

Exclusion bounds for neutral gauge bosons

Zoltán Péli

based on [2402.14786] with Z. Trócsányi

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ELTE

EÖTVÖS LORÁND
TUDOMÁNYEGYETEM



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Outline

What is a Z' boson?

- Free parameters
- Light Z' bosons
- Heavy Z' bosons
- Conclusions



A Z' boson is a hypothetical elementary particle in particle physics. Here's a detailed explanation of what it is:

What is a Z' Boson?

- **Hypothetical Particle:** The Z' boson (pronounced "Z-prime") is a proposed particle that extends beyond the particles described in the Standard Model of particle physics.
- **Gauge Boson:** Like the Z boson in the Standard Model, the Z' boson is a gauge boson. Gauge bosons are force carrier particles that mediate the fundamental forces of nature.

Free parameters

Minimal extension of the SM with Z'

- SM gauge group + $U(1)_Z$: new gauge field B'_μ
- Covariant derivative is modified:

$$D_\mu^{U(1)} = -i (y \mathbf{z}) \begin{pmatrix} g_y & -g_Z \eta \\ 0 & g_Z \end{pmatrix} \begin{pmatrix} B_\mu \\ B'_\mu \end{pmatrix}$$

- $\eta \propto$ kinetic mixing ($F'_{\mu\nu} F^{\mu\nu}$)

\mathbf{z} charges are defined
at $\eta(\mu_0) = 0$

- Rotate to mass eigenstates (3 neutral gauge bosons):

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

Extra fields

- New singlet scalar field χ with z_χ : make the Z' massive
- $z_\chi \sim$ normalize g_Z , such that $z_\chi := -1$
- New fermion fields ν_R (right handed neutrinos) with z_N : cancel gauge anomalies
- $z_N \sim$ neutrino mass generation mechanism: tree level Majorana mass term is allowed if $z_\chi + 2z_N = 0$ ($\sim \chi \bar{\nu}_R \nu_R^c$)

Z charge remarks

- 2 free Z charges: **anomaly cancellation + Yukawa masses + normalization of g_Z**

Fixes z_ϕ

$z_\chi := -1$

- Usually z_u and z_q are chosen as free ones \rightarrow **choose z_ϕ , z_N instead**
[hep-ph/0212073]

- **z_ϕ** and **η** appears only in the combination: **$z_\phi - \frac{\eta}{2}$**

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

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

- E.g.: in the B-L model: **$\mathcal{Z} = \mathbf{0}$**

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 :

$$-s_Z c_Z \frac{(1-\xi^2)}{\rho} = \frac{2}{\sqrt{g_Y^2 + g_L^2}} g_Z (z_\phi - \eta/2)$$

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This is BSM only !

- From global fits one has: $\rho = 1.00038 \pm 0.00020$ [PDG 2022]
- The tree level prediction is:

$$\rho = \frac{M_W^2}{M_Z^2 c_W^2} = 1 + (\xi^2 - 1) s_Z^2 \quad \begin{array}{l} [2305.1193] \\ [2306.01836] \end{array}$$

Light Z' bosons

Constraints

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

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

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- **Direct:** searches for $Z' \rightarrow \text{inv.}$: **BaBar** [1702.03327], **NA64** [1906.00176]

