Overview of LHCb results

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On behalf of the LHCb Collaboration
Broad a physics programme @ LHCb

About 450 papers encompassing heavy flavour physics, EWK, QCD, exotica searches, heavy-ions, ...
Overview

Several LHCb results shown in this conference:

• Lepton flavour universality – Lorenzo Capriotti [Tuesday ]
• EWK – Vuko Brigljevic [Today]
• B spectroscopy – Niladribihari Sahoo [Today]
• Multi-quark states – Antimo Palano [Today]
• Dark matter searches - Pablo Martinez Ruiz del Arbol [Tomorrow]

Here a personal selection of recent results from areas not covered by other speakers

• CP violation
• Rare Decays
• Charm spectroscopy
• Fixed-target physics
LHCb detector

**Dipole magnet**
4Tm bending power
Polarity +/-

**VELO**
$\sigma_{ip} \sim 20 \mu m$
(high $p^T$ tracks)

**Interact ion point**

**RICH detectors**
$\varepsilon(K) \sim 95%$
for 5% $\pi \rightarrow K$ misID

**TRACKING Systems**
$\Delta p/p = 0.5 - 0.8%$
(20-100 GeV)

**CALORIMETERS**
ECAL: $\sigma_{E/E} \sim 1\% \oplus 10%/\sqrt{E}$

**MUON system**
$\varepsilon(\mu) \sim 97%$
for 1-3% $\pi \rightarrow \mu$ misID

**Single arm spectrometer:**
Large acceptance for $b\bar{b}$ and $c\bar{c}$ in forward region
$2<n<5$

**Precision tracking and vertexing**
Excellent PID systems
Efficient leptonic and hadronic trigger
Large beauty and charm cross-sections in pp collisions at LHC energies:

$O(10^{11}) \ b\bar{b}$ pairs/fb$^{-1}$

$O(10^{12}) \ c\bar{c}$ pairs/fb$^{-1}$

in LHCb acceptance

Total integrated recorded luminosity approaching 9 fb$^{-1}$
Above target (8 fb$^{-1}$) thanks to excellent LHC performance
Indirect search of new physics through CKM metrology

CP violation in B decays

- Measurement of $\gamma$ with $B \rightarrow DK$
- Combination of measurements of $\gamma$

New sources of CPV, predicted in many BSM scenarios, may be revealed through effects in the KM mechanism.
Status of CKM

All constraints on the apex of Unitarity Triangle are consistent
The irreducible phase of the CKM matrix explains all CPV effects observed so far
Great success for the SM! Many experiments contributing

Still room for NP at 10-20% level
More precision necessary to reveal potential discrepancies
Crucial role played by theoretically “clean” measurements, particularly $\gamma$
B$^-$→DK$^-$: the golden mode for $\gamma$

\[ \gamma = \arg \left[ -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right] \]

Essentially no theoretical uncertainties:
- Tree-level only
- All hadronic unknowns determined from data

Experimental challenges:
- $V_{ub}$ mediated transitions involved $\Rightarrow$ Small BF
- Fully hadronic decays

Different methods to determine $\gamma$ depending on $f_D$ (final state common to $D^0$ and $\bar{D}^0$)

- **GLW**: $f_D = KK, \pi\pi$  

- **ADS**: $f_D = K\pi, K\pi\pi\pi$  

- **GGSZ**: $f_D = K_S\pi\pi, K_SKK$  

- **GLS**: $f_D = K_SK\pi$  

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8
\( \gamma \) from \( B^{-}\rightarrow DK^{-}, \ D\rightarrow K_{S}h^{+}h^{-} \)

Measure \( B^{\pm} \) rates in bins of \( K_{S}\pi\pi \) and \( K_{S}KK \) Dalitz Plots (DP) - Bins chosen to maximise sensitivity to \( \gamma \)

Fit for cartesian coordinates
\[
\begin{align*}
x_{\pm} &= r_{B} \cos (\delta_{B} \pm \gamma) \\
y_{\pm} &= r_{B} \sin (\delta_{B} \pm \gamma)
\end{align*}
\]
using external input from CLEO-c
No assumptions on D decay amplitude

