Neutrino physics at colliders

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GdR Neutrino
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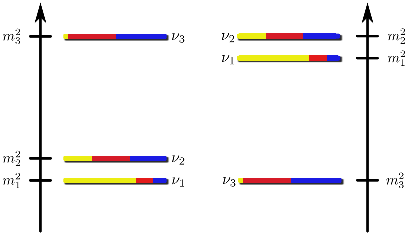
Neutrino phenomena

- Neutrino oscillations (best fit from nu-fit.org):

solar	$\theta_{12} \simeq 34^\circ$	$\Delta m^2_{21} \simeq 7.5 \times 10^{-5}\text{eV}^2$
atmospheric	$\theta_{23} \simeq 42^\circ$	$\lvert\Delta m^2_{23}\rvert \simeq 2.5 \times 10^{-3}\text{eV}^2$
reactor	$\theta_{13} \simeq 8.5^\circ$	

- Absolute mass scale:
  cosmology $\Sigma m_{\nu_i} < 0.23$ eV [Planck, 2016]
  β decays $m_{\nu_e} < 2.05$ eV [Mainz, 2005; Troitsk, 2011]



- Different mixing pattern from CKM, ν lightness $\overset{?}{\longleftarrow}$ Majorana ν

- SM: no ν mass term, lepton flavour is conserved
  $\Rightarrow$ need new Physics
  - Radiative models
  - Extra dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanisms $\rightarrow$ ν mass at tree-level
    + BAU through leptogenesis

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Dirac neutrinos ?

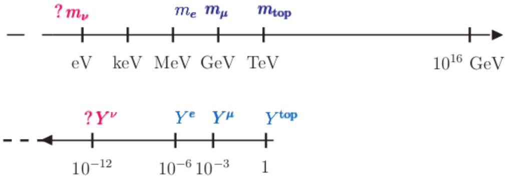
- Add gauge singlet (sterile), right-handed neutrinos ν_R $\Rightarrow \nu = \nu_L + \nu_R$

$$\mathcal{L}^{\text{leptons}}_{\text{mass}} = -Y_\ell \bar{L}\phi\ell_R - Y_\nu \bar{L}\tilde{\phi}\nu_R + \text{h.c.}$$

$\Rightarrow$ After electroweak symmetry breaking $\langle\phi\rangle = \binom{0}{\text{v}}$

$$\mathcal{L}^{\text{leptons}}_{\text{mass}} = -m_\ell \bar{\ell}_L \ell_R - m_D \bar{\nu}_L \nu_R + \text{h.c.}$$

$3\ \nu_R \Rightarrow$ 3 light active neutrinos: $m_\nu \lesssim 1\text{eV} \Rightarrow Y^\nu \lesssim 10^{-11}$



Majorana neutrinos ?

- Add gauge singlet (sterile), right-handed neutrinos ν_R
  $\mathcal{L}_{\text{mass}}^{\text{leptons}} = -Y_\ell \bar{L}\phi\ell_R - Y_\nu \bar{L}\tilde{\phi}\nu_R - \frac{1}{2}M_R\overline{\nu_R}\nu_R^c + \text{h.c.}$

  $\Rightarrow$ After electroweak symmetry breaking $\langle\phi\rangle = \binom{0}{\text{v}}$
  $\mathcal{L}_{\text{mass}}^{\text{leptons}} = -m_\ell \ell_L \ell_R - m_D \bar{\nu}_L \nu_R - \frac{1}{2}M_R\overline{\nu_R}\nu_R^c + \text{h.c.}$

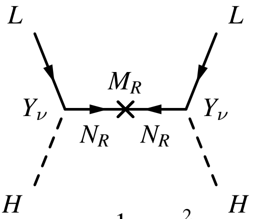
  $3\ \nu_R \Rightarrow$ 6 mass eigenstates: $\nu = \nu^c$

- ν_R gauge singlets
  $\Rightarrow M_R$ not related to SM dynamics, not protected by symmetries
  $\Rightarrow M_R$ between 0 and M_P

- Experimental test of the neutrino nature ?
  $\Rightarrow$ Processes that violate lepton number by $\Delta L = \pm 2$
  - $0\nu 2\beta$: see talks by A. Giuliani, T. Le Noblet, S. Calvez
  - same-sign dilepton at colliders
  - LNV meson decays

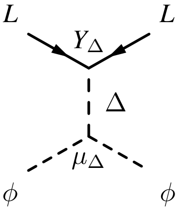
Minimal seesaw mechanisms

- Seesaw mechanism: new fields + lepton number violation
  $\Rightarrow$ Generate m_ν in a renormalizable way and at tree-level
- 3 minimal tree-level seesaw models $\Rightarrow$ 3 types of heavy fields
  - type I: right-handed neutrinos, SM gauge singlets
  - type II: scalar triplets
  - type III: fermionic triplets



