

# Doubling Down on Down-Type Diquarks

C. Englert, C. Mayer, W. Naskar, S. Renner

arXiv: 2410.00952

Christiane Mayer

University of Zürich

4th December 2024

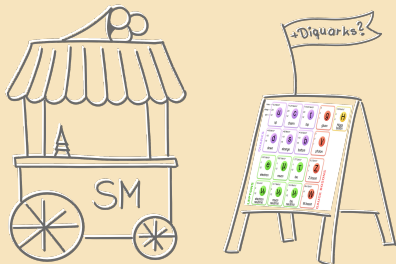
# Outline for today:

Diquark interactions

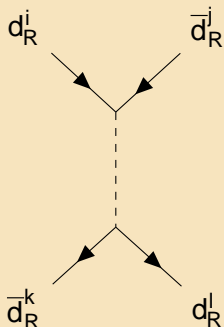
Constraints from collider  
phenomenology

Constraints from flavour  
phenomenology

Within a composite higgs  
model



# Why look for Diquarks?



focus only on diquarks with couplings to  $d_R$

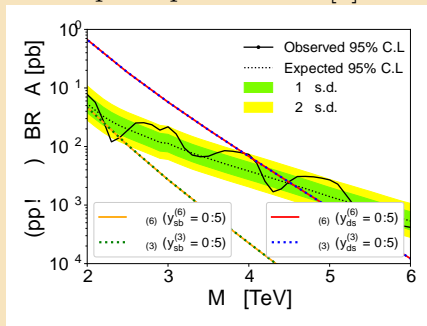
at tree level they \*only\* match to  $O_{dd}$  in dimension 6 SMEFT [1]

di cult to resolve at colliders

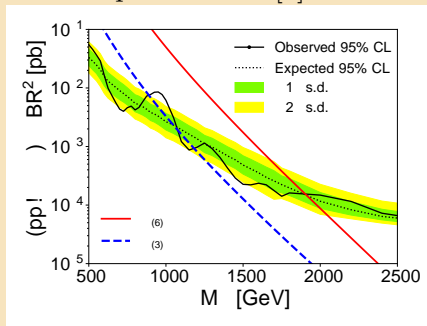
FCNCs at tree level



## LHC singly-resonant diquark production: [3]



## LHC diquark pair production: [4]



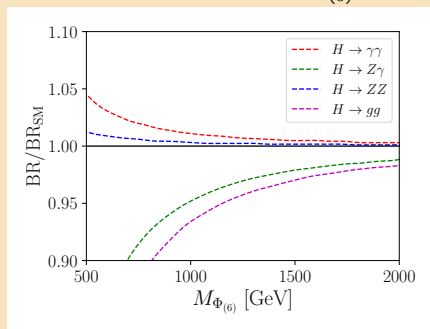
[3] A. M. Sirunyan et al. “Search for high mass dijet resonances with a new background prediction method in proton-proton collisions at  $\sqrt{s} = 13$  TeV”. In: *Journal of High Energy Physics* (2020). url: [http://dx.doi.org/10.1007/JHEP05\(2020\)033](http://dx.doi.org/10.1007/JHEP05(2020)033)

[4] A. Tumasyan et al. “Search for resonant and nonresonant production of pairs of dijet resonances in proton-proton collisions at  $\sqrt{s} = 13$  TeV”. In: *Journal of High Energy Physics* (2023). url: [http://dx.doi.org/10.1007/JHEP07\(2023\)161](http://dx.doi.org/10.1007/JHEP07(2023)161)

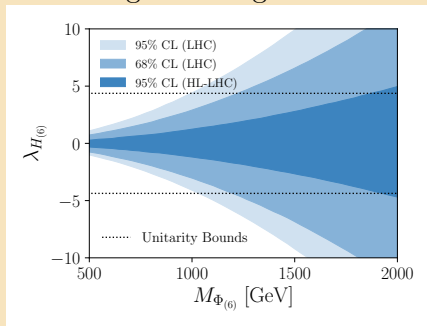
# Higgs Signal Strength

$$L \times \prod_{i=3,6} y_{H(i)}^2$$

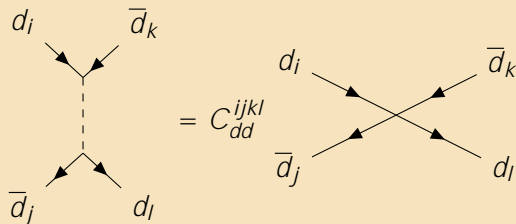
modified Higgs BR for  $H_{(6)} = 1$ :



constraints from LHC Higgs signal strengths:



