Baryon Number Violation in Leptoquark and Diquark Models

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Baryon number violation

Reasons to believe that baryon number is not a fundamental symmetry of Nature

- **matter-antimatter asymmetry of the Universe**
- **nonperturbative B violation in the Standard Model**
- **grand unification – proton decay**

Proton decay vs. model building

ΔB = 1 process

$$\mathcal{O}_6 \sim \frac{q\,q\,q\,l}{\Lambda^2}$$

- ➢ excluded up to the GUT scale $\Lambda \sim 10^{16}$ GeV

Two ways out :

① Impose baryon number conservation

② Consider only those models which have no tree-level proton decay

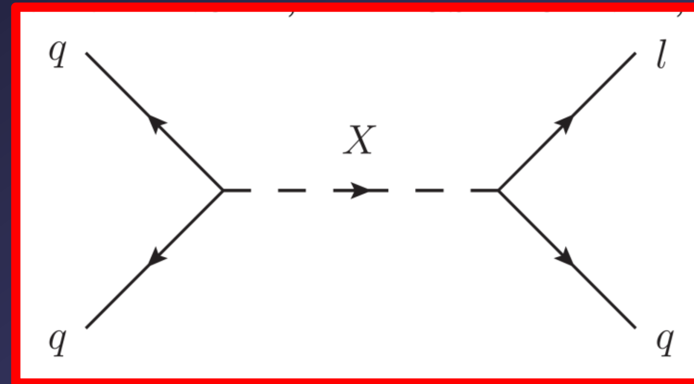
Scalar leptoquark and diquark models

operator	$SU(3) \times SU(2) \times U(1)$ rep. of X	B	L
XQQ, Xud	$\left(\bar{6}, 1, -1/3\right), \left(3, 1, -1/3\right)$	$-2/3$	0
XQQ	$\left(\bar{6}, 3, -1/3\right), \left(3, 3, -1/3\right)$	$-2/3$	0
Xdd	$(3, 1, 2/3), \left(\bar{6}, 1, 2/3\right)$	$-2/3$	0
Xuu	$\left(\bar{6}, 1, -4/3\right), \left(3, 1, -4/3\right)$	$-2/3$	0
$X\bar{Q}\bar{L}$	$(3, 1, -1/3), (3, 3, -1/3)$	$1/3$	1
$X\bar{u}\bar{e}$	$(3, 1, -1/3)$	$1/3$	1
$X\bar{d}\bar{e}$	$(3, 1, -4/3)$	$1/3$	1
$X\bar{Q}e, XL\bar{u}$	$(3, 2, 7/6)$	$1/3$	-1
$X\bar{L}d$	$\left(\bar{3}, 2, -1/6\right)$	$-1/3$	1

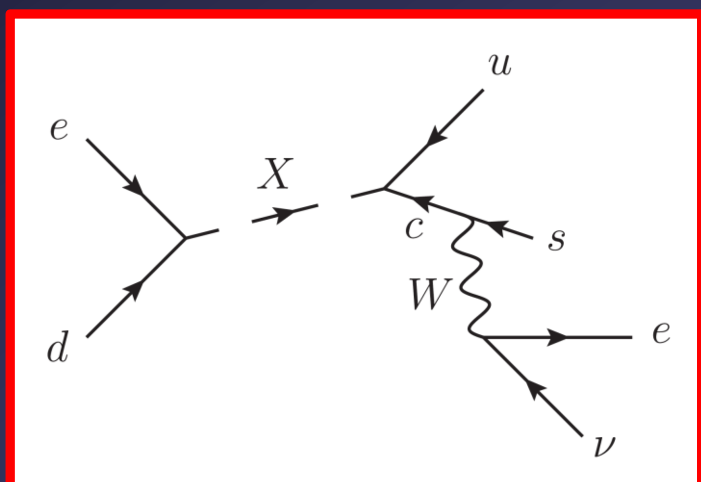
Arnold, BF, Wise, "Simplified models with baryon number violation but no proton decay", Phys. Rev. D 88, 035009 (2013), arXiv:1304.6119 [hep-ph]

