UNIVERSITÄT BERN

Collider bounds on BSM explanations of the discrepancy

Admir Greljo

25.03.2021, Mini-Workshop on Colour Allowed Non-Leptonic Tree-Level Decays

Exploiting dijet resonance searches for flavor physics

Marzia Bordone,[a,b] **Admir Greljo,**[c,d] **and David Marzocca**[e]

Contents

https://arxiv.org/pdf/2103.10332.pdf

3 General EFT analysis of $b \to cud_i$

$$R(X \to YZ) \equiv \mathcal{B}(X \to YZ)/\mathcal{B}(X \to YZ)_{\text{SM}}$$

$$\begin{aligned} R(\bar{B}^0_s \to D^+_s \pi^-) &= 0.704 \pm 0.074 \\ R(\bar{B}^0 \to D^+ K^-) &= 0.687 \pm 0.059 \\ R(\bar{B}^0_s \to D^{*+}_s \pi^-) &= 0.49 \pm 0.24 \\ R(\bar{B}^0 \to D^{*+} K^-) &= 0.66 \pm 0.13 \end{aligned} \quad , \qquad \rho = \begin{pmatrix} 1 & 0.36 & 0.16 & 0.092 \\ 0.36 & 1 & 0.072 & 0.16 \\ 0.16 & 0.072 & 1 & 0.40 \\ 0.092 & 0.16 & 0.40 & 1 \end{pmatrix}$$

NP?

2007.10338

Thanks to Martin Jung. See also the talk by Nico Gubernari.

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$$\begin{aligned} Q_{V_{LL}}^{ijkl} &= (\bar{u}_L^i \gamma_\mu d_L^j)(\bar{d}_L^k \gamma^\mu u_L^l) \\ Q_{V_{RR}}^{ijkl} &= (\bar{u}_R^i \gamma_\mu d_R^j)(\bar{d}_R^k \gamma^\mu u_R^l) \\ Q_{V_{LR}}^{ijkl} &= (\bar{u}_L^i \gamma_\mu d_L^j)(\bar{d}_R^k \gamma^\mu u_R^l) \\ Q_{S_{RL}}^{ijkl} &= (\bar{u}_L^i d_R^j)(\bar{d}_R^k u_L^l) \\ Q_{S_{LR}}^{ijkl} &= (\bar{u}_R^i d_L^j)(\bar{d}_L^k u_R^l) \\ Q_{S_{RR}}^{ijkl} &= (\bar{u}_L^i d_R^j)(\bar{d}_L^k u_R^l) \\ Q_{T_{RR}}^{ijkl} &= (\bar{u}_L^i \sigma_{\mu\nu} d_R^j)(\bar{d}_L^k \sigma^{\mu\nu} u_R^l) \end{aligned}$$

* at leading order in α_s and leading power in $1/m_b$

$$\begin{aligned} \mathcal{A}(\bar{B}_q \to D_q^+ P^-) =\, & \mathcal{A}(\bar{B}_q \to D_q^+ P^-)_{\rm SM} \times \\ & \Bigg\{ 1 + \frac{1}{2\sqrt{2} G_F V_{cb} V_{ui}^* C_2} \Bigg[\left(- a_{V_{LL}}^{cbiu} + a_{V_{RR}}^{cbiu} + a_{V_{LR}}^{cbiu} - a_{V_{LR}}^{uibc} \right) \\ & + \frac{m_P^2}{(m_u + m_{d_i})(m_b - m_c)} \left(a_{S_{RL}}^{cbiu} - a_{S_{LR}}^{cbiu} - a_{S_{RR}}^{cbiu} + a_{S_{RR}}^{uibc} \right) \Bigg] \Bigg\} \\ \mathcal{A}(\bar{B}_q \to D_q^{*+} P^-) =\, & \mathcal{A}(\bar{B}_q \to D_q^{*+} P^-)_{\rm SM} \times \\ & \Bigg\{ 1 + \frac{1}{2\sqrt{2} G_F V_{cb} V_{ui}^* C_2} \Bigg[\left(- a_{V_{LL}}^{cbiu} - a_{V_{RR}}^{cbiu} + a_{V_{LR}}^{cbiu} + a_{V_{LR}}^{uibc} \right) \\ & + \frac{m_P^2}{(m_u + m_{d_i})(m_b + m_c)} \left(a_{S_{RL}}^{cbiu} + a_{S_{LR}}^{cbiu} - a_{S_{RR}}^{cbiu} - a_{S_{RR}}^{uibc} \right) \Bigg] \Bigg\} \end{aligned}$$

$$R(X \to YZ) = \frac{|\mathcal{A}(X \to YZ)|^2}{|\mathcal{A}(X \to YZ)_{\rm SM}|^2}$$

3 General EFT analysis of $b \to cud_i$

* These are $a^{cbiu}_{V_{LL}}$, $a^{cbiu}_{V_{LR}}$, $a^{cbiu}_{S_{RR}}$ and $a^{cbiu}_{S_{RL}}$. The other half can not fit the data well.

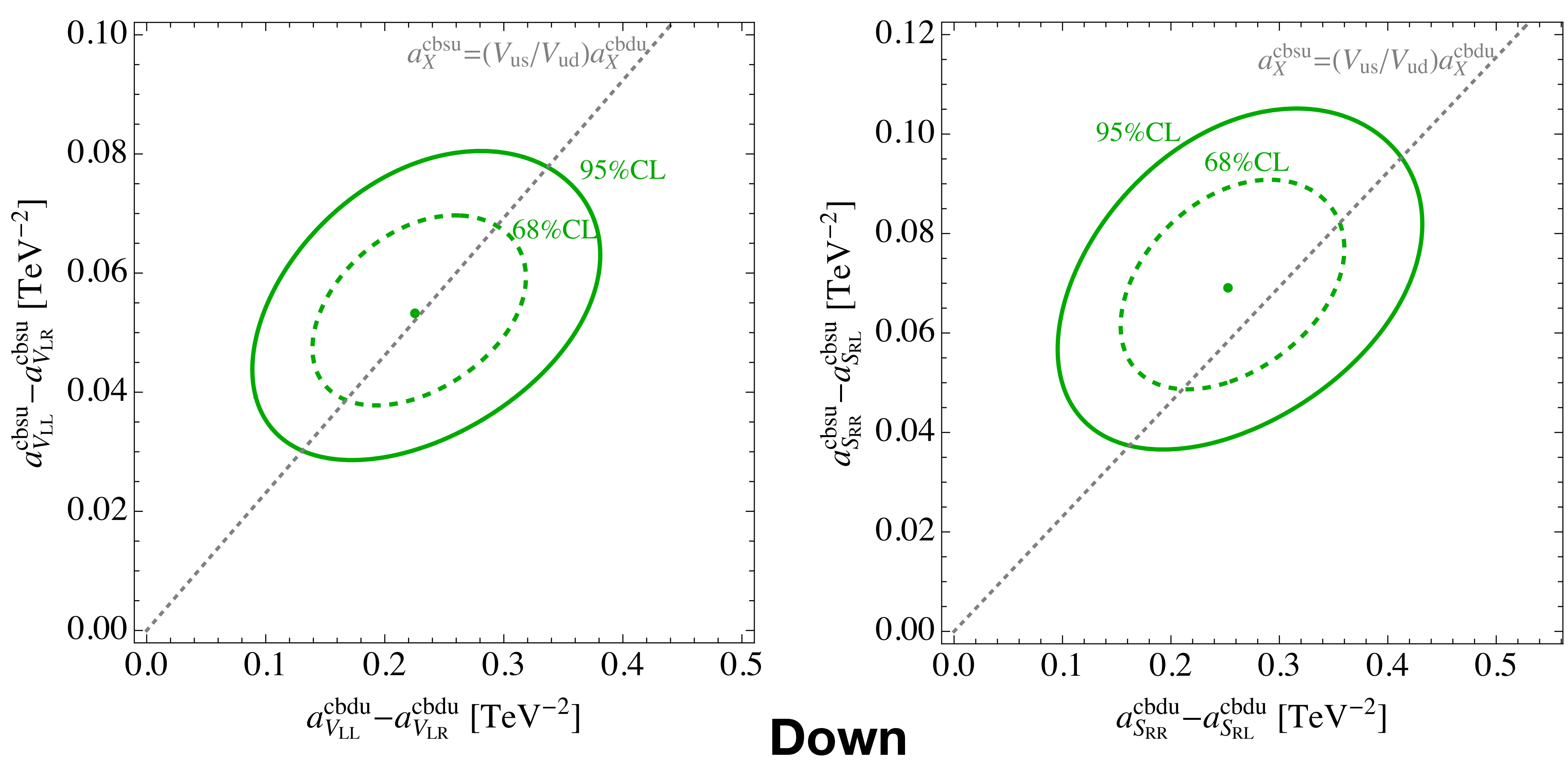
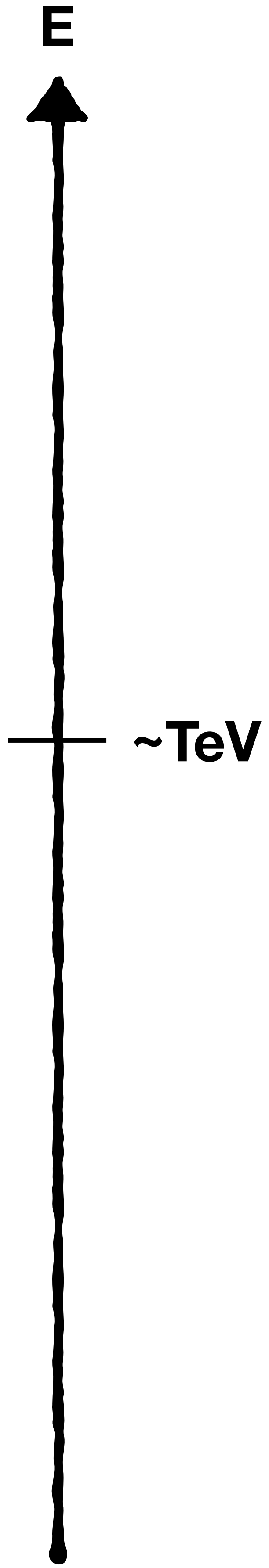
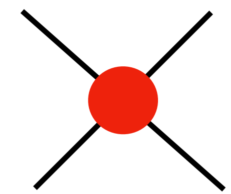


