10.11.21 12.11.21

What's in a hidden U(1)?

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Overview

- An abelian symmetry.
- $U(1)$ is among us and unbroken ~ massless photon.

Global $U(1)_B$, $U(1)_L$

- Appears as a remnant in most gauge extensions of the SM.

GUTs, Left-Right symmetry, etc.

- Very useful in model building ~ simplicity and applications

SUSY, Extradimensions, Neutrino mass, g-2 anomaly, Flavour anomalies, etc.

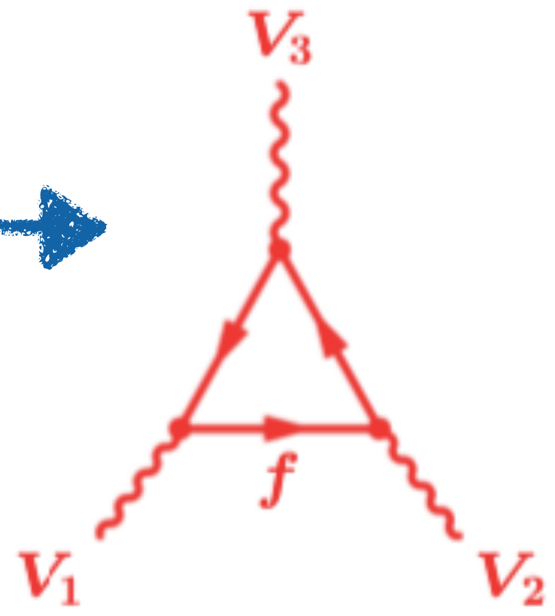
- Straight forward experimental signatures

The Physics of Heavy Z' Gauge Bosons, RMP 81, 1199 (0801.1345)

- Charge assignment is easier to decipher through observables

Z'

- Simple extension to SM: $\mathscr{G}_{SM} \times U(1)'$
- Z' couplings to SM fields start depending on the matter content added
- Anomalies → new fields f (vector-like)



Most of $U(1)'$ constructions need additional fermions to cancel the triangle anomalies.

- Numerous possibilities with no fixed rule: lepton specific, hadrophobic, etc.
- Signal for the commonly studied scenario at colliders involves only the associated neutral current with simple assumptions ~ $\mathscr{L} \subset g' J^\mu Z'_\mu$

$$J^\mu = f\,(q_L^f, q_R^f)$$

Quasi-Chiral : vector-like under SM but chiral under $U(1)'$.

SM as an example:

Neutral current : $\mathcal{L}_Z = \frac{g}{\cos\theta_W} J_Z^\mu Z_\mu$

- SM quarks : $J_Z^\mu = \overline{u_L}\,\gamma^\mu(\frac{1}{2} - Q\sin^2\theta_W)\,u_L + \overline{u_R}\,\gamma^\mu(0 - Q\sin^2\theta_W)\,u_R$
- Vector-like quarks :
  - Doublet :

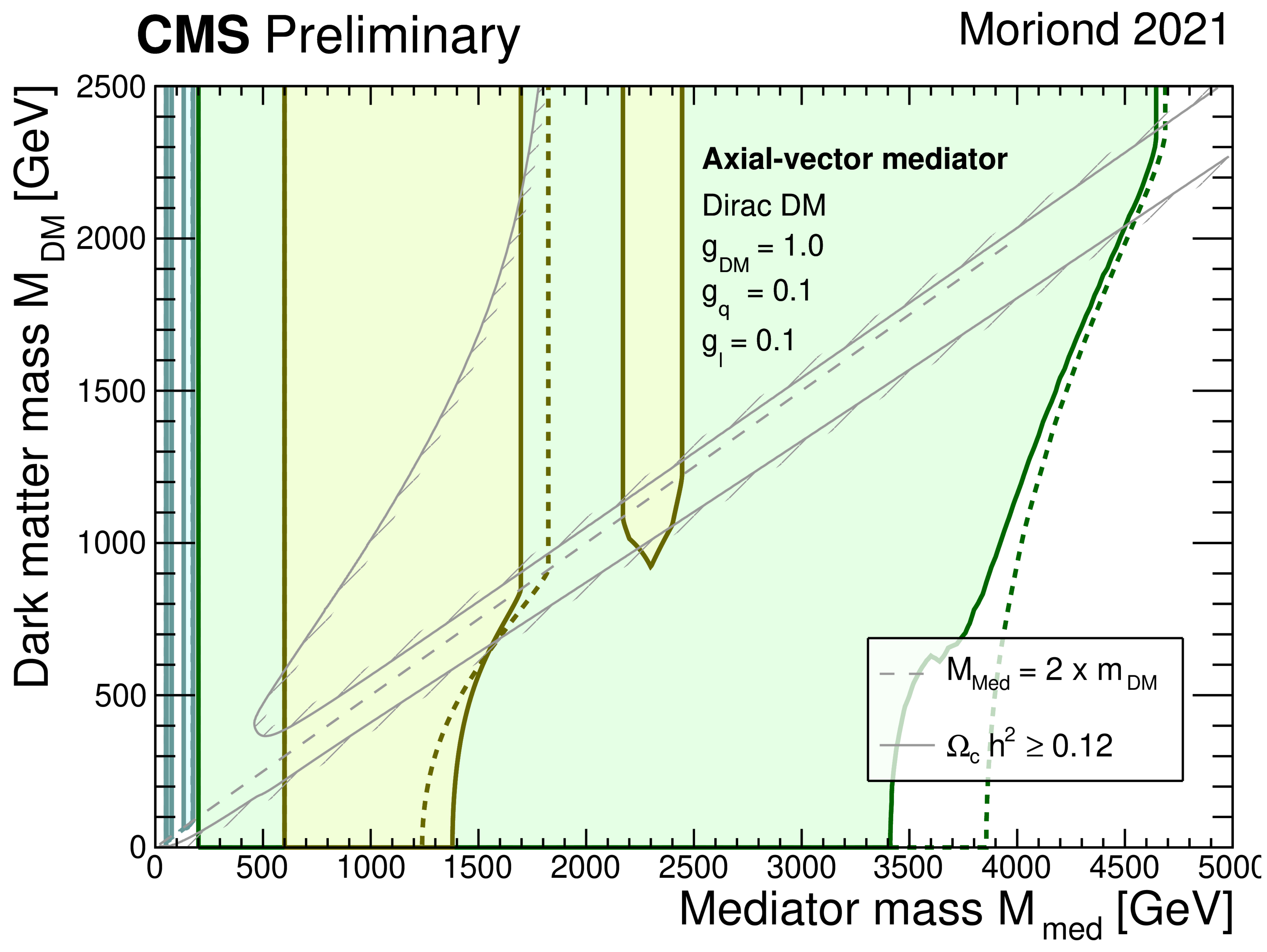
$$J_Z^\mu = \overline{xu_L}\,\gamma^\mu(\frac{1}{2} - Q\sin^2\theta_W)\,xu_L + \overline{xu_R}\,\gamma^\mu(\frac{1}{2} - Q\sin^2\theta_W)\,xu_R$$

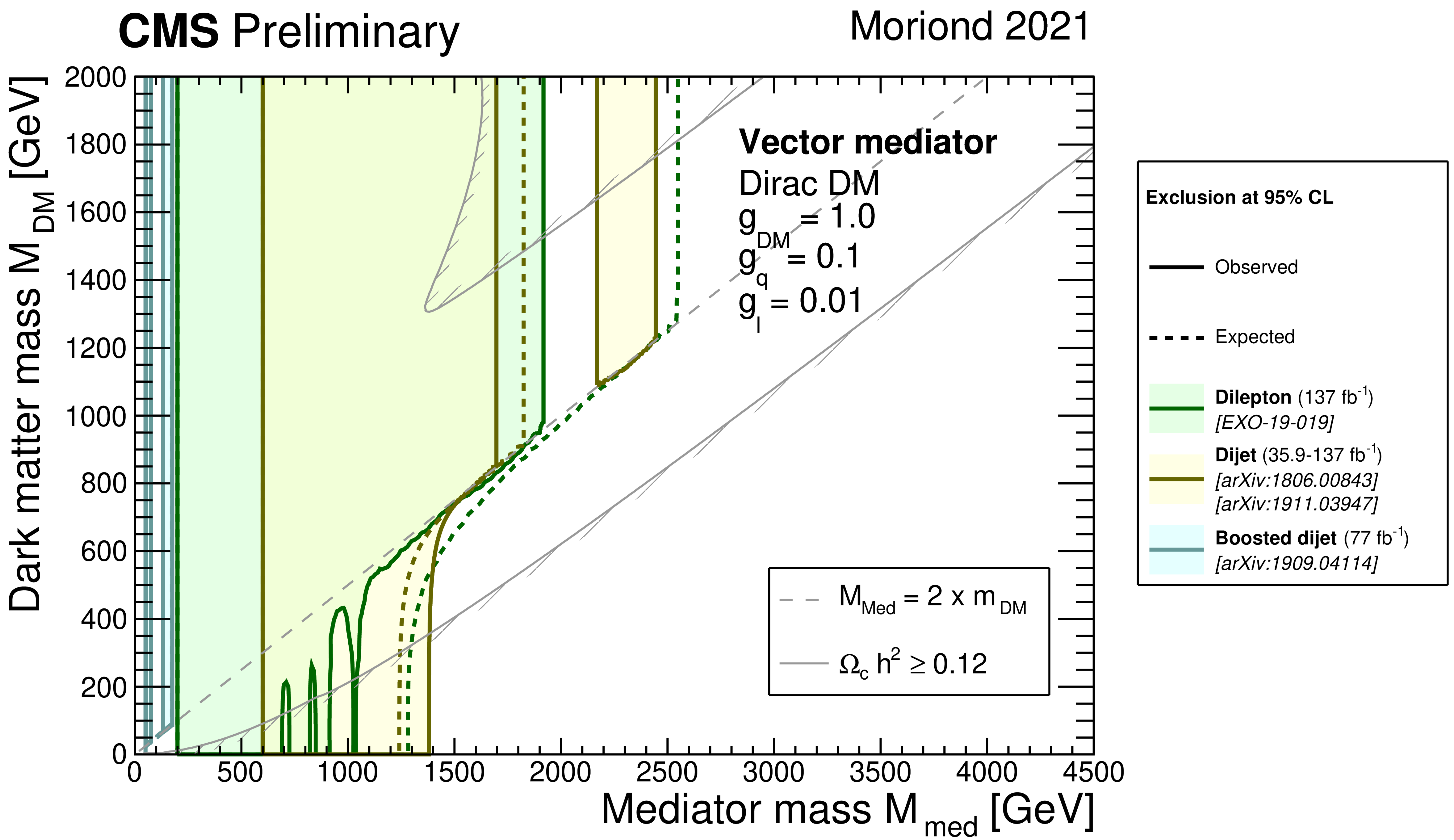
$$= (\frac{1}{2} - Q\sin^2\theta_W)\,\overline{xu}\,\gamma^\mu\,xu \equiv V$$

