Symmetries in $B \to D^* \ell \bar{\nu}$: Disentangling NP

Based on arXiv:2003.02533

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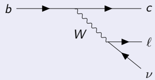
$b \to c\ell\nu$

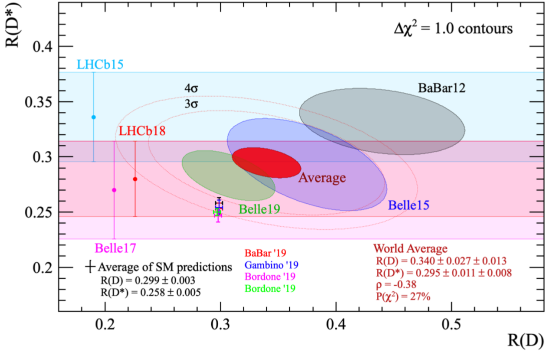
$b \to c\ell\nu$ transition



- Charged current process, tree level in the SM.
- Deviations (2σ) observed on LFU Ratios (τ vs e, μ)
- Tension of $\mathbf{3.1}\sigma$ when combining $R(D)$ and $R(D^*)$

$$R_{H_c} = \frac{\Gamma(H_b \to H_c \tau \bar{\nu}_\tau)}{\Gamma(H_b \to H_c \ell \bar{\nu}_\ell)}$$

- Lepton polarization (P_τ) for $B \to D^* \tau \bar{\nu}$ ($< 1\sigma$) (Belle)
- Longitudinal polarization (F_L) measured for $B \to D^* \tau \bar{\nu}$ (1.7σ) (Belle)
- Constraints on $\mathcal{B}(B_c \to \tau \bar{\nu})$ coming from the B_c^- lifetime (Li et al. '16; Alonso et al. '17)

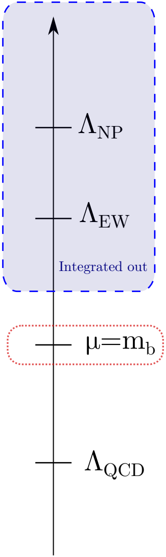


Separation of scales

We can profit of the different energy scales present:

Separation of scales

- Different kinds of physics happening at each scale
- Short distance contributions are integrated out and their effect is computed perturbately
- Long distance QCD contributions are factorized and computed with non-perturbative methods.



WET formalism

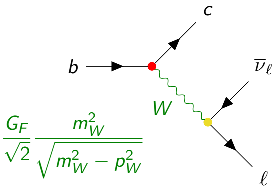
Local operator effective theory at lower scales than the electroweak scale. Non-local high energy processes are reduced to local operators as in Fermi Theory.

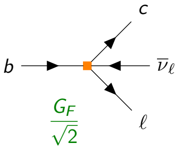
$$\mathcal{H}_{\text{eff}} \propto \sum_i \mathcal{C}_i \mathcal{O}_i \qquad \mathcal{C}_i = \mathcal{C}_i^{\text{SM}} + \mathcal{C}_i^{\text{NP}}$$

- Wilson operators ($\mathcal{O}_i$) contain the **long distance** structure.
- Wilson coefficients ($\mathcal{C}_i$) contain **short distance** dynamics. They are accurately computed in SM and would deviate in presence of NP. Operators absent or suppressed in the SM, can be introduced by NP.
- We want to constrain these Wilson coefficients from data.

$b \to c\ell\nu$ Effective Hamiltonian

$$\begin{aligned}\mathcal{H}_{\text{eff}} =& 4\frac{G_F}{\sqrt{2}} V_{cb} \Big[(1 + g_{V_L}) (\bar{c}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \nu_L) \\ &+ g_{V_R} (\bar{c}_R \gamma_\mu b_R)(\bar{\ell}_L \gamma^\mu \nu_L) \\ &+ g_{S_L} (\bar{c}_R b_L)(\bar{\ell}_R \nu_L) + g_{S_R} (\bar{c}_L b_R)(\bar{\ell}_R \nu_L) \\ &+ g_{T_L} (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \Big] + \text{h.c.}\end{aligned}$$





