Searching for imprints of the $B \to D\{\pi, K\}$ puzzle in high-pT observables

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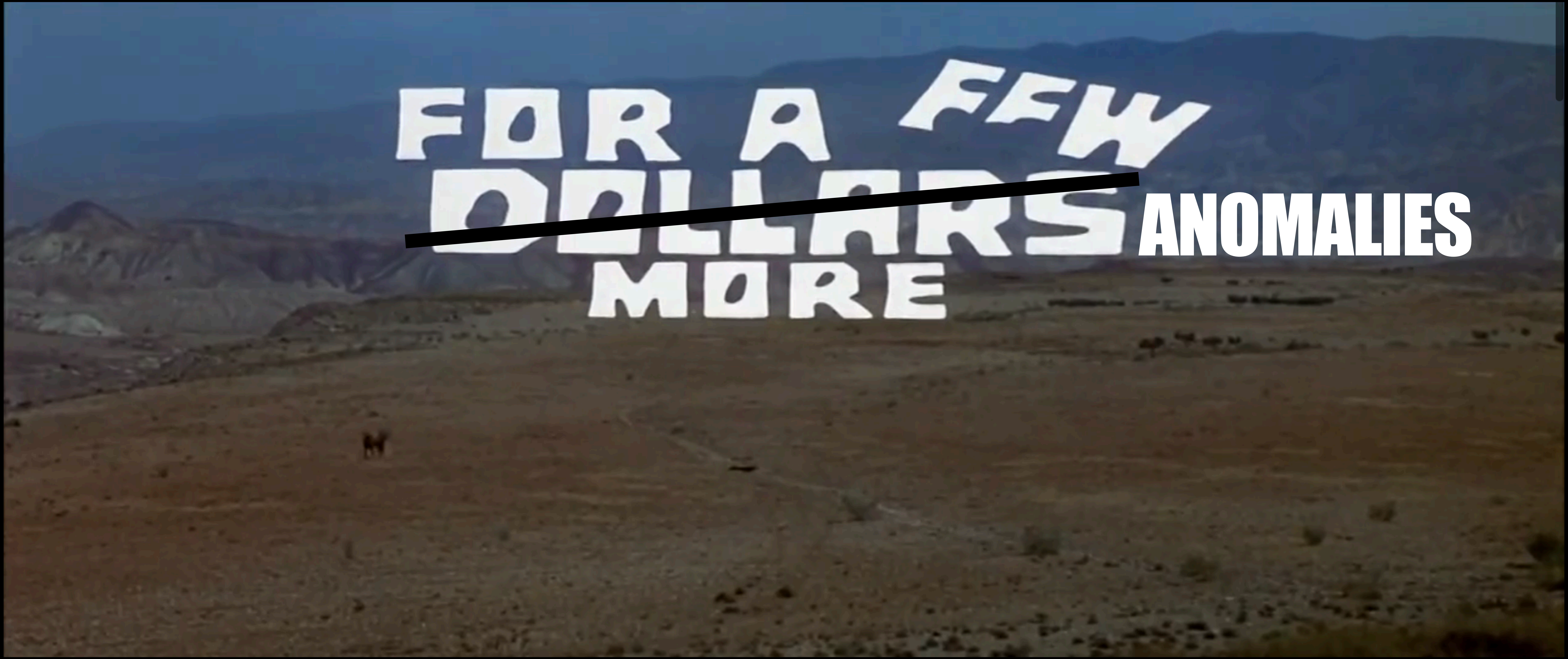
Based on: Marzia Bordone, Admir Greljo, DM [2103.10332]

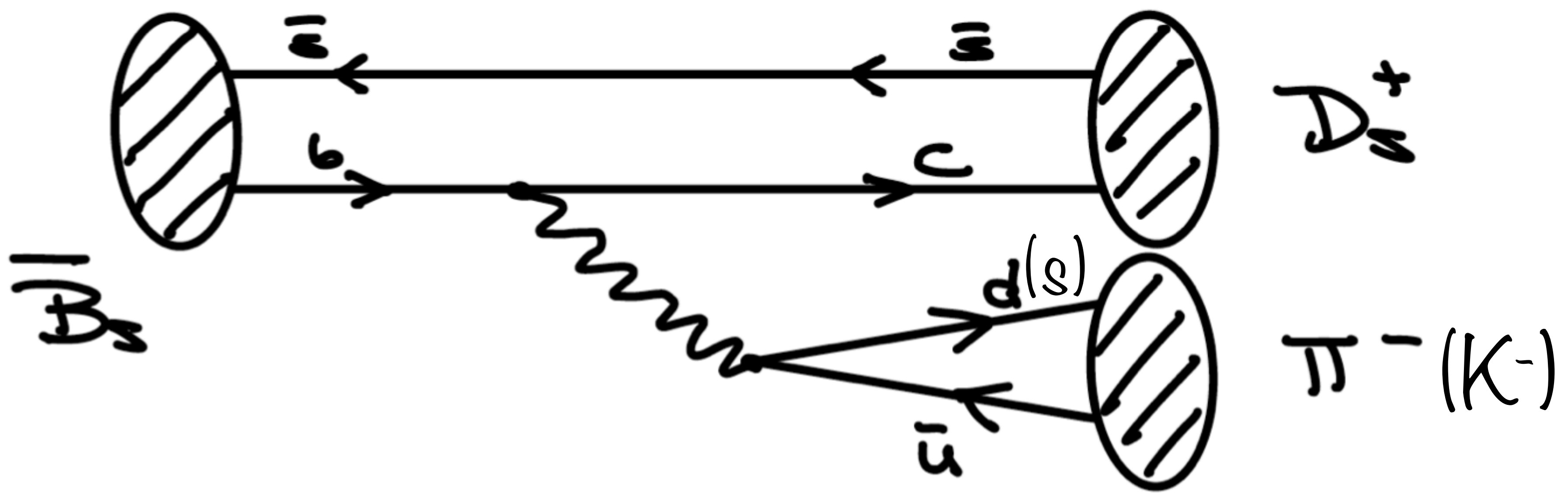
Beyond The Flavour Anomalies Workshop II - 22/04/2021


FOR A FEW
~~DOLLARS~~ ANOMALIES
MORE

A puzzle in $\bar{B}^0_{(s)} \to D^{(*)+}_{(s)}\{\pi^-, K^-\}$

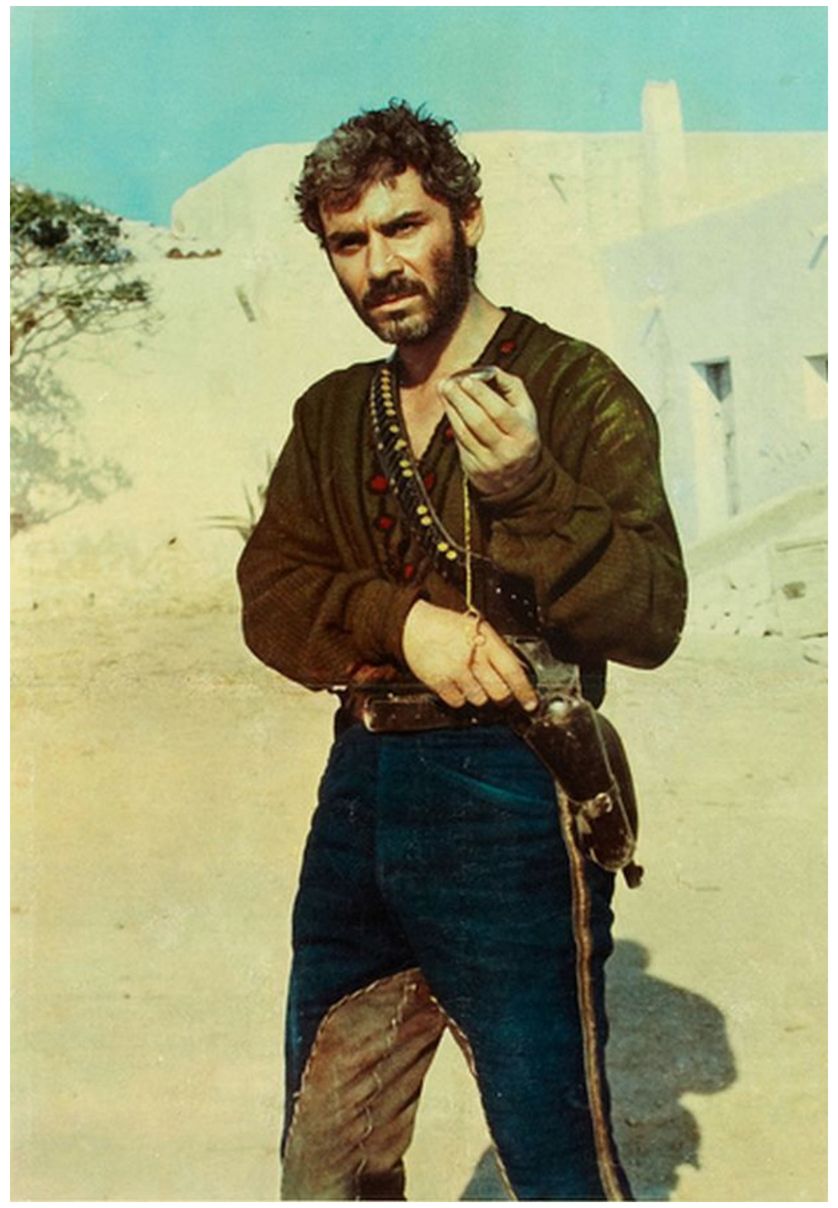
See talk by A. Lenz for more details.

$$b \to c\bar{u}d_i \qquad d_i = d, s$$



They are relatively simple and clean to predict, using to QCD factorisation and heavy-quark expansion See e.g. Beneke et al. [hep-ph/0006124]

These are tree-level weak decays in the SM, mildly suppressed by $V_{cb}\, V_{ud(s)}$.



A recent update of the Standard Model prediction, using updated values of CKM elements and higher-order computations, found a **tension with the experimental measurements** of **≳5σ**.

Bordone, Huber, Gubernari, van Dyk, Jung [2007.10338],

see also:
Fang-Min Cai, Wei-Jun Deng, Xin-Qiang Li, Ya-Dong Yang [2103.04138]

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

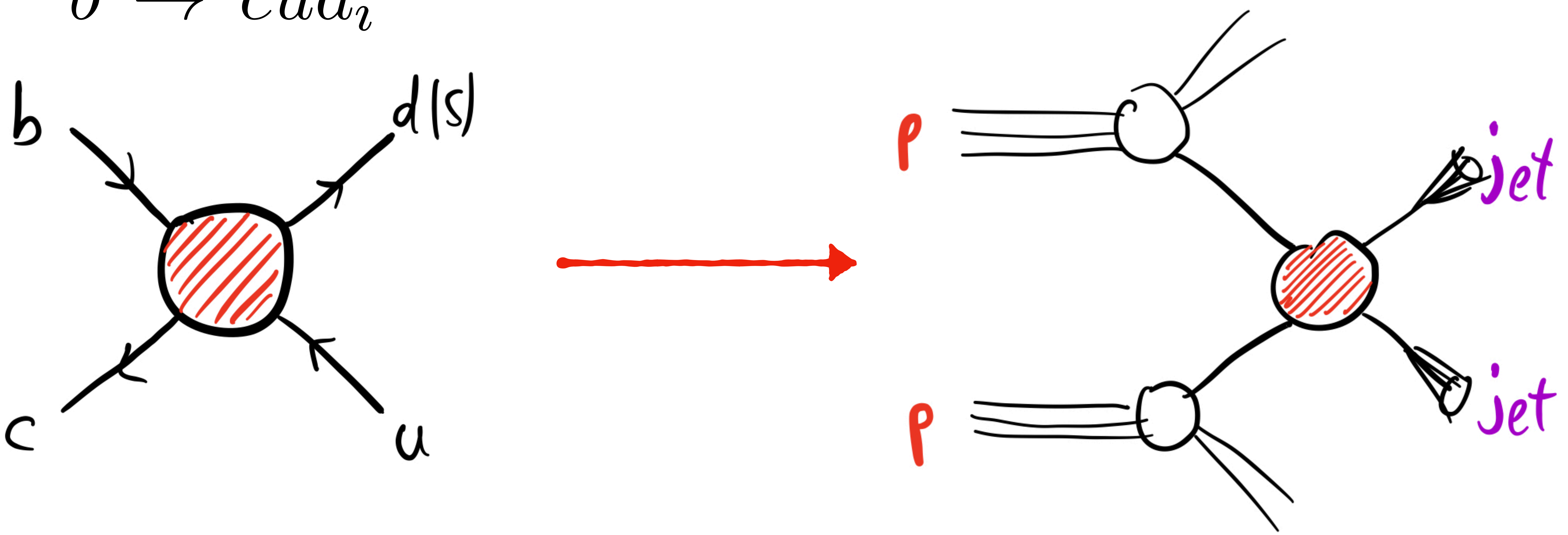
$$\begin{aligned} R(\bar{B}^0_s \to D_s^+\pi^-) &= 0.704 \pm 0.074 \\ R(\bar{B}^0 \to D^+K^-) &= 0.687 \pm 0.059 \\ R(\bar{B}^0_s \to D_s^{*+}\pi^-) &= 0.49 \pm 0.24 \\ R(\bar{B}^0 \to D^{*+}K^-) &= 0.66 \pm 0.13 \end{aligned} \qquad \rho = \begin{pmatrix} 1 & 0.36 & 0.16 & 0.092 \\ 0.36 & 1 & 0.072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

~ 30% depletion of the SM rates.

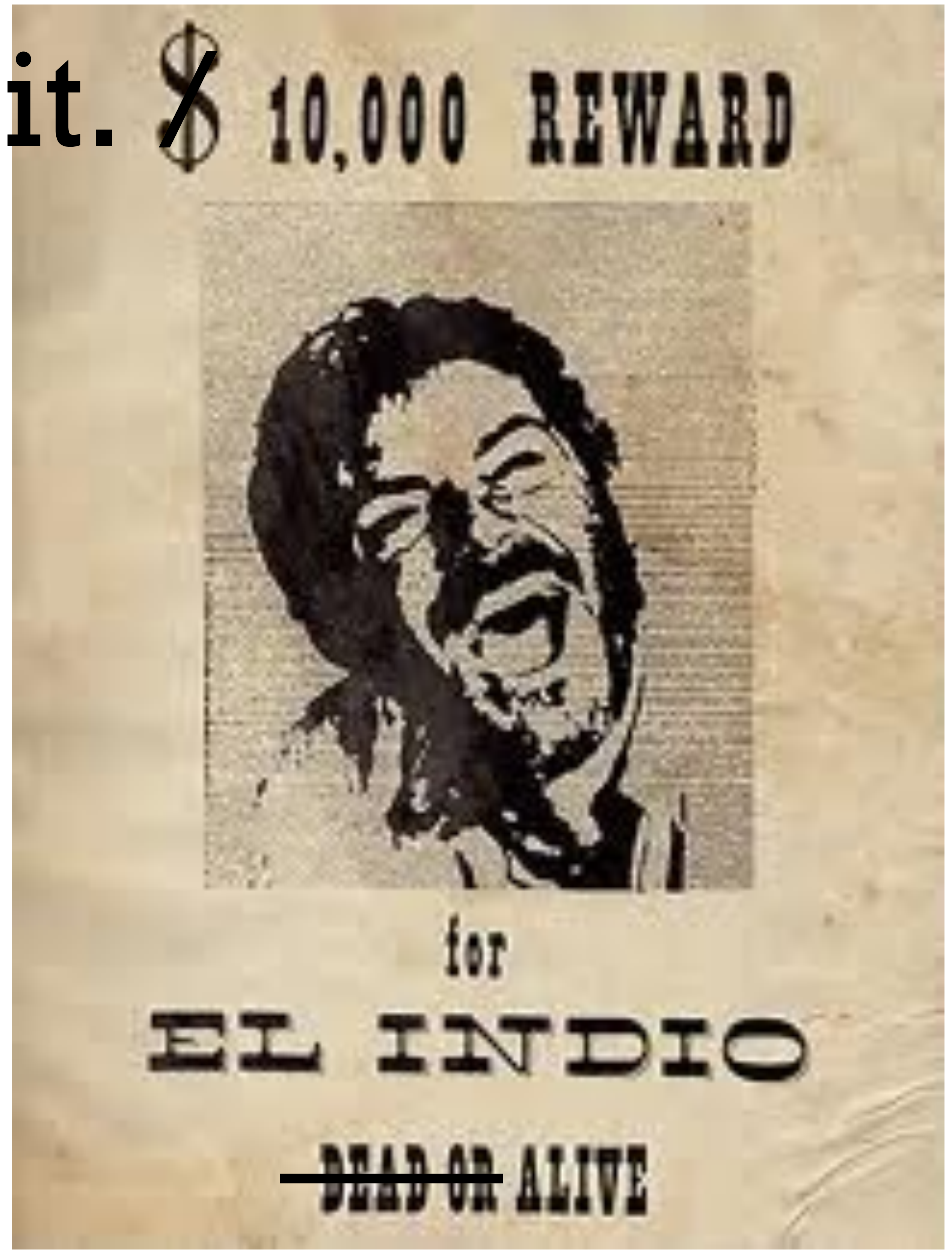
Towards a BSM interpretation

1. Is there a (possibly reasonable) New Physics explanation consistent with present flavor constraints?
2. What about di-jet limits from LHC?

$$b \to c\bar{u}d_i$$



Cit.