q_L^f q_R^f

- In most models, the SM fermions and the Electroweak Higgs boson carry non-trivial charges under the U(1), e.g. remnants from GUTs
- Other variations of the extra U(1) symmetry: hadro-phobic U(1), lepto-phobic U(1), extra U(1) coupling only to the third family of fermions, etc.

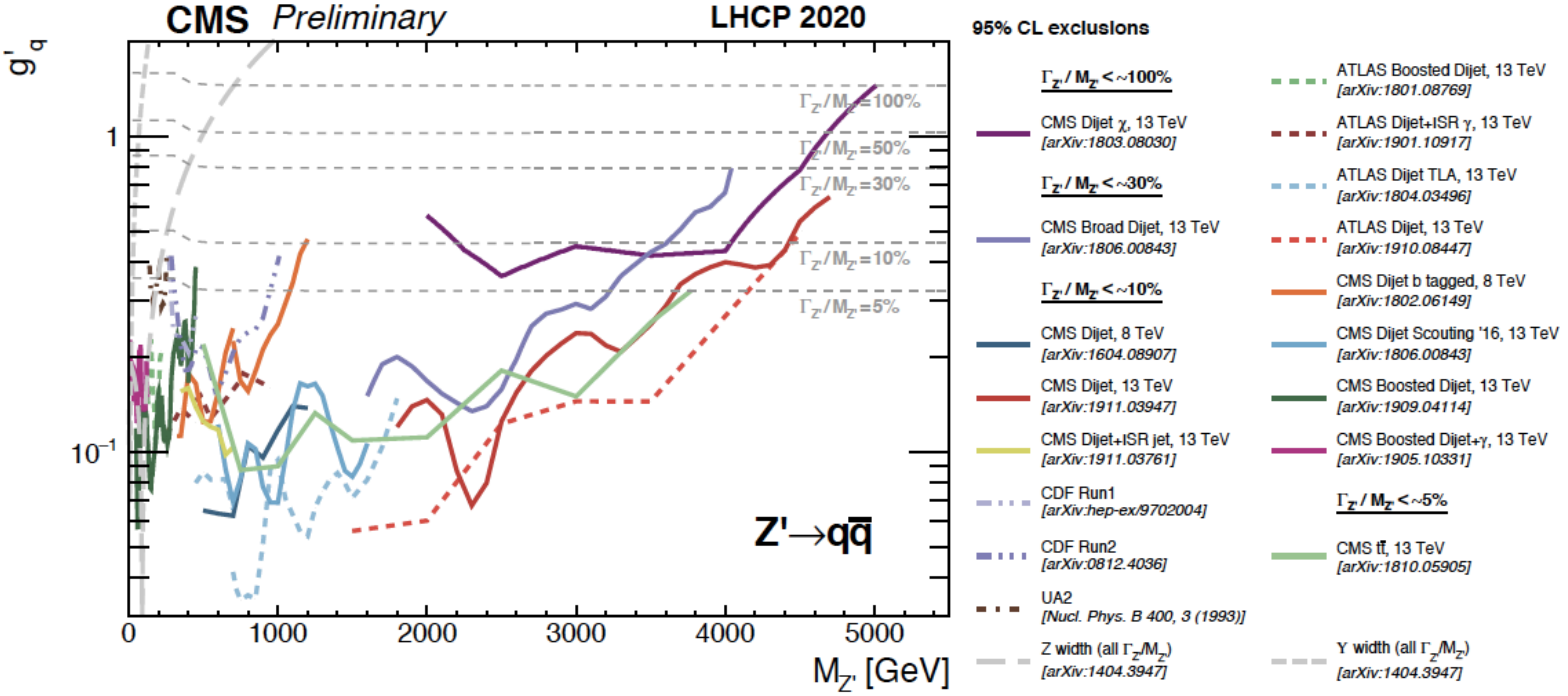
Z' exclusions





Z' exclusions

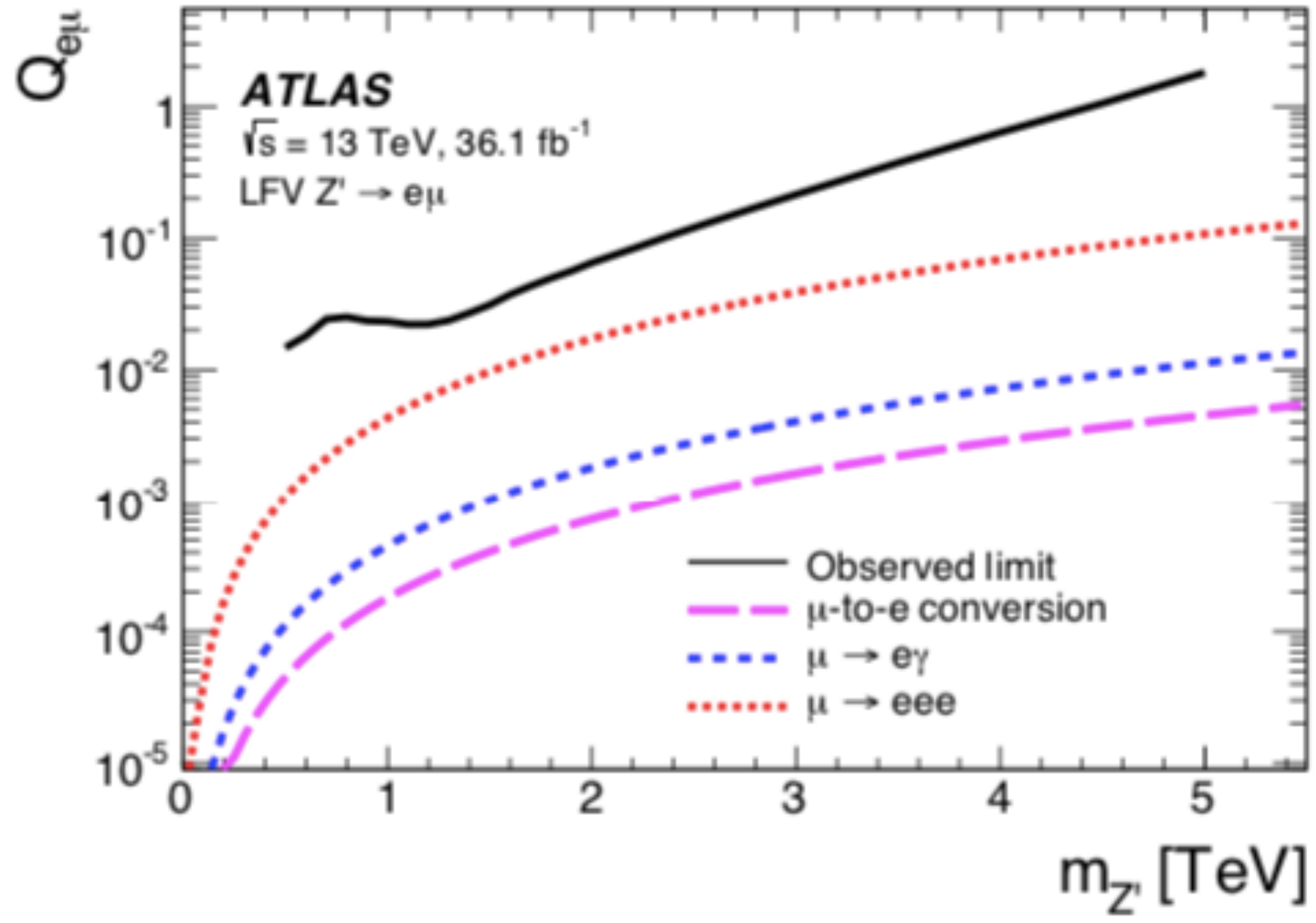
Leptophobic Z'