Tree-level proton decay

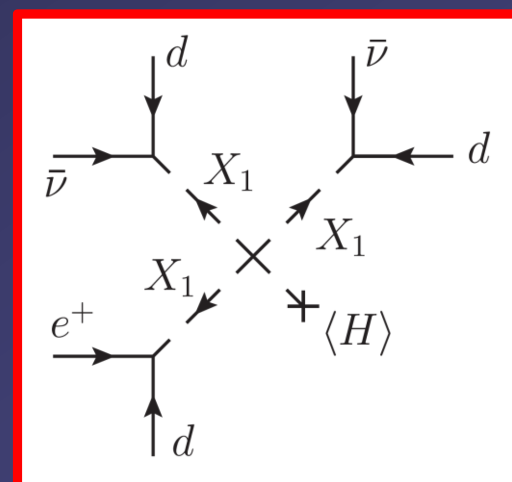
$(3,\ 1,\ -1/3),\ (3,\ 3,\ -1/3)$



$(3,\ 1,\ -4/3)$



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



Vector leptoquark and diquark models

Operator	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	p decay
$\overline{Q}^c_L \gamma^\mu u_R V_\mu$	3	2	$-5/6$	tree-level
	$\bar{6}$	2	$-5/6$	–
$\overline{Q}^c_L \gamma^\mu d_R V_\mu$	3	2	$1/6$	tree-level
	$\bar{6}$	2	$1/6$	–
$\overline{Q}_L \gamma^\mu L_L V_\mu$	3	$1, 3$	$2/3$	dim 5
$\overline{Q}^c_L \gamma^\mu e_R V^*_\mu$	3	2	$-5/6$	tree-level
$\overline{L}^c_L \gamma^\mu u_R V^*_\mu$	3	2	$1/6$	tree-level
$\overline{L}^c_L \gamma^\mu d_R V^*_\mu$	3	2	$-5/6$	tree-level
$\overline{u}_R \gamma^\mu e_R V_\mu$	3	1	$5/3$	dim 7
$\overline{d}_R \gamma^\mu e_R V_\mu$	3	1	$2/3$	dim 5

Assad, BF, Grinstein, "Baryon number and lepton universality violation in leptoquark and diquark models", arXiv:1708.06350 [hep-ph]

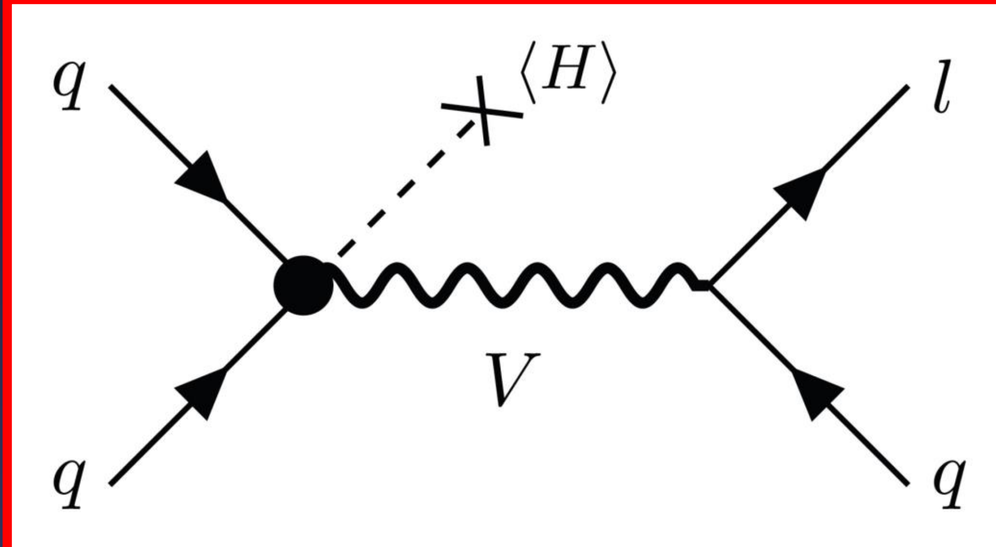
Viable leptoquark and diquark models

Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$ reps.
Scalar leptoquark	$(3,2)'_{\frac{7}{6}}$
Scalar diquark	$(3,1)_{\frac{2}{3}}, (6,1)_{-\frac{2}{3}}, (6,1)_{\frac{1}{3}}, (6,1)_{\frac{4}{3}}, (6,3)_{\frac{1}{3}}$
Vector leptoquark	$(3,1)'_{\frac{2}{3}}, (3,1)_{\frac{5}{3}}, (3,3)'_{\frac{2}{3}}$
Vector diquark	$(6,2)_{-\frac{1}{6}}, (6,2)_{\frac{5}{6}}$

