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Rare Decays at LHCb

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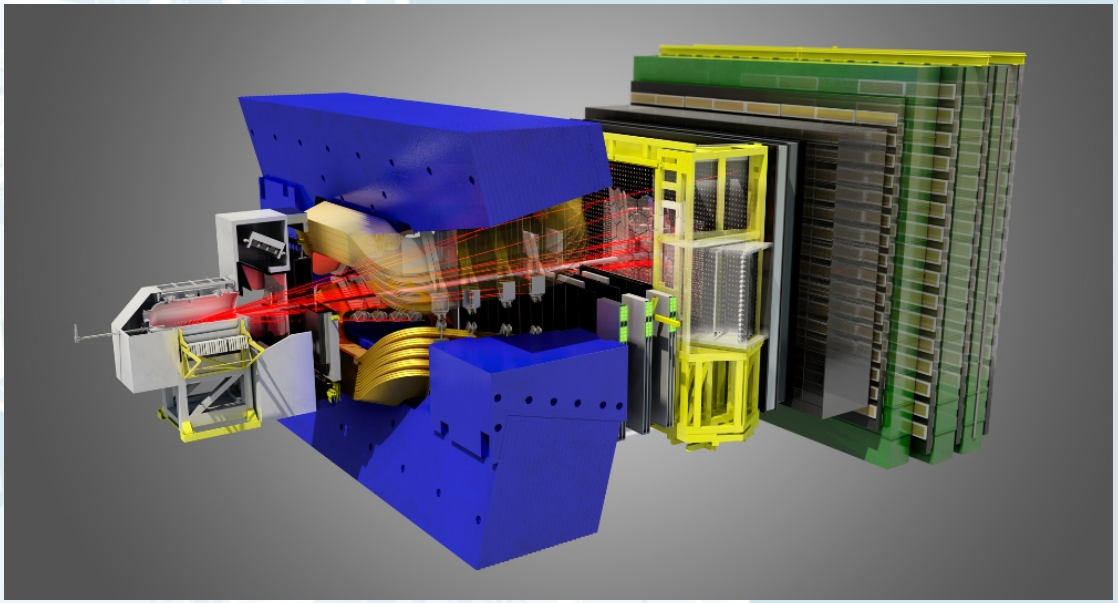
Introduction

LHCb is a forward-arm spectrometer full instrumented in the forward region ($2 < \eta < 5$) including:

- Excellent vertex resolution from a silicon strip detector surrounding the interaction point (VELO)
- Particle identification from two ring-imaging Cherenkov (RICH) detectors, calorimeter and muon system



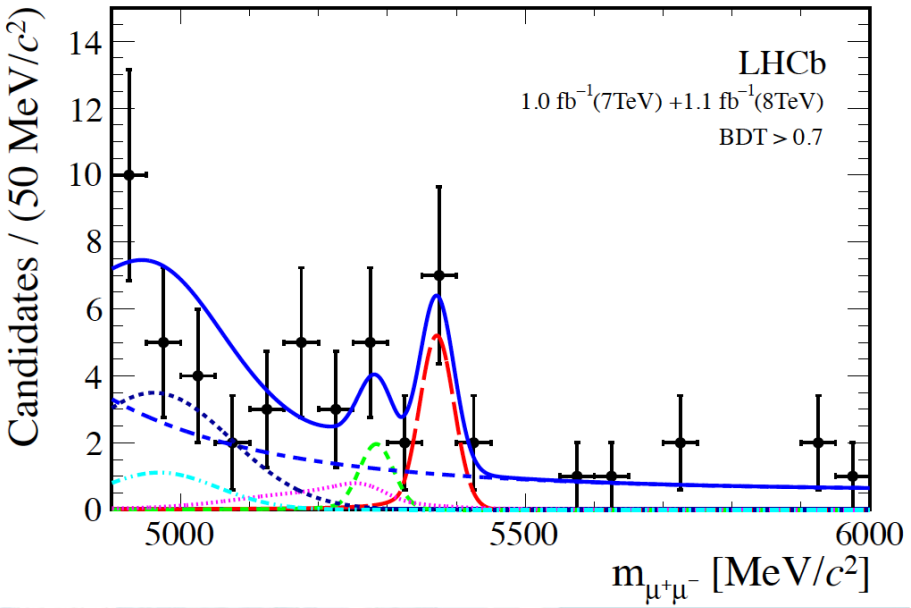
LHCb's core physics programme is to test the Standard Model at **high precision** and perform **indirect searches** for new physics in the decays of beauty and charm hadrons.

Rare b decays where $\Delta B = \Delta S = 1$ are flavour-changing neutral current (FCNC) processes, highly supressed in the SM, which provide an excellent opportunity to probe new physics.