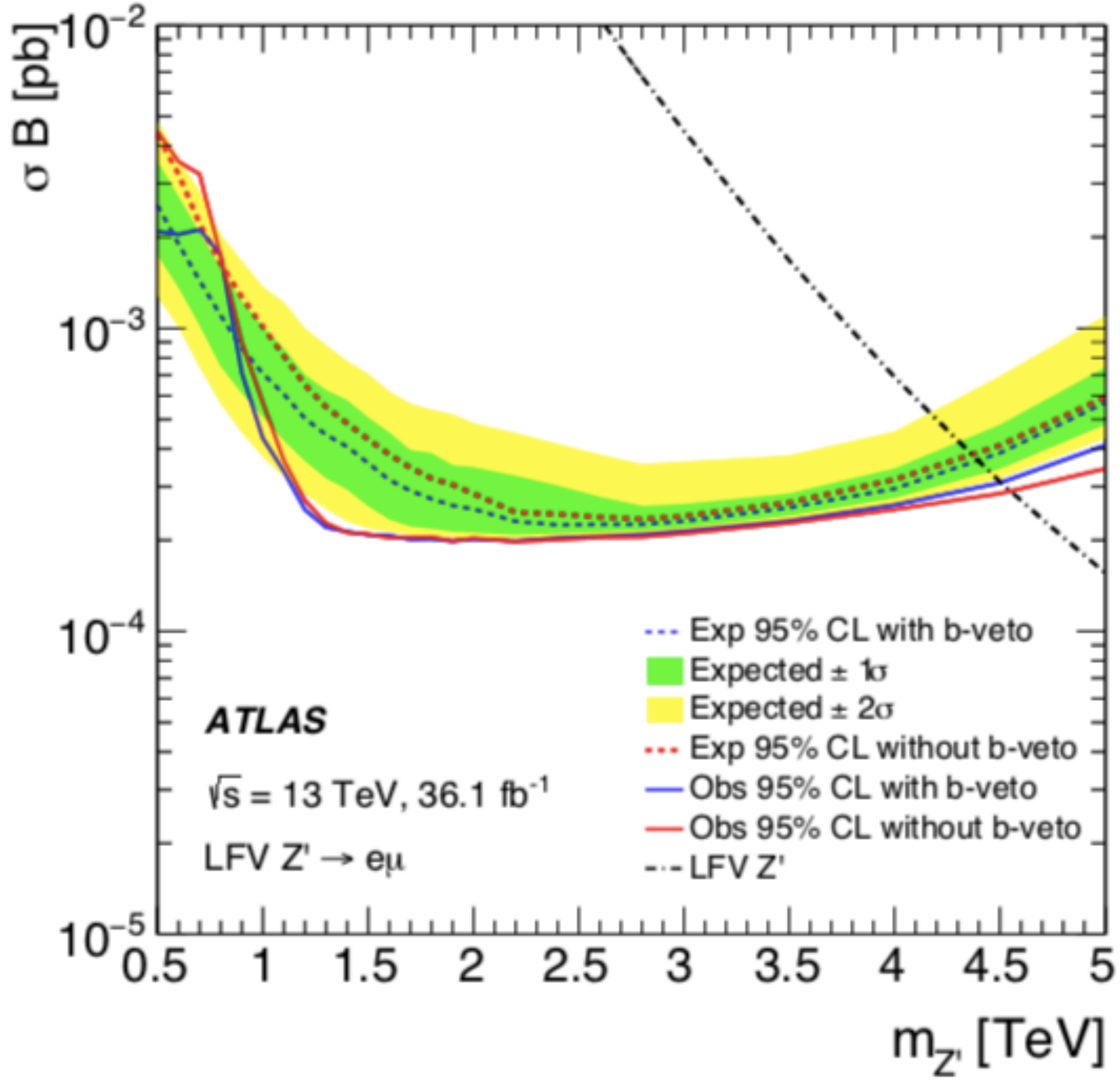
Z' exclusions

LFV searches for Z' at LHC

- Sequential Z_{SM}
- Z' couplings are SM like
- $Q_{ll'}$ represents the relative LFV strength



$$pp \to Z' \to \ell\ell'$$



TeV scale remnant $U(1)'$ from : $E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$

The unbroken symmetry at TeV scale:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'.$$

The unbroken $U(1)'$ at TeV scale:

$$Q' = \cos\theta \; Q_\chi + \sin\theta \; Q_\psi, \quad \tan\theta = \sqrt{5/3}.$$

$\tan\theta = \sqrt{5/3} \Rightarrow SN_i^c N_i^c$ term possible. (Neutrino Mass)

$$\begin{aligned} -\mathcal{L}_y = \; & y_{ij}^U Q_i U_j^c H_u + y_{ij}^D Q_i D_j^c H_d + y_{ij}^E L_i E_j^c H_d + y_{ij}^N L_i N_j^c H_u \\ & + y_{ij}^{XNd} XL_i^c XN_j H_d + y_{ij}^{XNu} XL_i XN_j H_u + y_{ij}^{TD} D_i^c XD_j T \\ & + y_{ij}^{TL} XL_i^c L_j T + y_{ij}^{SD} XD_i^c XD_j S + y_{ij}^{SL} XL_i^c XL_j S \\ & + y_{ij}^{SN} S N_i^c N_j^c + y_{ij}^{TXNN} T XN_i^c N_j^c + \text{H.C.} \end{aligned}$$

Divide $U(1)'$ charges by $4\sqrt{15}$

$SO(10)$	$SU(5)$	Fields	$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$
		Q_i	$(\mathbf{3}, \mathbf{2}, \mathbf{1/6}, \mathbf{1})$
		U_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, -\mathbf{2/3}, \mathbf{1})$
		E_i^c	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})$
		D_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3}, \mathbf{7})$
		L_i	$(\mathbf{1}, \mathbf{2}, -\mathbf{1/2}, \mathbf{7})$
		N_i^c / T	$(\mathbf{1}, \mathbf{1}, \mathbf{0}, -\mathbf{5})$
10	5	XD_i	$(\mathbf{3}, \mathbf{1}, -\mathbf{1/3}, -\mathbf{2})$
		XL_i^c, H_u	$(\mathbf{1}, \mathbf{2}, \mathbf{1/2}, -\mathbf{2})$
	$\bar{5}$	XD_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3}, -\mathbf{8})$
		XL_i, H_d	$(\mathbf{1}, \mathbf{2}, -\mathbf{1/2}, -\mathbf{8})$
1	1	XN_i, S	$(\mathbf{1}, \mathbf{1}, \mathbf{0}, \mathbf{10})$

Eur. Phys. J. C 78(2018) 35

K . Das, T . Li, S . Nandi, SKR

- No direct hint of a $U(1)$ extension yet. If present how can it hide?
- Very weakly coupled → very narrow resonance
- Many new exotic decay modes → very broad resonances

Cascade decays, dominant invisible decay to DM ?

- So what if it does not couple to SM directly?

Difficult to produce directly which is likely to keep it hidden

Rely on mixing, associated production, observation as a decay product ?

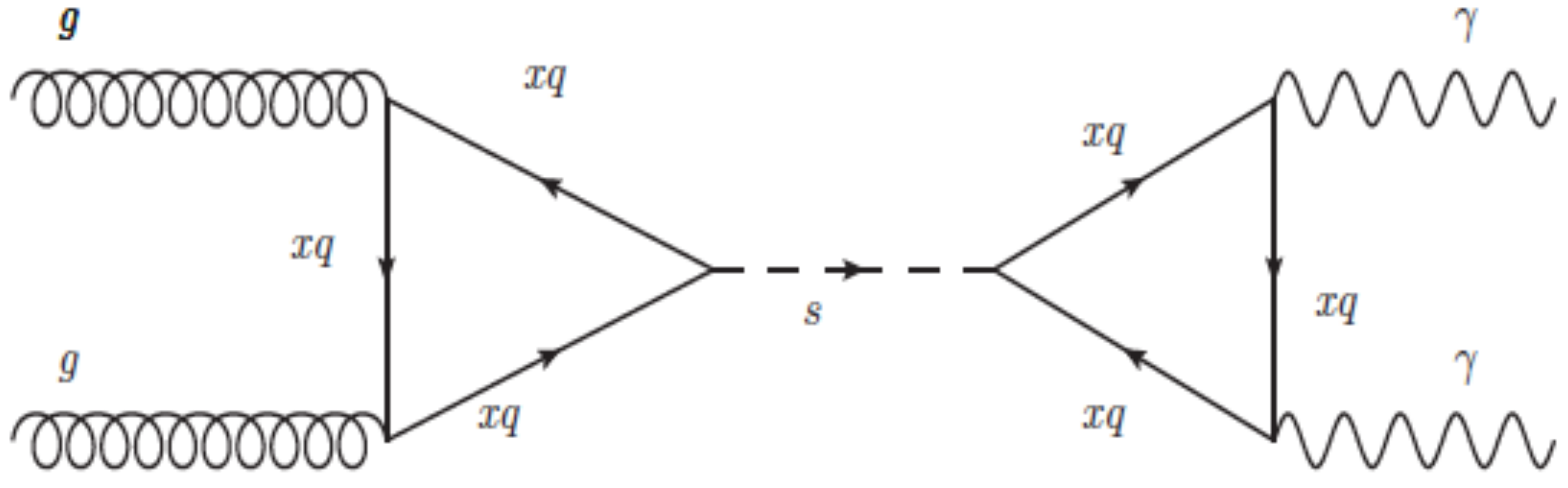
Vector-like quarks in a hidden $U(1)$ extension.

Grossmann, McElrath, Nandi, SKR; (PRD); 1006.5019

Hidden $U(1)$: Standard Model fields are neutral under $U(1)'$.

S_1	$(1, 1, 0, q')$
S_2	$(1, 1, 0, 0)$
xq_L	$(3, 1, -1/3, q')$ or $(3, 1, 2/3, q')$
xq_R	$(3, 1, -1/3, q')$ or $(3, 1, 2/3, q')$

- $-\mathcal{L}_{\rm Yukawa} \supset M_x\ \overline{xq_l}\ xq_R + Y_{xq}\ \overline{xq_l}\ q_R\ S_1 + f_X\ \overline{xq_L}\ xq_R\ S_2 + \rm H.C$



750 GeV diphoton excess in a U(1) hidden symmetry model.

Phys. Rev. D 93 095007 (2016), K. Das, S.K. Rai

- Z' connects to the SM sector through $< S_1 >$
- Direct production via $q - xq$ or $Z - Z'$ mixing
- Pair production via $S - H_{SM}$ mixing
- Production from the decay of heavy xq, S

Observable effects of vector-like quarks :

- Indirect observations
  - Rare top decays : $t \to Zq$ (FCNC)
  - Meson mixings and decay. (Tree level FCNC and VLQ in the loop).
  - Modifications to CKM matrix.
  - Modification of $Zc\bar{c}$, $Zb\bar{b}$, $Zu\bar{u}$, $Zd\bar{d}$ couplings.
  - S, T, U parameters (VLQ in the loop.)
  - Higgs coupling with gluons and photons.

