Searching for the Flavon at Current and Future Colliders

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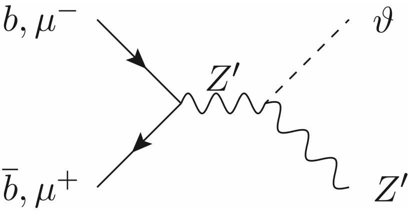

Based on arXiv:2212.07440 with Ben Allanach

Background

In spite of the updated R_K and R_{K^*}, several discrepant $b \to s\mu\mu$ observables remain:

- Branching ratios of $B \to K\mu\mu$, $B \to K^*\mu\mu$ and $B_s \to \phi\mu\mu$[1]
- Angular observables of $B \to K^*\mu\mu$[2]

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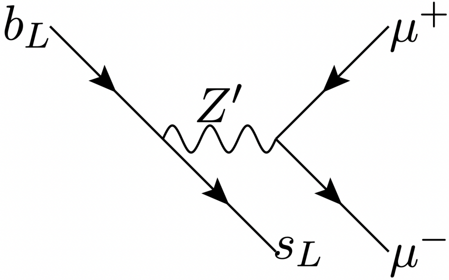
[1] LHCb, 1403.8044, 1606.04731, 2105.14007

[2] LHCb, 2003.04831, 2012.13241

A candidate explanation

Z' models with flavour non-universal couplings:



Another key motivation for flavour non-universal Z's: fermion mass puzzle[3]

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[3] E.g. Allanach and Davighi, 1809.01158

$B_3 - L_2$ model[4]

Gauge group:

$$\mathcal{G} = SU(3) \times SU(2) \times U(1) \times U(1)_{B_3 - L_2}$$

Field content:

$$\text{SM} + Z' + \theta \text{ (SM singlet scalar)} + 3\nu_R$$

Spontaneous symmetry breaking:

$$\langle \theta \rangle = \frac{v_\theta}{\sqrt{2}} \sim \mathcal{O}(\text{TeV}) \Rightarrow Z' \text{ becomes massive}$$

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[4] Alonso et al., 1705.03858; Bonilla et al, 1705.00915; Allanach, 2009.02197

Scalar potential

$$V(H,\theta) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_\theta^2 \theta^* \theta + \lambda_\theta (\theta^* \theta)^2 + \lambda_{\theta H} \theta^* \theta H^\dagger H$$

After symmetry breaking:

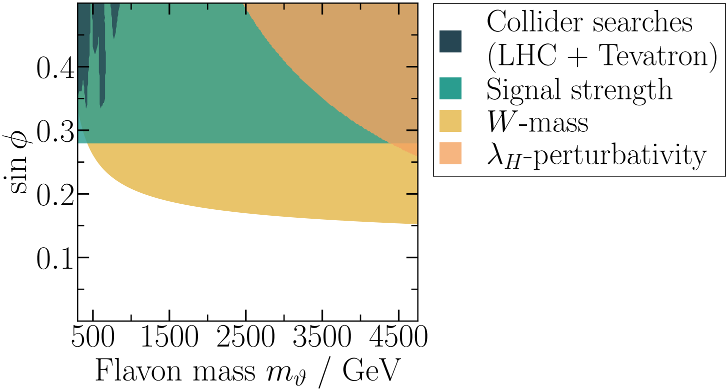
$$H = \left(0, \frac{v_H + h'}{\sqrt{2}}\right)^T, \qquad \theta = \frac{v_\theta + \vartheta'}{\sqrt{2}}$$

$V(H,\theta) \supset -\lambda_{\theta H} v_\theta v_H h' \vartheta' \Rightarrow$ non-diagonal mass matrix

Rotate into mass eigenbasis:

$$\begin{pmatrix} h \\ \vartheta \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} h' \\ \vartheta' \end{pmatrix}$$

Constraints on Higgs–flavon mixing



Mixing of magnitude $\sin\phi \lesssim 0.15$ allowed.

W boson mass[5] provides the strictest bound.

