Possible implications of B anomalies

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Anomaly: $B \to K^{(*)}\mu^+\mu^-$ versus ee

$$R_X = \frac{\mathcal{B}(\bar{B} \to X\,\mu^+\,\mu^-)}{\mathcal{B}(\bar{B} \to X\,e^+\,e^-)},$$ a hadronically ‘clean’ observable

Experimental and predicted values for R_K and R_{K^*}:

-	$R(K)$	$R(K^*)$ (low q^2)	$R(K^*)$ (high q^2)
SM	1	0.92	1
LHCb	$0.745 \pm 0.09 \pm 0.036$	$0.660^{+0.110}_{-0.070} \pm 0.024$	$0.685^{+0.113}_{-0.069} \pm 0.047$

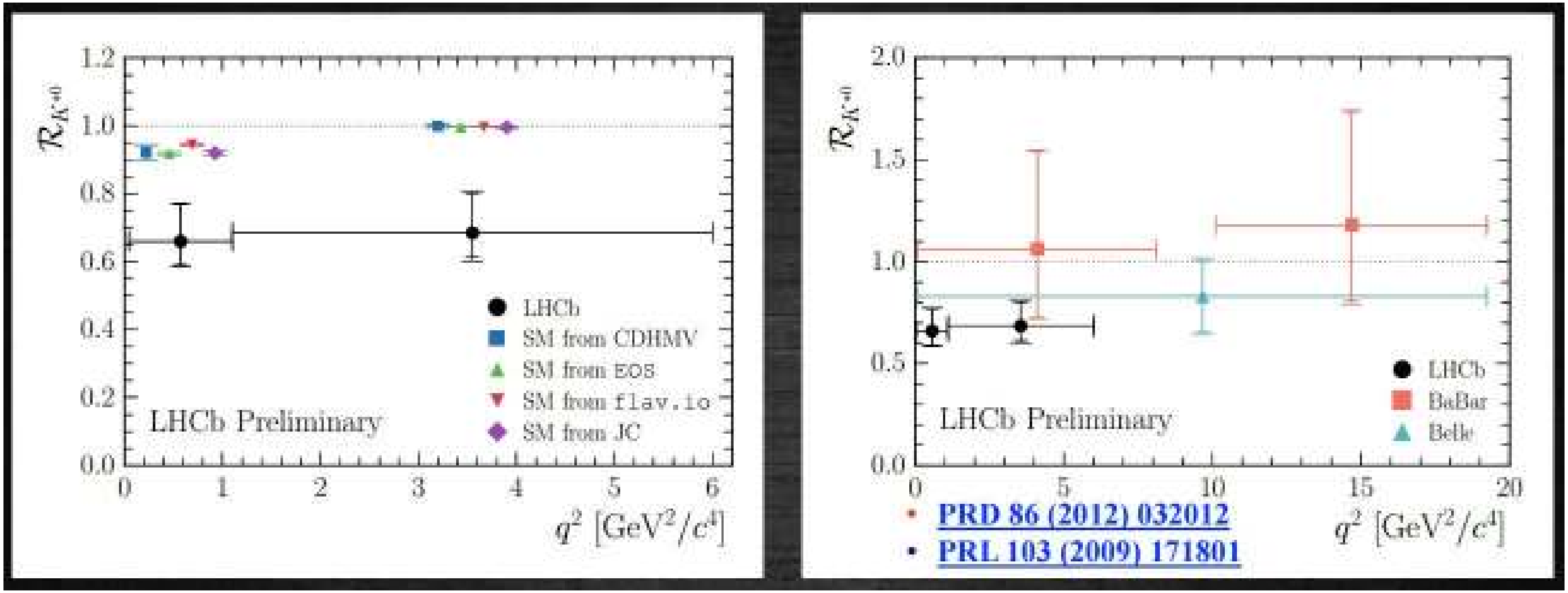
Correlated anomalies also seen in ‘dirty’ observables,

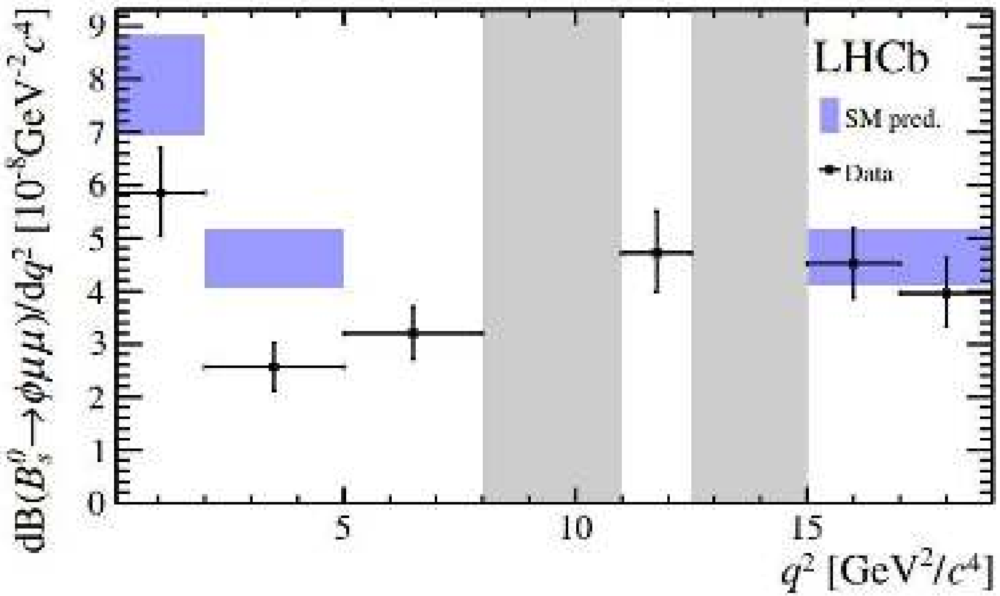
$B(B \to K^*\mu^+\mu^-)$, angular distribution P_5'

and

$$B(B_s \to \phi\mu^+\mu^-)$$

LHCb on R_{K^*}, $B_s \to \phi\mu\mu$, $B_s \to \mu\mu$





$$\frac{\mathrm{BR}(B_s \to \mu\mu)_{\mathrm{LHCb}}}{\mathrm{BR}(B_s \to \mu\mu)_{\mathrm{SM}}} = \frac{(3.0 \pm 0.6) \times 10^{-9}}{(3.65 \pm 0.23) \times 10^{-9}} = 0.82 \pm 0.20$$

Model-independent fit

The single effective operator (D'Amico *et al.*,1704.05438)

$$\mathcal{O}_{b_L\mu_L} = \frac{1}{\Lambda^2}(\bar{s}_L\gamma_\alpha b_L)(\bar{\mu}_L\gamma^\alpha\mu_L)$$

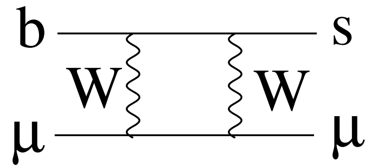
gives a good fit to the data, with $\Lambda \cong 36\,\mathrm{TeV}$.*
Should be $\cong -0.15 \times (\mathrm{SM\ contribution})$. 4σ significance

$\mathcal{O}_{b_L\mu_L}$ looks like Z' exchange, but Fierz rearrangement

$$\mathcal{O}_{b_L\mu_L} \to -\frac{1}{\Lambda^2}(\bar{s}_L\gamma_\alpha\mu_L)(\bar{\mu}_L\gamma^\alpha s_L)$$

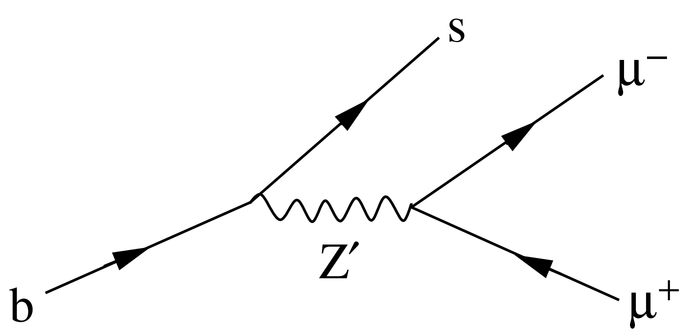
looks like vector leptoquark exchange.

