Exclusion bounds for neutral gauge bosons

Zoltán Péli

with Z. Trócsányi @ PRD 015027 / arXiv: [2402.14786]

ELTE
EÖTVÖS LORÁND
TUDOMÁNYEGYETEM

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Outline

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

What is a Z' boson?

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.

Motivation for extra neutral gauge bosons (Z')

- Fifth fundamental interaction?
- Breaking a larger gauge group with a scalar VeV $\rightarrow$ 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 (make Z' massive) and extended fermion sectors (cancel gauge anomalies)

Free parameters

Minimal extension of the SM with Z'

- SM gauge group + $U(1)_z$: new gauge field B'_μ

- Covariant derivative is modified:

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

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

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

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

Extra fields

- New singlet scalar field χ with z_χ: make the Z' massive

- z_χ~ normalize g_z, such that $z_\chi := -1$

- New fermion fields ν_R (right handed neutrinos) with z_N: cancel gauge anomalies

- 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 charge remarks

- 2 free z charges: anomaly cancellation + Yukawa masses + normalization of g_z

  Fixes z_ϕ $\quad$ $z_\chi := -1$

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

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

z charge remarks

- 2 free z charges: anomaly cancellation + Yukawa masses + normalization of g_z

  Fixes z_ϕ $\quad$ $z_\chi := -1$

  - Usually z_u and z_q are chosen as free ones → 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: $\boldsymbol{\mathcal{Z} = 0}$

Branching ratio examples

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

$M_{Z'} < 2m_{N_i}$?

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

- Heavy Z':

$\xi = M_{Z'}/M_Z$

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

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

The mixing parameter η

- z_ϕ and η appears only in the combination: $z_\phi - \frac{\eta}{2} =$ effective z-charge

- Multiple paradigms, but all need an arbitrary scale:

$$z_\phi - \frac{\eta(\mu_0)}{2} = 0 \text{ or } \eta(\mu_0) = 0$$

- 1st option may need large couplings → use the 2nd one

- Run the RG eqns. with largest possible variation: $\mu_0 = M_{\mathrm{Pl}}$

- We obtain uncertainty bands in $\mathcal{Z}$: different models may have the same pheno!

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:

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

Or we can just write
$(z_N\, g_z)\, \mathcal{Z}$

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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:

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

[2305.1193]

[2306.01836]

Light Z’ bosons

Constraints

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

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

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- **Direct:** searches for $Z' \to$ inv.: **BaBar** [1702.03327], **NA64** [1906.00176]
- **Direct:** searches for $Z' \to e^+e^-$: **FASER** [2308.05587]
- These experiments search for dark photons (A'):

Far from a complete list

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

[1801.04847]

