

# Low Scale Unification @ LHC

**Sebastian Ohmer**

Collaborators: Pavel Fileviez Pérez and Hiren H. Patel

P. Fileviez Pérez, SO, H. H. Patel, Phys.Lett.B735 (2014), [arXiv:1403.8029]

P. Fileviez Pérez, SO, Phys.Rev.D90 (2014), [arXiv:1405.1199]

SO, H. H. Patel, Phys.Rev.D92 (2015), [arXiv:1506.00954]

**MPIK Heidelberg**

14. April 2016

# Gauging Baryon and Lepton Number

- ▶ Promote global symmetries to local symmetries

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_{\ell}$$

P.Fileviez Pérez, M.B.Wise, Phys.Rev.D82(2010) [arXiv:1002.1754]

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- ▶ Theory with right-handed neutrinos not anomaly-free

$$\mathcal{A}_1^{SM}(SU(2)_L^2 \otimes U(1)_B) = 3/2, \quad \mathcal{A}_2^{SM}(U(1)_Y^2 \otimes U(1)_B) = -3/2$$

$$\mathcal{A}_3^{SM}(SU(2)_L^2 \otimes U(1)_\ell) = 3/2, \quad \mathcal{A}_4^{SM}(U(1)_Y^2 \otimes U(1)_\ell) = -3/2$$

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- ▶ Minimal number of new fermionic degrees of freedom: 8

# Leptobaryons $\sim (SU(2)_L, U(1)_Y, U(1)_B, U(1)_\ell)$

## Leptobaryon model VA

M. Duerr, P. Fileviez Pérez, M. B. Wise  
 Phys.Rev.Lett.110(2013)

[arXiv:1304.0576]

## Leptobaryon model A

P. Fileviez Pérez, SO, H. H. Patel  
 Phys.Lett.B735(2014)

[arXiv:1403.8029]

$$\Psi_L \sim (2, \pm 1/2, -3/2, -3/2),$$

$$\Psi_R \sim (2, \pm 1/2, 3/2, 3/2),$$

$$\eta_L \sim (1, \pm 1, 3/2, 3/2),$$

$$\eta_R \sim (1, \pm 1, -3/2, -3/2),$$

$$\chi_L \sim (1, 0, 3/2, 3/2),$$

$$\chi_R \sim (1, 0, -3/2, -3/2)$$

$$\Psi_L \sim (2, 1/2, 3/2, 3/2),$$

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$$\Sigma_L \sim (3, 0, -3/2, -3/2),$$

$$\chi_L \sim (1, 0, -3/2, -3/2)$$

# Introducing Leptobaryons

- ▶ New fermions with baryon and lepton number are introduced

 $\sim (2, 1/2, 3/2, 3/2)$  $\sim (2, 1/2, -3/2, -3/2)$  $\sim (3, 0, -3/2, -3/2)$  $\sim (1, 0, -3/2, -3/2)$

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$$\Psi_L \sim (2, 1/2, 3/2, 3/2)$$



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

$$\chi_L \sim (1, 0, -3/2, -3/2)$$

- ▶ Two new scalars needed to break  $U(1)_B \times U(1)_\ell$

$$S_B \sim (1, 0, 3, 3) \quad \text{and} \quad S_L \sim (1, 0, 0, 2)$$

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- ▶ Two new scalars needed to break  $U(1)_B \times U(1)_\ell$

$$S_B \sim (1, 0, 3, 3) \quad \text{and} \quad S_L \sim (1, 0, 0, 2)$$

- ▶ Here,  $v_L \gg v_B \Rightarrow$  neglect  $U(1)_\ell$

# Stability of the proton

Gauging baryon number  $\rightarrow$  proton stable  
 $\Rightarrow$  breaking  $U(1)_B \rightarrow$  proton unstable

**Is the proton unstable after breaking  $U(1)_B$ ?**

# Stability of the proton

Gauging baryon number  $\rightarrow$  proton stable  
 $\Rightarrow$  breaking  $U(1)_B \rightarrow$  proton unstable

- ▶ Only  $\Delta B = \pm 3$  interactions
- ▶ Possible higher order operator that is allowed mediating proton decay

$$\frac{c_B}{\Lambda^{15}} (QQQL)^3 S_B^*$$

- ▶ Breaking  $U(1)_B$  at low scales consistent with measured proton lifetime

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No desert is needed!

# Low Scale Unification

- ▶ Standard Model as low energy effective theory

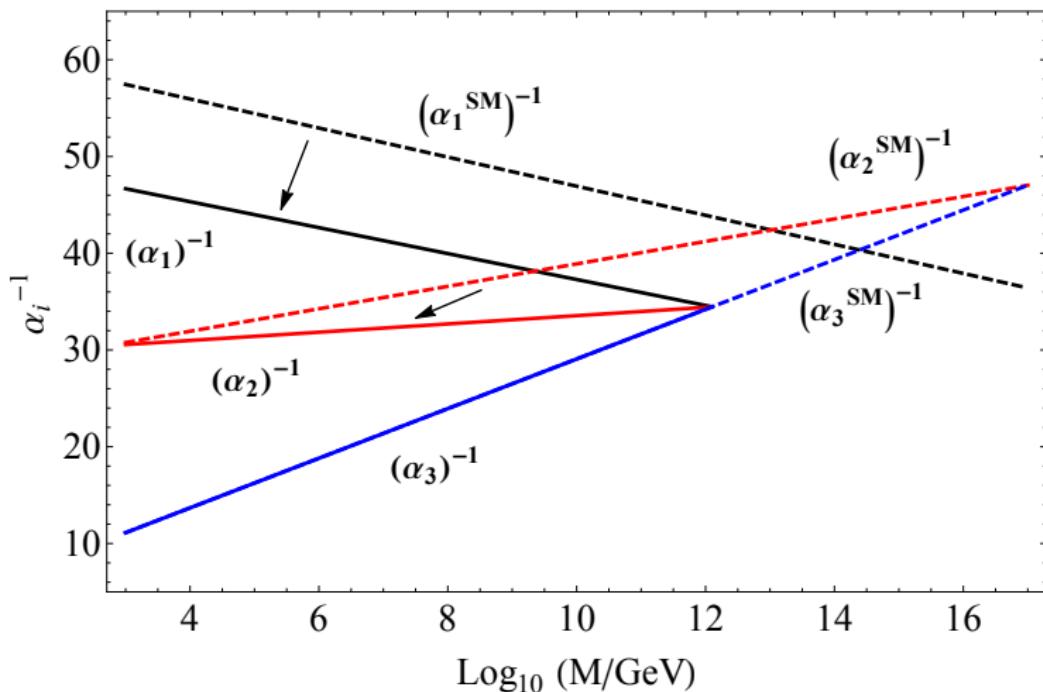
$$\begin{aligned}\mathcal{L} \supset & \frac{c_L}{\Lambda_L} \ell_L \ell_L H^2 + \frac{c_B}{\Lambda_B^2} q_L q_L q_L \ell_L \\ & + \frac{c_F}{\Lambda_F^2} (\bar{q}_L \gamma^\mu q_L) (\bar{q}_L \gamma_\mu q_L) + \dots,\end{aligned}$$

