Implications for new physics from a novel puzzle in $\overline{B}^0_{(s)} \to D^{(*)+}_{(s)} \{K^-, \pi^-\}$ decays

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[arXiv:2008.01086]

Mini-Workshop on Colour Allowed Non-Leptonic Tree-Level Decays, Universität Siegen,
April 1, 2021, ONLINE

KMI Nagoya University

Slide from Mick Mulder

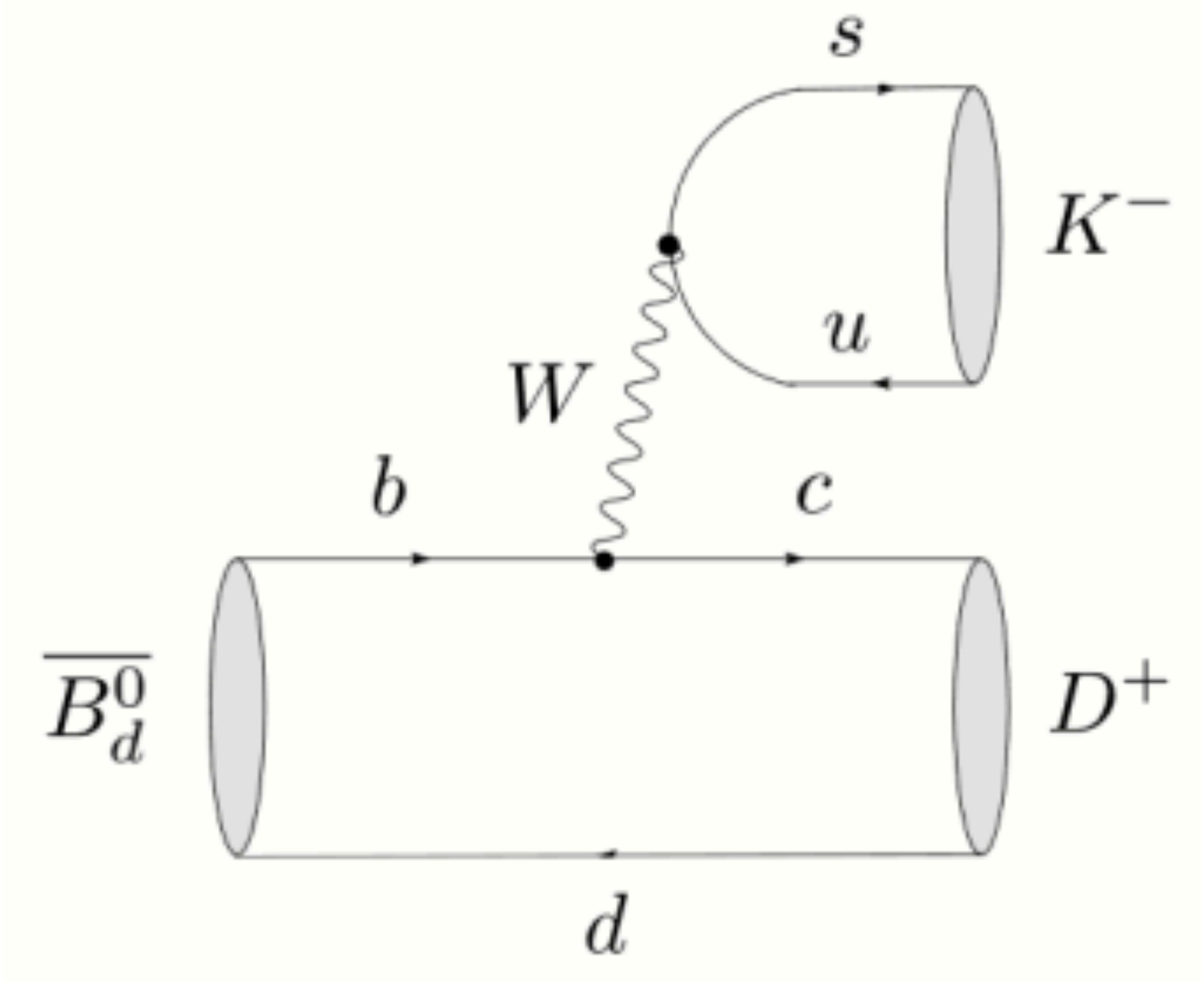
On the menu today: $B^0_{(s)} \to D^-_{(s)} h^+, \Lambda^0_b \to \Lambda^+_c h^-$

- **Non-leptonic tree-level:** $b \to c\bar{u}d(s)$ or $b \to u\bar{c}d(s)$ transitions
- **Colour allowed**: separate colour indices for $X_b - X_c$ and h systems
- **Main decay modes (focus of today):**
  - $B^0 \to D^{(*)-}\{K^+, \pi^+\}$
  - $B^+ \to \bar{D}^{(*)0}\{K^+, \pi^+\}$ (w. colour-suppressed contributions)
  - $B^0_s \to D^{(*)-}_s\{K^+, \pi^+\}$
  - $\Lambda^0_b \to \Lambda^+_c\{K^-, \pi^-\}$

  no penguin, no annihilation

  - Two types of transitions:
    - $B^0 \to D^{(*)-}K^+, B^0_s \to D^{(*)-}_s\pi^+$: tree-only decays
    - $B^0 \to D^{(*)-}\pi^+, B^0_s \to D^{(*)-}_s K^+$: tree + exchange decays

Example decay: $B^0 \to D^- K^+$



[Fleischer, arXiv:0802.2882]

Slide from Nico Gubernari

Fits to the available data

source	PDG	our fits (w/o QCDF)		QCDF prediction
scenario	—	no f_s/f_d	$(f_s/f_d)^{7\ \mathrm{TeV}}_{\mathrm{LHCb,sl}}$	—
χ^2/dof	—	$2.5/4$	$3.1/5$	—
$\mathcal{B}(\bar{B}^0_s \to D^+_s \pi^-)$	3.00 ± 0.23	3.6 ± 0.7	3.11 ± 0.25	4.42 ± 0.21
$\mathcal{B}(\bar{B}^0 \to D^+ K^-)$	0.186 ± 0.020	0.222 ± 0.012	0.224 ± 0.012	0.326 ± 0.015
$\mathcal{B}(\bar{B}^0 \to D^+ \pi^-)$	2.52 ± 0.13	2.71 ± 0.12	2.73 ± 0.12	—
$\mathcal{B}(\bar{B}^0_s \to D^{*+}_s \pi^-)$	2.0 ± 0.5	2.4 ± 0.7	2.1 ± 0.5	$4.3^{+0.9}_{-0.8}$
$\mathcal{B}(\bar{B}^0 \to D^{*+} K^-)$	0.212 ± 0.015	0.216 ± 0.014	0.216 ± 0.014	$0.327^{+0.039}_{-0.034}$
$\mathcal{B}(\bar{B}^0 \to D^{*+} \pi^-)$	2.74 ± 0.13	2.78 ± 0.15	2.79 ± 0.15	—
$\mathcal{R}^P_{s/d}$	16.1 ± 2.1	16.2 ± 3.3	14.0 ± 1.1	$13.5^{+0.6}_{-0.5}$
$\mathcal{R}^V_{s/d}$	9.4 ± 2.5	11.4 ± 3.6	9.6 ± 2.5	$13.1^{+2.3}_{-2.0}$
$\mathcal{R}^{V/P}_s$	0.66 ± 0.16	0.66 ± 0.16	0.66 ± 0.16	$0.97^{+0.20}_{-0.17}$
$\mathcal{R}^{V/P}_d$	1.14 ± 0.15	0.97 ± 0.08	0.97 ± 0.08	1.01 ± 0.11
$(f_s/f_d)^{7\ \mathrm{TeV}}_{\mathrm{LHCb}}$	—	$0.223^{+0.056}_{-0.038}$ *	0.260 ± 0.019	—
$(f_s/f_d)_{\mathrm{Tev}}$	—	$0.208^{+0.056}_{-0.038}$ *	0.243 ± 0.028	—

