Perspectives in $B$ Physics: Results from LHCb

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on behalf of the LHCb Collaboration

Outline:
- Introduction
- Unitarity Triangle
- Meson Mixing
- Rare $B$ decays

Supported by
Quark sector in Standard Model

Yukawa couplings to Higgs

$$\mathcal{L}_{\text{quarks}}^{\text{Y}} = -\frac{\nu}{\sqrt{2}} \left( \bar{d}_L Y_d d_R + \bar{u}_L Y_u u_R \right) + \text{h.c}$$

Quark masses

<table>
<thead>
<tr>
<th>Quark</th>
<th>Masses</th>
</tr>
</thead>
<tbody>
<tr>
<td>up</td>
<td>2.4</td>
</tr>
<tr>
<td>down</td>
<td>4.8</td>
</tr>
<tr>
<td>charm</td>
<td>104</td>
</tr>
<tr>
<td>bottom</td>
<td>1270</td>
</tr>
<tr>
<td>top</td>
<td>4200</td>
</tr>
<tr>
<td>top</td>
<td>171200</td>
</tr>
</tbody>
</table>

6 parameters

Flavor transitions across generations

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

3 +1 parameters

⇒ Rich phenomenology, well tested but very puzzling!

40 years: Discovery of the $\Upsilon$  [S. W. Herb et al. Phys. Rev. Lett. 39, 245 (1977)]
Effect of quark mixing - FCNCs

\[
\begin{pmatrix}
  u \\
  d
\end{pmatrix}
\begin{pmatrix}
  c \\
  s
\end{pmatrix}
\begin{pmatrix}
  t \\
  b
\end{pmatrix}
\rightarrow
\begin{array}{c}
  B^0 \\
  \bar{B}^0
\end{array}
\]

\[
\begin{pmatrix}
  d \\
  b
\end{pmatrix}
\begin{pmatrix}
  t
\end{pmatrix}
\begin{pmatrix}
  W
\end{pmatrix}
\]

\[
\Delta m_d = 0.5156 \pm 0.0061 \text{ ps}^{-1}
\]
Effects of CKM Phases – CP Violation

Example of CP violation: $B^\pm \rightarrow \pi^\pm$ KK

Remark: So far CPV has been seen only in meson decays. Recently LHCb reported evidence for CPV in baryon decays:

CPV in $\Lambda_b \rightarrow p\pi^-\pi^+\pi^-$ w/ 3.3$\sigma$

"New Physics" in Quantum-Loops

Standard Model

\[
\begin{align*}
\Lambda_+ &= 220 \text{NP} \\
W &\rightarrow t \\
\end{align*}
\]

New Physics

\[
\begin{align*}
Y &\rightarrow X \\
\end{align*}
\]

\[\mathcal{A}_{SM} + \mathcal{A}_{NP}\]

Search for deviations from Standard Model predictions:
Suppressed processes, observables w/ small theoretical errors
High-rate experiments to maximize sensitivity: LHC(b) / Belle-2
Heavy flavor production at LHC(b)

$$\sigma(pp \rightarrow b\bar{b}X)$$

7 TeV: $\approx 295 \ \mu$b
13 TeV: $\approx 600 \ \mu$b  

PRL 118, 052002 (2017)

$$\sigma(pp \rightarrow c\bar{c}X) \approx 20 \times \sigma_{bb}$$

Run 1 (in LHCb acceptance)

$$\begin{align*}
    pp: & \quad 18 \times 10^{13} \\
    c\bar{c}: & \quad 5.9 \times 10^{12} \\
    b\bar{b}: & \quad 2.6 \times 10^{11}
\end{align*}$$

$\sim 3$ fb$^{-1}$

Run 2: 2 fb$^{-1}$ at 13 TeV

effect. data: $\times 2$

Run II

Limit visible bunch cross. to $\sim 1.1$

$\rightarrow \mathcal{L} \approx 4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ (levelled)

Integrated Recorded Luminosity (L/fb)

