# $B$ decay anomalies and dark matter from strong dynamics

Jim Cline, McGill University

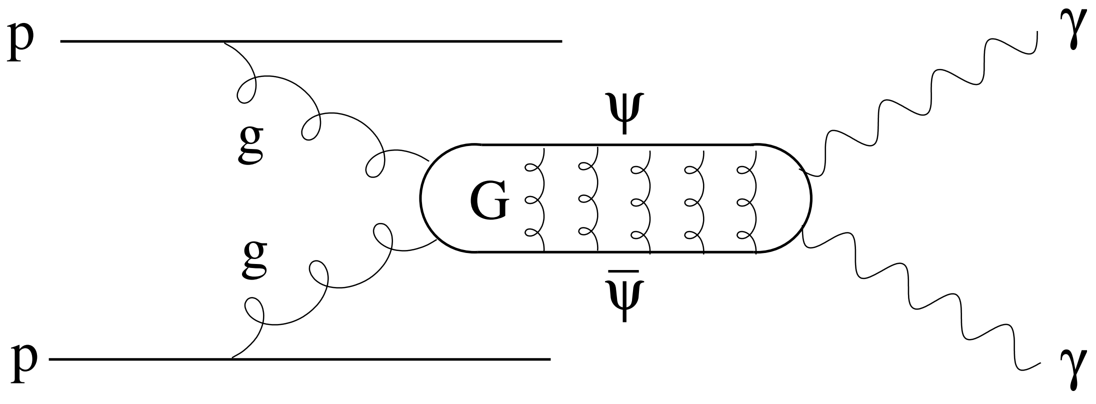
Lattice for BSM Physics 2018, CU Boulder, 6 April, 2018

# Strong dynamics beyond the SM

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

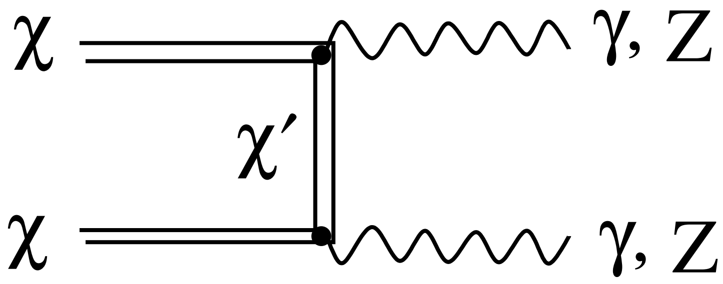
Need not be composite Higgs (technicolor), could be unconnected to electroweak symmetry breaking

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 | $0.745 \pm 0.09 \pm 0.036$ | $0.660^{+0.110}_{-0.070} \pm 0.024$ | $0.685^{+0.113}_{-0.069} \pm 0.047$ |

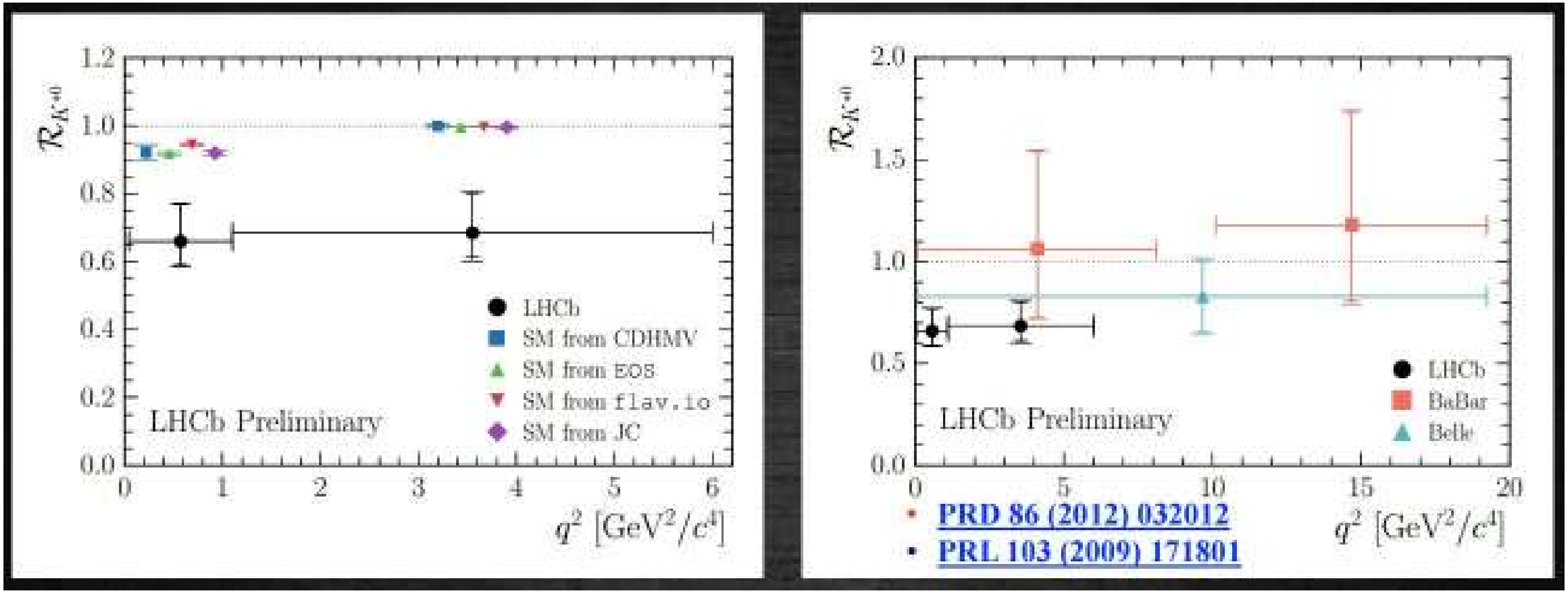
Correlated anomalies also seen in 'dirty' observables,

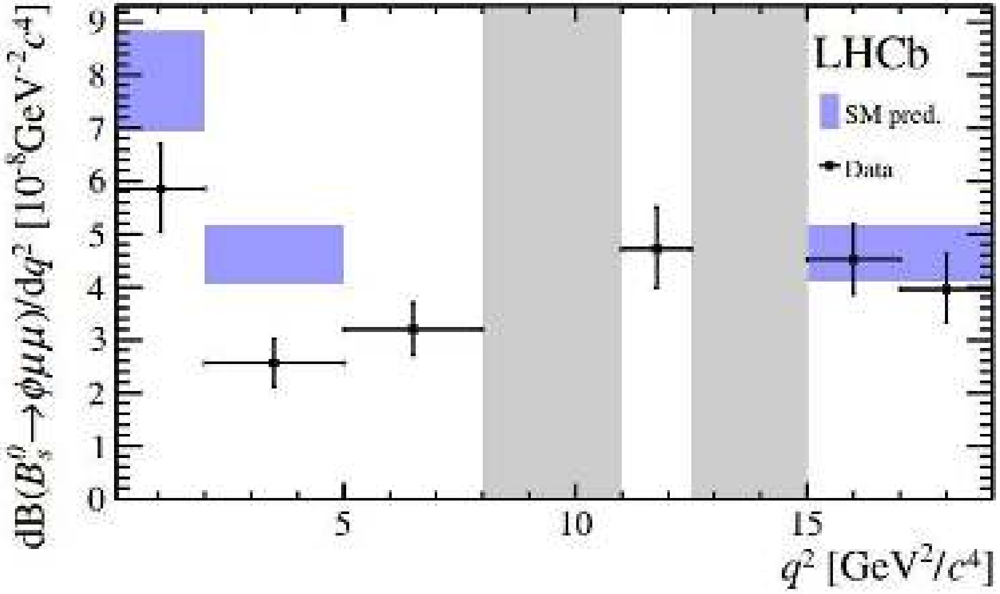
$B(B \to K^*\mu^+\mu^-)$, angular distribution $P_5'$

and

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

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





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

# Model-independent fit

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

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

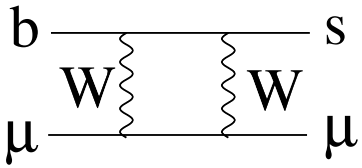
gives a good fit to the data, with $\Lambda \cong 36\,\mathrm{TeV}$.
Should be $\cong -0.15 \times (\mathrm{SM\ contribution})$. $4\sigma$ significance

