Rescattering contributions to $\bar{B}_{(s)} \to D_{(s)}^{(*)} M$

Syuhei Iguro

NAGOYA UNIVERSITY
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KAVLI IPMU
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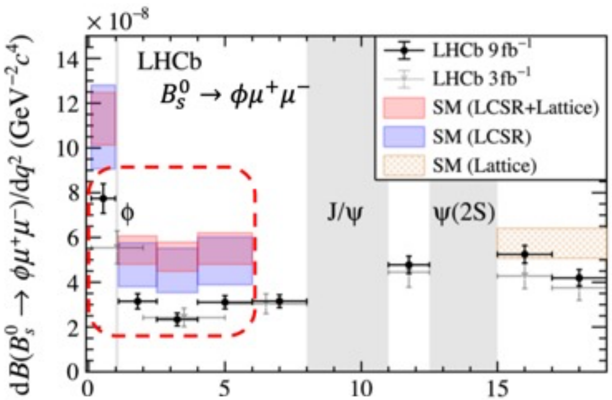
KIT Karlsruher Institut für Technologie
2021. 10 ~

Implications of LHCb measurements and future prospects 2021

arXiv:2109.10811 in collaboration with M. Endo and S. Mishima

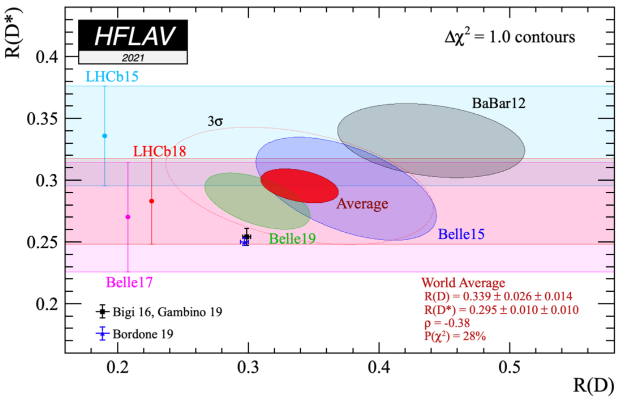
arXiv:2008.01086 in collaboration with T. Kitahara

There are interesting anomalies in B physics

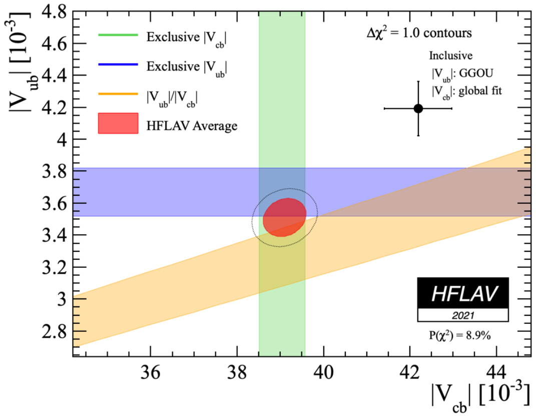


b->sμμ

See also 2110.09501



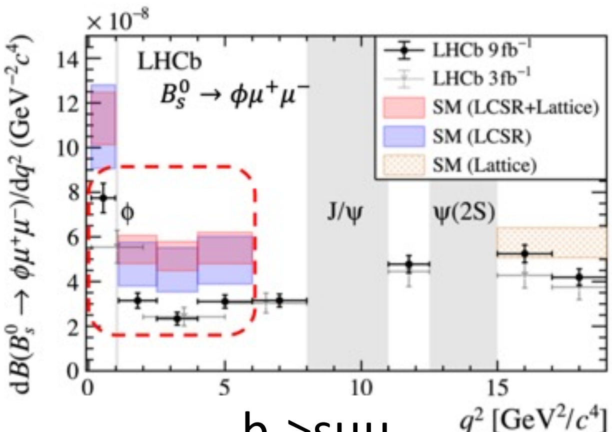
b->cτν



b->clν (l=e,μ)

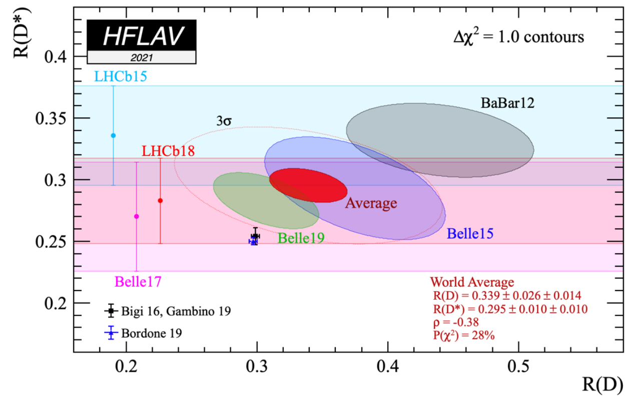
Involving leptons

There are interesting anomalies in B physics

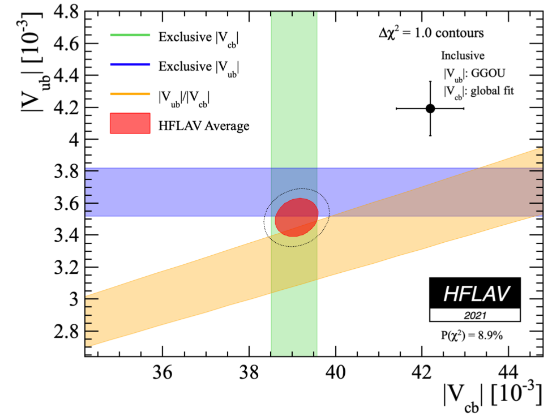


b->sμμ

See also 2110.09501



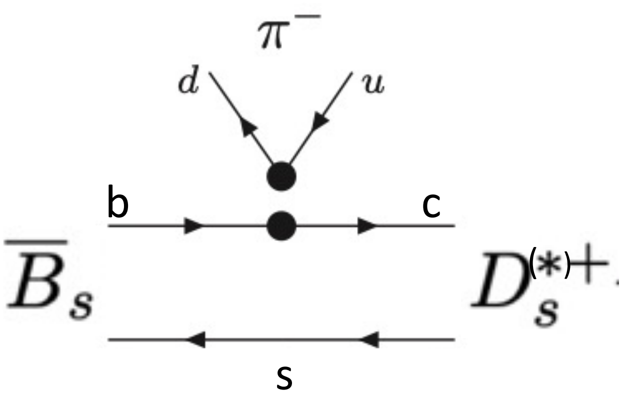
b->cτν



b->clν (l=e,μ)