- fits indicate that measurements are consistent
- discrepancy between measurements and theoretical predictions:

$\bar{B}^0_s \to D^+_s \pi^- \to 4\sigma$
$\bar{B}^0 \to D^+ K^- \to 5\sigma$
$\bar{B}^0_s \to D^{*+}_s \pi^- \to 2\sigma$
$\bar{B}^0 \to D^{*+} K^- \to 3\sigma$

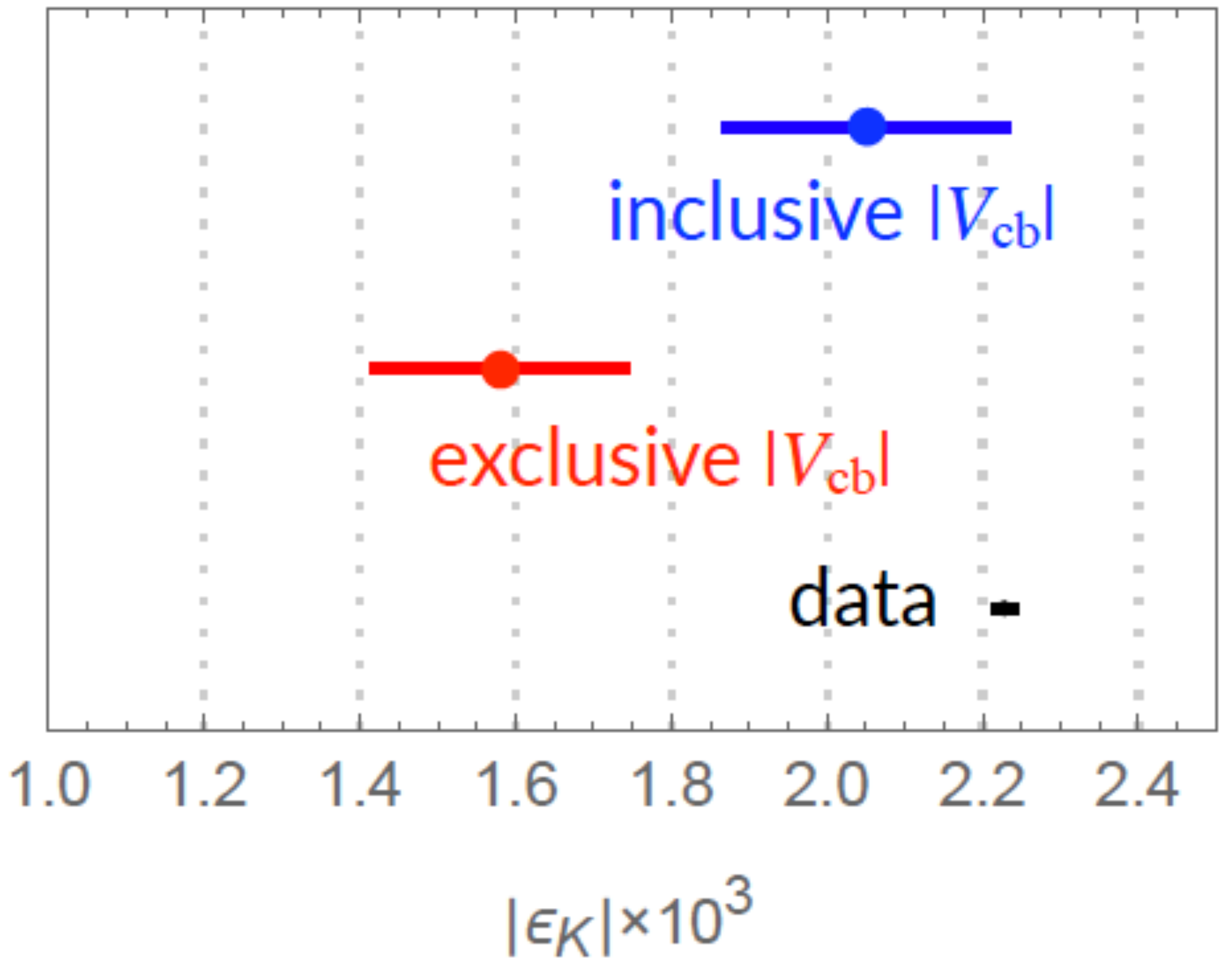
BR(exp.) < BR(SM pred. from QCDF)

SM amplitudes are uniformly larger by $\mathcal{O}(15\%)$

4.4σ level deviation

Explanation without new physics

- |Vcb| dependence?
  - [Bordone, Gubernari, Huber, Jung, van Dyk, 2007.10338] uses |Vcb| × 10^3 = 41.1(5) [average of inclusive and exclusive].
  - If the exclusive value, *e.g.*, |Vcb| × 10^3 = 39.25(56), the SM amplitudes are reduces by 4.5%
  - Then, however, 4.2σ tension appears in ε_K [LANL-SWME lattice, 1912.03024]
- Higher-order QCD corrections?
  - Unlikely. It has been estimated as $\mathcal{O}(1\%)$



New physics interpretation

- Effective Lagrangian

Factorized by SM CKM factor

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} \sum_q V_{cb} V_{uq}^* \sum_{i=1,2} C_i^q(\mu) Q_i^q(\mu) \,,$$

$$Q_1^q = (\bar{c}_L \gamma^\mu T^a b_L)(\bar{q}_L \gamma_\mu T^a u_L) \,,$$
$$Q_2^q = (\bar{c}_L \gamma^\mu b_L)(\bar{q}_L \gamma_\mu u_L) \,,$$