with  $\Lambda_L < 10^{14}$  GeV,  $\Lambda_B > 10^{15}$  GeV, and  $\Lambda_F > 10^4$  TeV

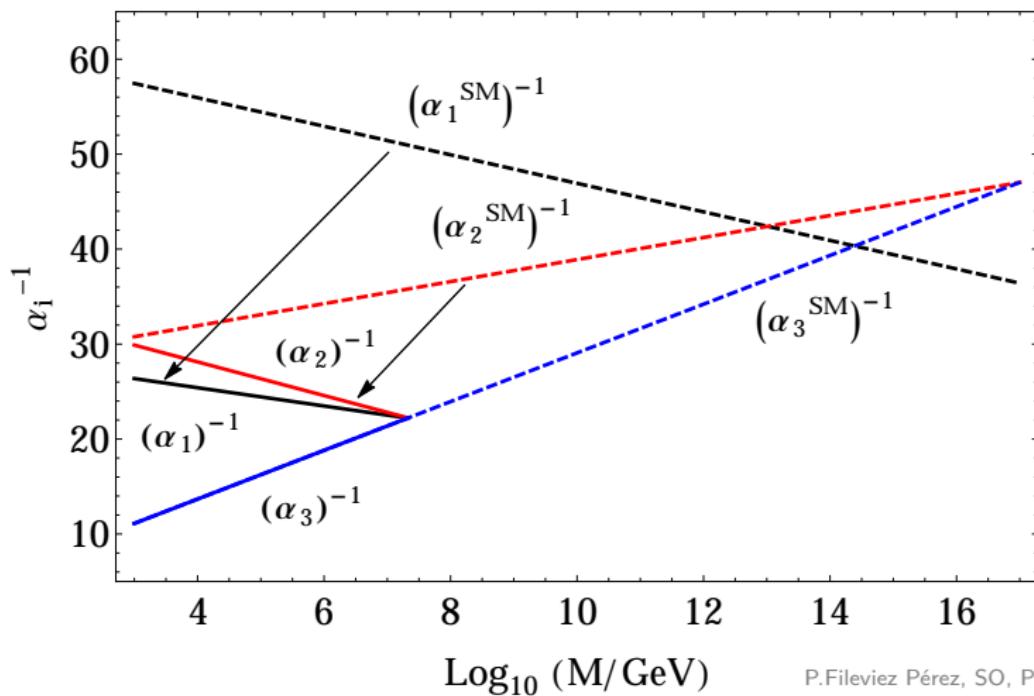
- ▶ Gauged baryon and lepton number forbid first two operators

**Is unification of the gauge couplings at  $\Lambda_{\text{GUT}} \sim 10^4$  TeV possible?**

# Evolution of Gauge Couplings with Leptobaryons



# Evolution adding four Generations of Leptobaryons



P.Fileviez Pérez, SO, Phys.Rev.D90(2014)

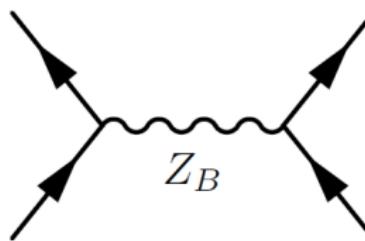
# Gauged Baryon Number @ LHC

- ▶ Leptobaryons too heavy to produce at LHC

$$m_\chi \gtrsim m_{Z_B} \simeq m_S$$

- ▶ Test baryonic symmetry breaking mechanism
- ▶ Search for  $Z_B$  via dijets resonances

$$pp \rightarrow Z_B \rightarrow jj$$



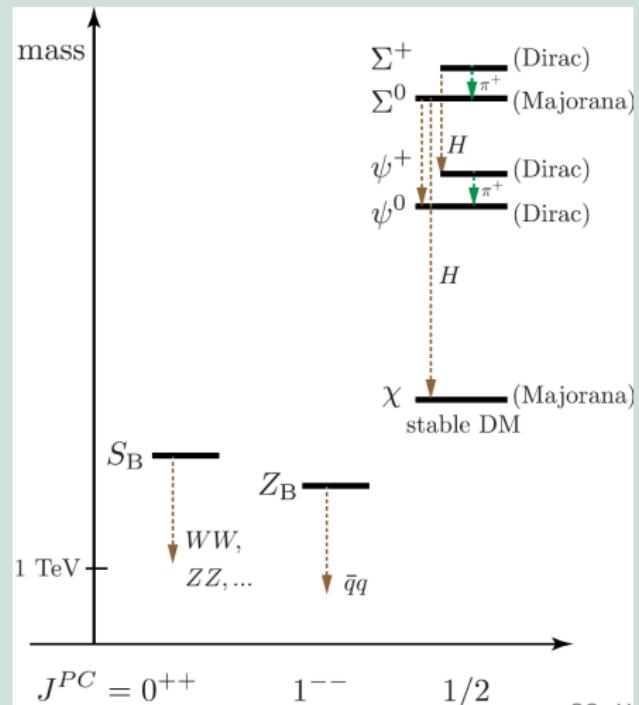
- ▶ Leptophobic  $\Rightarrow$  absence of dilepton resonances

