B and L as local symmetries: Dark matter, cosmology and physics at the LHC

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Aim of the talk

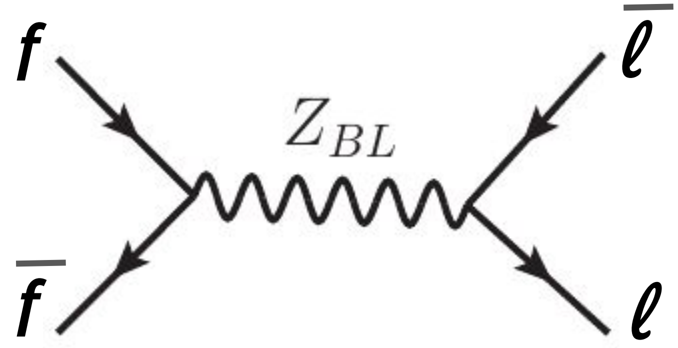
Discuss the phenomenology of minimal extensions of the SM where lepton and/or baryon number are promoted to local symmetries

$$\mathrm{SM} + \begin{cases} \mathrm{U}(1)_{B-L} \\ \mathrm{U}(1)_{L} \\ \mathrm{U}(1)_{B} \end{cases}$$

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

i) Dirac   ii) Majorana neutrinos

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 the *B-L* symmetry can be gauged

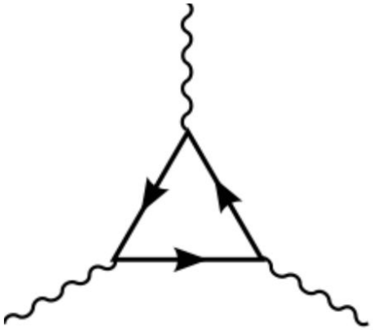
- New *B-L* gauge boson that can be searched for at colliders

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

Unbroken *B-L* and Dirac neutrinos

Anomaly cancellation:

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

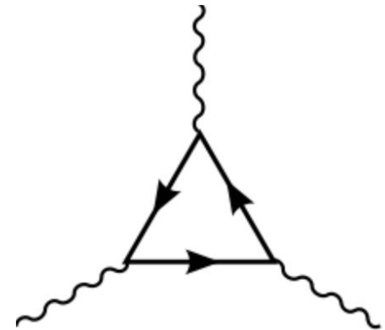


Dirac mass term: $Y_\nu^D\, \bar{l}_L i\sigma_2 H^* \nu_R$

Unbroken *B-L* and Dirac neutrinos

Anomaly cancellation:

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



Dirac mass term: $Y_\nu^D \, \bar{l}_L i\sigma_2 H^* \nu_R$ ✓

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

B-L broken in units different than 2 forbids the Majorana mass term

Neutrinos are Dirac fermions

Unbroken *B-L* and Dirac neutrinos

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}

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

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

To forbid Majorana mass term

Unbroken *B-L* and Dirac neutrinos

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

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

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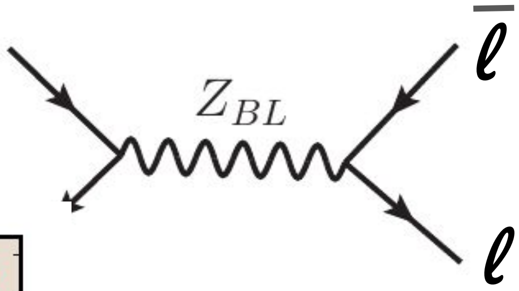
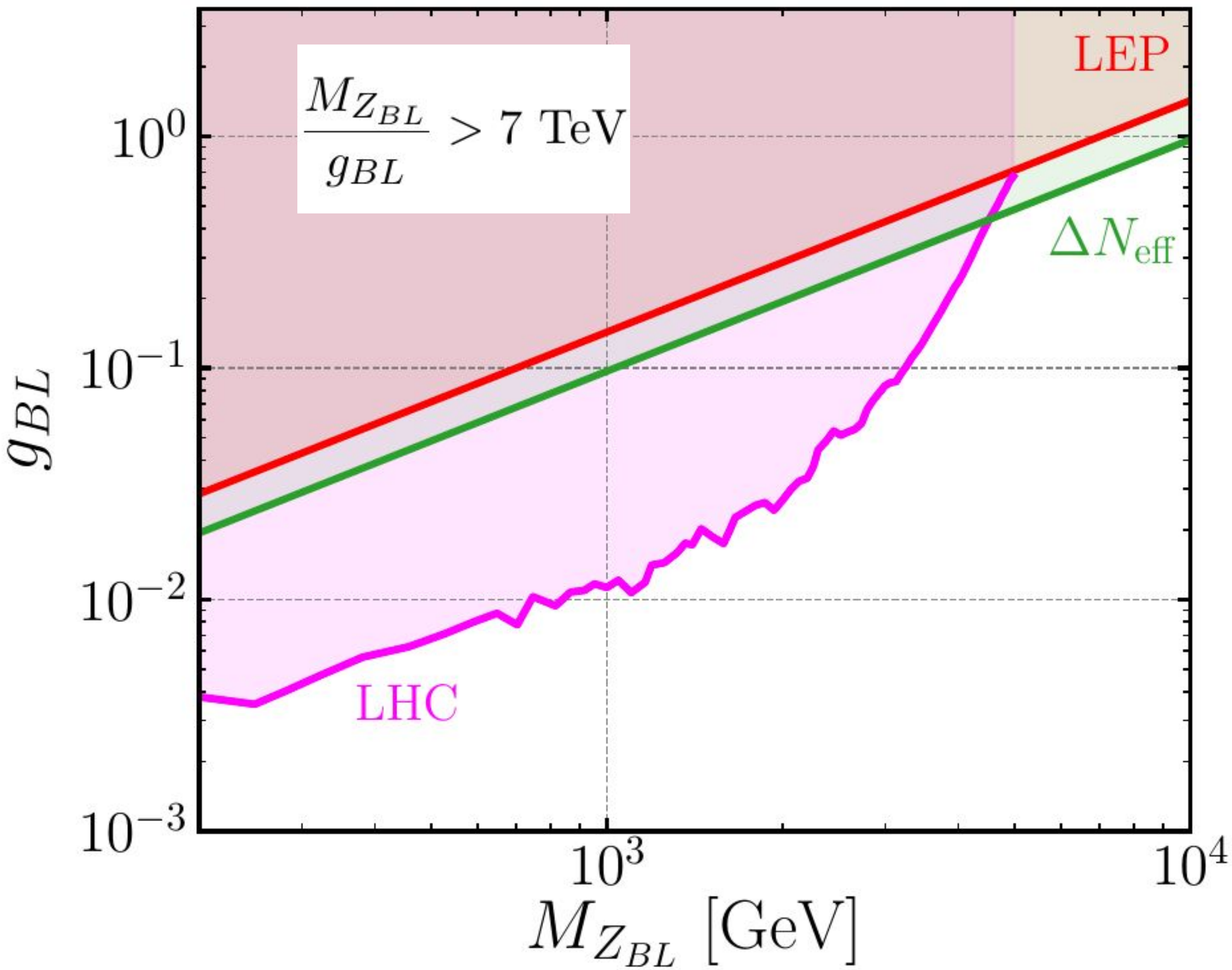
B - L as a local symmetry





[ATLAS '17]

LEP bound:
[Alioli, Farina, Pappadopulo, and Ruderman '18]

ΔN_{eff}
[Fileviez Perez, Murgui, ADP '19]

Broken *B-L* and Majorana neutrinos

Add scalar that breaks B-L in two units

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

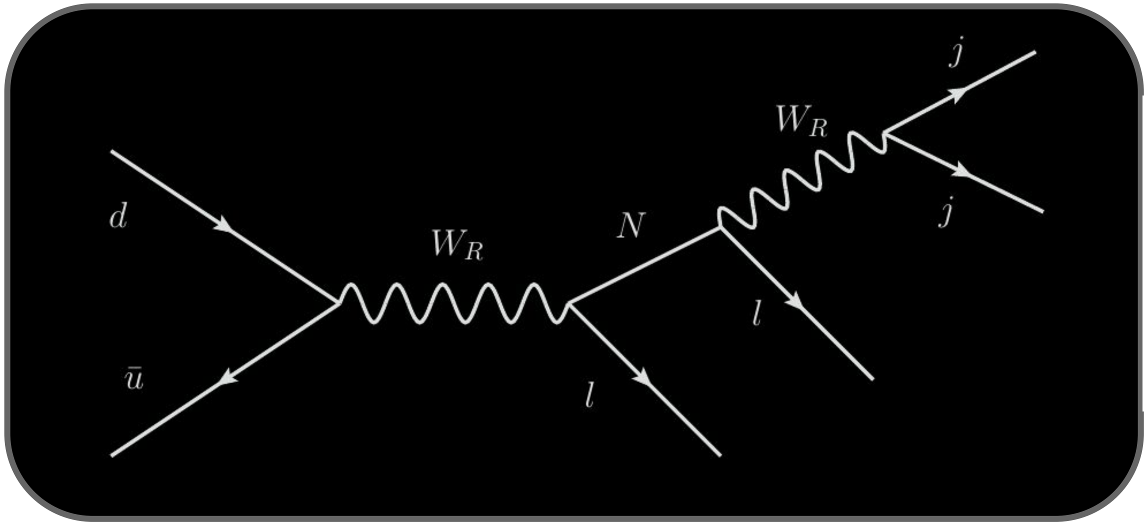
Allows Majorana mass term and implementation of type-I seesaw

$$-y_N S_{BL} N^T C N + \mathrm{h.\,c.} \subset \mathcal{L}$$

$$M_N = \sqrt{2} y_N \langle v_{BL} \rangle$$

$$m_\nu \simeq \frac{m_D^2}{M_N}$$

LNV at the LHC



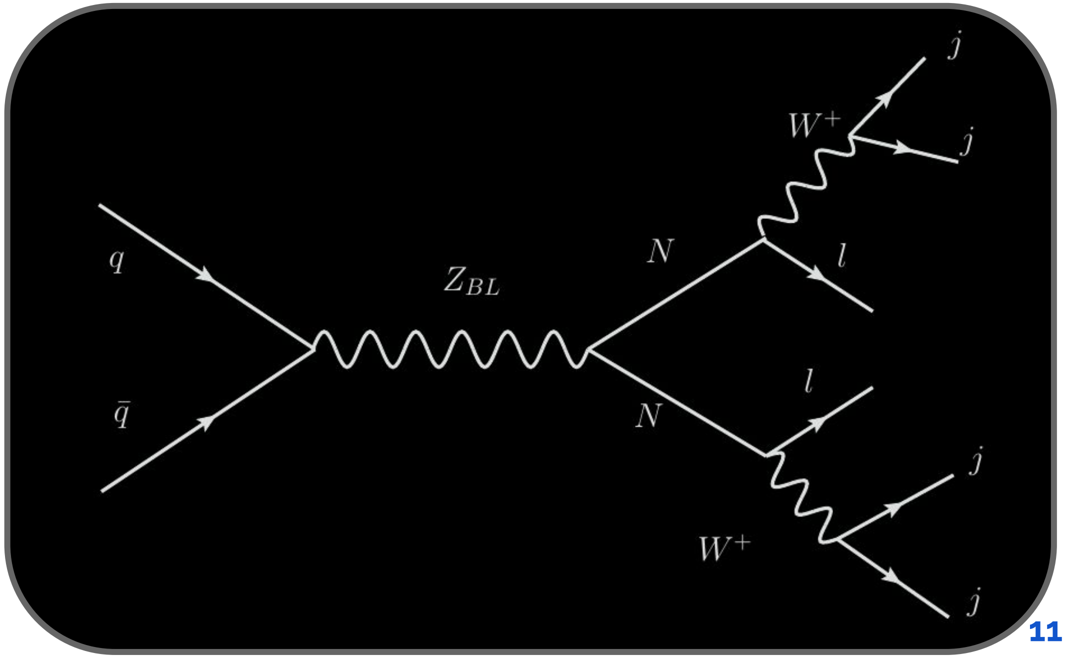
[Keung & Senjanovic '83]

Relying on *W and* neutrino mixing:
[Han & Zhang '06]

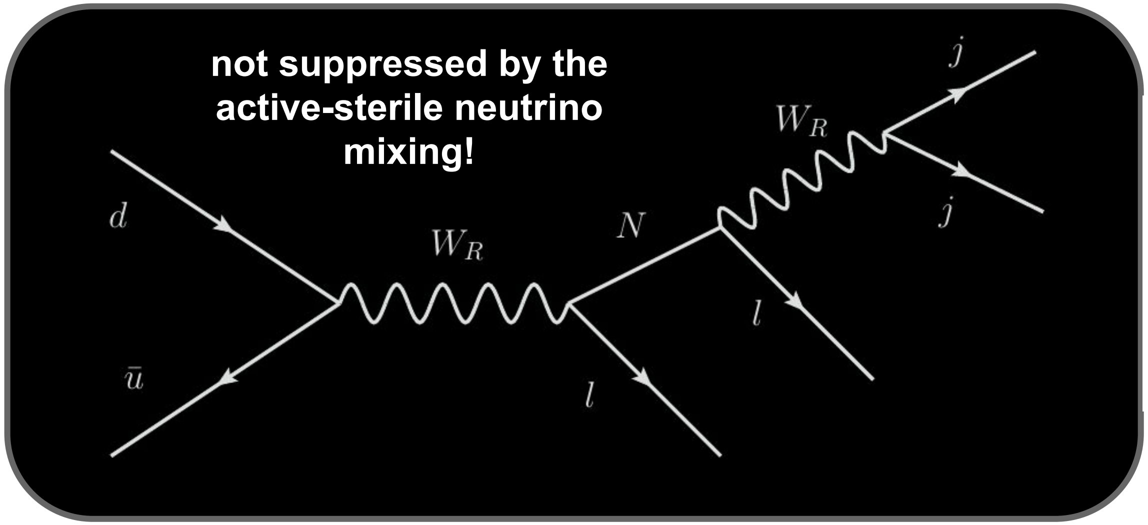
See slides by Richard Ruiz!

