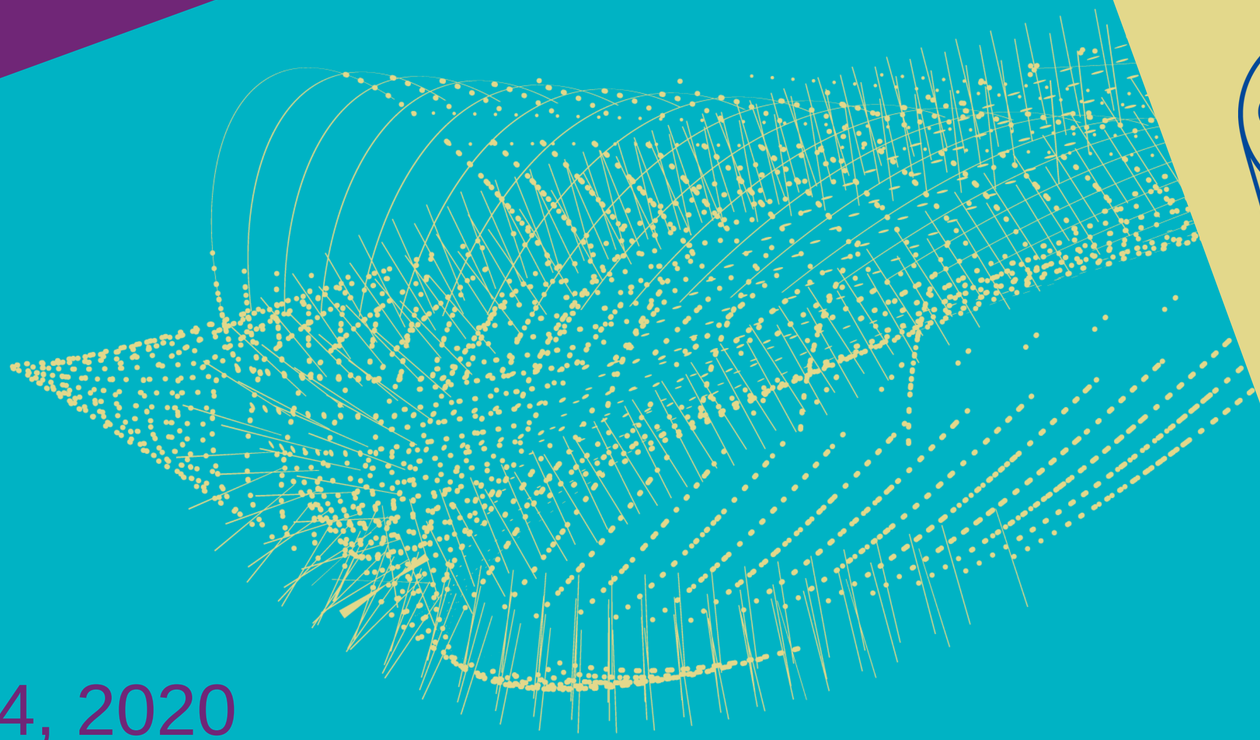
Nikhef

NWO

ATLAS EXPERIMENT

CERN



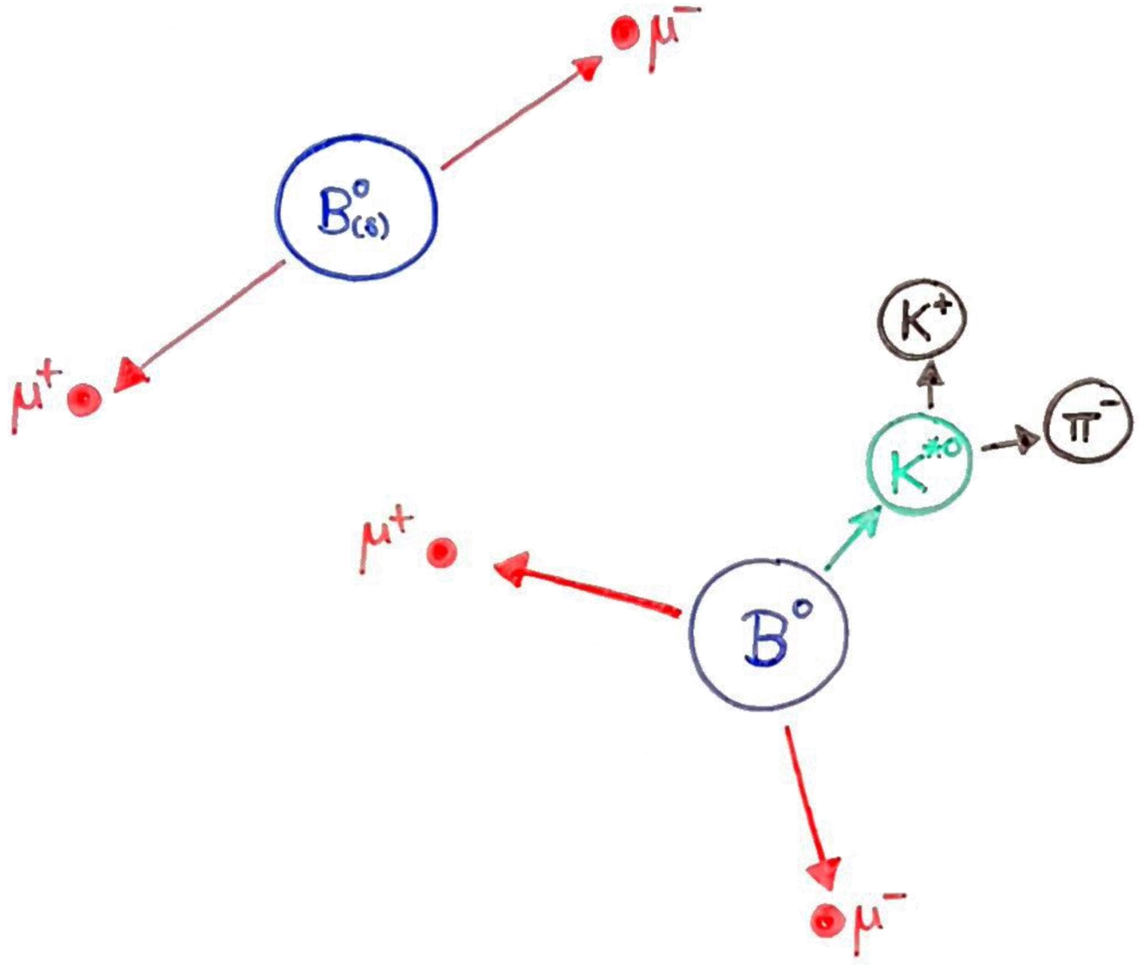
Beauty 2020, September 21-24, 2020

RARE B-DECAYS: UPDATE FROM ATLAS

Ann-Kathrin Perrevoort
on behalf of ATLAS
(ann-kathrin.perrevoort@cern.ch)

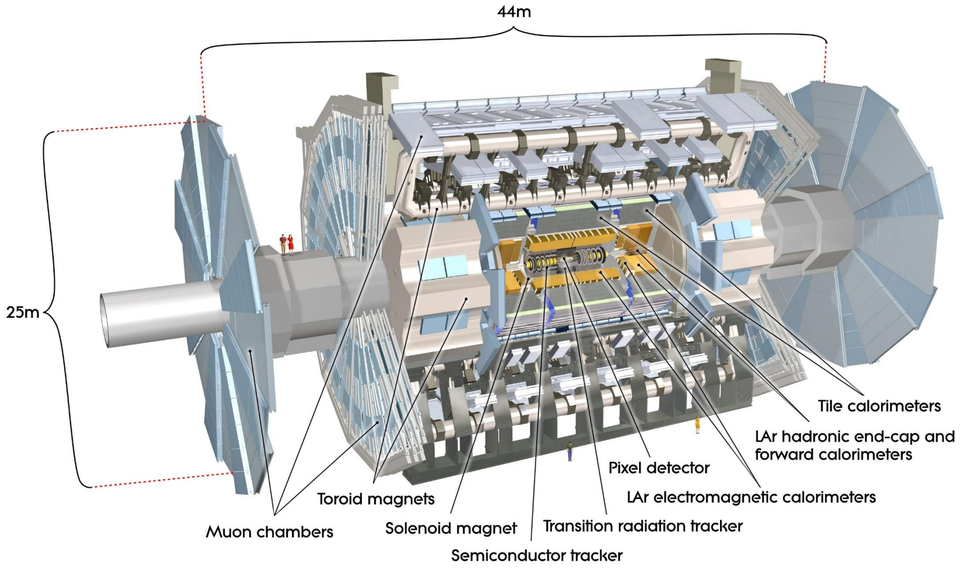
RARE B-DECAYS: UPDATE FROM ATLAS

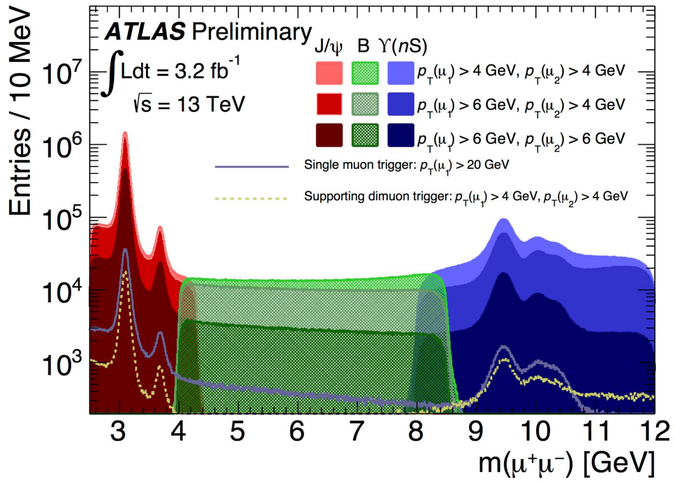
- B physics in ATLAS
- Branching fractions of $B^0_{(s)} \to \mu^+\mu^-$
- ATLAS measurement early Run 2 ($26.3\ \mathrm{fb}^{-1}$)
- ATLAS, CMS, LHCb combination
- Prospects for full Run 2 and HL-LHC
- Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$
- ATLAS measurement in Run 1 ($20.3\ \mathrm{fb}^{-1}$)
- Prospects for HL-LHC
- Conclusion

