Phenomenology of TeV-scale scalar Leptoquarks in the EFT

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Based on: arxiv: 1812.03178 (PRD100 (2019) no.5, 055020), SBS, Jonathan Cohen, Amarjit Soni, Jose Wudka
• A LQ-SMEFT framework: Effective Field Theory for TeV-scale LQ’s

- Low-energy lepton number violating (LNV) effect in the LQ-SMEFT
  • Neutrino masses

- New LQ’s Collider signatures in the LQ-SMEFT
  • “SMOKING GUN” LNV signals @ the LHC13 & beyond

• Summary and final notes
The “standard” renormalizable $\phi$SM framework:

$$\mathcal{L}_{\phi SM} = \mathcal{L}_{SM} + \mathcal{L}_{Y,\phi} + \mathcal{L}_{H,\phi}$$

$\phi(3,1,-1/3) = S_1$ considered for the B-anomalies...

Consider the SU(2) scalar singlets LQ: “down type”: $\phi(3,1,-1/3)$
“up-type”: $\phi(3,1,2/3)$
The “standard” renormalizable $\phi$SM framework:

$$\mathcal{L}_{\phi SM} = \mathcal{L}_{SM} + \mathcal{L}_{Y,\phi} + \mathcal{L}_{H,\phi}$$

$\phi(3,1,-1/3) = S_1$ considered for the B-anomalies ...

- **Scalar interactions:**

$$\mathcal{L}_{H,\phi} = |D_\mu \phi|^2 - M_\phi^2 |\phi|^2 + \lambda_\phi |\phi|^4 + \lambda_{\phi_H} |\phi|^2 |H|^2$$

- **Yukawa-like interactions (with Baryon # conservation):**

$$\mathcal{L}_{Y,\phi} = y^L_{q\ell} \bar{q}^c \tau_2 \ell^\phi + y^R_{ue} \bar{u}^c e \phi^*$$

- **Consider the SU(2) scalar singlets LQ:**

  - “down type”: $\phi(3,1,-1/3)$
  - “up-type”: $\phi(3,1,2/3)$
The message to convey: it is possible that new un-explored LQ phenomenology @ TeV-scale energies may be “hiding” in the tails of the UV physics

Effective Field Theory for “light” LQ’s may be important

Assume a light LQ to be one of the low-energy d.o.f and construct the “LQ-SMEFT”
The LQ-SMEFT framework:

\[ \mathcal{L} = \mathcal{L}_{\phi SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_i f_i O_i^{(n)} \]

The higher dim. \((n>4)\) effective opts \(O_i^{(n)}\) are constructed out of the SM + “light” LQ field

- Consider the SU(2)-singlets scalar LQ’s

\(\phi(3,1,-1/3)\) or \(\phi(3,1,2/3)\)

to be “light” fields ...
The LQ-SMEFT - physical picture

Intermediate heavy states of the underlying theory with $M_{\text{heavy}} > \Lambda$ that can be indirectly probed (in the EFT framework)

Light LQ’s: $M_\phi < \Lambda$

$\phi(3,1,-1/3)$ or $\phi(3,1,2/3)$

$$\mathcal{L} = \mathcal{L}_{\phi SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_i f_i O_i^{(n)}$$

( $O_i$ constructed out of the SM+LQ fields and SM symmetries)
The LQ-SMEFT with $\phi(3,1,-1/3)$ or $\phi(3,1,2/3)$

Some good reasons for a light (TeV-scale) scalar LQ

light scalar LQ’s + SM Higgs scenarios:
- $\phi(3,1,-1/3)$ + Higgs residing in the same representation; 10 dim multiplet in an SO(10) GUT framework
  Aydemir, Mandel, Mitra, arxiv:1902.08108
- scalar LQ’s + Higgs are PNGB’s of a composite GUT model
  e.g.,
  Gripaios, Nardecchia, Renner, JHEP 2015, arxiv:1412.1791
  Marzocca, JHEP 2018, arxiv:1803.10972
  Da Rold, Lamagna, JHEP 2019, arxiv:1812.08678

TeV-scale $\phi(3,1,-1/3)$ to address/explain B-anomalies ( $R_D^{(*)}$, $R_K^{(*)}$ )

e.g.,
  Sakaki, Tanaka, Tayduganov, Watanabe, PRD 2013, arxiv:1309.0301
  Hiller, Schmaltz, PRD 2014, arxiv:1408.1627
  Freytsis, Ligeti, Ruderman, PRD 2015, arxiv:1506.08896
  Alonso, Grinstein, Martin, Camalich, JHEP 2015, arxiv:1505.05164
  Bauer, Neubert, PRL 2016, arxiv:1511.01900
  Mandal, Mitra, Raz, PRD 2019, arxiv:1811.03561
The LQ-SMEFT – the case of $\phi(3,1,-1/3)$

• **dim. 5:** only 2 tree-level generated dim. 5 opts involving $\phi(3,1,-1/3)$: both violate lepton number by 2 units ...

