Angular analysis of modes with $b \to c\ell\bar{\nu}$ transition and new physics

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On 1912.03835 & 2004.06726

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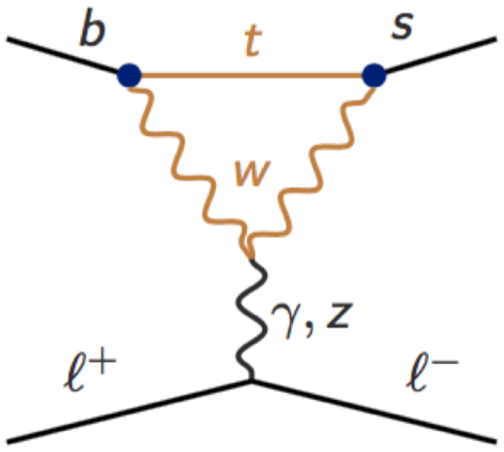
Outline

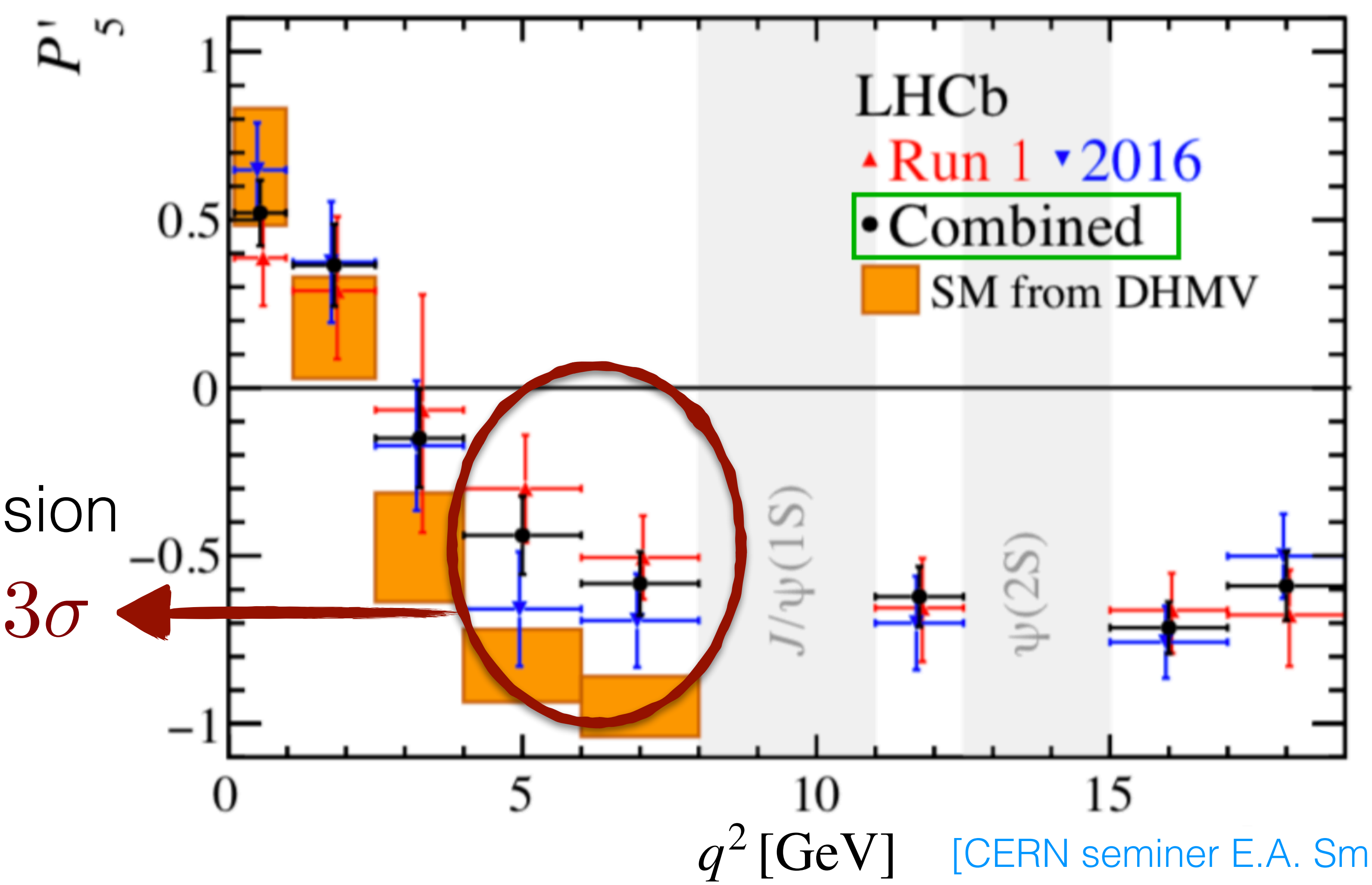
- Introduction
- Theoretical framework
- New physics effects
- Summary