- 2016 (6.5 TeV): 1.67 /fb
- 2015 (6.5 TeV): 0.32 /fb
- 2012 (4.0 TeV): 2.08 /fb
- 2011 (3.5 TeV): 1.11 /fb
- 2010 (3.5 TeV): 0.04 /fb
Heavy flavor production at LHC(b)

\[ \sigma(pp \rightarrow b \bar{b}X) \]

- 7 TeV: \( \approx 295 \ \mu b \)  
- 13 TeV: \( \approx 600 \ \mu b \)

\( \sigma(pp \rightarrow c \bar{c}X) \approx 20 \times \sigma_{bb} \)

Run 1 (in LHCb acceptance)
- \( pp: 18 \times 10^{13} \)
- \( cc: 5.9 \times 10^{12} \)
- \( bb: 2.6 \times 10^{11} \)

\(~ 3 \text{fb}^{-1} \)

Run 2: \( 2 \text{fb}^{-1} \) at 13 TeV

\( \times 2 \) effect.

Limit visible bunch cross. to \( \sim 1.1 \)
\( \rightarrow \mathcal{L} \approx 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \) (levelled)
Searching for NP - selected LHCb measurements

CKM Metrology

$\gamma$ via direct CPV
$\sin 2\beta$ via t-dep. CPV
$V_{ub}$ semilept. decays

B$_s$ - Mixing

$A_{mix} = |A_{mix}| e^{-i\phi_{mix}}$

Mixing and mixing phases

Rare decays - FCNCs

B$^0$ K$^{0*}$

angular distribution

B$_{d,s}$

rates

D$^0$ – Mesons

Mixing and CP violation

Penta-Quarks:
PRL 115 (2015) 072001
4-Quark exotics
arXiv:1606.07895;
arXiv:1606.07898
$\Omega_c$ states
arXiv:1703.04649

Hadron Spectroscopy
Unitarity Triangle – CKM Metrology

LEP, KTeV, NA48, BABAR, Belle, CDF, DØ, LHCb, CMS, ATLAS, …
Unitarity Triangle – CKM Metrology

LEP, KTeV, NA48, BABAR, Belle, CDF, DØ, LHCb, CMS, ATLAS, …

Over-constrain triangle:
trees ⇔ loops \((\gamma, V_{ub} \Leftrightarrow \sin 2\beta, \Delta m_s & \Delta m_s)\)
CKM-Phase $\gamma$

Interference between $b \to c$ and $b \to u$

- $V_{cb}$
- $V_{ub}$
- $f_D = KK, \pi \pi$ (CP state) - Gronau, London, Wyler (GLW)
- $f_D = K\pi$ and $\pi K$ (CKM favored/suppressed) - Atwood, Dunietz, Soni (ADS)
- $f_D =$ self conjugated Dalitz-modes - Giri, Grossman, Soffer, Zupan (GGSZ)

Theoretically clean. However, single measurement not very sensitive ($BR \sim 10^{-7}$). Need to combine many decay modes.

leads to direct CP violation in $B \to DK$ decays
Two examples for $B \to DK$

$B^\pm \to (K\pi)_D K^\pm$ mode ($BR \sim 10^{-7}$) was soon seen at LHCb. Being exploited for high-precision CP-violation measurements.

$B^- \to [\pi^- K^+]_D K^-$

$B^+ \to [\pi^+ K^-]_D K^+$

$B^- / B^+$ differences in multibody phase space ($D \to K_S \pi\pi\pi$ or $K_S KK$) Benefit from the high purity of signal.

ADS

GGSZ

JHEP 10 (2014) 097

PLB 760 (2016) 117

JHEP 10 (2014) 097
Combination of $\gamma$ ($B \rightarrow DK$)

Aim for 3 - 4° uncertainty after Run-2. The LHCb-Upgrade will allow for even higher sensitivity ($\sim 1°$).

