Recent results in flavour physics

Monica Pepe Altarelli (CERN)

On behalf of (mainly) LHCb
Why (heavy quark) flavour?

• A very rich field, and a vast laboratory to test the SM

• Heavy b mass $\rightarrow$ Easier to understand theoretically ($\alpha_s(m_b) \approx 0.2$, $\Lambda_{QCD}/m_b \approx 0.1$)

• b (and c) lifetimes long enough for experimental detection ($\tau_b \approx 1.5 \times 10^{-12} \text{ s}$)

• Sizeable CP violation expected in many b decays
  - Large CPV effects expected in processes which involve quarks from all three generations

• Most TeV new physics contains new sources of CP and flavour violation

• The observed baryon asymmetry of the Universe requires CPV beyond the SM
  - Not necessarily in flavour changing processes, nor necessarily in quark sector, it could originate from lepton sector
Flavour physics as a tool of discovery

• In the SM, some rare decays are forbidden at tree level and can only occur at loop level (penguin and box), e.g. $B_s \rightarrow \mu^+ \mu^-$

- A new particle, too heavy to be produced at the LHC, can still give sizeable effects when exchanged in a loop (e.g. modify BFs, angular distributions,...)

- Strategy: use well-predicted observables to look for deviations

- Indirect approach to New Physics searches, complementary to that of ATLAS/CMS and particularly relevant at this point!
A window on NP at high scales
The LHCb collaboration

- ~1250 members from 79 institutes in 18 countries
- ~450 publications, some with very high impact
- Main focus on heavy quark flavour...but plenty of other physics in the forward direction
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**Research Areas:**
- CKM & CPV
- EW and QCD
- Spectroscopy
- Semileptonic decays
- Rare decays
- Ions and fixed target
- Exotica searches
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- CKM & CPV
- Spectroscopy
- EW and QCD
- Rare decays
- Ions and fixed target
- Semileptonic decays
- Exotica searches
- 2018: the best year!
- Record in delivered and recorded Luminosity
- Legacy Run 2 analyses: i.e. Run 1 (3/fb) + (2x2/fb)\textsuperscript{2015/16} + (2x1.8/fb)\textsuperscript{2017} + (2x2.2/fb)\textsuperscript{2018} \rightarrow 
total equivalent to \sim 5x Run 1 dataset
Luminosity @ LHCb

- Experiment designed to run at constant luminosity throughout fills
  - $4 \times 10^{32}$ cm$^{-2}$ sec$^{-1}$ (to be raised to $2 \times 10^{33}$ cm$^{-2}$ sec$^{-1}$ in Run 3)
  - mean number of interactions/bunch crossing ~1
  - (Typical '18 peak Lumi for ATLAS/CMS $\sim 2 \times 10^{34}$ cm$^{-2}$ sec$^{-1}$, with ~37 interactions/bunch crossing, $\sim 150$/fb in Run 2)
LHCb detector: the essentials

- Forward acceptance
- Efficient trigger for hadronic and leptonic modes
- Acceptance down to low $p_T$
- Precision tracking and vertexing (VELO@8 mm from beam)
- Excellent PID
The LHCb trigger

- Fully optimised for flavour physics
- At first stage (L0) a hardware trigger fires on single hadrons, leptons and photons
- High Level Trigger (HLT): software application designed to reduce event rate from 1 M to ~10 k events/s, executed on a large computing cluster. Flexible design that can adapt to changing machine conditions and evolving physics programme
- Split HLT in two steps: buffer events to disk after HLT1 to perform online calibration & alignment
- HLT2 uses offline-quality calibration → more discriminant trigger
- Offline-quality reconstruction up-front
2018: last year of LHCb as we know it!

- LHCb is building its Upgrade I to be installed during LS2 (2019-20)
  - Higher Lumi: $4 \times 10^{32} \rightarrow 2 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$
  - more interactions per beam crossing: $\sim 1 \rightarrow \sim 5$
- Possible LHCb detector consolidation and modest enhancements in LS3 (2025) - ATLAS/CMS Phase II upgrades also in LS3
- Major LHCb Upgrade II in LS4 (2030) $\rightarrow$ Factor $\sim 10$ increase in $\mathcal{L}: \sim 1.5 \times 10^{34} /\text{cm}^2 /\text{s}$
Luminosity evolution

• Expression of Interest for LHCb Upgrade II (CERN-LHCC-2017-003) and physics case (CERN/LHCC 2018-027) submitted to LHCC
Luminosity evolution

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Belle II/SuperKEKB

Belle & BaBar: $\sim 1.1 \text{ ab}^{-1}$

Goal of Belle II/SuperKEKB

Run 3

arXiv:1808.10567
Some modes better suited for Belle-2, e.g. inclusive measurements, modes with several neutrals.

