Doubling Down on Down-Type Diquarks

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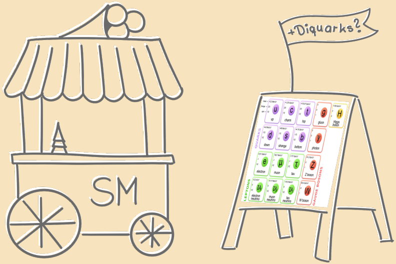
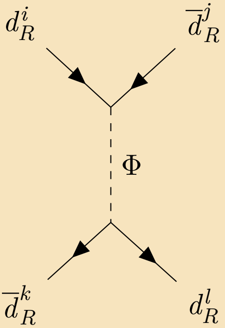
Outline for today:

- 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 $\mathcal{O}_{dd}$ in dimension 6 SMEFT [1]
- difficult to resolve at colliders
- FCNCs at tree level

[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

Down-type Scalar Diquarks [2]

Colour Sextet $\Phi_{(6)} \sim (\bar{\mathbf{6}}, \mathbf{1})_{2/3}$:

$$\mathcal{L}_{(6)} \supset -y_{ij}^{(6)} \Phi_{(6)}^{ab} d_{Ri}^{T(a|} C d_{Rj}^{|b)} + \text{h.c.}$$

$$y^{(6)} = \begin{pmatrix} y_{dd}^{(6)} & y_{ds}^{(6)} & y_{db}^{(6)} \\ y_{ds}^{(6)} & y_{ss}^{(6)} & y_{sb}^{(6)} \\ y_{db}^{(6)} & y_{sb}^{(6)} & y_{bb}^{(6)} \end{pmatrix}$$

Colour Triplet $\Phi_{(3)} \sim (\mathbf{3}, \mathbf{1})_{2/3}$:

$$\mathcal{L}_{(3)} \supset -y_{ij}^{(3)} \Phi_{(3)}^{a} \epsilon_{abc} d_{Ri}^{Tb} C d_{Rj}^{c} + \text{h.c.}$$

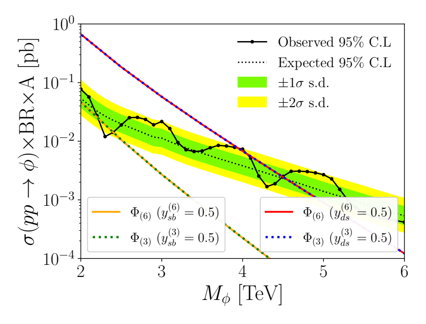
$$y^{(3)} = \begin{pmatrix} 0 & y_{ds}^{(3)} & y_{db}^{(3)} \\ -y_{ds}^{(3)} & 0 & y_{sb}^{(3)} \\ -y_{db}^{(3)} & -y_{sb}^{(3)} & 0 \end{pmatrix}$$

$\Rightarrow$ open parameters: $M_{(6)}$, $M_{(3)}$, $y_{ij}^{(6)} \in \mathbb{C}$, $y_{ij}^{(3)} \in \mathbb{C}$

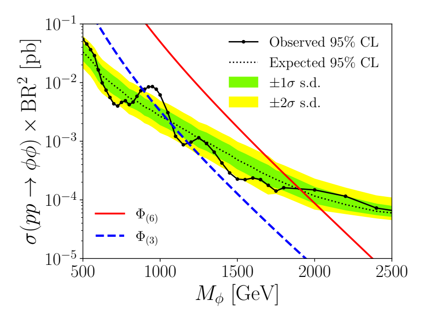
[2] Gian Francesco Giudice, Ben Gripaios, and Raman Sundrum. “Flavourful Production at Hadron Colliders”. In: *Journal of High Energy Physics* (2011). URL: http://arxiv.org/abs/1105.3161

LHC Resonance Searches

LHC singly-resonant diquark production: [3]



LHC diquark pair production: [4]



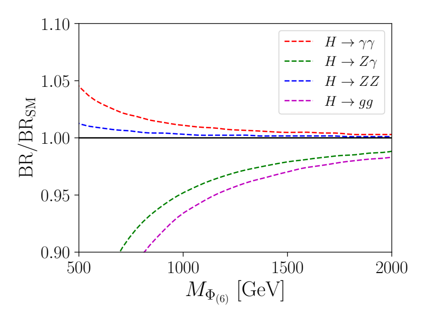
[3] A. M. Sirunyan et al. "Search for high mass dijet resonances with a new background prediction method in proton-proton collisions at $\sqrt{s} = 13$ TeV". In: *Journal of High Energy Physics* (2020). URL: http://dx.doi.org/10.1007/JHEP05(2020)033

