LHCb Measurements on Semileptonic
Decays of b-hadrons

Anna Lupato

on behalf of the LHCb Collaboration

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Charged current transitions

- Tree level quark transition with $W$ emission

**Advantages:**
- The contributes to decay rate can be factorized in weak and strong part
  \[ \frac{d \Gamma(B \to Xl \nu)}{dq^2} \propto G_F^2 |V_{bq}|^2 f(q^2)^2 \]
- The theoretical calculation can be simplified
  - Factorize long (form factors) and short (Wilson Coefficients) distance effects

**Challenges:**
- Missing neutrinos → lower resolutions
- Large partially reconstructed backgrounds
- Large and perfectly calibrated simulation samples needed for modeling signal and backgrounds
LHCb was originally designed for CP violation and rare beauty & charm decays.

But now it is a general purpose detector: *exotic spectroscopy, EW precision physics, heavy ions, fixed target program*...

LHCb is a spectrometer in the forward direction (2<\(\eta\)<5)

Excellent vertexing, tracking and particle identification

Low trigger threshold on hadrons, muons and photons

Production of all types of \(b\) and \(c\) hadrons

Run 1: 3 fb\(^{-1}\) @ \(\sqrt{s} = 7-8\) TeV

Run 2: 6 fb\(^{-1}\) @ \(\sqrt{s} = 13\) TeV
Recent LHCb semileptonic results

- Measurement of the ratios of branching fractions $R(D^*)$ and $R(D^0)$

- Test of Lepton flavour universality using $B^0 \rightarrow D^*\tau^+\nu$ decay with hadronic $\tau$ channels
  [Phys. Rev. D108 (2023) 012018]

- Observation of the decay $\Lambda^0_b \rightarrow \Lambda_c^+ \tau^-\bar{\nu}$

- Measurement of $D^*$ longitudinal polarization in $B^0 \rightarrow D^*\tau^+\nu$ decays
  [arXiv:2311.05224 – Submitted to PRD]

- First observation of the decay $B_s^0 \rightarrow K\mu^+\nu$ and a measurement of $|V_{ub}|/|V_{cb}|$
  [Phys. Rev. Lett. 126 081804]

- Measurement of $|V_{cb}|$ with $B_s^0 \rightarrow D_s^*\mu^+\nu$ decays
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Longitudinal D* polarization: beyond the LFU

- Lepton Flavour Universality tests using charged current decays of D and D* show a tension from the Standard Model of 3.2σ

- New physics can strongly affect the D* longitudinal polarization $F_L^{D*}$ also if LFU ratios align with the SM prediction [arXiv:1907.02257]

- Measured by Belle: $0.60 \pm 0.08 \pm 0.04$ [arXiv:1903.03102]

- The differential decays rate of $D^* \to D^0 \pi$ can be expressed as

$$\frac{d^2\Gamma}{dq^2d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2) \cos^2\theta_D.$$  

- $F_L^{D*}$ can be calculated as

$$F_L^{D*} = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$  

where

- $a_\theta$ and $c_\theta$ are linear combinations of the angular coefficients

$$a_{\theta_D}(q^2) = N^{unpol} \cdot \mathcal{P}D\mathcal{F}_{unpol}|_{\cos \theta_D=0},$$

$$c_{\theta_D}(q^2) = \frac{3}{2} N^{pol} \Delta_{bin}$$
Longitudinal $D^*$ polarization: signal selection

- **Dataset:** Run1 (3 fb$^{-1}$) and Run2 (2 fb$^{-1}$)

- **$B^0 \rightarrow D^* \tau^+ \nu$, $\tau^+ \rightarrow 3\pi^\pm(\pi^0)\nu**
  - good tau vertex reconstruction
  - large hadronic background

- **Most dominant: $B \rightarrow D^* 3\pi X$ (BF $\sim$ 100x signal)**
  - Suppressed by requiring the $\tau$ vertex to be downstream wrt B vertex along beam direction with a 4$\sigma$ significance
  - additional BDT in Run2 to reach Run1 (rejection $>99.9\%$)

- **$B \rightarrow D^* D^{+,0}_{(s)} X$ (BF $\sim$ 10x signal)**
  - Similar topology to that of signal but detached vertex due to non-negligible lifetime
  - Suppressed by rejecting candidates with extra charged tracks from $B/\tau$ vertex
  - rejected through isolation algorithm and BDT classifier, whose output used in template fit