In this talk...

A wide spectrum of rare decays are studied at LHCb. Highlights from this year include:

- First evidence of the $B_s^0 \to \mu^+\mu^-$ decay [Phys. Rev. Lett. 110, 021801 (2013), LHCb-PAPER-2012-043].
- Search for the $K_S^0 \to \mu^+\mu^-$ decay [JHEP 01 (2013) 090, LHCb-PAPER-2012-023].
- First limit on $B_{(s)}^0 \to \mu^+\mu^-\mu^+\mu^-$ decays [LHCb-PAPER-2012-049].



This talk focuses on the **most recent** measurements:

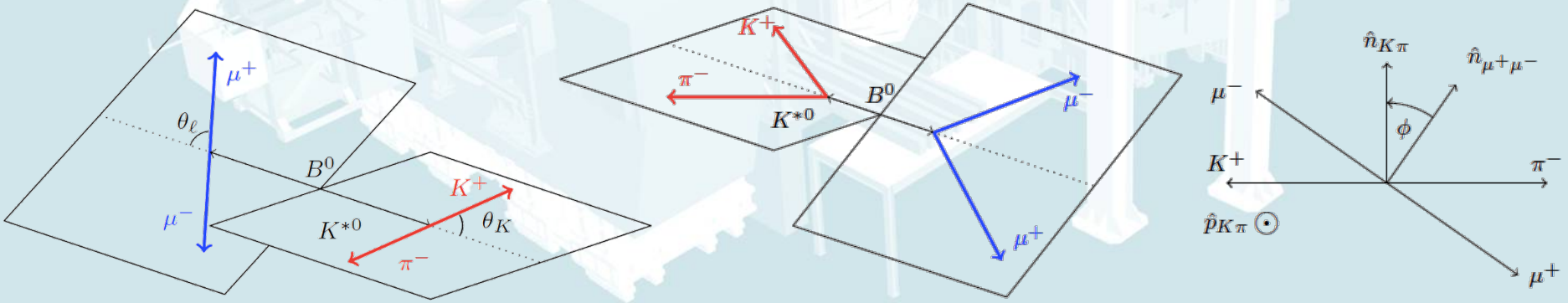
1. Branching fraction and angular analysis of $B_s^0 \to \phi^0\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$
2. Branching fraction of $B^0 \to K^{*0}e^+e^-$
3. Search for $D^0 \to \mu^+\mu^-$
4. Search for lepton flavour and baryon number violation

$b \to s$ FCNC Decays

$B_s^0 \to \phi^0 \mu^+ \mu^-$, $B^0 \to K^{*0} \mu^+ \mu^-$ and $B^0 \to K^{*0} e^+ e^-$ are all $b \to s$ FCNC transitions, forbidden at tree level in the SM which proceed via box and penguin diagrams. BSM particles can contribute in quantum loops.

The angular distributions provide excellent sensitivity to new particles. Branching fractions also probe NP but suffer from uncertainties in the hadronic form factors.

Decays characterised by three angles (θ_l, θ_k, ϕ) and the invariant mass of the two muons (q^2).



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

The differential branching fraction in each q^2 bin is measured using 1.0 fb^{-1} of $\sqrt{s}$ = 7 TeV 2011 data. $B_s^0 \to J/\psi\phi$ normalisation channel used according to

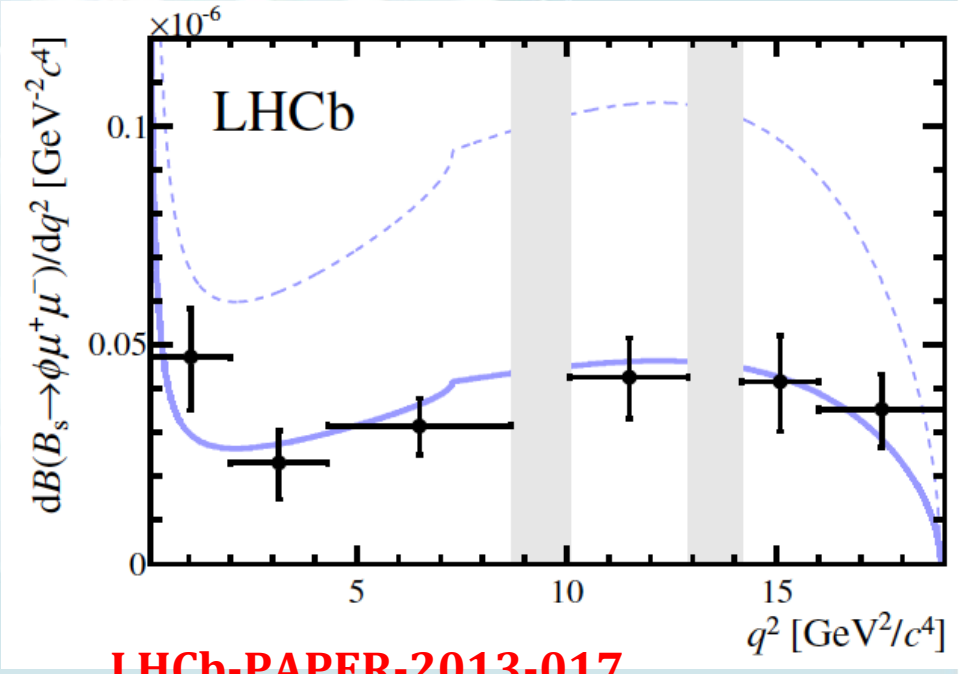
$$\frac{d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{dq^2} = \frac{1}{q^2_{max} - q^2_{min}} \frac{N_{sig}}{N_{J/\psi\phi}} \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\phi\mu^+\mu^-}} \mathcal{B}(B_s^0 \to J/\psi\phi)\mathcal{B}(J/\psi \to \mu^+\mu^-)$$

