Latest LFU results from LHCb

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Introduction

- Run 1 of the LHC provided us with a rich set of results
  - $\rightarrow$ Rise of the precision era for rare decays
  - $\rightarrow$ Large samples of semileptonic B-hadron decays
- Focus on results testing Lepton Flavour Universality in B-hadron decays
  - $\rightarrow$ Discuss latest measurements by LHCb hinting towards physics beyond the SM

Cracks appearing in the SM?

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1. **Tensions in measurements of decay rates and angular distributions of $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$**

2. **Tensions in ratio of branching fractions between $B^{+,0} \to K^{+,*0}\mu^+\mu^-$ and $B^{+,0} \to K^{+,*0}e^+e^-$**

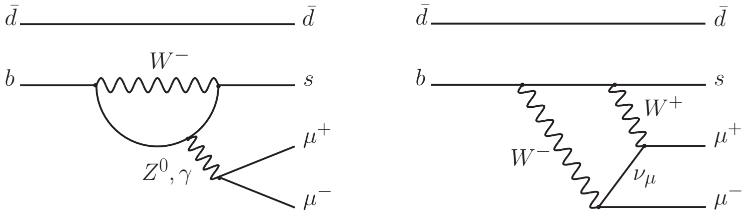
   $\to$ Test of LFU in loop level decays

3. **Tension in ratio of branching fractions between of $B^0 \to D^{(*)}\tau\nu$ and $B^0 \to D^{(*)}\mu\nu$)**

   $\to$ Test of LFU in tree level decays

Electroweak penguin processes

- $b \to s\ell^+\ell^-$ are FCNC transitions and are suppressed in SM
  $\to$ Only occur via loop or box processes



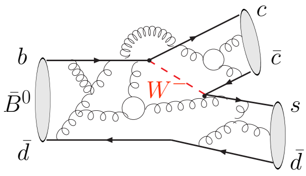
- New physics contributions at the same level as SM
  $\to$ Highly sensitive to effects of new physics
- New physics enters as virtual particles in loops
  $\to$ Access energy scales above available collision energy

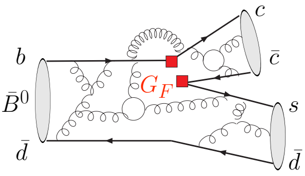
Formalism

- Model independent approach
- "Integrate" out heavy ($m \geq m_W$) field(s) and introduce set of Wilson coefficients C_i, and operators $\mathcal{O}_i$ encoding long and short distance effects

$$\mathcal{H}_{eff} \approx -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts(d)} \sum_i C_i^{SM} \mathcal{O}_i^{SM} + \sum_{NP} \frac{c_{NP}}{\Lambda^2_{NP}} \mathcal{O}_{NP}$$

- c.f. Fermi interaction and G_F





Sensitivity to New Physics

- Different decays probe different operators e.g:

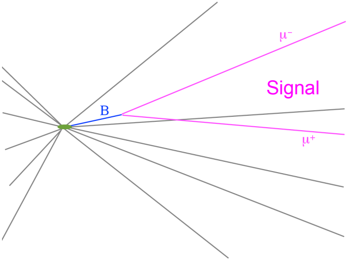
Operator $\mathcal{O}_i$	$B_{s(d)} \to X_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$	$B_{s(d)} \to X_{s(d)}\gamma$
$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}$	✓		✓
$\mathcal{O}_9 \sim (\bar{s}_L\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\ell)$	✓		
$\mathcal{O}_{10} \sim (\bar{s}_L\gamma^\mu b_L)(\bar{\ell}\gamma_5\gamma_\mu\ell)$	✓	✓	
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S,P}(\bar{\ell}\ell)_{S,P}$	(✓)	✓	

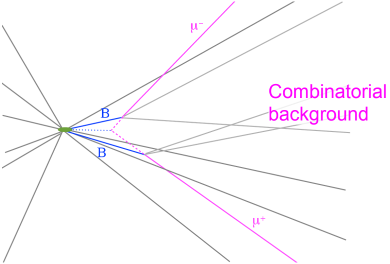
- In SM $C_{S,P} \propto m_\ell m_b/m_W^2$
- In SM chirality flipped $\mathcal{O}_7$ suppressed by m_s/m_b and rest are zero
- Different regions in dilepton mass squared (q^2) probe different mixtures of couplings

Experimental aspects I

Selection:

- Reduce combinatorial background using Multivariate classifiers, (typically Boosted Decision Tree)
  - Using kinematic and topological information
  - Variable choice based on minimising correlation with mass
- Reduce "peaking" backgrounds using particle-ID information
  - Exclusive decays with final state hadron(s) mis-Id
  - Estimate by mixture of MC and data-driven studies





