Gauge extensions of the SM: Neutrinos, dark matter and the LHC

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CASE WESTERN RESERVE UNIVERSITY EST. 1826

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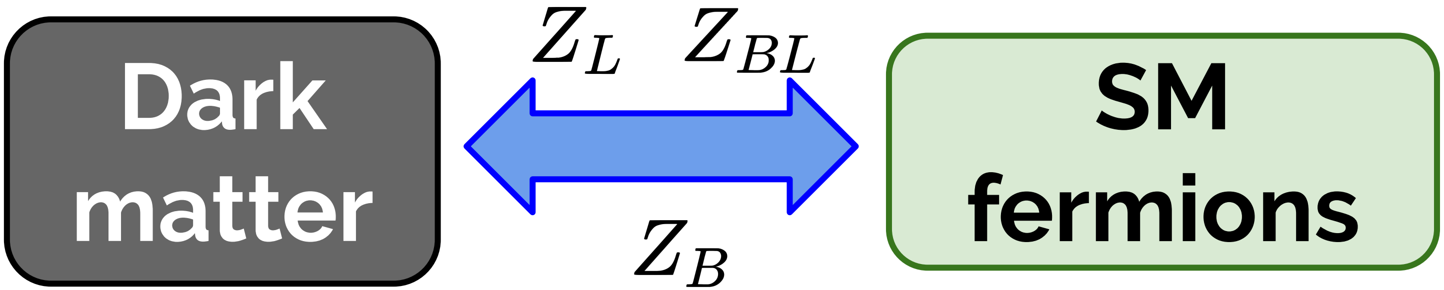
[arXiv:1904.01017] PRD 100 (2019) 015017

[arXiv: 1905.06344] PRD 100 (2019) 035041

Third paper to appear soon...

Aim of the talk

Discuss the phenomenology of gauge extensions of the SM that explain dark matter and neutrino masses



Outline of the talk

1. **Neutrino masses**

2. **$U(1)_{B-L}$ gauge extension of the SM**
   a. Dirac neutrinos and Dirac dark matter

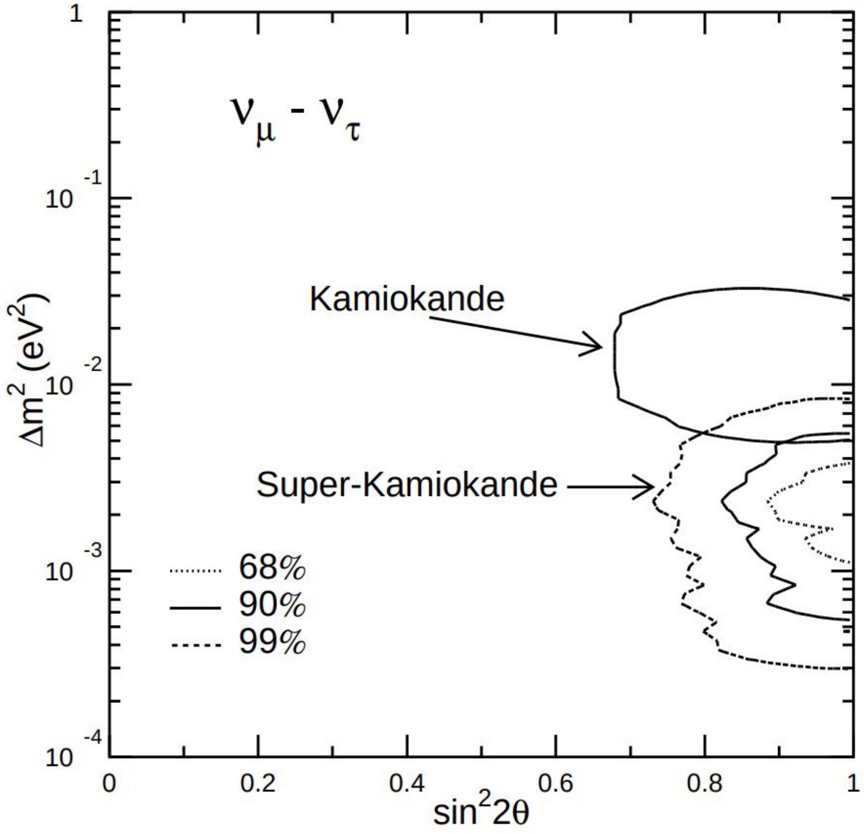
3. **$U(1)_{L}$ gauge extension**
   a. Dirac neutrinos and Majorana dark matter

4. **$U(1)_{B}$ gauge extension**
   a. Leptophobic mediator and Majorana dark matter

5. **Conclusions**

Neutrino masses

[Super-Kamiokande 1998]



The observation of neutrino oscillations implies that neutrinos have non-zero mass

Neutrino masses

In order to measure the neutrino mass directly we need to observe to high precision the electron's energy spectrum close to the endpoint in beta decay

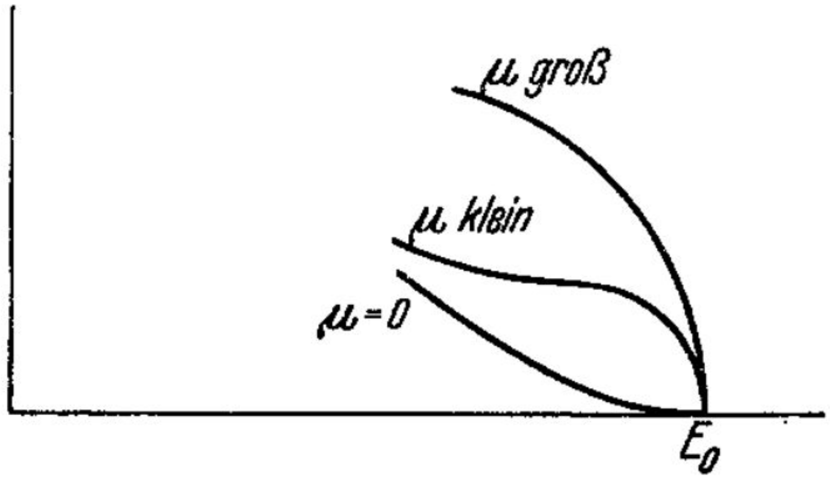


Fig. 1.

Fermi's sketch of the endpoint of beta-decay for massless, small and large neutrino mass

[Zeitschrift für Physik, 1934]

Neutrino masses

Direct kinematic method, beta-decay endpoint

Tritium *E*=18.6 keV (low endpoint energy!)

$$m_{\nu_e} < 1.1 \text{ eV} \quad (90\% \text{ CL})$$

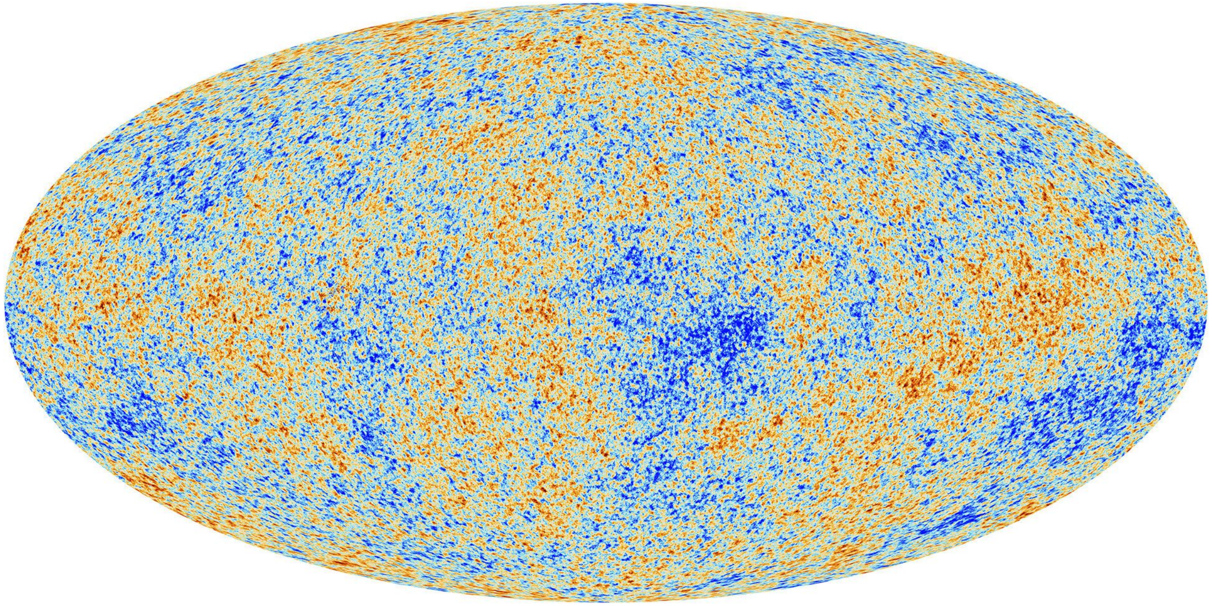
[KATRIN 2019]

Neutrino masses

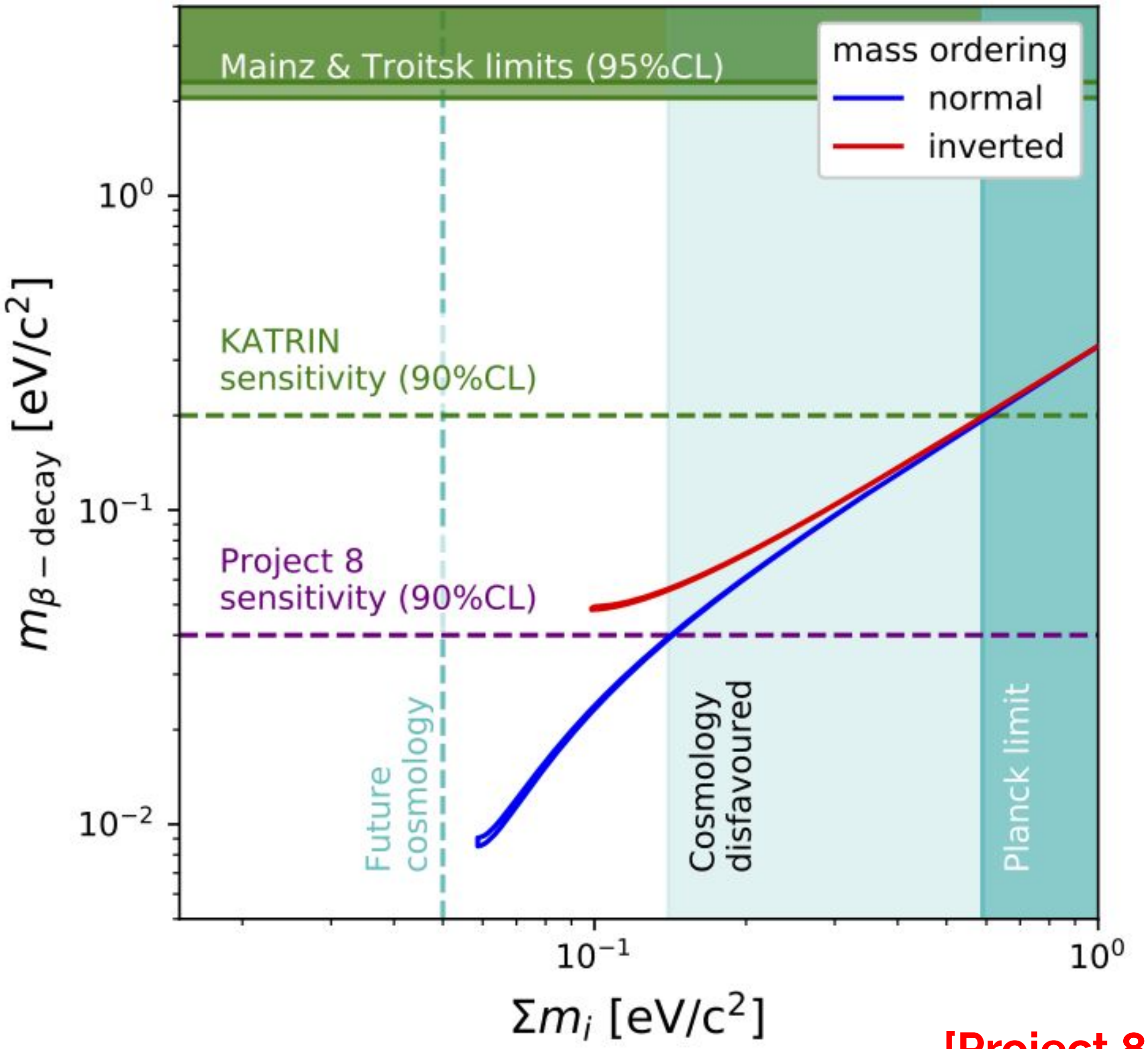
- CMB + BAO data gives bound on the sum of neutrino masses
- Model-dependent (assumes standard cosmology)

$$\sum m_{\nu_i} < 0.23 \text{ eV} \quad (95\% \text{ CL})$$

[PLANCK 2018]



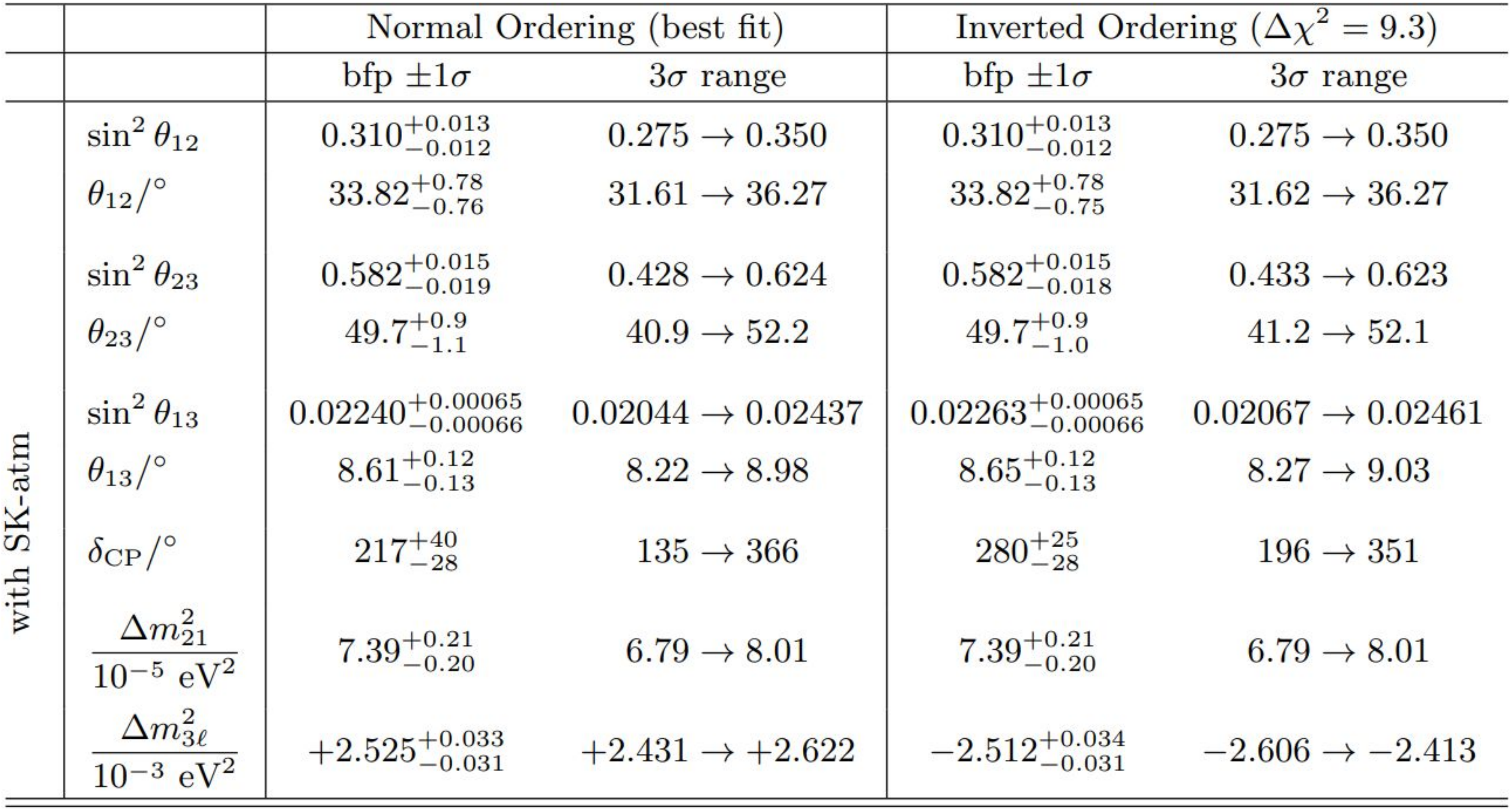
Neutrino masses



[Project 8 2018]

Neutrino masses

NuFIT 4.1 (2019)



		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
	$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
	$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
	$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{\mathrm{CP}}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$

The Standard Model needs to be extended to account for non-zero neutrino masses

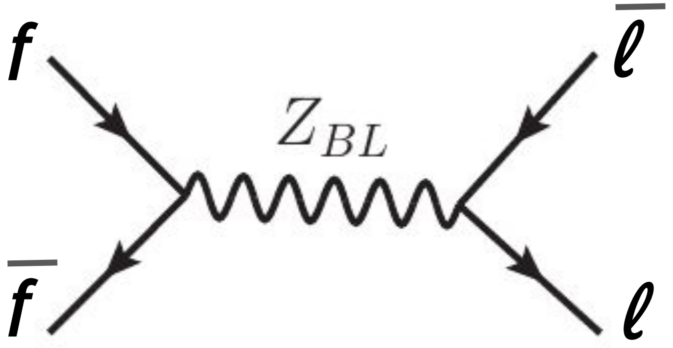
$$m_\nu \neq 0$$

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

Dirac neutrinos and Dirac DM

[Fileviez Perez, Murgui, ADP 2019]

B - *L* as a local symmetry



- In the SM, local symmetries play a crucial role. Its general structure is derived from:

$$\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \longrightarrow \mathrm{SU}(3)_c \otimes \mathrm{U}(1)_{\mathrm{EM}}$$

Following the SM we gauge the *B*-*L* symmetry

- New *B*-*L* gauge boson that can be searched for at colliders

Many authors have studied $\mathrm{U(1)}_{\mathrm{B\text{-}L}}$

Dirac neutrinos

B-L conservation

$$Y_\nu^D \, \bar{l}_L i\sigma_2 H^* \nu_R + \mathrm{h.\,c.}$$

$$m_\nu \leq \ \mathrm{eV} \qquad \Longrightarrow \qquad Y_\nu^D \leq 10^{-12}$$

What about the Majorana mass term?

$$\frac{1}{2} M_R \nu_R^T C \nu_R$$

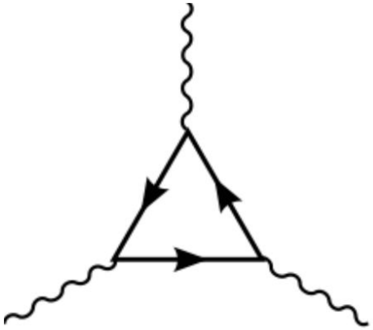
Dirac neutrinos

B-L conservation

What about the Majorana mass term? $\boxed{\xcancel{\frac{1}{2}M_R\nu_R^T C\nu_R}}$

- Promote *B-L* to a local symmetry
- New mediator $Z_{B\text{-}L}$

Anomaly cancellation:



$$3\nu_R \quad \Longrightarrow \quad \mathrm{U}(1)_{B-L}$$

This symmetry forbids the Majorana mass term

Dirac Neutrinos

$\mathrm{U}(1)_{B-L}$

In order to give mass to the *B-L* gauge boson we can :

1) Unbroken *B-L*: Stueckelberg mechanism Z_{BL}

2) Spontaneous symmetry breaking of *B-L* Z_{BL}

$$S_{BL} \sim (1,1,0,q_{BL})$$

$$\boxed{|q_{BL}| > 2}$$

To forbid Majorana mass term

Dirac Neutrinos

$\mathrm{U}(1)_{B-L}$

In order to give mass to the *B-L* gauge boson we can :

1) Unbroken *B-L*: Stueckelberg mechanism ***Z_BL***

2) Spontaneous symmetry breaking of *B-L* ***Z_BL***

$$S_{BL} \sim (1, 1, 0, q_{BL}) \qquad |q_{BL}| > 2$$

Stueckelberg scenario

$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(mZ_{\mu}^{BL} + \partial_{\mu}\sigma)(mZ_{BL}^{\mu} + \partial^{\mu}\sigma)}$$

The above Lagrangian is invariant under gauge transformations:

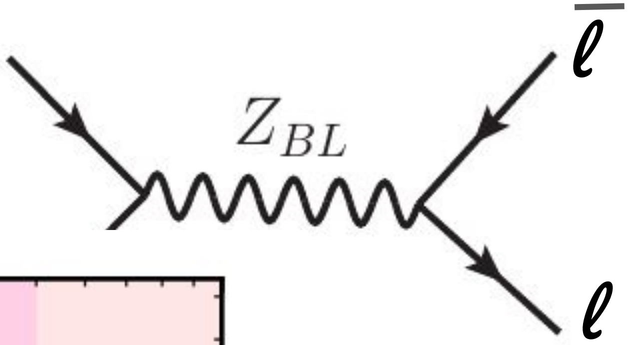
$$\delta Z_{BL}^{\mu} = \partial^{\mu}\lambda(x) \qquad \textbf{and} \qquad \delta\sigma = -M_{Z_{BL}}\lambda(x)$$

