Production and Decay of Heavy Flavor in ATLAS

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Overview

- Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays in *pp* collisions at $\sqrt{8}$TeV with the ATLAS detector.
- Measurement of *b*-hadron pair production with the ATLAS detector in proton-proton collisions at $\sqrt{8}$TeV
- Backup

$$B_d^0 \to K^* \mu^+ \mu^-$$

Preliminary result
http://cdsweb.cern.ch/record/2258146

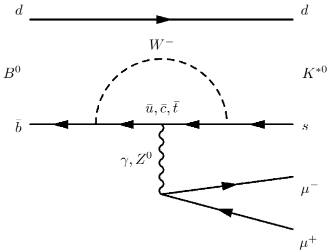
Motivation

Q: What are you trying to measure or search?

A: We are trying to measure the fraction of longitudinally polarized K^*, F_L, together with several angular parameters, S_3, S_4, $S_5 \ldots S_9$, associated to the process $B_d^0 \to K^*(\to K^+\pi^-)\mu^+\mu^-$.

Q: Why are you looking at this particular process?

A: This process involves FCNCs and therefore is not allowed at tree level in the SM.

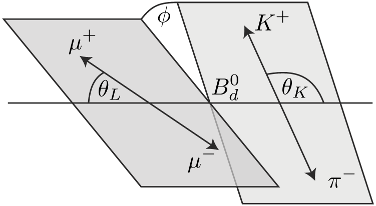


One of the diagrams that contributes to $B_d^0 \to K^*\mu^+\mu^-$ in the SM.

Additionally, LHCb has observed discrepancies between data and SM expectations with a significance of 3.4σ in this same type of measurement. CMS has also published the results of their studies.

$B_d^0 \to K^*\mu^+\mu^-$ Analysis Description

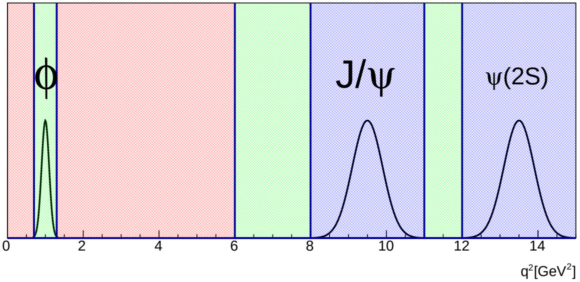
- **Data:** 20.3fb^{-1} collected by ATLAS, at $s = \sqrt{8}$TeV in 2012.
- **Observables:** $\cos\theta_K$, $\cos\theta_L$, ϕ and $m_{K\pi\mu^+\mu^-}$.
- **Binning:** The analysis is performed for different bins in q^2, where q is the mass of the dimuon system.



- **Parameters:** We want to extract F_L and $S_{3,4,5...9}$ from the data, but:
  - Large Form Factor Uncertainty $\Rightarrow$ reparametrize $S_i \to P_i$.
  - Low statistics $\Rightarrow$ apply trigonometric transformations, the *folding schemes*, $P_i \to P_i'$.
- **Due to the folding schemes:**
  - F_L and S_3 can be extracted from any of four folded versions of the data.
  - S_6 and S_9 cannot be extracted anymore. The forward-backward asymmetry can be written as $A_{FB} = 3S_6/4$.

Event Selection

- **Trigger:** Multiple triggers; which require at least one, two or three muons.
- **Dimuon:** Two muons originating from the same vertex.
- K^***:** Formed from two ID tracks with opposite charge.
- B_d^0**:** Formed from four tracks, and displaced from the primary vertex.
- **Mistagging:** Remove $\bar{B}_d^0$ vertices identified as B_d^0 by applying requirements on the $K\pi$ system's mass.
- q^2**:** The signal region is limited to avoid $J/\psi \to \mu^+\mu^-$ and $\phi \to \mu^+\mu^-$ backgrounds. It is also used to define the control regions.



