

# Constraining 3-3-1 Models at the LHC and Future Hadron Colliders

## International Conference on High Energy Physics

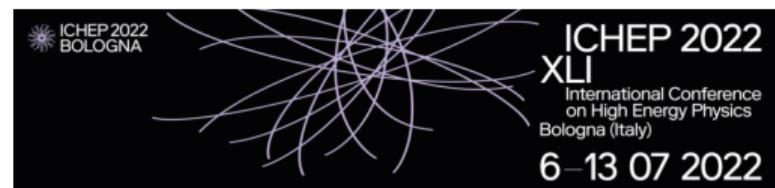
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**1 3-3-1 Models****2 Data, signal output and Methods****3 Signal production****4 Dark Matter****5 Conclusions**

## **3-3-1 Models**

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## Models based on the gauge symmetry $\mathcal{G}_{3-3-1} = \mathbf{SU}(3)_C \times \mathbf{SU}(3)_L \times \mathbf{U}(1)_X$ (3-3-1)

We analyzed two 3-3-1 models:

- ❶ 3-3-1 with right-handed neutrinos (*r.h.n*)<sup>[1,2]</sup>
- ❷ 3-3-1 with neutral lepton (3-3-1 *LHN*)<sup>[3,4]</sup>

The electric charge operator for 3-3-1 Models is,

$$\frac{Q}{e} = \frac{1}{2} \left( \lambda_3 - \frac{1}{\sqrt{3}} \lambda_8 \right) + \mathbf{X} \cdot \hat{\mathbf{I}},$$

where  $\lambda_{3,8}$  are the diagonal generators of  $SU(3)_C$  and  $\hat{\mathbf{I}}$  is the identity matrix that acts as a generator of  $U(1)_X$

These models are quite popular because they can explain:

- neutrino masses,
- dark matter,
- meson oscillations,
- collider physics,
- flavor violation,
- among others.

## Models based on the gauge symmetry $\mathcal{G}_{3-3-1} = \mathbf{SU}(3)_C \times \mathbf{SU}(3)_L \times \mathbf{U}(1)_X$

These 3-3-1 models contain three scalar triplets ( $\chi, \eta, \rho$ ) to give the masses of the fermions, these models experience a two-step spontaneous symmetry breaking:

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

The **3-3-1 r.h.n and LHN** models contain triplet and fermionic singlet fields given by,

$$f_{aL} = \begin{pmatrix} v_L^a \\ \ell_L^a \\ (v_R^a)^c \end{pmatrix}, \quad \ell_{aR}, \quad Q_{iL} = \begin{pmatrix} d_i \\ -u_i \\ d'_i \end{pmatrix}_L, \quad u_{iR}, \ d_{iR}, \ d'_{iR}, \quad Q_{3L} = \begin{pmatrix} u_3 \\ d_3 \\ T \end{pmatrix}_L, \quad u_{3R}, \ d_{3R}, \ T_R,$$

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

## Models based on the gauge symmetry $\mathcal{G}_{3-3-1} = \mathbf{SU}(3)_C \times \mathbf{SU}(3)_L \times \mathbf{U}(1)_X$

