Exclusion bounds for neutral gauge bosons

Zoltán Péli

based on [2402.14786] with Z. Trócsányi

ELTE
EÖTVÖS LORÁND
TUDOMÁNYEGYETEM

CATCH22+2

Dublin, May 1-5, 2024

Outline

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

Theory considerations for neutral gauge bosons

Motivation for extra neutral gauge bosons (Z')

- Z' appears after breaking a $U(1)$ gauge group (or higher)
- Fifth fundamental interaction?
- Breaking a larger gauge group with a scalar VeV → the unbroken subgroup has $U(1)$-s (e.g.: GUT, SUSY, string)
- Z' can connect to a secluded sector in the SM
- A discovery would have a lot of consequences: extended scalar [χ] (make Z' massive) and extended fermion sectors [$3 \times \nu_R$] (cancel gauge anomalies)

[0801.1345]

Minimal extension of the SM

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

- Covariant derivative is modified:

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

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

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

- Rotate to mass eigenstates:

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

z charge remarks

- 2 free z charges (due to anomaly cancellation + Yukawa masses +normalization)
- z_N ~ 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_ϕ appears only in the combination: $z_\phi - \frac{\eta}{2}$ → use this one

z charge remarks

- 2 free z charges (due to anomaly cancellation + Yukawa masses +normalization)
- $z_N \sim$ 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_ϕ appears only in the combination: $z_\phi - \frac{\eta}{2}$ → use this one
- In the branching ratios of Z' the combination appears:

$$\mathbf{Z} = \frac{z_\phi - \eta/2}{z_N} \quad \text{e.g.: } \mathrm{Br}(Z' \to \mathrm{inv.}) = \frac{(3+n_N)}{(3+n_N)+2\left(1-2\, c_W^2\, \mathbf{Z}\right)^2} \text{ for } M_{Z'} < m_\mu$$

- B-L model: $z_\phi = 0 \to \mathbf{Z} = \mathbf{0}$

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:

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

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:

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

This is BSM only !

- From global fits one has: $\rho = 1.00038 \pm 0.00020$
- The tree level model prediction is:

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

[2305.1193]

[2306.01836]

Light Z’ bosons

Constraints

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

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

Constraints

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

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

- **Direct:** searches for $Z' \to \text{inv.}$: **BaBar** [1702.03327], **NA64** [1906.00176]
- **Direct:** searches for $Z' \to e^+e^-$: **FASER** [2308.05587]

