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)

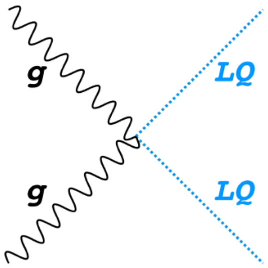
Outline

- 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**
  ⇒ should be copiously (QCD) pair produced @LHC if M_{LQ} ~ O(1 TeV)

- **Typical CSX is: $\sigma(pp \to \phi\phi^*) \sim$ <u>5(0.01) [fb]</u> for <u>M_ϕ ~ 1(2) TeV</u>**



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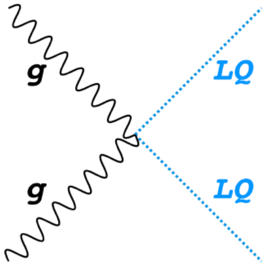
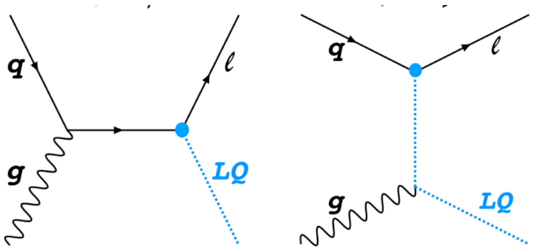


- Single LQ production via quark-gluon fusion $qg \to \phi l$ may also be important if Yukawa-like LQ-quark-lepton couplings are sizable

  -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: $\phi \rightarrow q_i e_j$, $q_i \nu_j$ $\left[\Gamma \sim (y_{\phi q l})^2 M_\phi / 16\pi\right]$

- 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 $pp \rightarrow \ell^{\pm} + j + \not{E}_T$
  - lepton + 2 light jets + missing ET $pp \rightarrow \ell^{\pm} + 2j + \not{E}_T$
  - 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) $pp \rightarrow \ell / \ell^+\ell^- + n \cdot j_b + \not{E}_T$
  - top-quark(s) + lepton(s) with or without missing ET (3[rd] gen. LQ) $pp \rightarrow \ell / \ell^+\ell^- + t / t\bar{t} + \not{E}_T$
  - …

  Model dependent …

No LQ signal yet; typical bounds are M_ϕ > 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 …)

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:

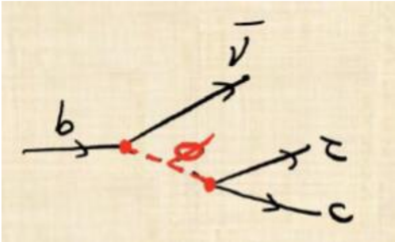
- $\phi(3,1,-1/3)$ + Higgs residing in the same representation; 10 dim multiplet in an SO(10) GUT framework
  Aydemir,Mandel,Mitra, arxiv:1902.08108

- 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 ϕSM framework:

consider the SU(2) scalar singlets LQ: "down type": ϕ(3,1,-1/3)
"up-type": ϕ(3,1,2/3)

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

ϕ(3,1,-1/3)	ϕ(3,1,2/3)
$\mathcal{L}_{Y,\phi} = y^L_{q\ell} \bar{q}^c i\tau_2 \ell \phi^* + y^R_{ue} \bar{u}^c e \phi^*$	none!

- **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 ϕSM 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

  Bauer, Heiles, Neubert, Thamm Eur. Phys. J. 2019 arxiv:1808.10323

- Fermionic DM

  Busoni, De Simone, Gramling, Morgante, Riotto JCAP 2014, arxiv:1402.1275

  Fedderke, Chen, Kolb, Wang JHEP 2014, arxiv:1404.2283

- RH neutrinos

  del Aguila, Bar-Shalom, Soni, Wudka Phys. Lett. 2009, arxiv:0806.0876

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

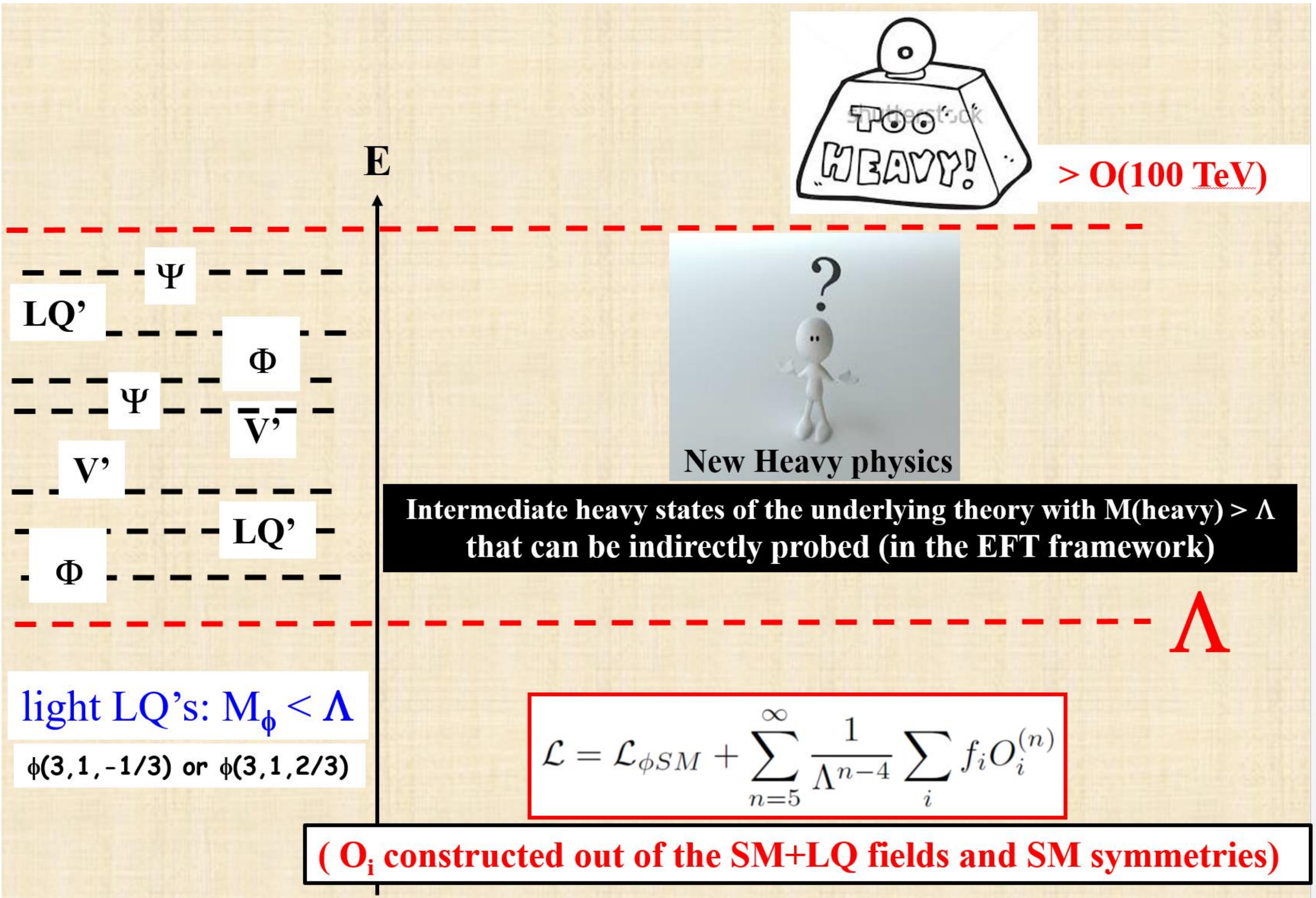
$$\mathcal{L} = \mathcal{L}_{\phi SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_i f_i O_i^{(n)}$$

