CKM* physics at hadron colliders

Mat Charles (Sorbonne Université/LPNHE) representing the LHCb collaboration

* meaning here: **flavour physics** that lets us make **serious, indirect tests of the SM** either by itself or in combination with other measurements
Quick reminder of the players

• At the Tevatron (p\bar{p}): D0 & CDF
  • 1.96 TeV CM

• At the LHC (pp): ATLAS, CMS & LHCb
  • 2010 and 2011: 7 TeV CM
  • 2012: 8 TeV CM
  • 2015-2018: 13 TeV CM

• LHCb usually runs at a much lower luminosity/pile-up than ATLAS & CMS
  • LHCb recorded about 3 fb\(^{-1}\) in Run1 (2010-2012) and so far about 5\(\frac{1}{2}\) fb\(^{-1}\) in Run2 (2015-2018)
  • ATLAS/CMS recorded about 26 fb\(^{-1}\) in Run1 and so far about 137 fb\(^{-1}\) in Run2

Caution: Run2 numbers are probably already out of date
Back in 2016...

- Barack Obama was the US president
- France hadn't won the world cup in a generation
- There were only 14 films in the Marvel Cinematic Universe
- And at CKM, the overview talk covered:

  - 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

What* have we learned since then?

* in CKM physics
The classic Unitarity Triangle

- Disclaimer: will use $\alpha, \beta, \gamma$ notation (rather than $\phi_{2,1,3}$)
- Before BABAR & Belle, hoped for O(1) BSM effects
- Today: triumph of CKM picture
- Focus instead on over-constraining the triangle, looking for pieces that don't fit.
- Requires many careful, precise measurements.

Fits from summer 2016. Hopefully it'll be time for an update soon! See talks on Thursday morning [WG4/5].

The classic Unitarity Triangle

- On LHCb side:
  - Many incremental improvements on $\gamma$
  - Constraints on $\beta$

- Also results from B-factories, notably on $\beta$ -- see next talk!

- Let's walk through new LHCb inputs, starting with $\gamma$...

Fits from summer 2016. Hopefully it'll be time for an update soon! See talks on Thursday morning [WG4/5].

http://www.utfit.org/UTfit/

http://ckmfitter.in2p3.fr/
• Can make tree-level measurements of $\gamma$ from interference of $b \rightarrow c$ ($V_{cb}$) and $b \rightarrow u$ ($V_{ub}$) decays

• Use two-step decays, often:
  • $B \rightarrow D^0 X$, $D^0 \rightarrow f$
  • $B \rightarrow \overline{D}^0 X$, $\overline{D}^0 \rightarrow f$

• Many choices for $X$, $f$...

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

• Aside: loop-level measurements of $\gamma$ also possible (see talks on Tuesday morning, WG 5)
• No single dominant mode.

• Game instead is to make many individual measurements, combine them. Recent LHCb combination:

<table>
<thead>
<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Method</th>
<th>Ref.</th>
<th>Dataset</th>
<th>Status since last combination [3]</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>
<td>Minor update PLB 777 (2018) 16</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+ h^-$</td>
<td>ADS</td>
<td>[15]</td>
<td>Run 1</td>
<td>As before PLB 760 (2016) 117</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>
<td>As before PRD 91, 112014 (2015)</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+ h^- \pi^0$</td>
<td>GLW/ADS</td>
<td>[16]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to K^0 h^+ h^-$</td>
<td>GGSZ</td>
<td>[17]</td>
<td>Run 1</td>
<td>As before JHEP 10 (2014) 097</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to K^0 h^+ h^-$</td>
<td>GGSZ</td>
<td>[18]</td>
<td>Run 2</td>
<td>New arXiv:1806.01202</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to K^0 h^+ h^-$</td>
<td>GLS</td>
<td>[19]</td>
<td>Run 1</td>
<td>As before PLB 733C (2014) 36</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>
<td>Minor update</td>
</tr>
<tr>
<td>$B^+ \to DK^{**}$</td>
<td>$D \to h^+ h^-$</td>
<td>GLW/ADS</td>
<td>[20]</td>
<td>Run 1 &amp; 2</td>
<td>Updated results JHEP 11 (2017) 156</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>
<td>New</td>
</tr>
<tr>
<td>$B^+ \to DK^{+\pi^-\pi^+\pi^+}$</td>
<td>$D \to h^+ h^-$</td>
<td>GLW/ADS</td>
<td>[21]</td>
<td>Run 1</td>
<td>As before PRD 92, 112005 (2015)</td>
</tr>
<tr>
<td>$B^0 \to DK^{*0}$</td>
<td>$D \to K^+ \pi^-$</td>
<td>ADS</td>
<td>[22]</td>
<td>Run 1</td>
<td>As before PRD 90, 112002 (2014)</td>
</tr>
<tr>
<td>$B^0 \to DK^{+\pi^-}$</td>
<td>$D \to h^+ h^-$</td>
<td>GLW-Dalitz</td>
<td>[23]</td>
<td>Run 1</td>
<td>As before PRD 93, 112018 (2016)</td>
</tr>
<tr>
<td>$B^0 \to DK^{*0}$</td>
<td>$D \to K^0 \pi^+ \pi^-$</td>
<td>GGSZ</td>
<td>[24]</td>
<td>Run 1</td>
<td>As before JHEP 08 (2016) 137</td>
</tr>
<tr>
<td>$B^0 \to D^+_s K^\pm$</td>
<td>$D^+_s \to h^+ h^- \pi^+$</td>
<td>TD</td>
<td>[25]</td>
<td>Run 1</td>
<td>Updated results JHEP 03 (2018) 059</td>
</tr>
<tr>
<td>$B^0 \to D^{+\pi^\pm}$</td>
<td>$D^+ \to K^+ \pi^- \pi^+$</td>
<td>TD</td>
<td>[26]</td>
<td>Run 1</td>
<td>New JHEP 06 (2018) 084</td>
</tr>
</tbody>
</table>

• Won't go through them individually, but just to illustrate...
\( \gamma \) from \( B^+ \to D K^+ \), \( D \to K_S h^+ h^- \)

- GGSZ method, using CLEO-c input for phase variation across Dalitz plot (a.k.a. "model-independent")

- LHCb Run2 data (2015+2016): \( \gamma = (87^{+11}_{-12})^\circ \)
  
  Combined with prior Run1 result: \( \gamma = (80^{+10}_{-9})^\circ \)

Good agreement between Run 1 and Run2 results.

\( \text{arXiv:1806.01202} \)
We are used to saying "\( \gamma \), the least-well-known angle of the CKM triangle".

... but uncertainties on \( \alpha \) around 5°, depending on statistical treatment. Being overtaken by \( \gamma \)!

e.g. HFLAV average: \( \alpha = (84.9^{+5.1}_{-4.5})^\circ \)

\[ \gamma = (74.0^{+5.0}_{-5.8})^\circ \]
\[ \beta \text{ from } B^0 \to J/\psi K_S, \ B^0 \to \psi(2S) K_S \]

- Classic time-dependent CPV measurement, golden mode for the B-factories.
- This analysis: \( J/\psi \to e^+e^-, \ \psi(2S) \to \mu^+\mu^- \) with Run I
- ... since \( J/\psi \to \mu^+\mu^- \) done previously, PRL 115, 031601 (2015)

\[
A_{[c\bar{c}]K_S^0}(t) \equiv \frac{\Gamma(\bar{B}^0(t) \to [c\bar{c}]K_S^0) - \Gamma(B^0(t) \to [c\bar{c}]K_S^0)}{\Gamma(\bar{B}^0(t) \to [c\bar{c}]K_S^0) + \Gamma(B^0(t) \to [c\bar{c}]K_S^0)}
= \frac{S \sin(\Delta m t) - C \cos(\Delta m t)}{\cosh(\Delta \Gamma t/2) + A_{\Delta \Gamma} \sinh(\Delta \Gamma t/2)} \approx S \sin(\Delta m t) - C \cos(\Delta m t)
\]

(taking \( \Delta \Gamma = 0 \))

