New physics searches via FCNC b → s ll decays at ATLAS

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UK Flavour Workshop
Durham, UK
September 5th, 2017

B physics in ATLAS

- very limited *(wo)*man power
  - but a good variety of analyses

- recent results on indirect new physics searches:
  - width difference $\Delta\Gamma_d/\Gamma_d$:
    - JHEP 1606 (2016) 081, arXiv:1605.07485
  - rare B decays: $B_{(s)} \rightarrow \mu^+\mu^-$:
    - EPJ C76 (2016) 513, arXiv:1604.04263
  - semi-rare B decays: $B \rightarrow K^* \mu^+\mu^-$:
    - ATLAS-CONF-2017-023
  - Time-dependent angular analysis in $B_s \rightarrow J/\psi\phi$:
    - prospects

width difference $\Delta\Gamma_d/\Gamma_d$

JHEP 1606 (2016) 081, arXiv:1605.07485

B_d lifetime difference

- Experimental sensitivity still below SM predictions

  $\Delta\Gamma_d/\Gamma_d$ (SM) = $(0.42 \pm 0.08) \times 10^{-2}$

  $\Delta\Gamma_d/\Gamma_d$ (WA) = $(0.1 \pm 1.0) \times 10^{-2}$

  - New physics could still hide in $\Delta\Gamma_d/\Gamma_d$
  - Increased precision and complementing measurement methods important

- ATLAS measurement: $L = 25.2\ fb^{-1}$, $\sqrt{s} = 7, 8$ TeV
  - Decay rate difference for light/heavy eigenstates shows $\Delta\Gamma_d/\Gamma_d$ dependency
  - Measured through relative ratio of B_d decays to $J/\psi K_s$ vs $J/\psi K^*(892)$

Method

- Untagged time-dependent B → f decay rate depends on f:

$$\Gamma[t,f] \quad \propto \quad e^{-\Gamma_q t}\left[\cosh\frac{\Delta\Gamma_q t}{2} + A_P A_{CP}^{dir}\cos(\Delta m_q t) + A_{\Delta\Gamma}\sinh\frac{\Delta\Gamma_q t}{2} + A_P A_{CP}^{mix}\sin(\Delta m_q t)\right]$$

where A_P is the particle/anti-particle production asymmetry
and A^{dir}_{CP}, $A_{\Delta\Gamma}$, and A^{mix}_{CP} are well-defined for CP/flavour eigenstates

- Base measurement on comparison of $B_d \to J/\psi K_s$ vs $B_d \to J/\psi K^*(892)$:
  - $J/\psi K_s$: $A^{dir}_{CP} = 0$, $A_{\Delta\Gamma} = \cos 2\beta$, $A^{mix}_{CP} = -\sin 2\beta$ (CP-specific)
  - $J/\psi K^*(892)$: $A^{dir}_{CP} = 1$, $A_{\Delta\Gamma} = 0$, $A^{mix}_{CP} = 0$ (flavour-specific)

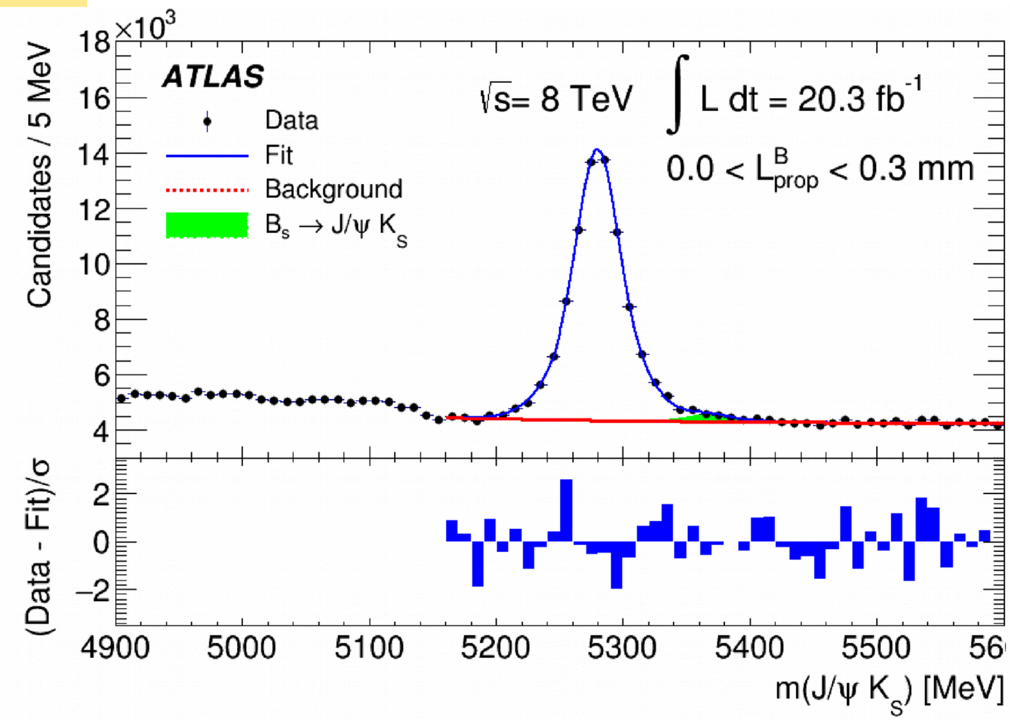
- Fit the ratio of CP/flavour eigenstates to determine ΔΓ:

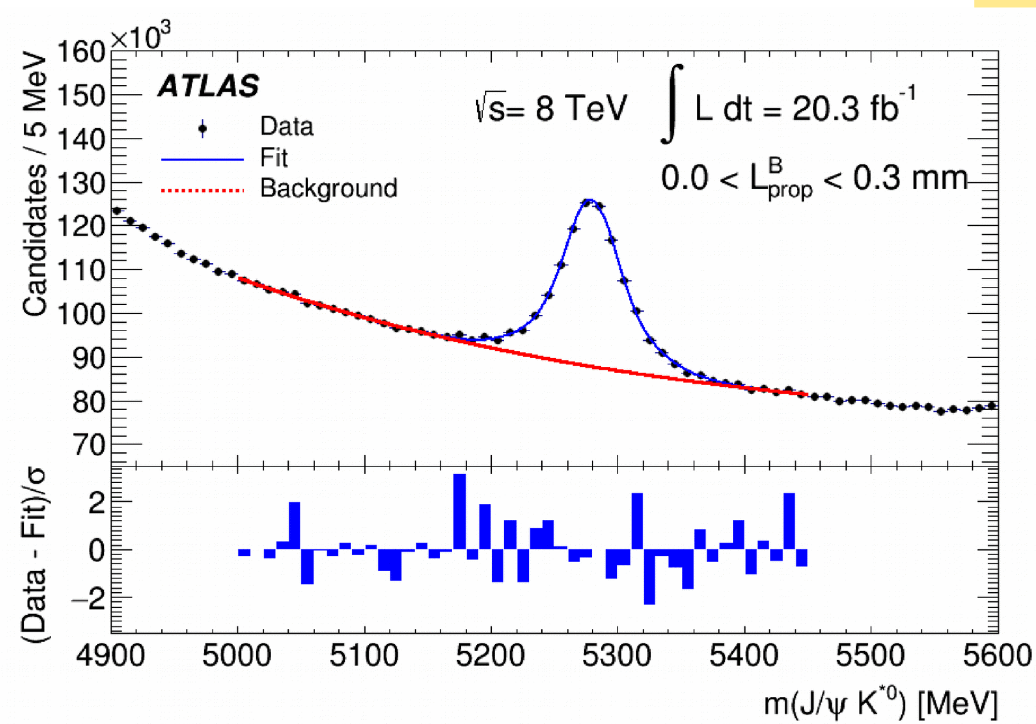
$$\frac{\Gamma[\psi K_s, t]}{\Gamma[\psi K^*, t]} = \frac{\cosh\frac{\Delta\Gamma_d t}{2} + \cos 2\beta \sinh\frac{\Delta\Gamma_d t}{2} - A_p \sin\Delta m_d t}{\cosh\frac{\Delta\Gamma_d t}{2} + A_p \cos\Delta m_d t}$$

  - Can determine ΔΓ and A_P from data

Extracting binned signal yields

- Signal counts are determined in bins of proper decay length
  - Use 10 bins between -0.3mm and 0.6mm
  - Yields determined through mass fits
  - Per-bin detector acceptance taken into account





Determination of A_P

- Production asymmetry derived from observed time-dependent asymmetry of J/ψK*(892) candidates (omitting CP violating mixing terms):

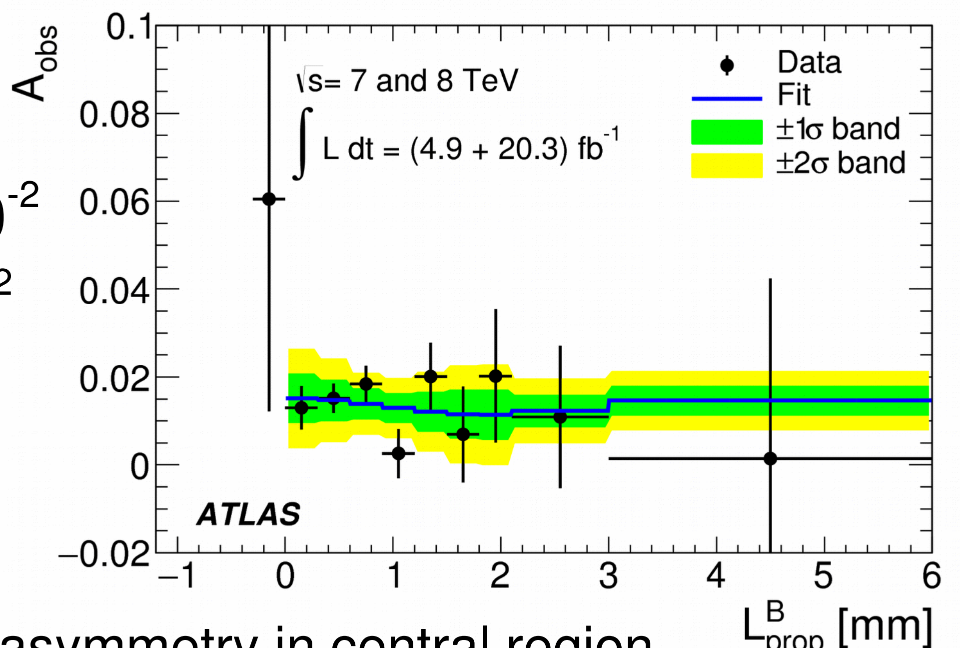
$$\Gamma[t, B/\bar{B} \to J\psi K^*] = e^{-\Gamma_d t}[\cosh \frac{\Delta\Gamma_d t}{2} \pm A_p \cos \Delta m t]$$

- cτ bins are fitted: the predicted A_{exp}, need to account for detector effects (mostly tracking asymmetry for charged K):

$$A_{exp,i} = (A_{det} + A_{osc,i})(1-2w)$$

K-π mis-id w~0.12

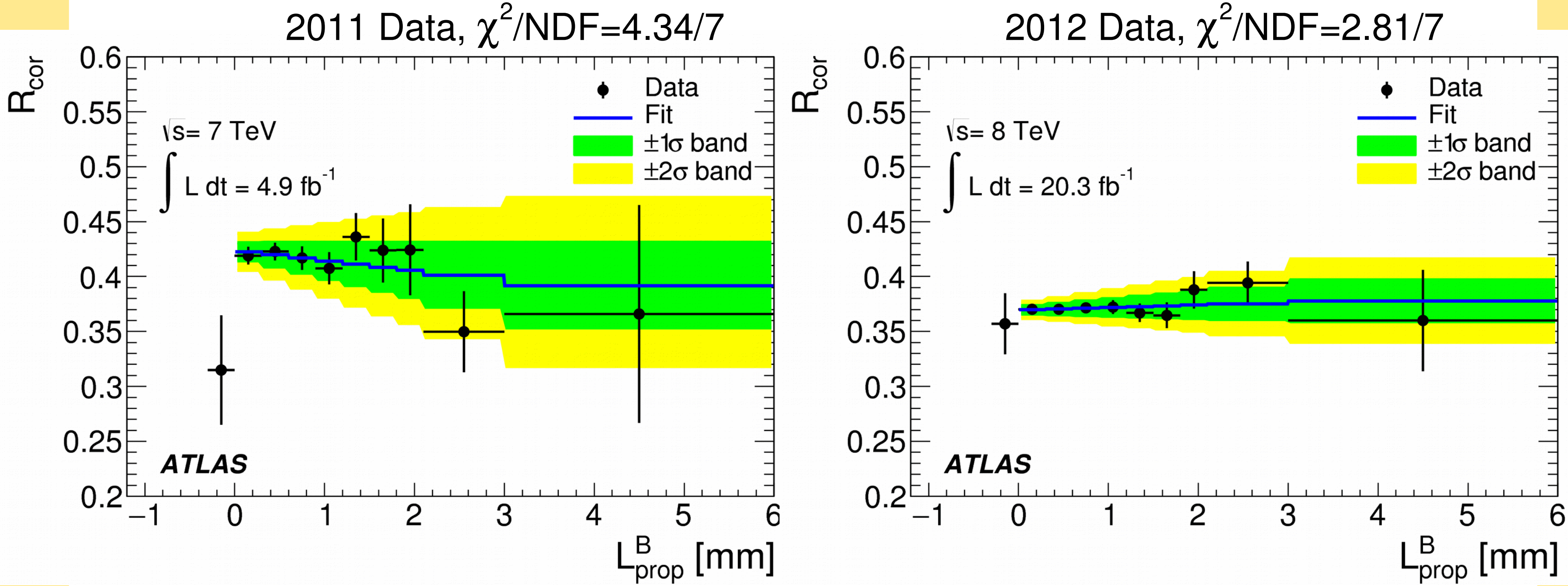
  - $\chi^2 = 6.50$, d.o.f = 7
  - $A_{det} = (1.33 \pm 0.24 \pm 0.30) \times 10^{-2}$
  - $A_P = (0.25 \pm 0.48 \pm 0.05) \times 10^{-2}$



