Anomaly-free gauge symmetries and B-decay anomalies

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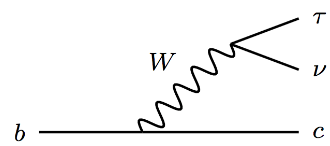
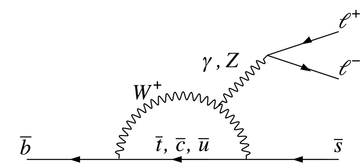
*1705.05643, *1704.08158, 1709.xxxxx

Outline

- B-decay anomalies: current status
- Global fits: structure of new physics
- Explanation via $U(1)'$ gauge symmetry:
  - Flavoured $B - L$
  - Other anomaly-free $U(1)'$
- ν_R dark matter & flavoured B-L

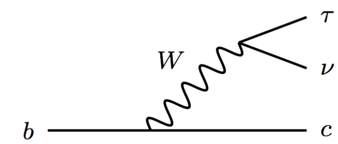
Anomalies in semi-leptonic B-decays





	$b \to c\tau\nu$	$b \to s\mu\mu$
Lepton Universality	$R(D), R(D^*)$	$R(K), R(K^*)$
Angular Distributions		$B \to K^*\mu\mu\ \ (P_5')$
Differential BR $(d\Gamma/dq^2)$		$B \to K^{(*)}\mu\mu$ $B_s \to \phi\mu\mu$ $\Lambda_b \to \Lambda\mu\mu$

$R(D)$ & $R(D^*)$



- Test of lepton flavour universality

$$\mathcal{R}_D^{(*)} = \frac{\Gamma\left(B \to D^{(*)}\tau\nu\right)}{\Gamma\left(B \to D^{(*)}\ell\nu\right)}$$

$R(D) \sim 2.3\sigma$
$R(D^*) \sim 3.4\sigma$

Combined: 4.1σ

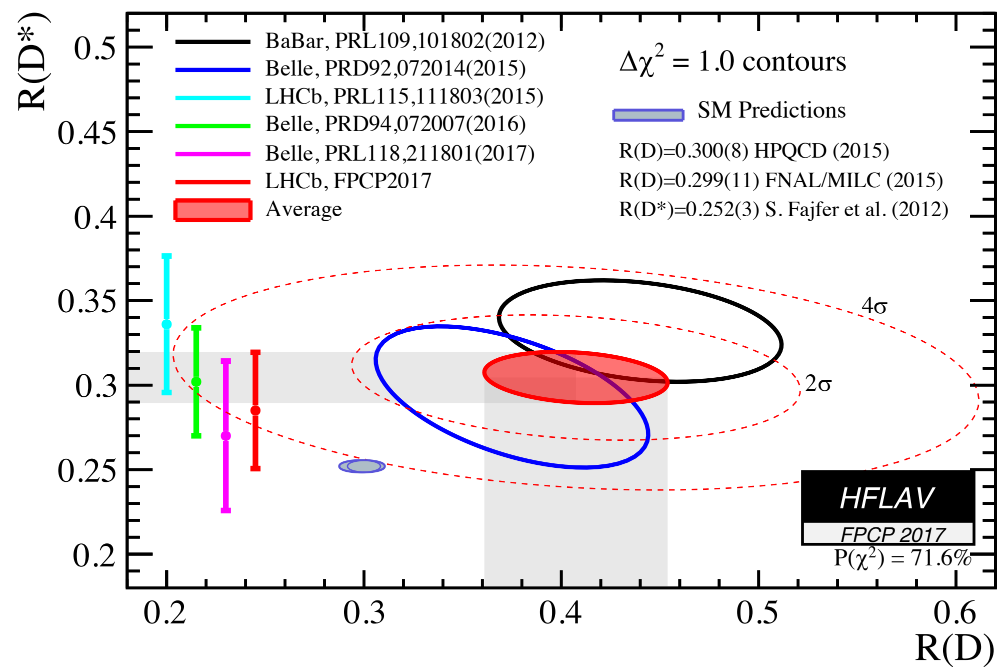
- Hadronic uncertainties reduced in ratio

- Various new physics explanations proposed:

  W', leptoquarks, …

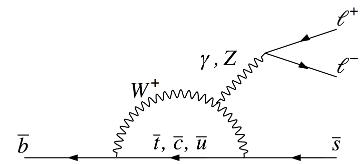
- Need large effect in tree-level decay

  large couplings, perturbativity?



$$b \to s\mu\mu$$

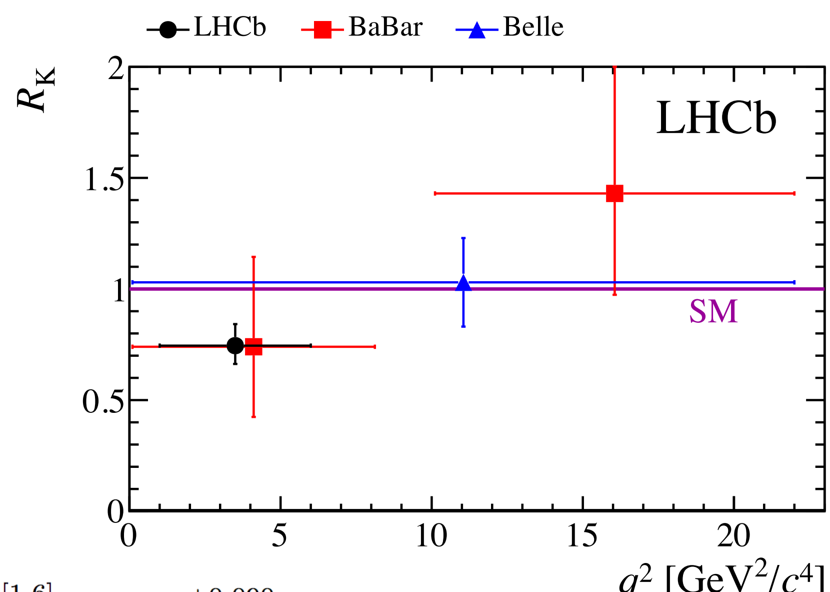
$R(K)$ & $R(K^*)$



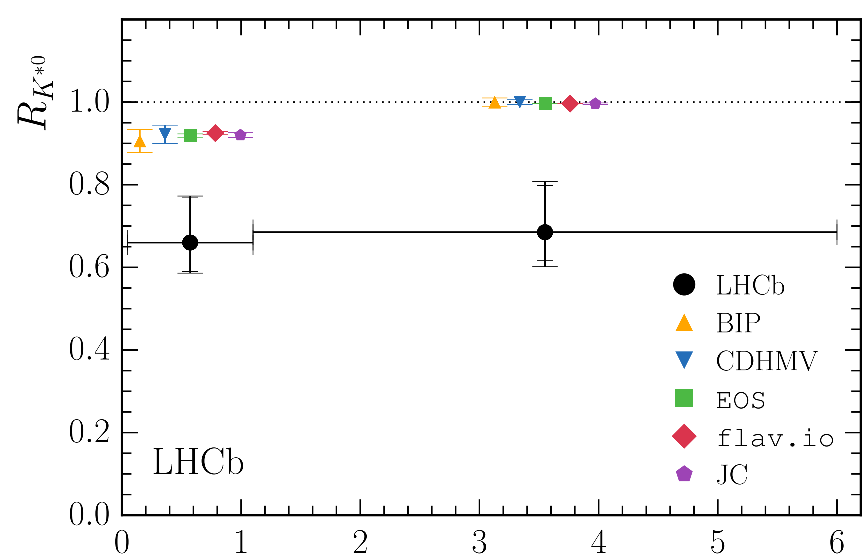
- Recently, hints of lepton flavour universality violation seen at LHCb in

$$\mathcal{R}_K^{(*)} = \frac{\Gamma\left(B \to K^{(*)}\mu^+\mu^-\right)}{\Gamma\left(B \to K^{(*)}e^+e^-\right)}$$

- Theoretically very clean, hadronic uncertainties cancel almost completely
- In the SM = 1 $\pm$ O(1%) (collinear log-enhanced QED corrections)

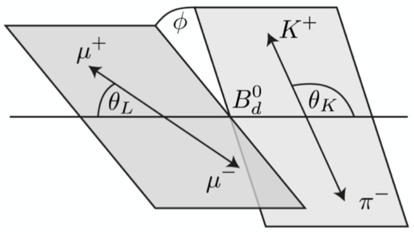


$R_K^{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$



$R_{K^*}^{[1.1,6]} = 0.685^{+0.113}_{-0.069} \pm 0.047$

$B \to K^* \mu\mu \, (P_5')$

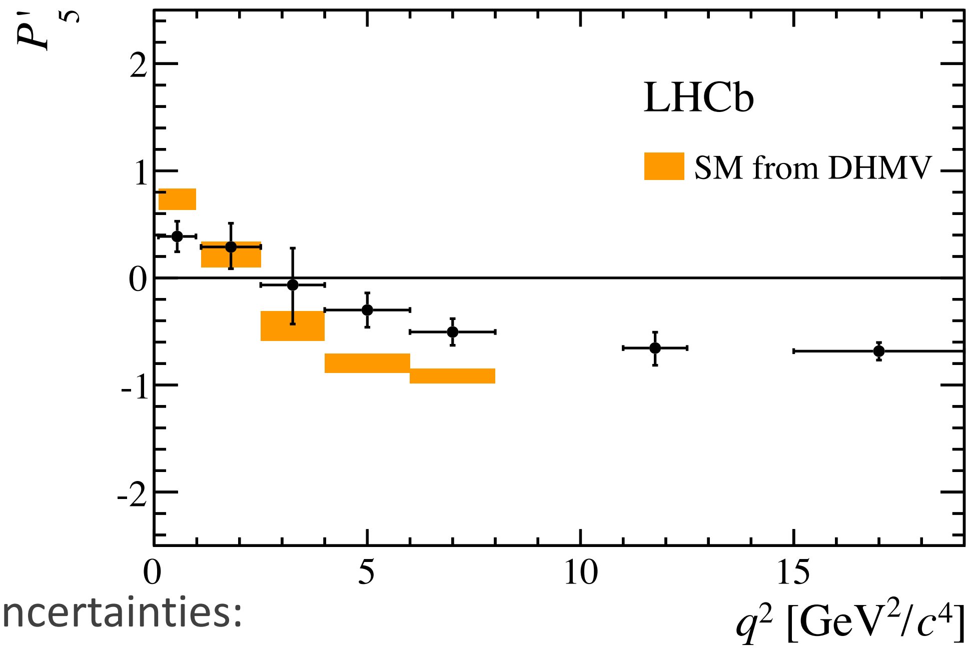


- First deviation from SM prediction in $b \to s\mu\mu$ seen in angular distributions in 2013
- LHCb performed complete angular analysis of decay: $B \to K^*(K\pi)\mu\mu$
- Measure set of ”optimized” observables with reduced form-factor uncertainties

LHCb 1512.04442

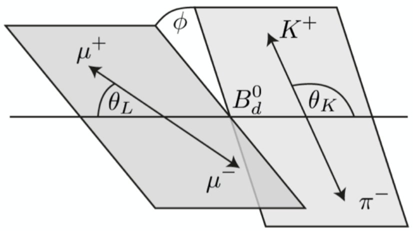
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\mathrm{L}}(1 - F_{\mathrm{L}})}}$$

Global fit: 3.4σ deviation from SM prediction



- Need to take into account hadronic uncertainties:
  both form-factors and non-factorisable (charm loops)

$B \to K^* \mu\mu \; (P_5')$



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Blake et al. 1703.10005

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

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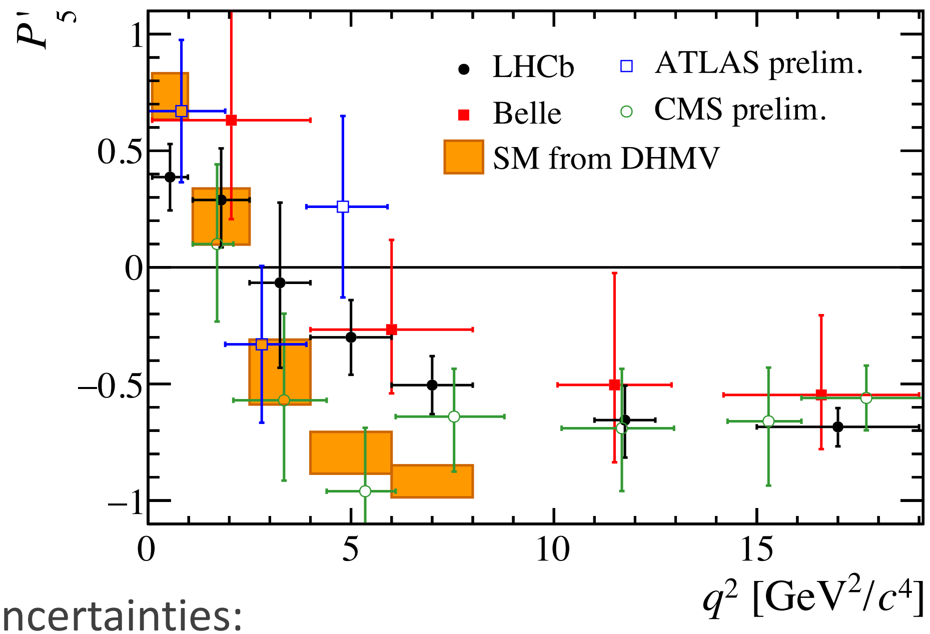

- Need to take into account hadronic uncertainties:
  both form-factors and non-factorisable (charm loops)

A hint of new physics?