C: CPV in direct decay (expect 0)
S=\( \sin 2\beta \): CPV in interference

LHCb

J/\psi K_S^0

Run I

\( m(J/\psi K_S^0) \) [MeV/c^2]

Candidates / (4.5 MeV/c^2)

LHCb

\( \psi(2S) K_S^0 \)

Candidates / (2.5 MeV/c^2)

JHEP 11 (2017) 170
Flavour tagging needed to measure TD asymmetry
- Opposite-side (muon; electron; kaon; charges of all tracks; charm)
- Same-side (pion; proton)
- Event-by-event mistag estimate (\( \eta \)) calibrated with control channels to obtain mistag probability (\( \omega \))
- \( B^+ \to J/\psi K^+ \) for OS, \( B^0 \to J/\psi K^{*0} \) for SS
- Simultaneous fit, sharing \( \Delta m, \tau \) but not CP observables.
$\beta$ from $B^0 \to J/\psi K_S$, $B^0 \to \psi(2S) K_S$

This Run I result, JHEP 11 (2017) 170

$C(B^0 \to J/\psi K^0_S) = 0.12 \pm 0.07 \pm 0.02$

$S(B^0 \to J/\psi K^0_S) = 0.83 \pm 0.08 \pm 0.01$

$C(B^0 \to \psi(2S) K^0_S) = -0.05 \pm 0.10 \pm 0.01$

$S(B^0 \to \psi(2S) K^0_S) = 0.84 \pm 0.10 \pm 0.01$

Prev. result, PRL 115, 031601 (2015)
(using $J/\psi \to \mu^+\mu^-$ decay mode, Run I)

$C(B^0 \to J/\psi K^0_S) = -0.038 \pm 0.032$

$S(B^0 \to J/\psi K^0_S) = 0.73 \pm 0.04$

- New modes!
- Still not as precise as BaBar+Belle, but getting there (and more data on tape).
- Compare HFLAV average of charmonium modes: $S = 0.699 \pm 0.017$
$B_{(s)} \rightarrow h^+ h'^-$

• Measurements from LHCb of
  • Time-dependent CP asymmetries in $B^0 \rightarrow \pi^+ \pi^-$: $C_{\pi^+\pi^-}, S_{\pi^+\pi^-}$
  • Time-dependent CP asymmetries in $B_s \rightarrow K^+ K^-$: $C_{K^+K^-}, S_{K^+K^-}, A_{K^+K^-}^{\Delta\Gamma}$
  • Time-integrated CP asymmetries in $B^0 \rightarrow K^+ \pi^-$: $A_{CP}^{B^0}$
  • Time-integrated CP asymmetries in $B_s \rightarrow \pi^+ K^-$: $A_{CP}^{B^0_s}$
$B_{(s)} \rightarrow h^+ h'^-$

- Measurements from LHCb of
  - Time-dependent CP asymmetries in $B^0 \rightarrow \pi^+ \pi^-$: $C_{\pi^+\pi^-}, S_{\pi^+\pi^-}$
  - Time-dependent CP asymmetries in $B_s \rightarrow K^+ K^-$: $C_{K^+K^-}, S_{K^+K^-}, A_{K^+K^-}^{\Delta \Gamma}$
  - Time-integrated CP asymmetries in $B^0 \rightarrow K^+ \pi^-$: $A_{CP}^{B_0}$
  - Time-integrated CP asymmetries in $B_s \rightarrow \pi^+ K^-$: $A_{CP}^{B_0}$

Gronau & London, PRL 65, 3381 (1990)
$B_{(s)} \rightarrow h^+ h'^-$

- Measurements from LHCb of
  - Time-dependent CP asymmetries in $B^0 \rightarrow \pi^+ \pi^-$: $C_{\pi^+\pi^-}, S_{\pi^+\pi^-}$
  - Time-dependent CP asymmetries in $B_s \rightarrow K^+ K^-$: $C_{K^+K^-}, S_{K^+K^-}, A^{\Delta\Gamma}_{K^+K^-}$
  - Time-integrated CP asymmetries in $B^0 \rightarrow K^+ \pi^-$: $A^{B^0}_{CP}$
  - Time-integrated CP asymmetries in $B_s \rightarrow \pi^+ K^-$: $A^{B^0}_{CP}$

Fleischer, PLB 459 (1999) 306
Fleischer, EPJC 52 (2007) 267

Constraints on $\beta, \gamma$

PRD 98, 032004 (2018)
$B_{(s)} \rightarrow h^+ h'^-$

- Measurements from LHCb of
  - Time-dependent CP asymmetries in $B^0 \rightarrow \pi^+ \pi^-$: $C_{\pi^+\pi^-}, S_{\pi^+\pi^-}$
  - Time-dependent CP asymmetries in $B_s \rightarrow K^+ K^-$: $C_{K^+K^-}, S_{K^+K^-}, A_{K^+K^-}^\Delta\Gamma$
  - Time-integrated CP asymmetries in $B^0 \rightarrow K^+ \pi^-$: $A_{CP}^{B^0}$
  - Time-integrated CP asymmetries in $B_s \rightarrow \pi^+ K^-$: $A_{CP}^{B_s}$

---

Ciuchini et al, JHEP 10 (2012) 29

---

PRD 98, 032004 (2018)
$B_{(s)} \rightarrow h^+ h'^-$

- Measurements from LHCb of
  - Time-dependent CP asymmetries in $B^0 \rightarrow \pi^+ \pi^-$: $C_{\pi^+\pi^-}, S_{\pi^+\pi^-}$
  - Time-dependent CP asymmetries in $B_s \rightarrow K^+ K^-$: $C_{K^+K^-}, S_{K^+K^-}, A^{\Delta\Gamma}_{K^+K^-}$
  - Time-integrated CP asymmetries in $B^0 \rightarrow K^+ \pi^-$: $A^B_{CP}^{0}$
  - Time-integrated CP asymmetries in $B_s \rightarrow \pi^+ K^-$: $A^B_{CP}^{s}$

\[ B_s \rightarrow \pi^+ K^- \]

\[ B^0 \rightarrow K^+ \pi^- \]

- Measurements from LHCb of
  - Time-dependent CP asymmetries in \( B^0 \rightarrow \pi^+ \pi^- \): \( C_{\pi^+\pi^-}, S_{\pi^+\pi^-} \)
  - Time-dependent CP asymmetries in \( B_s \rightarrow K^+ K^- \): \( C_{K^+K^-}, S_{K^+K^-}, A^{\Delta\Gamma}_{K^+K^-} \)
  - Time-integrated CP asymmetries in \( B^0 \rightarrow K^+ \pi^- \): \( A_{CP}^{B^0} \)
  - Time-integrated CP asymmetries in \( B_s \rightarrow \pi^+ K^- \): \( A_{CP}^{B^0} \)

Validity test of SM

\[ B(B_s \rightarrow \pi^+ K^-) \]
\[ B(B^0 \rightarrow K^+ \pi^-) \]

\[ \tau(B^0)/\tau(B_s) \]

He, EPJC 9 (1999) 443
Lipkin, PLB 621 (2005) 126
\( \mathbf{B}_{(s)} \rightarrow \mathbf{h}^+ \mathbf{h}'^- \)

