Angular Analysis of $B_d^0 \to K^{*0}\mu\mu$ at ATLAS

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FORTE
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Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays in pp collisions at $\sqrt{s} = 8\,\text{TeV}$ with the ATLAS detector (Run 1 data)

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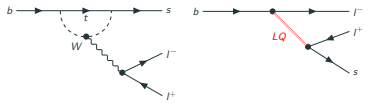
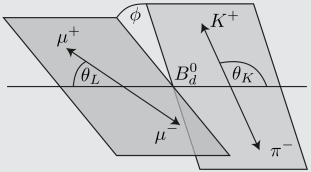
- Analysis of the decay angles in the $B^0 \to K^{*0}\mu\mu$ system, $m(\mu\mu)$ dependent
- ATLAS Run 1 data at $\sqrt{s} = 8\,\text{TeV}$



Measurement

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

- Extended unbinned maximum likelihood fit of the 3D decay angles distribution (and B-candidate mass and its uncertainty) in q^2 bins
  - Ignored range above $c\bar{c}$
- Blinded fit results
- Study of number of potential backgrounds from radiative resonant decays and other semileptonic rare decays
  - Treated in systematics, no need to include in default fit
- Detector acceptance from MC, factorized in all the three angles
- No K/π separation in ATLAS $\implies$ 11% wrong tag of B-flavor



Low statistics ($\sim$ 340 signal events) does not allow full fit $\Longrightarrow$ simplifications:

Angular distribution folding

- Full angular distribution $\rightarrow$ four simplier distributions
- Lost sensitivity to S_6 and S_9

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

$\Downarrow$

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{8\pi}\Bigg[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi\Bigg]$$

$$F_L, S_3, S_5, P_5^{'}: \begin{cases}\phi \rightarrow -\phi & \text{for } \phi < 0\\ \theta_L \rightarrow \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2}\end{cases} \Longrightarrow$$

Low statistics ($\sim$ 340 signal events) does not allow full fit $\Longrightarrow$ simplifications:

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B-candidate mass distribution pre-fits

- B-candidate mass distribution pre-fitted and fixed in the angular fit
- Mass nuisance parameters extract from fits to control channels ($B^0 \rightarrow J/\psi K^*$, $B^0 \rightarrow \psi(2S)K^*$)
- Procedure feasibility validated with toy-MC

Rough q^2 binning

- 3 bins only in q^2 [GeV^2]: (0.04 - 2), (2.0 - 4.0), (4.0 - 6.0)

Fit projections (P_5' example)

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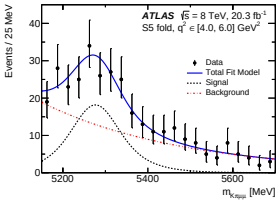
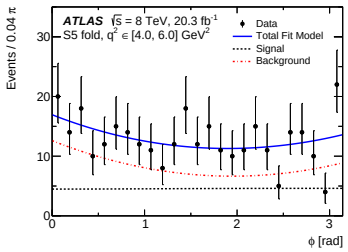
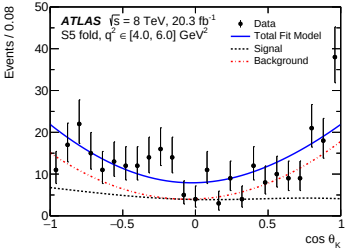
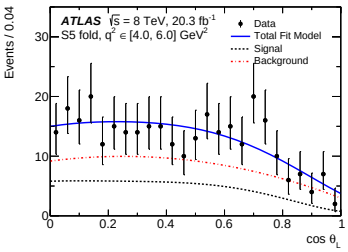
Extended unbinned maximum likelihood fit

- Left sideband cut to avoid contrib. from partially reconstructed B-decays
- Extracting S_i parameters $\rightarrow$ transformed to $P_i^{(\prime)}$ (including correlations)
- Dilution correction applied post-fit to S_5, S_8