$$\Delta \mathcal{L}_{\phi SM}^{(5)}(\phi) = \frac{f_\ell d_\phi H}{\Lambda_\ell d_\phi H} \ell d \tilde{H} \phi^* + \frac{f d^2_\phi^2}{\Lambda d^2_\phi^2} \tilde{d} d^c \phi^2 + \text{H.c.}$$
**The LQ-SMEFT – the case of $\phi(3,1,-1/3)$**

- **dim. 5:** only 2 tree-level generated dim. 5 opts involving $\phi(3,1,-1/3)$:
  
  Both violate lepton number by 2 units ...

\[
\Delta \mathcal{L}^{(5)}_{\phi SM} = \frac{f_{\ell d} \phi H}{\Lambda_{\ell d} \phi H} \bar{\ell} d \tilde{H} \phi^* + \frac{f d^2 \phi^2}{\Lambda d^2 \phi^2} \bar{d} d^c \phi^2 + \text{H.c.}
\]

**Intermediate heavy states**

$\Phi = \Phi(3,2,1/6)$
$\Psi = \Psi(1,1,0), \Psi(1,3,0), \Psi(3,2,-5/6)$

**Intermediate heavy states**

$\Phi = \Phi(6,1,-2/3)$
$\Psi = \Psi(1,1,0), \Psi(8,1,0)$

+ **the Weinberg operator:**

Also generated by $\Psi = \Psi(1,1,0)$ (type I seesaw) and/or $\Psi(1,3,0)$ (type III seesaw): 

\[
\frac{f_W}{\Lambda_W} \bar{\ell} c \tilde{H}^* \tilde{H}^\dagger \ell
\]
### The LQ-SMEFT – the case of $\phi(3, 1, -1/3)$

<table>
<thead>
<tr>
<th>$\phi$ multiplicity</th>
<th>The LQ-SMEFT @ dim. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi^6$ $\Rightarrow$</td>
<td>$</td>
</tr>
<tr>
<td>$\phi^4$ $\Rightarrow$</td>
<td>$\phi^4H^2$</td>
</tr>
<tr>
<td>$\phi^3$ $\Rightarrow$</td>
<td>$\phi^3\bar{\psi}\psi$</td>
</tr>
<tr>
<td>$\phi^2$ $\Rightarrow$</td>
<td>$</td>
</tr>
<tr>
<td>$\phi$ $\Rightarrow$</td>
<td>$\phi^2\psi^2D^2$, $\phi^2\psi^2D^2$, $\phi^2\psi^2H^2$</td>
</tr>
</tbody>
</table>

**e.g.,**

$$D^2 \times \bar{q}q^c \phi \rightarrow (\bar{q}D_\mu l^c)D^\mu \phi, (\bar{q}\sigma_{\mu\nu}l^c)B_{\mu\nu}^\mu \phi, (\bar{q}\sigma_{\mu\nu}\sigma^I l^c)W_I^\mu \phi, (\bar{q}\sigma_{\mu\nu}\lambda^A l^c)G_A^{\mu\nu} \phi$$

This is the complete list of dim.6 opts for $\phi(3, 1, -1/3)$ ...
Low-energy lepton number violating (LNV) effect in the LQ-SMEFT

New mechanisms for loop generated Majorana neutrino masses
loop generated

Majorana Neutrino masses

- Weinberg opt
  \[ \frac{f_W}{\Lambda_W} \overline{\nu} \bar{H}^{*} \tilde{H}^{\dagger} \nu \]

- Tree-level
  \[ \langle H \rangle \psi \langle \bar{H} \rangle \]

- 1-loop
  \[ \frac{f_{\ell d \phi H}}{\Lambda_{\ell d \phi H}} \overline{\nu} \bar{d} \tilde{H} \phi^{*} \]
  \[ \text{dim.} 4 \]

- 2-loop
  \[ \frac{f_{d^2 \phi^2}}{\Lambda_{d^2 \phi^2}} \overline{d} d \phi^2 \]
  \[ \text{dim.} 4 \]

SMEFT

LQ-SMEFT

Shaouly Bar-Shalom

NP Searches/BSM
BNL Forum 2019
**Majorana Neutrino masses**

**Weinberg opts**

\[
\frac{f_W}{\Lambda_W} \ell c \tilde{H}^* \tilde{H}^+ \ell
\]

**Tree-level**

\[
\langle \mathcal{H} \rangle \psi \langle \mathcal{H} \rangle
\]

\[\nu \rightarrow \nu\]

\[
m_{\nu} (\Lambda) \sim f_W \cdot \frac{v^2}{\Lambda_W}
\]

\[m_{\nu} < eV\]

both opts severely suppressed

(\(\Lambda\) too large to be relevant for LHC pheno ...)

