

Caltech



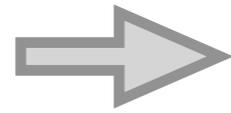
Theories for **B**aryon and **L**epton number **Violation**

Clara Murgui

In collaboration with P. Fileviez Pérez (CWRU), E. Golias (CWRU),
R. H. Li (CWRU), A. D. Plascencia (Frascati), and M. B. Wise (Caltech)

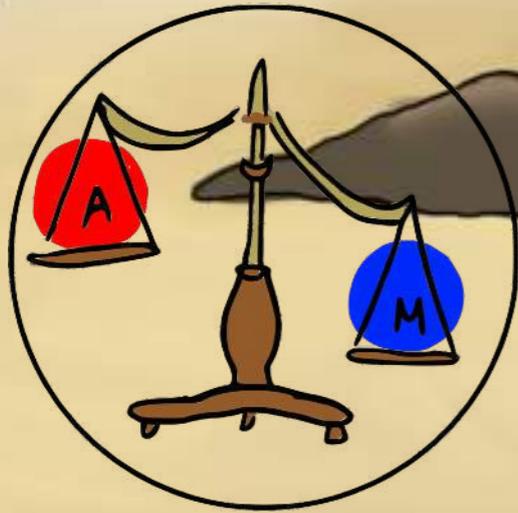
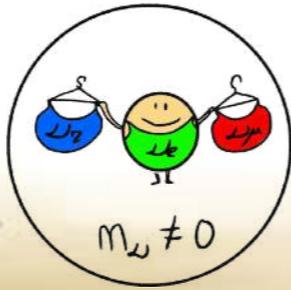
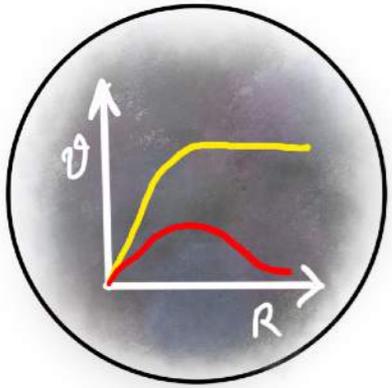
May 17th 2022

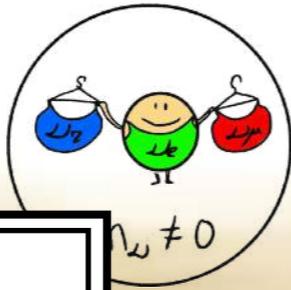
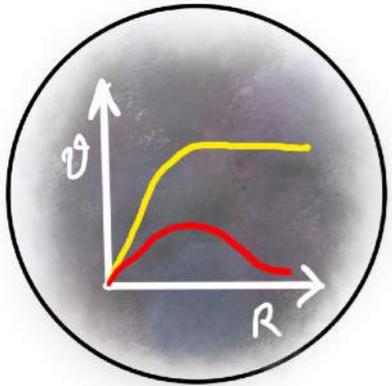
Snowmass Workshop, Cincinnati



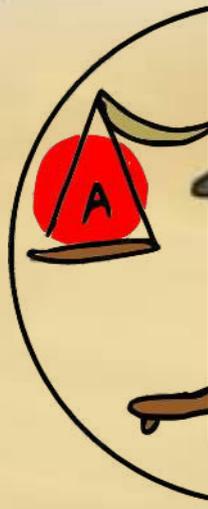
Extra symmetries:

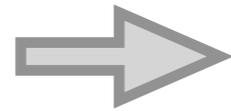
$$U(1)_{B-L}, U(1)_L, U(1)_B$$





Insert
Photo
Here

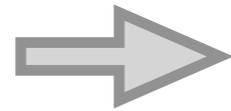




Extra symmetries:

$$U(1)_{B-L}, U(1)_L, U(1)_B$$

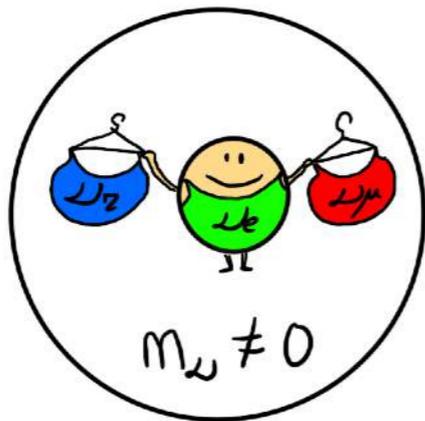
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \sum_i \frac{c_i}{\Lambda^{(n-4)}} \mathcal{O}_i$$

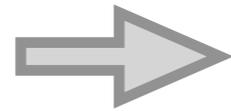


Extra symmetries:

$$U(1)_{B-L}, \quad \cancel{U(1)_L}, \quad U(1)_B$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_L}{\Lambda_L} \ell_L \ell_L H H +$$

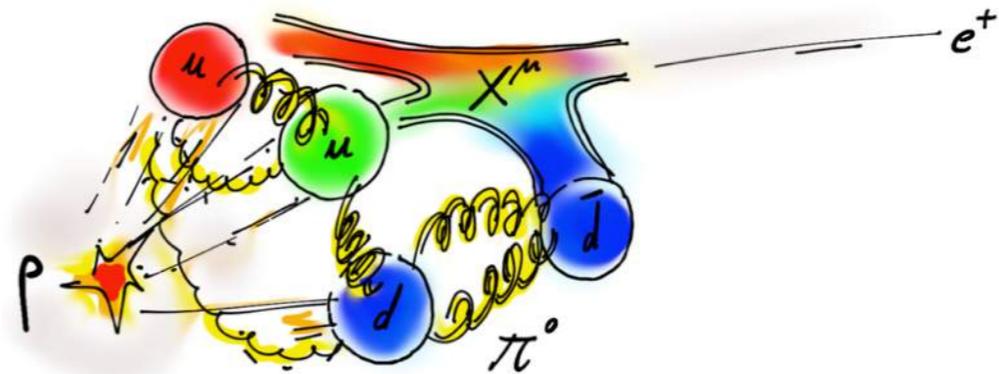
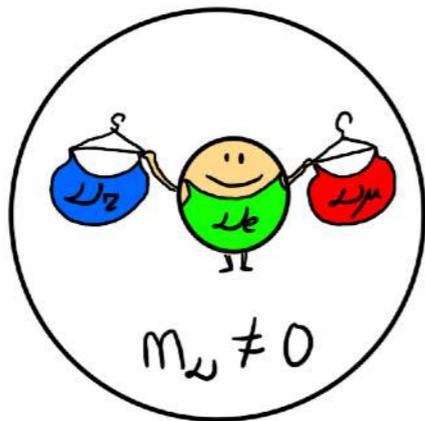




Extra symmetries:

$$U(1)_{B-L}, \quad \cancel{U(1)_L}, \quad \cancel{U(1)_B}$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_L}{\Lambda_L} \ell_L \ell_L H H + \frac{c_B}{\Lambda_B^2} Q_L Q_L Q_L \ell_L$$

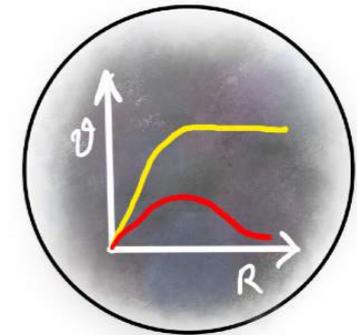


Outline

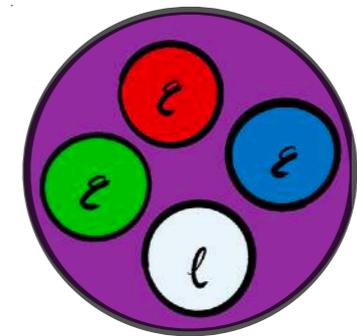
➔ Explicit B and L breaking



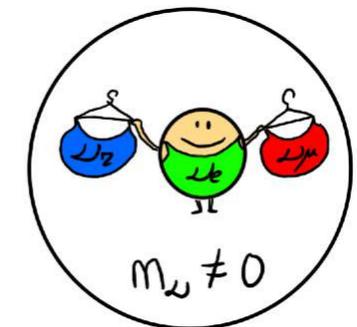
➔ Theories for Spontaneous B and L breaking



➔ Quark-Lepton Unification at the Low Scale



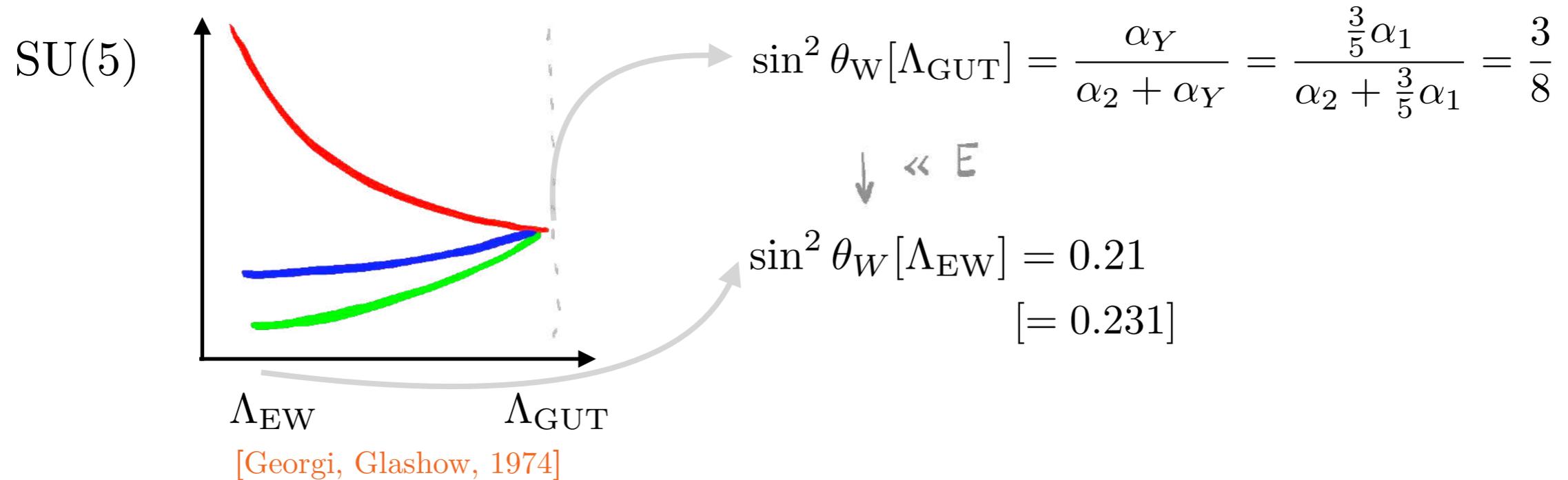
➔ Theories for Neutrino Masses



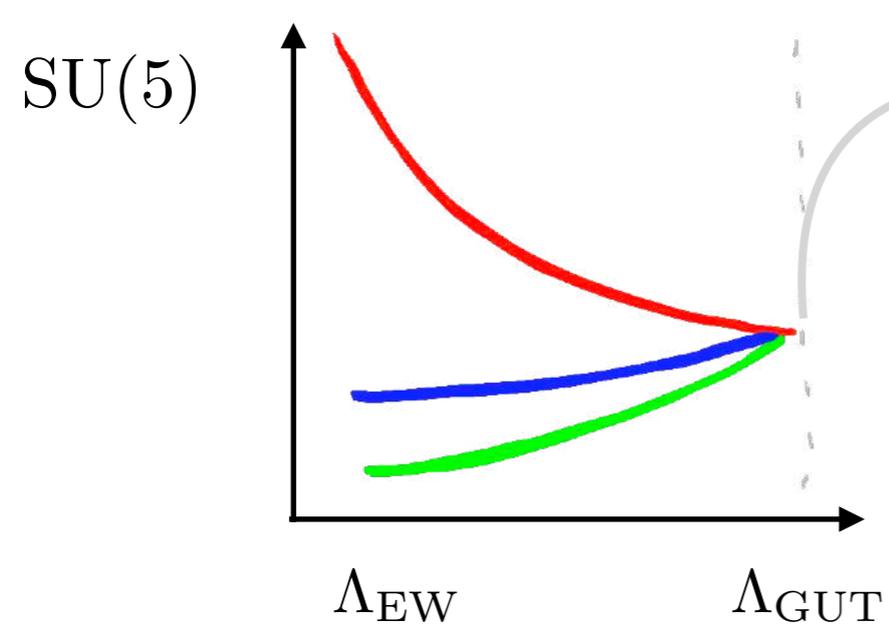
Explicit B and L breaking



Explicit B and L breaking



Explicit B and L breaking



$$\sin^2 \theta_W[\Lambda_{GUT}] = \frac{\alpha_Y}{\alpha_2 + \alpha_Y} = \frac{\frac{3}{5}\alpha_1}{\alpha_2 + \frac{3}{5}\alpha_1} = \frac{3}{8}$$

One SM family

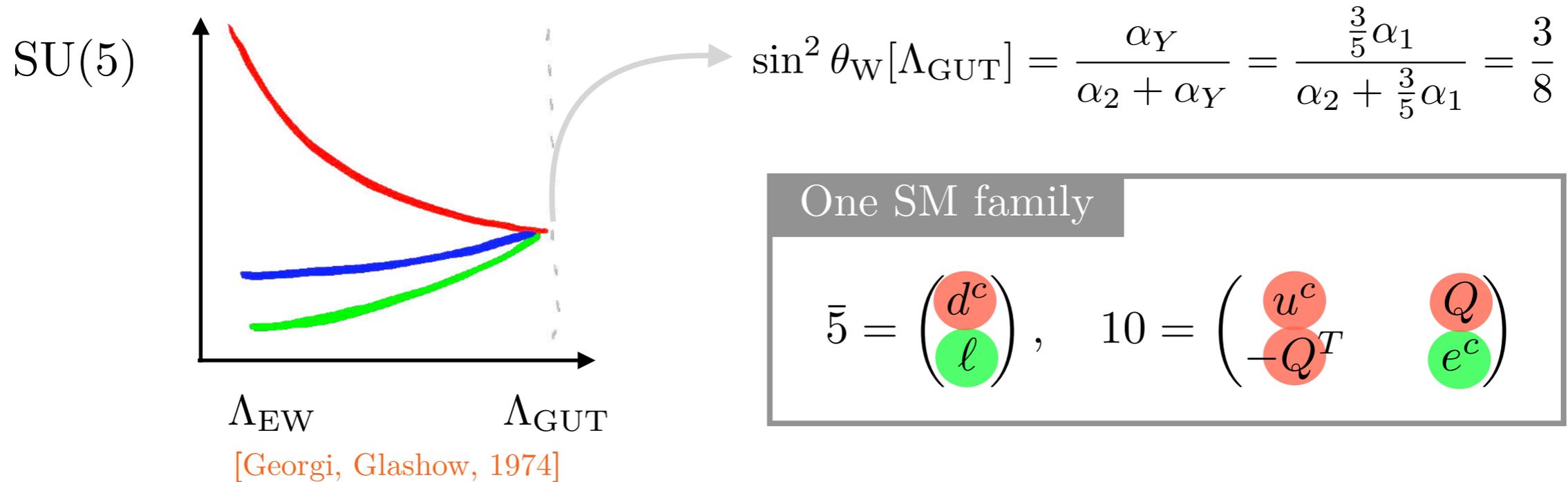
$$\bar{5} = \begin{pmatrix} d^c \\ \ell \end{pmatrix}, \quad 10 = \begin{pmatrix} u^c & Q \\ -Q^T & e^c \end{pmatrix}$$

[Georgi, Glashow, 1974]

$U(1)_B??$

$U(1)_L??$

Explicit B and L breaking



$$V_{24}^\mu = \begin{pmatrix} G^\mu & X^\mu \\ (X^\mu)^\dagger & W^\mu \end{pmatrix} + T_{24} B^\mu$$

U(1)_B??

U(1)_L??

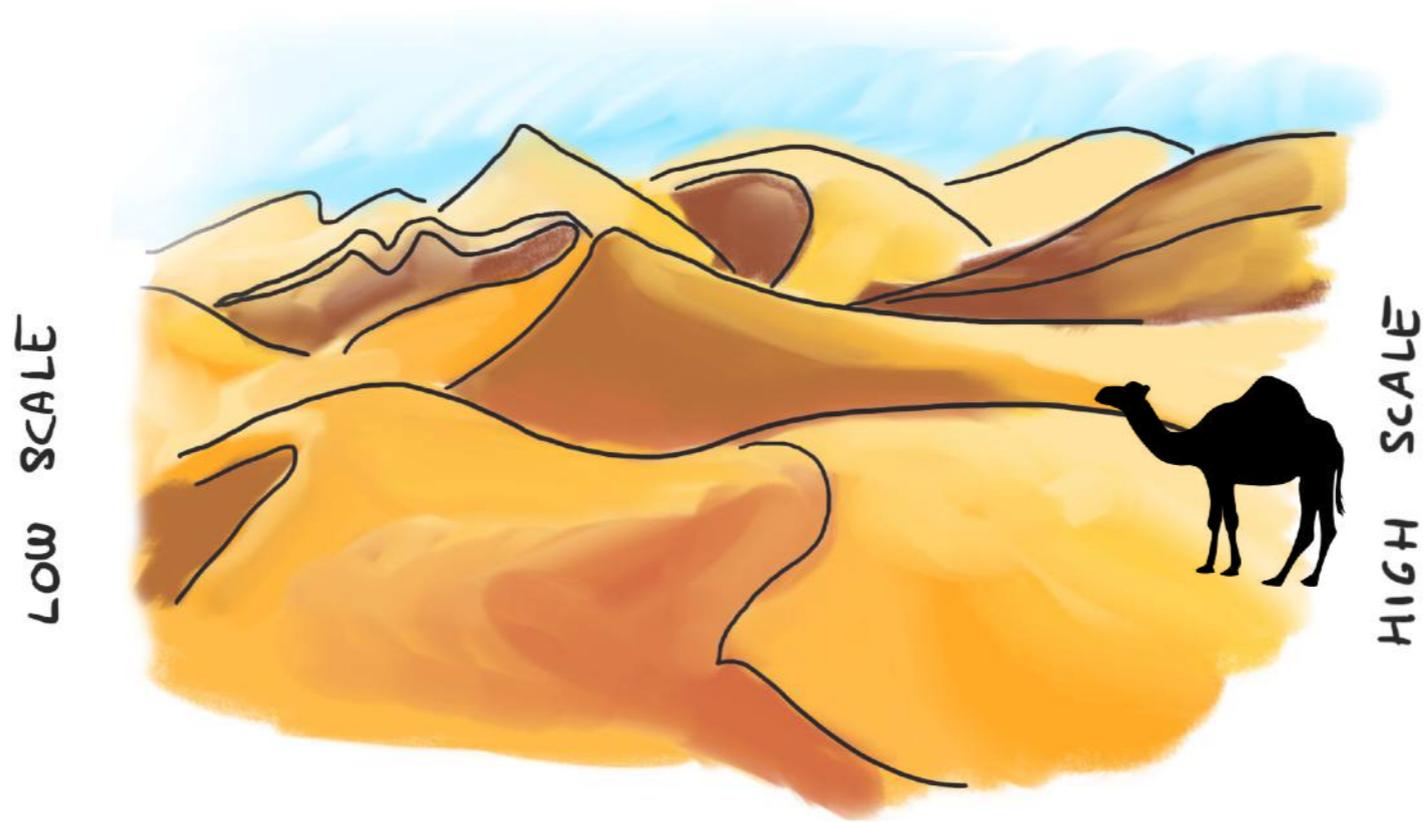
$$\mathcal{L}_{\text{Kin}} \supset \bar{q}^C \gamma_\mu q X^\mu + \bar{l}^C \gamma_\mu q X^\mu$$

$\tau_p \gtrsim 10^{34}$ years

$\Lambda_{\text{GUT}} \gtrsim$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} // + \frac{c_L}{\Lambda_L} \ell_L \ell_L H H + \frac{c_B}{\Lambda_B^2} Q_L Q_L Q_L \ell_L \dots$$

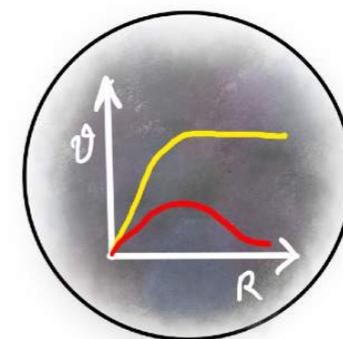
$\Delta L = 2$
 $\Delta B = 1$



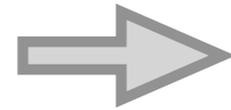
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_L}{\Lambda_L} \cancel{\ell_L \ell_L H H} + \frac{c_B}{\Lambda_B^2} \cancel{Q_L Q_L Q_L \ell_L} \dots$$

if $\Delta L \neq \pm 2$ if $\Delta B \neq \pm 1$

Theories for Spontaneous B and L breaking



Gauging Baryon and Lepton numbers



Extra symmetries:

$$U(1)_{B-L}, U(1)_L, U(1)_B$$

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X$$

[A. Pais, 1973]

[S. Rajpoot, 1988]

[R. Foot, G. C. Joshi, J. Lew, 1989]

[C. D. Carone, H. Murayama, 1995]

[H. Georgi, S. L. Glashow, 1996]

[P. Fileviez Pérez, M. B. Wise, 2010]

Gauging $U(1)_B$



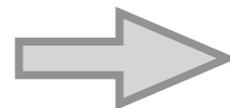
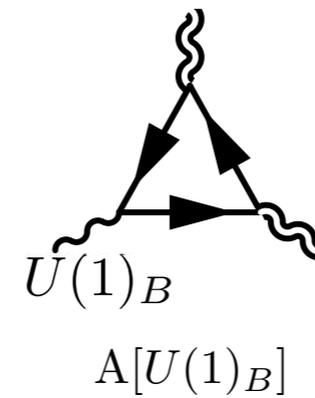
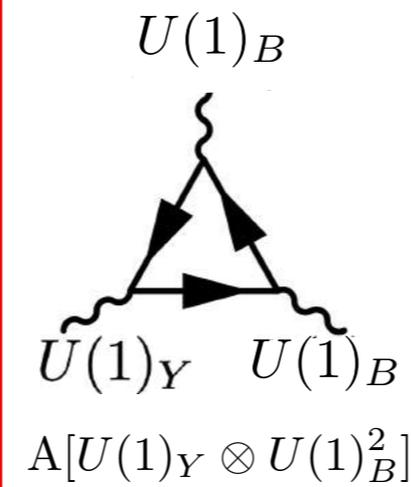
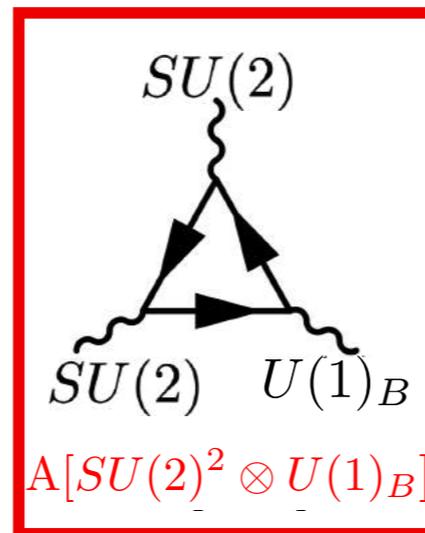
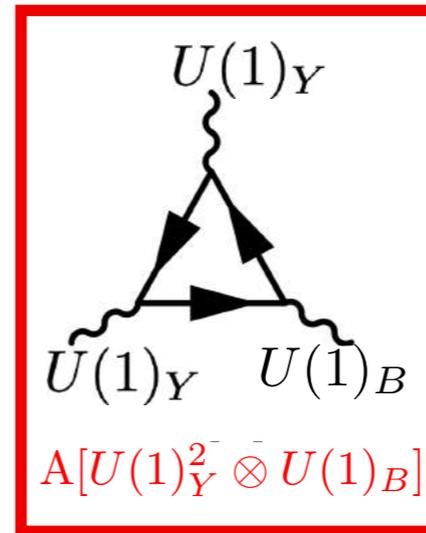
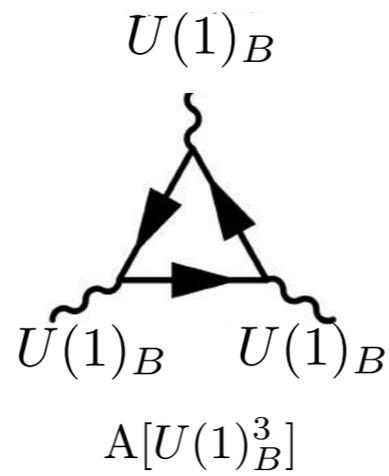
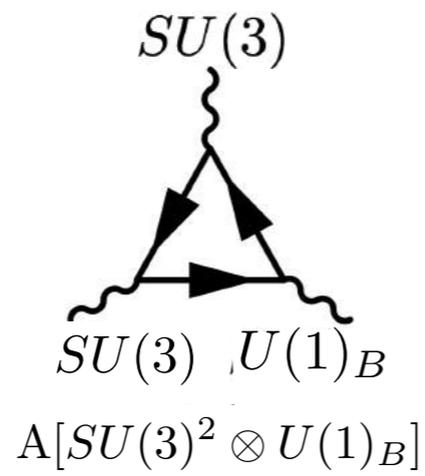
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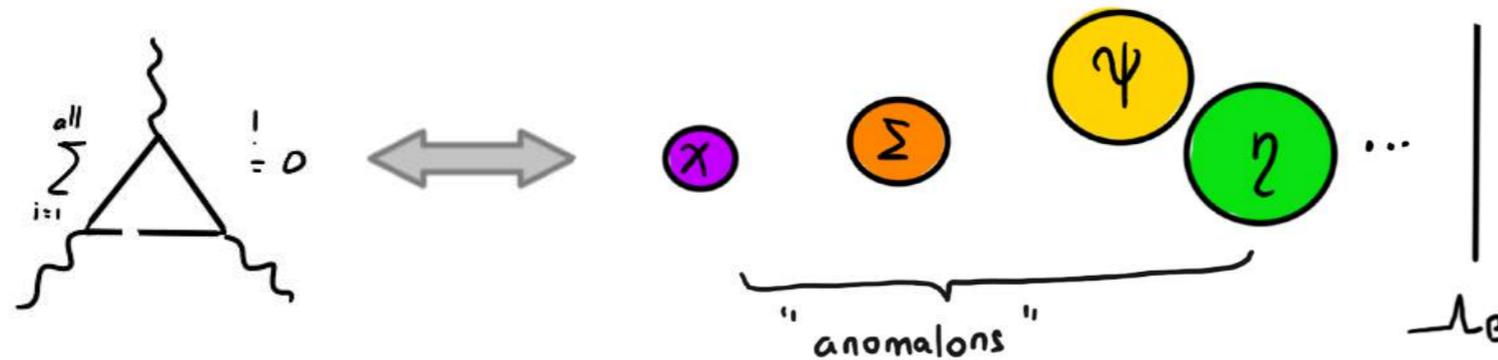
$$U(1)_X \rightarrow U(1)_{X=B}$$

Gauging $U(1)_B$



New fermions required!

Gauging $U(1)_B$



[M. Duerr, P. Fileviez-Perez, M. B. Wise, 2013]

$$\Psi_R \sim (1, 2, -1/2, \mathbf{B}_2)$$

$$\Psi_L \sim (1, 2, -1/2, \mathbf{B}_1)$$

$$\eta_R \sim (1, 1, -1, \mathbf{B}_1)$$

$$\eta_L \sim (1, 1, -1, \mathbf{B}_2)$$

$$\chi_R \sim (1, 1, 0, \mathbf{B}_1)$$

$$\chi_L \sim (1, 1, 0, \mathbf{B}_2)$$

[P. Fileviez-Perez, S. Ohmer, H. Patel, 2014]

$$\Psi_R \sim (1, 2, 1/2, -\mathbf{3}/2)$$

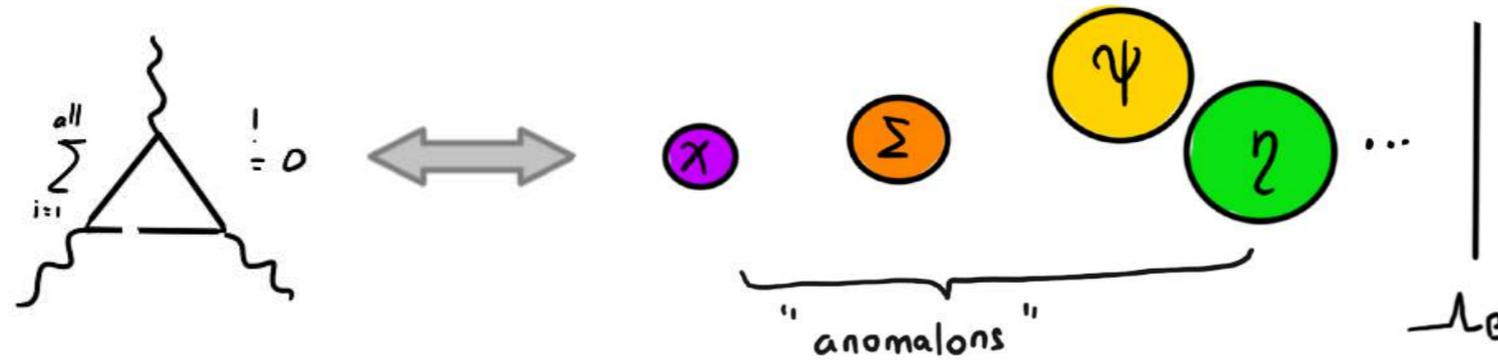
$$\Psi_L \sim (1, 2, 1/2, \mathbf{3}/2)$$

$$\Sigma_L \sim (1, 3, 0, -\mathbf{3}/2)$$

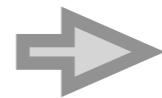
$$\chi_L^0 \sim (1, 1, 0, -\mathbf{3}/2)$$

➔ $B_2 - B_1 = 3$

Gauging $U(1)_B$



- Massive anomalous



$$S_B \sim (1, 1, 0, 3) \Rightarrow \Delta B = 3$$

Gauging $U(1)_B$



Proton stable!

- Massive anomalous

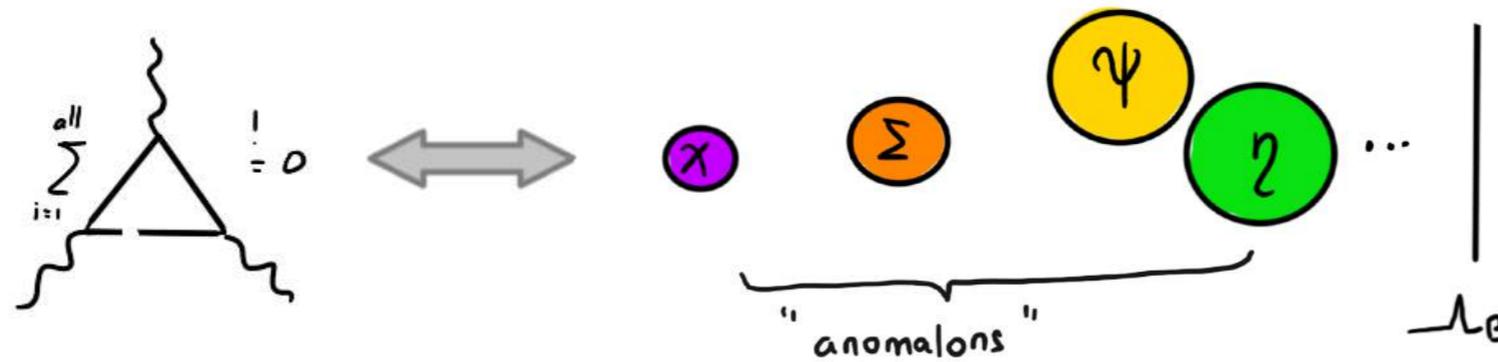
$\Rightarrow S_B \sim (1, 1, 0, 3) \Rightarrow \Delta B = 3$



How do we test this theory? :(

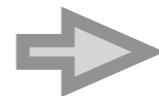
it might not exist...

Gauging $U(1)_B$



Proton stable!

- Massive anomalons



$$S_B \sim (1, 1, 0, 3) \Rightarrow \Delta B = 3$$

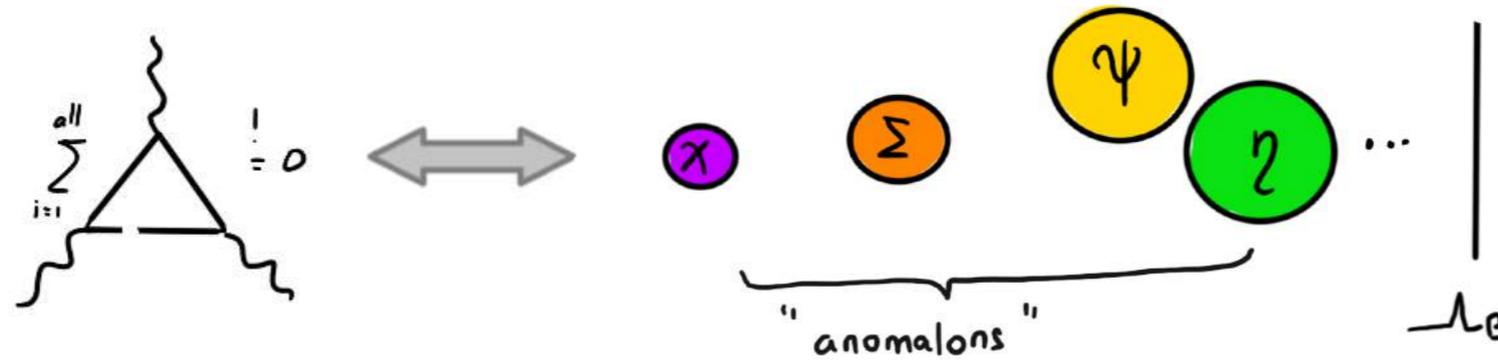
$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B$$

$\langle S_B \rangle$



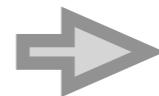
$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y + \boxed{\mathbb{Z}_2}$$

Gauging $U(1)_B$



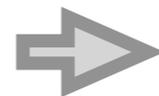
Proton stable!

- Massive anomalons

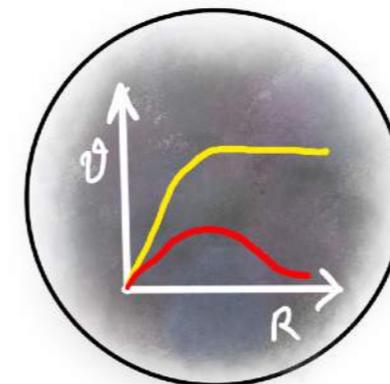


$$S_B \sim (1, 1, 0, 3) \Rightarrow \Delta B = 3$$

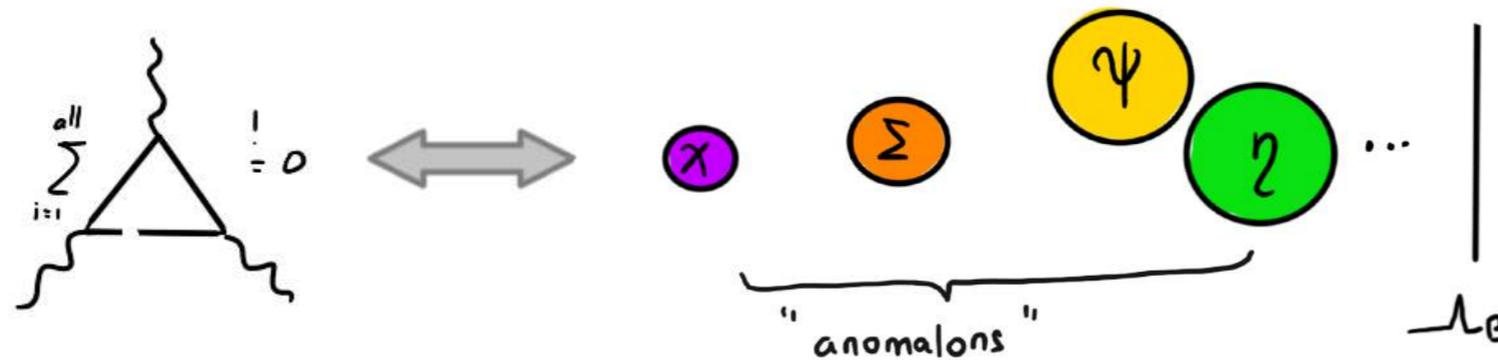
- Lightest neutral fermion



Cold dark matter candidate



Gauging $U(1)_B$



Proton stable!

- Massive anomalons $\Rightarrow S_B \sim (1, 1, 0, 3) \Rightarrow \Delta B = 3$
- Lightest neutral fermion \Rightarrow Cold dark matter candidate
- Simplest content to cancel anomalies \Rightarrow Dirac/ Majorana $n_B = \frac{3}{2}$

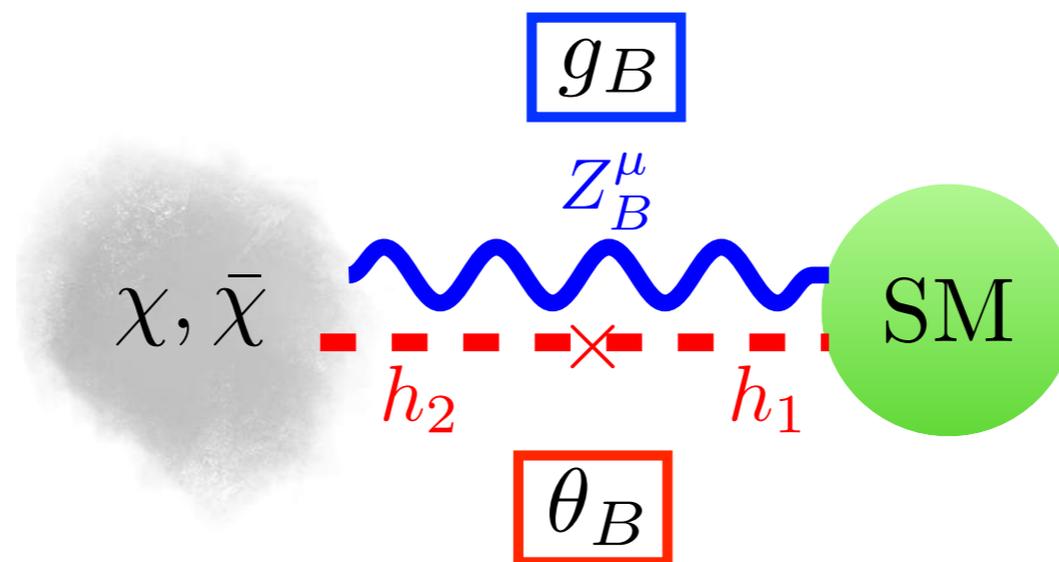
Dark Matter and the BNV scale

$$SSB, S_B \sim (1, 1, 0, 3)$$

χ gets mass from SSB !

