B decay anomalies and dark matter from strong dynamics

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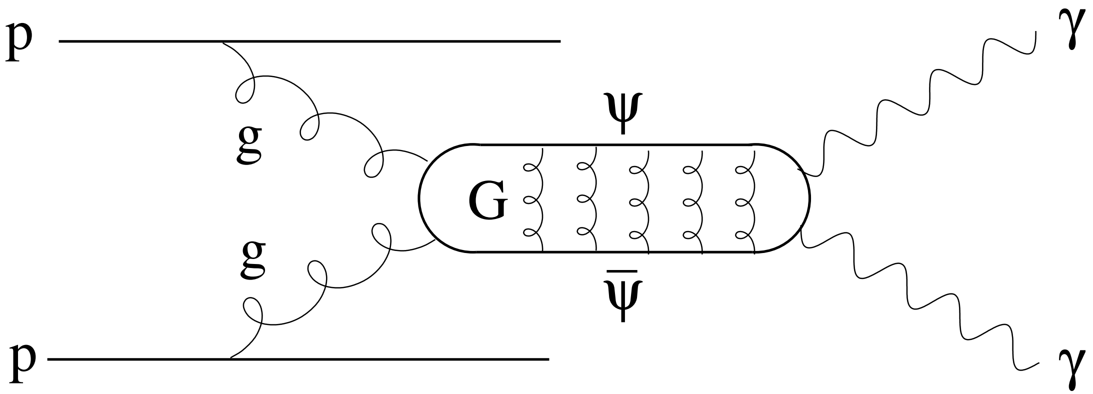
LFC17, Trento, 15 Sept. 2017

Strong dynamics beyond the SM

SU(3)$_c$ exists in nature; why not an additional SU(N)$_{hc}$ (hypercolor) at a higher scale?

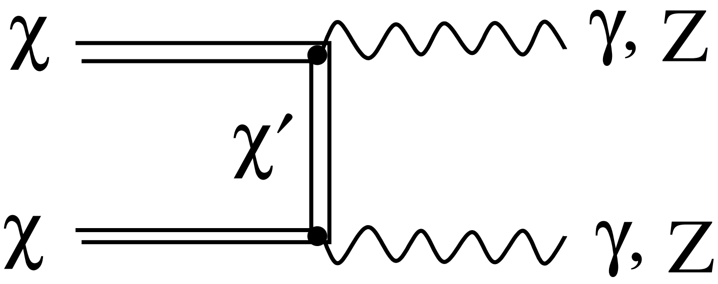
Need not be composite Higgs (technicolor), could be unconnected to electroweak symmetry breaking

Has proven useful for “explaining” past anomalies . . .



resonant 750 GeV diphotons at LHC

Craig, Draper, Kilic, Thomas 1512.07733 + many others



annihilation of partially composite DM to photons (Fermi 130 GeV anomaly)

JC, Frey, Moore 1208.2685

Strong dynamics beyond the SM

And dark matter model-building in a hidden sector:

- glueballs

  Forestell, Morrissey, Sigurdson, 1605.08048;
  Sony, Zhang, 1602.00714, 1610.06931, + Xiao 1704.02347;
  Acharya, Fairbairn, Hardy 1704.01804; Halverson, Nelson, Ruehle, 1609.02151

- mesons

  Lewis, Pica, Sannino 1109.3513; + Hietanen 1308.4130
  Hietanen, Pica, Sannino, Sondergaard 1211.0142, 1211.5021
  JC, Liu, Moore,1312.3325

- baryons

  Lattice Strong Dynamics (LSD) Collaboration, 1402.6656, 1301.1693
  Antipin, Redi, Strumia, Vigiani, 1503.08749
  Huo, Matsumoto, Tsai, Yanagida,1506.06929
  Fodor, Holland, Kuti, Mondal, Nogradi, Wong 1601.03302
  JC, Huang, Moore 1607.07865; Mitridate, Redi, Smirnov, Strumia 1707.05380

Partly motivated by cosmological hints of strong DM self-interactions, natural in composite models

New anomaly: $B \to K^{(*)}\mu^+\mu^-$ vs. 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	$0.745 \pm 0.09 \pm 0.036$	$0.660^{+0.110}_{-0.070} \pm 0.024$	$0.685^{+0.113}_{-0.069} \pm 0.047$

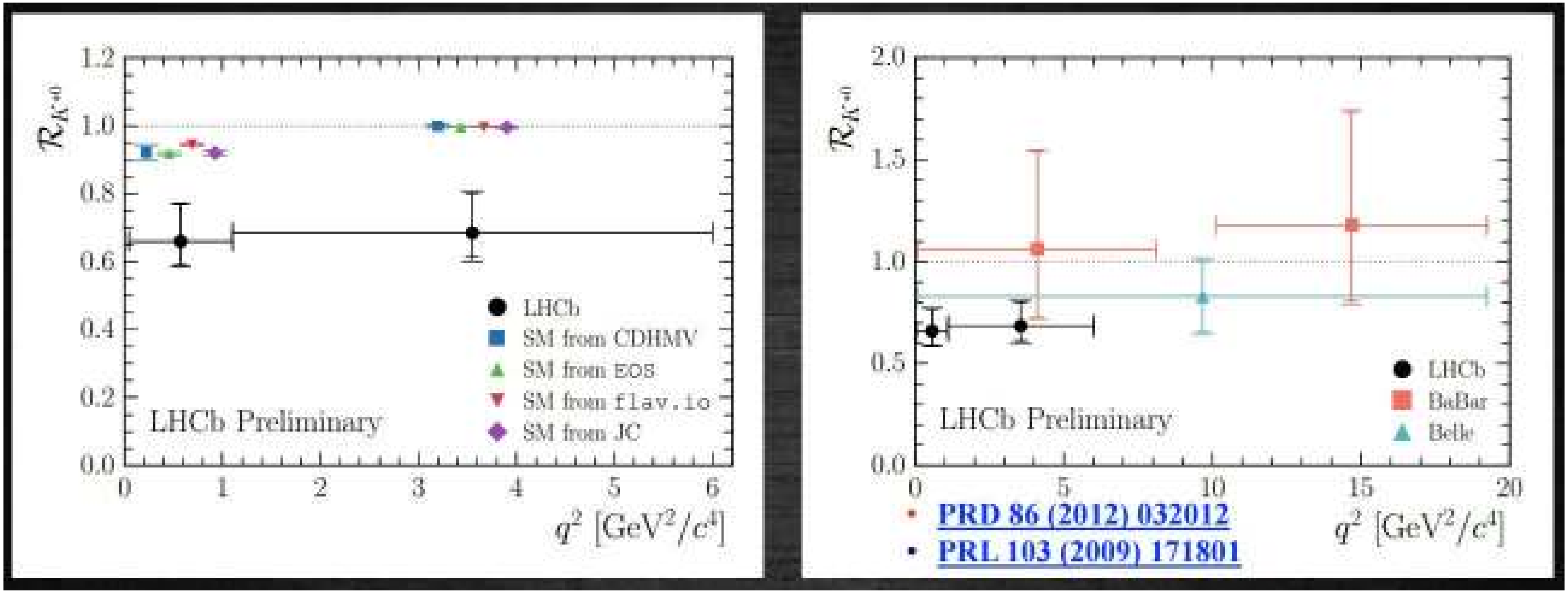
Correlated anomalies also seen in ‘dirty’ observables,

