What are the future $b \to c l \nu$ measurements?

Beyond the flavour anomalies III, Durham

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April 27, 2022

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Scope

- Semileptonic $b \to c\ell\nu$ decays have provided a wealth of physics measurements from lepton flavour universality (LFU), CKM parameters, tests of QCD, charm hadron properties, etc.
- Tensions exist:
  - LFU violation at 3σ tension wrt SM $\implies$ Hints of NP.
  - Inclusive/exclusive V_{cb} at 3σ tension $\implies$ NP unlikely.
- A rich physics programme ongoing to address LFU.
- What to expect from this talk?
  - Future sensitivity on the various LFU ratio $R(X_c)$.
  - Future measurements, complimentary to $R(X_c)$, expected from LHCb, Belle II, CMS.
  - Discussion on challenges, current scenario and prospects for such measurements.

Tests of lepton flavour universality (I)

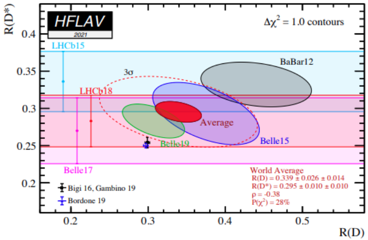
- Ratio of BFs involving different leptons are an excellent test of SM.

$$R(X_c) = \frac{BF(X_b \to X_c \ell \nu)}{BF(X_b \to X_c \ell' \nu)}$$

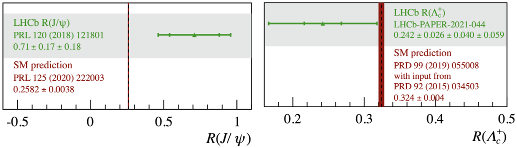
where $\ell, \ell' = e, \mu, \tau$.

- Measure various $R(X_c)$ to a precision comparable to SM prediction.
- Overcome hurdles to achieve this:
  - Limited simulation sample size.
  - Knowledge of excited/double-charm bkgs.
  - Precision/knowledge of form factors (FF).
  - Hadronic τ normalisations?

[HFLAV]



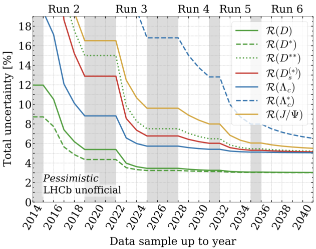
[LHCb]

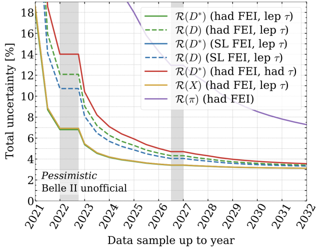


Tests of lepton flavour universality (II)

- **Current scenario**:
  - Available measurements include: $R(D^{(*)})$ (B-factories and LHCb), $R(J/\psi)$ and $R(\Lambda_c)$.
  - Several ongoing measurements at LHCb of which $R(D^{(*)})$ is most advanced.
  - CMS to soon enter the arena.
- **Future prospects**:
  - Projections of the sensitivity of various $R(X_c)$ for LHCb (top) and Belle-II (bottom) shown.
  - Future $R(X_c)$ include: $R(D^{**})$, $R(\Lambda_c^*)$, $R(D_s^{(*)})$.
  - Exploit light lepton ratios (NP in light leptons at per-mille level).

[Manuel Sevilla et al]





Complementary observables to probe new physics

- $R(X_c)$ are not the end of the story:
  - Some model dependence in integrated efficiencies / fit observables (q^2).
  - They do not fully exploit the phase space of the decay.
- Fully exploit the data by considering complementary observables to probe NP.
  - Production polarisation of charm hadrons X_c.
  - Polarisation of the lepton.
  - Forward-backward asymmetry.
  - Triple product asymmetry.
  - CP violation in the decay.
  - Differential shapes.
- **Let's discuss these observables in detail...**

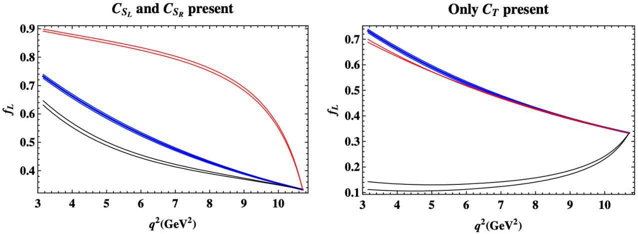
Production polarisation of charm hadron (I)

- An observable of interest is the production polarisation of the charm hadron (X_c), with non-zero spin, produced from $X_b \to X_c \tau \nu$ decays.
- An example includes fraction of longitudinally (L) polarised D^* from $B^0 \to D^{*-}\tau^+\nu$ decays

$$f_L^{D^*} = \frac{\Gamma(D_L^*)}{\Gamma(D_L^*) + \Gamma(D_T^*)} \approx 45\% \text{ in SM}\,.$$

- NP scenarios can modify $f_L^{D^*}$, particularly scalar ($C_{S_{L/R}}$) and tensor (C_T) currents. Below blue band represents SM, with other coloured bands representing NP.