[arXiv:2311.05224]
Longitudinal $D^*$ polarization: template fit

- $F_L^{D*}$ determined in two $q^2$ regions:
  - $q^2 > 7\text{GeV}^2/c^4$
  - $q^2 < 7\text{GeV}^2/c^4$

- $F_L^{D*}$ is extracted from $a_\theta$ and $c_\theta$ determined by splitting the simulated signal sample in
  - $N_{\text{unpolarized}} \propto a_\theta$
  - $N_{\text{polarized}} \propto c_\theta$

- 4D template fit:
  - $\tau$ lifetime
  - $q^2$
  - $\cos \theta_D$
  - Anti-$D_s$ BDT output

- Simulated $\cos \theta_D$ signal distribution corrected for reconstruction effect

- $\cos \theta_D$ distribution corrected through fully reconstructed control samples:
  - $D_s \rightarrow 3\pi^\pm$, $D^+ \rightarrow K^- 2\pi^+$, $D^0 \rightarrow K^- 3\pi^+$

- simultaneous fit to Run1 and Run2

- Dominant sources of systematic uncertainties:
  - limited size of simulations samples
  - form factors parametrization

[arXiv:2311.05224]
Longitudinal D* polarization: template fit

- Two different control samples are used to validate the D$_s^+$ backgrounds due to the poor knowledge of the BF and the relative fractions:
  - $D_s^+ \rightarrow 3\pi X$ to correct the BF relevant to $D_s^+$ meson production
  - $B \rightarrow D^{*-} D_s^+$ ($X$) decays to constrain the relative components in the final fit

- Results integrated over run1 and run2

\[
q^2 < 7 \text{ GeV}^2/c^4 : \quad 0.51 \pm 0.07 \text{ (stat)} \pm 0.03 \text{ (syst)},
\]
\[
q^2 > 7 \text{ GeV}^2/c^4 : \quad 0.35 \pm 0.08 \text{ (stat)} \pm 0.02 \text{ (syst)},
\]
\[
q^2 \text{ whole range} : \quad 0.43 \pm 0.06 \text{ (stat)} \pm 0.03 \text{ (syst)}.
\]

- All results are found compatible with the SM within 1$\sigma$

- Plan is to update the $F_L^{D*}$ value in parallel with the $R(D^*)$ measurement in hadronic $\tau$ channel.
• Measurement of the ratios of branching fractions $R(D^*)$ and $R(D^0)$ [Phys.Rev.Lett. 131 (2023) 111802]

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• Observation of the decay $\Lambda^0_b \to \Lambda_c^+ \tau \bar{\nu}$ [Phys. Rev. Lett. 128 (2022) 191803]

• Measurement of $D^*$ longitudinal polarization in $B^0 \to D^* \tau^+ \nu$ decays [arXiv:2311.05224 – Submitted to PRD]

• First observation of the decay $B^0_s \to K \mu^+ \nu$ and a measurement of $|V_{ub}|/|V_{cb}|$ [Phys. Rev. Lett. 126 081804]

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Measurement of $|V_{xb}|$

- The parameters of the CKM matrix must be constrained in order to:
  - test the unitarity of the CKM matrix
  - precisely measure the amount of CP violation in the quark sector
  → measurement of observables sensitive to the magnitudes of CKM matrix elements

- Measurements of $|V_{xb}|$ provide a crucial input for indirect searches of New Physics

- Discrepancy between exclusive and inclusive measurements: $\approx 3\sigma$ tension
  → new complementary measurements
Measurement of $|V_{xb}|$

- Two main ways to measure $|V_{ub}|$ and $|V_{cb}|$:
  - **Inclusive decays:**
    - $B^+ \to X_c l\nu, B^0 \to X_u l\nu$
    - Focus on all final states
    - Need to know QCD correction to parton level decay rate
  - **Exclusive decays:**
    - Focus on a single final state
    - Exclusive determinations rely on form factors (FF) to parameterize hadronic current as function of $q^2$ ($\mu\nu$ invariant mass): LQCD or QCD sum rules
    - Extracted in experimental measurement from data

- **Ground state hadrons** in the final are the golden modes for lattice QCD predictions and have the lowest theoretical uncertainties.

