$B_d \rightarrow K^{*0}\mu\mu$ with ATLAS

BEAUTY 2013

Anna Usanova

Innsbruck University
Institute for Astro- and
Particle Physics

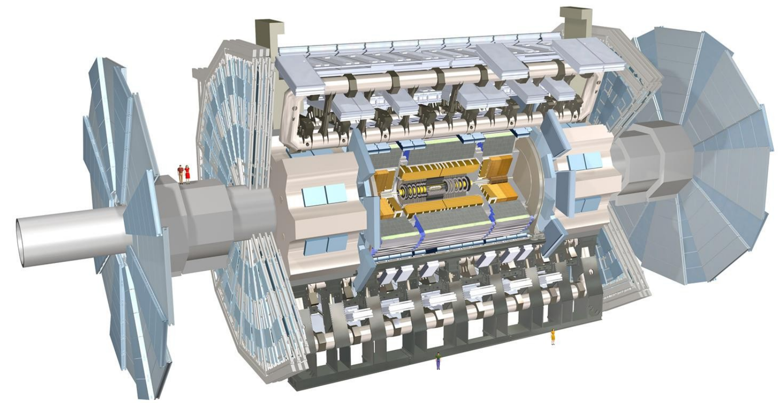
For the
ATLAS collaboration

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

Outline

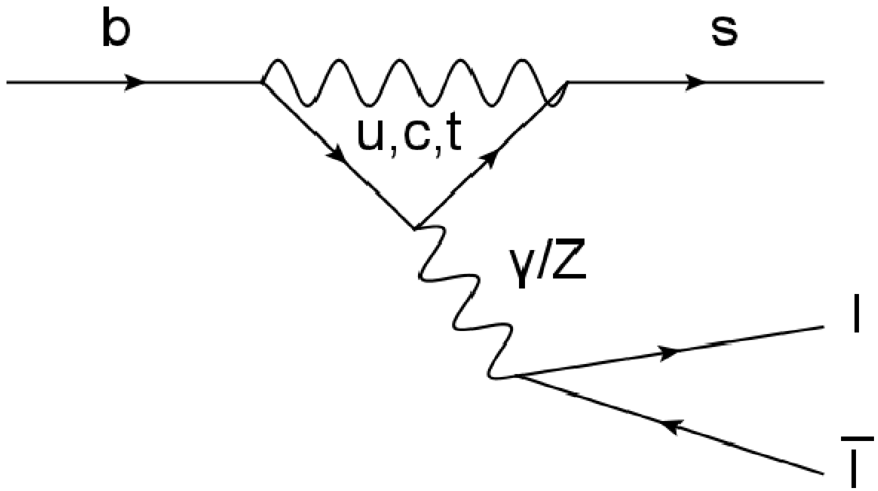
- Motivation
- Introduction
- Details of the analysis:
  - Data
  - Analysis strategy
  - Sources of systematic uncertainties
- Results, comparison
- Conclusions, outlook

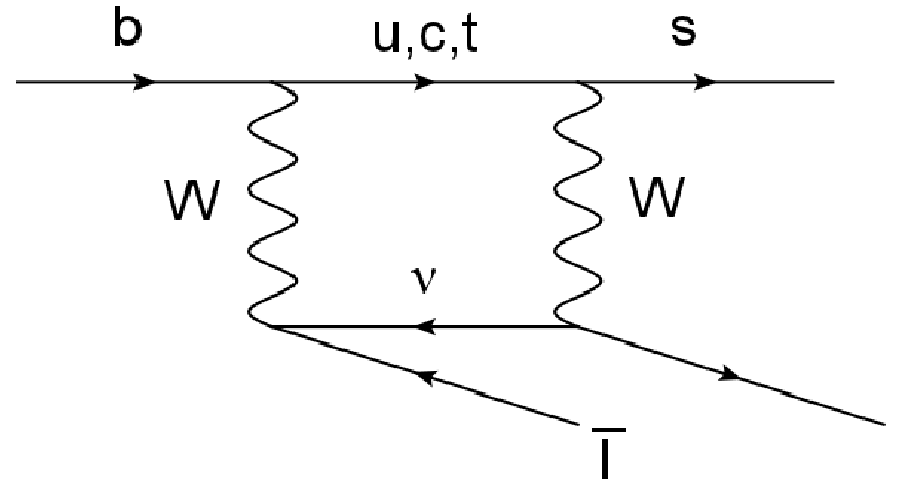
Outline



- Motivation
- Introduction
- Details of the analysis:
  - Data
  - Analysis strategy
  - Sources of systematic uncertainties
- Results, comparison
- Conclusions, outlook

Motivation





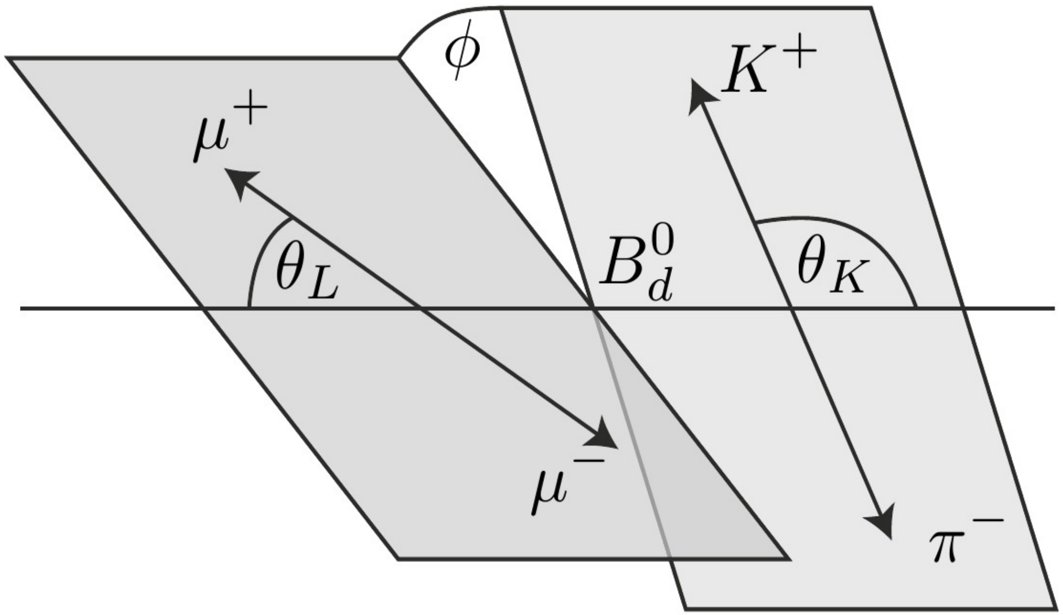
- $B_d \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ is one of the exclusive final states for $b \to sl^+l^-$
- Rare decay with a relatively small branching fraction

  $Br(B_d \to K^{*0}\mu^+\mu^-) = (1.06 \pm 0.1) \cdot 10^{-6}$ *http://pdg.lbl.gov*

- Can occur only on the loop level, as SM has no FCNCs on the tree level
- The angular distributions in these decays as a function of dilepton mass squared $q^2 = m^2(l^+l^-)$ are sensitive to many possible scenarios of physics beyond the SM

C.Bobeth et al. "Angular analysis of $B \to V (\to P_1P_2)\, l^+l^-$ decays" arXiv:1105.2659v1

Introduction



4 kinematic variables:
q^2 – invariant mass of the leptons
angles ϕ, θ_k, θ_l

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

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

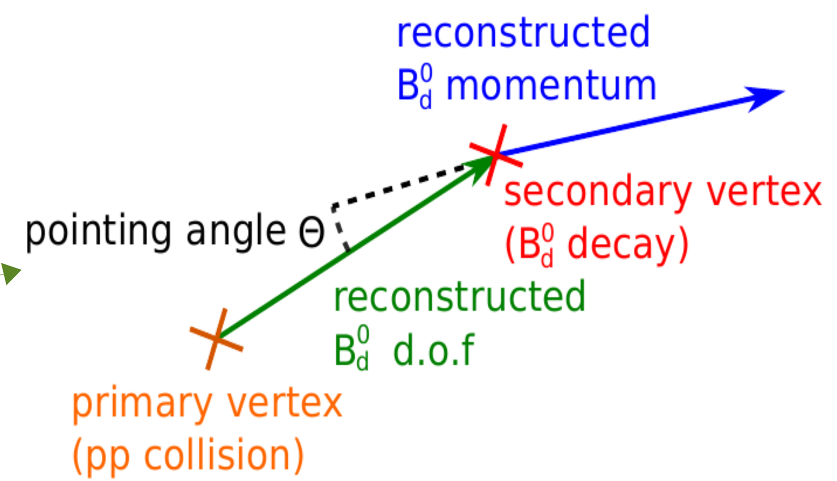
$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dq^2 d\cos\theta_K} = \frac{3}{2}F_L(q^2)\cos^2\theta_K + \frac{3}{4}\left(1-F_L(q^2)\right)\left(1-\cos^2\theta_K\right)$$

