Minimal anomaly free U(1) extensions: constraints, prospects & outlooks

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Particle Theory Seminar @ Uppsala University

Plan of my talk

- What is gauge anomaly?
- Why anomaly free theory?
- Minimal U(1) extensions
- Anomaly cancellation
- Green–Schwarz mechanism
- Prospects at HL-LHC & ILC
- Outlooks: collider & dark matter
- Summary and conclusions

Trivia: gauge anomaly

- Symmetry of Lagrangian → conserved current → conserved classically but not at the quantum level, the symmetry is anomalous
- Massless (QED) Dirac Lagrangian has chiral symmetry; the axial vector current is conserved

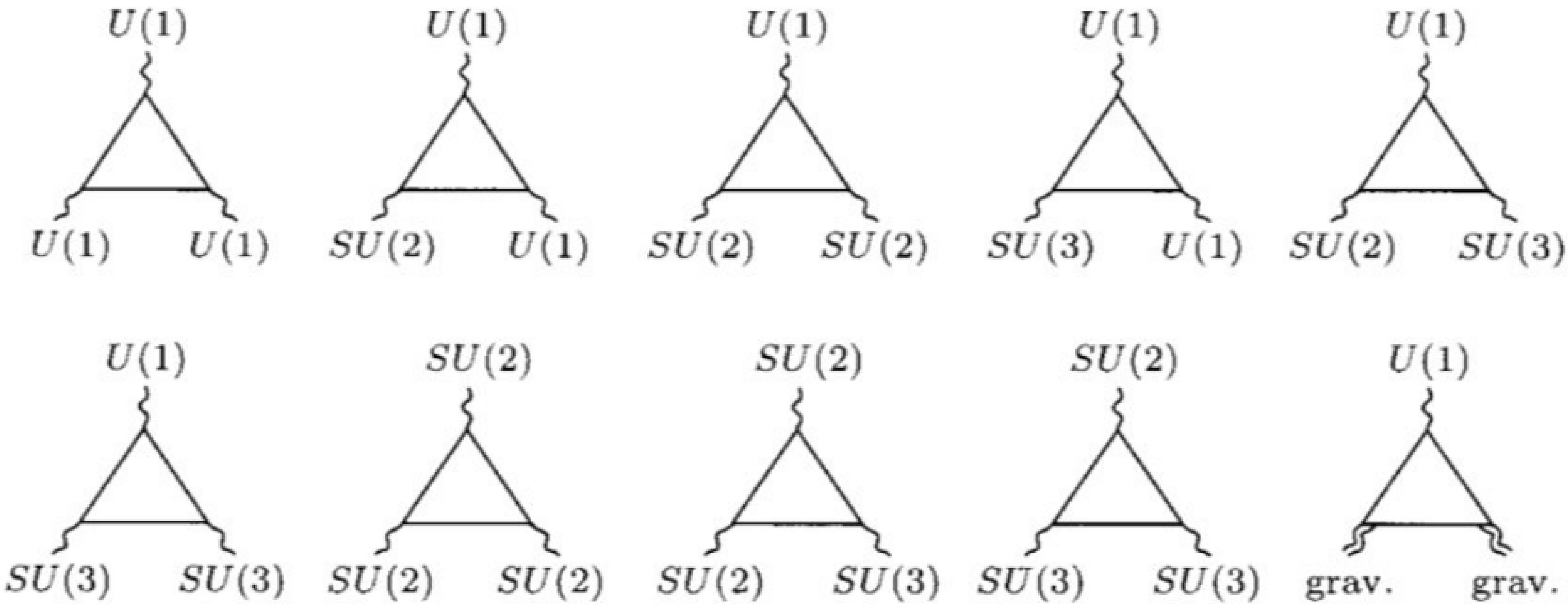
Classically: $$j^{\mu 5} = \bar{\psi}\gamma^{\mu}\gamma^{5}\psi; \quad \partial_{\mu} j^{\mu 5} = 0$$

Quantum level: $$\partial_{\mu} j^{\mu 5} = -\frac{e^2}{16\pi^2}\epsilon^{\alpha\beta\mu\nu}F_{\alpha\beta}F_{\mu\nu}$$

- Violations of Ward identities or equivalently breaking of gauge symmetry
- Gauge symmetry is required to make the theory unitary and Lorentz invariant
- Gauge anomalies occur only in even dimensions. Triangle diagrams in 4D with 3 gauge bosons attached (n = 1 + D/2)
- Triangle is enough. This is correct to all orders in perturbation theory

Adler & Bardeen, Phys. Rev. 182, 1517 (1969)

Gauge anomaly



P.C. from Peskin and Schroeder

SM is anomaly free

U(1) extensions of the SM

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_z$$
$$\Downarrow$$
$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$
$$\Downarrow$$
$$\mathrm{SU}(3)_c \times \mathrm{U}(1)_{EM}$$

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \underbrace{\mathrm{U}(1)_1 \times \mathrm{U}(1)_2}$$
$$\Downarrow$$
$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$
$$\Downarrow$$
$$\mathrm{SU}(3)_c \times \mathrm{U}(1)_{EM}$$

- Redefining gauge fields and rescaling gauge couplings, possible to make

$$\mathrm{U}(1)_1 \times \mathrm{U}(1)_2 \equiv \mathrm{U}(1)_Y \times \mathrm{U}(1)_z$$

- Gauge theory consists of several U(1)'s --> possibility of kinetic mixing
- Kinetic mixing can be rotated away at a given scale

U(1) extensions: mass generation

- A complex scalar gets TeV scale VEV

$\langle\Phi\rangle \to M_{Z'} \sim \mathrm{TeV}$

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_z$$
$$\Downarrow$$
$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$
$$\Downarrow$$
$$\mathrm{SU}(3)_c \times \mathrm{U}(1)_{EM}$$

- EWSB: Higgs mechanism

- Proca Lagrangian: mass term of gauge bosons spoils Gauge invariance

- Stückelberg mechanism $\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}(mA_\mu + \partial_\mu\sigma)^2$

Invariant under: $A_\mu \to A_\mu + \partial_\mu\epsilon \qquad \sigma \to \sigma - m\epsilon$

Axion

- Works for Abelian group but does not works for non-Abelian groups

- Introduced to address strong CP problem. U(1) Peccei-Quinn symmetry

$$\frac{g_s^2}{64\pi^2}\left(\Theta - \frac{\sigma}{f}\right)\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta}$$

Minimal models: assumptions

- Additional U(1) group which is broken by the VEV of a complex scalar
- SM fermions are the only fermions that are charged under SM gauge group
- 3-generations of RH neutrinos which are SM singlets but charged under U(1)
- Neutrinos obtain masses via a Type-I seesaw scenario
- Gauge charges are generation independent and EWSB occurs as in the SM

Anomaly free conditions

$$[\mathrm{SU}(2)_L]^2[\mathrm{U}(1)_z] \quad \Rightarrow \quad \mathrm{Tr}[\{T^i, T^j\}\, z] = 0$$

$$[\mathrm{SU}(3)_c]^2[\mathrm{U}(1)_z] \quad \Rightarrow \quad \mathrm{Tr}[\{T^a, T^b\}\, z] = 0$$

$$[\mathrm{U}(1)_Y]^2[\mathrm{U}(1)_z] \quad \Rightarrow \quad \mathrm{Tr}[Y^2 z] = 0$$

$$[\mathrm{U}(1)_Y][\mathrm{U}(1)_z]^2 \quad \Rightarrow \quad \mathrm{Tr}[Y z^2] = 0$$

$$[\mathrm{U}(1)_z]^3 \quad \Rightarrow \quad \mathrm{Tr}[z^3] = 0$$

Gauge-gravity anomaly $\Rightarrow$ $\mathrm{Tr}[z] = 0$

- 6 parameters and 4 independent equations → 2 free charges
- Most general solution to the anomaly cancellation conditions is

$$Q_f = aY_f + b(B_f - L_f)$$

Gauge charges

$$z_l = -3z_q; \quad z_d = 2z_q - z_u; \quad z_e = -2z_q - z_u;$$

$$\frac{1}{3}\sum_{k=1}^{n} z_k = -4z_q + z_u; \quad \left(\sum_{k=1}^{n} z_k\right)^3 = 9\sum_{k=1}^{n} z_k^3$$