<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>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow K^{0, h^+h^-}$</td>
<td>GGSZ</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow K_s^{0, K^+\pi^-}$</td>
<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>$D \rightarrow K_s^{0, \pi^+\pi^-}$</td>
<td>GGSZ</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D_s^{\mp}K^\pm$</td>
<td>$D_s^+ \rightarrow h^+h^-\pi^+$</td>
<td>TD</td>
</tr>
</tbody>
</table>

Agrees with BaBar and Belle and with prediction from CKM fits

- BaBar $\gamma = (69^{+17}_{-16})°$ PRD 87, 052015 (2013)
- Belle $\gamma = (68^{+15}_{-14})°$ arXiv:1301.2033 (2013)
- Indirect $\gamma = (65.3^{+1.0}_{-2.5})°$ CKM Fitter 2006

\[ \gamma = (72.2^{+6.8}_{-7.3})° \]
CKM Phase $\beta$

Interference mixing and decay

$A_{\text{mix}} = |A_{\text{mix}}| e^{i\phi_M}$

$\phi_M$ is the phase in the Standard Model, $\phi_M = 2\beta$

⇒ time dependent CPV:

$A_{CP}(t) \sim \eta_{CP} \sin 2\beta \sin(\Delta mt)$

“Golden decay” $B^0 \rightarrow J/\psi K_s$ (42560 evts)

$\sin 2\beta = 0.731 \pm 0.035 \pm 0.020$

(Stat. error BaBar: $\pm 0.036$ Belle: $\pm 0.029$)

World average (HFAG) $0.69 \pm 0.02$

Tensions w/ indirect value from CKM-Fit: 0.740
Unitarity Triangle: $|V_{ub}|$

$V_{ub}$ measurement thought impossible at LHC

- Use baryon decay $\Lambda_b \rightarrow p\mu\nu$, benefit from RICH & vertexing capabilities.
- Normalize to $\Lambda_b \rightarrow \Lambda_c \mu\nu$ and use lattice QCD to interpret result.

$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$$

errors: exp LQCD from $V_{cb}$

Nature Physics 10 (2015) 1038

Different LQCD calculations

PDG 2014

arXiv:1501.05373 (RBC/UKQCD)

arXiv:1503.07839 (FNAL/MILC)

arXiv:1503.01421 (RBC/UKQCD)
$B_s$ - Mixing

The time-dependent CP asymmetry is used to measure $\phi_s$.

\[ \Delta m_s = 17.768 \pm 0.023 \pm 0.006 \text{ ps}^{-1} \]

\[ \Delta m_s = 17.3 \pm 1.5 \text{ ps}^{-1} \]

Theorie (U. Nierste, 2012)
“Golden mode”: $B_s \rightarrow J/\psi \phi(KK)$

$m(KK) \approx 1.02$ GeV (ϕ region)

$\phi_s = 0.058 \pm 0.0490 \pm 0.006$ rad
$\Delta\Gamma = 0.0805 \pm 0.0091 \pm 0.0032$ ps$^{-1}$

PRL 114, 041801 (2015)

$m(KK) > 1.05$ GeV (above $\phi$)

$\phi_s = 0.12 \pm 0.11 \pm 0.03$ rad
$\Delta\Gamma = 0.066 \pm 0.018 \pm 0.019$ ps$^{-1}$

arXiv:1704.08217

New LHCb average for $\phi_s$

$\phi_s = 0.7 \pm 37.3$ mrad
(includes also $B_s \rightarrow J/\psi \pi\pi$, $D_sD_s$ data)

arXiv:1704.08217

53k evts

33k evts
Weak phase $\phi_s$

**ATLAS** and **CMS** have also measured $\phi_s$ in $B_s \rightarrow J/\psi\phi$ with full Run-1 statistics.

Impressive progress since initial measurements by CDF and D0: Uncertainty needs to be further reduced to reach SM precision.

