Angular analysis of $B_d \rightarrow K^* \mu^+ \mu^-$ decay with ATLAS

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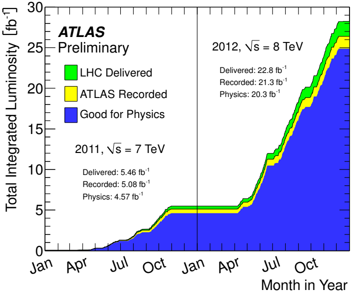
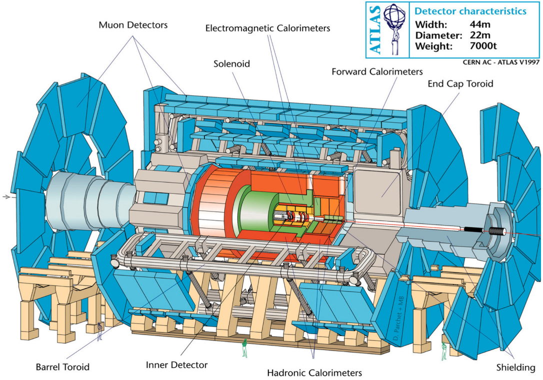
The ATLAS experiment

- Inner Detector: tracking, vertexing and momentum measurement
  - $|\eta| < 2.5$, $\sigma(d_0) \sim 10\ \mu m$
- Muon Spectrometer: trigger $|\eta| < 2.4$, muon identification $|\eta| < 2.7$

Run1 dataset:
25 fb^{-1} at 7 and 8TeV





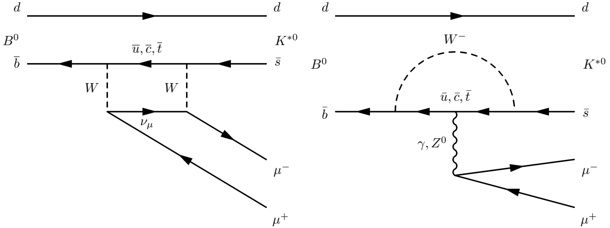
ATLAS B-physics programme

- Weak rare decays $\rightarrow$ CP violation, searches for new physics
  - leptonic $B^0_{(s)} \rightarrow \mu^+\mu^-$
  - semileptonic $B_d \rightarrow K^*\mu^+\mu^-$, $B^0_s \rightarrow \phi\,\mu^+\mu^-$, $B^+_u \rightarrow K^{(*)+}\mu^+\mu^-$
  - with J/ψ: $B^0_s \rightarrow J/\psi\,\phi$, $\Lambda_b \rightarrow J/\psi\,\Lambda$
- Production of beauty/charm hadrons and onia $\rightarrow$ QCD
  - cross-section (J/ψ, $\psi(2S)$, $\Upsilon(nS)$, χ_c)
  - polarisation
  - associated production ($J/\psi\,W^\pm$)
- B meson and baryon properties and spectroscopy
  - mass and lifetime measurements
  - search for new states

$B_d \to K^*\mu^+\mu^-$ decay in the Standard Model (SM)

Flavour changing neutral currents (FCNC)

- $b \to s\mu^+\mu^-$: box and pinguin diagrams



Effective field theory: $\mathcal{H}_{eff} = -\frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^* \sum_i C_i(\mu_s)\mathcal{O}(\mu_s)$

$$\mathcal{O}_7 = \frac{m_b}{e}\bar{s}\sigma^{\mu\nu}P_R bF_{\mu\nu}, \qquad \mathcal{O}'_7 = \frac{m_b}{e}\bar{s}\sigma^{\mu\nu}P_L bF_{\mu\nu},$$

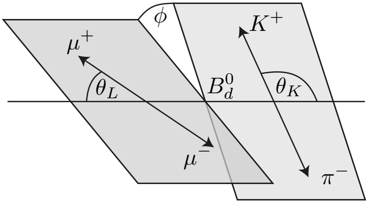
$$\mathcal{O}_9 = \bar{s}\gamma_\mu P_L b\bar{\ell}\gamma^\mu\ell, \qquad \mathcal{O}'_9 = \bar{s}\gamma_\mu P_R b\bar{\ell}\gamma^\mu\ell,$$

$$\mathcal{O}_{10} = \bar{s}\gamma_\mu P_L b\bar{\ell}\gamma^\mu\gamma_5\ell, \qquad \mathcal{O}_{10} = \bar{s}\gamma_\mu P_R b\bar{\ell}\gamma^\mu\gamma_5\ell,$$