SO, H. H. Patel, Phys.Rev. D92 (2015) 5, 055020, [arXiv:1506.00954]

# Gauged Baryon

## Leptobaryon Spectrum

- ▶ Leptobaryons
- ▶ Test baryons
- ▶ Search for



- ▶ Leptophobes

SO, H. H. Patel, Phys.Rev. D92 (2015) 5, 055020, [arXiv:1506.00954]

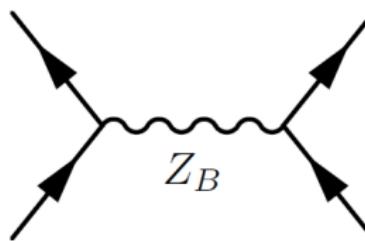
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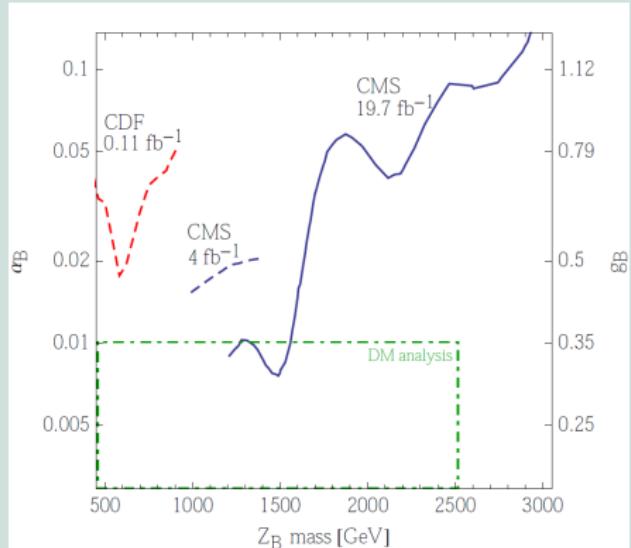
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# Gauged Baryon Number @ LHC

- ▶ Leptobaryons
- ▶ Test baryon number
- ▶ Search for new physics

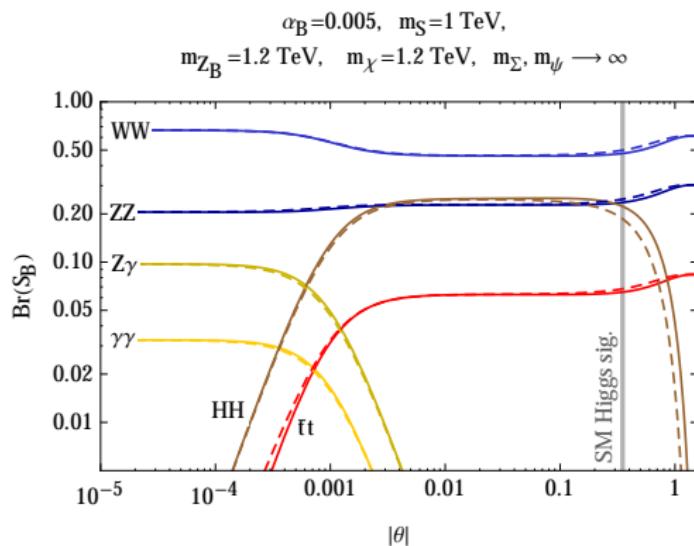
## Dijet Constraints



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SO, H. H. Patel, Phys.Rev. D92 (2015) 5, 055020, [arXiv:1506.00954]

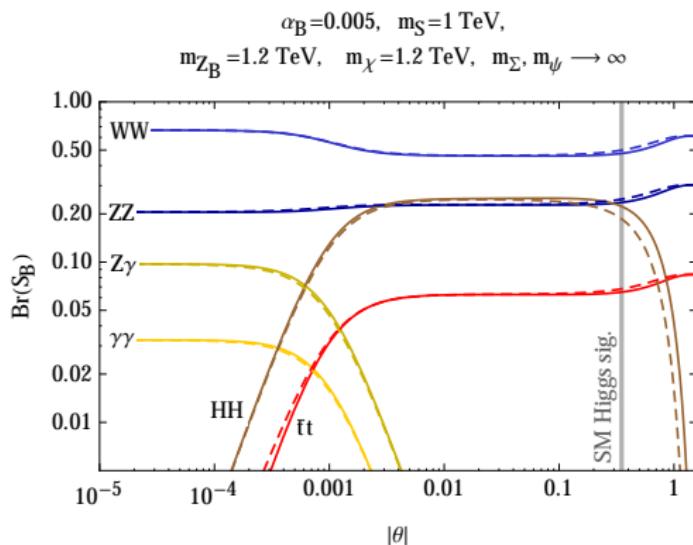
# Baryonic Higgs Decays



- ▶  $|\theta| \geq 10^{-3}$  inherits standard model Higgs decays

SO, H. H. Patel, Phys.Rev. D92 (2015) 5, 055020, [arXiv:1506.00954]

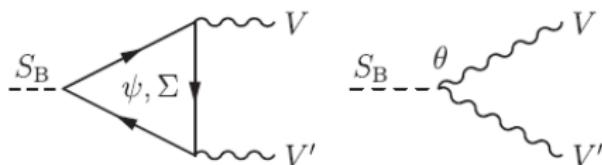
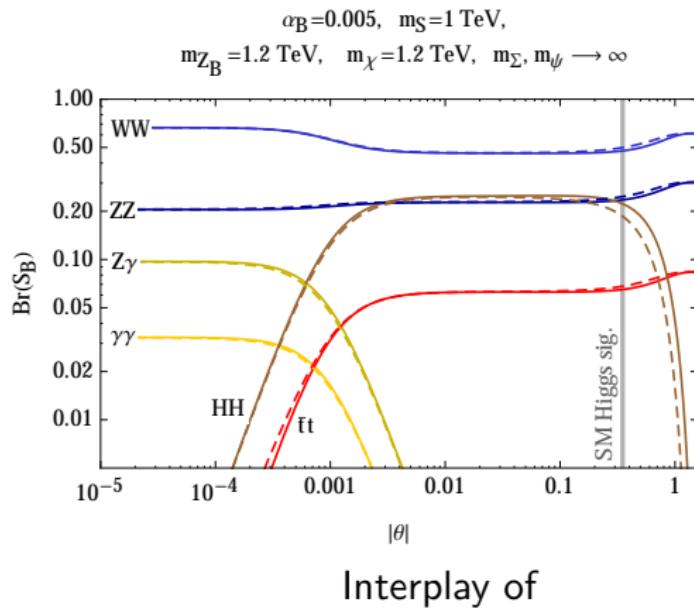
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- ▶  $|\theta| < 10^{-3}$  loop mediated decays to electroweak standard model gauge bosons