- **Measurements from LHCb of**
  - Time-dependent CP asymmetries in \( \mathbf{B}^0 \rightarrow \pi^+ \pi^- \): \( C_{\pi^+\pi^-}, S_{\pi^+\pi^-} \)
  - Time-dependent CP asymmetries in \( \mathbf{B}_s \rightarrow \mathbf{K}^+ \mathbf{K}^- \): \( C_{\mathbf{K}^+\mathbf{K}^-}, S_{\mathbf{K}^+\mathbf{K}^-}, A_{\mathbf{K}^+\mathbf{K}^-}^{\Delta \Gamma} \)
  - Time-integrated CP asymmetries in \( \mathbf{B}^0 \rightarrow \mathbf{K}^+ \pi^- \): \( A_{\mathbf{CP}}^{\mathbf{B}^0} \)
  - Time-integrated CP asymmetries in \( \mathbf{B}_s \rightarrow \pi^+ \mathbf{K}^- \): \( A_{\mathbf{CP}}^{\mathbf{B}_s^0} \)

\[
\begin{align*}
C_{\pi^+\pi^-} &= -0.34 \pm 0.06 \pm 0.01, \\
S_{\pi^+\pi^-} &= -0.63 \pm 0.05 \pm 0.01, \\
C_{\mathbf{K}^+\mathbf{K}^-} &= 0.20 \pm 0.06 \pm 0.02, \\
S_{\mathbf{K}^+\mathbf{K}^-} &= 0.18 \pm 0.06 \pm 0.02, \\
A_{\mathbf{K}^+\mathbf{K}^-}^{\Delta \Gamma} &= -0.79 \pm 0.07 \pm 0.10, \\
A_{\mathbf{CP}}^{\mathbf{B}^0} &= -0.084 \pm 0.004 \pm 0.003, \\
A_{\mathbf{CP}}^{\mathbf{B}_s^0} &= 0.213 \pm 0.015 \pm 0.007. 
\end{align*}
\]

**Validity test:**
\( \Delta = -0.11 \pm 0.04 \pm 0.03, \) consistent w/ SM (zero)

**PRD 98, 032004 (2018)**
- Classic mode $B_s \rightarrow J/\psi \phi$: no LHCb update since last CKM.

**$\phi_s$ 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

- However...
$\phi_s$ in $B_s \to J/\psi K^+ K^-$ above the $\phi$

- Angular analysis; 5D fit to (decay time, $m_{KK}$, 3 helicity angles)
- Separate data into two regions and fit simultaneously:
  - "low-mass" (near-$\phi$): $m_{KK} < 1050$ MeV
  - "high-mass": $m_{KK} > 1050$ MeV
- To avoid correlation with previous analysis, float physics parameters ($\phi_s$, $|\lambda|$, $\Gamma_s$, $\Delta\Gamma_s$) separately in each region
  - ... but share resonance parameters etc
\( \phi_s \) in \( B_s \rightarrow J/\psi \ K^+ \ K^- \) above the \( \phi \)

- **Results from this analysis:**
  \[
  \phi_s = 119 \pm 107 \pm 34 \text{ mrad}, \\
  |\lambda| = 0.994 \pm 0.018 \pm 0.006, \\
  \Gamma_s = 0.650 \pm 0.006 \pm 0.004 \text{ ps}^{-1}, \\
  \Delta\Gamma_s = 0.066 \pm 0.018 \pm 0.010 \text{ ps}^{-1}.
  \]

- **Combine with prev. analysis (\( \phi \) region):**
  \[
  \phi_s = -25 \pm 45 \pm 8 \text{ mrad}, \\
  |\lambda| = 0.978 \pm 0.013 \pm 0.003, \\
  \Gamma_s = 0.6588 \pm 0.0022 \pm 0.0015 \text{ ps}^{-1}, \\
  \Delta\Gamma_s = 0.0813 \pm 0.0073 \pm 0.0036 \text{ ps}^{-1}.
  \]

- **Combine with \( B_s \rightarrow J/\psi \ \pi^+ \ \pi^- \): (\( \Gamma_s \) and \( \Delta\Gamma_s \) unchanged)**
  \[
  \phi_s = 1 \pm 37 \text{ mrad} \\
  |\lambda| = 0.973 \pm 0.013
  \]

  **All very SM.**

- **And then another mode...**
\( \phi_s^{\bar{d}d} \) in \( B_s \to (K^+ \pi^-)(\pi^+ K^-) \)

- In general, \( \phi_s \) depends on the decay mode.
- Loop-dominated \( \Rightarrow \) sensitive to NP.
- This analysis: \( 750 < m_{\pi\pi} < 1600 \text{ MeV} \)
  - Scalar, vector, tensor resonances included
  - Upper limit chosen to avoid \( D^0 \to K\pi \)
  - Previous analyses just looked at the \( K^*(890) \)
- Time-dependent & flavour-tagged analysis
- Key results of amplitude fit:
  \[
  \phi_s^{\bar{d}d} \text{ [rad]} = -0.10 \pm 0.13 \pm 0.14 \\
  |\lambda| = 1.035 \pm 0.034 \pm 0.089
  \]

- Polarisations, relative contributions of resonances measured.

<table>
<thead>
<tr>
<th>Tagging algorithm</th>
<th>( \epsilon_{\text{tag}} \text{ [%]} )</th>
<th>( \epsilon_{\text{eff}} \text{ [%]} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>62.0 \pm 0.7</td>
<td>1.63 \pm 0.21</td>
</tr>
<tr>
<td>OS</td>
<td>37.1 \pm 0.7</td>
<td>3.70 \pm 0.21</td>
</tr>
<tr>
<td>Combination</td>
<td>75.6 \pm 0.6</td>
<td>5.15 \pm 0.14</td>
</tr>
</tbody>
</table>
\[ \phi_s \text{ overall} \]

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Mode</th>
<th>Dataset</th>
<th>( \phi_s^{ct} )</th>
<th>( \Delta \Gamma_s ) (ps(^{-1}))</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>( J/\psi )</td>
<td>9.0 fb(^{-1})</td>
<td>([-0.06 \pm 0.12, 05% \text{ CL}] \pm 0.006 \pm 0.026 \pm 0.009 )</td>
<td>[2]</td>
<td></td>
</tr>
<tr>
<td>D0</td>
<td>( J/\psi )</td>
<td>8.0 fb(^{-1})</td>
<td>([-0.55^{+0.30}_{-0.16}, 05% \text{ CL}] \pm 0.030 \pm 0.026 \pm 0.009 )</td>
<td>[3]</td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>( J/\psi )</td>
<td>4.9 fb(^{-1})</td>
<td>([+0.02 \pm 0.25, 05% \text{ CL}] \pm 0.053 \pm 0.021 \pm 0.010 )</td>
<td>[4]</td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>( J/\psi )</td>
<td>14.3 fb(^{-1})</td>
<td>([-0.11 \pm 0.08 \pm 0.00, 05% \text{ CL}] \pm 0.101 \pm 0.013 \pm 0.007 )</td>
<td>[5]</td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>above 2 combined</td>
<td></td>
<td>([-0.50 \pm 0.07 \pm 0.04, 05% \text{ CL}] \pm 0.085 \pm 0.011 \pm 0.007 )</td>
<td>[5]</td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>( J/\psi )</td>
<td>19.7 fb(^{-1})</td>
<td>([-0.075 \pm 0.007 \pm 0.001, 05% \text{ CL}] \pm 0.095 \pm 0.013 \pm 0.007 )</td>
<td>[6]</td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>( J/\psi K^- K^+ )</td>
<td>3.0 fb(^{-1})</td>
<td>([-0.005 \pm 0.009 \pm 0.006, 05% \text{ CL}] \pm 0.0805 \pm 0.0091 \pm 0.0032 )</td>
<td>[7]</td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>( J/\psi \pi^+ \pi^- )</td>
<td>3.0 fb(^{-1})</td>
<td>([-0.100 \pm 0.08 \pm 0.01, 05% \text{ CL}] \pm 0.104 \pm 0.013 \pm 0.007 )</td>
<td>[8]</td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>( J/\psi K^+ K^- )</td>
<td>3.0 fb(^{-1})</td>
<td>([-0.109 \pm 0.10 \pm 0.03, 05% \text{ CL}] \pm 0.159 \pm 0.018 \pm 0.010 )</td>
<td>[9]</td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>above 3 combined</td>
<td></td>
<td>([-0.01 \pm 0.07 \pm 0.04, 05% \text{ CL}] \pm 0.0805 \pm 0.0073 \pm 0.0036 )</td>
<td>[9]</td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>( \psi(2S) \phi )</td>
<td>3.0 fb(^{-1})</td>
<td>([-0.23^{+0.24}_{-0.14} \pm 0.02, 05% \text{ CL}] \pm 0.206 \pm 0.08 \pm 0.007 )</td>
<td>[10]</td>
<td></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, 05% \text{ CL}] \pm 0.085 \pm 0.007 )</td>
<td>[11]</td>
<td></td>
</tr>
<tr>
<td>All combined</td>
<td></td>
<td></td>
<td>([-0.02 \pm 0.031, 05% \text{ CL}] \pm 0.085 \pm 0.006 )</td>
<td>( m(K^+ K^-) &gt; 1.65 \text{ GeV/c}^2 )</td>
<td></td>
</tr>
</tbody>
</table>

**HFLAV average:** \( \phi_s^{c\bar{c}s} = - 0.021 \pm 0.031 \)
CPV in baryon decays

• Direct CPV expected in b baryons just like b mesons.
• ... but no 5σ observation so far. Evidence reported at CKM 2016 in $\Lambda_b \to p \pi^- \pi^+ \pi^-$:

New avenues: search for CP violation in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays from LHCb

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

$$C_T = \vec{p}_\pi \cdot (\vec{p}_{h_1} \times \vec{p}_{h_2}) \quad \bar{C}_T = \vec{p}_\pi \cdot (\vec{p}_{h_1} \times \vec{p}_{h_2})$$

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

New avenues: search for CP violation in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays from LHCb

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

What's new since then?