Low-energy EFT (dimension-6)

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_i C_i \mathcal{O}_i$$

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu b_L)\,(\bar{l}\gamma_\mu l) \qquad \mathcal{O}_9' = (\bar{s}\gamma_\mu b_R)\,(\bar{l}\gamma_\mu l)$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu b_L)\,(\bar{l}\gamma_\mu \gamma^5 l) \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\mu b_R)\,(\bar{l}\gamma_\mu \gamma^5 l)$$

$$\mathcal{O}_S = (\bar{s}_L b_R)\,(\bar{l}l) \qquad \mathcal{O}_S' = (\bar{s}_R b_L)\,(\bar{l}l)$$

$$\mathcal{O}_P = (\bar{s}_L b_R)\,(\bar{l}\gamma^5 l) \qquad \mathcal{O}_P' = (\bar{s}_R b_L)\,(\bar{l}\gamma^5 l)$$

$$\mathcal{O}_T = (\bar{s}\sigma_{\mu\nu} b)\,(\bar{l}\sigma_{\mu\nu} l)$$

$$\mathcal{O}_{T5} = (\bar{s}\sigma_{\mu\nu} b)\,(\bar{l}\sigma_{\mu\nu}\gamma^5 l)$$

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$$\cancel{\mathcal{O}_S = (\bar{s}_L b_R)\,(\bar{l}l)} \qquad \cancel{\mathcal{O}_S' = (\bar{s}_R b_L)\,(\bar{l}l)}$$

$(B_s \to \mu\mu)$

$$\cancel{\mathcal{O}_P = (\bar{s}_L b_R)\,(\bar{l}\gamma^5 l)} \qquad \cancel{\mathcal{O}_P' = (\bar{s}_R b_L)\,(\bar{l}\gamma^5 l)}$$

$(SU(2) \times U(1)_Y)$

$$\cancel{\mathcal{O}_T = (\bar{s}\sigma_{\mu\nu} b)\,(\bar{l}\sigma_{\mu\nu} l)}$$

$$\cancel{\mathcal{O}_{T5} = (\bar{s}\sigma_{\mu\nu} b)\,(\bar{l}\sigma_{\mu\nu}\gamma^5 l)}$$

(Alonso et al. 1407.7044)

Structure of NP

- Let's assume anomalies are due to new physics involving muons:
  - Requires destructive interference with SM in both $B \to K\mu\mu,\ B \to K^*\mu\mu$
  - Combination of R_K and R_K^* already tells us about the structure of possible NP:

$$\langle K^*|\bar{s}\gamma^\mu\gamma^5 b|B\rangle \qquad \langle K|\bar{s}\gamma^\mu b|B\rangle$$

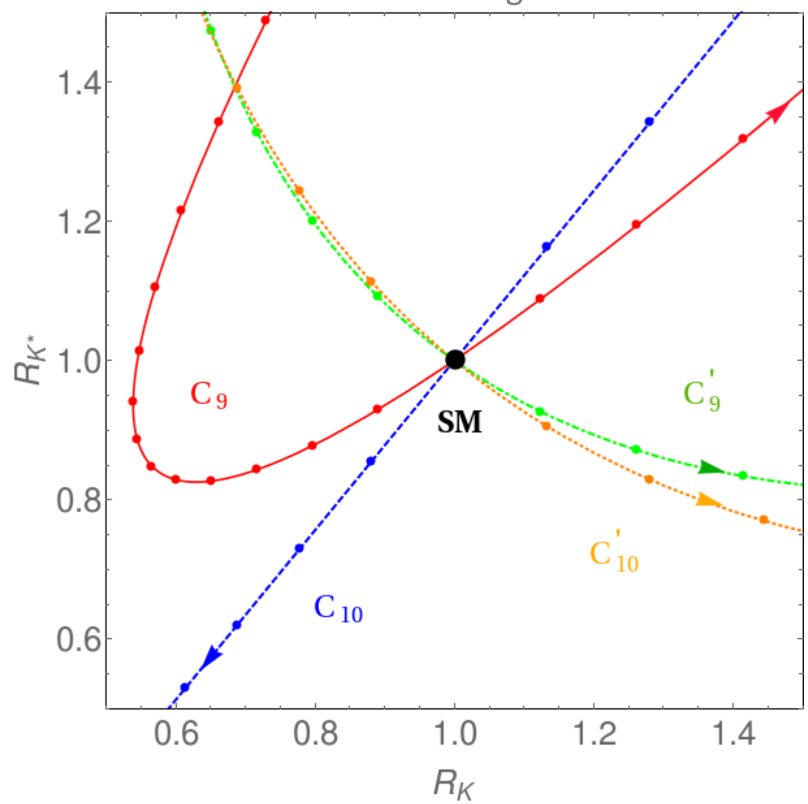
Geng et al. 1704.05446

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu b_L)\,(\bar{l}\gamma_\mu l)$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu b_L)\,(\bar{l}\gamma_\mu\gamma^5 l)$$

$$\mathcal{O}_9' = (\bar{s}\gamma_\mu b_R)\,(\bar{l}\gamma_\mu l)$$

$$\mathcal{O}_{10}' = (\bar{s}\gamma_\mu b_R)\,(\bar{l}\gamma_\mu\gamma^5 l)$$



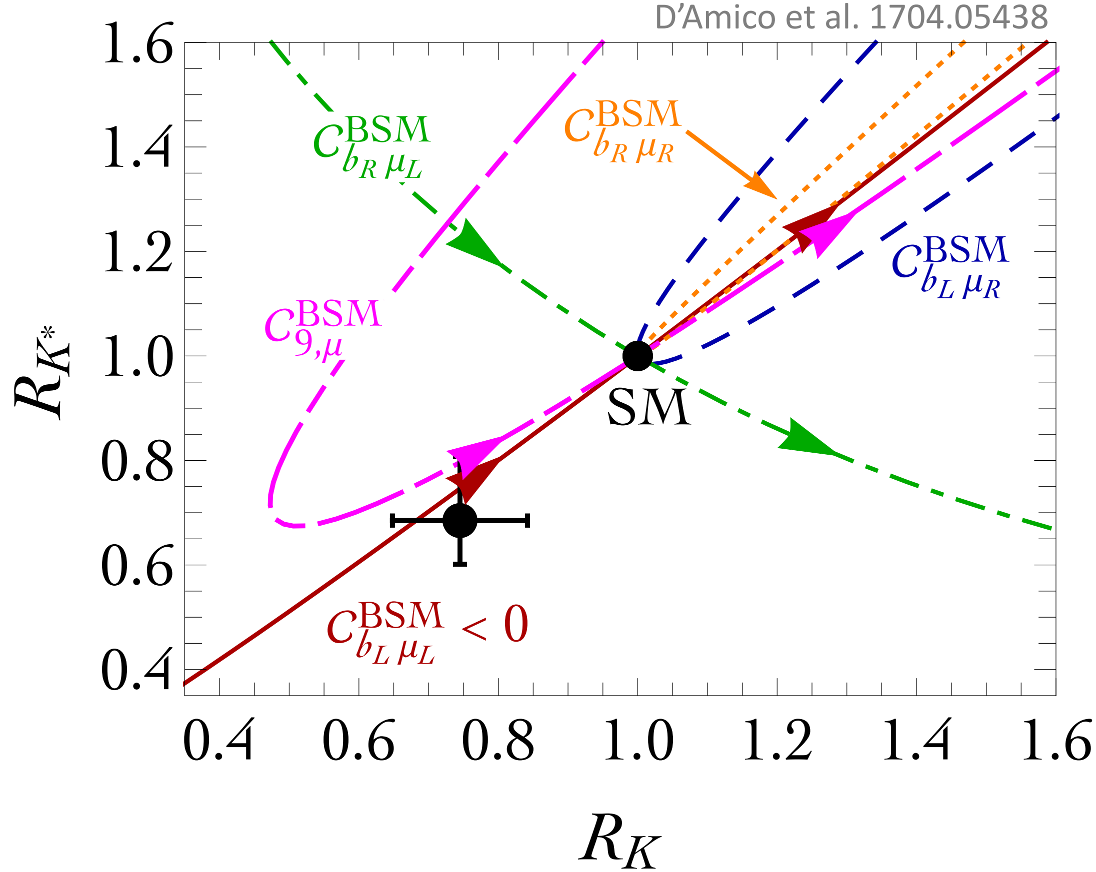
Structure of NP

- Explanation of both R_K and R_K^* requires coupling to LH quarks
- Lepton couplings less constrained

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu b_L)\left(\bar{l}\gamma_\mu l\right)$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu b_L)\left(\bar{l}\gamma_\mu \gamma^5 l\right)$$

D'Amico et al. 1704.05438

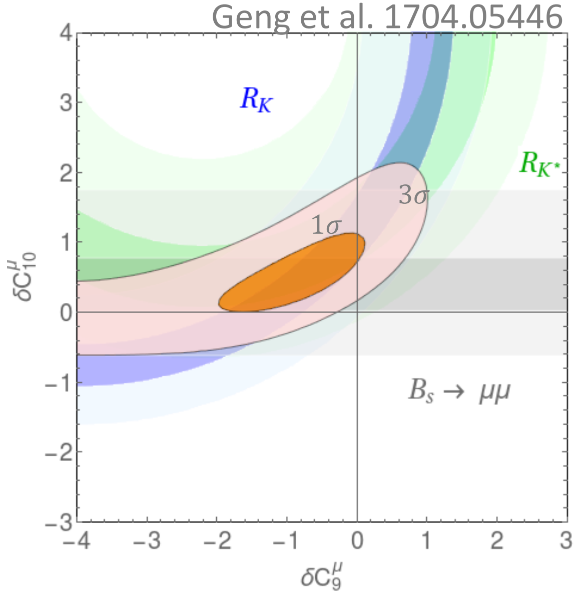


Global fit

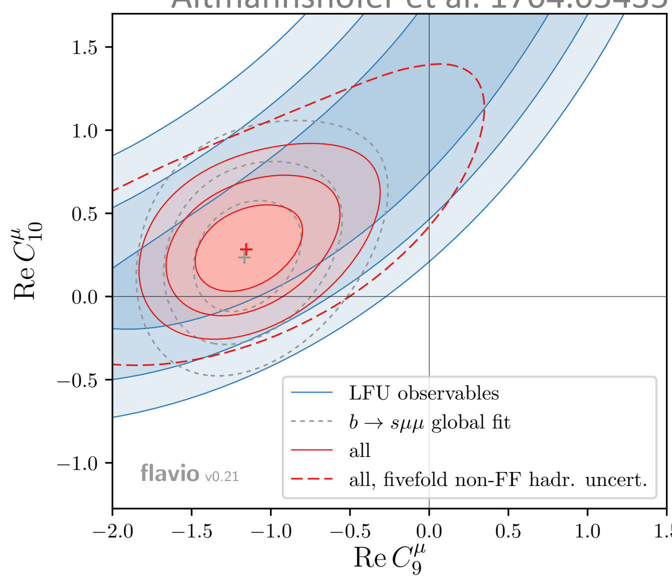
- Many groups performing global fits (differences in observables included and treatment of hadronic uncertainties)
- All find significant preference for new contribution to C_9

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu b_L)(\bar{l}\gamma_\mu l)$$