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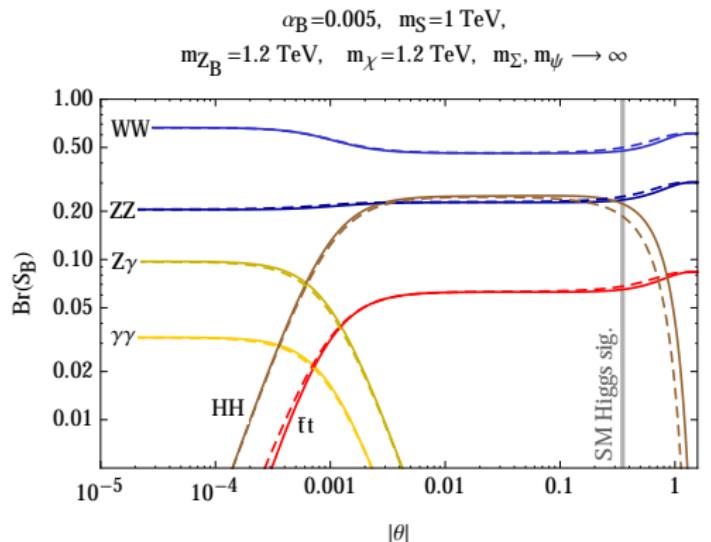
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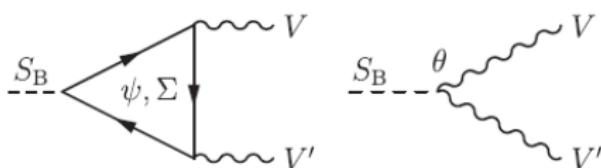
- ▶  $|\theta| \geq 10^{-3}$  inherits standard model Higgs decays
- ▶  $|\theta| < 10^{-3}$  loop mediated decays to electroweak standard model gauge bosons
- ▶ Leptobaryons leave footprint in loops

SO, H. H. Patel, Phys.Rev. D92 (2015) 5, 055020, [arXiv:1506.00954]

# Baryonic Higgs Decays



Interplay of

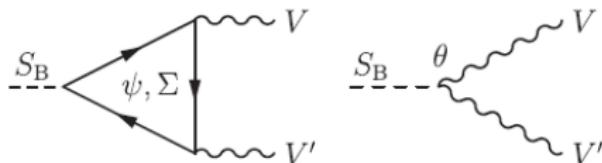
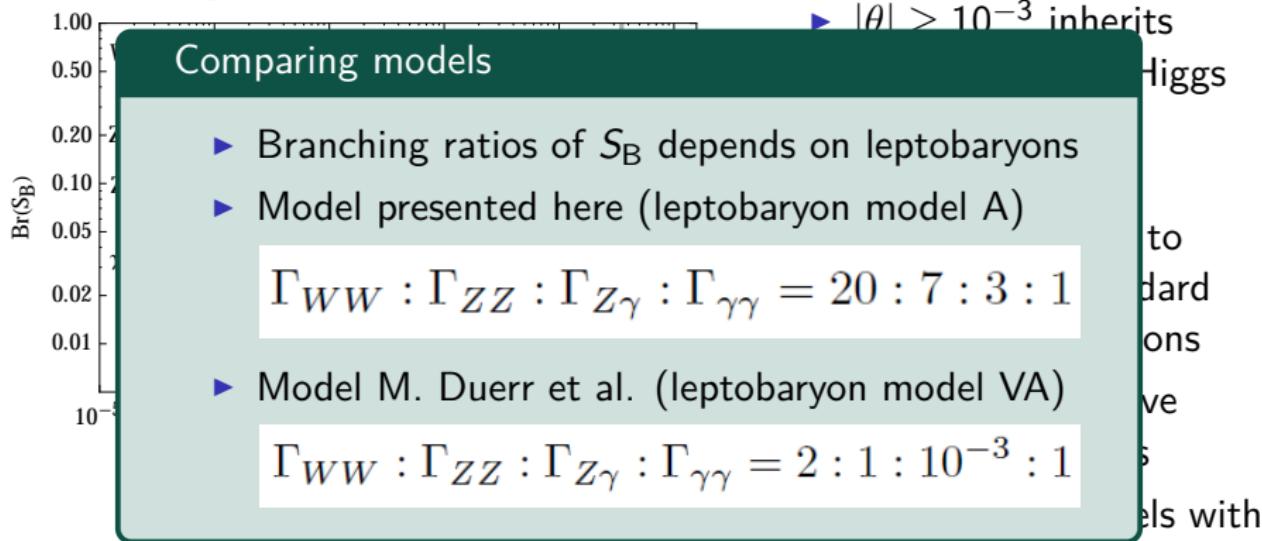


- ▶  $|\theta| \geq 10^{-3}$  inherits standard model Higgs decays
- ▶  $|\theta| < 10^{-3}$  loop mediated decays to electroweak standard model gauge bosons
- ▶ Leptobaryons leave footprint in loops
- ▶ Distinguish models with different fermionic content

SO, H. H. Patel, Phys.Rev. D92 (2015) 5, 055020, [arXiv:1506.00954]

# Baryonic Higgs Decays

$$\begin{aligned} \alpha_B &= 0.005, \quad m_S = 1 \text{ TeV}, \\ m_{Z_B} &= 1.2 \text{ TeV}, \quad m_\chi = 1.2 \text{ TeV}, \quad m_\Sigma, m_\psi \rightarrow \infty \end{aligned}$$



different fermionic content

SO, H. H. Patel, Phys.Rev. D92 (2015) 5, 055020, [arXiv:1506.00954]