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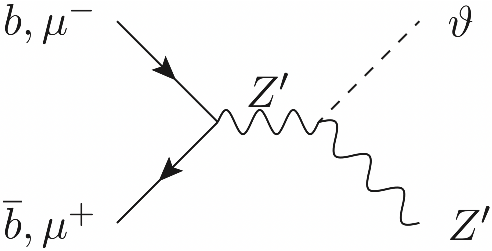
[5] 2022 world average prior to CDF-II measurement

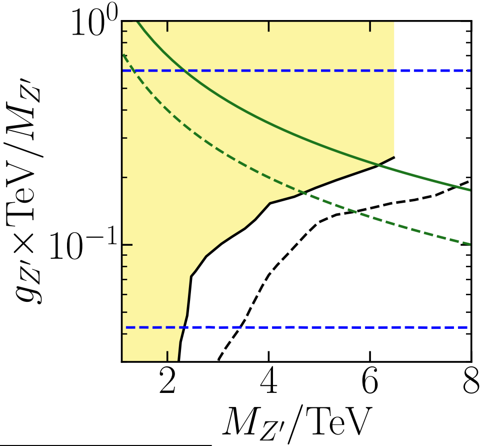
The flavonstrahlung process



Both hadron and muon colliders should have good sensitivity.

Collider simulations – strategy

Choose benchmark points in the $M_{Z'} - g_{Z'}$ plane[6] and compute flavonstrahlung cross-sections as a function of flavon mass.



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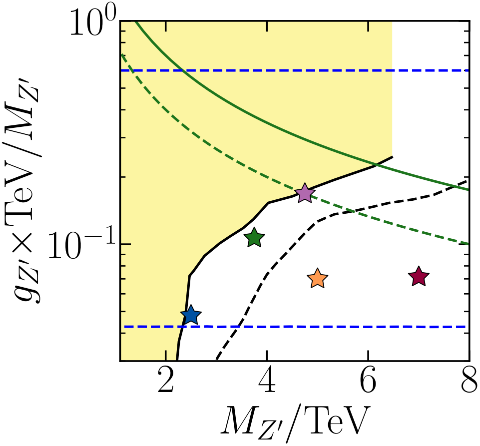
[6] Altmannshofer et al., 1403.1269, Azatov et al., 2205.13552

Benchmark points



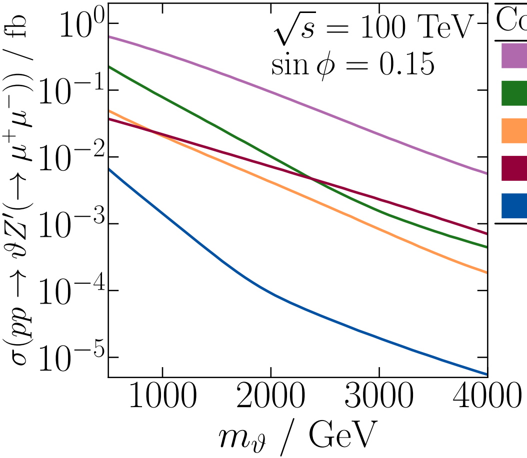
Future colliders

Consider two future colliders:

1. 100 TeV hadron collider (FCC-hh)
   Integrated luminosity $\sim 30\,\mathrm{ab}^{-1}$

2. 5 or 10 TeV muon collider with
   Integrated luminosities $\sim 1, 10\,\mathrm{ab}^{-1}$

Flavonstrahlung at FCC-hh

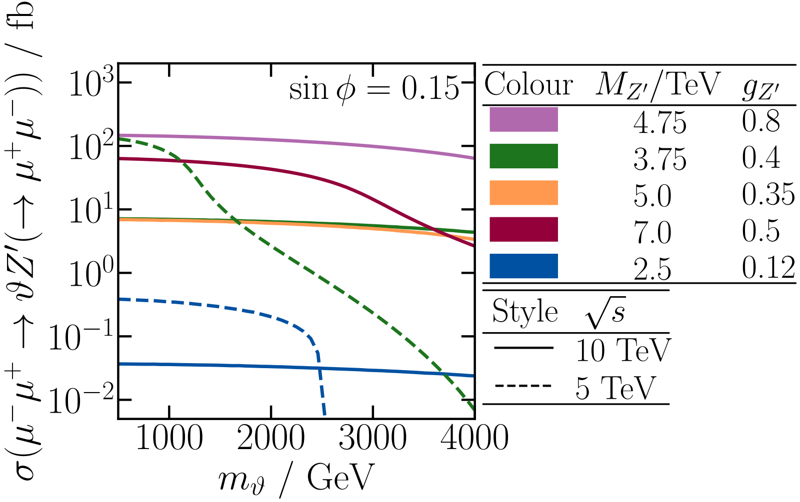


Colour	$M_{Z'}$/TeV	$g_{Z'}$
🟪	4.75	0.8
🟩	3.75	0.4
🟧	5.0	0.35
🟥	7.0	0.5
🟦	2.5	0.12

$\Rightarrow$ Can explore parameter space up to ~ 5 TeV flavon and Z' masses for $g_{Z'} \gtrsim 0.3$.