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Statistical Analysis(1)

The parameters of interest are extracted by carrying out an extended maximum likelihood fit with:

$$\mathcal{L} = \frac{e^{-n}}{N!} \prod_{k=1}^{N} \sum_{l} n_l P_{kl}(m_{K\pi\mu\mu}, \cos\theta_K, \cos\theta_L, \phi; \hat{p}, \hat{\theta})$$

Where l runs over background and signal, n_l corresponds to the signal and background fitted yields. k runs over the events, $\hat{p}$ are the parameters of interest and $\hat{\theta}$ the nuisance parameters.

Signal Model

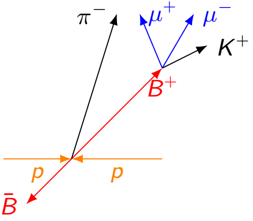
- Acceptance: Modeled by a polynomial in the angles, and extracted from simulated samples.
- Differential decay rate: Representing decay amplitude associated to the P-wave after a given folding scheme is applied.
- Mass dependence: Modified Gaussian PDF of mean m_0 and width $\xi\sigma$, where σ is the error in the B_d^0 candidate mass. Both m_0 and ξ are fixed by fits to the $K^* c\bar{c}$ control region (CR).

$$P_{k1} = \epsilon(\cos\theta_K)\epsilon(\cos\theta_L)\epsilon(\phi) \cdot g(\cos\theta_K, \cos\theta_L, \phi) \cdot G(m_{K\pi\mu\mu})$$

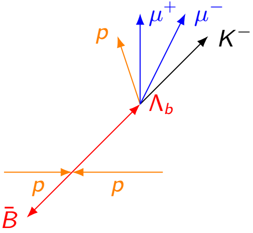
Background Model

- **Mass dependence:** Modeled by exponential function.
- **Angular dependence:** Modeled by Chebyshev polynomials of second order in $\cos\theta_L$, $\cos\theta_K$ and ϕ.

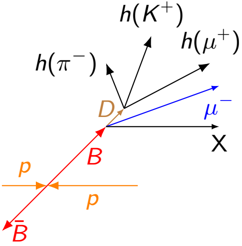
Q: Can you model all the sources of background with a polynomial?
A: Not perfectly, there are sources of background that show up in data and are accounted for as systematics:



Misreconstructed.



Peaking Background.



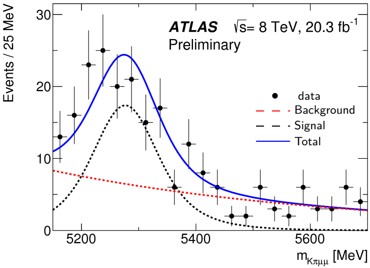
Partially Reconstructed.

Statistical Analysis(3)

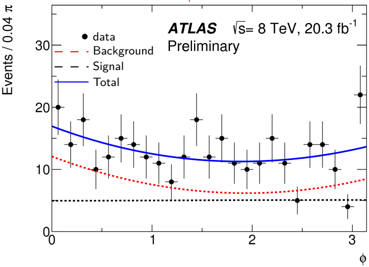
Fit Procedure

- Find the shape parameter of the background exponential PDF and the signal and background yields.
- Perform one fit per folding scheme to extract F_L and S_i.
- Assess biases.

$m_{K\pi\mu\mu}$



ϕ

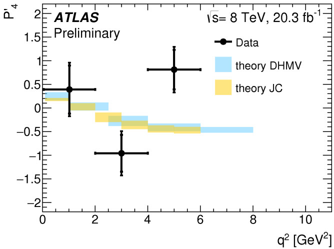


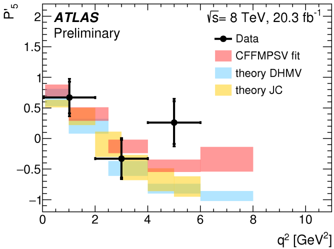
$q^2 \in [4,6]\text{GeV}^2$

Scheme: S_5

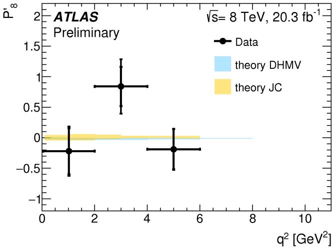
Results

The measured angular parameters are consistent with the SM expecations. here are small deviations in P_4', P_5' and P_8', consistent with LHCb.