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

b->cuq (q=d,s)



Tree level W exchange

b->cuq puzzle

	$BR^{exp}\times 10^3$	$BR^{SM,QCDF}\times 10^3$	
$\overline{B}_s \to D_s^+\pi^-$	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**
$\overline{B}_s \to D_s^{*+}\pi^-$	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

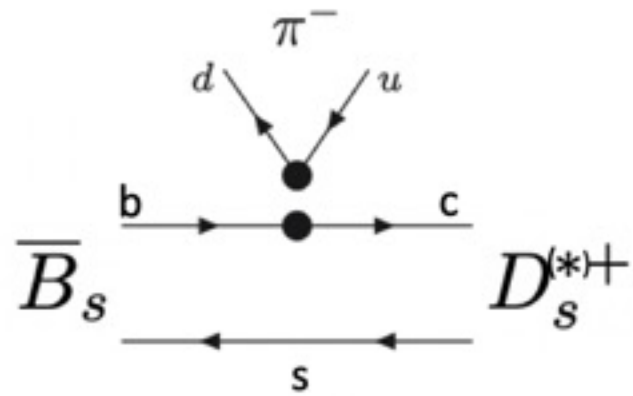
The decays are described by

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

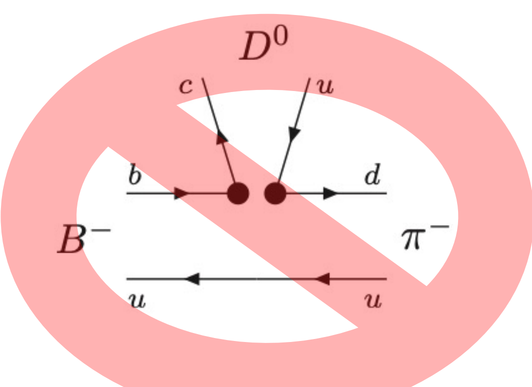
$$\mathcal{O}_1^q = (\bar{c}\gamma^\mu T^a P_L b)(\bar{q}\gamma_\mu T^a P_L u),$$

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

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



Color- suppressed, Penguin nor Exchange diagrams contribute since the involving quarks are all different.



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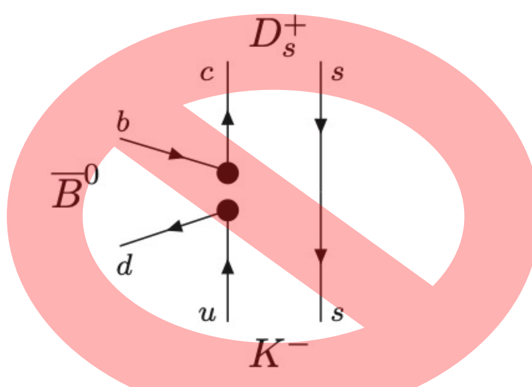
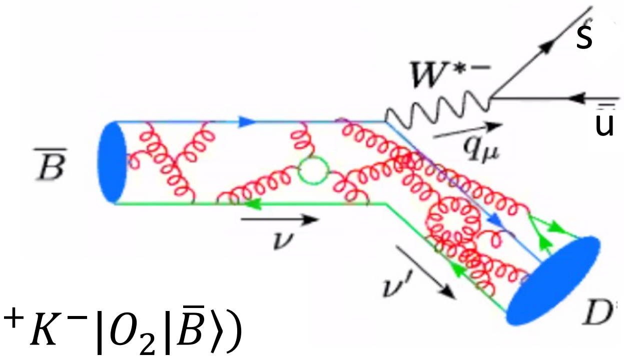


E

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 $1/\ m_b^0$

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.

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

Uncertainty in f_K is negligible (Lattice)

Factorization amplitude for B->D*P , B->DV can be calculated in a similar way

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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	PDG	2109.10811	

Theoretical uncertainty mainly comes from $V_{cb} \times$ FF

10 - 30% smaller amplitude can explain the data.

What is missing ?

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

  We used the result from Iguro Watanabe 2004. 10208: V_{cb}^{exc}=0.0397(6),,,.

  Adopting $V_{cb}^{inc} > V_{cb}^{exc}$ makes the situation worse!

- *NP effect*?

  We discuss from the next page.

- *O(Λ_{QCD}/m_b) sub-leading power corrections* ?

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

  - O(Λ_{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

NP possibilities?

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

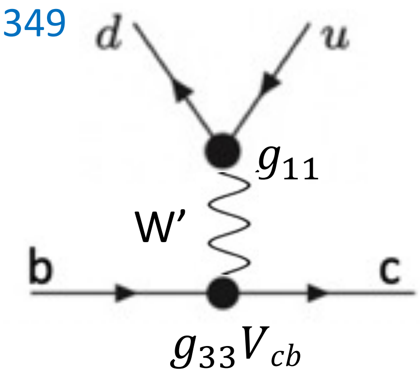
Interestingly such a large shift is still allowed by flavor observables.