For both Majorana and Dirac mass for neutrinos $z_k = -4z_q + z_u = \pm 1/2$

	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_z$
q_L	3	2	1/3	z_q
u_R	3	1	4/3	z_u
d_R	3	1	$-2/3$	$2z_q - z_u$
l_L	1	2	-1	$-3z_q$
e_R	1	1	-2	$-2z_q - z_u$
ν_R	1	1	0	z_k
H	1	2	$+1$	$-z_q + z_u$
φ	1	1	0	1

k-parametrization

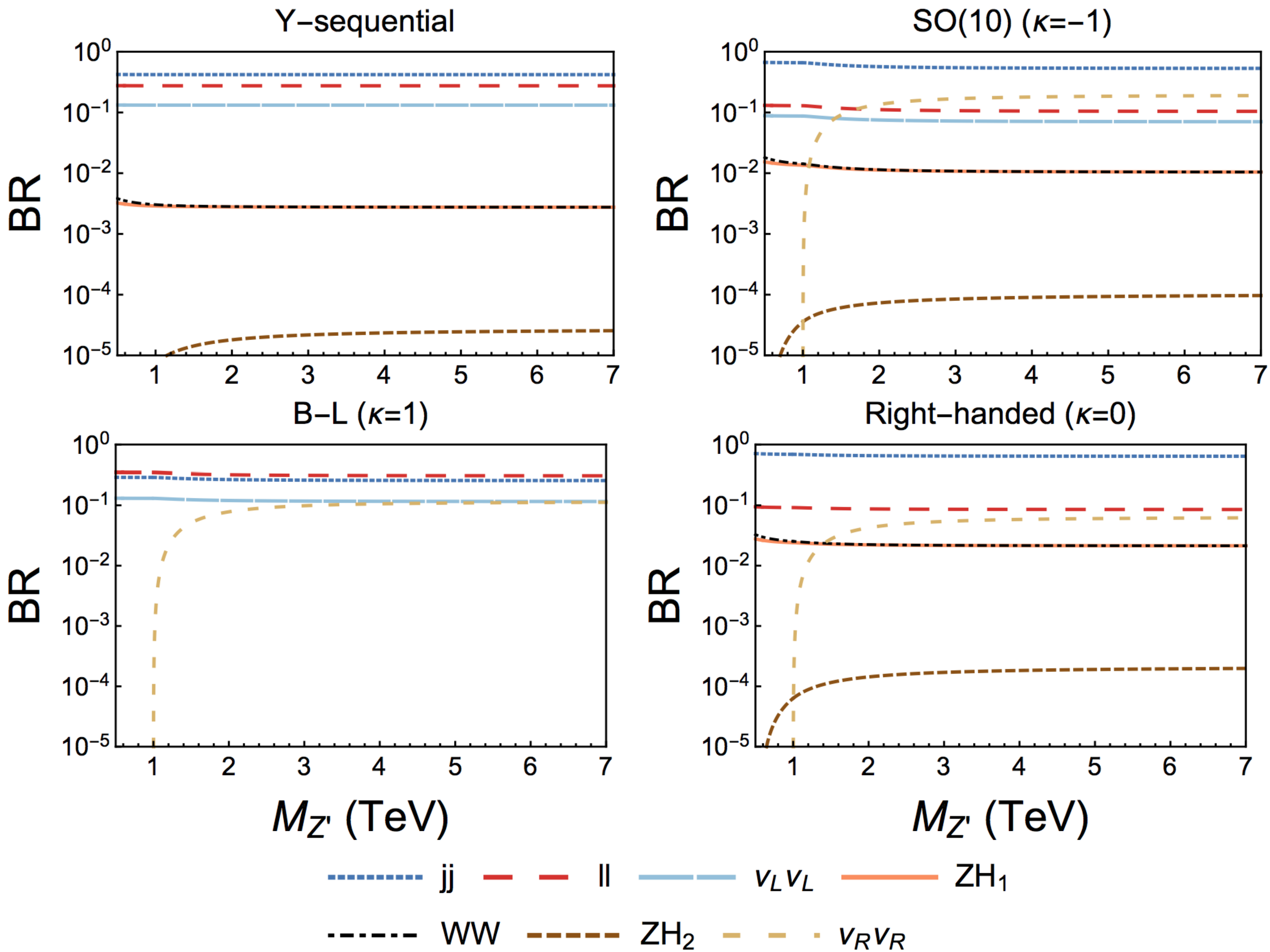
A model-independent approach

Model	$\kappa = z_q/z_u$
Gauged $B-L$	1
Y sequential	1/4
SO(10)-GUT	−1
Right-handed	0

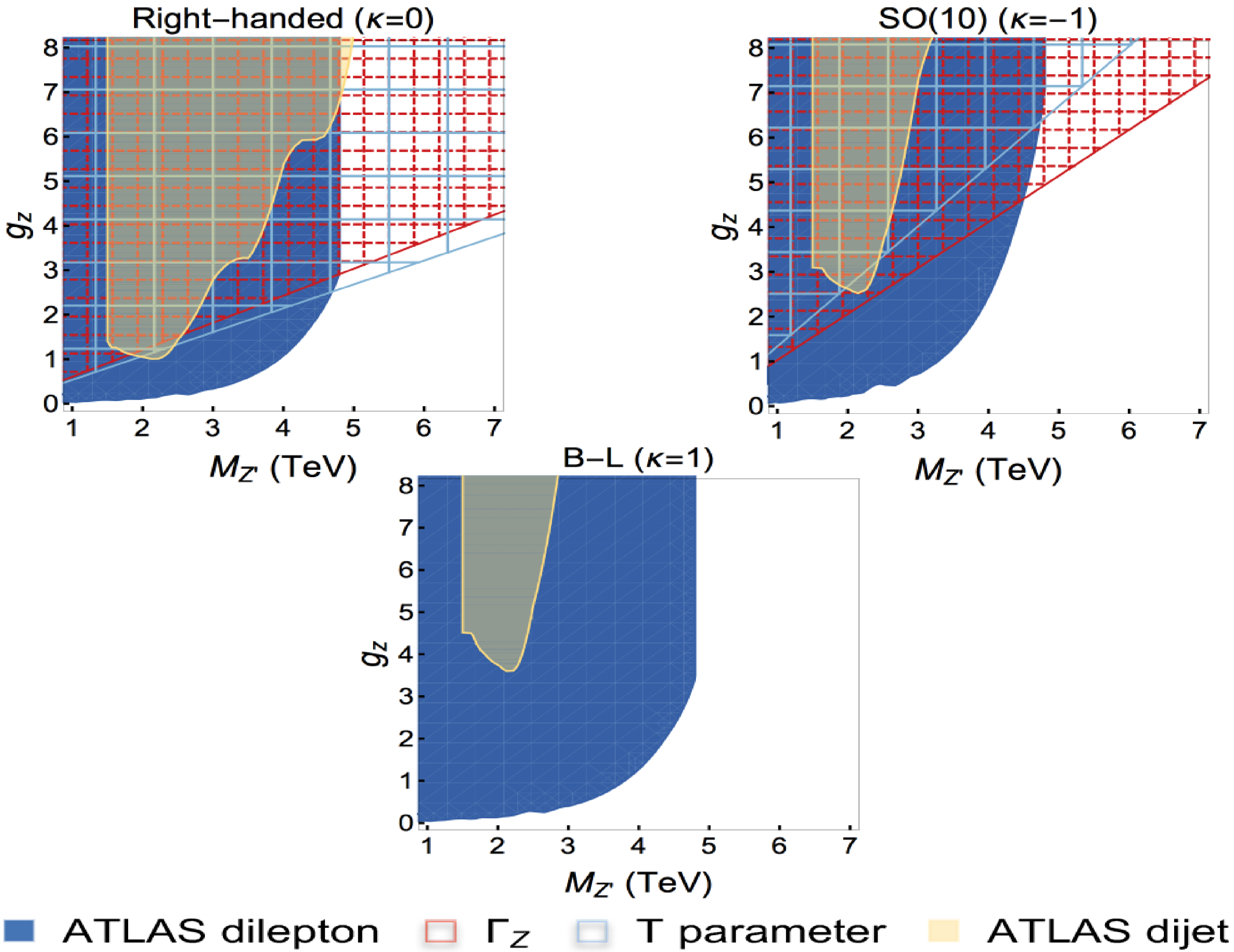
Special case: no RHN is
Required to cancel anomalies

$$\sigma\left(M_{Z'}, g_z, \kappa\right) = g_z^2 \left\{ a_L^u\left(M_{Z'}\right)\left(\frac{\kappa}{1-4\kappa}\right)^2 + a_R^u\left(M_{Z'}\right)\left(\frac{1}{1-4\kappa}\right)^2 + a_L^d\left(M_{Z'}\right)\left(\frac{\kappa}{1-4\kappa}\right)^2 + a_R^d\left(M_{Z'}\right)\left(\frac{2\kappa-1}{1-4\kappa}\right)^2 \right\}$$