The main ingredient is the neutral current that reads,

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

**Table 1:** Vector and Axial couplings of the  $Z'$  boson with fermions, with  $\alpha = 3 - 4 \sin^2 \theta_W$

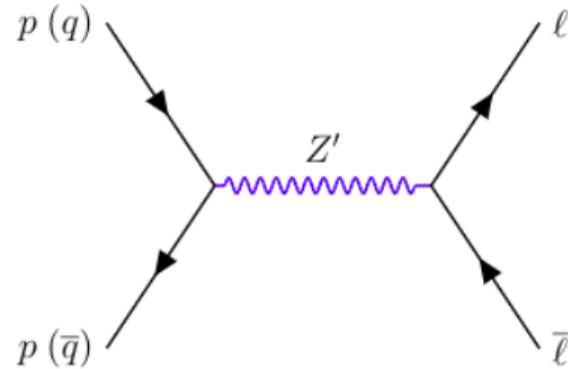
$g_{V(A)}^{(f)}$	Some $Z'$ interactions in the 3-3-1 model								
	$Z' \bar{u}u, \bar{c}c$	$Z' \bar{t}t$	$Z' \bar{d}d, \bar{s}s$	$Z' \bar{b}b$	$Z' \bar{\ell}\ell$	$Z' \bar{N}N$	$Z' \bar{v}_\ell v_\ell$	$Z' \bar{d}_i^i d_i^i$	$Z' \bar{T}T$
$g_V^{(f)}$	$\frac{3 - 8 \sin^2 \theta_W}{6\sqrt{\alpha}}$	$\frac{3 + 2 \sin^2 \theta_W}{6\sqrt{\alpha}}$	$\frac{3 - 2 \sin^2 \theta_W}{6\sqrt{\alpha}}$	$\frac{\sqrt{\alpha}}{6}$	$\frac{-1 + 4 \sin^2 \theta_W}{2\sqrt{\alpha}}$	$\frac{4\sqrt{\alpha}}{9}$	$\frac{\sqrt{\alpha}}{18}$	$-\frac{3 - 5 \sin^2 \theta_W}{3\sqrt{\alpha}}$	$\frac{3 - 7 \sin^2 \theta_W}{3\sqrt{\alpha}}$
$g_A^{(f)}$	$-\frac{1}{2\sqrt{\alpha}}$	$-\frac{1 - 2 \sin^2 \theta_W}{2\sqrt{\alpha}}$	$-\frac{3 - 6 \sin^2 \theta_W}{6\sqrt{\alpha}}$	$-\frac{1}{2\sqrt{\alpha}}$	$\frac{1}{2\sqrt{\alpha}}$	$-\frac{4\sqrt{\alpha}}{9}$	$-\frac{\sqrt{\alpha}}{18}$	$\frac{1 - \sin^2 \theta_W}{\sqrt{\alpha}}$	$-\frac{1 - \sin^2 \theta_W}{\sqrt{\alpha}}$

$$m_{Z'}^2 = \frac{g^2}{(3 - 4s_W^2)} \left( c_W^2 v_\chi^2 + \frac{v_\rho^2 + v_\eta^2 (1 - 2s_W^2)^2}{4c_W^2} \right) \quad m_{W'}^2 = \frac{g^2}{4} (v_\eta^2 + v_\chi^2), \quad m_{U^0}^2 = \frac{g^2}{4} (v_\rho^2 + v_\chi^2), \quad v^2 = v_\eta^2 + v_\rho^2 \simeq 246 \text{ GeV}$$

## **Data, signal output and Methods**

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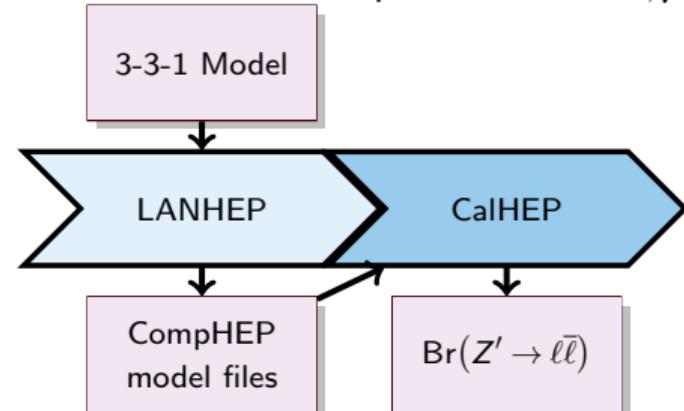
## Branching ratio of the $Z'$ boson in two charged leptons



$$\text{Br}(Z' \rightarrow \ell\bar{\ell}) = \frac{\Gamma(Z' \rightarrow \ell\bar{\ell})}{\Gamma_{Z'}},$$