Geng et al. 1704.05446



Altmannshofer et al. 1704.05435



	All		LFUV	
1D Hyp.	Best fit	Pull$_{\mathrm{SM}}$	Best fit	Pull$_{\mathrm{SM}}$
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	-1.10	5.7	-1.76	3.9
(LH) $\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}$	-0.61	5.2	-0.66	4.1

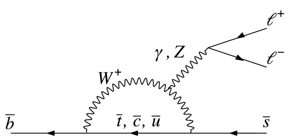
Capdevila et al. 1704.05340

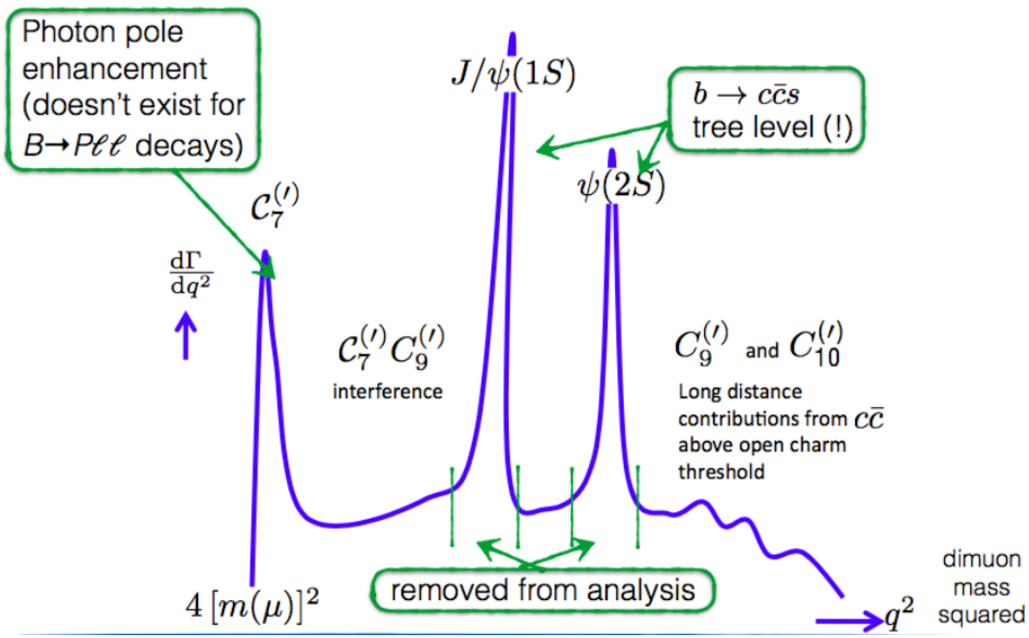
Significant deviation even with conservative assumptions!

$(C_9^{SM} = -C_{10}^{SM} = 4.27)$

What about low-q^2?

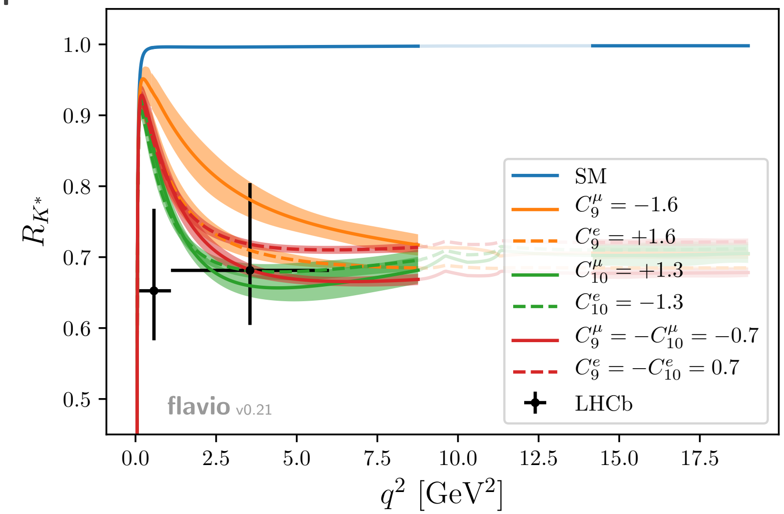
- Low-q^2 region in R_K^* cannot be fully explained by NP
- SM contribution enhanced by photon pole
- Not the case for R_K - possible cross-check for systematic effect in experiment

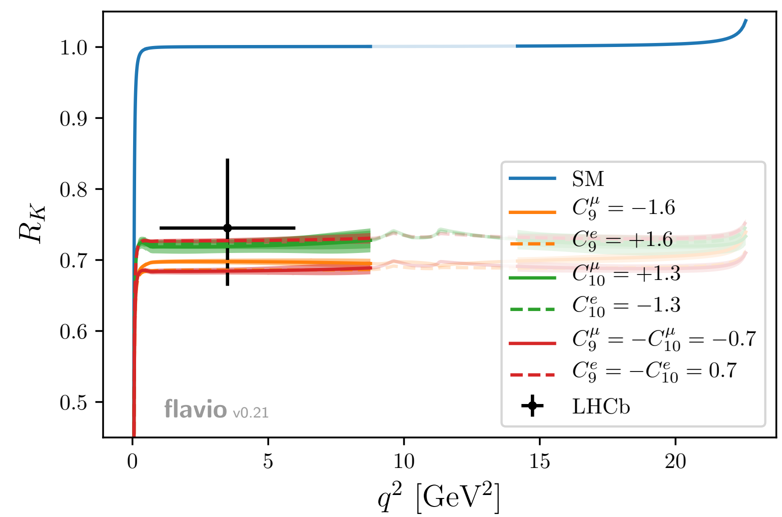




Credit: LHCb

Altmannshofer et al. 1704.05435





Distinguishing NP scenarios

- Can construct differences of angular observables in $B \to K^*(K\pi)\mu\mu$

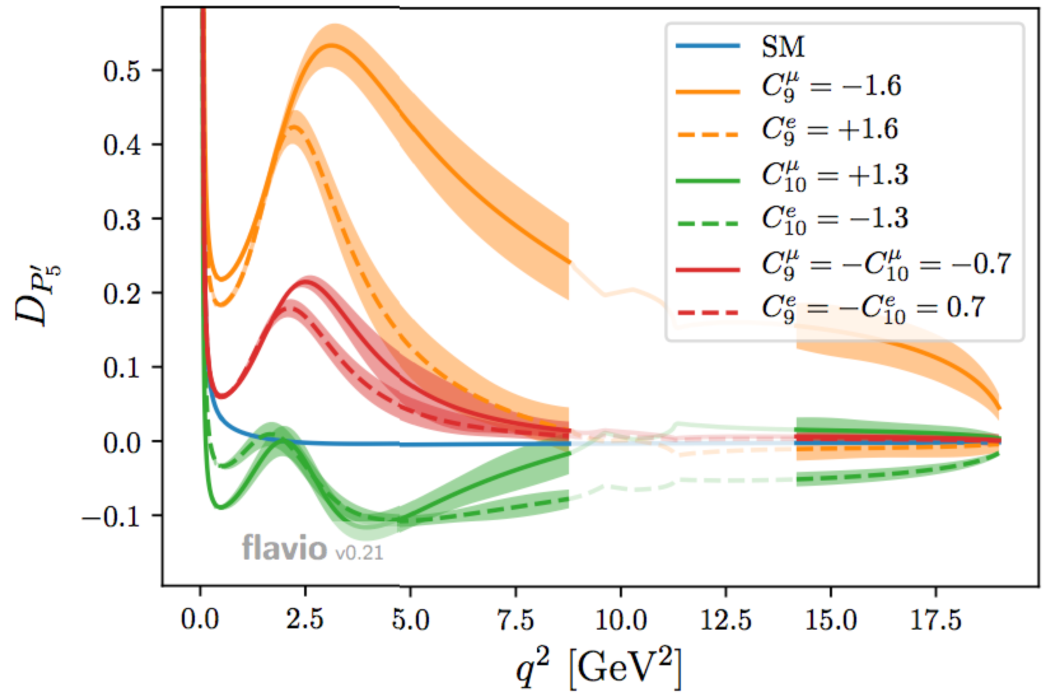
$$P_5'^{\mu} - P_5'^{e}$$

- Another test of lepton universality, reduced hadronic uncertainties

- Measured by Belle with limited statistics

- Has potential to distinguish NP scenarios

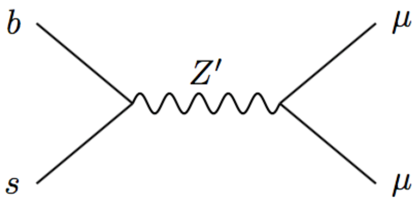
Altmannshofer et al. 1704.05435



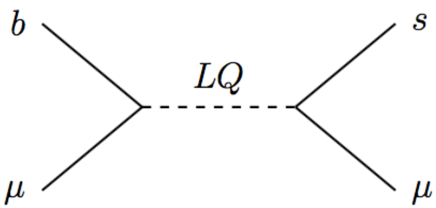
What could be the new physics?

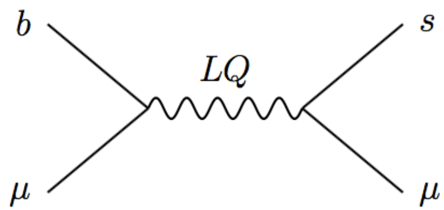
Types of NP

- Z'

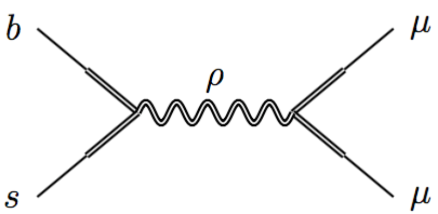


- Leptoquark
  (scalar, vector)

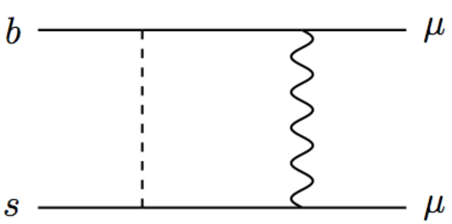




- Partial compositeness



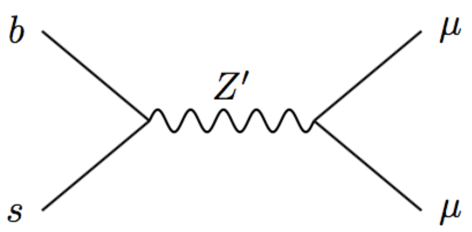
- Loop



U(1)’ explanations

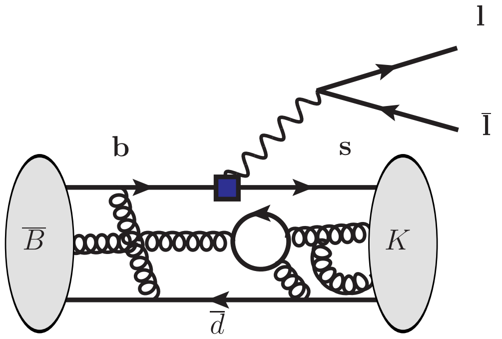
Necessary ingredients:

- Both quarks and leptons charged
- Flavour off-diagonal couplings



MUST also consider:

- Symmetry breaking
- Anomaly cancellation



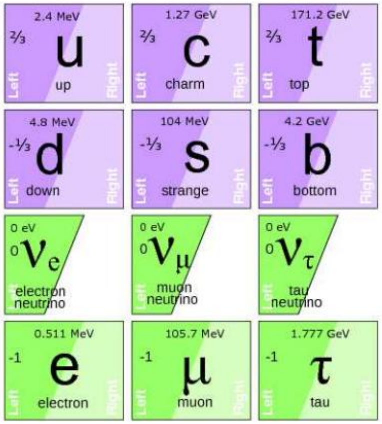
In principle many possibilities (just see the arxiv!)

What other motivation do we have?

Flavoured B-L

Motivation

- Simple, well-motivated extension of SM is addition of $3\nu_R$
  - Small neutrino masses from seesaw mechanism
  - Baryon asymmetry via leptogenesis



- $\mathrm{SM} + 3\nu_R$ has *exact* $U(1)_{B-L}$ global symmetry in limit of vanishing Majorana mass
  - Natural to promote global symmetry to a local symmetry
  - Majorana masses generated by spontaneous breaking

But, leptogenesis suggests very high $B - L$ breaking scale

→ Not so interesting phenomenologically!

Flavoured B-L

- Why should $B-L$ be universal?