Branching ratios



Exclusion limits



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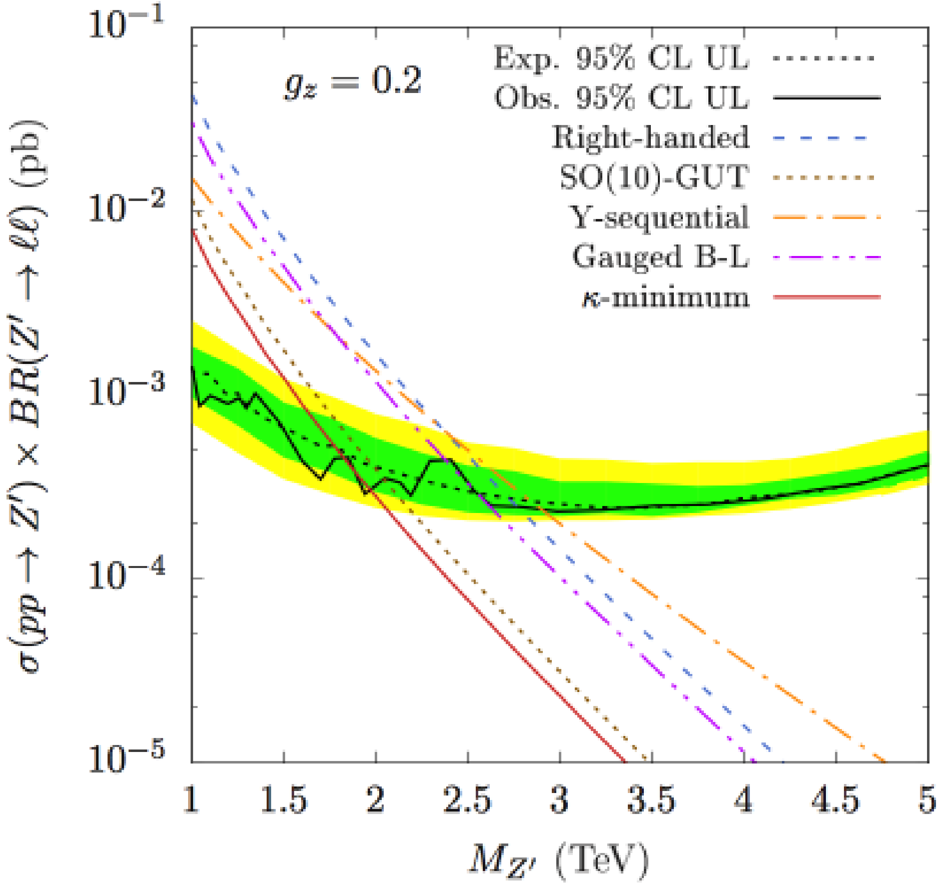
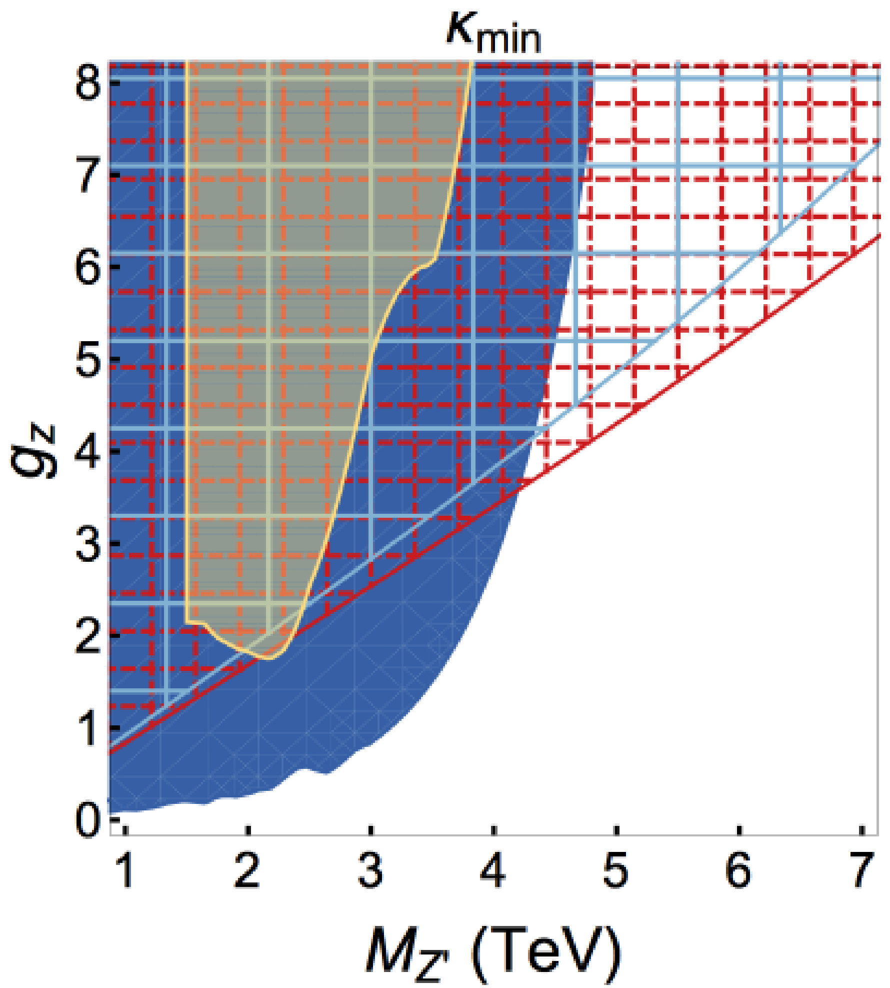




κ_{min} is the value for which $\sigma \times BR$ is minimum

Green–Schwarz mechanism

- A mechanism to cancel anomaly by introducing gauge-variant operators in the effective action
- Heavy chiral fermions are integrated out and at low energy their remnants appear as effective operators

$$\mathcal{L}_{GS} = \mathcal{L}_{kin} + \mathcal{L}_{PQ} + \mathcal{L}_{GCS}$$

$$\mathcal{L}_{kin} = -\frac{1}{4} F_z^{\mu\nu} F_{z,\mu\nu} + \frac{1}{2} \left(\partial^\mu a + M_I g_z B_z^\mu\right) \left(\partial_\mu a + M_I g_z B_{z,\mu}\right)$$

$$\mathcal{L}_{PQ} = \frac{1}{96\pi^2 M_I} a \, \varepsilon_{\mu\nu\rho\sigma} (C_{zzz} g_z^3 F_z^{\mu\nu} F_z^{\rho\sigma} + C_{zzy} g_z^2 g' F_z^{\mu\nu} F_Y^{\rho\sigma} + C_{zyy} g_z g'^2 F_Y^{\mu\nu} F_Y^{\rho\sigma}$$

$$+ D_2 g_z g^2 \mathrm{Tr}(F_W^{\mu\nu} F_W^{\rho\sigma}) + D_3 g_z g_S^2 \mathrm{Tr}(F_S^{\mu\nu} F_S^{\rho\sigma})),$$

$$\mathcal{L}_{GCS} = \frac{1}{48\pi^2} \varepsilon_{\mu\nu\rho\sigma} (g'^2 g_z E_{zyy} B_Y^\mu B_z^\nu F_Y^{\rho\sigma} + g' g_z^2 E_{zzy} B_Y^\mu B_z^\nu F_z^{\rho\sigma} +$$

$$g^2 g_z K_2 B_z^\mu \Omega_W^{\nu\rho\sigma} + g_S^2 g_z K_3 B_z^\mu \Omega_S^{\nu\rho\sigma}),$$

$$\Omega_{\nu\rho\sigma}^{S,W} = \frac{1}{3} \mathrm{Tr}\left[A_\nu^{S,W} (F_{\rho\sigma}^{S,W} - [A_\rho^{S,W}, A_\sigma^{S,W}]) + (\text{cyclic perm.})\right]$$

Gauge charges in GS setup

- New U(1) is broken to the SM gauge group at some high scale through the Stuckelberg mechanism → a massive Z′
- No right-handed neutrino and EWSB proceeds as usual like in the SM

Fields	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_z$
H	1	2	1	z_H
q_L	3	2	$1/3$	z_q
u_R	3	1	$4/3$	$z_u = z_q + z_H$
d_R	3	1	$-2/3$	$z_d = z_q - z_H$
ℓ_L	1	2	-1	z_ℓ
e_R	1	1	-2	$z_e = z_\ell - z_H$

- The general solution to the anomaly cancellation conditions is

$$Q_f^z = 3z_q B_f + z_\ell L_f + z_H \left\{ Y_f - (B-L)_f \right\}$$

Relations

Anomaly	Relation
$[\mathrm{U}(1)_z]^3$	$C_{zzz} = -z_h^3 - 3z_h z_l^2 - z_l^3 + 3z_h^2(z_l + 6z_q)$
$[\mathrm{U}(1)_z]^2\,[\mathrm{U}(1)_Y]$	$E_{zzy} = 4z_h(z_l + 3z_q)$ $C_{zzy} = 3E_{zzy}$
$[\mathrm{U}(1)_z]\,[\mathrm{U}(1)_Y]^2$	$E_{zyy} = 4(z_l + 3z_q)$ $C_{zyy} = \frac{3}{2}E_{zyy}$
$[\mathrm{SU}(2)_L]^2\,[\mathrm{U}(1)_z]$	$K_2 = (6z_q + 2z_l)$ $D_2 = -\frac{3}{2}K_2$
$[\mathrm{SU}(3)_C]^2\,[\mathrm{U}(1)_z]$	$K_3 = 0$ $D_3 = 0$

- One can ignore the gauge-gravity anomaly cancellation condition by assuming that gravity couples very weakly

