Exclusion bounds for neutral gauge bosons

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based on [2402.14786] with Z. Trócsányi

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Outline

- Theory considerations
- Light Z' bosons
- Heavy Z' bosons
- Conclusions

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Theory considrations for neutral gauge bosons

Motivation for extra neutral gauge bosons (Z')

- Appears after breaking a $U(1)$ gauge group (or higher)
- Fifth fundamental interaction?

Motivation for extra neutral gauge bosons (Z')

- Appears after breaking a $U(1)$ gauge group (or higher)
- Fifth fundamental interaction?
- Breaking a gauge group of rank r with a scalar VeV → the unbroken subgroup has at least $U(1)^r$ (GUT, SUSY, string)
- Connect a secluded sector to the SM
- A discovery would have a lot of consequences (extended scalar and fermion fermion sectors)

[0801.1345]

Minimal extension of the SM

- SM gauge group + $U(1)_z$:

$$\begin{pmatrix} B_\mu \\ W_\mu^3 \\ B'_\mu \end{pmatrix} = \begin{pmatrix} c_W & -s_W & 0 \\ s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_Z & -s_Z \\ 0 & s_Z & c_Z \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

- Z' needs mass → BEH not enough
- ABJ anomalies appear → need to cancel
- Z' affects tree level relations (ρ-param.)

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- Z' needs mass → BEH not enough → need new scalar
- ABJ anomalies appear → need to cancel → need new fermions
- Two free z charges

z charge remarks

- Tree level Majorana mass term is allowed if $z_\chi + 2z_N = 0$
- Here $z_N = 1/2$, but different normalization is possible
- If $z_N = 0$ then only Dirac mass term is allowed for neutrinos
- If $z_N > 1/2$, then Majorana mass terms are generated by higher dim. operator

z charge remarks

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- z_ϕ appears only in the combination: $z_\phi - \frac{\eta}{2}$
- η is a running coupling $\propto$ kinetic mixing for $U(1)_Y$ and $U(1)_z$

$$\mathrm{D}_\mu^{U(1)} = -\mathrm{i}\,(y\ z)\begin{pmatrix} g_y & -g_z\,\eta \\ 0 & g_z \end{pmatrix}\begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}\begin{pmatrix} B_\mu \\ B'_\mu \end{pmatrix}$$

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- In the branching ratios of Z' the combination appears:

$$\mathbf{Z} = \frac{z_\phi - \eta/2}{z_N}$$

Other free parameters:

- $M_{Z'}$ (or rather $\xi = M_{Z'}/M_Z$ to treat diff. mass scales)
- Either the mixing angle s_z or the new gauge coupling g_z:

$$-s_z c_z \frac{(1-\xi^2)}{\rho} = \frac{2}{\sqrt{g_Y^2+g_L^2}}\, g_z \left(z_\phi - \frac{\eta}{2}\right)$$

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This is BSM only !

- From global fits one has: $\rho = 1.00038 \pm 0.00020$

- The tree level model prediction is:

$$\rho = \frac{M_W^2}{M_Z^2 c_W^2} = 1 + (\xi^2 - 1) s_z^2$$

Light Z' bosons

Constraints

- **Indirect:** EW. Precision Observables → ρ-parameter

$$|s_z| < 4.5 \cdot 10^{-3} \text{or } |z_N\, g_z| < \frac{1.7\cdot 10^{-3}}{|\mathbf{Z}|} \text{ @ } 95\% \text{ C.L.}$$

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- **Direct:** searches for $Z' \rightarrow \text{inv.}$: **BaBar** [1702.03327], **Na64** [1906.00176]

- **Direct:** searches for $Z' \rightarrow e^+e^-$: **FASER** [2308.05587]

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- These experiments search for dark photons (A'):

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 + (e\epsilon) A'_\mu \sum_f Q_f \bar{f} \gamma^\mu f$$

Matching to dark photons

- Relate similar processes (which is searched for) [1801.04847]

- For NA64 and BaBar one has

$$e\epsilon = \frac{|v_{Z',\ell}|}{2 s_W c_W} \sqrt{\mathrm{Br}(Z' \to \mathrm{inv.})}$$

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- For the FASER, the A' is also required to decay in the detector → solve the matching equations

$$\Gamma(\pi^0 \to A' + \gamma)\mathrm{Br}(A' \to e^+e^-) = \Gamma(\pi^0 \to Z' + \gamma)\mathrm{Br}(Z' \to e^+e^-)$$

