$b \rightarrow s\ell\ell$ decays at LHCb

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Introduction

▶ Run 1 of the LHC provided us with a rich set of results
  → Rise of the precision era for rare decays

▶ Selective set of results with Run 1 and plans with Run 2 data and beyond in light of current anomalies

LHCb signal yields

channel	Run 1	Run 2	Run 3,4 (50fb^{-1})
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$	2,400	9,000	80,000
$B^0 \to K^{*+}(K^0_S\pi^+)\mu^+\mu^-$	160	600	5,500
$B^0 \to K^0_S\mu^+\mu^-$	180	650	5,500
$B^+ \to K^+\mu^+\mu^-$	4,700	17,500	150,000
$\Lambda_b \to \Lambda\mu^+\mu^-$	370	1500	10,000
$B^+ \to \pi^+\mu^+\mu^-$	93	350	3,000
$B^0_s \to \mu^+\mu^-$	15	60	500
$B^0 \to K^{*0}e^+e^-$ (low q^2)	150	550	5,000
$B_s \to \phi\gamma$	4,000	15,000	150,000

Naively scaling with luminosity and linear scaling of $\sigma_{b\bar{b}}$ with $\sqrt{s}$. Extrapolated yields rounded to the nearest 50/500

▶ Our measurements of $d\mathcal{B}/dq^2$ obtained by normalising rare yield to that of normalisation channel $B \to J/\psi K^*$

▶ For higher statistics decays, dominant uncertainty of integrated BF is the knowledge of $\mathcal{B}(B \to J/\psi K^*)$
  → More $b \to s\ell\ell$ decays in Run 1 than $B \to J/\psi K^*$ of B-factories!

▶ Dominant systematic uncertainty on BFs: Knowledge equivalent J/ψ BF
  → Belle2 could help here also resolving isospin asymmetries at $\Upsilon(4S)$ M.Jung [1510.03423]

▶ With the LHCb upgrade even "tough" modes will be sufficiently populated

An intriguing set of results

1. Measurements of differential branching fractions of $B \to K^{(*)}\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$
   ▷ 1σ to 3σ depending on final state

2. Tests of lepton universality between $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$
   ▷ 2.6σ

3. Angular analyses of $B \to K^{(*0)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$
   ▷ $\sim 3\sigma$

Measurements form a consistent picture.

Interpretations

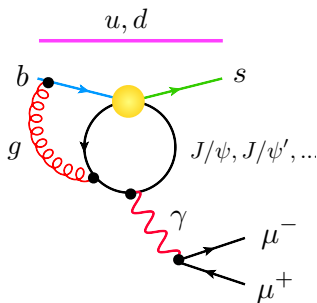▶ Several attempts to interpret $b \to s\mu^+\mu^-$ and $b \to s\gamma$ data
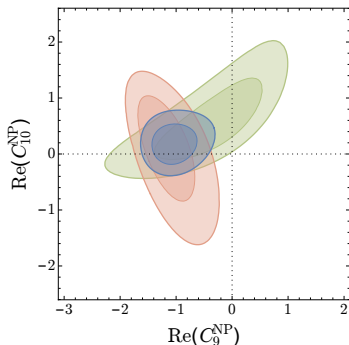
Altmannshofer,Straub[1503.06199]

▶ Modified vector coupling $C_9^{NP} \neq 0$ at $\sim 4\sigma$

$\to$ New vector Z', leptoquarks, vector-like confinement... Buttazzo et al [1604.03940], Bauer et al [PRL116,141802(2016)], Crivellin et al [PRL114,151801(2015)], Altmannshofer et al [PRD89(2014)095033]...

▶ Potential problem with our understanding of the contribution from $B \to X_{c\bar{c}}(\to \mu\mu)K$ Lyon,Zwicky [1406.0566], Altmannshofer,Straub[1503.06199], Ciuchini et al [1512.07157]...

