Doubly-charged scalars at high-energy and high-precision experiments

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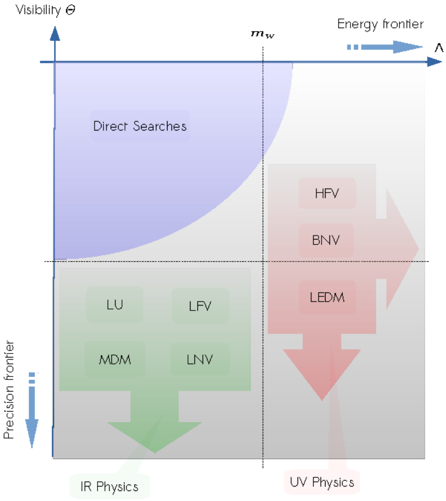
Outline

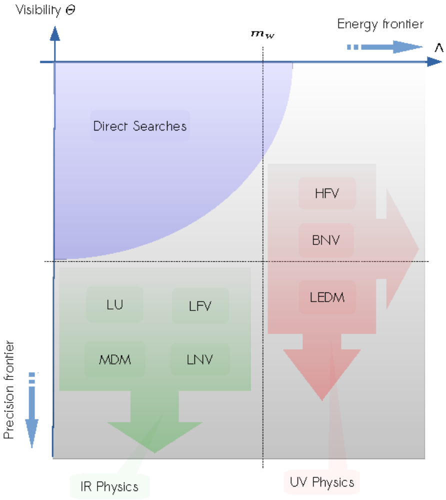
- Introduction: Energy versus Precision Frontier
- Example: LHC versus MOLLER
- Case study: Doubly charged scalar
- Conclusion

Energy versus Precision



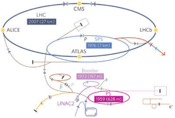
[Le Dall, Pospelov, Ritz (PRD '15)]

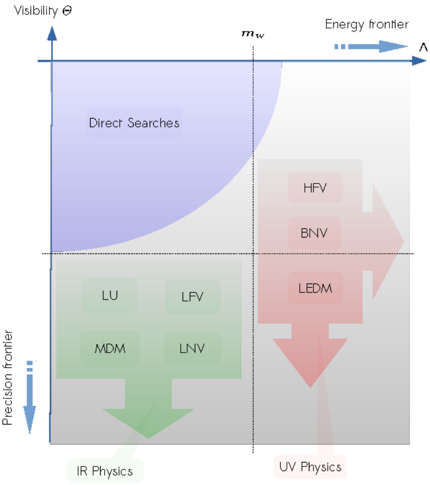
Energy versus Precision

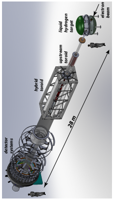


Complementary and intertwined. Need input from both to probe new physics.

Energy versus Precision



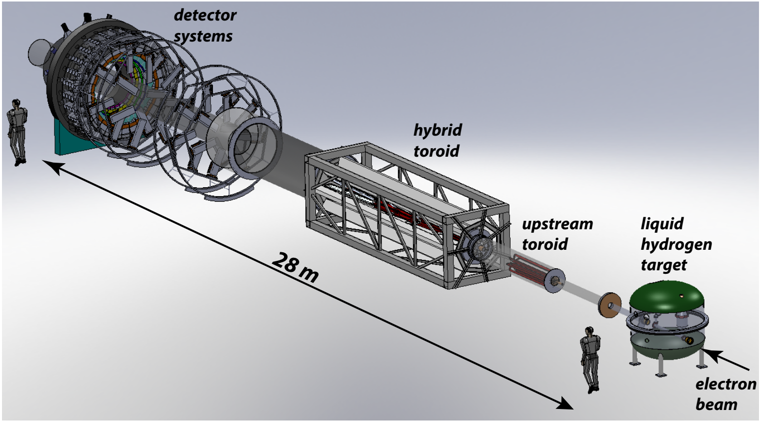




Example: LHC versus MOLLER

MOLLER Experiment

Measurement **O**f a **L**epton **L**epton **E**lectroweak **R**eaction

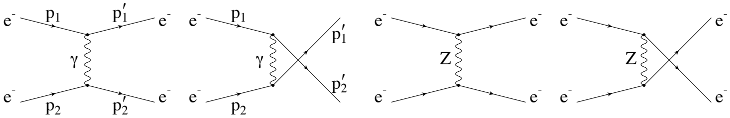


- Scattering of longitudinally polarized electrons off unpolarized electrons.
- Upgraded 11 GeV electron beam in Hall A at JLab.