- Systematics driven by mis-tag fraction uncertainties and |q/p|=1 assumption
- Consistent with LHCb measurement
- First LHC measurement of production asymmetry in central region

Determination of $\Delta\Gamma_d$

- Extract $c\tau$-dependent yields for K^* and K_s decays
- Fit $c\tau$-dependency leaving $\Delta\Gamma_d/\Gamma_d$ as the only free parameter



- Consistent result for the two datasets

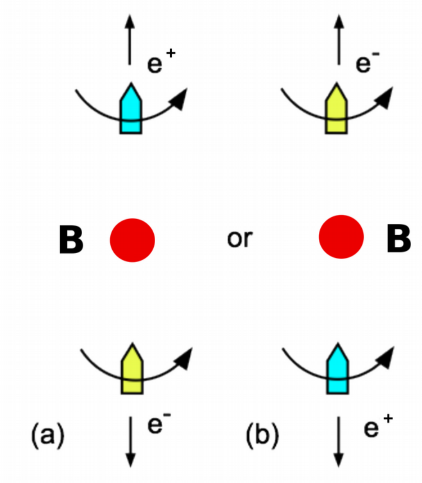
$$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-2}$$

- Currently the most precise single measurement available on the market!

rare B decays $B_{(s)} \rightarrow \mu^+\mu^-$

EPJ C76 (2016) 513, arXiv:1604.04263

Motivations and predictions

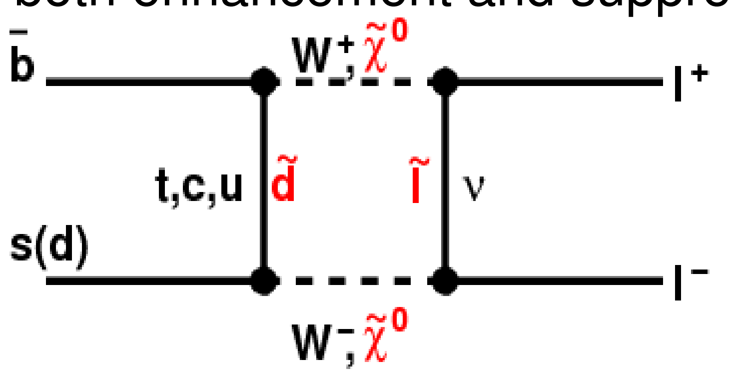


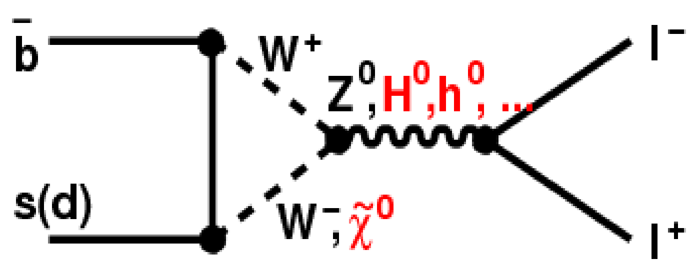
- Decays of B^0 and B^0_s into two leptons have to proceed through Flavour Changing Neutral Currents (FCNC)
  → forbidden at tree level in the SM
- In addition, they are CKM and helicity suppressed.
- Within the SM, they can be calculated with small theoretical uncertainties of order 6-8%

Bobeth et al., PRL 112 (2104) 101801 [includes NLO EM and NNLO QCD corrections]

meson type	Lepton type e	μ	τ
B^0	$(2.48 \pm 0.21)10^{-15}$	$(1.06 \pm 0.09)10^{-10}$	$(2.22 \pm 0.19)10^{-8}$
B^0_s	$(8.54 \pm 0.55)10^{-14}$	$(3.65 \pm 0.23)10^{-9}$	$(7.73 \pm 0.49)10^{-7}$

- Perfect ground for indirect new physics searches:
  - virtual new particles can contribute to the loop
  - both enhancement and suppression effects are possible





ATLAS analysis on full Run 1 data

ATLAS, EPJ C76 (2016) 513, arXiv:1604.04263

- ATLAS study on 25 fb^{-1} of Run 1 data
- measured via $B^{\pm} \rightarrow J/\psi\, K^{\pm}$ normalisation channel

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

$$\times \left[\mathcal{B}(B^+ \rightarrow J/\psi K^+) \times \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)\right]$$

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- correction for the efficiencies of the two channels

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- correction for the efficiencies of the two channels
- correction for the different hadronisation probabilities for B^0_S and B^0 vs $B^{\pm}$
- include the $B^{\pm}$ and J/ψ branching fractions

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- formula modified to take into account four trigger/data categories

Modified formula

- formula modified to take into account the three trigger categories and 2011 data
  - normalisation channel yield evaluated in each trigger and data category
  - same for the efficiency ratio

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N_{d(s)} \times \frac{f_u}{f_{d(s)}} \times \frac{1}{\mathcal{D}_{\text{norm}}}$$

$$\times \left[\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right]$$

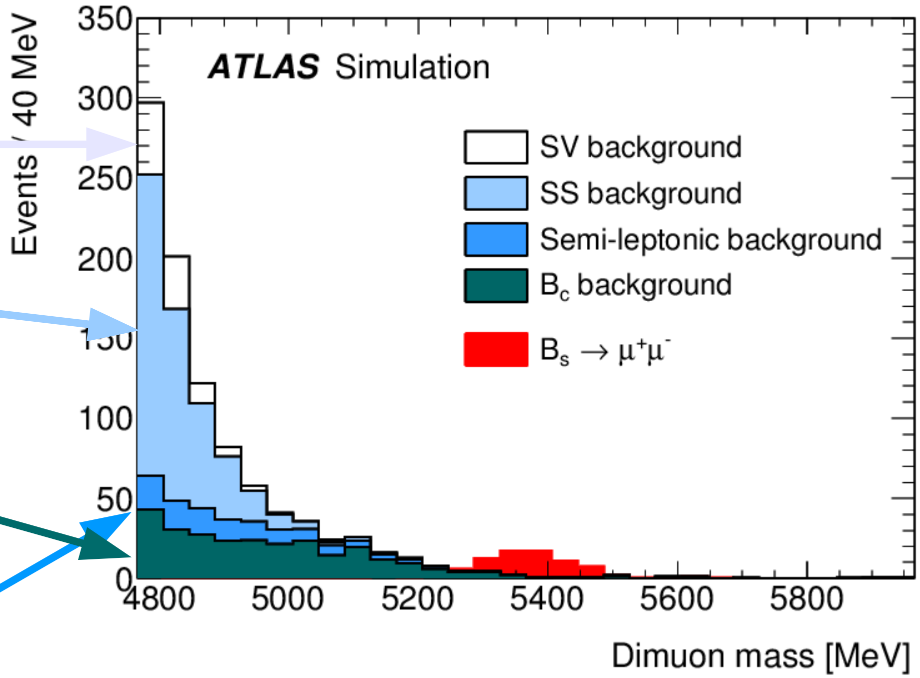
$$\mathcal{D}_{\text{norm}} = \sum_k N^k_{J/\psi K^+} \alpha_k \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^+}}\right)_k$$

- index *k* runs on the trigger and data categories
- α_k takes into account the prescaling factors

Background contributions

In order of relative magnitude:

- combinatorial background from opposite-side muons
- partially reconstructed B decays:
  - constituted by real muons
  - Same Vertex (SV): $B \to \mu\mu X$ decays like $B \to K^*\mu\mu$
  - Same Side (SS): semileptonic decay cascades ($b \to c\mu\nu \to s(d)\mu\mu\nu\nu$)
  - B_c decays: like $B_c \to J/\psi\ \mu\nu$
  - all these accumulate at low values of the dimuon invariant mass



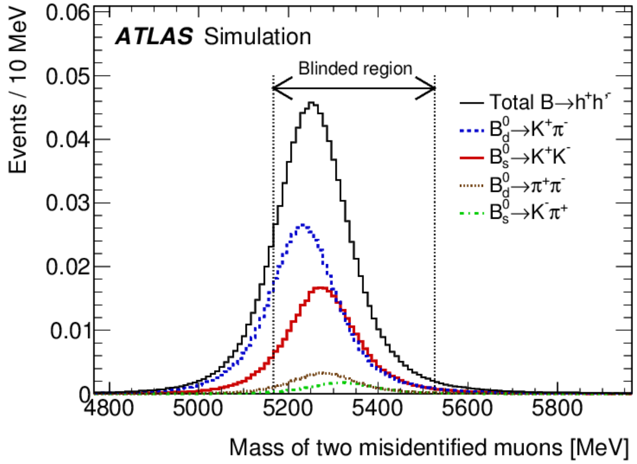
- semileptonic B and B_S decays:
  - one real muon and a charged hadron.
- peaking background from charmless hadronic $B_{(S)}$ decays:
  - B decays into two hadrons h (kaons and pions): $B^0_{(S)} \to hh'$
  - smaller component, but overlays with the signal in dimuon invariant mass

Fake-BDT against hadron misidentification

- studied on simulated samples of B →hh', signal B → μμ, and Λ_b → ph
- validated with data from φ → KK and $B^{\pm}$ → J/ψ $K^{\pm}$ decays.
- negligible misidentification of protons (< 0.01%)
- misidentification is 0.28%(0.12%) for K(π).

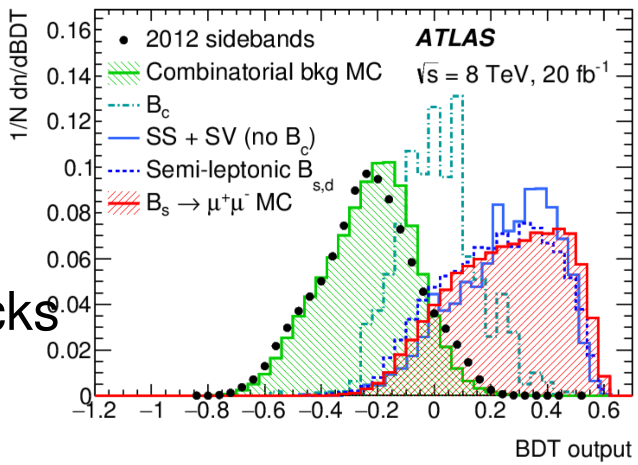
reduced by 0.4 with a dedicated *fake-BDT* with efficiency of prompt muons set at 95%

peaking-background events: 1.0±0.4



Continuum-BDT against combinatorial bkg

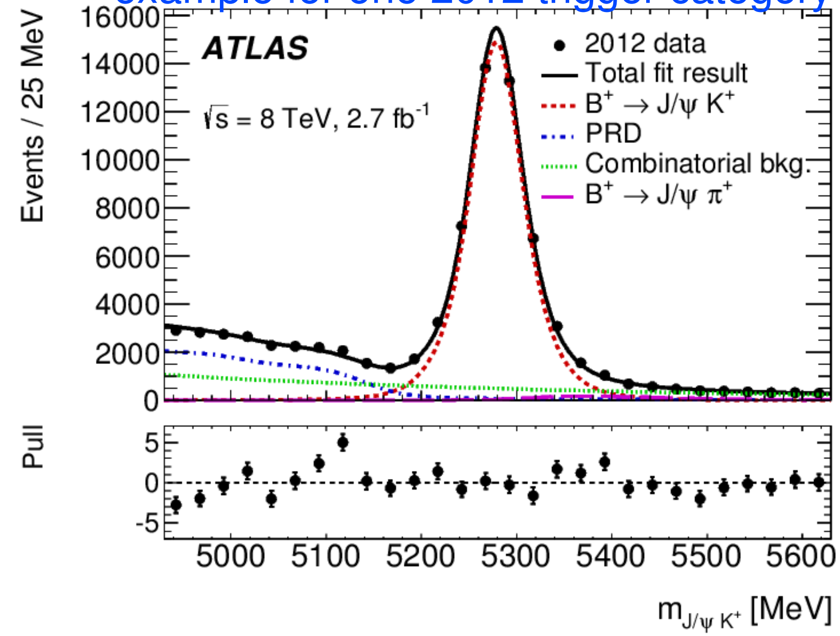
- MVA classifier used to discriminate from signal
- trained on MC samples and tested on mass sidebands
- 15 variables related to properties of B candidates, muons from the B decay, other tracks from the same collision and to pile-up vertices.



