Searches for new physics with heavy flavour at ATLAS

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on behalf of the ATLAS collaboration

Joint Institute for Nuclear Research

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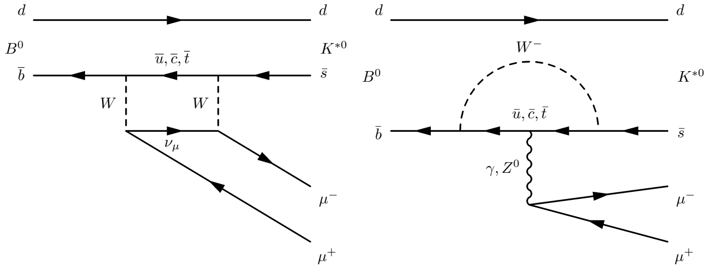
Introduction

- Studying heavy flavour decays provides an opportunity for indirect search for BSM physics
  - $b \to s\ell\ell$ transitions occur via FCNC processes
  - Forbidden in SM at tree level and thus sensitive to NP contributions in the loop diagrams
- ATLAS performs a good variety of B-physics studies
  - Serious challenges: trigger thresholds, severe pile-up conditions
  - Mainly limited to di-muon final states due to trigger
  - Optimal for studying (semi-)rare decays with two muons

- **In this talk:**
  - Angular analysis of $B^0 \to \mu^+\mu^- K^{*0}$ decay – ATLAS-CONF-2017-023
  - Studying rare decay $B^0_{(s)} \to \mu^+\mu^-$ – EPJC 76 (2016) 513, arXiv:1604.04263

- ★ Also at this conference: ★
  - Heavy quark physics at ATLAS and CMS (*Leonid Gladilin*)
  - Production and spectroscopy in heavy flavour at ATLAS (*Artem Maevskiy*)

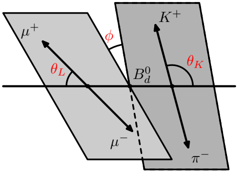
Angular analysis of $B^0 \to \mu^+\mu^- K^{*0}$ decay



- The decay occurs through "box" and "penguin" diagrams – possible contributions of NP heavy particles in the loops
- $\mathcal{B}(B^0 \to \mu^+\mu^- K^{*0}) = (1.03 \pm 0.06) \times 10^{-6}$
- Observables of interest are the angular distributions of the final state
- **ATLAS has studied this decay using Run-1 data of 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV**

Angular fit model

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



- Use optimized $P_i^{(\prime)}$ parameters to reduce dependence of S_i on hadronic form factors

$$P_1 = \frac{2S_3}{1-F_L}$$
$$P_2 = \frac{2}{3}\frac{A_{\mathrm{FB}}}{1-F_L}$$
$$P_3 = -\frac{S_9}{1-F_L}$$
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

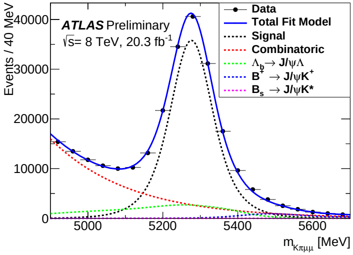
- The parameters are extracted in bins of q^2 – di-muon mass squared
- Statistics not sufficient for fitting the full angular distribution
- Use trigonometric *"folding"* to reduce the problem to 4 sets of fits for 3 parameters each: F_L, S_3 (P_1), and $S_{j=4,5,7,8}$ ($P_{j=4,5,6,8}$)
- E.g. for F_L, S_3, S_4:

$$\begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_L > \frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2}, \end{cases}$$

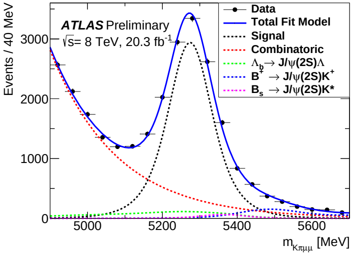
- Uncertainties on F_L and S_3 are compatible in all fits $\to$ the one with smallest systematics is taken
- S_6 (A_{FB}) and S_9 cannot be extracted with this approach