$$m_{A'}\Gamma_{A'} = M_{Z'}\Gamma_{Z'}$$

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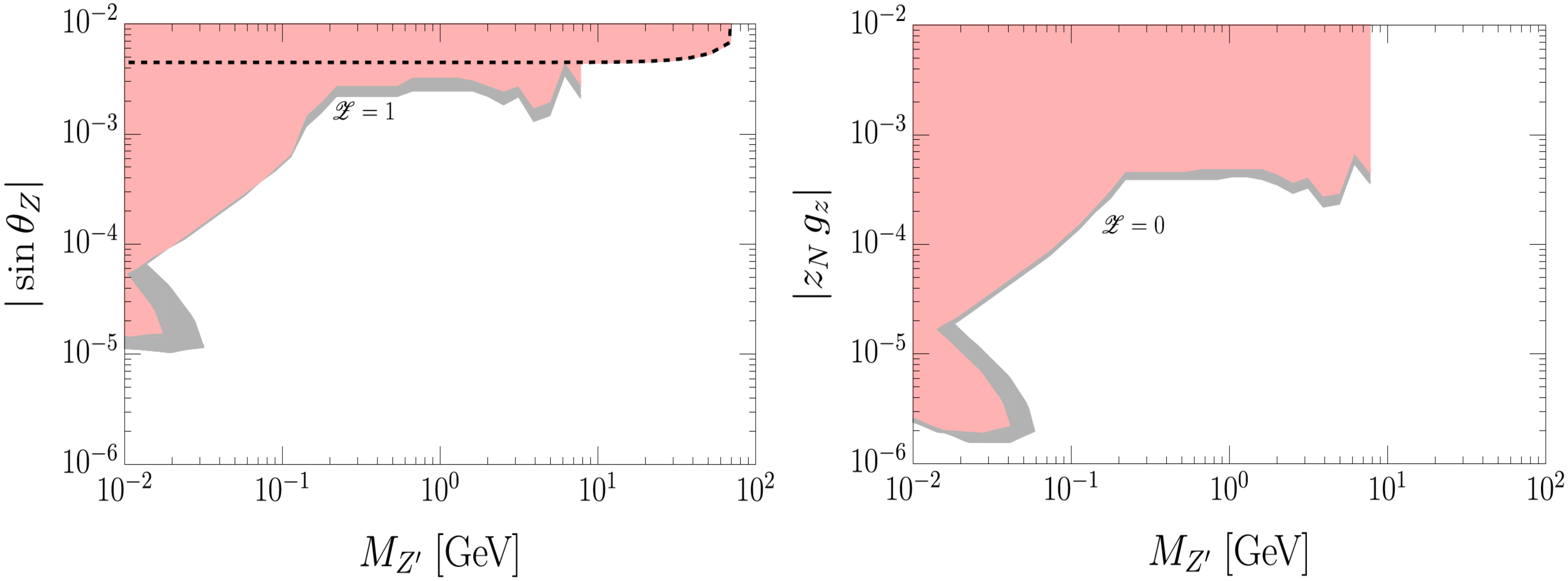
- For the FASER, the A' is also required to decay in the detector → solve the matching equations → for $M_{Z'} \ll m_\pi^0$:

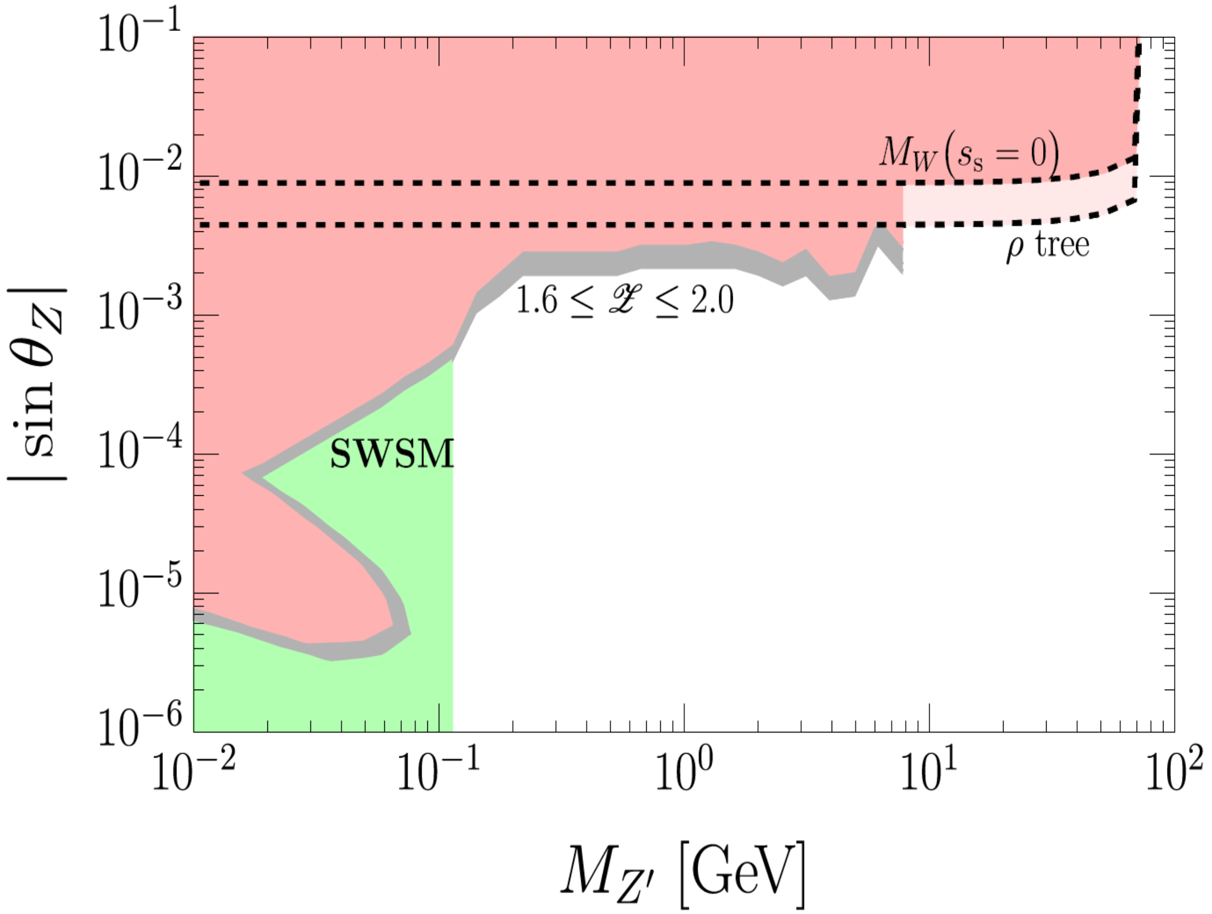
$$e\epsilon = \frac{|v_{Z',\ell}|}{2\, s_W c_W}\sqrt{\mathrm{Br}(Z' \to e^+e^-)} \ \textbf{and}\ M_{Z'} = \mathrm{Br}(Z' \to e^+e^-) M_{A'}$$

