$b \to s\ell^+\ell^-$ transitions

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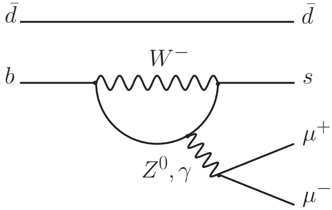
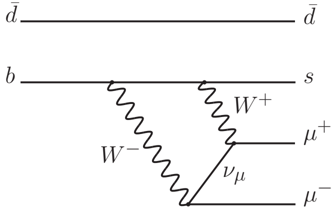
Introduction

- Run 1 of the LHC provided us with a rich set of results
  $\rightarrow$ Rise of the precision era for rare decays
- Branching fractions and angular analyses of $b \rightarrow s\ell\ell$ transitions indicating interesting tensions with the SM
  $\rightarrow$ Discuss latest measurements and prospects





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 $B \to J/\psi K^*$
- More $b \to s\ell\ell$ decays in Run 1 than $B \to J/\psi K^*$ of B-factories!

An intriguing set of results

1. Measurements of decay rates of $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$
   $\to$ Large theory uncertainties. But lattice calculations provide precision at large dimuon masses squared (q^2)

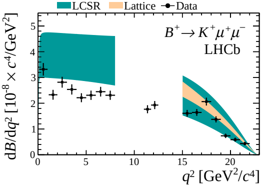
2. Angular analyses of $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$
   $\to$ Can access observables with reduced dependence on theory uncertainties

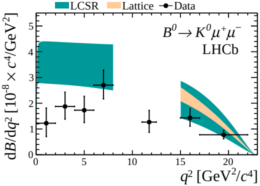
3. Measurements of ratios of decay rates of $B \to K^{(*)}\ell^+\ell^-$
   $\to$ Cancellations of hadronic form-factor uncertainties in predictions (see Harry's talk)

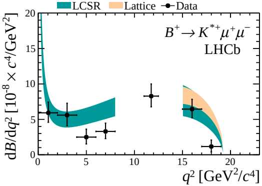
Differential branching fractions of $b \to s\mu^+\mu^-$ decays

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

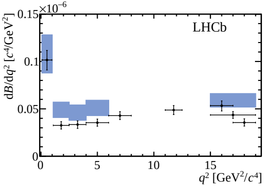
Experiment: [JHEP06(2014)133], [1606.04731], [JHEP09(2015)179], [JHEP06(2015)115], [JHEP06(2015)115]

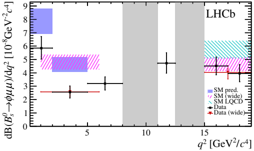


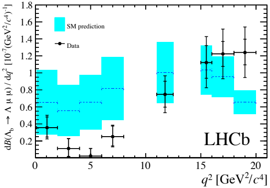




$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $B_s \to \phi\mu^+\mu^-$ [JHEP06(2015)115], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115]



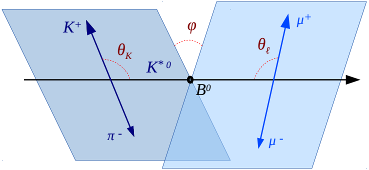




Theory: Bobeth et al [JHEP07(2011)067], Bharucha et al [JHEP08(2016)098], Detmold et al [PRD87(2013)], Horgan et al [PRD89(2014)]

- Measurements below SM prediction ($2 - 3\sigma$ depending on final state)
- Dominant systematic uncertainty: Knowledge equivalent J/ψ BF

$B^0 \to K^{*0}\mu^+\mu^-$



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

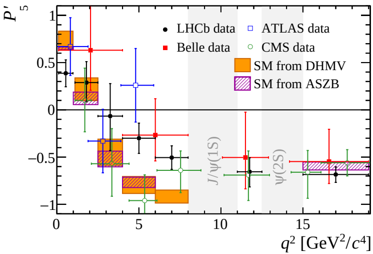
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