$$[R]^2\,[\mathrm{U}(1)_z] \to \mathrm{Tr}\,[z] \sim 3z_q + 2z_\ell - z_H$$

Various models

Non-chiral models $(z_H = 0)$

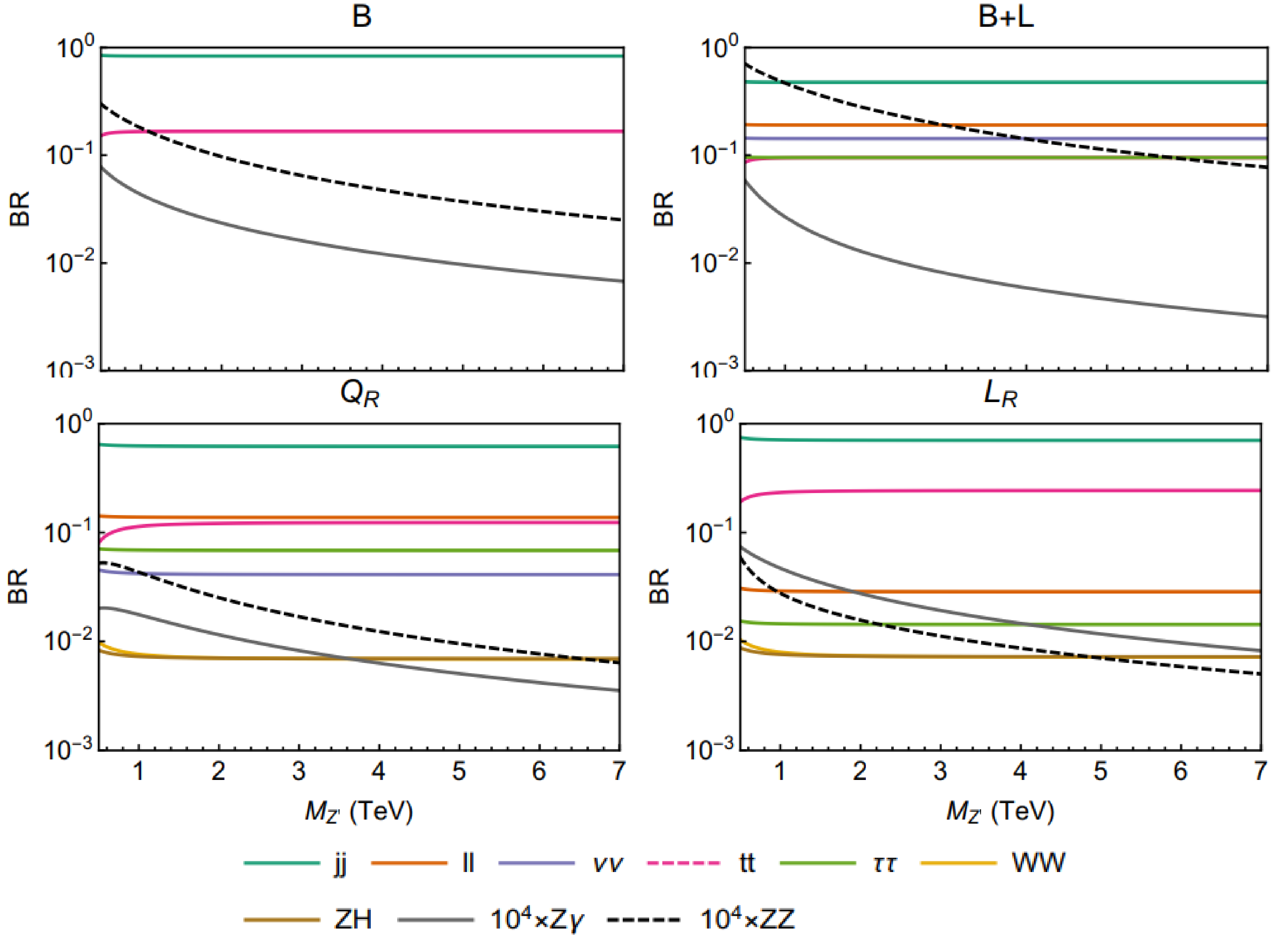
- Leptophobic:
  $Q_z^f = B_f; \quad z_q = 1/3, \ z_\ell = 0, \ z_H = 0$
- Fermiophobic:
  $Q_z^f = 0; \quad z_q = 0, \ z_\ell = 0, \ z_H = 0$
- Gravity model:
  $Q_f^z = z_\ell (L_f - 2B_f); \quad z_q = -(2/3) z_\ell; \quad z_H = 0$
- Quarkphobic:
  $Q_z^f = L_f; \quad z_q = 0, \ z_\ell = 1, \ z_H = 0$
- B-L model:
  $Q_z^f = B_f - L_f; \quad z_q = 1/3, \ z_\ell = -1, \ z_H = 0$
- B+L model:
  $Q_z^f = B_f + L_f; \quad z_q = 1/3, \ z_\ell = 1, \ z_H = 0$

Chiral models $(z_H \neq 0)$

- Y-sequential:
  $Q_f^z = z_H Y_f; \quad z_q = (1/3) z_H; \quad z_\ell = -z_H$
- Right-handed:
  $Q_f^z = z_H (Y_f - B_f + L_f); \quad z_q = 0; \quad z_\ell = 0$
- SO(10) GUT:
  $Q_f^z = -(1/2)(B_f - L_f) + (1/5) Y_f; \quad z_q = -1/10; \quad z_\ell = 3/10; \quad z_H = 1/5$
- Right-handed quark:
  $Q_f^z = z_H (Y_f - B_f) + (z_\ell + z_H) L_f; \quad z_q = 0$
- Left-handed lepton:
  $Q_f^z = 3 z_q B_f + z_\ell (2Y_f + L_f); \quad z_H = z_\ell$
- Right-handed lepton:
  $Q_f^z = (3z_q - z_H) B_f + z_H (Y_f + L_f); \quad z_\ell = 0$
- Axial lepton:
  $Q_f^z = (3z_q + z_\ell/2) B_f + (z_\ell/2)(L_f - Y_f)$
  $z_H = -z_\ell/2$
- Gravity model:
  $Q_f^z = -2 z_\ell B_f + 3(z_q + z_\ell) L_f + 3(3z_q + 2z_\ell) Y_f$
  $z_H = 3z_q + 2z_\ell$

Many possibilities, very rich phenomenology

Branching ratios



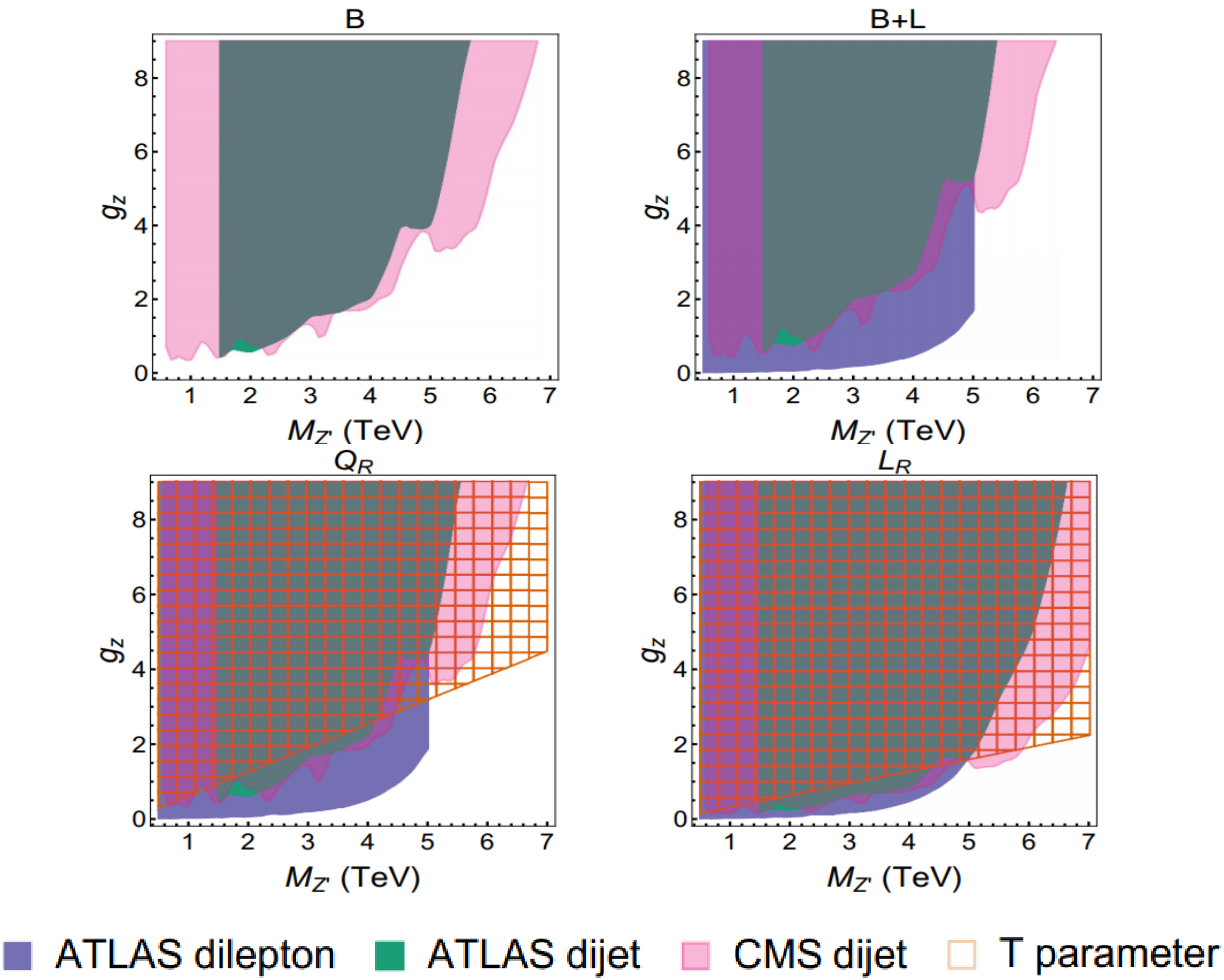
Unique signature

Axion couplings: $\mathcal{A}ZZ, \mathcal{A}Z'Z', \mathcal{A}\gamma\gamma, \mathcal{A}W^+W^-$

- Minimal setup axion is not physical, but simply a Goldstone boson
- Considering a more complicated Higgs sector, it is possible to furnish a physical axion and a Goldstone boson, through mixing with other scalar fields
- Unique signatures GS: $ZZ\gamma, ZZ'\gamma, Z'Z'\gamma$
- We are especially interested in $Z' \to ZZ$ and $Z' \to \gamma Z$ decays which, if observed, may give indications of the GS nature of the theory
- Production cross section can be written as