- Best fit point

$$\frac{C_2^{\rm NP}(m_b)}{C_2^{\rm SM}(m_b)} = -0.17 \pm 0.03 \,.$$

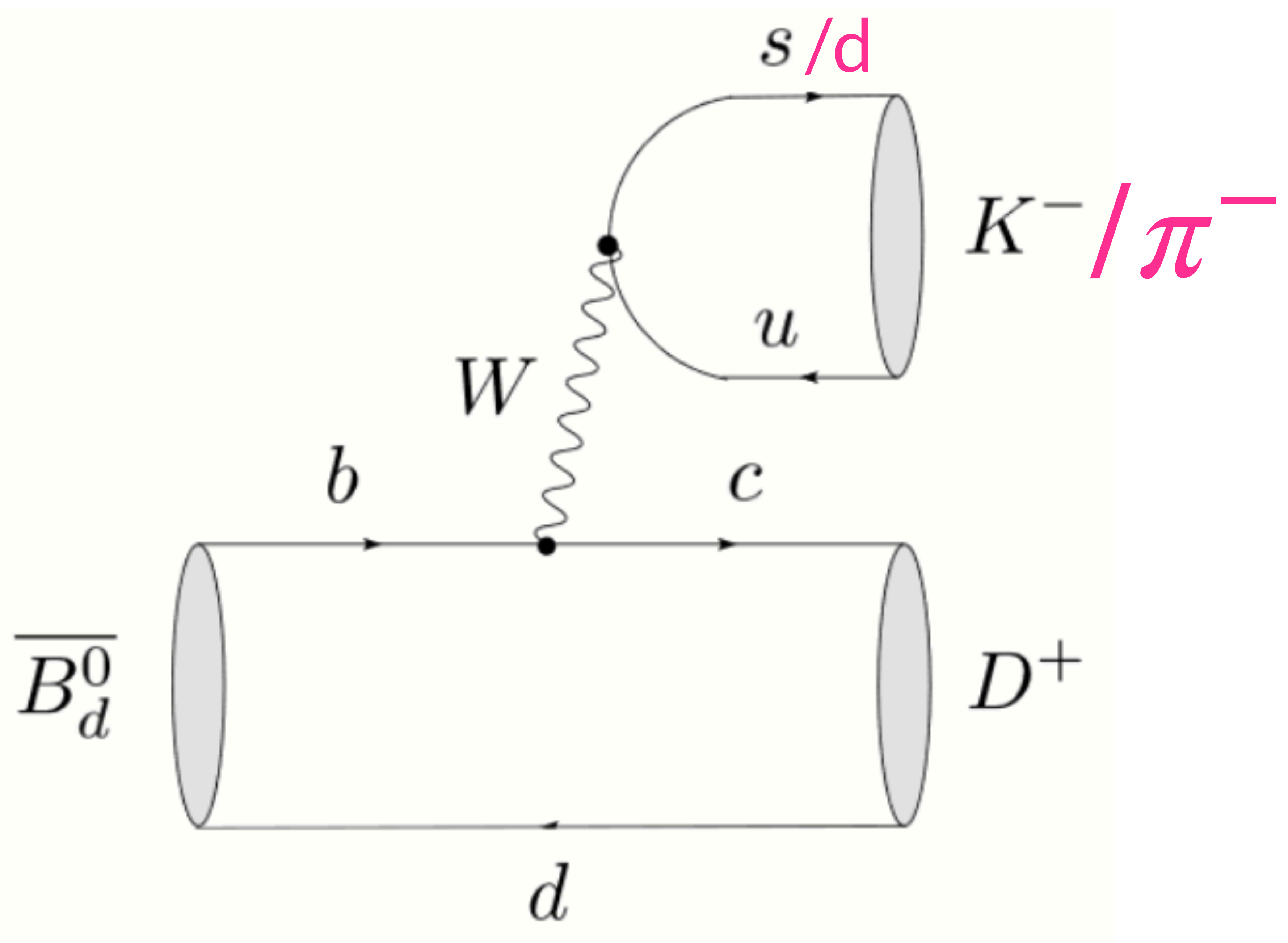
Compatible with lifetime measurements

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

- QCD RGE

$$\begin{pmatrix} C_1^{\rm NP}(m_b) \\ C_2^{\rm NP}(m_b) \end{pmatrix} = \begin{pmatrix} 1.36 & -0.87 \\ -0.19 & 1.07 \end{pmatrix} \begin{pmatrix} C_1^{\rm NP}(1\,{\rm TeV}) \\ C_2^{\rm NP}(1\,{\rm TeV}) \end{pmatrix} .$$

We consider W' model



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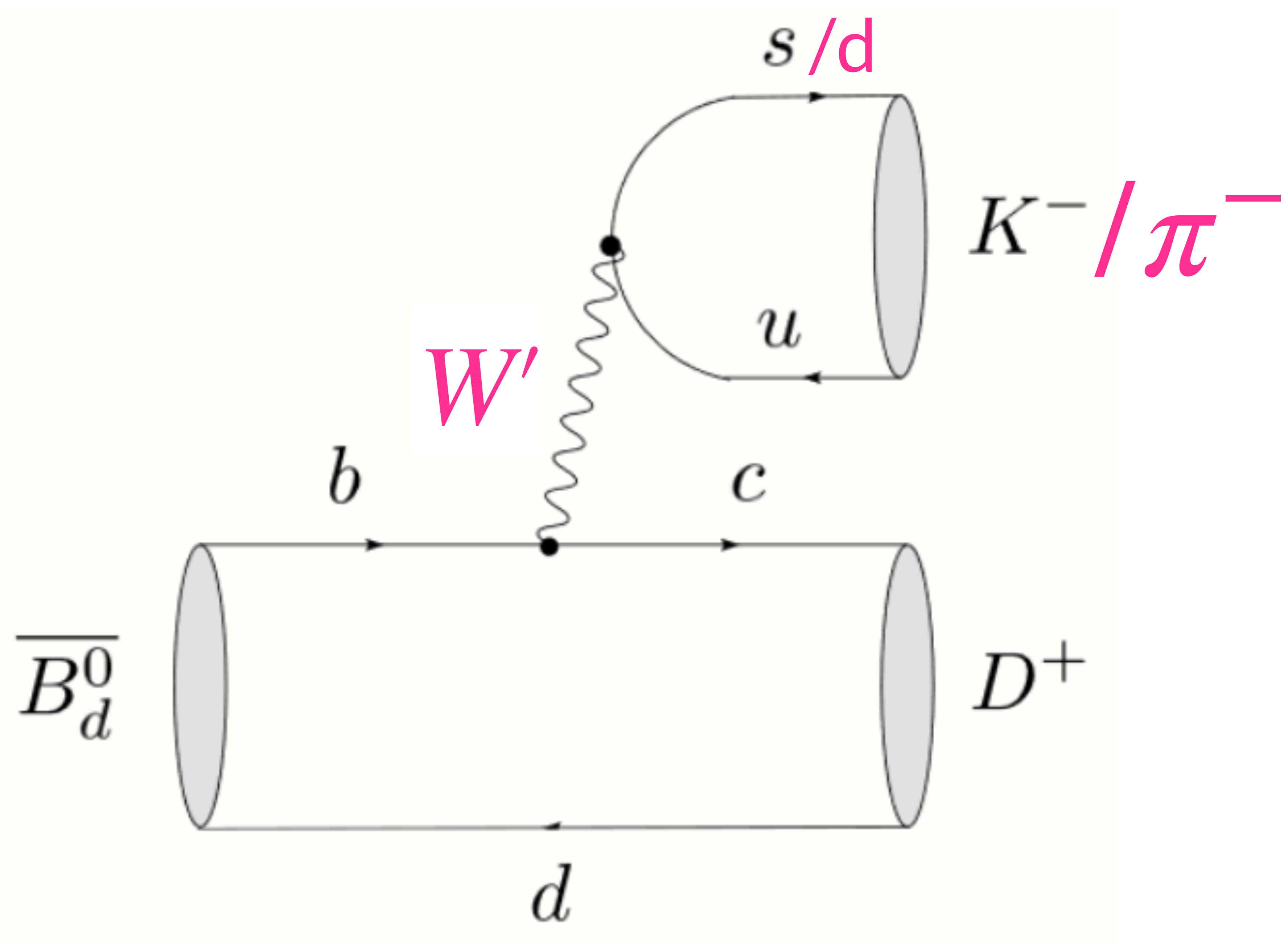