Others unique to LHCb, e.g. $B_s$, $B_c$, b-baryons, very rare modes.
The upgraded detector

- Less than 10% of all channels will be kept!
- NEW RO electronics
- NEW DAQ & data centre

40 MHz Readout
Software trigger only

Tracker scintillating fibres
Upstream Tracker (UT)
VELO pixels (5.1 mm from beam)

Calorimetry and muons: replace RO electronics & remove redundant components
RICH new photodetectors
The **NEW** detector

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RICH new photodetectors
Dismantling and installation already started! Tight timescale!

- VELO sensor tiles
- Testing device
- VELO module
- SciFI module
- SciFI Readout
- CALO electronics
- UT sensor
- UT staves construction
- Test of MUON electronics
- RICH MaPMTs under test
- PCIe40 boards
Approval in 1998 was non-trivial

- Some of the things said were
  - B factory experiments would do everything. If not, Tevatron experiments would do the rest. Thus, nothing important would be left.
  - General purpose LHC experiments can do the same physics as well
  - Steal precious LHC luminosity from the general purpose experiments
  - Resources are already limited
  - etc…

- But, finally we got it!
CPV in beauty and charm
CKM Matrix and $\gamma$

- The CKM matrix $V_{\text{CKM}}$ describes the decay of one quark to another by the emission of a $W$

$$
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
$$

- The probability of the transition from flavour $i$ to flavour $j$ is $\sim |V_{ij}|^2$
- Probability of $b$ to $c$ decay $\sim |V_{cb}|^2$

- $V_{\text{CKM}}$ depends on 3 mixing angles and 1 phase, which is the only source of CP violation in SM
- Phase only present with $N \geq 3$ generations (Nobel prize 2008)
  - With $N=2$, all phases can be removed $\rightarrow$ matrix real $\rightarrow$ no CPV
- These 4 parameters (3 angles, 1 phase) must be determined experimentally
- $V_{\text{CKM}}$ unitary: unitarity constraints can be seen as sum of three complex numbers closing a triangle in complex plane

$$\sum_{j} V_{ij} V_{jk}^* = 0 \text{ for } j \neq k$$

- Check consistency of Unitary Triangles through precise measurements
Measuring $\gamma$

- $\gamma$ easily accessible from tree-level processes
  - theoretically very clean $\delta\gamma/\gamma_{\text{th}} \sim \mathcal{O}(10^{-7})$
  - yields results unpolluted by NP
  - “SM Standard Candle”

- Golden mode $B^- \to DK^-$
  - Sensitivity from interference of $b \to c$ and $b \to u$ amplitudes through final states accessible to both $D^0$ and $ar{D}^0$
  - Many different methods and decay modes ($K\pi, K3\pi, KK, K_s^0\pi\pi, \ldots$)

- Uncertainty on world average $\sim 5^\circ$, driven by LHCb
- Consistent with indirect precision but.. not as precise

Derived from combination of observables in many $B \to DK$ decay channels
Measuring $\gamma$ in $B \rightarrow DK$ decays with 

$$D \rightarrow K^0_{s} \pi^+ \pi^-, K^0_{s} K^+ K^-$$

- D reconstructed using the three-body, self-conjugate final state
- Sensitivity to $\gamma$ by comparing Dalitz plot distributions for $B^+$ and $B^-$
- Input on strong phase difference between $D^0, \overline{D}^0$ decay amplitudes across Dalitz plot taken from quantum correlation of $D^0 \overline{D}^0$ pairs from $\psi(3770)$ decays $\rightarrow$ model independent measurement
- Analysis of $\sim 4500$ decays from 2 fb$^{-1}$ in Run 2

Binning chosen to maximize $\gamma$ sensitivity
Measuring $\gamma$ in $B \rightarrow DK$ decays with

