Rare heavy flavour decays at the LHC

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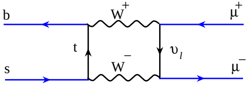
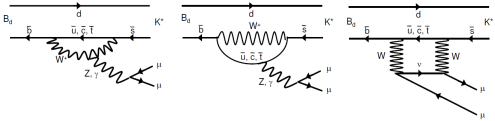
Frontiers in Particle Physics, Aspen 2014

Introduction

- Rare decays of heavy flavour mesons predominantly refers to $b \to s$ transitions.
- These are flavour-changing neutral currents and hence forbidden at tree level in the Standard Model.
- Physics beyond the Standard Model can modify a range of observables, from branching fractions to moments of the angular distribution of the final state particles.

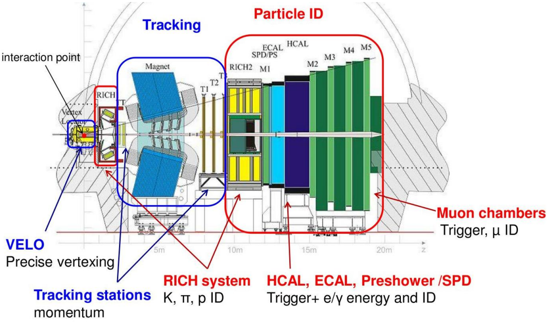




- $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$: Sensitive to new scalars and pseudo-scalars.
- $B^0 \to K^{*0}\mu^+\mu^-$: Sensitive to new scalars, pseudo-scalars, vectors and tensor contributions.

LHCb

- LHCb is a forward detector ($2 < \eta < 5$) designed to study heavy flavour physics

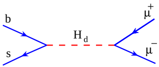


1. Trigger : 75-90% on leptonic *B* decays.
2. Vertex locater : σ_{IP} = 20 μm
3. Tracking : $\delta p/p = 0.4 - 0.6\%$
4. Hadron ID : ϵ_K = 95% efficient for 5% mis-ID
5. Muon ID : ϵ_μ = 98% efficient for 1% mis-ID

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

arXiv:1307.5024, doi:10.1103/PhysRevLett.111.101805

- $b \to s$ transition into a purely leptonic final state.
- Helicity suppressed and sensitive to new scalar and pseudoscalar contributions.
- SM: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.57 \pm 0.30) \times 10^{-9}$



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$$\mathcal{B}_{B_s^0 \to \mu^+\mu^-} = \mathcal{B}_{norm} \times \frac{\epsilon_{B_s^0 \to \mu^+\mu^-}}{\epsilon_{norm}} \times f_s/f_d \times \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{norm}} \quad (1)$$

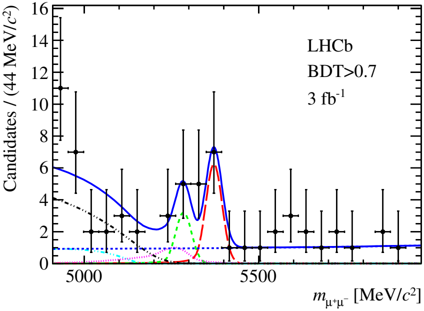
- LHCb analysis based on $3.0\,\text{fb}^{-1}$ of data.
- Two muons, separated from PV, mass range between 4.9 and 6 GeV/c^2.
- Measurement based on control channels $B_{d,s} \to h^+h^-$ and $B^+ \to J/\psi\ K^+$.
- Boosted decision tree based on kinematics and geometry of the decay and the event.
- Calibrated used data-derived methods from the control channels.
- Background estimated from $B_{d,s} \to h^+h^-$ mis-identification probability, combinatorial taken from mass sideband regions and simulation of specific physics background processes.
- Results calculated in bins of BDT classifier and invariant mass.

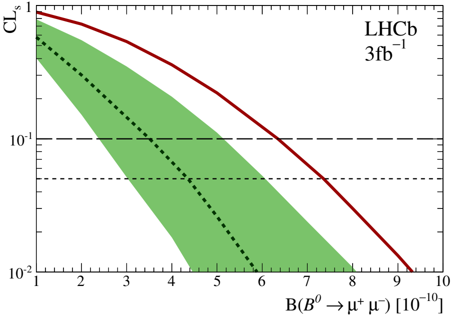
$B_s^0 \to \mu^+\mu^-$

LHCb results

arXiv:1307.5024, doi:10.1103/PhysRevLett.111.101805

- Results (high BDT bin)



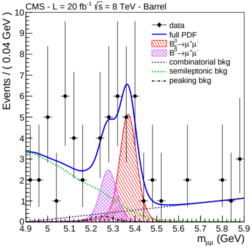


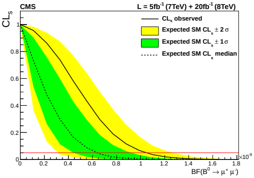
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.9^{+1.1}_{-1.0} \times 10^{-9}$
- $\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$
- Rarest *B* decay ever observed.