Non-zero opening angle between \((x-, y-)\) and \((x+, y+)\) equals 2 \( \gamma \)

\( \gamma = 80^{+10}_{-9} \degree \) \[\text{Run1+Run2, 5 fb}^{-1}\] Most precise determination of \( \gamma \) from single channel
Combination of tree-level measurements of $\gamma$

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

*New additions

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LHCb Preliminary

$B^+ \to DK^+, D \to 3\pi/hh'\pi^0$

$B^+ \to DK^+, D \to K^0_Shh$

$B^+ \to DK^+, D \to KK/K\pi/\pi\pi$

All $B^+$ modes

Full LHCb Combination
Updated combination of LHCb measurements of $\gamma$

Most precise measurement from single experiment

$\gamma = (74.0^{+5.0}_{-5.8})^0$

WA of direct measurements
$\gamma = (73.5^{+4.2}_{-5.1})^0$ HFLAV, winter 2018

Indirect measurement consistent within $\sim 2\sigma$
$\gamma = (65.8 \pm 2.2)^0$ UTFIT, summer 2018, preliminary

Small internal tensions [$B_s$ vs $B^+$ $\sim 2\sigma$] will be monitored as more data are analysed

The absolute highlight for CKM physics
P. Sphicas, this conference

$B^+, B^0, B_s$ combination is an LHCb triumph
P. Urquijo, ICHEP18
A holy grail

**CP violation in charm**

- CPV search with $D \rightarrow K\pi$

Charm = only up-type quark that forms weakly decaying hadrons. Unique physics access

CPV in the SM very small $O(10^{-3} - 10^{-4})$: not observed yet. Requires very large data samples.

Excellent prospects for observing new physics that could enhance it above SM level

LHCb has the largest data-sample of charmed hadrons on tape, and is ideally positioned to do these measurements
CPV and mixing with $D \rightarrow K\pi$

Very large data samples of both RS ($D^0 \rightarrow K^-\pi^+$) and, crucially, WS ($D^0 \rightarrow K^+\pi^-$)

CP-averaged time-dependent ratio of WS over RS

$$R(t) \approx R_D + \sqrt{R_D} \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

$$x' = x \cos\delta + y \sin\delta \quad x = \Delta m / \Gamma$$

$$y' = y \cos\delta - x \sin\delta \quad y = \Delta \Gamma / 2\Gamma$$

Variations of R with decay-time imply $D^0$-$\bar{D}^0$ mixing

Differing patterns between $D^0$ and $\bar{D}^0$ imply CPV
**R⁺(t) and R⁻(t)**

WS/RS yields measured separately for D⁰ [R⁺] and D⁰ bar [R⁻] tagged events as a function of decay time.

Soft-pion from D*± decays tags flavour at production, e.g. D*⁺ → D⁰π⁺

R⁺(t) ≠ R⁻(t) ⇒ CPV (direct + indirect)

R⁺(t) ≠ R⁻(t) ⇒ direct CPV

No differences observed

Fit ratios of yields in decay-time bins using three different hypotheses:

- CPV allowed (two sets of mixing parameters)
- No direct CPV
- No CPV (only one set of mixing parameters)
No CPV in charm! yet..

Assuming CP conservation

\[ x'^2 = (3.9 \pm 2.7) \cdot 10^{-5} \]
\[ y' = (5.28 \pm 0.52) \cdot 10^{-3} \]
\[ R_D = (3.454 \pm 0.031) \cdot 10^{-3} \]

Allowing for CPV

\[ A_D = \frac{(R_D^+ - R_D^-)}{(R_D^+ + R_D^-)} \]
\[ A_D = (-0.1 \pm 9.1) \cdot 10^{-3} \]

1.00 < |\( q/p \) | < 1.35

Most stringent bounds from single experiment
Another indirect way to probe NP

**Rare decays**

- Fully leptonic $B_{(s)} \rightarrow \mu\mu$
- Semileptonic $b \rightarrow sll$ and $b \rightarrow dll$
- Rare charm $D \rightarrow hh\mu\mu$

FCNC suppressed in SM hence NP effects can compete

New particles may significantly alter decay rates or phases.
Many observables, depending on final state
B\(^{(0)}\)\(_S\) → \(\mu^+\mu^-\) “a golden mode for SUSY”

