Recent results in b-physics from ATLAS

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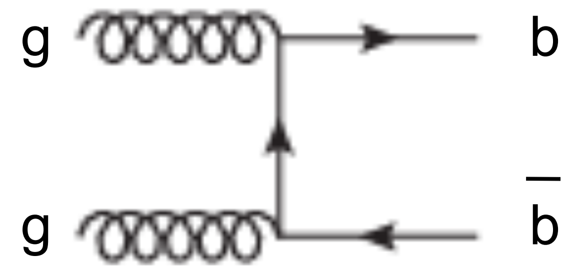
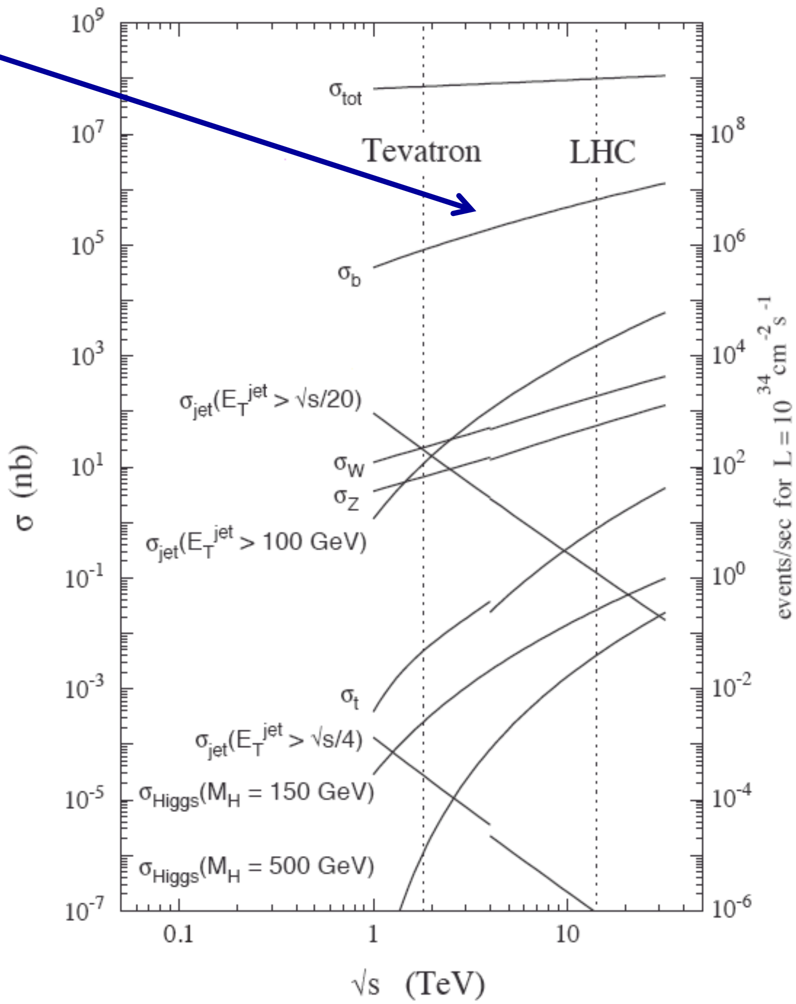
SILAFAE 2018
November 26-30, 2018
Lima, Peru

On behalf of the ATLAS Collaboration

b hadron production at the LHC

- *b hadrons (and anti-hadrons) are dominantly produced through strong interaction in pp collisions at the LHC*
  - *Example: gluon-gluon fusion*
  - *Large inclusive $b\bar{b}$ cross-section (~ 0.1 mb)*
  - *All b hadron types including Λ_b, B_c and B_s are produced*



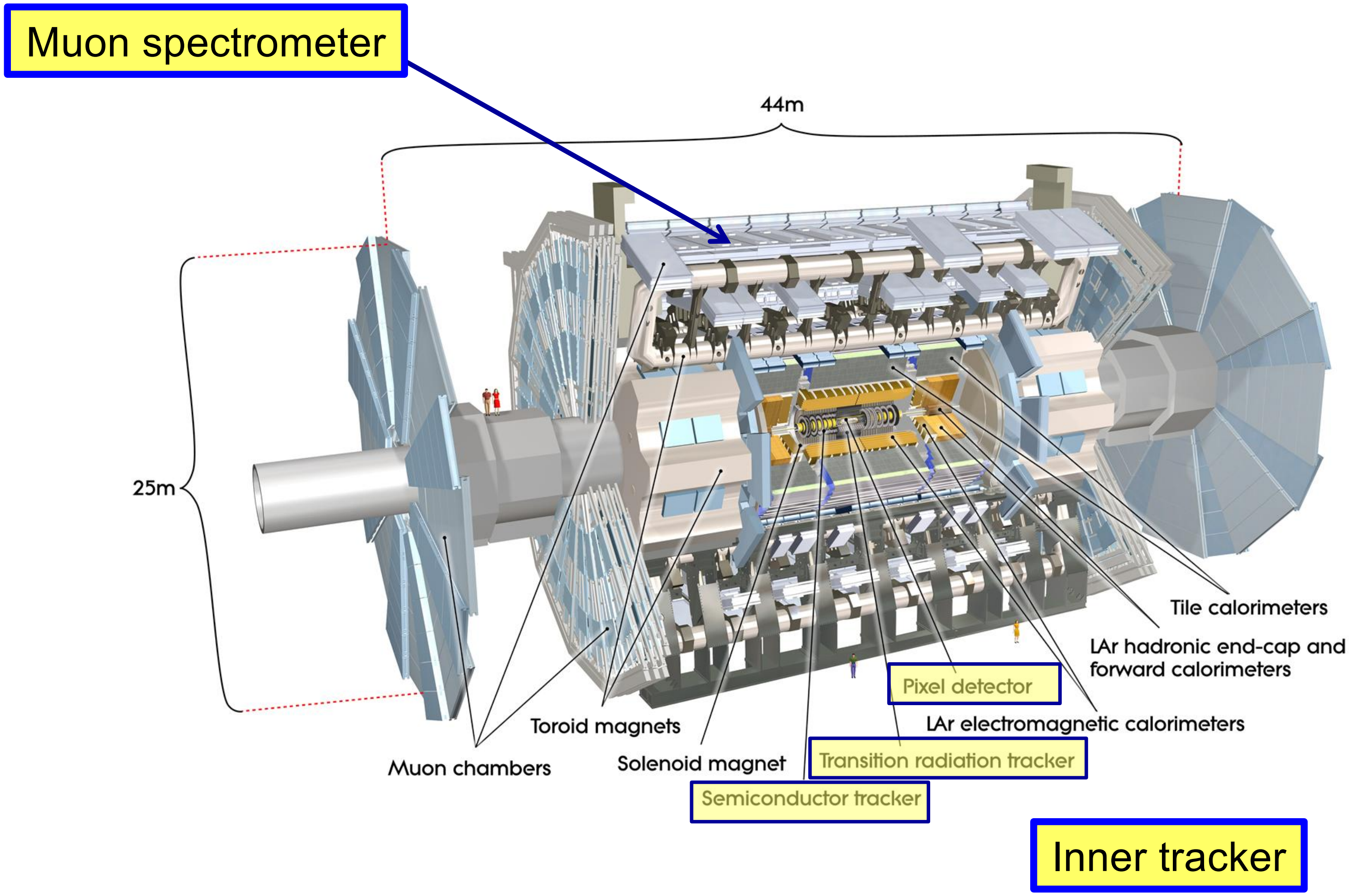


- *Unfortunately, it's hard to efficiently trigger on b hadron decays at the LHC*
  - *b decay products have relatively low p_T, predominantly produced in forward direction*
  - *Rare hadronic final states swamped by light hadron backgrounds*

- *Exceptions*
  - *Dedicated displaced vertex triggers (for example, LHCb)*
  - *Specific final states, e.g. including di-muons*

