Phenomenology of TeV-scale scalar Leptoquarks in the EFT

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Based on: arxiv: 1812.03178, JC, Shaouly Bar-Shalom (Technion), Amarjit Soni (BNL) & Jose Wudka (UC Riverside)
Outline

• Brief introduction & motivation

• 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 phenomenology (LNV) in the LQ-SMEFT
    • expectations & “SMOKING GUN” signals @ the LHC13 & beyond

• Summary and final notes
The LQ paradigm – some basic facts for LHC pheno

• LQ’s are colored fields
  \( \Rightarrow \) 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 facts 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 $M_\phi \sim 1(2) \text{ TeV}$

• Single LQ production via quark-gluon fusion $qg \rightarrow \phi l$ 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 facts for LHC pheno

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

- LQ categorized according to their couplings to a lepton-quark pair: 1st, 2nd or 3rd gen. LQs ...

- \Rightarrow rich and possibly surprising LQ's collider phenomenology:

  - lepton + light jet + missing ET  $pp \rightarrow l^\pm + j + \not{E}_T$
  - lepton + 2 light jets + missing ET  $pp \rightarrow l^\pm + 2j + \not{E}_T$
  - opposite-charged lepton pair + single light jet  $pp \rightarrow l^+l^- + j$
  - opposite-charged lepton pair + 2 light jets  $pp \rightarrow l^+l^- + 2j$
  - b-jet(s) + lepton(s) with or without missing ET (3rd gen. LQ)  $pp \rightarrow l^+l^- + n'b + \not{E}_T$
  - top-quark(s) + lepton(s) with or without missing ET (3rd gen. LQ)  $pp \rightarrow l^+l^- + \not{t}_T$
  - ...

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 3rd gen LQ ...
 Scalar LQ’s $\phi(3,1,-1/3)$ or $\phi(3,1,2/3)$

Some good reasons for a 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 renormalizable $\phi$SM framework:

consider the SU(2) scalar singlets LQ: “down type”: $\phi(3, 1, -1/3)$  
“up-type”: $\phi(3, 1, 2/3)$

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

\[ \mathcal{L}_{Y,\phi} = y_{q\ell} q^c \tau_2 \ell \phi^* + y_{ue} \bar{u}^c e \phi^* \]

- Scalar interactions:

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

⇒ the $\phi$SM model:

\[ \mathcal{L}_{\phi SM} = \mathcal{L}_{SM} + \mathcal{L}_{Y,\phi} + \mathcal{L}_{H,\phi} \]
Hybrid EFT’s are (quite) common

• **Axion models**
  
  Jaeckel, Jankowiak, Spannowsky Phys Dark Univ. 2013 arxiv:1212.3620
  

• **Fermionic DM**
  
  Busoni, De Simone, Gramling, Morgante, Riotto JCAP 2014, arxiv:1402.1275
  
  Fedderke, Chen, Kolb, Wang JHEP 2014, arxiv:1404.2283

• **RH neutrinos**
  
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 dof and construct the “LQ-SMEFT”
The LQ-SMEFT framework for the SU(2)-singlet scalar LQ’s
φ(3,1,-1/3) or φ(3,1,2/3)

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

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

- **Assume:**
  - low-energy d.o.f. \(\subset\) a single TeV-scale “light” LQ

\[ \phi(3,1,-1/3) \text{ or } \phi(3,1,2/3) \]
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 $\phi(3,1,2/3)$

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

( $O_i$ constructed out of the SM+LQ fields and SM symmetries)
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 ...

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

- **dim. 5**: only 2 tree-level generated dim. 5 opts involving $\phi(3,1,-1/3)$:
  
  $$\Delta L_{\phi SM}^{(5)} = \frac{f_\ell d \phi H}{\Lambda_\ell d \phi H} \bar{\ell} d \tilde{H} \phi^* + \frac{f_d^2 \phi^2}{\Lambda d^2 \phi^2} \bar{d} d^c \phi^2 + H.c.$$  