http://hallaweb.jlab.org/12GeV/Moller/pubs/moller_proposal.pdf

Parity-Violating Asymmetry

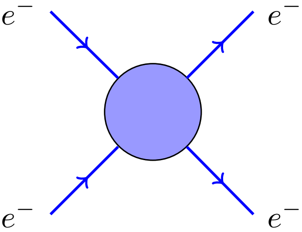
$$A_{\mathrm{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



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

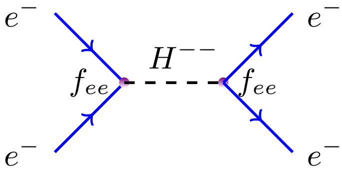
- For the MOLLER design, $A_{\mathrm{PV}}^{\mathrm{SM}} \approx 33$ ppb (including 1-loop effect).
- **Goal:** $\delta A_{\mathrm{PV}} = 0.7$ ppb. [Benesch *et al.* [MOLLER Collaboration], arXiv:1411.4088 [nucl-ex]]
- Achieve a 2.4% precision in the measurement of Q_W^e.

Sensitive to New Physics



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

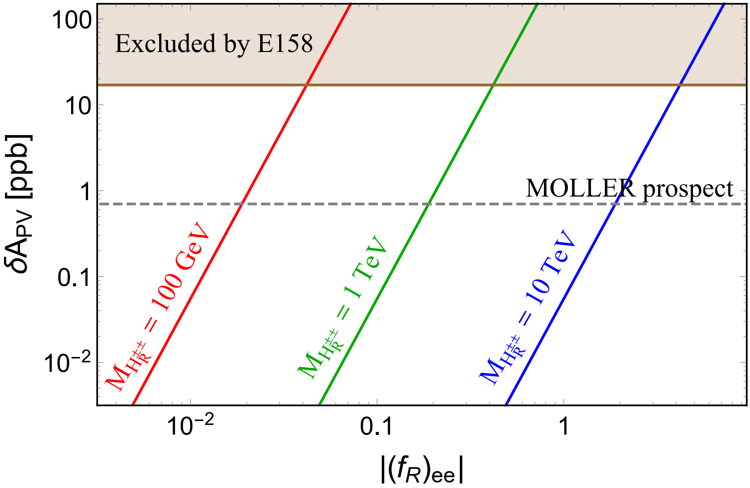
Case Study: Doubly Charged Scalar



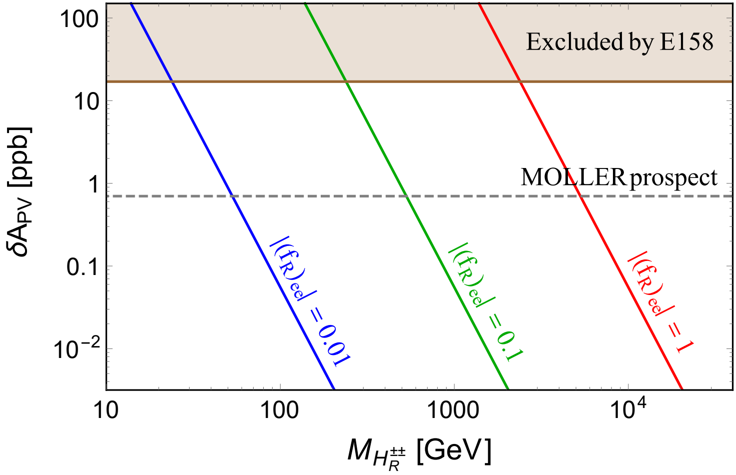
$$\mathcal{M}_{\mathrm{PV}} \sim \frac{|(f_L)_{ee}|^2}{2M^2_{H_L^{\pm\pm}}}(\bar{e}_L\gamma^\mu e_L)(\bar{e}_L\gamma_\mu e_L) + (L \leftrightarrow R) .$$

$$\text{MOLLER Sensitivity : } \quad \frac{M_{H^{\pm\pm}_{L,R}}}{|(f_{L,R})_{ee}|} \gtrsim 5.3\ \text{TeV} .$$