Introduction

- Angular distribution of multi-body semileptonic decay is powerful tool to access observables in B-physics

- E.g., long-standing discrepancy in $B \to K^*(\to K\pi)\mu\mu$





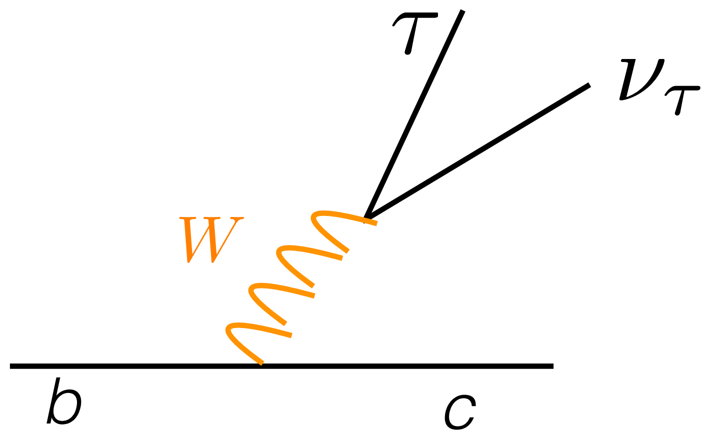
Local tension

$\sim 2-3\sigma$

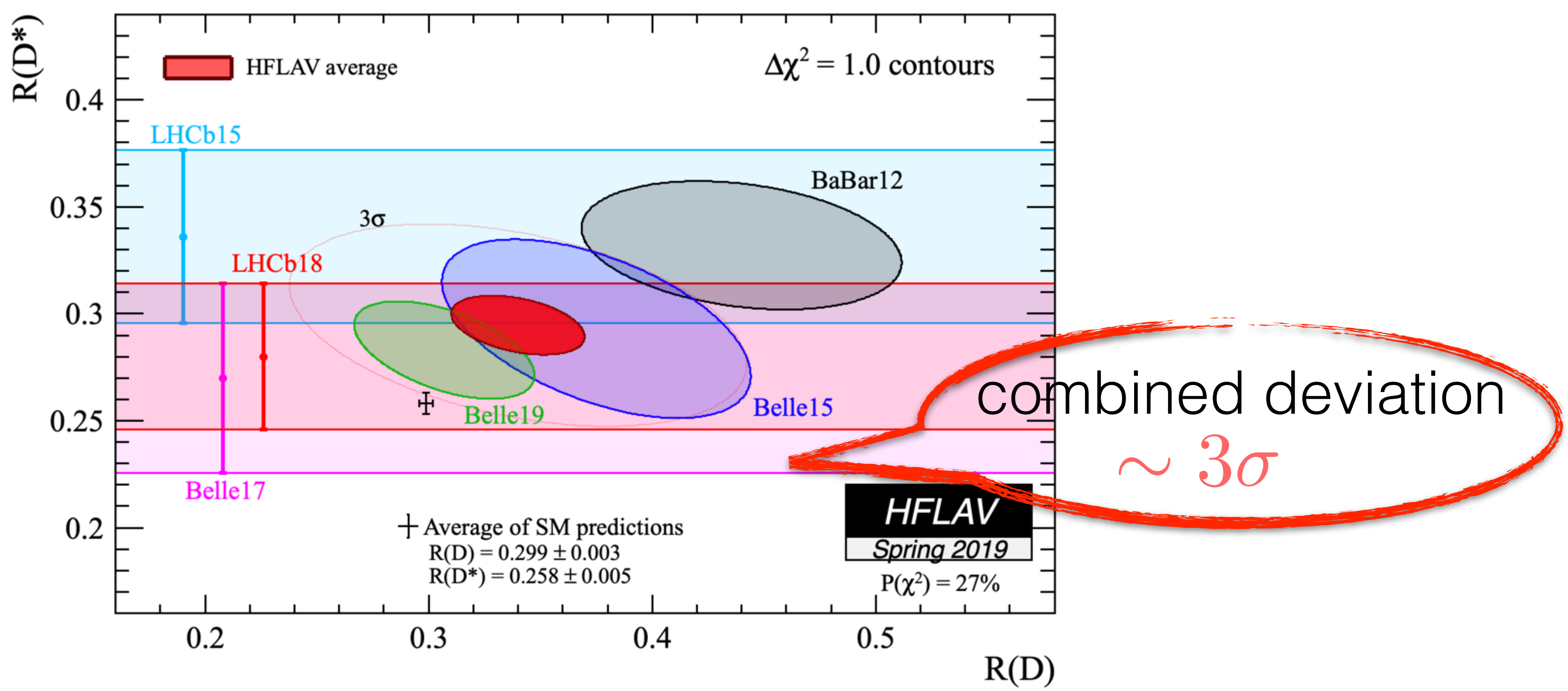
[CERN seminer E.A. Smith]

