B-anomalies at LHCb

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Introduction

• Interesting set of anomalies have appeared in measurements of $B$ decays:
  – Angular observables in $B^0 \rightarrow K^{*0} \mu\mu$
  – Branching fractions of several of $b \rightarrow sll$ processes
  – Lepton-flavour universality ratios in $b \rightarrow sll$ and $b \rightarrow cl\nu$ decays

• Extent of discrepancies depends on several theoretical issues
  – will try and highlight these issues
  – point out where experiment can provide some future input

• $B$-decays of interest when well-calculable process, sensitive to new physics can be measured…
A historical example – $B_d^0 \rightarrow K^{*0}\gamma$

- **In SM**: occurs through a dominating $W$-$t$ loop
- **Possible NP diagrams**: 
- Observed by CLEO in 1993, two years before the direct observation of the top quark
  - BF was expected to be $(2-4) \times 10^{-4}$
  - measured BF = $(4.5 \pm 1.7) \times 10^{-4}$

Theoretical Foundation

• The **Operator Product Expansion** is the theoretical tool that underpins rare decay measurements – rewrite SM Lagrangian as:

\[ \mathcal{L} = \sum_i C_i O_i \]

  – “Wilson Coefficients” \( C_i \)
    • Describe the short distance part, can compute *perturbatively* in given theory
    • Integrate out the heavy degrees of freedom that can't resolve at some scale \( \mu \)
  – “Operators” \( O_i \)
    • Describe the long distance, non-perturbative part involving particles below scale \( \mu \)
    • Account for effects of strong interactions and are difficult to calculate reliably

→ **Form a complete basis – can put in all operators from NP/SM**

• Mixing between different operators: \( C_i \rightarrow C_i^{\text{effective}} \)

• In *certain* observables the uncertainties on the operators cancel out – are then free from theoretical problems and measuring the \( C_i \) tells us about the heavy degrees of freedom – *independent of model*
LHCb data-taking

- Have analysed 3 fb$^{-1}$ of data taken during 2011, 12
  - Analysis of further $\sim$2 fb$^{-1}$ (with $\sim$1.5 cross-section) in progress
  - Have taken further 1.7 fb$^{-1}$ in 2017
Outline

• Angular observables in $B^0 \rightarrow K^{*0}\mu\mu$ and $b \rightarrow sll$ BF s

• Lepton-flavour universality ratios in $b \rightarrow sll$ decays

• Semileptonic $b \rightarrow c\ell\nu$ decays

• Some remarks about the future
Outline

• Angular observables in $B^0 \rightarrow K^{*0} \mu\mu$ and $b \rightarrow sll$ BFs

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• Some remarks about the future
$b \rightarrow sll$ decays

- $b \rightarrow sll$ decays involve flavour changing neutral currents $\rightarrow$ loop process

- Best studied decay $B^0 \rightarrow K^{*0}\mu\mu$

- Large number of observables: $BF$, $A_{CP}$ and angular observables – dynamics can be described by three angles $(\theta_l, \theta_K, \phi)$ and di-$\mu$ invariant mass squared, $q^2$
$B_d^0 \rightarrow K^{*0}_0 \mu\mu$ $C_i$ and form factors

- Amplitudes that describe the $B_d^0 \rightarrow K^{*0}_0 \mu\mu$ decay involve
  - The (effective) Wilson Coefficients: $C_{7}^{\text{eff}}$ (photon), $C_{9}^{\text{eff}}$ (vector), $C_{10}^{\text{eff}}$ (axial-vector)
  - Seven (!) form factors – primary origin of theoretical uncertainties

