Neutrinoless double beta decays in left-right symmetric models (and more)

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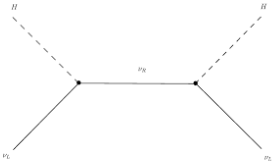
Outline

- Seesaw mechanisms and left-right symmetric model (LRSM)
- $0\nu\beta\beta$ in seesaw mechanisms
- $0\nu\beta\beta$ in LRSM
- Other probes of seesaw mechanisms and LRSM
  - low-energy high-precision MOLLER experiment
  - long-lived $H_{L,R}^{\pm\pm}$ at high-energy colliders
  - Searches of N_i and W_R at high-energy colliders
- Conclusion

Seesaw mechanisms & LRSM

Type-I seesaw

Minkowski '77; Mohapatra & Senjanović '80; Yanagida '79;
Gell-Mann, Ramond & Slansky '79; Glashow '80



- Basic Lagrangian to generate tiny neutrino masses

$$\mathcal{L} = -y_D \bar{L} \phi N + \frac{1}{2} \overline{N^C} M_N N$$

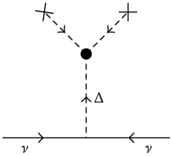
- Heavy-light neutrino mixing induced couplings

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W_\mu \bar{\ell}_\alpha \gamma^\mu P_L \left[U_{\alpha i} \nu_i + V_{\alpha j} N_j \right]$$

The heavy-light neutrino mixing will induce contributions of heavy neutrinos to $0\nu\beta\beta$!

Type-II seesaw

Konetschny & Kummer '77; Magg & Wetterich '80; Schechter & Valle '80;
Cheng & Li '80; Mohapatra & Senjanovic '81; Lazarides, Shafi & Wetterich '81



- One of the simplest seesaw frameworks to generate the tiny neutrino masses...

$$\mathcal{L} = -(f_L)_{\alpha\beta}\,\psi^{\mathsf{T}}_{L\alpha} C i\sigma_2 \Delta_L \psi_{L\beta} + \mu H^T i\sigma_2 \Delta_L^\dagger H + \text{H.c.},$$

$$\Delta_L = \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix}.$$

- Neutrino masses are given by

$$m_\nu = \sqrt{2}\, f_L v_L = U \widehat{m}_\nu U^{\mathsf{T}} \qquad \text{(with the VEV } \langle \delta_L^0 \rangle = v_L/\sqrt{2}\text{)}$$

- The coupling matrix f_L is fixed by neutrino oscillation data, up to the unknown lightest neutrino mass m_0, the neutrino mass hierarchy, and the Dirac & Majorana CP violating phases.

Parity violation since 1957

Figure: C. N. Yang, T. D. Lee & C. S. Wu

Left $\neq$ Right

Parity restoration

"As in my 1957 Rochester Conference lecture, we assume all P, C, T asymmetries observed are due to asymmetries in the solution — the asymmetries within our local big bang universe. The fundamental equations of physics remain P, C, T symmetric. Fifty years later, we may assume further that all such asymmetries are due to the spontaneous symmetry breaking mechanism generated by spin 0 Higgs field Φ. In such a picture, without ϕ all spin nonzero fields would be symmetry conserving and of zero mass; these should include besides graviton and photon, also $W^{\pm}$, Z^0, quarks and leptons."

— T. D. Lee, NPA **805** (2008) 54 [see also hep-ph/0605017]

(TeV-scale) left-right symmetric model:

Pati & Salam '74; Mohapatra & Pati '75; Senjonavić & Mohapatra '75

$$SU(2)_L \times U(1)_Y \Rightarrow SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

other options of LRSM, e.g. $SU(2)_L \times SU(2)_R \times U(1)_{Y_L} \times U(1)_{Y_R}$

Dev, Kazanas, Mohapatra, Teplitz & YCZ '16 [JCAP]; Dev, Mohapatra & YCZ '16 [JHEP]

Left-Right Symmetric Model (LRSM)

Pati & Salam '74; Mohapatra & Pati '75; Senjonavić & Mohapatra '75

- Heavy are added automatically to the SM:

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \in \left(\mathbf{2}, \mathbf{1}, \frac{1}{3}\right) \overset{\mathcal{P}}{\longleftrightarrow} Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \in \left(\mathbf{1}, \mathbf{2}, \frac{1}{3}\right)$$

$$\Psi_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \in (\mathbf{2}, \mathbf{1}, -1) \overset{\mathcal{P}}{\longleftrightarrow} \Psi_R = \begin{pmatrix} N_R \\ e_R \end{pmatrix} \in (\mathbf{1}, \mathbf{2}, -1)$$

- Electric charge and the hypercharge

$$Q = I_{3L} + I_{3R} + \frac{1}{2}(B - L)$$

- Tiny neutrino masses via seesaw mechanism(s) & heavy RHNs N
- Heavy gauge bosons W_R and Z_R from the $SU(2)_R \times U(1)_{B-L}$ sector.
- Heavy (and light) beyond SM scalars.

Scalar sector

Pati & Salam '74; Mohapatra & Pati '75; Senjonavić & Mohapatra '75

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\Delta_R\,(\mathbf{1},\mathbf{3},2)} SU(2)_L \times U(1)_Y \xrightarrow{\Phi\,(\mathbf{2},\mathbf{2},0)} U(1)_{\rm EM}$$

$$\begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix} \Rightarrow \begin{pmatrix} 0 & 0 \\ \langle \Delta_R^0 \rangle & 0 \end{pmatrix}$$

$\Rightarrow H_3^0,\ H_2^{\pm\pm}$

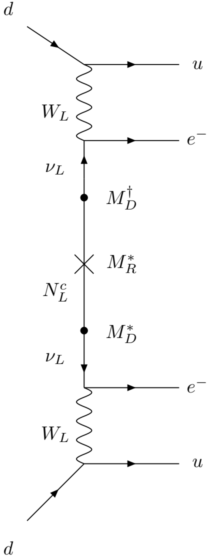
$$\begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow \begin{pmatrix} \langle \phi_1^0 \rangle & 0 \\ 0 & \langle \phi_2^0 \rangle \end{pmatrix}$$

$\Rightarrow h,\ H_1^0,\ A_1^0,\ H_1^\pm$

- Left-handed Δ_L is used to enable type-II seesaw.
- Left-handed Δ_L can decouple from the TeV scale physics:
  The parity restoration scale does not necessarily coincide with the $SU(2)_R$ breaking scale. [Chang, Mohapatra & Parida '84, Deshpande, Gunion, Kayser & Olness '91]
- Other $SU(2)_R$ breaking pattern: a right-handed doublet ϕ_R [Babu & Mohapatra '89 [PRL]; '90 [PRD]].