Event selection

- Inclusive set of 15 triggers to maximise statistics
  - single-, di- and tri-muon requirements at trigger level
- $|\eta_{\pi,K,\mu}| < 2.5$
- $p_{\mathrm{T}}(\pi, K) > 0.5$ GeV, $p_{\mathrm{T}}(\mu) > 3.5$ GeV
- $m(K\pi) \in [846, 946]$ MeV
- $m(\mu\mu K\pi) \in [5150, 5700]$ MeV
- $p_{\mathrm{T}}(K^{*0}) > 3$ GeV
- $\tau/\sigma_\tau > 12.75$
- $\cos\theta > 0.999$
- $\chi^2/\mathrm{n.d.f.}(B^0) < 2$
- If > 1 candidates in event, keep
  - best χ^2
  - smallest $|m(K\pi) - m_{PDG}(K^{*0})|/\sigma_{m(K\pi)}$
- Signal region of $q^2 \in [0.04, 6]$ GeV^2, vetoing $[0.98, 1.1]$ GeV^2 due to ϕ background
- **787 events pass signal selection**



$q^2 \in [8, 11]$ GeV^2



$q^2 \in [12, 15]$ GeV^2

Fit strategy

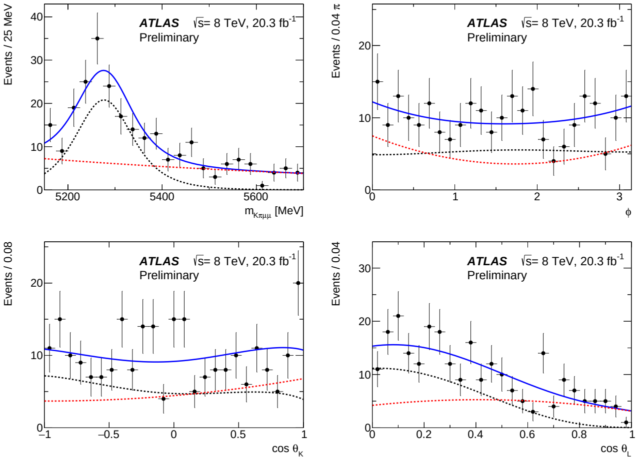
- Extended ML fit with each of the fit variants in bins of q^2

$$\mathcal{L} = \frac{e^{-N}}{n!} \prod_{i=1}^{n} \sum_{j} n_j P_{ij}(m_{K\pi\mu\mu}, \cos\theta_K, \cos\theta_L, \phi; \widehat{p}, \widehat{\theta}),$$

  - $j = 1, 2$ for signal and combinatorial background PDF (other backgrounds are considered only for systematics)
  - *first step:* fit the mass distribution to extract the nuisance parameters (signal/background yields, mass shapes)
    - m_0 and σ_0 are extracted from $J/\psi K^{*0}$ control region
  - *second step:* add angular distributions to extract the F_L and S $(P^{(\prime)})$
- Regions of q^2: [0.04, 2.0], [2.0, 4.0], [4.0, 6.0] GeV^2
- Also fit in [0.04, 4.0], [1.1, 6.0], [0.04, 6.0] GeV^2 to facilitate comparison with various predictions and experiments

Signal fit projection example

- Fit in $q^2 \in [0.04, 2.0]$ GeV^2 for S_5 folding scheme is shown



Signal

- *Mass:* Gaussian with per-event errors
- *Angles:* theoretical PDF, corrected by acceptance functions extracted from MC