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

Model example Boucenna et al 1608.01349

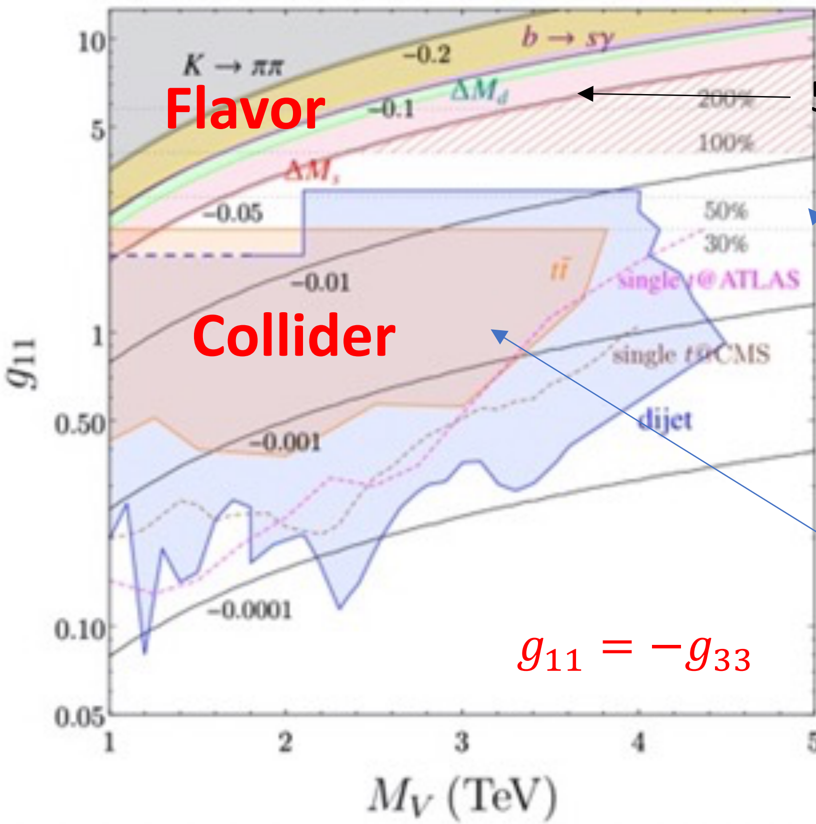
$$\left|\frac{C_2^{NP}(\Lambda_{NP})}{C_2^{SM}}\right| \sim 10\% = \frac{g_{11}\times g_{33}}{M_V^2}\frac{1}{4\sqrt{2}G_F} = \frac{g_{11}\times g_{33}}{1}\frac{(400\mathrm{GeV})^2}{M_V^2}$$



This W' (also Z') couples to valence quark and LHC can
easily test this scenario.

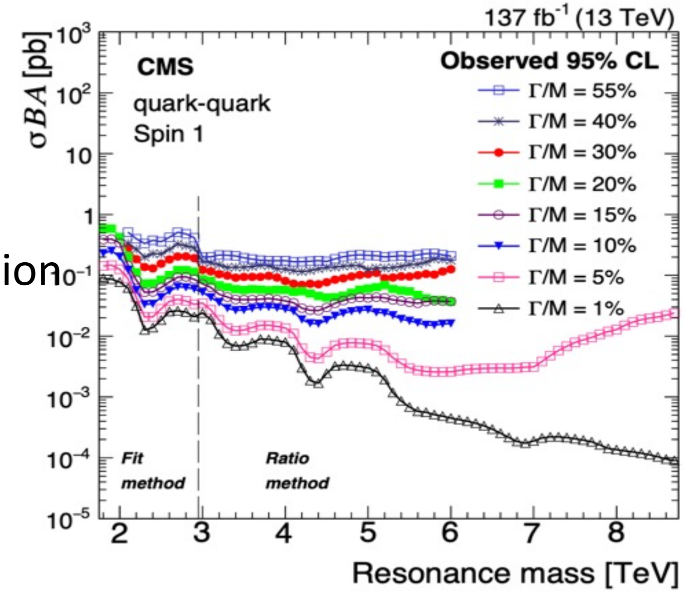
NP possibilities?

Syuhei Iguro, T. kitahara 2008.01086



5% deviation

Width dependent limit!



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

Resonance search at LHC

The dedicated collider analysis is necessary

If we can evade the collider constraint $C_2^{NP}/C_2^{SM} \sim$ - 0.05 is possible

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

Other possibilities?

- *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!

- *NP effect*?

Personally, it seems not easy!

- *O(Λ_{QCD}/m_b) sub-leading power corrections* ?

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

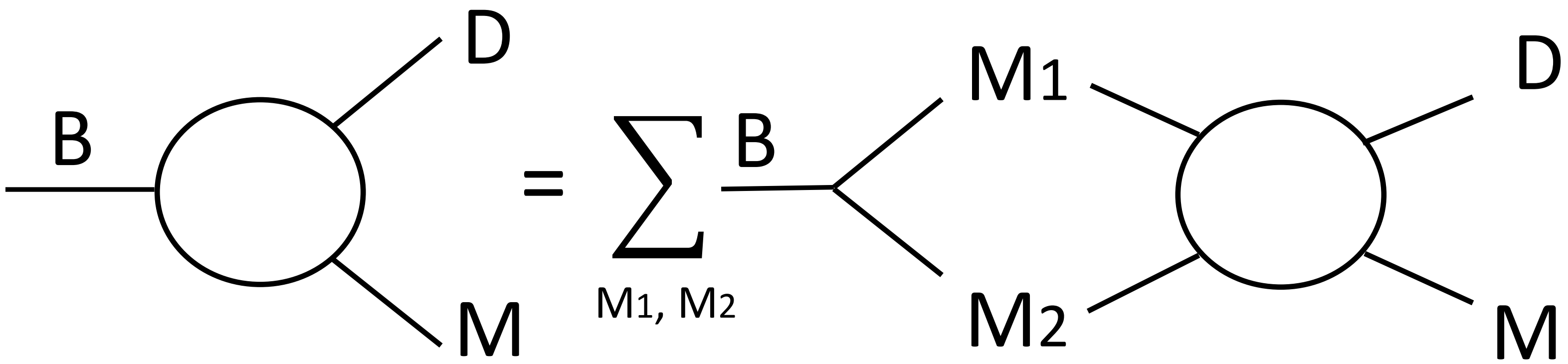
- O(Λ_{QCD}/m_b) chirality enhanced contribution is absent
- correction to LCDA is O($\alpha_s \Lambda^2/m_b^2$)
- Contribution from soft gluon exchange between BD system and light meson is small

- *Other power suppressed correction to QCDF?*

In reality, bottom mass is finite.