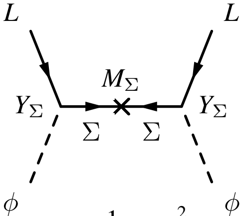
$$\mathrm{m}_\nu = -\frac{1}{2} Y_\nu^T \frac{\mathrm{v}^2}{M_R} Y_\nu$$

[Minkowski, 1977, Gell-Mann et al., 1979, Yanagida, 1979, Mohapatra and Senjanovic, 1980]



$$\mathrm{m}_\nu = -2 Y_\Delta \mathrm{v}^2 \frac{\mu_\Delta}{M_\Delta^2}$$

[Magg and Wetterich, 1980, Schechter and Valle, 1980, Wetterich, 1981, Lazarides et al., 1981, Mohapatra and Senjanovic, 1981]



$$\mathrm{m}_\nu = -\frac{1}{2} Y_\Sigma^T \frac{\mathrm{v}^2}{M_\Sigma} Y_\Sigma$$

[Foot et al., 1989]

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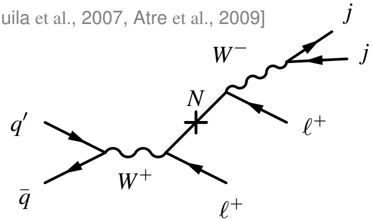
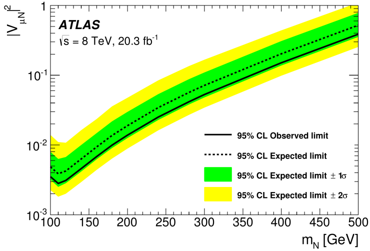
Searches for heavy Majorana neutrinos

- Golden channel: same-sign dilepton + dijet

  [Datta et al., 1994, Han and Zhang, 2006, del Aguila et al., 2007, Atre et al., 2009]



[ATLAS, JHEP07(2015)162]



- To be compared with EWPO:

  [Fernandez-Martinez et al., 2016]

  $|V_{\mu N}|^2 \leqslant 4.10^{-4}$ at 2σ

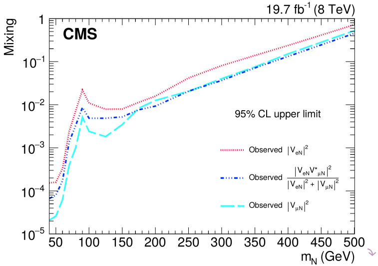
- LHC expected sensitivities at 2σ:

  [Alva et al., 2015]

$$\mathcal{L} = 100\,\text{fb}^{-1} \quad \rightarrow \quad m_N < 160\,\text{GeV}$$
$$\mathcal{L} = 1\,\text{ab}^{-1} \quad \rightarrow \quad m_N < 300\,\text{GeV}$$

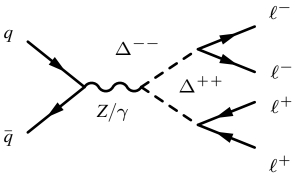
- Observation can be used to try to falsify leptogenesis [Deppisch et al., 2014]

[CMS, JHEP04(2016)169]



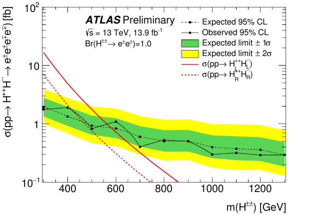
Searches for doubly-charged scalars

- Type II seesaw: $\mathrm{SU}(2)_L$ triplet $(\Delta^{++}, \Delta^{+}, \Delta^{0})$
- Golden channel: Pair production
  [Akeroyd and Aoki, 2005, Fileviez Perez et al., 2008, del Aguila and Aguilar-Saavedra, 2009, Melfo et al., 2012]

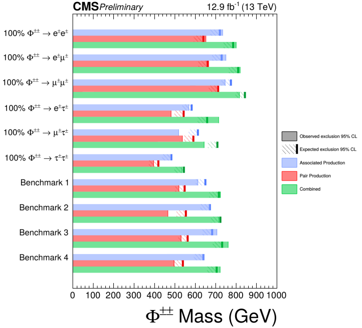


- Striking signal with same-sign lepton pairs
- Tensions with naturalness requirement
  [Farina et al., 2013, Chabab et al., 2016, Haba et al., 2016]...
  $\delta m_H < m_H \Rightarrow M_\Delta < \mathcal{O}(200)\,\mathrm{GeV}$

[ATLAS, ATLAS-CONF-2016-051]

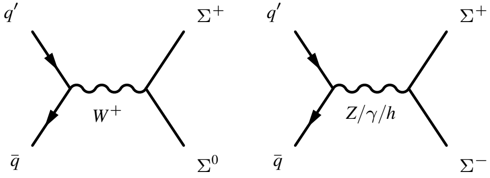


[CMS, CMS-PAS-HIG-16-036]



