gtrsim 7.3\ (5.4)\ \text{GeV}$$

and is more competative than other experiments!

Summary

New physics is motivated by many emperical and theoretical observations

- Dark matter, naturalness, flavor, ν masses

The scattering of EW bosons offers a unique probe of new physics

- access to spin, isospin, and QED configurations not accessible to, e.g., qq', $q\overline{q}$, and gg scattering
- enables direct production of new particles or probe EFT/ NSIs

Numerous neutrino mass models can be tested at colliders

- Lots of encouraging projections for sensitivity at the HL-LHC
- New VBS/VBF analyses $\Longrightarrow$ new territory LNV and cLFV

The **Snowmass Process** is underway!

- Community studies are iterative and we plan to keep up the work!
- Lots not covered todays, so go check out the review! [1711.02180]

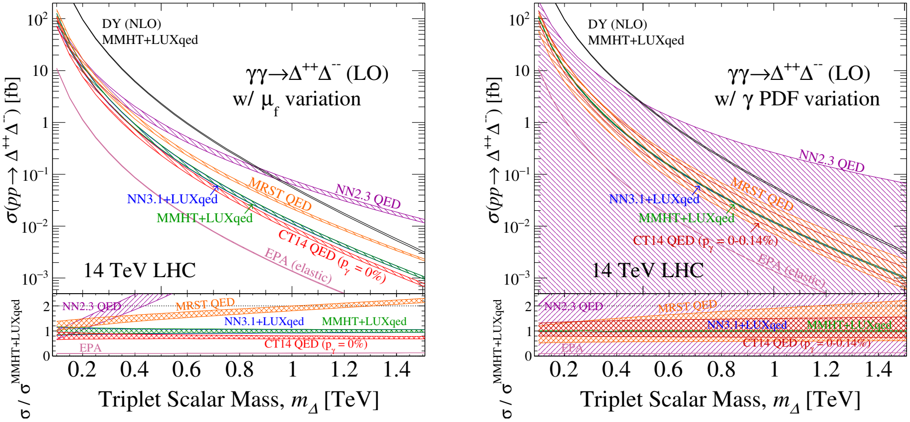
Thank you.

Backup

Photon PDFs

Historically, back-and-forth about importance of $\gamma\gamma \to \Delta^{++}\Delta^{--}$

- most PDFs in good agreement with some known exceptions



- **Warning**: NNPDF 2.3 QED (default in `MG5aMC`) has poor description of γ PDF; well-known and due to limited statistics (not modeling)