

The Standard Model (SM)

Problems of the Standard Mode

Supersymmet Standard Mod

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

Model Building Parameter Space

Donalis

 $\tilde{\chi}_1^0$ DM scenario Heavy Z boson $\tilde{\nu}_1$ DM scenario Muon Anomalous Magnetic Moment

Conclusion and Future Studies
New results

Exploring the supersymmetric $U(1)_{B-L} \times U(1)_R$ model with dark matter, muon g-2 and Z' mass limits

based on Phys. Rev. D 97, 015012

Özer Özdal¹ Mariana Frank¹

CONCORDIA UNIVERSITY¹

Winter Nuclear & Particle Physics Conference Mont Tremblant, Québec February 17, 2018





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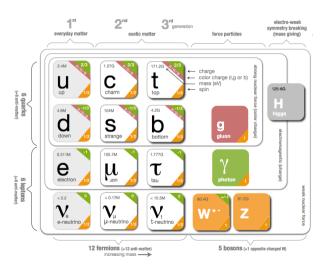
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$$G_{321} = SU(3)_C \otimes \underbrace{SU(2)_L \otimes U(1)_Y}_{I}$$



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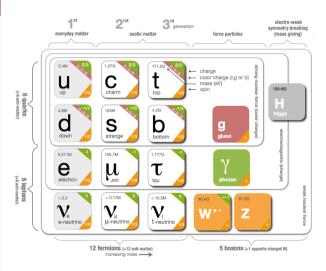
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$$G_{321} = SU(3)_C \otimes \underbrace{SU(2)_L \otimes U(1)_Y}_{\downarrow}$$
 $SU(3)_C \otimes U(1)_{EM}$



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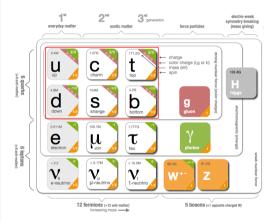
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$$G_{321} = SU(3)_C \otimes \underbrace{SU(2)_L \otimes U(1)_Y}_{\downarrow}$$

 $SU(3)_C \otimes U(1)_{EM}$

| | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | <i>I</i> ₃ | Q_{EM} |
|--|--|-----------------------|--------------------|
| $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ | $(3, 2, \frac{1}{3})$ | $\frac{1/2}{-1/2}$ | $\frac{2/3}{-1/3}$ |
| u _R | $(\overline{3}, 1, \frac{4}{3})$ | 0 | 2/3 |
| d _R | $(\overline{3}, 1, -\frac{2}{3})$ | 0 | -1/3 |



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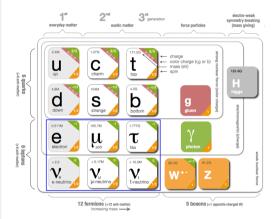
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$$SU(3)_C \otimes U(1)_{EM}$$

| | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | l ₃ | Q_{EM} |
|--|--|----------------|-------------------|
| $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ | $(3, 2, \frac{1}{3})$ | $1/2 \\ -1/2$ | 2/3 - 1/3 |
| u_R | $(\bar{\bf 3},{\bf 1},\frac{4}{3})$ | 0 | 2/3 |
| d_R | $(\bar{\bf 3},{\bf 1},-\frac{2}{3})$ | 0 | -1/3 |
| $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | (1, 2, -1) | $1/2 \\ -1/2$ | 0 -1 |
| e _R | $(\overline{1},1,-2)$ | o o | -1 |



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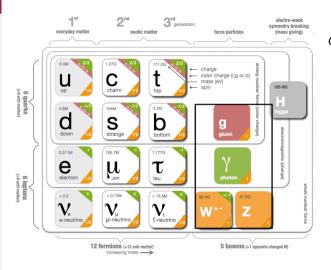
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The Standard Model of Particle Physics



$$G_{321} = SU(3)_C \otimes \underbrace{SU(2)_L \otimes U(1)_Y}_{SU(3)_C \otimes U(1)_{EM}}$$

$$SU(3)_C o G_\mu^a \qquad a=1,..,8$$
 $SU(2)_L o W_\mu^i \qquad i=1,2,3$

 $U(1)_{Y} \rightarrow B_{u}$



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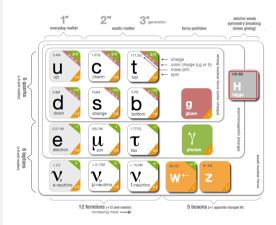
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The Standard Model of Particle Physics



