Summary remarks from a (poor) experimentalist’s point of view
Strength...

- \( \sim 4\sigma \) from the Standard Model
- Not a single experiment’s show
...and weaknesses (so far)

- Low-statistics measurements
- Need to combine various weak-evidence results to obtain a strong significance
Larger statistics, harsh environment

- In hadron collisions, things are not nearly as “nice” as in $\Upsilon(4S)$ decay at the B-factories
  - Unknown CM frame for $gg \to b\bar{b}$ production
  - Lots of additional particles in the event (showering, MPI etc)
  - Inclusive secondary vertex triggers are explicitly biased in missing mass

- Different handles are needed to deal with
  - Missing neutrinos $\Rightarrow$ underconstrained kinematics
  - Partial reconstruction of signal decay $\Rightarrow$
    - Large backgrounds from partially-reconstructed B decays with “missed” final state particles
      (e.g. $B \to D^{**}(n \geq 1\pi)\mu\nu$, $\bar{B} \to D^{**}H_c(\to \mu\nu XX)$)
Lower statistics, clean environment

- \( Y(4s) \rightarrow B\bar{B} \) decays are fully reconstructed:
  - hadronic B decay : tag
  - D or D* decays to hadrons
  - single \( e^\pm \) or \( \mu^\pm \)
  - conservation of charge and flavor
  - no additional charged particles - Belle vetoes additional \( \pi^0 \)
- kinematic selection : \( q^2 > 4 \text{ GeV}^2 \) to suppress \( D^{(*)}\bar{\nu} \)
- Background suppression by NN/BDT (combinatorial BG and \( D^{*\ast}\bar{\nu} \))
- Full Belle and BABAR data sample
LHCb $R(D^*)$ with muonic $\tau$ decay

- Projections of (left) $m_{\text{miss}}^2$ and (right) $E_\mu^*$ in bins of increasing $q^2$ from top to bottom.

- Full range of $q^2$ important for verifying modeling of resolution effects.
  - Requiring good fit for $D^*\mu\nu$ across the whole spectrum *and* consistency between fitted FFs and HFLAV average -> very strong constraint on simulation resolution & correlations.

- Cross check: verify that simulation cocktail at best fit point reproduces data kinematics well.

- Final result:
  $$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$
Improving on $R(D^*)$ systematics

Uncertainty breakdown from 2015 measurement:

- Previous result was $R(D^*) = 0.336 \pm 0.027 \pm 0.030$

- Systematic error dominates the pie, but is in turn mostly MC statistical error and uncertainty on the misID background

- Present status:
  - MC/data ratio improved dramatically
  - Improvements in low-momentum PID will dramatically decrease contamination from $h \rightarrow \mu$ misID
  - $R(J/\psi)$ analysis has led to better techniques to construct misID shapes

- ALSO: more signal data = more control data!
  - Form factors and shape corrections for backgrounds can be more precisely determined
  - Signal/normalization form factors will also be fitted more precisely
\[ R(D^0) \text{ vs } R(D^{*+}) \text{ with } D^0 \rightarrow K^-\pi^+ \text{ and } \tau \rightarrow \mu\bar{\nu}\nu \]

\[
\begin{align*}
\frac{B^- \rightarrow D^{*0}[\rightarrow D^0(\pi^0/\gamma)]\mu\bar{\nu}}{B^- \rightarrow D^0\mu\bar{\nu}} &\approx 2.5 \\
\frac{B^0 \rightarrow D^{*+}[\rightarrow D^0\pi^{missing}]\mu\bar{\nu}}{B^- \rightarrow D^0\mu\bar{\nu}} &\approx 0.75 \\
\frac{B^0_s \rightarrow D_s^{*+}[\rightarrow D^0K^{+missing}]\mu\bar{\nu}}{B^- \rightarrow D^0\mu\bar{\nu}} &\approx 0.06
\end{align*}
\]

- Muonic $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}$ served as a prototype due to simpler measurement structure, better handles on certain backgrounds.

- $B^- \rightarrow D^0\tau^-\bar{\nu}$ perfectly possible at LHCb
  - Strategy: simultaneous fit to disjoint $D^0\mu^-$ and $D^{*+}\mu^-$ samples
    - Feed-down from $D^*$ always present in $D^0\mu^-$ sample $\rightarrow$ correlation in $R(D)$ vs $R(D^*)$.
    - Simultaneously refitting $D^{*+}\mu^-$ sample helps control this
    - $D^0\mu^-$ sample is 5x larger than $D^{*+}\mu^-$
      - 75% is $D^*$ feed down $\rightarrow$ expect large reduction of statistical error
        - Additional data has more BG, so improvements will be more modest than simple $\sqrt{N_{D^*\tau\nu}}$, but still quite substantial
    - Challenge: template fit to such a huge dataset requires very careful evaluation and elimination of data/simulation differences everywhere possible
$R(D^+) \text{ vs } R(D^{*+})$