- $B_s$ decays are advantageous compared to $B^0/+$
  - Easier to calculate in LQCD due to heavier spectator quark → more precise predictions
Measurement of $|V_{ub}/V_{cb}|$

- The strategy:
  - **Dataset:** 2012, 2 fb$^{-1}$ @ 8 TeV
  - **Signal:** $B_s^0 \to K\mu^+\nu$
  - **Normalization:** $B_s^0 \to D_s\mu^+\nu$ where $D_s \to K^+K\pi^-$
  - **CKM extraction strategy:**
    \[
    \frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu_\mu)} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \frac{\text{FF}_K}{\text{FF}_{D_s,\text{Theory}}}
    \]

- The $|V_{ub}|/|V_{cb}|$ ratio is derived in two regions of $q^2$ ($\mu\nu$ invariant mass) to exploit different FF$_K$ calculation method:
  - Light cone sum rules (LCSR) @ low $q^2$ ($q^2 < 7 \text{ GeV}^2/c^4$)
  - LQCD @ high $q^2$ ($q^2 > 7 \text{ GeV}^2/c^4$)

Normalization mode FF$_{D_s}$ fully described by LQCD [Phys Rev D. 101 074513]
The $\text{FF}_K$

- Calculations from QCD light-cone sum rules are most precise at large recoil (low $q^2$)
  [JHEP 08 (2017) 112]

- Lattice QCD predictions provide a precise determination of the form factors at low recoil transfer (high $q^2$)
The backgrounds

- $B_s^0 \rightarrow K \mu^+ \nu$
  - main background originates from $H_b \rightarrow H_c(\rightarrow K X) \mu^+ X'$ (unreconstructed particles)
  - $B_s^0 \rightarrow K^* \rightarrow K \pi^0 \mu^+ \nu$
  - $B_s^0 \rightarrow [cc] \rightarrow \mu^+ \mu^- K X$

- $B_s^0 \rightarrow D_s \mu^+ \nu$
  - $B_s^0 \rightarrow D_s^* \rightarrow D_s \mu^+ \nu$
  - $B_s^0 \rightarrow D_s^{**} \mu^+ \nu$, $B_{u,s,d} \rightarrow D_s DX$ and $B_s^0 \rightarrow D_s^* \tau^+ \nu$

- To suppress background
  - the candidates are required to be isolated from the other tracks in the event
  - BDT classifiers exploit the kinematics of the decays

- The $B_s^0$ momentum can be calculated with a two fold ambiguity → regression model that exploit the $B_s$ flight information [JHEP 02 (2017) 021]
  - Ambiguity solved by selection the solution most consistent with the regression value
  - $\epsilon \approx 70\%$
Signal and normalization fits

- The measured ratio is

\[ R_{BF} \equiv \frac{\mathcal{B}(B_s^0 \rightarrow K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \rightarrow D^- \mu^+ \nu_\mu)} = \frac{N_K e_{D_s}}{N_{D_s} e_K} \times \frac{\mathcal{B}(D_s^- \rightarrow K^+ K^- \pi^-)}{[\text{Phys. Rev. Lett. 126 081804}]} \]

- A binned maximum likelihood fit to the $B_s$ corrected mass

\[ m_{\text{corr}} = \sqrt{m^2(Y \mu) + p_{\perp}^2(Y \mu) + p_{\perp}(Y \mu)}, \quad Y = K^-, D_s^- \]

- If only missing particle is a neutrino the corrected mass distribution will peak at the $B_s$ mass

- Resolution improved by rejecting events with a large corrected mass uncertainty (>100 MeV/c²)
Signal and normalization fits

\[ B_s^0 \rightarrow K^- \mu^+ \nu_\mu \] low \( q^2 \)

\[ B_s^0 \rightarrow K^- \mu^+ \nu_\mu \] high \( q^2 \)

- The largest systematic uncertainty is from the fit templates
- First observation of the decay \( B_s^0 \rightarrow K \mu^+ \nu \)

[Phys. Rev. Lett. 126 081804]
Extraction of $|V_{ub}|/|V_{cb}|$

- The obtained values are

$$\frac{B(B_s^0 \rightarrow K^- \mu^+ \nu_\mu)}{B(B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu)} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \frac{\text{FF}_{K}}{\text{FF}_{D_s}}$$

- $q^2 > 7 \text{ GeV}^2/c^4$:
  \[ \frac{B(B_s^0 \rightarrow K^- \mu^+ \nu_\mu)}{B(B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu)} = 1.66 \pm 0.08(\text{stat}) \pm 0.07(\text{syst}) \pm 0.05(D_s) \times 10^{-3} \]