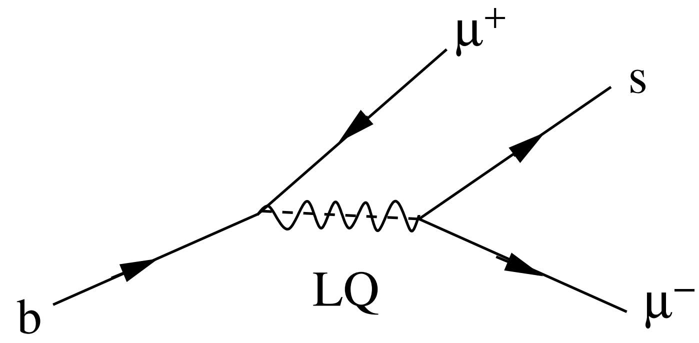
Of course, SM contribution comes at one loop



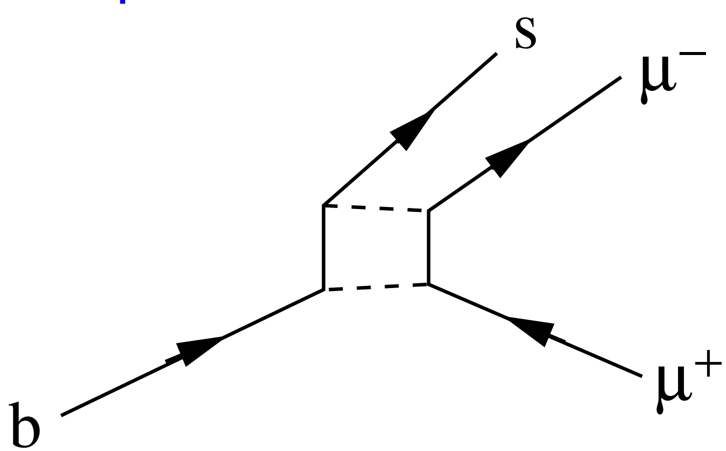
*Can improve fit somewhat by also including $\mathcal{O}_{b_Le_L}$

Popular models: Z' or leptoquark





or via new physics in loop



In this talk I present examples of each kind.

All three models happen to predict new physics at the TeV scale (not my goal), accessible to LHC!

Guiding principle

A theory of B decay anomalies should explain more than just B decay anomalies

- Z' model: spontaneously broken flavor symmetry is origin of the Z'; we explain origin of fermion masses.

  JC & J. Martin Camalich, 1706.08510

- Loop model: one of the particles in the loop is dark matter.

- Leptoquark model: the LQ is a composite "meson" from strong dynamics at the TeV scale. Dark matter is a composite "baryon."

  JC & J.Cornell, 1709.xxxxx

Z' model: bottom-up construction

Want to connect the anomalies to the origin of flavor.

Spontaneously broken gauged horizontal (flavor) symmetry could give SM Yukawa couplings, and Z's.

Chiral couplings $(\bar{s}_L \gamma_\alpha b_L)(\bar{\mu}_L \gamma^\alpha \mu_L)$ motivate the chiral flavor symmetry

$$\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$$

with SU(3)$_L$ acting on left-handed fermions,
and SU(3)$_R$ acting on right-handed fermions

It contains 16 Z's! We need only one to explain $R_{K^{(*)}}$

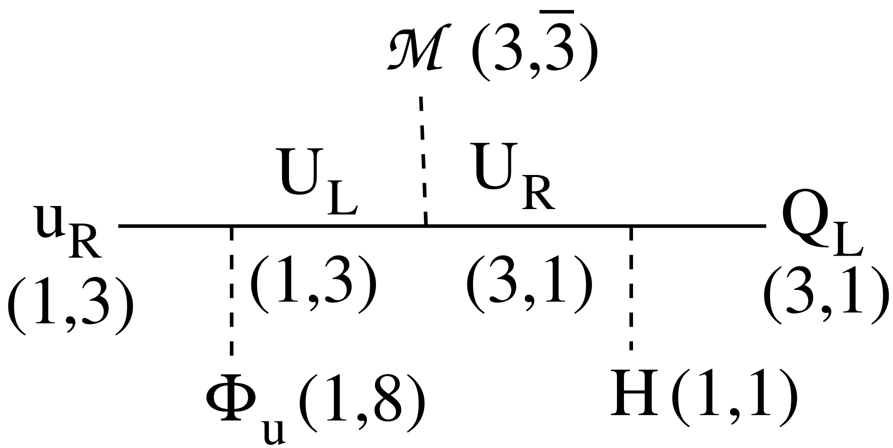
Expect $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R \to \mathrm{SU}(3)_L$ at scale of right-handed neutrino masses ($\gtrsim 10^{10}\,\mathrm{GeV?}$)

Flavor constraints imply SU(3)$_L \to$ U(1)$_{Z'}$ at $10^4\,\mathrm{TeV}$.

$\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ theory of flavor

$\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ symmetry forbids the usual Yukawa couplings $\bar{Q}^i_L \tilde{H} u_{R,i}$, $\bar{Q}^i_L H d_{R,i}$, $\bar{L}^i_L \tilde{H} \nu_{R,i}$, $\bar{L}^i_L H e_{R,i}$

We introduce new heavy fermions, $U_{L,R}$, $N_{L,R}$, $N_{L,R}$, $E_{L,R}$, and scalars $\mathcal{M}$, Φ_u, Φ_d, Φ_ν, Φ_ℓ to induce them,



giving

$$
\begin{aligned}
\mathcal{L}_{\rm yuk} &= \frac{1}{\Lambda_u}\bar{Q}_L \tilde{H}\langle\Phi_u\rangle u_R + \frac{1}{\Lambda_d}\bar{Q}_L H\langle\Phi_d\rangle d_R \\
&+ \frac{1}{\Lambda_l}\bar{L}_L H\langle\Phi_l\rangle l_R + \frac{1}{\Lambda_\nu}\bar{L}_L \tilde{H}\langle\Phi_\nu\rangle \nu_R
\end{aligned}
$$

Which Z'_L?

Only one of the 8 possible Z'_Ls is phenomenologically acceptable, ${Z'}^8_L$, coupling to SU(3) generator T^8:

$$T^8 = \frac{1}{2\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Other choices have too large K-$\bar{K}$ mixing.

I.e.,

$$T^3 = \tfrac{1}{2}\,\mathrm{diag}(1,-1,0)$$

contributes to K-$\bar{K}$ with only Cabibbo angle suppression, if fermion masses are minimally flavor violating . . . .

Quark Currents

Diagonalizing mass matrices as usual, via

$$f_L \to V_f^{L\dagger} f_L, \quad f_R \to V_f^{R\dagger} f_R$$

the left-handed Z' currents become

$$g_L\, \bar{f}_L (V_f^L T^8 V_f^{L\dagger}) \gamma^\mu f_L$$

Assume $V_u^L = \mathbf{1}$, then $V_d^L = V_{CKM}^\dagger \equiv V$. The up-type quark current remains diagonal, $\sim T^8$, while the down-type gets CKM-induced mixing (example of minimal flavor violation, MFV):

$$-\frac{\sqrt{3}}{2} g_L \left(V_{tb} V_{ts}^* \left(\bar{s}_L \gamma^\mu b_L\right) + V_{tb} V_{td}^* \left(\bar{d}_L \gamma^\mu b_L\right) + V_{ts} V_{td}^* \left(\bar{d}_L \gamma^\mu s_L\right) \right)$$

We want the first term for $R_{K^{(*)}}$, while the other two come without a choice, all with SM-like CKM structure

The last term affects K-$\bar{K}$ mixing, just within limits. Any other generator (*e.g.*, T^3) would make it too large!