$0\nu\beta\beta$ in seesaw mechanisms & LRSM

$0\nu\beta\beta$ in type-I seesaw



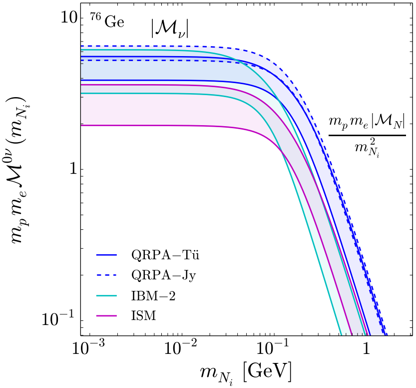
Heavy-light neutrino mixing [Casas & Ibarra '01 [NPB]]

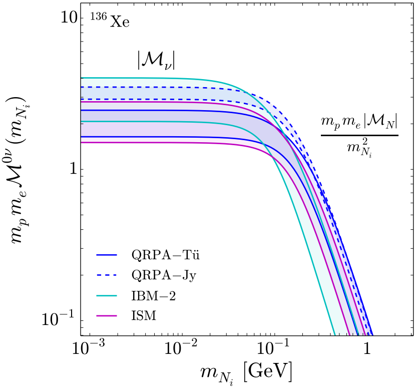
$$V_{eN_i} = i(U_{\rm PMNS})_{ek} H_{kj} \sqrt{\frac{m_j}{m_{N_i}}} \mathcal{R}^*_{ij}$$

$U_{\rm PMNS}$: light neutrino mixing matrix;
H: Hermitian matrix encoding deviations from unitarity in the light neutrino sector;
m_i: light neutrino mass;
m_{N_i}: heavy neutrino mass;
$\mathcal{R}$: arbitrary 2×2 orthogonal matrix

NMEs in type-I seesaw

Bolton, Deppisch & Dev '20 [JHEP]

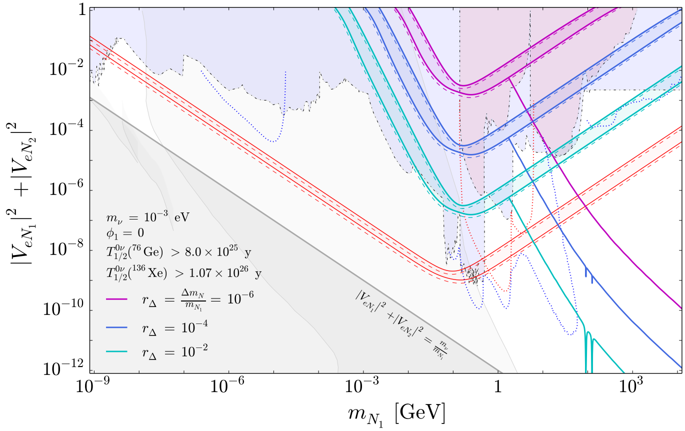




$$\sum_i \frac{m_i U_{ei}^2}{\langle \mathbf{p}^2 \rangle} + \sum_i \frac{m_{N_i} V_{eN_i}^2}{\langle \mathbf{p}^2 \rangle + m_{N_i}^2}$$

$0\nu\beta\beta$ limits in type-I seesaw

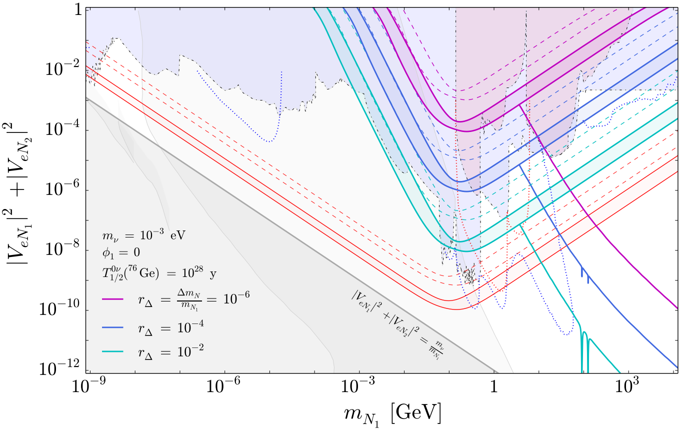
Bolton, Deppisch & Dev '20 [JHEP]



bands: uncertainties:
solid: ^{136}Xe; dashed: ^{76}Ge;
red: single heavy neutrino

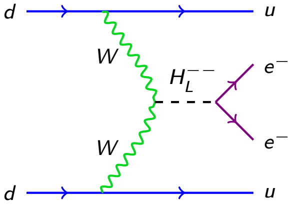
Future $0\nu\beta\beta$ prospects in type-I seesaw

Bolton, Deppisch & Bhupal Dev '20 [JHEP]



bands: uncertainties:
solid: ^{136}Xe; dashed: ^{76}Ge;
red: single heavy neutrino

$0\nu\beta\beta$ in type-II seesaw



The $H_L^{\pm\pm}$ contribution is highly suppressed by

$$\frac{(f_L)_{ee} v_L}{M^2_{H_L^{\pm\pm}}}$$

$0\nu\beta\beta$ in LRSM

Mohapatra & Vergados '81 [PRL]; Hirsch, Klapdor-Kleingrothaus & Panella '96 [PLB]; Dev, Goswami, Mitra & Rodejohann '13 [PRD]; Huang & Lopez-Pavon '14 [EPJC]; Dev, Goswami & Mitra '15 [PRD]; Deppisch, Gonzalo, Patra, Sahu & Sarkar '15 [PRD] Ge, Lindner & Patra1 '15 [JHEP]; Borah & Dasgupta '15 [JHEP]

