LHCb results on rare $B$ decays

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Review of recent LHCb results on rare $b$-hadron decays from Run I of the LHC.

1. Observation of $B_s^0 \rightarrow \mu^+ \mu^-$.  
2. Up-down asymmetry and $b \rightarrow s\gamma$ photon polarisation.  
3. $B \rightarrow K^{(*)}\mu^+ \mu^-$ branching fractions and angular distribution.  
4. Tests of MFV in $b \rightarrow \ell^+ \ell^-$ decays.

Most results are now based on the full dataset of 3 fb$^{-1}$ of integrated luminosity collected in 2011 (1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV) and 2012 (2 fb$^{-1}$ at $\sqrt{s} = 8$ TeV).
$B^0_{(s,d)} \rightarrow \mu^+ \mu^-$
$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

- $B^0$ and $B_s^0 \to \mu^+\mu^-$ are loop, CKM and helicity suppressed in the SM.
- Sensitive probe of models with reduced helicity suppression
e.g. models with extended Higgs sectors(e.g. MSSM, 2HDM, ...)
- Predicted precisely in the SM:

$$B(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

[Bobeth et al. PRL 112 101801 (2014)]

- $B^0 \to \mu^+\mu^-$ decay suppressed by further factor of $|V_{td}/V_{ts}|^2$. An important test of the MFV hypothesis.
Background rejection key for rare decay searches → use multivariate classifiers (BDTs) and tight particle identification requirements.

Calibrate the BDT response on MC or data ($B \rightarrow h^+ h^-$).

Normalise branching fraction w.r.t. a control mode (e.g. $B^+ \rightarrow J/\psi K^+$)

Correct for $B_s^0/B^0$ production using $f_s/f_d$. 
In 3 fb$^{-1}$ LHCb sees evidence for $B^0_s \rightarrow \mu^+ \mu^-$ at 4.0$\sigma$
with $\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (2.9^{+1.1}_{-1.0} +0.3) \times 10^{-9}$. [PRL 111 (2013) 101805]

In 20 fb$^{-1}$ CMS sees evidence for $B^0_s \rightarrow \mu^+ \mu^-$ at 4.3$\sigma$
with $\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$. [PRL 111 (2013) 101804]
Simultaneous analysis of the LHCb and CMS datasets, with shared signal parameters and nuisance parameters (where appropriate).

Data binned in BDT response for both experiments and by barrel and endcap regions for CMS.
CMS & LHCb $B_{(s,d)}^0 \rightarrow \mu^+ \mu^-$ combination

- Observe $B_s^0 \rightarrow \mu^+ \mu^-$ & see first evidence for $B^0 \rightarrow \mu^+ \mu^-$ ($3\sigma$), with
  
  $$ B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} $$
  $$ B(B^0 \rightarrow \mu^+ \mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10} $$

- Small correlation between $B^0$ and $B_s^0$ due to mass resolution.

  $\rightarrow$ Compatible with SM at $1.2\sigma$ ($B_s^0$) and $2.2\sigma$ ($B^0$)
Photon polarisation in $b \rightarrow s \gamma$
Photon polarisation in $b \rightarrow s \gamma$ decays

- $B^0 \rightarrow K^{*0} \gamma$ was the first penguin decay ever observed, by CLEO in 1992.\cite{PRL 71 (1993) 674}
- We know from the B-factories that $\mathcal{B}(b \rightarrow s \gamma)$ is compatible with SM expectation. What else do we know?

\[ b_{R(L)} \rightarrow W^- \rightarrow s_{L(R)} \gamma \]

\[ t \rightarrow \gamma_{L(R)} \]

In the SM, photons from $b \rightarrow s \gamma$ decays are predominantly left-handed ($C_7/C_7' \sim m_b/m_s$) due to the charged-current interaction.