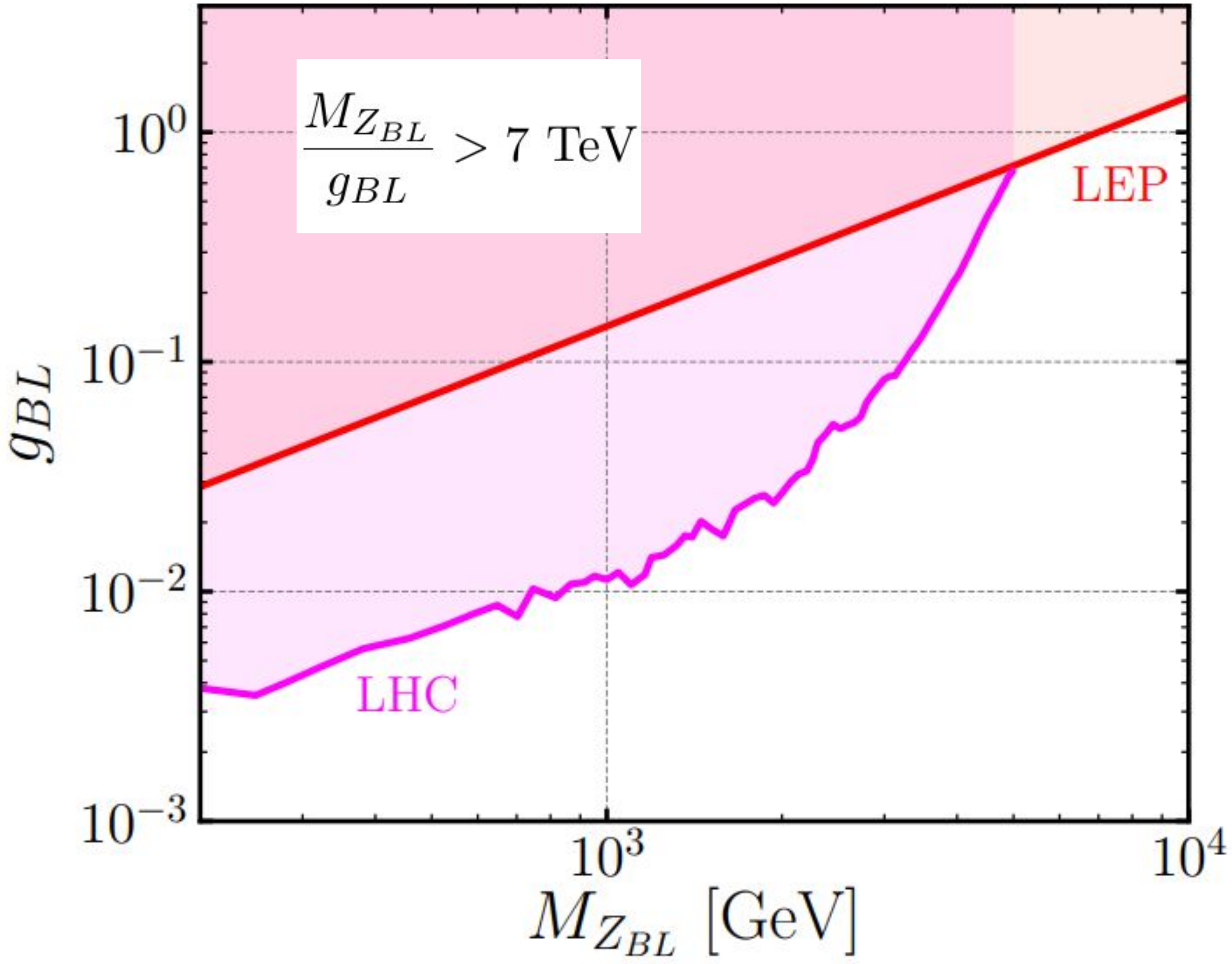
Massive gauge boson and σ field decouples from the theory

$$\begin{aligned}\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{m^2}{2}Z_{\mu}^{BL}Z_{BL}^{\mu} - \frac{1}{2\xi}(\partial_{\mu}Z_{BL}^{\mu})^2 \\ - \frac{1}{2}\partial_{\mu}\sigma\partial^{\mu}\sigma - \xi\frac{m^2}{2}\sigma^2\end{aligned}$$

For Abelian theories renormalizable and unitary

B - *L* as a local symmetry





[ATLAS 2017] **[Alioli, Farina, Pappadopulo, and Ruderman 2018]**

Bounds from cosmology

- In the early Universe, weak interactions keep neutrinos in thermal equilibrium with the plasma

$$\nu + \bar{\nu} \leftrightarrow e^- + e^+ \qquad \nu + e^\pm \leftrightarrow \nu + e^\pm \qquad \nu + \nu \leftrightarrow \nu + \nu$$

- As the rate of these interactions becomes smaller than the Hubble expansion rate, neutrinos decouple and propagate freely in the Universe

- After neutrinos decouple, electron-positron annihilation heats up the photon plasma, and hence, the neutrino temperature is a bit smaller than the one of photons

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

N_{eff} effective number of relativistic species

$$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\rm rad}-\rho_\gamma}{\rho_\gamma}\right) \qquad N_{\rm eff} = 3\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_\nu}{T_\gamma}\right)^4$$

T= 2-3 MeV (t=0.1 s) weak interactions cannot keep neutrinos in thermal equilibrium with electrons and positrons

$$N_{\rm eff}^{\rm SM} = 3.045$$

[Salas Pastor 2016]

Alexis Plascencia

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$$N_{\rm eff}^{\rm SM} = 3.045$$

[Salas Pastor 2016]

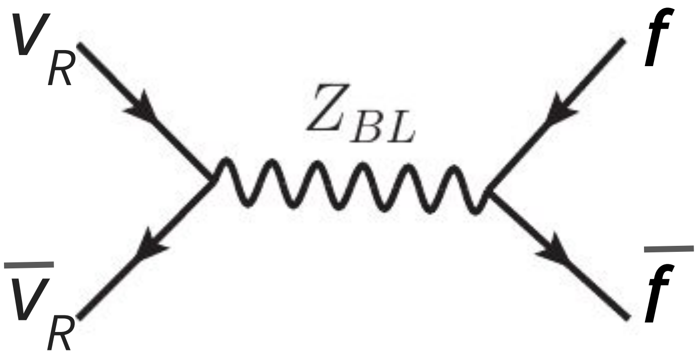
Deviation from 3 comes from- non-instantaneous decoupling, finite temperature corrections, etc...

Review: [Dolgov 2002]

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad \Rightarrow \quad \Delta N_{\rm eff} < 0.285,$$

[Planck 2018]

N_{eff} effective number of relativistic species

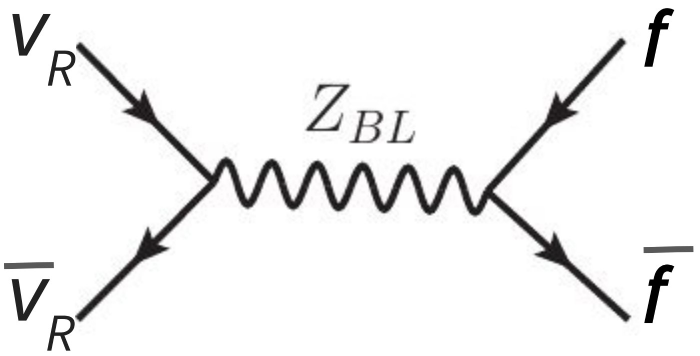


These interactions bring ν_R into thermal equilibrium in the early universe and they contribute to **N_{eff}**

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

N_{eff}

$\mathrm{U}(1)_{B-L}$

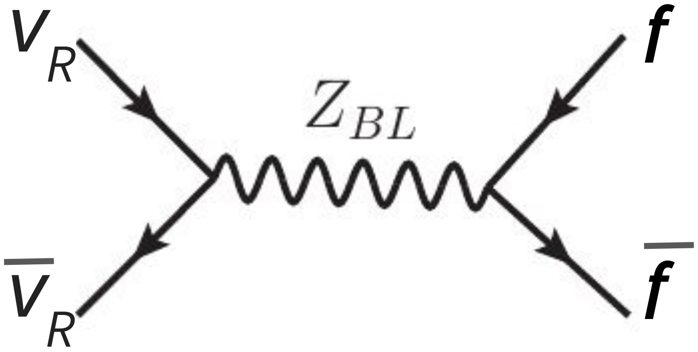


$$\boxed{\Gamma(T^{\mathrm{dec}}_{\nu_R}) = H(T^{\mathrm{dec}}_{\nu_R})}$$

$$\begin{aligned}\Gamma_{\nu_R}(T) &= n_{\nu_R}(T)\langle\sigma(\bar{\nu}_R\nu_R \to \bar{f}f)\,v_M\rangle \\ &= \frac{g^2_{\nu_R}}{n_{\nu_R}(T)}\int\frac{d^3\vec{p}}{(2\pi)^3}f_{\nu_R}(p)\int\frac{d^3\vec{k}}{(2\pi)^3}f_{\nu_R}(k)\sigma_f(s)v_M\end{aligned}$$

$$H(T) = \sqrt{\frac{8\pi G_N\rho(T)}{3}} = \sqrt{\frac{4\pi^3 G_N}{45}\left(g(T) + 3\frac{7}{8}g_{\nu_R}\right)}\,T^2$$

N_{eff}



$\mathrm{U}(1)_{B-L}$

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

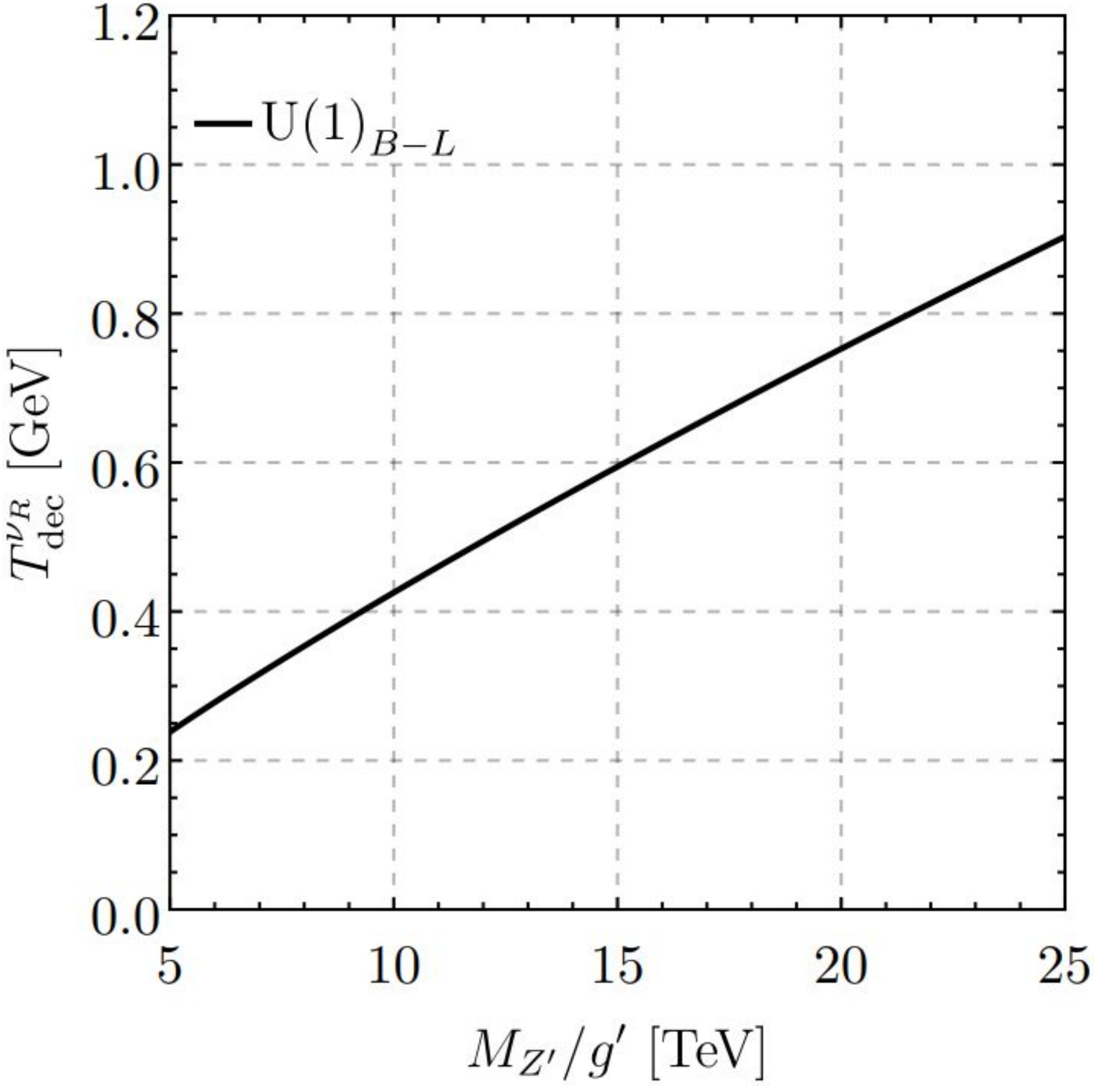
$$\sigma_{\bar{\nu}_R\nu_R\to\bar{f}f} = \frac{g'^4}{12\pi\sqrt{s}}\frac{1}{(s-M_{Z'}^2)^2+\Gamma_{Z'}^2M_{Z'}^2}\sum_f N_f^C n_f^2\sqrt{s-4M_f^2}\,(2M_f^2+s)$$

$$T_{\nu_R}^{\mathrm{dec}} \ll M_{Z'}$$

$$\Gamma_{\nu_R}(T) = \frac{49\pi^5T^5}{97200\xi(3)}\left(\frac{g'}{M_{Z'}}\right)^4\sum_f N_f^C n_f^2,$$

Decoupling T for ν_R

$\mathrm{U}(1)_{B-L}$



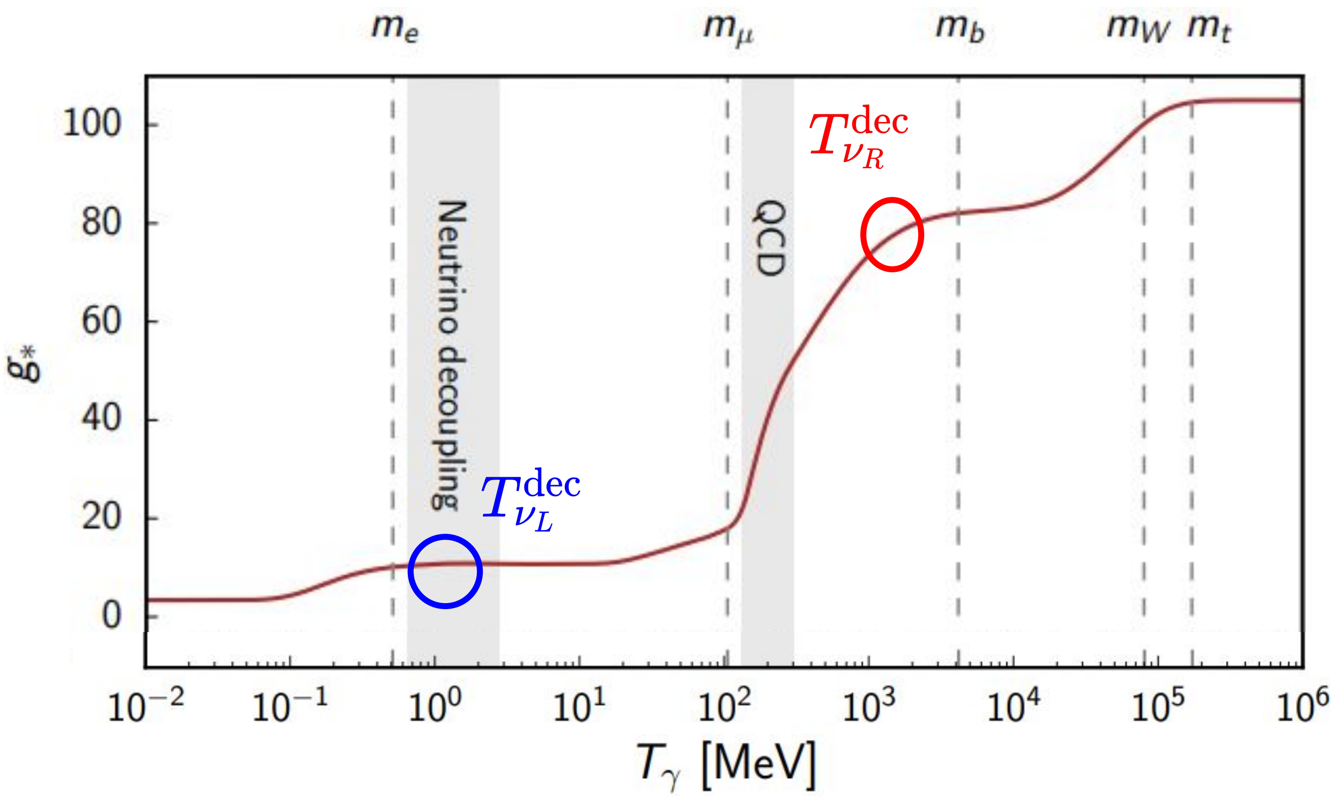
[Fileviez Perez, Murgui, ADP 2019]

N_{eff}

$\mathcal{O}(\mathrm{MeV})$

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

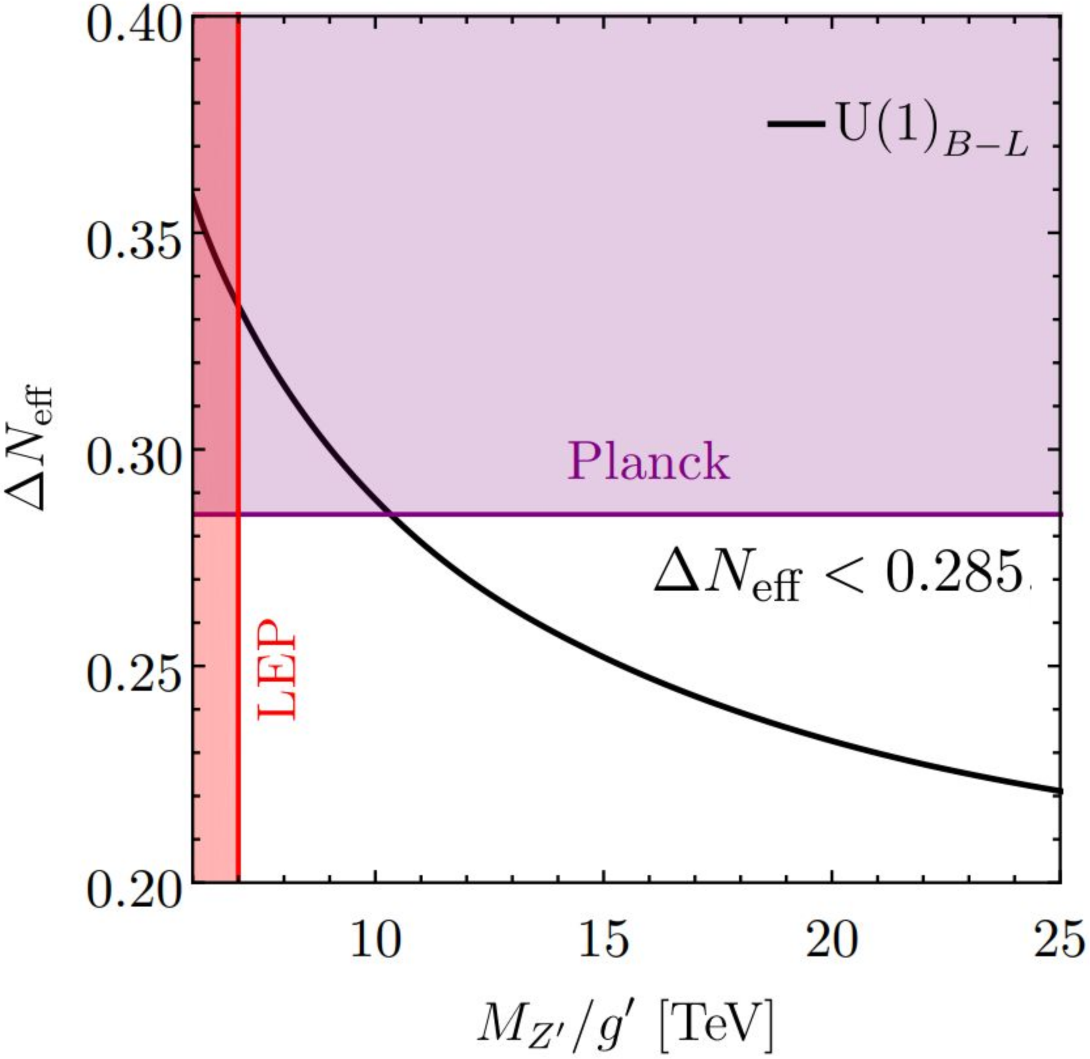
$\mathcal{O}(\mathrm{GeV})$



[Simons Observatory: Science Goal and Forecasts 2019] [Borsany et al 2016]

N_{eff}

$\mathrm{U}(1)_{B-L}$



$$\Delta N_{\rm eff} < 0.285$$

[Planck 2018]

$$\frac{M_{Z_{BL}}}{g_{BL}} > 10.33 \text{ TeV}$$

Stronger than the LEP & LHC bound

[Fileviez Perez, Murgui, ADP 2019]

N_{eff}

$\mathrm{U}(1)_{B-L}$

As long as V_R reached thermal equilibrium in early Universe, ΔN_{eff} goes asymptotically to

$$\Delta N_{\mathrm{eff}} \to 0.021$$

In other words, as long as $T_{reheating} > T_{equil}$ there will be a non-zero contribution to ΔN_{eff}

ΔN_{eff} can be sensitive to a high scale Z_{BL}!