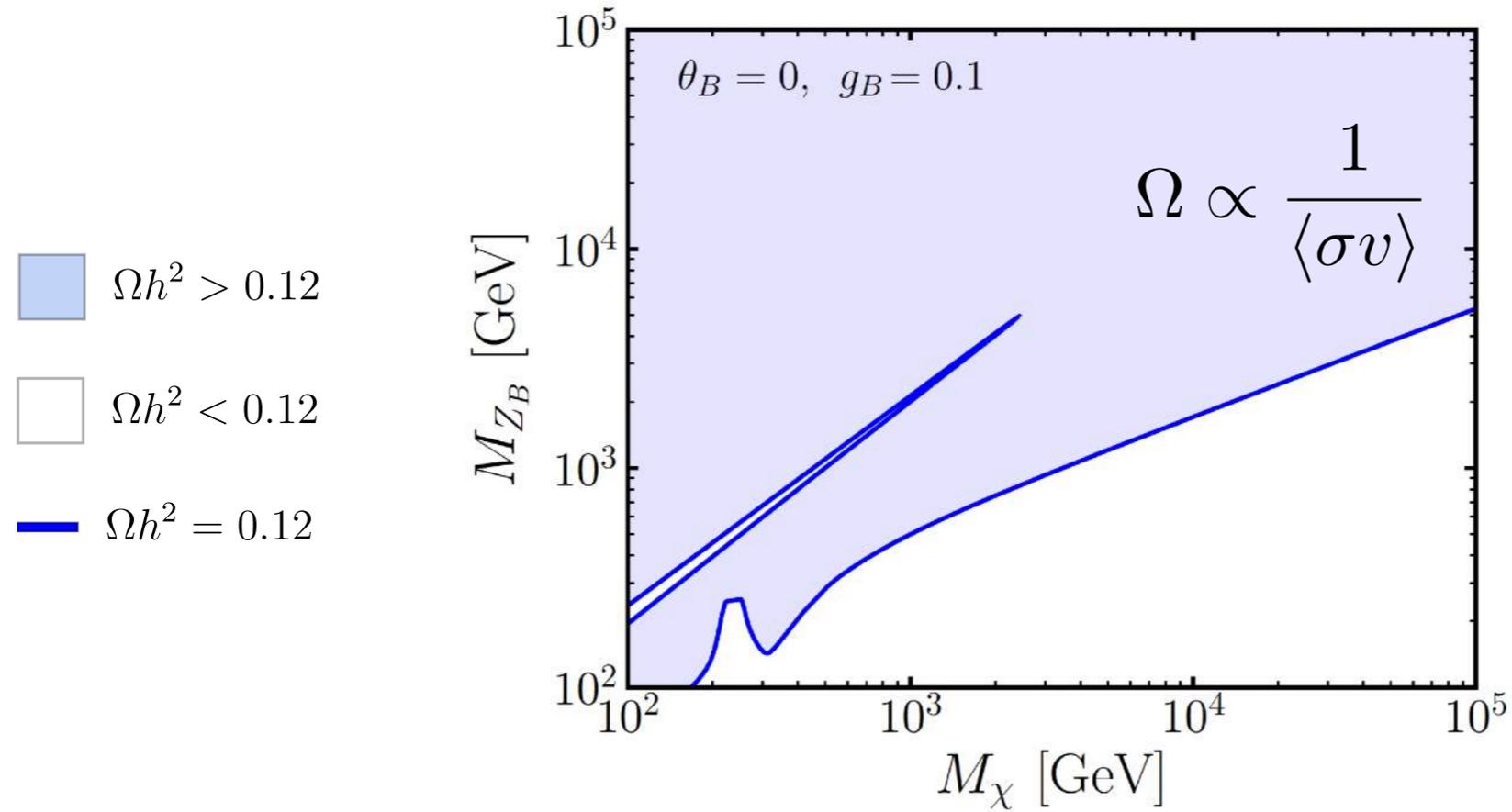
$$\mathcal{L}_{U(1)_B} \supset i \bar{\chi}_L D_\mu \gamma^\mu \chi_L + \underbrace{(D_\mu S_B)^\dagger (D^\mu S_B)}_{\text{SSB}} - \left(\frac{\lambda_\chi}{\sqrt{2}} \chi_L^T C \chi_L S_B + \text{h.c.} \right)$$

$$\xrightarrow{SSB} \frac{3}{2} g_B \bar{\chi} \gamma_\mu \gamma_5 \chi Z_B^\mu - \frac{1}{3} g_B \bar{q} \gamma_\mu q Z_B^\mu - \lambda_i \bar{\chi} \chi h_i - \frac{1}{2} M_\chi \chi^T C \chi$$

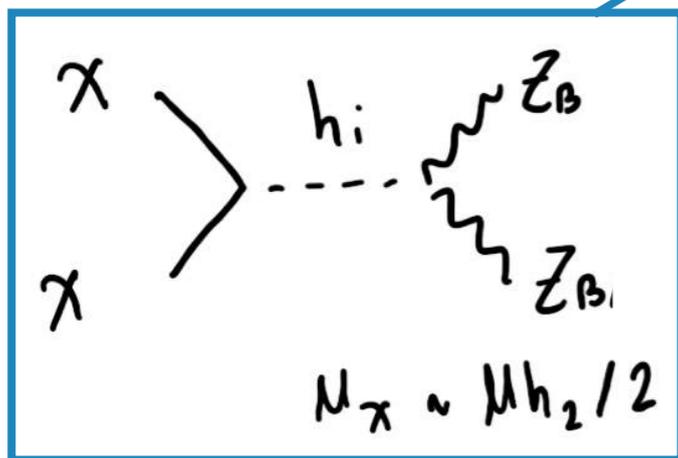
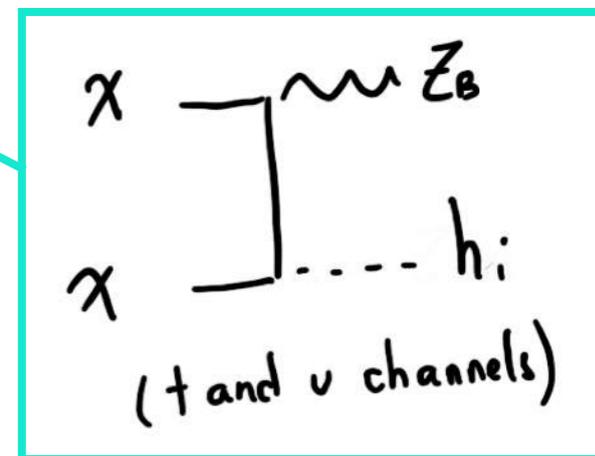
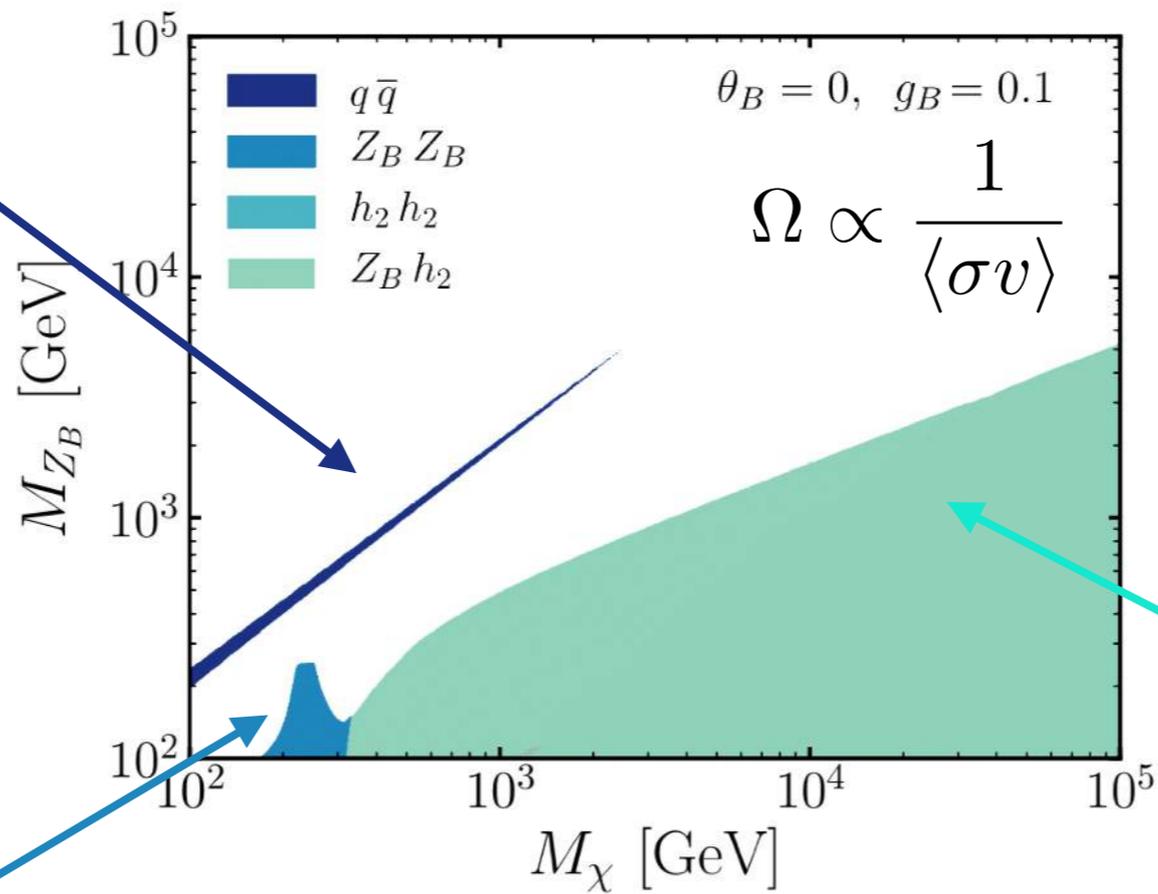
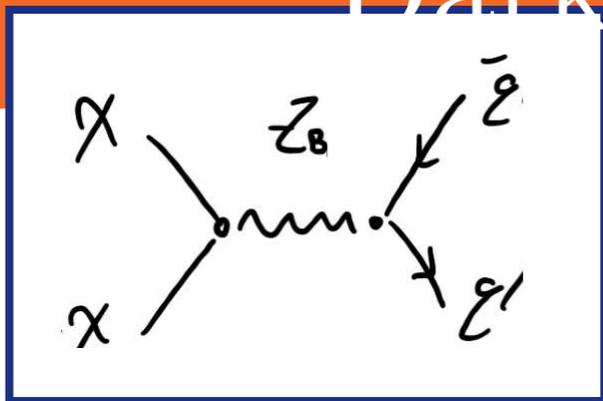


- Relevant parameters: $M_\chi, M_{Z_B}, g_B, M_{h_2}, \theta_B$

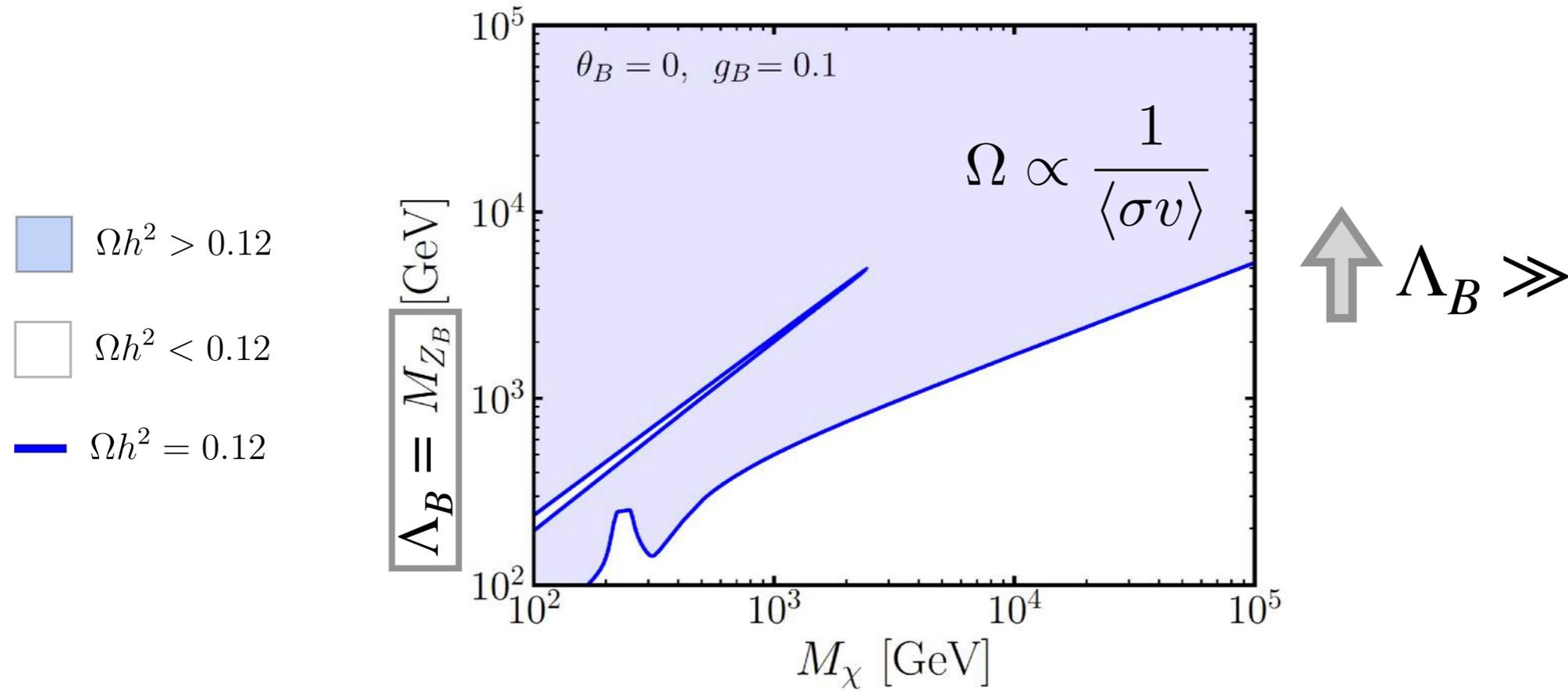
Dark Matter and the BNV scale



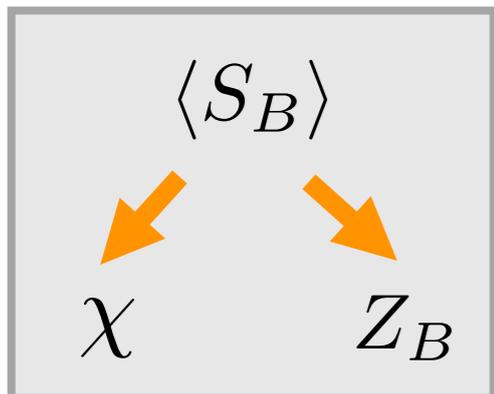
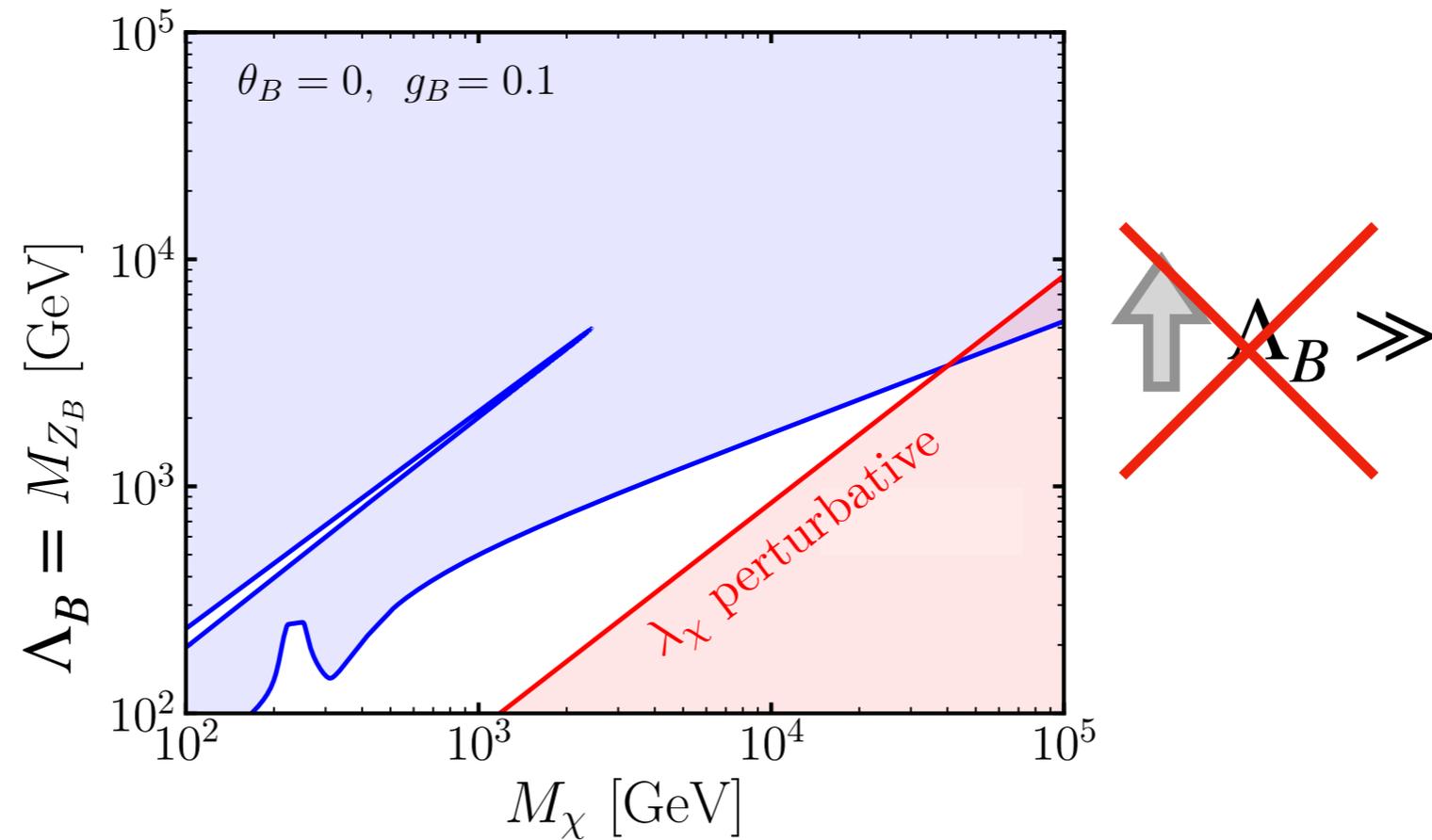
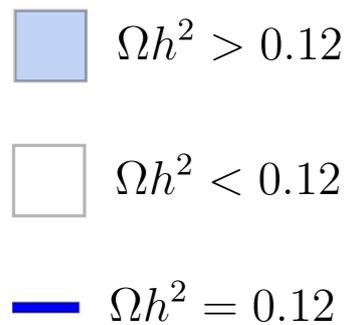
Dark Matter and the BNV scale



Dark Matter and the BNV scale



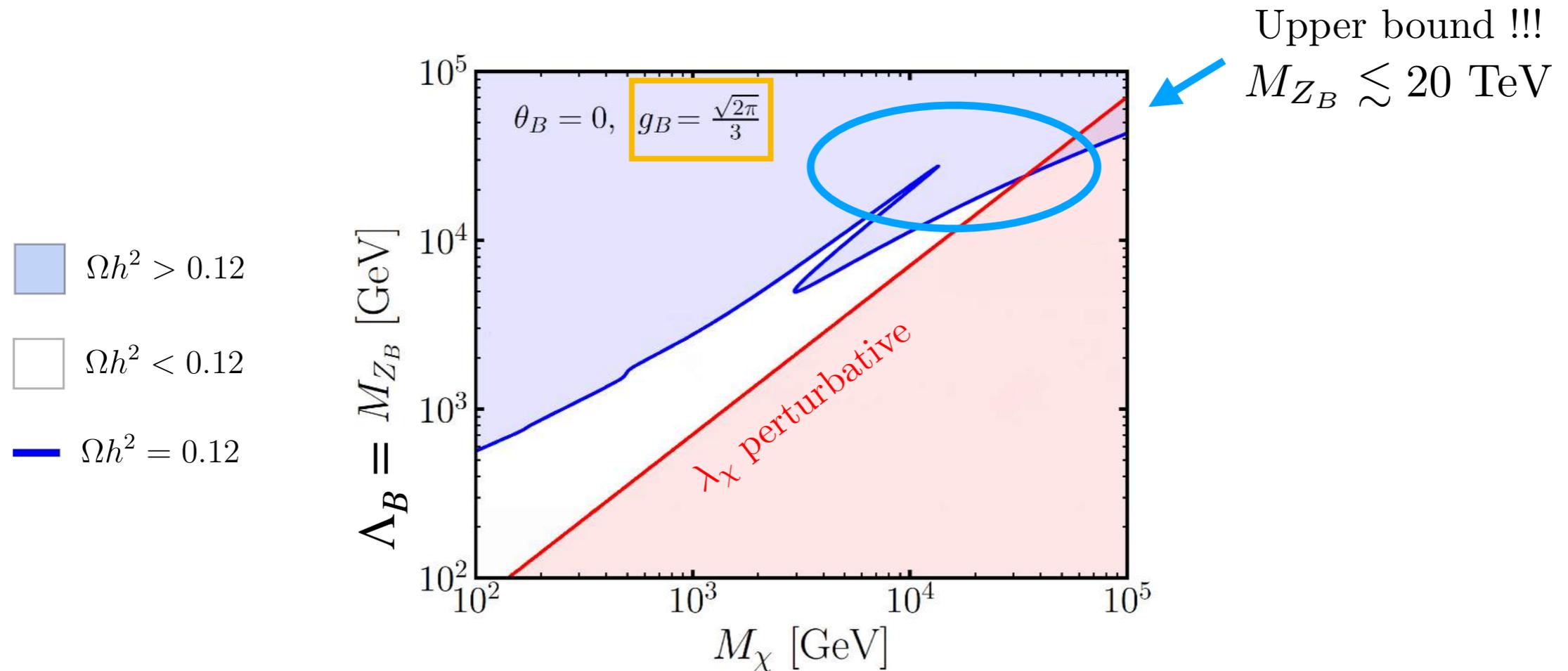
Dark Matter and the BNV scale



- Perturbativity sets an upper bound on the Yukawa coupling:

$$\frac{3 g_B}{\sqrt{2}} \frac{M_\chi}{M_{Z_B}} = \lambda_\chi \leq \mathcal{O}(1)$$

Dark Matter and the BNV scale



- Perturbativity sets an upper bound on the gauge coupling:

$$\mathcal{L} \supset g_B^2 (3)^2 S_B^\dagger S_B Z_{B\mu} Z_B^\mu \Rightarrow g_B \leq \frac{\sqrt{2\pi}}{3}$$

Dark Matter and the BNV scale



Dark Matter and the BNV scale

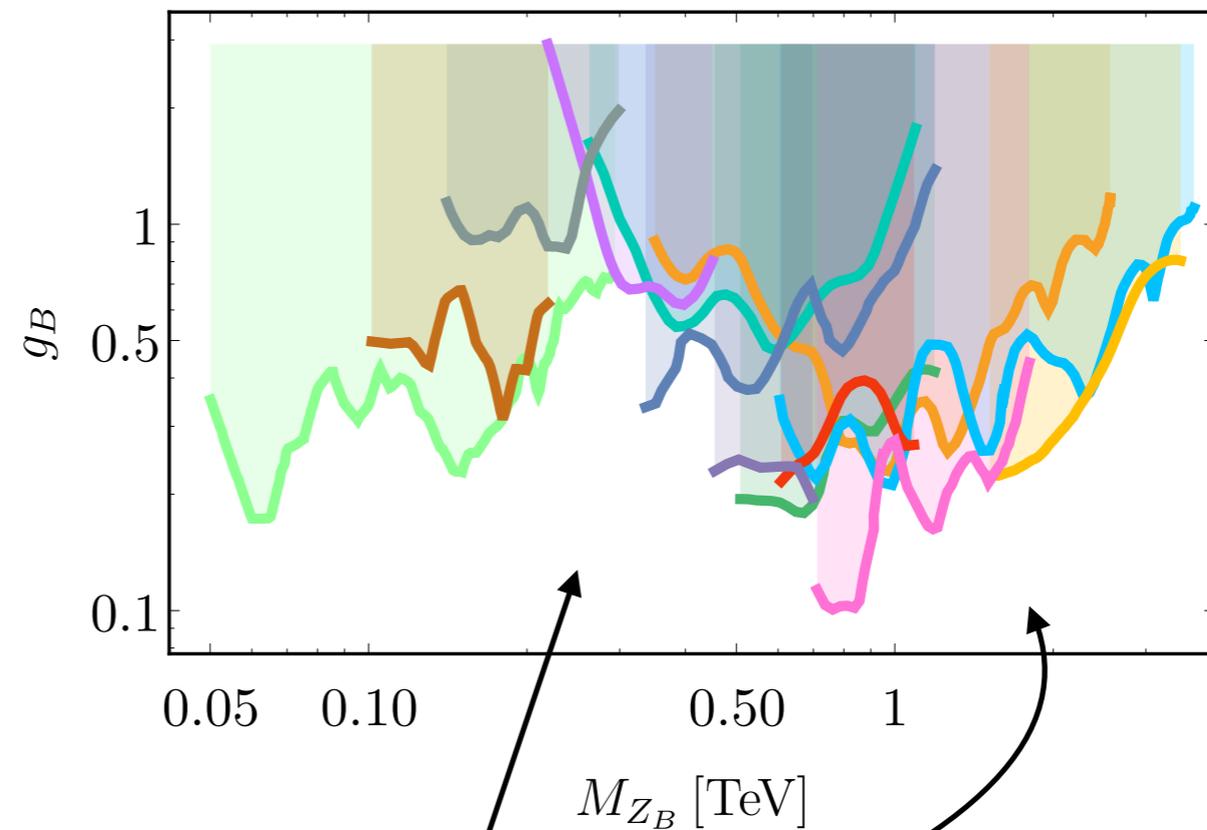
The theory **HAS TO** live at the **low scale!**



Collider bounds

- ATLAS 8 TeV, 20.3 fb⁻¹
- ATLAS 13 TeV, 3.6 fb⁻¹
- ATLAS 13 TeV, 29.3 fb⁻¹
- ATLAS 13 TeV, 36.1fb⁻¹
- ATLAS 13 TeV, 37 fb⁻¹
- CDF Run I
- CDF Run II
- CMS 8 TeV, 18.8 fb⁻¹
- CMS 8 TeV, 19.7 fb⁻¹
- CMS 13 TeV, 12.9 fb⁻¹
- CMS 13 TeV, 35.9 fb⁻¹
- & 41.1 fb⁻¹
- CMS 13 TeV, 36 fb⁻¹
- & 27 fb⁻¹
- UA2

$$\mathcal{L} \supset -\frac{1}{3}g_B\bar{q}Z_B^\mu\gamma_\mu q$$



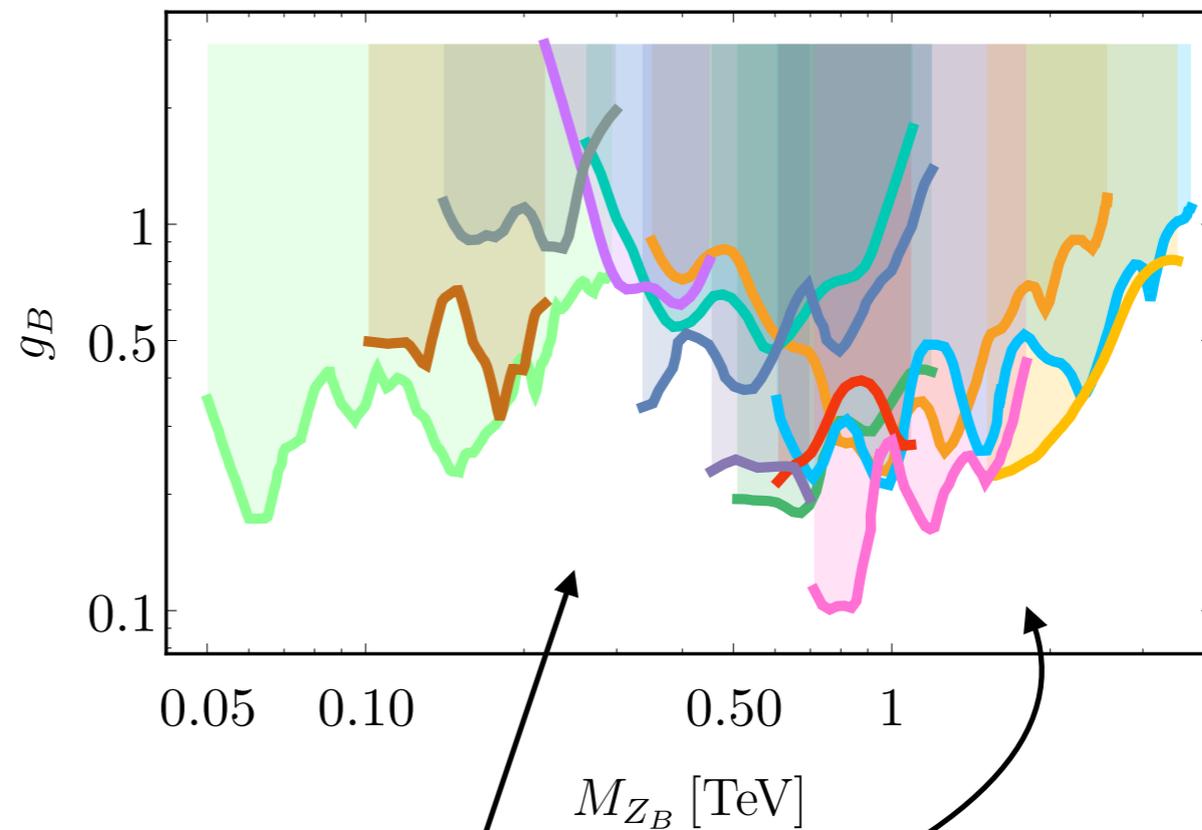
Room for a light new mediator!

[Di-jet searches at CMS and ATLAS-Run I & II]

Collider bounds

- ATLAS 8 TeV, 20.3 fb⁻¹
- ATLAS 13 TeV, 3.6 fb⁻¹
- ATLAS 13 TeV, 29.3 fb⁻¹
- ATLAS 13 TeV, 36.1fb⁻¹
- ATLAS 13 TeV, 37 fb⁻¹
- CDF Run I
- CDF Run II
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& 41.1 fb⁻¹
- CMS 13 TeV, 36 fb⁻¹
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Room for a light new mediator!

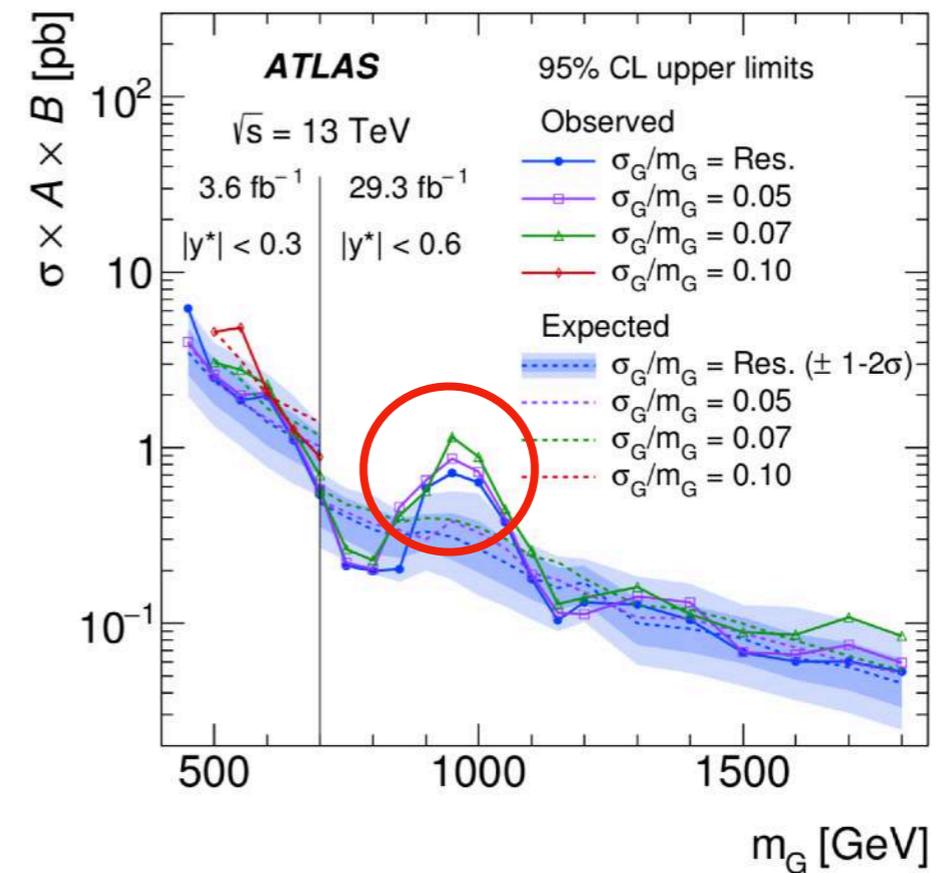
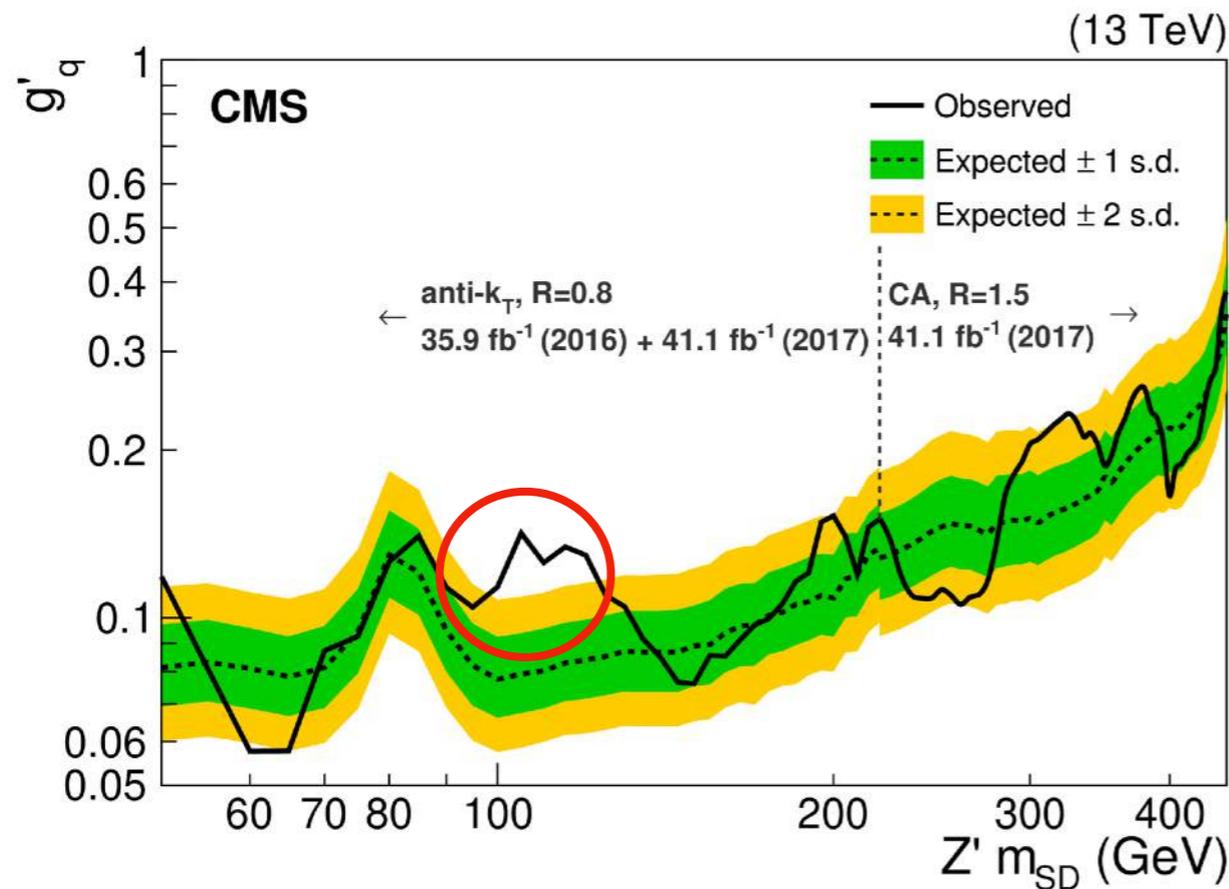
[Di-jet searches at CMS and ATLAS-Run I & II]

Collider bounds

$$\mathcal{L} \supset -\frac{1}{3} g_B \bar{q} Z_B^\mu \gamma_\mu q$$

CMS-EXO-18-012 ; CERN-EP-2019-176

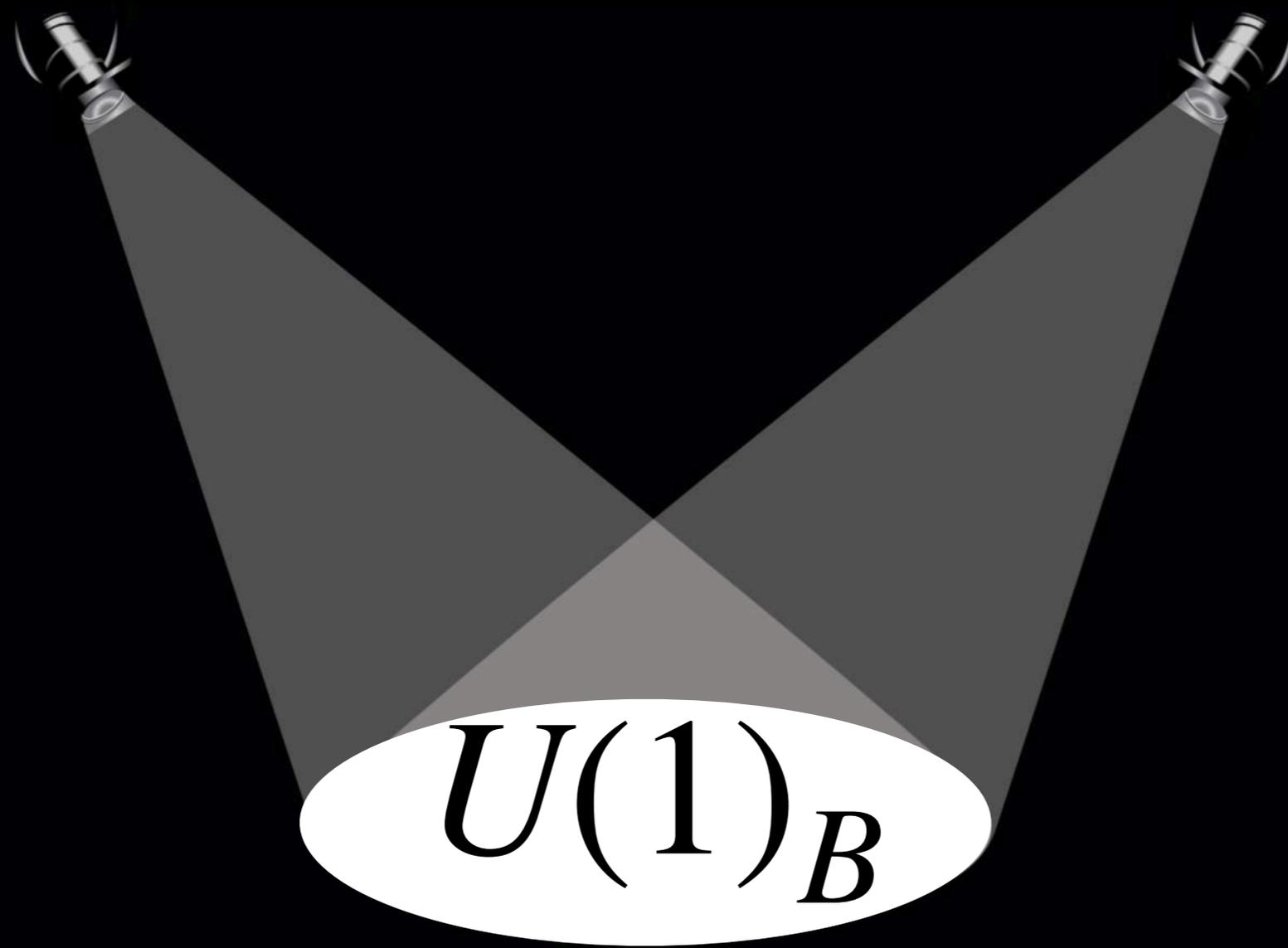
ATLAS; CERN-EP-2018-033



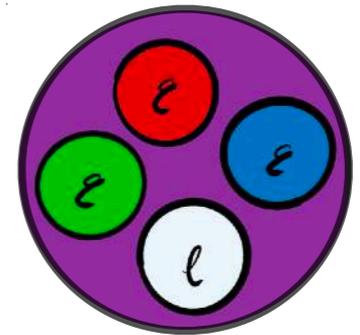
➡ $U(1)_B$ is a perfect candidate for a light gauge boson

Models for the spotlight ?