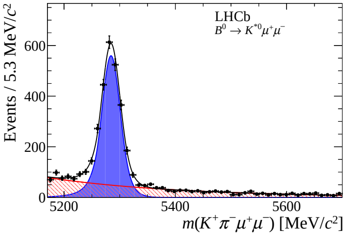
Experimental aspects II

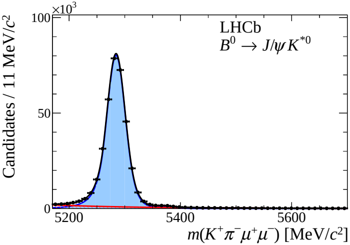
Normalisation:

- Make use of proxy-decay with similar topology and of known branching fraction ($\mathcal{B}$) to normalize against

$$\mathcal{B}(sig) = \frac{N_{sig}\epsilon_{sig}}{N_{prx}\epsilon_{prx}}\mathcal{B}(prx)$$

  - Reduces experimental uncertainties

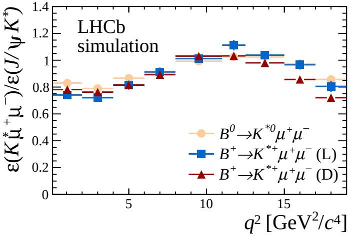


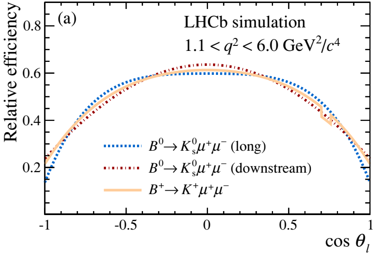


Experimental aspects III

Acceptance correction:

- Efficiency parametrised depending on type of measurement of $\mathcal{B}$
  - Differential with respect to di-muon mass squared (q^2) or angular distribution of decay products of the b-Hadron
- Efficiency (ϵ) obtained from MC corrected from data

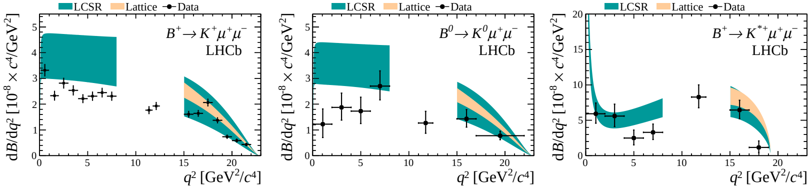




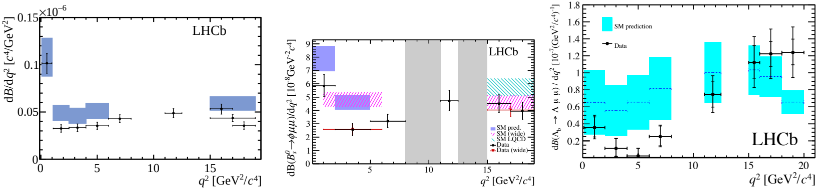
Differential branching fractions of $b \to s\mu^+\mu^-$ decays

- Measurement of $d\mathcal{B}/dq^2$ of $B \to K^{(*)}\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$

Experiment: [JHEP06(2014)133], [1606.04731], [JHEP09(2015)179], [JHEP06(2015)115], [JHEP06(2015)115]



$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $B_s \to \phi\mu^+\mu^-$ [JHEP06(2015)115], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115]



Theory: Bobeth et al [JHEP07(2011)067], Bharucha et al [JHEP08(2016)098], Detmold et al [PRD87(2013)], Horgan et al [PRD89(2014)]

- Measurements below SM prediction ($2 - 3\sigma$ depending on final state)
- Dominant systematic uncertainty: Knowledge equivalent J/ψ BF
  $\to$ Belle2 could help here also resolving isospin asymmetries at $\Upsilon(4S)$ M.Jung [1510.03423]

Angular analyses of $B^0 \to K^{*0}\mu^+\mu^-$ decays

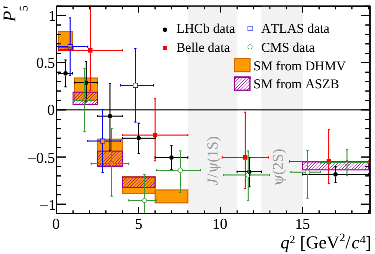
- Angular distribution of final state particles in $B^0 \to K^{*0}\mu^+\mu^-$ decays depends on (at least) 8 observables per B^0 flavour
- Depend on different combinations of Wilson coefficients
- Predictions more precise than $d\mathcal{B}/dq^2$ due to reduced dependence of hadronic parameters

- Combining measurements of $d\mathcal{B}/dq^2$ and angular distribution from LHCb, Belle, CMS, ATLAS as of Moriond 2017