Not much information on Z'

Hints of $Z - Z'$ mixing?

Direct observations at LHC :

- As Colored particles they will be pair produced.
- Mixing with SM quarks opens up decay modes for VLQ :

  Example: $+\frac{2}{3}$ charge: $xt \to W\,b,\ Z\,t,\ h\,t$

  $-\frac{1}{3}$ charge: $xb \to W\,t,\ Z\,b,\ h\,b.$

Production cross section via Z'

Hints of $Z - Z'$ mixing

as well as its mass ?

Neutrinophilic $U(1)$ model

$$\mathcal{L} \supset (D_\mu H_1)^\dagger D_\mu H_1 + (D_\mu H_2)^\dagger D_\mu H_2 + (D_\mu S)^\dagger D_\mu S - \mu_1 H_1^\dagger H_1 - \mu_2 H_2^\dagger H_2 - \mu_s S^\dagger S$$
$$+ i\overline{N}_L \gamma^\mu D_\mu N_L + i\overline{N}_R \gamma^\mu D_\mu N_R - \hat{M}_N \left(\overline{N}_L N_R + \overline{N}_R N_L\right) - \{Y_\nu \bar{l}_L H_2 N_R + h.c.\}$$
$$- \lambda_1 \left(H_1^\dagger H_1\right)^2 - \lambda_2 \left(H_2^\dagger H_2\right)^2 - \lambda_{12} H_1^\dagger H_1 H_2^\dagger H_2 - \lambda'_{12} \left|H_1^\dagger H_2\right|^2$$
$$- \lambda_s \left(S^\dagger S\right)^2 - \lambda_{1s} H_1^\dagger H_1 S^\dagger S - \lambda_{2s} H_2^\dagger H_2 S^\dagger S - \{Y_R S \overline{N}_R N_R^C + Y_L S \overline{N}_L N_L^C + \text{h.c.}\}$$
$$+ \left\{\mu_{12} H_1^\dagger H_2 + \text{h.c.}\right\}.$$

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Spin
H_1	1	2	$-1/2$	0	0
H_2	1	2	$-1/2$	$-q_x$	0
S	1	1	0	$2q_x$	0
N_L^i	1	1	0	q_x	$1/2$
N_R^i	1	1	0	q_x	$1/2$

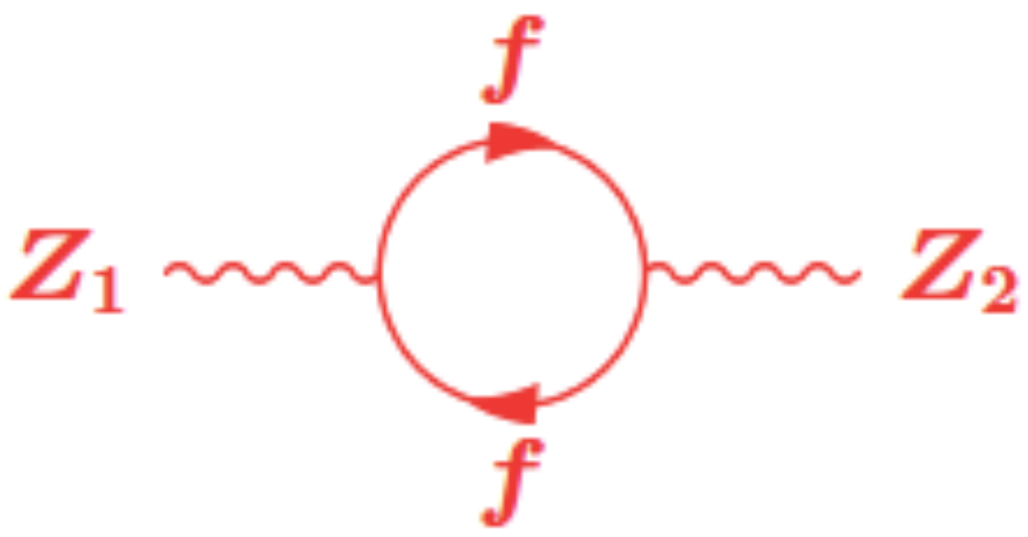
- Neutrino mass via inverse seesaw
- Z' again connects to the SM through $< S_1 >$ but now only to the charge neutral fermions
- Direct production via $Z - Z'$ mixing
- Pair production via $S - H_{SM}$ mixing
- Production from the decay of heavy neutrinos

$$\langle H_1 \rangle = \begin{pmatrix} \frac{v_1}{\sqrt{2}} \\ 0 \end{pmatrix}, \qquad \langle H_2 \rangle = \begin{pmatrix} \frac{v_2}{\sqrt{2}} \\ 0 \end{pmatrix}, \qquad \langle S \rangle = \frac{v_s}{\sqrt{2}}$$

Abdallah, Barik, SKR, Samui
e-print: 2106.01362, 2109.07980

Gauge kinetic mixing and masses of gauge bosons

$$\mathcal{L} \supset -\frac{1}{4}G^{a,\mu\nu}G^a_{\mu\nu} - \frac{1}{4}W^{b,\mu\nu}W^b_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}C^{\mu\nu}C_{\mu\nu} + \frac{1}{2}\tilde{g}B^{\mu\nu}C_{\mu\nu}\,,$$



$$M^2 = \frac{1}{4}\begin{pmatrix} g_1^2 v^2 & -g_1 g_2 v^2 & g_1\left(g_x' v^2 + 2g_x v_2^2\right) \\ -g_1 g_2 v^2 & g_2^2 v^2 & -g_2\left(g_x' v^2 + 2g_x v_2^2\right) \\ g_1\left(g_x' v^2 + 2g_x v_2^2\right) & -g_2\left(g_x' v^2 + 2g_x v_2^2\right) & {g_x'}^2 v^2 + 4g_x g_x' v_2^2 + 4g_x^2(v_2^2 + 4v_s^2) \end{pmatrix}$$

Mass matrix for single Z'

$$M^2_{Z-Z'} = \begin{pmatrix} M^2_{Z^0} & \Delta^2 \\ \Delta^2 & M^2_{Z'} \end{pmatrix}$$

- Eigenvalues $M^2_{1,2}$, mixing angle θ

$$\tan^2\theta = \frac{M^2_{Z^0} - M^2_1}{M^2_2 - M^2_{Z^0}}$$

constraints: Measurements at the Z-pole, Z width and decays

four-fermi operator interfering with γ, Z

Resonance in $pp, \bar{p}p \to e^+e^-, \mu^+\mu^-, \cdots$

Search for high-mass dilepton resonances using 139 fb^{-1} of pp collision data collected at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Phys. Lett. B 796 (2019) 68
1910.08447

Table 3: Observed and expected 95% CL lower limits on $m_{Z'}$ for three Z' gauge boson models, quoted to the nearest 100 GeV in the ee and $\mu\mu$ channels as well as their combination ($\ell\ell$).

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

Upper limits on mixing parameters $\xi_{Z\text{-}Z'}$ at 95% C.L.	$\xi_{Z\text{-}Z'}$	@$M_{V'}$ (TeV)
$pp \to W'/Z' \to WZ/WW\ (\to qqqq)$, $\mathcal{L}_{\text{int}} = 139$ fb^{-1}	$3.1 \cdot 10^{-4}$	1.3–5.0

arXiv:1912.02106v2

Redefining fields:

$$B^\mu = B'^\mu + \frac{\tilde{g}}{\sqrt{1-\tilde{g}^2}} C'^\mu ,$$
$$C^\mu = \frac{1}{\sqrt{1-\tilde{g}^2}} C'^\mu .$$

$\longrightarrow$

$$\begin{pmatrix} Z_\mu \\ Z'_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta' & \sin\theta' \\ -\sin\theta' & \cos\theta' \end{pmatrix} \begin{pmatrix} X_\mu \\ C'_\mu \end{pmatrix} ,$$

g_x : $U(1)'$ gauge coupling, g'_x : gauge-kinetic mixing

$Z - Z'$ mixing angle

$$\tan 2\theta' = \frac{2g_z\left(g'_x v^2 + 2g_x v_2^2\right)}{g_x'^2 v^2 + 4g_x g'_x v_2^2 + 4g_x^2(v_2^2 + 4v_s^2) - g_z^2 v^2} .$$

