Status and prospects for $B^0 \to K^{*0}\mu^+\mu^-$ at LHCb

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Flavour of New Physics in $b \to s$ transitions
Institut Henri Poincaré
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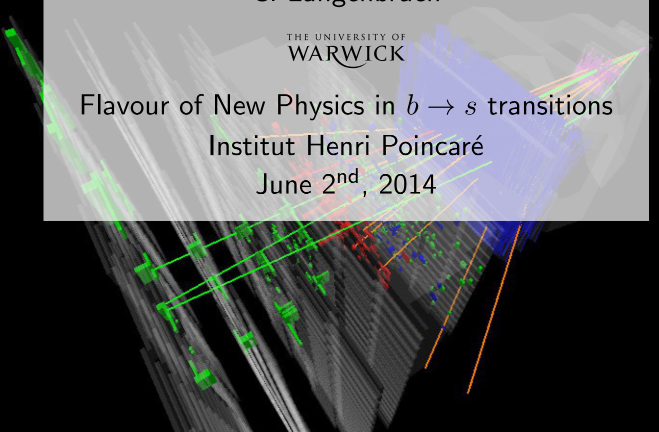
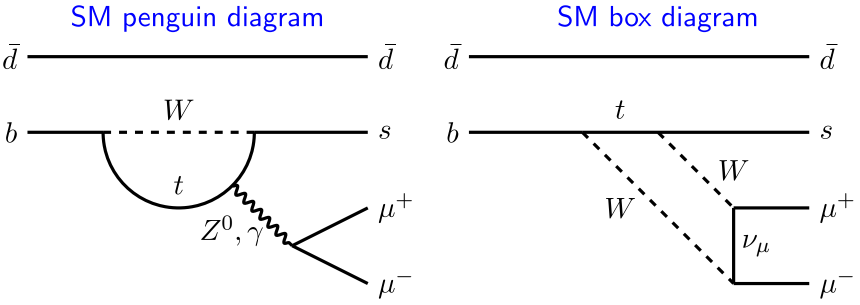
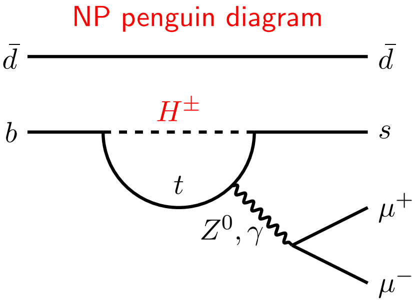


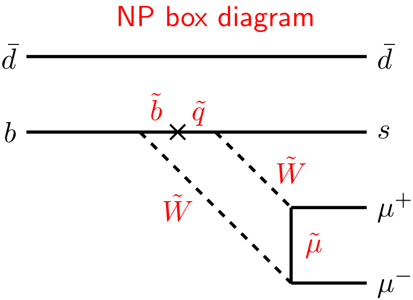
The decay $B^0 \to K^{*0}\mu^+\mu^-$ in the SM



- $B^0 \to K^{*0}\mu^+\mu^-$ is a $b \to s$ flavour changing neutral current (FCNC)
- Forbidden at tree level in the SM
- Allowed as quantum corrections at higher order $\to$ loop suppressed

The decay $B^0 \to K^{*0}\mu^+\mu^-$ in NP





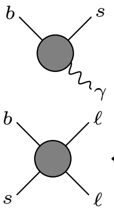
- New Physics amplitudes can appear at the same level as SM particles
- Potentially large modification of $\mathcal{B}$ and angular distributions
- New Particles do not have to be on shell $\to$ high masses acessible