For $g_{Z'} \lesssim 0.3$, the mass reach is more limited.

Flavonstrahlung at muon colliders



5 TeV: Excellent reach in the region $m_\vartheta + M_{Z'} \lesssim 7\,\text{TeV}$

10 TeV: ditto for $m_\vartheta + M_{Z'} \lesssim 15\,\text{TeV}$

Summary

The $B_3 - L_2$ model is well-motivated by $b \to s\mu^+\mu^-$and fermion mass puzzle.

The flavon field θ may mix with the SM Higgs at $\sin\phi \lesssim 0.15$ level.

Flavonstrahlung: a promising process for discovering the flavon.

Unlikely to be observed at the HL-LHC, but a 100 TeV FCC-hh or a 10 TeV muon collider would have excellent discovery prospects.

The End

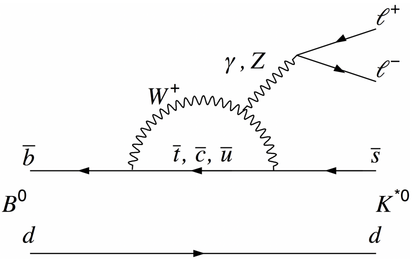
Thank you for listening!

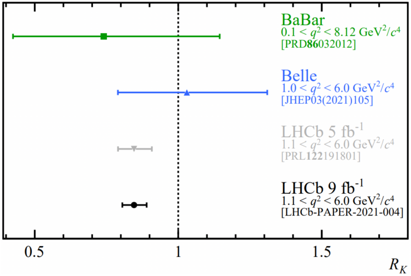
Backup slides

Lepton universality ratios

Defined as ratios:

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^{(*)}e^+e^-)} \approx 1 \text{ in SM}$$





$U(1)_{B_3-L_2}$ charge assignments

Q'_{iL}	u'_{iR}	d'_{iR}	L'_1	L'_2	L'_3	e'_{1R}	e'_{2R}	e'_{3R}
0	0	0	0	-3	0	0	-3	0
ν'_{1R}	ν'_{2R}	ν'_{3R}	Q'_{3L}	u'_{3R}	d'_{3R}	H'	θ'	
0	-3	0	1	1	1	0	1	

Fermion sector

$$\mathcal{L}_{Z'\psi} = -g_{Z'}\Big(\overline{Q'_{3L}}\not{Z}'Q'_{3L} + \overline{u'_{3R}}\not{Z}'u'_{3R} + \overline{d'_{3R}}\not{Z}'d'_{3R}$$
$$- 3\overline{L'_{2L}}\not{Z}'L'_{2L} - 3\overline{e'_{2R}}\not{Z}'e'_{2R} - 3\overline{\nu'_{2R}}\not{Z}'\nu'_{2R}\Big)$$

How to connect to $b \to s\mu^+\mu^-$? We need to specify the fermion mixing matrices

$$\mathbf{P}' = V_I\mathbf{P}$$

for $I \in \{u_L, d_L, e_L, \nu_L, u_R, d_R, e_R, \nu_R\}$.

Simple mixing ansatz

Use simplicity, ease of passing bounds and ability to explain B-anomalies as a guiding principle:

$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{sb} & -\sin\theta_{sb} \\ 0 & \sin\theta_{sb} & \cos\theta_{sb} \end{pmatrix},$$

Now, in the mass eigenbasis:

$$\mathcal{L}_{Z'\psi} \supset -g_{Z'}\left[\left(\frac{1}{2}\sin 2\theta_{sb}\overline{s}\not{Z}'P_L b + \text{H.c.}\right) - 3\overline{\mu}\not{Z}'\mu\right]$$

$$\mathcal{L}_{Z'\psi} \supset -g_{Z'}\left[\left(\frac{1}{2}\sin 2\theta_{sb}\overline{s}\not{Z}'P_L b + \text{H.c.}\right) - 3\overline{\mu}\not{Z}'\mu\right]$$

Integrate out $Z' \Rightarrow$ get contribution to the weak effective theory operator

$$\mathcal{H}_{\text{WET}} \supset \mathcal{C}_9\mathcal{N}(\overline{s}\gamma_\nu P_L b)(\overline{\mu}\gamma^\nu\mu)$$

with $\mathcal{C}_9 \sim \dfrac{g_{Z'}^2 \sin 2\theta_{sb}}{M_{Z'}^2}$.