LHCb sensitivity after **upgrade** expected to be better than 3 mrad.
CP Violation in B-mixing

\[ B^0 \rightarrow \bar{B}^0 \rightarrow \mu^- X \quad | \quad \bar{B}^0 \rightarrow B^0 \rightarrow \mu^+ X \]

\[ a_{s_l}^q \equiv \frac{\Gamma(B_q^0 \rightarrow B_q^0 \rightarrow \mu^+ X) - \Gamma(B_q^0 \rightarrow \bar{B}_q^0 \rightarrow \mu^- X)}{\Gamma(B_q^0 \rightarrow B_q^0 \rightarrow \mu^+ X) + \Gamma(B_q^0 \rightarrow \bar{B}_q^0 \rightarrow \mu^- X)} , \quad q = d, s \]

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**Diagram**

- Standard Model
- PRL 117, 061803 (2016)
- LHCb $D^{(*)\mu\nu X}$
- D0 $D^{(*)\mu\nu X}$
- BaBar $D^{*\mu}$
- BaBar $D^{\mu}$
- Belle $D^{*\mu}$
Direct CP violation: \( \Delta A_{CP} (D^0 \rightarrow h^+h^-) \)
- time integrated -
\[
\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)
\]

\begin{align*}
\text{D*-tag: } & \Delta A_{CP} = (-0.10 \pm 0.08 \pm 0.03) \% \\
\text{\mu-tag: } & \Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08) \% \\
\end{align*}

LHCb combination
\[
A_{CP} (KK) = (0.04 \pm 0.12 \pm 0.10) \% \\
A_{CP} (\pi\pi) = (0.07 \pm 0.14 \pm 0.11) \%
\]

Most precise measurements from a single experiment. No evidence of CP asymmetry.
CP violation – time dependent

\[ A_{CP}(t) \approx a_{dir}^f + A_{\Gamma} \frac{t}{\tau_D} \]

\[ A_{\Gamma} (KK) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3} \]
\[ A_{\Gamma} (\pi\pi) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3} \]

LHCb Run-1 combination
\[ A_{\Gamma} = (-0.29 \pm 0.28) \times 10^{-3} \]

\[ A_{\Gamma} \approx -a_{CP}^{ind} \]

\[ \Delta A_{CP} \approx \Delta a_{CP}^{dir} + a_{CP}^{ind} \frac{\Delta \langle t \rangle}{\tau} \]

HFAG arXiv:1612.07233

\[ a_{CP}^{ind} = (0.30 \pm 0.26) \times 10^{-3} \]
\[ \Delta a_{CP}^{dir} = (-1.34 \pm 0.70) \times 10^{-3} \]

arXiv:1702.06490

arXiv:1612.07233
Rare (FCNC) B Decays

\[ B^0 \rightarrow K^{0*} \mu^\pm \nu \]

\[ B_{d,s} \rightarrow K^{*0} \mu^\pm \nu \]
Very rare decays $B_{d,s} \rightarrow \mu^+ \mu^-$

**Standard Model:**

$B_s^0 \rightarrow \mu^+ \mu^-$

**SM prediction:**

$\text{BR}(B_s \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

$\text{BR}(B_d \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

**Sensitive for New Physics:**

(pseudo) scalar interactions

$B_s^0 \rightarrow H^-, H^0, A^0, \chi^0$
Combined CMS & LHCb Analysis

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

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

arXiv:1411.4413

CMS & LHCb

also:

Interesting sociological experiment
LHCb $B_{s,d} \rightarrow \mu\mu$ update

- Include 1.4 fb$^{-1}$ from Run-2: effectively doubles the dataset.
- Refined analysis: better background rejection

7.8$\sigma$ observation of $B_s \rightarrow \mu\mu$:
$$BR(B_s \rightarrow \mu\mu) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

No evidence yet for $B_d \rightarrow \mu\mu$:
$$BR(B_d \rightarrow \mu\mu) < 3.4 \times 10^{-10} \, (95\%CL)$$

Measurement from ATLAS
$$BR(B_s \rightarrow \mu\mu) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$
$$BR(B_d \rightarrow \mu\mu) < 4.2 \times 10^{-10} \, @95\%C.L.$$
Effective lifetime sensitive to scalar vs non-scalar New Physics contributions.

