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

Outline

- 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 ϕSM framework:

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

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

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

"up-type": $\phi(3,1,2/3)$

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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):

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

- Scalar interactions: $\mathcal{L}_{H,\phi} = |D_\mu \phi|^2 - M^2_\phi |\phi|^2 + \lambda_\phi |\phi|^4 + \lambda_{\phi H} |\phi|^2 |H|^2$

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**

ϕ(3,1,-1/3) or ϕ(3,1,2/3)

to be "light" fields …

The LQ-SMEFT - physical picture

> 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)

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

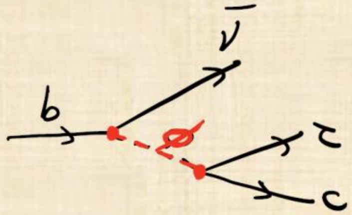
Aydemir,Mandel,Mitra, arxiv:1902.08108

- 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 ϕ(3,1,-1/3)

- **dim. 5:** only 2 tree-level generated dim. 5 opts involving ϕ(3,1,-1/3):

  both violate lepton number by 2 units …

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

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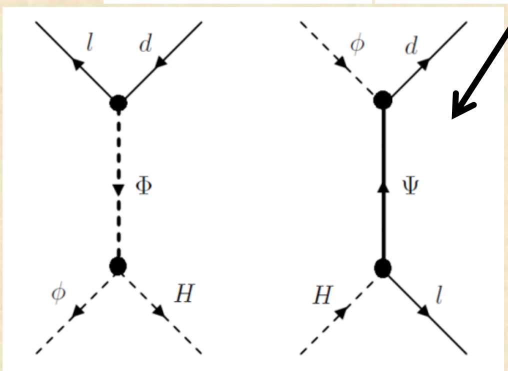
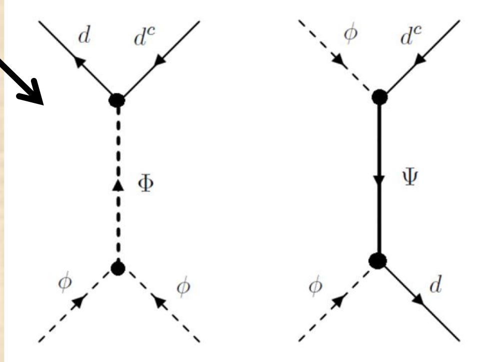


Intermediate heavy states

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

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

ϕ multiplicity	The LQ-SMEFT @ dim. 6
$\phi^6 \Rightarrow$	$(\phi^*\phi)^3$
$\phi^4 \Rightarrow$	**$\phi^4 H^2$**: $(H^\dagger H)(\phi^*\phi)^2$; **$\phi^4 D^2$**: $\lvert\phi\rvert^2 \lvert D\phi\rvert^2$
$\phi^3 \Rightarrow$	**$\phi^3\psi^2$**: $\lvert\phi\rvert^2(\overline{q}l^c\phi)$, $\lvert\phi\rvert^2(\overline{u}e^c\phi)$, $\lvert\phi\rvert^2(\overline{q^c}q\phi)$, $\lvert\phi\rvert^2(\overline{u^c}d\phi)$
$\phi^2 \Rightarrow$	**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 $\phi^*\phi$**: $(\phi^\dagger\lambda^a D_\mu\phi)(\bar{q}\lambda^a\gamma^\mu q)$; $(\phi^\dagger\lambda^a\phi)B^{\mu\nu}G^a_{\mu\nu}$
$\phi \Rightarrow$	**$\phi\psi^2 D^2$**: $D^2\times\overline{q}q^c\phi^*$; $D^2\times\overline{q}l^c\phi$; $D^2\times\overline{d^c}u\phi$; $D^2\times\overline{u}e^c\phi$ **$\phi\psi^2 HD$**: $(\overline{q}H)\gamma^\mu u^c D_\mu\phi^\dagger$; $(\overline{q}\tilde{H})\gamma^\mu d^c D_\mu\phi^\dagger$; $(\overline{q}\tilde{H})\gamma^\mu e^c D_\mu\phi$; $(\bar{l}H)\gamma^\mu u^c D_\mu\phi$; $(\bar{l}\tilde{H})\gamma^\mu d^c D_\mu\phi$ **$\phi\psi^2 H^2$**: $\lvert H\rvert^2\phi^\dagger\overline{q}q^c$; $\lvert H\rvert^2\phi\overline{q}l^c$; $\lvert H\rvert^2\phi\overline{d^c}u$; $\lvert H\rvert^2\phi\overline{u}e^c$; $\phi^\dagger(\overline{q}H)(H^\dagger q^c)$; $\phi(\overline{q}H)(H^\dagger l^c)$ 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 $\phi(3,1,-1/3)$ …

