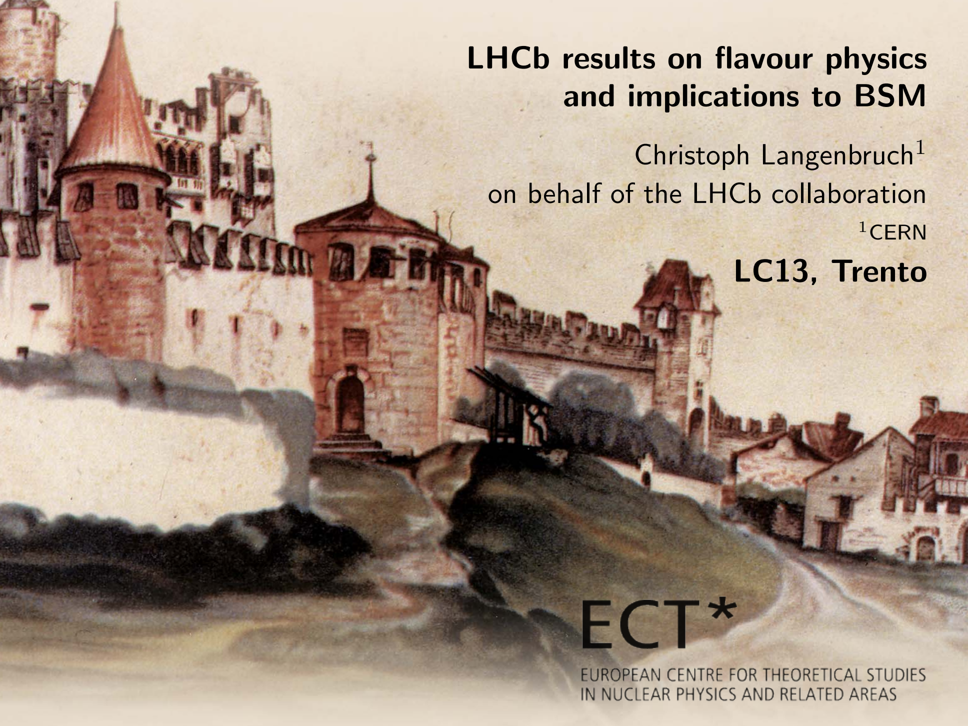

LHCb results on flavour physics and implications to BSM

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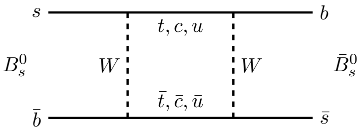
ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

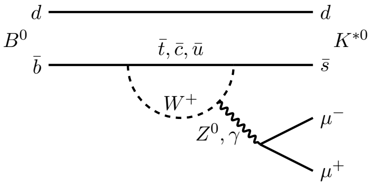
New Physics searches at LHCb

- Most New Physics models predict existence of new heavy particles
- New BSM particles can enter loop processes as virtual particles
- Particularly interesting: Flavour Changing Neutral Currents

$B_s^0 - \overline{B}_s^0$ mixing (box diagram)



$B^0 \to K^{*0}\mu\mu$ (penguin diagram)



- Compare SM predictions with LHCb's precision measurements
  $\to$ Indirect search for New Physics
- Higher mass scales accessible than with direct searches
- Pattern of deviations hints at the structure of New Physics

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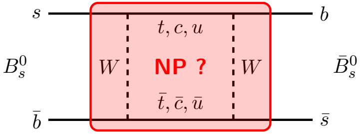
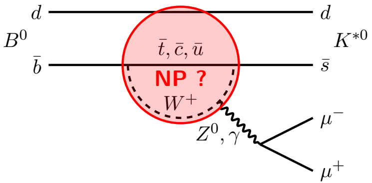


NP can induce new CPV phases

$B^0 \to K^{*0}\mu\mu$ (penguin diagram)



NP can affect $\mathcal{B}$, angular distributions

- Compare SM predictions with LHCb's precision measurements
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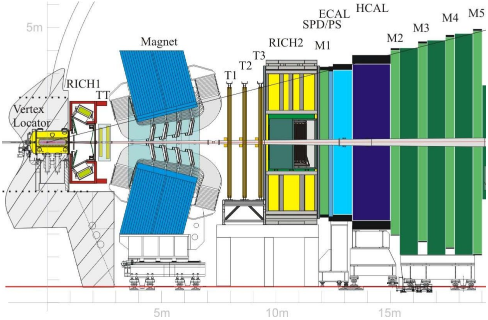
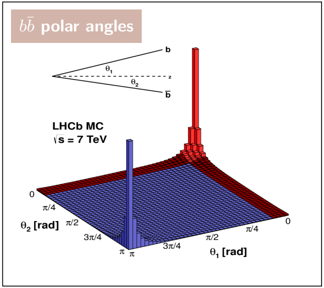
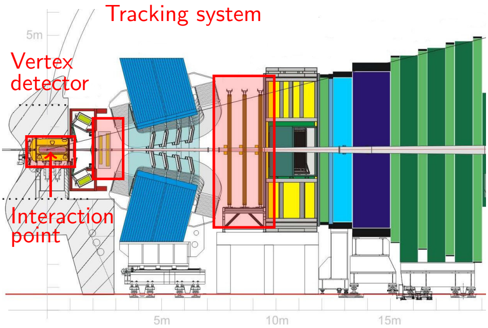
The LHCb experiment at the LHC

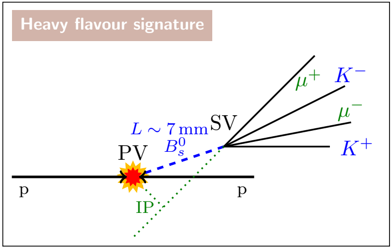




- $b\bar{b}$ produced correlated predominantly in forward (backward) direction $\rightarrow$ single arm forward spectrometer $(2 < \eta < 5)$
- Large $b\bar{b}$ production cross section $\sigma_{b\bar{b}} = (75.3 \pm 14.1)\,\mu\text{b}$ [Phys.Lett. B694 (2010)] in acceptance
- Huge $c\bar{c}$ cross section No time to cover LHCb's extensive charm program $\sigma_{c\bar{c}} = (1419 \pm 134)\,\mu\text{b}$ [Nucl. Phys. B871 (2013)] in acceptance