Normalisation B yield extraction

- unbinned maximum likelihood fit of the invariant mass $m_{J/\psi K} \rightarrow m_{\mu\mu K}$
- measurement of $J/\psi\pi$ over $J/\psi K$ ratio
  $\rho_{\pi/K} = 0.035 \pm 0.003 \pm 0.012$

example for one 2012 trigger category



$$\mathcal{D}_{\text{norm}} = \sum_k N^k_{J/\psi K^+} \alpha_k \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^+}} \right)_k$$

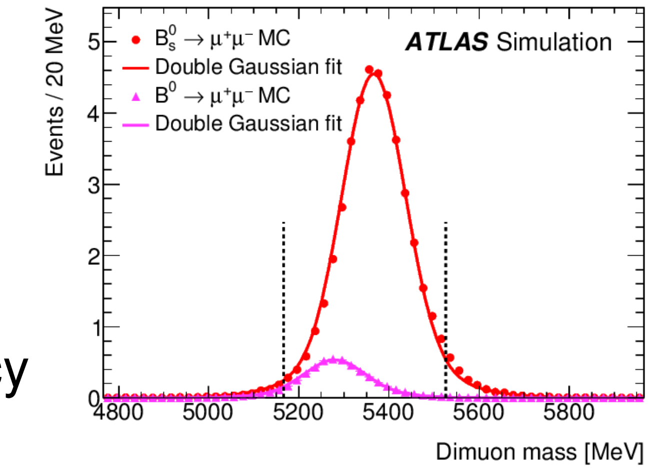
Efficiency ratio $\varepsilon_{\mu\mu}/\varepsilon_{J/\psi K}$

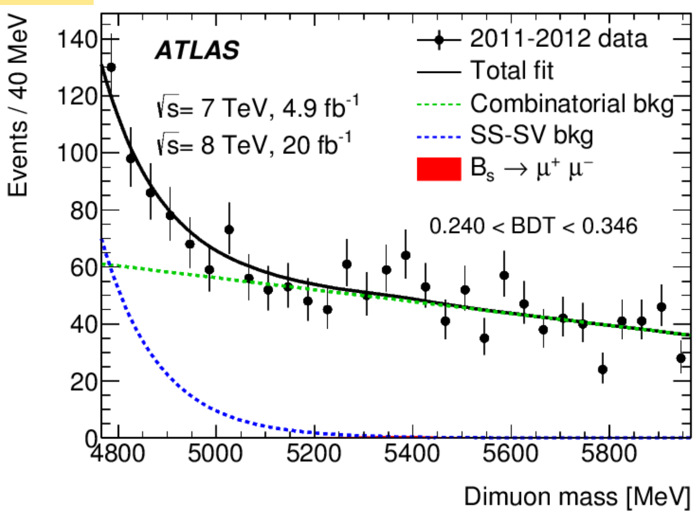
- efficiency ratio from MC
- systematic uncertainty from data-MC discrepancies
- For B^0_S: correction for lifetime difference of the B^0_S mass eigenstates:

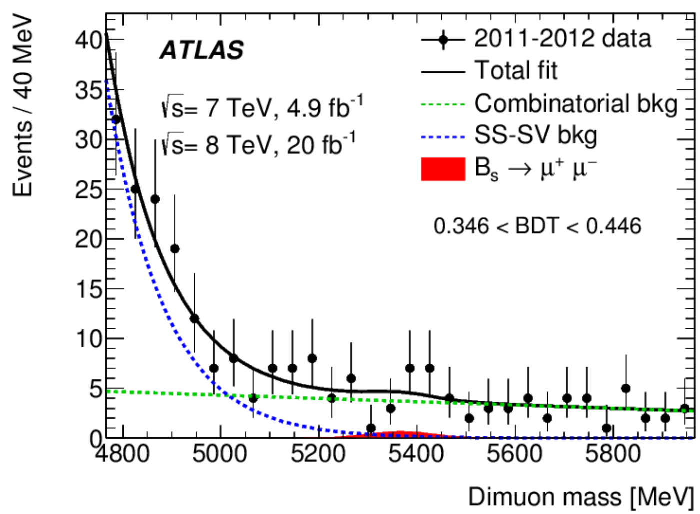
Total systematic uncertainty ±5.9% on the normalisation term D_{norm}

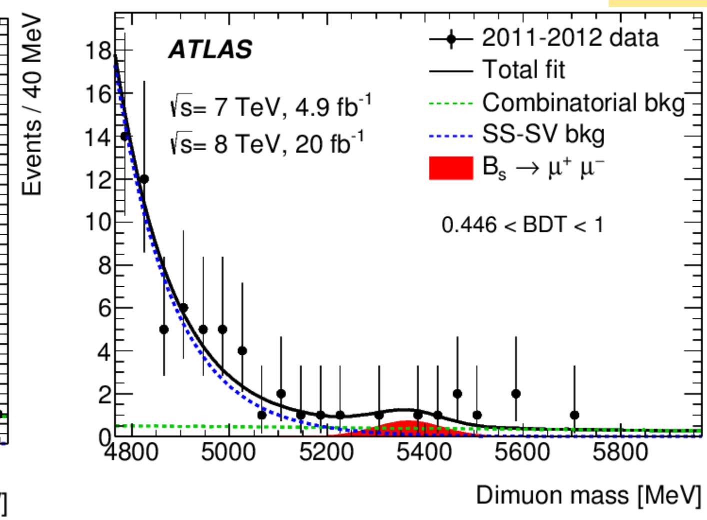
Signal yield extraction

- signal yields extracted with a unbinned maximum likelihood fit to the dimuon mass
- fit performed simultaneously in the three continuum-BDT bins with 18% signal efficiency









- yields constrained to be positive:
  - $N_S = 11$ and $N_d = 0$
- no constraints on positive yields:
  - $N_S = 16 \pm 12$ and $N_d = -11 \pm 9$

- fewer B^0_s events than expected
- no B^0 events
- Expected signal from SM
  - $N_S = 41$ and $N_d = 5$

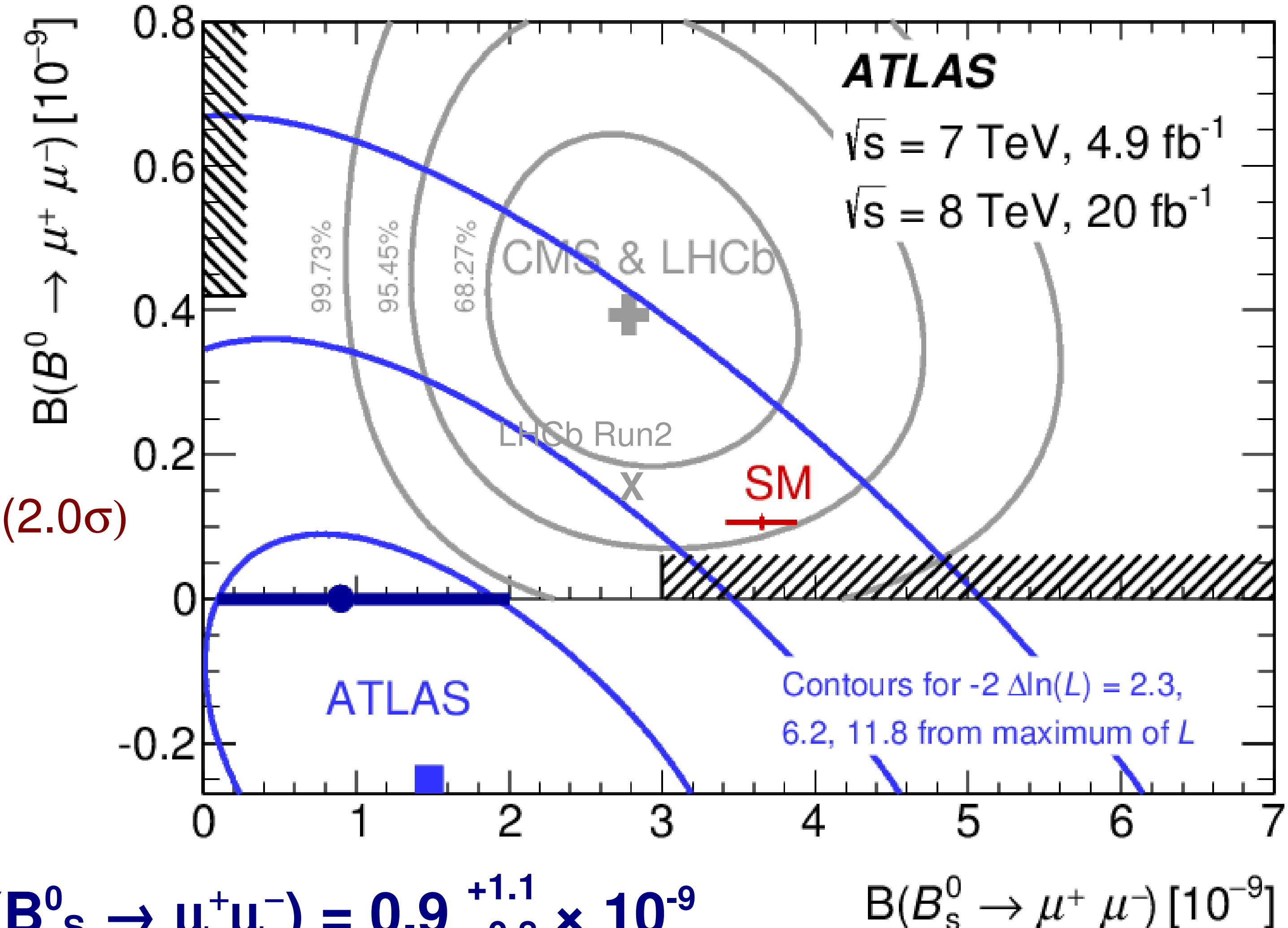
Branching ratio results

ATLAS, EPJ C76 (2016) 513, arXiv:1604.04263

$B(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$ at 95% CL

compatibility of the simultaneous fit with the SM: p-value = 0.048 (2.0σ)

reduced tension in B^0 with the SM with the new Run2 LHCb result
arXiv:1703.05747



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

Prospect on rare B decays $B_{(s)} \rightarrow \mu^+\mu^-$

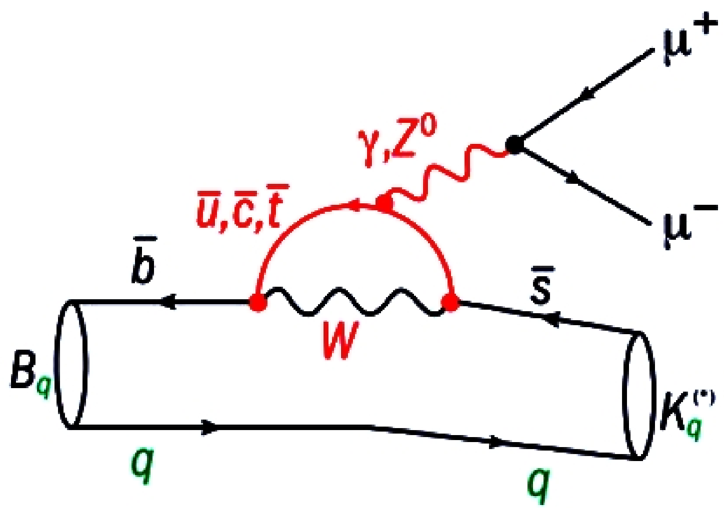
- Latest result available based on full Run 1 statistics
- Result is statistically limited: expect sensitivity to essentially scale with statistics
- Topological triggers exploited in Run 2 to maintain signal data taking efficiency

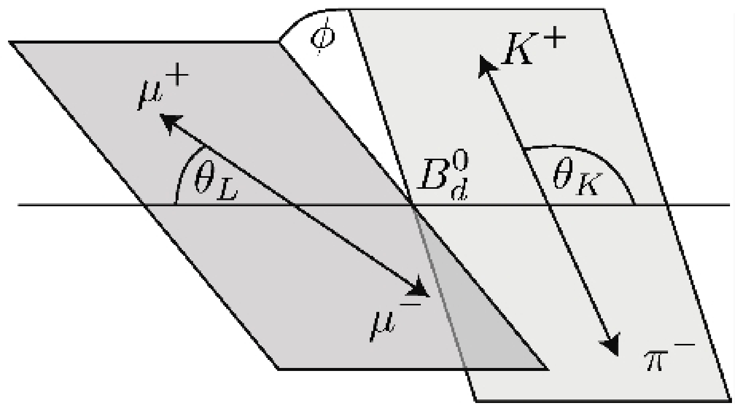
Angular analysis on $B \to K^*\mu\mu$

ATLAS-CONF-2017-023

Angular analysis on B → K*μμ

- another way to look at FCNC
  - occurs through a b → s transition with a BR ~ 1.1 10^{-6}
- angular distribution of the 4 particles in the final state sensitive to new physics for the interference of NP and SM diagrams





- decay described by three angles (θ_L, θ_K, ϕ) and the di-muon mass squared q^2 → the angular distribution is analysed in finite bins of q^2 as a function of θ_L, θ_K and ϕ.
- LHCb reports a 3.4σ deviation from the SM.