At tree level, only match onto  $O_{dd} = \bar{d}^i_R d^j_R \bar{d}^k_R d^l_R$  [1]



Sextet:

$$C_{dd}^{ijkl} = \frac{1}{2M_{(6)}^2} (y_{ik}^{(6)}) y_{jl}^{(6)},$$

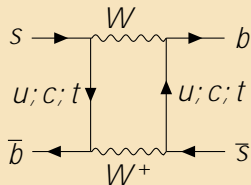
Triplet:

$$C_{dd}^{ijkl} = \frac{1}{M_{(3)}^2} (y_{ik}^{(3)}) y_{jl}^{(3)}$$

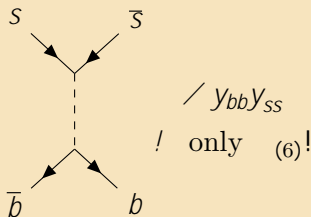
[1] B. Grzadkowski et al. “Dimension-six terms in the Standard Model Lagrangian”. In: *Journal of High Energy Physics* (2010). url: <http://arxiv.org/abs/1008.4884>

# Diquark Contributions to Neutral Meson Oscillations

$B_S \rightarrow \bar{B}_S$  in the SM



$B_S \rightarrow \bar{B}_S$  via Diquark Exchange



Change in  $B_S$  Meson mass splitting (from [5]):

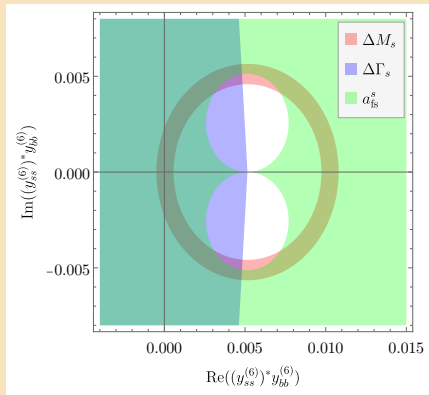
$$M_S = M_S^{\text{SM}} \left[ 1 + \frac{s(\text{NP})}{s(m_b)} \frac{\rho_{\frac{1}{2}}}{4G_F(V_{tb}V_{ts})^2 R_{\text{loop}}^{\text{SM}}} \frac{y_{bb}y_{ss}}{2M_{(6)}^2} \right]!$$

[5] Alexander Lenz and Ulrich Nierste. “Theoretical update of  $B_s$ - $B_s$ -bar mixing”. In: *Journal of High Energy Physics* (2007). url: <http://arxiv.org/abs/hep-ph/0612167>

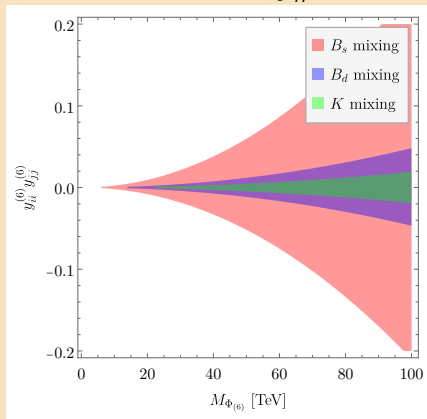


# Tree Level Contributions to Meson Oscillations

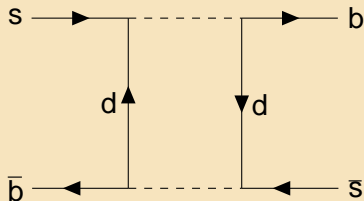
$B_s$  mixing at  $M_{(6)} = 5$  TeV:



Assuming real  $y_{ij}^{(6)}$ :



# Loop Contributions to Neutral Meson Oscillations



Diquark Loop Contributions to  $B_s$  meson oscillations

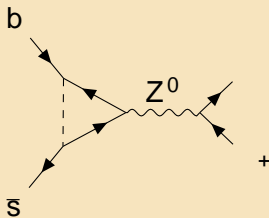
assume diagonal couplings  $y_{ii}^{(6)} = 0$

sensitive to o-diagonal elements of the sextet and the triplet coupling matrices

$$C_{dd}^{ij} = \frac{3}{256} \frac{1}{2M_{(6)}^2} ((y_{kj}^{(6)}) y_{ki}^{(6)})^2, \quad C_{dd}^{ij} = \frac{1}{64} \frac{1}{2M_{(3)}^2} ((y_{kj}^{(3)}) y_{ki}^{(3)})^2$$