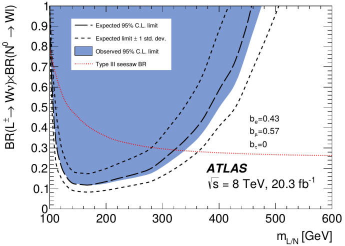
Searches for heavy leptons at the LHC

- Type III seesaw: $SU(2)_L$ triplet $(\Sigma^+, \Sigma^0, \Sigma^-)$
- Based on pair production $(\Sigma^\pm\Sigma^0,\ \Sigma^+\Sigma^-)$
  [Franceschini et al., 2008, Arhrib et al., 2010, Ruiz, 2015]

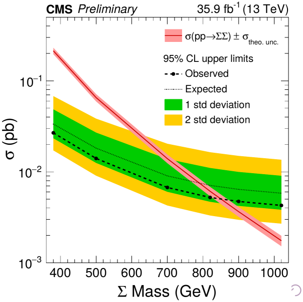


- Final states with multiple charged leptons (ATLAS: $2\ell + 2j$ from $W^\pm$, CMS: $\geqslant 3$)
- Naturalness criterion leads to [Farina et al., 2013]
  $\delta m_H < m_H \Rightarrow M_\Sigma < \mathcal{O}(1000)\,\mathrm{GeV}$

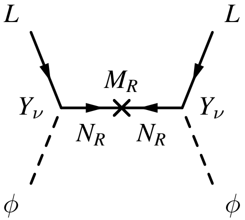
[ATLAS, PRD92(2015)032001]



[CMS, EXO-17-006]



Type I and low-scale seesaw



- Taking $M_R \gg m_D$ gives the "vanilla" type I seesaw

$$\mathrm{m}_\nu = -m_D^T M_R^{-1} m_D$$

- Cosmological limit: $\Sigma m_{\nu_i} < 0.23$ eV [Planck, 2016]

$$\mathrm{m}_\nu \sim 0.1\,\mathrm{eV} \Rightarrow \left| \begin{array}{l} Y_\nu \sim 1 \quad \text{and} \quad M_R \sim 10^{14}\,\mathrm{GeV} \\ Y_\nu \sim 10^{-6}\,\text{and} \quad M_R \sim 10^{2}\ \ \mathrm{GeV} \end{array} \right.$$

- Type I seesaw: m_ν suppressed by small active-sterile mixing

$$|V_{\ell N}| \sim \frac{m_D}{M_R} \sim 10^{-6}\sqrt{\frac{100\,\mathrm{GeV}}{M_R}}$$

- Cancellation in matrix product (from L nearly conserved [Kersten and Smirnov, 2007])
  → Low-scale seesaw with large active-sterile mixing, e.g.
  inverse seesaw [Mohapatra and Valle, 1986, Bernabéu et al., 1987]
  linear seesaw [Akhmedov et al., 1996, Barr, 2004, Malinsky et al., 2005]
  low-scale type I [Ilakovac and Pilaftsis, 1995] and others

LNV signals are suppressed

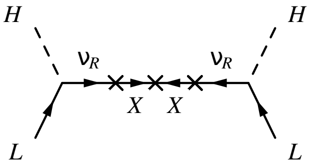
The inverse seesaw mechanism

- Lower seesaw scale from approximately conserved lepton number
- Add fermionic gauge singlets ν_R $(L = +1)$ and X $(L = -1)$

  [Mohapatra and Valle, 1986]

$$\mathcal{L}_{inverse} = -Y_\nu \overline{L}\tilde{\phi}\nu_R - M_R \overline{\nu_R^c} X - \frac{1}{2}\mu_X \overline{X^c} X + \text{h.c.}$$

with $m_D = Y_\nu \mathrm{v}\,, M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$



$$m_\nu \approx \frac{m_D^2}{M_R^2}\mu_X$$

$$m_{N_1,N_2} \approx \mp M_R + \frac{\mu_X}{2}$$

2 scales: μ_X and M_R

- Decouple neutrino mass generation from active-sterile mixing
- Inverse seesaw: $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 1\,\text{TeV}$

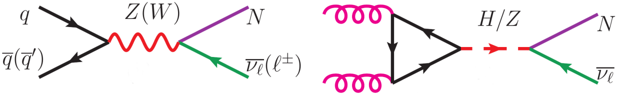
  $\Rightarrow$ within reach of the LHC and low energy experiments

Low-scale seesaw signatures at colliders

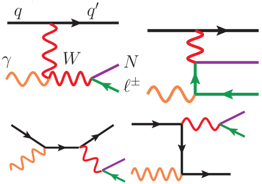
- Direct searches above m_H
  - LHC: LFV di-lepton + dijet [Arganda, Herrero, Marcano and **CW**, 2016]
    tri-lepton + missing E_T [del Aguila and Aguilar-Saavedra, 2009, Chen and Dev, 2012, Das and Okada, 2013, Bambhaniya et al., 2015]...
  - ILC/FCC-ee: single lepton + dijet
    [Das and Okada, 2013, Banerjee et al., 2015, Antusch et al., 2016]
- Direct searches below m_H
  - Higgs decays: invisible [Banerjee et al., 2013]
    visible
    [Bhupal Dev et al., 2012, Bandyopadhyay et al., 2013, Cely et al., 2013, Das et al., 2017]
  - Displaced vertices
    [Helo et al., 2014, Blondel et al., 2016, Dib and Kim, 2015, Gago et al., 2015, Antusch et al., 2016]
- Indirect searches
  - EWPO [del Aguila et al., 2008, de Blas, 2013, Fernandez-Martinez et al., 2016]
  - (semi)leptonic decays of mesons [Abada, Teixeira, Vicente and **CW**, 2014]
  - charged lepton flavour violation [Bernabéu et al., 1987]...
  - triple Higgs coupling [Baglio, **CW**, 2016, 2017]