JHEP 02 (2016) 104
arXiv:1512.04442

Angular analysis on B → K*μμ at ATLAS

ATLAS-CONF-2017-023

- angular distribution given by:

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

- ATLAS uses trigonometric relations to reduce the problem into 4 sets of fits for three parameters (F_L , S_3 and S_j with j=4,5,7,8) for each q^2 bin.
- the S parameters are translated into the $P^{(\prime)}$ parameters via

$$P_1 = \frac{2S_3}{1-F_L} \qquad P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

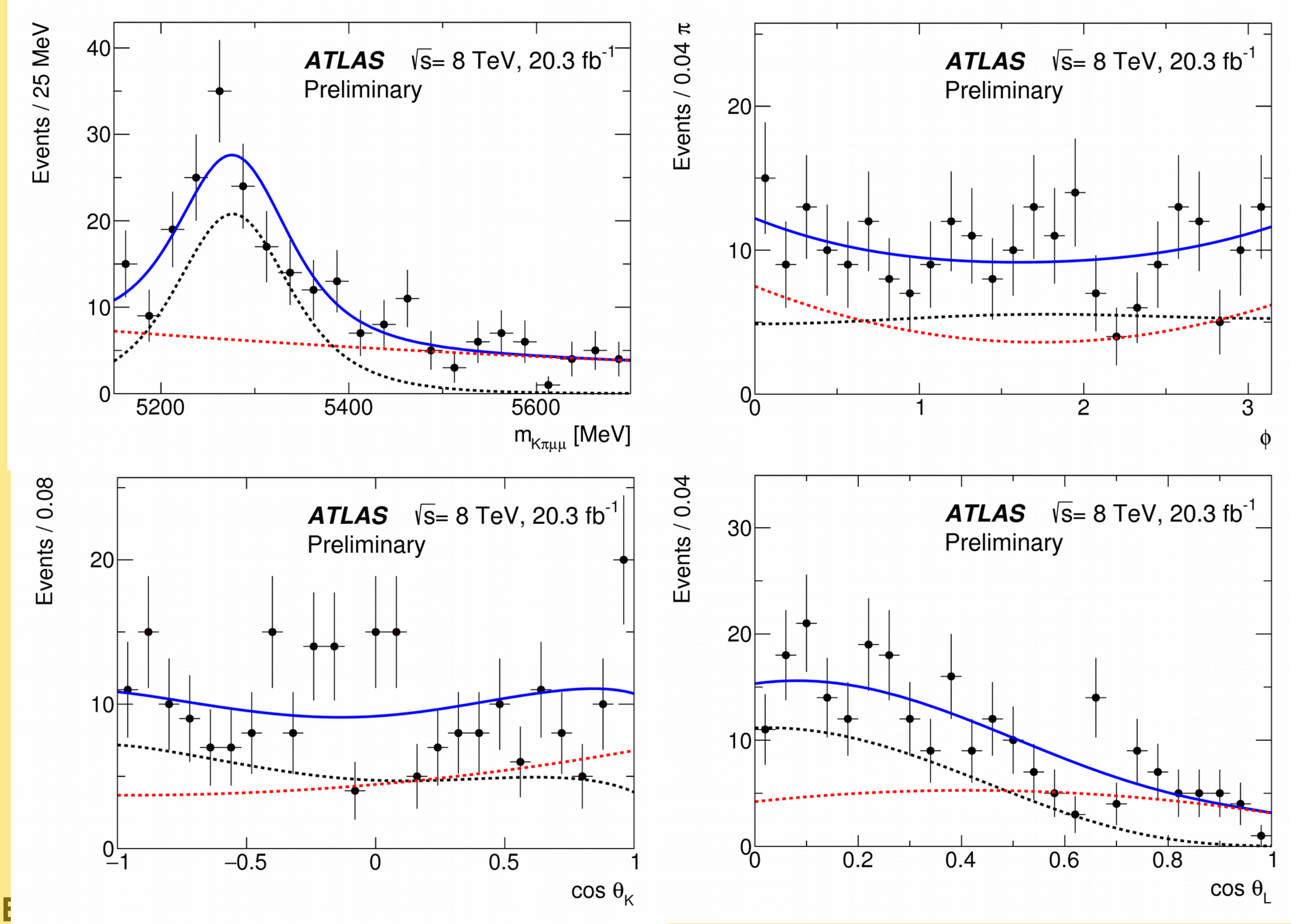
- the $P^{(\prime)}$ parameters are expected to have a reduced dependence on the hadronic form factors.

Analysis strategy for $B \rightarrow K^*\mu\mu$ at 8 TeV

- Data collected in 2012 at 8 TeV with 20.3 fb^{-1} data
- Measured in 6 (overlapping) bins of q^2 in the range [0.04, 6] GeV^2
- Selection of triggers with muon p_T thresholds starting at 4 GeV
- K* tagged by the kaon sign:
  - one candidate per event selected
  - dilution from mistag probability included in (1-2<w>):
    - <w> ~ 10.9(1)% with small dependence on q^2
- 787 events selected with $q^2 < 6$ GeV^2
- Vetoed [0.98, 1.1] GeV^2 region to exclude $\phi(1020)$
- Extended unbinned maximum likelihood fits in each of the fit variants in each q^2 bin:
  - two step fit procedure: first fit the invariant mass distribution
  - then add to the fit the angular distributions to extract the F_L and S(P) parameters
- Signal shape studies from control samples K^*J/ψ and $K^*\psi(2S)$
- Combinatorial background extracted in the fit, others in syst.

Fit projections

- Fit m(K*μμ), $\cos\theta_L$, $\cos\theta_K$ and ϕ to isolate signal and extract parameters of interest.



- Data shown for [0.04,2.0] GeV^2
- projections for the S_5 fit.
- Approx 106-128 signal events in 2 GeV^2 q^2 bin.
- Similar results for the other q^2 bins and other fit variants.

Results from the fits

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

signal and background yields from the first fit step

- Results obtained are generally statistically limited:

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

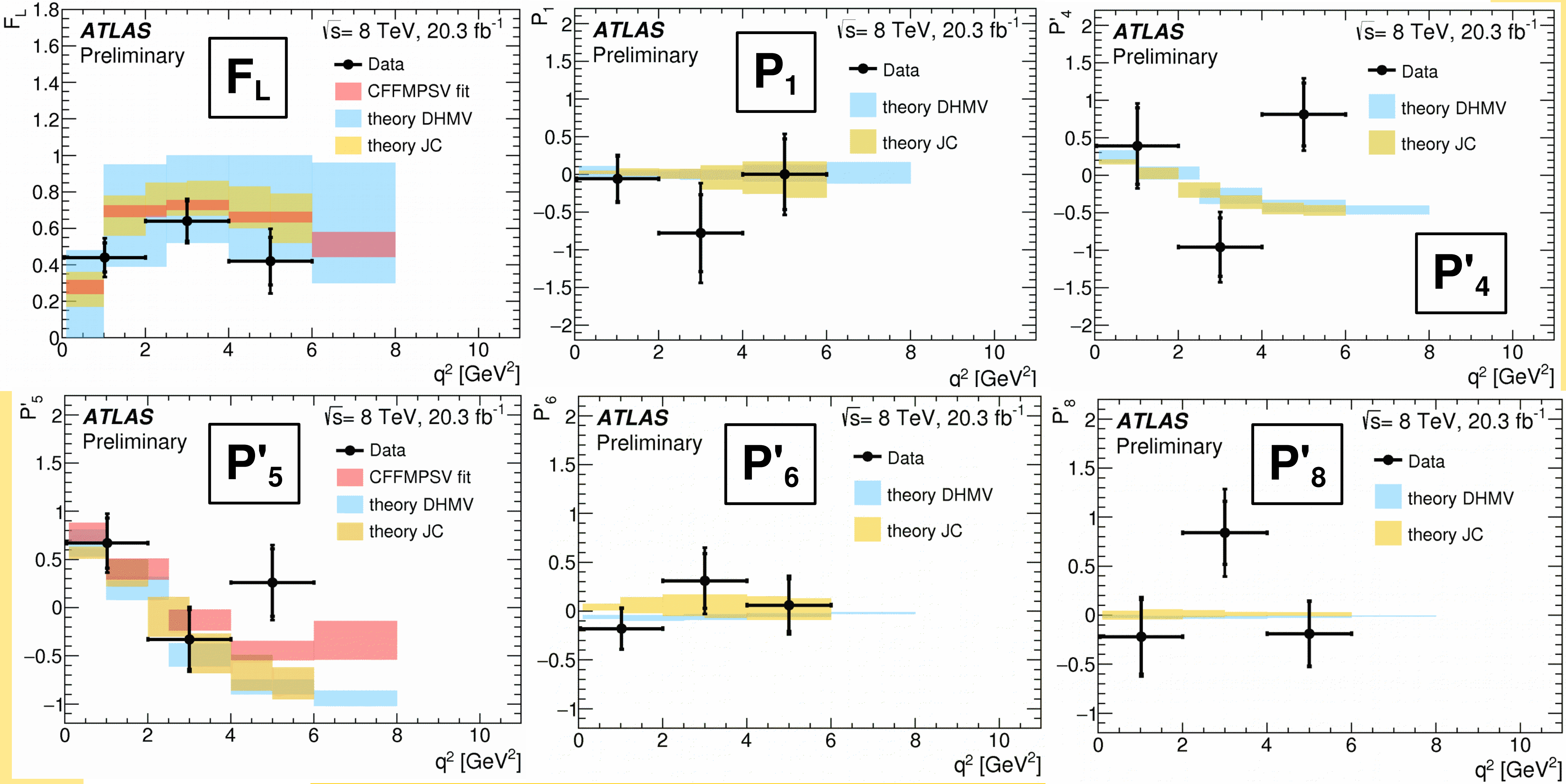
Systematic uncertainties

- Main systematic uncertainties come from backgrounds:
  - $\cos\theta_K \sim 1$ peaking component:
    - $B \to K/\pi\ \mu\mu + X$ and combinatoric $K\pi$ (fake K^*)
    - veto on three-body mass or $\cos\theta_K$ cut
  - $|\cos\theta_L| \sim 0.7$ peaking component:
    - partially reconstructed $B \to D \to X$ decays
    - veto around the charmed meson masses.
- background shape choice
- acceptance functions, alignment and B-field calibration
- S-wave contributions (~5%) result in a small systematic error.
- Other backgrounds from exclusive mode neglected in the fit are included and the systematic uncertainty assessed

- F_L: largest systematic from $\cos\theta_K$ and $\cos\theta_L$, backgrounds: 0.11
- S_j: systematics also from background uncertainties: 0.01-0.13

