New physics contributions to $\bar{B}_{(s)} \to D_{(s)}^{(*)} K/\pi$

Syuhei Iguro

2016.4~2021.3

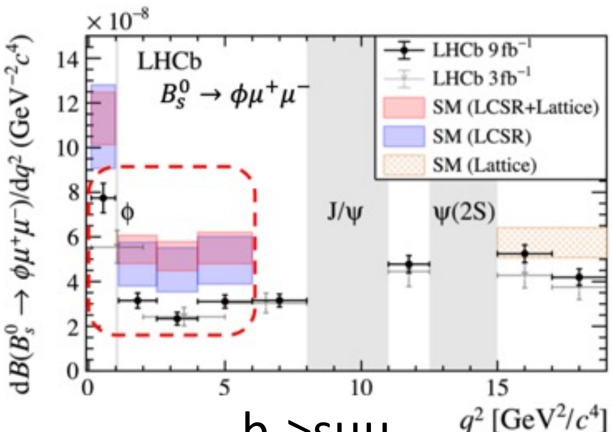
2021.4 ~2021.9

2021.10 ~

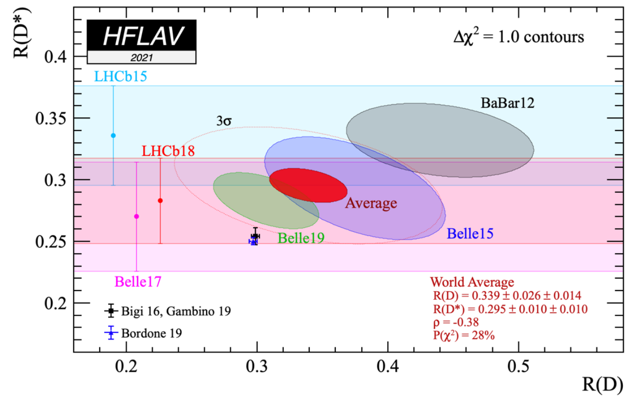
11th International Workshop on the CKM Unitarity Triangle 2021

arXiv:2008.01086 PRD *Rapid Communication* 102, 071701 (2020) with T. Kitahara
arXiv:2109.10811 with M. Endo and S. Mishima

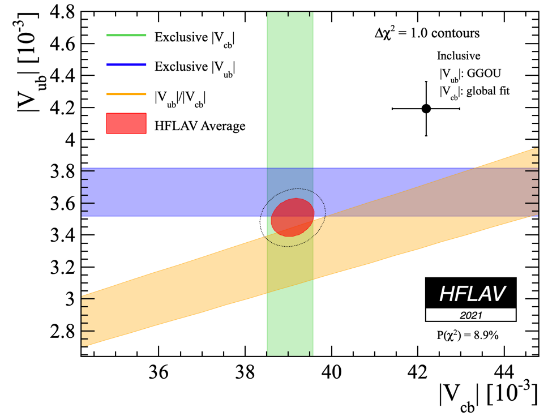
There are interesting anomalies in B physics



b->sμμ



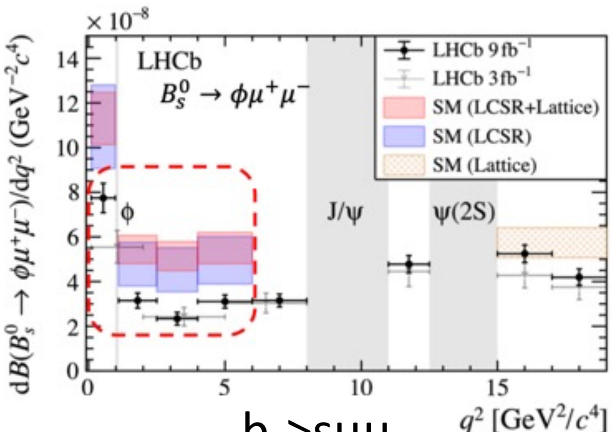
b->cτν



b->clν (l=e,μ)

