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

Based on arXiv:2003.02533

Marcel Algueró, Sébastien Descotes-Genon, Joaquim Matias, Martín Novoa-Brunet

Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

October 29, 2020
$b \rightarrow c \ell \nu$

$b \rightarrow c \ell \nu$ transition

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

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

- Lepton polarization ($P_\tau$) for $B \rightarrow D^* \tau \bar{\nu}$ ($< 1\sigma$) (Belle)
- Longitudinal polarization ($F_L$) measured for $B \rightarrow D^* \tau \bar{\nu}$ ($1.7\sigma$) (Belle)
- Constraints on $B(B_c \rightarrow \tau \bar{\nu})$ coming from the $B_c^-$ lifetime (Li et al. '16; Alonso et al. '17)
We can profit of the different energy scales present:

- 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.

\[ \mathcal{H}_{\text{eff}} \propto \sum_i C_i \mathcal{O}_i \quad \mathcal{C}_i = \mathcal{C}_i^{\text{SM}} + \mathcal{C}_i^{\text{NP}} \]

- Wilson operators \((\mathcal{O}_i)\) contain the long distance structure.
- Wilson coefficients \((C_i)\) 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.

- \[ b \rightarrow c\ell\nu \quad \text{Effective Hamiltonian} \]

\[ \mathcal{H}_{\text{eff}} = 4 \frac{G_F}{\sqrt{2}} V_{cb} \left[ (1 + g_{V_L})(\bar{c}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu \nu_L) ight. \\
+ g_{V_R}(\bar{c}_R\gamma_\mu b_R)(\bar{\ell}_L\gamma^\mu \nu_L) \\
+ g_{S_L}(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_{S_R}(\bar{c}_L b_R)(\bar{\ell}_R\nu_L) \\
\left. + g_{T_L}(\bar{c}_R\sigma^{\mu\nu} b_L)(\bar{\ell}_R\sigma^{\mu\nu} \nu_L) \right] + \text{h.c.} \]
Hadronic Inputs: Form factors

\[ \langle M|H_{\text{eff}}|B\rangle \propto \sum C_i \langle M|O_i|B\rangle \]

\[ \langle M|O_i|B\rangle = \sum_j K_{ij} F_{ij} \]

- The characteristic scales of hadron dynamics is \( \Lambda_{QCD} \) (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: $B \rightarrow D^* \ell \bar{\nu}$ angular observables

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

$\frac{d^4\Gamma}{dq^2 d \cos\theta_D d \cos\theta_D d\chi} = \frac{9}{32\pi} \left\{ l_{1c} \cos^2\theta_D + l_{1s} \sin^2\theta_D + [l_{2c} \cos^2\theta_D + l_{2s} \sin^2\theta_D] \cos 2\theta_\ell \\
+ [l_{6c} \cos^2\theta_D + l_{6s} \sin^2\theta_D] \cos \theta_\ell + [l_3 \cos 2\chi + l_9 \sin 2\chi] \sin^2\theta_\ell \sin^2\theta_D \right. \\
+ \left. [l_4 \cos \chi + l_8 \sin \chi] \sin 2\theta_\ell \sin 2\theta_D + [l_5 \cos \chi + l_7 \sin \chi] \sin \theta_\ell \sin 2\theta_D \right\}$
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 \textbf{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 $B \rightarrow K^* \ell \ell$ (Egede et al. 2010)

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

$$\vec{A} = \{\text{Re}[H_0], \text{Im}[H_0], \text{Re}[H_+], \text{Im}[H_+], \ldots\}$$

Given an infinitesimal transformation

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

$$\vec{\delta} \perp \nabla l_i \implies l_i \text{ unchanged}$$

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

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**

\[
\begin{align*}
l_{1s} &= 3l_{2s} \\
-4l_{3}l_{2c} &= -4l_{4}^{2} + l_{5}^{2} - l_{7}^{2} + 4l_{6}^{2} \\
-2l_{9}l_{2c} &= l_{5}l_{7} - 4l_{4}l_{8} \\
-4l_{2c}(\frac{1}{2}l_{6} + \frac{2}{3}l_{1s}) &= (2l_{4} + l_{5})^{2} + (l_{7} + 2l_{8})^{2} \\
-4l_{2c}(\frac{1}{2}l_{6} - \frac{2}{3}l_{1s}) &= (-2l_{4} + l_{5})^{2} + (l_{7} - 2l_{8})^{2}
\end{align*}
\]

**Massive relations**

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

- Massless relations generalize to more complicated relations for the massive case.
- How do we profit of these relations?
How to exploit these relations: $F_T^{D^*\text{alt}}$

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

$$F_T^{D^*\text{alt}} \equiv \frac{1}{\Gamma} \sqrt{(A l_3)^2 + (A l_9)^2 + \frac{1}{4}(B l_{6s})^2}$$

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

Where $A$ and $B$ are simple kinematical factors depending on $m_\ell^2/q^2$

- 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 $f(\langle I \rangle)$)?
Bininning issues?

\[ \langle \tilde{F}^{D^*}_{T \text{ alt}} \rangle \simeq \frac{1}{\Gamma} \sqrt{\langle A I_3 \rangle^2 + \langle A I_9 \rangle^2 + \frac{1}{4} \langle B I_{6s} \rangle^2} \]

- 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

![Graphs showing SM and \( g_{V_L} \) (C1) with \( m_\ell = m_\tau \) for various \( q^2 \) values and \( \langle \tilde{F}^{D^*}_T \rangle \) calculations](image)

(Algueró et al. '20)
Tensor Sensitivity

\( g_{S_L} = 4g_T \) (C0)

\( g_T \) (C5)

(Algueró et al. ’20)

\[(C0): g_{S_L} = 4g_T = -0.06 + i0.31 \]
\[(C5): \quad g_T = 0.11 - i0.18 \]
Tensor Tests

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

\[
\langle F_{D*}^{D* \text{ alt}} \rangle_{50 \text{ fb}^{-1}}^{\text{SM}} - \langle F_{L}^{D*} \rangle_{50 \text{ fb}^{-1}}^{\text{SM}} = 0.02 \pm 0.12
\]

\[
\langle F_{D*}^{D* \text{ alt}} \rangle_{\text{SM}}^{th} - \langle F_{L}^{D*} \rangle_{\text{SM}}^{th} = 0 \pm 0.01
\]

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:

\[
\langle F_{L}^{D* \text{ alt}} \rangle_{g_{T_L}}^{50 \text{ fb}^{-1}} - \langle F_{L}^{D*} \rangle_{g_{T_L}}^{50 \text{ fb}^{-1}} = 0.2 \pm 0.12
\]
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!
Symmetries in $B \rightarrow D^* \ell \bar{\nu}$: Disentangling NP

Based on arXiv:2003.02533

Marcel Algueró, Sébastien Descotes-Genon, Joaquim Matias, Martín Novoa-Brunet

Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

October 29, 2020
Back up
Experimental sensitivity of $B \rightarrow D^* \text{relations}$

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

$$\langle F_{\text{alt}}^{D^*} \rangle_{50 \text{ fb}^{-1}} = 0.47 \pm 0.12$$

to be compared with the standard determination

$$\langle F_{\text{L}}^{D^*} \rangle_{50 \text{ fb}^{-1}} = 0.45 \pm 0.01$$
Kinematical Factors

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

\[ A = \frac{m_\ell^2 + 2q^2}{q^2 - m_\ell^2} \quad B = 2 + \frac{m_\ell^2}{q^2} \]

Martín Novoa-Brunet (IJCLab)