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

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

The LQ-SMEFT - physical picture



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 …

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

The LQ-SMEFT – the case of ϕ(3,1,-1/3)

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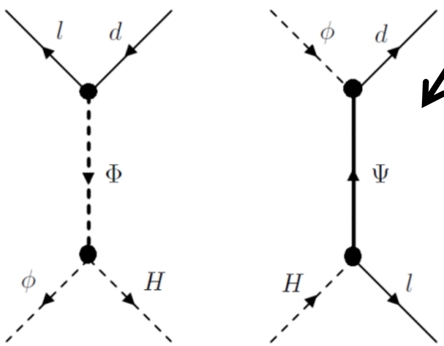
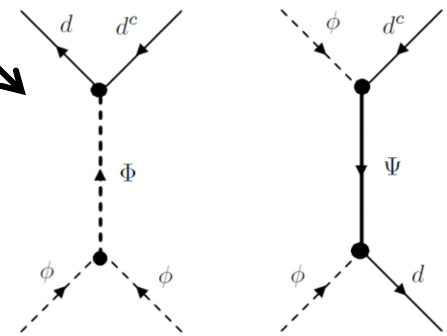




Intermediate heavy states

Φ=Φ(3,2,1/6)

Ψ=Ψ(1,1,0), Ψ(1,3,0), Ψ(3,2,-5/6)

Intermediate heavy states

Φ=Φ(6,1,-2/3)

Ψ=Ψ(1,1,0), Ψ(8,1,0)

\+ **the Weinberg operator;**

also generated by Ψ=Ψ(1,1,0) (type I seesaw) and/or Ψ(1,3,0) (type III seesaw): $\frac{f_W}{\Lambda_W}\bar{\ell}^c\tilde{H}^\star\tilde{H}^\dagger\ell$

The LQ-SMEFT – the case of ϕ(3,1,-1/3)

$$O_i^{(n)} \in \phi^a H^b \psi^c D^d$$

ϕ multiplicity	The LQ-SMEFT @ dim. 6		
ϕ^6 ⇒	$(\phi^* \phi)^3$		
ϕ^4 ⇒	**$\phi^4 H^2$**: $(H^\dagger H)(\phi^* \phi)^2$	**$\phi^4 D^2$**: $\lvert\phi\rvert^2 \lvert D\phi\rvert^2$	
ϕ^3 ⇒	**$\phi^3 \psi^2$**: $\lvert\phi\rvert^2 (\overline{q} l^c \phi)$, $\lvert\phi\rvert^2 (\overline{u} e^c \phi)$, $\lvert\phi\rvert^2 (\overline{q^c} q \phi)$, $\lvert\phi\rvert^2 (\overline{u^c} d \phi)$		
ϕ^2 ⇒	**ϕ^2xSM**: $\lvert\phi\rvert^2 \mathcal{O}^4_{SM}$	**$\phi^2 \psi^2 D$**: $\epsilon^{abc} \phi_a (D_\mu \phi)_b \bar{\ell} \gamma^\mu q_c$; $\epsilon^{abc} \phi_a (D_\mu \phi)_b \bar{e} \gamma^\mu d_c$	**octet $\phi^* \phi$**: $(\phi^\dagger \lambda^a D_\mu \phi)(\bar{q} \lambda^a \gamma^\mu q)$; $(\phi^\dagger \lambda^a \phi) B^{\mu\nu} G^a_{\mu\nu}$
ϕ ⇒	**$\phi \psi^2 D^2$**: $D^2 \times \overline{q} q^c \phi^*$; $D^2 \times \overline{q} l^c \phi$; $D^2 \times \overline{d^c} u \phi$; $D^2 \times \overline{u} e^c \phi$	**$\phi \psi^2 H D$**: $(\overline{q} H) \gamma^\mu u^c D_\mu \phi^\dagger$; $(\overline{q} \tilde{H}) \gamma^\mu d^c D_\mu \phi^\dagger$; $(\overline{q} \tilde{H}) \gamma^\mu e^c D_\mu \phi$; $(\bar{l} H) \gamma^\mu u^c D_\mu \phi$; $(\bar{l} \tilde{H}) \gamma^\mu d^c D_\mu \phi$	**$\phi \psi^2 H^2$**: $\lvert H\rvert^2 \phi^\dagger \overline{q} q^c$; $\lvert H\rvert^2 \phi \overline{q} l^c$; $\lvert H\rvert^2 \phi \overline{d^c} u$; $\lvert H\rvert^2 \phi \overline{u} e^c$; $\phi^\dagger (\overline{q} H)(H^\dagger q^c)$; $\phi (\overline{q} H)(H^\dagger l^c)$,