Figure 4. Low-energy EFT fit to $\bar{B}_q \to D_q^{+(*)} P^-$ decays. Dashed and solid lines show 68% and 95% CL regions for vector operators (**left panel**) and scalar operators (**right panel**). The gray dotted line is consistent with the relative size following the CKM ratio V_{us}/V_{ud}.

- We focus on weakly-coupled extensions of the SM.
- TeV-scale physics, likely tree-level.

Simplifed mediator models matching to the SMEFT





$[\mathcal{O}^{(1)}_{qq}]_{ijkl} = (\bar{q}^i_L \gamma_\mu q^j_L)(\bar{q}^k_L \gamma_\mu q^l_L)$	$[\mathcal{O}^{(3)}_{qq}]_{ijkl} = (\bar{q}^i_L \sigma^a \gamma_\mu q^j_L)(\bar{q}^k_L \sigma^a \gamma_\mu q^l_L)$
$[\mathcal{O}^{(1)}_{ud}]_{ijkl} = (\bar{u}^i_R \gamma_\mu u^j_R)(\bar{d}^k_R \gamma_\mu d^l_R)$	$[\mathcal{O}^{(8)}_{ud}]_{ijkl} = (\bar{u}^i_R T^A \gamma_\mu u^j_R)(\bar{d}^k_R T^A \gamma_\mu d^l_R)$
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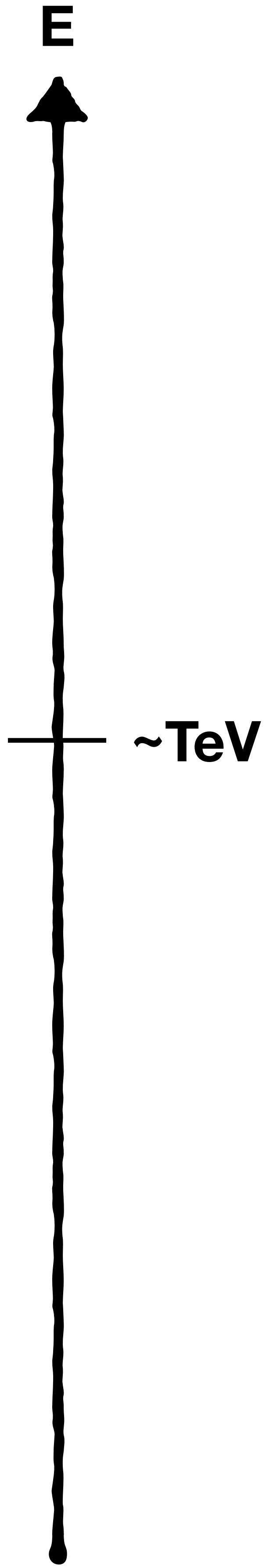
Table 3. SMEFT operators relevant for $b \to c\bar{u}d_i$ transitions.

Simplifed mediator models matching to the SMEFT



without also necessarily inducing dangerous $\Delta F = 2$ at tree-level

$$\text{spin-0:} \quad \begin{cases} \Phi_1 = (\mathbf{1}, \mathbf{2}, 1/2), \quad \Phi_8 = (\mathbf{8}, \mathbf{2}, 1/2), \\ \Phi_3 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3), \quad \Psi_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3), \quad \Phi_6 = (\mathbf{6}, \mathbf{1}, 1/3), \end{cases}$$

$$\text{spin-1:} \quad \{ \mathcal{Q}_3 = (\mathbf{3}, \mathbf{2}, 1/6), \quad \mathcal{Q}_6 = (\bar{\mathbf{6}}, \mathbf{2}, 1/6) \ .$$

$W' = (\mathbf{1}, \mathbf{3}, 0)$
2008.01086

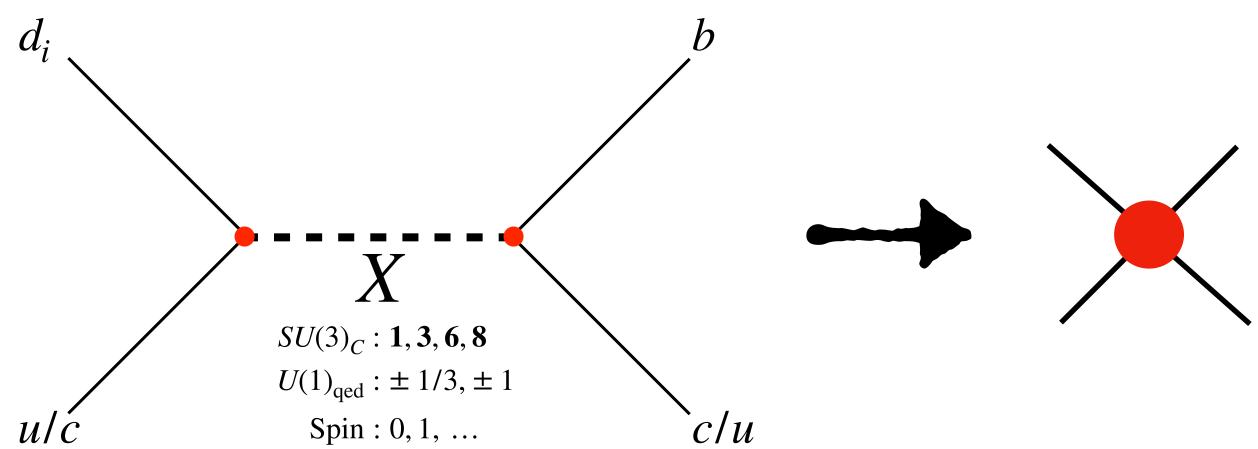


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Table 3. SMEFT operators relevant for $b \to c\bar{u}d_i$ transitions.