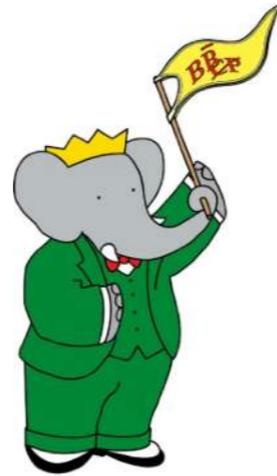
[1810.06646, 1901.10483, 1904.01017 2003.09426 2012.06599 2103.13397]



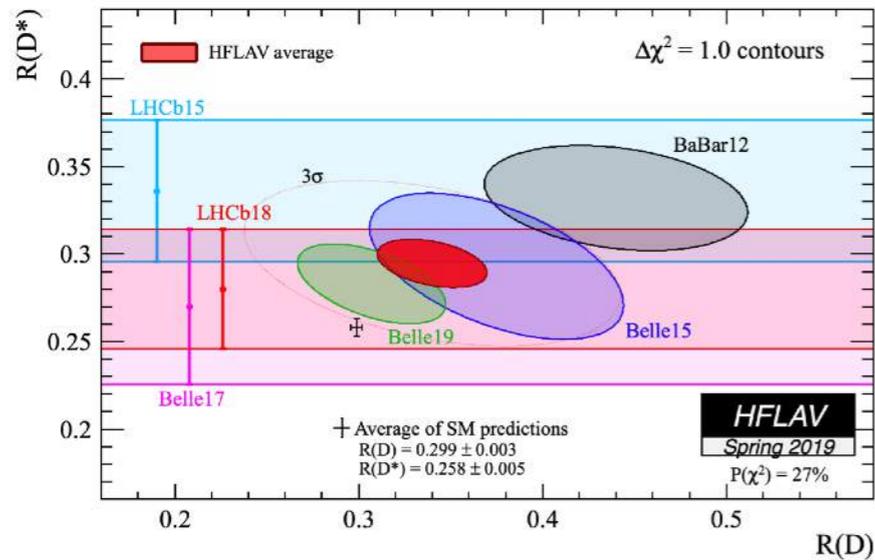
Quark-Lepton Unification at the Low Scale



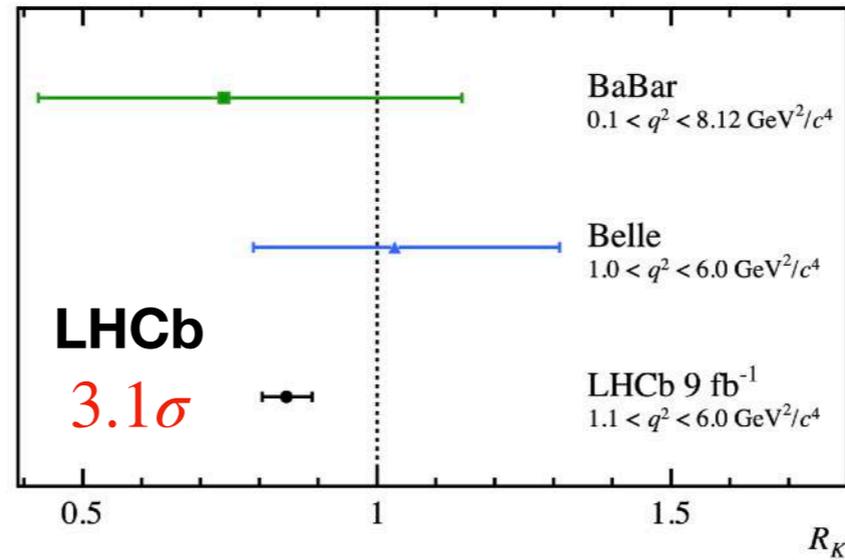
➔ Different experiments (LHCb, B-factories) have reported deviations of LFU



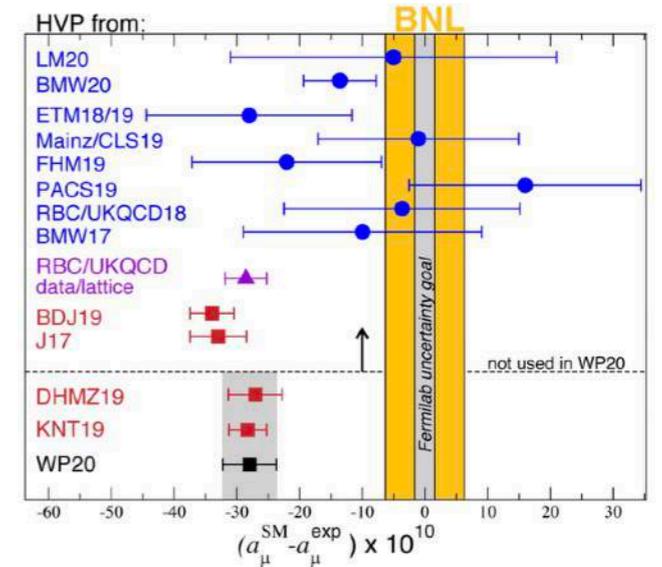
➔ Different experiments (LHCb, B-factories) have reported deviations of LFU



Charged anomalies



Neutral anomalies



(g-2) ????

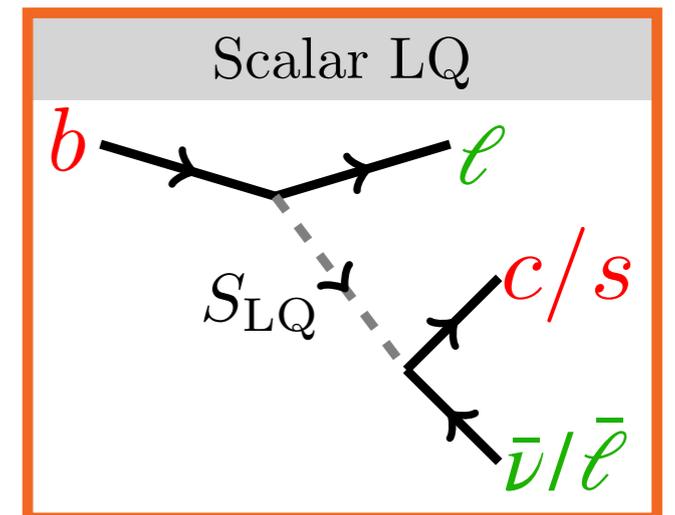
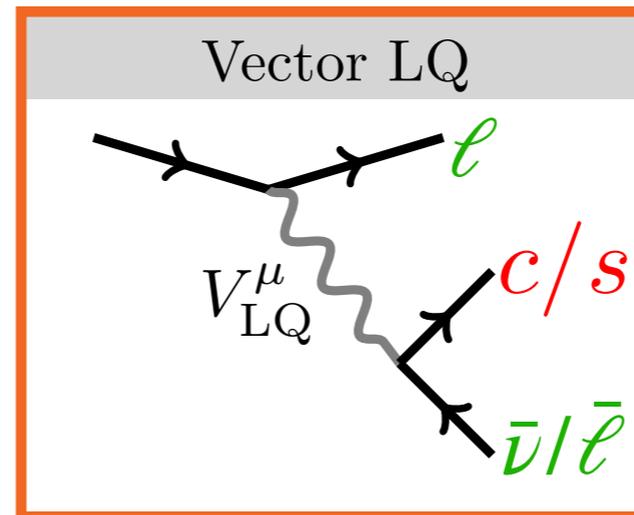
[See Angelo's & Stefan's and Bertrant's talk from yesterday]

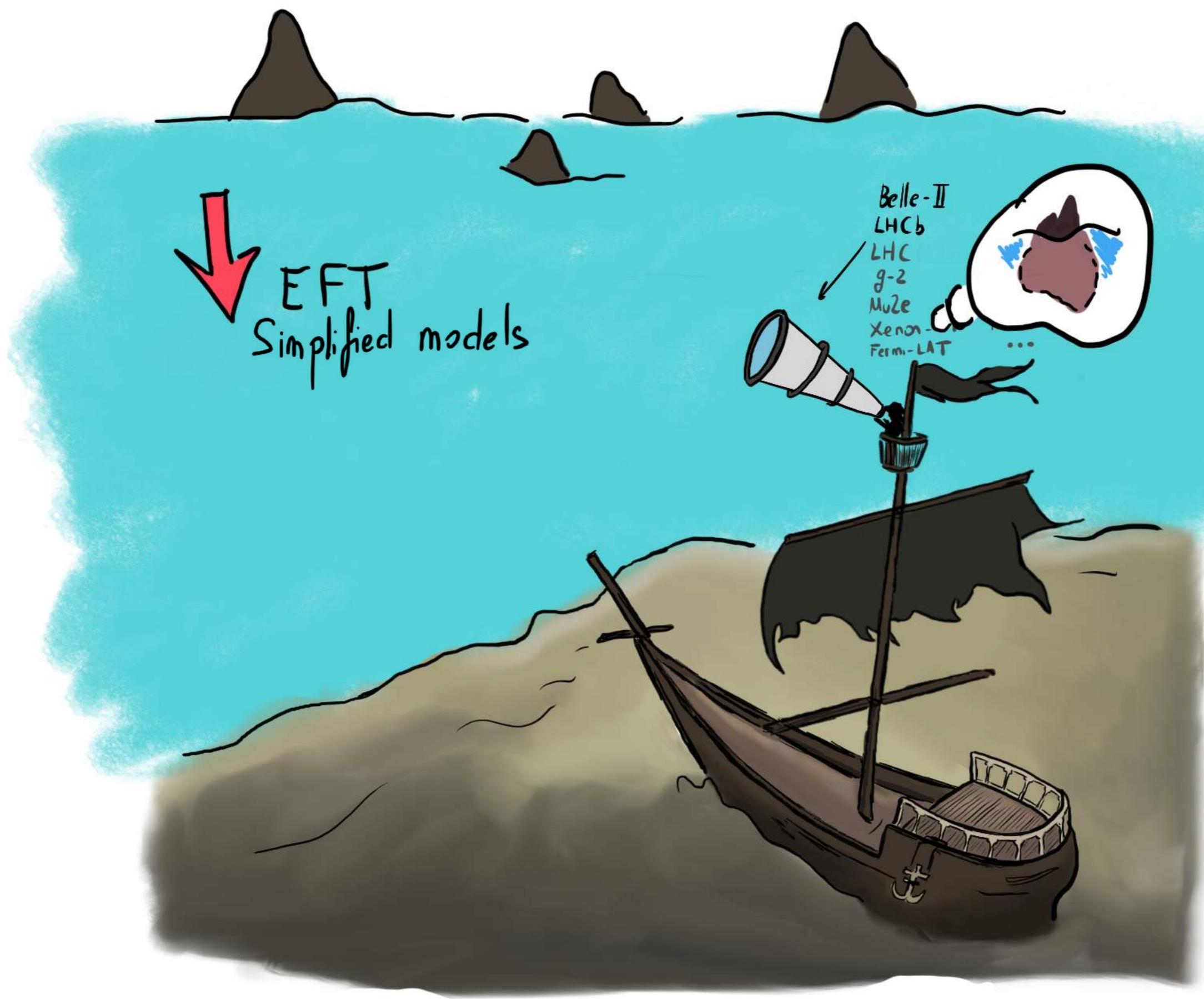
[See Peter's talk from yesterday]

[See Aida's & Jure's talk from today!]

➔ Leptoquarks are kind of nice

➔ Hints of TeV scale physics!





↓
EFT
Simplified models

Belle-II
LHCb
LHC
g-2
Mu2e
Xenon
Fermi-LAT
...





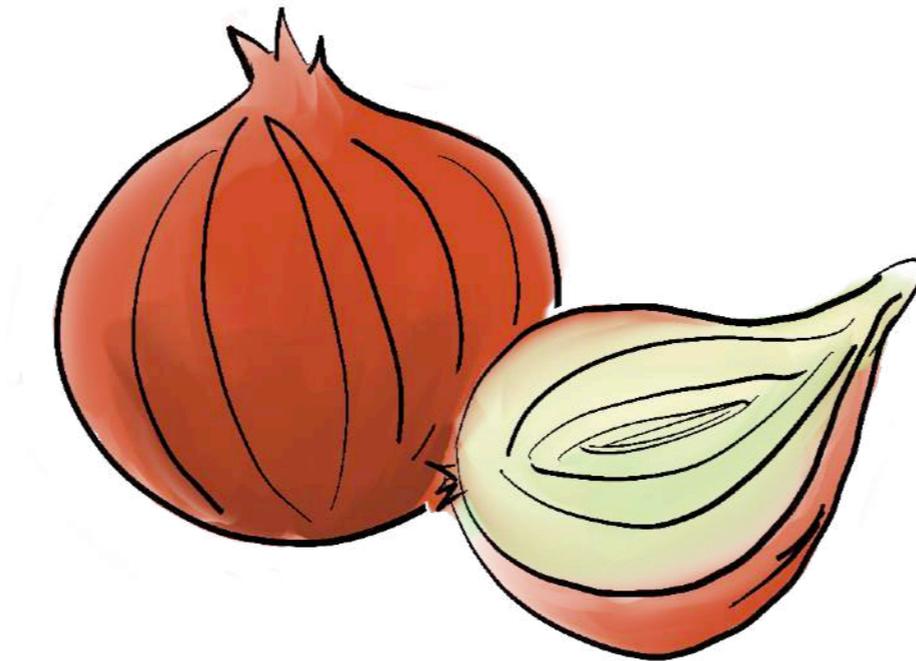
UV-COMPLETION

Belle-II
LHCb
LHC
g-2
Mu2e
Xenon-IT
Fermi-LAT
ADMETA
DUNE
LISA
Fermi-LAT
...

Quark-Lepton Unification

$$SU(4) \otimes SU(2) \otimes U(1)_R$$

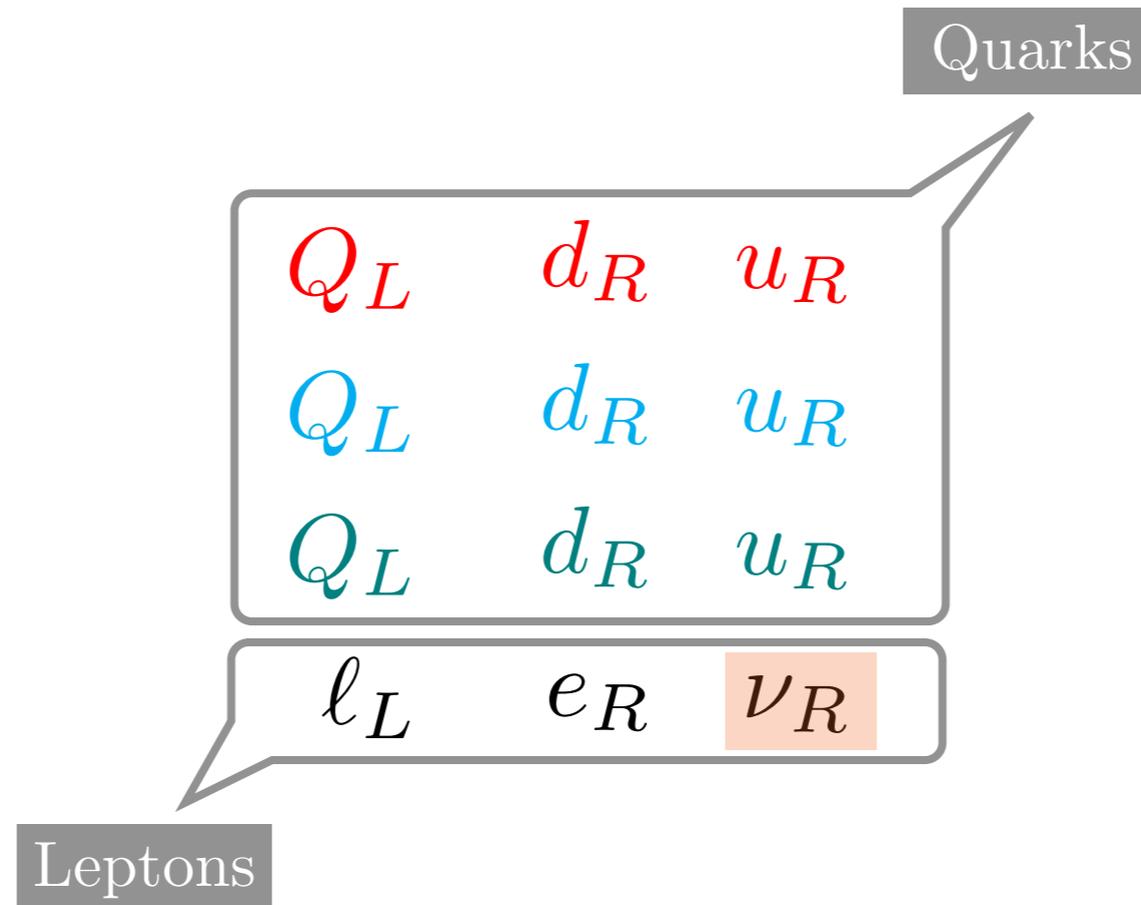
[Pati, Salam, 1974], [Smirnov, 1995], [Fileviez-Perez, Wise, 2013]



Quark-Lepton Unification

$$SU(4) \otimes SU(2) \otimes U(1)_R$$

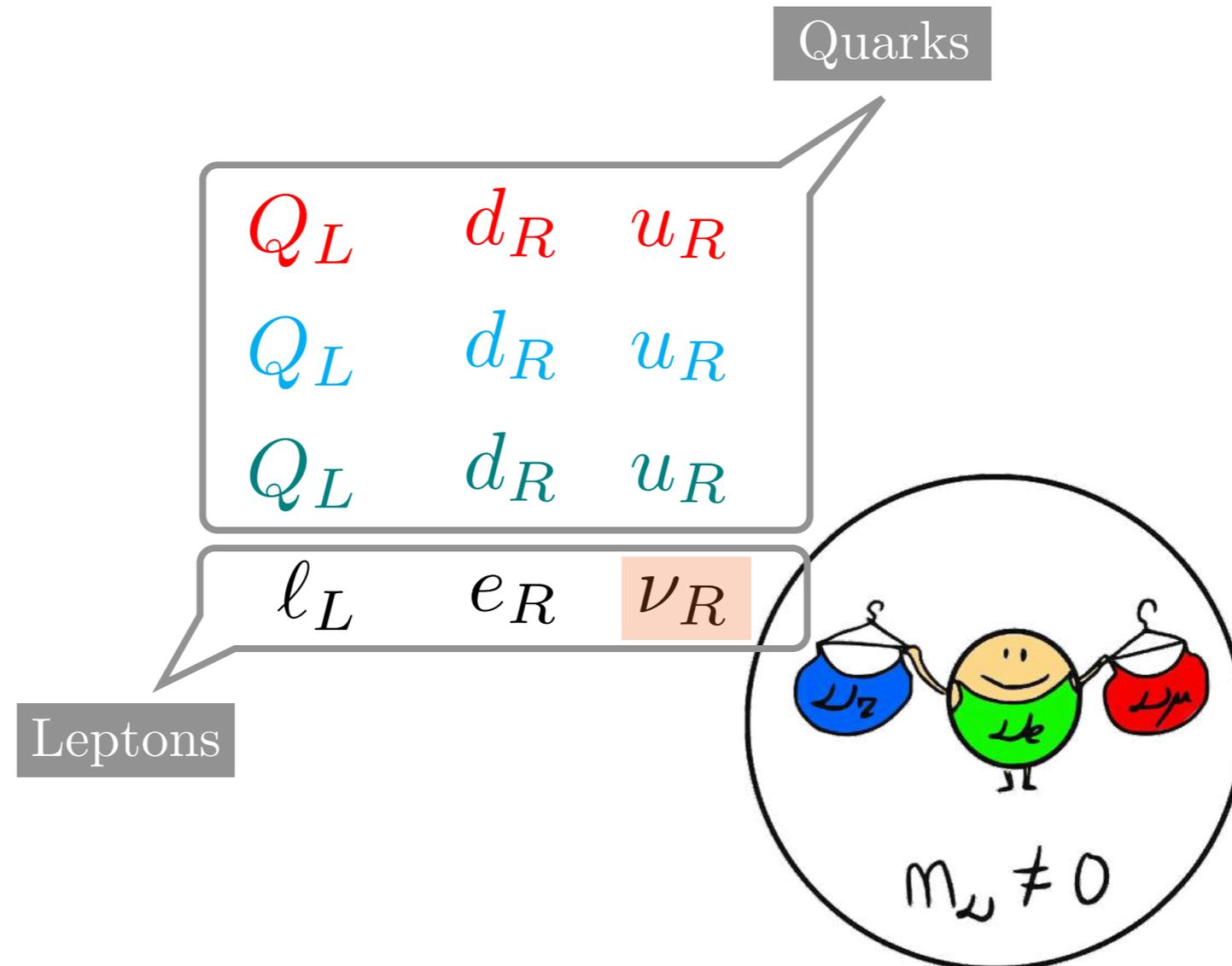
➔ Very economical fermion content [Pati, Salam, 1974]



Quark-Lepton Unification

$$SU(4) \otimes SU(2) \otimes U(1)_R$$

➔ Very economical fermion content [Pati, Salam, 1974]



Quark-Lepton Unification

$$SU(4) \otimes SU(2) \otimes U(1)_R$$

- ➔ Very economical fermion content
- ➔ Quarks and leptons are treated under the same footing

[Pati, Salam, 1974]

Q_L	d_R	u_R
Q_L	d_R	u_R
Q_L	d_R	u_R
ℓ_L	e_R	ν_R
F_{QL}	F_d	F_u

Leptons are just the fourth color of the quarks!

Quark-Lepton Unification

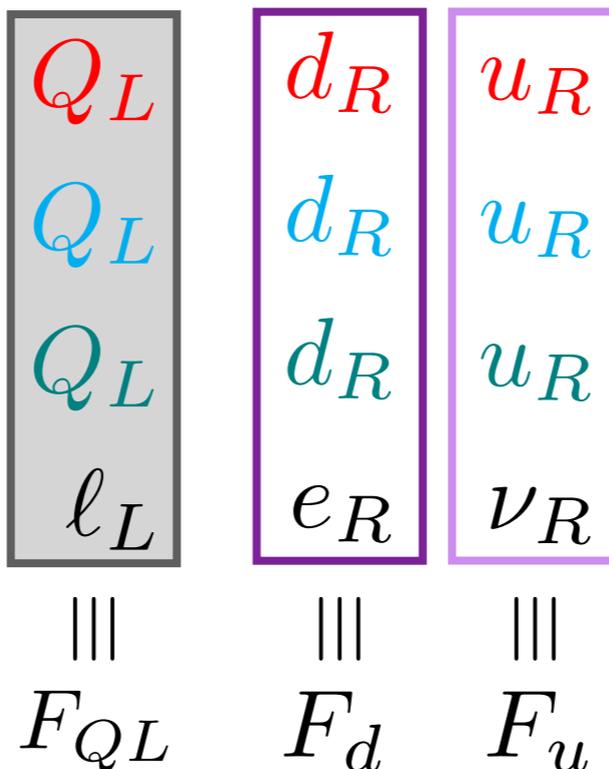
$$F_{QL} \sim (4, 2, 0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L$$

Left-handed fermions

$$F_u = (u^c \quad \nu^c)_L \sim (\bar{4}, 1, -1/2)$$

$$F_d = (d^c \quad e^c)_L \sim (\bar{4}, 1, 1/2)$$

Right-handed fermions



$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Quark-Lepton Unification

$$SU(4) \otimes SU(2) \otimes U(1)_R$$

- ➔ Very economical fermion content
- ➔ Quarks and leptons are treated under the same footing
- ➔ **Allows for a unification framework** [Pati, Salam, 1974]

$$SO(10) \supset SU(4) \otimes SU(2) \otimes U(1)_R$$

Quark-Lepton Unification

$$SU(4) \otimes SU(2) \otimes U(1)_R$$

- ➔ Very economical fermion content
- ➔ Quarks and leptons are treated under the same footing
- ➔ Allows for a unification framework
- ➔ **Only one step away from the SM**

$$U_1^\mu \sim (3, 1, 2/3)$$

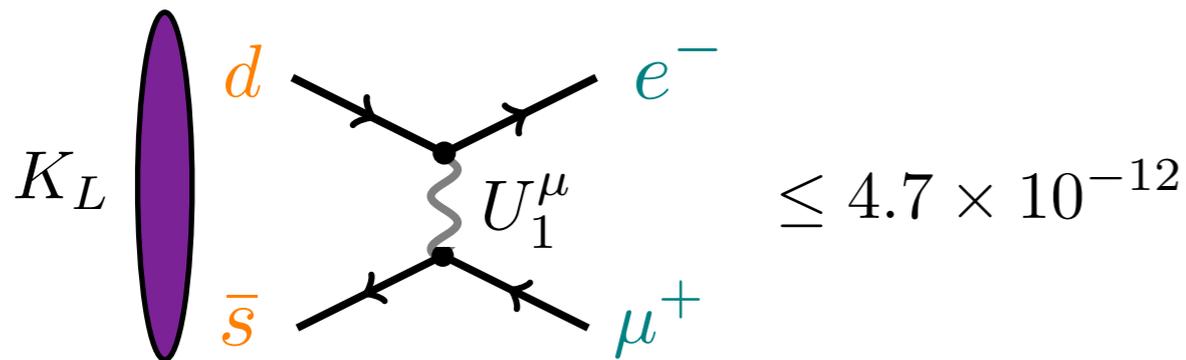
$$V_{15}^\mu \sim (15, 1, 0) \sim \underbrace{\begin{pmatrix} G^\mu & U_1^\mu \\ \dagger & 0 \end{pmatrix}}_{SU(4)_C} + T_4 B'^\mu$$

$$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle) \quad \Rightarrow \quad M_{U_1} \sim g_4 v_\chi \quad ?$$

$$\cancel{SU(4)_C} \otimes SU(2)_L \otimes \cancel{U(1)_R} \quad \Rightarrow \quad SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Quark-Lepton Unification



$$\mathcal{L}_K \supset \frac{g_4}{\sqrt{2}} U_1^\mu (\bar{Q}_L \gamma_\mu \ell_L + \bar{u}_R \gamma_\mu \nu_R + \bar{d}_R \gamma_\mu e_R) + \text{h.c.}$$

⇒ Only one step away from the SM

$$U_1^\mu \sim (3, 1, 2/3)$$

$$V_{15}^\mu \sim (15, 1, 0) \sim \underbrace{\begin{pmatrix} G^\mu & U_1^\mu \\ \dagger & 0 \end{pmatrix}}_{SU(4)_C} + T_4 B'^\mu$$

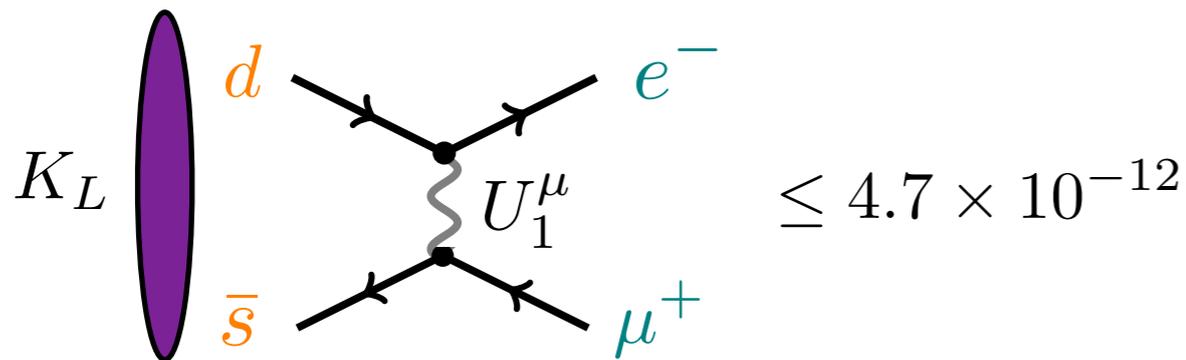
$$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle) \Rightarrow M_{U_1} \sim g_4 v_\chi \gtrsim 10^3 \text{ TeV}$$

$$\cancel{SU(4)_C} \otimes SU(2)_L \otimes \cancel{U(1)_R} \Rightarrow SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$



Quark-Lepton Unification



$$\mathcal{L}_K \supset \frac{g_4}{\sqrt{2}} U_1^\mu \left(\dots + \bar{d}_R U_R^\dagger \gamma_\mu E_R e_R \right) + \text{h.c.}$$

⇒ Only one step away from the SM

$$V_{15}^\mu \sim (15, 1, 0) \sim \begin{pmatrix} \boxed{G^\mu} & U_1^\mu \\ \dagger & 0 \end{pmatrix} + T_4 B'^\mu$$

$$\chi = (\chi_u, \chi_u, \chi_u, \langle \chi_R^0 \rangle) \Rightarrow M_{U_1} \sim g_4 v_\chi \gtrsim \cancel{10^3 \text{ TeV}}$$

Naive bound!

$$\cancel{SU(4)_c} \otimes SU(2)_L \otimes \cancel{U(1)_R} \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

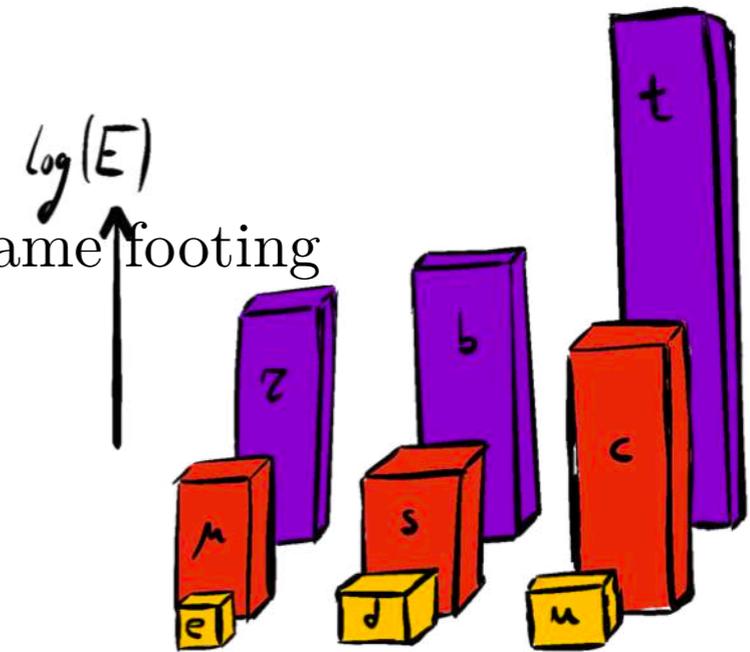
$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$



Quark-Lepton Unification

$$SU(4) \otimes SU(2) \otimes U(1)_R$$

- ➔ Very economical fermion content
- ➔ Quarks and leptons are treated under the same footing
- ➔ Only one step away from the SM
- ➔ Allows for a unification framework
- ➔ Predicts fermion flavor violation



[Fileviez-Perez, Wise, 2013]

$$\Phi \sim (15, 2, 1/2) = \begin{pmatrix} \Phi_{MW} & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2,$$

$$Y_4 = \sqrt{\frac{3}{2}} \frac{M_D - M_E}{v \sin \beta}$$

$$\tilde{R}_2 \equiv \Phi_3 \sim (\bar{3}, 2, -1/6)_{SM}$$

$$R_2 \equiv \Phi_4 \sim (3, 2, 7/6)_{SM}$$

Quark-Lepton Unification

$$SU(4) \otimes SU(2) \otimes U(1)_R$$

➔ Very economical fermion content

➔ Quarks and leptons are treated under the same footing

➔ Only one step away from the SM

➔ Allows for a unification framework

➔ Predicts fermion flavor violation

➔ **Baryon number is preserved at the renormalizable level**

$$V_{\text{scalar}} \supset \epsilon_{\alpha\beta\gamma} \cancel{\Phi_3^\alpha} \Phi_3^\beta \Phi_3^\gamma H$$

[C.M, M. B. Wise, 2021]

$$-\mathcal{L}_Y \supset Y_2 Q_L \Phi_3 (\nu^c)_L + Y_2 \ell_L \Phi_4 (u^c)_L + Y_4 Q_L \Phi_4^\dagger (e^c)_L + Y_4 \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

$$Q_B(\Phi_3) = -1/3,$$

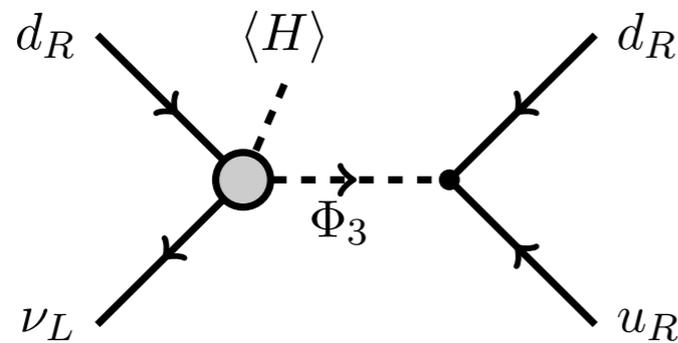
$$Q_L(\Phi_3) = 1,$$

$$Q_B(\Phi_4) = 1/3,$$

$$Q_L(\Phi_4) = -1$$

Quark-Lepton Unification

$$SU(4) \otimes SU(2) \otimes U(1)_R$$



$$\text{if } \Lambda \sim M_{\text{Pl}} \Rightarrow M_{\Phi_{3,4}} > 10^8 \text{ GeV}$$

[Arnold, Fornal,
Wise, 2013]

$$\frac{1}{\Lambda_{\text{PS}}^3} F_d^A F_u^B (\Phi^\dagger)_D^C \chi^D \chi^E H^\dagger \epsilon_{ABCE} \xrightarrow{\langle \chi \rangle} \frac{v_\chi^2}{\Lambda_{\text{PS}}^3} d_R^\alpha u_R^\beta (\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}$$

[C.M, M. B. Wise, 2021]

$$-\mathcal{L}_Y \supset Y_2 Q_L \Phi_3 (\nu^c)_L + Y_2 \ell_L \Phi_4 (u^c)_L + Y_4 Q_L \Phi_4^\dagger (e^c)_L + Y_4 \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