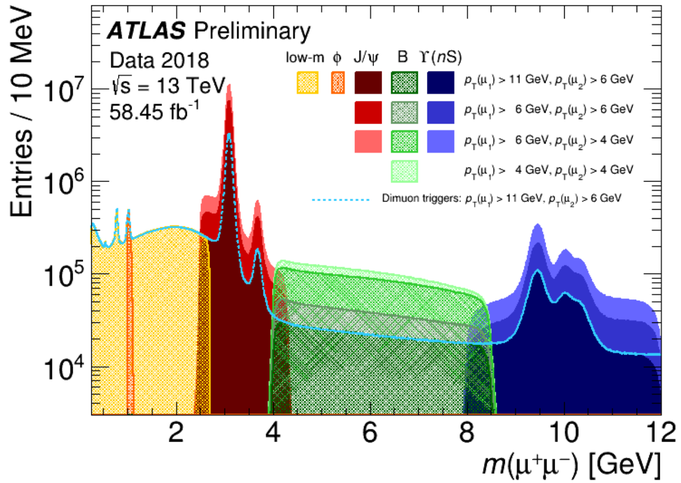


B -PHYSICS PROGRAM IN THE ATLAS EXPERIMENT

- ATLAS collected 139fb^{-1} of pp collisions at $\sqrt{s} = 13\text{TeV}$ in 2015-2018
- ~2.5 million $b\bar{b}$ pairs/sec produced
- B_s, B_c etc. accessible at the LHC
- Typical B physics trigger: low p_T, very low mass di-muon trigger using inner tracker and muon detectors
- ~150-200 events with $b\bar{b}$ pairs/sec recorded







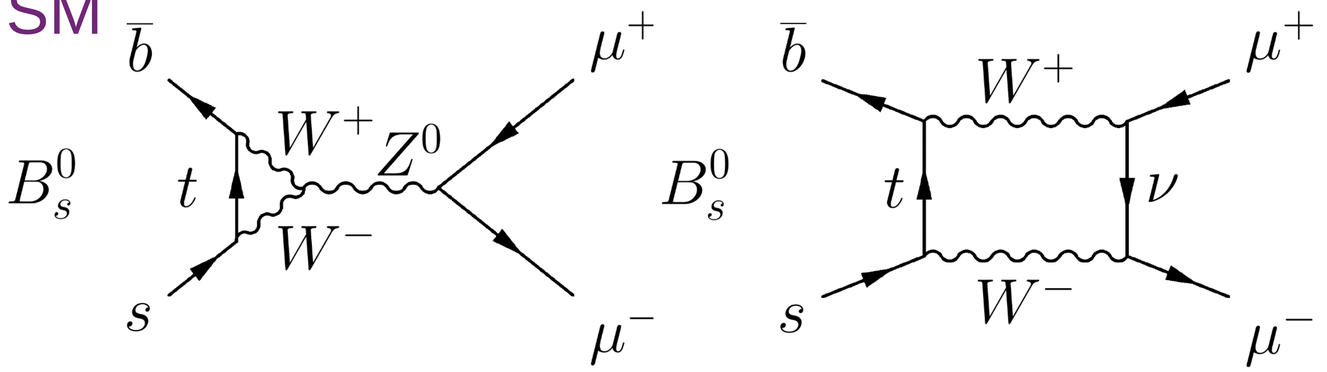
RARE B-DECAYS

- FCNC in the SM via loop and box diagrams
- $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ at $\mathcal{B} \sim 10^{-9}$
- $B^0 \to K^{*0}\mu^+\mu^-$ at $\mathcal{B} \sim 10^{-5}$

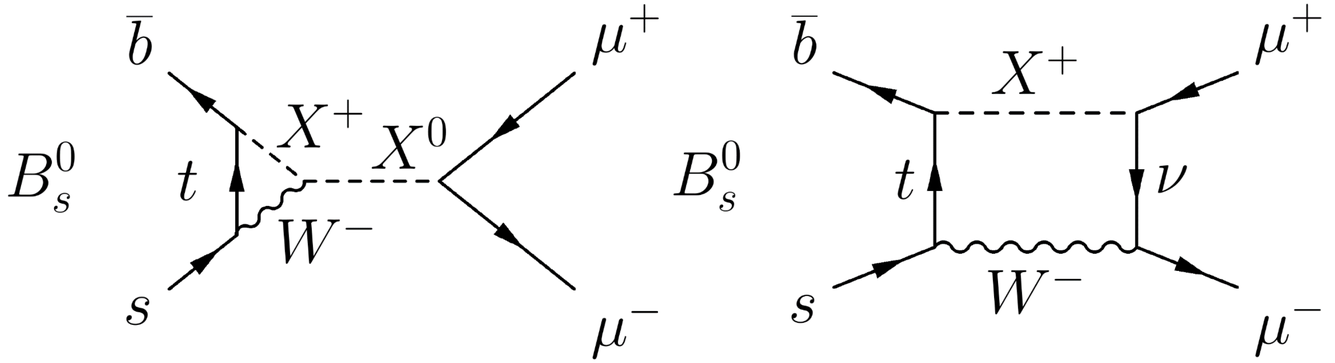
- Enhancements might arise from BSM contributions
- Measure $\mathcal{B}$ and differential angular decay distributions

Example $B_s^0 \to \mu^+\mu^-$

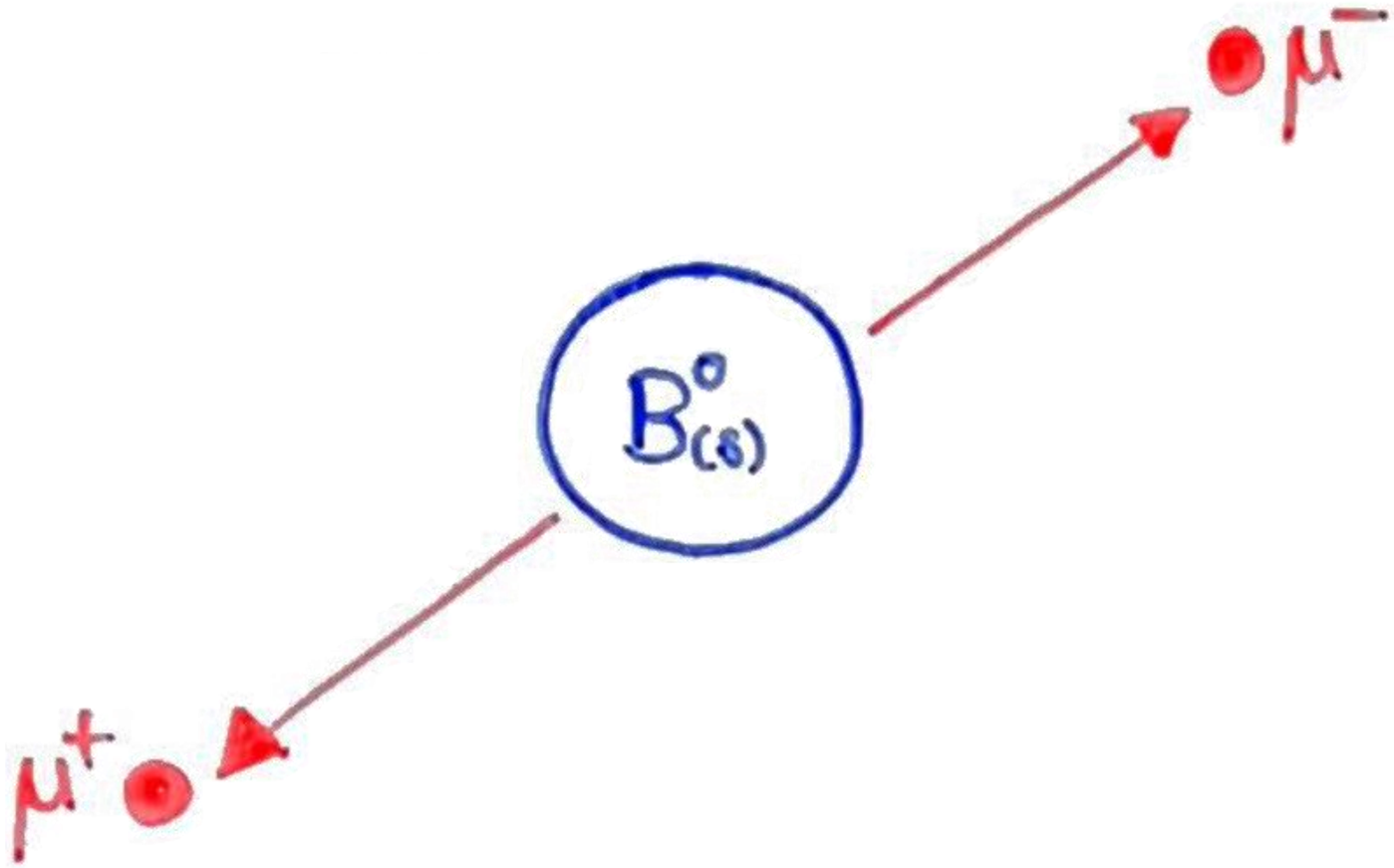
SM



BSM

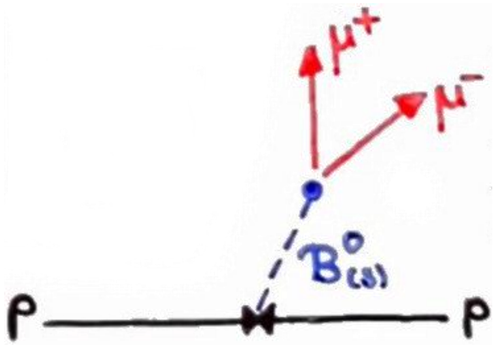


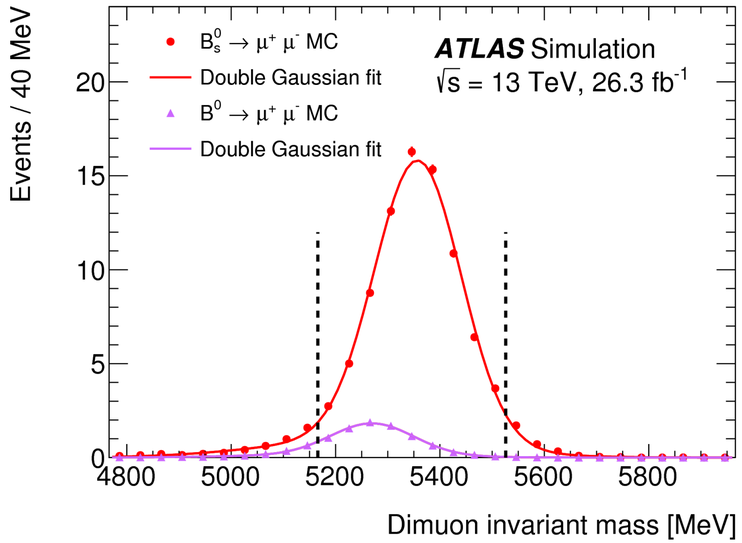
Branching Fractions of $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$