$A_{\Delta \Gamma}$ depends on effective lifetime $\tau_{\mu\mu}$
**b → s penguins: B→K*ℓ⁺ℓ⁻ and friends**

**Standard Model:**

\[ H = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum \left( C_i^{SM} + C_i^{NP} \right) O_i^{SM} + \sum \frac{C}{\Lambda_{NP}} O_{NP} \]

- \( O_7 \)
- \( O_9 \)
- \( O_{10} \)

Different \( q^2 \) probes different processes

**New Physics:** New operators (Lorentz structure / \( \mu\mu/ee \) coupl), modified Wilson coeff.

**Observables:** differential BR, angular distributions or lepton flavor violation
$B \to K^{*}\ell^+\ell^-$ and friends: differential BR

Consistent tendency to undershoot prediction at low $q^2$. Intriguing!
B→K*ℓ+ℓ− and friends: angular analysis

“Wu-Experiment” with B-mesons

Forward-backward asymmetry

\[ A_{FB} = \frac{N_F - N_B}{N_F + N_B} \]

K* longitudinal polarization

General pattern as predicted, mild tension (e.g. \( A_{FB} \)) at low \( q^2 \)

... other observables, which can be built from the measured amplitudes
**B → K*ℓ⁺ℓ⁻ and friends: angular analysis**

Constructed to be intrinsically robust against form factor uncertainties,

\[ P'_S = \frac{S_S}{\sqrt{F_L(1 - F_L)}} \]

(physically hard to visualize)

Effect seen with 1 fb⁻¹, persists with 3 fb⁻¹

Results encouraged the B-factories to dig deep into their data…

Belle, arXiv:1604.0402

… and also ATLAS and CMS presented measurements at Moriond 2017 (Run 1)

ATLAS-CONF-2017-023
CMS-PAS-BPH-15-007

**JHEP 02 (2016) 104**

3.7σ

(4-8 GeV²)

**SM: Descotes-Genon et al., JHEP 12 (2014) 125,**
B → K*ℓ⁺ℓ⁻ and friends: lepton universality

Observed tensions w/ μμ final state.
Do electrons behave the same way?

Very clean observable:
Test of lepton universality in R_K

\[ R_K = \frac{\mathcal{B}(B^\pm \rightarrow K^\pm \mu\mu)}{\mathcal{B}(B^\pm \rightarrow K^\pm ee)} \quad \text{SM} = 1 \]

(measured as double ratio, relative to B → KJ/ψ(II))

Electrons are a bit more difficult…

B → KJ/ψ(e+e−) control region

LHCb measurement for 1<q²<6 GeV²

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

-2.6σ w/r to SM  \text{ PRL 113 (2014) 151601}

Statistical fluctuation? What about \( R_{K^*} \)?
Measurement of $R_{K^*}$

- Analogous measurement for $B \rightarrow K^{*\ell^+\ell^-}$

$$R_{K^*} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0}\mu\mu)}{\mathcal{B}(B^0 \rightarrow K^{*0}ee)}$$

- Again measured as double ratio normalized to $B^0 \rightarrow K^*J/\psi(\mu\mu,ee)$

- 3 exclusive triggers for $K^*ee$:
  - On electron, On $K^*$, Not On signal

- Simulation corrected w/ efficiencies (PID, trigger) determined on data,

- Cross-check: $B(B^0 \rightarrow K^* J/\psi)$ is measured for muon and electron channel – a stringent test!

$$r_{J/\psi} = 1.043 \pm 0.006 \text{ (stat)} \pm 0.045 \text{ (syst)}$$

- Analysis performed in two $q^2$ bins
  - Low: $4m_\mu^2 < q^2 < 1.1 \text{ GeV}^2$
  - Central: $1.1 \text{ GeV}^2 q^2 < 6 \text{ GeV}^2$