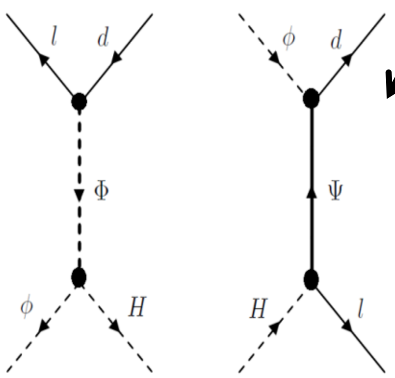
e.g., $D^2 \times \overline{q} l^c \phi \to (\overline{q} D_\mu l^c) D^\mu \phi \ , \ (\overline{q} \sigma_{\mu\nu} l^c) B^{\mu\nu} \phi \ , \ (\overline{q} \sigma_{\mu\nu} \sigma^I l^c) W_I^{\mu\nu} \phi \ , \ (\overline{q} \sigma_{\mu\nu} \lambda^A l^c) G_A^{\mu\nu} \phi$

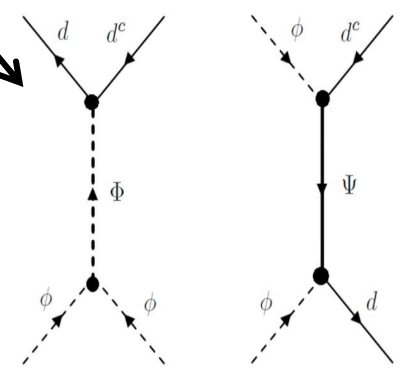
This is the complete list of dim.6 opts for ϕ(3,1,-1/3) …

Low-energy ΔL=2 effect from the dim.5 opts

expectations & constraints

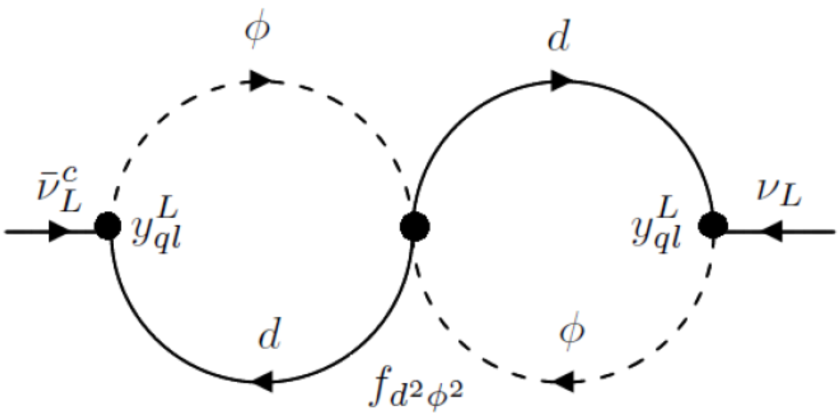
$$\Delta\mathcal{L}^{(5)}_{\phi SM} = \frac{f_{\ell d\phi H}}{\Lambda_{\ell d\phi H}}\bar{\ell} d\tilde{H}\phi^* + \frac{f_{d^2\phi^2}}{\Lambda_{d^2\phi^2}}\bar{d}d^c\phi^2 + \text{H.c.}$$





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:



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

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)

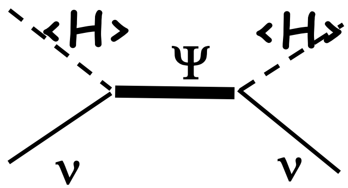
Neutrino masses

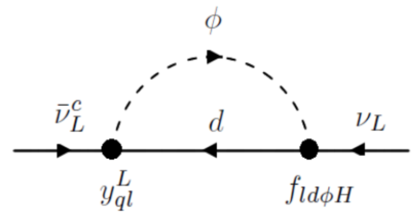
$$\frac{f_W}{\Lambda_W}\bar{\ell}^c\tilde{H}^\star\tilde{H}^\dagger\ell$$

Tree-level

$$\frac{f_{\ell d\phi H}}{\Lambda_{\ell d\phi H}}\bar{\ell}d\tilde{H}\phi^*$$

1-loop





m_ν < eV

both opts severely suppressed

We are left with a single class of viable dim.5 opts for TeV-scale physics

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

$$\frac{f_{d^2\phi^2}}{\Lambda_{d^2\phi^2}}\bar{d}d^c\phi^2$$

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

$$M_\phi < \Lambda_{d^2\phi^2} \sim O(\text{few TeV})\ \&\ f_{d^2\phi^2} \sim O(1)$$

Consider also the up-type $\phi(3,1,2/3)$; **4 possible dim.5 opts**

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

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: $M_\phi < \Lambda_{u2\phi2} \sim O(\text{few TeV})$ & $f_{u2\phi2} \sim O(1)$

signals of the LQ-SMEFT paradigm

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

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

$$\frac{f_{d^2\phi^2}}{\Lambda_{d^2\phi^2}}\bar{d}d^c\phi^2$$

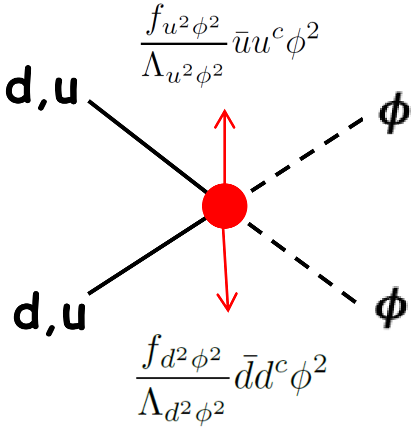
CSX's calculated with MadGraph5;

producing a dedicated UFO model for the LQ-SMEFT framework (using FeynRules ...)