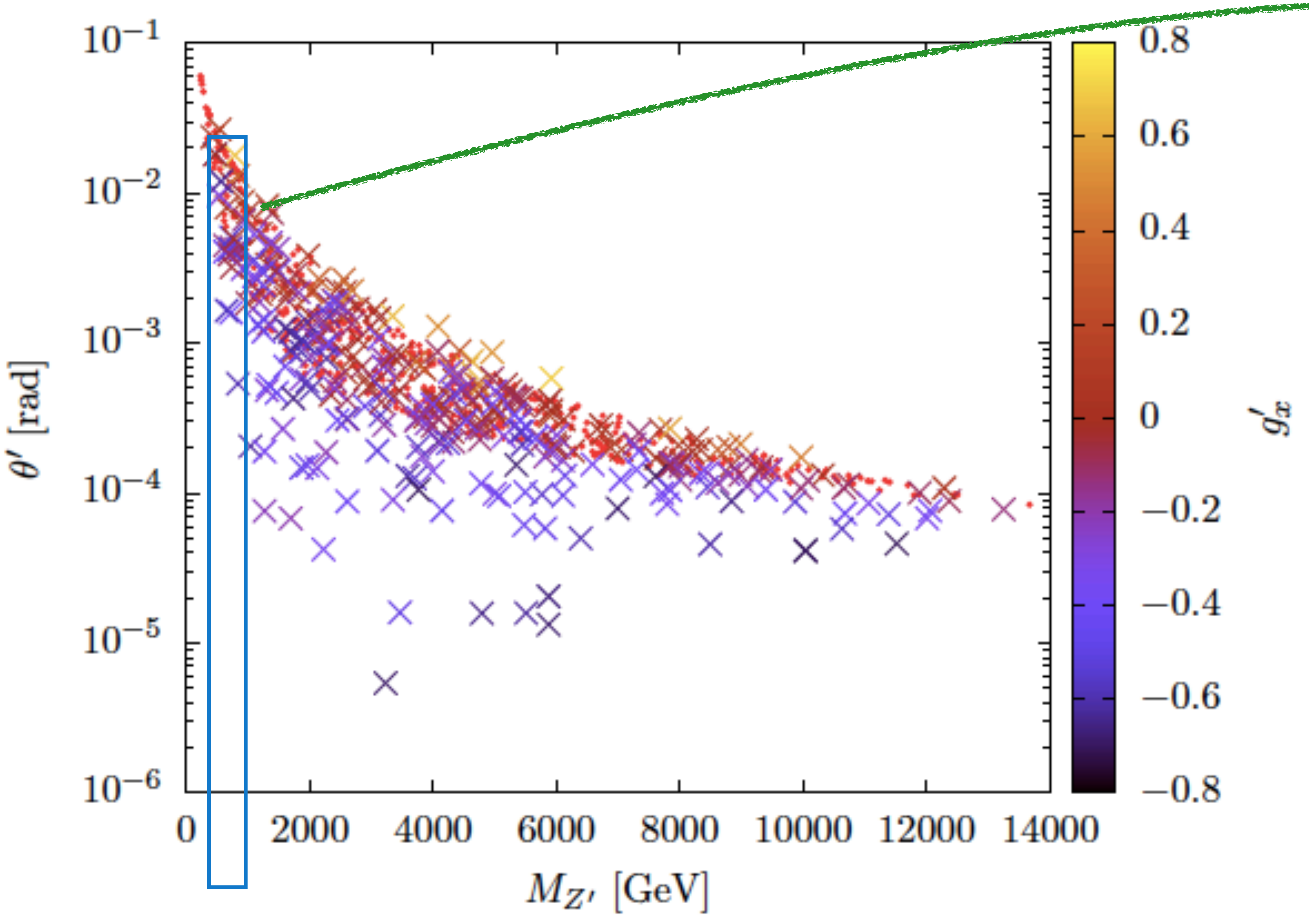
Non-zero θ' for $g'_x = 0$

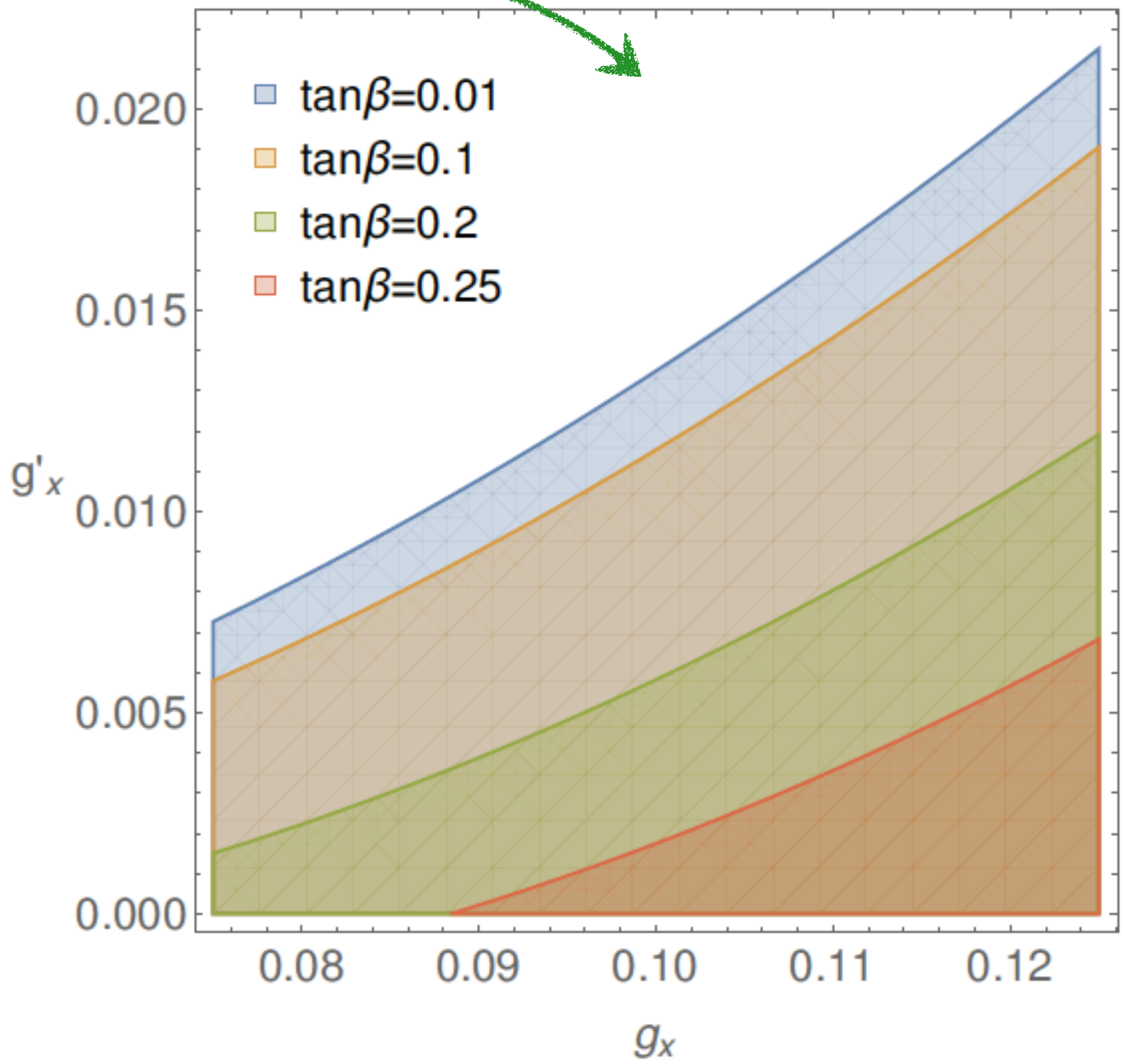
Numerator $\propto (2g_x + g'_x)$; $v_1 << v_2 \sim v$ $\longrightarrow$ cancelation leads to small mixing

Found to be disfavoured by Higgs data

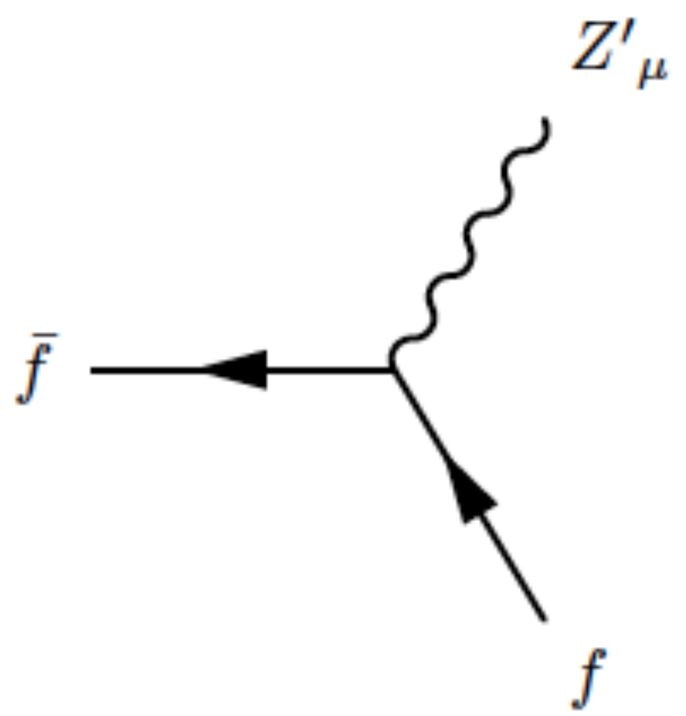
We note that $g'_x \lesssim 10^{-2}$ is sufficient to keep $\theta' < 10^{-3}$.