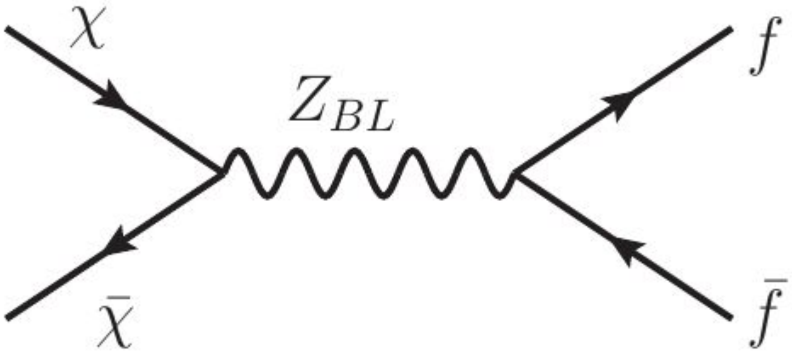
Dirac fermion as dark matter

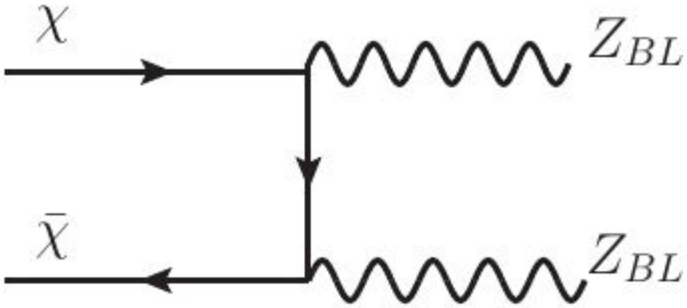
Introduce vector-like fermion with *B-L* charge

$$\chi \sim (1, 1, 0, n)$$

***n* ≠ 1** since n=1 allows mixing with neutrinos and decay

Non-renormalizable operators forbid *n* odd

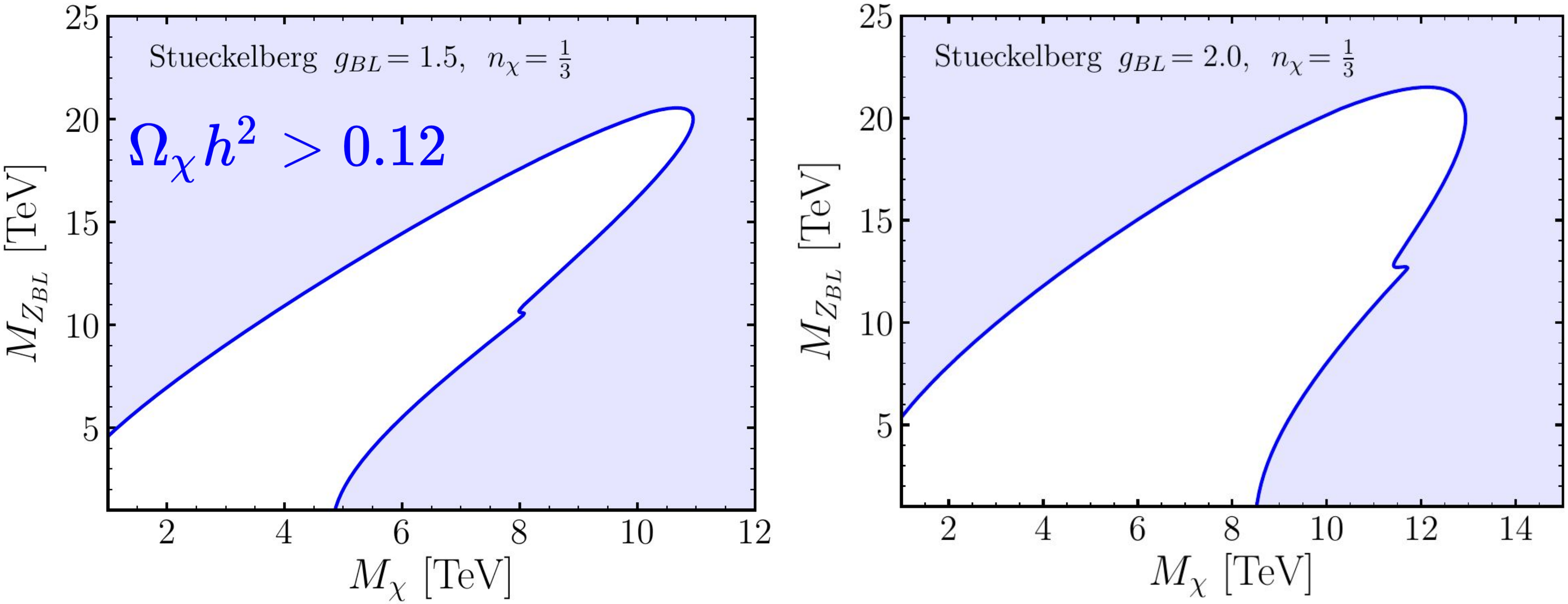




Dark Matter

$\mathrm{U}(1)_{B-L}$

$\Omega_\chi h^2 = 0.1200 \pm 0.0012$ [Planck 2018]



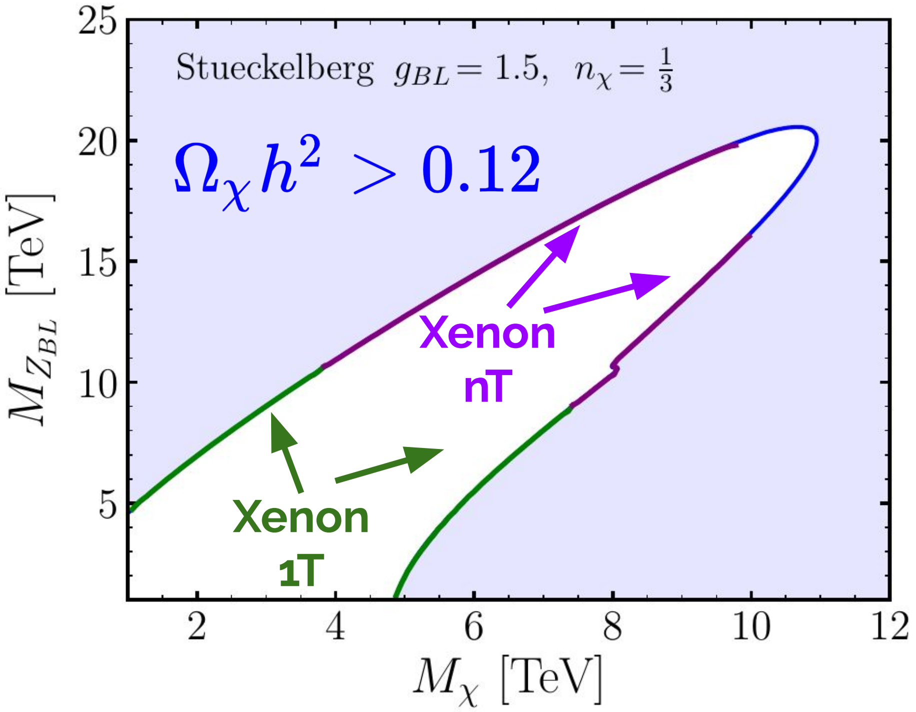
$$M_{Z_{BL}} \leq 22 \text{ TeV} \qquad M_\chi \leq 13 \text{ TeV}$$

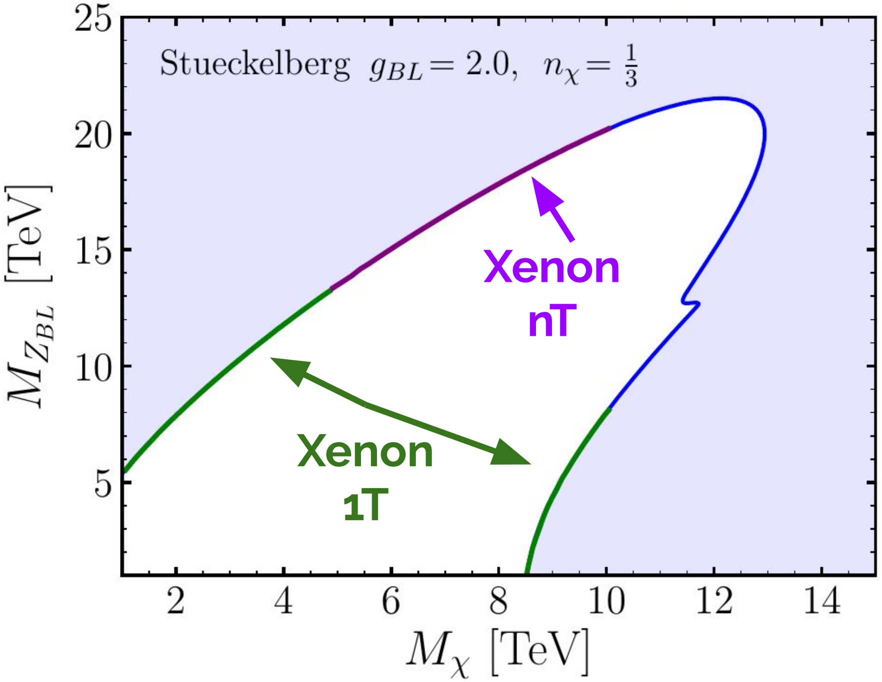
Note: Partial wave unitarity requires $M_{DM} < 240$ TeV weaker bound [Griest & Kamionkowski 1990]

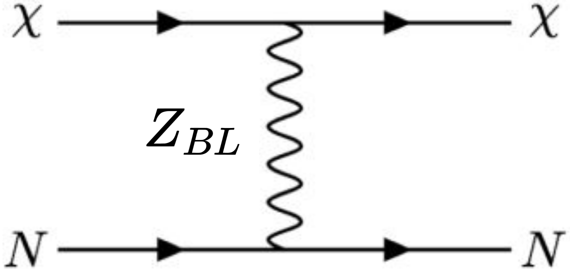
Dark Matter

$\mathrm{U}(1)_{B-L}$

— $\Omega_\chi h^2 = 0.1200 \pm 0.0012$ **[Planck 2018]**







Dark Matter

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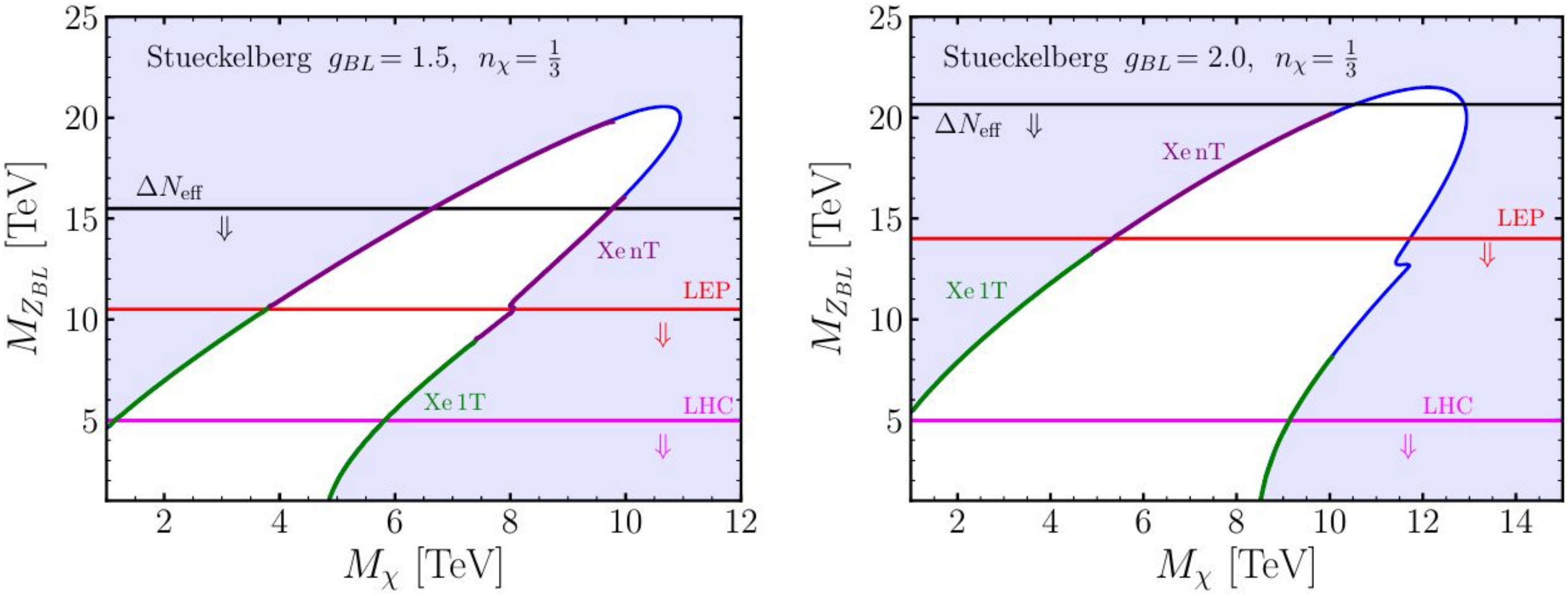
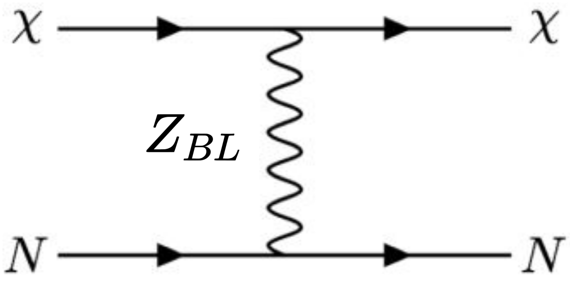


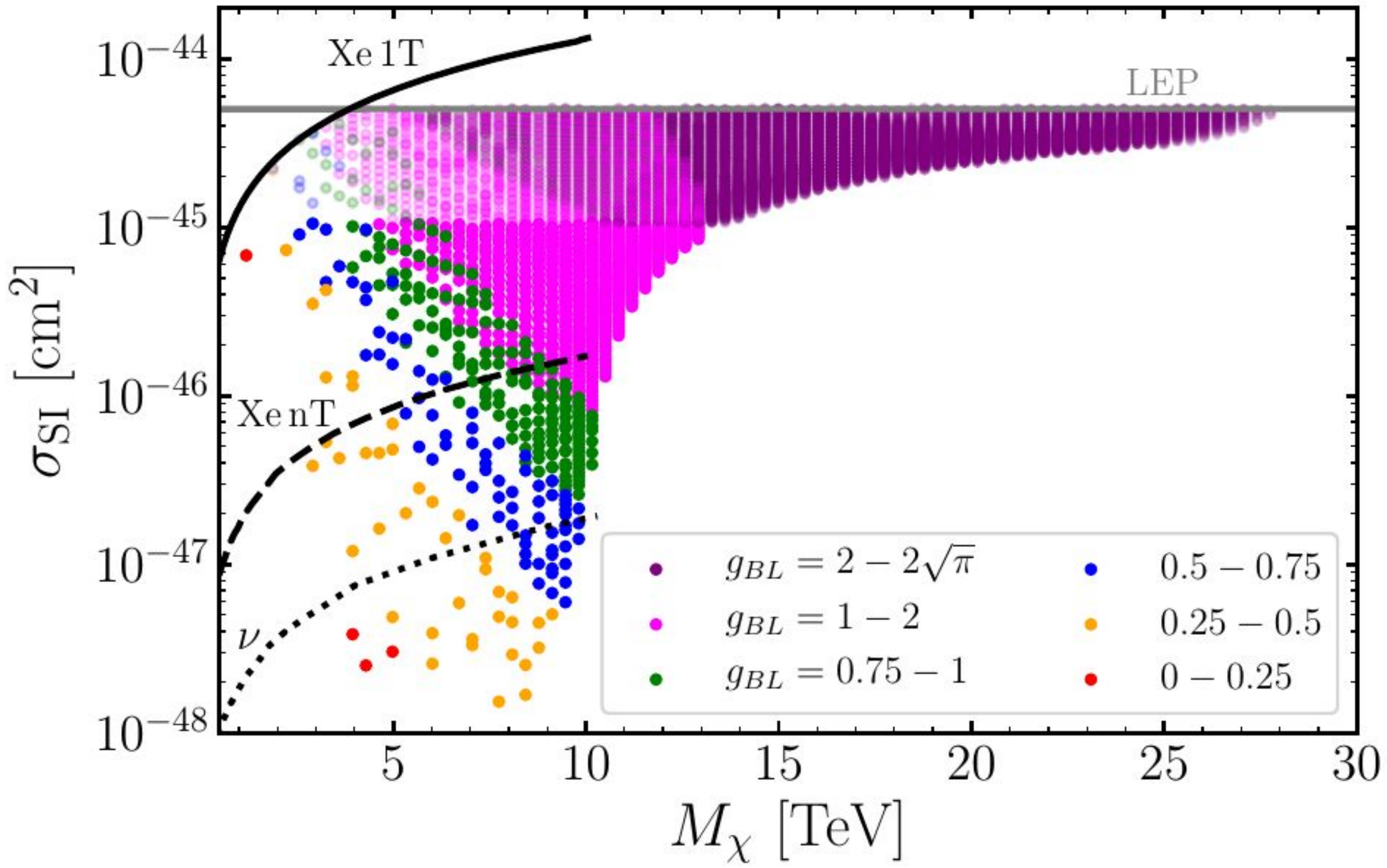
$\Delta N_{eff} < 0.285$ gives the strongest bound

Dark Matter - direct detection

$\mathrm{U}(1)_{B-L}$

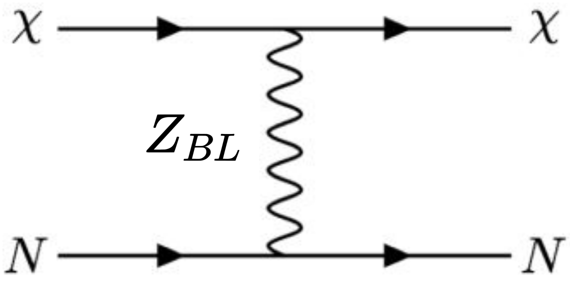


$$\sigma_{\mathrm{SI}} = \frac{m_N^2 M_\chi^2}{\pi(m_N + M_\chi)^2} \frac{n_\chi^2 g_{BL}^4}{M_{Z_{BL}}^4},$$

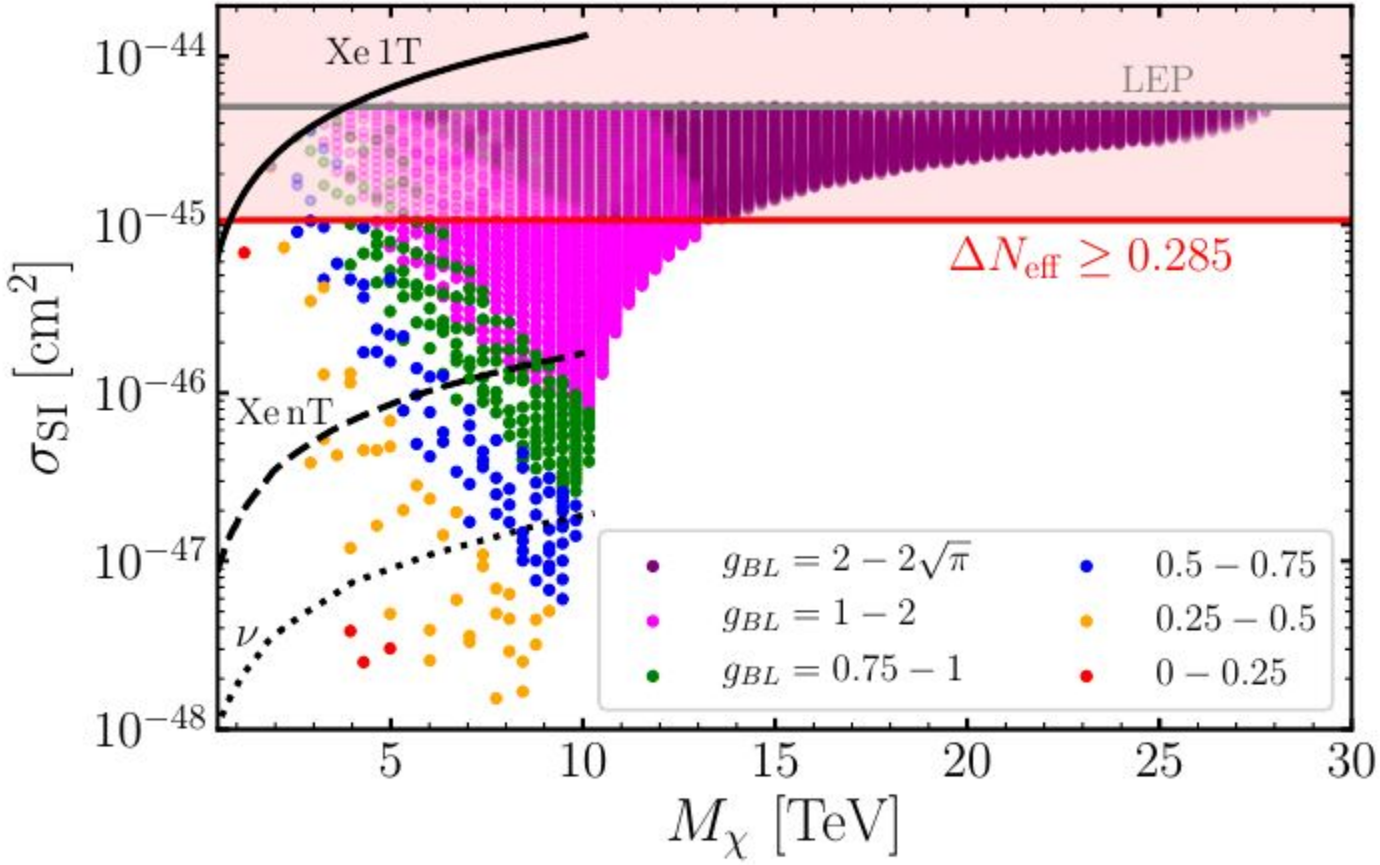


Dark Matter - direct detection

$\mathrm{U}(1)_{B-L}$



$$\sigma_{\mathrm{SI}} = \frac{m_N^2 M_\chi^2}{\pi(m_N + M_\chi)^2} \frac{n_\chi^2 g_{BL}^4}{M_{Z_{BL}}^4},$$



3. $U(1)_L$

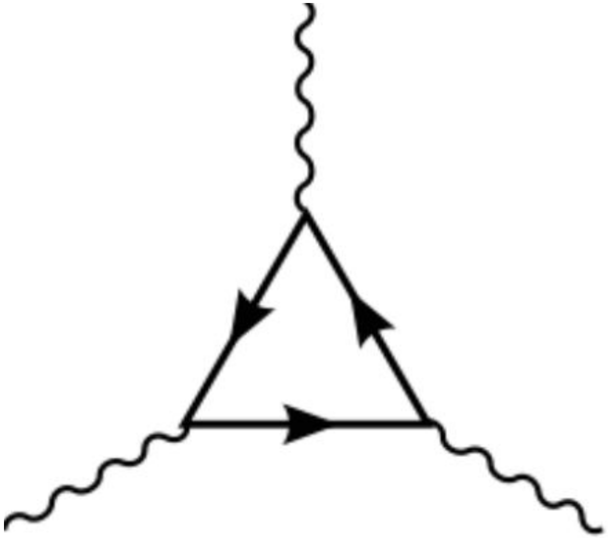
Dirac neutrinos and Majorana DM

[Fileviez Perez, Murgui, ADP 2019]

Gauging lepton number

$\mathrm{U}(1)_L$

- Promote lepton number to a local symmetry
- Need to add new fermions to cancel anomalies



$$\mathcal{A}_1\left(SU(3)^2 \otimes U(1)_L\right), \ \mathcal{A}_2\left(SU(2)^2 \otimes U(1)_L\right),$$
$$\mathcal{A}_3\left(U(1)_Y^2 \otimes U(1)_L\right), \ \mathcal{A}_4\left(U(1)_Y \otimes U(1)_L^2\right),$$
$$\mathcal{A}_5\left(U(1)_B\right), \ \mathcal{A}_6\left(U(1)_L^3\right).$$