Motivation

- Exciting discrepancies observed in charged current B decays also



$$R(D^{(*)}) \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}, \quad \ell \in \{e, \mu\}$$



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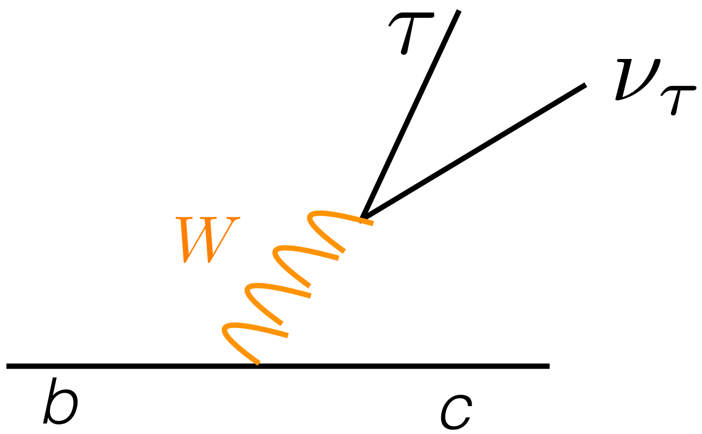
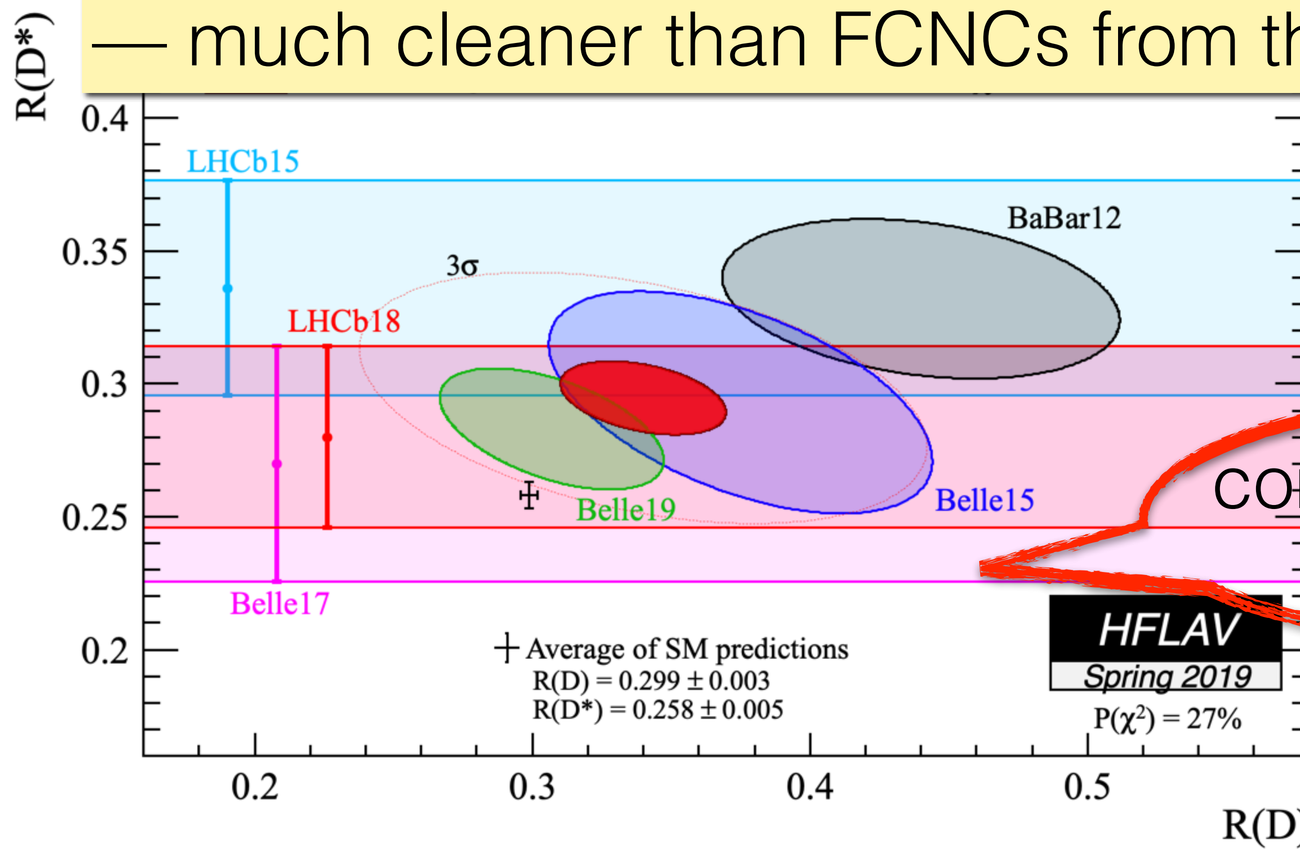