We need to characterise New Physics contributions to the decays, and connect with UV models.

Low-energy EFT dependence and fits

New Physics contributions to the decays: $\boldsymbol{\bar{B}^0_{(s)} \to D^{(*)+}_{(s)}\{\pi^-, K^-\}}$

$$\mathcal{L}_{\rm NP} = \sum_{i=1}^{7} (a_i\, \mathcal{Q}_i + a_i'\, \mathcal{Q}_i') + h.c.\,.$$

$$\begin{aligned}
\mathcal{Q}^{ijkl}_{V_{LL}} &= (\bar u^i_L \gamma_\mu d^j_L)(\bar d^k_L \gamma^\mu u^l_L)\,,\\
\mathcal{Q}^{ijkl}_{V_{RR}} &= (\bar u^i_R \gamma_\mu d^j_R)(\bar d^k_R \gamma^\mu u^l_R)\,,\\
\mathcal{Q}^{ijkl}_{V_{LR}} &= (\bar u^i_L \gamma_\mu d^j_L)(\bar d^k_R \gamma^\mu u^l_R)\,,\\
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\mathcal{Q}^{ijkl}_{T_{RR}} &= (\bar u^i_L \sigma_{\mu\nu} d^j_R)(\bar d^k_L \sigma^{\mu\nu} u^l_R)\,,
\end{aligned}$$

@ LO

$$\mathcal{A}(\bar B_q \to D_q^+ P^-) = \mathcal{A}(\bar B_q \to D_q^+ P^-)_{\rm SM} \times \Big\{1 + \frac{1}{2\sqrt{2} G_F V_{cb} V^*_{ui} C_2}\Big[\big(-a^{cbiu}_{V_{LL}} + a^{cbiu}_{V_{RR}} + a^{cbiu}_{V_{LR}} - a^{uibc}_{V_{LR}}\big) + \frac{m_P^2}{(m_u + m_{d_i})(m_b - m_c)}\big(a^{cbiu}_{S_{RL}} - a^{cbiu}_{S_{LR}} - a^{cbiu}_{S_{RR}} + a^{uibc}_{S_{RR}}\big)\Big]\Big\}$$

$$\mathcal{A}(\bar B_q \to D_q^{*+} P^-) = \mathcal{A}(\bar B_q \to D_q^{*+} P^-)_{\rm SM} \times \Big\{1 + \frac{1}{2\sqrt{2} G_F V_{cb} V^*_{ui} C_2}\Big[\big(-a^{cbiu}_{V_{LL}} - a^{cbiu}_{V_{RR}} + a^{cbiu}_{V_{LR}} + a^{uibc}_{V_{LR}}\big) + \frac{m_P^2}{(m_u + m_{d_i})(m_b + m_c)}\big(a^{cbiu}_{S_{RL}} + a^{cbiu}_{S_{LR}} - a^{cbiu}_{S_{RR}} - a^{uibc}_{S_{RR}}\big)\Big]\Big\}$$

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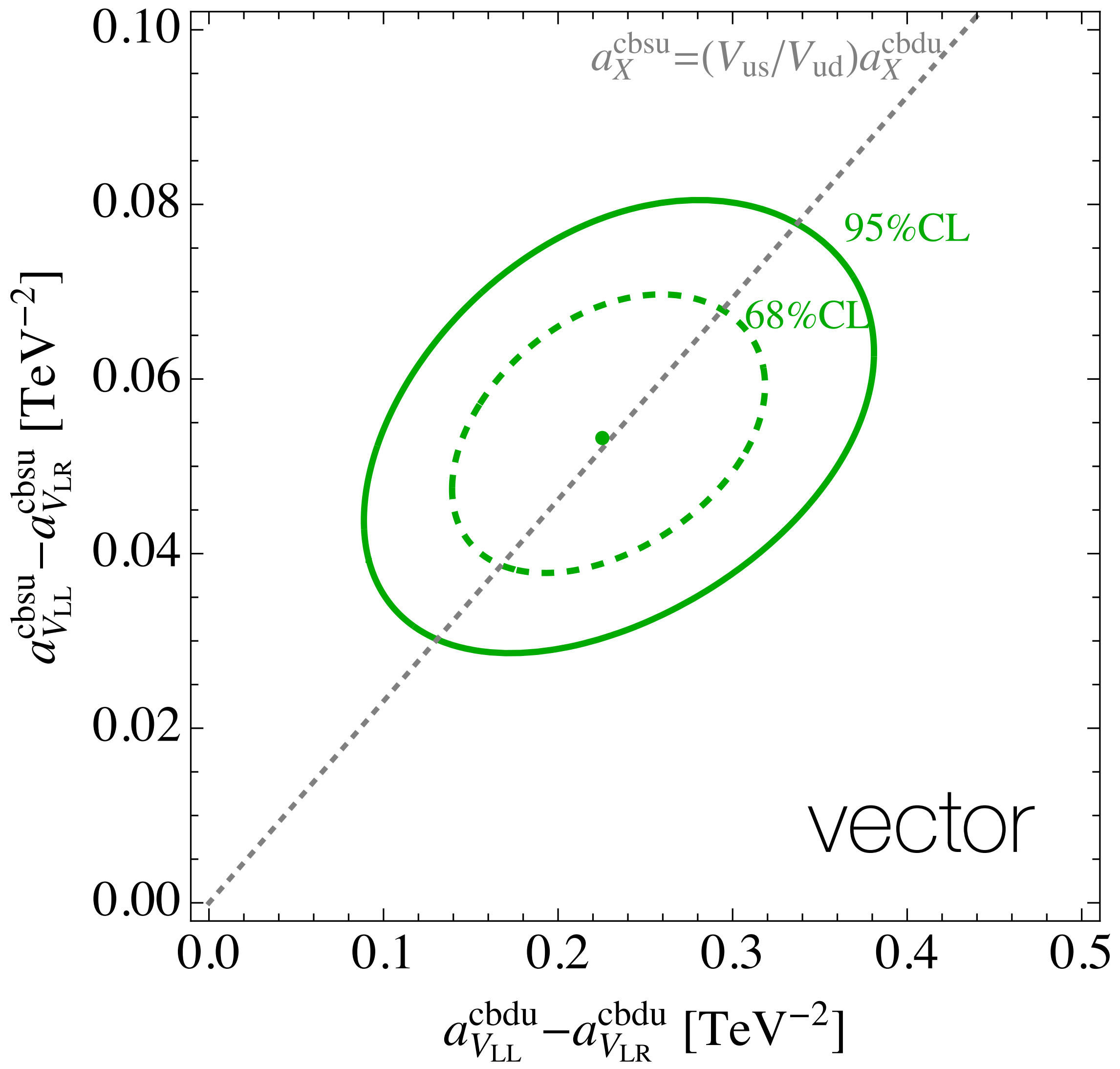

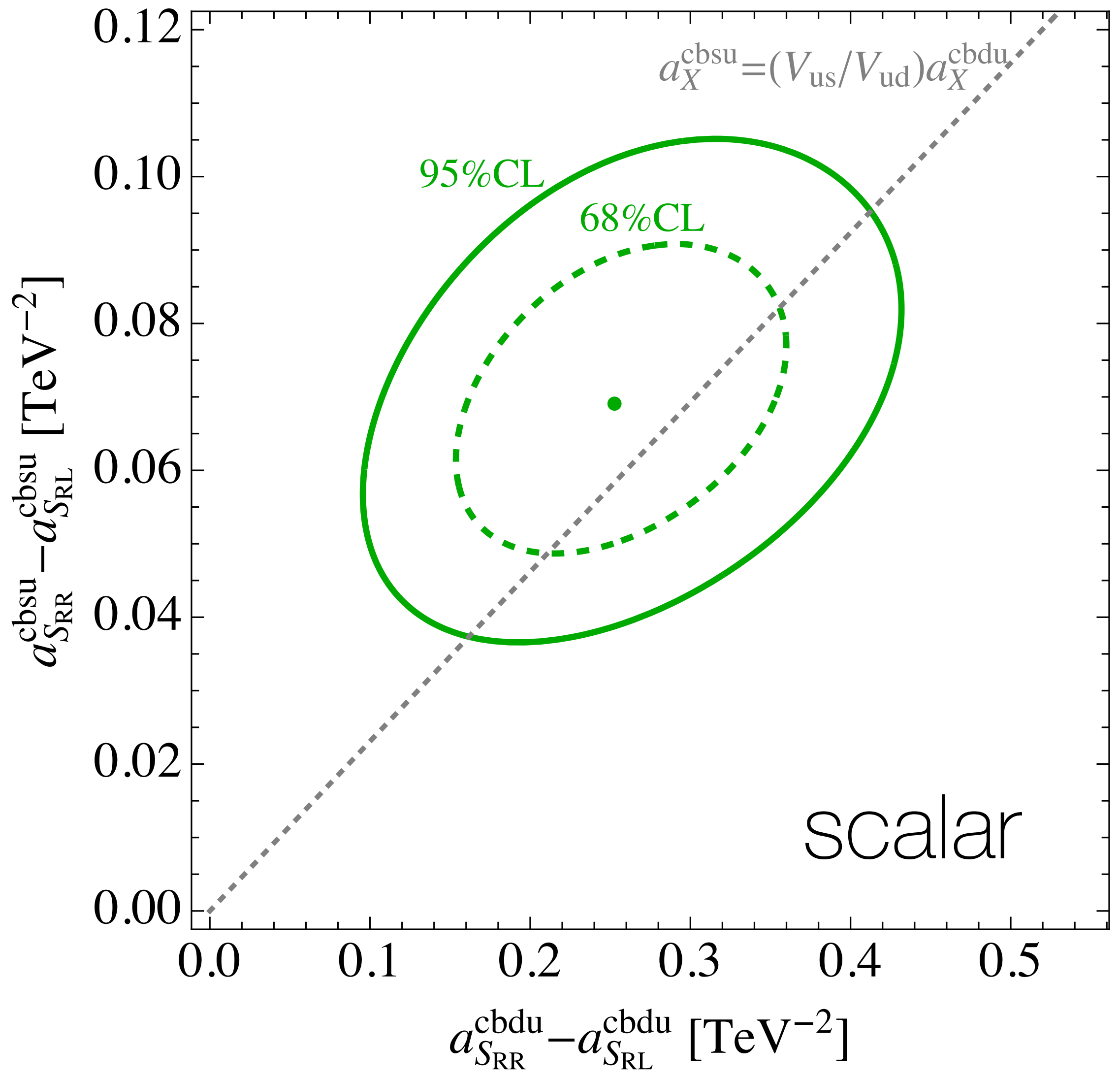

$$\text{vector:} \left\{ a^{cbdu}_{V_{LL}} - a^{cbdu}_{V_{LR}} \approx 0.23 V_{ud}\ \text{TeV}^{-2}\,, \quad a^{cbsu}_{V_{LL}} - a^{cbsu}_{V_{LR}} \approx 0.24 V_{us}\ \text{TeV}^{-2}\,, \right.$$

$$\text{scalar:} \left\{ a^{cbdu}_{S_{RR}} - a^{cbdu}_{S_{RL}} \approx 0.26 V_{ud}\ \text{TeV}^{-2}\,, \quad a^{cbsu}_{S_{RR}} - a^{cbsu}_{S_{RL}} \approx 0.31 V_{us}\ \text{TeV}^{-2}\,. \right.$$

Need TeV-scale New Physics that induces at tree-level a process that violates ALL QUARK FLAVORS!

Low-energy EFT dependence and fits

New Physics contributio

$$\mathcal{L}_{\rm NP} = \sum_{i=1}^{7} (a_i\, \mathcal{Q}_i + a_i'\, \mathcal{Q}_i') + h.c.$$

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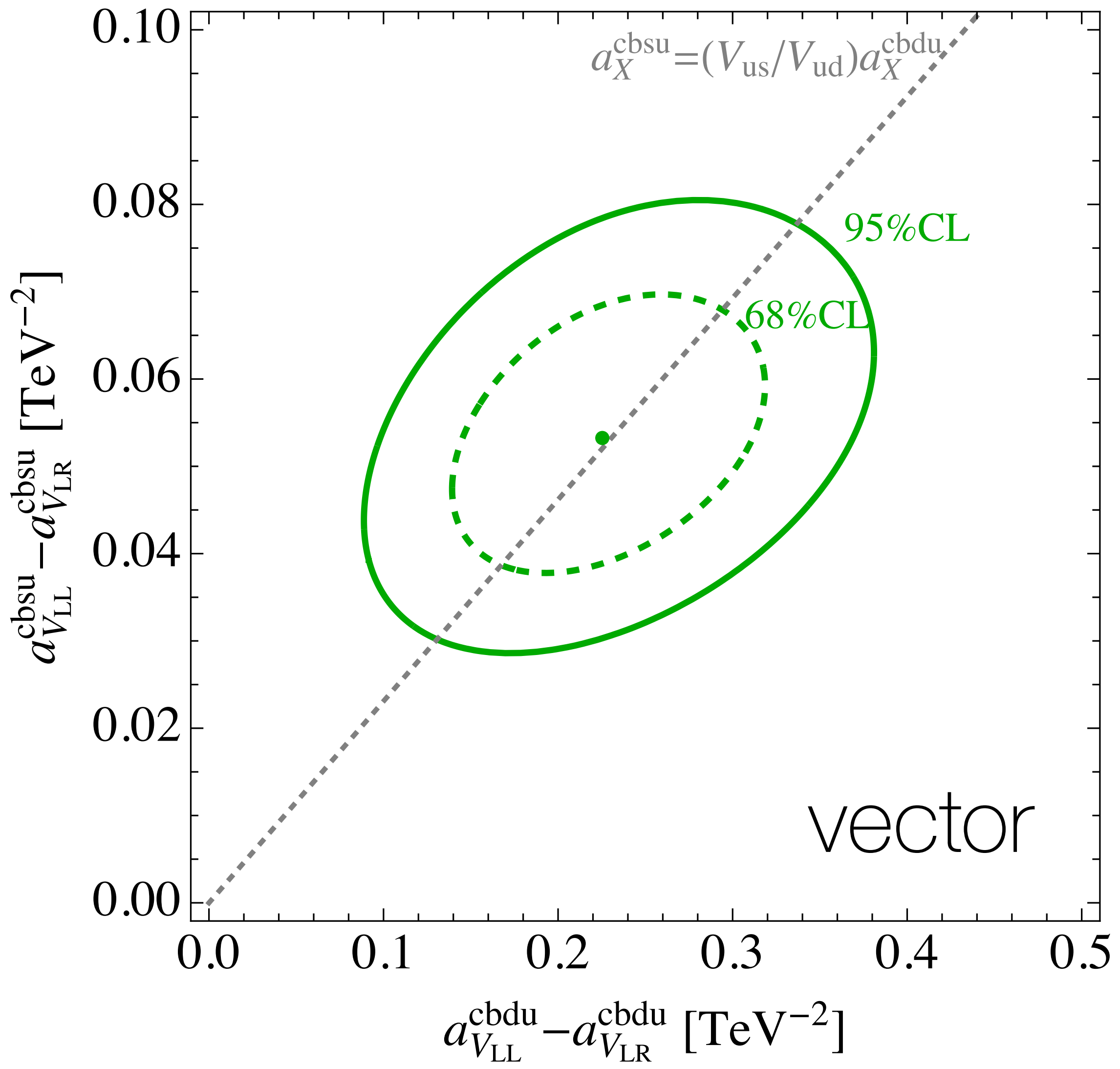
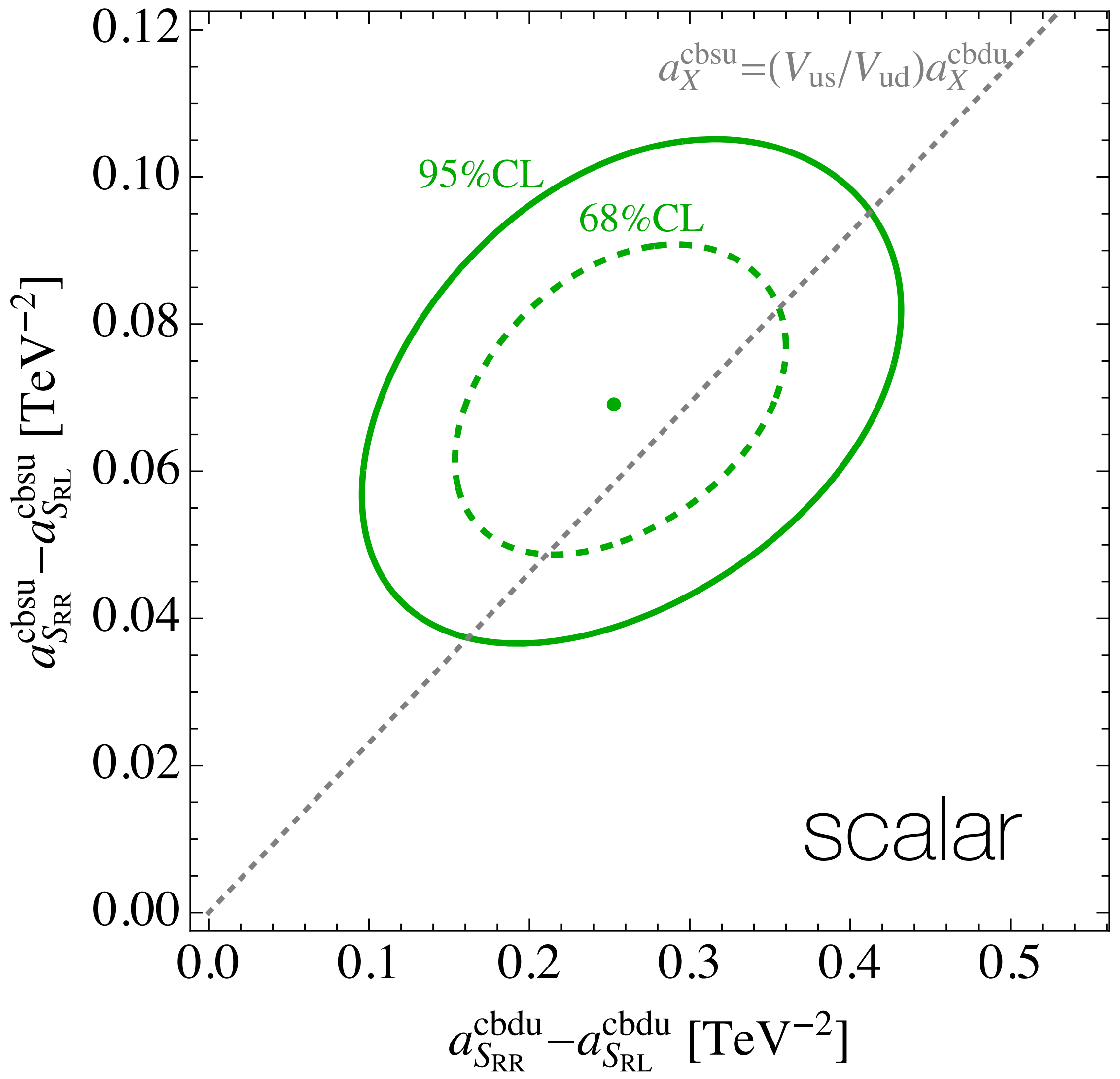
\end{aligned}$$