[Fileviez Perez, Han & Li '09]

Review:
[Cai, Han, Li & Ruiz '17]



LNV at the LHC



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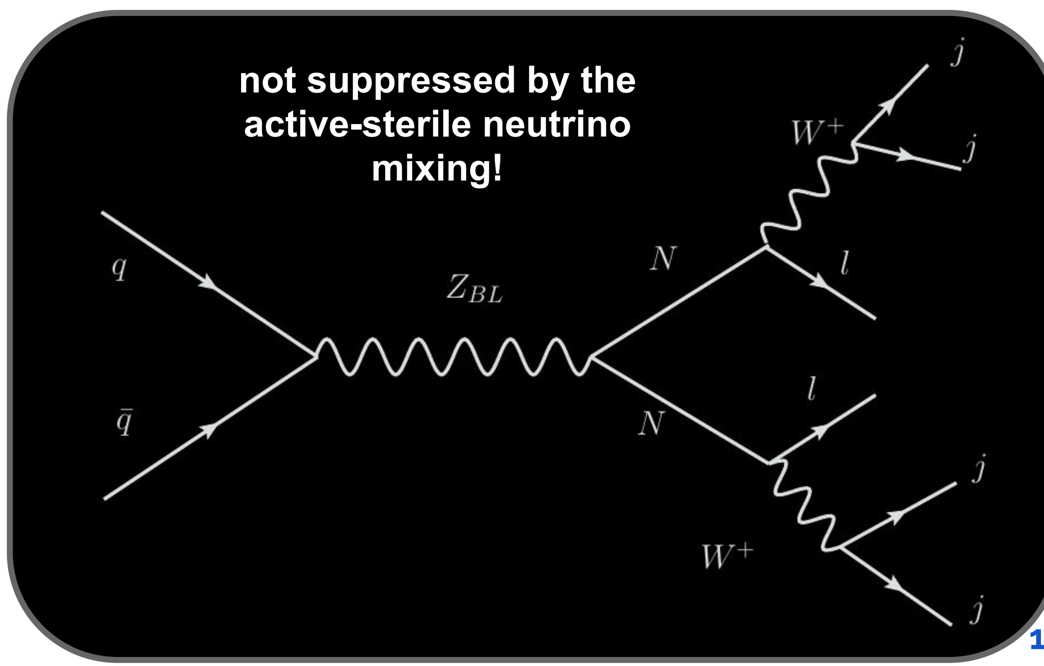


[Fileviez Perez, Han & Li '09]

Review:
[Cai, Han, Li & Ruiz '17]

LNV at the LHC

$$\sigma(q\bar{q} \to Z^*_{BL} \to N_i N_i)(\hat{s}) = \frac{g^4_{BL}}{648\pi\hat{s}} \frac{\left(\hat{s} - 4M^2_{N_i}\right)^{3/2}(2m_q^2 + \hat{s})}{\sqrt{\hat{s} - 4m_q^2}\left(M^2_{Z_{BL}}\Gamma^2_{Z_{BL}} + (\hat{s} - M^2_{Z_{BL}})^2\right)}$$

$$\Gamma(N_i \to \ell^- W^+) = \frac{g_2^2}{64\pi M_W^2}|V_{\ell i}|^2 M^3_{N_i}\left(1 + 2\frac{M_W^2}{M^2_{N_i}}\right)\left(1 - \frac{M_W^2}{M^2_{N_i}}\right)^2$$

$$V = V_{\rm PMNS}\, m^{1/2}\, R\, M^{-1/2}$$

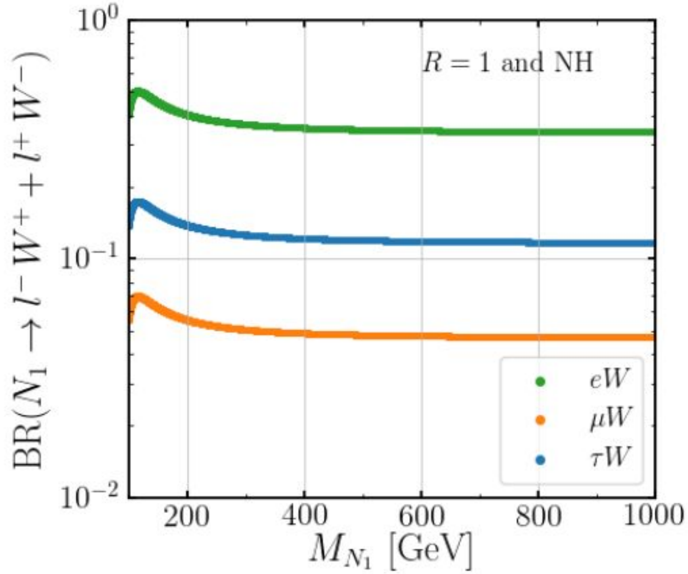
[Casas & Ibarra '01]

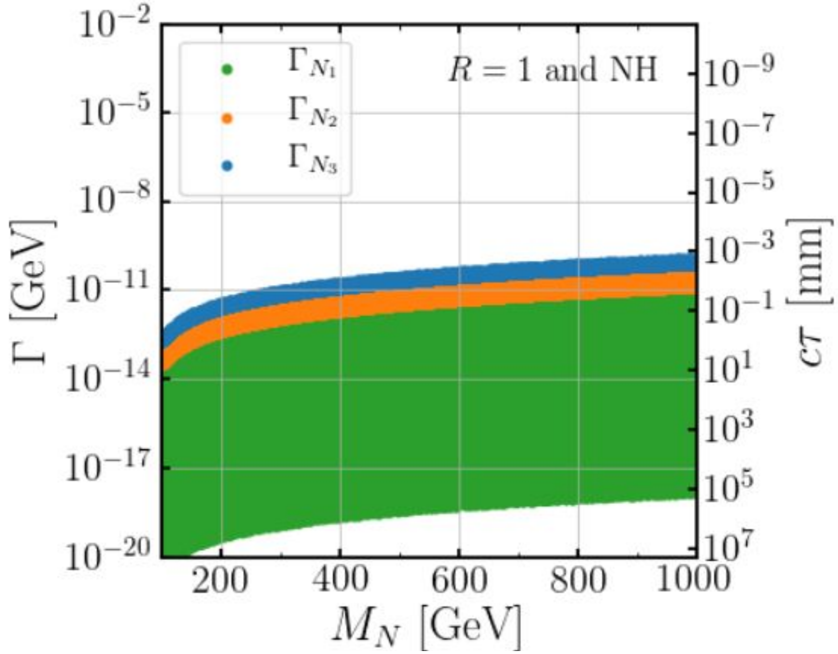
We explore the freedom in the R matrix, which is parametrized by three complex angles

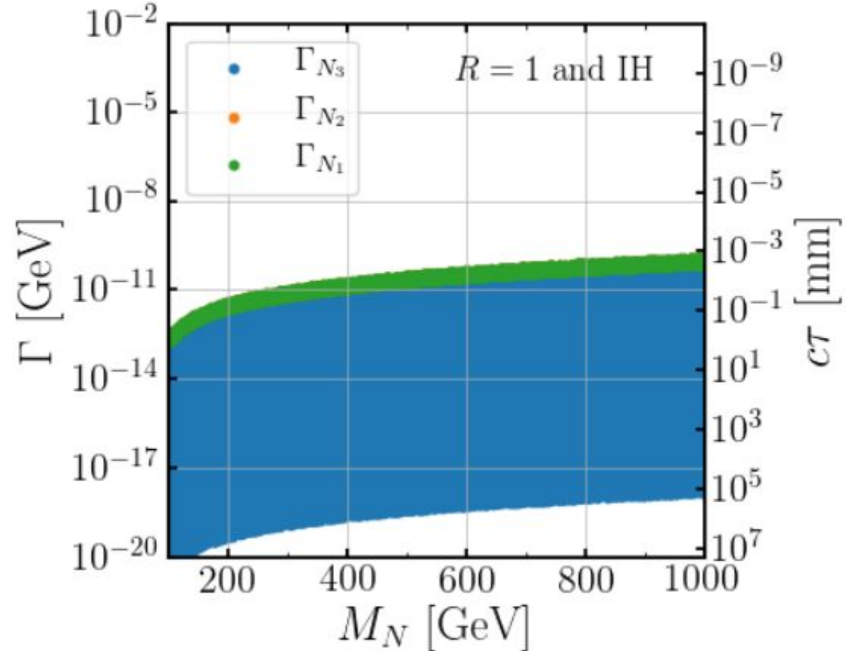
$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\omega_1} & s_{\omega_1} \\ 0 & -s_{\omega_1} & c_{\omega_1} \end{pmatrix} \begin{pmatrix} c_{\omega_2} & 0 & s_{\omega_2} \\ 0 & 1 & 0 \\ -s_{\omega_2} & 0 & c_{\omega_2} \end{pmatrix} \begin{pmatrix} c_{\omega_3} & s_{\omega_3} & 0 \\ -s_{\omega_3} & c_{\omega_3} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

LNV at the LHC

- In the simple case with ω_i=0 → R identity matrix
- Measuring the branching ratios of N_i can provide information about structure of R matrix





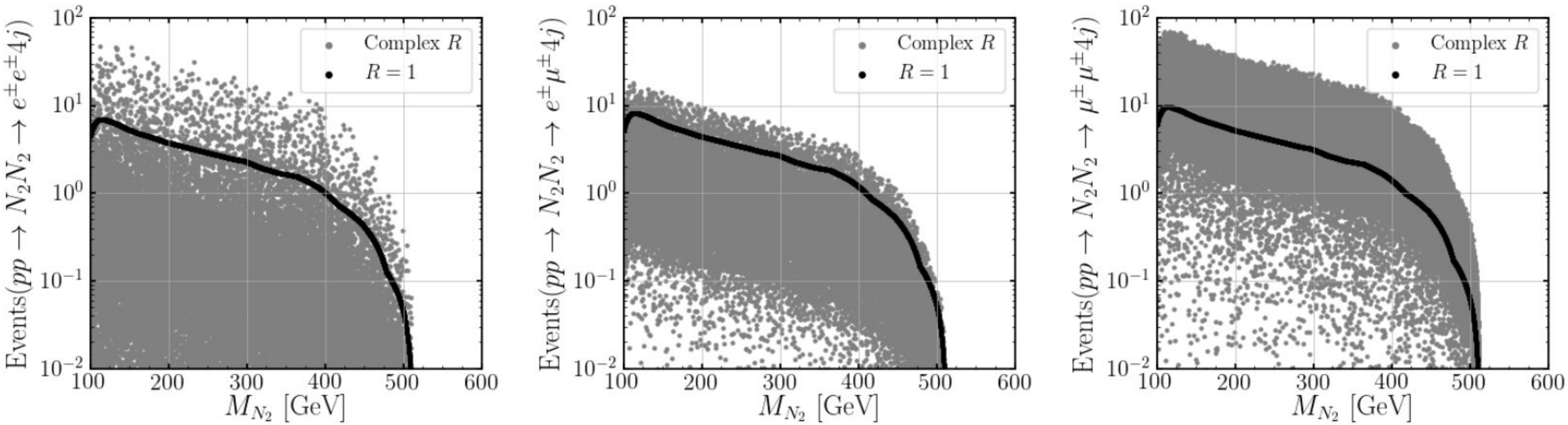


[Fileviez Perez & ADP '20]   see also [Fileviez Perez, Han & Li '09]

LNV at the HL-LHC

$$N_{\text{events}} = \mathcal{L} \times \sigma(pp \to N_i N_i) \times 2 \times \text{BR}^2(N_i \to l^{\pm} W^{\mp}) \times \text{BR}^2(W^{\mp} \to jj)$$

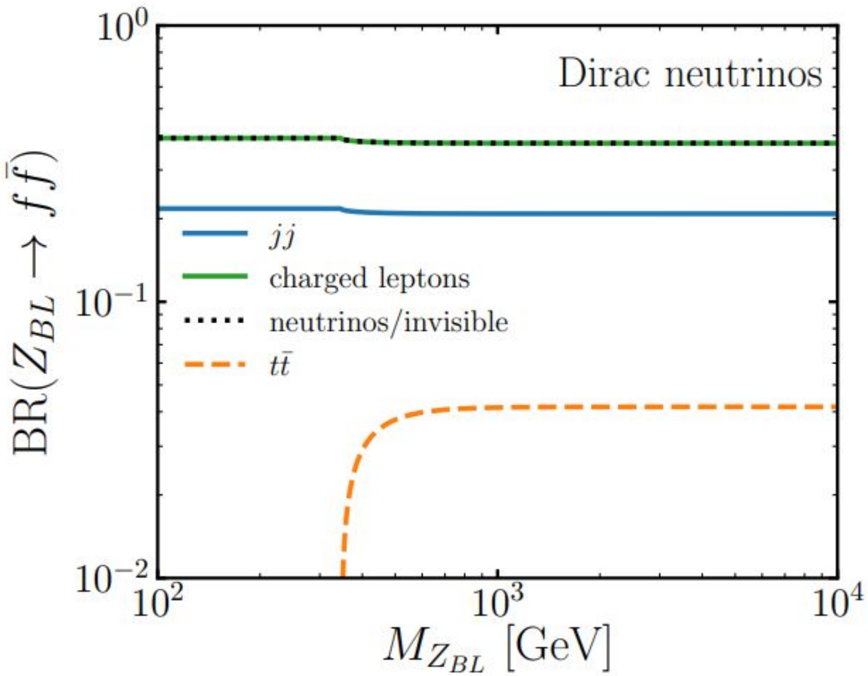
- The black dots correspond to $\omega_i = 0 \to V^2 \simeq m_\nu / M_N$
- For the gray points we scan the real and imaginary part from -π to π

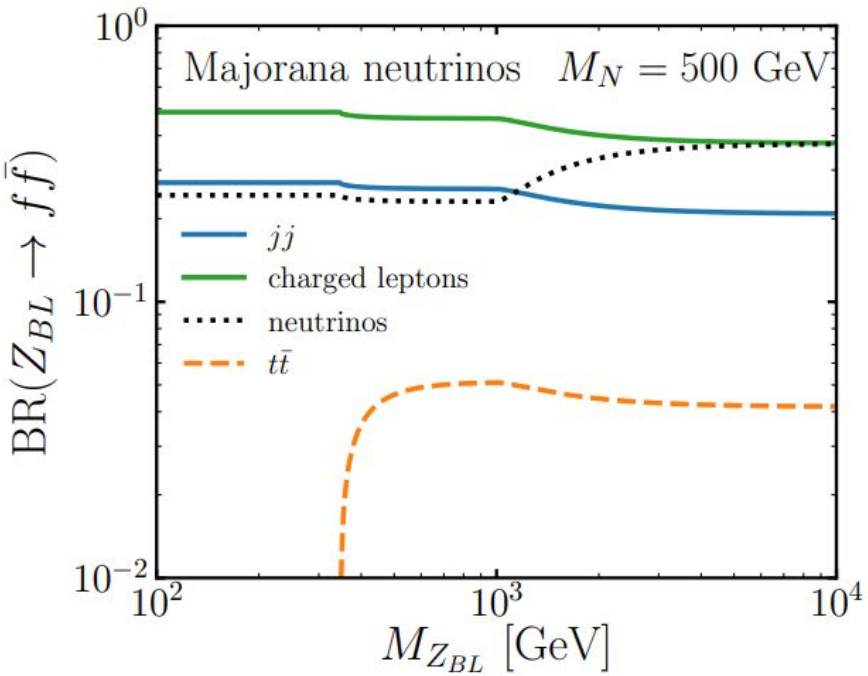


Dirac vs Majorana

Is there an alternative way to distinguish between the scenario with Dirac vs Majorana neutrinos?

Measure decay width of Z_{BL}



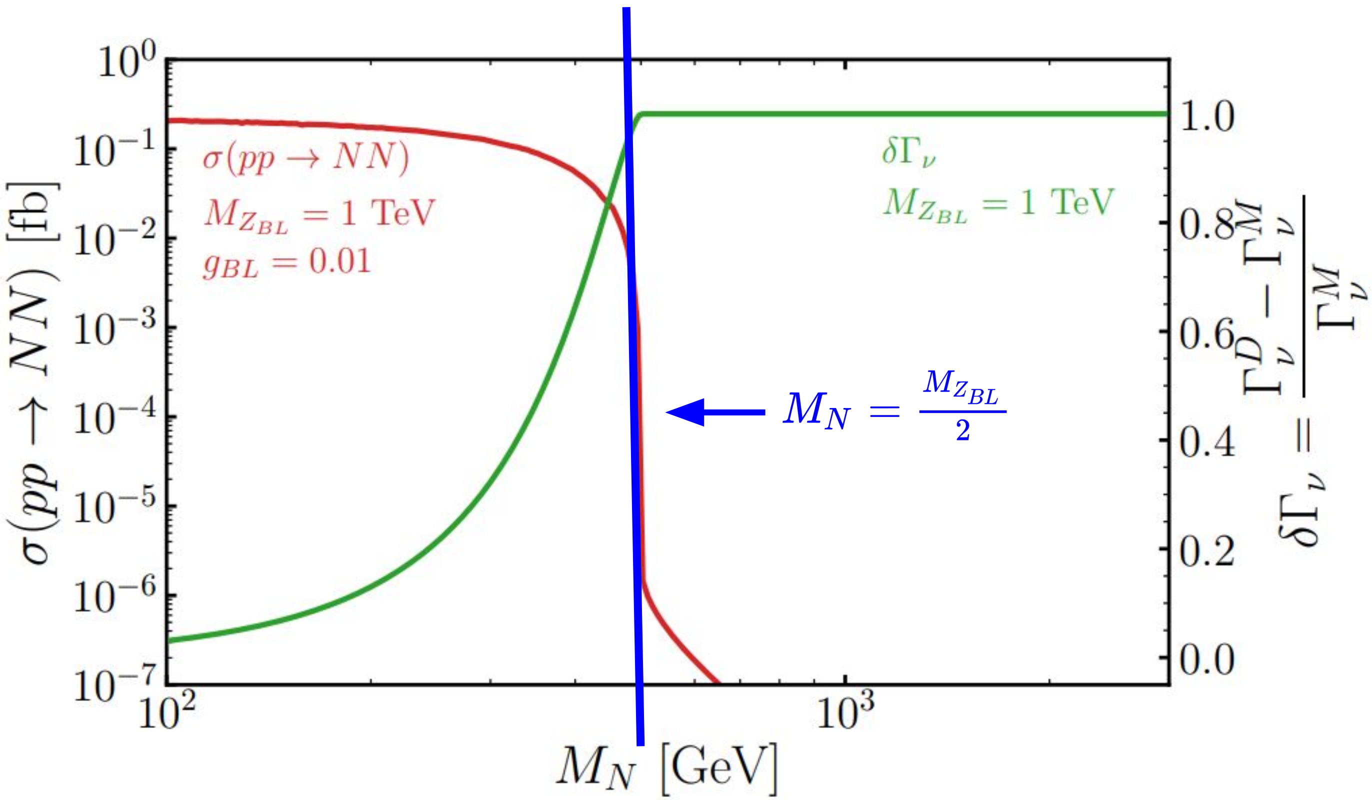


[Fileviez Perez & ADP '20]