In the SM the non-zero values are:

$$\mathcal{A}_2 = -\mathcal{A}_3 = 3/2$$

Anomaly-free model

$\mathrm{U}(1)_L$

Fields	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_L$
$\Psi_L = \begin{pmatrix} \Psi_L^0 \\ \Psi_L^- \end{pmatrix}$	1	2	$-\frac{1}{2}$	$-\frac{3}{2}$
$\Psi_R = \begin{pmatrix} \Psi_R^0 \\ \Psi_R^- \end{pmatrix}$	1	2	$-\frac{1}{2}$	$\frac{3}{2}$
η_R^-	1	1	-1	$-\frac{3}{2}$
η_L^-	1	1	-1	$\frac{3}{2}$
χ_R^0	1	1	0	$-\frac{3}{2}$
χ_L^0	1	1	0	$\frac{3}{2}$

[Duerr, Fileviez Perez & Wise 2013]

- Neutral fermion required for anomaly cancellation
- Automatically stable from remnant U(1)⟶Z_2 symmetry

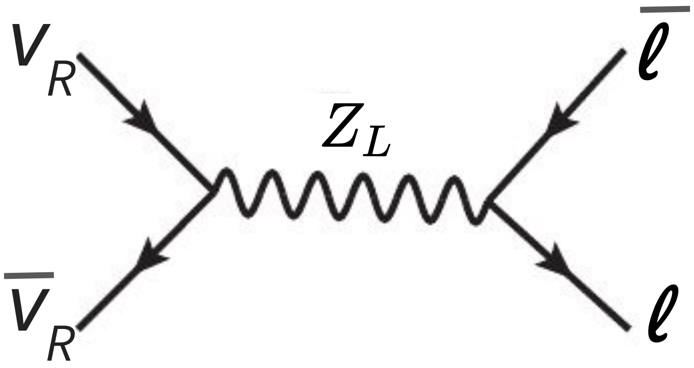
➡ DM Candidate 🙂

Dirac neutrinos

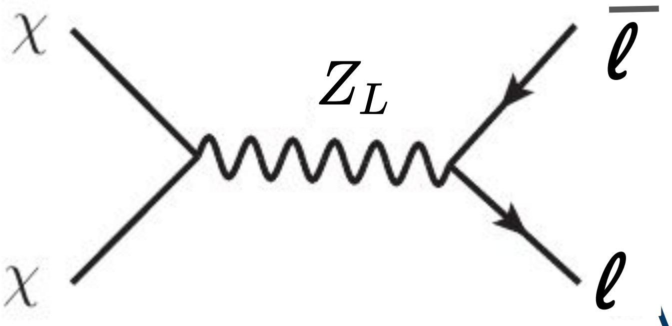
$\mathrm{U}(1)_L$

- Lepton number broken by 3 units: $\Delta L = \pm 3$ interactions

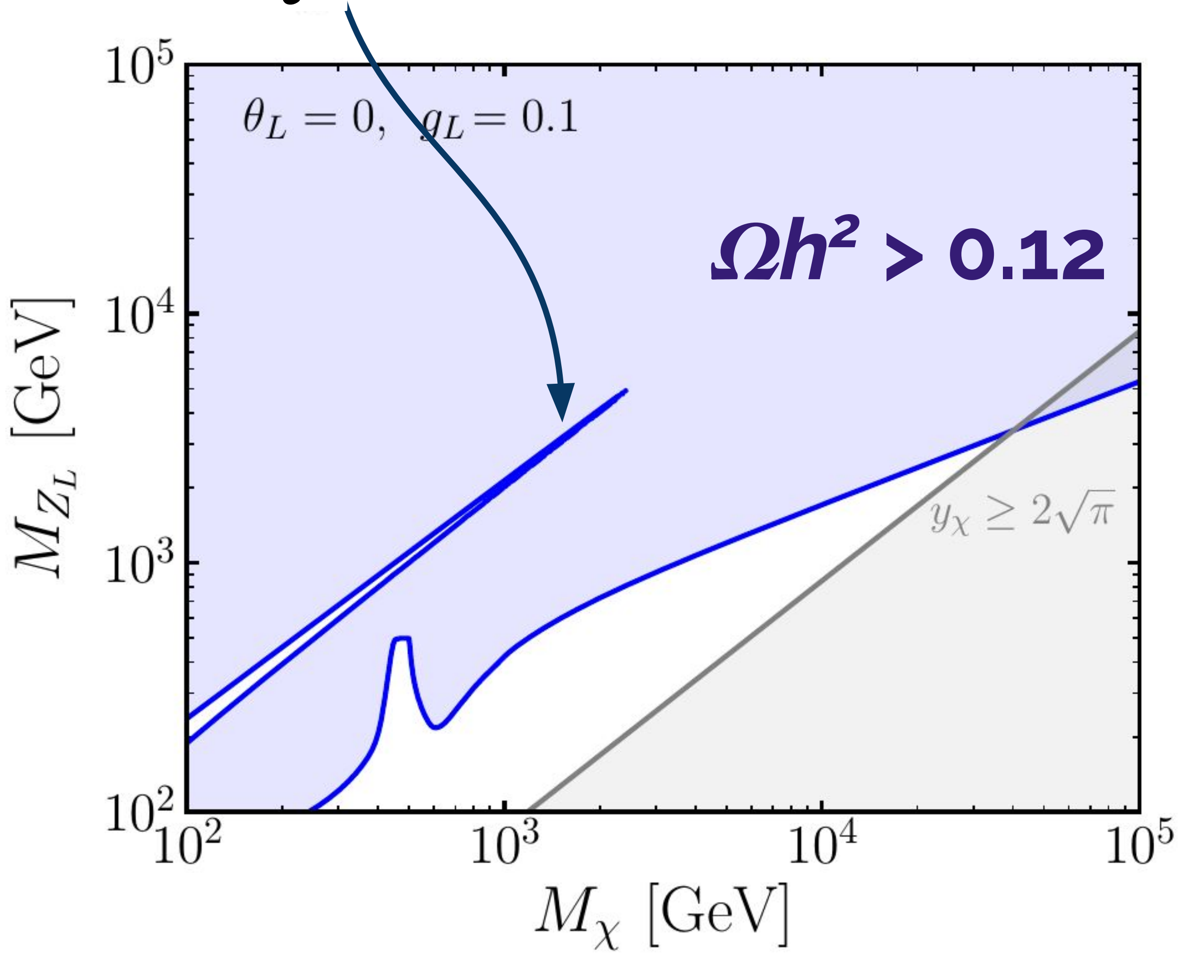
→ **Dirac neutrinos**



Constraints from N_{eff} also apply to this scenario!

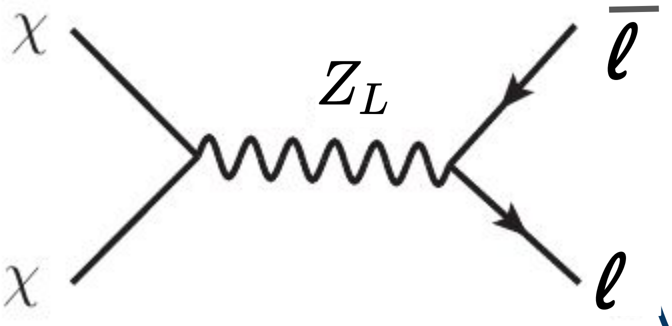


$$M_\chi \approx M_{Z_L}/2$$

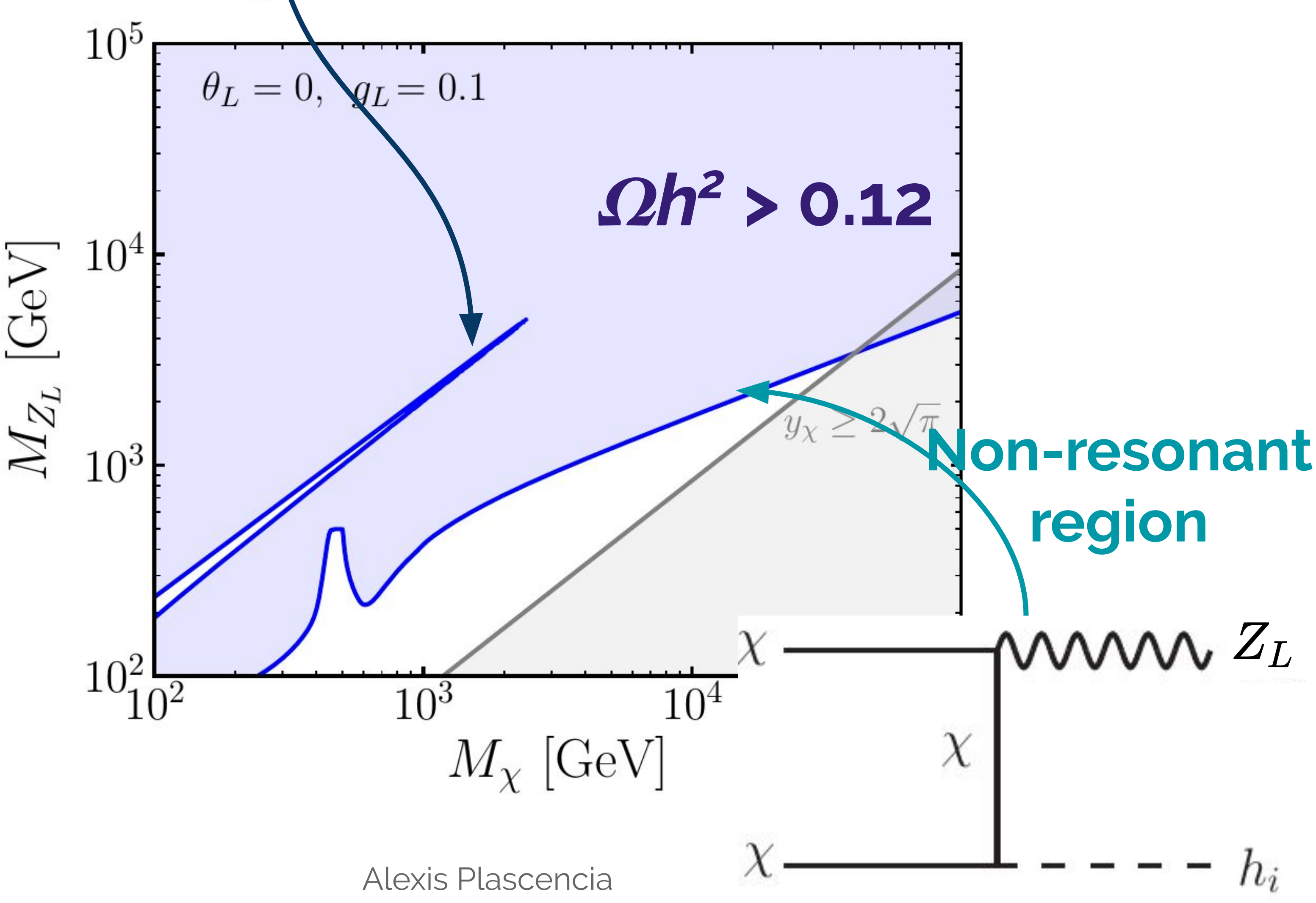


$\Omega h^2 > 0.12$

[Fileviez Perez, Murgui, ADP 2019]

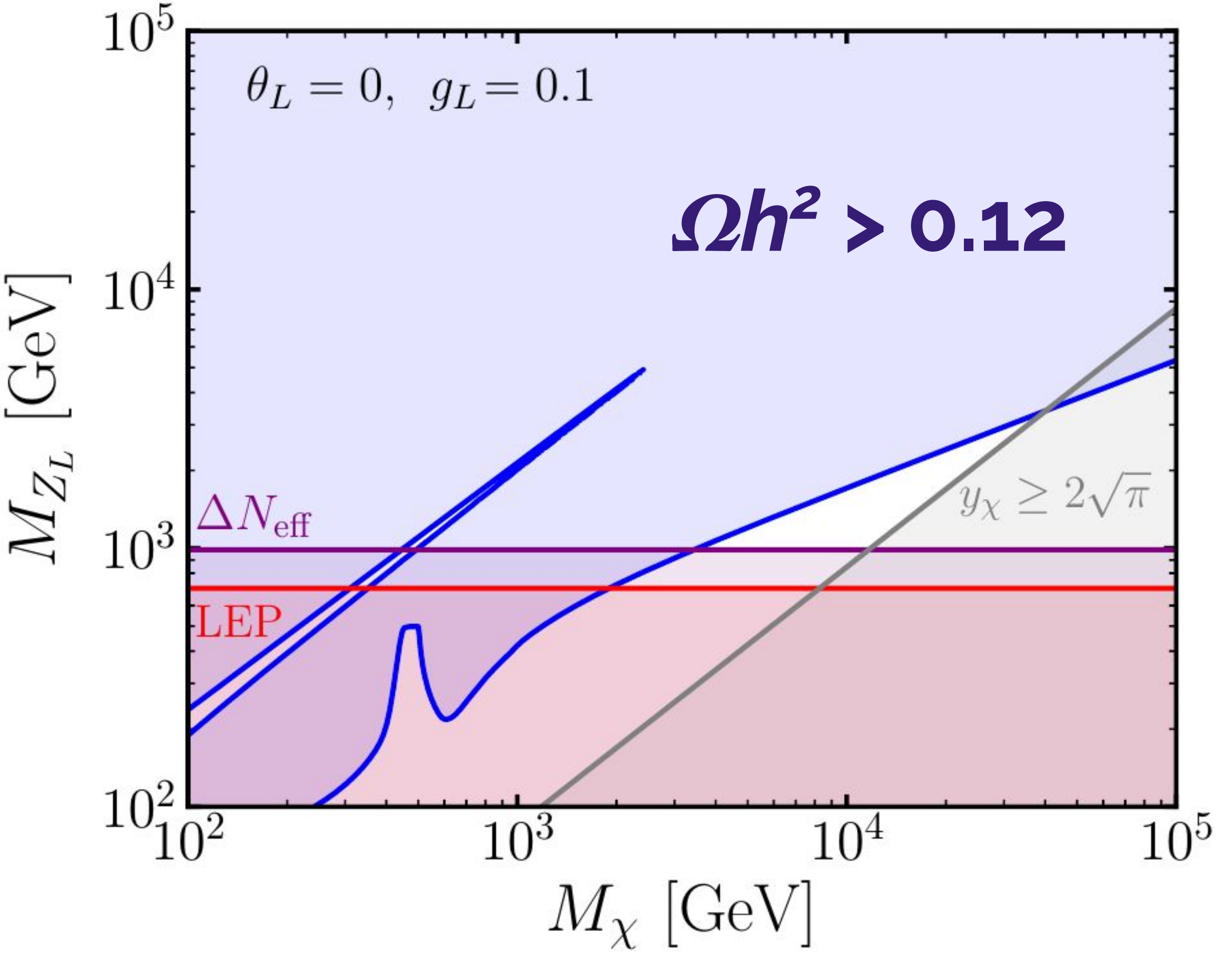


$$M_\chi \approx M_{Z_L}/2$$



$\Omega h^2 > 0.12$

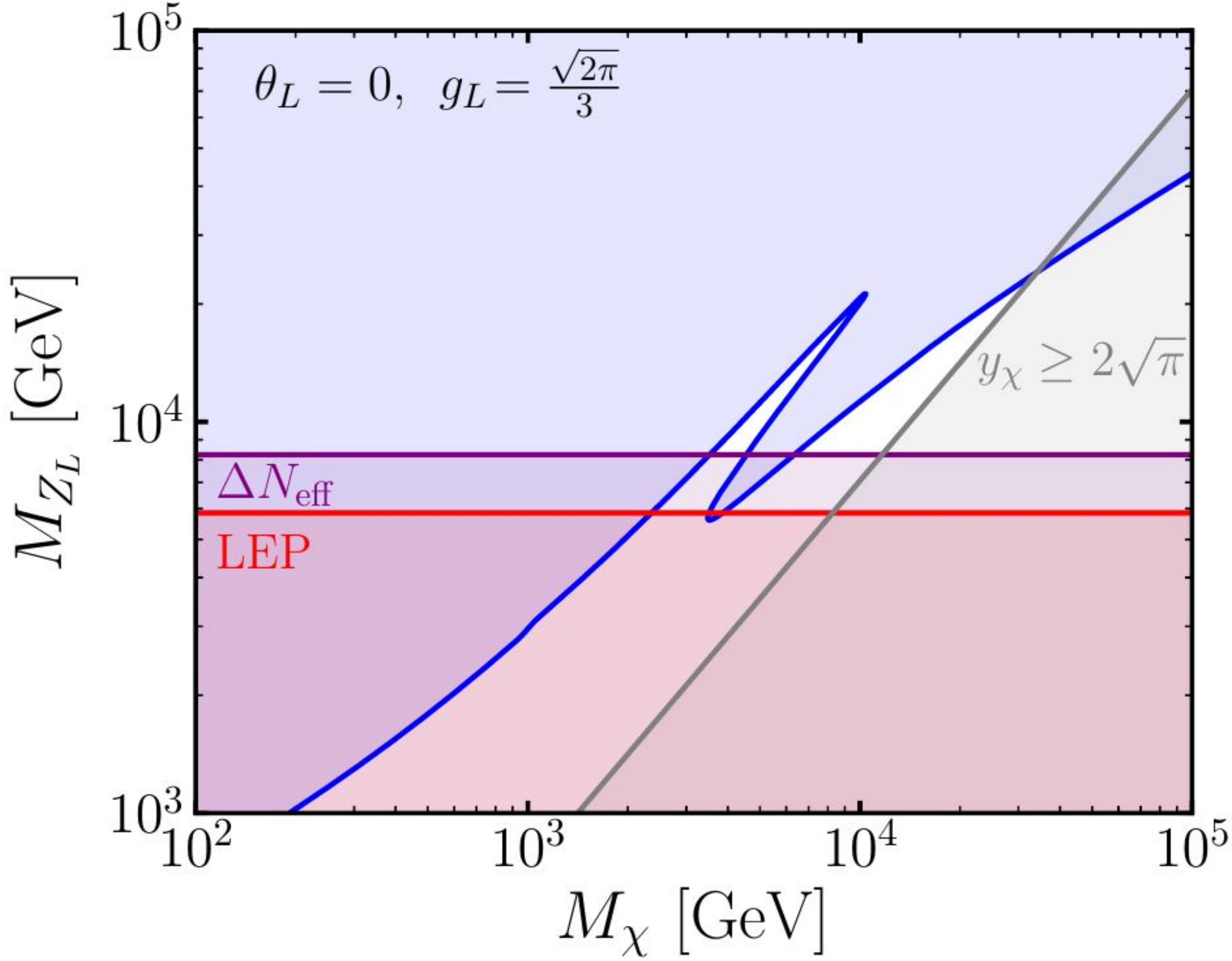
Non-resonant region


$\theta_L = 0, \;\; g_L = 0.1$
$\Delta N_{\rm eff}$
LEP
$y_\chi \geq 2\sqrt{\pi}$
M_{Z_L} [GeV]
M_χ [GeV]
10^2
10^3
10^4
10^5

$\Omega h^2 > 0.12$

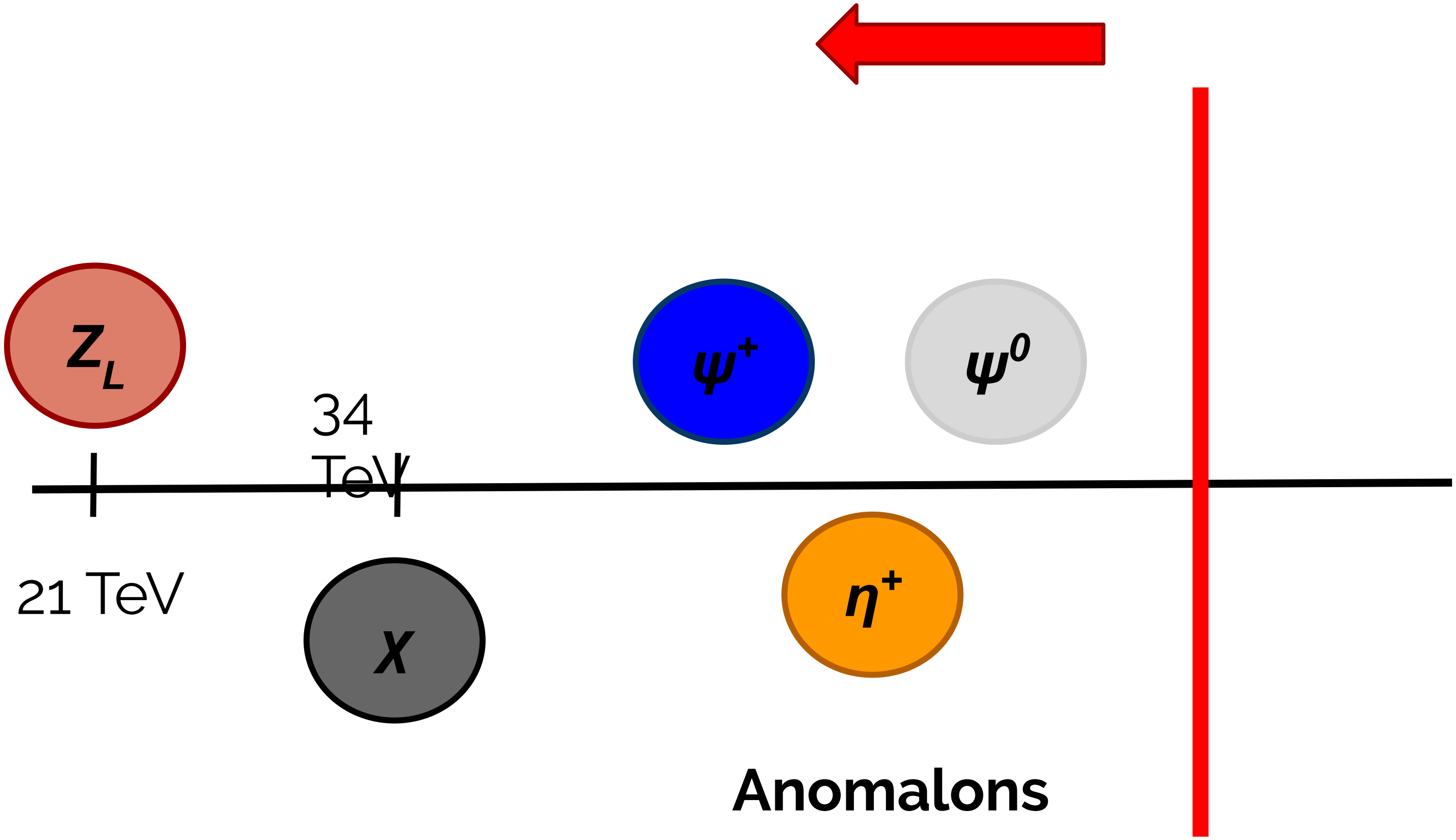
Perturbativity $g_L \leq \frac{\sqrt{2\pi}}{3} \approx 0.84$ and $\Omega h^2 \leq 0.12$