$$R(D^{(*)}) \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}, \quad \ell \in \{e, \mu\}$$

Motivates to measure angular observables — much cleaner than FCNCs from theory side



combined deviation $\sim 3\sigma$

Motivation

Properties	D^*	D_2^*
Spin	1^-	2^+
Mass (MeV)	2006	2461
Width (MeV)	< 2	47

- Full 4-body distribution for $\bar{B} \to D^*(\to D\pi)\ell\bar{\nu}$ with all possible dim-6 operators including ν_R

  [RM, Peñuelas, Murgui, Pich; *2004.06726*]

- Tensor mesons $D_2^*(2460)$ provides complementary information

  [RM; *1912.03835*]

  $\bar{B} \to D_2^*(\to D\pi)\ell\bar{\nu}$ → important background for $R(D^*)$

  $\mathrm{BR} \simeq \mathcal{O}(10^{-3})$ [Belle, BaBar '08]

Hamiltonian

- Most general dim-6 BSM Hamiltonian for $b \to c\ell\bar{\nu}$

$$\mathcal{H}_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \Big\{ \mathcal{O}^V_{LL} + \sum_{\substack{X=S,V,T \\ M,N=L,R}} C^X_{MN} \mathcal{O}^X_{MN} \Big\}$$

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$$\begin{aligned}
\mathcal{O}^S_{MN} &\equiv (\bar{c} P_M b) \left(\bar{\ell} P_N \nu\right) , \\
\mathcal{O}^V_{MN} &\equiv (\bar{c} \gamma^\mu P_M b) \left(\bar{\ell} \gamma_\mu P_N \nu\right) , \\
\mathcal{O}^T_{MN} &\equiv (\bar{c} \sigma^{\mu\nu} P_M b) \left(\bar{\ell} \sigma_{\mu\nu} P_N \nu\right) .
\end{aligned}$$

→ Sandwiched between mesons
form factors: non-perturbative

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Wilson coefficients:
perturbatively calculable