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

⇓

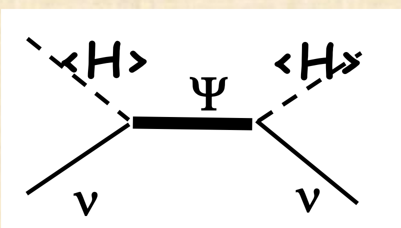
New mechanisms for loop generated Majorana neutrino masses

loop generated
Majorana Neutrino masses

Weinberg opt

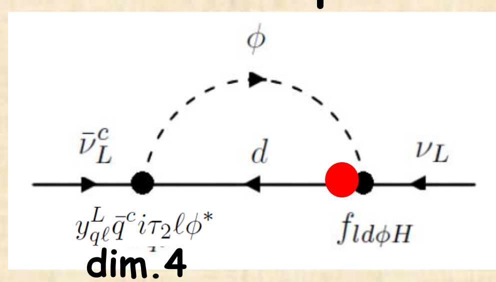
$$\boxed{\frac{f_W}{\Lambda_W}\bar{\ell}^c\tilde{H}^\star\tilde{H}^\dagger\ell}$$

Tree-level



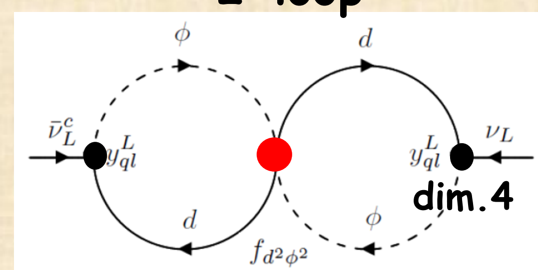
$$\boxed{\frac{f_{\ell d\phi H}}{\Lambda_{\ell d\phi H}}\bar{\ell}d\tilde{H}\phi^*}$$

1-loop



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

2-loop



SMEFT

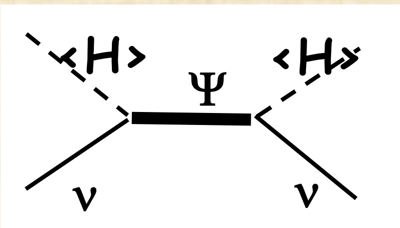
LQ-SMEFT

Majorana Neutrino masses

Weinberg opts

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

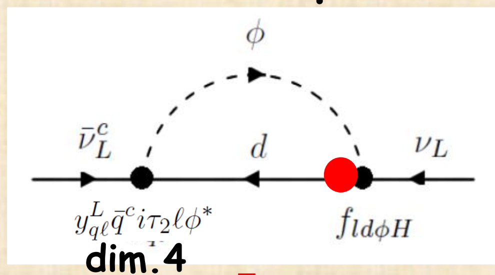
Tree-level



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

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

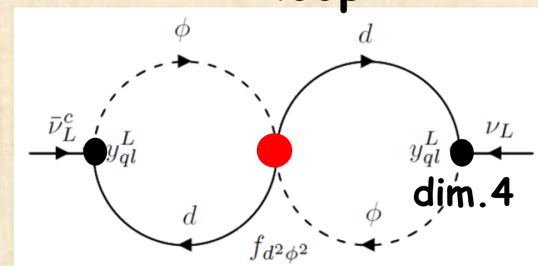
1-loop



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

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

2-loop



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

m_ν<eV

both opts severely suppressed

(Λ too large to be relevant for LHC pheno …)

m_ν<eV with Λ ~ O(1 TeV)

naturally generate sub-eV m_ν @ 2-loops with Λ ~ 5 TeV

$\Rightarrow$ no useful bound on $d^2\phi^2$ opts …

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

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

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

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

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

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

$\Lambda_{d^2\phi^2}$ ~ O(few TeV) & $f_{d^2\phi^2}$ ~ 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:

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

also not constrained: $\Lambda_{u2\phi2}$ ~ O(few TeV) & $f_{u2\phi2}$ ~ O(1)

signals of the LQ-SMEFT paradigm

New & surprising LNV (ΔL=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

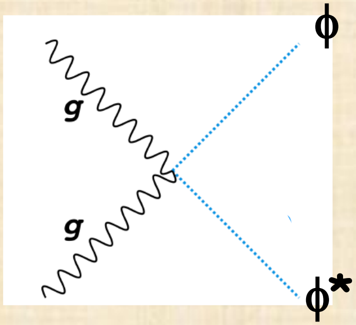
not necessary but provides an interesting example of the rich pheno involved and also connects to the B-anomalies …

easy to construct/impose: with a Z_3 generation symmetry

(more details in arxiv: 1812.03178)

