New perspectives on $|\Delta B|=2$ dynamics

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Workshop on Intersections of BSM Phenomenology and QCD for New Physics Searches

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Baryon number violation

Reasons to believe that *B* is not a fundamental symmetry of Nature:

- matter-antimatter asymmetry of the Universe
- nonperturbative *B* violation in the SM
- grand unification

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

Baryon number violation

ΔB=1 processes:

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- 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!)

|ΔB|=2 processes

Violating baryon number by two units:

- **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**

$|\Delta B|=2$ processes

- **Neutron-antineutron oscillations**

$$n \leftrightarrow \bar{n}$$

Current limit: $\tau_{n\bar{n}} \gtrsim 2.7 \times 10^8 \; s$

[Abe et al., Super-K Collaboration (2011)]

$\longrightarrow$ $\Lambda^5 \gtrsim (500 \text{ TeV})^5$

|ΔB|=2 processes

- **Neutron-antineutron oscillations**

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[Abe et al., Super-K Collaboration (2011)]

$\Rightarrow$ $\Lambda^5 \gtrsim (500\ \mathrm{TeV})^5$

- **Dinucleon decays**

$$p\,p \to K^+ K^+$$

Limit: $\tau_{^{16}O \to ^{14}C K^+ K^+} > 1.7 \times 10^{32}\ \mathrm{yr}$

[Litos et al., Super-K Collaboration (2014)]

$$n\,p \to e^+ \nu$$

Limit: $\tau_{np \to e^+ \nu} > 2.6 \times 10^{32}\ \mathrm{yr}$

[Takhistov et al., Super-K Collaboration (2015)]

$\Rightarrow$ $\Lambda^8 \gtrsim (10\ \mathrm{TeV})^8$

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)]

⑤ **SM or MSSM with additional multiplets**
[Ajaib, Gogoladze, Mimura, Shafi (2009); Gu, Sarkar (2011); Arnold, BF, Wise (2013), Herrmann (2014)]

① SO(10) GUT scale seesaw + TeV scalars

[Babu, Mohapatra (2012)]

- natural framework for small neutrino masses
- explains the neutrino mixing pattern
- SM gauge group up to SO(10) breaking scale
- diquarks (6,1,1/3), (6,1,-2/3) and (6,1,4/3) ~ TeV contained in the 126-plet or 54-plet Higgs
- gauge coupling unification at ~ 3 x 10^{15} GeV
- proton lifetime ~ 10^{34} years

① SO(10) and neutron-antineutron oscillations

[Babu, Mohapatra (2012)]

- **Lagrangian:**

$$\mathcal{L}_{\Delta B\neq 0} = f_{dd}\, d^c d^c \Delta_{d^c d^c} + \frac{f_{ud}}{\sqrt{2}}(u^c d^c + d^c u^c)\Delta_{u^c d^c} + f_{uu}\, u^c u^c \Delta_{u^c u^c} + \lambda v_{BL}\,(\Delta_{u^c d^c}\Delta_{u^c d^c}\Delta_{d^c d^c} + \Delta_{d^c d^c}\Delta_{d^c d^c}\Delta_{u^c u^c}) + h.c.$$

- **Amplitude for nnbar oscillations:**

$$G_{N-\bar{N}} \simeq \frac{\eta f_{ud}^2 f_{dd} \lambda v_{BL}}{M^4_{\Delta_{u^c d^c}} M^2_{\Delta_{d^c d^c}}}$$

- **Combined with a successful baryogenesis:**

$$\tau_{n\bar{n}} \sim 10^8 - 10^{11}\ s$$

② TeV scale seesaw with quark-lepton unification

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

- **Pati-Salam unification (including gauged *B-L*) above the seesaw scale**
- **TeV-scale color sextet scalars mediating neutron-antineutron oscillations**
- **low-scale baryogenesis needed to make predictions for nnbar oscillation frequency**
- **post-sphaleron baryogenesis requires** $\tau_{n\bar{n}} < 5 \times 10^{10}\ s$

⑤ Simplified models

[Arnold, BF, Wise (2013)]

- Search for the simplest models which violate baryon number but do not give rise to tree-level proton decay:

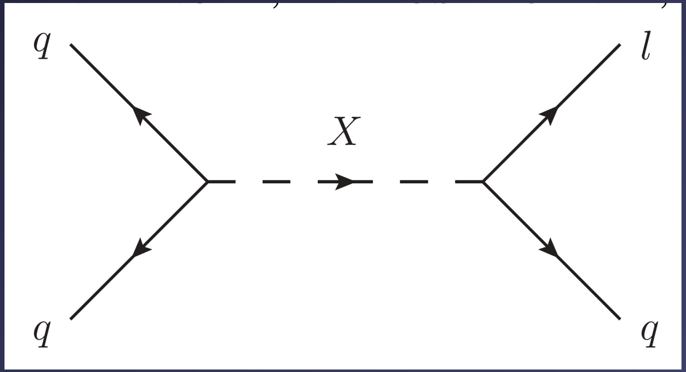
  - minimal new particle content
  - no global symmetries imposed
  - only renormalizable couplings

Possible renormalizable operators

operator	$SU(3)\times SU(2)\times U(1)$ rep. of X	B	L
XQQ, Xud	$(\bar{6},1,-1/3)$, $(3,1,-1/3)$	$-2/3$	0
XQQ	$(\bar{6},3,-1/3)$, $(3,3,-1/3)$	$-2/3$	0
Xdd	$(3,1,2/3)$, $(\bar{6},1,2/3)$	$-2/3$	0
Xuu	$(\bar{6},1,-4/3)$, $(3,1,-4/3)$	$-2/3$	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
$X\bar{L}d$	$(\bar{3},2,-1/6)$	$-1/3$	1
XLL	$(1,1,1)$, $(1,3,1)$	0	-2
Xee	$(1,1,2)$	0	-2

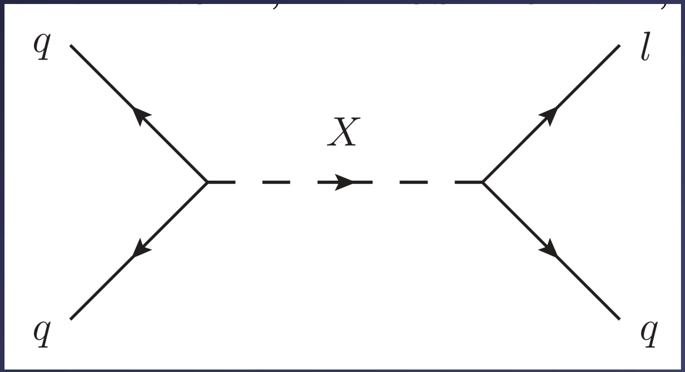
Tree-level proton decay

→ (3, 1, -1/3), (3, 3, -1/3)