~~$Q_B(\Phi_3) = -1/3,$~~

~~$Q_L(\Phi_3) = 1,$~~

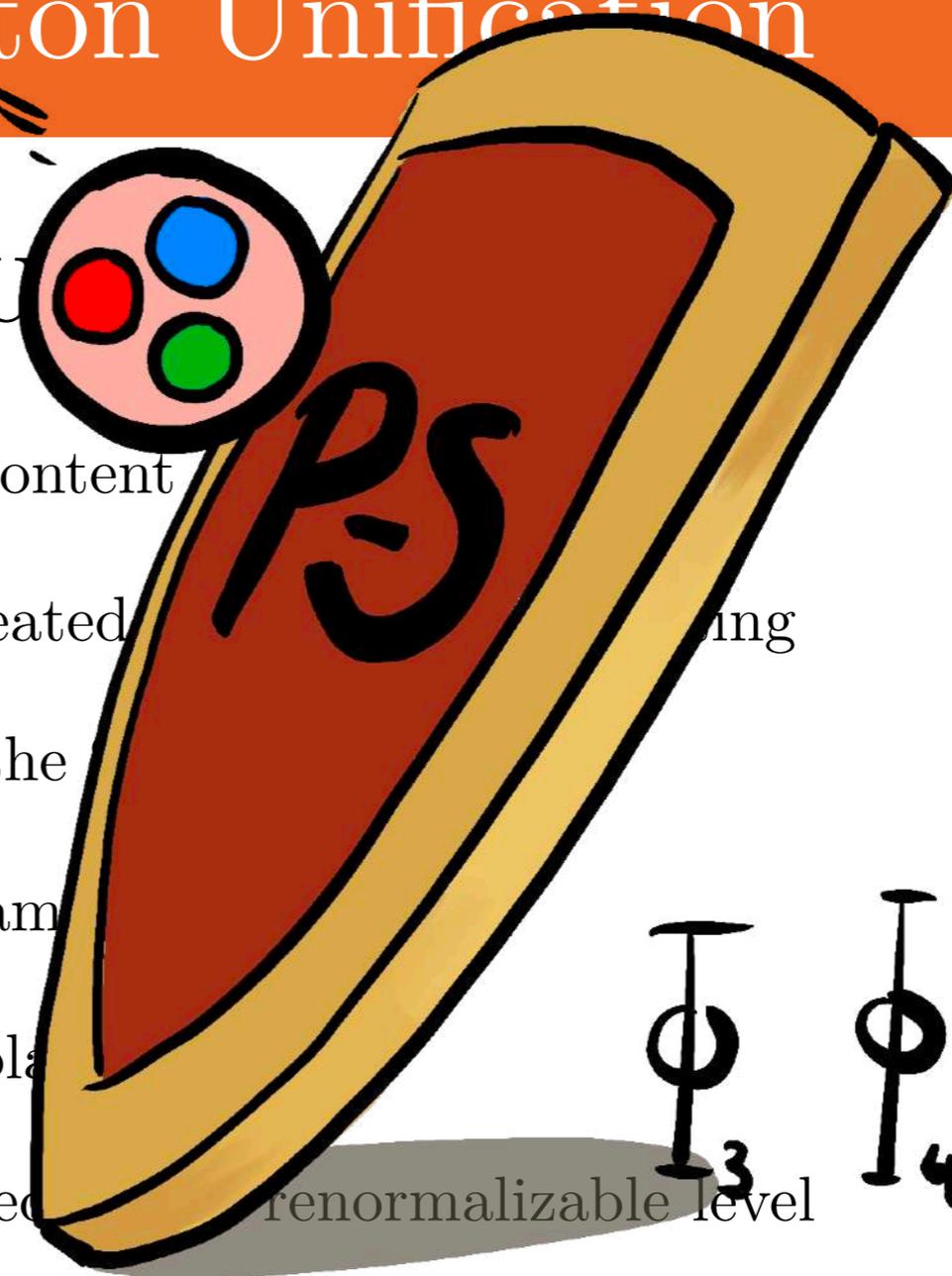
~~$Q_B(\Phi_4) = 1/3,$~~

~~$Q_L(\Phi_4) = -1$~~

$$\text{e.g. } \frac{1}{\Lambda} u_R^\alpha d_R^\beta (\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}, \quad \frac{1}{\Lambda} d_R^\alpha d_R^\beta \Phi_4^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}$$

Quark-Lepton Unification

$$SU(4) \otimes SU(2)$$



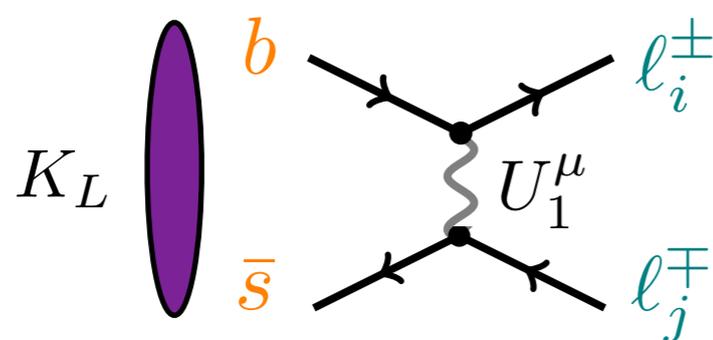
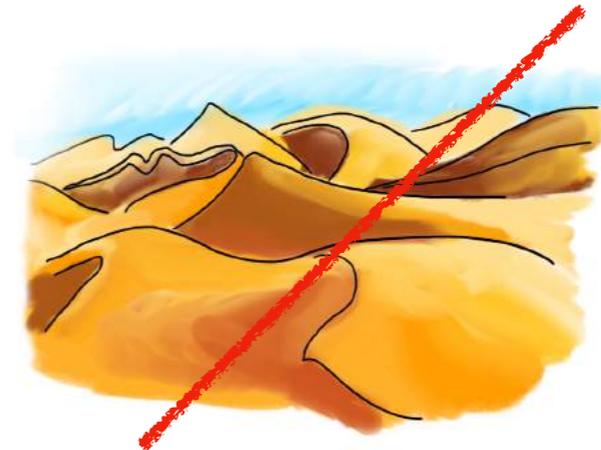
- ➔ Very economical fermion content
- ➔ Quarks and leptons are treated equally
- ➔ Only one step away from the Standard Model
- ➔ Allows for a unification framework
- ➔ Predicts fermion flavor violation
- ➔ Baryon number is preserved at the renormalizable level
- ➔ **PS-symmetry protects baryon number at the non-renormalizable too!**

[C.M, M.B. Wise, 2021]

Quark-Lepton Unification

$$SU(4) \otimes SU(2) \otimes U(1)_R$$

- ➔ Very economical fermion content
- ➔ Quarks and leptons are treated under the same footing
- ➔ Only one step away from the SM
- ➔ Allows for a unification framework
- ➔ Predicts fermion flavor violation
- ➔ Baryon number is preserved at the renormalizable level
- ➔ PS-symmetry protects baryon number at the non-renormalizable too!
- ➔ **Can be realized at the low scale**

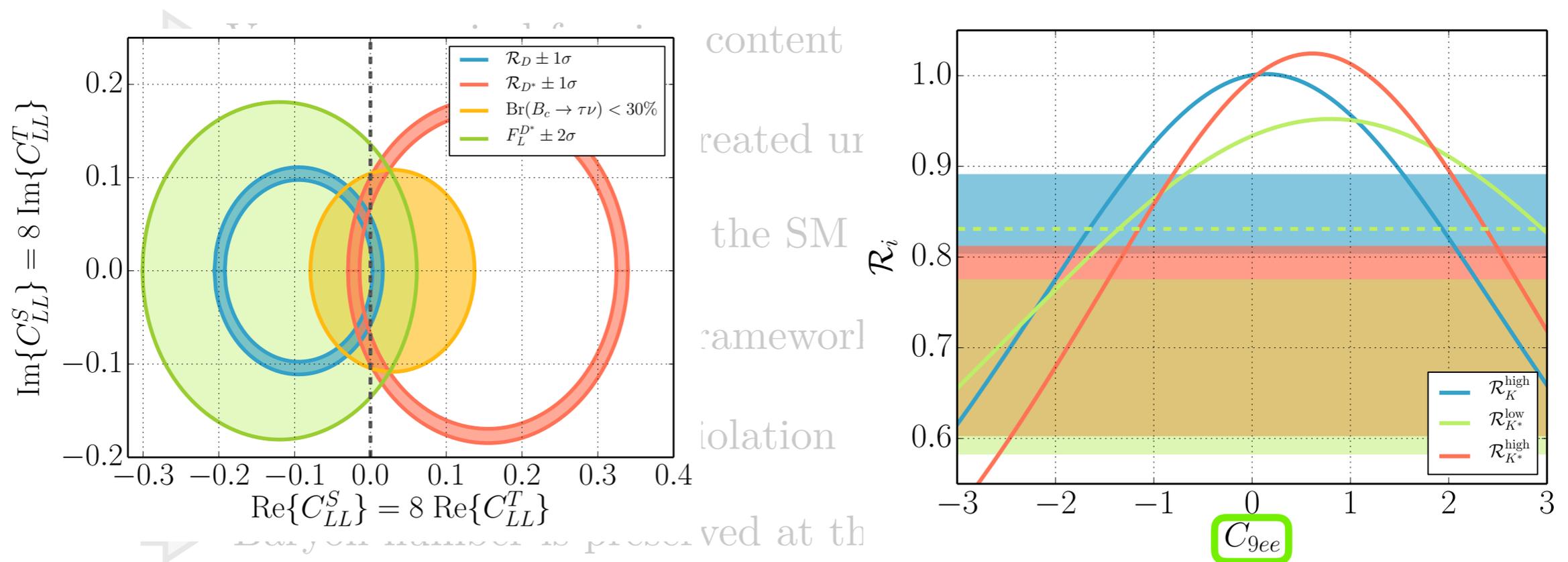


[Fileviez-Perez, Wise, 2013], [Fileviez-Perez, C.M., 2022]

$$M_{U_1} \gtrsim 74 \text{ TeV} \left(\frac{\alpha_4}{0.118} \right)^{1/2} \left| \frac{\cos \theta_c}{0.1} \right|^{1/2}$$

Quark-Lepton Unification

$$\text{SU}(4) \otimes \text{SU}(2) \otimes \text{U}(1)_R$$



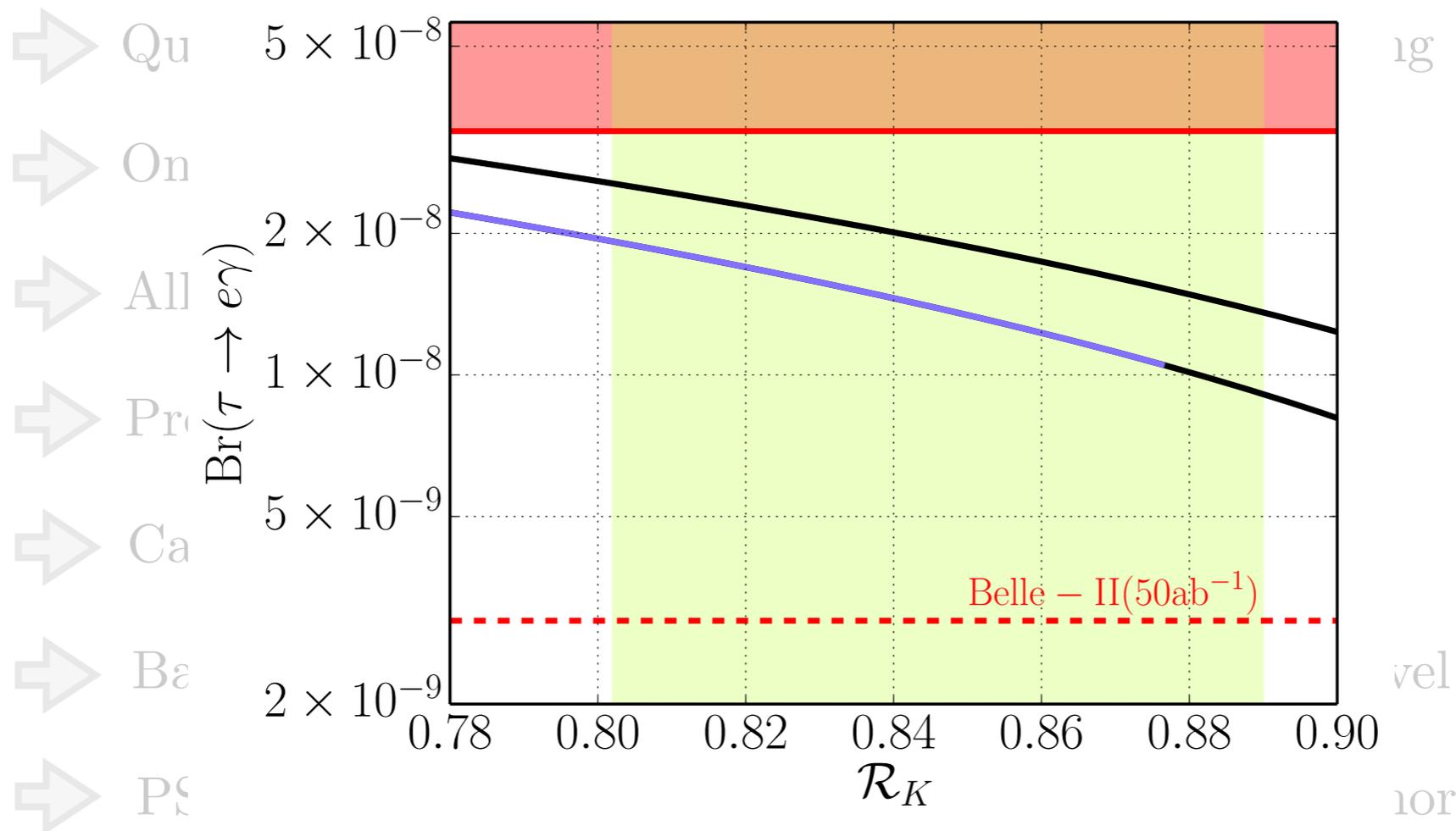
- ➔ PS-symmetry protects baryon number at the non-renormalizable too!
- ➔ Can be realized at the low scale
- ➔ Can address the ratios $\mathcal{R}_{K^{(*)}}$ and $\mathcal{R}_{D^{(*)}}$

[Fileviez-Perez, C.M., Plascencia, 2021], [Fileviez-Perez, C.M., 2022]

Quark-Lepton Unification

$$SU(4) \otimes SU(2) \otimes U(1)_R$$

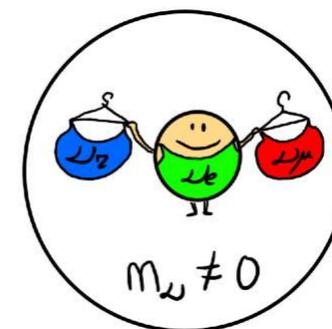
➔ Very economical fermion content



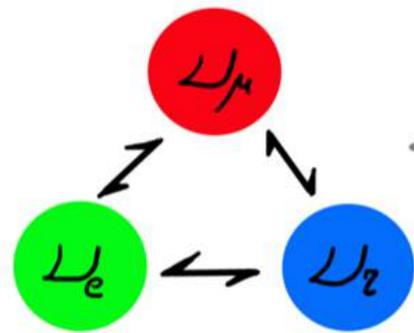
➔ Can address the ratios $\mathcal{R}_{K^{(*)}}$ and $\mathcal{R}_{D^{(*)}}$

➔ **And we'll be able to test that soon!** 😊 [P. Fileviez-Perez, C.M., 2022]

Theories for Neutrino Masses



Neutrinos are massive!



$$M_\nu \neq 0$$



SM content should be extended
(no clue about their nature)

e.g. $\nu_R \sim (1, 1, 0)$

[See Vincenzo's talk today]

$$\Delta L \neq 2$$

- Neutrinos are **Dirac**

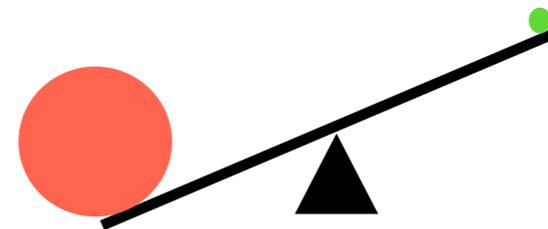
$$\mathcal{L}_\nu^D \supset Y_\nu \bar{\ell}_L \tilde{H} \nu_R + \text{h.c.}$$

$$m_\nu \leq 0.1 \text{ eV} \Rightarrow Y_\nu \leq 10^{-12}$$

$$\Delta L = 2$$

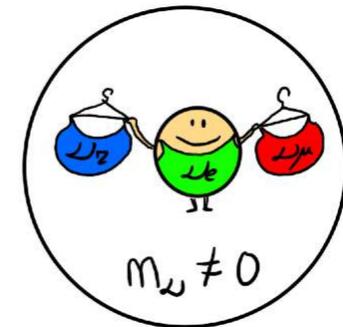
- Neutrinos are **Majorana**

$$\mathcal{L}_\nu^M \supset Y_\nu \bar{\ell}_L \tilde{H} \nu_R + \frac{1}{2} \nu_R^T C M_R \nu_R + \text{h.c.}$$



Theories for Neutrino Masses

Within explicit L breaking



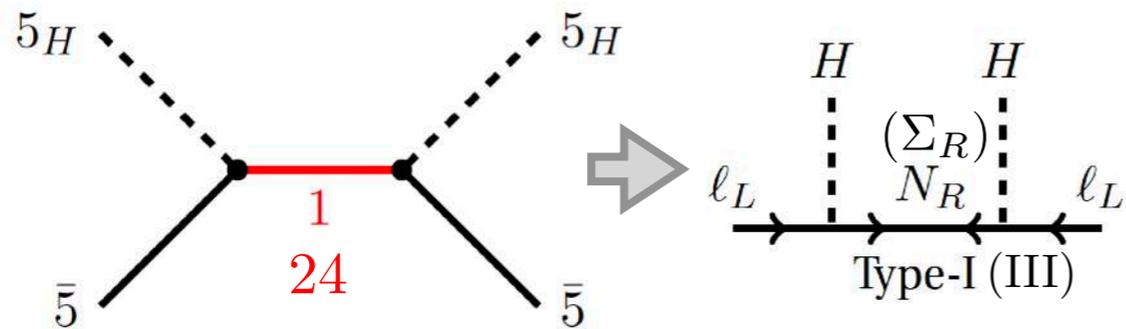
Within explicit L breaking [SU(5)]

Type-I/III seesaw

I: $Y_\nu^i \bar{5}_i 5_H 1 + M_\nu 1 1 + \text{h.c.}$

III: $Y_\nu^i \bar{5} 24 5_H + M_{24} \text{Tr}\{24^2\} + \lambda \text{Tr}\{24^2 24_H\} + \text{h.c.}$

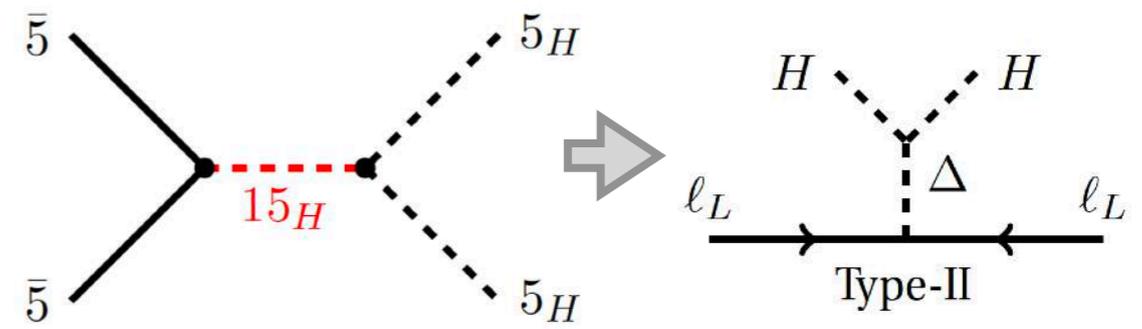
[B. Bajc, G. Senjanović, 2007] [B. Bajc, G. Senjanović, 2007]
 [I. Dorsner, P. Fileviez-Perez, 2007]



Type-II seesaw

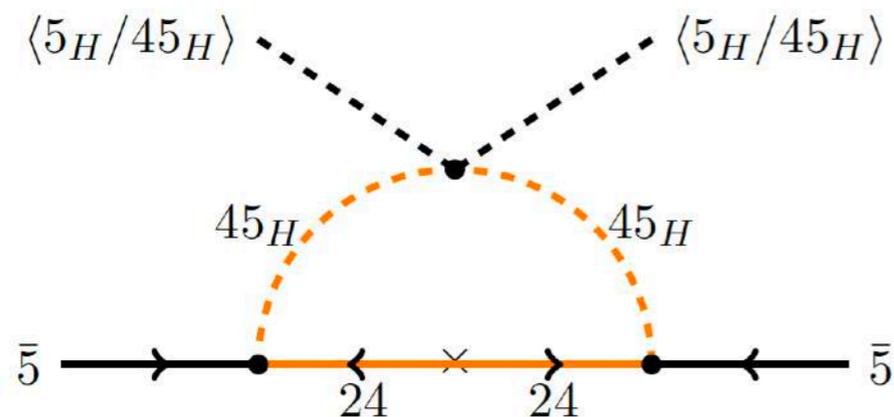
[I. Dorsner, P. Fileviez-Perez, 2005],
 [I. Dorsner, P. Fileviez-Perez, R. Gonzalez Felipe, 2006],
 [I. Dorsner, P. Fileviez-Perez, G. Rodrigo, 2007]

$$Y_\Delta \bar{5} \bar{5} 15_H + M_\Delta^2 15_H^* 15_H + \mu 5_H^* 5_H^* 15_H + \lambda 5_H^* 5_H^* 24_H 15_H + \text{h.c.}$$



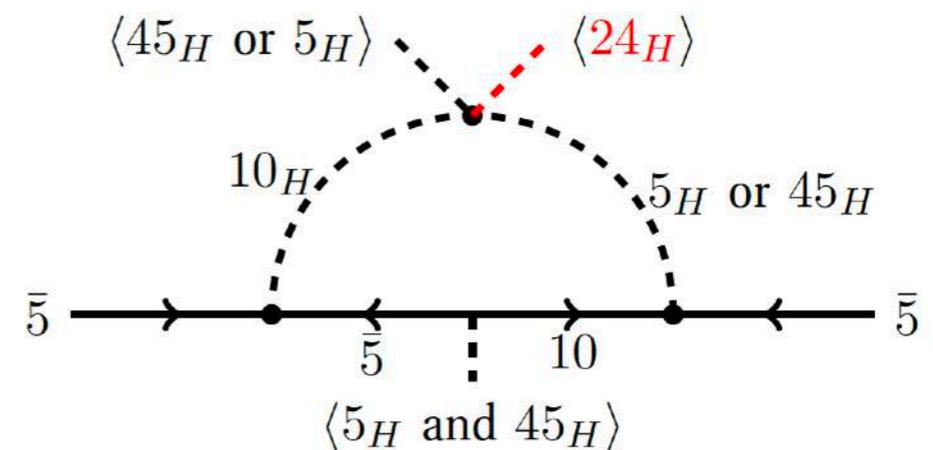
[P. Fileviez-Perez, M. Wise., 2009] Colored seesaw

$$Y_\nu \bar{5} 24 45_H + M_{24} \text{Tr}\{24^2\} + 45_H 45_H (\lambda_1 5_H^* 5_H^* + \lambda_2 5_H^* 45_H^* + \lambda_3 45_H^* 45_H^*)$$



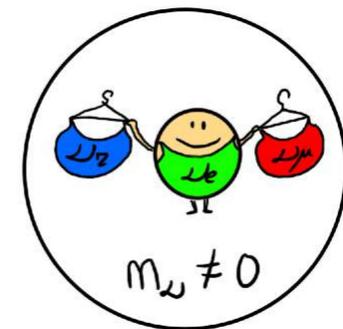
[P. Fileviez-Perez, C.M., 2016] Zee mechanism

$$\lambda \bar{5} \bar{5} 10_H + \bar{5} (Y_1 5_H^* + Y_2 45_H) 10 - \frac{1}{6} \mu 5_H 45_H 10_H^* + \lambda_{24} 5_H 45_H 24_H 10_H^* + \text{h.c.}$$



Theories for Neutrino Masses

Within spontaneous L breaking



Within spontaneous L breaking

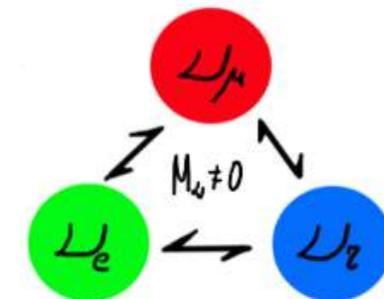
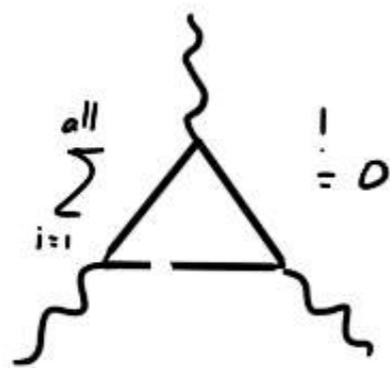


Extra symmetries:

$$U(1)_{B-L}, U(1)_L, U(1)_B$$

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X$$

$$U(1)_X \rightarrow U(1)_{X=B} \text{ or } U(1)_{X=L}$$



3 ν_R

only $U(1)_L$

Within spontaneous L breaking

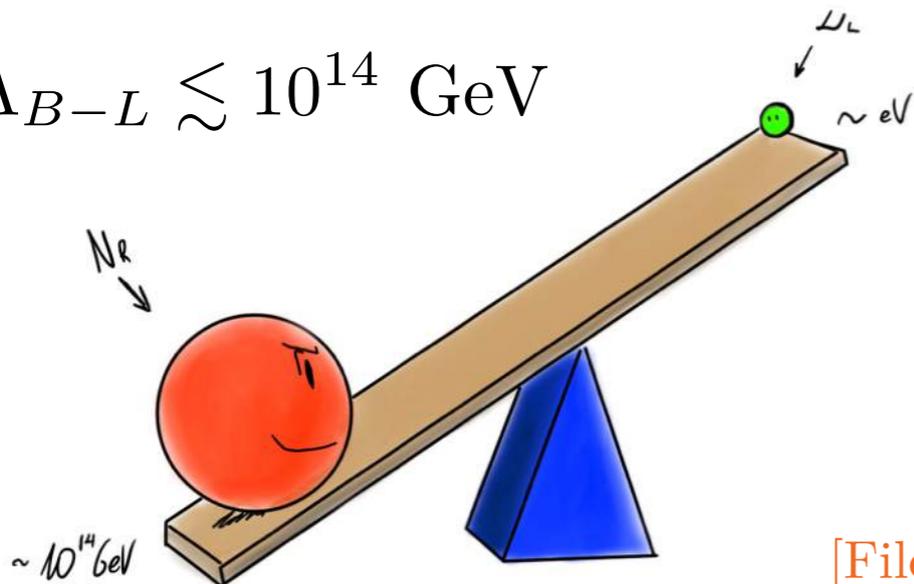
Majorana neutrinos

$$\cancel{U(1)}_{B-L} \Rightarrow \Delta(B-L) = 2$$
$$\langle S_{BL} \sim (1, 1, 0, 2) \rangle = v_{B-L}$$

$$\mathcal{L} \supset S_{BL}^* \nu_R \nu_R + \text{h.c.}$$

$$M_{\nu_R}, M_{Z_{BL}} \propto v_{B-L}$$

$$\Lambda_{B-L} \lesssim 10^{14} \text{ GeV}$$



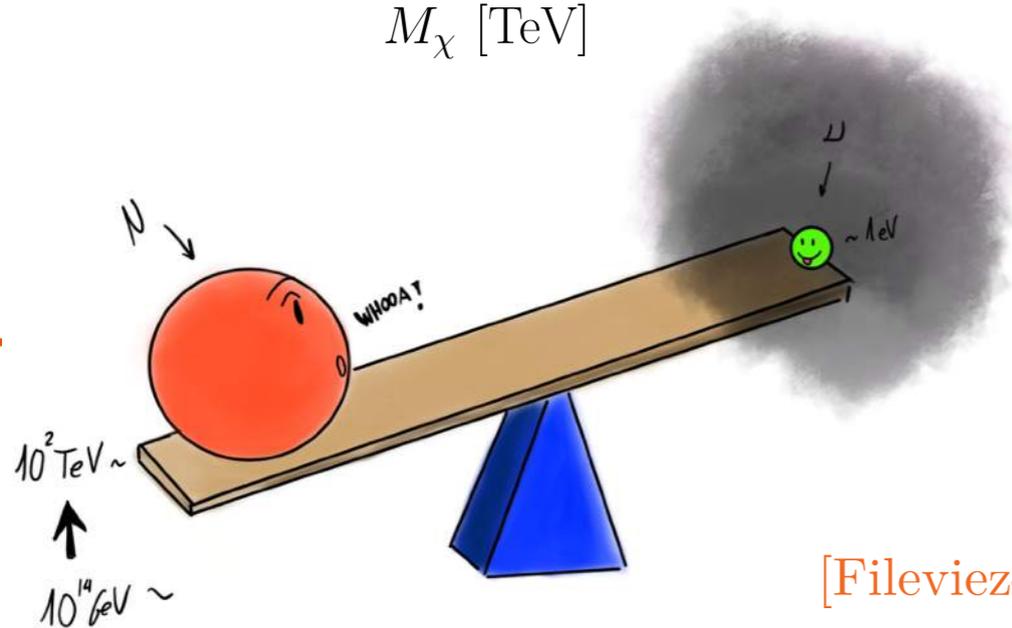
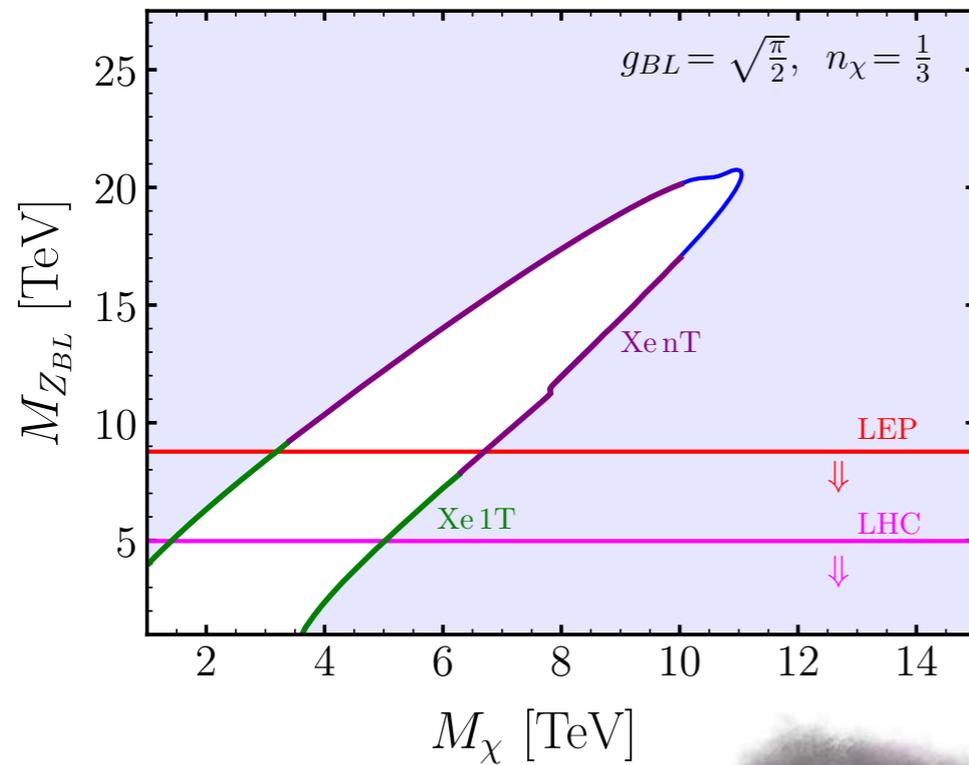
[Fileviez-Perez, C.M., 2018]

[P. Fileviez-Perez, E. Goliás, C.M., R. Li, A. Plascencia, 2019] [P. Fileviez-Perez, C.M., A. Plascencia, 2019]

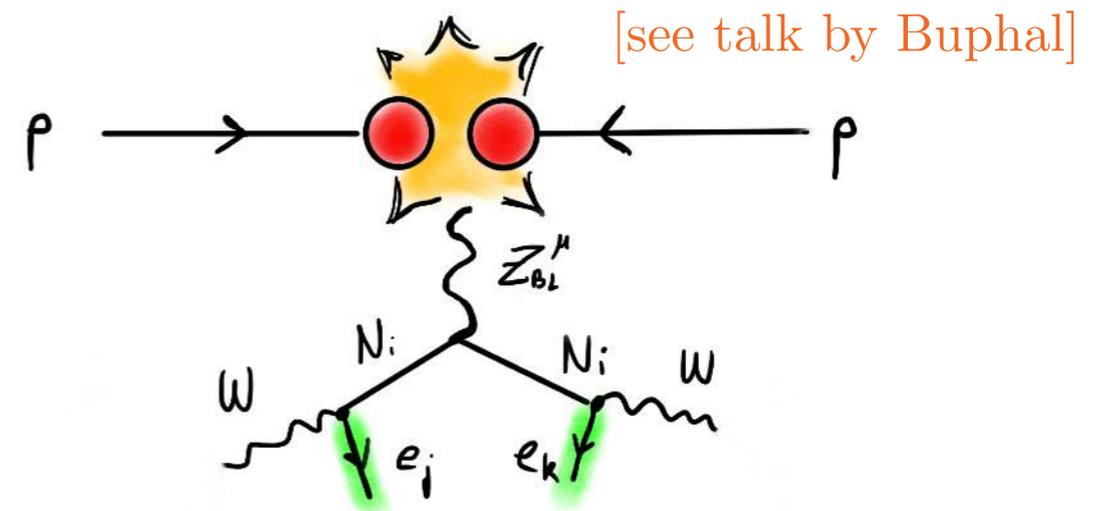
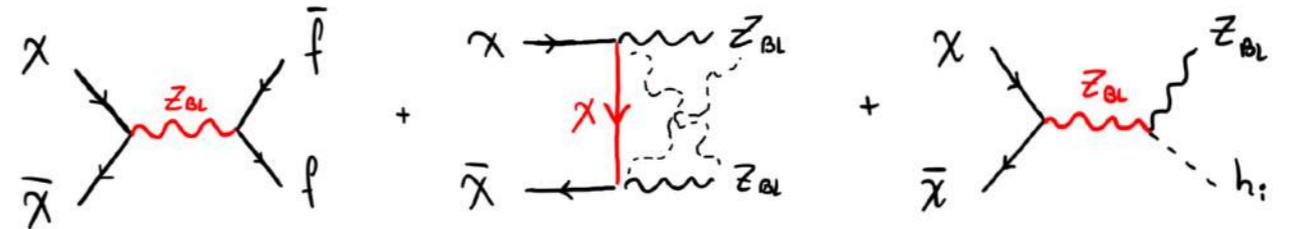
Within spontaneous L breaking

Majorana neutrinos

$$\cancel{U(1)_{B-L}} \Rightarrow \Delta(B-L) = 2$$



$$\Lambda_{LN} \lesssim \mathcal{O}(10) \text{ TeV}$$



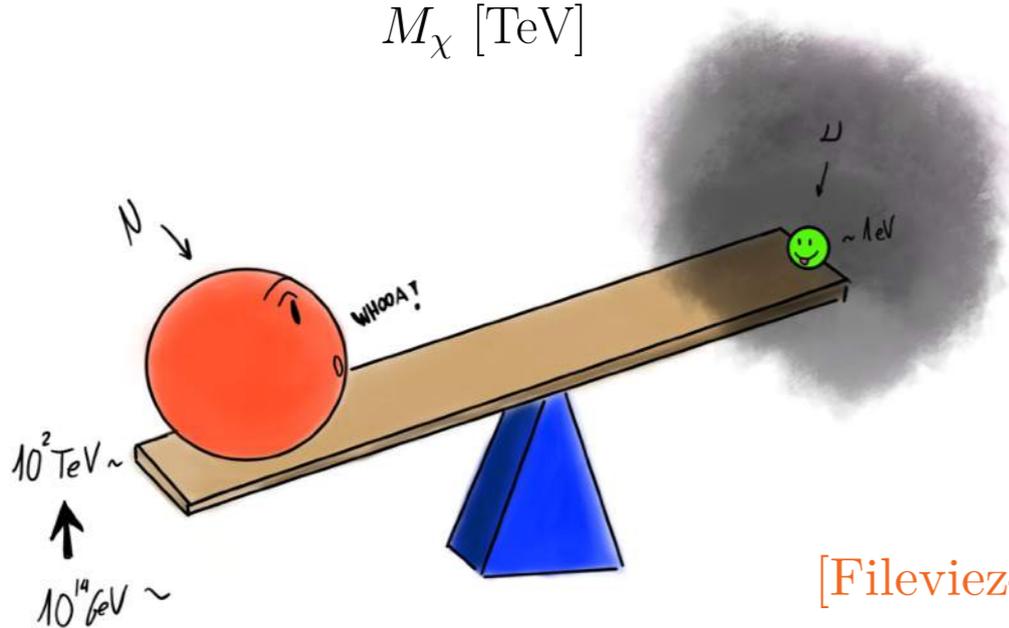
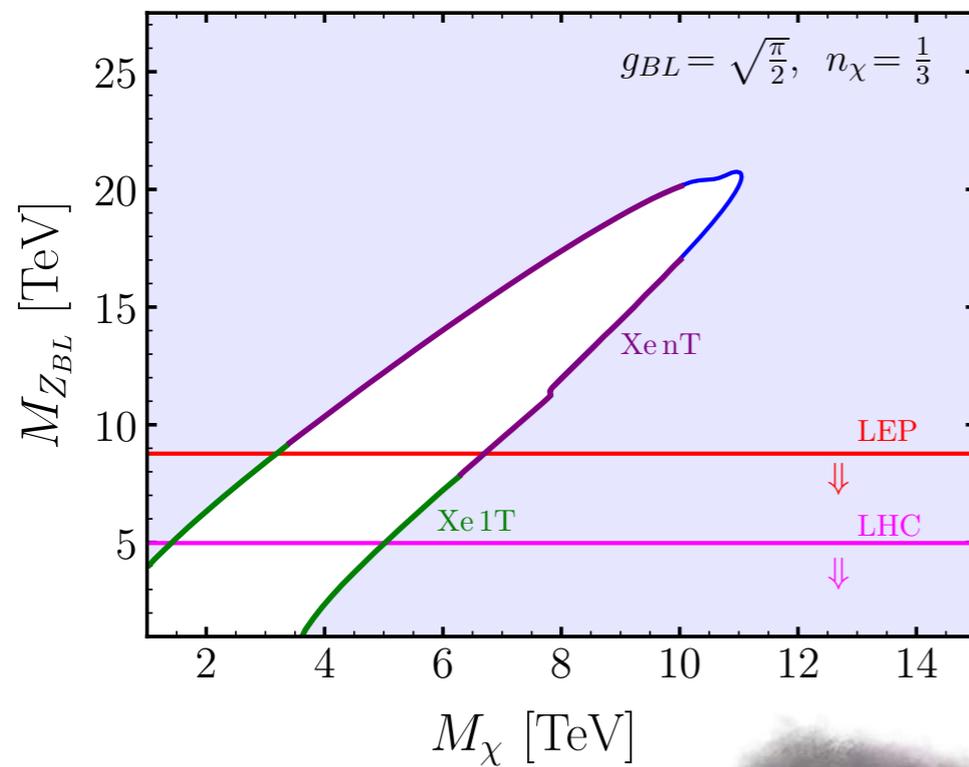
[Fileviez-Perez, C.M., 2018]