Direct searches above m_H: Production at the LHC

Drell-Yan   gluon fusion



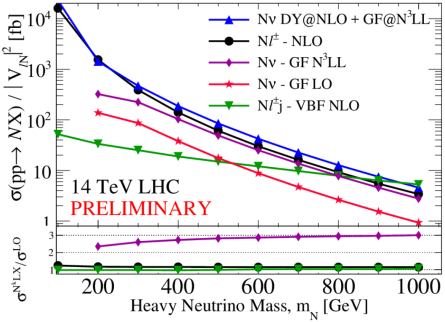
VBF



diagrams from [Degrande et al., 2016]

- Model files available for automated NLO calculation in phenomenological type I seesaw [Degrande et al., 2016]
- Extension to CPV scenario and low-scale seesaw models is undergoing validation [R. Ruiz and **CW**]
- Gluon fusion channel dominates at low masses
- VBF dominates at high masses

[Dev et al., 2014, Alva et al., 2015]



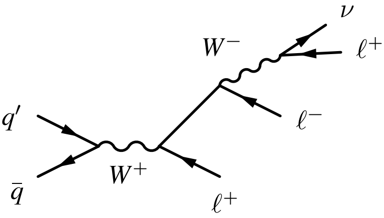
plot from R. Ruiz @ Pheno2017

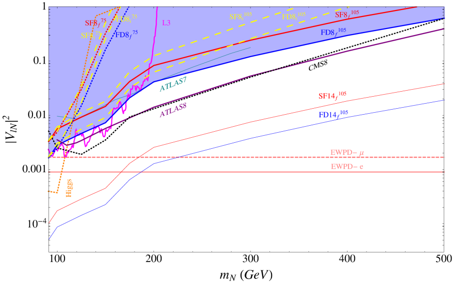
Trilepton signatures at the LHC

- LNV same-sign dilepton is suppressed in low-scale seesaw models

Searches for LNC signatures of heavy (pseudo)-Dirac neutrinos are needed and well-motivated

- First channel: $pp \to \ell^\pm \ell^\mp \ell^\pm \nu$ [del Aguila and Aguilar-Saavedra, 2009, Chen and Dev, 2012, Das and Okada, 2013, Bambhaniya et al., 2015]...



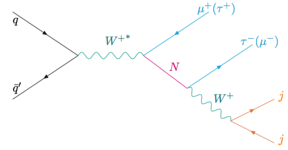


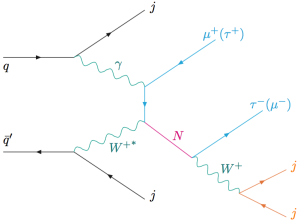
- With $\mathcal{L} = 300\,\text{fb}^{-1}$, sensitive to $m_N \lesssim 200\,\text{GeV}$

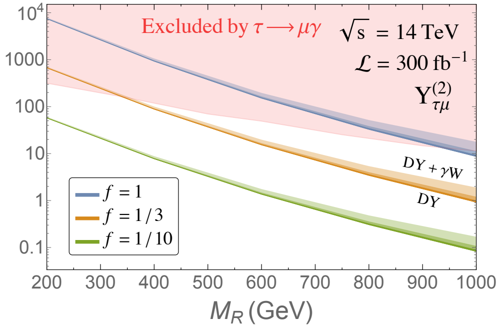
[Das and Okada, 2016]

LFV dilepton at the LHC

- Second channel: $pp \to \ell_\alpha^+ \ell_\beta^- jj$ [Arganda, Herrero, Marcano and **CW**, 2016]





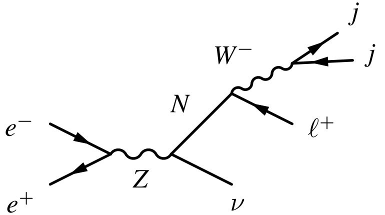


- Lower line: production only from Drell-Yan
  Shaded regions: $W\gamma$ fusion added with $p_T^{\max} = 10\,, 20\,, 40\,\text{GeV}$ (darker to lighter)
- Up to $\mathcal{O}(200)$ events, naively background free