ATLAS detector and data sample

- *Di-muon triggers with varying thresholds depending on instantaneous luminosity*



2 New ATLAS b Physics Analyses

Study of the rare decays of B^0_s and B^0 to muons

(ATLAS-CONF-2018-046)

[26.3 fb^{-1} of 13 TeV pp collisions taken in 2015+16]

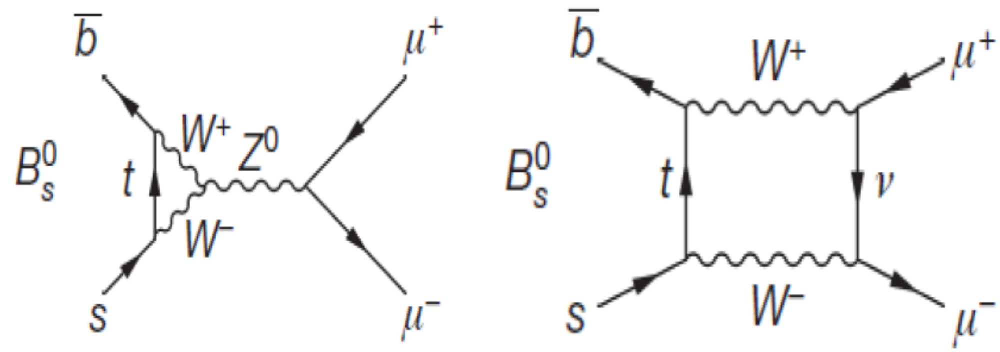
Angular analysis of $B^0 \rightarrow K^* \mu \mu$

(JHEP 10 (2018) 047)

[20 fb^{-1} of 8 TeV pp collisions taken in 2012]

Search for rare decays $B_{s,d} \to \mu\mu$

- *FCNC in the SM*
  - *Forbidden at tree level*
  - *Loop-processes highly suppressed through GIM mechanism*
  - *Predictions for charm and top quarks before their discovery*



- *BFs could be enhanced significantly through NP particles in the loop*

Standard Model predictions (Bobeth et al., PRL 112, 101801 (2014))

$$BF(B_s \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$$
$$BF(B_d \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$$

LHCb and CMS combination (Nature 522, 68 (2015))

$$BF(B_s \to \mu\mu) = \left(2.80^{+0.7}_{-0.6}\right) \times 10^{-9}$$
$$BF(B_d \to \mu\mu) = \left(3.9^{+1.6}_{-1.4}\right) \times 10^{-10}$$

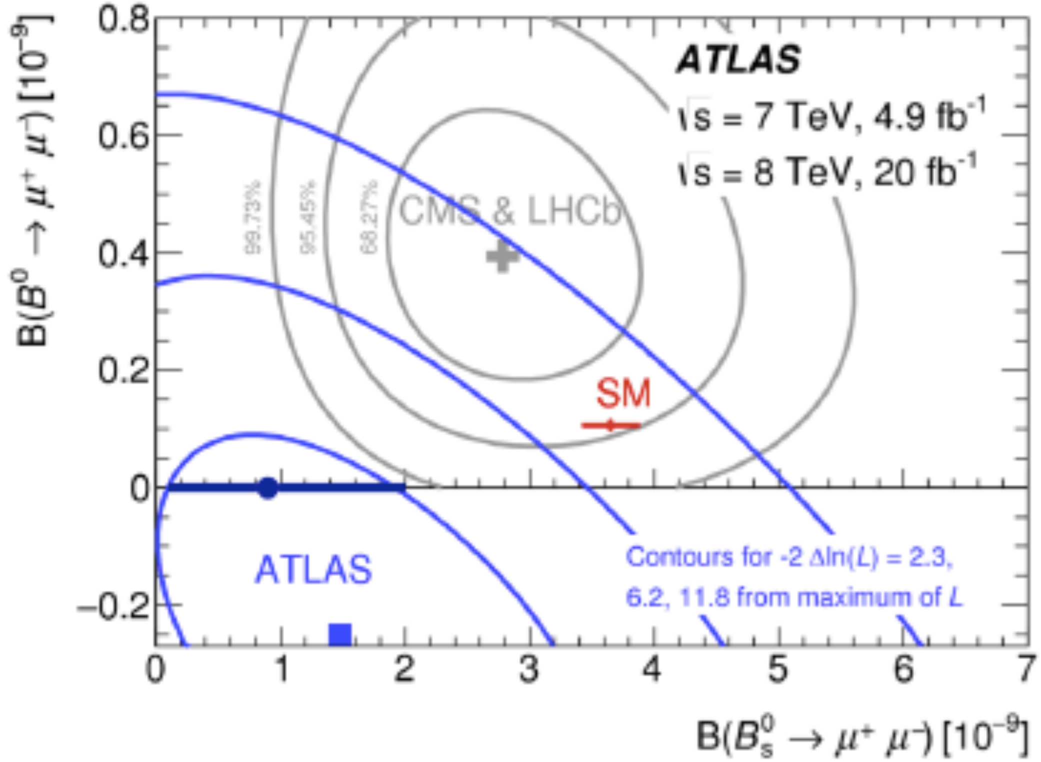
$B^0_{(s)} \to \mu^+\mu^-$

- *ATLAS Run 1 result*

  $B(B_s \to \mu\mu) = (0.9^{+1.1}_{-0.8})\times 10^{-9}$ and
  $B(B^0 \to \mu\mu) < 4.2\times 10^{-10}$@95% CL

  - *Compatible with SM at 2.3σ*
  - *Lower BFs compared to LHCb + CMS combination*
  - *Tension in B^0 BF reduced with the LHCb Run 2 measurement*

  (PRL118(2017)191801): $B(B^0 \to \mu\mu) < 3.4\times 10^{-10}$



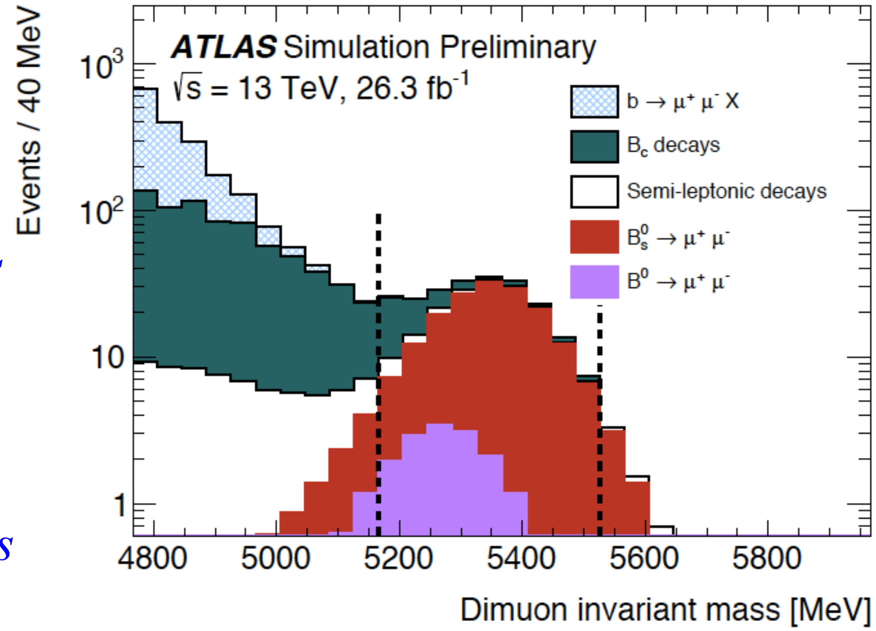
- *New Run 2 ATLAS Result*
  - *Based on 2015 and 2016 data*
    - *36.2 fb^{-1} dataset, effectively 26.3 fb^{-1} used for $B \to \mu\mu$ and 15.1 fb^{-1} for normalization mode $B \to J/\psi K$*