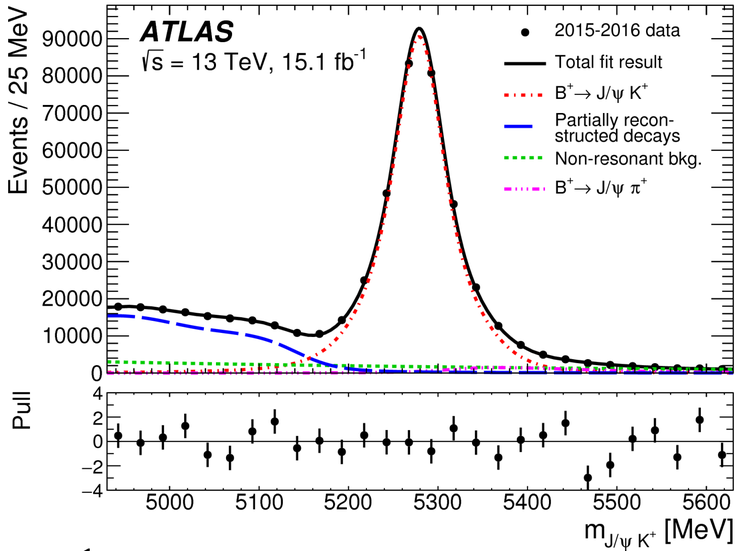


JHEP 04(2019) 098

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





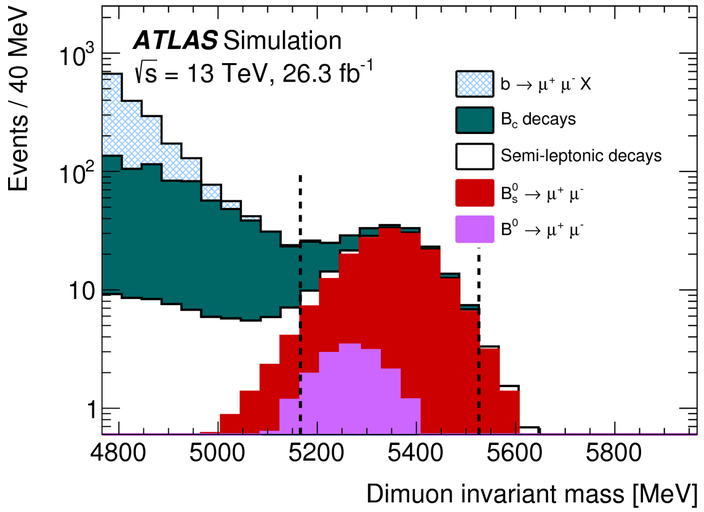


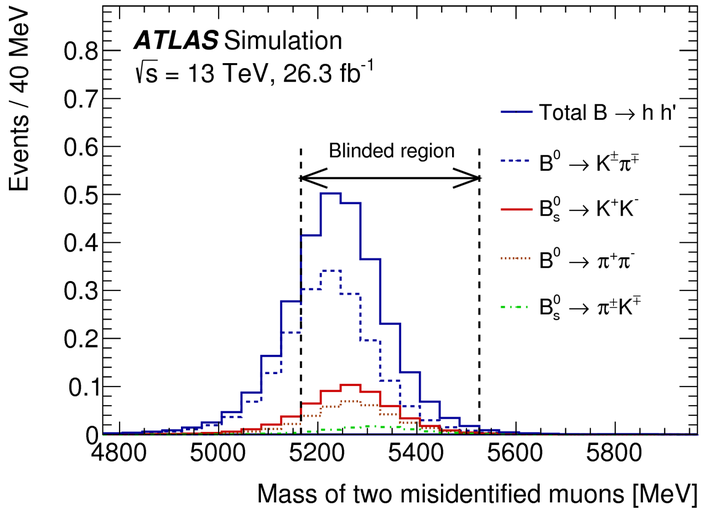
- ATLAS measurement of $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)$ using 26.3 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV (2015+2016)
- Using di-muon trigger
- Simultaneous fit of $\mathcal{B}(B^0 \to \mu^+\mu^-)$ and $\mathcal{B}(B^0_s \to \mu^+\mu^-)$
- Measurement relative to reference channel $B^+ \to J/\psi(\mu\mu)\, K^+$
- Separate signal from background using boosted decision tree (BDT) JHEP 04(2019) 098

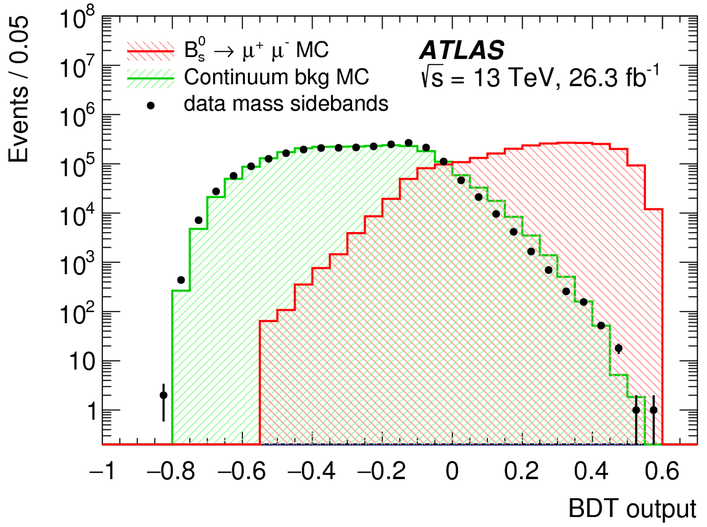
BRANCHING FRACTIONS OF $B^0_{(s)} \to \mu^+\mu^-$

JHEP 04(2019) 098

- Partially reconstructed b–hadron decays mostly at lower di-muon mass
- Peaking background: $B^0_{(s)}$ decays to π and K which are mis-identified as μ
- Continuum background: combinatorial background from μ of uncorrelated hadron decays; reduced with BDT

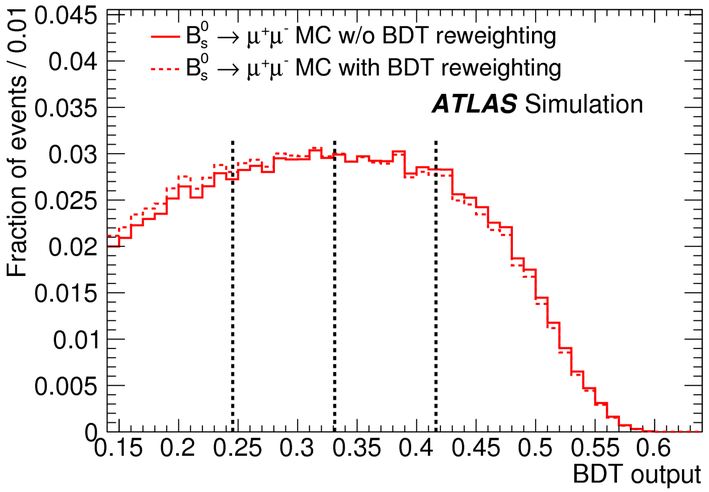




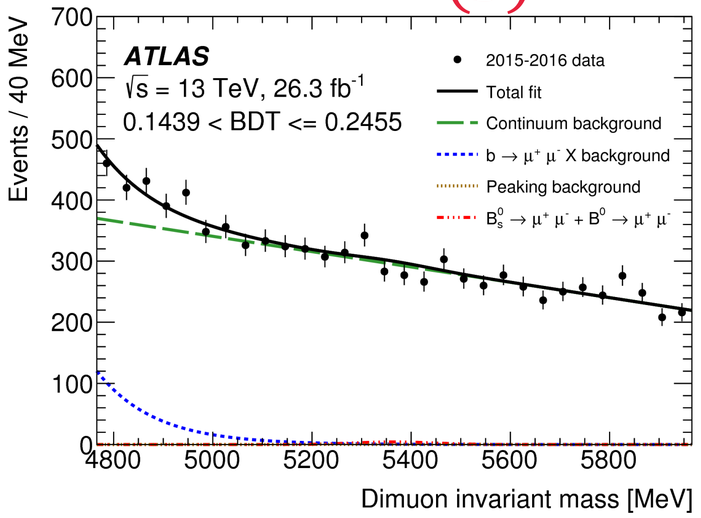


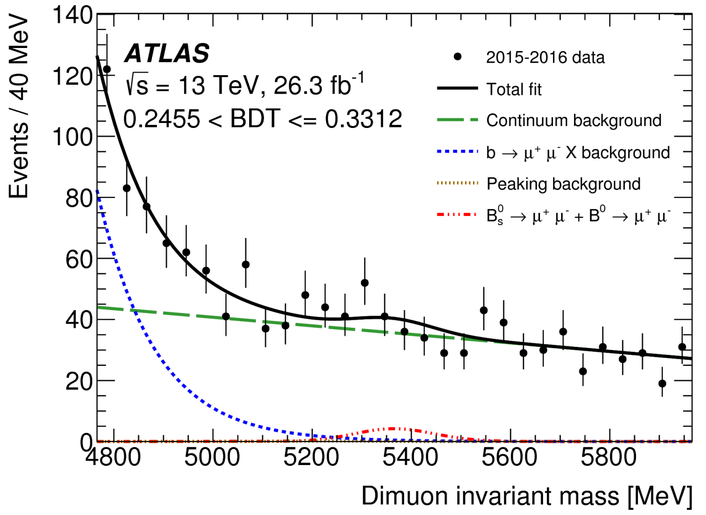
BRANCHING FRACTIONS OF $B^0_{(s)} \to \mu^+\mu^-$

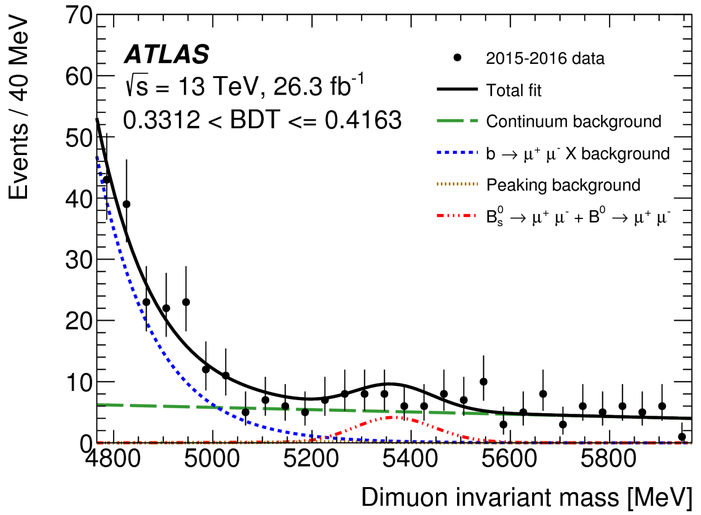
JHEP 04(2019) 098

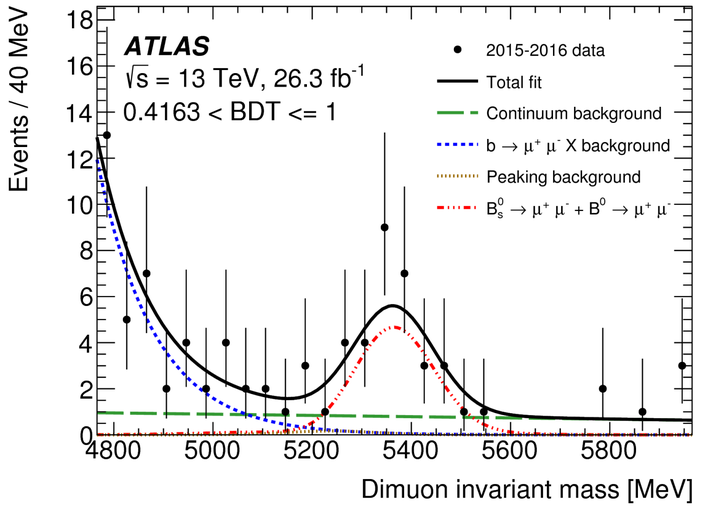


- Signal region divided in 4 BDT intervals with constant signal efficiency
- ➢ Fit extracts simultaneously $\mathcal{B}(B_s^0 \to \mu\mu)$ and $\mathcal{B}(B^0 \to \mu\mu)$

