Caltech

Local Baryon and Lepton Numbers

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Pavel Fileviez Perez, Elliot Golias, Alexis Plascencia

1904.01017, 1905.06344, 2003.09426, **2012.06599**

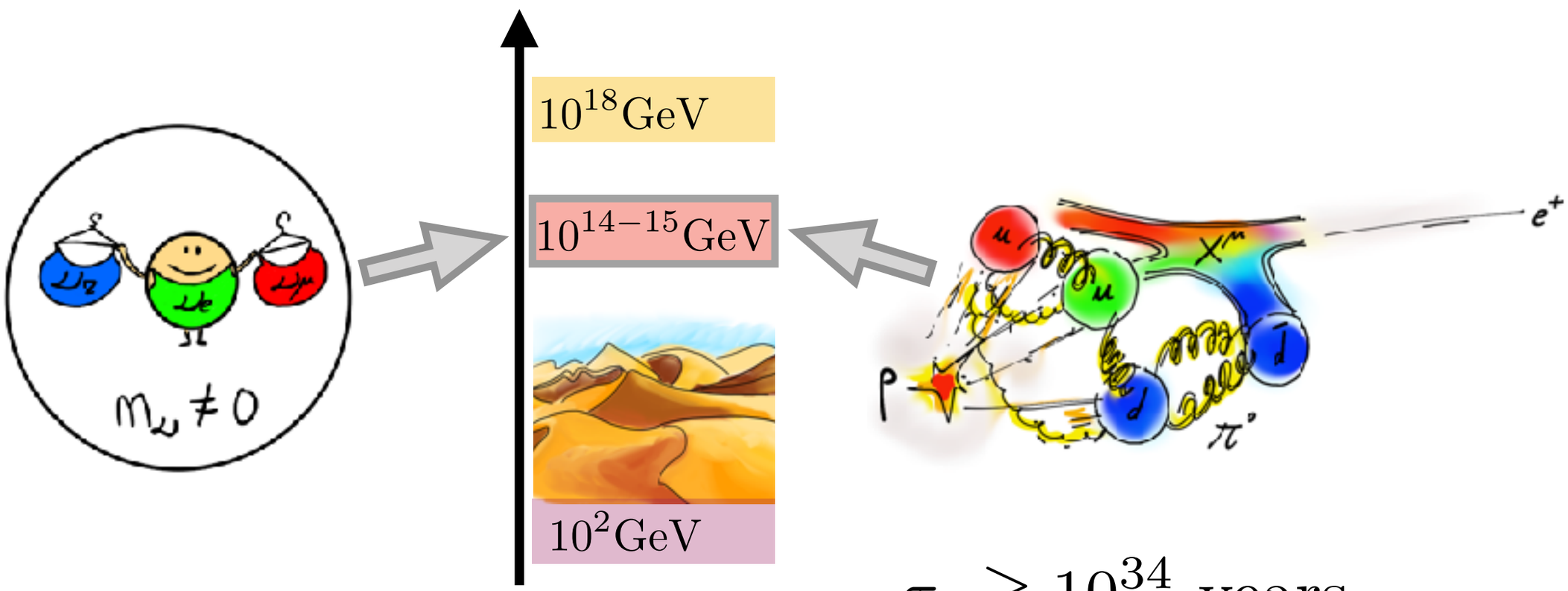
28th January 2021

Brookhaven National Laboratory

The New World

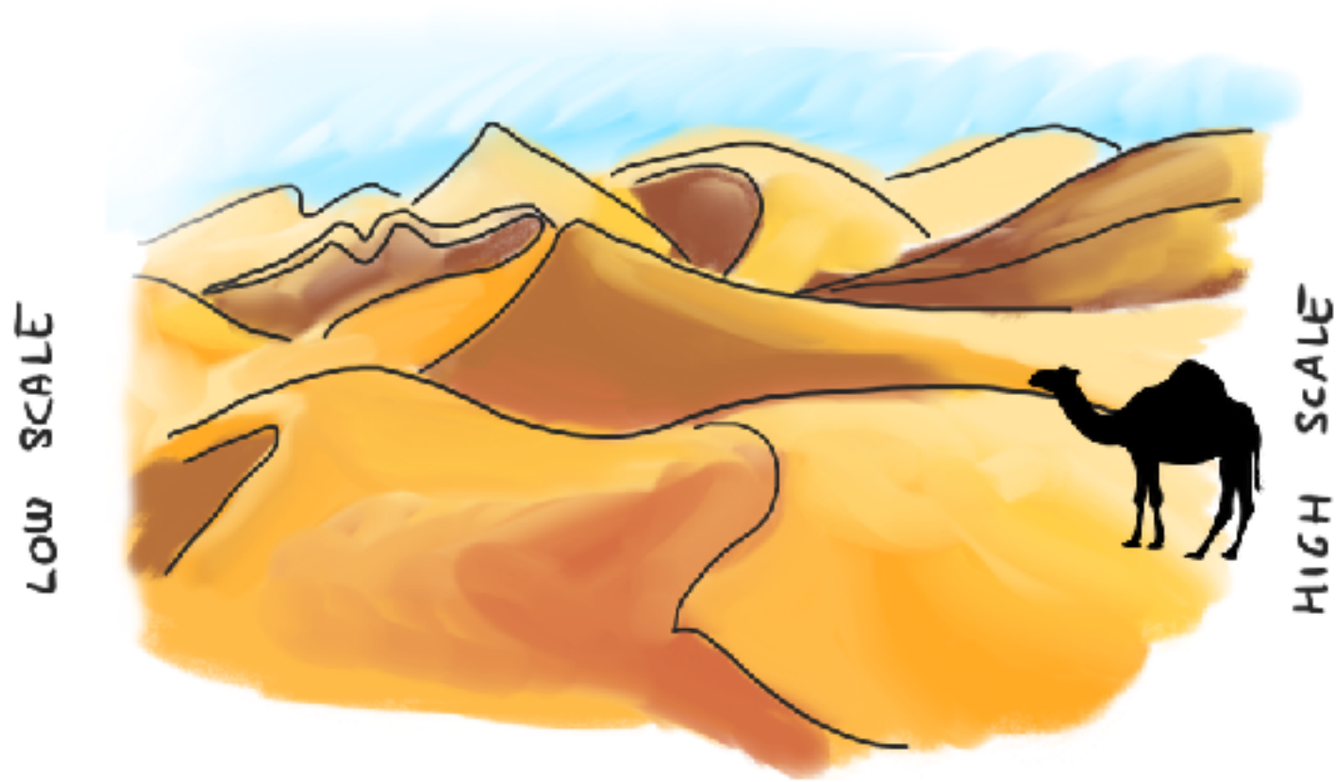
Beyond the Standard Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_L}{\Lambda_L}\ell_L\ell_L HH + \frac{c_B}{\Lambda_B^2}Q_L Q_L Q_L \ell_L \quad \ldots$$



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

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_L}{\Lambda_L}\ell_L\ell_L HH + \frac{c_B}{\Lambda_B^2}Q_L Q_L Q_L \ell_L \quad \ldots$$



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_L}{\Lambda_L}\ell_L\ell_L HH + \frac{c_B}{\Lambda_B^2}Q_L Q_L Q_L \ell_L \quad \ldots$$

if $\Delta L \neq \pm 2$

if $\Delta B \neq \pm 1$

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

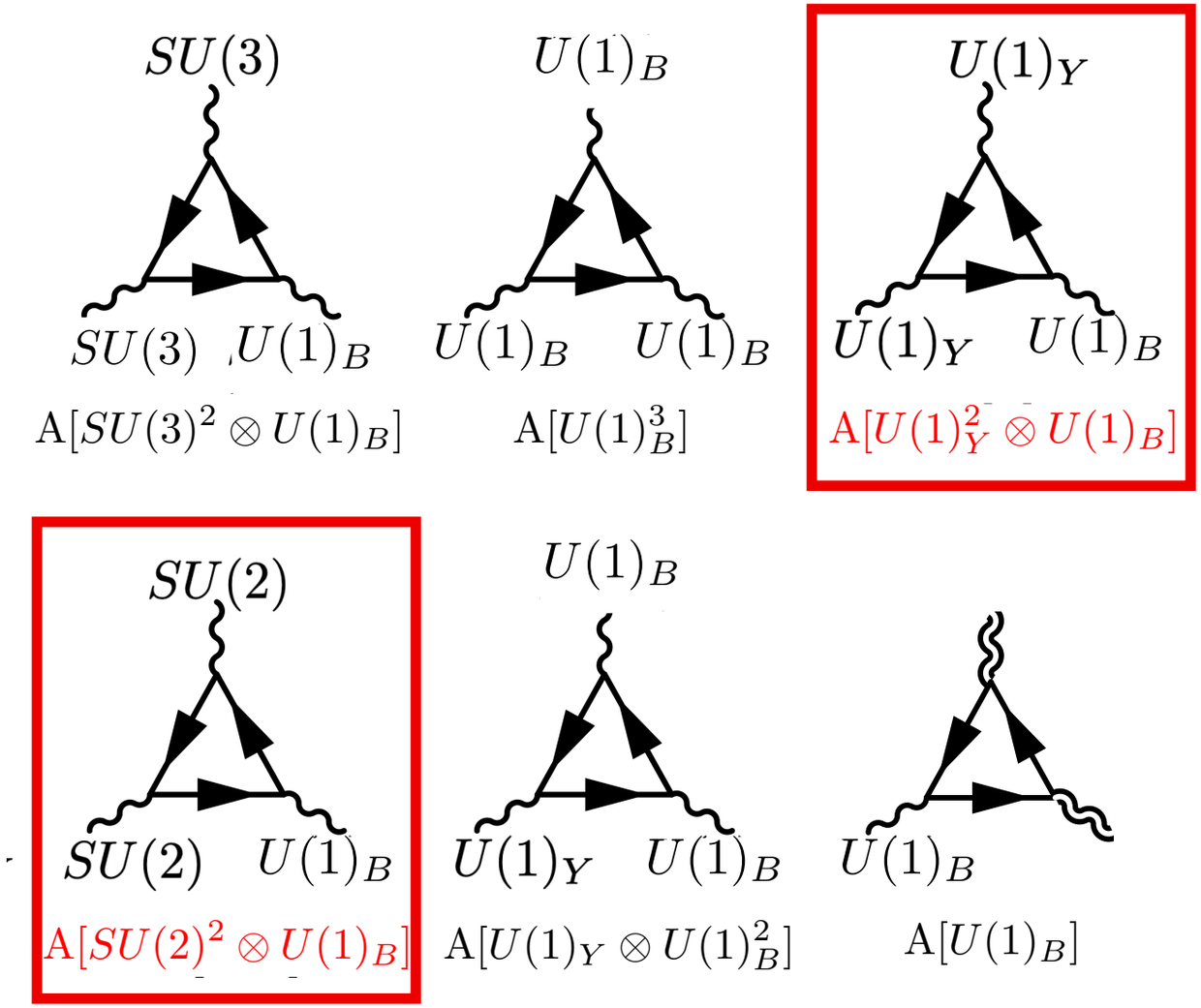
Extra symmetries:

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

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

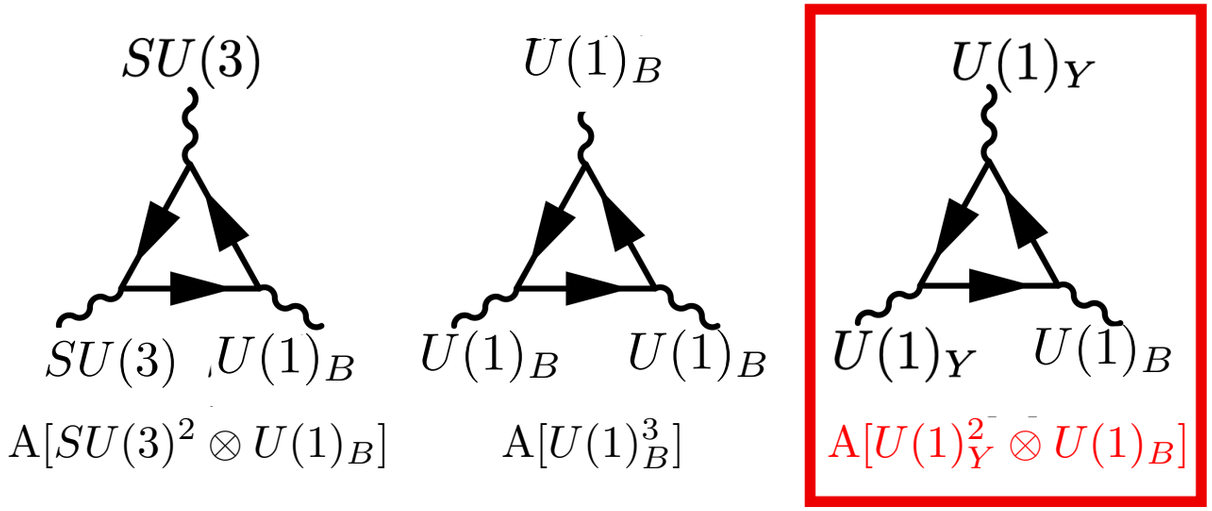
$$\boxed{U(1)_X \to U(1)_{X=B}}$$

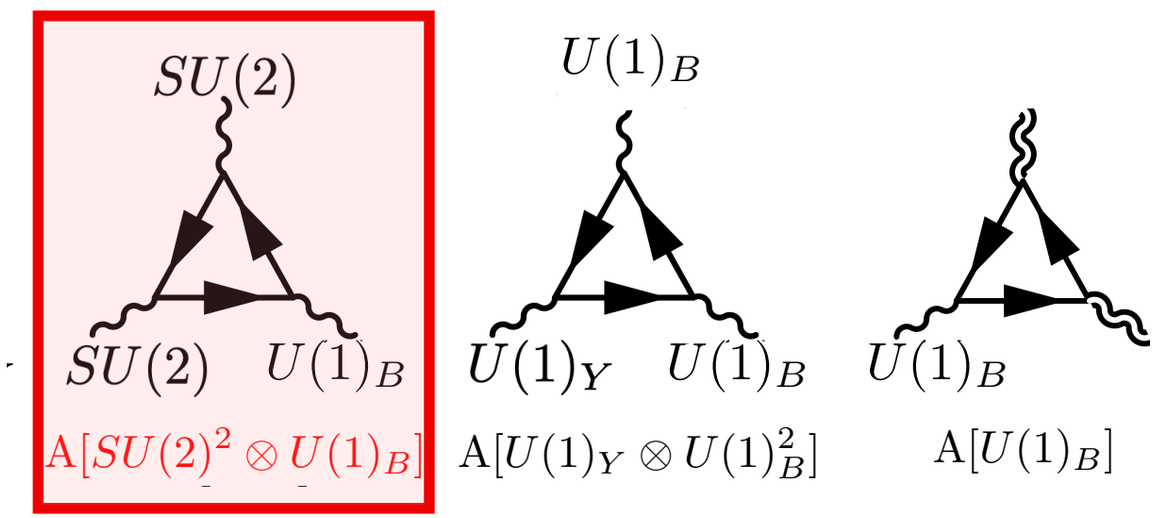
Anomaly cancellation



New fermions required!

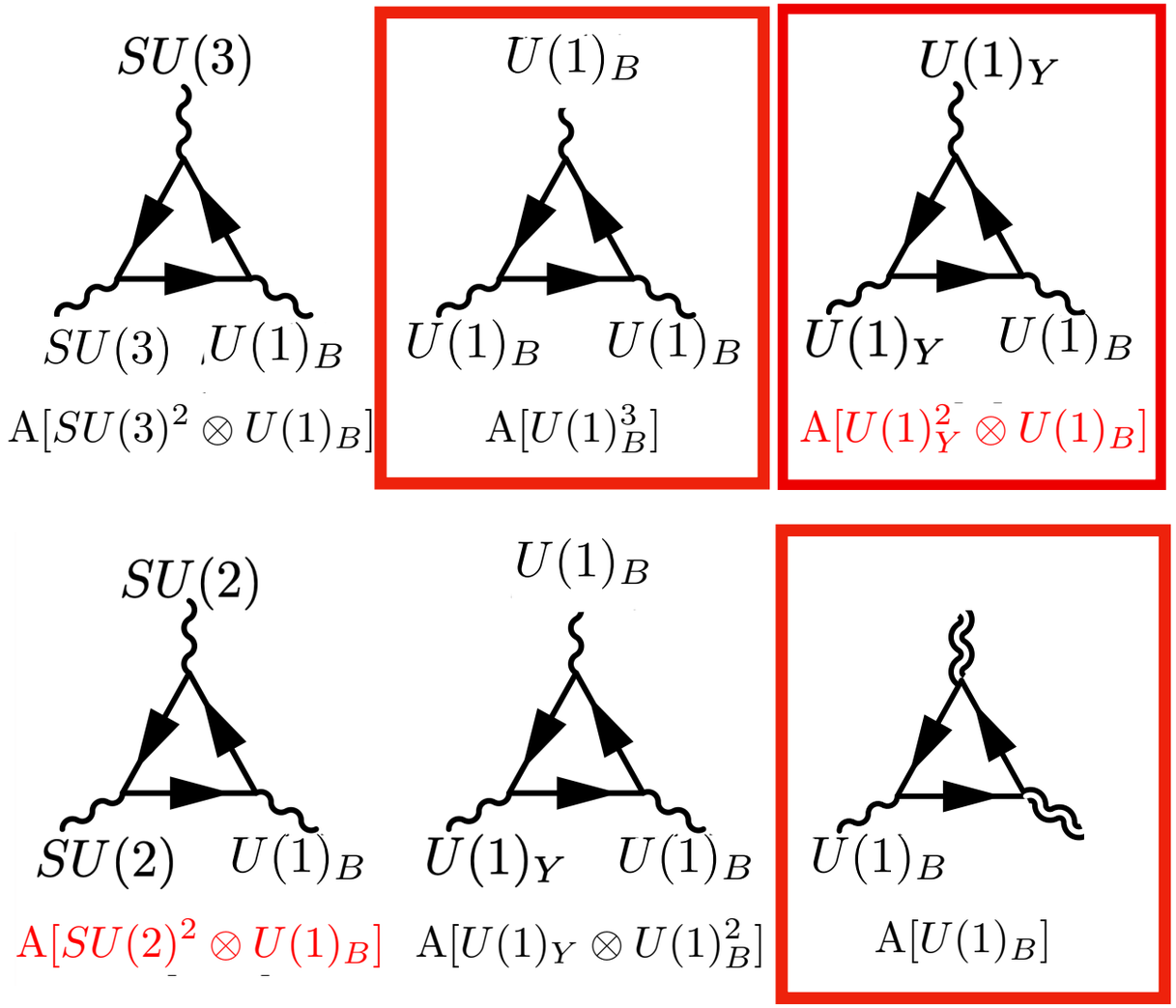
Anomaly cancellation





SU(2) non-trivial representation

Anomaly cancellation



SU(2) non-trivial representation

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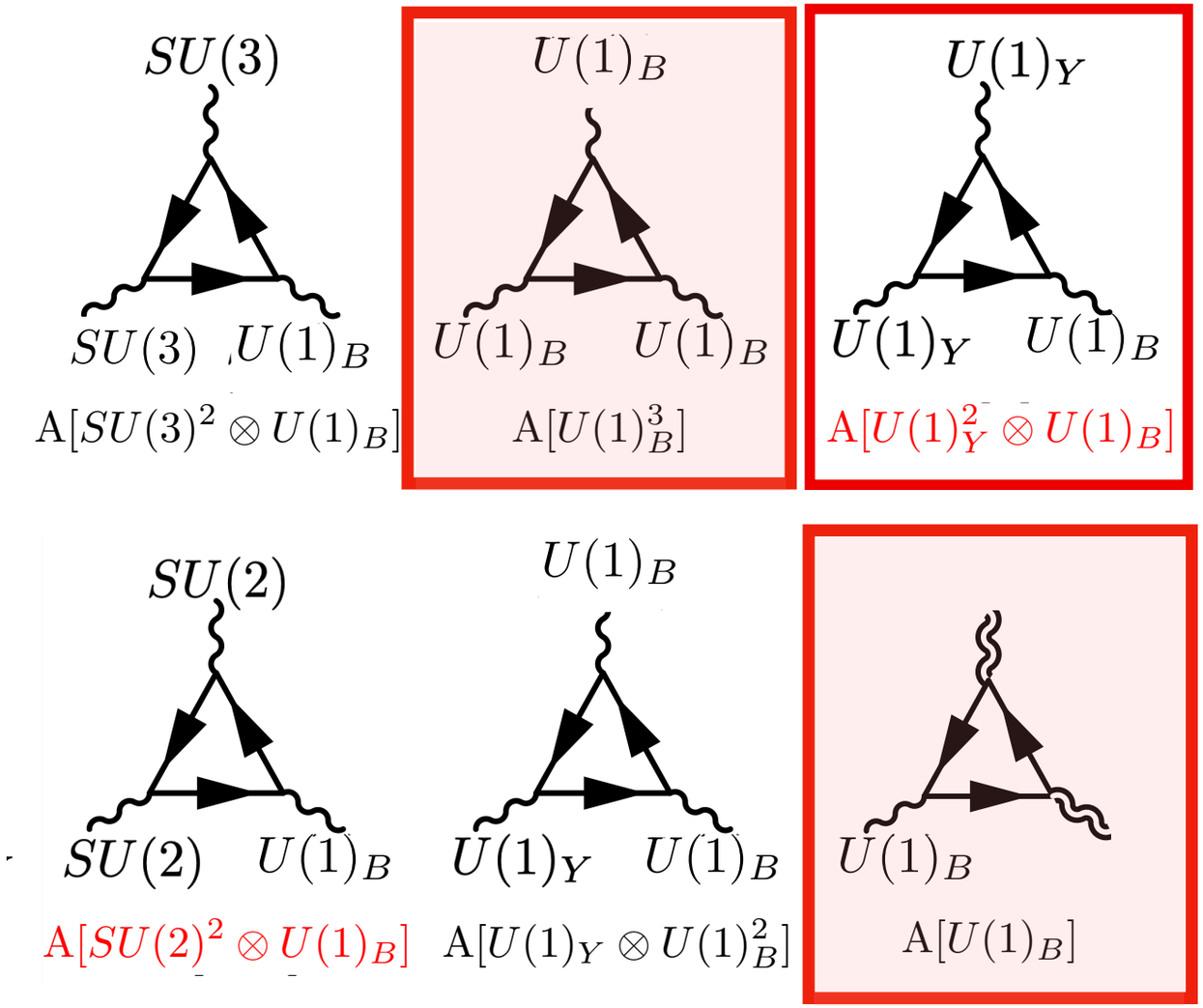
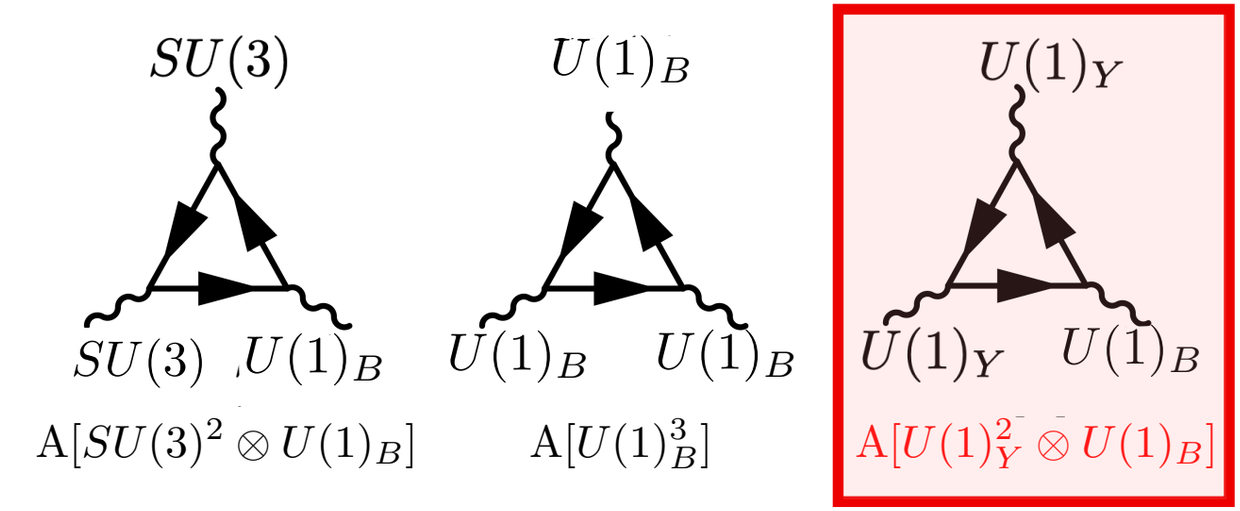
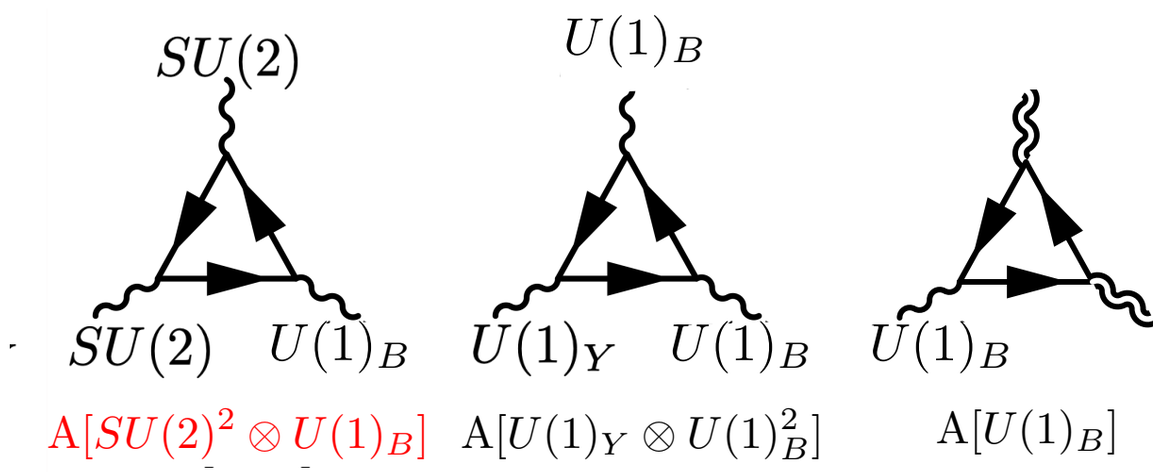


Anomaly cancellation





Gauging U(1)B

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

1403.8029

$$\Psi_L = \begin{pmatrix} \Psi_1^+ \\ \Psi_1^0 \end{pmatrix}_L \sim (\mathbf{1}, \mathbf{2}, 1/2, 3/2), \quad \Psi_R = \begin{pmatrix} \Psi_2^+ \\ \Psi_2^0 \end{pmatrix}_R \sim (\mathbf{1}, \mathbf{2}, 1/2, -3/2),$$

$$\Sigma_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}_L \sim (\mathbf{1}, \mathbf{3}, 0, -3/2), \quad \text{and} \quad \chi_L^0 \sim (\mathbf{1}, \mathbf{1}, 0, -3/2),$$

Gauging U(1)B

Proton stable!

- Massive anomalons ⇒ $S_B \sim (1,1,0,3) \Rightarrow \Delta B = 3$

How do we test this theory? :(

it might not exist...

Gauging U(1)B

Proton stable!

- Massive anomalons ⇒ $S_B \sim (1,1,0,3) \Rightarrow \Delta B = 3$

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

$$\Big\downarrow \langle S_B \rangle$$

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

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

- Simplest content to cancel anomalies ⇒ Majorana, $n_B = \dfrac{3}{2}$

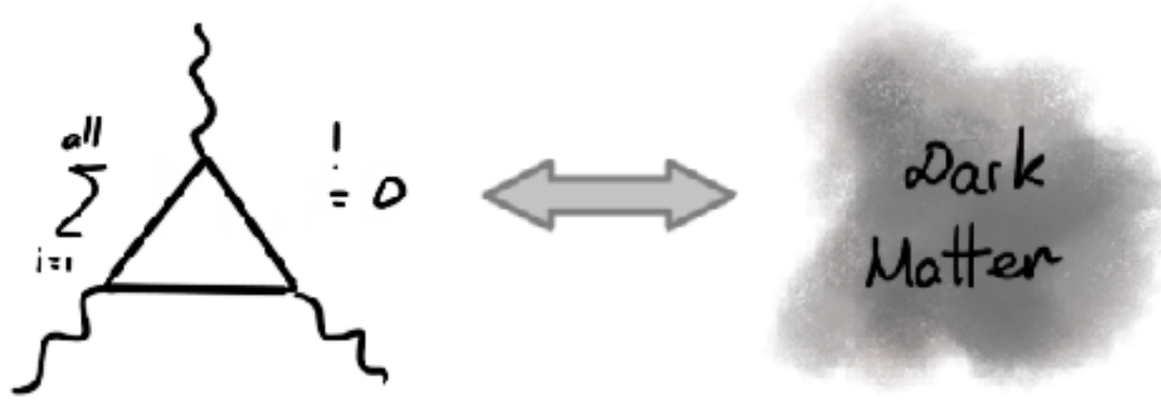
Gauging U(1)B

Extra symmetries:

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

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

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



Theoretical Framework

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

χ gets mass from SSB !