Can test $C_7/C_7'$ using:

- Mixing-induced CP violation \cite{Atwood et al PRL 79 (1997) 185-188},
- $\Lambda^0_b$ baryons \cite{Hiller & Kagan PRD 65 (2002) 074038},
- $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ at large recoil.
Photon polarisation from \( B^+ \rightarrow K^+ \pi^- \pi^+ \gamma \)

or \( B \rightarrow K^{**} \gamma \) decays such as \( B^+ \rightarrow K_1(1270) \gamma \).


- Can infer the photon polarisation from the up-down asymmetry of the photon direction in the \( K^+ \pi^- \pi^+ \) rest-frame. Unpolarised photons would have no asymmetry.
- This is conceptionally similar to the Wu experiment, which first observed parity violation.
At LHCb we reconstruct \( B^+ \to K^+ \pi^- \pi^+ \gamma \) decays using unconverted photons.

Observe \( \sim 13,000 \) signal candidates in \( 3 \text{ fb}^{-1} \).

There are a large number of overlapping resonances in the \( M(K^+ \pi^- \pi^+) \) mass spectra. No attempt is made to separate these in the analysis, we simply bin in 4 bins of \( M(K^+ \pi^- \pi^+) \).
Best fit, Unpolarised ($C_7 = C'_7$)

![Graphs showing $1/N \times dN/d\cos\theta$ for different mass intervals.]

- [1.1,1.3] GeV/$c^2$
- [1.4,1.6] GeV/$c^2$
- [1.6,1.9] GeV/$c^2$
Combining the 4 bins, observe non-zero photon polarisation at 5.2\(\sigma\).

Unfortunately you need to understand the hadronic system to know if the polarisation is predominantly left-handed, as expected in the SM.

→ First observation of photon polarisation in \(b \rightarrow s\gamma\) decays
\[ b \rightarrow s \ell^+ \ell^- \]

branching fractions and asymmetries
Branching fraction of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- At the LHC we are able to profit from the large $\sigma_{b\bar{b}}$ to reconstruct large samples of exclusive $b \rightarrow s \ell^+ \ell^-$ decays.
- Large increase in yields over B-factories for $\ell^\pm = \mu^\pm$.

Data set is split into bins of $q^2 = m(\mu^+ \mu^-)^2$ to measure $dB/dq^2$.

Normalise signal w.r.t. known $B \rightarrow J/\psi K^{(*)}$ branching fraction (largest source of systematic uncertainty).

Theory prediction from C. Bobeth et al. [JHEP 07 (2011) 067] (and references therein)
SM predictions based on

[JHEP 07 (2011) 067], [JHEP 01 (2012) 107]
Comment on branching fraction measurements

- There is a general tendency for the measured branching fractions to be smaller than the corresponding SM expectation. This trend is seen at both low and high $q^2$.
- Behaviour also seen in $B_s^0 \rightarrow \phi \mu^+ \mu^-$ decays. [JHEP 07 (2013) 084]

\[ C_9 = -1.0, \quad C'_{9'} = 1.2 \]
In the SM expect the partial widths of rare $B^+$ and $B^0$ decays to be almost identical

$$A_I = \frac{\Gamma[B^+ \to K^*(+) \mu^+ \mu^-] - \Gamma[B^0 \to K^{(*)0} \mu^+ \mu^-]}{\Gamma[B^+ \to K^*(+) \mu^+ \mu^-] + \Gamma[B^0 \to K^{(*)0} \mu^+ \mu^-]}$$

$A_I$ is of $O(1\%)$

Sensitive to spectator quark differences in the form-factors (exchange and annihilation processes).

Updated measurements are consistent with zero isospin asymmetry.
Direct $CP$ asymmetries

$$A_{CP} = \frac{\Gamma[\bar{B} \to \bar{K}(*)\mu^+\mu^-] - \Gamma[B \to K(*)\mu^+\mu^-]}{\Gamma[\bar{B} \to \bar{K}(*)\mu^+\mu^-] + \Gamma[B \to K(*)\mu^+\mu^-]}$$

expected to be tiny in SM, due to small size of $|V_{ub} V_{us}^*|$.  