[P. Fileviez-Perez, E. Golias, C.M., R. Li, A. Plascencia, 2019] [P. Fileviez-Perez, C.M., A. Plascencia, 2019]

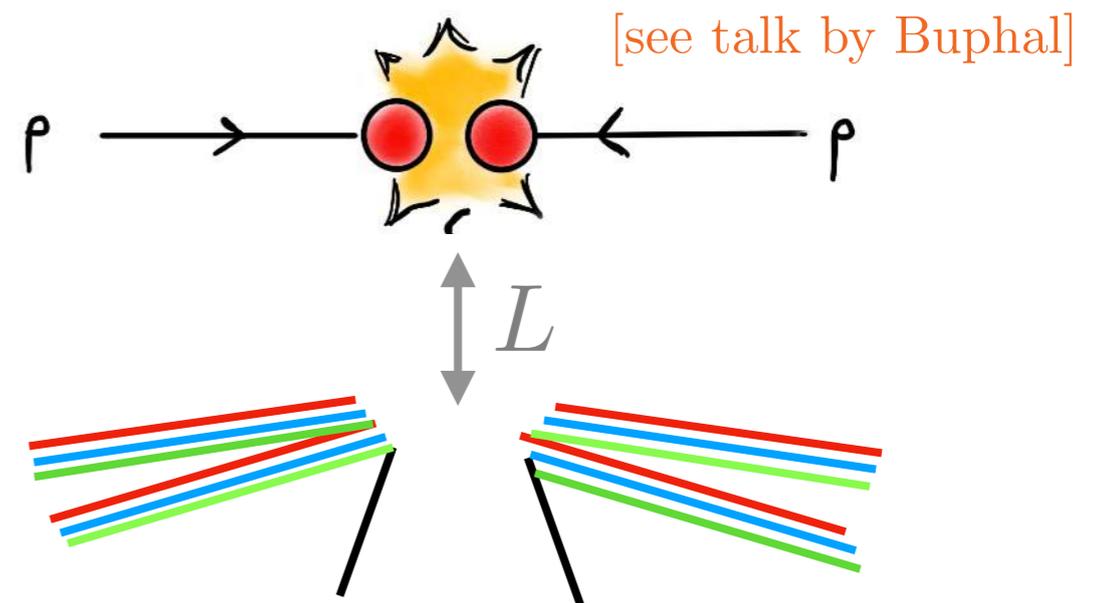
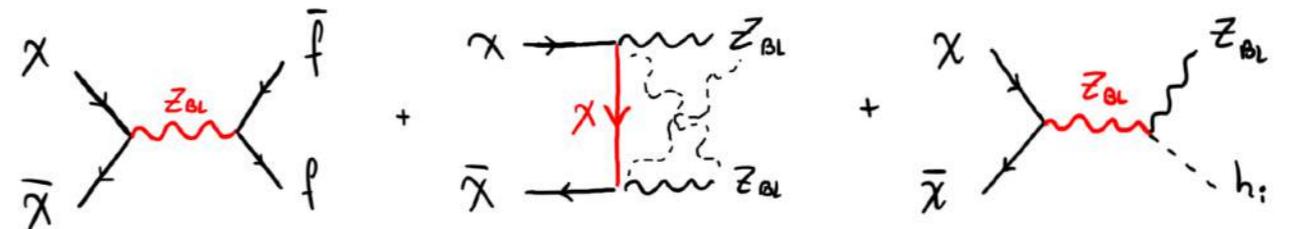
Within spontaneous L breaking

Majorana neutrinos

$$\cancel{U(1)_{B-L}} \Rightarrow \Delta(B-L) = 2$$



$$\Lambda_{LN} \lesssim \mathcal{O}(10) \text{ TeV}$$



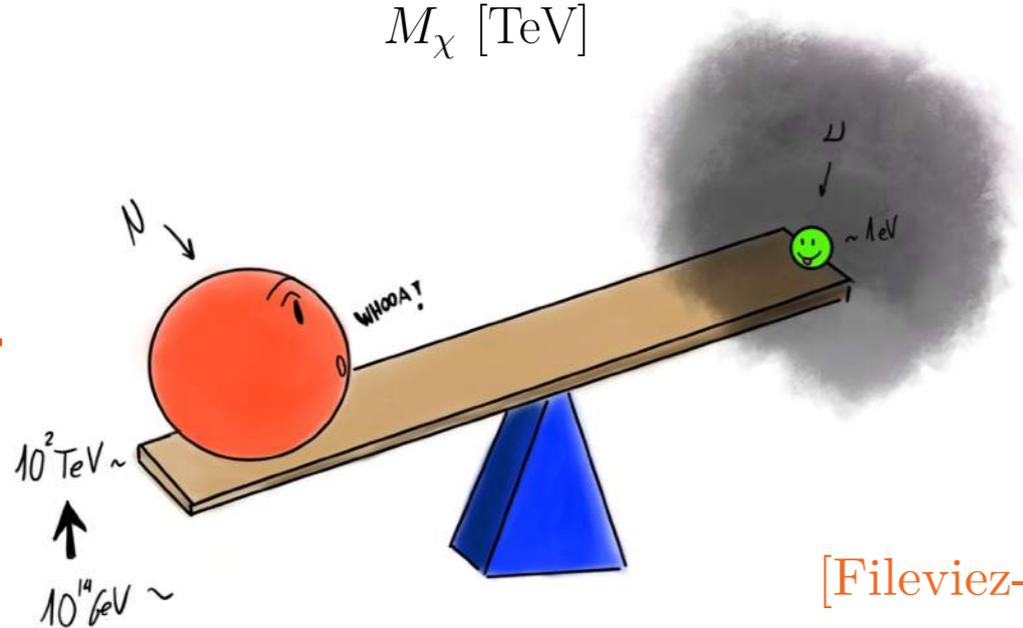
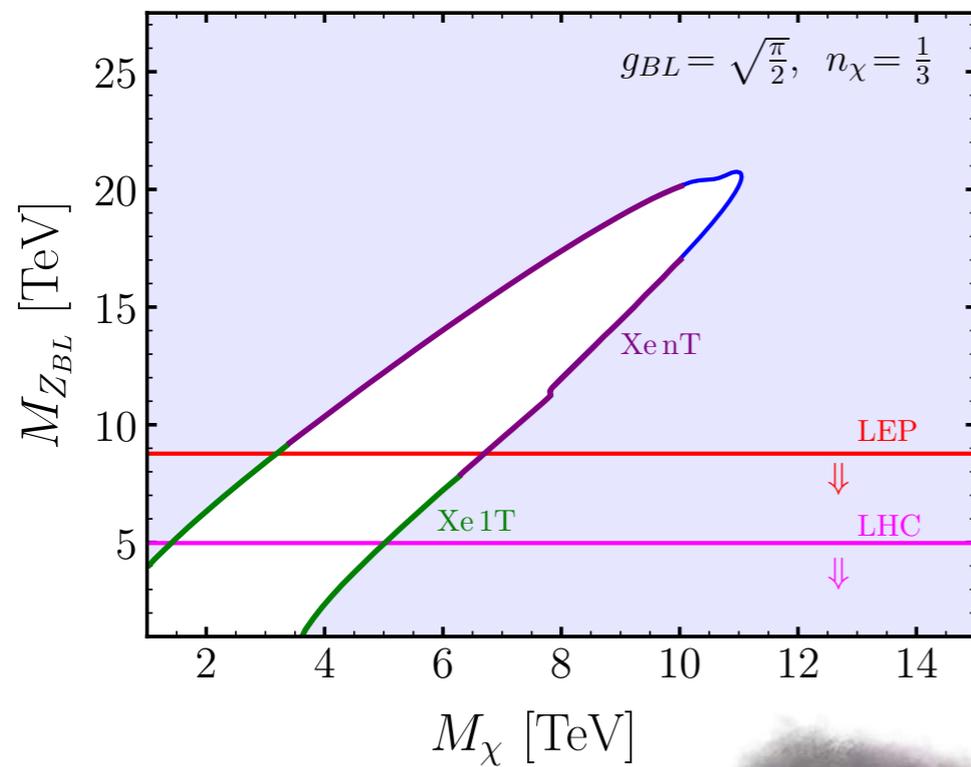
[Fileviez-Perez, C.M., 2018]

[P. Fileviez-Perez, E. Golias, C.M., R. Li, A. Plascencia, 2019] [P. Fileviez-Perez, C.M., A. Plascencia, 2019]

Within spontaneous L breaking

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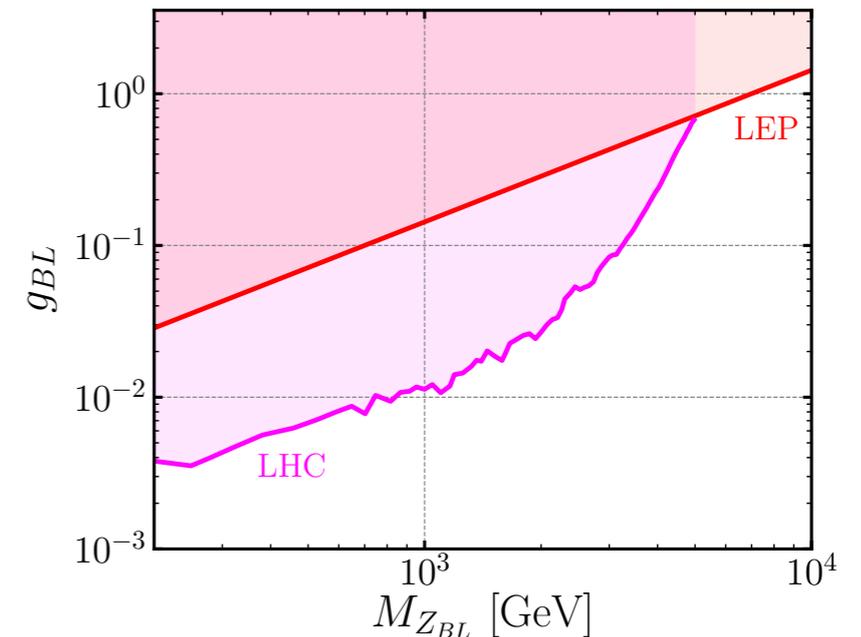
Dirac neutrinos

Unbroken $U(1)_{B-L}$

$$\cancel{U(1)_L} \Rightarrow S_L \sim (1, 1, 0, 3) \Rightarrow \Delta L = 3$$

LEP

$$\frac{M_{Z_L}}{g_L} > 7 \text{ TeV}$$



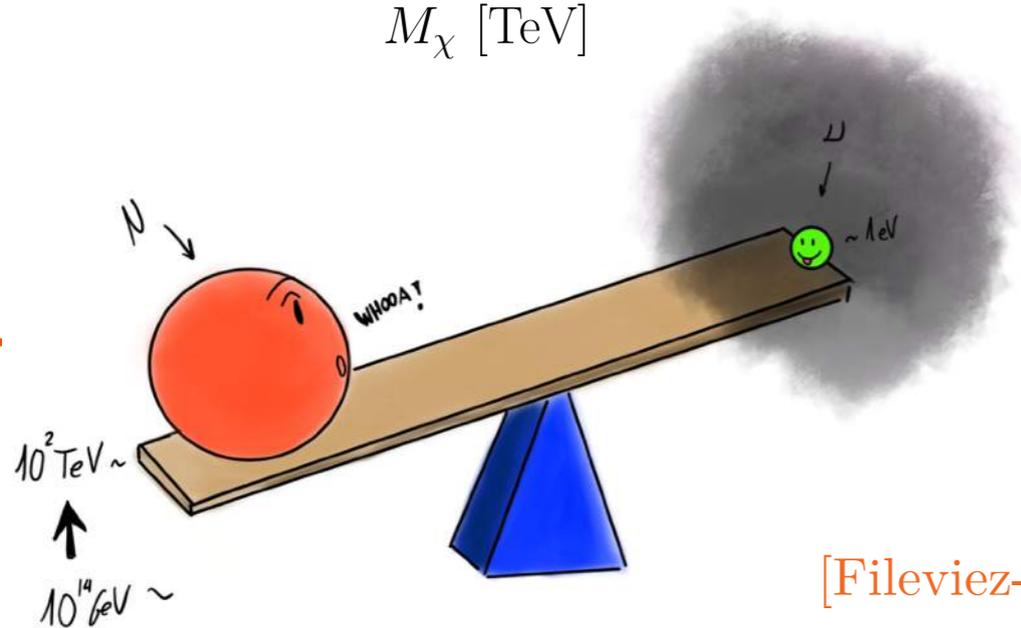
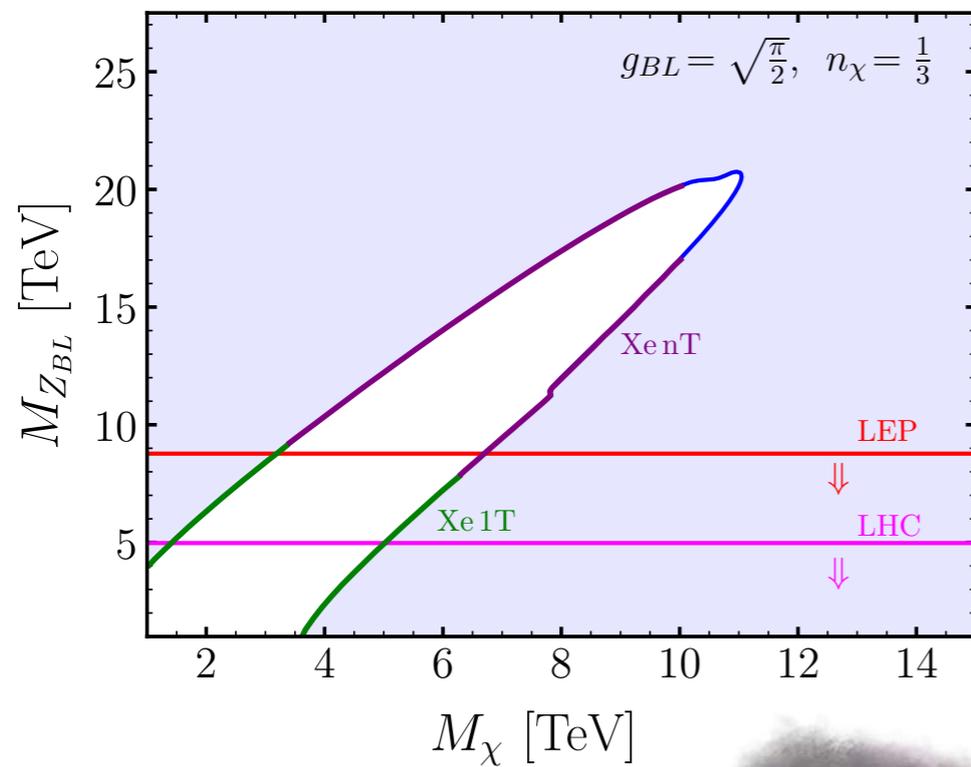
[Fileviez-Perez, C.M., 2018]

[P. Fileviez-Perez, E. Golias, C.M., R. Li, A. Plascencia, 2019] [P. Fileviez-Perez, C.M., A. Plascencia, 2019]

Within spontaneous L breaking

Majorana neutrinos

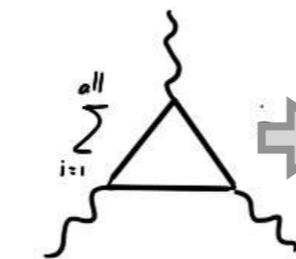
$$\cancel{U(1)_{B-L}} \Rightarrow \Delta(B-L) = 2$$



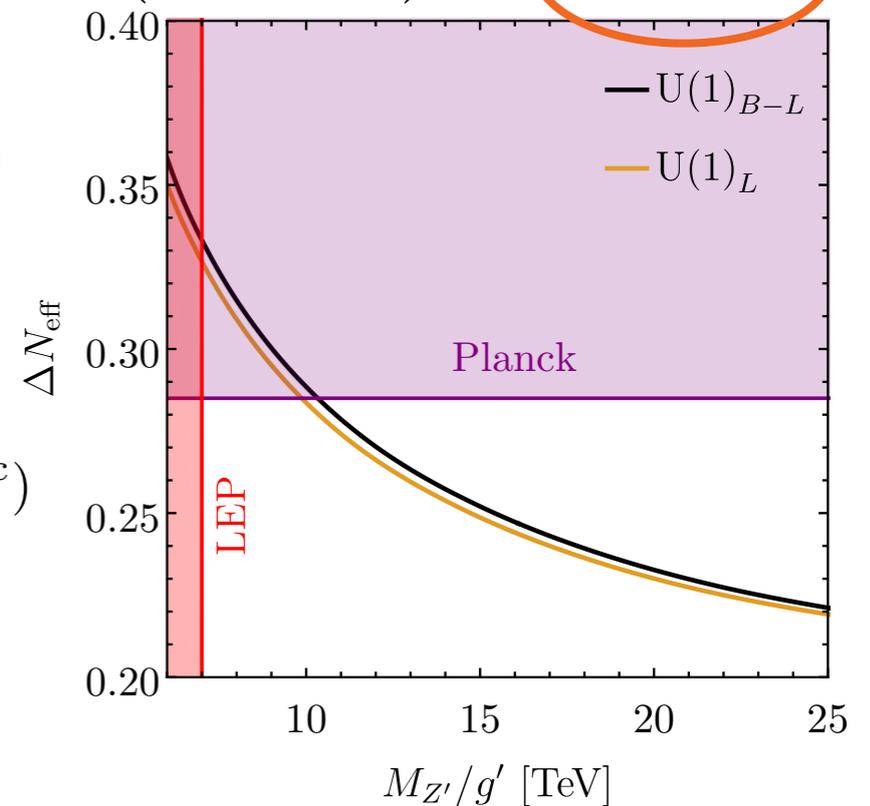
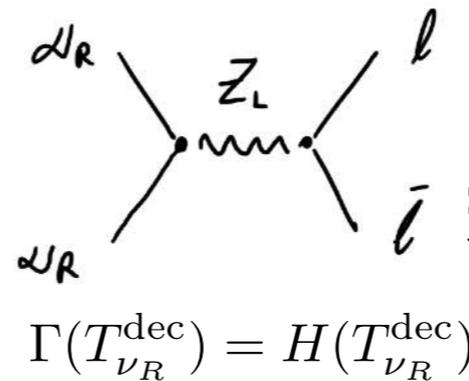
Dirac neutrinos

Unbroken $U(1)_{B-L}$

~~$U(1)_L$~~



$$S_L \sim (1, 1, 0, 3) \Rightarrow \Delta L = 3$$



$$\Delta N_{\text{eff}} < 0.285 \Rightarrow \frac{M_{Z_L}}{g_L} > 9.87 \text{ TeV}$$

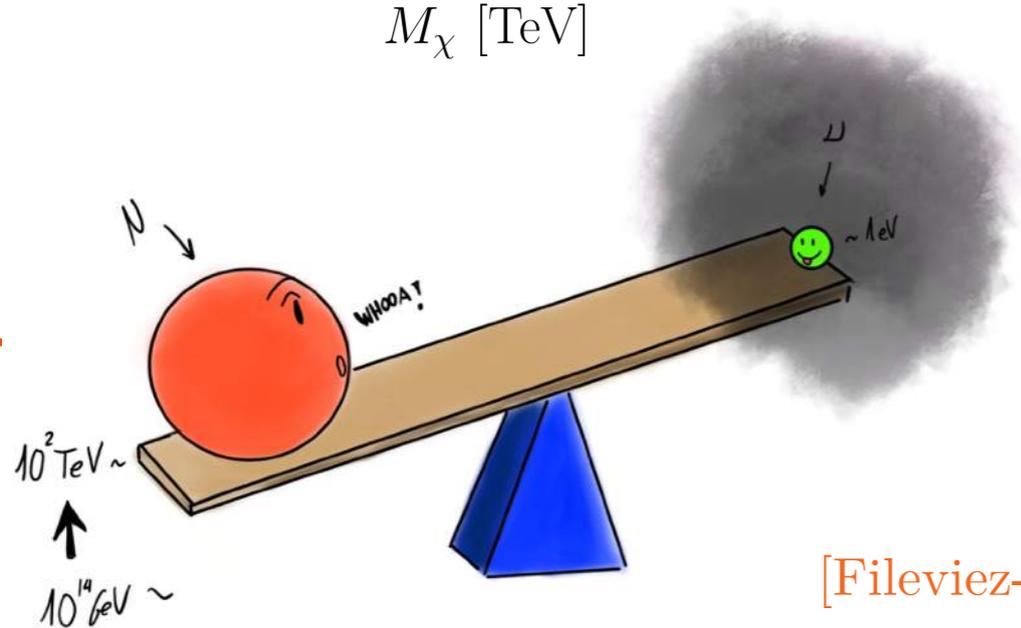
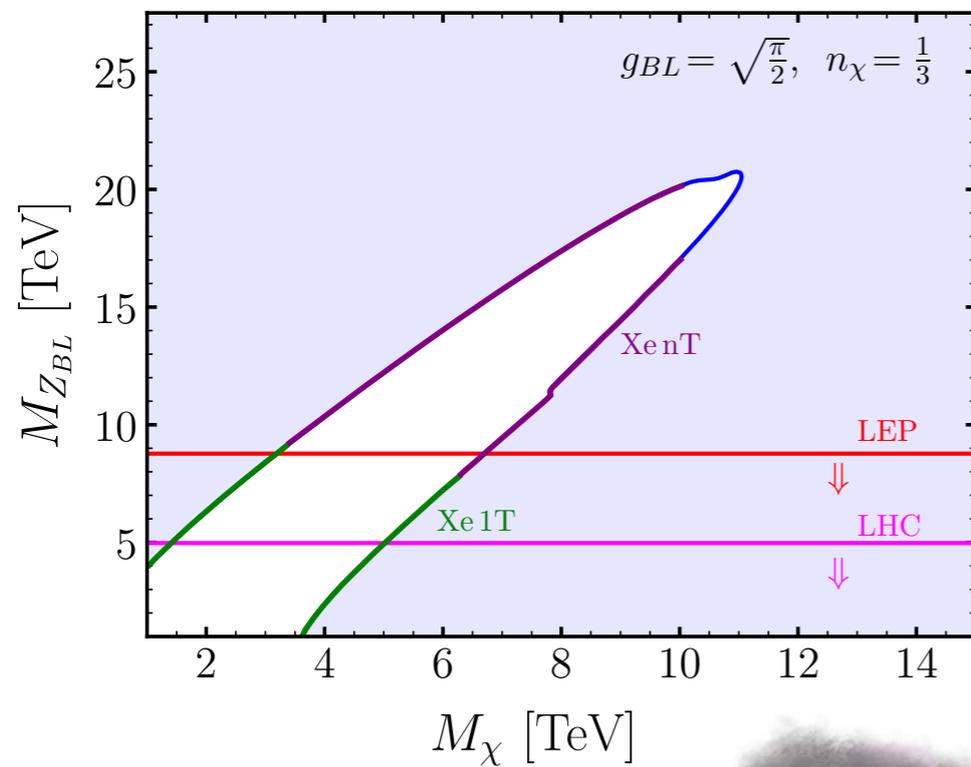
[Fileviez-Perez, C.M., 2018]

[P. Fileviez-Perez, E. Golias, C.M., R. Li, A. Plascencia, 2019] [P. Fileviez-Perez, C.M., A. Plascencia, 2019]

Within spontaneous L breaking

Majorana neutrinos

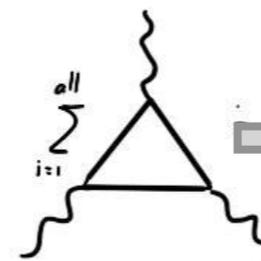
$$\cancel{U(1)_{B-L}} \Rightarrow \Delta(B-L) = 2$$



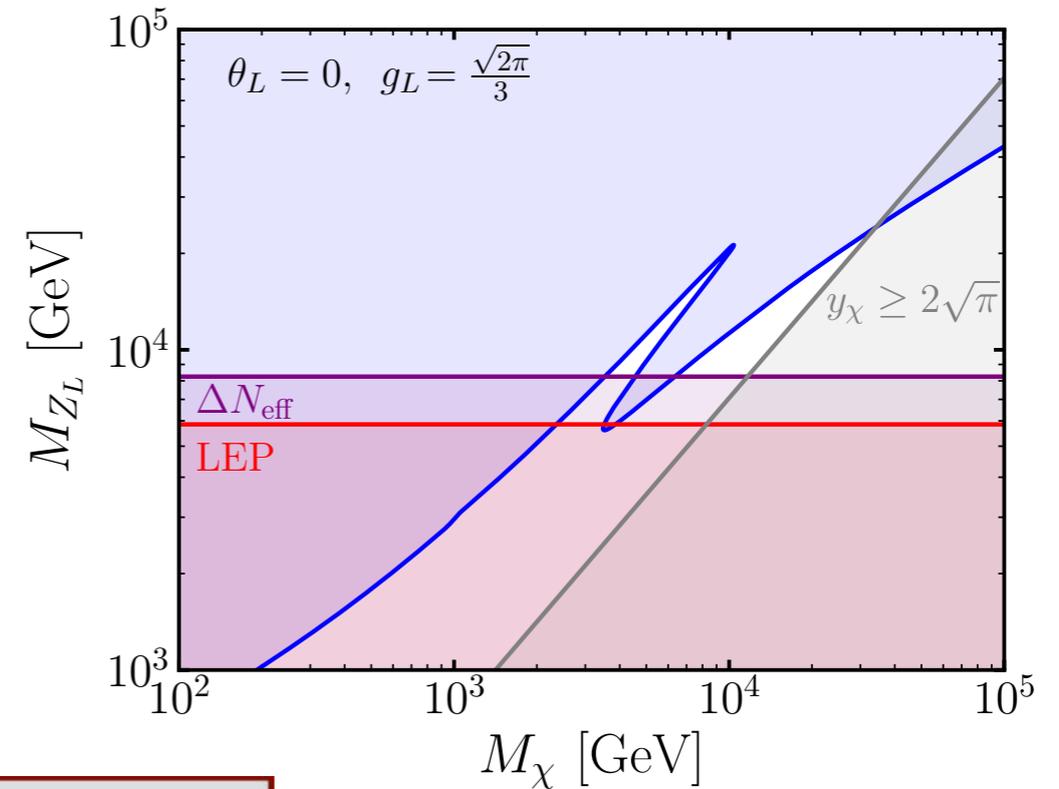
Dirac neutrinos

Unbroken $U(1)_{B-L}$

~~$U(1)_L$~~



$$S_L \sim (1, 1, 0, 3) \Rightarrow \Delta L = 3$$



CMB-S4
Next Generation CMB Experiment

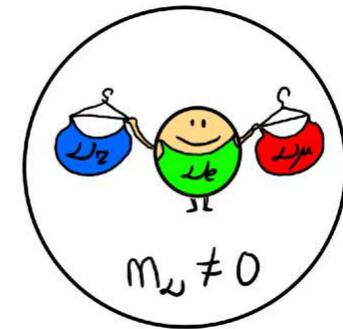
$$\Rightarrow \Delta N_{\text{eff}} < 0.06 \text{ at } 95\% \text{ C.L.}$$

[Fileviez-Perez, C.M., 2018]

[P. Fileviez-Perez, E. Golias, C.M., R. Li, A. Plascencia, 2019] [P. Fileviez-Perez, C.M., A. Plascencia, 2019]

Theories for Neutrino Masses

Within Quark-Lepton unification



Within Quark-Lepton unification

$$F_{QL} \sim (4, 2, 0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L$$

$$F_u = (u^c \quad \nu^c)_L \sim (\bar{4}, 1, -1/2)$$

$$F_d = (d^c \quad e^c)_L \sim (\bar{4}, 1, 1/2)$$

$$\mathcal{L}_Y = Y_1 F_{QL} F_u H + Y_3 H^\dagger F_{QL} F_d$$

$$M_u = Y_1 \frac{v_1}{\sqrt{2}}$$

$$M_\nu^D = Y_1 \frac{v_1}{\sqrt{2}}$$

$$M_D = Y_3 \frac{v_1}{\sqrt{2}}$$

$$M_E = Y_3 \frac{v_1}{\sqrt{2}}$$

$$H \sim (1, 2, 1/2)_{\text{SM}}$$

$$\cancel{SU(4)_c} \otimes SU(2)_L \otimes \cancel{U(1)_R} \Rightarrow SU(3)_c \otimes \cancel{SU(2)_L} \otimes \cancel{U(1)_Y} \Rightarrow SU(3)_c \otimes U(1)_Q$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Within Quark-Lepton unification

$$F_{QL} \sim (4, 2, 0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L$$

$$F_u = (u^c \quad \nu^c)_L \sim (\bar{4}, 1, -1/2)$$

$$F_d = (d^c \quad e^c)_L \sim (\bar{4}, 1, 1/2)$$

$$\mathcal{L}_Y = Y_1 F_{QL} F_u H + Y_3 H^\dagger F_{QL} F_d + Y_2 F_{QL} F_u \Phi + Y_4 \Phi^\dagger F_{QL} F_d + \text{h.c.}$$

$$M_u = Y_1 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}} \quad M_D = Y_3 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}},$$

$$M_\nu^D = Y_1 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}} \quad M_E = Y_3 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}}.$$

$$\Phi \sim (15, 2, 1/2) = \begin{pmatrix} \Phi_{\text{MW}} & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2, \quad H \sim (1, 2, 1/2)_{\text{SM}}$$

$$\cancel{SU(4)_c} \otimes SU(2)_L \otimes \cancel{U(1)_R} \Rightarrow SU(3)_c \otimes \cancel{SU(2)_L} \otimes \cancel{U(1)_Y} \Rightarrow SU(3)_c \otimes U(1)_Q$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

Within Quark-Lepton unification

- Add a fermion singlet $S \sim (1, 1, 0)$

$$-\mathcal{L}_{QL}^\nu = Y_5 F_u \chi S + \frac{1}{2} \mu S S + \text{h.c.}$$

$$\begin{aligned} & \langle \chi \rangle \\ & \Rightarrow M_\chi^D = Y_5 v_\chi / \sqrt{2} \end{aligned}$$

- Mass matrix for neutral fermions:

$$(\nu \ \nu^c \ S) \begin{pmatrix} 0 & M_\nu^D & 0 \\ (M_\nu^D)^T & 0 & M_\chi^D \\ 0 & (M_\chi^D)^T & \mu \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

$$M_\chi^D \gg M_\nu^D \gg \mu \Rightarrow m_\nu \approx \mu (M_\nu^D)^2 / (M_\chi^D)^2,$$

Within Quark-Lepton unification

- Add a fermion singlet $S \sim (1, 1, 0)$ Protected by fermion symmetry

$$-\mathcal{L}_{QL}^\nu = Y_5 F_u \chi S + \frac{1}{2} \mu S S + \text{h.c.}$$

$$\langle \chi \rangle \Rightarrow M_\chi^D = Y_5 v_\chi / \sqrt{2}$$

- Mass matrix for neutral fermions:

$$(\nu \ \nu^c \ S) \begin{pmatrix} 0 & \text{EW} & 0 \\ \text{EW} & 0 & \text{LQ} \\ 0 & \text{LQ} & \mu \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

$$M_\chi^D \gg M_\nu^D \gg \mu \Rightarrow m_\nu \approx \mu \text{EW} / \text{LQ}$$

Within Quark-Lepton unification

$$\Phi \sim (15, 2, 1/2) = \begin{pmatrix} \Phi_{\text{MW}} & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2, \quad H \sim (1, 2, 1/2)_{\text{SM}}$$

$$M_u = Y_1 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}}$$

$$M_\nu^D = Y_1 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}}$$

No need for $\langle \chi \rangle$ to be large!!

[P. Fileviez Perez and M. B. Wise 2013]

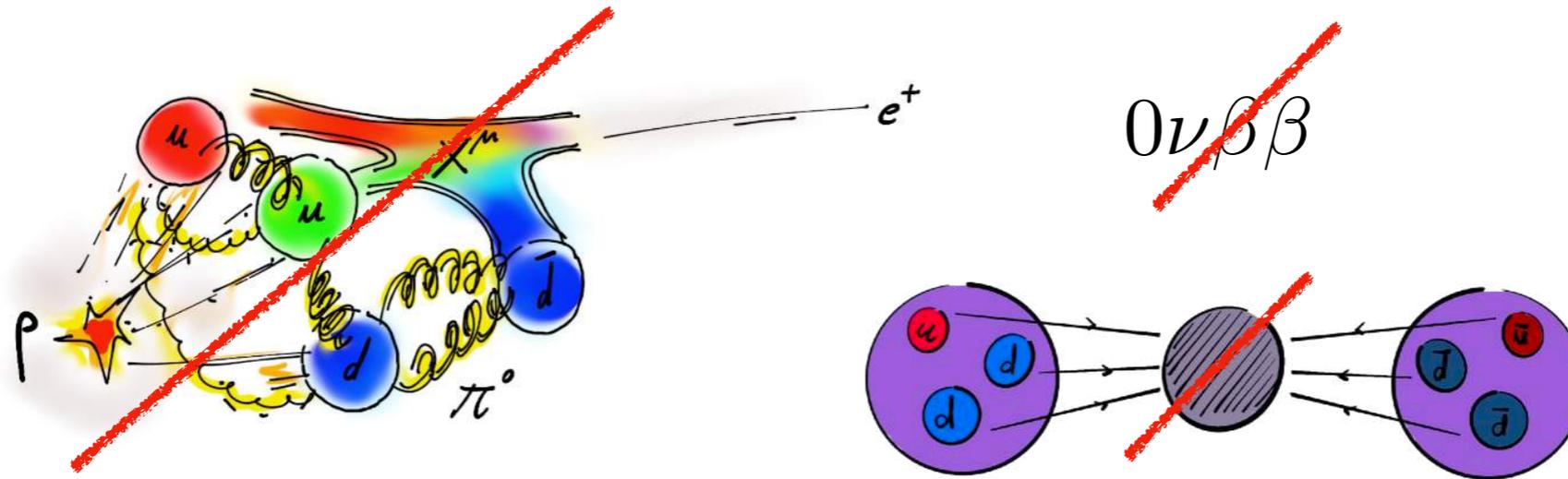
Inverse seesaw

$$(\nu \ \nu^c \ S) \begin{pmatrix} 0 & \text{EW} & 0 \\ \text{EW} & 0 & \text{LQ} \\ 0 & \text{LQ} & \mu \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

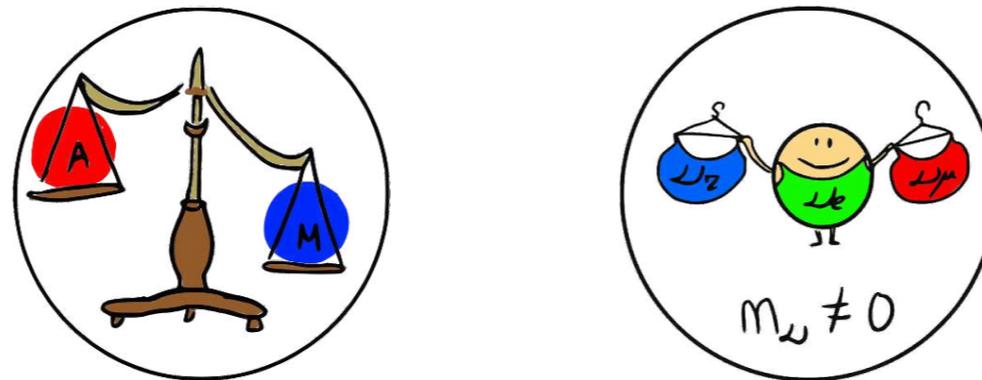
$$M_\chi^D \gg M_\nu^D \gg \mu \Rightarrow m_\nu \approx \mu \text{EW} / \text{LQ}$$

Summary

⇒ B and L are classical symmetries predicted by the SM which seem to be consistent with experiment.

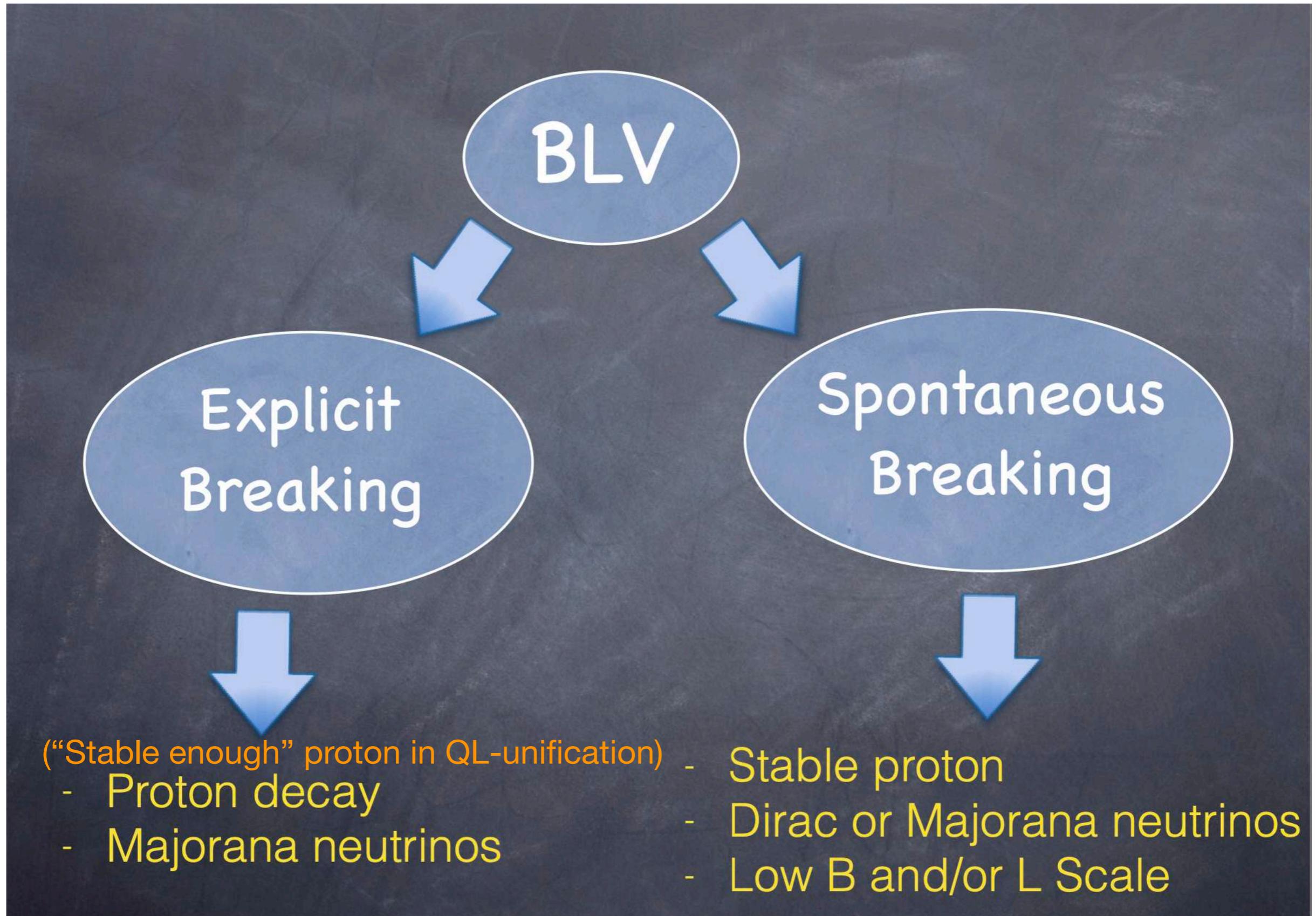


⇒ B and L are connected to fundamental questions of Nature.