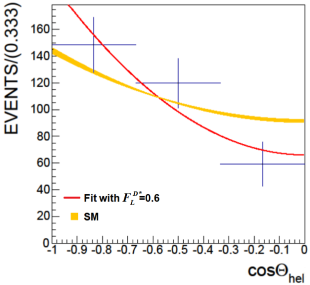
[A. K. Alokh et al]



Production polarisation of charm hadron (II)

- **Current scenario**:
  - First measurement by Belle in 2017 of $f_L^{D^*}$ using $B^0 \to D^{*-}\tau^+\nu$ decays, exploiting various $\overline{D}^0$ decays and one-prong τ^- decays. **Stands at 1.8σ tension wrt SM.**
  - Ongoing LHCb analysis of $f_L^{D^*}$ with $B^0 \to D^{*-}(\to \overline{D}^0\pi^-)\tau^+\nu$ decays, using three-prong τ^- decays.

[BaBar]



- **Future prospects**:
  - **Improve statistical precision on $f_L^{D^*}$** with Belle-II and LHCb Run III data (bkg. shape modelling becomes a limiting systematic).
  - **Extend to other modes?** e.g. $\Lambda_b \to \Lambda_c\tau\nu$ and $B \to D^{**}\tau\nu$ decays.
  - **Explore light lepton channels** e.g. difference of $f_L^{D^*}$ between electron and muon modes.

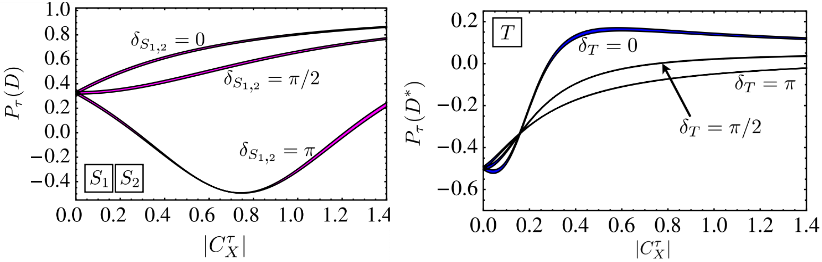
Polarisation of τ lepton (I)

- Leptons produced in the semileptonic $X_b \to X_c \tau \nu$ decays tend to be polarised.
- Measuring the τ lepton polarisation (P^τ) interesting to probe effects of NP.

$$P^\tau = \frac{\Gamma^{\lambda_\tau=+1/2} - \Gamma^{\lambda_\tau=+1/2}}{\Gamma^{\lambda_\tau=+1/2} + \Gamma^{\lambda_\tau=+1/2}}$$

- For example $P^\tau(D^{(*)})$ in $\overline{B} \to D^{(*)}\tau\overline{\nu}$ decays show large sensitivity to scalar ($S_{1,2}$) and tensor (T) currents (δ_X are the weak phase of the complex C_X^τ).

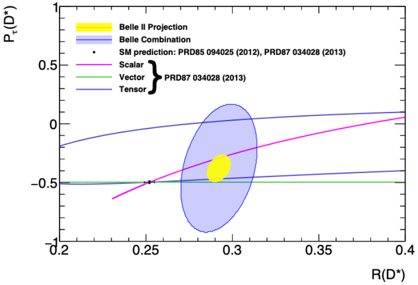
[M Tanaka et al]



Polarisation of τ lepton (II)

- **Current scenario**:
  - First measurement by Belle in 2017 of $P^{\tau}(D^*)$ using $\overline{B} \to D^* \tau^- \overline{\nu}$ decays, exploiting one-prong hadronic τ^- decays.
  - No other measurements exists.

[Belle-II]



- **Future prospects**:
  - **Improve precision on $P^{\tau}(D^*)$** with Belle-II data (the dominant systematic in prev. result from hadronic B background composition expected to improve also).
  - **$P^{\tau}(D^*)$ measurement plans** at LHCb with hadronic three-prong τ decays.
  - **Comparison of in-direct estimates of $P^{l=e,\mu}$ with light leptons** via differential decay measurements.