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

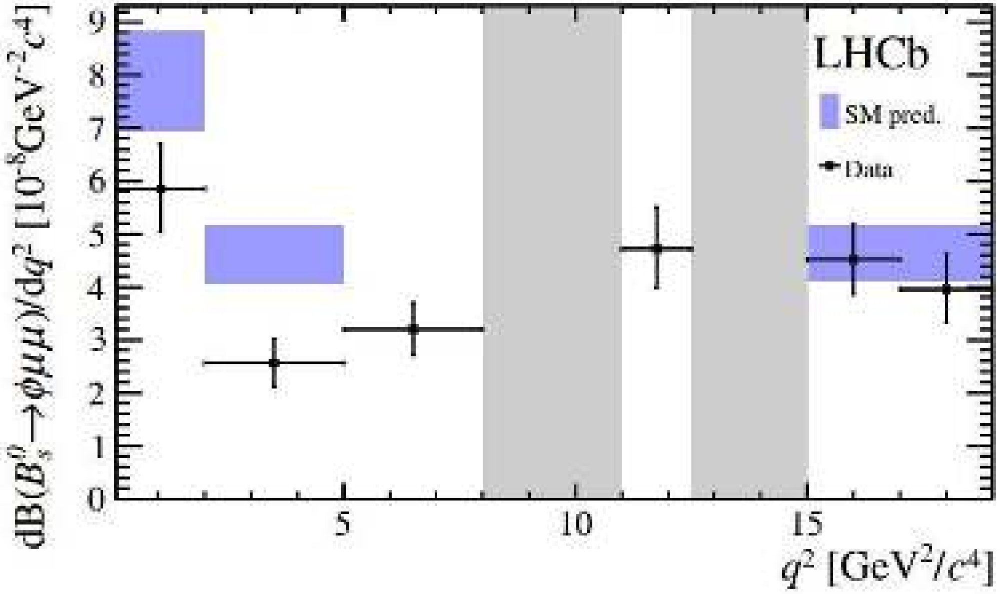
and

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

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



- PRD 86 (2012) 032012
- PRL 103 (2009) 171801



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

Model-independent fit

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

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

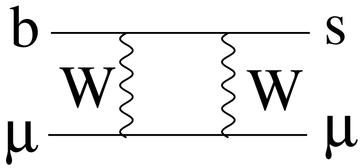
gives a good fit to the data, with $\Lambda \cong 36\,\mathrm{TeV}$.
Should be $\cong -0.15 \times (\mathrm{SM\ contribution})$. 4σ significance

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

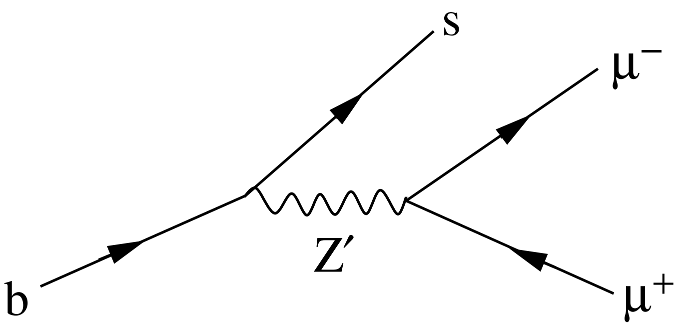
$$\mathcal{O}_{b_L\mu_L} \to -\frac{1}{\Lambda^2}(\bar{s}_L\gamma_\alpha\mu_L)(\bar{\mu}_L\gamma^\alpha s_L)$$

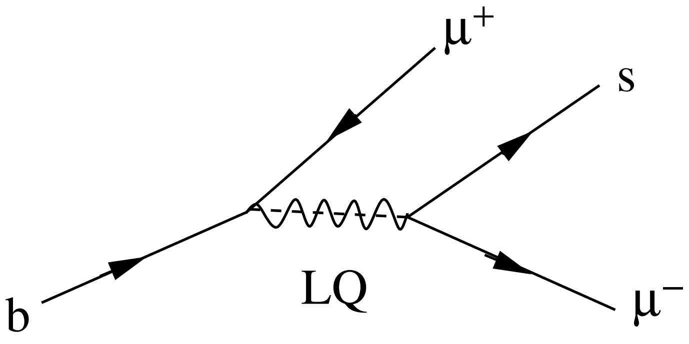
shows that vector leptoquark exchange also works.