- Fit also for S-wave observables (not shown)
- S_i terms depend on short- and long-distance parameters

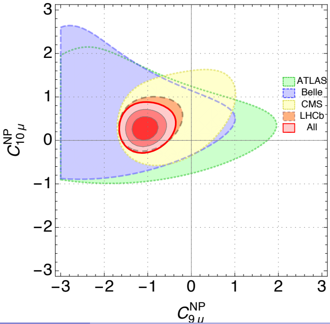
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

- Reparametrise angular distribution in terms of observables with reduced FF dependence (e.g P_5')
- Combining measurements of $d\mathcal{B}/dq^2$ and angular distribution from LHCb, Belle, CMS, ATLAS
  $\to$ Strong deviations particularly in dilepton vector coupling C_9
  $\to$ 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

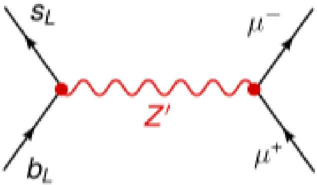


Matias et al [1704.05340], 3σ contours of individual expts

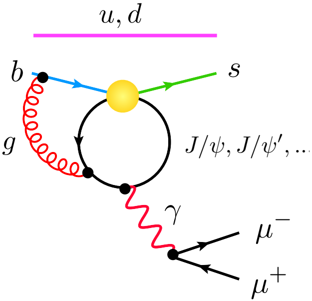


Interpretations

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



$\to$ 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]

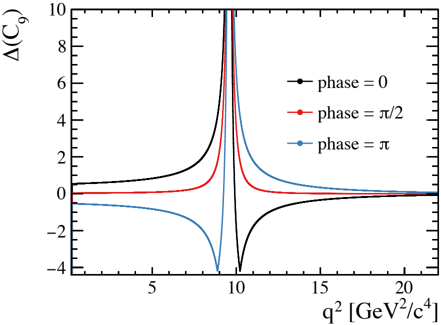


Potential problem with our understanding of the contribution from $B \to X_{c\bar{c}}(\to \mu\mu)K$ Lyon,Zwicky [1406.0566], Altmannshofer,Straub[1503.06199], Ciuchini et al [1512.07157]...

$\to$ 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

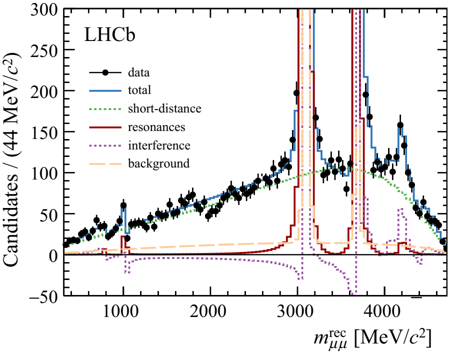


- Main culprit is the large $c\bar{c}$ component such as the J/ψ
  $\rightarrow$ Corrections to C_9^{eff} (ΔC_9) all the way down to $q^2 = 0$
  Effect strongly dependent on relative phase with penguin

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

- Write differential decay rate in terms of short- and long-distance contributions
  → 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 to obtain:
  → Relative phases between resonant and penguin amplitudes
  → C_9 and C_{10}
  → Further constrain lattice input Bailey et al [PRD93,025026(2016)] on form-factor $f_+(q^2)$

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

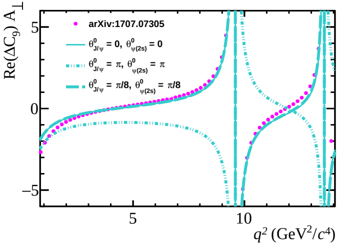
- Results show minimal interference with J/ψ and $\psi(2S)$ resonances
- J/ψ and $\psi(2S)$ resonances play sub-dominant role below their pole mass

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	$(6.04 \pm 3.93) \times 10^{-10}$