**1-loop**

\[
\frac{f_{\ell d \phi H}}{\Lambda_{\ell d \phi H}} \ell d \tilde{H} \phi^*
\]

\[
y_{qL}^c q^c \tau_2 \ell \phi^*
\]

\[\text{dim. 4}\]

\[
m_{\nu} (\Lambda) \sim \frac{3m_d}{16\pi^2} \frac{f \cdot y_{qL}^L v}{\sqrt{2}} \frac{\Lambda}{\Lambda^2} \ln \left( \frac{\Lambda^2}{M_{\phi}^2} \right)
\]

**2-loop**

\[
\frac{f_{d^2 \phi^2}}{\Lambda_{d^2 \phi^2}} d d^c \phi^2
\]

\[\text{dim. 4}\]

\[
m_{\nu} (\Lambda) \sim \frac{f \cdot (y_{qL}^L)^2 3m_d^2}{(16\pi^2)^2} \frac{\Lambda}{\Lambda^2} \cdot \ln^2 \left( \frac{\Lambda^2}{M_{\phi}^2} \right)
\]

\[m_{\nu} < eV\] with \(\Lambda \sim O(1 \text{ TeV})\)

naturally generate sub-eV \(m_{\nu}\)

@ 2-loops with \(\Lambda \sim 5 \text{ TeV}\)

\[\Rightarrow\] no useful bound on \(d^2 \phi^2\) opts ...

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NP Searches/BSM

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We are left with a single class of viable \( \text{dim.5} \) ops for TeV-scale physics

\[ \phi(3,1,-1/3) \]

\( O(1) \) Wilson coefficients & a TeV-scale cutoff:

\[ \Lambda_{d^2\phi^2} \sim O(\text{few TeV}) \quad \& \quad f_{d^2\phi^2} \sim O(1) \]
We are left with a single class of viable dim. 5 opts for TeV-scale physics.

\[ \phi(3,1,-1/3) \]

\[ \frac{f d^2 \phi^2}{\Lambda d^2 \phi^2} \]

\[ \frac{f u^2 \phi^2}{\Lambda u^2 \phi^2} \]

\[ \Lambda_d^{d^2 \phi^2} \sim O(\text{few TeV}) \quad \text{&} \quad f_{d^2 \phi^2} \sim O(1) \]

Consider also the up-type \( \phi(3,1,2/3) \):

4 possible dim. 5 opts

\[ \Delta L^{(5)}_{\phi SM} = \frac{f u^2 \phi^2}{\Lambda u^2 \phi^2} \bar{u} \bar{u}^c \phi^2 + \frac{f d^2 \phi^2}{\Lambda d^2 \phi^2} \bar{d} d^c \phi^2 + \frac{f q e \phi^2}{\Lambda q e \phi^2} \bar{q} e H \phi + \frac{f u^2 \phi^2}{\Lambda u^2 \phi^2} \bar{u} u^c \phi^2 + \text{H.c.} \]

Similar importance for \( \phi(3,1,2/3) \) production @LHC:

\[ \Lambda_u^{u^2 \phi^2} \sim O(\text{few TeV}) \quad \text{&} \quad f_{u^2 \phi^2} \sim O(1) \]

\[ \text{also not constrained: } \Lambda_u^{u^2 \phi^2} \sim O(\text{few TeV}) \quad \text{&} \quad f_{u^2 \phi^2} \sim O(1) \]
signals of the LQ-SMEFT paradigm

New & surprising LNV ($\Delta L=2$) LQ collider signatures @LHC13 & beyond

\[ \frac{f_u^2 \phi^2}{\Lambda_u^2 \phi^2} \bar{u}u^c \phi^2 \]

\[ \frac{f_d^2 \phi^2}{\Lambda_d^2 \phi^2} \bar{d}d^c \phi^2 \]

CSX’s calculated with MadGraph5;
producing a dedicated UFO model for the LQ-SMEFT framework (using FeynRules …)
Assume 3\textsuperscript{rd} generation LQ’s

not necessary but provides an interesting example of the rich pheno involved
and also connects to the B-anomalies ...

easy to construct/impose: with a $Z_3$ generation symmetry

(more details in arxiv: 1812.03178)
the $d^2\phi^2$ & $u^2\phi^2$ opts & $\phi\phi$ pair production

renormalizable $\phi$SM framework

QCD production

LQ-SMEFT framework

\[
\frac{f_u^2\phi^2}{\Lambda_u^2\phi^2} \bar{u}u^c \phi^2
\]

\[
\frac{f_d^2\phi^2}{\Lambda_d^2\phi^2} \bar{d}d^c \phi^2
\]
the $d^2\phi^2$ & $u^2\phi^2$ opts & $\phi\phi$ pair production

renormalizable $\phi$SM framework

LQ-SMEFT framework

opposite-charged $\phi\phi^*$ production

same-charge $\phi\phi$ production
the $d^2 \phi^2$ & $u^2 \phi^2$ opts & $\phi \phi$ pair production

renormalizable $\phi$SM framework

renormalizable $\phi$SM framework

LQ-SMEFT framework

QCD production

opposite-charged $\phi \phi^*$ production

same-charge $\phi \phi$ production

\[
\hat{\sigma}(pp_{(gg,qq)} \rightarrow \phi \phi^*) \propto \frac{1}{s}
\]

\[
\hat{\sigma}(pp_{(qq)} \rightarrow \phi \phi) = \frac{f_{u^2 \phi^2}}{\Lambda_{u^2 \phi^2}} \frac{f_{d^2 \phi^2}}{\Lambda_{d^2 \phi^2}} \frac{1 - \frac{4M^2_{\phi^2}}{\hat{s}}}{12\pi} \]