Just assuming no leptonic coupling

Sanity check from kaon

- How about $s \to u\bar{u}d$ bound from the kaon decays? Assuming CP-conserving W' contribution;

$$A_I = \langle (\pi\pi)_I | \mathcal{H}_{\rm eff}^{|\Delta S|=1} | K \rangle \text{ for } I = 0, 2$$

$$\mathrm{Re}A_0^{\rm exp} = (3.3201 \pm 0.0018) \times 10^{-7}\,\mathrm{GeV}\,,$$
$$\mathrm{Re}A_2^{\rm exp} = (1.4787 \pm 0.0031) \times 10^{-8}\,\mathrm{GeV}\,.$$

$$\mathrm{Re}A_0^{\rm SM} = (2.99 \pm 0.67) \times 10^{-7}\,\mathrm{GeV}\,,$$
$$\mathrm{Re}A_2^{\rm SM} = (1.50 \pm 0.15) \times 10^{-8}\,\mathrm{GeV}\,,$$

[RBC-UKQCD lattice, 2004.09440]

$\pm 20\,\%$ new physics contribution to $s \to u\bar{u}d$ amplitudes could be compatible with data

A $\mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2 \times \mathrm{U}(1)_Y$ model

- We consider an extended electroweak gauge group $\mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2 \times \mathrm{U}(1)_Y$ model, which contains heavy vector-like quarks and heavy SU(2) gauge multiplet
- After integrating out the vector-like quarks, the following effective Lagrangian is generated

[Boucenna, Celis, Fuentes-Martin, Vicente, Virto, 1608.01349]

$$\mathcal{L} = + \frac{g_{ij}}{2} Z'_\mu \bar{d}^i_L \gamma^\mu d^j_L - \frac{(VgV^\dagger)_{ij}}{2} Z'_\mu \bar{u}^i_L \gamma^\mu u^j_L - \frac{(Vg)_{ij}}{\sqrt{2}} W'^+_\mu \bar{u}^i_L \gamma^\mu d^j_L + \mathrm{H.c.}\,,$$

g_{ij} basis is defined by the first term

$$\Rightarrow \quad C_2^{q,W'}(M_V) = \frac{1}{4\sqrt{2} G_F M_V^2} \frac{(Vg)_{23}(Vg)^*_{1q}}{V_{cb} V^*_{uq}}\,.$$

Three scenarios

- We consider the fowling three scenarios

$$\mathcal{L} = + \frac{g_{ij}}{2} Z'_\mu \bar{d}^i_L \gamma^\mu d^j_L - \frac{(V g V^\dagger)_{ij}}{2} Z'_\mu \bar{u}^i_L \gamma^\mu u^j_L - \frac{(V g)_{ij}}{\sqrt{2}} W'^+_\mu \bar{u}^i_L \gamma^\mu d^j_L + \text{H.c.}\,,$$

$$g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & 0 \\ 0 & 0 & g_{33} \end{pmatrix}, \quad g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & g_{23} \\ 0 & g_{23} & 0 \end{pmatrix}, \quad g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & g_{23} \\ 0 & g_{23} & g_{33} \end{pmatrix},$$

Scenario1 Scenario2 Scenario3

Here, U(2) symmetry is imposed to avoid strong constraints from *K*- and *D*-meson mixings

Scenario1

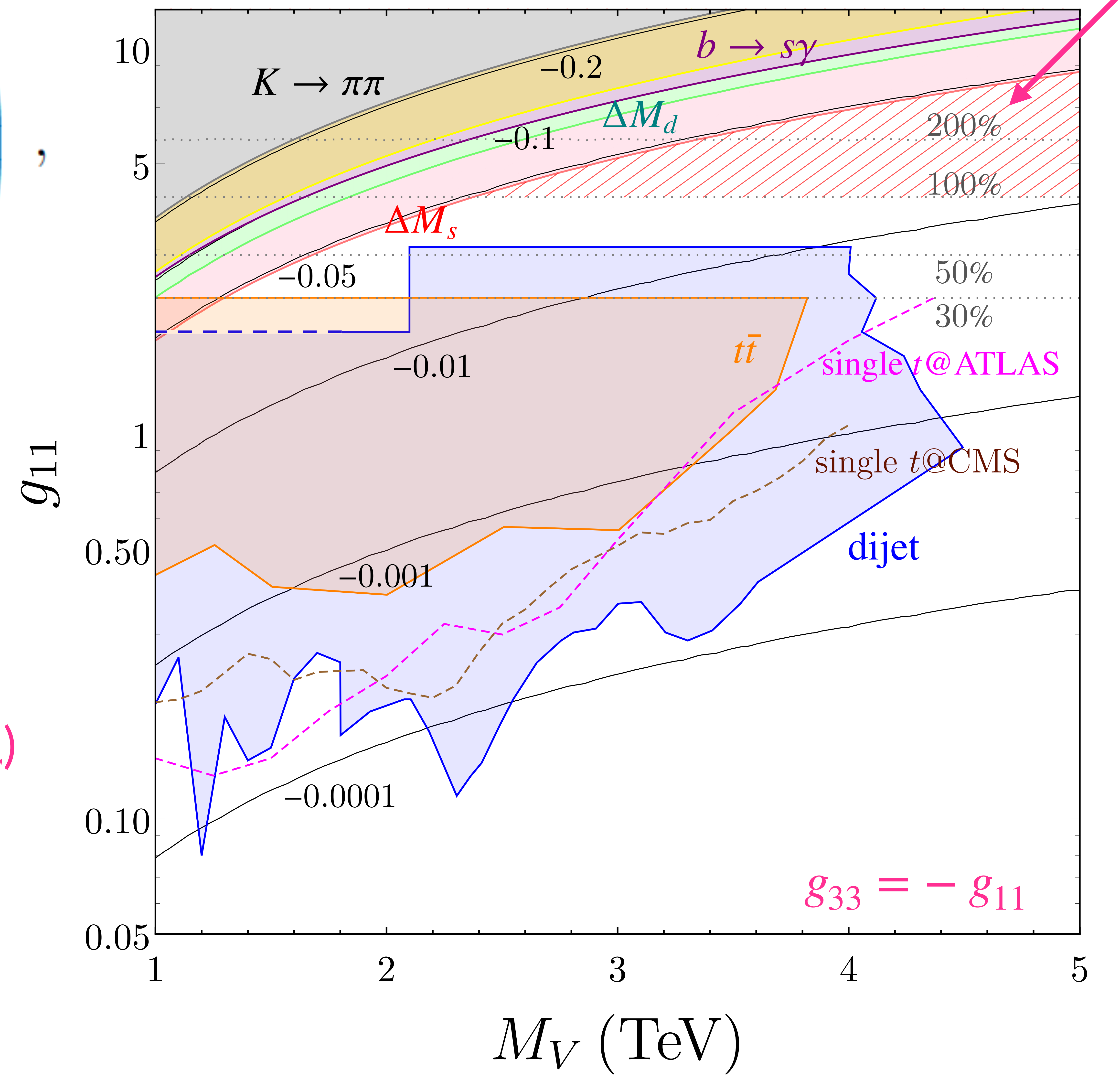
$$g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & 0 \\ 0 & 0 & g_{33} \end{pmatrix},$$

