Study of the decay $B_d^0 \to K^{*0}\mu^+\mu^-$ in ATLAS

ATLAS-CONF-2013-038 "Angular Analysis of $B_d^0 \to K^{*0}\mu^+\mu^-$ with the ATLAS Experiment"

Semen Turchikhin

Skobeltsyn Institute of Nuclear Physics
Moscow State University

on behalf of the ATLAS collaboration

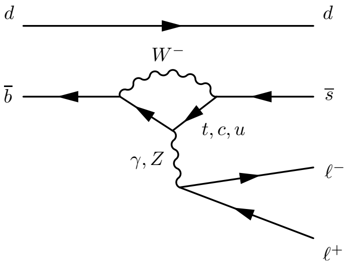
XXI International Workshop on Deep-Inelastic Scattering and Related Subjects

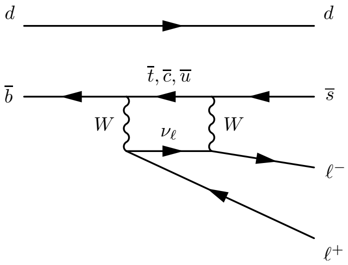
Marseilles, France

22–26 April 2013

Physics motivation

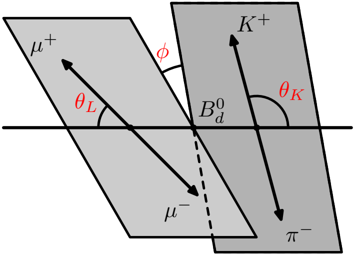
- $B_d^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ provides an exclusive final state for $b \to s\ell^+\ell^-$ processes
- Within the Standard Model the decay can occur via loop diagrams only
- $\mathscr{B}(B_d^0 \to K^{*0}\mu^+\mu^-) = (1.06 \pm 0.10) \times 10^{-6}$ (PDG) is rather small
- Angular parameters of the decay as functions of $q^2 = m^2(\mu^+\mu^-)$ are sensitive to many possible New Physics contributions (see e.g. C. Bobeth et al. *"Angular analysis of $B \to V(\to P_1P_2) + \bar{\ell}\ell$ decays"*, arXiv:1105.2659)
  - Shapes of muon forward-backward asymmetry A_{FB} and longitudinal polarization fraction F_L are shown to be independent on long-distance effects (D. Melikhov, N. Nikitin, S. Simula, *Phys. Lett. B* **430** *(1998) 332*)





Decay kinematics

- 4 kinematic variables
  - q^2 – di-lepton invariant mass squared
  - 3 angles: θ_L, θ_K, ϕ
- Not enough statistics to perform a fit to 4-differential distribution
- Integrate over 2 of 3 angles:

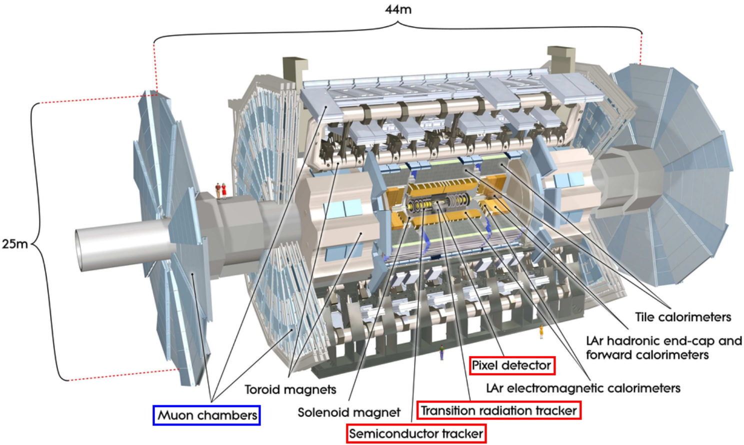


$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dq^2 d\cos\theta_L} = \frac{3}{4}F_L(q^2)(1-\cos^2\theta_L) + \frac{3}{8}(1-F_L(q^2))(1+\cos^2\theta_L) + A_{FB}(q^2)\cos\theta_L$$

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dq^2 d\cos\theta_K} = \frac{3}{2}F_L(q^2)\cos^2\theta_K + \frac{3}{4}(1-F_L(q^2))(1-\cos^2\theta_K)$$

- F_L – fraction of longitudinally polarized K^{*0}s
- A_{FB} – muons forward-backward asymmetry

