Search for the 3-3-1 symmetry at the LHC and Future Colliders

Yoxara Sánchez Villamizar

In collaboration with:

Farinaldo Queiroz, A. S. de Jesus, J. W. F. Valle, A. Alves, L. Duarte, Y. M. Oviedo-Torres, S. Kovalenko

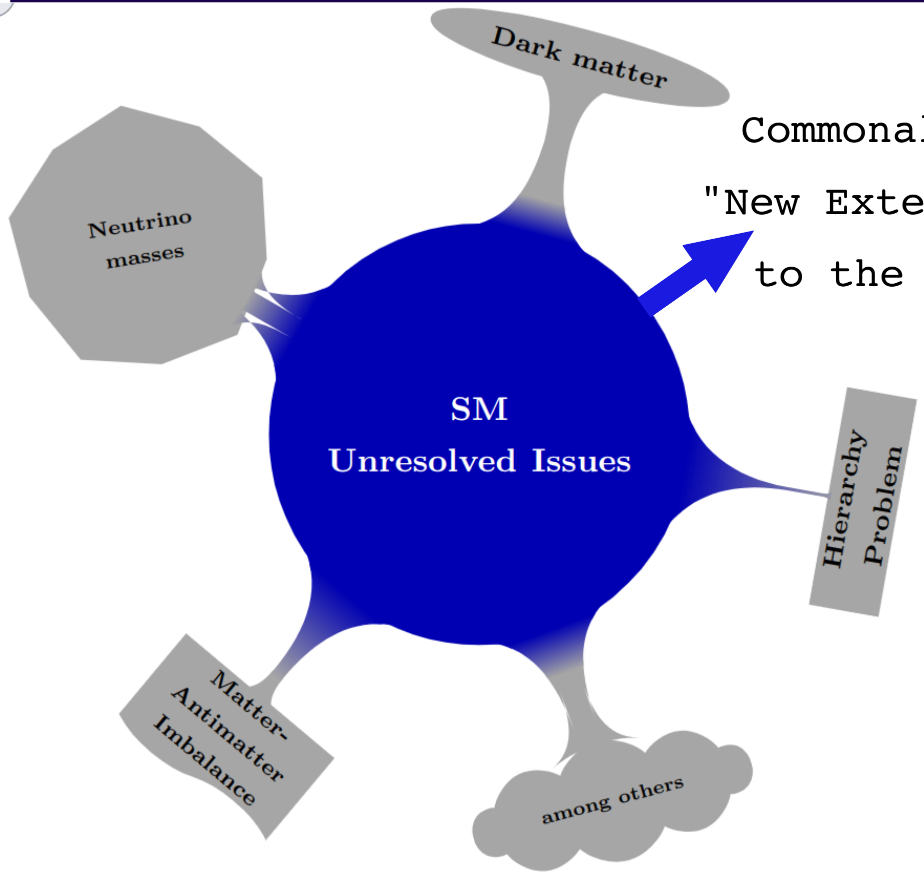
Based on: arXiv: 2312.03851 and 2203.02520

FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

UFABC

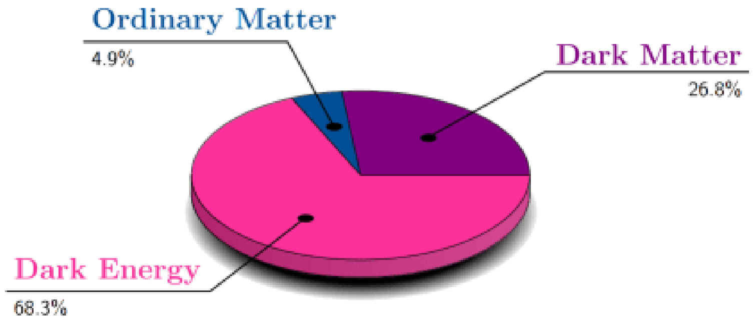
CCNH
CENTRO DE CIÊNCIAS NATURAIS E HUMANAS

- Introduction
- Constraining 3-3-1 Models at the LHC and Future Hadron Colliders
- $g_\mu - 2$ in 3-3-1 Models in colliders
- Conclusions



Commonality:

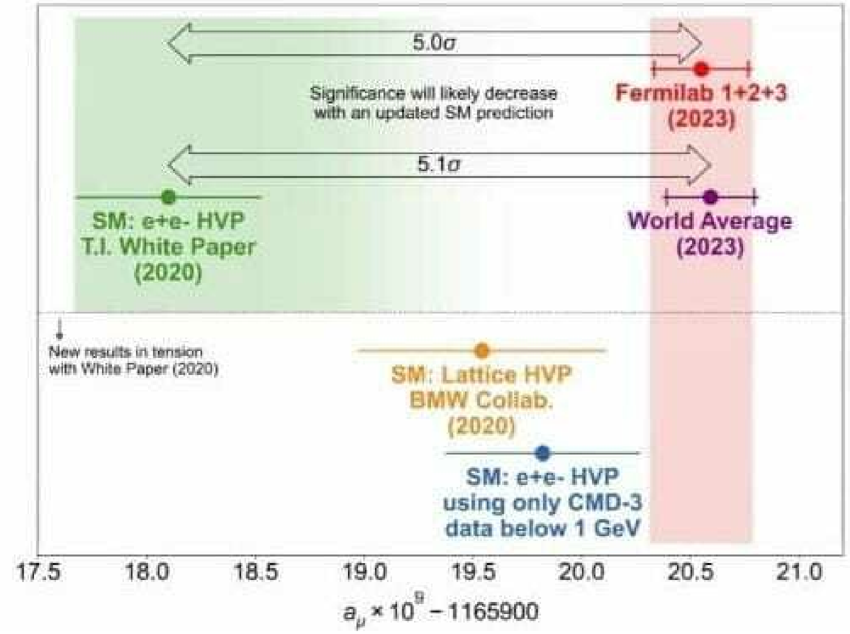
"New Extensions to the SM?"

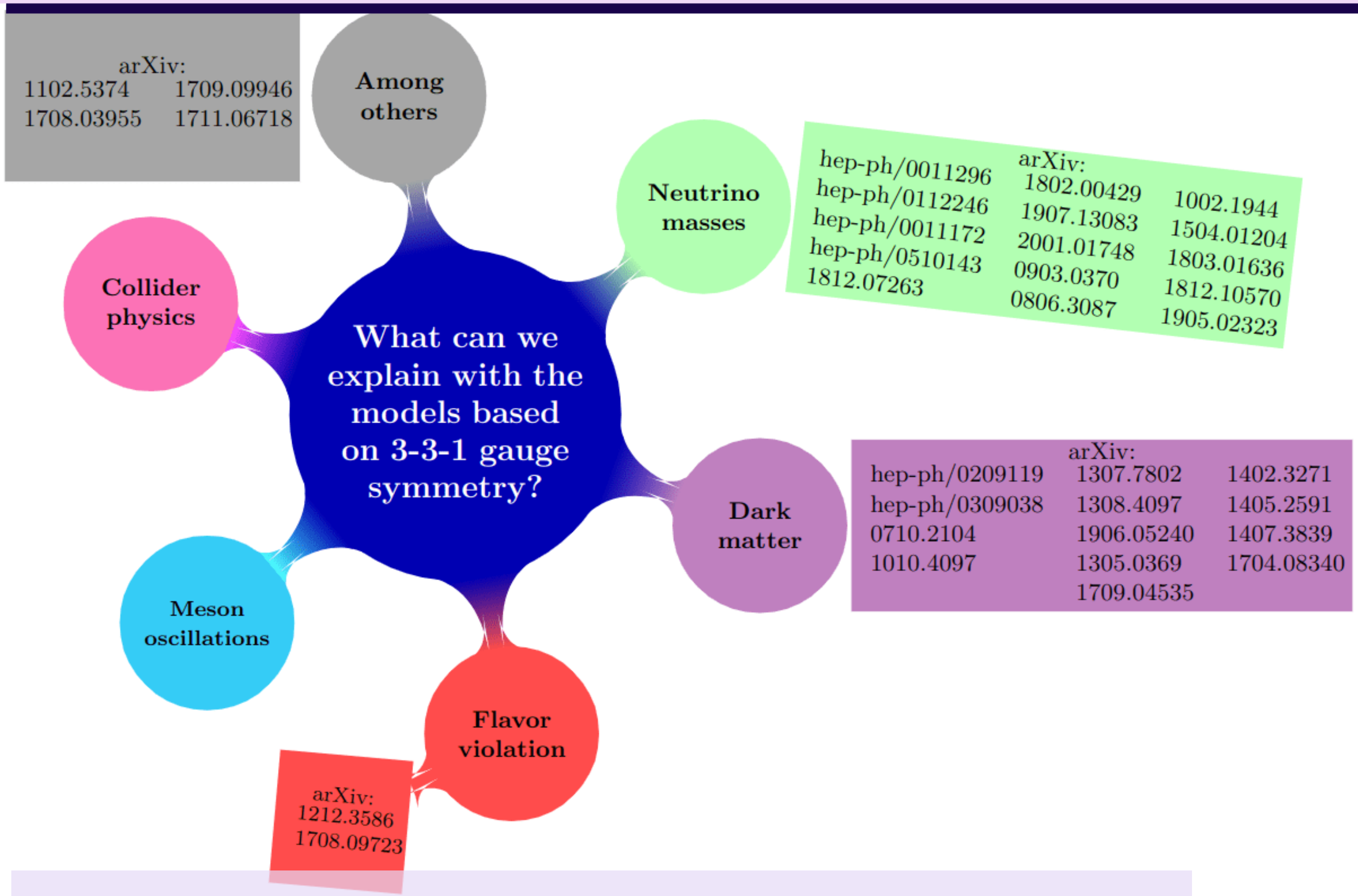


Muon Anomalous Magnetic Moment (a_μ)

Summary of the $g_\mu - 2$ anomaly over the years.