[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

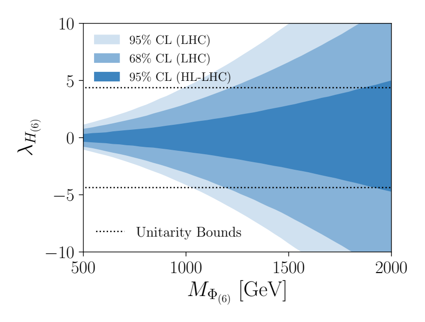
Higgs Signal Strength

$$\mathcal{L} \supset -\sum_{i=3,6} \lambda_{H_{(i)}} \left(\Phi_H^\dagger \Phi_H\right) \left(\Phi_{(i)}^\dagger \Phi_{(i)}\right)$$

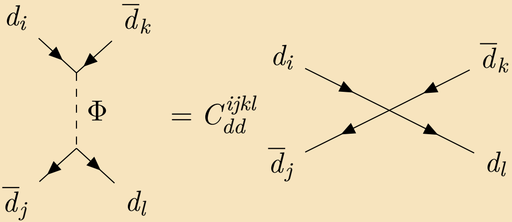
modified Higgs BR for $\lambda_{H_{(6)}} = 1$:



constraints from LHC Higgs signal strengths:



At tree level, only match onto $\mathcal{O}_{dd} = \overline{d^i}_R \gamma^\mu d^j_R \overline{d^k}_R \gamma_\mu d^l_R$ [1]



Sextet:

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

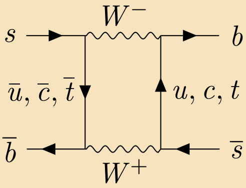
Triplet:

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

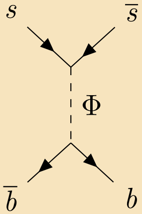
[1] B. Grzadkowski et al. "Dimension-six terms in the Standard Model Lagrangian". In: *Journal of High Energy Physics* (2010). URL: http://arxiv.org/abs/1008.4884

Diquark Contributions to Neutral Meson Oscillations

$B_s \to \bar{B}_s$ in the SM



$B_s \to \bar{B}_s$ via Diquark Exchange



$\propto y_{bb} y_{ss}^*$

$\to$ only $\Phi_{(6)}$!

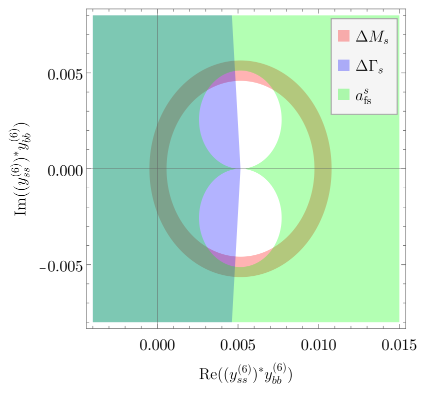
Change in B_s Meson mass splitting (from [5]):

$$\Delta M_s = \Delta M_s^{\text{SM}} \left| 1 - \left(\frac{\alpha_s(\mu_{\text{NP}})}{\alpha_s(m_b)} \right)^{6/23} \frac{\sqrt{2}}{4 G_F (V_{tb} V_{ts}^*)^2 R_{\text{loop}}^{\text{SM}}} \left(\frac{\mathbf{y_{bb} y_{ss}^*}}{\mathbf{2 M_{(6)}^2}} \right) \right|$$

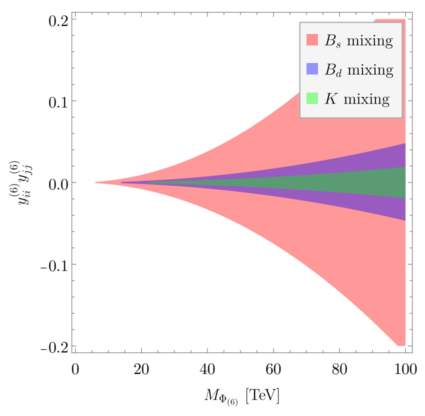
[5] Alexander Lenz and Ulrich Nierste. "Theoretical update of Bs-Bs-bar mixing". In: *Journal of High Energy Physics* (2007). URL: http://arxiv.org/abs/hep-ph/0612167