ATLAS detector



This analysis uses

- Inner Detector for tracks measurement
- Muon Spectrometer for muons identification

Data and MC samples

4.9 fb^{-1} pp collision data collected with ATLAS at $\sqrt{s} = 7$ TeV in 2011

- Trigger selection based on single muon or di-muon signature

MC samples produced with PYTHIA were used for selection optimization:

- $B_d^0 \to K^{*0}\mu^+\mu^-$ (signal)
- $B_d^0 \to K^{*0}J/\psi(\to \mu^+\mu^-)$ (main peaking background)
- $b\bar{b} \to \mu^+\mu^- X$
- $c\bar{c} \to \mu^+\mu^- X$
- Drell-Yan

Event selection

Baseline selection

- $p_T(\mu) > 3.5$ GeV
- $p_T(K,\pi) > 0.5$ GeV
- $|\eta(\mu,K,\pi)| < 2.5$
- $\chi^2/\text{n.d.f.}(\mu^+\mu^-) < 10$
- $846 < M(K^{*0}) < 946$ MeV

- J/ψ and $\psi(2S)$ di-muon mass regions at 3σ are excluded from further analysis

$\sim$ 26M events from the data survive the baseline selection

Optimized selection

Suppress *combinatorics and Drell-Yan:*

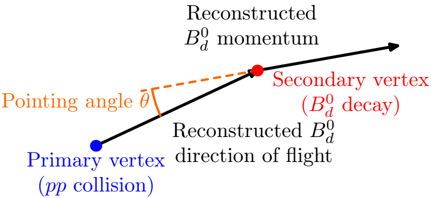
- $\chi^2/\text{n.d.f.}(B_d^0) < 2.0$
- $\tau/\Delta\tau(B_d^0) > 12.75$
- $\cos\theta > 0.999$

Suppress K^{*0} *not from* B *decay*

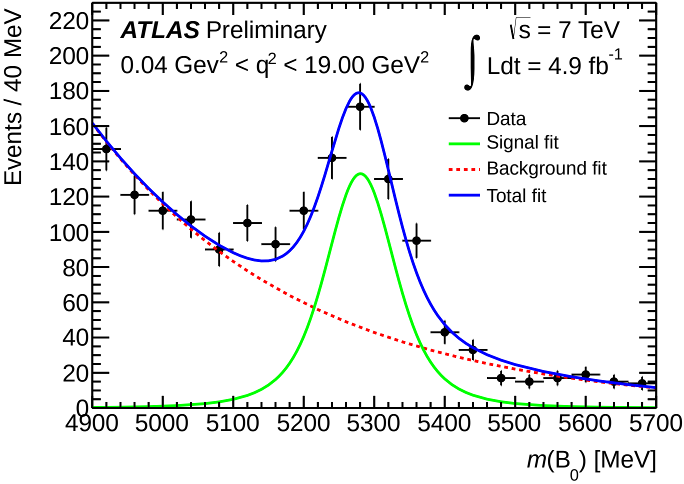
- $p_T(K^{*0}) > 3$ GeV

Suppress *radiative charmonia decays:*

- $\Delta M = |\,(M(B_d^0)_{\text{rec}} - M(B_d^0)_{\text{PDG}}) - (M(\mu^+\mu^-)_{\text{rec}} - M(J/\psi)_{\text{PDG}})\,| >$ 130 MeV
- same with $M(\psi(2S))_{\text{PDG}}$



Signal observation



- **Full di-muon mass range with J/ψ and $\psi(2S)$ regions excluded**
- **Signal yield $N_{\rm sig} = 466 \pm 34$**

Binning in q^2

Bins are identical to those used by Belle

- $0.04 < q^2 < 2.00$ GeV^2 – no angular analysis performed due to low statistics
- $2.00 < q^2 < 4.30$ GeV^2
- $4.30 < q^2 < 8.68$ GeV^2
- $8.68 < q^2 < 10.09$ GeV^2 – J/ψ mass region, excluded
- $10.09 < q^2 < 12.86$ GeV^2
- $12.86 < q^2 < 14.18$ GeV^2 – $\psi(2S)$ mass region, excluded
- $14.18 < q^2 < 16.00$ GeV^2
- $16.00 < q^2 < 19.00$ GeV^2

- $1.00 < q^2 < 6.00$ GeV^2

Fit strategy (1)

Extended unbinned maximum likelihood fit in each q^2 bin
Sequential fit: first fit $m(K\pi\mu\mu)$ distribution, then the angular distributions with mass term parameters fixed.