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

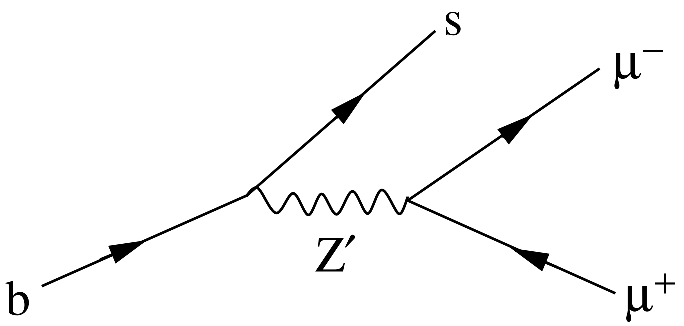
$$\mathcal{O}_{b_L\mu_L} \to -\frac{1}{\Lambda^2}(\bar{s}_L\gamma_\alpha\mu_L)(\bar{\mu}_L\gamma^\alpha s_L)$$

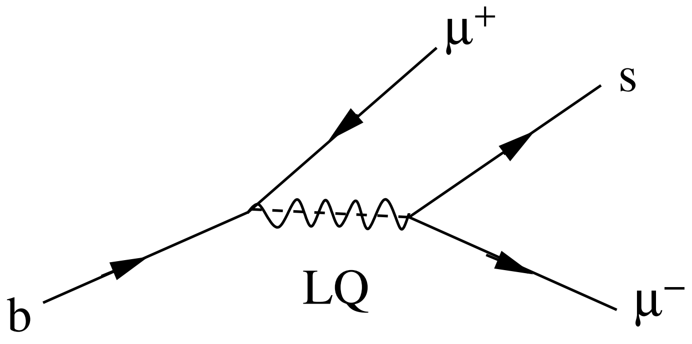
shows that vector leptoquark exchange also works.

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

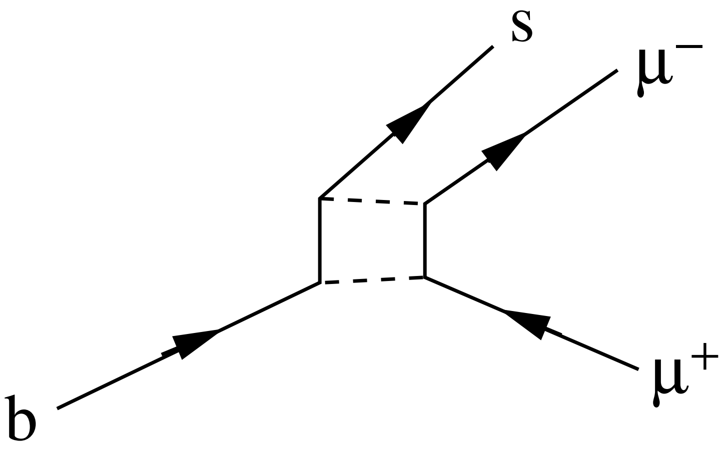


# Popular models: $Z'$ or leptoquark





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

based on arXiv:1710.02140 [Phys. Rev. D 97, 015013 (2018)]

# A simple model with strong dynamics

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

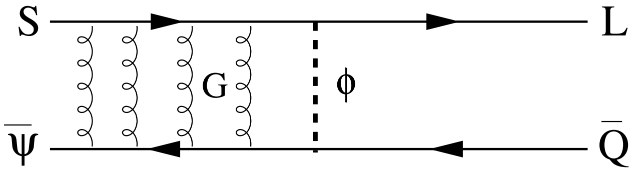
| | SU(3) | SU(2)$_L$ | U(1)$_y$ | U(1)$_{\rm em}$ | SU(N)$_{\rm HC}$ | $Z_2$ |
|---|---|---|---|---|---|---|
| $\Psi$ | $3$ | $1$ | $2/3$ | $2/3$ | $N$ | $-1$ |
| $S$ | $1$ | $1$ | $0$ | $0$ | $N$ | $-1$ |
| $\phi$ | $1$ | $2$ | $-1/2$ | $(0,-1)$ | $\bar N$ | $-1$ |

$\Leftarrow$ dark matter!

Couplings to SM left-handed quarks and leptons:

$$\mathcal{L} = \tilde\lambda_f\,\bar Q_{f,a}\,\phi^a_A\Psi^A + \lambda_f\,\bar S_A\phi^{*A}_\alpha\,L^\alpha_f \qquad \left(\begin{array}{c}\alpha = \mathrm{SU}(2),\\ A = \text{hypercolor}\end{array}\right)$$

$\bar\Psi S$ bound state is composite leptoquark, pseudoscalar $\Pi$ or vector $\Phi_\mu$,

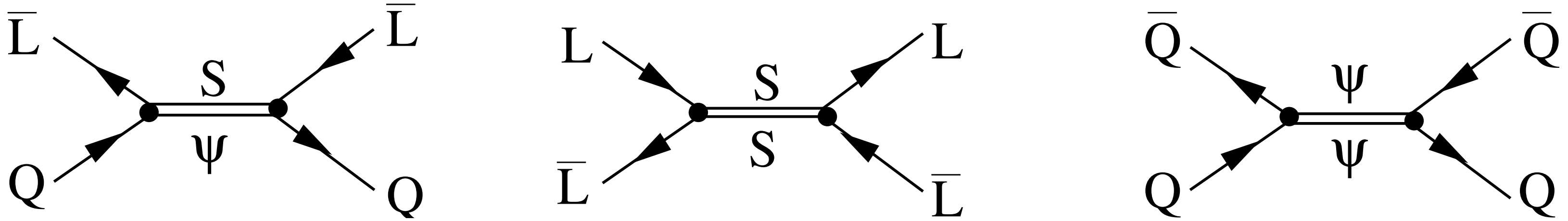


$$\langle 0|(\bar S\gamma_\mu\gamma_5\Psi)|\Pi\rangle = f_\Pi\,p^\mu_\Pi, \qquad \langle 0|(\bar S\gamma_\mu\Psi)|\Phi_\lambda\rangle = f_\Phi\,m_\Phi\epsilon^\mu_\lambda$$

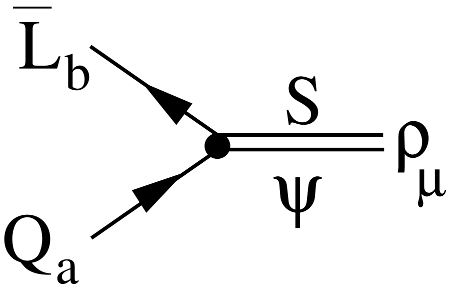
Pseudoscalar couplings to quarks and leptons are suppressed by $m_q$ or $m_l$, only vector can couple more strongly.