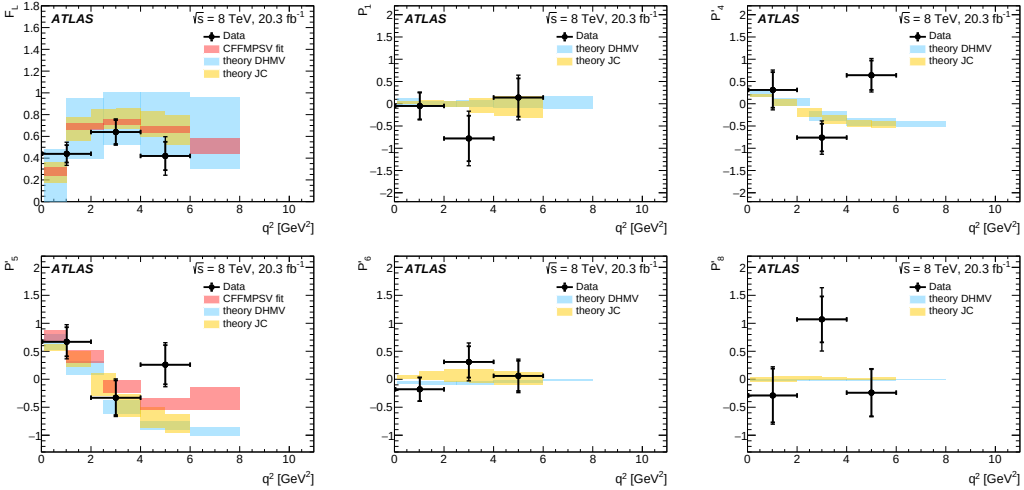








- Results $\sim$ compatible with SM, largest (local) deviations of 2.7σ for P_5' and P_4'
- Run 2 analysis in progress, similar analysis approach



Summary

- Ongoing and future analyses expected to follow the binned approach, possibly extract more parameters, wider q^2 range, and make technical improvements (selection, fits)
- Binning driven by available statistics, but no problem to accommodate any agreed bin-edges
- Possible deviations: resolution drives bin edges near resonances ($\phi \to \mu\mu$ veto, distance from $c\bar{c}$)

Thank you

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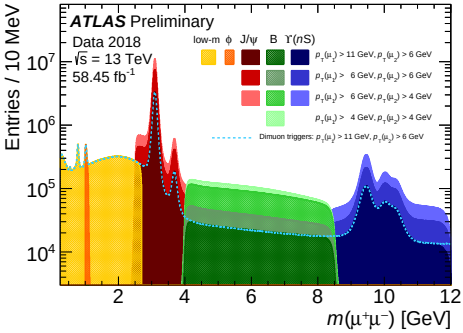
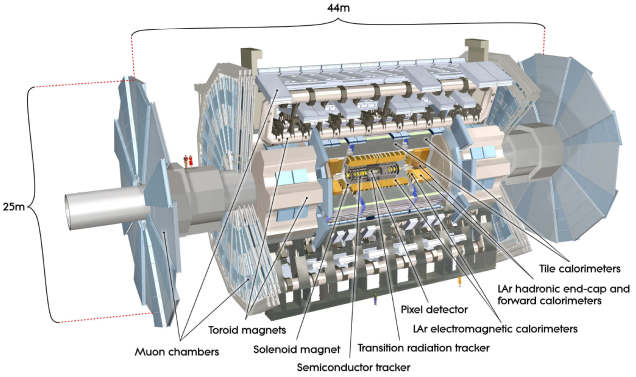
Backup

B-Physics at ATLAS

- Producing 2.5 M $b\bar{b}$ pairs/second, B_s, B_c, Λ_b, etc. available
- Program focused mostly on muonic final states, fully reconstructable
- Typical trigger: low-p_T di-muons at low invariant mass, using information from tracker and muon detectors
- B-physics trigger rate up to ~ 200 Hz





Triggers

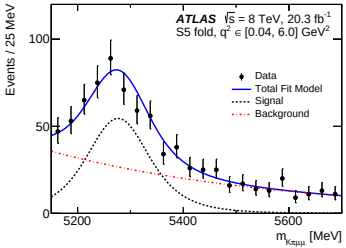
- Limited by rate of HW-based L1 system
- Combination of 19 single-/di-/tri-muon triggers
- Dimuon typically with 4(6) GeV thresholds

Offline selection optimized on MC (cherry pick)

