Revisiting type-II seesaw: the high-energy and high-precision frontier tests

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NuTheories: Beyond the 3×3 Paradigm at Current and Near-Future Facilities
PITT PACC, University of Pittsburgh

based on

P. S. B. Dev, M. J. Ramsey-Musolf & YCZ, PRD**98**(2018)055013 [1806.08499]
P. S. B. Dev & YCZ, JHEP**10**(2018)199 [1808.00943]

Outline

- Type-II seesaw
- MOLLER sensitivity to $H_{L,R}^{\pm\pm}$
  - sensitivity of MOLLER
  - prospect of $H_L^{\pm\pm}$ in type-II seesaw
  - prospect of $H_R^{\pm\pm}$ in LRSM
- Displaced vertex searches of $H_{L,R}^{\pm\pm}$
  - current prompt same-sign dilepton constraints and the Heavy Stable Charged Particle searches
  - DV prospects of $H_L^{\pm\pm}$ at HL-LHC, FCC-hh and ILC
  - DV prospects of $H_R^{\pm\pm}$ at HL-LHC, FCC-hh and ILC
- Conclusion

type-II seesaw

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...

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

with the left-handed triplet

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

- 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.

Important couplings of $H_L^{\pm\pm} = \delta_L^{\pm\pm}$

Perez, Han, Huang, Li & Wang '08; Melfo, Nemevšek, Nesti, Senjanović & Zhang '11

- Gauge couplings to γ/Z bosons:
  production at hadron/lepton colliders

- Gauge interaction $H_L^{\pm\pm} W^\mp W^\mp$ ($\propto v_L$):
  inducing decay $H_L^{\pm\pm} \to W^{\pm(*)} W^{\pm(*)}$
- Gauge interaction $H_L^{\pm\pm} H^\mp W^\mp$:
  production at hadron/lepton colliders
  inducing decay $H_L^{\pm\pm} \to H^{\pm(*)} W^{\pm(*)}$
- Scalar interaction $H_L^{\pm\pm} H^\mp H^\mp$:
  inducing decay $H_L^{\pm\pm} \to H^{\pm(*)} H^{\pm(*)}$

- Yukawa couplings $(f_L)_{\alpha\beta} H_L^{\pm\pm} \ell_\alpha^\mp \ell_\beta^\mp$:
  - $\alpha\beta = ee$: $e^- e^-$ scattering (MOLLER experiment, high-precision test)
  - $\alpha \neq \beta$: low-energy LFV processes (e.g. $\mu \to e\gamma$)
  - inducing decay $H_L^{\pm\pm} \to \ell_\alpha^\pm \ell_\beta^\pm$ (potentially LFV)
  - production at hadron/lepton colliders [Dev, Mohapatra & YCZ, 1803.11167]

Long-lived $H_L^{\pm\pm}$

- Decay through the Yukawa couplings (suppressed by m_ν^2/v_L^2)

$$\Gamma(H_L^{\pm\pm} \to \ell_\alpha^\pm \ell_\beta^\pm) \;=\; \frac{M_{H_L^{\pm\pm}}}{8\pi(1+\delta_{\alpha\beta})} \frac{|(m_\nu)_{\alpha\beta}|^2}{v_L^2}\,,$$

- Decay through the gauge interactions
  (suppressed by v_L^2 and potentially the phase-space)

$$\Gamma(H_L^{\pm\pm} \to W^\pm W^\pm) \;=\; \frac{G_F^2 v_L^2 M_{H_L^{\pm\pm}}^3}{2\pi}\sqrt{1-4x_W}(1-4x_W+12x_W^2)\,,$$

$$(\text{with } x_W \equiv m_W^2/M_{H_L^{\pm\pm}}^2)$$

Four-body decay for off-shell W-boson pairs

$$H_L^{\pm\pm} \to W^{\pm *} W^{\pm *} \to f\bar{f}' f'' \bar{f}'''\,,$$

Neglecting the following decay modes

- $H_L \to H^{\pm(*)} W^{\pm(*)}$:
  - The mass splitting $\Delta M = M_{H_L^{\pm\pm}} - M_{H^\pm} > 60$ GeV is disfavored by current electroweak precision data; [Aoki, Kanemura, Kikuchi & Yagyu '12]
  - For $M_{H_L^{\pm\pm}} - M_{H^\pm} \lesssim 1$ GeV, this channel is negligible.
- $H_L \to H^{\pm(*)} H^{\pm(*)}$:
  - Depending on the triplet scalar coupling;
  - Due to electroweak precision constraints, both $H^\pm$ are expected to be off-shell.

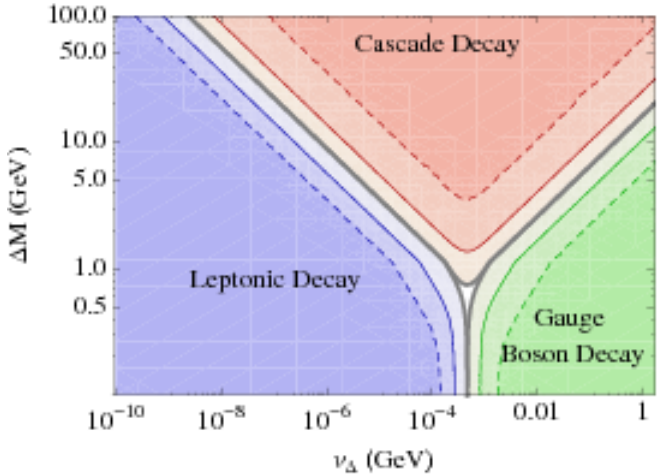
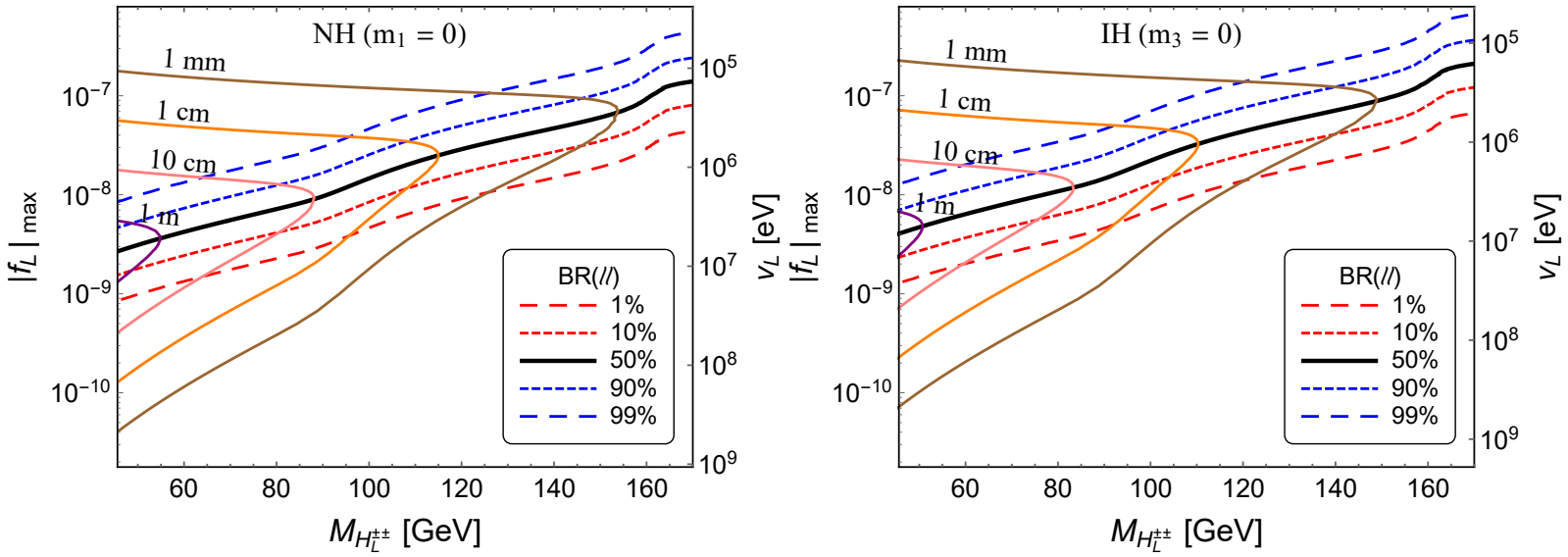


Figure: From Melfo, Nemevšek, Nesti, Senjanović & Zhang '11

$\Rightarrow$ Displaced searches of $H_L^{\pm\pm}$ at LHC and future lepton/hadron colliders (high-energy frontier)

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



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

Assuming lightest neutrino mass $m_0 = 0$.

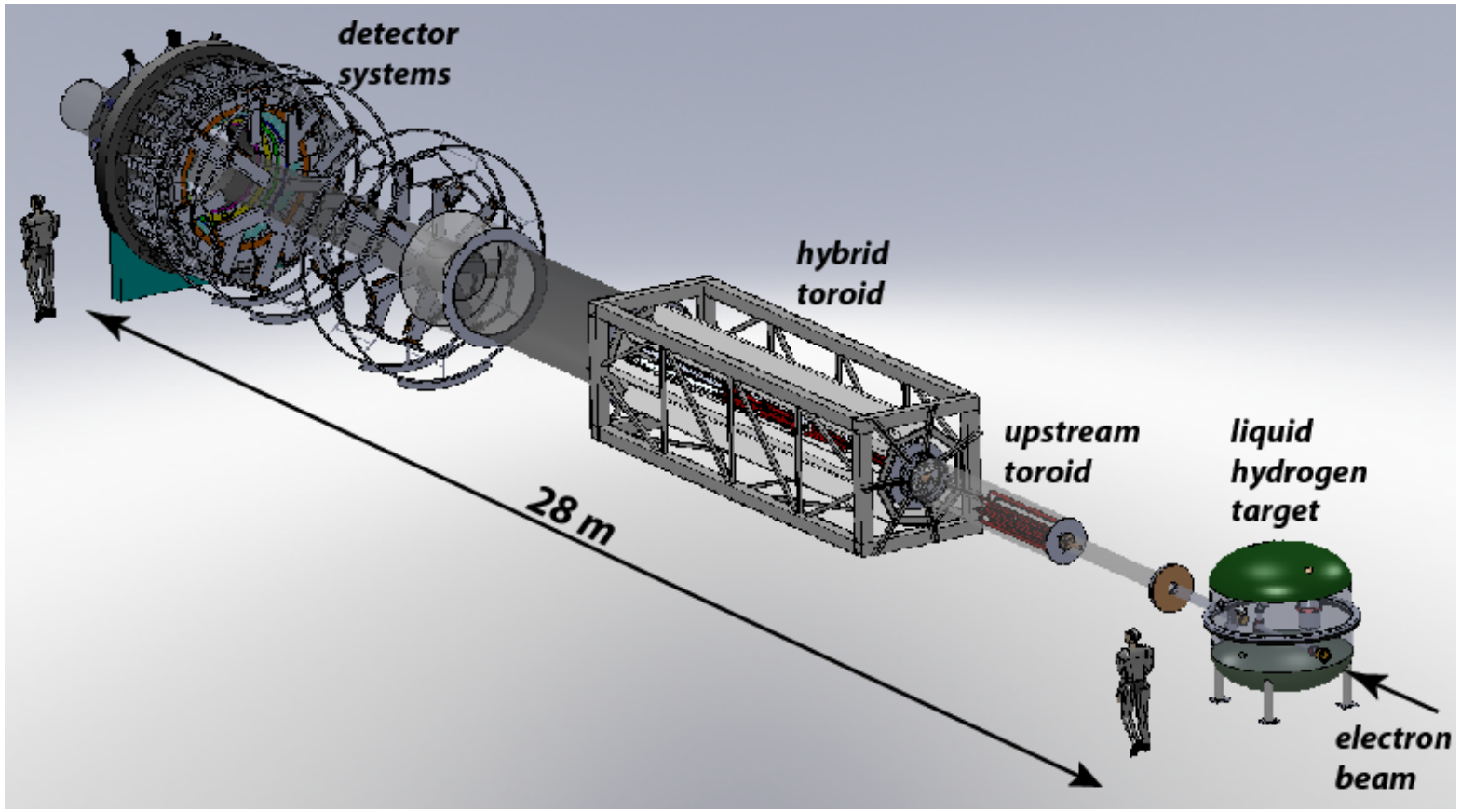
$$v_L |f_L|_{\rm max} \;\simeq\; \begin{cases} 0.027\,{\rm eV}\,, & \text{for NH with } m_1 = 0\,, \\ 0.048\,{\rm eV}\,, & \text{for IH with } m_3 = 0\,. \end{cases}$$

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

MOLLER experiment

(**M**easurement **O**f a **L**epton **L**epton **E**lectroweak **R**eaction)