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

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

$\cancel{\Lambda}_B$

$$M_\chi = \sqrt{2}\, \lambda_\chi v_B$$

$$M_{Z_B} = 3\, g_B v_B$$

$$\Rightarrow \quad \frac{3\, g_B}{\sqrt{2}} \frac{M_\chi}{M_{Z_B}} = \lambda_\chi$$

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

Theoretical Framework

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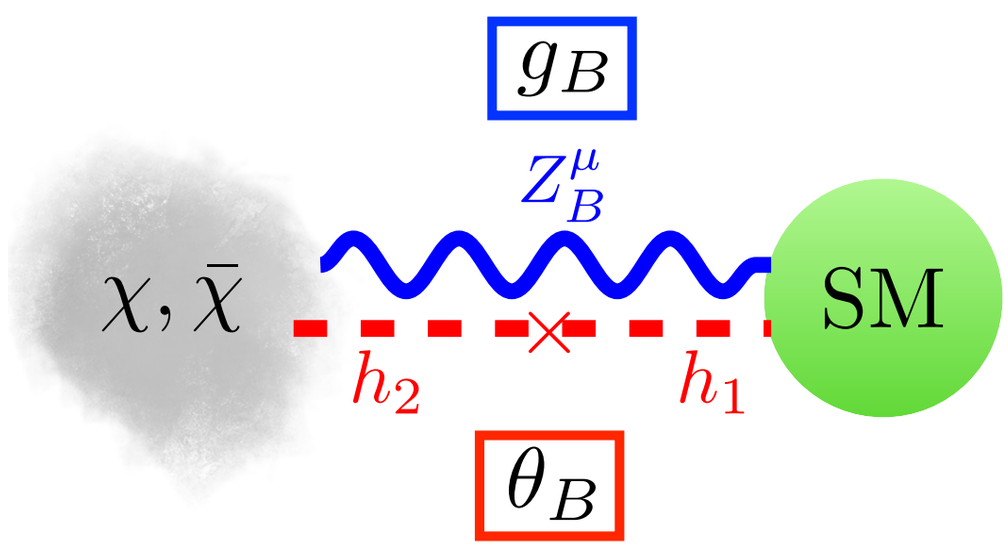
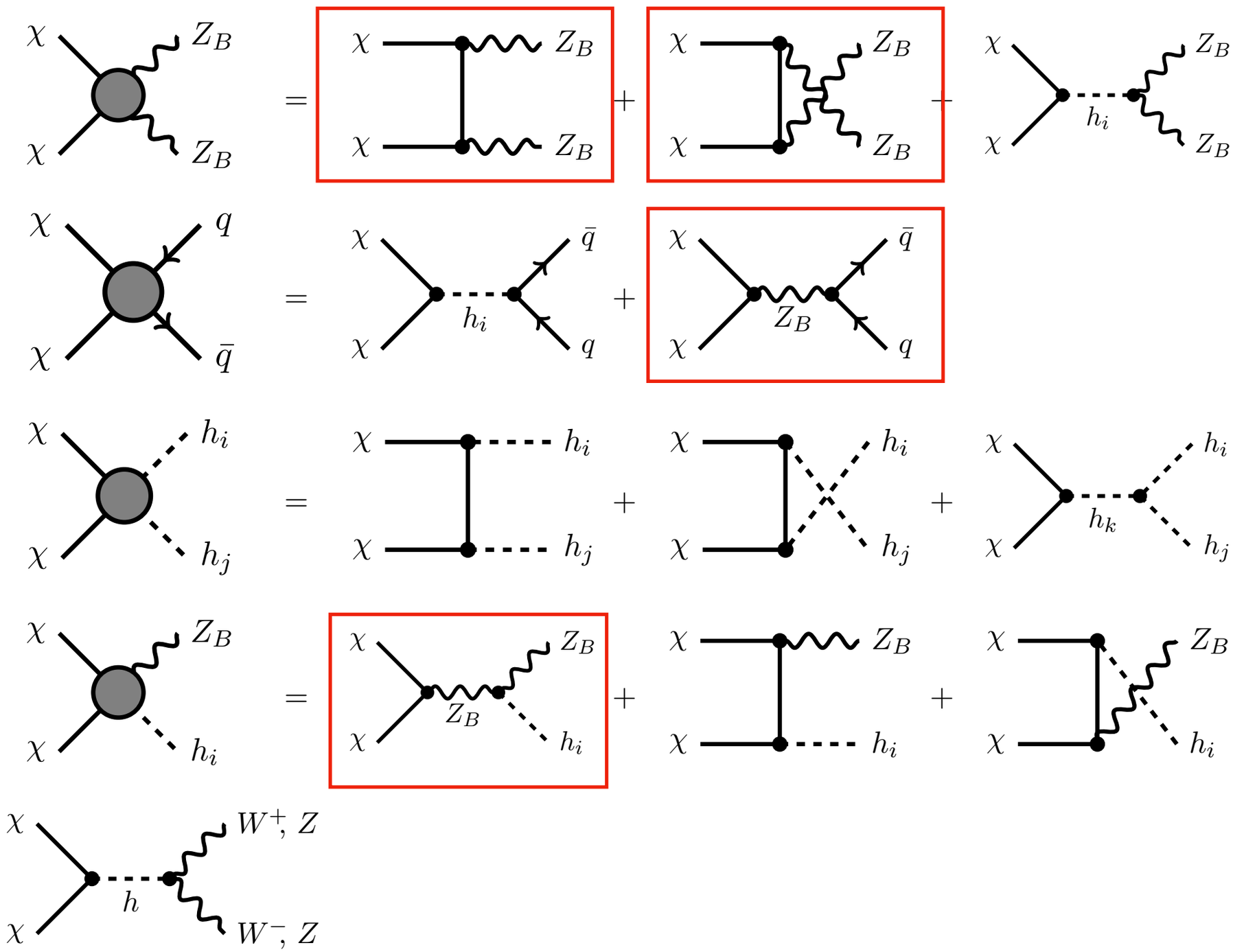
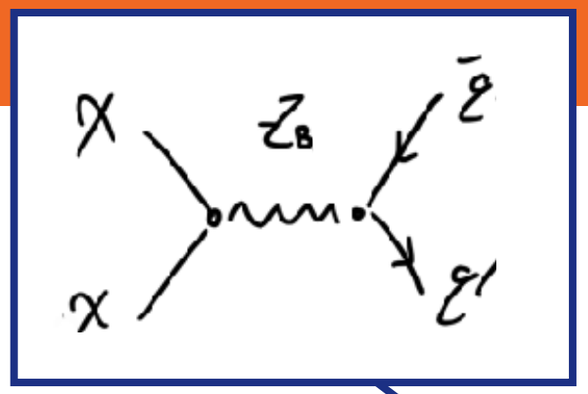


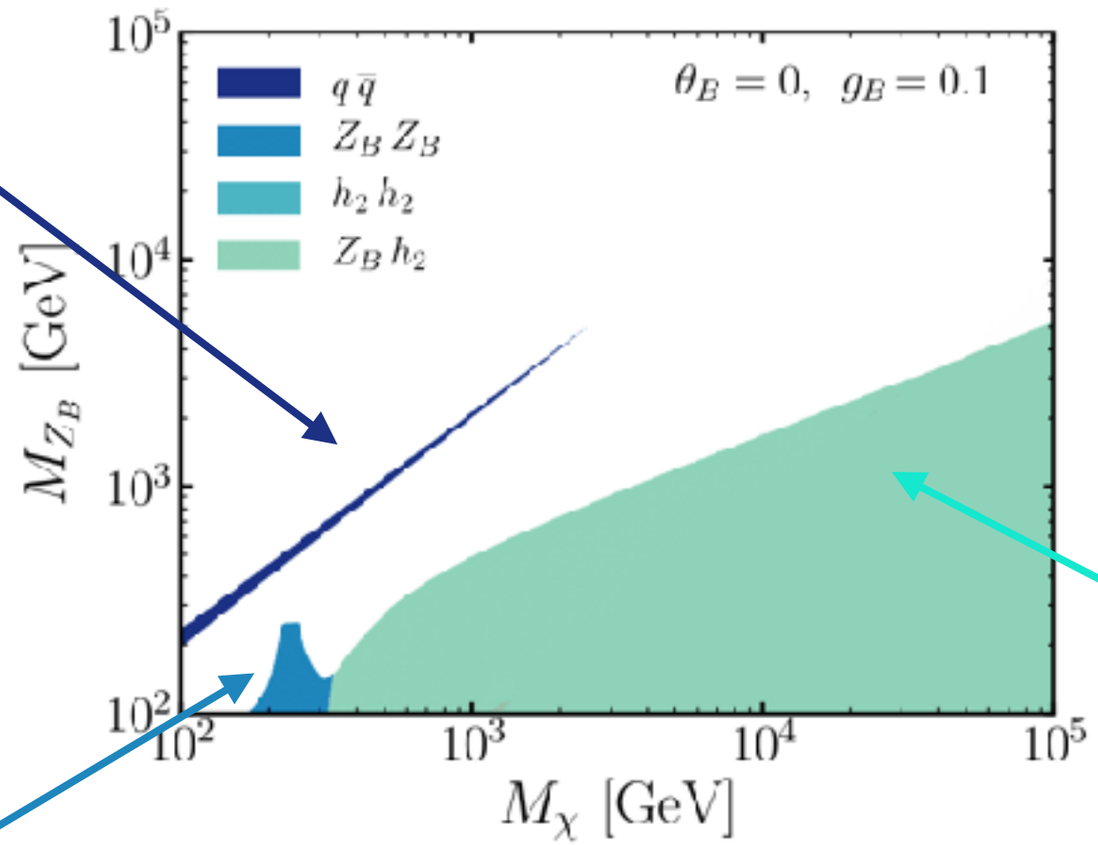
- Relevant parameters: $M_\chi,\ M_{Z_B},\ g_B,\ M_{h_2},\ \theta_B$

DM annihilation channels

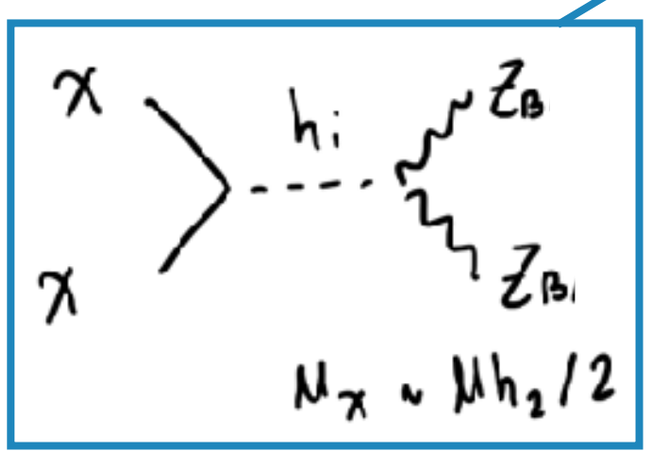


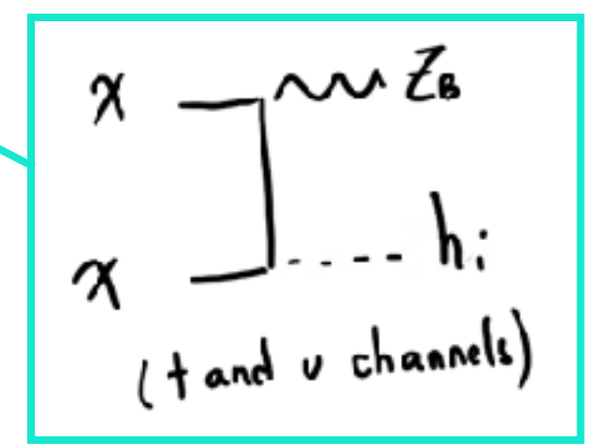
Relic Density



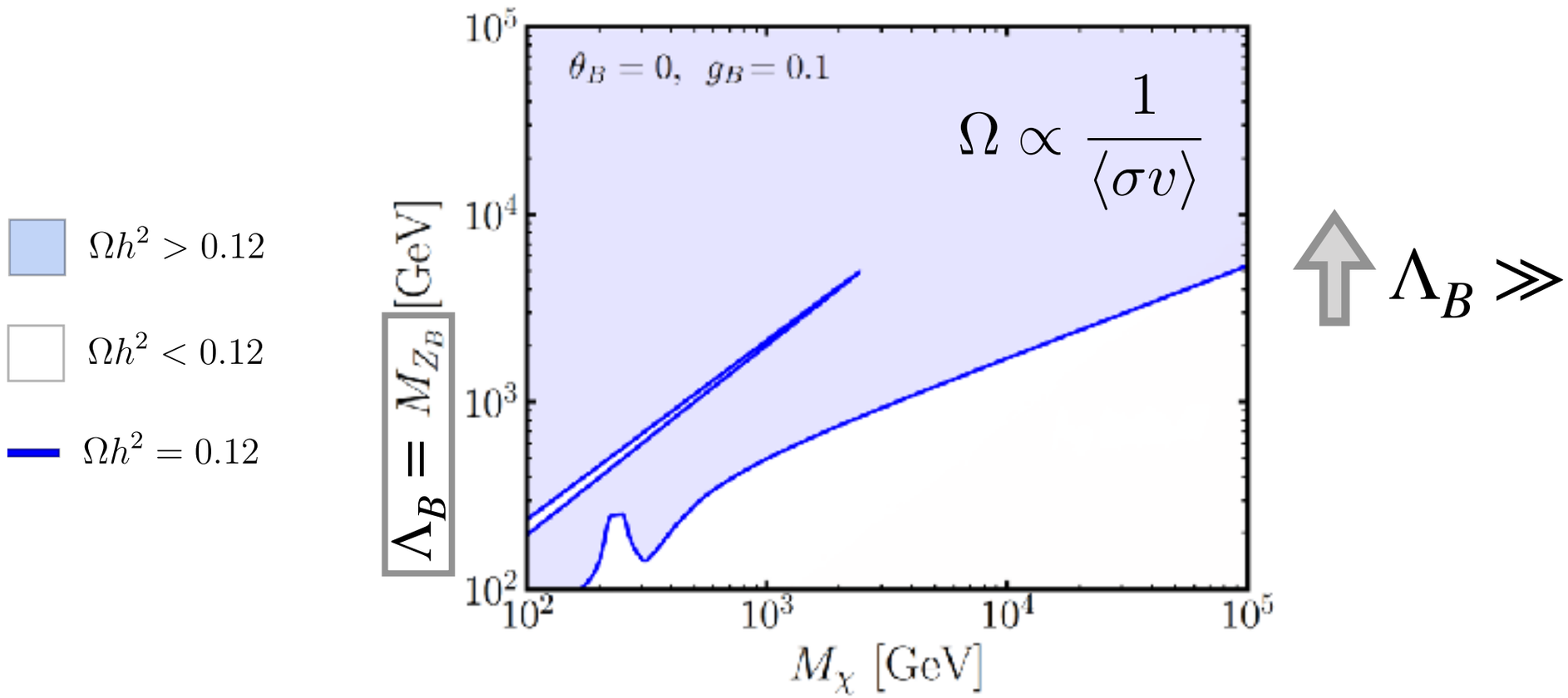


$$\Omega \propto \frac{1}{\langle \sigma v \rangle}$$

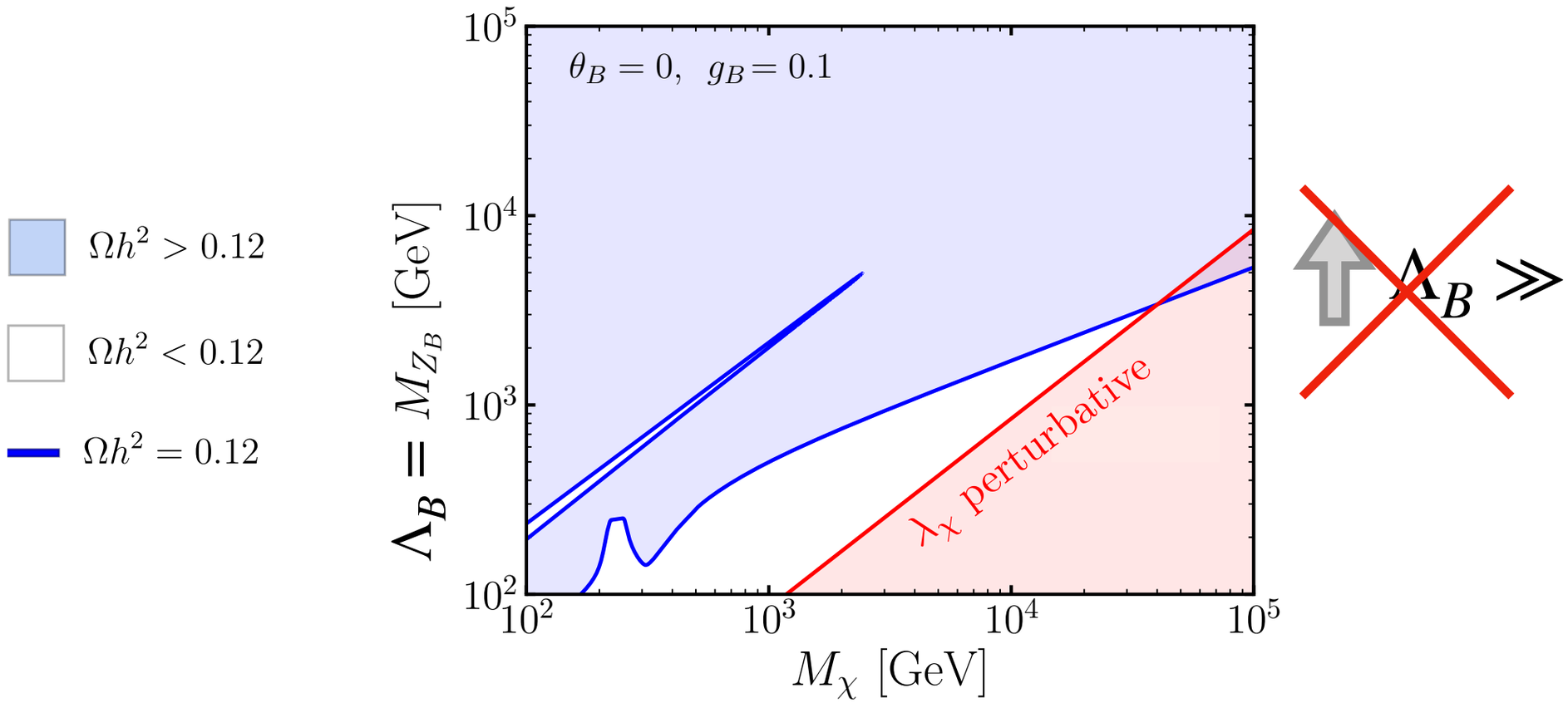


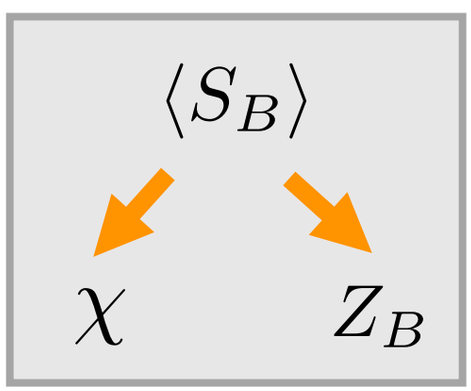


Relic Density



Relic Density

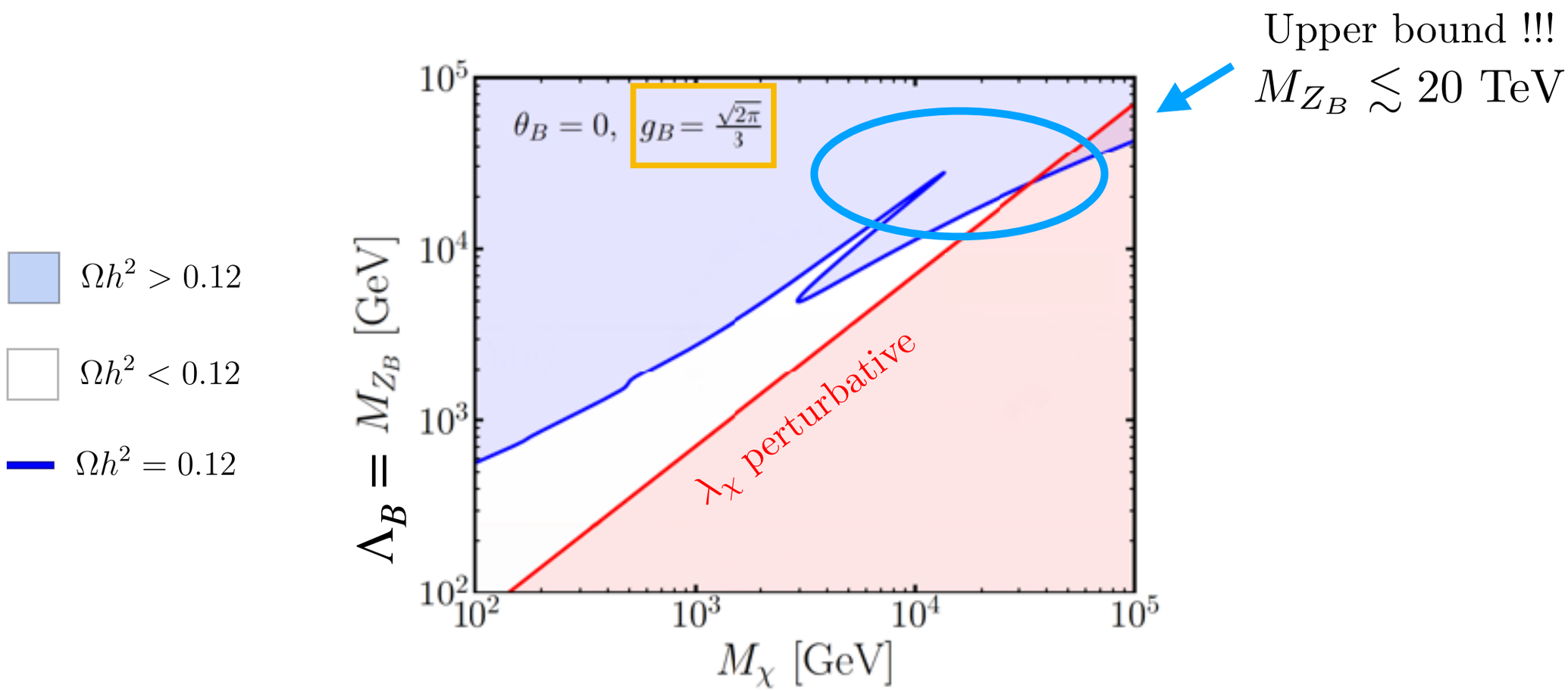




- Perturbativity sets an upper bound on the Yukawa coupling:

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

Relic Density



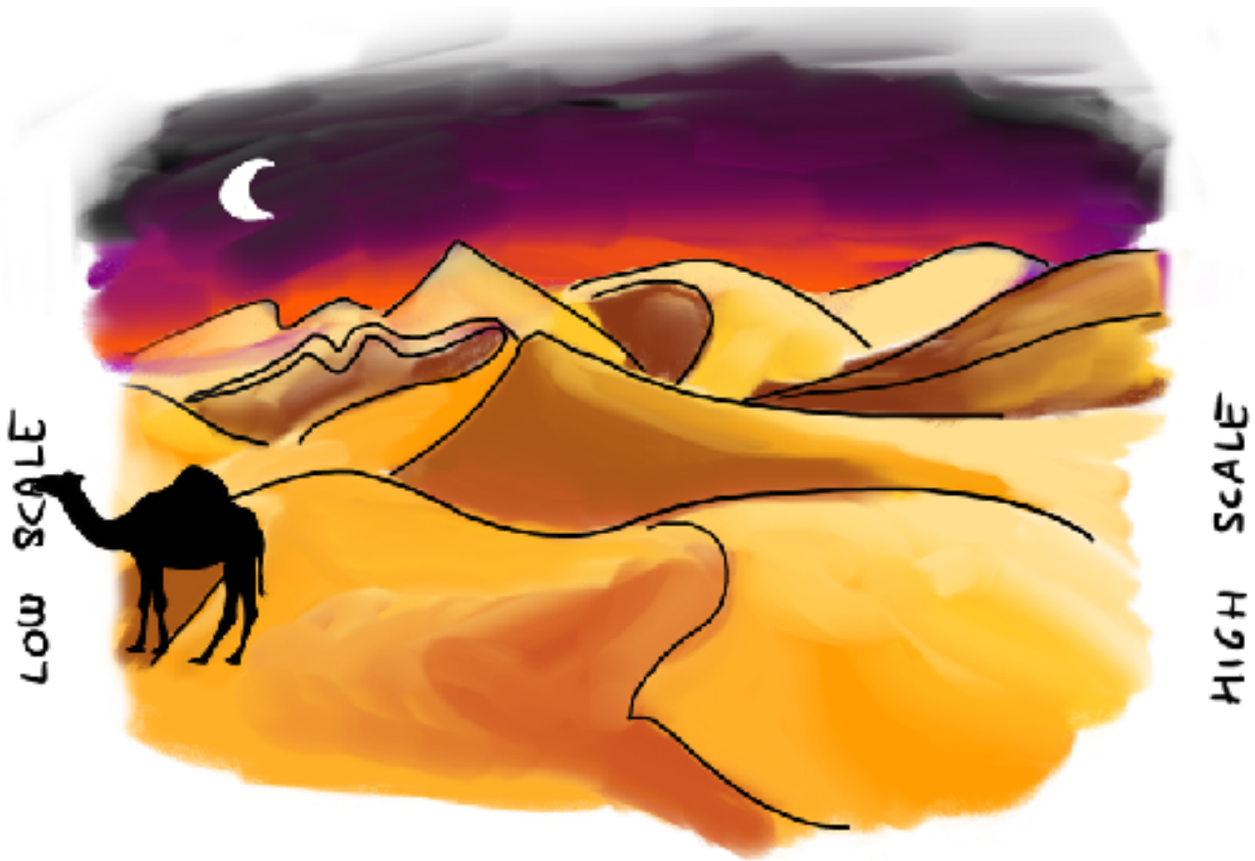
- Perturbativity sets an upper bound on the gauge coupling:

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

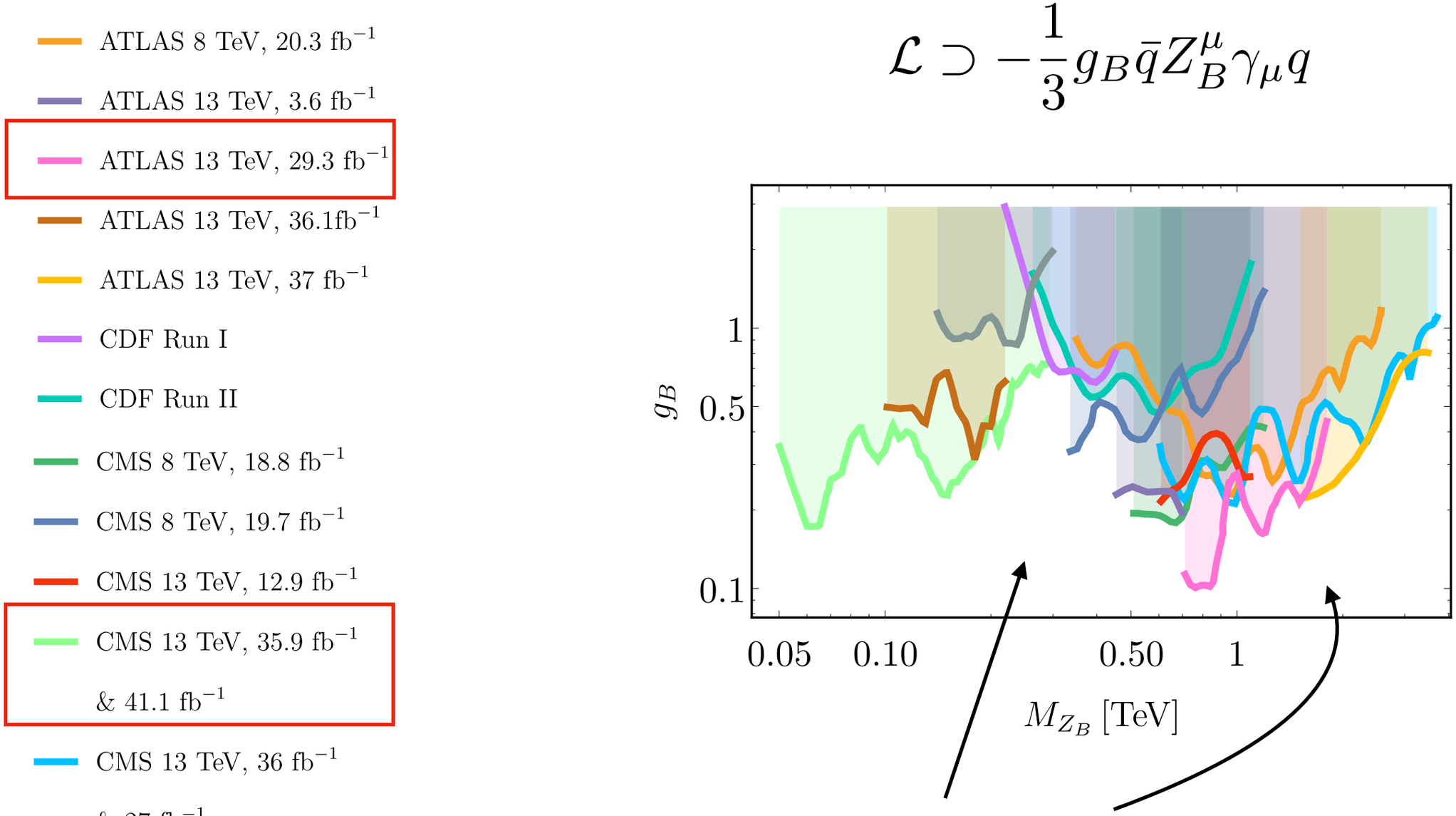
Upper bound

Upper bound

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



Collider bounds



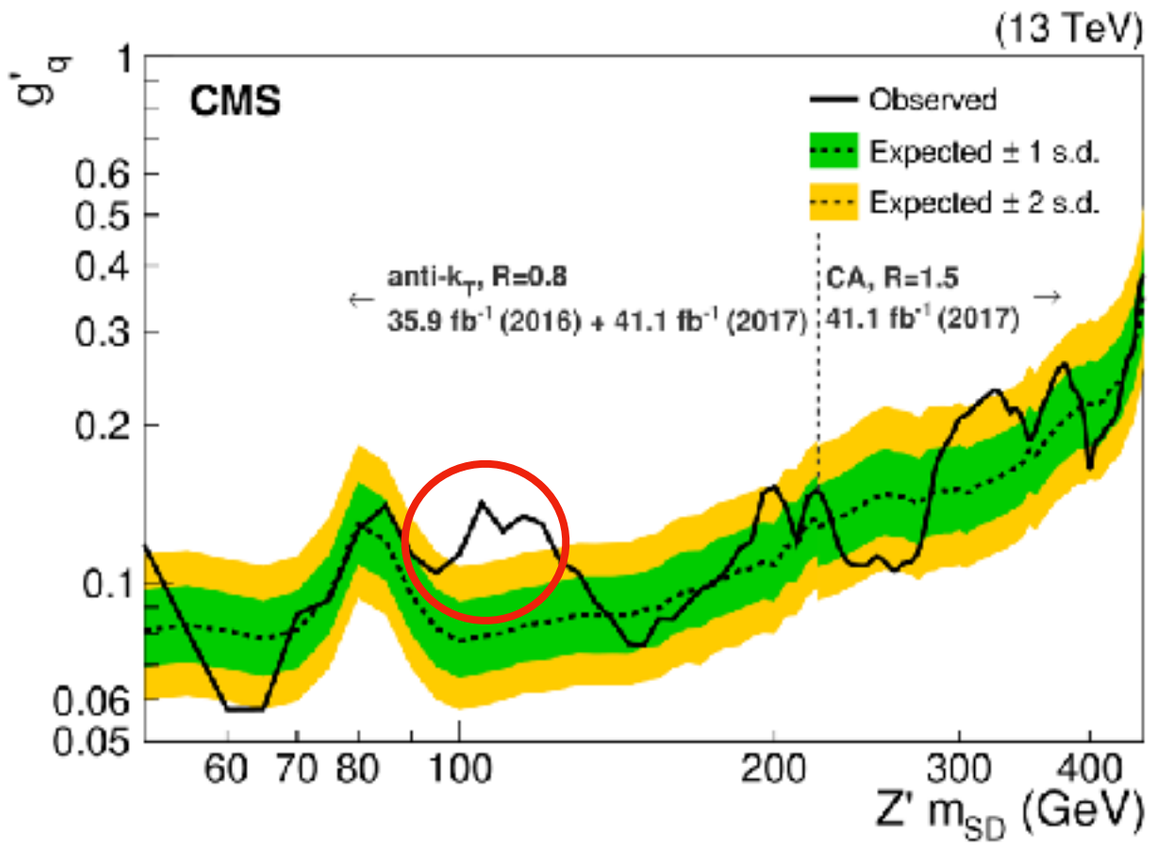
Room for a light new mediator!

