B physics at hadron machines

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on behalf of the LHCb collaboration with results from

9th International Workshop on the CKM Unitarity Triangle
TIFR, Mumbai
Outline

• *CP* violation in the interference between *B*-meson mixing and decay
• *CP* violation in *B*-meson mixing
• *B*-meson width and mass differences
• Photon polarisation in $B_s \rightarrow \phi \gamma$
• Tree-level determination of $\gamma$
• Searches for *CP* violation in *b* baryons
• Measurement of $|V_{ub} / V_{cb}|$
• Leptonic and charmless hadronic rare decays
• Angular analysis of $B^0 \rightarrow K^* \mu^+ \mu^-$ decays
• Lepton Flavour Universality tests
An astonishing success

- Don’t forget: relevant inputs from Lattice QCD and great work from the Heavy Flavour Averaging Group
  - http://www.slac.stanford.edu/xorg/hfag

- Great success of the Standard Model CKM picture!
  - All of the measurements agree in a highly profound way
  - In the presence of relevant New Physics effects, the various contours would not cross each other in a single point
Nevertheless...

- Although the Standard Model works beautifully up to a few hundred GeV, **it must be an effective theory valid up to some scale**
- The good reasons to believe that it is incomplete are still there, e.g.
  - Missing dark matter candidate
  - *CP* violation for dynamical generation of BAU largely insufficient
- We must search for
  - New particles, interactions, symmetries (and their breaking)
  - New sources of *CP* violation
Cross-section vs luminosity

• Several experiments at different machines contributed/contributing to the field in the last 15 years

• Lower luminosity but larger cross section at hadron machines allow for unprecedented samples to be collected

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \mathcal{L} , dt , [\text{fb}^{-1}] )</th>
<th>( \sigma_{\text{beauty}} , [\mu\text{b}] )</th>
<th>End of life</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar + Belle</td>
<td>1600 (total)</td>
<td>0.001 ([e^+e^- \text{ at } Y(4S)])</td>
<td>2008/2010</td>
</tr>
<tr>
<td>CDF + D0</td>
<td>24 (total)</td>
<td>100 ([p\bar{p} \text{ at } 2 \text{ TeV}])</td>
<td>2011</td>
</tr>
<tr>
<td>ATLAS + CMS</td>
<td>150 (so far)</td>
<td>250-500 ([pp \text{ at } 7-13 \text{ TeV}])</td>
<td>&gt; 2030</td>
</tr>
<tr>
<td>LHCb*</td>
<td>5 (so far)</td>
<td>250-500 ([pp \text{ at } 7-13 \text{ TeV}])</td>
<td>&gt; 2030</td>
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</tbody>
</table>

* Forward detector optimised for heavy flavour physics with levelled luminosity to limit pileup effects
One milestone of modern beauty physics

- Golden mode $B_s \rightarrow J/\psi \phi$ proceeds (mostly) via a $b \rightarrow c\bar{c}s$ tree diagram
- Interference between $B_s$ mixing and decay graphs
- Measures the phase-difference $\phi_{s}$ between the two diagrams, precisely predicted in the SM to be $\phi_{s} = -37.4 \pm 0.7$ mrad → can be altered by New Physics
  - But also affected by small pollution of sub-leading SM amplitudes that must be taken under control
\( \phi_s \) from \( b \to c\bar{c}s \) transitions

- Several measurements at the Tevatron and the LHC
- World average
  - \( \phi_s = -30 \pm 33 \) mrad
- Still compatible with the SM at the present level of precision
**CP violation in $B_s \to \phi \phi$**

- Gluonic $b \to s\bar{s}s$ penguin
- LHCb result with full Run 1 data set
  - $\sim 4000$ signal candidates
  - $\phi_s^{\phi\phi} = -170 \pm 150 \pm 30$ mrad
- No sign of discrepancy yet, but overall precision comparable to golden $b \to c\bar{c}c\bar{s}$ modes
- Great prospects for LHCb Run-3 with higher instantaneous luminosity and improved trigger