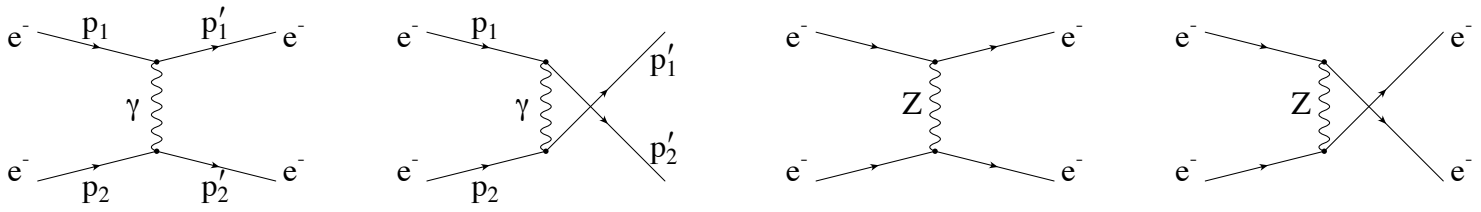
MOLLER Collaboration, 1411.4088; `https://moller.jlab.org/moller_root/`



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



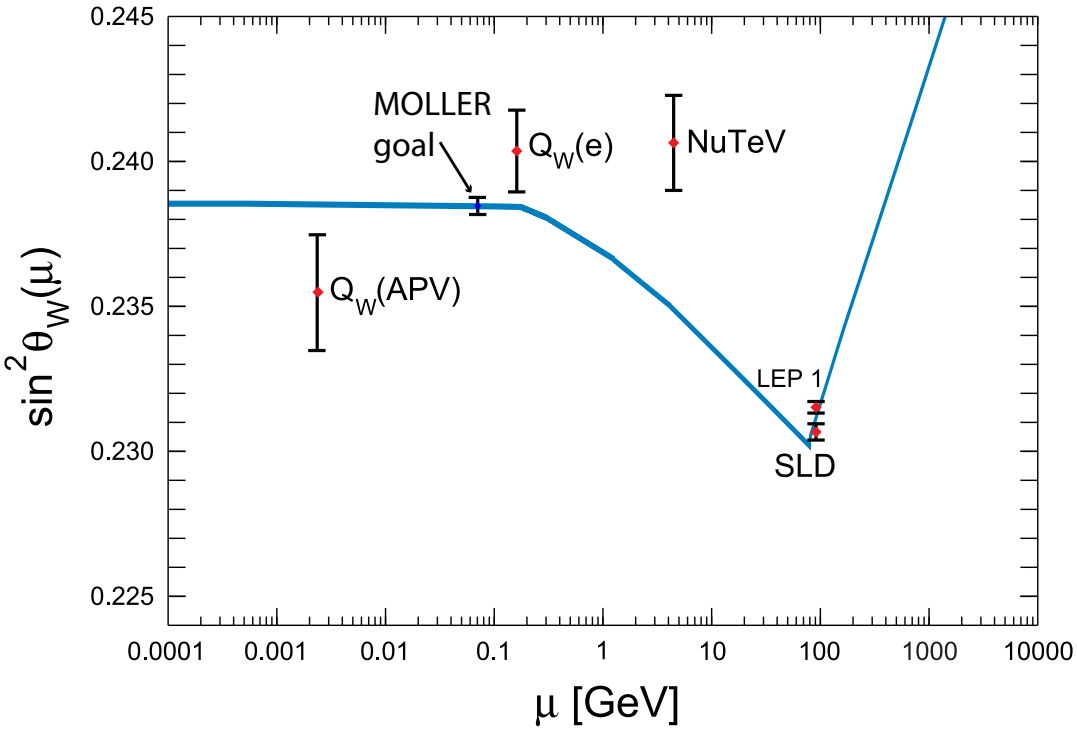
$$A_{\rm PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{2y(1-y)}{1+y^4+(1-y)^4} Q_W^e \,,$$

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

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

Precision measurement of the weak mixing angle

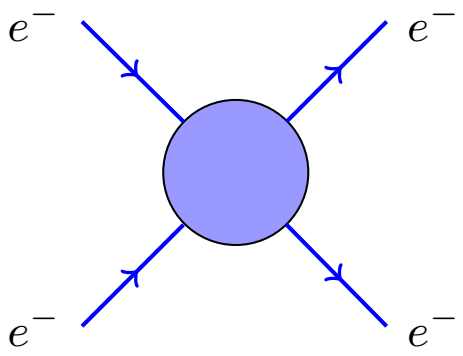
MOLLER Collaboration, 1411.4088; https://moller.jlab.org/moller_root/



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.

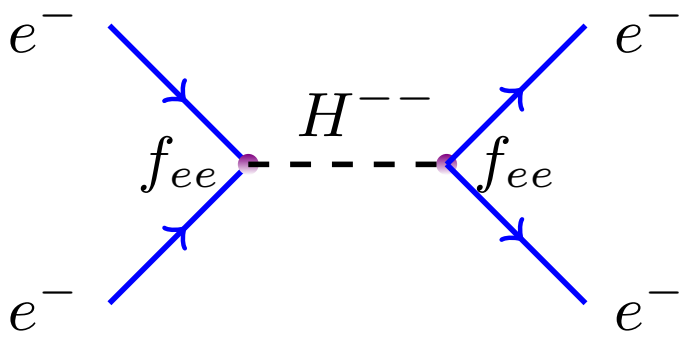
Sensitivity to four-electron contact interaction

MOLLER Collaboration, 1411.4088



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

Sensitivity to doubly-charged scalar



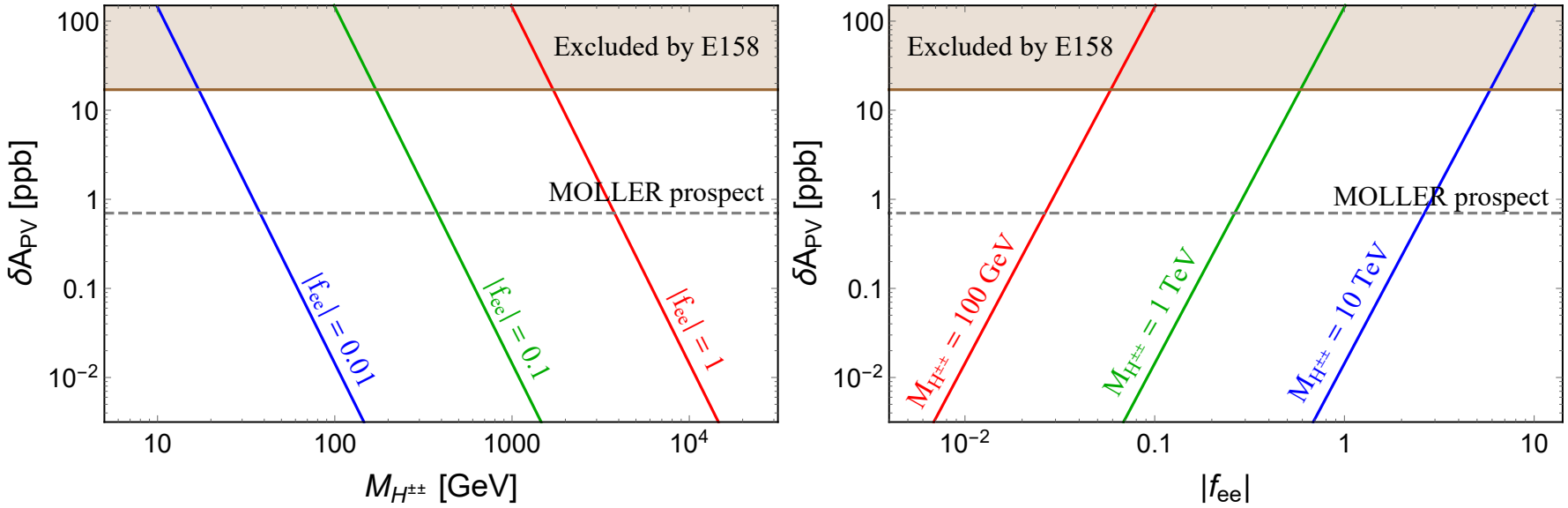
$$\mathcal{M}_{\rm PV} \sim \frac{|(f_L)_{ee}|^2}{2M^2_{H_L^{\pm\pm}}}(\bar{e}_L\gamma^\mu e_L)(\bar{e}_L\gamma_\mu e_L) + (L \leftrightarrow R)\,.$$

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

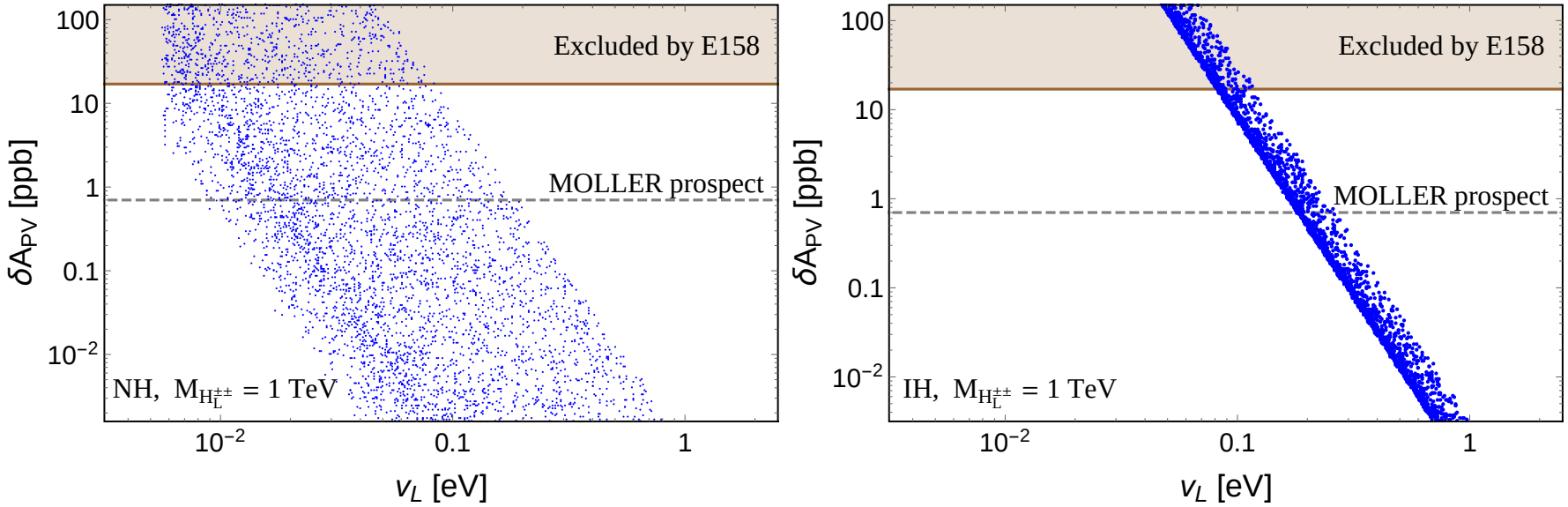
$$\frac{M_{H_L^{\pm\pm}}}{|(f_L)_{ee}|} \gtrsim 3.7\ \mathrm{TeV} \quad \text{(at the 95\% C.L.)}$$

Sensitivity to doubly-charged scalar

SLAC E158 Collaboration, hep-ex/0504049



Sensitivity to v_L

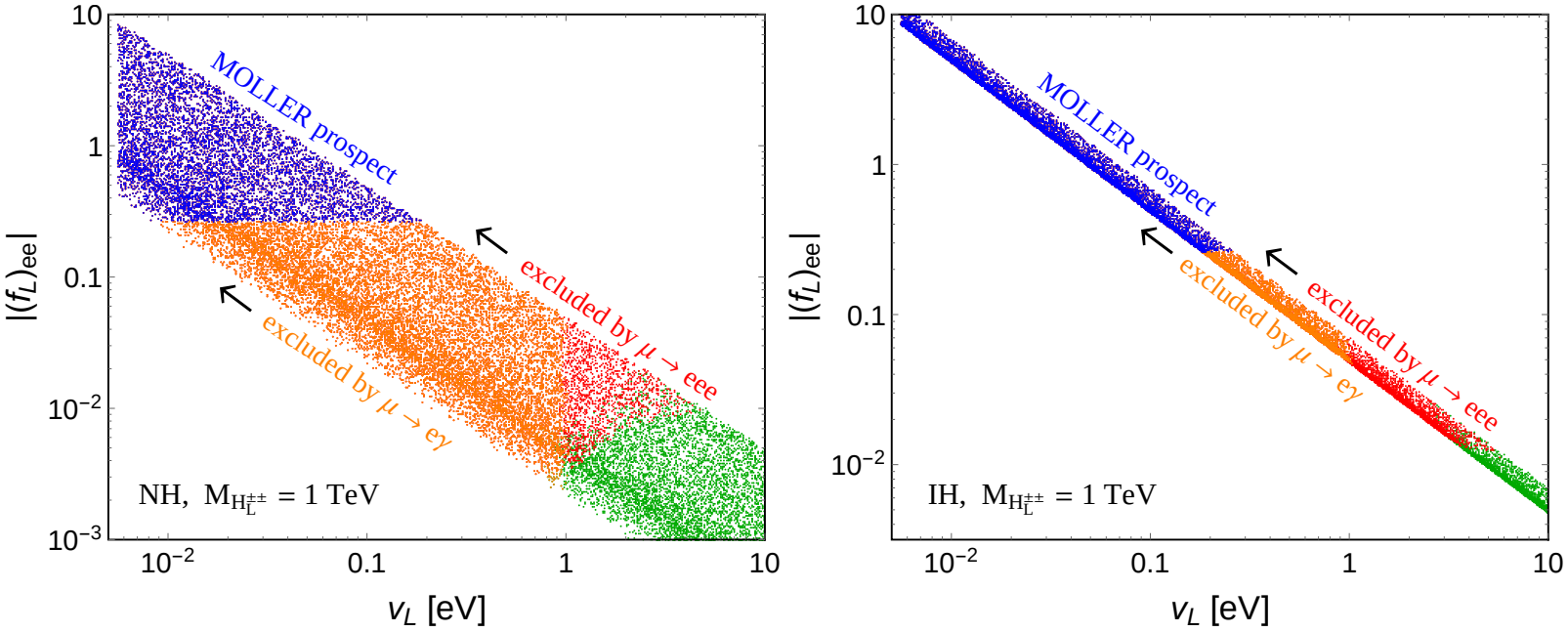


- Neutrino oscillation data within their 2σ ranges;
- Lightest neutrino mass $m_0 \in [0, 0.05]\,\mathrm{eV}$;
- Dirac and Majorana phases $\in [0,\ 2\pi]$.