$\to$ Mimics vector-like new physics effects (corrections to C_9)

Impact on dilepton vector coupling

▶ Dependence of observables on vector couplings enters through
$C_9^{eff} = C_9 + Y(q^2)$

$\rightarrow Y(q^2)$ summarises contributions from $bs\bar{q}q$ operators

P. Owen
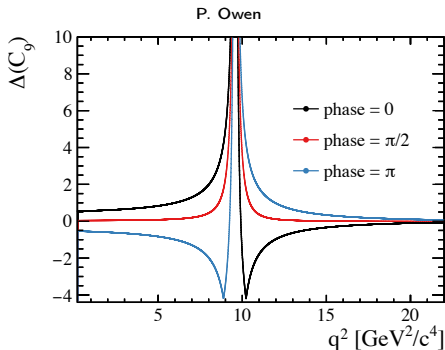
▶ At low q^2 main culprit is the J/ψ

$\rightarrow$ Corrections to C_9^{eff} (ΔC_9) all the way down to $q^2 = 0$

$\rightarrow$ **Effect strongly dependent on relative phase with penguin**

▶ More data will help resolve apparent q^2 dependence of C_9

Measuring phase differences [Eur. Phys. J. C(2017)77:161]

▶ Measure relative phase between narrow resonances and penguin amplitudes

▶ Use expression of differential decay rate in terms of short- and long-distance contributions

$\rightarrow$ Model resonances as relativistic Breit–Wigners multiplied by relative scale and phase inspired by Lyon Zwicky [1406.0566], Hiller et al. [1606.00775]

$$\rightarrow C_9^{eff} = \sum_j \eta_j e^{i\delta_j} A_{res}(q^2) + C_9$$
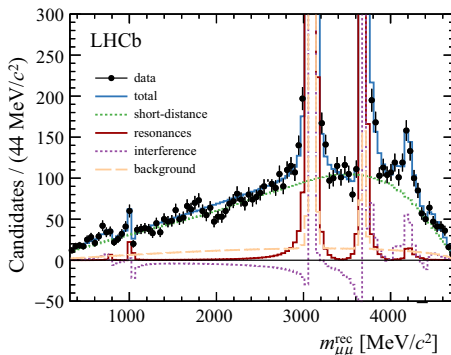
▶ Fit dimuon spectrum of $B^+ \rightarrow K^+\mu^+\mu^-$ to obtain:

$\rightarrow$ Relative phases between resonant and penguin amplitudes

$\rightarrow C_9$ and C_{10}

$\rightarrow$ Further constrain lattice input Bailey et al [PRD93,025026(2016)] on form-factor $f_+(q^2)$

▶ Note have 4 degenerate solutions for phases depending on relative sign between J/ψ and $\psi(2s)$ phases

Measuring phase differences cont'd

- ▶ Results show minimal interference with J/ψ and $\psi(2S)$ resonances

  → Given this model, the J/ψ and $\psi(2S)$ resonances play sub-dominant role below their pole mass

- ▶ Phases of $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ in good agreement with Lyon Zwicky [1406.0566]
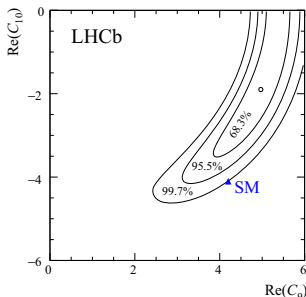
| Resonance	J/ψ negative/$\psi(2S)$ negative	
	Phase [rad]	Branching fraction
$\rho(770)$	-0.35 ± 0.54	$(1.71 \pm 0.25) \times 10^{-10}$
$\omega(782)$	0.26 ± 0.39	$(4.93 \pm 0.59) \times 10^{-10}$
$\phi(1020)$	0.47 ± 0.39	$(2.53 \pm 0.26) \times 10^{-9}$
J/ψ	-1.66 ± 0.05	–
$\psi(2S)$	-1.93 ± 0.10	$(4.64 \pm 0.20) \times 10^{-6}$
$\psi(3770)$	-2.13 ± 0.42	$(1.38 \pm 0.54) \times 10^{-9}$
$\psi(4040)$	-2.52 ± 0.66	$(4.17 \pm 2.72) \times 10^{-10}$
$\psi(4160)$	-1.90 ± 0.64	$(2.61 \pm 0.84) \times 10^{-9}$
$\psi(4415)$	-2.52 ± 0.36	$(6.04 \pm 3.93) \times 10^{-10}$