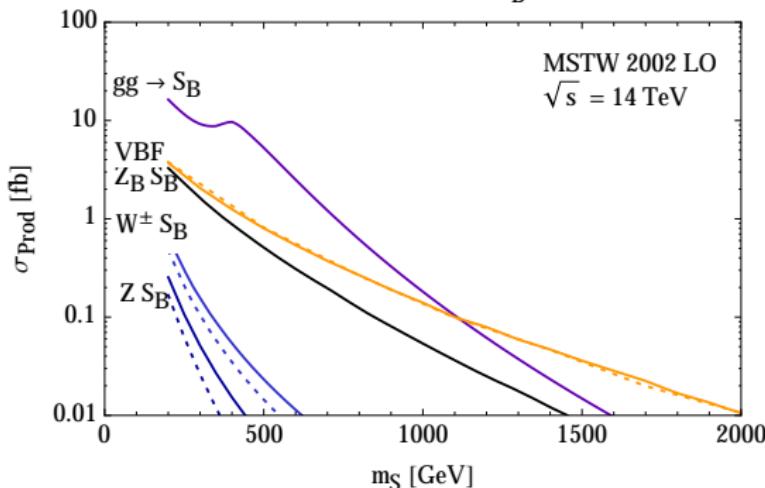
# Conclusions

- ▶ Standard Model and proton stability as motivation for gauged baryon and lepton number
- ▶ Introduce model with minimal fermionic degrees of freedom and minimal number of multiplets (leptobaryons)
- ▶ Low scale unification with stable proton
- ▶ Test symmetry breaking mechanism at LHC
- ▶ Infer leptobaryons via loop decays at LHC

Future work: embedding of gauged baryon number into unified theories, multicomponent dark matter and low scale lepton number violation

# Baryonic Higgs Production

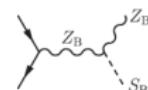
$$\alpha_B = 0.005, \quad \theta = \pm 0.05, \quad M_{Z_B} = 1.2 \text{ TeV}$$



- ▶  $S_B$  inherits standard model Higgs production channels

Associated production

$$q\bar{q} \rightarrow Z_B S_B$$

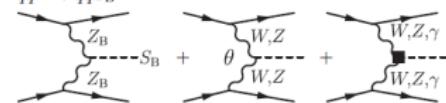


$$q\bar{q} \rightarrow W^\pm S_B, Z S_B$$



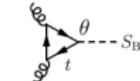
Vector boson fusion

$$q\bar{q} \rightarrow q\bar{q} S_B$$



Gluon fusion

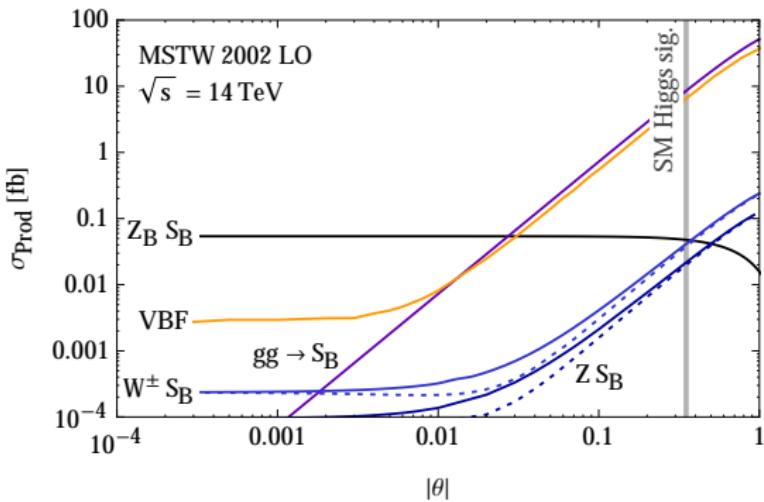
$$gg \rightarrow S_B$$



SO, H. H. Patel, Phys.Rev. D92 (2015) 5, 055020, [arXiv:1506.00954]

# Baryonic Higgs Production

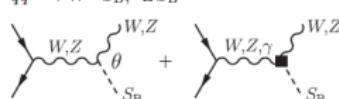
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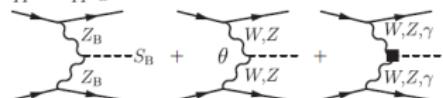
$$q\bar{q} \rightarrow Z_B S_B$$

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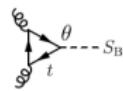
Vector boson fusion

$$\bar{q}q \rightarrow \bar{q}q S_B$$



Gluon fusion

$$gg \rightarrow S_B$$



- For small mixing angles ( $|\theta| < 0.02$ ) associated production dominates
- Loop suppressed contributions take over

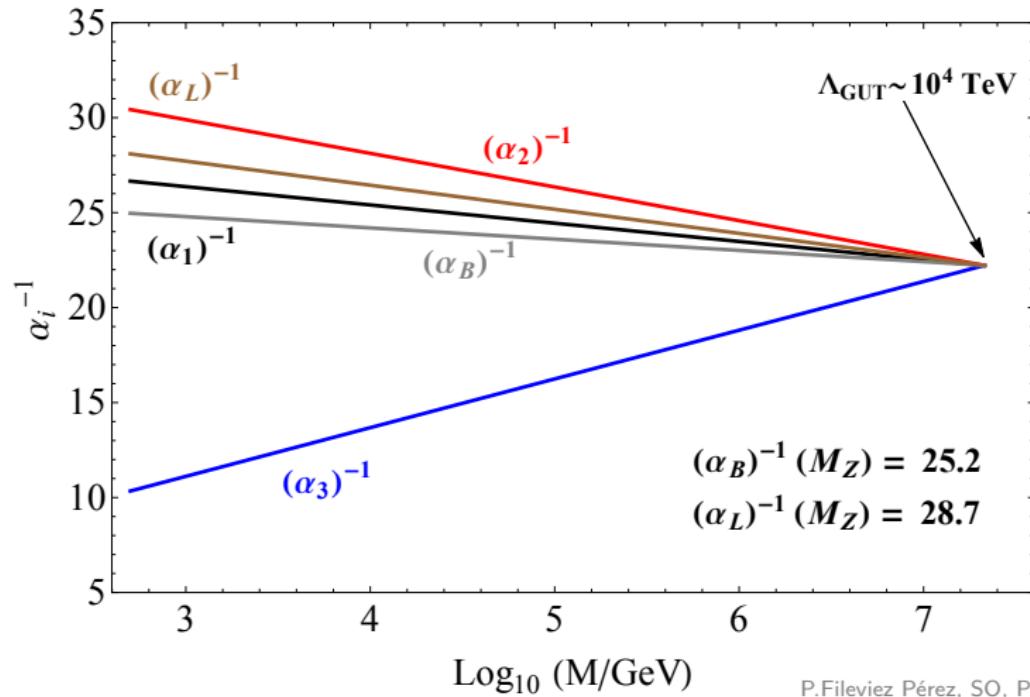
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# Unification Scales