CSX falls with $E$

CSX grows with $E$
**the $d^2\phi^2$ & $u^2\phi^2$ opts & $\phi\phi$ pair production**

**renormalizable $\phi$SM framework**

QCD production

**opposite-charge $\phi\phi^*$ production**

\[ \hat{\sigma}(pp_{(gg,qq)} \rightarrow \phi\phi^*) \propto \frac{1}{s} \]

*CSX drops with $E_\text{CM}$*

**LQ-SMEFT framework**

\[ \frac{f_{u^2\phi^2}}{\Lambda u^2\phi^2} \bar{u}u \phi^2 \]

\[ \frac{f_{d^2\phi^2}}{\Lambda d^2\phi^2} \bar{d}d \phi^2 \]

**same-charge $\phi\phi$ production**

\[ \hat{\sigma}(pp_{(qq)} \rightarrow \phi\phi) = \frac{f_{q2\phi^2}}{\Lambda^2 q2\phi^2} \left(1 - \frac{4M^2}{\hat{s}}\right)^{1/2} \]

*CSX grows with $E_\text{CM}$*

**Collider signature**

$pp \rightarrow \phi\phi^* \rightarrow \tau^+\tau^-$, *opposite-sign leptons*

$pp \rightarrow \phi\phi \rightarrow \tau^+\tau^+, \tau^-\tau^-$, *same-sign leptons !!!*
**the $d^2\phi^2$ & $u^2\phi^2$ opts & $\phi\phi$ pair production**

**expectations: NP scale $\Lambda=5$ TeV**

<table>
<thead>
<tr>
<th>LQ-SMEFT (dim.5: $\Lambda=5$ TeV)</th>
<th>$L_{\phi\text{SM}}$ (dim. 4)</th>
</tr>
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<tbody>
<tr>
<td>$d^2\phi^2$: $pp_{(dd)} \rightarrow \phi\phi$</td>
<td>$u^2\phi^2$: $pp_{(uu)} \rightarrow \phi\phi$</td>
</tr>
<tr>
<td>QCD: $pp_{(gg,qq)} \rightarrow \phi\phi^*$</td>
<td></td>
</tr>
<tr>
<td>$\sigma(M_{\phi}=1 \text{ TeV})$</td>
<td>14 fb</td>
</tr>
<tr>
<td>$\sigma(M_{\phi}=2 \text{ TeV})$</td>
<td>0.3 fb</td>
</tr>
</tbody>
</table>

LQ-SMEFT LQ signals are much larger than “standard” QCD LQ-production.

*e.g., $M(LQ) \sim 2$ TeV*

a factor of 1000 enhancement for same-charge LQ pair-prod.!
Asymmetric $\phi\phi$ vs $\phi^*\phi^*$ prod (enhanced dd/uu pdf’s …)
An important extra handle

Asymmetric $\phi\phi$ vs $\phi^*\phi^*$ prod (enhanced dd/uu pdf’s …)

$\hat{\sigma}(pp_{(qq)} \rightarrow \phi\phi) \gg \hat{\sigma}(pp_{(qq)} \rightarrow \phi^*\phi^*)$
LNV signatures from same-charge $\phi\phi$ pair production:

When the LQ decays to 3$^{rd}$ gen fermions:
(note: decay of $\phi(3,1,2/3) \rightarrow$ quark+lepton are pure EFT ...)

<table>
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<td>3$^{rd}$ gen $\phi(3,1,-1/3)$</td>
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<tr>
<td>$d^2\phi^2$: $pp_{(dd)} \rightarrow \phi\phi$</td>
</tr>
<tr>
<td>$\phi\phi \rightarrow tt\tau^+\tau^-$</td>
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<td>$\phi\phi \rightarrow \tau^+\tau^+ + 2j_b$</td>
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same-charge $\phi\phi$ prod yield same-sign lepton pairs!
**LNV signatures from same-charge $\phi\phi$ pair production:**

When the LQ decays to 3\textsuperscript{rd} gen fermions:

(\textit{note: decay of }$\phi(3,1,2/3) \rightarrow$ quark+lepton are pure EFT ...)