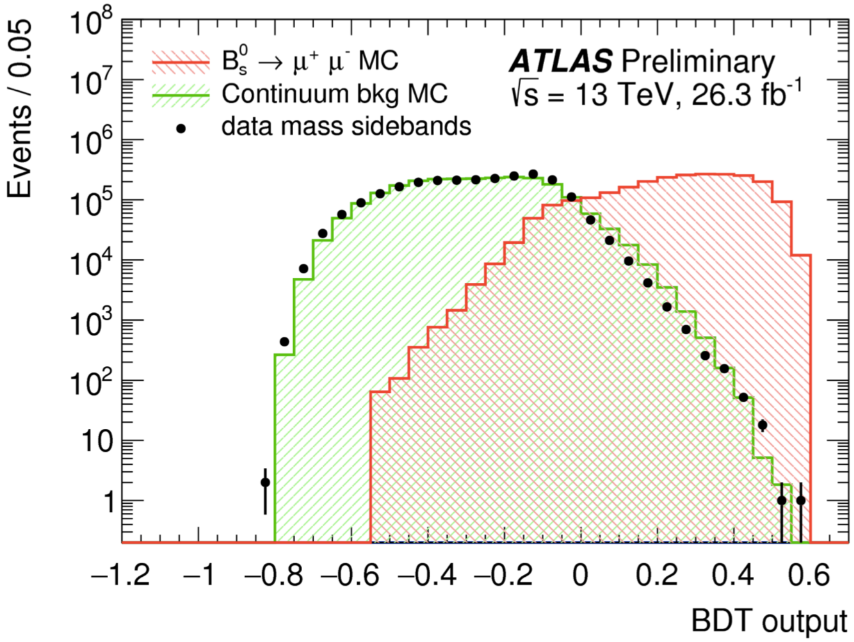
$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}} \times [\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)] \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_{d(s)}}$$

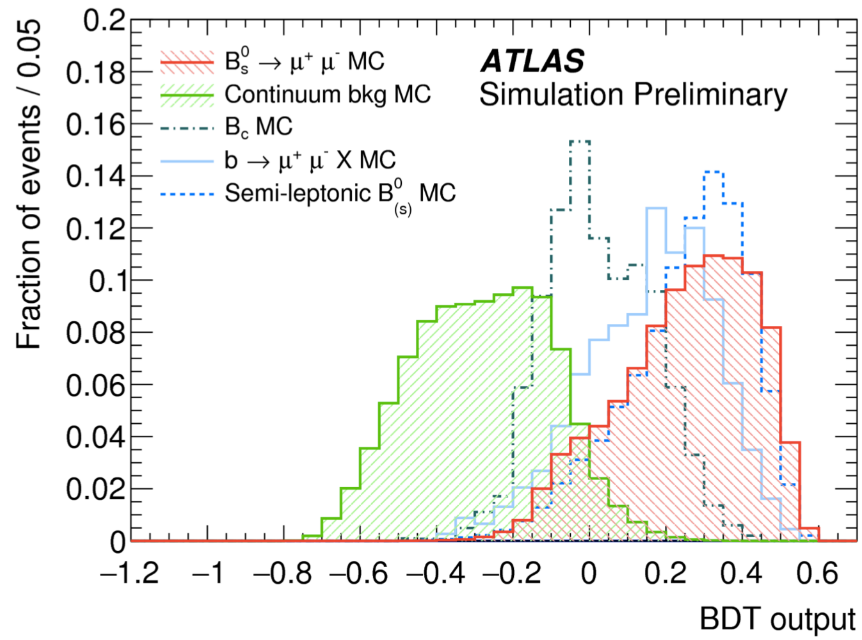
  - *Trigger*
    - *Higher thresholds than Run 1 [4-6 GeV p_T, positive B transverse decay length required at trigger level]*

Backgrounds

- *Combinatorial ($b \to \mu X$, $bb \to \mu\mu X$)*
  - *15-variable Boosted Decision Tree (BDT) used to reject this background*
  - *Trained and tested on simulated events and data sidebands*
- *Partially reconstructed ($b \to \mu\mu X$)*
  - *$B \to \mu\mu X$, $B \to c\mu X$, $B_c \to J/\psi\mu\nu$ backgrounds accumulate at lower mass*
- *Semileptonic*

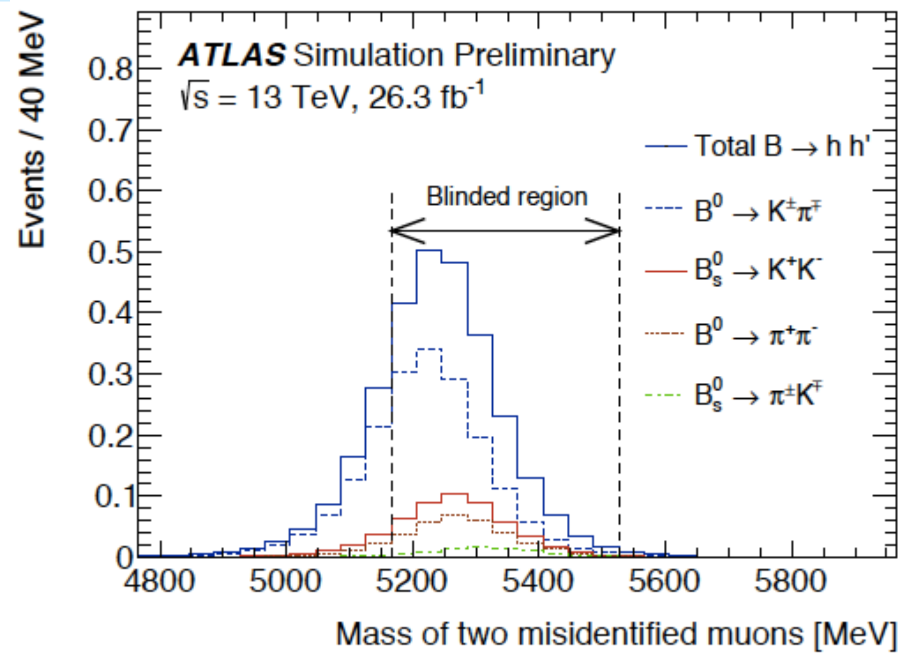


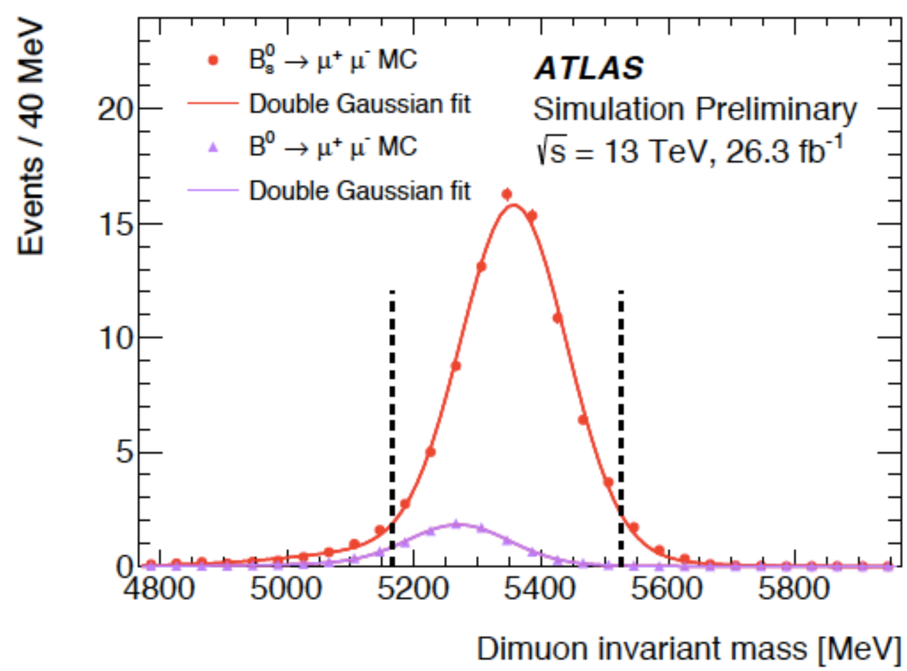




Peaking Background and Mass Resolution

- $B \to hh'$ ($h = \pi^{\pm}, K^{\pm}$) accumulates in the signal region
- Studied with MC-simulated samples and validated in data control regions
- Fake rates using "tight" muon selection
  - π: 0.1 %
  - K: 0.08 %
  - p: < 0.01 %
- B^0 and B_s peaks overlap due to limited B mass resolution
  - Separately statistically, expect negative correlation between B^0 and B_s signal yields