# Composite-induced anomalous decays

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



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



$$= \underbrace{\left(\frac{N_{\rm HC}}{4m_\rho}\right)^{1/2} \frac{\tilde{\lambda}_a\lambda_b^*\,(m_S+m_\Psi)\psi(0)}{(m_\phi^2+m_S\,m_\Psi)}}_{g_\rho^{ab}}\,(\bar{Q}_a\gamma^\mu L_b)\,\rho_\mu$$

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

To fit $B$-decay anomaly, need

$$\frac{g_\rho^{22}\,g_\rho^{32*}}{m_\rho^2} = -\frac{1\times 10^{-3}}{\rm TeV^2}$$

# Leptoquark coupling to $L$ and $Q$

Effective coupling $g_\rho^{ab}$ can be inferred from decay rate of bound state $\rho_\mu \to L_b \bar{Q}_a$ (Kang, Luty 0805.4642)

$$\Gamma(\rho_\mu \to L_b \bar{Q}_a) = \sigma v_{\rm rel}(S\bar{\Psi} \to L_b \bar{Q}_a)\, |\psi(0)|^2 = \frac{|g_\rho^{ab}|^2}{24\pi}\, m_\rho$$

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

We take nonrelativistic $-1/r + r$ (Cornell) potential

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

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

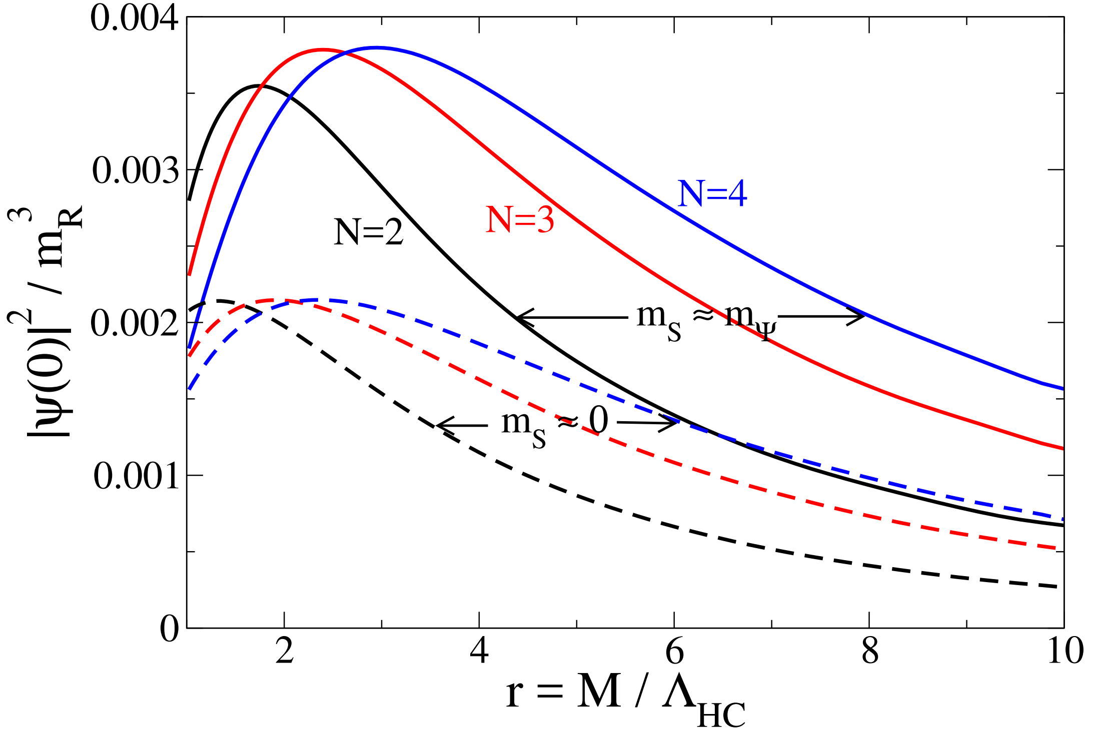
Minimize energy, find $\mu_*$ and binding energy $E_b$ in terms of $\Lambda_{\rm HC}$ and constituent mass $M$.

Wave function at origin $= \psi(0) = \mu_*^{3/2}/\sqrt{8\pi}$.
Bound state mass $= m_\Phi = 2M + E_b$.
Works well for $J/\Psi$ and $\Upsilon$ (if gluon vertex loop correction is included)

# Nonperturbative input

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

$$|\psi(0)|^2/m_\rho^3 \equiv \zeta(r)$$



Maximized near $M \sim (2-3)\,\Lambda_{\rm HC}$ and $m_S \lesssim m_\Psi$.

Then

$$|\lambda_2^2\,\tilde\lambda_2\,\tilde\lambda_3| = 0.3\left(\frac{M}{\rm TeV}\right)^2\left(\frac{3}{N_{\rm HC}}\right)$$

