Recent experimental results in flavour physics

Marco Gersabeck (The University of Manchester) on behalf of the LHCb collaboration including results from other flavour experiments

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Introduction

- $\sim 3.5\sigma$ $(g - 2)_\mu$ anomaly
- $\sim 3.5\sigma$ non-standard like-sign dimuon charge asymmetry
- $\sim 3.5\sigma$ enhanced $B \to D^{(*)}\tau\nu$ rates
- $\sim 3.5\sigma$ suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$
- $\sim 3\sigma$ tension between inclusive and exclusive determination of $|V_{ub}|$
- $\sim 3\sigma$ tension between inclusive and exclusive determination of $|V_{cb}|$
- $2 - 3\sigma$ anomaly in $B \to K^*\mu^+\mu^-$ angular distributions
- $2 - 3\sigma$ SM prediction for $\epsilon'/\epsilon$ below experimental result
- $\sim 2.5\sigma$ lepton flavor non-universality in $B \to K\mu^+\mu^-$ vs. $B \to K\ell^+\ell^-$
- $\sim 2.5\sigma$ non-zero $h \to \tau\mu$
Introduction

• A good number of often-cited tensions
  - Some will be statistical fluctuations
  - But if uncertainties can be trusted some should evolve into real anomalies
  - Worth having a closer look
  - Should investigate broadly even if some seem more attractive than others
• Huge potential for flavour measurements to reveal BSM physics
  - Will not cover all of these today
Spectroscopy

A brief visit to the world of many states
Tetraquarks and Pentaquarks

- Two pentaquark candidates discovered in 2015 decaying to $J/\psi p$
  - $P_c(4380), P_c(4450)$
  - Model-independent confirmation in 2016
- Four tetraquark candidates observed decaying to $J/\psi \phi$
  - First full amplitude analysis
  - Three new states plus one known suspect
  - $X(4140), X(4274), X(4500), X(4700)$
Towards further confirmation

- $P_c(4450)$ just above $\chi_{c1p}$ threshold
- First observation of $\Lambda_b \to \chi_{c1p}$ and $\chi_{c2p}$
  - Can be used to test exotic nature of $P_c$
- Strangeness hidden charm pentaquark state predicted to decay into $J/\psi \Lambda$
  - Observed $\Xi_b^{-} \to J/\psi \Lambda K$ decays
- Phase-space analyses to follow

LHCb-PAPER-2017-011

arXiv: 1701.05274
\( \Omega_c \) gets excited

- 5 new narrow states observed in \( \Xi^+_c K \) spectrum
  - \( m = 3.3 \pm 0.12 \) GeV
  - \( \Gamma = 1 - 10 \) MeV
  - New excited \( \Omega_c \) states
- Expected feed-down seen and taken into account
- Sidebands and same-sign combinations show no structures

arXiv:1703.04639, accepted by PRL
CP violation

3 quark generations or more?
CP violation in mixing

- Look for $\bar{B} \rightarrow l^+$ decays
  - Forbidden directly, requires $\bar{B} \rightarrow B$ oscillation
- Measure asymmetry of $\bar{B} \rightarrow l^+$ and $B \rightarrow l^-$ rates
  - CP violation in mixing
- SM expectation far below current sensitivity
- Can measure this separately for $B_d$ and $B_s$ mesons
  - Separate access to $A_{sl}(B_d)$ & $A_{sl}(B_s)$
- Alternatively look for same-sign lepton pairs and compare $l^+l^+$ with $l^-l^-$
  - Measures combination of $A_{sl}(B_d)$ & $A_{sl}(B_s)$
Latest results

• D0 dimuon measurement differs from SM by about 3σ
  ➡ Difficult to motivate by non-SM physics
• Direct measurements of $a_{sli}(B_d)$ & $a_{sli}(B_s)$ show agreement with SM
• Possible differences in SM contribution to observables?
• LHCb has best single measurement of $a_{sli}(B_d)$ and $a_{sli}(B_s)$
  ➡ Latest: $a_{sli}(B_s) = (0.39 \pm 0.26 \pm 0.20)\%$
    PRL 117 (2016) 061803

• ATLAS now contributing constraints on potential direct CP violation contributions
  ➡ Using top decays
  ➡ No firm conclusion on D0 anomaly yet

JHEP 02 (2017) 071
News on $\beta$

- Combined BaBar and Belle analysis ($1.1\text{ab}^{-1}$)
- Time-dependent analysis of $B^0 \rightarrow D^{(*)0} h^0$ with $D^0 \rightarrow K\pi\pi\pi$ decays
- First evidence for $\cos(2\beta) > 0$
- Excludes second solution of unitarity triangle fit
Improving $\gamma$ precision