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\textit{same-charge }$\phi\phi$\textit{ prod yield same-sign lepton pairs!}

In contrast to the conventional QCD LQ pair-prod signals:

<table>
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<th>$L_{\phi SM}$ (dim. 4)</th>
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<tr>
<td>$3^{\text{rd}}$ gen $\phi(3,1,-1/3)$ or $\phi(3,1,2/3)$</td>
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<tr>
<td>\textbf{QCD}: $pp_{(gg,qq)} \rightarrow \phi\phi^*$</td>
</tr>
<tr>
<td>$\phi\phi^* \rightarrow \bar{t}t\tau^+\tau^-, \bar{t}t+E_T$</td>
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<td>$\phi\phi^* \rightarrow \tau^+\tau^- + 2\cdot j_b$</td>
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</table>
LNV signatures from same-charge $\phi \phi$ pair production:

| LQ-SMEFT (dim.5) |  
|------------------|---|
| $3^{\text{rd}}$ gen $\phi(3,1,-1/3)$ | $3^{\text{rd}}$ gen $\phi(3,1,2/3)$ |
| $d^2 \phi^2: pp_{(dd)} \rightarrow \phi \phi$ | $u^2 \phi^2: pp_{(uu)} \rightarrow \phi \phi$ |
| $\phi \phi \rightarrow t \bar{t} \tau^- \tau^-$ | $\phi \phi \rightarrow t \bar{t} + E_T$ |
| | $\phi \phi \rightarrow \tau^+ \tau^+ + 2 \cdot j_b$ |

- Typical rates at 13 TeV LHC with 300 fb$^{-1}$ (after top-decays ...): $M_\phi = 1 \text{ TeV} \& \Lambda = 5 \text{ TeV}$
  - 5000 positively charged $\tau^+ \tau^+$ events via $pp \rightarrow \phi \phi \rightarrow \tau^+ \tau^+ + 2 \cdot j_b$
  - 500 negatively charged $\tau^- \tau^-$ events via $pp \rightarrow \phi \phi \rightarrow \tau^- \tau^- + 2 \cdot j_b + 4 \cdot j$
  - 50 positively charged $l^+ l^+$ events via $pp \rightarrow \phi \phi \rightarrow l^+ l^+ + 2 \cdot j_b + E_T$

Much smaller rate for corresponding opposite-charged lepton pair events!
extra handle for these LQ-SMEFT signals

Asymmetric same-sign lepton production:

\[
\phi(3,1,-1/3) \quad \phi(3,1,2/3)
\]

\[
N(tt\tau^-\tau^-) >> N(\bar{t}t\tau^+\tau^+) \quad N(\tau^+\tau^+ + 2j_b) >> N(\tau^-\tau^- + 2j_b)
\]

\Rightarrow \text{Useful double-charge asymmetry with no irreducible backg. e.g.,}

\[
A_{\tau\tau} \equiv \frac{\sigma(pp \to \tau^-\tau^- + X_j) - \sigma(pp \to \tau^+\tau^+ + X_j)}{\sigma(pp \to \tau^-\tau^- + X_j) + \sigma(pp \to \tau^+\tau^+ + X_j)} \approx 100%
\]

\(X_j = \text{any accompanying jet}\)
Unfortunately, LHC13 can be sensitive to these same-charge $\phi\phi$ signals only up to $M_\phi \sim 1-2$ TeV

$CSX(\phi\phi)$ drops sharply with $M_\phi$ @LHC13 due to the limited phase-space

$\phi\phi$ pair production @ higher energy colliders
Future higher-energy hadron colliders will be sensitive to the LQ-SMEFT dynamics up to LQ masses of \( M_\phi \sim 5 \text{ TeV}\) & NP scale of \( \Lambda \sim 15 \text{ TeV}\) i.e., with CSX's for same-sign charged leptons larger than \( \sigma \sim O(1 \text{ fb})\).
• Introducing the LQ-SMEFT framework:

- LQ assumed to be one of the “light” fields
- Sidestep model dependencies in LQ phenomenology

- Going beyond the renormalizable LQ Lag. has interesting outcomes:

- 2-loop sub-eV Majorana neutrino masses:
  - Lowering the typical $\Delta L=2$ scale by orders of magnitudes ($\Lambda \ll 10$ TeV)

- Leading effects from several new $\Delta L=2$ dim.5 effective opts
  - Effects of higher dim LQ opts $\gg$ effects from “standard” dim4 LQ terms