$$\Gamma_{Z'} = \sum_X \Gamma(Z' \rightarrow 2X),$$

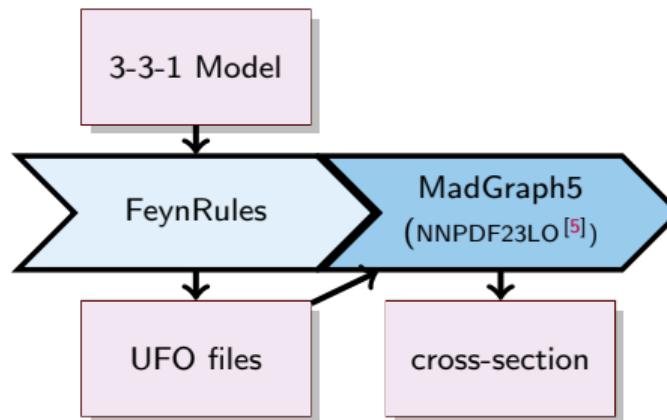
being  $X$  the SM and new particles,  $\ell = e, \mu$ .



**Figure 1:** Feynman diagram for the popular Drell-Yan-type process of the channel production  $Z' \rightarrow \ell^+\ell^-$ , which is the official search in the LHC.

**Table 2:** Implemented benchmark sets (BMs) corresponding to mass values of the heavy exotic quarks  $q'$  and the heavy neutral lepton  $N$

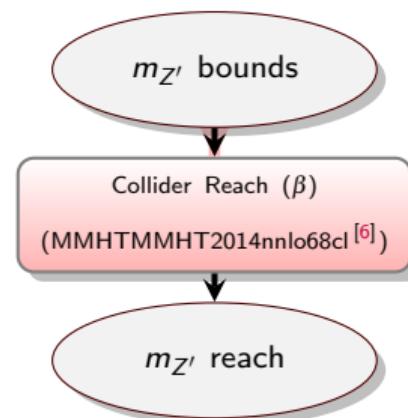
Model	3-3-1 LHN										3-3-1 RHN			
	BM	BM 1	BM 2	BM 3	BM 4	BM 6	BM 7	BM 5	BM 8	BM 9	BM 10	BM 1	BM 2	BM 3
$M_{q'} [\text{TeV}]$	10	1	1.5		2			1	0.5	10		1	1.5	2
$M_N [\text{TeV}]$		10			2.5	4	2	1	10	0.5			N/A	



## Mass range HL, HE and FCC-hh

We forecast the mass range on this boson to different high luminosity (HL) and high energy (HE) configurations, and to the forthcoming FCC-hh hadron collider:

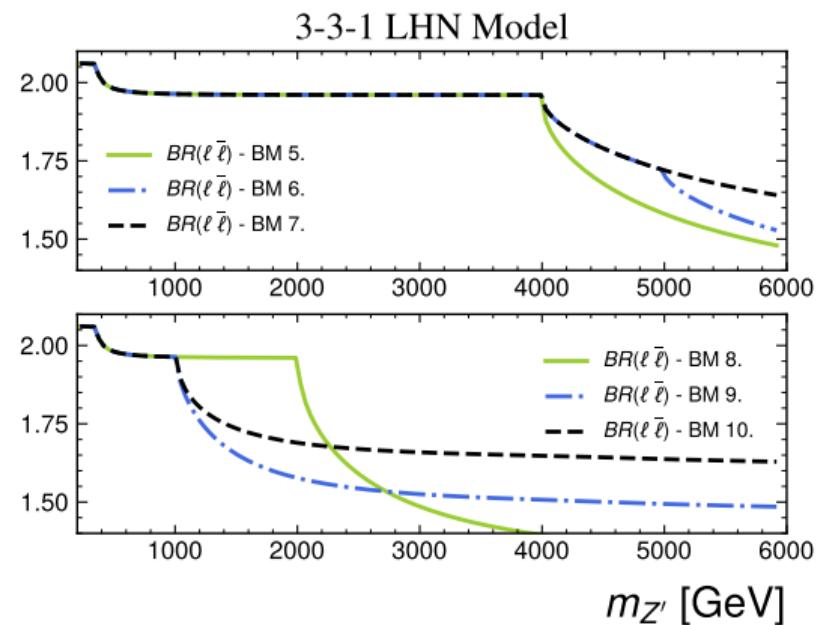
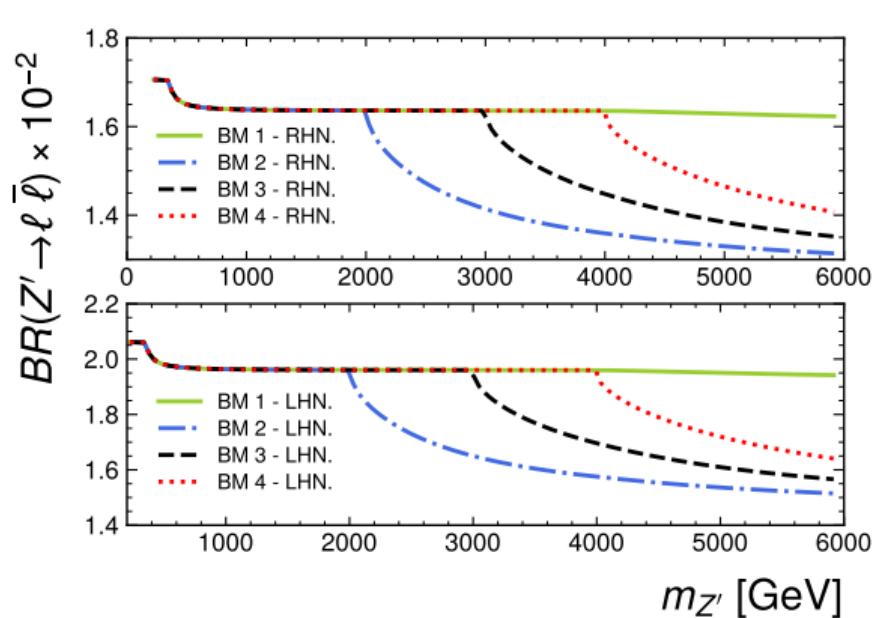
- HL:  $\sqrt{s} = 13 \text{ TeV}$ ,  
 $L_{int} = 139 \text{ fb}^{-1}, 300 \text{ fb}^{-1}, 500 \text{ fb}^{-1}, \text{ and } 3000 \text{ fb}^{-1}$
- HE-HL:  $\sqrt{s} = 14 \text{ TeV}$  and  $27 \text{ TeV}$ ,  
 $L_{int} = 139 \text{ fb}^{-1}, 300 \text{ fb}^{-1}, 500 \text{ fb}^{-1}, \text{ and }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



## **Signal production**

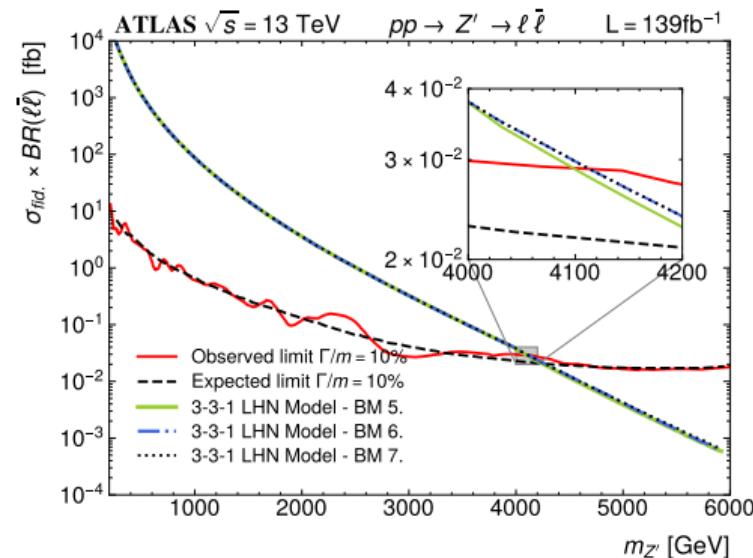
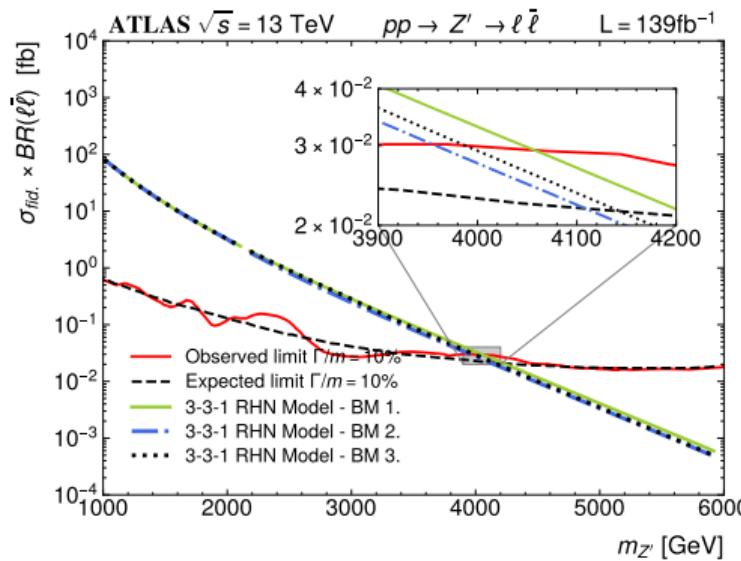
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## Branching ratios