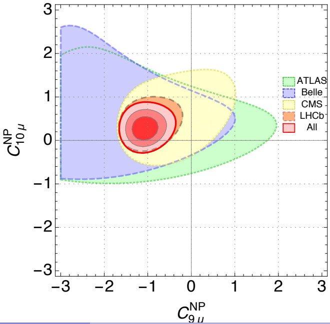
  $\rightarrow$ Strong deviations particularly in dilepton vector coupling C_9

  $\rightarrow$ Tension at $4.5\sigma - 5\sigma$ level e.g Altmannshofer et al [1703.09189], Matias et al [1704.05340]

ATLAS,CMS,Belle,LHCb at Moriond 2017

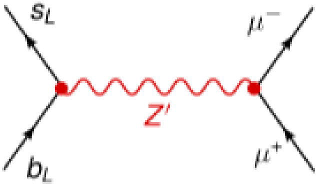


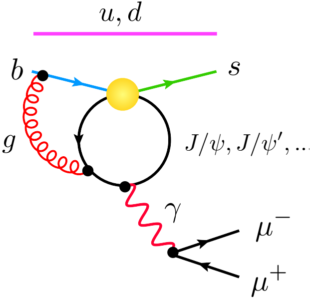
Matias et al [1704.05340], 3σ contours of individual expts



First Interpretation

- Several attempts to interpret $b \to s\mu^+\mu^-$ and $b \to s\gamma$ data





$\rightarrow$ New vector Z', leptoquarks, vector-like confinement... evading direct detection searches
Buttazzo et al [1604.03940], Bauer et al [PRL116,141802(2016)], Crivellin et al [PRL114,151801(2015)], Altmannshofer et al [PRD89(2014)095033]... Diptomoy et al [PRD89(2014)071501], Descotes-Genon et al [PRD88(2013)074002]

- 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]...

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

- LHCb measurement of these effects in $B^+ \to K^+\mu^+\mu^-$ indicate its not charm
  LHCb [Eur. Phys.J. C(2017)77:161]

Test of LFU in $b \to s\ell^+\ell^-$ I

- Measurement of: $R_{K^{(*)}} = \dfrac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$
  - Precise theory prediction due to cancellation of hadronic uncertainties
- Expected to be 1 in SM (pre-FSR and for $q^2 \gg m_\ell^2$) as Higgs contribution is m_ℓ suppressed
- Measurement performed as double ratio:

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

$\rightarrow$ Cancellation of experiment related systematic uncertainties

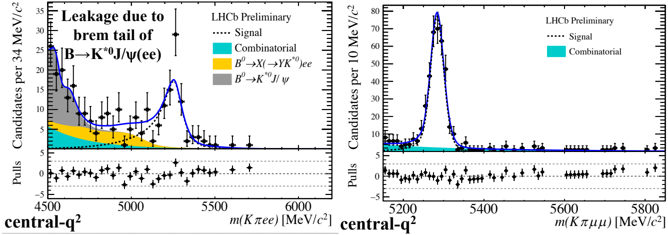
Experimental challenge in $b \to se^+e^-$:

- Compared to muons, reduced mass resolution and q^2 migration
  $\rightarrow$ Due to bremsstrahlung losses for electrons traversing the detector

Test of LFU in $b \to s\ell^+\ell^-$ II

- Attempt to recover these photons however recovery imperfect due to:
  - Energy threshold of $E_{\mathrm{T}} > 75\mathrm{MeV}$
  - Calorimeter acceptance
  - Presence of energy deposits mistaken as brem photons
- Measurement in reconstructed q^2 region is corrected to true q^2, accounting for bin-migrations using simulated events calibrated to data
- Correct back to pre-Final State Radiation measurement of $R_{K^{(*)}}$ using PHOTOS Golonka et al [hep-ph/0506026]
  - Systematic uncertainty accounts for model dependence of migration correction

Left: $B \to K^{*0}e^+e^-$, Right: $B \to K^{*0}\mu^+\mu^-$



Results of LFU tests I

- New measurement of $R_{K^{*0}}$ presented at April CERN seminar
  $\rightarrow$ Paper appearing soon
- Performed in two q^2 bins:
  - Low q^2 bin sensitive primarily to C_7 (lepton universal)
  - Middle q^2 bin mostly sensitive to combination of C_9 and C_{10}
- Analyses were blind with huge number of cross-checks including ensuring that:

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

  Compatible with unity and constant as a function of kinematics of decay and particle multiplicity
- Similarly

$$\mathcal{R}_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

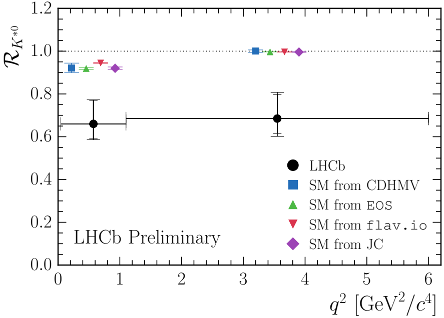
$$r_\gamma = \frac{\mathcal{B}(B^0 \to K^{*0}\gamma(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

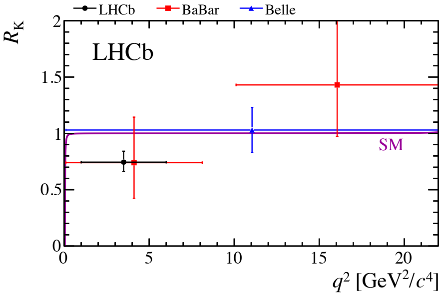
  Compatible with expectations

Results of LFU tests I

Using Run1 only data:

Left: R_{K^*} New!, Right: R_K PRL [PRL113(2014)151601]





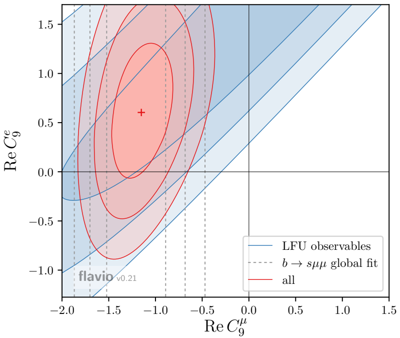
Isidori et al [EPJC76(2016)440], Matias et al [JHEP06(2016) 092], Jaeger et al [1412.3183], Straub [Flavio], van Dyk [EOS]

- LHCb-PAPER-2017-013, appearing in arXiv next week
  R_K in $1.1 < q^2 < 6\text{GeV}^2/c^4$: 2.6 σ from SM
  R_{K^*} in $0.045 < q^2 < 1.1$ and $1.1 < q^2 < 6$ GeV$^2/c^4$: 2.2-2.5 σ from SM in each q^2 bin
- Systematic uncertainty $\sim 30\%$ of statistical. Dominated by corrections to the simulation.

Further Interpretation

- Tensions in $R_{K^{(*)}}$ compatible with differential branching fraction and angular distribution measurements of $b \to s\mu\mu$

  $\to$ New physics in C_9 that couples to muons but not electrons
- Including LFU observables in global fits indicates new physics ($> 5\sigma$)
- Exact level depends on details of hadronic parameters (active discussion)
- But! LFU measurements offer extremely clean observables to test SM



Altmannshofer et al [1704.05435]

- Run2 data will help to further clarify this situation

  $\to$ Measurements at high q^2 are critical and are underway

  $\to$ Ratios using $B_s \to \phi\ell\ell$, $\Lambda_b \to \Lambda^*\ell\ell$ etc underway

See talk by Sebastian for more information

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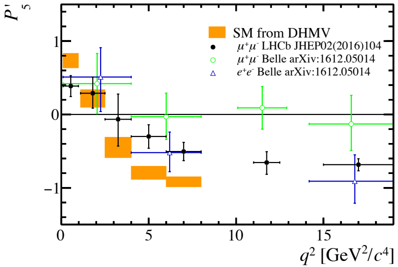

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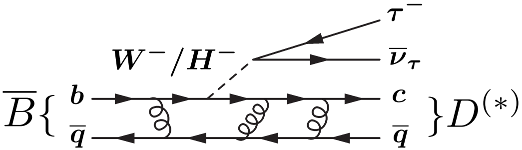
  $\to$ Ratios using $B_s \to \phi\ell\ell$, $\Lambda_b \to \Lambda^*\ell\ell$ etc underway
- $\to$ Angular analyses of $B^0 \to K^{*0}e^+e^-$, $B^+ \to K^+e^+e^-$ underway
- $\times 4$ more events by end of Run2
- Belle2, LHCb upgrade and LHCb upgrade++ have a lot to offer

See talk by Sebastian for more information

$\bar{B}^0 \to D^{*+}\tau\bar{\nu}$

- Test lepton universality by measuring $R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(\bar{B}\to D^{(*)}\ell\bar{\nu})}$
- Sensitive to NP coupling differently to 1st and 3rd generations (e.g charged Higgs)
- Note this is a tree-level test of universality compared to $\frac{\mathcal{B}(B\to Kee)}{\mathcal{B}(B\to K\mu\mu)}$