- ▶ Constrains on C_9 and C_{10} consistent agreement with other global analyses [Straub et al Flavio]
- ▶ Interference with resonances exclude $C_9 = 0$ at more than 5σ!
- ▶ Significantly improve precision on b_1^+ and b_2^+
- ▶ Working on measurement in $B^0 \to K^{*0}\mu^+\mu^-$
  - ▷ Phases per helicity amplitude

Measurement of $B_s \rightarrow \mu^+ \mu^-$ [arXiv:1703.05747]

- ▶ The process $B_s \rightarrow \mu^+ \mu^-$ is both GIM and helicity suppressed in SM
- ▶ Small theoretical uncertainties (Lattice QCD for needed for B meson decay constants)

  $\rightarrow$ Increased sensitivity to effects of new physics entering in dilepton (pseudo-)scalar and axial-vector couplings

- ▶ Experimental challenge: Reduce huge background from combinations of muons from different B decays
- ▶ $\mathcal{B}(B \rightarrow \mu X) \sim 10\%$
  $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) \sim 10^{-9}$
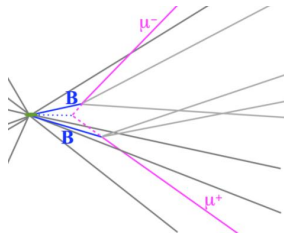
  $\rightarrow$ Use a mulitvariate classifier to separate signal and background
 $\rightarrow$ Use of PID to reduce peaking backgrounds from $B \rightarrow hh$, $B \rightarrow \mu h$

▶ Accounting for increase in cross-section: Run1+Run2∼ 1.75×Run1
▶ Improvements in isolation algorithem → lower backgrounds compared to previous publication

▶ Fit dimuon mass in bins of multivariate classifier to determine signal yield
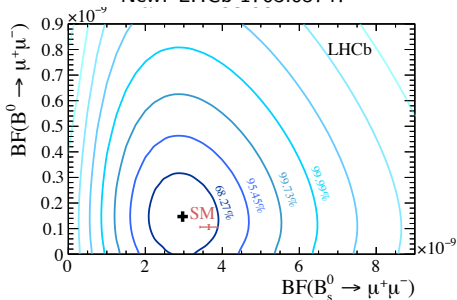▶ Cross-check yields of peaking backgrounds through control samples in the data
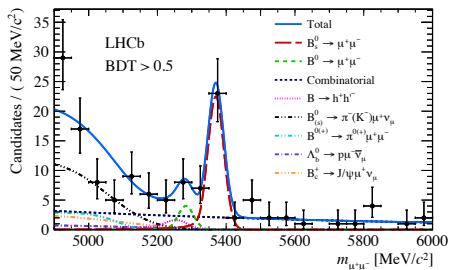
Nature 522, 68-72
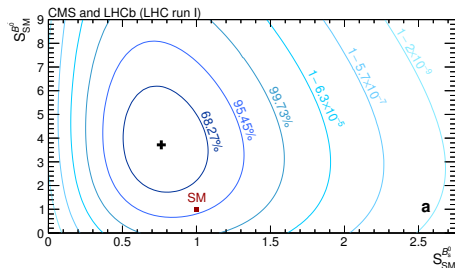
New: LHCb 1703.05747

- ▶ New result consistent with SM. Observation of $B_s^0 \to \mu^+\mu^-$ by LHCb alone
- ▶ Also performed first measurement of the effective lifetime
  $\tau(B_s \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05$ ps
  $\to$ More data required to test SM

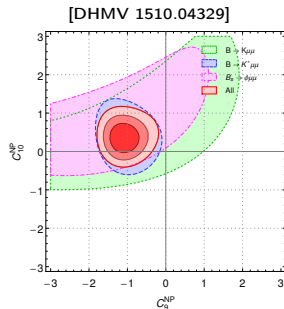# Full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP02(2016)104]