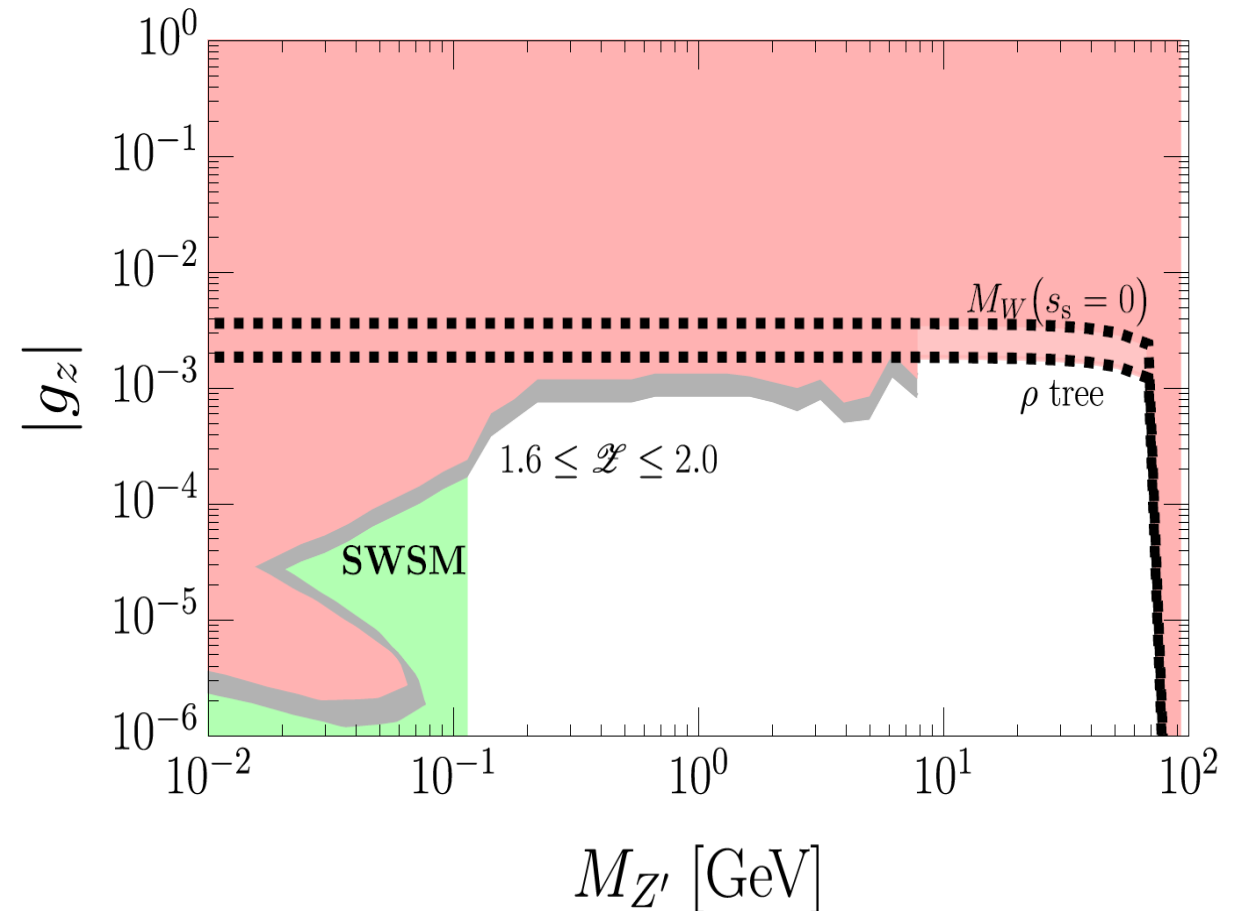
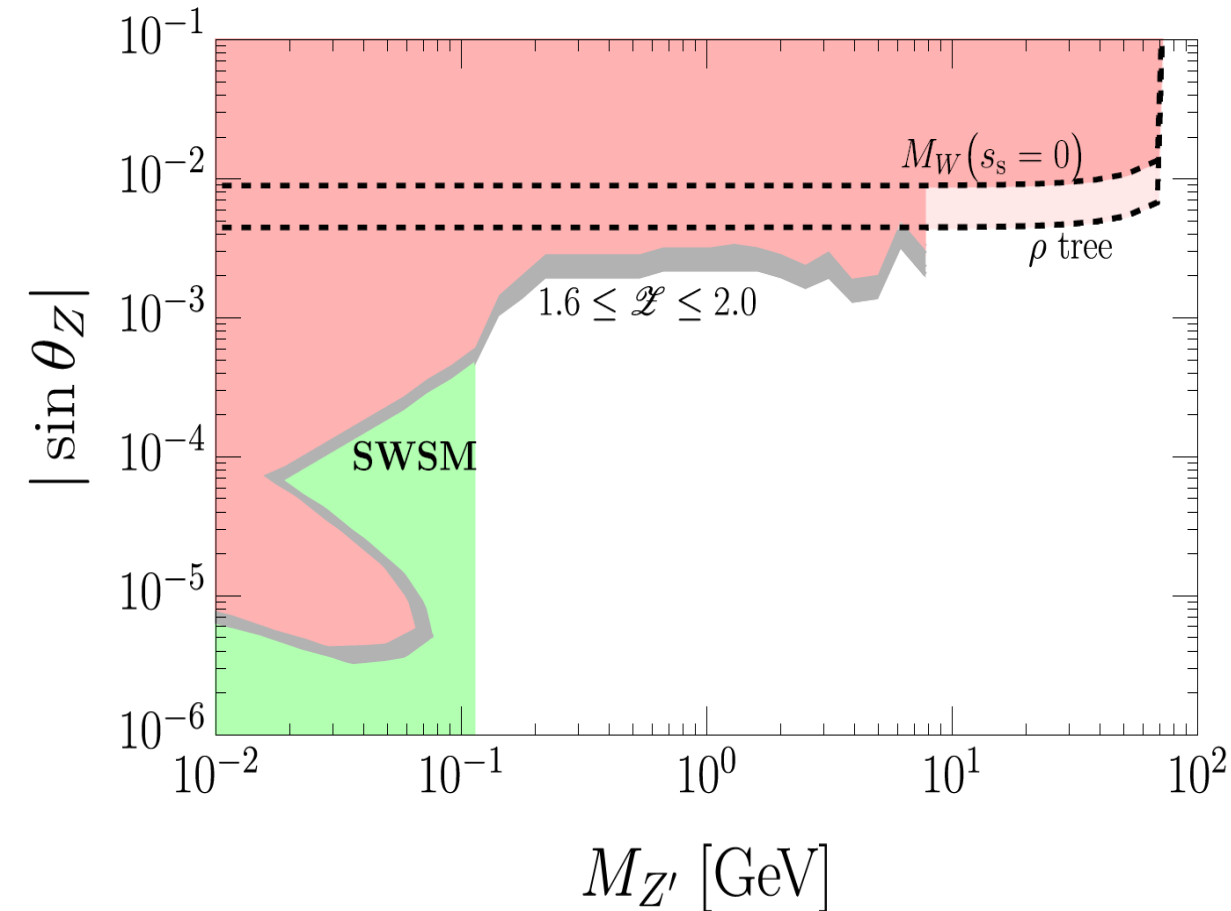
- **Direct:** searches for $Z' \rightarrow e^+ e^-$: **FASER** [2308.05587]

Far from a complete list

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

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 + (e\epsilon) A'_\mu \sum_f Q_f \bar{f} \gamma^\mu f \rightarrow \epsilon(M_{Z'}, |s_Z|, \mathcal{Z}) \text{ or } \epsilon(M_{Z'}, |z_N g_Z|, \mathcal{Z})$$

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



Uncertainty due to sterile neutrinos + running of η : thickness of gray line
 (Is the Z' kinematically allowed to decay into the sterile neutrinos?)