Match to best-fit $\mathcal{C}_9$ and eliminate $\sin\theta_{sb}$ as an independent variable.

Other fermionic mixing matrices

Besides V_{d_L}, which is fixed by $b \to s\mu\mu$ data,

$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{sb} & -\sin\theta_{sb} \\ 0 & \sin\theta_{sb} & \cos\theta_{sb} \end{pmatrix},$$

we also set $V_{d_R} = 1, V_{e_R} = 1, V_{e_L} = 1$ and $V_{u_R} = 1.$

These imply $V_{u_L} = V_{d_L} V_{\mathrm{CKM}}^{\dagger}$ and $V_{\nu_L} = U_{\mathrm{PMNS}}^{\dagger}$

Yukawa matrices in more detail

$U(1)_{B_3-L_2}$ invariance restricts the form of the quark Yukawas:

$$Y_u \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad Y_d \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}.$$

Recall $M_u = V_{u_L}^\dagger Y_u V_{u_R}$ and $M_d = V_{d_L}^\dagger Y_d V_{d_R}$ These imply

$$V_{\mathrm{CKM}} = V_{u_L}^\dagger V_{d_L} \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$U(1)_{B_3-L_2}$ model:

$$V_{\text{CKM}} \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

Experimentally:

$$V_{\text{CKM}} \approx \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.009 & 0.04 & 1 \end{pmatrix}$$

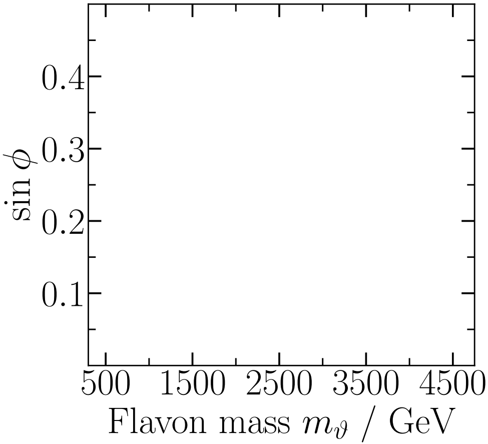
$\Rightarrow$ $U(1)_{B_3-L_2}$ model serves as a TeV scale starting point for more detailed model-building.

Lepton Yukawas

The $U(1)_{B_3-L_2}$ symmetry enforces for leptons:

$$Y_e \sim \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}.$$

Constraints on Higgs–flavon mixing



Collider constraints

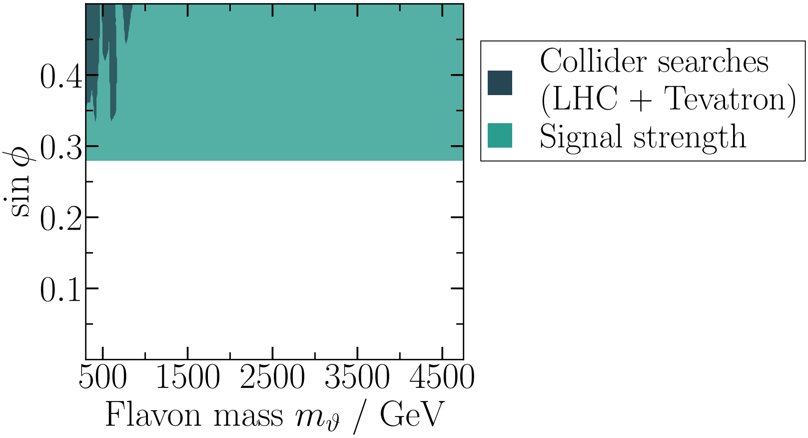
Higgs signal strength

$h' = \cos\phi\, h + \sin\phi\, \vartheta$
$\Rightarrow$ SM Higgs interactions scaled by $\cos\phi$

$\Rightarrow$ ATLAS combination result gives $\sin\phi < 0.28$.