Black contours:

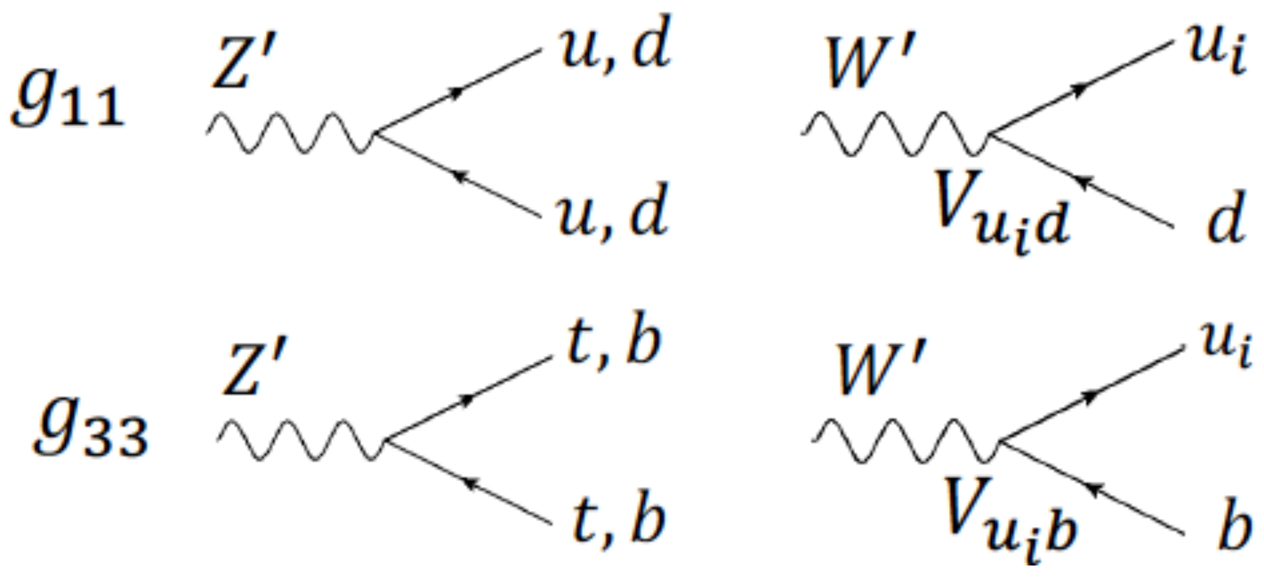
$$\frac{C_2^{\rm NP}(m_b)}{C_2^{\rm SM}(m_b)}$$