This story
is not going to be a fairy tail…





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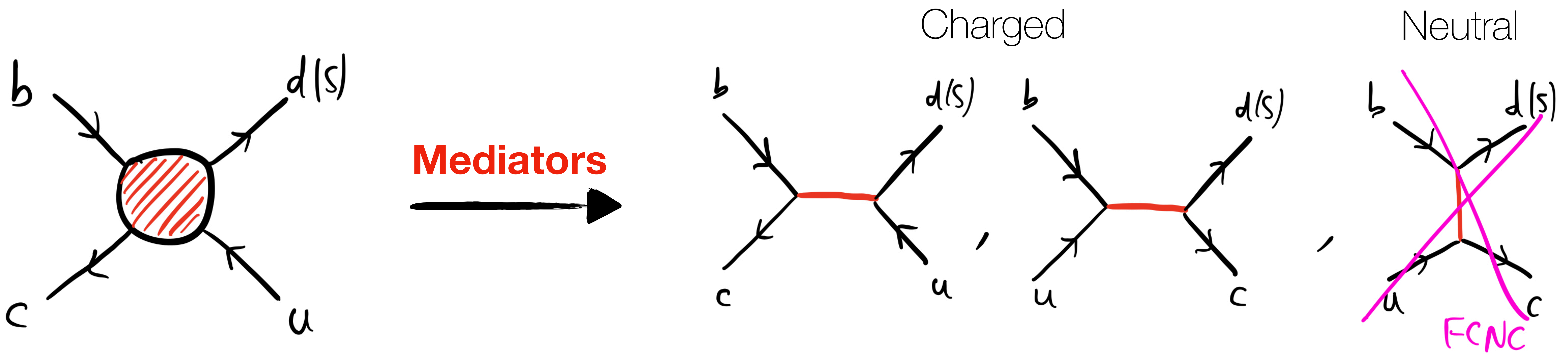
Need TeV-scale New Physics that induces at tree-level a process that violates ALL QUARK FLAVORS!

Which mediators?



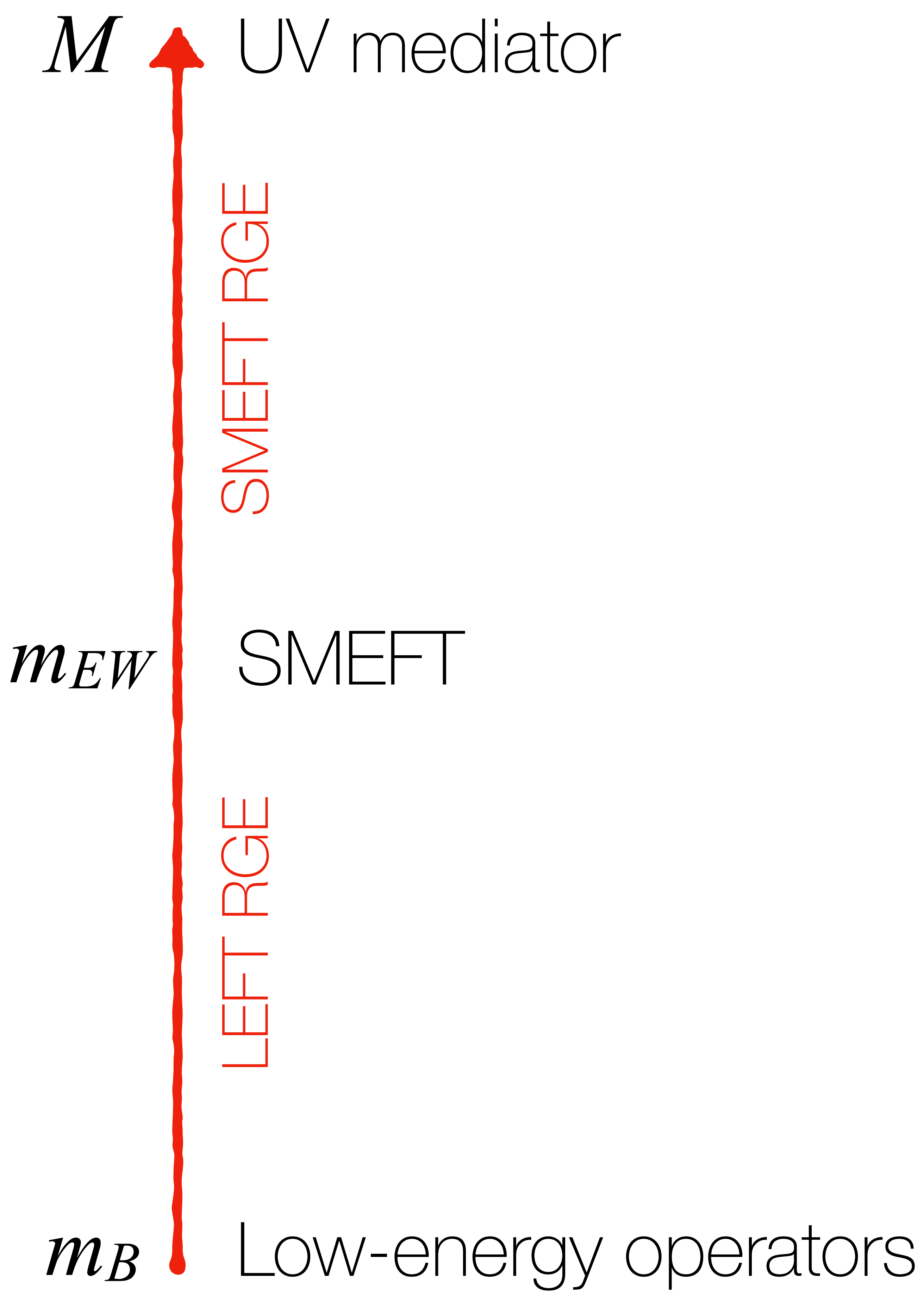
Neutral mediators necessarily couple to FCNC > excluded by tree-level FCNC.

Charged mediators have to be above ~100 GeV (color-less) or ~1 TeV (colored).

→ **We need tree-level mediators above the EW scale.**

*Loop models would be even more disfavoured by dijet (light and strongly coupled to quarks, see backup)

From the B scale to the UV



SMEFT operators:

$$
\begin{aligned}
[\mathcal{O}_{qq}^{(1)}]_{ijkl} &= (\bar{q}_L^i \gamma_\mu q_L^j)(\bar{q}_L^k \gamma_\mu q_L^l)\,, & [\mathcal{O}_{qq}^{(3)}]_{ijkl} &= (\bar{q}_L^i \sigma^a \gamma_\mu q_L^j)(\bar{q}_L^k \sigma^a \gamma_\mu q_L^l)\,,\\
[\mathcal{O}_{ud}^{(1)}]_{ijkl} &= (\bar{u}_R^i \gamma_\mu u_R^j)(\bar{d}_R^k \gamma_\mu d_R^l)\,, & [\mathcal{O}_{ud}^{(8)}]_{ijkl} &= (\bar{u}_R^i T^A \gamma_\mu u_R^j)(\bar{d}_R^k T^A \gamma_\mu d_R^l)\,,\\
[\mathcal{O}_{qd}^{(1)}]_{ijkl} &= (\bar{q}_L^i \gamma_\mu q_L^j)(\bar{d}_R^k \gamma_\mu d_R^l)\,, & [\mathcal{O}_{qd}^{(8)}]_{ijkl} &= (\bar{q}_L^i T^A \gamma_\mu q_L^j)(\bar{d}_R^k T^A \gamma_\mu d_R^l)\,,\\
[\mathcal{O}_{qu}^{(1)}]_{ijkl} &= (\bar{q}_L^i \gamma_\mu q_L^j)(\bar{u}_R^k \gamma_\mu u_R^l)\,, & [\mathcal{O}_{qu}^{(8)}]_{ijkl} &= (\bar{q}_L^i T^A \gamma_\mu q_L^j)(\bar{u}_R^k T^A \gamma_\mu u_R^l)\,,\\
[\mathcal{O}_{quqd}^{(1)}]_{ijkl} &= (\bar{q}_L^i u_R^j)(i\sigma^2)(\bar{q}_L^k d_R^l)\,, & [\mathcal{O}_{quqd}^{(8)}]_{ijkl} &= (\bar{q}_L^i T^A u_R^j)(i\sigma^2)(\bar{q}_L^k T^A d_R^l)\,.
\end{aligned}
$$

Possible **tree-level mediators**,
that do not ***necessarily*** also induce tree-level meson mixing:

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

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

W' case studied by Iguro and Kitahara [2008.01086]:
meson mixing excludes a full explanation of the anomaly, and strong couplings required even for a partial explanation.

$^{(\dagger)}$ The heavy Higgs requires aligned couplings and no mixing with SM Higgs.

Model example and flavour bounds

Among the possible tree-level mediators, one that **doesn't mediate meson-mixing at tree-level** is:

Scalar sextet di-quark

$$\Phi_6 = (\mathbf{6}, \mathbf{1}, 1/3)$$

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

Can fit the "anomaly" with **only two couplings**:

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

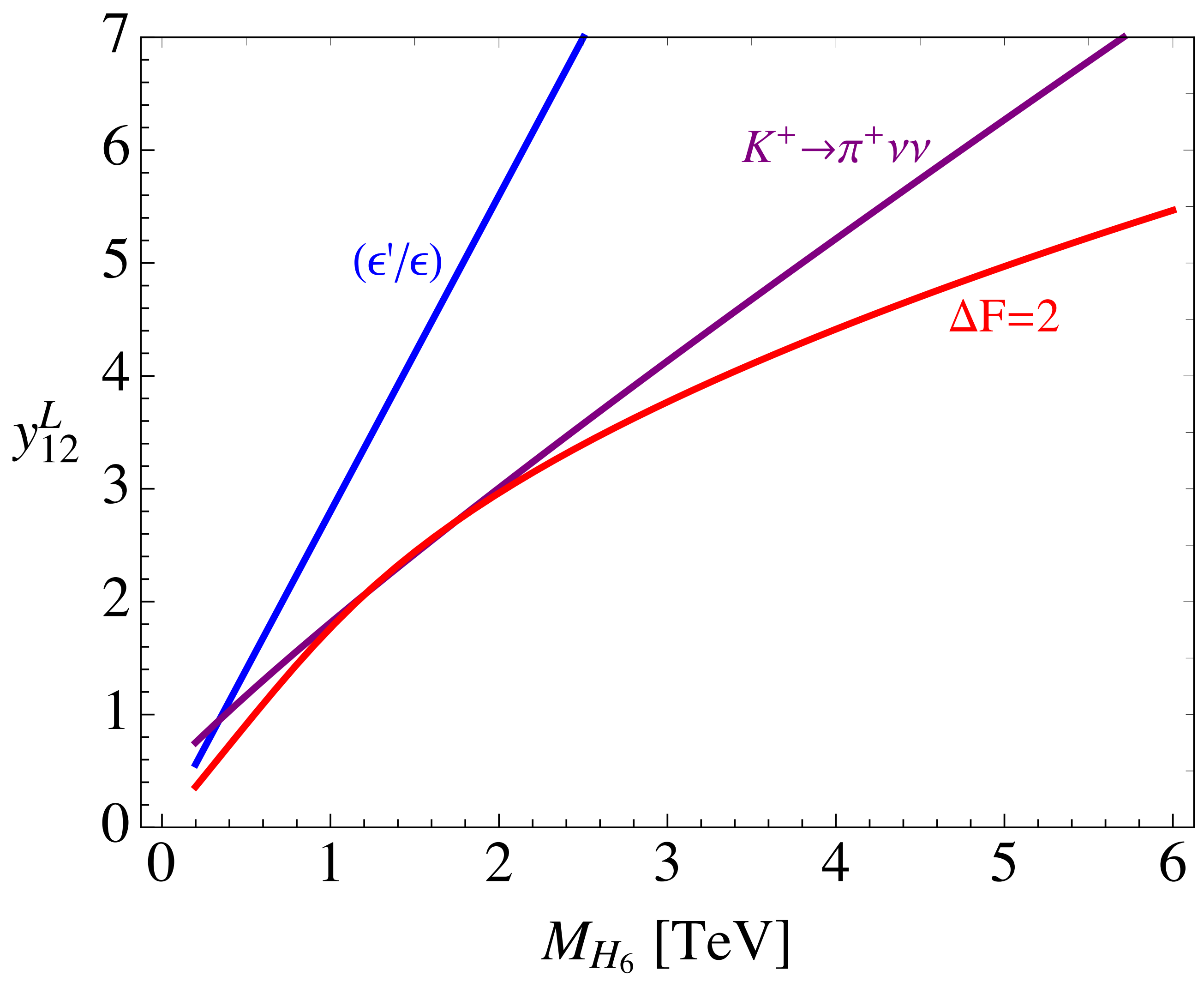
$$a^{cbdu}_{S_{RR}} \approx \frac{2}{3} \kappa^S_{\text{RGE}} V_{cs} \frac{y^{L*}_{12} y^R_{13}}{M^2_{H_6}} \approx \frac{0.26 V_{cs}}{\text{TeV}^2}$$

$$a^{cbsu}_{S_{RR}} \approx -\frac{2}{3} \kappa^S_{\text{RGE}} V_{cd} \frac{y^{L*}_{12} y^R_{13}}{M^2_{H_6}} \approx \frac{-0.31 V_{cd}}{\text{TeV}^2}$$

$\kappa^S_{\text{RGE}} \approx 1.65\,(1.85)$ for $M_{\Phi_6} = 1\,(5)$ TeV

Meson mixing, and other rare decays, are however generated at loop level.