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Assuming no CPV

$B^+ - B^-$ yields

[CLEO, PRD 82 (2010) 112006]
Measuring $\gamma$ in $B \to D K$ decays with $D \to K_s^0 \pi^+ \pi^-$, $K_s^0 K^+ K^-$

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Combining with Run 1

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Combining with Run1

$$\gamma = (87^{+11}_{-12})^\circ$$

Most precise measurement from a single analysis (fixes a single, narrow solution)
Updated LHCb $\gamma$ combination

- Nice complementarity of the input methods, which vary in precision and number of solutions

<table>
<thead>
<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Method</th>
<th>Ref.</th>
<th>Dataset</th>
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<tbody>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
<td>GLW</td>
<td>[14]</td>
<td>Run 1 &amp; 2</td>
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<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
<td>ADS</td>
<td>[15]</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+\pi^-\pi^+\pi^-$</td>
<td>GLW/ADS</td>
<td>[15]</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-\pi^0$</td>
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<td>[16]</td>
<td>Run 1</td>
</tr>
<tr>
<td>New</td>
<td>$B^+ \to DK^+$</td>
<td>$D \to K_s^0h^+h^-$</td>
<td>GGSZ</td>
<td>[17]</td>
</tr>
<tr>
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<td>$D \to K_s^0h^+h^-$</td>
<td>GGSZ</td>
<td>[18]</td>
</tr>
<tr>
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<td>$D \to K_s^0K^+\pi^-$</td>
<td>GLS</td>
<td>[19]</td>
</tr>
<tr>
<td>New</td>
<td>$B^+ \to D^*K^+$</td>
<td>$D \to h^+h^-$</td>
<td>GLW</td>
<td>[14]</td>
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<td></td>
<td>$B^+ \to DK^{*+}$</td>
<td>$D \to h^+h^-$</td>
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<td>[20]</td>
</tr>
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<td></td>
<td>$B^+ \to DK^{+}\pi^+$</td>
<td>$D \to h^+h^-$</td>
<td>GLW/ADS</td>
<td>[21]</td>
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<tr>
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<td>$B^0 \to DK^{*0}$</td>
<td>$D \to K^+\pi^-$</td>
<td>ADS</td>
<td>[22]</td>
</tr>
<tr>
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<td>$B^0 \to DK^{+}\pi^-$</td>
<td>$D \to h^+h^-$</td>
<td>GLW-Dalitz</td>
<td>[23]</td>
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<tr>
<td></td>
<td>$B^0 \to DK^{*0}$</td>
<td>$D \to K_s^0\pi^+\pi^-$</td>
<td>GGSZ</td>
<td>[24]</td>
</tr>
<tr>
<td>New</td>
<td>$B^0 \to D_s^+K^\pm$</td>
<td>$D_s^+ \to h^+h^-\pi^+$</td>
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<td>[25]</td>
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<tr>
<td>New</td>
<td>$B^0 \to D^+\pi^\pm$</td>
<td>$D^+ \to K^+\pi^-\pi^+$</td>
<td>TD</td>
<td>[26]</td>
</tr>
</tbody>
</table>

The power of the combination ($B^+$)
Updated LHCb $\gamma$ combination

- Breakdown by B meson type (results consistent at 2$\sigma$ level)

- Indirect constraints give $\gamma = (65.8 \pm 2.2)^\circ$ (UTfit, summer 2018, prel.)
  - Slight tension to be monitored as precision improves
  - Measurement statistically dominated (3$^\circ$ to 4$^\circ$ precision at the end of Run 2)
Evolving constraints
Evolving constraints

- Major impact of LHCb
What about charm?