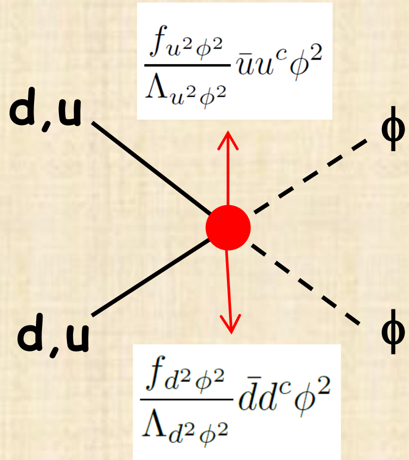
the $d^2\phi^2$ & $u^2\phi^2$ opts & $\phi\phi$ pair production

renormalizable ϕSM framework



QCD production

LQ-SMEFT framework



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

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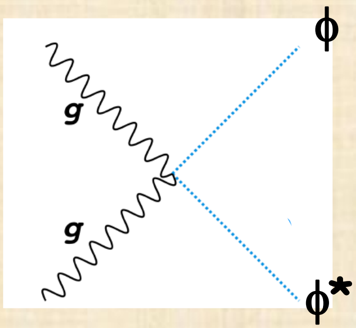
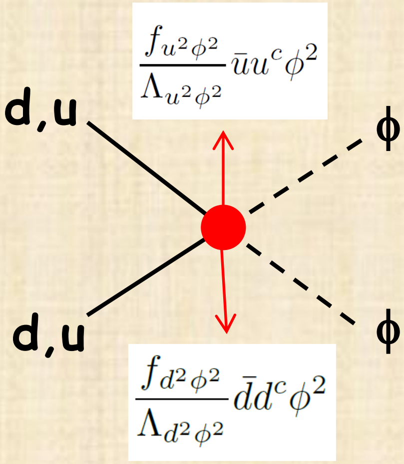


QCD production

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

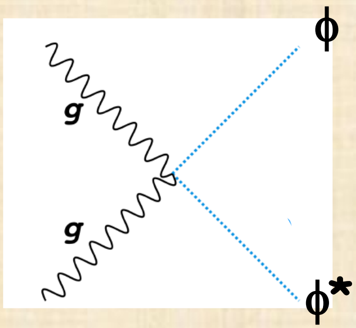
LQ-SMEFT framework



same-charge $\phi\phi$ production

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

renormalizable ϕSM framework



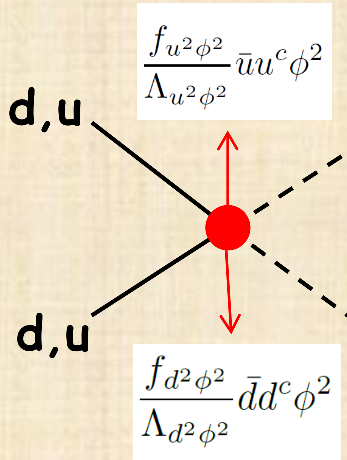
QCD production

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

CSX falls with E

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

LQ-SMEFT framework



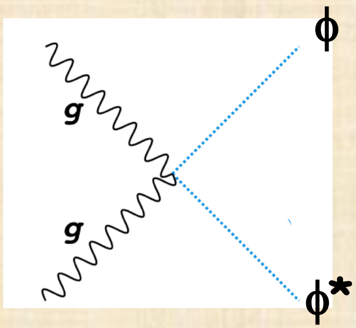
same-charge $\phi\phi$ production

CSX grows with E

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

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

renormalizable ϕSM framework



QCD production

opposite-charged ϕϕ* production

CSX drops with E

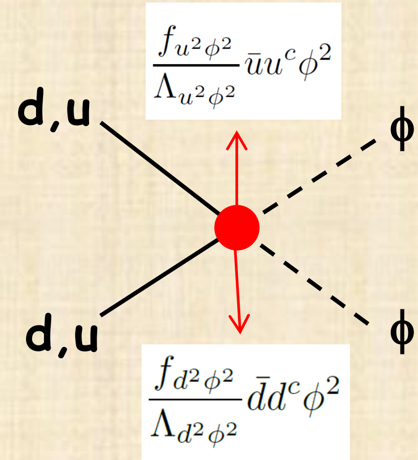
$$\hat{\sigma}\left(pp_{(gg,qq)} \to \phi\phi^*\right) \propto \frac{1}{\hat{s}}$$

Collider signature

pp → ϕϕ* → τ+τ-

opposite-sign leptons

LQ-SMEFT framework



same-charge ϕϕ production

CSX grows with E

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

Collider signature

pp → ϕϕ → τ+τ+, τ-τ-

same-sign leptons !!!