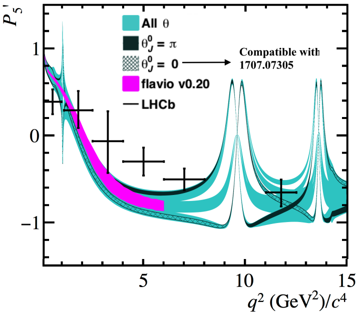
- Does not tell us anything about $B^0 \to K^{*0}\mu^+\mu^-$, dedicated analysis required
  - One phase per helicity amplitude per resonances

Measuring charm effect in $B^0 \to K^{*0}\mu^+\mu^-$

- Can compare model of long-distance contributions with predictions such as BCDV [1707.07305]
- More details appearing in Pomery, KP, Egede, Blake, Owen [1709.XXXXX]

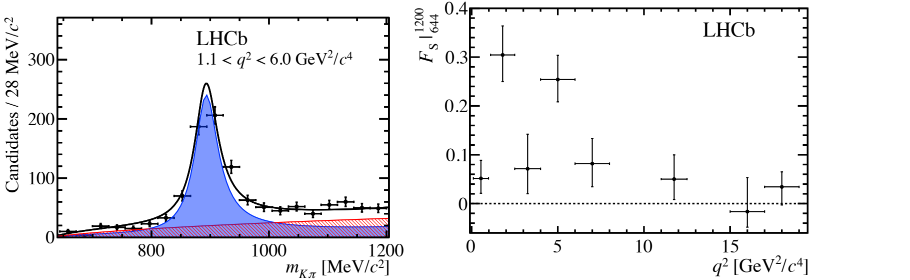


- Determining the phases is critical as impact on observables is large
- Ongoing work to perform measurement including resonances above open charm threshold
- Update of measurement of binned observables with Run2 data also underway



Other $K^+\pi^-$ states in $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047]

- Measure S-wave fraction in $644 < m_{K\pi} < 1200$ MeV$/c^2$ [JHEP11(2016)047]
  $\to$ Enables first determination of P-wave only $B^0 \to K^{*0}(892)\mu^+\mu^-$ differential branching fraction



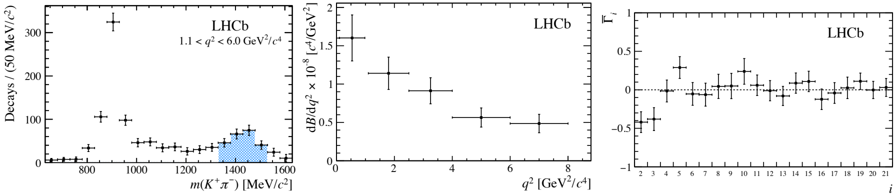
- Additional data should provide sensitivity to potential non-resonant P-wave contributions
  $\to$ Orthogonal constraints provided theory uncertainties under control Das et al [1406.6681] What are prospects here? Our measurements could help

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]

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

  $\rightarrow$ No significant D-wave component observed in contrast to $B^0 \rightarrow J/\psi K^+\pi^-$

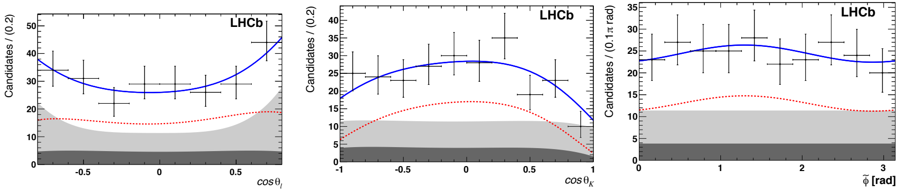


- In Run 1: 230 candidates, by Run 4 7500 candidates ($\times 3$ as many candidates as current $B^0 \rightarrow K^{*0}(892)\mu^+\mu^-$ yield)

  $\rightarrow$ Estimates of $B \rightarrow K^*_{J=0,2}$ 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?