Muon sample 3-5x larger
RK* Results

<table>
<thead>
<tr>
<th>LHCb Preliminary</th>
<th>low-$q^2$</th>
<th>central-$q^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{R}_{K^*0}$</td>
<td>$0.660 \pm 0.110_{0.070} \pm 0.024$</td>
<td>$0.685 \pm 0.113_{0.069} \pm 0.047$</td>
</tr>
<tr>
<td>95% CL</td>
<td>[0.517–0.891]</td>
<td>[0.530–0.935]</td>
</tr>
<tr>
<td>99.7% CL</td>
<td>[0.454–1.042]</td>
<td>[0.462–1.100]</td>
</tr>
</tbody>
</table>

Systematics:
- correction of simulation
- Kinematic selection
- Residual background due to $B^0 \rightarrow K^* J/\psi$

6.5…7.5% for central $q^2$ (depending on trigger sample)
B→K*ℓ⁺ℓ⁻ and friends: Interpretation?

Before the measurements of \( R_{K^*} \):
- Fits give >5σ pulls w.r.t. SM
- allowing for non-SM Wilson coefficients (\( C_9 \)) improves the p-value of the fits.

New \( R_{K^*} \) measurement:
- Fits into this picture (certainly for the central \( q^2 \) bin) Triggered a several papers.
  Example: arXiv:1704.05340

Situation intriguing - more work needed:

Theory: Theoretical error of some observables.
Experiment: LHCb Run-2 updates on \( R_K \), \( R_{K^*} \) and even \( R_\phi \)
Other Hints for LFV

\[ R(D^*) \equiv \frac{\mathcal{B}(B\to D^*\tau\nu)}{\mathcal{B}(B\to D^*\mu\nu)} \]

B→D*τν:
- Tree decay, not rare, only difficult
- Sensitivity to possible charged Higgs
- B-factory legacy

Was thought to be impossible at LHCb (cannot reconstructing full event):
- Reconstruct \( \tau\to\mu\nu\nu \)
- Disentangle signal from \( B^0\to D^*\mu\nu \) and other backgrounds by fitting \( E_{\mu}^* \) and \( m_{miss}^2 \) (rest frame of B) in bins of \( q^2 \)
\[ R(D^*) \equiv \frac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(B \to D^* \mu \nu)} \]

+2.1\sigma above SM

\[ R(D^*) = 0.336 \pm 0.027 \pm 0.030 \]

Systematics dominated by model uncertainties.

- New HFAG average 3.9\sigma away from SM prediction (0.252\pm0.003).
- New measurements including \( R(D^*) \) w/ \( \tau \to \pi \pi \pi \nu \) will come soon
At the End

- Precision flavor physics is an excellent tool to search for effects of New Physics beyond the TeV scale.
- Flavour-physics measurements at the LHC are adding to the impressive knowledge from the B-factories and Tevatron.
- Many of these results show good compatibility with the SM (for now), some signs of tension (LFV) are emerging.
- LHCb’s physics program beyond flavour physics: EW precision measurements, direct NP searches, forward physics, fixed target physics, heavy ion physics

Future:

8 fb⁻¹  + 50 fb⁻¹
2019  2021  2024  2027  2030

Run 2 LS2 Run 3 LS3 Run 4 LS4

2018
50 ab⁻¹
Belle-II

Install LHCb phase-I Upgrade
Install HL-LHC and ATLAS & CMS phase-II Upgrades

Supported by Bundesministerium für Bildung und Forschung

Interest HL LHCb
+ 300 fb⁻¹
Backup
$\Xi_c^+$ candidates are combined to kaons with opposite charge
(tight PID requirement and $p_T(\Xi_c^+K^-) > 4.5 \text{ GeV}$)