Angular analysis on B → K*μμ at 8 TeV

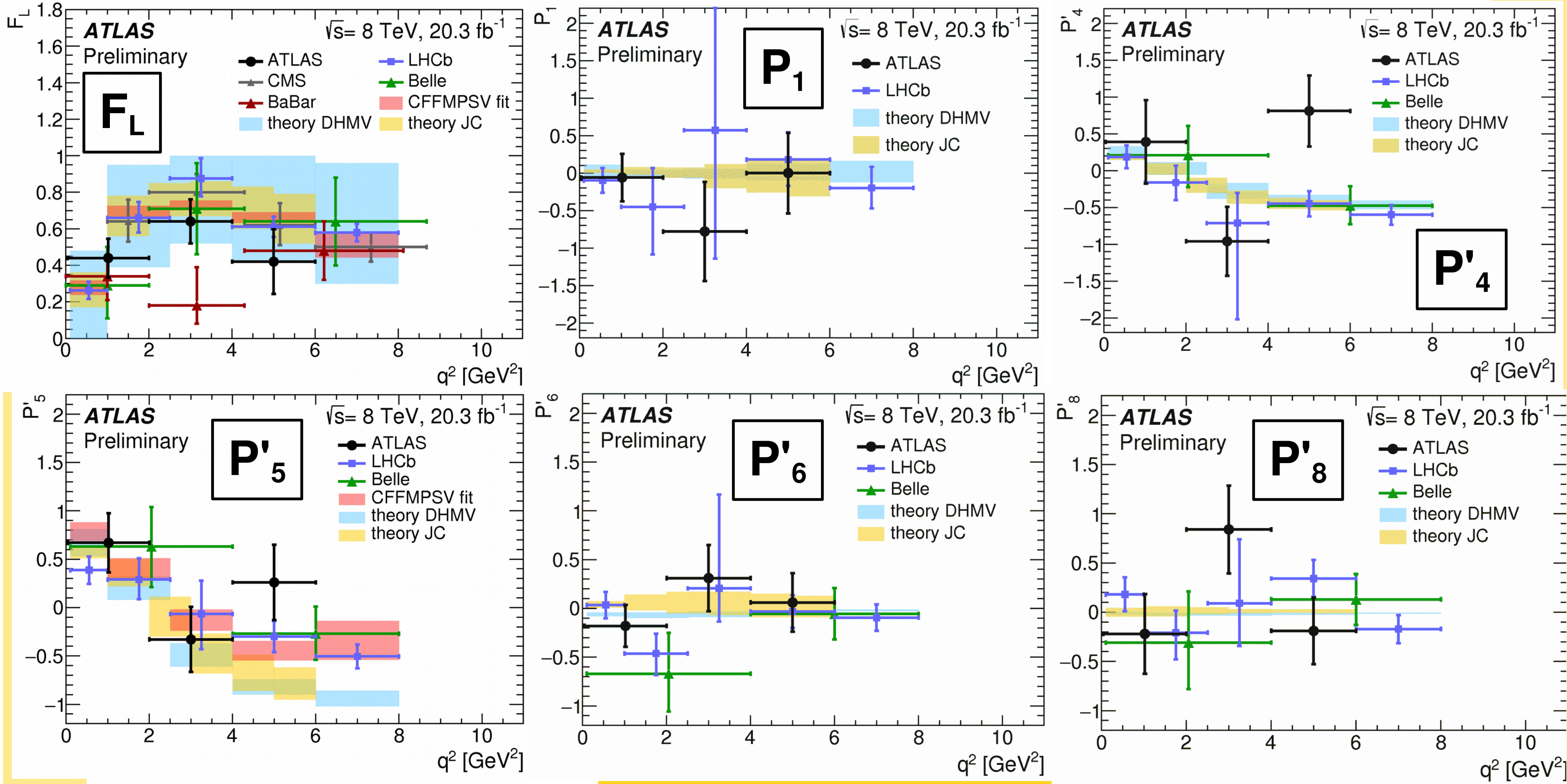
- Results are compatible with theoretical calculations & fits:



OPE and LHCb data fit: CFFMPSV: Ciuchini et al.; JHEP 06 (2016) 116.
QCD factorisation: DMVH: Decotes-Genon et al.; JHEP 12 (2014) 125.
JC: Jäger-Camalich; Phys. Rev. D93 (2016) 014028.

Angular analysis on B → K*μμ at 8 TeV

- Deviations of about 2.5σ (2.7σ) from DHMV in P'_4(P'_5) in [4,6] GeV^2



CFFMPSV: Ciuchini et al.; JHEP 06 (2016) 116.
DHMV: Decotes-Genon et al.; JHEP 12 (2014) 125.
JC: Jäger-Camalich; Phys. Rev. D93 (2016) 014028.

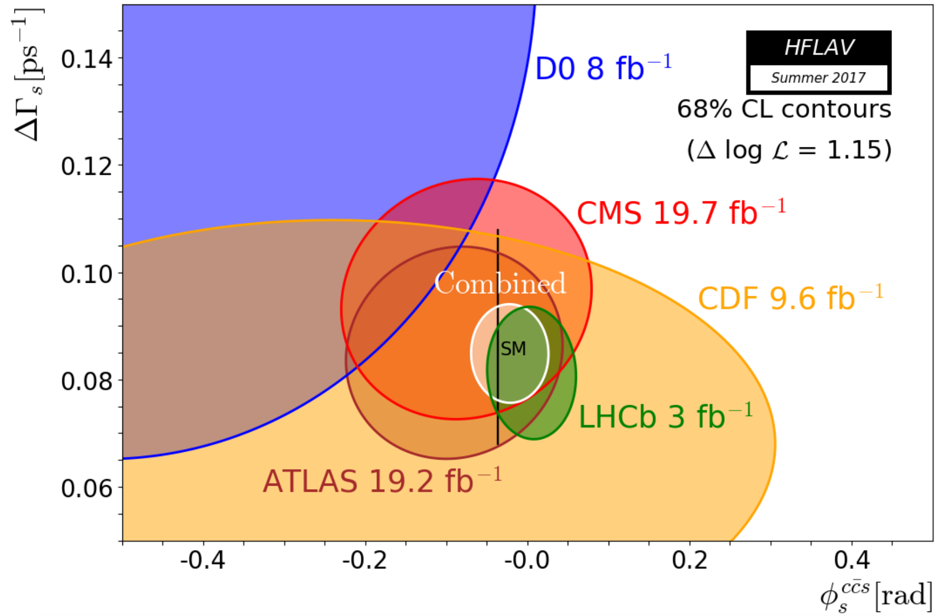
Time-dependent angular analysis on $B_s \to J/\psi\phi$

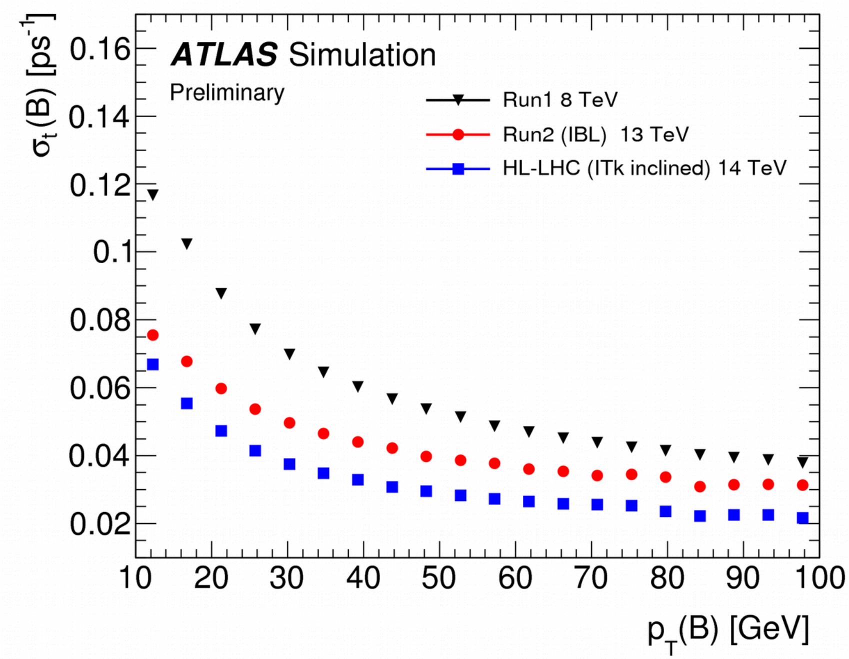
JHEP 08 (2016) 147, arXiv:1601.03297

Time-dependent angular analysis of J/ψϕ

- Time-dependent angular analysis
  - BLUE method used to combine 2011/2012 results
  - Combination is statistically limited
  - Precision determined by cτ resolution

- No new result approved yet
- Run 2 dataset collection continues with comparable efficiency
- Expect extrapolation to scale essentially with luminosity
- Cτ resolution improvement from IBL in Run 2 will improve effective tagging dilution by x4

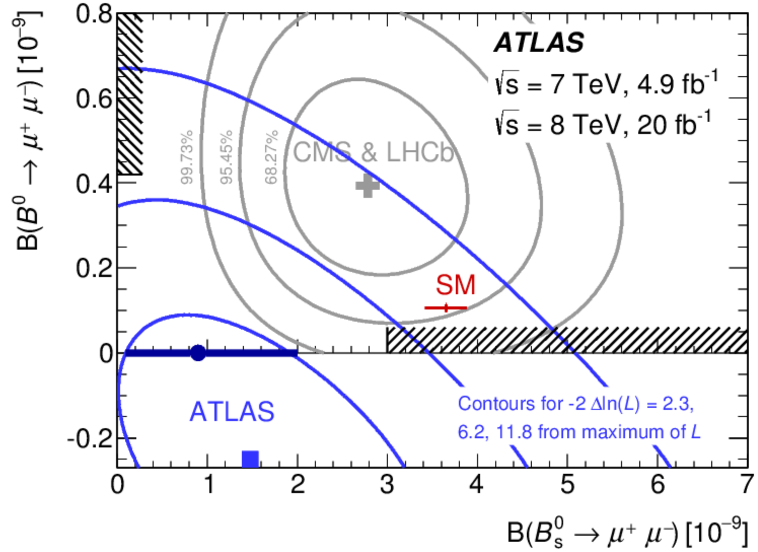




Conclusions

- B_d width difference extracted on Run 1

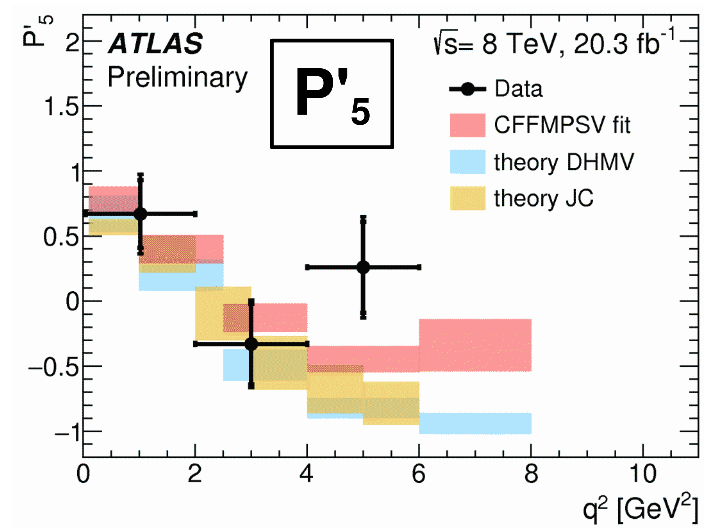
  $\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.4) \times 10^{-2}$



- Run 1 study on rare B decays into muons

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

  $B(B^0 \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-10}$ at 95% CL



- B to K*μμ angular analysis on 20 fb^{-1} of 8 TeV data with better background understanding and improved fit strategy
  - still statistically limited
  - results in agreement with predictions and fits.

- B physics in ATLAS is healthily challenging and very much alive.