P_4' and P_5' are 2.5σ and 2.7σ away from the SM calculation of DHMV in the $q^2 \in [4,6]\mathrm{GeV}^2$ bin. P_8' also shows a disagreement in the $q^2 \in [2,4]\mathrm{GeV}^2$ bin.



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$$b\bar{b} \to J/\psi + \mu$$

arXiv:1705.03374v2 [hep-ex]

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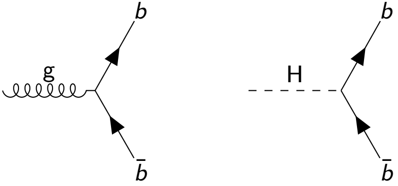
Analysis Description

Q: What do you want to measure/search for?
A: The differential cross section production for $b\bar{b}$ down to zero opening angle.

Q: Why is this measurement important?
A: This is an important background for Higgs boson production and it is important to constrain its theoretical estimate.



The measurement identifies the b quarks through a J/ψ and a muon.

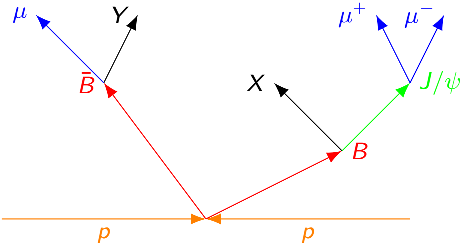
- J/ψ decaying into two muons from B meson or from excited $c\bar{c}$ states.
- A muon from a decay $b \rightarrow c \rightarrow \mu + X$.

The differential cross sections are binned in $\Delta R(J/\psi, \mu)$, $\Delta y(J/\psi, \mu)$, $p_T(J/\psi, \mu)$...

Data and Event Selection

Data: 11.4fb^{-1} of 2012 data collected at $\sqrt{s} = 8\text{TeV}$.

- **Trigger:** Requires events to have two muons consistent with having originated in a J/ψ.
- **Muons:** Are formed from ID tracks and MS segments.
- J/ψ**:** Has to be formed from two oppositely charged muons, consistent with having originated from a J/ψ meson and matched with two trigger muons.
- **Third Muon:** Is the remaining highest p_T muon.

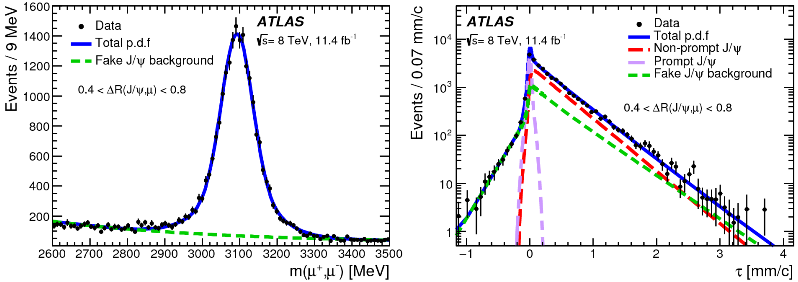


Analysis Steps and J/ψ Fit

Goal: Estimate the fiducial cross section corresponding to events containing a $J/\psi \to \mu^+\mu^-$ originating from a B meson and a muon coming from a different B meson through semileptonic decays.

How?

- Correct for inefficiencies from muon reconstruction and the trigger.
- The yield of events with a non-prompt J/ψ is found with a 2D fit to data.
- Find the events with a third muon and a non-prompt J/ψ.
- Correct for detector resolution effects.

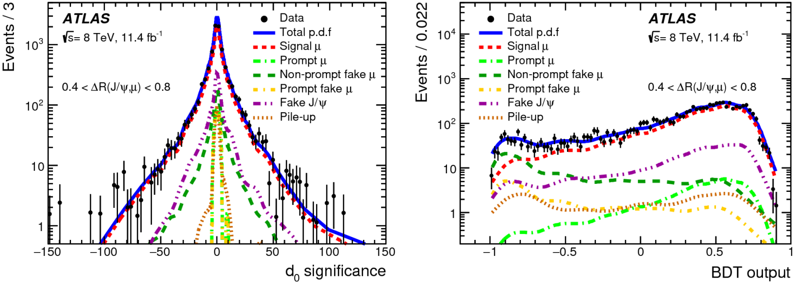


Third Muon Fit

Another 2D fit is used to extract the yield of events with a non-prompt third muon, with variables:

- **BDT score:** The third muon in background events can be fake or real.
- $d_0/\sigma(d_0)$ Is used to reject events with non-prompt muons.