- Extremely small level of CPV expected in charm mixing and decays offers the opportunity for very sensitive null tests of the CKM picture.
- Recent LHCb measurement of charm-mixing parameter $y_{CP}$
- Compare decay width $\Gamma_{CP}$ from decays to CP-even eigenstates ($D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+\pi^-$) with decay width $\Gamma$ to CP-mixed states ($D^0 \rightarrow K^-\pi^+$)

$$y_{CP} \equiv \frac{\Gamma_{CP}}{\Gamma} - 1$$

- $y_{CP}$ differs from zero because of mixing.
- $y_{CP}$ differs from $y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$ in presence of CPV (with $\Gamma_1, \Gamma_2$ decay widths of CP-even (odd) eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$)
- Reconstruct $D^0$s from semi-muonic B decays $B^-(B^0) \rightarrow D^0 \mu^- \bar{\nu}_\mu X$
Measurement of the charm mixing parameter $y_{CP}$

- Measurement of $y_{CP}$ from $K^+K^-$ mode most precise from single experiment
- Combination consistent and as precise as current world average
- Also consistent with known value of mixing parameter $y$ (0.62±0.07) %

No evidence of CPV in $D^0 - \bar{D}^0$ mixing
Tests of Lepton Flavour Universality
Lepton Flavour Universality

- The property that the three charged leptons \((e, \mu, \tau)\) couple in a universal way to the SM gauge bosons.

- In the SM the only flavour non-universal terms are the three lepton masses: \(m_\tau/m_\mu/m_e \leftrightarrow 3477/207/1\).

- If NP couples in a non-universal way to the three lepton families, then we can discover it by comparing classes of rare decays involving different lepton pairs (e.g. \(e/\mu\) or \(\mu/\tau\)).
The family of $R$ ratios

- Comparing the rates of $B \to H\mu^+\mu^-$ and $B \to H\mu^+\mu^-$ allows precise testing of lepton flavour universality

$$R_H \left[ q^2_{\text{min}}, q^2_{\text{max}} \right] = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \frac{d\Gamma(B \to He^+e^-)}{dq^2}} , \quad q^2 = m^2(\ell\ell)$$

- $B \to s\ell\ell$ flavour-changing neutral currents with amplitudes involving loop diagrams

- These ratios are clean probes of NP:
  - Sensitive to possible new interactions that couple in a non-universal way to electrons and muons
  - Small theoretical uncertainties because hadronic uncertainties cancel:
    - in SM, $R_H = 1$ neglecting lepton masses, with QED corrections at $\sim \%$ level
The $R_{K^*}$ ratio

$$R_{K^*0} \left[ q^2_{\text{min}}, q^2_{\text{max}} \right] = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \frac{d\Gamma(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{dq^2}}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \frac{d\Gamma(B^0 \rightarrow K^{*0} e^+ e^-)}{dq^2}}, \quad K^*(892)^0 \rightarrow K^+ \pi^-$$

- LHCb performed measurement in two $q^2$ bins:
  - Low-$q^2$ bin: $[0.045, 1.1]$ GeV$^2$
  - Central-$q^2$ bin: $[1.1, 6.0]$ GeV$^2$
A very challenging measurement!

- Lepton identification is anything but universal!
  - Electrons emit a large amount of bremsstrahlung, degrading mass resolution → need to recover energy using clusters in the calorimeter
  - Due to higher occupancy of calorimeters, trigger thresholds are higher for electrons (~2.5 to 3.0 GeV) than for muons (~1.5 to 1.8 GeV) → decays with electrons also selected using hadron trigger either fired by $K^*$ products or by any other particle in the event not associated with signal
Measure as a double ratio

- To mitigate muon and electron differences due to bremsstrahlung and trigger, measurement performed as a double ratio with “resonant” control modes $B^0 \rightarrow J/\psi K^*$, which are not expected to be affected by NP:

$$R_{K^{*0}} = \frac{B(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{B(B^0 \rightarrow K^{*0} J/\psi(\rightarrow \mu^+ \mu^-))} \bigg/ \frac{B(B^0 \rightarrow K^{*0} e^+ e^-)}{B(B^0 \rightarrow K^{*0} J/\psi(\rightarrow e^+ e^-))}$$

- Relevant experimental quantities: yields & efficiencies for the four decays

- Similarities between the experimental efficiencies of the non resonant and resonant modes ensure a substantial reduction of systematic uncertainties in the double ratio (absolute size of e.g. tracking, PID or trigger efficiencies do not need to be known exactly, only ratios between rare mode and control mode matter)
Results

Comparison with SM predictions

\[ R_{K^0} = \begin{cases} 0.66^{+0.11}_{-0.07} \text{ (stat)} \pm 0.03 \text{ (syst)} & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2 \\ 0.69^{+0.11}_{-0.07} \text{ (stat)} \pm 0.05 \text{ (syst)} & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2 \end{cases} \]