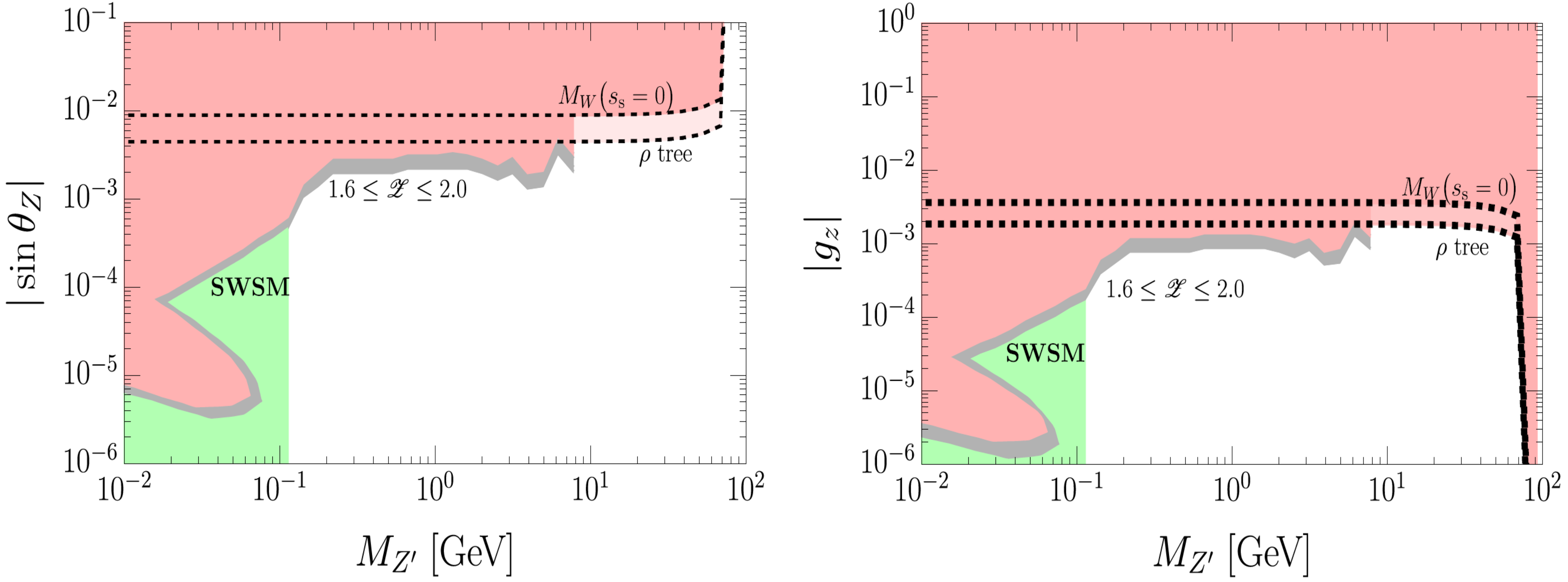
Far from a complete list

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

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

[1801.04847]

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



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

Heavy Z’ bosons

Constraints

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

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

Constraints

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

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

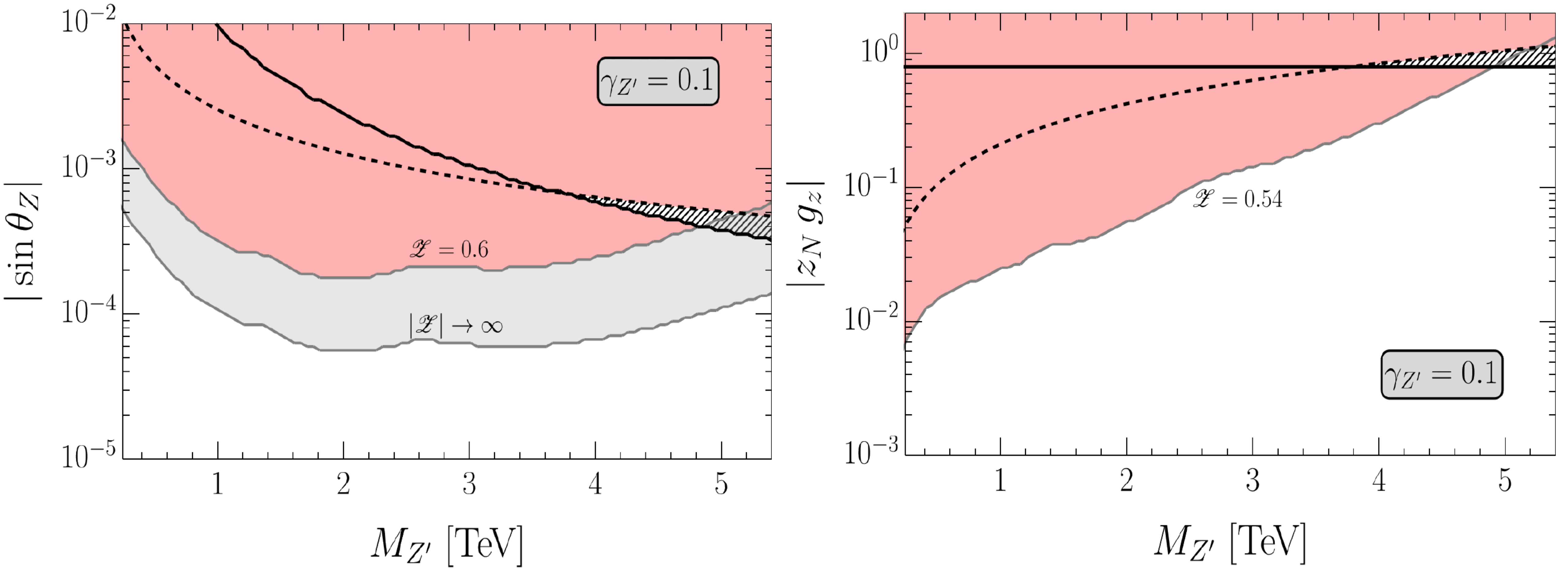
- **Direct:** searches in the LHC (**ATLAS** [1903.06248] and **CMS** [2103.02708]) in dilepton final states:

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

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

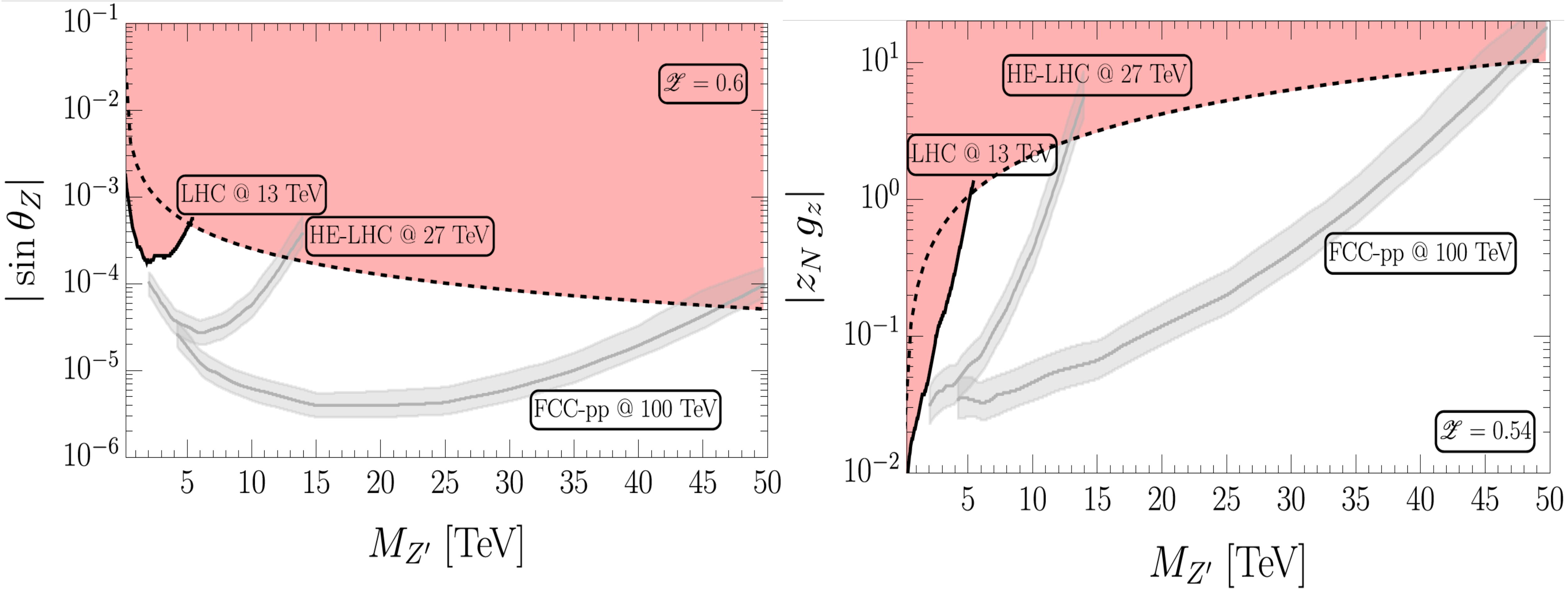
- experiments use assumptions for $\gamma_{Z'} = \Gamma_{Z'}/M_{Z'}$

Sample exclusion bounds



There is a **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 $M_{Z'}$ 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):

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

- Potentially relevant for FCC-hh

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

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

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

- Choose z_N and z_ϕ to be free

Branching ratios

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

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

- 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:

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

- $v_{Z',f}$ 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

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

Matching to dark photons

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

- For NA64 and BaBar one has

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

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

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

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

Matching to dark photons

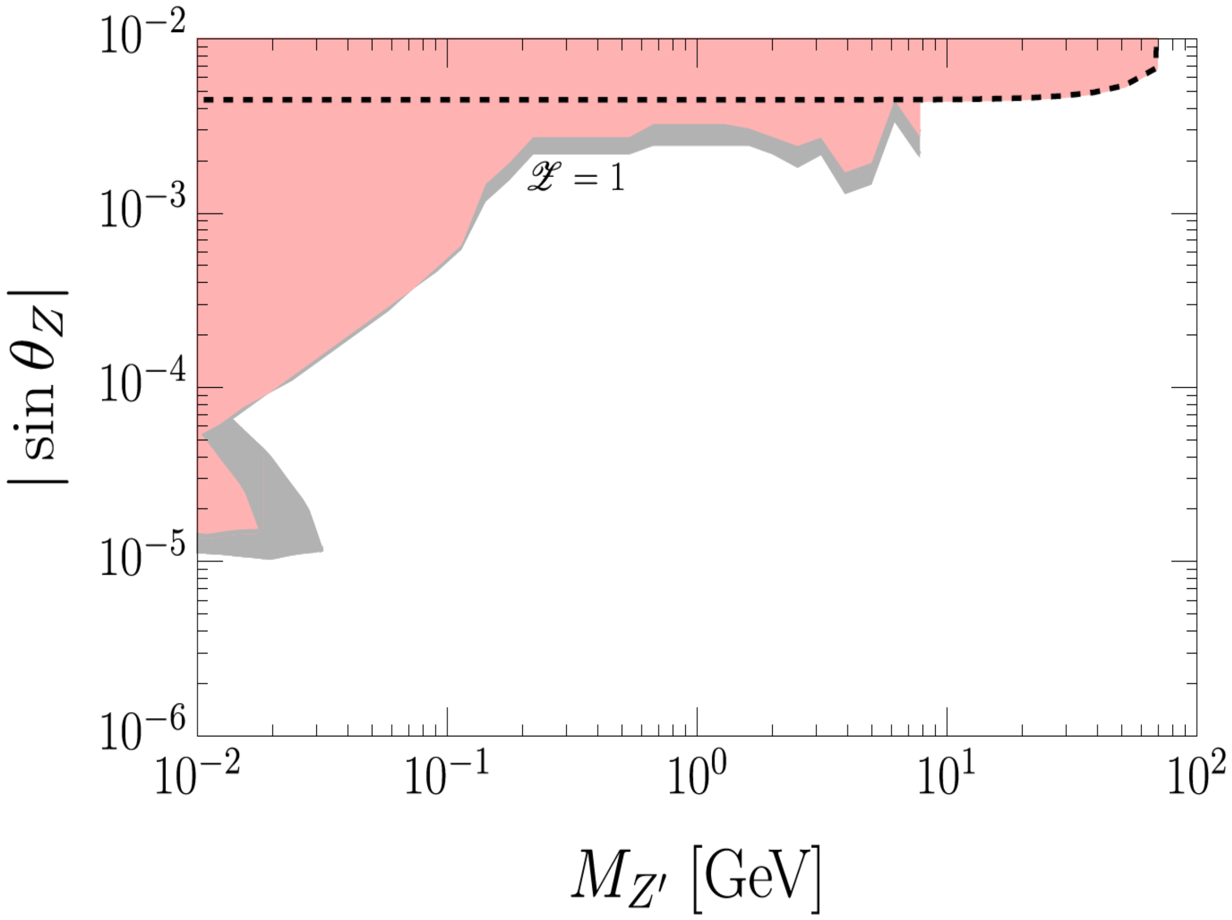
- Relate similar processes (which is searched for) [1801.04847]
- For NA64 and BaBar one has

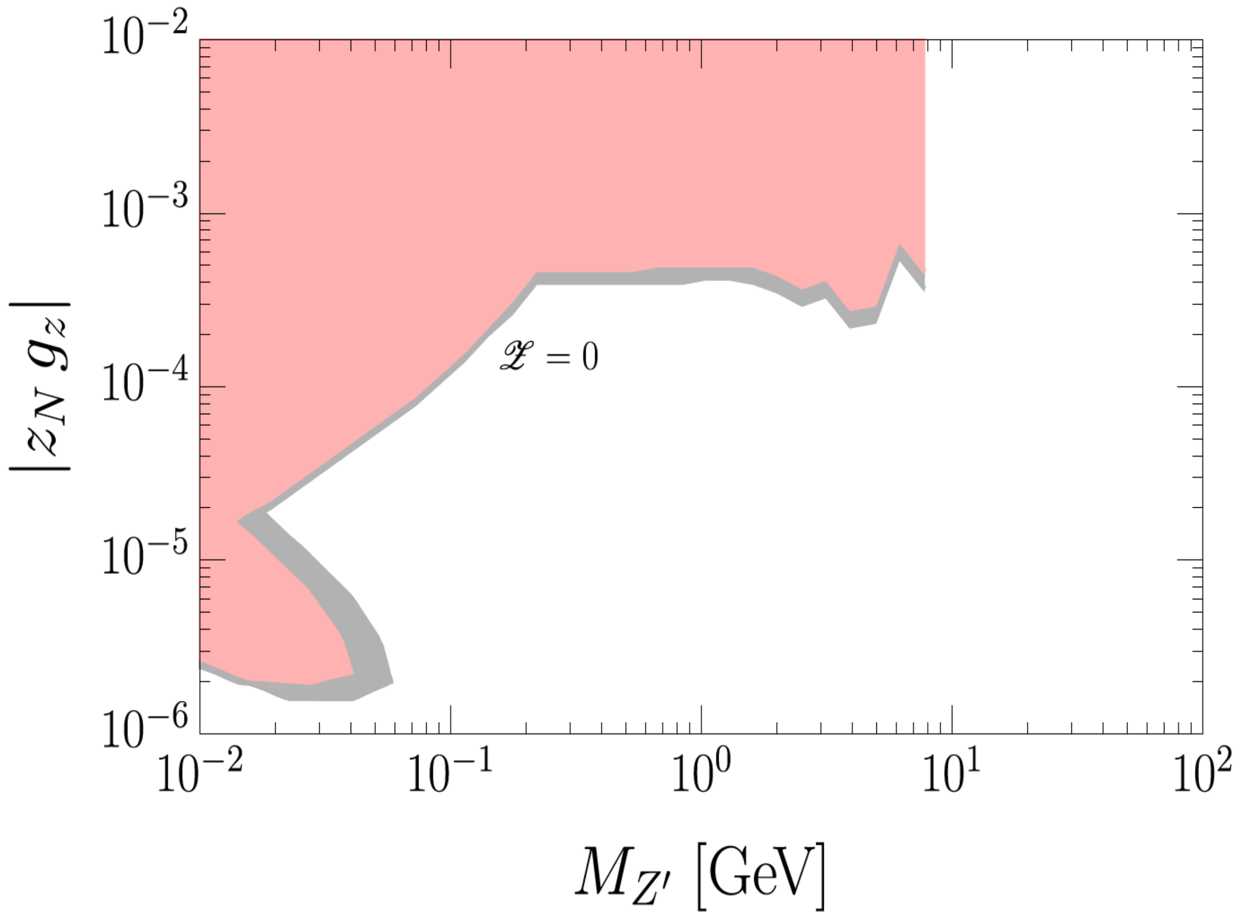
$$e\epsilon = \frac{|v_{Z',\ell}|}{2 s_W c_W}\sqrt{\mathrm{Br}(Z' \to \mathrm{inv.})}$$