$$\sigma(pp \rightarrow \phi\phi)_{\text{dim5}} \gg \sigma(pp \rightarrow \phi\phi^*)_{\text{QCD}}$$
• “smoking gun” same-sign lepton pair signals at the LHC13 & beyond:
  - with highly asymmetric double-charge rates:
    \[ \sigma(pp \to \phi\phi) \gg \sigma(pp \to \phi^*\phi^*) \to \text{yielding e.g.,} \]
    \[ N(pp \to \tau^+\tau^+ + 2 \cdot j_b) \gg N(pp \to \tau^-\tau^- + 2 \cdot j_b) \]
    \[ N(pp \to \tau^-\tau^- + 2 \cdot j_b + 4 \cdot j) \gg N(pp \to \tau^+\tau^+ + 2 \cdot j_b + 4 \cdot j) \]
    \[ N(pp \to \ell^+\ell^+ + 2 j_b + E_T) \gg N(pp \to \ell^-\ell^- + 2 j_b + E_T) \]
  - & CSX’s much larger than the “standard” opposite-sign lepton pairs signals:
    \[ \sigma(pp \to \phi\phi \to \ell^\pm\ell^\mp + X) \gg \sigma(pp \to \phi\phi^* \to \ell^\pm\ell^\mp + X) \]
  - sensitivities up to \( M(LQ) \sim 2 \text{ TeV} \) @LHC13 [\( \Lambda \sim 5 \text{ TeV} \)]
    \( M(LQ) \sim 5 \text{ TeV} \) @FCC-hh100 [\( \Lambda \sim 15 \text{ TeV} \)]

  further thoughts: extending the LQ-SMEFT framework to more LQ types
Backups & more slides
The LQ paradigm – some basic fact for LHC pheno …

- LQ’s are colored fields
  ⇒ should be copiously (QCD) pair produced @LHC if $M_{LQ} \sim O(1 \text{ TeV})$

- Typical CSX is: $\sigma(pp \rightarrow \phi\phi^*) \sim 5(0.01) \text{ [fb]}$ for $M_\phi \sim 1(2) \text{ TeV}$
The LQ paradigm – some basic fact for LHC pheno …

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- Single LQ production via quark-gluon fusion $qg \to \phi\ell$ may also be important
  if Yukawa-like LQ-quark-lepton couplings are sizable

- e.g., if the LQ is a “1st generation scalar LQ”;

these channels are however model dependent!
The LQ paradigm – some basic fact for LHC pheno …

• LQ's decay via: \( \phi \rightarrow q_i e_j \), \( q_i \nu_j \)
  \[ \Gamma \sim (\gamma_{\phi q})^2 \frac{M_\phi}{16\pi} \]

• LQ categorized according to their couplings to a lepton-quark pair:
  \( 1^{st}, 2^{nd} \) or \( 3^{rd} \) gen. LQs …

• \( \Rightarrow \) rich and possibly surprising LQ's collider phenomenology:
  - lepton + light jet + missing ET
    \( pp \rightarrow \ell^+ \ell^- + j + \not{E}_T \)
  - lepton + 2 light jets + missing ET
    \( pp \rightarrow \ell^+ \ell^- + 2j + \not{E}_T \)
  - opposite-charged lepton pair + single light let
    \( pp \rightarrow \ell^+ \ell^- + j \)
  - opposite-charged lepton pair + 2 light lets
    \( pp \rightarrow \ell^+ \ell^- + 2j \)
  - b-jet(s) + lepton(s) with or without missing ET \( (3^{rd} \) gen. LQ)
    \( pp \rightarrow \ell^+ \ell^- + n \cdot j_b + \not{E}_T \)
  - top-quark(s) + lepton(s) with or without missing ET \( (3^{rd} \) gen. LQ)
    \( pp \rightarrow \ell^+ \ell^- + t\bar{t} + \not{E}_T \)
  - …

No LQ signal yet; typical bounds are \( M_\phi > 1 \) TeV, depending on the underlying \( \phi \rightarrow \) quark+lepton decay pattern and/or on the LQ generation (typically lower bounds for \( 3^{rd} \) gen LQ …)
**Neutrino masses**

\[ \frac{f_W}{\Lambda_W} \ell \bar{c} H^* \bar{H}^\dagger \ell \]

**Tree-level**

- \[ \langle H \rangle \]
- \[ \langle H^* \rangle \]
- \[ \nu \]
- \[ \nu \]

\[ m_\nu (\Lambda) \sim f_W \cdot \frac{v^2}{\Lambda_W} \]

**1-loop**

- \[ \frac{f_\ell d \phi_H}{\Lambda_{\ell d \phi_H}} \bar{c} \ell \bar{H} \phi^* \]

\[ m_\nu (\Lambda) \sim \frac{3 m_d f \cdot y_{q_L} y_{\ell \phi} v}{16 \pi^2 \sqrt{2}} \Lambda \ln \left( \frac{\Lambda^2}{M_\phi^2} \right) \]

\[ m_\nu < eV \]

**no useful bound**

if \( \phi \) is a 3\(^{rd} \) gen LQ with \( y_{q_L} \sim O(1) \)

\[ y_{\nu e}^R << 1 \]

i.e., if \( y_{\nu e}^R \sim 0.1 \) or smaller, then \( M_\phi < \Lambda \sim O(\text{few TeV}) \) & \( f_d^2 \phi^2 \sim O(1) \) are allowed ...