Lepton Currents

Without V_l^L rotation, T^8 has the wrong structure: predicts $R_{K^{(*)}} = 1$, with $B \to K\tau^+\tau^-$ having the anomaly. Instead we need

$$V_l^L T^8 V_l^{L\dagger} \cong \frac{1}{2\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

i.e., V_l^L must be close to a permutation. If $V_l^R = V_l^L$, it means that lepton masses were in the "wrong" order in original basis:

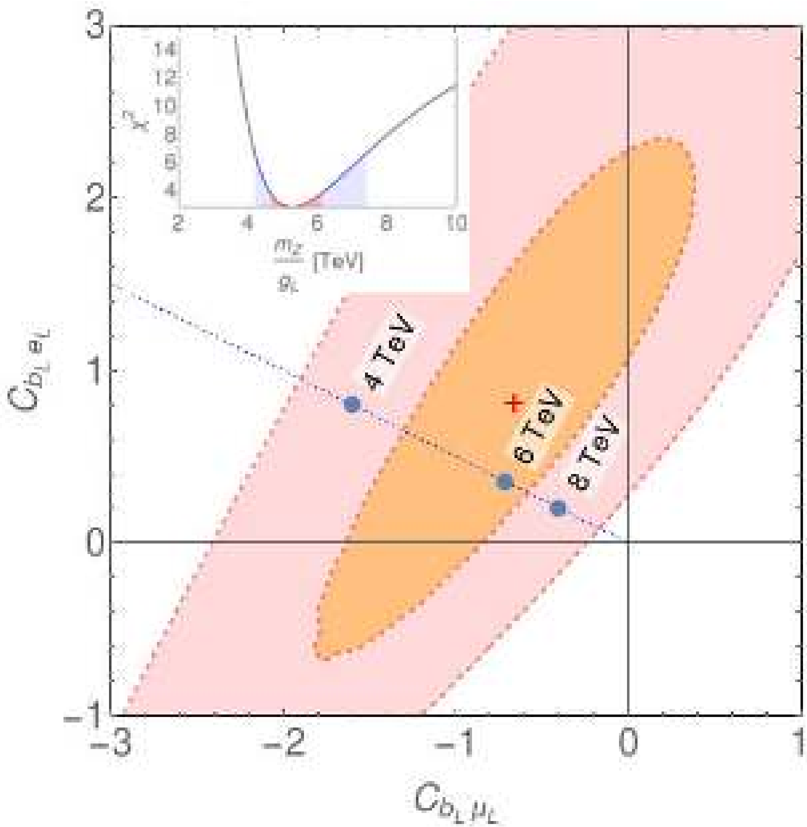
$$m_l = \begin{pmatrix} m_\mu & 0 & 0 \\ 0 & m_\tau & 0 \\ 0 & 0 & m_e \end{pmatrix}$$

This may seem weird, but nothing forbids it!

Fitting $R_{K^{(*)}}$ (plus $B_s \to \mu^+\mu^-$)*

Uniquely: we predict not only deficit in $B \to K^{(*)}\mu^+\mu^-$, but a (2$\times$ smaller) excess in $B \to K^{(*)}e^+e^-$. Unavoidable, due to tracelessness of SU(3) generators. Defining

$$H_{\rm eff} = -V_{tb}V_{ts}^*\frac{\alpha_{\rm em}}{4\pi v^2}\sum_{l=e,\mu} C_{bl}(\bar s_L\gamma_\mu b_L)(\bar l_L\gamma^\mu l_L)$$



we get best fit (with $C_{be} = -\frac{1}{2}C_{b\mu}$) at

$$C_{b\mu} = -0.93, \quad C_{be} = +0.46,$$

Implies

$$\frac{m_{Z'}}{g_L} = 5.3^{+0.8}_{-0.6}\,{\rm TeV}$$

* $B_s \to \mu^+\mu^-$ agrees well in our fit

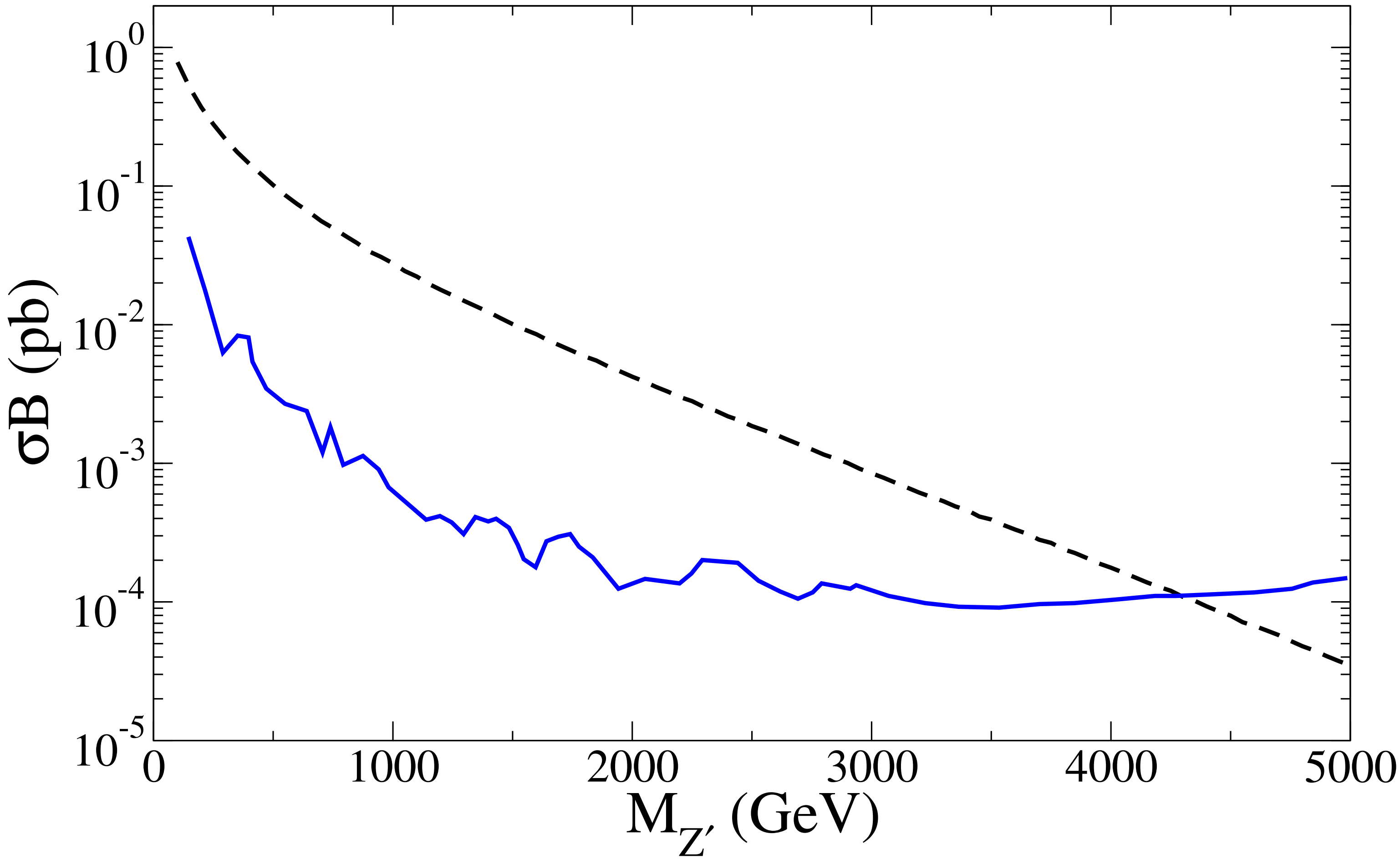
Constraints / Predictions

The model predicts several signals, some close to experimental limits:

- 11% *excesses* in $B \to K^{(*)} e^+ e^-$, $K^{(*)} \tau^+ \tau^-$ but no deviation in $B \to K^{(*)} \nu\bar{\nu}$ (interference vanishes)
- Similar excesses/deficits for $B \to \pi^0\, l^+ l^-$, $\rho^0\, l^+ l^-$
- Resonant production of Z' decaying to $l^+ l^-$ at LHC, and vectorlike quarks at a few TeV
- New contributions to K-$\bar{K}$ and B-$\bar{B}$ mixing
- Deviations in $Z \to \ell\ell$, CKM unitarity
- Possible lepton flavor violation, $\mu \to 3e$, $\tau \to 3l$

Resonant dileptons

$q\bar{q} \to Z' \to ll$ is constrained by ATLAS search (ATLAS-CONF-2017-027)
Our Z' has unsuppressed couplings to light quarks $\Longrightarrow$ large production cross section.