Current value of $g_\mu - 2$	Standard deviation	Year	Reference
$\Delta a_\mu = (261 \pm 78) \times 10^{-11}$	3.3σ	2009	[arXiv:0901.0306, Phys. Rev. D 98, 030001]
$\Delta a_\mu = (325 \pm 80) \times 10^{-11}$	4.05σ	2012	[arXiv:1210.7184]
$\Delta a_\mu = (287 \pm 80) \times 10^{-11}$	3.6σ	2013	[arXiv:1311.2198]
$\Delta a_\mu = (377 \pm 75) \times 10^{-11}$	5.02σ	2015	[arXiv:1507.02943]
$\Delta a_\mu = (313 \pm 77) \times 10^{-11}$	4.1σ	2017	[arXiv:1705.00263]
$\Delta a_\mu = (270 \pm 36) \times 10^{-11}$	3.7σ	2018	[arXiv:1802.02995]
$\Delta a_\mu = (250 \pm 48) \times 10^{-11}$	5.0σ	2023	[arXiv:2308.06230]





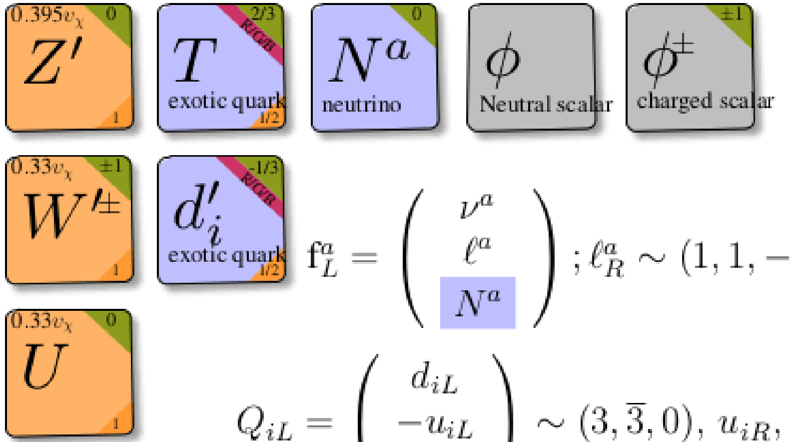
The scalar sector contains 3 scalar triplets (χ, η, ρ) to give the masses of the fermions and one scalar sextet to generate neutrino masses via a type II seesaw mechanism. The 3-3-1 gauge symmetry experiences the following spontaneous symmetry breaking: $\mathrm{SU(3)}_C \times SU(3)_L \times U(1)_X \xrightarrow{\langle\chi\rangle} \mathrm{SU(2)_L} \times \mathrm{U(1)_Y} \xrightarrow{\langle\eta\rangle,\ \langle\rho\rangle} \mathrm{U(1)_Q}$ with $v_\chi \gg v_\eta, v_\rho$

3-3-1 with neutral lepton (*3-3-1 LHN*):

New particles in the $\mathcal{G}_{3-3-1} = \mathbf{SU(3)_C} \times \mathbf{SU(3)_L} \times \mathbf{U(1)_Y}$

$$\mathbf{Q/e} = (\lambda_3 + (\beta)\lambda_8)/2 + \mathbf{XI}, \quad \beta = -1/\sqrt{3}$$

$$\mathbf{SU(3)}_L \times U(1)_X \xrightarrow{\langle\chi\rangle = v_\chi} \mathbf{SU(2)}_L \times \mathbf{U(1)}_Y \xrightarrow{\langle\eta\rangle = v_\eta,\ \langle\rho\rangle = v_\rho} \mathbf{U(1)}_Q$$



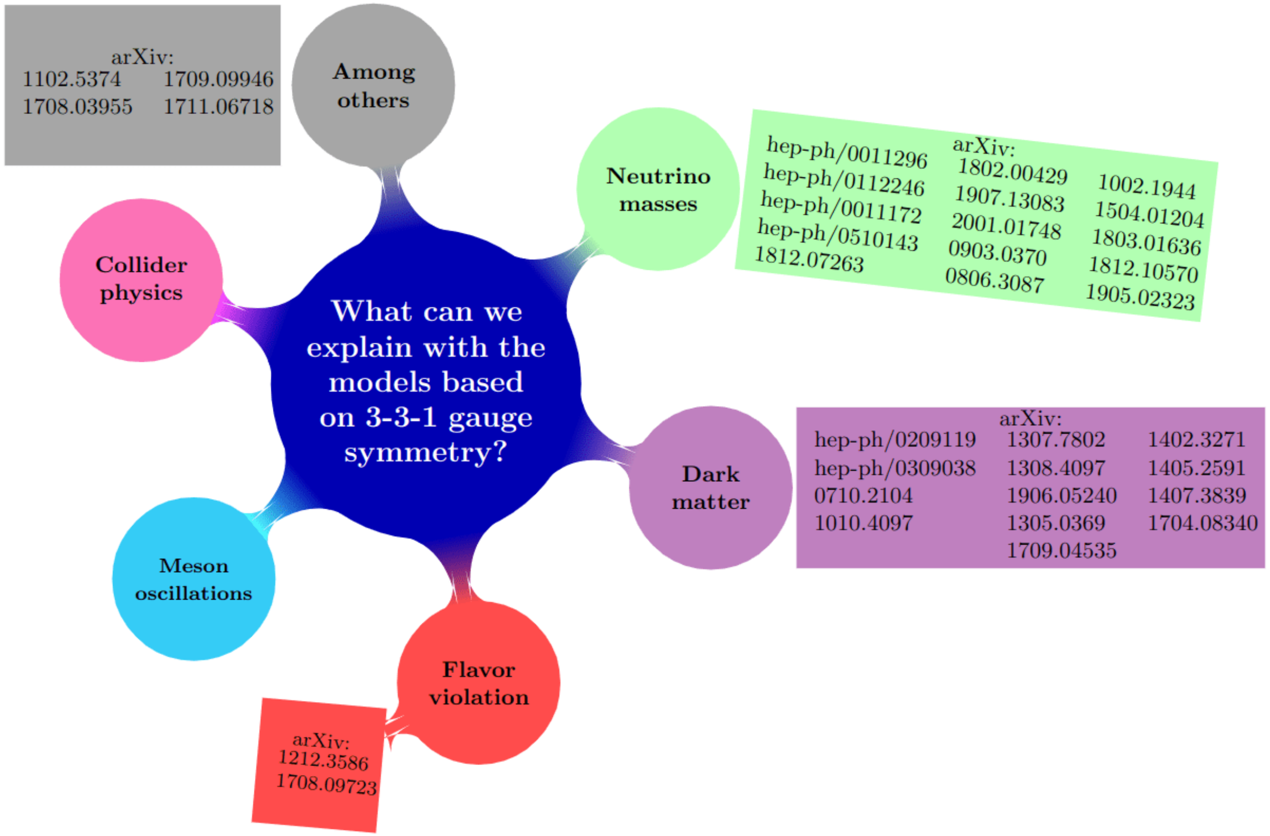
$$\mathrm{f}^a_L = \begin{pmatrix} \nu^a \\ \ell^a \\ N^a \end{pmatrix};\ \ell^a_R \sim (1,1,-1),\ N^a_R \sim (1,1,0)$$

$$Q_{iL} = \begin{pmatrix} d_{iL} \\ -u_{iL} \\ d'_{iL} \end{pmatrix} \sim (3,\bar{3},0),\ u_{iR},\ d_{iR},\ d'_{iR},$$

$$Q_{3L} = \begin{pmatrix} u_{3L} \\ d_{3L} \\ T_L \end{pmatrix} \sim (3,3,1/3),\ u_{3R},\ d_{3R},\ T_R.$$

where $a = 1,2,3$ and $i = 1,2$ indicate the generation indices, d'_i and T are the exotic quarks (q'). In the **3-3-1 LHN**, a new heavy neutral lepton N^a_L replaces the $(\nu^a_R)^c$ in the lepton triplet. Besides, a right-handed neutral fermion N^a_R

$$\mathcal{L}^{NC}_{Z'ff} = \frac{g}{2c_W}\bar{f}\gamma^\mu\left[\mathrm{g}_V^{(f)} + \gamma_5 \mathrm{g}_A^{(f)}\right] f Z'_\mu.$$