Comparison with BaBar & Belle

BIP: arXiv:1605.07633
CDHMV: arXiv:1510.04239, 1605.03156, 1701.08672
JC: arXiv:1412.3183

LHCb: JHEP 08 (2017) 055
\[ \int \mathcal{L} \, dt \sim 3 \text{ fb}^{-1} \]
Cross-checks

- very stringent test of absolute scale of efficiencies that does not benefit from the cancellation of the experimental systematics from the double ratio, also has small statistical uncertainty

- compatible with being independent of decay kinematics ($p_T, \eta$ of the $B^0$ candidate) and track multiplicity

- in agreement with JHEP 04 (2017) 142

- $B(B^0 \to K^{*0} \mu^+ \mu^-)$ in agreement with JHEP 08 (2017) 055

- $B(B^0 \to K^{*0} \gamma)$ compatible with expectation

- If corrections to simulation are not accounted for, the ratio of the efficiencies (and thus $R_{K^*}$) changes by less than 5%

\[ r_{J/\psi} = \frac{B(B^0 \to K^{*0} J/\psi(\to \mu^+ \mu^-))}{B(B^0 \to K^{*0} J/\psi(\to e^+ e^-))} = 1.043 \pm 0.006 \pm 0.045 \]
A reminder: $R_K$

- LHCb published an analysis of $R_K$ based on Run 1 ($\int \mathcal{L} \, dt \sim 3\text{fb}^{-1}$)

\[
R_K \left[q_{\text{min}}^2, q_{\text{max}}^2\right] = \frac{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} dq^2 \frac{d\Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{dq^2}}{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} dq^2 \frac{d\Gamma(B^+ \rightarrow K^+ e^+ e^-)}{dq^2}}, \quad 1 < q^2 < 6 \text{ GeV}^2
\]

- Also measured as a double ratio wrt $B^+ \rightarrow J/\psi(\rightarrow \ell^+ \ell^-)K^+$

- ~250 $B^+ \rightarrow K^+ e^+ e^-$ candidates (~1200 dimuon candidates)

$R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)}$

(~12% precision)

LHCb: PRL 113 (2014) 151601

BaBar: PRD 86 (2012) 032012

Belle: PRL 103 (2009) 171801
What happens next?

- $R_K$ analysis to be updated soon with much improved sensitivity

- Improvements to offline processing

- Adding part of Run 2 data (2015, 16) gives ~2 fb$^{-1}$ but with nearly twice cross-section and better trigger

- $~250 \rightarrow 900$ $B^+ \rightarrow K^+ e^+ e^-$ candidates

- Expected previous uncertainty of ~12% to shrink to ~7%

- In main trigger category, systematic effects controlled at 2-3% level

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Run 2

Can make analogous measurement with $R_K^*$ update with Run 2 data - still expect it to be statistically limited

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<thead>
<tr>
<th>Observable</th>
<th>LW</th>
<th>LW 2023</th>
<th>LHCb</th>
<th>Belle II</th>
<th>Upgrade II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_K$ ($q^2 &lt; 7.5$ GeV$^2$)</td>
<td>0.1</td>
<td>0.11</td>
<td>0.065</td>
<td>0.08, 0.06, 0.18</td>
<td></td>
</tr>
<tr>
<td>$R_K$ ($q^2 &lt; 6$ GeV$^2$)</td>
<td>0.1</td>
<td>0.05</td>
<td>0.025</td>
<td>0.031</td>
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</tr>
<tr>
<td>$R_K^*$ ($q^2 &lt; 6$ GeV$^2$)</td>
<td>0.032</td>
<td>0.0136</td>
<td>0.007</td>
<td>0.008, 0.02, 0.02, 0.05</td>
<td></td>
</tr>
</tbody>
</table>

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**Belle II Physics Book:** arXiv:1808.10567

LHCb: CERN-LHCC 2018-027

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Short term:

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Long term:

- Improvements to offline processing

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(Very)

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Other experimental inputs

• In 2018 CMS have put in place a new trigger strategy in which a sizeable fraction of the trigger bandwidth is dedicated to flavour physics

• They have on tape an unbiased sample of $\sim 10^{10}$ B hadrons (tag on B-tag side by requiring muons with significant impact parameter, no requirement on the other side)