Direct flavon searches

Compare model prediction with experimental exclusion limits from the non-observation of the flavon.


0.4
0.3
0.2
0.1
$\sin\phi$
500
1500
2500
3500
4500
Flavon mass m_ϑ / GeV
Collider searches (LHC + Tevatron)
Signal strength

More constraints

Perturbativity: Impose $|\lambda_i| < 4\pi$

W boson mass: Take M_Z, G_F and α as experimental inputs. Obtain a (recursive) prediction for M_W:

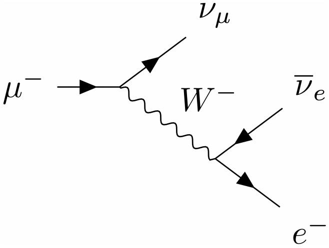
$$M_W^2 = \frac{1}{2} M_Z^2 \left[1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_F M_Z^2} [1 + \Delta r(M_W^2)]} \right].$$

W boson mass

Match 4-Fermi theory muon decay amplitude with $U(1)_{B_3-L_2}$ 1-loop amplitude:

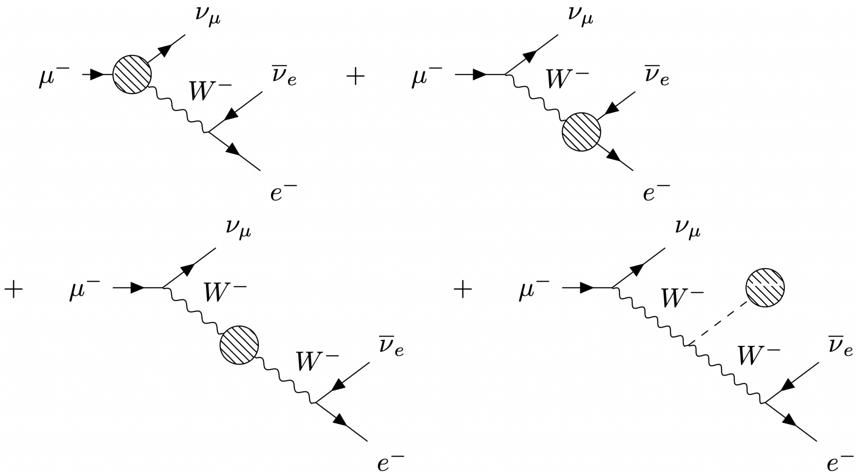
$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8M_W^2 s_W^2}(1+\Delta r)$$

Tree-level in the $U(1)_{B_3-L_2}$ model:



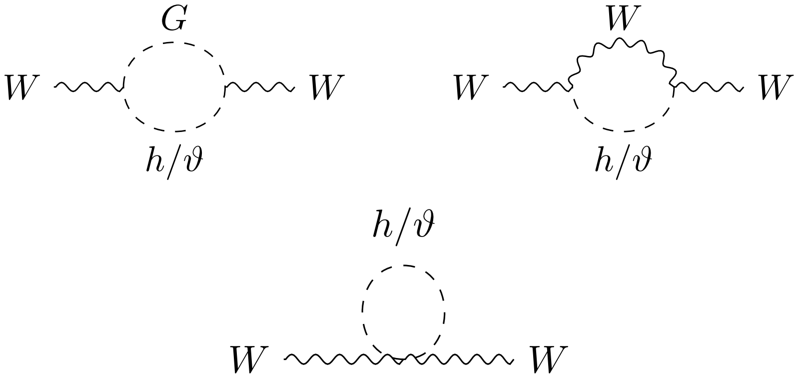
Obtain a prediction for M_W and compare with experiment (pre-CDF 2022 world average).

1-loop



ν_μ
μ^-
W^-
$\overline{\nu}_e$
e^-
$+$
ν_μ
μ^-
W^-
$\overline{\nu}_e$
e^-
$+$
ν_μ
μ^-
W^-
W^-
$\overline{\nu}_e$
e^-
$+$
ν_μ
μ^-
W^-
W^-
$\overline{\nu}_e$
e^-

Flavon induced contributions:[7]



$+$ similar set of diagrams for Z boson self-energy.