Tree Level Contributions to Meson Oscillations

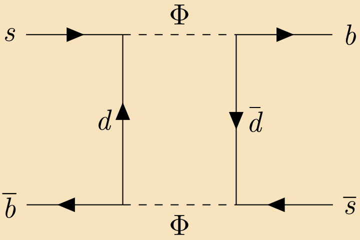
B_s mixing at $M_{(6)}$ =5 TeV:



Assuming real $y^{(6)}_{ii}$:



Loop Contributions to Neutral Meson Oscillations



Diquark Loop Contributions to B_s meson oscillations

- assume diagonal couplings $y^{(6)}_{ii} = 0$
- sensitive to off-diagonal elements of the sextet and the triplet coupling matrices

Sextet:

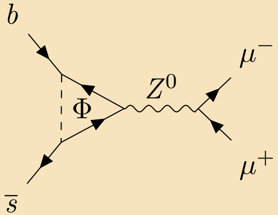
$$C^{ij}_{dd} = -\frac{3}{256\pi^2 M^2_{(6)}}((y^{(6)}_{kj})^* y^{(6)}_{ki})^2,$$

Triplet:

$$C^{ij}_{dd} = \frac{1}{64\pi^2 M^2_{(3)}}((y^{(3)}_{kj})^* y^{(3)}_{ki})^2$$

(Semi-) Leptonic Meson Decays

Example:
$B_s \to \mu^+ \mu^-$



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

in SMEFT:

$$\mathcal{O}_{dd} = \overline{d^i}_R \gamma^\mu d^j_R \overline{d^k}_R \gamma_\mu d^l_R$$

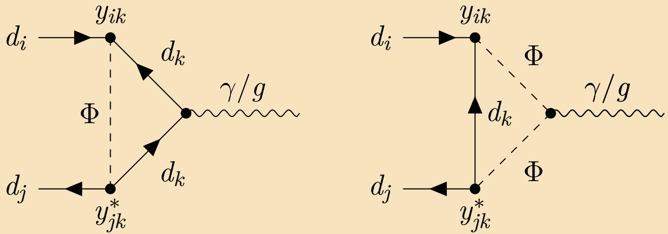
$\to$ generates $\mathcal{O}_{Hd} = (iH^\dagger \overleftrightarrow{D^\mu} H)(d^i_R \gamma_\mu d^j_R)$
through renormalisation group running

$\to$ this can be calculated in `smelli` [6]

[6] Peter Stangl. *smelli – the SMEFT Likelihood.* 2020. URL: http://arxiv.org/abs/2012.12211

Radiative Meson Decays

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



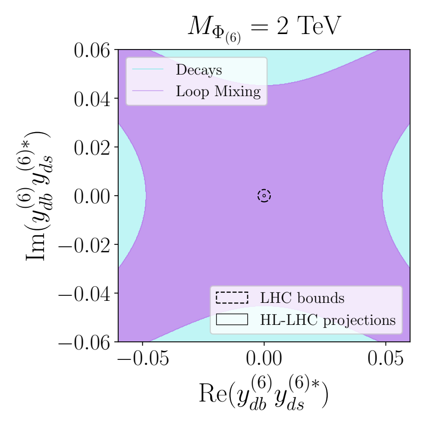
these match on to operators O_{dB} and O_{dG}:

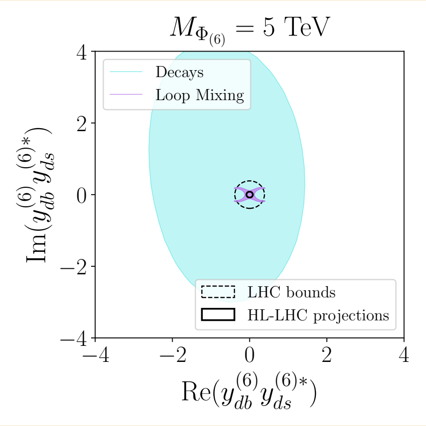
$$\mathcal{L} \supset C_{dB}^{ij}\,(\bar{q}_i \sigma^{\mu\nu} P_R d_j)\, H B_{\mu\nu} + C_{dG}^{ij}\left(\bar{q}_i \sigma^{\mu\nu} T^A P_R d_j\right) H G^A_{\mu\nu} + \text{h.c.}$$