$B_d \to K^*\mu^+\mu^-$ decay in SM

Final state $B_d \to K^*(K\pi)\ \mu^+\mu^-$

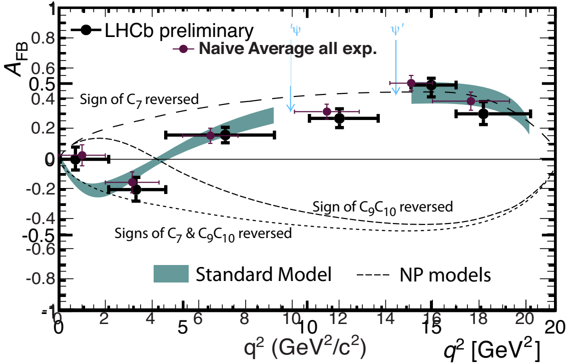
- 3 helicity angles and dimuon invariant mass q^2
- self-tagging decay (B^0or $\overline{B^0}$ if $K^+\pi^-$ or $K^-\pi^+$)



Measurements: usually as function of q^2

- traditional: A_{FB}, F_L, A_I, $R_{K^{(*)}} = \mathrm{d}\Gamma(K^*\mu\mu)/\mathrm{d}\Gamma(K^*ee)$, zero-crossing points
- optimized: F_L and S_i, F_L and $P_i^{(\prime)}$

Example of new physics signatures:



arXiv:1212.6374 [hep-ph]

$B_d \to K^*\mu^+\mu^-$ decay in SM

Differential decay rate (optimized):

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

$$P_1 = \frac{2S_3}{(1-F_L)},\quad P_2 = \frac{2}{3}\frac{A_{FB}}{(1-F_L)},\quad P_3 = -\frac{S_9}{(1-F_L)},$$
$$P'_{4,5,6} = \frac{S_{4,5,6}}{\sqrt{F_L(1-F_L)}},\quad P'_6 = \frac{S_7}{\sqrt{F_L(1-F_L)}}$$

$B_d \to K^*\mu^+\mu^-$ decay in SM

- small number of events $\to$ folding of angular distributions

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

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

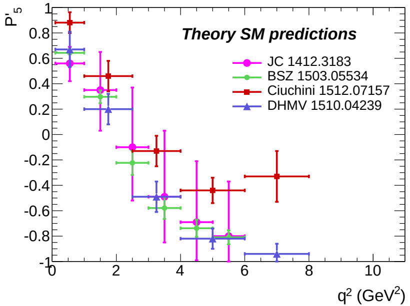
$$P_5^{'}, S_5 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_l \to \pi - \theta_l & \text{for } \theta_l > \frac{\pi}{2} \end{cases}$$

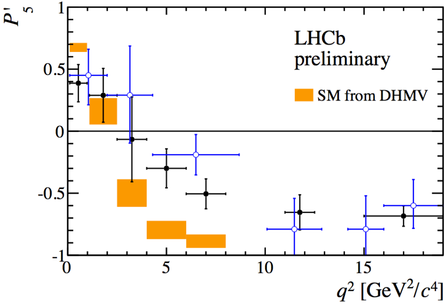
$$P_8^{'}, S_8 : \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \frac{\pi}{2} \\ \phi \to -\pi - \phi & \text{for } \phi < -\frac{\pi}{2} \\ \theta_l \to \pi - \theta_l & \text{for } \theta_l > \frac{\pi}{2} \\ \theta_k \to \pi - \theta_k & \text{for } \theta_l > \frac{\pi}{2} \end{cases}$$

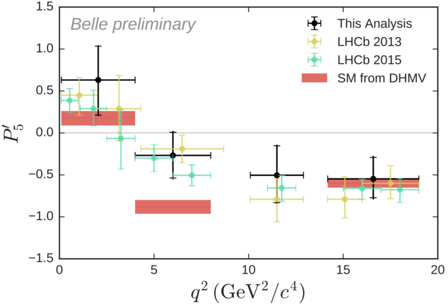
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K\ d\phi dq^2} = \frac{9}{8\pi}\left[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin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

- loss of sensitivity to S_6, S_8 a A_{FB}

$B_d \to K^*\mu^+\mu^-$ experimental status







ATLAS analysis of $B_d \rightarrow K^*\mu^+\mu^-$

Dataset: ATLAS-CONF-2017-023

- $20.3\ \mathrm{fb}^{-1}$, taken at $\sqrt{s} = 8$ TeV in 2012

Reconstruction and selection:

- preselection: p_T dráh, ID hits, min. 1 combined muon
- baseline: $|\eta| < 2.5$, $m(K^*) = [846, 946]$ MeV, $m(B) = [5150, 5700]$ MeV
  $p_\mathrm{T}(\mu) > 3.5$ GeV, $p_\mathrm{T}(\pi, K) > 0.5$ GeV
- final cuts: $\sigma_\tau/\tau > 12.75$, pointing $\cos\theta > 0.999$, $\chi^2/ndf(B) < 2$,
  $p_\mathrm{T}(K^*) > 3$ GeV, $|(m(B) - m_{PDG}(B)) - (m(\mu\mu) - m_{PDG}(J/\psi))| < 130$ MeV
- trigger - 15 most frequent triggers
- control regions: J/ψ (q^2= [8,11] GeV^2), $\psi(2S)$ (q^2= [12,15] GeV^2)
- signal q^2= [0.04,6] GeV^2 except of ϕ region q^2= [0.98,1.1] GeV^2
- if > 1 candidate/event: candidate with higher $\sigma_m(K^*)/m(K^*)$

Monte Carlo datasets

Signal:

Process	Generator	Dataset	Events
$B_d \to K^* \mu^+ \mu^-$	EvtGen, flat	208445	50M
$B_d \to K^* \mu^+ \mu^-$	EvtGen, SM	208446	5M
$\overline{B_d} \to K^* \mu^+ \mu^-$	EvtGen	208447	5M
$B_d \to K^+ \pi^- \mu^+ \mu^-$	EvtGen	208451	50M

Inclusive backgrounds:

Process	Generator	Dataset	Events
$b\bar{b} \to \mu^+ \mu^- X$	Pythia	208301	20M
$b\bar{b} \to \mu^+ \mu^- X$	EvtGen	208303	1M
$b\bar{b} \to \mu^+ \mu^- X$ AA	Pythia	208308	40M
$b\bar{b} \to \mu^+ \mu^- X$ AB	Pythia	208309	48M
$b\bar{b} \to \mu^+ \mu^- X$ BA	Pythia	208310	48M
$b\bar{b} \to \mu^+ \mu^- X$ BB	Pythia	208311	130M
$c\bar{c} \to \mu^+ \mu^- X$	Pythia	208312	50M

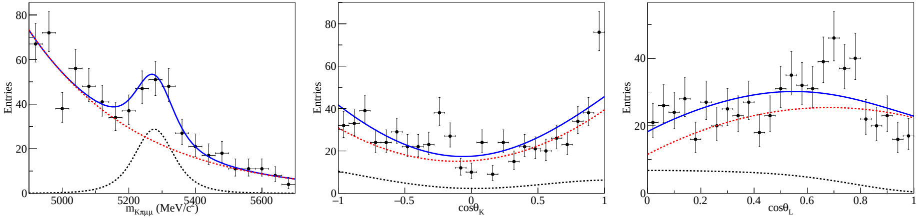
Monte Carlo datasets

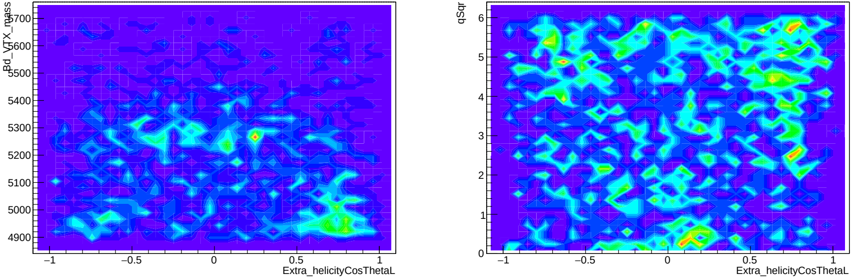
Exclusive backgrounds:

Process	Generator	Dataset	Events
$B_s \to J/\psi\ \phi$	Pythia	208400	5M
$\Lambda_b \to \Lambda J/\psi$	Pythia	208404	5M
$\overline{\Lambda_b} \to \Lambda J/\psi$	Pythia	208405	5M
$B \to K_s J/\psi$	Pythia	208412	5M
$B \to K_s \psi(2S)$	Pythia	208423	4M
$\Lambda_b \to \Lambda\psi(2S)$	Pythia	208424	1M
$\overline{\Lambda_b} \to \Lambda\psi(2S)$	Pythia	208425	1M
$B^+ \to J/\psi K^+$	Pythia	208430	2.5M
$B^+ \to J/\psi\pi^+$	Pythia	208432	1M
$B^- \to J/\psi K^-$	Pythia	208436	2.5M
$B^+ \to K^{*+}(K^0\pi^+)\mu^+\mu^-$	EvtGen	208440	5M
$B_s \to \phi\mu^+\mu^-$	EvtGen	208441	5M
$B_d \to J/\psi K^*$	EvtGen	208448	5M
$B_d \to \psi(2S)K^*$	EvtGen	208449	5M
$B^+ \to K^+\mu^+\mu^-$	EvtGen	208450	5M
$B_s \to J/\psi K^*$	EvtGen	208452	5M
$B_d \to K^*\phi$	EvtGen	208455	5M
$\Lambda_b \to \Lambda(p^+K^-)\mu^+\mu^-$	EvtGen	208456	5M
$\Lambda_b \to p^+K^-\mu^+\mu^-$	EvtGen	208457	5M

Background

Data q^2= [4,6] GeV^2





Background: partially reconstructed decays $B \to D \to X$

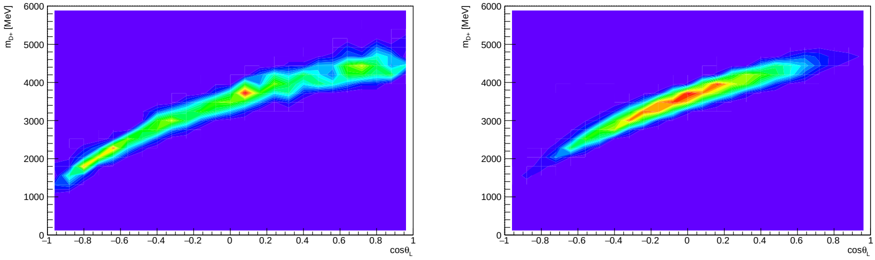


Fig: Example for $M(K\pi\pi)$, dáta vs. MC

- $D^0 \to K\pi$: m $(K_\pi\ \pi_K)$
- $D^\pm \to K\pi\pi$: m $(K\ \pi\ \mu_\pi)$, m $(\pi_K\ K_\pi\ \mu_\pi)$, m $(K_\pi\ \pi\ \mu_K)$
- $D_s^\pm \to KK\pi$: m $(K\ \pi_K\ \mu_\pi)$, m $(K\ \pi\ \mu_K)$, m $(K_\pi\ \pi_K\ \mu_K)$
- $D_s^{*+} \to KK\pi$: m $(K\ \pi_K\ \mu_\pi)$, m $(K\ \pi\ \mu_K)$, m $(K_\pi\ \pi_K\ \mu_K)$
- $B^+ \to K^+\mu^+\mu^-$, $B^+ \to \pi^+\mu^+\mu^-$

Background: partially reconstructed decays

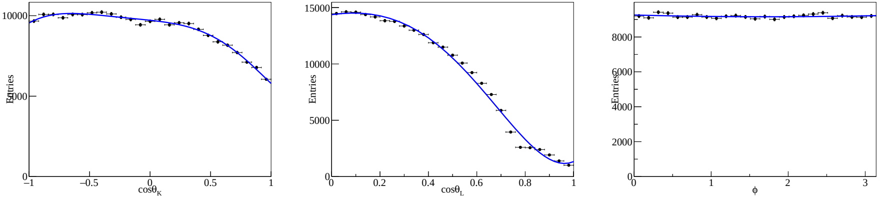
Other hypotheses: checked but not found

- $B \to J/\psi K^*$ (double-swap) - MC shows isotropic angular distributions
- $B_s \to J/\psi\phi$ - only 1 event
- $B^+ \to K^{*+}\mu\mu$ - MC shows similar angular distributions as signal
- $\Lambda_b \to pK\mu\mu$ and $\Lambda_b \to \Lambda^*(pK)\mu\mu$
- $D \to K\pi\mu\nu$ (bez ν) - covered by D vetoes
- $B \to \Lambda_c^{\pm} \to pK\pi$ - covered by D vetoes
- $B \to \pi\mu\nu$, $B_s \to K\mu\nu$, $\Lambda_b \to p\mu\nu$ - only 1 μ in final state