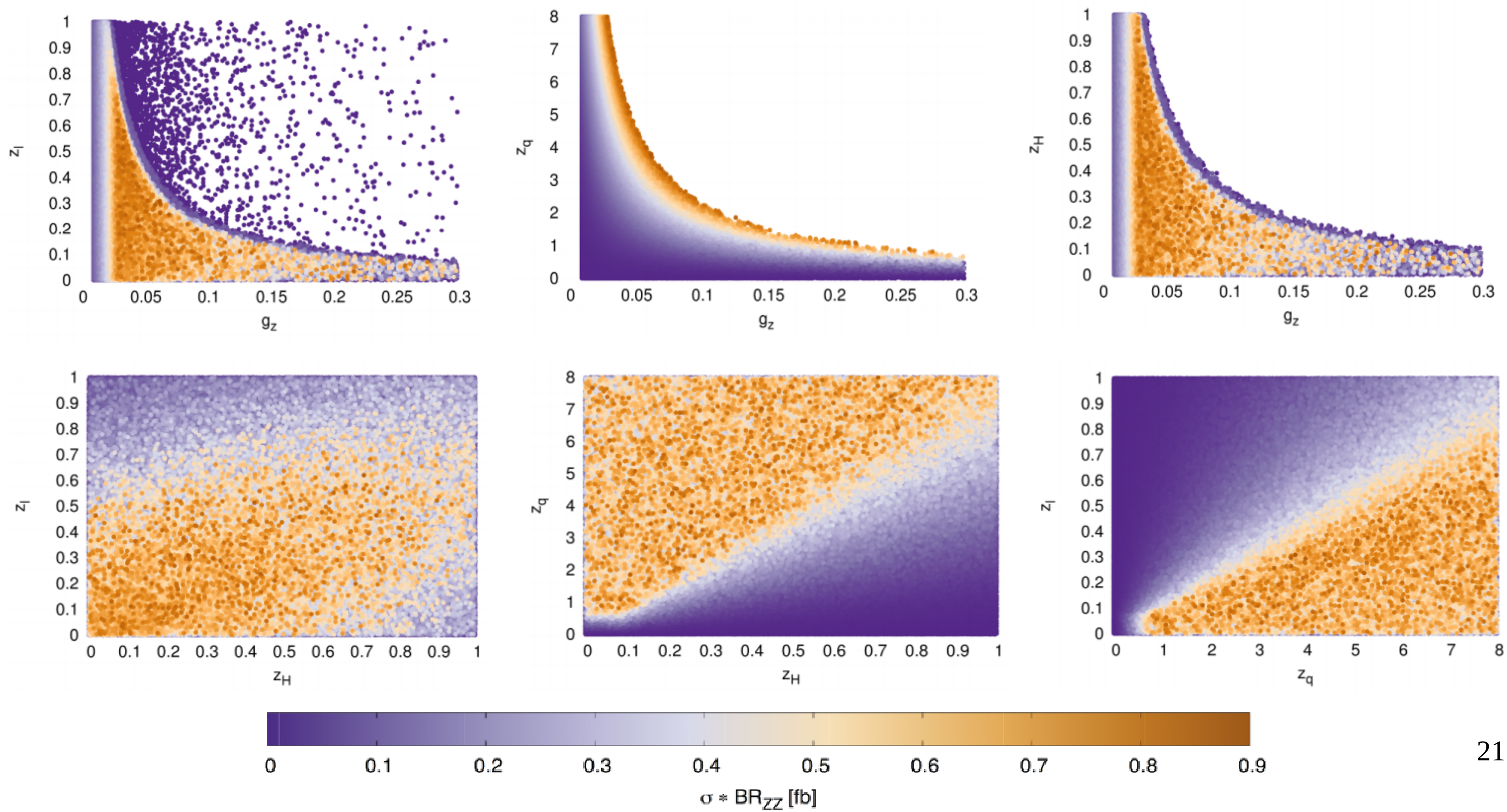
$$\sigma\left(M_{Z'}, g_z, z_q, z_H\right) = \frac{g_z^2}{4}\left[a^u\left(M_{Z'}\right)\left\{z_q^2 + \left(z_q + z_H\right)^2\right\} + a^d\left(M_{Z'}\right)\left\{z_q^2 + \left(z_q - z_H\right)^2\right\}\right]$$

Exclusion limits: various models



Prospect: GS-Z′ at HL-LHC

- Random Scan: $0.5 \text{ TeV} < M_{Z'} < 0.8 \text{ TeV}, \quad 0.01 < g_z < 0.3, \quad 0 < z_H, z_\ell < 1.0, \quad 0 < z_q < 8,$
- Constraints: ATLAS dilepton ATLAS dijet CMS dijet T parameter



Prospect: GS-Z' at HL-LHC

- Unique signatures: $Z' \to ZZ; \quad Z' \to Z\gamma$

- Very small branching and therefore very challenging to observe

  At $3000\ \mathrm{fb}^{-1}$ integrated luminosity

  $$M_{Z'} \sim 0.5\ \mathrm{TeV} \to \sigma \times \mathrm{BR}(Z' \to ZZ) \sim 1.0\ \mathrm{fb} \to N = 3000$$

  $$M_{Z'} \sim 0.5\ \mathrm{TeV} \to \sigma \times \mathrm{BR}(Z' \to Z\gamma) \sim 0.25\ \mathrm{fb} \to N = 750$$

- If there is GS-Z', it is expected to show up in the dijet/dilepton channels before the discovery in the ZZ/Zy channels

- In 750 GeV context: Is an 'axizilla' possible for di-photon resonance?

PLB 755 (2016) 190-195

- We have axion couplings $AZZ, AZ'Z', A\gamma\gamma, AW^+W^-$

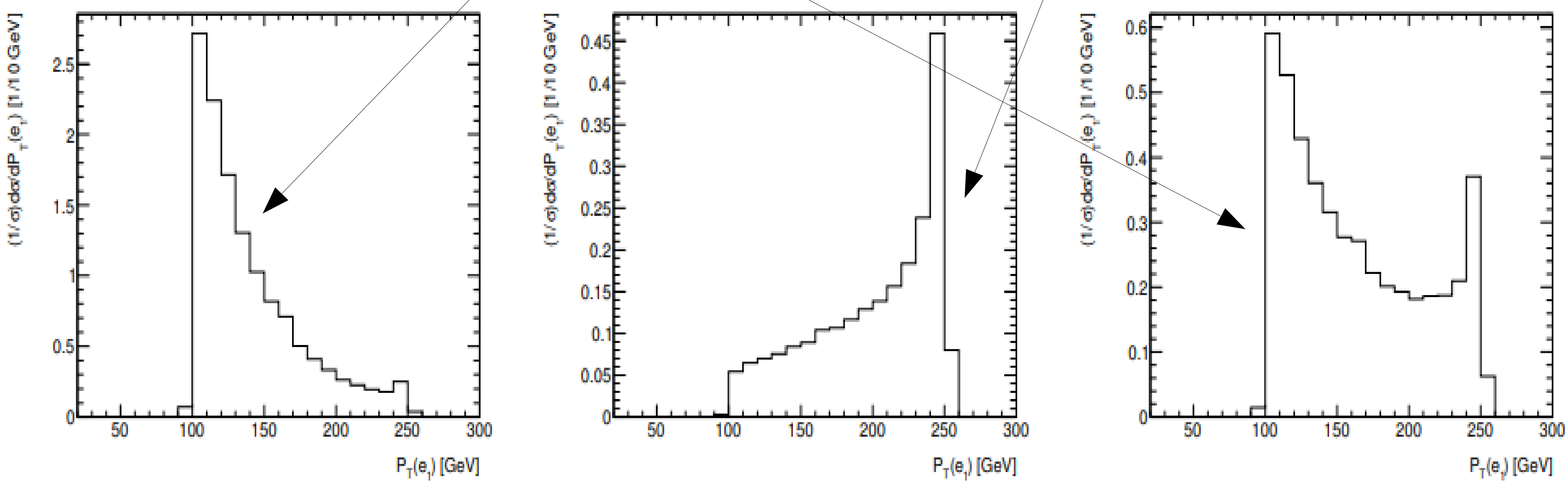
- Axionic dark matter, cosmological implications?

Prospect: Z' at ILC

$$\sigma_{\rm tot}(e^+e^- \to e^+e^-) = \sigma_{\rm SM} + \kappa^2\sigma_I(M_{Z'}) + \kappa^4\sigma_{\rm BSM}(M_{Z'})$$