Give an upper bound on the scale



Upper bound on lepton number breaking scale

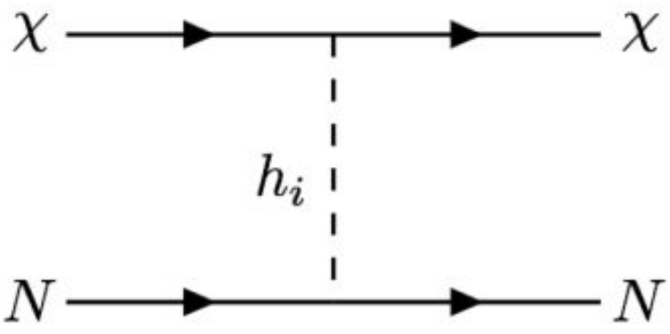
All masses connected to $<v>_L$ and hence there is an upper bound for the full model

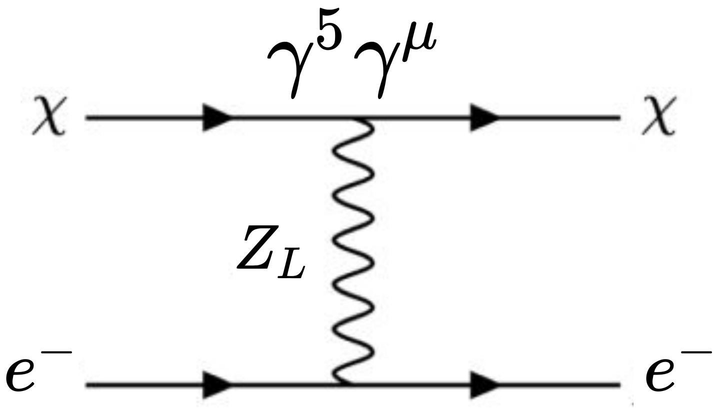


Direct Detection

$\mathrm{U}(1)_L$

Z_L does not couple to quarks





suppressed by Higgs mixing

$\theta < 0.3$ for $M_{H2} > 200$ GeV

For lighter M_{H_2} stronger bound

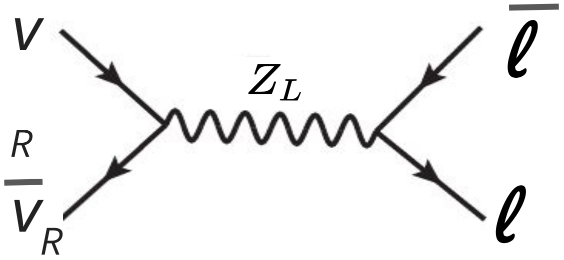
[Ilnicka, Robens, Stefaniak 2018]

Due to axial coupling,

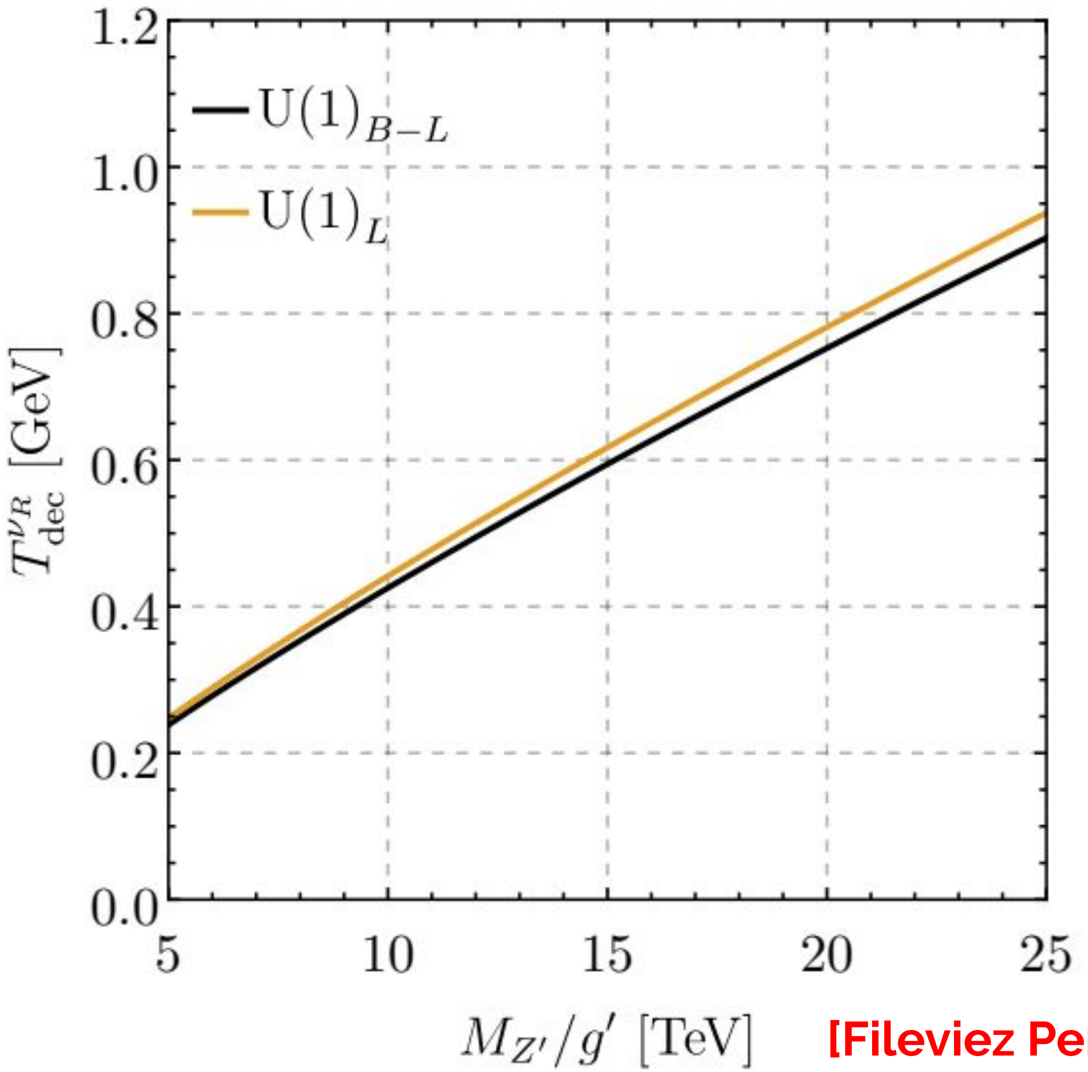
velocity suppressed v~10^{-3}

Direct detection constraints can be avoided with $\sin\theta < 0.1$

N_{eff}

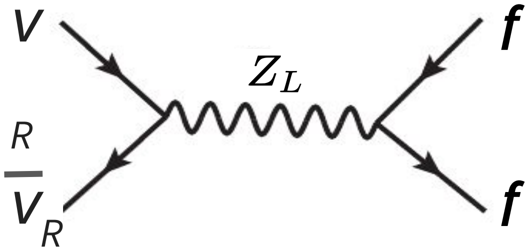


$\mathrm{U}(1)_L$

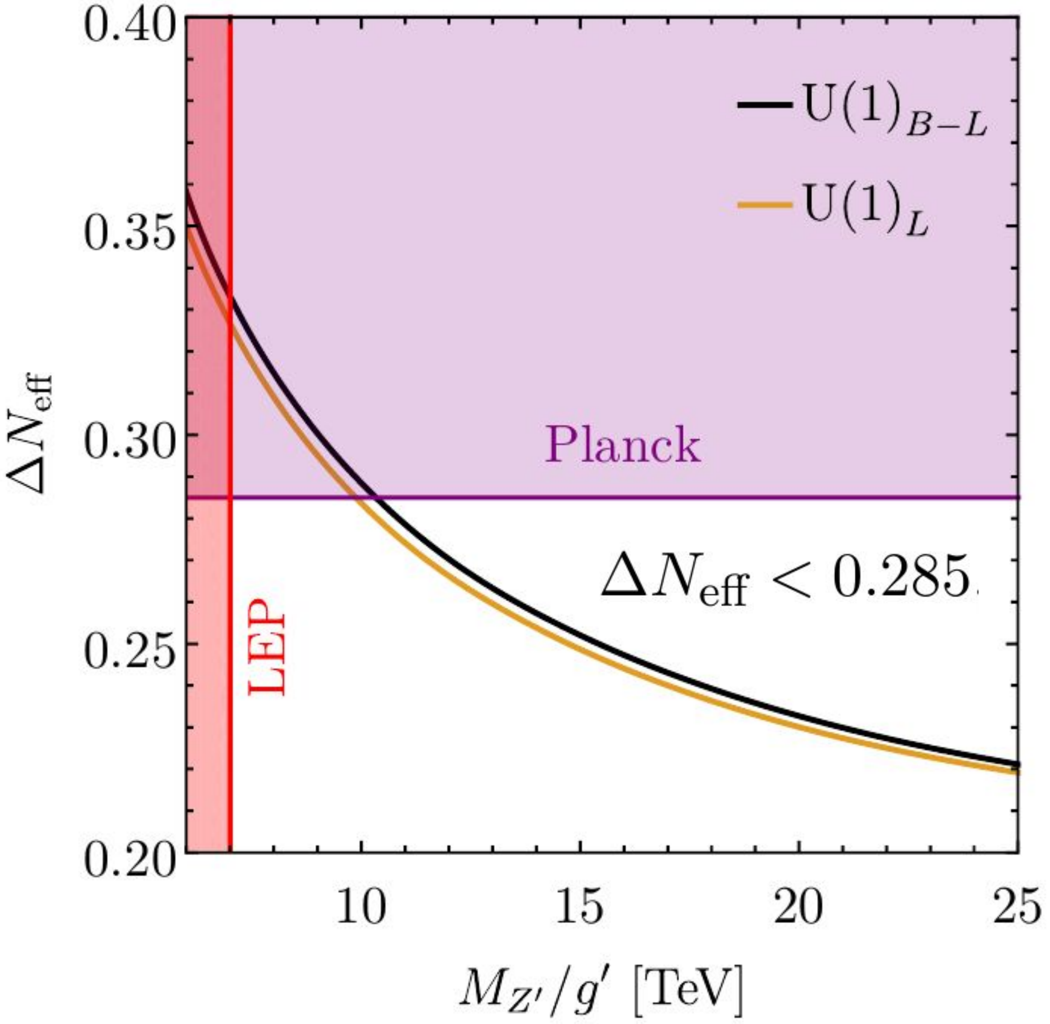


[Fileviez Perez, Murgui, ADP 2019]

N_{eff}



$\mathrm{U}(1)_L$



$\Delta N_{\rm eff} < 0.285$

[Planck 2018]

$$\boxed{\frac{M_{Z_L}}{g_L} > 9.87 \text{ TeV}}$$

[Fileviez Perez, Murgui, ADP 2019]

Next generation CMB experiments

CMB-S4
Next Generation CMB Experiment

Projection for CMB Stage-IV:

$$\Delta N_{\rm eff} < 0.06 \quad \text{at } 95\% \, \text{CL}$$

[CMB-S4 Science Book 2016]

- Array of ground-based telescopes in South Pole and Chile
- Joint NSF and DOE project
- Observing late 2020s

SIMONS
OBSERVATORY

- Telescope array in the Atacama Desert, Chile
- Funded
- Observing 2020's

$$\Delta N_{\rm eff} < 0.12 \;\; \text{at } 95\% \, \text{CL}$$

[Simons Observatory: Science Goal and Forecasts 2019]

Next generation CMB experiments

CMB-S4
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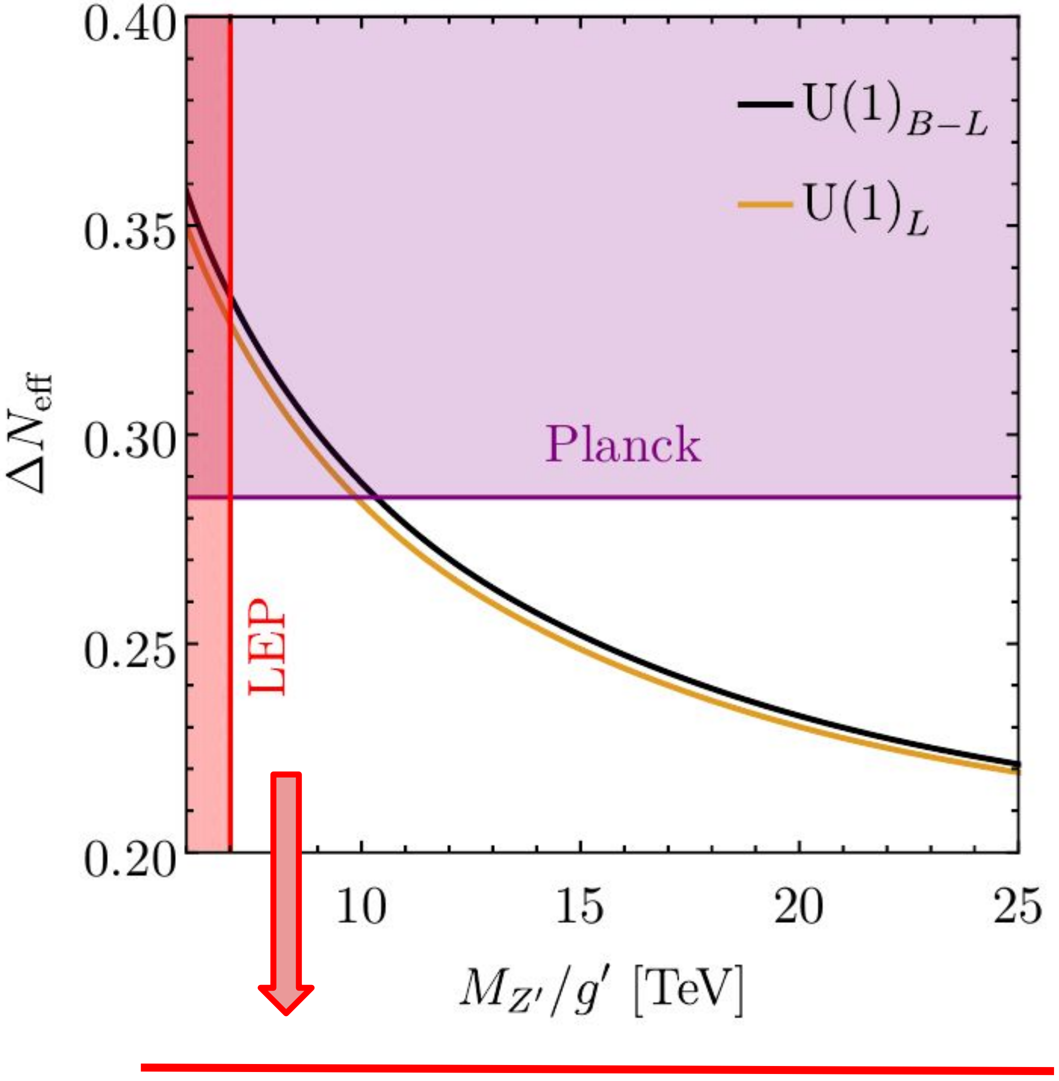
[Simons Observatory: Science Goal and Forecasts 2019]

N_{eff} gives strongest bound



Next generation CMB experiments could fully probe the parameter space that also explains thermal dark matter

CMB-S4

$$\Delta N_{\rm eff} < 0.06$$

Baryogenesis

$\mathrm{U}(1)_L$

These models explain dark matter and neutrino masses

Need to explain matter-antimatter asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

$$\eta_{B\,\mathrm{BBN}} = (5.80 - 6.60) \times 10^{-10}$$

$$\eta_{B\,\mathrm{CMB}} = (6.02 - 6.18) \times 10^{-10}$$

- Baryogenesis in $\mathrm{U(1)}_L$ [and $\mathrm{U(1)}_B$]
- New scalar *S* to induce 1st order PT and CP-violation
- Chiral asymmetry for DM χ

[Carena, Quirós, Zhang, 2019]

4. $U(1)_B$

Majorana DM, gamma lines and LHC pheno

[Fileviez Perez, Golias, Li, Murgui, ADP 2019]

[Fileviez Perez, Murgui, ADP 2020]

Gauging baryon number

$\mathrm{U}(1)_B$

- Promote baryon number to a local symmetry
- Need to add new fermions to cancel anomalies
- Spin-1 mediator Z_B that only talks to quarks, consistent completion of simplified models of dark matter
- Dark matter is predicted by anomaly cancellation and its stability is guaranteed by remnant U(1)→Z_2 symmetry

Simplified Dark Matter

χ: Majorana DM

Z_B : Leptophobic mediator

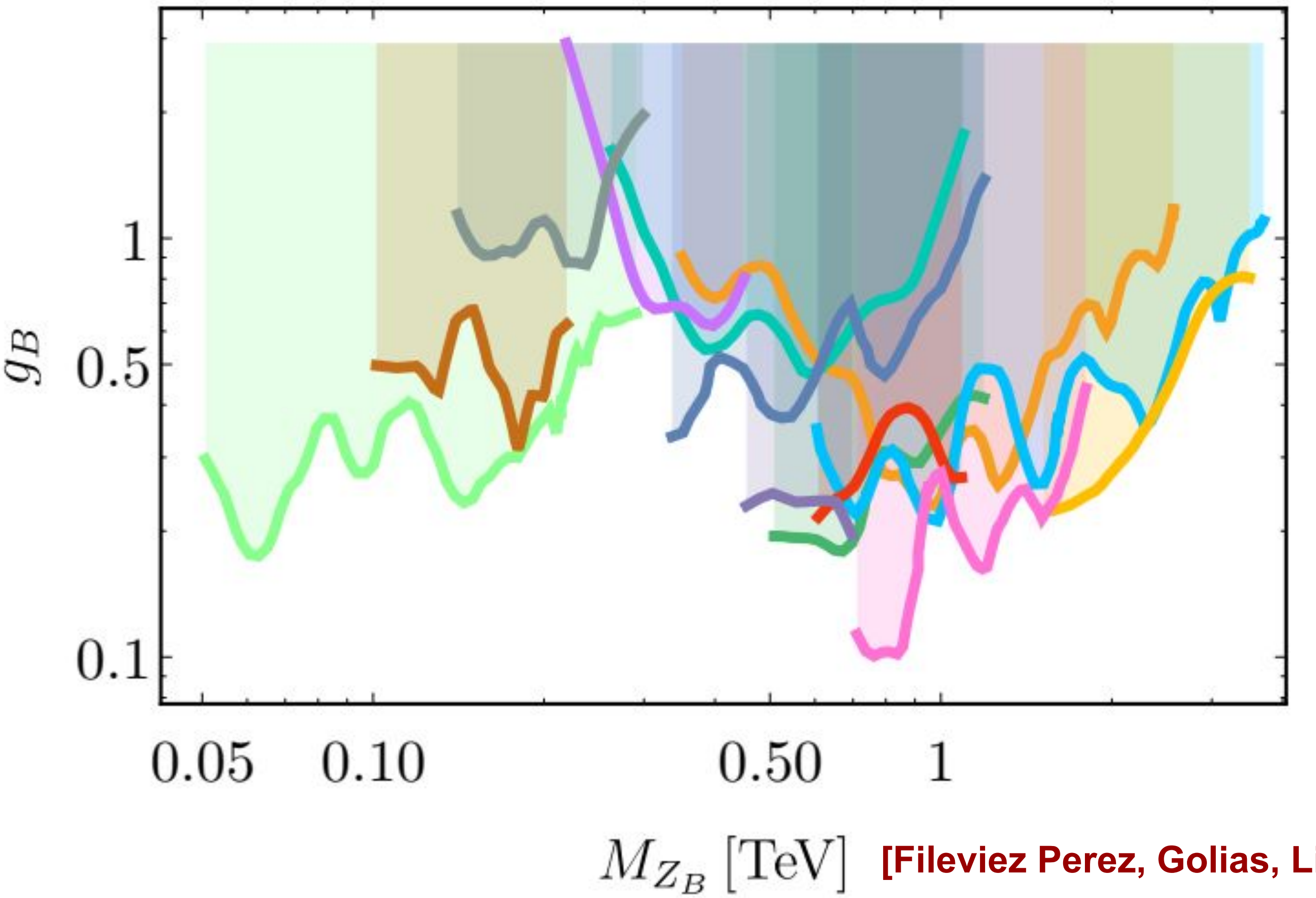
$$\boxed{\mathcal{L} \supset \frac{3}{4}\underbrace{g_B \bar{\chi}\gamma^\mu\gamma^5\chi}_{\textbf{Axial}} Z^B_\mu - \frac{1}{3}\underbrace{g_B \bar{q}\gamma^\mu q Z^B_\mu}_{\textbf{Vector}} + \frac{M_\chi}{2v_B}\sin\theta_B \bar{\chi}\chi h_1 - \frac{M_\chi}{2v_B}\cos\theta_B \bar{\chi}\chi h_2}$$

the free parameters in the model are:

$$\boxed{M_\chi, \quad M_{Z_B}, \quad M_{h_2}, \quad \theta_B, \quad g_B.}$$

LHC bounds on leptophobic gauge boson

- No LEP bound for this scenario
- Di-jet searches at CMS and ATLAS - Run I & II



[Fileviez Perez, Golias, Li, Murgui 2018]