\[
\begin{align*}
A_{\perp}^{L(R)} &= N\sqrt{2\lambda}\left\{ \left( C_9^{\text{eff}} + C_9^{\prime\text{eff}} \right) \mp \left( C_{10}^{\text{eff}} + C_{10}^{\prime\text{eff}} \right) \right\} \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} \left( C_7^{\text{eff}} + C_7^{\prime\text{eff}} \right) T_1(q^2) \\
A_{\parallel}^{L(R)} &= -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{ \left( C_9^{\text{eff}} - C_9^{\prime\text{eff}} \right) \mp \left( C_{10}^{\text{eff}} - C_{10}^{\prime\text{eff}} \right) \right\} \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} \left( C_7^{\text{eff}} - C_7^{\prime\text{eff}} \right) T_2(q^2) \\
A_{0}^{L(R)} &= -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{ \left( C_9^{\text{eff}} - C_9^{\prime\text{eff}} \right) \mp \left( C_{10}^{\text{eff}} - C_{10}^{\prime\text{eff}} \right) \right\} \left[ (m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}} \right] \\
&\quad + 2m_b \left( C_7^{\text{eff}} - C_7^{\prime\text{eff}} \right)[(m_B^2 + 3m_{K^*} - q^2)T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2} T_3(q^2)]
\end{align*}
\]

→ BF$s$ have relatively large theoretical uncertainties
\[ B^0 \to K^{*0} \mu\mu \]

- Try to use observables where theoretical uncertainties cancel e.g. Forward-backward asymmetry \( A_{FB} \) of \( \theta_1 \) distn
\[ B^0 \rightarrow K^{*0} \mu \mu \] angular analysis

- LHCb performed first full angular analysis [JHEP 02 (2016) 104]
  - Extracted the full set of CP-avg’d angular terms and correlations
  - Determined full set of CP-asymmetries

- Vast majority of observables in agreement with SM predns, giving some confidence in theory control of form-factors
**B^0 \rightarrow K^{*0}\mu\mu** angular analysis

- CMS and ATLAS confirm these findings

Form-factor independent obs.

- At low and high $q^2$, (leading order) relations between the various form factors allow a number of form-factor “independent” observables to be constructed.

- E.g. in the region $1 < q^2 < 6 \text{ GeV}^2$, relations reduce the seven form-factors to just two – allows to form quantities like:

$$P_5' \sim \frac{\text{Re}(A_0^L A_{\perp}^{L*} - A_0^R A_{\perp}^{R*})}{\sqrt{(|A_0^L|^2 + |A_0^R|^2)(|A_{\perp}^L|^2 + |A_{\perp}^R|^2 + |A_{\parallel}^L|^2 + |A_{\parallel}^R|^2)}}$$

which are form-factor independent at leading order.

- In fact, can form a complete basis ($P^{(i)}$ series) in which there are six form-factor independent and two form-factor dependent observables ($F_L$ and $A_{FB}$).
$B^0 \rightarrow K^{*0} \mu\mu$ angular analysis

- Form-factor “independent” $P_5'$ has a local discrepancy in two bins – (subsequently confirmed by Belle)
  $\rightarrow 3.4\sigma$ discrepancy with the vector coupling $\Delta C_9 = -1.04 \pm 0.25$

Figure 8: The optimised angular observables in bins of $q^2$, determined from a maximum likelihood fit to the data. The shaded boxes show the SM prediction taken from Ref. [14].

[JHEP 02 (2016) 104] [PRL 118 (2017) 111801]
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[PRL 118 (2017) 111801]

[JHEP 02 (2016) 104]

[ATLAS-CONF-2017-023]

[arXiv:1710.02846]
b→sll branching fractions

- Several b→sll branching fractions measured at LHCb show some tension with predictions, particularly at low q^2

\[ \text{JHEP 11 (2016) 047, JHEP 04 (2017) 142} \]

\[ \text{JHEP 09 (2015) 179} \]

\[ \text{JHEP 06 (2015) 115} \]

\[ \text{JHEP 06 (2014) 133} \]
Several theory groups have interpreted results by performing global fits to $b \to sll$ data e.g. [arXiv:1704.05340, EPJC(2017)77:377]

Consistent picture, tensions solved simultaneously by a modified vector coupling ($\Delta C_9 \neq 0$) at $>3\sigma$ but discussion of residual hadronic uncertainties (…)
Could the SM prediction be wrong?

- Largest individual uncertainty on $P_5'$ from $c\bar{c}$-loop effects

- Theorists have started to look critically at their predictions – $O_{1,2}$ operators have a component that could mimic a NP effect in $C_9$ through $c\bar{c}$ loop

- Recent paper fits parameterisation to theory and auxiliary data to try and determine $c\bar{c}$ effect

[arXiv:1707.07305]
Could the SM predn be wrong?