Total branching fraction measured as

[7.07 +0.64(stat) –0.59(stat) ± 0.17(syst) ± 0.71(input)] ×10^{-7}

using previous measurement of $B_s^0 \to J/\psi\phi$ [Phys. Rev. D87 (2013) 072004].

Compared to SM predictions in the range 14.5×10^{-7} and 19.2×10^{-7} which have uncertainties of the order 20-30%.



LHCb-PAPER-2013-017

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

Measurement of angular observables: F_L, S_3, A_6 and A_9 in six bins of q^2. T-odd asymmetry A_9 is particularly sensitive to large CP violating phases from BSM physics.

Integrating over two angles results in one expression for each decay angle:

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_K} = \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) + \frac{3}{2}F_\mathrm{L}\cos^2\theta_K,$$

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell} = \frac{3}{8}(1-F_\mathrm{L})(1+\cos^2\theta_\ell) + \frac{3}{4}F_\mathrm{L}(1-\cos^2\theta_\ell) + \frac{3}{4}A_6\cos\theta_\ell,$$

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\Phi} = \frac{1}{2\pi} + \frac{1}{2\pi}S_3\cos 2\Phi + \frac{1}{2\pi}A_9\sin 2\Phi,$$

F_L

A_6

S_3 and A_9

Candidates selected using multivariate boosted decision tree trained on $B_s^0 \to \phi\, J/\psi(\mu^+\mu^-)$ decays from data.