*Phys. Rev. D90 (2014) 052011*
But never forget your first love

\[ \mathcal{A}_{J/\psi K_S^0}(t) = \frac{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S^0) - \Gamma(B^0(t) \rightarrow J/\psi K_S^0)}{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S^0) + \Gamma(B^0(t) \rightarrow J/\psi K_S^0)} \]

\[ = S_{J/\psi K_S^0} \sin(\Delta m_d t) - C_{J/\psi K_S^0} \cos(\Delta m_d t). \]

- **BaBar**: 0.657 ± 0.036 ± 0.012  
  *Phys. Rev. D79 (2009) 072009*
- **Belle**: 0.670 ± 0.029 ± 0.013  
- **LHCb**: 0.731 ± 0.035 ± 0.020  
**CP violation from $B^0 \rightarrow D^+D^-$**

- LHCb recently measured time-dependent CP violation in the $B^0 \rightarrow D^+D^-$ decay
  - Complementary information on $\sin 2\beta$ through $b \rightarrow c\bar{c}d$ transitions
  - Comparison with $B^0 \rightarrow J/\psi K_S$ constrains penguin contributions to $B \rightarrow DD$
  - Tagging power: $(8.1 \pm 0.6)\%$

- Consistent with SM and no penguin pollution
  - i.e. $S \approx -0.75 \ ( -\sin 2\beta)$ and $C=0$

\[
A_{DD}(t) = \frac{\Gamma(B^0(t) \rightarrow D^+D^-) - \Gamma(B^0(t) \rightarrow D^+D^-)}{\Gamma(B^0(t) \rightarrow D^+D^-) + \Gamma(B^0(t) \rightarrow D^+D^-)} = S_{CP} \sin(\Delta m_d t) - C_{CP} \cos(\Delta m_d t)
\]

\[
S_{CP} = -0.54 \pm 0.17 \ (\text{stat}) \pm 0.05 \ (\text{sys})
\]

\[
C_{CP} = 0.26 \pm 0.18 \ (\text{stat}) \pm 0.02 \ (\text{sys})
\]

LHCb-PAPER-2016-037 arXiv:1608.06620
**CP violation in $B_s$-$\bar{B}_s$ mixing**

- **CP** violation in neutral $B$-meson mixing manifests itself if

  \[
  \mathcal{P}(B_q \rightarrow \bar{B}_q) \neq \mathcal{P}({\bar{B}}_q \rightarrow B_q)
  \]

- Interest triggered by a measurement from D0 yielding an anomalous like-sign dimuon asymmetry
  

- Precise measurements of semileptonic asymmetries from LHCb

- Run-1 measurement of $a_{sl}(B_s)$ using $B_s \rightarrow D_s(KK\pi)\mu\nu X$ decays from LHCb

Note: $a_{sl}(B_d)$ and $a_{sl}(B_s)$ are very small in the SM

\[
a_{sl}^d = (2.22 \pm 0.27) \times 10^{-5} \text{ for } B_d^0
\]

\[
a_{sl}^s = (-4.7 \pm 0.6) \times 10^{-4} \text{ for } B_s^0
\]

Artuso, Borissov, Lenz [arXiv:1511.09466]

\[
a_{sl}^s = (0.39 \pm 0.26\text{(stat)} \pm 0.20\text{(syst)})\%
\]

Measurement of the $B^0$ width difference

- Recent measurement of $\Delta \Gamma_d / \Gamma_d$ by ATLAS
  - Comparing decay-time distributions of $B^0 \rightarrow J/\psi K_S$ and $B^0 \rightarrow J/\psi K^{*0}$

$$\Delta \Gamma_d / \Gamma_d = (-0.1 \pm 1.1 \text{ (stat.)} \pm 0.9 \text{ (syst.)}) \times 10^{-2}$$

Efficiency-corrected ratio of the observed decay length distributions

- Most precise measurement from a single experiment to date
Measurement of the $B^0$ mass difference

• Mixing frequency $\Delta m_d$ measured with full Run-1 sample
  – 1.6M $B^0 \rightarrow D^-\mu^+\nu X$ decays
  – 0.8M $B^0 \rightarrow D^*^-\mu^+\nu X$ decays

• Using four tagging categories of different mistag rate
  $\Delta m_d = (505.0 \pm 2.1 \pm 1.0)$ ns$^{-1}$