Background

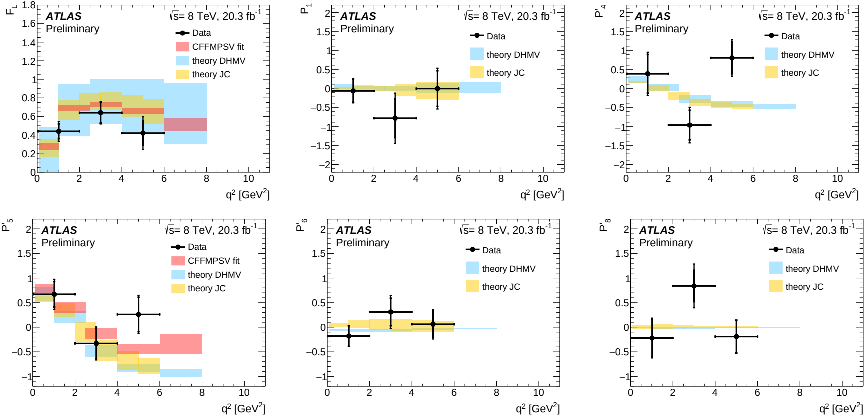
- *Mass:* exponential
- *Angles:* PDF factorized into 1D terms – 2$^{\text{nd}}$ order Chebychev polynomials

Systematics

- Combinatorial $K\pi$ pairs peaking at $\cos\theta_K$ around 1.0
  - cut $\cos\theta_K < 0.9$
- $B \to DX$ and $B^+ \to K^+(\pi^+)\mu^+\mu^-$ decays peaking at $|\cos\theta_L|$ around 0.7
  - build and veto such decay candidates
- Angular background PDF shape choice
- Acceptance functions factorization
  - mostly affects S_4
- Combinatorial background modelling and normalisation
  - varying mass range for the fit
- Tracker alignment and magnetic field causing rapidity and momentum scale biases
- Other less contributing sources
  - Intrinsic bias of the fit
  - $p_{\mathrm{T}}(B^0)$ discrepancy
  - S-wave contribution
  - Exclusive backgrounds peaking in $m(\mu\mu K\pi)$
  - Dilution due to flavour mis-tagging

Results: comparison to predictions

fit-based prediction using LHCb data CFFMPSV: Ciuchini et al. JHEP 06 (2016) 116, arXiv:1512.07157
QCD factorisation approaches DHMV: Descotes-Genon et al. JHEP 12 (2014) 125, arXiv:1407.8526
JC: Jäger and Camalich PRD 93 (2016) 014028, arXiv:1412.3183



- Deviations for P_4' and P_5' from DHMV calculation are 2.5σ and 2.7σ, respectively
- Consistent with those reported by LHCb
- All measurement are within 3σ of the range covered by the predictions

Results: comparison to predictions

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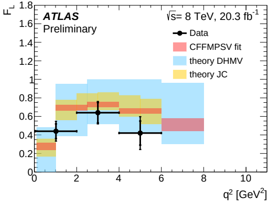
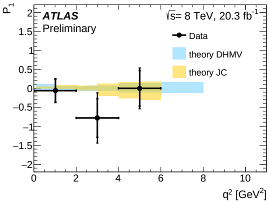
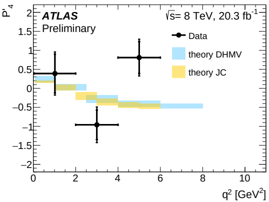
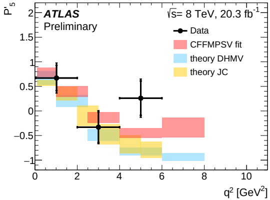
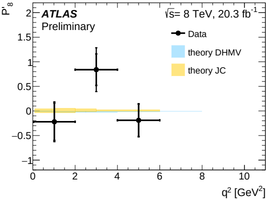








q^2 [GeV^2]	P'_5
$[0.04, 2.0]$	$0.67 \pm 0.26 \pm 0.16$
$[2.0, 4.0]$	$-0.33 \pm 0.31 \pm 0.13$
$[4.0, 6.0]$	$0.26 \pm 0.35 \pm 0.17$
$[0.04, 4.0]$	$0.32 \pm 0.21 \pm 0.10$
$[1.1, 6.0]$	$0.01 \pm 0.21 \pm 0.07$
$[0.04, 6.0]$	$0.27 \pm 0.19 \pm 0.07$