**\( \nu \)-less 2\( \beta \) (O\( \nu \)\( \beta \beta \)) decay**

\[ \frac{f d^2 \phi^2}{\Lambda d^2 \phi^2} \bar{d} d c \phi^2 \]

\[ \text{dim. 4} \]

\[ y_{\nu e}^R u^c e \phi^* \]

\[ \frac{\Lambda d^2 \phi^2}{\text{TeV}} \geq 150 \cdot \frac{f d^2 \phi^2 \cdot |y_{\nu e}^R|^2}{(M_\phi/\text{TeV})^4} \]

**both opts severely suppressed**

\[ \text{e.g., if } \phi \text{ is a 3}\(^{rd} \) gen LQ with } y_{q_L} \sim O(1) \text{ then } f_{\ell d \phi H} < O(10^{-6}) \text{ for } \Lambda \sim O(1 \text{ TeV}) \]
Neutrino masses – a note

The heavy fermionic state $\Psi(1,1,0)$ can generate all dim. 5 opt's:

$$\frac{f_W}{\Lambda_W} \bar{\ell}^c \tilde{H}^* \tilde{H}^+ \ell \quad \frac{f_{\ell d^2 \phi} H}{\Lambda_{\ell d \phi}} \bar{\ell} d \tilde{H} \phi^* \quad \frac{f_{d^2 \phi^2}}{\Lambda_{d^2 \phi^2}} \bar{d} d^c \phi^2$$

Therefore, there are several scenarios that do not require small couplings:

1. $\Psi(1,1,0)$ generates all dim. 5 opt's: Weinberg, $\ell d \phi H$ and $d^2 \phi^2$ with a typical scale of $M_\Psi \sim O(10^{14} \text{ GeV})$. In this case, $m_\nu < eV$ is generated @ tree-level via type I seesaw by the Weinberg opt whereas the 1-loop and 2-loop contributions from $\ell d \phi H$ and $d^2 \phi^2$ respectively are negligible.

2. $\Psi(1,3,0)$ generates both Weinberg and $\ell d \phi H$ while $d^2 \phi^2$ is generated by a different mediator. Then, with $M_\Psi \sim O(10^{14} \text{ GeV})$, $m_\nu < eV$ is generated at tree-level through the type I or III seesaw by the Weinberg opt, and the 1-loop contribution from the dim.5 opt $\ell d \phi H$ is subdominant.

3. The Weinberg opt is not relevant to neutrino masses (there are no heavy states that generate it ...). In this case $m_\nu < eV$ may still be generated @ 1-loop or 2-loop through the dim.5 opt $\ell d \phi H$ or $d^2 \phi^2$ respectively (rather than through a seesaw ...), if these opt's are generated @ tree-level by other heavy mediators.
LQ-SMEFT with $\phi(3,1,-1/3)$ & $\phi(3,1,2/3)$

@dim.5

\[ \frac{f_W}{\Lambda_W} \bar{\ell} \ell \tilde{H}^* \tilde{H}^+ \ell \]

dim.5 SM fields: Weinberg opt

\[ \Delta L_{\phi SM}^{(5)} = \frac{f_{\ell d \phi H}}{\Lambda_{\ell d \phi H}} \bar{\ell} d \tilde{H}^* \phi^* + \frac{f_{d^2 \phi^2}}{\Lambda_{d^2 \phi^2}} \bar{d} d^c \phi^2 + \text{H.c.} \]

dim.5 $\phi(3,1,2/3)$ opts

\[ \Delta L_{\phi SM}^{(5)} = \frac{f_{u u \phi H}}{\Lambda_{u u \phi H}} \bar{u} u \tilde{H}^* \phi^* + \frac{f_{\ell d \phi H}}{\Lambda_{\ell d \phi H}} \bar{\ell} d \tilde{H}^* \phi^* + \frac{f_{q e \phi H}}{\Lambda_{q e \phi H}} \bar{q} e H^* \phi + \frac{f_{u^2 \phi^2}}{\Lambda_{u^2 \phi^2}} \bar{u} u^c \phi^2 + \text{H.c.} \]

dim.5 $\phi(3,1,-1/3)$ opts

• If both up & down-type SU(2) singlet scalar LQ's are included as light DOF then four more dim.5 opts:

\[ \bar{q} \ell c \phi^* \phi^* u, \bar{u} e c \phi^* \phi^* u, \bar{q} q c \phi \phi \phi u \text{ and } \bar{u} u c \phi \phi u \]
Assume $3^{\text{rd}}$ generation LQ’s

(couple dominantly to $3^{\text{rd}}$ gen. lepton-quark pairs)

- **easy to construct:** with a $Z_3$ generation symmetry, under which the physical SM fermions transform as:

\[
\psi^k \rightarrow e^{i\alpha(\psi^k)\tau_3} \psi^k, \quad \tau_3 \equiv 2\pi/3
\]

- **A simple example:**
  - fermion charges: $\alpha(\psi^k) = k$, $k =$ generation index
  - LQ charge: $\alpha(\phi) = 3$