Dirac vs Majorana

$$\delta\Gamma_\nu \equiv \frac{\Gamma_\nu^D - \Gamma_\nu^M}{\Gamma_\nu^M}$$

- $\delta\Gamma_\nu$ is largest when $M_N > M_{ZBL}/2$
- This measurement is **complementary** to *pp→NN* production
- Can provide hint on the nature of neutrinos



Dirac neutrinos ⇒

$$\Gamma_{\nu}^{D} = \sum_{i=1}^{3} \Gamma\left(Z_{BL} \to \nu_i \bar{\nu}_i\right) = 6 g_{BL}^2 \frac{M_{Z_{BL}}}{24\pi}$$

$$\Gamma_{\nu}^{M} = \sum_{i=1}^{3} \Gamma\left(Z_{BL} \to \nu_i \nu_i\right) + \sum_{i=1}^{3} \Gamma\left(Z_{BL} \to N_i N_i\right)$$

$$= 3 g_{BL}^2 \frac{M_{Z_{BL}}}{24\pi} + \sum_{i=1,2,3} g_{BL}^2 \frac{M_{Z_{BL}}}{24\pi} \left(1 - \frac{4 M_{N_i}^2}{M_{Z_{BL}}^2}\right)^{3/2}$$

⇐ **Majorana neutrinos**

Dirac neutrinos

$$\Gamma_\nu^D = \sum_{i=1}^{3} \Gamma\left(Z_{BL} \to \nu_i \bar{\nu}_i\right) = 6 g_{BL}^2 \frac{M_{Z_{BL}}}{24\pi}$$

$$\Gamma_\nu^M = \sum_{i=1}^{3} \Gamma\left(Z_{BL} \to \nu_i \nu_i\right) + \sum_{i=1}^{3} \Gamma\left(Z_{BL} \to N_i N_i\right)$$

$$= 3 g_{BL}^2 \frac{M_{Z_{BL}}}{24\pi} + \sum_{i=1,2,3} g_{BL}^2 \frac{M_{Z_{BL}}}{24\pi} \left(1 - \frac{4M_{N_i}^2}{M_{Z_{BL}}^2}\right)^{3/2}$$

Majorana neutrinos

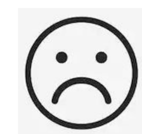
$$i)\ \mathrm{BR}(Z_{BL} \to \text{neutrinos}) \simeq 23\%$$

- The channel $Z_{BL} \to N_i N_i$ kinematically closed
- Unable to directly produce $N_i N_i$. Nevertheless, we will have indirect evidence that neutrinos are **Majorana fermions**

$$ii)\ 23\% < \mathrm{BR}(Z_{BL} \rightarrow \text{neutrinos}) < 38\%$$

- Both channels $Z_{BL} \rightarrow \nu_i \nu_i$ and $Z_{BL} \rightarrow N_i N_i$ are open
- The **Majorana** nature can be further confirmed by direct observation of LNV at colliders.

$$i)\ \mathrm{BR}(Z_{BL} \rightarrow \text{neutrinos}) \simeq 38\%$$



- Hard to disentangle the nature of neutrinos since we can either be in the case with Dirac neutrinos or the one with Majorana neutrinos and $M_N << M_{ZBL}$

[Fileviez Perez & ADP '20]

Bounds from cosmology

- In the thermal history of the Universe, after neutrinos decouple, electron-positron annihilation heats up the photon plasma.
- The neutrino temperature is a bit smaller than the one of photons

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

and the effective number of relativistic species is:

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

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 '16]

N_{eff} effective number of relativistic species

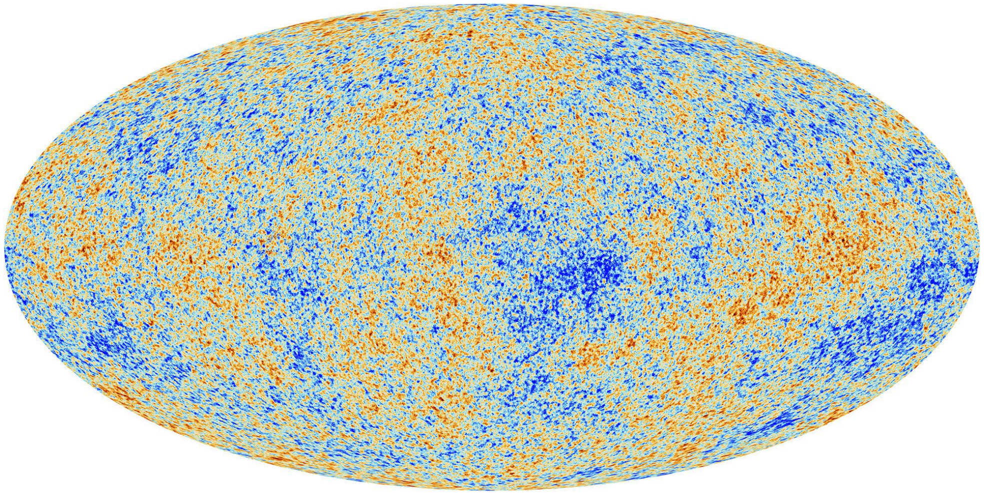
Deviation from 3 comes from- non-instantaneous decoupling, finite temperature corrections, etc...

Review: [Dolgov '02]

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

$$\text{at } 95\%\,\text{CL}$$

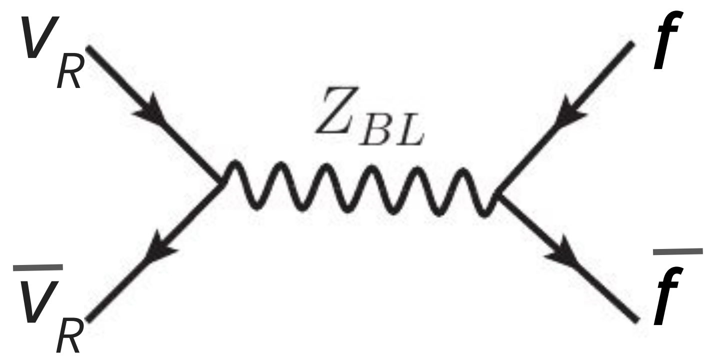
[Planck '18]



N_{eff} effective number of relativistic species

Unbroken *B-L*

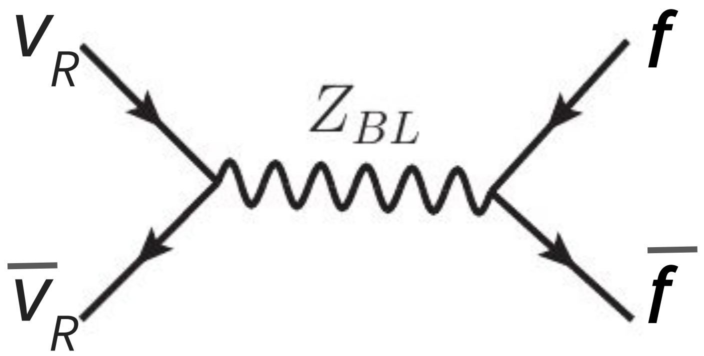
Dirac neutrinos



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

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

N_{eff}



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

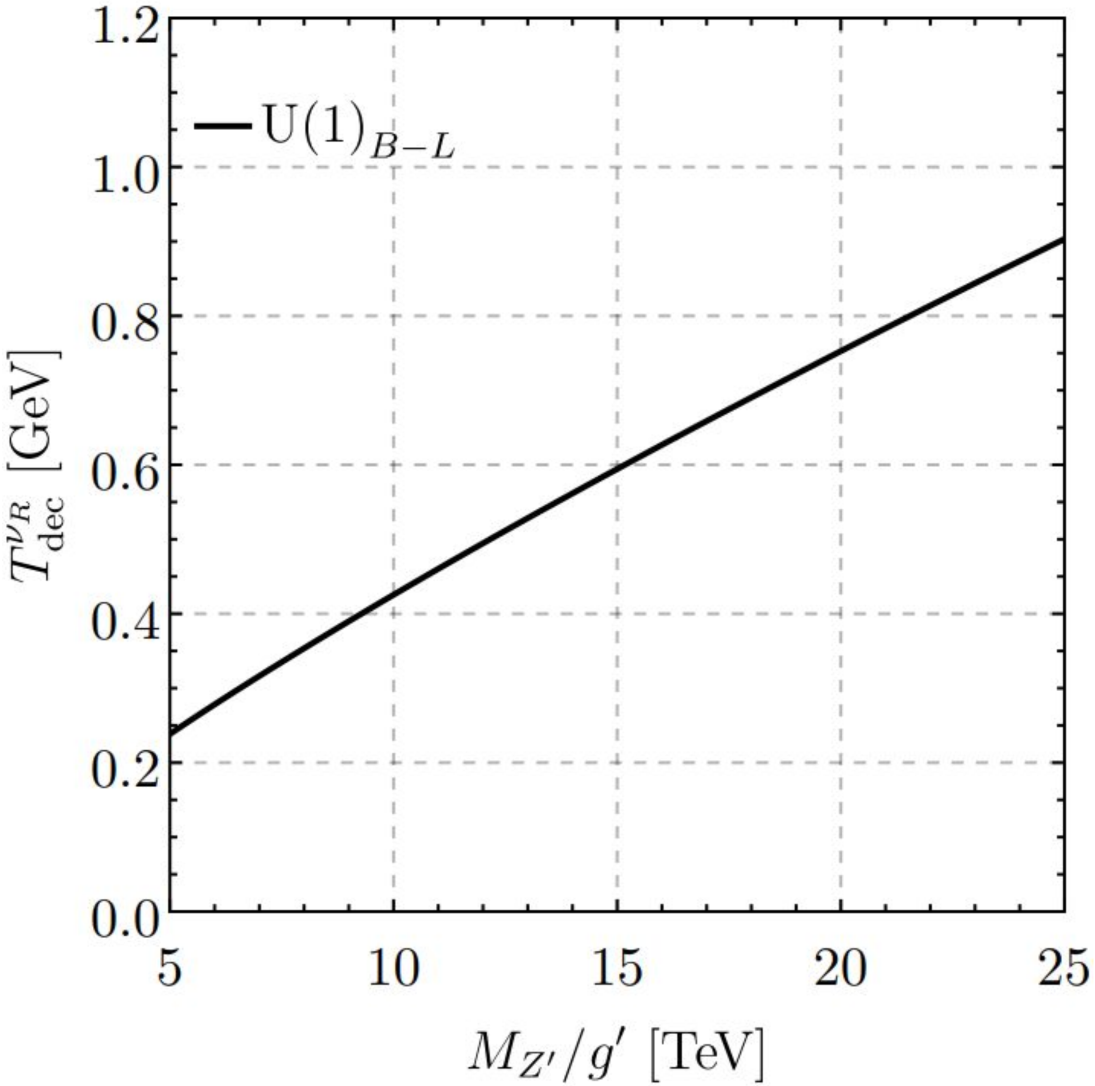
$$\Gamma(T^{\rm dec}_{\nu_R}) = H(T^{\rm dec}_{\nu_R})$$

$$\sigma_{\bar{\nu}_R\nu_R\to\bar{f}f} = \frac{g'^4}{12\pi\sqrt{s}}\frac{1}{(s-M^2_{Z'})^2+\Gamma^2_{Z'}M^2_{Z'}}\sum_f N^C_f n^2_f\sqrt{s-4M^2_f}\,(2M^2_f+s)$$

$$T^{\rm dec}_{\nu_R} \ll M_{Z'} \qquad \Gamma_{\nu_R}(T) = \frac{49\pi^5 T^5}{97200\xi(3)}\left(\frac{g'}{M_{Z'}}\right)^4 \sum_f N^C_f n^2_f,$$

Decoupling T for ν_R

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



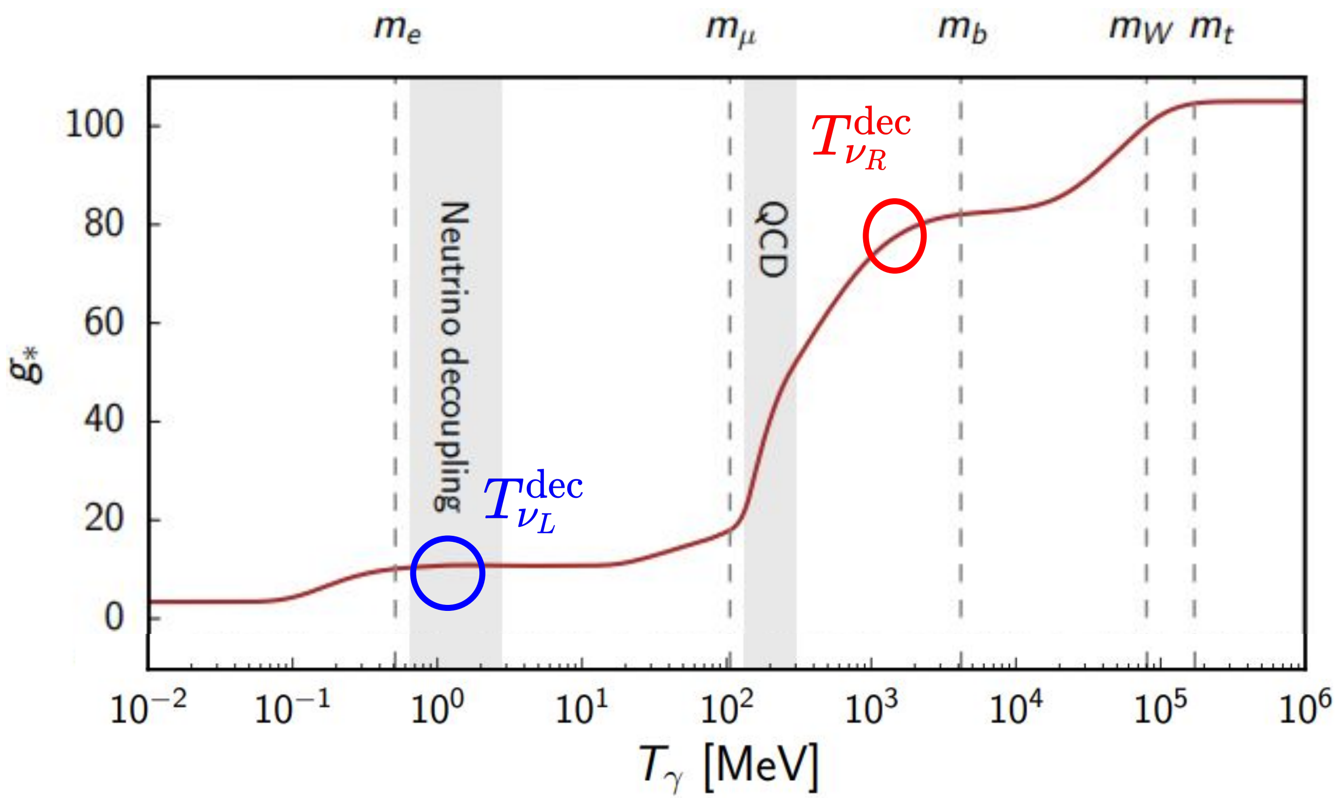
[Fileviez Perez, Murgui, ADP '19]