Normalization Channel

- *Extract $B^{\pm}$ yield with unbinned ML fit*
- *Relative efficiency to signal mode determined from MC simulation*
  - *Data/MC difference treated as systematic uncertainty*
  - *2.7% correction for B_s effective lifetime*

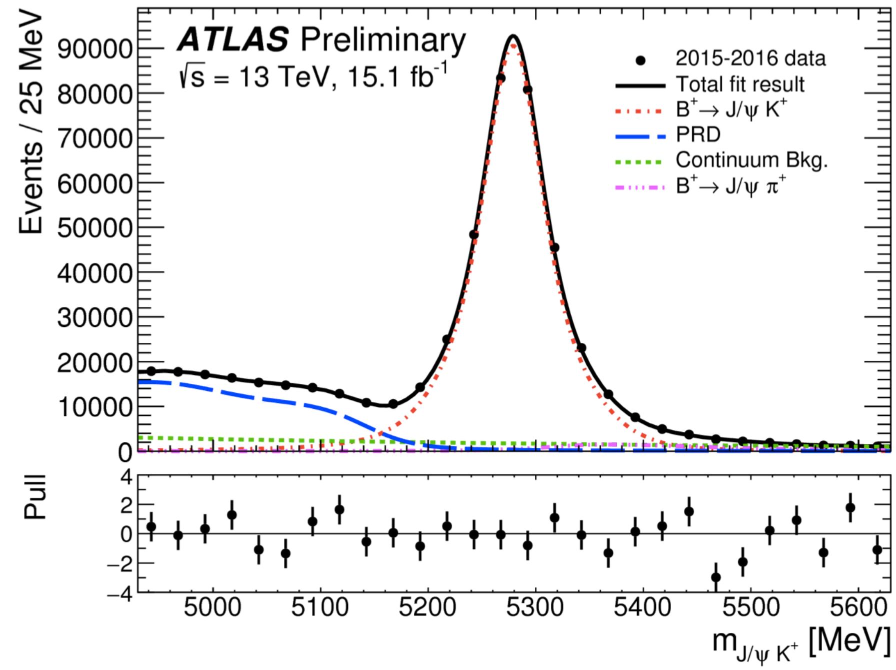
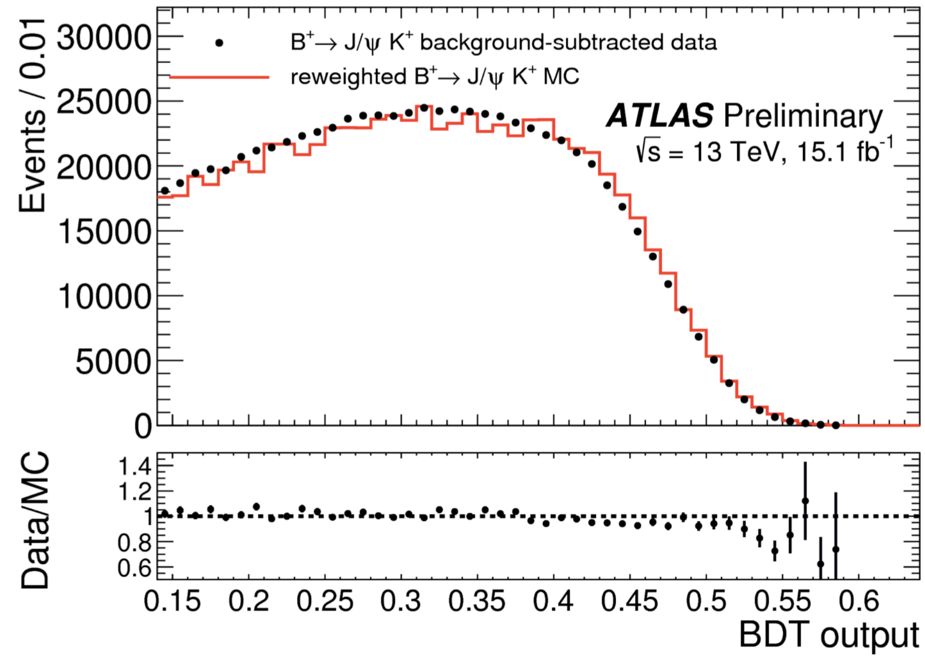


Table 2: Summary of the uncertainties in R_ε.

Source	Contribution [%]
Statistical	0.8
BDT input variables	3.2
Kaon tracking efficiency	1.5
Muon trigger and reconstruction	1.0
Kinematic reweighting (DDW)	0.8
Pile-up reweighting	0.6

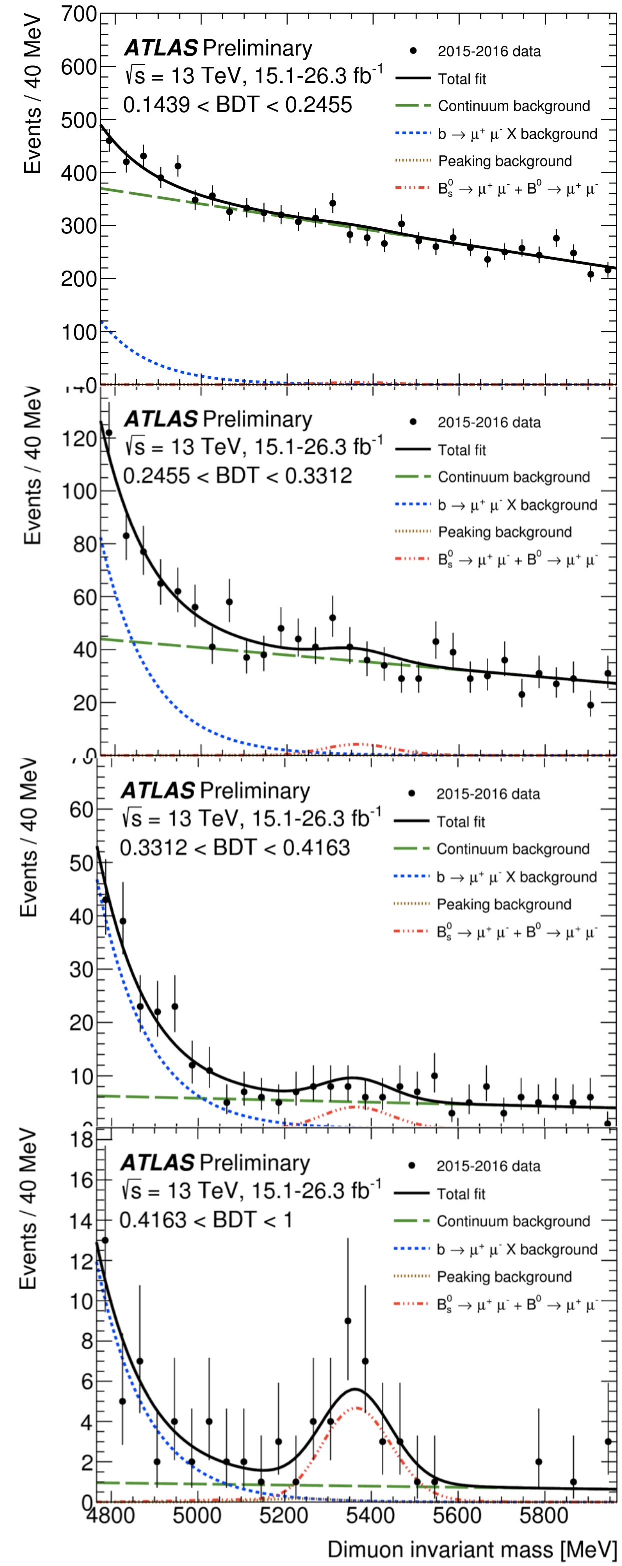


Signal Yields

- *Unbinned ML fit to m(μμ) distribution in 4 BDT bins*
- *Model PDFs*
  - *Signal and peaking background*
    - *3 double-Gaussians with common mean*
  - *Combinatorial background*
    - *1st-order polynomial*
  - *bb ⟶ μμX and semi-leptonic backgrounds*
    - *Exponentials*
- *Extracted yields*
  - $N_s = 80 \pm 22$ $N_d = -12 \pm 20$
- *Fitted yields are consistent with SM expectations:*
  - $N_s = 91$ $N_d = 10$
- *Extracted branching fractions*