$Z - Z'$ mixing angle dictated parameter space

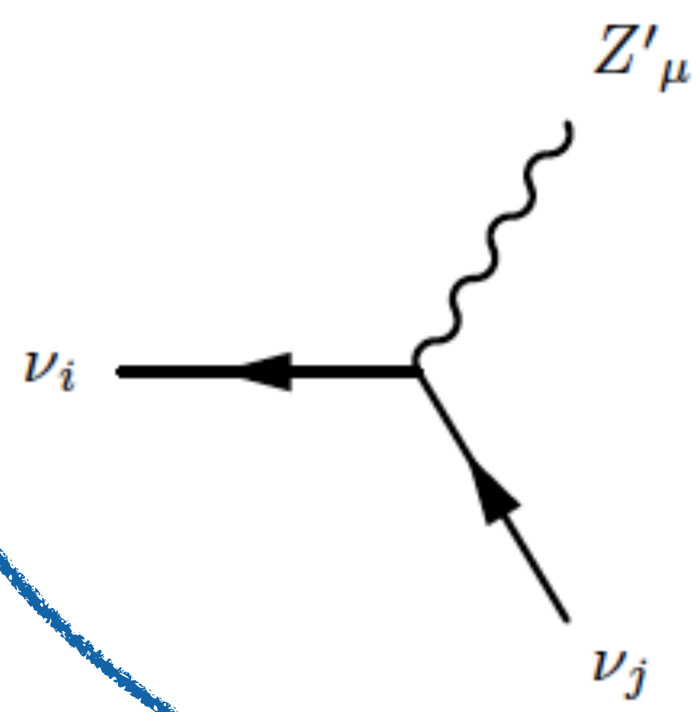




$\theta' \leq 10^{-3}$ in $g_x - g'_x$ plane for $v_s = 2$ TeV



$$i\left(\frac{e\, s_{\theta'}}{s_W c_W}\left(T^3 - Q_f s_W^2\right) + g'_x c_{\theta'}\left(T^3 - Q_f\right)\right)\gamma^\mu P_L - i\left(\frac{e\, s_{\theta'}}{s_W c_W} Q_f s_W^2 + g'_x c_{\theta'} Q_f\right)\gamma^\mu P_R$$



$$\frac{i}{2}\left(\left(\frac{e\, s_{\theta'}}{2\, s_W c_W} + \frac{g'_x}{2} c_{\theta'}\right)\sum_{k=1}^{3}\mathcal{N}_{ik}\mathcal{N}^*_{jk} - g_x c_{\theta'}\left(-\sum_{k=6}^{9}\mathcal{N}_{ik}\mathcal{N}^*_{jk} + \sum_{k=4}^{6}\mathcal{N}_{ik}\mathcal{N}^*_{jk}\right)\right)\gamma^\mu P_L$$

$$-\frac{i}{2}\left(\left(\frac{e\, s_{\theta'}}{2\, s_W c_W} + \frac{g'_x}{2} c_{\theta'}\right)\sum_{k=1}^{3}\mathcal{N}^*_{ik}\mathcal{N}_{jk} - g_x c_{\theta'}\left(-\sum_{k=6}^{9}\mathcal{N}^*_{ik}\mathcal{N}_{jk} + \sum_{k=4}^{6}\mathcal{N}^*_{ik}\mathcal{N}_{jk}\right)\right)\gamma^\mu P_R$$

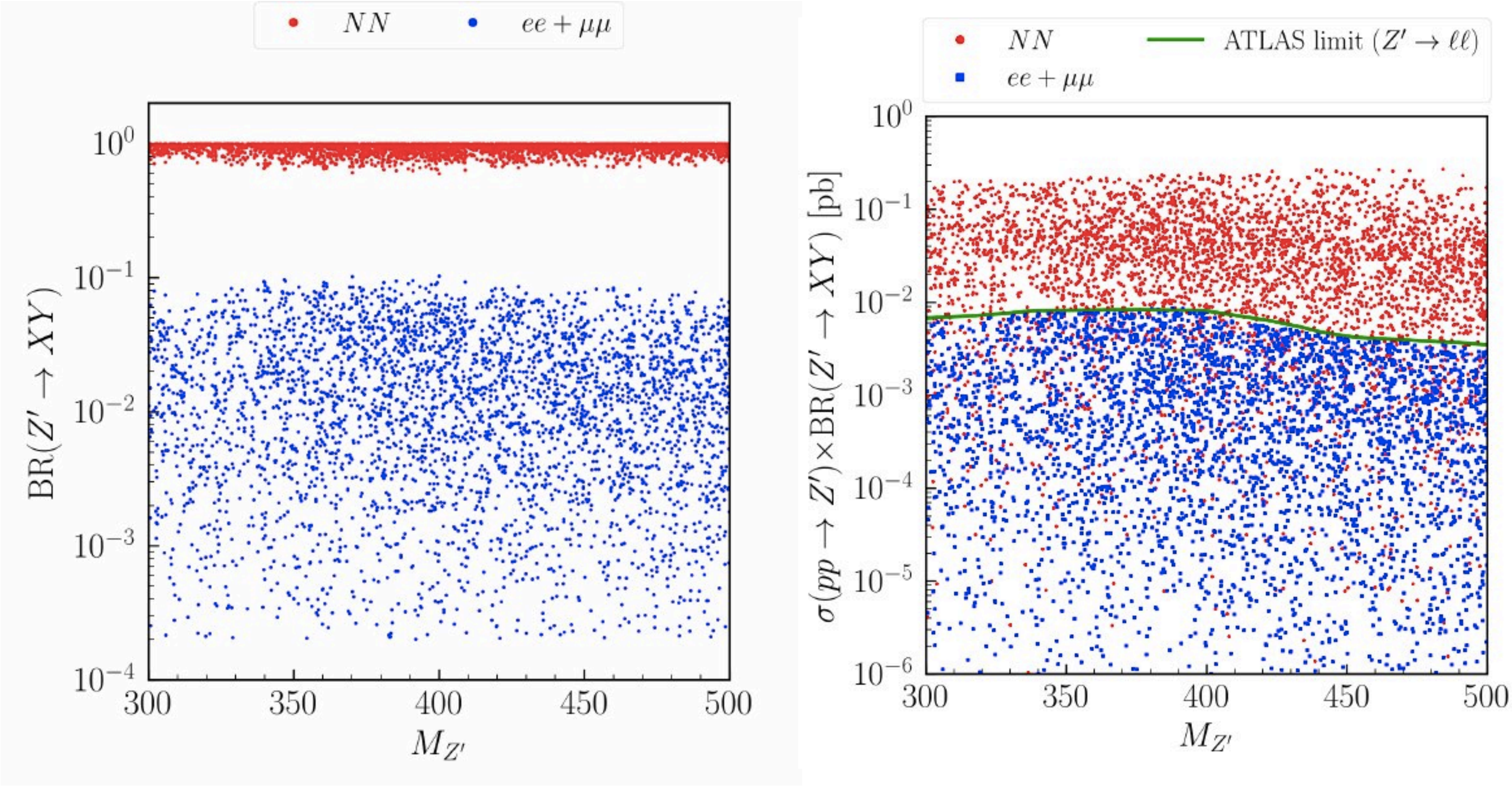
$\mathcal{N}$ is the neutrino mixing matrix

Signal: $pp \rightarrow Z' \rightarrow N\, N$

$2M_N < M_{Z'}$:

$Z' \rightarrow N\, N \simeq 100\,\%$:

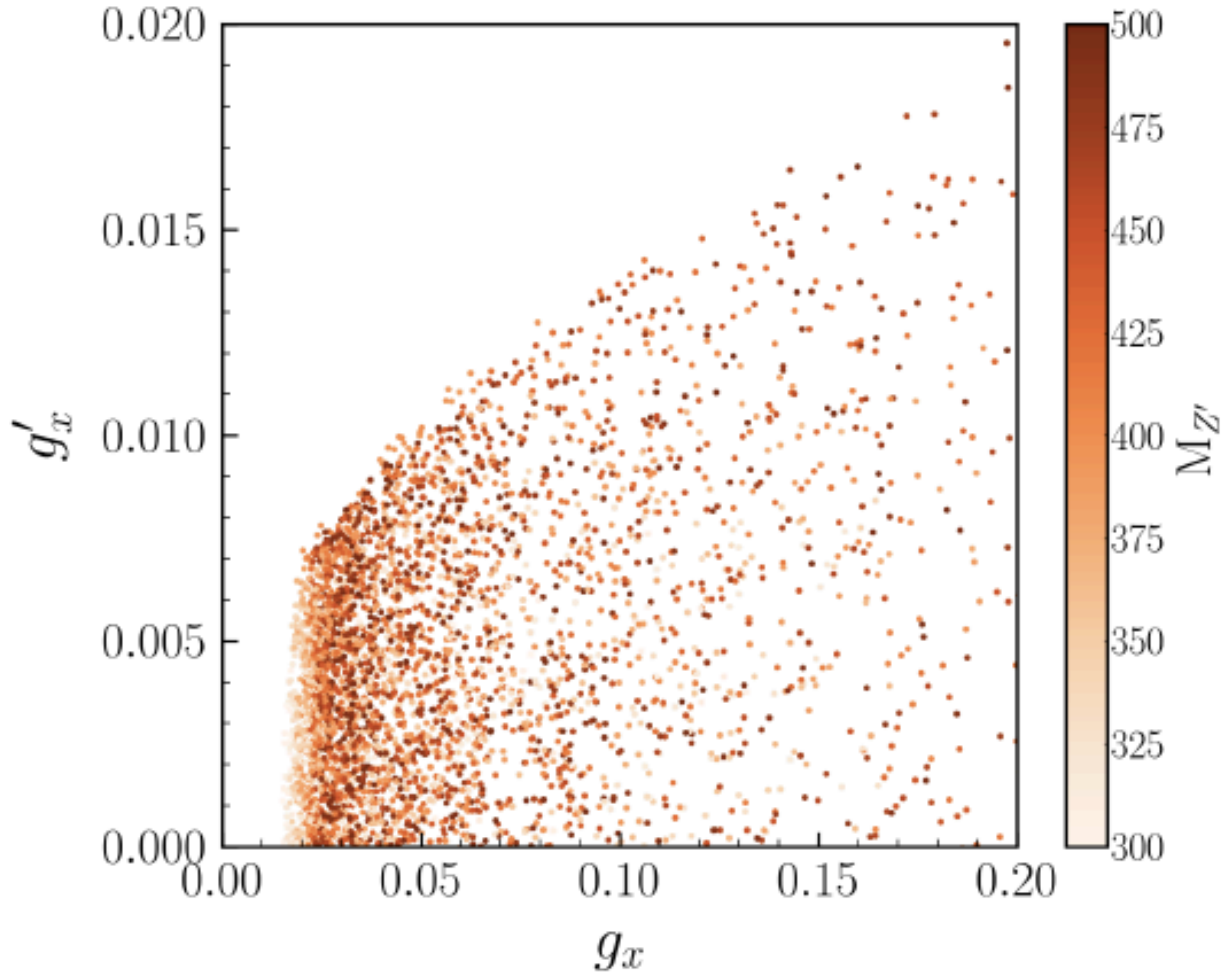
$g_x' < 0.02$



NN
$ee+\mu\mu$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
BR($Z' \to XY$)
300
350
400
450
500
$M_{Z'}$
NN
ATLAS limit ($Z' \to \ell\ell$)
$ee+\mu\mu$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\sigma(pp \to Z') \times$BR($Z' \to XY$) [pb]
300
350
400
450
500
$M_{Z'}$