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

expectations: NP scale Λ=5 TeV

	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: $pp_{(gg,qq)} \to \phi\phi^*$
$\sigma(M_\phi$=1 TeV)	14 fb	77 fb	3 fb
$\sigma(M_\phi$=2 TeV)	0.3 fb	3 fb	0.005 fb

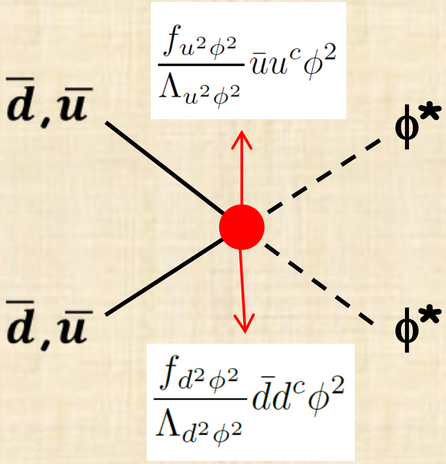
$>>$

LQ-SMEFT LQ signals are much larger than "standard" QCD LQ-production

e.g., M(LQ) ~ 2 TeV

a factor of 1000 enhancement for same-charge LQ pair-prod. !

An important extra handle



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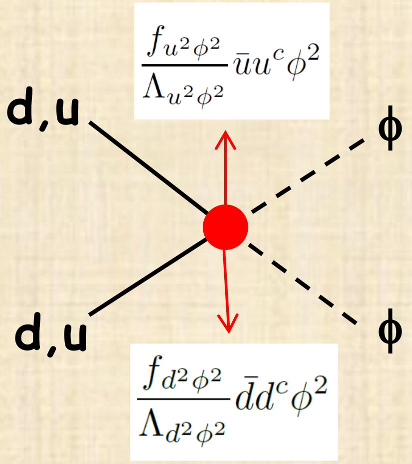
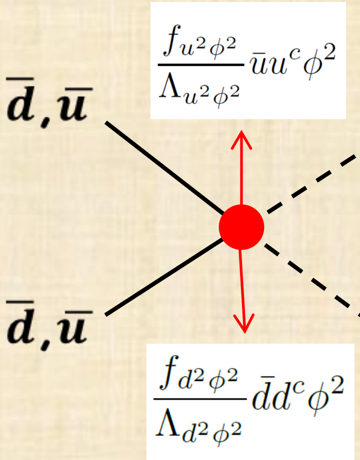


$$\hat{\sigma}(pp_{(qq)} \to \phi\phi) \gg \hat{\sigma}(pp_{(\overline{qq})} \to \phi^*\phi^*)$$

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

An important extra handle



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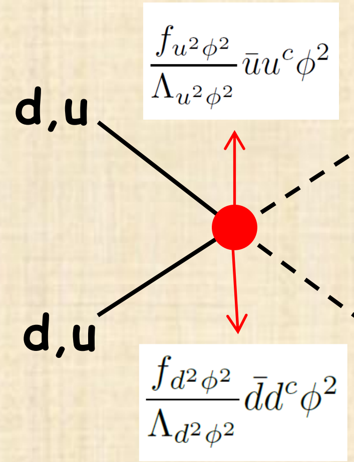

$$\hat{\sigma}\left(pp_{(qq)} \to \phi\phi\right) \gg \hat{\sigma}\left(pp_{(\overline{qq})} \to \phi^*\phi^*\right)$$

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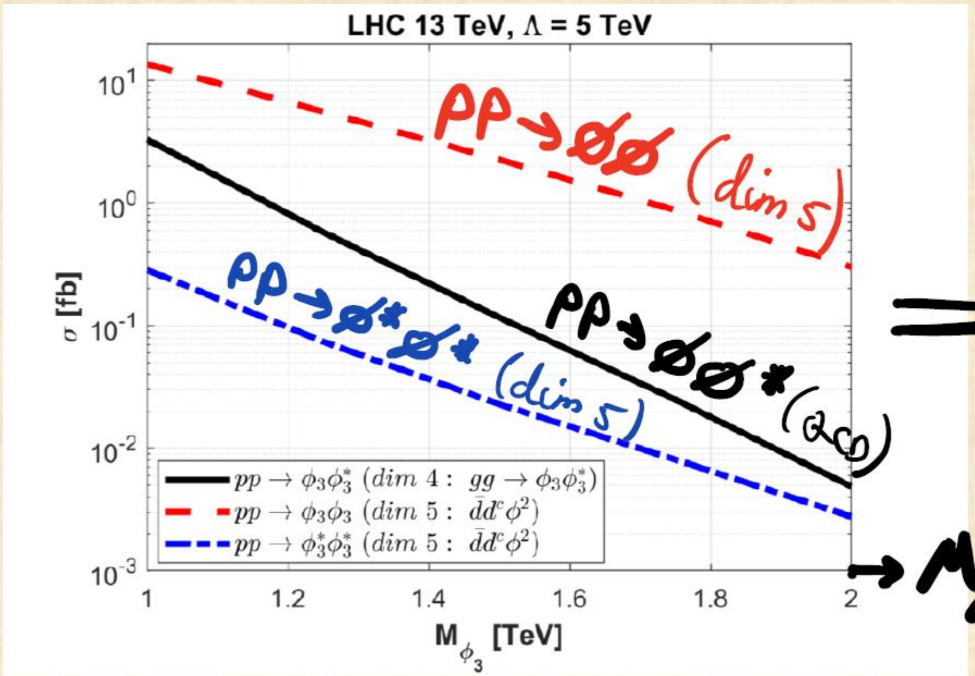