Flavor constraint (ΔM_s) comes from W-W' box $\propto g_{11} \times g_{33}$

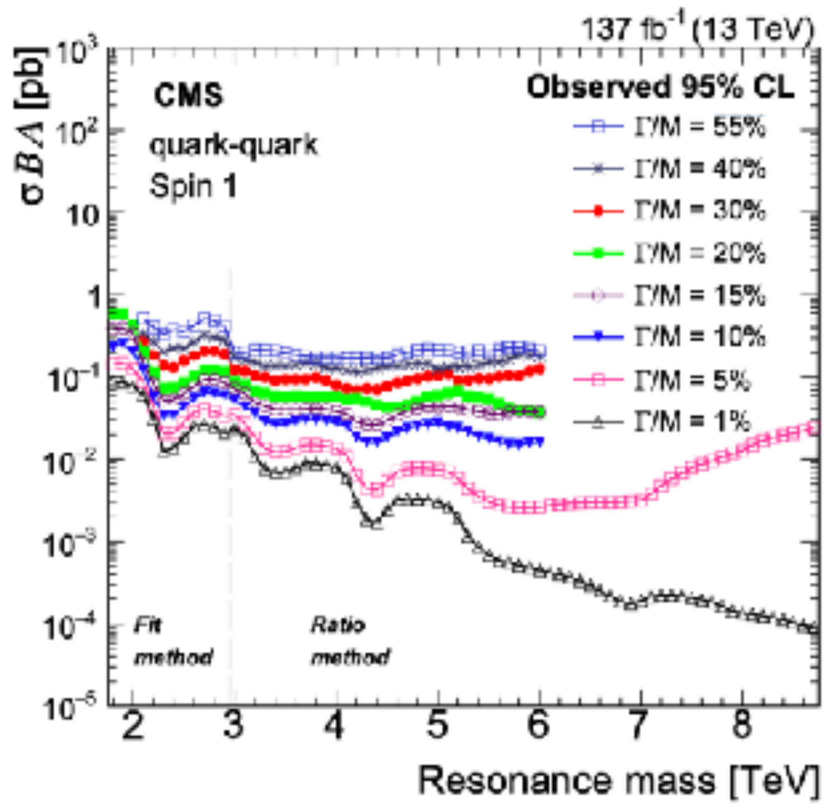
Width > 100%



Strong bounds comes from direct search by LHC



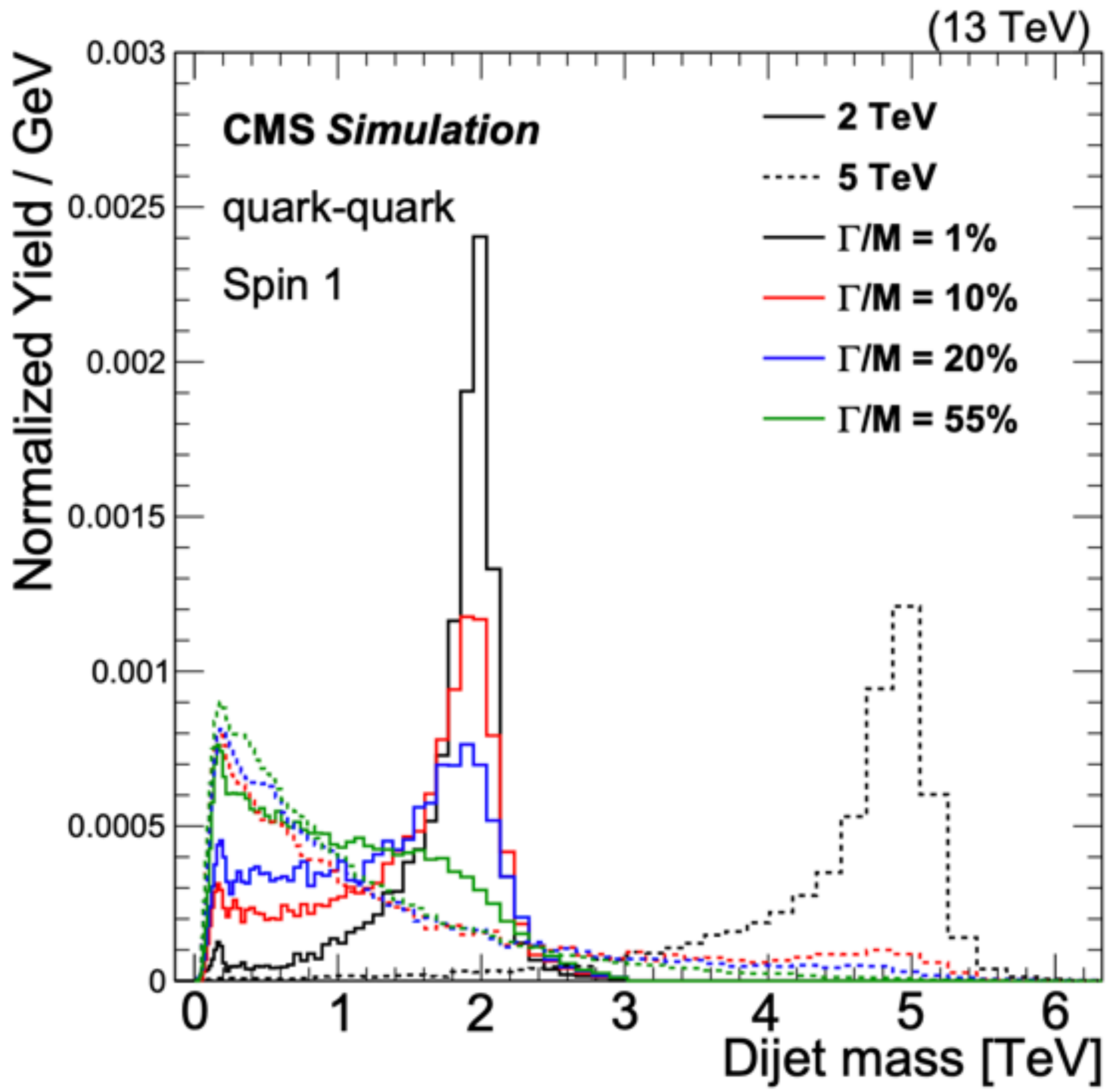
We rescaled the width-dependent limit

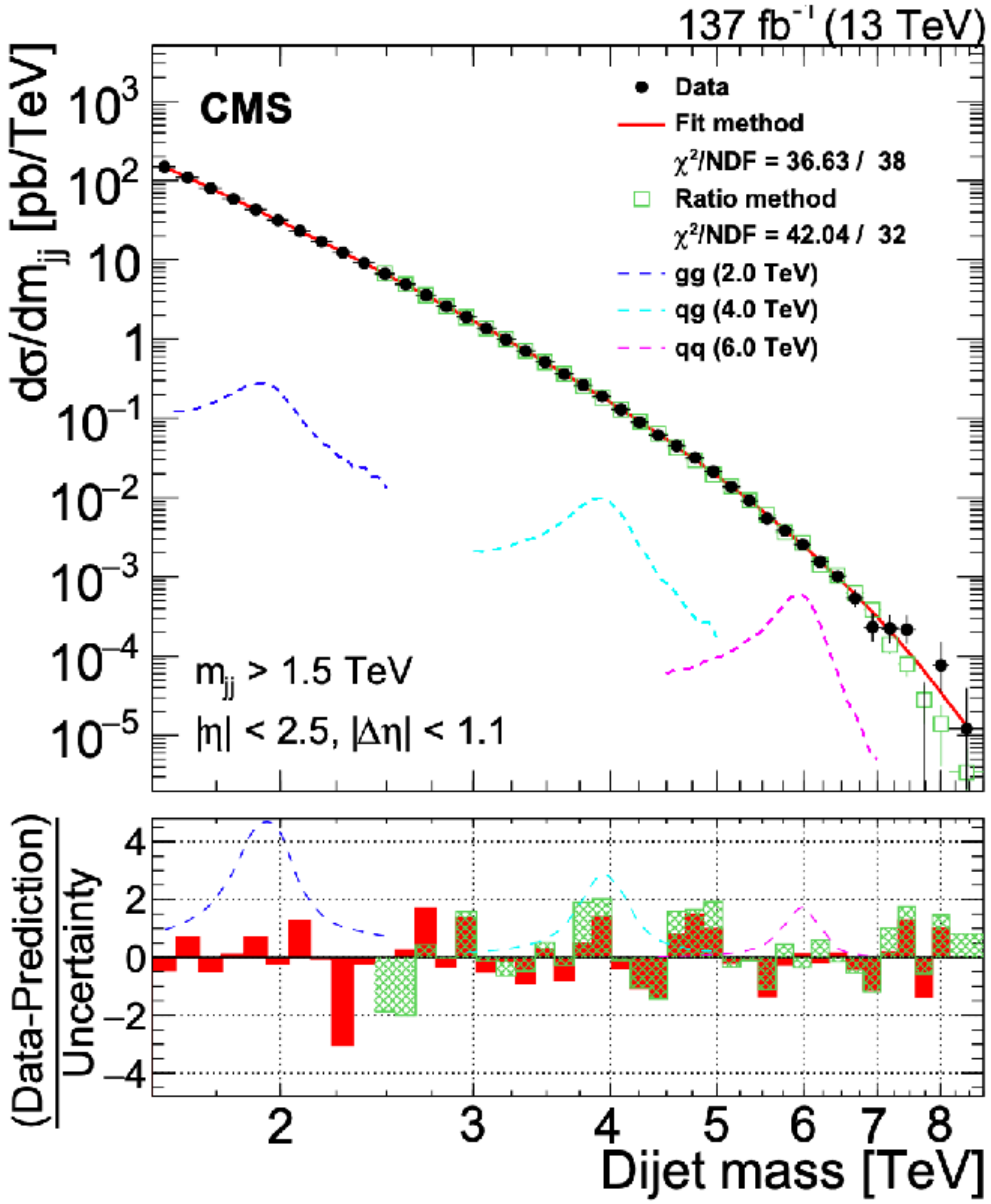


[CMS 1911.03947]