Abdallah, Barik, SKR, Samui; 2106.01362

Scatter plot of points satisfying experimental constraints

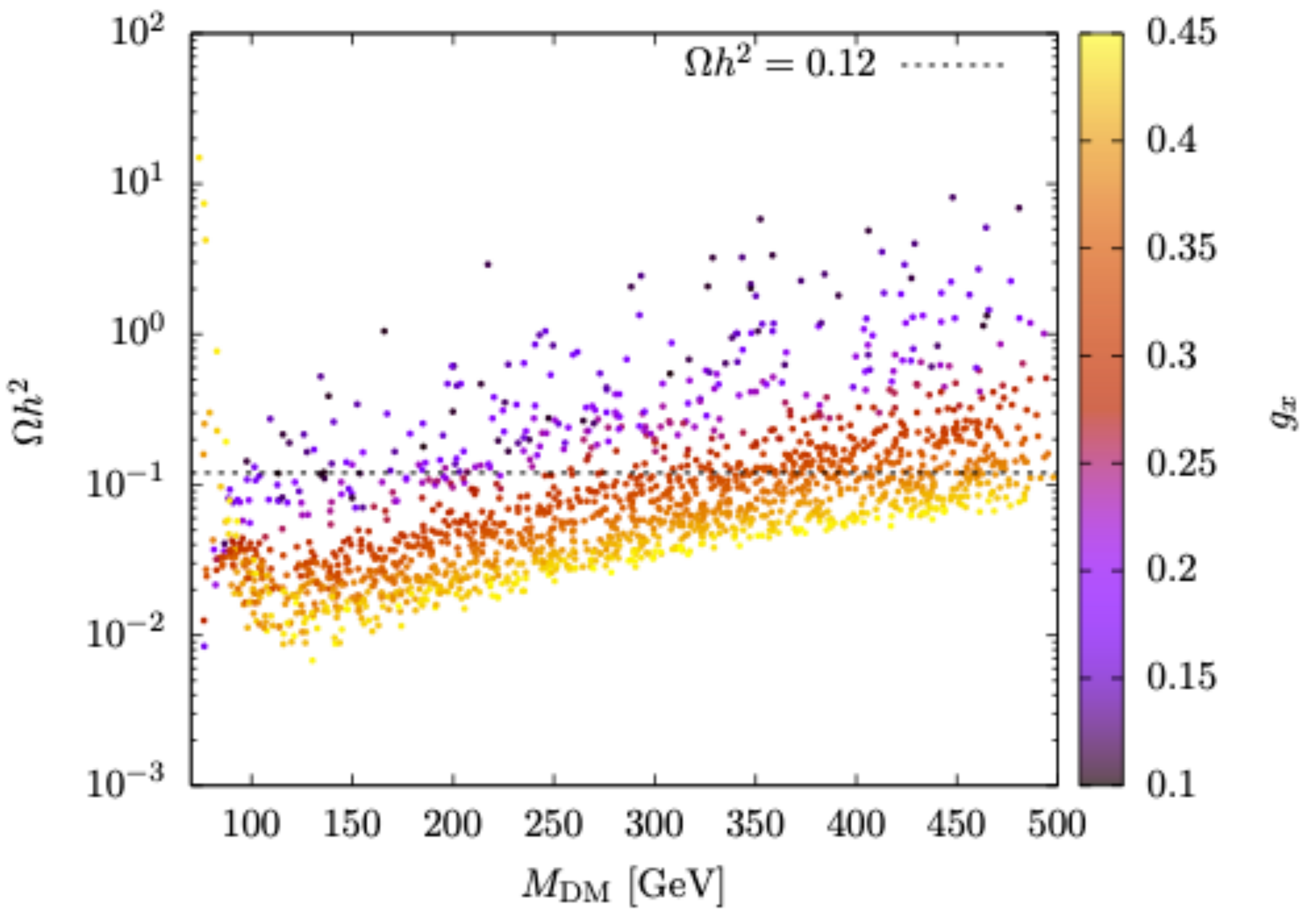


Signal: $N \to \ell W, \nu Z$

- $4\ell + \not{E}_T$
- $3\ell + 2j + \not{E}_T$
- $2\ell + 4j + \not{E}_T$
- $4j + \not{E}_T$ (when only $N \to \nu Z$ decay is considered.)

Z' phenomenology is only dependent on kinetic mixing and its coupling to exotic sector

- What if we now get rid of the Z-Z' mixing too?
- Set $\tan\beta = v_2/v_1 \simeq 10^{-5}$ and $g'_x = 0$
- Makes the Z' practically invisible to SM fields
- In addition choose $Y_{\nu_{11}} \lesssim 10^{-27}, Y_{\nu_{1j}} = 0$ which makes the lightest N_k stable (DM candidate)



Dominant annihilation channels

$N_k N_l \to Z' Z', H_s H_s, H_s Z'$ $(k, l = 4,5)$

Light Z' and/or H_s

$$pp \to h_{1,2} \to Z' Z' .$$

Abdallah, Barik, SKR, Samui; 2109.07980
Accomando et.al. 1708.03650; Amrith et.al. 1811.11452

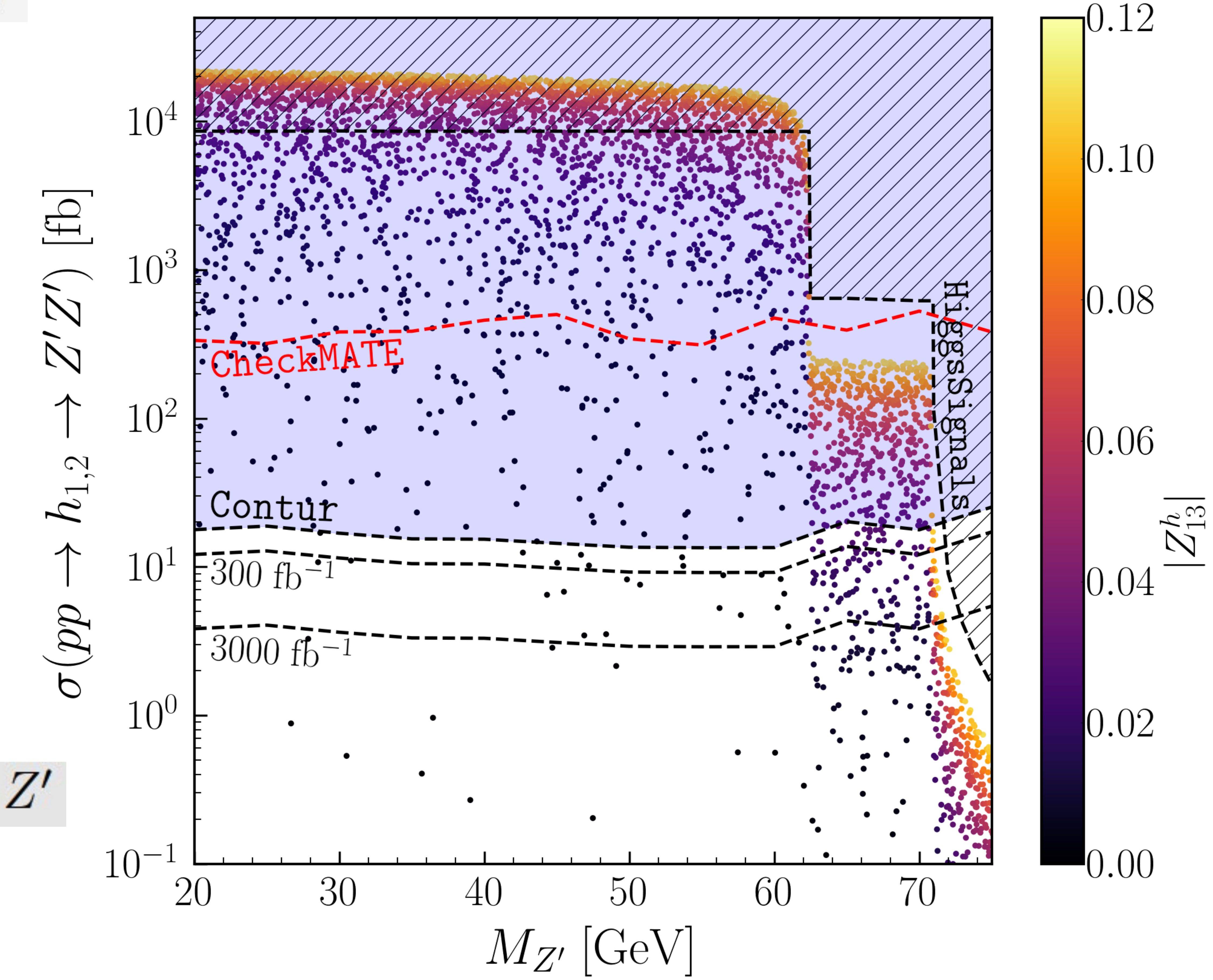
G. Aad *et al.* (ATLAS), JHEP **07**, 005 (2021), arXiv:2103.01918 [hep-ex].