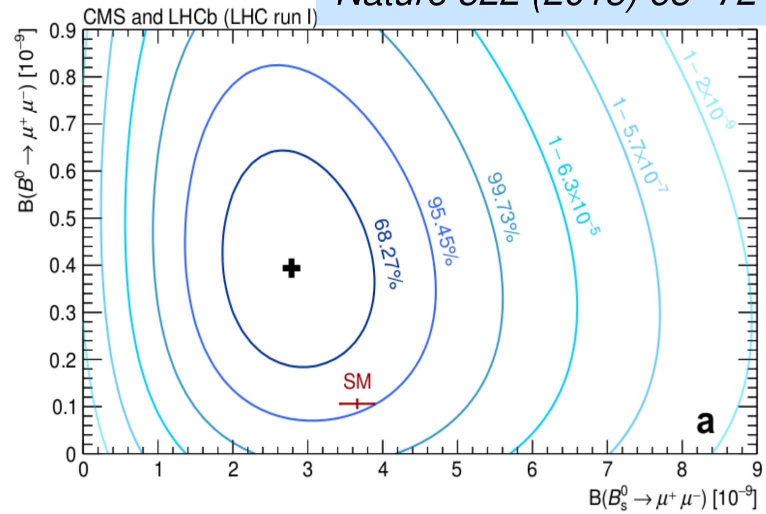
back-up slides

Systematic table for K*μμ angular analysis

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	–	–

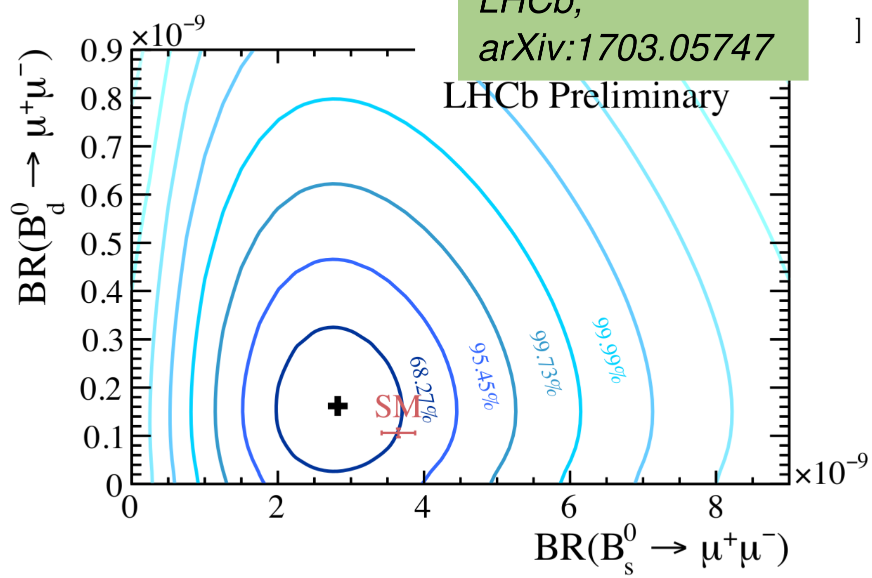
Previous and latest results

CMS and LHCb, Nature 522 (2015) 68--72



- Combination from CMS and LHCb:
  - 6σ observation for the B^0_S channel:
    $$B(B^0_s \to \mu^+\mu^-) = (2.8\ ^{+0.7}_{-0.6})\ 10^{-9}$$
  - 3σ evidence for the B^0 channel:
    $$B(B^0 \to \mu^+\mu^-) = (3.9\ ^{+1.6}_{-1.4})\ 10^{-10}$$
  - some tension with the SM

LHCb, arXiv:1703.05747

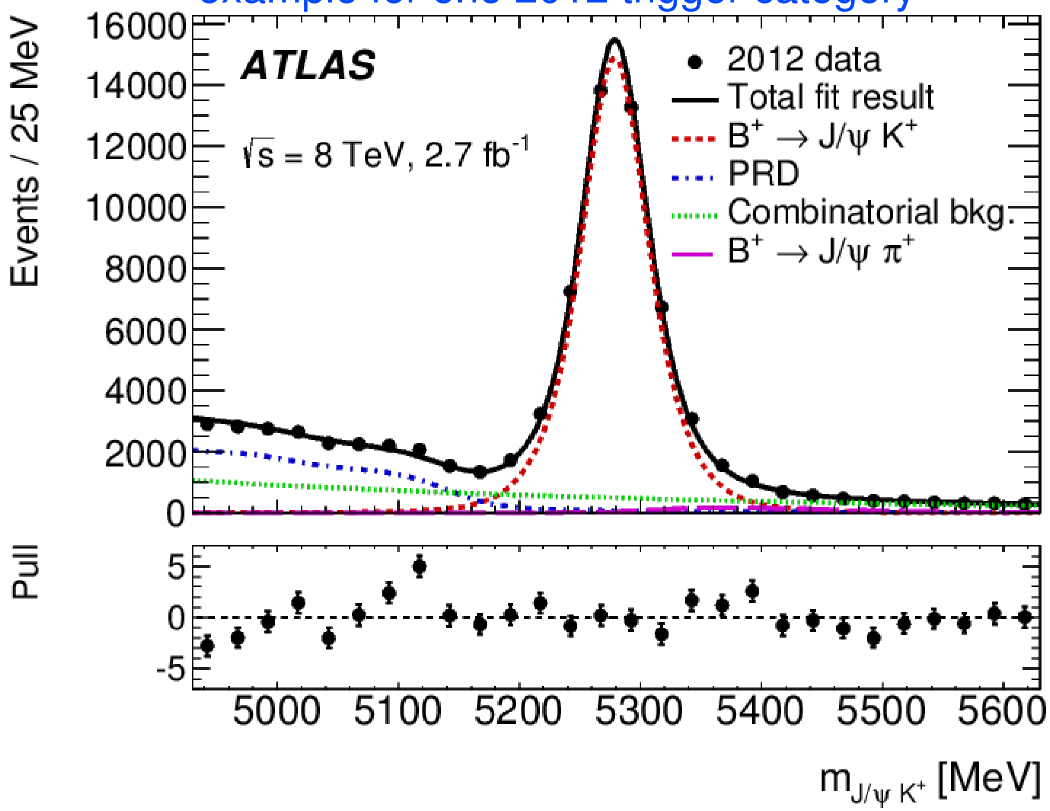


- Latest result from LHCb on Run2:
  - 7.8σ observation for the B^0_S channel
    $$B(B^0_s \to \mu^+\mu^-) = (2.8 \pm 0.6)\ 10^{-9}$$
  - 1.9σ effect for the B^0 channel:
    $$B(B^0 \to \mu^+\mu^-) = (1.6\ ^{+1.1}_{-0.9})\ 10^{-10}$$
    $$< 3.4\ 10^{-10}$$
  - reduced tension with the SM

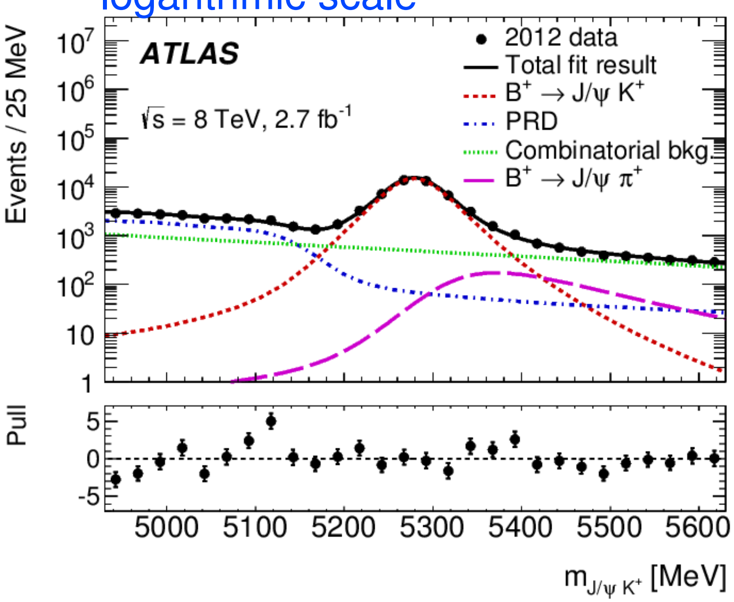
Normalisation B yield extraction

- applied fake-BDT and continuum-BDT selections (optimised for signal)
- yields extracted separately in the 4 categories:
  three trigger categories for 2012 and 2011 data
- unbinned maximum likelihood fit of the invariant mass $m_{J/\psi K} \to m_{\mu\mu K}$
- measurement of J/ψπ over J/ψK ratio $\rho_{\pi/K} = 0.035 \pm 0.003 \pm 0.012$

example for one 2012 trigger category



logarithmic scale



Efficiency ratio $\varepsilon_{\mu\mu}/\varepsilon_{J/\psi K}$

$$\mathcal{D}_{\text{norm}} = \sum_k N^k_{J/\psi K^+} \alpha_k \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^+}}\right)_k$$

- in each category (k) the efficiency ratio is obtained from MC
- p_T and η MC spectra are tuned on data from the reference channels:
- residual trigger efficiency differences from tag&probe studies on J/ψ and Υ
- systematic uncertainty from data-MC discrepancies:
  assessed from the data-MC comparisons of the discriminating variables used in the continuum-BDT: dominant systematic contribution to D_{norm}
  - isolation requires tuning in the $B^{\pm}$ mode:
  - central value of the efficiency ratio corrected with this tuning
- For B^0_S:
  - correction for lifetime difference between the B^0_S mass eigenstates: lifetime from SM prediction and efficiency correction (+4%) from MC

Total correction to the central value of the efficiency ratio:

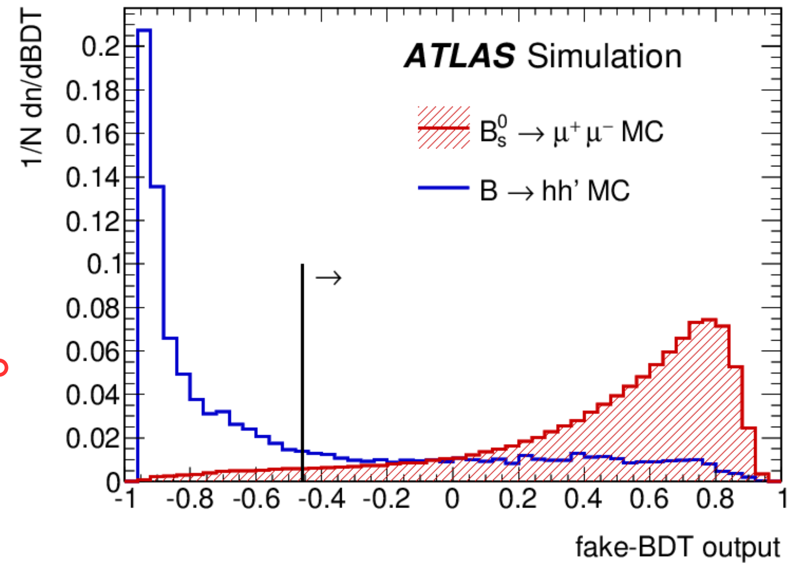
+3% for B^0 and -1% for B^0_S (including the lifetime correction)

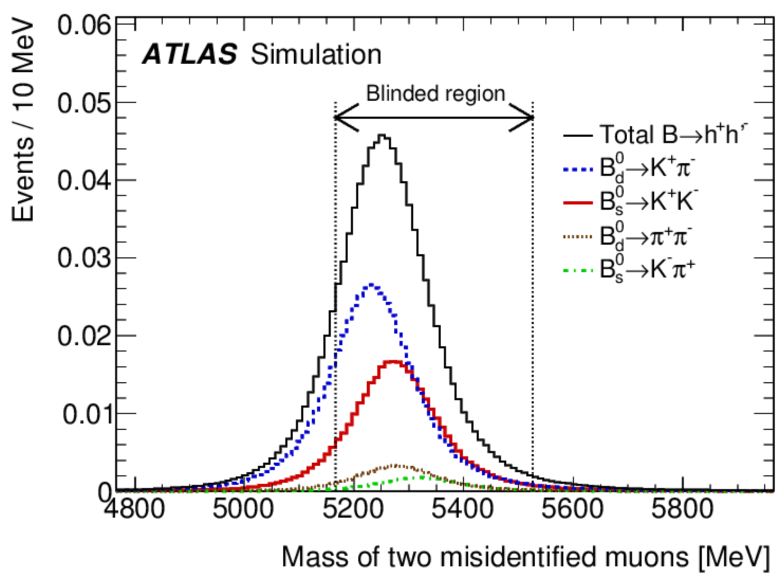
Total systematic uncertainty ±5.9% on the normalisation term D_{norm}

Fake-BDT against hadron misidentification

- studied on simulated samples of B →hh', signal B → μμ, and Λ_b → ph
- validated with data from φ → KK and $B^{\pm}$ → J/ψ $K^{\pm}$ decays.
- negligible probability of misidentification of protons (< 0.01%)
- probability of misidentification is about 0.28% for kaons and 0.12% for pions.

reduced of 0.4 with a dedicated *fake-BDT* with efficiency of prompt muons set at 95%