to fit $B$ decay anomalies

# A working model

We can fit $B$ decay anomaly with

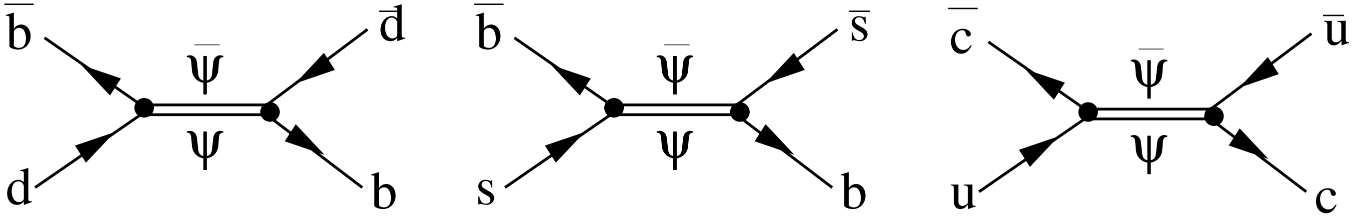
and

$$m_\psi \cong m_\phi \cong m_S \cong 2.5\,\Lambda_{\rm HC} \cong 1\,{\rm TeV}$$

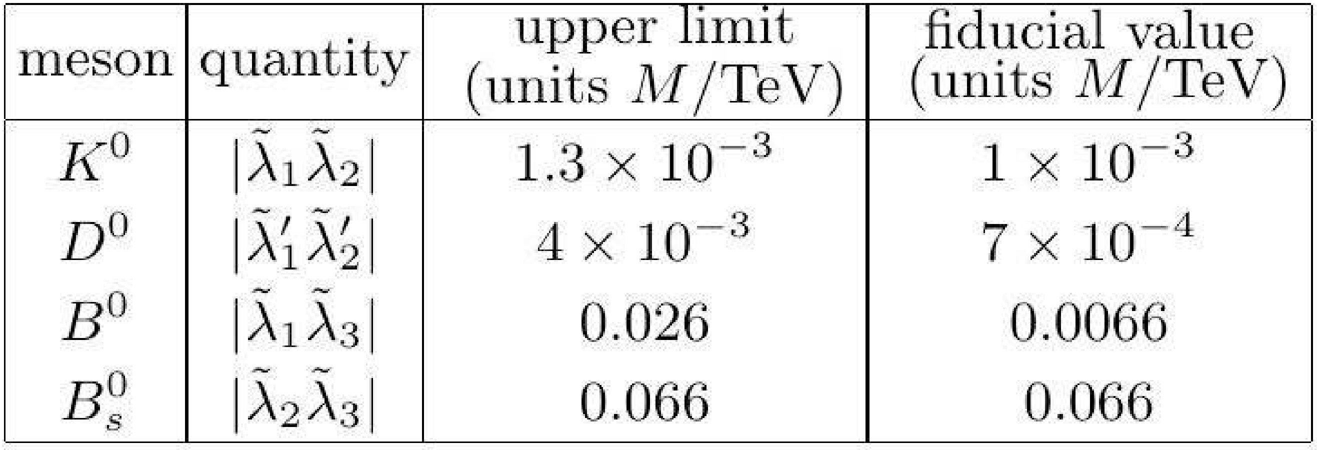
$$\tilde\lambda_1 = 0.01, \quad \tilde\lambda_2 = -0.1, \quad \tilde\lambda_3 = 0.66, \quad \lambda_2 = 2.1$$

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 close to experimental limits.



| meson | quantity | upper limit (units $M$/TeV) | fiducial value (units $M$/TeV) |
|---|---|---|---|
| $K^0$ | $\lvert\tilde\lambda_1\tilde\lambda_2\rvert$ | $1.3\times10^{-3}$ | $1\times10^{-3}$ |
| $D^0$ | $\lvert\tilde\lambda'_1\tilde\lambda'_2\rvert$ | $4\times10^{-3}$ | $7\times10^{-4}$ |
| $B^0$ | $\lvert\tilde\lambda_1\tilde\lambda_3\rvert$ | 0.026 | 0.0066 |
| $B^0_s$ | $\lvert\tilde\lambda_2\tilde\lambda_3\rvert$ | 0.066 | 0.066 |

# Reducing the flavor tension

We can adjust parameters somewhat:

$$\frac{|\lambda_2^2\tilde\lambda_2\tilde\lambda_3|}{M^2} \text{ is fixed by } B \text{ anomalies}$$

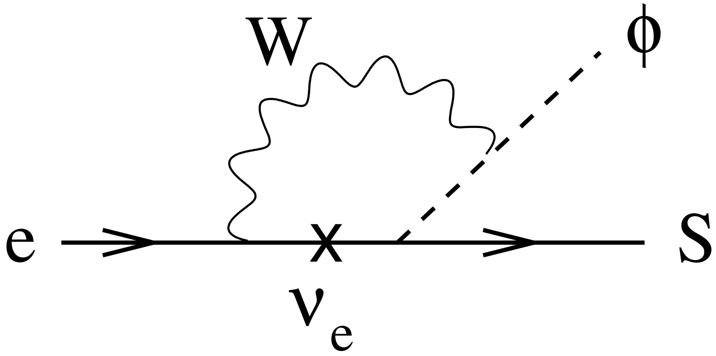
$$\frac{|\tilde\lambda_i^2\tilde\lambda_j^2|}{M^2} \text{ is constrained by FCNCs}$$

*E.g.*, lowering $M$ to $800\,\mathrm{GeV}$ and all $\tilde\lambda_i$ by 0.8 with $\lambda_2$ fixed reduces meson mixing rates by factor $0.8^4 \cong 0.4$.

Allowing $\lambda_2 > 2.1$ can further reduce FCNCs.

# Lepton flavor violation

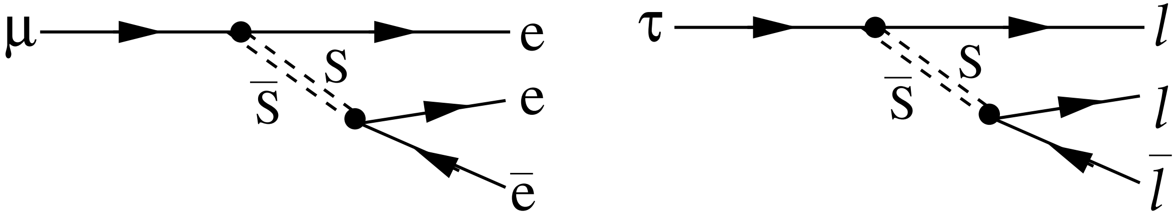
Nothing forces us to turn on couplings $\lambda_{1,3}$ to $e, \tau$,



Radiative contributions from $\lambda_2$ are suppressed by neutrino masses, can be ignored.

but it looks strange to take $\lambda_2 \sim 1$ and $\lambda_{1,3} = 0$.

If $\lambda_{1,3} \neq 0$, products $\lambda_1\lambda_2$, $\lambda_3\lambda_2$ are constrained by rare decays $\mu \to 3e$, $\tau \to 3\ell$



leading to the limits

$$|\lambda_1| < 0.2, \qquad |\lambda_3| < 0.9$$

# FCNC Radiative decays

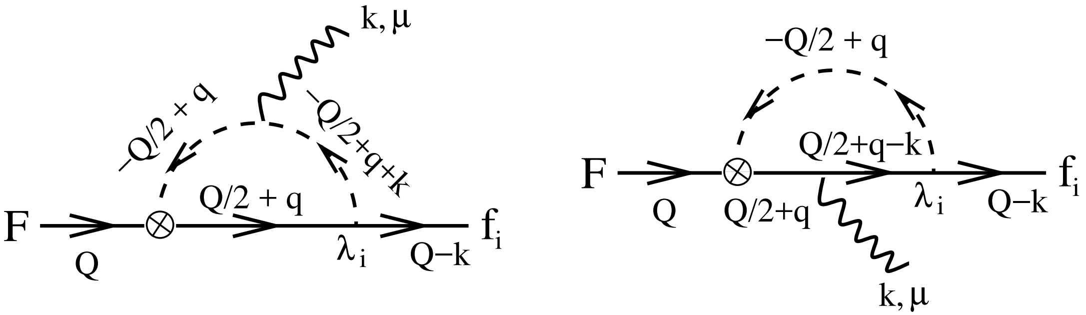
Radiative transitions $\mu \to e\gamma$, $b \to s\gamma$ are induced by heavy composite fermions,

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

They have mass-mixing with SM quarks and leptons,

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

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 30 below experimental limit

$\mu \to e\gamma$ ($\tau \to \mu\gamma$) limit implies $\lambda_1 < 7 \cdot 10^{-4}$ ($\lambda_3 < 0.6$).
More stringent than $\mu \to 3e$