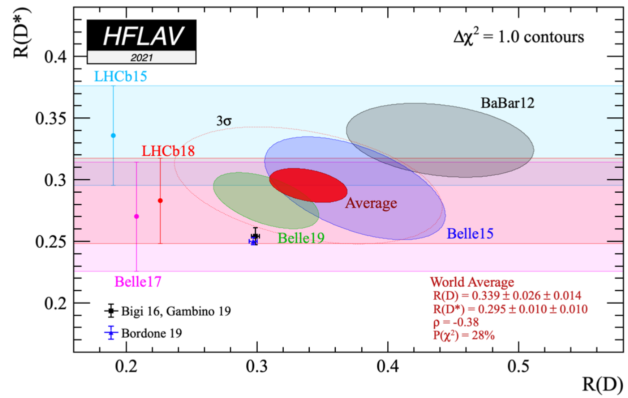
Semileptonic decay

There are interesting anomalies in B physics



b->sμμ

See also 2110.09501



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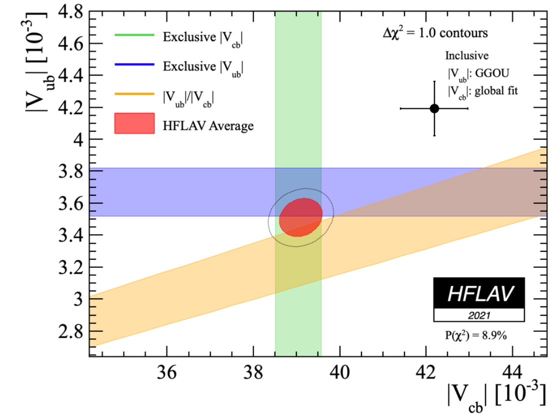
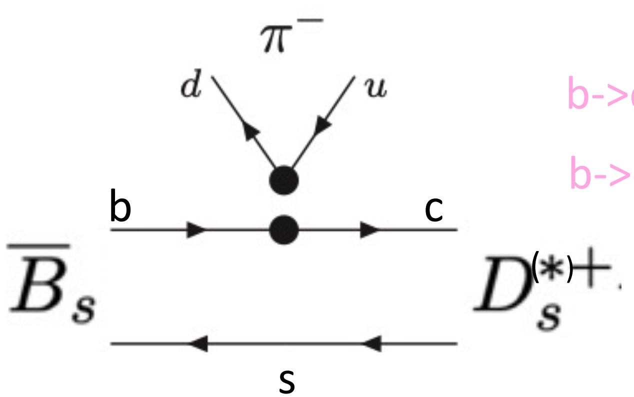


b->clν (l=e,μ)

We also have coherent deviations in hadronic 2-body B meson decays

b->cuq (q= both d,s)



Tree level W exchange

b->cuq puzzle

		$BR^{exp}\times10^3$	$BR^{SM,QCDF}\times10^3$	
b->cud	$\overline{B}_s \to D_s^+\pi^-$	3.00 ± 0.23	4.09 ± 0.21	**3.5σ**
b->cus	$\overline{B}^0 \to D^+K^-$	0.186 ± 0.020	0.303 ± 0.015	**4.7σ**
	$\overline{B}_s \to D_s^{*+}\pi^-$	2.0 ± 0.5	4.46 ± 0.22	**4.5σ**
	$\overline{B}^0 \to D^{*+}K^-$	0.212 ± 0.015	0.327 ± 0.016	**5.3σ**
		PDG	2109.10811	

See also Bordone et al 2007.10338, Cai et al2103.04138, Fleischer et al 2109.04950 for SM predictions. BaBar, Belle, LHCb are consistent.

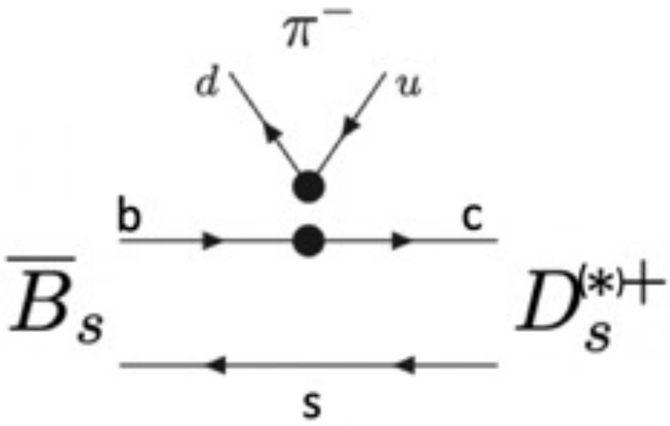
Color allowed $B \to D^{(*)}M$ within the SM