Data and MC used

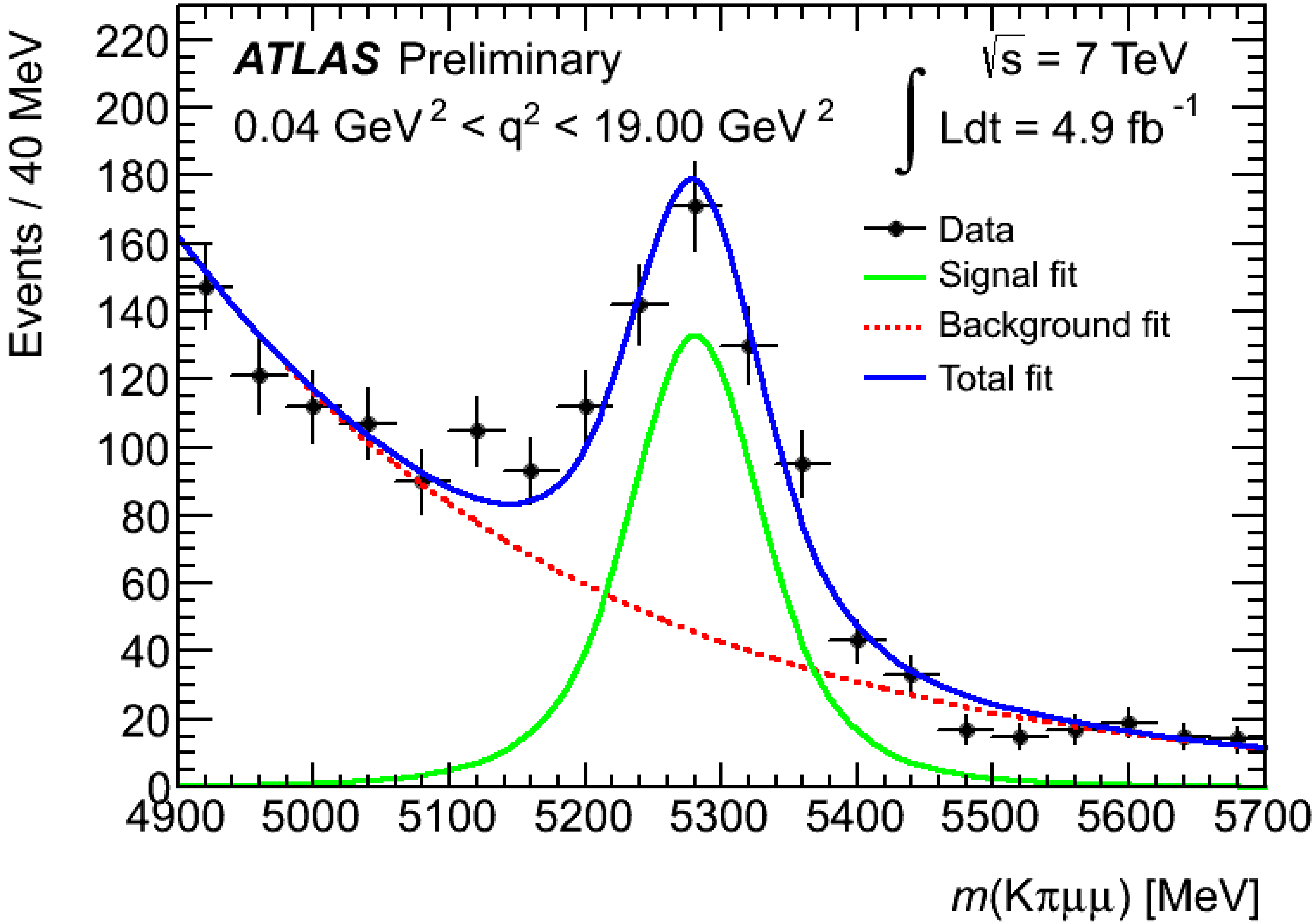
- 4.9 fb^{-1} collected with ATLAS in 2011 at $\sqrt{s} = 7$ TeV
  - Single- and dimuon triggers
- MC event samples (PythiaB) used for selection optimization:
  - $B_d \rightarrow K^{0*}\mu\mu$ (signal)
  - bb $\rightarrow \mu\mu X$
  - cc $\rightarrow \mu\mu X$
  - Drell-Yan
  - $B_d \rightarrow J/\psi K^*$

Event selection

- Based on cuts
- Baseline:
  - $p_T(\mu) > 3.5$ GeV
  - $|\eta| < 2.5$ for all tracks
  - $\chi^2/n.d.f\,(\mu\mu) < 10$
  - $846 < M(K^{*0}) < 946$ MeV
  - $p_T(K) > 0.5$ GeV
  - $p_T(\pi) > 0.5$ GeV
- J/ψ, $\Psi'(2S)$ regions are excluded
- Selection (cut values are optimized):
  - $\tau/\Delta\tau\,(B_d) > 12.75$
  - $\cos(\theta) > 0.999$
  - $\chi^2/n.d.f.\,(B_d) < 2.0$
  - $p_T(K^*) > 3$ GeV
  - $|(M(B^0)_{rec} - M(B^0)_{PDG})| - |(M(\mu\mu)_{rec} - M(J/\psi)_{PDG})| > 130$ MeV



Signal observation



In full range of dimuon mass, with J/ψ, Ψ'(2S) regions excluded

q^2 bins

Data is separated into 9 regions of dimuon mass [GeV^2] – binning identical to Belle

- $0.04 < q^2 < 2.00$ No angular analysis performed due to low number of events
- $2.00 < q^2 < 4.30$
- $4.30 < q^2 < 8.68$
- $8.68 < q^2 < 10.09$ J/ψ
- $10.09 < q^2 < 12.86$
- $12.86 < q^2 < 14.18$ ψ'(2S)
- $14.18 < q^2 < 16.00$
- $16.00 < q^2 < 19.00$
- $1.00 < q^2 < 6.00$

Fit strategy

- Extended unbinned maximum likelihood fit

Mass term — Angular terms

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

Acceptance functions, taking into account detector and cuts effects on angular shape. Polynomials obtained from fit to signal MC sample

- Sequential fit approach: first mass distribution is fitted, then a multidimensional dataset is fitted with fixed parameters of the mass PDF

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

Performed individually in each q^2 bin

- Mass distribution: signal → gaussian with per-event errors, background → exponential

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

Fit strategy

- Angular terms

  - Signal

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

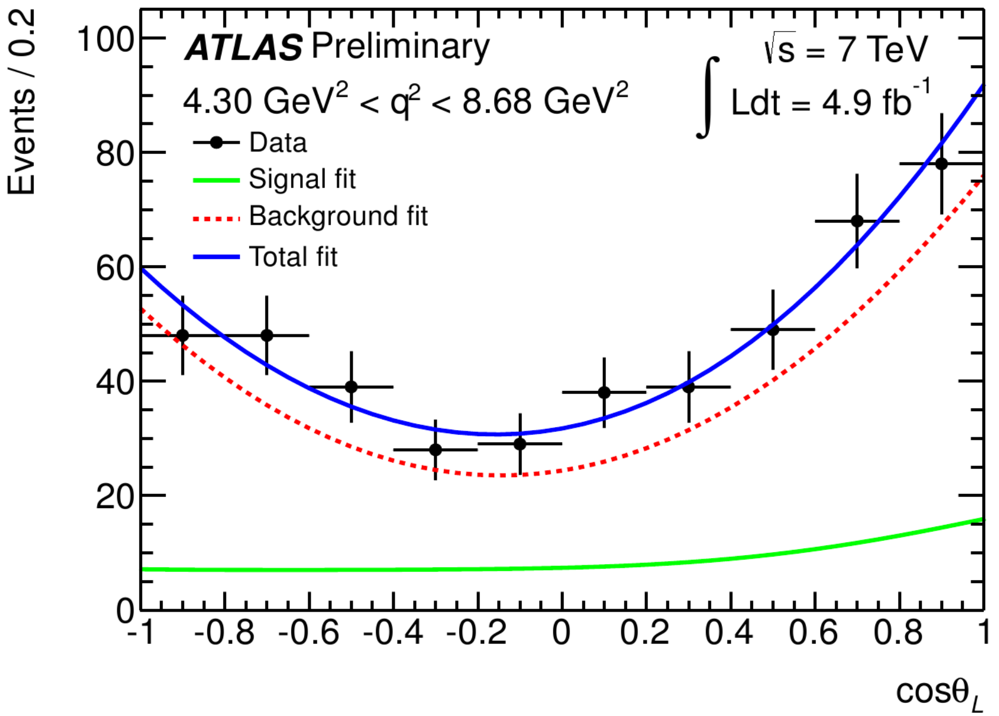
$$\mathcal{A}_{K,\mathrm{sig}}(\cos\theta_{K,i}) = \frac{3}{2}F_L(\cos\theta_{K,i})^2 + \frac{3}{4}(1-F_L)\left(1-(\cos\theta_{K,i})^2\right)$$

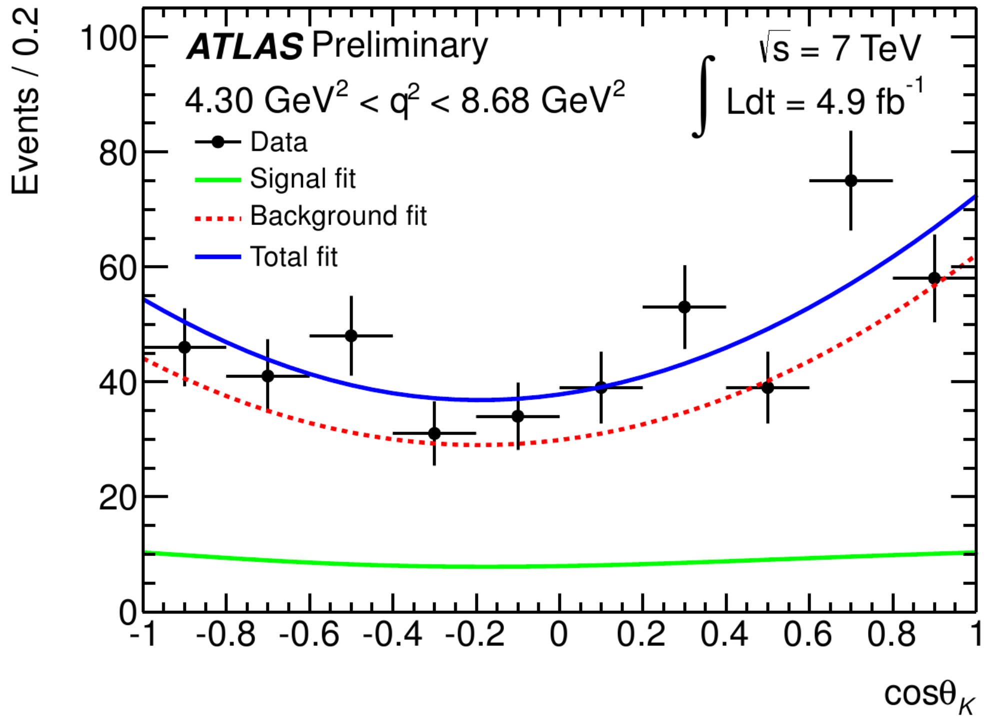
  - Background – 2nd order Chebyshev polynomials

$$\mathcal{A}_{L,\mathrm{bckg}}(\cos\theta_{L,i}) = 1 + p_1\cos\theta_{L,i} + p_2\left(2(\cos\theta_{L,i})^2 - 1\right)$$