• Rate exceeds 5 kHz near the end of the fill, when pileup is low, not to exceed buffer capacity

• Data are parked (→ no prompt reconstruction, opportunistic reconstruction during LS2, but over 1 billion events already processed for monitoring and trigger optimisation)
Intriguing set of results in differential branching fractions for $b \rightarrow s \mu \mu$ transitions

- In general, data tend to be lower than theory predictions at low $q^2$
- Comparison limited by theoretical knowledge of form factors
$b \to d \ell^+ \ell^-$ transitions

- First observation of $B^+ \to \pi^+ \mu^+ \mu^-$ and $\Lambda_b^0 \to p \pi^- \mu^+ \mu^-$ and first evidence for $B^0 \to \pi^+ \pi^- \mu^+ \mu^-$ and $B^0_s \to K^{*0} \mu^+ \mu^-$
- Decays with BF $\mathcal{O}(10^{-8})$
- Ratios of rates for $b \to d \ell^+ \ell^-$, $b \to s \ell^+ \ell^-$ give access to $|V_{td}|/|V_{ts}|$
Another puzzling result in tree-level $b \rightarrow c$ transitions
LFU studies in $B \to D^{(*)} \tau \nu$ decays

- Different class of decays (tree-level charged current with $V_{cb}$ suppression)
- Not at all rare: $\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu \tau) \sim 1\%$, problem is the background
- Lepton-universality ratio $R(D^*)$: $R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu \tau)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu \mu)}$
  - sensitive to any NP model coupling preferentially to third generation leptons
- Predicted theoretically at $\sim 1\text{-}2\%$: $R(D)_{SM} = 0.299 \pm 0.003$
  $R(D^*)_{SM} = 0.258 \pm 0.005$ [HFLAV 2018]
- Studied by Belle, BaBar and LHCb
$R(D^*)$: Experimental challenges

- Experimentally very difficult at the LHC (considered unfeasible)
- As opposed to B factories, the rest of the event does not provide any useful kinematic constraint. (However, profit from large boost and huge B production.)
- At least two neutrinos in the final state (three if using $\tau \to \mu \nu \nu$)
- Two LHCb measurements, in muonic and hadronic $\tau$ decays:

\[
\begin{align*}
\tau^+ &\to \mu^+ \nu_\mu \bar{\nu}_\tau, \quad \tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau \\
D^{*-} &\to D^0 (\to K^+ \pi^-) \pi^-
\end{align*}
\]

- Three-prong mode used for the first time!
- A semileptonic decay with no (charged) lepton in final state (one $K$, five $\pi$)
\[ R(D^*) \] with \( \tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau \)

- Fit in \( m_{miss}^2 = (P_B^\mu - P_D^\mu - P_\mu^\mu)^2, q^2 = (P_B^\mu - P_D^\mu)^2, E_\mu \)

- \( R(D^*) = 0.336 \pm 0.027 \text{ (stat)} \pm 0.030 \text{ (syst)} \) \( \sim 2 \sigma > \text{SM} \)

\[ \int \mathcal{L} \, dt \sim 3 \text{ fb}^{-1} \]

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\[ R(D^{*}) \text{ with } \tau^{+} \rightarrow \pi^{+}\pi^{-}\pi^{+}(\pi^{0})\bar{\nu}_{\tau} \]

- Separation between \( B \) and \( 3\pi \) vertices (\( \Delta z > 4\sigma_{\Delta z} \)) crucial to obtain the required rejection of \( B \rightarrow D^{*}3\pi X \) (BF~100 x signal)

- Remaining double-charm background (\( D^{*}D(s)X \), (BF~10 x signal, same vertex topology) suppressed by employing a multivariate classifier

\[ R(D^*) = 0.291 \pm 0.019 \text{ (stat)} \pm 0.026 \text{ (syst)} \pm 0.013 \text{ (ext)} \]

\( \sim 1 \sigma > \text{SM} \)
• All experiments see an excess wrt SM predictions
• Tension at $\sim 3.8 \sigma$ level (Bigi et al, arXiv:1707.09509) INTRIGUING!
• $\sim 20\%$ effect on $R(D^*)$ (more precise, larger BF and less feed-down)
Testing LFU with $B_c$ decays

- Generalization of $R(D^*)$ to $B_c$:
  \[ R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)} \]

- Signal reconstructed using $\tau \to \mu \nu \nu$, with $B_c^+ \to J/\psi \mu^+ \nu_\mu$ as norm.