Alexis Plascencia

LHC bounds on leptophobic gauge boson

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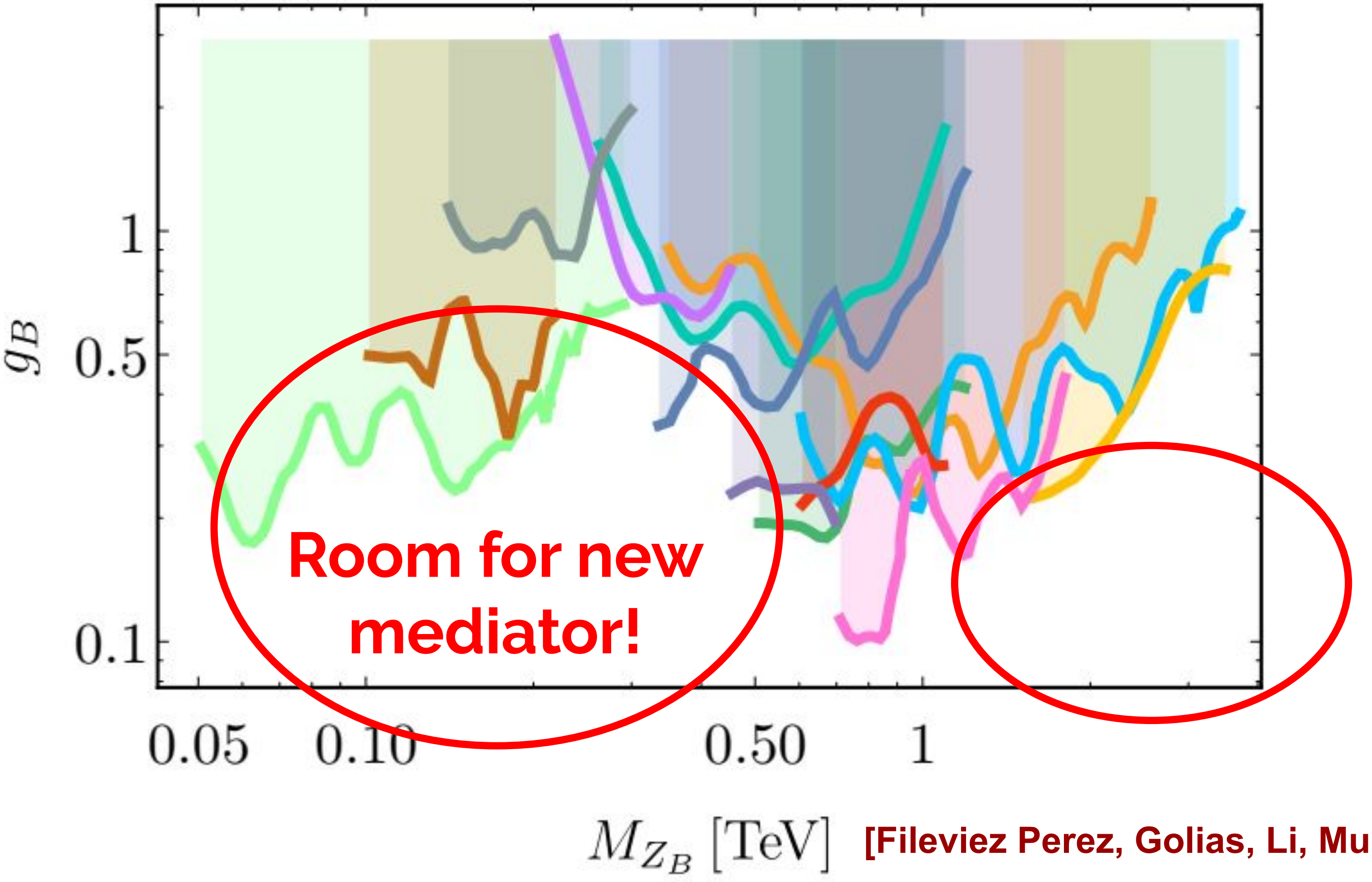
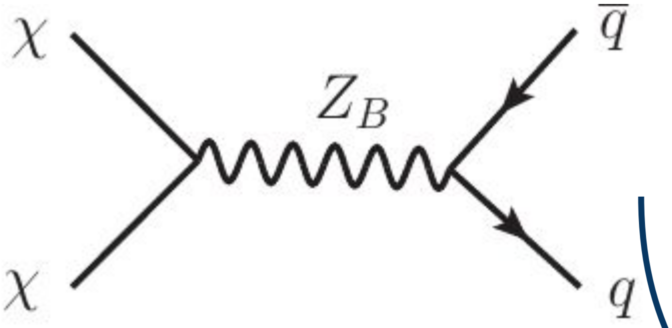
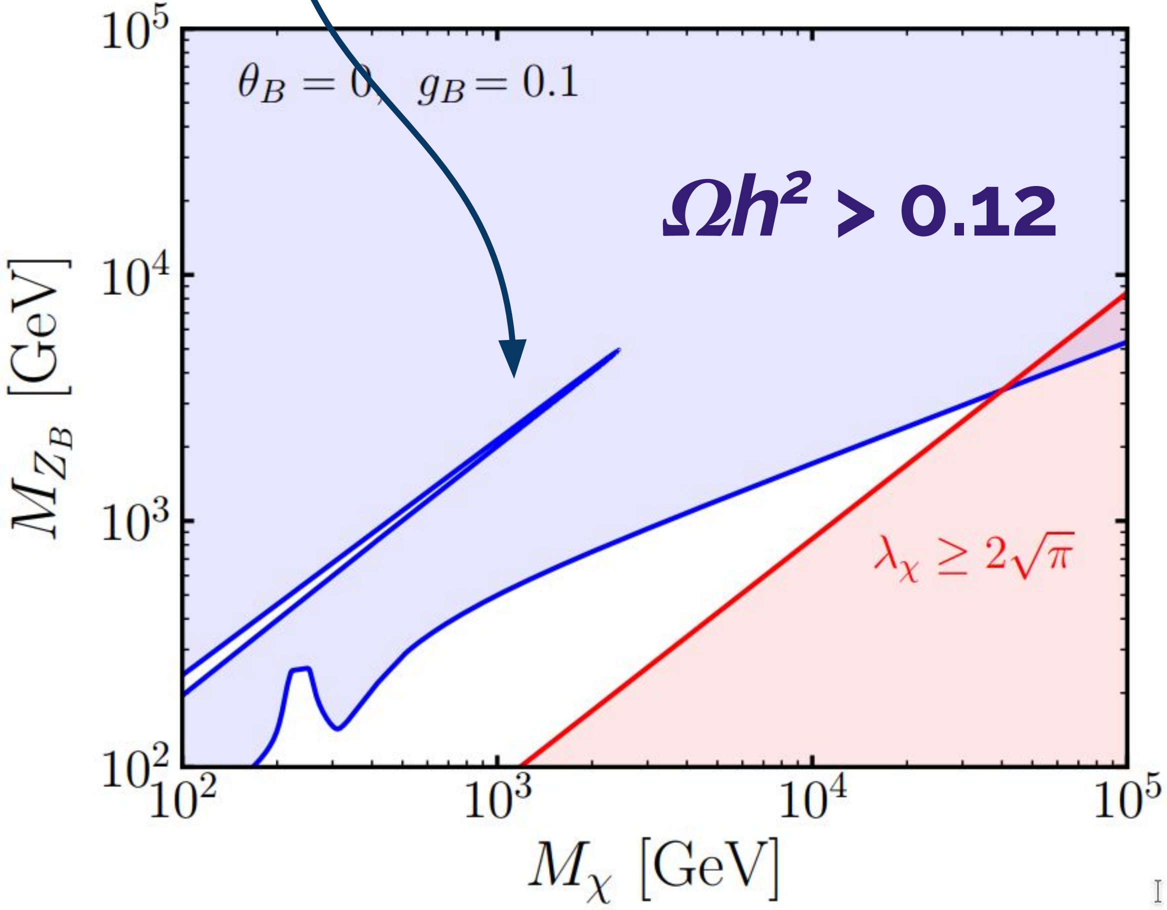


[Fileviez Perez, Golias, Li, Murgui 2018]

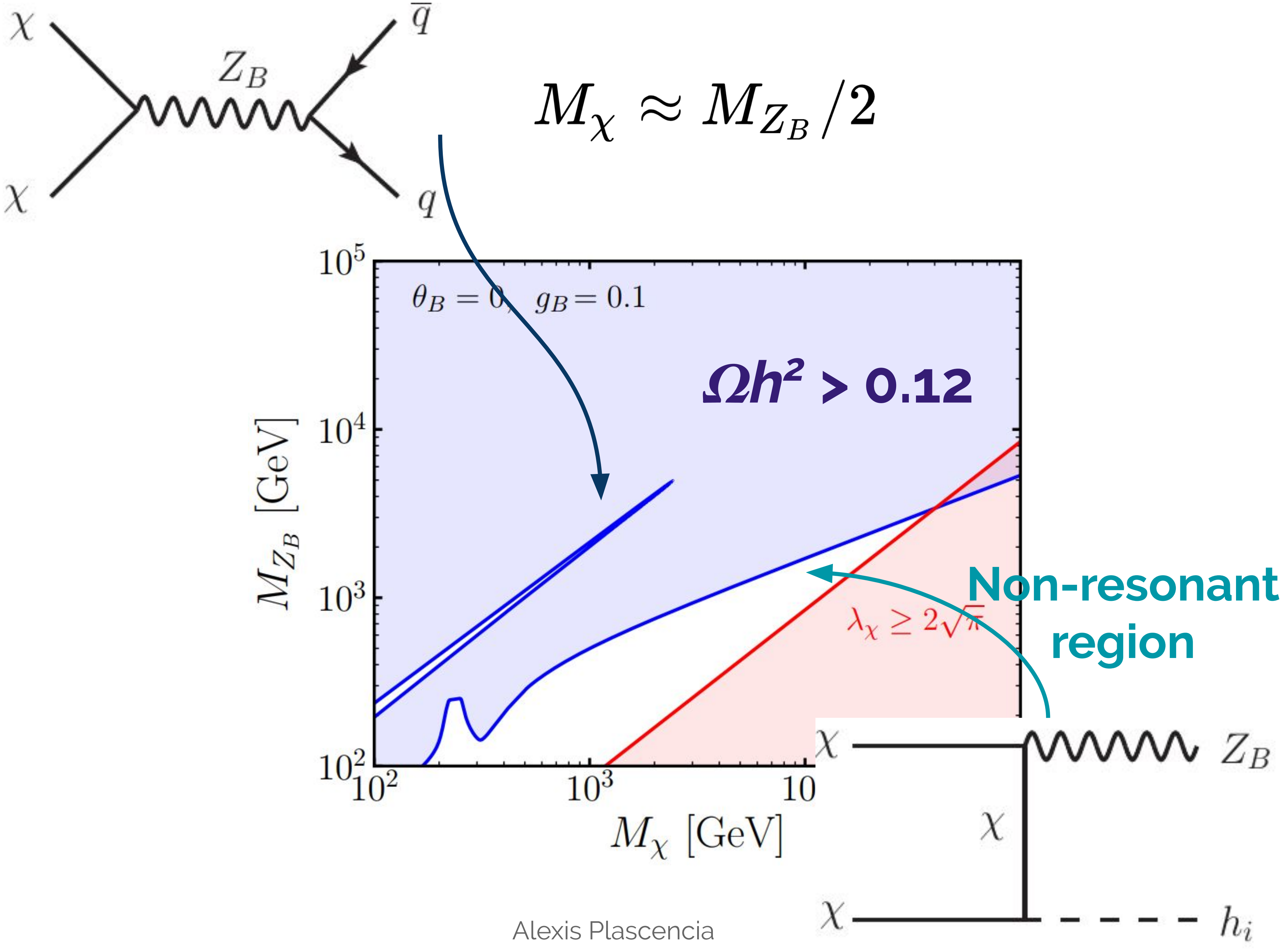


$$M_\chi \approx M_{Z_B}/2$$



$\Omega h^2 > 0.12$

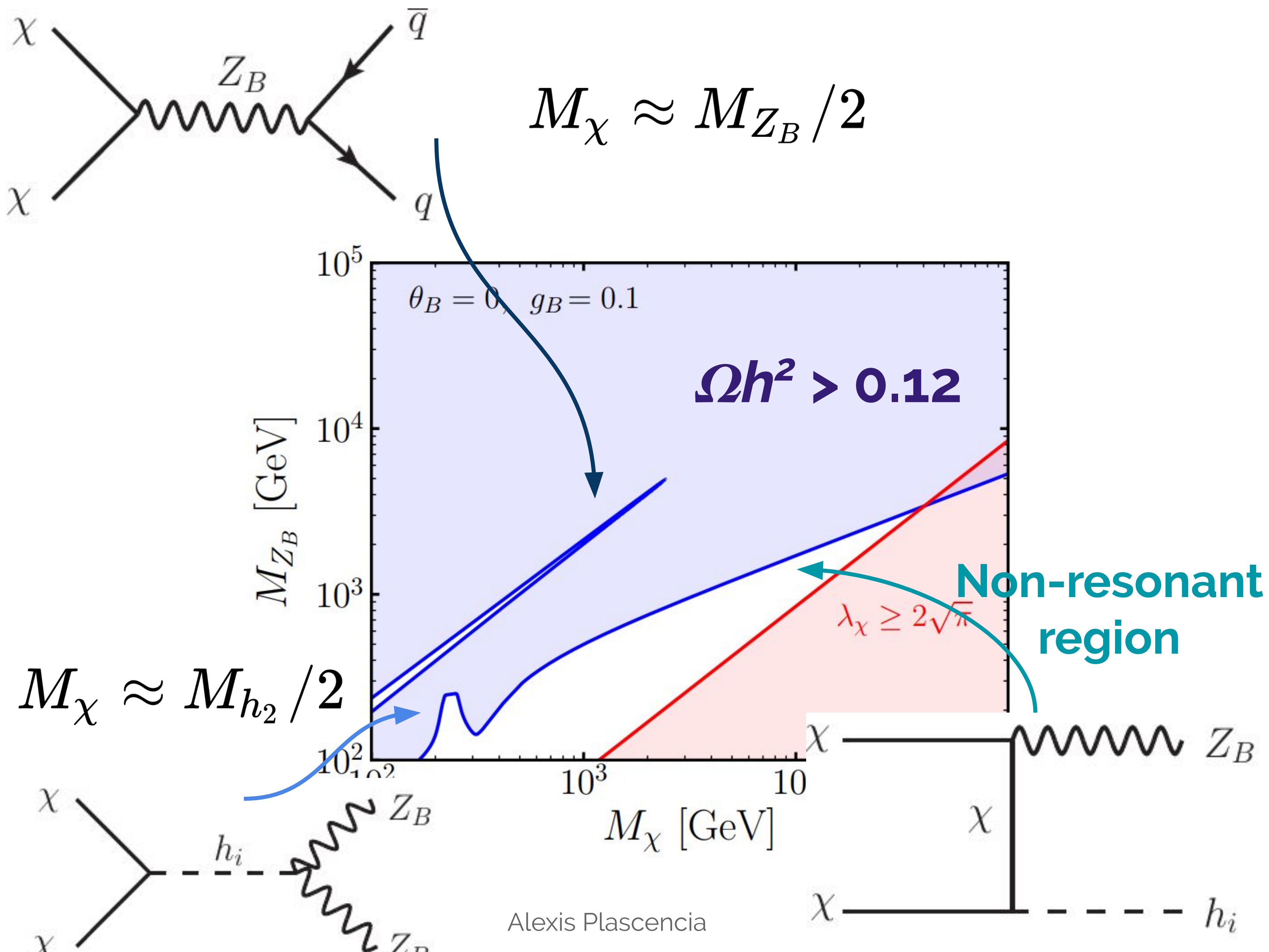
[Fileviez Perez, Golias, Li, Murgui, ADP 2019]



$$M_\chi \approx M_{Z_B}/2$$

Ωh^2 > 0.12

Non-resonant region



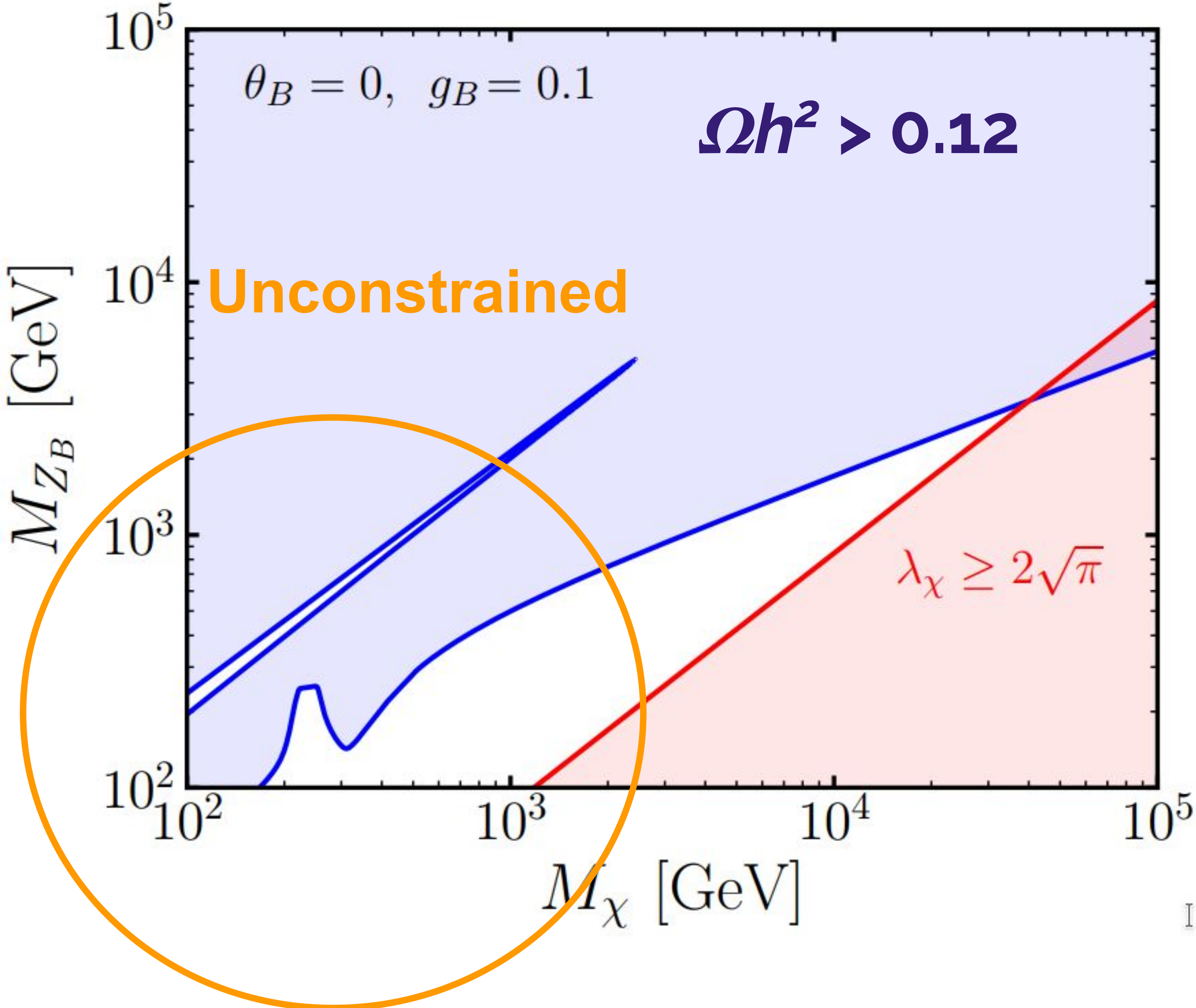
$M_\chi \approx M_{Z_B}/2$

$\Omega h^2 > 0.12$

Non-resonant region

$M_\chi \approx M_{h_2}/2$

Results

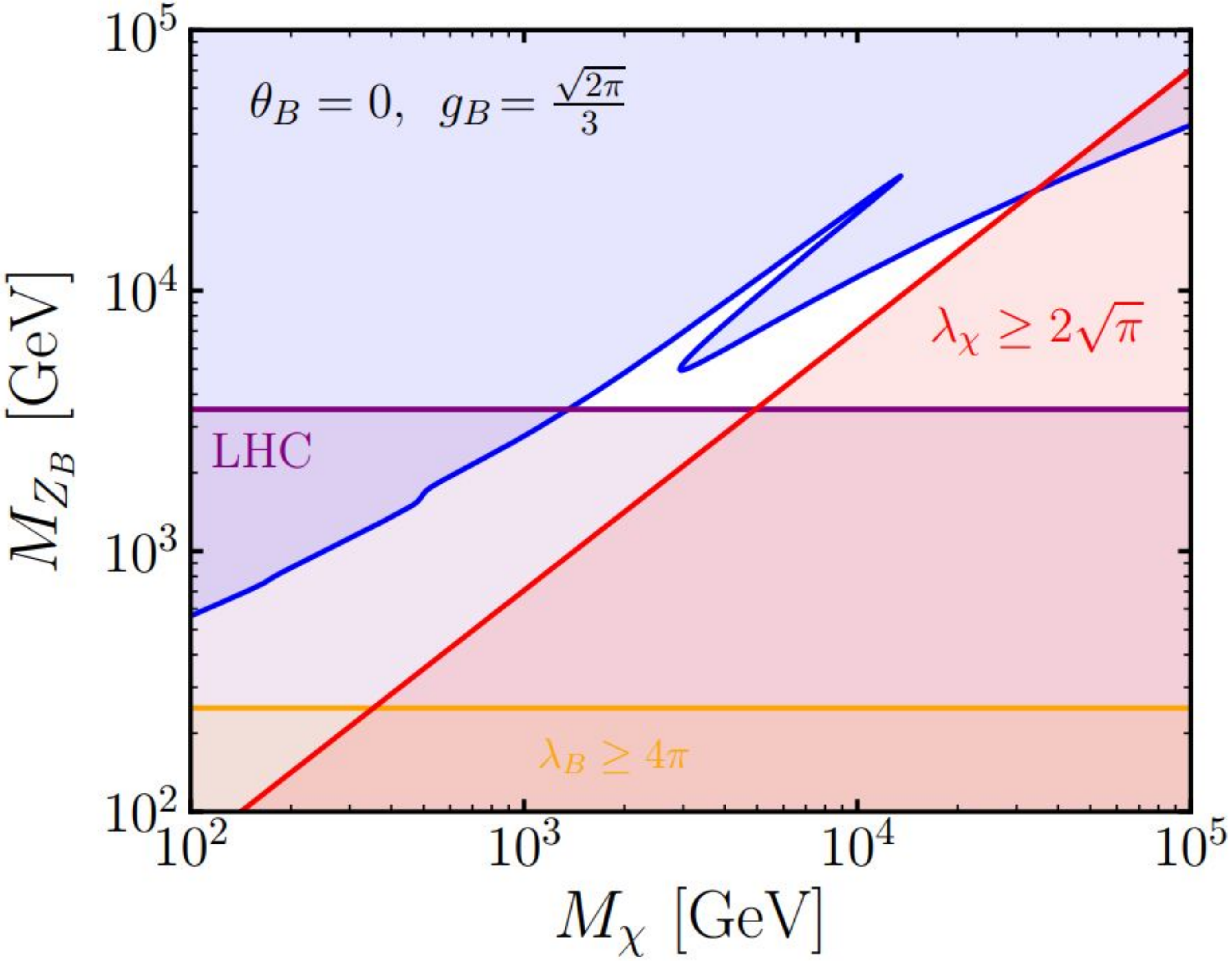


$\Omega h^2 > 0.12$

Unconstrained

Perturbativity $g_B \leq \frac{\sqrt{2\pi}}{3} \approx 0.84$ and $\Omega h^2 \leq 0.12$