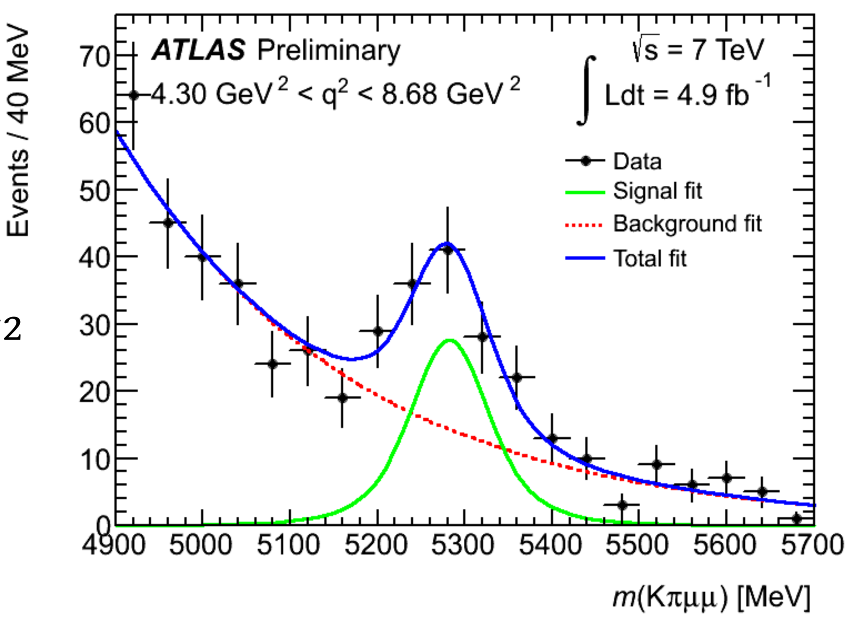
$$\mathcal{A}_{K,\mathrm{bckg}}(\cos\theta_{K,i}) = 1 + p_1\cos\theta_{K,i} + p_2\left(2(\cos\theta_{K,i})^2 - 1\right)$$

Example of the fit





4.30 GeV^2 < q^2 < 8.68 GeV^2



Systematic uncertainties

- Mass fit region
- Angular background shape
- Contribution of $B^+ \rightarrow \mu^+\mu^- K^+$ events
- Acceptance effects
- Fit mode (sequential fit approach)
- Sources that were studied but found negligible:
  - S-wave contribution
  - $B_s \rightarrow \phi\mu^+\mu^-$ contribution
  - Bias due to the fit model (linearity, 1D-2D)

Systematic uncertainties

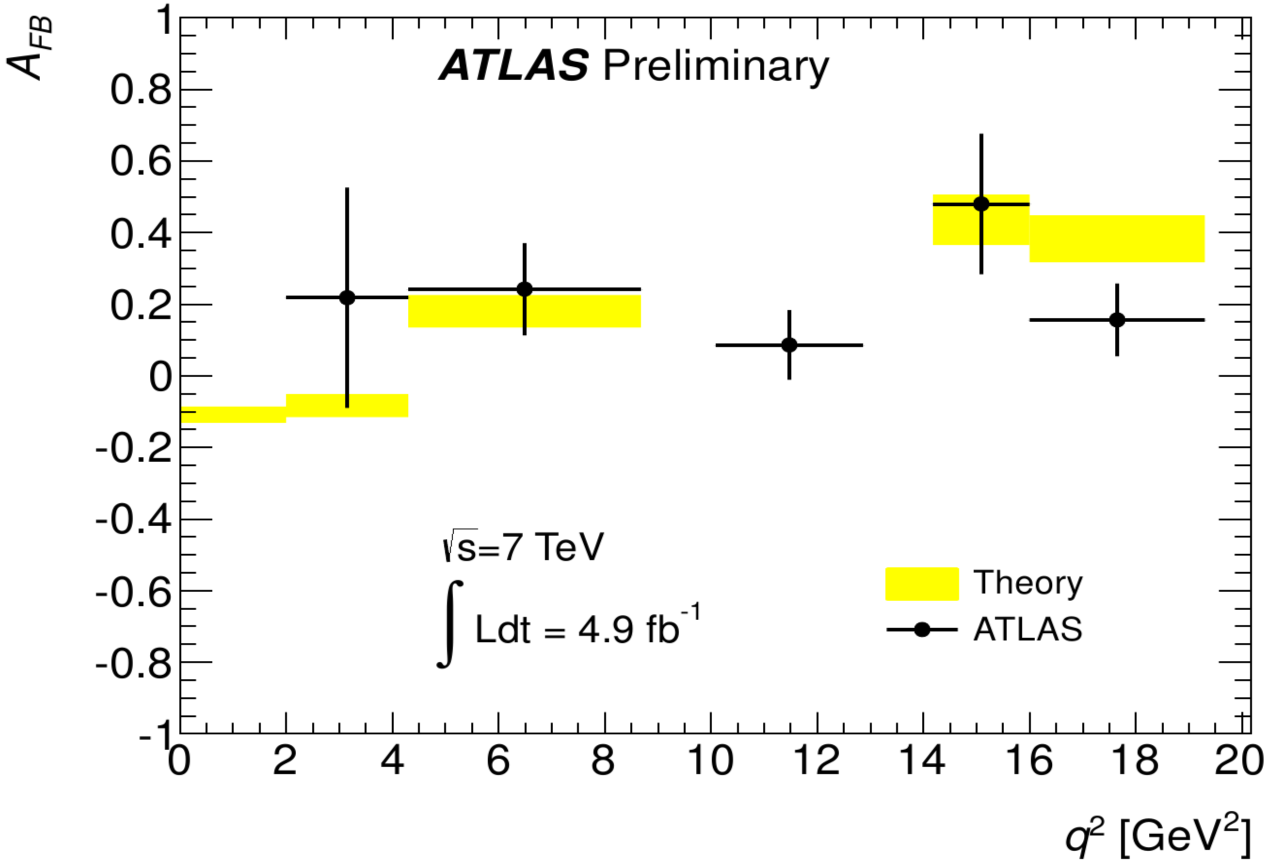
A_{FB}

q^2 range (GeV^2)	fit region	ang. fit	$B^\pm \to K^\pm \mu^+ \mu^-$	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

q^2 range (GeV^2)	fit region	ang. fit	$B^\pm \to K^\pm \mu^+ \mu^-$	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

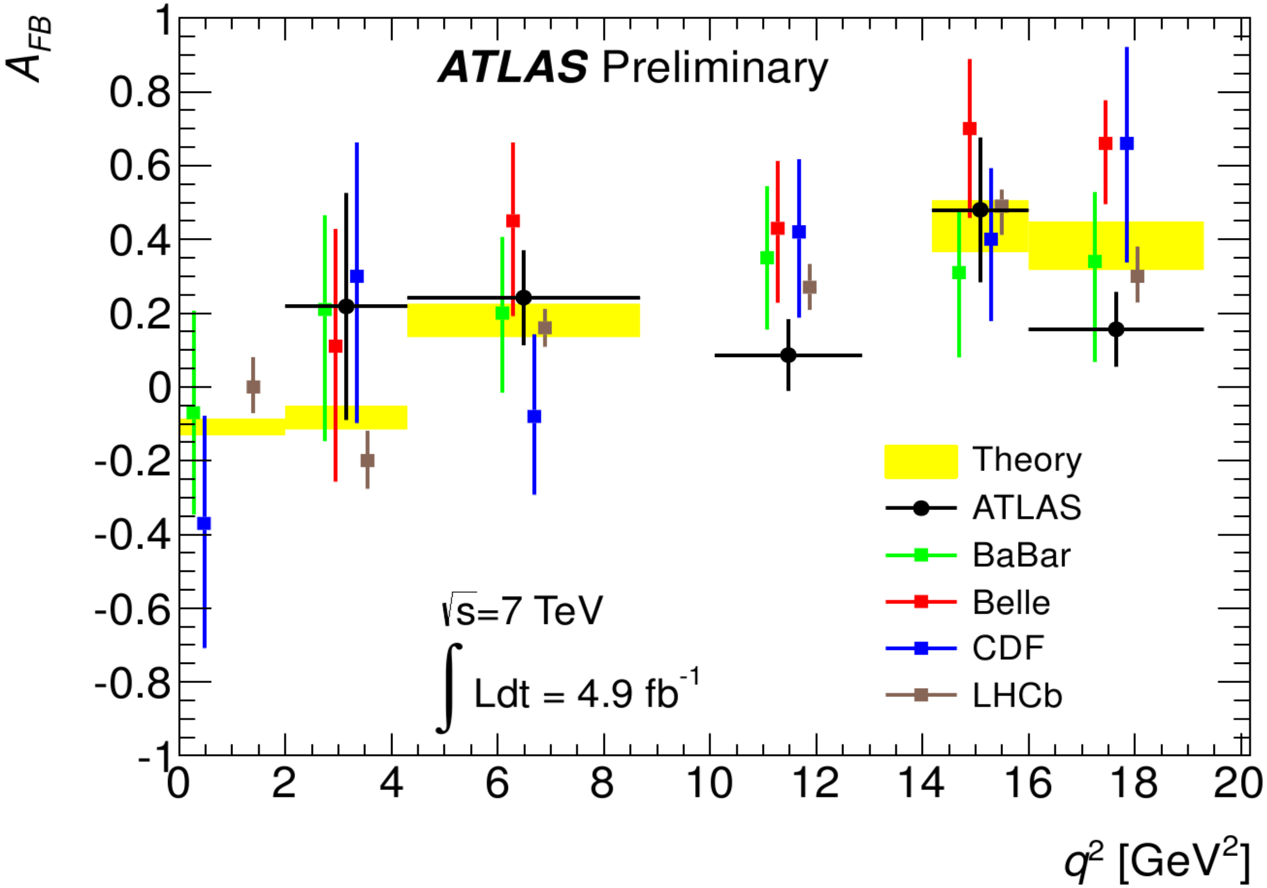
Result: A_{FB}



Theory prediction: arXiv:1105.2659v1

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	$0.07 \pm 0.20 \pm 0.07$	$0.18 \pm 0.15 \pm 0.03$