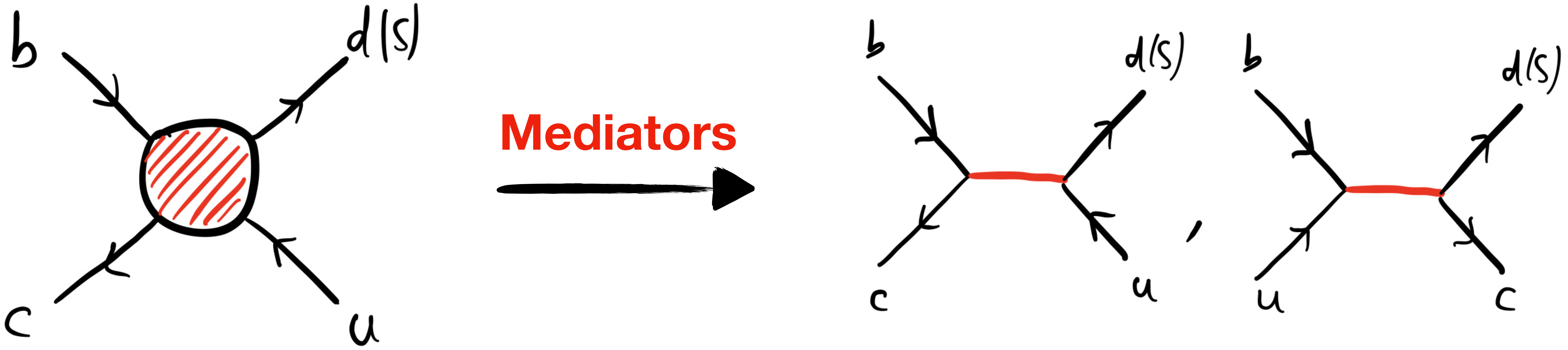
Flavor bounds can be avoided!



Non-trivial result, given the **wild** flavor structure.

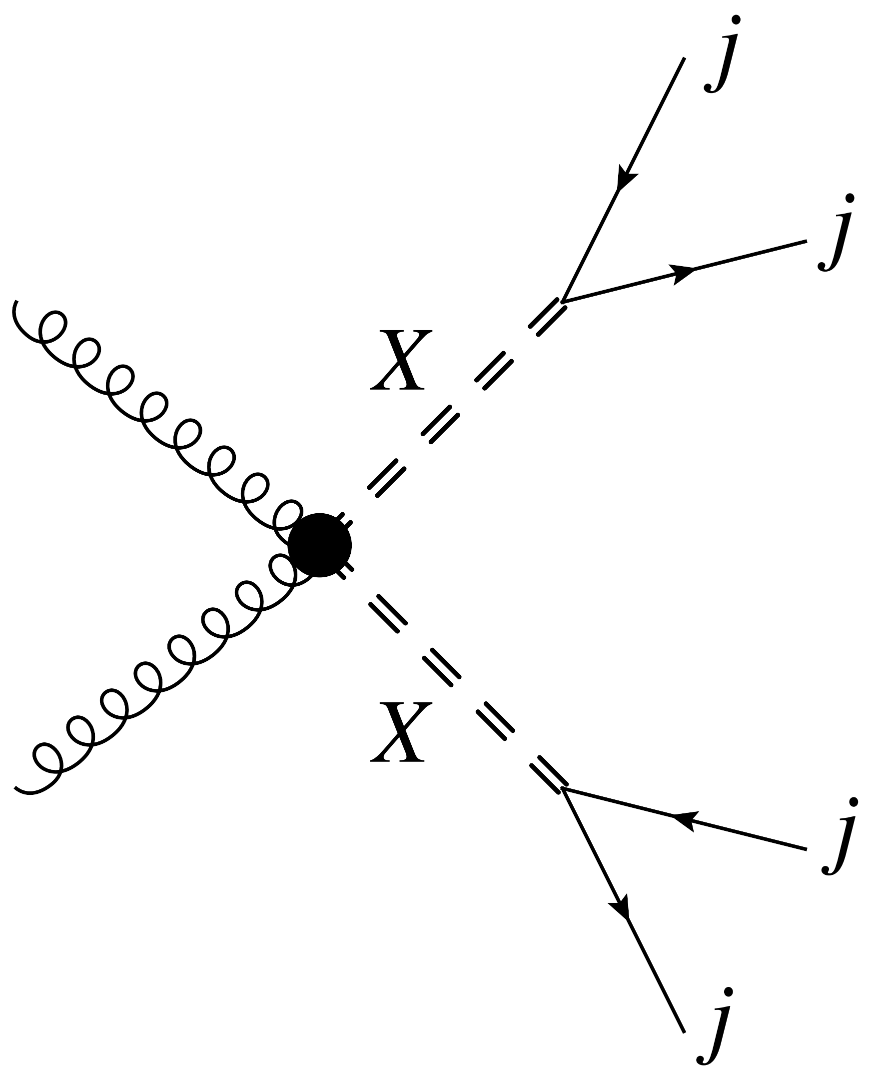
Already huge improvement w.r.t. W' model.