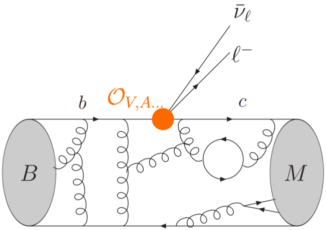
Hadronic Inputs: Form factors

$$\langle M|\mathcal{H}_{\text{eff}}|B\rangle \propto \sum \mathcal{C}_i \langle M|\mathcal{O}_i|B\rangle$$

$$\langle M|\mathcal{O}_i|B\rangle = \sum_j K_{ij} \quad F_{ij}$$

Kinematical factor

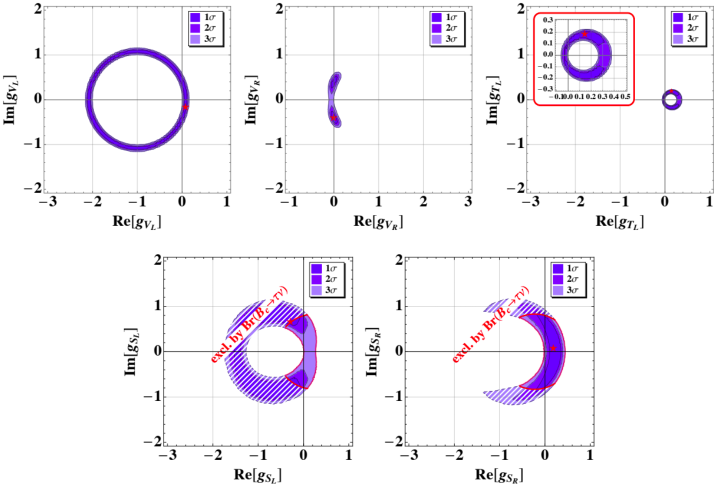
Form factor
(Scalar function)



- The characteristic scales of hadron dynamics is Λ_{QCD} (Non pertubative techniques are required)
- As many form factors as Lorentz structures available **(higher spin $\Rightarrow$ more form factors)**
- Usually obtained through Lattice QCD or Light-Cone Sum Rules which work in different kinematical regimes **(sizeable uncertainties)**

Global Fits for $b \to c\ell\nu$

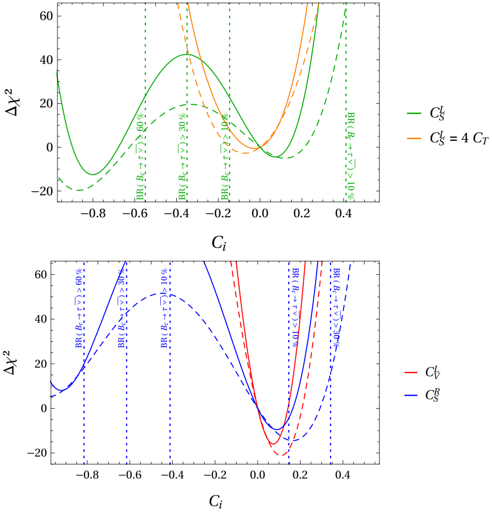
(Freytsis et al. '15; Alok et al. '18; Bhattacharya et al. '19; Kumar et al. '19; Murgui et al. '19; Bečirević et al. '19; Blanke et al. '19)



(Bečirević et al. '19)

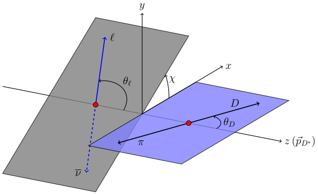
Global Fits for $b \to c\ell\nu$

- V-A current (i.e. change on the "$b \to c\ell\nu$ Fermi constant") is the favoured scenario, but other scenarios are not excluded
- We need more information to disentangle the NP scenarios

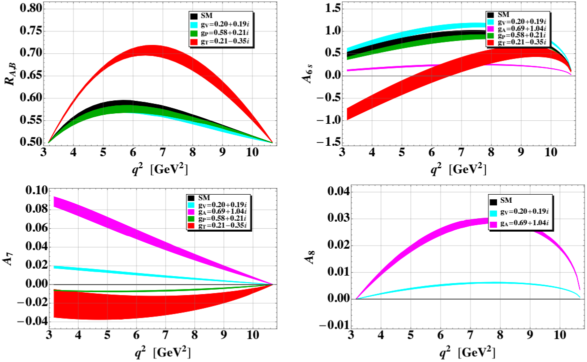


(Blanke et al. '19)

Disentangling NP scenarios: $B \to D^* l \bar{\nu}$ angular observables



(Bečirević et al. '19)



(Bečirević et al. '19)

