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

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Outline

- **Introduction**: Energy versus Precision Frontier
- **Example**: LHC versus MOLLER
- **A case study**: Doubly charged scalar
- **Conclusion**
Two Frontiers: Energy versus Precision

[Le Dall, Pospelov, Ritz (PRD ’15)]
Two Frontiers: Energy versus Precision

Complementary and intertwined. Need input from both to probe new physics.
Two Frontiers: Energy versus Precision

FIG. 7: MOLLER Experiment Overview: Layout of the target, spectrometer and detectors.

In order to achieve the necessary rate, the liquid hydrogen target is planned to be 150 cm long. This requires a cryogenic target system capable of handling a heat load of \( \sim 5 \text{ kW} \) from the beam. This would be the highest power liquid hydrogen target constructed, but it would be based on successful experience with the operation of the Qweak target which successfully operated up to 180 \( \mu \text{A} \) with a total power of 2.9 kW [29]. The final design of the MOLLER target will make use of computational fluid dynamics (CFD), a key recent development which has been validated by the successful operation of the Qweak target. From the physics point of view, the most important design consideration is suppression of density fluctuations at the timescale of the helicity flip rate, which can ruin the statistical reach of the flux integration technique. Preliminary estimates based on operational experience with the Qweak target [29] suggest that density variation can be maintained at \( \sim 26 \text{ ppm} \) at 1.92 kHz (compared to the expected counting statistics width of \( \sim 83 \text{ ppm/pair} \) at 75 \( \mu \text{A} \)), corresponding to acceptable 5% excess noise.

A precision collimation system carefully designed to minimize backgrounds will accept all Møller scattered electrons in the polar angle range \( \sim \pm 60 \text{ to } 120 \text{ mrad} \) (corresponding to a lab polar scattering angle range of 5 mrad < \( \theta_{\text{lab}} < 17 \text{ mrad} \)). The spectrometer system that focusses these scattered particles is designed to achieve two goals: 100% azimuthal acceptance and the ability to focus the scattered Møller flux over a large fractional momentum bite with adequate separation from backgrounds. These considerations have led to a unique solution involving two back-to-back sets of toroidal coils, one of them of conventional geometry (albeit long and quite skinny) while the other is of quite novel geometry. Due to the special nature of identical particle scattering, it is possible to achieve 100% azimuthal acceptance in such a system by choosing an odd number of coils. The idea is to accept both forward and backward (in center of mass angle) Møllers in each bite. Since these are identical particles, those that are accepted in one bite also represent all the statistics available in the bite that is diametrically opposed (180° +), which is the sector that is blocked due to the presence of a toroidal coil. An event with a forward angle scattered Møller electron that azimuthally scatters into a blocked sector is detected via its backward angle scattered partner in the open sector diametrically opposed, and vice versa. The focussing and separation of the scattered Møller electrons is challenging due to their large scattered energy range \( E_{\text{lab}} = 1.78 \text{ GeV} \) and the need to separate them from the primary background of elastic and inelastic electron-proton scattering. The solution is a combination of two toroidal magnets which together act in a non-linear way on the charged particle trajectories. The first is a conventional toroid placed 6 m downstream of the target and the second, a novel “hybrid” toroid placed between 10 and 16 m downstream of the target. Each of the two toroidal fields is constructed out of seven identical coils uniformly spaced in the azimuth. The “hybrid” toroid has several novel features to provide the required field to focus the large range of electron scattering angles and momenta. It has four current return paths, as shown in Fig. 8 and some novel bends that minimize the field in certain critical regions. A preliminary engineering design of this hybrid toroid with realistic conductor, water systems and so on.
MOLLER Experiment

Measurement Of a Lepton Lepton Electroweak Reaction

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

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \]

For the MOLLER design, \( A_{PV}^{SM} \approx 33 \) ppb (including 1-loop effect).