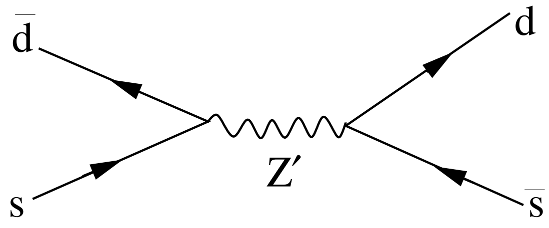
we adjust limit to compensate for smaller branching ratio into ee in our model

Requires $m_{Z'} > 4.3\,\mathrm{TeV}$, hence $g_L > 0.7$

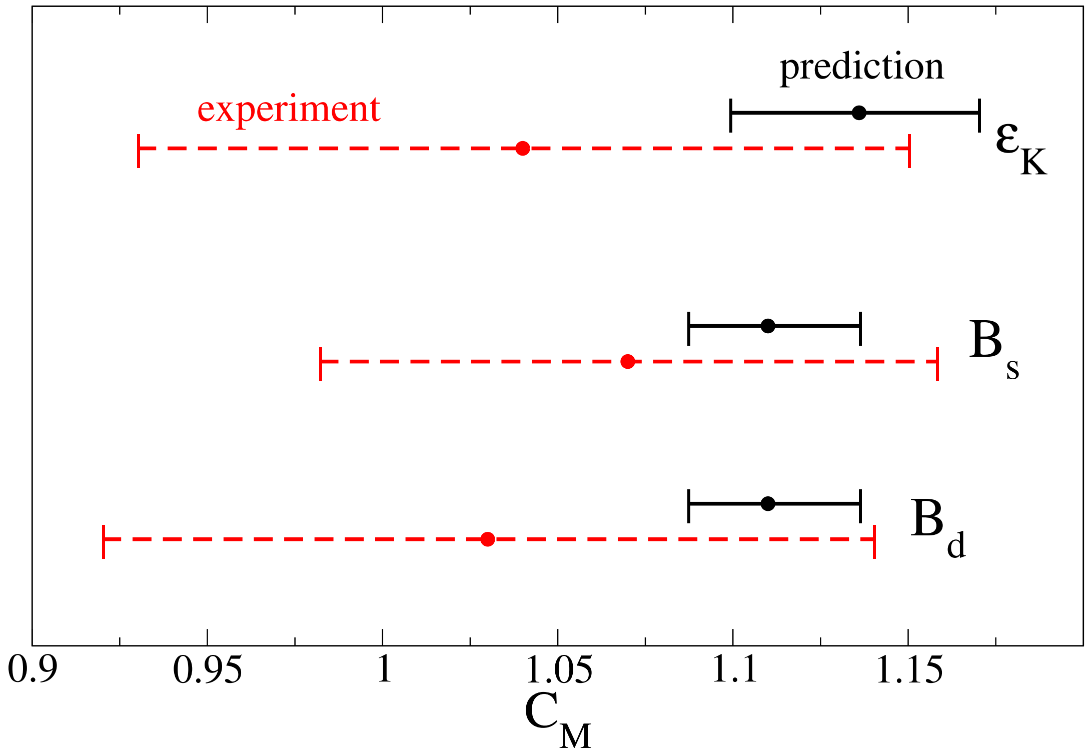
Meson-antimeson mixing

We predict new physics contribution to K-$\bar{K}$, B_d-$\bar{B}_d$, B_s-$\bar{B}_s$ mixing,

$$C_K^{NP}(\bar{s}_L\gamma^\mu d_L)^2$$



New contributions still compatible with current limits



$$C_{\varepsilon_K} = \frac{\text{Im}\langle K^0|\mathcal{H}_{\text{w}}|\bar{K}^0\rangle}{\text{Im}\langle K^0|\mathcal{H}_{\text{w}}^{\text{SM}}|\bar{K}^0\rangle}$$

$$C_{B_q} = \left|\frac{\langle B_q|\mathcal{H}_{\text{w}}|\bar{B}_q\rangle}{\langle B_q|\mathcal{H}_{\text{w}}^{\text{SM}}|\bar{B}_q\rangle}\right|$$

LHC observables

We already expect $m_{Z'} \sim \mathrm{few\ TeV}$, in reach of LHC? What about heavy fermions?

$$\mathcal{L}_{\rm yuk} \ni \lambda''_u \bar{U}_L \mathcal{M} U_R + \lambda''_d \bar{D}_L \mathcal{M} D_R + \lambda''_l \bar{E}_L \mathcal{M} E_R + \lambda''_\nu \bar{N}_L \mathcal{M} N_R$$

Since $\langle\mathcal{M}\rangle$ gives mass to Z',

$$\frac{m_{Z'}}{g_L} = \langle\mathcal{M}\rangle = 5.3\,\mathrm{TeV} \tag{1}$$

heavy fermion masses are

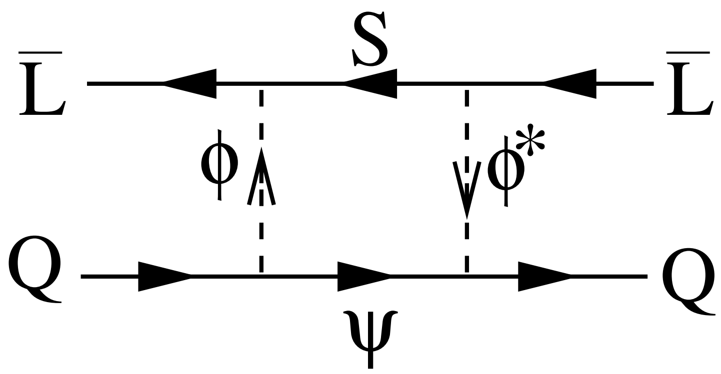
$$M_f = \lambda''_f \langle\mathcal{M}\rangle = \lambda''_f \times 5.3\,\mathrm{TeV}$$

also in reach of LHC. These are heavy vector-like quarks and leptons F, decaying to SM fermion f plus Higgs,

$$q\bar{q} \to F\bar{F} \ \ \mathrm{or}\ \ gq \to FH, \quad F \to fH$$

Part 2: B anomalies and dark matter

A simple way to get B anomaly from a loop diagram: introduce new fermions ψ, S and scalar doublet ϕ



$$\mathcal{L} = \tilde{\lambda}_f \bar{Q}_{f,a} \phi^a \Psi + \lambda_f \bar{S} \phi^*_a L^a_f$$

f = flavor index, a = $\mathrm{SU}(2)_L$ index

Couples only to LH SM fermions; induces desired operator

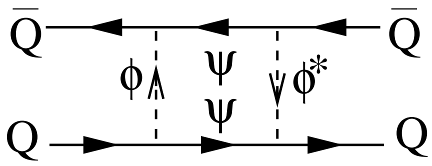
$$\mathcal{L} = -\frac{\tilde{\lambda}_2 \tilde{\lambda}_3^* \lambda_2^2}{96\pi^2 M^2} (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L) \times f_1(m_S/M)$$

where $M \sim m_\phi \sim m_\Psi \gtrsim m_S$.