CKM and helicity suppressed, tiny BF in SM:
\[
\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9} \\
\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}
\]
Bobeth et al., PRL 112 (2014) 101801

Precisely predicted
⇒ very sensitive to NP

Bs → \(\mu\mu\) first observed with CMS+LHCb Run1 data
Nature 522(2015)68

LHCb 2017 update uses Run1(3fb\(^{-1}\)) + Run2(1.4 fb\(^{-1}\))
Bs → \(\mu\mu\) finally observed by a single experiment!
(7.8\(\sigma\))

\[
\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad (\sim 20\%)
\]

Also first lifetime measurement
\[
\tau_{eff}(B_s(t) \rightarrow \mu^+\mu^-) = (2.04 \pm 0.44 \pm 0.05) ps
\]

It could be affected by NP via large \(\Delta\Gamma_s\)
More data needed to be sensitive
**b→sμμ decay rates**

Differential branching fractions measured with Run1 data

In general, data tend to be lower than SM prediction at low $q^2$ (~1-3 $\sigma$)

Comparison limited by theoretical uncertainties [form factors]
$B^0 \rightarrow K^{*0}\mu\mu$ angular analysis

3.4 $\sigma$ global significance

Tempting anomaly.: the angular distribution parameter $P_5$ was built to be robust against FF uncertainties. Even more tempting when considered together with the other $b\rightarrow sll$ anomalies, particularly the hints of LFUV (see talk by Lorenzo Capriotti and J. Kamenik on Tuesday).

Need to improve experimental precision and theoretical understanding of hadronic corrections. Run2 data will shed more light.
\[ \Lambda_b \to \Lambda \mu \mu \] angular analysis

- Another b->s\mu\mu transition in baryon sector
  - Spin \( \frac{1}{2} \) fermions \( \Rightarrow \) system described by 5 angles
  - Fit angular distribution, 34 observables (some vanish if lambda is unpolarised)

\[
\frac{d^5 \Gamma}{d\Omega} = \frac{3}{32\pi^2} \sum_{i}^{34} K_i f_i(\Omega)
\]

- Analysis use 3fb\(^{-1}\) Run1 + 2fb\(^{-1}\) Run2 data
- Fit performed in high \( q^2 \) region
  \( 15 < q^2 < 20 \text{ GeV}^2 \)
  where yields allows full angular analysis
  (~600 signal events)
- First analysis of this kind
  Consistent with SM expectation

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b→dll transitions

Increased interest in the suppressed b→dll transition due to the b→sll anomalies

Already observed: B⁺→π⁺μ⁺μ⁻, B⁰→π⁻π⁺μ⁺μ⁻, Λ_b→pπ⁻μ⁺μ⁻

LHCb 2018: first evidence for B_s→K*⁰μ⁺μ⁻ [3.4 σ]

\[ \mathcal{B}(B^0_s \rightarrow \bar{K}^{*0} \mu^+ \mu^-) = [2.9 \pm 1.0 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.3 \text{ (norm)}] \times 10^{-8} \]

Measured BF consistent with SM prediction O(10⁻⁸) and naïve scaling by |Vtd/Vts|^2 of B⁰→K*⁰μ⁺μ⁻ branching fraction

Angular distributions and LFU studies with future LHCb upgrade data-sample
Rare charm: $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$

$D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ and $D^0 \rightarrow K^+ K^- \mu^+ \mu^-$ are the rarest charm decays observed [BF $O(10^{-7})$] LHCb, PRL119(2017)181805

Sensitive to NP but need to mitigate effects from long-distance contributions

We can now look at kinematic correlations between final states particles, which provide discrimination between short and long-distance contributions

5 fb$^{-1}$, Run1+Run2

$D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ results

$A_{FB} = $ Forward-backward asymmetry
$A_{2\phi} = $ Triple product asymmetry
$A_{CP} = $ CP asymmetry