Correct the observed asymmetry $A_{RAW}$ for production ($A_P$) and detection ($A_D$) asymmetries using $B \to K(*)J/\psi$.

$$A_{CP}(B \to K(*)\mu^+\mu^-) = A_{RAW} - A_D - \kappa A_P \approx A_{RAW} - A_{RAW}^{K(*)J/\psi}$$

Kinematic differences between $B \to K(*)J/\psi$ and $B \to K(*)\mu^+\mu^-$ accounted for by re-weighting.

Additional cancellation of left-right detector asymmetries by averaging data taken with $+ve$ and $-ve$ magnet polarities.
Direct $CP$ asymmetries

\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \]

\[ B^+ \rightarrow K^+ \mu^+ \mu^- \]

- Results are consistent with $A_{CP} = 0$, i.e. consistent with SM expectation.
Anatomy of the $B^0 \to K^{*0} \mu^+ \mu^-$ decay

No photon ($C_7$) enhancement of $B \to K \mu^+ \mu^-$ decays at low $q^2$. 

$\frac{d\Gamma}{dq^2}$

$C_7^{(i)} C_9^{(i)}$ interference

$C_9^{(i)}$ and $C_{10}^{(i)}$

Long distance contributions from $c\bar{c}$ above open charm threshold

$4[m(\mu)]^2$

$q^2$
Broad $c\bar{c}$ contributions at high $q^2$

- $B^+ \to K^+ \mu^+ \mu^-$ data shows clear resonant structure.
- First observation of $B^+ \to \psi(4160)K^+$ and $\psi(4160) \to \mu^+ \mu^-$. 
  [PRL 111 (2013) 112003]

- Beylich, Buchalla & Feldman Theory calculations take $c\bar{c}$ contributions into account (through an OPE) but not their resonant structure. 
  [EPJC 71 (2011) 1635]
\[ b \rightarrow s \ell^+ \ell^- \]

angular distributions
Single angle ($\theta_l$) and two parameters describe the decay

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta_l} = \frac{3}{4} (1 - F_H)(1 - \cos^2 \theta_l) + \frac{1}{2} F_H + A_{FB} \cos \theta_l$$

$F_H$ corresponds to the fractional contribution of (pseudo)scalar and tensor operators to $\Gamma$.

Angular distribution is only +ve for $A_{FB} \leq F_H/2$ and $F_H \geq 0$.

In SM expect of $A_{FB} \approx 0$ and $F_H \approx 0$. 

**Figure (a)** $1 < q^2 < 6 \text{ GeV}^2/c^4$

**Figure (b)** $15 < q^2 < 22 \text{ GeV}^2/c^4$
\( B^+ \rightarrow K^+ \mu^+ \mu^- \) angular distribution

- Perform two-dimensional likelihood fit to \( M(K^+ \mu^+ \mu^-) \) and \( \cos \theta_\mu \)

\[
\begin{array}{c}
\text{(a) } 1.1 < q^2 < 6.0 \text{ GeV}^2/c^4 \quad \text{LHCb} \\
\text{(b) } 15.0 < q^2 < 22.0 \text{ GeV}^2/c^4 \quad \text{LHCb}
\end{array}
\]

- to determine \( A_{FB} \) and \( F_H \) in bins of \( q^2 \)

\[
\begin{array}{c}
A_{FB} \\
F_H
\end{array}
\]

Results are consistent with SM expectations.

T. Blake | Rare B decays
Angular distribution of the $B^0 \to K^{*0} \mu^+ \mu^-$ decay is sensitive to the virtual photon polarisation and new left- and right-handed (axial)vector currents.

Decay described by three angles ($\theta_\ell, \theta_K, \phi$) and the dimuon invariant mass squared, $q^2$.