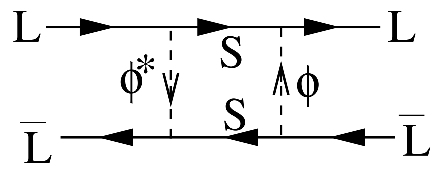
S can be neutral under SM: dark matter candidate

Challenge: flavor constraints

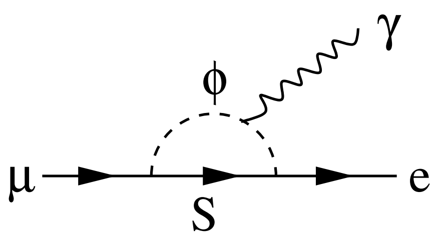
New contributions to meson mixing and flavor violating decays,



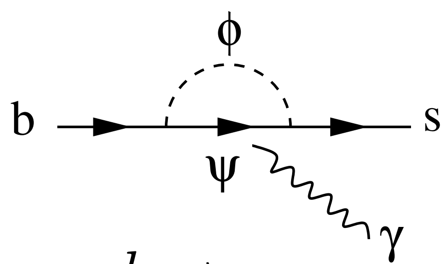
$K \leftrightarrow \bar{K},\ B \leftrightarrow \bar{B},\ B_s \leftrightarrow \bar{B}_s$



$\mu \to 3e, \quad \tau \to \ell_i \ell_j \ell_k$



$\mu \to e\gamma$



$b \to s\gamma$

In particular, $b \to s\mu^+\mu^-$ and B_s-$\bar{B}_s$ mixing both depend on $\tilde{\lambda}_{2,3}$:

$$\frac{\tilde{\lambda}_2 \tilde{\lambda}_3^* \lambda_2^2}{M^2} \cong \left(\frac{1}{1.0\,\mathrm{TeV}}\right)^2, \quad \frac{|\tilde{\lambda}_2 \tilde{\lambda}_3|}{M} \lesssim \frac{1}{1.7\,\mathrm{TeV}}$$

$$\Longrightarrow \quad |\lambda_2| > 1.3 \left(\frac{M}{\mathrm{TeV}}\right)^{1/2}$$ need largish coupling, $M \sim$ TeV

A (barely) working model

With $M = 2\,\mathrm{TeV}$ and couplings to d_i and μ,

$$\tilde{\lambda}_1 = 0.06, \quad \tilde{\lambda}_2 = -0.7, \quad \tilde{\lambda}_3 = 2.0, \quad \lambda_2 = 2.0$$

we saturate constraints on B and D meson mixing; couplings to u_i are $\tilde{\lambda}'_i = V_{CKM,ij}\,\tilde{\lambda}_j$:

$$\tilde{\lambda}'_{1,2,3} = -0.09,\ -0.65,\ \ 2.0$$

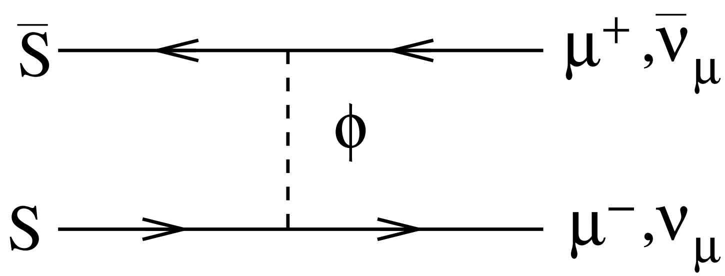
Lepton flavor violation: $\mu \to 3e$ implies $\lambda_1 < 0.3$, and

$$\mu \to e\gamma \implies \lambda_1 < 0.008$$

(Analogous $b \to s\gamma$ amplitude is 4 times smaller than upper limit)

Flavor constraints squeeze us into small (but not absurd) region of parameter space

Dark matter constraints

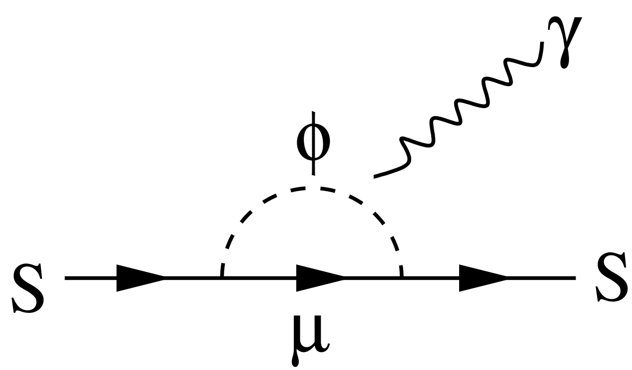


Dark matter relic density can be realized through $S\bar{S} \to \mu^+\mu^- + \nu_\mu\bar{\nu}_\mu$ annihilation in early universe.

$$\sigma v_{\rm rel} = \frac{|\lambda_2|^4\, m_S^2}{8\pi\,(m_\phi^2 + m_S^2)^2}$$

Gives correct relic density if $m_S \cong 360\,{\rm GeV}$

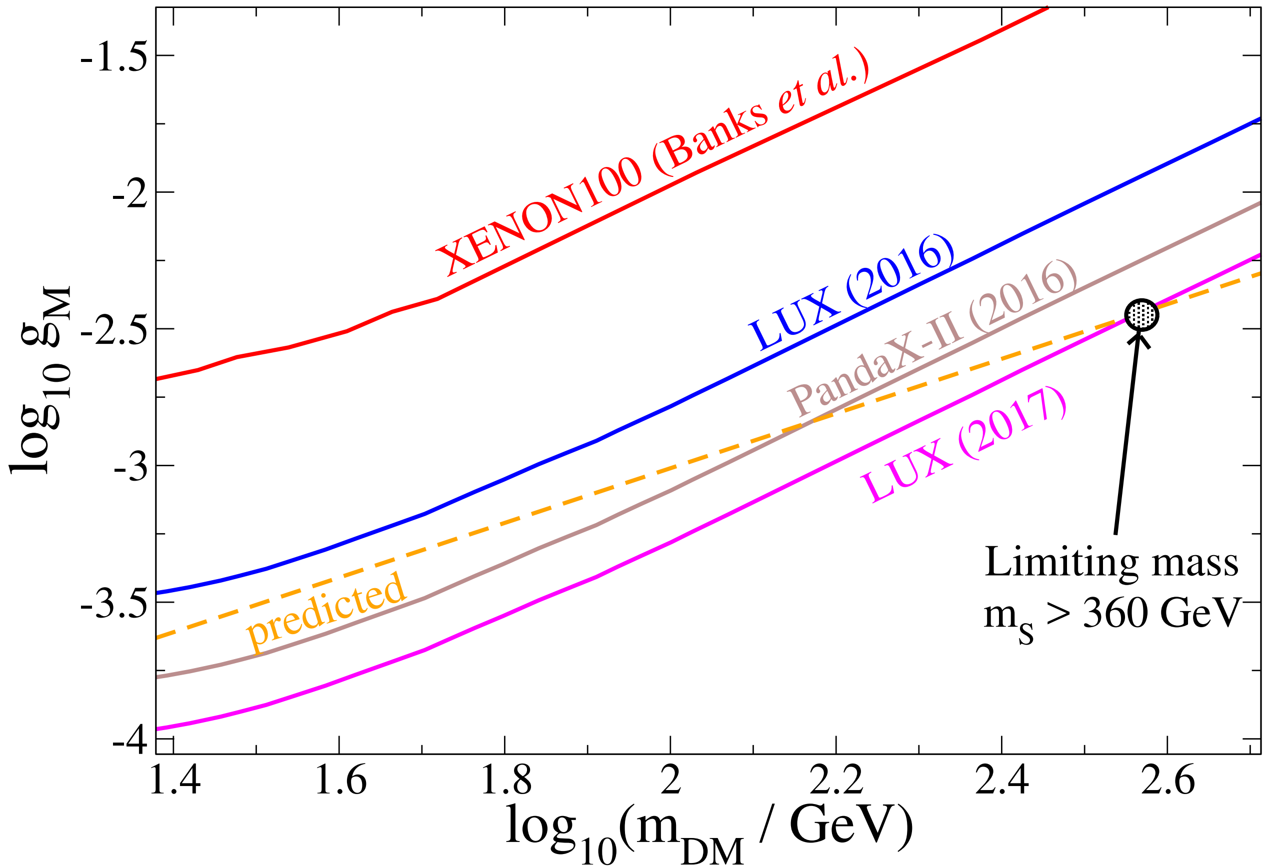
Dark matter gets a magnetic moment $\mu_S = \frac{3|\lambda_2|^2 e\, m_S}{32\pi^2\, m_\phi^2}$ from