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

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

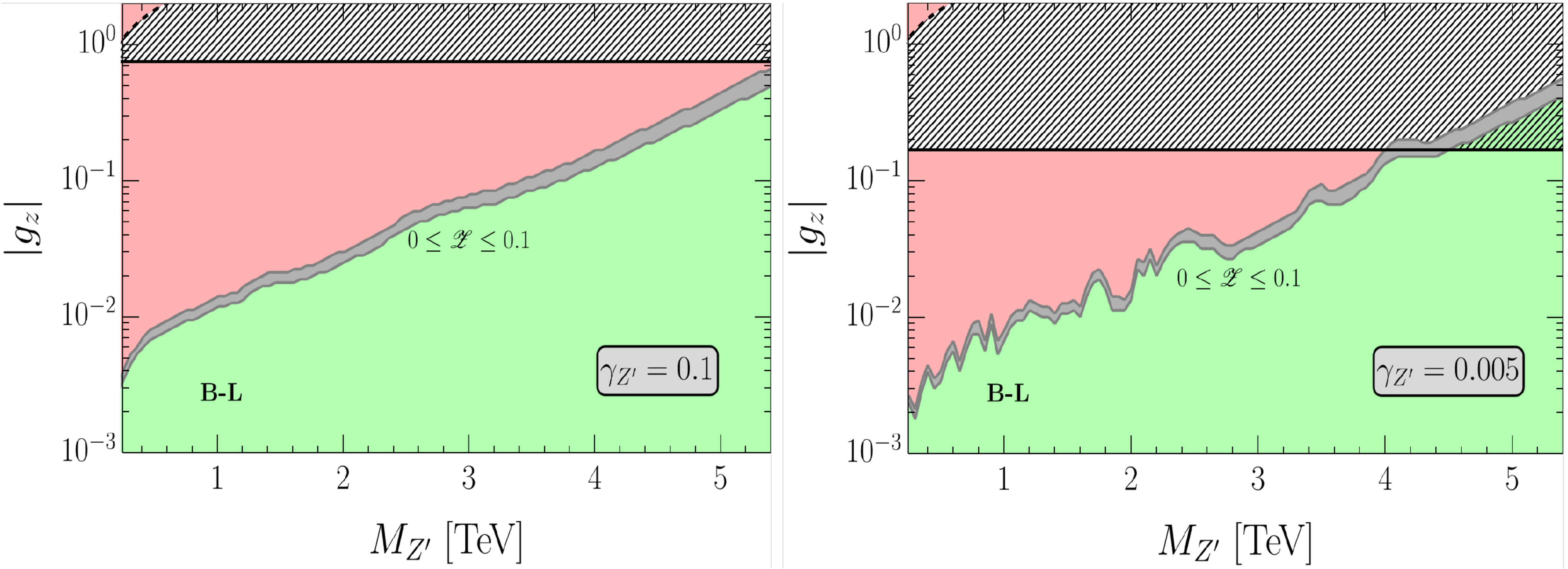
Sample exclusion bounds





Uncertainty due to sterile neutrinos: thickness of gray line

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



Uncertainty due to sterile neutrinos + running of η