Build CP averaged observables, $S_i = (J_i + \bar{J}_i)/(\Gamma + \bar{\Gamma})$, or CP asymmetries.
Angular distribution depends on 11 angular terms:

\[
d[\Gamma[B^0 \to K^{*0} \mu^+ \mu^-]] = \frac{9}{32\pi} \left[ J_1^s \sin^2 \theta_K + J_1^c \cos^2 \theta_K + J_2^s \sin^2 \theta_K \cos 2\theta_\ell + J_2^c \cos^2 \theta_K \cos 2\theta_\ell + J_3^s \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + J_6^s \sin^2 \theta_K \cos \theta_\ell + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + J_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]

where the $J_i$'s are bilinear combinations of seven decay amplitudes $A_{L,R}^L$, $A_{L,R}^R$, $A_0^{L,R}$ & $A_t$ ($L/R$ for the chirality of the $\mu^+ \mu^-$ system).

- Large number of terms simplified by angular folding, e.g. $\phi \to \phi + \pi$ if $\phi < 0$ to cancel terms in $\cos \phi$ and $\sin \phi$, or integration.
\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \text{ angular distribution} \]

- Angular distribution depends on 11 angular terms:

\[
\frac{d^4\Gamma[B^0 \rightarrow K^{*0} \mu^+ \mu^-]}{d \cos \theta_{\ell} d \cos \theta_K d\phi d q^2} = \frac{9}{32\pi} \left[ J_1^s \sin^2 \theta_K + J_1^c \cos^2 \theta_K + J_2^s \sin^2 \theta_K \cos 2\theta_\ell + J_2^c \cos^2 \theta_K \cos 2\theta_\ell + J_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + J_6 \sin^2 \theta_K \cos \theta_\ell + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + J_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]

where the \( J_i \)'s are bilinear combinations of seven decay amplitudes \( A^{L,R}_||, A^{L,R}_\perp, A^{L,R}_0 \) & \( A_t \) (\( L/R \) for the chirality of the \( \mu^+ \mu^- \) system).

- Large number of terms simplified by angular folding, e.g. \( \phi \rightarrow \phi + \pi \) if \( \phi < 0 \) to cancel terms in \( \cos \phi \) and \( \sin \phi \), or integration.
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ observables

ATLAS (prelim.) [ATLAS-CONF-2013-038], CMS 5.2 fb$^{-1}$ [PLB 727 (2013) 77], LHCb 1 fb$^{-1}$ [JHEP 08 (2013) 131]

Theory prediction from Bobeth et al. [JHEP 07 (2011) 067] and references therein.
$P'_5$ anomaly

- Can also apply different angular foldings to access other terms.

SM predictions from [Decotes-Genon et al. JHEP 05 (2013) 137]

- Focus on observables where leading form-factor uncertainties cancel, e.g. $P'_{4,5} = S_{4,5}/\sqrt{F_L(1 - F_L)}$.
- In 1 fb$^{-1}$, LHCb observes a local discrepancy of 3.7$\sigma$ in $P'_5$ (probability that at least one bin varies by this much is 0.5%).
Lepton Universality
Lepton universality?

- Dominant SM processes couple with equal strength to leptons:

\[ R_K[1, 6] = \frac{\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{\Gamma[B^+ \to K^+ e^+ e^-]} = 1 \pm O(10^{-3}) . \]

- Small differences from unity come from Higgs penguin contributions & phasespace.

Conceptually simple, but experimentally challenging (due to bremsstrahlung emission from the \( e^\pm \)).
$R_K$ experimental status

- Take double ratio with $B^+ \rightarrow J/\psi K^+$ decays to cancel possible systematic biases from electron/muon reconstruction.
- Correct for migration of events in and out of $1 < q^2 < 6 \text{ GeV}^2/c^4$ using MC and $J/\psi$ line-shape in data.
- Have also checked that $R_K$ at $q^2 = m^2_{J/\psi}$ is consistent with unity within uncertainties.

In 3 fb$^{-1}$ LHCb determines

$$R_K = 0.745^{+0.090}_{-0.074}\text{(stat)}^{+0.036}_{-0.036}\text{(syst)}$$

which is consistent with SM expectation at $2.6\sigma$. 

$b \rightarrow d \ell^+ \ell^-$
Observation of $B^+ \rightarrow \pi^+ \mu^+ \mu^-$

- In SM, rate of $b \rightarrow d$ process is suppressed by $|V_{td}/V_{ts}|^2$ with respect to $b \rightarrow s$.