# (Semi-) Leptonic Meson Decays

Example:  
 $B_s \rightarrow \ell^+ \ell^-$



sensitive to:  $y_{db}y_{ds} (+ y_{sb}y_{ss} + y_{bb}y_{bs})$

in SMEFT:

$$O_{dd} = \bar{d}_R^i d_R^j \bar{d}_R^k d_R^l$$

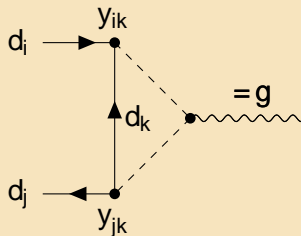
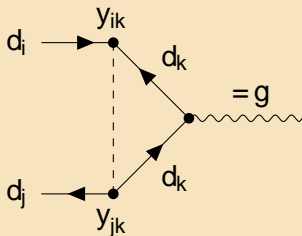
! generates  $O_{Hd} = (iH^\dagger D_\mu H)(\bar{d}_R^i d_R^j)$

through renormalisation group running

! this can be calculated in smelli [6]

# Radiative Meson Decays

diquark contributions to  $d_i \rightarrow d_j$  or  $d_i \rightarrow d_j g$ :



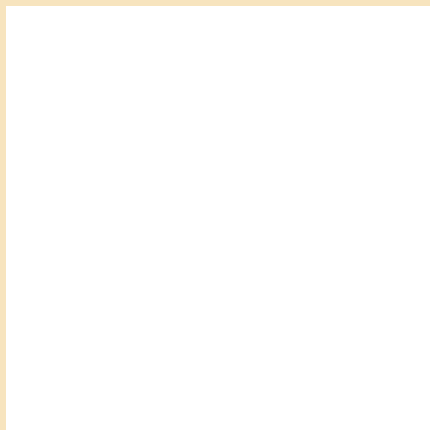
these match on to operators  $O_{dB}$  and  $O_{dG}$ :

$$\mathcal{L} = C_{dB}^{ij} (\bar{q}_i P_R d_j) H B + C_{dG}^{ij} \bar{q}_i T^A P_R d_j H G^A + \text{h.c.}$$

! after calculating  $C_{dB}^{ij}$  and  $C_{dG}^{ij}$  this can also be computed in smelli

# Combined constraints on $o$ -diagonal couplings

Example:  $y_{db}y_{ds}$ , relevant for  $B_s$  mixing at loop level:



# Diquarks in a Composite Higgs Model

both the Higgs boson and a diquark could be Goldstone bosons of a spontaneously broken strong sector

paradigm of partial fermion compositeness determines Yukawas:

$$(Y_u)_{ij} \sim g \frac{1}{\Lambda} Q_i^u; \quad (Y_d)_{ij} \sim g \frac{1}{\Lambda} Q_i^d$$

as well as the diquark coupling strengths:

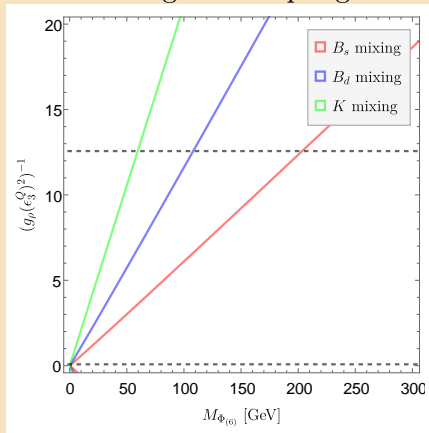
$$Y_{ij} = \frac{1}{g \left( \frac{\Lambda}{3} \right)^2} \begin{matrix} 0 & & & & & 1 \\ & dd(1:54 & 10^6) & ds(6:56 & 10^6) & db(1:73 & 10^5) \\ & ds(6:56 & 10^6) & ss(2:80 & 10^5) & sb(7:41 & 10^5) \\ & db(1:73 & 10^5) & sb(7:41 & 10^5) & bb(1:96 & 10^4) \end{matrix} \begin{matrix} C \\ A \end{matrix};$$