$\Lambda = 5$ TeV $\Longrightarrow$

$\to M_\phi$ [TeV]

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

When the LQ decays to 3rd gen fermions:

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

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

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

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

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

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

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

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

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3rd gen $\phi(3,1,-1/3)$	3rd gen $\phi(3,1,2/3)$
$d^2\phi^2$: $pp_{(dd)} \to \phi\phi$	$u^2\phi^2$: $pp_{(uu)} \to \phi\phi$
$\phi\phi \to tt\tau^-\tau^-$	$\phi\phi \to tt+\cancel{E}_T$
	$\phi\phi \to \tau^+\tau^+ + 2\cdot j_b$

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

  M_ϕ=1 TeV & Λ=5 TeV

  - 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 $pp \to \phi\phi \to l^+l^+ + 2\cdot j_b + \cancel{E}_T$

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

extra handle for these LQ-SMEFT signals

Asymmetric same-sign lepton production:

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

$$N(tt\tau^-\tau^-) >> N(\bar{t}\bar{t}\tau^+\tau^+)\ ,\ N(\tau^+\tau^+ + 2\cdot j_b) >> N(\tau^-\tau^- + 2\cdot j_b)$$

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

X_j = any accompanying jet

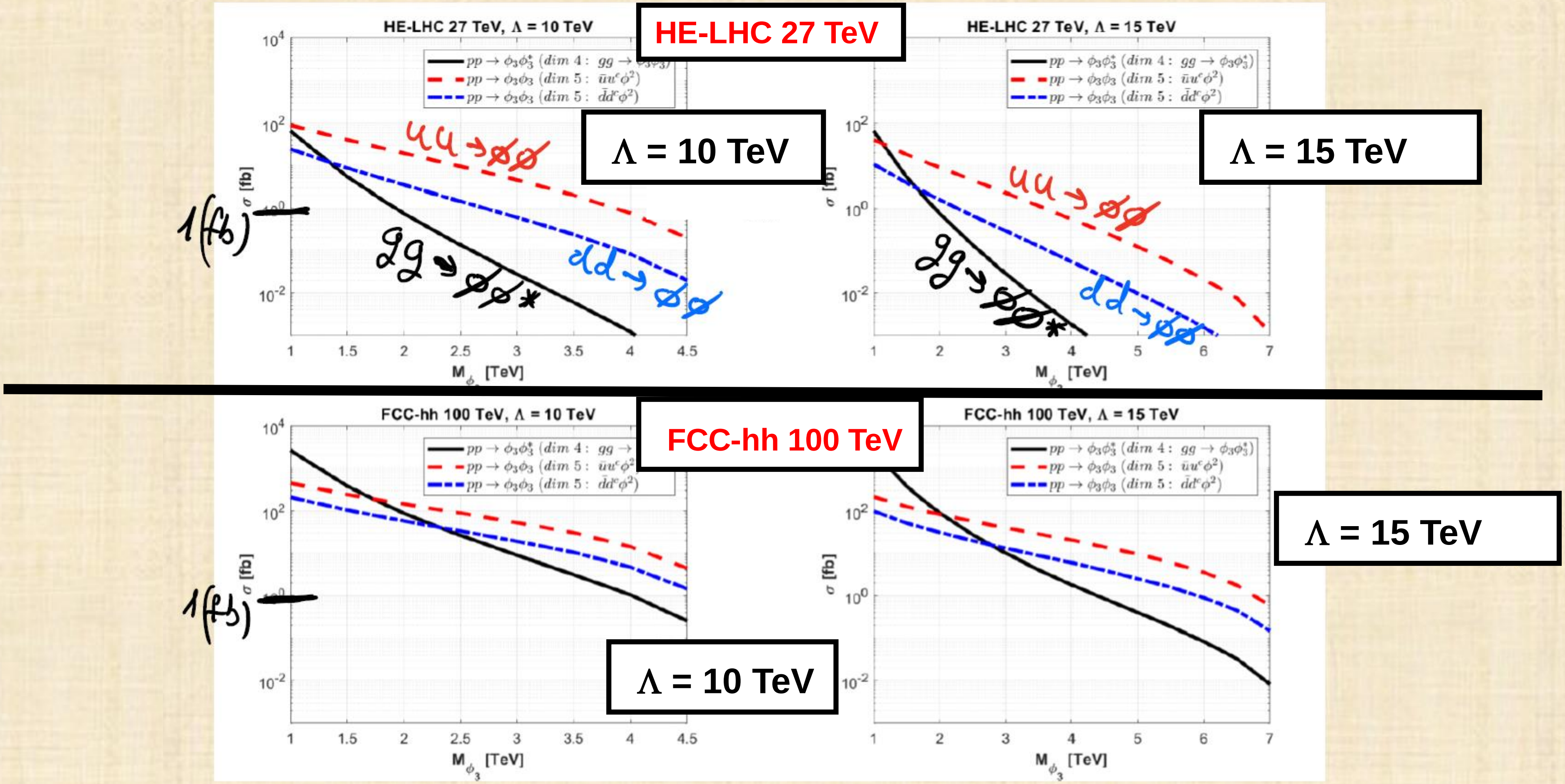
$$\mathcal{A}_{\tau\tau} \equiv \frac{\sigma(pp \to \tau^-\tau^- + X_j) - \sigma(pp \to \tau^+\tau^+ + X_j)}{\sigma(pp \to \tau^-\tau^- + X_j) + \sigma(pp \to \tau^+\tau^+ + X_j)} \sim 100\%$$