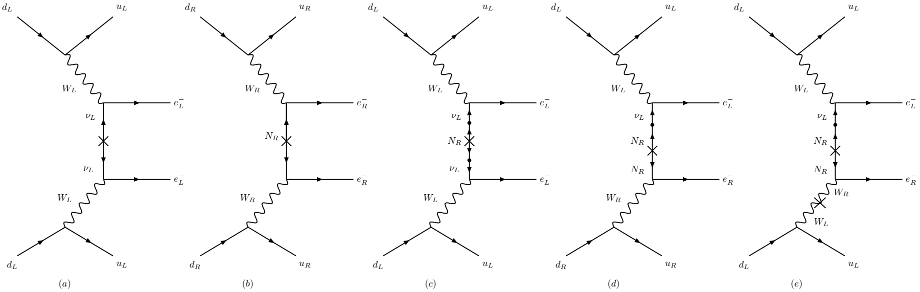


Figure: Contributions $\mathcal{A}_\nu$, $\mathcal{A}_{N_R}^R$, $\mathcal{A}_{N_R}^L$, $\mathcal{A}_\lambda$, $\mathcal{A}_\eta$ to $0\nu\nu\beta\beta$ in LRSM

Different contributions to $0\nu\beta\beta$

Different contributions to $0\nu\beta\beta$ in LRSM

Dev, Goswami & Mitra '15 [PRD]

$$\eta_\nu = \frac{1}{m_e}\sum_i U_{ei}^2 m_i \,, \qquad \eta_\lambda = \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sum_i U_{ei} T_{ei}^* \,,$$

$$\eta_{N_R}^R = m_p \left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \sum_i \frac{V_{ei}^{*2}}{M_i} \,, \qquad \eta_\eta = \tan\xi \sum_i U_{ei} T_{ei}^* \,,$$

$$\eta_{N_R}^L = m_p \sum_i \frac{S_{ei}^2}{M_i} \,,$$

Neutrino mixing mattix

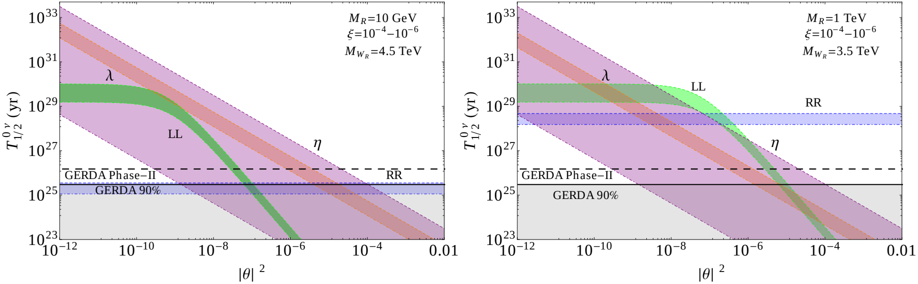
$$\mathcal{V} = \begin{pmatrix} U & S \\ T & V \end{pmatrix} , \quad S,\, T \sim iUH\sqrt{\frac{m_j}{M_i}}\mathcal{R}^*$$

$W - W_R$ mixing

$$\xi \simeq \frac{\kappa_1 \kappa_2}{v_R^2} \simeq \frac{2\kappa_2}{\kappa_1}\left(\frac{M_{W_L}}{M_{W_R}}\right)^2$$

Different contributions to $0\nu\beta\beta$

Dev, Goswami & Mitra '15 [PRD]



$0\nu\beta\beta$ limits on heavy-light neutrino mixing angle

Dev, Goswami & Mitra '15 [PRD]

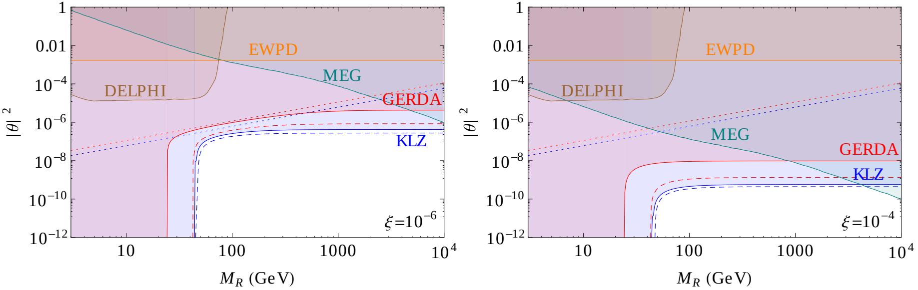
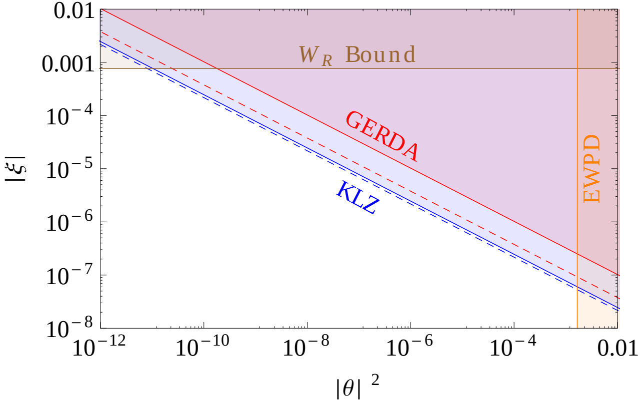


Figure: Setting $M_{W_R} = 3.5$ TeV [ATLAS, 1809.11105; 1904.12679]

- Dotted lines: Standard seesaw with only LL contribution;
- Solid/dashed: NME uncertainties;
- DELPHI: Z decay limits;
- EWPD: Electroweak precision data limits;
- MEG: $\mathrm{BR}(\mu \to e\gamma)$ limits.

$0\nu\beta\beta$ limits on $W - W_R$ mixing

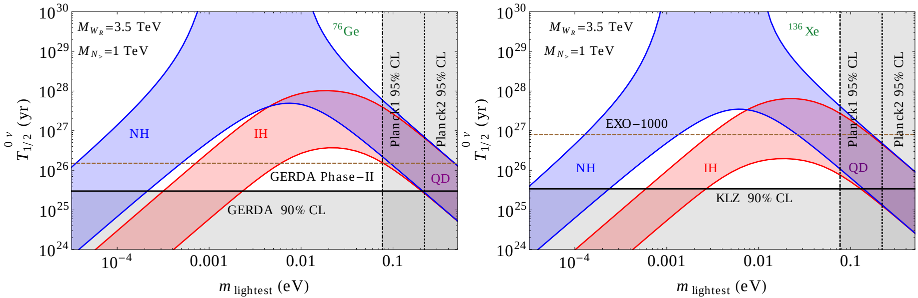
Dev, Goswami & Mitra '15 [PRD]



- Solid/dashed: NME uncertainties;
- W_R limits 3.8 - 5 TeV for 100 GeV $< m_N <$ 1.8 TeV [ATLAS, 1809.11105; 1904.12679];
- EWPD: Electroweak precision data limits.