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):

$$\frac{f_W}{\Lambda_W} \bar{\ell}^c \tilde{H}^* \tilde{H} \ell$$
<table>
<thead>
<tr>
<th>$\phi$ multiplicity</th>
<th>\textbf{The LQ-SMEFT @ dim. 6}</th>
</tr>
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</table>
| $\phi^6$  | $\phi^6$  | \begin{align*}  
\phi^6 & \implies \phi^4 H^2 \\
& \implies (H^\dagger H) (\phi^* \phi)^2 \\
& \implies |\phi|^2 |D\phi|^2 \\
\phi^4 \implies & \phi^4 D^2  \\
& \implies |\phi|^2 (\bar{q}l^c \phi), |\phi|^2 (\bar{u}e^c \phi), |\phi|^2 (\bar{q}q \phi), |\phi|^2 (\bar{u}d \phi) \\
\phi^3 \implies & \phi^3 \psi^2  \\
& \implies |\phi|^2 (\bar{q}l^c \phi), |\phi|^2 (\bar{u}e^c \phi), |\phi|^2 (\bar{q}q \phi), |\phi|^2 (\bar{u}d \phi)  \\
\phi^2 \implies & \phi^2 \times \text{SM}  \\
& \implies |\phi|^2 O_{SM}^4  \\
& \implies \epsilon^{abc} \phi_a (D_\mu \phi)_b \tilde{\ell} \gamma^\mu q_c  \\
& \implies \epsilon^{abc} \phi_a (D_\mu \phi)_b \bar{e} \gamma^\mu d_c  \\
\phi \implies & \phi^2 \psi^2 D^2  \\
& \implies D^2 \times \bar{q}q^c \phi^*  \\
& \implies D^2 \times \bar{q}l^c \phi  \\
& \implies D^2 \times \bar{d}c \phi  \\
& \implies D^2 \times \bar{u}e^c \phi  \\
\psi^2 \phi^2 & \implies \phi^2 \psi^2 D  \\
& \implies (\bar{q}H) \gamma^\mu u^c D_\mu \phi^\dagger  \\
& \implies (\bar{q}H) \gamma^\mu d^c D_\mu \phi^\dagger  \\
& \implies (\bar{l}H) \gamma^\mu e^c D_\mu \phi  \\
& \implies (\bar{l}H) \gamma^\mu u^c D_\mu \phi  \\
\psi^2 \phi^2 & \implies \phi^2 \psi^2 H  \\
& \implies H^{\dagger 2} \phi^\dagger \bar{q}q^c  \\
& \implies H^{\dagger 2} \phi \bar{q}l^c  \\
& \implies H^{\dagger 2} \phi \bar{d}c^u  \\
& \implies H^{\dagger 2} \phi \bar{u}e^c  \\
& \implies \phi^\dagger (\bar{q}H)(H^\dagger l^c)  \\
& \implies \phi (\bar{q}H)(H^\dagger l^c)  \\
\text{e.g.,} & D^2 \times \bar{q}l^c \phi \rightarrow (\bar{q}D_\mu l^c) D^\mu \phi, (\bar{q}D^\mu l^c) B^{\mu\nu} \phi, (\bar{q}D^\mu \sigma^I l^c) W^{\mu\nu} \phi, (\bar{q}D^\mu \lambda^A I^c) G^{\mu\nu} \phi  \\
This is the complete list of dim.6 opts for $\phi(3,1,-1/3)$ ...
Low-energy $\Delta L=2$ effect from the dim.5 opts

Expectations & constraints

$$\Delta \mathcal{L}_{\phi SM}^{(5)} = \frac{f_{\ell d \phi} H}{\Lambda_{\ell d \phi H}} \bar{\ell} d \bar{H} \phi^* + \frac{f_{d^2 \phi^2}}{\Lambda_{d^2 \phi^2}} \bar{d} d \phi^2 + \text{H.c.}$$
Neutrino masses

The operator \[ \frac{f d^2 \phi^2}{\Lambda d^2 \phi^2} \bar{d}d^c \phi^2 \] contributes only at 2-loop:

\[
\begin{align*}
\bar{\nu}_L^c & \quad y_{qL}^L & \quad \nu_L \\
\phi & \quad d & \quad \phi
\end{align*}
\]

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

Therefore, no useful bound can be set on \( \Lambda d^2 \phi^2 \) (d-quark operator still relevant for colliders whereas s and b-quark operators can generate sub-eV neutrino mass)
We are left with a single class of viable dim. 5 opts for TeV-scale physics

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

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

\[ M_\phi < \Lambda d^2 \phi^2 \sim O(\text{few TeV}) \] and \[ f_{d^2 \phi^2} \sim O(1) \]
Consider also the up-type $\phi(3,1,2/3)$; 4 possible dim. 5 opts

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

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

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

also not constrained: $M_\phi < \Lambda_{u^2 \phi^2} \sim O(\text{few TeV})$ & $f_{u^2 \phi^2} \sim O(1)$
signals of the LQ-SMEFT paradigm

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

CSX's calculated with MadGraph5;
producing a dedicated UFO model for the LQ-SMEFT framework (using FeynRules ...)