**Figure 2:** Branching ratio for the  $Z' \rightarrow \ell^\pm \ell^\mp$  decay channel as a function to  $m_{Z'}$

$$\sigma(pp \rightarrow Z') \times BR(Z' \rightarrow \ell\bar{\ell})$$



**Figure 3:** Solid red and dashed black lines symbolize  $\sigma_{\text{fid.}} \times BR(\ell\bar{\ell})$  upper limits at 95%CL as a function of  $Z'$  mass for the dilepton channel  $Z' \rightarrow \ell\bar{\ell}$  in the ATLAS experiment (A. Collaboration, 2019)<sup>[7]</sup> with  $p_T > 30$  GeV and  $|\eta| < 2.5$ . Solid yellowgreen, dash-dot blue, and black dotted lines represent the theoretical production of the  $\sigma(pp \rightarrow Z') \times BR(Z' \rightarrow \ell\bar{\ell})$ .

$$\sigma(pp \rightarrow Z') \times BR(Z' \rightarrow \ell\bar{\ell})$$

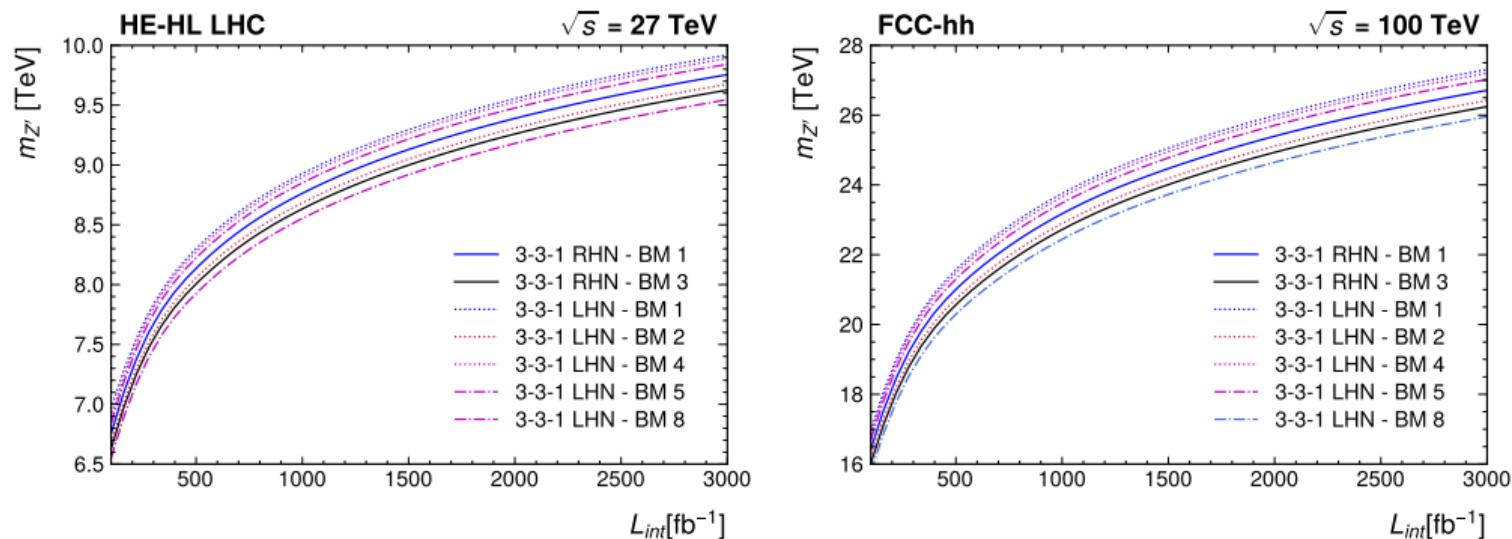
**Table 3:**  $m_{Z'}$  lower bounds considering the dilepton signal data at the LHC<sup>[7]</sup> and the theoretical signal production for the 3-3-1 RHN and LHN models.