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

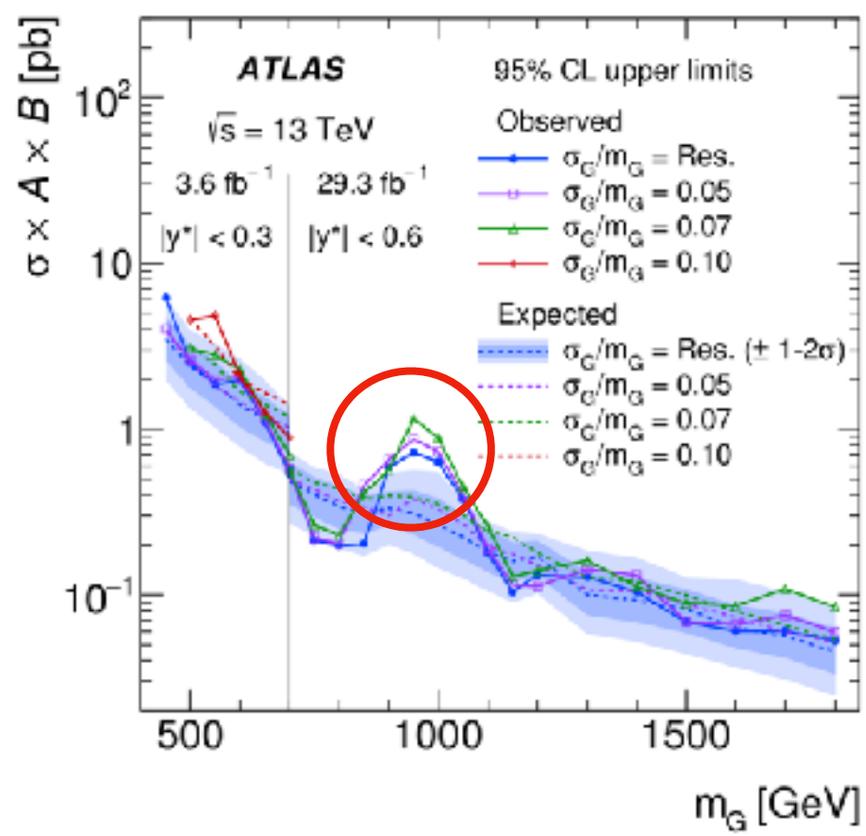
Collider bounds

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

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

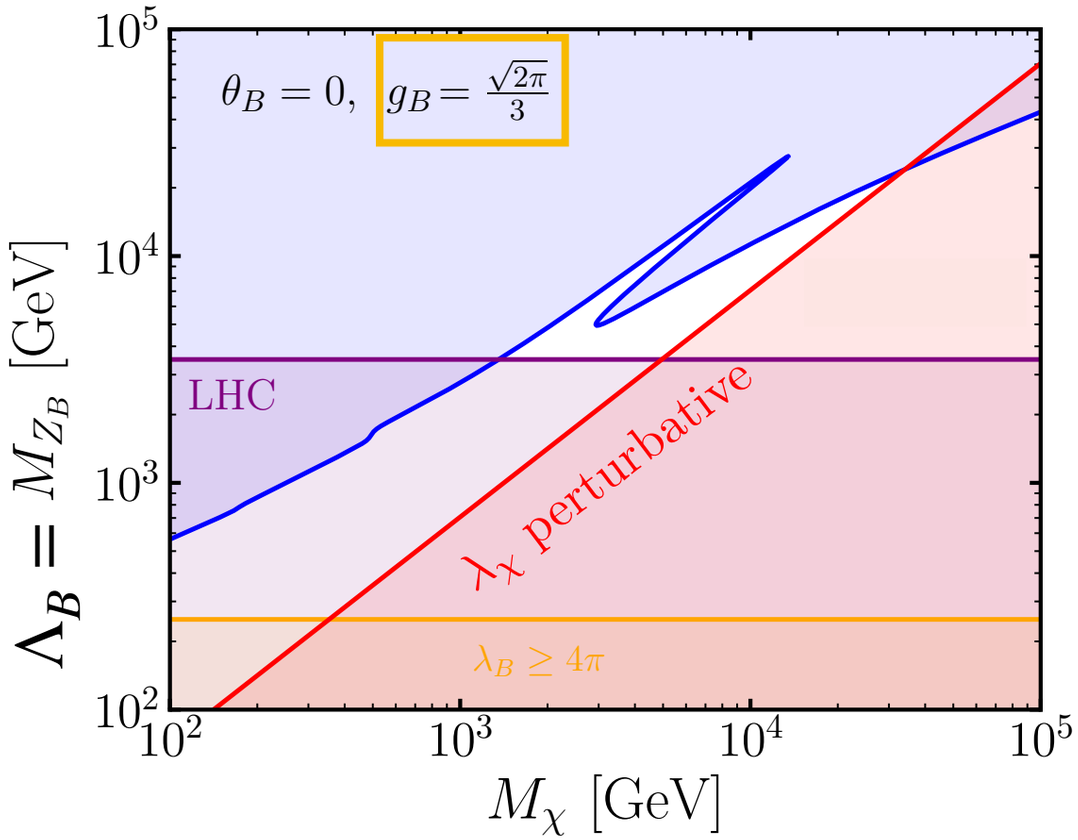


ATLAS; CERN-EP-2018-033



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

Direct searches



How could we notice

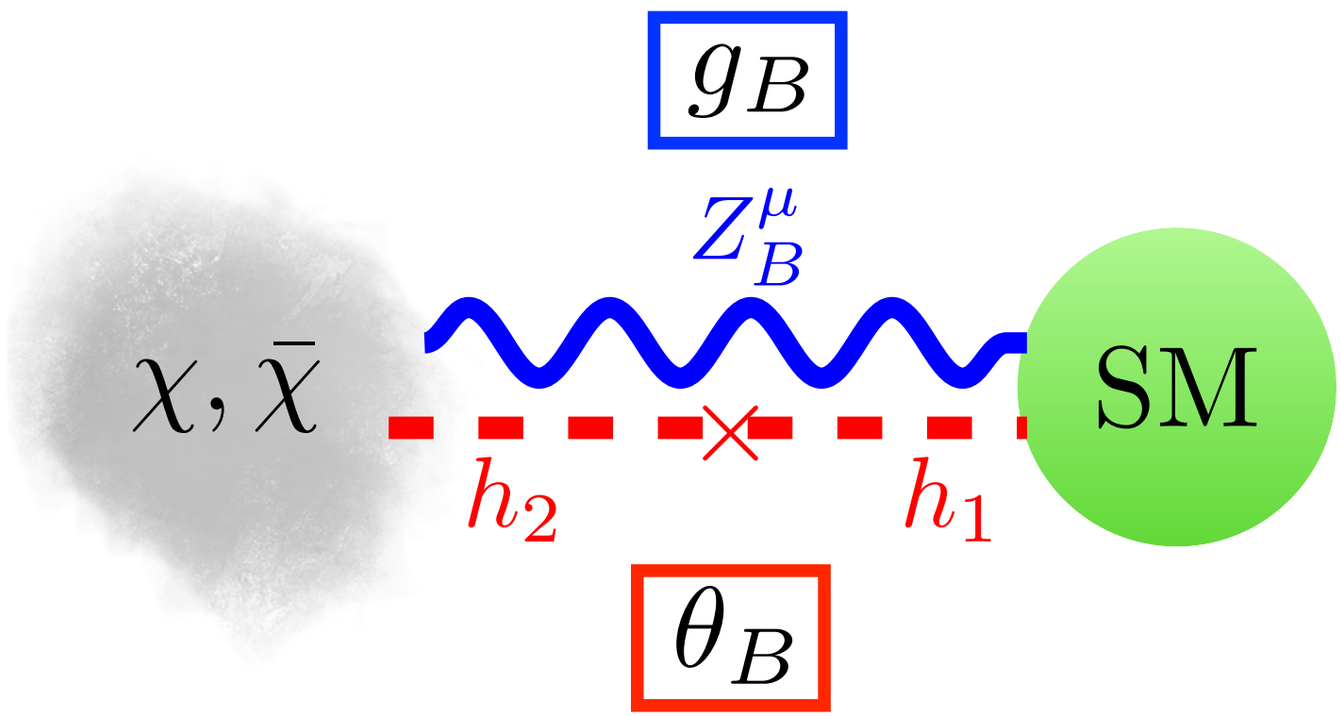
a

light

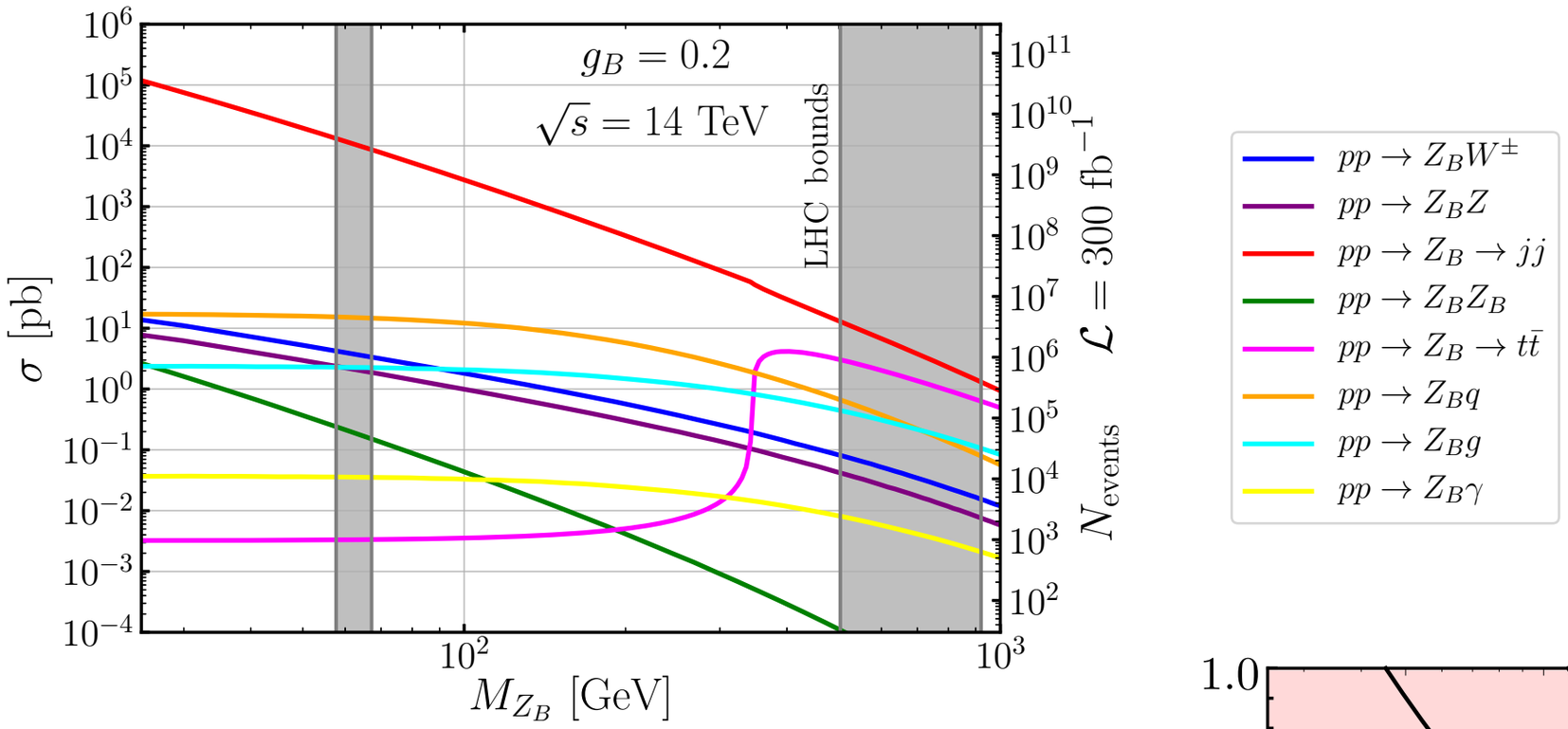
leptophobic

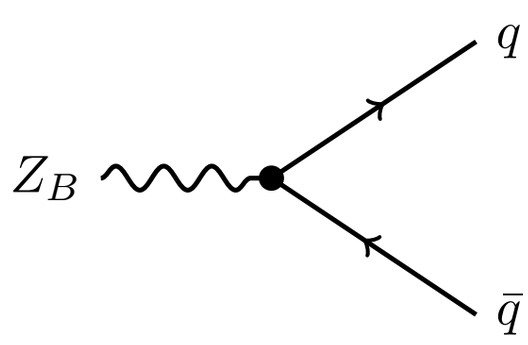
gauge boson?

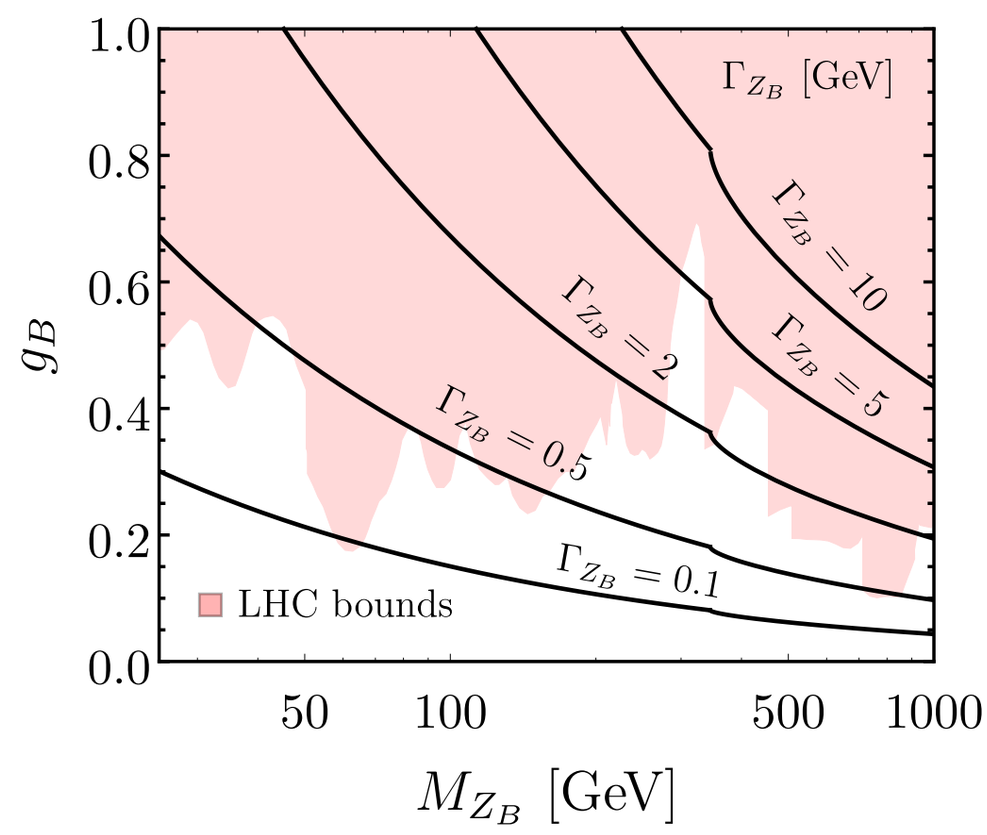
Portals to the new sector



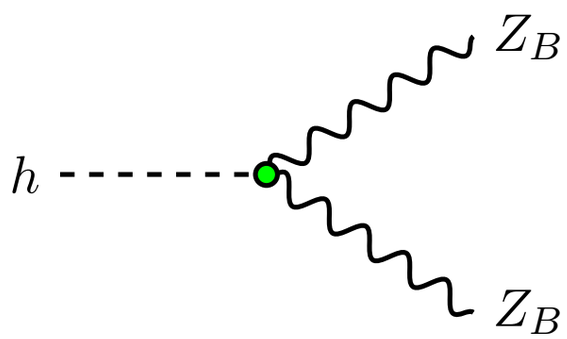
Associated production Z_B

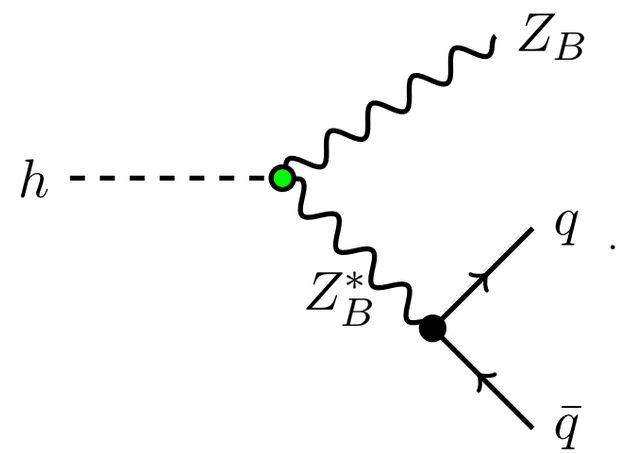


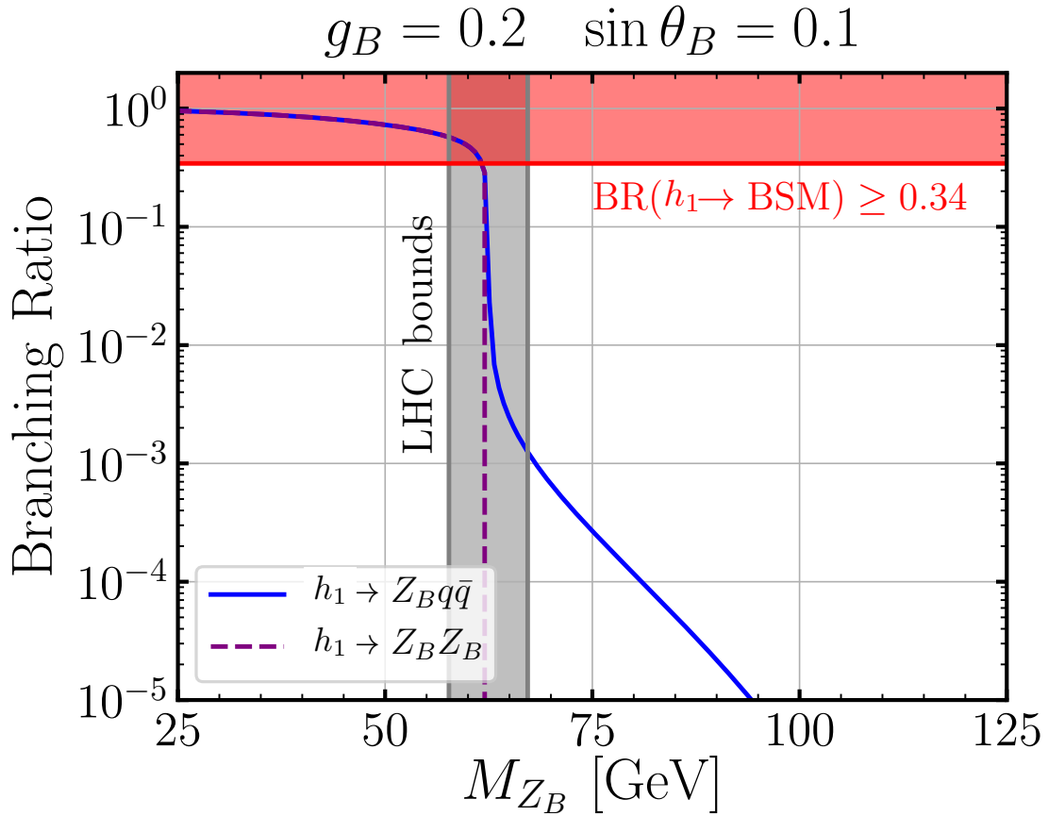


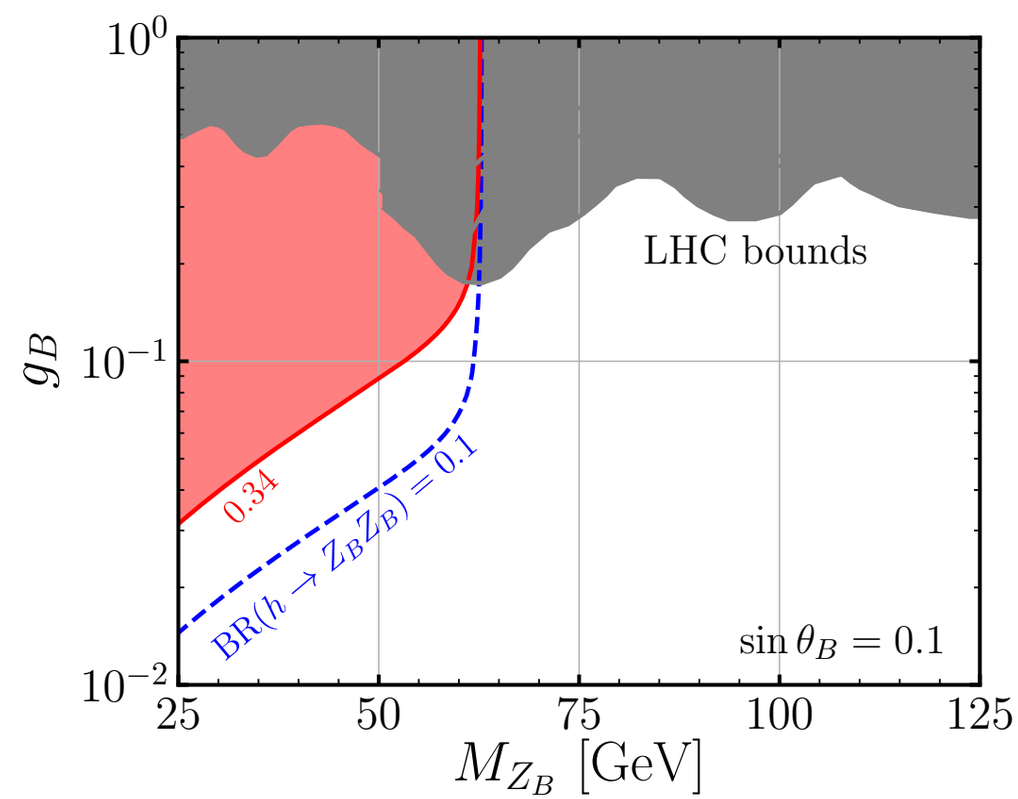


Exotic SM Higgs decays









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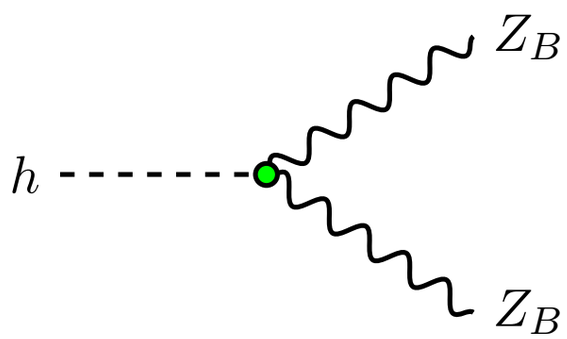
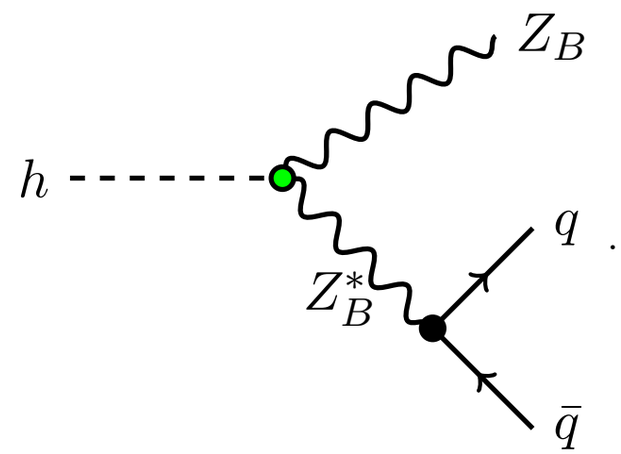
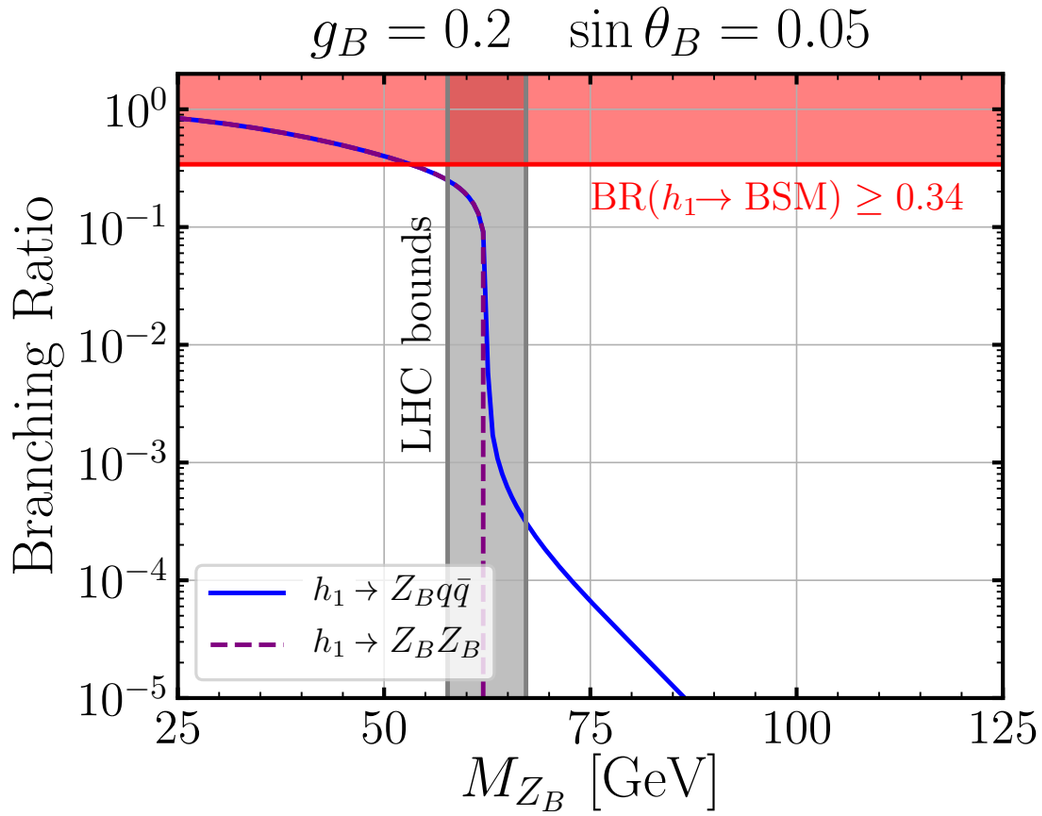
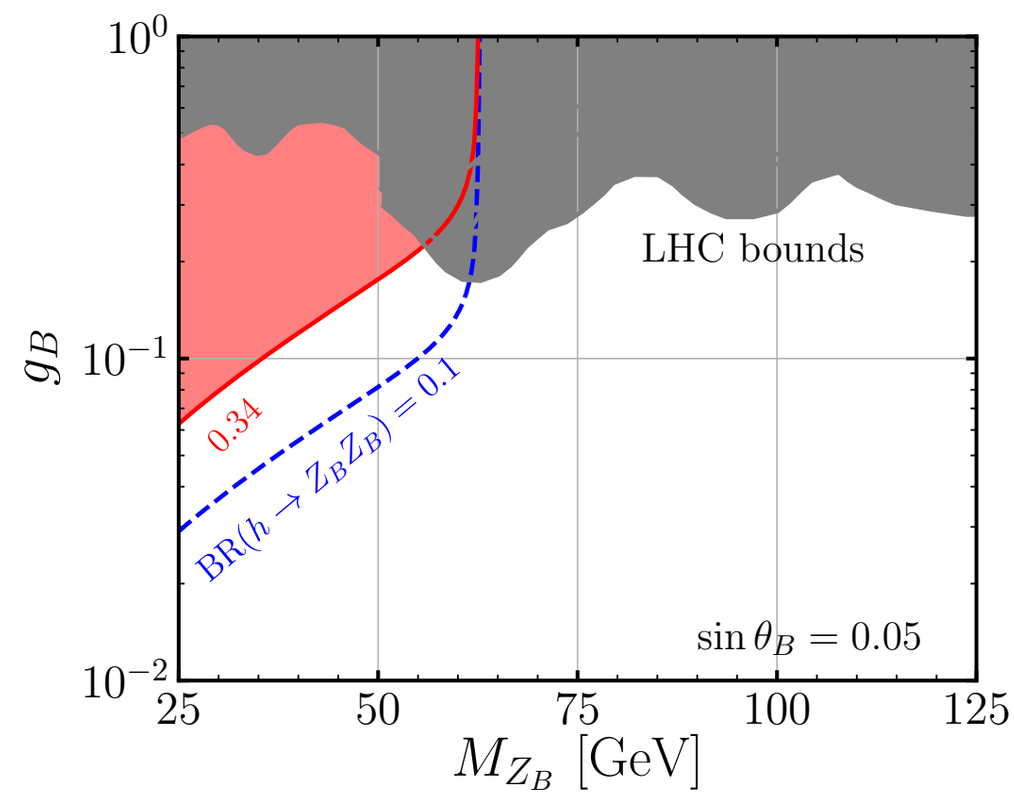