Matching to dark photons

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

- For NA64 and BaBar one has

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

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

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

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

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

Matching to dark photons

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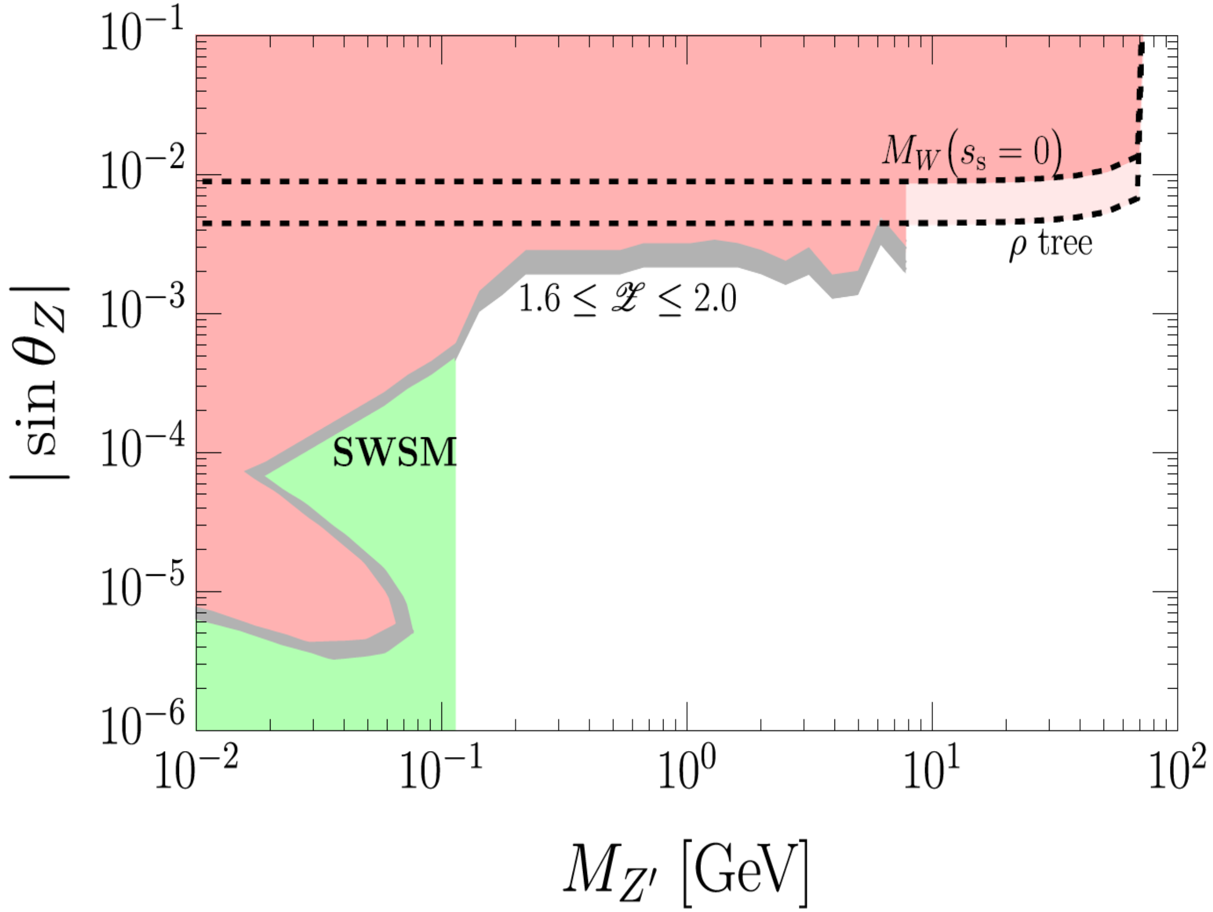
- For NA64 and BaBar one has