Third muon background contributions from non-prompt J/ψ mesons make this fit harder $\Rightarrow$ fit for events with J/ψ mesons with $\tau < 0.25$ and later correct for this.

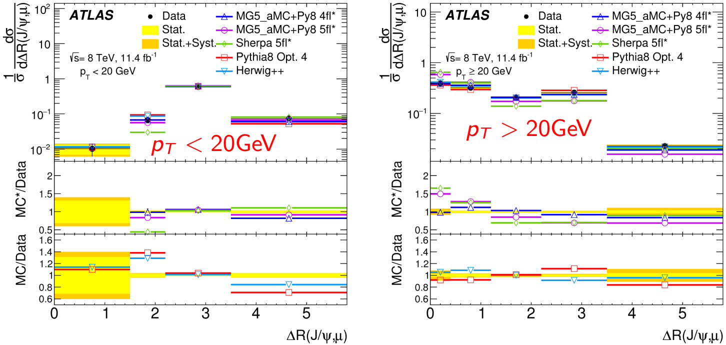


Results

The fiducial cross section is measured to be:

$$\sigma(B(\to J/\psi[\to \mu^+\mu^-] + X)B(\to \mu + X)) = 17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst})\ \text{nb}$$

- Due to the accuracy of the LO calculation used to produce the simulated samples the theory-experiment comparison is done with the *normalized* differential cross section rather than the differential cross section.
- Several settings and generators are used in the comparison.



Summary

- Two B physics analyses using data collected by the ATLAS detector in 2012 have been reviewed.

- We reviewed a measurement of the angular parameters associated to $B_d^0 \to K^* \mu^+ \mu^-$. The data supports the SM predictions, except for a couple of parameters that are at 2.5σ and 2.7σ from the SM. This is in agreement with what LHCb observed.

- We also reviewed a measurement of the normalized differential cross section of $b\bar{b}$ production. The results agree with some theory predictions more than with others; and therefore might offer insights to the theory community.

BACKUP

$B_d^0 \to K^*\mu^+\mu^-$ P-wave Decay Amplitude

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_L\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3(1-F_L)}{4}\sin^2\theta_K$$
$$+ F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L$$
$$- F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big]$$

Above is the expression corresponding to the P-wave's decay amplitude of the process. The S-wave and other higher angular momentum components are neglected.

$B_d^0 \to K^*\mu^+\mu^-$ Event Selection(1)

- **Trigger:** Using 19 trigger chains, largest contribution coming from dimuon triggers, specially from one requiring a muon with at least 4GeV and another with at least 6GeV. Signal efficiency is 29%.

- **Muons:** Built from ID tracks combined with MS segments. Satisfy $p_T(\mu) > 3.5$GeV, $|\eta| < 2.5$.

- **Tracks:** Reconstructed with ID and used to identify kaons and pions. Required to have $p_T > 500$MeV.

- **Dimuon:** Two muons with opposite charges are required to come from the same vertex with $\chi^2/NDF < 10$.

- **K*:** Two tracks with opposite charges are used to reconstruct it. It has to satisfy $p_T(K^*) > 3$GeV and $m(K^*) \in [846, 946]$MeV. Kaon and pion mass hypothesis are assigned to both tracks, building two candidates. Event kinematics are used to remove extra candidate.