Contribution to muon anomalous magnetic moment

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

is too small to explain outstanding discrepancy

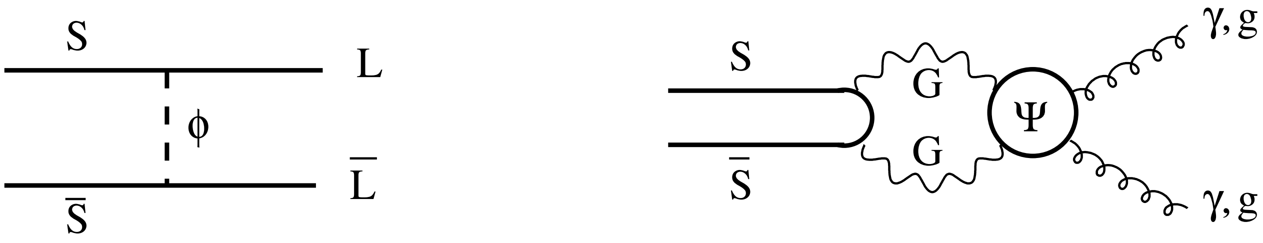
# Composite dark matter

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

In our model, dark matter is the “baryonic” bound state $\Sigma = S^{N_{\rm HC}}$

Its stability is ensured by hyperbaryon conservation, analogous to baryons in SM

$\eta'$-like $S\bar S$ meson can decay to $\mu\bar\mu$, $gg$, $\gamma\gamma$

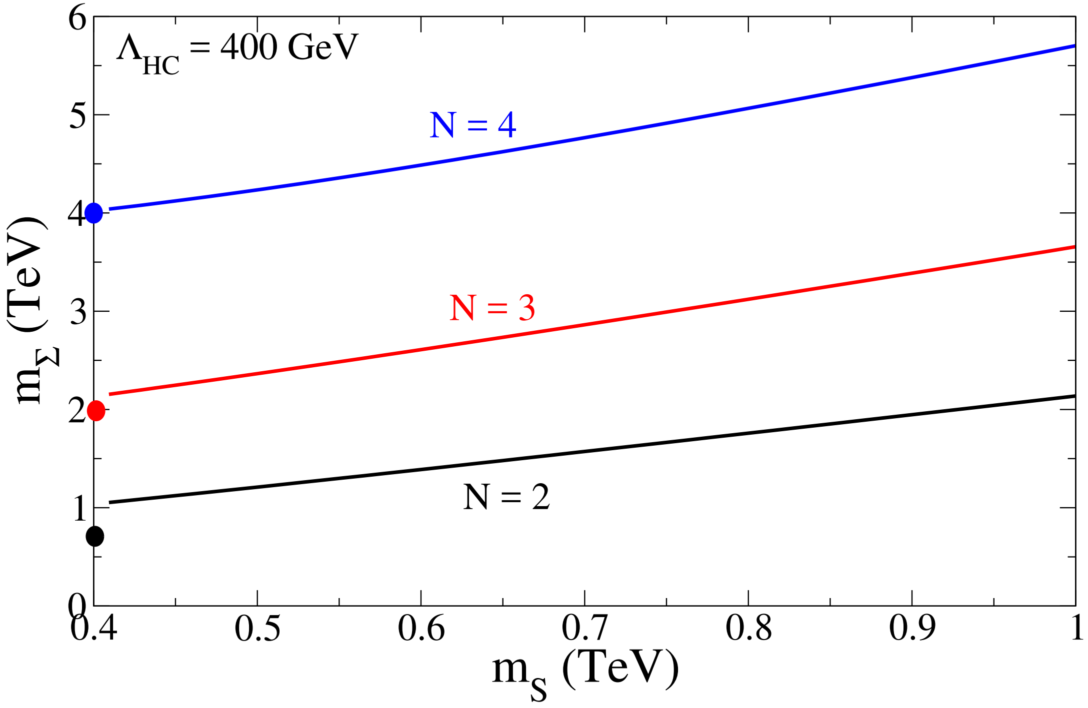


# Dark matter mass

The potential model for baryons is a little different; Coulomb attraction and string tension between $qq$ are smaller than for $q\bar{q}$,

$$V_c \to \frac{V_c}{N_{\rm HC}-1}, \qquad \sigma \to \sim \frac{\sigma}{15} \text{ (fit to QCD)}$$

and must sum over all $qq$ pairs.



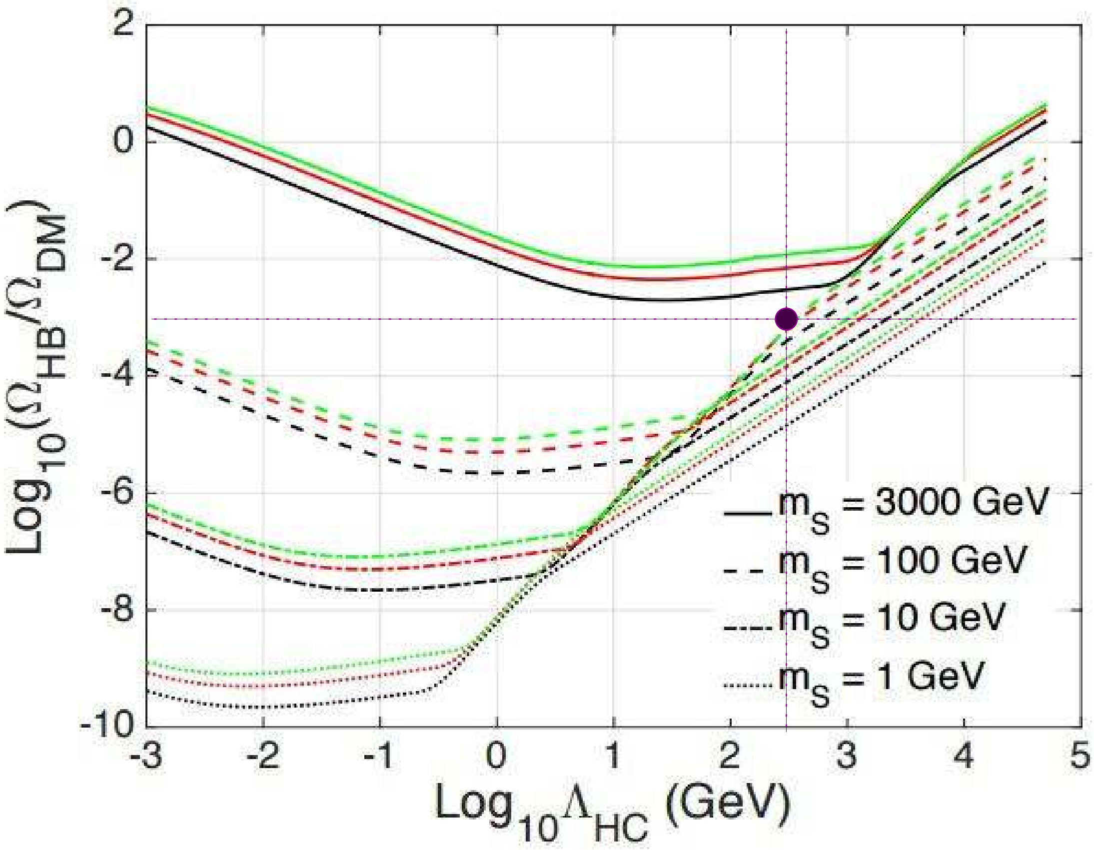
DM mass is

$$\begin{aligned} m_\Sigma &= N_{\rm HC}\, m_S + E_b \\ &\sim (1-6)\ \text{TeV} \end{aligned}$$

where $E_b$ = binding energy

# Dark matter relic density

Cosmology of “baryonic” bound states was studied in
JC, Huang, Moore 1607.07865; Mitridate *et al.*, 1707.05830