$n_F$	$M_U$ (TeV)	$k_1$
1	$1.24 \cdot 10^9$	2.05
2	$4.96 \cdot 10^6$	2.67
4	$2.14 \cdot 10^4$	3.62
5	$4.58 \cdot 10^3$	3.99

Table: Solutions for unification scale  $M_U$  with  $M_F = 500$  GeV.

# Low Scale Unification



P.Fileviez Pérez, SO, Phys.Rev.D90(2014)

# Leptobaryons as Dark Matter

$$\mathcal{L} = -y_\Psi \bar{\Psi}_R \Psi_L S_B^* - y_\chi \chi_L \chi_L S_B - y_\Sigma \text{Tr} \Sigma_L^2 S_B$$

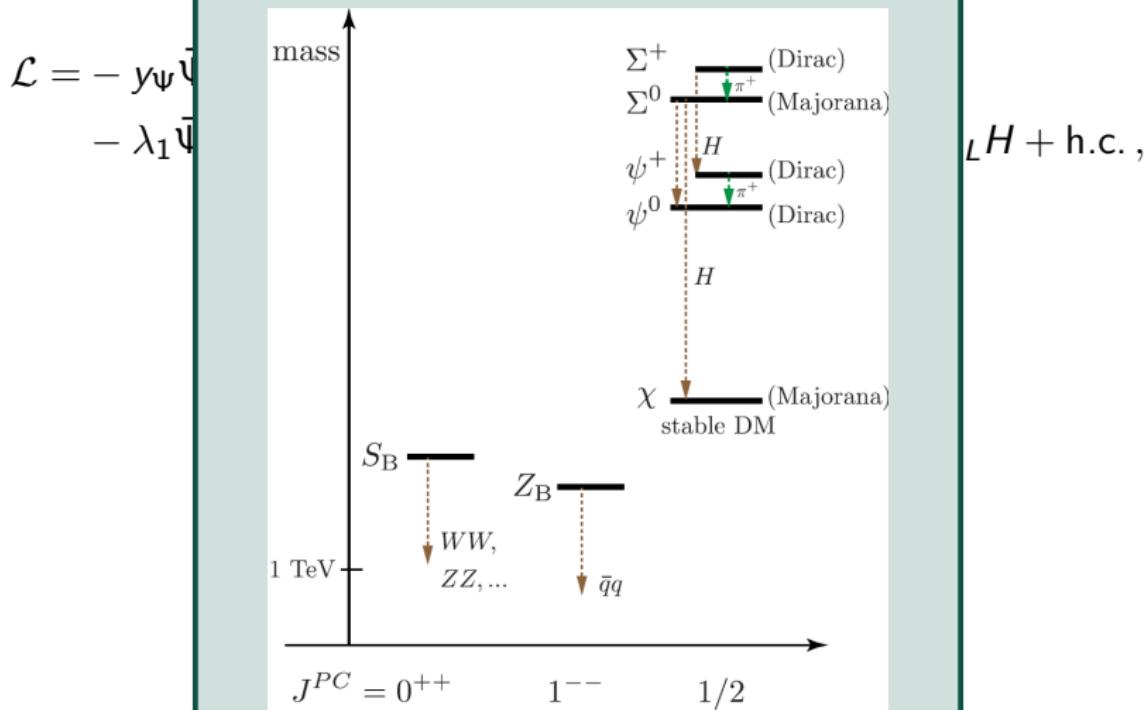
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$$-\lambda_1 \bar{\Psi}_R H \chi_L - \lambda_2 H^\dagger \Psi_L \chi_L - \lambda_3 H^\dagger \Sigma_L \Psi_L - \lambda_4 \bar{\Psi}_R \Sigma_L H + \text{h.c.},$$

# Leptobaryon

## Leptobaryon Spectrum



# Leptobaryons as Dark Matter

$$\begin{aligned}\mathcal{L} = & -y_\Psi \bar{\Psi}_R \Psi_L S_B^* - y_\chi \chi_L \chi_L S_B - y_\Sigma \text{Tr} \Sigma_L^2 S_B \\ & - \lambda_1 \bar{\Psi}_R H \chi_L - \lambda_2 H^\dagger \Psi_L \chi_L - \lambda_3 H^\dagger \Sigma_L \Psi_L - \lambda_4 \bar{\Psi}_R \Sigma_L H + \text{h.c.},\end{aligned}$$

- ▶ Breaking  $U(1)_B$  induces  $Z_2$  symmetry

$$\Psi_L \rightarrow -\Psi_L,$$

$$\bar{\Psi}_R \rightarrow -\bar{\Psi}_R,$$

$$\Sigma_L \rightarrow -\Sigma_L,$$

$$\chi_L \rightarrow -\chi_L$$

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$$\begin{aligned}\mathcal{L} = & -y_\Psi \bar{\Psi}_R \Psi_L S_B^* - y_\chi \chi_L \chi_L S_B - y_\Sigma \text{Tr} \Sigma_L^2 S_B \\ & - \lambda_1 \bar{\Psi}_R H \chi_L - \lambda_2 H^\dagger \Psi_L \chi_L - \lambda_3 H^\dagger \Sigma_L \Psi_L - \lambda_4 \bar{\Psi}_R \Sigma_L H + \text{h.c.},\end{aligned}$$