- Is it possible to hide W' in low dijet-mass and broad-width regime?
- If fine, $C_2(NP)/C_2(SM) \sim -0.05$ is possible

[CMS 1911.03947]





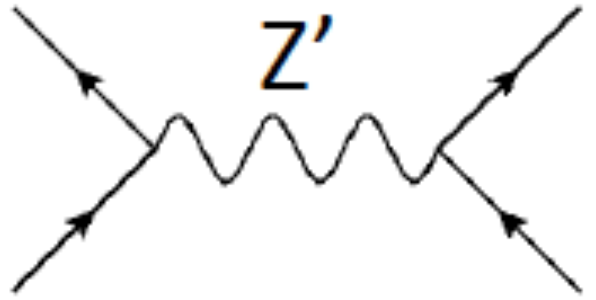
Scenario2

$$g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & g_{23} \\ 0 & g_{23} & 0 \end{pmatrix},$$

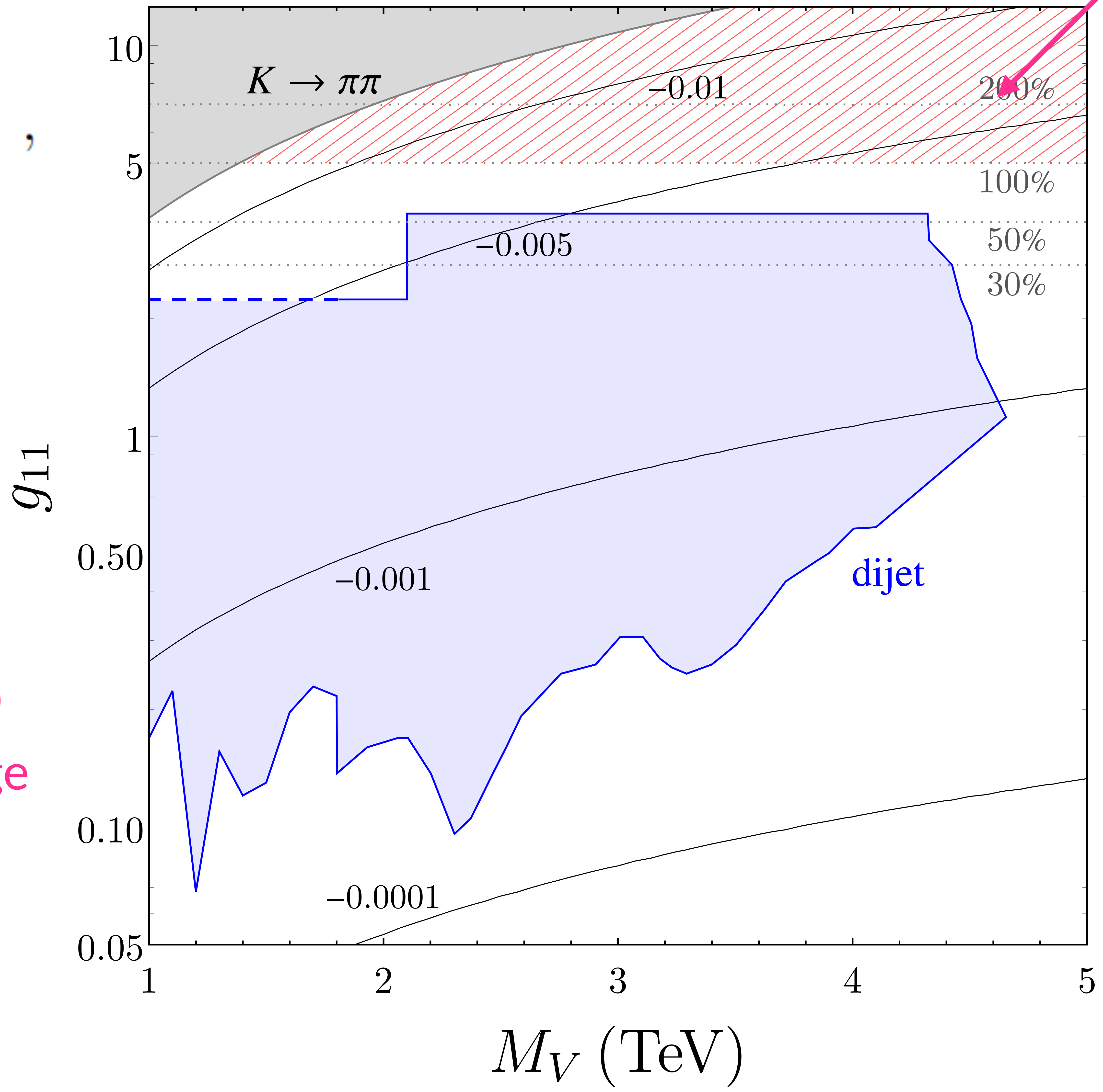
Black contours:

$$\frac{C_2^{\rm NP}(m_b)}{C_2^{\rm SM}(m_b)}$$

Flavor constraint (ΔM_s) comes from Z'-exchange $\propto |g_{23}|^2$



Width > 100%



$$\frac{C_2^{NP}(\Lambda_{NP})}{C_2^{SM}} \sim \frac{g_{11} \times g_{23}}{4\sqrt{2} G_F M_V^2 V_{cb}}$$