The procedure checked to give same results as single-step fit except the lowest q^2 bin (included in systematics there).

- Mass fit (*in each q^2 bin*):

$$\mathcal{L} = \prod_{i=1}^{N} [N_{\text{sig}} \cdot \mathcal{M}_{\text{sig}}(m_i, \delta_{m_i}) + N_{\text{bckg}} \cdot \mathcal{M}_{\text{bckg}}(m_i)]$$

- Signal mass PDF – gaussian with per-candidate errors:

$$\mathcal{M}_{\text{sig}}(m_i, \delta_{m_i}) = \frac{1}{\sqrt{2\pi} s_m \delta_{m_i}} \exp\left(\frac{-(m_i - m_{B_d^0})^2}{2(s_m \delta_{m_i})^2} \right)$$

- Background mass PDF – exponential

$$\mathcal{M}_{\text{bckg}}(m_i) = e^{-\lambda \cdot m_i}$$

Fit strategy (2)

- Angular fit (*in each q^2 bin*):

$$\mathcal{L} = \prod_{i=1}^{N} [N_{\rm sig}^{\rm fix} \cdot \mathcal{M}_{\rm sig}(m_i, \delta_{m_i} | {\rm fixed}) \cdot \mathcal{A}_{L,{\rm sig}}(\cos\theta_{L,i}) \cdot \alpha_L(\cos\theta_{L,i}) \cdot \mathcal{A}_{K,{\rm sig}}(\cos\theta_{K,i}) \cdot \alpha_K(\cos\theta_{K,i}) + N_{\rm bckg}^{\rm fix} \cdot \mathcal{M}_{\rm bckg}(m_i | {\rm fixed}) \cdot \mathcal{A}_{L,{\rm bckg}}(\cos\theta_{L,i}) \cdot \mathcal{A}_{K,{\rm bckg}}(\cos\theta_{K,i})]$$

- Signal PDFs:

$$\mathcal{A}_{L,{\rm sig}}(\cos\theta_{L,i}) = \frac{3}{4} F_L(q^2)\left(1 - \cos^2\theta_{L,i}\right) + \frac{3}{8}\left(1 - F_L(q^2)\right)\left(1 + \cos^2\theta_{L,i}\right) + A_{FB}(q^2)\cos\theta_{L,i}$$

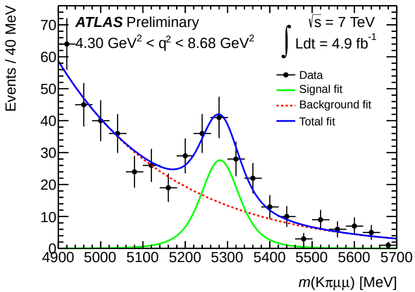
$$\mathcal{A}_{K,{\rm sig}}(\cos\theta_{K,i}) = \frac{3}{2} F_L(q^2)\cos^2\theta_{K,i} + \frac{3}{4}\left(1 - F_L(q^2)\right)\left(1 - \cos^2\theta_{K,i}\right)$$

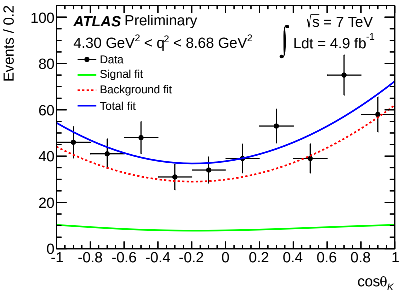
- Background PDF – linear combination of Chebyshev polynomials up to 2$^{\rm nd}$ order:

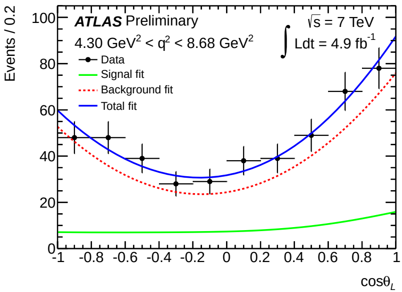
$$\mathcal{A}_{L(K),{\rm bkg}} = 1 + p_{1L(K)}\cos\theta_{L(K),i} + p_{2L(K)}\left(2\cos^2\theta_{L(K),i} - 1\right)$$

- $\alpha_L(\cos\theta_{L,i})$, $\alpha_K(\cos\theta_{K,i})$ – acceptance functions taking into account detector and selection effect on the angular shapes