Assume 3rd generation LQ's

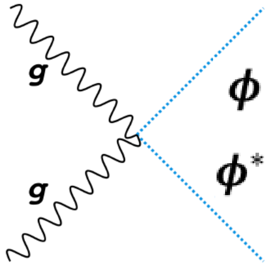
(couple dominantly to 3rd gen. lepton-quark pairs)

$d^2\phi^2$ & $u^2\phi^2$ opts effects $\phi\phi$ pair production:



$$\hat{\sigma}(pp_{(qq)} \to \phi\phi) = \frac{f^2_{q2\phi2}}{\Lambda^2_{q2\phi2}} \cdot \frac{\left(1 - \frac{4M^2_\phi}{\hat{s}}\right)^{1/2}}{12\pi}$$

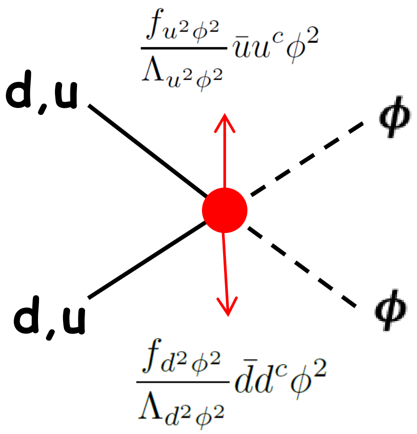
same-charge ϕϕ production



QCD production: $\hat{\sigma}(pp_{(gg,qq)} \to \phi\phi^*) \,\alpha\, \frac{1}{\hat{s}}$

opposite-charged ϕϕ* production

$d^2\phi^2$ & $u^2\phi^2$ opts effects $\phi\phi$ pair production:



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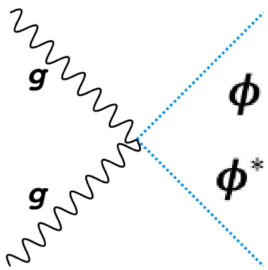
same-charge ϕϕ production



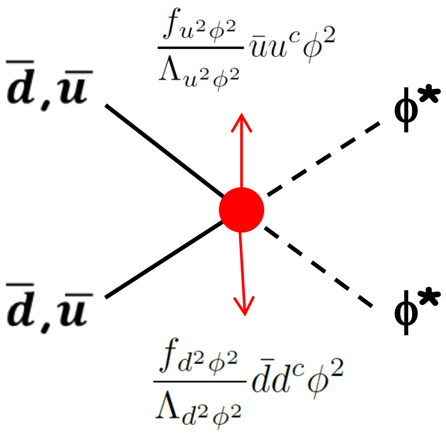
QCD production: $\hat{\sigma}(pp_{(gg,qq)} \to \phi\phi^*) \propto \frac{1}{\hat{s}}$

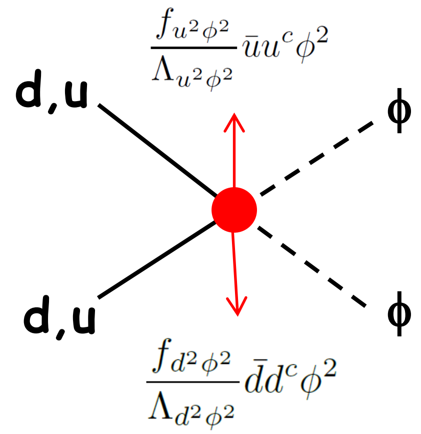
opposite-charged ϕϕ* production

expectations with NP scale Λ=5 TeV @LHC13

	LQ-SMEFT (dim.5: Λ=5 TeV)		$L_{\phi SM}$ (dim. 4)
	$d^2\phi^2$: $pp_{(dd)} \to \phi\phi$	$u^2\phi^2$: $pp_{(uu)} \to \phi\phi$	QCD: $pp_{(gg,qq)} \to \phi\phi^*$
σ(M_ϕ=1 TeV)	14 fb	77 fb	3 fb
σ(M_ϕ=2 TeV)	0.3 fb	3 fb	0.005 fb

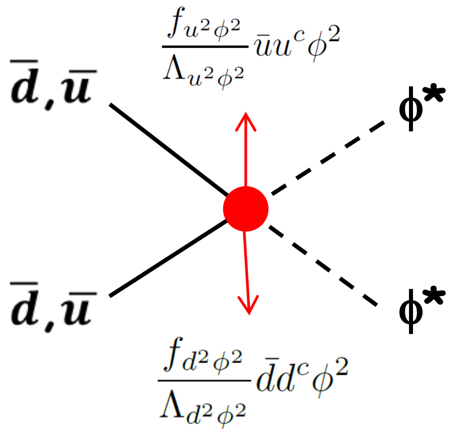
>>

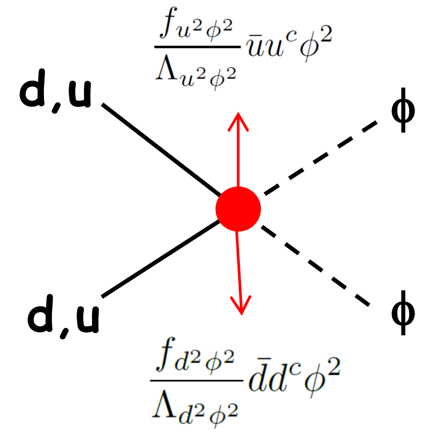




$$\hat{\sigma}\left(pp_{(qq)} \to \phi\phi\right) \gg \hat{\sigma}\left(pp_{(\overline{qq})} \to \phi^*\phi^*\right)$$