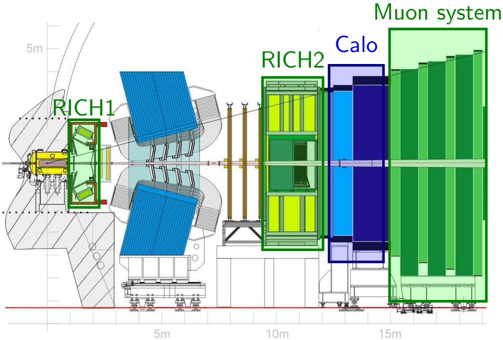
The LHCb detector: Tracking

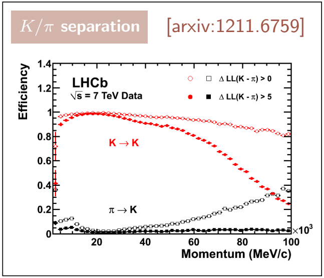




- Excellent Impact Parameter (IP) resolution ($20\,\mu\mathrm{m}$)
  $\rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim 40\,\mathrm{fs}$
  $\rightarrow$ Resolve fast B_s^0 oscillations
- Excellent momentum ($\delta p/p \sim 0.4 - 0.6\%$) and inv. mass resolution
  $\rightarrow$ Low combinatorial background

The LHCb detector: Particle identification and Trigger





- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$ $\epsilon_{\pi\to\mu} \sim$ 1-3%
- 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
  Muonic modes: $\epsilon_{\text{Trigger}}(B_s^0 \to \mu^+\mu^-) \sim 90\%$
  Hadronic modes: $\epsilon_{\text{Trigger}}(B^0 \to h^+h^-) \sim 50\%$

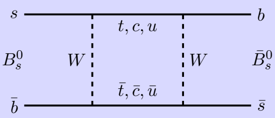
CP Violation

CP Violation

- Hunt for CPV phases induced by NP

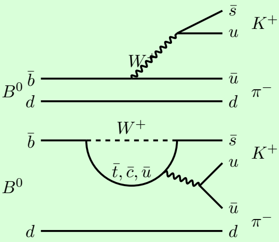
Types of CP violation

CPV in mixing "indirect CP violation"



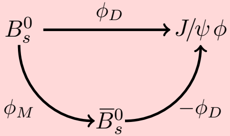
- interference between absorptive/dispersive mixing amplitude
- different mixing probability $B \to \bar{B}$ vs. $\bar{B} \to B$
- small in SM

CPV in decay "direct CP violation"



- interference between decay amplitudes with different weak and strong phases
- different decay rates $B \to f$ vs. $\bar{B} \to \bar{f}$
- strong phases difficult in theory

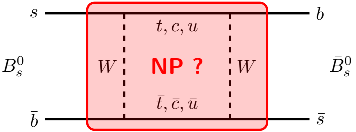
CPV in interference of mixing and decay



- interference between decay and decay after mixing
- different decay rates $B \to f_{\rm CP}$ vs. $\bar{B} \to f_{\rm CP}$
- "golden modes"

CPV in mixing: Flavour specific asymmetry $a_{\rm sl}^s$

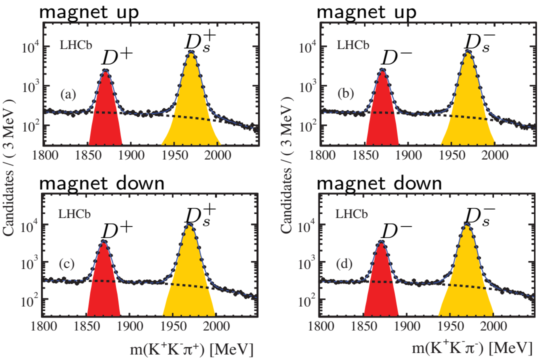
- Flavour specific asymmetry
  $a_{\rm sl}^s = \frac{\Gamma(\overline{B}_s^0(t)\to f) - \Gamma(B_s^0(t)\to \bar{f})}{\Gamma(\overline{B}_s^0(t)\to f) + \Gamma(B_s^0(t)\to \bar{f})}$

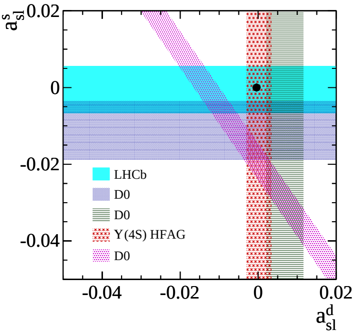


- Non-zero if CP is violated in B_s^0 mixing
  $\mathrm{Prob}(B_s^0 \to \overline{B}_s^0) \neq \mathrm{Prob}(\overline{B}_s^0 \to B_s^0)$
- Tiny in the SM
  $a_{\rm sl}^s = (1.9 \pm 0.3) \times 10^{-5}$ [A. Lenz arxiv:1205.1444]
- Sensitive to possible NP contributions to B_s^0 mixing
- LHCb uses $f = D_s^- \mu^+ X$ as final state
- Production asymmetry $a_P \sim \mathcal{O}(1\%)$ washed out by rapid B_s^0 oscillation!

$$A_{\rm raw} = \frac{N(D_s^-\mu^+) - N(D_s^+\mu^-)}{N(D_s^-\mu^+) + N(D_s^+\mu^-)} = \frac{a_{\rm sl}^s}{2} + \left[a_P - \frac{a_{\rm sl}^s}{2}\right] \times \underbrace{\frac{\int e^{-\Gamma_s t}\cos(\Delta m_s t)\epsilon(t)}{\int e^{-\Gamma_s t}\cosh(\Delta\Gamma_s t/2)\epsilon(t)}}_{=2\times 10^{-3} \text{ for LHCb acceptance}}$$