- 12 independent angular observables!
- Sensitivity to different NP scenarios
- But dependent on hadronic inputs

$$
\begin{aligned}
\frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_\ell d\chi} = \frac{9}{32\pi}\Big\{ & I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D + \left[I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D\right]\cos 2\theta_\ell \\
& + \left[I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D\right]\cos\theta_\ell + \left[I_3\cos 2\chi + I_9\sin 2\chi\right]\sin^2\theta_\ell\sin^2\theta_D \\
& + \left[I_4\cos\chi + I_8\sin\chi\right]\sin 2\theta_\ell\sin 2\theta_D + \left[I_5\cos\chi + I_7\sin\chi\right]\sin\theta_\ell\sin 2\theta_D \Big\}
\end{aligned}
$$

$B \to D^* l \bar{\nu}$ angular observables symmetries [2003.02533]

Activity and interesting results to disentangle NP, but there is still some room for improvement in the determination of form factors.

Can we distinguish different NP scenarios without the need of hadronic inputs?

- In the absence of tensor currents several symmetries appear that can be used to define relations in between the angular observables which are **not affected by hadronic uncertainties**.
- Testing these relations is a probe of the hypothesis of tensor NP
- Alternatively, consistency test in the absence of tensor among angular observables

How to check if and how many of these relations exist?

Following what has been done for $B \to K^* \ell\ell$ (Egede et al. 2010)

We can consider the angular coefficients (I_i) as being bilinears in the helicity amplitudes

$$\vec{A} = \{\mathrm{Re}[H_0], \mathrm{Im}[H_0], \mathrm{Re}[H_+], \mathrm{Im}[H_+], ...\}$$

Given an infinitesimal transformation

$$\vec{A}' = \vec{A} + \vec{\delta}$$

$$\vec{\delta} \perp \vec{\nabla} I_i \implies I_i \,\mathrm{unchanged}$$

$$\text{number of dependencies } = \#(I_i) - rank(\nabla_j I_i)$$

In the presence of tensor currents, no dependencies are found.
In the absence of them, we find **5 different dependencies**.

Relations coming from symmetries

- Some of them are trivial, but some others are not evident if not searched methodically

Massless Relations

$$
\begin{aligned}
I_{1s} &= 3I_{2s} \\
-4I_3 I_{2c} &= -4I_4^2 + I_5^2 - I_7^2 + 4I_8^2 \\
-2I_9 I_{2c} &= I_5 I_7 - 4I_4 I_8 \\
-4I_{2c}\left(\tfrac{1}{2}I_{6s} + \tfrac{2}{3}I_{1s}\right) &= (2I_4 + I_5)^2 + (I_7 + 2I_8)^2 \\
-4I_{2c}\left(-\tfrac{1}{2}I_{6s} + \tfrac{2}{3}I_{1s}\right) &= (-2I_4 + I_5)^2 + (I_7 - 2I_8)^2
\end{aligned}
$$

Massive relations

$$
0 = I_{1s}\left(1 - \frac{m_\ell^2}{q^2}\right) - I_{2s}\left(3 + \frac{m_\ell^2}{q^2}\right)
$$

$$\vdots$$

- Massless relations generalize to more complicated relations for the massive case.
- How do we profit of these relations?

How to exploit these relations: $F_T^{D* \,\mathrm{alt}}$

We can combine several of these relations to reduce the number of observables involved and enhance the sensitivity to tensor currents

$$F_T^{D^* \,\mathrm{alt}} \equiv \frac{1}{\Gamma}\sqrt{(A\, I_3)^2 + (A\, I_9)^2 + \frac{1}{4}(B\, I_{6s})^2}$$

$$F_T^{D^* \,\mathrm{alt}} = F_T^{D^*} \qquad \text{when} \quad g_{T_L} = 0$$

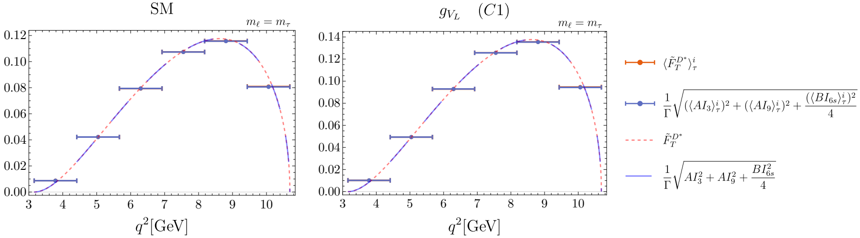
Where A and B are simple kinematical factors depending on m_ℓ^2/q^2

- Testing these relations is a probe of the need of tensor NP
- Non linear relations: Are these relations preserved after binning ($\langle f(I)\rangle$ vs $f(\langle I\rangle)$)?