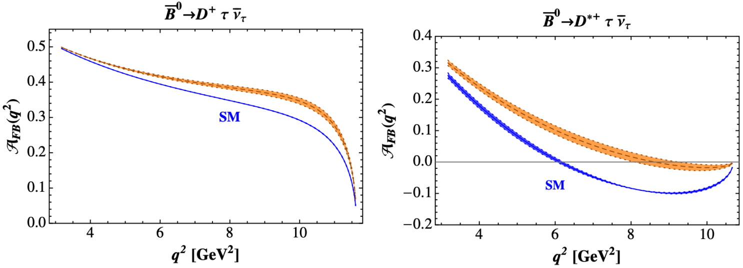
Forward-backward asymmetry (I)

- A quantity of interest that can be inferred from differential decay rate measurement is forward-backward asymmetry

$$\langle A_{FB}^{\tau} \rangle = \int A_{FB}^{\tau}(q^2) = \frac{\int_0^1 \frac{d\Gamma^{\tau}}{dq^2 d\cos(\theta_\ell)} d\cos(\theta_\ell) - \int_{-1}^0 \frac{d\Gamma^{\tau}}{dq^2 d\cos(\theta_\ell)} d\cos(\theta_\ell)}{\frac{d\Gamma^{\tau}}{dq^2}}$$

- For example $A_{FB}^{\tau}(D^{(*)})$ in $\overline{B} \to D^{(*)}\tau\overline{\nu}$ decays is very sensitivity to NP contributions.

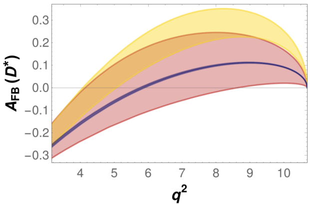
[P. Biancofiore et al]



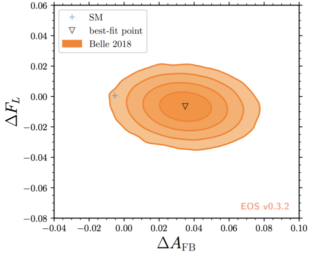
Forward-backward asymmetry (II)

- **Current scenario**:
  - **Semitauonic**: Differential decay rate measurement of $\overline{B} \to D^{(*)}\tau^-\overline{\nu}$ decays available by Belle and BaBar.
    - $A^{\tau}_{FB}(D^{(*)})$ prediction from $b \to c\tau\nu$ global fit is consistent with SM (top-left fig.).
  - **Light leptons**: Differential distb. for various b-hadron species available from B factories and LHCb.
    - Recent study of $\overline{B} \to D^*\ell^-\overline{\nu}$ decays by Belle shows 4σ tension wrt SM (bottom-left fig.).
- **Future prospects**:
  - **Differential measurements** involving different lepton species will improve the experimental precision on this observables significantly.

[C. Murgui et al]



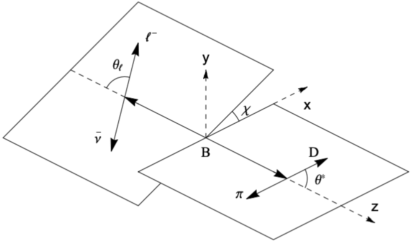
[C. Bobeth et al]



Triple product asymmetries (I)

- Amplitudes, with same strong phase but different weak phases, contributing to multi-body semileptonic decays can give rise to CP-violating angular asymmetries.
  - **Non-zero asymmetry would be smoking gun signal for NP**.
  - Interfering SM and NP amplitudes must have different Lorentz structures.
- Asymmetries of this type, for example, can measured by analysing the phase space of $\overline{B}^0 \to D^{*+}(\to D^0\pi^+)\tau^-\overline{\nu}$ (multi-pion τ decay can also be exploited).
  - Of interest is angle χ obtained from scalar triple product of final state momenta.

[D. London et al]



Triple product asymmetries (II)

- Measuring a non-zero CP angular asymmetry $\implies$ non-zero angular coefficient of $\sin(\chi)$ terms, equal in magnitude for particle and anti-particle decays.