- Combining LHCb measurements of $B(s)\to DK^{(*)}$ decays
- BaBar average: $\Rightarrow (70\pm18)^{\circ}$
- Belle average: $\Rightarrow (73\pm14)^{\circ}$
- LHCb improves by factor 2
- All based on tree decays
  - $\Rightarrow$ SM measurements
  - $\Rightarrow$ Access to beyond SM particles through loops in $\gamma$ measurements using $B\to hh(h)$ decays

*CKMFitter Summer 2014
CP violating phase $\phi_s$

- First measurement in $B_s \to J/\psi KK$ with $m_{KK}$ above $\phi$ resonance
- Preliminary results:

$$\phi_s = 119 \pm 107 \pm 34 \text{ mrad}$$
CP violation in Baryons

- CP violation has never been measured in baryons
- Study local triple-product asymmetries
  - in bins of phase space
  - in bins of decay-plane angle
- Triple-products are robust against systematic uncertainties
- Angular bins for $\Lambda_b \rightarrow p\pi^-\pi^+\pi^-$ show $3.3\sigma$ deviation from no-CPV hypothesis
- Weaker signals in phase-space binning and smaller $\Lambda_b \rightarrow p\pi^-K^+K^-$ sample
CPV in charm

- Mass difference of eigenstates still unknown

- No sign of indirect CPV
  - How long will super-weak constraint remain valid?
  - $A_{\Gamma}$ now constraint to $3 \times 10^{-4}$ \textit{arXiv:1702.06490}

- Some low p-values in tests for CPV in multi-body ($D^0 \rightarrow 4\pi$) decays \textit{arXiv:1612.03207}
  - Too early to make a claim
Rare decays

Plenty to learn from the not so plentiful
B⁰ → μμ

- LHCb update with Run 2 data
- First single-experiment observation of Bs → μμ (7.8σ)
- No significant signal for Bd → μμ (1.6σ)
- SM looks very healthy here
- First measurement of effective lifetime

\[ \tau(B_s \rightarrow \mu^+\mu^-) = 2.04\pm0.44\pm0.05\text{ps} \]
\[ B_s \rightarrow \tau^+ \tau^- \]

- First direct limit on \( B_s \) decay
  \[ B(B_s \rightarrow \tau^+ \tau^-) < 6.8 \times 10^{-3} \]
- World best limit on \( B_d \) decay
  \[ B(B_d \rightarrow \tau^+ \tau^-) < 2.1 \times 10^{-3} \]
- Both at 95% CL

\[ \text{Candidates} \]

\[ \text{Pull} \]

\[ \text{Neural network output} \]
**K*μμ and friends**

- LHC analyses based on full Run 1 data
  - Awaiting Run 2 updates
- LHCb performs full angular analysis
- Belle, ATLAS and CMS use angular folding, differences in observables, background treatment and control modes

LHCb: JHEP 02 (2016) 104
Belle: BELLE-CONF-1603
ATLAS: ATLAS-CONF-2017-023
CMS: CMS-PAS-BPH-15-008
DHMV: JHEP 12(2014)125
ASZB: EPJC 75 (2015) 382
K*μμ and friends

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Also investigating related b→sll channels
- e.g. slight tension in BF(B_s→φμμ)

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JHEP 09 (2015) 179
more $K^*\mu\mu$ friends

- Fits with different phase hypotheses for long-distance contributions
- Minimal influence on short-distance branching fraction
  - Found to be below SM
  - Improved modelling shows no significant change w.r.t. previous analysis of these data
- Scan of Wilson coefficients disfavours SM solution
- Analyses of other channels underway
  - More complex if hadron not pseudo-scalar

$B^+ \rightarrow K\mu\mu$
Lepton flavour universality

A basic principle under attack
Lines of attack

• Tree-level processes
  - $b \rightarrow c\nu$: $R(D)$, $R(D^*)$, … in beauty
  - $c \rightarrow d\nu$: $R(K)$, $R(K^*)$, … in charm

• Penguin/FCNC processes
  - $b \rightarrow d/\bar{s}l$: $R(K)$, $R(K^*)$, … in beauty
  - Charm FCNC remain to be observed
- SM disfavoured by $3.9\sigma$
- New Belle measurement on $R(D^*)$
- Many related measurements in the making
  - $R(J/\psi), R(D^{**}),$ baryonic
- Form factors show no strong impact on discrepancy with SM
  - Bernlochner, Ligeti, Papucci, Robinson, 1703.05330
- Plenty of room for BSM
LU tests in charm