- Largest background from light $b$ hadrons to $J/\psi$ with a $\pi$ or $K$ misidentified as $\mu$.

$R(J/\psi) = 0.71 \pm 0.17\text{(stat)} \pm 0.18\text{(syst)}$

Higher by $\sim 2\sigma$ than SM prediction (0.25-0.28)
What happens next?

- Extend analyses to full Run2 statistics (will take time!)
  - from ~1300 to ~6000 events in hadronic mode
  - goal is to be competitive with world average

- A whole programme of semi-tauonic measurements, e.g.
  
  \[
  \begin{align*}
  R(D) : B^+ & \rightarrow D^0 \tau^+ \nu_\tau \\
  R(D^*) : B^0 & \rightarrow D^{*-} \tau^+ \nu_\tau \\
  R(D_s^{(*)}) : B^{0}_{s} & \rightarrow D_s^{(*)} \tau^+ \nu_\tau \\
  R(\Lambda_b) : \Lambda_b & \rightarrow \Lambda_c^{(*)} \tau^+ \nu_\tau 
  \end{align*}
  \]
  
  First expected result, simultaneous fit to $D^0\mu^+\& D^{*-}\mu^+$ (Still Run 1- based)

- Waiting for Belle II ~1.5% projected sensitivity on $R(D^*)$ with 5 ab$^{-1}$
Possible explanations of the anomalies

- **Statistical fluctuations?**: unlikely given the number and pattern of the effects?
- **Experimental artefacts?**: these are difficult measurements; have the systematic uncertainties been correctly estimated?
- **Theoretical uncertainties?**: large theoretical uncertainties from hadronic form factors, but LFU tests should be robust
- **A cocktail of the above?**
- **New Physics only once all the above have been excluded...**
    - “the case of an SU(2)\textsubscript{L}-singlet vector leptoquark emerges as a particularly simple and successful framework.”
  - The large amount of data still to be analysed by LHCb and high-p\textsubscript{T} LHC experiments, as well as from future Belle II, will certainly shed more light on the origin of these effects
Conclusions

• Lots of measurements in flavour only a few of which were highlighted here

• Dramatic improvements to the already impressive knowledge accumulated by the B-factories and Tevatron. Healthy competition from Belle II, ATLAS & CMS very welcome!

• Precise measurements of flavour observables provide a powerful way to probe for NP effects beyond the SM, complementing direct searches for NP

• Most of these results show good compatibility with the SM, but some signs of tension are emerging

• Need to analyse Run 2 to test these hints

• In LHCb we are working hard to prepare for the future: ready to instal upgraded detector in ’19-20 and also thinking about a possible Upgrade II for the the ultimate exploitation of the LHC for flavour physics in the HL-LHC era

• Belle II and the LHCb Upgrade(s) will open up a new frontier in precision
A few extra slides
$R_X$ – experimental challenges
**R_K update – other q^2 regions**

- (In SM) little \(B^+ \rightarrow K^+e^+e^-\) signal with \(q^2 < 1.0\) GeV^2

- Can add high \(q^2\) bin – difficulty same for \(R_K\) and \(R_{K^*}\)
  - Rare decays with higher \(K(\ast)\) resonances can leak into signal region from below in \(m_{Kee}\)
  - \(\psi(2S)K^*\) decays can leak into signal region on the upper side
  - Signal sandwiched between these and hence difficult to fit reliably