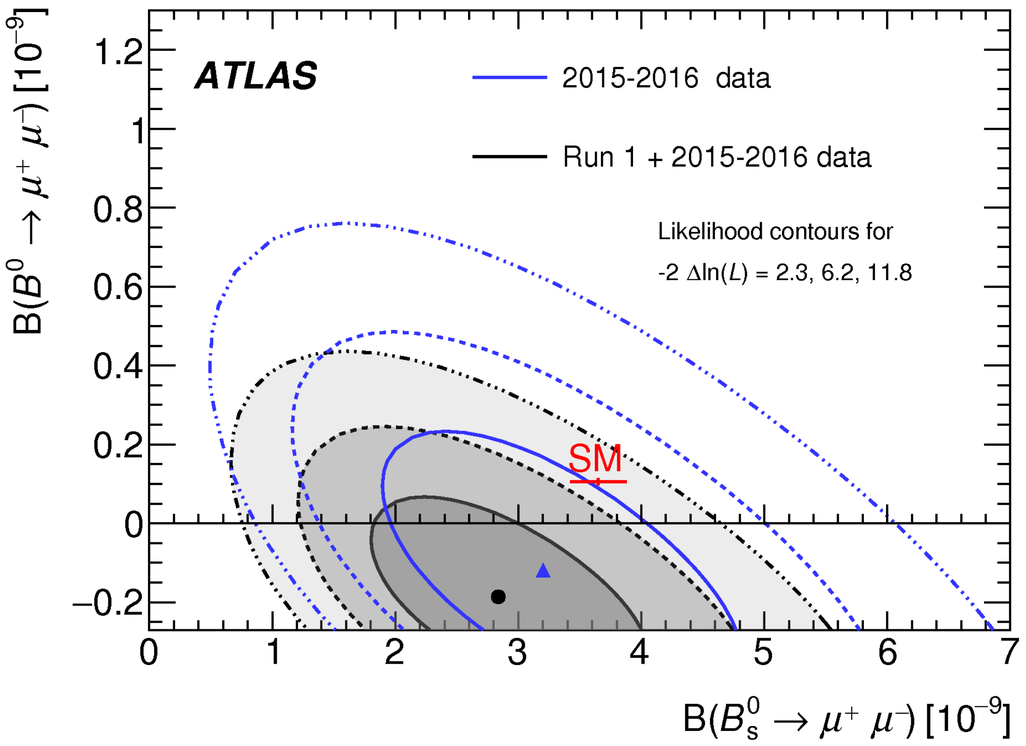








BRANCHING FRACTIONS OF $B^0_{(s)} \to \mu^+\mu^-$



Standard Model [JHEP 10(2019)232](#)

$\mathcal{B}(B^0_s \to \mu\mu) = (3.66 \pm 0.14) \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu\mu) = (1.03 \pm 0.05) \times 10^{-10}$

Run 2

$\mathcal{B}(B^0_s \to \mu\mu) = (3.2^{+1.1}_{-1.0}) \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu\mu) < 4.3 \times 10^{-10}$ at 95% CL

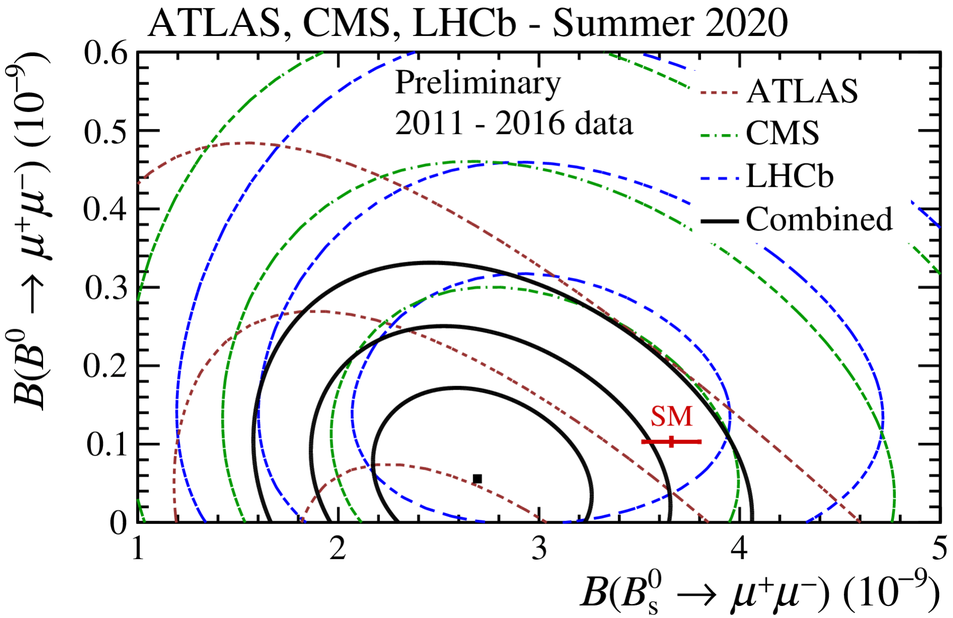
Run 1 + Run 2 (2015-2016)

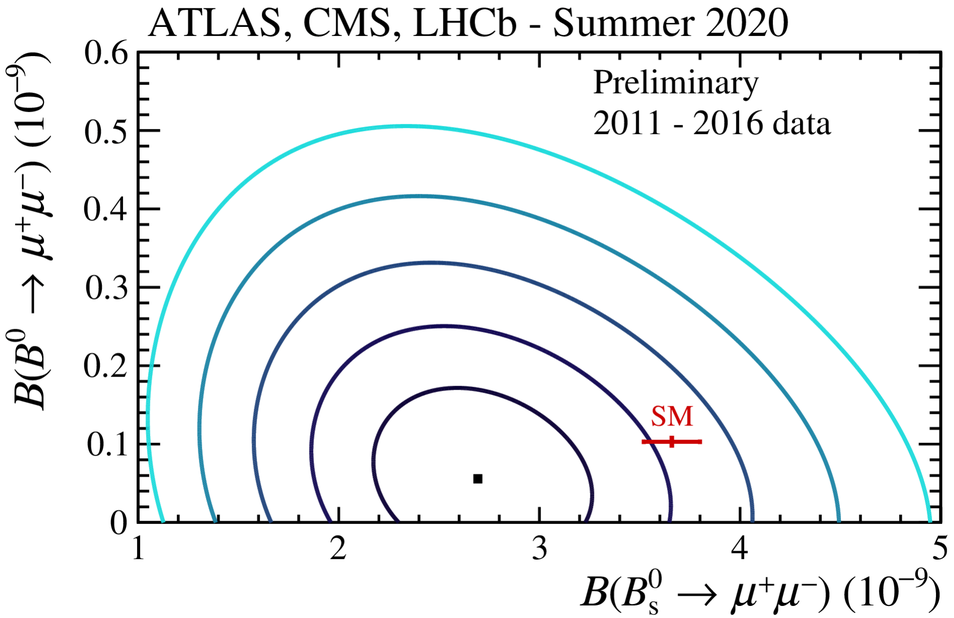
$\mathcal{B}(B^0_s \to \mu\mu) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu\mu) < 2.1 \times 10^{-10}$ at 95% CL

[JHEP 04(2019) 098](#)

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





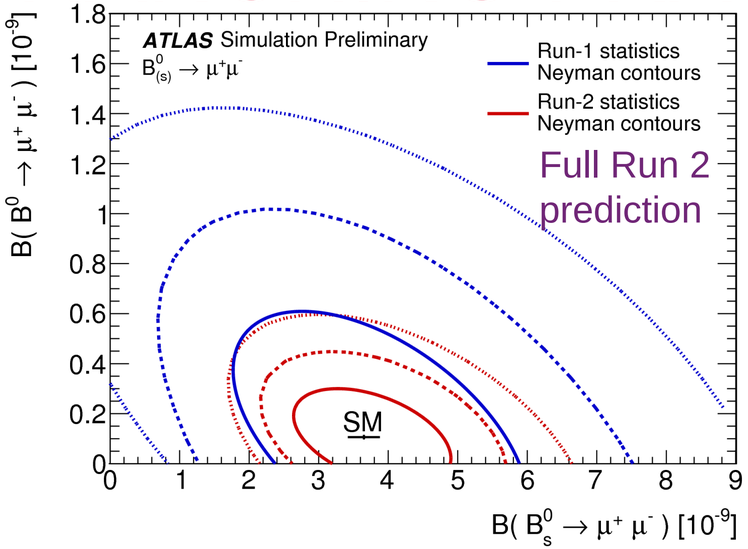
Combination ATLAS, CMS, LHCb for Run 1 + Run 2 ((2015 +) 2016)

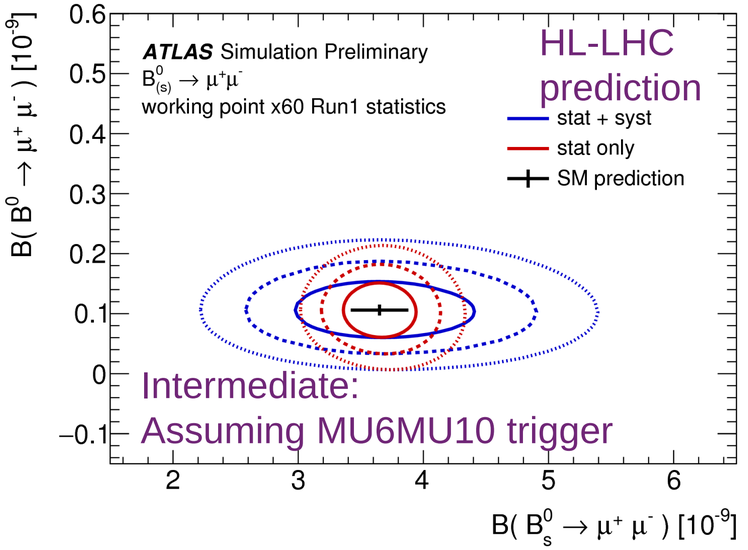
$\mathcal{B}(B^0_s \to \mu\mu) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu\mu) < 1.9 \times 10^{-10}$ at 95% CL