  Gauge anomalies cancel within each generation independently

- *Two* heavy ν_R are sufficient for both see-saw and leptogenesis

  (Frampton, Glashow, Yanagida '02)

Flavoured $B-L$ could survive at low energies ~TeV

- One ν_R remains light and can be a dark matter candidate

$U(1)_{(B-L)_3}$

- Consider gauged $U(1)_{B-L}$ with only 3^{rd} generation fermions charged:

$$T^q = \frac{1}{3}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad T^l = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

Vectorial $U(1)$ with same charges for LH and RH fields

SM Higgs is taken to be neutral under $U(1)_{(B-L)_3}$

Yukawa Structure

- However, off-diagonal Yukawa couplings involving 3rd generation are now forbidden

$$Y_d = \begin{pmatrix} \hat{Y}_d^{2\times 2} & 0 \\ 0 & Y_b \end{pmatrix}$$

→ Require a mechanism to generate these upon $U(1)_{(B-L)_3}$ breaking

Two general possibilities:

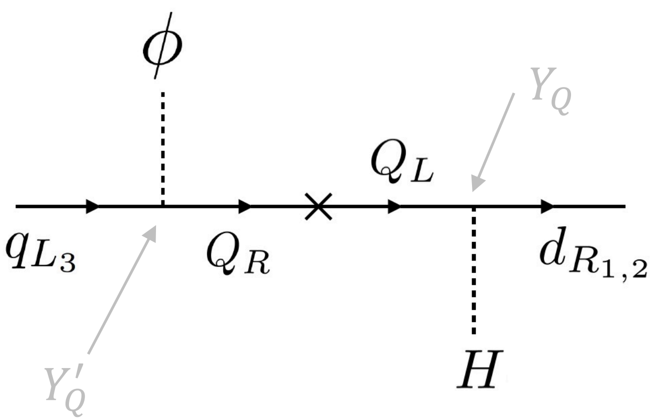
- Additional Higgs doublets charged under $U(1)_{(B-L)_3}$
- ✓ New vector-like fermions

Yukawa Structure

For general 3x3 Yukawa couplings, introduce:

- $U(1)_{(B-L)_3}$ neutral *V-L* fermions: $Q_{L,R}, U_{L,R}, D_{L,R}, L_{L,R}, E_{L,R}, N_{L,R}$

- SM singlet scalars ($U(1)'$ *breaking*): $\phi_l(+1), \phi_q(+\frac{1}{3})$



$$\begin{pmatrix} \bar{q}_{L_{1,2}} & \bar{q}^3_L \end{pmatrix} H \begin{pmatrix} \hat{Y}_d^{2\times 2} & -\frac{Y'_D \phi_q^*}{M_D} Y_D \\ -\frac{Y'_Q \phi_q}{M_Q} Y_Q^T & Y_b \end{pmatrix} \begin{pmatrix} d_{R_{1,2}} \\ b_R \end{pmatrix}$$

Z'_{BL3} in the mass basis

- Z' interactions not flavour diagonal after rotation to the mass basis.

$$J_\mu = \sum_f \bar{f} U_f^\dagger T_f U_f \gamma_\mu f \ ,$$

- Can have new physical mixing angles involving the 3rd generation, beyond those present in the *CKM* and *PMNS* matrices

- Take a simplifying ansatz:
  - For LH fields allow for two new angles, θ_q, θ_l, corresponding to rotations in 2 - 3 generations
  - Suppressed rotation of RH fields (decouple SU(2) doublet V-L fermions)

Explicitly:

$$U_{e_L} = R^{23}(\theta_l), \qquad U_{d_L} = R^{23}(\theta_q),$$

$$U_{\nu_L} = R^{23}(\theta_l) U_{PMNS}, \qquad U_{u_L} = R^{23}(\theta_q) V_{CKM}^\dagger,$$

$b \rightarrow s\mu\mu$ in $U(1)_{(B-L)_3}$

- Integrating out Z'_{BL3} at tree-level gives contribution to Wilson coefficients C_9, C_{10} :

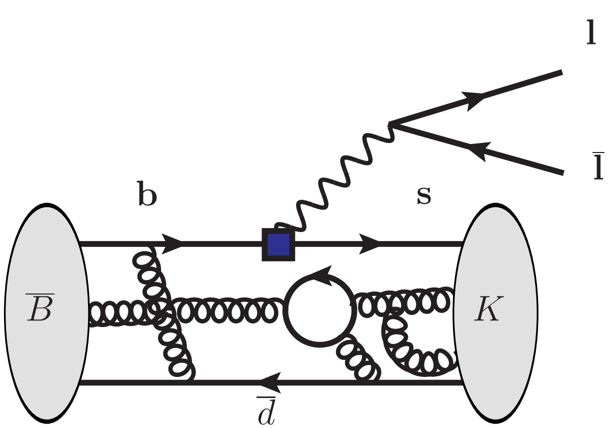
$$\delta C_9^\mu = -\delta C_{10}^\mu = -\frac{\pi}{\alpha\sqrt{2}G_F V_{tb}V_{ts}^*}\frac{g^2 s_{\theta_q} c_{\theta_q} s_{\theta_l}^2}{3M^2}$$

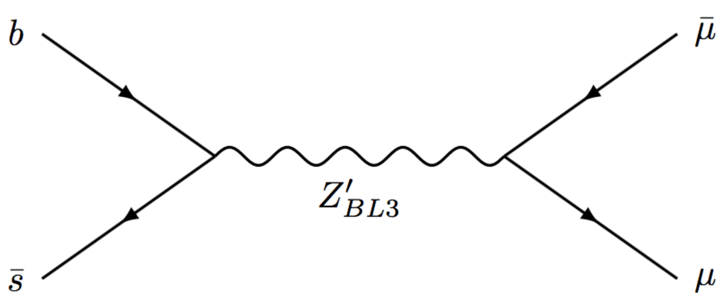
$$\mathcal{O}_9^l = \frac{\alpha}{4\pi}\left(\bar{s}\gamma_\mu b_L\right)\left(\bar{l}\gamma_\mu l\right)$$

$$\mathcal{O}_{10}^l = \frac{\alpha}{4\pi}\left(\bar{s}\gamma_\mu b_L\right)\left(\bar{l}\gamma_\mu \gamma^5 l\right)$$

- Best-fit requires $\delta C_9 = -\delta C_{10} \simeq -0.6$ → Z'_{BL3} masses in TeV range

$(C_9^{SM} = -C_{10}^{SM} = 4.27)$





Z'_{BL3} Phenomenology

- Meson mixing

  $\Delta m_{B_s}, \Delta m_D$ mass difference in $B_s - B_s$, $D^0 - D^0$ oscillations provide *strong* constraints

- B decays

  $B_s \to \mu\mu$: consistent with both SM and best-fit for δC_{10}

  $B \to K^{(*)}\nu\nu$: guaranteed by SU(2)

- Lepton flavour violation

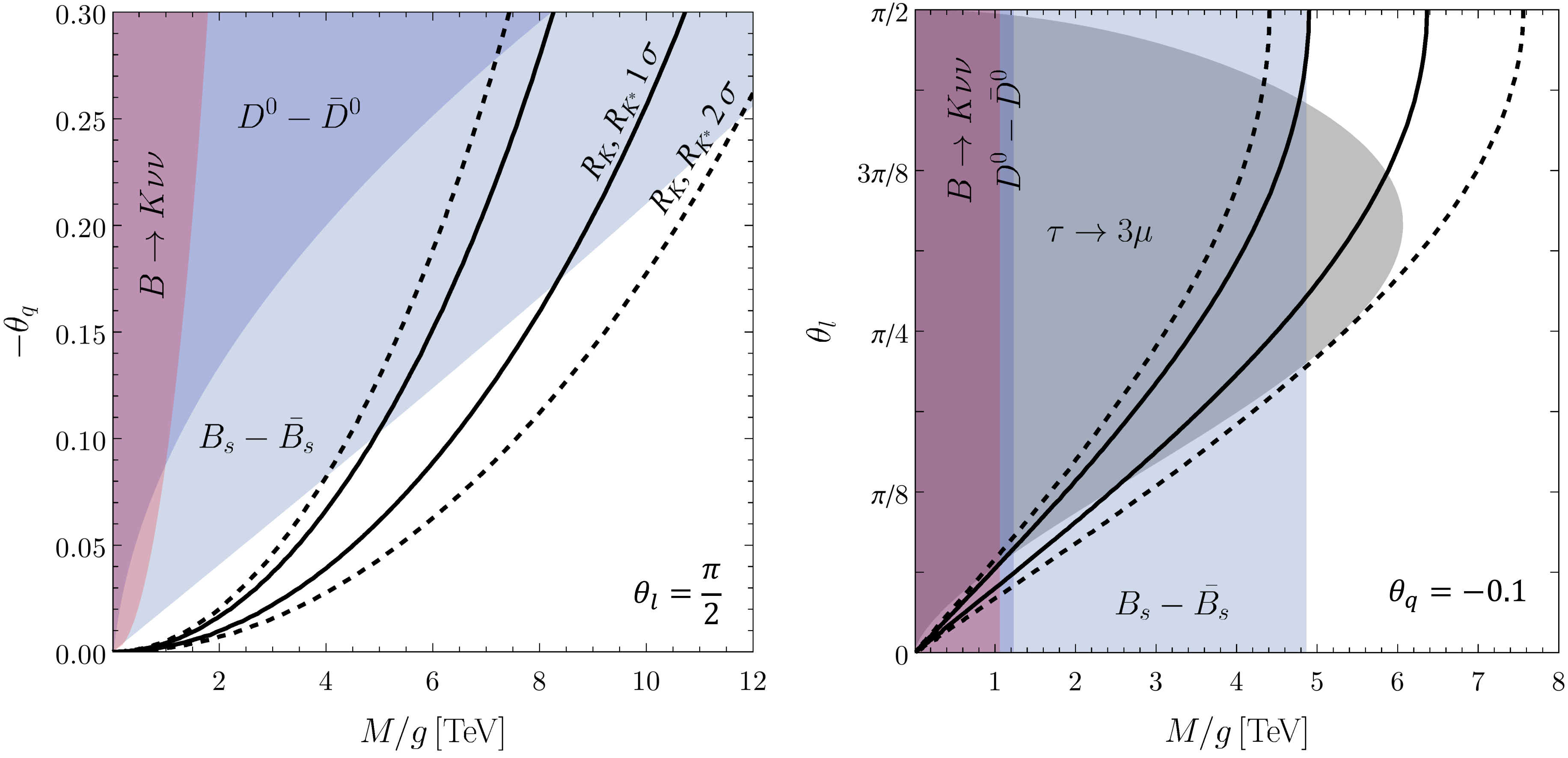
  $\tau \to \mu\mu\mu, \tau \to \mu\gamma$: already disfavours large mixing in lepton sector