- Effect can be parameterised as function of three helicity amplitudes, \( h_{+-0} \)
  - Absorb effect of these amplitudes into a helicity dependent shift in \( C_9 \)
    \[
    C_9^{\text{SM}} + \Delta C_9^{+-0}(q^2) \quad \text{cf.} \quad C_9^{\text{SM}} + \Delta C_9^{\text{NP}}
    \]
  - Look for \( q^2 \) and helicity dependence of shift in \( C_9 \)

Factor 5 increase in non-FF hadronic uncert. cannot account for effect seen

"The absence of a \( q^2 \) and helicity dependence is intriguing, but cannot exclude a hadronic effect as the origin of the apparent discrepancies"
Could the SM predn be wrong?

- What about the form factors, could they be wrong?
  - Would give a correlated effect in other observables
  - Even if double errors, don’t get close to explaining anomalies

- An experimental problem?
What if SM predn are correct?

- Need a new vector contribution \( \rightarrow \) adjusts \( C_9 \) Wilson Coefficient; \( C_9^{NP} = -C_{10}^{NP} \) (V-A) also still compatible with fits

- Very difficult to generate in SUSY models:
  
  “[\( C_9 \) remains] SM-like throughout the viable MSSM parameter space, even if we allow for completely generic flavour mixing in the squark section”

- Models with composite Higgs/UED have same problem

- **Could generate observed deviation with a Z’ or LQ**
What if SM predn are correct?

• Discrepancies have got enough interest st model builders have started to step-in

- **Z’**
- **$SU(2)_L$ singlet or triplet**
- **Leptoquark**
- **Spin 0 or 1**
- **New scalars/vectors, also leptoquarks possible**

• For a review see, e.g. D.Straub @ Instant workshop on B meson anomalies
Direct searches

• Measurements give constraints on mass, coupling plane – in order to understand how heavy e.g. LQ might be, need a model for couplings
  – Couple only to b-s (and hence avoid lots of other expt'al constraints)?
    → LQ can be ~TeV but then very difficult to measure directly
  – Invent full model with coupling to other quarks?
    → LQ can then be ~30TeV and even a 100TeV future collider might not be able to do the job (!)
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• Some remarks about the future
The plot thickens: $R_K$

- The ratio of $b\rightarrow s\mu\mu$ and $b\rightarrow s\text{ee}$ branching fractions, $R$, is a theoretically pristine quantity, precisely predicted in the SM
  \[ R_{K^*,0,K} = \frac{\text{BF}(B^0,\rightarrow K^{*0},+\mu\mu)}{\text{BF}(B^0,\rightarrow K^{*0},+\text{ee})} \]

- Whatever hadronic uncertainties affect $b\rightarrow s\text{ll}$ decays, they should cancel in this ratio

- 2014 LHCb measurement of $R_K$,
  \[ R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)}^{+0.036}_{-0.036} \text{ (syst)} \]
  already generated some excitement, despite being consistent with SM at 2.6$\sigma$ level

  - Measured value is what would result from $\Delta C_9^{\text{ee}}=0$, $\Delta C_9^{\mu\mu}=-1$
    i.e. could account for angular data, BFs and this $R_K$ ratio by changing only $C_9^{\mu\mu}$
Lepton universality measurements

- Have recently added analogous measurement using \( K^{*0}\ell\ell \) instead of \( K^{+}\ell\ell \rightarrow R_{K^{*0}} \)

- Find,
  - low \( q^2 \): 2.1-2.3\( \sigma \) below SM predn
  - ctl \( q^2 \): 2.4-2.5\( \sigma \) below SM predn

- Cue a new wave of global fits (…)

\[ JHEP 08 (2017) 055 \]
$R_{K^{*0}}$ – experimental issues
Cross-checking R ratios

- $R_X$ measurements made exploiting double ratio wrt equivalent $J/\psi$ decay modes in order to cancel experimental systematic uncertainties
  
  $$R_{K^*0} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} / \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