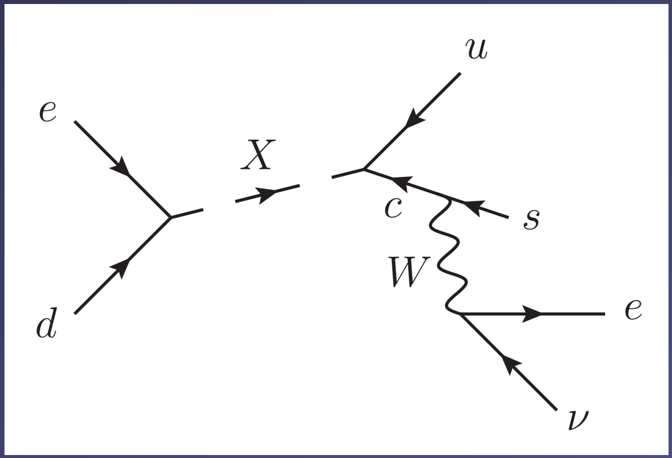


Tree-level proton decay

$(3,\ 1,\ \text{-}1/3),\ (3,\ 3,\ \text{-}1/3)$

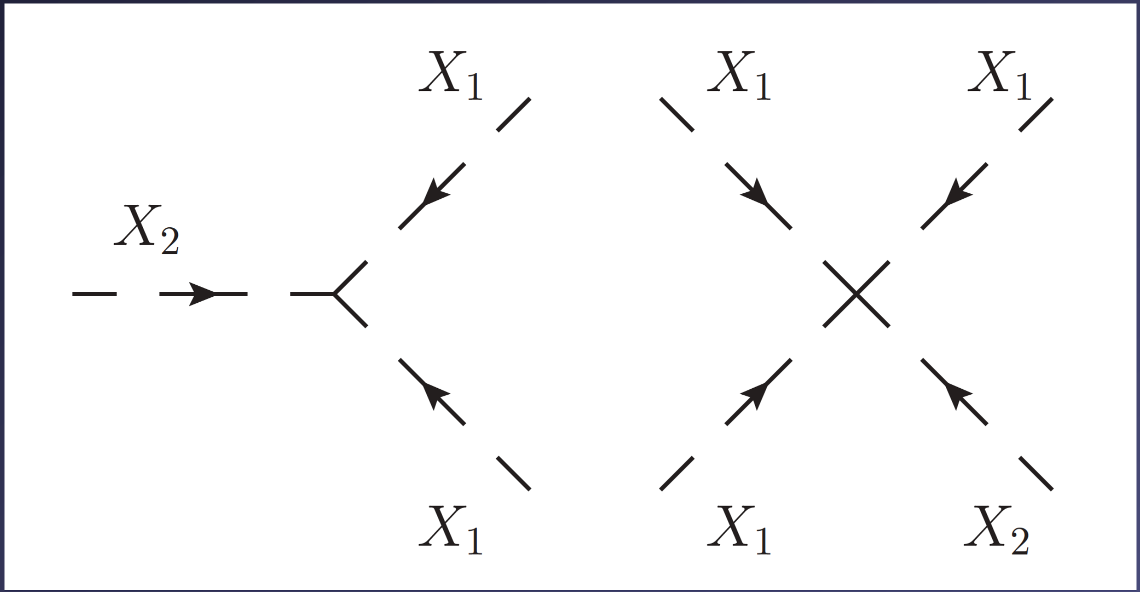


$(3,\ 1,\ \text{-}4/3)$



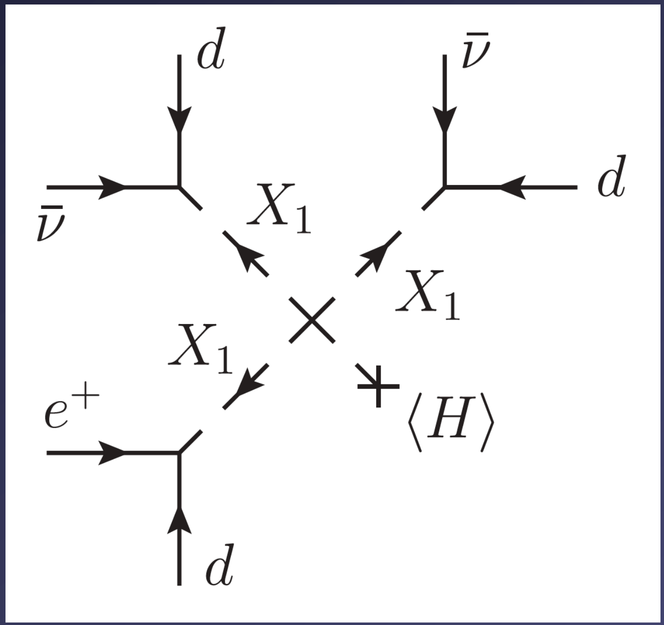
Baryon number violation

- *B*-violation arises from the scalar potential
- only two types of scalar interactions which may violate baryon number without proton decay:



Tree-level proton decay

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



$$p \rightarrow \pi^+ \pi^+ e^- \nu\, \nu$$

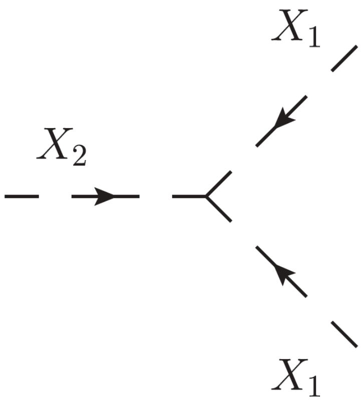
Scalar representations without proton decay