In this work we tested meson-meson scattering contribution.

Quasi-elastic rescattering

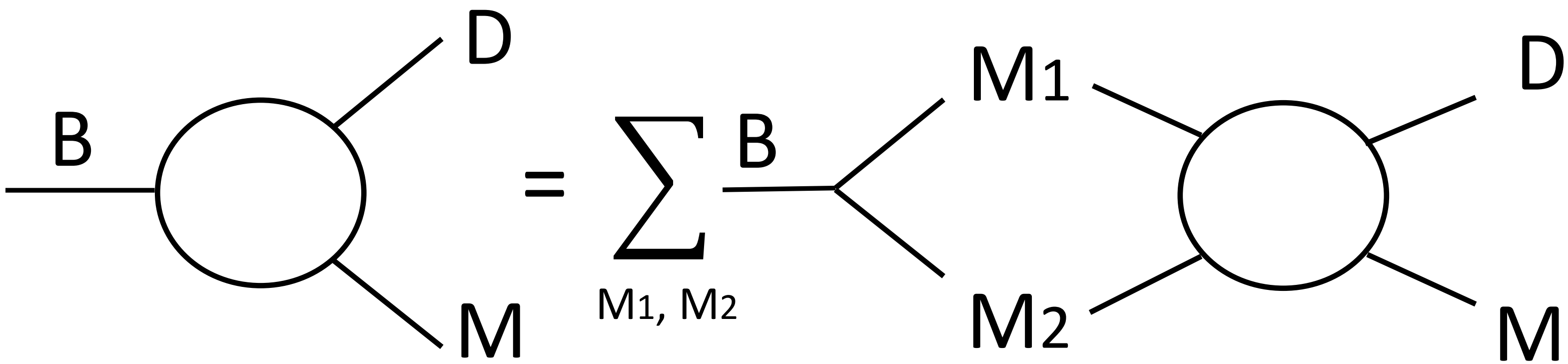


M_1, M_2 are intermediate states.
The rescattering can occur among the final states with the same quantum number.

Chua et al 0112148, 0504084, 0712.1882

$$S_{\rm res}^{1/2} = e^{i\delta_{\overline{15}}} \sum_{a=1}^{15} |\overline{\mathbf{15}}; a\rangle\langle\overline{\mathbf{15}}; a| + e^{i\delta_{\mathbf{6}}} \sum_{b=1}^{6} |\mathbf{6}; b\rangle\langle\mathbf{6}; b| + \sum_{m,n=\bar{\mathbf{3}},\bar{\mathbf{3}}'} \sum_{c=1}^{3} |m; c\rangle\, \mathcal{U}_{mn}^{1/2} \langle n; c|$$

Quasi-elastic rescattering



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Chua et al 0112148, 0504084, 0712.1882

This contribution is expected to be small for $B \to M_l M_{l'}$ (M_l: light meson).
They fly apart immediately after the B decay (5GeV) and they can not communicate.

In $B \to DM_l$ decays D is not light, and then the effect might be not negligible

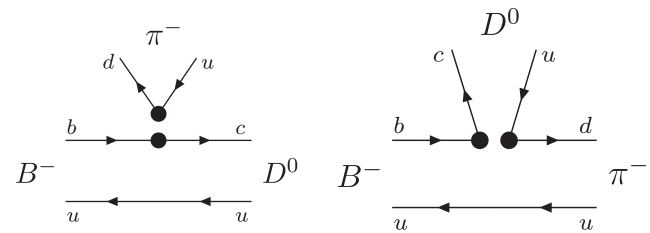
This effect is negligible in large m_b limit, but m_b is finite in reality.

Our question

How the situation can be relaxed including this rescattering effects ?

Tensions in color allowed and suppressed modes

Transition	$\{S, I_z\}$	Mode	Amplitude	Data
$b \to c\bar{u}d$	$\{1,-1\}$	$\overline{B}_s \to D_s^+\pi^-$	T_D	30.0 ± 2.3
		$\overline{B}_s \to D^0 K^0$	C_P	4.3 ± 0.9
$b \to c\bar{u}s$	$\{-1,0\}$	$\overline{B}^0 \to D^+K^-$	T_D	1.86 ± 0.20
		$\overline{B}^0 \to D^0\overline{K}^0$	C_P	0.52 ± 0.07



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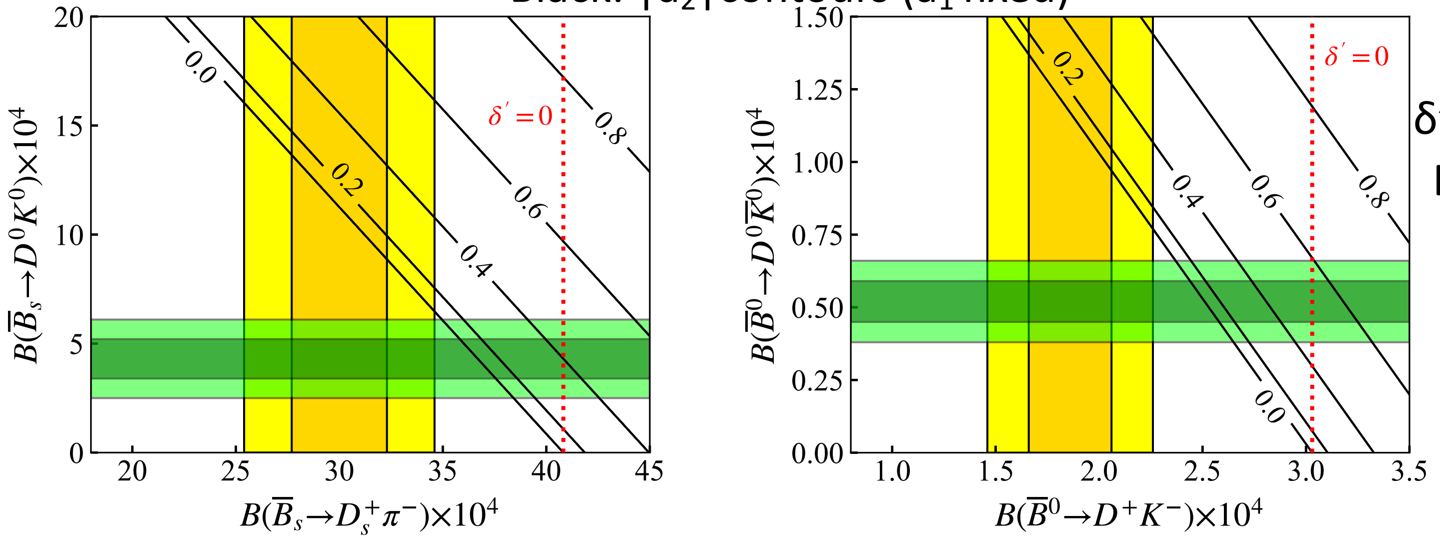
Rescattering in those decays is parametrized with δ'