- ▶ Breaking  $U(1)_B$  induces  $Z_2$  symmetry

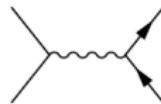
$$\begin{aligned}\Psi_L &\rightarrow -\Psi_L, \\ \bar{\Psi}_R &\rightarrow -\bar{\Psi}_R, \\ \Sigma_L &\rightarrow -\Sigma_L, \\ \chi_L &\rightarrow -\chi_L\end{aligned}$$

- ▶ Lightest leptobaryon **automatically** stable

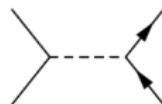
# Dark Matter Annihilation

## Resonant annihilation channels

$$\chi\chi \rightarrow \bar{q}q$$



**velocity suppressed**



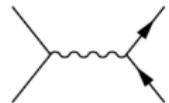
**velocity + mixing suppressed**

- ▶ Both velocity suppressed due to Majorana nature of  $\chi$

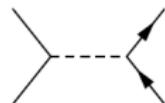
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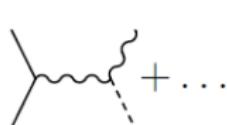
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## Non-resonant annihilation channels

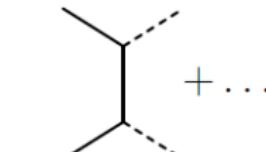
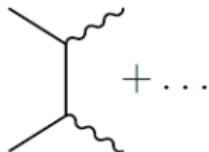
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$$\chi\chi \rightarrow S_B S_B$$

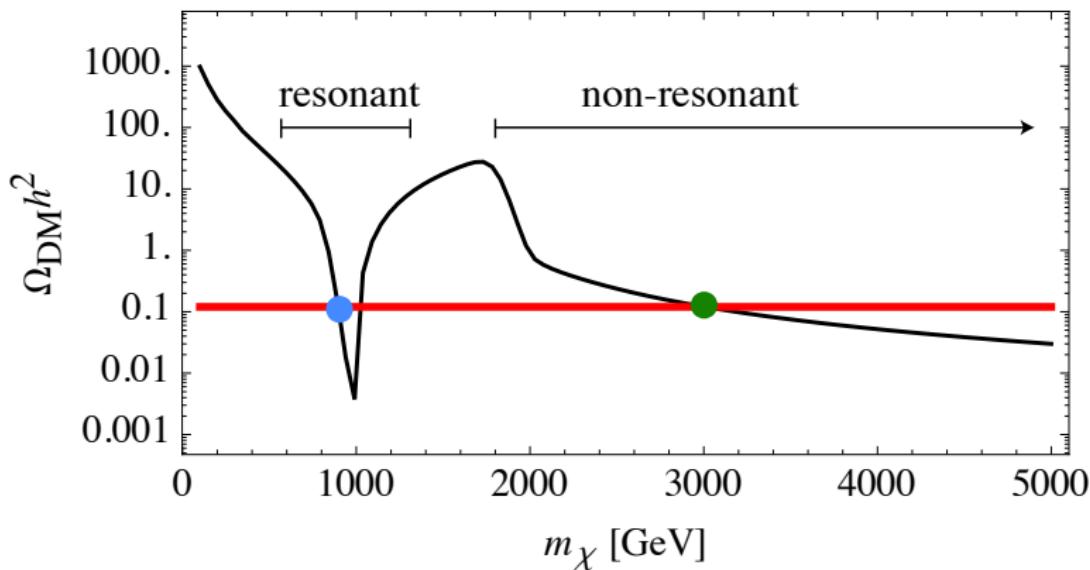


**velocity unsuppressed**



**velocity suppressed**

# Dark Matter Thermal Abundance



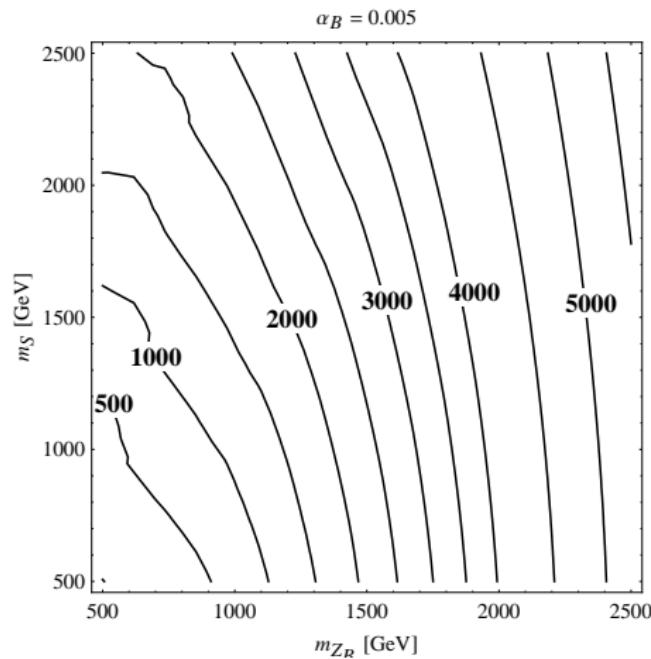
- Resonant annihilation  $\rightarrow$  light dark matter

- Non-resonant annihilation  $\rightarrow$  heavy dark matter

SO, H. H. Patel, Phys.Rev. D92 (2015) 5, 055020, [arXiv:1506.00954]

# Non-Resonant Dark Matter

- ▶ Five free parameters:  $m_\chi$ ,  $m_{Z_B}$ ,  $\alpha_B$ ,  $m_S$ ,  $\theta$
- ▶ Calculate dark matter abundance in limit  $\theta \rightarrow 0$