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





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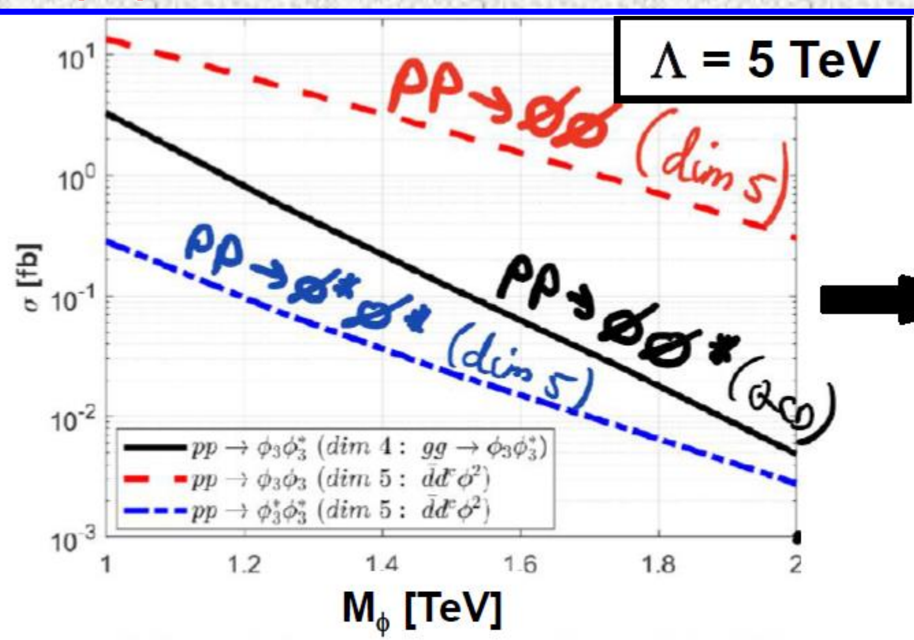
For "down type" LQ:



→ LHC 13

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 …)

LQ-SMEFT (dim.5)	
3rd gen $\phi(3,1,-1/3)$	3rd gen $\phi(3,1,2/3)$
$d^2\phi^2$: $pp_{(dd)} \rightarrow \phi\phi$	$u^2\phi^2$: $pp_{(uu)} \rightarrow \phi\phi$
$\phi\phi \rightarrow tt\tau^-\tau^-$	$\phi\phi \rightarrow tt+\not{E}_T$
	$\phi\phi \rightarrow \tau^+\tau^+ + 2\cdot j_b$

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	$\phi\phi \rightarrow \tau^+\tau^+ + 2\cdot j_b$

Same-charge $\phi\phi$ production yields same-sign lepton pairs!

In contrast to the conventional QCD LQ pair production signals:

$L_{\phi SM}$ (dim. 4)
3rd gen $\phi(3,1,-1/3)$ or $\phi(3,1,2/3)$
QCD: $pp_{(gg,qq)} \rightarrow \phi\phi^*$
$\phi\phi^* \rightarrow \bar{t}t\tau^+\tau^-$, $\bar{t}t+\not{E}_T$
$\phi\phi^* \rightarrow \tau^+\tau^- + 2\cdot j_b$, $2\cdot j_b + \not{E}_T$
$\phi\phi^* \rightarrow t\tau^+/t\tau^- + j_b + \not{E}_T$

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

LQ-SMEFT (dim.5)	
3^{rd} gen $\phi(3,1,-1/3)$	3^{rd} gen $\phi(3,1,2/3)$
$d^2\phi^2$: $pp_{(dd)} \to \phi\phi$	$u^2\phi^2$: $pp_{(uu)} \to \phi\phi$
$\phi\phi \to tt\tau^-\tau^-$	$\phi\phi \to tt + \not{E}_T$
	$\phi\phi \to \tau^+\tau^+ + 2 \cdot j_b$

- Typical rates at 13 TeV LHC with 300 fb^{-1} (after top-decays ...):

  <u>M_ϕ=1 TeV & Λ=5 TeV</u>

  - 5000 positively charged $\tau^+\tau^+$ events via $pp \to \phi\phi \to \tau^+\tau^+ + 2 \cdot j_b$
  - 500 negatively charged $\tau^-\tau^-$ events via $pp \to \phi\phi \to \tau^-\tau^- + 2 \cdot j_b + 4 \cdot j$
  - 50 positively charged l^+l^+ events via $pp \to \phi\phi \to l^+l^+ + 2 \cdot j_b + \not{E}_T$