• World’s best single measurement, more precise than previous world average
Photon polarisation in $B_s \rightarrow \phi\gamma$

• Fit untagged decay-time rate

$$\Gamma_{B_s^0 \rightarrow \phi\gamma}(t) \propto e^{-\Gamma_s t} \left[ \cosh (\Delta \Gamma_s t/2) - A^\Delta \sinh (\Delta \Gamma_s t/2) \right]$$

$$A^\Delta \approx \sin 2\psi \cos \varphi_s \quad \tan \psi \equiv \frac{A(\overline{B}_s^0 \rightarrow \phi\gamma_R)}{A(\overline{B}_s^0 \rightarrow \phi\gamma_L)}$$

• Control acceptance by using $B^0 \rightarrow K^{*0}\gamma$ decays

• First result on photon polarisation!

$$A^\Delta = -0.98^{+0.46}_{-0.52} + 0.23 - 0.20$$

• To be compared with

$$A^\Delta_{SM} = 0.047^{+0.029}_{-0.025}$$
Tree-level determination of $\gamma$

- $\gamma$ is still the least known angle of the Unitarity Triangle

- Theoretically clean measurement from tree-level transitions $\Rightarrow$ genuine experimental effort!

- Two main routes
  - Time-independent measurements, e.g. using $B \rightarrow DK$ decays
  - Time-dependent analyses with $B_s$ decays, e.g. $B_s \rightarrow D_s K$

- Combining a plethora of independent decay modes is the key to achieve the ultimate precision
Experimental status for $\gamma$

- New combination of all available measurements from LHCb

<table>
<thead>
<tr>
<th>B decay</th>
<th>D decay</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow Dh^+$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW/ADS</td>
</tr>
<tr>
<td>$B^+ \rightarrow Dh^+$</td>
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<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow K_s^0h^+h^-$</td>
<td>GGSZ</td>
</tr>
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<td>GLS</td>
</tr>
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<td>GLW/ADS</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^{*0}$</td>
<td>$D \rightarrow K^+\pi^-$</td>
<td>ADS</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^{+}\pi^-$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW-Dalitz</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^{*0}$</td>
<td>$D \rightarrow K_s^0\pi^+\pi^-$</td>
<td>GGSZ</td>
</tr>
<tr>
<td>$B^0 \rightarrow D_s^{+}\bar{K}^-$</td>
<td>$D_s^+ \rightarrow h^+h^-\pi^+$</td>
<td>TD</td>
</tr>
</tbody>
</table>

- Significantly more precise than previous results

$\gamma = (69^{+17}_{-16})^\circ$

$\gamma = (68^{+15}_{-14})^\circ$

$\gamma = (72.2^{+6.8}_{-7.3})^\circ$
New avenues: search for CP violation in $\Lambda_b \rightarrow p\pi^-\pi^+\pi^-$ decays from LHCb

- CP violation has never been observed in the decays of any baryonic particle
- $\Lambda_b \rightarrow p\pi^-\pi^+\pi^-$ decays used to search for CP-violating asymmetries in triple products of final-state particle momenta

$$C_T = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+})$$

$$\bar{C}_T = \vec{p}_\bar{p} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-})$$

$$\bar{A}_T(C_T) = \frac{N(\bar{C}_T > 0) - N(\bar{C}_T < 0)}{N(\bar{C}_T > 0) + N(\bar{C}_T < 0)}$$

$$A_T(C_T) = \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)}$$

CP-violating observable $\alpha_{CP}$

$$\alpha_{CP} = \frac{1}{2} (A_T - \bar{A}_T)$$
New avenues: search for $CP$ violation in $\Lambda_b \to \rho \pi^- \pi^+ \pi^-$ decays from LHCb

- Local $CP$-violating effects studied as a function of the relative orientation between the decay planes formed by the $\rho \pi^-$ and the $\pi^+ \pi^-$ systems ($\Phi$)
- An evidence for $CP$ violation at the $3.3 \sigma$ level is found
- This represents the first evidence of $CP$ violation in the baryon sector

LHCb-PAPER-2016-030  arXiv:1609.05216
$|V_{ub}/V_{cb}|$ from $\Lambda_b \rightarrow p\mu\nu$ decays at LHCb