Example of the fit in a q^2 bin ($4.30 < q^2 < 8.68$ GeV^2)







Systematic uncertainties

- Ranges of the mass fit region
  - Differ in q^2 bins due to ΔM cut effect
- Angular background shapes
  - Varied between 2nd and 3rd Chebyshev polynomials
- Contribution of $B^{\pm} \to \mu^+\mu^- K^{\pm}$ events
  - Estimated by removing potential $B^{\pm} \to \mu^+\mu^- K^{\pm}$ candidates
- Angular acceptance effects
  - Mainly from limited MC statistics; various signal angular shapes tested
- Sequential fitting approach
  - Non-negligible only in $2.00 < q^2 < 4.30$ GeV^2 bin due to low statistics

- Following sources found to be negligible
  - Contribution from S-wave ($B_d^0 \to K^+\pi^-\mu^+\mu^-$ decays)
  - Contribution from $B_s \to \phi(\to K^+K^-)\mu^+\mu^-$ events
  - Background mass shape
  - Possible bias due to angular fit approach (neglecting correlations)

Systematic uncertainties (cont.)

A_{FB} systematics

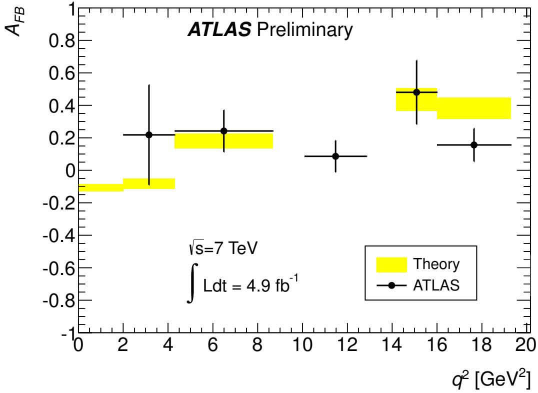
q^2 range (GeV^2)	fit region	ang. fit	$B^\pm \to \mu^+\mu^- K^\pm$	acc. maps	fit	SUM
$2.00 < q^2 < 4.30$	0.02	0.01	0.08	0.01	0.10	0.136
$4.30 < q^2 < 8.68$	0.00	0.01	0.01	0.01		0.013
$10.09 < q^2 < 12.86$	0.03	0.01	0.02	0.00		0.031
$14.18 < q^2 < 16.00$	0.03	0.01	0.03	0.02		0.050
$16.00 < q^2 < 19.00$	0.02	0.01	0.02	0.01		0.026
$1.00 < q^2 < 6.00$	0.05	0.01	0.02	0.04		0.069

F_L systematics

q^2 range (GeV^2)	fit region	ang. fit	$B^\pm \to \mu^+\mu^- K^\pm$	acc. maps	fit	SUM
$2.00 < q^2 < 4.30$	0.01	0.01	0.02	0.01	0.05	0.058
$4.30 < q^2 < 8.68$	0.01	0.01	0.00	0.02		0.021
$10.09 < q^2 < 12.86$	0.04	0.01	0.00	0.02		0.042
$14.18 < q^2 < 16.00$	0.01	0.01	0.02	0.01		0.025
$16.00 < q^2 < 19.00$	0.02	0.01	0.01	0.00		0.023
$1.00 < q^2 < 6.00$	0.02	0.01	0.00	0.03		0.034