$$\text{sensitive to } v_L \lesssim 0.3\,\mathrm{eV} \times \left(\frac{M_{H_L^{\pm\pm}}}{1\,\mathrm{TeV}}\right)^{-1}$$

LFV constraints

process	current data	constraints
$\mu^- \to e^- e^+ e^-$	$< 1.0 \times 10^{-12}$	$M_{H_L^{\pm\pm}} / \sqrt{\lvert (f_L)^\dagger_{ee} (f_L)_{e\mu} \rvert} > 208\ \mathrm{TeV}$
$\mu^- \to e^- \gamma$	$< 4.2 \times 10^{-13}$	$M_{H_L^{\pm\pm}} / \sqrt{\lvert \sum_\ell (f_L)^\dagger_{\mu\ell} (f_L)_{e\ell} \rvert} > 61\ \mathrm{TeV}$



If an anomalous δA_{PV} could be observed by MOLLER, the simplest type-II seesaw has to be extended to accommodate the deviation, like the left-right models.

type-II seesaw extended to be
left-right symmetric

Left-right symmetric model (LRSM)

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

- A right-handed triplet is introduced to break the $SU(2)_R$ gauge symmetry

$$\Delta_R \;=\; \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix}$$

- The right-handed Yukawa interaction

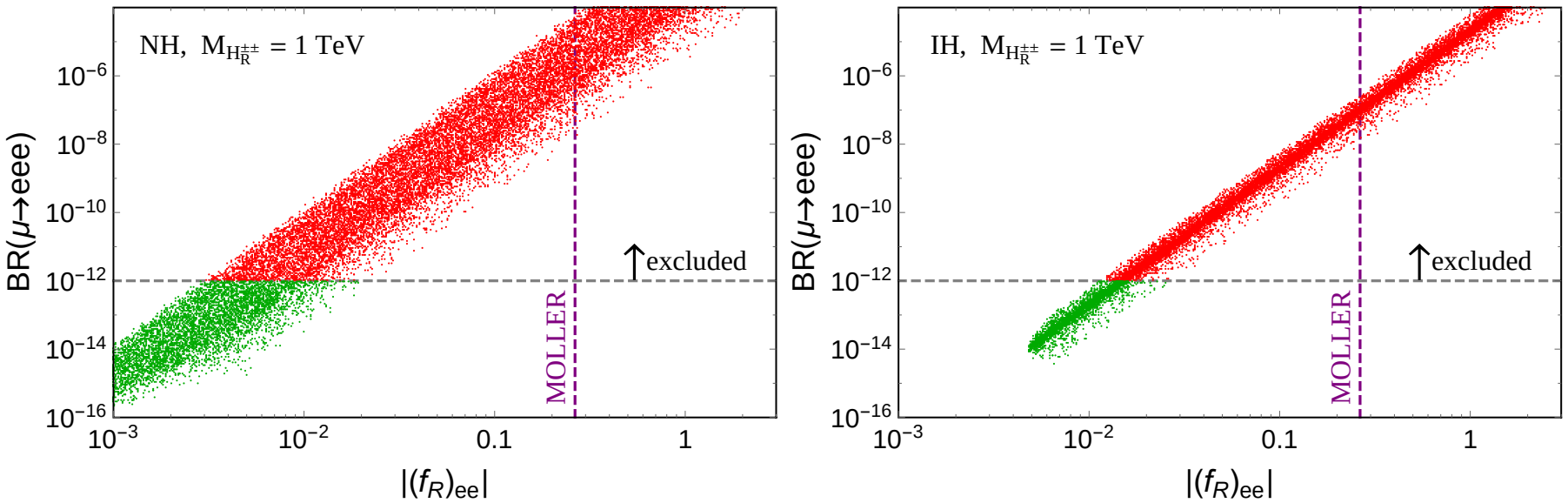
$$\mathcal{L}_Y \;=\; -(f_R)_{\alpha\beta}\,\psi_{R\alpha}^{\mathsf{T}} C i\sigma_2 \Delta_R \psi_{R\beta} \;+\; \mathrm{H.c.},$$

- Neutrino masses

$$m_\nu \;\simeq\; -m_D M_N^{-1} m_D^{\mathsf{T}} + \sqrt{2} f_L v_L\,,$$

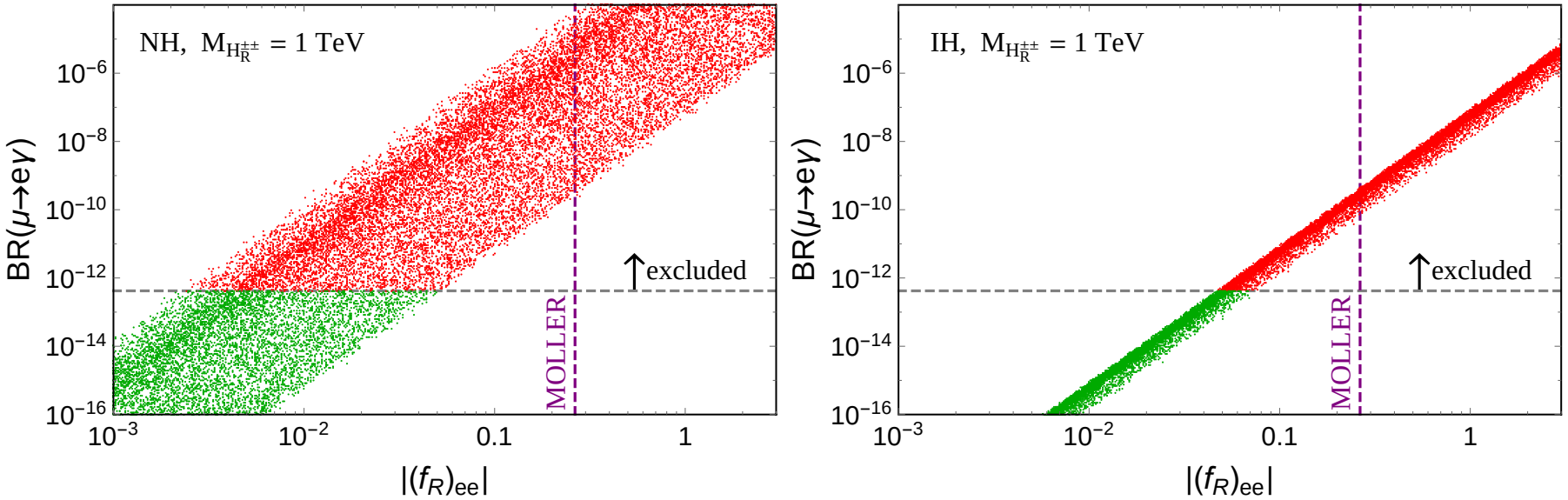
Assuming type-II dominance, and parity-symmetry dictates $f_L = f_R$

LFV constraints



The LFV constraints apply equally to f_R.

LFV constraints



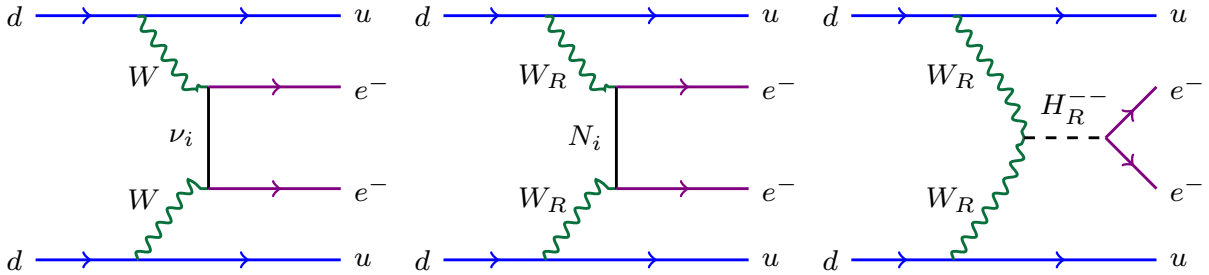
The LFV constraints apply equally to f_R.

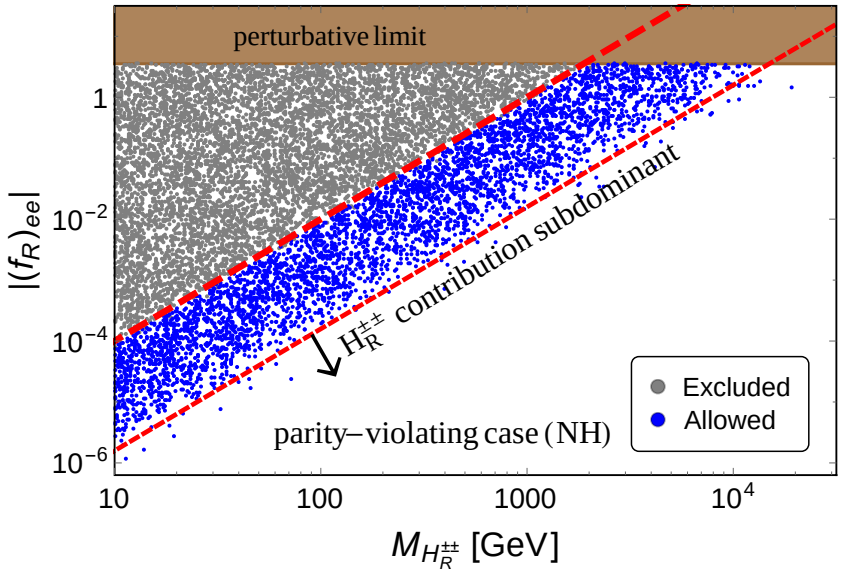
LRSM with parity violation

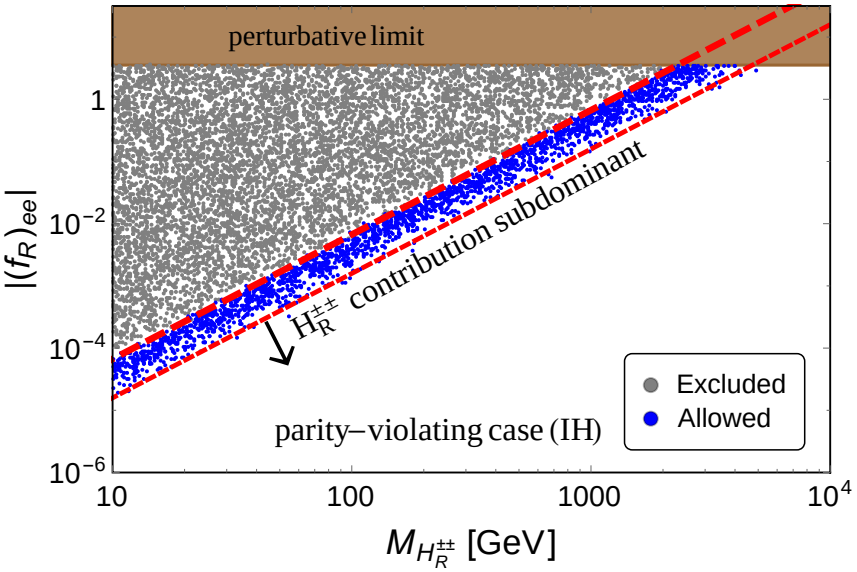
Chang, Mohapatra & Parida '84

- Parity-restoration scale $\neq SU(20_R$ scale;
- Δ_L could decouple from the TeV-scale physics
  avoiding fine-tuning in the scalar potential and/or unacceptably large neutrino masses;
- The couplings $f_L \neq f_R$ and f_R is not *directly* relevant to neutrino oscillation data;
- $(f_R)_{ee}$ could be viewed as a *free* parameter.