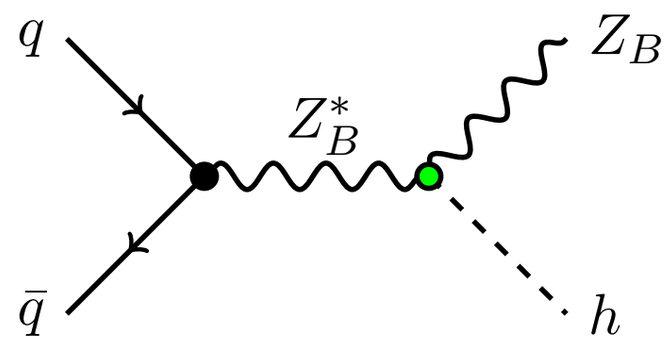




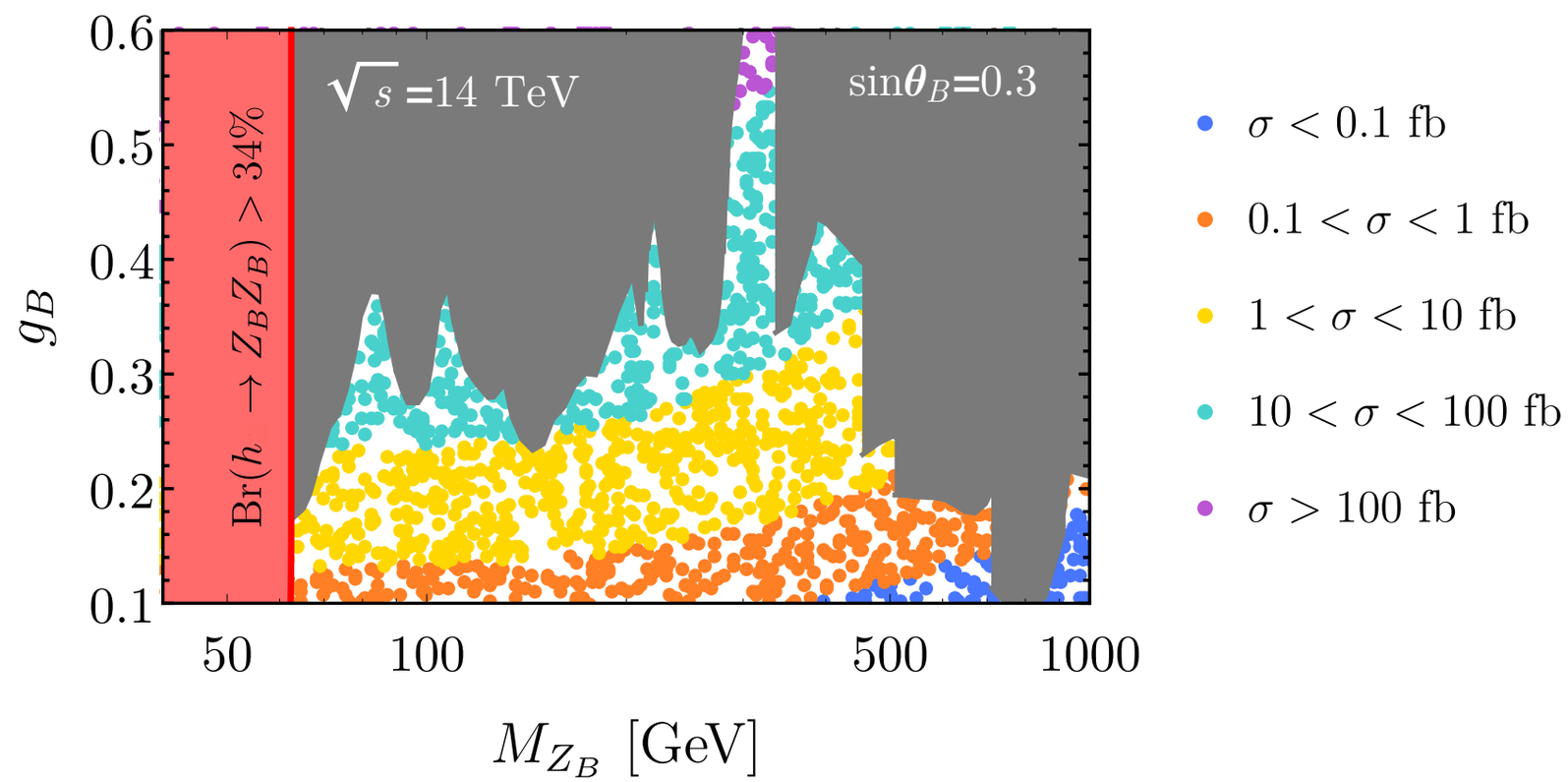


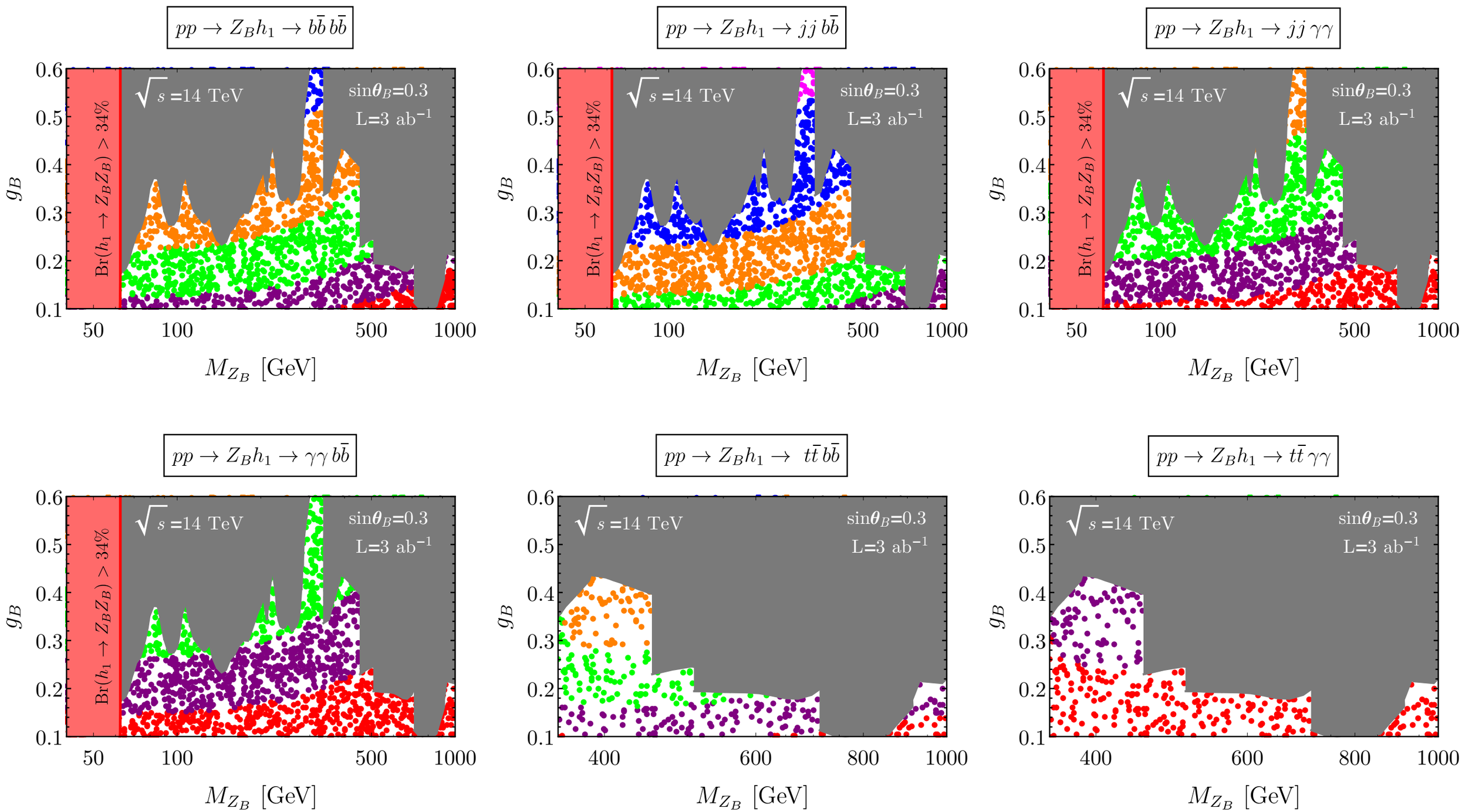
Associated production Z_B

$pp \to Z_B^* \to Z_B h,$

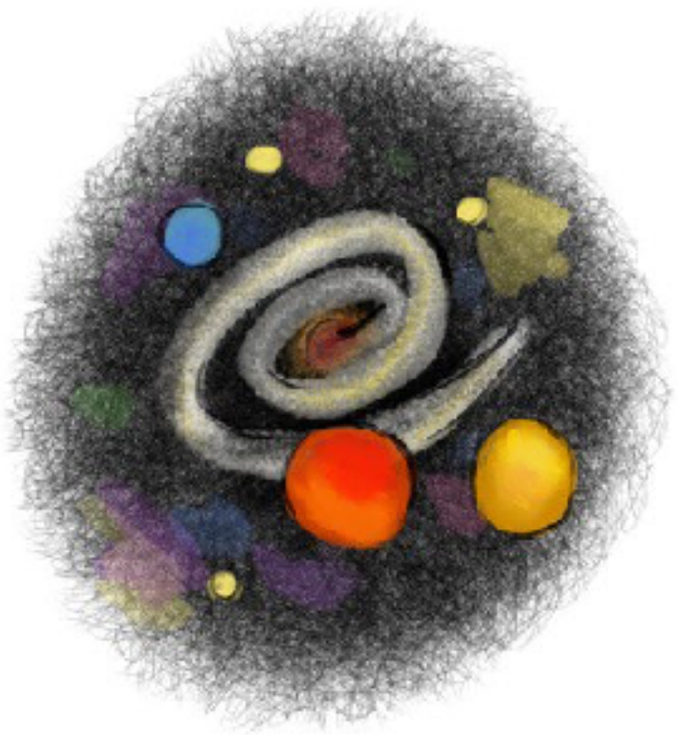


$\sigma(pp \to Z_B^* \to Z_B h_1)$

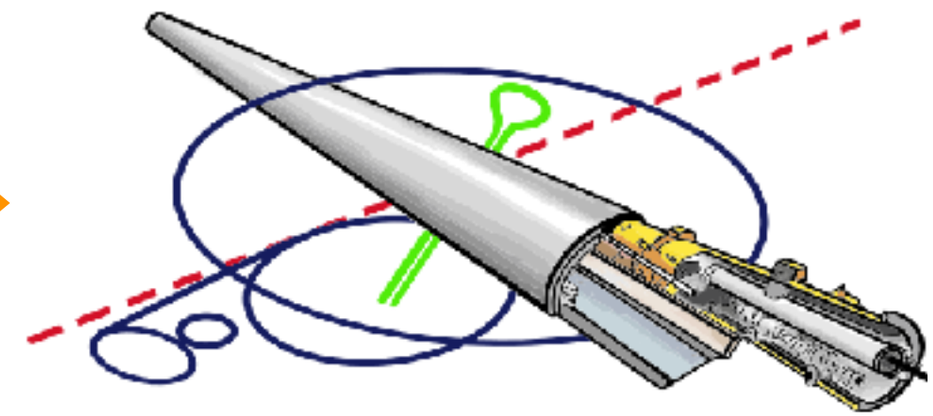



$pp \to Z_B h_1 \to b\bar{b}\, b\bar{b}$
$pp \to Z_B h_1 \to jj\, b\bar{b}$
$pp \to Z_B h_1 \to jj\, \gamma\gamma$
$pp \to Z_B h_1 \to \gamma\gamma\, b\bar{b}$
$pp \to Z_B h_1 \to t\bar{t}\, b\bar{b}$
$pp \to Z_B h_1 \to t\bar{t}\, \gamma\gamma$
$\sqrt{s}$ =14 TeV
$\sin\theta_B$=0.3
L=3 ab^{-1}
$\mathrm{Br}(h_1 \to Z_B Z_B) > 34\%$
g_B
M_{Z_B} [GeV]
$N_{\rm events} > 10^5$
$10^4 < N_{\rm events} < 10^5$
$10^3 < N_{\rm events} < 10^4$
$10^2 < N_{\rm events} < 10^3$
$10 < N_{\rm events} < 10^2$
$N_{\rm events} < 10$

Exploiting the connection DM - colliders

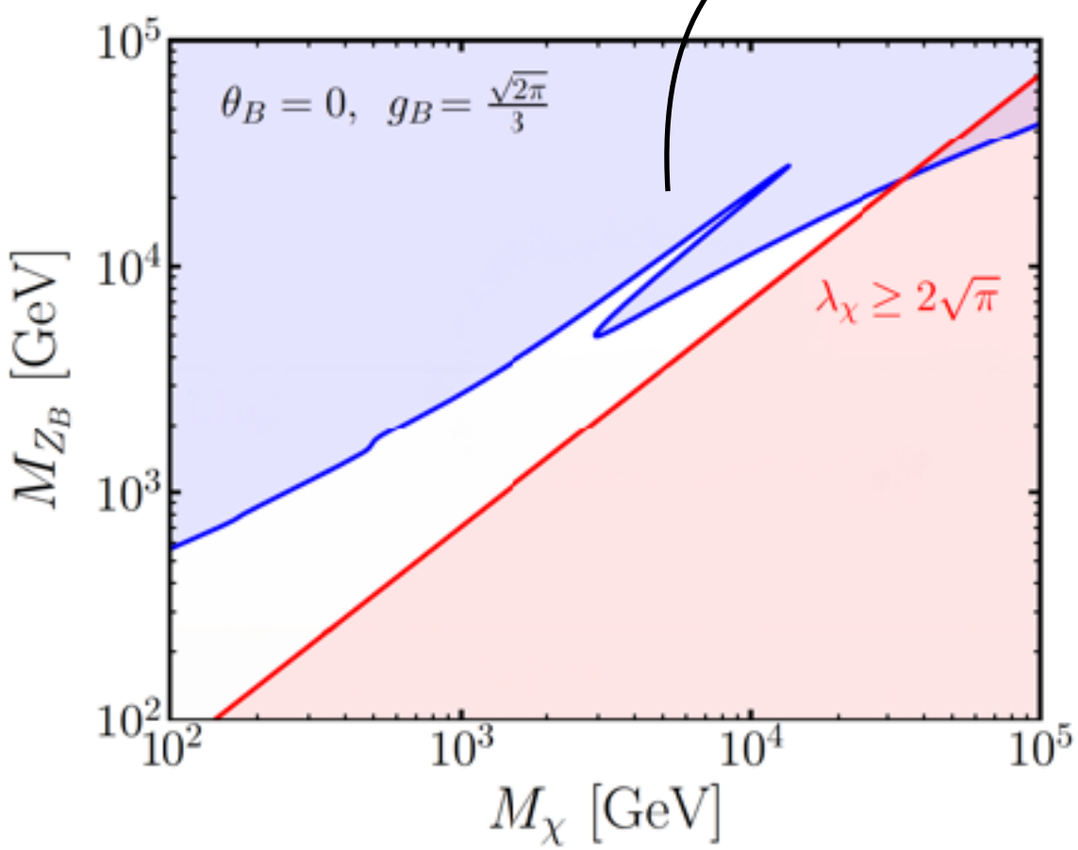


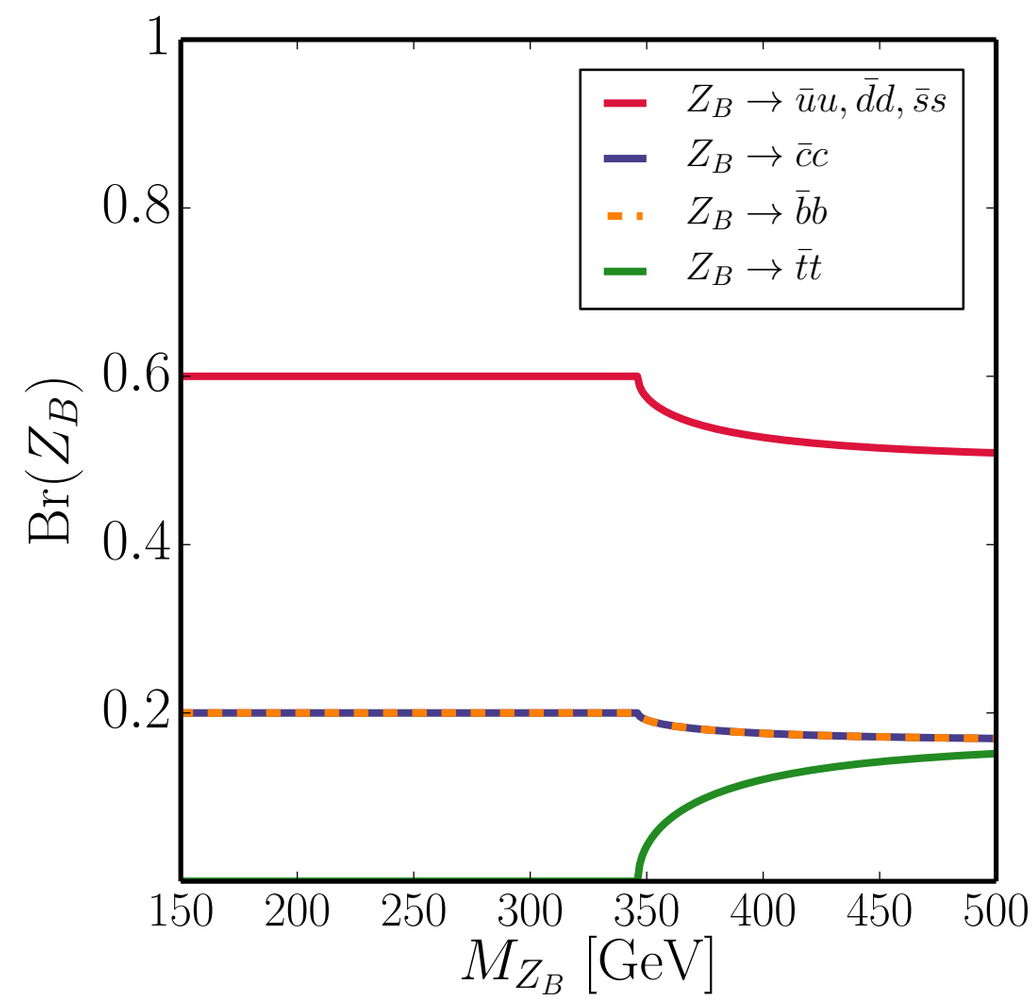
$U(1)_B$



Exploiting the connection DM - colliders

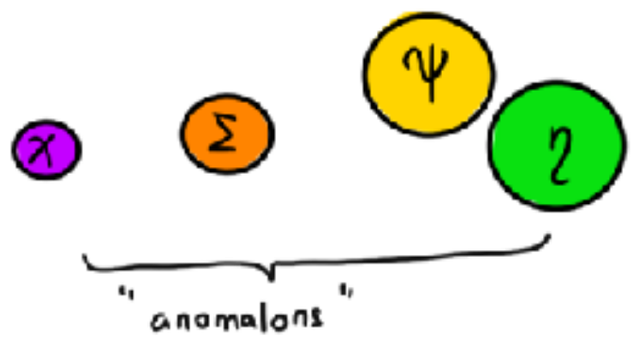
$\Lambda_B < 20$ TeV



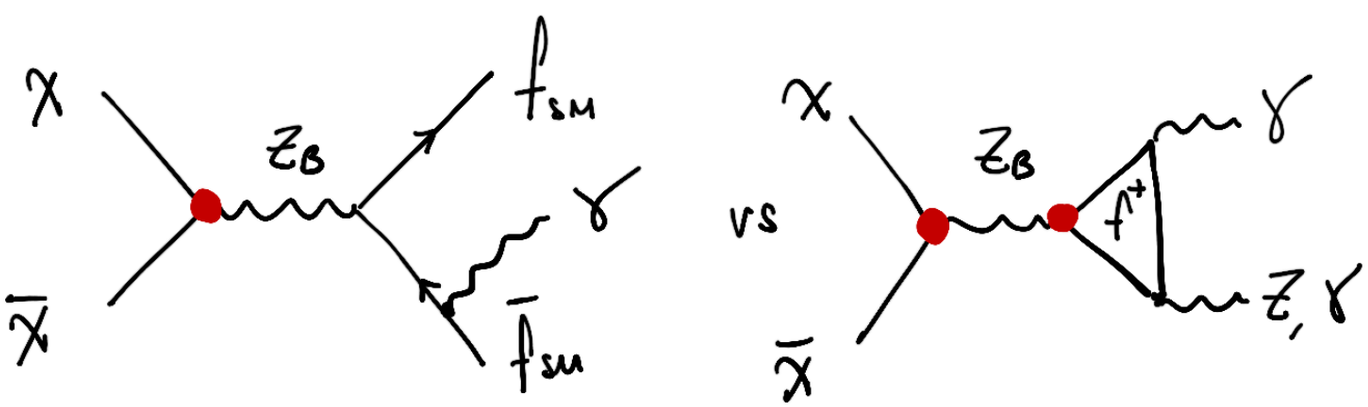


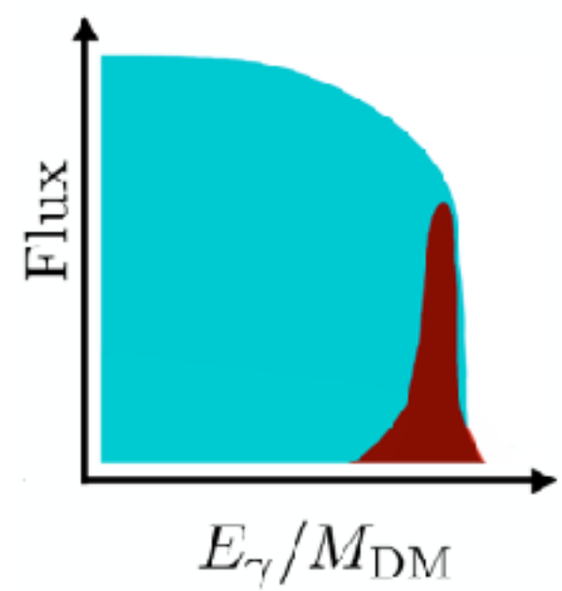
$$\Rightarrow Z_B \not\to \bar{\chi}\chi, \bar{F}F$$

Indirect searches

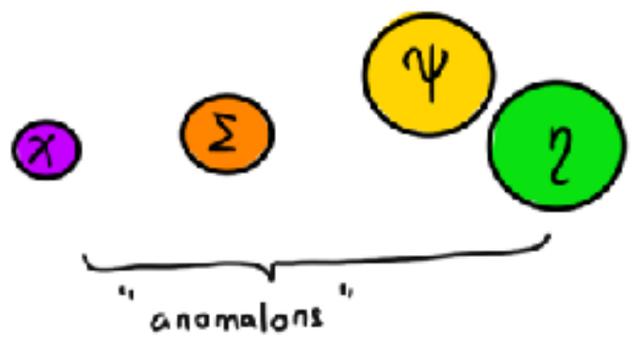


$$\gamma_\mu \gamma_5 Z_B^\mu$$

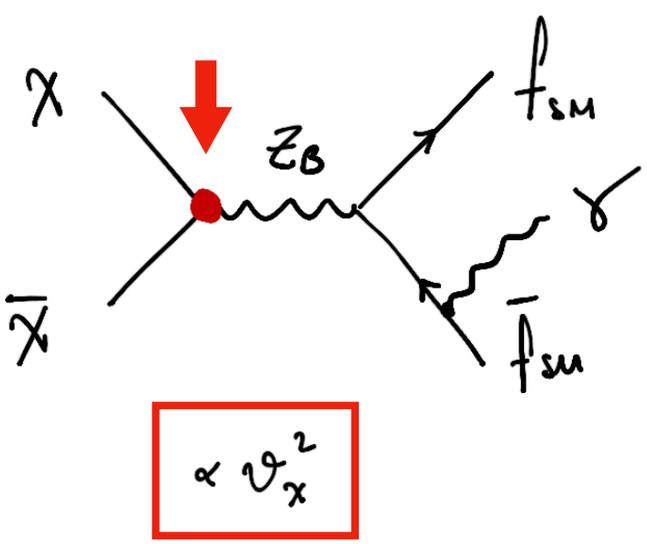


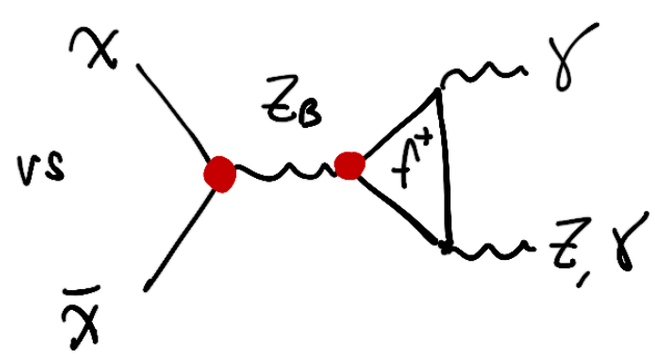


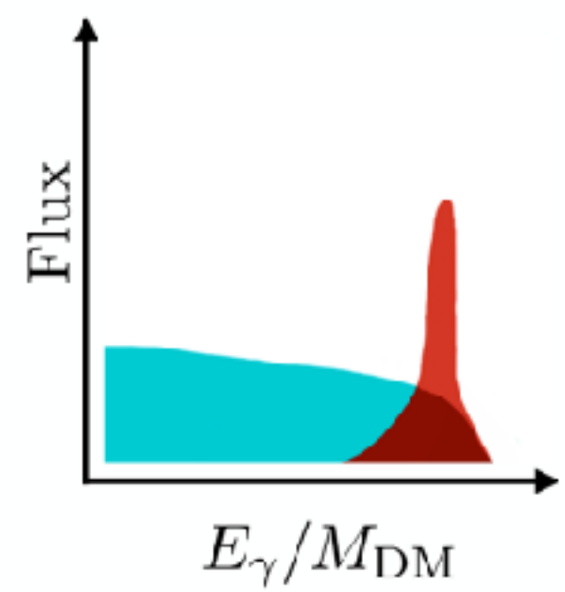
Indirect searches



$$\gamma_\mu \gamma_5 Z_B^\mu$$

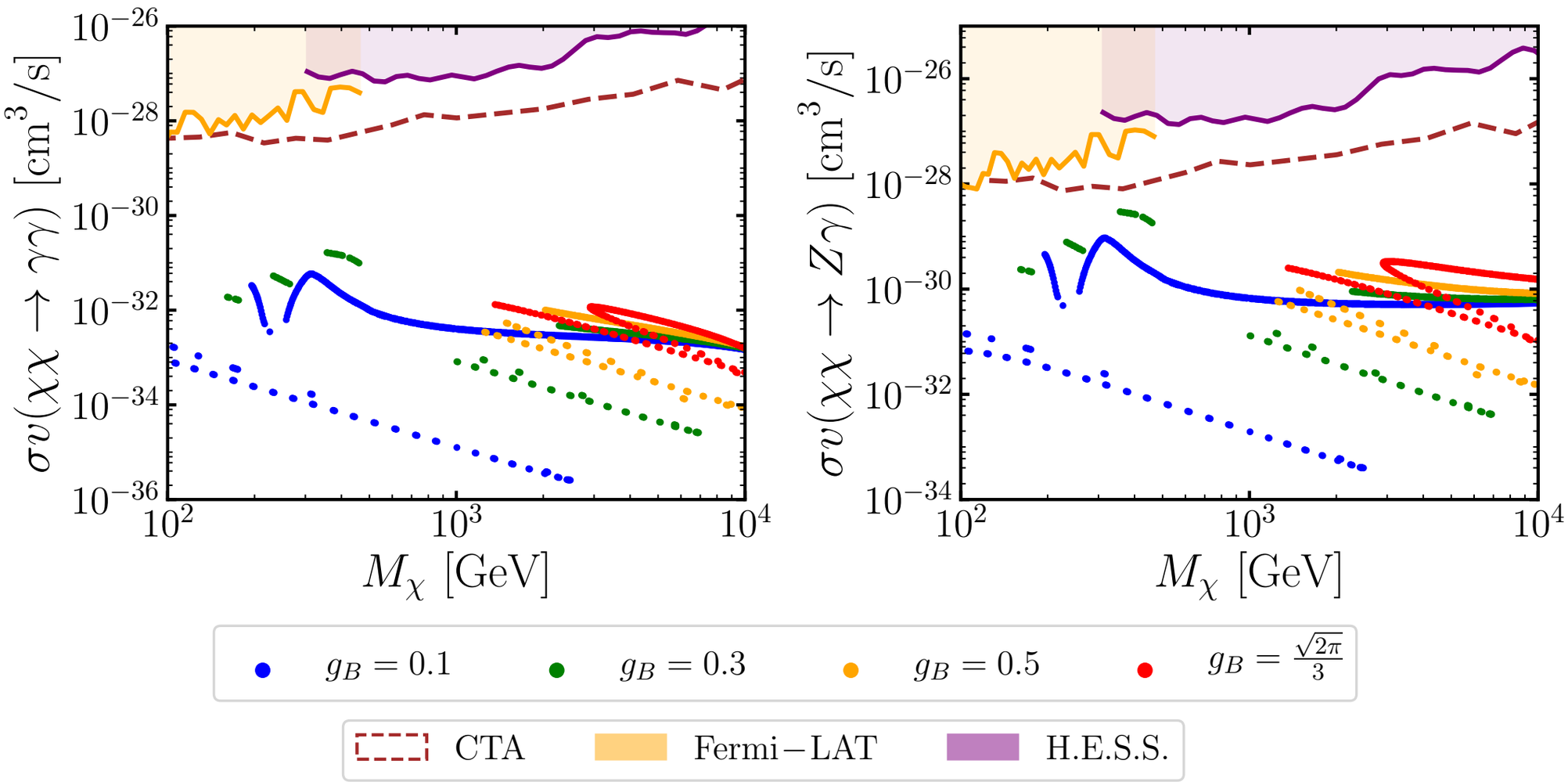




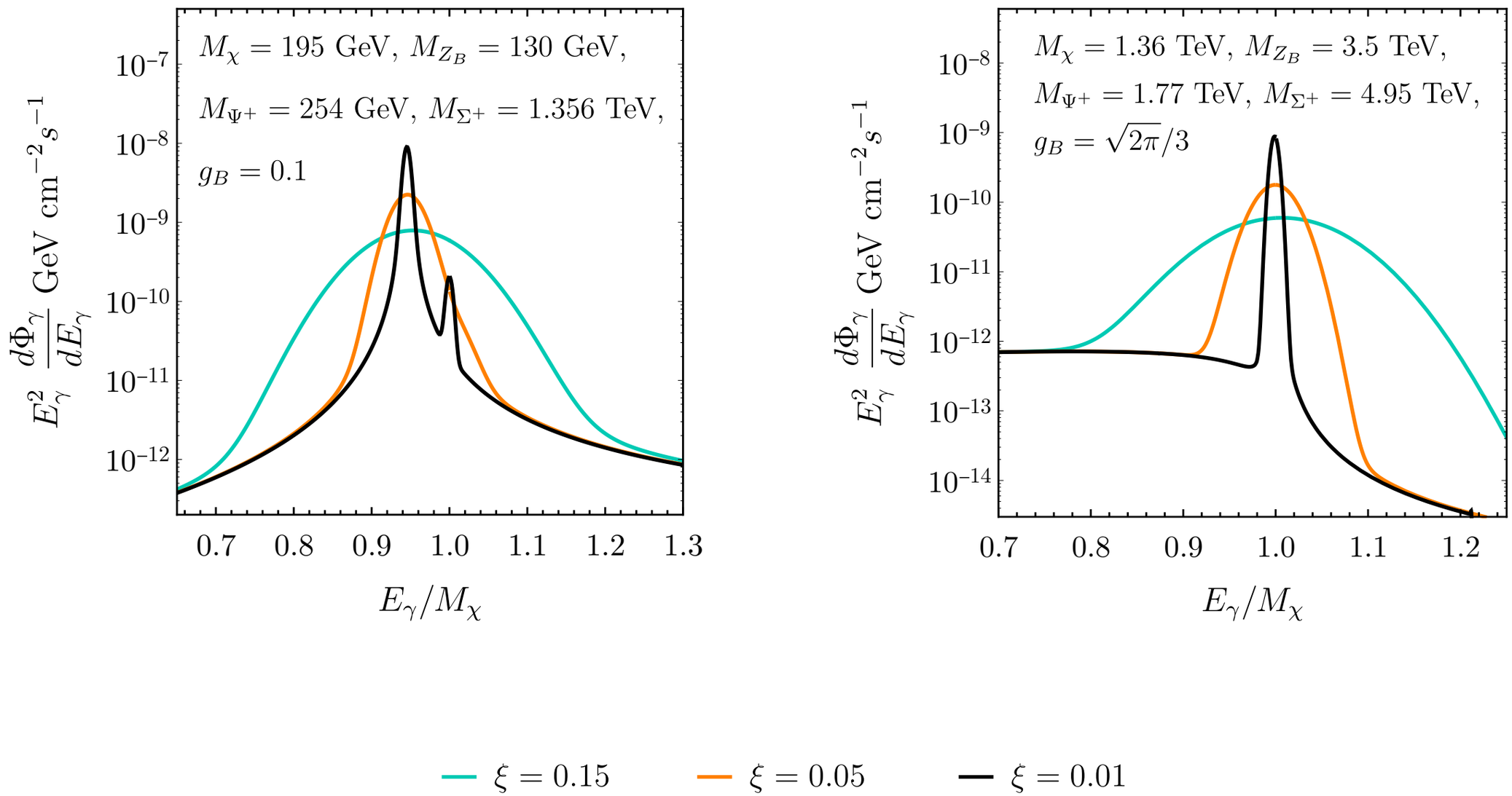


$$|\mathcal{M}|^2_{\rm FSR} = \frac{M_q^2}{M_{Z_B}^2} A + v^2 B + \mathcal{O}(v^4)$$