$10^6 \Xi_c^+$

Binned $\chi^2$ fit
### Spectroscopy: New $\Omega_c$ states

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>Yield</th>
<th>$N_\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_c(3000)^0$</td>
<td>$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$4.5 \pm 0.6 \pm 0.3$</td>
<td>$1300 \pm 100 \pm 80$</td>
<td>20.4</td>
</tr>
<tr>
<td>$\Omega_c(3050)^0$</td>
<td>$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$0.8 \pm 0.2 \pm 0.1$</td>
<td>$970 \pm 60 \pm 20$</td>
<td>20.4</td>
</tr>
<tr>
<td>$\Omega_c(3066)^0$</td>
<td>$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$</td>
<td>$3.5 \pm 0.4 \pm 0.2$</td>
<td>$1740 \pm 100 \pm 50$</td>
<td>23.9</td>
</tr>
<tr>
<td>$\Omega_c(3090)^0$</td>
<td>$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$</td>
<td>$8.7 \pm 1.0 \pm 0.8$</td>
<td>$2000 \pm 140 \pm 130$</td>
<td>21.1</td>
</tr>
<tr>
<td>$\Omega_c(3119)^0$</td>
<td>$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$</td>
<td>$1.1 \pm 0.8 \pm 0.4$</td>
<td>$480 \pm 70 \pm 30$</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td>$&lt; 2.6$ MeV, 95% CL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Omega_c(3188)^0$</td>
<td>$3188 \pm 5 \pm 13$</td>
<td>$60 \pm 15 \pm 11$</td>
<td>$1670 \pm 450 \pm 360$</td>
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</tr>
<tr>
<td>$\Omega_c(3066)_{fd}$</td>
<td></td>
<td></td>
<td>$700 \pm 40 \pm 140$</td>
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</tr>
<tr>
<td>$\Omega_c(3090)_{fd}$</td>
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<td>$220 \pm 60 \pm 90$</td>
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<tr>
<td>$\Omega_c(3119)_{fd}$</td>
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<td></td>
<td>$190 \pm 70 \pm 20$</td>
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</tr>
</tbody>
</table>
J/Ψp resonances - pentaquark states

Need to add two states with content uudccbar. Best fit has J=3/2 and 5/2 with opposite parities.

$P_c(4380)$:
$M = 4380 \pm 8 \pm 29 \text{ MeV},$
$\Gamma = 205 \pm 18 \pm 86 \text{ MeV}$

$P_c(4450)$:
$M = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV},$
$\Gamma = 39 \pm 5 \pm 19 \text{ MeV}$
Long standing interest in $J/\psi \Phi$ spectrum in $B^+ \rightarrow J/\psi \Phi K^+$, where CDF saw a narrow structure [PRL 102 (2009) 242002] dubbed the $X(4140)$. Confirmed by D0 [PRD 89 (2014) 012004] & CMS [PRL B 734 (2014) 261], but not by LHCb in early 0.37 fb⁻¹ analysis [PRD 85 (2012) 091103(R)].

A good description of spectrum requires four (!) non-standard contributions, all of which are present at $>5\sigma$ level. $X(4140)$ found to have larger width than previous analyses, and its quantum numbers are found to be $1^{++}$. This structure can also be described by a below threshold $D_s D_s^* \text{cusp.}$
SEARCH FOR $X(5568)^\pm$

Claimed observation/evidence of an exotic state ($bsud$) by DØ collaboration

✓ $X(5568)^\pm \rightarrow B_s^0\pi^\pm$, $B_s^0 \rightarrow J/\psi \phi$, $J/\psi \rightarrow \mu^+\mu^-$, $\phi \rightarrow K^+K^-$