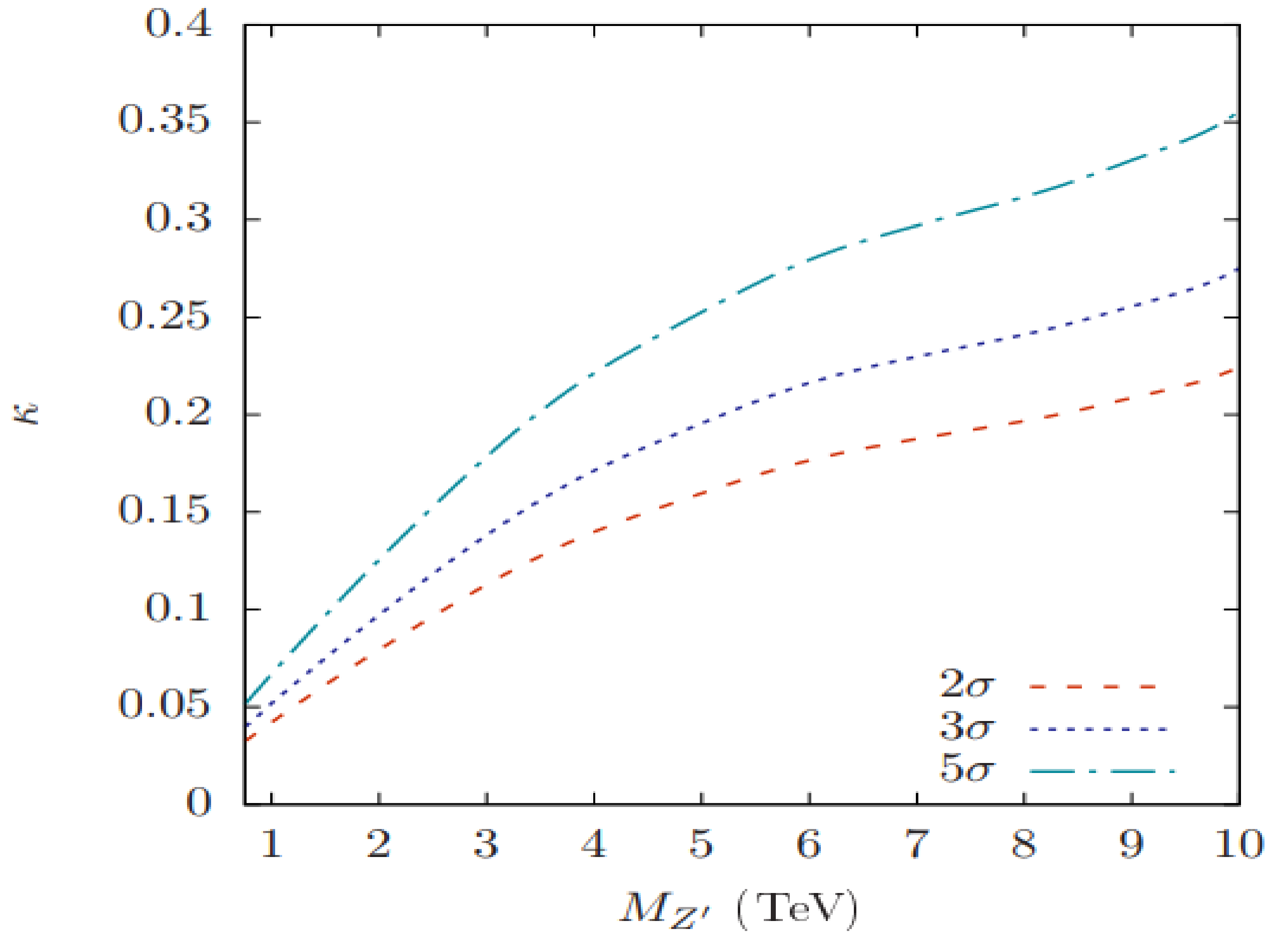
$$\mathcal{L} \supset \kappa\ Z'e^+e^-$$

$M_{Z'} = 1$ TeV; $\sqrt{s} = 0.5$ TeV



$$p_T(e_1), p_T(e_2) > 100 \text{ GeV}; \quad |\eta(e_1)|, |\eta(e_2)| < 2.5; \quad \Delta R(e_1, e_2) > 0.4$$

Prospect: Z' at ILC



$\sqrt{s} = 0.5$ TeV

$\mathcal{L} = 100\ \text{fb}^{-1}$

$$\sigma = \frac{\mathcal{N}_s}{\sqrt{\mathcal{N}_B}}$$

- Simple minded analysis with $p_T(e_1), p_T(e_2) > 200$ GeV
- Can be improved by using multivariate analysis, optimal observable methods

Outlooks: RHN pair production & other…

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
q_L^i	**3**	**2**	$1/6$	$(1/6)x_H + (1/3)x_\Phi$
u_R^i	**3**	**1**	$2/3$	$(2/3)x_H + (1/3)x_\Phi$
d_R^i	**3**	**1**	$-1/3$	$-(1/3)x_H + (1/3)x_\Phi$
ℓ_L^i	**1**	**2**	$-1/2$	$(-1/2)x_H - x_\Phi$
e_R^i	**1**	**1**	-1	$-x_H - x_\Phi$
H	**1**	**2**	$-1/2$	$(-1/2)x_H$
N_R^j	**1**	**1**	0	$-x_\Phi$
Φ	**1**	**1**	0	$+2x_\Phi$

Table 1: Particle content of the minimal $U(1)_X$ model, where $i, j = 1, 2, 3$ ar indices. Without loss of generality, we fix $x_\Phi = 1$.

From PRD, 97, 115023 (2018) and EPJC, 78, 696 (2018) by A. Das, N. Okada and D. Raut

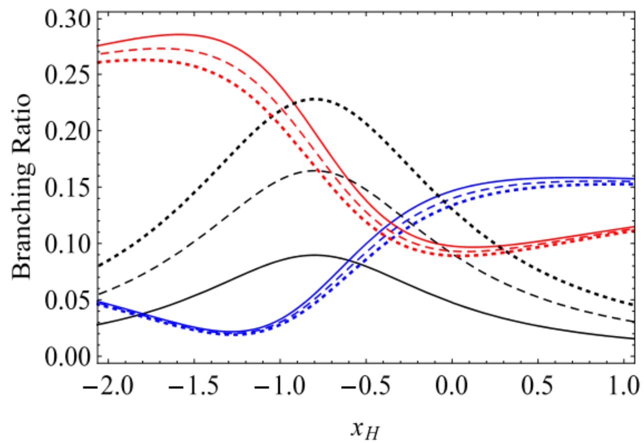


Figure 1: The branching ratios of Z' boson as a function of x_H with a fixed $m_{Z'} = 3$ TeV. The solid lines correspond to $m_{N^1} = m_{Z'}/4$ and $m_{N^{2,3}} > m_{Z'}/2$; the dashed (dotted) lines correspond to $m_{N^{1,2}} = m_{Z'}/4$ and $m_{N^3} > m_{Z'}/2$ ($m_{N^{1,2,3}} = m_{Z'}/4$). From top to bottom, the solid (red, black and blue) lines at $x_H = -1$ are the branching ratios to the first generations of jets (up and down quarks), RHNs , and charged leptons, respectively. The lines for the RHN final states correspond to the sum of the branching ratio to all possible RHNs.

- Three new particles:

$$Z',\ N_R,\ H_2$$

$$Z' \to N_R N_R;\quad Z' \to Z H_2;\quad \cdots$$

- Displaced vertices, correlated collider searches are very important

Neutrino mass

Demanding U(1)z invariance

- Majorana mass term: D = 5 Weinberg operator

$$\frac{1}{M}\left(\bar{\ell}_L^c H\right)\left(\ell_L H\right) \Rightarrow 4z_q = z_u$$

- In general: D > 5 effective operators $\tilde{\phi} = \{\phi, \phi^\dagger\}$

$$\frac{1}{M}\left(\frac{\tilde{\phi}}{M}\right)^n \left(\bar{\ell}_L^c H\right)\left(\ell_L H\right) \Rightarrow 8z_q - 2z_u = \pm n$$

- Dirac mass term: D = 4 renormalizable operator

$$\bar{\ell}_L \nu_R \tilde{H} \Rightarrow z_k = -4z_q + z_u$$

- In general: D > 5 effective operators

$$\left(\frac{\tilde{\phi}}{M}\right)^m \bar{\ell}_L \nu_R \tilde{H} \Rightarrow z_k + 4z_q - z_u = \pm m$$

- Majorana mass term: right-handed neutrino

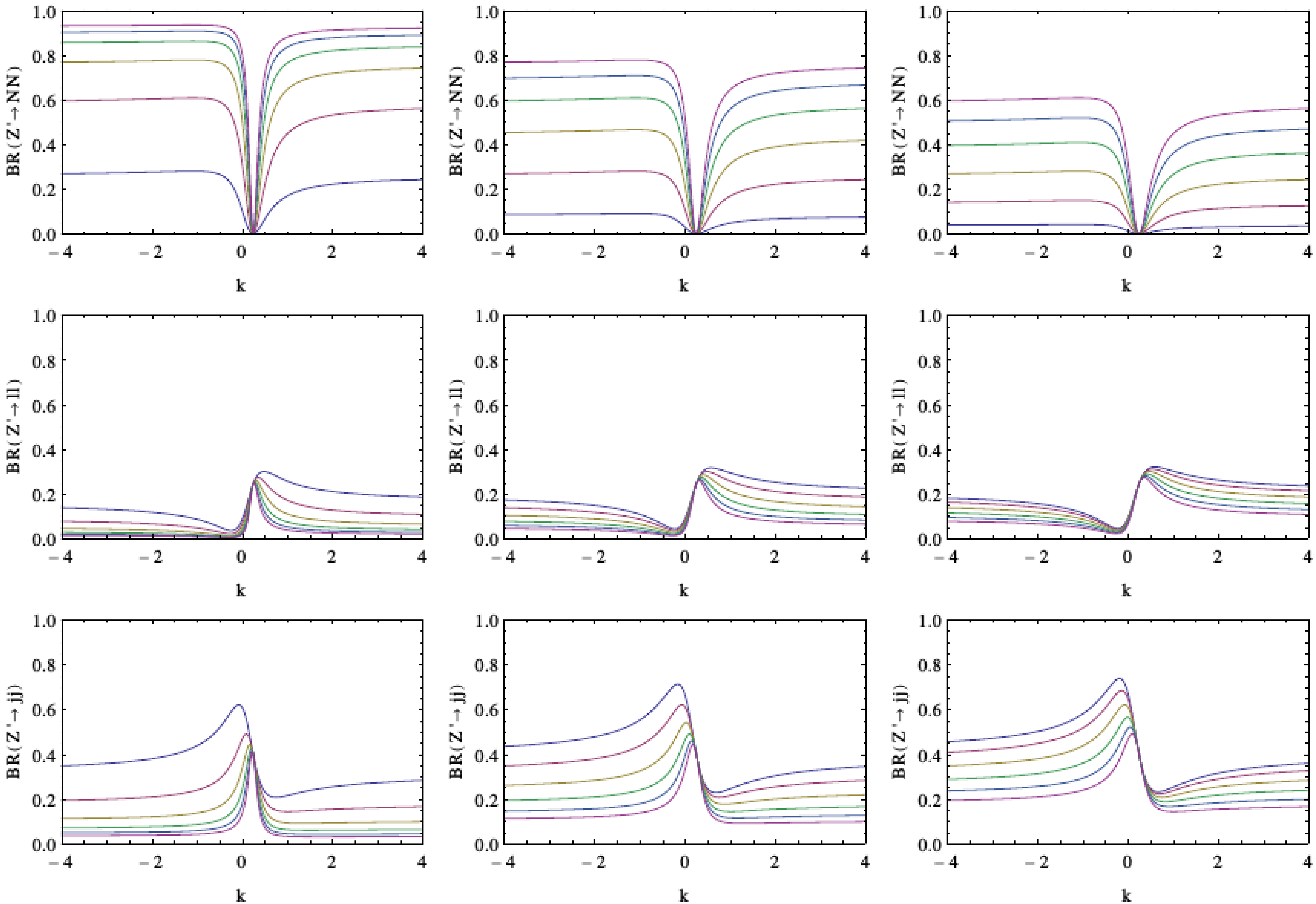
$$M\left(\frac{\tilde{\phi}}{M}\right)^{n'} \bar{\nu}_R^c \nu_R \Rightarrow z_k = \pm\frac{n'}{2}$$