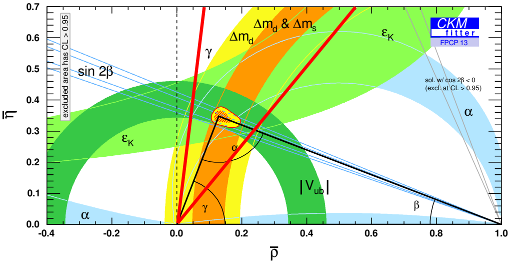
CPV in mixing: Flavour specific asymmetry $a_{\rm sl}^s$

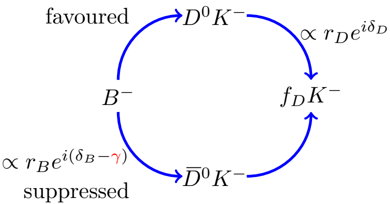




- Detection asymmetry measured on data using control channels ($b \to J/\psi\, X$, $D^{*+} \to D^0\pi^+$)
- $a_{\rm sl}^s = (-0.06 \pm 0.50_{\rm stat} \pm 0.36_{\rm syst})\%$ [arxiv:1308.1048]
  Most precise mesurement of this quantity
- Excellent agreement with the SM
- No confirmation of the D0 same-sign dilepton anomaly

CKM angle γ from tree decays

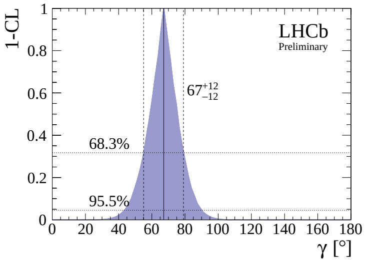




- CKM matrix dominant source of CPV in the quark sector
- More precise measurement of the SM needed to test for possibly small contributions from NP
- CKM angle γ is least well constrained CKM parameter
  $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$, $\gamma = (68.0^{+8.0}_{-8.5})^\circ$ [CKMfitter], $\gamma = (70.8 \pm 7.8)^\circ$ [UTfit]
- Determination from tree level $B^- \to D[\to f_D]K^-$ decays with f_D accessible from both D and $\bar{D}$
- No loop contributions $\to$ no NP effects expected

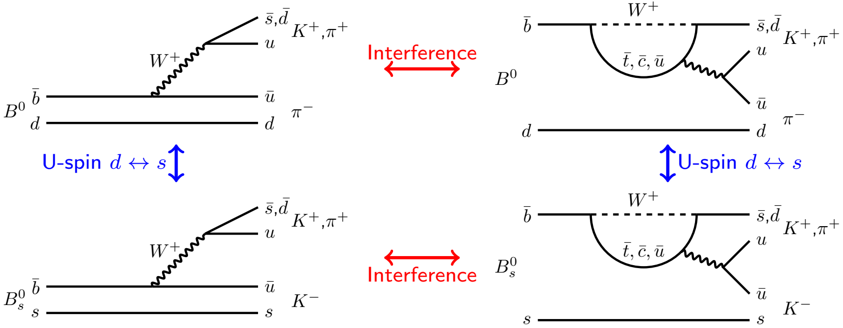
γ determination methods depending on D final state

- CP eigenstates K^+K^-, $\pi^+\pi^-$ (Gronau, London, Wyler) [PLB 713 (2012) 351]
- Flavour-specific states $K^\pm\pi^\mp$, $K^\pm\pi^\mp\pi^\pm\pi^\mp$ (Atwood, Dunietz, Soni) [PLB 713 (2012) 351], [PLB 723 (2013) 44]
- 3-body final states $K^0_S\pi^+\pi^-$, $K^0_S K^+K^-$ (Giri, Grossman, Soffer, Zupan) Compare interference patterns in Dalitz plots from B^+ and B^- decays $1\,\text{fb}^{-1}$ [PLB 718 (2012) 43], $3\,\text{fb}^{-1}$ [LHCb-CONF-2013-006]
- Preliminary combination of $1\,\text{fb}^{-1}$ GLW/ADS and $3\,\text{fb}^{-1}$ GGSZ



- Most precise γ measurement to date
- $\gamma = (67 \pm 12)^\circ$ [LHCb-CONF-2013-006]

CPV in 2-body charmless B decays

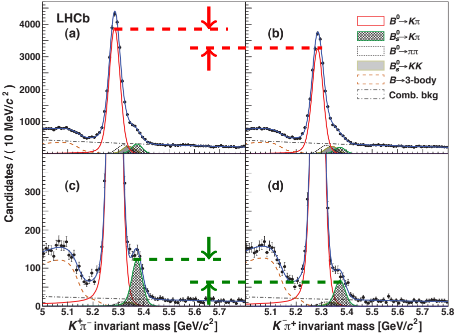


- Direct CP violation due to interference of $b \to u$ tree and $b \to s(d)$ penguin
- Measures γ in the SM, sensitive to possible NP contributions in the loop
- Exploit U-spin relation between B^0 and B_s^0 decays to determine strong phases [Fleischer, EPJC 52 (2007) 267]

1. Time-integrated CP asymmetry in $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$
2. Time-dependent CP asymmetry in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$

Time-integrated CPV in 2-body charmless B decays

[PRL 110 (2013) 221601]



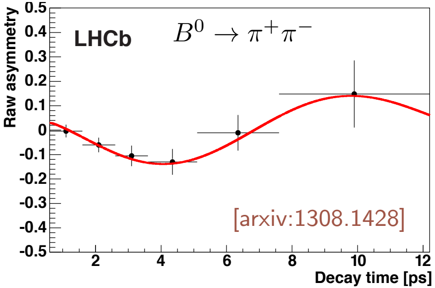
- Most precise measurement of A_{CP} in $B^0 \to K^+\pi^-$
  $A_{\mathrm{CP}}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007_{\mathrm{stat}} \pm 0.003_{\mathrm{syst}}$
- First observation of CPV in B_s^0 decays with 6.5σ significance
  $A_{\mathrm{CP}}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04_{\mathrm{stat}} \pm 0.01_{\mathrm{syst}}$
- Test of U-spin symmetry [Lipkin, PLB 621 (2005) 126]
  $$\Delta = \frac{A_{\mathrm{CP}}(B^0 \to K^+\pi^-)}{A_{\mathrm{CP}}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0$$
- LHCb measures $\Delta = -0.02 \pm 0.05_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}$