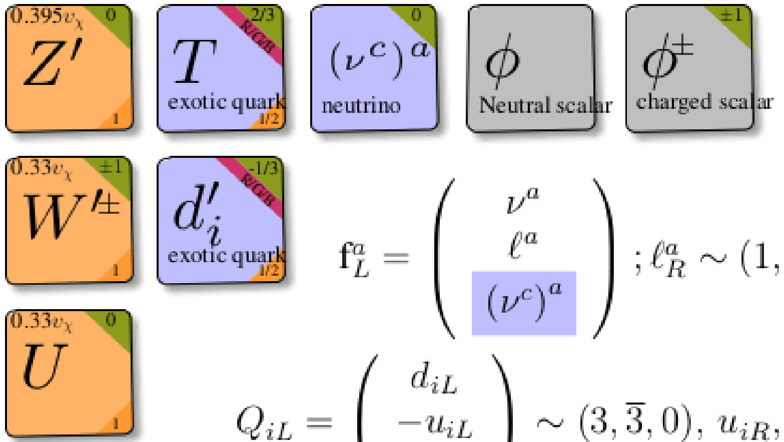


3-3-1 with right-handed neutrinos (r.h.n):

New particles in the $\mathcal{G}_{3-3-1} = \mathbf{SU(3)_C} \times \mathbf{SU(3)_L} \times \mathbf{U(1)_Y}$

$$\mathbf{Q/e} = (\lambda_3 + (\beta)\lambda_8)/2 + \mathrm{XI}, \quad \beta = -1/\sqrt{3}$$

$$\mathbf{SU(3)}_L \times U(1)_X \xrightarrow{\langle\chi\rangle = v_\chi} \mathbf{SU(2)}_L \times \mathbf{U(1)}_Y \xrightarrow{\langle\eta\rangle = v_\eta,\ \langle\rho\rangle = v_\rho} \mathbf{U(1)}_Q$$



$$\mathrm{f}_L^a = \begin{pmatrix} \nu^a \\ \ell^a \\ (\nu^c)^a \end{pmatrix}; \ \ell_R^a \sim (1,1,-1)$$

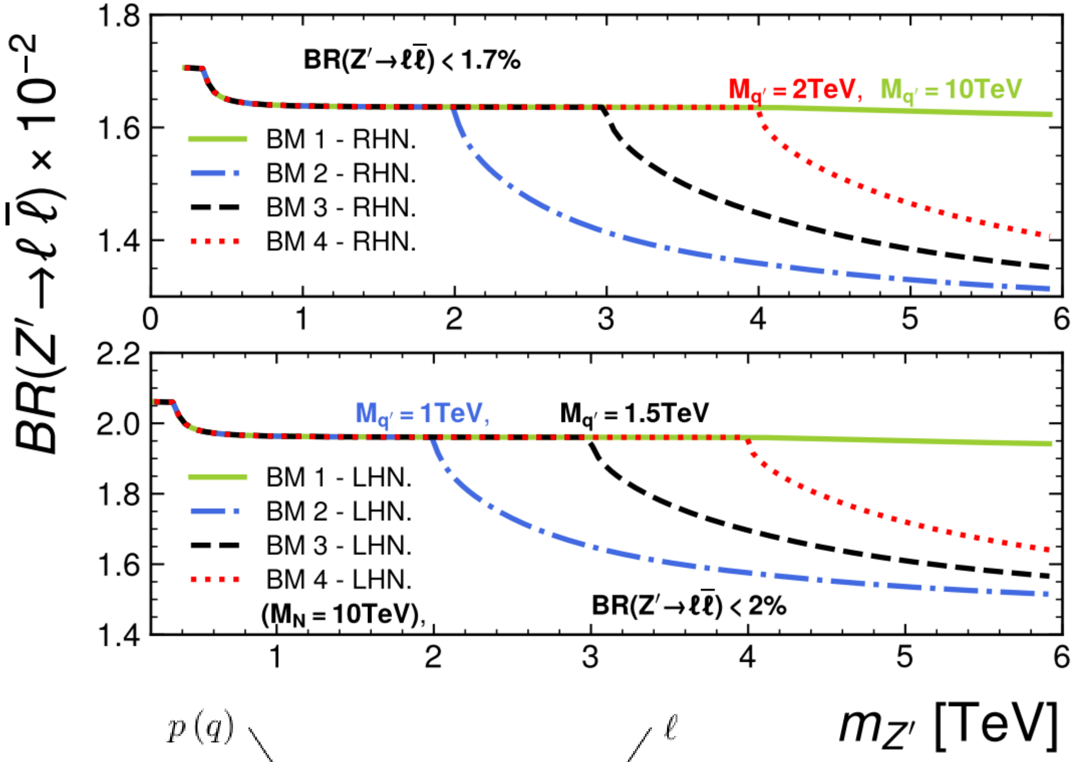
$$Q_{iL} = \begin{pmatrix} d_{iL} \\ -u_{iL} \\ d'_{iL} \end{pmatrix} \sim (3,\overline{3},0),\ u_{iR},\ d_{iR},\ d'_{iR},$$

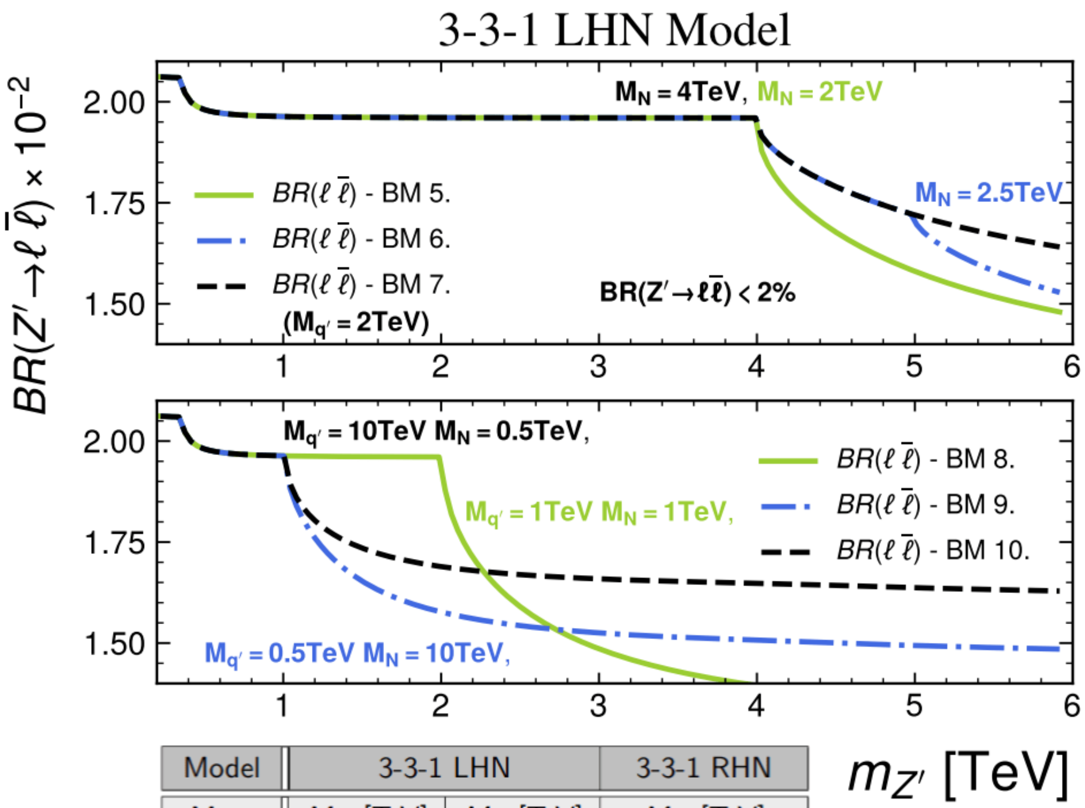
$$Q_{3L} = \begin{pmatrix} u_{3L} \\ d_{3L} \\ T_L \end{pmatrix} \sim (3,3,1/3),\ u_{3R},\ d_{3R},\ T_R.$$

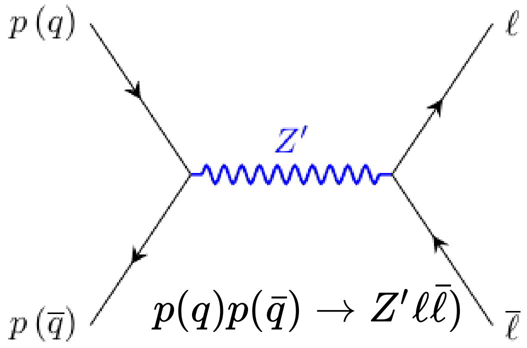
$$u_i = \overline{u}, \overline{c},\ d_i = \overline{d}, \overline{s},\ u_3 = t \text{ and } d_3 = b.$$

where $a = 1,2,3$ and $i = 1,2$ indicate the generation indices, d'_i and T are the exotic quarks (q'). In the **3-3-1 LHN**, a new heavy neutral lepton N_L^a replaces the $(\nu_R^a)^c$ in the lepton triplet. Besides, a right-handed neutral fermion N_R^a

$$\mathcal{L}^{NC}_{Z'ff} = \frac{g}{2c_W}\overline{f}\gamma^\mu\left[g_V^{(f)} + \gamma_5 g_A^{(f)}\right] f Z'_\mu.$$