SM contribution comes at one loop;
sensitive probe of new physics

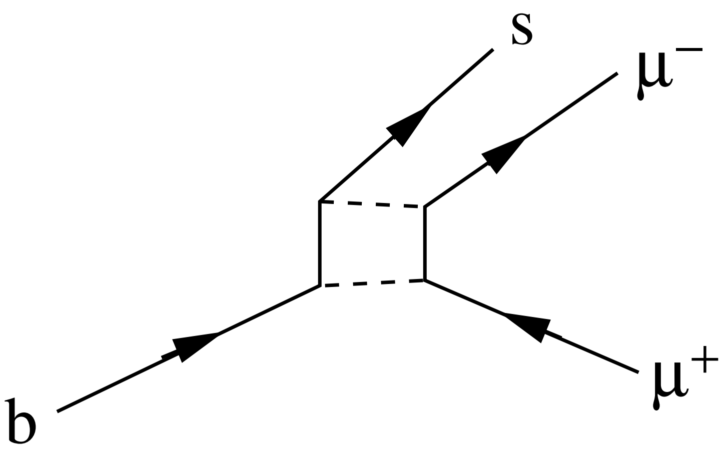


Popular models: Z' or leptoquark





or via new physics in loop



In this talk I present a model with composite leptoquark and dark matter, and new strong dynamics at the TeV scale

A simple model with strong dynamics

New particles: vectorlike quark partner Ψ, RH neutrino partner S, inert Higgs doublet ϕ, charged under SU(N)$_{\rm HC}$ and accidental Z_2:

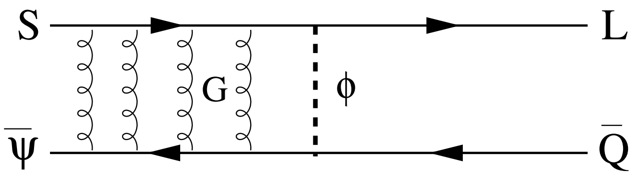
	SU(3)	SU(2)$_L$	U(1)$_y$	U(1)$_{\rm em}$	SU(N)$_{\rm HC}$	Z_2
Ψ	3	1	$2/3$	$2/3$	N	-1
S	1	1	0	0	N	-1
ϕ	1	2	$-1/2$	$(0,-1)$	$\bar N$	-1

⇐ dark matter!

Couplings to SM left-handed quarks and leptons:

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

$\bar\Psi S$ bound state is composite leptoquark, pseudoscalar Π or vector Φ_μ,

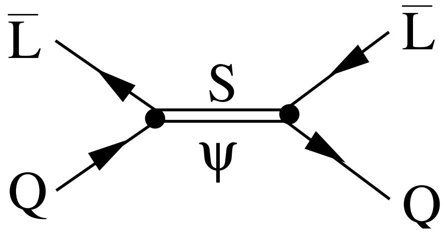


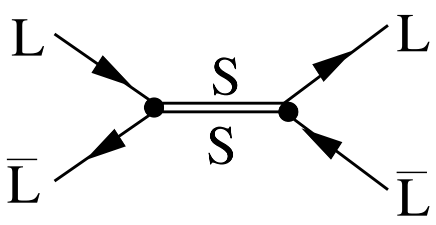
$$\langle 0|(\bar S\gamma_\mu\gamma_5\Psi)|\Pi\rangle = f_\Pi\, p^\mu_\Pi, \qquad \langle 0|(\bar S\gamma_\mu\Psi)|\Phi_\lambda\rangle = f_\Phi\, m_\Phi \epsilon^\mu_\lambda$$

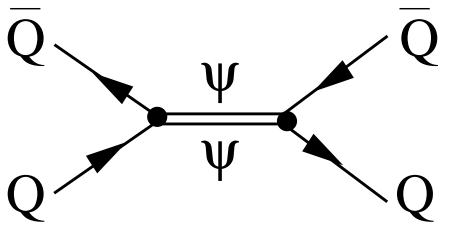
Pseudoscalar couplings to quarks and leptons are suppressed by m_q or m_l, only vector can couple more strongly.

Composite-induced anomalous decays

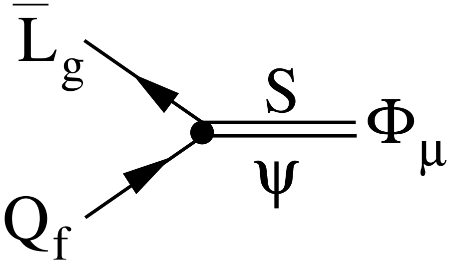
Besides leptoquark, we get other composite vectors mediating flavor-changing neutral currents







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



$$= \underbrace{\left(\frac{N_{\rm HC}}{m_\Phi}\right)^{1/2} c_{\rm loop}\,\frac{\tilde\lambda_f\lambda_g\, M\psi(0)}{(m_\phi^2+M^2)}}_{g_\Phi}\,(\bar Q_f\gamma^\mu L_g)\,\Phi_\mu$$

where $M = m_\Psi \gtrsim m_S$ and ψ = wave function of bound state

To fit B-decay anomaly, need

$$c_{\rm loop}\, N_{\rm HC}\, |\lambda_2^2\tilde\lambda_2\tilde\lambda_3|\,\frac{|\psi(0)|^2}{m_\Phi^3}\,\frac{M^2}{(m_\phi^2+M^2)^2} = \frac{1\times 10^{-3}}{\rm TeV^2}$$

Leptoquark coupling to L and Q

Effective coupling g_Φ can be inferred from decay rate of bound state $\Phi_\mu \to L\bar{Q}$ (Kang, Luty 0805.4642)

$$\Gamma(\Phi_\mu \to L\bar{Q}) = \sigma v_{\rm rel}(S\bar{\Psi} \to L\bar{Q})|\psi(0)|^2 c_{\rm loop} = \frac{g_\Phi^2}{24\pi} m_\Phi$$

To compute bound state mass m_Φ and wave function at origin $\Psi(0)$, need model of confinement.

We take nonrelativistic $-1/r + r$ potential

$$V_c = -\frac{\alpha_{\rm HC}}{2r}\left(N_{\rm HC} - \frac{1}{N_{\rm HC}}\right) + 2(N_{\rm HC} - 1)\Lambda_{\rm HC}^2\, r$$

and hydrogen-like ansatz $\psi \sim e^{-\mu_* r/2}$.