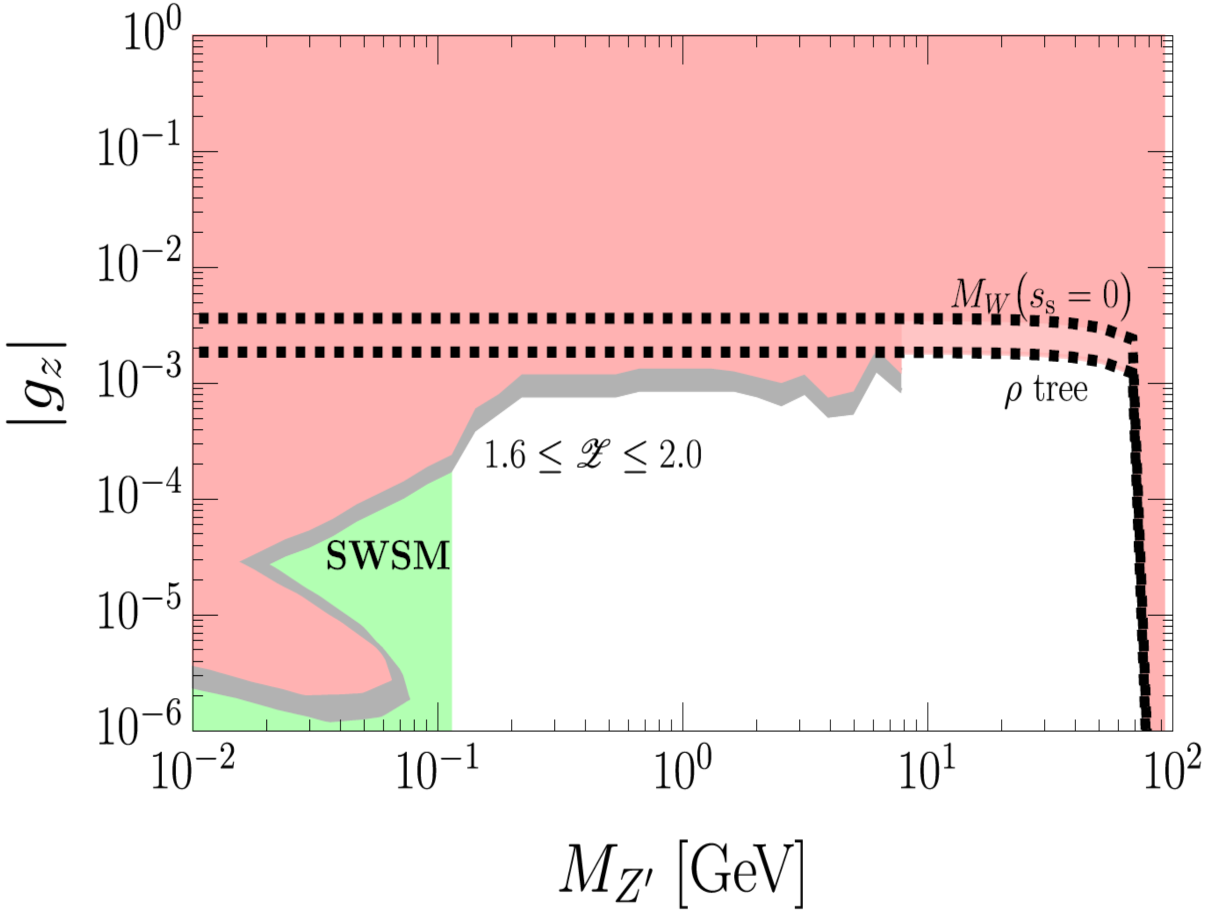
$$e\epsilon = \frac{|v_{Z',\ell}|}{2 s_W c_W} \sqrt{\mathrm{Br}(Z' \to \mathrm{inv.})}$$