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

B-violating models without proton decay

Model 1.	$X_1 = (\bar{6}, 1, -1/3), \;\; X_2 = (\bar{6}, 1, 2/3)$
Model 2.	$X_1 = (\bar{6}, 3, -1/3), \;\; X_2 = (\bar{6}, 1, 2/3)$
Model 3.	$X_1 = (\bar{6}, 1, 2/3), \;\; X_2 = (\bar{6}, 1, -4/3)$
Model 4.	$X_1 = (3, 1, 2/3), \;\; X_2 = (\bar{6}, 1, -4/3)$
Model 5.	$X_1 = (\bar{6}, 1, -1/3), \;\; X_2 = (1, 1, 1)$
Model 6.	$X_1 = (\bar{6}, 3, -1/3), \;\; X_2 = (1, 1, 1)$
Model 7.	$X_1 = (\bar{6}, 3, -1/3), \;\; X_2 = (1, 3, 1)$
Model 8.	$X_1 = (\bar{6}, 1, 2/3), \;\; X_2 = (1, 1, -2)$
Model 9.	$X_1 = (3, 1, 2/3), \;\; X_2 = (1, 1, -2)$

B-violating models without proton decay



$X_1 = (\bar{6}, 1, -1/3), \;\; X_2 = (\bar{6}, 1, 2/3)$

$X_1 = (\bar{6}, 3, -1/3), \;\; X_2 = (\bar{6}, 1, 2/3)$

$X_1 = (\bar{6}, 1, 2/3), \;\; X_2 = (\bar{6}, 1, -4/3)$

$X_1 = (3, 1, 2/3), \;\; X_2 = (\bar{6}, 1, -4/3)$

Model 5. $X_1 = (\bar{6}, 1, -1/3), \;\; X_2 = (1, 1, 1)$

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B-violating models without proton decay

nnbar oscillations

$X_1 = (6, 1, -1/3), \quad X_2 = (6, 1, 2/3)$

$X_1 = (\bar{6}, 3, -1/3), \quad X_2 = (\bar{6}, 1, 2/3)$

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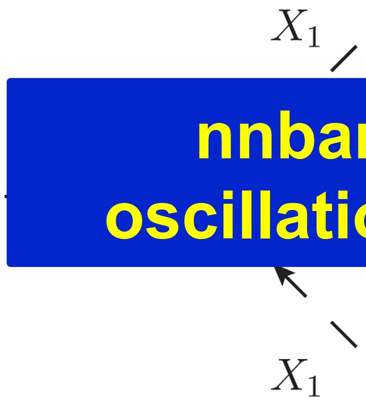
B-violating models without proton decay



nnbar oscillations

$$X_1 = (6,1,-1/3), \quad X_2 = (6,1,2/3)$$
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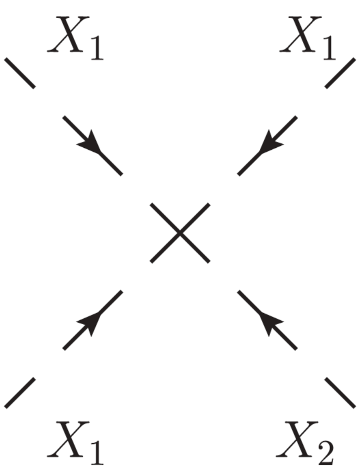
$$X_1 = (\bar{6},1,2/3), \quad X_2 = (\bar{6},1,-4/3)$$
$$X_1 = (3,1,2/3), \quad X_2 = (\bar{6},1,-4/3)$$



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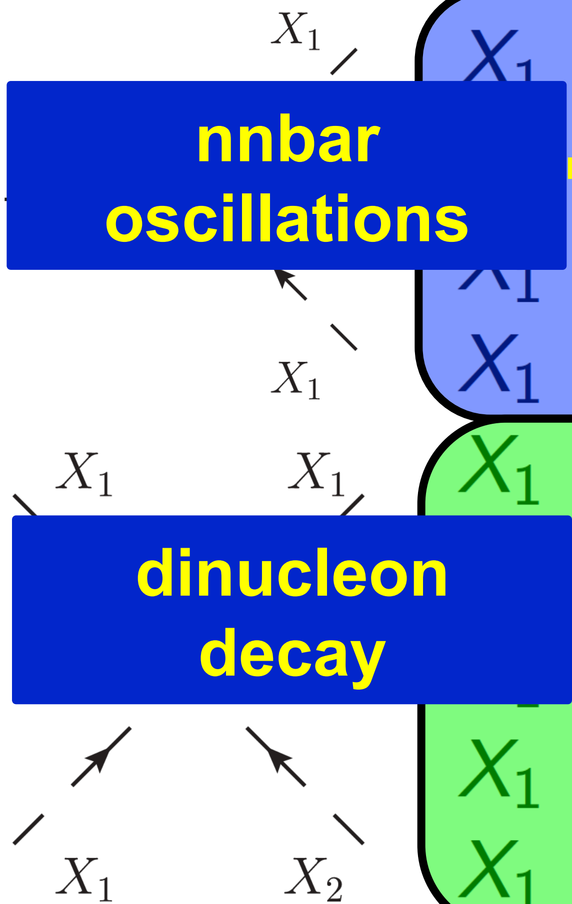
B-violating models without proton decay



nnbar oscillations

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dinucleon decay

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$$X_1 = (3, 1, 2/3), \quad X_2 = (1, 1, -2)$$

The model

- New scalars:

$$X_1 = (\bar{6}, 1, -1/3) \quad \text{and} \quad X_2 = (\bar{6}, 1, 2/3)$$

- Interactions:

$$\mathcal{L} = -\, g_1^{ab} X_1^{\alpha\beta} \left(Q_{L\alpha}^{a} \epsilon\, Q_{L\beta}^{b} \right) - g_2^{ab} X_2^{\alpha\beta} (d_{R\alpha}^{a} d_{R\beta}^{b})$$
$$-\; g_1^{\prime ab} X_1^{\alpha\beta} (u_{R\alpha}^{a} d_{R\beta}^{b}) + \lambda X_1^{\alpha\alpha'} X_1^{\beta\beta'} X_2^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}$$