$$4z_q - z_u = \pm\frac{m'}{2}$$

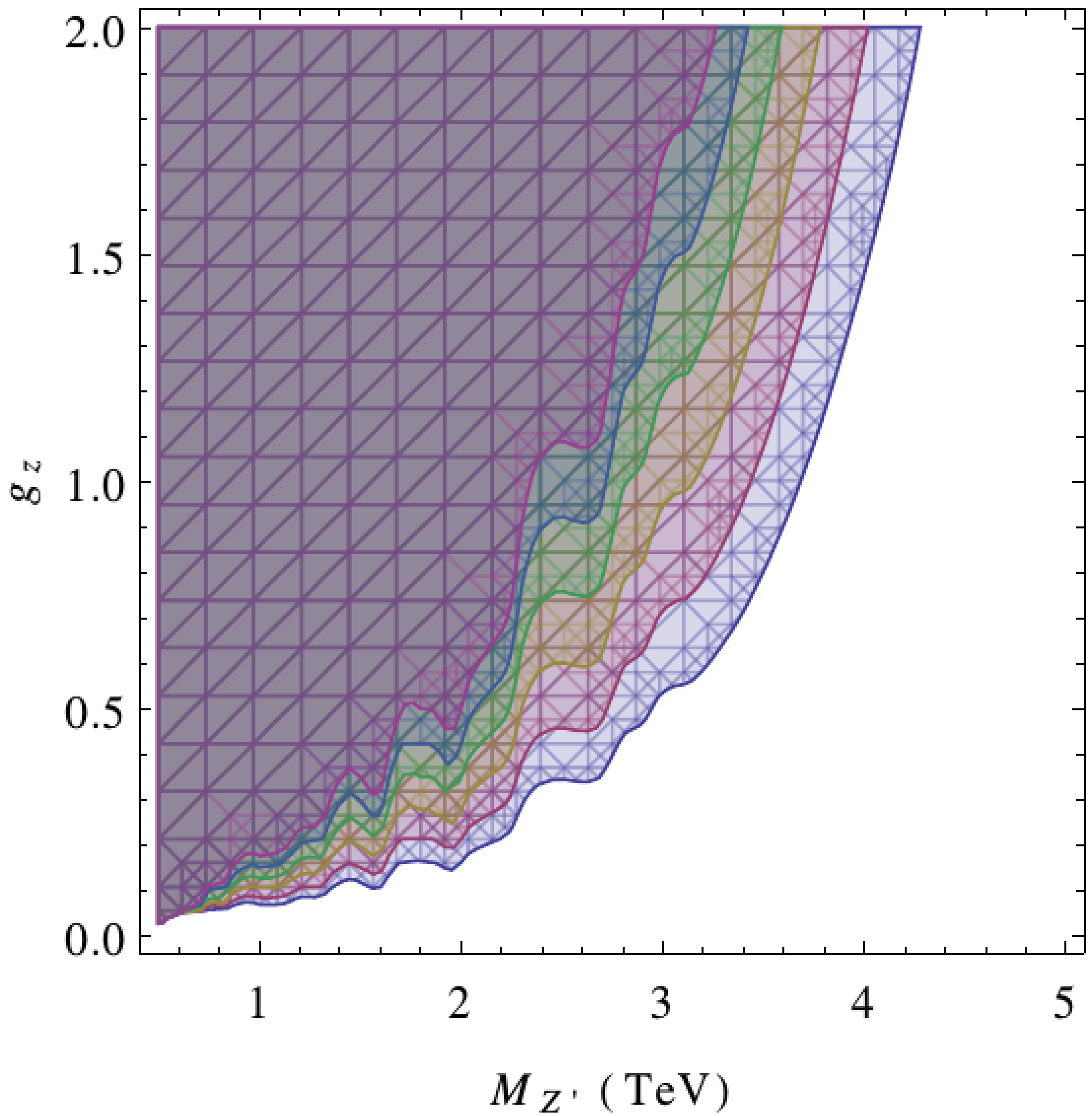
$$z_k = \pm\frac{n'}{2}$$

Branching ratio: Z'