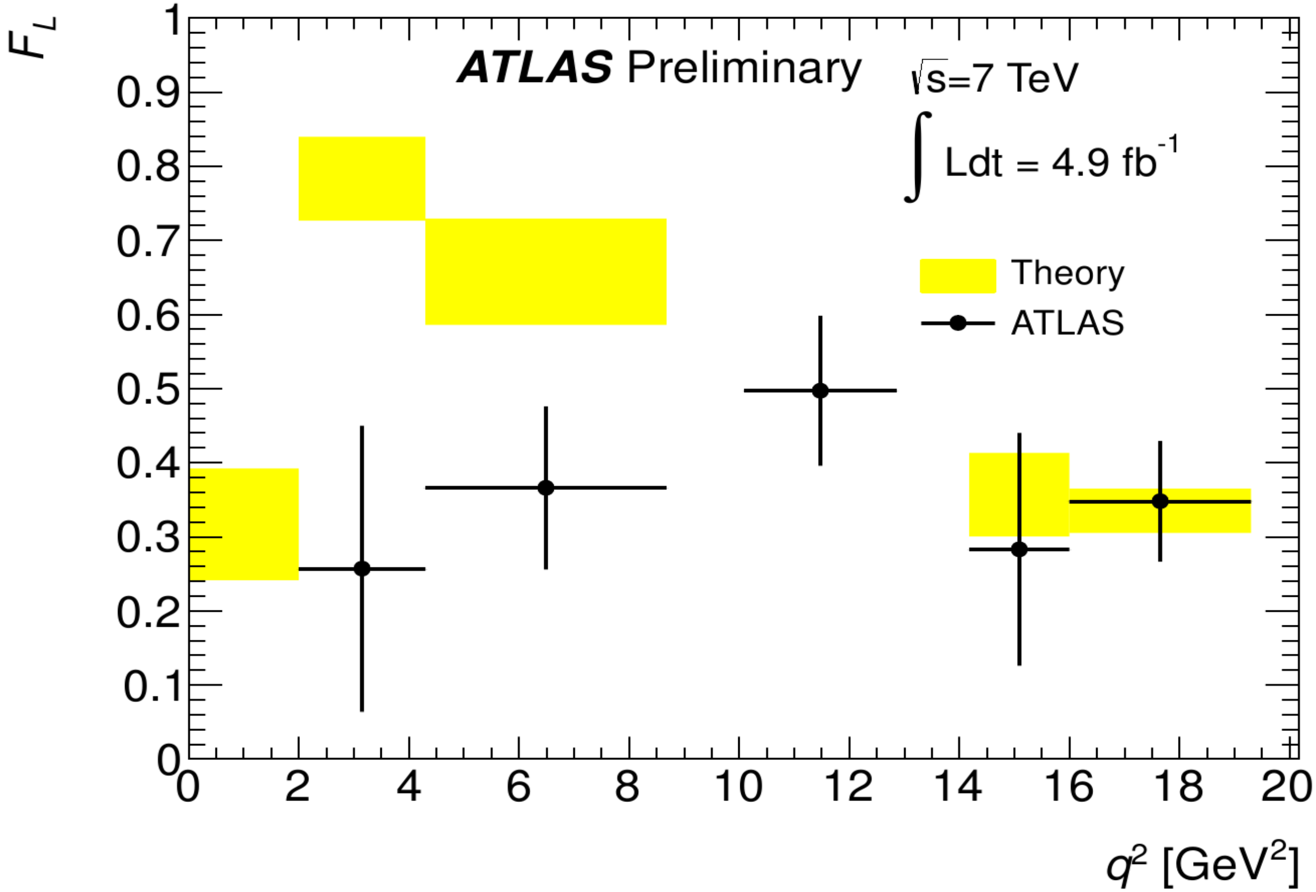
Result: A_{FB}



BaBar: arXiv:0804.4412
Belle: arXiv:0904.0770
CDF: arXiv: 1108.0695
LHCb: http://cds.cern.ch/record/1427691

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	$0.07 \pm 0.20 \pm 0.07$	$0.18 \pm 0.15 \pm 0.03$

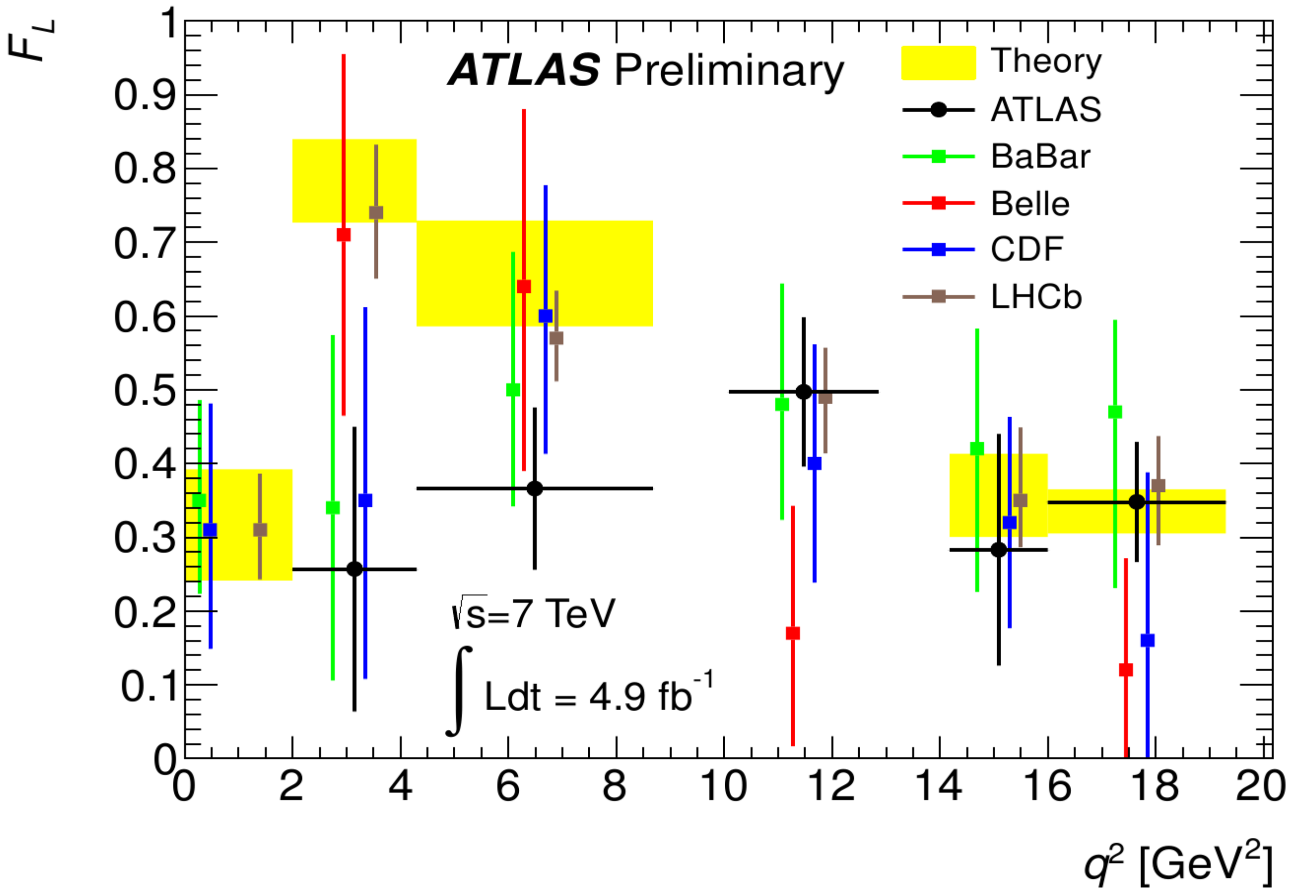
Result: F_L



Theory prediction:
arXiv:1105.2659v1

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	$0.07 \pm 0.20 \pm 0.07$	$0.18 \pm 0.15 \pm 0.03$

Result: F_L



BaBar: arXiv:0804.4412
Belle: arXiv:0904.0770
CDF: arXiv: 1108.0695
LHCb: http://cds.cern.ch/record/1427691

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	$0.07 \pm 0.20 \pm 0.07$	$0.18 \pm 0.15 \pm 0.03$