Neutrinoless double-beta decay ($0\nu\beta\beta$)

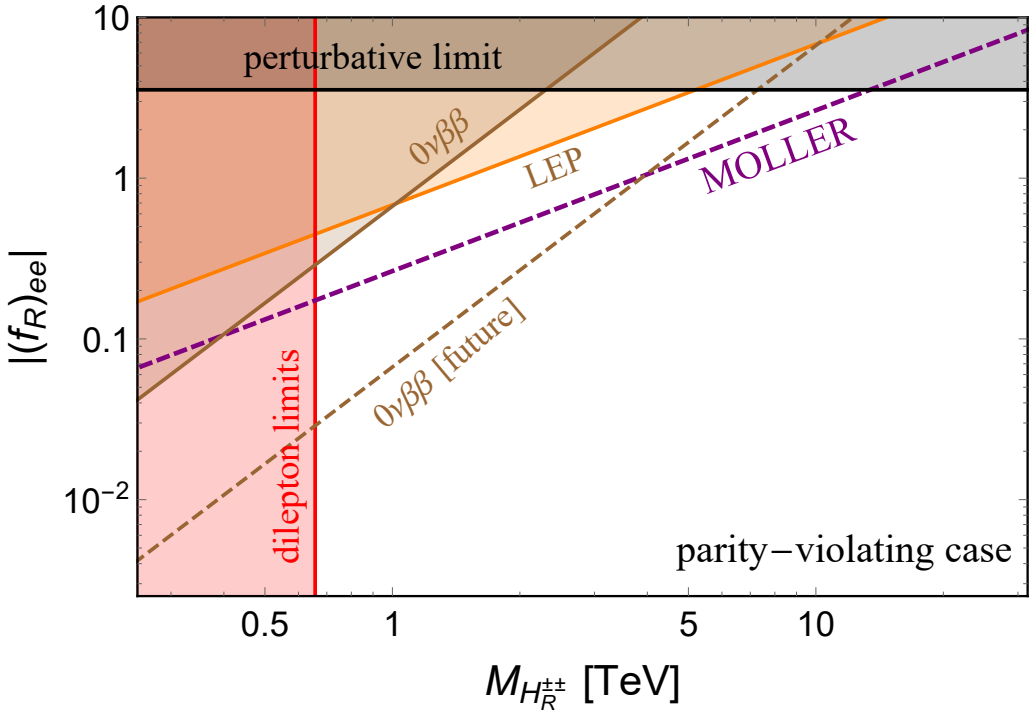






$$\eta_{\delta_R} = m_p \left(\frac{g_R}{g_L}\right)^4 \left(\frac{m_W}{M_{W_R}}\right)^4 \frac{\sqrt{2}(f_R)_{ee} v_R}{M^2_{H_R^{\pm\pm}}}$$

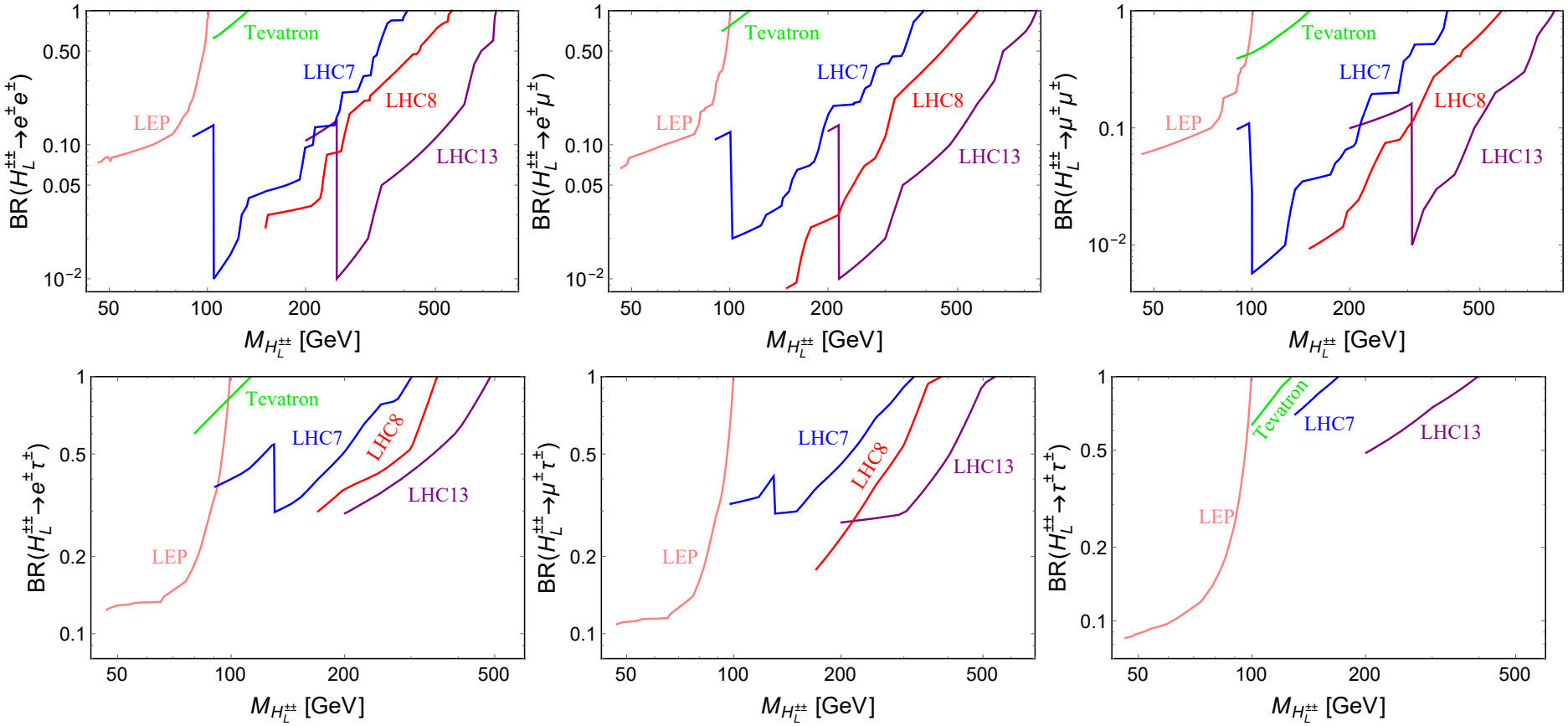
MOLLER prospect



The MOLLER experiment could probe a sizable parameter space, beyond the current low and high-energy constraints.

Displaced vertex searches of $H_L^{\pm\pm}$ at colliders

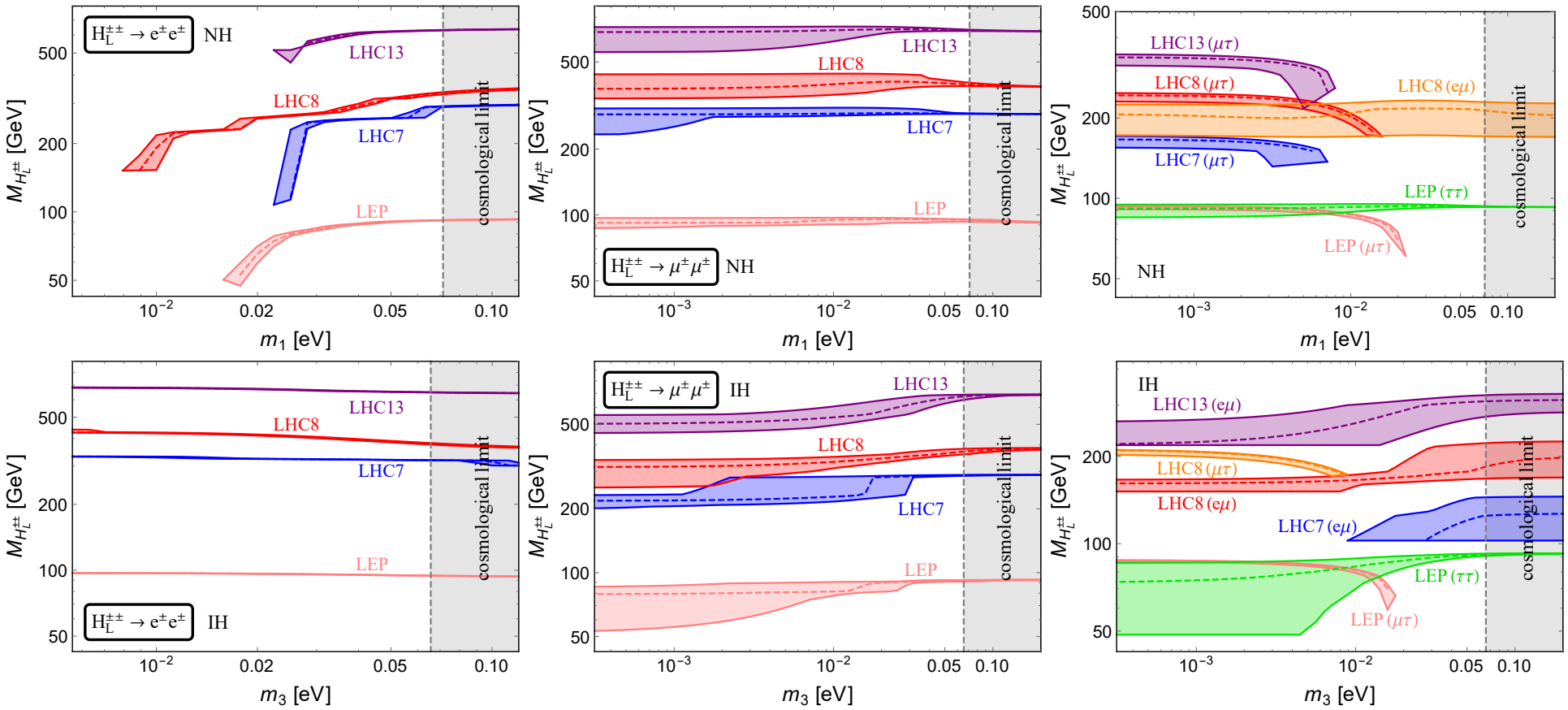
Same-sign dilepton constraints on $H_L^{\pm\pm}$



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;

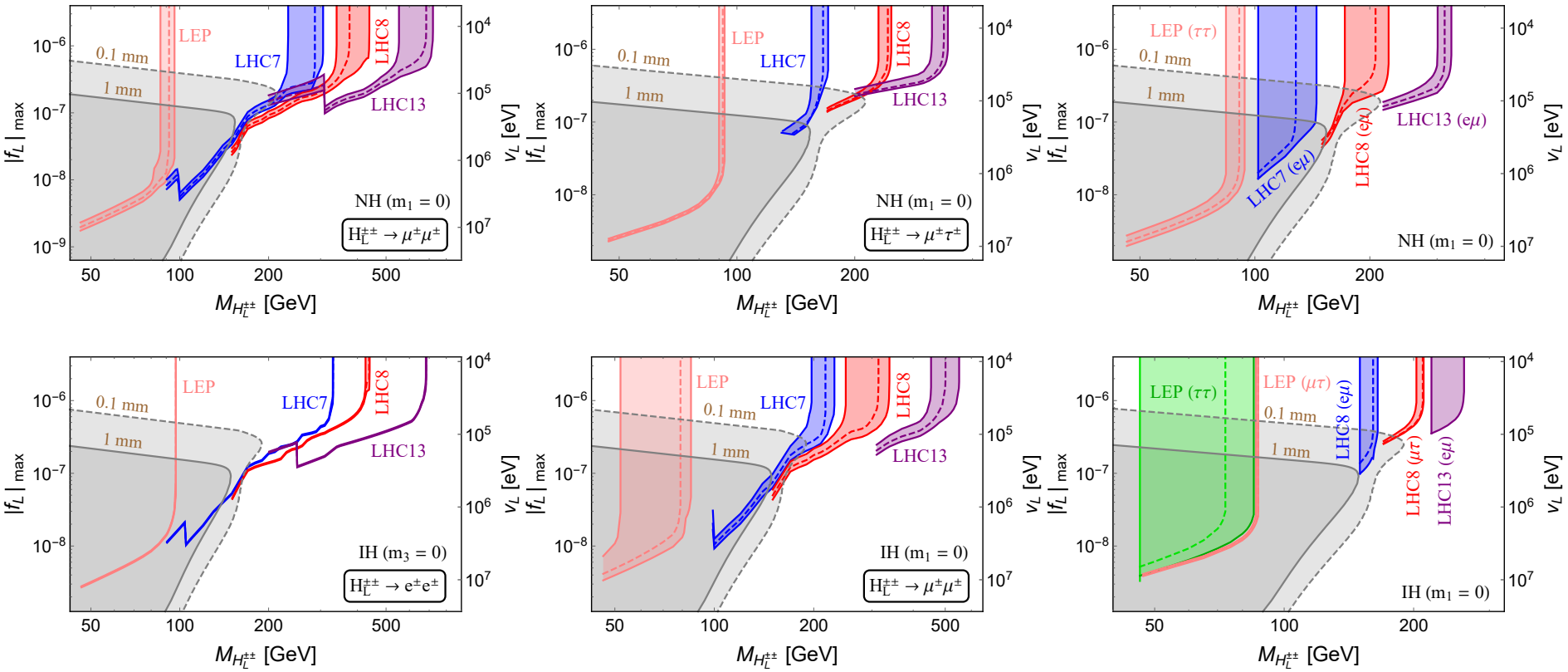
CMS, CMS-PAS-HIG-11-007; CMS-PAS-HIG-14-039; CMS-PAS-HIG-16-036

