CKM metrology and B decays
adding a strange flavour to the $|V_{cb}|$ puzzle

Mirco Dorigo (INFN Trieste)
for the LHCb Collaboration

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CKM metrology

Status

• Pletora of measurements confirm CKM paradigm at high precision.

• B decays
  - Angles from CPV measurements, getting more and more precise.
  - Oscillations constrain $|V_{td}|$&$|V_{ts}|$. Limited by theory uncertainties.
  - $|V_{cb}|$&$|V_{ub}|$ (mainly) from B-factories, long standing puzzle.
The puzzle
Inclusive vs Exclusive

- LHCb entered the game with measurement of $|V_{ub}|/|V_{cb}|$ [Nature Physics 11 (2015) 743].

- $\Lambda_b$ decays, different source of systematics uncertainties. Bring independent information.

- $B_s$ sector promising too, for both $|V_{ub}|$ ($B_s \rightarrow K(*)\mu\nu$) and $|V_{cb}|$ ($B_s \rightarrow D_s(*)\mu\nu$)
Adding strangeness to the $|V_{cb}|$ puzzle

- LHCb potential triggered interesting theoretical work on $B_s$ decays (eg. see talk by N. Gubernari)
- Promising lattice QCD calculations, expect very good precision for $B_s$ form factors to extract $|V_{cb}|$
  - calculation on the full $q^2$ spectrum already available for $B_s \rightarrow D_s \mu \nu$ decays [PRD 101 (2020) 074513]
  - For $B_s \rightarrow D_s^{(*)} \mu \nu$ good precision at zero-recoil [PRD 99 (2019) 114512] Awaiting full spectrum calculation.
Bs@LHCb

- 6 years of 7-8-13 TeV pp collisions at 40 MHz (9 fb$^{-1}$).
- About $10^{10}$ B$_s$/fb$^{-1}$ produced @LHCb vs $10^5$ B$_s$/fb$^{-1}$ @Belle Y(5S).
- O($10^3/s$) B$_s$ reconstructible and interesting for physics.
- Store online 40-80% of them using muons, $p_T$ and displacement.
- Talking about several hundred thousands of B$_s$ decays on tape.
- Large potential for a $|V_{cb}|$ measurement with $B_s \rightarrow D_s^{(*)}\mu\nu$ decays.
Challenges

Know the number of $B_s$ produced

- $pp \rightarrow bbX$ cross section known with $O(10\text{-}15\%)$ precision [PRL 118 (2017) 052002, PRL 119 (2017) 169901]. Limit possible precision on $|V_{cb}|$ to $O(5\text{-}8\%)$.

- Use instead a normalisation channel: $B^0 \rightarrow D(*)\mu\nu$ reconstructed in the same dataset and final state $[KK\pi]\mu$.

- $B_s$-to-$B^0$ relative production ($f_s/f_d$) known at 5% [PRD 100 (2019) 031102]. Dominant uncertainty on $|V_{cb}|$ at 2.5%.
Challenges

Discriminate signal and background

- Unreconstructed neutrino, cannot close the $B_s$ kinematic à la B-factories.
  - No clean peaks to discriminate the signal decays and the background.
  - Recover part of the missing mass.

$$m_{\text{corr}} \equiv \sqrt{m^2(D_s^-\mu^+) + p_\perp^2(D_s^-\mu^+) + p_\perp^2(D_s^-\mu^+)}$$
Challenges

B rest-frame kinematics

- $|V_{cb}|$ extracted from measurement of decay rate as a function of recoil $w$ ($D_s^*(\mu\nu)$ energy in the $B_s$ rest frame).
- Would need to approximate $w$ because of the missing neutrino.
- New approach, use $p_{\bot}(D_s^-)$. Fully reconstructed and highly correlated with $w$.
- Very good sensitivity to the form factors, which are functions of $w$. 