Background

Result:

- D veto 30 MeV and B veto 50 MeV around $m_{D/B}$
- acceptance maps, e.g. q^2= [0.04,6] GeV^2



- difference of fit wrt. nominal fit = systematics

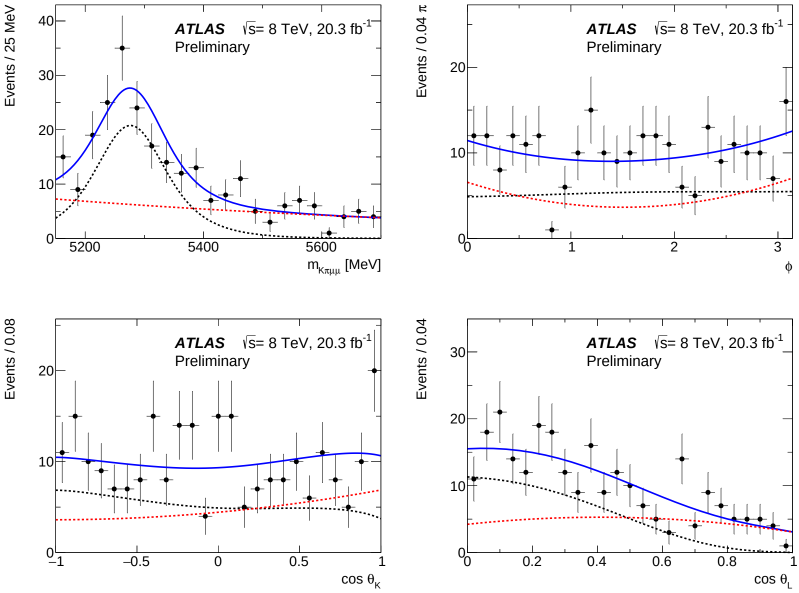
Fitting

- acceptance maps from MC sample generated with flat angular distributions
- extract nuisance parameters from control regions - $m_B, \sigma_m B$ (Gauss),
- fold distributions $\rightarrow$ 4 sets of fits
- mass prefit - number of signal a bkg evens
- angular fits

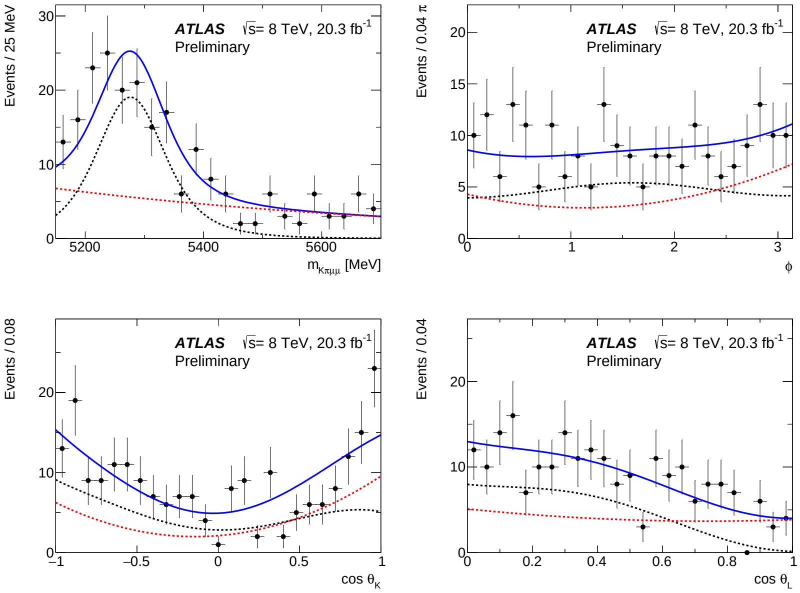
Fitted yields:

$q^2[(\mathrm{GeV}^2)]$	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

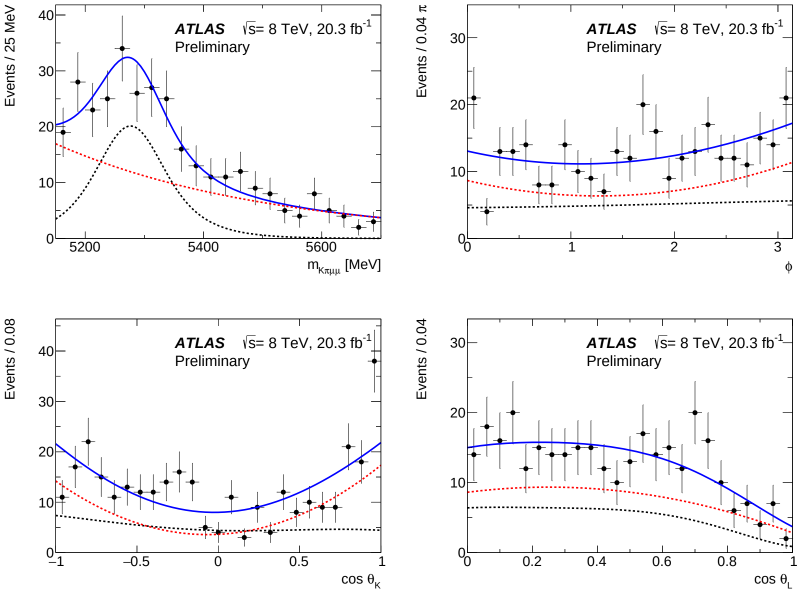
Fit results: S4, bin q^2= [0.04,2] GeV^2



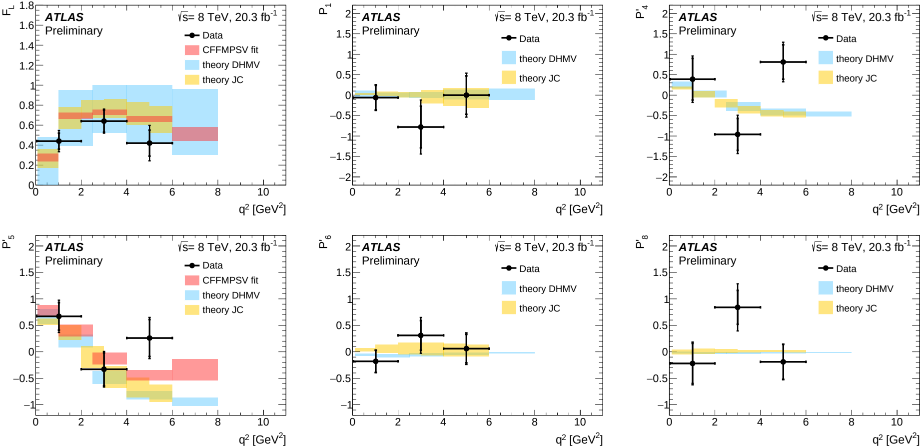
Fit results: S4, bin q^2= [2,4] GeV^2



Fit results: S4, bin q^2= [4,6] GeV^2

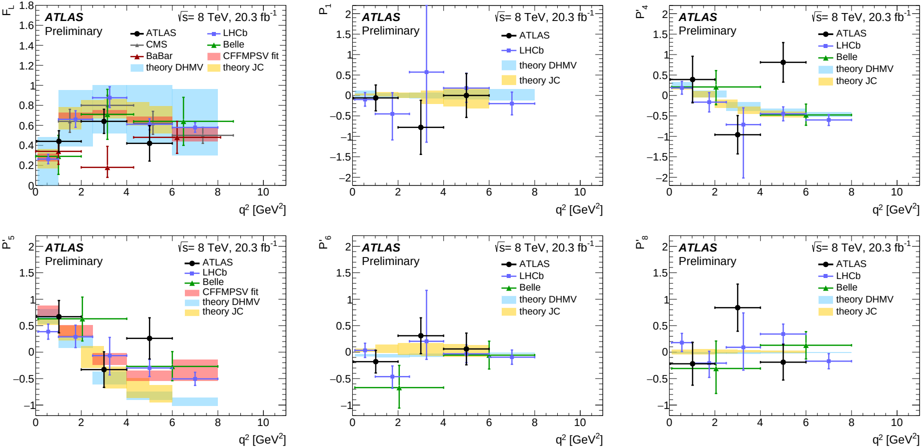


Results



ATLAS
Preliminary
√s= 8 TeV, 20.3 fb⁻¹
Data
CFFMPSV fit
theory DHMV
theory JC
F_L
P_1
P'_4
P'_5
P'_6
P'_8
q² [GeV²]

Results


ATLAS
Preliminary
√s= 8 TeV, 20.3 fb-1
ATLAS
CMS
BaBar
theory DHMV
LHCb
Belle
CFFMPSV fit
theory JC
F_L
P_1
P'_4
P'_5
P'_6
P'_8
q2 [GeV2]