- Direct Z' searches

  LHC $Z' \to \mu\mu$ searches already probing masses up to several TeV

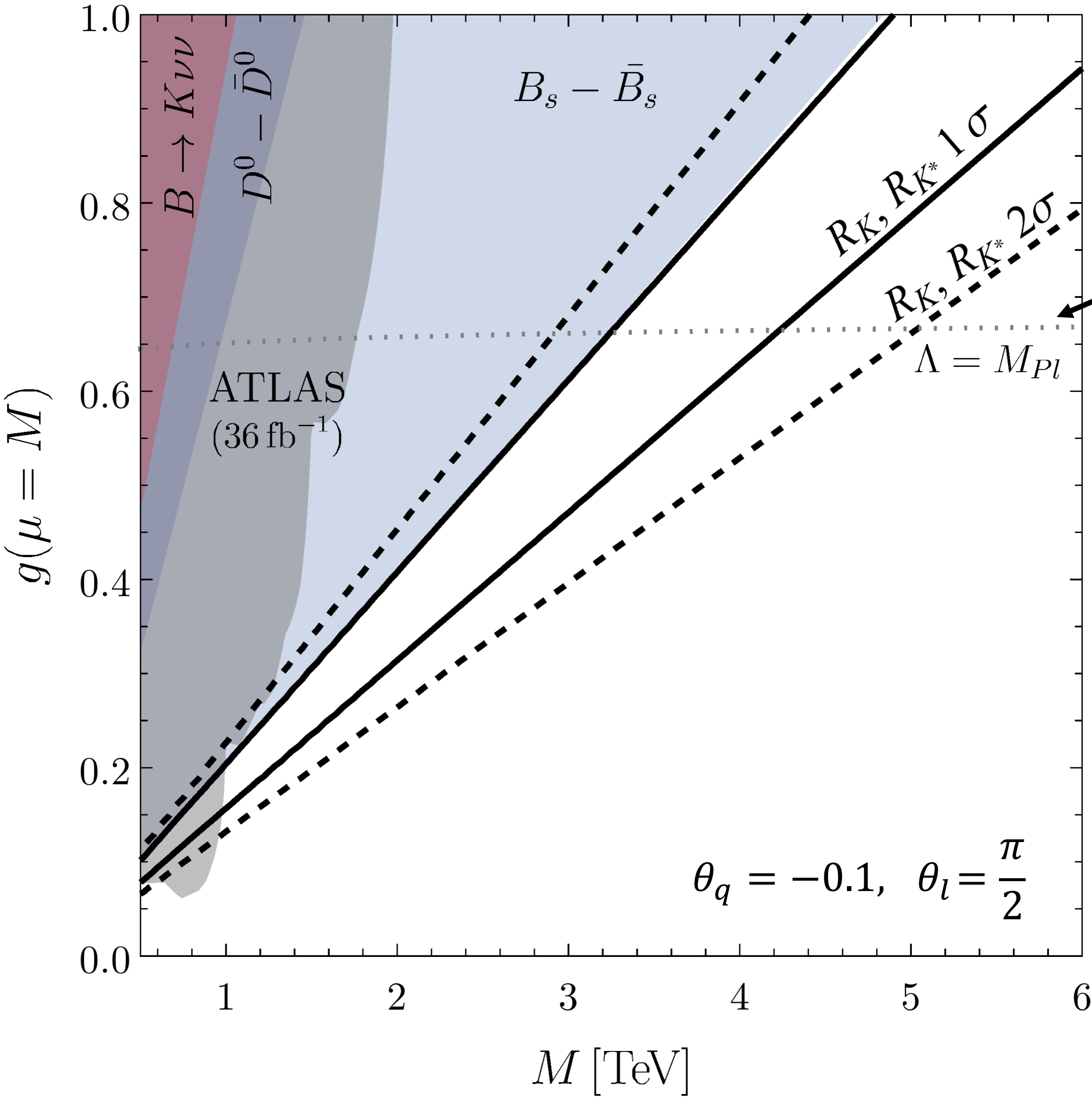
  Weaker limits in this model due to small $bb \to Z'$ cross-section

Results



0.30
0.25
0.20
0.15
0.10
0.05
0.00
$-\theta_q$
$D^0 - \bar{D}^0$
$B \to K\nu\nu$
$B_s - \bar{B}_s$
$R_K, R_{K^*}\, 1\sigma$
$R_K, R_{K^*}\, 2\sigma$
$\theta_l = \frac{\pi}{2}$
2
4
6
8
10
12
$M/g\,[\mathrm{TeV}]$
$\pi/2$
$3\pi/8$
$\pi/4$
$\pi/8$
0
θ_l
$B \to K\nu\nu$
$D^0 - \bar{D}^0$
$\tau \to 3\mu$
$B_s - \bar{B}_s$
$\theta_q = -0.1$
1
2
3
4
5
6
7
8
$M/g\,[\mathrm{TeV}]$

Results



Perturbativity

$$\beta(g) = \frac{142}{27}\frac{g^3}{(4\pi)^2}$$

Some other U(1)′ possibilities...

➢ *Anomaly cancellation* gives non-trivial restrictions on possible models

Example: with only $\mathrm{SM} + 3\nu_R$ and a few (mostly phenomenological) assumptions

- Vectorial $U(1)$ symmetries
- Two RH neutrinos have large Majorana masses for leptogenesis
- Suppression of $K - K$ and $D^0 - D^0$oscillations

Exist only two classes of anomaly-free $U(1)$:

$(B-L)_3$

$a = 0$

i) $$T_Q = \mathrm{diag}\left(\mathrm{a}, \mathrm{a}, \frac{1}{3} - 2\mathrm{a}\right), \ \mathrm{T_L} = \mathrm{diag}(0, 0, -1),$$

ii) $$T_Q = \mathrm{diag}(\mathrm{a}, \mathrm{a}, -2\mathrm{a}), \quad \mathrm{T_L} = \mathrm{diag}(0, 1, -1)$$

$L_\mu - L_\tau$ (Crivellin et al. 1503.03477)

Local Flavour Symmetries

Within SM + $3\nu_R$, largest* anomaly-free local symmetry extension $G_{SM}\times G'$

$$G_{SM}\times SU(3)_Q\times SU(3)_L\times U(1)_{B-L}$$

- Any *vectorial* $U(1)$ can be embedded into this larger flavour group, including both previous classes

- Many interesting model building opportunities…

*largest does *not* mean it contains them all

$SU(3)_H \times U(1)_{B-L} \to U(1)_h$

- To explain the anomalies, need a $U(1)$ symmetry connecting quarks and leptons
- Natural starting point is $SU(3)_H$ "horizontal" symmetry

  Can be further combined with Pati-Salam unification: $\mathrm{SU}(4) \times SU(2)_L \times SU(2)_R \times SU(3)_H$

- Break $SU(3)_H \times U(1)_{B-L} \to U(1)_h$ with two triplet scalars ~(3, -1)

$$T_h^q = \frac{1}{3}\begin{pmatrix} \frac{4}{3} & 0 & 0 \\ 0 & \frac{4}{3} & 0 \\ 0 & 0 & -\frac{5}{3} \end{pmatrix} \qquad T_h^l = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -3 \end{pmatrix}$$

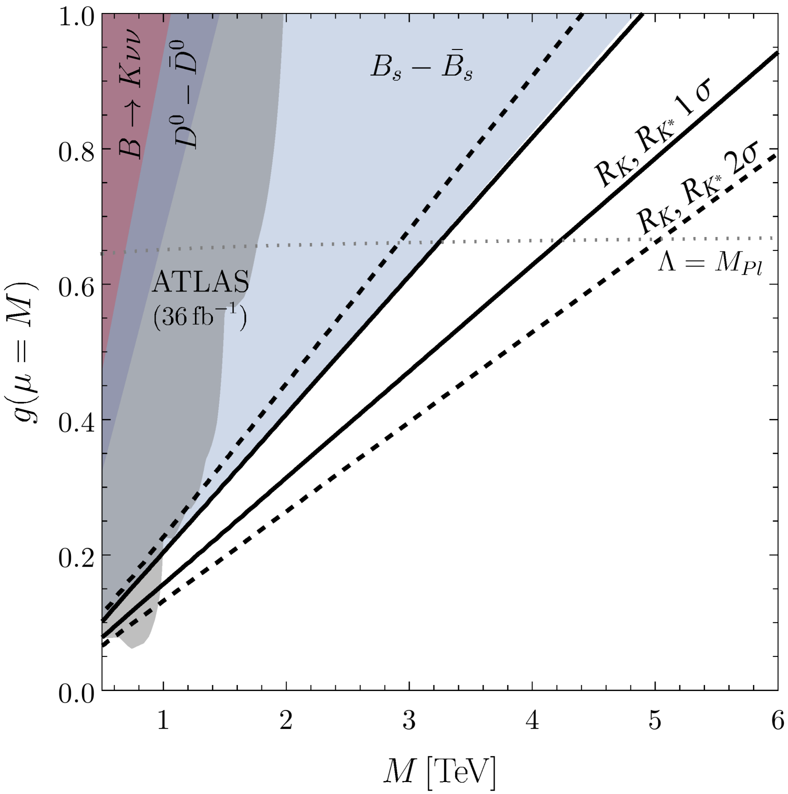
Residual $U(1)_h$ is combination of T_8 in $SU(3)$ and $B-L$

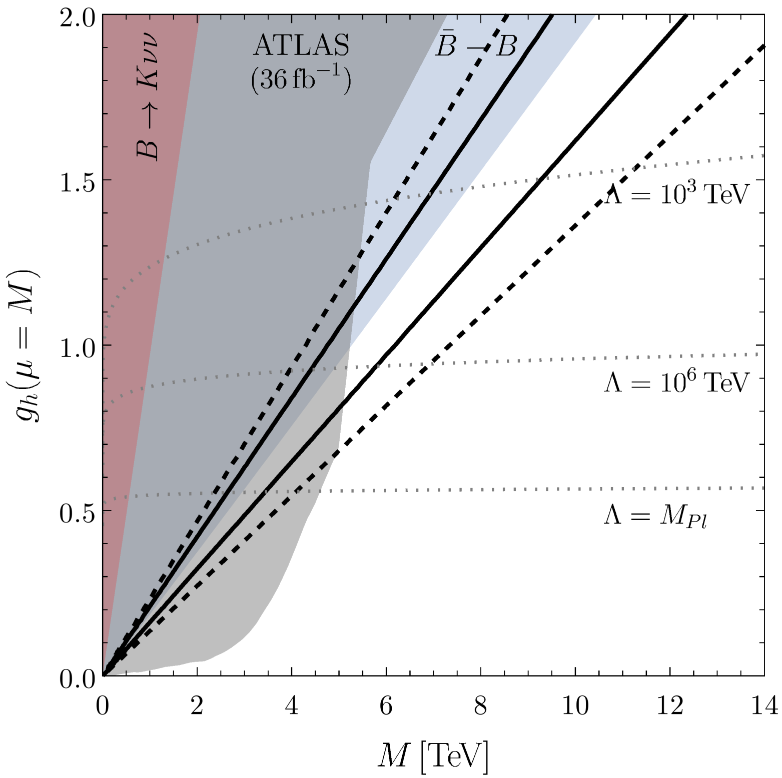
$U(1)_{(B-L)_3}$ and $U(1)_h$ comparison

$SU(3)_H \times U(1)_{B-L} \to U(1)_h$

$(B-L)_3$

$T_Q \sim \left(\frac{4}{3}, \frac{4}{3}, -\frac{5}{3}\right), \quad T_L \sim (0,0,-3)$





- $U(1)_{(B-L)_3}$ evades otherwise strong LHC bounds from $Z' \to \mu\mu$
- Can remain perturbative up to the Planck scale

Flavoured B-L DM

ν_R Dark Matter

- $U(1)_{(B-L)_3}$ contains a natural dark matter candidate:

  lightest RH neutrino

- Mass forbidden by gauge symmetry

- Majorana mass can be generated upon $U(1)_{(B-L)_3}$ breaking:

  Introduce an $U(1)_{(B-L)_3}$ breaking scalar, Φ(+2)

$$\mathcal{L}_{DM} = \frac{i}{2}\bar{\chi}\partial\!\!\!/\chi + \frac{g}{2}Z'_\mu\bar{\chi}\gamma^5\gamma^\mu\chi - \boxed{(\frac{y}{2}\bar{\chi}\Phi\chi_L} + h.c.)$$

- Annihilation via new gauge interactions → standard thermal WIMP

DM Stability

- Impose $\mathbb{Z}_2$ symmetry to guarantee DM stability

RH ν DM (-), everything else (+)

- Forbids dangerous Yukawa couplings

$$Y_\nu = \begin{pmatrix} \hat{Y}_\nu^{2\times 2} & 0 \\ -\frac{Y_L' \phi_l}{M_L} Y_L^T & 0 \end{pmatrix}$$

- Solves potential problem with light RH neutrino raising active neutrino masses, and washing out lepton asymmetry

$$\frac{1}{M_{\nu_R}} \simeq \begin{pmatrix} \frac{1}{\hat{M}_{\nu_R}^{2\times 2}} & -\frac{\langle \phi_l \rangle}{y \langle \Phi \rangle \hat{M}_{\nu_R}} y \\ -\lambda_\phi^T \frac{\langle \phi_l \rangle}{\langle \Phi \rangle \hat{M}_{\nu_R}} & \frac{1}{y \langle \Phi \rangle} \end{pmatrix}$$

Some other U(1)′ possibilities…

- *Anomaly cancellation* gives non-trivial restrictions on possible models

Example: with only $\mathrm{SM} + 3\nu_R$ and a few (mostly phenomenological) assumptions

- Vectorial $U(1)$ symmetries
- Two RH neutrinos have large Majorana masses for leptogenesis
- Suppression of $K - K$ and $D^0 - D^0$ oscillations
- RH neutrino dark matter

$(B-L)_3$

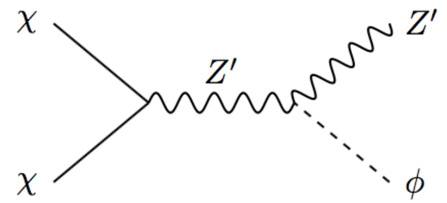
$a = 0$

Exist only *one* class of anomaly-free $U(1)$:

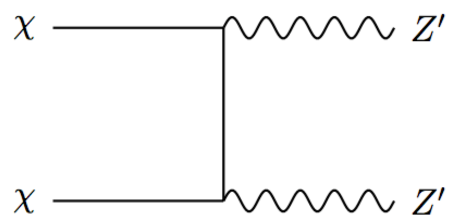
i) $$T_Q = \mathrm{diag}\left(\mathrm{a}, \mathrm{a}, \frac{1}{3} - 2\mathrm{a}\right), \;\; \mathrm{T_L} = \mathrm{diag}(0, 0, -1),$$

DM Annihilation

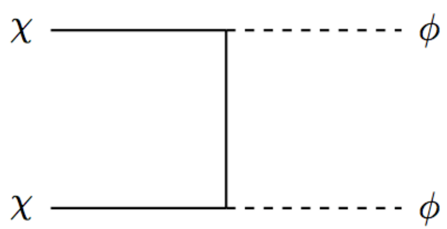
Four main annihilation channels:



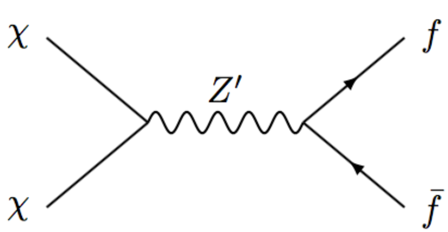
s-wave, dominates when kinematically open



s-wave, p-wave enhanced



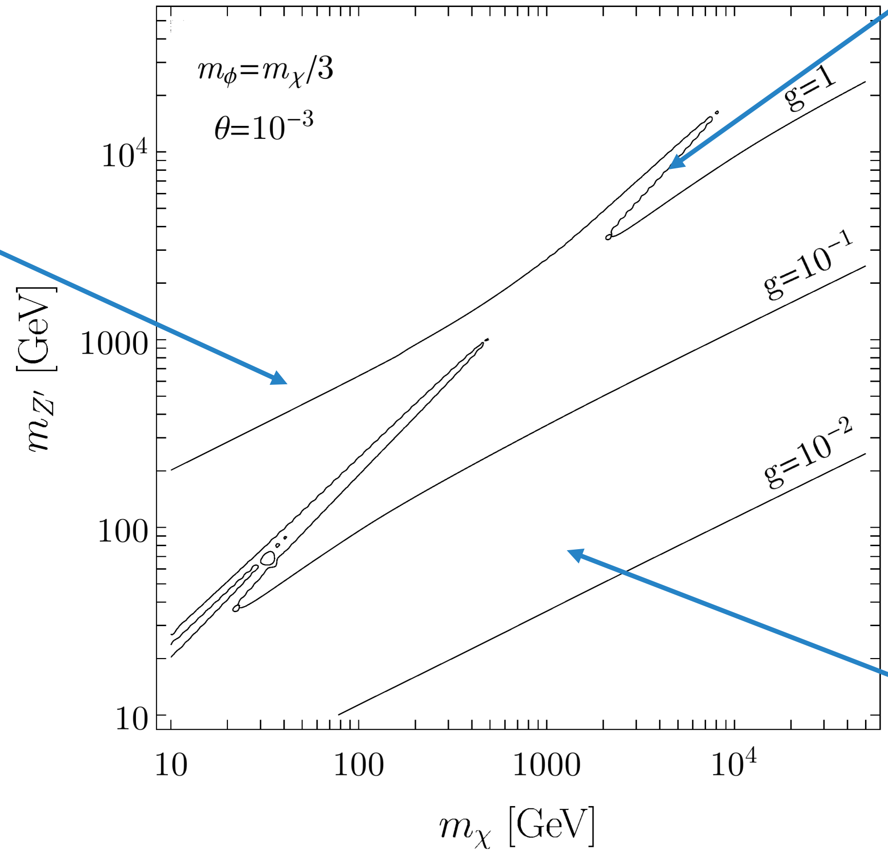
p-wave



p-wave

Relic density

- Relic density calculated with MicrOMEGAs
- Fix gauge coupling to satisfy correct relic density
  → 4 free parameters: $m_\chi,\ m_{Z'},\ m_\phi,\ \theta$



$m_\chi \approx m_{Z'}/2$

$\chi\chi \to \phi\,\phi$
$\chi\chi \to f f$

$\chi\chi \to \phi Z'$
$(\chi\chi \to Z'\,Z')$

Unitarity/perturbativity

- Even in simplified models, partial wave perturbative unitarity gives strong bounds

$$\chi\chi \to \chi\chi, \quad \phi\phi \to \phi\phi$$

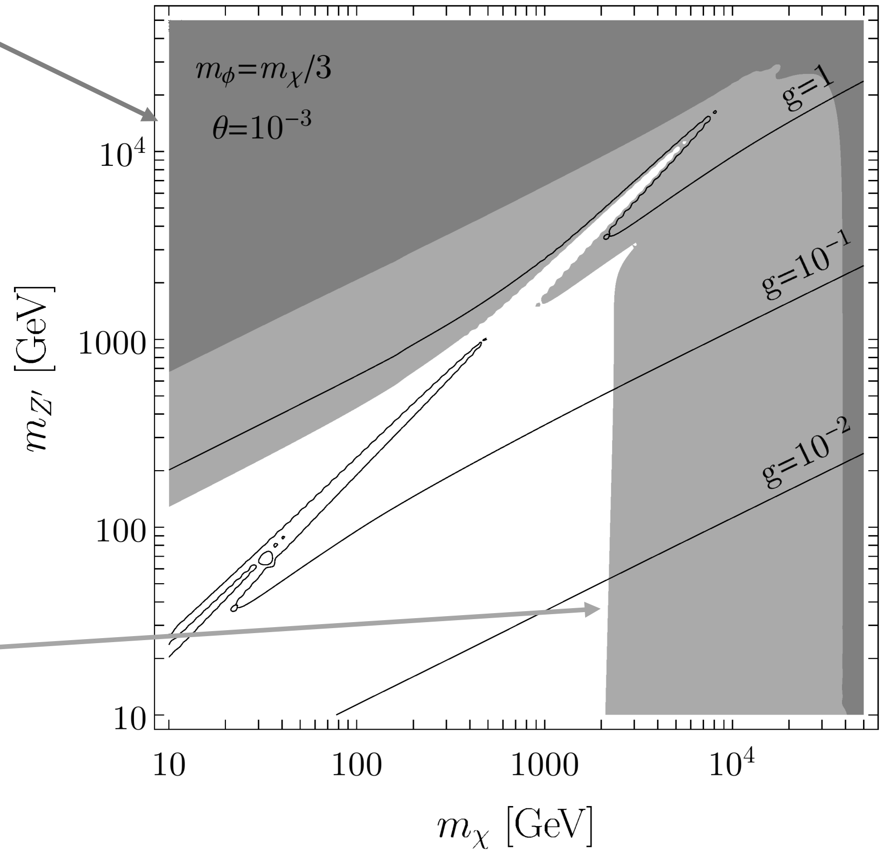
$$g < \sqrt{4\pi}$$

$$y < \min(\sqrt{8\pi}, \sqrt{\frac{32\pi}{3}\frac{m_{Z'}}{g}})$$

(Duerr et al. 1606.07609)

- Can also impose perturbativity of couplings to high scales (i.e. no Landau pole below M_{Pl})

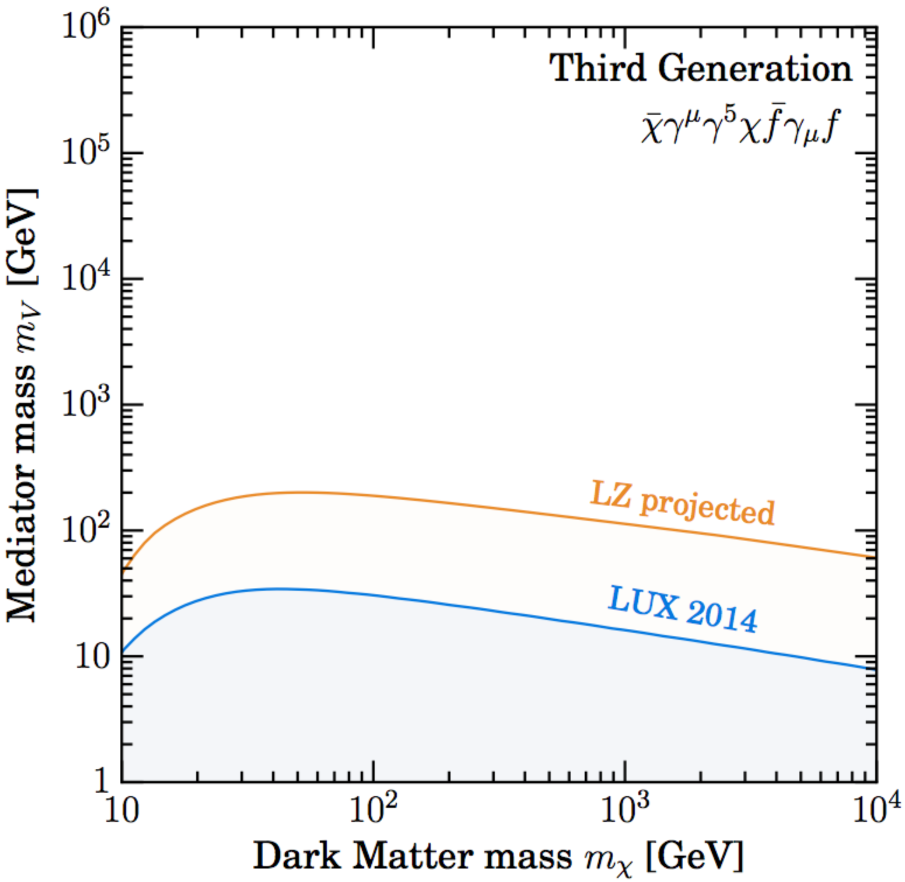
→ *Significantly* stronger bounds



DM Direct Detection

- DM-nucleon scattering mediated by Z' is velocity suppressed
- Further suppression due to lack of Z' coupling to light quarks
- Coupling introduced in RGE running down to nuclear scale
- Current (and future) limits very weak

Simplified model limit



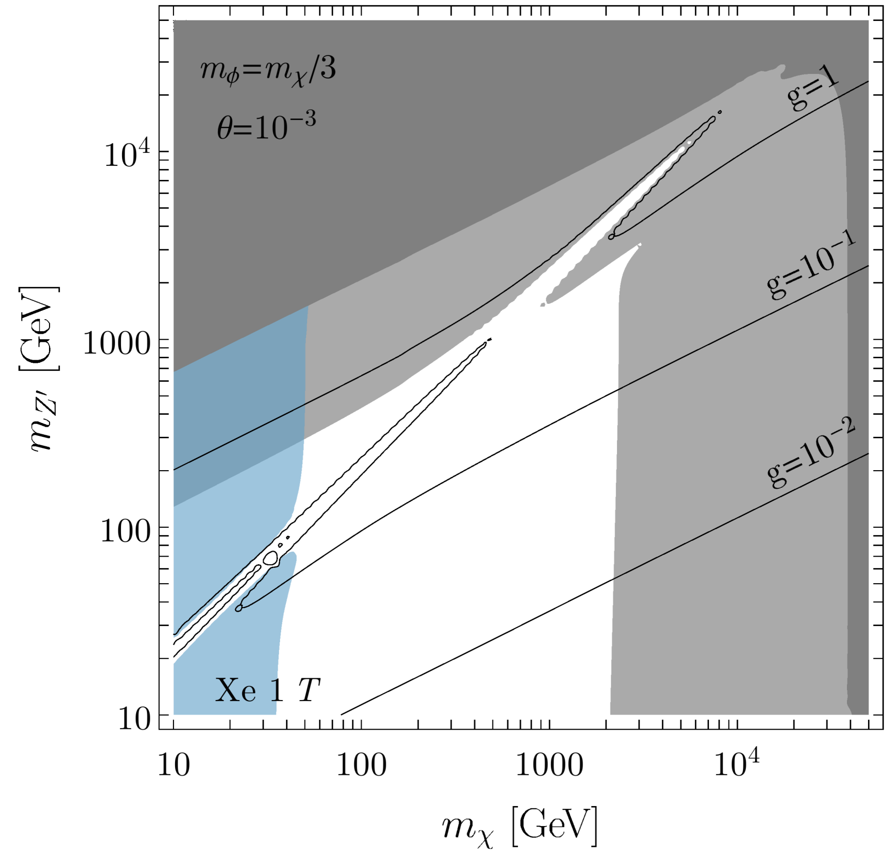
D'Eramo et al. 1605.04917

DM Direct Detection

- DM-nucleon scattering mediated by Z' is velocity suppressed
- Further suppression due to lack of Z' coupling to light quarks
- Higgs-ϕ mixing leads to spin-independent scattering

$$\mathcal{L} \supset (\phi^\dagger \phi)(H^\dagger H)$$

- At the very least, radiatively generated at two-loop
- Obtain limits even for very small mixing angles