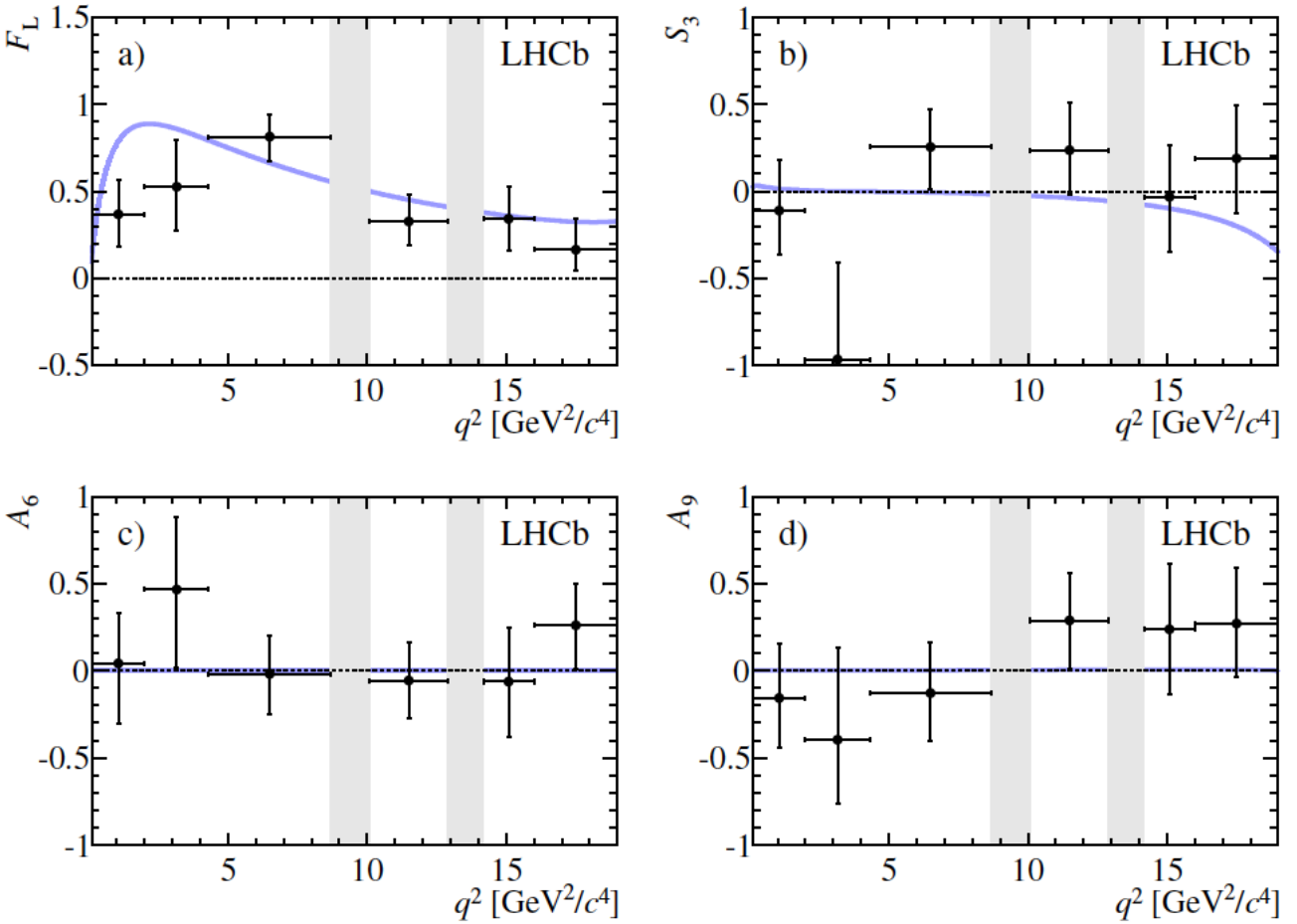
$B_s^0 \to \phi\mu^+\mu^-$ Angular Observables

Angular acceptance corrected using simulated events – dominant source of systematic uncertainty.

Three 2D maximum likelihood fits in each angle and the B_s mass are performed in each q^2 bin.

All angular observables in agreement with leading order Standard Model predictions.

LHCb-PAPER-2013-017



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

The differential branching fraction in each q^2 bin is calculated using 1.0 fb^{-1} of $\sqrt{s}$ = 7 TeV 2011 data. $B_s^0 \to \phi\, J/\psi$ used as a control channel according to

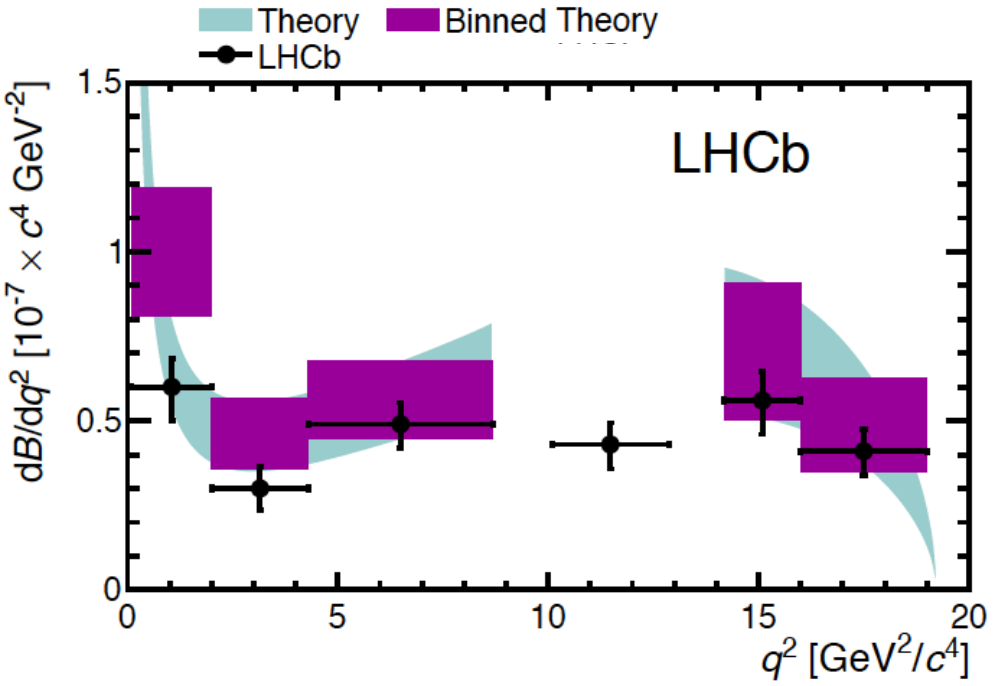
$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2} = \frac{1}{q^2_{\mathrm{max}} - q^2_{\mathrm{min}}} \frac{N_{\mathrm{sig}}}{N_{K^{*0}J/\psi}} \frac{\varepsilon_{K^{*0}J/\psi}}{\varepsilon_{K^{*0}\mu^+\mu^-}} \times \mathcal{B}(B^0 \to K^{*0} J/\psi) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

Ratio of efficiencies determined from event weights obtained from simulation.

