Results and prospects on bottom physics

Vincenzo Vagnoni
CERN and INFN Bologna
on behalf of the LHCb collaboration
with results from

- Flagship results and novelties in CP violation and rare decays
- Flavour anomalies
- Upcoming and long-term prospects
The CKM Unitarity Triangle

\[ V_{CKM} = \begin{pmatrix} d & \lambda & A\lambda^3(\bar{\rho} - i\bar{\eta}) \\ c & 1 - \frac{\lambda^2}{2} & \cdot A\lambda^2 \\ t & A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 \cdot 1 \end{pmatrix} \]

From CKM matrix unitarity

- UT defined by two parameters only \( \rightarrow \) can be overconstrained
- The height (irreducible complex phase \( \bar{\eta} \)) controls the strength of CP violation in the Standard Model
Where we are

- 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
- But...
... physicists are never satisfied!

- Although the Standard Model (of particle physics) works beautifully up to a few hundred GeV, **it must be an effective theory valid up to some scale $\Lambda$**
- 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 and interactions
  - New sources of $CP$ violation
Precision measurements of $CP$ violation and rare decays: why important?

- Instead of searching for NP particles directly produced, look for their indirect effects to low energy processes (e.g. $b$-hadron decays)

- General amplitude decomposition in terms of couplings and scales in presence of sizeable SM contributions, NP effects might be hidden
  - Need high precision measurements of theoretically clean observables

- Note: from present picture in the flavour sector, still room for NP at 10-20%

- Studying $CP$-violating and flavour-changing processes two fundamental tasks can be accomplished
  - Identify new symmetries (and their breaking) beyond the SM
  - Probe mass scales not accessible directly at nowadays colliders
A luminous (and beautiful) world!

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

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \mathcal{L} ) dt [fb(^{-1})]</th>
<th>( \sigma_{\text{beauty}} ) [( \mu \text{b} )]</th>
<th>End of life</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>530 (total)</td>
<td>0.001 [e(^+)e(^-) at ( \Upsilon )(4S)]</td>
<td>2008</td>
</tr>
<tr>
<td>Belle</td>
<td>1040 (total)</td>
<td>0.001 [e(^+)e(^-) at ( \Upsilon )(4S)]</td>
<td>2010</td>
</tr>
<tr>
<td>CDF/D0</td>
<td>12 (total)</td>
<td>100 [pp at 2 TeV]</td>
<td>2011</td>
</tr>
<tr>
<td>ATLAS/CMS</td>
<td>55 (so far)</td>
<td>250-500 [pp at 7-13 TeV]</td>
<td>&gt; 2030</td>
</tr>
<tr>
<td>LHCb*</td>
<td>4.2 (so far)</td>
<td>250-500 [pp at 7-13 TeV]</td>
<td>&gt; 2030</td>
</tr>
</tbody>
</table>

* Forward detector optimised for beauty and charm 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 $\rightarrow$ 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 $b \rightarrow c \bar{c}s$ 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

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Mode</th>
<th>Dataset</th>
<th>$\phi_{c \bar{c}s}^{c\bar{c}s}$ [rad]</th>
<th>$\Delta \Gamma_c$ [ps$^{-1}$]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>$J/\psi \phi$</td>
<td>9.6 fb$^{-1}$</td>
<td>$[-0.60, +0.12]$, 68% CL</td>
<td>+0.068 $\pm$ 0.026 $\pm$ 0.009</td>
<td>Phys. Rev. Lett. 109, 171802 (2012)</td>
</tr>
<tr>
<td>D0</td>
<td>$J/\psi \phi$</td>
<td>8.0 fb$^{-1}$</td>
<td>$-0.55^{+0.38}_{-0.36}$</td>
<td>+0.163 $^{+0.065}_{-0.064}$</td>
<td>Phys. Rev. D85, 032006 (2012)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$J/\psi \phi$</td>
<td>4.9 fb$^{-1}$</td>
<td>$+0.12 \pm 0.25 \pm 0.05$</td>
<td>+0.053 $\pm$ 0.021 $\pm$ 0.010</td>
<td>Phys. Rev. D90, 052007 (2014)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$J/\psi \phi$</td>
<td>14.3 fb$^{-1}$</td>
<td>$-0.123 \pm 0.089 \pm 0.041$</td>
<td>+0.096 $\pm$ 0.013 $\pm$ 0.007</td>
<td>arXiv:1601.03297</td>
</tr>
<tr>
<td>ATLAS</td>
<td>above 2 combined</td>
<td></td>
<td>$-0.098 \pm 0.084 \pm 0.040$</td>
<td>+0.083 $\pm$ 0.011 $\pm$ 0.007</td>
<td>arXiv:1601.03297</td>
</tr>
<tr>
<td>CMS</td>
<td>$J/\psi \phi$</td>
<td>19.7 fb$^{-1}$</td>
<td>$-0.075 \pm 0.097 \pm 0.031$</td>
<td>+0.095 $\pm$ 0.013 $\pm$ 0.007</td>
<td>Phys. Lett. B757, 97–120 (2016)</td>
</tr>
<tr>
<td>LHCb</td>
<td>$J/\psi K^+ K^-$</td>
<td>3.0 fb$^{-1}$</td>
<td>$-0.058 \pm 0.049 \pm 0.006$</td>
<td>+0.0805 $\pm$ 0.0091 $\pm$ 0.0033</td>
<td>Phys. Rev. Lett. 114, 041801 (2015)</td>
</tr>
<tr>
<td>LHCb</td>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>3.0 fb$^{-1}$</td>
<td>$+0.070 \pm 0.068 \pm 0.008$</td>
<td>—</td>
<td>Phys. Lett. B736, 186 (2014)</td>
</tr>
<tr>
<td>LHCb</td>
<td>above 2 combined</td>
<td></td>
<td>$-0.010 \pm 0.039$(tot)</td>
<td>—</td>
<td>Phys. Rev. Lett. 114, 041801 (2015)</td>
</tr>
<tr>
<td>LHCb</td>
<td>$D_s^+ D_s^-$</td>
<td>3.0 fb$^{-1}$</td>
<td>$+0.02 \pm 0.17 \pm 0.02$</td>
<td>—</td>
<td>Phys. Rev. Lett. 113, 211801 (2014)</td>
</tr>
</tbody>
</table>