All $C^X_{MN} = 0$ in the SM

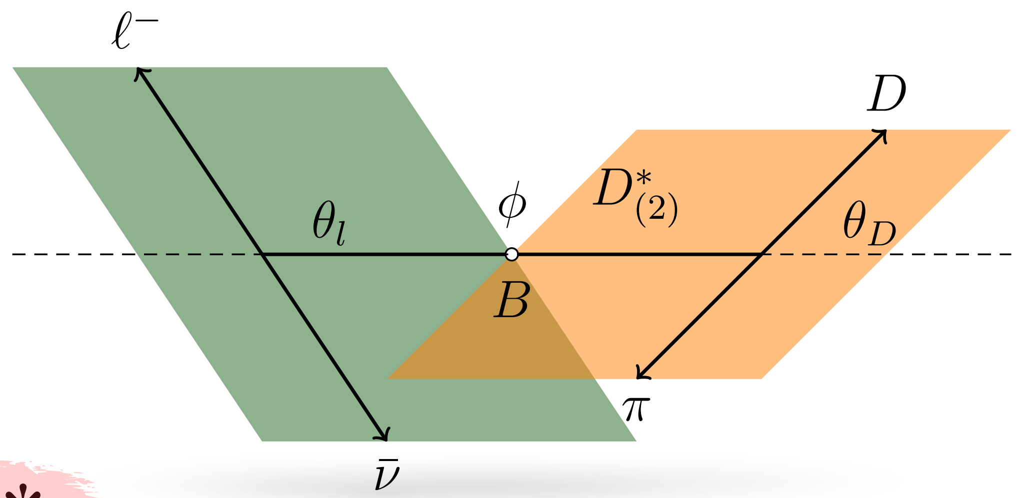
→ Simple distribution

$$\mathcal{O}^S_{MN} \equiv (\bar{c} P_M b)\left(\bar{\ell} P_N \nu\right),$$
$$\mathcal{O}^V_{MN} \equiv (\bar{c}\gamma^\mu P_M b)\left(\bar{\ell}\gamma_\mu P_N \nu\right),$$
$$\mathcal{O}^T_{MN} \equiv (\bar{c}\sigma^{\mu\nu} P_M b)\left(\bar{\ell}\sigma_{\mu\nu} P_N \nu\right).$$

Sandwiched between mesons
→ form factors: non-perturbative

BSM physics induce new Wilson coefficients

Distribution



$$\frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_l d\phi} =$$

D^*	D_2^*
$\frac{9}{32\pi}\Big[I_1^c \cos^2\theta_D + I_1^s \sin^2\theta_D$	$\frac{15}{128\pi}\Big[I_1^c(3\cos^2\theta_D - 1)^2 + 3I_1^s \sin^2 2\theta_D$
$+\left(I_2^c \cos^2\theta_D + I_2^s \sin^2\theta_D\right)\cos 2\theta_l$	$+\left(I_2^c(3\cos^2\theta_D - 1)^2 + 3I_2^s \sin^2 2\theta_D\right)\cos 2\theta_l$
$+I_3 \sin^2\theta_D \sin^2\theta_l \cos 2\phi$	$+3I_3 \sin^2 2\theta_D \sin^2\theta_l \cos 2\phi$
$+I_4 \sin 2\theta_D \sin 2\theta_l \cos\phi$	$+2\sqrt{3}I_4(3\cos^2\theta_D - 1)\sin 2\theta_D \sin 2\theta_l \cos\phi$
$+I_5 \sin 2\theta_D \sin\theta_l \cos\phi$	$+2\sqrt{3}I_5(3\cos^2\theta_D - 1)\sin 2\theta_D \sin\theta_l \cos\phi$
$+\left(I_6^s \sin^2\theta_D + I_6^c \cos^2\theta_D\right)\cos\theta_l$	$+\left(3I_6^s \sin^2 2\theta_D + I_6^c(3\cos^2\theta_D - 1)^2\right)\cos\theta_l$
$+I_7 \sin 2\theta_D \sin\theta_l \sin\phi$	$+2\sqrt{3}I_7(3\cos^2\theta_D - 1)\sin 2\theta_D \sin\theta_l \sin\phi$
$+I_8 \sin 2\theta_D \sin 2\theta_l \sin\phi$	$+2\sqrt{3}I_8(3\cos^2\theta_D - 1)\sin 2\theta_D \sin 2\theta_l \sin\phi$
$+I_9 \sin^2\theta_D \sin^2\theta_l \sin 2\phi\Big]$	$+3I_9 \sin^2 2\theta_D \sin^2\theta_l \sin 2\phi\Big]$

Framework

- Easily distinguishable via uni-angular distribution in θ_D

$$\frac{d^2\Gamma_{D^*_{(2)}}}{dq^2\, d\cos\theta_D} = \begin{cases} \frac{3}{4}\left[F_T^{D^*} \sin^2\theta_D + 2\, F_L^{D^*} \cos^2\theta_D\right]\Gamma_f^{D^*} \\ \frac{5}{8}\Big[F_L^{D_2^*} + 6(F_T^{D_2^*} - F_L^{D_2^*})\cos^2\theta_D + 3(3F_L^{D_2^*} - 2F_T^{D_2^*})\cos^4\theta_D\Big]\Gamma_f^{D_2^*} \end{cases}$$

$$\Gamma_f^{D^*_{(2)}} \equiv d\Gamma^{D^*_{(2)}}/dq^2$$

effective for analysis with low statistics

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$$\Gamma_f^{D^*_{(2)}} \equiv d\Gamma^{D^*_{(2)}}/dq^2$$

effective for analysis with low statistics

- Difference in inputs: Form factors

Theory	D^*	D_2^*
HQET	CNL [hep-ph/9712417]	[1711.03110]
LCSR	[1811.00983]	[1908.00847]
Lattice	[HPQCD, 1711.11013]	