Most precise determination of the differential branching fraction to date.

Results are in agreement with the Standard Model.

LHCb-Paper-2013-019



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

Measurement of **differential branching fraction** and angular observables: F_L, $S_3(A_T^2)$, $A_{FB}(A_T^{Re})$, A_9 in six bins of q^2.

Requring that $q^2 >> 4m_\mu^2$ and folding the angle ϕ the angular distribution reduces to

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}} = \frac{9}{16\pi}\Big[F_\mathrm{L}\cos^2\theta_K + \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) - F_\mathrm{L}\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_\mathrm{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\Big]$$

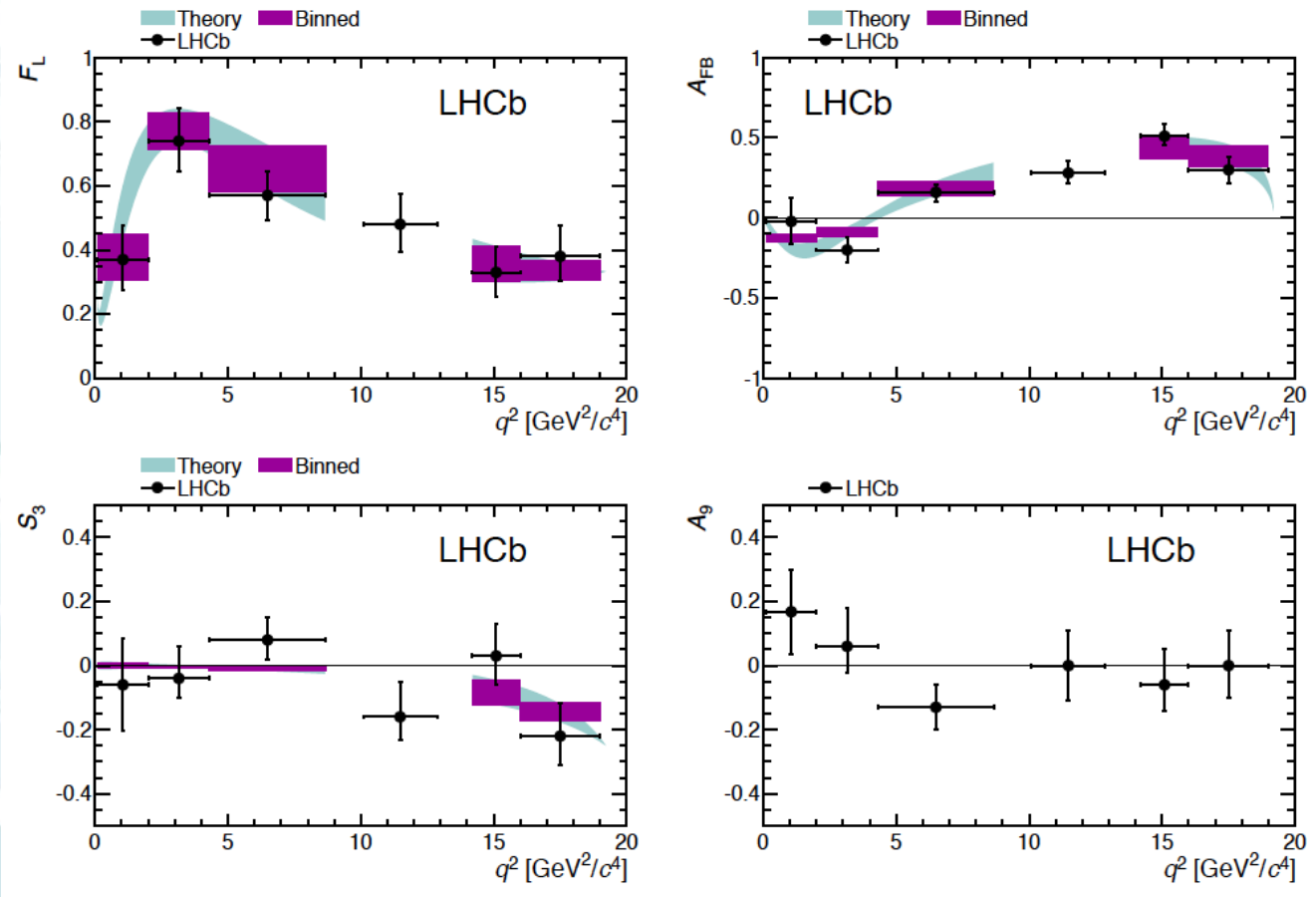
Candidates selected using multivariate boosted decision tree trained on $B_s^0 \to K^{*0}\,J/\psi(\mu^+\mu^-)$ decays from data.