All asymmetries predicted to be tiny in the SM

$A_{FB}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (3.3 \pm 3.7 \pm 0.6)\%,$
$A_{2\phi}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (-0.6 \pm 3.7 \pm 0.6)\%,$
$A_{CP}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (4.9 \pm 3.8 \pm 0.7)\%,$
$A_{FB}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (0 \pm 11 \pm 2)\%,$
$A_{2\phi}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (9 \pm 11 \pm 1)\%,$
$A_{CP}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (0 \pm 11 \pm 2)\%,$

All consistent with zero
First measurement of this kind with rare charm!
Hadron spectroscopy

Recent results on charmed baryons

For results on beauty spectroscopy, see contribution by N.Sahoo

For results on multiquark states, see contribution by A.Palano
• First observation of this doubly-charmed baryon in the decay $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$


• Measurement of the lifetime critical to confirm its nature. Result consistent with expectations from weak decays

$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022} \pm 0.014$ ps

PhysRevLett 121 (2018) 052002

• Recently observed also in $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$

Combined mass:

$m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65 \text{ (stat)} \pm 0.31 \text{ (syst)} \text{ MeV}/c^2$
$\Omega^0_c$ lifetime

- About 1000 $\Omega^0_c \rightarrow pK^- K^- \pi^+$ from $\Omega^-_b \rightarrow \Omega^0_c \mu^- \nu_\mu X$
- Measured wrt $D^+ \rightarrow K^- \pi^+ \pi^+$ from $B \rightarrow D^+ \mu^- \nu_\mu X$ to reduce systematic uncertainties

$$\tau(\Omega^0_c) = 268 \pm 24 \text{ (stat)} \pm 10 \text{ (syst)} \pm 2(D^+) \text{ fs}$$

4 times larger than and not consistent with current PDG average (69 ± 12 fs)
Fixed target physics
Something beyond flavour
LHCb fixed target-like geometry well suited for fixed-target physics

A small amount of noble gas (He, Ne, Ar,..) can be injected in the beam pipe around the LHCb interaction region (~±20m) using SMOG (System for Measuring Overlap with Gas)

Rich and varied programme
Important synergies with astro-particle physics
Antiproton production in pHe

- Ratio of antiproton to proton flux in cosmic rays measured precisely by AMS-02 and PAMELA

Main anti-p production mechanism: interaction of cosmic-ray protons with interstellar medium (H, He)

Excess observed at high T, though can be accommodated within current uncertainties

Predictions limited by knowledge of anti-p production cross-sections.

Large uncertainties on cross-section from models of hadronic interactions [predictions vary by a factor ~2]
Anti-proton production in pHe

- Proton energy 6.5 TeV, $\sqrt{s_{NN}} = 110$ GeV
- 0.5 nb$^{-1}$, most data from a single LHC fill (5h)
- Exploit excellent PID capabilities to count antiprotons in (p, PT) bins

- First measurement of antiproton production in pHe collision
- Precision well below the spread among models (uncertainty <10% for most bins)
- Crucial input for interpreting the results from space-born experiments in the 10-100 GeV region
LHCb upgrades

What’s ahead of us?
Upgrade I in construction

- will allow to run at 5 x current instant luminosity
- aim to collect 50 fb$^{-1}$ by LS4
- detector consolidation and modest enhancement foreseen in LS3 (start of HL-LHC)
LHCb Upgrade I detector

All sub-detectors read-out at 40 MHz for a fully software trigger

**VELO**
New pixel vertex detector

**UT**
New silicon Upstream Tracker

**RICH detectors**
New RICH optics and photodetector

**MUON system**
New electronics

**CALORIMETERS**
New electronics

**SciFi**
New SCIntillator Fiber tracker

**Interaction point**

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LHCb Upgrade I: essentially a new detector at LHC!

- Less than 10% of LHCb detector channels will be kept
- 100% of R/O electronics will be replaced
- NEW DAQ system and DATA CENTER

©F.Alessio
LHCb Upgrade I: sub-detector construction underway

Velo module

UT sensor

RICH MAMPT under test

SciFi Module

UT staves constructions

Calorimeter electronics

Test of muon electronics
LHCb Upgrade II

- Major detector upgrade in LS4 (2030)
  - Expression of Interest [CERN-LHCC-2017-003]
- Aim to run at 10 x Upgrade I luminosity and collect 300 fb\(^{-1}\)
  - Challenging conditions for flavour physics
    (number of visible interactions/bunch crossing \sim 50)
- Physics case document released last month [CERN-LHCC-2018-027]
- LHCb may be the only large-scale flavour physics experiment to run in HL-LHC era
More information here
Conclusion

• Flavour physics is a powerful probe for physics beyond the SM. Indirect searches of new physics with flavour are complementary to direct searches. Flavour extends the new physics reach of LHC to scales beyond the collision energy.