- Need observed yield of each decay mode and (ratio of) selection efficiencies
  - Bremsstrahlung and trigger give main differences between
  - Cancel effect by comparing to $J/\psi$ modes with similar issues
Cross-checking R ratios

- Test control of the absolute scale of the efficiencies by instead measuring the single ratio,
  \[ r_{J/\psi} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+\mu^-))}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+e^-))} \]
  where we do not benefit from this cancellation

- \( r_{J/\psi} \) known to be lepton universal at \( \sim \% \) level

- Measure \( r_{J/\psi} = 1.043 \pm 0.006 \) (stat) \( \pm 0.045 \) (syst), result is independent of the decay kinematics, binning in quantities that would expect bremsstrahlung and trigger to depend on see completely uniform result
Cross-checking R ratios

• Extent of the cancellation of residual systematics verified by measuring the double ratio, $R_{\psi(2S)}$, where $B^0 \rightarrow K^*\psi(2S) \rightarrow l^+l^-$ decays used in place of $B^0 \rightarrow K^*l^+l^-$

• Find compatible with unity, $\sigma_{\text{stat}} \sim 2\%$

• Further check at low $q^2$ : measure $BF(B^0 \rightarrow K^*\gamma)$ where $\gamma$ converts to $e^+e^-$, again result compatible with PDG

• Various data-driven adjustments made to simulation in order to reproduce trigger-, PID-, tracking- efficiencies observed with data control channels, even if turn these off completely, result shifts by $<5\%$
Global fits revisited

- Using *just* the theoretically clean observables, $R_K$, $R_{K^*}$ and $BF(B \rightarrow \mu\mu)$, fits exclude SM at 3.6$\sigma$ level

- NB: have more than twice data again in-hand
Global fits revisited

- Adding the angular and branching fractions observables to the LFU ratios, the size of the discrepancy $\rightarrow >5\sigma$ [see e.g. arXiv:1704.05340]

... but community understandably still reluctant to call this NP
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Semileptonic anomaly

- A further anomaly is seen in semileptonic B decays
  - Tree-level process in SM
  - Good theoretical control due to factorisation of hadronic and leptonic parts but again use lepton universality ratio to access theoretically pristine quantity e.g. in case of \( b \rightarrow c l \bar{\nu} \) transition,
    \[
    R(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \rightarrow D(\ast)\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D(\ast)\ell^- \bar{\nu}_\ell)}
    \]
  - SM predictions
    - \( R(D) = 0.300(8) \) \[EPJ C77 (2017)112\]
    - \( R(D^*)=0.252(3) \) \[PRD 85 (2012) 094025\]
  - Recent updates take into account alternative extrapolation for form-factors and differential distributions from Belle data,
    - \( R(D)=0.258(5) \) \[arXiv:1707.09977\]
    - \( R(D^*)=0.260(8) \) \[arXiv:1707.09509\]
LHCb result – leptonic $\tau$

- 3D fit to $(m_{\text{miss}}^2, E_\mu^*, q^2)$
- $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
- $2.1\sigma$ above SM prediction
- Dominant systematics from MC statistical uncertainty and background from hadrons misidentified as muons
LHCb result – 3-prong $\tau$

- Largest residual background $B \to D^* D_S[\to 3\pi X]$
- Train BDT to separate from signal using $3\pi$ dynamics, visible mass, momenta etc.
- 3D fit to (BDT, $\tau_\tau$, $q^2$)
- $R(D^*) = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$
  - 3rd uncertainty from $B(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$ and $B(B^0 \to D^{*-}\mu^+\nu)$
- $0.9\sigma$ above SM prediction
Global fit to semileptonic decays

- Combination of results with those from Babar/Belle shows excellent agreement
- World average value SM predictions shows a $4.1\sigma$ tension – updated theory can change this by $\sim 0.5\sigma$
Simultaneous explanation of the anomalies?