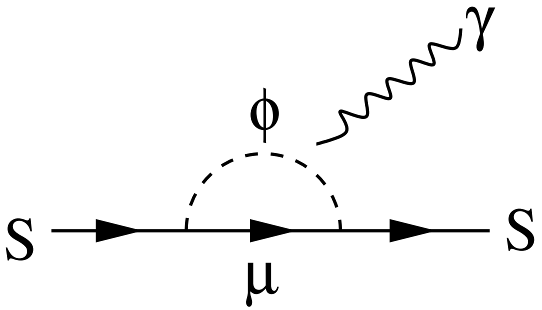
Before confinement phase transition, $S\bar{S} \to GG$ ($G =$hypergluon), depleting relic density

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

We do not specify the mechanism for getting an asymmetry
(after all, origin of baryon asymmetry is unknown)

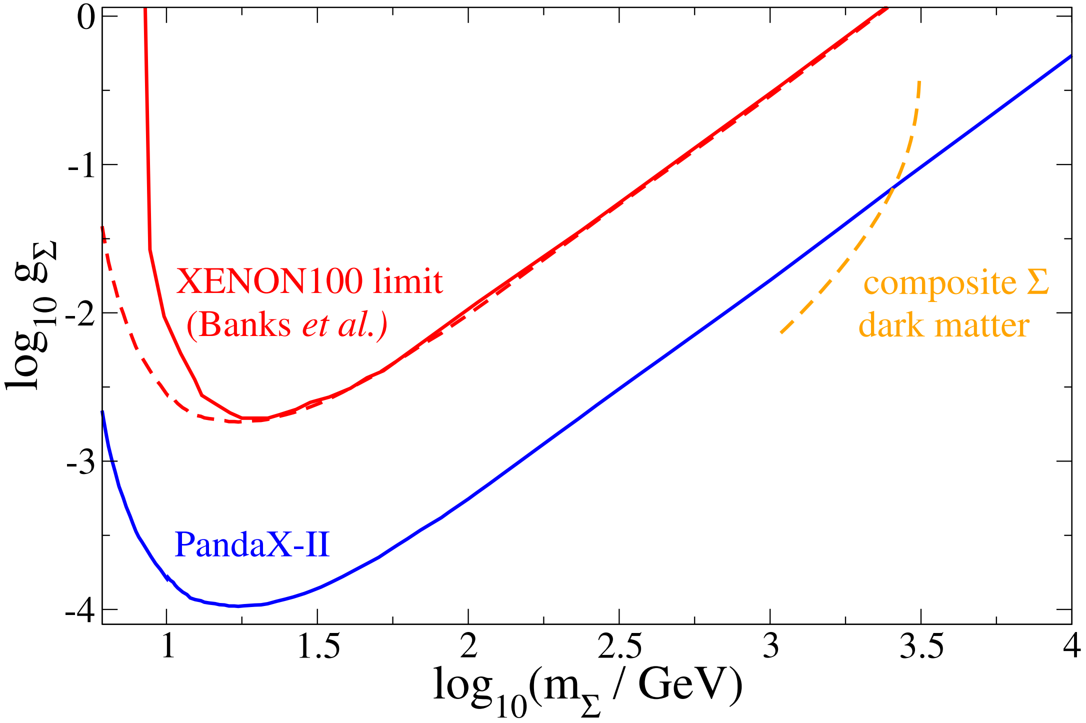
# Direct detection

$S$ gets a magnetic moment $\mu_S$ at one loop:



$$\mu_S = \frac{e|\lambda_2|^2 m_S}{32\pi^2\, m_\phi^2}\, f\left(\frac{m_S}{m_\phi}\right)$$

If $N_{\rm HC}$ odd, $\Sigma$ has magnetic moment and quark model predicts $\mu_\Sigma \cong N_{\rm HC}\,\mu_S$. $\Sigma$ scatters from protons.

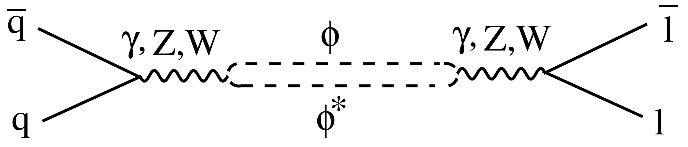


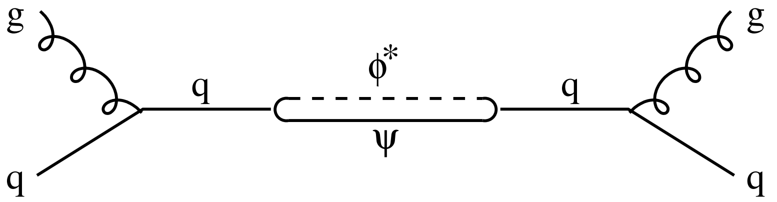
← Direct detection constraint on gyromagnetic ratio (updated from Banks, Fortin, Thomas 1007.5515)

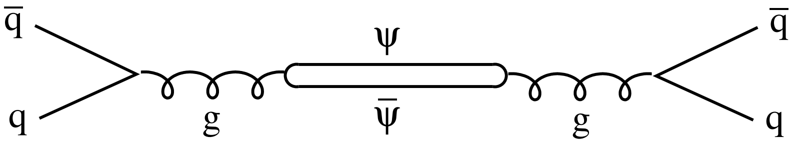
implies $m_S \lesssim 800\,\mathrm{GeV}$

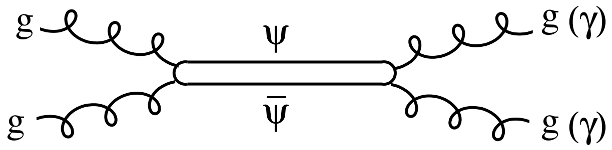
# LHC constraints

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









Probed by LHC searches for dijets, diphotons, dileptons

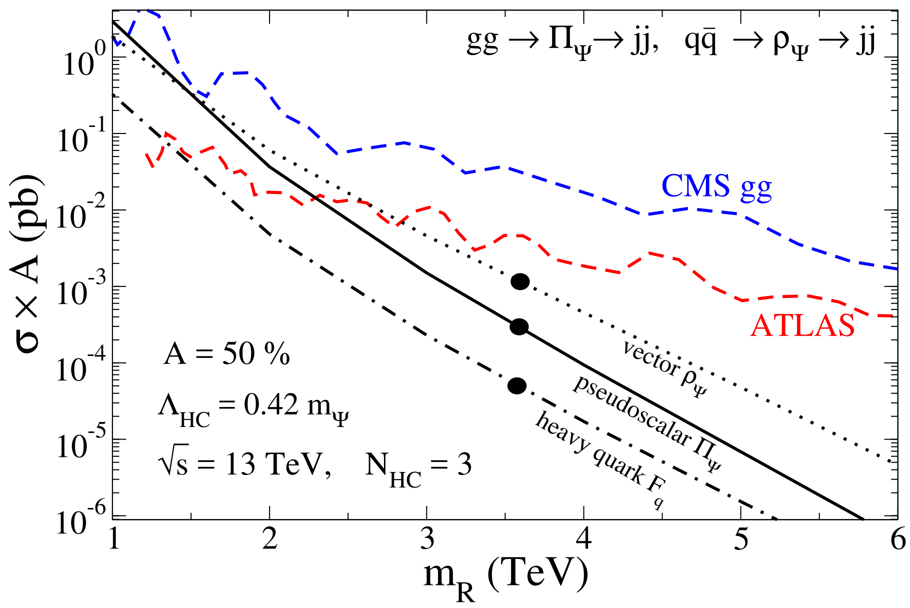
*E.g.*, $\rho_\Psi = \Psi\bar\Psi$ bound state is like quarkonium,