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

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

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

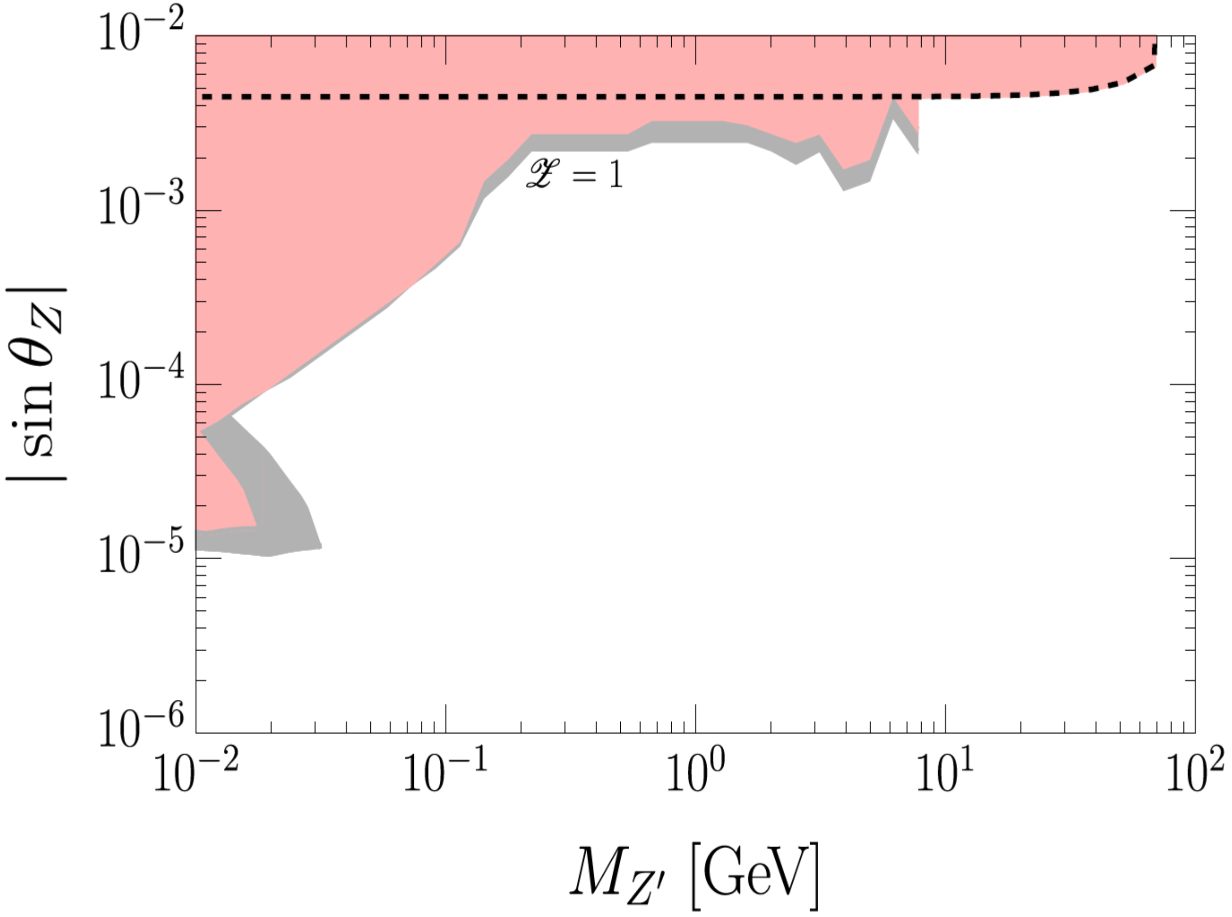


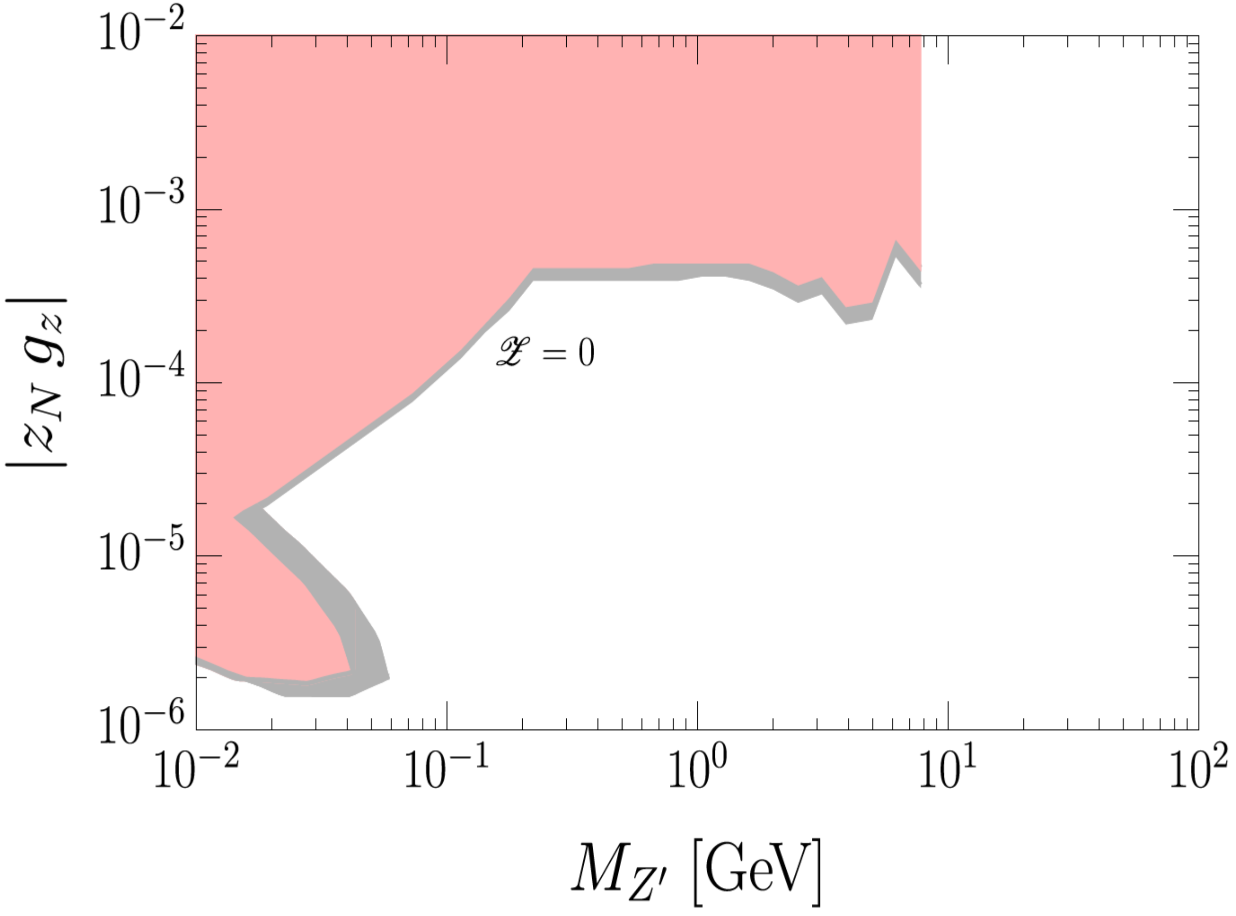


Uncertainty due to sterile neutrinos + running of η: thickness of gray line

(Is the Z' kinematically allowed to decay into the sterile neutrinos?)

Sample exclusion bounds