Assad, BF, Grinstein, "Baryon number and lepton universality violation in leptoquark and diquark models", arXiv:1708.06350 [hep-ph]

Dimension five proton decay

$$\frac{1}{\Lambda}\,(\overline{Q}_L^c H^\dagger)\gamma^\mu d_R V_\mu$$



$$\tau_p \approx (2.5\times 10^{32}\ \text{years})\left(\frac{M}{10^4\ \text{TeV}}\right)^4\left(\frac{\Lambda}{M_{\text{Pl}}}\right)^2$$

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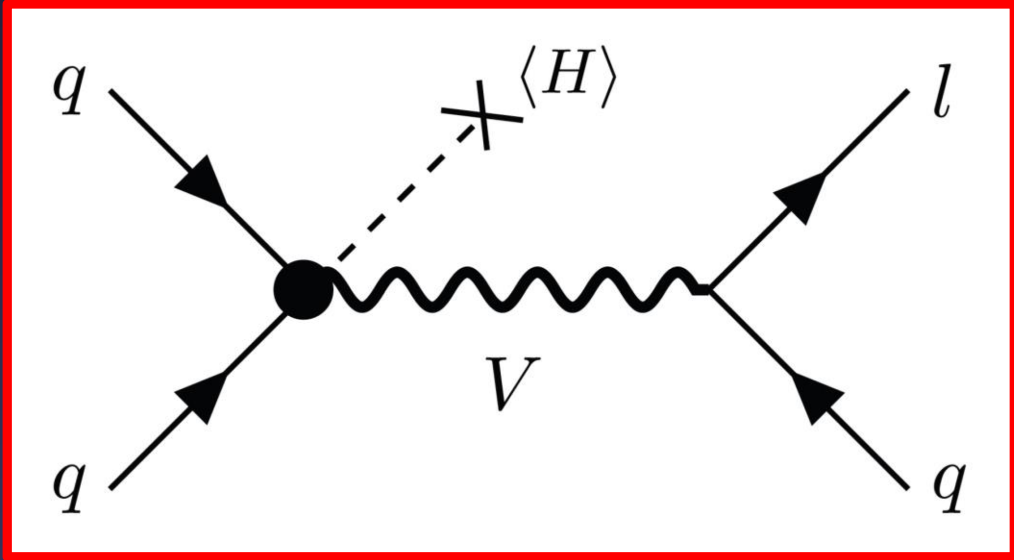

$$\tau_p \approx (2.5\times 10^{32}\ \text{years})\left(\frac{M}{10^4\ \text{TeV}}\right)^4\left(\frac{\Lambda}{M_{\text{Pl}}}\right)^2$$

$U(1)_{B-L}$ would forbid those operators

Vector leptoquark model

Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$ reps.
Scalar leptoquark	$(3,2)'_{\frac{7}{6}}$
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Vector leptoquark	$(3,1)'_{\frac{2}{3}}$ $(3,1)_{\frac{5}{3}}$, $(3,3)'_{\frac{2}{3}}$
Vector diquark	$(6,2)_{-\frac{1}{6}}$, $(6,2)_{\frac{5}{6}}$

Lepton universality violation

$$V = (3,1)_{\frac{2}{3}}$$

- One of three leptoquark models providing an explanation for the B decay anomalies

$$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu\mu)}{\Gamma(B \to K^{(*)}ee)}$$

$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}l\nu)}$$

Pati-Salam unification

$$V = (3,1)_{\frac{2}{3}}$$

- Origin: gauge boson of the Pati-Salam group

$$\mathrm{SU}(4) \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$$

- Dimension five proton decay operators forbidden

$$(4,2,1) = (3,2)_{\frac{1}{6}} \oplus (1,2)_{-\frac{1}{2}}$$
$$(\bar{4},1,2) = (\bar{3},1)_{\frac{1}{3}} \oplus (\bar{3},1)_{-\frac{2}{3}} \oplus (1,1)_1 \oplus (1,1)_0$$