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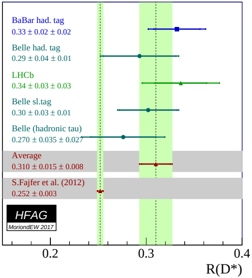
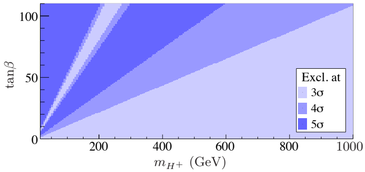




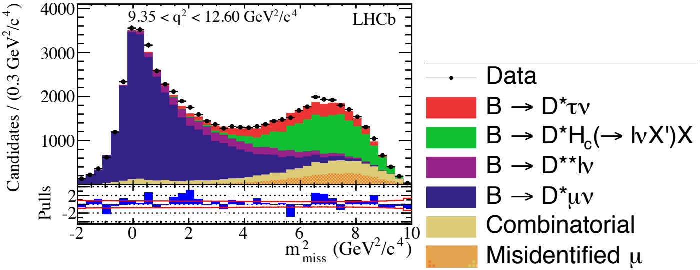
BaBar [PRD 88,072012]

- Measurements from B factories using $\tau \to \ell\nu\nu$ and $\tau \to$hadrons decays combining D and D^* final states
- Tension with SM and severely constrain TypeII 2HDM models

$\bar{B}^0 \to D^{*+}\tau\bar{\nu}$ challenges at LHCb

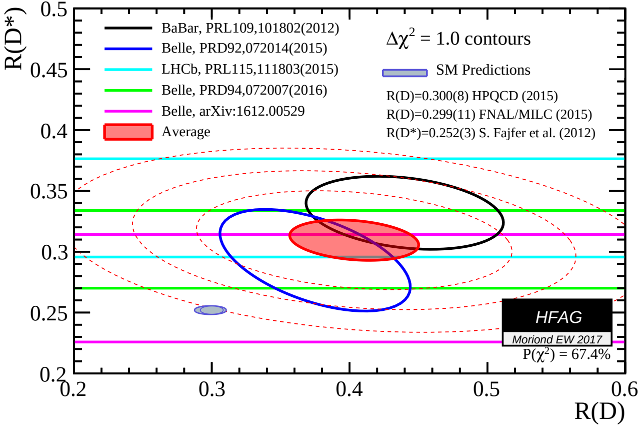
- Only D^{*+} for now with $\tau \to \mu\nu\nu$
  $\to$ No narrow peak to fit in any distribution
- Use B flight direction to measure transverse component of missing momentum
- Assume no missing momentum along flight direction of B
  $\to$ 18% resolution on B momentum
  $\to$ Template fit to rest frame quantities m^2_{missing}, E_μ, q^2

[PRL 115(2015)112001]



$\bar{B}^0 \to D^{*+}\tau\bar{\nu}$ global fit

3.9σ tension with SM



- LHCb uncertainty split between statistical and systematic.
- Dominant systematic uncertainty: MC template statistics

$\bar{B}^0 \to D^{*+}\tau\bar{\nu}$ global fit

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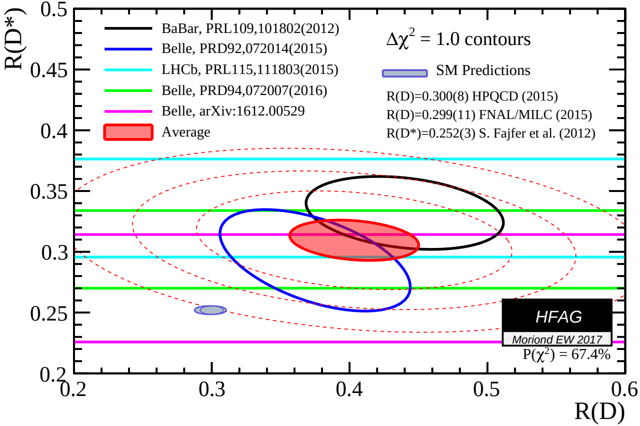


- Analysis with Run2 data underway (4$\times$ the yield by end of Run2)
- More final states: $R(D)$, $R(D^*)$ with $\tau \to$hadrons, $B_c \to J/\psi\tau\nu$, $\Lambda_b \to \Lambda_c\tau\nu$, $B \to p\bar{p}\tau\nu$...

Putting it all together

- Can models be constructed to explain all the anomalies presented?

Putting it all together

- Can models be constructed to explain all the anomalies presented?

Yes!