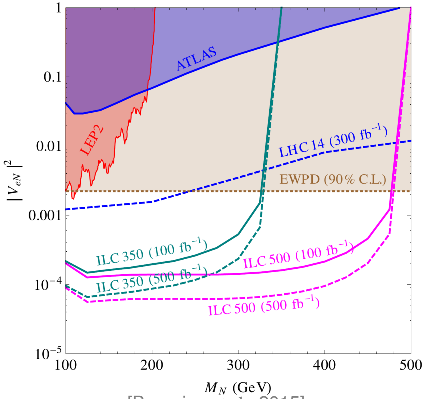
Production and decays at e^+e^- colliders

- Many possible channels: $\ell\nu jj$, $\ell\ell\nu\nu$, $\nu\nu jj$, $\nu\nu\nu\nu$ [Antusch et al., 2016]
- Most promising channel: $\ell\nu jj$

  [Das and Okada, 2013, Banerjee et al., 2015, Antusch et al., 2016]



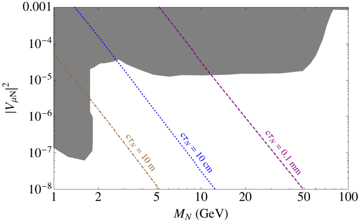
- LNC process: not suppressed in low-scale seesaw
- Process with the largest cross-section
- Can probe large mass range, up to $\sim 0.95\sqrt{s}$



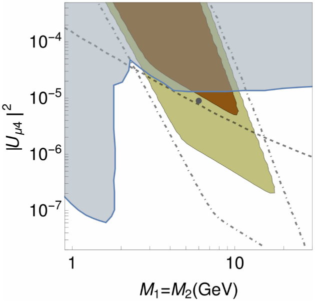
[Banerjee et al., 2015]

Searches below m_W: displaced vertices

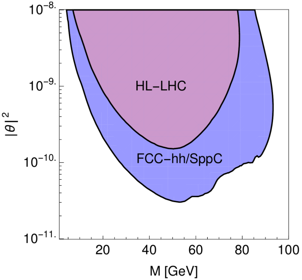
- Very clean experimental signature
- Uses the large samples of W, Z and H available at colliders
- Can probe active-sterile mixing below 10^{-5}



[Izaguirre and Shuve, 2015]



LHC14, $\mathcal{L} = 300\,\text{fb}^{-1}$ [Gago et al., 2015]



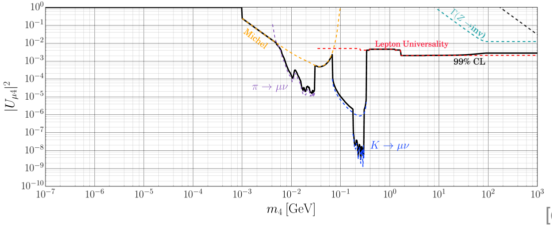
[Antusch et al., 2016]

Summary of direct searches

- LHC should be sensitive to heavy sterile neutrino with $m_N \leqslant 200\,\mathrm{GeV}$
  Future colliders could push direct searches to a few TeV[Golling et al., 2016]
- **Important to consider LNC final state as well**
- Displaced vertex searches are extremely powerful when below m_W
- Lots of phenomenological activity:
  - (automated) NLO production cross-sections
  - New sensitivity studies and search strategies
  - New constraints set from LHC data
- Exclusion limits on Δ^{++} for type II seesaw already in tension with naturalness considerations
- Exclusion limits on type III seesaw leptons pushed to $\sim 800\,\mathrm{GeV}$ by CMS
- Indirect searches allow to push searches to the multi-TeV range

Electroweak precision observables

- Based on global fit to observables that include Z and $W^\pm$ decays
  [del Aguila et al., 2008, de Blas, 2013, Fernandez-Martinez et al., 2016]
- Kinematically inaccessible heavy N decreases Z and W decay widths
  $\Rightarrow$ Limits independent of the heavy neutrino masses above m_Z



[de Gouvêa and Kobach, 2016]

- Currently provide the strongest constraints on heavy neutrino mixing above m_H

mixing	2σ limit
$\lvert V_{eN}\rvert$	0.05
$\lvert V_{\mu N}\rvert$	0.021
$\lvert V_{\tau N}\rvert$	0.075

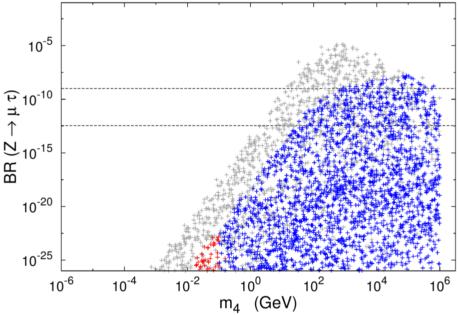
[Fernandez-Martinez et al., 2016]