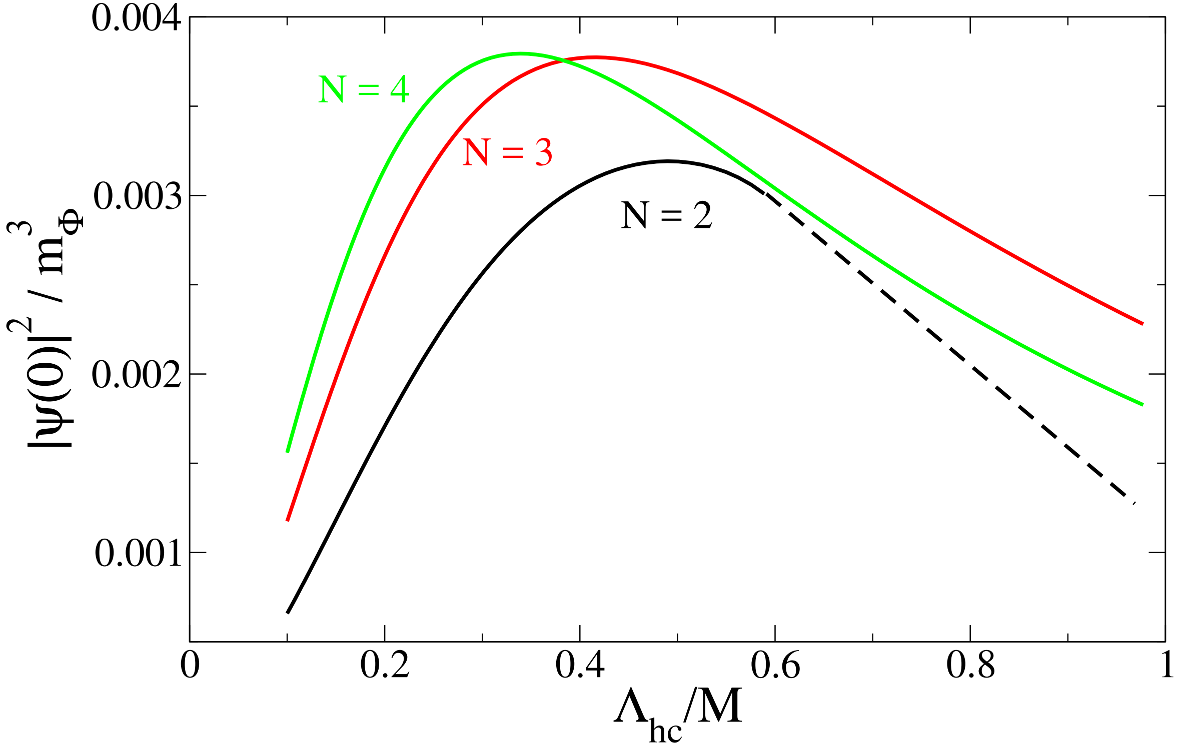
Minimize energy, find μ_* and binding energy E_b in terms of $\Lambda_{\rm HC}$ and constituent mass m.

Wave function at origin $= \psi(0) = \mu_*^{3/2}/\sqrt{8\pi}$.
Bound state mass $= m_\Phi = 2M + E_b$.
Works quite well for J/Ψ!

Nonperturbative input

All nonperturbative physics in effective coupling is in a dimensionless function of $\Lambda_{\rm HC}/M$:

$$\frac{|\psi(0)|^2}{m_\Phi^3} = f(\Lambda_{\rm HC}/M)$$



Optimized near
$\Lambda_{\rm HC} = 0.4\, M$
if $N_{\rm HC} = 3$.

Then $$|\lambda_2^2 \tilde\lambda_2 \tilde\lambda_3| = 0.29 \left(\frac{M}{700\,{\rm GeV}}\right)^2 \left(\frac{m_\phi^2 + M^2}{2M^2}\right)^2$$

A working model

We can fit B decay anomaly with

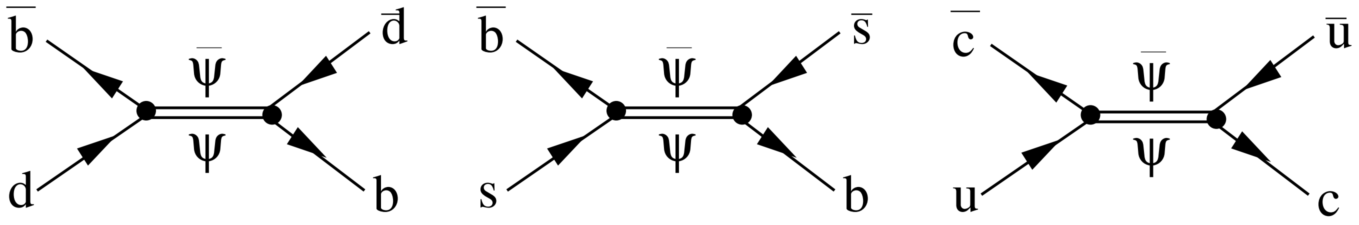
$$m_\psi \cong m_\phi \cong m_S \cong 2.5\Lambda_{\rm HC} \cong 700\,{\rm GeV}$$

and

$$\tilde\lambda_1 = 0.022, \quad \tilde\lambda_2 = -0.29, \quad \tilde\lambda_3 = 0.80, \quad |\lambda_2| = 1.08$$

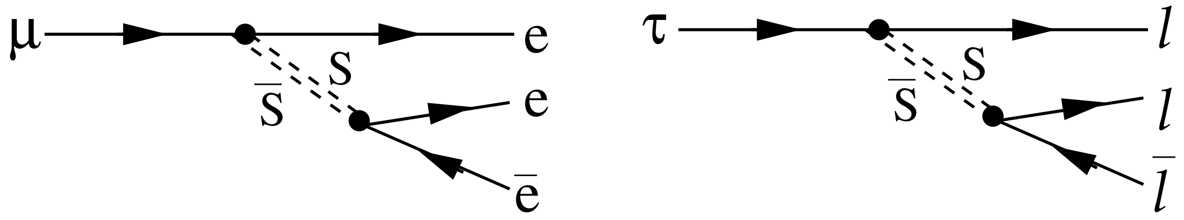
There is no flavor protection mechanism, FCNCs are large.