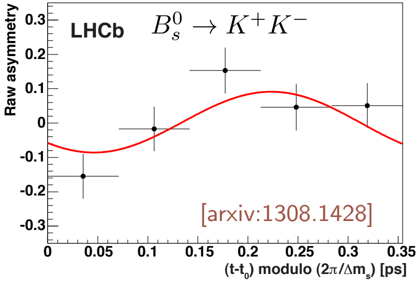
Time-dependent CPV in 2-body charmless B decays

- Time dependent CP asymmetry, *e.g.* $B^0 \to \pi^+\pi^-$:

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0 \to \pi^+\pi^-, t) - \Gamma(B^0 \to \pi^+\pi^-, t)}{\Gamma(\overline{B}^0 \to \pi^+\pi^-, t) + \Gamma(B^0 \to \pi^+\pi^-, t)} \propto -C_{\pi\pi}\cos(\Delta m t) + S_{\pi\pi}\sin(\Delta m t)$$

- Use Flavour tagging algorithms to infer B flavour at production





- Good agreement with BaBar/Belle

$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$$
$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$$

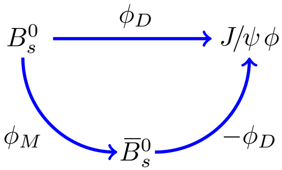
- $(C_{\pi\pi}, S_{\pi\pi}) \neq (0,0)$ at 5.6σ

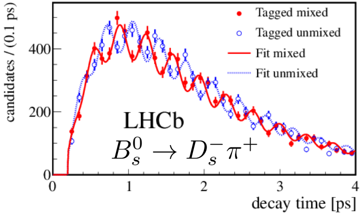
- First measurement

$$C_{KK} = +0.14 \pm 0.11 \pm 0.03$$
$$S_{KK} = +0.30 \pm 0.12 \pm 0.04$$

- $(C_{KK}, S_{KK}) \neq (0,0)$ at 2.7σ

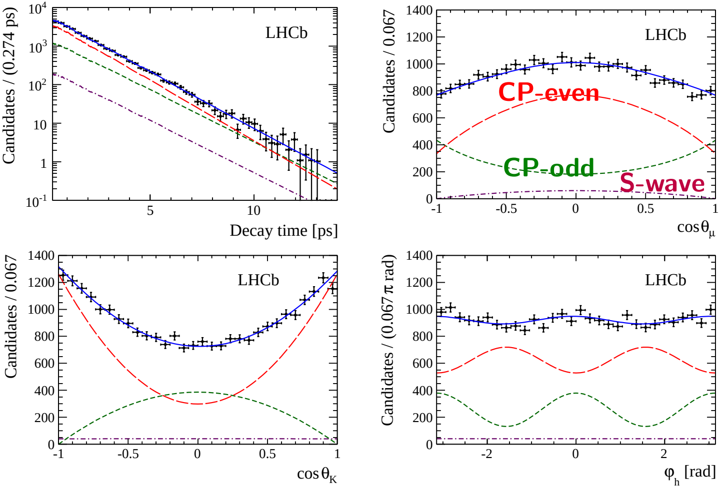
CP violating phase ϕ_s





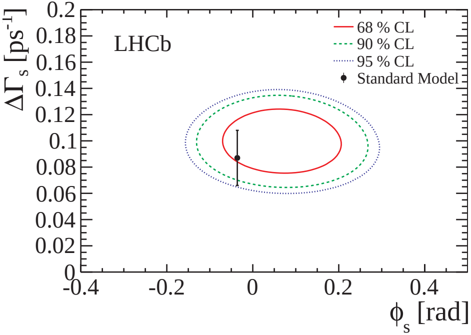
- CP violating in interference between mixing and decay: $\phi_s = \phi_M - 2\phi_D$
- Precise SM prediction: $\phi_s^{\mathrm{SM}} = -(0.0367 \pm 0.0014)\,\mathrm{rad}$ [CKMfitter]
- BSM particles can affect B_s^0 mixing phase: $\phi_s = \phi_s^{\mathrm{SM}} + \Delta\phi_s^{\mathrm{NP}}$
- Time dependent CP asymmetry
  $$A_{\mathrm{CP}}(t) = \frac{\Gamma(\overline{B}_s^0 \to f_{\mathrm{CP}}, t) - \Gamma(B_s^0 \to f_{\mathrm{CP}}, t)}{\Gamma(\overline{B}_s^0 \to f_{\mathrm{CP}}, t) + \Gamma(B_s^0 \to f_{\mathrm{CP}}, t)} = \eta_f \boxed{\sin\phi_s} \sin(\boxed{\Delta m_s} t)$$
- Need to resolve fast $B_s^0 - \overline{B}_s^0$ oscillation, dedicated measurement of
  $\boxed{\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\,\mathrm{ps}^{-1}}$ [New J. Phys. 15 (2013) 053021]
- η_f CP eigenvalue of f_{CP}

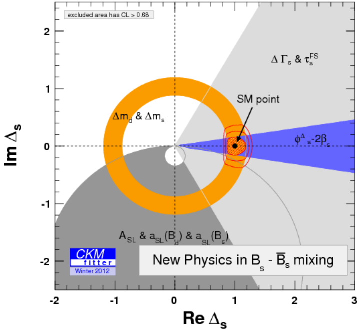
Angular analysis of $B_s^0 \to J/\psi\,\phi$



- Final state $J/\psi\,\phi$ admixture of CP-even and CP-odd
  $\to$ Angular analysis to disentangle 3 polarisation amplitudes + S-wave

ϕ_s Result and Implications





[PRD 87, 112010 (2013)]

[A. Lenz et al. PRD 86]

- $\phi_s = (0.07 \pm 0.09 \pm 0.01)\,\mathrm{rad}$ $\Delta\Gamma_s = (0.100 \pm 0.016 \pm 0.003)\,\mathrm{ps}^{-1}$
- Combined with $B_s^0 \to J/\psi \pi^+\pi^-$: $\phi_s = (0.01 \pm 0.07 \pm 0.01)\,\mathrm{rad}$
- Model ind. fit [A. Lenz et al. PRD 86] → Good agreement with the SM