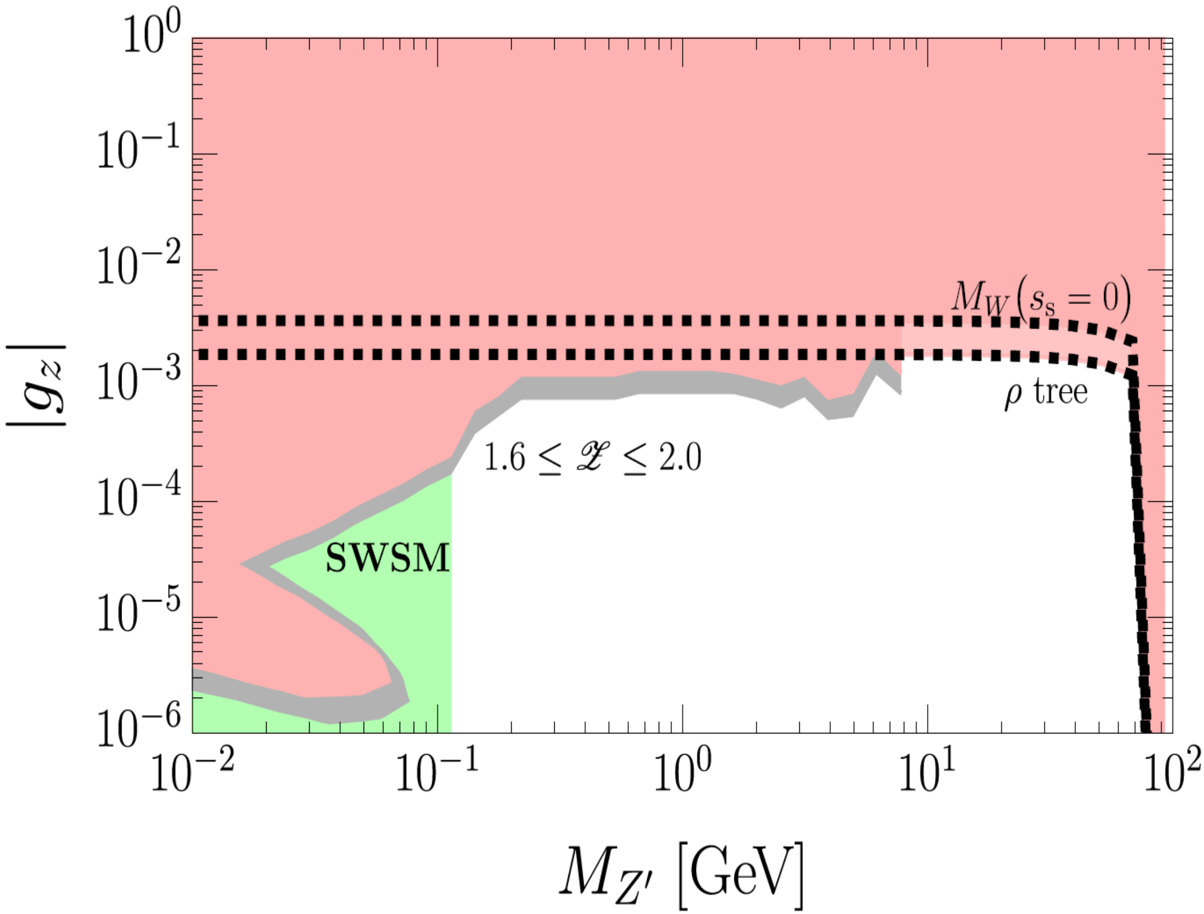
Sample exclusion bounds



Uncertainty due to sterile neutrinos: **thickness of gray line**

SWSM: $z_\phi = 1$ and $z_N = 1/2$

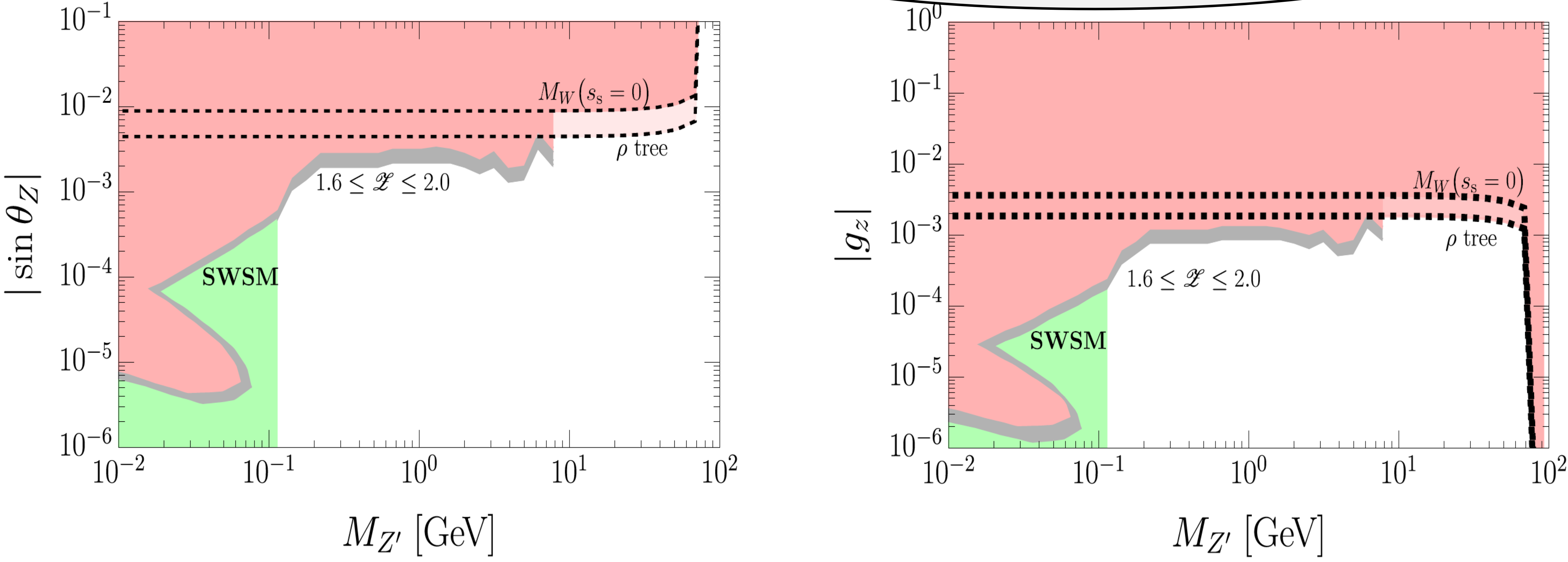




Uncertainty due to sterile neutrinos + running of η: thickness of gray line

SWSM: $z_\phi = 1$ ...

See Zoltán Trócsányi's talk from yesterday!



Uncertainty due to sterile neutrinos + running of η: thickness of gray line

Heavy Z’ bosons

Constraints

- **Indirect:** EW. Precision Observables $\rightarrow$ ρ-parameter

$$|s_Z| < 2.5 \cdot 10^{-3} \left[\frac{1\ \mathrm{TeV}}{M_{Z'}}\right] \quad \text{or} \quad |z_N\, g_Z\,| < \frac{0.11}{|\mathbf{Z}|}\left[\frac{M_{Z'}}{1\ \mathrm{TeV}}\right] \text{ @ 95\% C.L.}$$