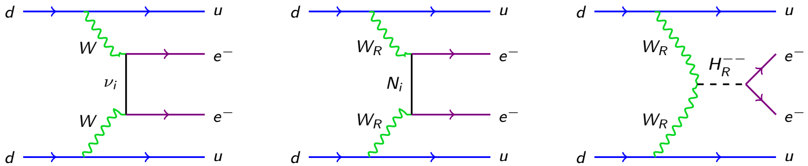
$0\nu\beta\beta$ limits on m_0

Dev, Goswami & Mitra '15 [PRD]



$0\nu\beta\beta$ in LRSM: $H_R^{\pm\pm}$ contribution

Mohapatra & Vergados '81 [PRL]; Hirsch, Klapdor-Kleingrothaus & Panella '96 [PLB]; Dev, Goswami, Mitra & Rodejohann '13 [PRD]; Huang & Lopez-Pavon '14 [EPJC]; Dev, Goswami & Mitra '15 [PRD]; Deppisch, Gonzalo, Patra, Sahu & Sarkar '15 [PRD] Ge, Lindner & Patra1 '15 [JHEP]; Borah & Dasgupta '15 [JHEP]



Neglecting the contributions due to

$W - W_R$ mixing and heavy-light neutrino mixing.

The $H_L^{\pm\pm}$ contribution is highly suppressed by $(f_L)_{ee} v_L / M^2_{H_L^{\pm\pm}}$

$0\nu\beta\beta$ in LRSM: $H_R^{\pm\pm}$ contribution

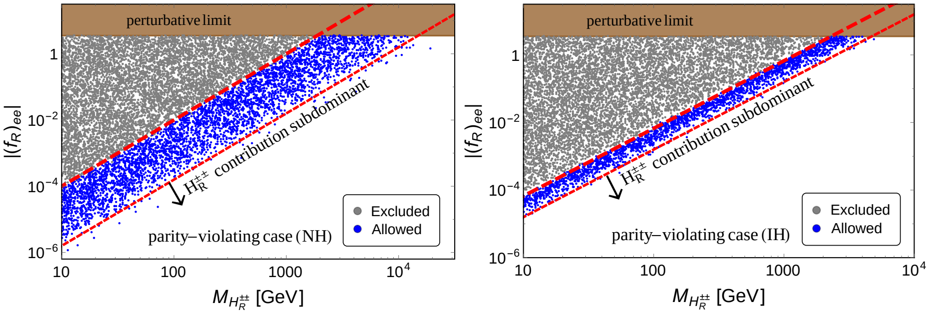
Barry & Rodejohann '13 [JHEP]; Dev, Ramsey-Musolf & YCZ '18 [PRD]

RR and $H_R^{\pm\pm}$ contributions:

$$\begin{aligned}
\eta_N &= m_p \left(\frac{g_R}{g_L}\right)^4 \left(\frac{m_W}{M_{W_R}}\right)^4 \sum_i \frac{V_{ei}^2}{M_{N_i}} \\
&= \frac{m_p}{4} \left(\frac{v_{\rm EW}}{v_R}\right)^4 \sum_i \frac{V_{ei}^2}{M_{N_i}}, \\
\eta_{\delta_R} &= m_p \left(\frac{g_R}{g_L}\right)^4 \left(\frac{m_W}{M_{W_R}}\right)^4 \frac{\sqrt{2}(f_R)_{ee} v_R}{M_{H_R^{\pm\pm}}^2} \\
&= \frac{m_p}{2\sqrt{2}} \left(\frac{v_{\rm EW}}{v_R}\right)^4 \frac{(f_R)_{ee} v_R}{M_{H_R^{\pm\pm}}^2}, \\
\frac{\eta_N}{\eta_{\delta_R}} &\sim \frac{M_{N_i}^2}{M_{H_R^{\pm\pm}}^2}
\end{aligned}$$

$H_R^{\pm\pm}$ contribution to $0\nu\beta\beta$

Dev, Ramsey-Musolf & YCZ '18 [PRD]



$v_R = 5\sqrt{2}$ TeV;

$f_L \neq f_R$ in parity-violating LRSM:

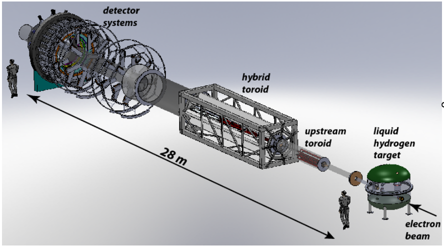
the couplings of heavy neutrinos are free parameters.

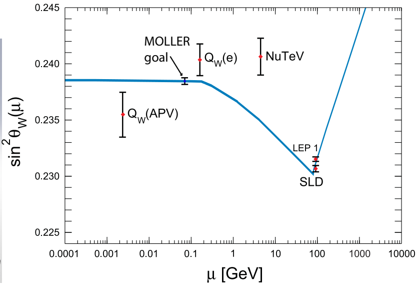
$H^{\pm\pm}$ @ MOLLER experiment

MOLLER experiment

(Measurement Of a Lepton Lepton Electroweak Reaction)

MOLLER Collaboration, 1411.4088; `https://moller.jlab.org/moller_root/`





Primary Goal:

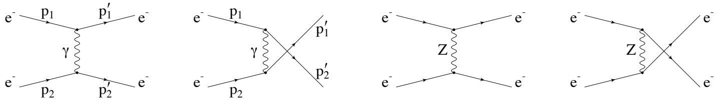
Precision measurement of $A_{\rm PV}$ to the level of 0.7 ppb ($A_{\rm PV}^{\rm SM} \simeq 33$ ppb);

An overall fractional accuracy of 2.4% for Q_W^e.