$$p(q)p(\bar{q}) \to Z'\ell\bar{\ell}$$

$$\ell = e, \mu$$

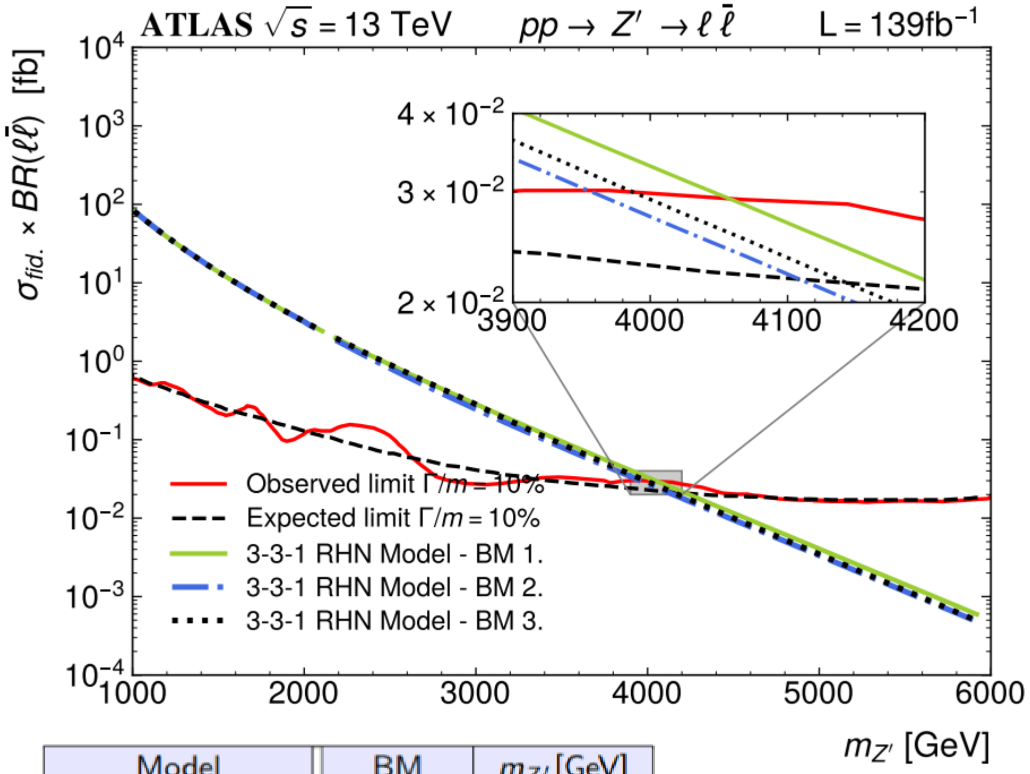
$$\mathrm{Br}\left(Z' \to \ell\bar{\ell}\right) = \frac{\Gamma\left(Z' \to \ell\bar{\ell}\right)}{\Gamma_{Z'}}$$

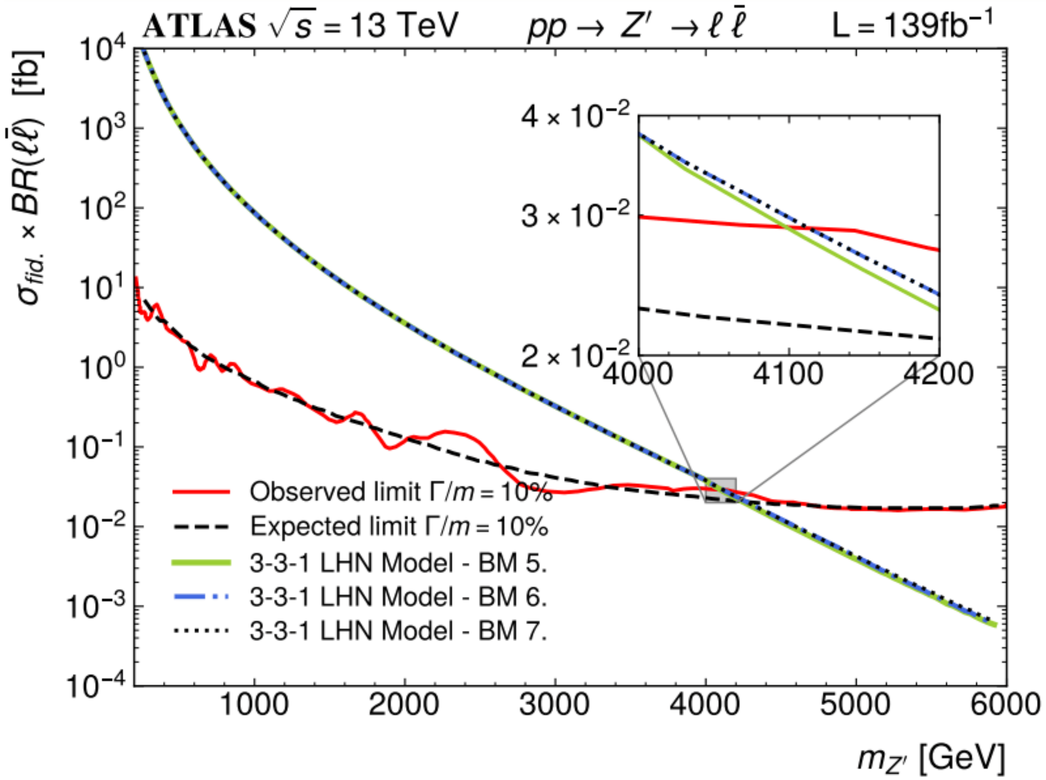
$$\Gamma_{Z'} = \sum_X \Gamma\left(Z' \to 2X\right)$$

X : SM and new particles.

Model	3-3-1 LHN		3-3-1 RHN
Mass	$M_{q'}$ [TeV]	M_N [TeV]	$M_{q'}$ [TeV]
BM1	10	10	10
BM2	1	10	1
BM3	1.5	10	1.5
BM4	2	10	2
BM5	2	2	not applicable
BM6	2	2.5	not applicable
BM7	2	4	not applicable
BM8	1	1	not applicable
BM9	0.5	10	not applicable
BM10	10	0.5	not applicable

The Z' decays into new scalars are strongly suppressed or kinematically forbidden for the implemented BMs



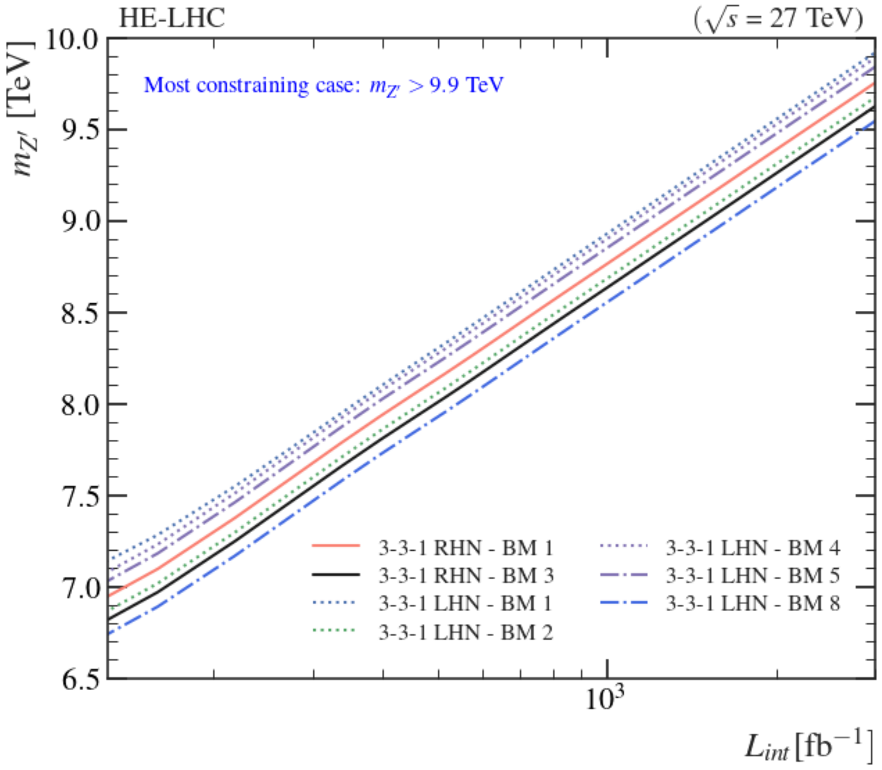


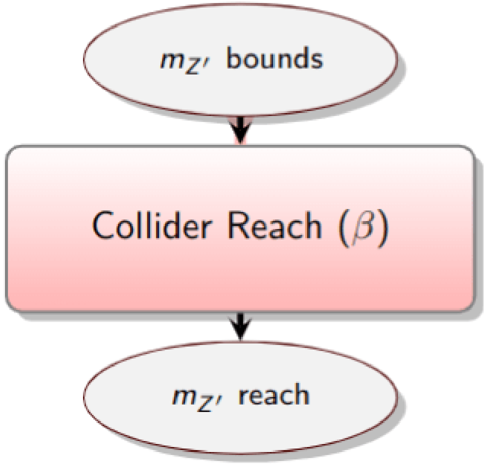
Model	BM	$m_{Z'}$ [GeV]
3-3-1 RHN	BM 1 [1]	4052
	BM 2	3960
	BM 3 [2]	3989
	BM 4	4040
3-3-1 LHN	BM 1	4132
	BM 2	4013
	BM 3	4060
	BM 4 BM 6 BM 7	4118
	BM 5	4094
	BM 8	3950