Heavy Z’ bosons

Constraints

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

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

Constraints

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

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

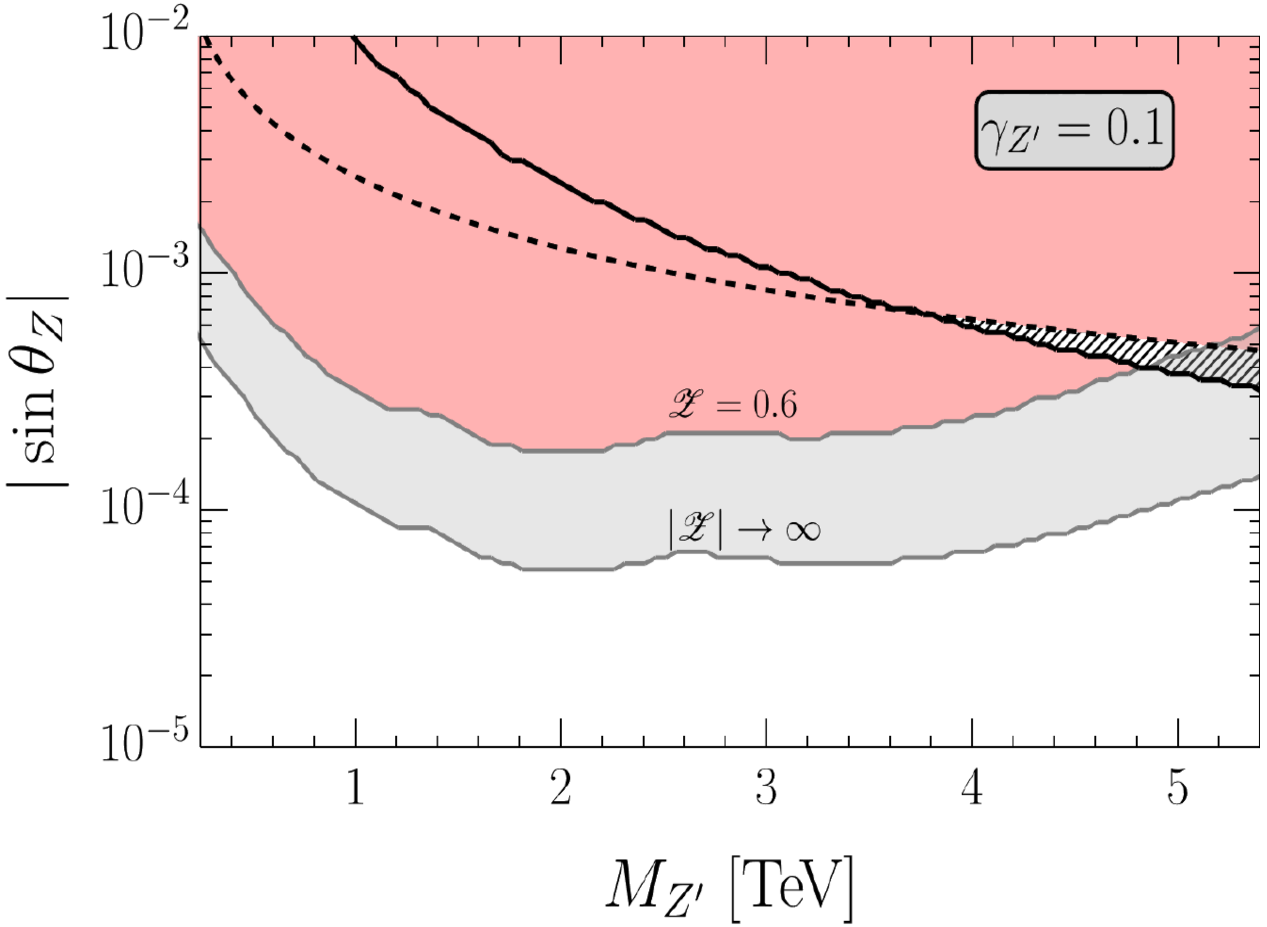
- **Direct:** searches in the LHC (**ATLAS** [1903.06248] and **CMS** [2103.02708]) in dilepton final states:

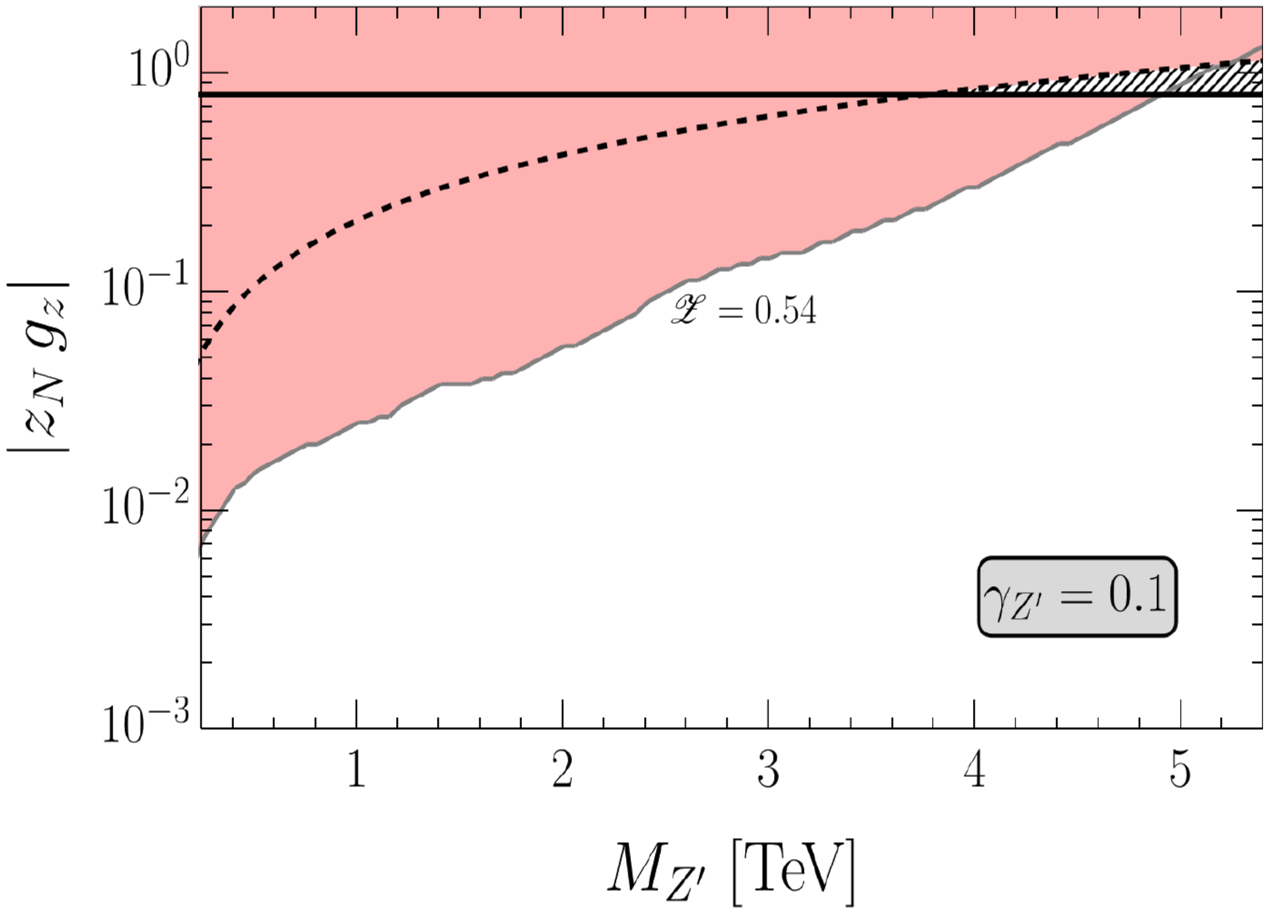
$$p + p \to Z' + X \to \ell^+\ell^- + X$$