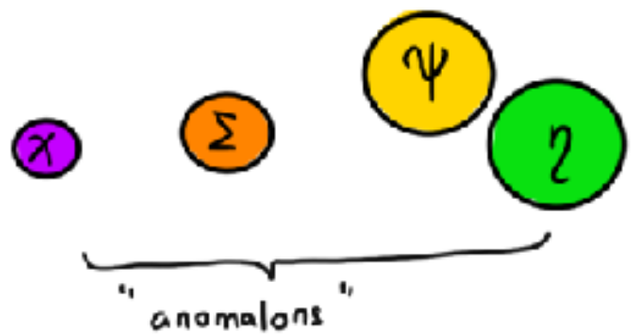
Indirect searches



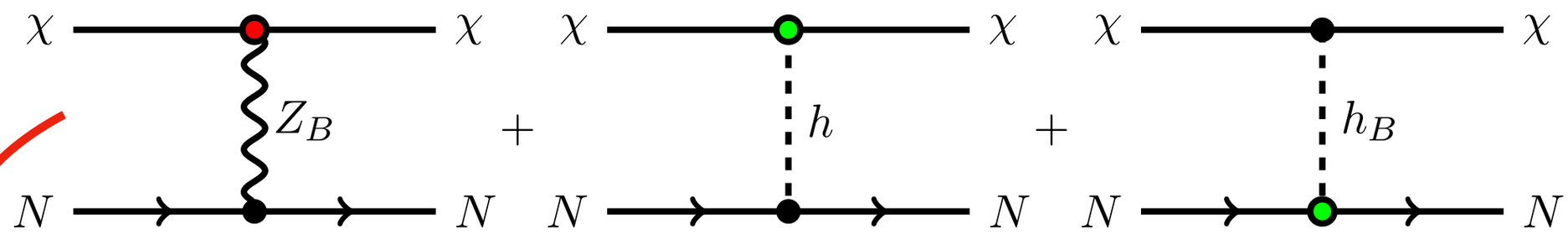
Indirect searches



Direct searches



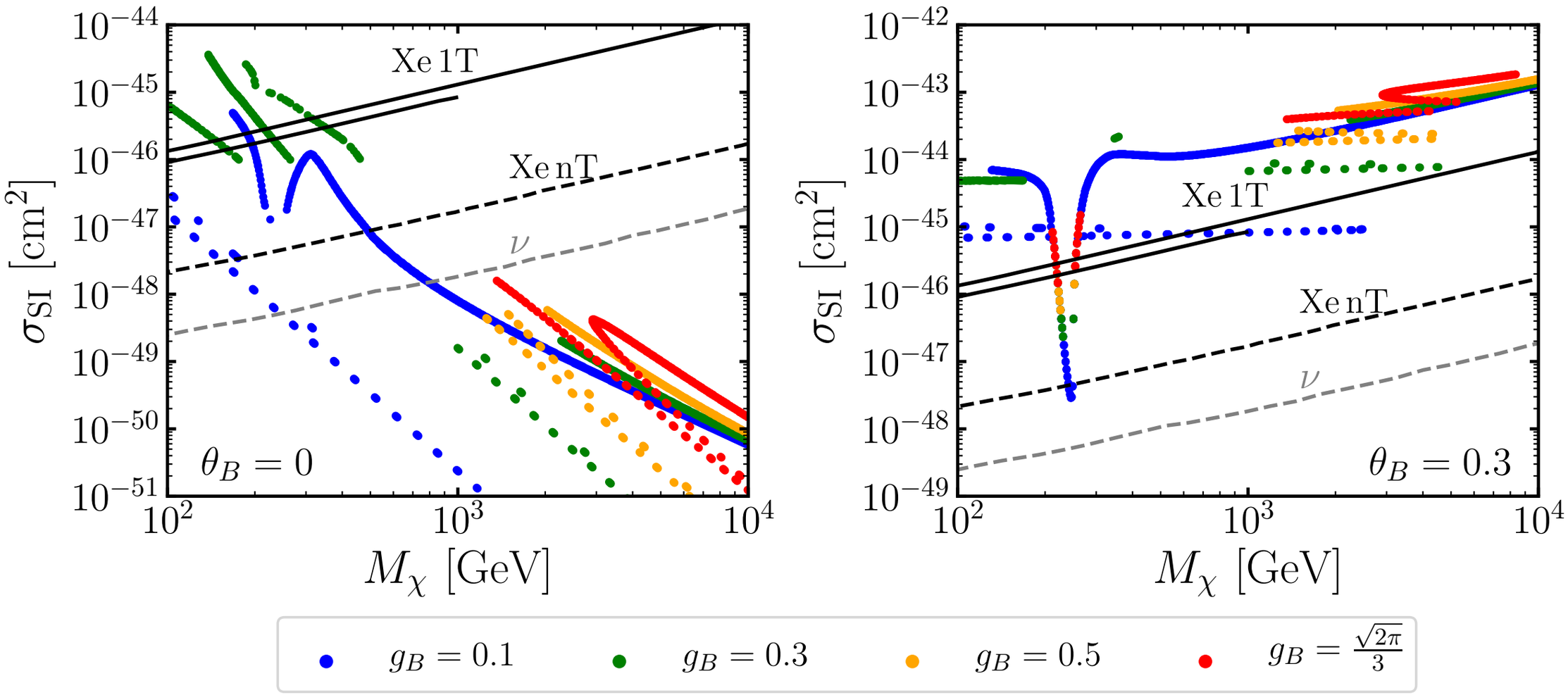
$$\gamma_\mu \gamma_5 Z_B^\mu$$



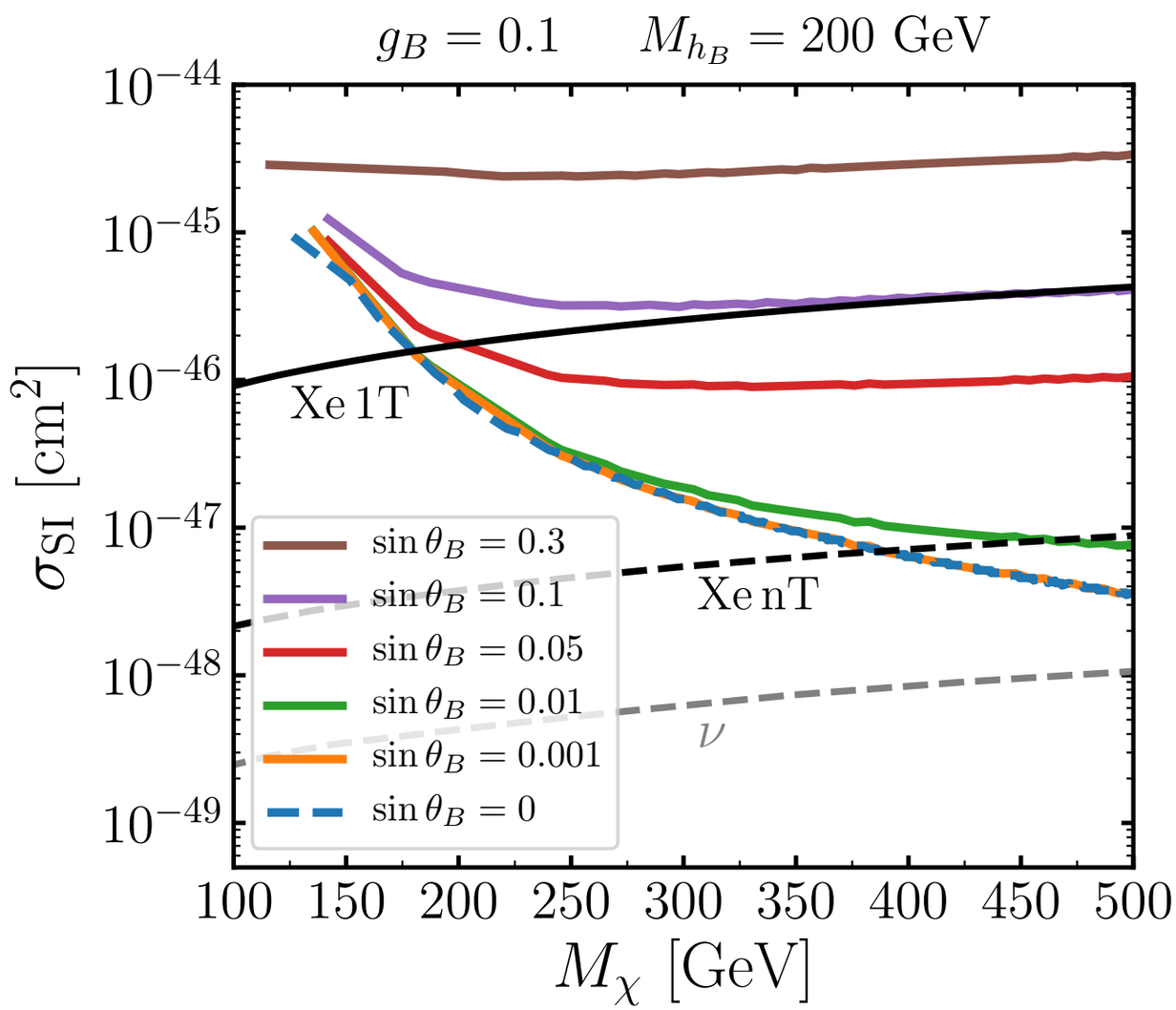
$$\sigma^{\rm SI}_{\chi N}(Z_B) = \frac{27}{8\pi}\frac{g_B^4 M_N^2}{M_{Z_B}^4} v^2$$

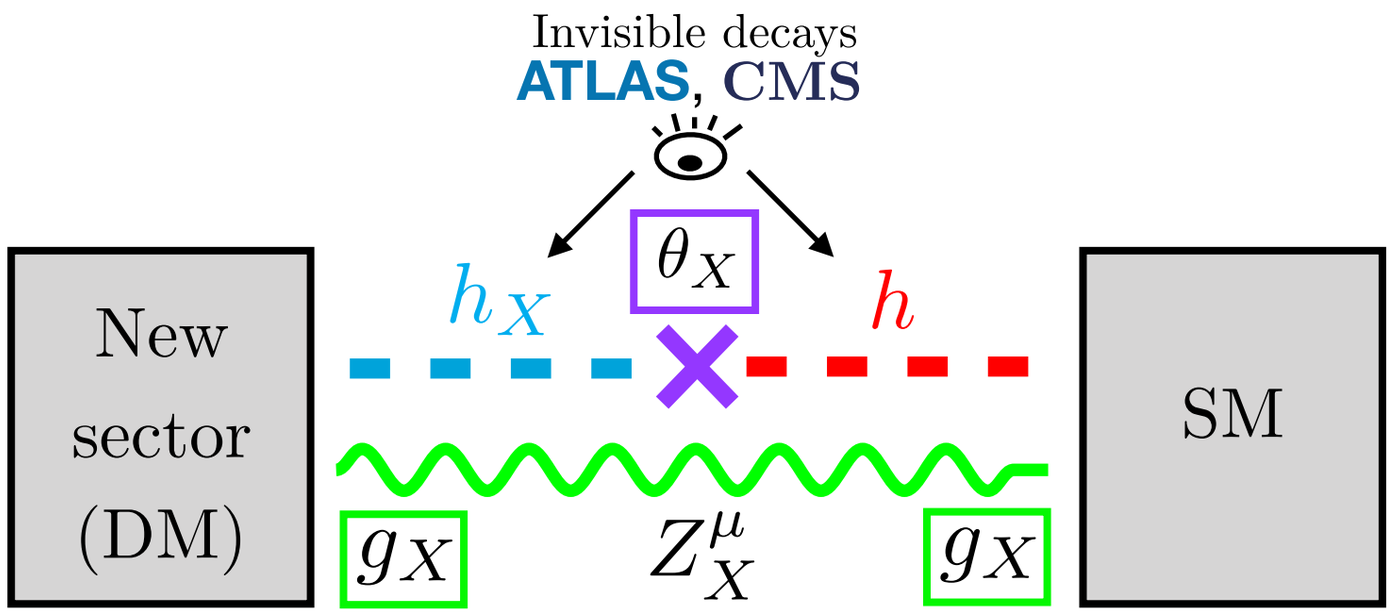
$$\sigma^{\rm SI}_{\chi N}(h_i) = \frac{72\, G_F}{16\pi\sqrt{2}} \sin^2(2\theta_B) M_N^4 \frac{g_B^2 M_\chi^2}{M_{Z_B}^2}\left(\frac{1}{M_{h_1}^2} - \frac{1}{M_{h_2}^2}\right)^2 f_N^2$$

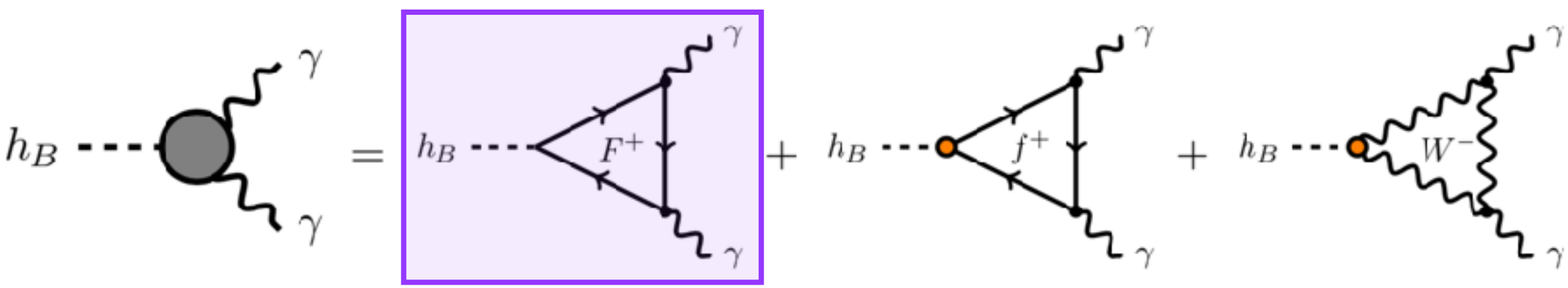
Direct searches



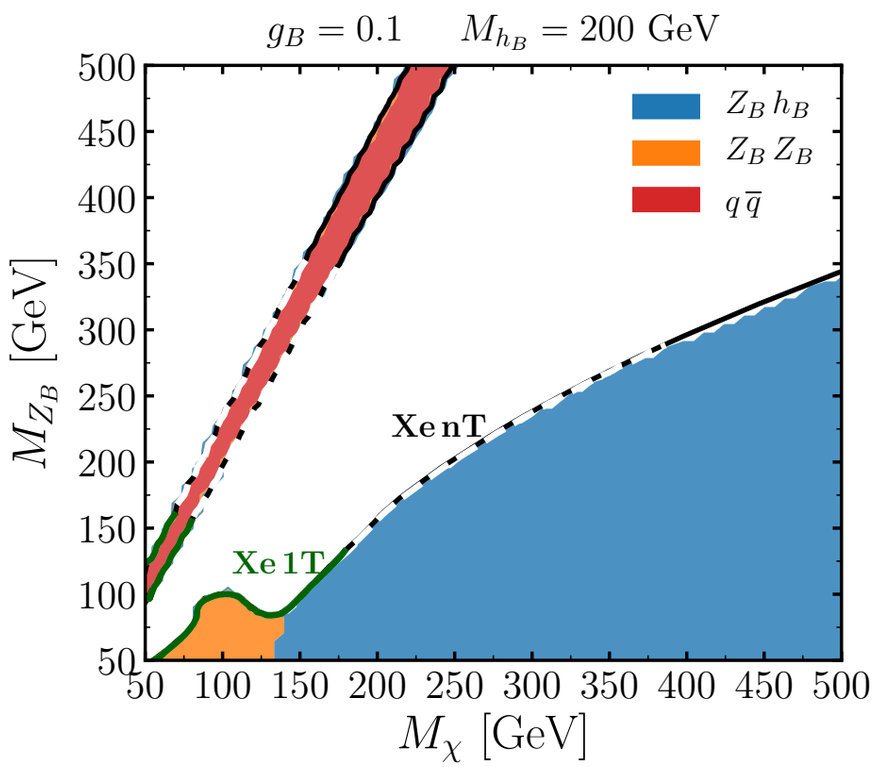
Direct searches

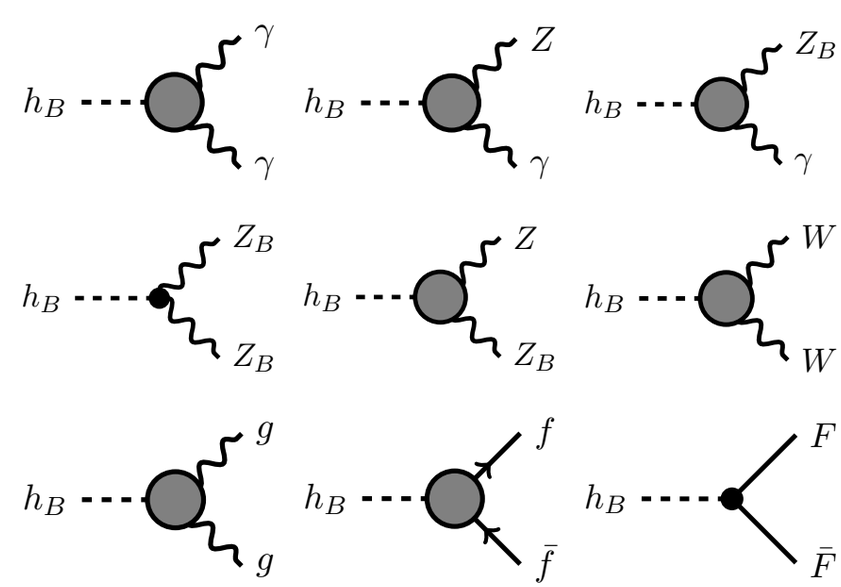



Invisible decays
ATLAS, CMS
New sector (DM)
h_X
θ_X
h
SM
g_X
Z_X^μ
g_X


h_B
γ
γ
=
h_B
F^+
γ
γ
+
h_B
f^+
γ
γ
+
h_B
W^-
γ
γ

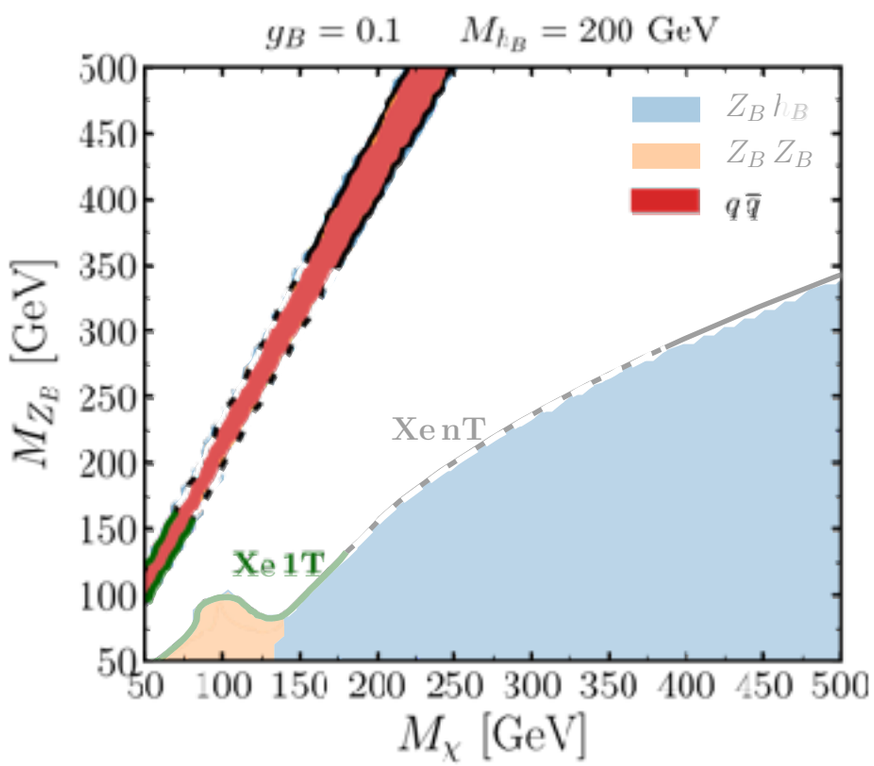
Baryonic Higgs

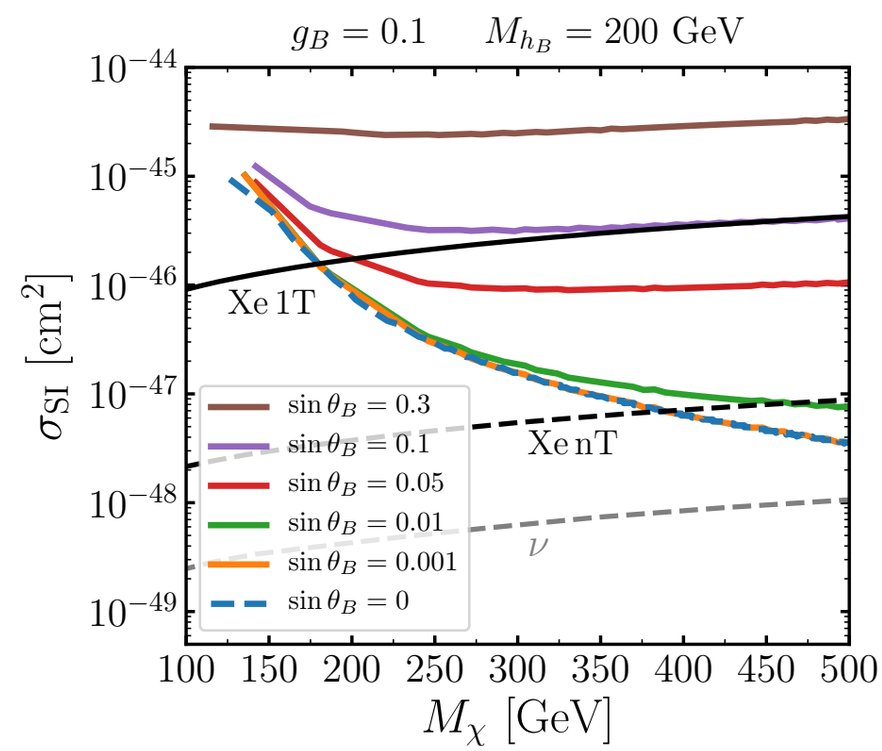




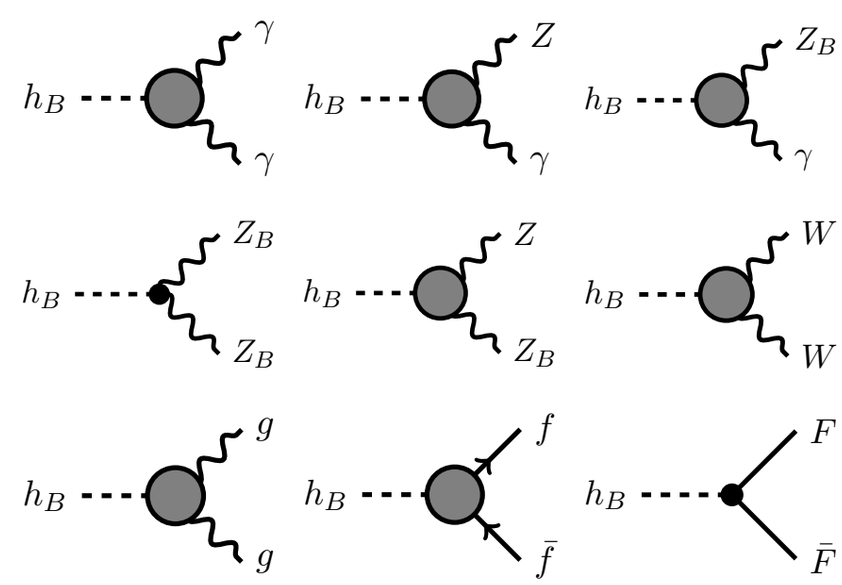
Baryonic Higgs

I



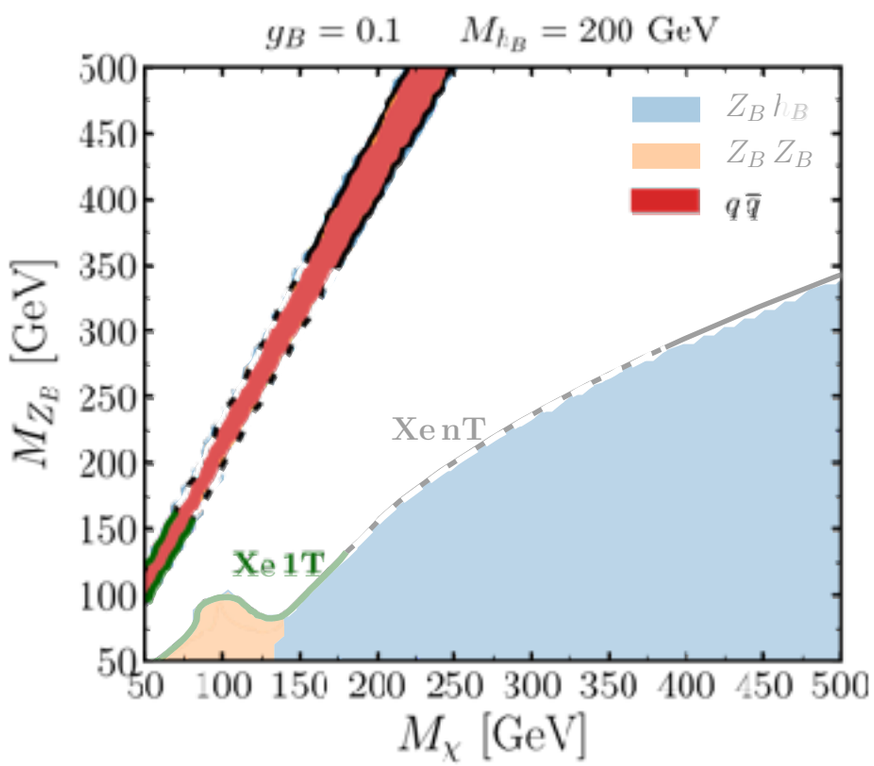


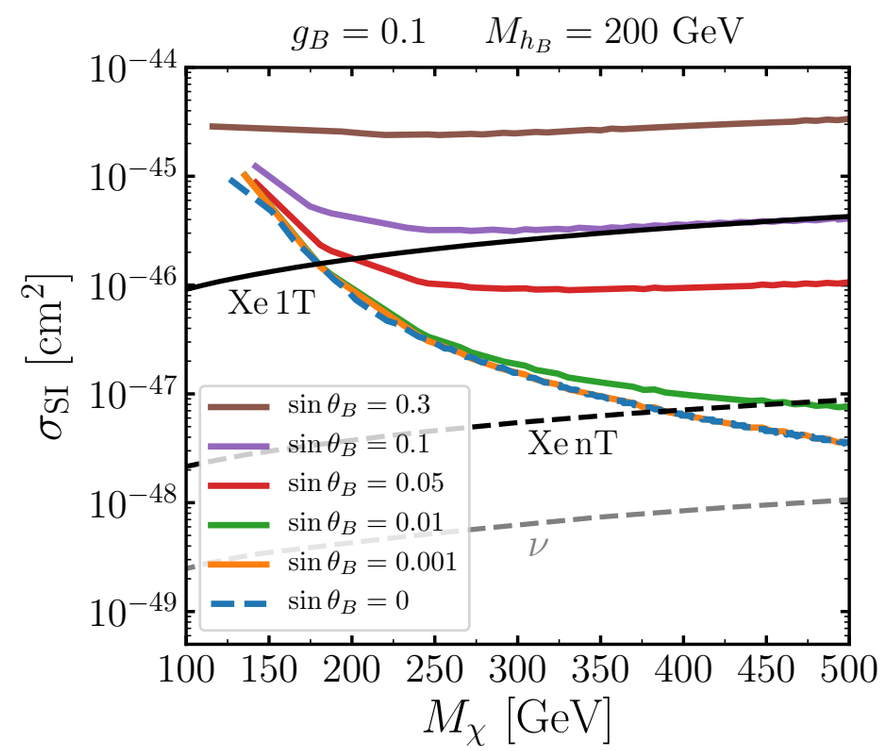
$$M_{Z_B} \sim 2M_\chi$$



Baryonic Higgs

I





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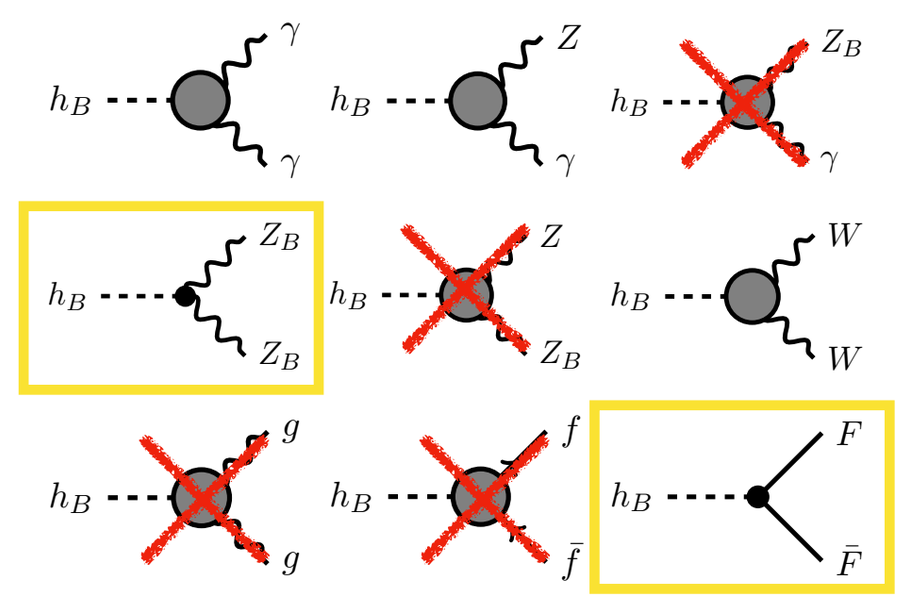

Baryonic Higgs

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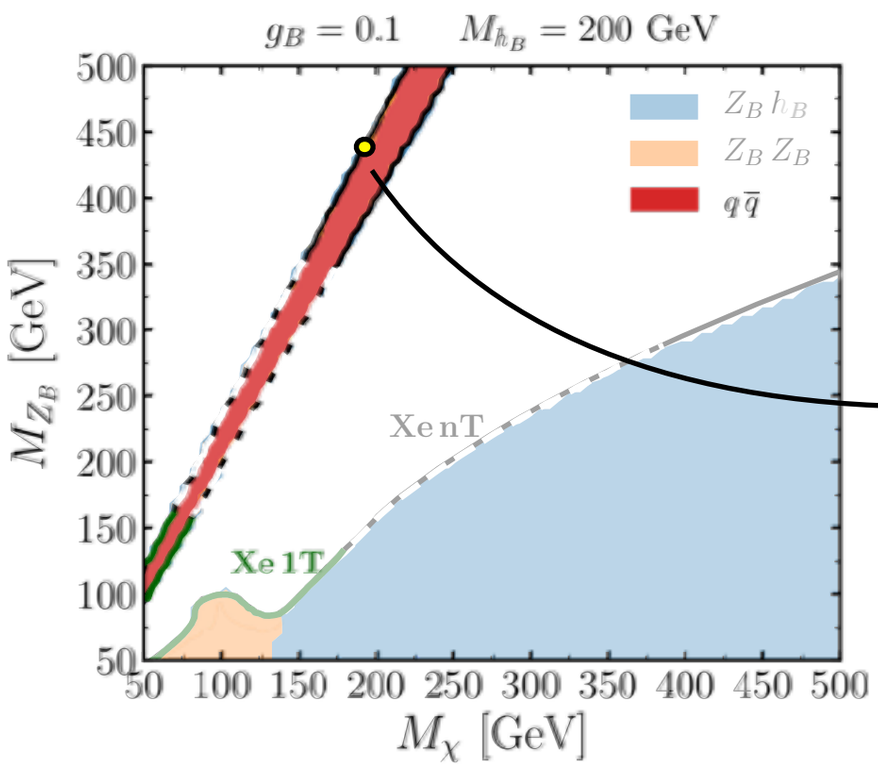

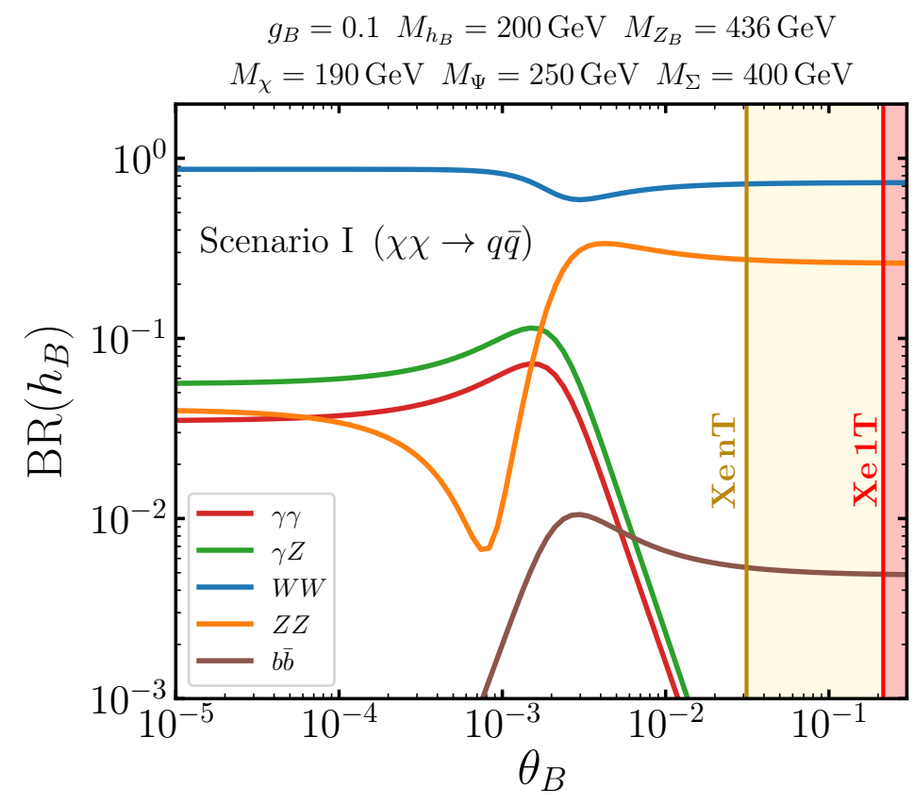

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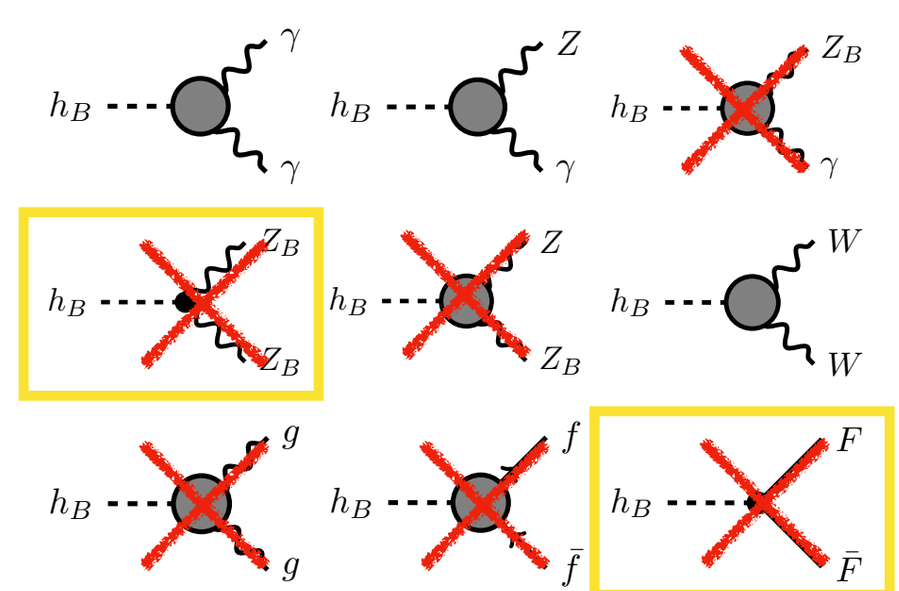