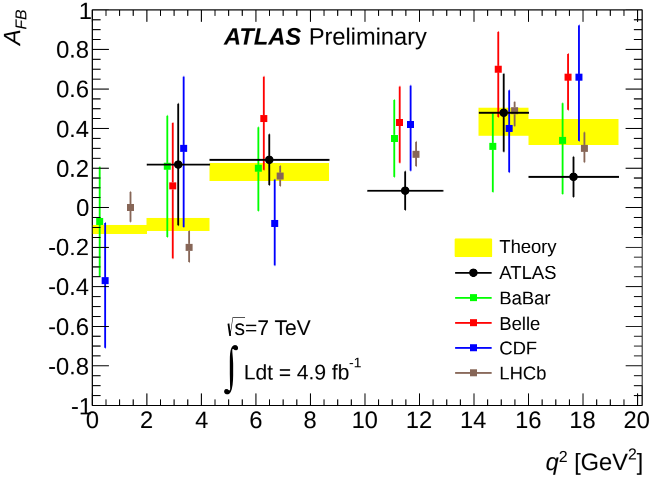
A_{FB} results

Theoretical prediction from C. Bobeth et al. arXiv:1105.2659



q^2 range (GeV^2)	N_{sig}	A_{FB}	F_L
$2.00 < q^2 < 4.30$	19±8	$0.22 \pm 0.28 \pm 0.14$	$0.26 \pm 0.18 \pm 0.06$
$4.30 < q^2 < 8.68$	88±17	$0.24 \pm 0.13 \pm 0.01$	$0.37 \pm 0.11 \pm 0.02$
$10.09 < q^2 < 12.86$	138±31	$0.09 \pm 0.09 \pm 0.03$	$0.50 \pm 0.09 \pm 0.04$
$14.18 < q^2 < 16.00$	32±14	$0.48 \pm 0.19 \pm 0.05$	$0.28 \pm 0.16 \pm 0.03$
$16.00 < q^2 < 19.00$	149±24	$0.16 \pm 0.10 \pm 0.03$	$0.35 \pm 0.08 \pm 0.02$
$1.00 < q^2 < 6.00$	42±11	$0.07 \pm 0.20 \pm 0.07$	$0.18 \pm 0.15 \pm 0.03$

A_{FB} results comparison

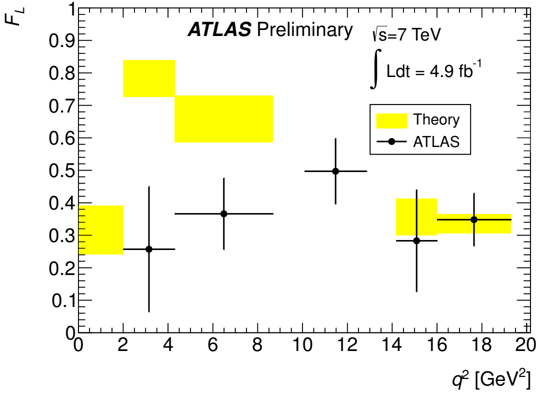


Other experiments results:

- BaBar arXiv:0804.4412
- Belle arXiv:0904.0770
- CDF arXiv:1108.0695
- LHCb LHCb-CONF-2012-008
- CMS CMS-PAS-BPH-11-009 (not yet included in the plot)

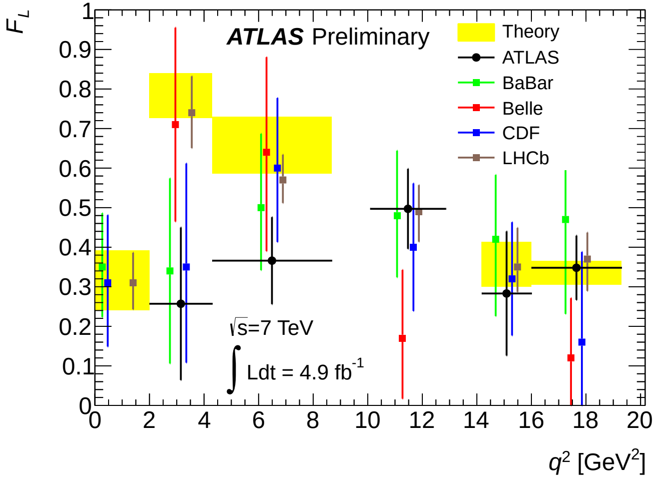
F_L results

Theoretical prediction from arXiv:1105.2659



q^2 range (GeV^2)	N_{sig}	A_{FB}	F_L
$2.00 < q^2 < 4.30$	$19\pm\ 8$	$0.22 \pm 0.28 \pm 0.14$	$0.26 \pm 0.18 \pm 0.06$
$4.30 < q^2 < 8.68$	88 ± 17	$0.24 \pm 0.13 \pm 0.01$	$0.37 \pm 0.11 \pm 0.02$
$10.09 < q^2 < 12.86$	138 ± 31	$0.09 \pm 0.09 \pm 0.03$	$0.50 \pm 0.09 \pm 0.04$
$14.18 < q^2 < 16.00$	32 ± 14	$0.48 \pm 0.19 \pm 0.05$	$0.28 \pm 0.16 \pm 0.03$
$16.00 < q^2 < 19.00$	149 ± 24	$0.16 \pm 0.10 \pm 0.03$	$0.35 \pm 0.08 \pm 0.02$
$1.00 < q^2 < 6.00$	42 ± 11	$0.07 \pm 0.20 \pm 0.07$	$0.18 \pm 0.15 \pm 0.03$