Description of FCNC processes in effective field theory

- Effective Hamiltonian for $b \to s$ FCNC transition

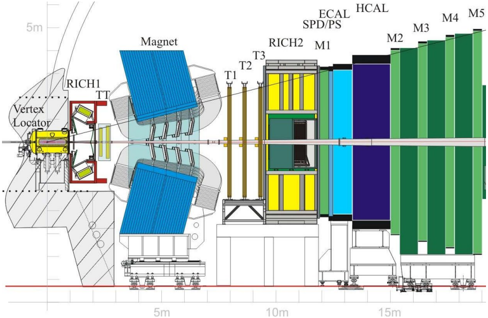
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

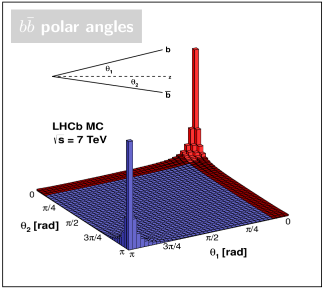
- Wilson coefficients C_i encode short-distance physics and possible NP effects
- $\mathcal{O}_i$ local operators with different Lorentz structure
- $\mathcal{O}_i'$ helicity flipped operators, m_s/m_b suppressed



Operator		
$\mathcal{O}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu})$	photon penguin
$\mathcal{O}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$	ew. penguin
$\mathcal{O}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$	
$\mathcal{O}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$	scalar penguin
$\mathcal{O}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$	pseudoscalar penguin

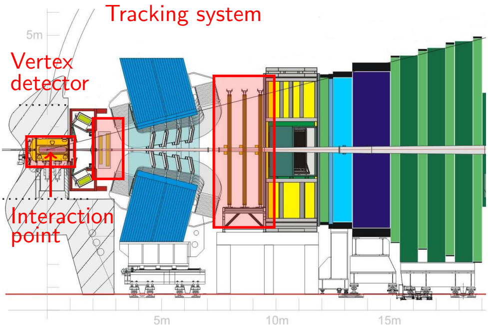
The LHC as heavy flavour factory

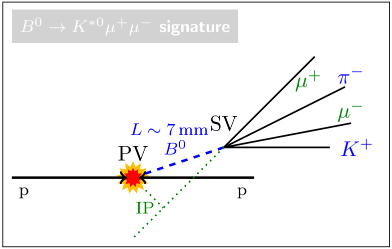




- $b\bar{b}$ produced correlated predominantly in forward (backward) direction $\rightarrow$ single arm forward spectrometer ($2 < \eta < 5$)
- Large $b\bar{b}$ production cross section $\sigma_{b\bar{b}} = (75.3 \pm 14.1)\,\mu\text{b}$ [Phys.Lett. B694 (2010)] in acceptance
- $\sim 1 \times 10^{11}$ produced $b\bar{b}$ pairs in 2011, excellent environment to study $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and other rare decays

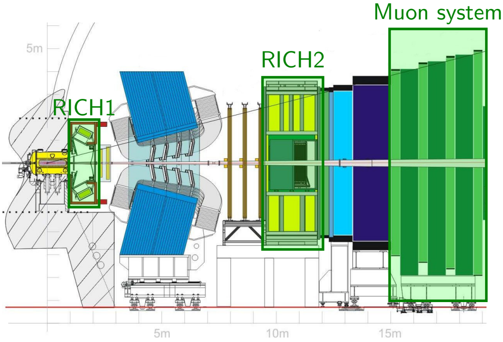
The LHCb detector: Tracking

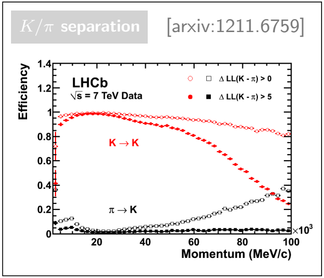




- Excellent Impact Parameter (IP) resolution $(20\,\mu\mathrm{m})$
  $\to$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim 40\,\mathrm{fs}$
  $\to$ Good separation of primary and secondary vertices
- Excellent momentum $(\delta p/p \sim 0.4 - 0.6\%)$ and inv. mass resolution
  $\to$ Low combinatorial background