N_{eff}

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

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

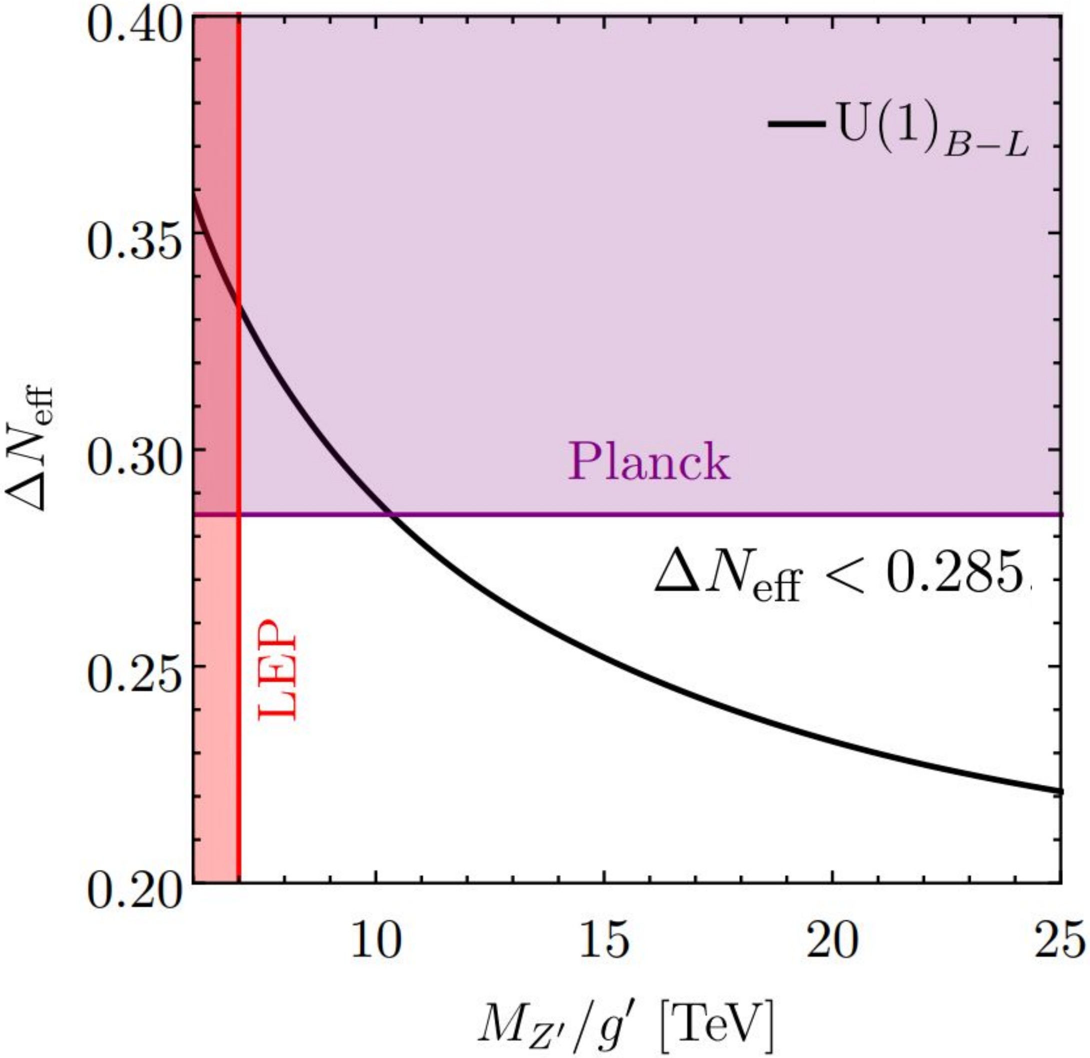
$\mathcal{O}(\mathrm{GeV})$



[Simons Observatory: Science Goal and Forecasts '19] [Borsany et al '16]

N_{eff}

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



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

at 95% CL

[Planck '18]

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

Stronger than the LEP & LHC bound for large couplings and/or $M_{Z'} > 4$ TeV

[Fileviez Perez, Murgui, ADP '19]

N_{eff}

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

As long as ν_R reach 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}!

A very light Z_{BL} can also thermalize and contribute to N_{eff}
[Abazajian & Heeck '19]

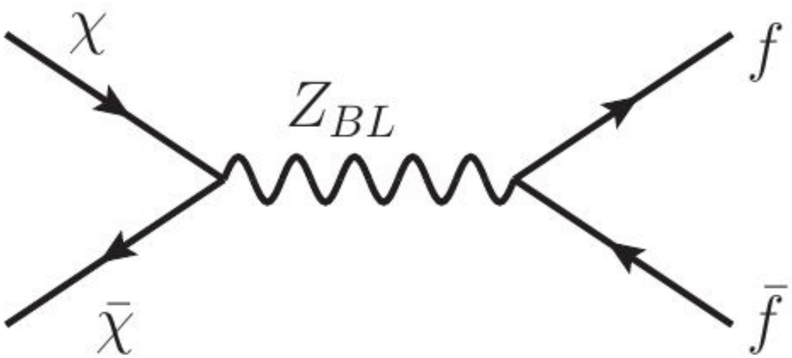
Dirac fermion as dark matter

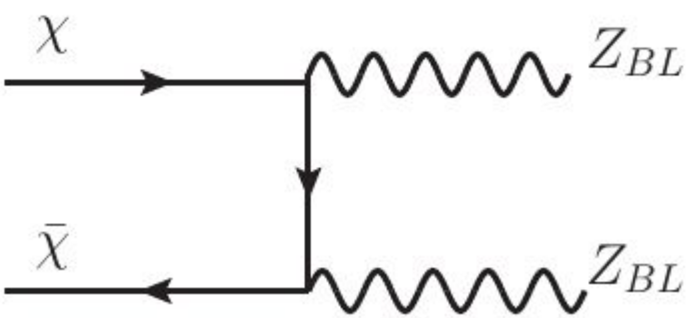
Introduce vector-like fermion with *B-L* charge

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

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

Non-renormalizable operators forbid *n* odd

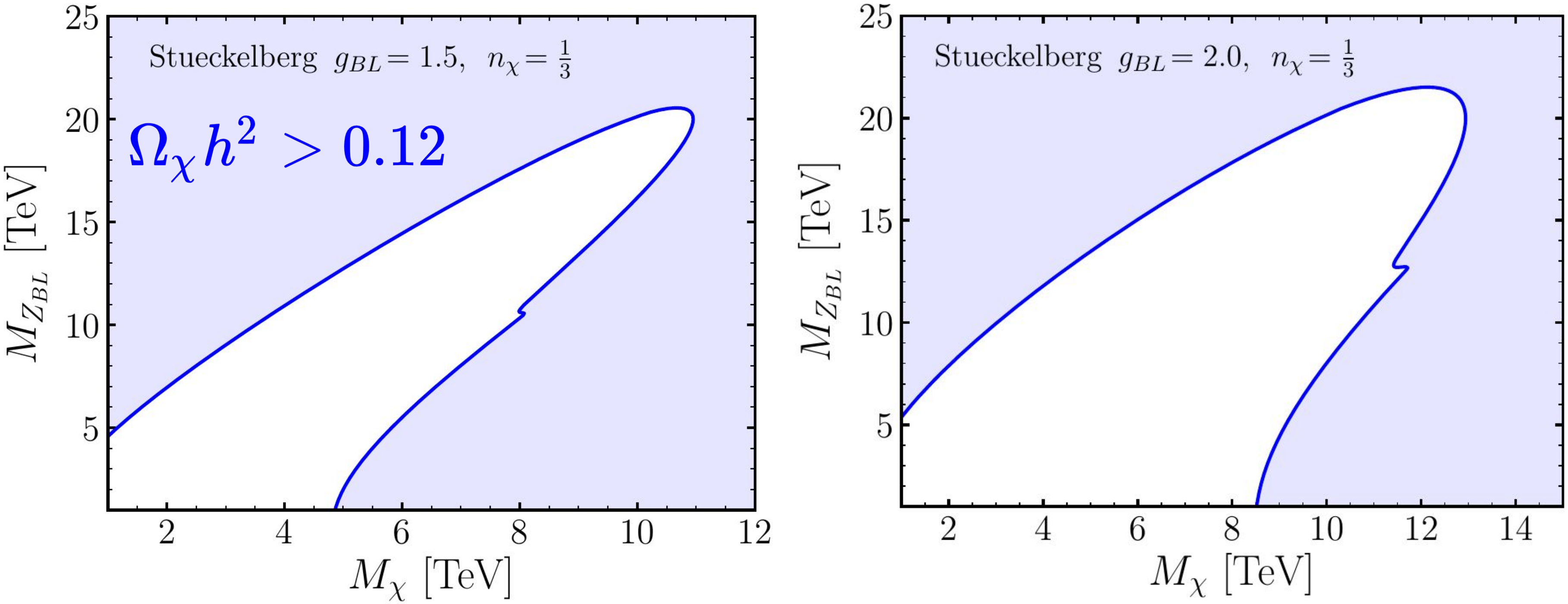




Dark Matter

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

$\Omega_\chi h^2 = 0.1200 \pm 0.0012$ **[Planck '18]**



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

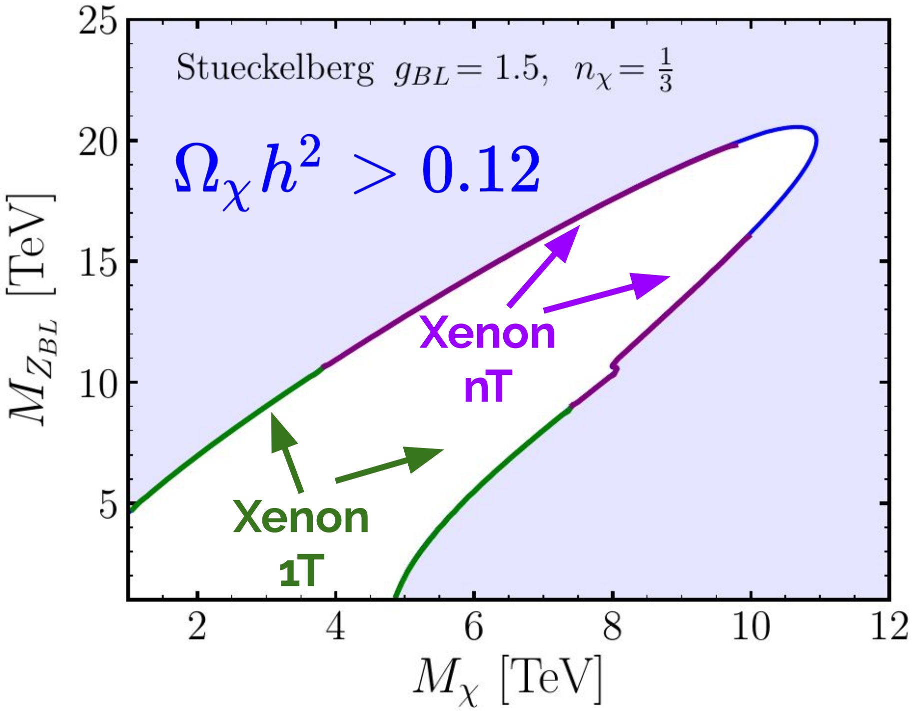
Note: Partial wave unitarity requires $M_{DM} < 240$ TeV weaker bound

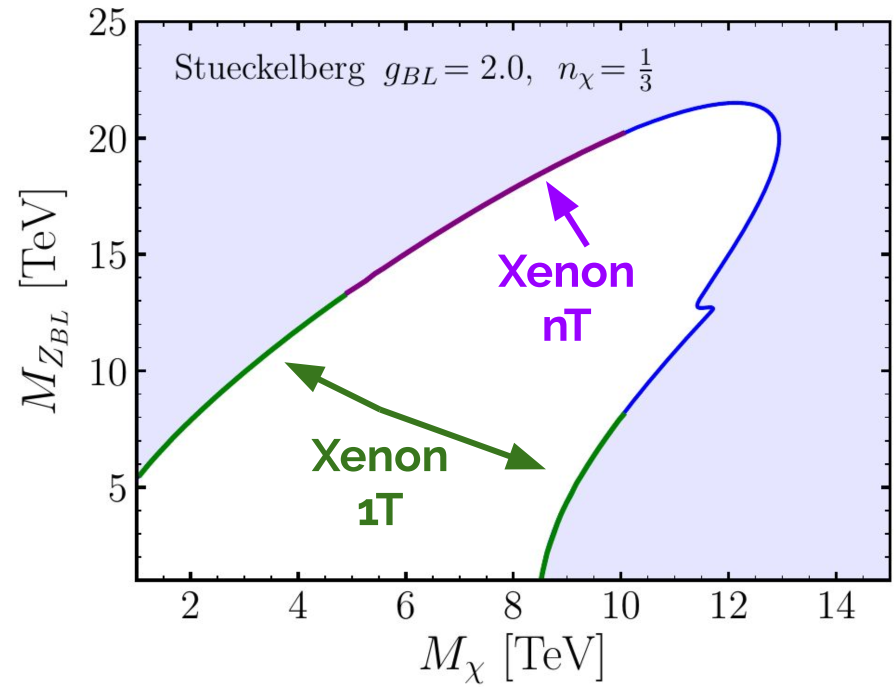
[Griest & Kamionkowski '90]

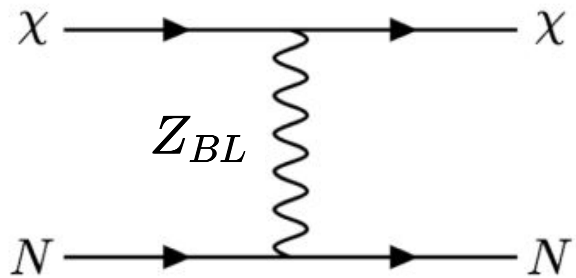
Dark Matter

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

$\Omega_\chi h^2 = 0.1200 \pm 0.0012$ **[Planck '18]**







Dark Matter

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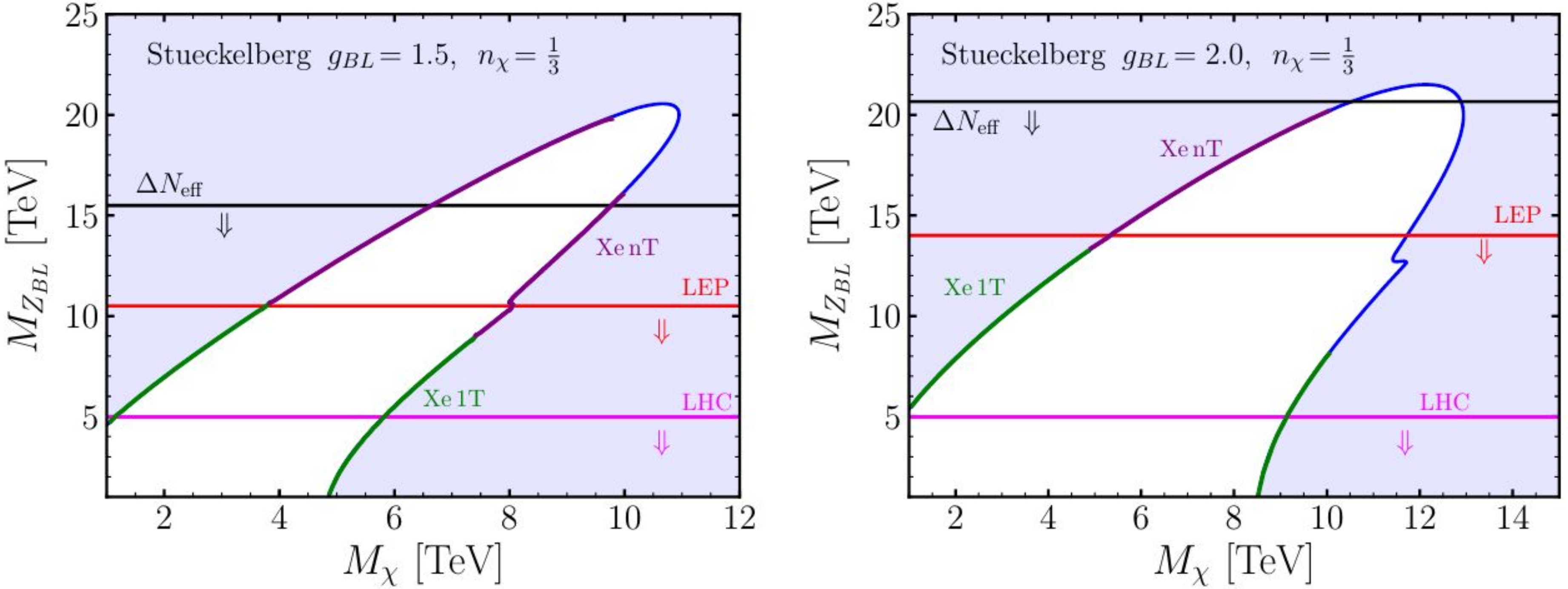
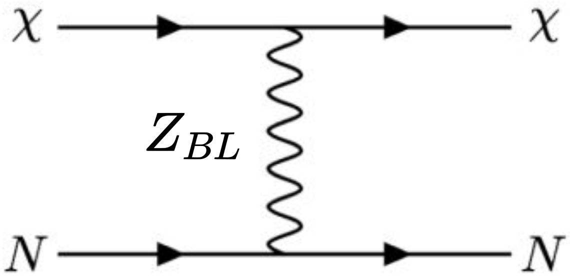