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.21^{+0.96+0.49}_{-0.91-0.30}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.3 \times 10^{-10}$$

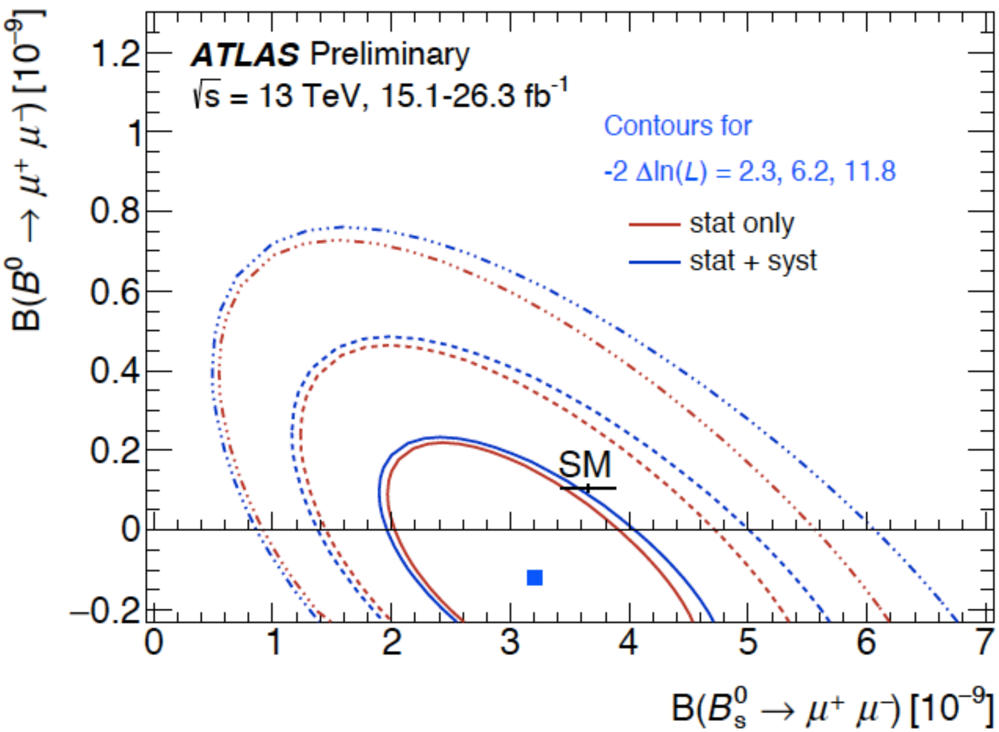


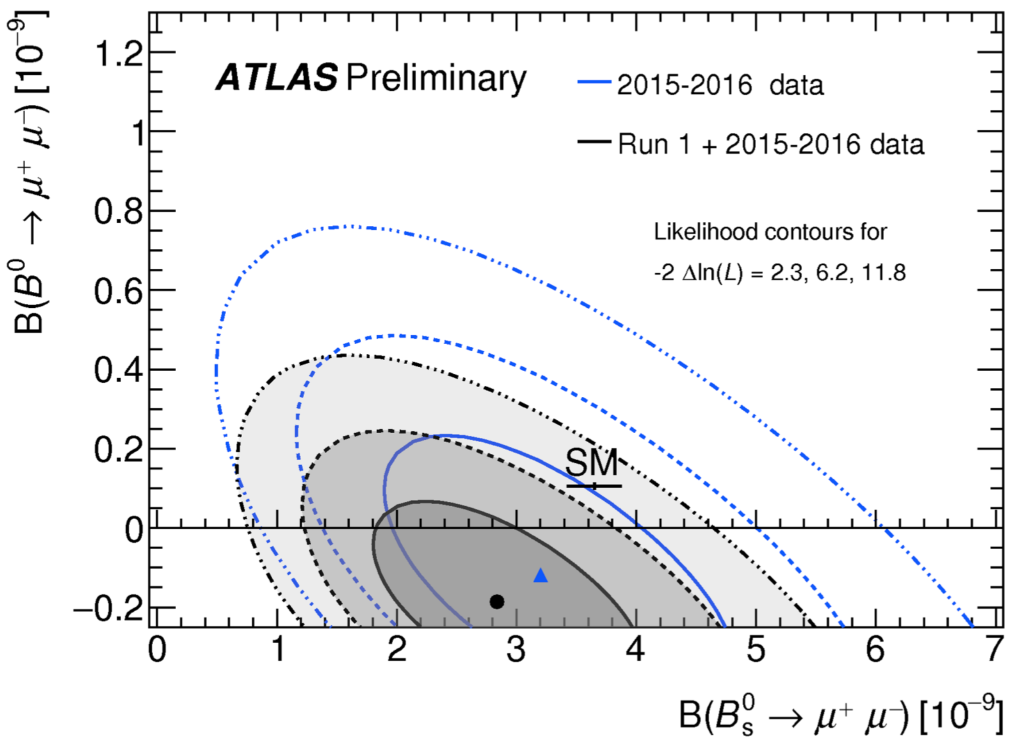
Run 2 Results and Run1+2 Combination

- *Run 2 Results:*

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.21^{+0.96+0.49}_{-0.91-0.30}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.3 \times 10^{-10}$$





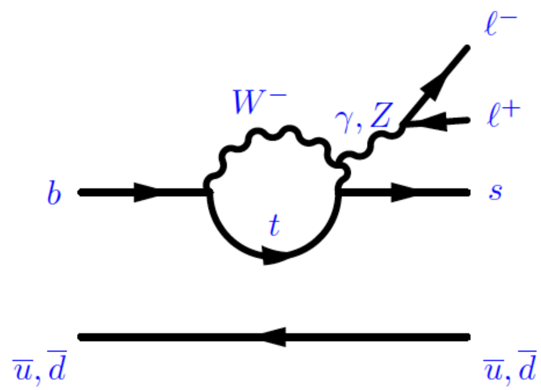
- *Run 1+ Run 2 (2015+'16) Combination:*

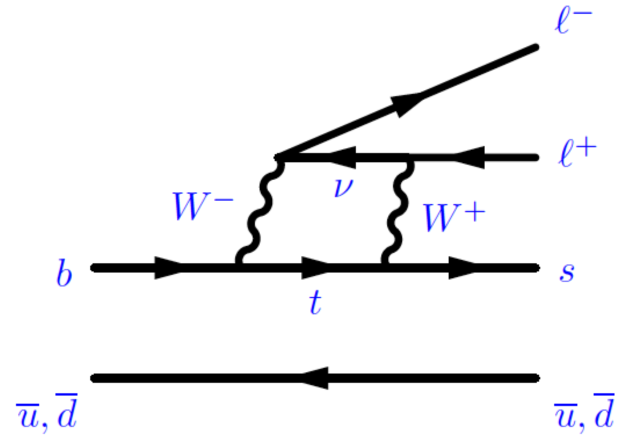
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8 \pm 0.7) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (-1.9 \pm 1.6) \times 10^{-10}$$