Case Study: Doubly Charged Scalar

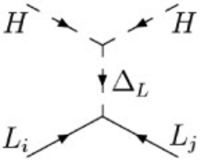


Case Study: Doubly Charged Scalar



Why Doubly Charged Scalar?

Explains neutrino mass via **Type-II Seesaw**



$$\mathcal{L}_Y = -(f_L)_{ij}\,\psi^{\mathsf{T}}_{L,\,i} C \mathrm{i}\sigma_2 \Delta_L \psi_{L,\,j} + \text{H.c.}$$

$$m_\nu = \sqrt{2} f_L v_L = U_{\text{PMNS}} \widehat{m}_\nu U^{\mathsf{T}}_{\text{PMNS}}\,.$$

[Schechter, Valle (PRD ’80); Mohapatra, Senjanović (PRD ’81); Lazarides, Shafi, Wetterich (NPB ’81)]

Fixes all the elements of f_L

(up to an overall scale, depending on the absolute neutrino mass)

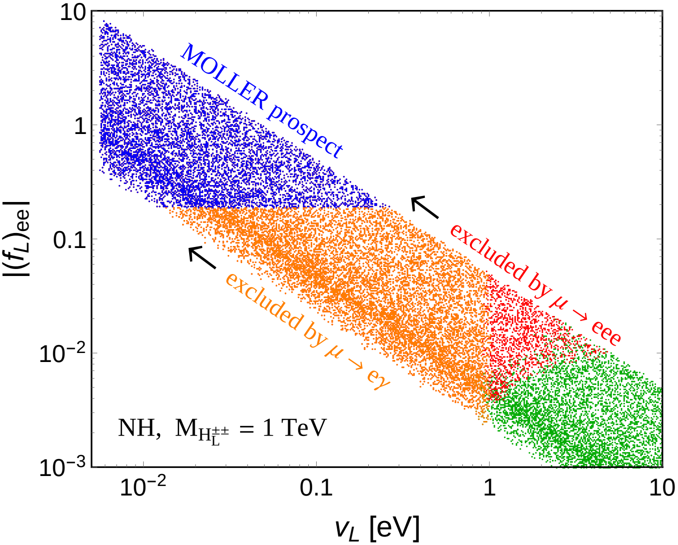
LFV Constraints

[BD, Rodejohann, Vila (NPB '17)]