Contributions to B^0-$\bar B^0$, B^0_s-$\bar B^0_s$, D^0-$\bar D^0$ mixing amplitudes



are factor ~ 2 below experimental limits.

Lepton-flavor violating decays



require

$$|\lambda_1| < 0.13, \qquad |\lambda_3| < 1.7$$

FCNC Radiative decays

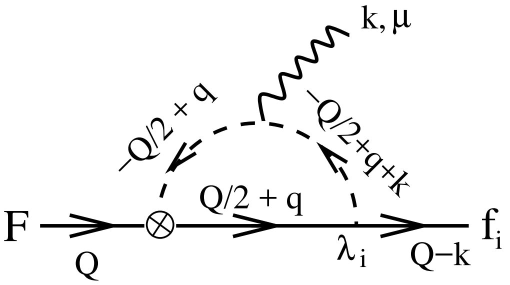
Radiative transitions $\mu \to e\gamma$, $b \to s\gamma$ are induced by heavy composite fermions,

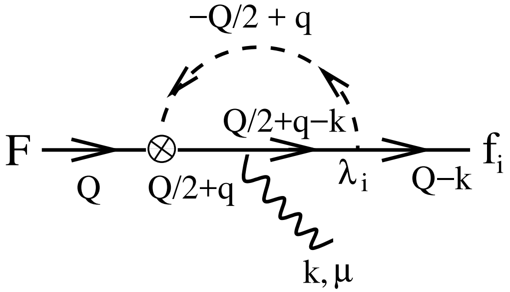
$$F_l = S\phi \text{ (lepton partner)} \;\;\&\;\; F_q = \Psi\phi \text{ (quark partner)}$$

They have mass-mixing with SM quarks and leptons,

$$\tilde\lambda_f \bar Q_{f,a}\, \phi^a \Psi + \lambda_f \bar S \phi^*_a\, L^a_f \quad \to \quad \frac{\psi(0)}{\sqrt{M}} \left(\tilde\lambda_f \bar Q_f F_q + \lambda_f \bar F_\ell L_f \right)$$

And they have transition magnetic moments with SM quarks and leptons, (Guberina, Kühn, Peccei, Rückl 1980)





Mass diagonalization induces FCNC transition moments

Transition magnetic moments

We find transition moments for the SM fermions

$$e q_f \frac{\overset{(\sim)}{\lambda}_i \overset{(\sim)}{\lambda}_j |\psi(0)|^2 m_f^j}{2\, M\, M_F^4} (\bar{f}_{L,i}\, \sigma_{\mu\nu} f_{R,j}) F^{\mu\nu}$$

$b \to s\gamma$ amplitude is factor of 10 below experimental limit

$\mu \to e\gamma$ limit implies $\lambda_1 < 10^{-3}$.

Contribution to muon anomalous magnetic moment

$$(g-2)_\mu = 2 \frac{m_\mu^2 |\lambda_2|^2 |\psi(0)|^2}{M\, M_F^4} = 4 \times 10^{-11}$$

is too small to explain outstanding discrepancy.

Composite dark matter

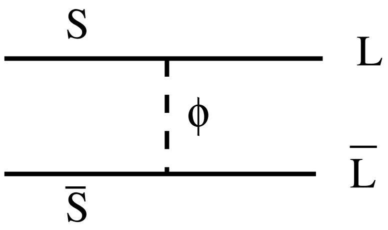
Vectorlike confinement generically produces a stable relic—the lightest particle charged under SU(N)$_{\rm HC}$

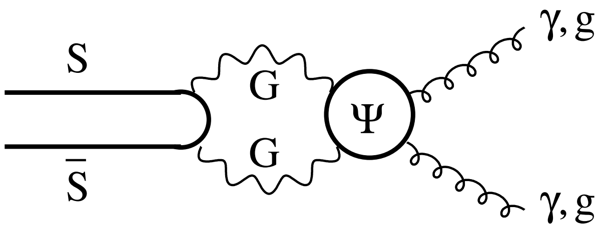
JC, Huang, Moore 1607.07865: better make it neutral under SM quantum numbers or we have problematic charged relic.

Even if electrically neutral, color or SU(2)$_L$ charge typically ruled out by direct dark matter searches.

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

(Pion-like $S\bar S$ meson can decay to $\mu\bar\mu$, gg, $\gamma\gamma$)