Baryonic Higgs

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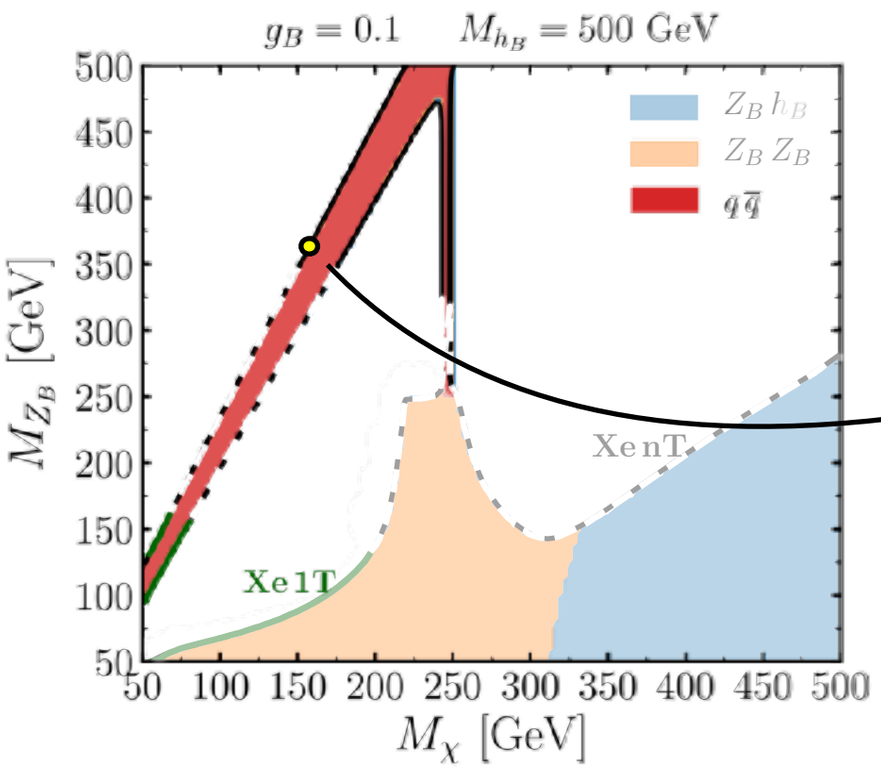

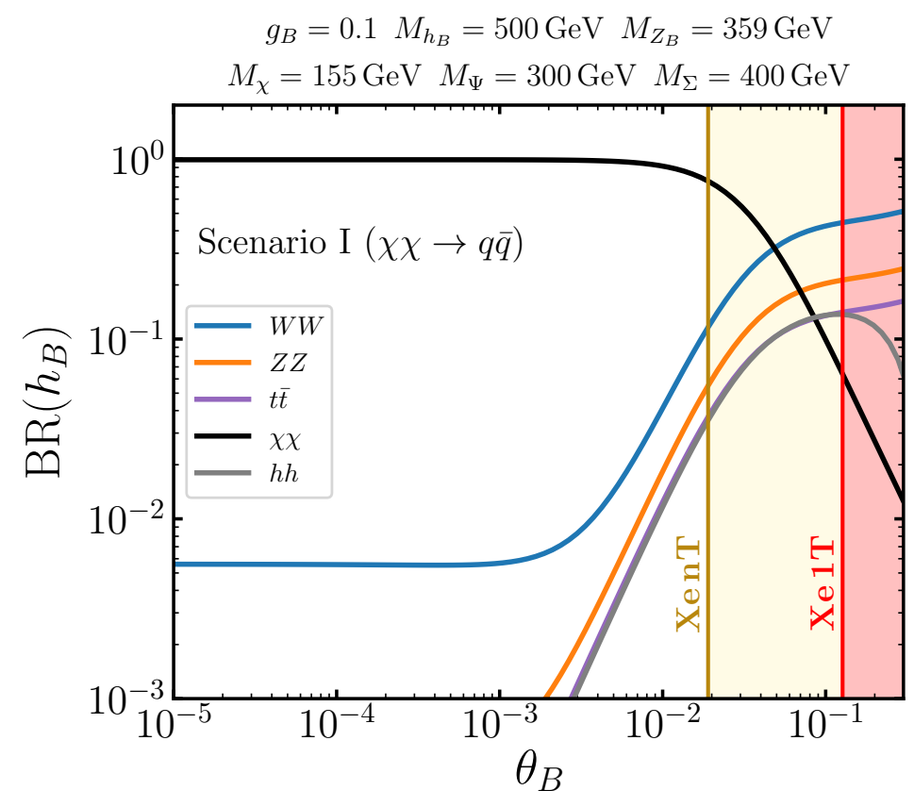

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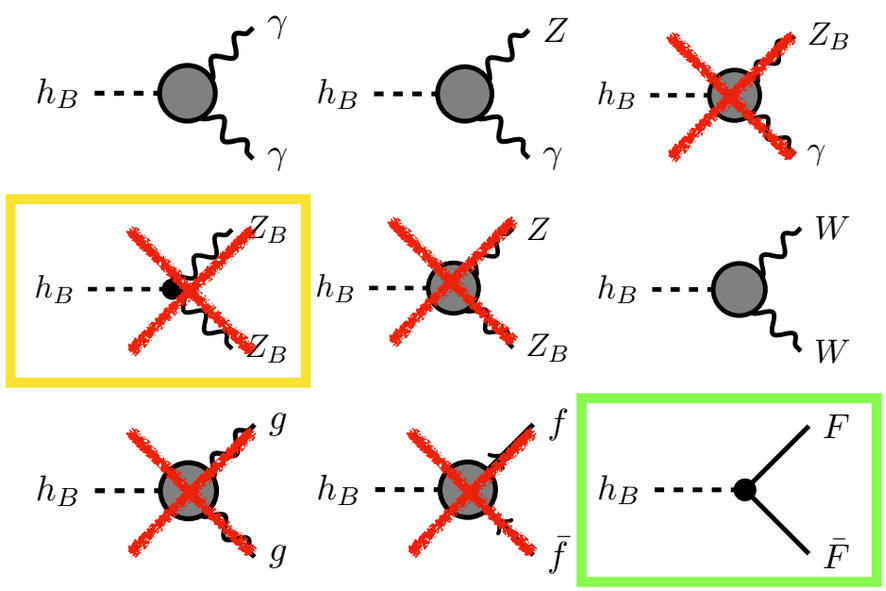
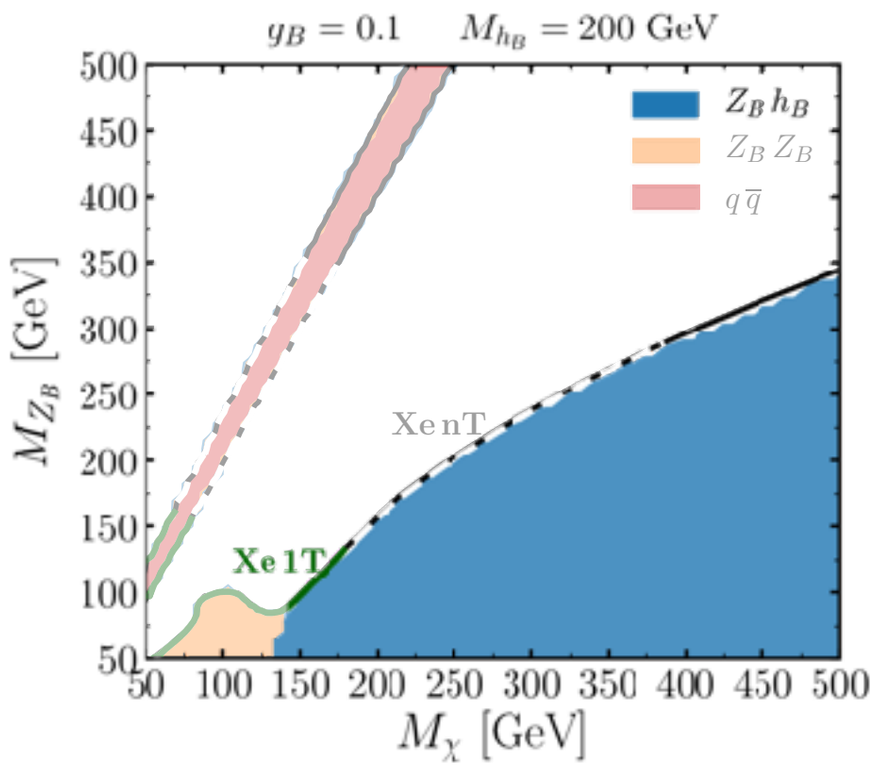
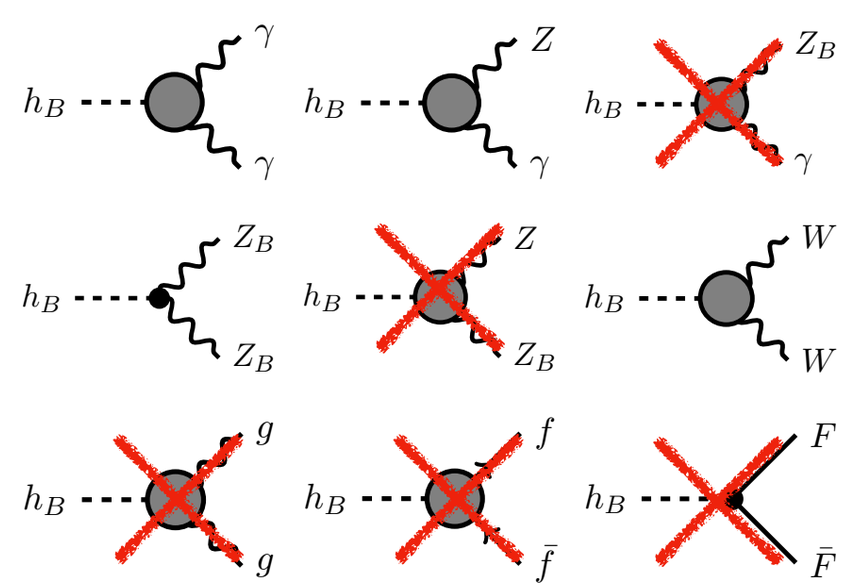


Baryonic Higgs

II

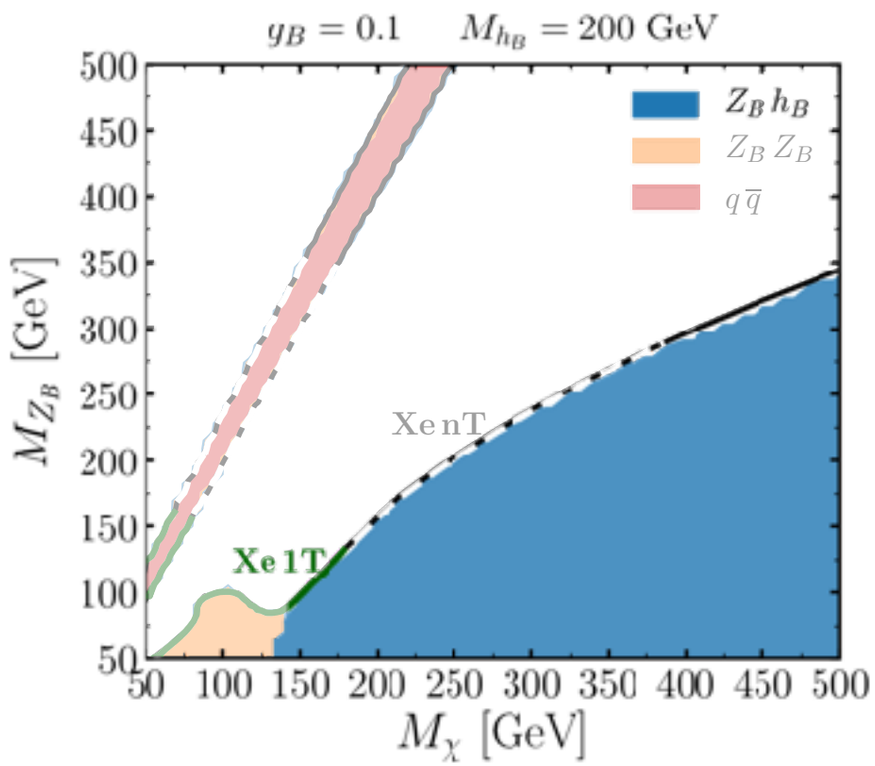


$$\Rightarrow h_B \not\to \bar{\chi}\chi$$



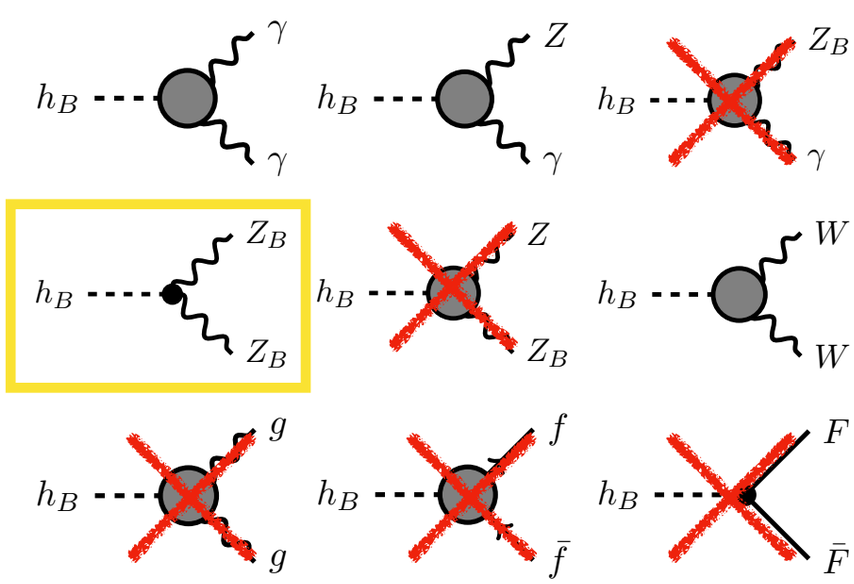
Baryonic Higgs

II



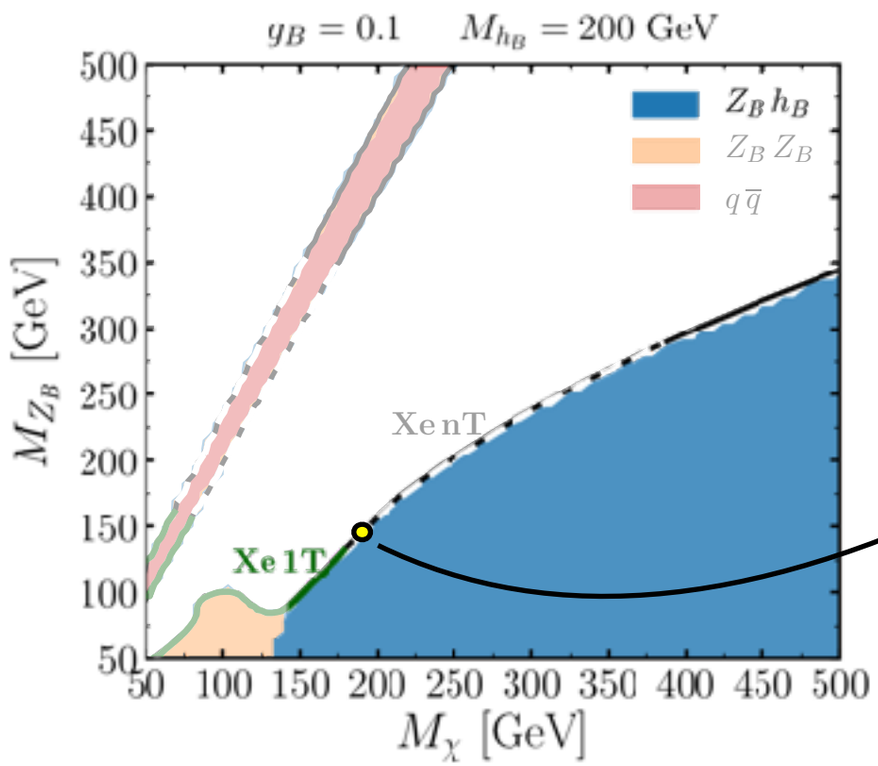
$$\Rightarrow h_B \not\to \bar{\chi}\chi$$

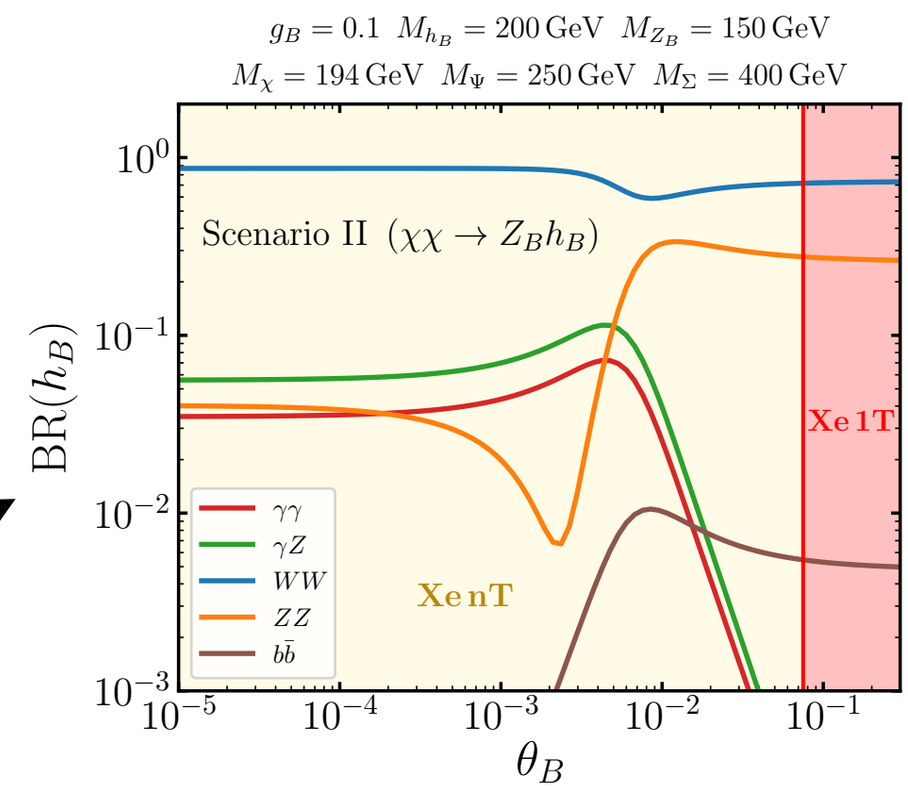
$$\Omega h^2 \sim 0.12 \quad \Rightarrow \quad M_{Z_B} \lesssim M_\chi$$



Baryonic Higgs

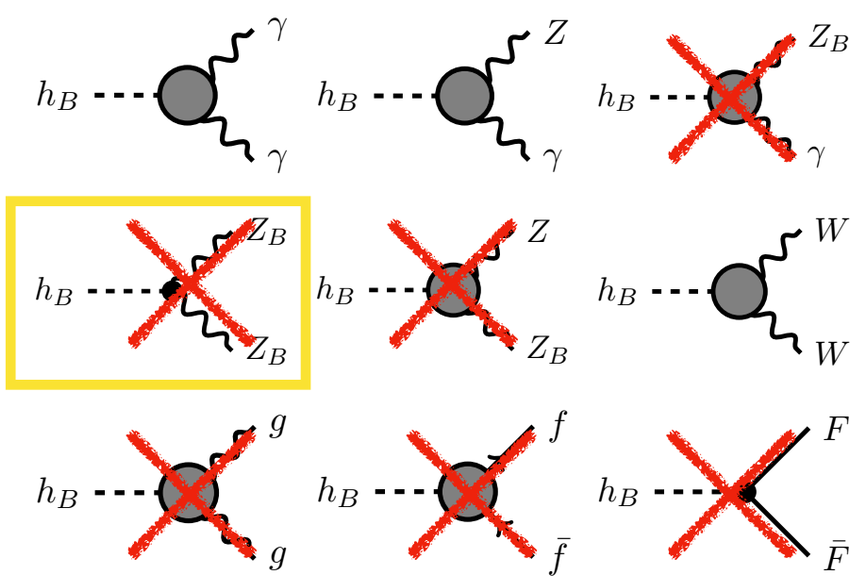
II





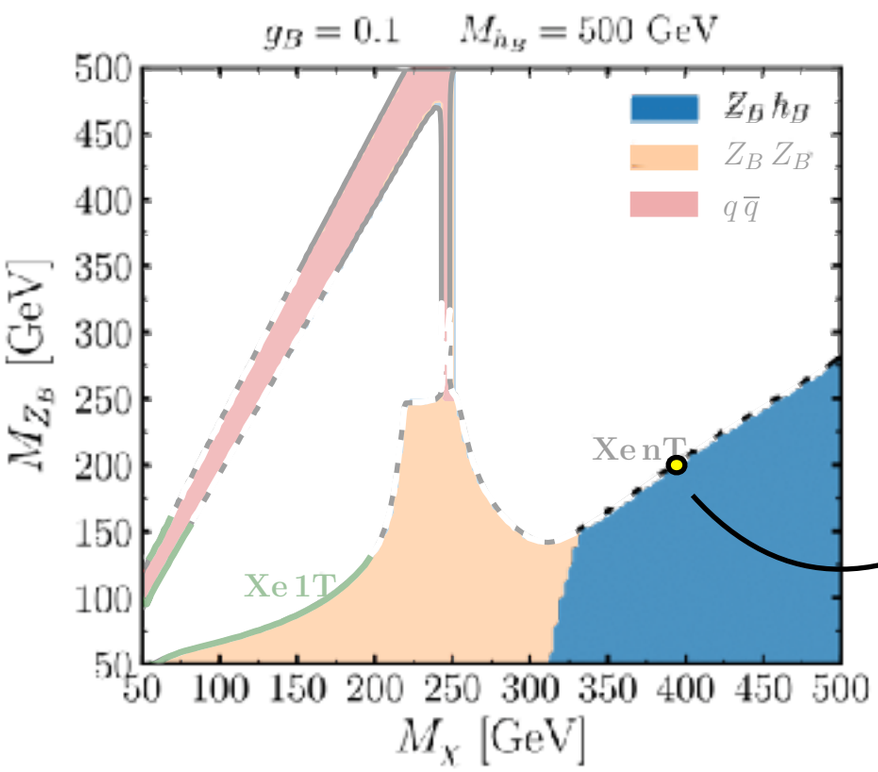
$$\Rightarrow h_B \not\to \bar{\chi}\chi$$

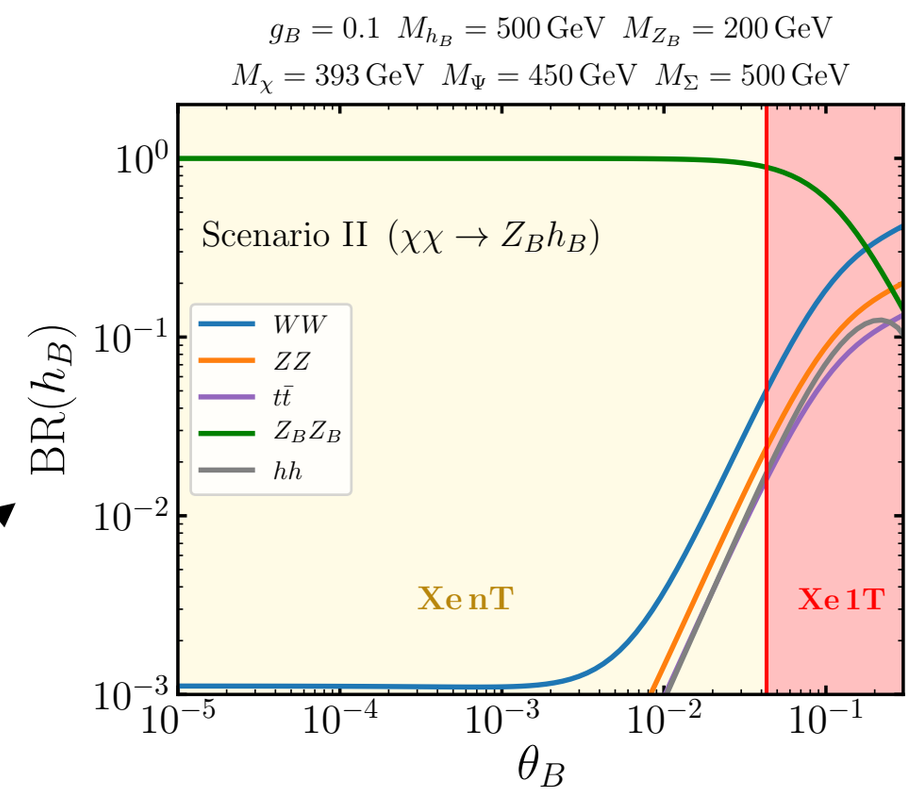
$$\Omega h^2 \sim 0.12 \quad \Rightarrow \quad M_{Z_B} \lesssim M_\chi$$



Baryonic Higgs

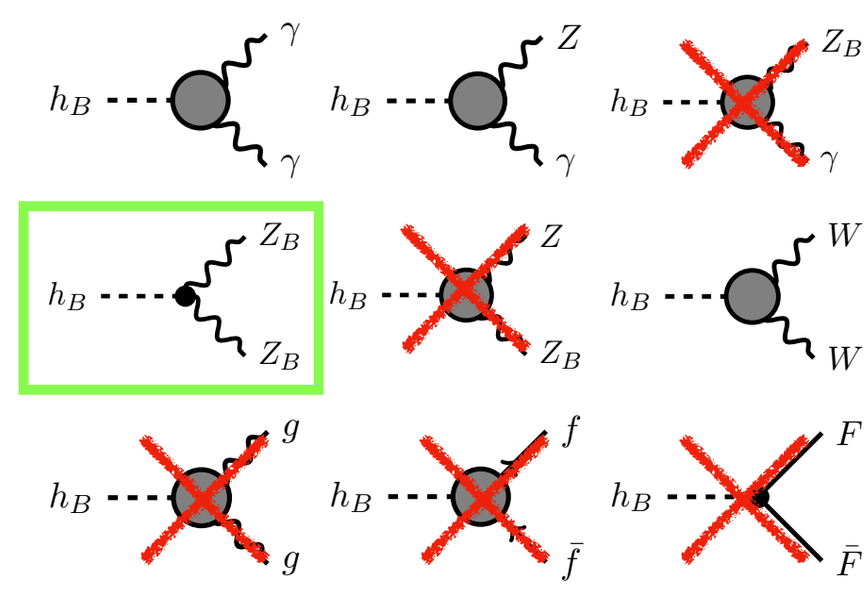
II





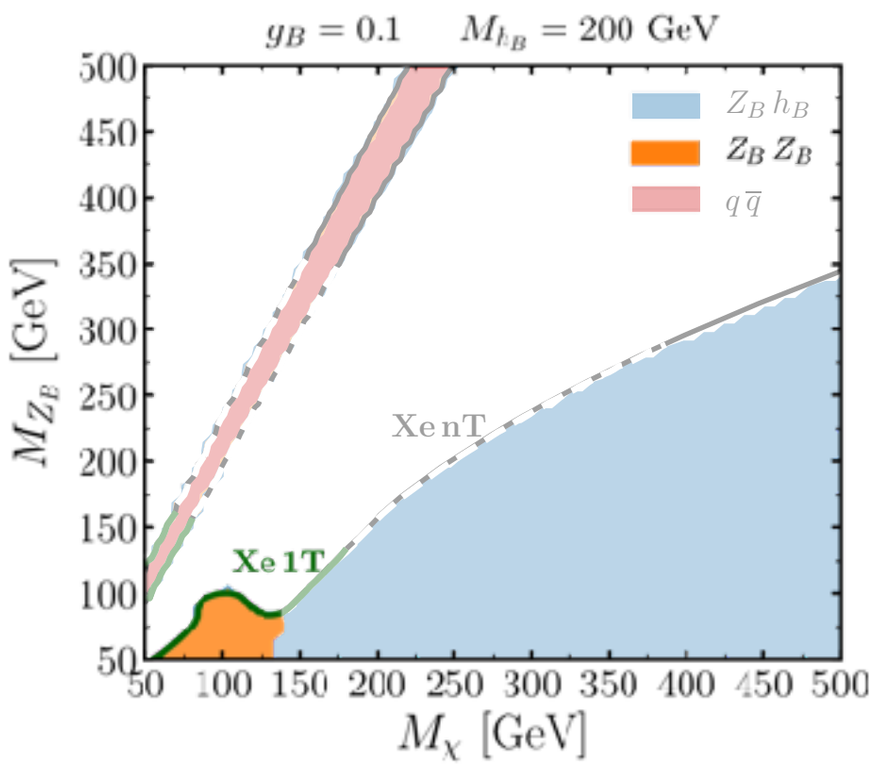
$$\Rightarrow h_B \not\to \bar{\chi}\chi$$

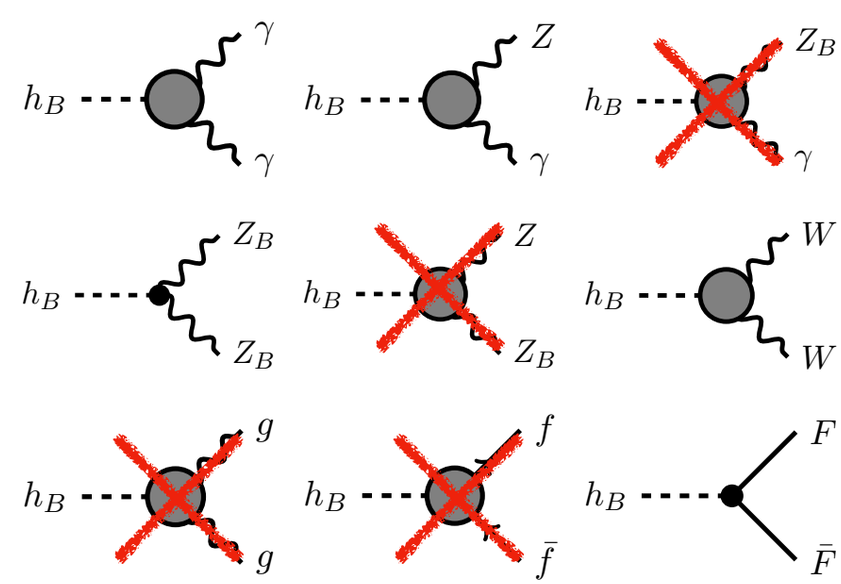
$$\Omega h^2 \sim 0.12 \quad \Rightarrow \quad M_{Z_B} \lesssim M_\chi$$