Assume 3\textsuperscript{rd} generation LQ's
(couple dominantly to 3\textsuperscript{rd} gen. lepton-quark pairs)
**$d^2\phi^2$ & $u^2\phi^2$ opts effects $\phi\phi$ pair production:**

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

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

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

**opposite-charged $\phi\phi^*$ production**
\( d^2 \phi^2 \) & \( u^2 \phi^2 \) opts effects \( \phi \phi \) pair production:

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

same-charge \( \phi \phi \) production

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

opposite-charged \( \phi \phi^* \) production

expectations with NP scale \( \Lambda=5 \) TeV @LHC13

<table>
<thead>
<tr>
<th></th>
<th>LQ-SMEFT (dim. 5: ( \Lambda=5 ) TeV)</th>
<th>( L_{\phi SM} ) (dim. 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d^2 \phi^2 ): ( pp_{(dd)} \rightarrow \phi \phi )</td>
<td>14 fb</td>
<td>77 fb &gt; &gt;</td>
</tr>
<tr>
<td>( u^2 \phi^2 ): ( pp_{(uu)} \rightarrow \phi \phi )</td>
<td>3 fb</td>
<td>3 fb</td>
</tr>
<tr>
<td>QCD: ( pp_{(gg,qq)} \rightarrow \phi \phi^* )</td>
<td>0.3 fb</td>
<td>0.005 fb</td>
</tr>
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</table>
Asymmetric $\phi\phi$ vs $\phi^*\phi^*$ prod (enhanced $d\bar{d}/u\bar{u}$ pdf's ...)

$\hat{\sigma}(pp_{(qq)} \rightarrow \phi\phi) \gg \hat{\sigma}(pp_{(qq)} \rightarrow \phi^*\phi^*)$
Asymmetric $\phi\phi$ vs $\phi^*\phi^*$ prod (enhanced $dd/uu$ pdf's ...)

For “down type” LQ:

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

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

<table>
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<td>3rd gen $\phi(3,1,-1/3)$</td>
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<td>$d^2\phi^2$: $pp_{(dd)} \rightarrow \phi\phi$</td>
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<td>$\phi\phi \rightarrow \tau^+\tau^+2\cdot j_b$</td>
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Same-charge $\phi\phi$ production yields same-sign lepton pairs!

In contrast to the conventional QCD LQ pair production signals:

<table>
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<td>3rd gen $\phi(3,1,-1/3)$ or $\phi(3,1,2/3)$</td>
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<tr>
<td>QCD: $pp_{(gg,qq)} \rightarrow \phi\phi^*$</td>
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<td>$\phi\phi^* \rightarrow tt\tau^+\tau^-, \tilde{t}t+E_T^\tau$</td>
</tr>
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<td>$\phi\phi^* \rightarrow \tau^+\tau^+2\cdot j_b, 2\cdot j_b+E_T^\tau$</td>
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<tr>
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<td>$\phi\phi \rightarrow \tau^+\tau^+ + 2\cdot j_b$</td>
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- Typical rates at 13 TeV LHC with 300 fb$^{-1}$ (after top-decays ...):
  $M_\phi = 1$ TeV & $\Lambda = 5$ 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-sign lepton pair events!
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 $M_\phi \sim 5$ TeV & NP scale of $\Lambda \sim 15$ TeV i.e., with CSX’s for same-sign charged leptons larger than $\sigma \sim O(1 \text{ fb})$
Conclusion

• Introducing the LQ-SMEFT framework:
  - LQ assumed to be one of the "light" fields
  - leading effects from several new $\Delta L=2$ dim. 5 effective opts
    (beyond the well known higher scale Weinberg opt):
      - new LNV same-sign lepton pair signals @multi-TeV colliders
      - 2-loop Majorana Neutrino masses from NP scales $\Lambda \sim O(5 \text{ TeV})$

• "smoking gun" same-sign lepton pair signals at the LHC13 with
  asymmetric double-charge rates
  and CSX's much larger than the
  "standard" opposite-sign lepton pair signals

• Sensitivities up to $M(LQ) \sim 2 \text{ TeV} \ @LHC13 [\Lambda \sim 5 \text{ TeV}]$
  & $M(LQ) \sim 5 \text{ TeV} \ @FCC-hh100 [\Lambda \sim 15 \text{ TeV}]$
Backups & more slides
In addition to single LQ prod. can also have t-channel LQ exchanges:

which are important for large yukawa coupling $y \gtrsim O(1)$ and can give better access to the large LQ mass regime (where LQ pair production is phase-space suppressed).
Yukawa-like interactions of this type only contain the term:

\[ y^R_{d^i d^j} \bar{d}^R_{ci} d^R_{cj} \phi \]

Which violates baryon #, and in the presence of higher dim operators may mediate proton decay.