- **Current scenario**:
  - Ongoing analysis at LHCb with semimuonic $\overline{B}^0 \to D^{*+}(\to D^0\pi^+)\mu^-\overline{\nu}$ decays (Bkg. and other experimental effects can introduce a fake signal).
- **Future prospects**:
  - **Other semimuonic channels** e.g. $\Lambda_b \to \Lambda_c(\to pK_S)\mu^-\nu$ can be studied at LHCb. **Electron channels** can also be explored with LHCb Run III data.
  - For **semitauonic channels**, three-prong τ decays can be exploited at LHCb.
  - **Interest within Belle-2** to pursue this.

[D. London et al]

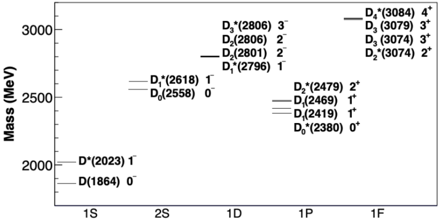
Not suppressed	Coupling	Angular Function
$\mathrm{Im}(\mathcal{A}_\perp \mathcal{A}_0^*)$	$\mathrm{Im}[(1+g_L+g_R)(1+g_L-g_R)^*]$	$-\sqrt{2}\sin 2\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_\parallel \mathcal{A}_\perp^*)$	$\mathrm{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$2\sin^2\theta_\ell \sin^2\theta^* \sin 2\chi$
$\mathrm{Im}(\mathcal{A}_{SP} \mathcal{A}_{\perp,T}^*)$	$\mathrm{Im}(g_P g_T^*)$	$-8\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_0 \mathcal{A}_\parallel^*)$	$\mathrm{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$-2\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$
Suppressed by $m_\ell/\sqrt{q^2}$	Coupling	Angular Function
$\mathrm{Im}(\mathcal{A}_0 \mathcal{A}_{\parallel,T}^*)$	$\mathrm{Im}[(1+g_L-g_R)g_T^*]$	$8\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_\parallel \mathcal{A}_{0,T}^*)$	$\mathrm{Im}[(1+g_L-g_R)g_T^*]$	$-8\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_t \mathcal{A}_{\perp,T}^*)$	$\mathrm{Im}[(1+g_L-g_R)g_T^*]$	$-8\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_\perp \mathcal{A}_{SP}^*)$	$\mathrm{Im}[(1+g_L+g_R)g_P^*]$	$-2\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$
Suppressed by m_ℓ^2/q^2	Coupling	Angular Function
$\mathrm{Im}(\mathcal{A}_\parallel \mathcal{A}_\perp^*)$	$\mathrm{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$-2\sin^2\theta_\ell \sin^2\theta^* \sin 2\chi$
$\mathrm{Im}(\mathcal{A}_t \mathcal{A}_\perp^*)$	$\mathrm{Im}[(1+g_L+g_R)(1+g_L-g_R)^*]$	$2\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_\perp \mathcal{A}_0^*)$	$\mathrm{Im}[(1+g_L+g_R)(1+g_L-g_R)^*]$	$\sqrt{2}\sin 2\theta_\ell \sin 2\theta^* \sin\chi$

Table 5. The CP-violating terms in the angular distribution, their corresponding NP couplings, and the angular functions to which they contribute.

NP induced CP violation in decay (I)

- In the presence of NP, semileptonic decays that proceed via several interfering resonance states could exhibit CP violation in the decay.
  - **Non-zero CP asymmetry would be a smoking gun signal for NP**. Help break the ambiguities arising in the constraining of the imaginary part of the WC.
  - Interfering resonances (with relative strong phase) must have different spins and the SM and NP currents (with relative weak phase) must have different lorentz structure.
- Asymmetries of this type, for example, can be exhibited in $\overline{B} \to D^{**}(\to D^{(*)}\pi)\tau\overline{\nu}$ decays.
  - Spectroscopy of D^{**} important as it affects not only kinematics but HQET expansion of form factors

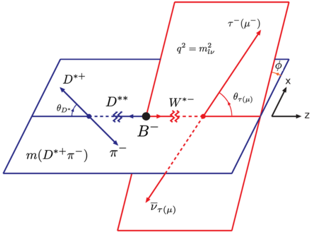
[S. Godfrey et al]

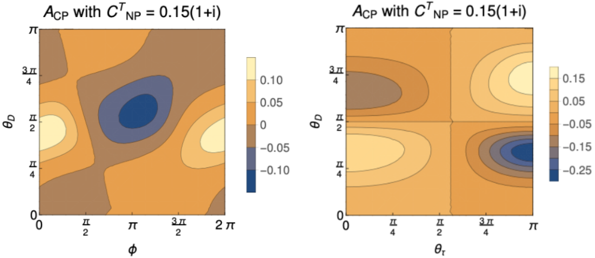


NP induced CP violation in decay (II)