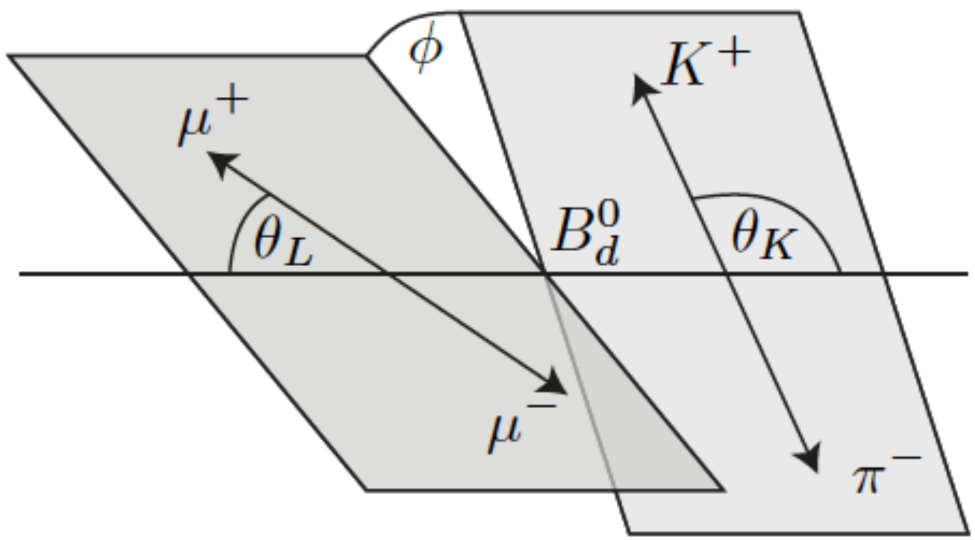
Angular analysis of $B_d \rightarrow K^* \mu \mu$

- *Rare flavor-changing neutral current decay*
  - *Loop/box diagram is sensitive to new physics*
  - *$BR(B_d \rightarrow K^* \mu \mu) = (1.02 \pm 0.09) \times 10^{-6}$*





- *Angular distributions (θ_L, θ_K, and ϕ) are analyzed in 2 GeV^2 bins of the di-muon invariant mass squared (q^2)*



- *LHCb and Belle have reported 3.4 σ and 2.6 σ deviations from the Standard Model [JHEP 02 (2016) 104, PRL 118 (2017) 111801]*

Angular analysis of $B_d \to K^* \mu\, \mu$

- *The decay angular distribution is given by*

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

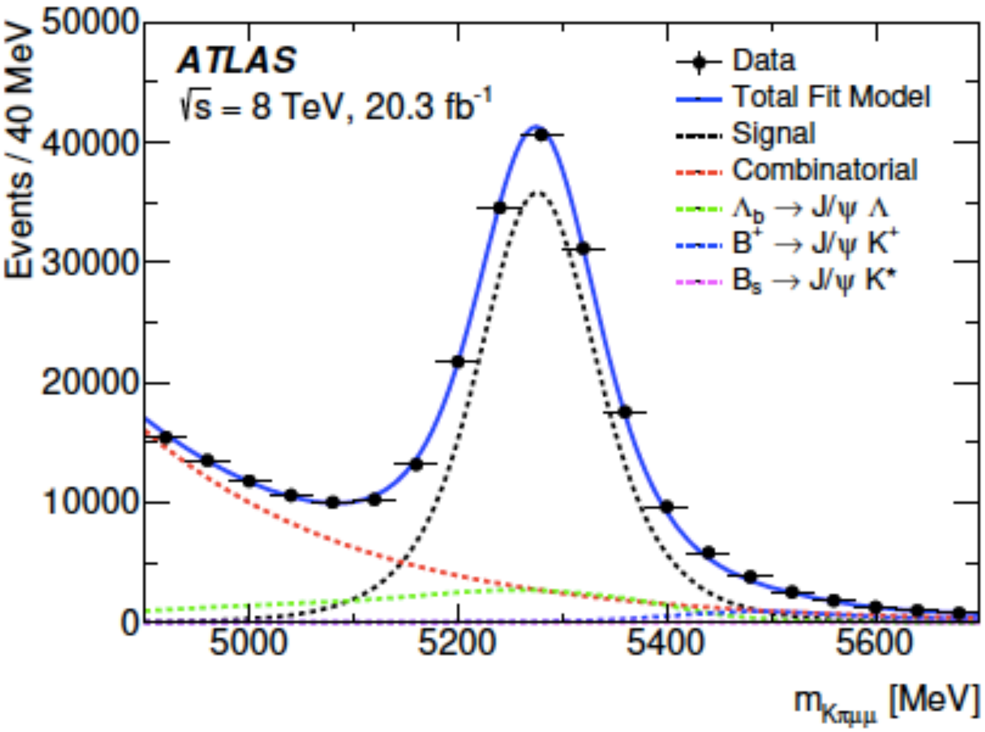
- *ATLAS use trigonometric identities to determine F_L, S_3 and S_i (i = 4,5,7,8) in 4 separate fits for each q^2 bin*
- *S_i parameters are translated into the theoretically cleaner $P^{(\prime)}_i$ parameters*

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

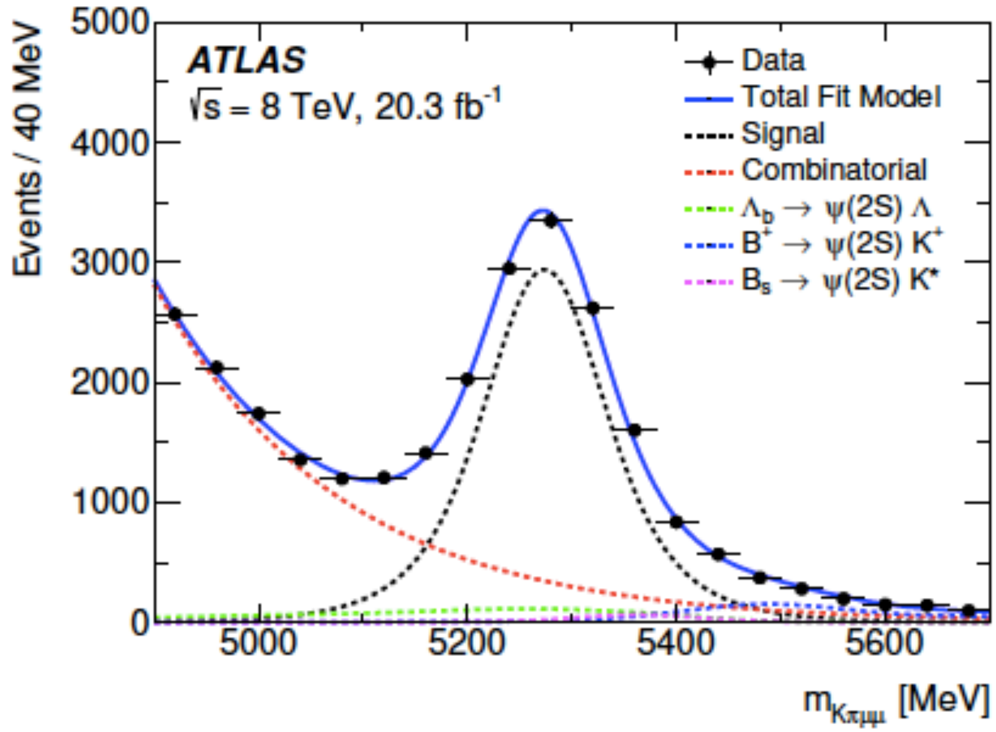
Angular analysis of $B_d \rightarrow K^* \mu\mu$