Assume this coupling is vanishingly small.
LQ-SMEFT with $\phi(3,1,-1/3)$ & $\phi(3,1,2/3)$ @dim.5

$$\frac{f_W}{\Lambda_W} \bar{\ell}^c \tilde{H}^* \tilde{H}^\dagger \ell$$

**dim.5 SM fields: Weinberg opt**

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

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

$$\Delta \mathcal{L}^{(5)}_{\phi_{SM}} = \frac{f_{\ell u} \phi_H}{\Lambda_{\ell u \phi_H}} \bar{\ell} u \tilde{H} \phi^* + \frac{f_{\ell d} \phi_H}{\Lambda_{\ell d \phi_H}} \bar{\ell} d H \phi^* + \frac{f_{q_e \phi H}}{\Lambda_{q_e \phi_H}} \bar{q} e H \phi + \frac{f_{u^2 \phi^2}}{\Lambda_{u^2 \phi^2}} \bar{u} u^c \phi^2 + \text{H.c.}$$

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

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

$$\bar{q} \ell^c \phi^*_d \phi_u^*, \bar{u} e^c \phi^*_d \phi_u^*, \bar{q} q^c \phi_d \phi_u \text{ and } \bar{d} u^c \phi_d \phi_u$$
Neutrino masses

The 2-loop contribution:

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

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

- **d-quark**: 2-loop neutrino mass is too small \( m_\nu \sim 10^{-4} \text{ eV} \) for \( f d^2 \phi^2 \cdot (y_{d\nu}^L)^2 \sim \mathcal{O}(1) \), therefore no useful bound can be set on \( \bar{d}d^c \phi^2 \).

- **s-quark**: resulting mass consistent with oscillation data \( m_\nu \sim \text{eV} \) for a NP scale of several TeV and \( f s^2 \phi^2 \cdot (y_{s\nu}^L)^2 \sim \mathcal{O}(1) \) therefore no useful bound can be put on \( \bar{s}s^c \phi^2 \).

- **b-quark**: We obtain \( m_\nu \sim \text{KeV} \) for \( f b^2 \phi^2 \cdot (y_{b\nu}^L)^2 \sim \mathcal{O}(1) \) and a NP scale of several TeV. Therefore either \( \Lambda b^2 \phi^2 \sim \mathcal{O}(1000) \text{ TeV} \) or \( f b^2 \phi^2 \cdot (y_{b\nu}^L)^2 \sim \mathcal{O}(10^{-3}) \).
**Neutrino masses**

$$\frac{f_W}{\Lambda_W} \bar{\ell} c \tilde{H}^* \tilde{H}^+ \ell$$

**Tree-level**

$$\langle H \rangle \quad \Psi \quad \langle H \rangle$$

$$\nu \quad \nu$$

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

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

$$m_\nu < eV$$

**1-loop**

$$\frac{f \ell \ell \phi H}{\Lambda \ell \ell \phi H} \bar{\ell} d \tilde{H} \phi^*$$

$$\bar{\nu}_L \quad d \quad \nu_L$$

$$y_{\phi R}^L i \tau_2 \ell' \phi^*$$

**dim. 4**

$$n_{-} 2\beta (0n\beta\beta) \text{ decay}$$

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

$$d \quad \phi \quad \bar{u} \quad e$$

$$y_{ue} R^u \bar{u}^c e \phi^*$$

**dim. 4**

$$\frac{\Lambda d^2 \phi^2}{\text{TeV}} \gtrsim 150 \cdot \frac{f d^2 \phi^2 \cdot |y_{ue}^R|^2}{(M_\phi/\text{TeV})^4}$$

**no useful bound**

if $\phi$ is a 3rd gen LQ with $y_{ue} \ll 1$

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

**both opts severely suppressed**

e.g., if $\phi$ is a 3rd gen LQ with $y_{ql}^L \sim \text{O(1)}$
then $f_{\ell \ell \phi H} \sim \text{O(10^{-6})}$ for $\Lambda \sim \text{O(1 TeV)}$
Neutrino masses