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

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

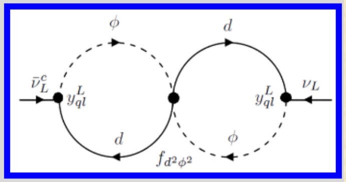


Future higher-energy hadron colliders will be sensitive to the LQ-SMEFT dynamics up to LQ masses of <u>M_ϕ ~ 5 TeV & NP scale of Λ ~ 15 TeV</u>
i.e., with CSX's for same-sign charged leptons larger than σ ~ O(1 fb)

SUMMARY

CONCLUSION

- **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 ($\Lambda <$ 10 TeV)



  - leading effects from several new $\Delta L=2$ dim.5 effective opts
    - effects of higher dim LQ opts >> effects from "standard" dim4 LQ terms

$$\boxed{\sigma(pp \to \phi\phi)_{\mathrm{dim5}} \gg \sigma(pp \to \phi\phi^\star)_{\mathrm{QCD}}}$$

SUMMARY

CONCLUSION

- "smoking gun" same-sign lepton pair signals at the LHC13 & beyond:
  - with highly asymmetric double-charge rates:

$$\sigma(pp \to \phi\phi) \gg \sigma(pp \to \phi^\star\phi^\star) \longrightarrow \text{yielding e.g.,}$$

$$N(pp \to \tau^+\tau^+ + 2\cdot j_b) \gg N(pp \to \tau^-\tau^- + 2\cdot j_b)$$

$$N(pp \to \tau^-\tau^- + 2\cdot j_b + 4\cdot j) \gg N(pp \to \tau^+\tau^+ + 2\cdot j_b + 4\cdot j)$$

$$N(pp \to \ell^+\ell^+ + 2j_b + \not{E}_T) \gg N(pp \to \ell^-\ell^- + 2j_b + \not{E}_T)$$

  - & CSX's much larger than the "standard" opposite-sign lepton pairs signals:

$$\sigma(pp \to \phi\phi \to \ell^\pm\ell^\pm + X) \gg \sigma(pp \to \phi\phi^\star \to \ell^\pm\ell^\mp + X)$$

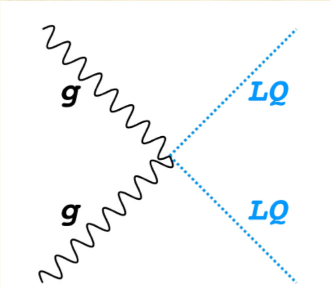
  - sensitivities up to M(LQ) ~ 2 TeV @LHC13 [Λ~5 TeV]
    M(LQ) ~ 5 TeV @FCC-hh100 [Λ~15 TeV]

further thoughts: extending the LQ-SMEFT framework to more LQ types

Backups & more slides

The LQ paradigm – some basic fact for LHC pheno …

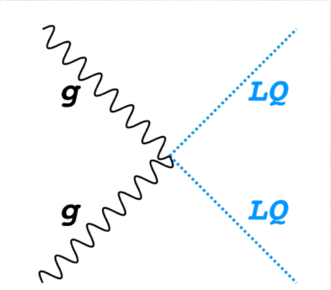
- **LQ's are colored fields**
  $\Rightarrow$ should be copiously (QCD) pair produced @LHC if M_{LQ} ~ O(1 TeV)