The decays are described by

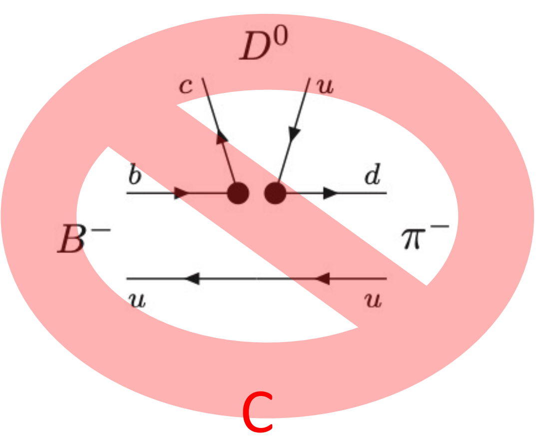
$$\mathcal{H}_W = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s} V_{cb}V_{uq}^*(C_1\mathcal{O}_1^q + C_2\mathcal{O}_2^q) + \text{h.c.},$$

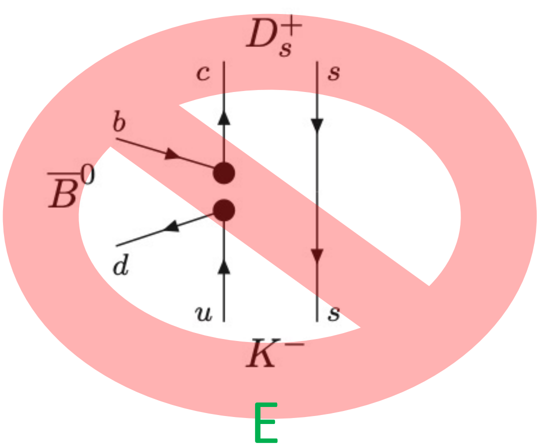
$$\mathcal{O}_1^q = \left(\bar{c}\gamma^\mu T^a P_L b\right)\left(\bar{q}\gamma_\mu T^a P_L u\right),$$
$$\mathcal{O}_2^q = \left(\bar{c}\gamma^\mu P_L b\right)\left(\bar{q}\gamma_\mu P_L u\right),$$

with $C_1(m_b) \sim -0.3, C_2(m_b) \sim 1$



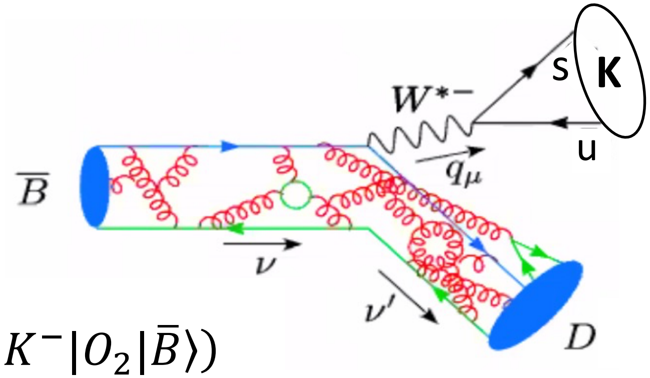
Penguin, Color- suppressed and Exchange diagrams does not contribute since the involving quarks are all different.





Theoretically clean

Factorization amplitude



$$A(\bar{B} \to D^+K^-) = \frac{G_F V_{us}^* V_{cb}}{\sqrt{2}}\left(C_1\langle D^+K^-|O_1|\bar{B}\rangle + C_2\langle D^+K^-|O_2|\bar{B}\rangle\right)$$

The non factorizable soft gluon exchange contribution between BD system and K is suppressed. *Bjorken (89)*

Soft collinear effective theory shows the contribution is absent at leading order

Bauer et al. 0107002

$$= \frac{i\ G_F V_{us}^* V_{cb}}{\sqrt{2}}(m_B^2 - m_D^2)a_1(D^+K^-)\ f_K\ F_0^{B\to D}(m_K^2)$$

$a_1(D^+K^-)$ is calculated in pQCD at NNLO. See also Beneke et al 2107.03819 for QED correction

$$a_1(D^+K^-) = (1.069^{+0.009}_{-0.012}) + \left(0.046^{+0.023}_{-0.015}\right)i$$ *Huber et al, 1606.02888*

$V_{cb} \times\ F_0^{B\to D}(m_K^2)$: LCSR, Belle data, QCDSR, Lattice Iguro Watanabe 2004.10208.