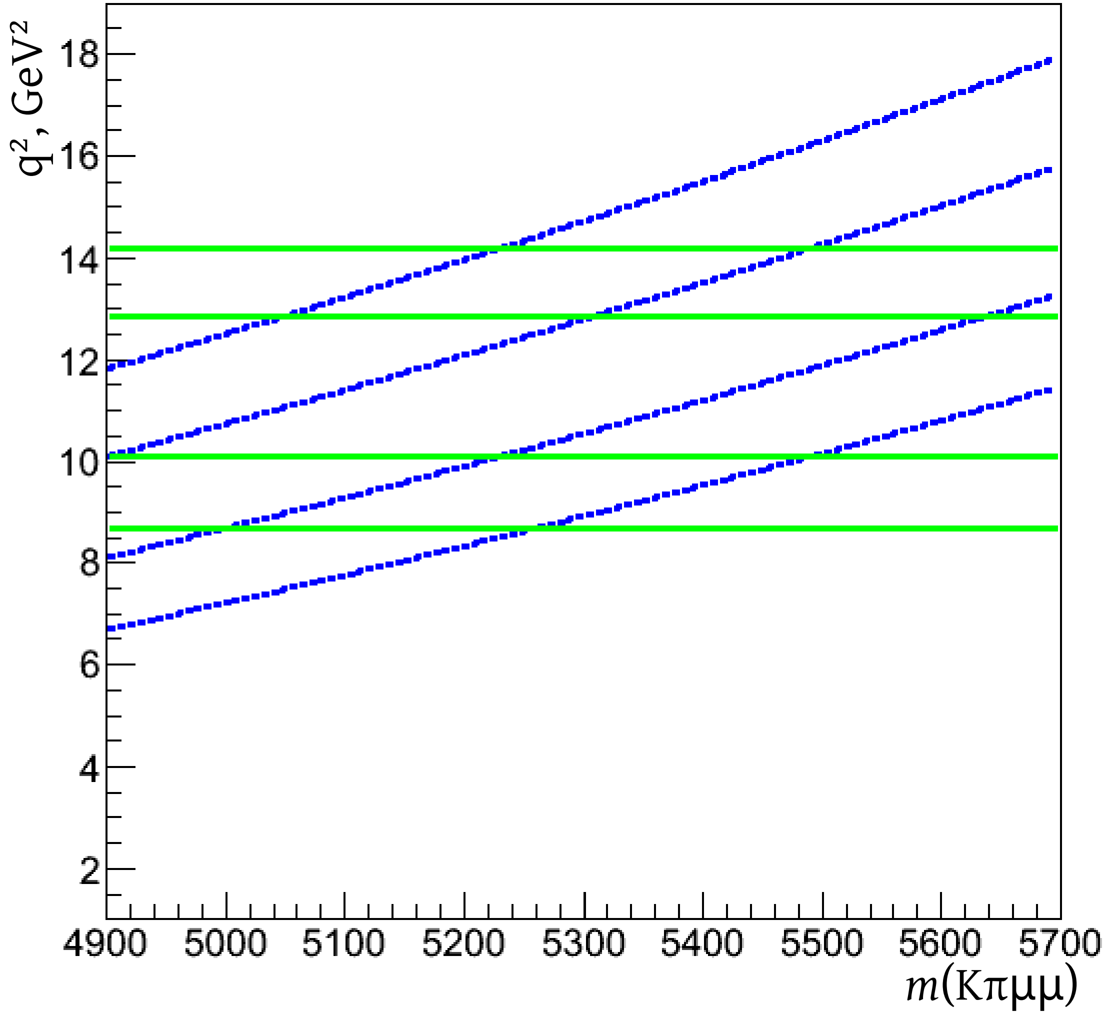
Conclusions, outlook

- We performed an analysis of 2011 data to study the angular distribution of $B_d \rightarrow K^{*}\mu^{+}\mu^{-}$ decay
- 466 signal events were observed, A_{FB} and F_L values measured
- We have looked at various sources of possible systematic uncertainties; statistical errors dominate
- Our result is consistent with the other experiments
- We are looking forward to the analysis of the data collected with ATLAS in 2012
- There is a lot of space for improvement

Backup slides

Fits in other q^2 bins

2D plot



q², GeV²
18
16
14
12
10
8
6
4
2
4900
5000
5100
5200
5300
5400
5500
5600
5700
m(Kπμμ)

Theoretical distributions

$$\frac{8\pi}{3}\frac{d^4\Gamma}{dq^2\,d\cos\theta_\ell\,d\cos\theta_K\,d\phi} = (J_{1s}+J_{2s}\cos2\theta_\ell+J_{6s}\cos\theta_\ell)\sin^2\theta_K$$
$$+(J_{1c}+J_{2c}\cos2\theta_\ell+J_{6c}\cos\theta_\ell)\cos^2\theta_K$$
$$+(J_3\cos2\phi+J_9\sin2\phi)\sin^2\theta_K\sin^2\theta_\ell$$
$$+(J_4\cos\phi+J_8\sin\phi)\sin2\theta_K\sin2\theta_\ell$$
$$+(J_5\cos\phi+J_7\sin\phi)\sin2\theta_K\sin\theta_\ell$$

3D →

$$4m_\mu^2 \le q^2 \le (m_{B_d^0}-m_{K^{*0}})^2, \quad -1\le\cos\theta_L\le1,$$
$$-1\le\cos\theta_K\le1, \quad 0\le\phi\le2\pi$$

$$\frac{1}{\langle\Gamma\rangle}\frac{d^2\langle\Gamma\rangle}{d\cos\theta_\ell\,d\cos\theta_K} = \frac{9}{32}\Big[2\langle F_L\rangle\cos^2\theta_K+(1-\langle F_L\rangle)(1-\cos^2\theta_K)$$
$$-2\langle F_L\rangle\cos^2\theta_K(2\cos^2\theta_\ell-1)$$
$$+(1-\langle F_L\rangle)(1-\cos^2\theta_K)\cos^2\theta_\ell$$
$$+\frac{8}{3}\langle A_{FB}\rangle\cos\theta_\ell(1-\cos^2\theta_K)\Big]$$

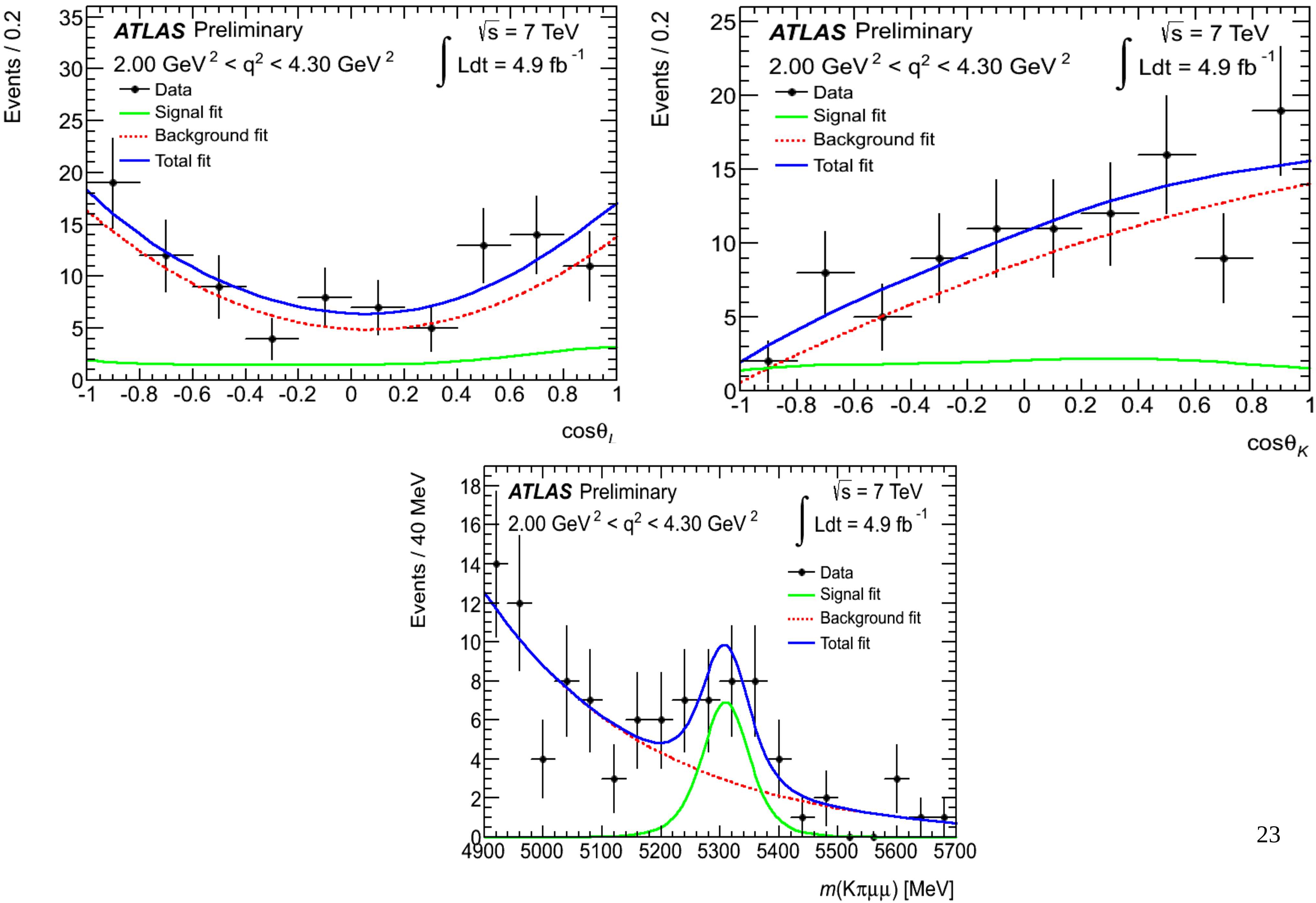
2D →

$$\frac{1}{\langle\Gamma\rangle}\frac{d\langle\Gamma\rangle}{d\cos\theta_\ell} = \frac{1}{\langle\Gamma\rangle}\int_{-1}^{1}d\cos\theta_K\,\frac{d^2\langle\Gamma\rangle}{d\cos\theta_\ell\,d\cos\theta_K} =$$
$$\frac{9}{16}\left[\left(1-\frac{1}{3}\langle F_L\rangle\right)+\left(\frac{1}{3}-\langle F_L\rangle\right)(2\cos^2\theta_\ell-1)\right.$$
$$\left.+\frac{16}{9}\langle A_{FB}\rangle\cos\theta_\ell\right]$$
$$=\frac{3}{4}\langle F_L\rangle(1-\cos^2\theta_\ell)+\frac{3}{8}(1-\langle F_L\rangle)(1+)+\langle A_{FB}\rangle\cos\theta_\ell$$