$B_d^0 \to K^* \mu^+ \mu^-$ Event Selection(2)

- B_d^0: Is obtained by fitting the two muon tracks and the two K^* tracks, we require:
  - $\chi^2/NDF < 2$ for the vertex fit.
  - $\tau/\sigma(\tau) > 12.5$ is used to suppress combinatorial background, where τ is the lifetime of B_d^0.
  - $m(B_d^0) \in [5150, 5700]$MeV. This is an asymmetric mass window, used to remove partially reconstructed decays $b\bar{b} \to \mu^+\mu^- X$ that would otherwise get into the signal region.
  - $\cos\Theta > 0.999$, where Θ is the angle between the B_d^0 momentum and the vector joining the primary and B_d^0 vertex.
  - **Mistagging:** There are more than one candidates in 12% of events in data.
    - **4% with multiple hadron tracks corresponding to multiple K^*:** The candidate with the lowest B_d^0 χ^2/NDF is selected.
    - **96% with two hadron tracks, but multple possible mass assignemts:** Pick candidate with the lowest $|m(K\pi) - m(K^*)|/\sigma(m(K\pi))$

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$B_d^0 \to K^* \mu^+ \mu^-$ Event Selection(3)

- **q^2:** Starts at 0.04GeV^2. Required to be outside $[0.98, 1.1]$GeV to avoid picking up $\phi(1020) \to \mu^+\mu^-$ decays. Region beyond 6GeV contains J/ψ radiative decays and is not used.

Control Regions: In order to fix the width and mean of the PDF modeling the B_d^0 mass distribution, two control regions are created by requiring $q^2 \in [8, 11]$GeV and $q^2 \in [12, 15]$GeV.

Yield: After all the requirements we get 787 events.

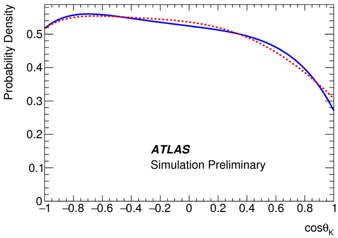
Mistagging: As a consequence of the signal region requirements, some $B_d^0 \to K^* \mu^+ \mu^-$ events in data are classified as $\bar{B}_d^0 \to \bar{K}^* \mu^+ \mu^-$ and viceversa. The mistag causes a *dilution* effect in S_5 and S_8, which is compensated by dividing by $1 - 2\omega$. Where ω is the mistagging probability.

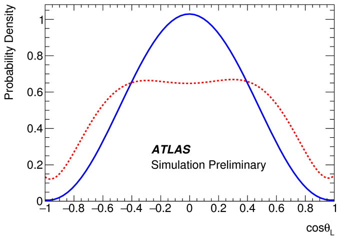
$B_d^0 \to K^* \mu^+ \mu^-$ Simulated Samples

- **Signal Simulated Samples:** $B_d^0 \to K^* \mu^+ \mu^-$ and $\bar{B}_d^0 \to \bar{K}^* \mu^+ \mu^-$ samples with angular distributions following the SM. A $B_d^0 \to K^* \mu^+ \mu^-$ sample with flat angular distributions and $F_L = 1/3$.
- **Background Simulated Samples:** 7 inclusive samples for background generated with EvtGen and Pythia and 11 background samples generated with Pythia.

$B_d^0 \to K^* \mu^+ \mu^-$ Signal Acceptance

A signal sample with flat angular distributions was produced to assess the signal acceptance, defined as the ratio of the corresponding distributions at reconstructed level and particle level.





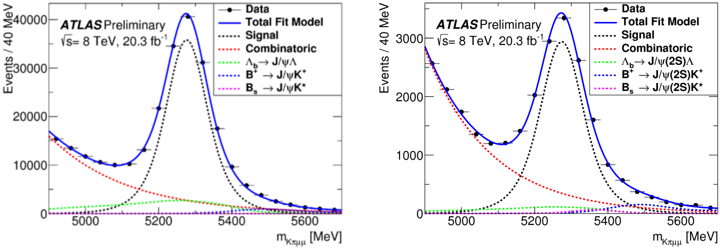
Acceptance functions plotted with respect to $\cos\theta_K$ and $\cos\theta_L$. The solid line corresponds to the $q^2 \in [0.04, 2.0]$GeV bin, while the dashed line corresponds to the $q^2 \in [4, 6]$GeV bin.

The angular distributions are *shaped* by:

- $\cos\theta_L$: Reduced at high and low values by trigger and p_T requirements on the muons.
- $\cos\theta_K$: Affected by reconstruction of $K\pi$ system.