Uncertainty in f_K and V_{us} is negligible

LCSR dominance at $q^2 = m_K^2$

Current situation

	$BR^{exp} \times 10^3$	$BR^{SM,QCDF} \times 10^3$	
$\overline{B}_s \to D_s^+ \pi^-$	3.00 ± 0.23	4.09 ± 0.21	**3.5σ**
$\overline{B}^0 \to D^+ K^-$	0.186 ± 0.020	0.303 ± 0.015	**4.7σ**
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Theoretical uncertainty mainly comes from $V_{cb} \times$ FF

10 - 30% smaller amplitude can explain the data.

Missing piece?

- *V_{cb}, B-> D, D* form factor?*

We use the result from Iguro Watanabe 2004. 10208: V_{cb}^{exc}=0.397(6),,,.
Adopting $V_{cb}^{inc} > V_{cb}^{exc}$ makes the situation worse!

- *$O(\Lambda_{QCD}/m_b)$ sub-leading power corrections ?*

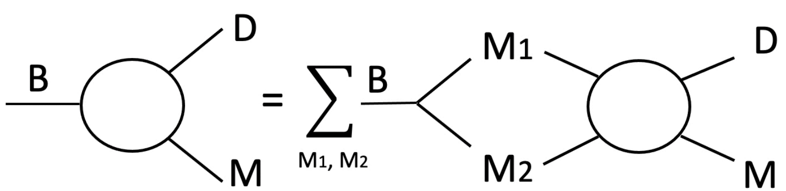
Expected to be small: O(0.1)% Bordone et al 2007.10338

- $O(\Lambda_{QCD}/m_b)$ chirality enhanced contribution is absent
- correction to LCDA is $O(\alpha_s \Lambda^2/m_b^2)$
- Contribution from soft gluon exchange between BD system and light meson is small

- *Other power suppressed correction to QCDF?*

In reality, bottom mass is finite.

meson-meson rescattering contribution is tested Iguro, Endo Mishima 2109.10811



We found the rescattering does not solve the discrepancy

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- ***New Physics?***

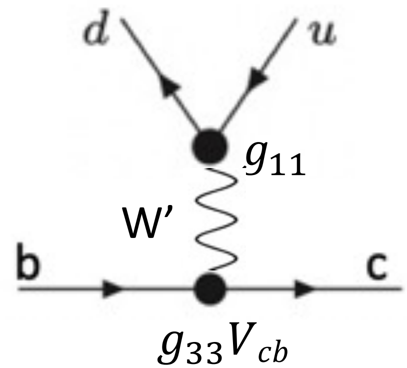
NP possibilities?

In order to explain the discrepancy,
O(10)% downward shift from the SM amplitude is necessary.

Interestingly such a large shift is still allowed by flavor observables.
Lenz et al 1912.07621.

We need a charged mediator (for instance W', not LQ)
The naïve NP scale for this puzzle is estimated as

$$\left|\frac{C_2^{NP}(\Lambda_{NP})}{C_2^{SM}}\right| \sim 10\% = \frac{g_{11}\times g_{33}}{M_V^2}\frac{1}{4\sqrt{2}G_F} = \frac{g_{11}\times g_{33}}{1}\frac{(400\mathrm{GeV})^2}{M_V^2}$$



Our model

We will focus on the $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ model

See also for other NP analyses, Bordone et al 2103.10332, Cai et al 2103.04138..

The model contains heavy vector-like quarks and
heavy SU(2) gauge multiplet.
After integrating out the heavy fermion,
the following effective Lagrangian is generated next page

Our model has an additional $SU(2)_L$ -> W' and Z'

Model

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

Free parameters

-> g_{ij}, m_V

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} \sum_q V_{cb} V^*_{uq} \sum_{i=1,2} C^q_i(\mu) Q^q_i(\mu)$$

$$Q^q_1 = (\bar{c}_L \gamma^\mu T^a b_L)(\bar{q}_L \gamma_\mu T^a u_L)\,,$$
$$Q^q_2 = (\bar{c}_L \gamma^\mu b_L)(\bar{q}_L \gamma_\mu u_L)\,,$$

We want to change C_2 by 20%

M. Bordone, et al 2007.10338

-> O(10) % of tree level W contribution!