Lepton universality violation

$$V = (3,1)_{\frac{2}{3}}$$

- **M = 16 TeV consistent with B decay anomalies**

  Assad, BF, Grinstein, arXiv:1708.06350 [hep-ph]

- **Flavor matrices have to be tuned to avoid meson decay constraints**

- **Additional vector-like matter permits natural flavor parameters**

  Calibbi, Crivellin, Li, arXiv:1709.00692 [hep-ph]

Baryon number violation

ΔB = 1 processes:

$$\mathcal{O}_6 \sim \frac{q\,q\,q\,l}{\Lambda^2}$$

- probe physics up to the GUT scale ~ 10^{16} GeV

ΔB = 2 processes:

$$\mathcal{O}_9 \sim \frac{q\,q\,q\,q\,q\,q}{\Lambda^5}$$

- probe a lower energy scale ~ hundreds of TeV
  (not necessarily!) ⟶ $\Lambda^5 \gtrsim (500\ \mathrm{TeV})^5$

$|\Delta B| = 2$ processes

Violating baryon number by two units:

- **sign of new physics!**
- **closely related to physics behind neutrino masses if $B - L$ is a fundamental symmetry**
- **probe physics in the TeV – GUT region**
- **hope for baryogenesis**

Models with $|\Delta B|=2$

① **SO(10) GUT scale seesaw with TeV scalars**

[Babu, Mohapatra (2012)]

② **TeV scale seesaw with quark-lepton unification**

*[Mohapatra, Marshak (1980), Babu, Dev, Mohapatra (2009);
Babu, Dev, Fortes, Mohapatra (2013)]*

③ **TeV scale extra dimensions**

[Dvali, Gabadadze (2002); Nussinov, Shrock (2002); Winslow, Ng (2010)]

④ **Supersymmetric and superstring models**

[Zwirner (1983), Mohapatra, Valle (1986); Goity, Sher (1995)]

① **SM or MSSM with additional multiplets**

*[Ajaib, Gogoladze, Mimura, Shafi (2009); Gu, Sarkar (2011);
Arnold, BF, Wise (2013), Herrmann (2014)]*

Vector diquark model

Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$ reps.
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Vector diquark model

- Only one new vector representation

$$V_\mu = \begin{pmatrix} V_u \\ V_d \end{pmatrix}_\mu^{\alpha\beta} = (6,2)_{-\frac{1}{6}}$$

- Lagrangian

$$\mathcal{L}_V = -\frac{1}{4}(D_{[\mu}V_{\nu]})^\dagger D^{[\mu}V^{\nu]} + M^2 V_\mu^\dagger V^\mu - \left[\lambda_{ij}\,(\overline{Q}_L^c)^i_\alpha \gamma^\mu (d_R)^j_\beta (V^\dagger)^{\alpha\beta}_\mu + \text{h.c.}\right]$$