BPH 20 003

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





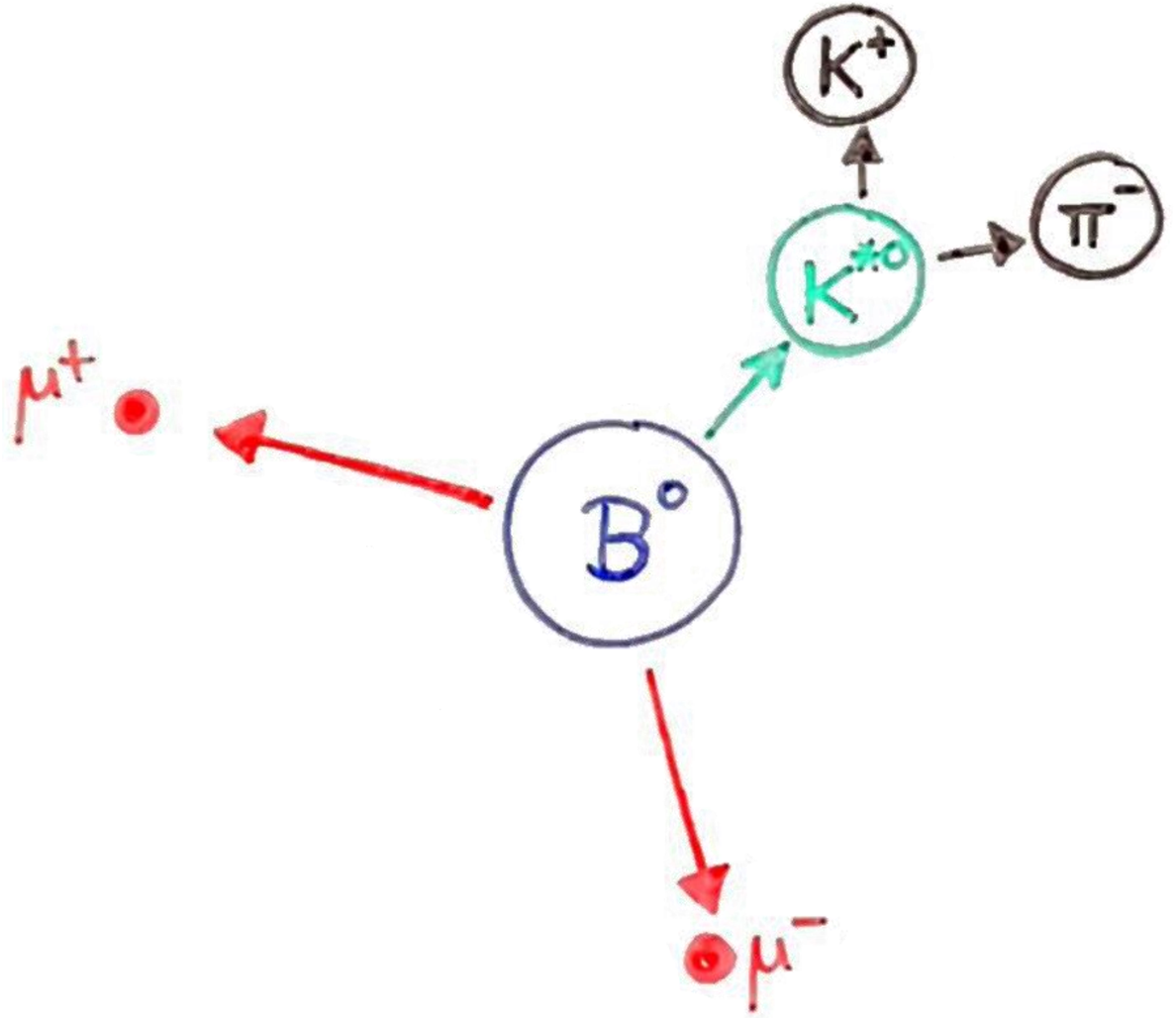
Extrapolation of Run 1 results to full Run 2 and HL-LHC

- Increase in luminosity from 25 fb^{-1} to 130 fb^{-1}/3 ab^{-1}
- Increase in $\sqrt{s}$ from 7/8TeV to 13TeV
- Trigger efficiencies and detector performance

Uncertainty on $\mathcal{B}$	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$		$\mathcal{B}(B^0 \to \mu^+\mu^-)$	
	stat [10^{-10}]	stat + syst [10^{-10}]	stat [10^{-10}]	stat + syst [10^{-10}]
Run 2	7.0	8.3	1.42	1.43
HL-LHC: Conservative	3.2	5.5	0.53	0.54
HL-LHC: Intermediate	1.9	4.7	0.30	0.31
HL-LHC: High-yield	1.8	4.6	0.27	0.28

ATL PHYS PUB 2018-005

Angular Analysis of $B^0 \to K^{*0}\mu^+\mu^-$

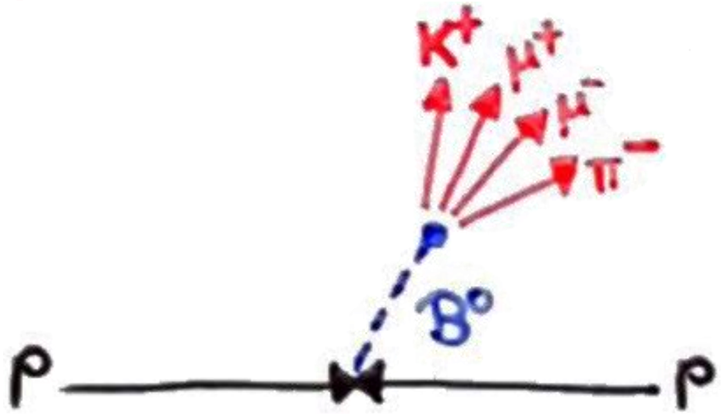


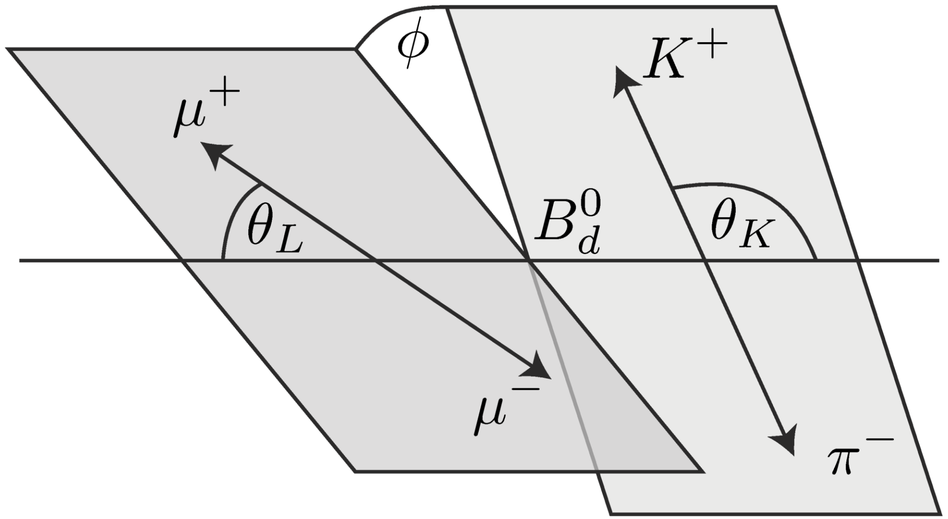
JHEP 10(2018) 047

ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

- ATLAS measurement of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ using 20.3 fb^{-1} of pp collision data at $\sqrt{s} = 8\ \text{TeV}$ (2012)

- Analysis of angular distributions of $\cos\theta_\text{L}$, $\cos\theta_\text{K}$ and ϕ, and $m(K\pi\mu\mu)$ in bins of $q^2 = m^2(\mu^+\mu^-) \in [0.04,6.0]\text{GeV}^2$
- Combination of 19 trigger chains (1μ, 2μ, 3μ)
- Trigonometric folding of angular parameters
- Control regions for $B^0 \to K^{*0}c\bar{c}$ decays





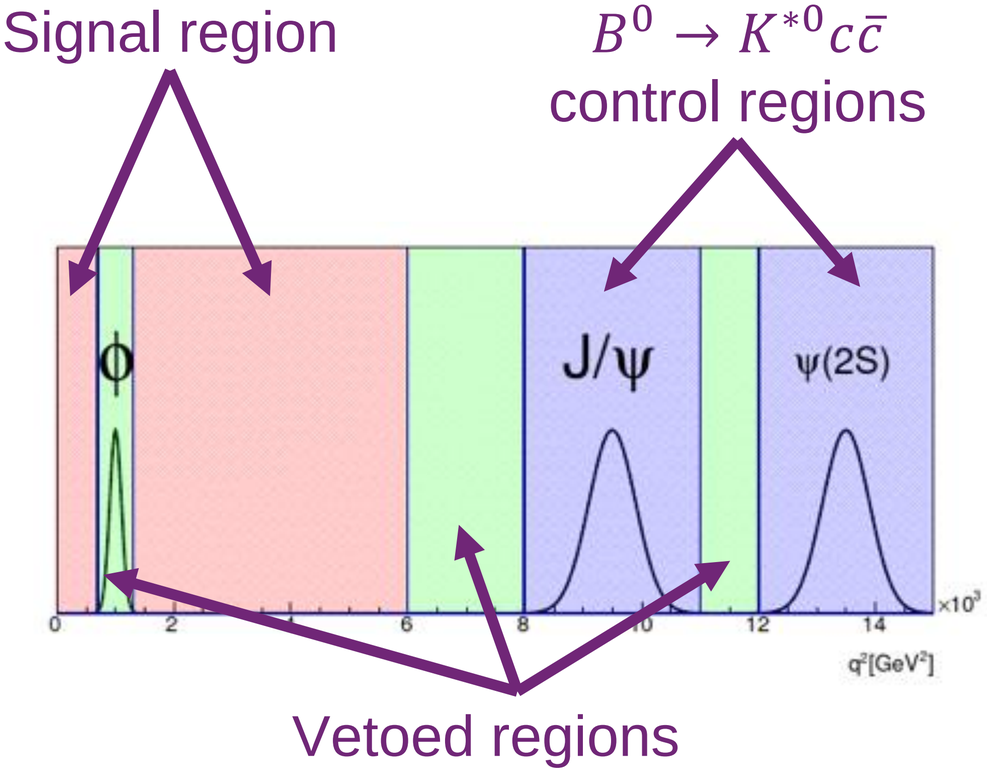
JHEP 10(2018) 047

ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

- Mass peak parameters from $B^0 \to K^{*0}J/\psi$ and $B^0 \to K^{*0}\psi(2S)$ control regions