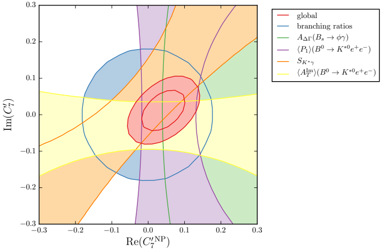
$B^0 \to K^{*0} e^+ e^-$ angular analysis LHCb [JHEP04(2015)064]

- Measure angular observables in $0.0004 < q^2 < 1\text{GeV}^2$
  $\to$ dominated by C_7' contributions
- ~ 150 signal candidates $\to$ Fit in $cos\theta_\ell$, $cos\theta_K$ and "folded" ϕ to measure A_{T2}, A_T^{Im}, A_T^{Re}, F_L



- Measurements complementary to BFs and $A_{CP}(t)$ of $B \to K^*\gamma$ and $B_s \to \phi\gamma$
- Provide one of strongest constraints to C_7'

Paul, Straub [1608.02556]



$B^0 \to K^{*0}e^+e^-$ angular analysis prospects

- With Run2, by 2018 data expect $B^0 \to K^{*0}e^+e^-$ yield:
  - ~ 400 in $0.045 < q^2 < 1.1$ GeV^2
  - ~ 500 in $1.1 < q^2 < 6$ GeV^2
  - Similar to $B^0 \to K^{*0}\mu^+\mu^-$ with Run1 data in same bin

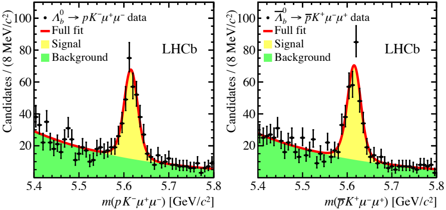
  $\to$ Measurements of multiple angular observables possible through multi-dimensional ML fits

  $\to$ Different experimental effects compared to $R_K^{(*)}$
  - Larger backgrounds than muon case will require good understanding of their angular distribution
  - More robust methods also being investigated

Measurements with $\Lambda_b \to \Lambda^*(\to pK)\mu^+\mu^-$ LHCb [JHEP06(2017)108]

Using Run1 data, perform first observation of this mode and 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 asymmetries have different dependencies on strong phases and sensitivities to NP



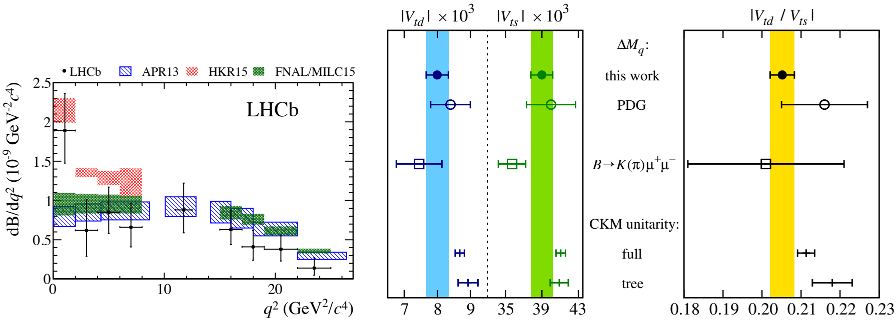
$$\Delta\mathcal{A}_{CP} = (-3.5 \pm 5.0\,(\text{stat}) \pm 0.2\,(\text{syst})) \times 10^{-2},$$
$$a_{CP}^{\widehat{T}\text{-odd}} = (\ \ 1.2 \pm 5.0\,(\text{stat}) \pm 0.7\,(\text{syst})) \times 10^{-2},$$

- No evidence for CP asymmetry observed

$B^+ \to \pi^+\mu^+\mu^-$ LHCb [JHEP10(2015)034]