Vincenzo Vagnoni, CKM 2016

CPV in baryon decays?

Searches in other 4-body decays: no evidence.

<table>
<thead>
<tr>
<th></th>
<th>( \Lambda_b^0 \to pK^-\pi^+\pi^- )</th>
<th>( \Lambda_b^0 \to pK^-K^+K^- )</th>
<th>( \Xi_b^0 \to pK^-K^-\pi^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_T) odd (%)</td>
<td>(-0.60 \pm 0.84 \pm 0.31 )</td>
<td>(-1.56 \pm 1.51 \pm 0.32 )</td>
<td>(-3.04 \pm 5.19 \pm 0.36 )</td>
</tr>
<tr>
<td>( a_{CP} ) odd (%)</td>
<td>(-0.81 \pm 0.84 \pm 0.31 )</td>
<td>(1.12 \pm 1.51 \pm 0.32 )</td>
<td>(-3.58 \pm 5.19 \pm 0.36 )</td>
</tr>
</tbody>
</table>

Example mass plots:

(after splitting by baryon number and triple-product variable
=> each plot represents about \(1/4\) of the signal in that mode)
CPV in baryon decays?

Searches in other 4-body decays: no evidence.

Searches in 2-body decays: no evidence.

\[ A_{CP}^{pK^-} = -0.020 \pm 0.013 \pm 0.019 \]

\[ A_{CP}^{p\pi^-} = -0.035 \pm 0.017 \pm 0.020 \]

Example mass plots (simultaneous fit to 8 final states)

(after splitting by baryon number => each plot represents about \(\frac{1}{2}\) of the signal in that mode)
CPV in baryon decays?

Searches in other 4-body decays: no evidence.
Searches in 2-body decays: no evidence.

Search in $\Lambda_b \rightarrow pK^-\mu^+\mu^-$: no evidence of CPV (but first observation of the decay mode!)

$$\Delta A_{CP} = (-3.5 \pm 5.0 \text{ (stat)} \pm 0.2 \text{ (syst)}) \times 10^{-2}$$

$$a_{CP}\hat{T}_{\text{odd}} = (1.2 \pm 5.0 \text{ (stat)} \pm 0.7 \text{ (syst)}) \times 10^{-2}$$

Example mass plot:

(after splitting by baryon number and triple-product variable => plot represents about $1/4$ of the signal)
CPV in baryon decays?

Searches in other 4-body decays: no evidence.
Searches in 2-body decays: no evidence.
Search in $\Lambda_b \rightarrow p K^- \mu^+ \mu^-$: no evidence of CPV

• Strangely elusive!
• Awaiting update of $\Lambda_b \rightarrow p \pi^- \pi^+ \pi^-$ with more stats
Other studies

Search for CPV in $B^- \rightarrow D_s^- D^0$, $B^- \rightarrow D^- D^0$ (expected to be small, $\sim 10^{-2}$, in SM)

$$A^{CP}(B^- \rightarrow D_{s}^- D^0) = (-0.4 \pm 0.5 \pm 0.5)\%$$

$$A^{CP}(B^- \rightarrow D^- D^0) = (2.3 \pm 2.7 \pm 0.4)\%$$

Amplitude analysis of $B^0 \rightarrow K_s \pi^+ \pi^-$, first observation of CPV in $B^0 \rightarrow K^*(892)^+ \pi^-$

$$A_{CP}(K^*(892)^- \pi^+) = -0.308 \pm 0.060 \pm 0.011 \pm 0.012 \quad 6\sigma$$

$$A_{CP}((K \pi)_0^- \pi^+) = -0.032 \pm 0.047 \pm 0.016 \pm 0.027$$

$$A_{CP}(K^*_2(1430)^- \pi^+) = -0.29 \pm 0.22 \pm 0.09 \pm 0.03$$

$$A_{CP}(K^*(1680)^- \pi^+) = -0.07 \pm 0.13 \pm 0.02 \pm 0.03$$

$$A_{CP}(f_0(980)K_s^0) = 0.28 \pm 0.27 \pm 0.05 \pm 0.14$$

Leptons in B decays

• Very rare & forbidden decays often sensitive to NP.
• Several well-known anomalies
• Apparent pattern of effects at 2, 3, even 4\sigma...
• ... but no 5\sigma observation so far. At last CKM:

<table>
<thead>
<tr>
<th>Angular analysis of $B^0 \rightarrow K^* \mu^+ \mu^-$</th>
<th>More LFU tests</th>
<th>LFU in $B \rightarrow D^{(*)}\tau\nu$</th>
</tr>
</thead>
</table>
| • 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 → more efforts needed to clarify the picture [see e.g. JHEP 06 (2016) 116]
| • Ratio ($R_K$) of branching fractions of $B^+ \rightarrow K^+\mu^+\mu^-$ to $B^+ \rightarrow K^+\ell^+\ell^-$ expected to be unity in the SM with excellent precision
  $R_K = \frac{B(\ell^+\ell^-)}{B(\mu^+\mu^-)}$  
  – 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. $R_{\tau}$
| • Ratio $R_{D^{(*)}\tau\nu}$ = $\frac{B(\tau\nu)}{B(\mu\mu)}$ 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 $b \rightarrow c\tau\nu$ are ongoing at Belle and LHCb
  • LHCb can also perform measurements with other $b$ hadrons
    e.g. $B\rightarrow J/\psi K^*$, $B\rightarrow J/\psi K_S$ decays will help to better understand the global picture → stay tuned! |

<table>
<thead>
<tr>
<th>$P'_{5}$ in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$</th>
<th>$R_K$ in $B^+ \rightarrow K^+ \ell^+ \ell^-$</th>
<th>$R(D), R(D^<em>)$ in $B \rightarrow D^{(</em>)}l^+\nu_l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4\sigma global</td>
<td>2.6\sigma at low $q^2$</td>
<td>HFLAV: 4\sigma overall</td>
</tr>
</tbody>
</table>

What's new since CKM 2016?

Vincenzo Vagnoni, CKM 2016
Very rare & forbidden decays

- $B_s \rightarrow \mu^+ \mu^-$ first observed by CMS & LHCb jointly [Nature 522 (2015) 68]
- See also ATLAS measurement [EPJC 76 (2016) 513]
- Update from LHCb with 4.4/fb (Run1 + partial Run2)
  - Significance 7.8$\sigma$
  - BR measured: $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ assuming that only heavy mass eigenstate decays to $\mu^+ \mu^-$ (per SM)
  - Effective lifetime measured: $2.04 \pm 0.44 \pm 0.05$ ps consistent with SM: $\tau(B_s \rightarrow \mu^+ \mu^-) = \tau_{B_s} / (1 - y_s)$
  - Upper limit: $B(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \times 10^{-10}$ @ 95% CL

$B_s \rightarrow \mu^+ \mu^-$ candidates / (50 MeV/c²)

- Total
- $B_s^0 \rightarrow \mu^+ \mu^-$
- $B^0 \rightarrow \mu^+ \mu^-$
- Combinatorial
- $B_s^{(*)} \rightarrow h^+h^-$
- $B_s^{(*)} \rightarrow \pi^0(K^0)\mu^+\nu_\mu$
- $B_s^{(*)} \rightarrow \pi^0(K^0)\mu^+\mu^-$
- $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu$
- $B_c^- \rightarrow J/\psi\mu^-\bar{\nu}_\mu$

Decay time [ps] 32
ATLAS estimated sensitivities

- At HL-LHC (3000 fb⁻¹), can measure \( B(B^0 \rightarrow \mu^+ \mu^-) \) precisely.