Observables

- *CP* averaged asymmetries

$$A_{FB} = \frac{1}{\Gamma_f}\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \, \frac{d^2(\Gamma - \bar{\Gamma})}{dq^2 d\cos\theta_l}$$

$$A_4 = \frac{1}{\Gamma_f}\left[\int_{-\pi/2}^{\pi/2} - \int_{\pi/2}^{3\pi/2}\right] d\phi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_D \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \, \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\cos\theta_l d\cos\theta_D d\phi}$$

$$A_5 = \frac{1}{\Gamma_f}\left[\int_{-\pi/2}^{\pi/2} - \int_{\pi/2}^{3\pi/2}\right] d\phi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_D \int_{-1}^1 d\cos\theta_l \, \frac{d^4(\Gamma - \bar{\Gamma})}{dq^2 d\cos\theta_l d\cos\theta_D d\phi}$$

$$A_7 = \frac{1}{\Gamma_f}\left[\int_0^{\pi} - \int_{\pi}^{2\pi}\right] d\phi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_D \int_{-1}^1 d\cos\theta_l \, \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\cos\theta_l d\cos\theta_D d\phi}$$

$$A_8 = \frac{1}{\Gamma_f}\left[\int_0^{\pi} - \int_{\pi}^{2\pi}\right] d\phi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_D \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \, \frac{d^4(\Gamma - \bar{\Gamma})}{dq^2 d\cos\theta_l d\cos\theta_D d\phi}$$

- ϕ distribution: $$\frac{d^2\Gamma}{dq^2\, d\phi} = \frac{1}{2\pi}\Gamma_f\left[1 + A_3\cos 2\phi + A_9 \sin 2\phi\right]$$