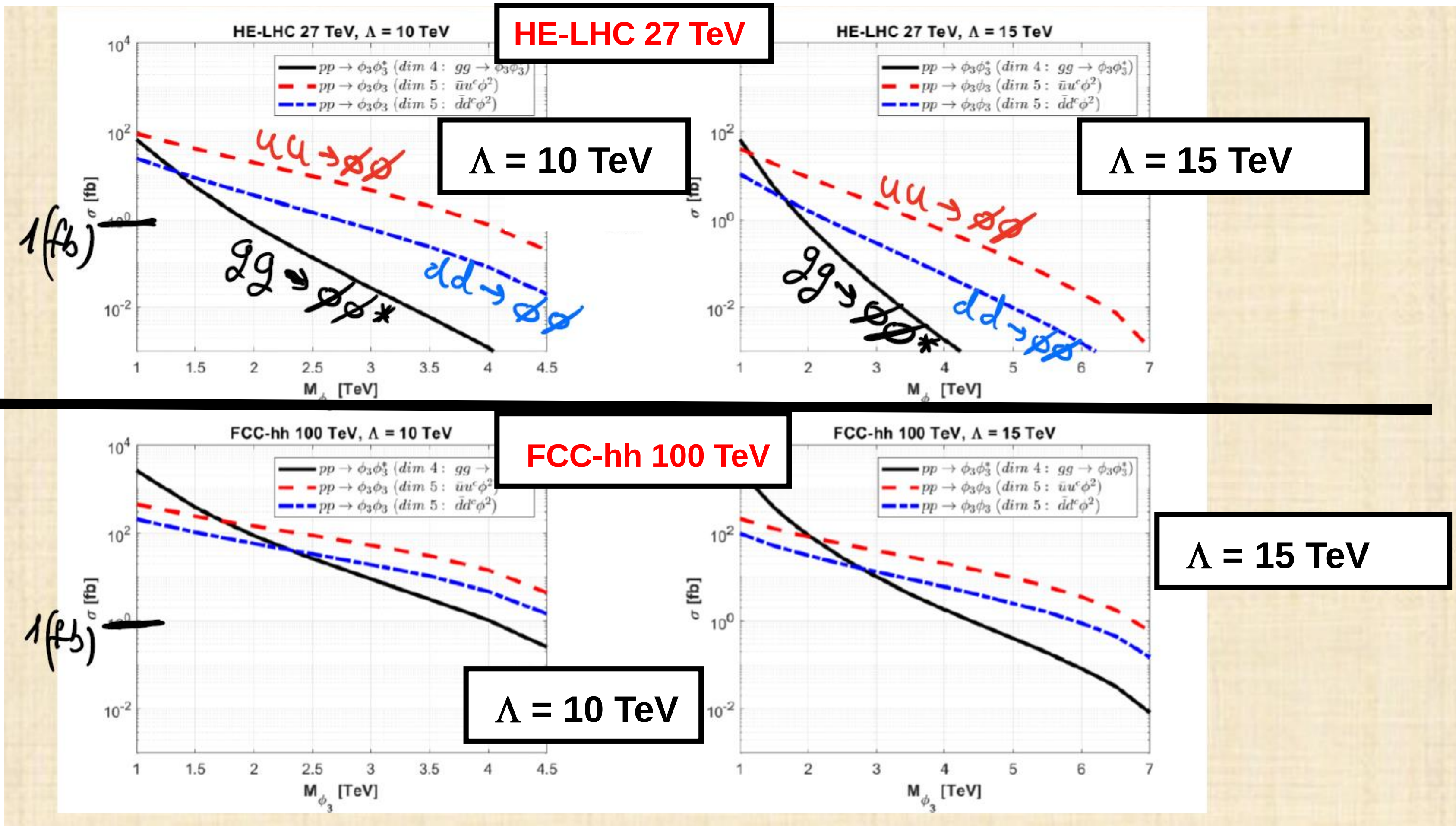
Much smaller rate for corresponding opposite-sign lepton pair events !

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_ϕ @LHC13 due to the limited phase-space

$\phi\phi$ pair production @ higher energy colliders

ϕϕ pair production @ higher energy colliders



Future higher-energy hadron colliders will be sensitive to the LQ-SMEFT dynamics up to LQ masses of M_ϕ ~ 5 TeV & NP scale of Λ ~ 15 TeV
i.e., with CSX's for same-sign charged leptons larger than σ ~ O(1 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 $\Lambda \sim O(5\ \text{TeV})$

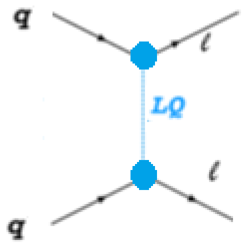
- "smoking gun" same-sign lepton pair signals at the LHC13 with <u>asymmetric double-charge rates</u> and CSX's much larger than the "standard" opposite-sign lepton pair signals

- Sensitivities up to M(LQ) ~ 2 TeV @LHC13 [Λ~5 TeV] & M(LQ) ~ 5 TeV @FCC-hh100 [Λ~15 TeV]

Backups & more slides

The large yukawa coupling case y $\gtrsim$ O(1)

- 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).

up-type LQ $\phi(3,1,2/3)$ @ renormalizble level

- Yukawa-like interactions of this type only contain the term:

$$y^R_{d^i d^j}\, \bar{d}^{ci}_R d^j_R \phi$$

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

➡ Assume this coupling is vanishingly small

LQ-SMEFT with ϕ(3,1,-1/3) & ϕ(3,1,2/3) @dim.5

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

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 ϕ(3,1,2/3) opts

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

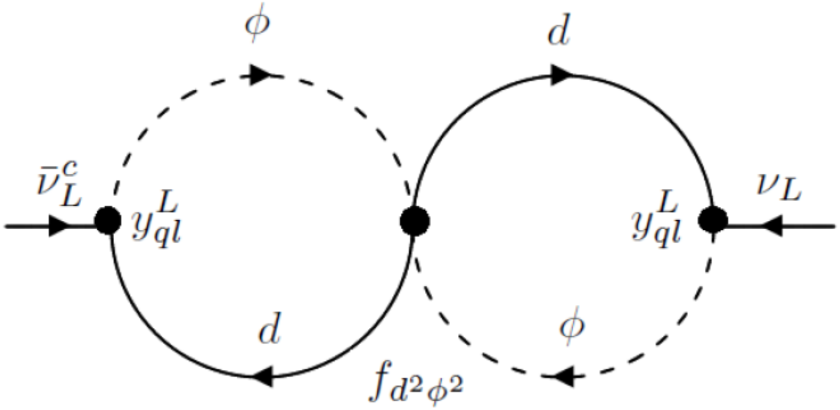
dim.5 ϕ(3,1,-1/3) opts

- 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 $\frac{f_{d^2\phi^2}}{\Lambda_{d^2\phi^2}}\bar{d}d^c\phi^2$ contribution:



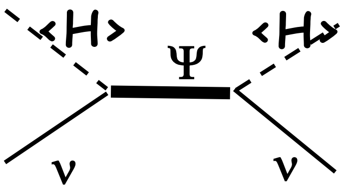
$$m_\nu(\Lambda) \sim \frac{f \cdot \left(y_{q\ell}^L\right)^2}{(16\pi^2)^2}\frac{3m_d^2}{\Lambda} \cdot \ln^2\left(\frac{\Lambda^2}{M_\phi^2}\right)$$