F_L results comparison



Other experiments results:

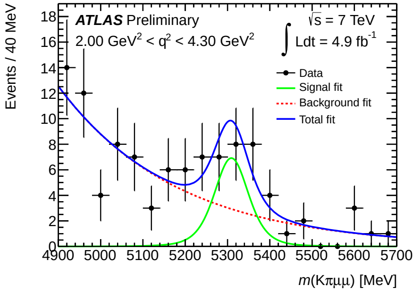
- BaBar arXiv:0804.4412
- Belle arXiv:0904.0770
- CDF arXiv:1108.0695
- LHCb LHCb-CONF-2012-008
- CMS CMS-PAS-BPH-11-009 (not yet included in the plot)

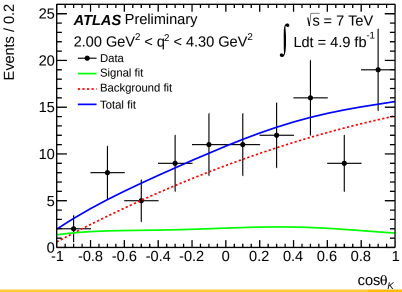
Conclusions

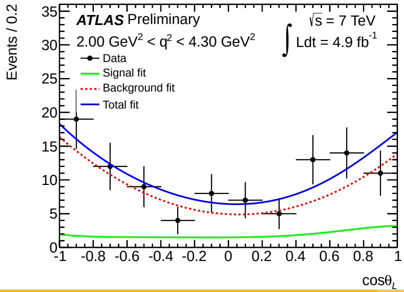
- Analysis has been performed on 2011 ATLAS data to study the angular distributions of $B_d^0 \to K^{*0}\mu^+\mu^-$ decay
- 466 signal events were observed
- A_{FB} and F_L have been measured as functions of di-muon invariant mass
- Various sources of systematic uncertainties were studied; the statistical errors were found to be dominant
- No significant disagreement with the SM predictions was found
- The results are consistent with other experiments (BaBar, Belle, CDF and LHCb)
- We are looking forward to analyse the data collected in 2012

Backup slides

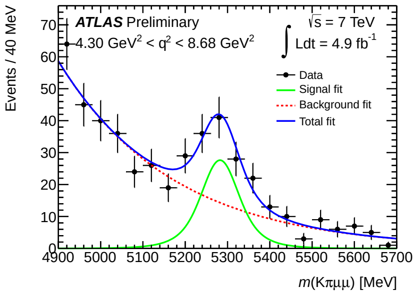
Fit results in various q^2 bins: $2.00 < q^2 < 4.30$ GeV^2