Approx. precision of LHCb measurement on prev. slide

"Conservative" HL-LHC (15xRun1)

"High-yield" HL-LHC (75xRun1)
Very rare & forbidden decays

- $B_s \to \tau^+ \tau^-$ expected to have larger BR...
- ... but experimentally tougher
  $\Rightarrow$ never observed
- Search: $(B^0, B_s) \to \tau^+ \tau^-$ with $\tau \to \pi^- \pi^+ \pi^- \nu_{\tau}$
  - Mass resolution too poor to disentangle the two
- Use pion kinematics to identify signal (good-$\tau$) and control regions:
  $\tau^- \to a_d(1260)^-\nu_\tau, \ a_1(1260)^- \to \rho(770)^0\pi^-$
- Fit output of a NN selector with signal & control regions:

Assuming negligible $B^0 \to \tau^+ \tau^-$, $B(B_s \to \tau^+ \tau^-) < 6.8 \times 10^{-3}$ @ 95% CL 
... first limit on this process

Assuming negligible $B_s \to \tau^+ \tau^-$, $B(B^0 \to \tau^+ \tau^-) < 2.1 \times 10^{-3}$ @ 95% CL 
... improves on previous BaBar limit by factor 2.6
Very rare & forbidden decays

- $B(s) \rightarrow \mu^\pm e^\mp$ forbidden in SM; sensitive to BSM CLFV
- Search with LHCb Run1 data.
- Fit in bins of BDT output, presence/absence of brems photon for $e^\pm$
- No signal; set limits at 95% CL:
  - $B(B^0 \rightarrow \mu^\pm e^\mp) < 1.3 \times 10^{-9}$
  - $B(B_s \rightarrow \mu^\pm e^\mp) < 6.3 \times 10^{-9}$
    [or $7.2 \times 10^{-9}$ if dominated by light mass eigenstate instead]
- Normalisation: $B^0 \rightarrow K^+ \pi^-$ and $B^+ \rightarrow J/\psi K^+$
Lepton flavour universality

Notation: \( R_H = \frac{\int \frac{d\Gamma(B\rightarrow H\mu^+\mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B\rightarrow He^+e^-)}{dq^2} dq^2} \)

- ... i.e. ratio of BF to H\(\mu\mu\), Hee.
- Theoretically very clean: hadronic uncertainties cancel in ratio.
- In SM, close to 1 (small differences due to phase space):

Example: predictions for \( R_{K^*} \)
in two \( q^2 \) ranges. Refs defined in arXiv:1705.05802

<table>
<thead>
<tr>
<th>( q^2 ) range [GeV^2/c^4]</th>
<th>( R_{K^*}^{SM} )</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>([0.045, 1.1])</td>
<td>0.906 ± 0.028</td>
<td>BIP [26]</td>
</tr>
<tr>
<td></td>
<td>0.922 ± 0.022</td>
<td>CDHMV [27–29]</td>
</tr>
<tr>
<td></td>
<td>0.919 ± 0.004/0.003</td>
<td>EOS [30,31]</td>
</tr>
<tr>
<td></td>
<td>0.925 ± 0.004</td>
<td>flav.io [32–34]</td>
</tr>
<tr>
<td></td>
<td>0.920 ± 0.007/0.006</td>
<td>JC [35]</td>
</tr>
<tr>
<td>([1.1, 6.0])</td>
<td>1.000 ± 0.010</td>
<td>BIP [26]</td>
</tr>
<tr>
<td></td>
<td>1.000 ± 0.006</td>
<td>CDHMV [27–29]</td>
</tr>
<tr>
<td></td>
<td>0.9968 ± 0.0005/0.0004</td>
<td>EOS [30,31]</td>
</tr>
<tr>
<td></td>
<td>0.9964 ± 0.005</td>
<td>flav.io [32–34]</td>
</tr>
<tr>
<td></td>
<td>0.996 ± 0.002</td>
<td>JC [35]</td>
</tr>
</tbody>
</table>
Use double ratio to cancel systematics:

\[
R_{K^*0} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))} / \frac{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))}{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}
\]
The corresponding 95.4% confidence level intervals are $[0, 2.4–2.5]$ standard deviations for the central values.

The results, which represent the most precise measurements of the $K^0_L$ ratio, are consistent with, but more precise than, BABAR & Belle.

**Compatibility with / deviation from SM depends on what model you choose, but roughly:**

- **2.1 - 2.3σ** in low-$q^2$ region
- **2.4 - 2.5σ** in central-$q^2$ region

**Compatible with, but more precise than, BABAR & Belle.**
Lepton flavour universality II

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

\[ R(J/\psi) \equiv \frac{B_c^+ \to J/\psi \tau^+\nu_\tau}{B_c^+ \to J/\psi \mu^+\nu_\mu} \]

At last CKM, 3.9\(\sigma\) tension (HFLAV)

\[ \Delta\chi^2 = 1.0 \text{ contours} \]

BaBar, PRL109,101802 (2012)
Belle, PRD92,072014 (2015)
LHCb, PRL115,111803 (2015)
Belle, PRD94,072007 (2016)
Belle, arXiv:1608.06391
Average

R(D) = 0.300(8) HPQCD (2015)
R(D) = 0.299(11) FNAL/MILC (2015)
R(D^*) = 0.252(3) S. Fajfer et al. (2012)

HFAG Summer 2016

P(\chi^2) = 70\%
\begin{align*}
R(D^*) & \equiv \frac{B^0 \to D^{*+} \tau^- \bar{\nu}_\tau}{B^0 \to D^{*+} \mu^- \bar{\nu}_\mu} \\
R(D^*)
\end{align*}

\begin{itemize}
\item Reconstruct \( \tau \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau \), complementary to previous measurement of \( R(D^*) \)
\item Normalise in steps. First measure \( B^0 \to D^{*0} \tau^+ \nu_\tau \) relative to topologically similar \( B^0 \to D^{*-} \pi^+ \pi^- \pi^+ \):
\begin{align*}
\mathcal{K}(D^{*-}) & \equiv \frac{\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^{*-} 3\pi)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{1}{\mathcal{B}(\tau^+ \to 3\pi \bar{\nu}_\tau) + \mathcal{B}(\tau^+ \to 3\pi \pi^0 \bar{\nu}_\tau)}
\end{align*}
\end{itemize}

\begin{itemize}
\item \( N_{\text{sig}} \) from fit to \((q2, \text{decay time of tau, BDT output})\)
\item \( N_{\text{norm}} \) from fit to \( m(D^{*-} \pi^+ \pi^- \pi^+) \)
\item Then, use known \( \mathcal{B} \)'s of \([B^0 \to D^{*0} \tau^+ \nu_\tau]\) and \([B^0 \to D^{*-} \mu^+ \nu_\mu]\):
\begin{align*}
\mathcal{R}(D^{*-}) = \mathcal{K}(D^{*-}) \times \frac{\mathcal{B}(B^0 \to D^{*-} 3\pi)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)}
\end{align*}
\end{itemize}

Input: avg of BABAR, Belle, LHCb
Input: HFLAV

References:

PRL 120, 171802 (2018)
PRD 97, 072013 (2018)
$R(D^*) \equiv \frac{\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau}{\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu}$

- **$N_{\text{sig}} = 1296 \pm 86$**

  $\mathcal{B}(D^{*-}) = 1.97 \pm 0.13$ (stat) $\pm 0.18$ (syst)

- **Putting it all together:**
  
  $R(D^{*-}) = 0.291 \pm 0.019$ (stat) $\pm 0.026$ (syst) $\pm 0.013$ (ext)

- **Systematics dominated.**
  
  - Several all of similar size; not going to be easy to reduce them all.