- **d-quark:** 2-loop neutrino mass is too small $m_\nu \sim 10^{-4}\ \mathrm{eV}$ for $f_{d^2\phi^2} \cdot \left(y_{d\nu}^L\right)^2 \sim \mathcal{O}(1)$, therefore no useful bound can be set on $\bar{d}d^c\phi^2$
- **s-quark:** resulting mass consistent with oscillation data $m_\nu \sim \mathrm{eV}$ for a NP scale of several TeV and $f_{s^2\phi^2} \cdot \left(y_{s\nu}^L\right)^2 \sim \mathcal{O}(1)$ therefore no useful bound can be put on $\bar{s}s^c\phi^2$
- **b-quark:** We obtain $m_\nu \sim \mathrm{KeV}$ for $f_{b^2\phi^2} \cdot \left(y_{b\nu}^L\right)^2 \sim \mathcal{O}(1)$ and a NP scale of several TeV. Therefore either $\Lambda_{b^2\phi^2} \sim \mathcal{O}(1000)$ TeV or $f_{b^2\phi^2} \cdot \left(y_{b\nu}^L\right)^2 \sim \mathcal{O}(10^{-3})$

Neutrino masses

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

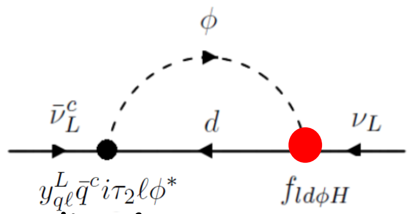
Tree-level



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

$$\frac{f_{\ell d\phi H}}{\Lambda_{\ell d\phi H}}\bar{\ell} d \tilde{H}\phi^*$$

1-loop



$$m_\nu(\Lambda) \sim \frac{3m_d}{16\pi^2}\frac{f \cdot y^L_{q\ell}}{\sqrt{2}}\frac{v}{\Lambda}\ln\left(\frac{\Lambda^2}{M_\phi^2}\right)$$

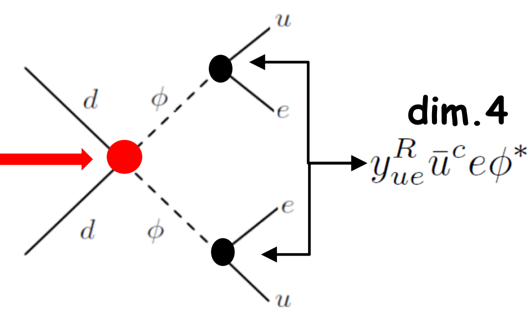
m_ν < eV

both opts severely suppressed

e.g., if ϕ is a 3[rd] gen LQ with y_{ql}^L ~O(1)
then $f_{ld\phi H}$ < O(10^{-6}) for Λ ~ O(1 TeV)

ν-less 2β (0νββ) decay

$$\frac{f_{d^2\phi^2}}{\Lambda_{d^2\phi^2}}\bar{d}d^c\phi^2$$



$$\frac{\Lambda_{d^2\phi^2}}{\text{TeV}} \gtrsim 150 \cdot \frac{f_{d^2\phi^2}\cdot |y^R_{ue}|^2}{(M_\phi/\text{TeV})^4}$$

no useful bound if ϕ is a 3[rd] gen LQ with y_{ue}^R << 1

i.e., if y_{ue}^R ~ 0.1 or smaller,
then M_ϕ < Λ ~ O(few TeV) & $f_{d2\phi2}$ ~ O(1)
are allowed …

Neutrino masses

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

$$\frac{f_W}{\Lambda_W}\bar{\ell}^c\tilde{H}^\star\tilde{H}^\dagger\ell \qquad \frac{f_{\ell d\phi H}}{\Lambda_{\ell d\phi H}}\bar{\ell}d\tilde{H}\phi^* \qquad \frac{f_{d^2\phi^2}}{\Lambda_{d^2\phi^2}}\bar{d}d^c\phi^2$$

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

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

2. $\Psi(1,3,0)$ generates both Weinberg and $ld\phi H$ while $d^2\phi^2$ is generated by a different mediator. Then, with $M_\Psi \sim O(10^{14}$ GeV), m_ν<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 $ld\phi H$ is subdominant.

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

Assume 3rd generation LQ's

(couple dominantly to 3rd gen. lepton-quark pairs)

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

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

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

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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 $\phi(3,1,-1/3)$:

$$\mathcal{L}_{Y,\phi_3} \approx y^L_{q_3\ell_3}\left(\bar{t}^c_L\tau_L + \bar{b}^c_L\nu_{\tau L}\right)\phi^* + y^R_{u_3e_3}\bar{t}^c_R\tau_R\phi^* + \text{H.c.}$$

Z_3 gen. symmetry is exact in the limit of a diagonal CKM; Z_3-breaking ~ off-diagonal CKM …

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

Breaking the Z_3 generation symmetry @ E>Λ

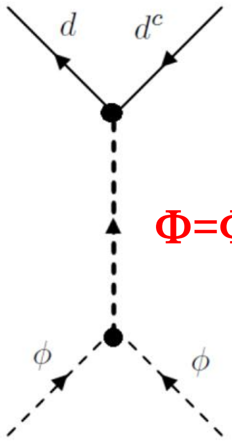
In the SM sector

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:

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

If e.g., $\Lambda \sim 1.5$, 3 or 5 TeV and $f_{uH,dH} \sim O(1)$, then the Resulting effective Yukawa couplings:
$Y_{eff} = f_{qH} \cdot v^2/\Lambda^2 \sim O(y_b), O(y_c)$ or $O(y_s)$, respectively …

In the LQ sector



If $\Phi(3,2,1/6)$ couples to 1[st] and/or 2[nd] generation down-quarks & ϕ is a 3[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 ~ $g_{\Phi dd} \cdot g_{\Phi\phi\phi}/M_\Phi$

Matching to the EFT framework: $g_{\Phi dd} \cdot g_{\Phi\phi\phi} \rightarrow f_{d2\phi 2}$, $M_\Phi \rightarrow \Lambda_{d2\phi 2}$

$$\frac{f_{d^2\phi^2}}{\Lambda_{d^2\phi^2}} \bar{d} d^c \phi^2$$

> O(100 TeV)

E

Ψ

LQ'

Φ

Ψ

V'

V'

LQ'