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

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

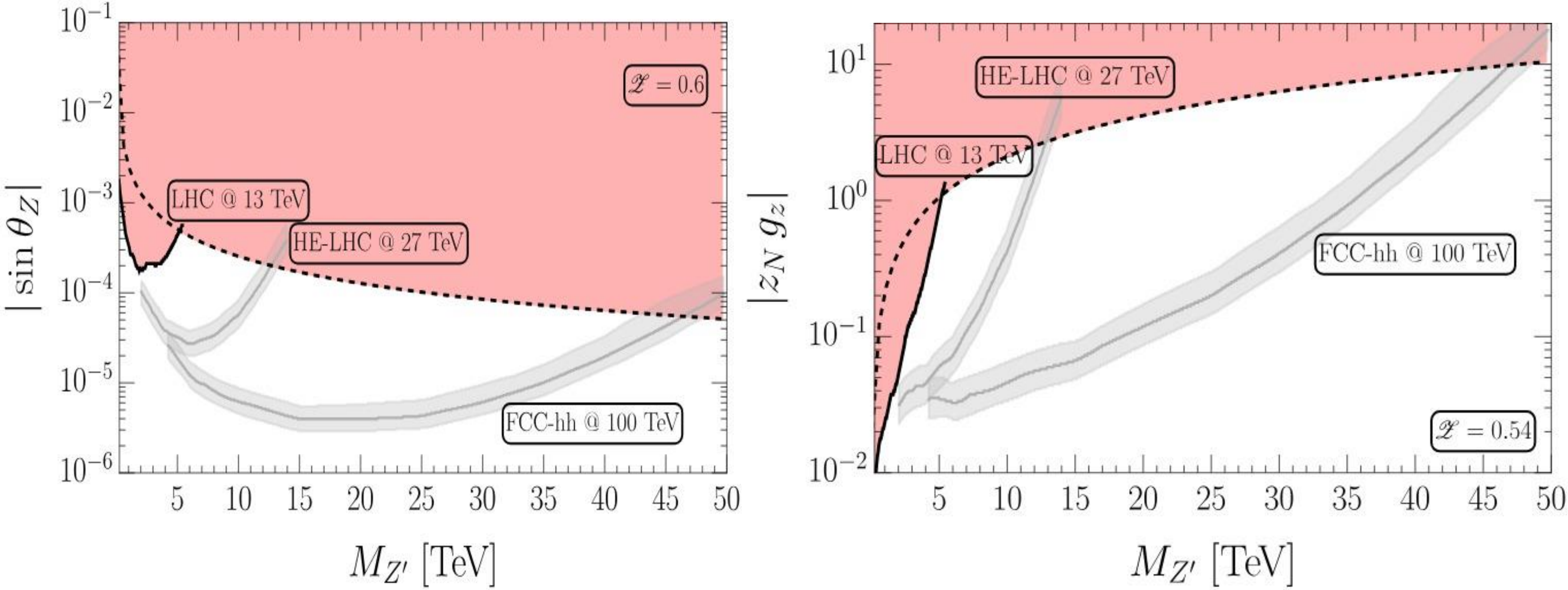
Model independent bounds?