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Mitesh Patel
Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb</th>
<th>LHCb 2025</th>
<th>Belle II</th>
<th>Upgrade II</th>
<th>ATLAS &amp; CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EW Penguins</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_K$ ($1 &lt; q^2 &lt; 6 \text{ GeV}^2 c^4$)</td>
<td>0.1 [274]</td>
<td>0.025</td>
<td>0.036</td>
<td>0.007</td>
<td>–</td>
</tr>
<tr>
<td>$R_K^*$ ($1 &lt; q^2 &lt; 6 \text{ GeV}^2 c^4$)</td>
<td>0.1 [275]</td>
<td>0.031</td>
<td>0.032</td>
<td>0.008</td>
<td>–</td>
</tr>
<tr>
<td>$R_\phi, R_{pK}, R_{\pi}$</td>
<td>–</td>
<td>0.08, 0.06, 0.18</td>
<td>–</td>
<td>0.02, 0.02, 0.05</td>
<td>–</td>
</tr>
<tr>
<td><strong>CKM tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$, with $B^0 \rightarrow D^- K^+$</td>
<td>$(^{+17}_{-22})^\circ$ [136]</td>
<td>4$^\circ$</td>
<td>–</td>
<td>1$^\circ$</td>
<td>–</td>
</tr>
<tr>
<td>$\gamma$, all modes</td>
<td>$(^ {+1.5}_{-5.8})^\circ$ [167]</td>
<td>1.5$^\circ$</td>
<td>1.5$^\circ$</td>
<td>0.35$^\circ$</td>
<td>–</td>
</tr>
<tr>
<td>$\sin 2\beta$, with $B^0 \rightarrow J/\psi K^0_S$</td>
<td>0.04 [609]</td>
<td>0.011</td>
<td>0.005</td>
<td>0.003</td>
<td>–</td>
</tr>
<tr>
<td>$\phi$, with $B^0 \rightarrow J/\psi \phi$</td>
<td>49 mrad [44]</td>
<td>14 mrad</td>
<td>–</td>
<td>4 mrad</td>
<td>22 mrad [610]</td>
</tr>
<tr>
<td>$\phi$, with $B^0 \rightarrow D^+ D^-$</td>
<td>170 mrad [49]</td>
<td>35 mrad</td>
<td>–</td>
<td>9 mrad</td>
<td>–</td>
</tr>
<tr>
<td>$\phi$, with $B^0 \rightarrow D^0 D^-$</td>
<td>154 mrad [94]</td>
<td>39 mrad</td>
<td>–</td>
<td>11 mrad</td>
<td>Under study [611]</td>
</tr>
<tr>
<td>$a_1^\phi$, with $B^0 \rightarrow \phi\phi$</td>
<td>$33 \times 10^{-4}$ [211]</td>
<td>$10 \times 10^{-4}$</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>$</td>
<td>6% [201]</td>
</tr>
<tr>
<td>$B_{s0}^0, B^0 \rightarrow \mu^+ \mu^-$</td>
<td>90% [264]</td>
<td>34%</td>
<td>–</td>
<td>10%</td>
<td>21% [612]</td>
</tr>
<tr>
<td>$B(B^0 \rightarrow \mu^+ \mu^-)/B(B^0 \rightarrow \mu^+ \mu^-)$</td>
<td>22% [264]</td>
<td>8%</td>
<td>–</td>
<td>2%</td>
<td>–</td>
</tr>
<tr>
<td>$S_{\mu\mu}$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.2</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow \tau^+ \tau^-$ LUV studies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(D^*)$</td>
<td>0.026 [215,217]</td>
<td>0.0072</td>
<td>0.005</td>
<td>0.002</td>
<td>–</td>
</tr>
<tr>
<td>$R(J/\psi)$</td>
<td>0.24 [220]</td>
<td>0.071</td>
<td>–</td>
<td>0.02</td>
<td>–</td>
</tr>
<tr>
<td><strong>Charm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta A_{CP}(KK \rightarrow \pi \pi)$</td>
<td>$8.5 \times 10^{-4}$ [613]</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$5.4 \times 10^{-4}$</td>
<td>$3.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$A_{\Gamma}$ (≈ $x \sin \phi$)</td>
<td>$2.8 \times 10^{-4}$ [240]</td>
<td>$4.3 \times 10^{-5}$</td>
<td>$3.5 \times 10^{-4}$</td>
<td>$1.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$x \sin \phi$ from $D^0 \rightarrow K^+ \pi^-$</td>
<td>$13 \times 10^{-4}$ [228]</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$4.6 \times 10^{-4}$</td>
<td>$8.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$x \sin \phi$ from multibody decays</td>
<td>–</td>
<td>$(K3\pi) 4.0 \times 10^{-5}$</td>
<td>$(K^0\pi\pi) 1.2 \times 10^{-4}$</td>
<td>$(K3\pi) 8.0 \times 10^{-6}$</td>
<td>–</td>
</tr>
</tbody>
</table>