Φ

Intermediate heavy states of the underlying theory with M(heavy) > Λ that can be indirectly probed (in the EFT framework)

Λ

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)

Constructing the EFT

- Quantum number specification:

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

- Scalars:

$$H:\ \text{SM scalar isodoubet} \sim (1,\, 2,\, 1/2)$$

$$\tilde{H}:\ \text{SM scalar isodoubet} \sim (1,\, 2,\, -1/2)$$

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

- Fermions

left-handed	right-handed
$l \sim (1,\, 2,\, -1/2)$	$l^c \sim (1,\, 2,\, 1/2)$
$q \sim (3,\, ,\, 2,\, 1/6)$	$q^c \sim (\bar{3},\, ,\, 2,\, -1/6)$
$u^c \sim (\bar{3},\, 1,\, -2/3)$	$u \sim (3,\, 1,\, 2/3)$
$d^c \sim (\bar{3},\, 1,\, 1/3)$	$d \sim (3,\, 1,\, -1/3)$
$e^c \sim (1,\, 1,\, 1)$	$e \sim (1,\, 1,\, -1)$

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

B. Henning, X. Lu, T. Melia, H. Murayama, JHEP 1708 (2017) 016, arXiv:1512.03433

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 ...)

LQ-SMEFT (dim.5)		$L_{\phi SM}$ (dim. 4)
3rd gen $\phi(3,1,-1/3)$	3rd gen $\phi(3,1,2/3)$	3rd gen $\phi(3,1,-1/3)$ or $\phi(3,1,2/3)$
$d^2\phi^2$: $pp_{(dd)} \rightarrow \phi\phi$	$u^2\phi^2$: $pp_{(uu)} \rightarrow \phi\phi$	QCD: $pp_{(gg,qq)} \rightarrow \phi\phi^*$
$\phi\phi \rightarrow tt\tau^-\tau^-$	$\phi\phi \rightarrow tt+\not{E}_T$	$\phi\phi^* \rightarrow \bar{t}t\tau^+\tau^-$, $\bar{t}t+\not{E}_T$
$\phi\phi \rightarrow 2 \cdot j_b+\not{E}_T$	$\phi\phi \rightarrow \tau^+\tau^+ +2 \cdot j_b$	$\phi\phi^* \rightarrow \tau^+\tau^- +2 \cdot j_b$, $2 \cdot j_b+\not{E}_T$
$\phi\phi \rightarrow t\tau^- +j_b+\not{E}_T$	$\phi\phi \rightarrow t\tau^+ +j_b+\not{E}_T$	$\phi\phi^* \rightarrow t\tau^+/t\tau^- + j_b+\not{E}_T$

Extra handle for these LQ-SMEFT signals

- Asymmetric same-sign lepton production, e.g, :

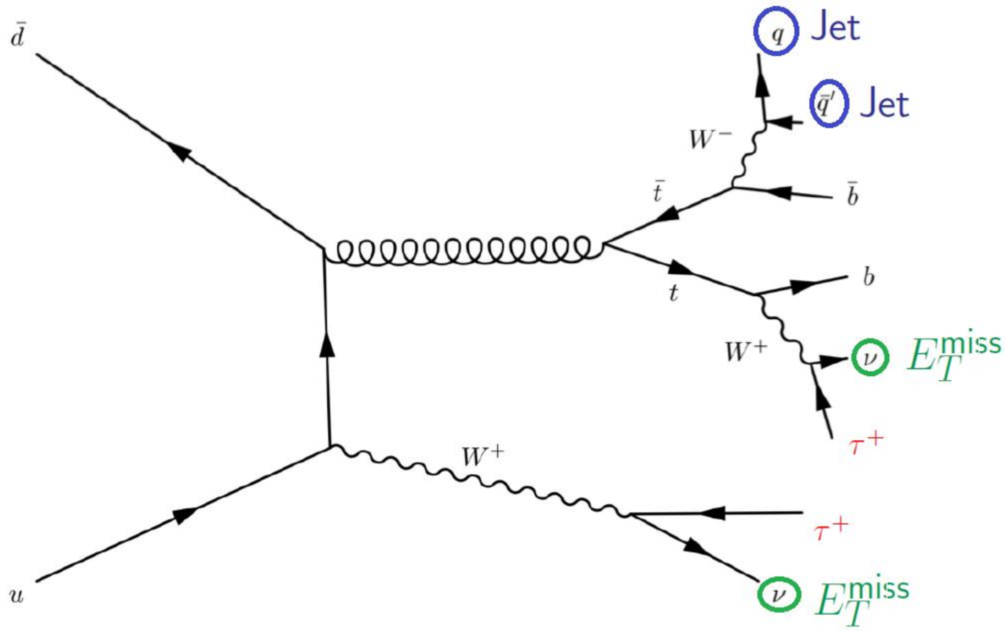
$N(tt\tau^-\tau^-) \underbrace{>>}_{\phi(3,1,-1/3)} N(\bar{t}\bar{t}\tau^+\tau^+)$, $N(\tau^+\tau^+ + 2\cdot j_b) \underbrace{>>}_{\phi(3,1,2/3)} N(\tau^-\tau^- + 2\cdot j_b)$

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

$$A_{\tau\tau} \equiv \frac{|\sigma\left(pp \to \tau^-\tau^- + X_j\right) - \sigma\left(pp \to \tau^+\tau^+ + X_j\right)|}{\sigma\left(pp \to \tau^-\tau^- + X_j\right) + \sigma\left(pp \to \tau^+\tau^+ + X_j\right)} \sim 1$$

X_j = any accompanying jet

Same-sign dilepton SM BG



- Main SM BG necessarily has $\not{E}_T$
- Additional BG from fake/misidentified leptons is subdominant
- Can also have higher jet-multiplicities mimicking signals with $\not{E}_T$
- Focus on same-sign signals without $\not{E}_T$
- SM BG is controlled via "no MET" veto
- Signal yields prompt and well isolated same-sign leptons (emanate from TeV-scale particles)