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

As before, angular acceptance corrected using event weights calculated using simulated events – dominant source of systematic uncertainty.

4D fits to three angles and mass performed in each q^2 bin to simultaneously determine F_L, S_3, A_{FB}, A_9.

The zero-crossing point in A_{FB} is also determined as $q_0^2 = 4.9 \pm 0.9$ GeV$^2/c^4$



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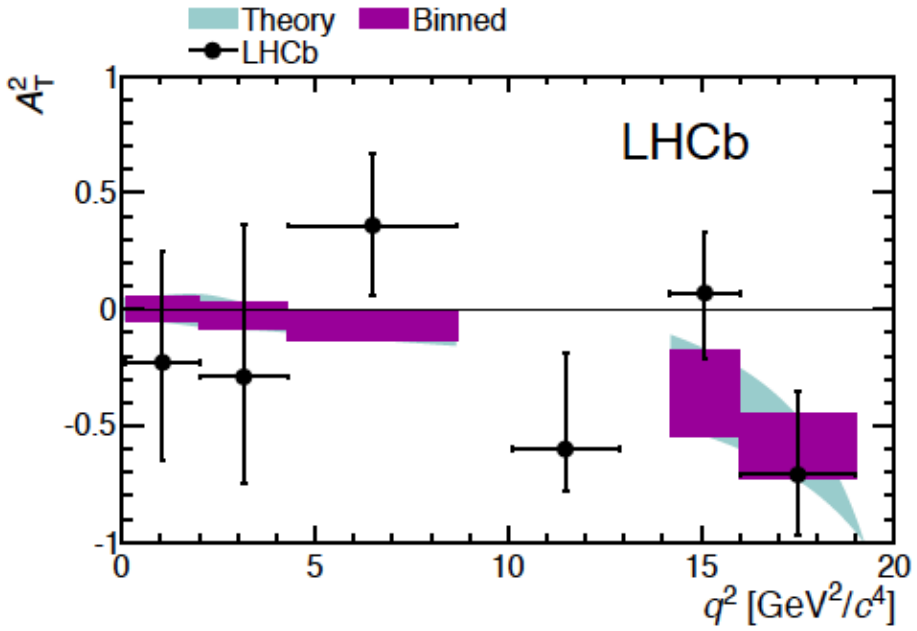
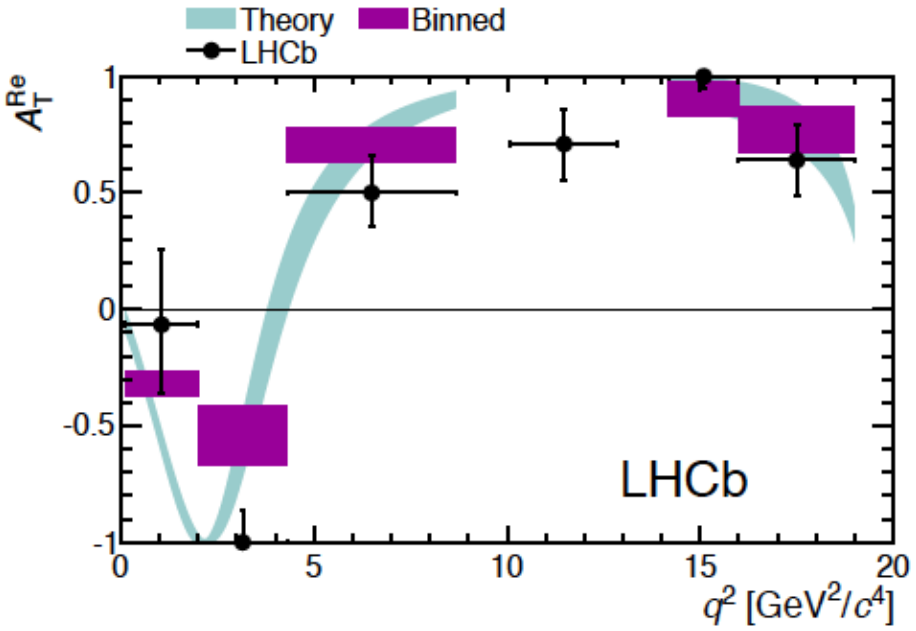
$B^0 \to K^{*0}\mu^+\mu^-$ Angular Observables

A second set of fits are performed to determine transverse amplitudes $\mathbf{A_T^2}$ and $\mathbf{A_T^{Re}}$ – theoretically cleaner.