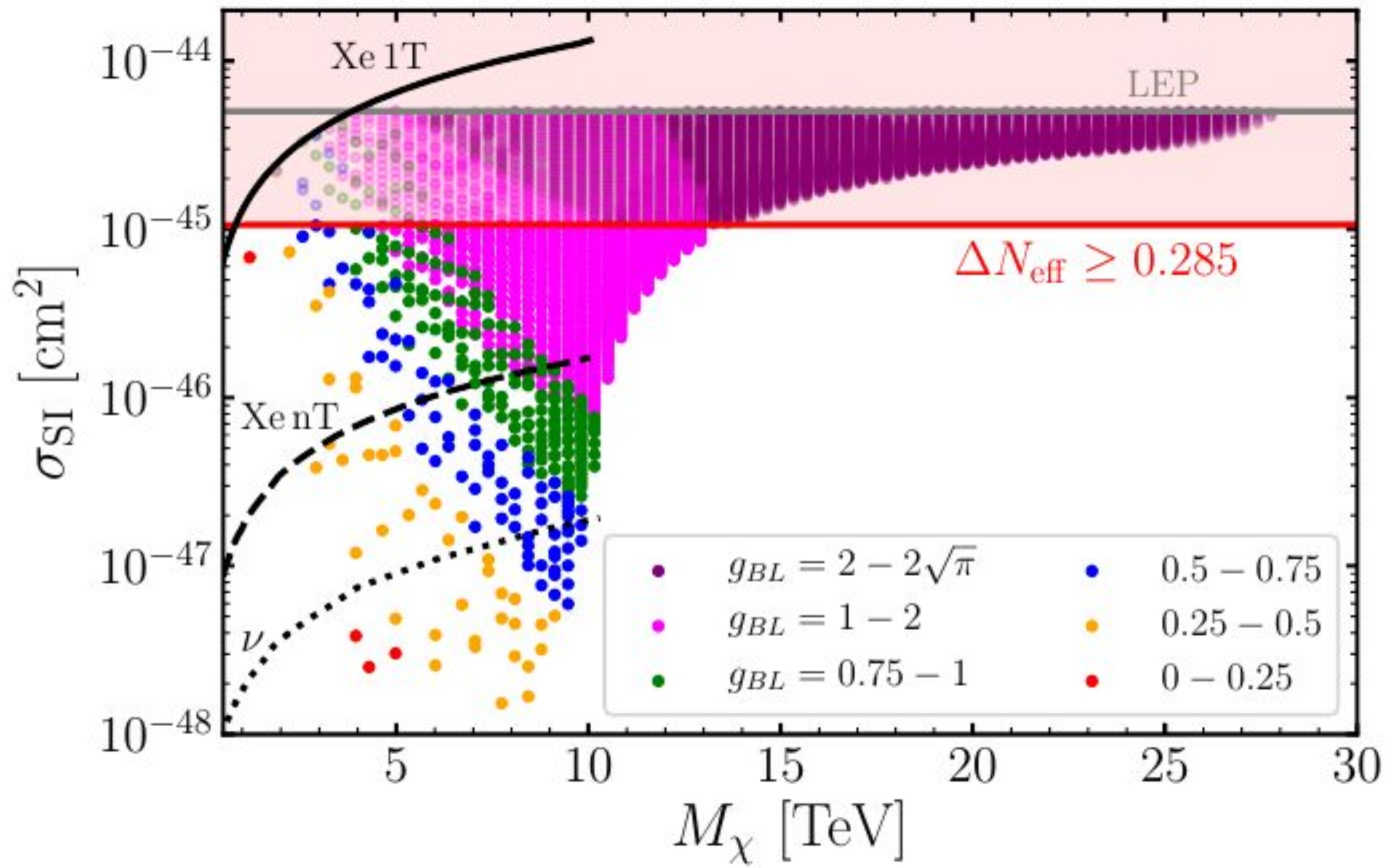
$\Delta N_{eff} < 0.285$ gives the strongest bound

Dark Matter - direct detection

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



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



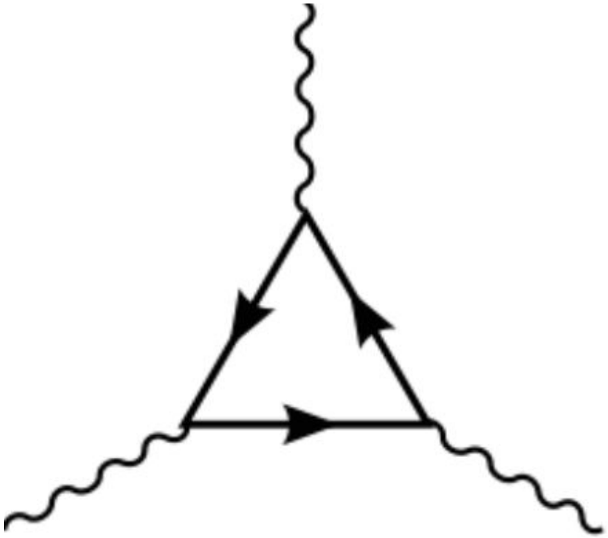
2. $U(1)_L$

Dirac neutrinos and cosmology

Gauging lepton number

$U(1)_L$

- 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

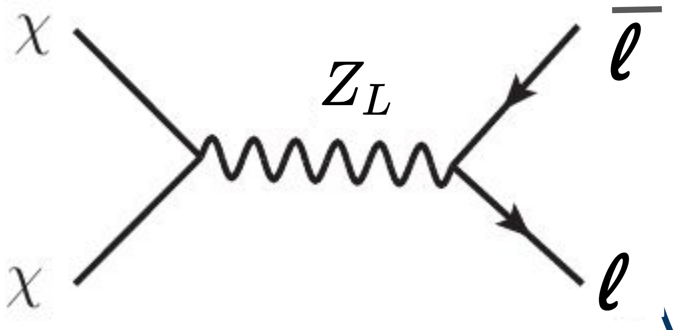
$\mathrm{U}(1)_L$

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	$\frac{3}{2}$

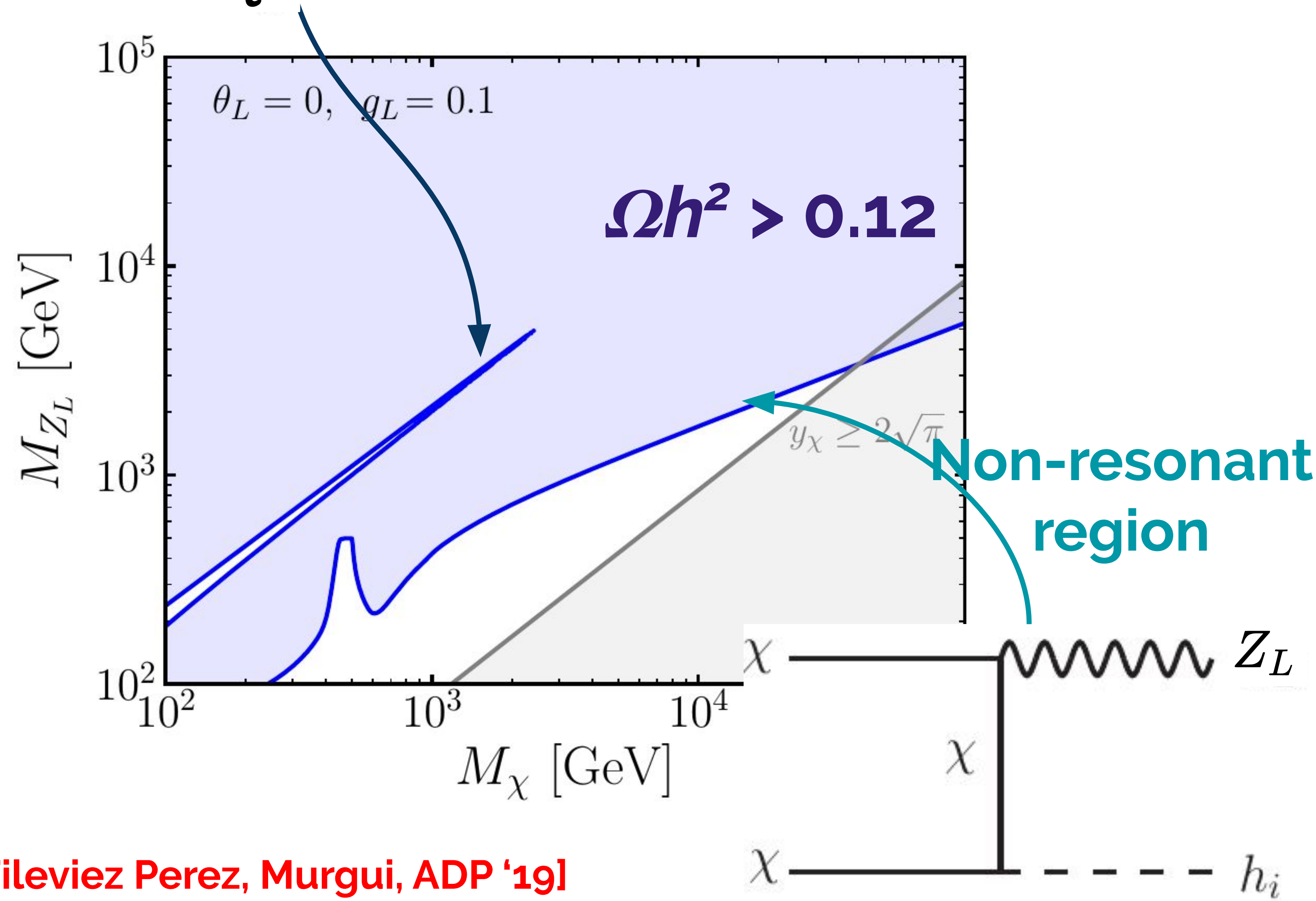
[Duerr, Fileviez Perez & Wise '13]

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

⟶ DM Candidate 

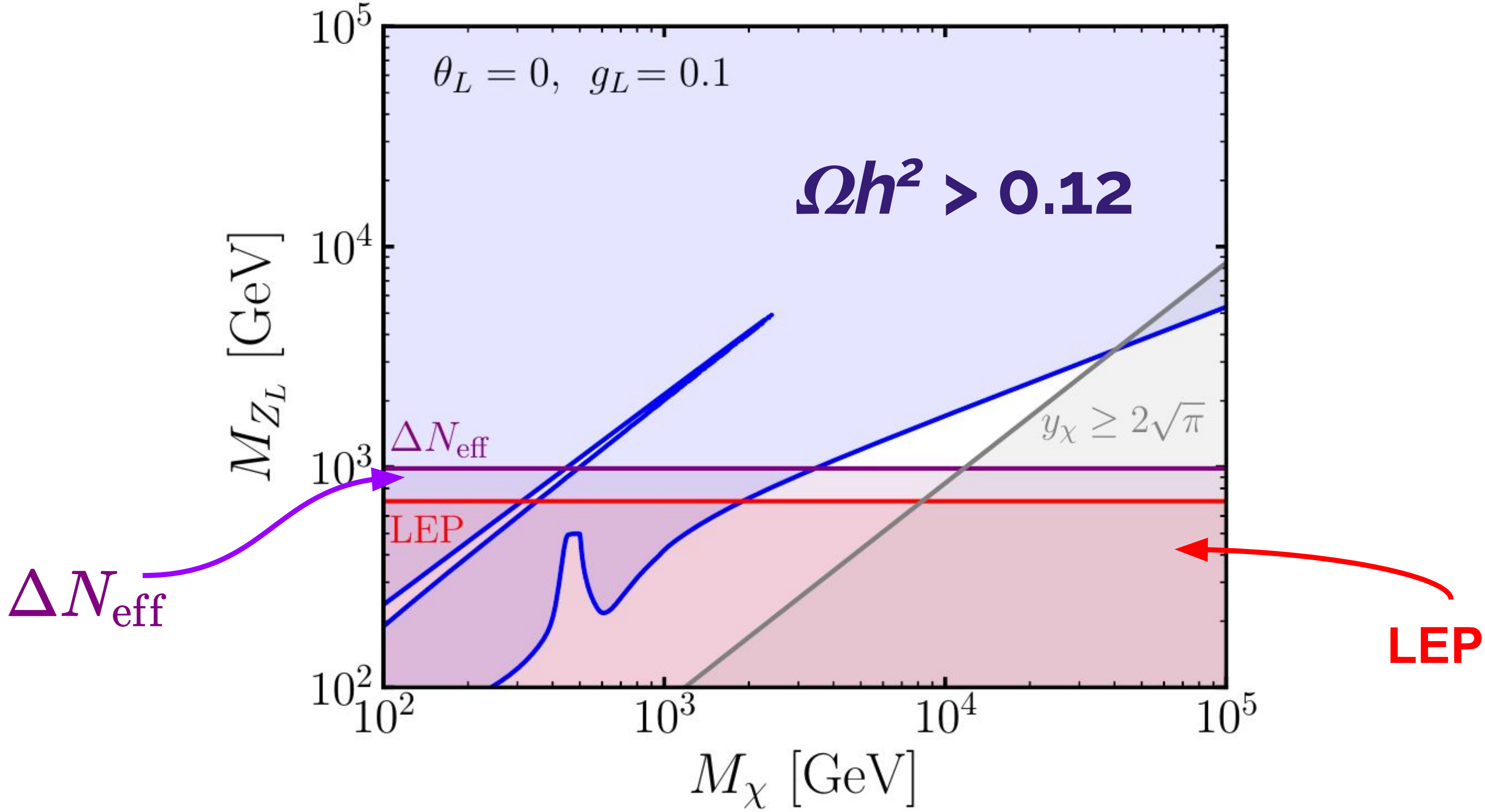


$$M_\chi \approx M_{Z_L}/2$$



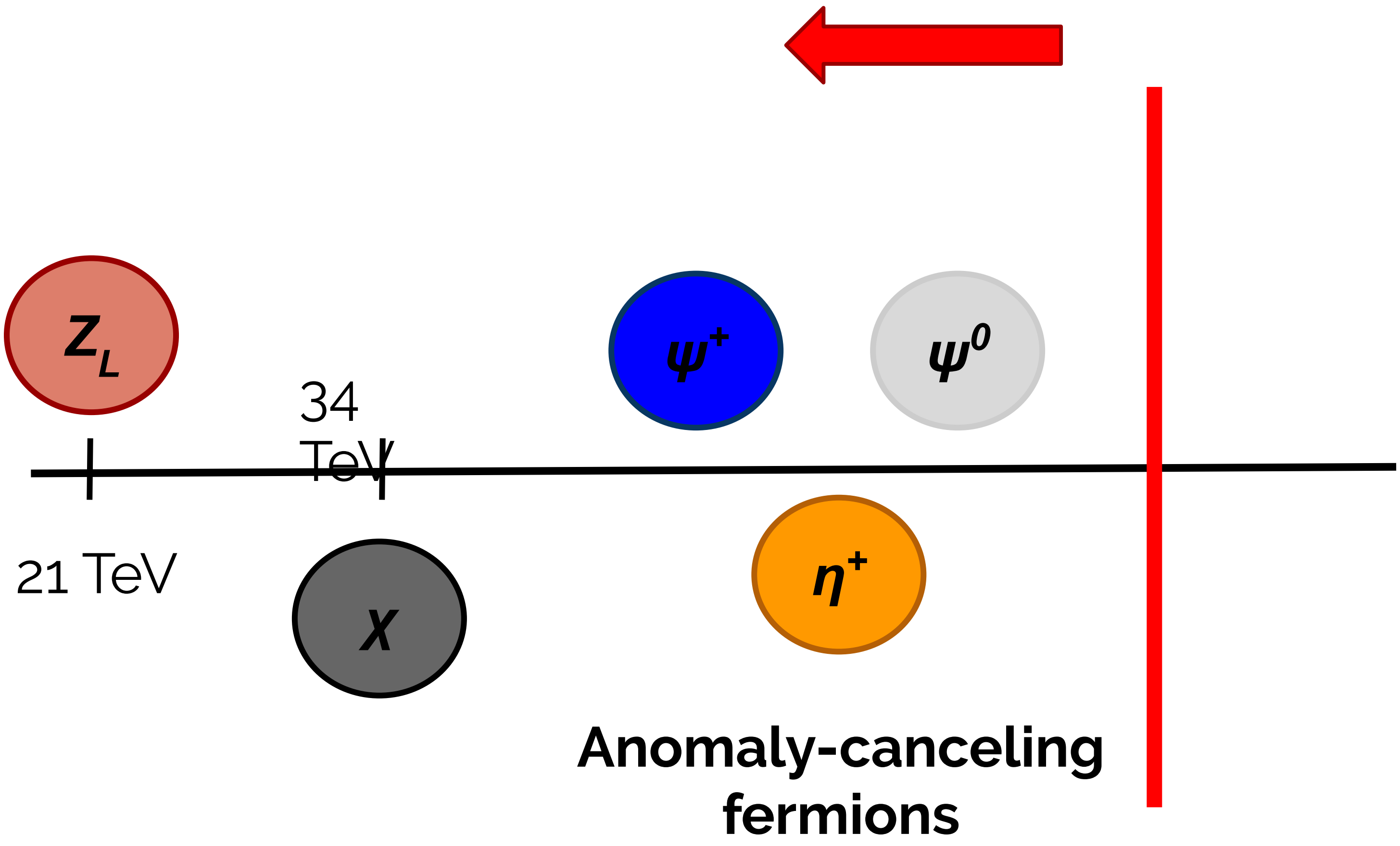
[Fileviez Perez, Murgui, ADP '19]