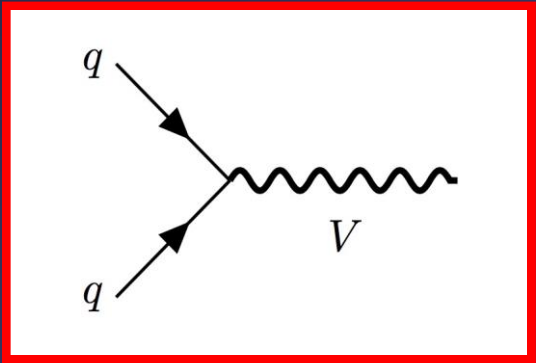
LHC phenomenology

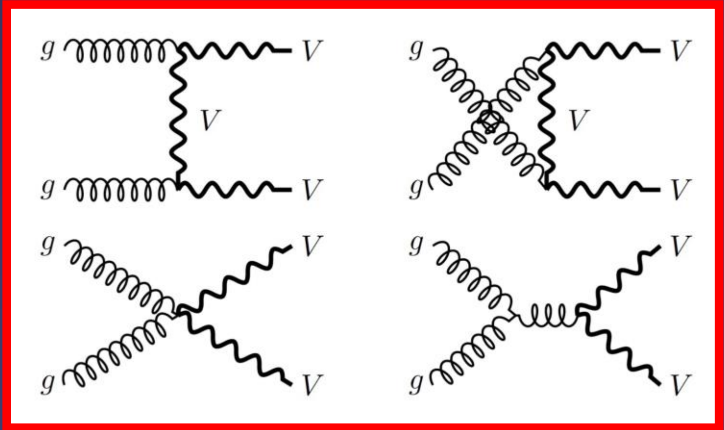
$$\mathcal{L}_V = -\frac{1}{4}(D_{[\mu}V_{\nu]})^\dagger D^{[\mu}V^{\nu]} + M^2 V_\mu^\dagger V^\mu - \left[\lambda_{ij}\,(\overline{Q}{}^c_L)^i_\alpha \gamma^\mu (d_R)^j_\beta (V^\dagger)^{\alpha\beta}_\mu + \text{h.c.}\right]$$

Dijet and four-jet searches:

$$M_{\lambda\approx 1} \gtrsim 8\ \text{TeV}$$

$$M_{\lambda\ll 1} \gtrsim 2.5\ \text{TeV}$$

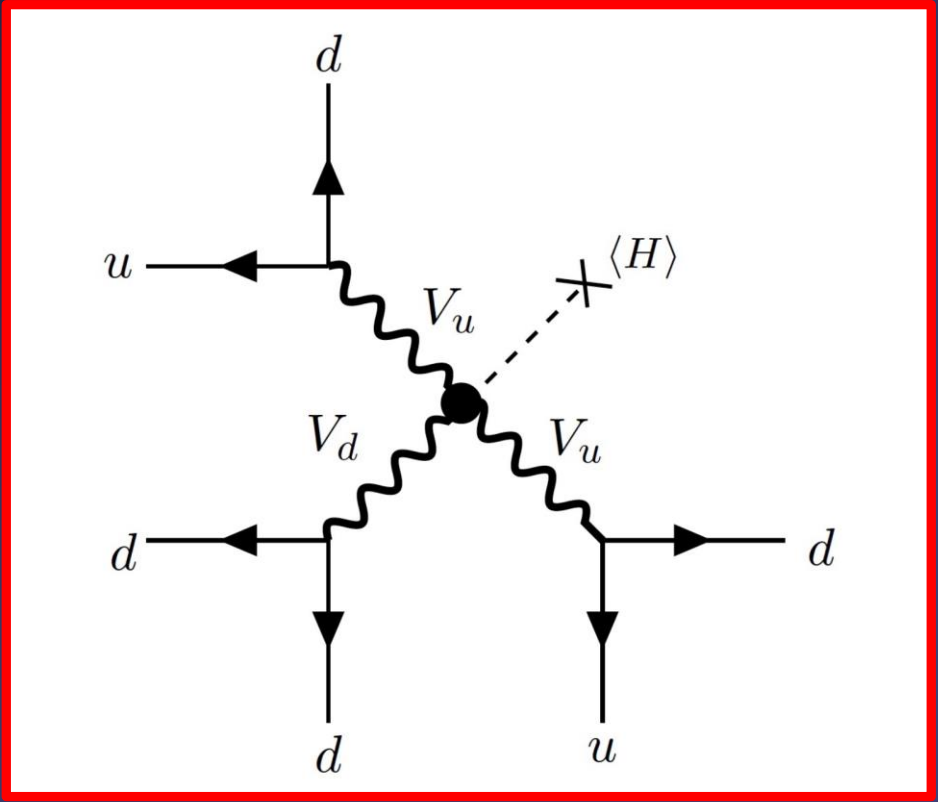




Neutron-antineutron oscillations

$$\mathcal{O}_2 = \frac{c_2}{\Lambda}\left[\partial_\mu (V^\mu)^{\alpha\alpha'} \epsilon V_\nu^{\beta\beta'}\right]\left[(V^\nu)^{\delta\delta'} \epsilon H\right] \epsilon_{\alpha\beta\delta}\, \epsilon_{\alpha'\beta'\delta'}$$