Heavy Z' bosons

Constraints

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

$$|s_z| < 2.5 \cdot 10^{-3} \left[\frac{1 \text{ TeV}}{M_{Z'}} \right] \text{ or } |z_N g_z| < \frac{0.11}{|z|} \left[\frac{M_{Z'}}{1 \text{ TeV}} \right] @ 95\% \text{ C.L.}$$

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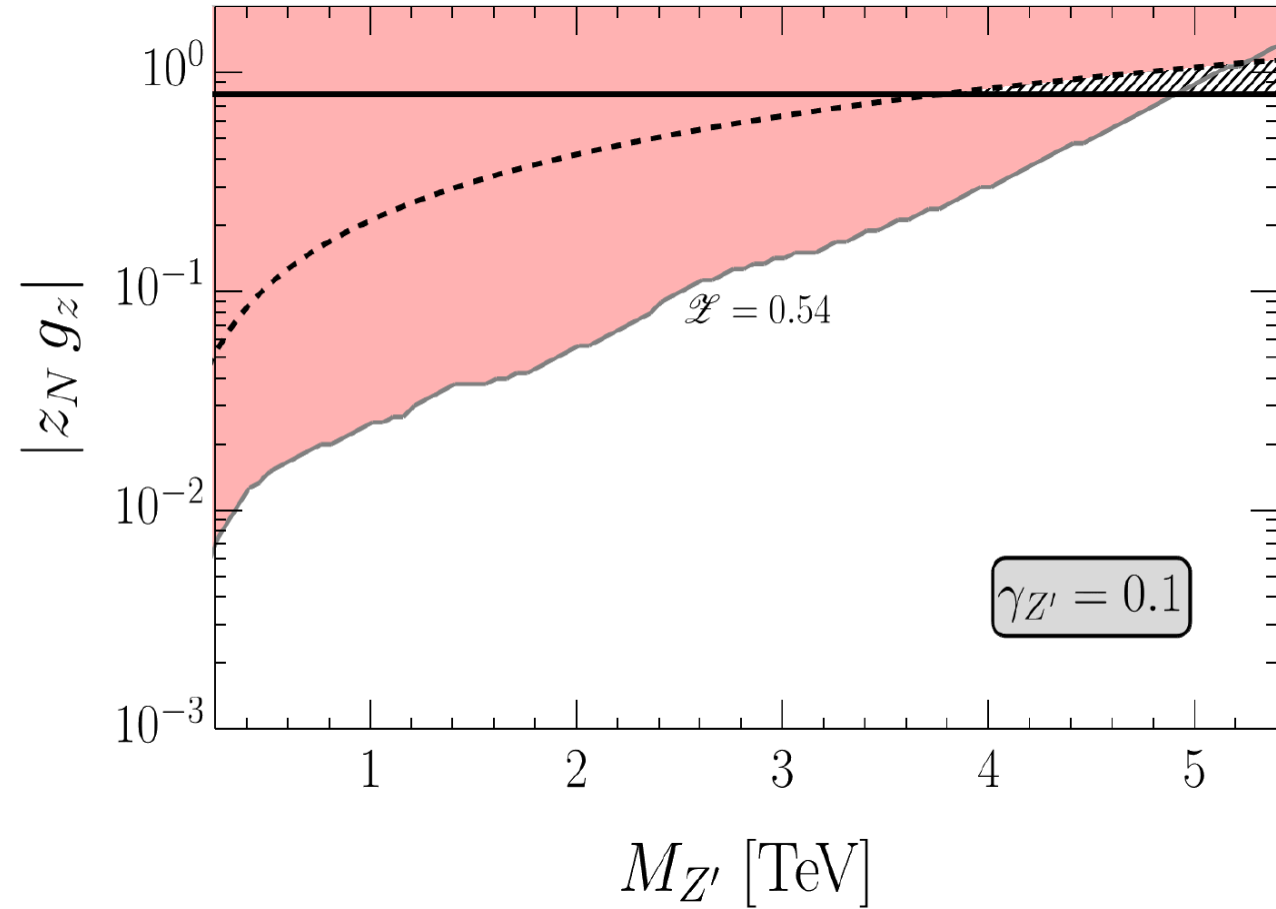
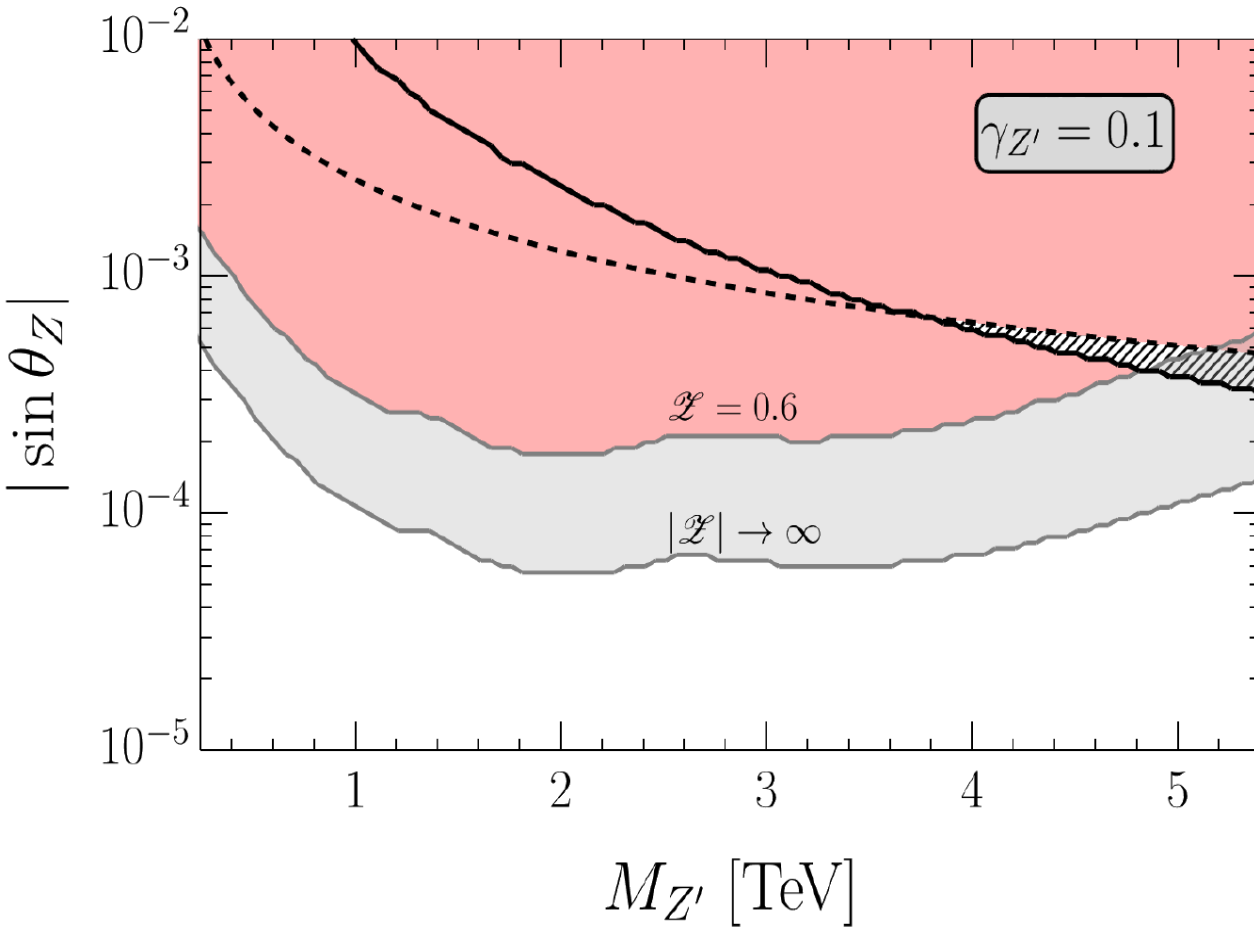
- **Direct:** searches in the LHC (**ATLAS** [1903.06248] and **CMS** [2103.02708]) in dilepton final states:

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

$p + p \rightarrow Z' + X \rightarrow \ell^+ \ell^- + X$

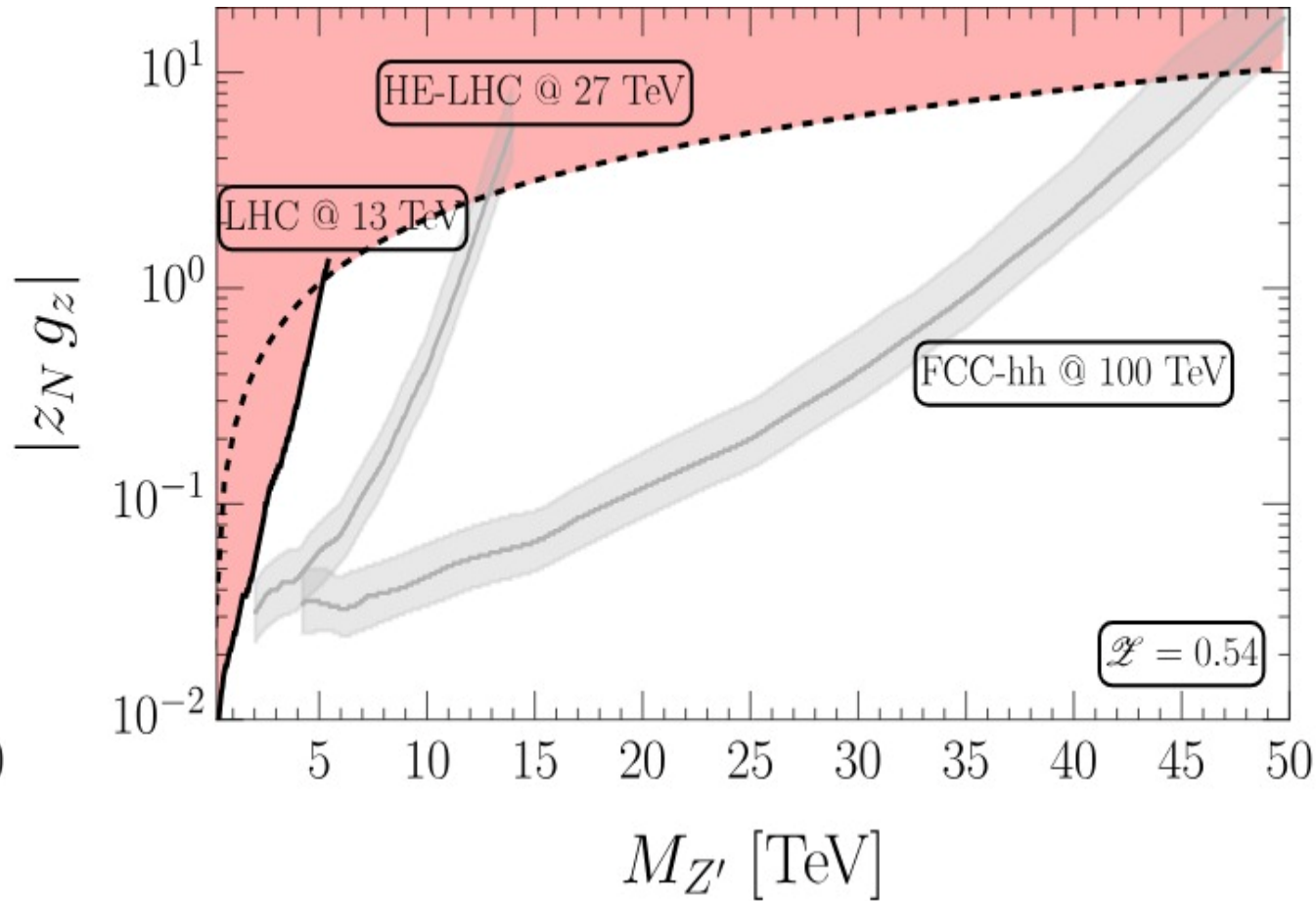
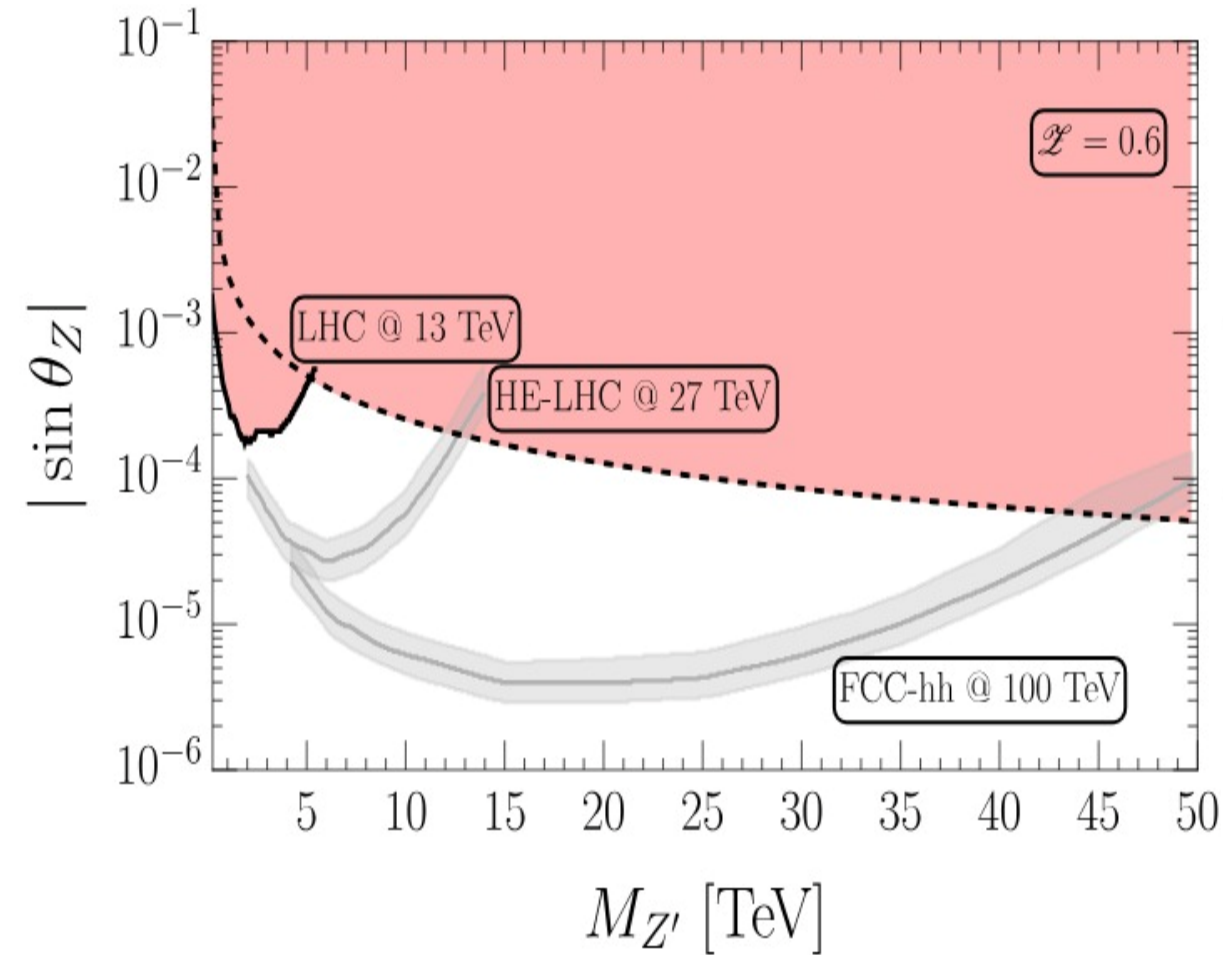
- experiments use assumptions for $\gamma_{Z'} = \Gamma_{Z'}/M_{Z'}$

Model independent bounds?



There is a \mathcal{Z} value corresponding to a *loosest* bound!

Projections for future colliders



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

Interesting process

- For **very large** $M_{Z'}$ (~ 10 TeV) the decay

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

might dominate over the leptonic decay of the Z' !