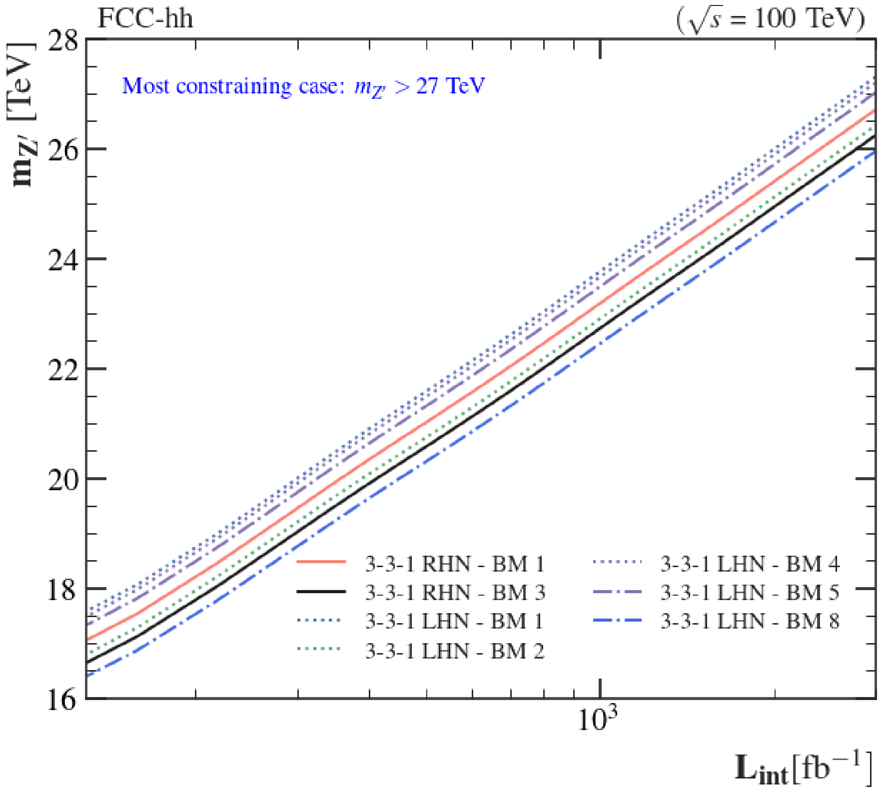
Solid red and dashed black lines symbolize $\sigma_{\text{fid.}} \times \text{BR}(\ell\bar{\ell})$ upper limits at $95\%\text{CL}$ as a function of Z' mass for the dilepton channel $Z' \to \ell\bar{\ell}$ in the ATLAS experiment [A. Collaboration, Physics Letters B 796, 68 (2019)] with $p_{\text{T}} > 30$ GeV and $|\eta| < 2.5$. Solid yellow-green, dash-dot blue, and black dotted lines represent the theoretical production of the $\sigma(pp \to Z') \times BR(Z' \to \ell\bar{\ell})$.

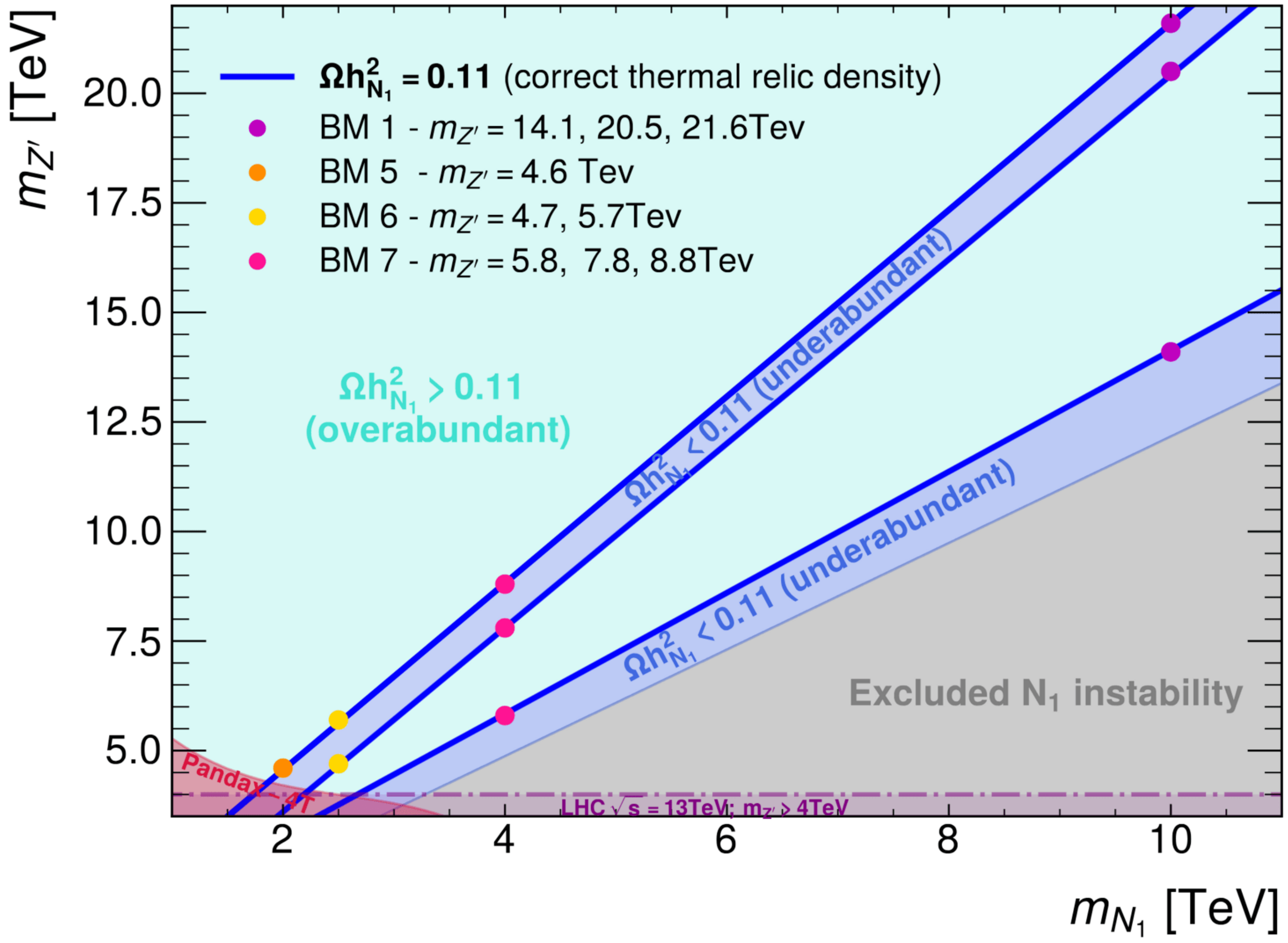
- HL: $\sqrt{s}$ =13 TeV,
  L_{int} = 139 fb^{-1}, 300 fb^{-1}, 500 fb^{-1}, and 3000 fb^{-1}
- HE-HL: $\sqrt{s}$ =14 TeV and 27 TeV,
  L_{int} = 139 fb^{-1}, 300 fb^{-1}, 500 fb^{-1}, and 3000 fb^{-1}
- FCC-hh: $\sqrt{s}$ = 100 TeV,
  L_{int} = 139 fb^{-1}, 300 fb^{-1}, 500 fb^{-1}, and 3000 fb^{-1}

Most restrictive case when $\sqrt{s} = 14\text{TeV} : m_{Z'} > 5.8\text{TeV}$







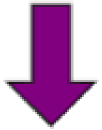


Parameter space $m_{Z'} \times m_{N_1}$ plane that explains the $\Omega h^2_{N_1}$.

N_1: candidate to the DM.
It is the lightest
$N_i \to N_i, N_2$

Current and projected direct detection bounds: XENON or PANDAX collaborations

Phys. Rev. Lett. **121**, 111302
Phys. Rev. Lett. **127**, 261802
E. Aprile *et al* JCAP11(2020)031



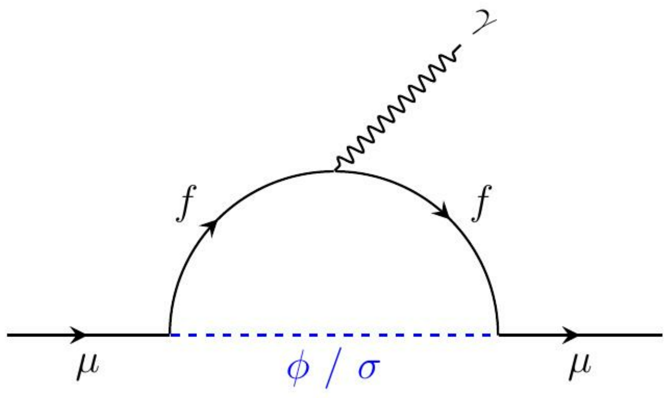
significantly surpassed by current LHC data

$$\Delta a_\mu = \frac{\lambda'^2}{8\pi^2}\int_0^1 \mathrm{d}x \sum_b \frac{(g^s_{2b})^2 P^+(x) + \left(g^p_{2b}\right)^2 P^-(x)}{(1-x)(1-x\,\lambda'^2)+x\epsilon_b^2\lambda'^2}$$

$P^\pm(x) = x^2\,(1 - x \pm \epsilon_b)\,, \epsilon_b = \frac{m_b}{m_\mu}, \lambda' = \frac{m_\mu}{m_\phi}, g^s_{2b}$ and g^p_{2b} being the scalar and pseudoscalar couplings of this new scalar with the muon and other particles in the same vertex, represented by the subscript b.