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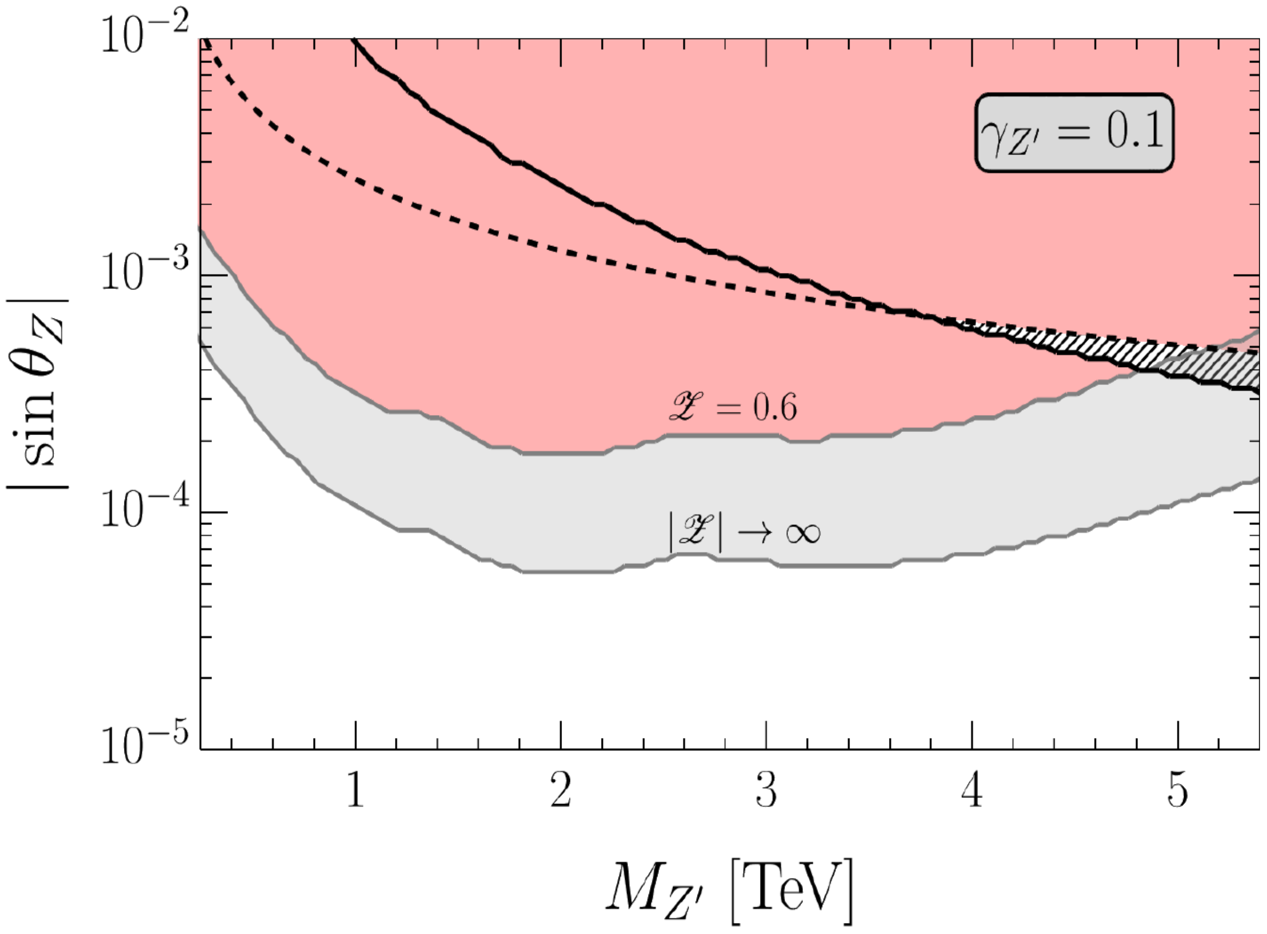
- **Direct:** searches in the LHC (**ATLAS** [1903.06248] and **CMS** [2103.02708]) for dilepton final states:

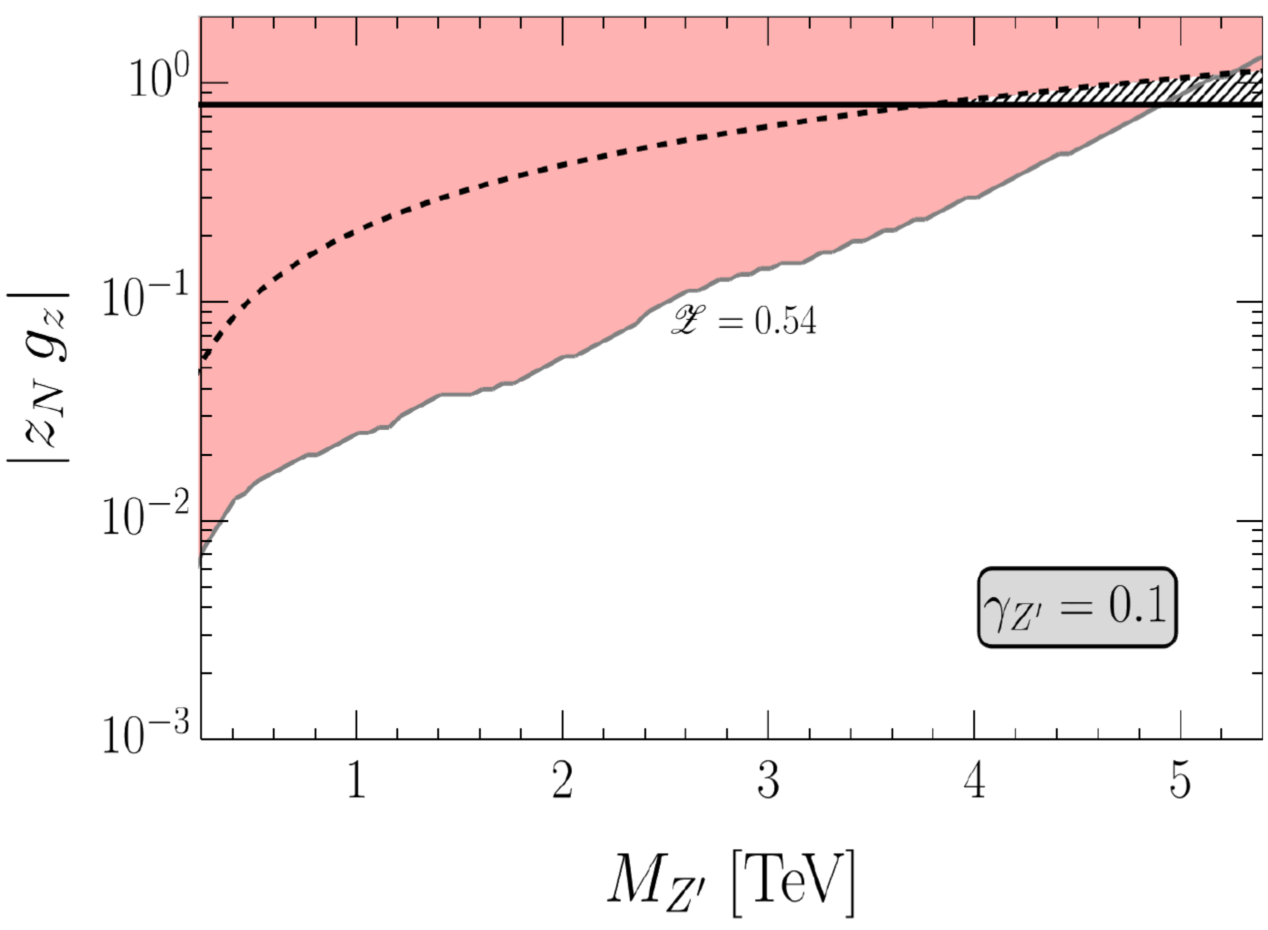
$$p + p \to Z' + X \;\to \ell^+\ell^- + X$$