Charged lepton flavour violation

- Sensitive to a new physics scale as large as $\Lambda \sim 1000\,\mathrm{TeV}$
- ATLAS search for $\tau \to 3\mu$: Br$< 3.76 \times 10^{-7}$ [ATLAS, 2016]
- ATLAS search for LFV Z decays: Br$(Z \to \tau\mu) < 1.69 \times 10^{-5}$ [ATLAS, 2016]
  Br$(Z \to e\mu) < 7.5 \times 10^{-7}$ [ATLAS, 2016]

  in agreement with previous sensitivity studies [Davidson et al., 2012]
- Huge sensitivity improvement expected from future e^+e^- collider

  [Abada et al., 2015b, Abada et al., 2015a, De Romeri et al., 2017]



[Abada et al., 2015b]

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A new opportunity

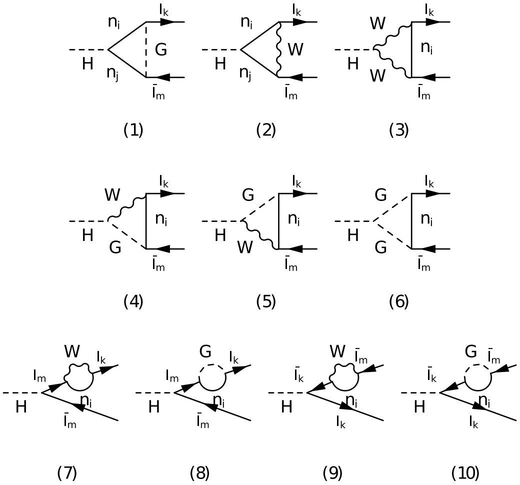
- Huge effort to measure Higgs properties: mass, width, couplings

Use the Higgs sector to probe neutrino mass models

- $H\bar{\ell}_i\ell_j$:
  - Contribution negligible in the SM → evidence of new physics if observed
  - Sensitive to off-diagonal Yukawa couplings Y_ν
  - Complementary to other LFV searches
- HHH:
  - Reconstruct the scalar potential
    → validate the Higgs mechanism as the origin of EWSB
  - Sizeable SM 1-loop corrections ($\mathcal{O}(10\%)$)
    → Quantum corrections cannot be neglected
  - One of the main motivations for future colliders
  - Sensitive to diagonal Yukawa couplings Y_ν

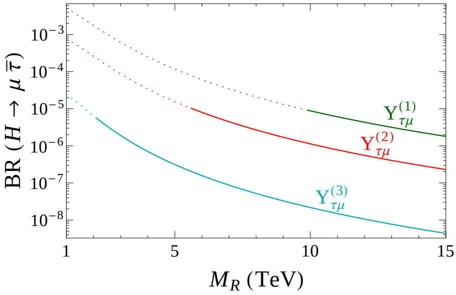
Lepton flavour violating Higgs decays I

- Arise at the one-loop level
  [Arganda, Herrero, Marcano, **CW**, 2015]



- Formulas adapted from [Arganda et al., 2005]
- Diagrams 1, 8, 10 dominate at large M_R
- Enhancement from:
  -$\mathcal{O}(1)$ Y_ν couplings
  -TeV scale n_i

Lepton flavour violating Higgs decays II



- $\mathrm{Br}(H \to \tau\mu) < 1.20\%$ [CMS-PAS-HIG-16-005]
  $\mathrm{Br}(H \to \tau\mu) < 1.43\%$ [ATLAS, EPJC77(2017)70]
- Dotted: excluded by $\tau \to \mu\gamma$
  Solid: allowed by LFV, LUV, etc
- $\mathrm{Br}^{\max}(H \to \mu\bar{\tau}) \sim 10^{-5}$
- Similarly, $\mathrm{Br}^{\max}(H \to e\bar{\tau}) \sim 10^{-5}$

- Approximate formula for large Y_ν:

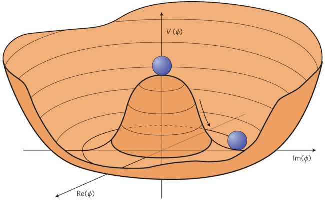
$$\mathrm{Br}^{\mathrm{approx}}_{H\to\mu\bar{\tau}} = 10^{-7}\,\frac{\mathrm{v}^4}{M_R^4}\left|(Y_\nu Y_\nu^\dagger)_{23} - 5.7(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{23}\right|^2$$

- In a supersymmetric model, $\mathrm{Br}^{\max}(H \to \mu\bar{\tau}) \sim 10^{-2}$ [Arganda, Herrero, Marcano, **CW**, 2016]
  $\Rightarrow$ Within LHC reach

The triple Higgs coupling

- Scalar potential before EWSB:

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



- After EWSB: $m_H^2 = 2\mu^2\,, \quad \text{v}^2 = \mu^2/\lambda$

$$\phi = \begin{pmatrix} 0 \\ \frac{\text{v}+H}{\sqrt{2}} \end{pmatrix} \to V(H) = \frac{1}{2}m_H^2 H^2 + \frac{1}{3!}\lambda_{HHH}H^3 + \frac{1}{4!}\lambda_{HHHH}H^4$$

and

$$\lambda^0_{HHH} = -\frac{3M_H^2}{\text{v}}\,, \quad \lambda^0_{HHHH} = -\frac{3M_H^2}{\text{v}^2}$$