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

\[
\frac{f_W}{\Lambda_W} \ell^c \tilde{H}^* \tilde{H}^\dagger \ell \quad \frac{f_{\ell d\phi H}}{\Lambda_{\ell d\phi H}} \ell d \tilde{H} \phi^* \quad \frac{f_{d^2 \phi^2}}{\Lambda_{d^2 \phi^2}} \bar{d} d^c \phi^2
\]

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.
Assume 3\textsuperscript{rd} generation LQ's

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

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

$$\psi^k \rightarrow e^{i\alpha(\psi^k)\tau_3} \psi^k, \quad \tau_3 \equiv \frac{2\pi}{3}$$

\[\alpha(\psi^k) = Z_3 \text{ charges}\]
Assume 3rd generation LQ's

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$\alpha(\psi^k) = Z_3$ charges

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

For 3rd gen $\phi(3, 1, -1/3)$:

$$\mathcal{L}_{Y,\phi_3} \approx y_{q_{3\ell}}^L \psi_3 \left( \bar{t}_L^c \tau_L + \bar{b}_L^c \nu_{\tau L} \right) \phi^* + y_{u_{3e}}^R \bar{t}_R^c \tau_R \phi^* + \text{H.c.}$$

$Z_3$ 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:

\[ \Delta L_{qH} = \frac{H^+ H}{\Lambda^2} \cdot \left( f_{uH} q_L \tilde{H} u_R + f_{dH} q_L H d_R \right) + h.c. \]

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

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

In the LQ sector

If \( \Phi(3,2,1/6) \) couples to 1\(^{\text{st}}\) and/or 2\(^{\text{nd}}\) generation down-quarks & \( \phi \) is a 3\(^{\text{rd}}\) 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: \( g_{\Phi dd} \cdot g_{\Phi \phi} \rightarrow f_{d2\phi^2}, M_{\Phi} \rightarrow \Lambda d_{2\phi^2} \)
New Heavy physics

**light LQ's:** $M_\phi < \Lambda$

**$\phi^{(3,1,-1/3)}$ or $\phi^{(3,1,2/3)}$**

Intermediate heavy states of the underlying theory with $M(heavy) > \Lambda$

that can be indirectly probed (in the EFT framework)

New Heavy physics

$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_{i} f_i \mathcal{O}^{(n)}_i$

(O, constructed out of the SM+LQ fields and SM symmetries)

$(O_i)$
Constructing the EFT

- Quantum number specification:

\( (SU(3), SU(2), U(1)) \)

- Scalars:

\[ H : \text{SM scalar isodoublet} \sim (1, 2, 1/2) \]

\[ \hat{H} : \text{SM scalar isodoublet} \sim (1, 2, -1/2) \]

\[ \phi : \text{leptoquark} \sim (3, 1, -1/3) \]

- Fermions

<table>
<thead>
<tr>
<th>left-handed</th>
<th>right-handed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l \sim (1, 2, -1/2) )</td>
<td>( l^c \sim (1, 2, 1/2) )</td>
</tr>
<tr>
<td>( q \sim (3, 2, 1/6) )</td>
<td>( q^c \sim (\bar{3}, 2, -1/6) )</td>
</tr>
<tr>
<td>( u^c \sim (\bar{3}, 1, -2/3) )</td>
<td>( u \sim (3, 1, 2/3) )</td>
</tr>
<tr>
<td>( d^c \sim (\bar{3}, 1, 1/3) )</td>
<td>( d \sim (3, 1, -1/3) )</td>
</tr>
<tr>
<td>( e^c \sim (1, 1, 1) )</td>
<td>( e \sim (1, 1, -1) )</td>
</tr>
</tbody>
</table>

Dim 5 and dim 6 operator expansions validated with Mathematica package:

**LNV signatures from same-charge $\phi\phi$ pair production:**

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

(note: decay of $\phi(3,1,2/3) \rightarrow$ 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>$3^\text{rd}$ gen $\phi(3,1,-1/3)$</td>
<td>$3^\text{rd}$ 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>
Extra handle for these LQ-SMEFT signals

- Asymmetric same-sign lepton production, e.g.,
  \[ N(tt\tau^-\tau^-) \gg N(\bar{t}t\tau^+\tau^+) , N(\tau^+\tau^+ + 2\cdot j_b) \gg N(\tau^-\tau^- + 2\cdot j_b) \]
  \[ \phi(3,1,-1/3) \quad \phi(3,1,2/3) \]

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

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

\[ X_j = \text{any accompanying jet} \]
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)