**Goal:** \( \delta A_{PV} = 0.7 \) ppb. [J. 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

\[ \frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{2G_F|\Delta Q_W^e|}} \approx 7.5 \text{ TeV} \]
Case Study: Doubly Charged Scalar

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

MOLLER Sensitivity: \[ \frac{M_{H_{L,R}^{\pm \pm}}}{|(f_{L,R})_{ee}|} \gtrsim 5.3 \text{ TeV}. \]
Case Study: Doubly Charged Scalar

\[ \delta A_{PV} \] [ppb] vs. \[ M_{H_L^{++}} \] [GeV]

- \[ |f_{L}^{ee}| = 0.01 \]
- \[ |f_{L}^{ee}| = 0.1 \]
- \[ |f_{L}^{ee}| = 1 \]

MOLLER prospect

[BD, Ramsey-Musolf, Zhang '18]
Neutrino Mass via **Type-II Seesaw**

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

\[
m_\nu = \sqrt{2} f_L v_\Delta = U \hat{m}_\nu U^T.
\]

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

Fixes the elements of \( f_L \) (up to an overall scale)
## LFV Constraints

<table>
<thead>
<tr>
<th>Process</th>
<th>Experimental limit on BR</th>
<th>Constraint on</th>
<th>Bound × (\left(\frac{M_{HL}}{100 \text{ GeV}}\right)^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu \rightarrow e\gamma)</td>
<td>(&lt; 4.2 \times 10^{-13})</td>
<td>(</td>
<td>(f_L^\dagger f_L)_{e\mu}</td>
</tr>
<tr>
<td>(\mu \rightarrow 3e)</td>
<td>(&lt; 1.0 \times 10^{-12})</td>
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<td>(f_L)_{\mu e}</td>
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<td>(\tau \rightarrow e\gamma)</td>
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<td>(\tau \rightarrow \mu\gamma)</td>
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<tr>
<td>(\tau \rightarrow e^+e^-e^-)</td>
<td>(&lt; 2.7 \times 10^{-8})</td>
<td>(</td>
<td>(f_L)_{\tau e}</td>
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<td>(f_L)_{\tau \mu}</td>
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<td>(&lt; 2.1 \times 10^{-8})</td>
<td>(</td>
<td>(f_L)_{\tau \mu}</td>
</tr>
</tbody>
</table>

[BD, Rodejohann, Vila (NPB '17)]
MOLLER versus LFV

\[ |(f_L)_{ee}| \]

NH, \( M_{H_L^{\pm\pm}} = 1 \text{ TeV} \)

excluded by \( \mu \rightarrow eee \)

excluded by \( \mu \rightarrow e\gamma \)

[BD, Ramsey-Musolf, Zhang '18]
MOLLER versus LFV

\[ |(f_L)_{ee}| \]

IH, \( M_{H_L^{\pm}} = 1 \text{ TeV} \)

excluded by \( \mu \rightarrow eee \)

excluded by \( \mu \rightarrow e\gamma \)

[BD, Ramsey-Musolf, Zhang '18]
Parity-Violating Left-Right Model

\[ \mathcal{L}_Y \supset - (f_R)_{ij} \psi_{R,i}^\dagger \sigma_2 \Delta_R \psi_{R,j} + \text{H.c.} \]

- Could have $f_R \neq f_L$ at low scale. [Chang, Mohapatra, Parida (PRL '84)]
- $f_R$ is not related to the neutrino oscillation data.
- LFV constraints do not restrict $(f_R)_{ee}$ anymore.
- Other relevant constraints:
  - Neutrinoless double beta decay
  - Bhabha scattering at LEP: $e^+ e^- \rightarrow e^+ e^-$. 
  - Drell-Yan process at LHC: $pp \rightarrow \gamma^*/Z^* \rightarrow H^{++} H^{--}$.
- Future prospects at ILC/CLIC: $e^+ e^- \rightarrow e^\pm e^\pm H_R^\mp\mp$ and $e^\pm \gamma \rightarrow e^\mp H_R^{\pm\pm}$.

[BD, Mohapatra, Zhang ’18]
Parity-Violating Left-Right Model

\[ |(f_R)_{ee}| \]

parity-violating case
\[ \text{ee} \rightarrow \text{ee} \]

MOLLER
dilepton limits

\[ 0\nu\beta\beta [\text{NH}] \]
[\text{IH}]

ILC
CLIC
perturbative limit

[BD, Ramsey-Musolf, Zhang ’18]
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 $\sim 20$ TeV.

- For the parity-violating left-right scenario, goes well beyond the current constraints, as well as the future collider sensitivities.