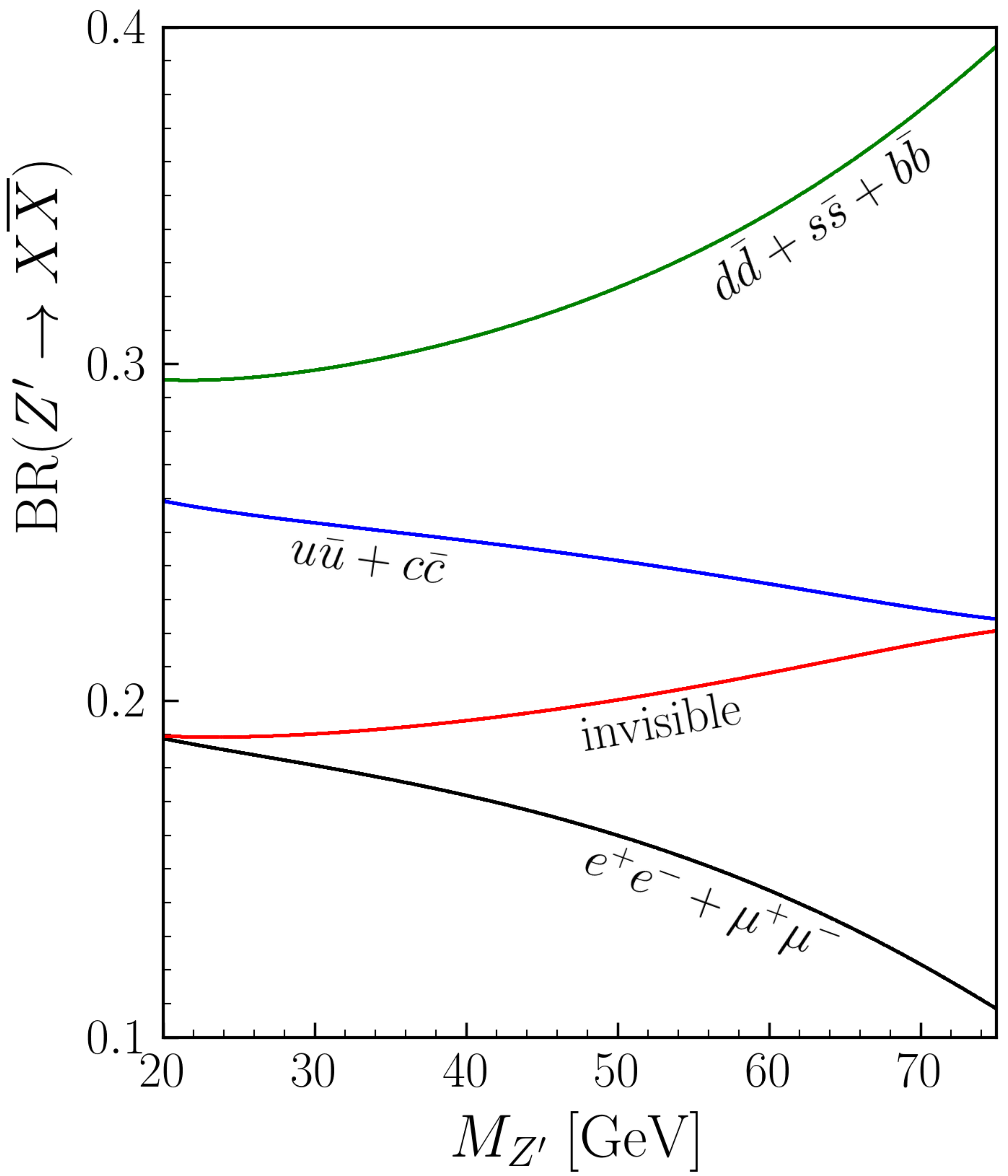
↓

measurement of the 4 lepton final state in the SM

↓

discovery channel for our Z'



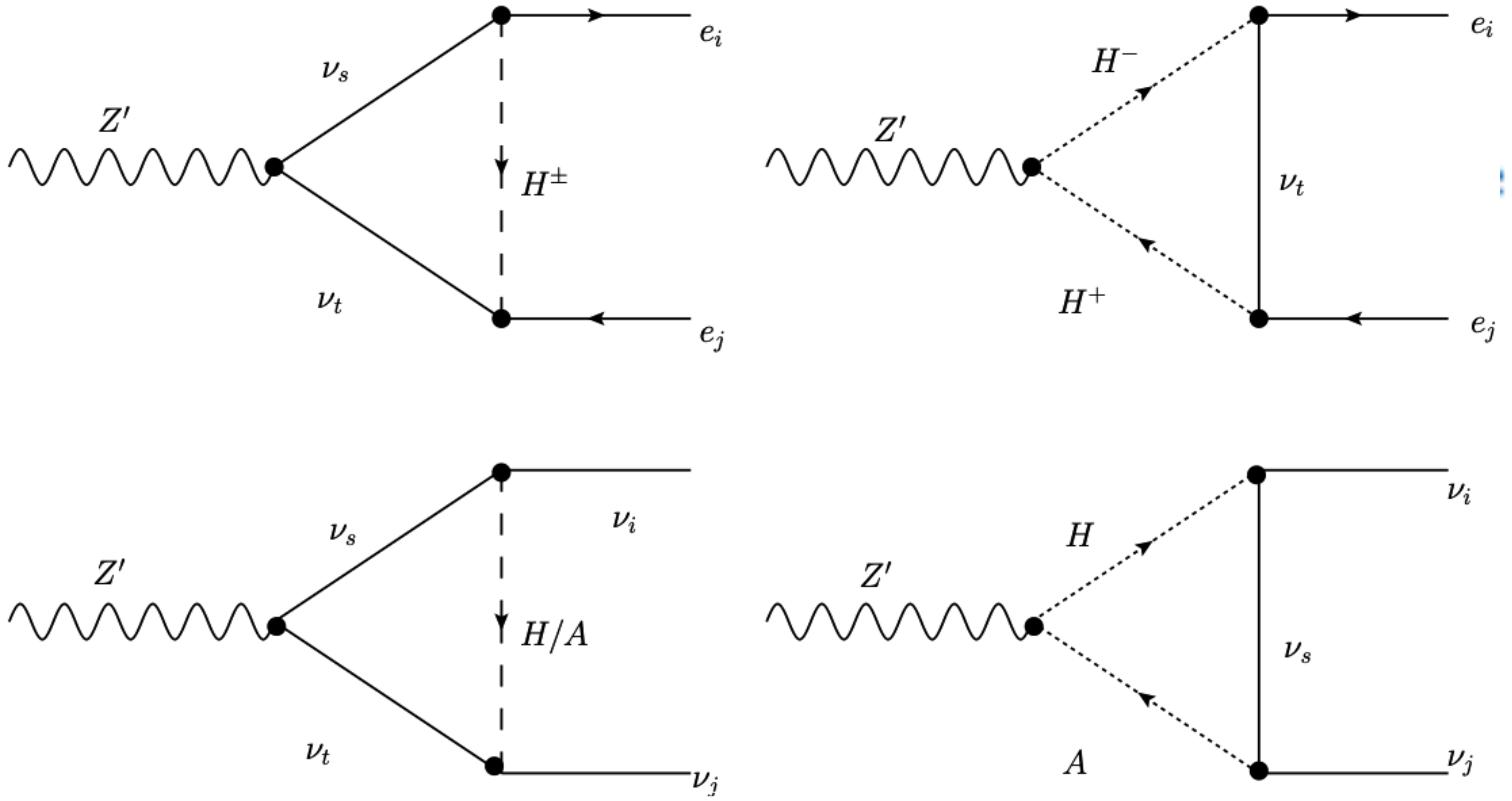


Interplay of Z' coupling to the singlet scalar with coupling strength g_x while the scalars are produced via gluon-gluon fusion helps probe the light gauge boson at LHC via Higgs sector

LFV signals through Higgs at LHC and ILC

Abdallah, Barik, SKR, Samui; 2109.07980

- Another interesting possibility when Z' decays radiatively due to $Y_{\nu_{ij}}$
- The $Y_{\nu_{ij}} \bar{\ell}_i H_2 N_j$ in the Lagrangian determines how large the radiative decay is.
- $Y_\nu \sim 10^{-2}$ gives loop induced decays comparable to tree-level width for $g'_x \sim 10^{-5}, \theta' \sim 10^{-5}$ mixing and $g_x \sim g_{EW}$.



effective vertex of $Z' l_k \overline{l_n}$

$$\mathcal{M}_{z' l_k l_n^+} = i f_{kn} \gamma^\mu P_L$$

The partial decay width for

$$\Gamma(Z' \to l_i \overline{l_j}) = \frac{M_{z'}}{24\pi} |f_{ij}|^2$$

Z' decay	$\sum \nu_a \nu_b$	$\sum \ell_a^+ \ell_a^-$	$\sum \ell_a^\pm \ell_b^\mp$	$\sum j\, j$	$\Gamma_{Z'}$ (GeV)
$Y_{\nu_{ij}}^{i\neq j} \sim 0,\ Y_\nu^{ii} \sim 10^{-3}$	$0.23\,(10^{-3})$	$0.16\,(10^{-4})$	$0\,(10^{-4})$	$0.61\,(0)$	2×10^{-9}
$Y_{\nu_{ij}}^{i\neq j} \sim 0.08,\ Y_\nu^{ii} \sim 0.2$	$10^{-5}\,(0.8)$	$10^{-5}\,(0.135)$	$0\,(0.065)$	$10^{-5}\,(0)$	3×10^{-4}

Summary

- With no clear hints of BSM physics at LHC we must explore the possibility of hidden symmetries in the data.
- $U(1)$ is one of the simplest and well motivated scenarios to consider.
- I showed through a few examples how a light Z' can show itself at experiments even when not connected to the SM sector directly but with gauge coupling strength similar to g_{EW}.
- Experimental signatures change as the modes of interactions change.
- Role of very long-lived Z' in this scenario, LFV, ILC expectations, DM, (g-2) at 2-loop, etc. are things being looked at currently.
- A closer look for such symmetries in accumulated data could show the need for new search strategies at LHC and future colliders.