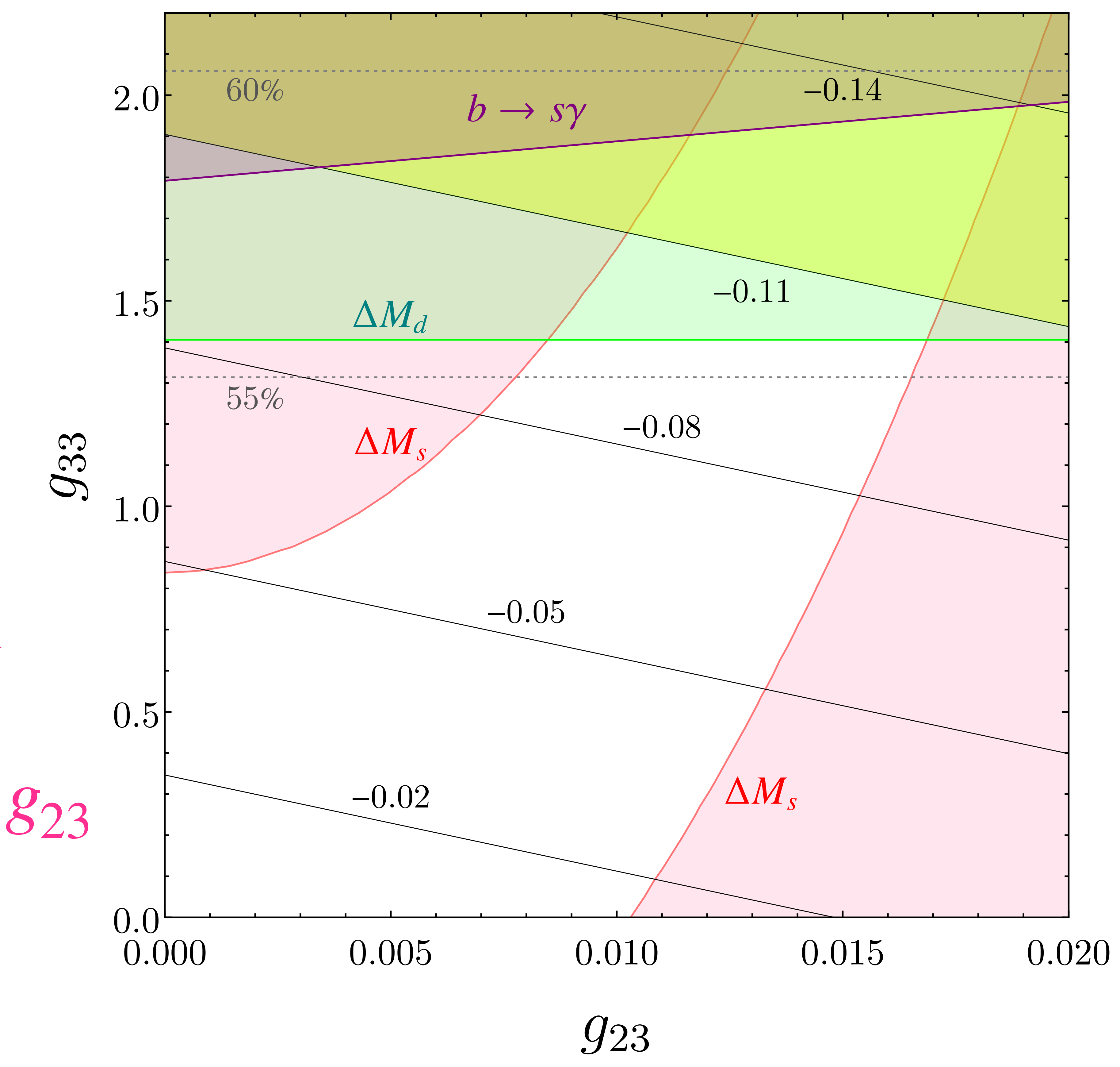
Enhancement by $\frac{1}{V_{cb}} \sim 25$

g_{23} is saturated under the flavor constraints on this plane

Scenario3

$$g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & g_{23} \\ 0 & g_{23} & g_{33} \end{pmatrix},$$

$$M_V = 1\,\text{TeV and } g_{11} = -3.6.$$



Contribution to ΔM_s can be cancelled

$\Delta M_s^{W'} < 0, \ \Delta M_s^{Z'} > 0$

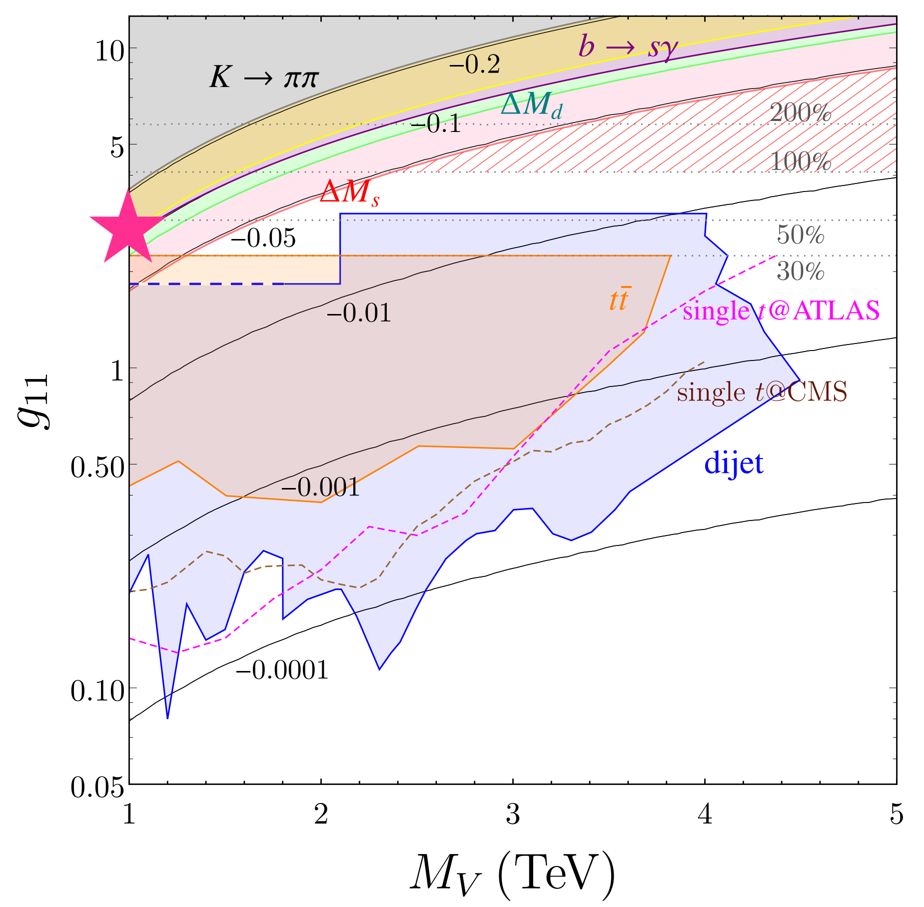
W-W' box Z' tree level

Then constraint from ΔM_d is important!

$\Delta M_d / \Delta M_s$ would give additional bound

C$_2$(NP)/C$_2$(SM) ∼ -0.10 would be possible

Scenario1



non-zero g_{23}

Conclusions

- W' from an additional SU(2) can partially cancel the large SM colour-allowed tree-level amplitude by
  $C_2^{\rm NP}/C_2^{\rm SM} = -\,\mathcal{O}(10\%)$
  as long as the collider constraint can be evaded.

- The more dedicated collider analysis for low-dijet mass and the broad width regime would be important to exclude such W'

Backup