The model

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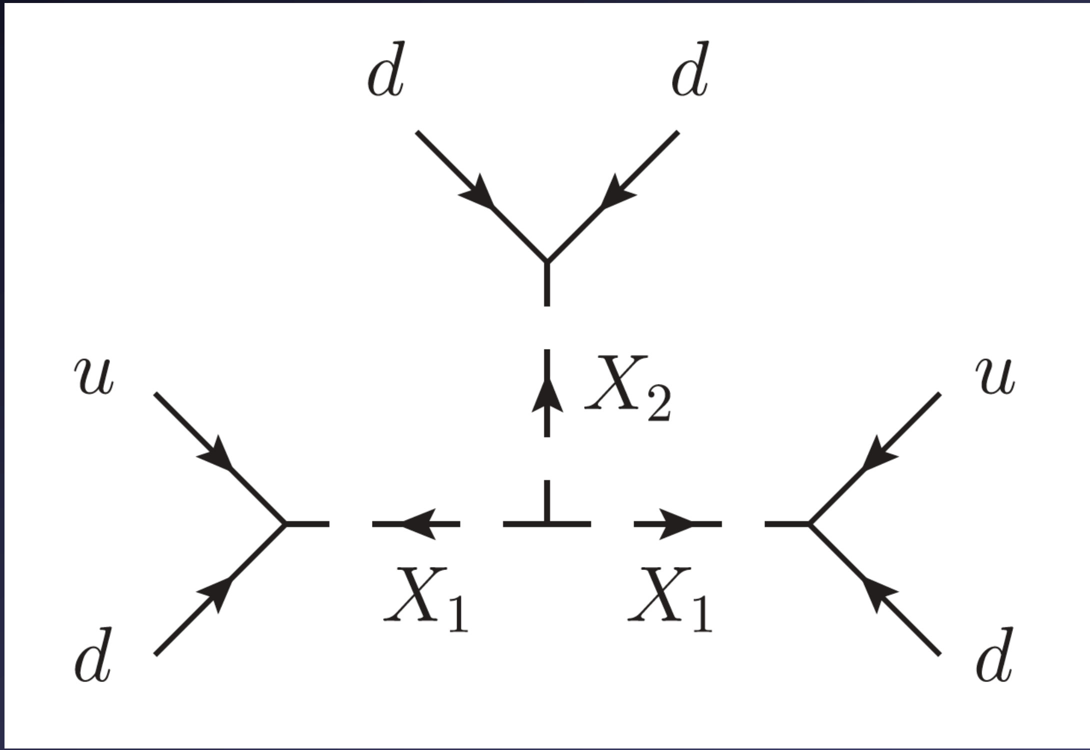
Neutron-antineutron oscillations



$$\mathcal{L} = - g_1^{ab} X_1^{\alpha\beta} \left(Q^a_{L\alpha} \epsilon \, Q^b_{L\beta} \right) - g_2^{ab} X_2^{\alpha\beta} (d^a_{R\alpha} d^b_{R\beta})$$

$$- \; g_1'^{ab} X_1^{\alpha\beta} (u^a_{R\alpha} d^b_{R\beta}) + \lambda X_1^{\alpha\alpha'} X_1^{\beta\beta'} X_2^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}$$

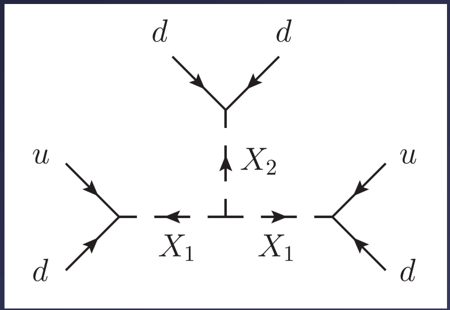
Neutron-antineutron oscillations

Transition matrix element

$$\Delta m = \langle \bar{n} | \mathcal{H}_{\rm eff} | n \rangle$$

Neglecting g_1 the effective $|\Delta B|=2$ Hamiltonian:

$$\mathcal{H}_{\rm eff} = -\frac{(g_1'^{11})^2 g_2^{11} \lambda}{4 M_1^4 M_2^2} d_{Ri}^{\dot\alpha} d_{Ri'}^{\dot\beta} u_{Rj}^{\dot\gamma} d_{Rj'}^{\dot\delta} u_{Rk}^{\dot\lambda} d_{Rk'}^{\dot\chi} \epsilon_{\dot\alpha\dot\beta} \epsilon_{\dot\gamma\dot\delta} \epsilon_{\dot\lambda\dot\chi}$$
$$\times \left(\epsilon_{ijk}\epsilon_{i'j'k'} + \epsilon_{i'jk}\epsilon_{ij'k'} + \epsilon_{ij'k}\epsilon_{i'jk'} + \epsilon_{ijk'}\epsilon_{i'j'k} \right) + \mathrm{h.c.}$$



$$\mathcal{L} = - g_1^{ab} X_1^{\alpha\beta} \left(Q_{L\alpha}^a \epsilon\, Q_{L\beta}^b \right) - g_2^{ab} X_2^{\alpha\beta} (d_{R\alpha}^a d_{R\beta}^b)$$
$$- g_1'^{ab} X_1^{\alpha\beta} (u_{R\alpha}^a d_{R\beta}^b) + \lambda X_1^{\alpha\alpha'} X_1^{\beta\beta'} X_2^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma}\epsilon_{\alpha'\beta'\gamma'}$$

Neutron-antineutron oscillations

Using the vacuum insertion approximation and the general form of the hadronic matrix element:

$$\langle 0 | d^{\dot\alpha}_{Ri} d^{\dot\beta}_{Rj} u^{\dot\gamma}_{Rk} | n(p,s) \rangle = -\frac{1}{18} \beta \epsilon_{ijk} (\epsilon^{\dot\alpha\dot\gamma} u^{\dot\beta}_R(p,s) + \epsilon^{\dot\beta\dot\gamma} u^{\dot\alpha}_R(p,s)).$$

where $\beta \simeq 0.01 \ \mathrm{GeV}^3$ *[Tsutsui et al., CP-PACS and JLQCD Collaboration (2004)]*

we find:

$$|\Delta m| = 2\lambda\beta^2 \frac{|(g_1'^{11})^2 g_2^{11}|}{3 M_1^4 M_2^2}$$

Neutron-antineutron oscillations

Matrix element

$$|\Delta m| = 2\lambda\beta^2 \frac{|(g_1'^{11})^2 g_2^{11}|}{3M_1^4 M_2^2}$$

Current limit:

$$|\Delta m| < 2 \times 10^{-33}\ \mathrm{GeV}$$

[Abe et al., Super-K Collaboration (2011)]

Future sensitivity:

$$|\Delta m| \simeq 7 \times 10^{-35}\ \mathrm{GeV}$$

[Kamyshkov (2012), unpublished]

Neutron-antineutron oscillations

Matrix element

$$|\Delta m| = 2\lambda\beta^2 \frac{|(g_1^{\prime 11})^2 g_2^{11}|}{3M_1^4 M_2^2}$$