Lower limit on $H_L^{\pm\pm}$ mass in the limit of small v_L



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

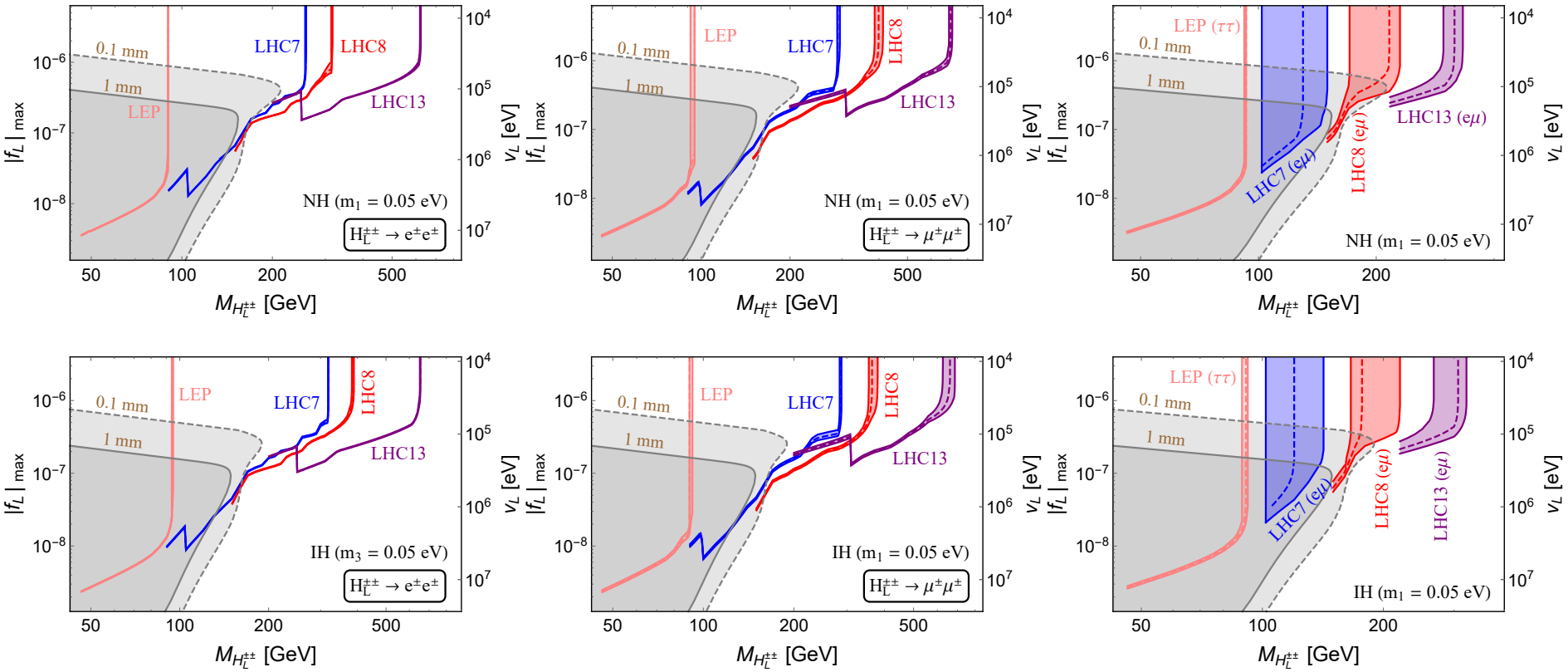
Lower limit on $H_L^{\pm\pm}$ mass ($m_0 = 0$)



Predominant decay mode $H_L^{\pm\pm} \to \ell_\alpha^\pm \ell_\beta^\pm,\ W^{\pm(*)} W^{\pm(*)}$

Dashed lines: central values of neutrino oscillation data;
Colorful bands: 3σ uncertainties

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

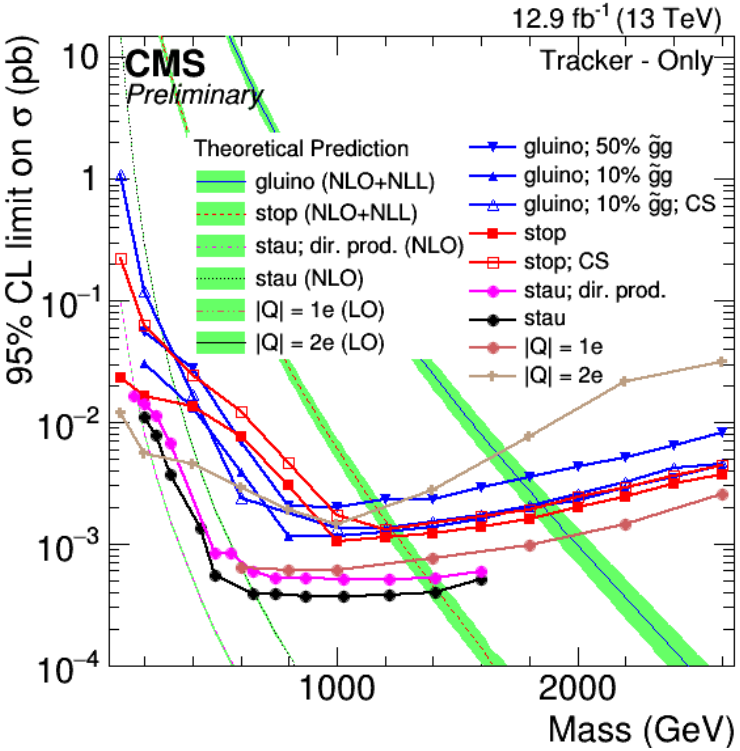


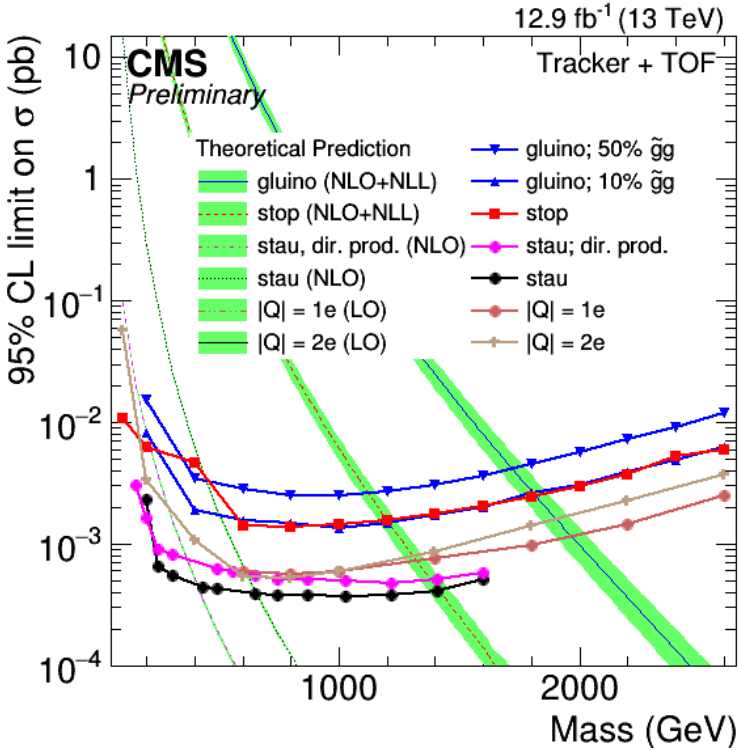
Predominant decay mode $H_L^{\pm\pm} \to \ell_\alpha^\pm \ell_\beta^\pm,\ W^{\pm(*)} W^{\pm(*)}$

Dashed lines: central values of neutrino oscillation data;
Colorful bands: 3σ uncertainties

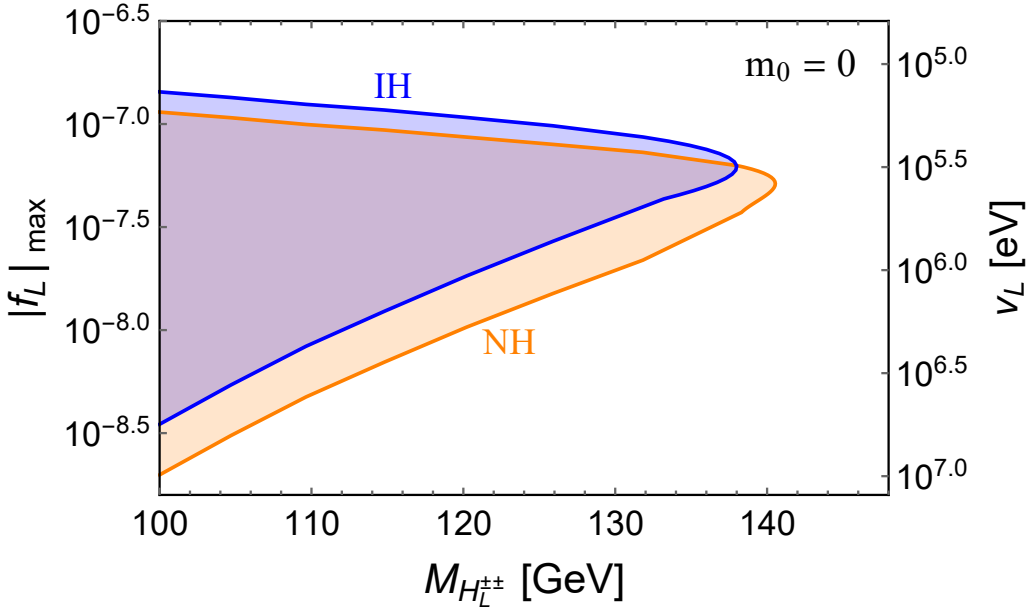
Heavy Stable Charged particle (HSCP) searches

CMS-PAS-EXO-16-036





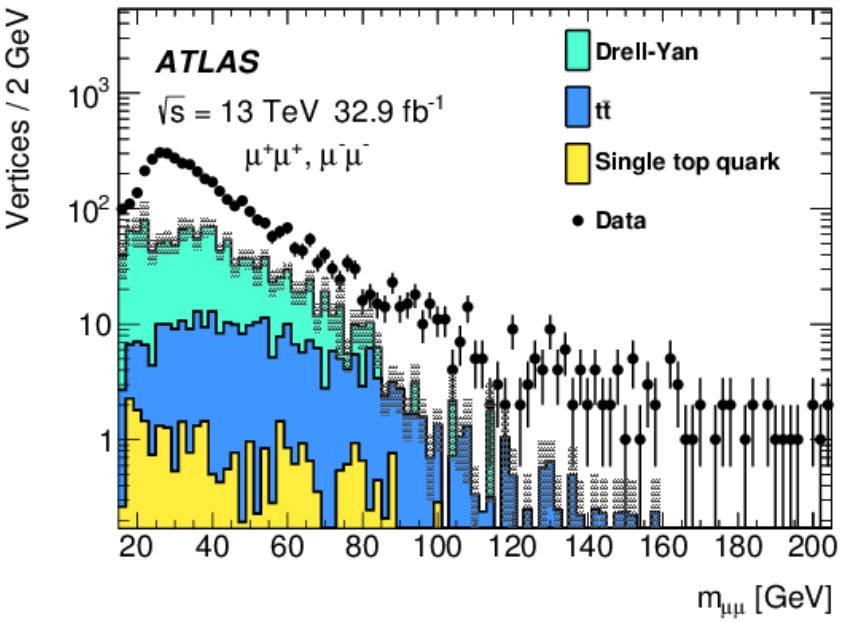
HSCP constraints on $H_L^{\pm\pm}$

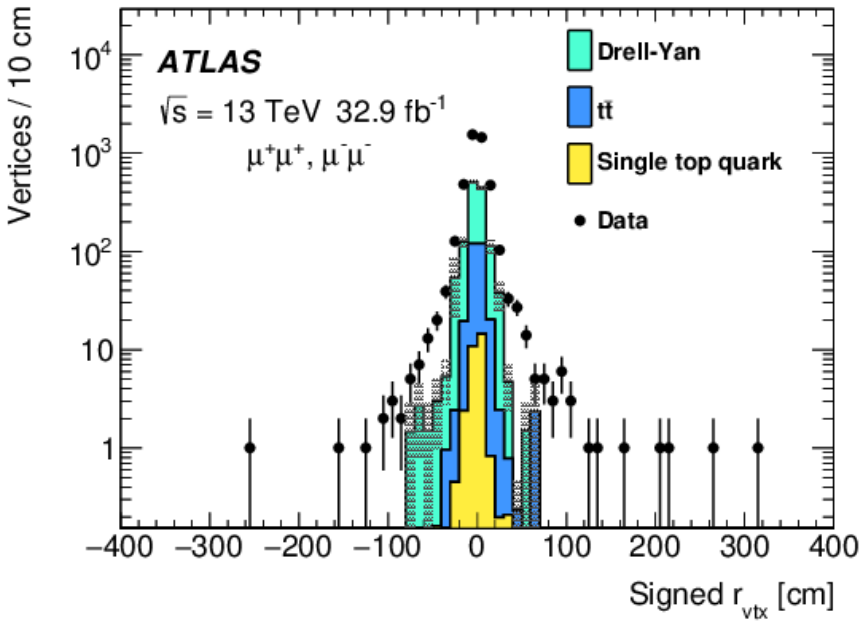


- Long-lived $H_L^{\pm\pm}$ decays outside either the inner silicon tracker or the whole detector.
- We use conservatively only the "tracker-only" analysis.
- The decay length $43\,\mathrm{mm} < bc\tau_0(H_L^{\pm\pm}) < 1100\,\mathrm{mm}$.