- Measure $\mathcal{B}(\Lambda_b \rightarrow p\mu\nu)$ relative to $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c\mu\nu)$ in the high $q^2$ region where the theory uncertainty is smaller

$$\frac{\mathcal{B}(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu)_{q^2>15\text{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c\mu\nu)_{q^2>7\text{GeV}^2/c^4}} = \frac{N(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu)}{N(\Lambda_b \rightarrow (\Lambda_c \rightarrow pK\pi)\mu^-\bar{\nu}_\mu)} \times \frac{\epsilon(\Lambda_b \rightarrow (\Lambda_c \rightarrow pK\pi)\mu^-\bar{\nu}_\mu)}{\epsilon(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu)} \times \mathcal{B}(\Lambda_c \rightarrow pK\pi)$$

- Use Belle measurement of $\mathcal{B}(\Lambda_c \rightarrow pK\pi)$
  - Phys. Rev. Lett. 113 (2014) 042002

$$R_{\text{exp}} = R_{\text{theory}}(|V_{ub}|^2/|V_{cb}|^2)$$

$$R_{\text{theory}} = 1.471 \pm 0.095 \pm 0.109$$

$|V_{ub}/V_{cb}|$ from $\Lambda_b \rightarrow p\mu\nu$ decays at LHCb

$$M_{\text{corr}} = \sqrt{p_{\perp}^2 + M_{p\mu}^2 + p_{\perp}}$$

$$\mathcal{B}(\Lambda_c^+ \rightarrow pK^+\pi^-) = 9.5 \pm 4.7\%$$

$$\mathcal{B}(\Lambda_c^0 \rightarrow N^*\mu^-\bar{\nu}_\mu) = 2.3\%$$

$$\Lambda_b^0 \rightarrow N^*\mu^-\bar{\nu}_\mu \text{ shape} = 1.5\%$$

$$\Lambda_b^0 \rightarrow N^*\mu^-\bar{\nu}_\mu \text{ lifetime} = 1.4\%$$

$$\Lambda_b^0 \rightarrow N^*\mu^-\bar{\nu}_\mu \text{ isolation} = 1.0\%$$

$$\Lambda_b^0 \rightarrow N^*\mu^-\bar{\nu}_\mu \text{ form factor} = 0.5\%$$

$$\Lambda_b^0 \rightarrow N^*\mu^-\bar{\nu}_\mu \text{ kinematics} = 0.4\%$$

$$\Lambda_b^0 \rightarrow N^*\mu^-\bar{\nu}_\mu \text{ PID} = 0.2\%$$

$$\mathcal{B}(\Lambda_b^0 \rightarrow p\mu\nu)_{q^2>15 \text{ GeV/c}^2} = 1.00 \pm 0.04 \pm 0.08 \times 10^{-2}$$

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-\bar{\nu}_\mu)_{q^2>7 \text{ GeV/c}^2} = 0.083 \pm 0.004\text{ (expt)} \pm 0.004\text{ (lattice)}$$

Nature Physics 10 (2015) 1038
Rare decays as another avenue to New Physics

$B_{d,s} \rightarrow \mu^+ \mu^-$ from CMS and LHCb

- CMS and LHCb have performed a combined fit to their full Run 1 data sets

  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$

  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$

- $B_s \rightarrow \mu \mu$ $6.2\sigma$ significance was first observation
  - Compatibility with the SM at $1.2\sigma$

- Excess of events at the $3\sigma$ level observed for the $B^0 \rightarrow \mu \mu$ hypothesis with respect to background-only
  - Compatible with SM at $2.2\sigma$

Nature 522 (2015) 68
$B_{d,s} \rightarrow \mu^+\mu^-$ history
$B_{d,s} \rightarrow \mu^+ \mu^-$ searches at ATLAS

- Recently also ATLAS published their searches with the full Run-1 dataset
  - No significant signal is seen
  - A $p$-value of 4.8% ($2\sigma$) is found for the compatibility of the results with the SM prediction

\[
\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (0.9_{-0.8}^{+1.1}) \times 10^{-9}
\]

\[
\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 4.2 \times 10^{-10} \text{ (95\% CL)}
\]