---

**Updated HFLAV -- 3.6-3.8\sigma tension**

**Two projections of fits for $N_{\text{sig}}$ in bins of BDT**
\[ R(J/\psi) = \frac{B^+_c \rightarrow J/\psi \, \tau^+ \nu_\tau}{B^+_c \rightarrow J/\psi \, \mu^+ \nu_\mu} \]

- SM predictions: \( R(J/\psi) \sim 0.25-0.28 \)
- Uses \( \tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\tau \)
  
  \( \Rightarrow \) final state for both numerator & denominator is \( \mu \mu \mu \)
- Templated fit to \( (m^2_{\text{miss}}, B_c \text{ decay time}) \) in eight kinematic bins
- \( 1400 \pm 300 \text{ signal}, 19140 \pm 340 \text{ normalisation} \)

\[ R(J/\psi) = \frac{\mathcal{B}(B^+_c \rightarrow J/\psi \, \tau^+ \nu_\tau)}{\mathcal{B}(B^+_c \rightarrow J/\psi \, \mu^+ \nu_\mu)} = 0.71 \pm 0.17 \text{ (stat)} \pm 0.18 \text{ (syst)} \]

... within 2\( \sigma \) of the SM prediction.

**Dominant sys err:**
\( B_c \rightarrow J/\psi \) form factors

**PRL 120, 121801 (2018)**
b→s and b→d transitions

SM contributions...

... and maybe BSM too?

Supersymmetry

... or your favourite model...

Leptoquarks

New heavy gauge bosons

Introduction

Rare decays as sensitive probes for New Physics

Rare decays in the SM

Possible contributions from NP

Leptoquarks

New heavy gauge bosons

Flavour Anomalies

SM contributions...

... and maybe BSM too?

Supersymmetry

... or your favourite model...

Thanks to C. Langenbruch
Observables

• We can look at distributions of decay rate vs $q^2$
• ...or do a full angular analysis and look at angular observables vs $q^2$
• Use "optimised" variables to help cancel hadronic effects, e.g. $P'_5$
• To pull the information together, use Wilson coefficients:

\[ H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i \]

\[ \Delta H_{NP} = -\kappa_i O_i \]

\[ \Lambda_{NP}^2 \]

• Main interest in EW penguin operators: $C_9$, $C'_9$, $C_{10}$, $C'_{10}$
• So, what's new since last CKM?


Thanks to C. Langenbruch
Angular analysis of $B^+ \rightarrow K^+ \mu^- \mu^+$

$\sqrt{s}=8$ TeV, 20.5 fb$^{-1}$

- 2D fit of $A_{FB}$ and $F_H$ (scalar/pseudoscalar/tensor contribution) in bins of $q^2$. SM predictions close to zero.

- Control regions: $B^+ \rightarrow K^+ J/\psi$, $B^+ \rightarrow K^+ \psi(2S)$

- Total yield outside control regions in $1<q^2<22$ GeV: $2286 \pm 73$

Consistent with SM.

arXiv:1806.00636

Angular analysis of $B^0 \rightarrow K^{*0} \mu^- \mu^+$

$\sqrt{s}=8$ TeV, 20.5 fb$^{-1}$

• More complex final state => need more angular observables! Here, focus on $P_1$, $P'_5$.
• Same dataset previously used to measure $A_{FB}$ of muons, $K^{*0}$ longitudinal polarisation $FL$, and $dB/dq^2$. [PLB 753 (2016) 424]
• 4D fits in $q^2$ bins, as fn of mass and three angles $\theta_1$, $\theta_K$, $\phi$.
• Parameters $A_{FB}$, $FL$, $FS$ fixed to values from previous analysis; this drives the largest systematic uncertainty.

Example fit projection from one $q^2$ bin

Figure 1: Illustration of the angular variables $\theta_1$ (left), $\theta_K$ (middle), and $\phi$ (right) for the decay $B^0 \rightarrow K^{*0}(K^+\pi^-)\mu^+\mu^-$.  

![Figure 1: Illustration of the angular variables $\theta_1$ (left), $\theta_K$ (middle), and $\phi$ (right) for the decay $B^0 \rightarrow K^{*0}(K^+\pi^-)\mu^+\mu^-$](image-url)
Angular analysis of $B^0 \rightarrow K^{*0} \mu^- \mu^+$

$\sqrt{s}=8$ TeV, 20.5 fb$^{-1}$

- 1397 signal events
- Results in agreement with SM, qualitatively compatible with LHCb.

![Graph](graph.png)
Angular analysis of $B^0 \rightarrow K^{*0} \mu^- \mu^+$

- Same final state, general approach (angular analysis in bins of $q^2$)
  - but focus on low-$q^2$ region, 0.04 to 6.0 GeV$^2$
- Overall signal yield: $342 \pm 39$
- Compatible with predictions and with LHCb, CMS, Belle.

Example fit projection from $q^2$ range used

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

<table>
<thead>
<tr>
<th>$q^2$ [GeV$^2$]</th>
<th>$n_{\text{signal}}$</th>
<th>$n_{\text{background}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0.04, 2.0]</td>
<td>128 ± 22</td>
<td>122 ± 22</td>
</tr>
<tr>
<td>[2.0, 4.0]</td>
<td>106 ± 23</td>
<td>113 ± 23</td>
</tr>
<tr>
<td>[4.0, 6.0]</td>
<td>114 ± 24</td>
<td>204 ± 26</td>
</tr>
<tr>
<td>[0.04, 4.0]</td>
<td>236 ± 31</td>
<td>233 ± 32</td>
</tr>
<tr>
<td>[1.1, 6.0]</td>
<td>275 ± 35</td>
<td>363 ± 36</td>
</tr>
<tr>
<td>[0.04, 6.0]</td>
<td>342 ± 39</td>
<td>445 ± 40</td>
</tr>
</tbody>
</table>

CFFMPSV: JHEP 1606 (2016) 116
DHMV: JHEP 1412 (2014) 125
Angular analysis of \( \Lambda_b \to \Lambda \mu^- \mu^+ \)

- Run1+2015+2016. Updates & expands on PAPER-2015-009
- Study angular moments at high-\(q^2\) (low hadronic recoil): \(15 < q^2 < 20\ \text{GeV}^2/c^4\)
- System has 5 d.o.f. due to spins in final state, \(\Lambda_b^0\) polarisation
- Full angular distribution can be written as sum of 34 terms:
  \[
  \frac{d^5 \Gamma}{d\Omega} = \frac{3}{32\pi^2} \sum_{i}^{34} K_i f_i(\vec{\Omega})
  \]
  ... though most \((i>10)\) vanish in limit of small \(\Lambda_b^0\) polarisation
- Consistent with SM (EOS)

\[
\begin{align*}
A_{FB}^\ell &= \frac{3}{2} K_3 = -0.39 \pm 0.04 \pm 0.01 \\
A_{FB}^h &= K_4 + \frac{1}{2} K_5 = -0.30 \pm 0.05 \pm 0.02 \\
A_{FB}^{\ell h} &= \frac{3}{4} K_6 = +0.25 \pm 0.04 \pm 0.01
\end{align*}
\]

arXiv:1808.00264 First 10 observables
Polarisation, helicity in $\Lambda_b \rightarrow \Lambda J/\psi$

$\sqrt{s}=7$ TeV, 5.2 fb$^{-1}$
$\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$

- ... but we can also measure the polarisation!
- Done by CMS (in different kinematic region)
- Also determine angular parameters describing decay.

$P = 0.00 \pm 0.06,$
$\alpha_1 = 0.14 \pm 0.14,$
$\alpha_2 = -1.11 \pm 0.04,$
$\gamma_0 = -0.27 \pm 0.08,$

$$|T_{++}|^2 = 0.05 \pm 0.04,$$
$$|T_{+0}|^2 = -0.10 \pm 0.04,$$
$$|T_{-0}|^2 = 0.51 \pm 0.03,$$
$$|T_{--}|^2 = 0.52 \pm 0.04,$$
• If interpreted as NP, simplest explanation: shift in $C_9$
  • leptoquarks? $Z'$?
• ... or is it just hadronic SM gunge (charm loops)?
• For more, see plenary talks on Friday.