$B_s^0 \to \mu^+\mu^-$
CMS results

arXiv:1307.5025, doi:10.1103/PhysRevLett.111.101804

- Use $5\,\mathrm{fb}^{-1}$ at $7\,\mathrm{TeV}$ from 2011 and $20\,\mathrm{fb}^{-1}$ at $8\,\mathrm{TeV}$ from 2012.
- Normalise to $B^+ \to J/\psi\ K^+$, take f_s/f_d from LHCb.
- Use MVA discriminant based on information from track and muon chambers.
- Variables independent of pile-up (up to 30PVs!)
- Simultaneous fit to $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ in bins of MVA classifier.





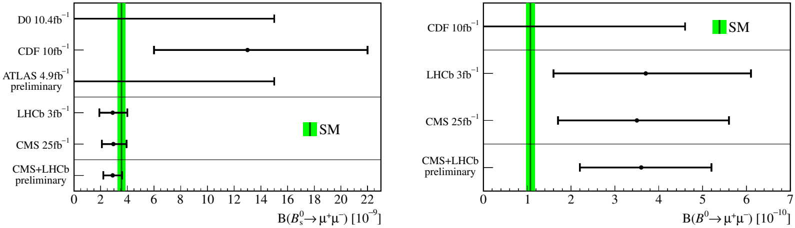
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$
- $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$

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

LHCb and CMS combination

CMS-PAS-BPH-13-007 ; LHCb-CONF-2013-012

- Combine both results from experiements.
- Shared normalisation and inputs.
- Account for known correlations, integrate of B_s^0 and B^0 time depedence.

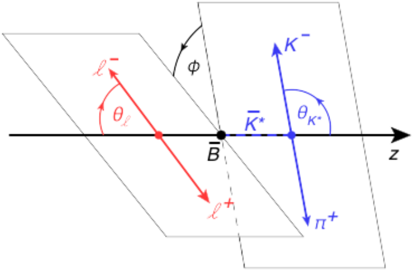


- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.6\pm^{+1.6}_{-1.4}) \times 10^{-10}$

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

Introduction

- $B^0 \to K^{*0}\mu^+\mu^-$ is a $b \to s\ell^+\ell^-$ transition
- Described by three angles ($\cos\theta_l$,$\cos\theta_K$,ϕ) and the di-muon invariant mass squared (q^2).



- There are contributions from the photon, vector and tensor operators and from their interference from the right-handed counterparts.

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

Angular analysis

- Analysis based on measurements of the angular distribution

$$\frac{d^4\Gamma}{dq^2\,d\cos\theta_K\,d\cos\theta_l\,d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$

$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$

$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$

$$+J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big], \qquad (1)$$

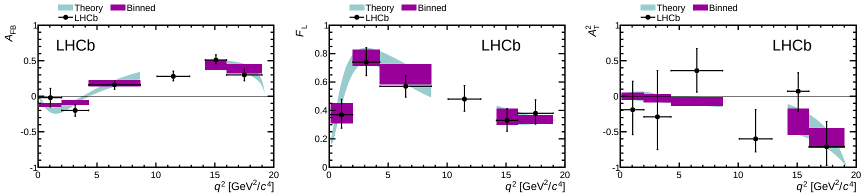
- Angular coefficients constructed from combinations of the K^{*0} transversity amplitudes.
- Amplitudes depend on the Wilson coefficients and $B^0 \to K^*$ form factors.
- Construct angular observables that maximise sensitivity to Wilson coefficients!
- Possible to make precise theoretical predictions for each of these observables (Altmannshofer [arXiv:0811.1214], Kruger [arXiv:0502060], Egede [arXiv:0807.2589], Bobeth [arXiv:1006.5013] for example).

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

Results from LHCb (1)

arXiv:1304.6325, doi:10.1007/JHEP08(2013)131

- Analysis based on 1.0 fb^{-1} of data collected in 2011.
- Event selection based on kinematic variables and topology of the decay.
- Events corrected for detector acceptance to restore ‘true’ angular distribution.
- Three observables: A_{FB}, F_{L} and A_{T}^2.