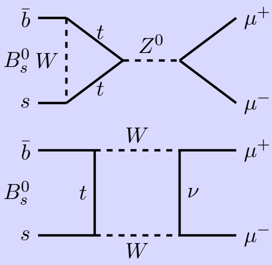
Rare Decays

- Searching for the effect of New Particles in rare decays

Rare decays in effective field theory

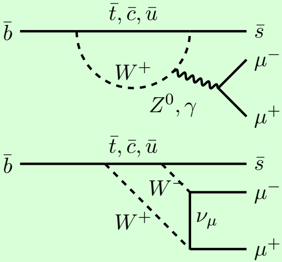
- Effective Hamiltonian for $b \to s$ FCNC transition
  $\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$
- Wilson coefficients $C_i^{(\prime)}$ encode short-distance physics and possible NP
- $\mathcal{O}_i$ local operators, $\mathcal{O}_i'$ helicity flipped, m_s/m_b suppressed

$B^0_{(s)} \to \mu^+\mu^-$



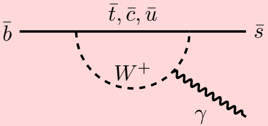
$C_S^{(\prime)}, C_P^{(\prime)}, C_{10}^{(\prime)}$

$b \to s\mu^+\mu^-$



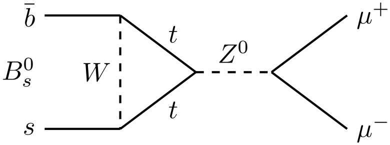
$C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

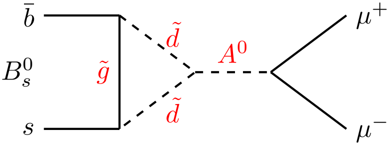
$b \to s\gamma$



$C_7^{(\prime)}$

$B^0_{(s)} \to \mu^+\mu^-$



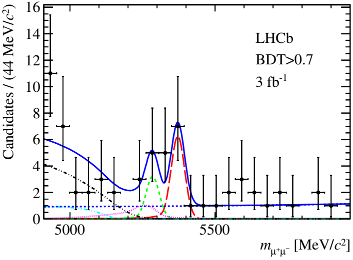


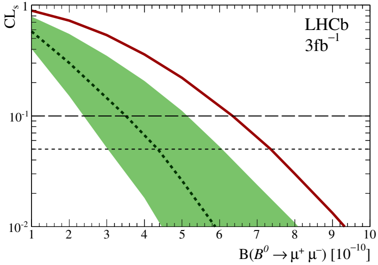
- Purely leptonic $b \to s$ FCNC $\to$ Theoretically and experimentally clean
- Very rare decay: Loop, CKM and helicity suppressed
- Sensitive to NP in the scalar and pseudoscalar sector

$$\mathcal{B}(B_q \to \mu^+\mu^-) \propto |V_{tb}V_{tq}|^2[(1-\frac{4m_\mu^2}{M_B^2})|C_S - C_S'|^2 + |(C_P - C_P') + \frac{2m_\mu}{M_B^2}(C_{10} - C_{10}')|^2]$$

- SM prediction [A. J. Buras et al. Eur.Phys.J. C72 (2012) 2172]
  $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$
- Accounting for $\Delta\Gamma_s \neq 0$ [A. J. Buras et al. JHEP07 (2013) 077]
  $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.56 \pm 0.18) \times 10^{-9}$
- In the MSSM $\mathcal{B}(B^0_s \to \mu^+\mu^-) \propto \tan^6\beta / m_A^4$

$B^0_{(s)} \to \mu^+\mu^-$ results



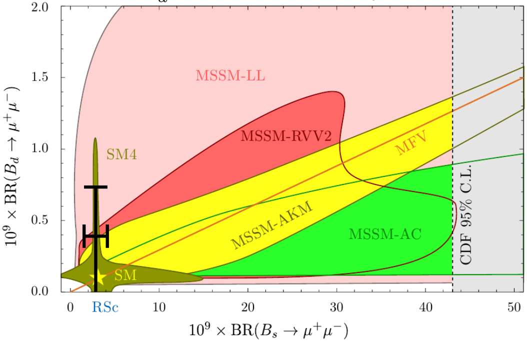


- Significance of observed $B^0_s \to \mu^+\mu^-$ signal 4σ
- Upper limit $\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95% CL
- Resulting (time integrated) branching fractions [PRL 111 (2013) 101805]
  $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}(\text{stat})\,^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9}$
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1}(\text{stat})\,^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10}$
- Combination with CMS [arxiv:1307.5025]
  $\to$ Observation of $B^0_s \to \mu^+\mu^-$ with $> 5\sigma$ [LHCb-CONF-2013-012]

$B_s^0 \to \mu^+\mu^-$ Implications

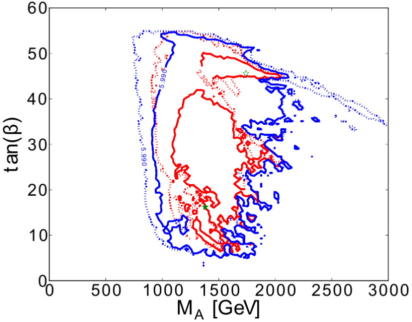
[D. Straub arxiv:1012.3893]

+LHCb $B_d^0 \to \mu^+\mu^-$ limit, $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$



[Buchmueller et al. EPJ C72 (2012) 2243]

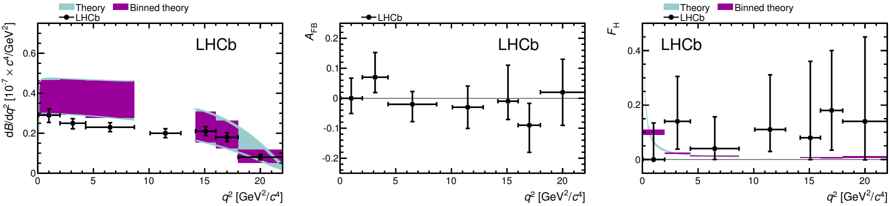
$B_s^0 \to \mu^+\mu^-$, XENON100, direct searches



- $\mathcal{B}(B_{(s)}^0 \to \mu^+\mu^-)$ significantly constrains parameter space of NP models