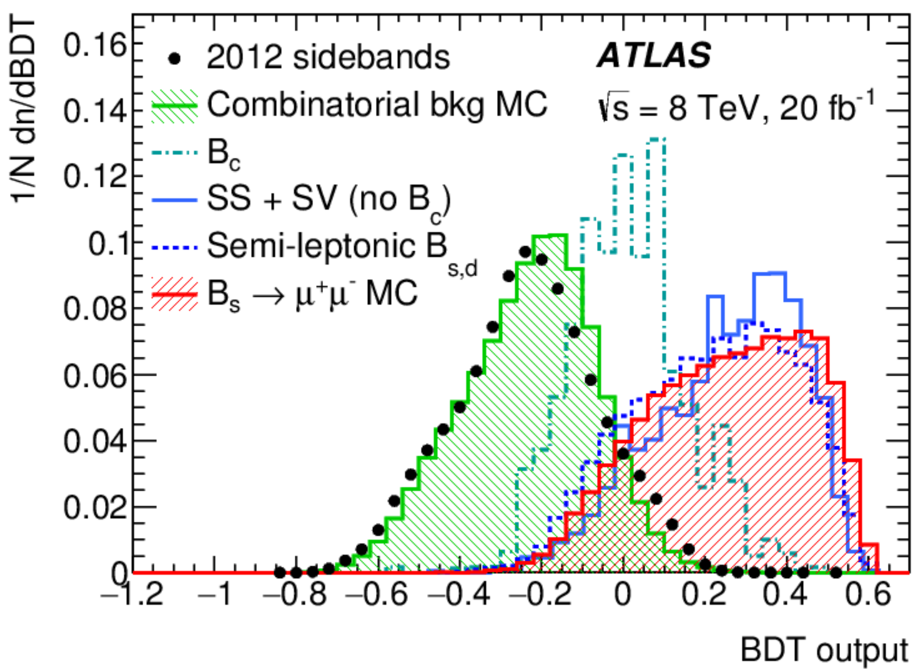




Use $B^{\pm}$ → J/ψ$K^{\pm}$ yield and efficiency ratio to normalise B →hh' (like for the signal): the total number of peaking-background events feeding into our events is 1.0±0.4

Continuum-BDT against combinatorial bkg

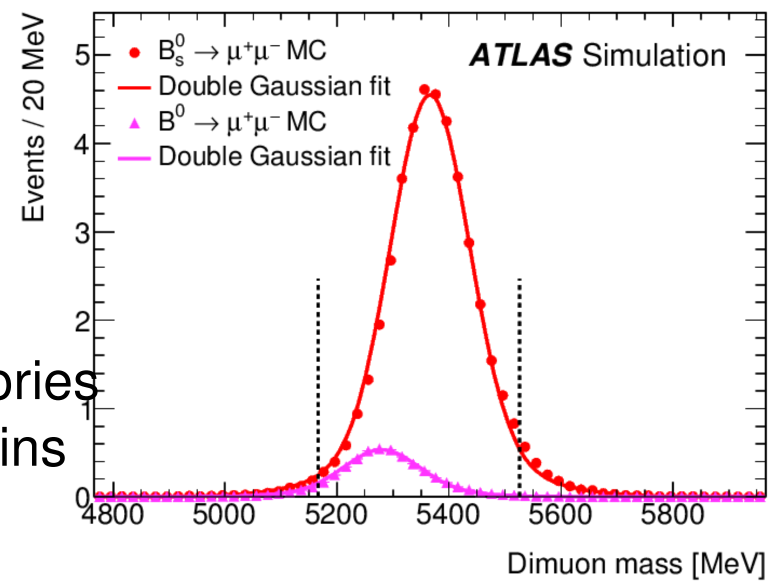
- combinatorial background: muon pairs from uncorrelated decays of hadrons produced in hadronisation of b and $\bar{b}$ quarks (or c and $\bar{c}$ quarks).
- separated from signal with a MVA classifier:
- 15 variables related to the B candidate, to the muons from the B, to the other tracks from the same collision and to pile-up vertices.



- training of the continuum-BDT done on a large MC sample of uncorrelated b (c) and $\bar{b}$ ($\bar{c}$) hadrons with forced decays into final states containing muons: 1.4G MC events
- tested on high-mass sideband data: not perfect data-MC agreement, but sample good enough for training, which is the sole use of this sample.
- B-related backgrounds behave like signal: SS-SV, semileptonic decays, peaking background

Signal yield extraction

- signal yields (N_d and N_S) extracted with a unbinned maximum likelihood fit to the dimuon invariant mass distribution
- fit performed simultaneously in the categories corresponding to three continuum-BDT bins with constant signal efficiency (18%)



- *signal*: two Gaussian distributions with common mean, shape constrained across continuum-BDT bins and fixed to the MC shapes, varied for systematic uncertainty
- *SS-SV background*: exponential distribution, parameters floated in the fit, shape constrained across the continuum-BDT bins, independent normalisations.
- *peaking background*: two Gaussian distributions constrained across continuum-BDT bins and fixed to the MC shapes, normalisation fixed to 1.0±0.4 total events
- *continuum background*: first order polynomial, parameters floated, shape loosely constrained across the continuum-BDT bins, independent normalisations

- systematics obtained by varying all the above:

$$\sigma_{syst}(N_S) = \sqrt{2^2 + (0.06 \times N_S)^2} \quad \text{and} \quad \sigma_{syst}(N_d) = 3 \text{ events}$$

Branching fraction extraction

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N_{d(s)} \times \frac{f_u}{f_{d(s)}} \times \frac{1}{\mathcal{D}_{\text{norm}}}$$

$$\times \left[\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right]$$

$$\mathcal{D}_{\text{norm}} = \sum_k N^k_{J/\psi K^+} \alpha_k \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^+}}\right)_k$$

ATLAS PRL 115 (2015) 262001

The normalization includes:

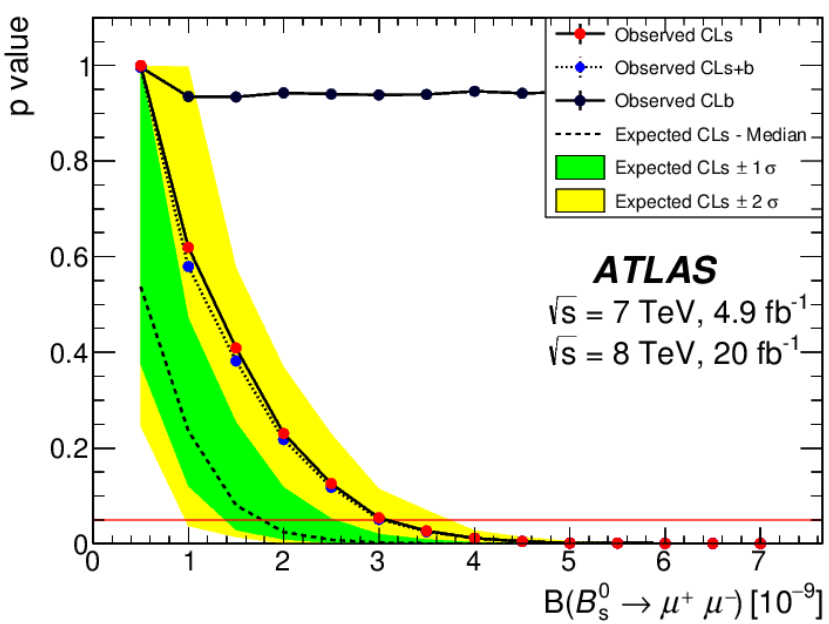
- $B^{\pm}$ branching fraction (world averages)
- the fragmentation fraction f_u/f_S from the ATLAS measurement of f_S/f_d performed in the same p_T, η range: 0.240 ± 0.020 (8% systematic)
- the efficiency ratios and $B^{\pm}$ yields in the D_{norm} term
- The total uncertainty in the normalisation is
  - ±11% for $BR(B^0_S \to \mu^+\mu^-)$
  - ± 7% for $BR(B^0 \to \mu^+\mu^-)$

Result for the B^0_s branching fraction

- central value obtained with non-negative branching fractions
- the errors obtained by a frequentist belt, using pseudo-MC experiments and include both statistic and systematic uncertainties.
- the systematic uncertainty is
  - $\sigma_{syst} = \pm\, 0.3 \times 10^{-9}$

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

- the upper limit @ 95% CL from CLs is
  - $B(B^0_S \to \mu^+\mu^-) < 3.0 \times 10^{-9}$
- the observed compatibility with the null hypothesis (only background) has
  - $p = 0.08\ (1.4\sigma)$
- the expectation for a SM signal is
  - $p = 0.0011\ (3.1\sigma)$