• Flavour physics is the LHCb main purpose but a broad programme even beyond flavour has been developed.

• ~100 papers since last “LHC days” in Split by LHCb. Only a few presented here.
  • CKM metrology: improving precision. Uncertainty on angle $\gamma$ now $\sim 5^\circ$.
  • No CPV violation in charm observed yet, but precision has reached interesting region $O(10^{-2}-10^{-3})$ [SM predictions in the range $10^{-3}-10^{-4}$].
  • Rare decays: good consistency of data with SM in most cases, setting strong constraints on BSM scenarios, but some alluring tensions have emerged.
  • Hadron spectroscopy also providing exciting/puzzling results.
  • Fixed target programme: unique among LHC experiments. Important inputs to cosmic rays studies.

• Many key measurements will still be limited by statistics after upcoming LHCb upgrade (Upgrade I, installation in 2019-20). Strong physics case for a second major upgrade in the HL-LHC era (Upgrade II, $\sim 2030$).
Thank You
### Projected sensitivity

<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>
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</thead>
<tbody>
<tr>
<td><strong>EW Penguins</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_K^*$ ($1 &lt; q^2 &lt; 6 \text{GeV}^2c^4$)</td>
<td>0.1</td>
<td>0.025</td>
<td>0.036</td>
<td>0.007</td>
<td>–</td>
</tr>
<tr>
<td>$R_{K^*}$ ($1 &lt; q^2 &lt; 6 \text{GeV}^2c^4$)</td>
<td>0.1</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 $B^0_s \to D^+_s K^-$</td>
<td>($\frac{+17}{-22}$)$^0$</td>
<td>4$^0$</td>
<td>–</td>
<td>1$^0$</td>
<td>–</td>
</tr>
<tr>
<td>$\gamma$, all modes</td>
<td>($\frac{+50}{-35}$)$^0$</td>
<td>1.5$^0$</td>
<td>1.5$^0$</td>
<td>0.35$^0$</td>
<td>–</td>
</tr>
<tr>
<td>$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$</td>
<td>0.04</td>
<td>0.011</td>
<td>0.005</td>
<td>0.003</td>
<td>–</td>
</tr>
<tr>
<td>$\phi_s$, with $B^0_s \to J/\psi \phi$</td>
<td>49 mrad</td>
<td>14 mrad</td>
<td>–</td>
<td>4 mrad</td>
<td>22 mrad</td>
</tr>
<tr>
<td>$\phi_s$, with $B^0_s \to D^+_s D^-$</td>
<td>170 mrad</td>
<td>35 mrad</td>
<td>–</td>
<td>9 mrad</td>
<td>–</td>
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<tr>
<td>$\phi^{x_s}$, with $B^0_s \to \phi \phi$</td>
<td>154 mrad</td>
<td>39 mrad</td>
<td>–</td>
<td>11 mrad</td>
<td>Under study</td>
</tr>
<tr>
<td>$q_{st}$</td>
<td>$33 \times 10^{-4}$</td>
<td>$10 \times 10^{-4}$</td>
<td>–</td>
<td>$3 \times 10^{-4}$</td>
<td>–</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>$</td>
<td>6%</td>
</tr>
<tr>
<td>$B^0_s, B^0 \to \mu^+ \mu^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B^0 \to \mu^+ \mu^-) / B(B^0_s \to \mu^+ \mu^-)$</td>
<td>90%</td>
<td>34%</td>
<td>–</td>
<td>10%</td>
<td>21%</td>
</tr>
<tr>
<td>$\tau_{B^0_s \to \mu^+ \mu^-}$</td>
<td>22%</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>0.2</td>
<td>–</td>
</tr>
<tr>
<td>$b \to c \ell^- \bar{\nu}_\ell$ LUV studies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(D^*)$</td>
<td>0.026</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</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>$\Delta A_{CP}(s K - s \pi)$</td>
<td>$8.5 \times 10^{-4}$</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>$A_T (\approx x \sin \phi)$</td>
<td>$2.8 \times 10^{-4}$</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 $D^0 \to K^+ \pi^-$</td>
<td>$13 \times 10^{-4}$</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>
LHCb Upgrade II