$B^+ \to K^+\mu^+\mu^-$

- Decay described by $q^2 = m^2(\mu^+\mu^-)$ and one angle θ_ℓ
  $$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}\cos\theta_\ell} = \frac{3}{4}(1-F_\mathrm{H})(1-\cos^2\theta_\ell) + \frac{1}{2}F_\mathrm{H} + A_\mathrm{FB}\cos\theta_\ell$$
- Measure $\mathrm{d}\Gamma/\mathrm{d}q^2$, A_FB and F_H in bins of q^2
- Veto charmonium resonances $B^+ \to J/\psi K^+$, $B^+ \to \psi(2S)K^+$
  $\to$ use for normalisation and calibration
- Good agreement with SM predictions
  [Bobeth et al. JHEP 1201 (2012) 107], [Bobeth et al. JHEP07 (2011) 067]



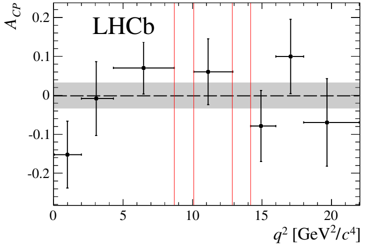
[JHEP02(2013)105]

$B^+ \to K^+\mu^+\mu^-$

Measure CP asymmetry

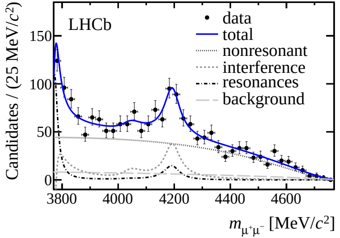
- $A_{\mathrm{CP}} = \frac{\Gamma(B^-\to K^-\mu^+\mu^-)-\Gamma(B^+\to K^+\mu^+\mu^-)}{\Gamma(B^-\to K^-\mu^+\mu^-)+\Gamma(B^+\to K^+\mu^+\mu^-)}$

  $= 0.000 \pm 0.033_{\mathrm{stat}} \pm 0.005_{\mathrm{syst}} \pm 0.07_{\mathrm{norm}}$
- Good agreement with SM prediction
- Details in [arxiv:1308.1340]



Observation of $\mu^+\mu^-$ resonance at high q^2

- Mass $4191\,^{+9}_{-8}$ MeV/c^2, width $65\,^{+22}_{-16}$ MeV/c^2
- Compatible with known $\psi(4160)$
- Amounts to $\sim 20\%$ of $K^+\mu^+\mu^-$ at high q^2
- Could affect angular distributions at high q^2
- Details in [arxiv:1307.7595]

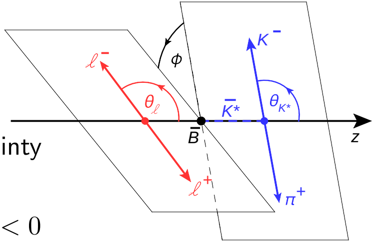


$B^0 \to K^{*0}\mu^+\mu^-$

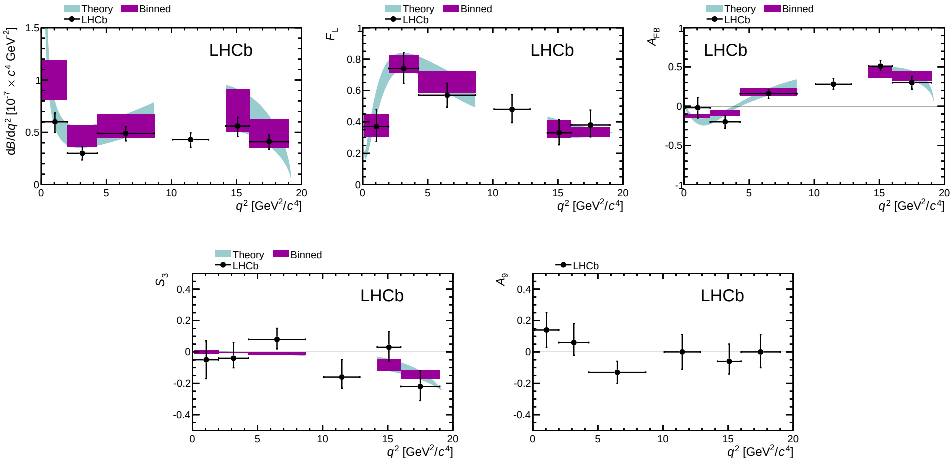
- Differential branching fraction: 3 decay angles θ_ℓ, θ_K, $\Phi \to$ 8 observables

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell d\cos\theta_K d\Phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\Phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\Phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\Phi + \tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\Phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\Phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\Phi\Big]$$

- $F_L(q^2)$, $A_{FB}(q^2)$, $S_i(q^2)$ functions of Wilson coefficients $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$
- q^2 dependence given by hadronic form factors $\to$ large part of theory uncertainty
- Simultaneous fit not possible with $1\,\text{fb}^{-1}$ $\to$ Angular foldings, *e.g.* $\Phi \to \Phi+\pi$ for $\Phi < 0$ cancels terms $\propto S_{4,5,7,8}$



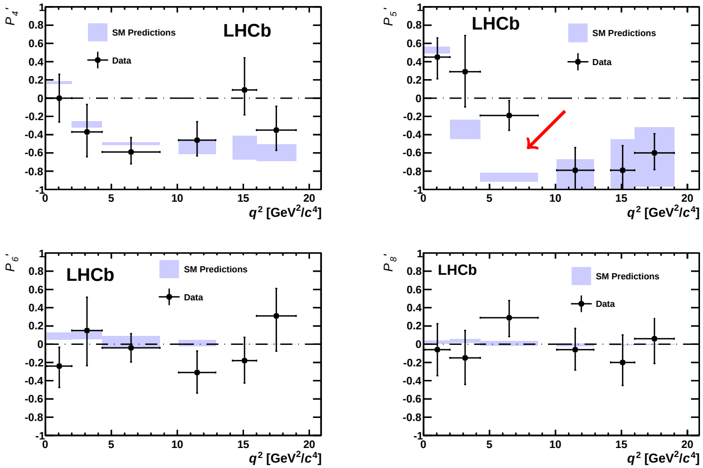
$B^0 \to K^{*0}\mu^+\mu^-$ angular observables