$$G_{321} = SU(3)_C \otimes \underbrace{SU(2)_L \otimes U(1)_Y}_{\downarrow}$$

 $SU(3)_C \otimes U(1)_{EM}$

| | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | l ₃ | Q_{EM} |
|---|--|----------------|-------------------|
| $Q = \begin{pmatrix} u_L \\ d_I \end{pmatrix}$ | $(3, 2, \frac{1}{3})$ | $1/2 \\ -1/2$ | 2/3 - 1/3 |
| u_R | $(\overline{3}, 1, \frac{4}{3})$ | 0 | 2/3 |
| d_R | $(\bar{\bf 3},{\bf 1},-\frac{2}{3})$ | 0 | -1/3 |
| $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | (1, 2, -1) | $1/2 \\ -1/2$ | $0 \\ -1$ |
| e_R | $(\overline{1},1,-2)$ | 0 | -1 |
| $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ | (1, 2, 1) | $1/2 \\ -1/2$ | 1 0 |



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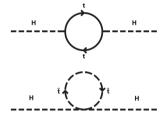
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The Standard Model cannot be a complete theory!

Gauge Hierarchy Problem!





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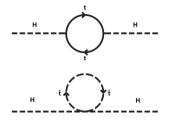
 $\tilde{\chi}_1^0$ DM scenario Heavy Z boson $\tilde{\nu}_1$ DM scenario Muon Anomalous Magnetic Moment

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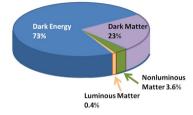
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Dark Matter?





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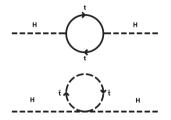
 $\widetilde{\chi}_1^0$ DM scenario Heavy Z boson $\widetilde{\nu}_1$ DM scenario Muon Anomalous Magnetic Moment

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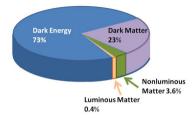
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Dark Matter?



Neutrino Masses & Oscillations!





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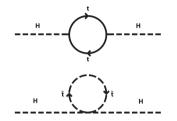
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 $\tilde{\chi}_1^0$ DM scenario Heavy Z boson $\tilde{\nu}_1$ DM scenario Muon Anomalous

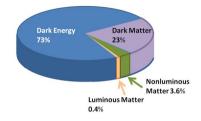
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The Standard Model cannot be a complete theory!

Gauge Hierarchy Problem!



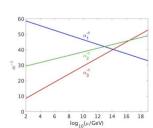
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Neutrino Masses & Oscillations!



Why $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$?





Minimal Supersymmetric Standard Model (MSSM)

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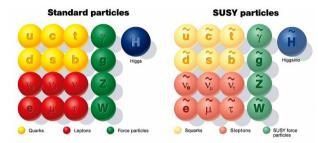
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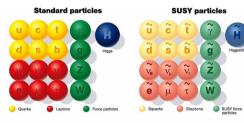
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Minimal Supersymmetric Standard Model (MSSM)

| | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | <i>I</i> ₃ | $Q_{ m EM}$ |
|--|--|-----------------------|---------------|
| $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ | $(3, 2, \frac{1}{3})$ | $1/2 \\ -1/2$ | $2/3 \\ -1/3$ |
| u_R | $(\overline{\bf 3},{\bf 1},{4\over 3}) \ (\overline{\bf 3},{\bf 1},-{2\over 2})$ | 0 | 2/3 -1/3 |
| $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | $(3, 1, -\frac{3}{3})$ (1, 2, -1) | $\frac{1/2}{-1/2}$ | 0 -1 |
| e_R | $(\overline{1},1,-2)$ | 0 | -1 |
| $H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$ | (1, 2, 1) | $1/2 \\ -1/2$ | 1 0 |
| $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$ | (1, 2, 1) | $1/2 \\ -1/2$ | 1 0 |