Collider

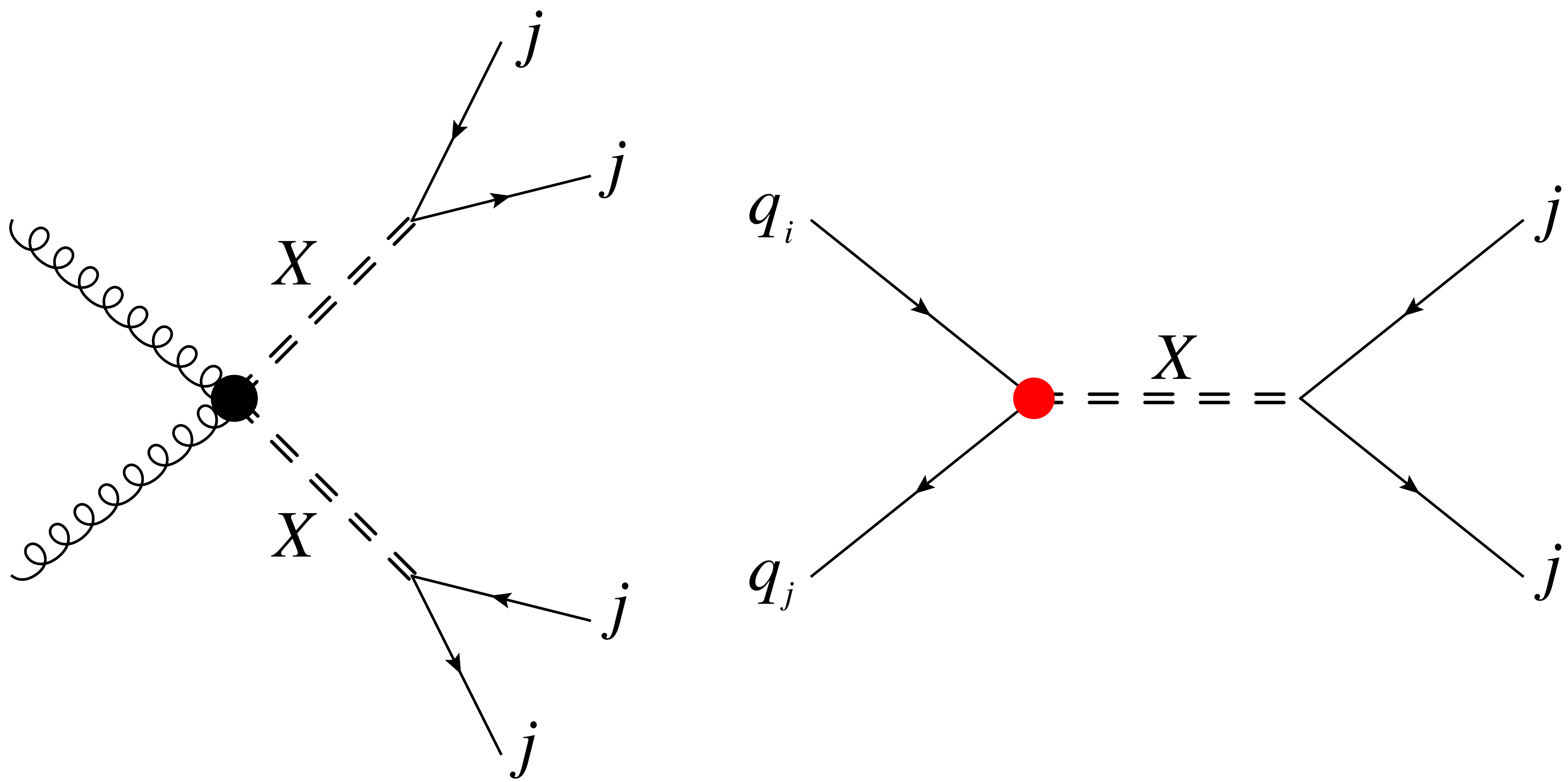


Figure 1. Representative Feynman diagrams for the pair production $pp \to XX \to (jj)(jj)$ (**left diagram**) and the single production $pp \to X \to jj$ (**right diagram**) of a dijet resonance X at the LHC. The constraints from the existing searches are reported in Section 2 for different representations and flavor interactions.

Collider

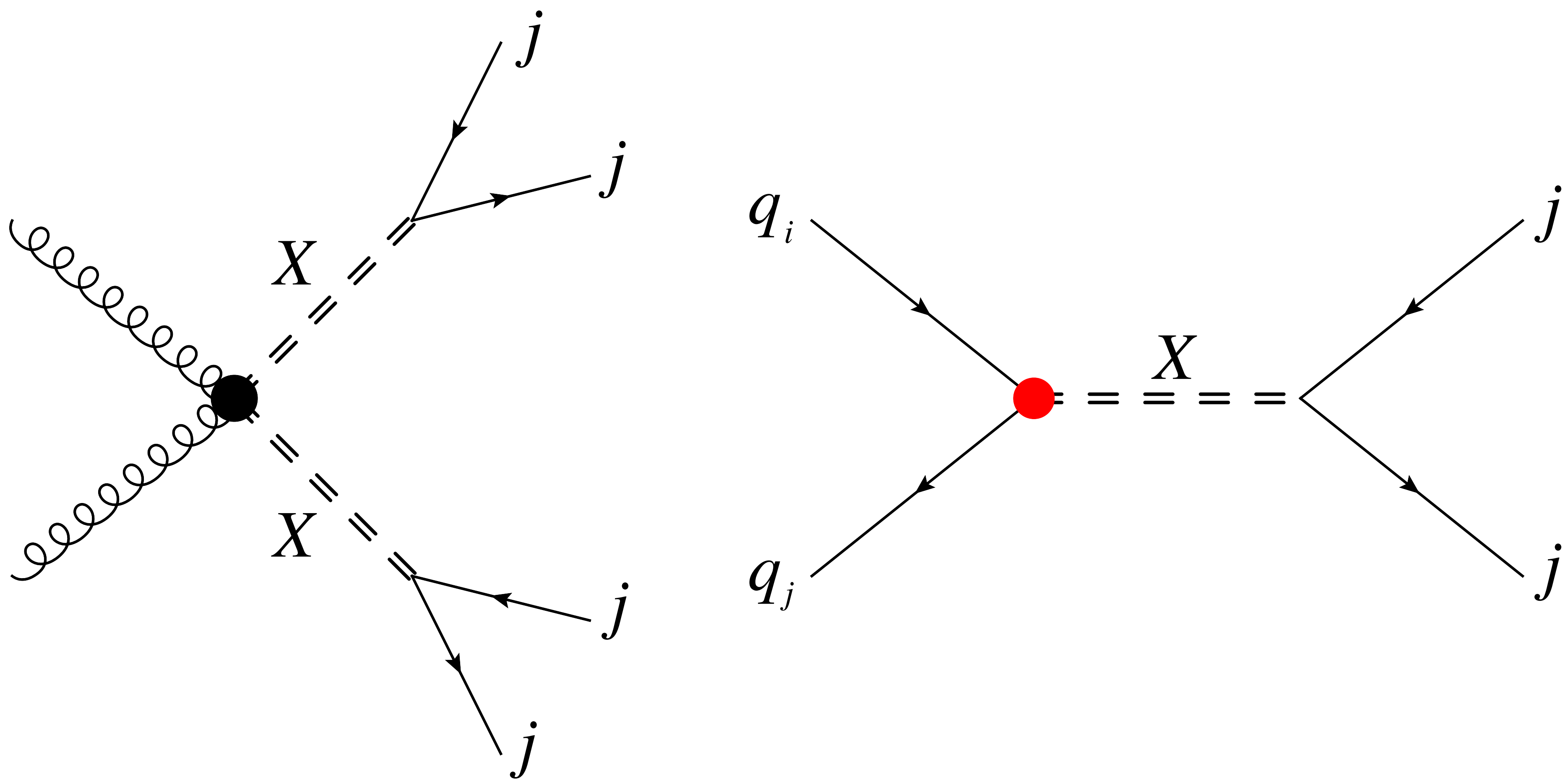


Figure 1. Representative Feynman diagrams for the pair production $pp \to XX \to (jj)(jj)$ (**left diagram**) and the single production $pp \to X \to jj$ (**right diagram**) of a dijet resonance X at the LHC. The constraints from the existing searches are reported in Section 2 for different representations and flavor interactions.

- In the most general case, when additional (sizeable) interactions are present, the resonance decays (promptly) to either dijet, charged leptons, top quark, electroweak gauge bosons, or exotic charged particles.
- For comparable rates, the dijet final state is hardest to detect at hadron colliders due to the overwhelming QCD background.