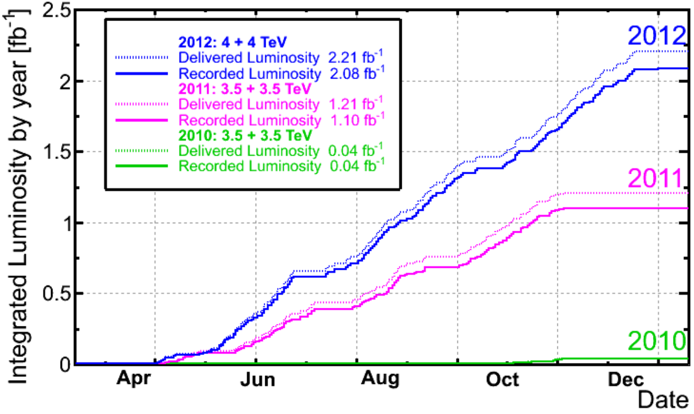
The LHCb detector: Particle identification and Trigger





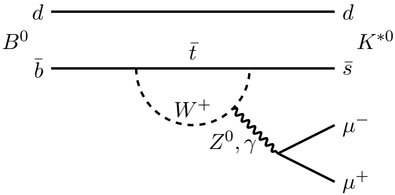
- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$ $\epsilon_{\pi\to\mu} \sim 1\text{-}3\%$
- Good $K\pi$ separation via RICH detectors $\epsilon_{K\to K} \sim 95\%$ $\epsilon_{\pi\to K} \sim 5\%$
  $\to$ Reject peaking backgrounds
- High trigger efficiencies, low momentum thresholds
  Muons: $p_{\mathrm{T}} > 1.76\,\mathrm{GeV}$ at L0, $p_{\mathrm{T}} > 1.0\,\mathrm{GeV}$ at HLT1
  $B \to J/\psi X$: $\epsilon_{\text{Trigger}} \sim 90\%$

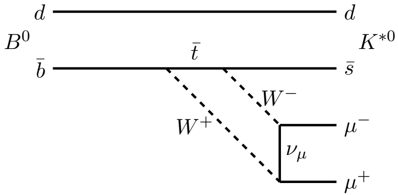
Data taken by LHCb



- Published results I will discuss today only use $1\,\mathrm{fb}^{-1}$ taken in 2011
- Full data sample of $3\,\mathrm{fb}^{-1}$ currently under study

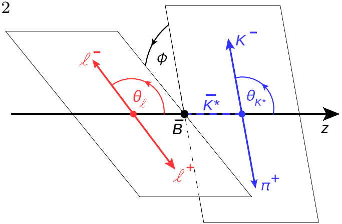
$B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$ final state





Decay fully described by three helicity angles $\theta_\ell, \theta_K, \Phi$ and q^2

- q^2: four momentum transfer squared, $q^2 = m(\mu^+\mu^-)^2$
- θ_ℓ: angle between the direction of μ^+ (μ^-) and direction opposite B^0 ($\overline{B}^0$) in $\mu^+\mu^-$ rest frame
- θ_K: angle between the direction of K and direction opposite B^0 ($\overline{B}^0$) in $K\pi$ rest frame
- Φ: angle between the $\mu^+\mu^-$ plane and the $K\pi$ plane in the B^0 ($\overline{B}^0$) system



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

- Four-differential decay rate for $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$

$$\frac{d^4\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\Phi} = \frac{9}{32\pi}\big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K$$
$$+ (I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K)\cos 2\theta_\ell$$
$$+ I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\Phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\Phi$$
$$+ I_5 \sin 2\theta_K \sin\theta_\ell \cos\Phi$$
$$+ (I_6^s \sin^2\theta_K + I_6^c \cos^2\theta_K)\cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\Phi$$
$$+ I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\Phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\Phi\big]$$