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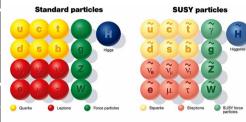
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| | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | I ₃ | $Q_{ m EM}$ |
|--|--|----------------|---------------|
| $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ | $(3, 2, \frac{1}{3})$ | $1/2 \\ -1/2$ | $2/3 \\ -1/3$ |
| u_R d_R | $(\overline{\bf 3},{\bf 1},{4\over 3}) \ (\overline{\bf 3},{\bf 1},-{2\over 3})$ | 0 | 2/3 -1/3 |
| $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | (1, 2, -1) | $1/2 \\ -1/2$ | 0 -1 |
| e_R | $(\overline{1},1,-2)$ | 0 | -1 |
| $H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$ | (1, 2, 1) | $1/2 \\ -1/2$ | 1 0 |
| $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$ | (1, 2, 1) | $1/2 \\ -1/2$ | 1 0 |



$$W = \mu H_u H_d + Y_u^{ij} Q_i H_u u_j^c - Y_d^{ij} Q_i H_d d_j^c - Y_e^{ij} L_i H_d e_j^c$$



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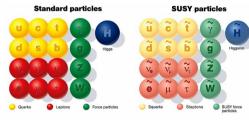
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| | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | <i>I</i> ₃ | Q_{EM} |
|---|--|-----------------------|-------------------|
| $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ | $(3, 2, \frac{1}{3})$ | $1/2 \\ -1/2$ | 2/3 - 1/3 |
| u_R | $(\overline{\bf 3},{\bf 1},{4\over 3}) \ (\overline{\bf 3},{\bf 1},-{2\over 3})$ | 0 | 2/3 |
| $\frac{d_R}{1 - \left(\nu_L\right)}$ | J | 1/2 | -1/3 |
| $L = \begin{pmatrix} u_L \\ e_L \end{pmatrix}$ e_R | (1, 2, -1) $(\overline{1}, 1, -2)$ | $-1/2 \\ 0$ | $-1 \\ -1$ |
| $H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$ | (1, 2, 1) | 1/2 -1/2 | 1 0 |
| $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$ | (1, 2, 1) | 1/2 -1/2 | 1 0 |



$$W = \mu H_u H_d + Y_u^{ij} Q_i H_u u_i^c - Y_d^{ij} Q_i H_d d_i^c - Y_e^{ij} L_i H_d e_i^c$$

Solutions to the SM problems:

- No Gauge Hierarchy Problem!
- Dark Matter Candidate
- Gauge Coupling Unification



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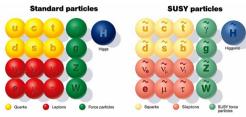
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| $Q = \begin{pmatrix} u_L \\ d_I \end{pmatrix}$ | $(3, 2, \frac{1}{3})$ | $1/2 \\ -1/2$ | 2/3 - 1/3 |
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| e _R | $(\overline{1},1,-2)$ | 0 | -1 |
| $H_u = \begin{pmatrix} H_u^+ \\ H_0^+ \end{pmatrix}$ | (1, 2, 1) | 1/2 | 1 |
| $H_u^0 - H_u^0$ | (1, 2, 1) | -1/2 | 0 |
| $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$ | $(1, \overline{2}, 1)$ | 1/2 | 1 |
| H_d^- | (1, 2, 1) | -1/2 | 0 |



 $W = \mu H_u H_d + Y_u^{ij} Q_i H_u u_i^c - Y_d^{ij} Q_i H_d d_i^c - Y_e^{ij} L_i H_d e_i^c$

Solutions to the SM problems:

- No Gauge Hierarchy Problem!
- Dark Matter Candidate
- Gauge Coupling Unification

But still..

- Neutrino mass ?
 - μ Problem
- MSSM requires substantial fine-tuning



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$U(1)_{B-L} \times U(1)_R$ Extended MSSM

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Supersymmetric $U(1)_{B-L} \times U(1)_R$ Model (BLRinvSeesaw)

GUT-inspired U(1)_{B-L}× U(1)_R extended MSSM symmetry breaking scheme

$$SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

 $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
 $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$



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 $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
 $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$

$$W = W_{MSSM} + Y_{\nu}^{ij} L_i H_u N_i^c + Y_s^{ij} N_i^c \mathcal{X}_R S - \mu_R \overline{\mathcal{X}}_R \mathcal{X}_R + \mu_S SS$$