- Deviations for P'_4 and P'_5 from DHMV calculation are 2.5σ and 2.7σ, respectively
- Consistent with those reported by LHCb
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Comparison to predictions and other measurements

fit-based prediction using LHCb data CFFMPSV: Ciuchini et al. JHEP 06 (2016) 116, arXiv:1512.07157
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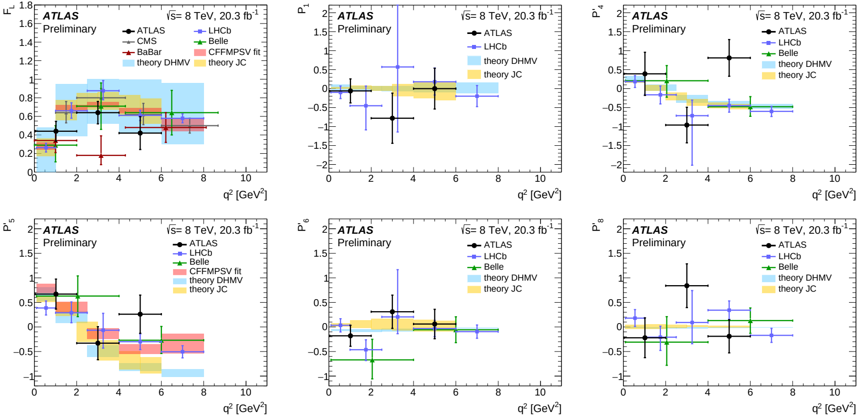
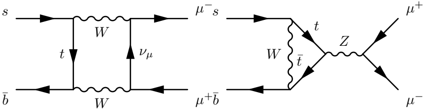


- Deviations for P_4' and P_5' from DHMV calculation are 2.5σ and 2.7σ, respectively
- Consistent with those reported by LHCb
- All measurement are within 3σ of the range covered by the predictions

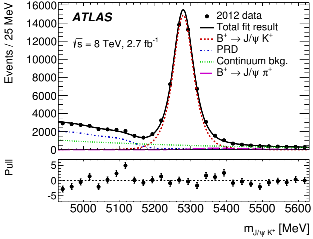
Study of $B^0_{(s)} \to \mu^+\mu^-$ rare decay

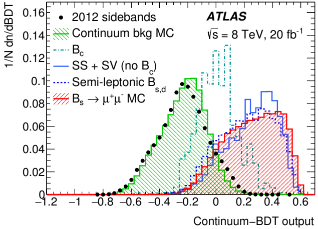


- FCNC process, CKM and helicity suppressed
- SM predictions:
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$
- Experimentally very clear signature sensitive to NP
- ATLAS analysis uses full Run-1 data of 25 fb^{-1} at $\sqrt{s} = 7$ and 8 TeV
- Signal decay $\mathcal{B}$ measured w.r.t. reference mode $B^+ \to J/\psi(\mu^+\mu^-)K^+$

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}} \times [\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)] \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_{d(s)}}$$

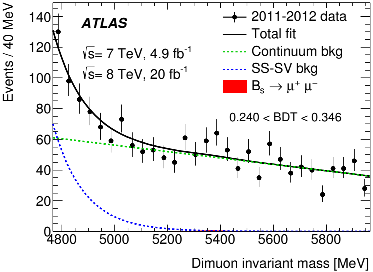
  - Many uncertainties reduced
- Complicated multi-variate event selection
  - *"Continuum-BDT"* to suppress combinatorial muon pairs
  - *"Fake-BDT"* for mis-identified muons suppression (e.g. from $B^0_{(s)} \to \pi K$ decays)