- CP asymmetry is enhanced if measured as a function of phase space observable.
- **Current scenario**:
  - No measurement of CPV in decay exists.
  - (Not CPV) Belle and BaBar have studied D^{**} spectroscopy with light lepton $\overline{B} \to D^{**} l \overline{\nu}$ modes.
  - (Not CPV) Ongoing LHCb analysis probes differential rate and D^{**} spectroscopy with $B^- \to D^{*+}\pi^-\mu^-\overline{\nu}$ decays.
- **Future prospects**:
  - Both Belle-II and LHCb can study CPV $\overline{B} \to D^{**}\ell\overline{\nu}$ decays with all lepton species.
  - Explore other channels at LHCb e.g. $\Lambda_b \to \Lambda_c^* \ell^- \nu$.

[D. Aloni et al]





Full Angular analysis (I)

With enough data one can measure all the angular coefficients

- q^2 dependent coefficients J_i $\rightarrow$ some integration
- Many coefficients requires much data
- Each angular term should be orthogonal $\rightarrow$ straightforward to fit
  - For LHCb likely correlated due to resolution
- **Requirements**
  - Good understanding of experimental resolution
  - Complete understanding of angular distributions of backgrounds

[D. Hill et al]

$$\begin{aligned}\frac{d^4\Gamma}{dq^2\, d(\cos\theta_D)\, d(\cos\theta_L)\, d\chi} \propto\; & I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D \\ & + [I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D]\cos 2\theta_L \\ & + [I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D]\cos\theta_L \\ & + [I_3\cos 2\chi + I_9\sin 2\chi]\sin^2\theta_L\sin^2\theta_D \\ & + [I_4\cos\chi + I_8\sin\chi]\sin 2\theta_L\sin 2\theta_D \\ & + [I_5\cos\chi + I_7\sin\chi]\sin\theta_L\sin 2\theta_D\,,\end{aligned}$$

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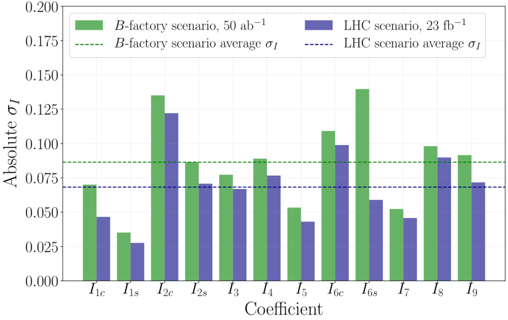


Publish data

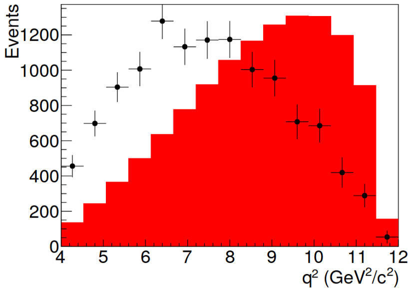
Can we publish our data sets?

- Unfold and efficiency correct distributions

Prospects

- Expected from Belle II
  - Publication of q^2 distribution by Belle disfavours 2HDM
  - Any chance of multi-dimensional distributions?
- Trickier from LHCb
  - So far fit differential distribution (i.e. q^2 or E_μ^*) to extract τ signal
  - More backgrounds
  - Bigger influence of resolution - do we unfold ourselves or provide a response matrix?

[Belle II]



Direct parameter fits

We could fit directly for FF or NP WCs

- Direct link of data $\rightarrow$ physics
- Assuming all relevant variables fitted should get most out of the data

Prospect:

- In LHCb's plans?
- Expected from Belle II?

Drawbacks:

- A single data set will not tell you everything - choices must be made
- How to combine measurements or re-analyse with new theory inputs?
- A snapshot in time/predilections of the experimenter

Conclusions/Discussion

Common challenges:

- Understanding detector resolution
- Understanding of backgrounds
  - More angular fit variables $\rightarrow$ harder to validate all backgrounds
  - Particularly difficult for LHCb, in progress: [JHEP 06, 177 (2021)]

Questions:

- Are ratios of branching fractions still interesting?
  - If so, for how much longer? Is it the quickest way to get to $5\,\sigma$?
- Is there an appetite for directly fitting WC/FF?
- Can experiments provide data to theory directly?
  - Pertinent subject for CKM determinations
  - How do we unfold / forward fold?