Displaced same-sign dilepton searches: SM backgrounds

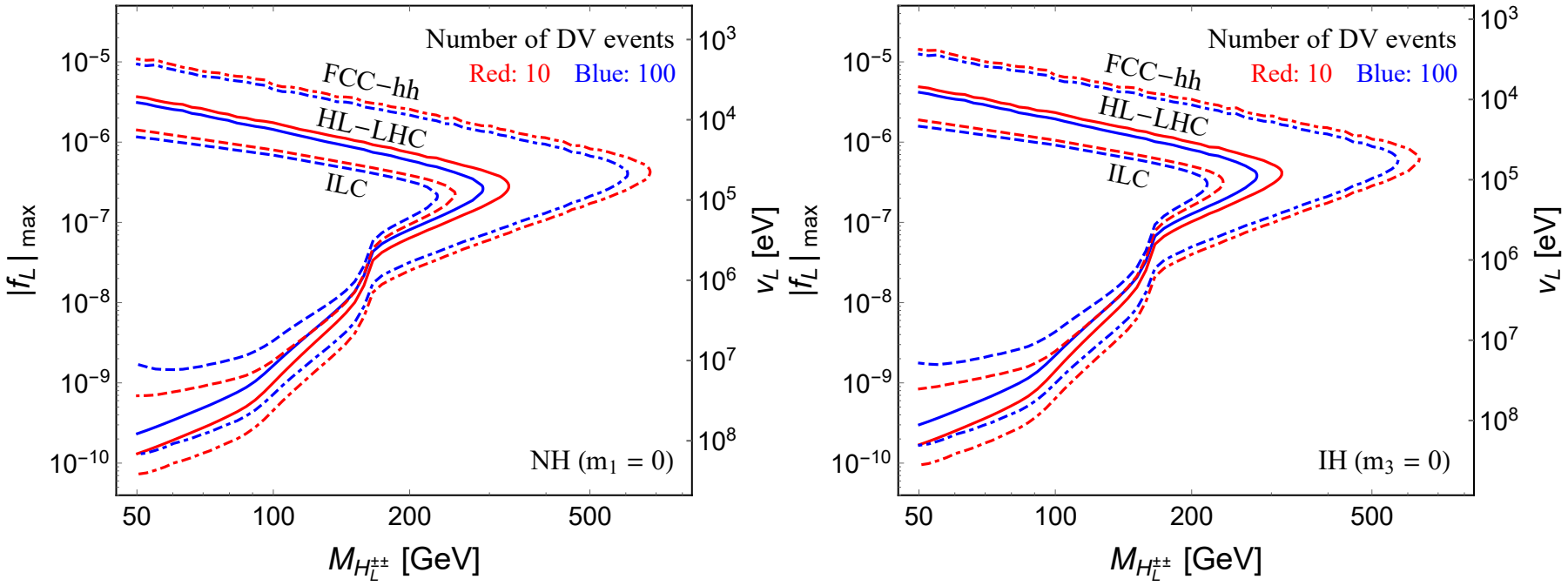
ATLAS, 1808.03057





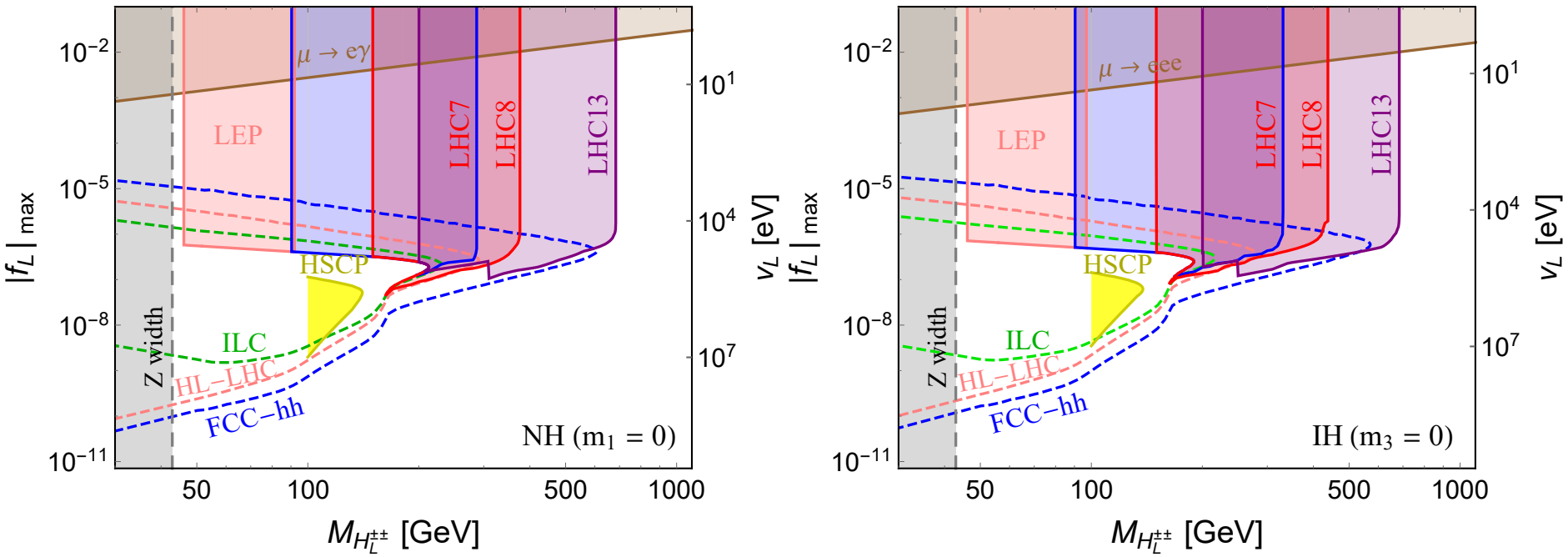
- Dominant background: low-mass Drell-Yan processes $pp \to e^+e^-$, $\mu^+\mu^-$, with the charges of the electron or muon misidentified (and the electron misidentified as a muon or vice versa), depending largely on $m_{\ell\ell'}$ and $r_{\rm vtx}$.
- The dileptons from Drell-Yan processes tend to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

DV prospects of $H_L^{\pm\pm}$



- HL-LHC 14 TeV, 3000 fb^{-1}; FCC-hh 100 TeV, 30 ab^{-1}; ILC 1 TeV, 1 ab^{-1};
- K-factor for HL-LHC & FCC-hh taken conservatively to be 1.2 and 1 for ILC;
- Counting only the decays $H_L^{\pm\pm} \to e^\pm e^\pm$, $e^\pm \mu^\pm$, $\mu^\pm \mu^\pm$;
- Decay length $1\,\mathrm{mm} < bc\tau_0(H_L^{\pm\pm}) < 1\,(3)$ m;
- Basic cuts $p_T(\ell) > 25\,(10)$ GeV, $|\eta(\ell)| < 2.5$, $\Delta\phi(\ell\ell') > 0.4$, requiring at least one displaced $H_L^{\pm\pm}$ to be reconstructed.

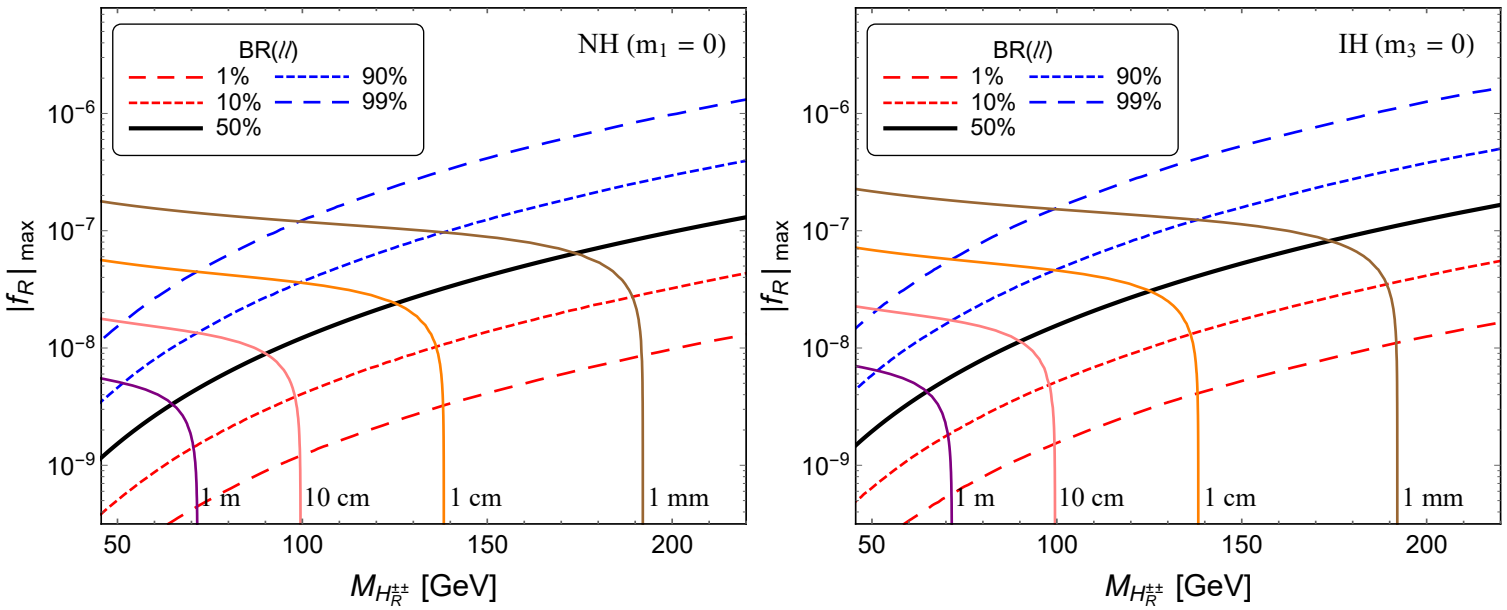
Complementarity



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

...for $H_R^{\pm\pm}$ in LRSM

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



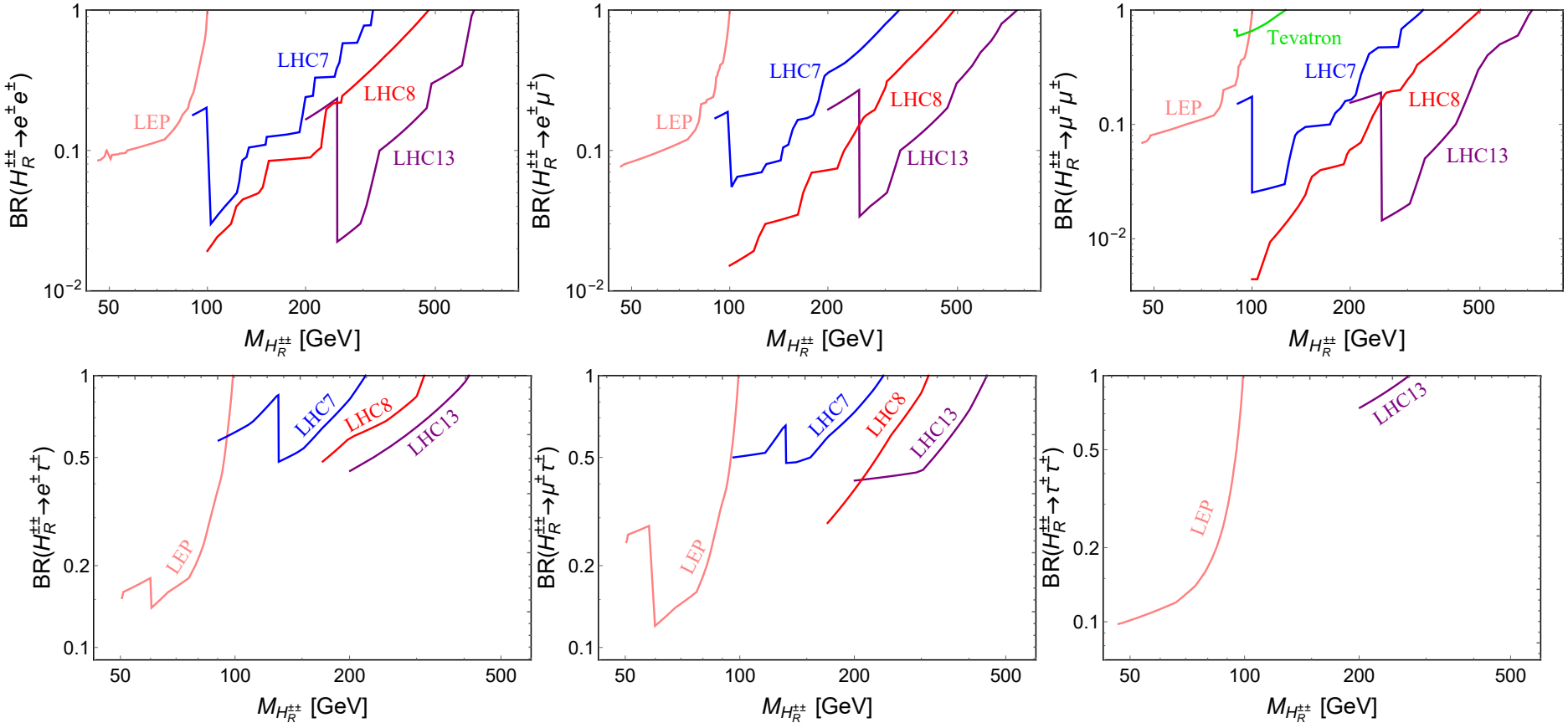
$$\Gamma_{\rm total}(H_R^{\pm\pm}) \;=\; \Gamma(H_R^{\pm\pm} \to \ell_\alpha \ell_\beta) + \Gamma(H_R^{\pm\pm} \to W_R^{\pm *} W_R^{\pm *})\,.$$

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.