Constrained by direct detection

Direct detection

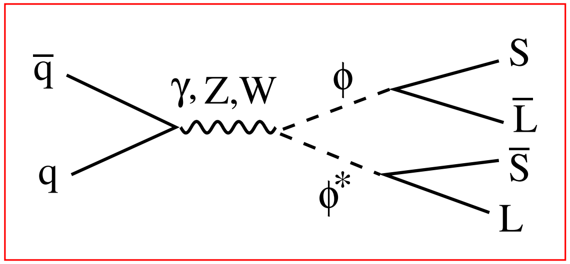
Constraint from magnetic moment interaction with protons:

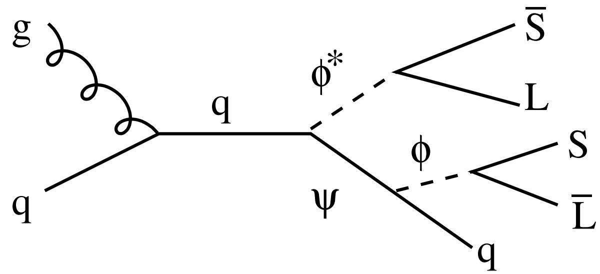


Limit is marginally satisfied for chosen parameters:
must make λ_2, $\tilde{\lambda}_3$ and m_ϕ even bigger to relax the tension.

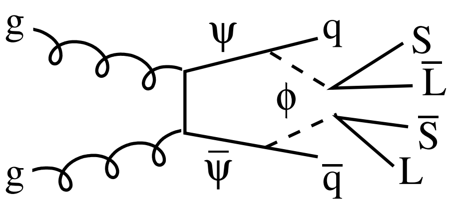
LHC constraints

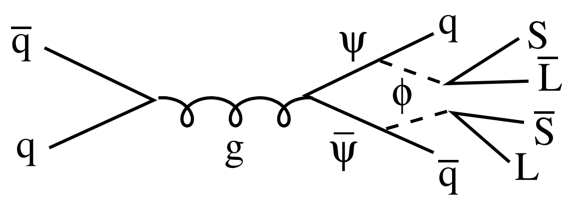
Production of new ϕ, Ψ particles necessarily gives dark matter (missing energy)

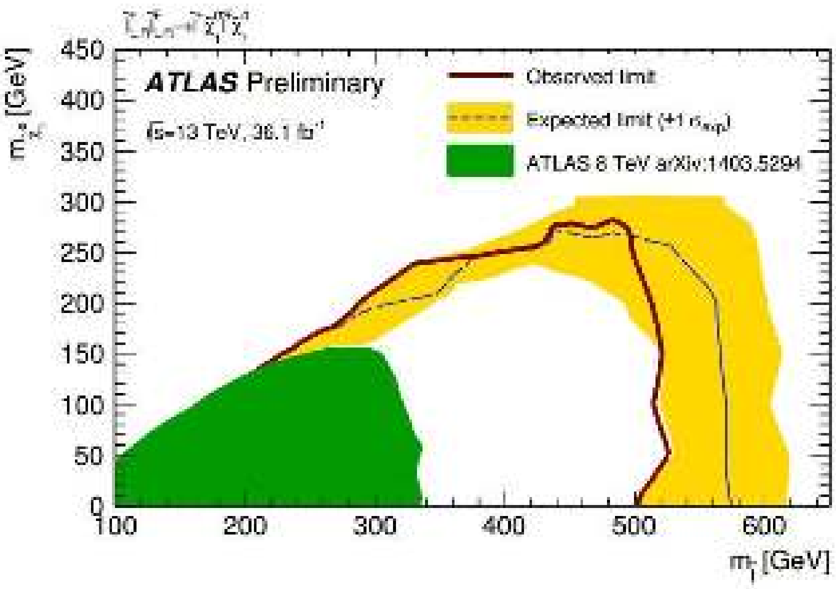




looks like sleptons!



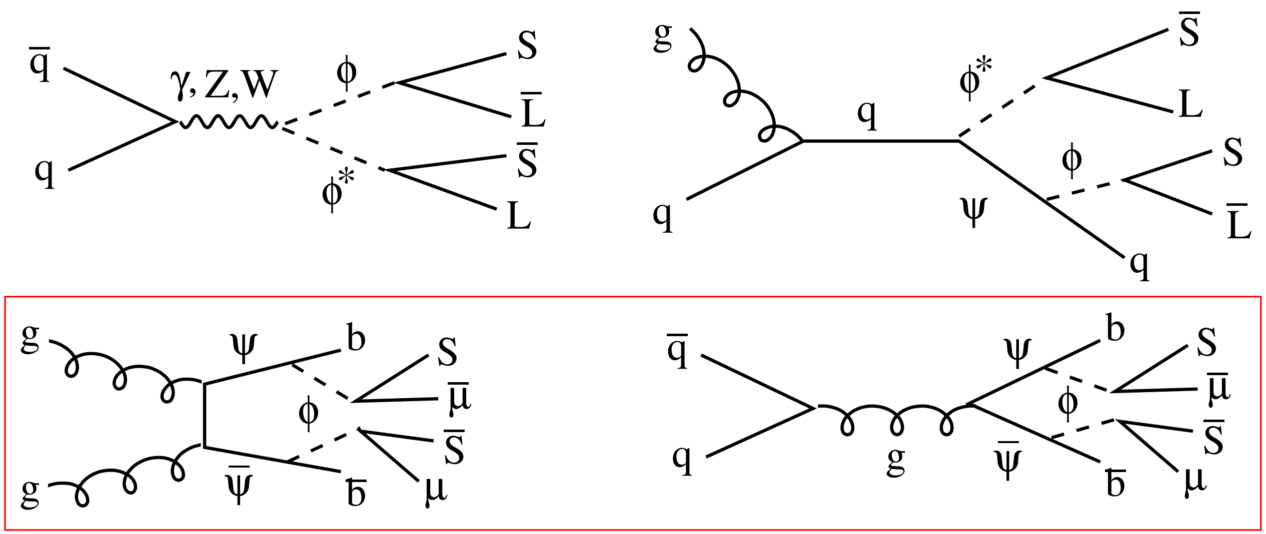




ATLAS slepton search is insensitive in our region $m_\phi = 2.4\,\mathrm{TeV}$, $m_S = 360\,\mathrm{GeV}$

LHC constraints

$\Psi \to b\mu^+ S$ resembles stop decay $\tilde{t} \to bW \to b\mu^+\nu_\mu$,



looks like stop pairs

ATLAS search must be reinterpreted to get limits . . .