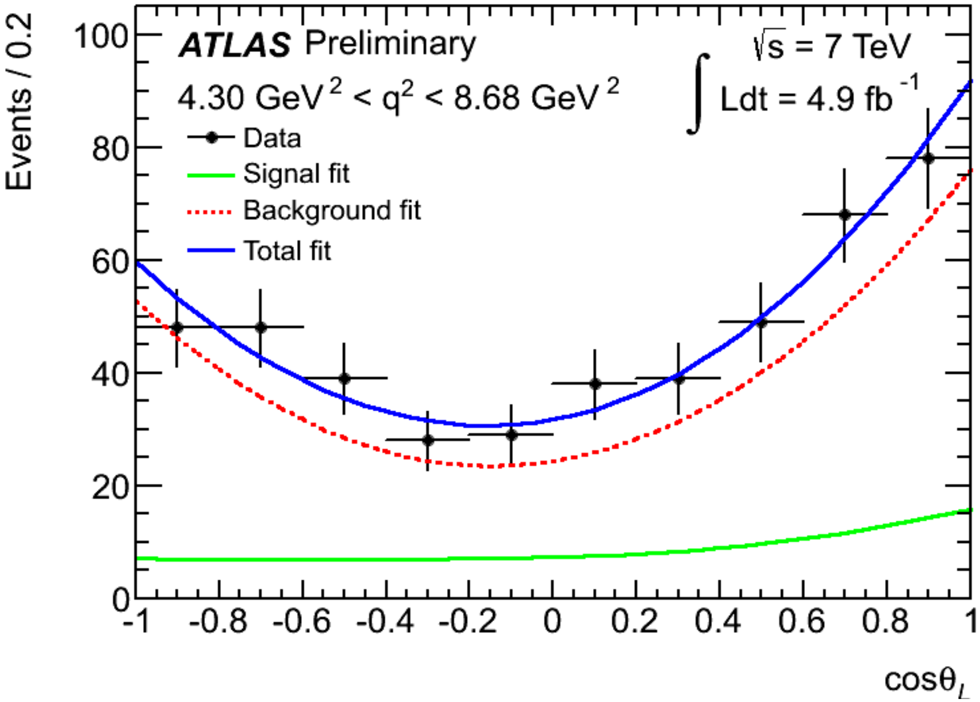
$$\frac{1}{\langle\Gamma\rangle}\frac{d\langle\Gamma\rangle}{d\cos\theta_K} = \frac{1}{\langle\Gamma\rangle}\int_{-1}^{1}d\cos\theta_\ell\,\frac{d^2\langle\Gamma\rangle}{d\cos\theta_\ell\,d\cos\theta_K} =$$
$$\frac{3}{2}\langle F_L\rangle\cos^2\theta_K+\frac{3}{4}(1-\langle F_L\rangle)(1-\cos^2\theta_K)$$

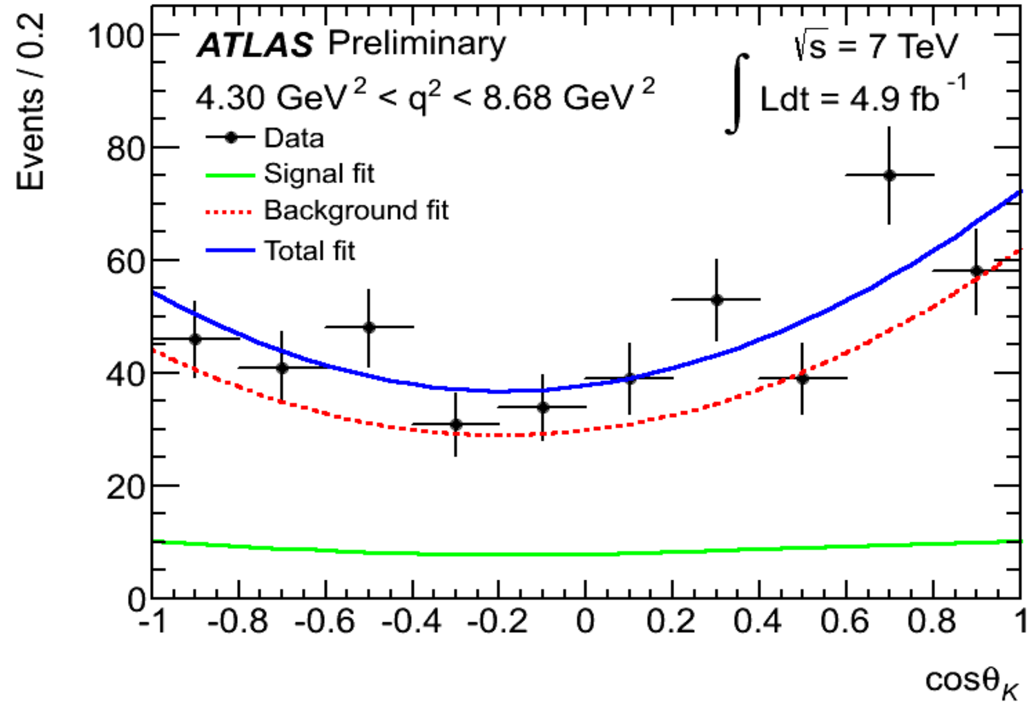
1D

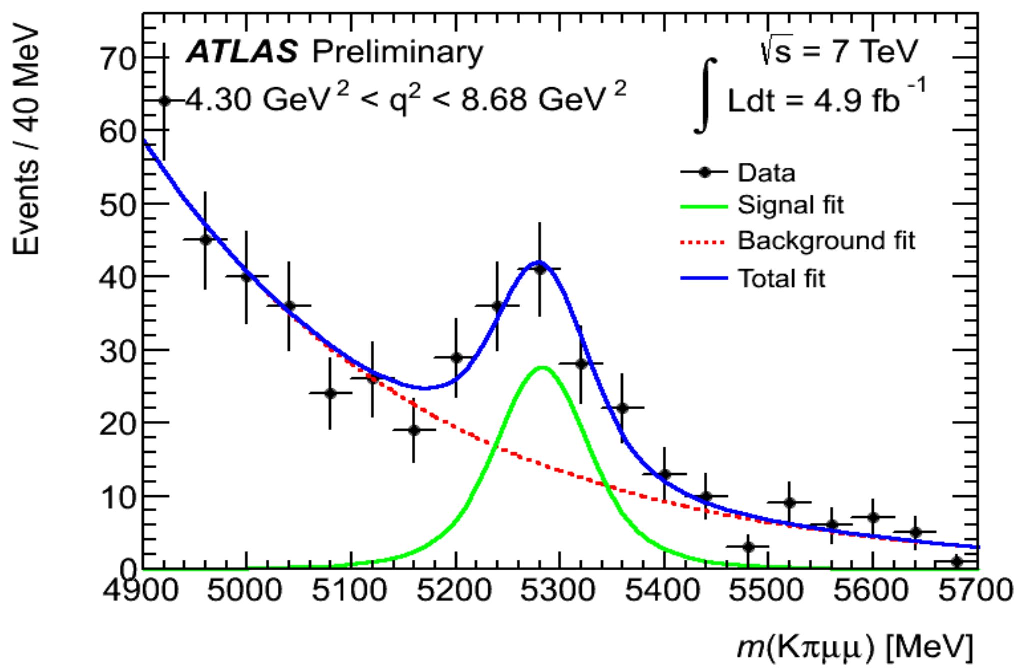
$2.00 < q^2 < 4.30$


ATLAS Preliminary
2.00 GeV² < q² < 4.30 GeV²
√s = 7 TeV
∫ Ldt = 4.9 fb⁻¹
Data
Signal fit
Background fit
Total fit
Events / 0.2
cosθ_L
cosθ_K
Events / 40 MeV
m(Kπμμ) [MeV]

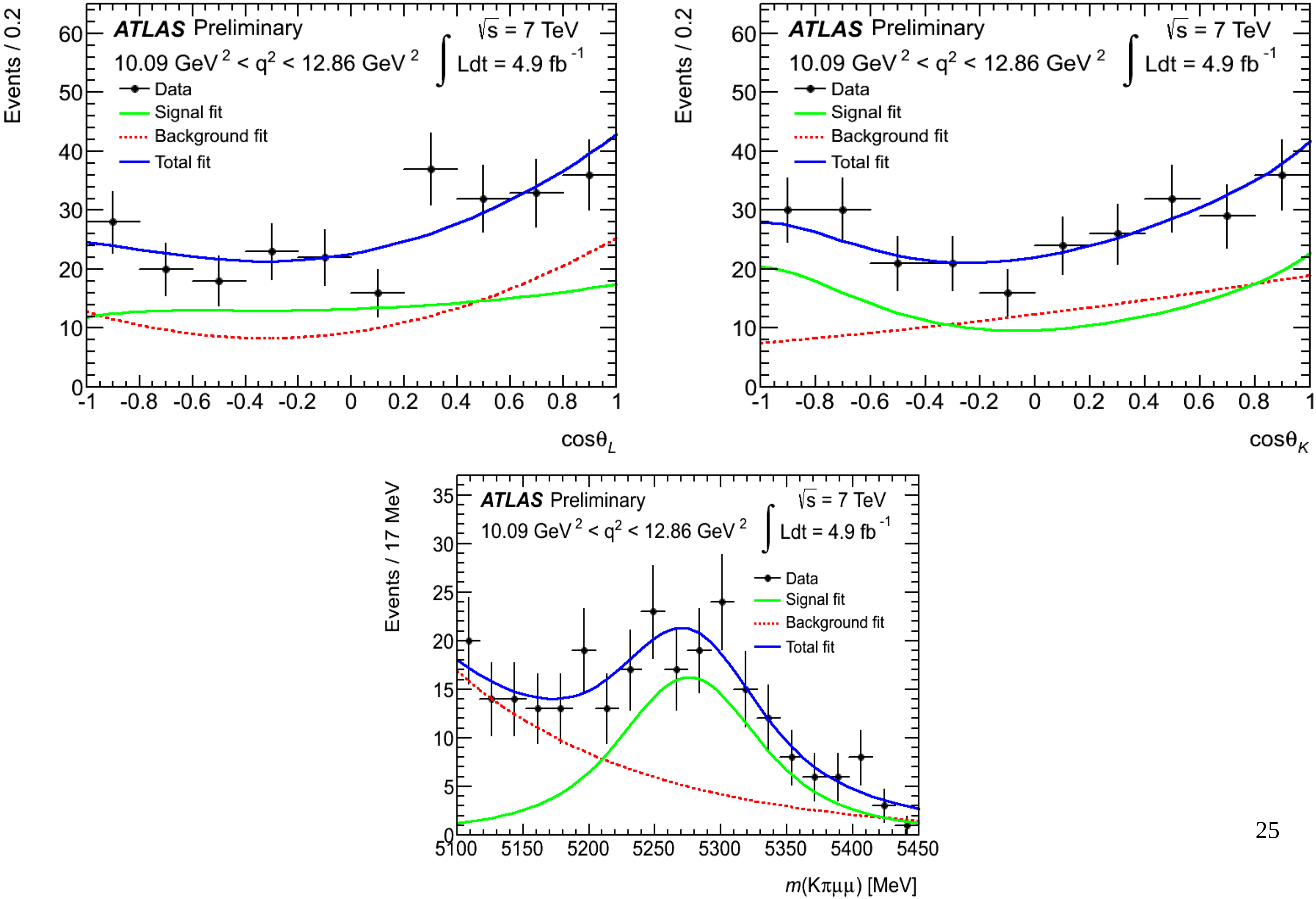
$4.30 < q^2 < 8.68$


ATLAS Preliminary
√s = 7 TeV
4.30 GeV² < q² < 8.68 GeV²
∫ Ldt = 4.9 fb⁻¹
Data
Signal fit
Background fit
Total fit
Events / 0.2
cosθ_L
0
20
40
60
80
100
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