+ latest LHCb result with $B_s \rightarrow \psi(2S) \phi$ [LHCb-PAPER-2016-027 in preparation]
**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
  
  – PRD 89 (2014) 012002

- Precise measurements of semileptonic asymmetries from LHCb do not confirm the anomaly

- Latest measurement of $a_{s1}(B_s)$ using $B_s \rightarrow D_s(KK\pi)\mu\nuX$ decays

\[
\frac{N(D_{s-}^{\mu^+}) - N(D_{s+}^{\mu^-})}{N(D_{s-}^{\mu^+}) + N(D_{s+}^{\mu^-})}
\]

Note: $a_{s1}(B_d)$ and $a_{s1}(B_s)$ are very small in the SM

\[
a_{s1}^s = (2.22 \pm 0.27) \times 10^{-5} \text{ for } B_s^0
\]

\[
a_{s1}^d = (-4.7 \pm 0.6) \times 10^{-4} \text{ for } B^0
\]

Artuso, Borissov, Lenz [arXiv:1511.09466]

PRL 117 (2016) 061803

\[
a_{s1}^s = (0.39 \pm 0.26\text{(stat)} \pm 0.20\text{(syst)})\%
\]
Some novelties in the $B^0$-$\bar{B}^0$ system too

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

- New measurement of width difference $\Delta \Gamma_d / \Gamma_d$ by ATLAS
  - Comparing decay-time distributions of $B^0 \rightarrow J/\psi K_S$ and $B^0 \rightarrow J/\psi K^{*0}$
  $\Delta \Gamma_d / \Gamma_d = (-0.1 \pm 1.1 \text{ (stat.)} \pm 0.9 \text{ (syst.)}) \times 10^{-2}$
  JHEP 06 (2016) 081, SM-like
- Most precise single measurement of $\Delta \Gamma_d / \Gamma_d$ to date
Tree-level determination of $\gamma$

- $\gamma$ is 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>
<td>$D \rightarrow h^+\pi^-\pi^+\pi^-$</td>
<td>GLW/ADS</td>
</tr>
<tr>
<td>$B^+ \rightarrow Dh^+$</td>
<td>$D \rightarrow h^+h^-\pi^0$</td>
<td>GLW/ADS</td>
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<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow K^0_S h^+h^-$</td>
<td>GGSZ</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
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<td>GLS</td>
</tr>
<tr>
<td>$B^+ \rightarrow Dh^+\pi^-\pi^+$</td>
<td>$D \rightarrow h^+h^-$</td>
<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>$D \rightarrow K^0_S \pi^+\pi^-$</td>
<td>GGSZ</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^+_s K^\pm$</td>
<td>$D^+_s \rightarrow h^+h^-\pi^+$</td>
<td>TD</td>
</tr>
</tbody>
</table>

- Significantly more precise than previous results from the $B$-factories and the Tevatron
Rare decays as another avenue to New Physics