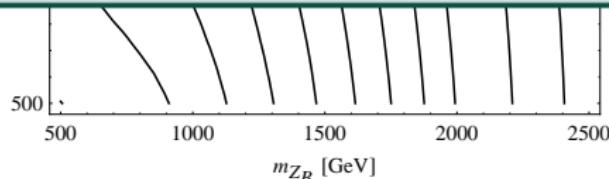


# Non-Resonant Dark Matter

- ▶ Five Vacuum Metastability
- ▶ Can

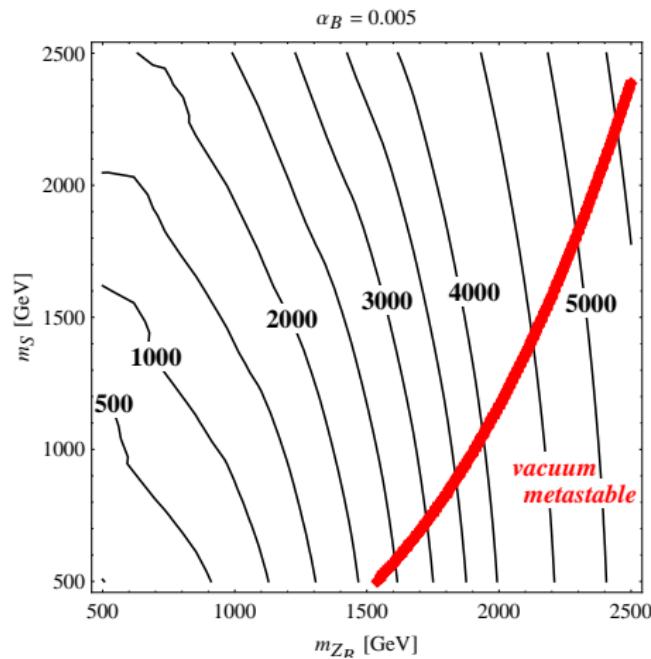
- ▶ Leptobaryons destabilize vacuum in  $S_B$  direction
- ▶ Solve one-loop  $\overline{\text{MS}}$  renormalization group equation for the baryonic Higgs quartic self-coupling
- ▶ Demand self-consistency

$$m_{\psi, \Sigma, \chi} \lesssim 0.86 \left( \frac{m_{Z_B} m_S}{g_B} \right)^{1/2}$$



# Non-Resonant Dark Matter

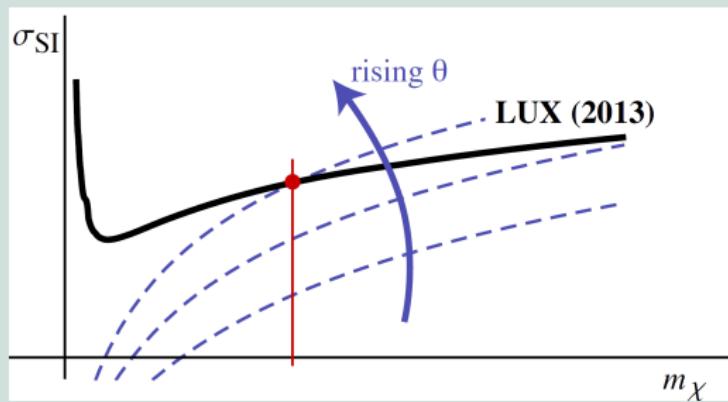
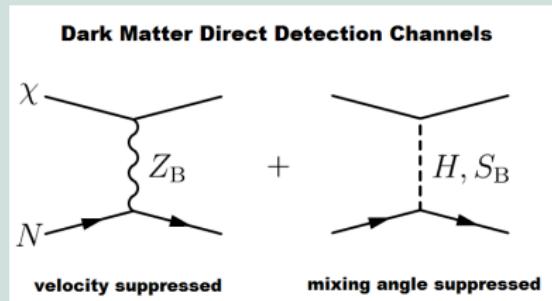
- ▶ Five free parameters:  $m_\chi$ ,  $m_{Z_B}$ ,  $\alpha_B$ ,  $m_S$ ,  $\theta$
- ▶ Calculate dark matter abundance in limit  $\theta \rightarrow 0$



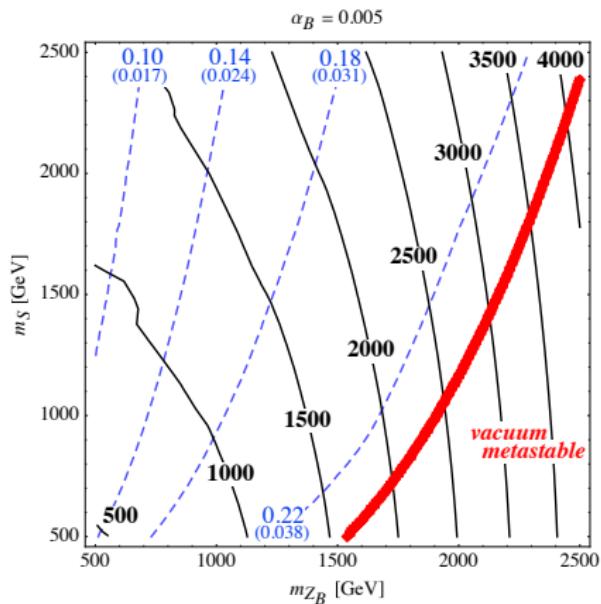
## Non-R

Direct Detection Bounds on  $\theta$ 

- ▶ Five
- ▶ Ca



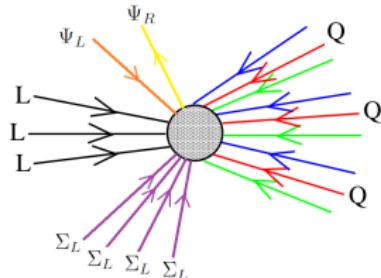
# Non-Resonant Dark Matter



- ▶ Constrain mixing angle by direct detection experiments
- ▶ Find bound  $\theta \lesssim 0.09$
- ▶ LHC Higgs signal strength measurements  $\theta \lesssim 0.35$

# Baryon Asymmetry with Leptobaryons

- ▶ Baryon asymmetry in the Universe → Leptogenesis
- ▶ Leptobaryons carry  $SU(2)_L$  charge and modify sphalerons



- ▶ Final baryon asymmetry as function of initial  $B - L$  asymmetry

$$B_f = \frac{32}{99} \Delta(B - L)_{\text{SM}} \approx 0.32 \Delta(B - L)_{\text{SM}}$$

P.Fileviez Pérez, SO, H.H.Patel,  
Phys.Lett.B735(2014)

$$B_f^{\text{SM}} = \frac{28}{79} \Delta(B - L)_{\text{SM}} \approx 0.35 \Delta(B - L)_{\text{SM}}$$

J.A.Harvey, M.S.Turner,  
Phys.Rev.D42(1990)