A model with strong dynamics

A simple but profound elaboration:

Let ϕ, S and Ψ be charged under a confining SU(N)$_{\rm HC}$ hypercolor interaction with scale $\Lambda_{\rm HC}$:

$$\mathcal{L} \to \tilde\lambda_f\, \bar Q_{f,a}\, \phi^a_A \Psi^A + \lambda_f\, \bar S_A \phi^{*A}_a\, L^a_f$$

Integrate out ϕ and Fierz transform:

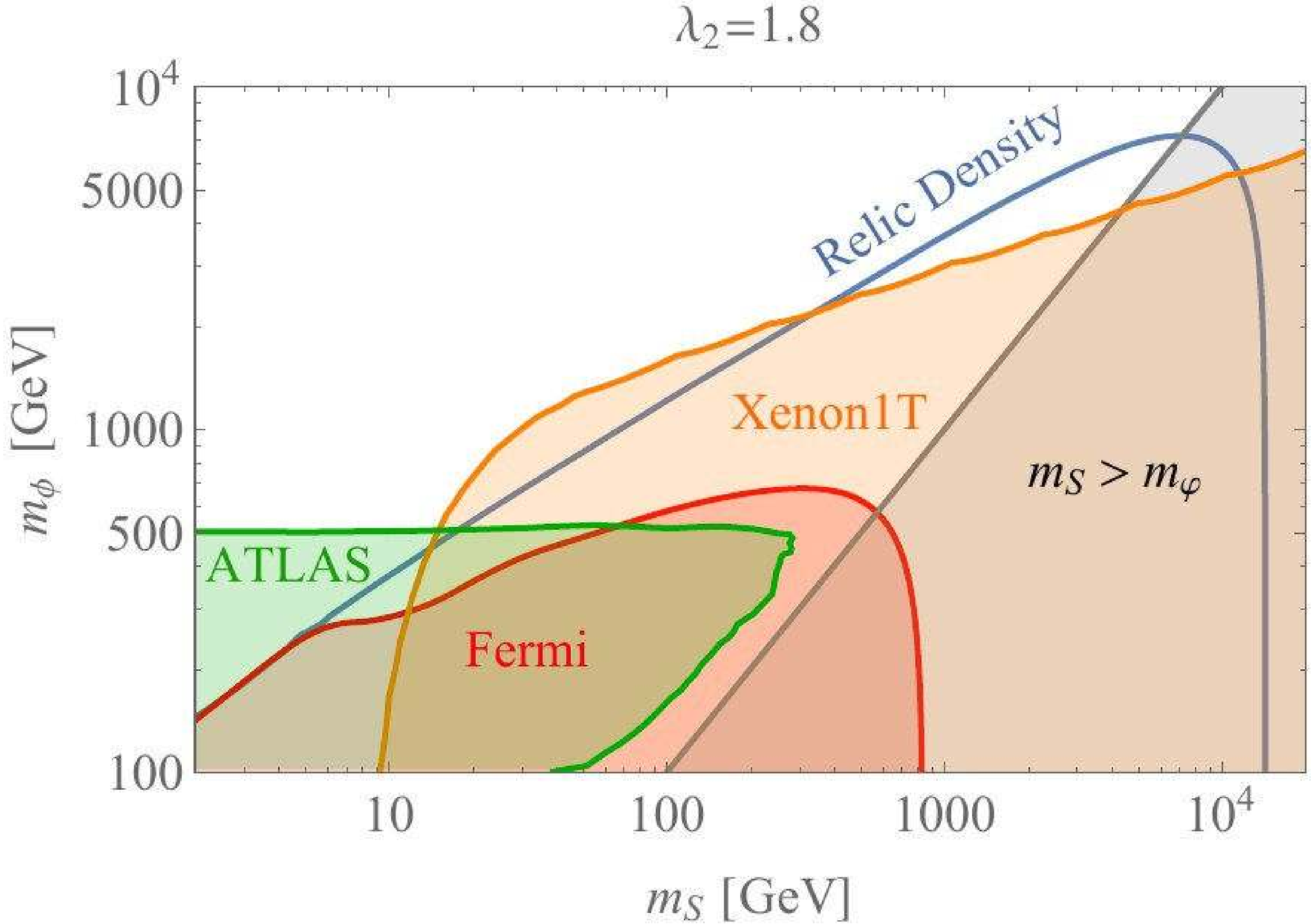
$$\frac{\tilde\lambda_f \lambda_g}{m_\phi^2 + \Lambda_{\rm HC}^2} (\bar Q_f \Psi)(\bar S L_g) = \frac{\tilde\lambda_f \lambda_g}{2\,(m_\phi^2 + \Lambda_{\rm HC}^2)} (\bar Q_f \gamma^\mu L_g)(\bar S_A \gamma_\mu \Psi^A)$$

$(\bar S \gamma_\mu \Psi)$ is interpolating field for a composite vector leptoquark!

Now we get new physics from tree-level exchange of composite particles, avoiding loop suppression factor.

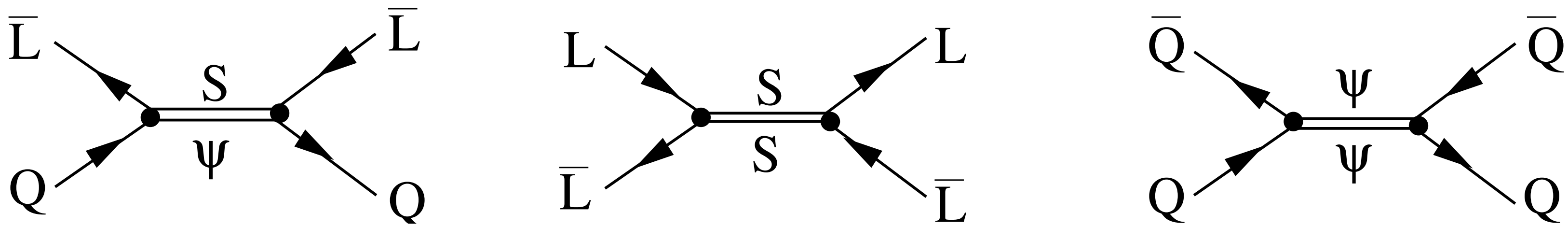
Global constraints

Direct detection dominates over ATLAS and indirect detection

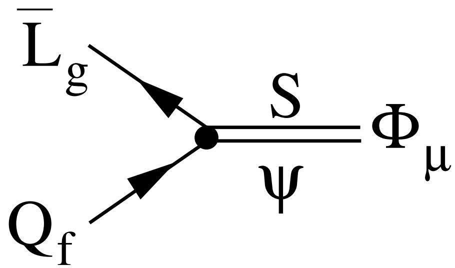


Tree-level anomalous decays

The box diagrams of previous model become tree-level exchange of different kinds vector “meson” bound states



The effective interaction is, *e.g.*,



$$\sim \frac{\tilde{\lambda}_f \lambda_g m_\Phi f_\Phi}{m_\phi^2 + \Lambda_{\rm HC}^2} \, (\bar{Q}_f \gamma^\mu L_g) \, \Phi_\mu$$

$f_\Phi \sim \Lambda_{\rm HC}$ is the vector leptoquark decay constant

Tree diagram has same structure as box diagram, with replacement

$$\frac{1}{96\pi^2} \to \frac{f_X^2 \, m_\phi^2}{4(m_\phi^2 + \Lambda_{\rm HC}^2)^2} \sim \frac{1}{16} \text{ if } m_\phi \sim \Lambda_{\rm HC}$$

Couplings can be smaller by factor ~ 3.

A robust working model

We fit B decay anomaly with $m_\phi \sim \Lambda_{\rm HC} \sim 1\,{\rm TeV}$ and

$$|\tilde\lambda_1| = 0.011, \quad |\tilde\lambda_2| = 0.14, \quad |\tilde\lambda_3| = 0.39, \quad |\lambda_2| = 0.55$$

Meson mixing amplitudes are factor of ~ 2 below experimental limits.