2.1 Pair production of dijet resonances

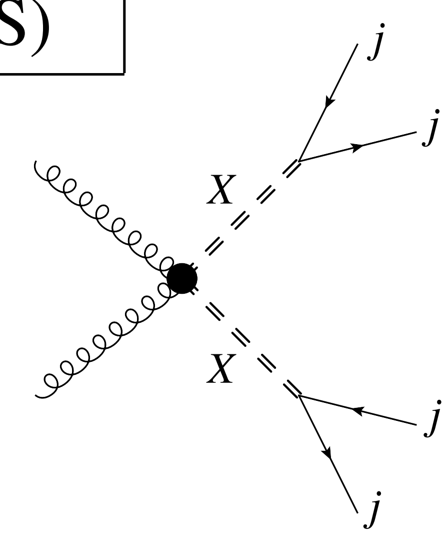
- The pair production rate is robustly set by the resonance mass m_X and its gauge representation.

$$\text{(LEP – II)} \quad m_{X^{\pm 1/3}} \gtrsim 80\,\text{GeV}\,,\; m_{X^{\pm 1}} \gtrsim 95\,\text{GeV}$$

ATLAS and CMS searches at 13 TeV with about $36\,\text{fb}^{-1}$

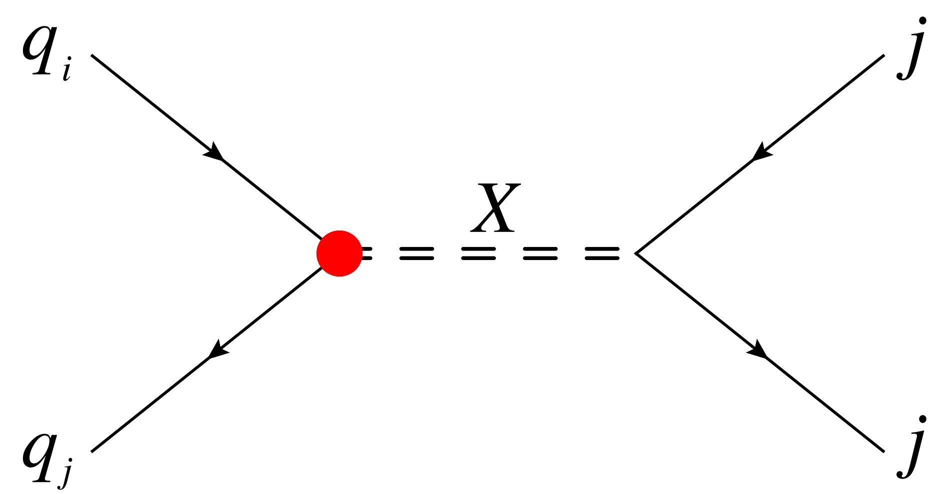
Scalar	**(3,1)**	**(6,1)**	**(8,1)**
$m_X >$	410 GeV (ATLAS) 520 GeV (CMS)	820 GeV (ATLAS) 950 GeV (CMS)	1050 GeV (ATLAS) 1000 GeV (CMS)
Scalar	**(3,3)**	**(6,3)**	**(8,2)**
$m_X >$	620 GeV (ATLAS) 750 GeV (CMS)	1200 GeV (ATLAS) 1200 GeV (CMS)	1200 GeV (ATLAS) 1200 GeV (CMS)

*From LEP II onwards



2.2 Dijet resonance

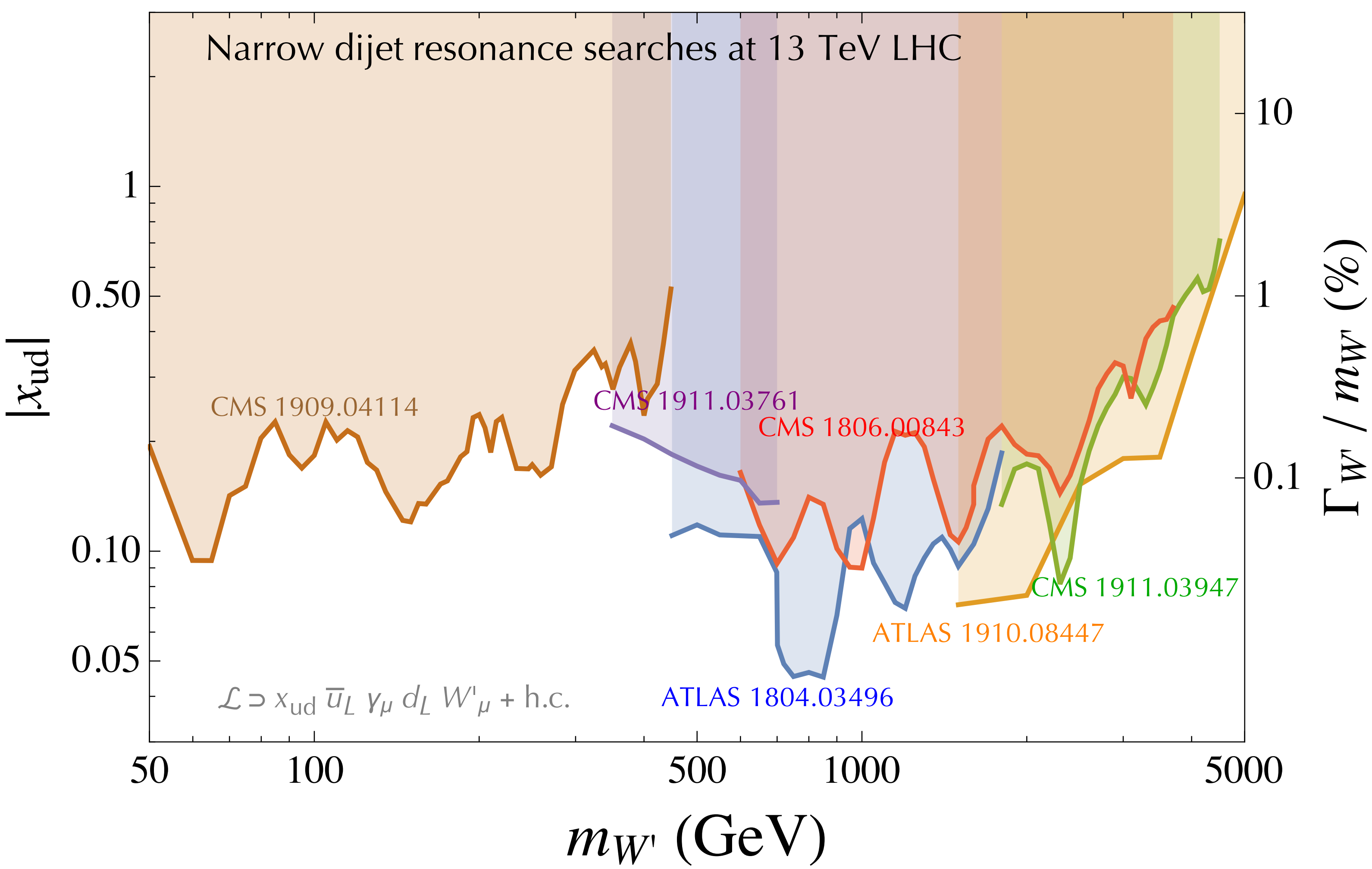
W' example



$$\mathcal{L} \supset x_{ij}\, \bar{u}_L^i \gamma^\mu d_L^j\, W'_\mu + \text{h.c.}$$

$$\Gamma_{W' \to u^i \bar{d}^j} = \frac{m_{W'}}{8\pi} |x_{ij}|^2$$

$$\sigma(pp \to W') = \frac{8\pi^2}{3 s_0} \frac{\Gamma_{W' \to u^i \bar{d}^j}}{m_{W'}} \int_\tau^1 dx\, \frac{1}{x}\, f^p_{u^i}(x)\, f^p_{\bar{d}^j}(\tau/x)$$



2.2 Dijet resonance : General case

Xud couplings

$$(0,\mathbf{1}): \qquad \mathcal{L} \supset x_{ij}\, X\, \bar{q}_i P_X q'_j \; + \text{h.c.}\,,$$

$$(0,\mathbf{3}): \qquad \mathcal{L} \supset x_{ij}\, X^\alpha\, \epsilon_{\alpha\beta\gamma}\, \bar{q}^{c\beta}_i P_X q'^{\gamma}_j + \text{h.c.}\,,$$

$$(0,\mathbf{6}): \qquad \mathcal{L} \supset x_{ij}\, X^m\, S^m_{\alpha\beta}\, \bar{q}^{c(\alpha|}_i P_X q'^{|\beta)}_j + \text{h.c.}\,,$$

$$(0,\mathbf{8}): \qquad \mathcal{L} \supset x_{ij}\, X^A\, \bar{q}_i T^A P_X q'_j \; + \text{h.c.}\,,$$

$$(1,\mathbf{1}): \qquad \mathcal{L} \supset x_{ij}\, X_\mu\, \bar{q}_i \gamma^\mu P_X q'_j \; (+\text{h.c.})\,,$$

$$(1,\mathbf{3}): \qquad \mathcal{L} \supset x_{ij}\, X^\alpha_\mu\, \epsilon_{\alpha\beta\gamma}\, \bar{q}^{c\beta}_i \gamma^\mu P_X q'^{\gamma}_j + \text{h.c.}\,,$$

$$(1,\mathbf{6}): \qquad \mathcal{L} \supset x_{ij}\, X^m_\mu\, S^m_{\alpha\beta}\, \bar{q}^{c(\alpha|}_i \gamma^\mu P_X q'^{|\beta)}_j + \text{h.c.}\,,$$