DM Indirect Detection

- $\chi\chi \to \phi Z'$ and $\chi\chi \to Z'Z'$ annihilation are s-wave

  $\to$ in principle lead to gamma-ray signals

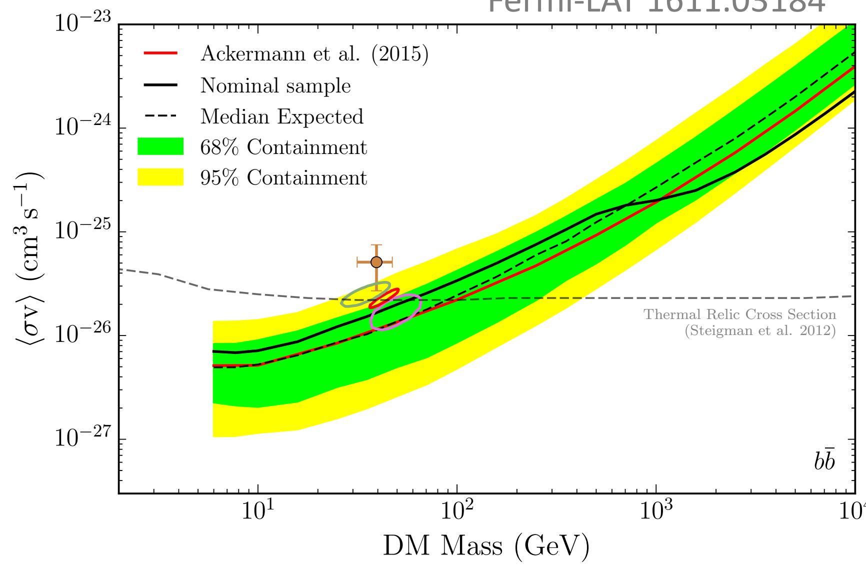
- For $\chi\chi \to Z'Z'$, p-wave enhanced by $m_\chi^4/m_{Z'}^4$

  $\to$ xsec today suppressed compared to thermal relic xsec

- Only need to consider $\chi\chi \to \phi Z'$
  - Multibody SM final-state (eg. $\phi Z' \to bbbb$)
  - Significant Z' BR to ν

$\to$ Current Fermi dwarf limits negligible

Fermi-LAT 1611.03184



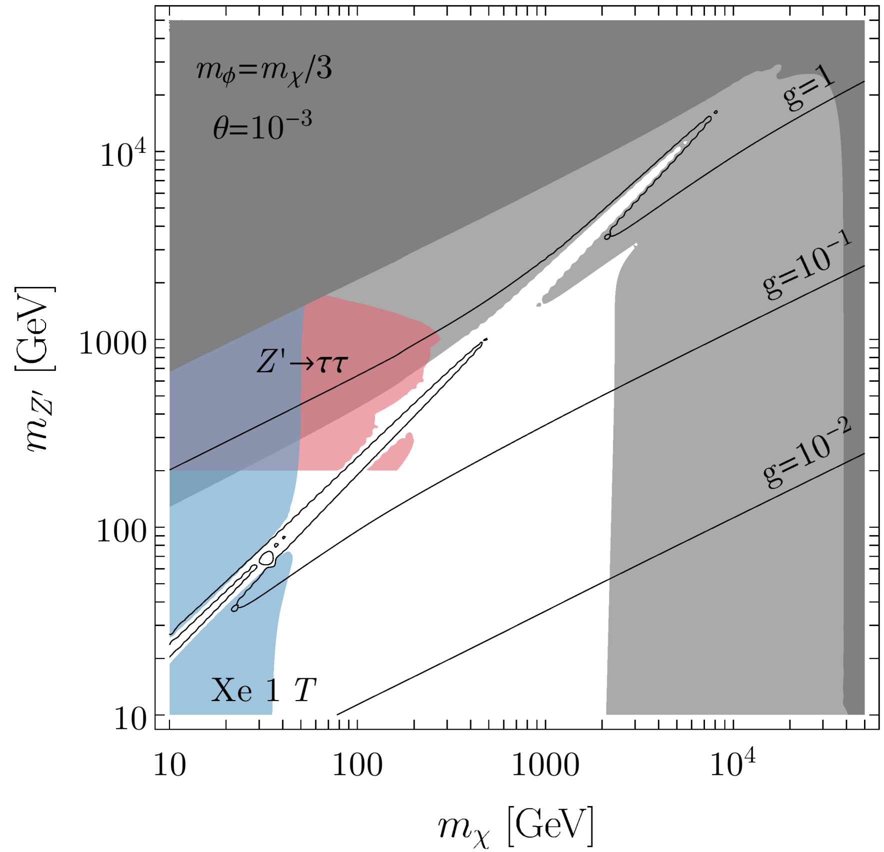
LHC Searches

- Collider bounds relatively weak due to suppressed $bb \to Z'$ cross-section

- Precise limits depend on rotation to mass basis

- Minimal/conservative assumption:
  $$Z' \to \tau\tau$$

- Stronger limits if coupling to light leptons



Z - Z' Mixing

- Generically have Z - Z' kinetic mixing

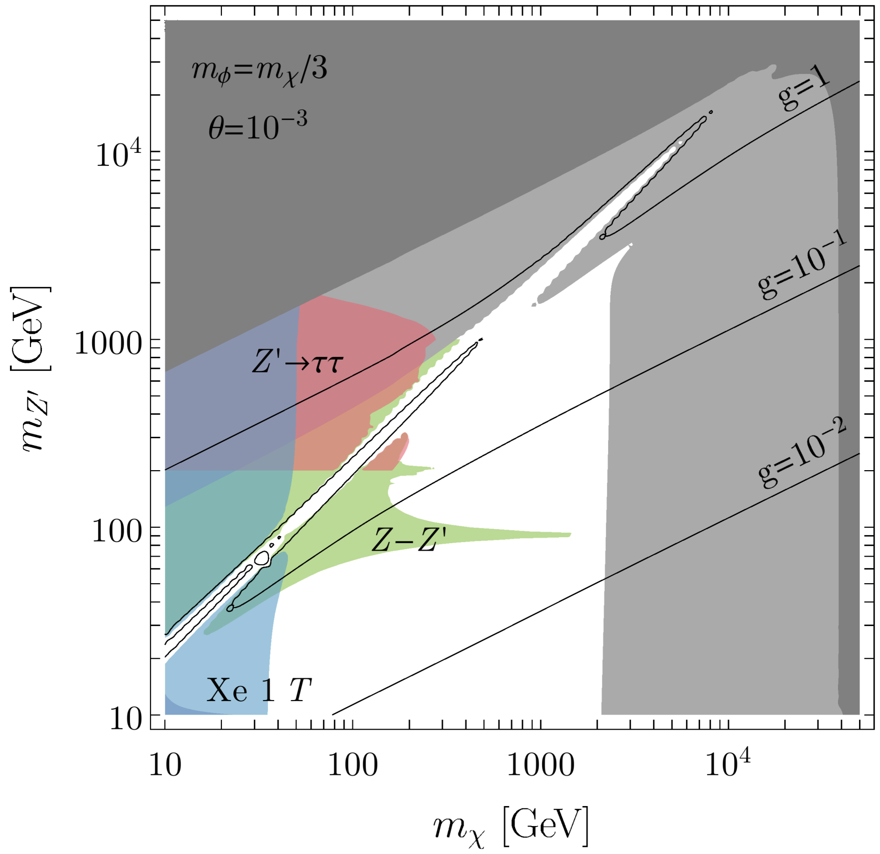
$$\varepsilon B^{\mu\nu} F'_{\mu\nu}$$

- Generated by RGE evolution, even if vanishing at high scales (e.g. Λ_{GUT})

$$\varepsilon(m_{Z'}) \sim \frac{2 g_Y g'}{9\pi^2} \log \frac{\Lambda}{m_{Z'}}$$

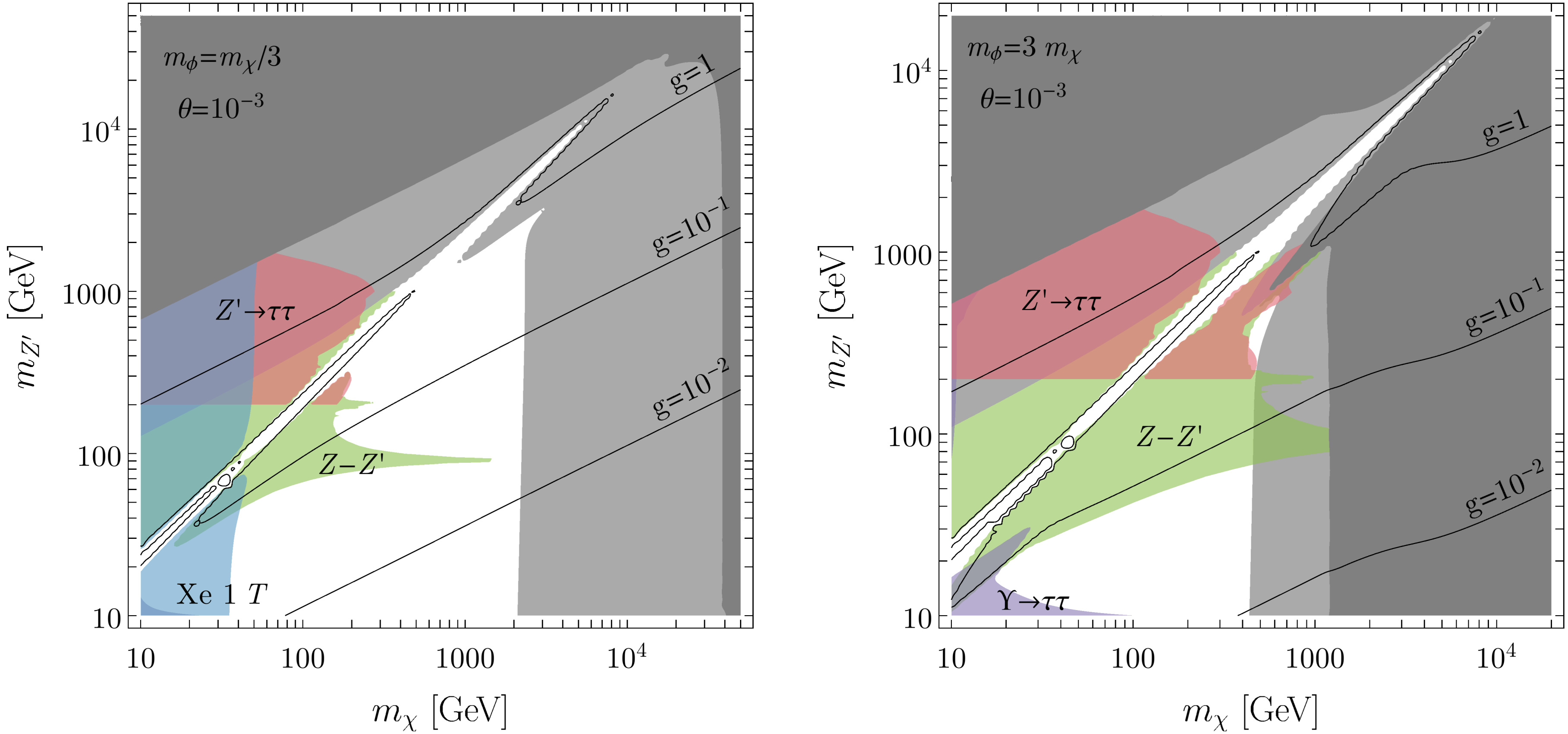
- Modifies the Z mass → strong constraints from electroweak precision measurements