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$$|\Delta m| \simeq 7 \times 10^{-35}\ \mathrm{GeV}$$

[Kamyshkov (2012), unpublished]

Regime (1): $M_1 = M_2 \equiv M$, and $g_1^{\prime 11} = g_2^{11} = 1$, $\lambda = M$,

Regime (2): $M_2 > M_1$ $\quad M_1 = 5\ \mathrm{TeV}$ $\quad \lambda = M_2$

Neutron-antineutron oscillations

Regime (1):

$$M_1 = M_2 \equiv M$$

Current limit:

$$M \gtrsim 500 \text{ TeV}$$

Future sensitivity:

$$M \gtrsim 1000 \text{ TeV}$$

Neutron-antineutron oscillations

Regime (2):

$$M_1 = 5\ \mathrm{TeV} \qquad M_2 > M_1$$

Current limit:

$$M_2 \gtrsim 5 \times 10^{13}\ \mathrm{GeV}$$

Future sensitivity:

$$M_2 \gtrsim 1.5 \times 10^{15}\ \mathrm{GeV}$$

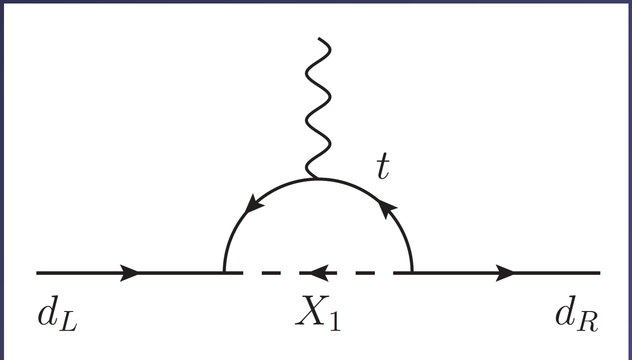
Experimental constraints

- **LHC single or pair production of *X_1***

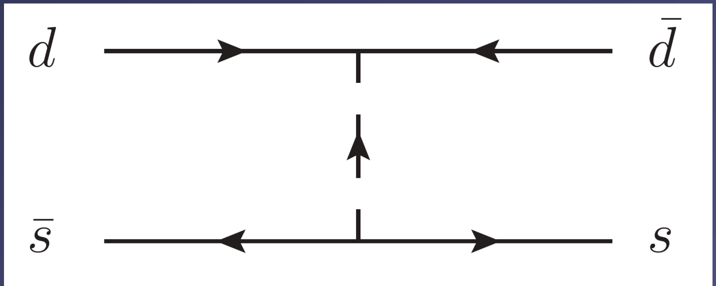
$$M_1 \gtrsim 1\ \mathrm{TeV}$$

[Richardson, Winn (2012)]

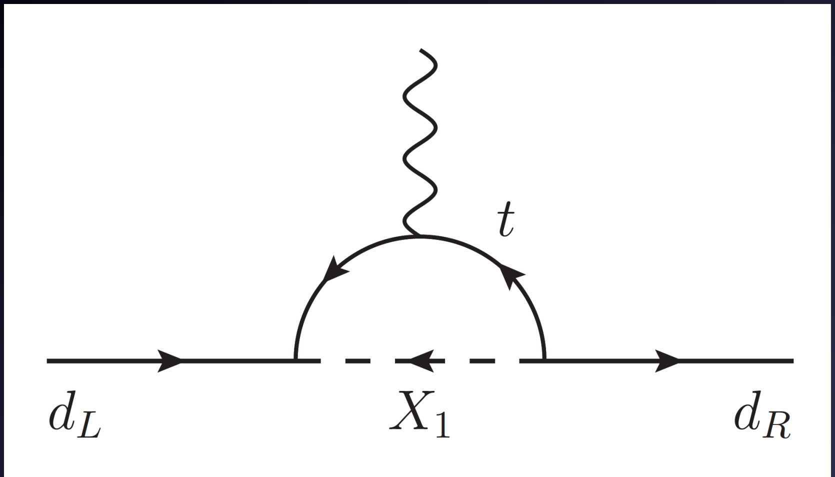
- **Neutron electric dipole moment**



- **Neutral kaon mixing**



Neutron EDM



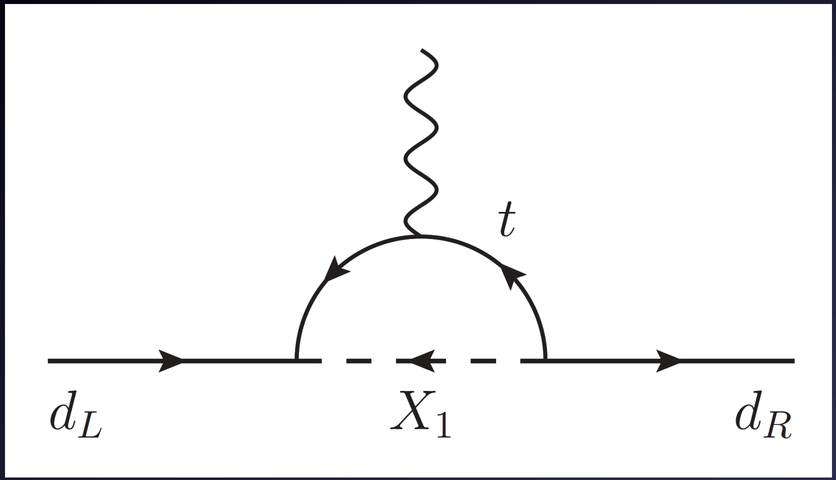
$$|d_d| \simeq \frac{m_t}{6\pi^2 M_1^2} \log\left(\frac{M_1^2}{m_t^2}\right) \left|\mathrm{Im}[g_1^{31}({g'}_1^{31})^*]\right| \ e\ \mathrm{cm}$$

$$d_n \simeq \frac{4}{3} d_d$$

$$d_n^{\mathrm{exp}} < 2.9 \times 10^{-26} \ e\ \mathrm{cm}$$

[Baker et al. (2006)]