From flavour to LHC

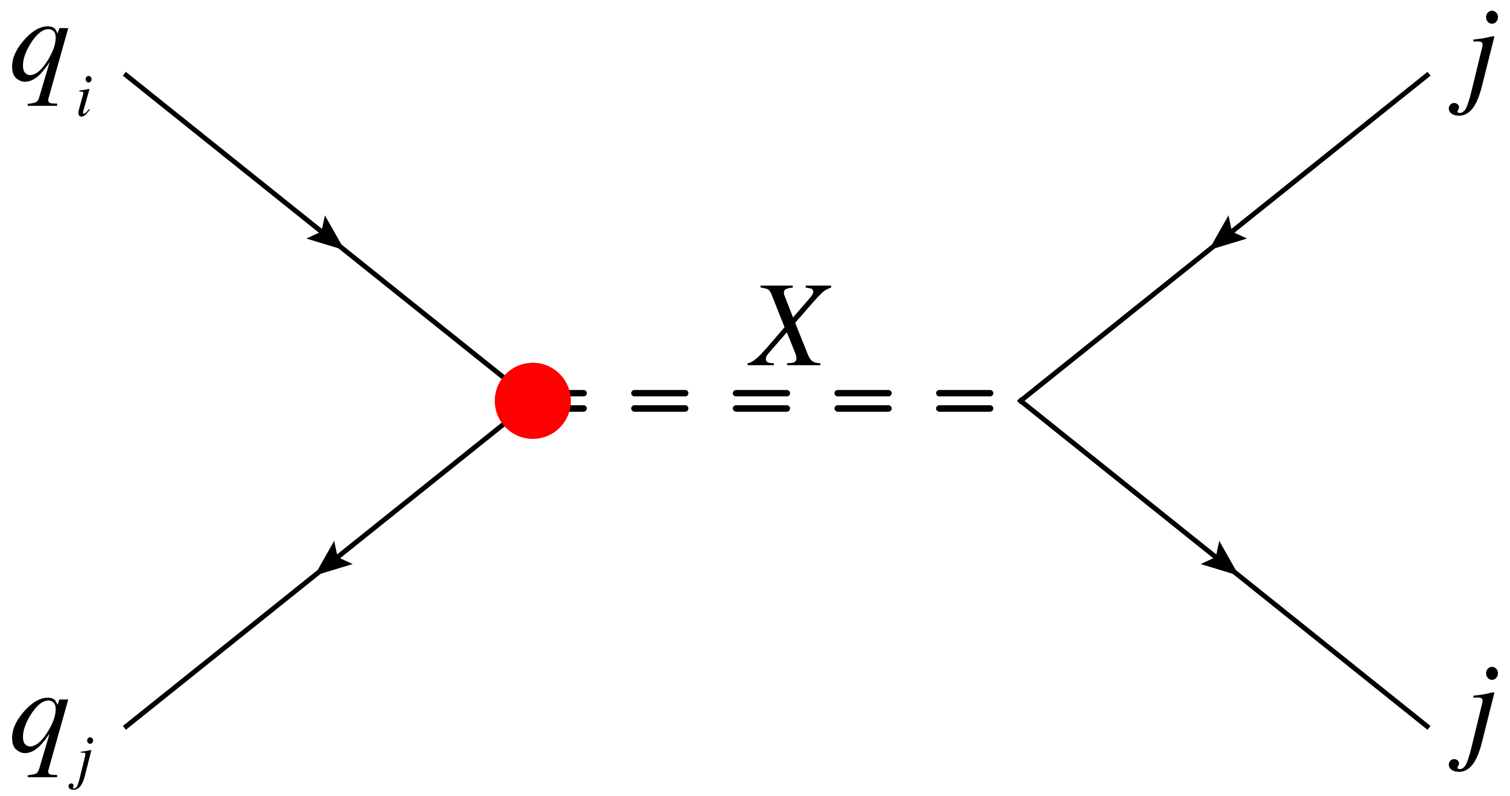


Necessarily charged, possibly colored

Gauge pair-production → 2 dijet pairs

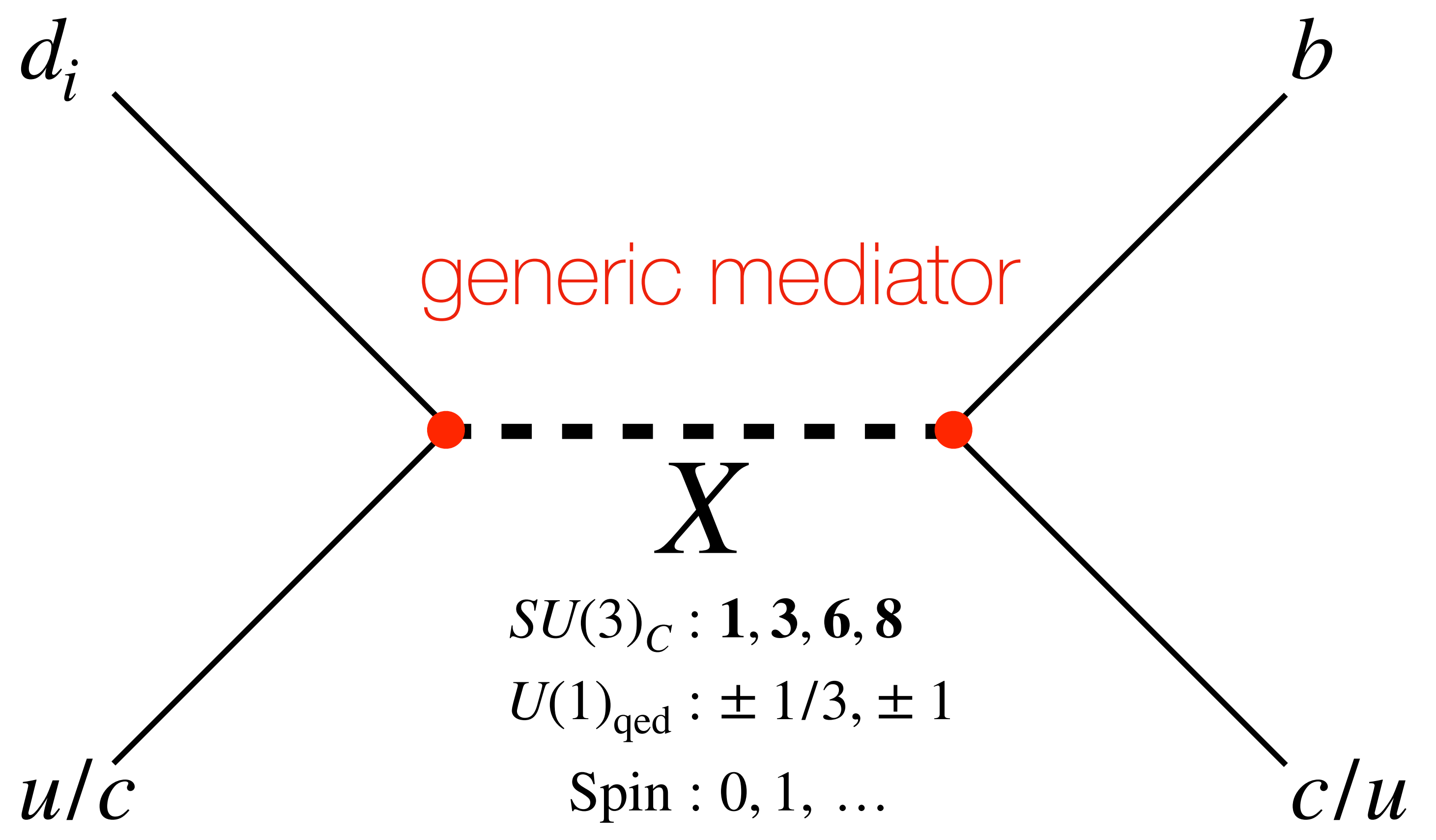


s-channel production → dijet resonance

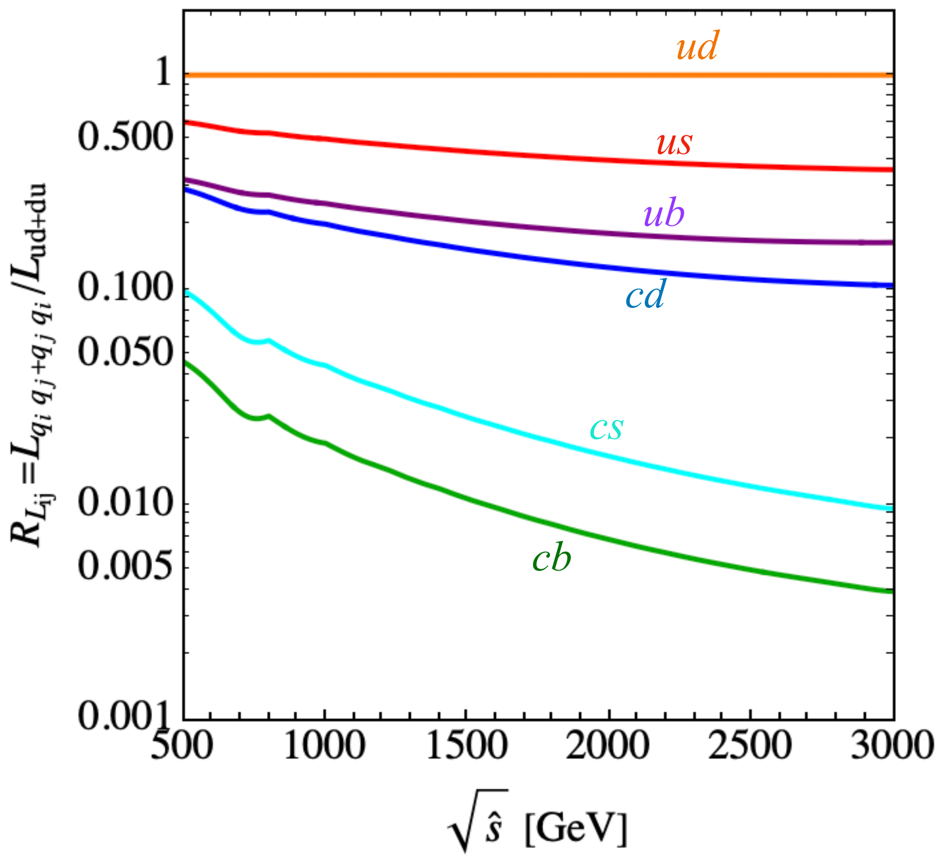


General di-jet constraints

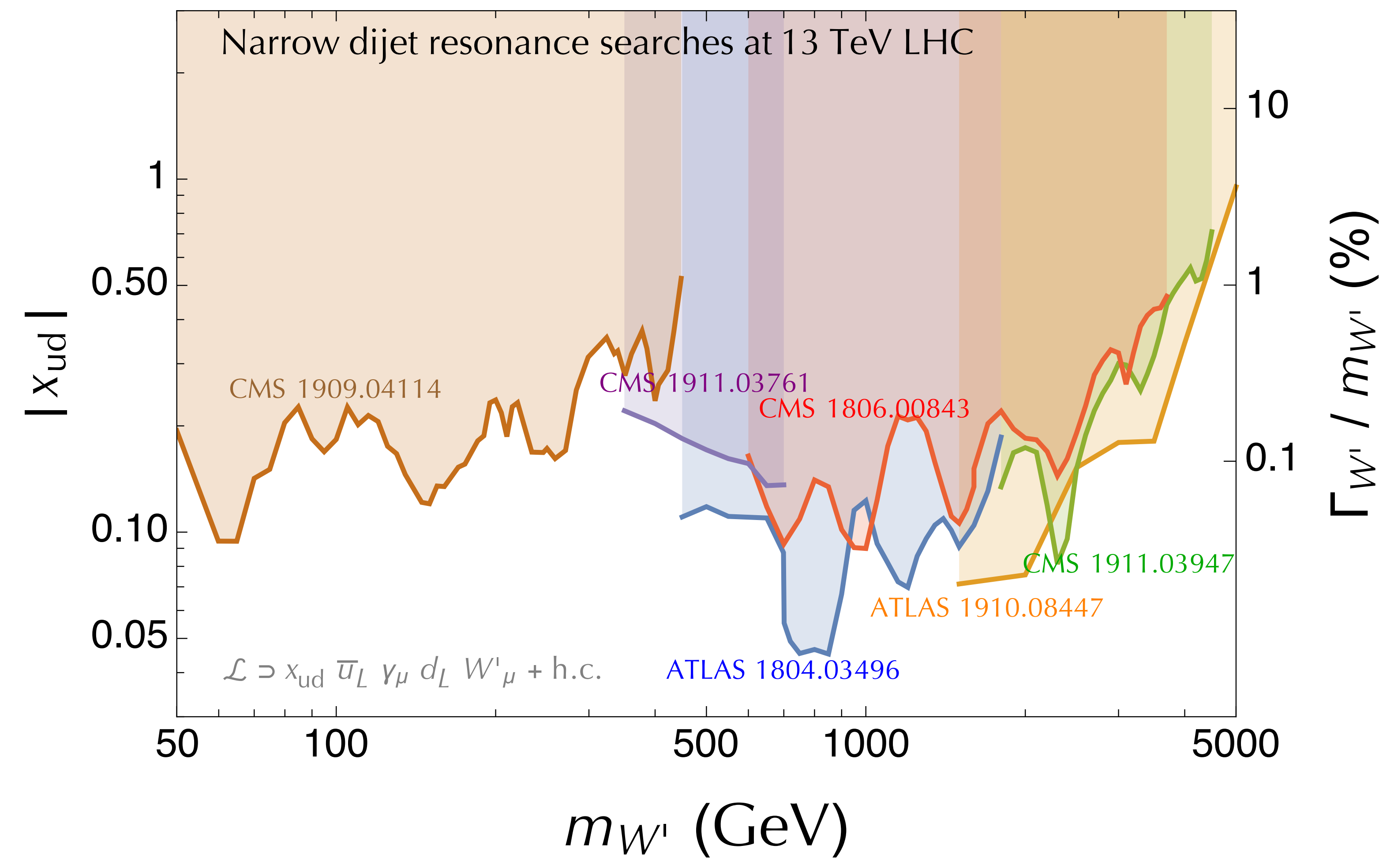
Any mediator for $b \to c\, \bar{u}\, d(s)$ will necessarily also induce an **s-channel resonance in di-jet** distribution at LHC:



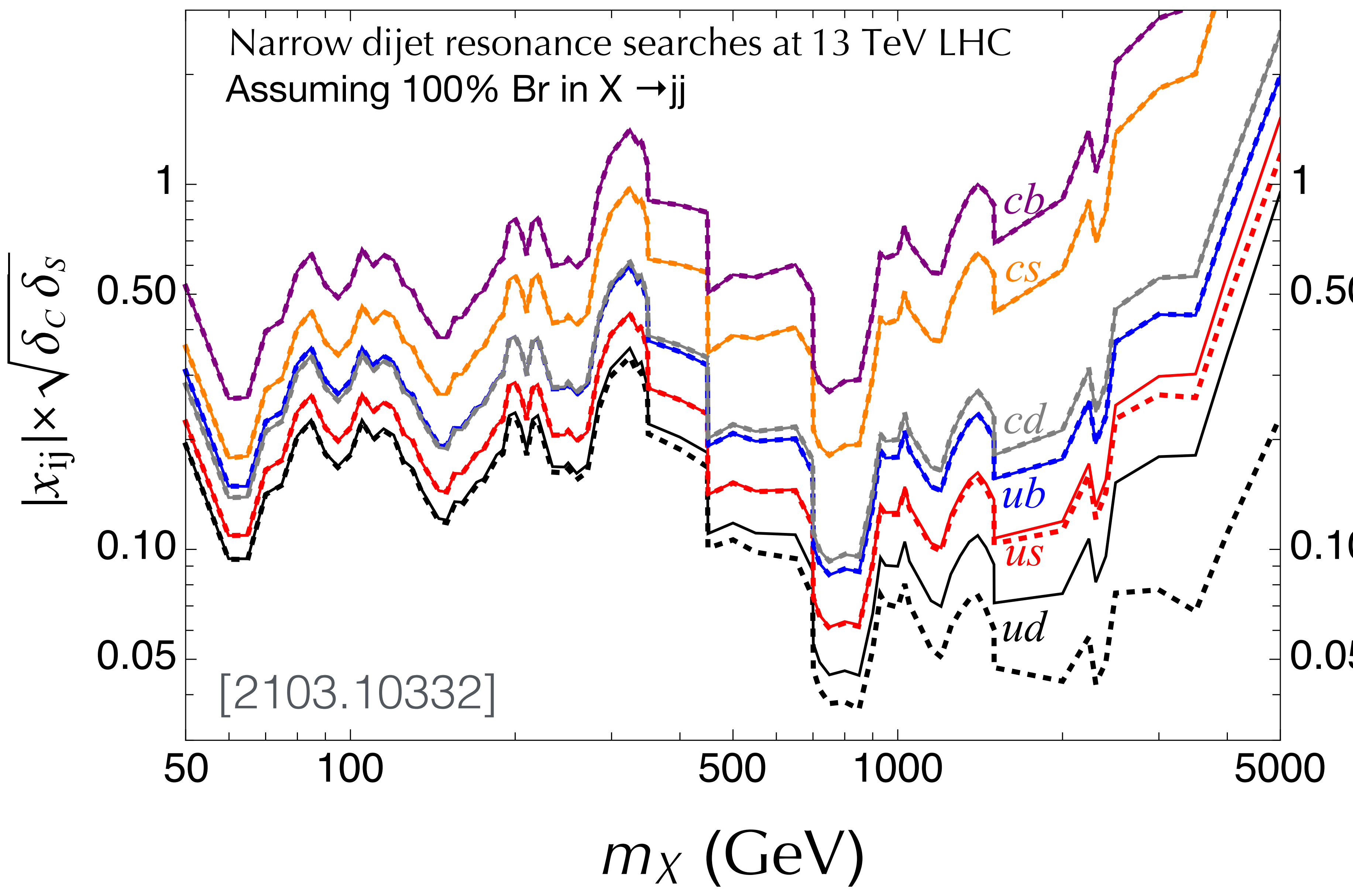
Ratio of $\mathbf{q\bar{q}}$ luminosities



di-jet constraints on narrow $\mathrm{W'}$



General di-jet constraints on narrow res.



Normalizing the production and decay rate to the one of a heavy W' vector one has:

$$\frac{\Gamma(X \to u^i d^j)}{m_X} = \gamma_C\, \gamma_S\, \frac{\Gamma(W' \to u^i d^j)}{m_{W'}}$$

$$\frac{\sigma(pp \to X)}{\sigma(pp \to W')} = \delta_C \delta_S$$

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

spin	γ_S	δ_S
scalar	$\frac{3}{2}$	$\frac{1}{2}$
vector	1	1

$SU(3)_c$	γ_c	δ_c
1	1	1
3	$\frac{2}{3}$	2
6	$\frac{1}{3}$	2
8	$\frac{1}{6}$	$\frac{4}{3}$

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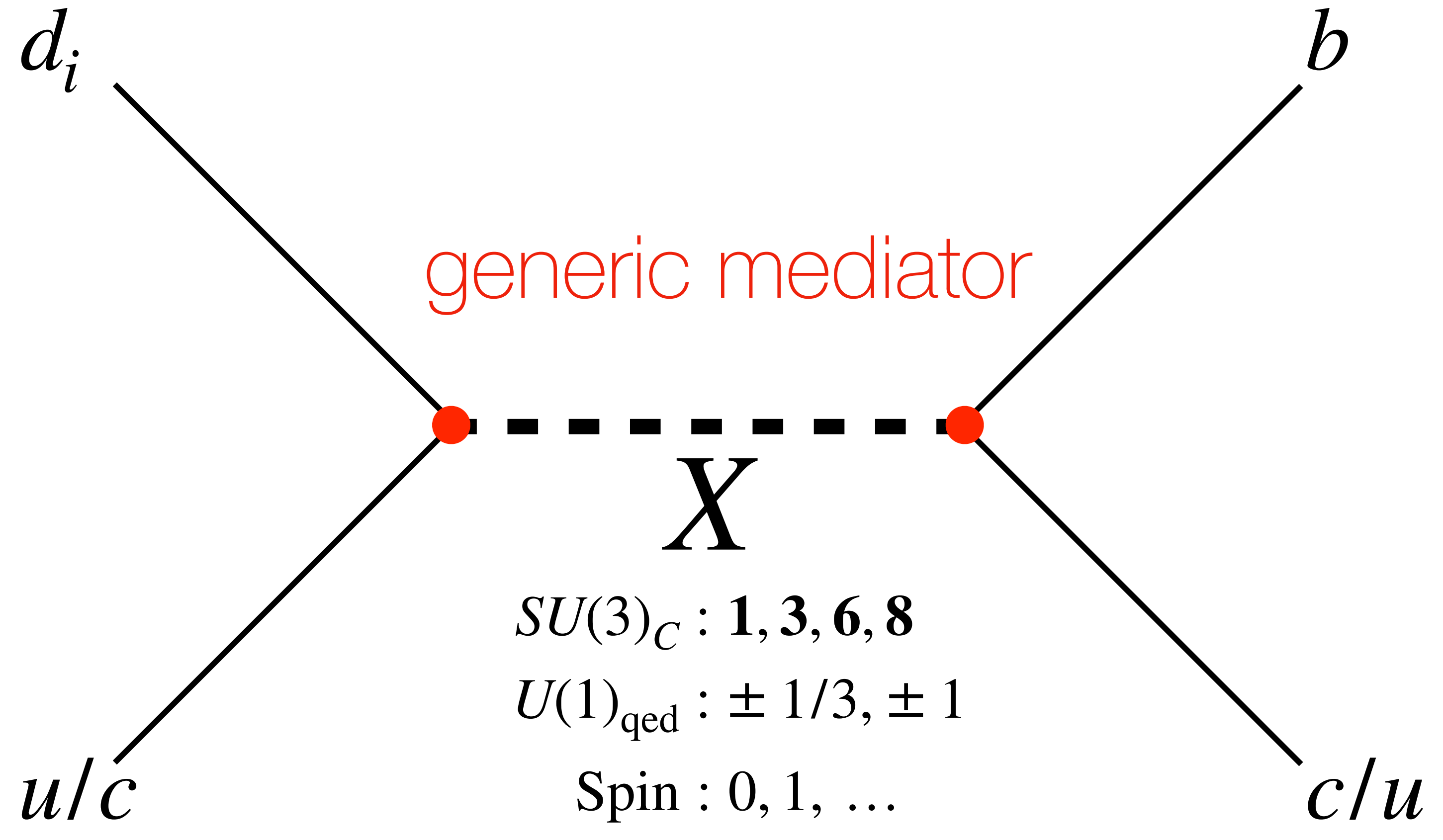

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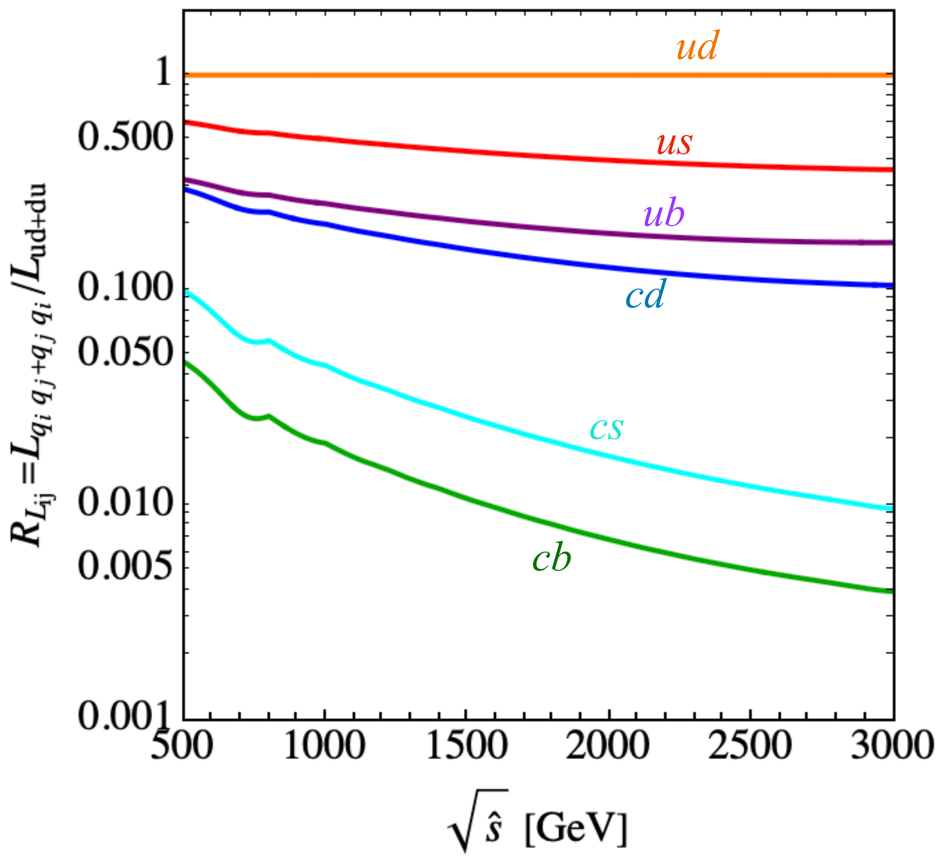
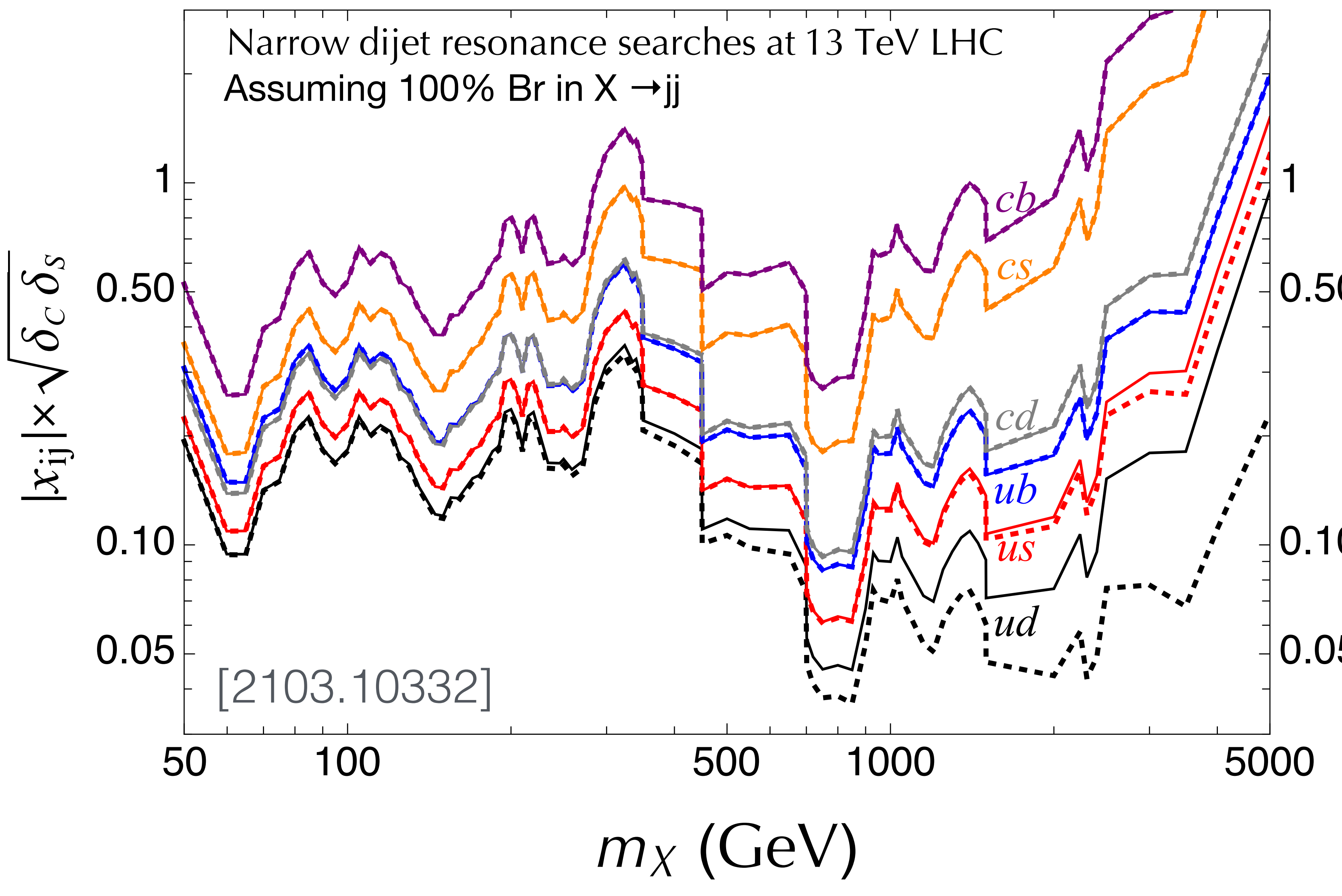


These **limits** can be directly **applied** to **all possible** tree-level **mediators** contributing to **generic hadronic decays**.