⇒ Understanding how they are broken is of utmost importance.

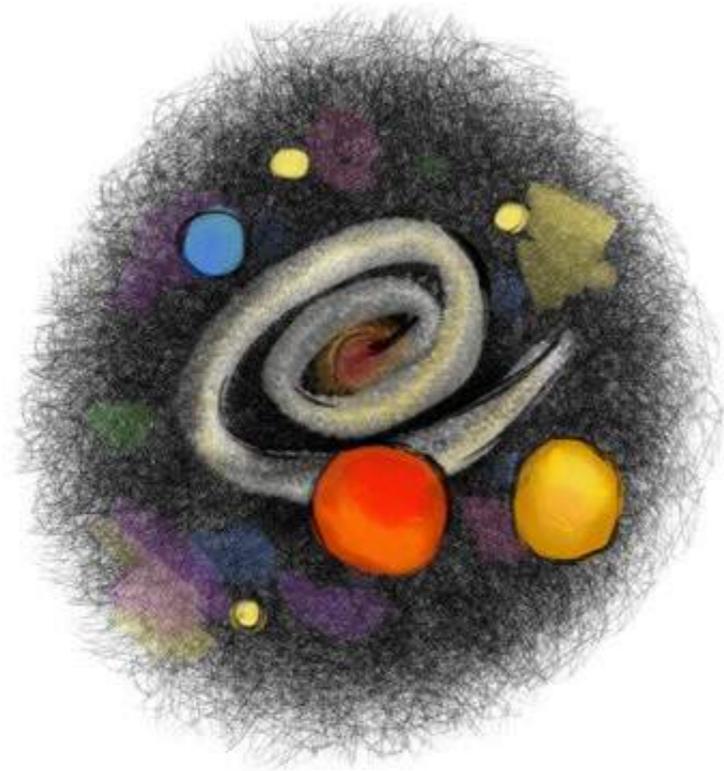
[borrowed from Pavel's talk]



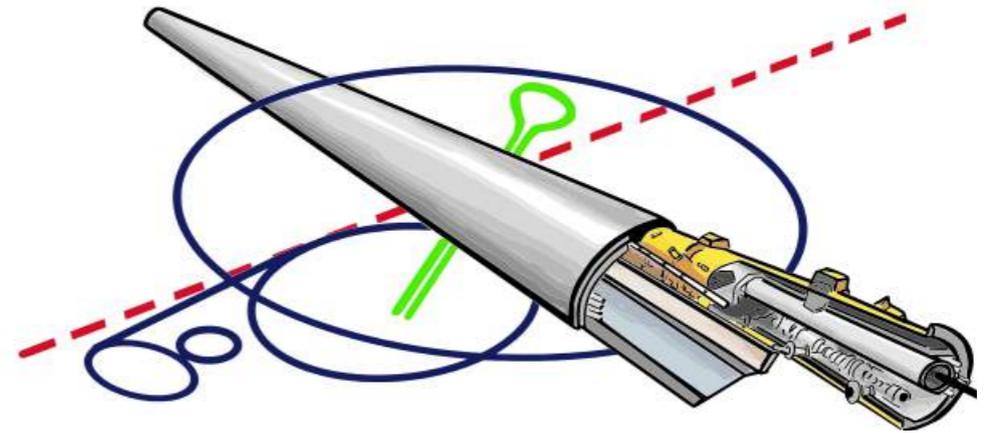
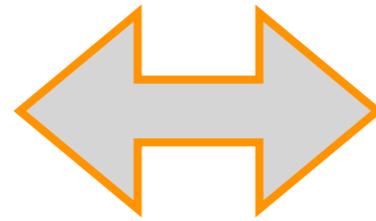
Thank you!

Back-up slides

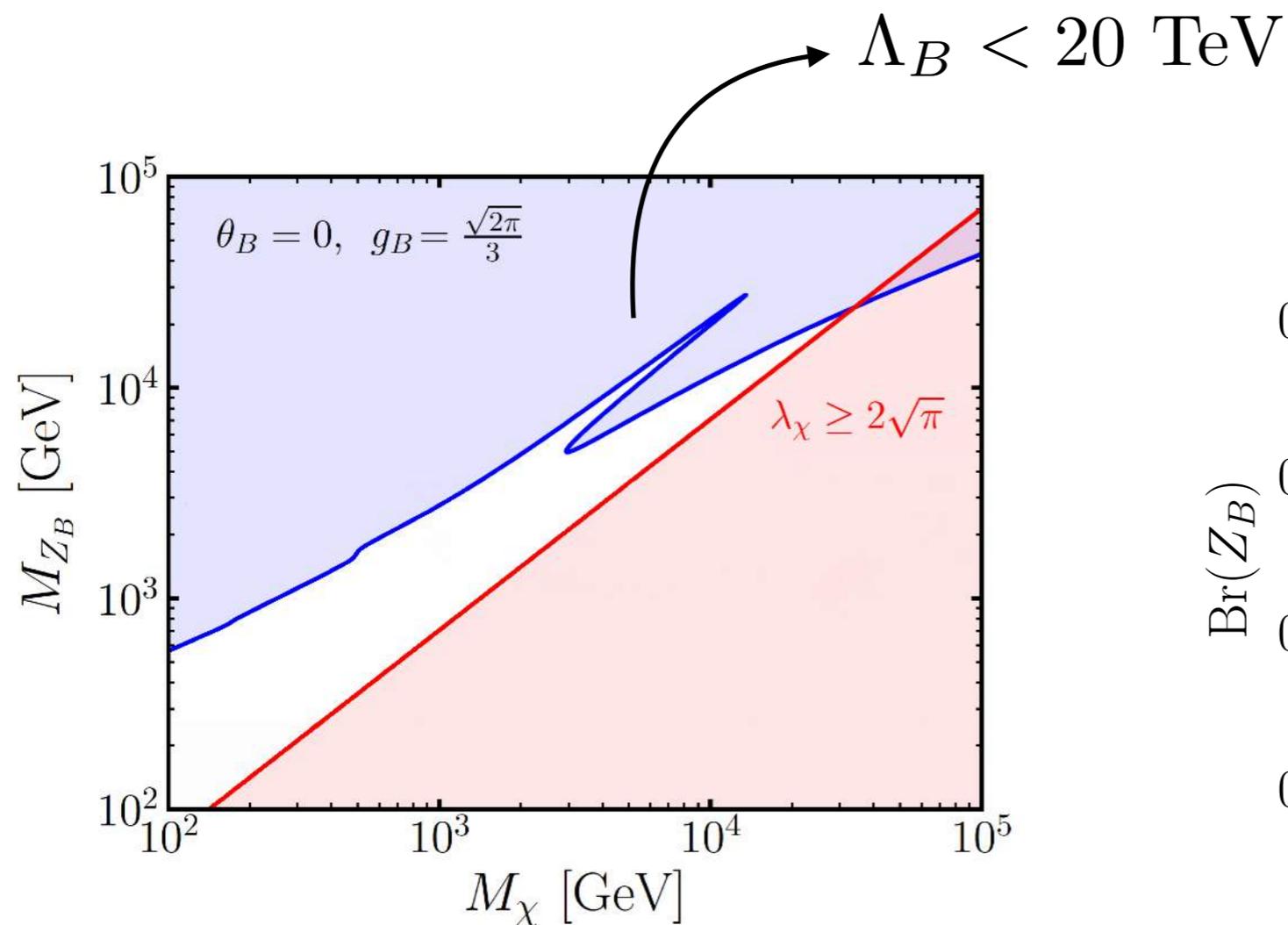
Exploiting the connection DM - colliders



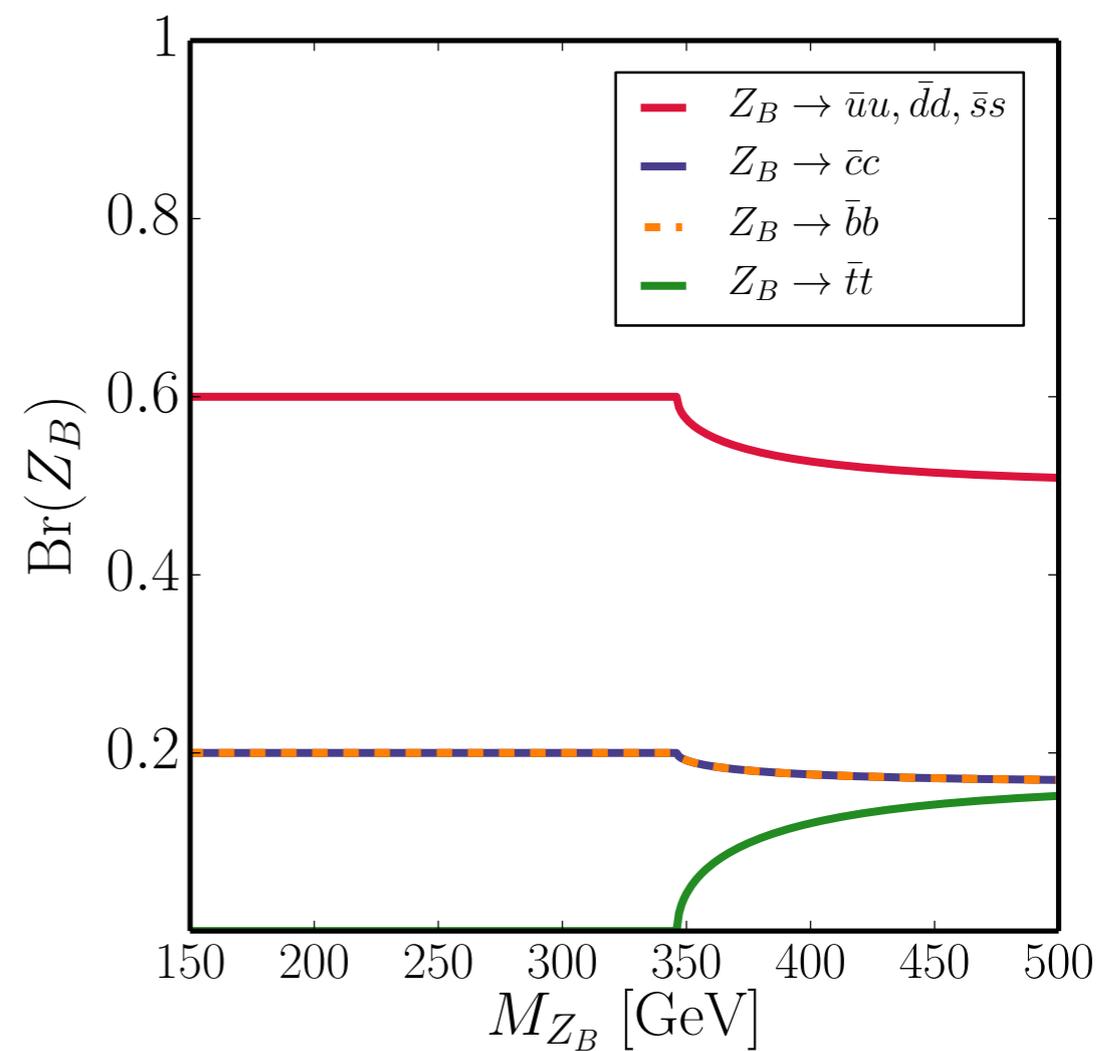
$U(1)_B$



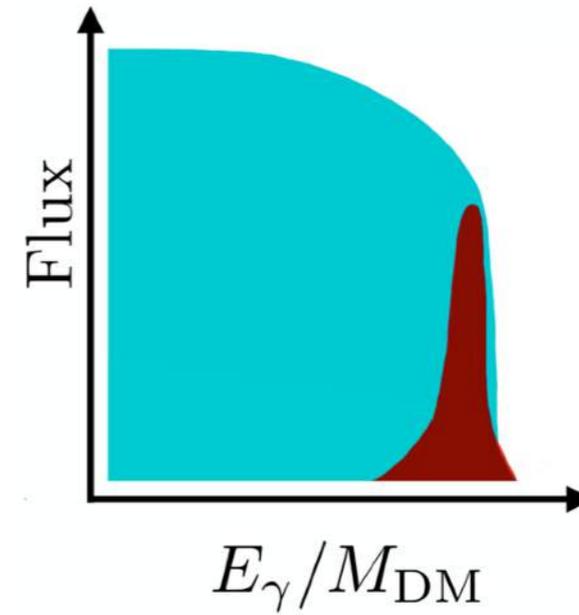
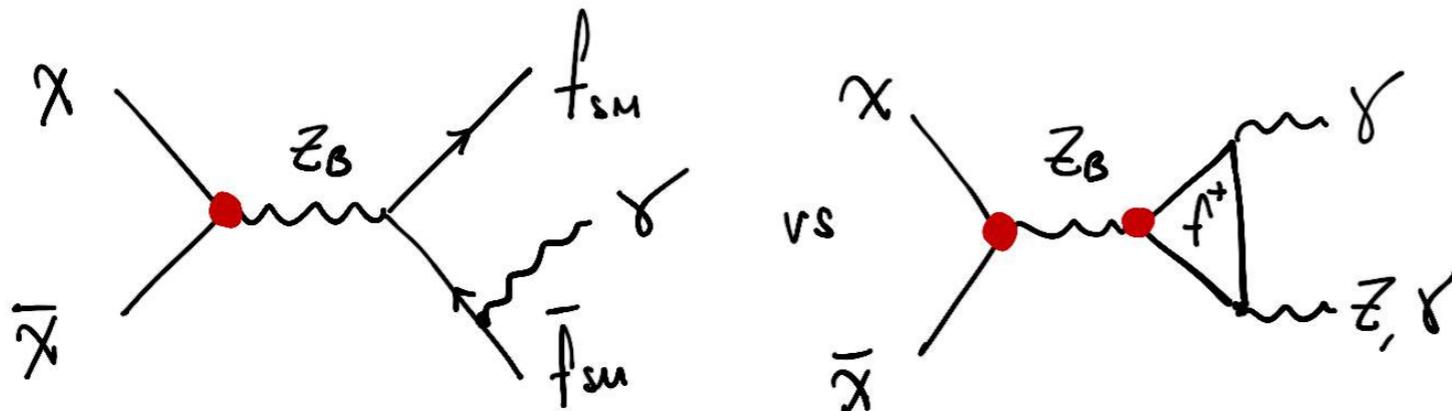
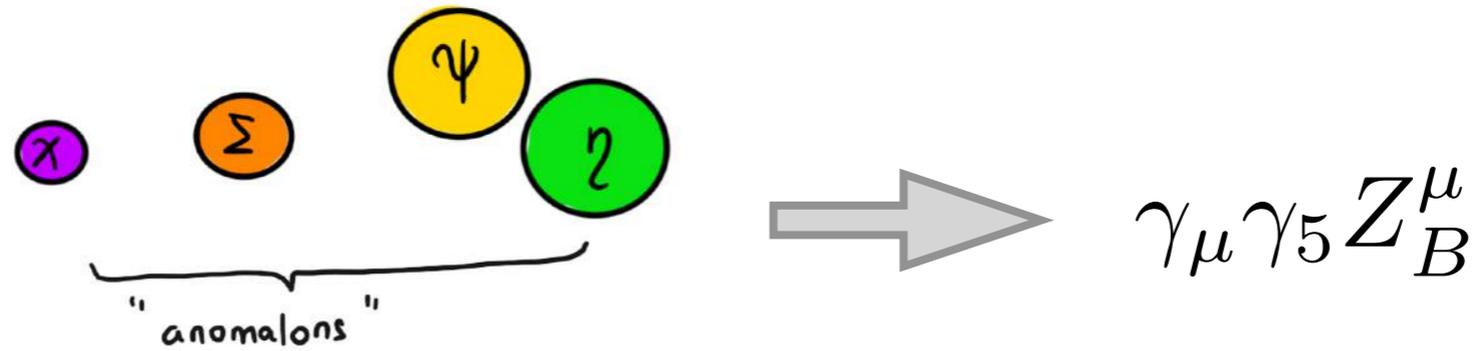
Exploiting the connection DM - colliders



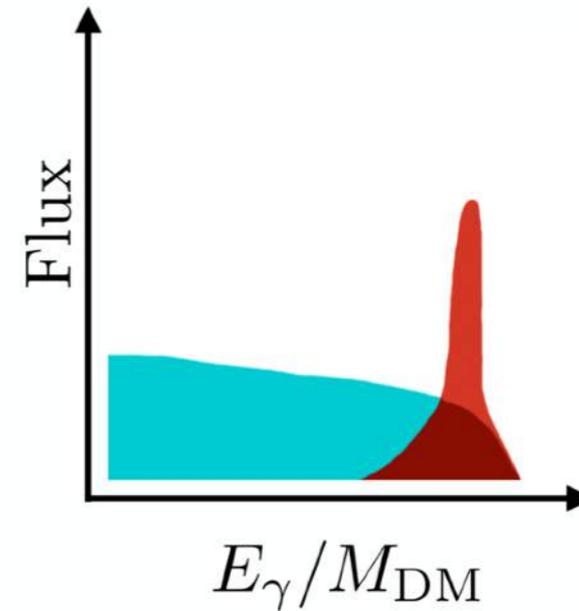
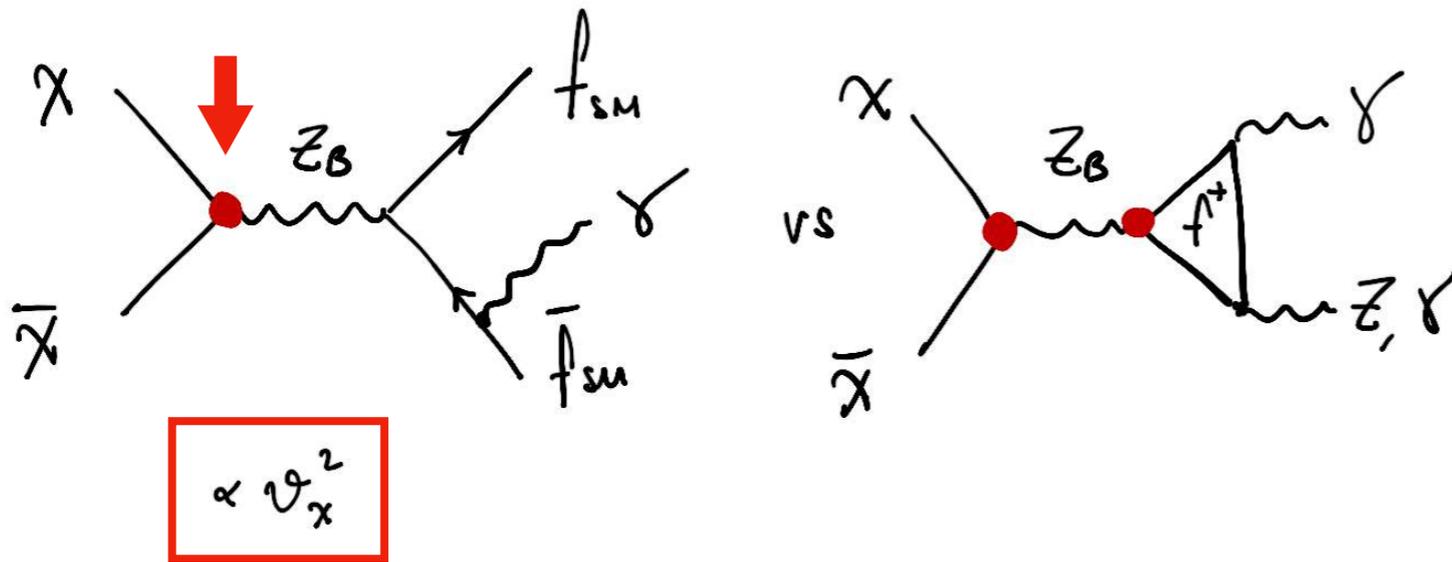
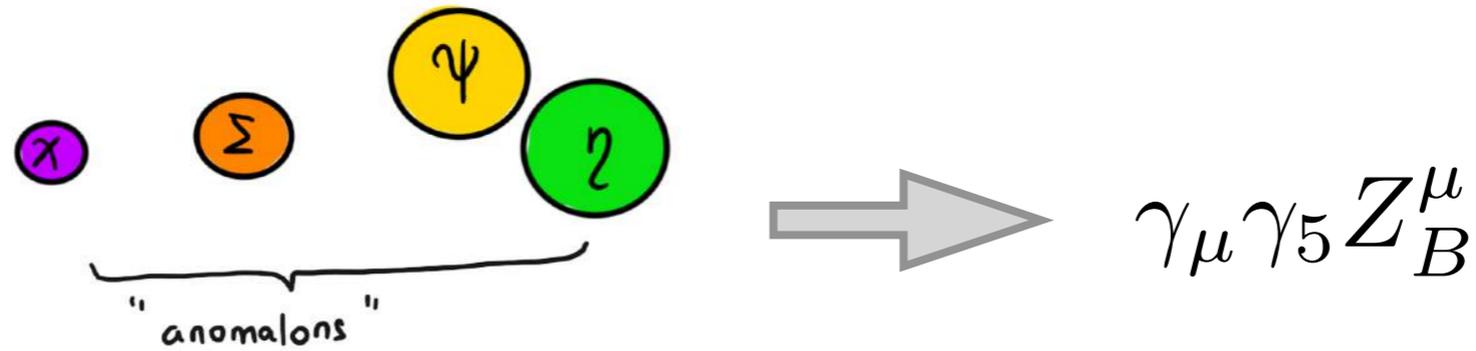
$\Rightarrow Z_B \not\rightarrow \bar{\chi}\chi, \bar{F}F$



Indirect searches

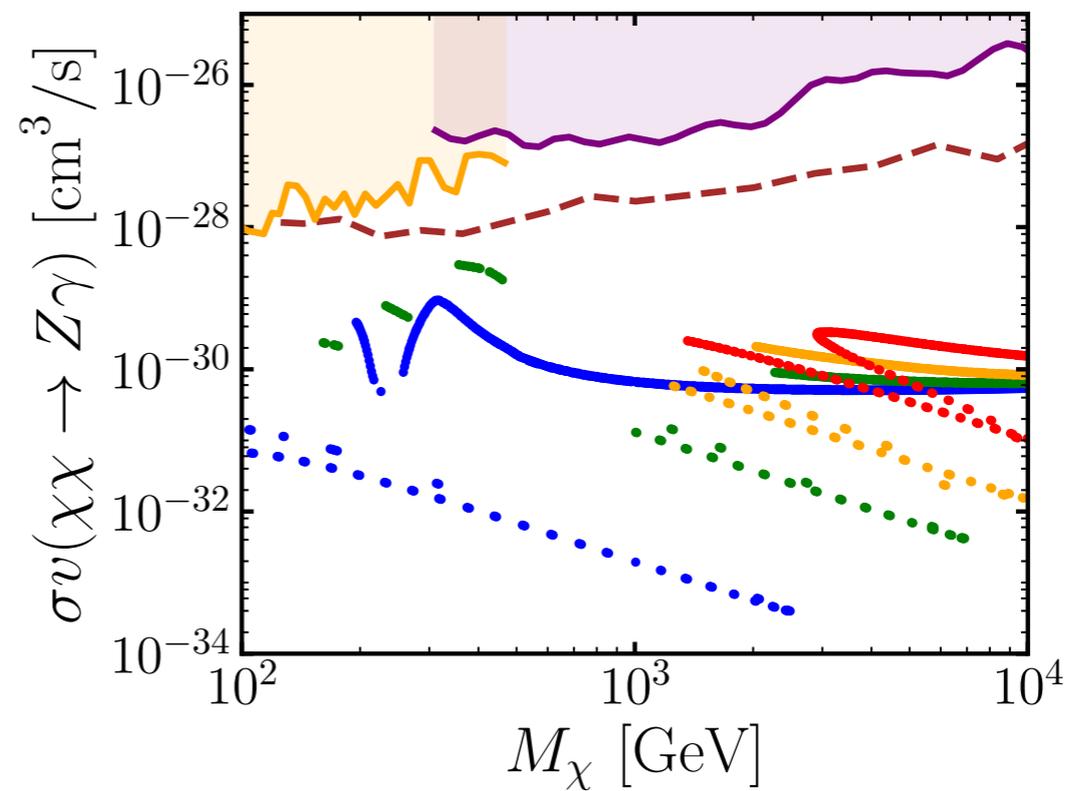
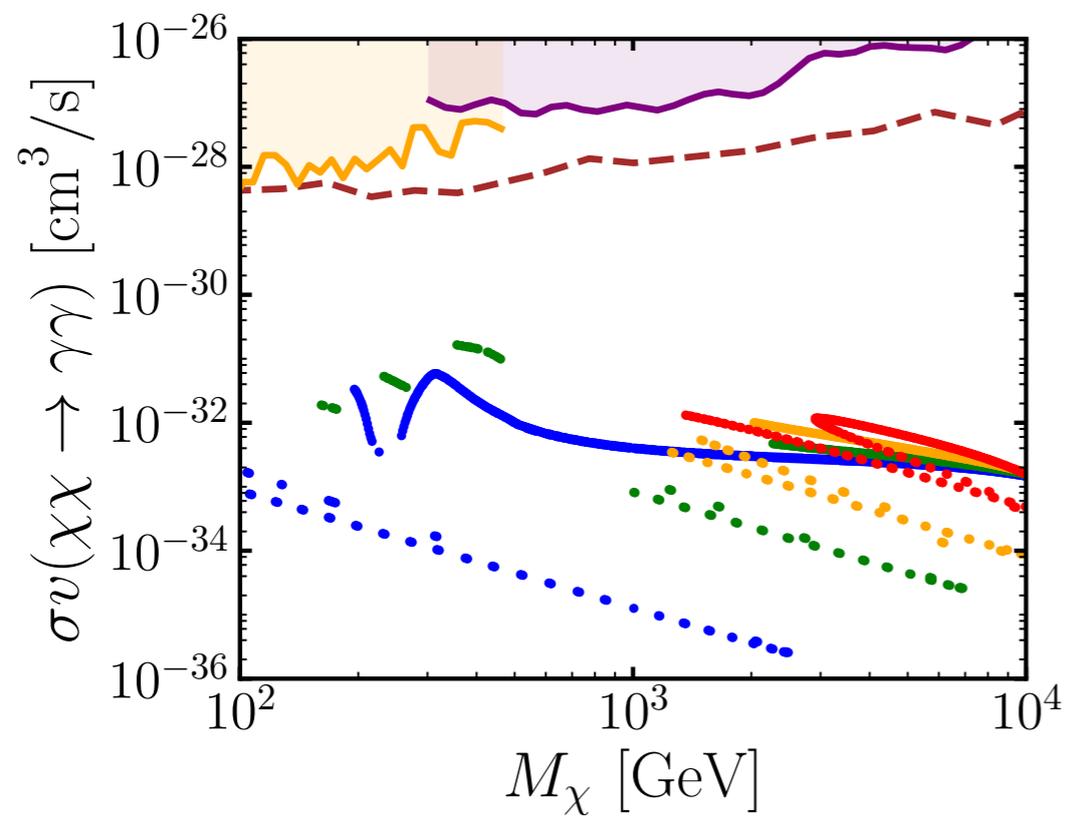


Indirect searches

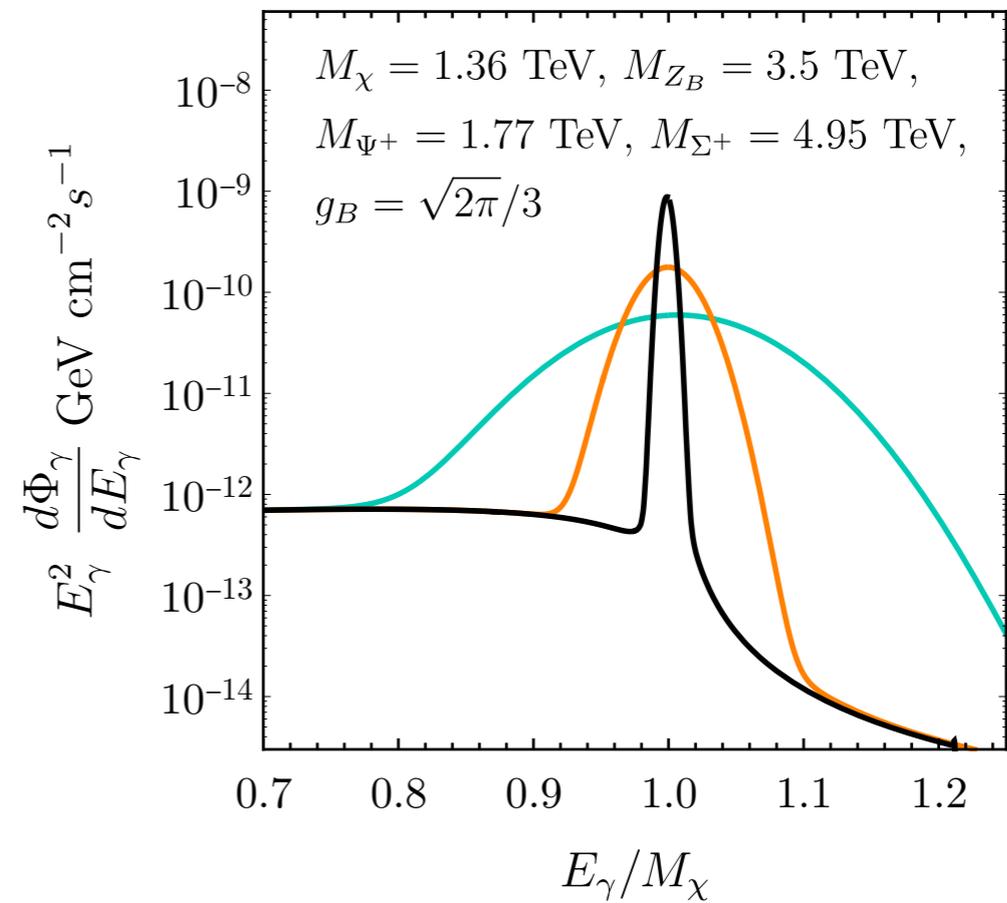
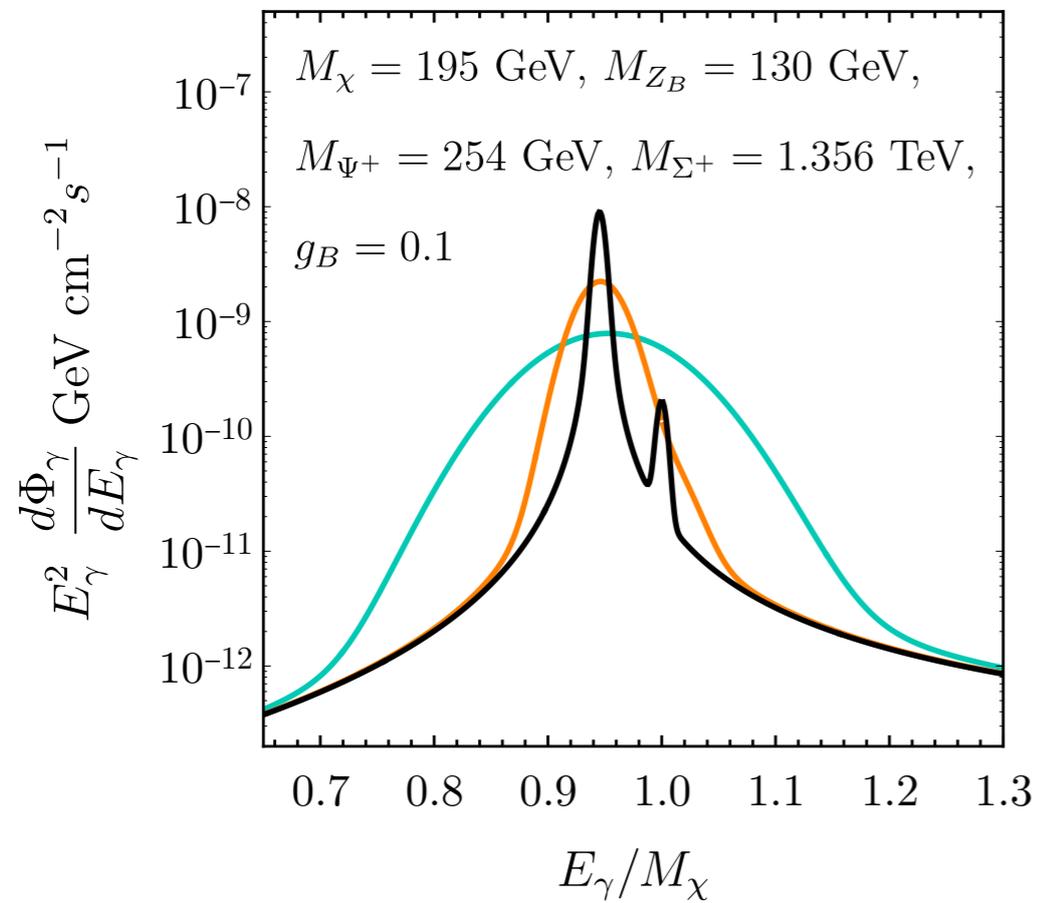


$$|\mathcal{M}|_{\text{FSR}}^2 = \frac{M_q^2}{M_{Z_B}^2} A + v^2 B + \mathcal{O}(v^4)$$

Indirect searches

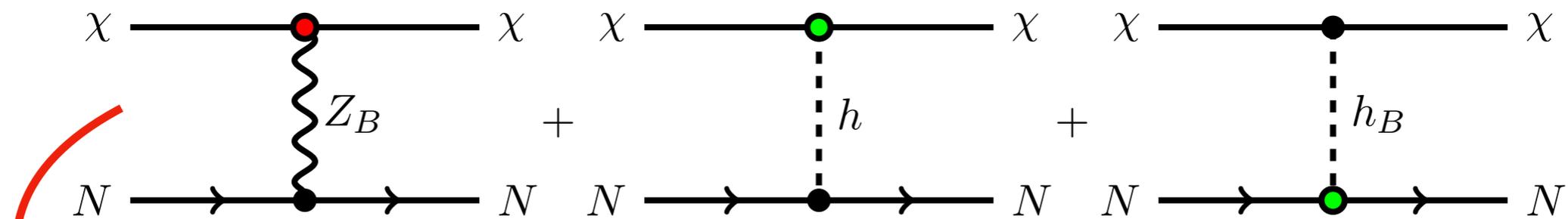
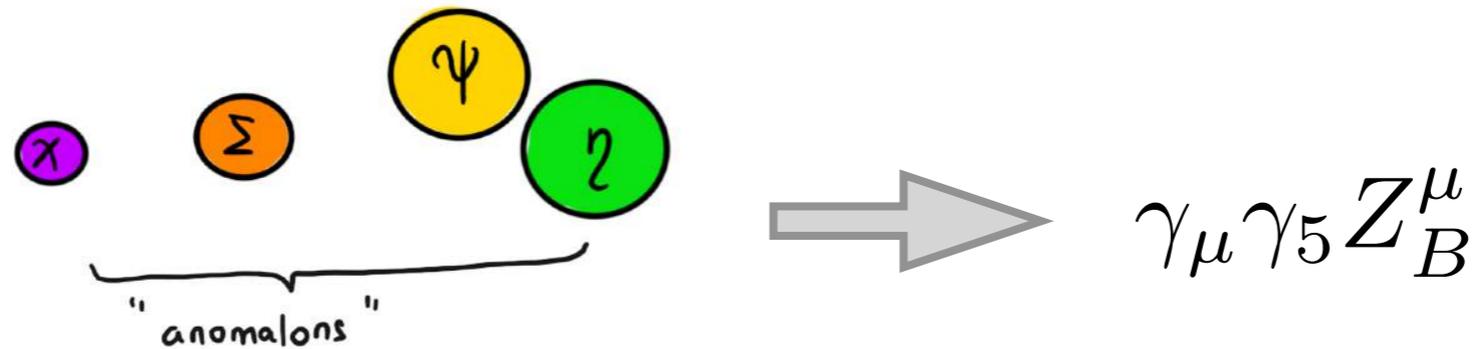