Baryonic Higgs

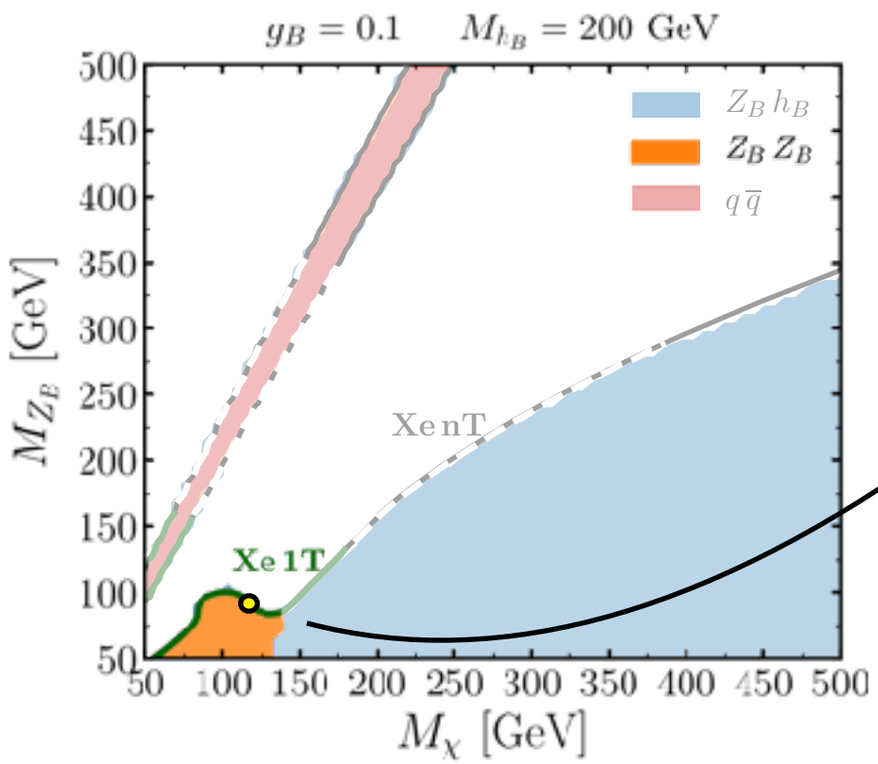
III

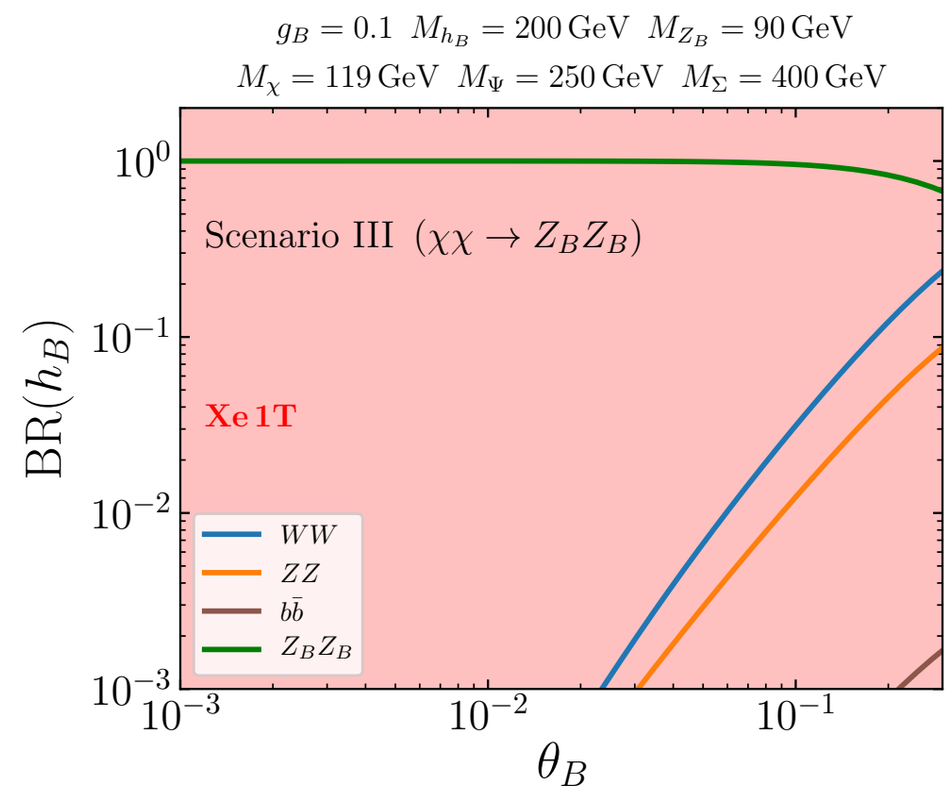


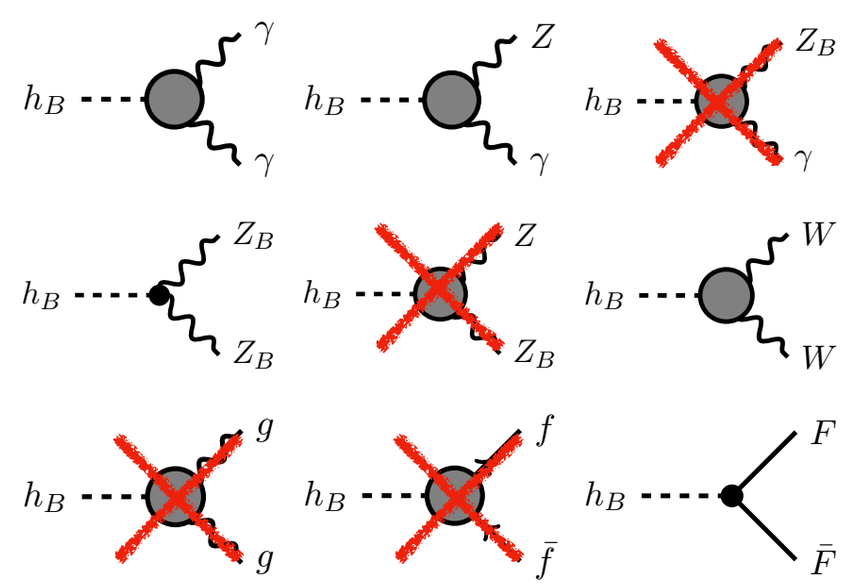


Baryonic Higgs

III

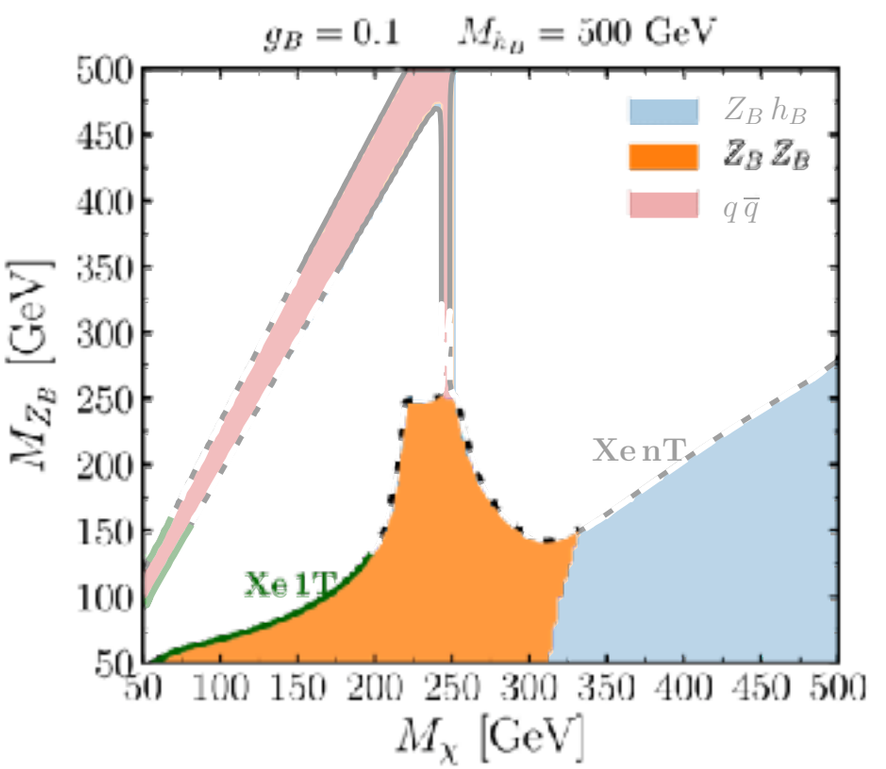






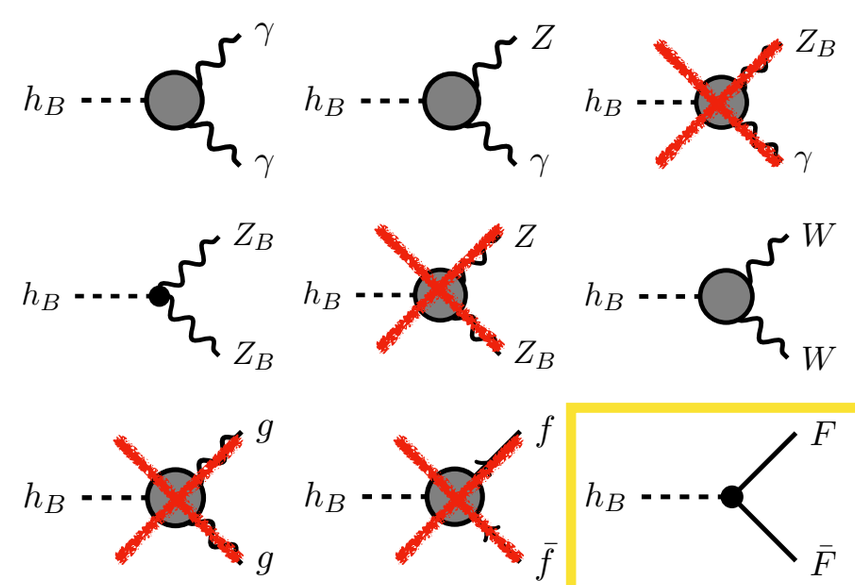
Baryonic Higgs

III



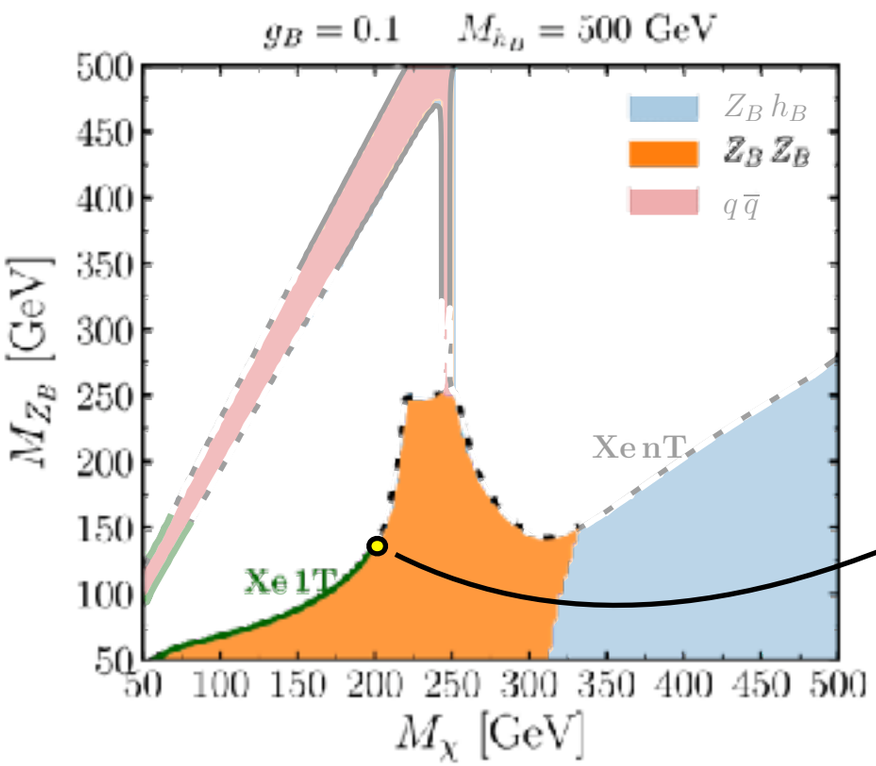
$$M_\chi \lesssim M_{h_B}$$

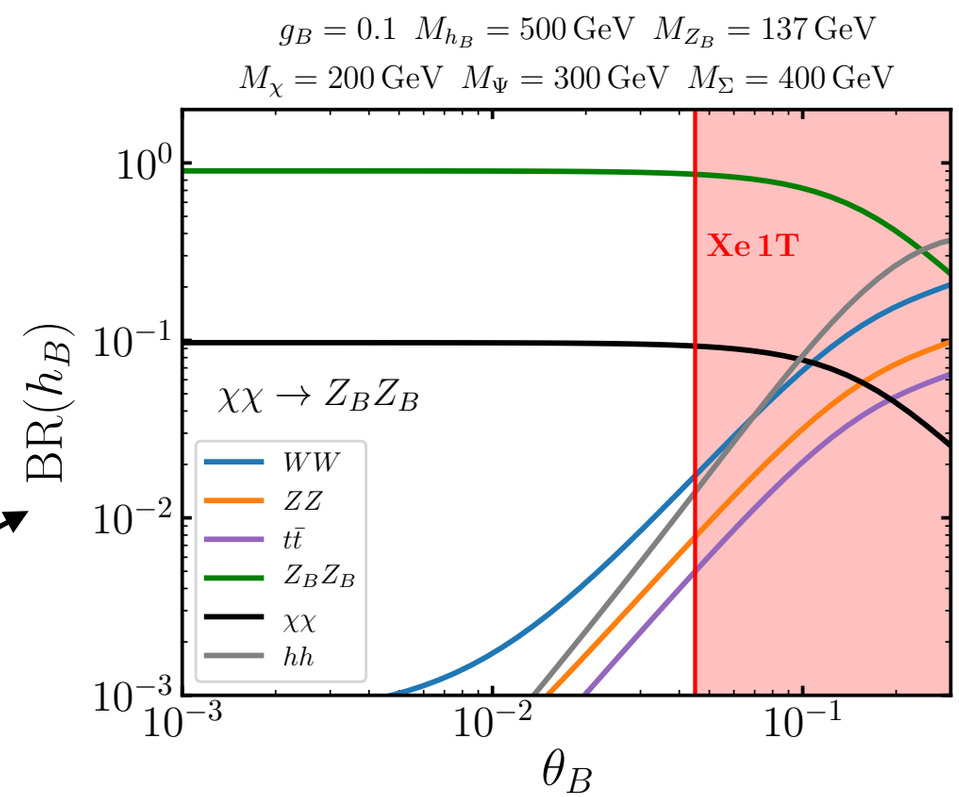
$$M_{h_B} \gtrsim 2M_{Z_B}$$



Baryonic Higgs

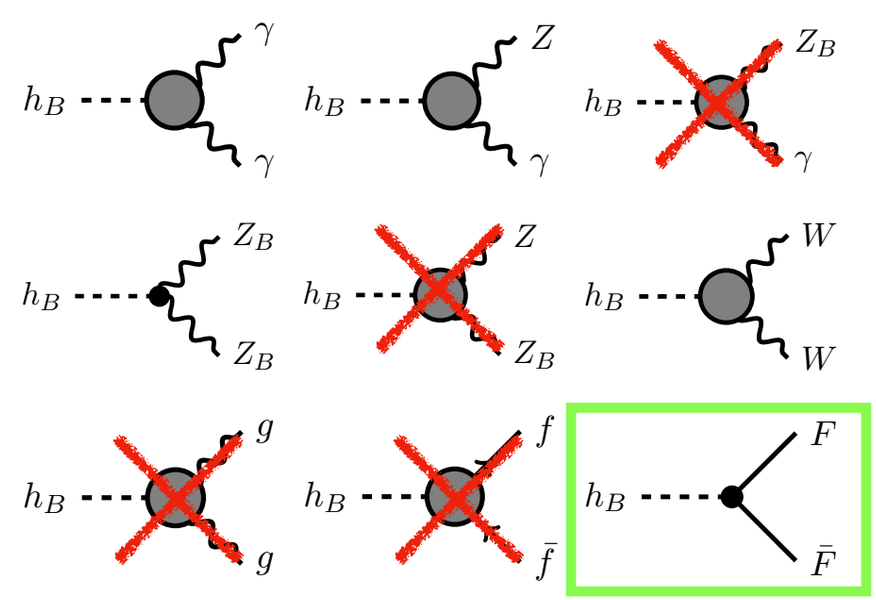
III



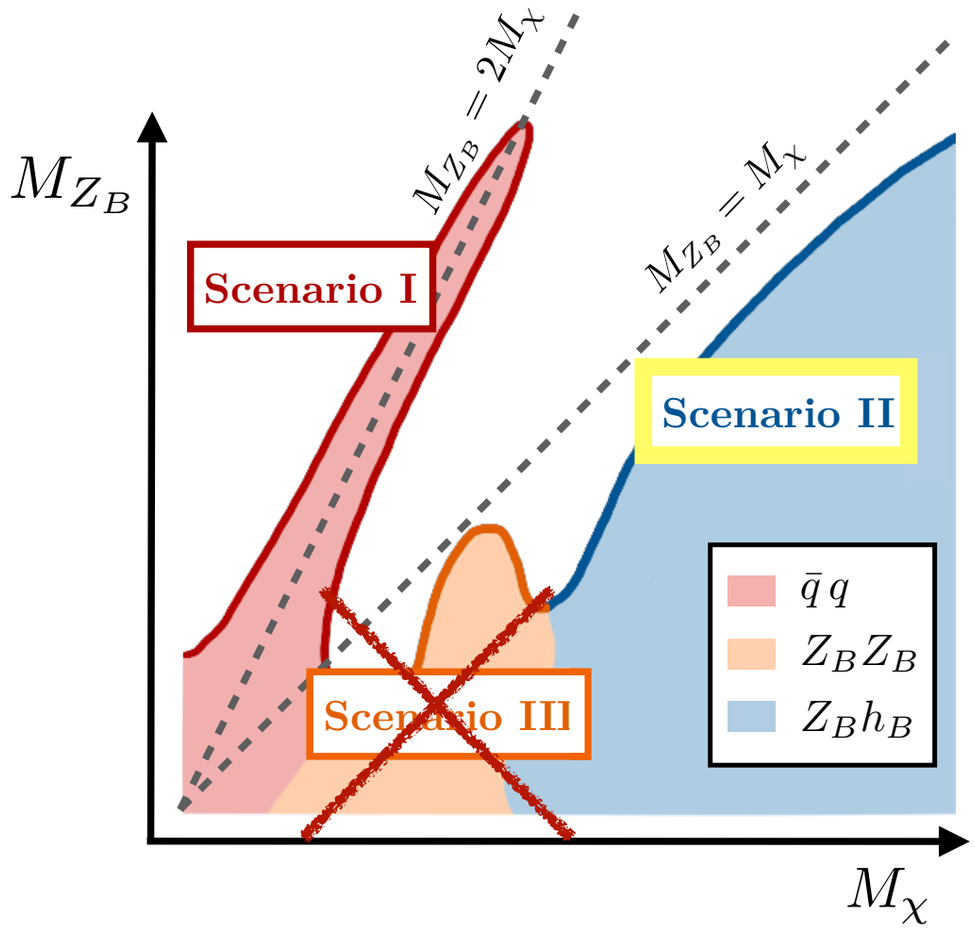


$$M_\chi \lesssim M_{h_B}$$

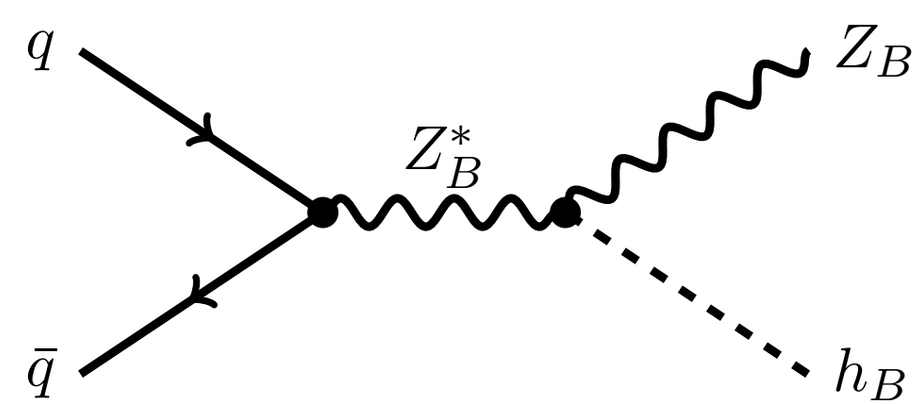
$$M_{h_B} \gtrsim 2M_{Z_B}$$



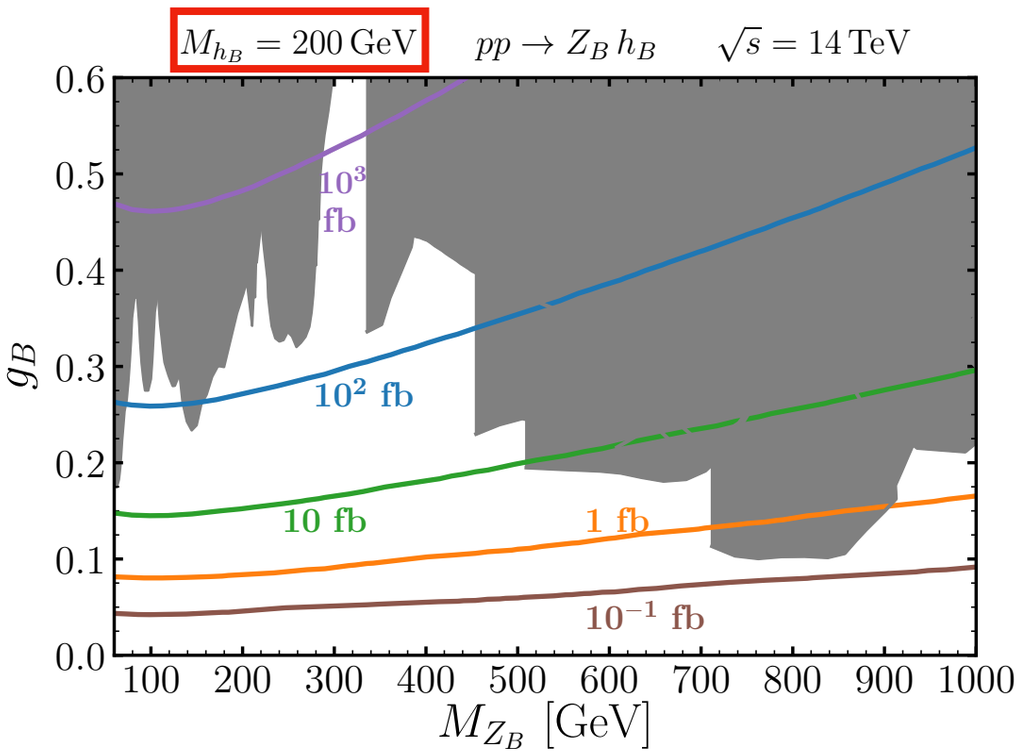
Baryonic Higgs

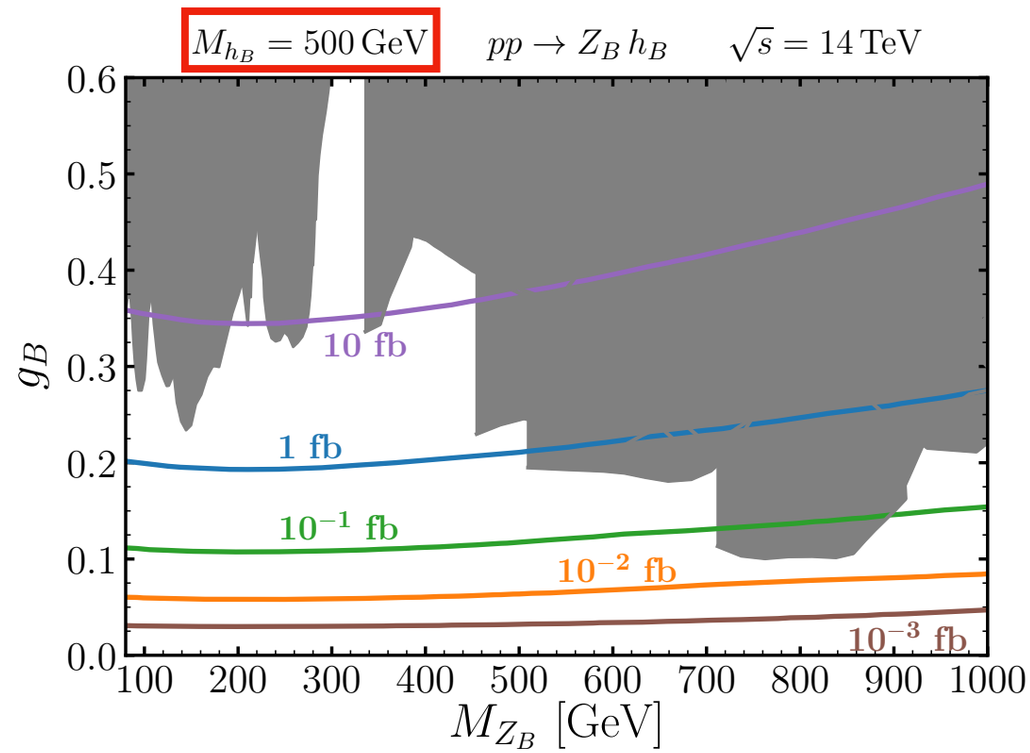


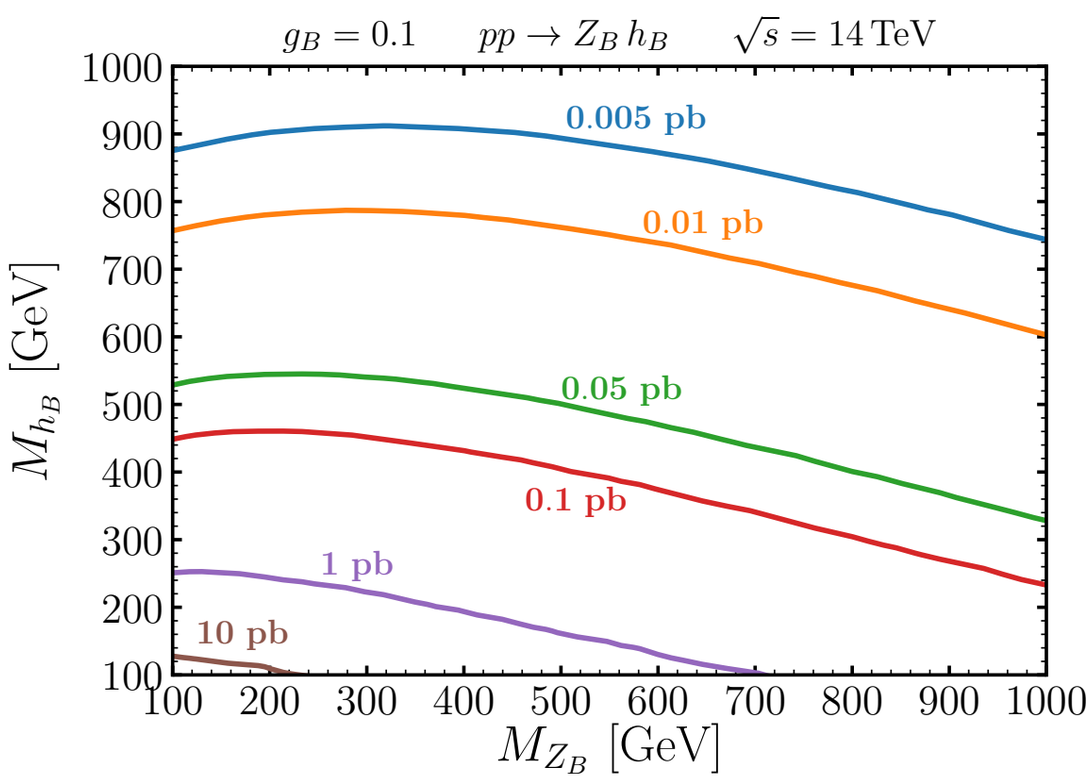
$\theta_B \to 0$

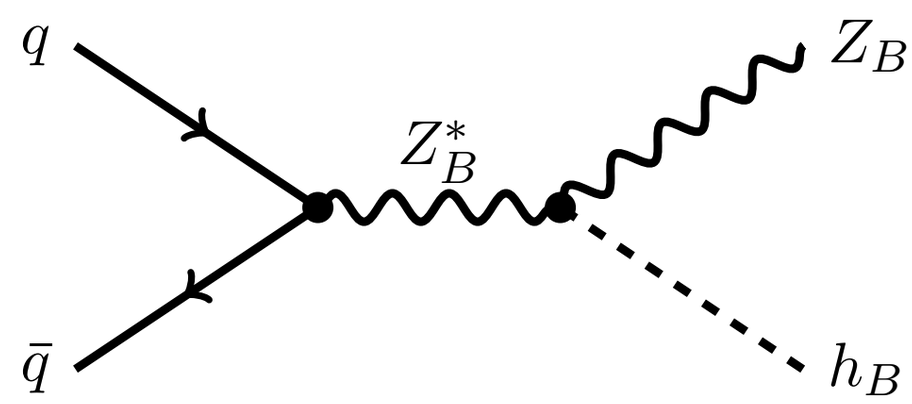


Baryonic Higgs

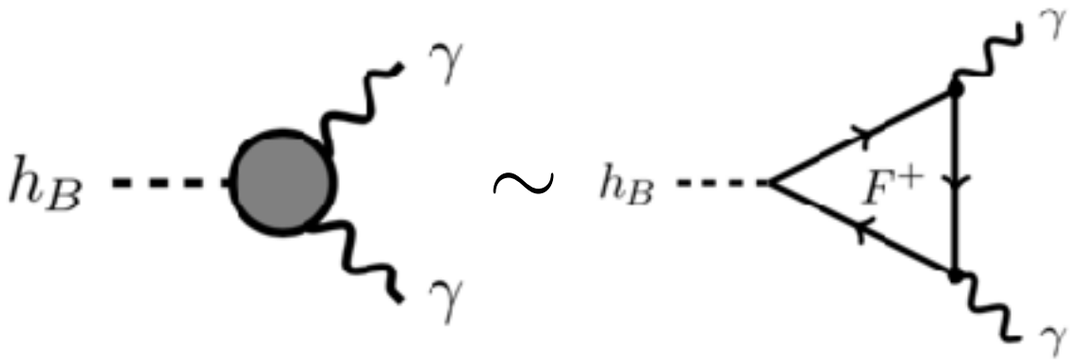


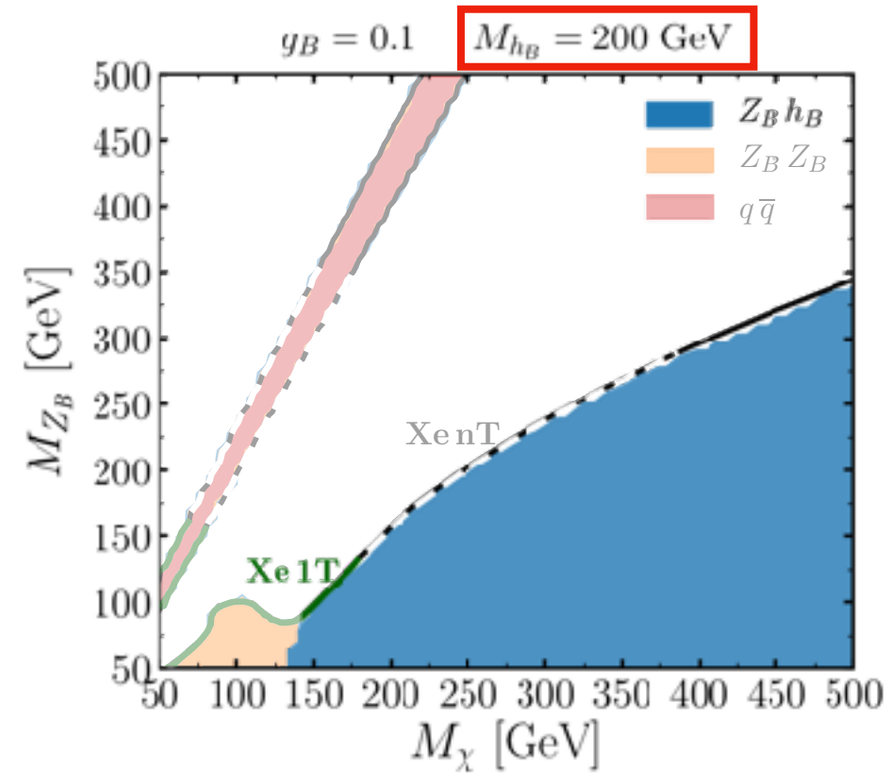


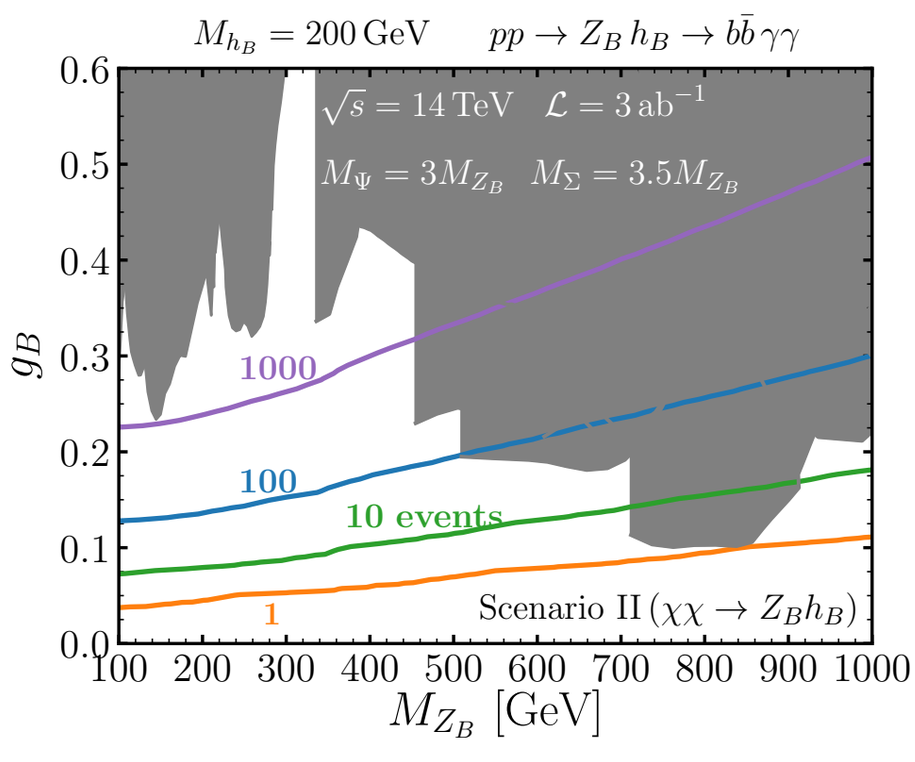


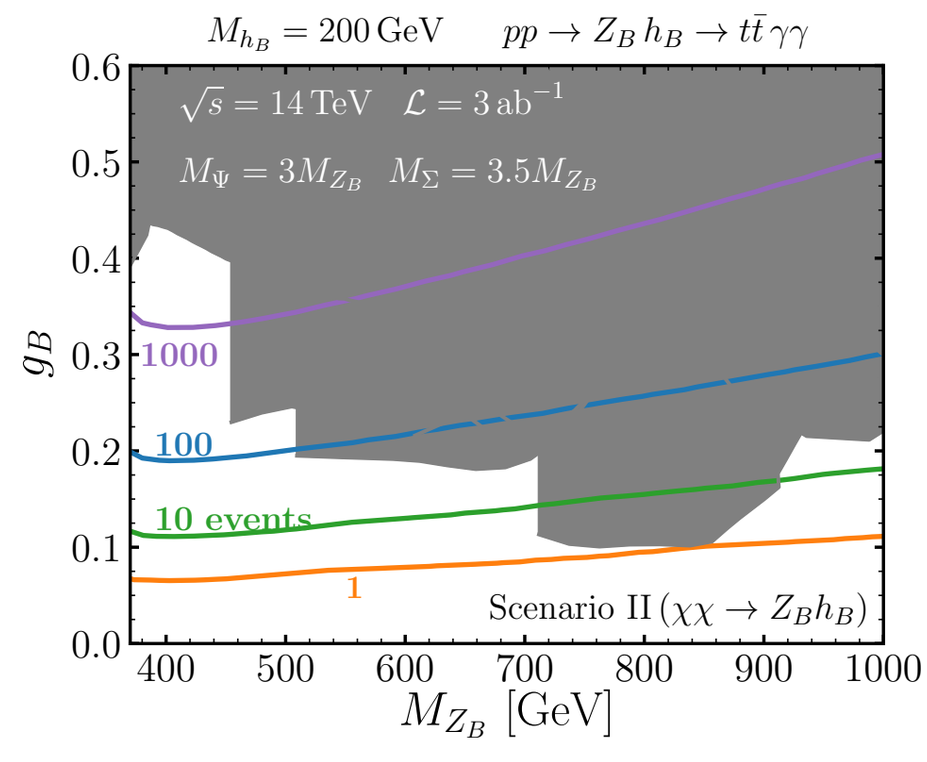


Baryonic Higgs

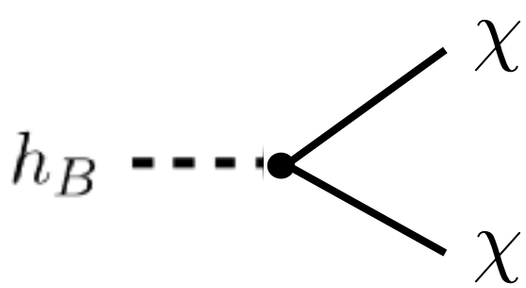


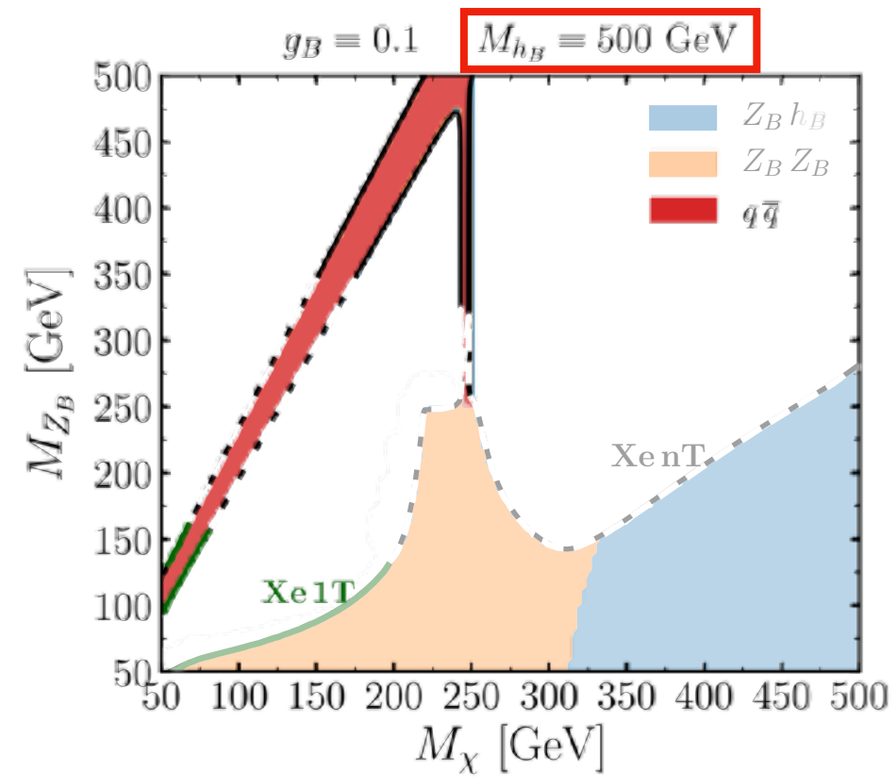


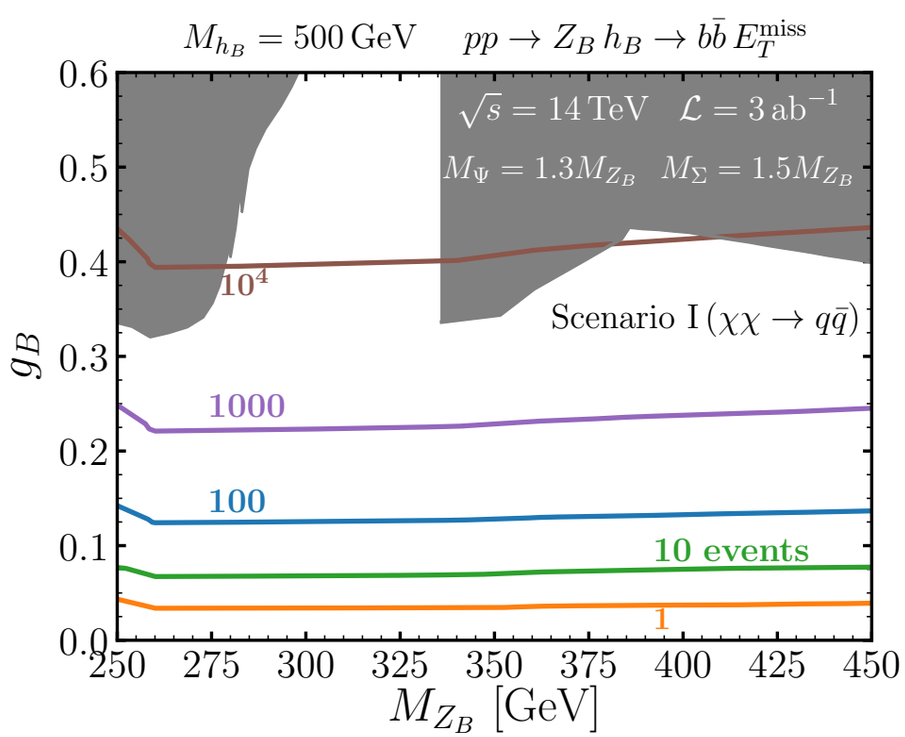


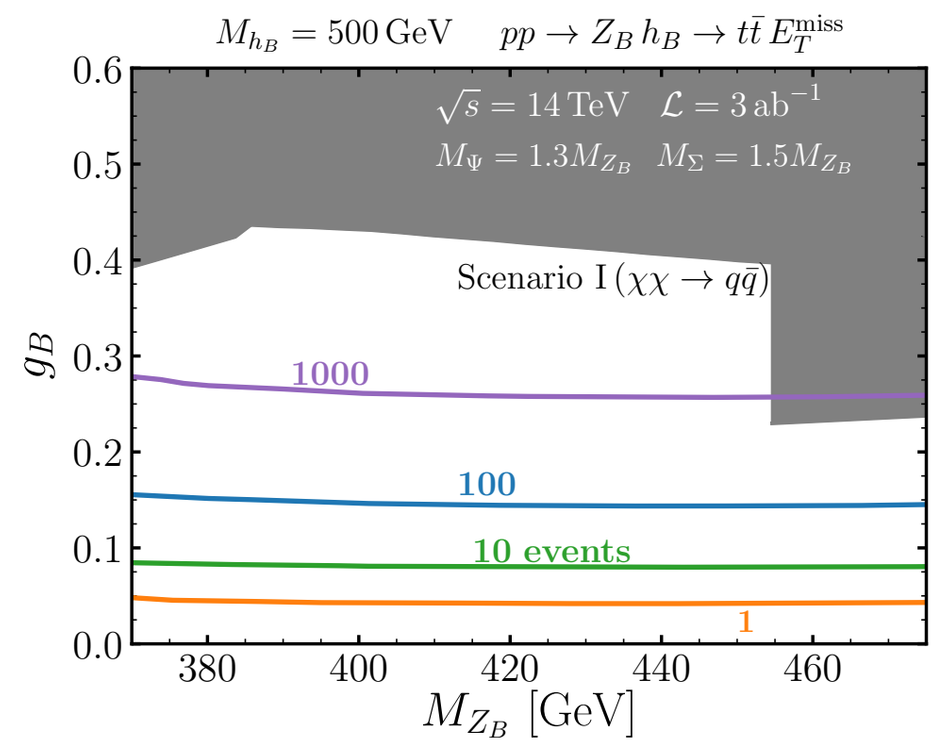


Baryonic Higgs









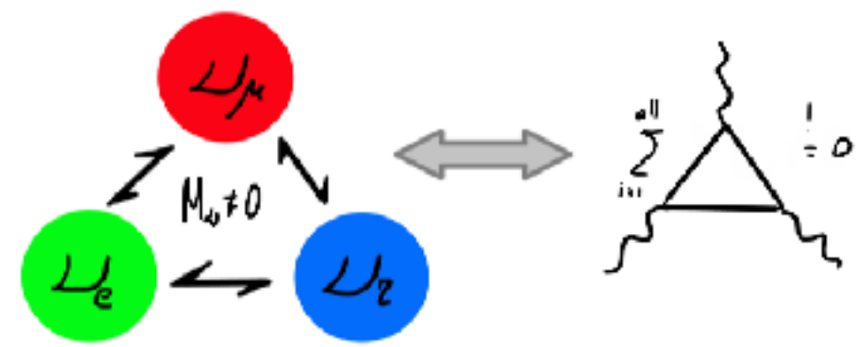
$U(1)_B$

???
$U(1)_L$

Local Lepton Number

Neutrinos are Dirac!

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



Local Lepton Number

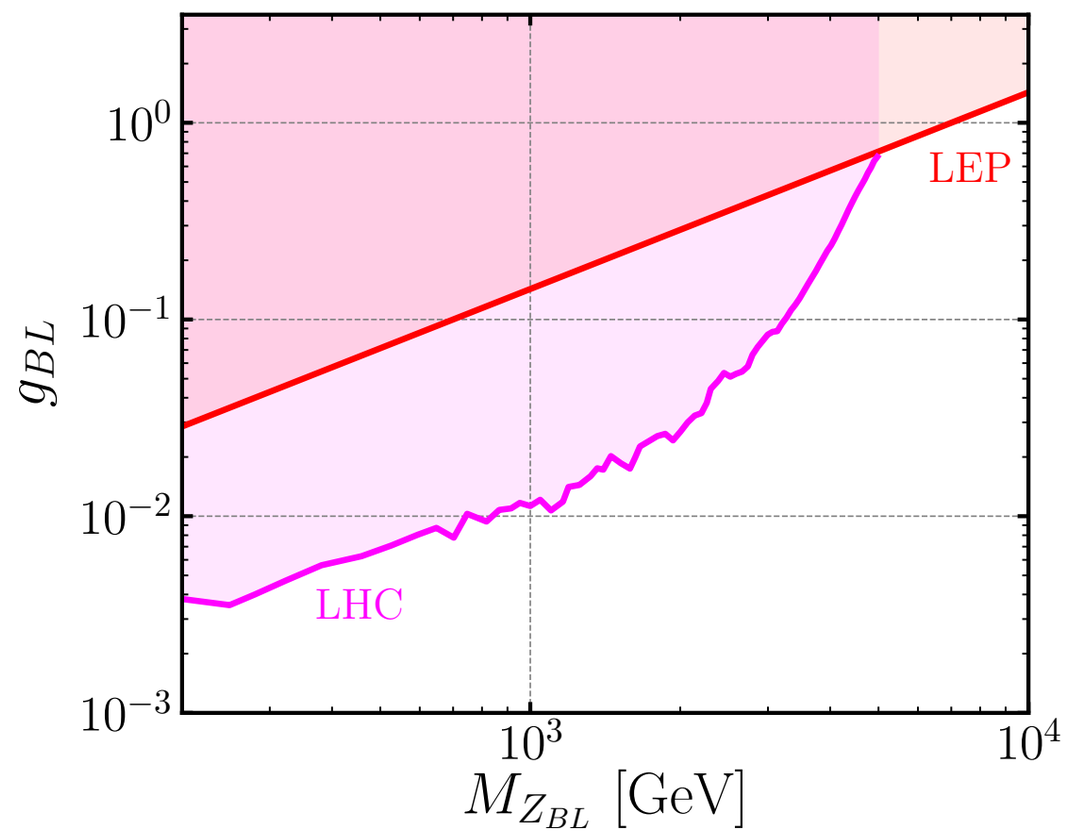
Neutrinos are Dirac!

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

- Majorana dark matter candidate