Unphysical phase

$$\mathcal{A}^{\rm FSI}_{q,S,I_z} \sim \mathcal{S}^{1/2}_{S,I_z}\ \mathcal{A}^{\rm fact}_{q,S,I_z} \qquad \mathcal{S}^{1/2}_{1,-1} = \mathcal{S}^{1/2}_{-1,0} = \frac{e^{i\delta_{\overline{15}}}}{2}\begin{pmatrix} 1+e^{i\delta'} & 1-e^{i\delta'} \\ & 1+e^{i\delta'} \end{pmatrix}$$

Black: $|a_2|$ contours (a_1 fixed)



δ'=0: no rescattering

Effectively $|a_2| \sim C_P$

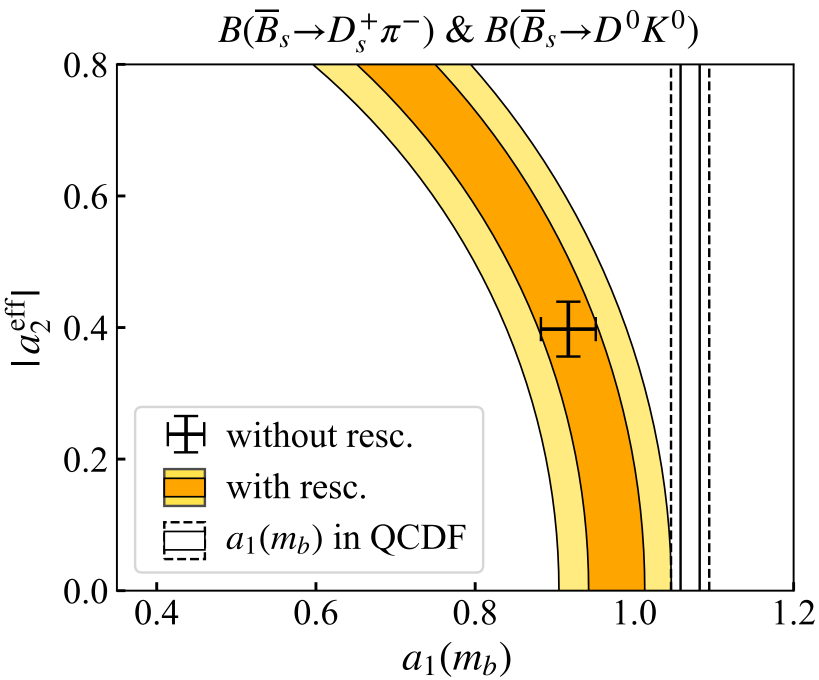
Even if we take a_2 and δ' as free parameters,

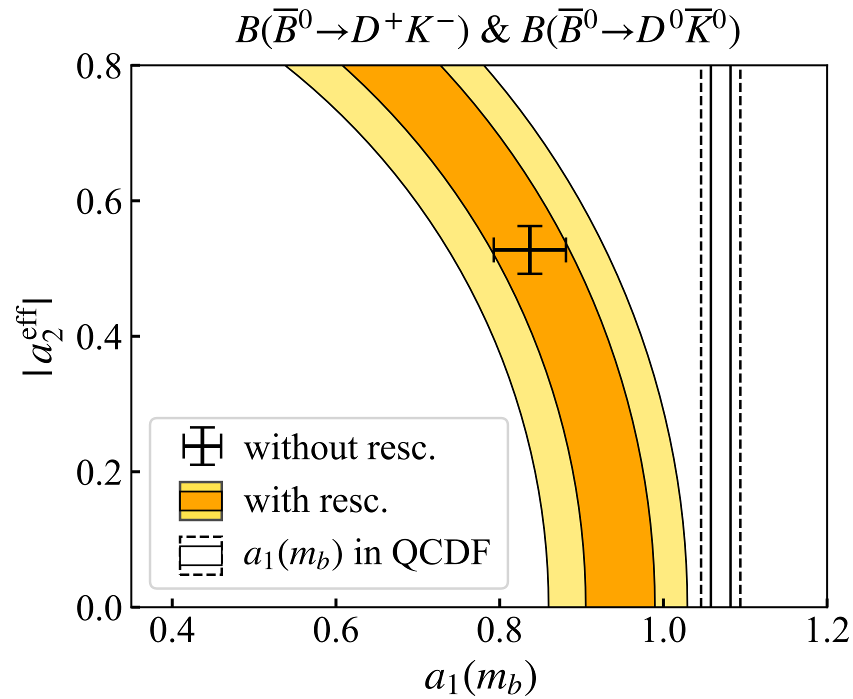
we can not explain both color allowed and suppressed modes simultaneously

a_1 fit in color allowed and suppressed modes

Last page: SM + rescattering can not explain the data

How large NP contribution to a_1 is favored?





$a_1(m_b)^{\rm fit} < a_1(m_b)$ is observed!