General di-jet constraints on narrow res.



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The Showdown

Fitting the anomaly vs. dijet - Colored mediators

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

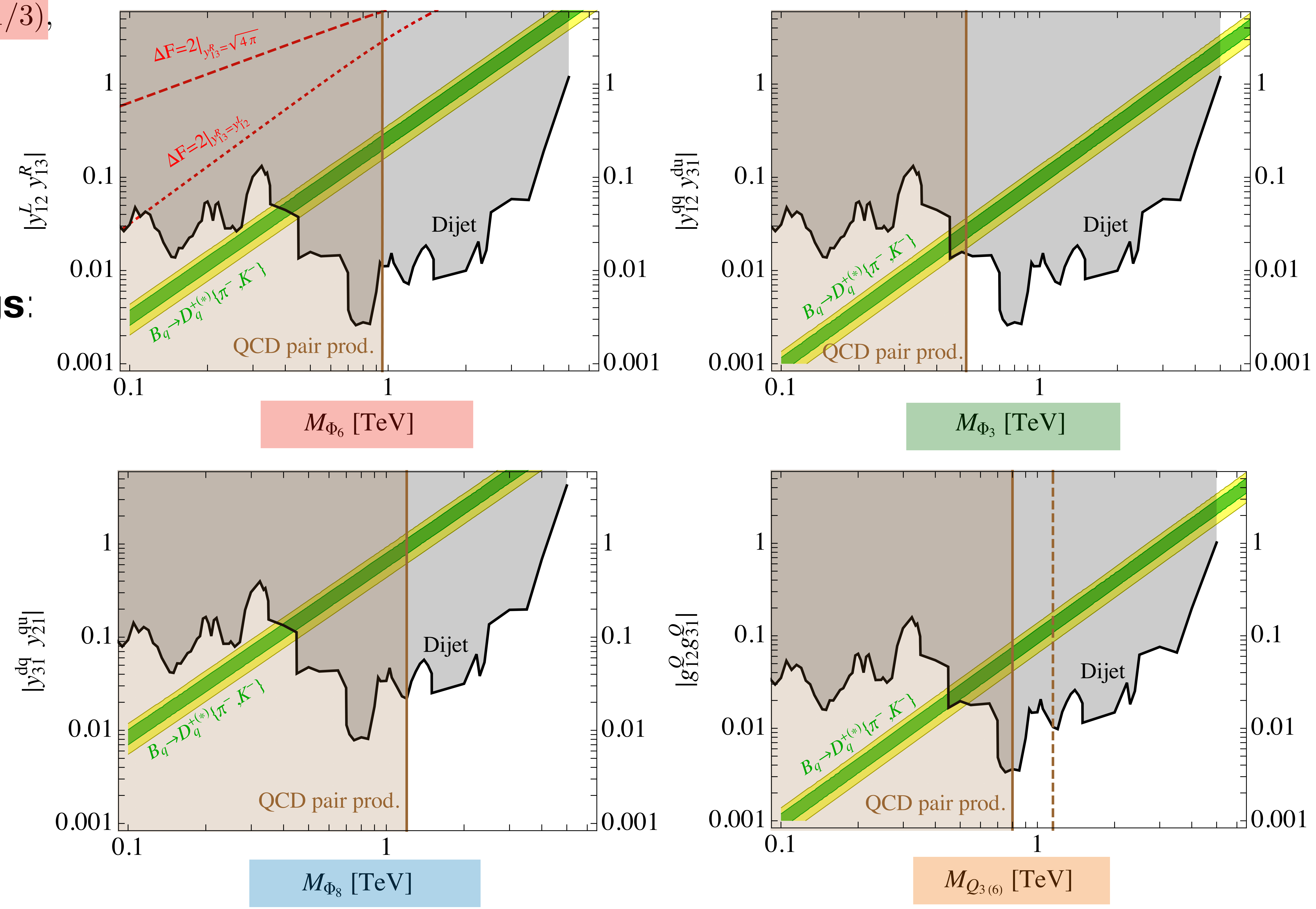
spin-1: $\{\mathcal{Q}_3 = (\mathbf{3}, \mathbf{2}, 1/6), \quad \mathcal{Q}_6 = (\bar{\mathbf{6}}, \mathbf{2}, 1/6)$.

For each scenario, we choose the **most favourable combination of couplings**: largest contribution to the anomaly, with smallest constraint from dijets.

All the colored mediators are excluded, <u>for all couplings range where the model is perturbative</u>.

Dijet constraints are stronger than bounds from FCNC (loop-generated).

$|y_1\, y_2| = |y_1|\, |y_2| < |y_1|^{\max}\, |y_2|^{\max}$



Fitting the anomaly vs. dijet - Colored mediators

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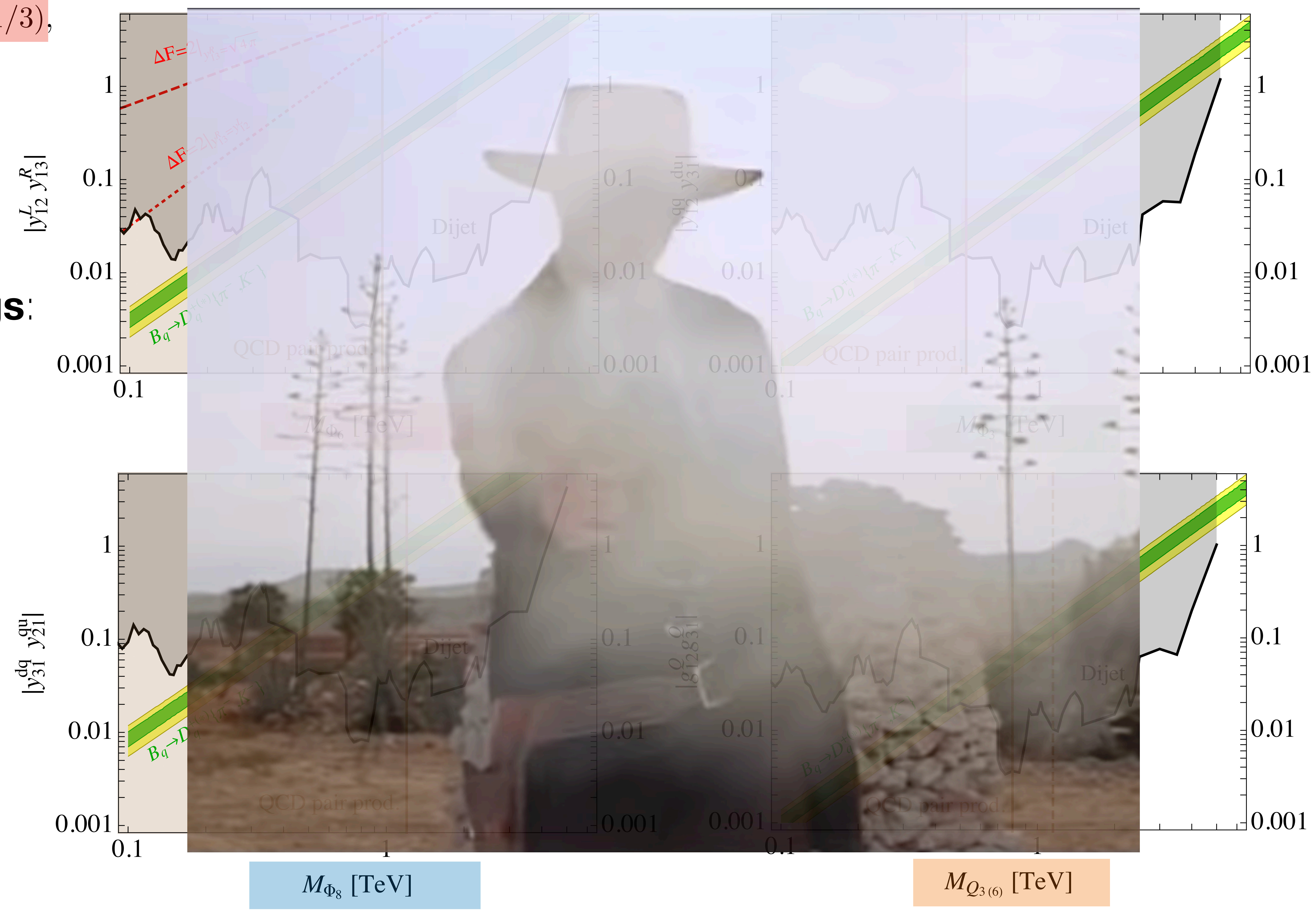


Fitting the anomaly vs. dijet - Scalar Doublet

$\Phi_1 = (\mathbf{1}, \mathbf{2}, 1/2)$ i.e. a heavy Higgs doublet.

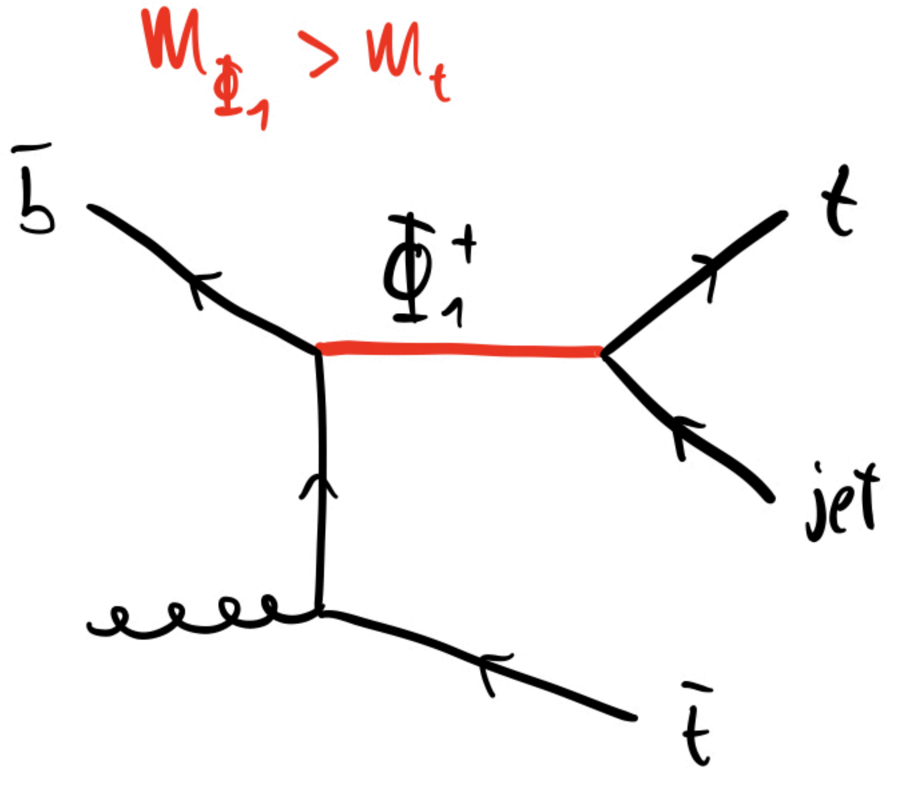
Needs **precise alignment in flavour space** and **no mixing with SM Higgs**, to avoid tree-level contributions to meson mixing:

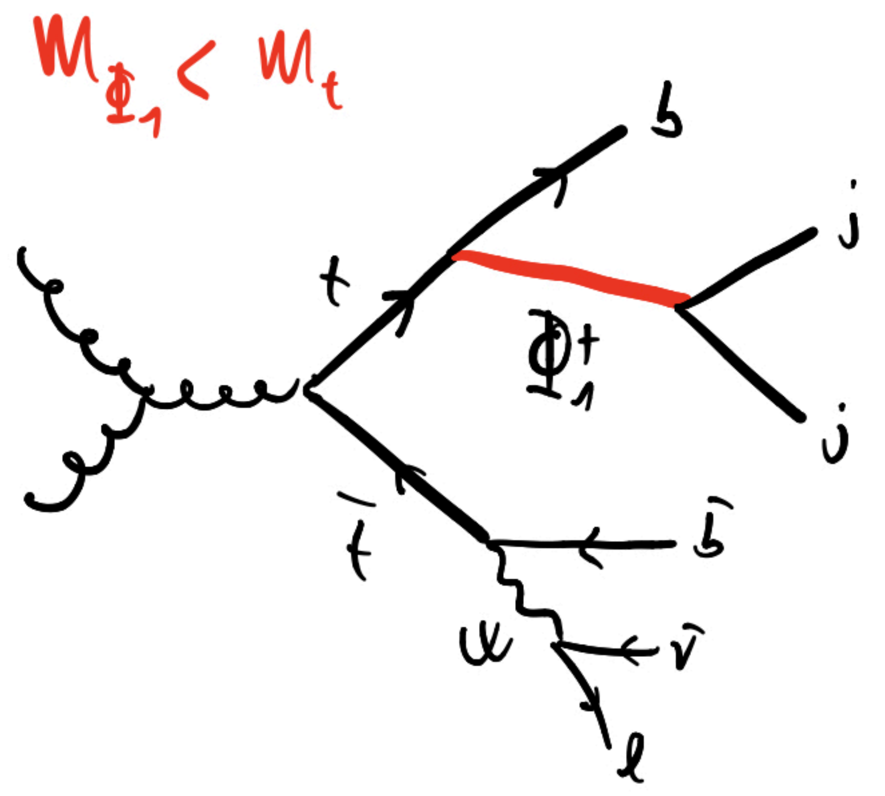
$$\mathcal{L}^{\rm Yuk}_{\Phi_1} = y_i^d \, \Phi_1^\dagger \bar{d}_R^i q_L^i + \text{h.c.},$$