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 $M_{Z'}$ (~ 10 TeV) 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):

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

- Potentially relevant for FCC-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 $p + p \to Z' + X \to \ell^+\ell^- + X$ searches there is a least severe bound: model independent constraints

Thank you for your attention!

Backup

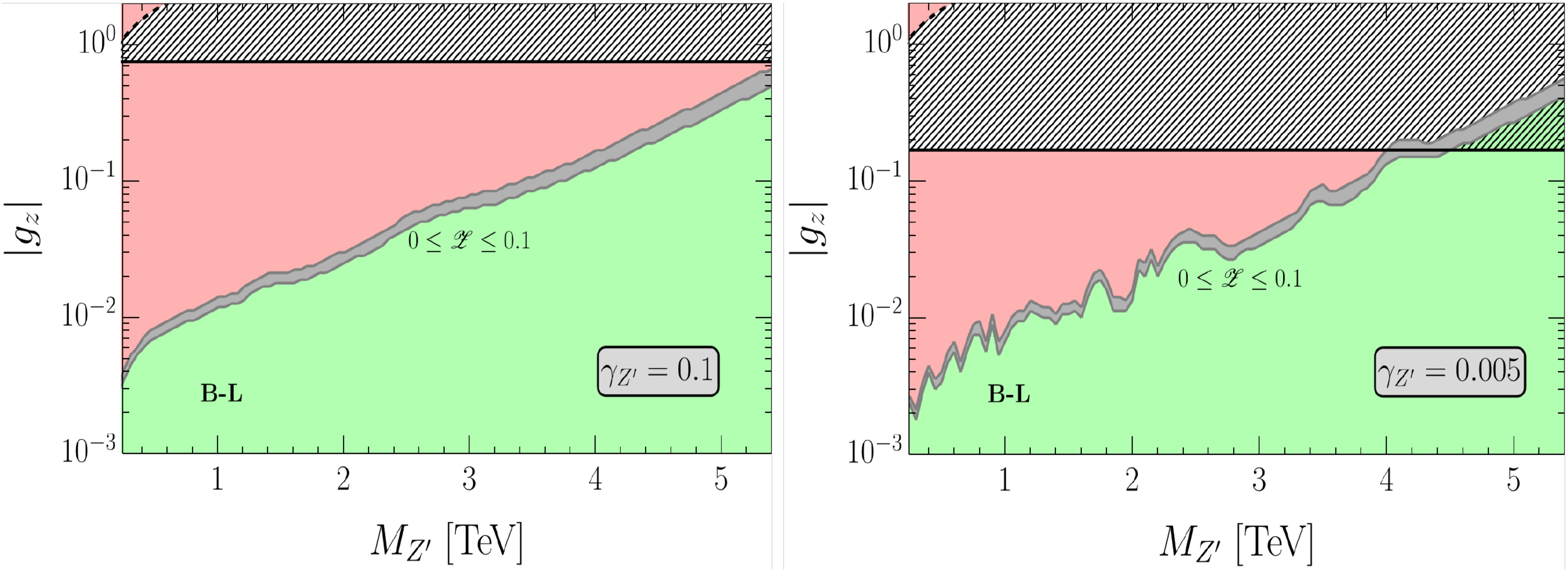
V-A couplings

- Most of the Z' phenomenology depends on:

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

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

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



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