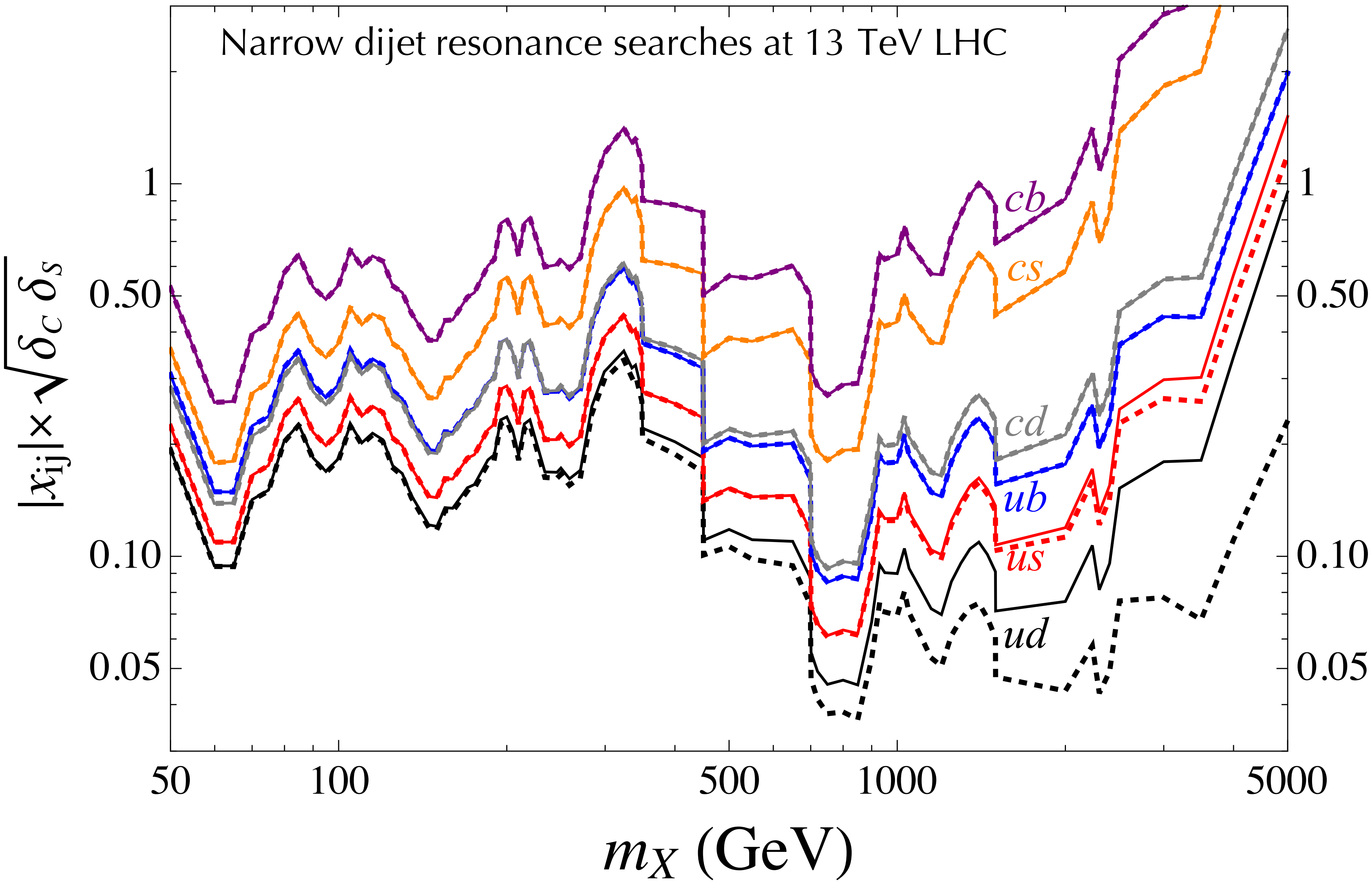
$$(1,\mathbf{8}): \qquad \mathcal{L} \supset x_{ij}\, X^A_\mu\, \bar{q}_i T^A \gamma^\mu P_X q'_j \; (+\text{h.c.})\,,$$

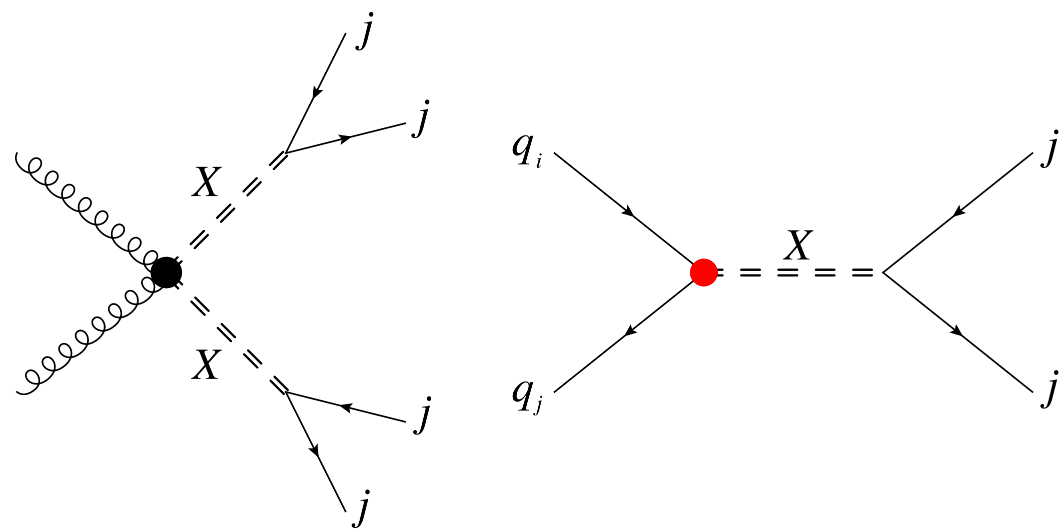
2.2 Dijet resonance : General case

$X\,ud$ couplings

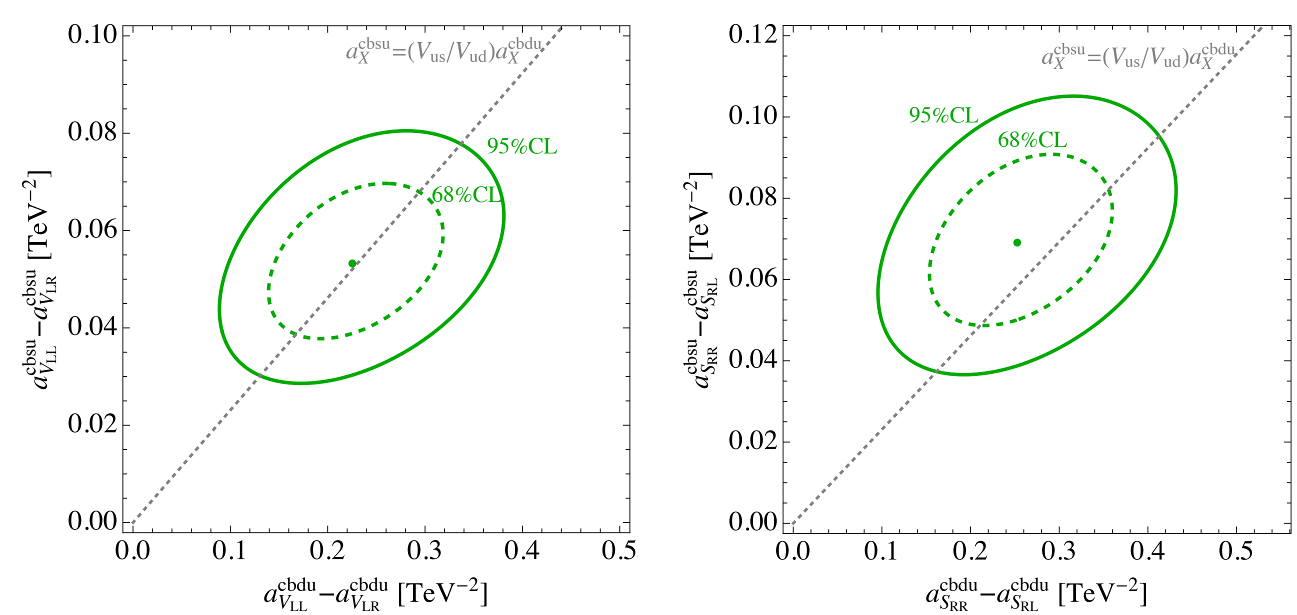
$SU(3)_c$	**1**	**3**	**6**	**8**
δ_C	1	2	2	4/3
γ_C	1	2/3	1/3	1/6