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

$$\frac{\sigma(pp \rightarrow Z' + X \rightarrow ZWW + X)}{\sigma(pp \rightarrow Z' + X \rightarrow \ell\ell + X)} = \frac{\text{Br}(Z' \rightarrow Z + W^+ + W^-)}{\text{Br}(Z' \rightarrow \ell^+ + \ell^-)} = 0.4 \left(\frac{z^2}{2 - 6z + 5z^2} \right) \left[\frac{M_{Z'}}{10 \text{ TeV}} \right]^2$$

- **Potentially relevant for FCC-hh**

Conclusions

- **Useful parametrization**: different $U(1)$ extensions can be investigated on the same footing
- The **parametrization** can be also be used in models with no sterile neutrinos, e.g: **in the $L_\mu - L_\tau$ model**
- ρ can be used to **quickly assess** the constraints from **EWPO**
- In the $p + p \rightarrow Z' + X \rightarrow \ell^+ \ell^- + X$ searches there is a **least severe bound: model independent constraints**

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
- χ : new singlet scalar
- N : right handed (sterile) neutrinos
- Choose z_N and z_ϕ to be free

Branching ratios

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

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

- Heavy Z' :

$$\text{Br}(Z' \rightarrow \ell^+ \ell^-) = \frac{2 - 6 \mathbf{Z} + 5 \mathbf{Z}^2}{16 - 32 \mathbf{Z} + \mathbf{Z}^2 (41 + C_{W,S} \xi^2)}$$

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:

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

- $v_{Z',f}$ 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 $(s_Z, \xi, \mathbf{Z}) \leftrightarrow (z_N g_Z, \mathbf{Z})$

Matching to dark photons

- Relate similar processes (which is searched for) [1801.04847]
- For **NA64** and **BaBar** one has

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

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

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

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

Matching to dark photons

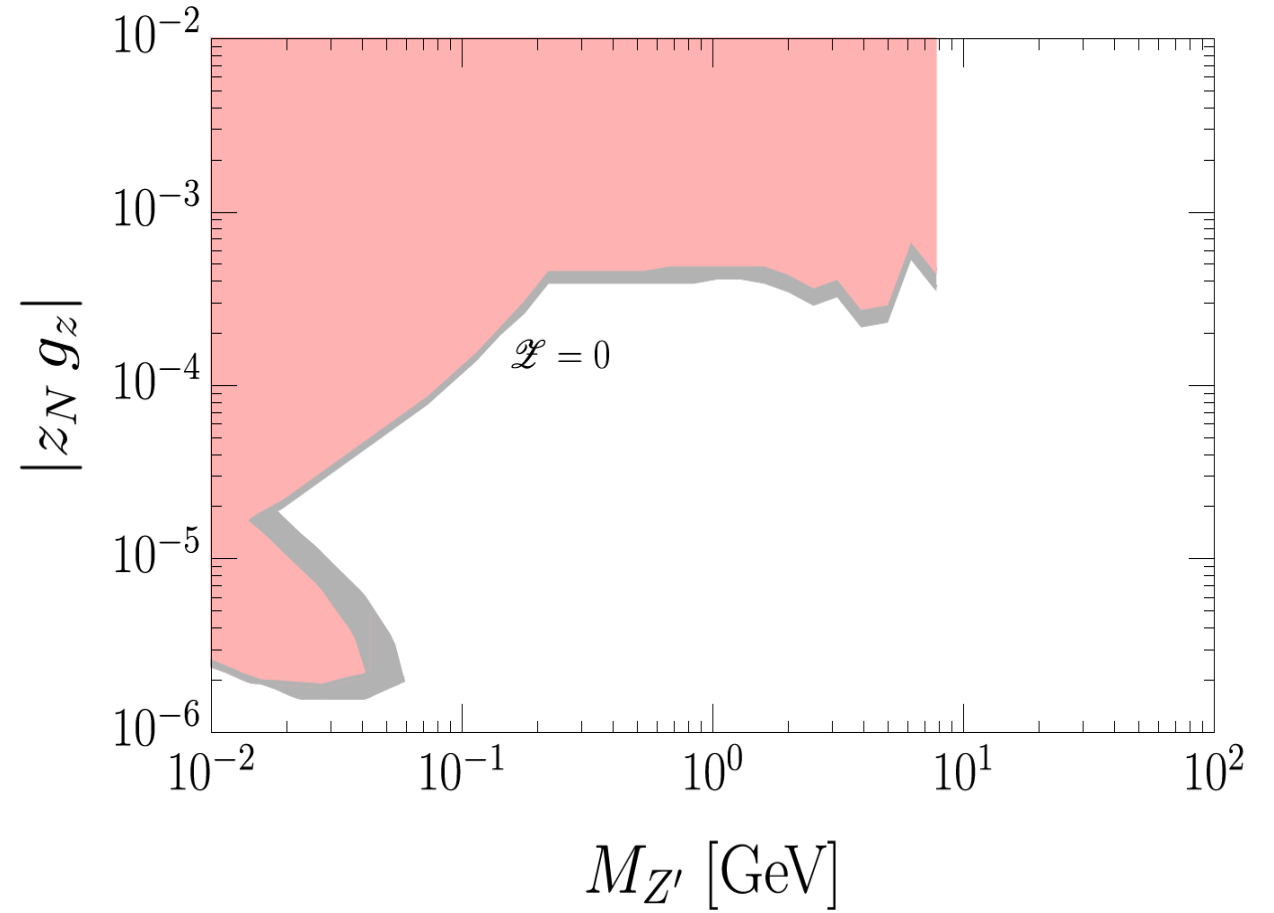
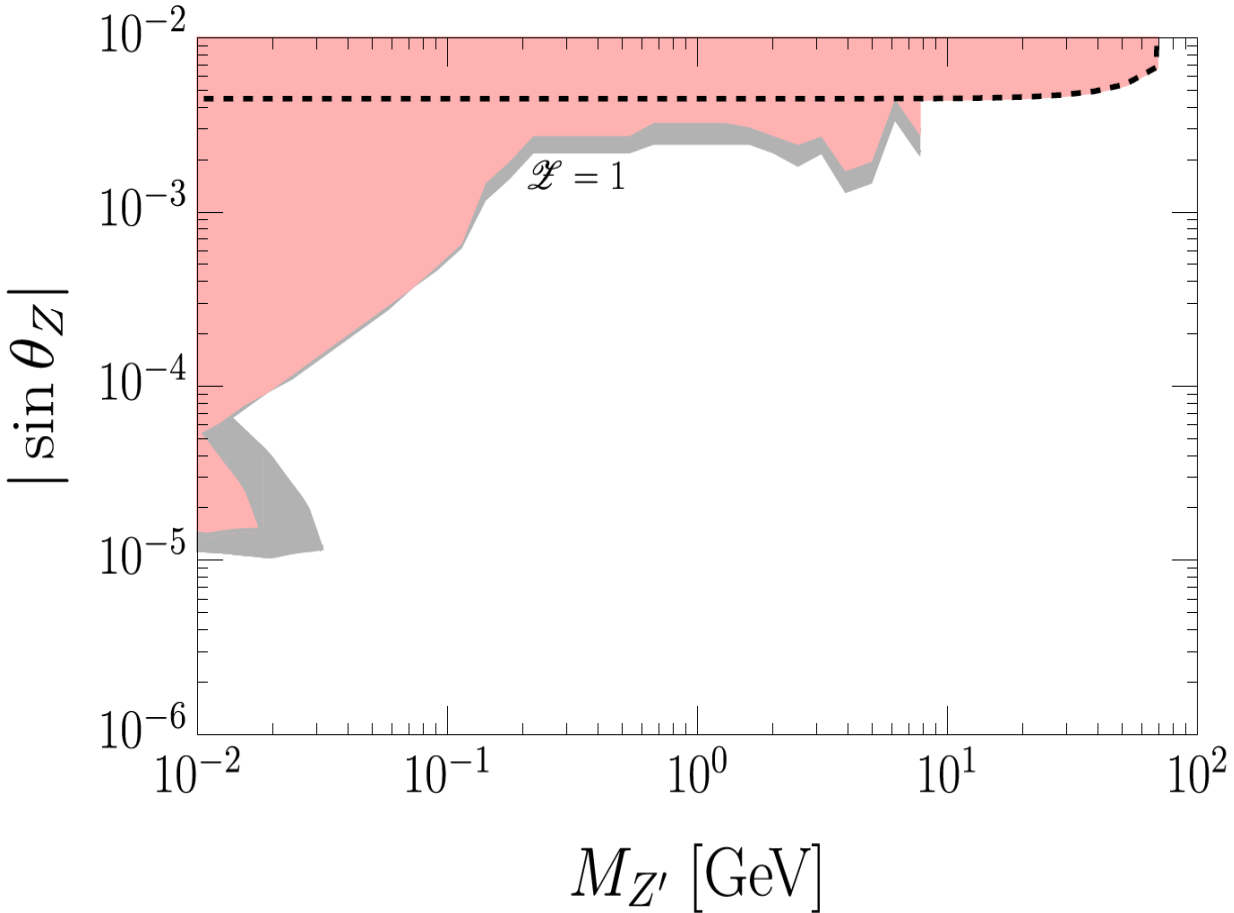
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- For the FASER, the A' is also required to decay in the detector \rightarrow solve the matching equations \rightarrow for $M_{Z'} \ll m_\pi^0$:

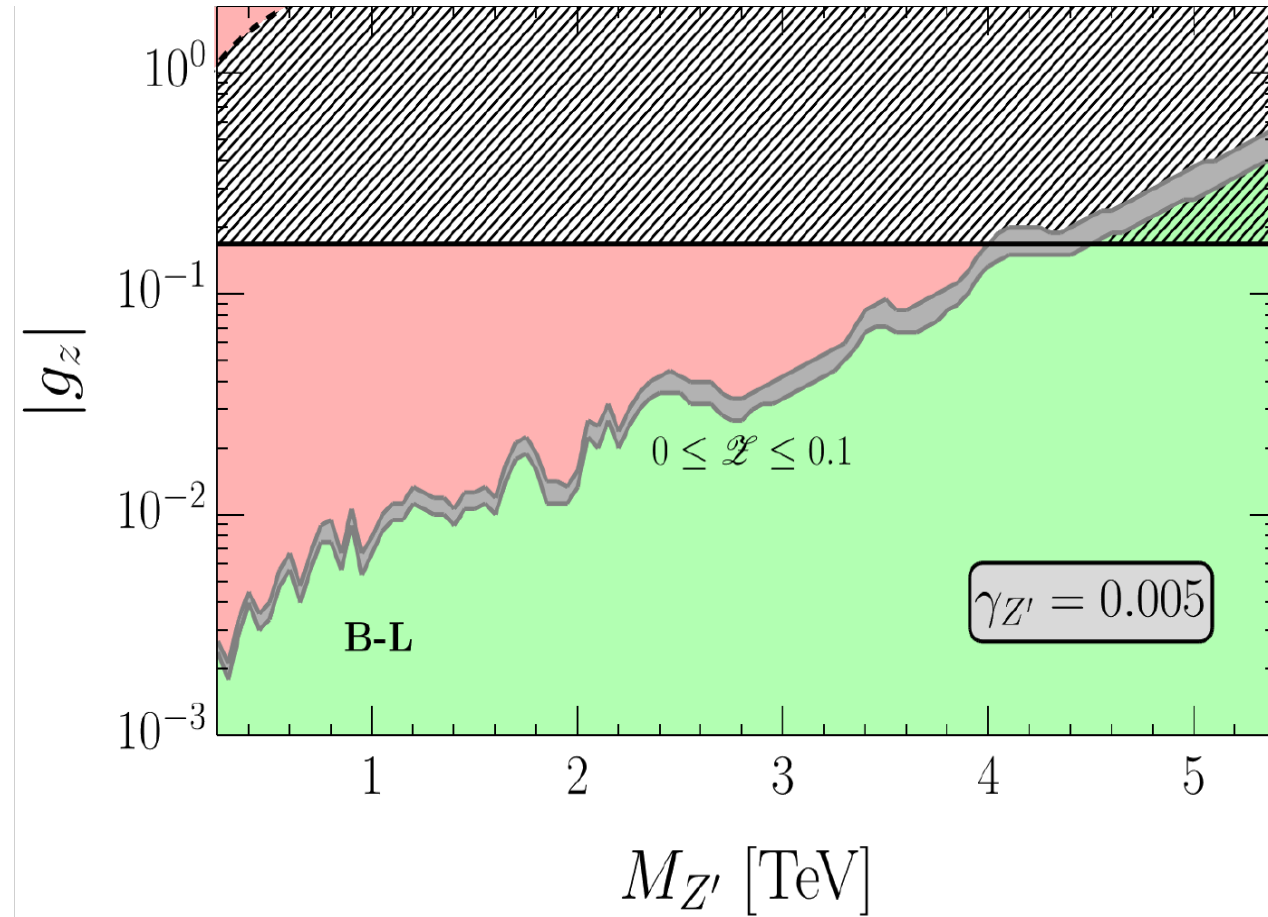
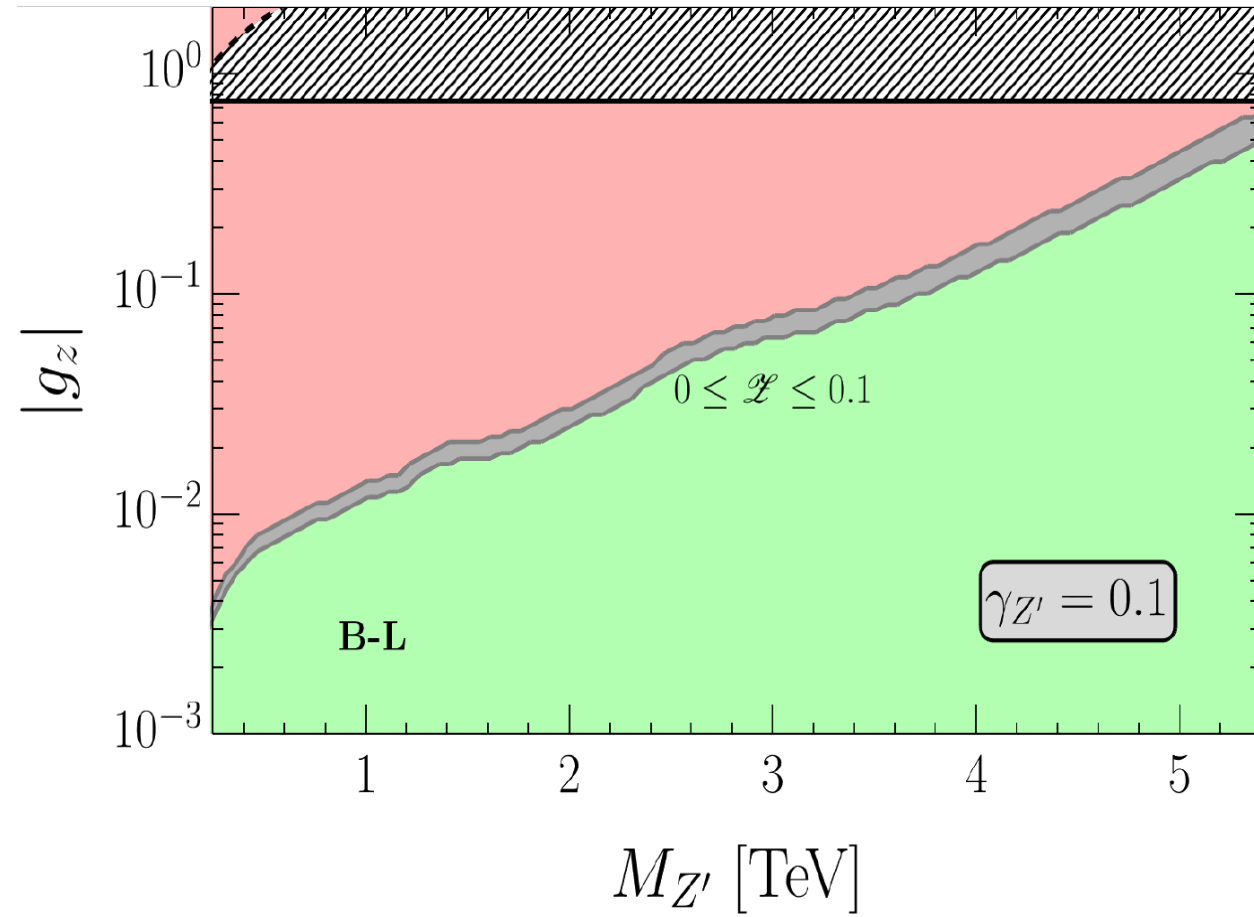
$$e\epsilon = \frac{|v_{Z',\ell}|}{2s_W c_W} \sqrt{\text{Br}(Z' \rightarrow e^+e^-)} \quad \text{and} \quad M_{Z'} = \text{Br}(Z' \rightarrow e^+e^-) M_{A'}$$

Sample exclusion bounds



Uncertainty due to sterile neutrinos: thickness of gray line

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



Uncertainty due to sterile neutrinos + running of η