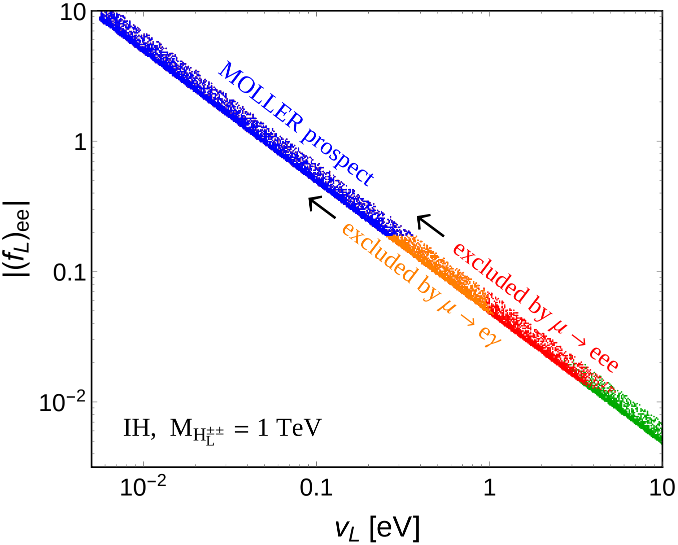
Process	Experimental limit on BR	Constraint on	Bound $\times \left(\frac{M_{H_L}}{100\ \text{GeV}}\right)^2$
$\mu \to e\gamma$	$< 4.2 \times 10^{-13}$	$\lvert(f_L^\dagger f_L)_{e\mu}\rvert$	$< 2.4 \times 10^{-6}$
$\mu \to 3e$	$< 1.0 \times 10^{-12}$	$\lvert(f_L)_{\mu e}\rvert\lvert(f_L)_{ee}\rvert$	$< 2.3 \times 10^{-7}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	$\lvert(f_L^\dagger f_L)_{e\tau}\rvert$	$< 1.6 \times 10^{-3}$
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	$\lvert(f_L^\dagger f_L)_{\mu\tau}\rvert$	$< 1.9 \times 10^{-3}$
$\tau \to e^+e^-e^-$	$< 2.7 \times 10^{-8}$	$\lvert(f_L)_{\tau e}\rvert\lvert(f_L)_{ee}\rvert$	$< 9.2 \times 10^{-5}$
$\tau \to \mu^+\mu^-e^-$	$< 2.7 \times 10^{-8}$	$\lvert(f_L)_{\tau\mu}\rvert\lvert(f_L)_{\mu e}\rvert$	$< 6.5 \times 10^{-5}$
$\tau \to e^+\mu^-\mu^-$	$< 1.7 \times 10^{-8}$	$\lvert(f_L)_{\tau e}\rvert\lvert(f_L)_{\mu\mu}\rvert$	$< 7.3 \times 10^{-5}$
$\tau \to e^+e^-\mu^-$	$< 1.8 \times 10^{-8}$	$\lvert(f_L)_{\tau e}\rvert\lvert(f_L)_{\mu e}\rvert$	$< 5.3 \times 10^{-5}$
$\tau \to \mu^+e^-e^-$	$< 1.5 \times 10^{-8}$	$\lvert(f_L)_{\tau\mu}\rvert\lvert(f_L)_{ee}\rvert$	$< 6.9 \times 10^{-5}$
$\tau \to \mu^+\mu^-\mu^-$	$< 2.1 \times 10^{-8}$	$\lvert(f_L)_{\tau\mu}\rvert\lvert(f_L)_{\mu\mu}\rvert$	$< 8.1 \times 10^{-5}$

$$\mu \to eee: \quad \frac{M_{H_L^{\pm\pm}}}{\sqrt{|(f_L)^\dagger_{ee}(f_L)_{e\mu}|}} > 208\ \text{TeV}, \qquad \mu \to e\gamma: \quad \frac{M_{H_L^{\pm\pm}}}{\sqrt{|\sum_\ell (f_L)^\dagger_{\mu\ell}(f_L)_{e\ell}|}} > 61\ \text{TeV}.$$

MOLLER versus LFV



MOLLER versus LFV

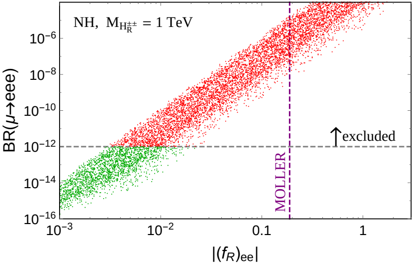


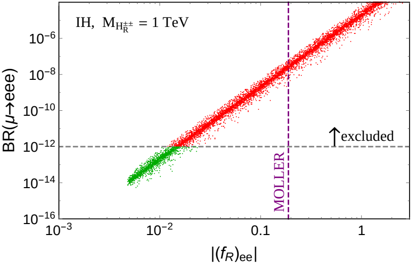
Left-Right Symmetric Model

[Pati, Salam ’74; Mohapatra, Pati ’75; Mohapatra, Senjanović ’75]

$$\mathcal{L}_Y \;=\; -\,(f_L)_{ij}\,\psi^{\mathsf{T}}_{L,\,i} C i\sigma_2 \Delta_L \psi_{L,\,j} - (f_R)_{ij}\,\psi^{\mathsf{T}}_{R,\,i} C i\sigma_2 \Delta_R \psi_{R,\,j} \;+\; \text{H.c.}$$

- L-R symmetry demands that $f_L = f_R$ (and $g_L = g_R$).
- Similar neutrino mass and LFV constraints also apply to f_R.