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

The LQ paradigm – some basic fact for LHC pheno …

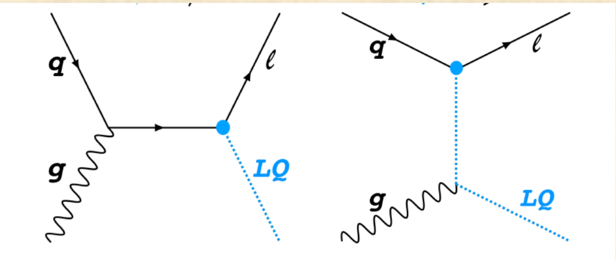
- LQ's are colored fields
  $\Rightarrow$ should be copiously (QCD) pair produced @LHC if M_{LQ} ~ O(1 TeV)



- Typical CSX is: $\sigma(pp \to \phi\phi^*) \sim$ 5(0.01) [fb] for $M_\phi \sim$ 1(2) TeV

- 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 fact for LHC pheno …

- LQ's decay via: $\phi \to q_i e_j$, $q_i \nu_j$ $\left[\Gamma \sim (y_{\phi ql})^2 M_\phi/16\pi\right]$

- 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 $pp \to \ell^\pm + j + \cancel{E}_T$
  - lepton + 2 light jets + missing ET $pp \to \ell^\pm + 2j + \cancel{E}_T$
  - opposite-charged lepton pair + single light let $pp \to \ell^+\ell^- + j$
  - opposite-charged lepton pair + 2 light lets $pp \to \ell^+\ell^- + 2j$
  - b-jet(s) + lepton(s) with or without missing ET (3^{rd} gen. LQ) $pp \to \ell/\ell^+\ell^- + n \cdot j_b + \cancel{E}_T$
  - top-quark(s) + lepton(s) with or without missing ET (3^{rd} gen. LQ) $pp \to \ell/\ell^+\ell^- + t/t\bar{t} + \cancel{E}_T$
  - …

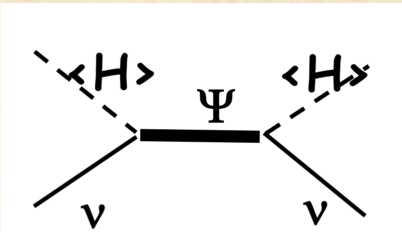
Model dependent …

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

Neutrino masses

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

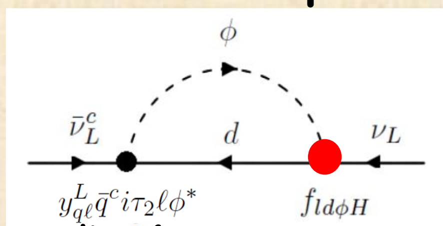
Tree-level



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

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

1-loop



dim.4

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

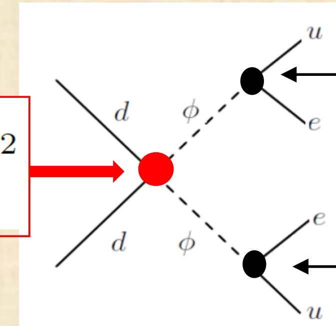
m_ν<eV

both opts severely suppressed

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

ν-less 2β (0νββ) decay

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



dim.4
$y_{ue}^R \bar{u}^c e \phi^*$

$$\frac{\Lambda_{d^2\phi^2}}{\mathrm{TeV}} \gtrsim 150 \cdot \frac{f_{d^2\phi^2} \cdot |y_{ue}^R|^2}{(M_\phi/\mathrm{TeV})^4}$$

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

i.e., if $y_{ue}^R \sim 0.1$ or smaller,
then $M_\phi < \Lambda \sim O(\text{few TeV})$ & $f_{d2\phi2} \sim O(1)$
are allowed …

Neutrino masses – a note

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

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

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.