Flavon contribution scales as $\sim \alpha \ln(m_\vartheta^2/M_Z^2)$

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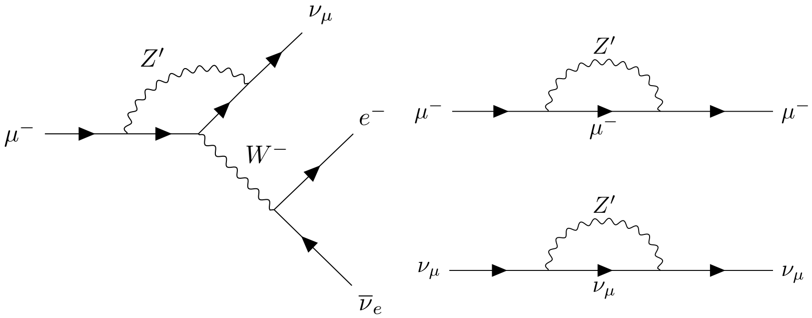
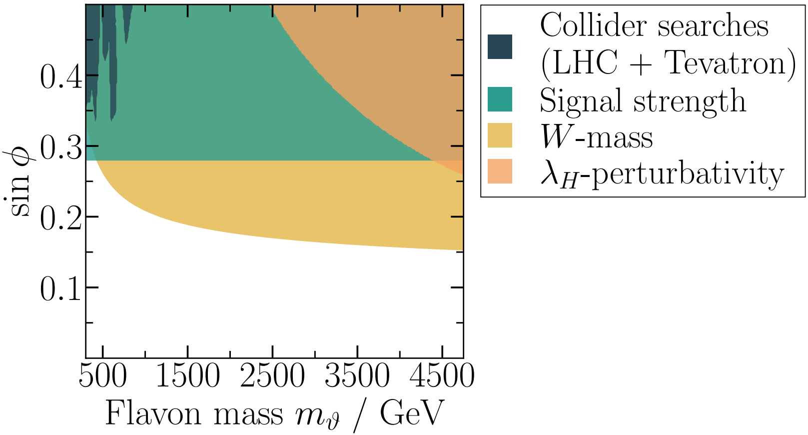
[7] López-Val and Robens, 1406.1043

Z' induced contributions:



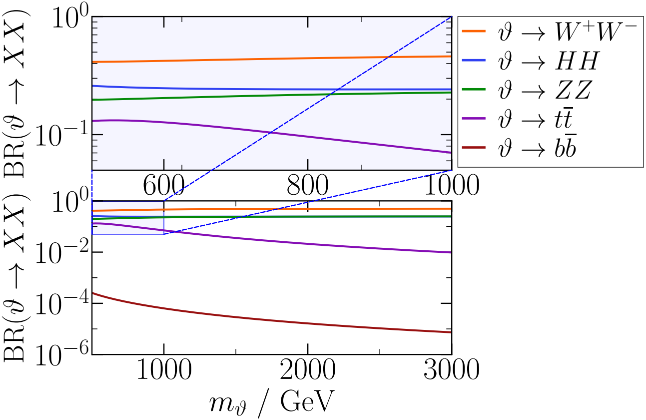
These diagrams contribute at order $g_{Z'}^2 m_\mu^2 / M_{Z'}^2$

$\Rightarrow$ the non-decoupling flavon contributions dominate the effect on M_W.

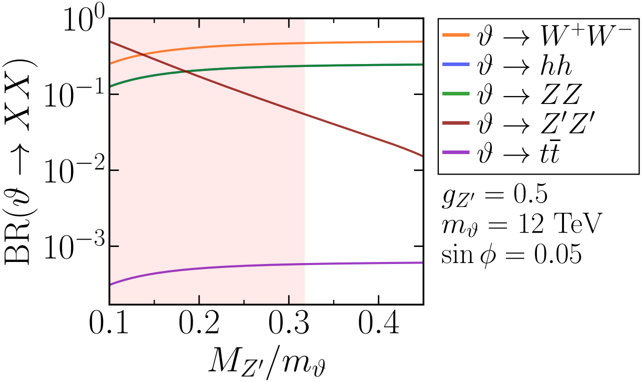


0.4
0.3
0.2
0.1
$\sin\phi$
500
1500
2500
3500
4500
Flavon mass m_ϑ / GeV
Collider searches (LHC + Tevatron)
Signal strength
W-mass
λ_H-perturbativity

Flavon branching ratios



Flavon branching ratios (heavy flavon)