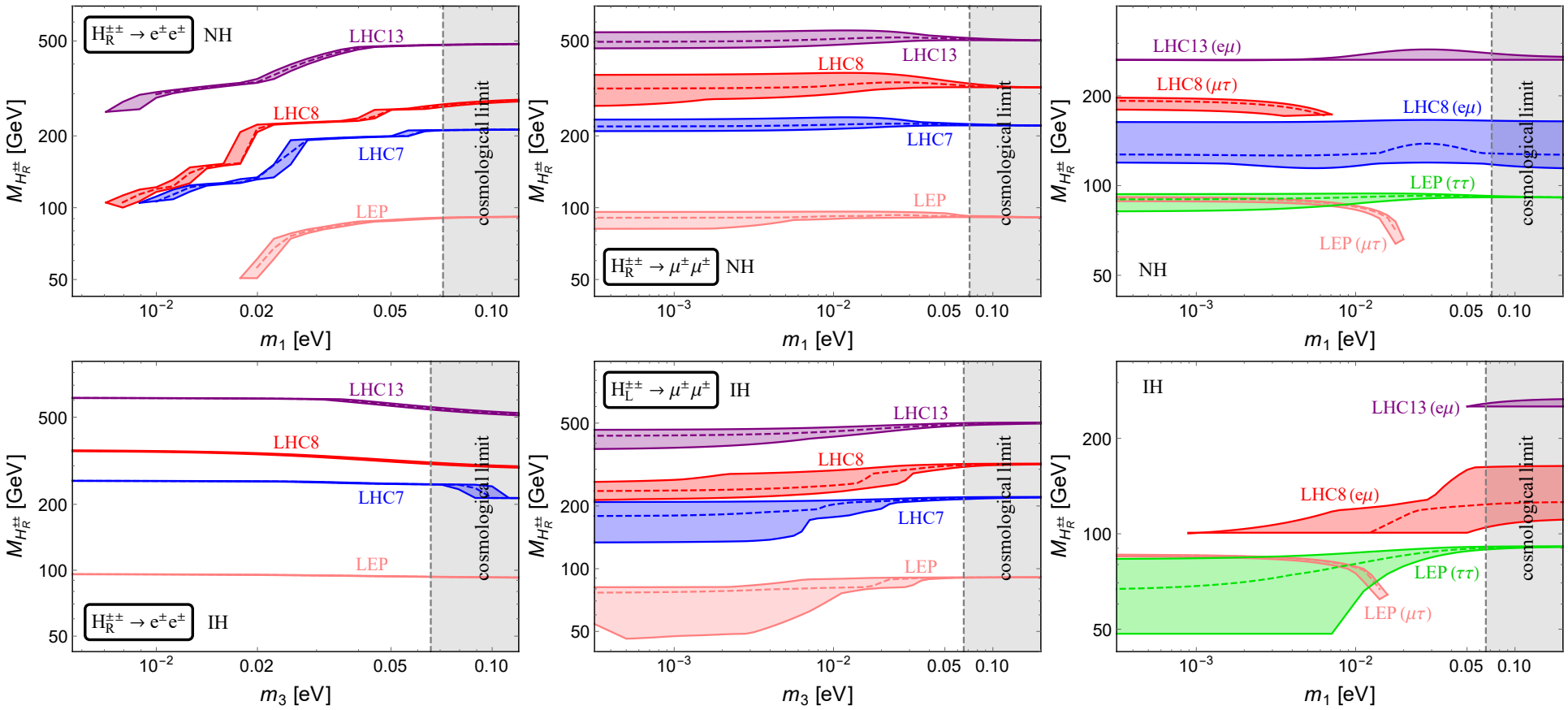
Same-sign dilepton constraints on $H_R^{\pm\pm}$



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

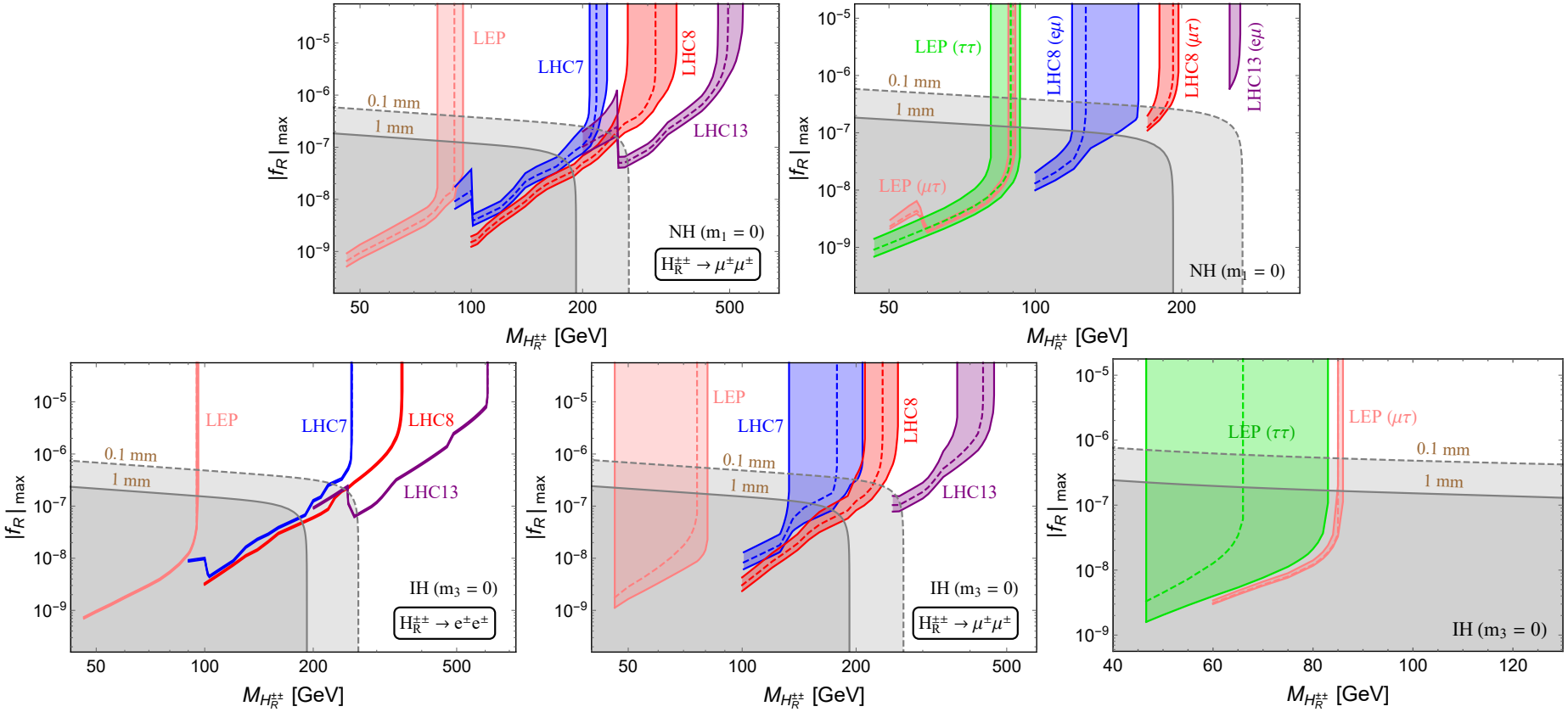
To some extent weaker than the $H_L^{\pm\pm}$ limits

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



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

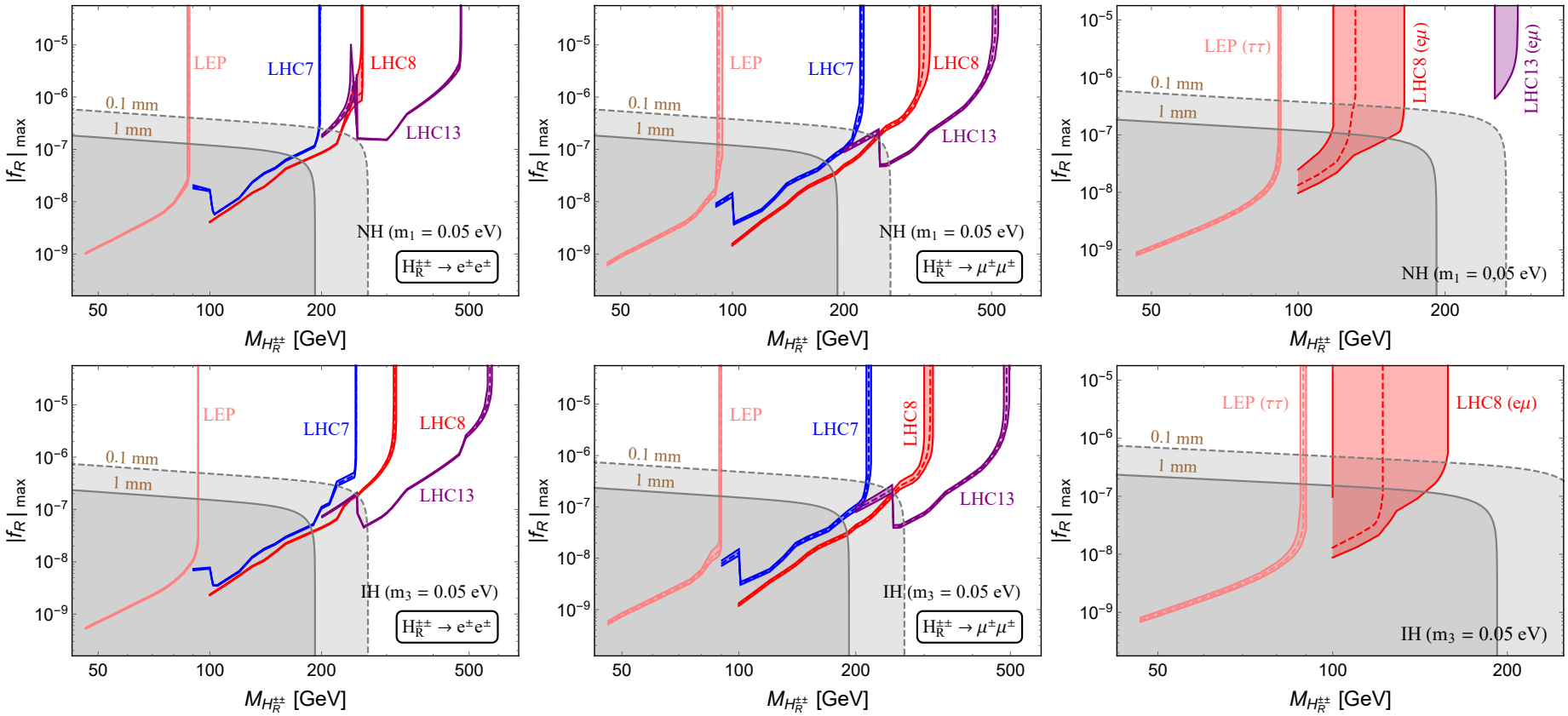
Lower limit on $H_R^{\pm\pm}$ mass ($m_0 = 0$)



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

Dashed lines: central values of neutrino oscillation data;
Colorful bands: 3σ uncertainties