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

Combined constraints on off-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:

$$(Y_u)_{ij} \approx g_\rho \epsilon_i^Q \epsilon_j^u, \qquad (Y_d)_{ij} \approx g_\rho \epsilon_i^Q \epsilon_j^d$$

as well as the diquark coupling strengths:

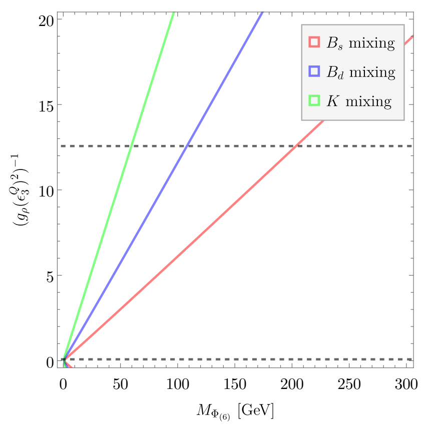
$$y_{ij} = \left(\frac{1}{g_\rho (\epsilon_3^q)^2}\right) \begin{pmatrix} \alpha_{dd}(1.54\times10^{-6}) & \alpha_{ds}(6.56\times10^{-6}) & \alpha_{db}(1.73\times10^{-5}) \\ \alpha_{ds}(6.56\times10^{-6}) & \alpha_{ss}(2.80\times10^{-5}) & \alpha_{sb}(7.41\times10^{-5}) \\ \alpha_{db}(1.73\times10^{-5}) & \alpha_{sb}(7.41\times10^{-5}) & \alpha_{bb}(1.96\times10^{-4}) \end{pmatrix},$$

[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

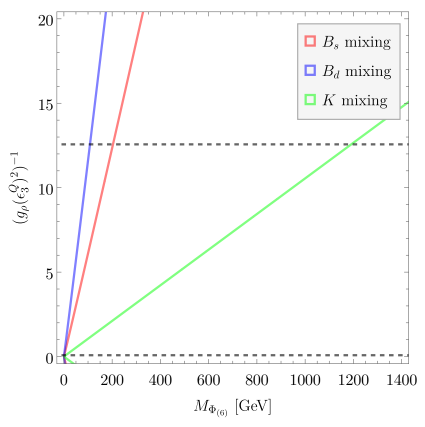
Diquarks in a Composite Higgs Model

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

Assuming real couplings:



Most constraining phases:



Conclusion

- We found model-independent constraints on the diquark masses and couplings
- Strongest constraints on diagonal couplings of $\Phi_{(6)}$ 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

Conclusion

- We found model-independent constraints on the diquark masses and couplings
- Strongest constraints on diagonal couplings of $\Phi_{(6)}$ from neutral meson mixing
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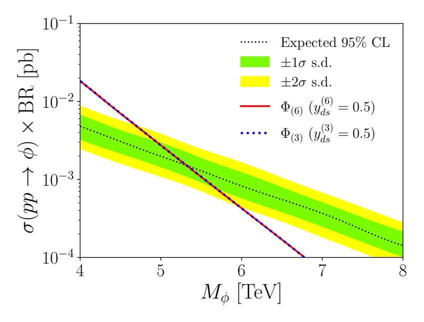
Thank you for listening!

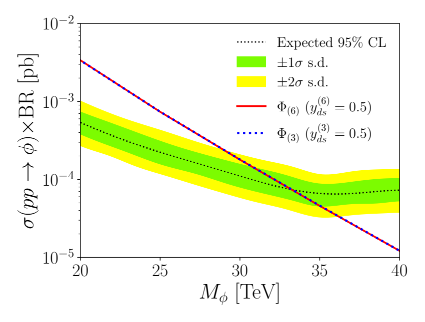
-BACKUP SLIDES-

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:

$$M_{12}^s = M_{12}^{\mathrm{SM},s} \cdot \Delta_s$$

$$\Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$

$\rightarrow$ contribution to observables:

$$\Delta M_s = \Delta M_s^{\mathrm{SM}} |\Delta_s|$$

$$\Delta\Gamma_s = 2|\Gamma_{12}^s| \cos(\phi_s^{SM} + \phi_s^\Delta)$$

$$a_{\mathrm{fs}}^s = \frac{|\Gamma_{12}^s|}{|M_{12}^{\mathrm{SM},s}|} \frac{\sin(\phi_s^{\mathrm{SM}} + \phi_s^\Delta)}{|\Delta_s|}$$

from [8] we can identify:

$$\Delta_s = 1 - \left(\frac{\alpha_s(\mu_{\mathrm{NP}})}{\alpha_s(m_b)}\right)^{6/23} \frac{\sqrt{2}\, C_{dd}^{sbsb}}{4 G_F (V_{tb} V_{ts}^*)^2 R_{\mathrm{loop}}^{\mathrm{SM}}}; \qquad C_{dd}^{sbsb} = \frac{(y_{ss}^{(6)})^* y_{bb}^{(6)}}{2 M_{\Phi_{(6)}}^2}$$