Control Region Fits

Q: How can we reduce the number of degrees of freedom in the mass fit used to extract the nuisance parameters?



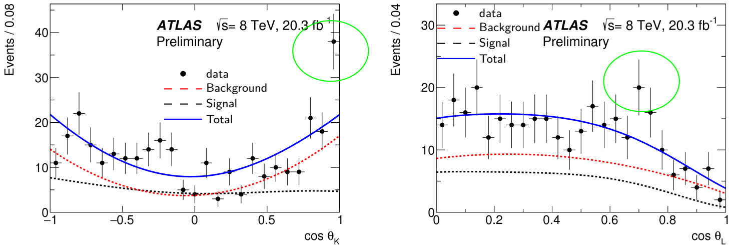
At the left, the fit to $m_{K\pi\mu\mu}$ for the $K^* J/\psi$ CR. At the right the same fit for the $K^* \psi(2S) CR$.

A: We can use the $K^* J/\psi$ and $K^* \psi(2S)$ control regions in data to extract m_0 and ξ. The simulated samples show that these variables are the same as in the signal region.

$B_d^0 \to K^*\mu^+\mu^-$ Systematics

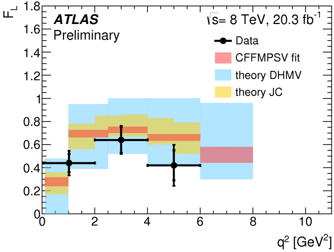
There are 13 sources of systematics, the largest stem from:

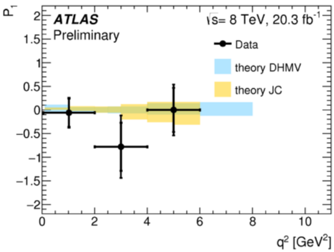
- Background components that have not been taken into account in the background model.
- The functional form of the background parametrization.
- The values of the acceptance function.
- The limitations in the knowledge of the ID alignment and the magnetic field.

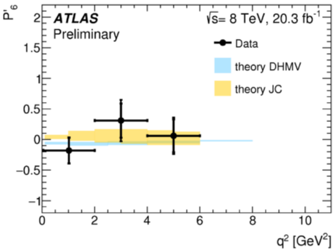


Fitted angular distributions in data for $q^2 \in [4,6]$GeV and the S_5 folding scheme. The excess at $\cos\theta_K \approx 1$ and $|\cos\theta_L| \approx 0.7$ are caused by background components missing in the fit.

$B_d^0 \to K^* \mu^+ \mu^-$ Angular Parameters







The three figures show the angular parameters F_L, P_1 and P'_6 binned in q^2 and compared with theory predictions.

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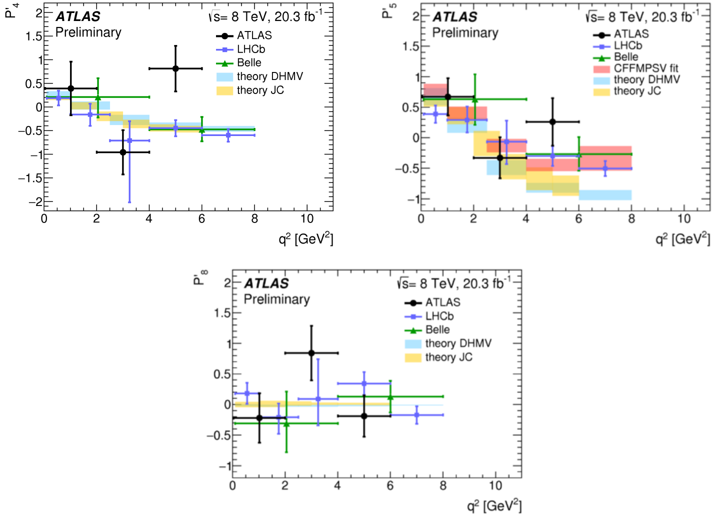
$B_d^0 \to K^*\mu^+\mu^-$ ATLAS vs LHCb and Belle



The three figures show the angular parameters P_4', P_5' and P_8' binned in q^2 and compared with LHCb and Belle.