| Superfield | $SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$ | Generation |
|-------------------------|---|------------|
| ĝ | $(3, 2, 0, +\frac{1}{6})$ | 3 |
| $\hat{	ilde{d}}^c$ | $(\bar{3}, 1, +\frac{1}{2}, -\frac{1}{6})$ | 3 |
| \hat{u}^c | $(\bar{\bf 3},{\bf 1},-\frac{\bar{\bf 1}}{2},-\frac{\bar{\bf 1}}{6})$ | 3 |
| Ĺ | $(1, 2, 0, -\frac{1}{2})$ | 3 |
| \hat{e}^c | $(1, 1, +\frac{1}{2}, +\frac{1}{2})$ | 3 |
| $\hat{oldsymbol{ u}}^c$ | $(1, 1, -\frac{7}{2}, +\frac{7}{2})$ | 3 |
| Ŝ | $(1, 1, \tilde{0}, 0)^{T}$ | 3 |
| \hat{H}_u | $(1, 2, +\frac{1}{2}, 0)$ | 1 |
| \hat{H}_d | $(1, 2, -\frac{1}{2}, 0)$ | 1 |
| $\hat{\chi}_R$ | $(1, 1, +\frac{1}{2}, -\frac{1}{2})$ | 1 |
| $\hat{\bar{\chi}}_R$ | $(1, 1, -\frac{1}{2}, +\frac{1}{2})$ | 1 |



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Supersymmetric $U(1)_{B-L} \times U(1)_R$ Model (BLRinvSeesaw)

GUT-inspired $U(1)_{B-I} \times U(1)_{R}$ extended MSSM symmetry breaking scheme

$$SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

 $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
 $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$

$$W = W_{MSSM} + Y_{\nu}^{ij} L_i H_u N_i^c + Y_s^{ij} N_i^c \mathcal{X}_R S - \mu_R \overline{\mathcal{X}}_R \mathcal{X}_R + \mu_S SS$$

| Superfield | $SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$ | Generations |
|--|--|-------------|
| <u> </u> | $(3, 2, 0, +\frac{1}{6})$ | 3 |
| $egin{array}{l} \hat{Q} \ \hat{d}^c \ \hat{u}^c \ \hat{L} \end{array}$ | $(\bar{\bf 3},{\bf 1},+\frac{1}{2},-\frac{1}{6})$ | 3 |
| \hat{u}^c | $(\bar{\bf 3},{\bf 1},-\frac{1}{2},-\frac{1}{6})$ | 3 |
| Ĺ | $(1, 2, 0, -\frac{1}{2})$ | 3 |
| \hat{e}^c | $(1, 1, +\frac{1}{2}, +\frac{1}{2})$ | 3 |
| $\hat{oldsymbol{ u}}^c$ $\hat{oldsymbol{S}}$ | $(1, 1, -\frac{1}{2}, +\frac{1}{2})$ | 3 |
| Ŝ | $(1, 1, \tilde{0}, 0)$ | 3 |
| \hat{H}_u | $(1, 2, +\frac{1}{2}, 0)$ | 1 |
| \hat{H}_d | $(1, 2, -\frac{1}{2}, 0)$ | 1 |
| $\hat{\chi}_R$ | $(1, 1, +\frac{1}{2}, -\frac{1}{2})$ | 1 |
| $\frac{\hat{X}_R}{\hat{X}_R}$ | $(1, 1, -\frac{1}{2}, +\frac{1}{2})$ | 1 |

Motivation

- Neutrino mass problem → Solved!
 - Extra DM candidate
 - Better resolution to muon g-2
- Relatively light Higgs boson masses



Parameter Space of BLRinvSeesaw

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Parameter Space of BLRinvSeesaw

Universal Boundary Conditions

| Parameter | Scanned range | Parameter | Scanned range |
|--------------|---------------|------------------------------|----------------------|
| m_0 | [0., 3.] TeV | v_R | [6.5, 20.] TeV |
| $M_{1/2}$ | [0., 3.] TeV | $\mathit{diag}(Y^{ij}_{ u})$ | [0.001, 0.99] |
| A_0/m_0 | [-3., 3.] | $diag(Y_s^{ij})$ | [0.001, 0.99] |
| $\tan\beta$ | [0., 60.] | sign of μ | positive |
| $	aneta_{R}$ | [1., 1.2] | sign of μ_R | positive or negative |