- Frontline Run2 analysis on $R(D^{(*)})$ from LHCb
  - Why not Run1? No trigger!
    - Run1 analysis piggybacked on loose $D^0 \to K^-\pi^+$ charm trigger
    - Other (three+ body) Run1 exclusive charm triggers all cut tightly to remove charm from beauty
  - For Run2:
    - Dedicated trigger optimized around original $R(D^*)$ selection for $D^+ \to K^-\pi^+\pi^+$ and others ($D^0, D_s^+, \Lambda_c^+$)
      - Tests on $D^0 \to K^-\pi^+$ version showed 60% improvement in signal efficiency compared Run1 trigger strategy

- Other improvements being explored

- Result is expected to be of similar or better precision as existing measurements
R(D*) measurement using $\tau \rightarrow 3\pi \nu$ decays

- Hadronic $\tau \rightarrow 3\pi \nu$ and $\tau \rightarrow 3\pi\pi^0\nu$ decays used to reconstruct the $\tau$ lepton.

$$K(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-}\tau\nu)}{\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+)}$$

- Signal and normalisation decays share the same visible final state.
- Most of the systematic uncertainties cancel in the ratio.
- $R(D^*)$ is then obtained using external inputs:

$$R(D^*) = K(D^*) \times \frac{\mathcal{B}(B^0 \rightarrow D^*\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \rightarrow D^*\mu\nu)}$$
The $B \to D^*3\pi X$ background: detached-vertex method

- **Most abundant background** (~100 times signal) due to ("prompt") $B \to D^*3\pi X$, where the $3\pi$ comes from the B vertex.

- Suppressed (3 orders of magnitude) by requiring minimum **distance between B and $\tau$ vertices** ($>4\sigma_{\Delta z}$), thanks to the excellent vertex resolution (VELO).

- ~35% efficient on signal.

- Only possible due to the excellent LHCb vertex detector (VELO) resolution.
FIT RESULTS

- **3D fit to** $q^2$, $t_\tau$ and BDT output.

- Fit components described by templates obtained from simulation (validated in control samples):
  - $q^2$ (8 bins).
  - $t_\tau$ (8 bins): important to separate $D^+$ component (large lifetime).
  - BDT output (4 bins).

- $N_{\text{sig}} = 1273 \pm 85$ (6.5% stat. uncertainty)

- $K(D^*) = 1.93 \pm 0.12$ (stat) $\pm 0.17$ (syst)

- $R(D^*) = 0.286 \pm 0.019 \pm 0.033$ (1$\sigma$ compatible with SM)
Prospects for hadronic analysis

- Including LHC run-2 data, expected improvement in precision (both statistical and systematic) of a factor of 2 for $R(D^*)$.

- Important to reduce external uncertainties, i.e. precision in $BF(B^0 \rightarrow D^*3\pi)$. Belle data could help on this. Other normalisation channel possible, i.e.: $B^0 \rightarrow D^* - D_s^+ (D_s^+ \rightarrow 3\pi)$, but branching fractions measurements are not precise enough ($> 10\%$).

- Systematic uncertainty due to knowledge of double-charmed decays $B \rightarrow D^*DX$, could be reduced with input from BES on inclusive $D \rightarrow 3\pi X$ decays.

- Next step is to study the $q^2$ shape and angular distributions ($D^*$ polarisation …).

- The method can be used to perform measurements in other semitauonic B decays: $R(D^0)$, $R(D^+)$, $R(\Lambda_c^{(*)})$, $R(D_s^+)$, $R(p\bar{p})$, $R(J/\Psi)$ …

- Some of these measurements only possible at LHCb ($B_{c^+}$, $\Lambda_b$).
New avenues

3D template fit: $B_c$ decay-time, $m_{\text{miss}}^2$, $Z$

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$$

- Compatible with SM at 2 $\sigma$.
- First evidence of decay $B^+ \rightarrow J/\psi \tau^+ \nu_\tau$.
- Largest systematics from $B_c \rightarrow J/\psi$ form-factor and limited simulation sample size - both can be improved.

- Lattice form-factor calculation is on the way - see Andrew Lytle.
And upcoming avenues

- Same strategy as $R(D^*)$, the goal is to measure:

$$R(\Lambda_c) = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^- \mu^- \nu_\mu)}$$

- Precise prediction from LQCD: $R_{SM}(\Lambda_c) = 0.3328 \pm 0.0074^{\text{stat}} \pm 0.0070^{\text{syst}}$ [1]

- Probing LFU with a baryon with a different spin structure

- Use of $\Lambda_b \rightarrow \Lambda_c 3\pi$ as normalization channel

- Measurement of $R(\Lambda_c)$ on both Run1 and Run2 datasets with an error estimation of:
  - 4\% for $\varepsilon_{\text{stat}}$
  - 6-10\% for $\varepsilon_{\text{syst}}$
  - 7\% of uncertainty due to normalization

[1]: [W. Detmold, C. Lehner, S. Meinel, PRD 92, 054503 (2015)]
And upcoming avenues

\[ \Lambda_b \rightarrow \Lambda_c^* \tau \nu_\tau \] – Explore the spin structure of the possible new physics.