Binning issues?

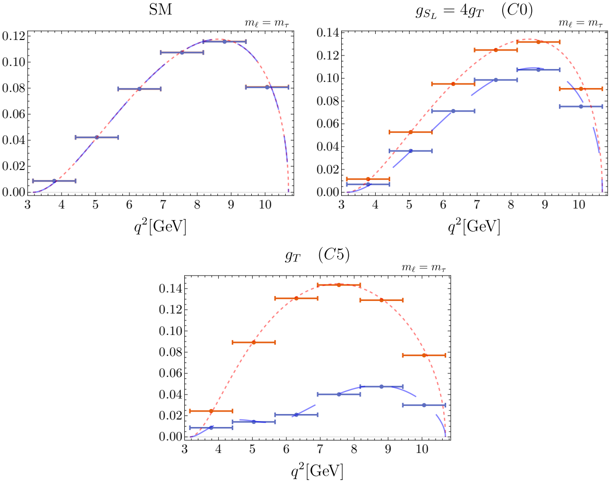
$$\langle \tilde{F}_T^{D^*\,\mathrm{alt}} \rangle \simeq \frac{1}{\Gamma}\sqrt{\langle A\, I_3\rangle^2 + \langle A\, I_9\rangle^2 + \frac{1}{4}\langle B\, I_{6s}\rangle^2}$$

- We tested the effect of binning in different NP scenarios (bfp of global fits)
- Effect of binning $\lesssim 1\%$ for a single bin !
- With more bins the effect is further reduced
- Test of consistency in the absence of tensor



(Algueró et al. '20)

Tensor Sensitivity



(Algueró et al. '20)

$(C0)$: $g_{S_L} = 4g_T = -0.06 + i\,0.31$ $\qquad$ $(C5)$: $\qquad g_T = 0.11 - i0.18$

Tensor Tests

Using estimates for a "SM-like" 50 fb^{-1} hadron collider scenario (Hill et al. '19)

$$\langle F_L^{D*\,\mathrm{alt}} \rangle_{\mathrm{SM}}^{50\ \mathrm{fb}^{-1}} - \langle F_L^{D*} \rangle_{\mathrm{SM}}^{50\ \mathrm{fb}^{-1}} = 0.02 \pm 0.12$$

$$\langle F_L^{D*\,\mathrm{alt}} \rangle_{\mathrm{SM}}^{th} - \langle F_L^{D*} \rangle_{\mathrm{SM}}^{th} = 0 \pm 0.01$$

In the presence of tensor NP currents this difference is no longer 0 and assuming the experimental uncertainties do not depend on their presence, we could expect some sensitivity:

$$\langle F_L^{D*\,\mathrm{alt}} \rangle_{g_{T_L}}^{50\ \mathrm{fb}^{-1}} - \langle F_L^{D*} \rangle_{g_{T_L}}^{50\ \mathrm{fb}^{-1}} = 0.2 \pm 0.12$$

Conclusions

Interesting future prospects that might help disentangle the different NP solutions to the current $b \to c\ell\nu$ anomalies.

- Angular observables of $B \to D^* l\nu$ will help disentangle NP scenarios.
- Relations in $B \to D^* l\nu$ provide a robust test of the presence of tensor currents (independent of assumptions on form factors).
- Conversely, consistency test among angular observables in the absence of tensor currents
- Binning issues on these relations are negligible.

Thank You!

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Back up

Experimental sensitivity of $B \to D^*$ *relations*

Using estimates for a 50 fb^{-1} hadron collider scenario (Hill et al. '19)

$$\langle F_L^{D*\,\mathrm{alt}} \rangle_{50\ \mathrm{fb}^{-1}} = 0.47 \pm 0.12$$

to be compared with the standard determination

$$\langle F_L^{D*} \rangle_{50\ \mathrm{fb}^{-1}} = 0.45 \pm 0.01$$

Kinematical Factors

$$F_T^{D^*\,\mathrm{alt}} \equiv \frac{1}{\Gamma}\sqrt{(A\, I_3)^2 + (A\, I_9)^2 + \frac{1}{4}(B\, I_{6s})^2}$$

$$A = \frac{m_\ell^2 + 2q^2}{q^2 - m_\ell^2} \qquad\qquad B = 2 + \frac{m_\ell^2}{q^2}$$