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

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

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

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

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

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

Nature 522 (2015) 68
$B_{d,s} \rightarrow \mu^+ \mu^-$ 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% is found for the compatibility of the results with the SM prediction

\[
\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}
\]
\[
\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 4.2 \times 10^{-10} \text{ (95% CL)}
\]

arXiv:1604.04263
Charmless rare decays from LHCb

- Particular class of decays that can proceed only through so-called annihilation diagrams
  - Very useful to test QCD calculations
- $B^0 \to K^+K^-$ decay observed for the first time after many years of searches
  - Significance 5.8$\sigma$

$$B(B^0 \to K^+K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8}$$
$$B(B_s^0 \to \pi^+\pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}$$

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

LHCb-PAPER-2016-036 in preparation
At the dawn of a revolution?
Lepton Flavour Universality in $B \to D^{(*)}\tau\nu$

- Ratio $R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\mu\nu)}$ 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

- The ball is mainly in the experiments’ court!
  - But also theory is at work
New result on $B \to D^{(*)} \tau \nu$ from Belle

- $\mathcal{R}(D^*) = 0.302 \pm 0.030\text{(stat)} \pm 0.011\text{(syst)}$
  - First measurement of $\mathcal{R}(D^*)$ using semileptonic tag.

- $\mathcal{R}(D^*) = 0.276 \pm 0.034\text{(stat)}^{+0.029}_{-0.026}\text{(syst)}$
  - First measurement of $\tau$ polarization in $B \to D^* \tau \nu$ decay.

- $\mathcal{P}_\tau = -0.44 \pm 0.47\text{(stat)}^{+0.20}_{-0.17}\text{(syst)}$

- $\mathcal{B}(\bar{B}^0 \to D^{*-} \pi^+ \pi^- \pi^+) = (7.26 \pm 0.11 \pm 0.31) \cdot 10^{-3}$
  - to be submitted to PRD

• Also BaBar still contributing to the global endeavour

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 → stay tuned!
Other flavour anomalies

- Angular analysis of $B^0 \rightarrow K^* \mu^+ \mu^-$
  - Observables are $q^2$ (dimuon mass squared) and 3 angles (helicity basis)
  - Angular distributions provide many observables sensitive to different sources of NP see e.g. JHEP 05 (2013) 137
  - Some global theoretical fits require non-SM contributions to accommodate the data e.g. JHEP 06 (2016) 092
  - However, genuine QCD effects can also be an explanation e.g. JHEP 06 (2016) 116
  - more efforts needed to clarify the picture

- 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
  - Observation of LFU violation would be a clear sign of NP
  - LHCb observed a $2.6\sigma$ deviation from SM in the low $q^2$ region PRL 113 (2014) 151601
  - New measurements expected soon, e.g. $R_{K^*}$
First evidence 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
  - Local $CP$-violating effects studied as a function of the 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 in preparation
Beauty cross section at 7 and 13 TeV

• Production of $b$ quarks in high energy $pp$ collisions at the LHC provides a sensitive test of QCD computations and constraints for PDFs

• LHCb measured the cross-section for the process $pp \rightarrow b\bar{b}X$ at two different centre-of-mass energies within $2 < \eta < 5$

• Measurement done using semileptonic decays of $b$-flavored hadrons decaying into a charmed hadron in association with a muon

• The ratio of 13 to 7 TeV cross sections appears to depart from FONLL theory predictions at low $\eta$
  – Upcoming measurements with exclusive decays will provide further inputs to drive theory developments
## 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 $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$

- LHC is delivering luminosity at an incredibly high pace in Run-2
  - Prospects in the table above might be conservative
- Note that beauty production cross section roughly doubles passing from 7 to 13-14 TeV $pp$ collisions
- LHCb upgrade comes already after Run-2, whereas the HL (phase-2) ATLAS and CMS upgrades come after Run-3
- LHCb is starting to consider a phase-2 upgrade for Run 5+

Forthcoming LHCb upgrade and Belle II

- LHCb upgraded detector after Run-2 → instantaneous luminosity will be raised by a factor 5 from $4 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ to $2 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- The hardware trigger stage will be eliminated, and the trigger will become fully software based
  - running at 40 MHz and recording 20 kHz of output rate
- Some changes to the readout system, plus replacement of RICH photodetectors and of tracking detectors
- Very exciting prospects from the SuperKEKB machine and new Belle II detector
  - SuperKEKB will deliver almost two orders of magnitude larger integrated luminosity than KEKB
- Expected to start ramping up some time in 2019
- Eagerly waiting for new outstanding results!
Concluding remarks

• The SM is a stubborn animal, indeed!

• 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

• If instead, as we all hope, new particles will be detected in direct searches, flavour physics will be a crucial ingredient to understand the structure of what lies beyond the SM