- $q^2 < 7 \text{ GeV}^2/c^4$:
  \[ \frac{B(B_s^0 \rightarrow K^- \mu^+ \nu_\mu)}{B(B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu)} = 3.25 \pm 0.21(\text{stat}) \pm 0.16(\text{syst}) \pm 0.09(D_s) \times 10^{-3} \]

\[ |V_{ub}|/|V_{cb}|_{(low)} = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008(D_s) \pm 0.0030(\text{FF}) \]

\[ |V_{ub}|/|V_{cb}|_{(high)} = 0.0946 \pm 0.0030(\text{stat}) \pm 0.0024(\text{syst}) \pm 0.0013(D_s) \pm 0.0068(\text{FF}) \]

Discrepancy related to the difference in the theoretical calculations of the form factors.
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  [Phys. Rev. D 101 072004]
$|V_{cb}|: \text{ with } B_s^0 \rightarrow D_s^{(*)}\mu^+\nu \text{ decays}$

[Phys. Rev. D 101 072004]

- Signal: $B_s^0 \rightarrow D_s^{(*)}\mu^+\nu$ where $D_s \rightarrow \varphi(\rightarrow K^+K^-)\pi$, $\gamma$ or $\pi^0$ not reconstructed

- Normalization: $B^0 \rightarrow D^{(*)}\mu^+\nu$

- Both channels reconstructed in the same final states

- Extract $|V_{cb}|$ from

$$\mathcal{R}^* \equiv \frac{\mathcal{B}(B_s^0 \rightarrow D_s^{*-}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \rightarrow D_s^{*-}\mu^+\nu_\mu)} \quad \mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \rightarrow D_s^{-}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \rightarrow D^{-}\mu^+\nu_\mu)}$$

- external input:
  - hadronization fractions $f_s/f_d$ [PRD(2019)031102]
  - branching fractions [PDG]
$|V_{cb}|$: with $B_s^0 \to D_s^{*-} \mu^+ \nu$ decays

[Phys. Rev. D 101 072004]

- Due to the undetected neutrino we cannot determine precisely the $q^2$ use variable $p_{\perp}(D_s)$ with respect to B flight distance:
  - high correlated with hadron recoil $w$
  - fully recostructible

- \[
  \frac{d^4\Gamma(B \to D^{*} \mu \nu)}{dw \, d\cos{\theta_{\mu}} \, d\cos{\theta_{D}} \, d\chi} = \frac{3m_B^3 m_{D^*}^2 G_F^2}{16(4\pi)^4} \eta_{EW}^2 |V_{cb}|^2 |A(w, \theta_{\mu}, \theta_{D}, \chi)|^2
\]

- \[
  w = v_B \cdot v_{D^*} = \left( m_B^2 + m_{D^*}^2 - q^2 \right) / (2m_B m_{D^*})
\]

- 2-D template fit to $M_{\text{corr}}$ and $p_{\perp}(D_s)$ identify the signal yields and provides a simultaneous measurement of the ratios $R^{(*)}$ and the form factors
$|V_{cb}|$: with $B_s^0 \rightarrow D_s^{*}\mu^+\nu$ decays

[Phys. Rev. D 101 072004]

- FF Parametrizations used:
  - CLN and BGL

- The results are

  \[
  |V_{cb}|_{CLN} = (41.1 \pm 0.6(stat) \pm 0.9(syst) \pm 1.2(ext)) \times 10^{-3} \\
  |V_{cb}|_{BGL} = (42.3 \pm 0.8(stat) \pm 0.9(syst) \pm 1.2(ext)) \times 10^{-3}
  \]

- First measurement of $|V_{cb}|$ using $B_s$ and in a hadronic environment

- Compatible with world average for both inclusive and exclusive determinations

- Confirms trend that parametrisation is not responsible for inclusive vs exclusive disagreements

- New $f_s/f_d \rightarrow V_{cb}$ [arXiv:2103.06810]

  \[
  |V_{cb}|_{CLN} = (40.8 \pm 0.6(stat) \pm 0.9(syst) \pm 1.1(ext)) \times 10^{-3} \\
  |V_{cb}|_{BGL} = (41.7 \pm 0.8(stat) \pm 0.9(syst) \pm 1.1(ext)) \times 10^{-3}
  \]
Conclusion

• Broad SL physics program at LHCb

• Successful Run1 and Run2: $3+6 \text{ fb}^{-1}$, still many analysis ongoing

• Upgrade Phase I:
  • 10 times more data (20 times more hadronic events)
  • Complementarity with Belle
  • Synergy between LHCb, ATLAS and CMS on some important channels

• Strong program beyond flavour exploiting unique acceptance