- $I_i(q^2)$ combinations of K^{*0} spin amplitudes sensitive to $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$
- CP-averages $S_i = (I_i + \bar{I}_i)/\frac{d(\Gamma+\bar{\Gamma})}{dq^2}$, CP-asymmetries $A_i = (I_i - \bar{I}_i)/\frac{d(\Gamma+\bar{\Gamma})}{dq^2}$
- For $m_\ell = 0$: 8 CP averages S_i, 8 CP-asymmetries A_i
- Simultaneous fit of 8 observables not possible with the 2011 data set
  $\to$ Angular folding $\Phi \to \Phi + \pi$ for $\Phi < 0$ cancels terms $\propto \sin\Phi, \cos\Phi$

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$I_i(q^2)$ depend on K^{*0} spin amplitudes $A_0^{L,R}$, $A_\parallel^{L,R}$, $A_\perp^{L,R}$

For completeness

$$I_1^s = \frac{(2+\beta_\mu^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right] + \frac{4m_\mu^2}{q^2}\Re(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*})$$

$$I_1^c = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\Re(A_0^L A_0^{R*}\right]$$

$$I_2^s = \frac{\beta_\mu^2}{4}\left\{|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right\}$$

$$I_2^c = -\beta_\mu^2\left\{|A_0^L|^2 + (L \to R)\right\}$$

$$I_3 = \frac{\beta_\mu^2}{2}\left\{|A_\perp^L|^2 - |A_\parallel^L|^2 + (L \to R)\right\}$$

$$I_4 = \frac{\beta_\mu^2}{\sqrt{2}}\left\{\Re(A_0^L A_\parallel^{L*}) + (L \to R)\right\}$$

$$I_5 = \sqrt{2}\beta_\mu\left\{\Re(A_0^L A_\perp^{L*}) - (L \to R)\right\}$$

$$I_6 = 2\beta_\mu\left\{\Re(A_\parallel^L A_\perp^{L*}) - (L \to R)\right\}$$

$$I_7 = \sqrt{2}\beta_\mu\left\{\Im(A_0^L A_\parallel^{L*}) - (L \to R)\right\}$$

$$I_8 = \frac{\beta_\mu^2}{\sqrt{2}}\left\{\Im(A_0^L A_\perp^{L*}) + (L \to R)\right\}$$

$$I_9 = \beta_\mu^2\left\{\Im(A_\parallel^{L*} A_\perp^L) + (L \to R)\right\}$$

K^{*0} spin amplitudes $A_0^{L,R}$, $A_\parallel^{L,R}$, $A_\perp^{L,R}$

For completeness

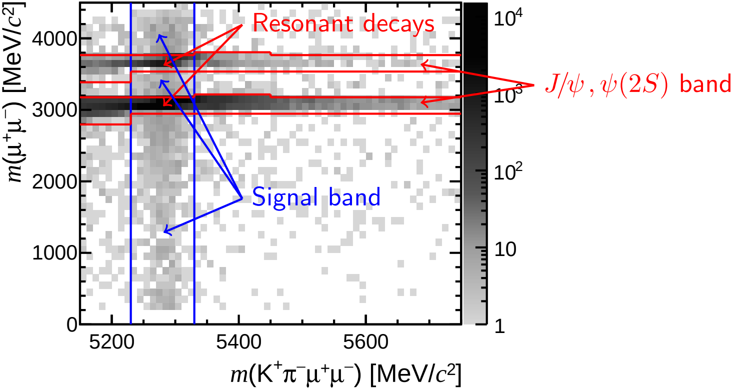
$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(\mathbf{C_9^{eff}} + \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} + \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{V(q^2)}}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} + \mathbf{C_7^{\prime eff}})\mathbf{T_1(q^2)}\right\}$$

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

$$A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A_1(q^2)} - \lambda\frac{\mathbf{A_2(q^2)}}{m_B + m_{K^*}}\right] + 2m_b(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\left[(m_B^2 + 3m_{K^*} - q^2)\mathbf{T_2(q^2)} - \frac{\lambda}{m_B^2 - m_{K^*}^2}\mathbf{T_3(q^2)}\right]\right\}$$