Scanned parameter space



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Experimental Constraints

| Observable | Constraints | Observable | Constraints | |
|---|----------------|-----------------------------------|-------------------------------|--|
| m_{h_1} | [122, 128] GeV | $m_{\widetilde{t}_1}$ | ≥ 730 GeV | |
| $m_{\widetilde{g}}$ | > 1.75 TeV | $m_{\chi_1^\pm}$ | ≥ 103.5 GeV | |
| $m_{\widetilde{	au}_1}$ | ≥ 105 GeV | $m_{\widetilde{b}_1}$ | ≥ 222 GeV | |
| $m_{\widetilde{q}}$ | ≥ 1400 GeV | $m_{\widetilde{	au}_1}$ | > 81 GeV | |
| $m_{\widetilde{e}_1}$ | $> 107 \; GeV$ | $m_{\widetilde{\mu}_1}$ | > 94 GeV | |
| $\chi^2(\hat{\mu})$ | ≤ 2.3 | $BR(\mathcal{B}^0_s	o\mu^+\mu^-)$ | $[1.1, 6.4] 	imes 10^{-9}$ | |
| $rac{{ m BR}({m B} 	o 	au u_	au)}{{ m BR}_{{m SM}}({m B} 	o 	au u_	au)}$ | [0.15, 2.41] | $BR(B^0	o X_s\gamma)$ | $[2.99, 3.87] \times 10^{-4}$ | |
| $m_{Z'}$ | > 3.5 TeV | $\Omega_{DM}h^2$ | [0.09-0.14] | |



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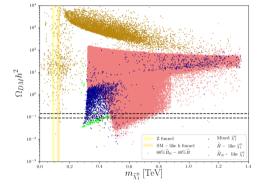
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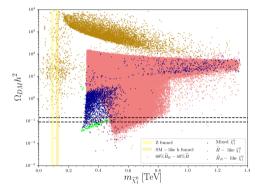
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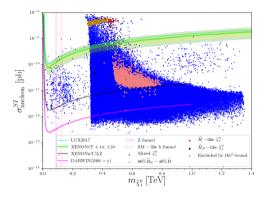
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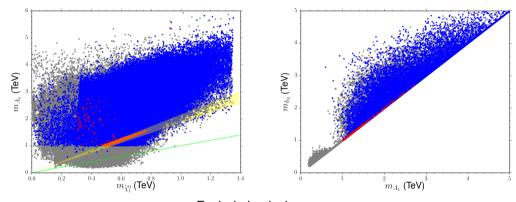
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Case I: Neutralino $\tilde{\chi}_1^0$ Dark Matter Scenario

Funnel Channels $\rightarrow m_{A_1}, m_{h_3}$



- Excluded solutions
- •Solutions consistent with all constraints except for the relic density bound
- •Solutions consistent with all constraints including the relic density bound



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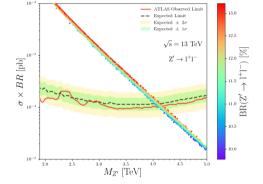
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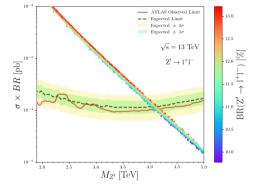
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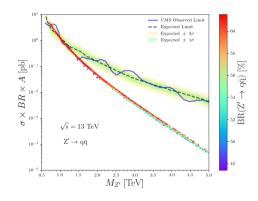
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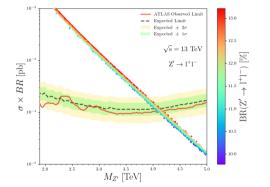
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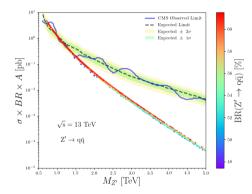
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Z' mass limit





 $M_{Z'}>3.5 \text{ TeV}$



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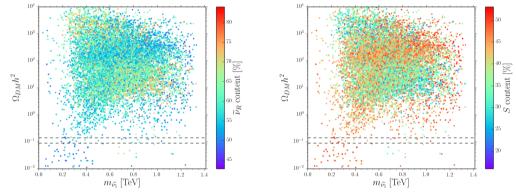
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Case II: Sneutrino $\tilde{\nu}_1$ Dark Matter Scenario



Only 16 solutions out of 100,000 total solutions are consistent with the relic density bound.



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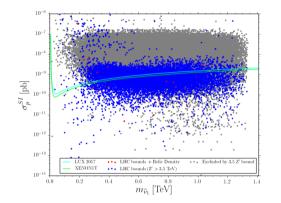
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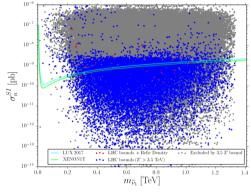
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The Effect of Z' mass in $\widetilde{\nu}_1$ DM Scenario