Contribution

$$C^{q,W'}_2(M_V) = \frac{1}{4\sqrt{2} G_F M^2_V} \frac{(Vg)_{23}(Vg)^*_{1q}}{V_{cb} V^*_{uq}}$$

V:CKM

$(Vg)^*_{1q} \sim V_{ud} g_{11}$ for q=d

$\sim V_{us} g_{11}$ for q=s

$(Vg)_{23} \sim V_{cs} g_{23} + V_{ts} g_{33}$

Phenomenological assumption

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

Our model has an additional $SU(2)_L$ -> W' and Z'

Model

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

Free parameters

-> g_{ij}, m_V

$\mathcal{L} = -$ ... $_L)(\bar{q}_L \gamma_\mu T^a u_L)\,,$

$(\bar{q}_L \gamma_\mu u_L)\,,$

ge C_2 by 20%

/ contribution!

Scenario 1: $g_{11} \times g_{33} \neq 0, g_{23} = 0$

Scenario 2: $g_{11} \times g_{23} \neq 0, g_{33} = 0$

Scenario 3: $g_{11} \times g_{33} \times g_{23} \neq 0$

Contribution

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

V:CKM

$(Vg)_{1q} \sim V_{ud} g_{11}$ for q=d

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Phenomenological assumption

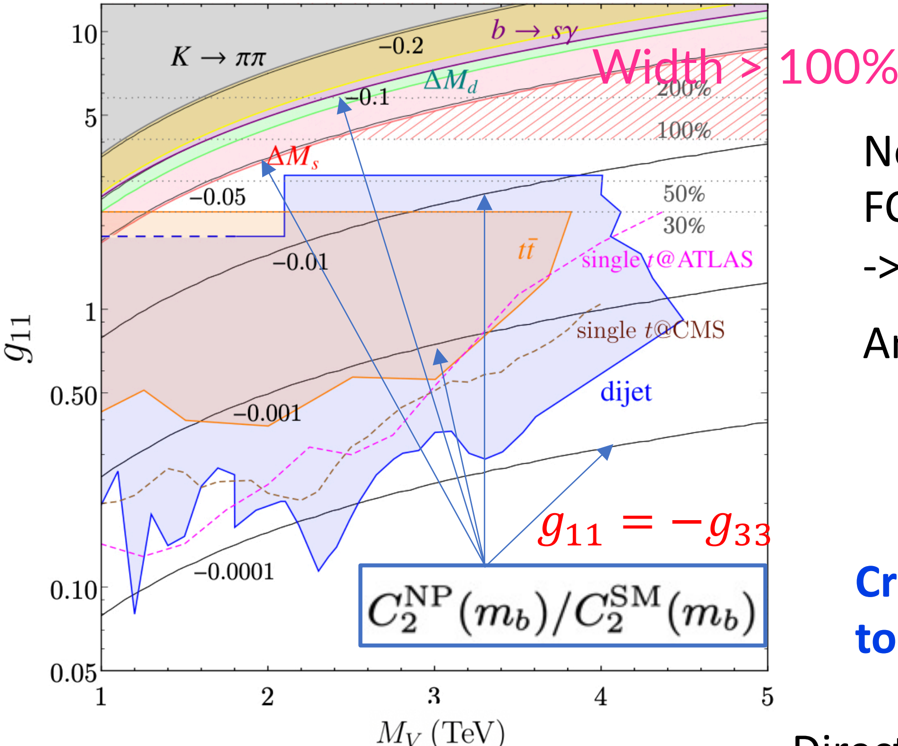
$$g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & g_{23} \\ 0 & g_{23} & g_{33} \end{pmatrix}$$

$g_{11} = g_{22}$ **: U2 symmetry ->GIM**

Scenario 1: $g_{11} \times g_{33} \neq 0, g_{23} = 0$

$$\frac{C_2^{NP}(\Lambda_{NP})}{C_2^{SM}} \sim \frac{g_{11} \times g_{33}}{4\sqrt{2} G_F M_V^2}$$