- Wilson coefficients $C_{7,9,10}^{(\prime)\mathrm{eff}}$
- Seven form factors (FF) $V(q^2)$, $A_{0,1,2}(q^2)$, $T_{1,2,3}(q^2)$ encode hadronic effects and require non-perturbative calculation
- Low $q^2 \leq 6\,\mathrm{GeV}^2$
  $\rightarrow \xi_{\perp,\parallel}$ (soft form factors)
- Large $q^2 \geq 14\,\mathrm{GeV}^2$
  $\rightarrow f_{\perp,\parallel,0}$ (helicity form factors)
- Theory uncertainties:
  - FF from non-perturbative calculations
  - Λ/m_b corrections ("subleading corrections")

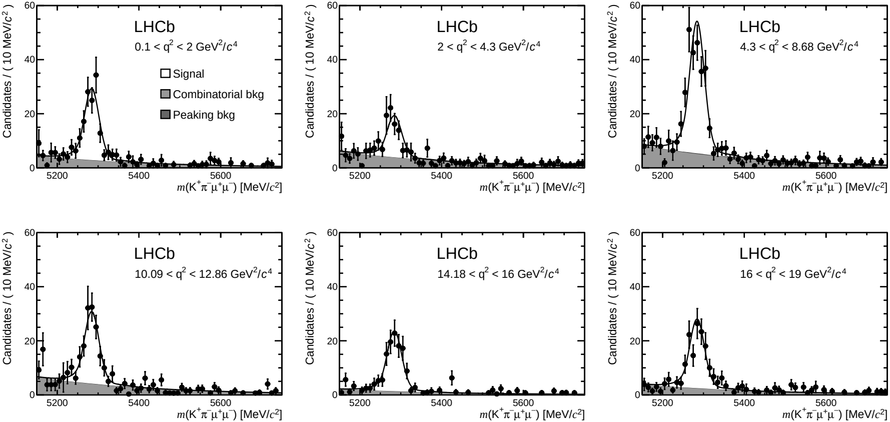
Analysis strategy



- Veto of $B^0 \to J/\psi\, K^{*0}$ and $B^0 \to \psi(2S) K^{*0}$ (valuable control channels!)
- Suppression of peaking backgrounds with PID
  Rejection of combinatorial background with BDT

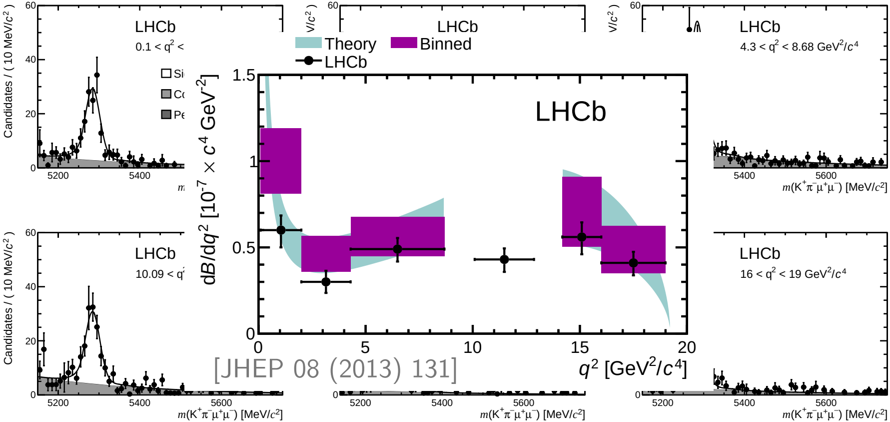
1. Determine the differential branching fraction in q^2 bins
2. Determine angular observables in multidimensional likelihood fit

$B^0 \to K^{*0}\mu^+\mu^-$ signal yield (2011)