Fit Values

q^2 [GeV^2]	n_{signal}	$n_{\text{background}}$
$[0.04, 2.0]$	128 ± 22	122 ± 22
$[2.0, 4.0]$	106 ± 23	113 ± 23
$[4.0, 6.0]$	114 ± 24	204 ± 26
$[0.04, 4.0]$	236 ± 31	233 ± 32
$[1.1, 6.0]$	275 ± 35	363 ± 36
$[0.04, 6.0]$	342 ± 39	445 ± 40

Yields of signal and background for different q^2 bins coming from the preliminary mass fit.

q^2 [GeV^2]	F_L	S_3	S_4	S_5	S_7	S_8
$[0.04, 2.0]$	$0.44 \pm 0.08 \pm 0.07$	$-0.02 \pm 0.09 \pm 0.02$	$0.19 \pm 0.25 \pm 0.10$	$0.33 \pm 0.13 \pm 0.06$	$-0.09 \pm 0.10 \pm 0.02$	$-0.11 \pm 0.19 \pm 0.07$
$[2.0, 4.0]$	$0.64 \pm 0.11 \pm 0.05$	$-0.15 \pm 0.10 \pm 0.07$	$-0.47 \pm 0.19 \pm 0.10$	$-0.16 \pm 0.15 \pm 0.05$	$0.15 \pm 0.14 \pm 0.09$	$0.41 \pm 0.16 \pm 0.15$
$[4.0, 6.0]$	$0.42 \pm 0.13 \pm 0.12$	$0.00 \pm 0.12 \pm 0.07$	$0.40 \pm 0.21 \pm 0.09$	$0.13 \pm 0.18 \pm 0.07$	$0.03 \pm 0.13 \pm 0.07$	$-0.09 \pm 0.16 \pm 0.04$
$[0.04, 4.0]$	$0.52 \pm 0.07 \pm 0.06$	$-0.05 \pm 0.06 \pm 0.04$	$-0.19 \pm 0.16 \pm 0.09$	$0.16 \pm 0.10 \pm 0.04$	$0.01 \pm 0.08 \pm 0.05$	$0.15 \pm 0.13 \pm 0.10$
$[1.1, 6.0]$	$0.56 \pm 0.07 \pm 0.06$	$-0.04 \pm 0.07 \pm 0.03$	$0.03 \pm 0.14 \pm 0.07$	$0.00 \pm 0.10 \pm 0.03$	$0.02 \pm 0.08 \pm 0.06$	$0.09 \pm 0.11 \pm 0.08$

q^2 [GeV^2]	P_1	P_4'	P_5'	P_6'	P_8'
$[0.04, 2.0]$	$-0.06 \pm 0.30 \pm 0.10$	$0.39 \pm 0.51 \pm 0.25$	$0.67 \pm 0.26 \pm 0.16$	$-0.18 \pm 0.21 \pm 0.04$	$-0.22 \pm 0.38 \pm 0.14$
$[2.0, 4.0]$	$-0.78 \pm 0.51 \pm 0.42$	$-0.96 \pm 0.39 \pm 0.26$	$-0.33 \pm 0.31 \pm 0.13$	$0.31 \pm 0.28 \pm 0.19$	$0.84 \pm 0.32 \pm 0.31$
$[4.0, 6.0]$	$0.00 \pm 0.47 \pm 0.26$	$0.81 \pm 0.42 \pm 0.24$	$0.26 \pm 0.35 \pm 0.17$	$0.06 \pm 0.27 \pm 0.13$	$-0.19 \pm 0.33 \pm 0.07$
$[0.04, 4.0]$	$-0.22 \pm 0.26 \pm 0.16$	$-0.38 \pm 0.31 \pm 0.22$	$0.32 \pm 0.21 \pm 0.10$	$0.01 \pm 0.17 \pm 0.10$	$0.30 \pm 0.26 \pm 0.19$
$[1.1, 6.0]$	$-0.17 \pm 0.31 \pm 0.14$	$0.07 \pm 0.28 \pm 0.18$	$0.01 \pm 0.21 \pm 0.07$	$0.03 \pm 0.17 \pm 0.11$	$0.18 \pm 0.22 \pm 0.16$
$[0.04, 6.0]$	$-0.15 \pm 0.23 \pm 0.10$	$0.07 \pm 0.26 \pm 0.18$	$0.27 \pm 0.19 \pm 0.07$	$0.03 \pm 0.15 \pm 0.10$	$0.11 \pm 0.21 \pm 0.14$

Angular parameters obtained after the fit for different q^2 bins.