Simplified models				
Model	Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Inert Scalar	ϕ	1	2	1
Vector-like Fermion	E	1	1	-2
	ϕ	1	2	1
	ψ	1	2	-1
	σ	1	2	1
3-3-1 model				
Model	Field	$SU(3)_C$	$SU(3)_L$	$U(1)_X$
3-3-1	f	1	3	-1/3
	N	1	1	0
	ϕ	1	3	2/3

A. Inert Scalar

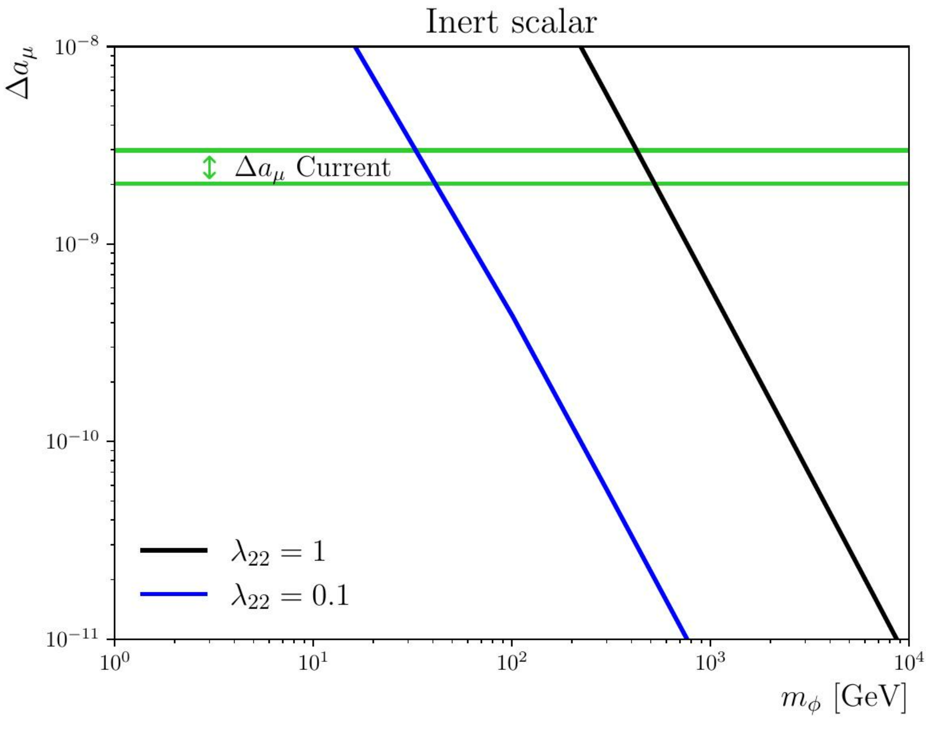


$$\mathcal{L} = \lambda_{ab}\bar{L}_{aL}\phi e_{bR} + h.c.$$

L_{aL} is the SM lepton doublet, λ_{ab} is the Yukawa coupling.

This could explain the $g_\mu - 2$ anomaly for $0.0076\mathrm{GeV}^{-1} < y/m_\phi < 0.0102\mathrm{GeV}^{-1}$.

With the configurations $\lambda_{22} = 1$ and $\lambda_{22} = 0.1$ we are capable of addressing the anomaly for masses of $m_\phi = 400 - 550\mathrm{GeV}$ and $m_\phi = 30 - 40\mathrm{GeV}$ respectively.



B. Vector-like Fermions

1. Vector-like fermion plus a scalar singlet: $\mathcal{L} = \lambda_{ab}\bar{E}_{aR}\sigma\mu_R + h.c$

   If E and σ are a singlet under $SU(2)_L$

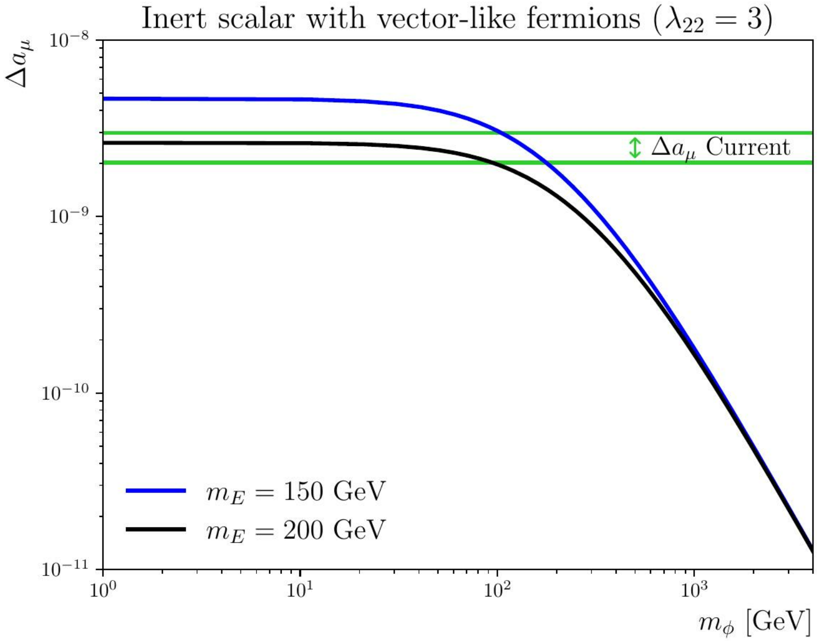
2. Vector-like fermion plus a scalar doublet: $\mathcal{L} = \lambda_{ab}\bar{L}_{aL}\phi E_{bR} + h.c.$

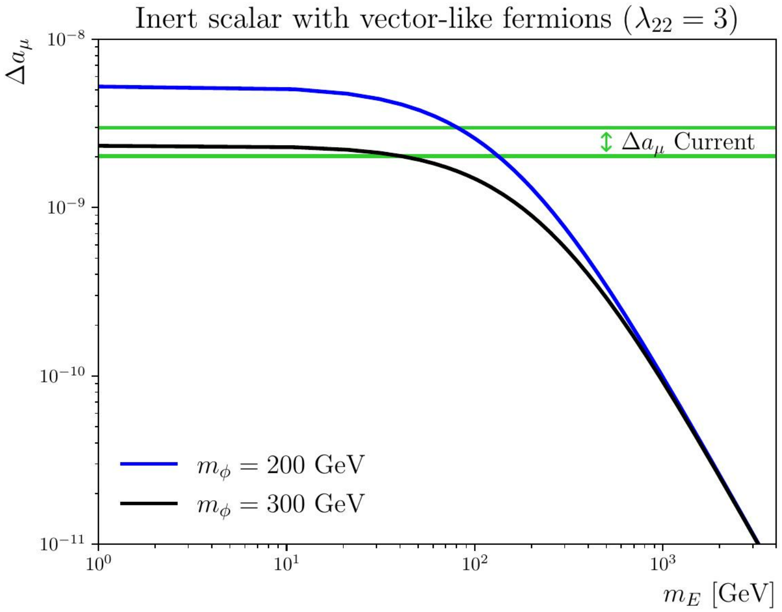
   E is an exotic-charged fermion and ϕ is an inert double

3. Vector-like fermion doublet plus an inert scalar doublet: $\mathcal{L} = \lambda_{ab}\bar{\psi}_{aL}\sigma\mu_{bR} + h.c.$

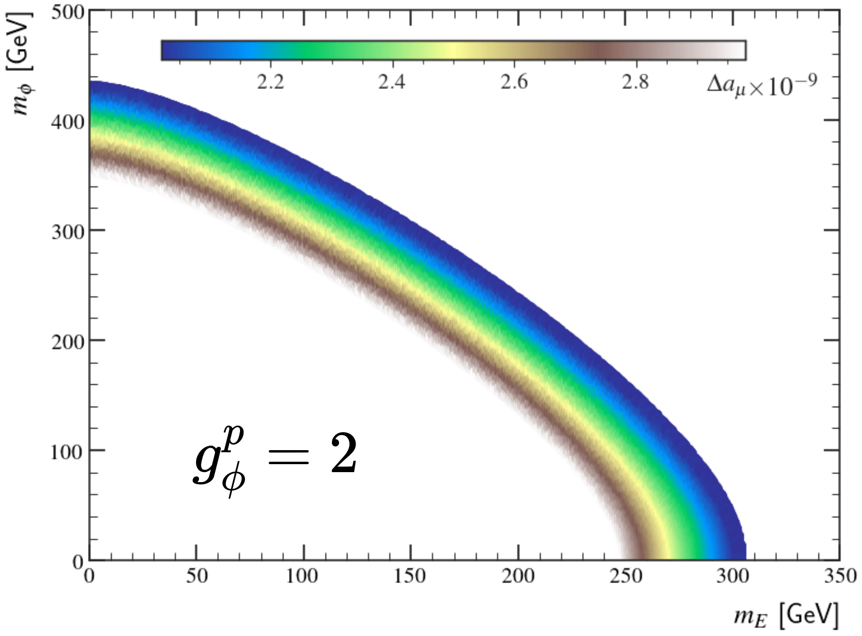
   ψ is a fermion doublet under $SU(2)_L$ and σ is an inert scalar doublet