See talk by Sebastian for more information

Summary

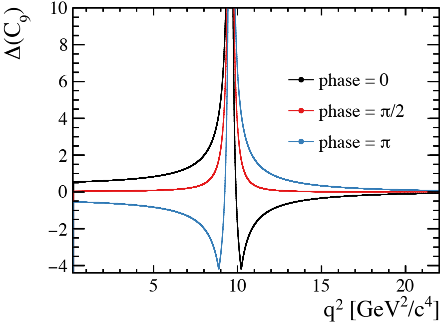
- The large dataset from Run1 of the LHC has revealed an intriguing set of results
- Measurements of tree-level and loop-level B-hadron decays revealing tensions with the SM of $\sim 4\sigma$ and $\sim 5\sigma$ respectively
- Consistent picture emerging in $b \to s\ell\ell$ with new physics in dimuon vector coupling
  - Measurements statistically limited$\to$Run2 analyses ongoing
  - Plethora of additional observables and final states are under studied

Backup

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

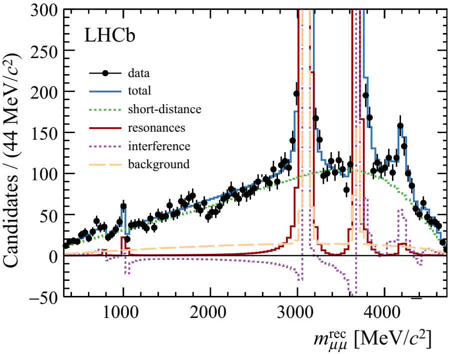


- At low q^2 main culprit is the J/ψ
  $\rightarrow$ Corrections to C_9^{eff} (ΔC_9) all the way down to $q^2 = 0$
  $\rightarrow$ **Effect strongly dependent on relative phase with penguin**
- More data will help resolve apparent q^2 dependence of C_9

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]

  $$\rightarrow C_9^{eff} = \sum_j \eta_j e^{i\delta_j} A_{res}(q^2) + C_9$$

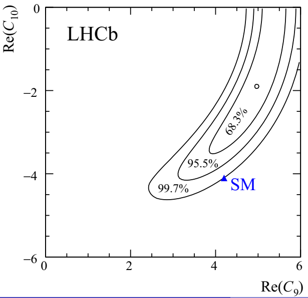


- Fit dimuon spectrum of $B^+ \rightarrow K^+\mu^+\mu^-$ to obtain:
  $\rightarrow$ Relative phases between resonant and penguin amplitudes
  $\rightarrow$ C_9 and C_{10}
  $\rightarrow$ Further constrain lattice input Bailey et al [PRD93,025026(2016)] on form-factor $f_+(q^2)$
- Note have 4 degenerate solutions for phases depending on relative sign between J/ψ and $\psi(2s)$ phases

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

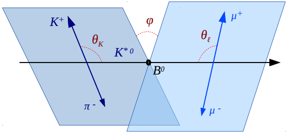
- Results show minimal interference with J/ψ and $\psi(2S)$ resonances
  $\rightarrow$ Given this model, the J/ψ and $\psi(2S)$ resonances play sub-dominant role below their pole mass
- Phases of $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ in good agreement with Lyon Zwicky [1406.0566]

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 $B^0 \rightarrow K^{*0}\mu^+\mu^-$
  - Phases per helicity amplitude

3. Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



- Differential decay rate of $B^0 \to K^{*0}\mu^+\mu^-$ and $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$:

$$\frac{\mathrm{d}^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega}) \quad \text{and}$$
$$\frac{\mathrm{d}^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega}) ,$$

- I_i: bilinear combinations of 6 P-wave and 2 S-wave helicity amplitudes (since K^{*0} can be found in $J = 1$ and $J = 0$)
- Reparametrise distribution in terms of:

$$S_i = (I_i + \bar{I}_i) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right) \quad \text{and}$$
$$A_i = (I_i - \bar{I}_i) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right).$$

- Determine various S_i or A_i by a 3+1D angular $m_{K\pi}$ distribution in bins of q^2

Angular terms

i	I_i	f_i
$1s$	$\frac{3}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm L}\rvert^2 + \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$	$\sin^2\theta_K$
$1c$	$\lvert\mathcal{A}_0^{\rm L}\rvert^2 + \lvert\mathcal{A}_0^{\rm R}\rvert^2$	$\cos^2\theta_K$
$2s$	$\frac{1}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm L}\rvert^2 + \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$	$\sin^2\theta_K \cos 2\theta_l$
$2c$	$-\lvert\mathcal{A}_0^{\rm L}\rvert^2 - \lvert\mathcal{A}_0^{\rm R}\rvert^2$	$\cos^2\theta_K \cos 2\theta_l$
3	$\frac{1}{2}\left[\lvert\mathcal{A}_\perp^{\rm L}\rvert^2 - \lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2 - \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2\right]$	$\sin^2\theta_K \sin^2\theta_l \cos 2\phi$
4	$\sqrt{\frac{1}{2}}\mathrm{Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin 2\theta_K \sin 2\theta_l \cos\phi$
5	$\sqrt{2}\mathrm{Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin 2\theta_K \sin\theta_l \cos\phi$
$6s$	$2\mathrm{Re}(\mathcal{A}_\parallel^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_\parallel^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin^2\theta_K \cos\theta_l$
7	$\sqrt{2}\mathrm{Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin 2\theta_K \sin\theta_l \sin\phi$
8	$\sqrt{\frac{1}{2}}\mathrm{Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin 2\theta_K \sin 2\theta_l \sin\phi$
9	$\mathrm{Im}(\mathcal{A}_\parallel^{\rm L*}\mathcal{A}_\perp^{\rm L} + \mathcal{A}_\parallel^{\rm R*}\mathcal{A}_\perp^{\rm R})$	$\sin^2\theta_K \sin^2\theta_l \sin 2\phi$