- Fit of N_{sig} in q^2 bins
- Use $B^0 \to J/\psi\, K^{*0}$ as normalisation channel
- SM prediction [C. Bobeth et al. JHEP 07 (2011) 067]
- Data somewhat low but large theory uncertainties due to FF

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



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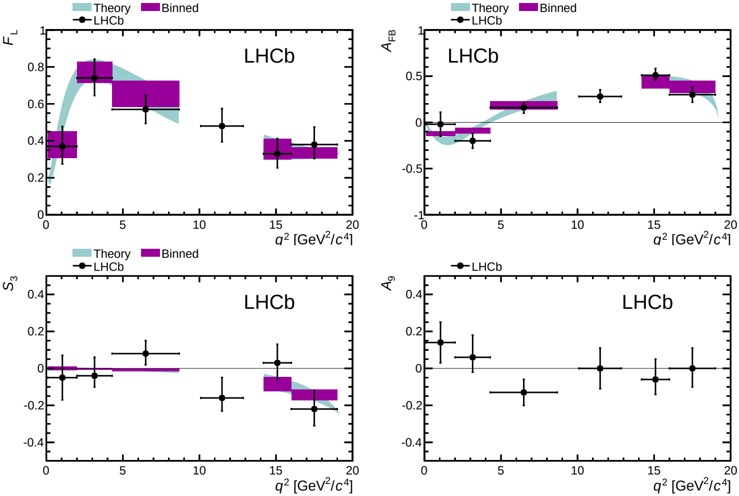
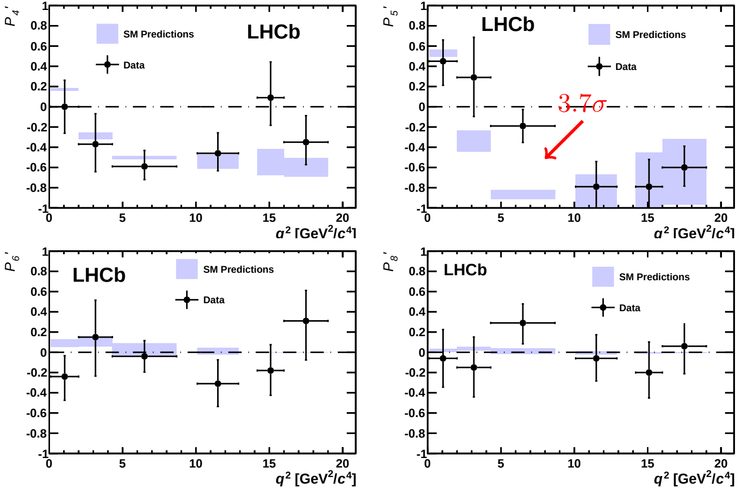
$B^0 \to K^{*0}\mu^+\mu^-$ angular observables I



- Results [JHEP 08 (2013) 131] in good agreement with SM prediction [C. Bobeth et al. JHEP 07 (2011) 067]

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

- Use different angular foldings for remaining four angular observables
- Use less form factor dependent parameterization $P'_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_L(1-F_L)}}$
- 3.7σ deviation from SM prediction [JHEP 05 (2013) 137] in P'_5



[PRL 111, 191801 (2013)]

Interpretations of the P_5' discrepancy

Possible interpretations

1. Statistical fluctuation
   Probability in 1/24 bins (Look-elsewhere effect): 0.5%
2. New Physics
   What type of NP could generate deviation?
   - Best fit with $\Delta C_9^{\mathrm{NP}} \sim -1.5$
   - Possible candidate: Z' $\mathcal{O}(1\,\mathrm{TeV})$
   - See also:
     [Altmannshofer et al. EPJC 73 (2013) 2646]
     [Beaujean et al. arXiv:1310.2478]
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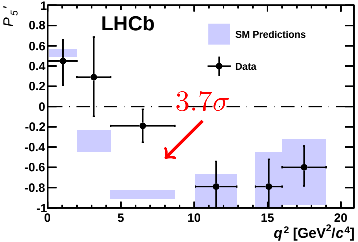
3. Theory uncertainties
   Λ/m_b *corrections?*