Neutron EDM



$$|d_d| \simeq \frac{m_t}{6\pi^2 M_1^2} \log\left(\frac{M_1^2}{m_t^2}\right) \left|\mathrm{Im}[g_1^{31}(g'^{31}_1)^*]\right| \quad e \ \mathrm{cm}$$

$$d_n \simeq \tfrac{4}{3} d_d$$

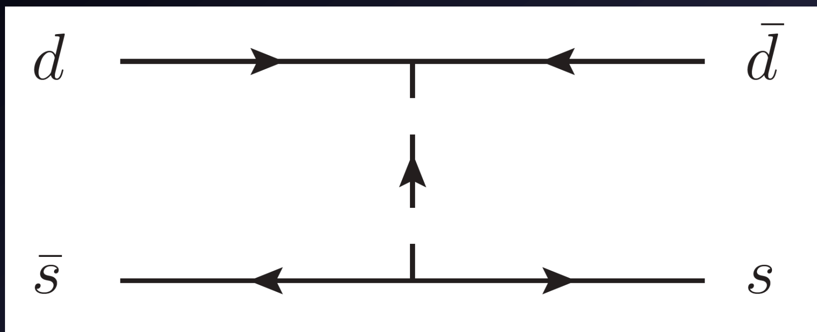
$$d_n^{\mathrm{exp}} < 2.9 \times 10^{-26} \quad e \ \mathrm{cm}$$

[Baker et al. (2006)]

$$M_1 \simeq 500 \ \mathrm{TeV} \longrightarrow \left|\mathrm{Im}[g_1^{31}(g'^{31}_1)^*]\right| \lesssim 6 \times 10^{-3}$$

$$M_1 \simeq 5 \ \mathrm{TeV} \longrightarrow \left|\mathrm{Im}[g_1^{31}(g'^{31}_1)^*]\right| \lesssim 10^{-6}$$

Neutral kaon mixing



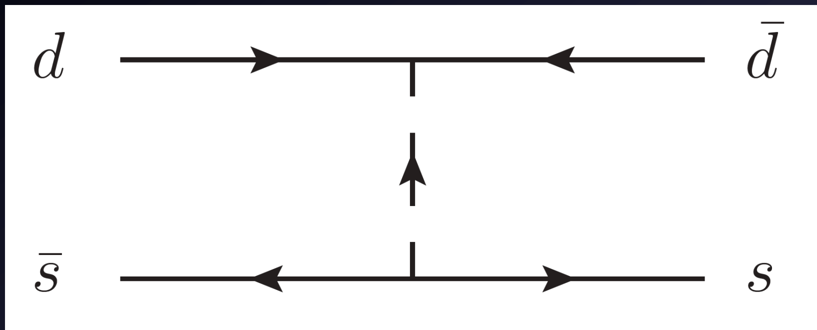
$$\mathcal{H}_{\rm eff} = \frac{g_2^{22}\left(g_2^{11}\right)^*}{M_2^2}(s_{R\alpha}s_{R\beta})(d_R^{*\alpha}d_R^{*\beta}) \to \frac{g_2^{22}\left(g_2^{11}\right)^*}{2M_2^2}(\bar{d}_R^{\alpha}\gamma^{\mu}s_{R\alpha})(\bar{d}_R^{\alpha}\gamma_{\mu}s_{R\alpha})$$

Constraints: *[Isidori, Nir, Perez (2010)]*

$$\left|{\rm Re}\left[g_2^{22}\left(g_2^{11}\right)^*\right]\right| < 1.8\times 10^{-6}\left(\frac{M_2}{1\ {\rm TeV}}\right)^2$$

$$\left|{\rm Im}\left[g_2^{22}\left(g_2^{11}\right)^*\right]\right| < 6.8\times 10^{-9}\left(\frac{M_2}{1\ {\rm TeV}}\right)^2$$

Neutral kaon mixing



$$\mathcal{H}_{\text{eff}} = \frac{g_2^{22}\left(g_2^{11}\right)^*}{M_2^2}(s_{R\alpha}s_{R\beta})(d_R^{*\alpha}d_R^{*\beta}) \rightarrow \frac{g_2^{22}\left(g_2^{11}\right)^*}{2M_2^2}(\bar{d}_R^{\alpha}\gamma^{\mu}s_{R\alpha})(\bar{d}_R^{\alpha}\gamma_{\mu}s_{R\alpha})$$

Constraints: *[Isidori, Nir, Perez (2010)]*

For M_2=500 TeV:

$$\left|\text{Re}\left[g_2^{22}\left(g_2^{11}\right)^*\right]\right| < 1.8 \times 10^{-6}\left(\frac{M_2}{1\ \text{TeV}}\right)^2$$