$$\sigma = \frac{4\pi^2}{3s}\frac{\Gamma_{Z'}}{M_{Z'}}\text{Br}(Z' \to \ell^+\ell^-)\sum_q \text{Br}(Z' \to \bar{q}q)\, w_q(s, M_{Z'})$$

- experiments use assumptions for $\Gamma_{Z'}/M_{Z'}$

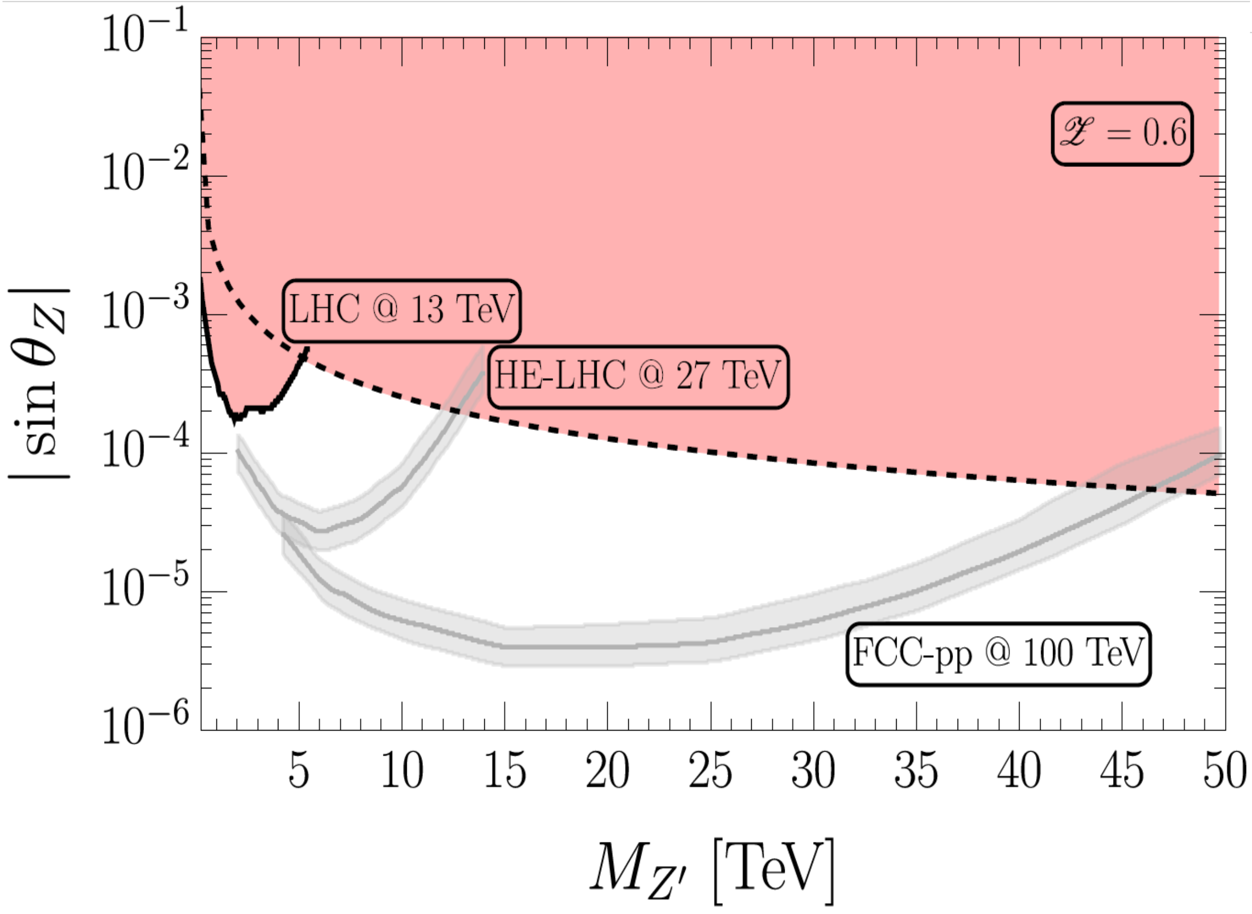
Sample exclusion bounds

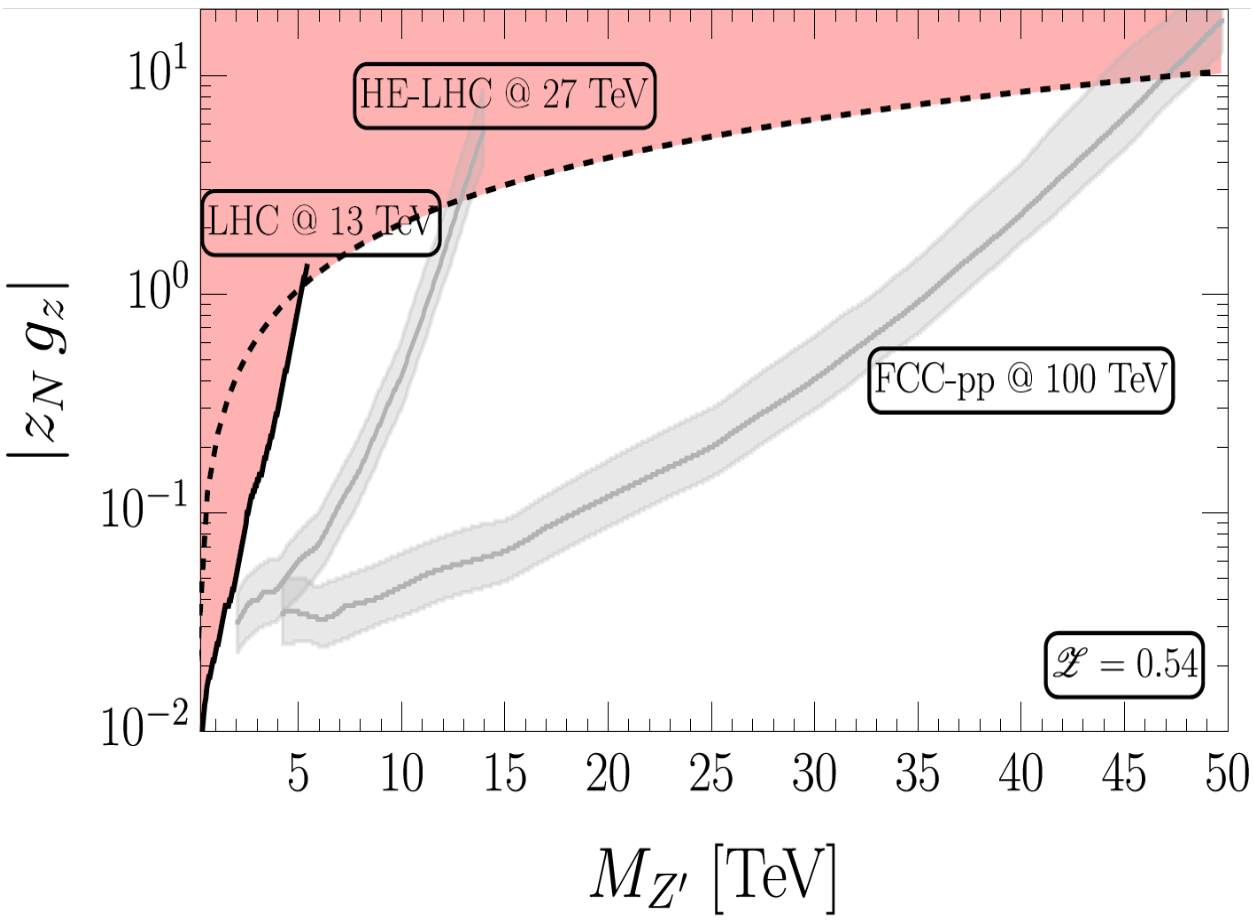




There is a **Z** value (0.6 for s_Z and 0.54 for $|z_N g_z|$) corresponding to a ***loosest*** bound!

Projections for future colliders





…using detector simulations for the HE-LHC and FCC-hh

Interesting process

- For very large $M_{Z'}$ the decay

$$Z' \to Z + W^+ + W^-$$

might dominate over the leptonic decay of the Z'!

- The ratio of the branching fractions (also the cross sections' in the NWA):

$$\frac{\mathrm{Br}(Z' \to Z + W^+ + W^-)}{\mathrm{Br}(Z' \to \ell^+ + \ell^-)} = 0.4 \left(\frac{\mathcal{Z}^2}{2 - 6\mathcal{Z} + 5\mathcal{Z}^2}\right) \left[\frac{M_{Z'}}{10\ \mathrm{TeV}}\right]^2$$

- Potentially relevant for FCC-pp

Conclusions

- Useful parametrization: different $U(1)$ extensions can be investigated on the same footing
- ρ can be used to quickly assess the constraints from EWPO
- $(M_{Z'}, s_z)$ bounds from ρ are model independent!
- Direct searches provide more stringent constraints
- In the $p + p \to Z' + X \to \ell^+\ell^- + X$ searches there is a least severe bound: model independent constraints

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Thank you for your attention!