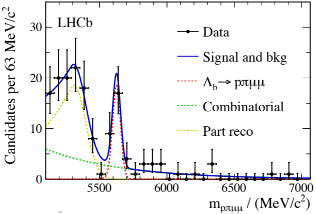
- Very relevant if tensions persist → test MFV nature of new physics
- Latest lattice results enable further precision tests of CKM paradigm
  Buras,Blanke[1602.04020], FNAL/MILC[1602.03560]
- Current measurement from penguin decays of $|V_{td}/V_{ts}| = 0.201 \pm 0.020$
  FNAL/MILC[PRD93,034005(2016]

LHCb [JHEP10(2015)034] FNAL/MILC[1602.03560], FNAL/MILC[PRD93,034005(2016)]



- Ongoing measurement of $B_s \to \bar{K}^{*0}\mu^+\mu^-$. Larger datasets will make an angular analysis of this decay an interesting prospect

$\Lambda_b \to p\pi\mu^+\mu^-$ LHCb [JHEP04(2017)029]



- 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

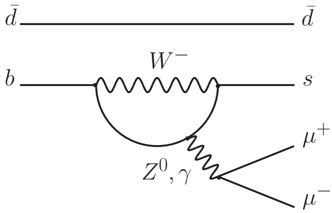
Summary

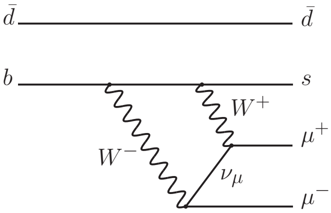
- Run 1 and 2 of the LHC introduce precision era in rare B-decay measurements
- Precision reveals tensions. Run2 data aimed at understanding these
  $\rightarrow$ Clarify the impact of $c\bar{c}$ and other resonances in $B \rightarrow K^{(*)}\mu^+\mu^-$ observables
  $\rightarrow$ Update of $B \rightarrow K^{*0}\mu^+\mu^-$ 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

Electroweak penguin processes

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





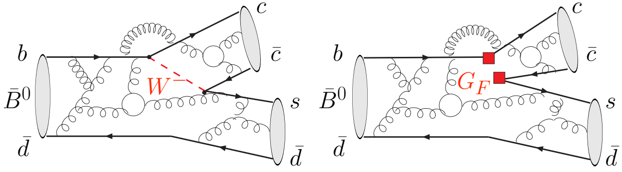
- New physics contributions at the same level as SM
  $\to$ Highly sensitive to effects of new physics
- New physics enters as virtual particles in loops
  $\to$ Access energy scales above available collision energy

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:

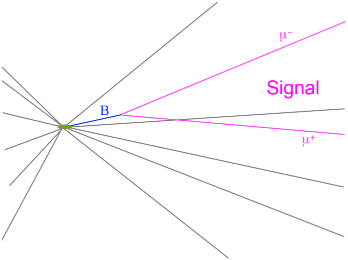
Operator $\mathcal{O}_i$	$B_{s(d)} \to X_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$	$B_{s(d)} \to X_{s(d)}\gamma$
$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}$	✓		✓
$\mathcal{O}_9 \sim (\bar{s}_L\gamma^{\mu}b_L)(\bar{\ell}\gamma_{\mu}\ell)$	✓		
$\mathcal{O}_{10} \sim (\bar{s}_L\gamma^{\mu}b_L)(\bar{\ell}\gamma_5\gamma_{\mu}\ell)$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

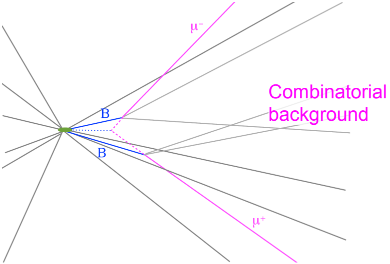
- In SM $C_{S,P} \propto m_\ell m_b/m_W^2$
- In SM chirality flipped $\mathcal{O}_7$ suppressed by m_s/m_b and rest are zero
- Different regions in dilepton mass squared (q^2) probe different mixtures of couplings