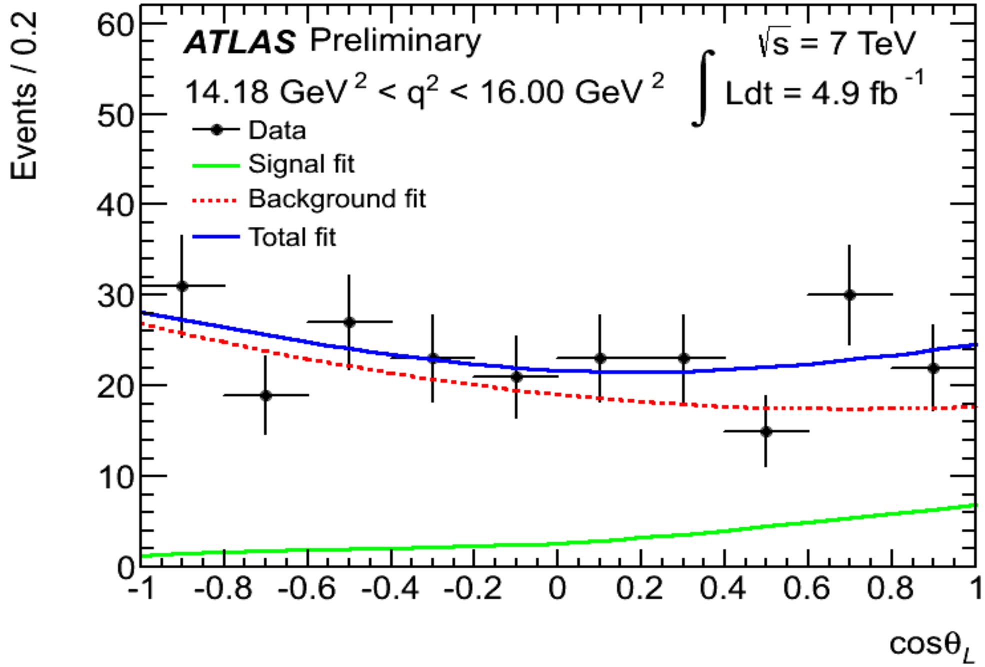

ATLAS Preliminary
√s = 7 TeV
4.30 GeV² < q² < 8.68 GeV²
∫ Ldt = 4.9 fb⁻¹
Data
Signal fit
Background fit
Total fit
Events / 0.2
cosθ_K
0
20
40
60
80
100
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1


ATLAS Preliminary
√s = 7 TeV
4.30 GeV² < q² < 8.68 GeV²
∫ Ldt = 4.9 fb⁻¹
Data
Signal fit
Background fit
Total fit
Events / 40 MeV
m(Kπμμ) [MeV]
0
10
20
30
40
50
60
70
4900
5000
5100
5200
5300
5400
5500
5600
5700

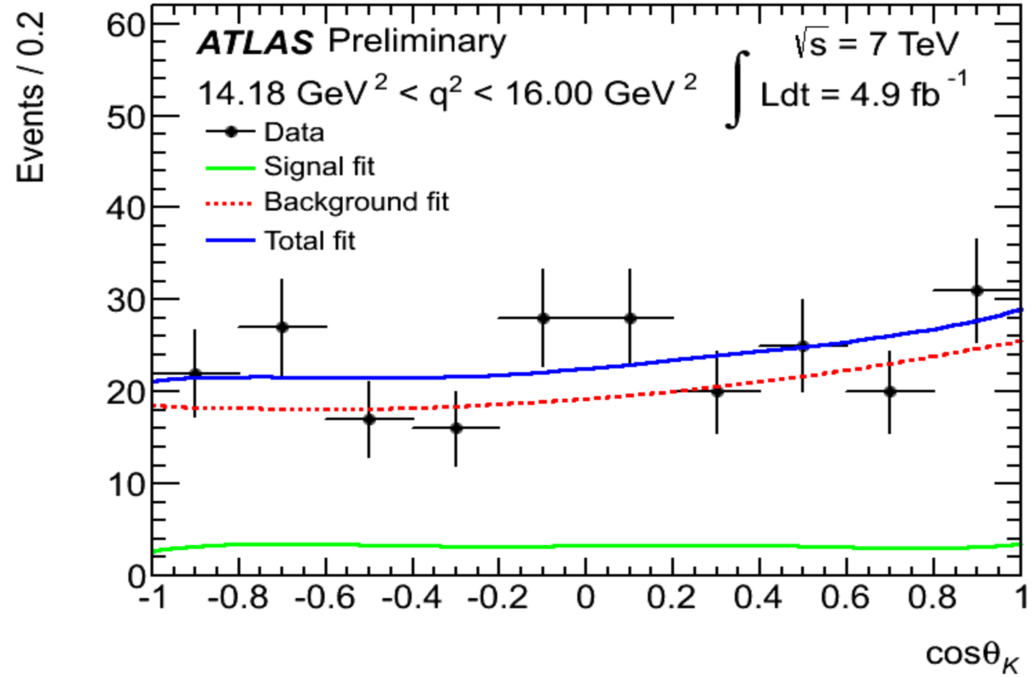
$10.09 < q^2 < 12.86$


ATLAS Preliminary
10.09 GeV^2 < q^2 < 12.86 GeV^2
$\sqrt{s}$ = 7 TeV
$\int$ Ldt = 4.9 fb^{-1}
Data
Signal fit
Background fit
Total fit
Events / 0.2
$\cos\theta_L$
$\cos\theta_K$
Events / 17 MeV
$m(K\pi\mu\mu)$ [MeV]

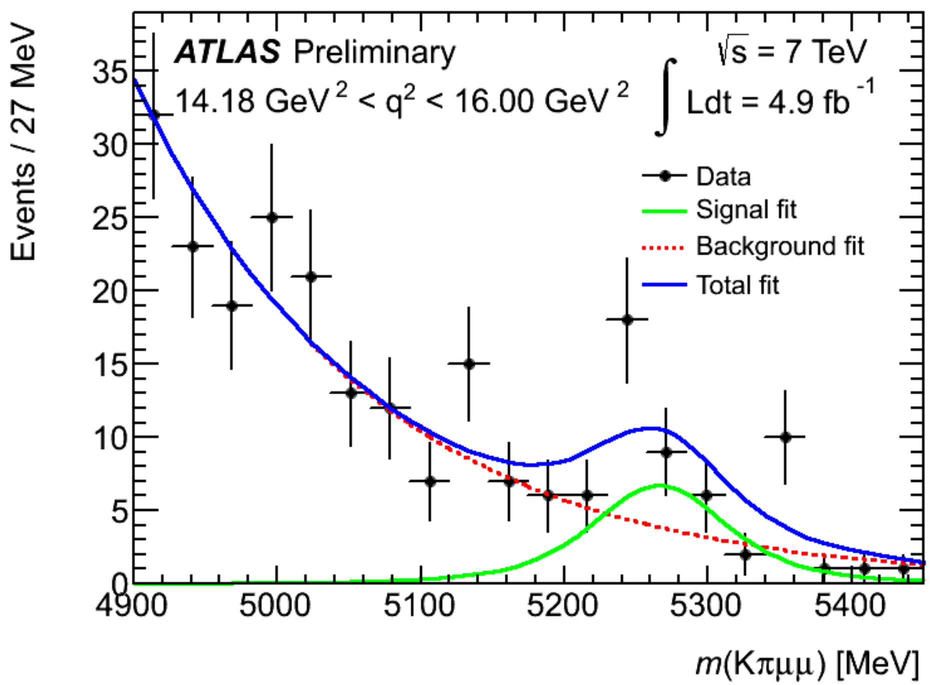
$14.18 < q^2 < 16.00$



ATLAS Preliminary
14.18 GeV² < q² < 16.00 GeV²
√s = 7 TeV
∫ Ldt = 4.9 fb⁻¹
Data
Signal fit
Background fit
Total fit
Events / 0.2
cosθ_L

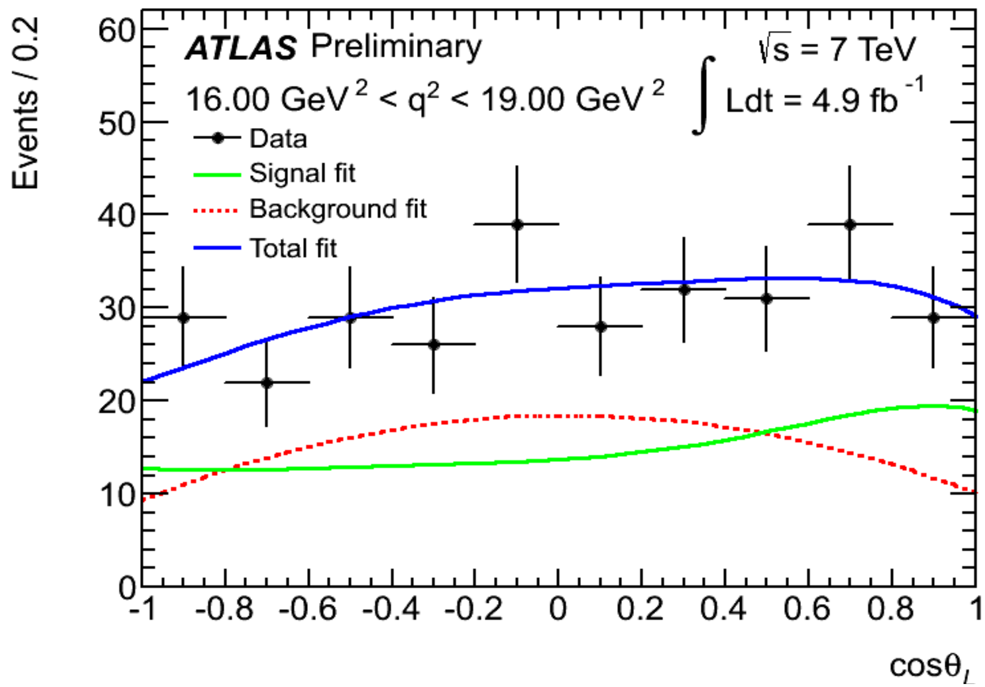


ATLAS Preliminary
14.18 GeV² < q² < 16.00 GeV²
√s = 7 TeV
∫ Ldt = 4.9 fb⁻¹
Data
Signal fit
Background fit
Total fit
Events / 0.2
cosθ_K