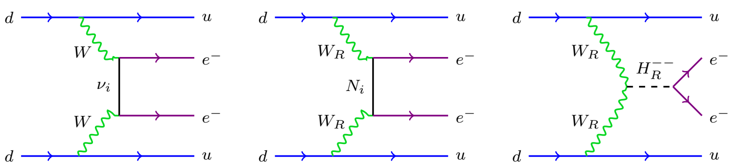
Parity-Violating Left-Right Model

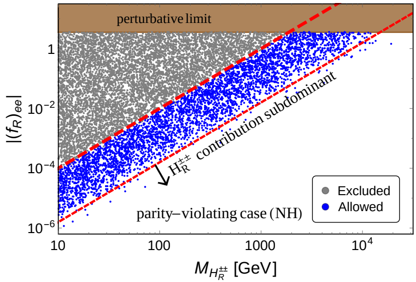
- Discrete P-symmetry breaking scale could be decoupled from the $SU(2)_R$-breaking scale. [Chang, Mohapatra, Parida (PRL '84)]
- No Δ_L in the low-energy theory.

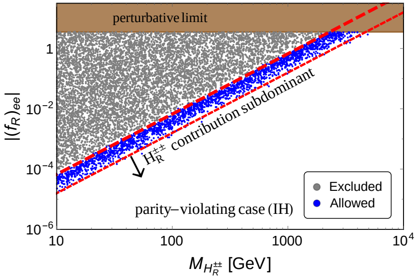
$$\mathcal{L}_Y \;=\; -\,(f_R)_{ij}\,\psi^{\mathsf{T}}_{R,\,i} C \mathrm{i}\sigma_2 \Delta_R \psi_{R,\,j} \;+\; \text{H.c.}.$$

- Allows $f_R \neq f_L$ (and $g_L \neq g_R$) at low scale.
- f_R is not related to the neutrino oscillation data.
- LFV constraints do not restrict $(f_R)_{ee}$ anymore.

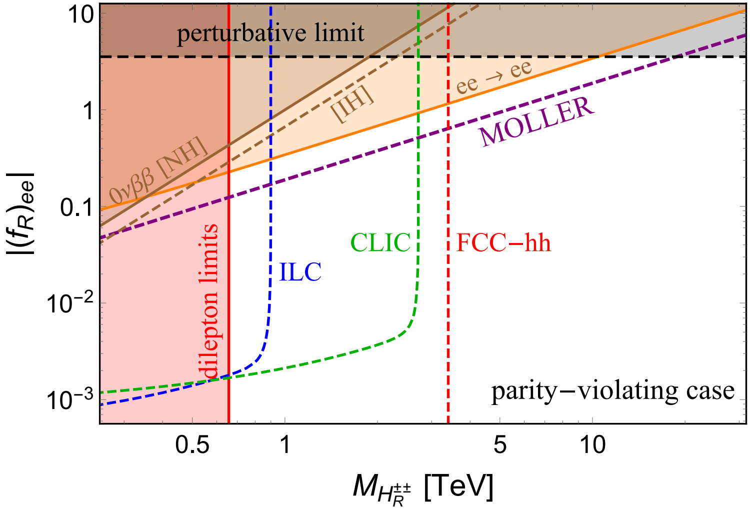
Neutrinoless Double Beta Decay







MOLLER Prospects



Conclusion

- Complementarity between the high-energy and high-precision experiments.
- We considered a case study of doubly-charged scalars.
- Can be probed at the MOLLER experiment up to ~ 20 TeV.
- For the minimal type-II seesaw, LFV constraints are stronger.
- For the parity-violating left-right scenario, MOLLER can go well beyond the current constraints, as well as the future collider prospects.