- Using 1 fb$^{-1}$ of integrated luminosity we observed the decay $B^+ \rightarrow \pi^+ \mu^+ \mu^-$.

- Key challenge is controlling combinatorial background and background from $B^+ \rightarrow K^+ \mu^+ \mu^-$ where the $K^\pm$ is incorrectly identified as a $\pi^\pm$.

- Measured branching fraction

$$\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) = (2.3 \pm 0.6 \pm 0.1) \times 10^{-8}$$

is consistent with the SM expectation.
In 3 fb$^{-1}$, observe $B_s^0$ signal and see evidence for $B^0$ (at 4.8σ), with

$$\mathcal{B}(B^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) = (8.6 \pm 1.5 \text{ (stat)} \pm 0.7 \text{ (syst)} \pm 0.7 \text{ (norm)}) \times 10^{-8}$$

$$\mathcal{B}(B_s^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) = (2.11 \pm 0.51 \text{ (stat)} \pm 0.15 \text{ (syst)} \pm 0.16 \text{ (norm)}) \times 10^{-8}$$

in $0.5 < m(\pi^+\pi^-) < 1.3 \text{ GeV}/c^2$. 

New result [arXiv:1412.6433]
\( \pi^+ \pi^- \) system consistent with \( \rho(770) \) and \( f_0(980) \) for the \( B^0 \) and \( B_s^0 \), respectively.

- We are starting to build up the necessary ingredients to perform global analyses of \( b \to d \) processes.
Large $b$ and $c$ and $t$ production cross section makes the LHC an excellent flavour factory.

Are we starting to see some tension with the SM in $b \to s \ell^+ \ell^-$ decays?

Many analyses are still to be updated with the full Run I dataset. Many new results to come for the winter conferences.
Fin
Angular observables $J_i(q^2)$ for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

\[
J_1^s = \frac{(2 + \beta_\mu^2)}{4} \left[ |A_L|^2 + |A_R|^2 + (L \rightarrow R) \right] + \frac{4m_\mu^2}{q^2} \Re (A_L A_R^* + A_L^* A_R^*)
\]

\[
J_1^c = |A_L|^2 + |A_R|^2 + \frac{4m_\mu^2}{q^2} \left[ |A_t|^2 + 2 \Re (A_L^0 A_R^0) \right]
\]

\[
J_2^s = \frac{\beta_\mu^2}{4} \left\{ |A_L|^2 + |A_R|^2 + (L \rightarrow R) \right\}
\]

\[
J_2^c = -\beta_\mu^2 \left\{ |A_R|^2 + (L \rightarrow R) \right\}
\]

\[
J_3 = \frac{\beta_\mu^2}{2} \left\{ |A_L|^2 - |A_R|^2 + (L \rightarrow R) \right\}
\]

\[
J_4 = \frac{\beta_\mu^2}{\sqrt{2}} \left\{ \Re (A_L^0 A_R^*) + (L \rightarrow R) \right\}
\]

\[
J_5 = \sqrt{2} \beta_\mu \left\{ \Re (A_L^0 A_L^*) - (L \rightarrow R) \right\}
\]

\[
J_6 = 2 \beta_\mu \left\{ \Re (A_R^0 A_L^*) - (L \rightarrow R) \right\}
\]

\[
J_7 = \sqrt{2} \beta_\mu \left\{ \Im (A_L^0 A_L^*) - (L \rightarrow R) \right\}
\]

\[
J_8 = \frac{\beta_\mu^2}{\sqrt{2}} \left\{ \Im (A_L^0 A_R^*) + (L \rightarrow R) \right\}
\]

\[
J_9 = \beta_\mu^2 \left\{ \Im (A_R^0 A_L^*) + (L \rightarrow R) \right\}
\]

\[ B^0 \to K^{*0} \mu^+ \mu^- \text{ decay amplitudes} \]