$A_{3,4,5}, A_{FB} \propto$ Real part of the amplitude

$A_{7,8,9} \propto$ Imaginary part → Null tests of SM

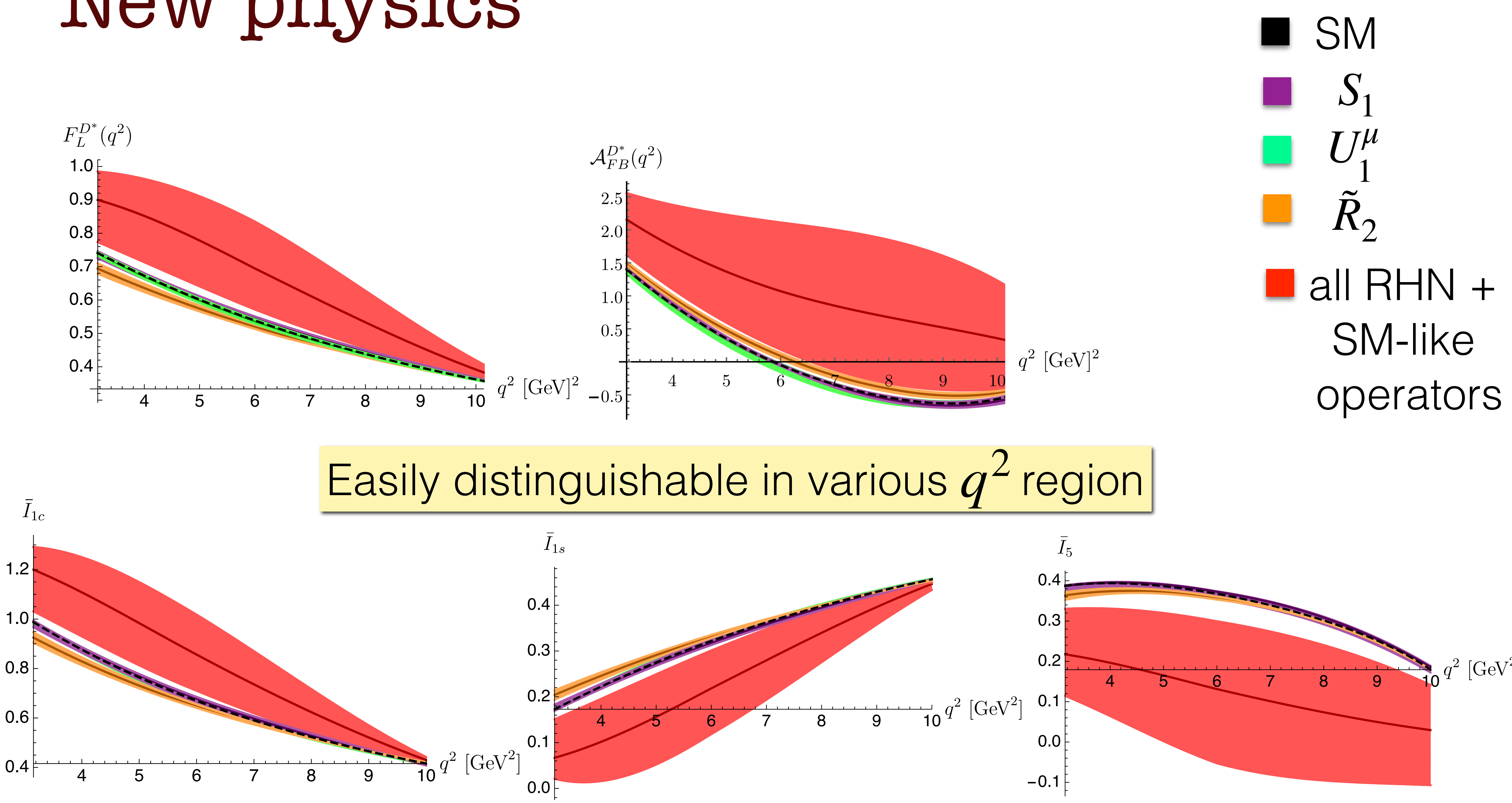
New Physics

- Fit to all measured observables in $B \to D^{(*)}\ell\bar{\nu}$ including differential BR in q^2 & limit from $\mathscr{B}(B_c \to \tau\bar{\nu}) \leq 10-30\,\%$

Mediators	Operators	Pull	Best fit*
	$\mathcal{O}^{V}_{LL}, \mathcal{O}^{S,V,T}_{LR}, \mathcal{O}^{S,V,T}_{RR}$	2.4	$C^V_{LR} = 1.34^{+0.25}_{-0.60}$, $C^S_{LR} = -0.92^{+0.22}_{-0.15}$, $C^T_{RR} = -0.123^{+0.069}_{-0.077}$
$S_1(\bar{3}, 1, 1/3)$	$\mathcal{O}^{S,V,T}_{RR}$	3.3	$C^V_{RR} = 0.422^{+0.071}_{-0.126}$
$U^{\mu}_1(3, 1, 2/3)$	$\mathcal{O}^{V}_{RR}, \mathcal{O}^{S}_{LR}$	3.2	$C^V_{RR} = 0.39^{+0.07}_{-0.08}$
$\tilde{R}_2(3, 2, 1/6)$	$\mathcal{O}^{S,T}_{RR}$	2.9	$C^T_{RR} = 0.054^{+0.009}_{-0.011}$

* shown only the non-zero WCs at 1σ

New physics



Angular observables with new physics operators

Summary

- 4-body angular distribution provides plethora of observables

- Charged current transitions are theoretically simpler compared to FCNC modes — sensitive to BSM operators

- D^* & D_2^* are easily separable from distribution

- Zero-crossings of asymmetries provide relation among form factors — can be tested at experiments

- Caution for modes with τ due to neutrinos in final state
— experimentally challenging
— further decay of τ modifies the angular distribution

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Backup

Angular coefficients

$$I_1^c = N_F\left[2\left(1+\frac{m_\tau^2}{q^2}\right)\left(|\mathcal{A}_0^L|^2+4\,|\mathcal{A}_{T\,0}^L|^2\right)-\frac{16m_\tau}{\sqrt{q^2}}\,\mathcal{R}\mathrm{e}[\mathcal{A}_0^L\mathcal{A}_{T\,0}^{L\,*}]+\frac{4m_\tau^2}{q^2}\,|A_{tP}^L|^2+(L\to R)\right],$$

$$I_1^s = N_F\left[\frac{1}{2}\left(3+\frac{m_\tau^2}{q^2}\right)\left(|\mathcal{A}_\perp^L|^2+|\mathcal{A}_\parallel^L|^2\right)+2\left(1+\frac{3m_\tau^2}{q^2}\right)\left(|\mathcal{A}_{T\,\perp}^L|^2+|\mathcal{A}_{T\,\parallel}^L|^2\right)-8\,\frac{m_\tau}{\sqrt{q^2}}\,\mathcal{R}\mathrm{e}[\mathcal{A}_\perp^L\mathcal{A}_{T\,\perp}^{L\,*}+\mathcal{A}_\parallel^L\mathcal{A}_{T\,\parallel}^{L\,*}]+(L\to R)\right],$$