[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

[8] Luca Di Luzio et al. "ΔM_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
ΔM_s	$18.4^{+0.7}_{-1.2}\text{ps}^{-1}$ [8]	$17.765 \pm 0.006\text{ps}^{-1}$ [9]
$\Delta\Gamma_s$	$(0.096 \pm 0.039)\text{ps}^{-1}$ [5]	$(0.0828 \pm 0.0046)\text{ps}^{-1}$ [9]
a^s_{fs}	0.0000206 ± 0.0000057 [5]	-0.00015 ± 0.0007 [9]
ΔM_d	$0.533^{+0.022}_{-0.036}\text{ps}^{-1}$ [8]	$(0.5065 \pm 0.0019)\text{ps}^{-1}$ [9]
a^d_{fs}	$(-4.8^{+1.0}_{-1.2}) \cdot 10^{-4}$ [5]	-0.002 ± 0.0016 [9]

Table: Observables in B Meson Oscillations

[8]Luca Di Luzio et al. "ΔM_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

$\mathrm{Re}\, C_K^1$	$[-9.6, 9.6] \cdot 10^{-13}\mathrm{GeV}^{-2}$ [10]
$\mathrm{Im}\, C_K^1$	$[-4.4, 2.8] \cdot 10^{-15}\mathrm{GeV}^{-2}$ [10]

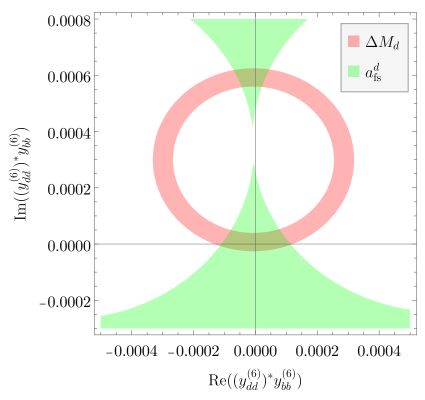
Table: Kaon Oscillation Wilson Coefficient, 95% allowed range

A	0.839551
λ	0.224917
$\bar{\rho}$	0.11857
$\bar{\eta}$	0.363674
R_{loop}	1.310×10^{-3}
G_F	1.1663787×10^{-5}

Table: Other Input Parameters

[10] UTfit Collaboration et al. "Model-independent constraints on Delta F=2 operators and the scale of New Physics". In: *Journal of High Energy Physics* (2008). URL: http://arxiv.org/abs/0707.0636

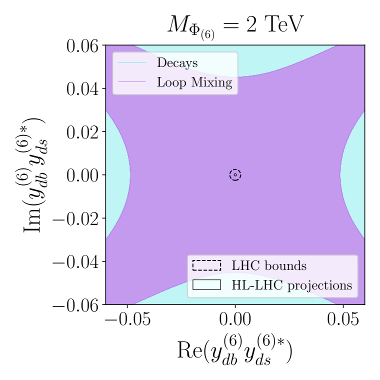
B_d mixing constraints:

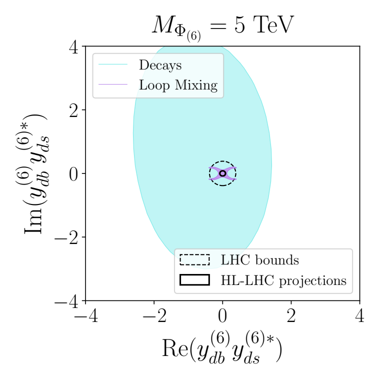


$$\text{Re}(y_{dd}^{*(6)} y_{ss}^{(6)}) < [-2.4, 2.4] \times 10^{-5}$$

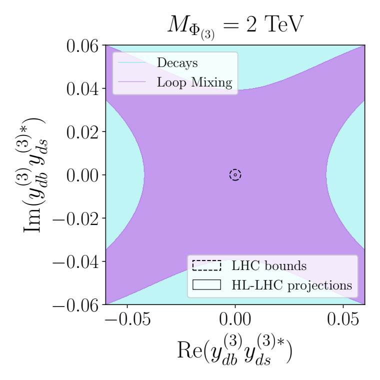
$$\text{Im}(y_{dd}^{*(6)} y_{ss}^{(6)}) < [-1.1, 0.7] \times 10^{-7}$$