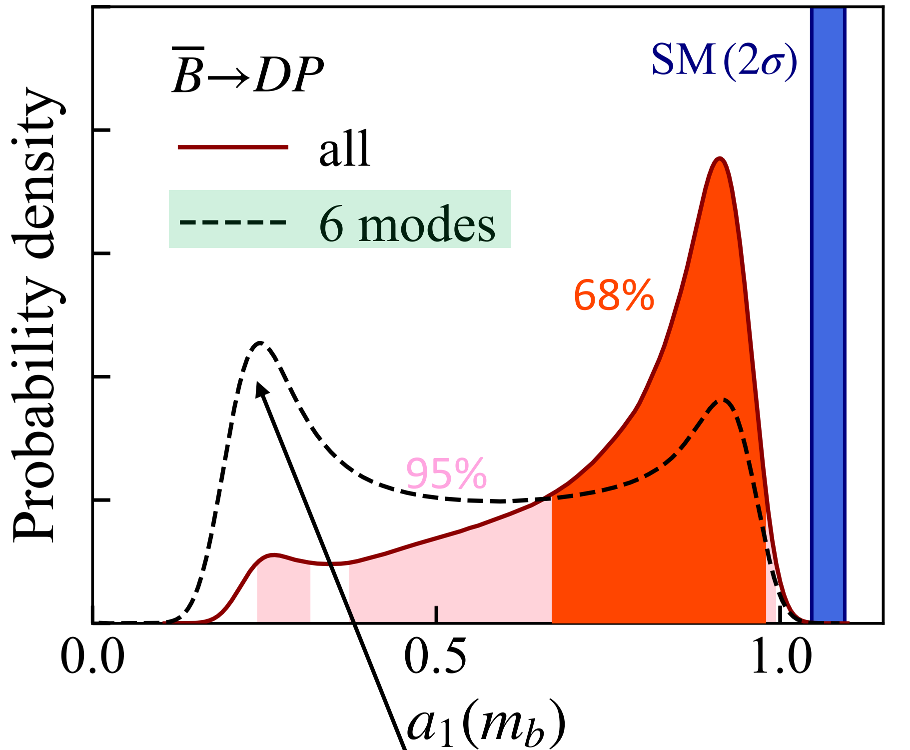
There is parametric redundancy and large a_2 is not easy to accept (power suppressed).

We will perform the global fit using the available modes

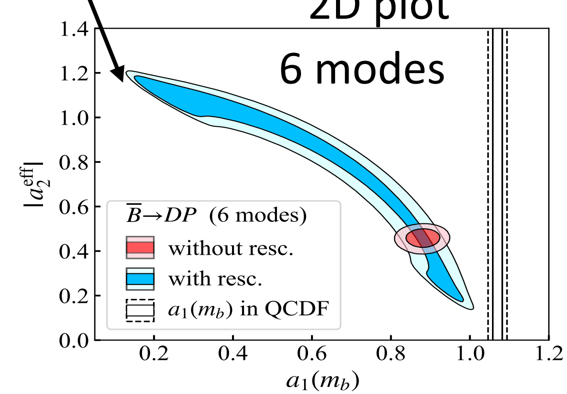
a_1 fit result for B -> DP

Assuming SU(3) flavor symmetry
we performed the global fit

Transition	$\{S, I_z\}$	Mode	Amplitude	Data
$b \to c\bar{u}d$	$\{1,-1\}$	$\overline{B}_s \to D_s^+\pi^-$	T_D	30.0 ± 2.3
		$\overline{B}_s \to D^0 K^0$	C_P	4.3 ± 0.9
	$\{0,-3/2\}$	$B^- \to D^0\pi^-$	$T_D + C_P$	46.8 ± 1.3
	$\{0,-1/2\}$	$\overline{B}^0 \to D^+\pi^-$	$T_D + E$	25.2 ± 1.3
		$\overline{B}^0 \to D^0\pi^0$	$\frac{1}{\sqrt{2}}(-C_P + E)$	2.63 ± 0.14
		$\overline{B}^0 \to D^0\eta$	$\frac{c_\phi}{\sqrt{2}}(C_P + E)$	2.36 ± 0.32
		$\overline{B}^0 \to D^0\eta'$	$\frac{s_\phi}{\sqrt{2}}(C_P + E)$	1.38 ± 0.16
		$\overline{B}^0 \to D_s^+ K^-$	E	0.27 ± 0.05
$b \to c\bar{u}s$	$\{-1,0\}$	$\overline{B}^0 \to D^+K^-$	T_D	1.86 ± 0.20
		$\overline{B}^0 \to D^0\overline{K}^0$	C_P	0.52 ± 0.07
	$\{-1,-1\}$	$B^- \to D^0K^-$	$T_D + C_P$	3.63 ± 0.12
	$\{0,-1/2\}$	$\overline{B}_s \to D_s^+K^-$	$T_D + E$	$2.27 \pm 0.19^\dagger$
		$\overline{B}_s \to D^0\eta$	$-s_\phi C_P + \frac{c_\phi}{\sqrt{2}}E$	—
		$\overline{B}_s \to D^0\eta'$	$c_\phi C_P + \frac{s_\phi}{\sqrt{2}}E$	—
		$\overline{B}_s \to D^0\pi^0$	$\frac{1}{\sqrt{2}}E$	—
		$\overline{B}_s \to D^+\pi^-$	E	—