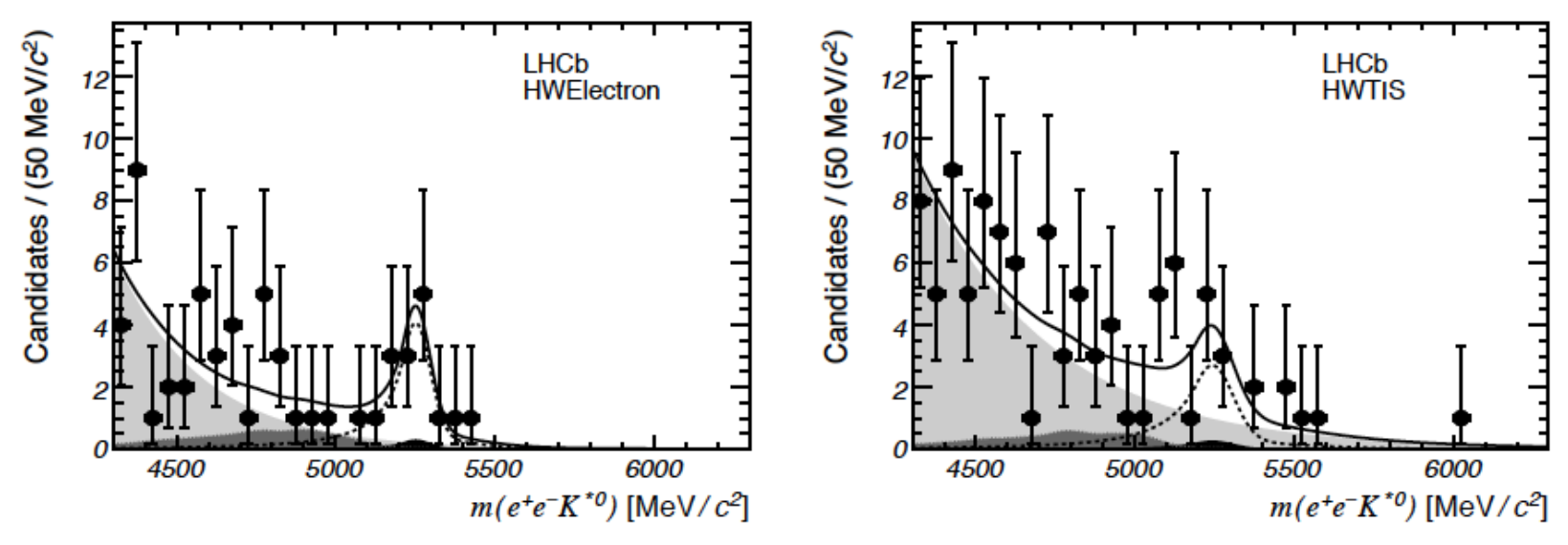
All results are in agreement with the Standard Model.

LHCb-Paper-2013-019

$B^0 \to K^{*0} e^+ e^-$ Branching Fraction

Branching fraction measurement is the first step towards a full angular analysis.

The differential branching fraction is measured in the low di-lepton mass region 30 – 1000 MeV/c^2.



$$\mathcal{B}(B^0 \to K^{*0} e^+ e^-)^{30-1000\,\mathrm{MeV}/c^2} = (3.1\,^{+0.9}_{-0.8}\,^{+0.2}_{-0.3} \pm 0.2) \times 10^{-7}$$

In agreement with SM predictions

LHCb-Paper-2013-005

Search for $D^0 \to \mu^+\mu^-$

In the SM FCNC processes in the D sector are highly supressed by the GIM mechanism due to the absence of a heavy down type quark.

Branching fraction predicted to be $O(10^{-11})$ in the SM but can be enhanced by BSM physics such as R-parity violating models and models with Randall-Sundrum warped extra dimensions.

In this measurement decays are reconstructed as $D^{*+} \to D^0(\mu^+\mu^-)\pi^+$

Dominant backgrounds are:

- Peaking background from 2-3 body D decays where hadrons are misidentified as muons
- Combinatorial background from semilelptonic b and c hadron decays

BDT trained on simulated events and $D^0 \to \mu^+\mu^-$ sidebands from data.