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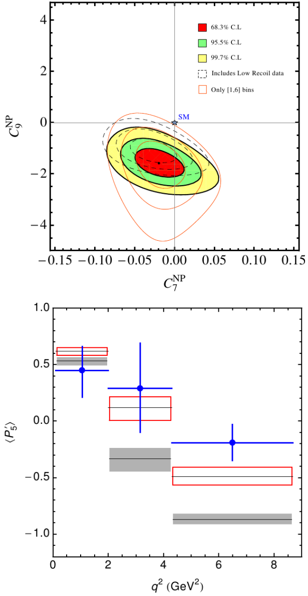

[S. Descotes-Genon et al. PRD 88, 074002 (2013)]

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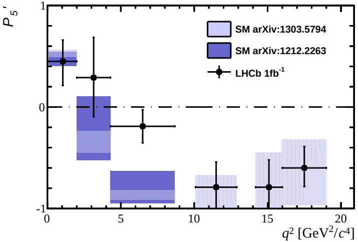

[Jäger et al., JHEP 1305 (2013) 043]

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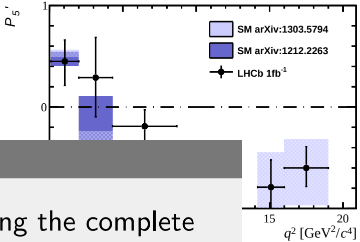


(2013) 043]

Tasks for LHCb

- Analysis of $B^0 \to K^{*0}\mu^+\mu^-$ using the complete $3\,\text{fb}^{-1}$ data sample
- Analysis of complementary $b \to s\ell\ell$ penguin decays $\to$ see Kostas' talk tomorrow

[Beaujean et al. arXiv:1310.2478]
[Hurth et al. arXiv:1312.5267]

3. Theory uncertainties
   Λ/m_b *corrections?*

Angular analysis using $3\,\text{fb}^{-1}$ of data

- 2011 $1\,\text{fb}^{-1}$ data sample: $N_{\text{sig}} \approx 900$
- 2011+2012 $3\,\text{fb}^{-1}$ data sample: Naive estimate[1] $\sim$ factor 3 larger

$3\,\text{fb}^{-1}$ Plans

1. Determine angular observables without angular folding
   Allows to give correlation matrix
2. Switch from Belle q^2 binning
   Ideally finer binning
3. S-wave was treated as systematic uncertainty
   - Dedicated analysis in wider $m_{K\pi}$ mass window
   - Include component in angular analysis
4. q^2 unbinned analysis methods
   - Fit of q^2 dependent helicity amplitudes
   - Direct fit of Wilson coefficients

[1] Disregarding several improvements in selection

The $K\pi$ S-Wave contribution

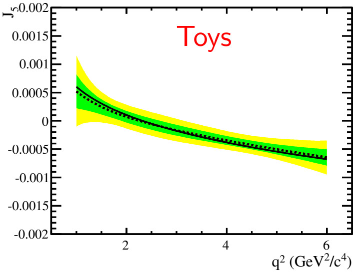
- Can have sizeable contribution with $K\pi$ system in spin 0 configuration
- Systematic in previous analysis, Can significantly bias observables for larger statistics [T. Blake et al.]
- Angular distribution [J. Matias], [D. Becirevic et al.]