- Number of theory papers try and find a simultaneous explanation for the $R_D$ and $b \rightarrow sll$ anomalies
  - Possible with both tree level mediator and with tree- and loop-level mediators
  - Reduces the NP scale of $b \rightarrow s\mu \mu$ to <9 TeV
  - Options include scalar and vector LQ and some colourless vector
  - Constraints from $B$-mixing, limits on $B \rightarrow K\nu\nu$ important

One Leptoquark to Rule Them All: A Minimal Explanation for $R_D^{(\tau \tau)}$, $R_K$ and $(g-2)_\mu$

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We show that by adding a single new scalar particle to the Standard Model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $B \rightarrow K^{(*)}\ell^+\ell^-$ decays, the enhanced $B \rightarrow D^{(*)}\ell\nu$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $B \rightarrow K^{(*)}\ell\nu$ decay rates and a new-physics contribution to $B_\tau - B_\mu$ mixing close to the current central fit value.
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A glimpse of the future – $B_d^0 \rightarrow K^{*0}_0 \mu\mu$

- Measure the effect of $c\bar{c}$ loops
- At low $q^2$, $\Delta C_{9}^{+0}(q^2)$ term arises mainly from interference rare decay and $J/\psi$
- Measure phase of interference by fitting differential rate (and angles)
- LHCb has performed such a fit for $B^+ \rightarrow K^+\mu^+\mu^-$ [EJPC (2017) 77:161], considerably more complex for $B^0 \rightarrow K^{*0}_0 \mu\mu$ but principle the same
A glimpse of the future – $B^0 \rightarrow \mu^+ \mu^-$

- Many single-particle explanations of anomalies predict $C_9^{NP} = -C_{10}^{NP}$ (data still compatible with such a soln)

- If this were the case would expect to see effect in $B^0 \rightarrow \mu^+ \mu^-$ decays
  - Helicity and GIM suppressed
  - Dominant contribution from $Z$-penguin diagram
  - Precise predictions for BFs :
    \[ B(B_s^0 \rightarrow \mu \mu) = (3.66 \pm 0.23) \times 10^{-9} \]
    \[ B(B_d^0 \rightarrow \mu \mu) = (1.06 \pm 0.09) \times 10^{-10} \]
  - Can be altered by modified $C_{10}$ or new scalar/pseudoscalar
A glimpse of the future – $B^0 \rightarrow \mu^+ \mu^-$

- Many single-particle explanations of anomalies predict $C_{9}^{NP} = -C_{10}^{NP}$ (data still compatible with such a soln).

- No evidence for any deviation from SM so far… but this measurement will be important for the future!
A glimpse of the future – $R_X$

- Programme of additional $R_X$ measurements just starting:
  - Update $R_K$ and $R_{K^*}$ – with new data
  - Add high $q^2$ regions
  - Add new measurements $R(\phi)$, $R(K\pi\pi)$, $R(\Lambda)$...
  - Add CKM-suppressed decays e.g. $R(\pi)$

- Can also widen search for lepton-flavour violating decays e.g. $ll'$, $Kll'$ expected for LQ models
A glimpse of the future – $P_5'$

- Can make ratio of $P_5'(e)$ and $P_5'(\mu) \rightarrow Q_5$

- Thus far, only done by Belle – full angular analysis of $B^0 \rightarrow K^{*0}ee$ in progress at LHCb

[PRL 118 (2017) 111801]
A glimpse of the future – semilep.

- Working on a simultaneous measurement of $R(D)$, $R(D^*)$, as well as $R(D^+)$, $R(\Lambda_c)$ in both leptonic and 3-prong cases.
- Cabibbo suppressed decay $\Lambda_B \rightarrow p\ell\nu$ experimentally difficult at LHCb, as no vertex to give B decay point that is needed for $\tau$ reconstruction.
  - $B^+ \rightarrow p\bar{p}\ell\nu$ an experimentally viable alternative.
Conclusions
Conclusions

• Interesting set of anomalies observed in B decays – given experimental precision and theoretical uncertainties, none of them are yet compelling

• Near-term updates should clarify the situation and can help constrain some of the theoretical issues

• Wide range of new measurements will be added to broaden the constraints on the underlying physics

• At LHCb, full Run-2 dataset will give factor ~4 more data than Run-I on timescale that Belle-2 will start running