$$I_2^c = -2\,N_F\left(1-\frac{m_\tau^2}{q^2}\right)\left(|\mathcal{A}_0^L|^2-4\,|\mathcal{A}_{T\,0}^L|^2+(L\to R)\right),$$

$$I_2^s = \frac{1}{2}\,N_F\left(1-\frac{m_\tau^2}{q^2}\right)\left(|\mathcal{A}_\perp^L|^2+|\mathcal{A}_\parallel^L|^2-4\left(|\mathcal{A}_{T\,\perp}^L|^2+|\mathcal{A}_{T\,\parallel}^L|^2\right)+(L\to R)\right),$$

$$I_3 = N_F\left(1-\frac{m_\tau^2}{q^2}\right)\left(|\mathcal{A}_\perp^L|^2-|\mathcal{A}_\parallel^L|^2-4\left(|\mathcal{A}_{T\,\perp}^L|^2-|\mathcal{A}_{T\,\parallel}^L|^2\right)+(L\to R)\right),$$

$$I_4 = \sqrt{2}\,N_F\left(1-\frac{m_\tau^2}{q^2}\right)\mathcal{R}\mathrm{e}[\mathcal{A}_0^L\mathcal{A}_\parallel^{L\,*}-4\,\mathcal{A}_{T\,0}^L\mathcal{A}_{T\,\parallel}^{L\,*}+(L\to R)],$$

$$I_5 = 2\sqrt{2}\,N_F\left[\mathcal{R}\mathrm{e}[(\mathcal{A}_0^L-2\,\frac{m_\tau}{\sqrt{q^2}}\,\mathcal{A}_{T\,0}^L)\,(\mathcal{A}_\perp^{L\,*}-2\,\frac{m_\tau}{\sqrt{q^2}}\,\mathcal{A}_{T\,\perp}^{L\,*})-(L\to R)]-\frac{m_\tau^2}{q^2}\,\mathcal{R}\mathrm{e}[A_{tP}^{L\,*}\,(\mathcal{A}_\parallel^L-2\,\frac{\sqrt{q^2}}{m_\tau}\mathcal{A}_{T\,\parallel}^L)+(L\to R)]\right],$$

$$I_6^c = N_F\,\frac{8m_\tau^2}{q^2}\,\mathcal{R}\mathrm{e}[A_{tP}^{L\,*}\,(\mathcal{A}_0^L-2\,\frac{\sqrt{q^2}}{m_\tau}\,\mathcal{A}_{T\,0}^L)+(L\to R)],$$

$$I_6^s = 4\,N_F\,\mathcal{R}\mathrm{e}[(\mathcal{A}_\parallel^L-2\,\frac{m_\tau}{\sqrt{q^2}}\,\mathcal{A}_{T\,\parallel}^L)(\mathcal{A}_\perp^{L\,*}-2\,\frac{m_\tau}{\sqrt{q^2}}\mathcal{A}_{T\,\perp}^{L\,*})-(L\to R)],$$

$$I_7 = -2\sqrt{2}\,N_F\left[\mathcal{I}\mathrm{m}[(\mathcal{A}_0^L-2\,\frac{m_\tau}{\sqrt{q^2}}\,\mathcal{A}_{T\,0}^L)\,(\mathcal{A}_\parallel^{L\,*}-2\,\frac{m_\tau}{\sqrt{q^2}}\,\mathcal{A}_{T\,\parallel}^{L\,*})-(L\to R)]+\frac{m_\tau^2}{q^2}\,\mathcal{I}\mathrm{m}[A_{tP}^{L\,*}\,(\mathcal{A}_\perp^L-2\,\frac{\sqrt{q^2}}{m_\tau}\,\mathcal{A}_{T\,\perp}^L)+(L\to R)]\right],$$

$$I_8 = \sqrt{2}\,N_F\left(1-\frac{m_\tau^2}{q^2}\right)\mathcal{I}\mathrm{m}[\mathcal{A}_0^{L\,*}\mathcal{A}_\perp^L-4\,\mathcal{A}_{T\,0}^{L\,*}\mathcal{A}_{T\,\perp}^L+(L\to R)],$$

$$I_9 = 2\,N_F\left(1-\frac{m_\tau^2}{q^2}\right)\mathcal{I}\mathrm{m}[\mathcal{A}_\parallel^L\mathcal{A}_\perp^{L\,*}-4\,\mathcal{A}_{T\,\parallel}^L\mathcal{A}_{T\,\perp}^{L\,*}+(L\to R)].$$