Indirect searches



— $\xi = 0.15$ — $\xi = 0.05$ — $\xi = 0.01$

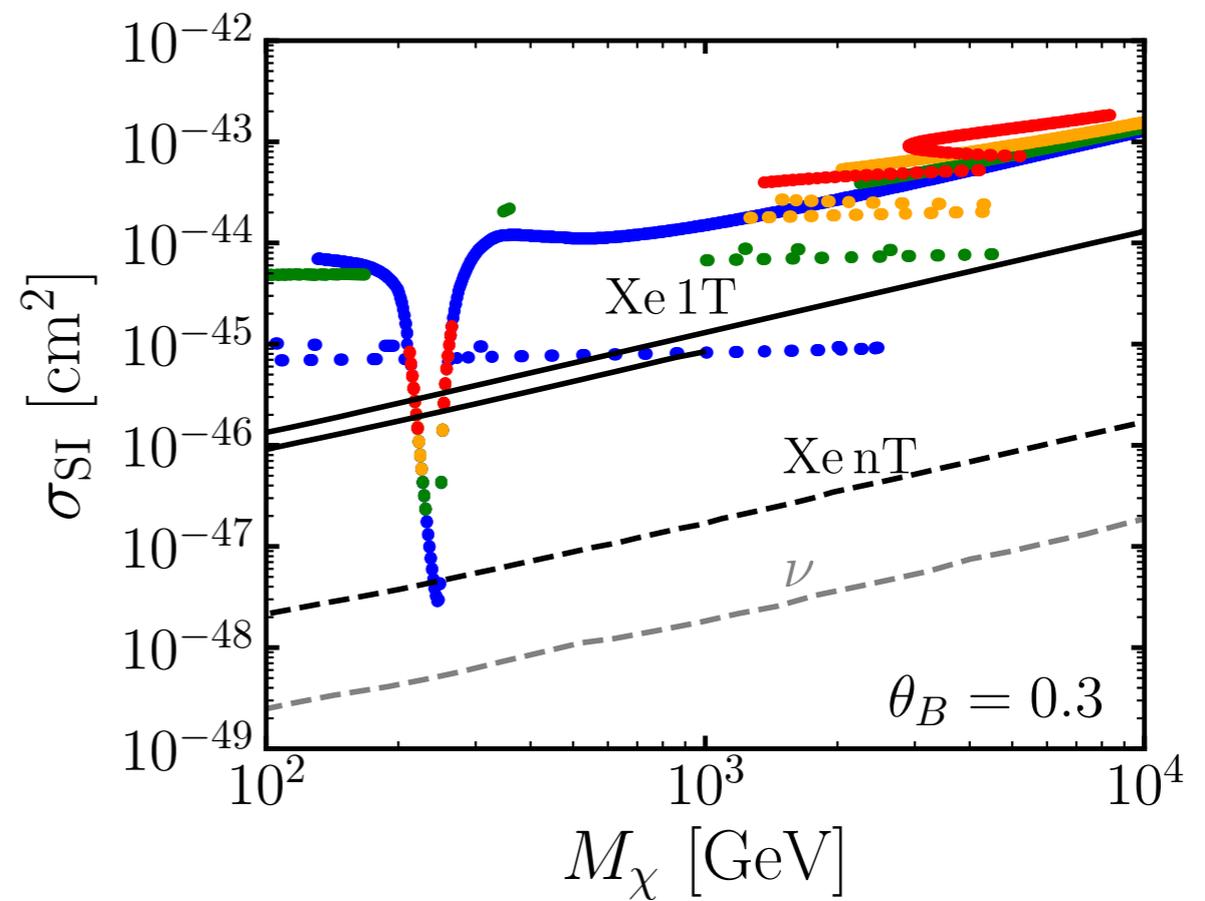
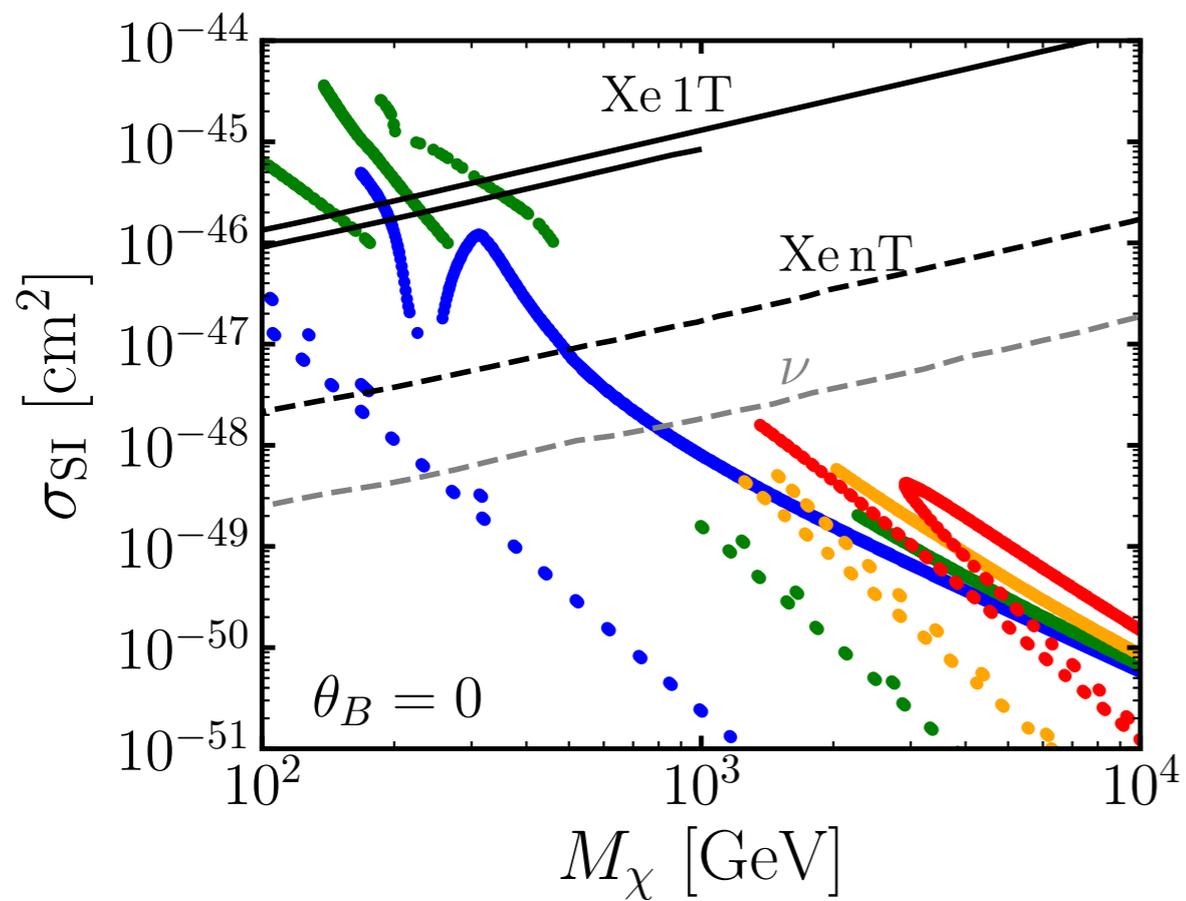
Direct searches



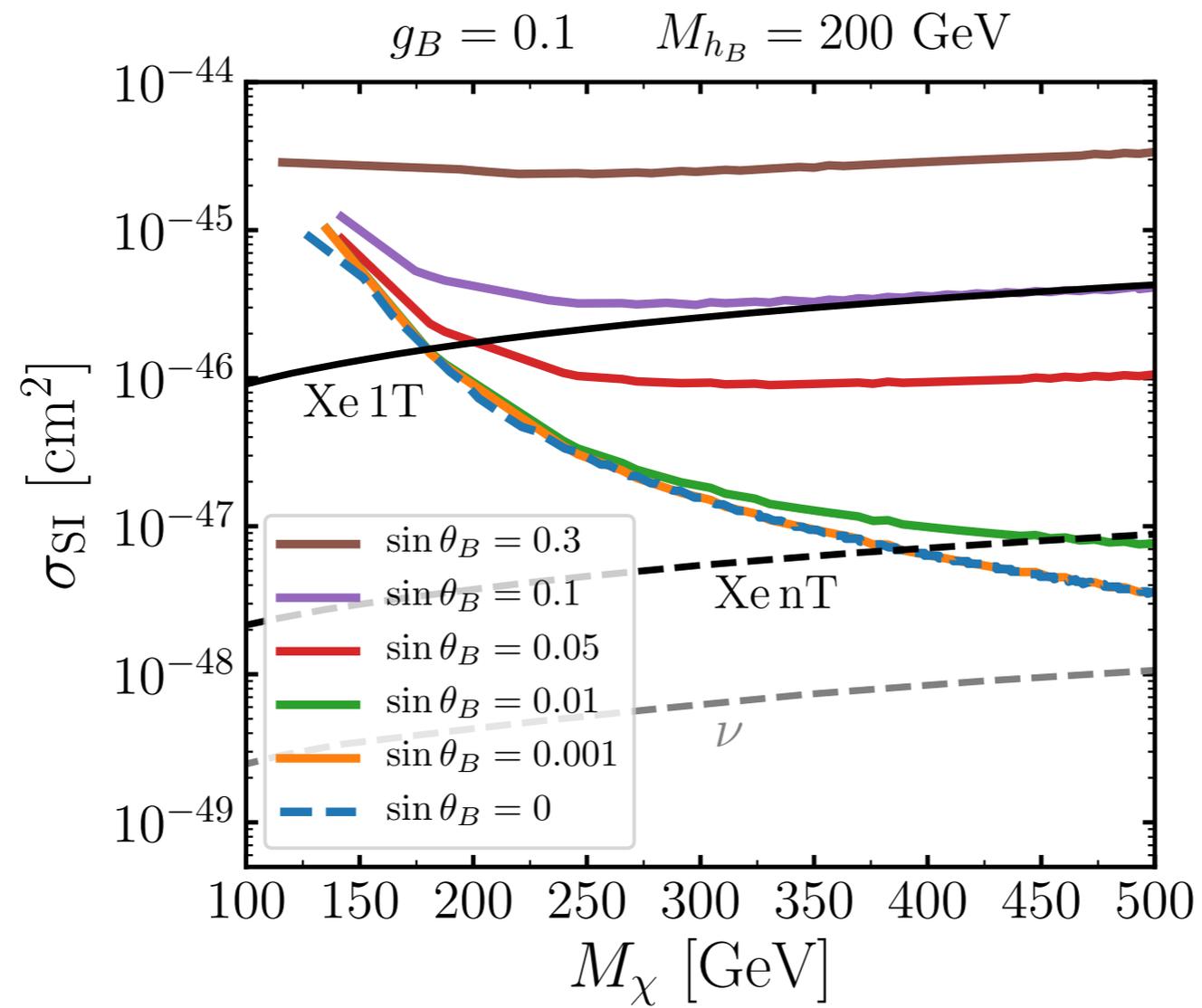
$$\sigma_{\chi N}^{\text{SI}}(Z_B) = \frac{27}{8\pi} \frac{g_B^4 M_N^2}{M_{Z_B}^4} v^2$$

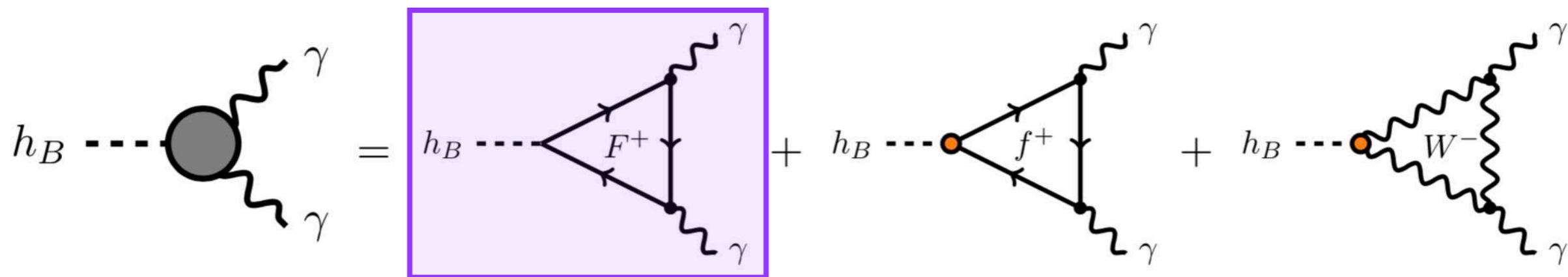
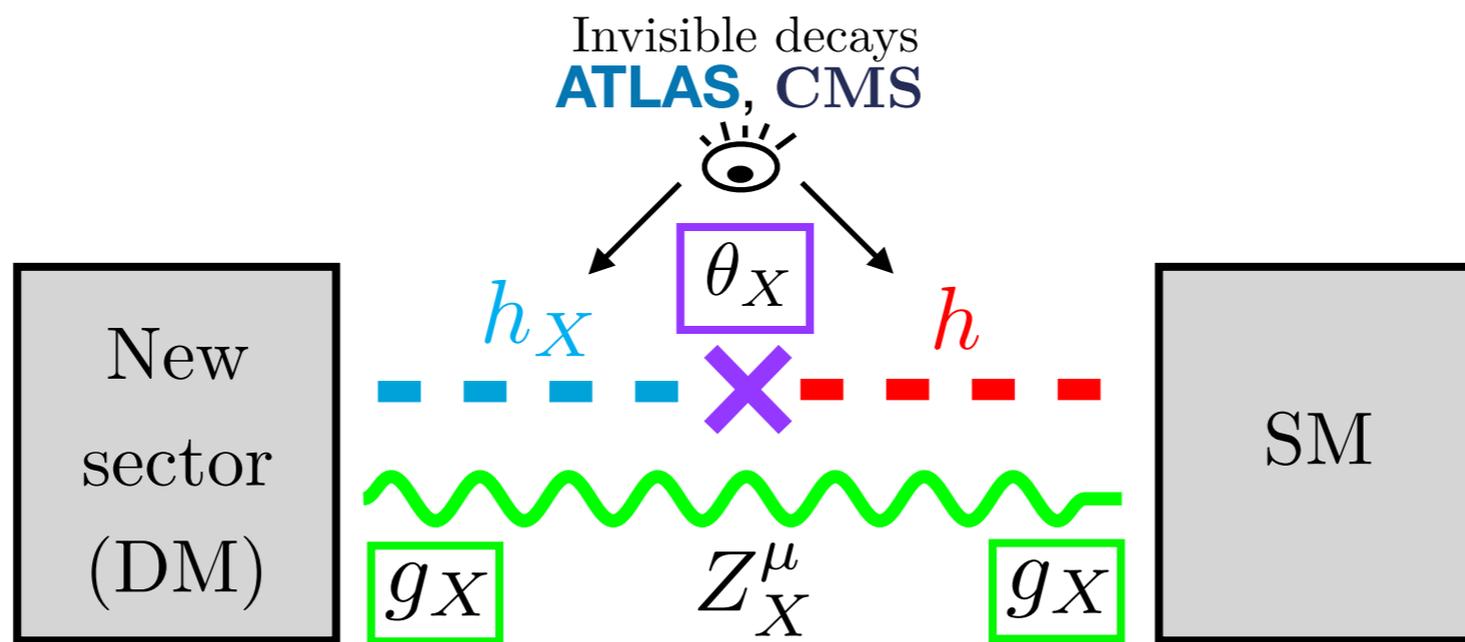
$$\sigma_{\chi N}^{\text{SI}}(h_i) = \frac{72 G_F}{16\pi\sqrt{2}} \sin^2(2\theta_B) M_N^4 \frac{g_B^2 M_\chi^2}{M_{Z_B}^2} \left(\frac{1}{M_{h_1}^2} - \frac{1}{M_{h_2}^2} \right)^2 f_N^2$$

Direct searches

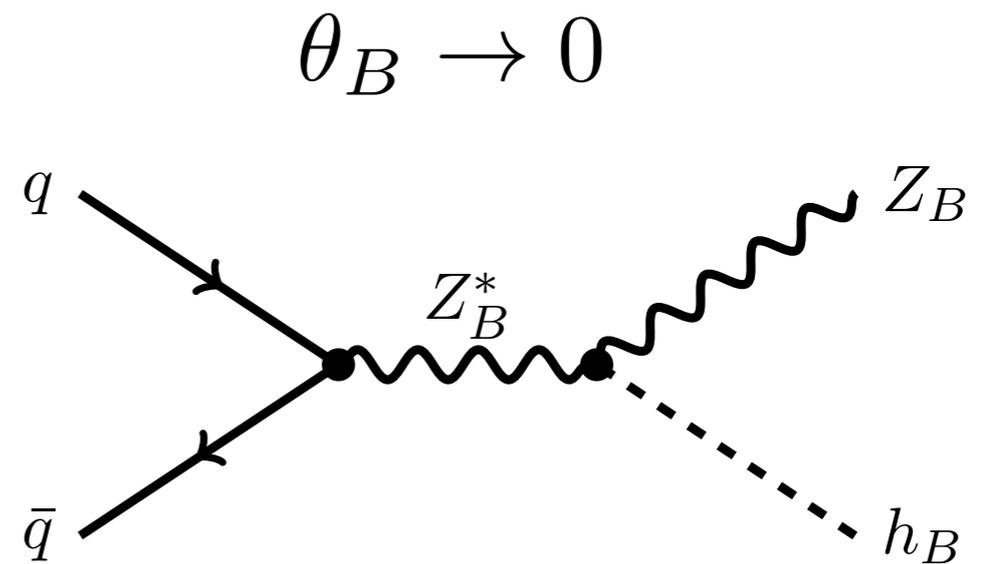
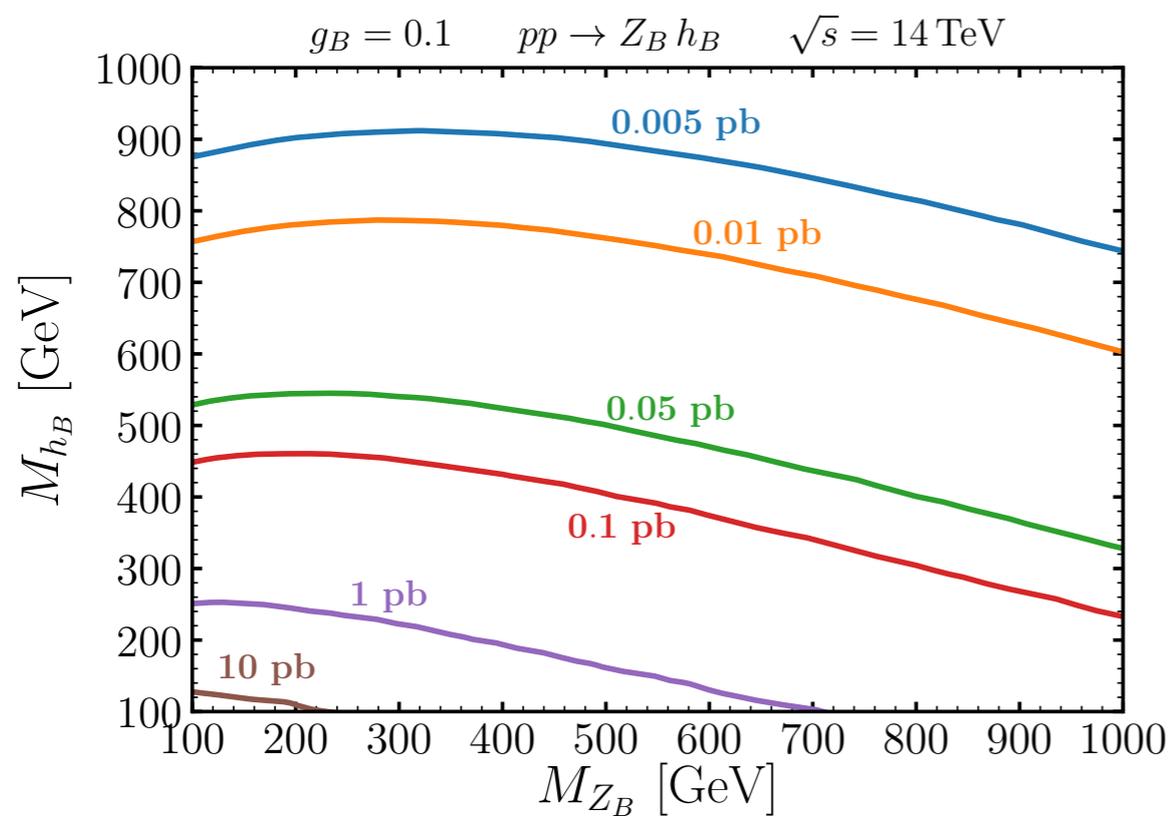
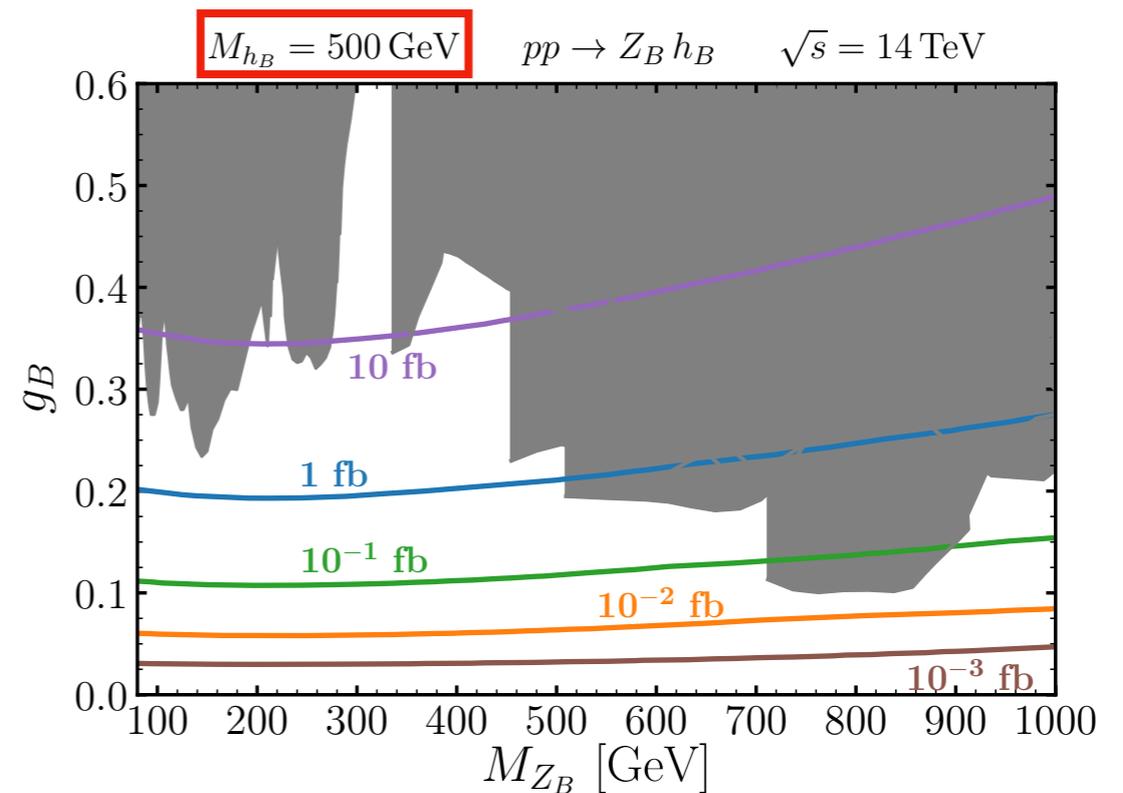
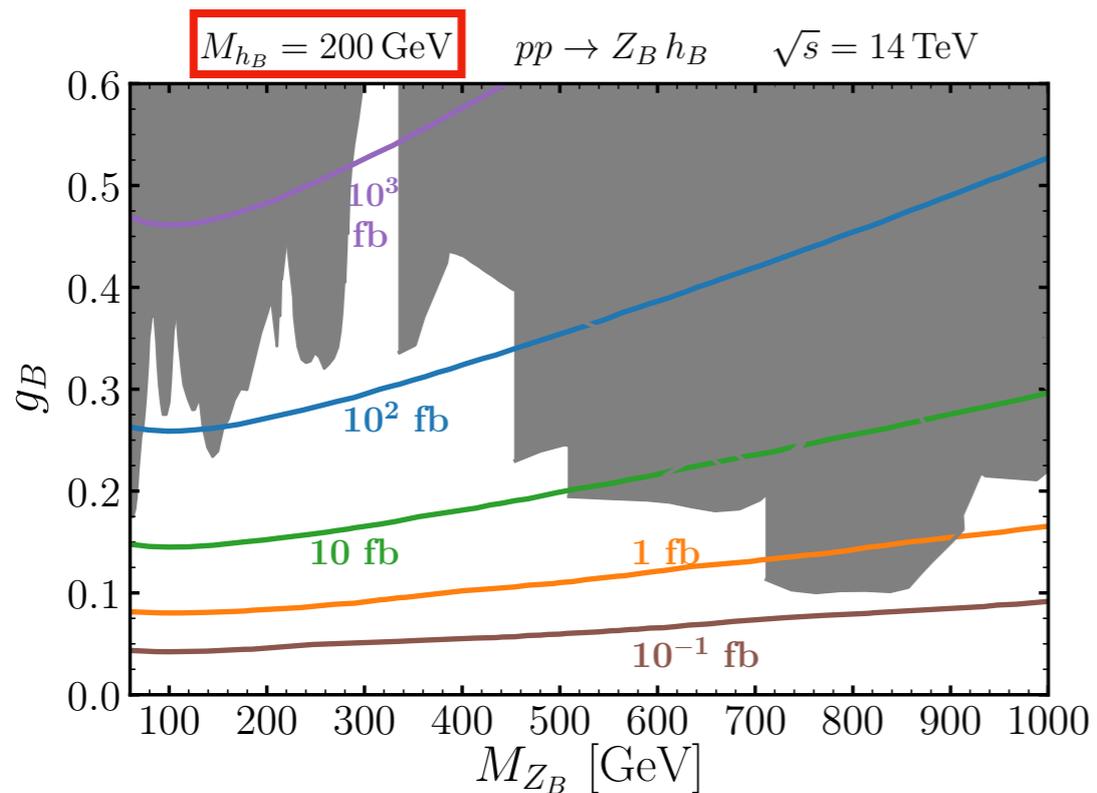


Direct searches

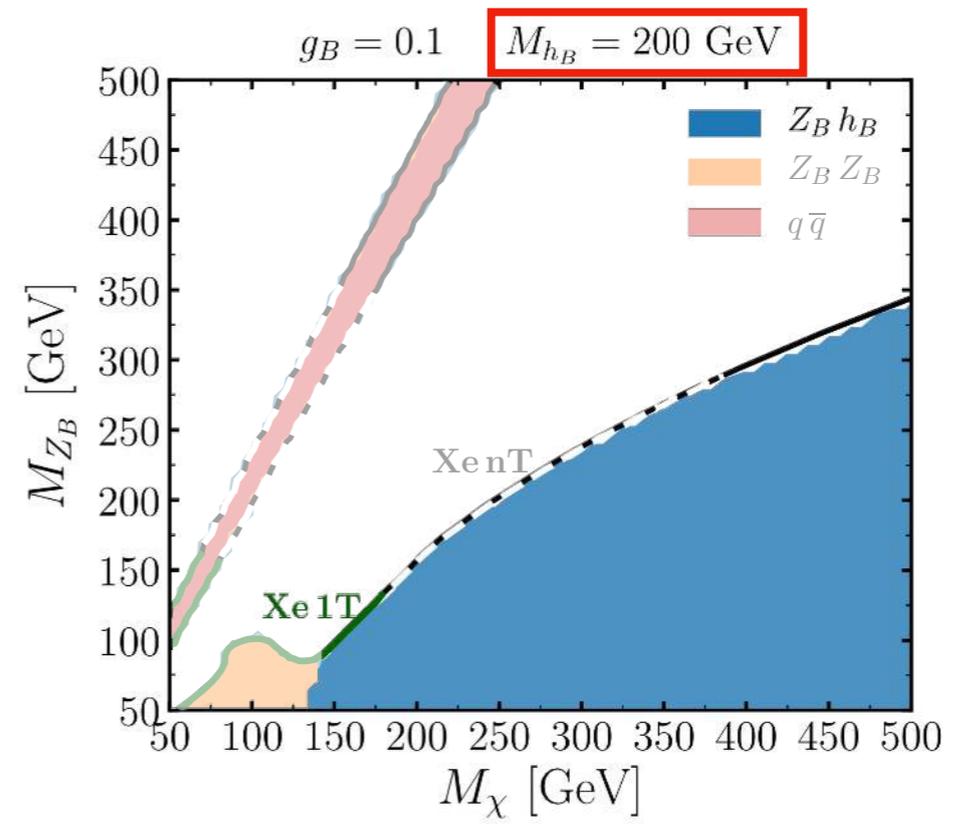
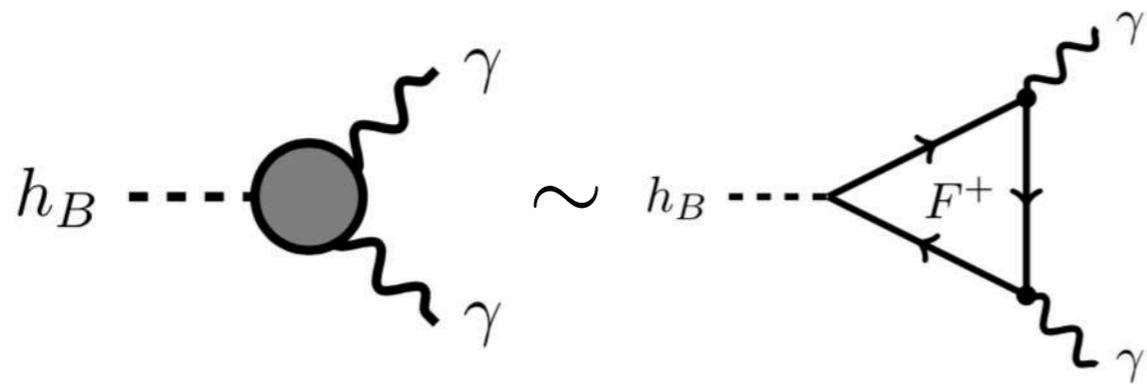




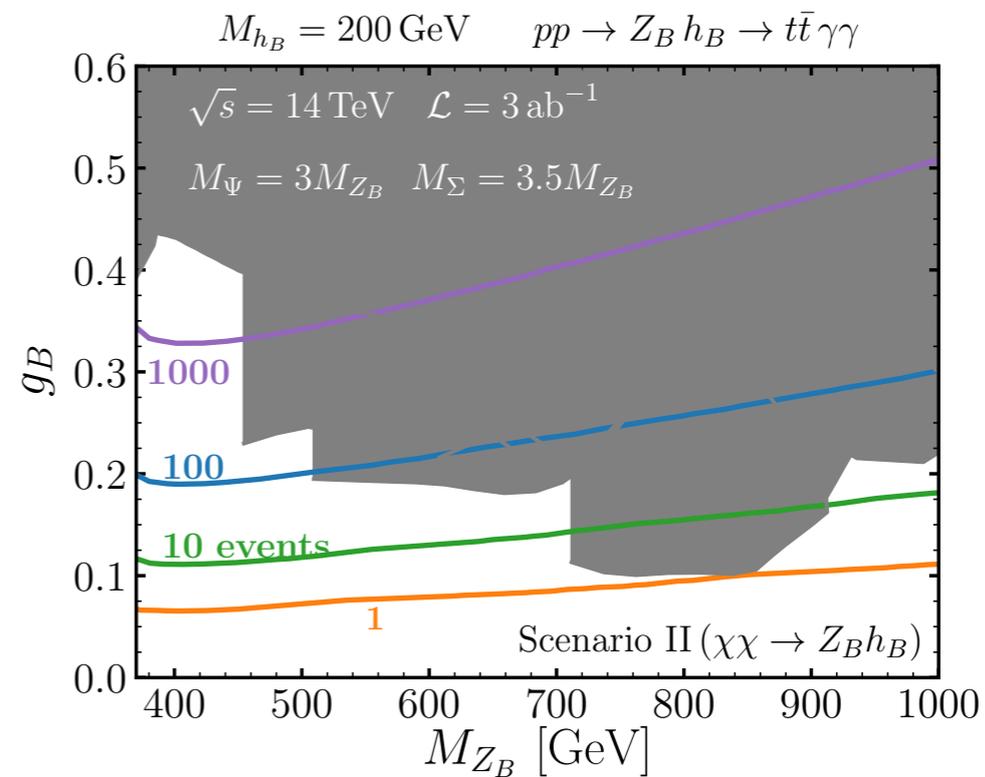
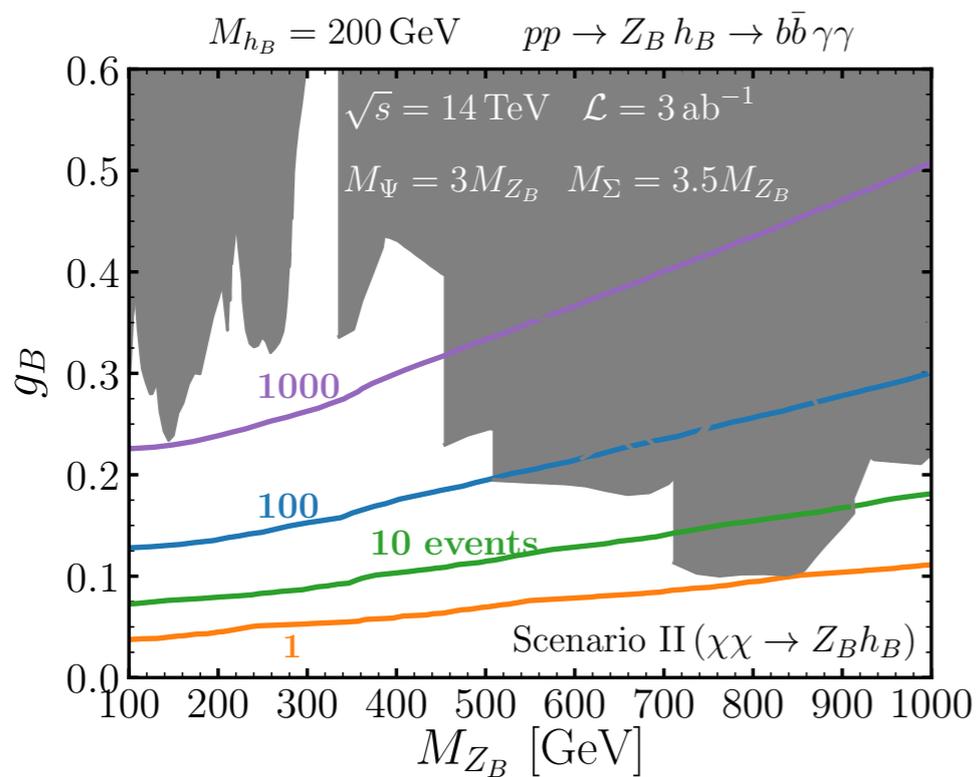
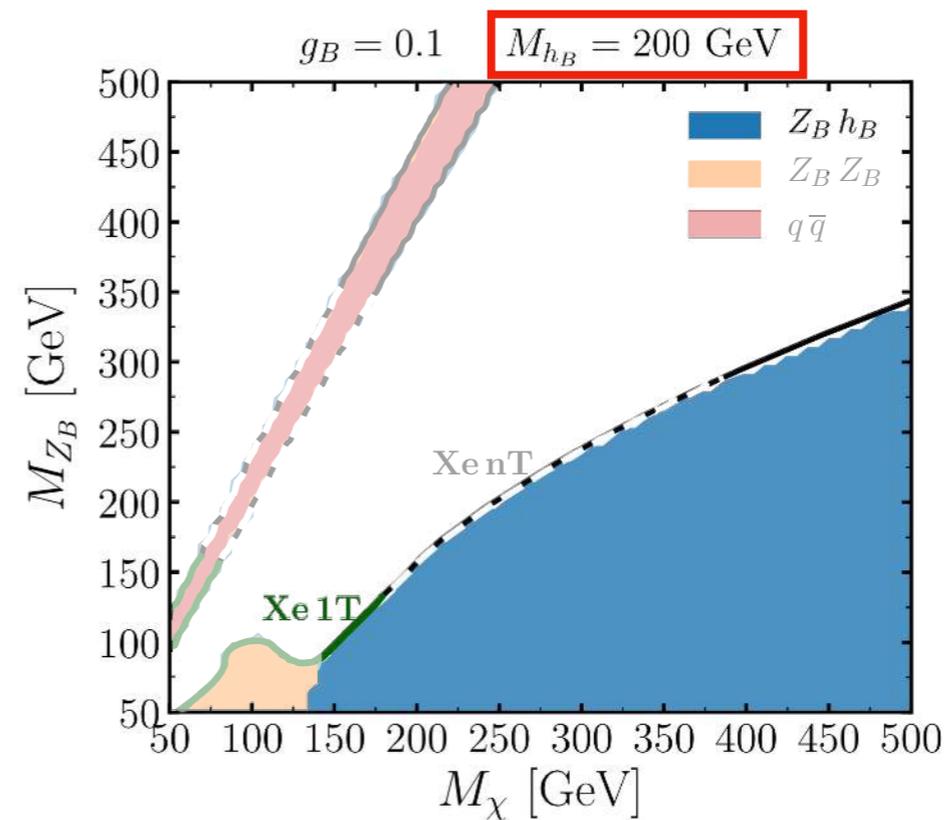
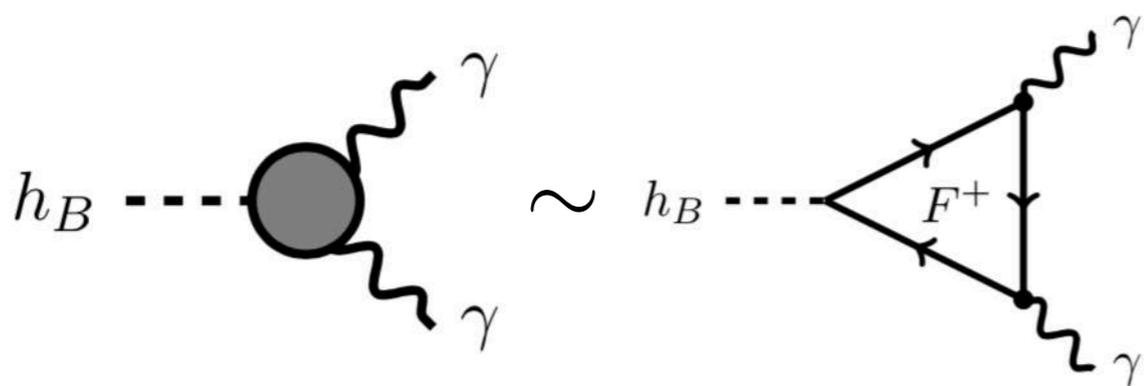
Baryonic Higgs