Simplified models				
Model	Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Inert Scalar	ϕ	1	2	1
Vector-like Fermion	E	1	1	-2
	ϕ	1	2	1
	ψ	1	2	-1
	σ	1	2	1
3-3-1 model				
Model	Field	$SU(3)_C$	$SU(3)_L$	$U(1)_X$
3-3-1	f	1	3	-1/3
	N	1	1	0
	ϕ	1	3	2/3



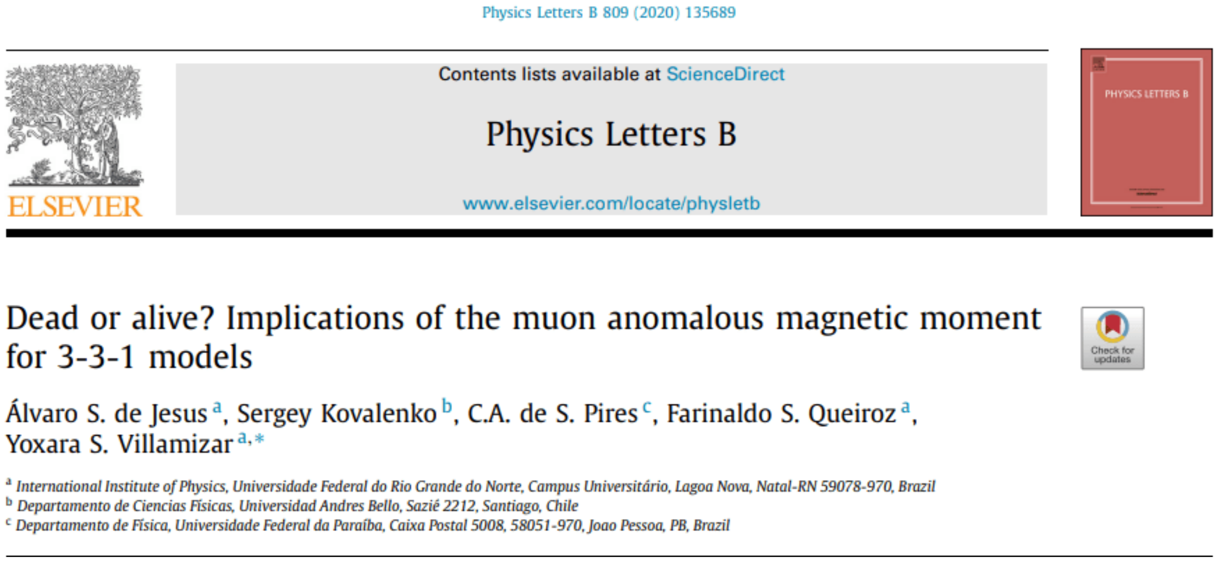


$\Delta a_\mu = (250 \pm 48) \times 10^{-11}$



We have explored new physics contributions to a_μ on the $SU(3)_C \times SU(3)_L \times U(1)_X$ gauge symmetry

None of the models can accommodate the anomaly in agreement with existing bounds.


Physics Letters B 809 (2020) 135689

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

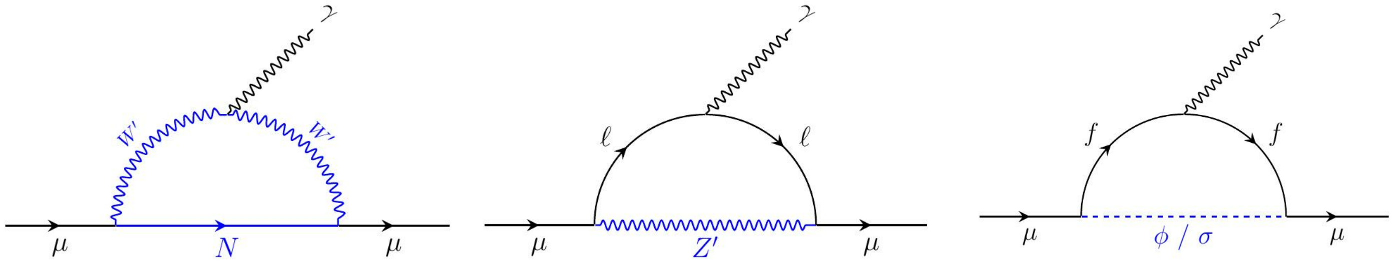
ELSEVIER

Dead or alive? Implications of the muon anomalous magnetic moment for 3-3-1 models

Álvaro S. de Jesus [a], Sergey Kovalenko [b], C.A. de S. Pires [c], Farinaldo S. Queiroz [a], Yoxara S. Villamizar [a,*]

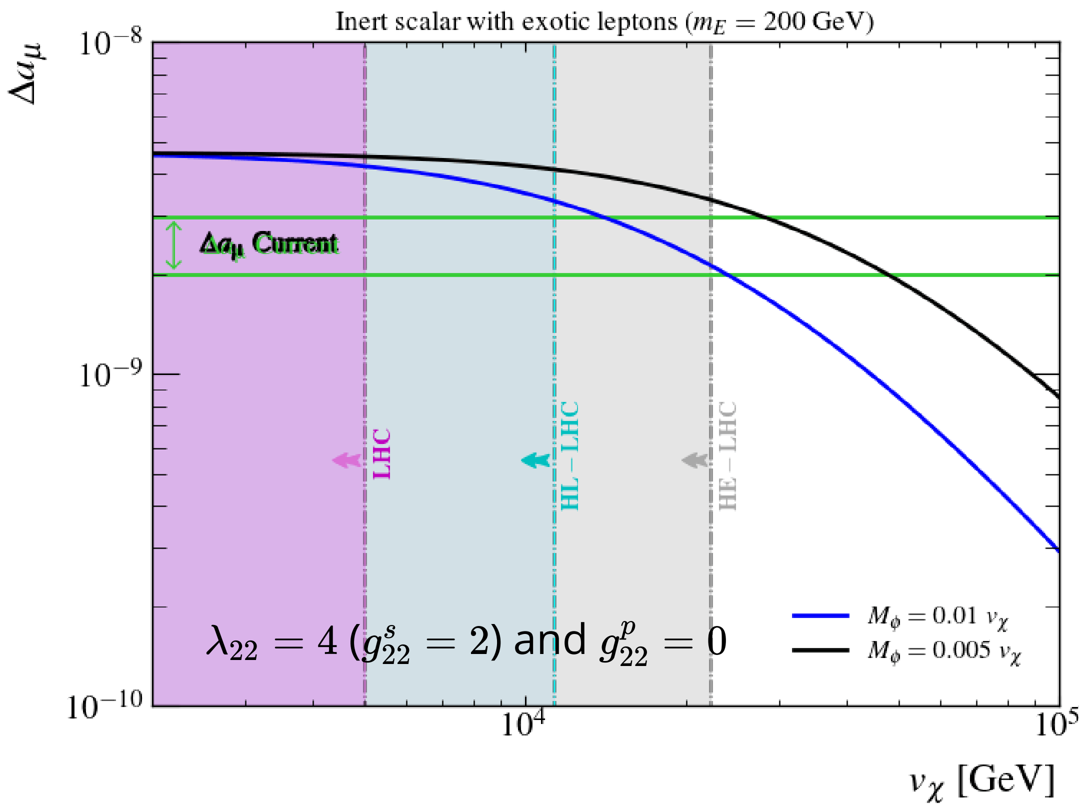
[a] International Institute of Physics, Universidade Federal do Rio Grande do Norte, Campus Universitário, Lagoa Nova, Natal-RN 59078-970, Brazil
[b] Departamento de Ciencias Físicas, Universidad Andres Bello, Sazié 2212, Santiago, Chile
[c] Departamento de Física, Universidade Federal da Paraíba, Caixa Postal 5008, 58051-970, Joao Pessoa, PB, Brazil