EWK penguins
LFUV in $b \rightarrow c l \nu$?

$$R(D^*) \equiv \frac{\overline{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau}{\overline{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu}$$

**Updated HFLAV -- 3.6-3.8\(\sigma\) tension**
LFUV in $b \to s l l$?

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

2.6$\sigma$ low

2-2.5$\sigma$ low
$\mathbf{B^0 \to K^{*0}(K\pi)\mu\mu:}$ angular analysis

Study decay rate as a function of muon invariant mass and three angles

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\
\left. + \frac{1}{2}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l \\
- F_L \cos^2 \theta_K \cos 2\theta_l + S_0 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_6 \sin 2\theta_K \sin \theta_l \cos \phi \\
+ \frac{1}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right] 
\]

$F_L$, fraction of longitudinal polarisation of $K^{*0}$

Set of observables with reduced hadronic uncertainties defined using ratios

\[ P_{4,5,8}' = \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}} \]

Independent of form-factors at leading order

S.Descotes-Genon et al., JHEP01(2013)048

Compatibility of LHCb result with SM: 3.4\sigma
**b→sμμ anomalies interpretations**

Global fits to b→sμμ measurements including branching fractions and angular observables

- Good consistency among measurements
- ~4-5 σ deviation wrt SM for Wilson coefficient C₉

Possible NP scenarios (among others)

SM explanations not ruled out:
- uncertainties from poorly understood charm loop contributions

Note: charm-loop contributions are lepton-flavour universal.
\[ B^{(0)}_s \rightarrow \mu^+ \mu^- \]

consistent with SM

PRL 118, 191801 (2017)

Setting strong constraints on NP models, e.g., SUSY

D. Straub, arXiv:1012.3893

* Courtesy J. Coelho

* Courtesy J. Coelho
\[ \sin 2\beta \text{ from } B^0 \to J/\psi K^0_S \text{ and } B^0 \to \psi(2S) K^0_S \]

\[ \sin(2\beta) \equiv \sin(2\phi_1) \]

LHCb Run1 result dominated by statistical uncertainties

Precision competitive with BaBar and Belle

Indirect constraint: 0.740 \([-0.020\ -0.025]\) CKMFITTER

JHEP11(2017)170
2\beta+\gamma \text{ from } B^0 \rightarrow D^{\pm}\pi^{\mp} \text{ decays}

CP violating phase from time-dependent asymmetries of $B^0$ and $B^0$bar rates vs decay

3 fb$^{-1}$, Run1

Large yields but small CP asymmetries
(suppressed by ratio of suppressed over favoured decay amplitudes)

Used to constrain $\gamma$, using $\beta$ from external measurements
\[ \phi_s \text{ from } B_s \rightarrow J/\pi \phi \]

Ignoring small penguin contributions \( \phi_s = -2\beta_s \)

Most recent LHCb result (Run1) include \( B_s \rightarrow J/\pi \phi, B_s \rightarrow J/\pi \pi \pi, B_s \rightarrow J/\pi \) KK above \( \phi(1020) \)

**JHEP 08(2017)037**

\[ \phi_s = 1 \pm 37 \text{ mrad} \]
\[ |\lambda| = 0.973 \pm 0.013 \]
\[ \Gamma_s = 0.6588 \pm 0.0022 \pm 0.0015 \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.0813 \pm 0.0073 \pm 0.0036 \text{ ps}^{-1} \]

Good agreement with SM: \(-2\beta_s = -37 \pm 0.6 \text{ mrad}\)

[CKMfitter, Phys. Rev. D84, 033005 (2011), updated with Summer 2016 results],

HFLAV 2018 combined precision on \( \phi_s \): 33 mrad