- Z_L does not couple to quarks
- Direct detection constraints can be avoided with $\sin\theta < 0.1$



Upper bound on lepton number breaking scale

All masses connected to $\langle v \rangle_L$ and hence there is an upper bound for the full model

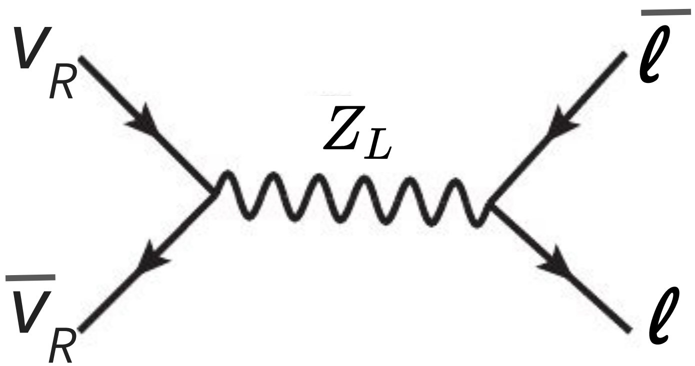


Dirac neutrinos

$U(1)_L$

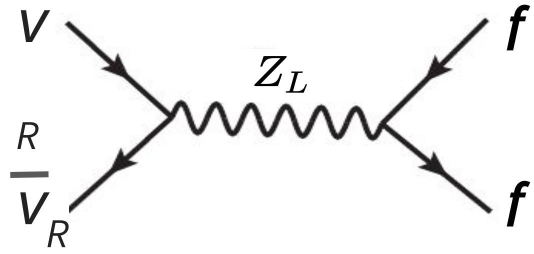
- Spontaneous breaking of lepton number
- Lepton number broken by 3 units: $\Delta L = \pm 3$ interactions

→ **Dirac neutrinos**

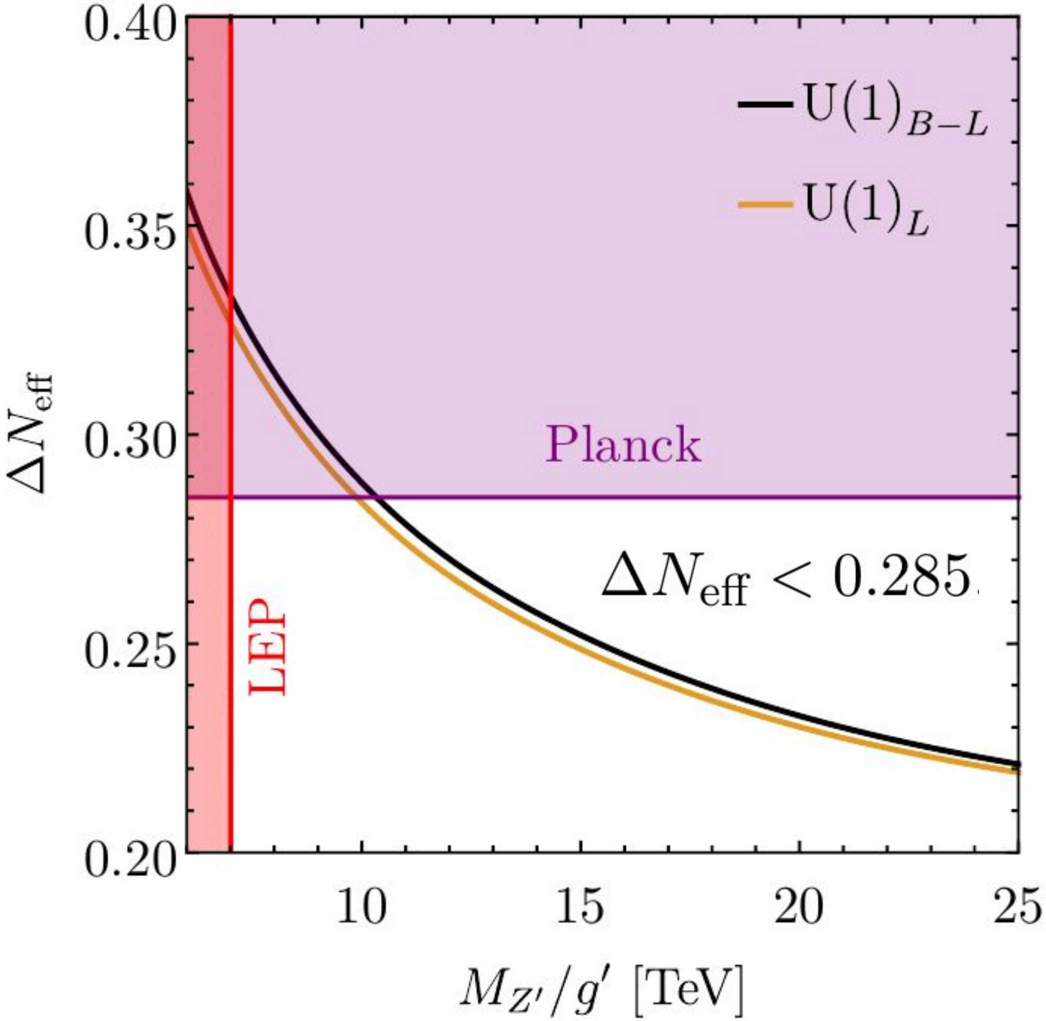


Constraints from N_{eff} also apply to this scenario!

N_{eff}



$\mathrm{U}(1)_L$



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

[Planck '18]

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

[Fileviez Perez, Murgui, ADP '19]

Stronger than the LEP bound: $\frac{M_{Z_L}}{g_L} > 7$ TeV

Next generation CMB experiments

- 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 '19]

Next generation CMB experiments

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

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

[Simons Observatory: Science Goal and Forecasts '19]

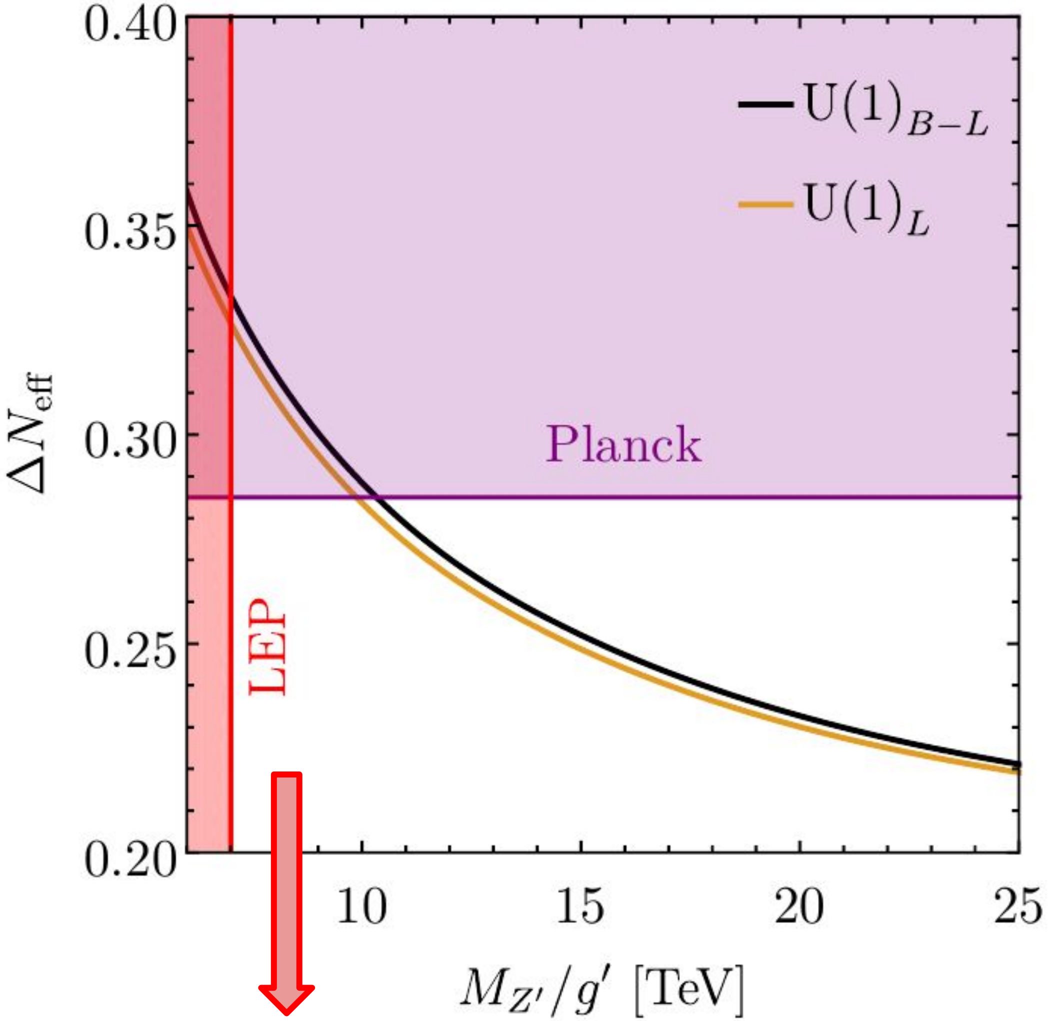
Projection for CMB Stage-IV:

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

[CMB-S4 Science Book '16]

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

N_{eff} gives strongest bound



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

CMB-S4

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

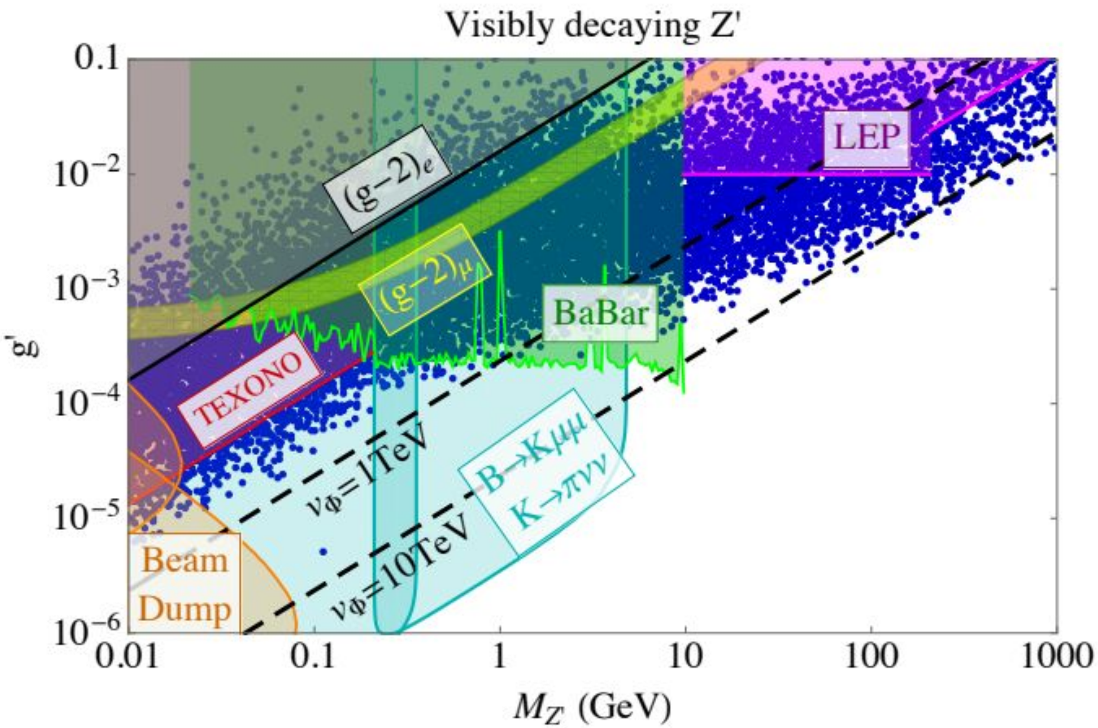
Baryogenesis in $U(1)_L$

These models explain dark matter and neutrino masses

Need to explain matter-antimatter asymmetry:

$$\eta_{B\,\mathrm{BBN}} = (5.80 - 6.60) \times 10^{-10}$$
$$\eta_{B\,\mathrm{CMB}} = (6.02 - 6.18) \times 10^{-10}$$

- New scalar S to induce 1st order PT and CP-violation
- Chiral asymmetry for DM χ ➡ lepton asymmetry



[Carena, Quirós, Zhang, '19]

3. $U(1)_B$

LHC phenomenology and dark matter

Anomaly cancellation

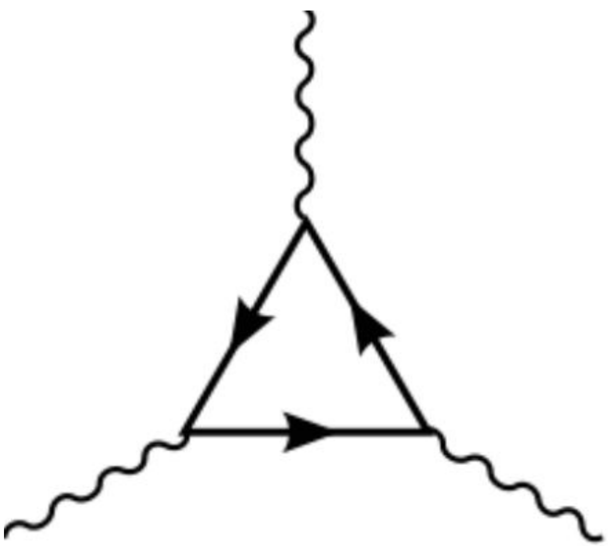
- Baryon number broken by 3 units: $\Delta B = \pm 3$ interactions

  → 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 '13]