Give an upper bound on the scale



Gauging baryon number

- Baryon number is an accidental global symmetry in the SM
- Only broken by non-perturbative effects - SU(2) instantons
- Spontaneous breaking

$$\underbrace{\mathrm{U}(1)_B}_{\text{Local gauge symmetry}} \qquad \langle S_B \rangle \neq 0$$

gauge boson: $\boldsymbol{Z_B}$

[Pais 1973]
[Fileviez Perez & Wise 2011]

Anomaly cancellation

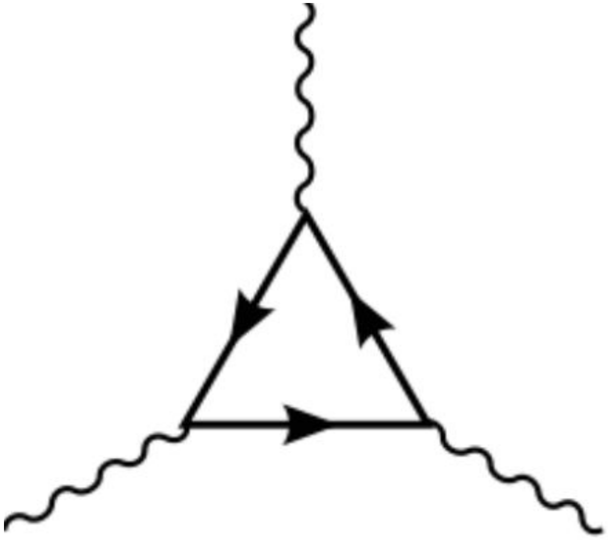
- Baryon number broken by 3 units: $\Delta B=\pm 3$ interactions

  → No proton decay

- Need to add new fermions to cancel anomalies

  Neutral fermion required for anomaly cancellation

  → DM Candidate ☺



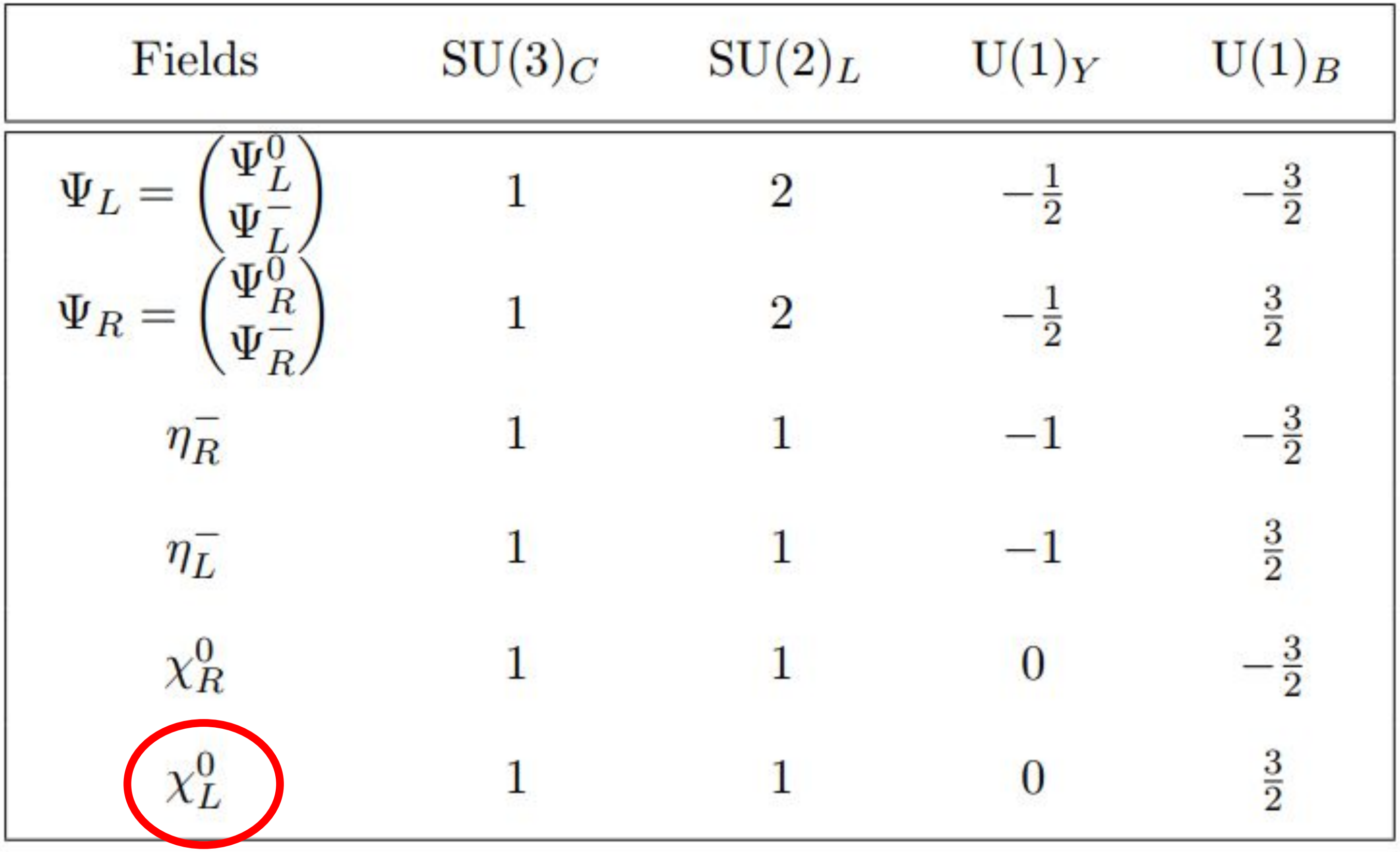
$$\mathcal{A}_1\left(SU(3)^2\otimes U(1)_B\right),\ \mathcal{A}_2\left(SU(2)^2\otimes U(1)_B\right),$$
$$\mathcal{A}_3\left(U(1)_Y^2\otimes U(1)_B\right),\ \mathcal{A}_4\left(U(1)_Y\otimes U(1)_B^2\right),$$
$$\mathcal{A}_5\left(U(1)_B\right),\ \mathcal{A}_6\left(U(1)_B^3\right).$$

In the SM the non-zero values are:

$$\mathcal{A}_2=-\mathcal{A}_3=3/2$$

Anomaly cancellation

[Duerr, Fileviez Perez, Wise 2013]



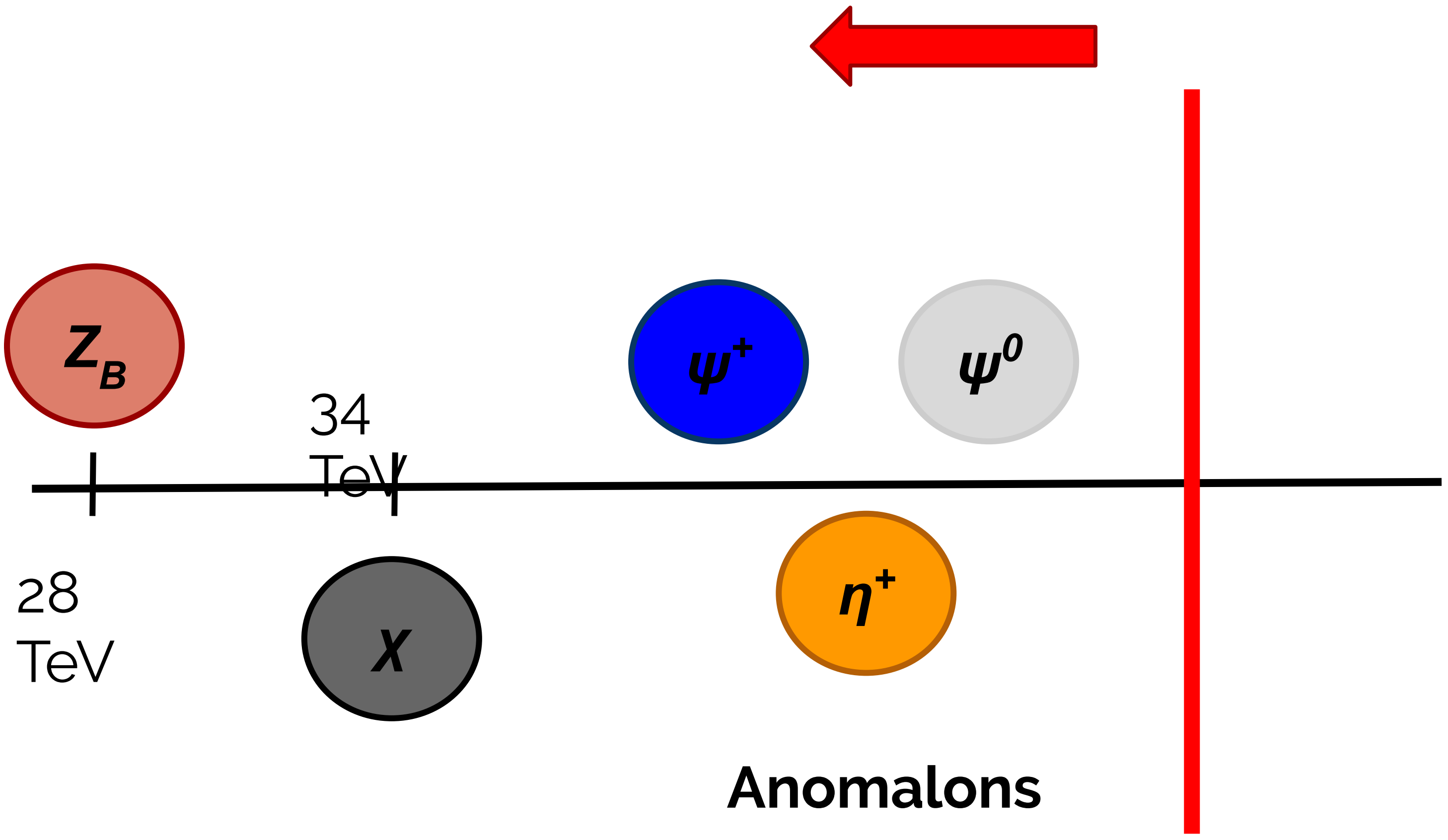
Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$\Psi_L = \begin{pmatrix} \Psi_L^0 \\ \Psi_L^- \end{pmatrix}$	1	2	$-\frac{1}{2}$	$-\frac{3}{2}$
$\Psi_R = \begin{pmatrix} \Psi_R^0 \\ \Psi_R^- \end{pmatrix}$	1	2	$-\frac{1}{2}$	$\frac{3}{2}$
η_R^-	1	1	-1	$-\frac{3}{2}$
η_L^-	1	1	-1	$\frac{3}{2}$
χ_R^0	1	1	0	$-\frac{3}{2}$
χ_L^0	1	1	0	$\frac{3}{2}$

DM

For Model II see
[Ohmer, Fileviez Perez, Patel 2014]

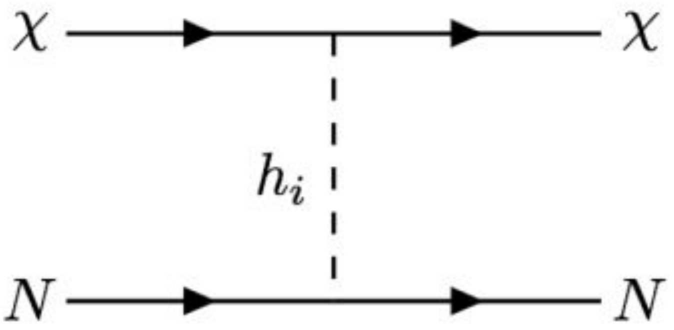
Upper bound on baryon number breaking scale

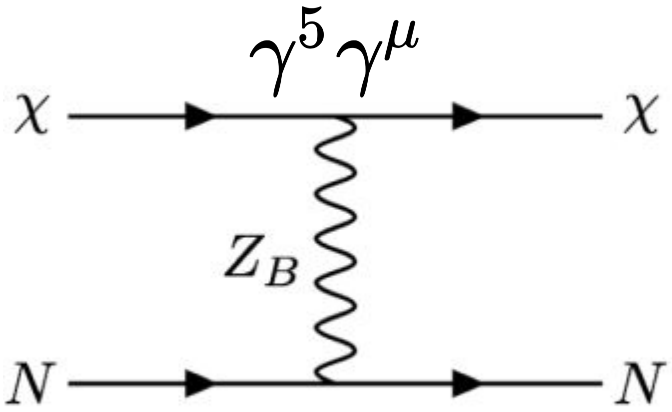
All masses connected to v_B and hence there is an upper bound for the full model



Direct Detection

$$\sigma_{\chi N}^{\mathrm{TOT}} = \sigma_{\chi N}(h_i) + \sigma_{\chi N}^{0}(Z_B)v^2$$





suppressed by Higgs mixing

$\theta < 0.3$ for $M_{H2} > 200$ GeV

For lighter M_{H2} stronger bound

[Ilnicka, Robens, Stefaniak 2018]

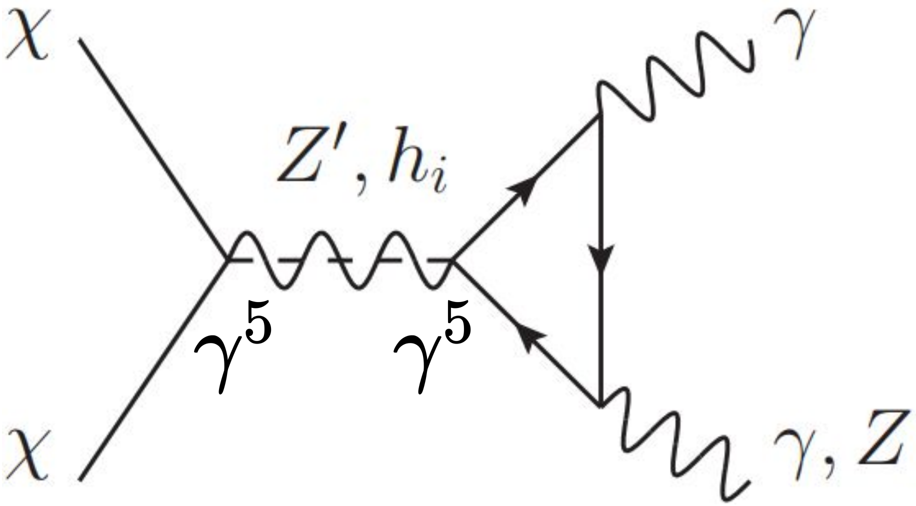
Due to axial coupling,

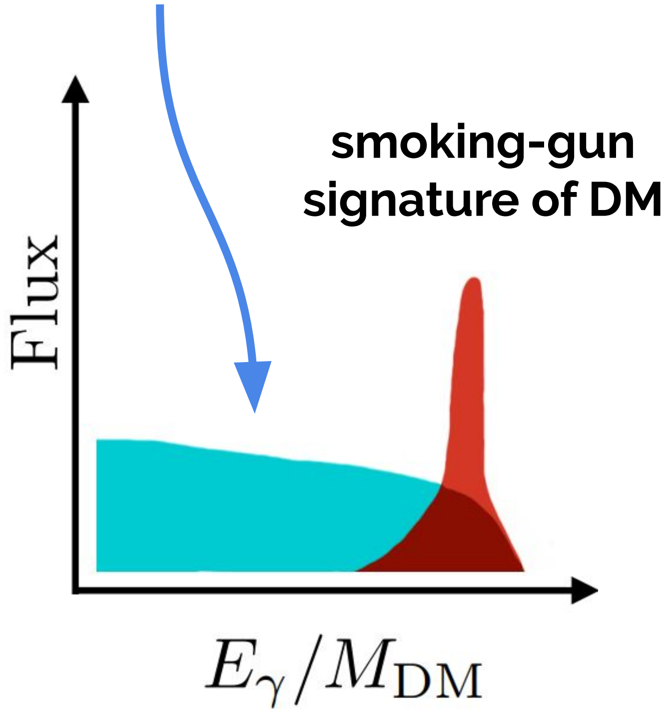
velocity suppressed $v{\sim}10^{-3}$

Direct detection constraints can be avoided

Gamma lines

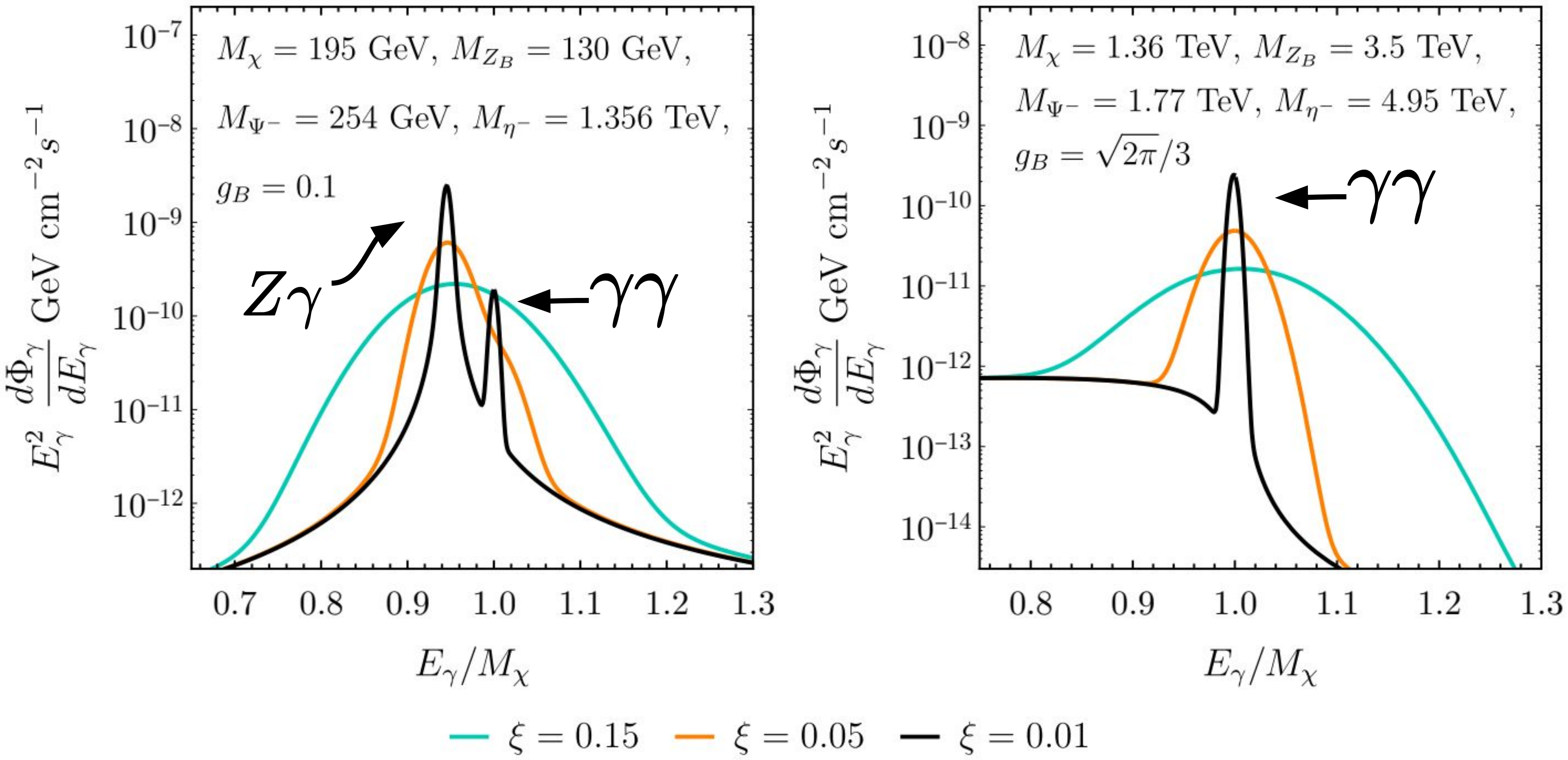
- DM annihilation into $\gamma\gamma$ possible. Thanks to new fermions required for anomaly cancellation in the loop.
- Peak at $E = M_{DM}$ in the gamma spectrum
- Continuum is velocity suppressed, because of axial coupling





smoking-gun signature of DM

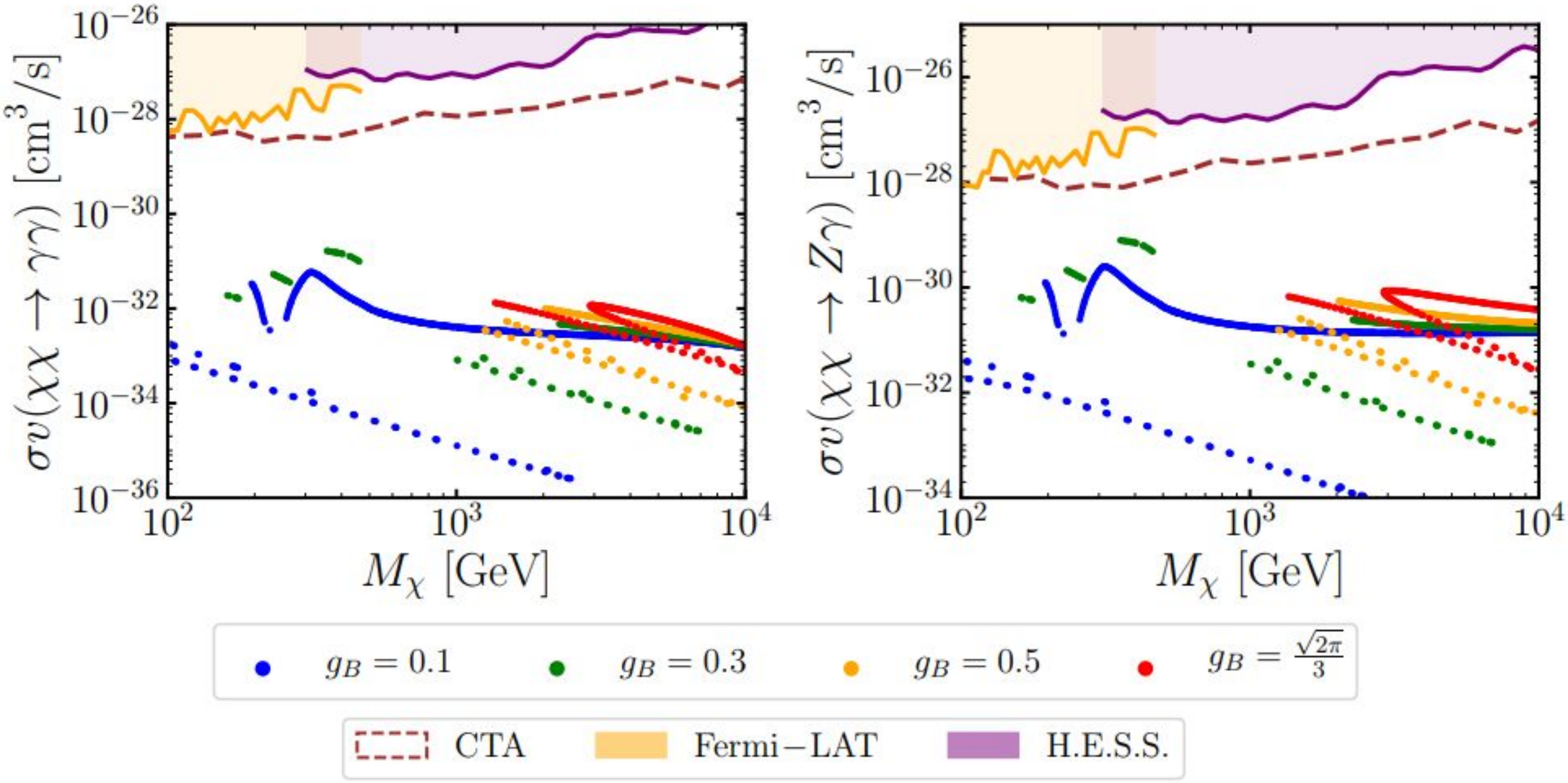
Gamma lines $\Omega h^2 = 0.12$



[Fileviez Perez, Golias, Li, Murgui, ADP 2019]