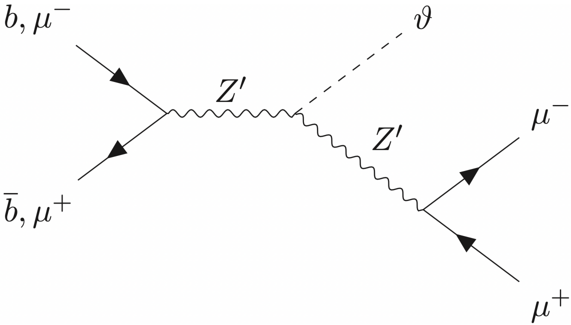


Which final state to look for?

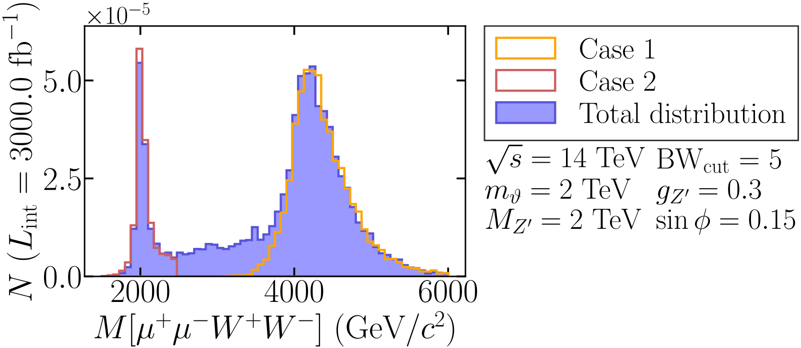
Leading final states:

1. The flavon decays into WW, ZZ or hh (or $Z'Z'$). Hard to say which one is best.
2. The Z' decays primarily into a di-muon pair.

Thus compute:

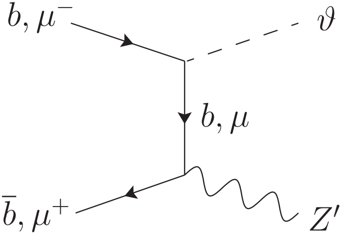


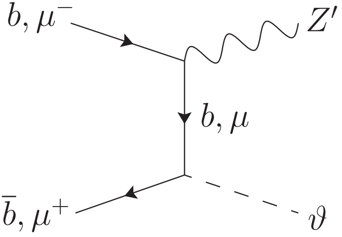
Two resonances



The relative sizes of the two peaks depend on the flavon and Z' mass, as well as the final state studied.

Fermion exchange in the *t*-channel

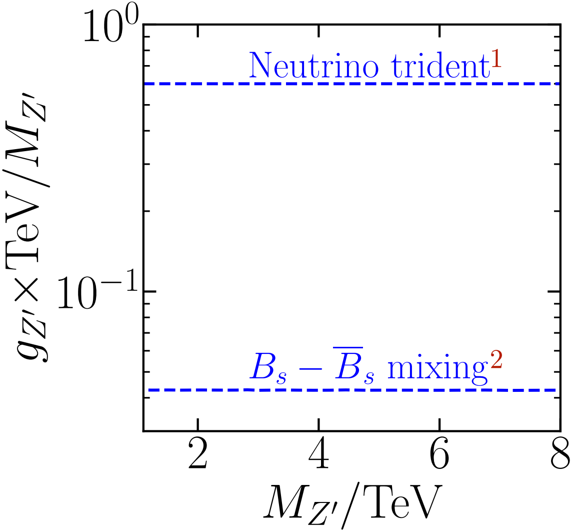




Contribution to $\vartheta Z'$ production cross-section typically of order 0.1% or less.

Ignored in this work.