Global fit of the $b \rightarrow s \mu^+ \mu^-$ measurements incl. $B$ and angular obs.

Tensions can be reduced by shift in $C_9$, significances $\ll 4-5$

Consistency between angular observables and branching fractions

Many other global fits

[arxiv:1704.05340] [JHEP 06 (2016) 092] [NPB 909 (2016) 737]...
Recreation from memory of slide by M. Pennington, Hirschegg 2007, using diagram from CMS: JHEP 03 (2018) 167

Physics at the LHC will be all about SUSY*! Why do you bother studying hadrons? They're dinosaurs!

* Substitute "lepton flavour anomalies" if you prefer...
Spectroscopy

Recreation from memory of slide by M. Pennington, Hirschegg 2007 using diagram from CMS: JHEP 03 (2018) 167
\( \chi_{b1}(3P) \) and \( \chi_{b2}(3P) \)

- Individual states \( \chi_{b1}(3P) \) and \( \chi_{b2}(3P) \) resolved & observed for the first time.
- \( \chi_{b0}(3P) \) \( \rightarrow \gamma \gamma \) BF negligible.
- Consistent with conventional states.

Merged \( \chi_b(3P) \) structure observed by ATLAS: [PRL 108 (2012) 152001](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.108.152001)
The ongoing X(5568) mystery
Feb 2016: D0 reported a narrow structure in the $B_s^0 \pi^\pm$ spectrum (with $B_s^0 \to J/\psi \phi$). Manifestly exotic $\bar{b}sqq$ resonance.

Yield: $133\pm31$ events
Significance: $6.1\sigma$ stat, or $5.1\sigma$ stat+sys (inc LEE)

Eff-cor yield ratio $\rho(X/B_s^0)$:

10 $< p_T(B_s^0) < 15$ GeV/$c$: $(9.1 \pm 2.6 \pm 1.6)$\%
15 $< p_T(B_s^0) < 30$ GeV/$c$: $(8.2 \pm 1.9 \pm 1.4)$\%

average: $(8.6 \pm 1.9 \pm 1.4)$\%

Mass and width:

$m = 5567.8 \pm 2.9$ (stat) $^{+0.9}_{-1.9}$ (syst) MeV/$c^2$
$\Gamma = 21.9 \pm 6.4$ (stat) $^{+5.0}_{-2.5}$ (syst) MeV

But then...
Aug 2016: LHCb tries to confirm peak, finds nothing despite larger $B_s^0$ sample, extra mode.

Upper limits set on $(X/Bs)$ cor. yield ratio:

$$
\rho_{LHCb}^{X} (p_T(B_s^0) > 5 \text{ GeV}) < 0.011 \ (0.012)
$$

$$
\rho_{LHCb}^{X} (p_T(B_s^0) > 10 \text{ GeV}) < 0.021 \ (0.024)
$$

$$
\rho_{LHCb}^{X} (p_T(B_s^0) > 15 \text{ GeV}) < 0.018 \ (0.020)
$$

at 90% (95%) CL

...vs $(8.6 \pm 1.9 \pm 1.4)\%$ at D0 (but different environment)

And then...
**X(5568): Nor at CMS**

17 Dec 2017: CMS tries to confirm peak, also finds nothing.

49k $B_s^0$
Add $\pi^\pm$, try various $p_T$ cuts...

$B_s^0 \rightarrow J/\psi \ K^+K^-$

$\rho_X < 1.1\%$ at 95\% CL for $p_T(B_s^0) > 10\text{ GeV}$ and $\rho_X < 1.0\%$ at 95\% CL for $p_T(B_s^0) > 15\text{ GeV}$.

... vs $(8.6 \pm 1.9 \pm 1.4)\%$ at D0, but again different production environment.

And just 10 days later...
X(5568) : Nor at CDF

27 Dec 2017: CDF searches, finds nothing, sets UL.

$\mathcal{B}_s^0 \rightarrow J/\psi \phi$

3.6k $\mathcal{B}_s^0$

Add $\pi^\pm$...

Limit on corrected yield ratio: $\rho(X/B_s) < 6.7\%$ at 95\% CL

...vs $(8.6 \pm 1.9 \pm 1.4)\%$ at D0.

NB same environment

And then just two days later...
X(5568) : D0 still sees it!

29 Dec 2017: D0 publishes second analysis with different decay mode: semileptonic
B_s^0 → D_s^- μ^+ X... 3.2σ signal!

ρ(X/Bs) = \left[ 7.3^{+2.8}_{-2.4} \text{ (stat)} +^{0.6}_{-1.7} \text{ (syst)} \right] \%

<table>
<thead>
<tr>
<th></th>
<th>Semileptonic</th>
<th>Hadronenic (from Ref. [15])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cone cut</td>
<td>No cone cut</td>
</tr>
<tr>
<td>Fitted mass, MeV/c^2</td>
<td>5566.4^{+3.4}_{-2.8} +1.5</td>
<td>5566.7^{+3.6}_{-3.4} +1.0</td>
</tr>
<tr>
<td>Fitted width, MeV/c^2</td>
<td>2.0^{+9.5}_{-2.0} +2.8</td>
<td>6.0^{+9.5}_{-6.0} +1.9</td>
</tr>
<tr>
<td>Fitted number of signal events</td>
<td>121^{+51}_{-34} +9</td>
<td>139^{+51}_{-63} +11</td>
</tr>
<tr>
<td>Local significance</td>
<td>4.3σ</td>
<td>4.5σ</td>
</tr>
<tr>
<td>Significance with systematics</td>
<td>3.2σ</td>
<td>3.4σ</td>
</tr>
<tr>
<td>Significance with LEE+systematics</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

But a few weeks afterwards...
X(5568) : But ATLAS does not

6 Feb 2018: ATLAS joins the fray!

53k B_s^0
Add π±, try various p_T cuts...

Limit on corrected yield ratio:
\[ \rho(X/B_s^0) < 1.5\% \text{ at } 95\% \text{ CL for } p_T(B_s^0) > 10 \text{ GeV/c} \]
\[ \rho(X/B_s^0) < 1.6\% \text{ at } 95\% \text{ CL for } p_T(B_s^0) > 15 \text{ GeV/c} \]

Wow.
The ongoing X(5568) mystery

• This remains a mystery.
• LHC samples have much larger $B_s^0$ stats and disfavour D0 result assuming conventional heavy quark production.
• ... but cannot rule it out absolutely due to different production environments.
• CDF has the same environment as D0 and does not confirm it... but lower stats => the UL does not fully rule it out.
  • But perhaps by adding more decay modes, this might be resolved.

• LHCb was quicker off the mark (data model is better optimised for B physics) but ATLAS and CMS Run1 data samples had comparable statistics in the end.
• Bodes well for future spectroscopy studies at the big detectors!
Charmed baryon spectroscopy

• ... is very interesting these days, but since it's neither "b-hadrons" nor "CKM" I had better move right along.
Summary

• Exciting times!
• Much going on; much to do.
• Much attention focused on lepton anomalies right now
  • If confirmed, we have another revolution on our hands!
  • ... but first we have to see if they are confirmed.
• But we should not forget the rest of the programme:
  • If anomalies are real, underlying NP will surely manifest in other places
    => look for other signs with more flavour physics
  • If anomalies confirmed, next task will be to understand that NP
    => need more information & constraints => more flavour physics
  • If anomalies not confirmed: back to business! More flavour physics.

• For me, key question is: if this is real, what other effects does it imply we'll see? Where should we look for them?
• I look forward to hearing answers on Friday morning!
What do we mean by "CKM physics"?
Immediate answer: physics sensitive to the CKM matrix
What do we mean by "CKM physics"?