The Effect of Z' mass in $\widetilde{\nu}_1$ DM Scenario

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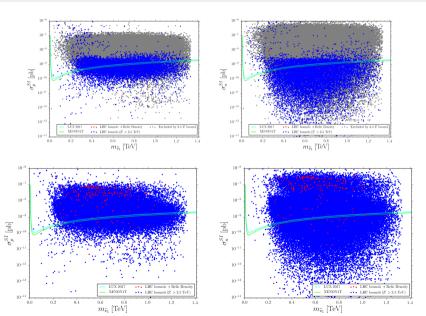
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$$\Delta a_{\mu} = a_{\mu}^{\mathrm{exp}} - a_{\mu}^{\mathrm{SM}}$$

$$= 28.7 \times 10^{-10}$$



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$$\Delta a_{\mu} = a_{\mu}^{\mathrm{exp}} - a_{\mu}^{\mathrm{SM}}$$

$$= 28.7 \times 10^{-10}$$





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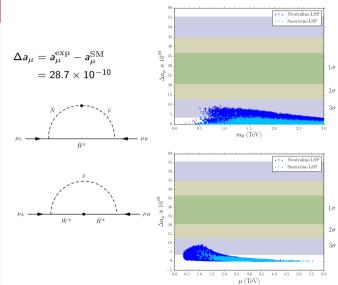
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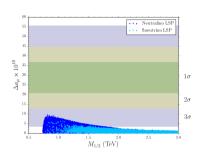
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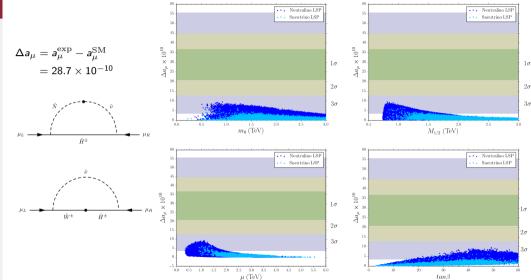
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New results based on the non-universality in \mathcal{X}_R masses

Tadpole equations are solved in $(\mu, B_\mu, m_{\overline{\mathcal{X}}_R}^2, m_{\mathcal{X}_R}^2)$ basis $m_{\overline{\mathcal{X}}_R}^2 \neq m_{\mathcal{X}_R}^2 \neq m_0^2$ at M_{GUT}



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New results based on the non-universality in \mathcal{X}_R masses

Tadpole equations are solved in
$$(\mu, B_\mu, m_{\overline{\mathcal{X}}_R}^2, m_{\mathcal{X}_R}^2)$$
 basis $m_{\overline{\mathcal{X}}_R}^2 \neq m_{\mathcal{X}_R}^2 \neq m_0^2$ at M_{GUT}

| Parameter | Scanned range | Parameter | Scanned range |
|------------|---------------|------------------------------|----------------|
| m_0 | [0., 3.] TeV | v _R | [6.5, 20.] TeV |
| $M_{1/2}$ | [0., 3.] TeV | $	extit{diag}(Y_ u^{ij})$ | [0.001, 0.99] |
| A_0/m_0 | [-3., 3.] | $diag(Y_s^{ij})$ | [0.001, 0.99] |
| $tan\beta$ | [0., 60.] | sign of μ | positive |
| $	aneta_R$ | [1., 1.2] | μ_R | [-4.2, 6.] TeV |
| | | $\Delta m_{\mathcal{X}_R}^2$ | [0, 10.] TeV |

where
$$\Delta m_{\mathcal{X}_R}^2 = m_{\overline{\mathcal{X}}_R}^2 - m_{\mathcal{X}_R}^2$$



$\widetilde{\chi}_1^0$ DM based on the non-universality in \mathcal{X}_R masses

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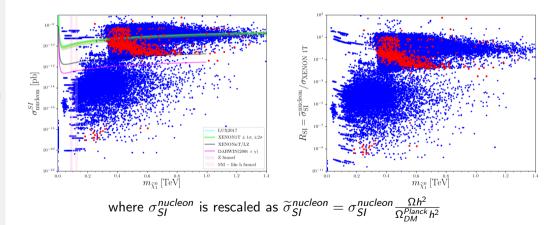
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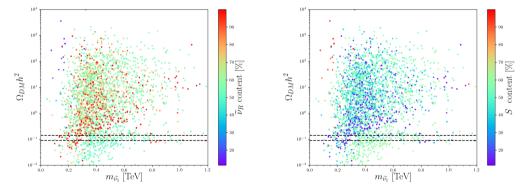
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Sneutrino DM solutions can be also obtained with $M_{Z'} > 3.5$ TeV bound.



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Thank you!