$B_s \to D_s^{\ast} \mu \nu$

LHCb Simulation
Fitting the differential decay rate for $|V_{cb}|$ and form factors

- Analyse inclusive sample of $D_s\mu$ final state ($D_s^*$ partially reconstructed).
- Fit as a function of $m_{\text{corr}}$ and $p_\perp$ to determine $|V_{cb}|$ and form factors.
  Use 2D templates to model data distribution including efficiency $\varepsilon(p_\perp, m_{\text{corr}})$.

\[
\frac{dN_{\text{obs}}}{dp_\perp dm_{\text{corr}}} = \mathcal{N} \frac{d\Gamma(|V_{cb}|, h_{A_1}, \ldots)}{dp_\perp dm_{\text{corr}}} \varepsilon(p_\perp, m_{\text{corr}})
\]

- Normalisation $\mathcal{N}$ contains measured $B^0$ reference yields, input branching fractions, $B_s$-to-$B^0$ production probabilities $f_s/f_d$, and $B_s$ lifetime.
BGL form factors


$$|V_{cb}| = (42.3 \pm 0.8\text{(stat)} \pm 0.9\text{(syst)} \pm 1.2\text{(ext)}) \times 10^{-3}$$

χ²/n df=276/284

p-value of 63%
Results
CLN form factors

Test also with model from Caprini, Lellouch and Neubert (CLN, NPB 530 (1998) 153). No significant difference found. Obtain

$$|V_{cb}| = (41.4 \pm 0.6 \text{(stat)} \pm 0.9 \text{(syst)} \pm 1.2 \text{(ext)}) \times 10^{-3}$$
Systematic uncertainties & BR

- Dominant: external inputs, 3% relative on $|V_{cb}|$ (mostly from $f_s/f_d$).
- 2nd largest: knowledge of $D_{(s)}\to K K \pi$ Dalitz structure, 2% relative on $|V_{cb}|$.
- 3rd largest: knowledge of background contamination, 1% relative on $|V_{cb}|$.

By product of the analysis, first measurements of relative BR:

$$\frac{\mathcal{B}(B^0_s \to D^- s \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^- \mu^+ \nu_\mu)} = 1.09 \pm 0.05 \text{ (stat)} \pm 0.06 \text{ (syst)} \pm 0.05 \text{ (ext)}$$

$$\frac{\mathcal{B}(B^0_s \to D^{*-} s \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)} = 1.06 \pm 0.05 \text{ (stat)} \pm 0.07 \text{ (syst)} \pm 0.05 \text{ (ext)}$$

$$\frac{\mathcal{B}(B^0_s \to D^- s \mu^+ \nu_\mu)}{\mathcal{B}(B^0_s \to D^{*-} s \mu^+ \nu_\mu)} = 0.464 \pm 0.013 \text{ (stat)} \pm 0.043 \text{ (syst)}$$

[PRD 101 (2020) 072004]
Supporting the form factors
Measurement of w distribution for $B_s \rightarrow D_s^* \mu \nu$ decays

• Independent data set. Fully reconstruct the $D_s^* \rightarrow D_s \gamma$ by selecting the soft photon in a cone around the $D_s$ flight direction.
Supporting the form factors
Measurement of w distribution for $B_s \to D_s^* \mu \nu$ decays

- Use a MVA based algorithm to approximate w, the energy of the $D_s^*$ in the $B_s$ rest frame [JHEP 02 (2017) 021].

- Fit the corrected mass in bins of the approximate w.

- Unfold efficiency and resolution using MC.

- Good agreement of the measured distribution w.r.t. form factors measured in the $|V_{cb}|$ analysis.
Summary

- First measurement of the shape of the $w$ distribution in $B_s \rightarrow D_s^* \mu \nu$ decays.
- First measurement of $|V_{cb}|$ at a hadron collider, using both $B_s \rightarrow D_s \mu \nu$ and $B_s \rightarrow D_s^* \mu \nu$ decays.
- In agreement with both exclusive and inclusive measurements.

$|V_{cb}|_{\text{CLN}} = (41.4 \pm 0.6 \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 1.2 \text{ (ext)}) \times 10^{-3}$

$|V_{cb}|_{\text{BGL}} = (42.3 \pm 0.8 \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 1.2 \text{ (ext)}) \times 10^{-3}$