$$\varepsilon \leq \ 10^{-1} - 10^{-2}$$



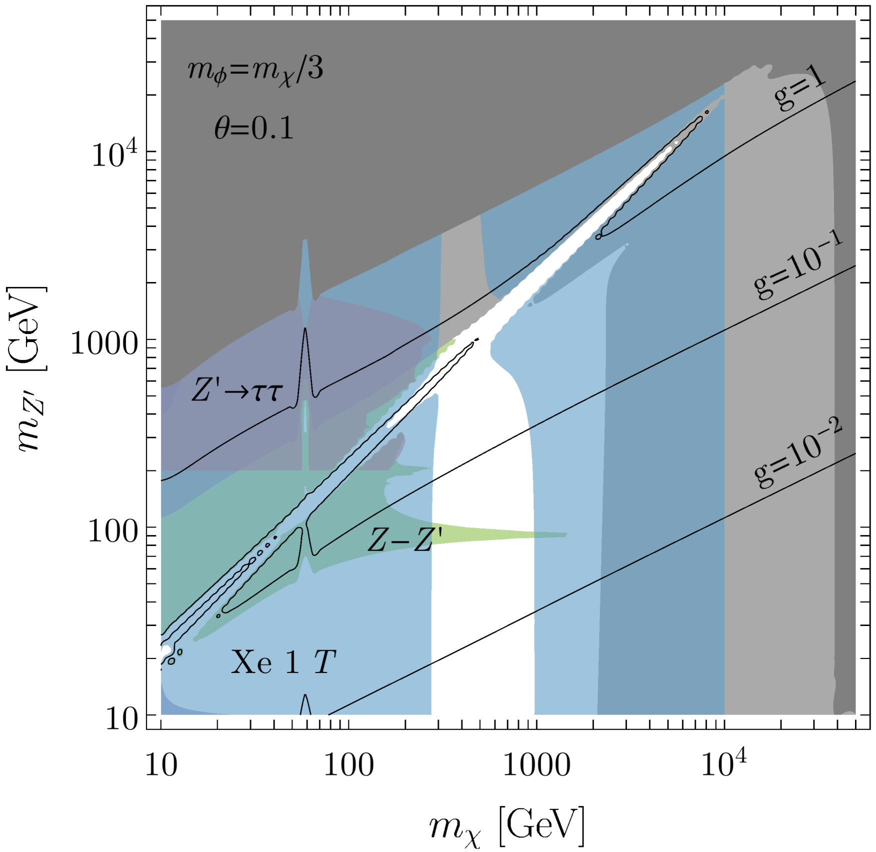
$m_\phi = 3m_\chi$

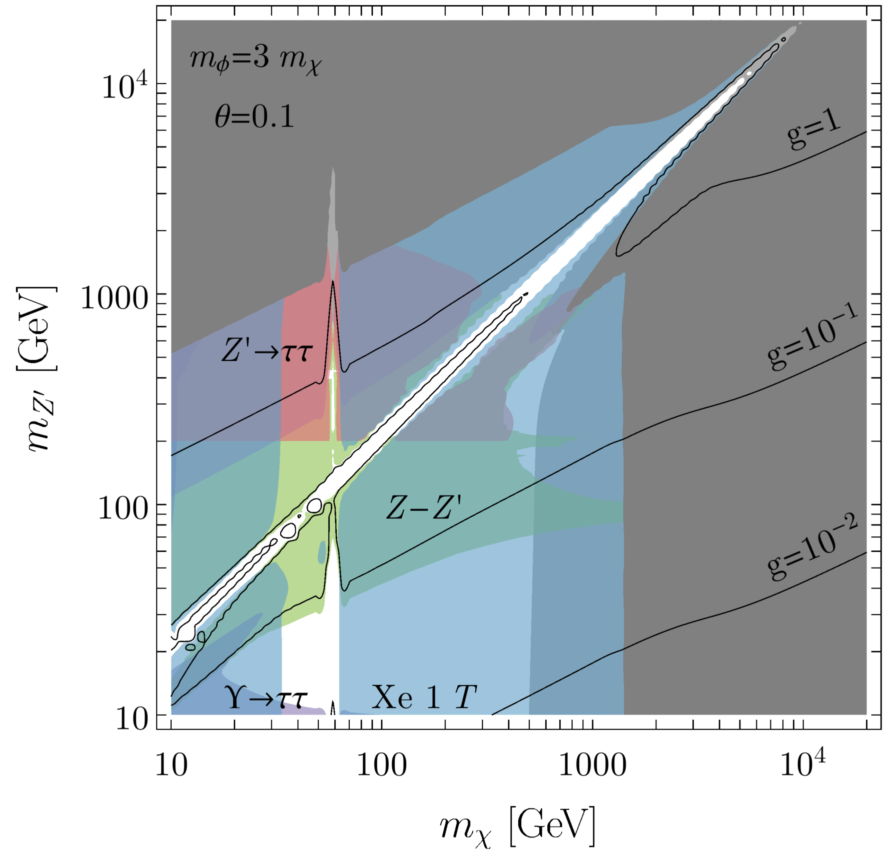
- For heavy scalar, $\chi\chi \to \phi Z'$ annihilation channel forbidden
- Larger gauge coupling required for correct relic density
  → stronger perturbativity constraints
- Reduced direct detection bound due to increased m_ϕ



Higgs-ϕ Mixing ($\theta = 0.1$)

- Large Higgs-ϕ mixing strongly constrained by direct detection
- Exception when $m_\phi \approx m_h$ due to destructive interference





- Also bounds from Higgs measurements, invisible decays

DM & B anomalies?

Can we explain B anomalies & DM simultaneously?

→ Yes!

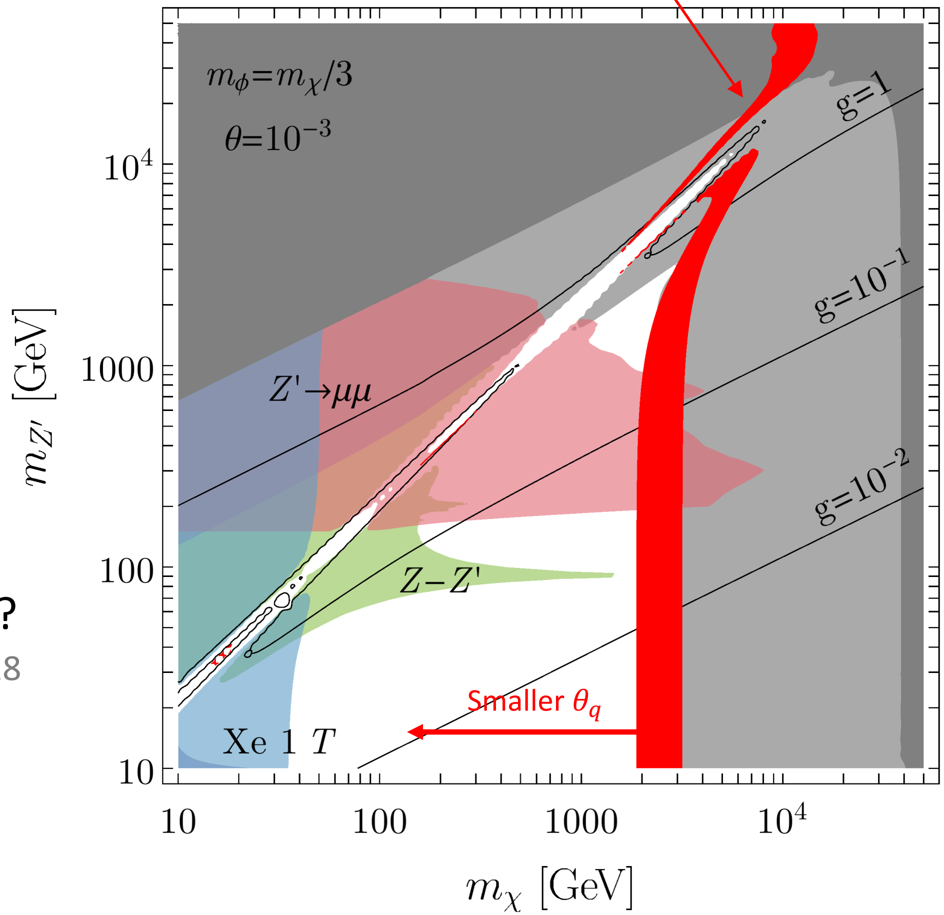
- Smaller mixing angle (θ_q) preferred

- Large Z' mass region has strong constraints from $Z' \to \mu\mu$

- Plenty of parameter space at low mass
  → possible to probe via Drell-Yan at LHC?

1408.1075, 1412.0018

$R_K, R_K^* \ @ \ 1\sigma$
$\theta_q = -0.1$



Summary (I)

- Recently, number of interesting anomalies in $b \to s\mu\mu$
- In particular, hints of lepton flavour universality violation
  - Theoretically clean $R(K)$ & $R(K^*)$
- Even with most conservative assumptions, global fits show $\sim 4\sigma$ deviation from SM prediction
- Current LHCb results are Run I data
  - If same deviations seen in larger Run II sample, a purely statistical fluctuation would be highly unlikely
- Important results from Belle II in the future

Summary (II)

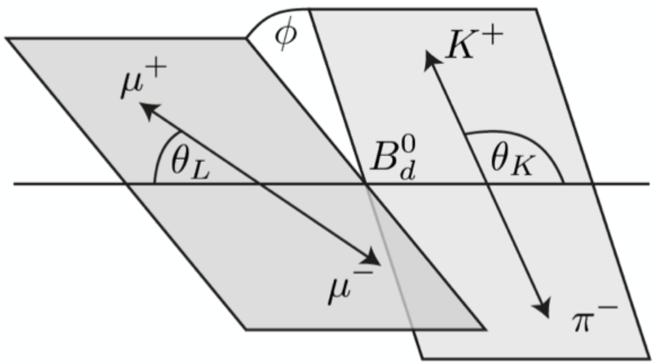
- Several possible NP explanations, Z', leptoquarks, compositeness, …
- Gauged $U(1)_{(B-L)_3}$ is a simple SM extension, consistent with seesaw and leptogenesis, that can explain recent anomalies and is valid up to the Planck scale
- One RH neutrino remains light and can be a WIMP dark matter candidate
- Relevant mass scales may be within reach of direct production at LHC – complementarity between precision measurements and direct searches

Backup

$B \to K^*(K\pi)\mu\mu \quad (P_5')$

CP averaged differential decay rate:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l$$
$$-F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$



$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$$

F_L: Fraction of longitudinal polarization of K^*

$B \to K^{(*)}\mu\mu$ Interference

$R(K)$:

$$\frac{d\Gamma_K}{dq^2} = \mathcal{N}_K |\vec{k}|^3 f_+(q^2)^2 \left(\left| C_{10}^\ell + C_{10}'^\ell \right|^2 + \left| C_9^\ell + C_9'^\ell + 2\frac{m_b}{m_B + m_K} C_7 \frac{f_T(q^2)}{f_+(q^2)} - 8\pi^2 h_K \right|^2 \right) + \mathcal{O}(\frac{m_\ell^4}{q^4}) + \frac{m_\ell^2}{m_B^2} \times O(\alpha_s, \frac{q^2}{m_B^2} \times \frac{\Lambda}{m_b}),$$

$R(K^*)$:

$$\frac{d\Gamma_0}{dq^2} = \mathcal{N}_{K^*0} |\vec{k}|^3 V_0(q^2)^2 \left(\left| C_{10}^\ell - C_{10}'^\ell \right|^2 + \left| C_9^\ell - C_9'^\ell + \frac{2m_b}{m_B} C_7 \frac{T_0(q^2)}{V_0(q^2)} - 8\pi^2 h_{K^*0} \right|^2 \right) + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

Rotation to Mass Basis

$$U_{d_L} = \begin{pmatrix} \mathbf{V}_L^d & -\frac{Y_D' \phi_q^*}{M_D Y_b} Y_D \\ \frac{Y_D'^* \phi_q}{M_D^* Y_b^*} Y_D^\dagger \mathbf{V}_L^d & 1 \end{pmatrix} + \mathcal{O}(\epsilon^2)$$

$$U_{d_R} = \begin{pmatrix} \mathbf{V}_R^d & -\frac{Y_Q'^* \phi_q^*}{M_Q^* Y_b^*} Y_Q^* \\ \frac{Y_Q' \phi_q}{M_Q Y_b} Y_Q^T \mathbf{V}_R^d & 1 \end{pmatrix} + \mathcal{O}(\epsilon^2)$$

- V-L fermions can be relatively heavy and still easily generate CKM-sized mixing angles

- RH rotations can be naturally suppressed by decoupling M_Q