- Results [JHEP08 (2013) 131] in good agreement with the SM predictions [C. Bobeth et al. JHEP07 (2011) 067]

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

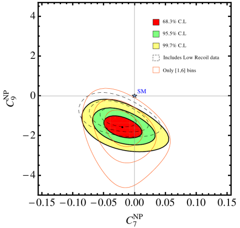
- Remaining angular observables determined by different angular folding
- Less form-factor dependent param. [S. Descotes-Genon et al. JHEP05 (2013) 137]
- 3.7σ discrepancy in P_5', Probability in 1/24 bins: 0.5% [arxiv:1308.1707]

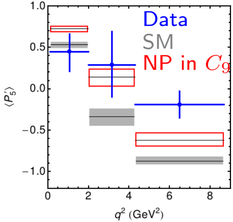


$B^0 \to K^{*0}\mu^+\mu^-$ Implications

- S. Descotes-Genon et al. see improved agreement with a reduced C_9

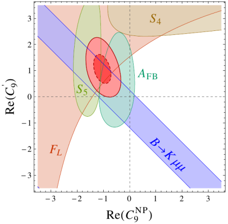
[arxiv:1307.5683]

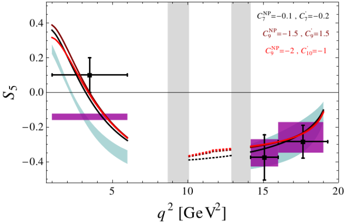




- W. Altmannshofer et al. combine with other experiments/channels
  Best fit result with shifts of C_9 and C_9'

[arxiv:1308.1501]





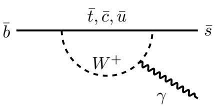
- Need update with full $3\,\text{fb}^{-1}$ LHCb data sample sample to clarify

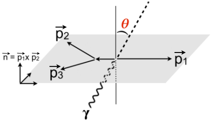
$B^+ \to K^+\pi^+\pi^-\gamma$

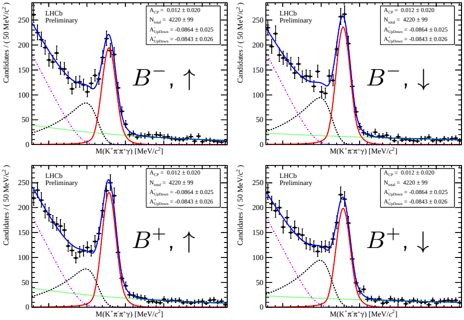
- $B^+ \to K^+\pi^+\pi^-\gamma$ a radiative FCNC
- Angle Θ carries information on γ polarization (left handed in SM)
- In New Physics models, γ can have right handed component
- Up-down asymmetry

$$A_{\rm ud} = \frac{\int_0^1 \frac{d\Gamma}{d\cos\Theta} d\cos\Theta - \int_{-1}^0 \frac{d\Gamma}{d\cos\Theta} d\cos\Theta}{\int_{-1}^1 \frac{d\Gamma}{d\cos\Theta} d\cos\Theta}$$

- $A_{\rm ud} = -0.085 \pm 0.019_{\rm stat} \pm 0.003_{\rm syst}$
  $\to 4.6\sigma$ evidence for γ polarization
- First determination of CP asymmetry in the decay $B^+ \to K^+\pi^+\pi^-\gamma$
  $A_{\rm CP} = -0.007 \pm 0.015_{\rm stat} \pm 0.008_{\rm syst}$







[LHCb-CONF-2013-009]

Conclusions

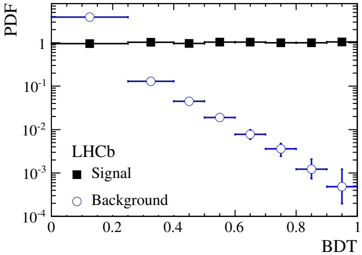
- The precision measurement of CP violation and the study of rare FCNC decays constitute powerful probes for New Physics
  Complementary to direct searches, high mass scales accessible
- Good agreement with the SM expectations seen so far
  Strong constraints on several NP models
- Interesting deviation in one angular observable in $B^0 \to K^{*0}\mu^+\mu^-$
  Updated study with full data sample needed to confirm
- Most presented results are statistically limited and do not yet use the full data sample
  $\to$ Stay tuned for more exciting results!

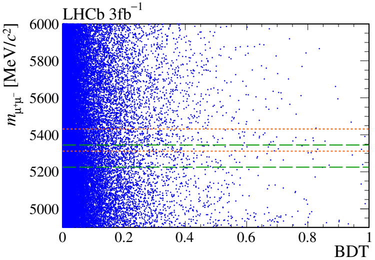
Backup

$B^0_{(s)} \to \mu^+\mu^-$ analysis strategy

- Select two well identified muons with good common vertex separated from all pp vertices
- Classify events as signal/background via
  1. Multivariate classifier (BDT):
     Calibrate signal: $B \to h^+h^-$ data
     Calibrate bkg.: dimuon sidebands
  2. Invariant $\mu^+\mu^-$ mass:
     Resolution from $J/\psi, \Upsilon$ resonances
- Normalise using $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$, consistent results
- $\mathcal{B}_{\rm sig} = \mathcal{B}_{\rm cal} \times \frac{\epsilon^{\rm rec}_{\rm cal}\epsilon^{\rm sel}_{\rm cal}}{\epsilon^{\rm rec}_{\rm sig}\epsilon^{\rm sel}_{\rm sig}} \times \frac{\epsilon^{\rm trig}_{\rm cal}}{\epsilon^{\rm trig}_{\rm sig}} \times \frac{f_{\rm cal}}{f_{\rm sig}} \times \frac{N_{\rm sig}}{N_{\rm cal}}$

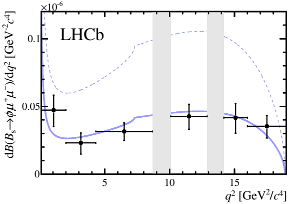
from MC, checked on data	from data	hadronization fraction ratio
- Perform extended unbinned ML fit in BDT bins