At “leading order”

\[
A_{\perp}^{L(R)} = N\sqrt{2} \lambda \left\{ \left[ (C^{\text{eff}}_{9} + C^{\prime\text{eff}}_{9}) \mp (C^{\text{eff}}_{10} + C^{\prime\text{eff}}_{10}) \right] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} (C^{\text{eff}}_{7} + C^{\prime\text{eff}}_{7}) T_1(q^2) \right\}
\]

\[
A_{\parallel}^{L(R)} = -N\sqrt{2} (m_B^2 - m_{K^*}^2) \left\{ \left[ (C^{\text{eff}}_{9} - C^{\prime\text{eff}}_{9}) \mp (C^{\text{eff}}_{10} - C^{\prime\text{eff}}_{10}) \right] \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} (C^{\text{eff}}_{7} - C^{\prime\text{eff}}_{7}) T_2(q^2) \right\}
\]

\[
A_0^{L(R)} = -\frac{N}{2m_{K^*} \sqrt{q^2}} \left\{ \left[ (C^{\text{eff}}_{9} - C^{\prime\text{eff}}_{9}) \mp (C^{\text{eff}}_{10} - C^{\prime\text{eff}}_{10}) \right] [(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*}) A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}}]
+ 2m_b (C^{\text{eff}}_{7} - C^{\prime\text{eff}}_{7}) [(m_B^2 + 3m_{K^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2} T_3(q^2)] \right\}
\]

\[
A_t = \frac{N}{\sqrt{q^2}} \sqrt{\lambda} \left\{ 2(C^{\text{eff}}_{10} - C^{\prime\text{eff}}_{10}) + \frac{q^2}{m_{\mu}} (C^{\text{eff}}_{p} - C^{\prime\text{eff}}_{p}) \right\} A_0(q^2)
\]

\[
A_S = -2N\sqrt{\lambda} (C_{S} - C_{S}) A_0(q^2)
\]

- \( C_i \) are Wilson coefficients that we want to measure (they depend on the heavy degrees of freedom).
- \( A_0, A_1, A_2, T_1, T_2 \) and \( V \) are form-factors (these are effectively nuisance parameters).
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ at LHCb

Using 1 fb$^{-1}$ of integrated luminosity
Comments on angular distribution

- The L & R indices refer to the chirality of the leptonic system.
  - Different due to the axial vector contribution to the amplitudes.
- If $C_{10} = 0$, $A_{0,\|,\perp}^L = A_{0,\|,\perp}^R$ and the angular distribution reduces to the one for $B^0 \to K^{*0} J/\psi$.
- Zero-crossing point of $A_{FB}$ comes from interplay between the different vector-like contributions.
- In the SM there are 7 different amplitudes that contribute, corresponding to different polarisations states:
  - $K^*$ on-shell $\to$ 3 polarisation states $\epsilon_{K^*}(m = +, -, 0)$
  - $V^*$ off-shell $\to$ 4 polarisation states $\epsilon_{K^*}(m = +, -, 0, t)$
- $A_t$ corresponds to a longitudinally polarised $K^*$ and time-like $\mu^+ \mu^-$. It’s suppressed, so can be neglected.
Analysis conceptually similar to that of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay, except can not separate $B_s^0$ and $\bar{B}_s^0$ final states.

Normalise w.r.t. $B_s^0 \rightarrow J/\psi \phi$ to determine $d\mathcal{B}/dq^2$.

The LHCb results are consistent with those of CDF.
The LHCb detector

Forward arm spectrometer covering $2 < \eta < 5$. 

$b\bar{b}$ production in forward direction
Reconstructing rare $b$-hadrons at LHCb

- No beam constraint at LHC and large detector occupancy.
  - Signatures with missing energy are difficult to reconstruct.

- Determine branching fractions / asymmetries normalised w.r.t. $B \to J/\psi K^{(*)}$ decays to cancel possible systematic effects.
  - Improvement in $\mathcal{B}(B \to J/\psi K^{(*)})$ from B Factories would reduce our systemic uncertainties.