Experimental constraints

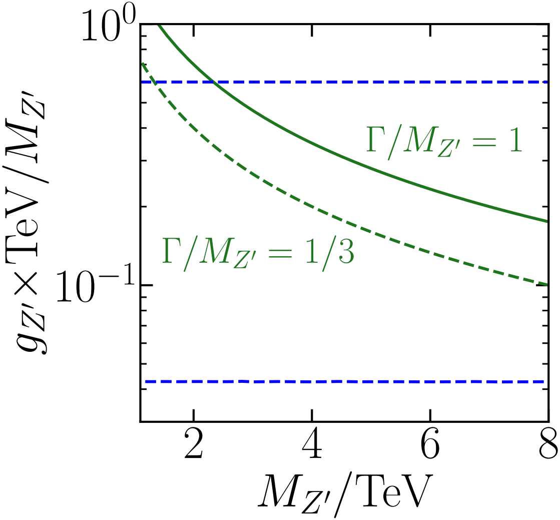


[1] Altmannshofer et al., 1403.1269

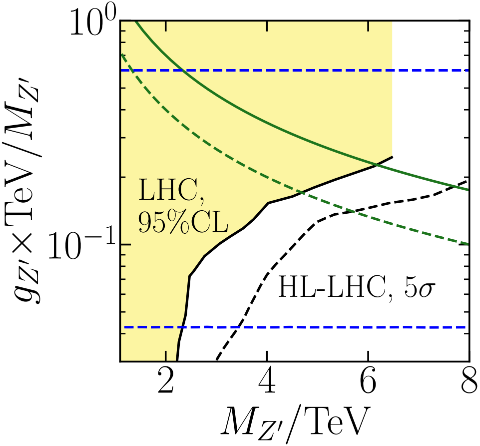
[2] Azatov et al., 2205.13552

Perturbativity of the Z'

For a heavy gauge boson: $\Gamma \sim M_{Z'} g_{Z'}^2$.

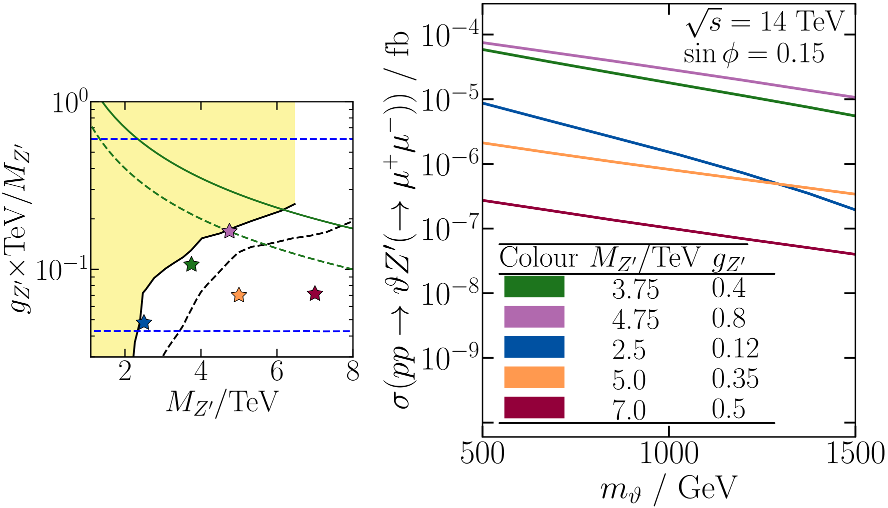


Collider searches for Z'



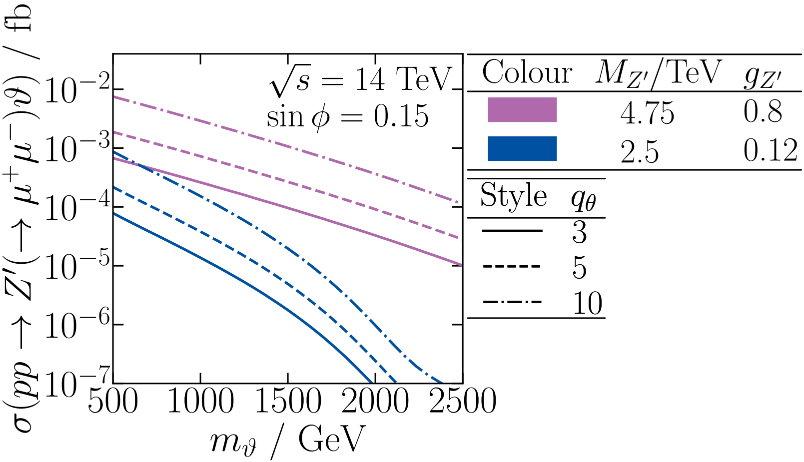
Azatov et al., 2205.13552

HL-LHC



$\Rightarrow$ Very unlikely to be observed at the HL-LHC if $q_\theta = 1$.

But we may vary the charge:



⇒ A corner of the parameter space discoverable at HL-LHC.