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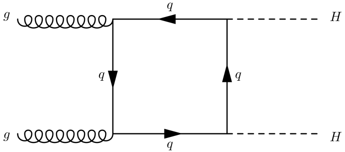
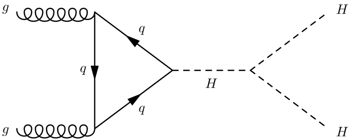
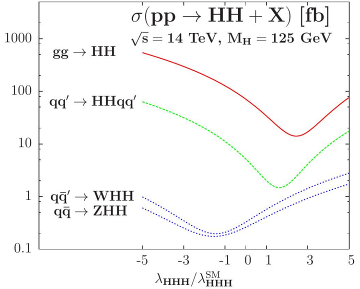
Experimental measurement of the HHH coupling

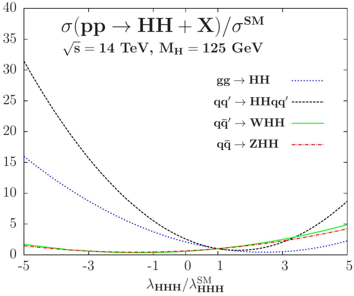
- Extracted from HH production





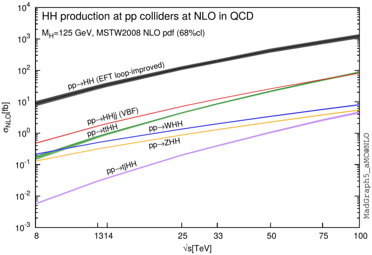
- Destructive interference between diagrams with and without λ_{HHH}



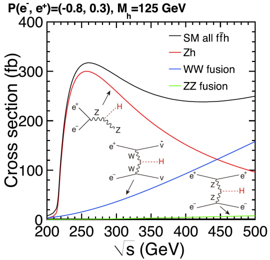


- Most sensitive channel in the SM: VBF [Baglio et al., 2013]

Future sensitivities to the SM HHH coupling



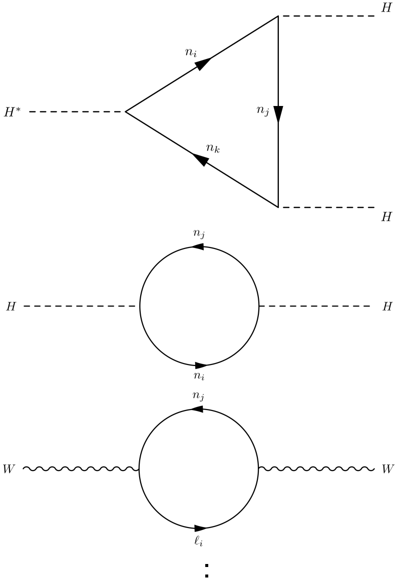
[Contino et al., 2016]



[Fujii et al., 2015]

- At hadron colliders
  - Production: gg dominates, VBF cleanest
  - HL-LHC: $\sim 50\%$ for ATLAS or CMS [CMS-PAS-FTR-15-002] and [Baglio et al., 2013]
    $\sim 35\%$ combined
  - FCC-hh: 8% per experiment with 3 ab^{-1} using only $b\bar{b}\gamma\gamma$ [He et al., 2016]
    $\sim 5\%$ combining all channels
- At e^+e^- collider
  - Main production channels: Higgs-strahlung and VBF
  - ILC: 27% at 500 GeV with 4 ab^{-1} [Fujii et al., 2015]
    10% at 1 TeV with 5 ab^{-1} [Fujii et al., 2015]

Beyond SM: simplified 3+1 model



- Impact of a new Dirac fermion coupled through the neutrino portal
- New 1-loop diagrams and new counterterms [Baglio and **CW**, 2016]
- Strongest experimental constraints on active-sterile mixing: EWPO [de Blas, 2013]

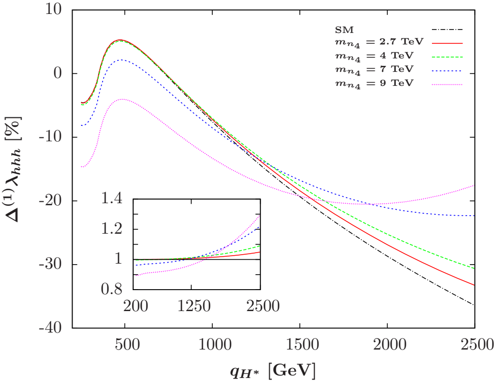
$$|V_{e4}| \leqslant 0.041$$
$$|V_{\mu 4}| \leqslant 0.030$$
$$|V_{\tau 4}| \leqslant 0.087$$

- Loose (tight) perturbativity of λ_{HHH}:

$$\left(\frac{\max|(V^\dagger V)_{i4}|\, g_2\, m_{n_4}}{2M_W}\right)^3 < 16\pi\ (2\pi)$$