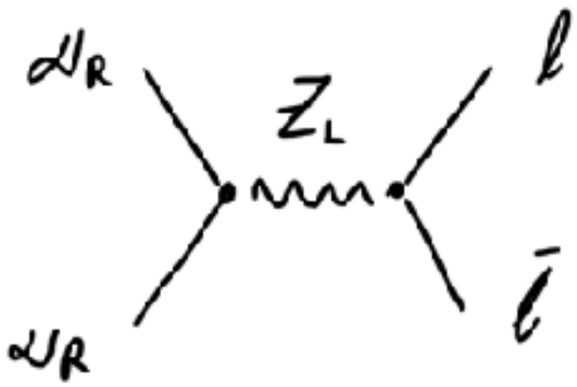
LEP

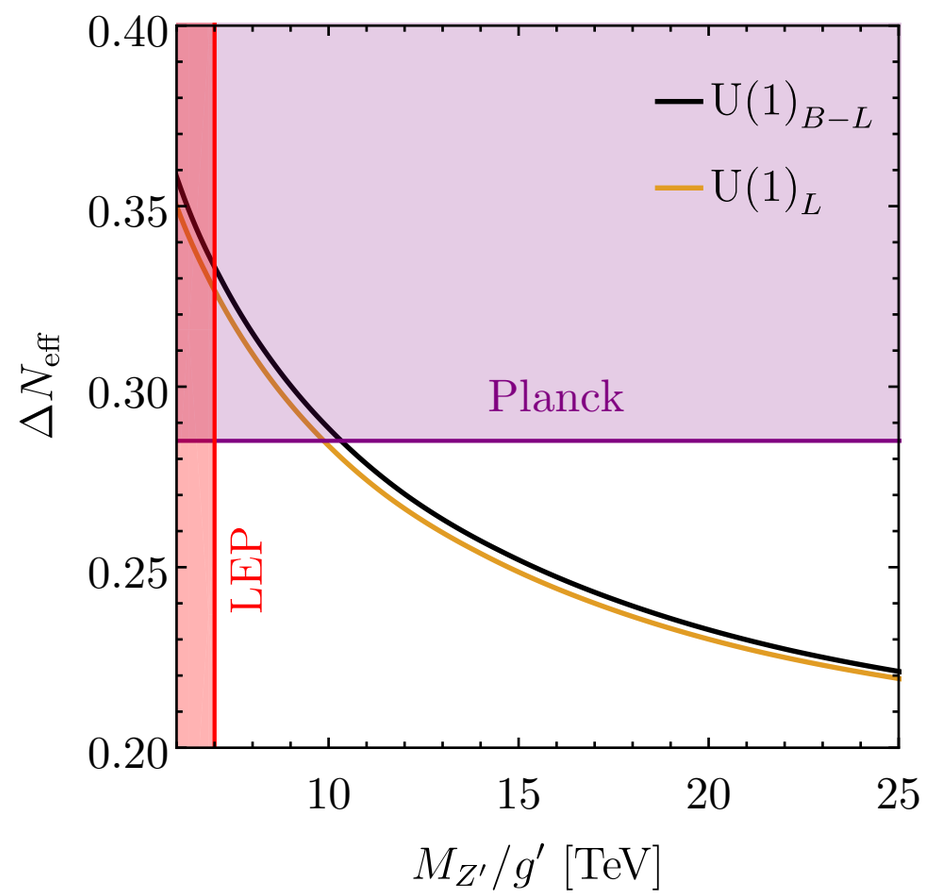
$$\frac{M_{Z_L}}{g_L} > 7 \text{ TeV}$$



Light Relics

- $\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm SM} = N_{\nu_R}\left(\frac{T_{\nu_R}}{T_{\nu_L}}\right)^4 = N_{\nu_R}\left(\frac{g(T_{\nu_L}^{\rm dec})}{g(T_{\nu_R}^{\rm dec})}\right)^{\frac{4}{3}}$





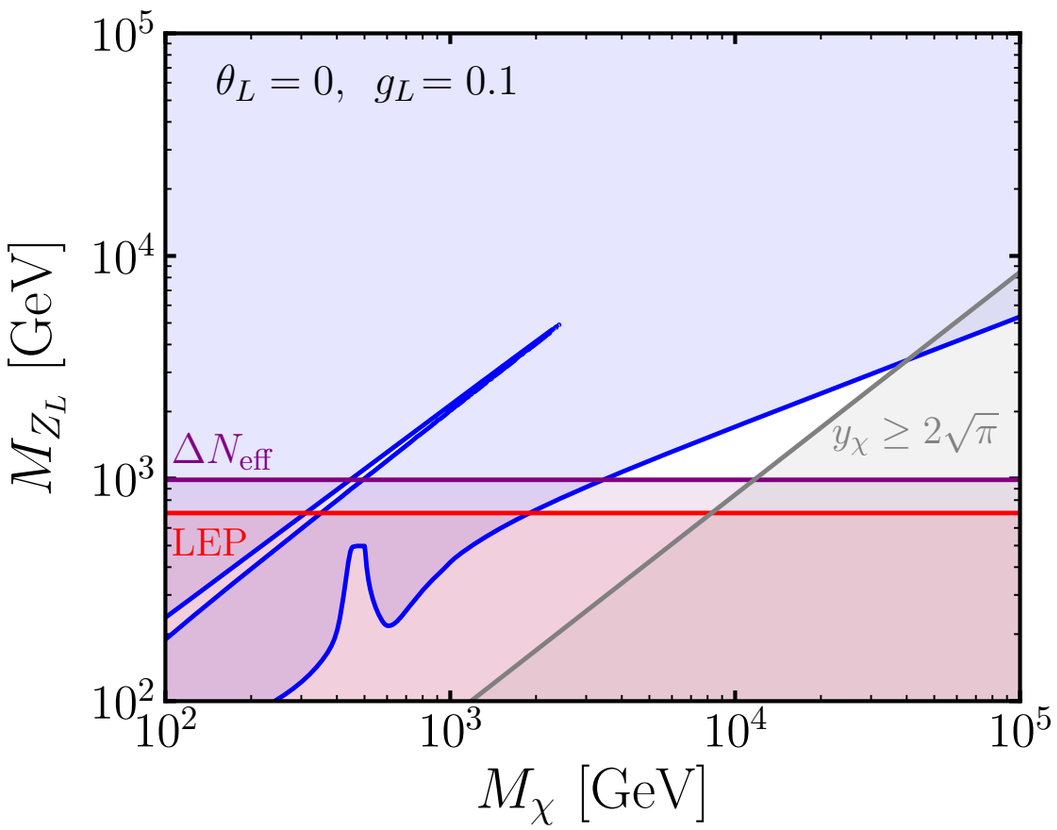
- Decoupling temperature:

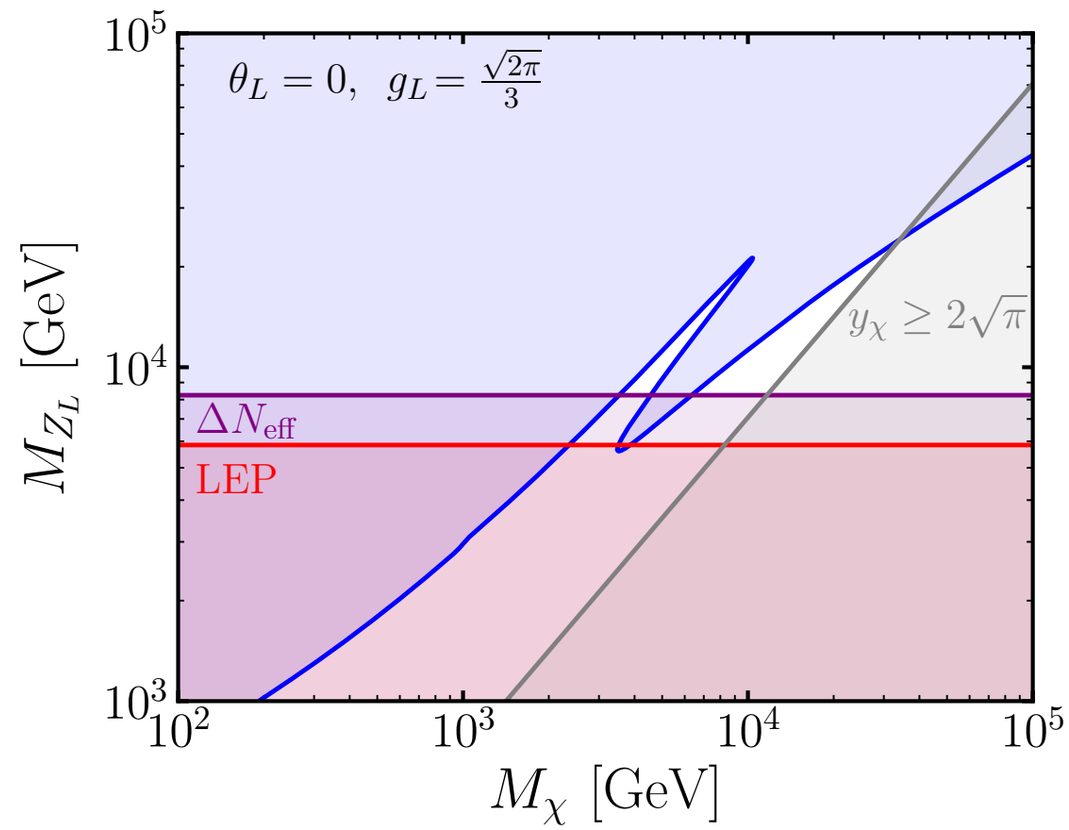
$$\Gamma(T_{\nu_R}^{\rm dec}) = H(T_{\nu_R}^{\rm dec})$$

- Bounds from Planck:

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad \Rightarrow \Delta N_{\rm eff} < 0.285 \quad \Rightarrow \frac{M_{Z_L}}{g_L} > 9.87 \text{ TeV}$$

Local Lepton Number

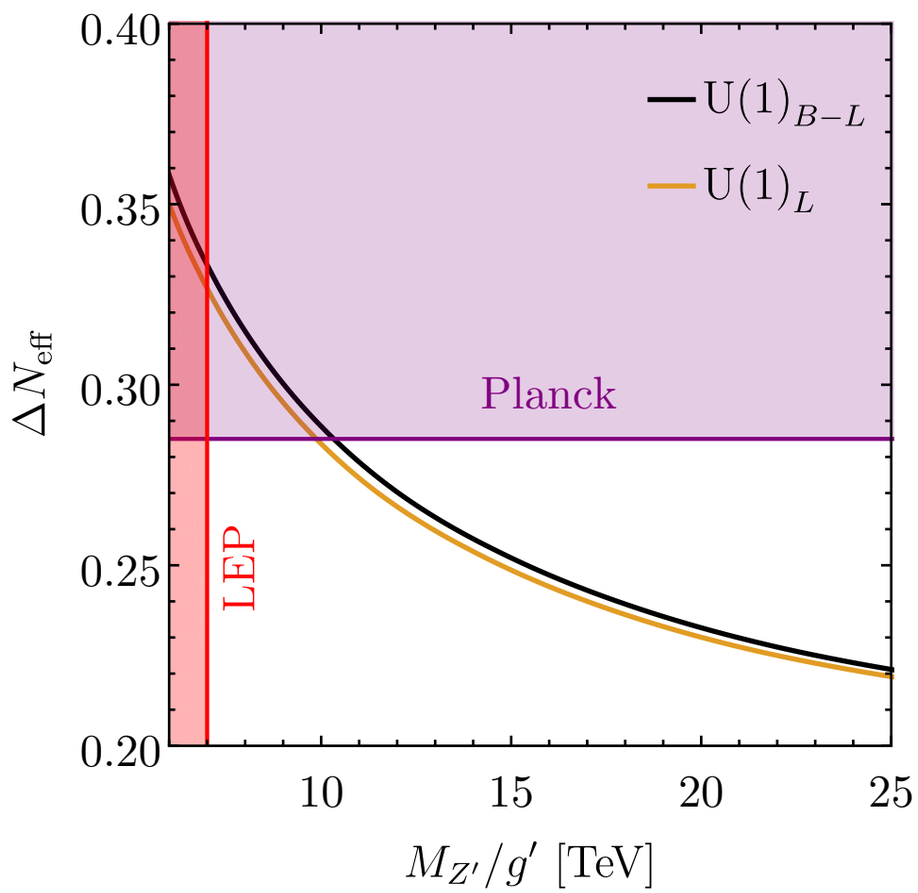




Local Lepton Number

$\Delta N_{\rm eff} < 0.12$ at 95% C.L.

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



Local U(1)B/L

- Consistency of the theory (anomaly cancellation) requires a DM candidate and predicts the stability of the proton.

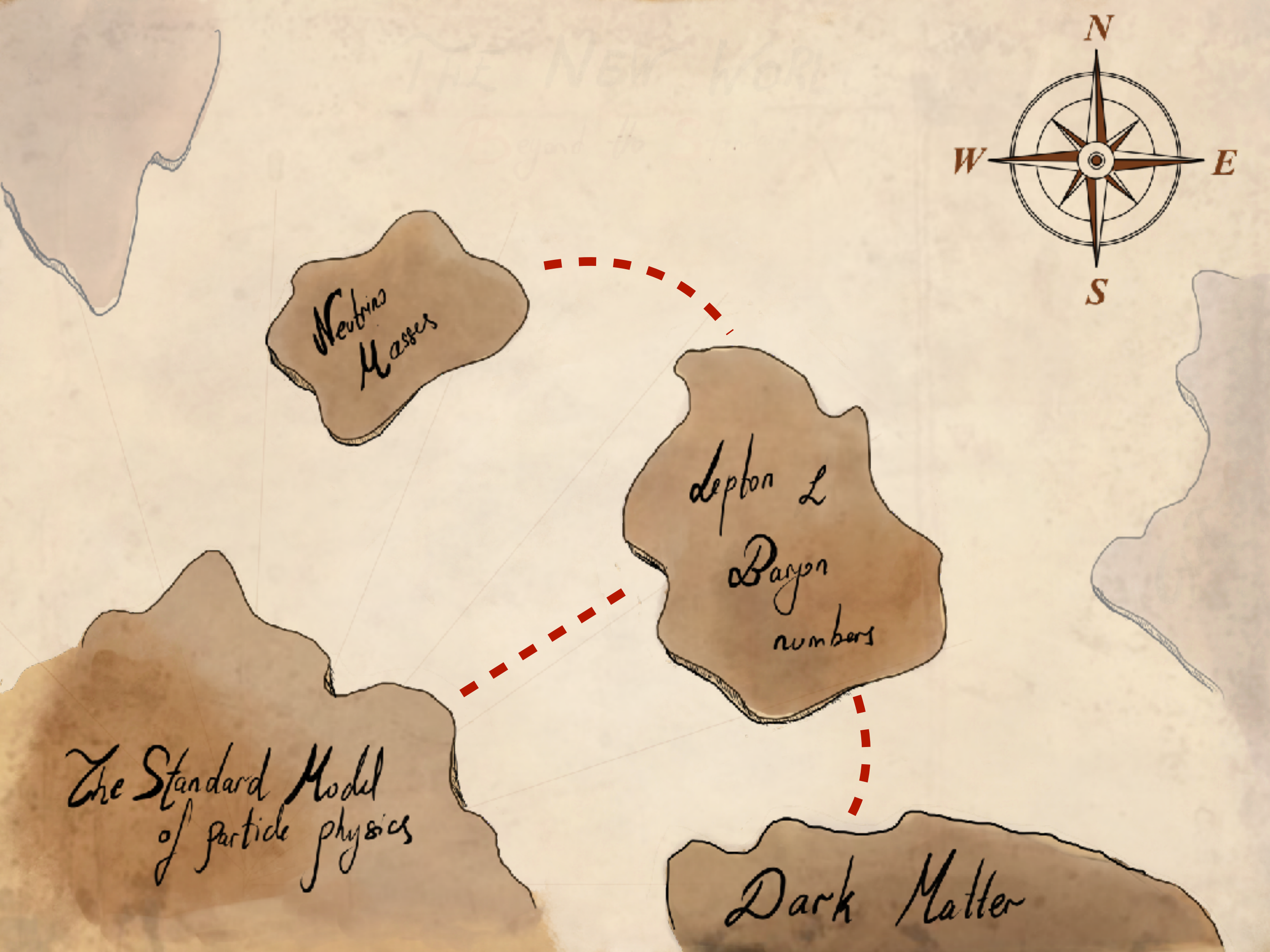
- The cosmological bound imposes an absolute upper bound on U(1)B at **20 TeV**!

- Its light leptophobic mediator could be seen at the LHC.

- The upcoming bounds on the number of effective relativistic species will be able to falsify this theory.

- The Majorana DM enjoys a rich phenomenology regarding DM direct and indirect detection experiments.

- Correlations between signals at colliders and at DM experiments!


N
W
E
S
Neutrino Masses
Lepton L
Baryon
numbers
The Standard Model
of particle physics
Dark Matter

Thank you!