spin	**0**	**1**
δ_S	1/2	1
γ_S	3/2	1





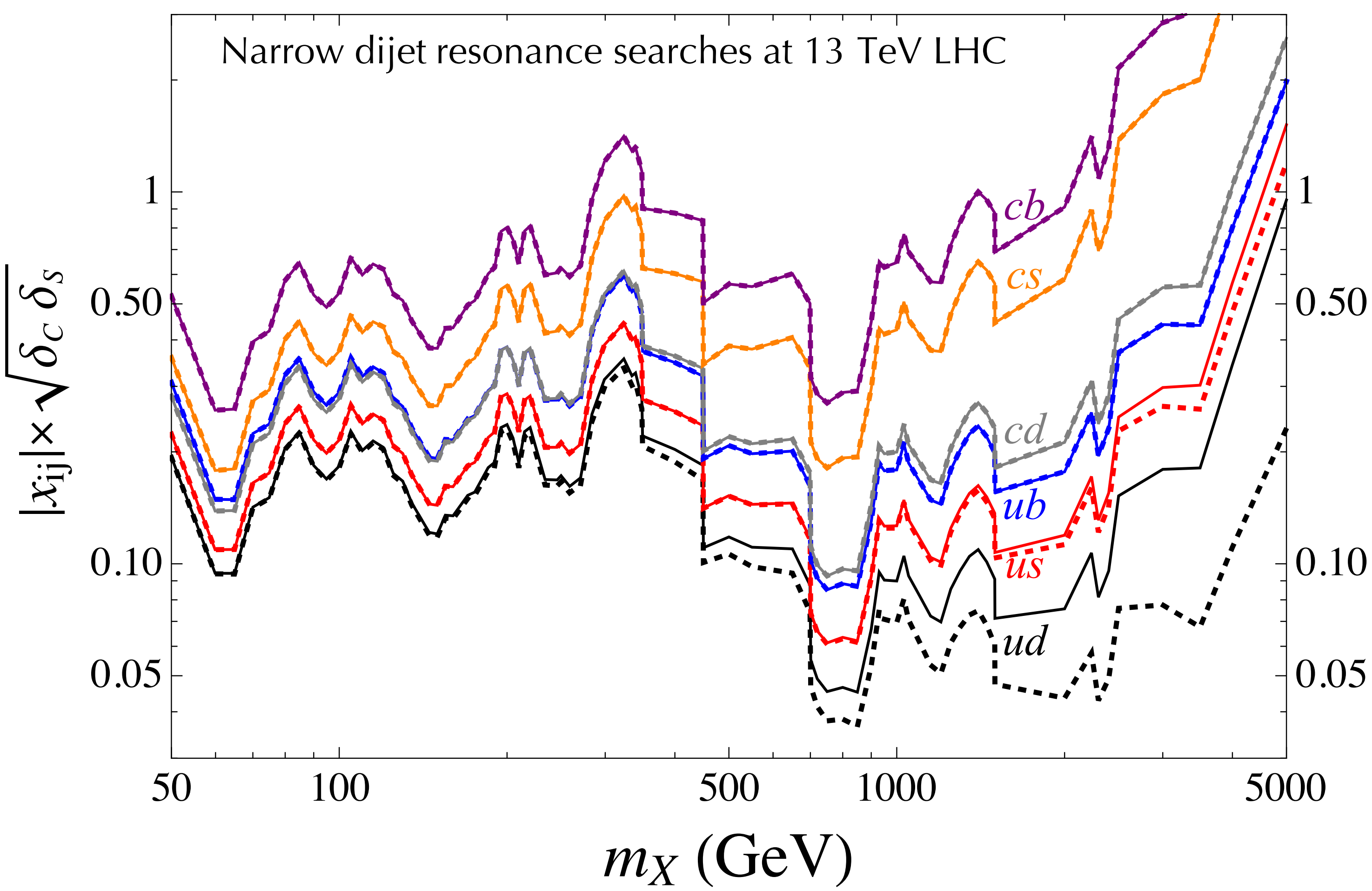
Combination



Non-leptonic meson decays depend on the product of two couplings when the resonance is integrated out at tree level. In particular, the product of the couplings entering those decays satisfies

$$|x_{q^i q^j}\, x^*_{q^k q^l}| = |x_{q^i q^j}| \times |x_{q^k q^l}| \,, \tag{4.2}$$

where both terms on the right-hand side are simultaneously constrained from non-observation of $\sigma(pp \to X \to jj)$ at high-p_T. Using this inequality, we can limit NP contributions in $\bar{B}_q \to D_q^{(*)+}\{\pi, K\}$ decays.



Model example

Color-sextet diquark $\mathbf{\Phi_6}$

$$\mathcal{L}_{\Phi_6} \supset y^L_{ij} \mathbf{\Phi}_6^{\alpha\beta\dagger} \bar{q}^{c\,(\alpha|}_{Li} (i\sigma_2) q^{|\beta)}_{Lj} + y^R_{ij} \mathbf{\Phi}_6^{\alpha\beta\dagger} \bar{u}^{c\,(\alpha|}_{Ri} d^{|\beta)}_{Rj} + \text{h.c.}$$

$$y^L = \begin{pmatrix} 0 & y^L_{12} & 0 \\ -y^L_{12} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad y^R = \begin{pmatrix} 0 & 0 & y^R_{13} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$U(2)_q$ symmetry

Model example

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$U(2)_q$ symmetry

$$a^{cbdu}_{S_{RR}} \approx \frac{2}{3} \kappa^S_{\mathrm{RGE}} V_{cs} \frac{y^{L*}_{12} y^R_{13}}{M^2_{\Phi_6}} \approx \frac{0.26 V_{cs}}{\mathrm{TeV}^2}, \qquad a^{cbsu}_{S_{RR}} \approx -\frac{2}{3} \kappa^S_{\mathrm{RGE}} V_{cd} \frac{y^{L*}_{12} y^R_{13}}{M^2_{\Phi_6}} \approx \frac{-0.31 V_{cd}}{\mathrm{TeV}^2}$$