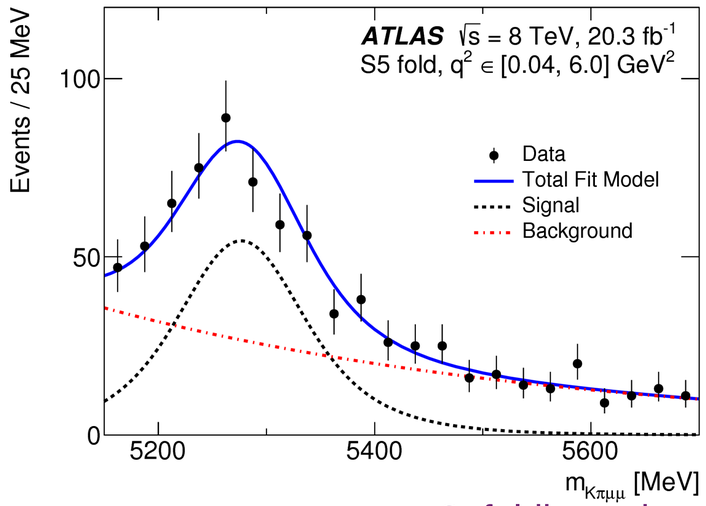
- Combinatorial background suppressed by kinematic selections
- $D^0/D^+_{(s)}$ mass veto for $B^0 \to D^0/D^+_{(s)}X$ decays
- Fake K^{*0} (combinations of $K\pi$) and $B^+ \to K^+/\pi^+\mu^+\mu^- \longrightarrow$ syst. uncertainty

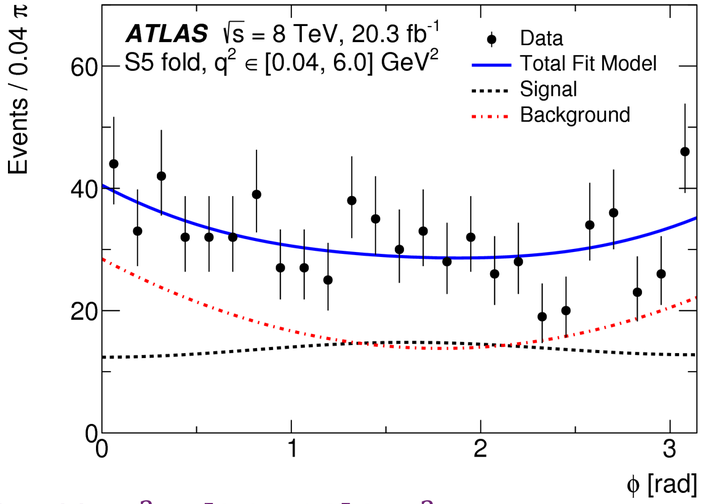
- Multiple $K\pi\mu\mu$ candidates: choose best candidate by χ^2 and $m(K\pi)$ selections



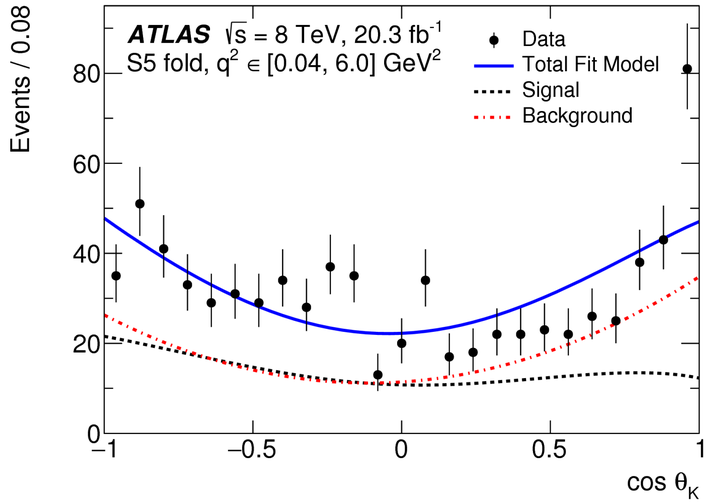
JHEP 10(2018) 047

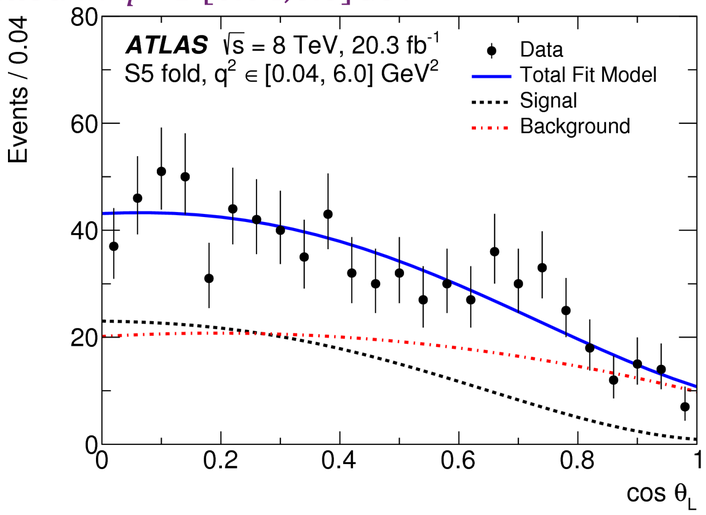
ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$





S_5 folding scheme fitted in $q^2 \in [0.04,6.0]\mathrm{GeV}^2$





Fit of $m(K\pi\mu\mu)$, $\cos\theta_\mathrm{L}$, $\cos\theta_\mathrm{K}$ and ϕ in bins of $q^2 \in [0.04,6.0]\mathrm{GeV}^2$ to extract

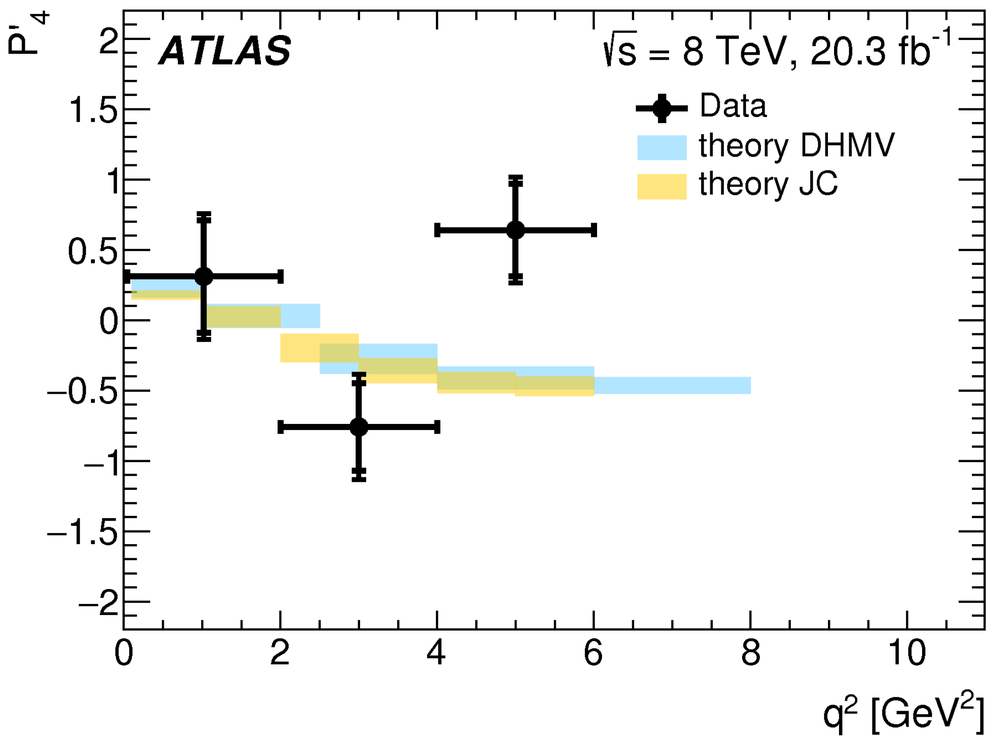
- F_L (longitudinal polarisation of K^{*0})
- Angular parameters $S_i (\to P_j^{(\prime)})$

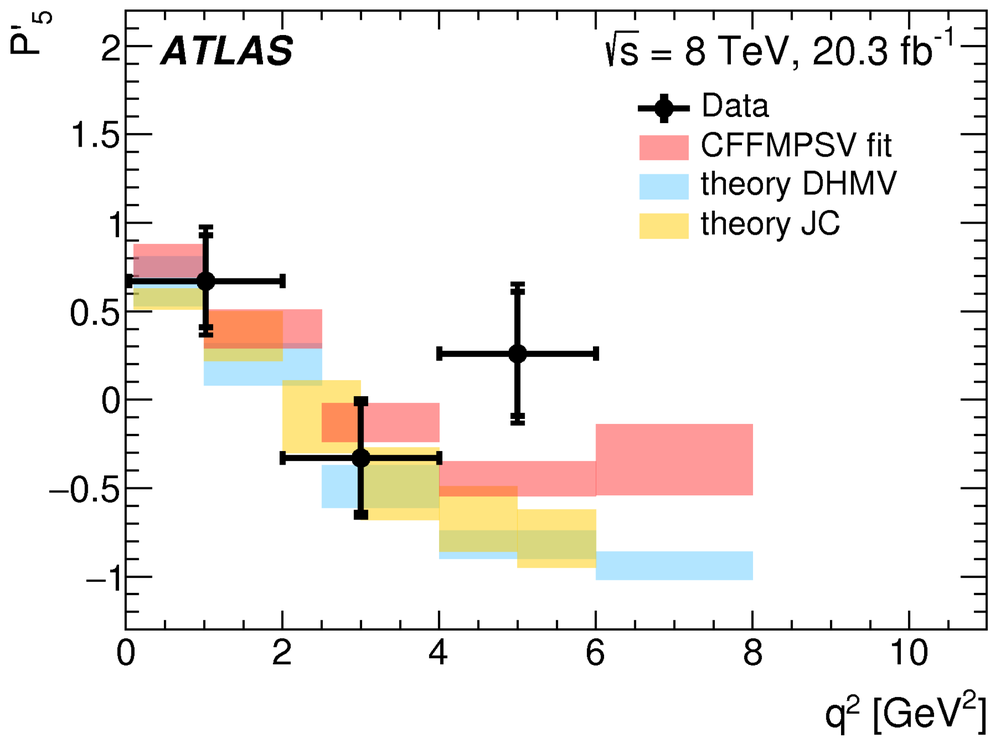
Low statistics

- Trigonometric folding
- 4 fits with 3 parameters (F_L, S_3, $S_{i=4,5,7,8}$) per q^2 bin