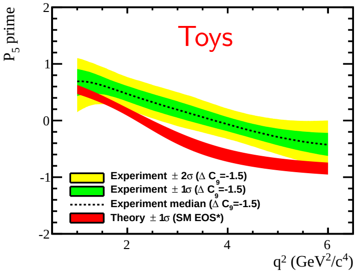
$$\begin{aligned}\frac{1}{\Gamma_{\text{full}}}\frac{\mathrm{d}^3\Gamma_{\text{full}}}{\mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_K \mathrm{d}\phi} = & \frac{1}{\Gamma_{K^{*0}}}\frac{\mathrm{d}^3\Gamma_{K^{*0}}}{\mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_K \mathrm{d}\phi}(1-F_S) \\ & + \frac{3}{16\pi}\Big[F_S\sin^2\theta_\ell + A_{S1}\sin^2\theta_\ell\cos\theta_K \\ & \quad + A_{S2}\sin 2\theta_\ell\sin\theta_K\cos\phi + A_{S3}\sin\theta_\ell\sin\theta_K\cos\phi \\ & \quad + A_{S4}\sin\theta_\ell\sin\theta_K\sin\phi + A_{S5}\sin 2\theta_\ell\sin\theta_K\sin\phi\Big]\end{aligned}$$

- 6 additional observables, challenging
- Separate analysis to determine $\mathrm{d}\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/\mathrm{d}q^2$ and the S-wave fraction using fit to $m_{\mathrm{K}\pi\mu\mu}, m_{\mathrm{K}\pi}$ and $\cos\theta_K$

Fit for helicity amplitudes

- Parametrise q^2 dependence of amplitudes with ansatz $A^{L,R}_{\|,\perp,0}(q^2) \sim \alpha + \beta q^2 + \gamma/q^2$
- Fit amplitudes in the $1 < q^2 < 6\,\mathrm{GeV}^2$ region
- From amplitudes can build any observable and correlations

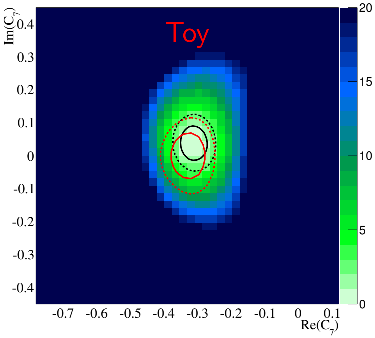




- Continuous q^2 shape increases sensitivity to new physics

Direct fit for Wilson coefficients

- Use the four differential decay rate $\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2}$ as PDF
- Full theory calculation implemented in [EOS] and [SuperIso]
- Use all available information as input: $\vec{\Omega}$, q^2, decay flavour
- Perform ub ML fit for $\mathcal{C}_i^{(\prime)}$ and nuisance parameters (FFs etc.)
- Better sensitivity to underlying physics than observables



- Using expected signal yield in 2012
- Red: Fit of angular observables
- Black: Direct fit of Wilson coefficients

Prospects for $B^0 \to K^{*0}\mu^+\mu^-$ in 2018 and beyond

- LHCb is expected to collect an additional $5\,\text{fb}^{-1}$ in 2015-2017
- Afterwards LHCb upgrade [CERN-LHCC-2012-007]

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B^0_s mixing	$2\beta_s$ $(B^0_s \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ $(B^0_s \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B^0_s)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta^{\text{eff}}_s(B^0_s \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta^{\text{eff}}_s(B^0_s \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K^0_S)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta^{\text{eff}}_s(B^0_s \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B^0_s \to \phi\gamma)/\tau_{B^0_s}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\,A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ $(B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	γ $(B^0_s \to D_s K)$	–	11°	2.0°	negligible
	β $(B^0 \to J/\psi\, K^0_S)$	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Conclusions

- $B^0 \to K^{*0}\mu^+\mu^-$ an ideal environment to search for NP effects in $b \to s$ FCNCs
- Many observables in good agreement with the SM
- Interesting deviations in
  - 3.7σ local deviation in P_5'
  - $\mathrm{d}\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/\mathrm{d}q^2$ lower than predictions
- Analysis of the full $3\,\mathrm{fb}^{-1}$ data sample on the way
- Run II and LHCb upgrade will improve LHCb's sensitivity even further