$m' = 1$ $\qquad$ $m' = 2$ $\qquad$ $m' = 3$

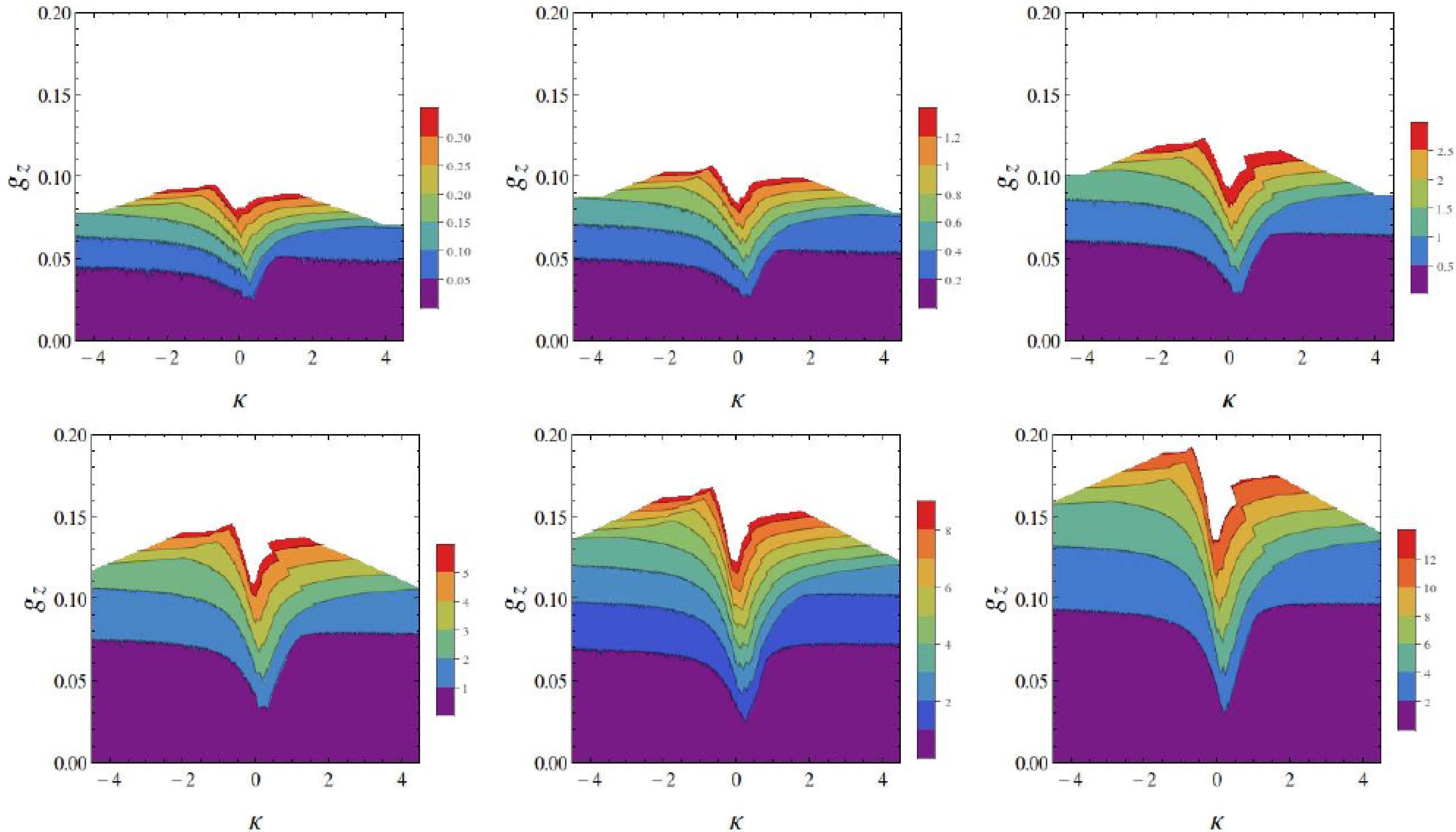


Exclusion from dilepton data



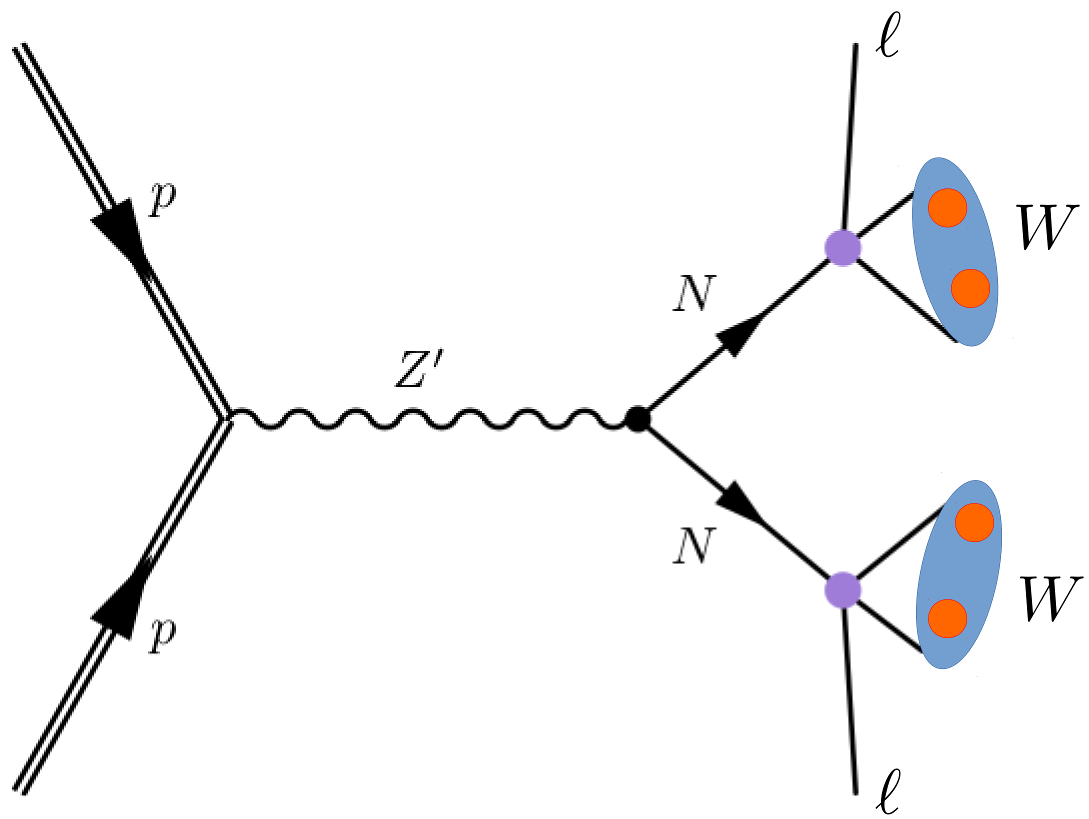
$$m' = 1$$

Allowed by the dilepton data



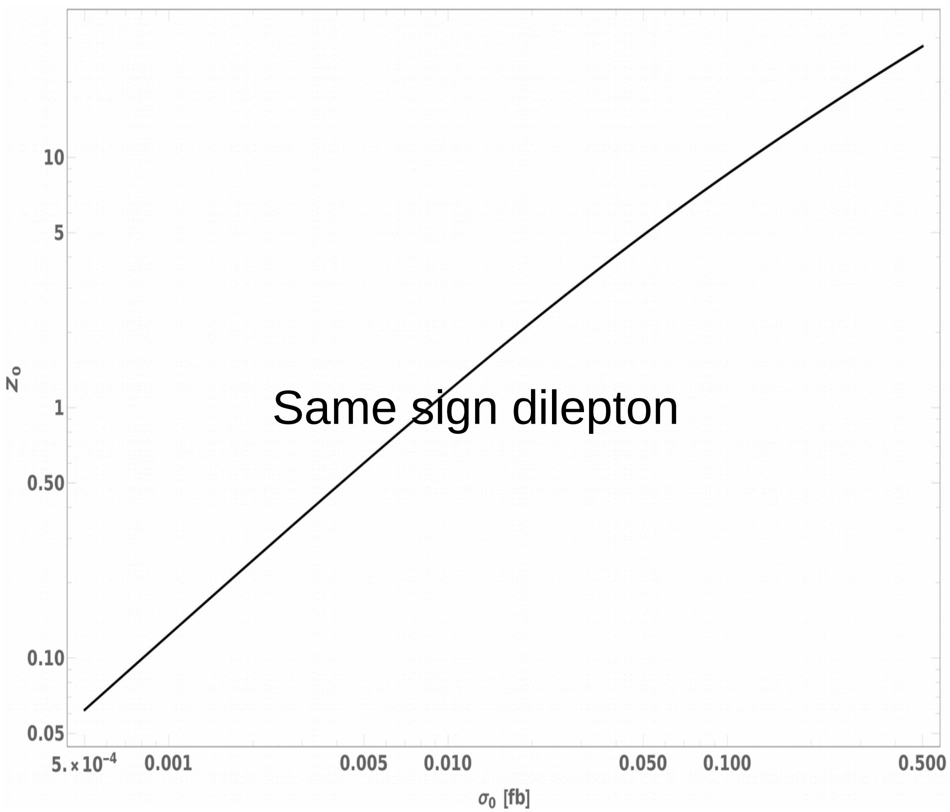
$m' = 1; \quad M_{Z'} = 1.5$ TeV

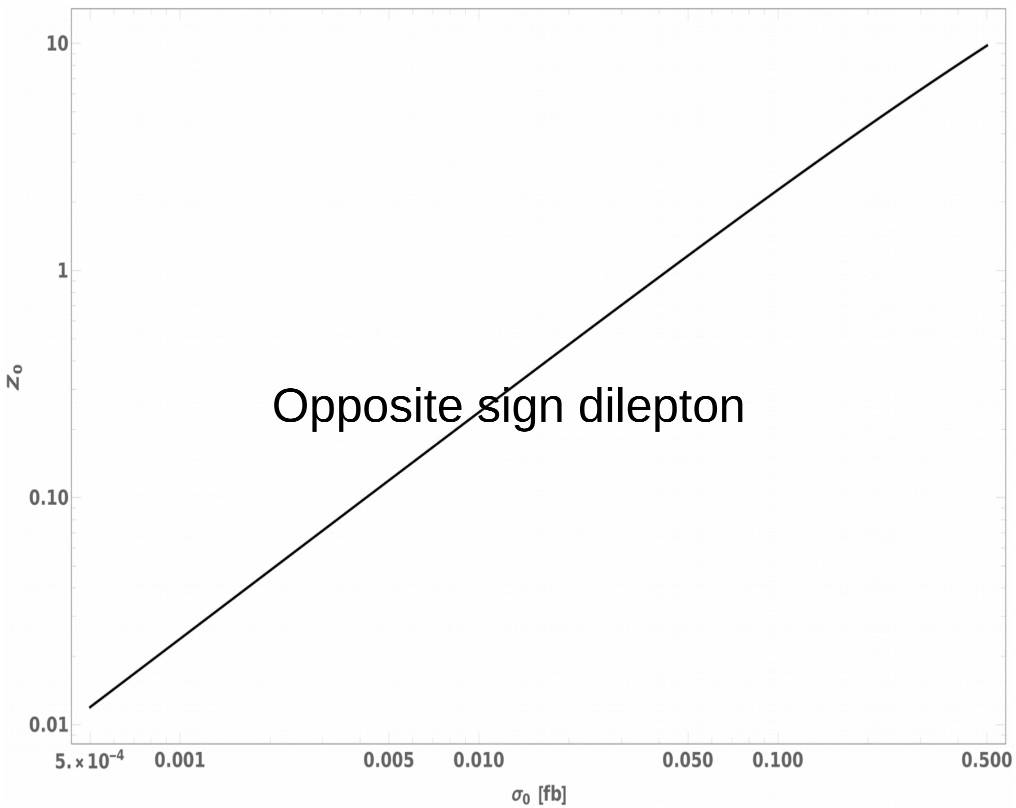
Z' → NN channel



Same-sign OR opposite-sign dilepton +
two-boosted W-jet (two prong)

Sensitivity @ HL-LHC





- We have to translate cross sections in terms of model parameters
- Plan to investigate symmetric and asymmetric channels with other decay modes of N → Zν, Hν
- Multivariate analysis to improve the sensitivity especially lower mass region

Outlooks: dark matter models

- Anomaly-Free Dark Matter Models are not so Simple
  by Ellis, Fairbairn, Tunney, JHEP, 08 053 (2017)
- Phenomenological Constraints on Anomaly-Free Dark Matter Models
  by Ellis, Fairbairn, Tunney, arXiv:1807.02503
- They have considered fermionic dark matter particles to cancel gauge anomalies
- Can we think of a next-to-minimal anomaly free setup with DM and RHN to have seesaw mechanism?
- Mass generation with combined Higgs-Stükelberg mechanism can lead to massive axions. Can they be DM?

Summary and conclusions

- We consider minimal anomaly free U(1) extensions of the SM
- Anomalies are cancelled by introducing chiral fermions or through the Green-Schwarz mechanism
- Using EWPT constraints, 13 TeV LHC data, …. , we constrain minimal anomaly free U(1) extensions of the SM
- We introduce a model independent parametrization for these class of models
- Project-1: (ongoing) New signatures like RHN pair productions, correlated collider analysis with Z', RHN and heavy scalar
- Project-2: Combined Higgs-Stuckelberg mechanism, axion (light or heavy) DM, in context of Green-Schwarz mechanism
- Project-3: Anomaly free U(1) dark matter models with RHN to have seesaw mechanism