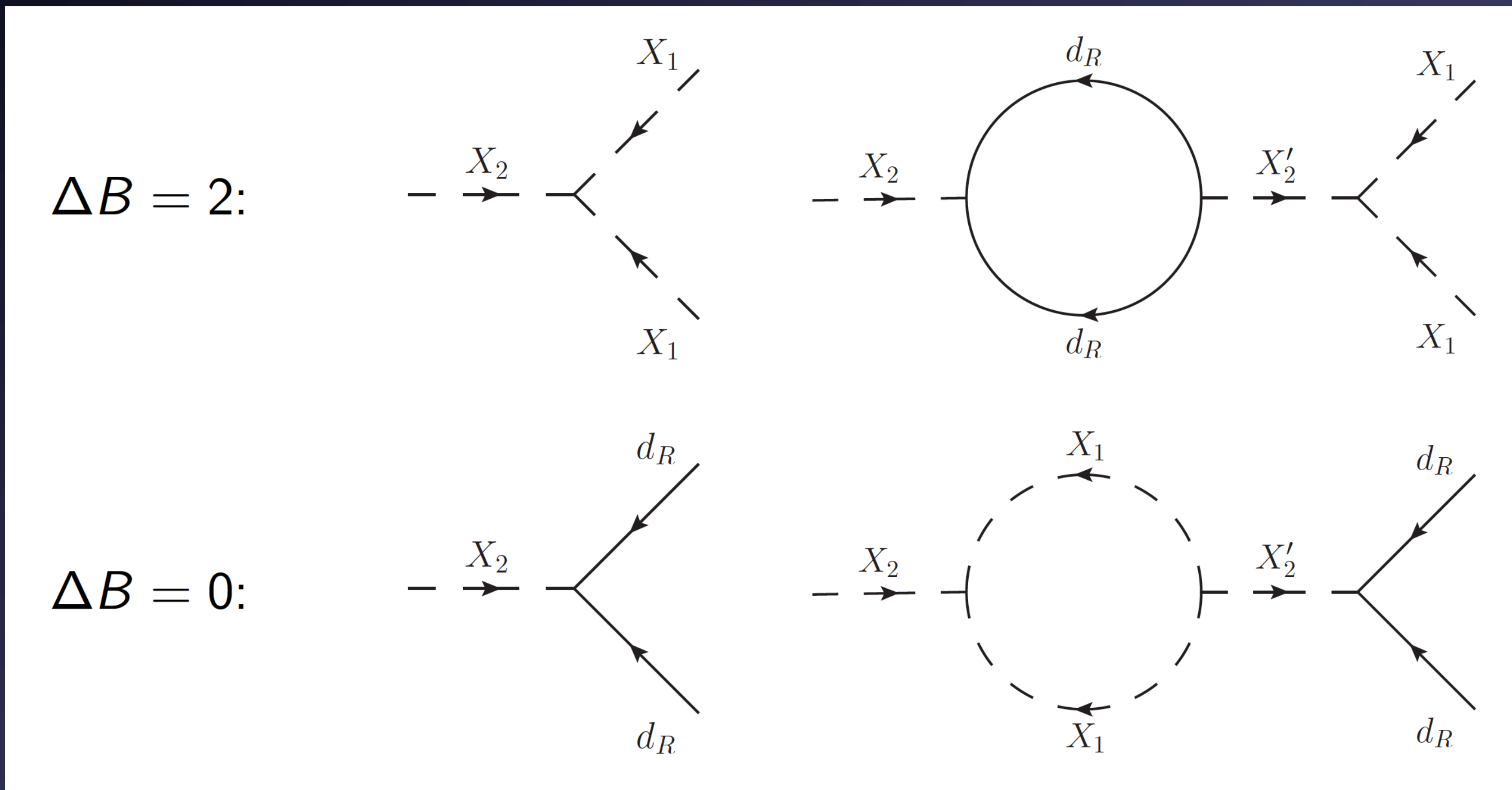
= 0.45

$$\left|\text{Im}\left[g_2^{22}\left(g_2^{11}\right)^*\right]\right| < 6.8 \times 10^{-9}\left(\frac{M_2}{1\ \text{TeV}}\right)^2$$

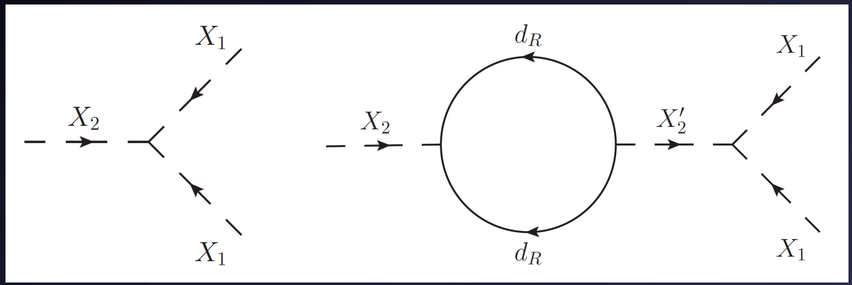
= 1.7×10^{-3}

Baryon asymmetry

Decays of X_2:



Baryon asymmetry



Assumption:

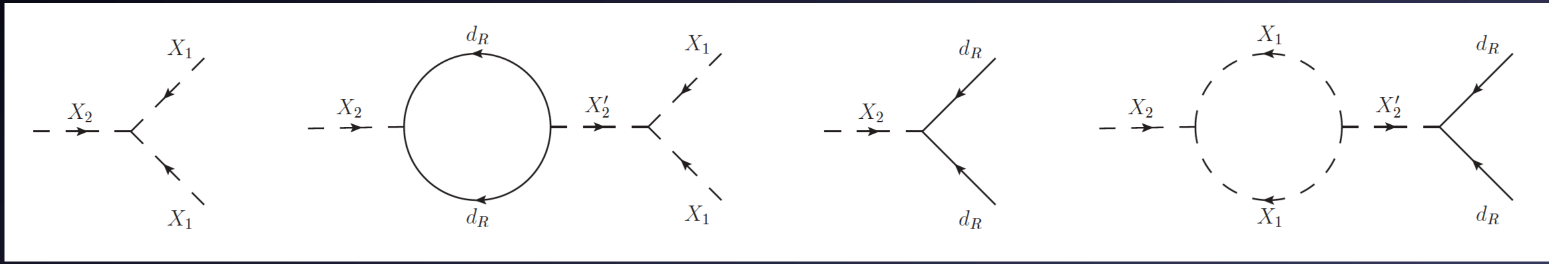
$$\frac{\lambda}{M_2}, \frac{\tilde{\lambda}}{M_2} \ll g_2, \tilde{g}_2$$

Heavy scalar decay rates:

$$\Gamma(X_2 \to \overline{X}_1 \overline{X}_1) = \frac{3\lambda}{8\pi M_2} \times \left[\lambda - \tilde{\lambda} \frac{M_2^2}{4\pi(M_2^2 - \tilde{M}_2^2)} \mathrm{Im}(\mathrm{Tr}(g_2^\dagger \tilde{g}_2))\right],$$

$$\Gamma(\overline{X}_2 \to X_1 X_1) = \frac{3\lambda}{8\pi M_2} \times \left[\lambda + \tilde{\lambda} \frac{M_2^2}{4\pi(M_2^2 - \tilde{M}_2^2)} \mathrm{Im}(\mathrm{Tr}(g_2^\dagger \tilde{g}_2))\right].$$

Baryon asymmetry



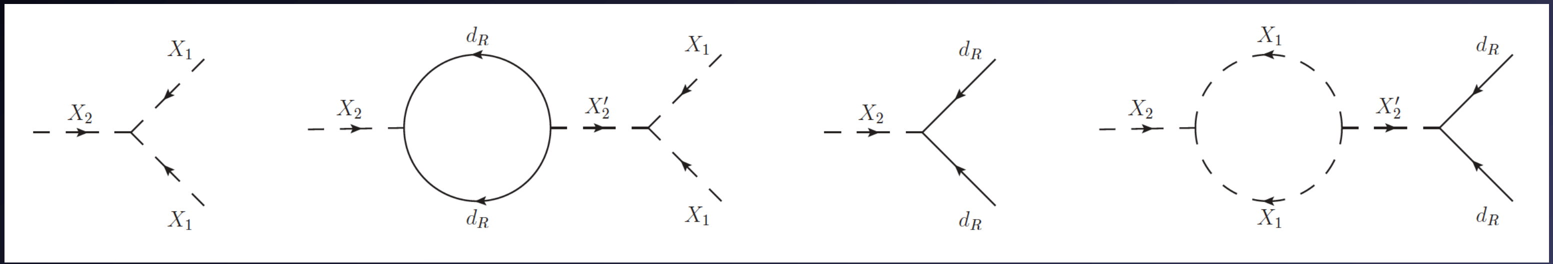
Branching ratios and final state baryon numbers:

Decay	Br	B_f
$X_2 \to \overline{X}_1 \overline{X}_1$	r	$4/3$
$X_2 \to \overline{d}_R \overline{d}_R$	$1 - r$	$-2/3$
$\overline{X}_2 \to X_1 X_1$	$\bar{r}$	$-4/3$
$\overline{X}_2 \to d_R d_R$	$1 - \bar{r}$	$2/3$

Net baryon number:

$$\Delta n_B = \frac{6}{\pi\,\mathrm{Tr}(g_2^\dagger g_2)} \frac{1}{\tilde{M}_2^2 - M_2^2} \,\mathrm{Im}\Big[\lambda\,\tilde{\lambda}^*\,\mathrm{Tr}(g_2^\dagger\,\tilde{g}_2)\Big]$$

Baryon asymmetry



Branching ratios and final state baryon numbers:

Decay	Br	B_f
$X_2 \to \overline{X}_1 \overline{X}_1$	r	$4/3$
$X_2 \to \overline{d}_R \overline{d}_R$	$1-r$	$-2/3$
$\overline{X}_2 \to X_1 X_1$	$\bar{r}$	$-4/3$
$\overline{X}_2 \to d_R d_R$	$1-\bar{r}$	$2/3$

Net baryon number:

$$\Delta n_B = \frac{6}{\pi\,\mathrm{Tr}(g_2^\dagger g_2)} \frac{1}{\tilde{M}_2^2 - M_2^2} \mathrm{Im}\left[\lambda\,\tilde{\lambda}^*\,\mathrm{Tr}(g_2^\dagger\,\tilde{g}_2)\right]$$

Washout effects important! *[Herrmann (2014)]*

Conclusions

- Processes with $\Delta B=2$ provide complimentary searches for baryon number violation to those at the LHC and proton decay experiments.
- Many models require that a $\Delta B=2$ signal should be seen in the upgraded searches.
- A discovery would have a profound impact on our understanding of the Universe.


Thank you!


Thank you!

Back-up slide

- **Model 2:**

$$X_1 = (\bar{6}, 3, -1/3),\ X_2 = (\bar{6}, 1, 2/3),$$

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta A} (Q_{L\alpha}^a \epsilon \tau^A Q_{L\beta}^b) - g_2^{ab} X_2^{\alpha\beta} (d_{R\alpha}^a d_{R\beta}^b) + \lambda X_1^{\alpha\alpha' A} X_1^{\beta\beta' A} X_2^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}.$$

- **Model 3:**

$$X_1 = (\bar{6}, 1, 2/3),\ X_2 = (\bar{6}, 1, -4/3),$$

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta} (d_{R\alpha}^a d_{R\beta}^b) - g_2^{ab} X_2^{\alpha\beta} (u_{R\alpha}^a u_{R\beta}^b) + \lambda X_1^{\alpha\alpha'} X_1^{\beta\beta'} X_2^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}.$$

Back-up slide

- **Model 4:**

$$X_1 = (3, 1, 2/3),\ X_2 = (\bar{6}, 1, -4/3),$$

$$\mathcal{L} = -g_1^{ab} X_{1\alpha}(d^a_{R\beta} d^b_{R\gamma})\epsilon^{\alpha\beta\gamma} - g_2^{ab} X_2^{\alpha\beta}(u^a_{R\alpha} u^b_{R\beta}) + \lambda X_{1\alpha} X_{1\beta} X_2^{\alpha\beta}.$$

- **Model 5:**

$$X_1 = (\bar{6}, 1, -1/3),\ X_2 = (1, 1, 1),$$

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta}(Q^a_{L\alpha}\epsilon Q^b_{L\beta}) - g_2^{ab} X_2(L^a_L \epsilon L^b_L) - g_1'^{ab} X_1^{\alpha\beta}(u^a_{R\alpha} d^b_{R\beta}) + \lambda X_1^{\alpha\alpha'} X_1^{\beta\beta'} X_1^{\gamma\gamma'} X_2 \epsilon_{\alpha\beta\gamma}\epsilon_{\alpha'\beta'\gamma'}.$$

Back-up slide

- **Model 6:**

$$X_1 = (\bar{6}, 3, -1/3),\ X_2 = (1, 1, 1)$$

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta A} (Q_{L\alpha}^a \epsilon \tau^A Q_{L\beta}^b) - g_2^{ab} X_2 (L_L^a \epsilon L_L^b) + \lambda X_1^{\alpha\alpha' A} X_1^{\beta\beta' B} X_1^{\gamma\gamma' C} X_2 \epsilon^{ABC} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}.$$

- **Model 7:**

$$X_1 = (\bar{6}, 3, -1/3),\ X_2 = (1, 3, 1),$$

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta A} (Q_{L\alpha}^a \epsilon \tau^A Q_{L\beta}^b) - g_2^{ab} X_2^A (L_L^a \epsilon \tau^A L_L^b) + \lambda X_1^{\alpha\alpha' A} X_1^{\beta\beta' B} X_1^{\gamma\gamma' C} X_2^D \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'} \times (\delta^{AB}\delta^{CD} + \delta^{AC}\delta^{BD} + \delta^{AD}\delta^{BC}).$$

Back-up slide

- **Model 8:**

$$X_1 = (\bar{6}, 1, 2/3),\ X_2 = (1, 1, -2),$$

$$\mathcal{L} = -g_1^{ab} X_1^{\alpha\beta} (d^a_{R\alpha} d^b_{R\beta}) - g_2^{ab} X_2 (e^a_R e^b_R) + \lambda X_1^{\alpha\alpha'} X_1^{\beta\beta'} X_1^{\gamma\gamma'} X_2 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}.$$

- **Model 9:**

$$X_1 = (3, 1, 2/3),\ X_2 = (1, 1, -2),$$

$$\mathcal{L} = -g_1^{ab} X_{1\alpha} (d^a_{R\beta} d^b_{R\gamma}) \epsilon^{\alpha\beta\gamma} - g_2^{ab} X_2 (e^a_R e^b_R) + \lambda X_{1\alpha} X_{1\beta} X_{1\gamma} X_2 \epsilon^{\alpha\beta\gamma}.$$