10	$\frac{1}{3}\left[\lvert\mathcal{A}_{\rm S}^{\rm L}\rvert^2 + \lvert\mathcal{A}_{\rm S}^{\rm R}\rvert^2\right]$	1
11	$\sqrt{\frac{4}{3}}\mathrm{Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_0^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_0^{\rm R*})$	$\cos\theta_K$
12	$-\frac{1}{3}\left[\lvert\mathcal{A}_{\rm S}^{\rm L}\rvert^2 + \lvert\mathcal{A}_{\rm S}^{\rm R}\rvert^2\right]$	$\cos 2\theta_l$
13	$-\sqrt{\frac{4}{3}}\mathrm{Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_0^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_0^{\rm R*})$	$\cos\theta_K \cos 2\theta_l$
14	$\sqrt{\frac{2}{3}}\mathrm{Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\parallel^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin\theta_K \sin 2\theta_l \cos\phi$
15	$\sqrt{\frac{8}{3}}\mathrm{Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K \sin\theta_l \cos\phi$
16	$\sqrt{\frac{8}{3}}\mathrm{Im}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\parallel^{\rm L*} - \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K \sin\theta_l \sin\phi$
17	$\sqrt{\frac{2}{3}}\mathrm{Im}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\perp^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K \sin 2\theta_l \sin\phi$

Amplitudes I

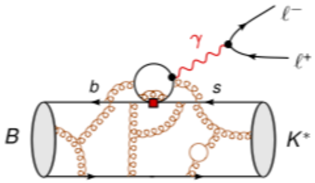
[JHEP 0901(2009)019] Altmannshofer et al.

$$A_{\perp}^{L(R)} = N\sqrt{2\lambda}\left\{\left[(\mathbf{C_9^{eff}} + \mathbf{C_9'^{eff}}) \mp (\mathbf{C_{10}^{eff}} + \mathbf{C_{10}'^{eff}})\right]\frac{\mathbf{V(q^2)}}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} + \mathbf{C_7'^{eff}})\mathbf{T_1(q^2)}\right\}$$

$$A_{\parallel}^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9'^{eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}'^{eff}})\right]\frac{\mathbf{A_1(q^2)}}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} - \mathbf{C_7'^{eff}})\mathbf{T_2(q^2)}\right\}$$

$$A_{0}^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9'^{eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}'^{eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A_1(q^2)} - \lambda\frac{\mathbf{A_2(q^2)}}{m_B + m_{K^*}}\right]\right.$$
$$\left. + 2m_b(\mathbf{C_7^{eff}} - \mathbf{C_7'^{eff}})\left[(m_B^2 + 3m_{K^*} - q^2)\mathbf{T_2(q^2)} - \frac{\lambda}{m_B^2 - m_{K^*}^2}\mathbf{T_3(q^2)}\right]\right\}$$

- $\mathbf{C_i^{eff}}$: Wilson coefficients (including 4-quark operator contributions)
- $\mathbf{A_i}$, $\mathbf{T_i}$ and $\mathbf{V_i}$: 7 $B \to K^*$ form factors



Amplitudes II

- At leading order and for large dimuon masses squared (q^2) below $\sim 6\text{GeV}^2/c^4$, form factors reduce to $\xi_\perp$,$\xi_\parallel$:

$$A_\perp^{L,R} = \sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\text{eff}} + \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\text{eff}} + \mathcal{C}_7^{\text{eff}\prime})\right]\xi_\perp(E_{K^*})$$

$$A_\parallel^{L,R} = -\sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime})\right]\xi_\perp(E_{K^*})$$

$$A_0^{L,R} = -\frac{Nm_B(1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}}\left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + 2\hat{m}_b(\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime})\right]\xi_\parallel(E_{K^*})$$

- Can build form factor independent observables using ratios of bilinear amplitude combinations [JHEP 1301(2013)048] Descotes-Genon et al. e.g:

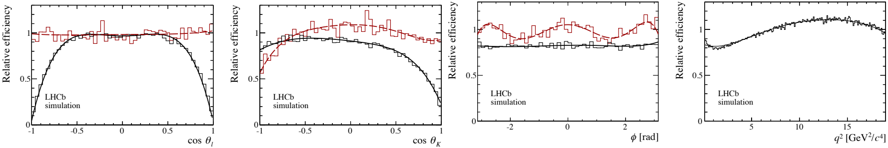
$$P_5^{\prime} \sim \frac{Re(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{(|A_0^L|^2+|A_0^R|^2)(|A_\perp^L|^2+|A_\perp^R|^2+|A_\parallel^L|^2+|A_\parallel^R|^2)}}$$

Acceptance correction

- Trigger, reconstruction and selection efficiency distorts the angular and q^2 distribution of $B^0 \to K^{*0}\mu^+\mu^-$
- Acceptance correction parametrised using 4D Legendre polynomials
- Use moment analysis in $B^0 \to K^{*0}\mu^+\mu^-$ MC to obtain coefficients c_{klmn}
- Cross-check acceptance in $B^0 \to J/\psi K^{*0}$

$$\varepsilon(\cos\theta_\ell, \cos\theta_K, \phi, q^2) = \sum_{klmn} c_{klmn} P_k(\cos\theta_\ell) P_l(\cos\theta_K) P_m(\phi) P_n(q^2)$$

1D projections



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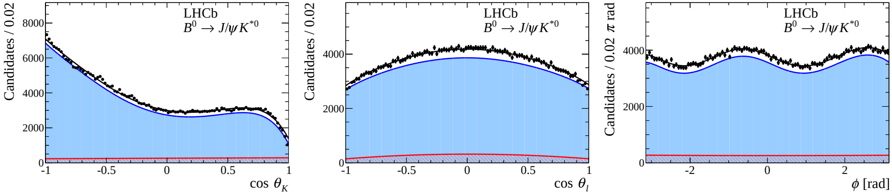
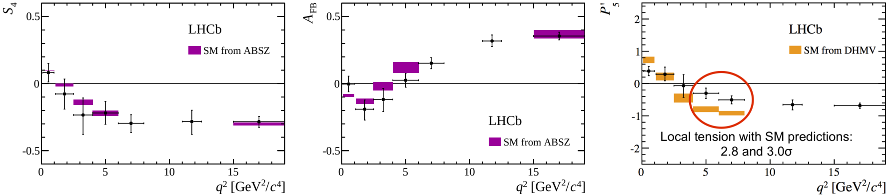


Angular analysis results

- LHCb has performed the first full angular analysis of the decay through a maximum likelihood fit to the data
  $\rightarrow$ Measurement of the full set of CP-averaged and CP-asymmetric angular terms and their correlations

  $\rightarrow$ Also determine the "less form-factor dependent" observables $P_i^{(\prime)}$

[JHEP02(2016)104]

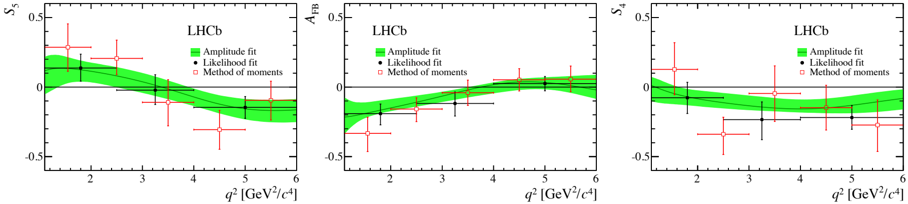


- Also measure all observables using a principal moment analysis of the angular distribution
  - Robust estimator even for small datasets $\rightarrow$ finer q^2 binning
  - Statistically less precise than result of maximum likelihood fit

Zero crossing points

- Determine zero crossing points of S_4, S_5 and A_{FB} by parametrising the angular distribution in terms of q^2 dependent decay amplitudes
- Choose a q^2 ansatz to model the six complex amplitudes:
  $A^{L,R}_{0,\perp,\parallel} = \alpha_i + \beta_i q^2 + \gamma_i / q^2$ Egede,Patel,KP [JHEP06(2015)084]

[JHEP02(2016)104]



The zero crossing points measured are:

$$q_0^2(S_5) \in [2.49, 3.95]\mathrm{GeV}^2/c^4 \text{ at } 68\% \text{ C.L.}$$
$$q_0^2(A_{\mathrm{FB}}) \in [3.40, 4.87]\mathrm{GeV}^2/c^4 \text{ at } 68\% \text{ C.L.}$$
$$q_0^2(S_4) < 2.65\mathrm{GeV}^2/c^4 \text{ at } 95\% \text{ C.L.}$$