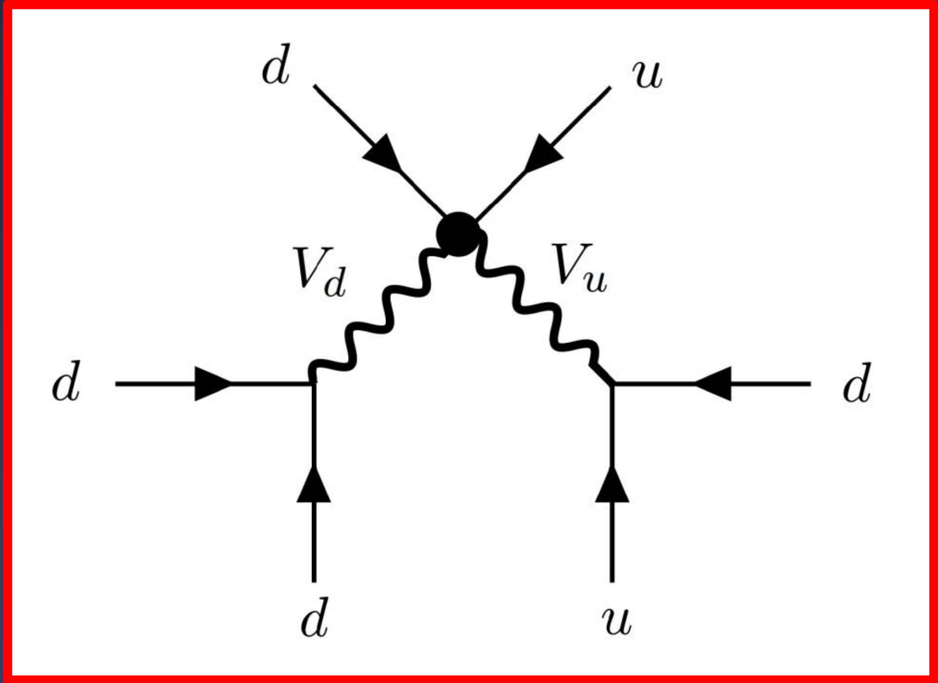
$$(6, 2)_{-\frac{1}{6}}$$



Neutron-antineutron oscillations

$$\mathcal{O}_1 = \frac{c_1}{\Lambda} V_\mu^{\alpha\alpha'} \epsilon V_\nu^{\beta\beta'} (\bar{u}_R^c)^\delta \sigma^{\mu\nu} d_R^{\delta'} \epsilon_{\alpha\beta\delta} \epsilon_{\alpha'\beta'\delta'}$$

$$(6, 2)_{-\frac{1}{6}}$$



Neutron-antineutron oscillations

- Effective Hamiltonian

$$\mathcal{H}_{\rm eff} \approx -\frac{\lambda_{11}^{2}}{M^4\Lambda}(\overline{d}_L^c)^{\alpha}\gamma_\mu d_R^{\alpha'}(\overline{u}_L^c)^{\beta}\gamma_\nu d_R^{\beta'}(\overline{u}_L^c)^{\delta}\sigma^{\mu\nu}d_R^{\delta'}$$
$$\times\left(\epsilon_{\alpha\beta\delta}\,\epsilon_{\alpha'\beta'\delta'}+\epsilon_{\alpha'\beta\delta}\,\epsilon_{\alpha\beta'\delta'}+\epsilon_{\alpha\beta'\delta}\,\epsilon_{\alpha'\beta\delta'}+\epsilon_{\alpha\beta\delta'}\,\epsilon_{\alpha'\beta'\delta}\right)$$
$$+\,\mathrm{h.c.}$$

- Transition matrix element

$$\left|\langle\bar{n}|\mathcal{H}_{\rm eff}|n\rangle\right| \approx \frac{10^{-4}\,|\lambda_{11}^{2}|}{M^4\Lambda}\,\mathrm{GeV}^6$$

Neutron-antineutron oscillations

- Experimental limit on the diquark mass

$$M \gtrsim 2.5 \text{ TeV} \left(\frac{10^8 \text{ TeV}}{\Lambda} \right)^{1/4}$$

- Current and future sensitivity assuming $\Lambda \approx M$

$$M \gtrsim 90 \text{ TeV} \quad \longrightarrow \quad M \approx 175 \text{ TeV}$$

Conclusions

- Only several leptoquark and diquark models are free from tree-level proton decay
- Dimension five proton decay is a problem for low-scale leptoquark models and requires a larger symmetry at higher energies
- Neutron-antineutron oscillations can be mediated by a single vector diquark


Thank you!