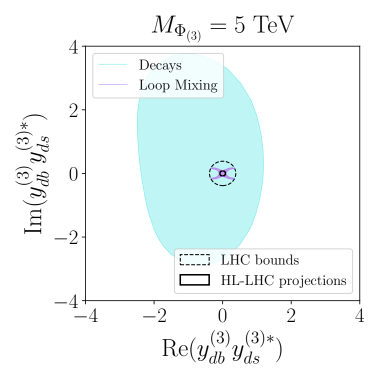
Off-diagonal couplings $y_{db}^{(6)} y_{ds}^{(6)*}$ (from B_s mesons)



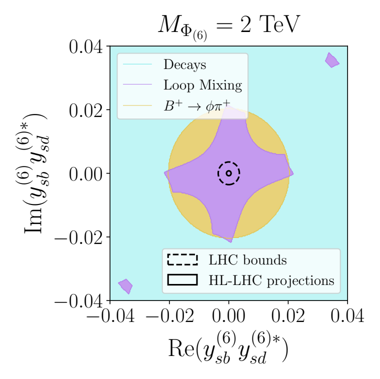


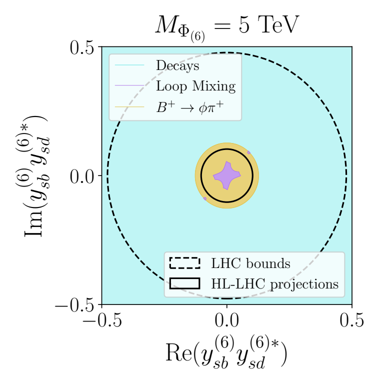
Off-diagonal couplings $y_{db}^{(3)} y_{ds}^{(3)*}$ (from B_s mesons)



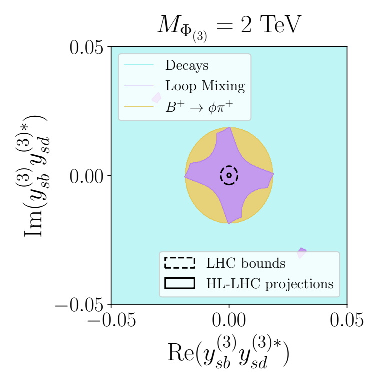


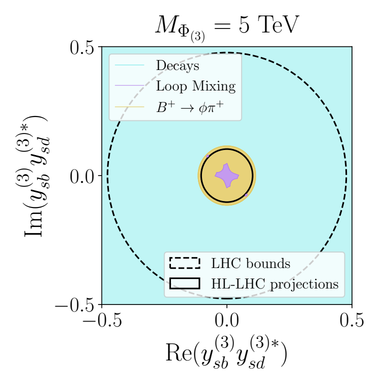
Off-diagonal couplings $y_{sb}^{(6)} y_{sd}^{(6)*}$ (from B_d mesons)



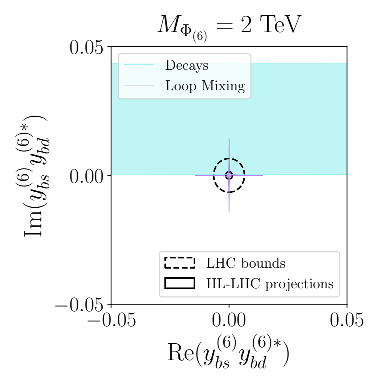


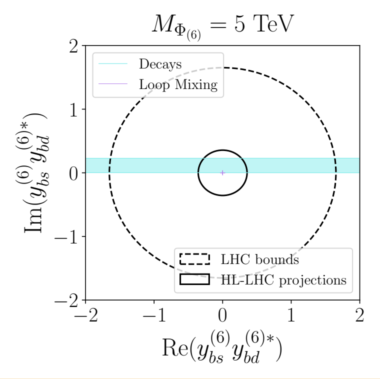
Off-diagonal couplings $y_{sb}^{(3)} y_{sd}^{(3)*}$ (from B_d mesons)





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





Off-diagonal couplings $y_{bs}^{(3)} y_{bd}^{(3)*}$ (from Kaons)