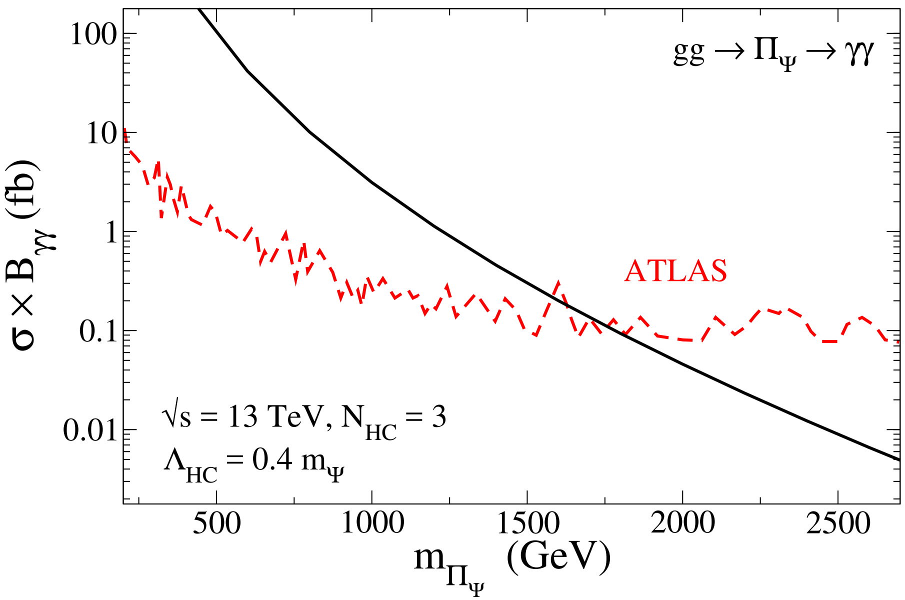
$$\sigma(q\bar q \to \rho_\Psi) = N_{\rm HC}\frac{64\pi^3\alpha_s^2|\psi(0)|^2}{9\, m^3_{\rho_\Psi}}\,\delta(s - m_B^2)$$

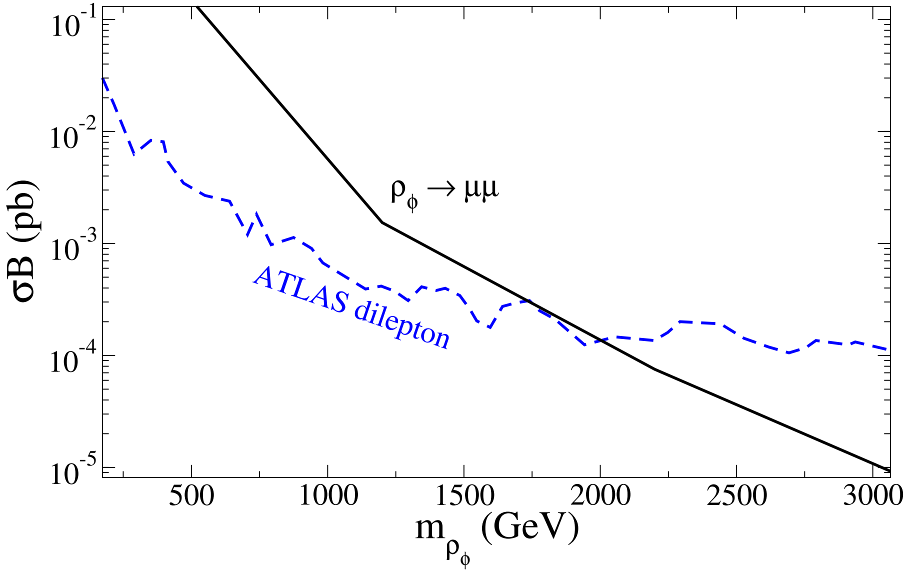
hence (recall $\zeta = \psi(0)^2/m^3_{\rho_\Psi}$)

$$\sigma(pp \to \rho_\Psi) = N_{\rm HC}\frac{64\pi^3\alpha_s^2}{9\, s}\,\zeta\,\mathcal{L}_{\rm parton}$$

# Dijet, diphoton, dilepton limits





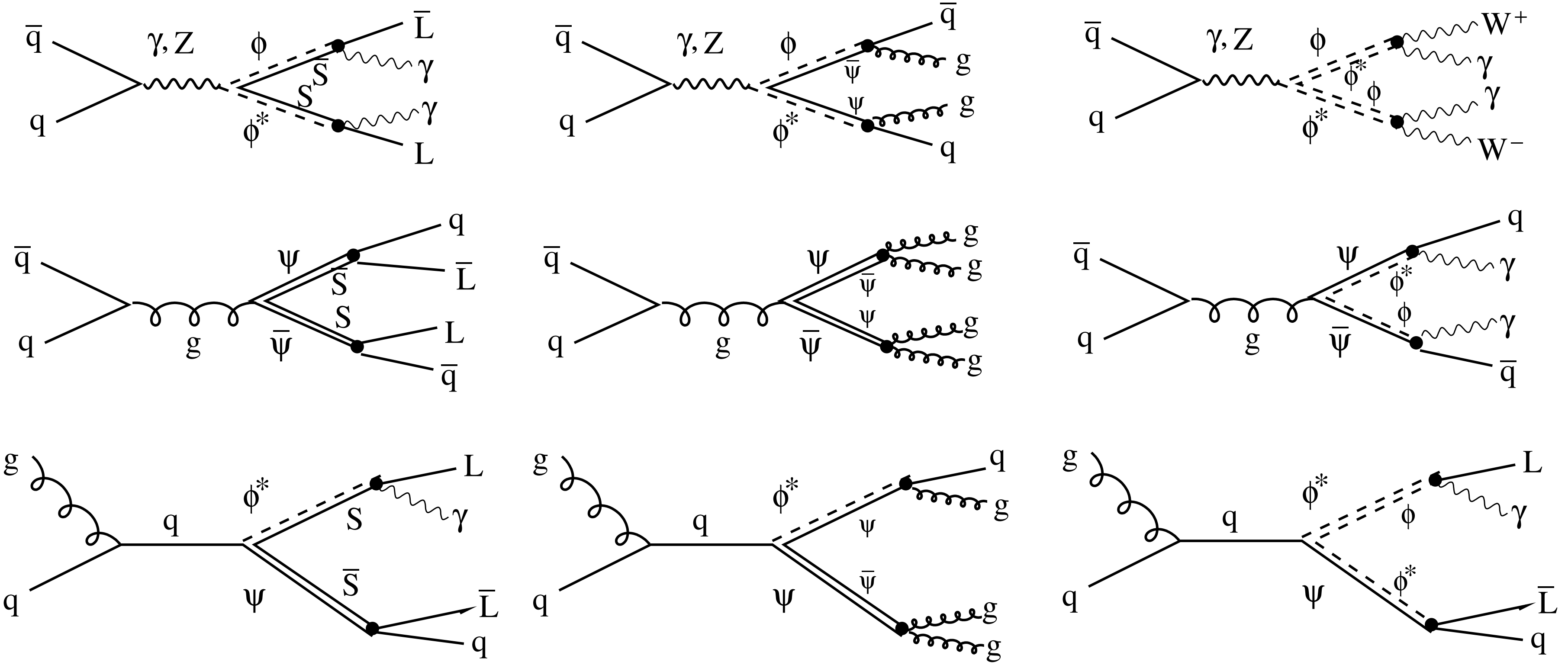


Bound state masses must exceed $2.3\,\mathrm{TeV}$ (dijet)

This implies limit $m_\Psi > 820\,\mathrm{GeV}$ for $N_{\rm HC} = 3$, $\Lambda_{\rm HC}/m_\Psi = 0.4$.