Parity-violating asymmetry

MOLLER Collaboration, 1411.4088; https://moller.jlab.org/moller_root/

Scattering of longitudinally polarized electrons off unpolarized electrons, using the upgraded 11 GeV beam in Hall A at JLab



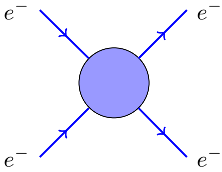
$$A_{\rm PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{G_F m_e E}{\sqrt{2}\pi\alpha} \frac{2y(1-y)}{1+y^4+(1-y)^4} Q_W^e \,,$$

$E(E')$: incident beam (scattered electron) energy; $\quad y = 1 - E'/E$;

$Q_W^e = 1 - 4\sin^2\theta_W$ (tree level)

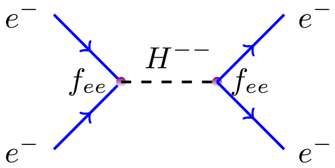
Sensitivity to four-electron contact interaction

MOLLER Collaboration, 1411.4088



$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2} G_F |\Delta Q_W^e|}} \simeq 7.5 \text{ TeV},$$

Sensitivity to doubly-charged scalar



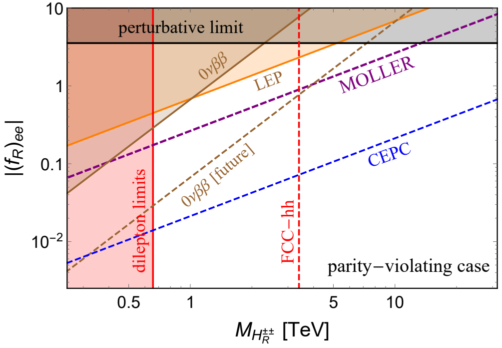
$$\mathcal{M}_{\rm PV} \sim \frac{|(f_L)_{ee}|^2}{2M^2_{H_L^{\pm\pm}}}(\bar{e}_L\gamma^\mu e_L)(\bar{e}_L\gamma_\mu e_L) + (L \leftrightarrow R)\,.$$

Keeping only the left-handed part: $|g_{LL}|^2 = |(f_L)_{ee}|^2/2$ & $g_{RR} = 0$:

$$\frac{M_{H_L^{\pm\pm}}}{|(f_L)_{ee}|} \gtrsim 3.7\ {\rm TeV} \quad \text{(at the 95\% C.L.)}$$

MOLLER prospect

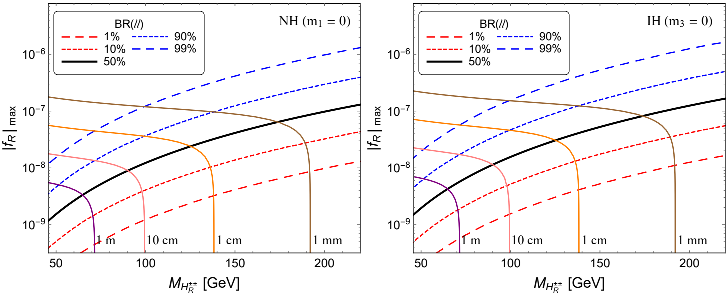
Dev, Ramsey-Musolf & YCZ '18 [PRD]



dilepton limits: direct LHC searches;
LEP: $e^+e^- \to e^+e^-$ limits;
CEPC: luminosity = 1 ab^{-1};
FCC-hh: luminosity = 30 ab^{-1}

Long-lived $H_R^{\pm\pm}$ in LRSM

Proper lifetime of $H_R^{\pm\pm}$



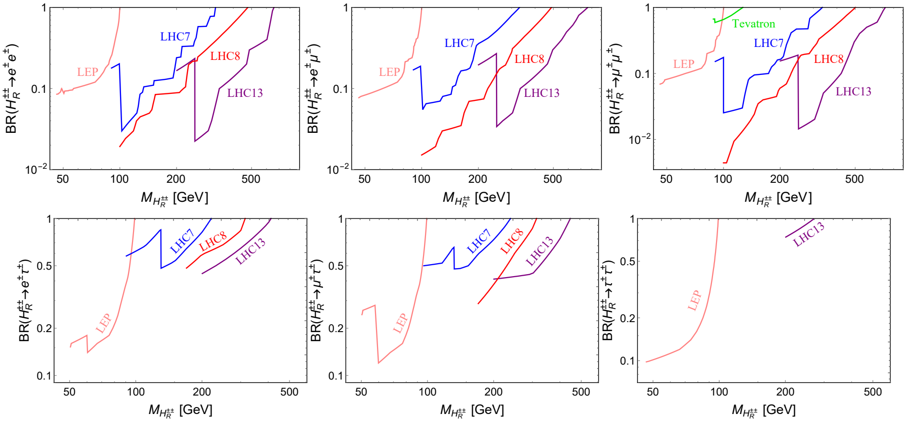
$$\Gamma_{\rm total}(H_R^{\pm\pm}) \;=\; \Gamma(H_R^{\pm\pm} \to \ell_\alpha^\pm \ell_\beta^\pm) + \Gamma(H_R^{\pm\pm} \to W_R^{\pm *} W_R^{\pm *})\,.$$

Assuming lightest neutrino mass $m_0 = 0$.

Assuming $f_L = f_R$, $g_L = g_R$ and $v_R = 5\sqrt{2}$ TeV.

$H_R^{\pm\pm} \to W_R^{\pm *} W_R^{\pm *}$ highly suppressed by W_R mass.