Lepton flavor constraints give

$$\mu \to e\gamma \implies \lambda_1 < 0.008, \qquad \tau \to 3\mu \implies \lambda_3 < 0.22$$

Couplings smaller, upper limits no longer saturated

There are also composite vectorlike heavy fermions

$$F_q = \Psi\phi^* = \text{quark partner}, \quad F_\ell = S\phi^* = \text{lepton partner}$$

that mix with SM Q and L doublets

Composite dark matter

Dark matter is the “baryonic” bound state $\Sigma = S^{N_{\rm HC}}$, previously studied

JC, Huang, Moore 1607.07865; Mitridate *et al.,* 1707.05830

Before confinement phase transition, $S\bar S \to GG$ ($G =$hypergluon), depleting relic density

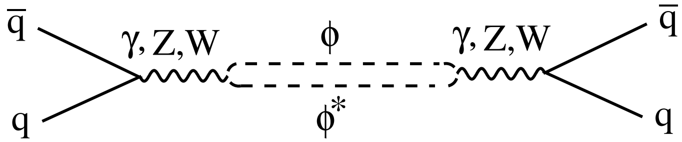
Thermal relic density too small by factor $\gtrsim 100$: need dark matter <u>asymmetry</u>

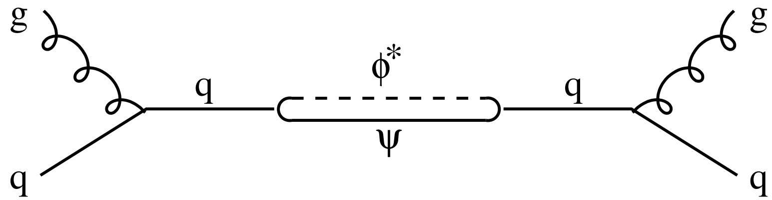
S magnetic moment μ_S from loop as before. If $N_{\rm HC}$ odd, $\mu_\Sigma \sim N_{\rm HC}\,\mu_S$, while $m_\Sigma \sim N_{\rm HC}\,\Lambda_{\rm HC}$ (quark model). Direct detection constraint weakened:

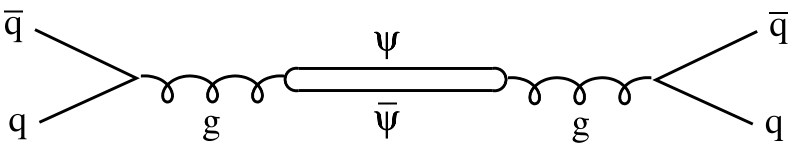
$$m_S < 500\,{\rm GeV}\ \ \text{if}\ \ N_{\rm HC} = 3,\ \ m_\phi = m_\Sigma = {\rm TeV}$$

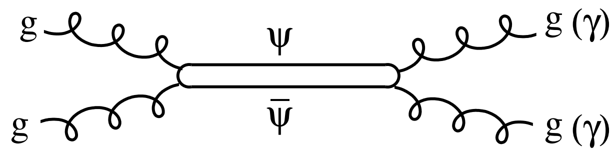
LHC constraints

Dominant signal is resonant production of bound state vector and pseudoscalar “mesons” or quark partner









Constrained by LHC searches for dijets, diphotons

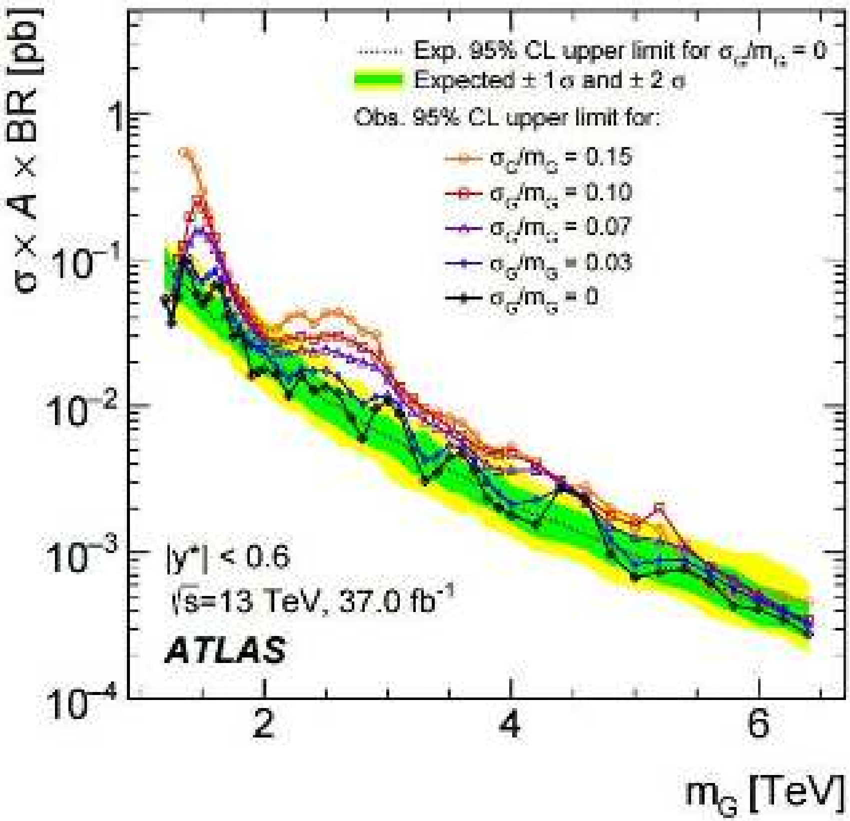
E.g., $V = \Psi\bar{\Psi}$ bound state is like quarkonium,

$$\sigma(q\bar{q} \to V) = \frac{132\pi^2\alpha_s^2|\psi(0)|^2}{9\,m_V^3}\,\delta(s - m_B^2)$$

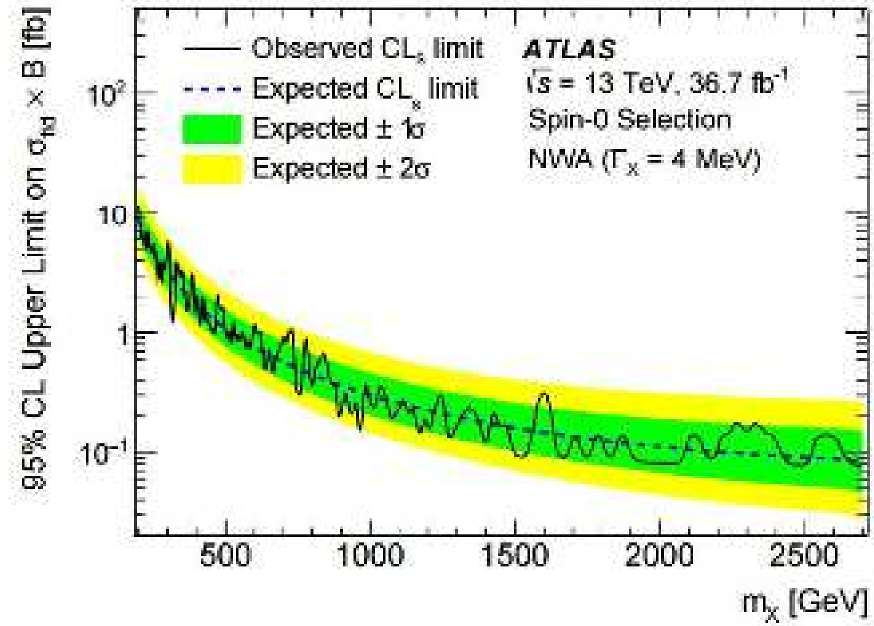
with $|\psi(0)|^2 \sim m_V \Lambda_{\rm HC}^2$, and

$$\sigma(pp \to V) = \frac{132\pi^2\alpha_s^2\Lambda_{\rm HC}^2}{9\,s\,m_V^2}\,\mathcal{L}_{\rm parton} \cong 9\,{\rm fb} \lesssim \text{ATLAS limit}$$

Dijet and diphoton limits



Dijet limit allows $m_V \lesssim 3\,\mathrm{TeV}$ for vector "meson"



Pseudoscalar P production cross section is

$$\sigma(pp \to P) = \frac{\pi^2 \Gamma(P \to gg)}{8 s m_P} \mathcal{L}_{\rm parton} \cong 0.02\,\mathrm{pb \ for}\ m_P = 1\,\mathrm{TeV}$$

and $B(P \to \gamma\gamma) = 0.006$, so $\sigma B = 0.1\,\mathrm{fb}$, $<$ diphoton limit

Conclusions

- B decay anomalies seem the best current hope of new physics
- If true, we may hope that the underlying theory explains more than just the $R_K^{(*)}$ observations
- Our examples hint that new heavy states may be soon discovered at LHC:
  - resonant Z' in dileptons
  - vectorlike quark or lepton partners
  - composite resonances in dijets
  - $\ldots ?$