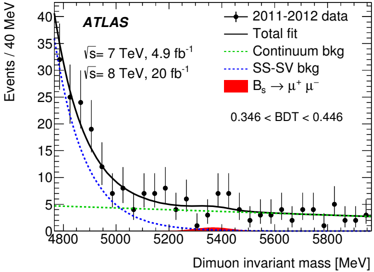


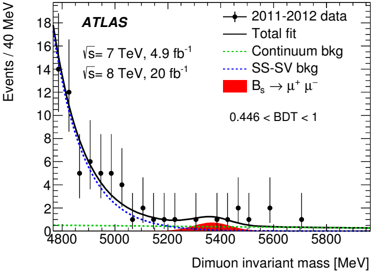


$B^0_{(s)} \to \mu^+\mu^-$ signal fits

- ML fit in 3 bins of continuum-BDT with with equal 18% signal efficiency
- Yields positively constrained:
  - $N_s = 11,\ N_d = 0$
- No constraints:
  - $N_s = 16 \pm 12,\ N_d = -11 \pm 9$
- SM expectation:
  - $N_s = 41,\ N_d = 5$







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

Measured $\mathcal{B}$:

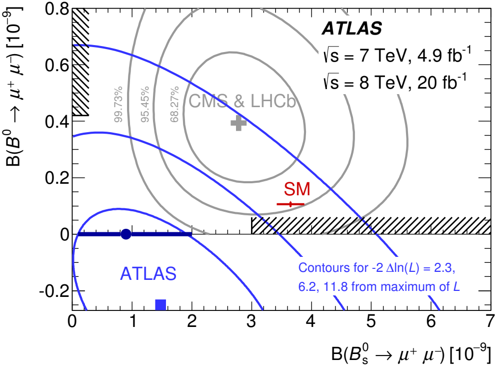
- $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$

95% C.L. limits are set:

- $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 3.0 \times 10^{-9}$
- $\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$

Compatibility of the simultaneous fit with the SM:

- $p = 4.8\%\ (2.0\sigma)$



- ATLAS result is compatible with CMS and LHCb Run-1 measurements
- Tension in B^0 is reduced with the Run-2 LHCb measurement (PRL 118 (2017) 191801, arXiv:1703.05747)
  - *LHCb Run-2*: $\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ @ 95% C.L.
- ATLAS analysis on Run-2 data is on-going

Summary

- Two NP-sensitive B-physics analysis were presented:
- Angular analysis of $B^0 \to \mu^+\mu^- K^{*0}$ decay – ATLAS-CONF-2017-023
  - Uses Run-1 $\sqrt{s} = 8$ TeV data, 20.3 fb^{-1}
  - Results are compatible with theoretical predictions and other experiments
  - Measurement still statistically limited
- Studying rare decay $B^0_{(s)} \to \mu^+\mu^-$ – EPJC 76 (2016) 513, arXiv:1604.04263
  - Full Run-1 data used, 25 fb^{-1}
  - *Expected sensitivity* comparable to that of CMS or LHCb
  - Lower *observed signal* than theirs, agreement with SM at 2.0σ level
  - Working hard on $\sqrt{s} = 13$ TeV data analysis
- **Keep in touch for new Run-2 results!**

Thank you!

Backup slides

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

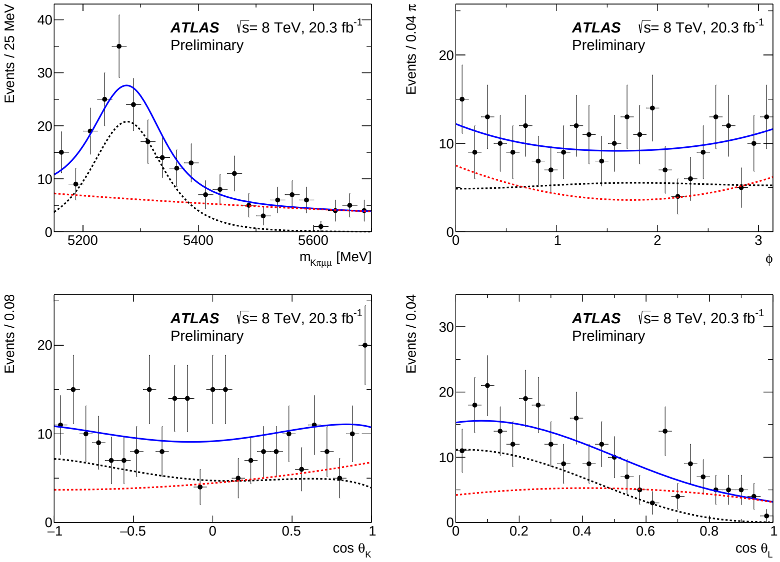
- Signal yields are $\sim$ uniform across q^2
- Statistical uncertainty dominates the measurement of F_L, S and $P^{(\prime)}$