$g_{11} \times g_{33} < 0$



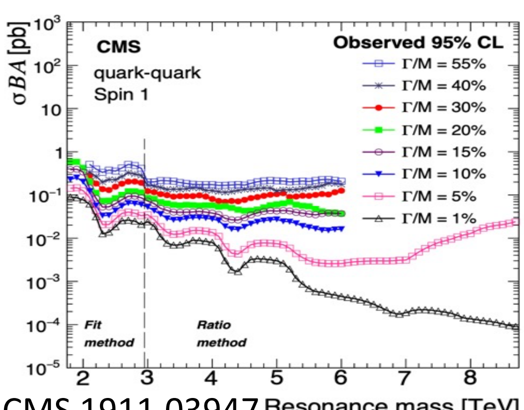
Flavor constraint

No tree level FCNC in this scenario.
FCNC appears at 1-loop level mediated by W'
->constraint from ΔM_d, ΔM_s, $b \to s\gamma$ $\propto g_{11} \times g_{33}$
Another one is obtained from $K \to \pi\pi \propto |g_{11}|^2$

Collider constraint

Cross section at LHC is large since W' and Z' talk to valence quark

Direct searches $t\bar{t}$, dijet, single top for W', Z' are severe

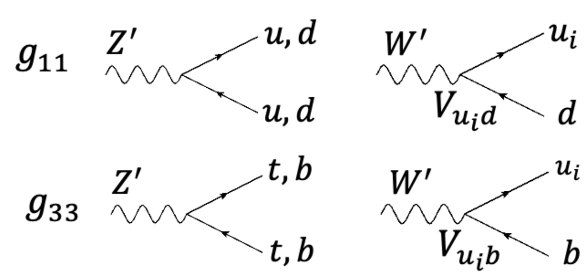


CMS 1911.03947

Width dependent limit!

$$\frac{\Gamma_V}{M_V} = \frac{2|g_{11}|^2 + |g_{33}|^2}{16\pi}$$

Also, single top search assume NWA



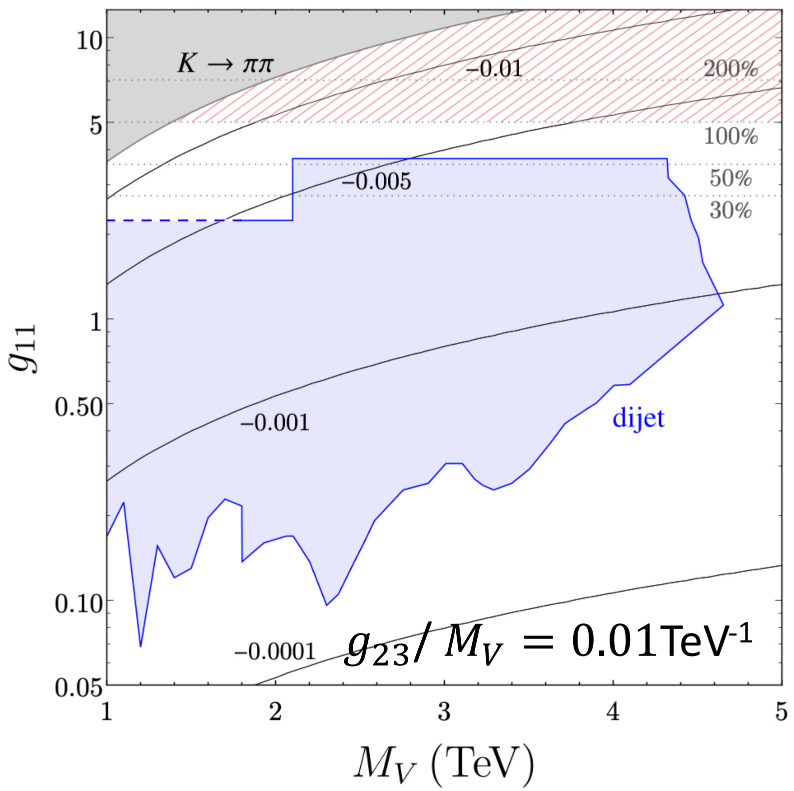
If we evade the collider constraint C_2^{NP}/C_2^{SM} ~-0.05 is possible

Scenario 2: $g_{11} \times g_{23} \neq 0, g_{33} = 0$

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

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

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



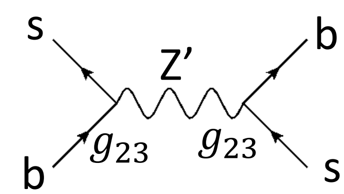
Again, width dependence of the constraint is important!