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





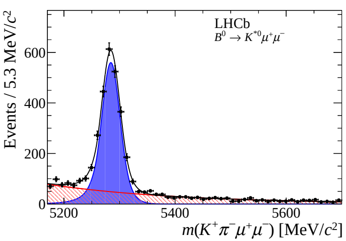
Experimental aspects II

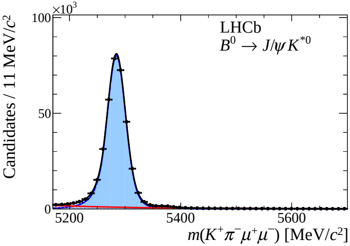
Normalisation:

- 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

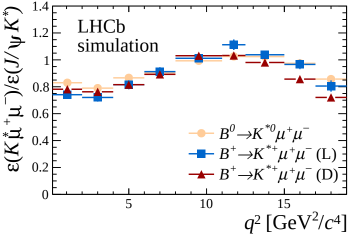


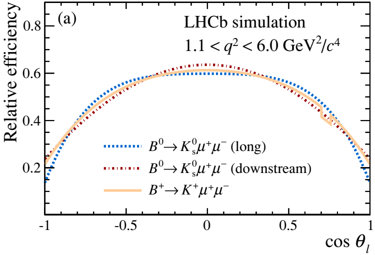


Experimental aspects III

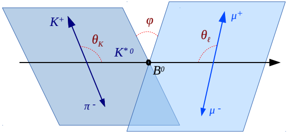
Acceptance correction:

- 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





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:

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

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

- 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	$\sqrt{\frac{1}{2}}{\rm Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_{\parallel}^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_{\parallel}^{\rm R*})$	$\sin 2\theta_K \sin 2\theta_l \cos\phi$
5	$\sqrt{2}{\rm Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_{\perp}^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_{\perp}^{\rm R*})$	$\sin 2\theta_K \sin\theta_l \cos\phi$
$6s$	$2{\rm Re}(\mathcal{A}_{\parallel}^{\rm L}\mathcal{A}_{\perp}^{\rm L*} - \mathcal{A}_{\parallel}^{\rm R}\mathcal{A}_{\perp}^{\rm R*})$	$\sin^2\theta_K \cos\theta_l$
7	$\sqrt{2}{\rm Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_{\parallel}^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_{\parallel}^{\rm R*})$	$\sin 2\theta_K \sin\theta_l \sin\phi$
8	$\sqrt{\frac{1}{2}}{\rm Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_{\perp}^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_{\perp}^{\rm R*})$	$\sin 2\theta_K \sin 2\theta_l \sin\phi$
9	${\rm Im}(\mathcal{A}_{\parallel}^{\rm L*}\mathcal{A}_{\perp}^{\rm L} + \mathcal{A}_{\parallel}^{\rm R*}\mathcal{A}_{\perp}^{\rm R})$	$\sin^2\theta_K \sin^2\theta_l \sin 2\phi$

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	$\sqrt{\frac{4}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_0^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_0^{\rm R*})$	$\cos\theta_K$
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	$-\sqrt{\frac{4}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_0^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_0^{\rm R*})$	$\cos\theta_K \cos 2\theta_l$
14	$\sqrt{\frac{2}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_{\parallel}^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_{\parallel}^{\rm R*})$	$\sin\theta_K \sin 2\theta_l \cos\phi$
15	$\sqrt{\frac{8}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_{\perp}^{\rm L*} - \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_{\perp}^{\rm R*})$	$\sin\theta_K \sin\theta_l \cos\phi$
16	$\sqrt{\frac{8}{3}}{\rm Im}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_{\parallel}^{\rm L*} - \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_{\perp}^{\rm R*})$	$\sin\theta_K \sin\theta_l \sin\phi$
17	$\sqrt{\frac{2}{3}}{\rm Im}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_{\perp}^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_{\perp}^{\rm R*})$	$\sin\theta_K \sin 2\theta_l \sin\phi$