[7] David B. Kaplan. Flavor at ssc energies: A new mechanism for dynamically generated fermion masses. In: Nuclear Physics B 365.2 (1991), pp. 259-278. issn: 0550-3213. doi: [https://doi.org/10.1016/S0550-3213\(05\)80021-5](https://doi.org/10.1016/S0550-3213(05)80021-5)

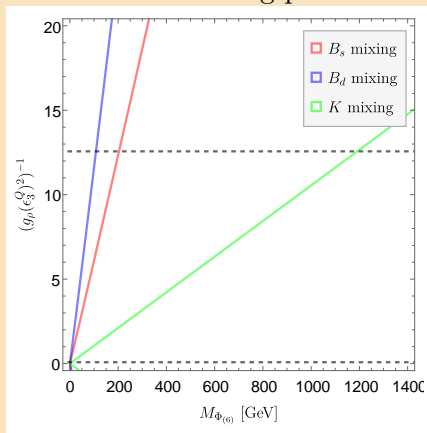
# Diquarks in a Composite Higgs Model

) strongest constraints from the tree level contributions to neutral meson oscillations from the sextet

Assuming real couplings:



Most constraining phases:



We found model-independent constraints on the diquark masses and couplings

Strongest constraints on diagonal couplings of  $(6)$  from neutral meson mixing

Collider and flavour constraints both needed to test the full parameter space

Diquarks in a composite higgs model still allowed to have masses around 1 TeV



We found model-independent constraints on the diquark masses and couplings

Strongest constraints on diagonal couplings of  $(6)$  from neutral meson mixing

Collider and flavour constraints both needed to test the full parameter space

Diquarks in a composite higgs model still allowed to have masses around 1 TeV

Thank you for listening!

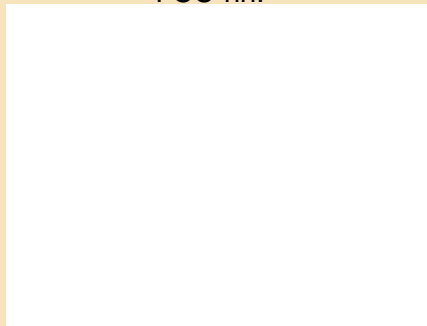
**-BACKUP SLIDES-**

# HL-LHC and FCC-hh collider constraints

HL-LHC:



FCC-hh:



# Diquark Contributions to $B_s$ Mixing

from [5] parameterise NP contributions to  $B_s$  mixing in terms of:

$$M_{12}^s = M_{12}^{\text{SM};s} + \dots$$

$$s = j + s_j e^{i\phi_s}$$

from [8] we can identify:

$$s = 1 + \frac{s(\text{NP})}{s(m_b)} \frac{p \bar{2} C_{dd}^{\text{sbsb}}}{4G_F (V_{tb} V_{ts})^2 R_{\text{loop}}^{\text{SM}}}; \quad C_{dd}^{\text{sbsb}} = \frac{(y_{ss}^{(6)}) y_{bb}^{(6)}}{2M^2} \quad (6)$$

! contribution to observables:

$$M_s = M_s^{\text{SM}} + s_j$$

$$s = 2j + s_{12} \cos(\phi_s^{\text{SM}} + \phi_s)$$

$$a_{fs}^s = \frac{j + s_{12} \cos(\phi_s^{\text{SM}} + \phi_s)}{j + s_j} \frac{\sin(\phi_s^{\text{SM}} + \phi_s)}{j + s_j}$$

[5] Alexander Lenz and Ulrich Nierste. Theoretical update of  $B_s$ - $B_s$ -bar mixing. In: Journal of High Energy Physics (2007). url : <http://arxiv.org/abs/hep-ph/0612167>

[8] Luca Di Luzio et al.  $M_s$  theory precision confronts flavour anomalies. In: Journal of High Energy Physics (2019). url : <http://arxiv.org/abs/1909.11087>

# B Meson Observables

Observable	Theory	Experiment
$M_s$	$18.4^{+0.7}_{-1.2} \text{ps}^{-1}$ [8]	$17.765 \pm 0.006 \text{ps}^{-1}$ [9]
$\Gamma_s$	$(0.096 \pm 0.039) \text{ps}^{-1}$ [5]	$(0.0828 \pm 0.0046) \text{ps}^{-1}$ [9]
$a_{fs}^s$	$0.0000206 \pm 0.0000057$ [5]	$0.00015 \pm 0.0007$ [9]
$M_d$	$0.533^{+0.022}_{-0.036} \text{ps}^{-1}$ [8]	$(0.5065 \pm 0.0019) \text{ps}^{-1}$ [9]
$a_{fs}^d$	$(4.8^{+1.0}_{-1.2}) \cdot 10^{-4}$ [5]	$0.002 \pm 0.0016$ [9]