ATLAS,CMS Moriond 2017. Plot courtesy of Tom Blake

- ▶ Working hard to update this analysis with Run2 data
- ▶ Run1 analysis statistically dominated
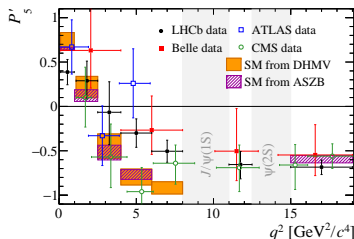
- ▶ Full Run2 dataset expect factor of ~ 2 improvement in stat. precision
  - → Still stat. dominated
- ▶ Important to increase precision in C_{10} as well

[DHMV 1510.04329]

Imaginary contributions to C_9 and C_{10}

▶ We have measured complete set of CP asymmetric observables LHCb [JHEP02(2016)104]

   → Sensitive to imaginary NP contributions

Altmannshofer et al [EPJC(2013)73], LHCb [JHEP02(2016)104]
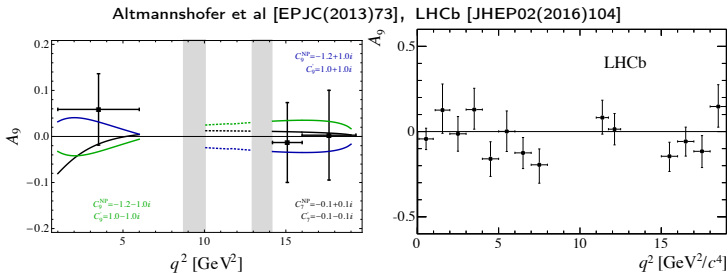
▶ With 300fb^{-1} collected by Run 5, LHCb could have $\sim$500,000 $B^0 \rightarrow K^{*0}\mu^+\mu^-$

   ▷ More than entire Run 1 $B^0 \rightarrow J/\psi K^{*0}$ sample!

▶ Uncertainties in plots shrink by $\sim \times 10$ assumptions about systs

   → Sensitive to NP contributions of order shown

Other $K^+\pi^-$ states [JHEP11(2016)047]

▶ Measure S-wave fraction in $644 < m_{K\pi} < 1200$ MeV/c^2 [JHEP11(2016)047]

  → Enables first determination of P-wave only $B^0 \to K^{*0}(892)\mu^+\mu^-$ differential branching fraction
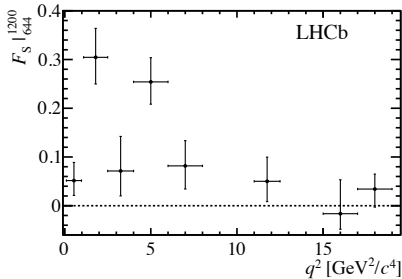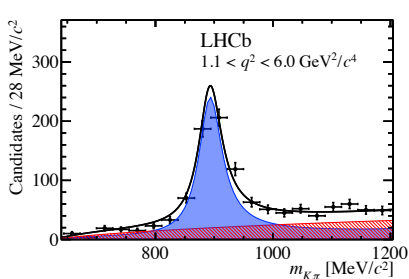
▶ Additional data should provide sensitivity to potential non-resonant P-wave contributions

  → Orthogonal constraints provided theory uncertainties under contro Das et al [1406.6681] What are prospects here? Our measurements could help

Other $K^+\pi^-$ states cont'd [JHEP12(2016)065]

▶ Angular moment and differential branching fraction analysis in $1330 < m_{K\pi} < 1530$ MeV/c^2 [JHEP12(2016)065]

→ Measure 40 normalised angular moments sensitive to interference between S-, P- and D-wave