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

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

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 $\phi(3,1,2/3)$ opts

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

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

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

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

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:

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

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

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

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

$$\mathcal{L}_{Y,\phi_3} \approx y^L_{q_3\ell_3}\left(\bar{t}^c_L \tau_L + \bar{b}^c_L \nu_{\tau L}\right)\phi^* + y^R_{u_3 e_3}\bar{t}^c_R \tau_R \phi^* + \text{H.c.}$$

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

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

Breaking the Z_3 generation symmetry @ E>Λ

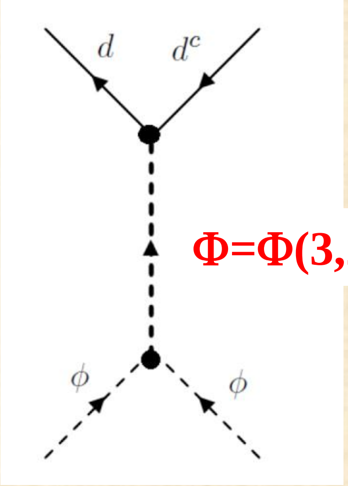
In the SM sector

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., Λ ~ 1.5, 3 or 5 TeV and $f_{uH,dH}$ ~ 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



$\Phi=\Phi(3,2,1/6)$

If $\Phi(3,2,1/6)$ couples to 1st and/or 2nd generation down-quarks & ϕ is a 3rd 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: $g_{\Phi dd} \cdot g_{\Phi\phi\phi} \rightarrow f_{d2\phi2}$, $M_\Phi \rightarrow \Lambda_{d2\phi2}$

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

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 $\phi(3,1,2/3)$
$d^2\not{\phi}^2$: $pp_{(dd)} \rightarrow \phi\phi$	$u^2\not{\phi}^2$: $pp_{(uu)} \rightarrow \phi\phi$	QCD: $pp_{(gg,qq)} \rightarrow \phi\phi^*$
$\phi\phi \rightarrow tt\tau^-\tau^-$	$\phi\phi \rightarrow tt+\not{E}_T$	$\phi\phi^* \rightarrow \bar{t}t\tau^+\tau^-$, $\bar{t}t+\not{E}_T$
$\phi\phi \rightarrow 2\cdot j_b+\not{E}_T$	$\phi\phi \rightarrow \tau^+\tau^+ + 2\cdot j_b$	$\phi\phi \rightarrow \tau^+\tau^- + 2\cdot j_b$, $2\cdot j_b+\not{E}_T$
$\phi\phi \rightarrow t\tau^- + j_b+\not{E}_T$	$\phi\phi \rightarrow t\tau^+ + j_b+\not{E}_T$	$\phi\phi \rightarrow t\tau^+/t\tau^- + j_b+\not{E}_T$

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

  $N(tt\tau^-\tau^-) >> N(\bar{t}\bar{t}\tau^+\tau^+)$, $N(\tau^+\tau^+ + 2\cdot j_b) >> N(\tau^-\tau^- + 2\cdot j_b)$

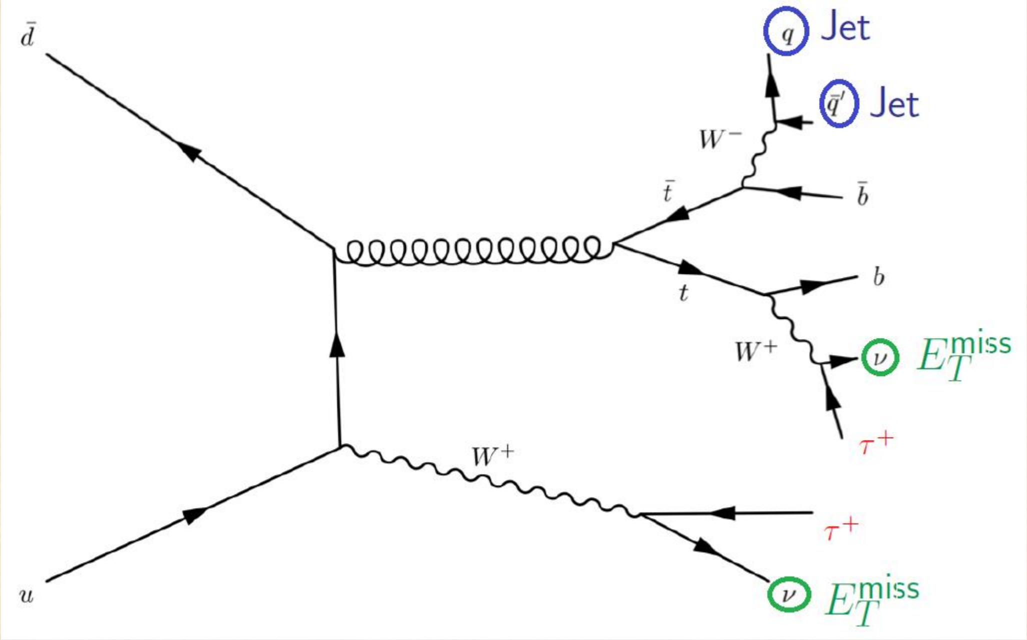
- $\Rightarrow$ Useful double-charge asymmetries with no irreducible backg, e.g.,

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

X_j = any accompanying jet

extra handle for these LQ-SMEFT signals

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)