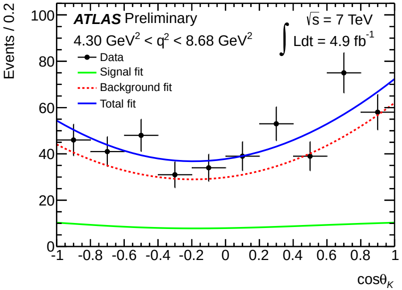


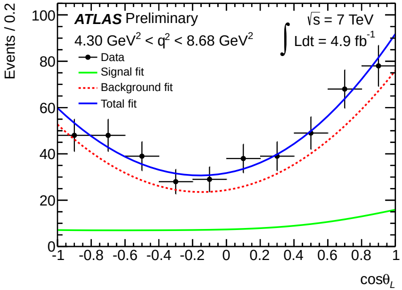




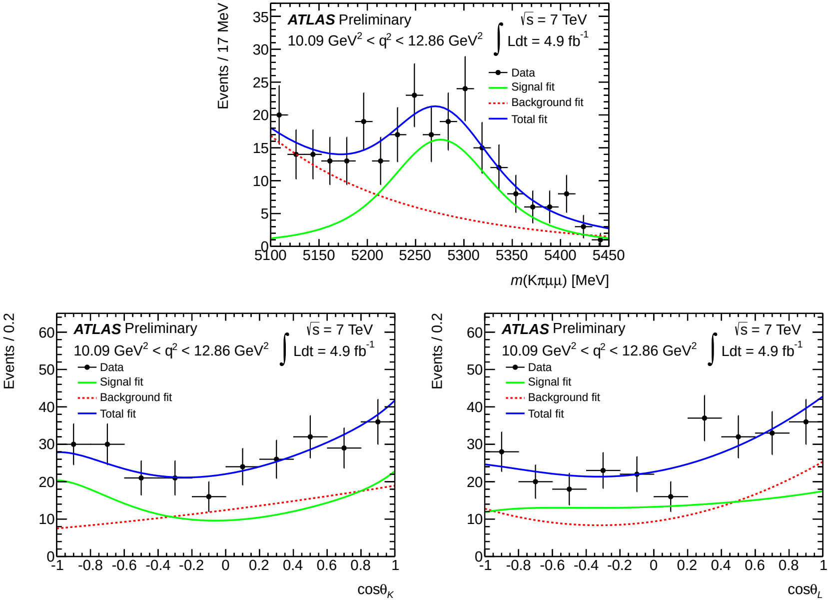
Fit results in various q^2 bins: $4.30 < q^2 < 8.68$ GeV^2



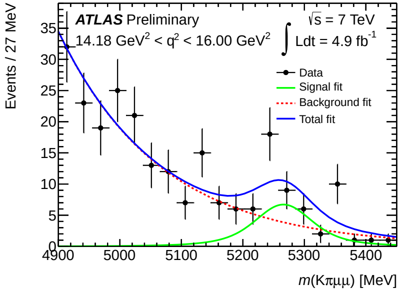


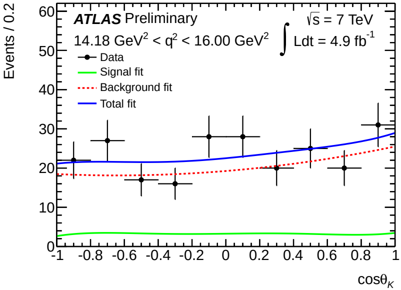


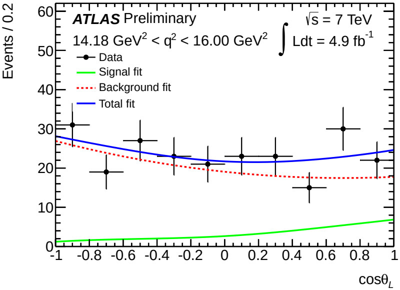
Fit results in various q^2 bins: $10.09 < q^2 < 12.86$ GeV^2



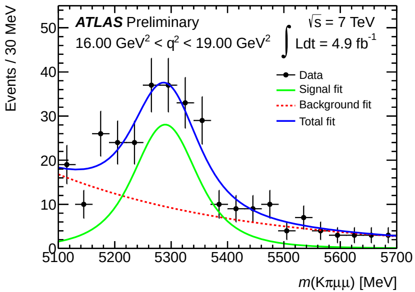
Fit results in various q^2 bins: $14.18 < q^2 < 16.00$ GeV^2

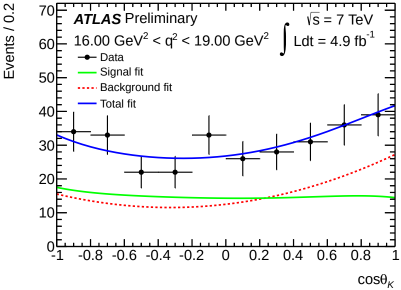


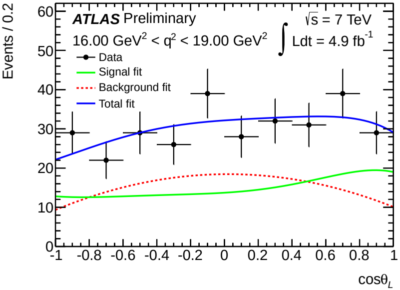




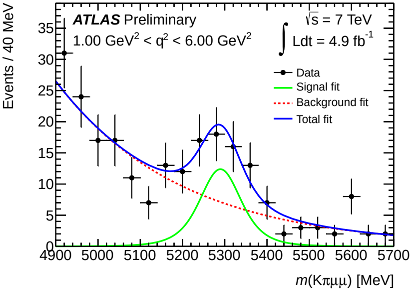
Fit results in various q^2 bins: $16.00 < q^2 < 19.00$ GeV^2