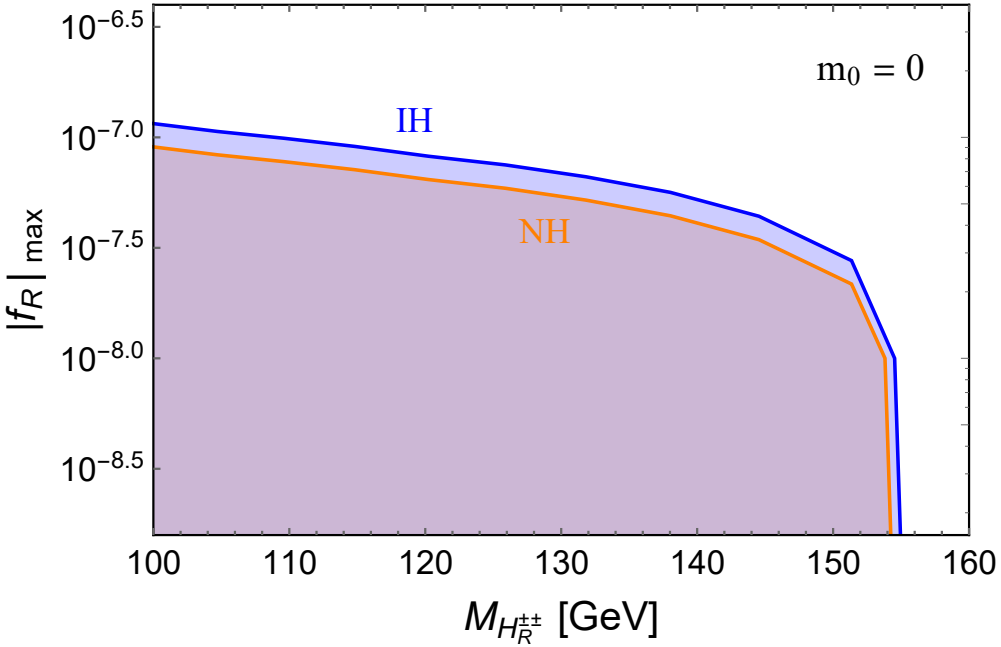
Lower limit on $H_R^{\pm\pm}$ mass ($m_0 = 0.05$ eV)



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

Dashed lines: central values of neutrino oscillation data;
Colorful bands: 3σ uncertainties

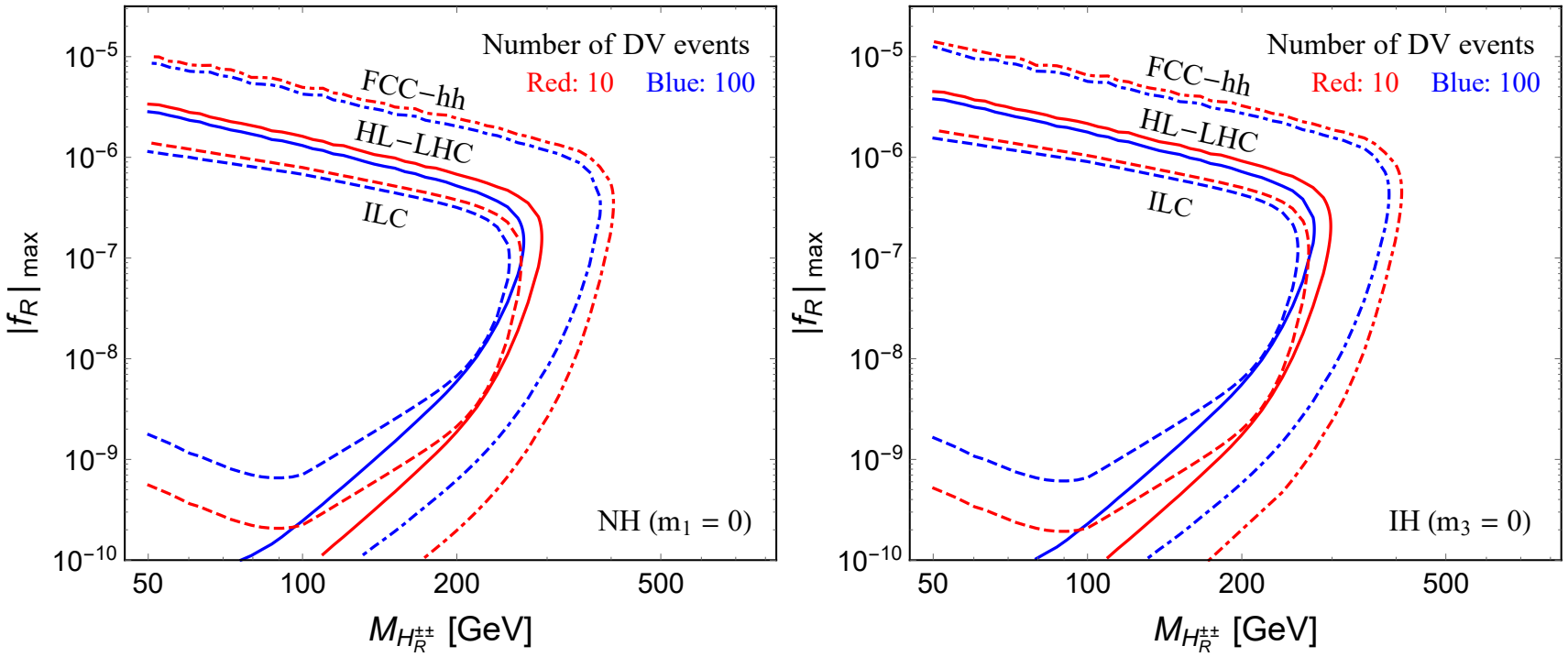
HSCP constraints on $H_R^{\pm\pm}$



- 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 $43\,\mathrm{mm} < bc\tau_0(H_R^{\pm\pm}) < 1100\,\mathrm{mm}$.

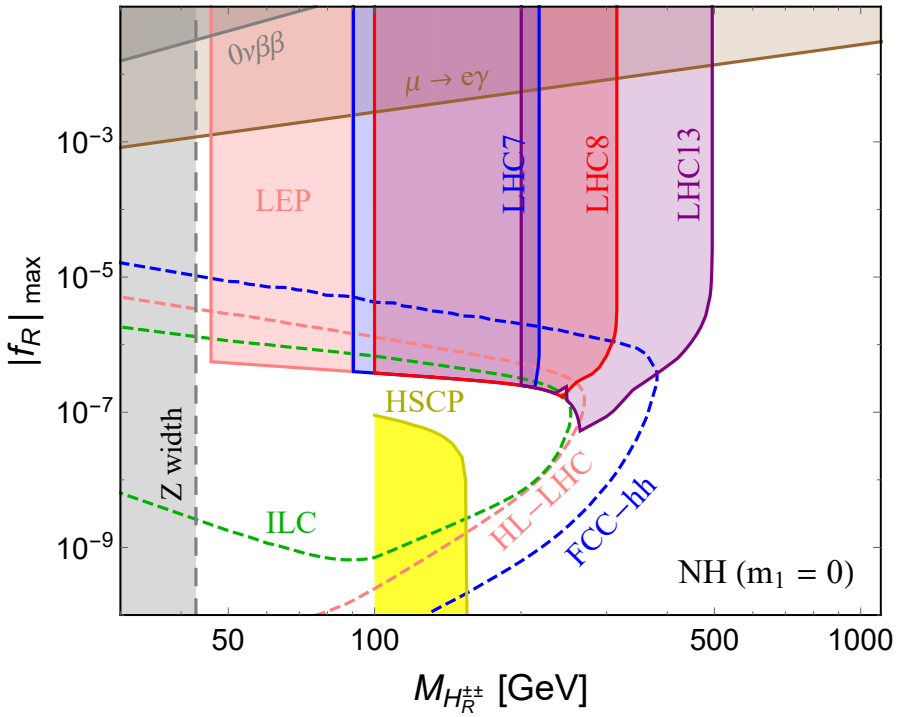
Very different from the $H_L^{\pm\pm}$ case

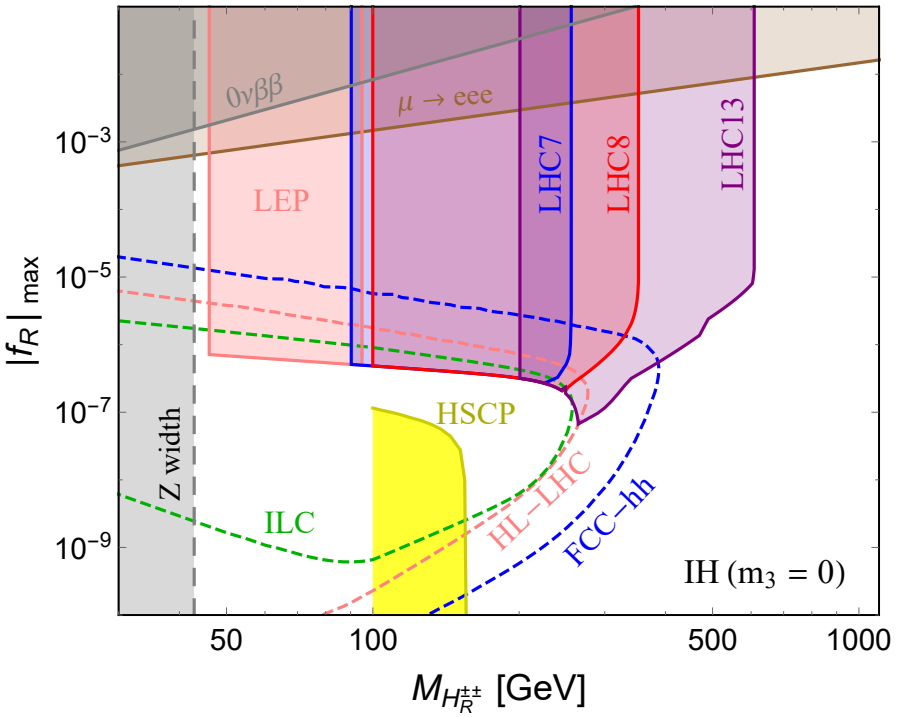
DV prospects of $H_R^{\pm\pm}$



- 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.

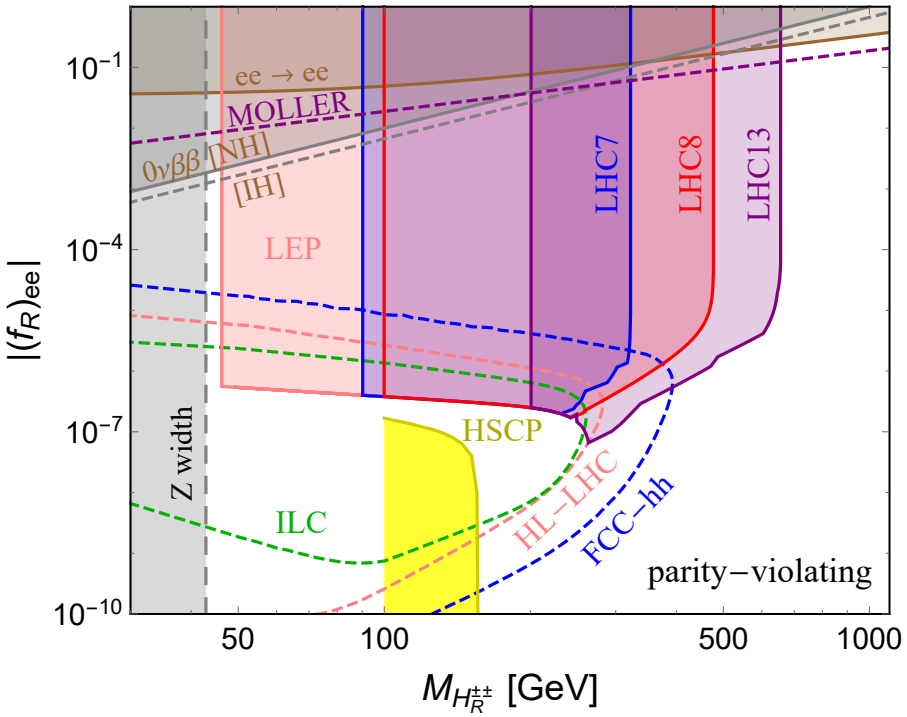
Complementarity





- 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.

Conclusion

- The MOLLER experiment is sensitive to doubly-charged scalars up to hte scale of ~ 10 TeV.
- In the minimal type-II seesaw, the LFV constraints (e.g. $\mu \to e\gamma$) are stronger; however, in parity-violating MOLLER could go beyond the $0\nu\beta\beta$ limits.
- In type-II seesaw $H_L^{\pm\pm}$ might be long-lived in a sizable parameter space, depending on the Yukawa couplings f_L (or equivalently v_L); in LRSM, H_R could also long-lived, for small f_R and TeV-scale v_R.
- A broad region of the parameter space could be probed at HL-LHC, ILC (FCC-hh): $10^{-10} \lesssim |f_{L,R}| \lesssim 10^{-6}$ and $m_Z/2 < M_{H^{\pm\pm}} \lesssim 200$ (500) GeV.
- The low-energy high-precision and high-energy experiments are largely complementary to each other in the (in)direct searches of $H^{\pm\pm}$.

Thank you for your attention!