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

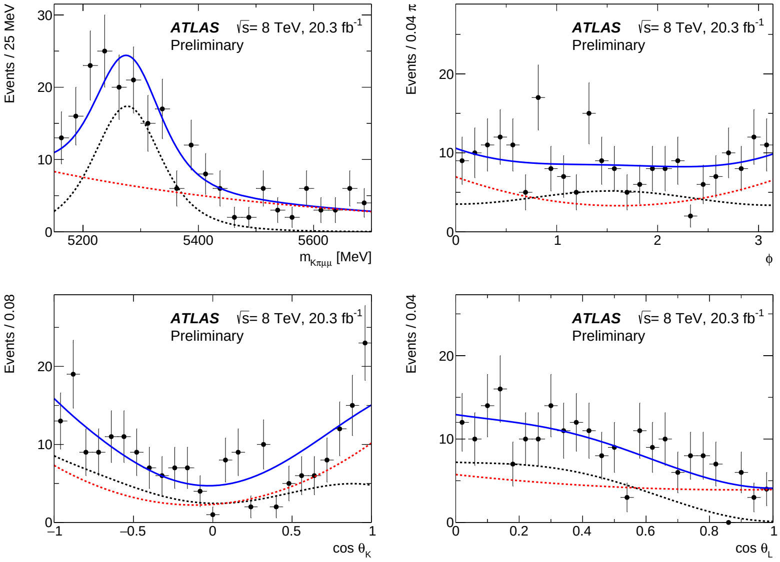
q^2 [GeV^2]	F_L	S_3	S_4	S_5	S_7	S_8
[0.04, 2.0]	$0.44 \pm 0.08 \pm 0.07$	$-0.02 \pm 0.09 \pm 0.02$	$0.19 \pm 0.25 \pm 0.10$	$0.33 \pm 0.13 \pm 0.06$	$-0.09 \pm 0.10 \pm 0.02$	$-0.11 \pm 0.19 \pm 0.07$
[2.0, 4.0]	$0.64 \pm 0.11 \pm 0.05$	$-0.15 \pm 0.10 \pm 0.07$	$-0.47 \pm 0.19 \pm 0.10$	$-0.16 \pm 0.15 \pm 0.05$	$0.15 \pm 0.14 \pm 0.09$	$0.41 \pm 0.16 \pm 0.15$
[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]	$0.56 \pm 0.07 \pm 0.06$	$-0.04 \pm 0.07 \pm 0.03$	$0.03 \pm 0.14 \pm 0.07$	$0.00 \pm 0.10 \pm 0.03$	$0.02 \pm 0.08 \pm 0.06$	$0.09 \pm 0.11 \pm 0.08$
[0.04, 6.0]	$0.50 \pm 0.06 \pm 0.04$	$-0.04 \pm 0.06 \pm 0.03$	$0.03 \pm 0.13 \pm 0.07$	$0.14 \pm 0.09 \pm 0.03$	$0.02 \pm 0.07 \pm 0.05$	$0.05 \pm 0.10 \pm 0.07$

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]	$-0.15 \pm 0.23 \pm 0.10$	$0.07 \pm 0.26 \pm 0.18$	$0.27 \pm 0.19 \pm 0.07$	$0.03 \pm 0.15 \pm 0.10$	$0.11 \pm 0.21 \pm 0.14$