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

<sup>1</sup>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.

<sup>2</sup>The lower bound of BM 3 for the 3-3-1 RHN model is equivalent to those of BM 9 in the 3-3-1 LHN model.

## HE-HL and FCC-hh colliders



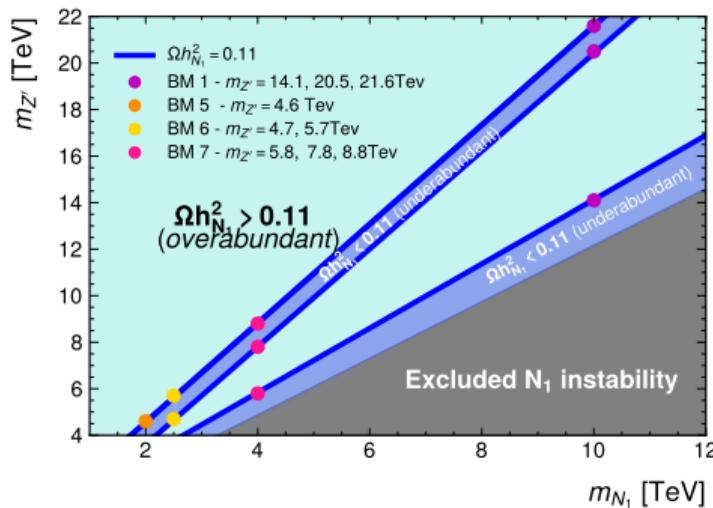
**Figure 4:**  $m_{Z'}$  Vs  $L_{\text{int}}$  ( $\sqrt{s} = 27 \text{ TeV}$  and  $100 \text{ TeV}$ ) for some BMs considered in this work

Most constraining cases:  $m_{Z'} > 5.8 \text{ TeV}$  ( $\sqrt{s} = 14 \text{ TeV}$ ),  $m_{Z'} > 9.9 \text{ TeV}$  ( $\sqrt{s} = 27 \text{ TeV}$ ), and  $m_{Z'} > 27 \text{ TeV}$  ( $\sqrt{s} = 100 \text{ TeV}$ )

# **Dark Matter**

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## Thermal Production



**Figure 5:** Parameter space  $m_{Z'} \times m_{N_1}$  plane that explains the thermal relic density. In the gray region,  $N_1$  is not stable.

$\Omega h^2 = 0.11$ <sup>[8]</sup> is the curve that yields the correct relic density (solid blue curves shown in Fig. 5).

The current and projected direct detection bounds, from XENON or PANDAX collaborations<sup>[9,10,11]</sup> are significantly surpassed by current LHC data.

## **Conclusions**

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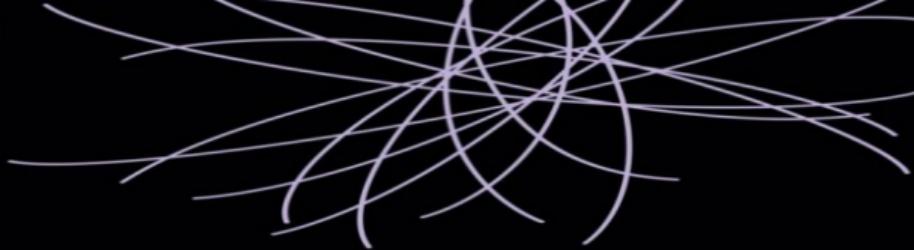
## Conclusions

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

# References

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THANK YOU SO MUCH FOR  
YOUR ATTENTION!

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QUESTIONS & COMMENTS