Immediate answer: physics sensitive to the CKM matrix

... but that's both too broad and too narrow.
  - e.g. you don't want to hear about BF measurements of SCS decays
  - e.g. you do want to hear about lepton flavour universality tests
What do we mean by "CKM physics"?
Immediate answer: physics sensitive to the CKM matrix
... but that's both too broad and too narrow.
  e.g. you don't want to hear about BF measurements of SCS decays
  e.g. you do want to hear about lepton flavour universality tests
What we really mean is: (roughly)
  flavour physics
  that lets us make serious, indirect tests of the SM
  either by itself
  or in combination with other measurements
Other people are covering charm+kaons and theory/pheno, so I'll focus on the b system.
LHCb results 2017/18

See: http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

(Too many to list here! 60 papers in 2017 and 30 in 2018, plus 5 CONF notes, plus some new results.)
CMS results 2017/18

• CKM:  
  [arXiv:1806.00636](https://arxiv.org/abs/1806.00636): Angular analysis of the decay $B^+ \rightarrow K^+\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV
  
  
  
  [Phys. Lett. B 781 (2018) 517](https://doi.org/10.1016/j.physletb.2018.06.011): Measurement of angular parameters from the decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV

• Non-CKM:  
  [Phys. Rev. Lett. 121 (2018) 092002](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.092002): Observation of the $\chi_b(3P)$ and $\chi_b(3P)$ and measurement of their masses
  
  [Phys. Rev. Lett. 120, 202005 (2018)](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.202005): Search for the $X(5568)$ state decaying into $B_s\pi^\pm$ in proton-proton collisions at $\sqrt{s} = 8$ TeV
  
  
  [CMS-PAS-BPH-13-002](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH): Measurement of production cross sections times branching fraction of $B_c^+ \rightarrow J/\psi \pi^+$ and $B^+ \rightarrow J/\psi K^+$ in pp collisions at $\sqrt{s} = 7$ TeV at CMS
  
  [CMS-PAS-BPH-16-003](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH): Observation of the $B_s^*(5840)^0 \rightarrow B^0 K_S$ decay and studies of excited Bs mesons in proton-proton collisions at $\sqrt{s} = 8$ TeV

• See also:  
  [CMS-DP-2018-036](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH): Heavy Flavour distributions from CMS with 2018 data at $\sqrt{s} = 13$ TeV
  
  [CMS-DP-2018-014](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH): 2017 B-Physics trigger efficiencies
ATLAS results 2017/18

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

• "CKM":
  • ATL-PHYS-PUB-2018-005: Prospects for the $\mathcal{B}(B_s \rightarrow \mu^+\mu^-)$ measurements with the ATLAS detector in the Run 2 and HL-LHC data campaigns
  • arXiv:1805.04000: Angular analysis of $B^0 \rightarrow K^*\mu^+\mu^-$ decays in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

• Non-"CKM":
  • Phys. Rev. Lett. 120 (2018) 202007: Search for a Structure in the $B_s\pi^\pm$ Invariant Mass Spectrum with the ATLAS Experiment
  • JHEP 11 (2017) 62: Measurement of b-hadron pair production with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV
D0 results 2017/18

https://www-d0.fnal.gov/d0_publications/d0_pubs_list_runII_bytopic_byyear.html#b

• Non-CKM:
  • arXiv:1807.00183: Evidence for $Z_c(3900)^\pm$ in semi-inclusive decays of $b$-flavored hadrons
  • Phys. Rev. D 97, 092004 (2018): Study of the $X(5568)^\pm$ state with semileptonic decays of the $B_s$ meson
CDF results 2017/18

https://www-cdf.fnal.gov/physics/new/bottom/bottom.html

- Non-CKM:
  - *Phys. Rev. Lett. 120, 202006 (2018)*: A search for the exotic meson \(X(5568)\) with the Collider Detector at Fermilab
Other studies

Search for baryon-number-violating oscillations: $\Xi^0_b \rightarrow \Xi^0_b$

Tag initial state via decay of narrow resonances: $\Xi^0_b \rightarrow \Xi^0_b \pi^-$

Fit same-sign/opposite-sign ratio as function of decay time

$\tau_{\text{mix}} > 13 \text{ ps} @ 95\% \text{ CL}$
TD CPV in $B_s \to D_s^\mp K^\pm$

- Interference between mixing & decay
  $\Rightarrow$ sensitive to $(\gamma - 2\beta_s)$

- Fit in two stages:
  - Fit to obtain signal weights ($B_s$ mass, $D_s$ mass, PID)
  - Flavour-tagged, time-dependent sFit
  - Calibration/control mode: $B_s \to D_s \pi$

$$V_{cb} \times V_{us}^* \approx \lambda^3$$

$$V_{ub} \times V_{cs} \approx \lambda^3$$
TD CPV in $B_s \rightarrow D_s^{\mp} K^{\pm}$

Fit results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_f$</td>
<td>$0.730 \pm 0.142 \pm 0.045$</td>
</tr>
<tr>
<td>$A_f^{\Delta \Gamma}$</td>
<td>$0.387 \pm 0.277 \pm 0.153$</td>
</tr>
<tr>
<td>$A_f^{\Delta \Gamma}$</td>
<td>$0.308 \pm 0.275 \pm 0.152$</td>
</tr>
<tr>
<td>$S_f$</td>
<td>$-0.519 \pm 0.202 \pm 0.070$</td>
</tr>
<tr>
<td>$S_{-f}$</td>
<td>$-0.489 \pm 0.196 \pm 0.068$</td>
</tr>
</tbody>
</table>

External input

+ phi_s:

$\phi_s = -0.030 \pm 0.033$ rad,

$\gamma = (128^{+17}_{-22})^\circ,$

$\delta = (358^{+13}_{-14})^\circ,$

$r_{D_sK} = 0.37^{+0.10}_{-0.09},$

Compatible at 2.3sigma with LHCb avg for gamma
TD CPV in $B^0 \rightarrow D^{\mp} \pi^\pm$

- Similar story: interference between mixing & decay
  => sensitive to $(\gamma+2\beta)$

\[
|\sin(2\beta + \gamma)| \in [0.77, 1.0], \\
\gamma \in [5, 86]^\circ \cup [185, 266]^\circ, \\
\delta \in [-41, 41]^\circ \cup [140, 220]^\circ,
\]
Excited $B_c^+$ states

- Expect two structures in $B_c^+\pi^+\pi^-$
  - $B_c(2^1S_0)^+ \rightarrow B_c^+\pi^+\pi^-$
  - $B_c(2^3S_1)^+ \rightarrow B_c^{*+}\pi^+\pi^-$, $B_c^{*+} \rightarrow B_c^+\gamma$
- Higher production rate of $B_c(2^3S_1)^+$
- $B_c(2^1S_0)^+$ peak at its mass, predicted to be $\sim [6830,6890]$ MeV
- $B_c(2^3S_1)^+$ peak offset from its true mass by missing photon; separation between the two peaks is $\Delta M \equiv [M(B_c^{*+}) - M(B_c^+)] - [M(B_c^{(2S)^+}) - M(B_c(2S)^+)]$
  and is predicted to be $[0, 35]$ MeV
- So ATLAS may be seeing
  - Just $B_c(2^1S_0)^+$
  - Just $B_c(2^3S_1)^+$ with missing photon
  - Mixture of $B_c(2^1S_0)^+$ and $B_c(2^3S_1)^+$

Chen & Kuang, PRD 46, 1165 (1992)
Eichten & Quigg, PRD 49, 5845 (1994)
Fulcher, PRD 60, 074006 (1999)
Godfrey, PRD 70, 054017 (2004)
Wei & Guo, PRD 81, 076005 (2010)
Excited $B_c^+$ states

In 2017: LHCb doesn't confirm the observation with a larger $B_c^+$ sample

$B_c^+ \rightarrow J/\psi \pi^+ (3325 \pm 73)$  
$M(J/\psi \pi^+) [\text{MeV}/c^2]$

- UL on yield ratio (resonance/$B_c^+$) set as function of mass for different hypotheses, see backups.
- LHCb & ATLAS results in mild tension but not incompatible given uncertainties & different kinematics, efficiencies (low vs high $p_T$).
- LHC experiments should be able to clear this up with Run2 data.