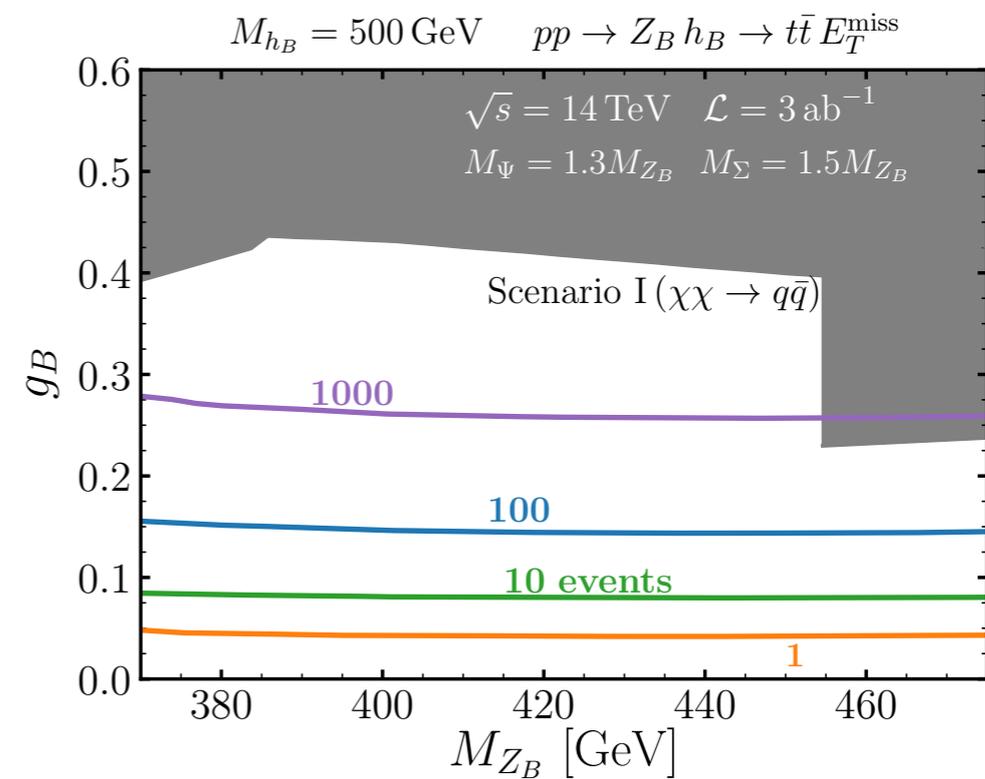
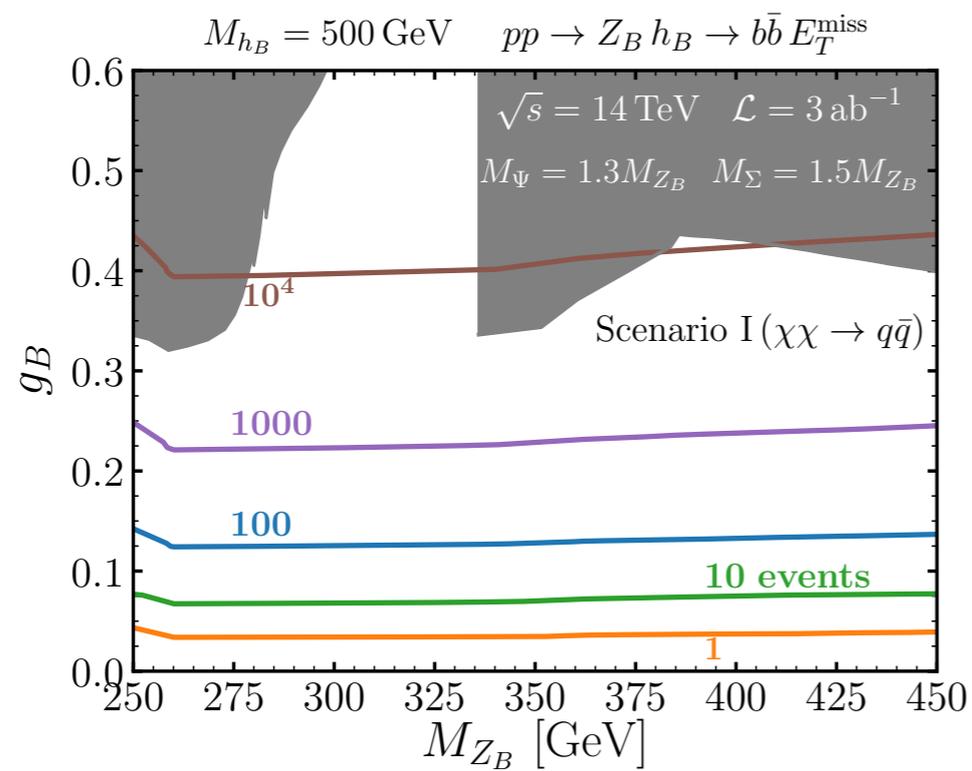
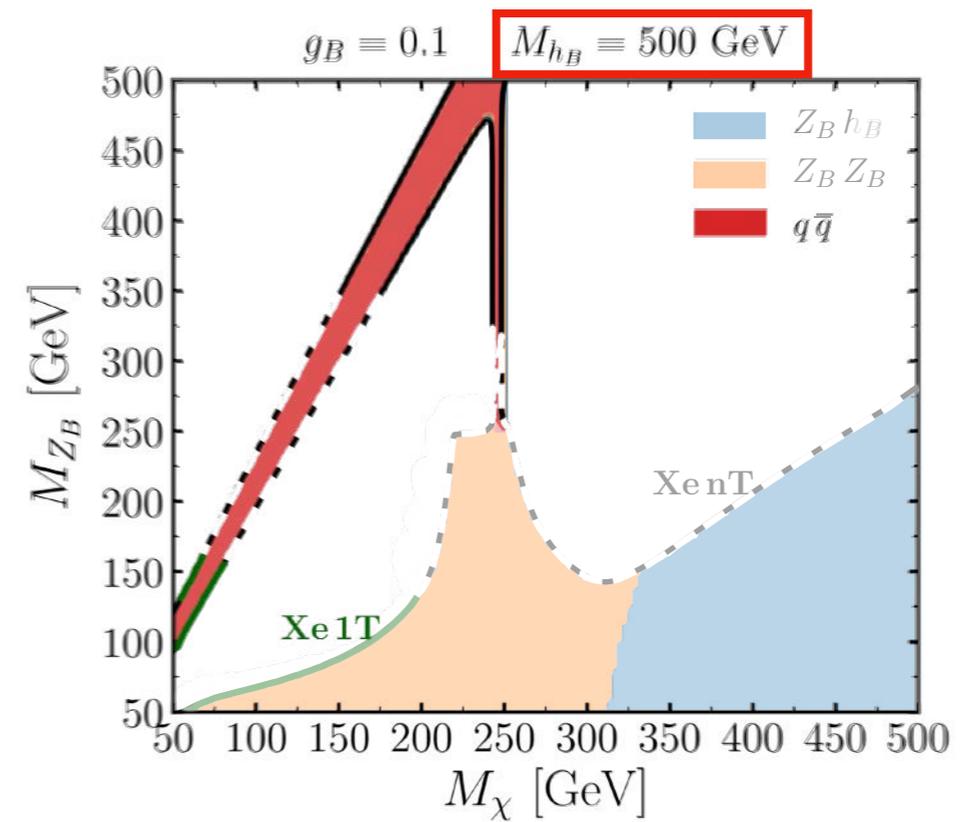
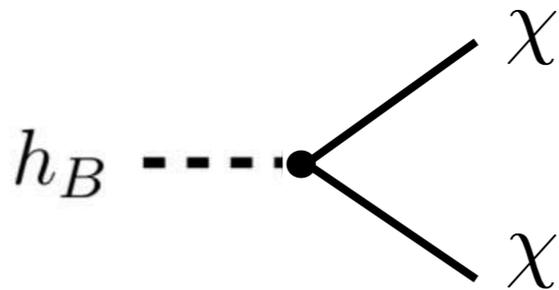
Baryonic Higgs



Baryonic Higgs



Baryonic Higgs



Gauging both Lepton and Baryon Numbers

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$$

$$\begin{aligned} \Psi_L &= \begin{pmatrix} \Psi_1^+ \\ \Psi_1^0 \end{pmatrix}_L \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2}) & \Psi_R &= \begin{pmatrix} \Psi_2^+ \\ \Psi_2^0 \end{pmatrix}_R \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2}, -\frac{3}{2}, -\frac{3}{2}) \\ \Sigma_L &= \frac{1}{\sqrt{2}} \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}_L \sim (\mathbf{1}, \mathbf{3}, 0, -\frac{3}{2}, -\frac{3}{2}) & \chi_L &\sim (\mathbf{1}, \mathbf{1}, 0, -\frac{3}{2}, -\frac{3}{2}) \end{aligned}$$

Gauging both Lepton and Baryon Numbers

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$$

$$\Psi_L = \begin{pmatrix} \Psi_1^+ \\ \Psi_1^0 \end{pmatrix}_L \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2}) \quad \Psi_R = \begin{pmatrix} \Psi_2^+ \\ \Psi_2^0 \end{pmatrix}_R \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2}, -\frac{3}{2}, -\frac{3}{2})$$
$$\Sigma_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}_L \sim (\mathbf{1}, \mathbf{3}, 0, -\frac{3}{2}, -\frac{3}{2}) \quad \chi_L \sim (\mathbf{1}, \mathbf{1}, 0, -\frac{3}{2}, -\frac{3}{2})$$

$$3 \times \nu_R \sim (\mathbf{1}, \mathbf{1}, 0, 0, \mathbf{1})$$

$$S_L \sim (\mathbf{1}, \mathbf{1}, 0, 0, \mathbf{2})$$

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$$-\mathcal{L}_I \supset y_1 \bar{\Psi}_R H \chi_L + y_2 H^\dagger \Psi_L \chi_L + y_3 H^\dagger \Sigma_L \chi_L + y_4 \bar{\Psi}_R \Sigma_L H$$

$$+ \lambda_\psi \bar{\Psi}_R \Psi_L S_B^* + \lambda_\chi \chi_L \chi_L S_B + \lambda_\Sigma \text{Tr} \Sigma_L^2 S_B + \lambda_\nu \nu_R \nu_R S_L + \text{h.c.}$$

Gauging both Lepton and Baryon Numbers

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Spontaneous B and L violation

- **Upper** bound on the **Baryon** Number Violation scale

$$\Omega h^2 < 0.12 \Rightarrow M_{Z_B} < \mathcal{O}(10) \text{ TeV}$$

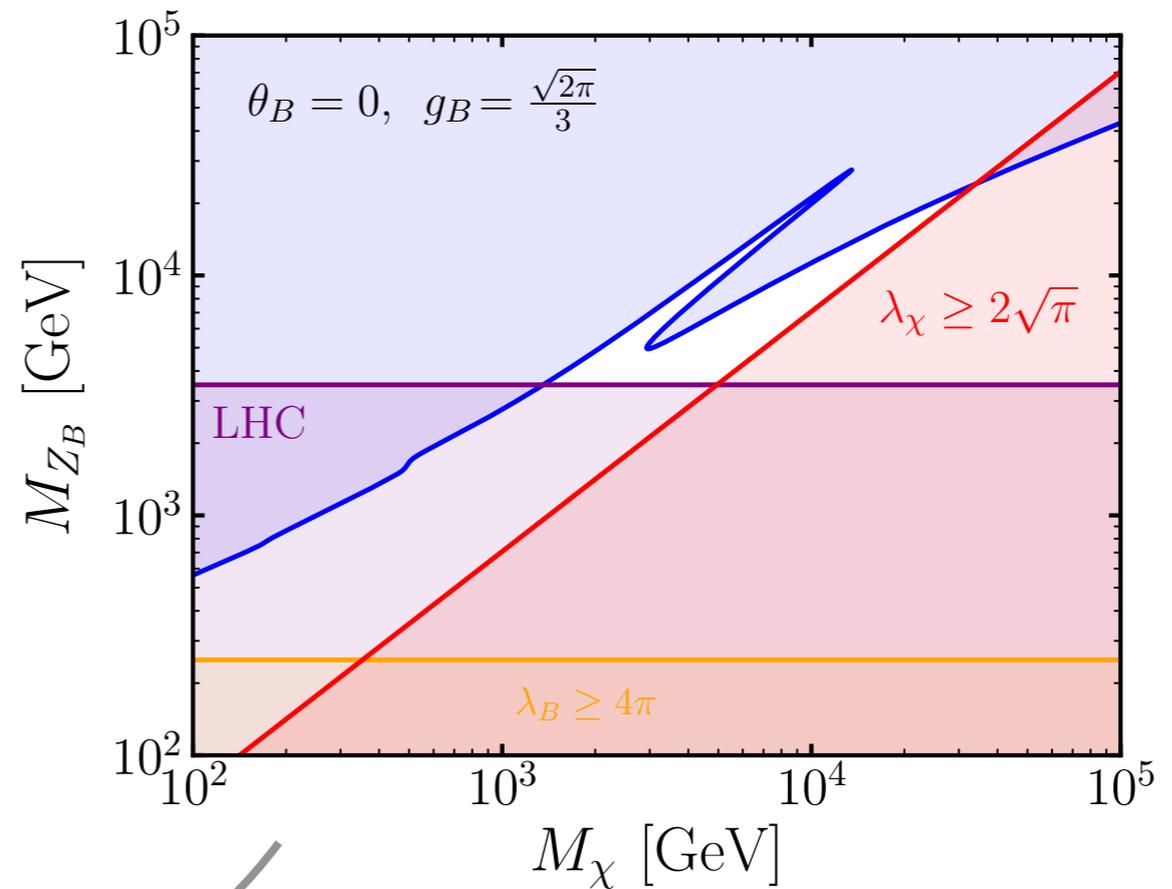
Energy



Dark matter
 $T_{EW} \sim 100 \text{ GeV}$

$U(1)_B$

SM



Leptogenesis

- In order to generate a L asymmetry, A. Sakharov, 1967:

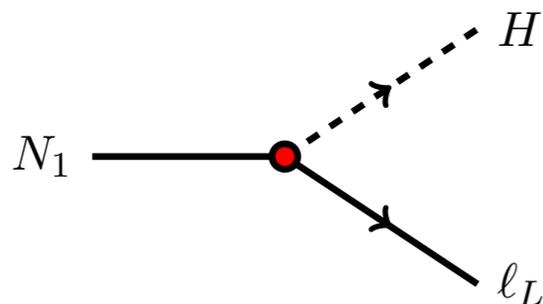
\mathcal{L} & \mathcal{CP}

$$\epsilon_1 \propto \text{Im} \left\{ \begin{array}{c} \text{Loop diagram: } N_1 \text{ enters, } \ell_L \text{ and } H \text{ exit} \\ \text{Triangle diagram: } N_1 \text{ enters, } \ell_L \text{ and } H \text{ exit} \end{array} \right\} \leq 10^{-16} \left(\frac{M_{N_1}}{\text{GeV}} \right)$$

Davidson-Ibarra

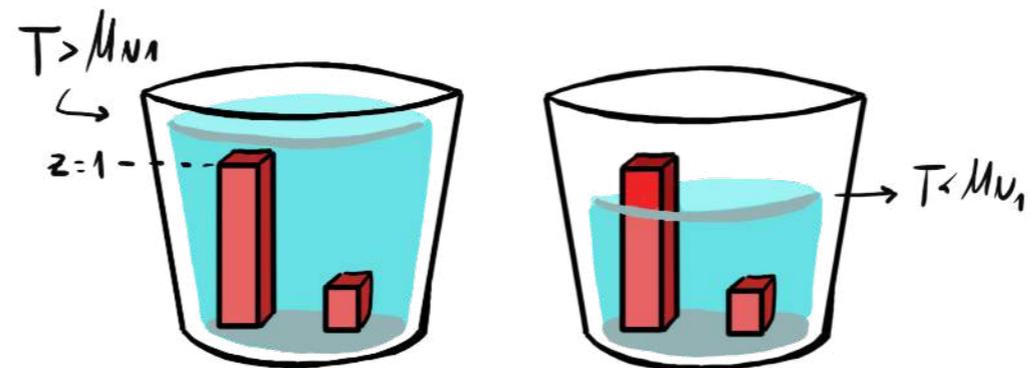
Lepton Number Violation

$$\mathcal{L}_{\Delta L=2} \supset \lambda_N \langle S_L \rangle N_R^T C N_R + Y_N \bar{\ell}_L i \sigma_2 H^* N_R + \text{h.c.}$$



Out-of-equilibrium

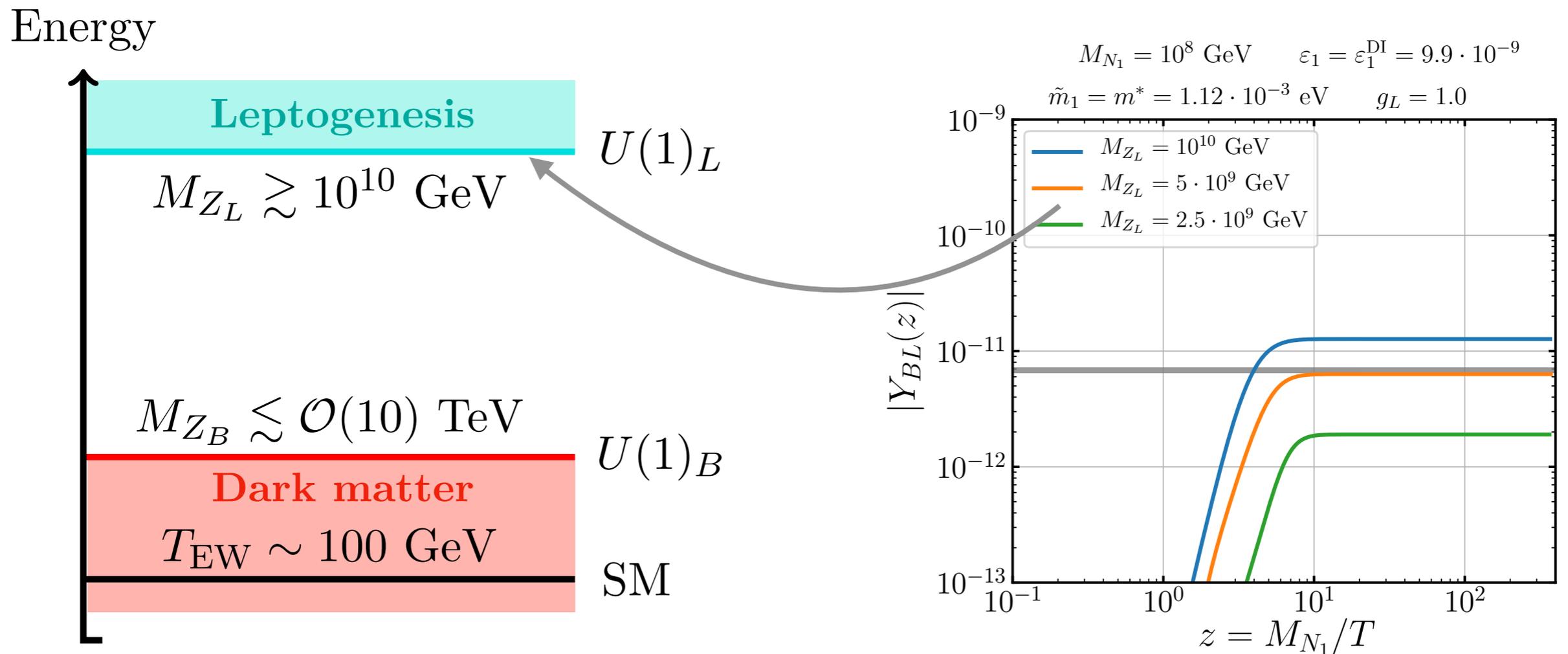
$$\Gamma_{N_1}[T = M_{N_1}] \lesssim 3H[T = M_{N_1}]$$



$$\Rightarrow \tilde{m}_1 \lesssim \frac{8 \sin^2 \theta_W}{\alpha} \sqrt{\frac{\pi^3 g_*[M_{N_1}]}{5}} \frac{M_W^2}{M_{\text{Pl}}} \sim 10^{-3} \text{ eV}$$

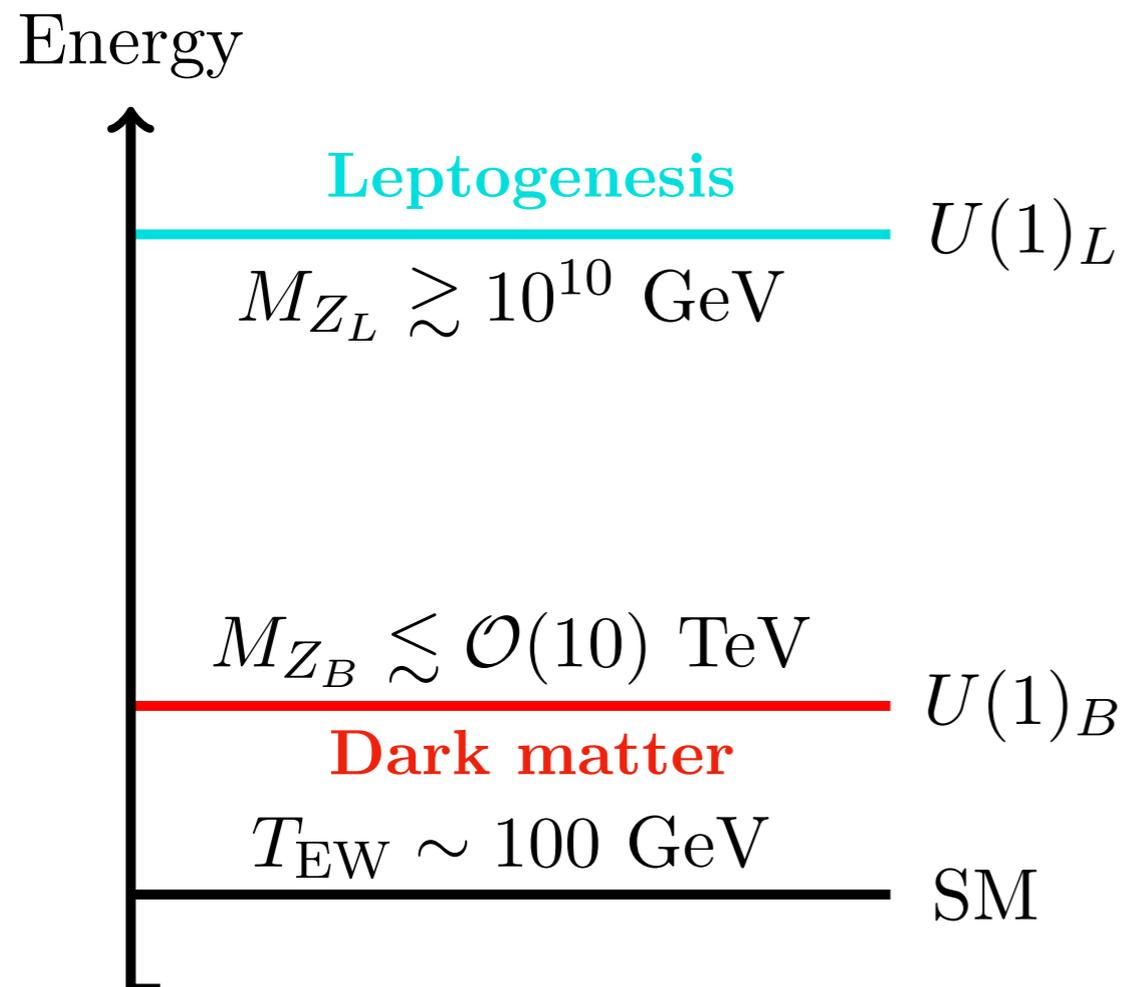
Leptogenesis

- **Lower** bound on the **Lepton** Number Violation scale



Baryogenesis

- Conversion to the baryon asymmetry



$$\Delta(B - L)_{\text{SM}}$$



sphalerons SU
 $(QQQL)^3$

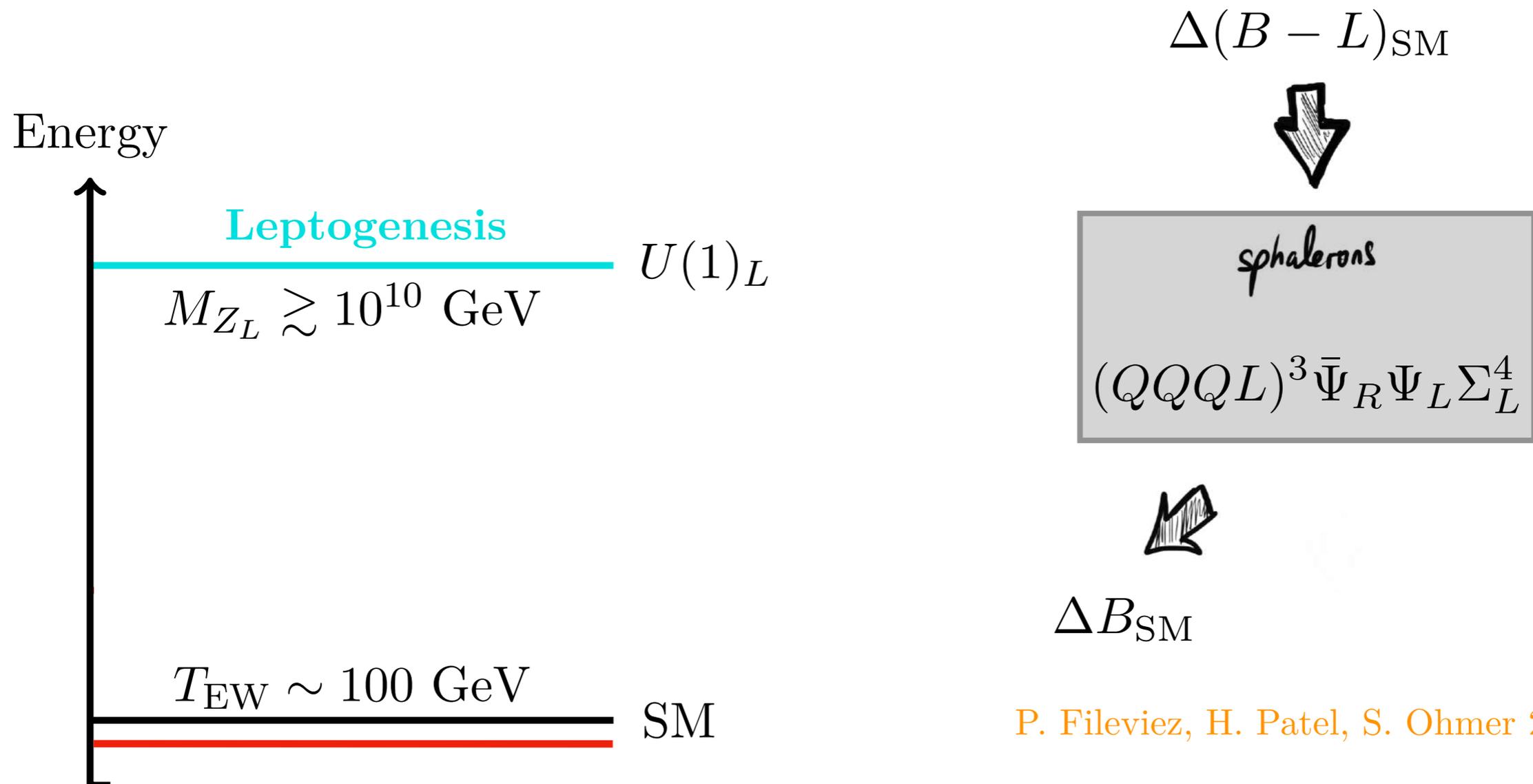


$$\Delta B_{\text{SM}}$$

J. A. Harvey, M.S. Turner, 1990

Baryogenesis

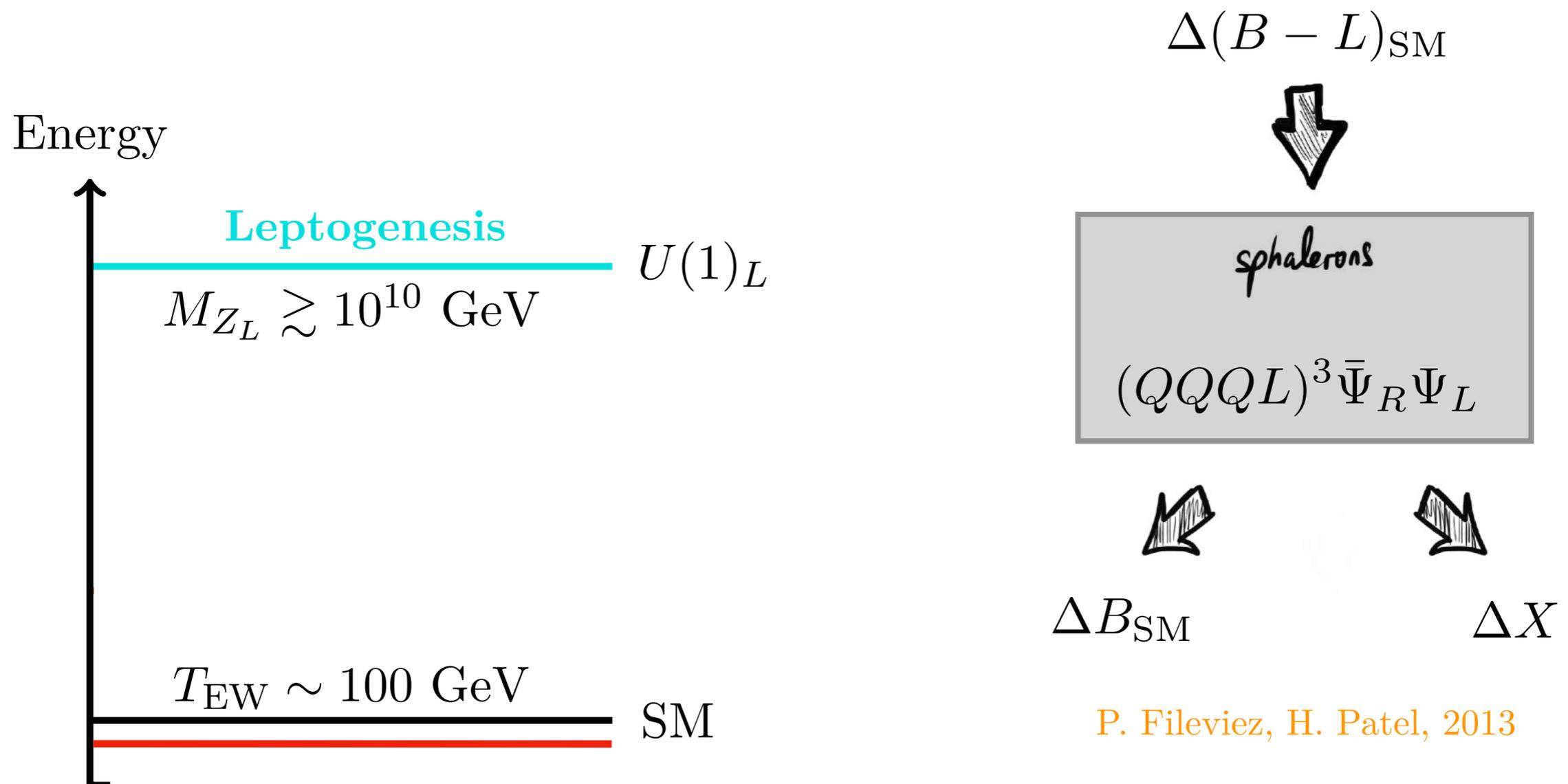
- Conversion to the baryon asymmetry



P. Fileviez, H. Patel, S. Ohmer 2015

Baryogenesis

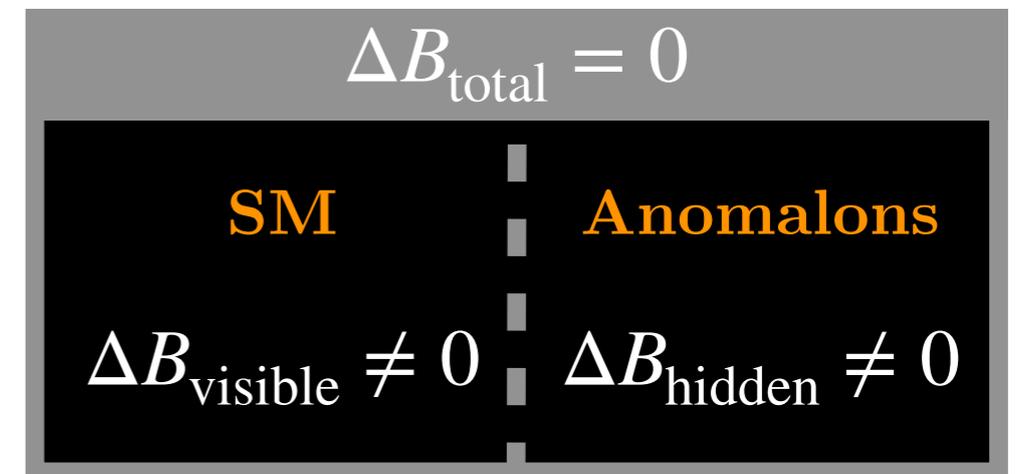
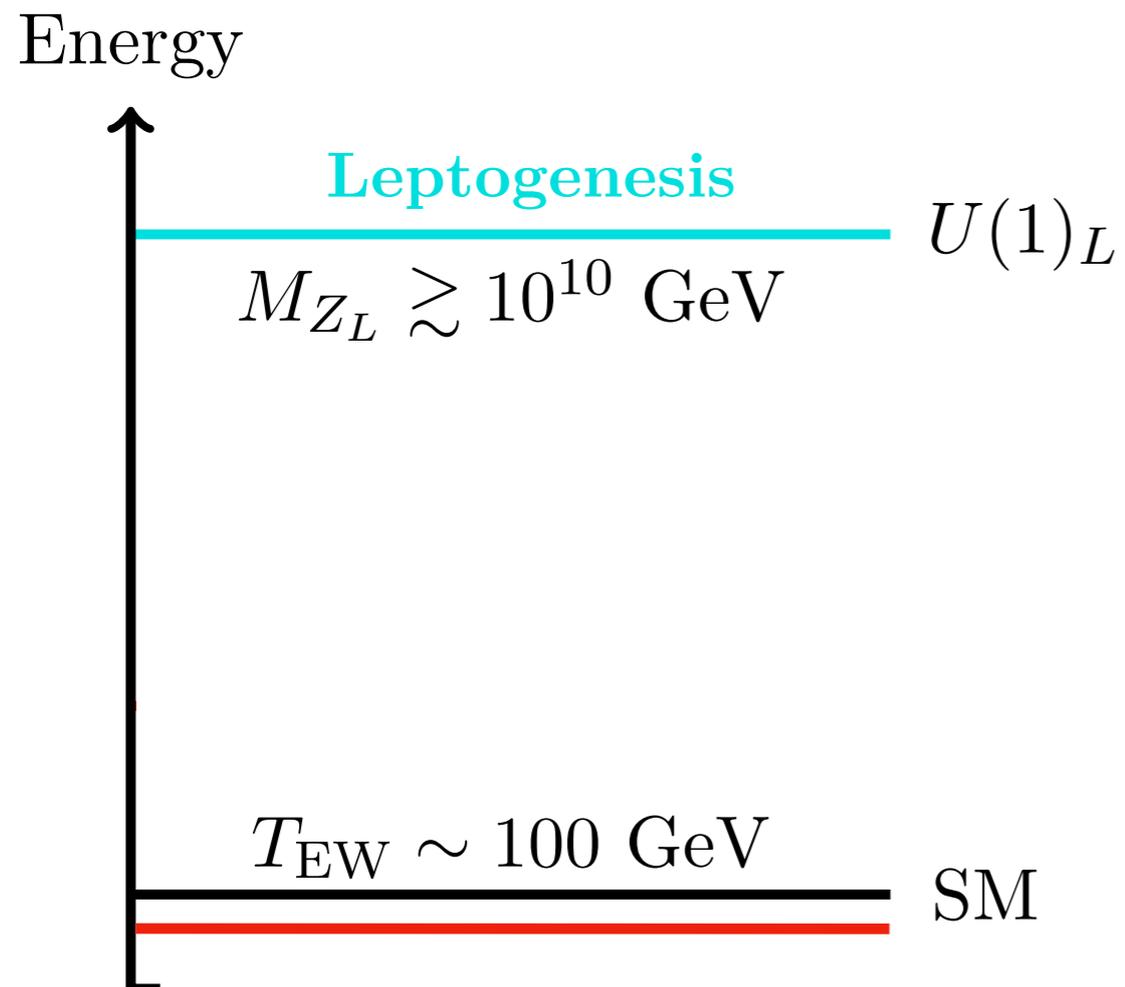
- Conversion to the baryon asymmetry



P. Fileviez, H. Patel, 2013

Baryogenesis

- Conversion to the baryon asymmetry



P. Fileviez, H. Patel, 2013

Kinetic mixing

$$\begin{aligned}
 \mathcal{L} \supset & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\text{Tr} W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\sin \epsilon}{2}B_{\mu\nu}B'^{\mu\nu} \\
 & + \frac{1}{8}(g_2W_{3\mu} - g_1B_\mu)(g_2W_3^\mu - g_1B^\mu)v_0^2 + \frac{1}{2}\mu_{B'}^2B'_\mu B'^\mu \\
 & - \sum_i \bar{\psi}_i \gamma^\mu [g_1(Y_L^i P_L + Y_R^i P_R)B_\mu + g_2 P_L T^a W_{a\mu}] \psi_i + g_B \sum_i \bar{\psi}_i \gamma^\mu Q_B \psi_i B'_\mu,
 \end{aligned}$$

$$\begin{aligned}
 M_{A_\mu}^2 &= 0, \\
 M_{Z,Z_B}^2 &= \frac{1}{8} (g_1^2 \sec^2 \epsilon + g_2^2) v_0^2 + \frac{1}{2} \mu_{B'}^2 \sec^2 \epsilon \\
 &\quad \pm \frac{1}{8} \sqrt{(4\mu_{B'}^2 \sec^2 \epsilon + (g_1^2 \sec^2 \epsilon + g_2^2)v_0^2)^2 - 16(g_1^2 + g_2^2)\mu_{B'}^2 v_0^2 \sec^2 \epsilon}
 \end{aligned}$$

$$\frac{\Delta M_Z}{M_Z^{\text{SM}}} = \frac{M_Z - M_Z^{\text{SM}}}{M_Z^{\text{SM}}} \leq \pm 2.3 \times 10^{-5}$$