For $3^{\text{rd}}$ gen $\phi(3, 1, -1/3)$:

\[
\mathcal{L}_{Y, \phi_3} \approx y^L_{q3} \ell_3 \left( \bar{t}^c_L \tau_L + \bar{b}^c_L \nu_{\tau L} \right) \phi^* + y^R_{u3} e_3 \bar{t}^c_R \tau_R \phi^* + \text{H.c.}
\]

$Z_3$ gen. symmetry is exact in the limit of a diagonal CKM; $Z_3$-breaking $\sim$ off-diagonal CKM ...

it is broken in the underlying heavy theory $\Rightarrow$ proportional to $v^2/\Lambda^2 \ll O(1)$ ...
In the SM sector

Generation breaking in the SM can be traced to the higher dim opts involving the Higgs and fermion fields: e.g., off-diagonal Yukawa couplings from the dim.6 opts:

\[
\Delta \mathcal{L}_{qH} = \frac{H^+ H}{\Lambda^2} \left( f_{uH} \bar{q}_L \tilde{H} u_R + f_{dH} \bar{q}_L H d_R \right) + h.c.
\]

If e.g., \( \Lambda \sim 1.5, 3 \) or 5 TeV and \( f_{uH, dH} \sim O(1) \), then the resulting effective Yukawa couplings:

\[
Y_{\text{eff}} = f_{qH} \cdot v^2/\Lambda^2 \sim O(y_b), O(y_c) \text{ or } O(y_s), \text{ respectively} \ldots
\]

If \( \Phi(3,2,1/6) \) couples to 1\textsuperscript{st} and/or 2\textsuperscript{nd} generation down-quarks & \( \phi \) is a 3\textsuperscript{rd} gen LQ, then the \( Z_3 \) gen symmetry is broken and the scale of gen breaking is \( M_{\Phi(3,2,1/6)} \):

\( \Phi(3,2,1/6) \) is the mediator of generation breaking …

The gen breaking effect is \( \sim g_{\Phi dd} \cdot g_{\Phi\phi}/M_{\Phi} \)

Matching to the EFT framework: \( g_{\Phi dd} \cdot g_{\Phi\phi} \rightarrow f_{d2\phi}, M_{\Phi} \rightarrow \Lambda_{d2\phi} \)

\[
\frac{f d^2 \phi^2}{\Lambda d^2 \phi^2}
\]
**LNV signatures from same-charge $\phi \phi$ pair production:**

When the LQ decays to 3\textsuperscript{rd} gen fermions:

(note: decay of $\phi(3,1,2/3)$ → quark+lepton are pure EFT ...)

<table>
<thead>
<tr>
<th>LQ-SMEFT (dim.5)</th>
<th>$L_{\phi SM}$ (dim. 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3\textsuperscript{rd} gen $\phi(3,1,-1/3)$</td>
<td>3\textsuperscript{rd} gen $\phi(3,1,2/3)$</td>
</tr>
<tr>
<td>$d^2 \phi^2$: $pp_{(dd)} \rightarrow \phi \phi$</td>
<td>$u^2 \phi^2$: $pp_{(uu)} \rightarrow \phi \phi$</td>
</tr>
<tr>
<td>$\phi \phi \rightarrow tt\tau^-\tau^-$</td>
<td>$\phi \phi \rightarrow tt+\not{E}_T$</td>
</tr>
<tr>
<td>$\phi \phi \rightarrow 2j_b+\not{E}_T$</td>
<td>$\phi \phi \rightarrow \tau^+\tau^+ + 2j_b$</td>
</tr>
<tr>
<td>$\phi \phi \rightarrow t\tau^- + j_b + \not{E}_T$</td>
<td>$\phi \phi \rightarrow t\tau^++ j_b + \not{E}_T$</td>
</tr>
</tbody>
</table>

- Asymmetric same-sign lepton production, e.g.,:
  \[ N(tt\tau^-\tau^-) >> N(tt\tau^+\tau^+) , N(\tau^+\tau^+ + 2j_b) >> N(\tau^-\tau^- + 2j_b) \]

- Useful double-charge asymmetries with no irreducible backg, e.g.,

\[
A_{\tau\tau} \equiv \frac{\sigma(pp \rightarrow \tau^-\tau^- + X_j) - \sigma(pp \rightarrow \tau^+\tau^+ + X_j)}{\sigma(pp \rightarrow \tau^-\tau^- + X_j) + \sigma(pp \rightarrow \tau^+\tau^+ + X_j)} \sim 1
\]

\[ X_j = \text{any accompanying jet} \]
Main SM BG necessarily has $E_T$
Additional BG from fake/misidentified leptons is subdominant
Can also have higher jet-multiplicities mimicking signals with $E_T$
Focus on same-sign signals without $E_T$
SM BG is controlled via “no MET” veto
Signal yields prompt and well isolated same-sign leptons (emanate from TeV-scale particles)