Search for $D^0 \to \mu^+\mu^-$

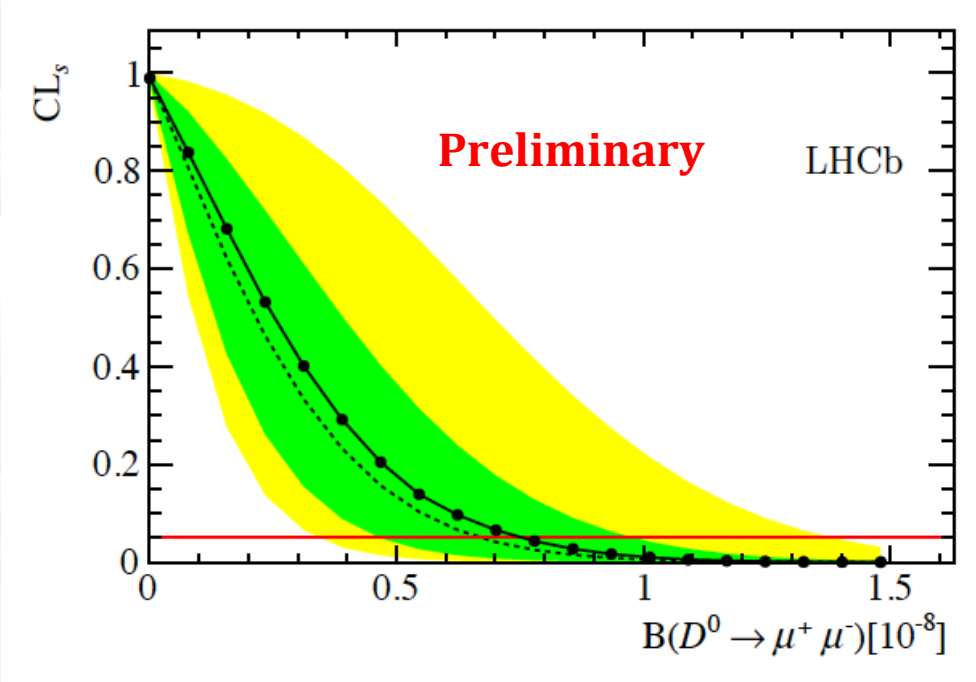
Branching fraction calculated as:

$$\frac{N_{D^{*+}\to D^0(\mu^+\mu^-)\pi^+}}{N_{\pi^+\pi^-}} \times \frac{\varepsilon_{\pi\pi}}{\varepsilon_{\mu\mu}} \times \mathcal{B}(D^0 \to \pi^+\pi^-)$$

using $D^{*+} \to D^0(\pi^+\pi^-)\pi^+$ as a normalisation channel.

Efficiencies are calculated from simulated events.

Yields extracted using 2D unbinned maximum likelihood fits to $\Delta m_{\mu\mu}$ and $m_{\mu\mu}$.



Analysis presented uses 0.9 fb^{-1} of $\sqrt{s}$ = 7 TeV 2011 data. No evidence for $D^0 \to \mu^+\mu^-$ decays and a limit is set of

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 7.6 \times 10^{-9} \text{ at } 95\% \text{ CL}$$

a factor of twenty improvement on previous measurements.

Paper in preparation.

Lepton flavour and baryon number violation

Charged lepton flavour violation and baryon number violation would be clear signals of BSM physics. LFV and BNV are searched for in the decays:

- $\tau^- \to \mu^- \mu^- \mu^+$
- $\tau^- \to p^- \mu^+ \mu^+$
- $\tau^- \to p^+ \mu^- \mu^-$

using 1.0 fb^{-1} of $\sqrt{s}$ = 7 TeV 2011 data.

Current best measurement from Belle

$$\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-) < 2.1 \times 10^{-8}$$

Phys. Lett. B687 (2010) 139

No signals are observed and limits of

$$\begin{aligned} \mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-) &< 8.0\ (9.8) \times 10^{-8}, \\ \mathcal{B}(\tau^- \to \bar{p} \mu^+ \mu^-) &< 3.3\ (4.3) \times 10^{-7}, \\ \mathcal{B}(\tau^- \to p \mu^- \mu^-) &< 4.4\ (5.7) \times 10^{-7}. \end{aligned}$$

at 90% CL are set.

LHCb-Paper-2013-014

Conclusions

Several world's best measurements have been presented.

All results are consistent with SM expectations.

More results are in the pipeline including:

- Search for $B \to e\mu$
- CP asymmetry in $B^+ \to K^+\mu^+\mu^-$
- $\Lambda_b \to \Lambda\mu^+\mu$ branching fraction

and improvements to existing measurements and addition of 2012 data.