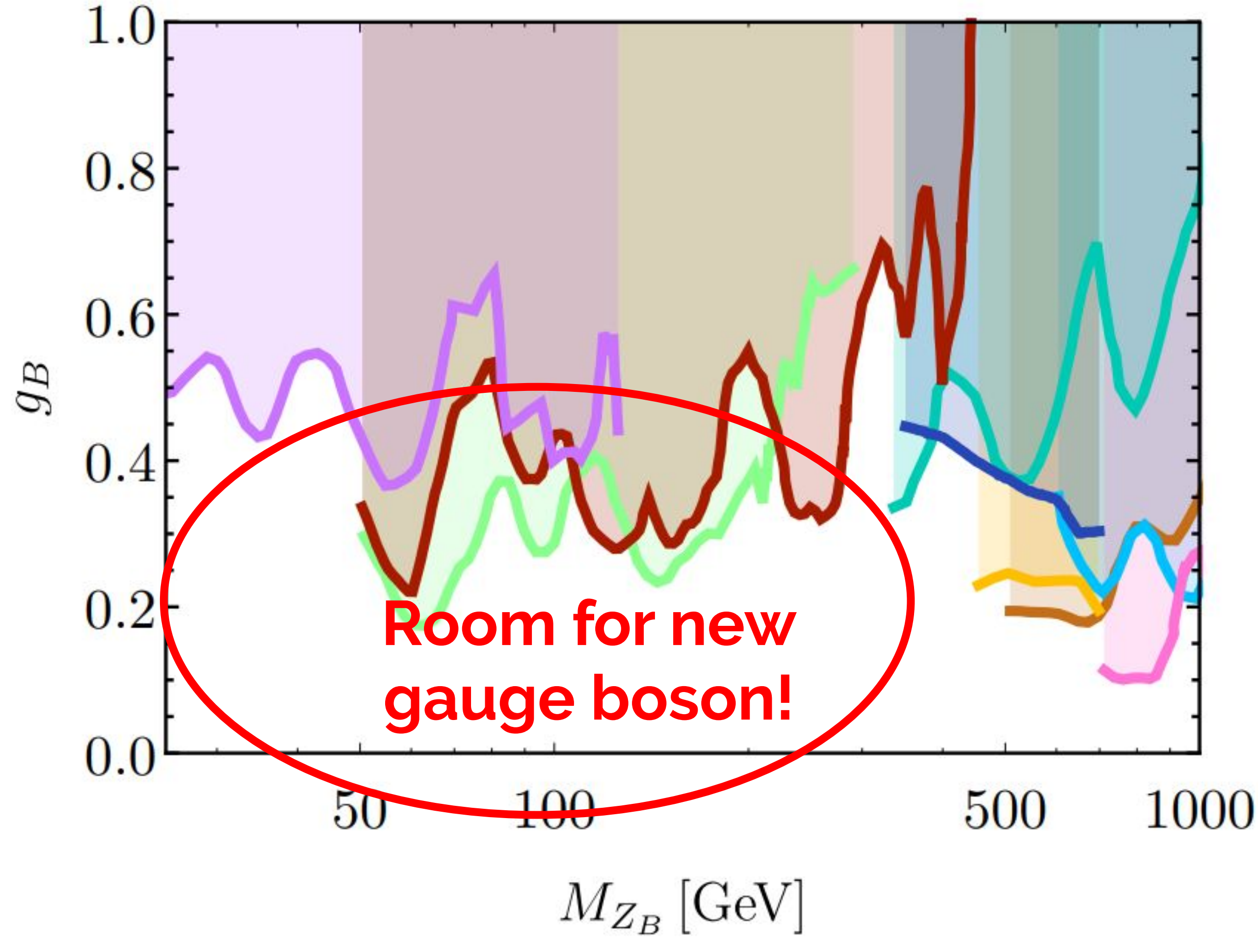
Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$\Psi_L = \begin{pmatrix} \Psi_L^0 \\ \Psi_L^- \end{pmatrix}$	1	2	$-\frac{1}{2}$	$-\frac{3}{2}$
$\Psi_R = \begin{pmatrix} \Psi_R^0 \\ \Psi_R^- \end{pmatrix}$	1	2	$-\frac{1}{2}$	$\frac{3}{2}$
η_R^-	1	1	-1	$-\frac{3}{2}$
η_L^-	1	1	-1	$\frac{3}{2}$
χ_R^0	1	1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

DM

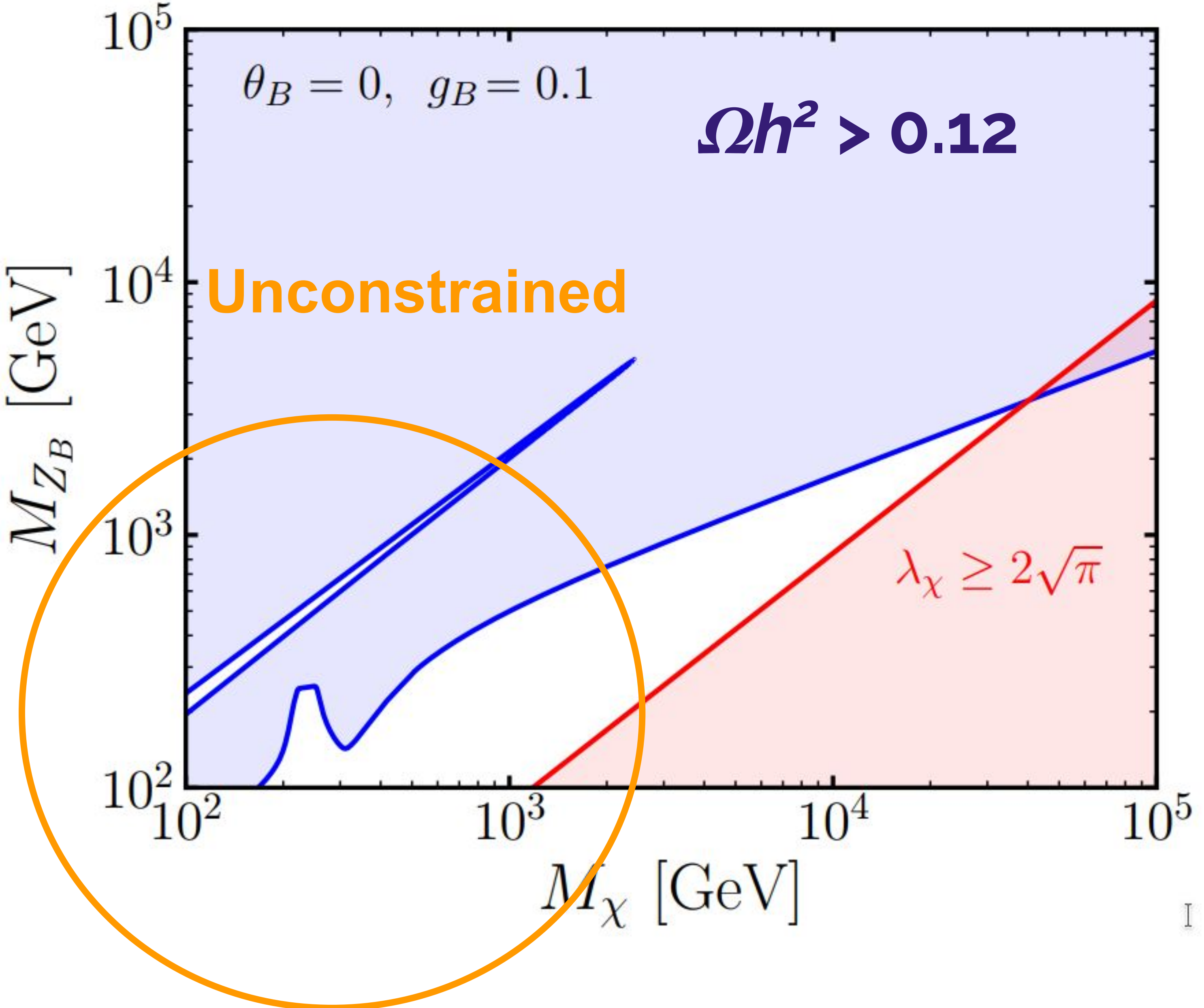
For Model II see
[Fileviez Perez, Ohmer, Patel '14]

LHC bounds on leptophobic gauge boson

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

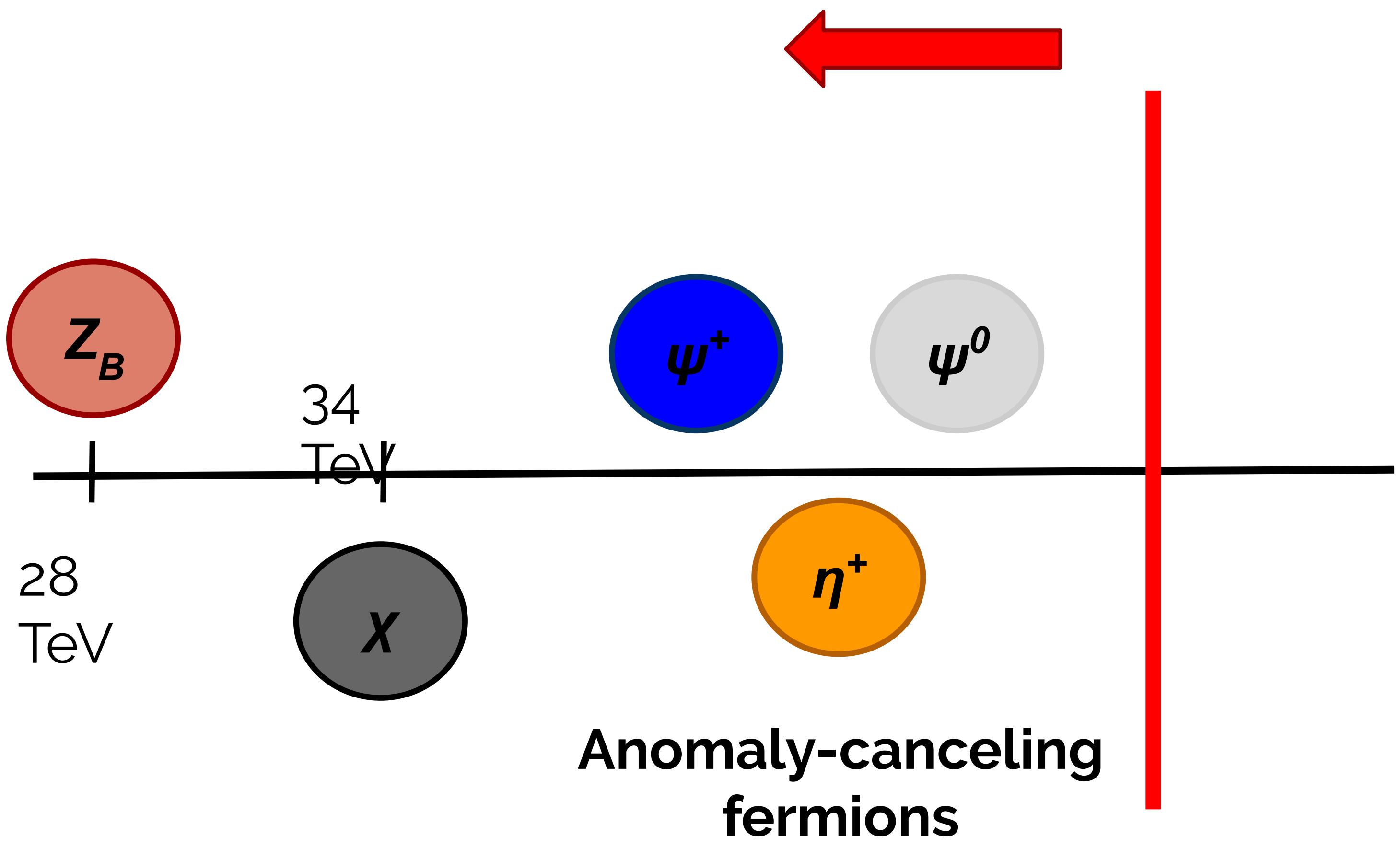


Results


$\theta_B = 0, \ g_B = 0.1$
$\Omega h^2 > 0.12$
Unconstrained
$\lambda_\chi \geq 2\sqrt{\pi}$
M_{Z_B} [GeV]
M_χ [GeV]
10^2
10^3
10^4
10^5

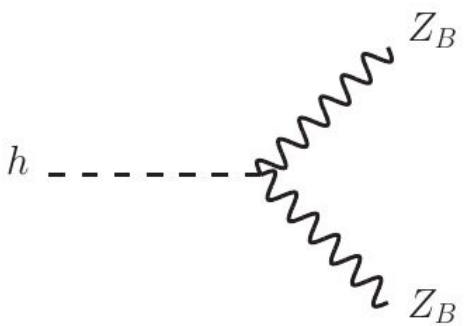
Upper bound on baryon number breaking scale

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



Exotic Higgs decays

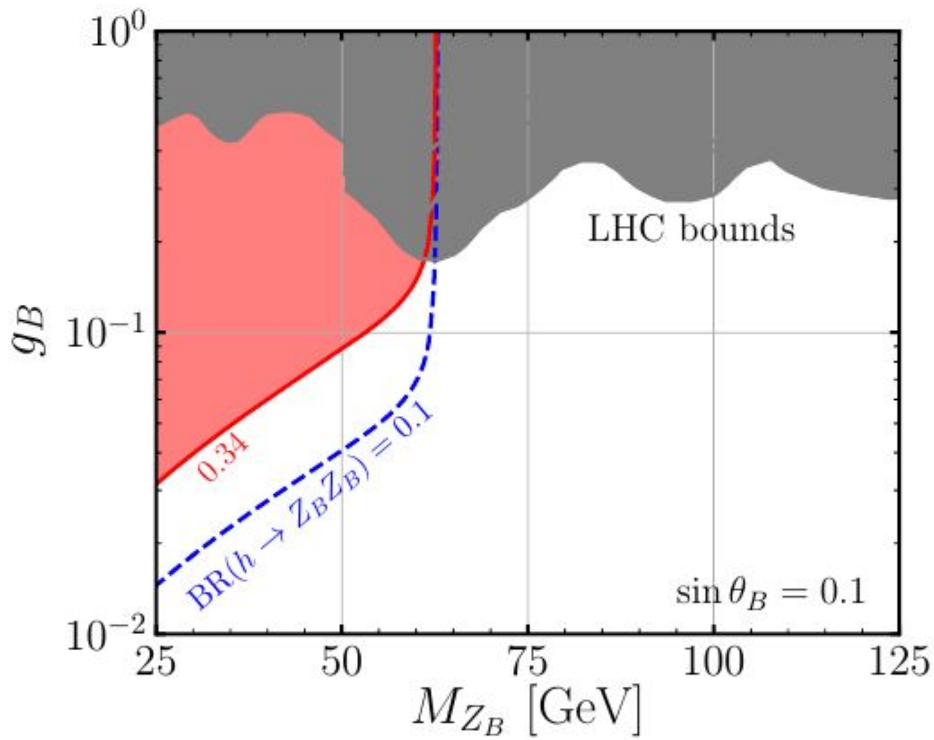
When $M_{Z_B} \leq M_h/2$:



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

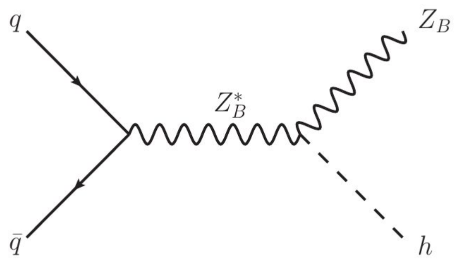
$$\mathrm{BR}(h \to \mathrm{BSM}) \leq 0.34$$

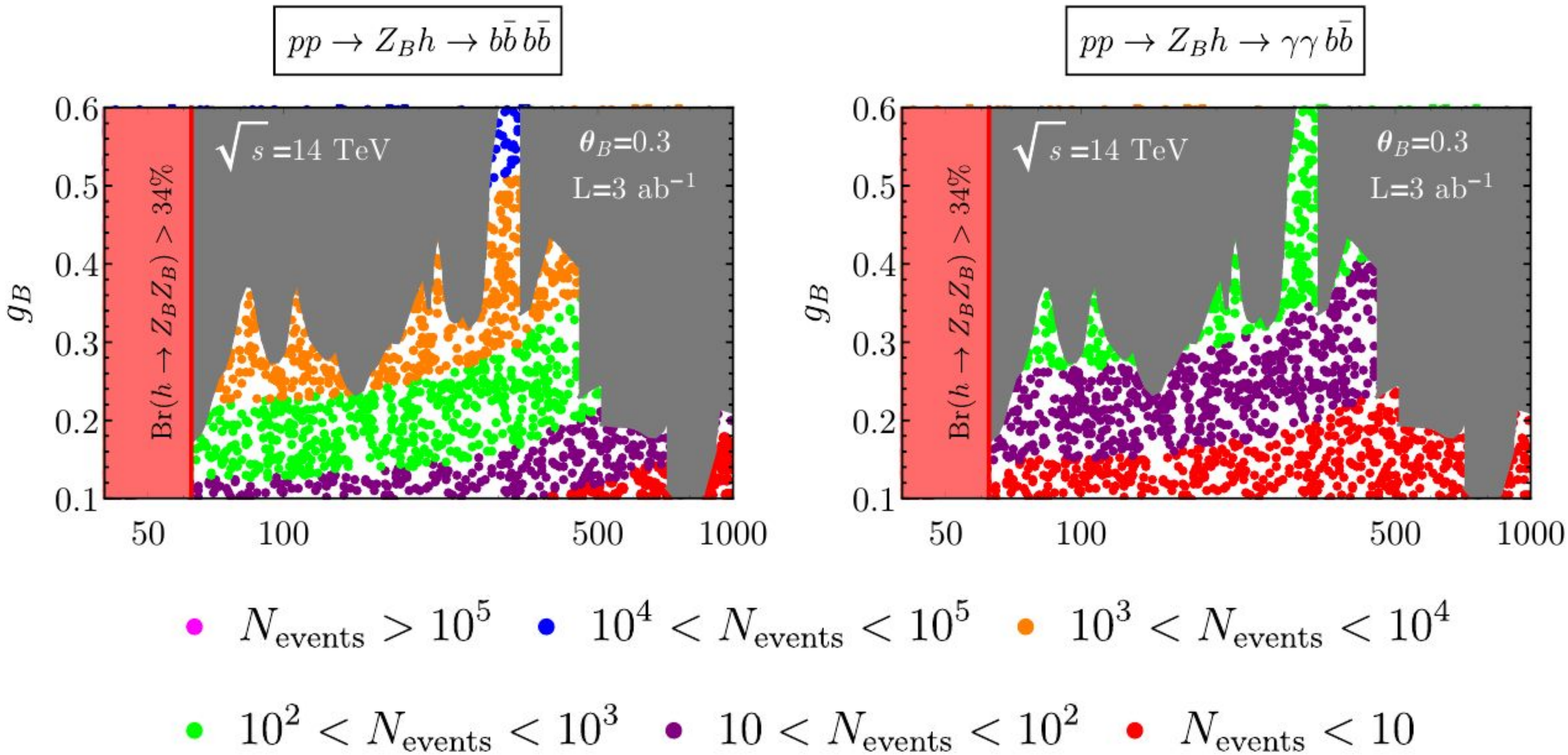
[ATLAS & CMS 1606.02266]