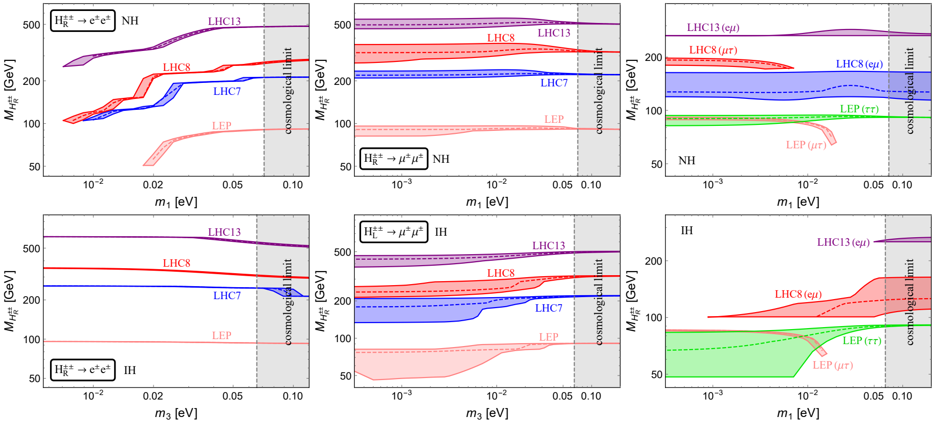
Same-sign dilepton constraints on $H_R^{\pm\pm}$



OPAL, hep-ex/0111059; DELPHI, hep-ex/0303026; L3, hep-ex/0309076;
CDF, hep-ex/0406073; 0808.2161; D0, 0803.1534; 1106.4250;
ATLAS, ATLAS-CONF-2011-127; 1412.0237; 1710.09748;
CMS, CMS-PAS-HIG-11-007; CMS-PAS-HIG-14-039; CMS-PAS-HIG-16-036

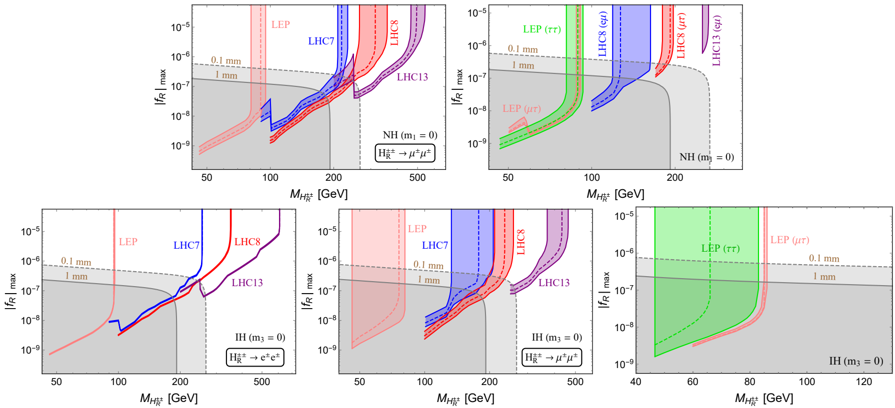
To some extent weaker than the $H_L^{\pm\pm}$ limits

Lower limit on $H_R^{\pm\pm}$ mass in the limit of large v_R



Predominant decay mode $H_R^{\pm\pm} \to \ell_\alpha^\pm \ell_\beta^\pm$

Lower limit on $H_R^{\pm\pm}$ mass ($m_0 = 0$)

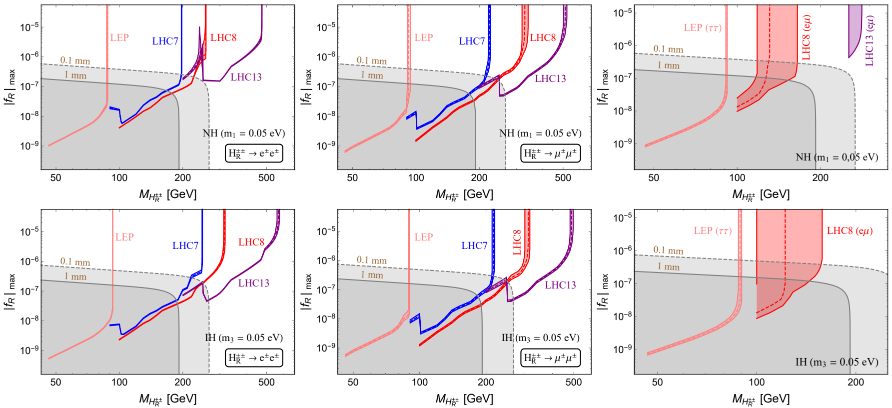


$$H_R^{\pm\pm} \to \ell_\alpha^\pm \ell_\beta^\pm, \; W_R^{\pm *} W_R^{\pm *}$$

Dashed lines: central values of neutrino oscillation data;

Colorful bands: 3σ uncertainties

Lower limit on $H_R^{\pm\pm}$ mass ($m_0 = 0.05$ eV)

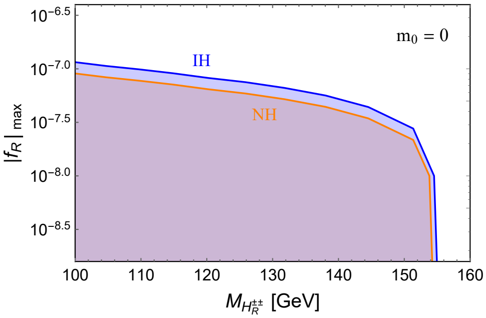


$$H_R^{\pm\pm} \to \ell_\alpha^\pm \ell_\beta^\pm, \; W_R^{\pm *} W_R^{\pm *}$$

Dashed lines: central values of neutrino oscillation data;

Colorful bands: 3σ uncertainties

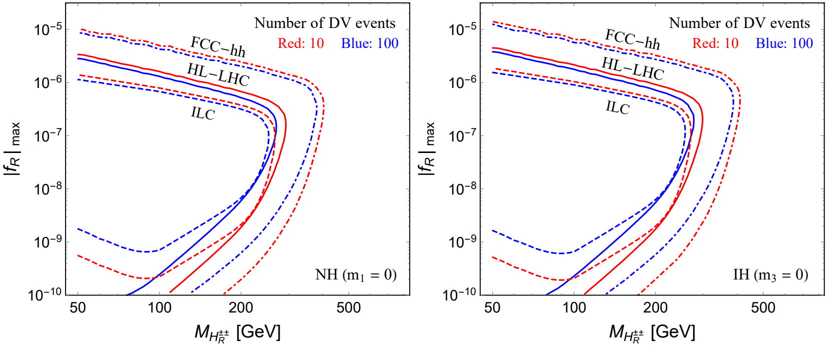
Heavy stable charged particle (HSCP) constraints on $H_R^{\pm\pm}$



- Long-lived $H_R^{\pm\pm}$ decays outside either the inner silicon tracker or the whole detector.
- We use conservatively only the "tracker-only" analysis.
- The decay length $43\,\mathrm{mm} < bc\tau_0(H_R^{\pm\pm}) < 1100\,\mathrm{mm}$.