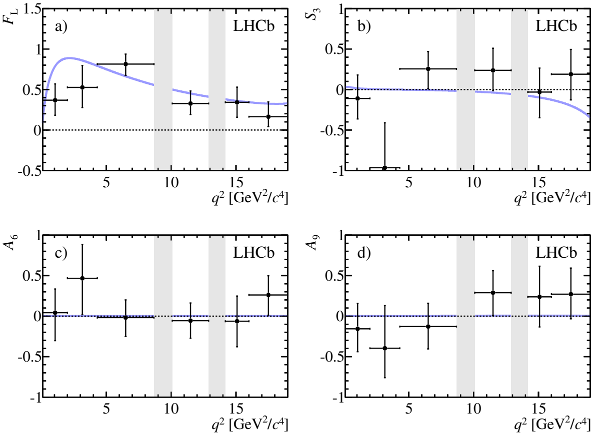




$B_s^0 \to \phi\mu^+\mu^-$

- Similar to $B^0 \to K^{*0}\mu^+\mu^-$, but in the B_s^0 system
- Not self-tagging $\to$ reduced number of untagged observables, but cleaner
- Angular observables in good agreement with predictions, $\mathcal{B}$ low





[JHEP 1307 (2013) 084]

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

- Following [Altmannshofer et. al], [Bobeth et. al]
- Differential decay rate for $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$:

$$\begin{aligned}\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) = \frac{9}{32\pi}\big[&J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K \\ &+ (J_2^s \sin^2\theta_K + J_2^c \cos^2\theta_K)\cos 2\theta_\ell \\ &+ J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\Phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\Phi \\ &+ J_5 \sin 2\theta_K \sin\theta_\ell \cos\Phi \\ &+ J_6^s \sin^2\theta_K \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\Phi \\ &+ J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\Phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\Phi\big]\end{aligned}$$

- For $B^0 \to K^{*0}\mu^+\mu^-$:
  Replace $J_{1,2,3,4,7} \to +\bar{J}_{1,2,3,4,7}$ and $J_{5,6,8,9} \to -\bar{J}_{5,6,8,9}$
  (depends on angular convention)
- Angular observables $J_i(q^2)$ depend on decay amplitudes $A^{L,R}_{0,\|,\perp}$ which in turn depend on the Wilson coefficients and form factors
- Alternative $S_i = (J_i + \bar{J}_i)/\frac{d\Gamma+\bar{\Gamma}}{dq^2}$, $A_i = (J_i - \bar{J}_i)/\frac{d\Gamma+\bar{\Gamma}}{dq^2}$

Angular observables $J_i(q^2)$ for $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$

For completeness

$$J_1^s = \frac{(2+\beta_\mu^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right] + \frac{4m_\mu^2}{q^2}\Re(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*})$$

$$J_1^c = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\Re(A_0^L A_0^{R*}\right]$$

$$J_2^s = \frac{\beta_\mu^2}{4}\left\{|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right\}$$

$$J_2^c = -\beta_\mu^2\left\{|A_0^L|^2 + (L \to R)\right\}$$

$$J_3 = \frac{\beta_\mu^2}{2}\left\{|A_\perp^L|^2 - |A_\parallel^L|^2 + (L \to R)\right\}$$

$$J_4 = \frac{\beta_\mu^2}{\sqrt{2}}\left\{\Re(A_0^L A_\parallel^{L*}) + (L \to R)\right\}$$

$$J_5 = \sqrt{2}\beta_\mu\left\{\Re(A_0^L A_\perp^{L*}) - (L \to R)\right\}$$

$$J_6 = 2\beta_\mu\left\{\Re(A_\parallel^L A_\perp^{L*}) - (L \to R)\right\}$$

$$J_7 = \sqrt{2}\beta_\mu\left\{\Im(A_0^L A_\parallel^{L*}) - (L \to R)\right\}$$

$$J_8 = \frac{\beta_\mu^2}{\sqrt{2}}\left\{\Im(A_0^L A_\perp^{L*}) + (L \to R)\right\}$$

$$J_9 = \beta_\mu^2\left\{\Im(A_\parallel^{L*} A_\perp^L) + (L \to R)\right\}$$

Decay amplitudes for $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$

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

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

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

$$A_t = \frac{N}{\sqrt{q^2}}\sqrt{\lambda}\left\{2(\mathbf{C_{10}^{eff}} - \mathbf{C_{10}'^{eff}}) + \frac{q^2}{m_\mu}(\mathbf{C_P^{eff}} - \mathbf{C_P'^{eff}})\right\}\mathbf{A_0(q^2)}$$

$$A_S = -2N\sqrt{\lambda}(\mathbf{C_S} - \mathbf{C_S})\mathbf{A_0(q^2)}$$

- Wilson coefficients $C_{7,9,10,S,P}^{(\prime)\mathrm{eff}}$
- Seven form factors: $V(q^2),\ A_{0,1,2}(q^2),\ T_{1,2,3}(q^2)$
- Low recoil (OPE, HQET): $f_{\perp,\parallel,0}$ (helicity form factors)
- Large recoil (QCDF, SCET): $\xi_{\perp,\parallel}$ (soft form factors)
- Additional corrections: Spectator interactions
  $\to$ Non-factorizable effects, weak annihilation [Beneke et. al]

LHCb upgrade schedule

year	$\int \mathcal{L} dt$
2010	$0.037\,\text{fb}^{-1}$ @ $7\,\text{TeV}$
2011	$1\,\text{fb}^{-1}$ @ $7\,\text{TeV}$
2012	$2\,\text{fb}^{-1}$ @ $8\,\text{TeV}$
2013 2014	LHC LS1
2015 2016 2017	$5\,\text{fb}^{-1}$ @ $13\,\text{TeV}$
2018 2019	LHC LS2, LHCb upgrade
2020 2021 2022	$5\,\text{fb}^{-1}/\text{year}$

- No clear deviations from the SM
- LHCb results statistically limited
- More statistics needed
  $\rightarrow$ LHCb upgrade
- Details in [CERN-LHCC-2012-007]

LHCb upgrade sensitivity

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

[CERN-LHCC-2012-007]