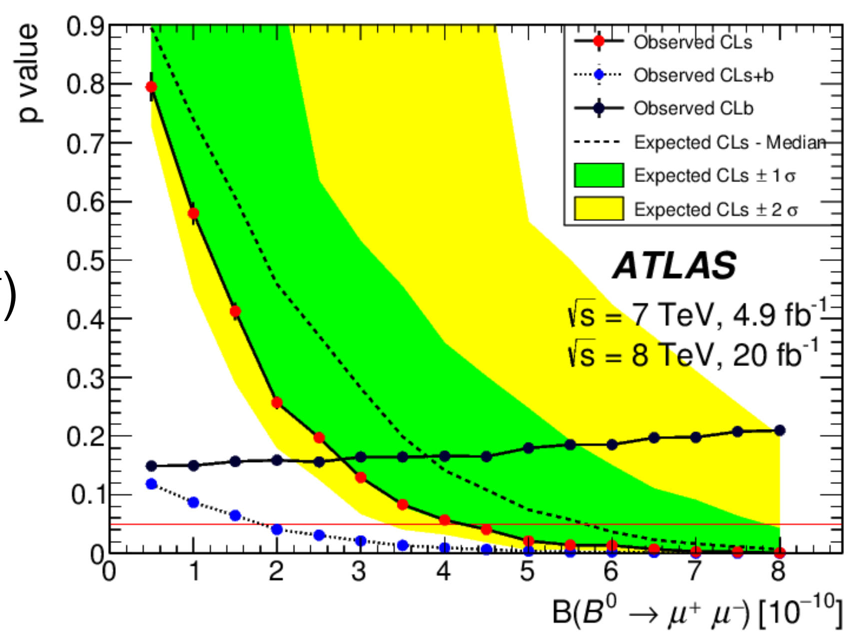


Result for the B^0 branching fraction

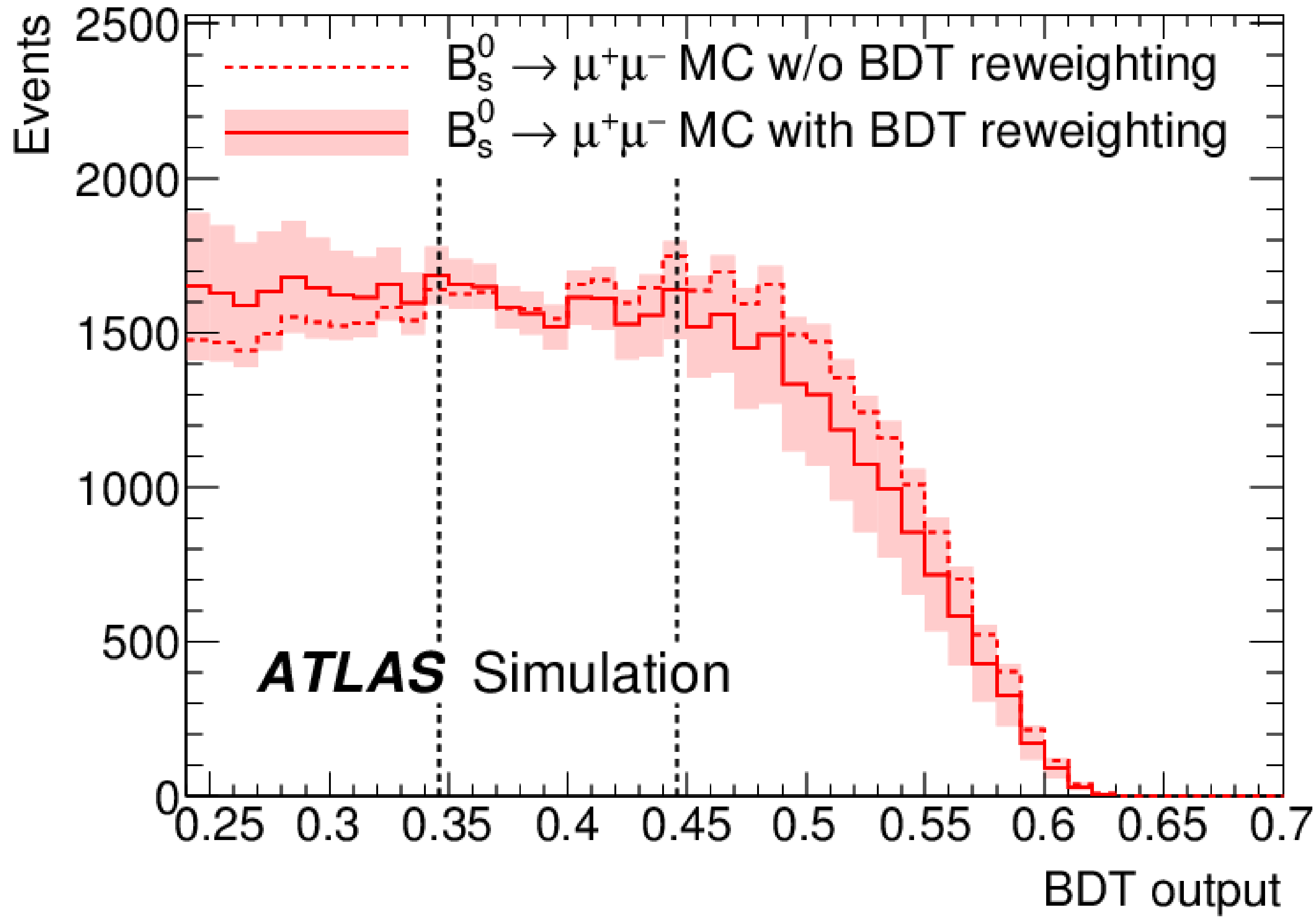
- upper limit set using CLs technique

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ at 95\% CL}$$

- no signal, $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ left free to be determined in the fit
- CL_b is ≈ 0.15 for $\mathcal{B}(B^0 \to \mu^+\mu^-)$ near 0:
  - -1σ fluctuation of background
- expected limit $< 5.7^{+2.1}_{-1.2} \times 10^{-10}$
- limit is higher than the SM prediction
  - $\mathcal{B}(B^0)_{SM} = (1.06 \pm 0.09) \times 10^{-10}$
- expected significance for $\mathcal{B}(B^0 \to \mu^+\mu^-)$ assuming the SM branching fraction is 0.2σ



Continuum-BDT bins



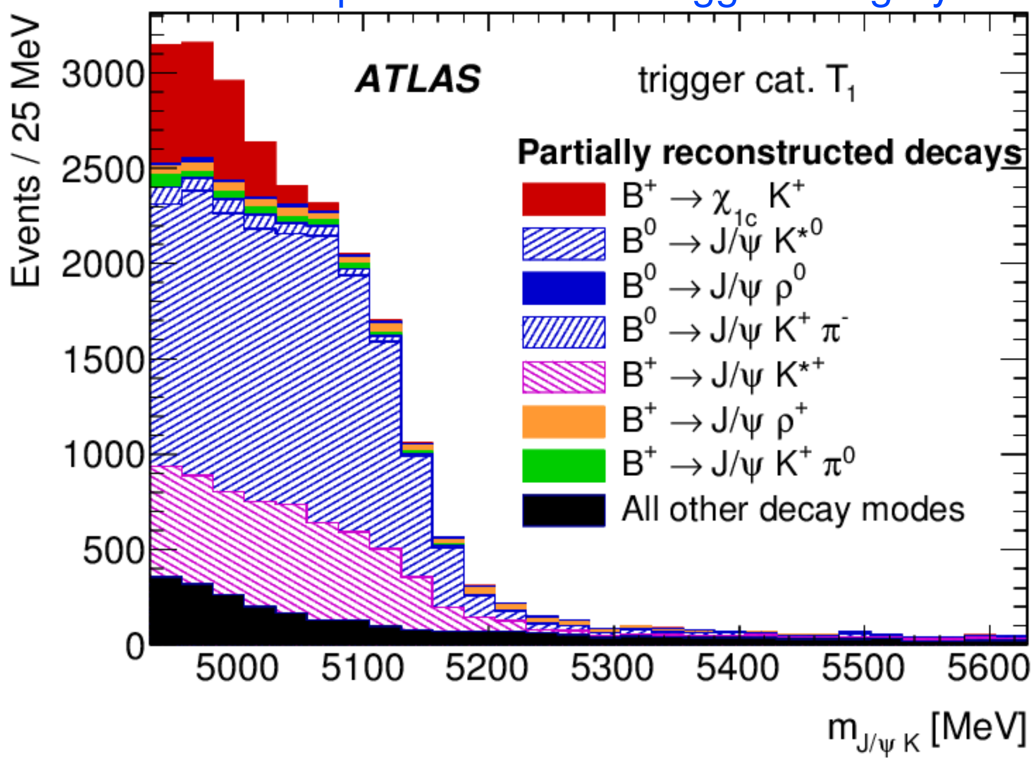
Total systematics on the BR extraction

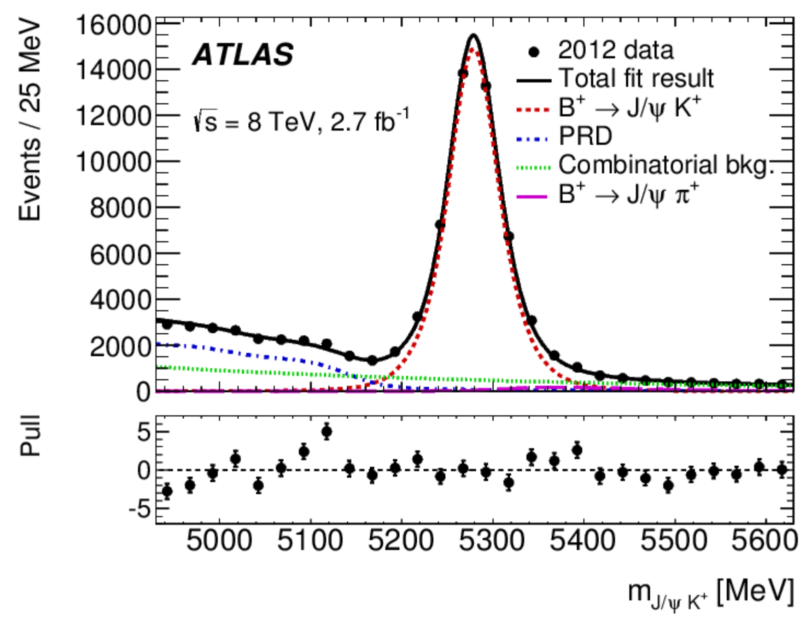
	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\mathcal{B}(B^0 \to \mu^+\mu^-)$
Scale uncertainties		
$\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu\mu)$ branching fractions	3.1%	3.1%
$B^0_{(s)}/B^+$ production ratio	8.3%	0
B^+ yield and $B^0_{(s)}/B^+$ efficiency ratio	5.9%	5.9%
Relative efficiency of continuum-BDT intervals	9%	9%
Signal and background model	6%	0
Total scale uncertainty	16%	11%
Offset uncertainties		
Signal and background model	0.2×10^{-9}	0.7×10^{-10}

Normalisation B yield extraction:

- yields extracted separately in the 4 categories:
  three trigger categories for 2012 and 2011 data
- unbinned maximum likelihood fit of the invariant mass $m_{J/\psi K} \rightarrow m_{\mu\mu K}$
- detailed study on partially reconstructed decays (PRD)

example for one 2012 trigger category





Ratio of b fragmentation fractions f_s/f_d

ATLAS, PRL 115, 262001 (2015),

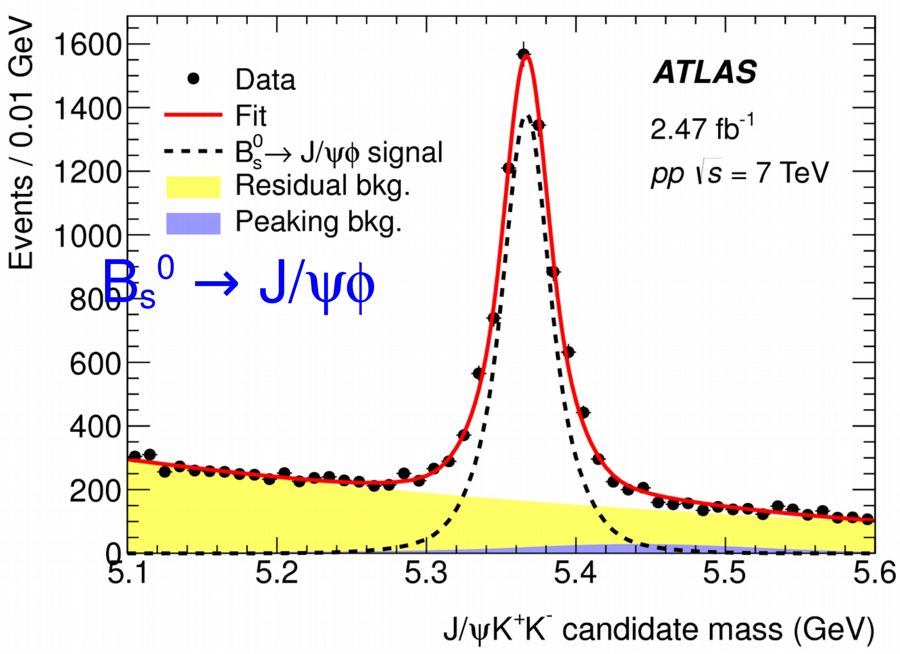
$B_s^0 \to J/\psi\phi$ and $B^0 \to J/\psi K^{*0}$ used to determine the ratio of fragmentation fractions f_s/f_d

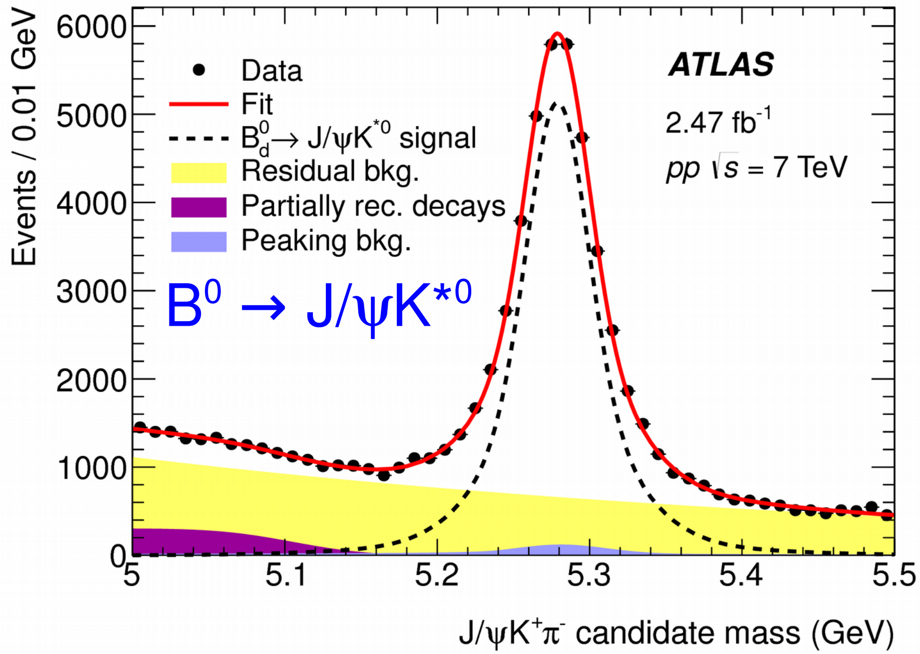
The ratio is extracted from measured signal yields, converted into B meson yields by correcting for the different efficiencies and by the decay BRs:

- yields from unbinned maximum likelihood fit to invariant mass spectra
- correction for acceptance and selection efficiency ratios in the two modes

$$\frac{f_s}{f_d} = \frac{N_{B_s^0}}{N_{B_d^0}} \frac{\mathcal{B}(B_d^0 \to J/\psi K^{*0})}{\mathcal{B}(B_s^0 \to J/\psi\phi)} \frac{\mathcal{B}(K^{*0} \to K^+\pi^-)}{\mathcal{B}(\phi \to K^+K^-)} \mathcal{R}_{\text{eff}}$$

2.47 fb





Ratio of b fragmentation fractions f_s/f_d

Final measurement:

$$f_s/f_d = 0.240 \pm 0.004(\text{stat}) \pm 0.010(\text{sys}) \pm 0.017(\text{th})$$

ATLAS, PRL 115, 262001 (2015),

- Uses pQCD calculation of branching fractions ratio [arXiv:1309.0313]
- Measurement in p_T and pseudorapidity intervals: no visible dependence
- Results compared to previous experimental results
  → historical tension between LEP/CDF
- Good agreement with recent LHCb results. Improving the world average
- Fundamental input for the rare decay $B_s \to \mu^+\mu^-$