- *Low-background, high-statistics $K^*\ J/\psi$ and $K^*\ \psi(2S)$ control samples*
  - *q^2 from 8-11 and from 12-15 GeV^2*
  - *used to extract nuisance parameters (m_B, σ_0) of the signal probability density function (p.d.f.) from data*

$B \rightarrow K^*\ J/\psi$ control sample

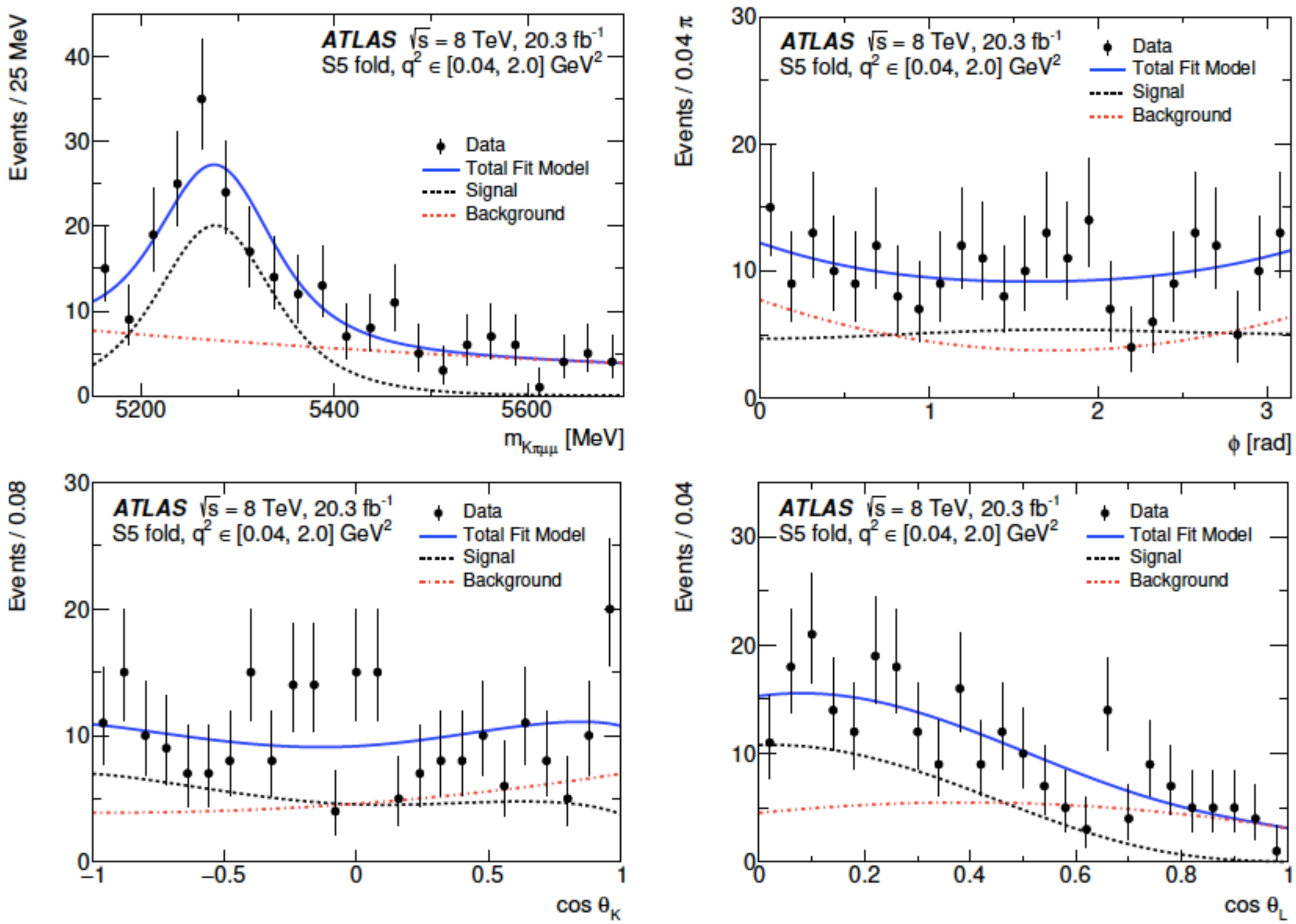


$B \rightarrow K^*\ \psi(2S)$ control sample



Angular analysis of $B_d \rightarrow K^* \mu \mu$

- *Simultaneous fit to cos θ_L, cos θ_K and φ distributions to isolate signal and extract parameters of interest*
  - *Mass p.d.f. parameters fixed to control region values*