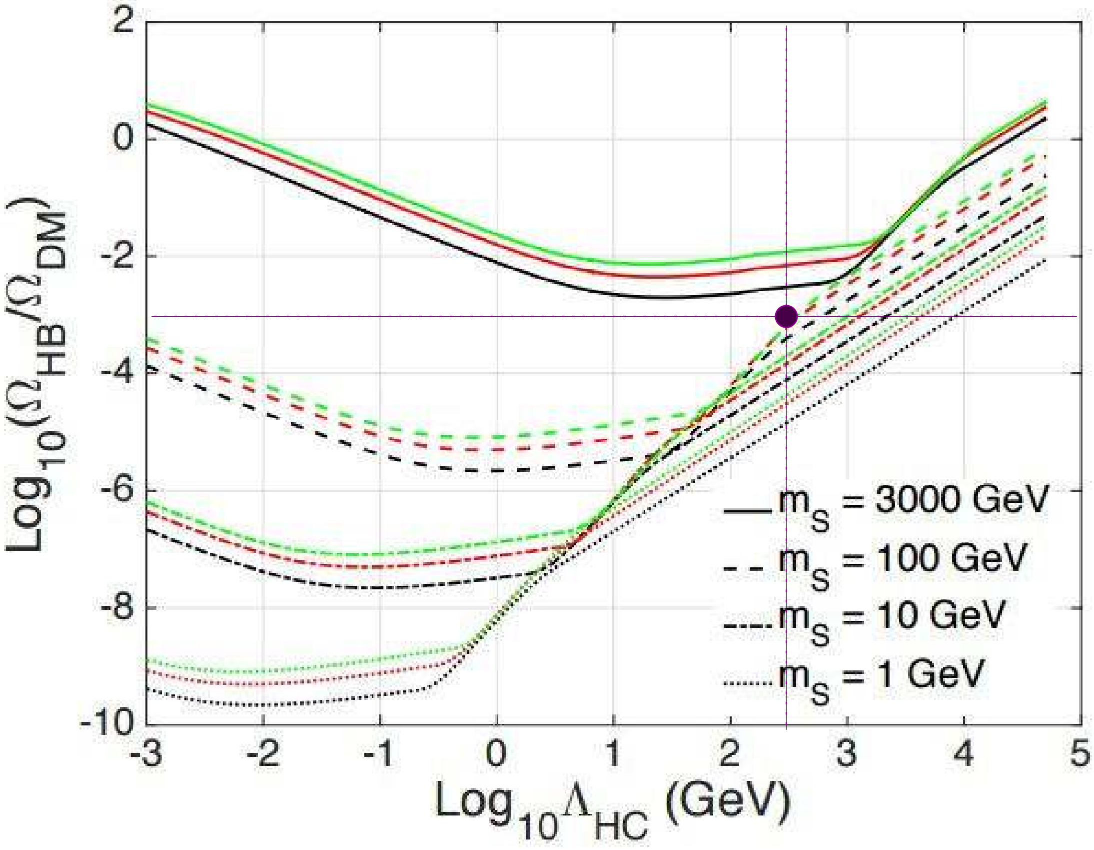




Dark matter relic density

Cosmology of “baryonic” bound states was studied in

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



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

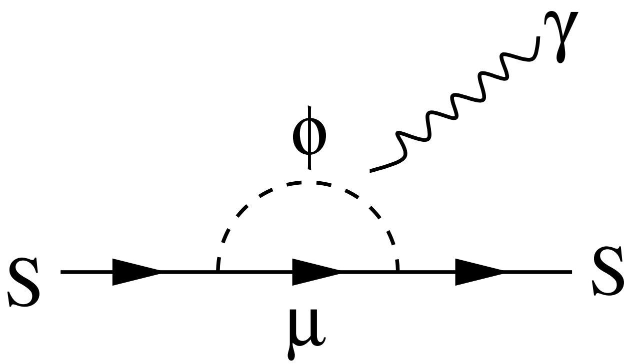
Thermal relic density too small by factor $\gtrsim 1000$: need dark matter asymmetry

We do not specify the mechanism for getting an asymmetry

(after all, origin of baryon asymmetry is unknown)

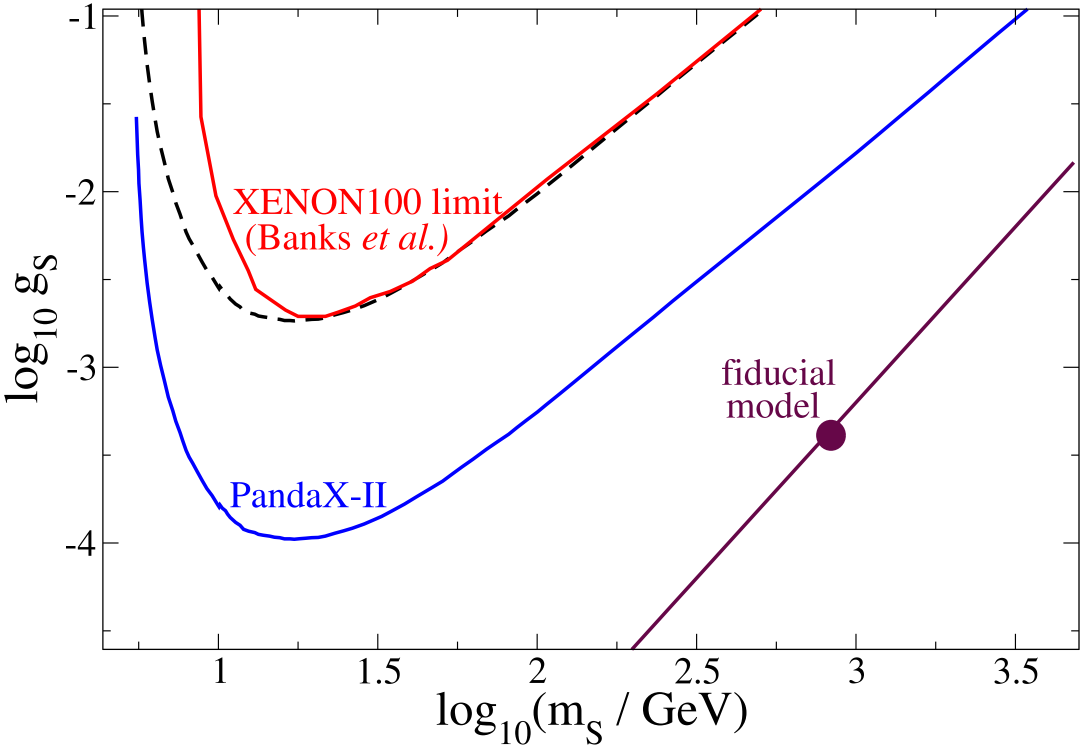
Direct detection

S gets a magnetic moment μ_S at one loop:



$$\mu_S = \frac{e|\lambda_2|^2 m_S}{64\pi^2 m_\phi^2}$$

Direct detection constraint on gyromagnetic ratio:

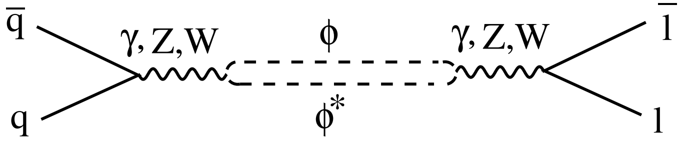


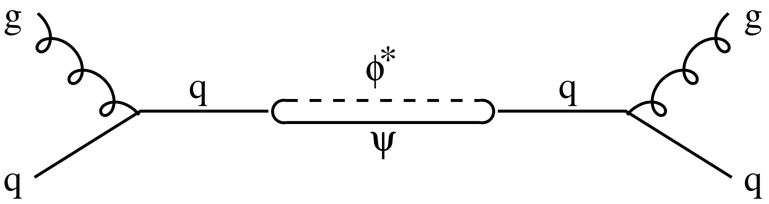
If $N_{\rm HC}$ odd, $\mu_\Sigma \sim N_{\rm HC}\,\mu_S$, while

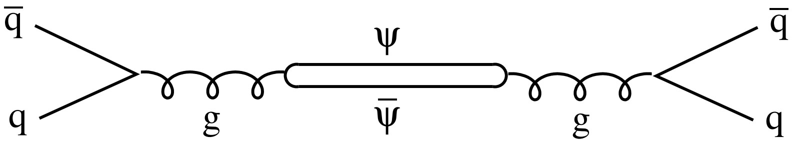
$m_\Sigma = 3\,m_S + E_b \cong 4.2\,\mathrm{TeV}$

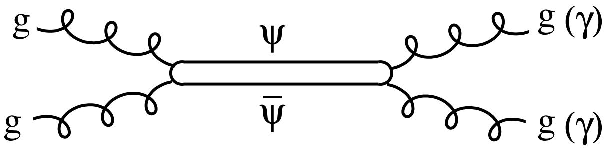
LHC constraints

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









Probed by LHC searches for dijets, diphotons

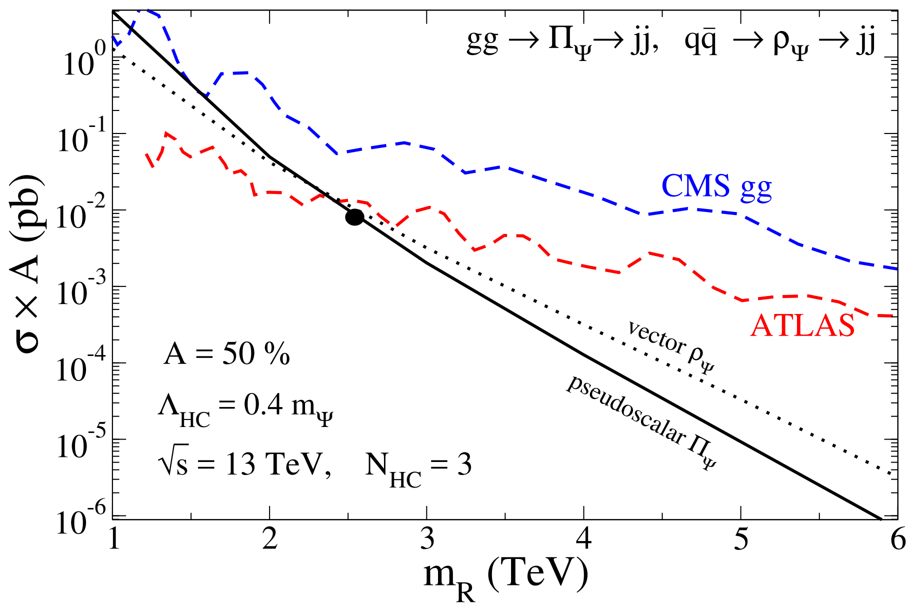
E.g., $\rho_\Psi = \Psi\bar{\Psi}$ bound state is like quarkonium,

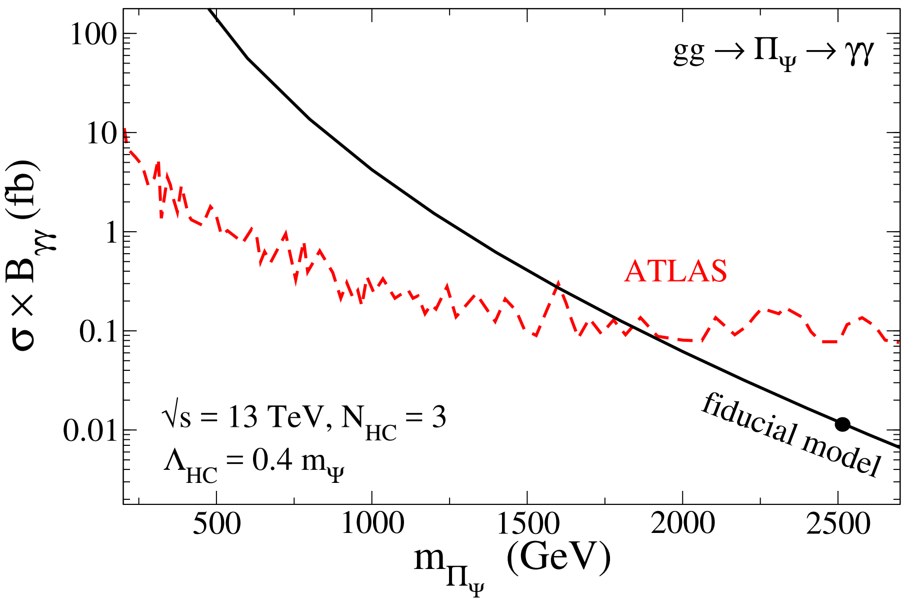
$$\sigma(q\bar{q} \to \rho_\Psi) = N_{\rm HC}\frac{64\pi^3\alpha_s^2|\psi(0)|^2}{3\,m_{\rho_\Psi}^3}\,\delta(s - m_B^2)$$

hence

$$\sigma(pp \to \rho_\Psi) = N_{\rm HC}\frac{64\pi^3\alpha_s^2\Lambda_{\rm HC}^2}{3\,s\,m_{\rho_\Psi}^2}\,\mathcal{L}_{\rm parton}$$