→ No significant D-wave component observed in contrast to $B^0 \to J/\psi K^+\pi^-$
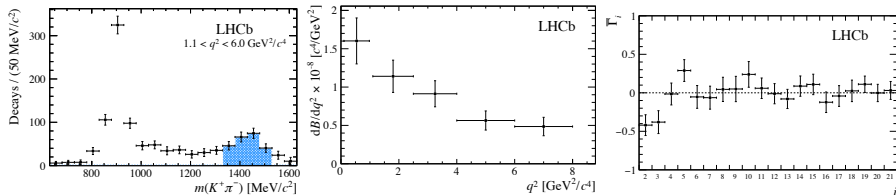
▶ In Run 1: 230 candidates, by Run 4 7500 candidates ($\times$3 as many candidates as current $B^0 \to K^{*0}(892)\mu^+\mu^-$ yield)

→ Estimates of $B \to K^*_{J=0,2}$ form-factors exist Lu et al [PRD85(2012)] but more input from theory required to constrain Wilson coefficients from these measurements. What are prospects here?
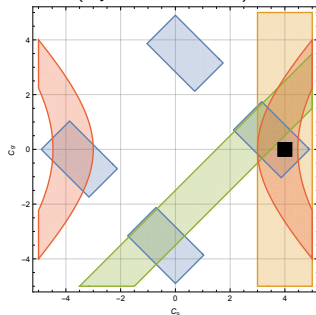
What about baryonic decays

- For example: Run 1: 370 $\Lambda_b \to \Lambda(\to p\pi)\mu^+\mu^-$ events

LHCb [JHEP06(2015)115]
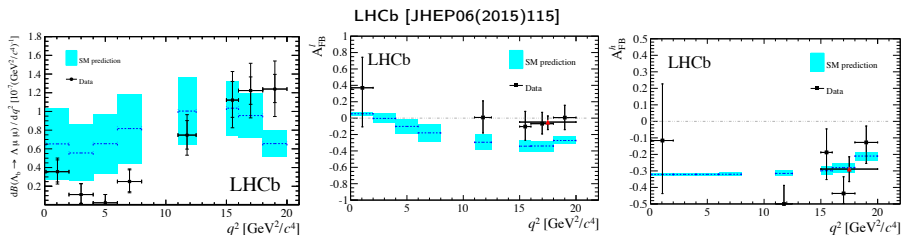
- Additional observables eg A_{FB}^p giving access to different combinations of Wilson coefficients

What about baryonic decays cont'd

vDyk, Meinel [1603.02974],[LHCb implications 2015]
(toy model low recoil)

F_L (common with $B \to K\mu^+\mu^-$)

A^ℓ_{FB} (common with $B \to K\mu^+\mu^-$)

$A^{\ell p}_{FB}$ (unique to $\Lambda_b \to \Lambda\mu^+\mu^-$ [not measured yet])

A^p_{FB} (unique to $\Lambda_b \to \Lambda\mu^+\mu^-$)

▶ Ongoing work on $\Lambda_b \to \Lambda^*(\to pK)\mu^+\mu^-$ BF measurement, CP asymmetry measurements etc

▶ With 10,000 candidates by Run 4 and 60,000 by Run 5, LHCb will uniquely contribute to these new observables

- Using Run1 data, perform first observation of this mode. Measure:
- The CP asymmetry relative to $\Lambda_b \to pKJ/\psi$ ($\Delta\mathcal{A}_{CP}$)
  - ▷ Cancellation of detector and production asymmetry
- The $\hat{T}$-odd CP asymmetry: $a_{CP}^{\hat{T}-odd} \equiv \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}})$
  - ▷ $A_{\hat{T}}(\overline{A}_{\hat{T}})$ is a triple product asymmetry of the $\Lambda_b(\overline{\Lambda}_b)$
- These aymmetries have different dependencies on strong phases and sensitivities to NP
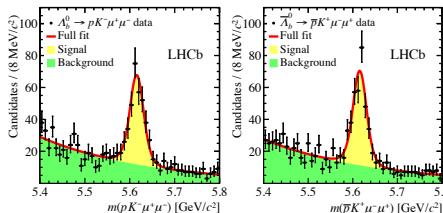
$$\Delta\mathcal{A}_{CP} = (-3.5 \pm 5.0 \,(\text{stat}) \pm 0.2 \,(\text{syst})) \times 10^{-2},$$
$$a_{CP}^{\hat{T}-\text{odd}} = (1.2 \pm 5.0 \,(\text{stat}) \pm 0.7 \,(\text{syst})) \times 10^{-2},$$