$q_L^i = (V^*_{ji} u_L^j, d_L^i)^T$

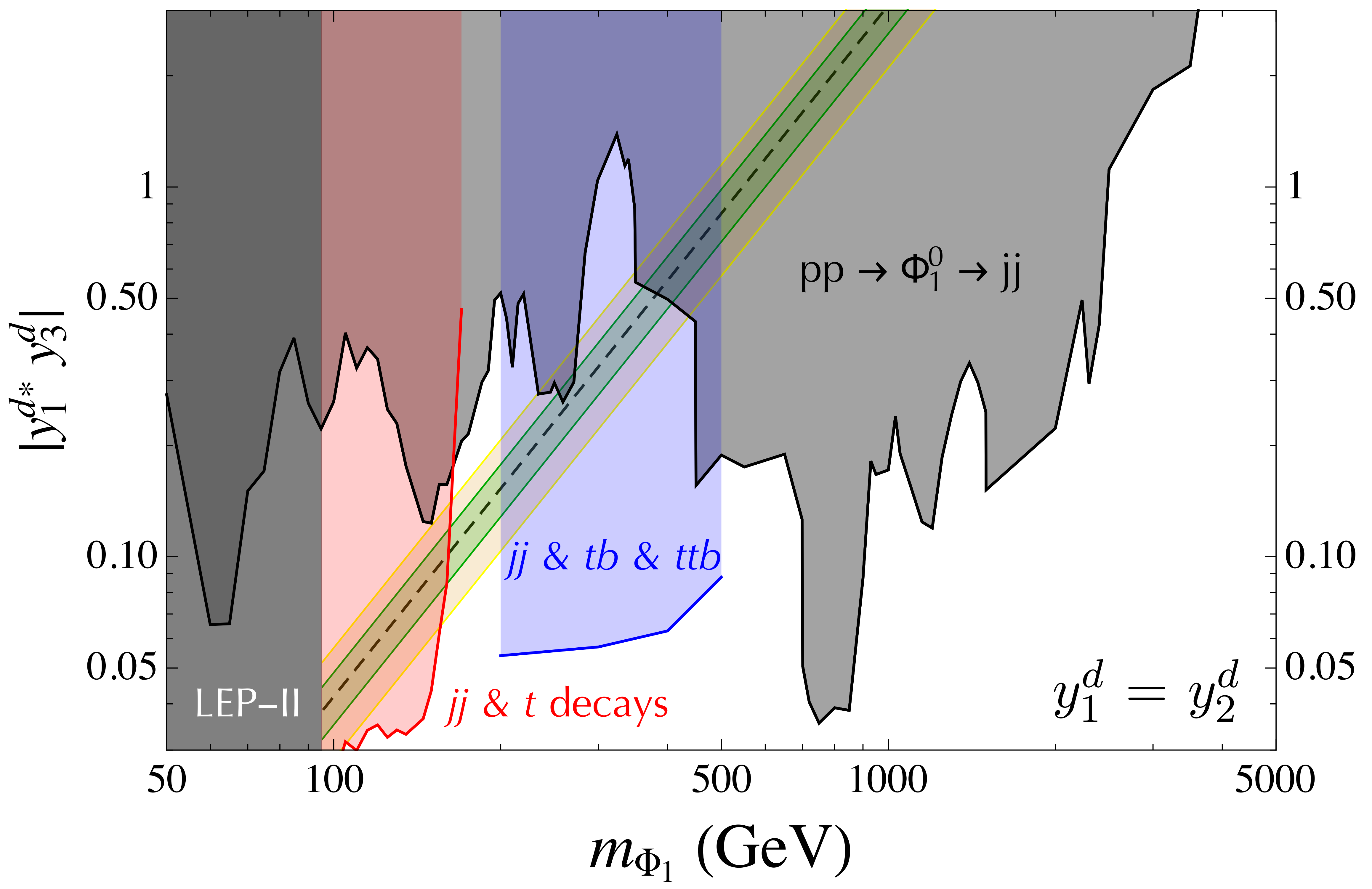
$$a^{cbiu}_{S_{RL}} = \kappa_{\rm RGE} V_{cb} V^*_{ui} \frac{y_3^{d*} y_i^d}{M^2_{\Phi_1}}$$

The coupling y^d_3 implies a large $\mathbf{\Phi_1^+}$ **t b** coupling.





Dijet bounds minimised (shown here) for the hierarchy: $|y_{1,2}| < |y_3|$



A **blind spot** remains around m_{top}:

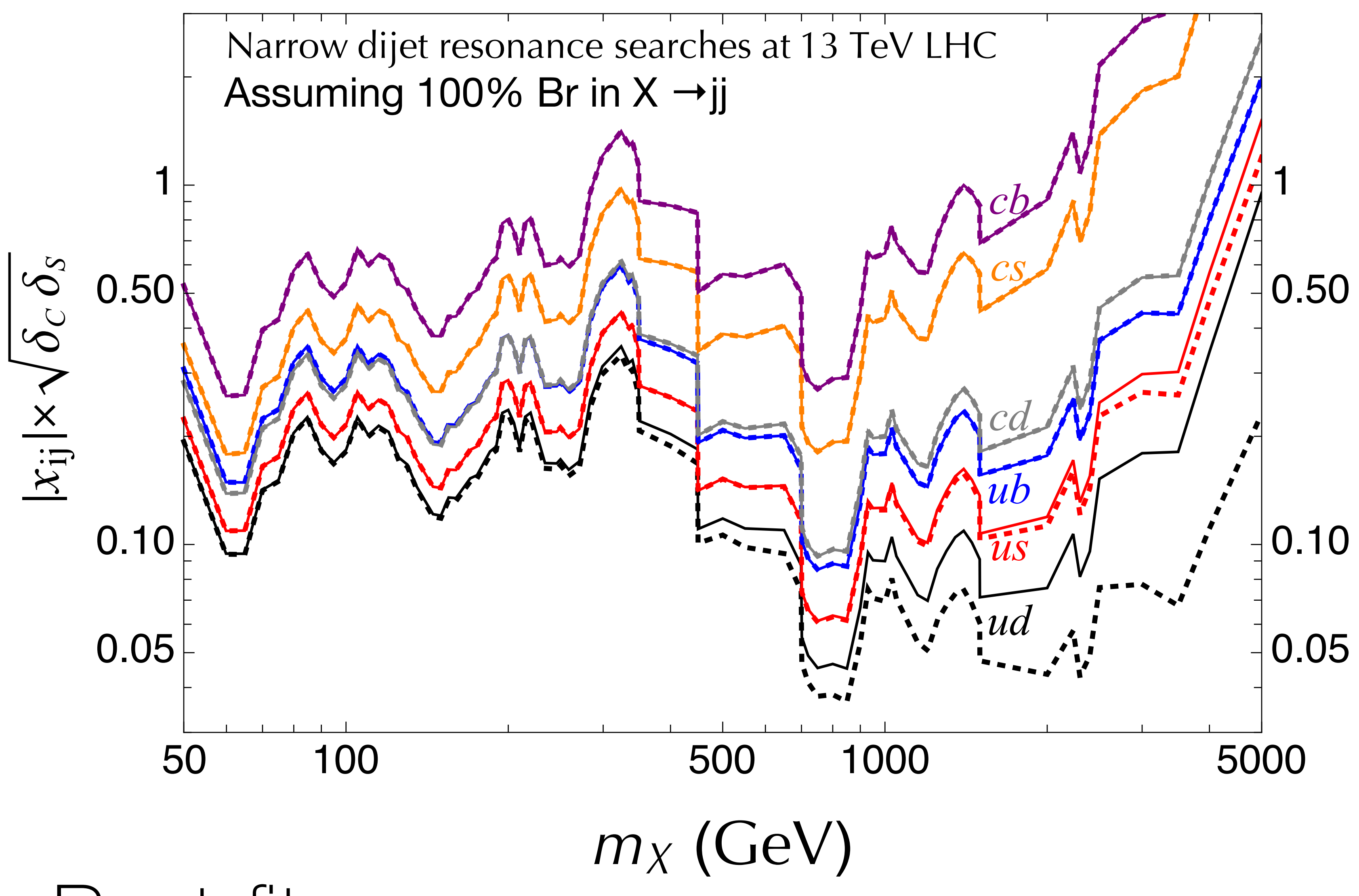
$m_{\Phi_1} \approx m_t$: $|y_1^d| < 0.22$, $|y_3^d| < 0.88$

… but LHC sensitivity is just behind the corner!

The End … ?

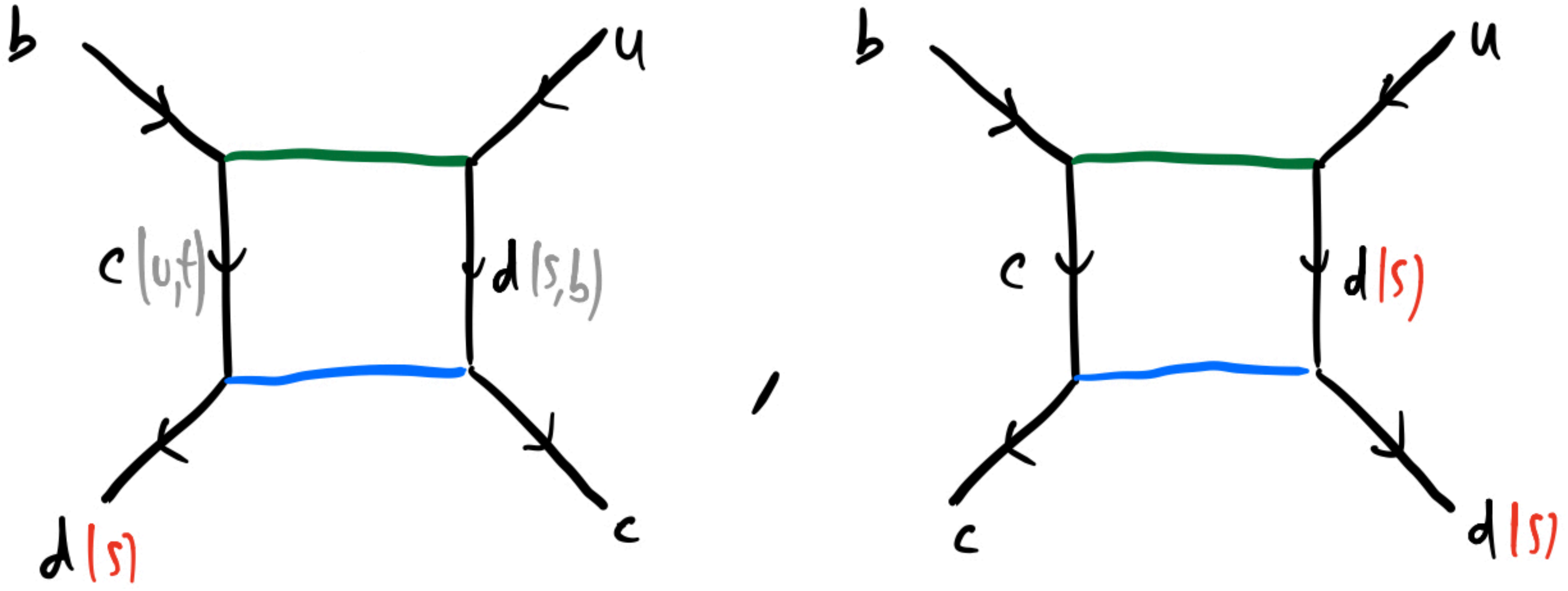
Backup

Loop models?



Requirements:

- No colored mediators (would be too heavy)
- No neutral mediators coupled to FCNC



Best-fit:

$$\sim \frac{y^4}{16\pi^2 M_X^2} \sim \frac{0.23}{\text{TeV}^2}$$

$$M_X \sim 160 \text{ GeV} \quad \text{for} \quad y \sim O(1)$$

These light mediators couple strongly to quarks: even larger dijet signals than tree-level mediators.

Four-quark operators

The SM background of the di-jet distribution is obtained by fitting data with a smooth function.
This doesn't allow to put limits on EFT operators, since they also induce a smooth energy dependence.

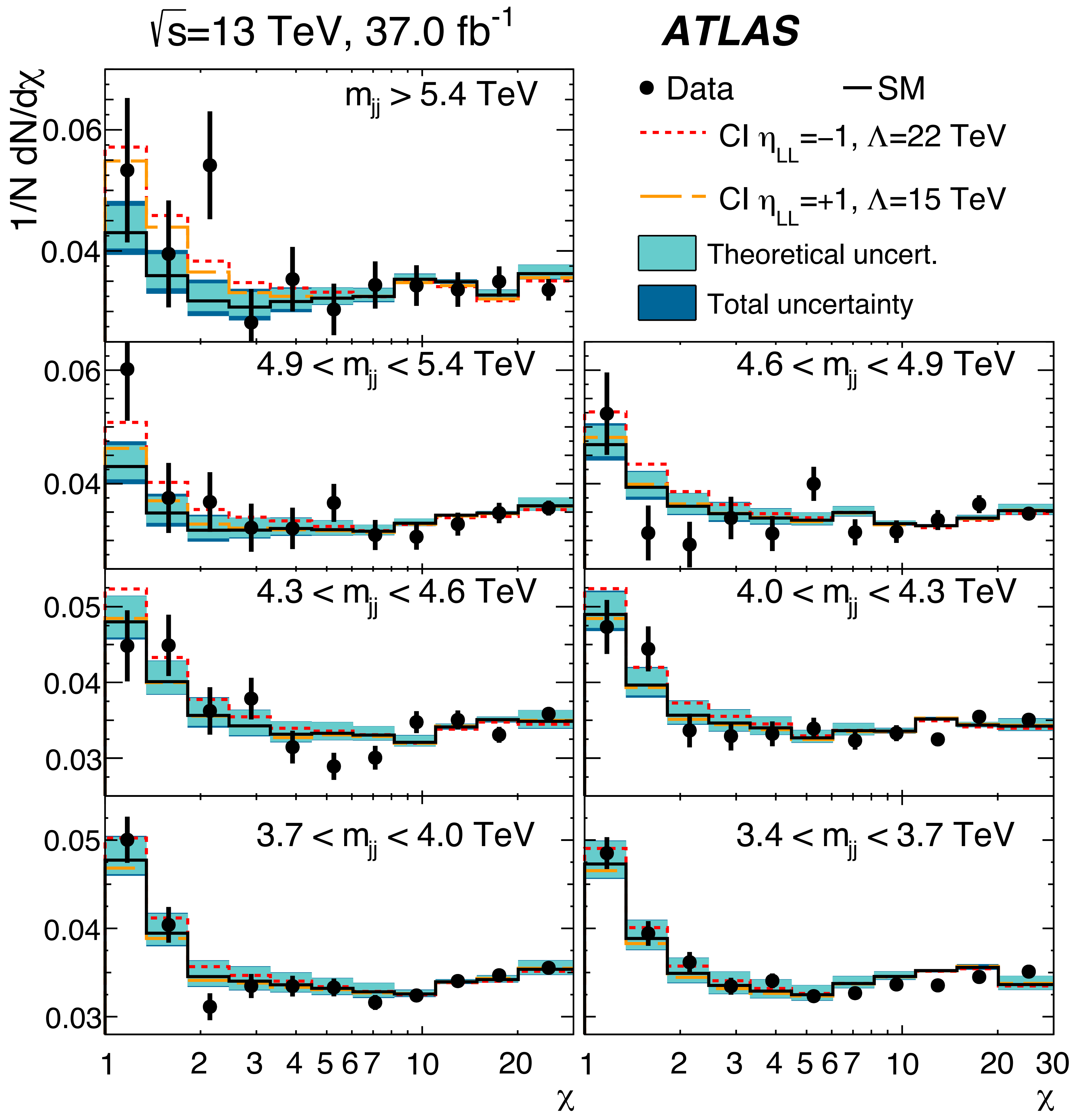
However, the shape of angular distributions (e.g. rapidity) can be more robustly predicted.

This can be used to put limits on four-quark contact interactions.

ATLAS [1703.09127]

$$\mathcal{L}_{qq} = \frac{2\pi}{\Lambda^2}[\,\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_L\gamma_\mu q_L)]\,,$$

Model	95% CL exclusion limit	
Contact interaction ($\eta_{LL} = -1$)	21.8 TeV	28.3 TeV
Contact interaction ($\eta_{LL} = +1$)	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV



We plan to generalize this to all four-quark operators.