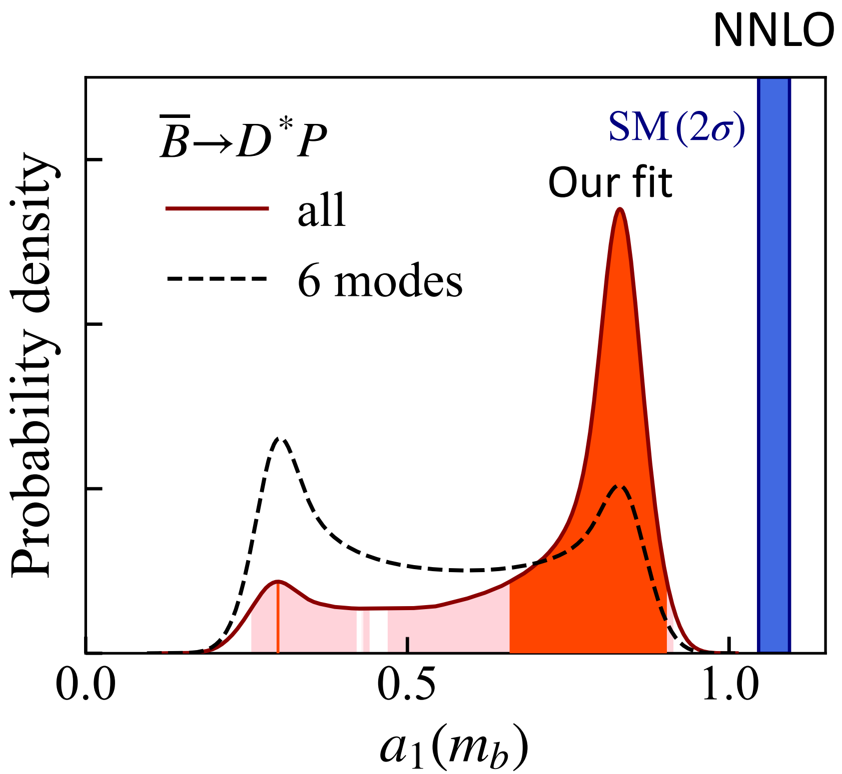
2D plot



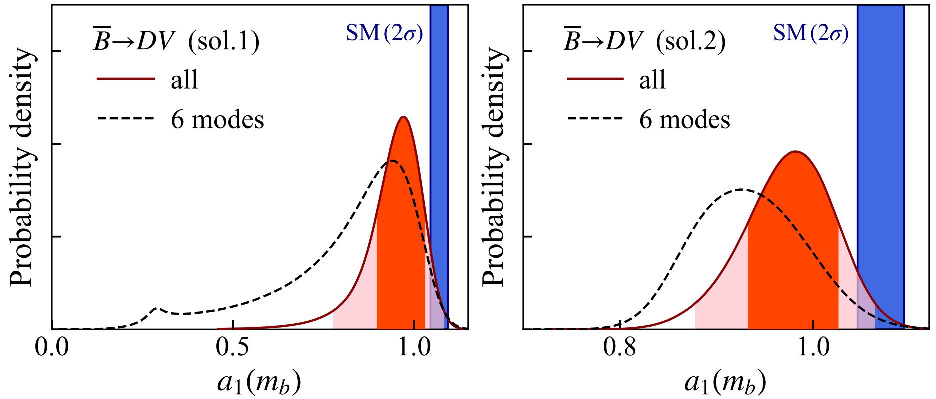
we consider rescattering effect, O(10)% shift in $a_1(m_b)$ is favored

a_1 fit result for B -> D*P, B -> DV

$\Delta a_1 = O(10)\%$ is again favored



In B-> DV case, U(3) symmetry allows us to reduce the rescattering parameters. There are two fit scenarios however, both of them favored the mild shift.



Even if we consider rescattering effect, O(10)% shift in $a_1(m_b)$ is favored

Summary

There are also coherent discrepancies in B->DM.

The QCDF predictions are larger than the experimental values.

The new physics explanation looks not easy since new particle couples to valence quarks significantly.

We studied whether the quasi-elastic rescattering can explain those deviations or not.

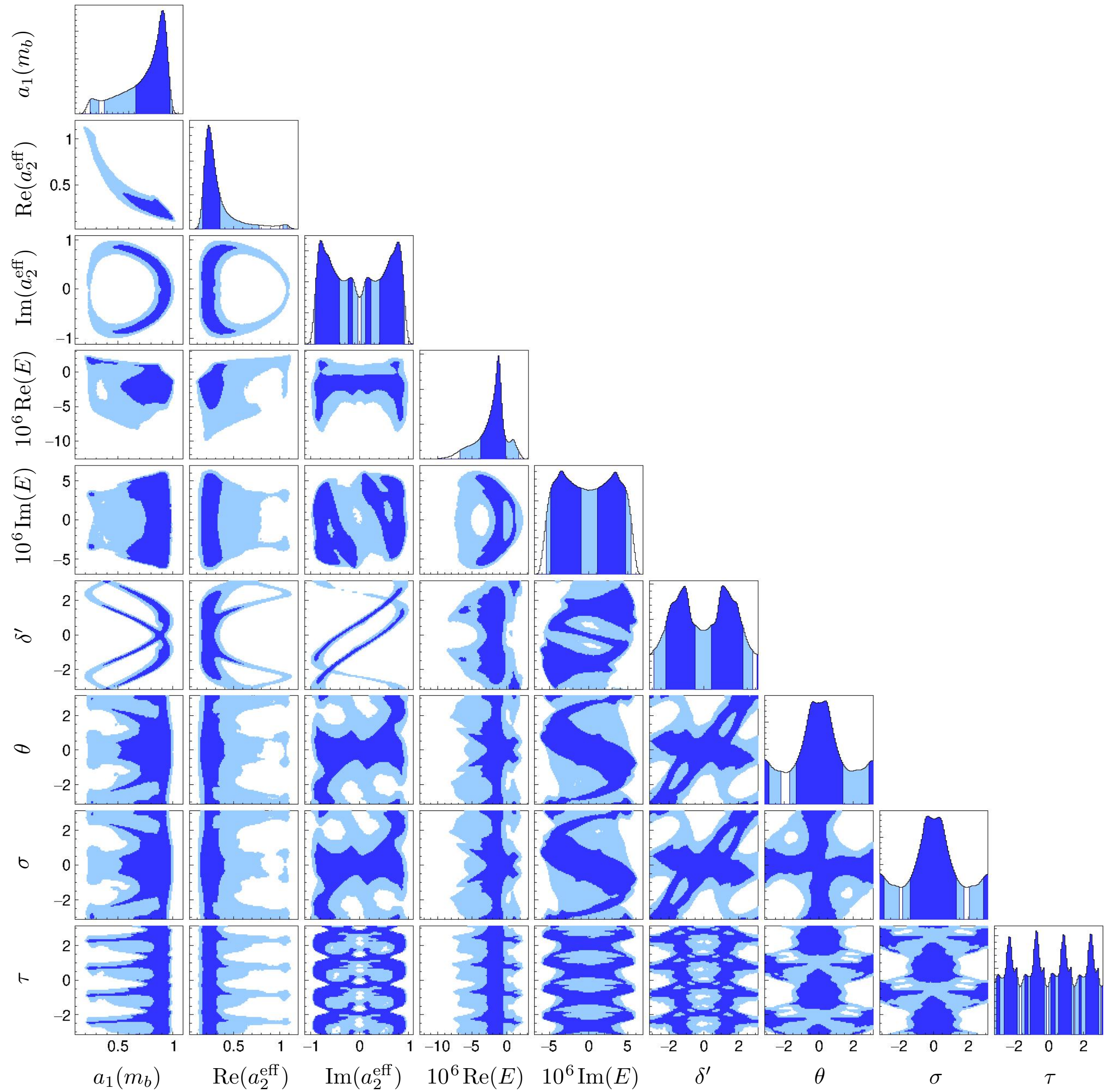
We found rescattering can not explain color allowed and color suppressed decays simultaneously.