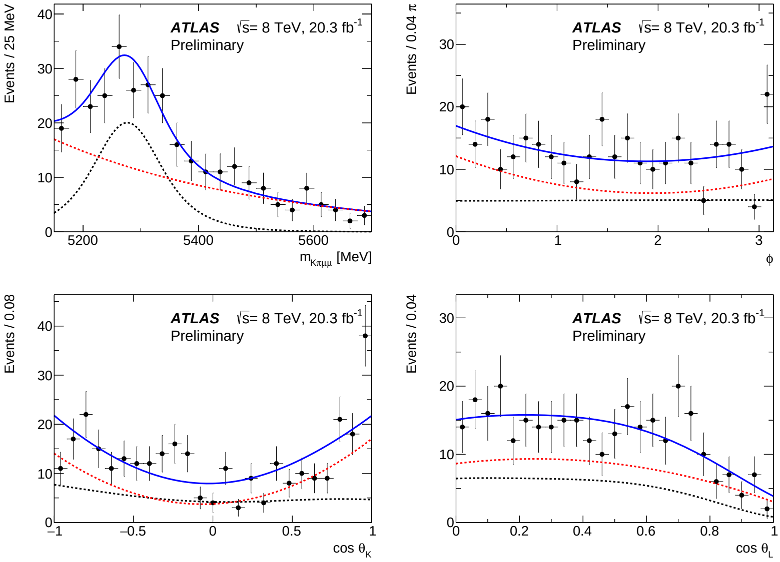
Fit projections: $q^2 \in [0.04, 2.0]$, S_5 fit



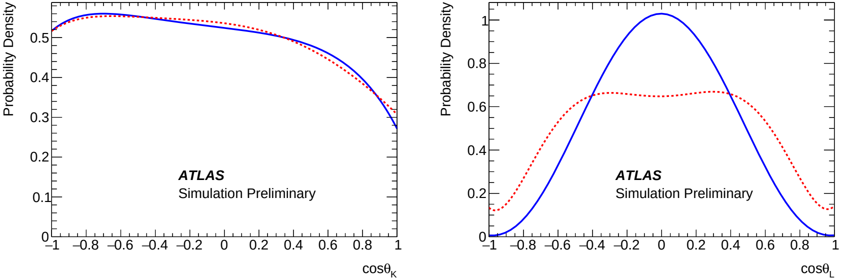
Fit projections: $q^2 \in [2.0, 4.0]$, S_5 fit



Fit projections: $q^2 \in [4.0, 6.0]$, S_5 fit



Angular acceptance corrections



- Blue: $q^2 \in [0.04, 2.0]$
- Red: $q^2 \in [4.0, 6.0]$

Largest systematics contributions

Source	F_L	S_3	S_4	S_5	S_7	S_8
Combinatoric $K\pi$ (fake K^*) background	0.03	0.03	0.05	0.03	0.06	0.13
D and B^+ veto	0.11	0.04	0.05	0.03	0.01	0.05
Background p.d.f. shape	0.04	0.04	0.03	0.02	0.03	0.01
Acceptance function	0.01	0.01	0.07	0.01	0.01	0.01
Partially reconstructed decay background	0.03	0.05	0.02	0.06	0.05	0.05
Alignment and B field calibration	0.02	0.04	0.05	0.03	0.04	0.03
Fit bias	0.01	0.01	0.02	0.02	0.01	0.04
Data/MC differences for p_T	0.02	0.02	0.01	0.01	0.01	0.01
S-wave	0.01	0.01	0.01	0.01	0.01	0.02
Nuisance parameters	0.01	0.01	0.01	0.01	0.01	0.01
Λ_b, B^+ and B_s background	0.01	0.01	0.01	0.01	0.01	0.01
Misreconstructed signal	0.01	0.01	0.01	0.01	0.01	0.01
Dilution	–	–	0.01	0.01	–	–