- So far only measurements of branching fractions
  ➡ All ratios above unity
- Direct measurement of ratio can exploit cancellation of uncertainties
- Further insight through $q^2$-dependent measurement
- To what degree will this be limited by knowledge of form factors?

\[
\begin{align*}
\frac{B(D^0 \rightarrow \pi e^- \nu_e)}{B(D^\ell \rightarrow \pi \mu^- \nu_\mu)} \\
\frac{B(D^0 \rightarrow K^+ (892) e^- \nu_e)}{B(D^\ell \rightarrow K^+ (892) \mu^- \nu_\mu)} \\
\frac{B(D^0 \rightarrow K e^- \nu_e)}{B(D^\ell \rightarrow K \mu^- \nu_\mu)}
\end{align*}
\]

based on latest BF PDG averages

\[
R^e_{\mu} / R_{\mu / e}(q^2)
\]

\[
S. Faijfer et al., PRD 91 (2015) 094009
\]
• Moderate tension with SM
  ➔ LHCb Run 1 result

• Would be clear theoretical signature

• Updates eagerly awaited…
\( R(K^*) \)

- Measuring double ratio

\[
R_{K*0} = \frac{B(B^0 \to K^{*0} \mu^+\mu^-)}{B(B^0 \to K^{*0} e^+e^-)} \cdot \frac{B(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{B(B^0 \to K^{*0} J/\psi(\to e^+e^-))}.
\]

- Measuring in two bins of \( q^2 \)
  
  \( \Rightarrow \) Low: 0.045-1.1, central: 1.1-6 GeV/c

- Using full Run 1 data

- Veto mis-ID and partially reconstructed background

- Fits separated by trigger three categories for electron mode
  
  \( \Rightarrow \) Results in good agreement

- Main systematics due to simulation corrections and residual backgrounds (for central \( q^2 \) bin)

- Cross-checks with various control channels
\[ R(K^*) = \frac{B(B^0 \rightarrow K^{*0} \mu^+\mu^-)}{B(B^0 \rightarrow K^{*0} J/\psi(\rightarrow \mu^+\mu^-))} / \frac{B(B^0 \rightarrow K^{*0} e^+e^-)}{B(B^0 \rightarrow K^{*0} J/\psi(\rightarrow e^+e^-))}. \]

- Measuring double ratio

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Preliminary results for $R(K^*)$

<table>
<thead>
<tr>
<th></th>
<th>low-$q^2$</th>
<th>central-$q^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{K^*0}$</td>
<td>$0.660 \pm 0.110 \pm 0.024$</td>
<td>$0.685 \pm 0.113 \pm 0.047$</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>
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Outlook

Towards a flavourful future
A flavourful decade

- Plus lots of activity on charged lepton flavour
  - MEG, mu3e, mu2e, COMET, g-2, ...
LHCb upgrade

Apr 2017

- With increased luminosity hadron channels would saturate
  - Limited by hardware trigger
- Upgrade to allow full detector readout at 40 MHz and increased luminosity: collect $\sim 8fb^{-1}$/ year
  - Requires several new detectors (all tracking plus RICH) and new readout electronics otherwise
- Full software trigger
  - Massively improved trigger efficiencies
  - Offline quality reconstruction in trigger
- Maintain/improve current level of detector performance
- Phase-Ib consolidation and Phase-II upgrade planned in LS3 and LS4

LHCb

LHCb run-1  LHC run-2  LHC run-3  LHC run-4

LHCb Phase-I upgrade  Phase-II

LHC run-1  LHC run-2  LHC run-3  LHC run-4


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UNDER CONSTRUCTION
Future potential

• Pure software trigger will significantly improve efficiencies,
  ➡ Particularly for soft final states
    ▶ Charm, tau, strange, multi-body
  ➡ Benefits exceeding increase in luminosity

• Healthy competition with Belle II during LHCb Phase-I upgrade

• LHCb Phase-II upgrade will boost yields by another order of magnitude
  ➡ The ultimate precision frontier

• Don’t forget the kaons…
Conclusion

• LHCb has taken over the leading role in flavour physics

• No smoking gun signal for physics beyond the SM

• Several hints demand more precise and complementary measurements as well as advances on the theoretical side

  ➡ New result shown on $R(K^*)$

• Good chance that strong signals will emerge with Run 2

  ➡ First results shown today

• Need LHCb upgrades to probe to Standard Model level precision

• Next decade will be flavourful

  ➡ Belle II, BESIII, COMET, $g-2$, LHCb Run 2, LHCb upgrade(s), MEG, mu2e, mu3e, NA62, …