Flavor constraint

Tree level FCNC in Z' -> ΔM_s:

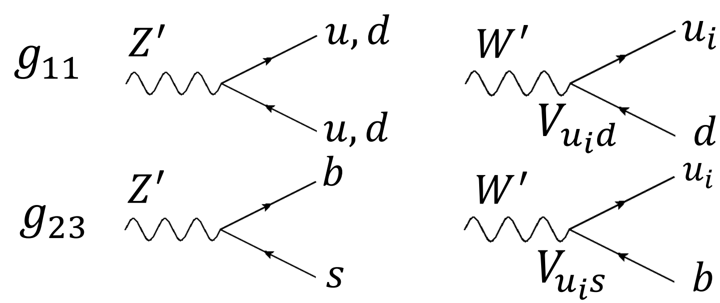
$|g_{23}|/\,M_V \leq 0.01\mathrm{TeV}^{-1}$

$g_{23} \ll g_{11}$



Collider constraint

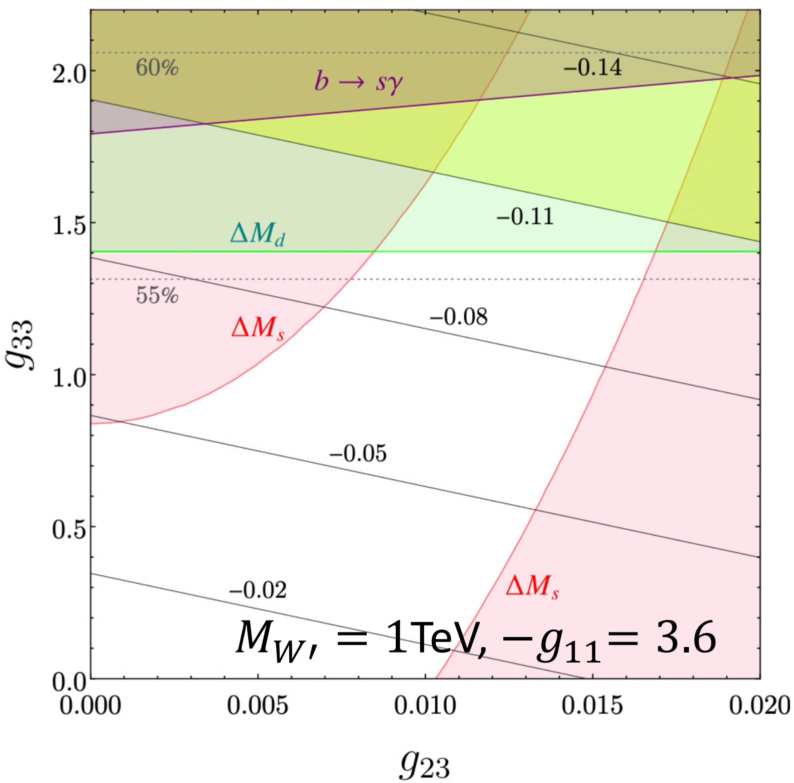
Z', W' decay into 2 jets -> dijet constraint!



If we evade the collider constraint $C_2^{NP}/C_2^{SM} \sim$ -0.01 is possible

Scenario 3: $g_{11} \times g_{23} \times g_{33} \neq 0$

$$\frac{C_2^{NP}(\Lambda_{NP})}{C_2^{SM}} \sim \frac{g_{11} \times g_{33}}{4\sqrt{2} G_F M_V^2} + \frac{g_{11} \times g_{23}}{4\sqrt{2} G_F M_V^2 V_{cb}}$$



If collider constraint can be avoided with the broad width, how much we can explain?

$$g_{11} \times g_{23} < 0, \;\; g_{11} \times g_{33} < 0$$

$K \to \pi\pi$: $|g_{11}| / M_V \lesssim 3.6$ TeV^{-1}

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!

If collider constraint can be avoided with the broad width
$C_2^{NP} / C_2^{SM} \sim$ -0.1 is possible by canceling the dangerous ΔM_s contribution.

The mode dedicated collider analysis is very important

Conclusion

W' from an additional $SU(2)_L$ can partially cancel the large SM color allowed amplitude

$C_2^{NP}/C_2^{SM} \sim$ -0.1

as long as the collider constraint is evaded.

The more dedicated collider analysis for low-dijet mass and the broad width regime is important to

exclude such W'.