Model details

$\boldsymbol{\Phi_6 = (6, 1, 1/3)}$

$$a^{cb\alpha u}_{V_{LL}} = -\frac{4}{3}\kappa^{V}_{\rm RGE}\sum_{i\neq\alpha;\, j=1,2} V_{ci}V^*_{uj}\frac{(y^{L*}_{\alpha i}y^{L}_{j3})}{M^2_{\Phi_6}}\,,$$
$$a^{cb\alpha u}_{V_{RR}} = \frac{1}{3}\kappa^{V}_{\rm RGE}\frac{(y^{R*}_{2\alpha}y^{R}_{13})}{M^2_{\Phi_6}}\,,$$
$$a^{cb\alpha u}_{S_{RR}} = \frac{2}{3}\kappa^{S}_{\rm RGE}\sum_{i\neq\alpha} V_{ci}\frac{y^{L*}_{\alpha i}y^{R}_{13}}{M^2_{\Phi_6}}\,,$$
$$a^{u\alpha bc}_{S_{RR}} = -\frac{2}{3}\kappa^{S}_{\rm RGE}\sum_{i=2,3} V_{ui}\frac{y^{L*}_{i3}y^{R}_{2\alpha}}{M^2_{\Phi_6}}\,,$$

$\Phi_3 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

$$a^{cb\alpha u}_{V_{LL}} = -\frac{4}{3}\kappa^{V_{LL}}_{\rm RGE}V_{ci}V^*_{uj}\frac{y^{qq*}_{j3}y^{qq}_{i\alpha}}{M^2_{\Phi_3}}$$
$$a^{cb\alpha u}_{S_{RR}} = -\frac{2}{3}\kappa^{S}_{\rm RGE}V_{ci}\frac{y^{du*}_{31}y^{qq}_{i\alpha}}{M^2_{\Phi_3}}\,,$$
$$a^{cb\alpha u}_{S_{LL}} = -\frac{2}{3}\kappa^{S}_{\rm RGE}V_{ui}\frac{y^{du*}_{\alpha 2}y^{qq}_{i3}}{M^2_{\Phi_3}}\,,$$

$$\mathcal{L}_{\Phi_3} \supset y^{qq}_{ij}\epsilon_{\alpha\beta\gamma}\Phi^{\alpha}_3\bar{q}^{\beta}_{Li}(i\sigma_2)q^{c\,\gamma}_{Lj} + y^{du}_{ij}\epsilon_{\alpha\beta\gamma}\Phi^{\alpha}_3\bar{d}^{\beta}_{Ri}u^{c\,\gamma}_{Rj} + \text{h.c.}$$

$$a^{cbdu}_{S_{RR}} = -2.6\frac{y^{qq}_{12}y^{du*}_{31}}{M^2_{\Phi_3}} \approx \frac{0.26V_{ud}}{\text{TeV}^2},\quad a^{cbsu}_{S_{RR}} = \frac{(-2.6y^{qq}_{22}+0.60y^{qq}_{12})y^{du*}_{31}}{M^2_{\Phi_3}} \approx \frac{0.31V_{us}}{\text{TeV}^2}$$

$\boldsymbol{\Phi_8 = (8, 2, 1/2)}$

$$\mathcal{L}_{\Phi_8} \supset y^{qu}_{ij}\Phi^{\alpha\dagger}_8 i\sigma_2\bar{q}^{T}_{Li}T^{\alpha}u_{Rj} + y^{dq}_{ij}\Phi^{\alpha\dagger}_8\bar{d}_{Ri}T^{\alpha}q_{Lj} + \text{h.c.}$$

$$a^{cbiu}_{S_{RR}} \approx 0.44V_{cs}\frac{y^{dq*}_{3i}y^{qu}_{21}}{M^2_{\Phi_8}}$$

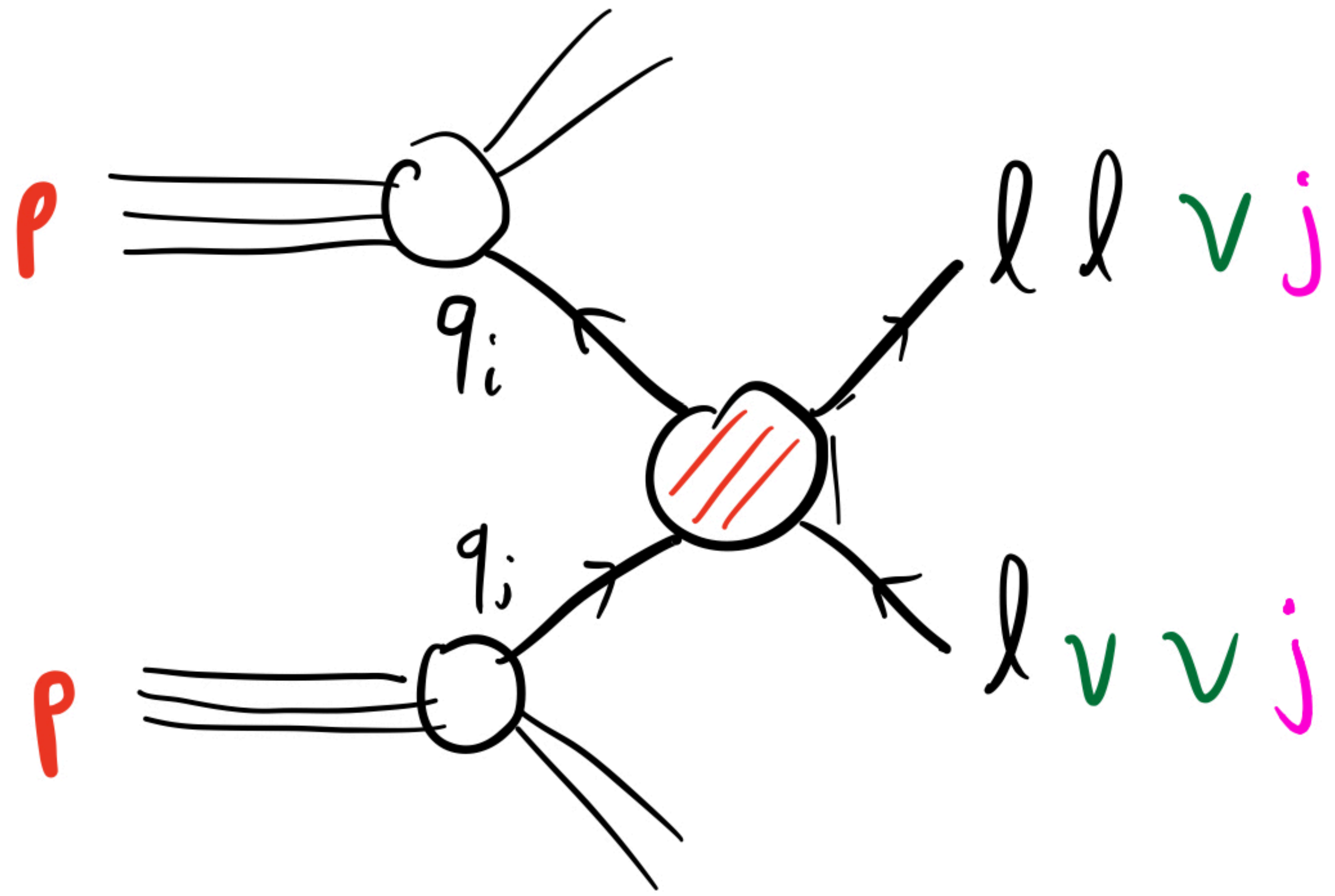
$\mathcal{Q}_3 = (\mathbf{3}, \mathbf{2}, 1/6)$ and $\mathcal{Q}_6 = (\bar{\mathbf{6}}, \mathbf{2}, 1/6)$

$$\mathcal{L}_{\mathcal{Q}} \supset g^{\mathcal{Q}_3}_{ij}\mathcal{Q}^{\alpha\mu\dagger}_3\epsilon_{\alpha\beta\gamma}\bar{d}^{\beta}_{Ri}\gamma_\mu(i\sigma_2)q^{c\gamma}_{Lj} + \frac{1}{2}g^{\mathcal{Q}_6}_{ij}\mathcal{Q}^{\alpha\beta\mu\dagger}_6\bar{d}^{(\alpha|}_{Ri}\gamma_\mu(i\sigma_2)q^{c|\beta)}_{Lj} + \text{h.c.}$$

$$a^{cbiu}_{S_{RL}} = \frac{4}{3}\kappa^{S}_{\rm RGE}V^*_{ui}V_{cj}\left(\frac{g^{\mathcal{Q}_3*}_{3i}g^{\mathcal{Q}_3}_{ij}}{M^2_{\mathcal{Q}_3}} - \frac{g^{\mathcal{Q}_6*}_{3i}g^{\mathcal{Q}_6}_{ij}}{M^2_{\mathcal{Q}_6}}\right)$$

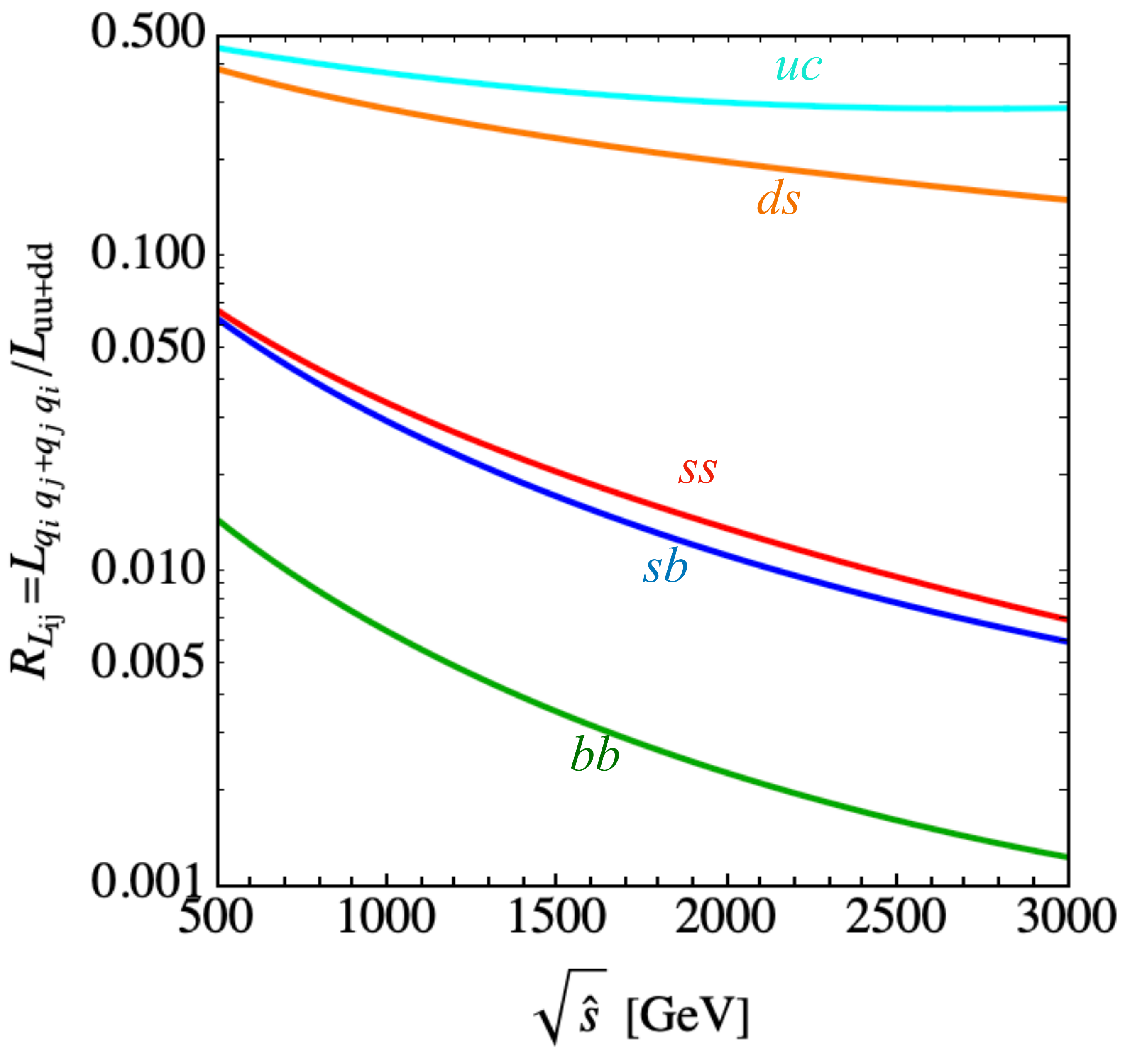
$$a^{cbdu}_{S_{RL}} \approx \frac{3.0V_{cs}V^*_{ud}}{M^2_{\mathcal{Q}}}g^{\mathcal{Q}*}_{31}g^{\mathcal{Q}}_{12} \approx -\frac{0.26V_{ud}}{\text{TeV}^2}\,,\quad a^{cbsu}_{S_{RL}} \approx \frac{3.0V_{cs}V^*_{ud}}{M^2_{\mathcal{Q}}}g^{\mathcal{Q}*}_{31}g^{\mathcal{Q}}_{22} \approx -\frac{0.31V_{us}}{\text{TeV}^2}$$

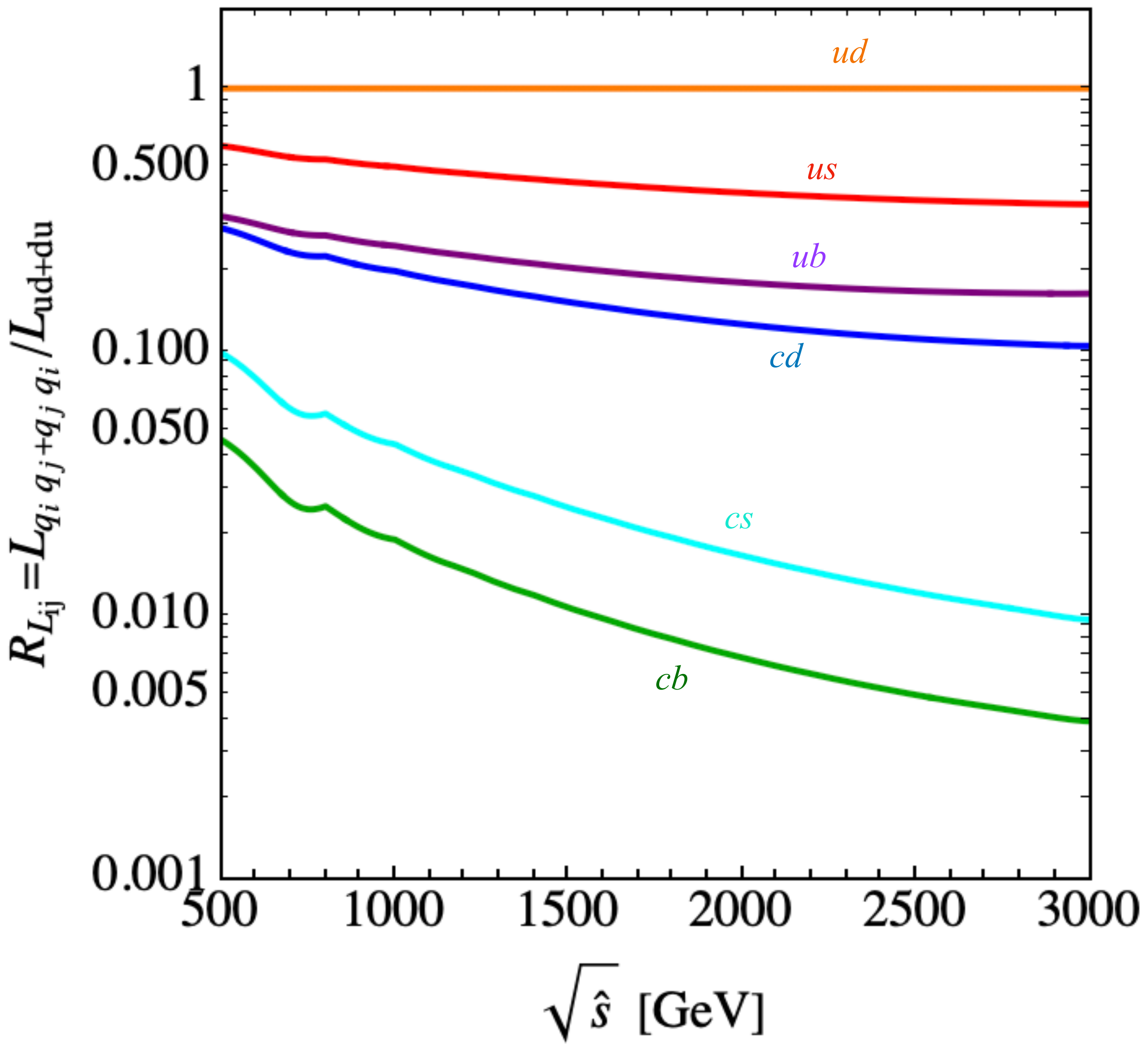
LHC as a “Flavor collider”



$$\mathcal{L}_{\bar{q}_i q_j}(\hat{s}, \mu_F) = \int_{\hat{s}/s_0}^{1} \frac{dx}{x} \underbrace{f_{\bar{q}_i}(x, \mu_F)\, f_{q_j}}_{\text{PDF}}\left(\frac{\hat{s}/s_0}{x}, \mu_F\right)$$

quark-antiquark luminosities





High-pT tails at LHC are directly sensitive to all flavour-violating couplings.