Amplitudes I

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

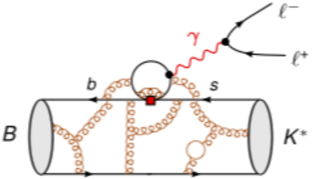
$$A_{\perp}^{L(R)} = N\sqrt{2\lambda}\left\{\left[(\mathbf{C_9^{eff}} + \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} + \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{V(q^2)}}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} + \mathbf{C_7^{\prime eff}})\mathbf{T_1(q^2)}\right\}$$

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

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

$$\left. + 2m_b(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\left[(m_B^2 + 3m_{K^*} - q^2)\mathbf{T_2(q^2)} - \frac{\lambda}{m_B^2 - m_{K^*}^2}\mathbf{T_3(q^2)}\right]\right\}$$

- $\mathbf{C_i^{eff}}$: 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 $\xi_\perp$,$\xi_\parallel$:

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

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

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

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

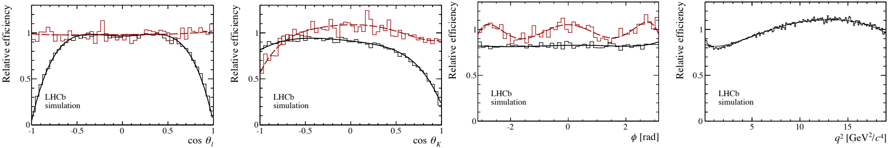
$$P_5^\prime \sim \frac{Re(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{(|A_0^L|^2 + |A_0^R|^2)(|A_\perp^L|^2 + |A_\perp^R|^2 + |A_\parallel^L|^2 + |A_\parallel^R|^2)}}$$

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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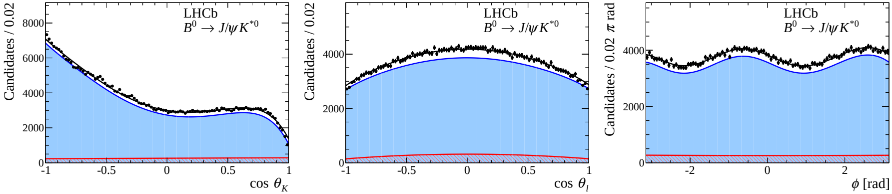
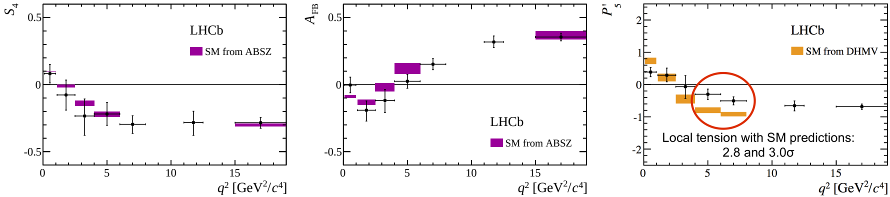


Angular analysis results

- 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]

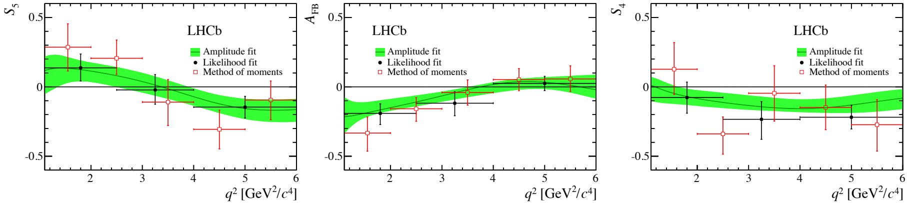


- Also measure all observables using a principal moment analysis of the angular distribution
  - Robust estimator even for small datasets $\rightarrow$ finer q^2 binning
  - Statistically less precise than result of maximum likelihood fit

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:

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