Even if we consider rescattering effect, O(10)% sift in $a_1(m_b)$ is favored

Further theoretical input and experimental data are necessary.

For instance Lattice constraints on form factor at non-zero recoil is nice.

B -> DP full correlation



B -> D*P

Transition	$\{S, I_z\}$	Mode	Amplitude	Data
$b \to c\bar{u}d$	$\{1, -1\}$	$\overline{B}_s \to D_s^{*+}\pi^-$	T_D	20 ± 5
		$\overline{B}_s \to D^{*0}K^0$	C_P	2.8 ± 1.1
	$\{0, -3/2\}$	$B^- \to D^{*0}\pi^-$	$T_{D^*} + C_P$	49.0 ± 1.7
	$\{0, -1/2\}$	$\overline{B}^0 \to D^{*+}\pi^-$	$T_{D^*} + E$	27.4 ± 1.3
		$\overline{B}^0 \to D^{*0}\pi^0$	$\frac{1}{\sqrt{2}}(-C_P + E)$	2.2 ± 0.6
		$\overline{B}^0 \to D^{*0}\eta$	$\frac{c_\phi}{\sqrt{2}}(C_P + E)$	2.3 ± 0.6
		$\overline{B}^0 \to D^{*0}\eta'$	$\frac{s_\phi}{\sqrt{2}}(C_P + E)$	1.40 ± 0.22
		$\overline{B}^0 \to D_s^{*+}K^-$	E	0.22 ± 0.03
$b \to c\bar{u}s$	$\{-1, 0\}$	$\overline{B}^0 \to D^{*+}K^-$	T_{D^*}	2.12 ± 0.15
		$\overline{B}^0 \to D^{*0}\overline{K}^0$	C_P	0.36 ± 0.12
	$\{-1, -1\}$	$B^- \to D^{*0}K^-$	$T_{D^*} + C_P$	$3.97^{+0.31}_{-0.28}$
	$\{0, -1/2\}$	$\overline{B}_s \to D_s^{*+}K^-$	$T_{D^*} + E$	$1.33 \pm 0.35^\dagger$
		$\overline{B}_s \to D^{*0}\eta$	$-s_\phi C_P + \frac{c_\phi}{\sqrt{2}}E$	—
		$\overline{B}_s \to D^{*0}\eta'$	$c_\phi C_P + \frac{s_\phi}{\sqrt{2}}E$	—
		$\overline{B}_s \to D^{*0}\pi^0$	$\frac{1}{\sqrt{2}}E$	—
		$\overline{B}_s \to D^{*+}\pi^-$	E	—

B -> DV

Transition	$\{S, I_z\}$	Mode	Amplitude	Data
$b \to c\bar{u}d$	$\{1, -1\}$	$\overline{B}_s \to D_s^+ \rho^-$	T_D	69 ± 14
		$\overline{B}_s \to D^0 K^{*0}$	C_V	4.4 ± 0.6
	$\{0, -3/2\}$	$B^- \to D^0 \rho^-$	$T_D + C_V$	134 ± 18
	$\{0, -1/2\}$	$\overline{B}^0 \to D^+ \rho^-$	$T_D + E$	76 ± 12
		$\overline{B}^0 \to D^0 \rho^0$	$\frac{1}{\sqrt{2}}(-C_V + E)$	3.21 ± 0.21
		$\overline{B}^0 \to D^0 \omega$	$\frac{1}{\sqrt{2}}(C_V + E)$	2.54 ± 0.16
		$\overline{B}^0 \to D^0 \phi$	0	—
		$\overline{B}^0 \to D_s^+ K^{*-}$	E	0.35 ± 0.10
$b \to c\bar{u}s$	$\{-1, 0\}$	$\overline{B}^0 \to D^+ K^{*-}$	T_D	4.5 ± 0.7
		$\overline{B}^0 \to D^0 \overline{K}^{*0}$	C_V	0.45 ± 0.06
	$\{-1, -1\}$	$B^- \to D^0 K^{*-}$	$T_D + C_V$	5.3 ± 0.4
	$\{0, -1/2\}$	$\overline{B}_s \to D_s^+ K^{*-}$	$T_D + E$	—
		$\overline{B}_s \to D^0 \phi$	$-C_V$	0.30 ± 0.05
		$\overline{B}_s \to D^0 \omega$	$\frac{1}{\sqrt{2}}E$	—
		$\overline{B}_s \to D^0 \rho^0$	$\frac{1}{\sqrt{2}}E$	—
		$\overline{B}_s \to D^+ \rho^-$	E	—