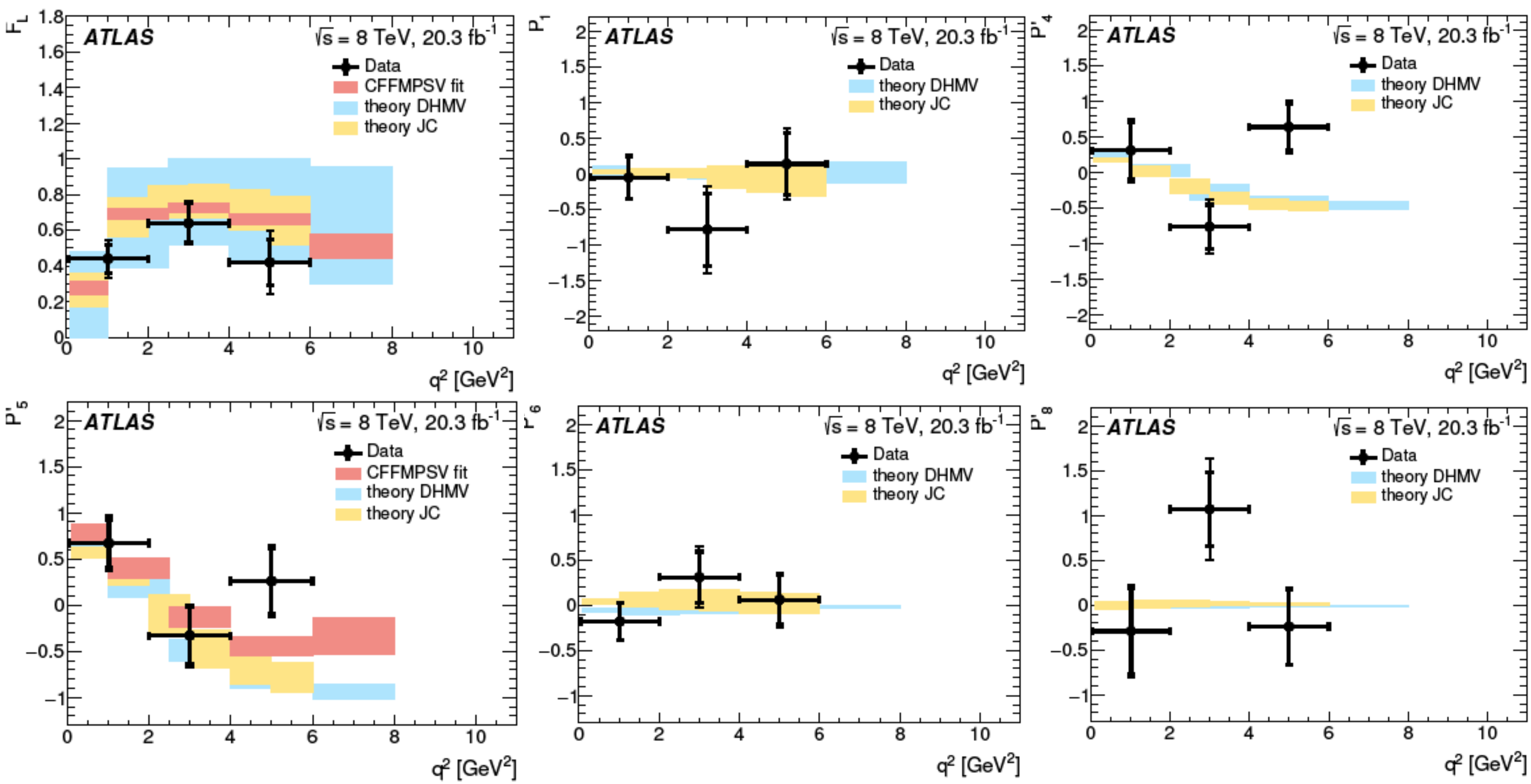


Total p.d.f (blue), signal (black) and background (red) contributions

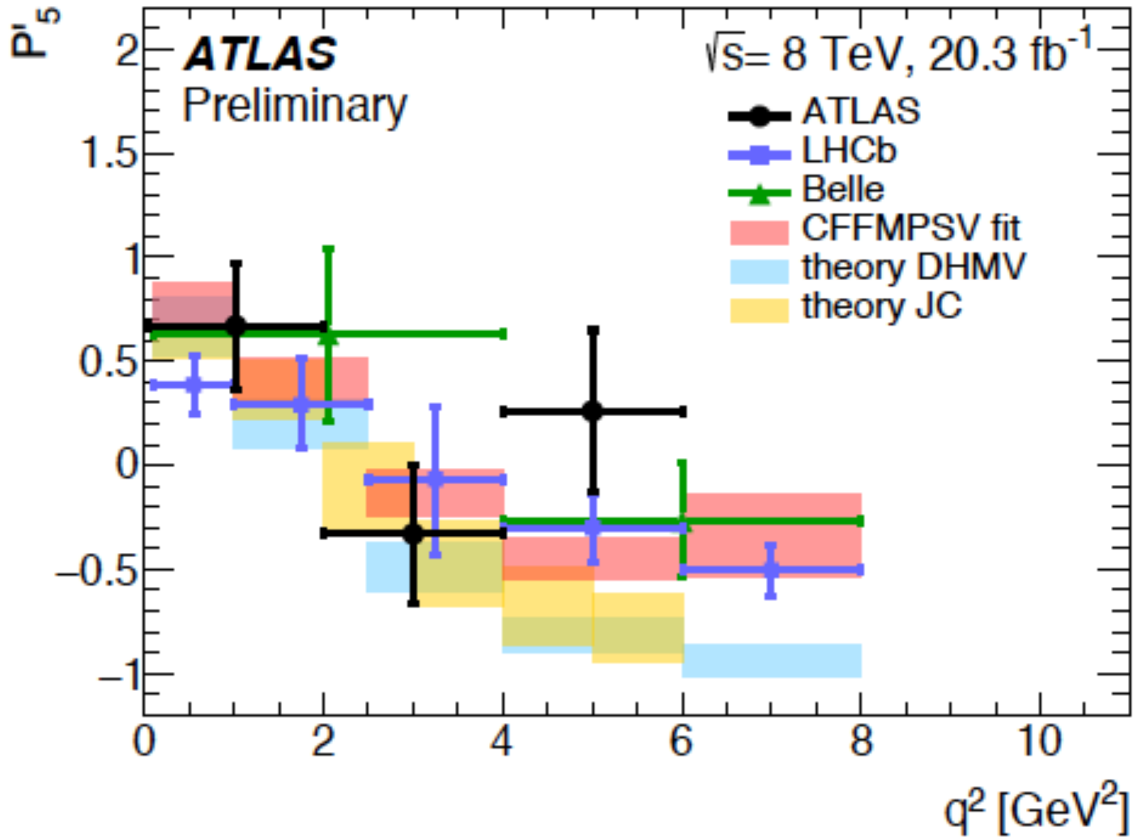
- *20.3 fb^{-1} of 8 TeV pp collision data*
- *Analyze data in three q^2 bins from 0.04 to 6.0 GeV^2*
  - *Data shown here for $0.04 < q^2 < 2$ GeV^2 overlaid with projections of signal and background p.d.f.s from the S_5 fit*
  - *128 ± 22 signal events in this q^2 bin*
  - *Similar results are obtained for the other q^2 bins and fits*

Angular analysis of $B_d \rightarrow K^* \mu\, \mu$

- *ATLAS results are compatible with theoretical calculations and fits*



Angular analysis of $B_d \rightarrow K^* \mu \mu$



- *2.7 σ deviation with DHMV for P'_4, P'_5 in $4 < q^2 < 6$ GeV^2 range*
- *New LHCb measurement compatible with SM (PLB 781 (2018) 517)*
- *All measurements are within 3 σ range covered by predictions*

Conclusions

- *Presented two recent ATLAS results in b physics*
  - *Results of angular analysis of rare decay $B_d \rightarrow K^* \mu\, \mu$ are consistent with the SM with some small tensions (JHEP 10 (2018) 047)*
  - *Results from Run 2 2015 and 2016 data of B_s and B^0 decays to $\mu\mu$ are consistent with the SM (ATLAS-CONF-2018-046)*

Back-Up Slides

Angular analysis of $B_d \rightarrow K^* \mu \mu$

- *Results are statistically limited*
  - *Fit values of F_L, S_3, and P_1 from the 4 fits are consistent with each other; reported is the result with the smallest systematic uncertainty*

q^2 [GeV^2]	F_L	S_3	S_4	S_5	S_7	S_8
[0.04, 2.0]	0.44±0.08±0.07	−0.02±0.09±0.02	0.15±0.20±0.10	0.33±0.13±0.08	−0.09±0.10±0.02	−0.14±0.24±0.09
[2.0, 4.0]	0.64±0.11±0.05	−0.15±0.10±0.07	−0.37±0.15±0.10	−0.16±0.15±0.06	0.15±0.14±0.09	0.52±0.20±0.19
[4.0, 6.0]	0.42±0.13±0.12	0.00±0.12±0.07	0.32±0.16±0.09	0.13±0.18±0.09	0.03±0.13±0.07	−0.12±0.21±0.05
[0.04, 4.0]	0.52±0.07±0.06	−0.05±0.06±0.04	−0.15±0.12±0.09	0.16±0.10±0.05	0.01±0.08±0.05	0.19±0.16±0.12
[1.1, 6.0]	0.56±0.07±0.06	−0.04±0.07±0.03	0.03±0.11±0.07	0.00±0.10±0.04	0.02±0.08±0.06	0.11±0.14±0.10
[0.04, 6.0]	0.50±0.06±0.04	−0.04±0.06±0.03	0.03±0.10±0.07	0.14±0.09±0.03	0.02±0.07±0.05	0.07±0.13±0.09

q^2 [GeV^2]	P_1	P'_4	P'_5	P'_6	P'_8
[0.04, 2.0]	−0.05±0.30±0.08	0.31±0.40±0.20	0.67±0.26±0.16	−0.18±0.21±0.04	−0.29±0.48±0.18
[2.0, 4.0]	−0.78±0.51±0.34	−0.76±0.31±0.21	−0.33±0.31±0.13	0.31±0.28±0.19	1.07±0.41±0.39
[4.0, 6.0]	0.14±0.43±0.26	0.64±0.33±0.18	0.26±0.35±0.18	0.06±0.27±0.13	−0.24±0.42±0.09
[0.04, 4.0]	−0.22±0.26±0.16	−0.30±0.24±0.17	0.32±0.21±0.11	0.01±0.17±0.10	0.38±0.33±0.24
[1.1, 6.0]	−0.17±0.31±0.13	0.05±0.22±0.14	0.01±0.21±0.08	0.03±0.17±0.12	0.23±0.28±0.20
[0.04, 6.0]	−0.15±0.23±0.10	0.05±0.20±0.14	0.27±0.19±0.06	0.03±0.15±0.10	0.14±0.27±0.17

- *Dominant systematics come from uncertainties in the background*
  - *partially reconstructed decays with open charm and incorrect $K\pi$ combinations (fake K^*)*
  - *$K\pi$ S-wave contributions results only in small systematic uncertainty*