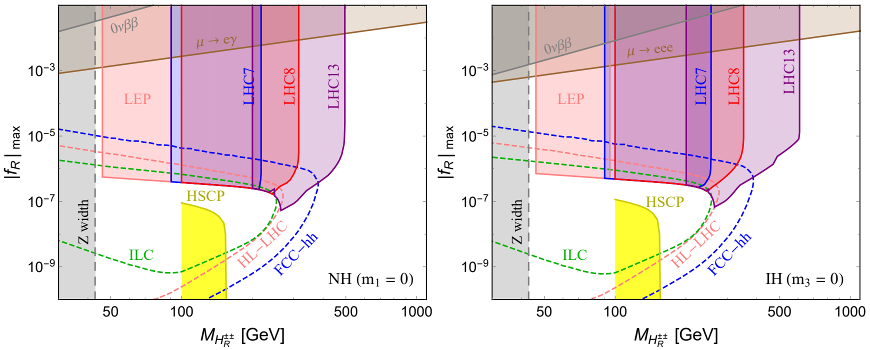
Very different from the $H_L^{\pm\pm}$ case

Displaced vertex (DV) prospects of $H_R^{\pm\pm}$



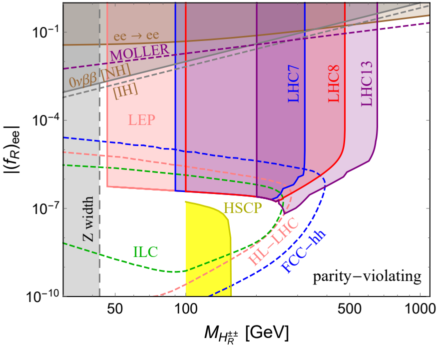
- Counting only the decays $H_L^{\pm\pm} \to e^\pm e^\pm,\ e^\pm \mu^\pm,\ \mu^\pm \mu^\pm$;
- Setting $g_R = g_L$ and the right-handed scale $v_R = 5\sqrt{2}$ TeV.

$0\nu\beta\beta$ limits vs. other limits/prospects



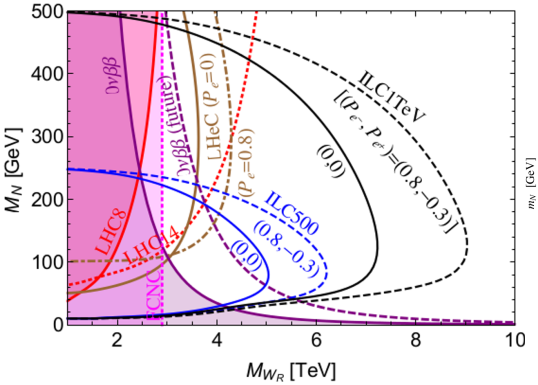
- Assuming at least 100 events for the DV sensitivities.
- The low-energy high-precision LFV measurements (such as $\mu \to eee$, $\mu \to e\gamma$ and $0\nu\beta\beta$), the prompt same-sign dilepton searches of $H_R^{\pm\pm}$ and the DV searches of $H_R^{\pm\pm}$ are largely complementary to each other in the LRSM.

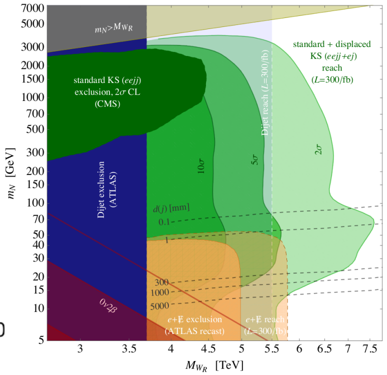
...for parity-violating LRSM



- Considering the simple scenario $H_R^{\pm\pm} \to e^{\pm}e^{\pm}$, $W_R^{\pm *}W_R^{\pm *}$.
- We do not have the LFV constraints e.g. $\mu \to e\gamma$, and MOLLER pops out...
- The low-energy high-precision LFV measurements (MOLLER and $0\nu\beta\beta$), the prompt same-sign dilepton searches of $H_R^{\pm\pm}$ and the DV searches of $H_R^{\pm\pm}$ are largely complementary to each other in the LRSM.

Biswal & Dev '17 [PRD]; Nemevek, Nesti & Popara '18 [PRD]





Conclusion

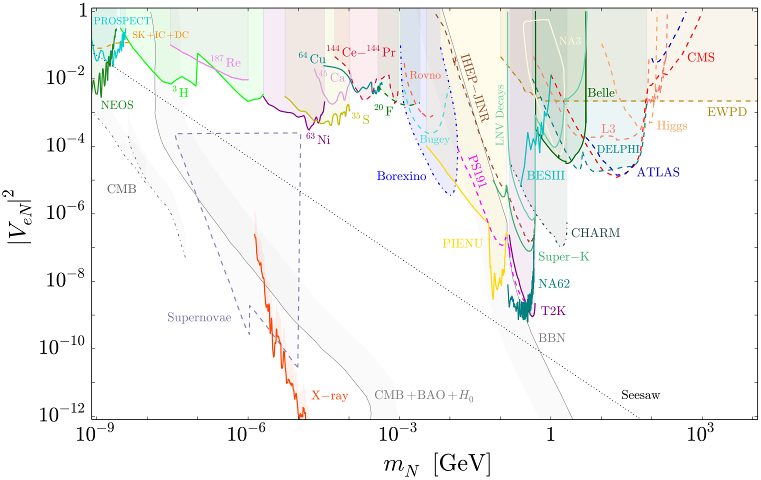
- In type-I seesaw and (minimal) LRSM, the contributions of N_i and $H_R^{\pm\pm}$ to $0\nu\beta\beta$ decays could be significant, depending on model details.
- The contributions of $H_L^{\pm\pm}$ to $0\nu\beta\beta$ is highly suppressed by v_L in type-II seesaw and LRSM.
- The $0\nu\beta\beta$ prospects of N, W_R and $H_R^{\pm\pm}$ can be cross checked in other experiments, such as MOLLER and direct searches at high-energy colliders.