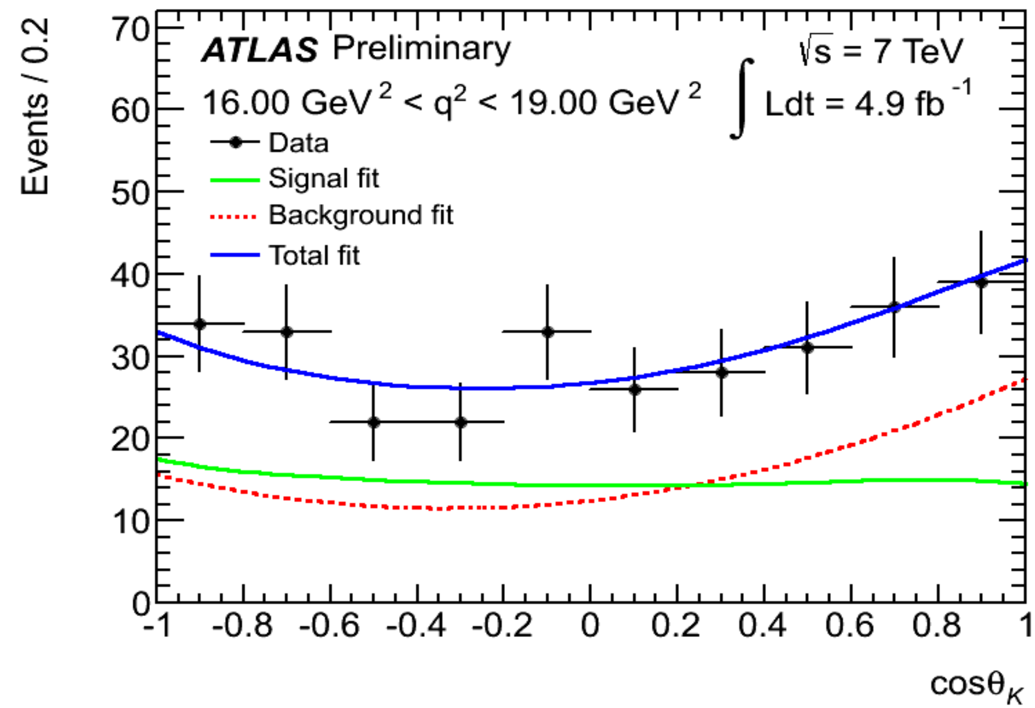


ATLAS Preliminary
14.18 GeV² < q² < 16.00 GeV²
√s = 7 TeV
∫ Ldt = 4.9 fb⁻¹
Data
Signal fit
Background fit
Total fit
Events / 27 MeV
m(Kπμμ) [MeV]

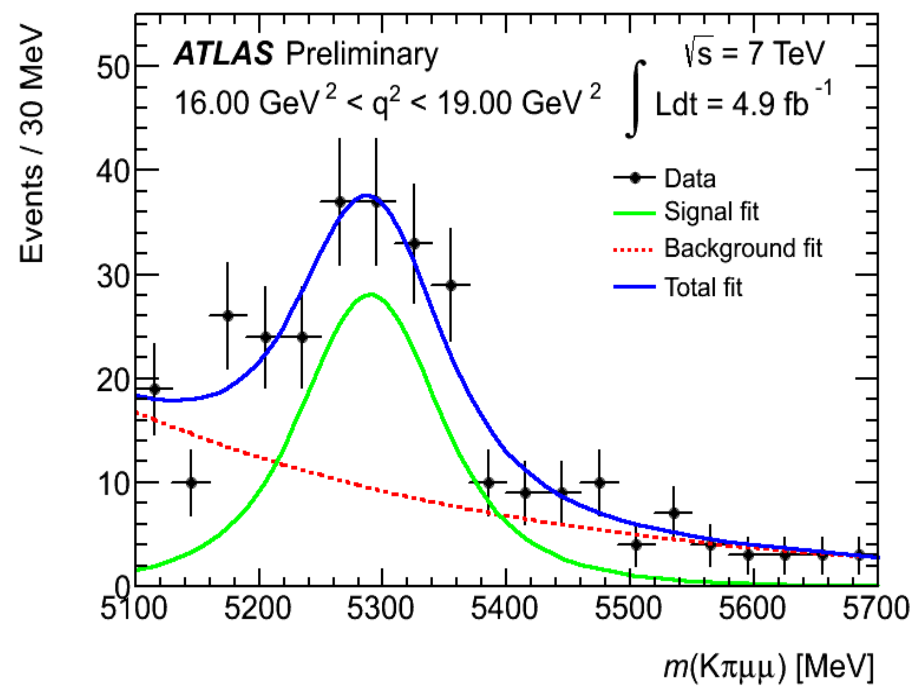
$16.00 < q^2 < 19.00$



ATLAS Preliminary
√s = 7 TeV
16.00 GeV² < q² < 19.00 GeV²
∫Ldt = 4.9 fb⁻¹
Data
Signal fit
Background fit
Total fit
Events / 0.2
cosθ_L

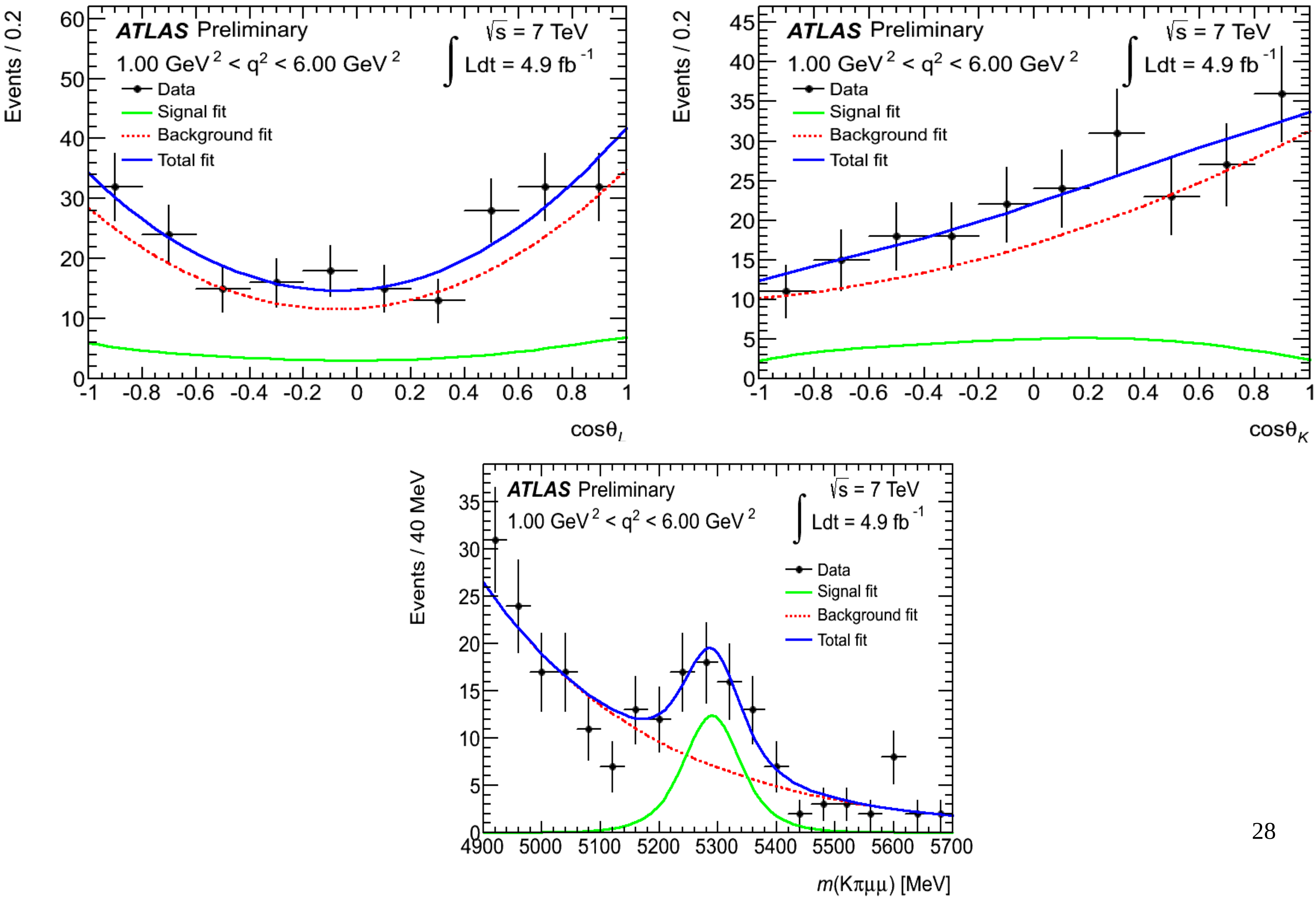


ATLAS Preliminary
√s = 7 TeV
16.00 GeV² < q² < 19.00 GeV²
∫Ldt = 4.9 fb⁻¹
Data
Signal fit
Background fit
Total fit
Events / 0.2
cosθ_K



ATLAS Preliminary
√s = 7 TeV
16.00 GeV² < q² < 19.00 GeV²
∫Ldt = 4.9 fb⁻¹
Data
Signal fit
Background fit
Total fit
Events / 30 MeV
m(Kπμμ) [MeV]

$1.00 < q^2 < 6.00$


ATLAS Preliminary
1.00 GeV² < q² < 6.00 GeV²
√s = 7 TeV
∫ Ldt = 4.9 fb⁻¹
Data
Signal fit
Background fit
Total fit
Events / 0.2
cosθ_L
cosθ_K
Events / 40 MeV
m(Kπμμ) [MeV]