Backup

z charge assignment

field	$SU(3)_c$	$SU(2)_L$	y	z
Q_L	3	2	$\frac{1}{6}$	$z_q = \frac{1}{3}(z_\phi - z_N)$
U_R	3	1	$\frac{2}{3}$	$z_u = \frac{1}{3}(4z_\phi - z_N)$
D_R	3	1	$-\frac{1}{3}$	$z_d = -\frac{1}{3}(2z_\phi + z_N)$
ℓ_L	1	2	$-\frac{1}{2}$	$z_\ell = z_N - z_\phi$
N_R	1	1	0	z_N
e_R	1	1	-1	$z_e = z_N - 2z_\phi$
ϕ	1	2	$\frac{1}{2}$	z_ϕ
χ	1	1	0	$z_\chi = -1$

- Cancel anomalies
- Yukawa mass terms
- Fix all but two z charges

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- χ : new singlet scalar
- N: right handed (sterile) neutrinos

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- Choose z_N and z_ϕ to be free

Branching ratios

- Light Z' with $M_{Z'} < m_\mu$:

$$\mathrm{Br}(Z' \to \mathrm{inv.}) = \frac{(3+n_N)}{(3+n_N) + 2(1 - 2\, c_W^2\, \mathbf{Z})^2}$$

- Heavy Z':

$$\mathrm{Br}(Z' \to \ell^+ \ell^-) = \frac{2 - 6\,\mathbf{Z} + 5\,\mathbf{Z}^2}{16 - 32\,\mathbf{Z} + \mathbf{Z}^2(41 + C_{w,s}\xi^2)}$$

The param $C_{w,s} \simeq 1.4 \cdot 10^{-4}$ is from three-body decays

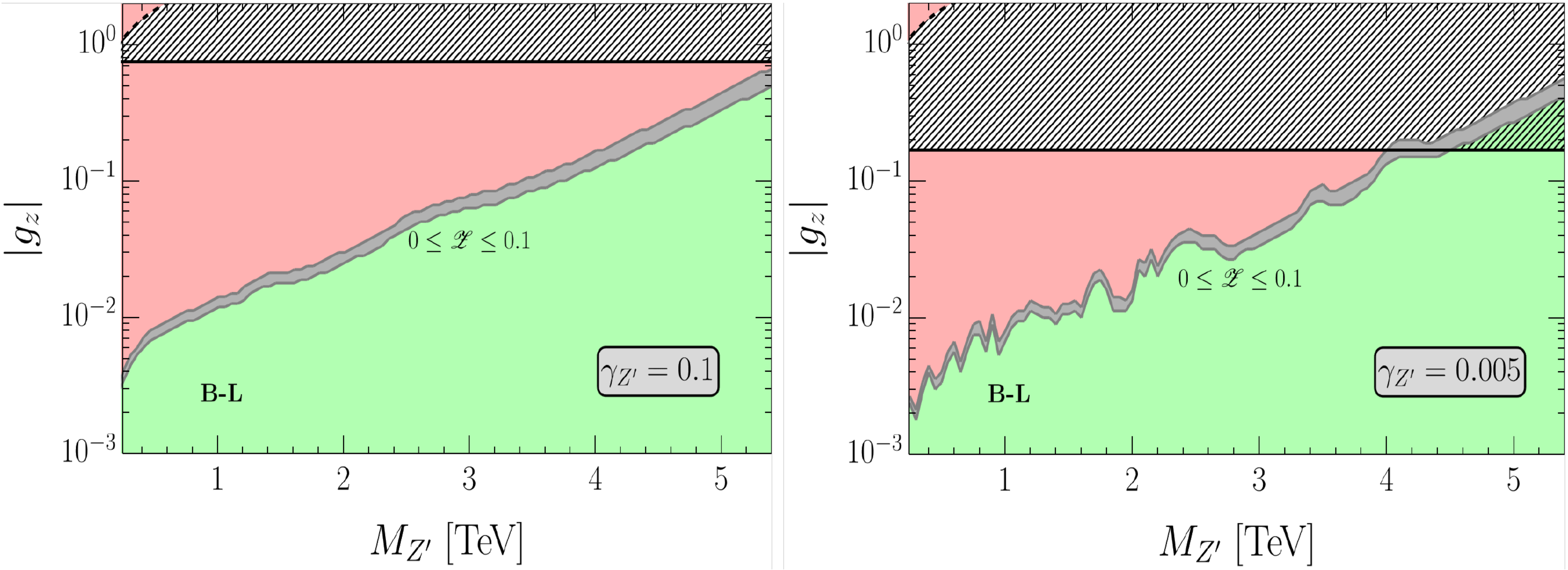
V-A couplings

- Most of the Z' phenomenology depends on:

$$\mathcal{L}_{\rm NC}^{(Z')} = -\frac{e}{2s_w c_w} Z'_\mu \sum_f \bar{f}\gamma^\mu \left(v_{Z',f} - a_{Z',f}\gamma^5\right) f$$

- $v_{Z',f}$ and $a_{Z',f}$ are pretty simple for $\xi \gg 1$ and $\xi \ll 1$
- For instance: $a_{Z',f}$ is negligible for $\xi \ll 1$
- but $a_{Z',f} = \pm\frac{1}{2} s_z \xi^2$ for $\xi \gg 1$
- The vector cps. depend on $(s_z, \xi, \mathbf{Z}) \leftrightarrow (z_N\ g_z, \mathbf{Z})$

B-L: $z_\phi = 0$ and $z_N = 1/2$



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