Thank you for your attention!

backup slides

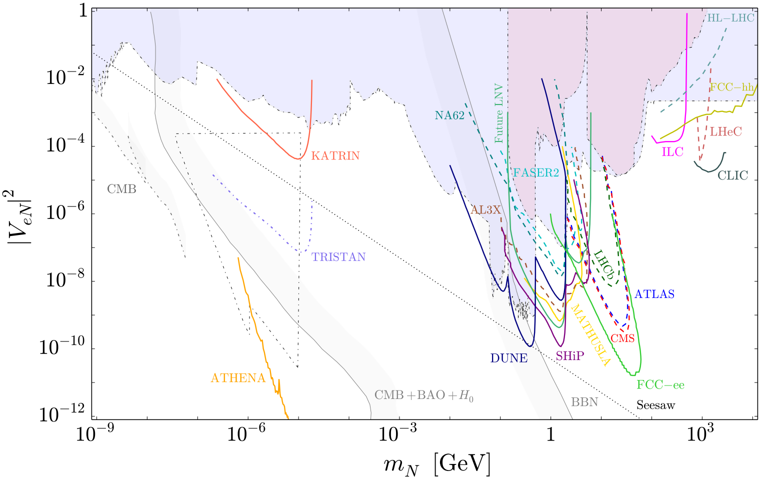
Heavy-light neutrino mixing limits

Bolton, Deppisch & Dev '20 [JHEP]



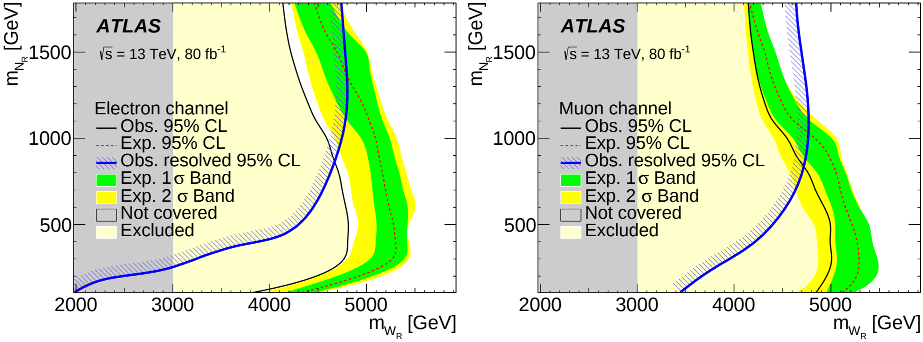
Heavy-light neutrino mixing prospects

Bolton, Deppisch & Dev '20 [JHEP]



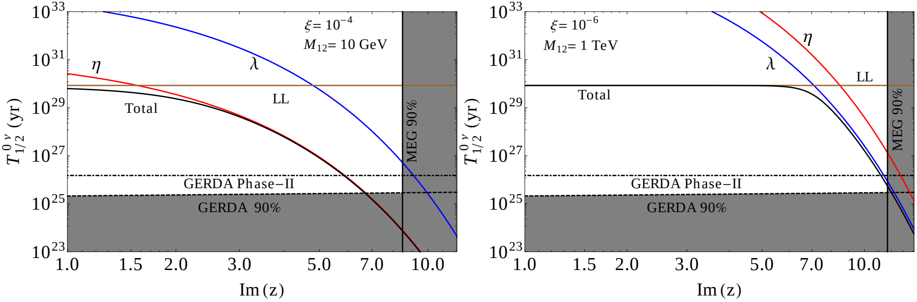
LHC limits on N_R and W_R

ATLAS, 1904.12679



Different contributions to $0\nu\beta\beta$

Dev, Goswami & Mitra '15 [PRD]

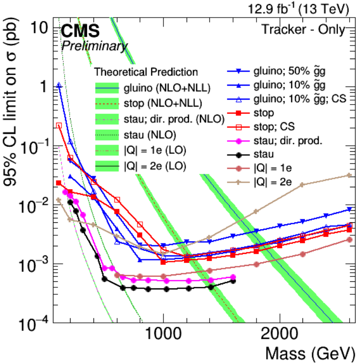


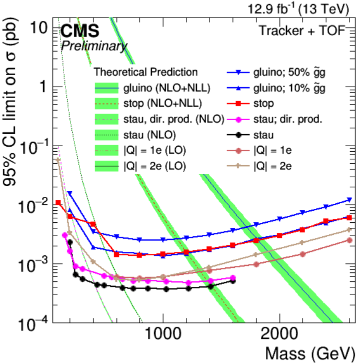
Arbitrary orthogonal matrix:

$$R = \begin{pmatrix} 0 & \cos z & -\sin z \\ 0 & \sin z & \cos z \\ 1 & 0 & 0 \end{pmatrix}$$

Heavy Stable Charged particle (HSCP) searches

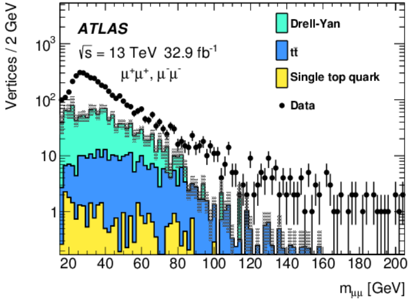
CMS-PAS-EXO-16-036

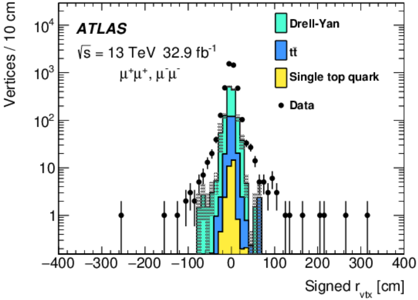




Displaced same-sign dilepton searches: SM backgrounds

ATLAS, 1808.03057





- Dominant background: low-mass Drell-Yan processes $pp \to e^+e^-$, $\mu^+\mu^-$, with the charges of the electron or muon misidentified (and the electron misidentified as a muon or vice versa), depending largely on $m_{\ell\ell'}$ and $r_{\rm vtx}$.
- The dileptons from Drell-Yan processes tend to be back-to-back , which could be easily distinguished from the four-body process $pp \to H_L^{++}H_L^{--} \to \ell_\alpha^\pm \ell_\beta^\pm \ell_\gamma^\mp \ell_\delta^\mp$.