$$|y^L_{12} y^R_{13}| < |y^L_{12}|^{\max} |y^R_{13}|^{\max}$$

$$us \to \Phi_6 \qquad ub \to \Phi_6$$

Model example

Color-sextet diquark Φ_6

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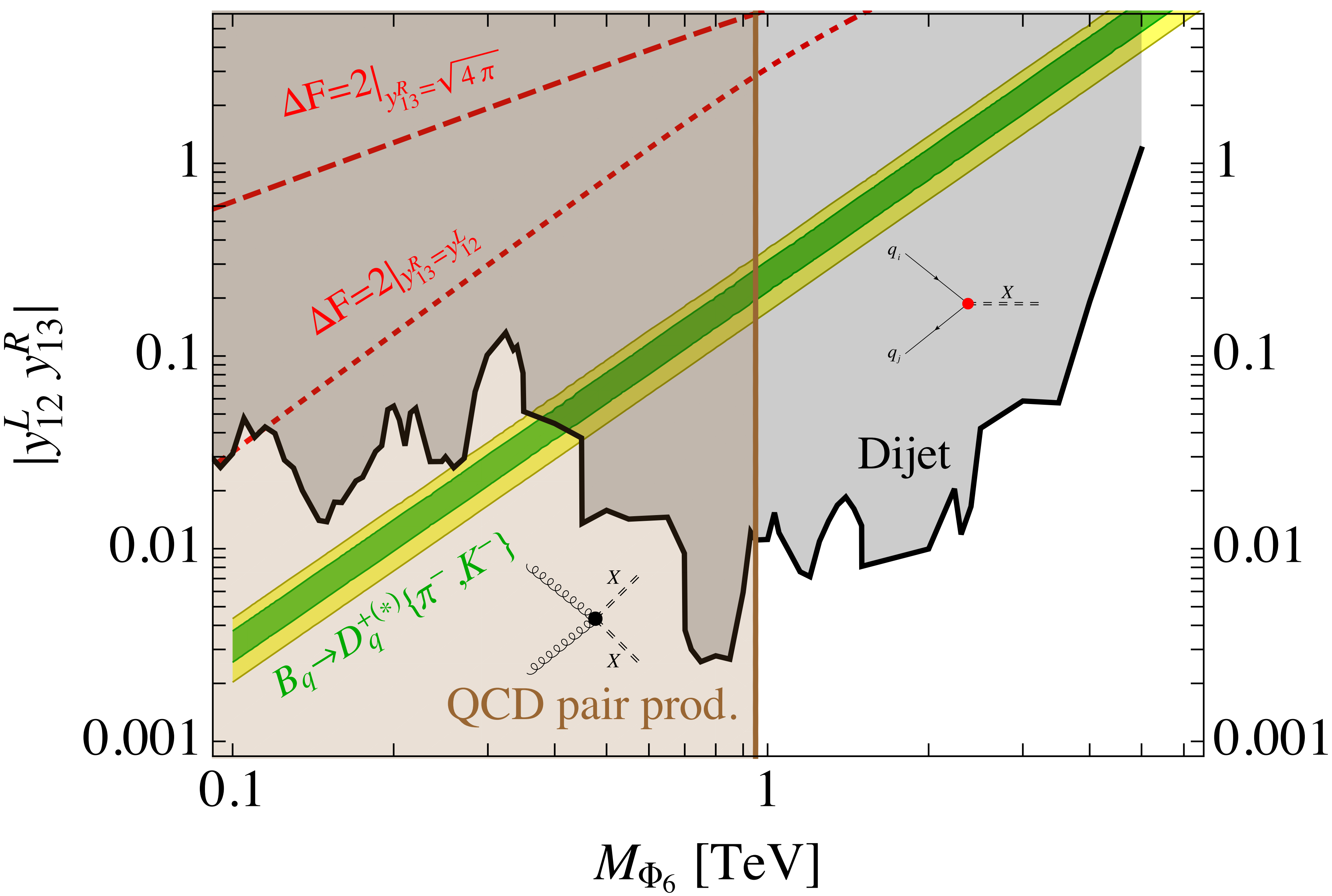
$U(2)_q$ symmetry

$$\frac{\Gamma_{\Phi_6}}{M_{\Phi_6}} = \frac{8|y^L_{12}|^2 + |y^R_{13}|^2}{16\pi}$$



Model example

Color-sextet diquark Φ_6

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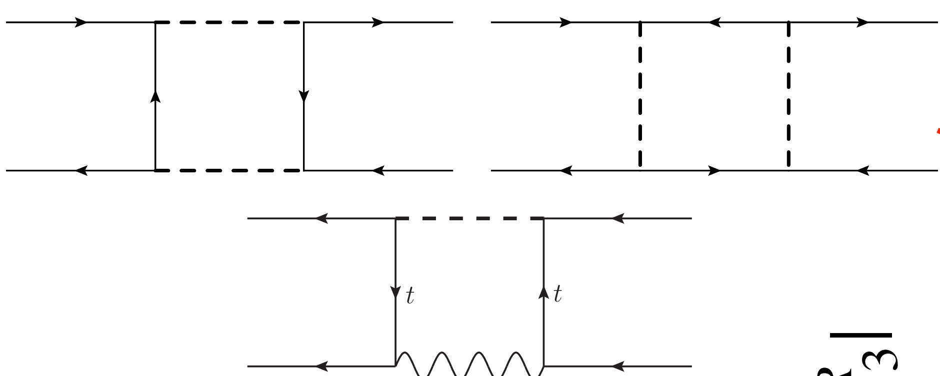
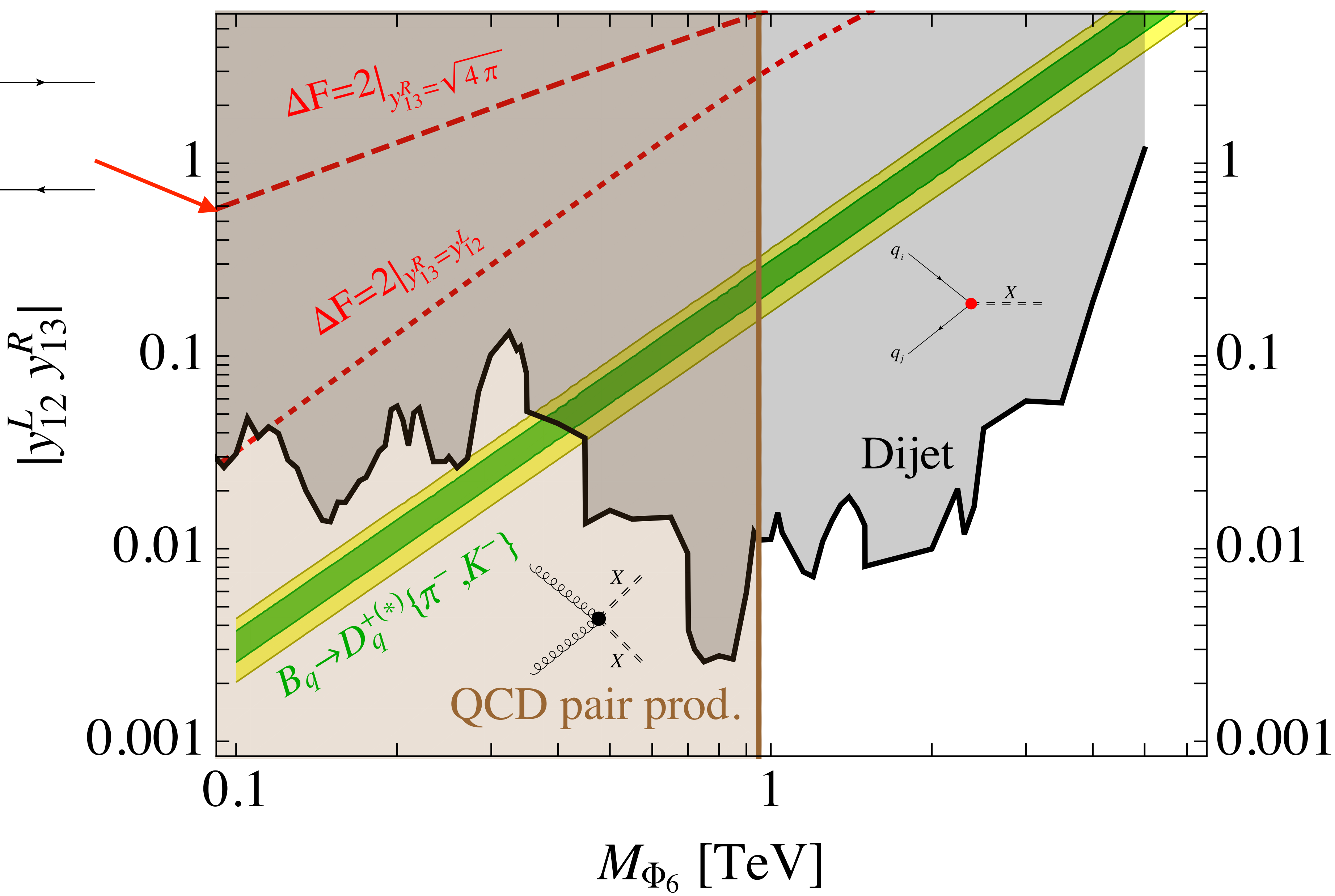
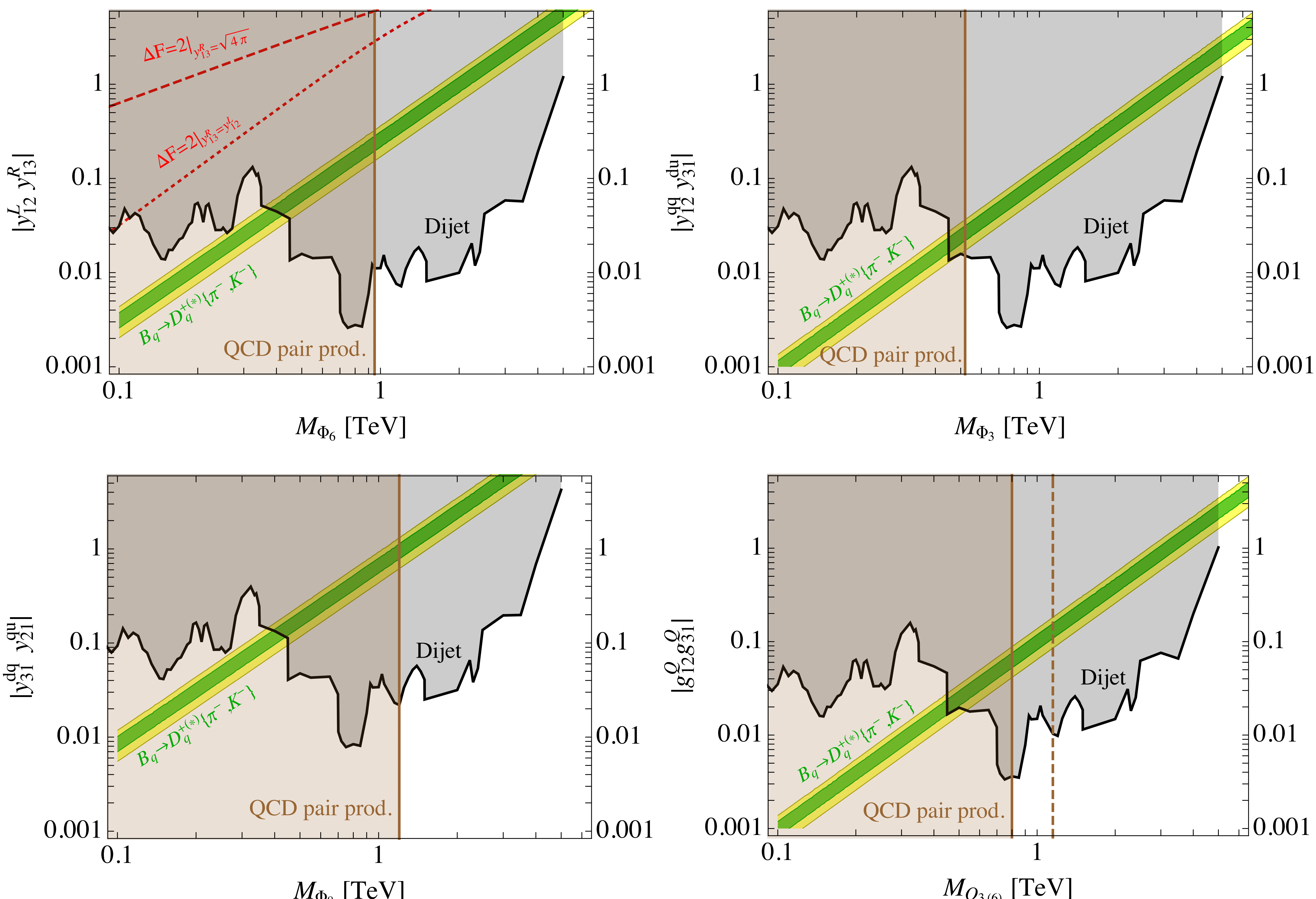
$U(2)_q$ symmetry