Charmless rare decays from LHCb

- Particular class of decays that can proceed only through so-called annihilation diagrams
- \( B^0 \rightarrow K^+K^- \) decay observed for the first time after many years of searches
  - Significance 5.8\( \sigma \)

\[
\mathcal{B}(B^0 \rightarrow K^+K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8} \\
\mathcal{B}(B^0_s \rightarrow \pi^+\pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}
\]

- The \( B^0 \rightarrow K^+K^- \) is the rarest \( B \)-meson decay into a fully hadronic final state ever observed

LHCb-PAPER-2016-036  arXiv:1610.08288
Angular analysis of $B^0 \rightarrow K^* \mu^+ \mu^-$

- Well established “anomaly”
  - Observables are $q^2$ (dimuon mass squared) and 3 angles
  - Angular distributions provide many observables sensitive to different sources of New Physics see e.g. JHEP 05 (2013) 137
  - Some global theoretical fits require non-SM contributions to accommodate the data see e.g. JHEP 06 (2016) 092
  - However, genuine QCD effects can also be an explanation

$\rightarrow$ more efforts needed to clarify the picture see e.g. JHEP 06 (2016) 116
LFU in $B \to D^{(*)} \tau \nu$

- Ratio $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)} \tau \nu) / \mathcal{B}(B \to D^{(*)} \mu \nu)$ is sensitive e.g. to charged Higgs scenarios

- Measurements of $R(D)$ and $R(D^{*})$ by BaBar, Belle and LHCb
  - Overall average shows a $4\sigma$ discrepancy from the SM

- More analyses about $b \to c \tau \nu$ are ongoing at Belle and LHCb

- LHCb can also perform measurements with other $b$ hadrons
  - e.g. $B_s$, $B_c$ and $\Lambda_b$ decays will help to better understand the global picture $\Rightarrow$ stay tuned!
More LFU tests

- Ratio ($R_K$) of branching fractions of $B^+ \rightarrow K^+ \mu^+ \mu^-$ to $B^+ \rightarrow K^+ e^+ e^-$ expected to be unity in the SM with excellent precision

\[
R_K = \frac{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} \frac{d\Gamma[B^+ \rightarrow K^+ \mu^+ \mu^-]}{dq^2}}{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} \frac{d\Gamma[B^+ \rightarrow K^+ e^+ e^-]}{dq^2}}
\]

- Observation of LFU violation would be a clear sign of New Physics
- LHCb observed a $2.6\sigma$ deviation from SM in the low $q^2$ region
- New measurements expected soon, e.g. $R_{K*}$
LHC luminosity prospects

<table>
<thead>
<tr>
<th></th>
<th>LHC era</th>
<th>HL-LHC era</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, CMS</td>
<td>25 fb^{-1}</td>
<td>100 fb^{-1}</td>
</tr>
<tr>
<td>LHCb</td>
<td>3 fb^{-1}</td>
<td>8 fb^{-1}</td>
</tr>
</tbody>
</table>

* assumes a future LHCb upgrade to raise the instantaneous luminosity to 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}

- LHC is delivering luminosity at an incredibly high pace in Run-2
  - And remember that beauty production cross section roughly doubles passing from 7 to 13-14 TeV pp collisions
- LHCb (phase-1) upgrade comes already after Run-2, whereas the HL (phase-2) ATLAS and CMS upgrades come after Run-3
- But LHCb is now promoting a phase-2 upgrade for Run 5+ too

http://www.hep.manchester.ac.uk/theatre-of-dreams/index.html
Concluding remarks

• LHC is nowadays a gold mine for our physics, and this is just started
  – Impressive harvest so far!
  – Still to exploit full Run-1 potential, and beginning to deploy that of Run-2
  – And exciting times ahead with Belle II approaching data taking

• Some interesting anomalies to be studied more in depth during Run-2 and beyond

• In the current unclear state with perspectives in fundamental physics, it is necessary to have a programme as diversified as possible
  – In the unfortunate event that no direct evidence of NP pops out of the LHC, flavour physics can play a key role to indicate the way for future developments of elementary particle physics
  – And otherwise, flavour physics will be a crucial ingredient to understand the structure of what lies beyond the SM

• Just an appetiser today ➔ new results to come in the course of the week not unveiled today!