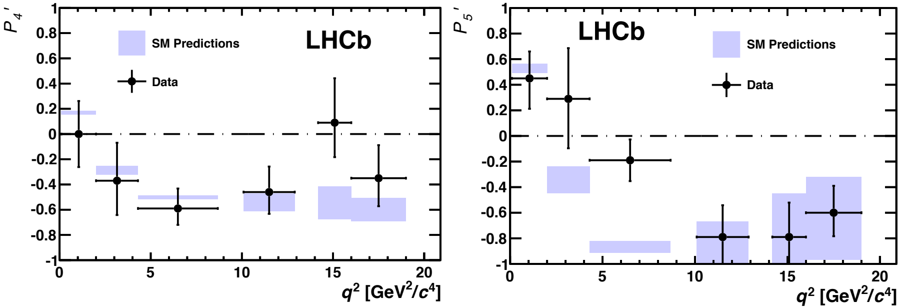
- World’s most precise measurements of these observables.
- First ever measurement of the zero-crossing point of A_{FB}, $q_0^2 = 4.0 \pm 0.9\,\mathrm{GeV}^2/c^4$.

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

Results from LHCb (2)

arXiv:1308.1707, doi: 10.1103/PhysRevLett.111.191801

- New basis of observables which are independant of $B \to K^{*0}$ form factor uncertainties to leading order (Matias [arXiv: 1202.4266]).



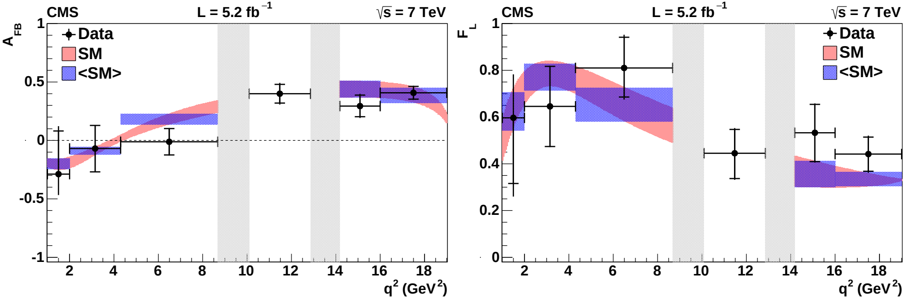
- 3.7σ tension in $P_5\ldots$!
- 0.5% probability to see a deviation assuming 24 independant measurements of $B^0 \to K^{*0}\mu^+\mu^-$.
- Currently there is no new physics explanation for this effect.

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

CMS analysis

arXiv:1308.3409, doi:10.1016/j.physletb.2013.10.017

- Analysis based on $5\,\text{fb}^{-1}$ of data collected in 2011.
- Measurements of A_{FB} and F_{L} and the differential branching fraction of $B^0 \to K^{*0}\mu^+\mu^-$.
- Trigger on high p_{T} muons.
- Select good quality muons and use kinematic and topological selection optimised for signal significance.
- Efficiency calculation based on simulation.

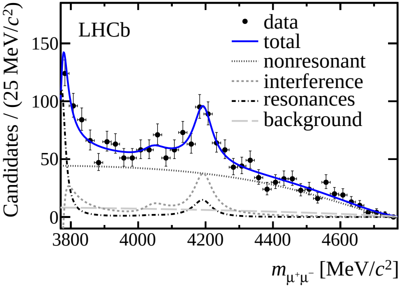


$B^+ \to K^+\mu^+\mu^-$

Low recoil, high q^2 region

arXiv:1307.7595, doi:10.1103/PhysRevLett.111.112003

- Observation of higher charmonium resonances in $B^+ \to K^+\mu^+\mu^-$ at high q^2.
- Measurement based on full 3.0 fb^{-1} dataset.



- Evidence of $B^+ \to$ ■(4160)K^+.
- $\mathcal{B}(B^+ \to$ ■(4160)$K^+) = 5^{1.3}_{1.2} \pm 3.0 \times 10^{-4}$
- No sign of the $B^+ \to$ ■(4040)K^+.
- Important to consider these contributions in measurements in the low recoil - high q^2 region.

Summary

- Rare decays of B^0 and B_s^0 mesons are powerful probes of new physics.
- LHCb, CMS and ATLAS have sufficient datasets to measure decays with $\mathcal{B} < 10^{-8}$!
- $B_s^0 \to \mu^+\mu^-$ has a clean signature and is sensitive to new scalars and pseudo-scalars.
- Evidence of $B_s^0 \to \mu^+\mu^-$ from LHCb and CMS and discovery of $B_s^0 \to \mu^+\mu^-$ with combined dataset from LHCb and CMS.
- Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ extends sensitivity into vectors and tensor contributions.
- Measurements from LHCb are most precise to date and show possible hints at deviations from the SM.
- However, observation of resonances in $B^+ \to K^+\mu^+\mu^-$ indicates opportunity to perform spectroscopy.
- LHCb plans to collect $10\,\text{fb}^{-1}$ of data after Run II of the LHC, giving us exciting times ahead!