$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}$ MeV/$c^2$

$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}$ MeV/$c^2$

N.B. $m(\Xi_b) \sim 5790$ MeV

✓ Fraction of $B_s^0$ from $X^\pm$ decay: $\rho_{X}^{DØ} = (8.6 \pm 1.9 \pm 1.4)\%$

\[\text{LHCb} \]
\[N(B_s) = 65k \]
\[\sigma_{\text{Res}} = 15 \text{ MeV} \]
\[S/B = 10 \]

\[m(D_s^-\pi^+) \text{ (MeV)} \]

\[\text{Candidates / (3 MeV)} \]

\[\text{LHCb} \]
\[N(B_s) = 45k \]
\[\sigma_{\text{Res}} = 6 \text{ MeV} \]
\[S/B = 50 \]

\[m(J/\psi \phi) \text{ (MeV)} \]

\[\text{Candidates / (3 MeV)} \]

\[\text{LHCb} \]

\[\text{LHCb} \quad \rho_{T}(B_s^0) > 5 \text{ GeV} \]

\[\text{Combinatorial} \]

\[\text{No signal in 3 fb}^{-1} \]

\[m(B_s^0\pi^+) \text{ (MeV)} \]

\[\text{Candidates / (5 MeV)} \]

\[\text{Pull} \]
Combination of $\gamma$ ($B \rightarrow DK$)

![Graph 1](image1)

$B_\tau^0$ decays
$B^0$ decays
$B^+$ decays
Combination

![Graph 2](image2)

GGSZ
GLW/ADS
Others
Combination
Possible Interpretation

Attempts to explain the “$V_{ub}$ inclusive vs exclusive” puzzle with help of right-handed currents: different sensitivity of the baryon result disfavors hypothesis.

LHCb result provides new ways to access $V_{ub}$. Look for complementary measurements, e.g. with $B_s \rightarrow K\mu\nu$. 
Constraints on New Physics

\[ \mathcal{A}_{\text{mix}} = \mathcal{A}_{\text{mix}}^{\text{SM}} + \mathcal{A}_{\text{mix}}^{\text{NP}} = \mathcal{A}_{\text{mix}}^{\text{SM}} \cdot (1 + \Delta) \]

Need to increase precision to disentangle NP phases of few degrees in \( B_d \) and \( B_s \) mixing

\[ B_s^0(\bar{b}s) < 20\% \]
\[ B_d^0(\bar{b}d) < 30\% \]
## Systematics of $R_{K^*}$

<table>
<thead>
<tr>
<th>Trigger category</th>
<th>low-$q^2$</th>
<th>central-$q^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOE</td>
<td>L0H</td>
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<tr>
<td>Corrections to simulation</td>
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<td>Trigger</td>
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<td>PID</td>
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<td>Kinematic selection</td>
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<td>Residual background</td>
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<td>Mass fits</td>
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<td>2.1</td>
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<td>Bin migration</td>
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<tr>
<td>$\tau_{J/\psi}$ flatness</td>
<td>1.6</td>
<td>1.4</td>
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<tr>
<td>Total</td>
<td>4.0</td>
<td>6.1</td>
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</table>
### Physics Reach

<table>
<thead>
<tr>
<th>Observable</th>
<th>LHCb 2017 (7 fb⁻¹)</th>
<th>Upgrade (+ 50 fb⁻¹)</th>
<th>Theory Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s$ Mixing phase $\phi_s$</td>
<td>0.025</td>
<td>0.008</td>
<td>$\sim0.003$</td>
</tr>
<tr>
<td>$\text{BR}(B_s \rightarrow \mu\mu)$</td>
<td>$0.5 \times 10^{-9}$</td>
<td>$0.15 \times 10^{-9}$</td>
<td>$0.3 \times 10^{-9}$</td>
</tr>
<tr>
<td>$\text{BR}(B_d \rightarrow \mu\mu)$ / $\text{BR } B_s \rightarrow \mu\mu$</td>
<td>$\sim100%$</td>
<td>$\sim35%$</td>
<td>$\sim5%$</td>
</tr>
<tr>
<td>CKM angle $\gamma$</td>
<td>4°</td>
<td>0.9°</td>
<td>small</td>
</tr>
<tr>
<td>CPV in D ($\Delta A_{CP}$)</td>
<td>$0.7 \times 10^{-3}$</td>
<td>$0.1 \times 10^{-3}$</td>
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</tbody>
</table>