Dijet and diphoton limits





Bound state masses must exceed $2.3\,\mathrm{TeV}$

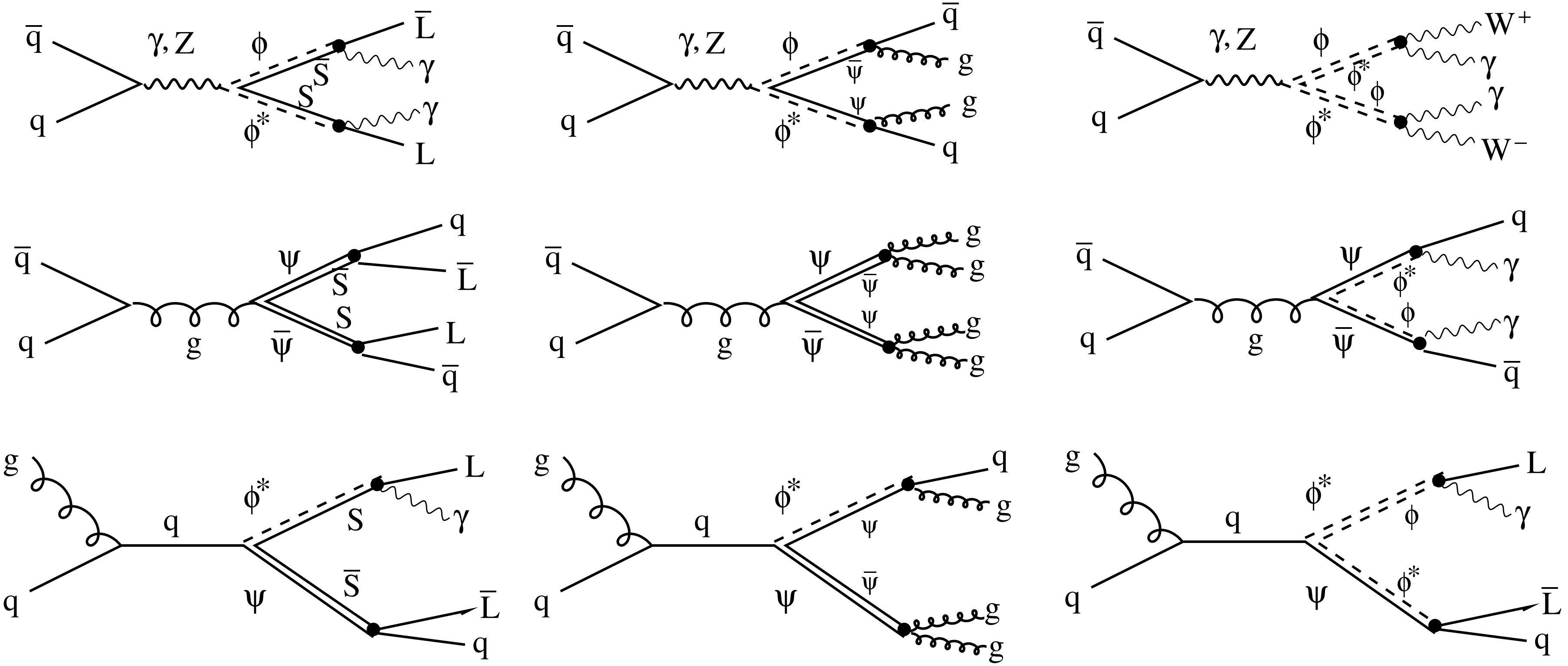
Larger masses will push up the couplings as

$$\overset{(\sim)}{\lambda}_i \sim \sqrt{M}$$

to fit B anomaly.

Pair production at LHC

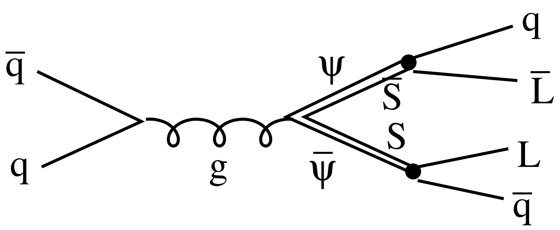
Besides resonant production, pair production could be relevant

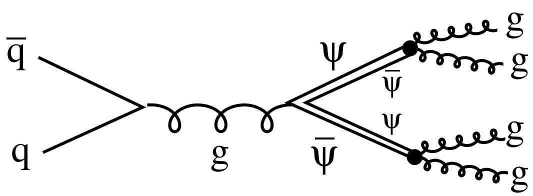


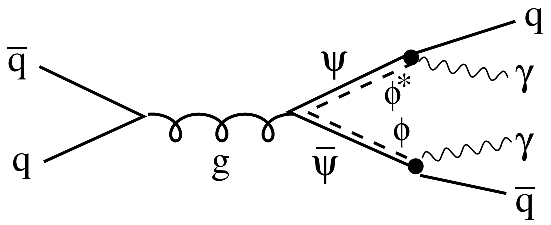
Need not be suppressed by wave function at origin since hadronization must occur following production of hypercolored constituents

Pair production at LHC

However cross section is very small; consider $q\bar{q} \to \Psi\bar{\Psi}$



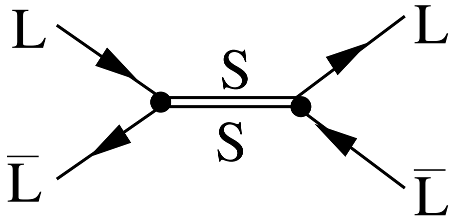




If $m_S \cong m_\phi \cong m_\Psi$, $M_{\rm res} = 2.5\,{\rm TeV}$, $\sqrt{s} = 13\,{\rm TeV}$,

$$\sigma(pp \to \Psi\bar{\Psi}) \sim 0.01\,{\rm fb}$$

Can be made larger by taking $m_S \ll m_\phi, m_\Psi$, but then LFV constraints become stronger,



requiring $\lambda_1 \ll 10^{-3}$.

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 example suggests that other flavor observables could be close to showing new anomalies
- It also contains new states with mass $\lesssim 3\,\mathrm{TeV}$ that could be accessible at LHC
- Nonperturbative studies of vectorlike confinement would be welcome for sharpening predictions. Lattice collaborations, opportunity for new models to explore