- Width limit: $\Gamma_{n_4} \leqslant 0.6\, m_{n_4}$

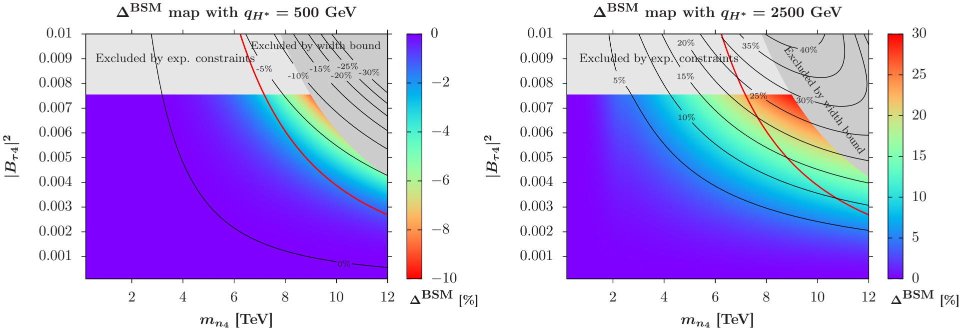
Momentum dependence



- $\Delta^{(1)}\lambda_{HHH} = \frac{1}{\lambda^0}\left(\lambda^{1r}_{HHH} - \lambda^0\right)$
- Assume $V_{\tau 4} = 0.087$, $V_{e4} = V_{\mu 4} = 0$
- Deviation of the BSM correction with respect to the SM correction in the insert
- $\max|(V^\dagger V)_{i4}|m_{n_4} = m_t$ $\to m_{n_4} = 2.7\,\text{TeV}$
  tight perturbativity of λ_{HHH} bound: $m_{n_4} = 7\,\text{TeV}$
  width bound: $m_{n_4} = 9\,\text{TeV}$

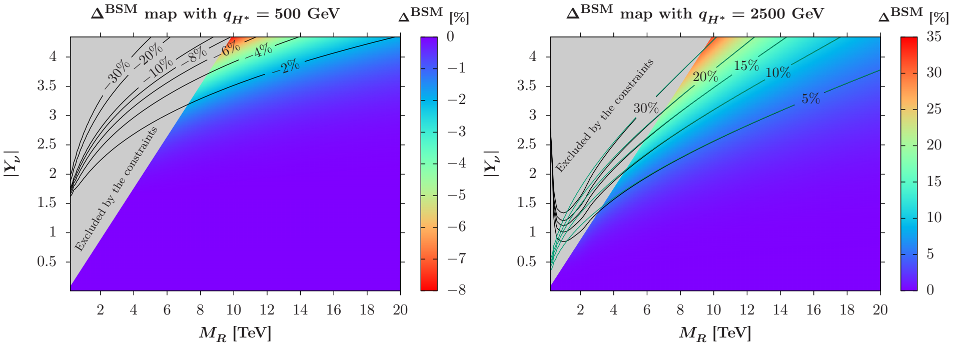
- Largest positive correction at $q_H^* \simeq 500\,\text{GeV}$, heavy ν decreases it
- Large negative correction at large q_H^*, heavy ν increases it

Results in 3+1 simplified model



- $\Delta^{\rm BSM} = \frac{1}{\lambda_{HHH}^{1r,{\rm SM}}}\left(\lambda_{HHH}^{1r,{\rm full}} - \lambda_{HHH}^{1r,{\rm SM}}\right)$
- Red line: tight perturbativity of λ_{HHH} bound
- Heavy ν effects at the limit of HL-LHC sensitivity (35%)
- Heavy ν effects clearly visible at the ILC (10%) and FCC-hh (5%)
- Similar behaviour for active-sterile mixing V_{e4} and $V_{\mu 4}$

Results extended to the inverse seesaw



- $\Delta^{\rm BSM} = \frac{1}{\lambda^{1r,{\rm SM}}_{HHH}}\left(\lambda^{1r,{\rm full}}_{HHH} - \lambda^{1r,{\rm SM}}_{HHH}\right)$
- Different calculation, with Majorana neutrinos [Baglio and **CW**, 2017]
- Diagonal Y_ν: full calculation in black, approximate formula in green

$$\Delta^{\rm BSM}_{\rm approx} = \frac{(1\ \text{TeV})^2}{M_R^2}\left(8.45\,{\rm Tr}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger) - 0.145\,{\rm Tr}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)\right)$$

- Sensitive to heavy neutrino with mass of $\mathcal{O}(10)$ TeV

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Conclusion

- ν oscillations $\rightarrow$ New physics is needed to generate masses and mixing
- LHC experiments have an active search program for new particles coming from seesaw mechanisms
  $\rightarrow$ Already put strong constraints on type II seesaw
- Both lepton number violating and lepton number conserving processes are important and should be considered
- Direct and indirect searches at colliders are complementary; applies as well to cosmological and precision observables
- Indirect searches at colliders can probe new regions above 10 TeV

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