$b\bar{b} \to J/\psi + \mu$ Event Selection

Data: 11.4fb^{-1} of 2012 data collected at $\sqrt{s} = 8\text{TeV}$.

- **Trigger:** Requires events to have two oppositely charged muons with $p_T > 4\text{GeV}$, $|\eta| < 2.4$, coming from the same vertex and with a dimuon mass in $[2.5, 4.3]\text{GeV}$.
- **Muons:** Are formed from ID tracks and MS segments. They have to have $p_T > 6\text{GeV}$ and $|\eta| < 2.5$. A minimum number of hits is required from the tracks.
- J/ψ**:** Have to be formed from two oppositely charged muons lying within $|\eta| < 2.3$, coming from the same vertex and with a dimuon mass in $[2.6, 3.5]\text{GeV}$. The reconstructed muons are required to be matched to the trigger muons. If multiple candidates are found in an event, the one with the mass closest to the PDG value is chosen.
- **Third Muon:** Is the remaining highest p_T muon and with $|\eta| < 2.5$.

$b\bar{b} \to J/\psi + \mu$ Fiducial Region

The final result is meant to be interpreted with respect to a fiducial volume defined at particle level by:

- In the events, the first B hadron decays into a J/ψ directly or through other decays.
- The J/ψ decays into two muons.
- There is a third muon from the semileptonic decay of the second B hadron.
- The muons are *dressed* with photons in $\Delta R < 0.1$, i.e. the four momenta of these photons are added to the muon, except when the photons come from hadron decays.
- The dressed muons should satisfy $p_T > 6$GeV.
- The J/ψ muons should be in $|\eta| < 2.3$ and the third muon in $|\eta| < 2.5$.

$b\bar{b} \to J/\psi + \mu$ Resolution Corrections and Systematics

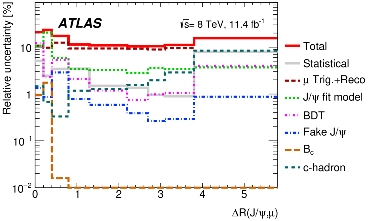
We need the *particle level* differential cross-section, therefore we have to correct for:

- **Bin migration:** Events in the same bin at particle level will move due to resolution effects at detector level.
- **Events in and out of Fiducial Region:** Events will leave and enter the fiducial region due to the same detector resolution effects.

Solution: Use simulated samples to *unfold* the detector effects. Given the coarse binning of the differential cross section, a simple ratio between particle and detector level distributions can provide the correction factors.

Main Systematics Associated To:

- Muon reconstruction efficiency corrections.
- J/ψ and background fit model.
- Trigger efficiency corrections.
- Statistical uncertainties.



Uncertainties affecting the cross section measurement for different bins in $\Delta R(J/\psi, \mu)$.

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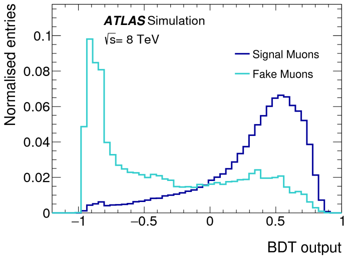
$b\bar{b} \to J/\psi + \mu$ BDT

The variables used for the training of the BDT that discriminates fake muons from real ones are:

- **Track deflection significance:** Largest significance for for difference in track curvatures, when these are calculated along the track.
- **Track deflection neighbour significance:** Largest significance of angular difference between segments built from adjacent hits in the ID.
- **Momentum balance significance:** Significance of the difference between muon momentum measured by the ID and MS.
- $|\eta|$**:** Larger for background muons.



BDT score distribution for fake and real muons.