- No evidence for CP asymmetry observed

- ▶ Very relevant if tensions persist $\to$ test MFV nature of new physics
- ▶ Latest lattice results enable further precision tests of CKM paradigm
  Buras,Blanke[1602.04020], FNAL/MILC[1602.03560]

- ▶ Current measurement from penguin decays of $|V_{td}/V_{ts}| = 0.201 \pm 0.020$
  FNAL/MILC[PRD93,034005(2016)]

LHCb [JHEP10(2015)034] FNAL/MILC[1602.03560], FNAL/MILC[PRD93,034005(2016)]
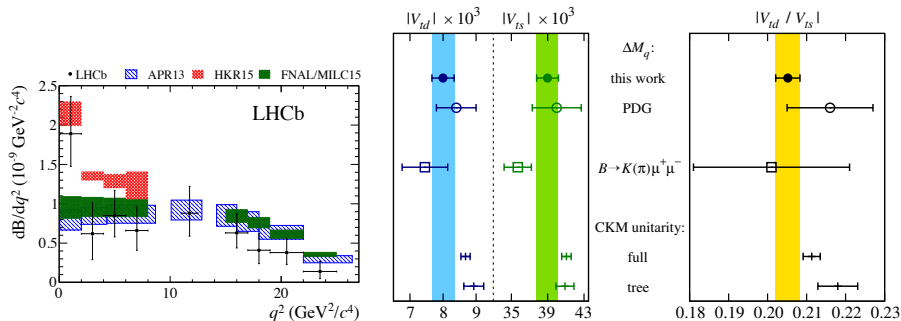
Baryonic $b \to d\mu^+\mu^-$ [arXiv:1701.08705]
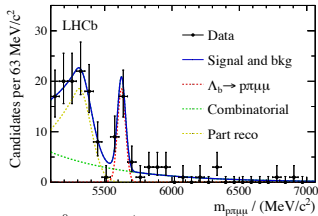
- First observation of baryonic $b \to d\mu^+\mu^-$ transition (5.5σ)
- Use Run1 data and measure relative to $\Lambda_b \to J/\psi p\pi$
- $\mathcal{B}(\Lambda_b \to p\pi\mu\mu) = (6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}$

- These decays will greatly benefit with Run 2 and beyond

- $b \to d\mu^+\mu^-$ the new $b \to s\mu^+\mu^-$:
- Run 1: 93 $B^+ \to \pi^+\mu^+\mu^-$, 40 $B^0 \to \pi^+\pi^-\mu^+\mu^-$
- 300fb^{-1}: 18,000 $B^+ \to \pi^+\mu^+\mu^-$ and 4,000 $B^+ \to \pi^+ e^+ e^-$
  (naive scaling)
- 300fb^{-1}: 8,000 $B^+ \to \pi^+\pi^-\mu^+\mu^-$ and 2,000 $B^+ \to \pi^+\pi^- e^+ e^-$
  (naive scaling)
  $\to$ Allows for precision MFV and MFV+LNU tests

Summary

- Run 1 and 2 of the LHC introduce precision era in rare B-decay measurements

- Precision reveals tensions. Run2 data aimed at understanding these

  $\rightarrow$ Clarify the impact of $c\bar{c}$ and other resonances in $B \rightarrow K^{(*)}\mu^+\mu^-$ observables

  $\rightarrow$ Update of $B \rightarrow K^{*0}\mu^+\mu^-$ on its way

  $\rightarrow$ Plethora of observables for $K^*_{J=0,2}$ states and baryonic decays

- Towards Run3,4 and beyond

  $\rightarrow$ Clear physics case for rare decays given stat precision

  $\rightarrow$ Big gains in $b \rightarrow d$ transitions and final states with electrons

  $\rightarrow$ Critical to maintain detector performance

Backup