JHEP 10(2018) 047

ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$





Comparisons with theoretical predictions (CFFMPSV DHMV JC)

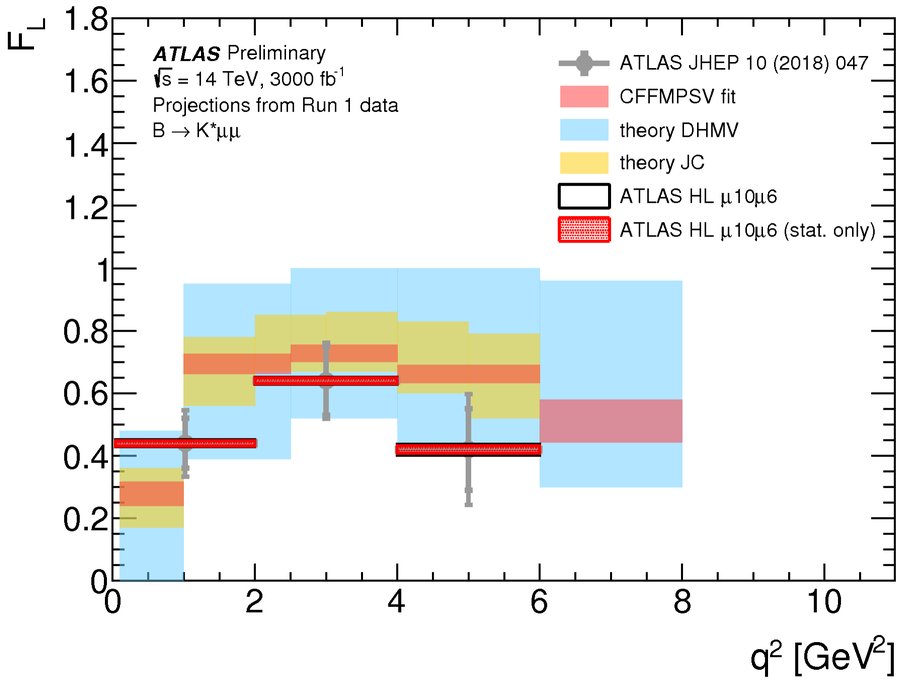
- Largest deviation: $\sim 2.7\sigma$ in P_4' and P_5' in $q^2 \in [4.0, 6.0]\,\mathrm{GeV}^2$ wrt DHMV
- Compatible with results by LHCb, CMS and Belle

JHEP 10(2018) 047

ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

Extrapolation of Run 1 results HL-LHC

- Increase in luminosity from 20 fb^{-1} to 3 ab^{-1}
- Increase in $\sqrt{s}$ from 8TeV to 14TeV
- Trigger efficiencies and detector performance



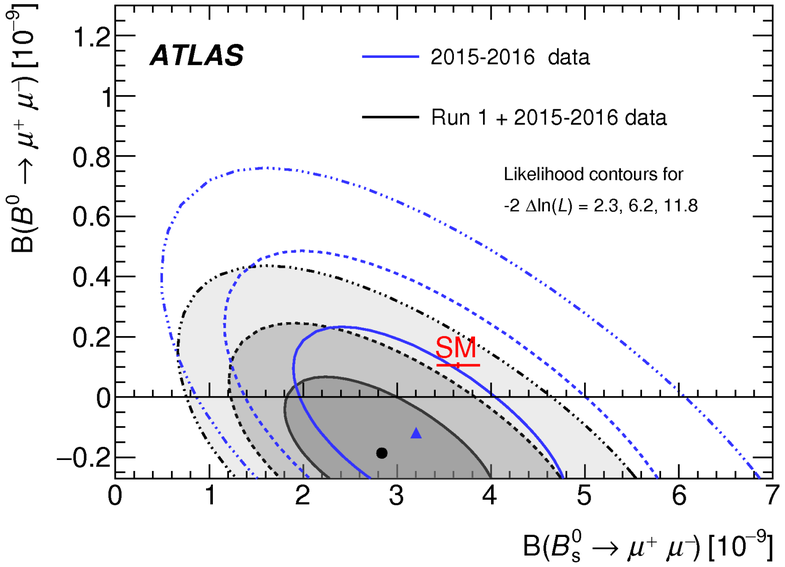
LHC phase	q^2 [GeV^2]	$\delta^{\text{tot}}_{F_L}$	$\delta^{\text{tot}}_{P_1}$	$\delta^{\text{tot}}_{P'_4}$	$\delta^{\text{tot}}_{P'_5}$	$\delta^{\text{tot}}_{P'_6}$	$\delta^{\text{tot}}_{P'_8}$
Run 1	[0.04, 2.0]	0.11	0.31	0.45	0.31	0.21	0.51
	[2.0, 4.0]	0.12	0.61	0.37	0.34	0.34	0.57
	[4.0, 6.0]	0.18	0.50	0.38	0.39	0.30	0.43
HL-LHC μ6μ6	[0.04, 2.0]	0.010	0.027	0.037	0.037	0.019	0.046
	[2.0, 4.0]	0.008	0.093	0.040	0.038	0.040	0.070
	[4.0, 6.0]	0.016	0.083	0.032	0.047	0.033	0.041
HL-LHC μ10μ6	[0.04, 2.0]	0.011	0.037	0.046	0.040	0.023	0.055
	[2.0, 4.0]	0.011	0.103	0.047	0.042	0.044	0.075
	[4.0, 6.0]	0.018	0.100	0.040	0.053	0.038	0.052
HL-LHC μ10μ10	[0.04, 2.0]	0.018	0.065	0.076	0.059	0.041	0.093
	[2.0, 4.0]	0.017	0.15	0.074	0.068	0.059	0.100
	[4.0, 6.0]	0.026	0.17	0.074	0.082	0.063	0.090

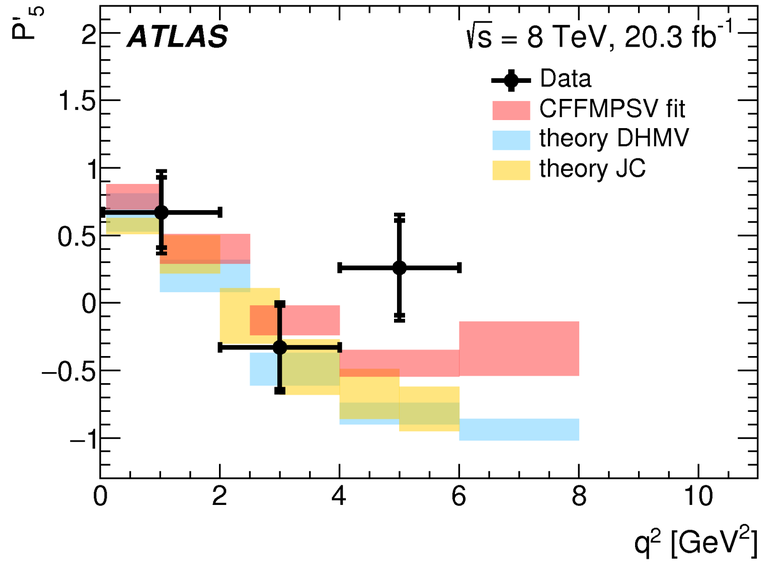
ATL PHYS PUB 2019 003

RARE B-DECAYS IN ATLAS

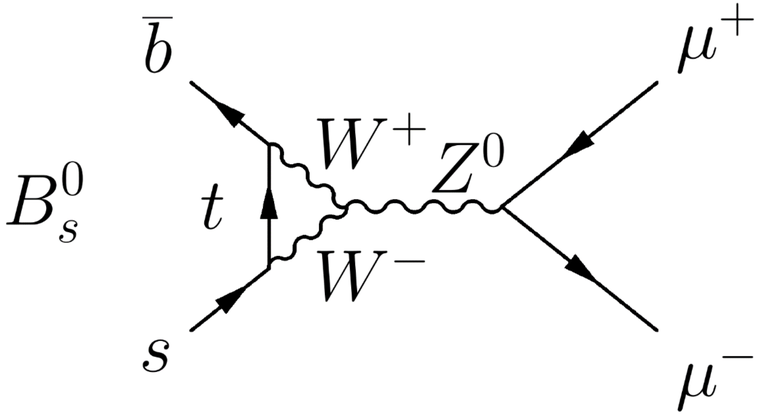
ATLAS has performed studies of rare B-decays

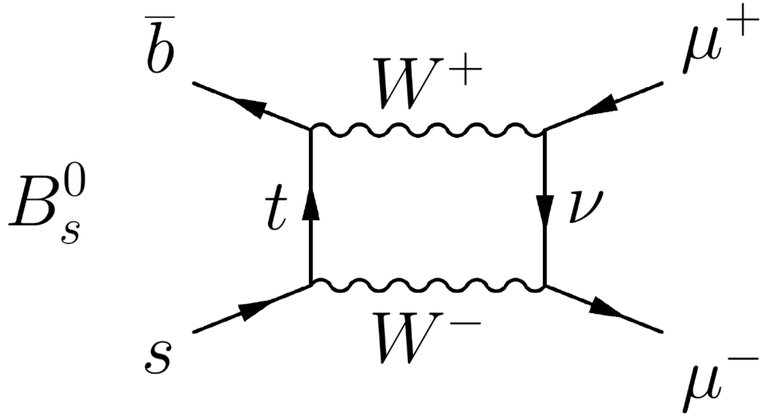
- $B_s^0 \rightarrow \mu^+\mu^-$ with 2015-2016 data:
- Branching fraction consistent with SM expectations and other experiments
- No $B^0 \rightarrow \mu^+\mu^-$ observed
- Combined results from ATLAS, CMS and LHCb
- Angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ with Run 1 data:
- Compatible with SM predictions and other experiments
- Both channels will profit from full Run 2 dataset and from the HL-LHC