$$\frac{\Gamma_{\Phi_6}}{M_{\Phi_6}} = \frac{8|y^L_{12}|^2 + |y^R_{13}|^2}{16\pi}$$



4.1 Colored mediators



4.2 Colorless scalar doublet model $\Phi_1 = (\mathbf{1}, \mathbf{2}, 1/2)$

- Pair production limits only from LEP-II

(designed ad-hoc to avoid tree-level contributions to meson mixing **)**

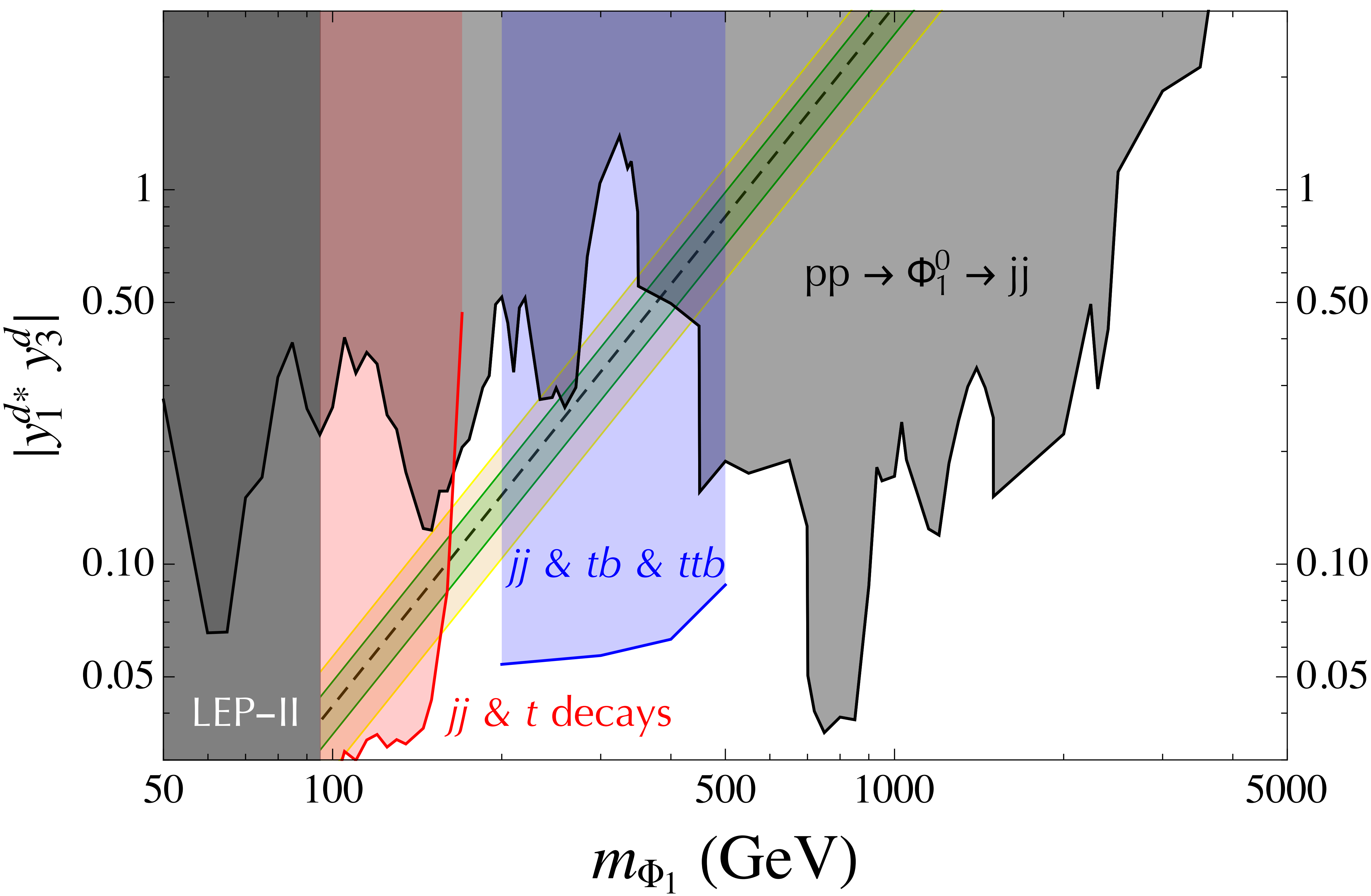
Benchmark I — The couplings of the extra scalar Φ_1 are exclusively to the right-handed down quarks and are diagonal in the down-quark mass basis,

$$\mathcal{L}_{\Phi_1}^{\rm Yuk} = y_i^d \, \Phi_1^\dagger \bar{d}_R^i q_L^i \, + {\rm h.c.}, \tag{4.14}$$

where $q_L^i = (V_{ji}^* u_L^j, d_L^i)^T$. Integrating out the scalar Φ_1, the LEFT operators $L_{ud}^{V1(8),LR}$ are generated at low energies, which contribute to the $a_{S_{RL}}^{ijkl}$ coefficients as

$$a_{S_{RL}}^{cbiu} = \kappa_{\rm RGE} V_{cb} V_{ui}^* \frac{y_3^{d*} y_i^d}{M_{\Phi_1}^2} \,, \tag{4.15}$$

4.2 Colorless scalar doublet model $\Phi_1 = (\mathbf{1}, \mathbf{2}, 1/2)$



4.2 Colorless scalar doublet model $\Phi_1 = (\mathbf{1}, \mathbf{2}, 1/2)$

$M_{\Phi_1} \sim m_t$, $y_3^d \sim 0.6$ and $y_2^d = y_1^d \sim 0.17$.

We could not excluded it by:

$\boldsymbol{\Delta F = 2}$ $\quad$ $\boldsymbol{Z \to b\bar{b}}$ $\quad$ $\boldsymbol{b \to s\ell^+\ell^-}$

Thanks