[Fileviez Perez, Golias, Murgui, ADP '20]

Associated Higgs Production





[Fileviez Perez, Golias, Murgui, ADP '20]

Conclusions

- **U(1)$_{B-L}$** for $M_N \leq M_{Z_{BL}}/2$ large cross-sections for **LNV**. For $M_N > M_{Z_{BL}}/2$ the decay width of Z_{BL} can help distinguish between Dirac and Majorana
- The **gauging of lepton and/or baryon** number leads to interesting cosmology and collider physics
- **U(1)$_L$** neutrinos are Dirac. Next generation CMB will fully test these theories (with thermal DM) using ΔN_{eff}
- **U(1)$_B$** can be at the low scale (GeV) and the LHC will probe this region. $h \to Z_B Z_B$ can have a large branching ratio
- Not overproducing DM $\Omega h^2 \leq 0.12$ implies an upper bound on all these theories < 35 TeV

Thank you!


thank you
danke
謝謝
рахмат
ngiyabonga
teşekkür ederim
Баярлалаа
спасибо
faafetai lava
mersi
kia ora
barka
welalin
tack
spas
dank je
misaotra
matondo
paldies
grazzi
mahalo
tapadh leat
gracias
vinaka
спасибі
blagodaram
kiitos
dankie
nanni
nandri
dhanyavad
mauruuru
köszönöm
akun
dankon
ačiū
хвала
asante
manana
obrigada
murakoze
tenki
bedankt
bayarlalaa
gràçie
hvala
enkosi
dziękuję
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mochchakkeram
дякую
mamnun
chokrane
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sulpáy
taiku
go raibh maith agat
sobodi
děkuji
sagolun
sukriya
kop khun krap
obrigado
mèsi
didi madloba
najis tuke
ありがとう
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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	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$\Psi_L = \begin{pmatrix} \Psi_L^+ \\ \Psi_L^0 \end{pmatrix}$	1	2	$\frac{1}{2}$	$\frac{3}{2}$
$\Psi_R = \begin{pmatrix} \Psi_R^+ \\ \Psi_R^0 \end{pmatrix}$	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]

Stueckelberg scenario

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

The above Lagrangian is invariant under gauge transformations:

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

Massive gauge boson and σ field decouples from the theory

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

For Abelian theories renormalizable and unitary

N_{eff}

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

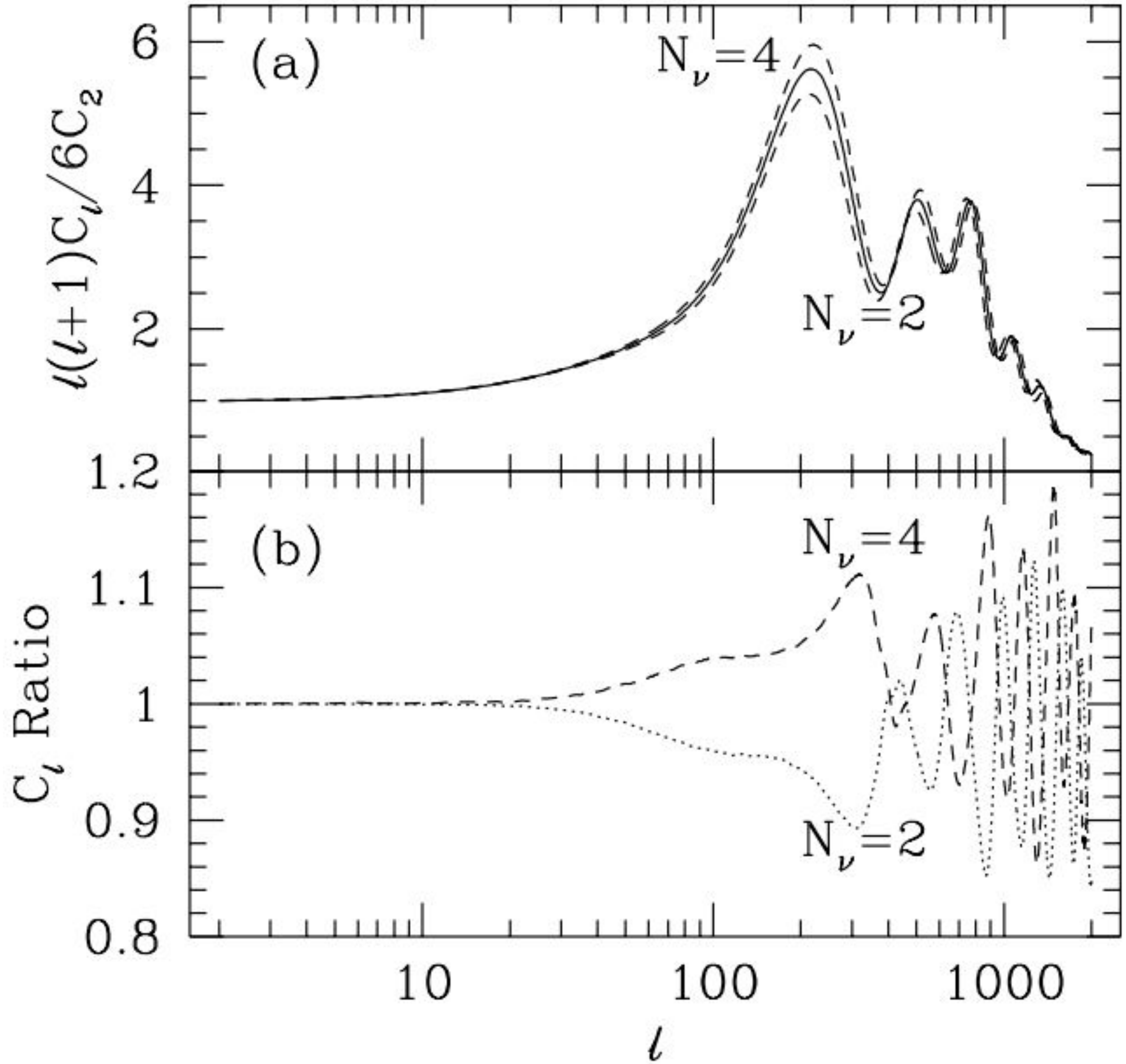
[Planck 2018]

Projection for CMB Stage-IV:

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

[CMB-S4 Science Book 2016]

N_{eff}

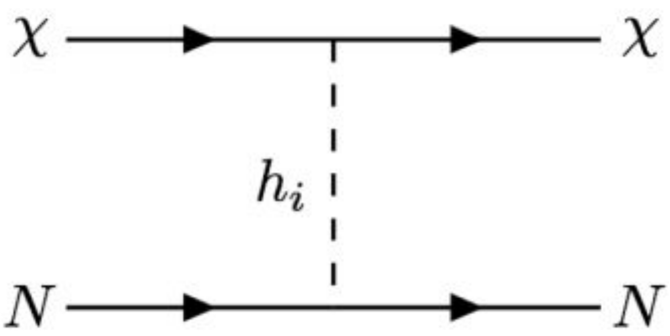


[Hu et al 1995]

Direct Detection

$\mathrm{U}(1)_L$

Z_L does not couple to quarks

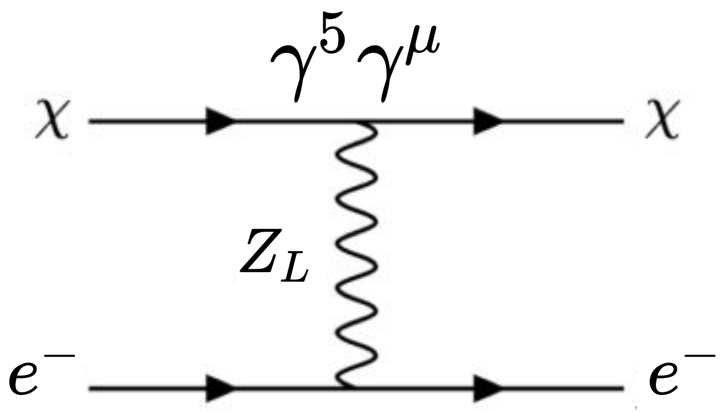


suppressed by Higgs mixing

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

For lighter M_{H2} stronger bound

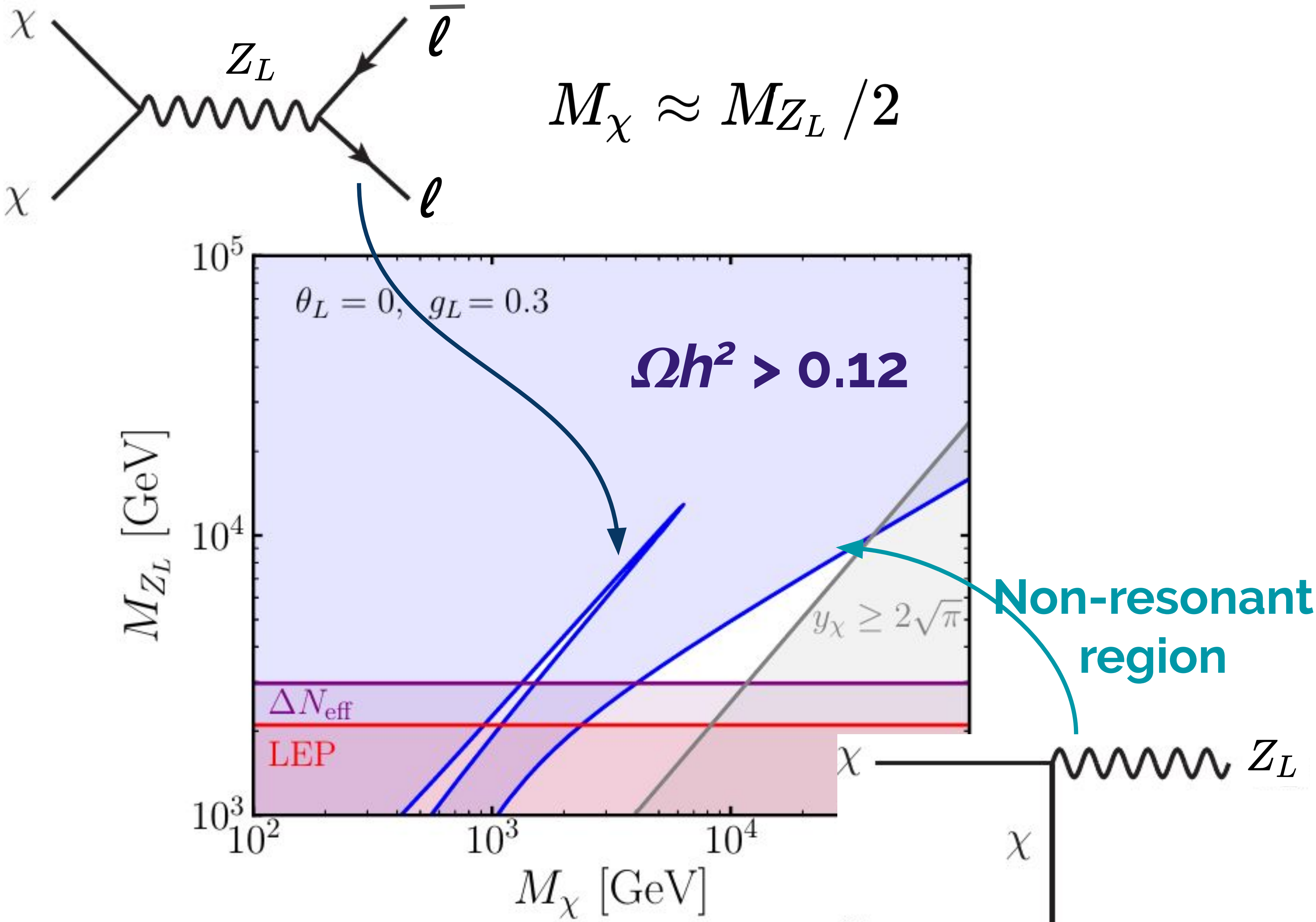
[Ilnicka, Robens, Stefaniak 2018]



Due to axial coupling,

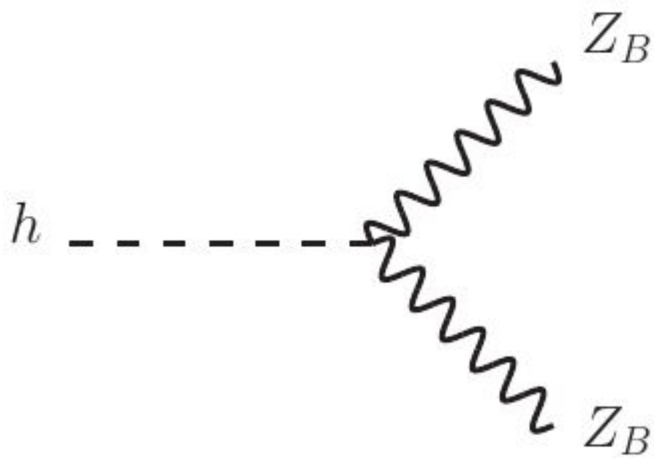
velocity suppressed $v \sim 10^{-3}$

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


χ
χ
Z_L
$\bar{\ell}$
ℓ
$M_\chi \approx M_{Z_L}/2$
$\theta_L = 0, \; g_L = 0.3$
$\Omega h^2 > 0.12$
$y_\chi \geq 2\sqrt{\pi}$
$\Delta N_{\rm eff}$
LEP
Non-resonant region
M_{Z_L} [GeV]
M_χ [GeV]
10^5
10^4
10^3
10^2
10^3
10^4
χ
χ
χ
Z_L
h_i

Exotic Higgs decays

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



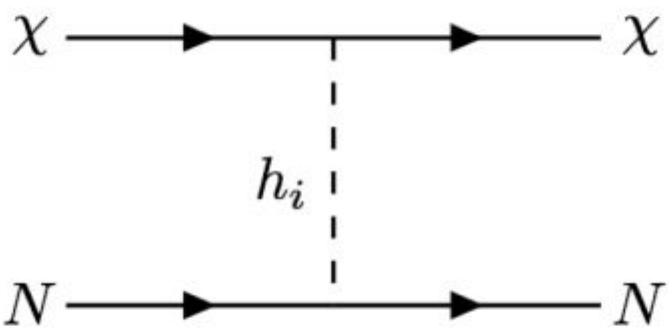
$$hZ_B^\mu Z_B^\nu : \ 2i\frac{M_{Z_B}^2}{v_B} g^{\mu\nu} \sin\theta_B ,$$

CMS and ATLAS combined analysis $\mathrm{BR}(h \rightarrow \mathrm{BSM}) \leq 0.34$

[ATLAS & CMS 1606.02266]

Direct Detection

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



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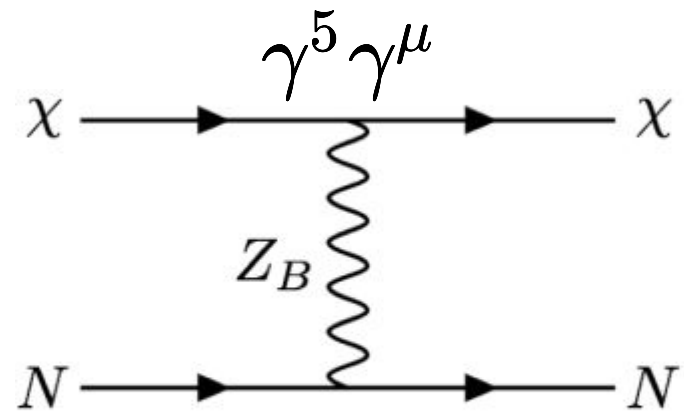

Due to axial coupling,

velocity suppressed v~10^{-3}

Direct detection constraints can be avoided