Gamma lines

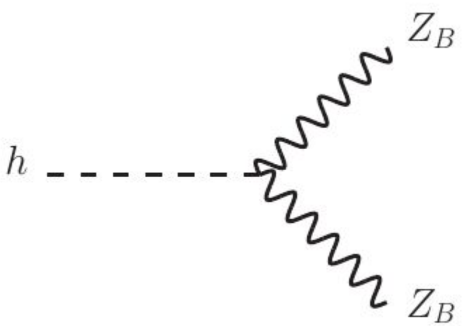
All points satisfy: $\Omega h^2 = 0.12$



[Fileviez Perez, Golias, Li, Murgui, ADP 2019]

Exotic Higgs decays

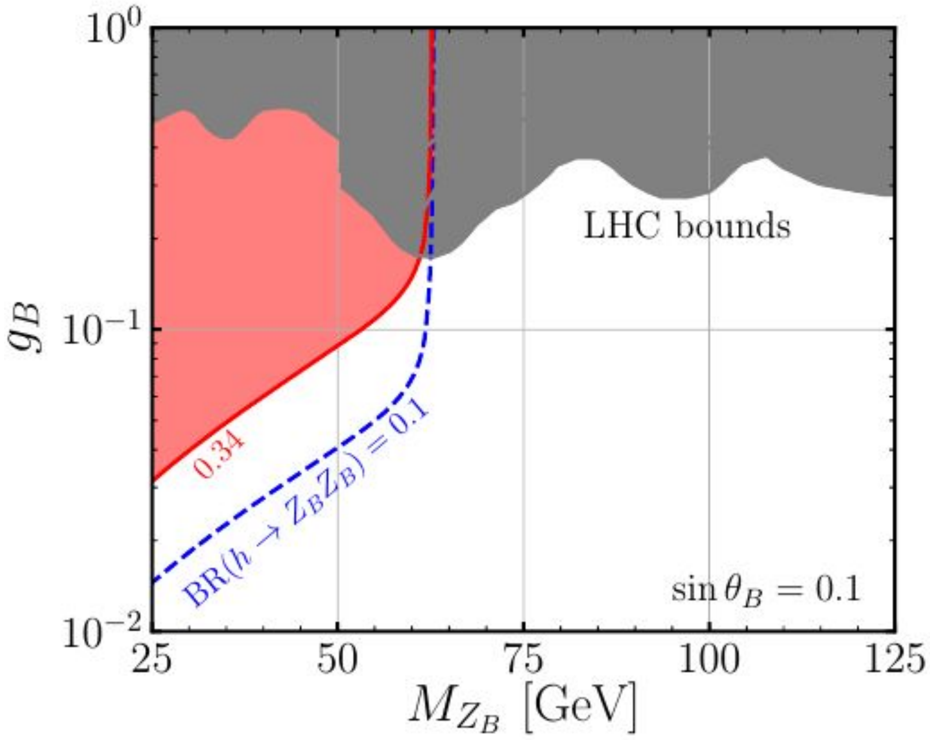
When $M_{Z_B} \leq M_h/2$:



$$h Z^{\mu}_{B} Z^{\nu}_{B} : \; 2i \frac{M^2_{Z_B}}{v_B} g^{\mu\nu} \sin\theta_B ,$$

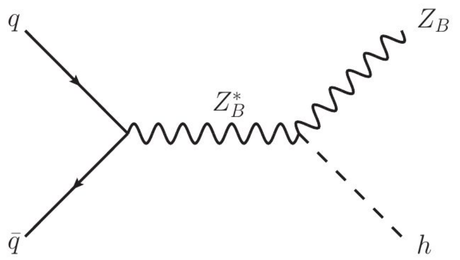
$$\boxed{\mathrm{BR}(h \to \mathrm{BSM}) \leq 0.34}$$

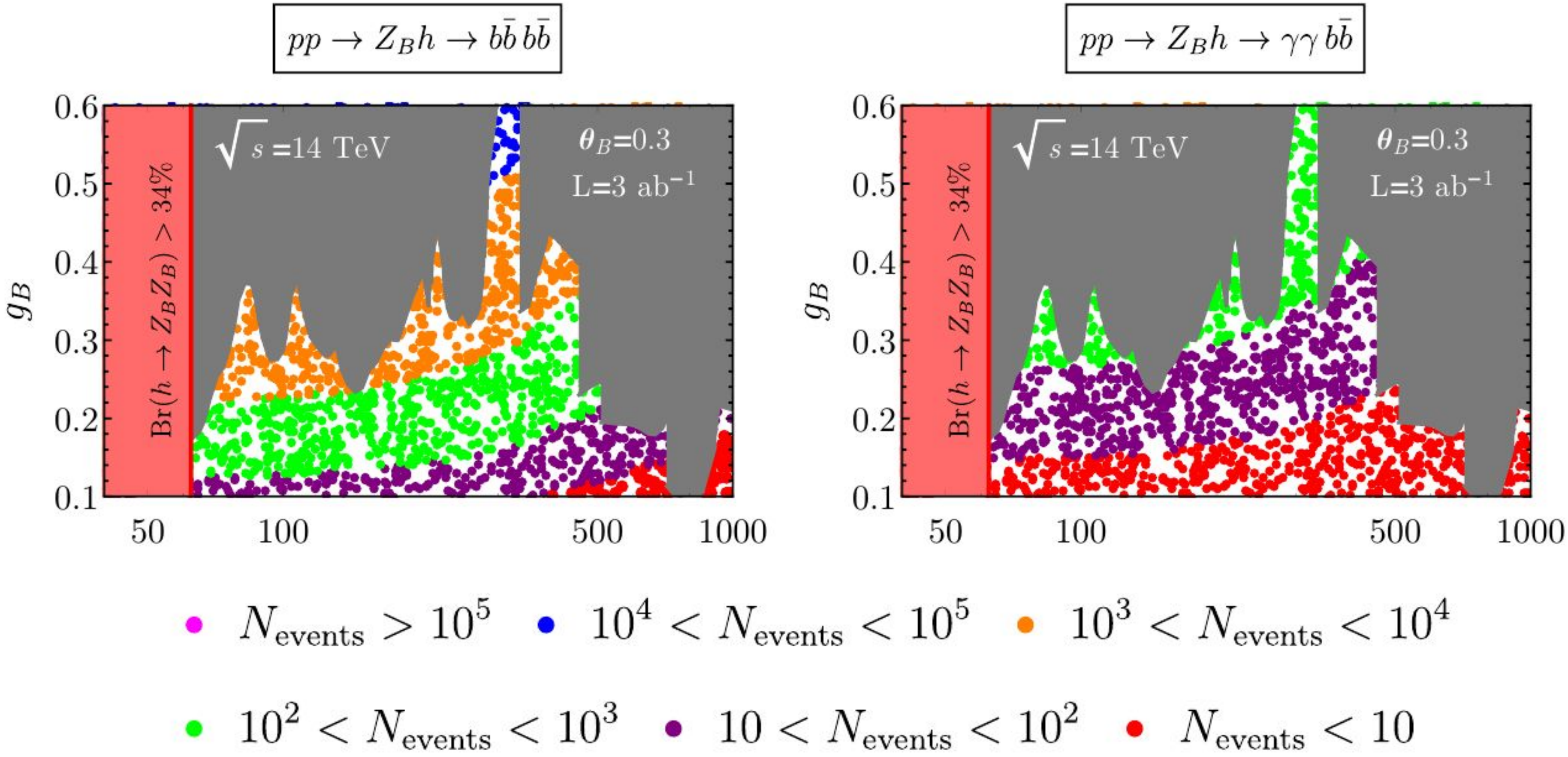
[ATLAS & CMS 1606.02266]



[Fileviez Perez, Murgui, ADP 2020]

Associated Higgs Production





[Fileviez Perez, Murgui, ADP 2020]

Paper coming out next week

Conclusions

- In $\mathbf{U(1)_L}$ and $\mathbf{U(1)_B}$ dark matter is predicted from gauge anomaly cancellation
- $\mathbf{U(1)_L}$ neutrinos are Dirac. Next generation CMB will fully test these theories (with thermal DM) using ΔN_{eff}
- $\mathbf{U(1)_B}$ can be at the low scale (GeV) and the LHC will probe this region
    - DM final state radiation velocity suppressed ⟶ gamma-ray lines can be observed in future
    - $h \to Z_B Z_B$ can have a large branching ratio
- Not overproducing $\Omega h^2 \leq 0.12$ implies an upper bound on all these theories < 35 TeV

Thank you!


рахмат
ngiyabonga
danke
謝謝
spas
teşekkür ederim
Баярлалаа
mersi
kia ora
barka
welalin
tack
mahalo
tapadh leat
спасибо
faafetai lava
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
kiitos
dankie
nanni
nandri
dhanyavad
thank you
gracias
хвала
asante
manana
bedankt
mauruuru
köszönöm
akun
dankon
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murakoze
tenki
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gràçie
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go raibh maith agat
sobodi
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sagolun
sukriya
kop khun krap
taiku
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didi madloba
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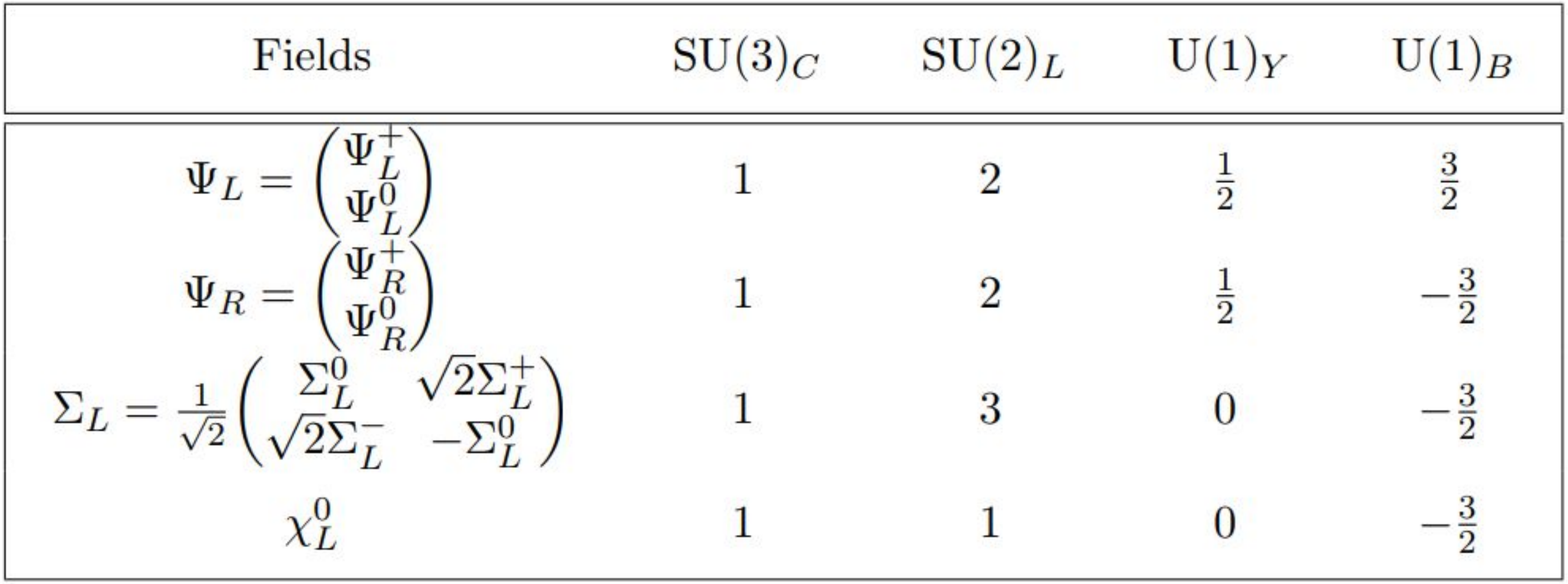
tanemirt
grazie
arigatô
takk
dakujem
trugarez
kam sah hamnida
rahmat
terima kasih
rahmet
ευχαριστώ
diolch
dhanyavadagalu
shukriya
mercé
мерси
তোমাকে ধন্যবাদ
감사합니다
xièxie
merci

Back-up

Model II



Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
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$\Psi_R = \begin{pmatrix} \Psi_R^+ \\ \Psi_R^0 \end{pmatrix}$	1	2	$\frac{1}{2}$	$-\frac{3}{2}$
$\Sigma_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \Sigma_L^0 & \sqrt{2}\Sigma_L^+ \\ \sqrt{2}\Sigma_L^- & -\Sigma_L^0 \end{pmatrix}$	1	3	0	$-\frac{3}{2}$
χ_L^0	1	1	0	$-\frac{3}{2}$

[Ohmer, Fileviez Perez, Patel 2014]

N_{eff}

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad \Rightarrow \quad \Delta N_{\rm eff} < 0.285,$$

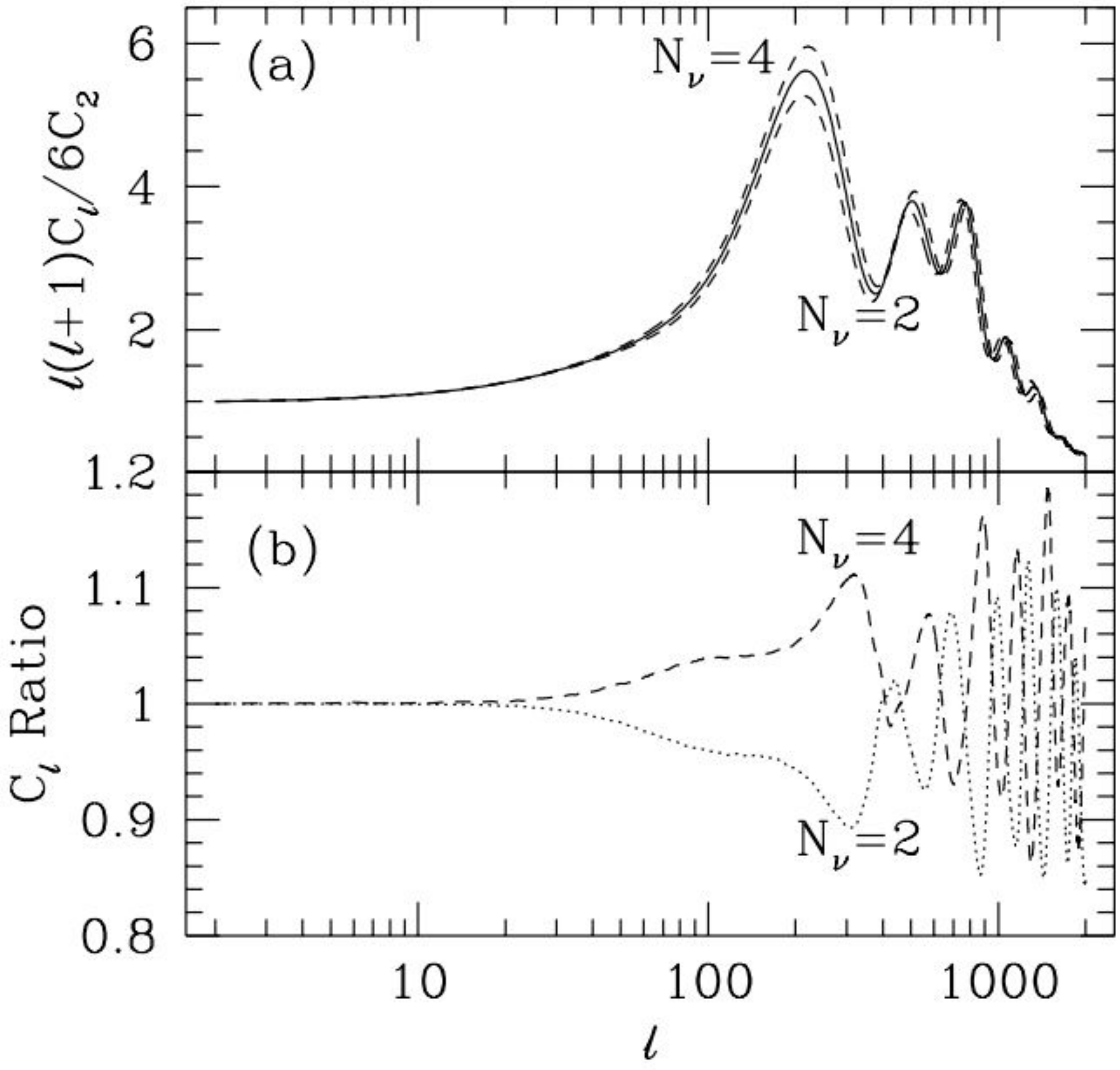
[Planck 2018]

Projection for CMB Stage-IV:

$$\Delta N_{\rm eff} < 0.06 \quad \text{at } 95\% \, \text{CL}$$

[CMB-S4 Science Book 2016]

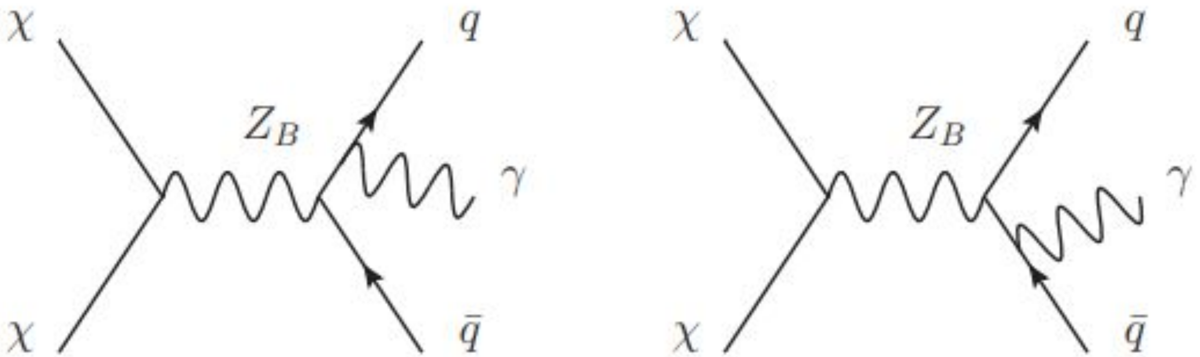
N_{eff}



[Hu et al 1995]

Alexis Plascencia

Final State Radiation



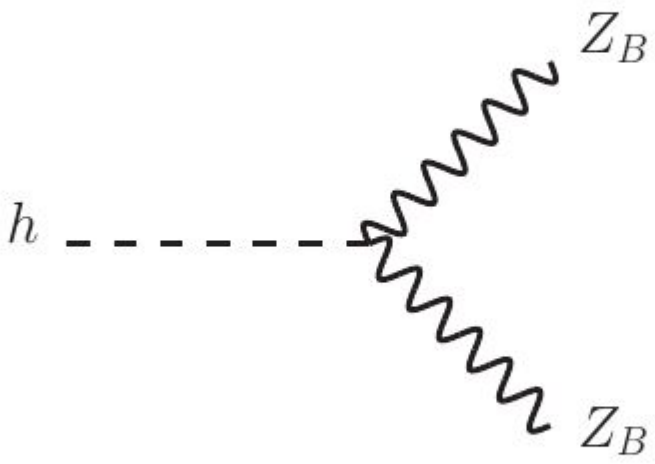
$$\boxed{|\mathcal{M}|^2_{\mathrm{FSR}} = \frac{M_q^2}{M_{Z_B}^2} A + v^2 B + \mathcal{O}(v^4),}$$

$$A = 12\pi\,\alpha\,g_B^4 Q_q^2 (M_{Z_B}^2 - 4M_\chi^2)^2 \frac{(E_q + E_\gamma - M_\chi)^2 \big(2(E_q - M_\chi)(E_q + E_\gamma - M_\chi) - 3M_q^2\big)}{M_{Z_B}^2 (E_q - M_\chi)^2 (E_q + E_\gamma - M_\chi)^2 ((4M_\chi^2 - M_{Z_B}^2)^2 + \Gamma_{Z_B}^2 M_{Z_B}^2)}, \tag{32}$$

$$B = 12\pi\,\alpha\,g_B^4 M_\chi^2 Q_q^2 \times$$
$$\frac{(2E_q M_\chi (E_\gamma^2 - 3E_\gamma M_\chi + 2M_\chi^2) - 2E_q^4 - 2E_q^3 (E_\gamma - 2M_\chi) - E_q^2 (E_\gamma^2 - 6E_\gamma M_\chi + 6M_\chi^2) - 2M_\chi^2 (E_\gamma - M_\chi)^2)}{M_{Z_B}^2 (E_q + E_\gamma - M_\chi)^2 ((4M_\chi^2 - M_{Z_B}^2)^2 + \Gamma_{Z_B}^2 M_{Z_B}^2)}. \tag{33}$$

Exotic Higgs decays

When $M_{Z_B} \leq M_h/2$:



$$hZ_B^\mu Z_B^\nu : \; 2i\frac{M_{Z_B}^2}{v_B} g^{\mu\nu} \sin\theta_B,$$

CMS and ATLAS
combined analysis

$$\mathrm{BR}(h \to \mathrm{BSM}) \leq 0.34$$

[ATLAS & CMS 1606.02266]