- B-decay vertex reconstruction, $\chi^2/\mathrm{ndf} < 2$
- B-hadron decay time significance $\tau/\sigma_\tau > 12.25$
- B-momentum pointing to collision vertex $\cos\theta > 0.999$
- Radiative tail cut: $\left|(m(B)\text{-}m_{\mathrm{pdg}}(B)) - (m(\mu\mu)\text{-}m_{\mathrm{pdg}}(J/\psi))\right| < 130\,\mathrm{MeV}$

Multiple candidates

- Candidates from different tracks $\rightarrow$ pick smallest vertex $\chi^2/\mathrm{ndf} < 2$
- Same tracks $\Rightarrow$ B or $\bar{B}$? $\rightarrow$ pick smallest $\left|m(K^*)\text{-}m_{\mathrm{pdg}}(K^*)\right|/\sigma_{m(K^*)}$



q^2 [GeV^2]	n_{signal}	$n_{\mathrm{background}}$
[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

Angular distribution foldings (complete)

- Not enough statistics for full 3D angular fit $\implies$ fold distributions, but lost sensitivity to S_6 (A_{FB}) and S_9

$$F_L, S_3, S_4, P_4^{'}: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_L > \frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2} \end{cases}$$

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{8\pi}\Big[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin\theta_\ell\cos\phi\Big]$$

$\cos\theta_L \in [0,1], \cos\theta_K \in [-1,1]$ and $\phi \in [0,\pi]$

$$F_L, S_3, S_5, P_5^{'}: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2} \end{cases}$$

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{8\pi}\Big[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi\Big]$$

$\cos\theta_L \in [0,1], \cos\theta_K \in [-1,1]$ and $\phi \in [0,\pi]$

$$F_L, S_3, S_7, P_6^{'}: \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \frac{\pi}{2} \\ \phi \to -\pi - \phi & \text{for } \phi < -\frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2} \end{cases}$$

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{8\pi}\Big[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi\Big]$$

$\cos\theta_L \in [0,1], \cos\theta_K \in [-1,1]$ and $\phi \in [-\pi/2, \pi/2]$

$$F_L, S_3, S_8, P_8^{'}: \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \frac{\pi}{2} \\ \phi \to -\pi - \phi & \text{for } \phi < -\frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2} \\ \theta_K \to \pi - \theta_K & \text{for } \theta_L > \frac{\pi}{2} \end{cases}$$

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{8\pi}\Big[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi\Big]$$

$\cos\theta_L \in [0,1], \cos\theta_K \in [-1,1]$ and $\phi \in [-\pi/2, \pi/2]$

- Large stat. errors $\Longrightarrow$ can afford very conservative approach to systematics
- Largest systematics from backgrounds modeling

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	0.04	0.06	0.16
D and B^+ veto	0.11	0.04	0.05	0.04	0.01	0.06
Background pdf shape	0.04	0.04	0.03	0.03	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	0.08	0.05	0.06
Alignment and B field calibration	0.02	0.04	0.05	0.04	0.04	0.04
Fit bias	0.01	0.01	0.02	0.03	0.01	0.05
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	0.03
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

- $|\cos\theta_K| < 0.9$
- veto B^+ or D hypothesis
- expo. / pol3
- factorization, signal MC test
- left B-mass sideband variation
- track p_T smearing
- toy-MC pulls
- data/MC $B - p_\mathrm{T}$ weights
- $B \to K\pi\mu\mu$, 5% fed to toy-MC
- control sample fit uncertainties
- toy-MC with peak. backgrounds
- B fit with $\bar{B}$ acceptance
- MC stat., ω vs $\bar{\omega}$

Backgrounds

Backgrounds from long-list found to have non-negligible contributions

- $B^+ \to K^{*+}\mu\mu$
- $B^+ \to K^+\mu\mu$
- $B_s^0 \to \phi\mu\mu$
- $\Lambda_b \to \Lambda(1520)\mu\mu$
- $\Lambda_b \to pK^-\mu\mu$
- $B^+ \to K\mu\mu, \pi\mu\mu$ peaking at $\cos(\theta_K) \sim 1.0$
- $B \to DX$ in left B-mass sideband peaking at $\cos(\theta_L) \sim 0.7$