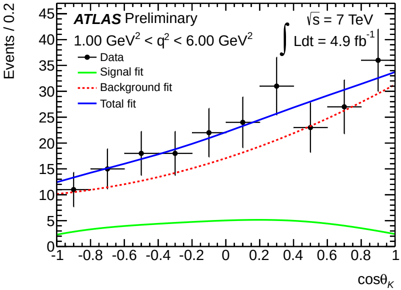


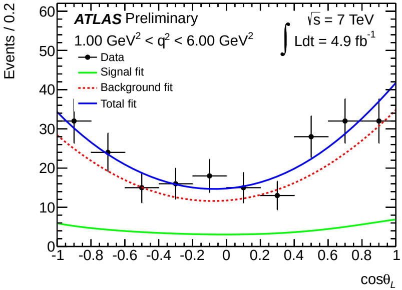




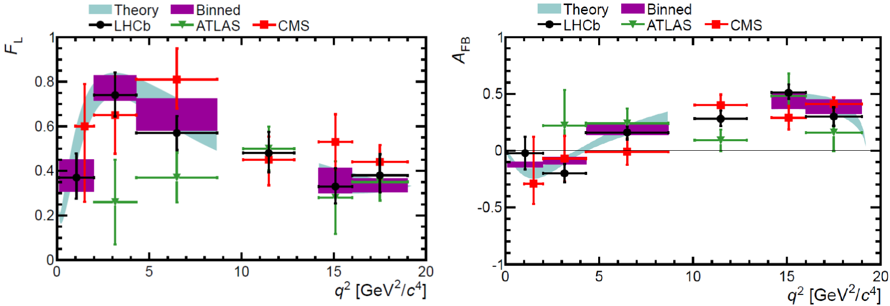
Fit results in various q^2 bins: $1.00 < q^2 < 6.00$ GeV^2





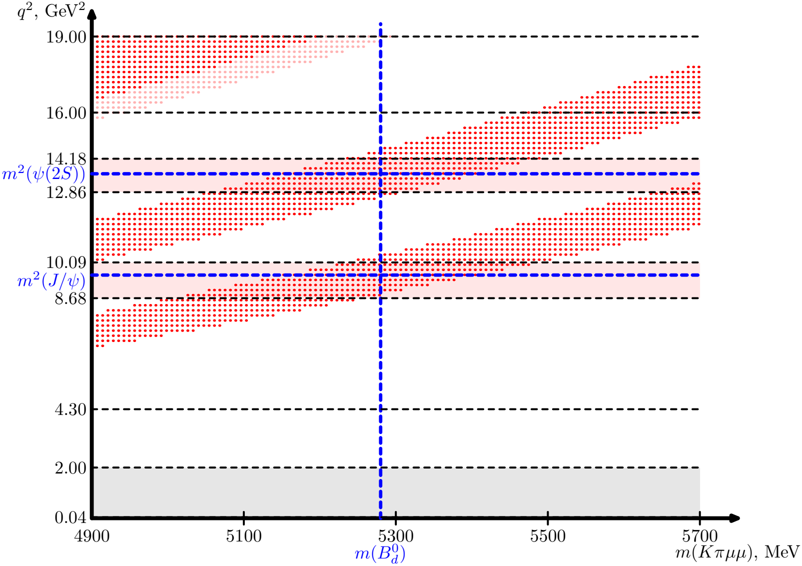


Comparison with other experiments



(Thanks to Tom Blake for the comparison plots including CMS results)

q^2 versus $m(K\pi\mu^+\mu^-)$



K^{*0} mis-reconstruction

- K^{*0} can be mis-reconstructed due to kaon-pion swapping
- Leads to $\cos\theta_L \to \cos(\pi - \theta_L) = -\cos\theta_L$, $\cos\theta_K \to -\cos\theta_K$
- It can affect only A_{FB}, since F_L enters the likelihood with $\cos^2\theta_K$
- The rate of mis-reconstruction is determined from MC and found to be $\eta_{K\pi} = (12.5 \pm 0.3)\%$
- Linear term in $\cos\theta_L$ fit changes $A_{FB}(q^2) \to (1 - 2\eta_{K\pi})A_{FB}(q^2)$:

$$\mathcal{A}_{L,\mathrm{sig}}(\cos\theta_{L,i}) = \frac{3}{4}F_L(q^2)\left(1 - \cos^2\theta_{L,i}\right) + \frac{3}{8}\left(1 - F_L(q^2)\right)\left(1 + \cos^2\theta_{L,i}\right) + (1 - \eta_{K\pi})A_{FB}(q^2)\cos\theta_{L,i}$$