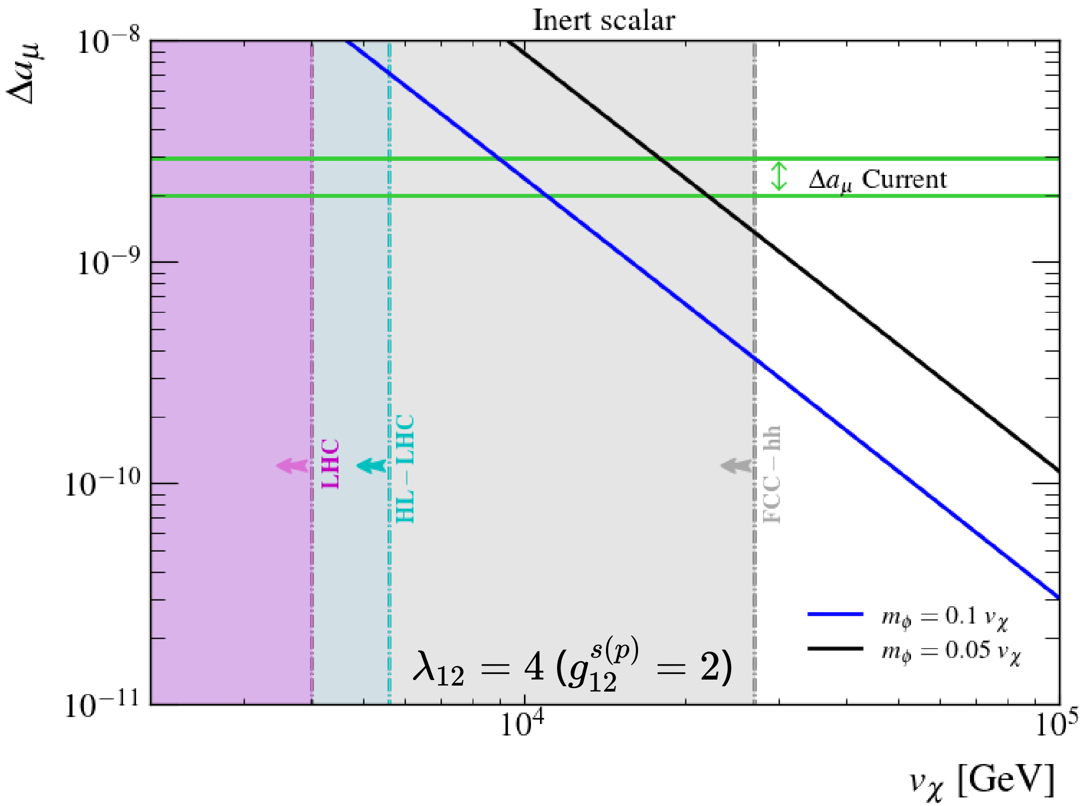
3-3-1 LHN model augmented by an inert scalar triplet.



The inert scalar triplet gets a mass from the quartic coupling in the scalar potential $(\lambda\phi^\dagger\phi\chi^\dagger\chi)$ after the scalar triplet χ acquires a vev:

$$m_\phi \sim \Lambda v_\chi$$





"We can see that current data cannot exclude the region of parameter space that can fit the anomaly. Future experiments, though, should be able to cover the parameter space that lies beyond the reach of current LHC searches, and produce a signal in future colliders, such as the FCC"

Currently, our focus is on exploring and analyzing theories BSM, using tools in HEP like @MadGraph5 for the generation and detailed study of events in particle physics

- ❖ We derived LHC bounds on two 3-3-1 models, assessing the impact of exotic Z' decays using dilepton data.
- ❖ We obtained solid lower mass bounds that range from 3.9~TeV to 4.1~TeV
- ❖ We also forecasted HL-LHC, HE-LHC, and FCC-hh mass reach
- ❖ We conclude that one could accommodate a few TeV thermal dark matter candidate in agreement with direct detection and collider bounds.

- ❖ The possibility of inert scalars was investigated to explain the $g_\mu - 2$ anomaly within 3-3-1 theories involving vector-like fermions.
- ❖ The viability of these particles was assessed in light of current experimental constraints.
- ❖ Parameter space regions that could explain the $g_\mu - 2$ anomaly were identified, with vector fermion masses between 250 – 300 GeV and inert scalar masses between 350 – 450 GeV.
- ❖ A new inert scalar triplet is proposed that could accommodate the anomaly while avoiding current restrictions.
- ❖ Future experiments should be able to cover the parameter space that lies beyond the reach of current LHC searches, and produce a signal in future colliders, such as the FCC

Yoxara Sánchez Villamizar

yoxarasv@sprace.org.br

Thank you so much
for your attention!

Acknowledgement

FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA
DO ESTADO DE SÃO PAULO

UFABC

UFRN
UNIVERSIDADE FEDERAL DO RIO GRANDE DO NORTE

Questions & Comments

Backup slides

Vector and axial couplings of the Z' boson with fermions in the 3-3-1 RHN and LHN models. In the 3-3-1 RHN model there are no interactions with the neutral heavy fermions. Apart from that, the Z' interactions are precisely the same as the 3-3-1 LHN model.

Z' interactions in the 3-3-1 Model		
Interaction	g'_V	g'_A
$Z'\bar{u}u, \bar{c}c$	$\frac{3-8\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$-\frac{1}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\bar{t}t$	$\frac{3+2\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$-\frac{1-2\sin^2\theta_W}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\bar{d}d, \bar{s}s$	$\frac{3-2\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$-\frac{3-6\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$
$Z'\bar{b}b$	$\frac{3-4\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$-\frac{1}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\bar{\ell}\ell$	$\frac{-1+4\sin^2\theta_W}{2\sqrt{3-4\sin^2\theta_W}}$	$\frac{1}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\bar{N}N$	$\frac{4\sqrt{3-4\sin^2\theta_W}}{9}$	$-\frac{4\sqrt{3-4\sin^2\theta_W}}{9}$
$Z'\bar{\nu}_\ell\nu_\ell$	$\frac{\sqrt{3-4\sin^2\theta_W}}{18}$	$-\frac{\sqrt{3-4\sin^2\theta_W}}{18}$
$Z'\overline{d^i_i}d^i_i$	$-\frac{3-5\sin^2\theta_W}{3\sqrt{3-4\sin^2\theta_W}}$	$\frac{1-\sin^2\theta_W}{\sqrt{3-4\sin^2\theta_W}}$
$Z'\bar{T}T$	$\frac{3-7\sin^2\theta_W}{3\sqrt{3-4\sin^2\theta_W}}$	$-\frac{1-\sin^2\theta_W}{\sqrt{3-4\sin^2\theta_W}}$

$m_{Z'}$ mass reach for all benchmark sets considered in this work at HE-HL and FCC-hh colliders by increasing the center-ofmass energy ($\sqrt{s}$) from 13 until $100\mathrm{TeV}$, and integral luminosity (L_{int}) from $139\mathrm{fb}^{-1}$ to $3000\mathrm{fb}^{-1}$, for the $3-3-1$ RHN and LHN models. Values of $m_{Z'}$ for HE-HL LHC appear between the fourth and sixth columns of the table, whereas for the FCC-hh collider, the $m_{Z'}$ reaches are shown in the seventh column, when increasing the luminosity (column three).

Model	BM sets	L_{int} (fb^{-1})	$m_{Z'}$(TeV)-13 TeV	$m_{Z'}$(TeV)-14 TeV	$m_{Z'}$(TeV)- 27 TeV	$m_{Z'}$(TeV)-100 TeV
3-3-1 RHN	BM 1[a]	139	4.052	4.288	6.987	17.180
		300	4.390	4.651	7.675	19.447
		500	4.613	4.892	8.136	21.006
		1000	4.916	5.217	8.763	23.175
		3000	5.388	5.727	9.755	26.711
	BM 2	139	3.960	4.189	6.801	16.548
		300	4.298	4.552	7.487	18.821
		500	4.521	4.793	7.947	20.363
		1000	4.825	5.119	8.574	22.514
		3000	5.298	4.699	9.566	26.030
	BM 3[b]	139	3.989	4.220	6.860	16.769
		300	4.327	4.583	7.547	19.016
		500	4.550	4.824	8.006	20.564
		1000	4.853	5.149	8.633	22.721
		3000	5.326	5.661	9.626	26.244
	BM 4	139	4.040	4.275	6.963	17.101
		300	4.378	4.638	7.651	19.364
		500	4.601	4.879	8.111	20.921
		1000	4.904	5.204	8.739	23.089
		3000	5.377	5.715	9.731	26.652

(Table continued)

Model	BM sets	$L_{\rm int}$ (fb^{-1})	$m_{Z'}$(TeV)-13 TeV	$m_{Z'}$(TeV)-14 TeV	$m_{Z'}$(TeV)- 27 TeV	$m_{Z'}$(TeV)-100 TeV
3-3-1 LHN	BM 1	139	4.132	4.374	7.149	17.709
		300	4.470	4.737	7.839	19.990
		500	4.693	4.978	8.301	21.571
		1000	4.995	5.303	8.928	23.755
		3000	5.467	5.812	9.920	27.306
	BM 2	139	4.013	4.246	6.908	16.924
		300	4.351	4.609	7.596	19.197
		500	4.574	4.850	8.056	20.731
		1000	4.877	5.175	8.683	22.894
		3000	5.350	5.686	9.675	26.421
	BM 3	139	4.060	4.297	7.003	17.233
		300	4.398	4.660	7.692	19.502
		500	4.621	4.901	8.153	21.062
		1000	4.924	5.225	8.780	23.233
		3000	5.396	5.736	9.772	26.770
	BM 4, 6, and 7	139	4.118	4.359	7.121	17.616
		300	4.456	4.722	7.811	19.902
		500	4.679	4.963	8.272	21.472
		1000	4.981	5.288	8.900	23.654
		3000	5.453	5.797	9.891	27.202
	BM 5	139	4.094	4.333	7.072	17.457
		300	4.432	4.696	7.761	19.736
		500	4.655	4.937	8.223	21.302
		1000	4.958	5.262	8.850	23.479
		3000	5.430	5.772	9.842	27.023
	BM 8	139	3.950	4.178	6.781	16.520
		300	4.288	4.541	7.467	18.753
		500	4.511	4.782	7.926	20.294
		1000	4.815	5.108	8.553	22.443
		3000	5.289	5.620	9.546	25.956

[a]The lower bounds of BM 1 for the 3-3-1 RHN model are equivalent to those of BM 10 in the 3-3-1 LHN model.
[b]The lower bounds of BM 3 for the 3-3-1 RHN model are equivalent to those of BM 9 in the 3-3-1 LHN model.