Table: Observables in B Meson Oscillations

[8] Luca Di Luzio et al.  $M_s$  theory precision confronts flavour anomalies. In: Journal of High Energy Physics (2019). url : <http://arxiv.org/abs/1909.11087>

[9] Particle Data Group et al. Review of Particle Physics. In: (2022). url : <https://academic.oup.com/ptep/article/doi/10.1093/ptep/ptac097/6651666>

[5] Alexander Lenz and Ulrich Nierste. Theoretical update of Bs-Bs-bar mixing. In: Journal of High Energy Physics (2007). url : <http://arxiv.org/abs/hep-ph/0612167>

# Input Parameters

$\text{Re}C_K^1$	[ 9:6; 9:6] $10^{13} \text{GeV}^2$ [10]
$\text{Im}C_K^1$	[ 4:4; 2:8] $10^{15} \text{GeV}^2$ [10]

Table: Kaon Oscillation Wilson Coefficient, 95% allowed range

A	0.839551 0.224917 0.11857 0.363674
$R_{\text{loop}}$	$1:310 \cdot 10^3$
$G_F$	$1:1663787 \cdot 10^5$

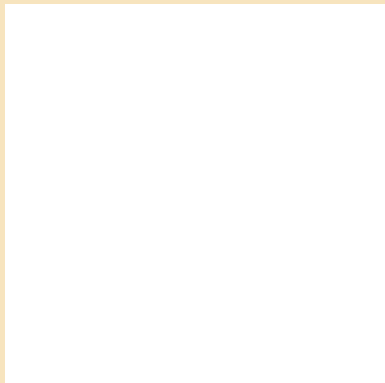
Table: Other Input Parameters

$B_d$  mixing constraints:

$$\text{Re}(y_{dd}^{(6)} y_{ss}^{(6)}) < [ 2:4; 2:4 ] 10^{-5}$$

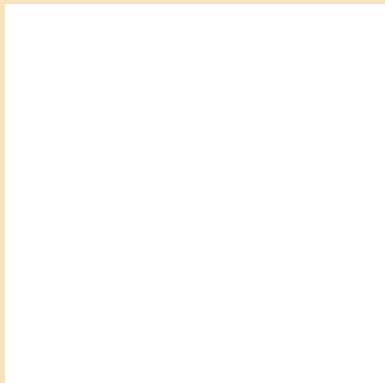
$$\text{Im}(y_{dd}^{(6)} y_{ss}^{(6)}) < [ 1:1; 0:7 ] 10^{-7}$$

# O -diagonal couplings $y_{db}^{(6)}$ $y_{ds}^{(6)}$ (from $B_s$ mesons)

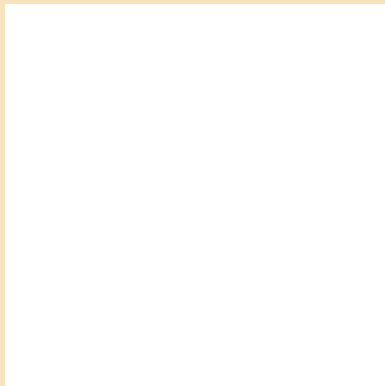




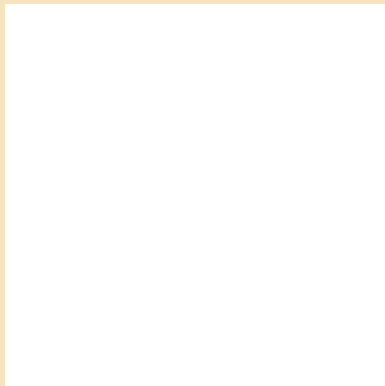
# O -diagonal couplings $y_{db}^{(3)}$ $y_{ds}^{(3)}$ (from $B_s$ mesons)



# O -diagonal couplings $y_{sb}^{(6)}$ $y_{sd}^{(6)}$ (from $B_d$ mesons)



# O -diagonal couplings $y_{sb}^{(3)}$ $y_{sd}^{(3)}$ (from $B_d$ mesons)



# Off-diagonal couplings $y_{bs}^{(6)} y_{bd}^{(6)}$ (from Kaons)