- Large baryon yield at LHCb - precision possible.
- Little feed-down from higher states.
- \[ \Lambda_c^* \rightarrow \Lambda_c \pi^+ \pi^- \] gives an extra reconstructable vertex.
- Needs theory input - work ongoing to measure FF at LHCb.

- Ultimately might like \[ R(\Lambda_c) v R(\Lambda_c^*) \]
Lots of work done and still to be done with $B$-factory data

- Experiments at $e^+e^-$ B Factories have played and will continue to play an important role in the study of leptonic and semileptonic $B$ decays, though low production cross sections place a high demand on luminosity - Belle II

- $Y(4s) \to B\bar{B}$ decays, unique advantages to measure $R_D$ and $R_{D^*}$
  - Hadronic tags combined with purely leptonic $\tau$ decays offer kinematic constraints for events with $3\nu$
  - The high degree of cancellation of experimental and theoretical uncertainties lead to reduced uncertainties
  - $D_{\tau\nu}$ have higher sensitivity to spin-0 couplings - Combined $D_{\tau\nu}$ and $D^{*\tau\nu}$ analyses gain information
  - Kinematic information, i.e. $q^2$, momenta and angles of $D^{(*)}$ and $\tau$, should provide information about non-SM contribution.

- Still, the analyses are very complex, and further scrutiny is advised!

- 2-body $\tau$ decays, $\tau \to \pi\nu$, $\rho\nu$, $a_1\nu$, carry information on the transverse helicity of the $\tau$, as demonstrated by Belle recently, should be further pursued

- s.l. tags are simpler, however, they compromise kinematic event information, challenging separation of signal and BG.
Study of $\tau$ polarisation at Belle

First observation of the $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ signal using only hadronic $\tau$ decays

$R(D^*) = 0.270 \pm 0.035\, \text{(stat.)}^{+0.028}_{-0.025}\, \text{(syst.)}$

$P_T(D^*) = -0.38 \pm 0.51\, \text{(stat.)}^{+0.21}_{-0.16}\, \text{(syst.)}$
And the game will soon become even more interesting!

Goal of Belle II/SuperKEKB

R(D), R(D*)
Milestone 5-10 ab⁻¹

Tiny beamspot: σx = 6 μm, σy = 0.06 μm, σz = 150 μm
(Good for tagging, D* and τ→πππ ν separation)
Belle II outlook

- Detector performance and algorithm improvements will allow for (conservatively):
  - Tag{Had, SL, Inclusive} x Signal {τ → l ν ν, τ → h ν} ~ 6 statistically independent approaches.
  - $B \rightarrow D^* \tau \nu$: 5 ab$^{-1}$ ~ 3% (down from about 8%)
  - $B \rightarrow D \tau \nu$: 5 ab$^{-1}$ ~ 6% (down from 16%) - though Belle yet to release R(D) with SL tag.
  - Improvements towards 50 ab$^{-1}$ heavily reliant on $B \rightarrow D^{**} l \nu$ and hadronic B decay improvements.
  - $B \rightarrow D^{**} \tau \nu$ will need to be studied to reduce bias on these channels.

- *Belle II working to mitigate beam background impact.*
Further inputs needed to the global endeavour

- It will not be possible to benefit from the tantalizing statistical precision of upcoming round of semitauonic measurements (LHCb, BELLE-II) without dedicated efforts on complementary measurements

- Hottest topics on the list:
  - Two- and Three-body Double charm events
  - Inclusive $D_s$ and $D^+$ decays to 3 pions

- $D_s \to \pi \pi \pi X$ inclusive branching fraction and its $3\pi$ resonant structure important inputs for the LHCb $B \to D^*\tau\nu$ analysis

- Based on recently collected 3fb$^{-1}$ $D_s^*D_s$ data, BESIII is able to provide unique information on $D_s \to \pi \pi \pi X$ inclusive mode

- The whole BESIII analysis could be pursued within a reasonable time scale of about one year
Theory debates
Our result with LCSR and strong unitarity bounds:

\[ R_{\tau,1}(D^*) = 0.232 \quad R_{\tau,2}(D^*) = 0.026, \]
\[ R(D^*) = 0.258(5)(^{+8}_{-7}) = 0.258^{+10}_{-9}. \]
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Even two!
HFLAV Hamletic doubts

And what should we do with the HFLAV plot then?
Experimental debates

Are we sure that we control D** background well enough and that there is not something common to all experiments we forgot about driving us to a wrong conclusion?
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Are we sure that we control D** background well enough and that there is not something common to all experiments we forgot about driving us to a wrong conclusion?

D** background is less important at LHCb and it’s very difficult to imagine what kind of systematics can be in common between B factories and LHCb data that we may have overlooked.
My personal view

- Let’s maintain an agnostic point of view, we have not discovered anything yet!
  - Need more work to keep theory under full control, as this may become more and more important in the forthcoming future, and urgent to develop predictions for further observables
  - Need more statistics and improvements in experimental results, as that will help to be more confident on whether systematic uncertainties are fully under control, and need to measure new observables and depict a coherent picture
R(X), live long and prosper!

Construction of command deck initiated by Guy in 1958