# Pair production at LHC

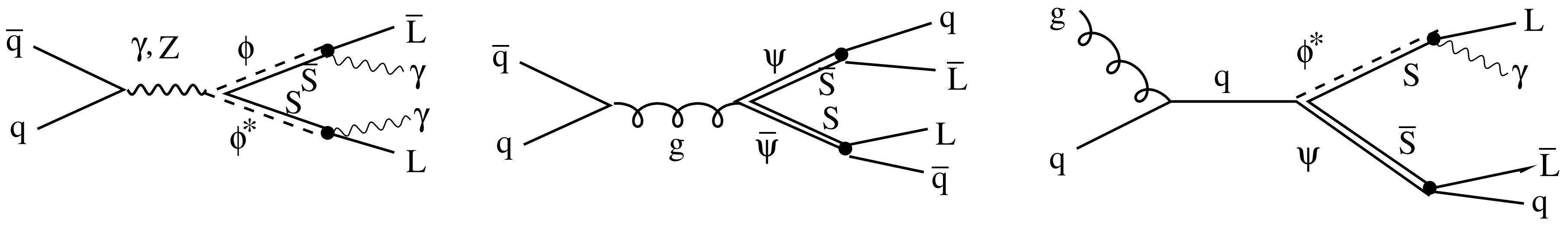
Besides resonant production, pair production could be relevant



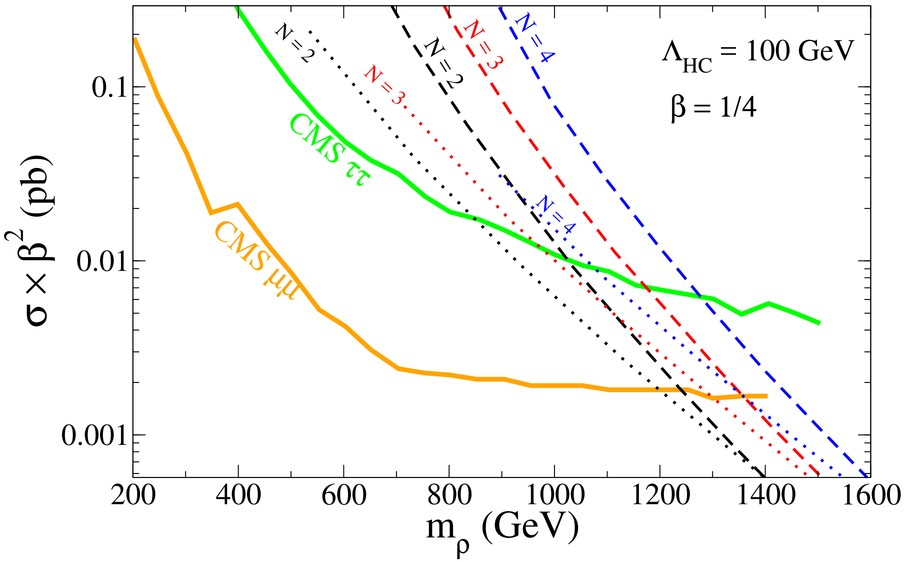
Need not be suppressed by wave function at origin since hadronization must occur following production of hypercolored constituents

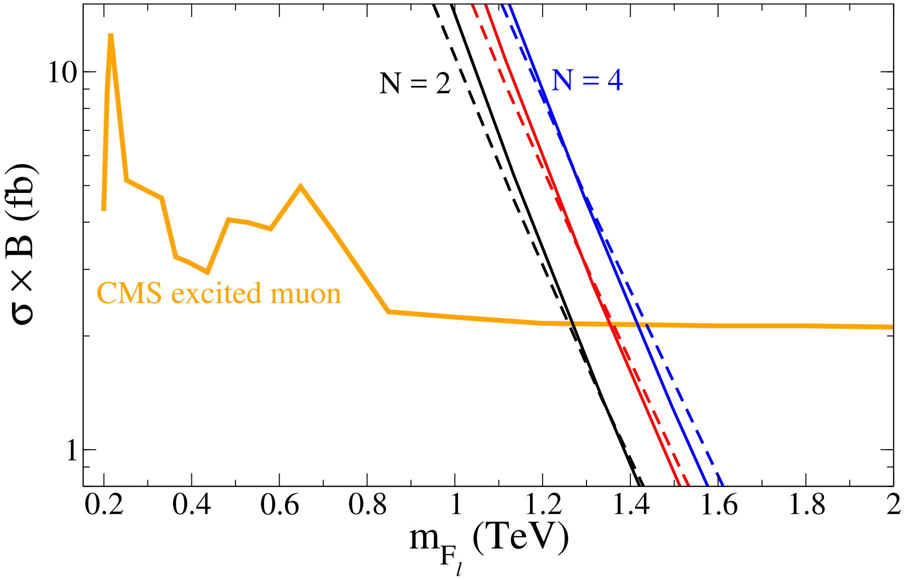
# Pair production at LHC

Pairs containing $S$ are lighter if $m_S < m_\Psi, m_\phi$, easiest to produce:



The bound states are leptoquarks $\rho$ or heavy lepton partners $F_\ell$; production constrained by CMS searches for $\rho \to \mu j$, $F_\ell \to \mu\gamma$





($\beta =$ branching ratio of leptoquark into charged $\mu$ or $\tau$)

# Putting it on the lattice

$N_{\rm HC} = 3$ is promising for phenomenology.

Then our model is QCD with 4 flavors of heavy quarks (one lighter than the rest, to get dark matter) plus one heavy scalar quark.

We want the quark masses (possibly excepting $m_S$) $\gtrsim \Lambda_{\rm HC}$ ;
no chiral limit needed.

To compute:

- masses and decay constants of the "mesons" (can be bosonic or fermionic);
- mass and magnetic moment of the lightest baryon $SSS$

Importance of the scalar:

- We can write a much simpler and more explicit model (compared to most composite Higgs models) by virtue of the scalar $\phi$; it allows direct coupling of new fermions to left-handed SM fermions
- The SM quantum numbers carried by the scalar allow one of the fermions to be dark matter (If we tried to make the scalar be the dark matter, it would not work because of confinement, *e.g.*, $\epsilon^{ABC}\phi_A\phi_B\phi_C = 0$ and $\phi\phi^*$ bound state can decay to $\mu^+\mu^-$ by $S$ exchange)

# 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