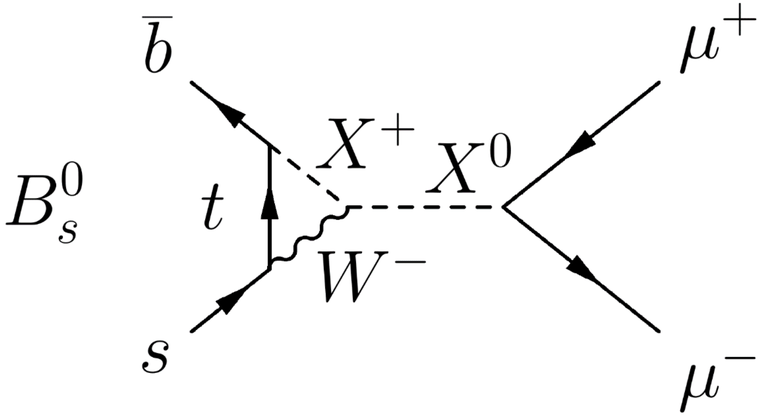


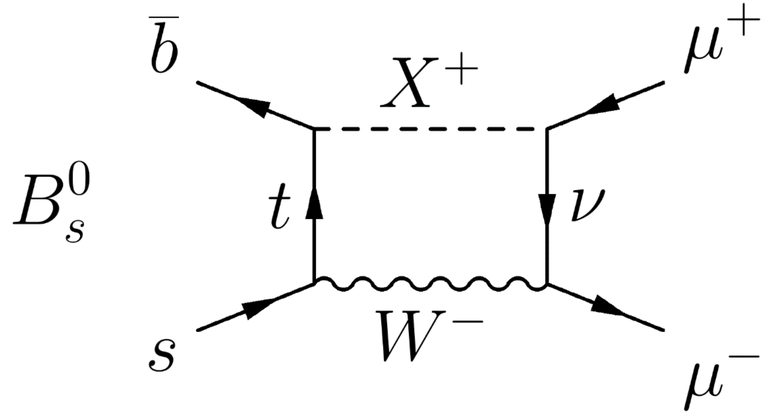


BRANCHING FRACTIONS OF $B^0_{(s)} \to \mu^+\mu^-$









JHEP 04(2019) 098

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

- Measurement of $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)$ relative to reference channel $B^+ \to J/\psi(\mu\mu)\, K^+$

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

JHEP 04(2019) 098

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

Expected systematic uncertainties on $\mathcal{B}(B^0_{(s)} \to \mu\mu)$

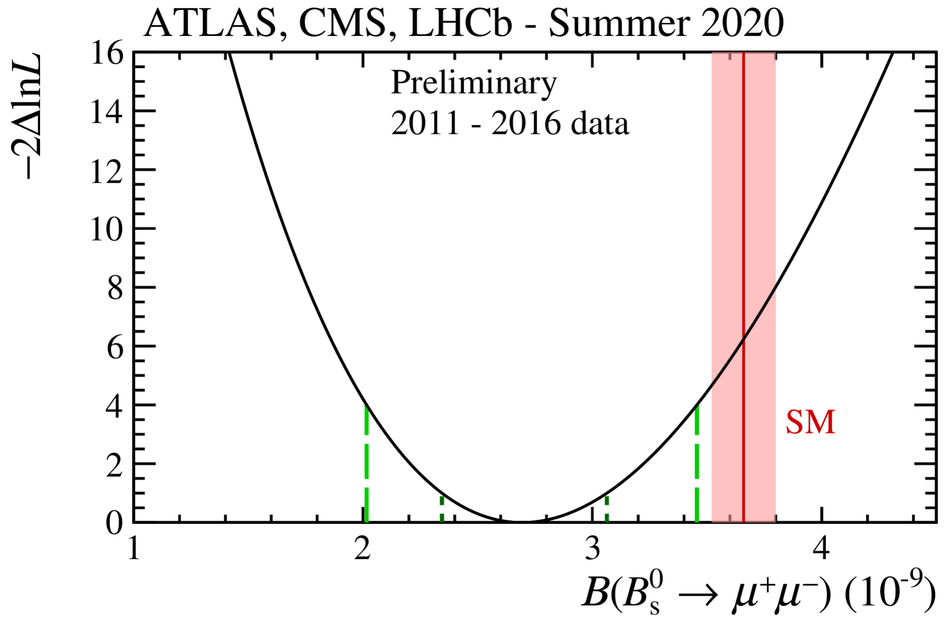
Source	B^0_s [%]	B^0 [%]
f_s/f_d	5.1	-
B^+ yield	4.8	4.8
R_ε	4.1	4.1
$\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$	2.9	2.9
Fit systematic uncertainties	8.7	65
Stat. uncertainty (from likelihood est.)	27	150

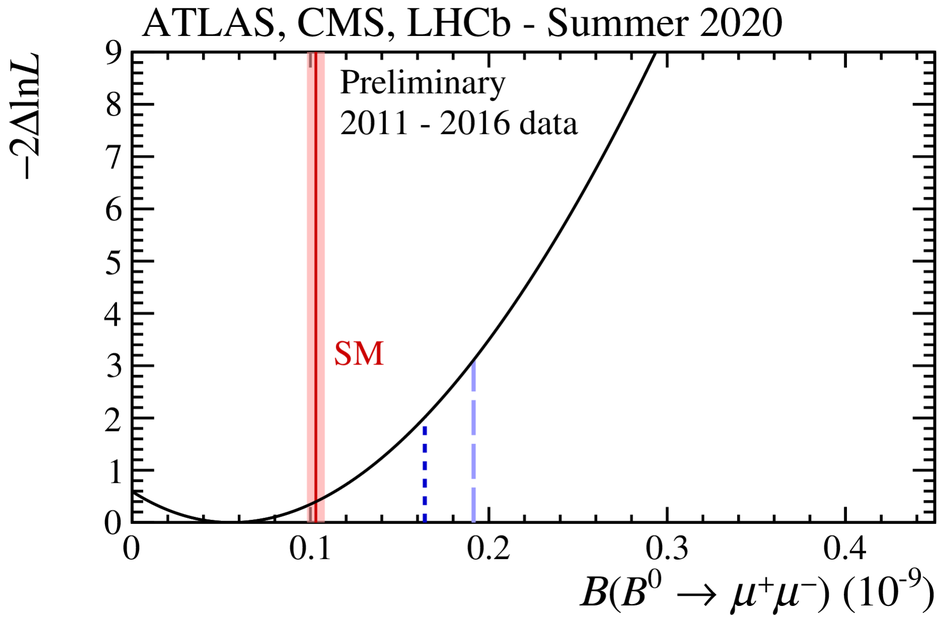
Uncertainties on R_ε

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

JHEP 04(2019) 098

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





Combination ATLAS, CMS, LHCb for Run 1 + Run 2 ((2015 +) 2016)

$\mathcal{B}(B_s^0 \to \mu\mu) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$

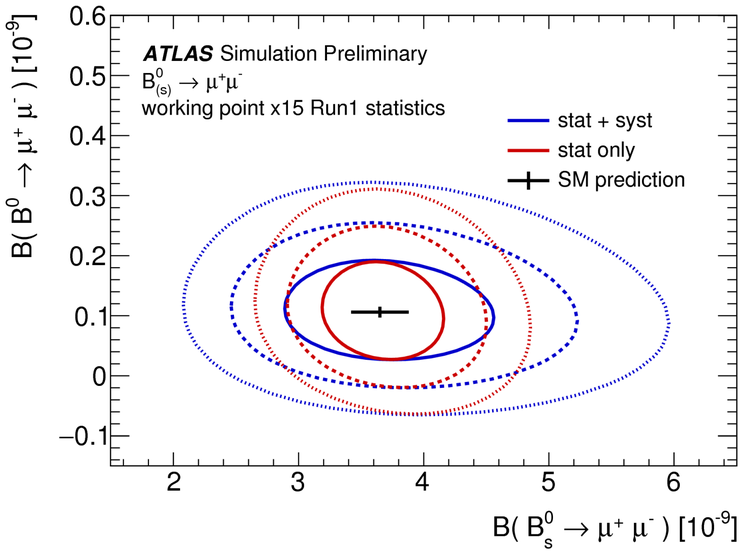
$\mathcal{B}(B^0 \to \mu\mu) < 1.9 \times 10^{-10}$ at 95% CL

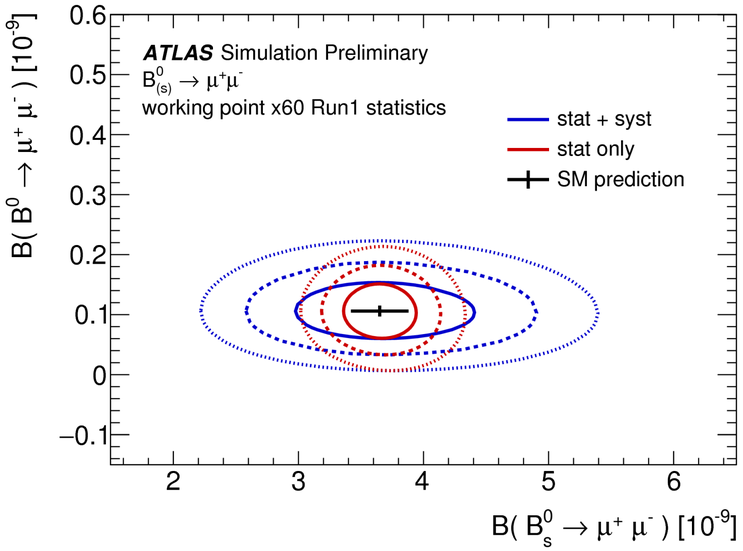
BPH 20 003

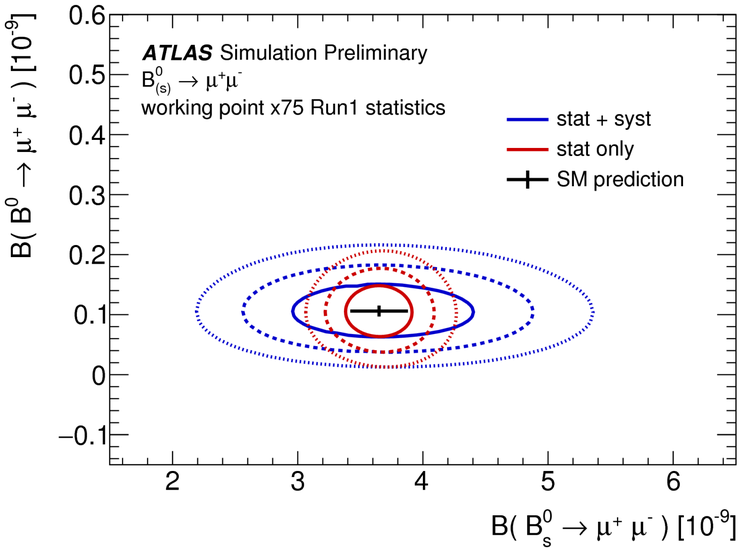
BRANCHING FRACTIONS OF $B^0_{(s)} \to \mu^+\mu^-$

Extrapolation of Run 1 results to HL-LHC

- Conservative: 2MU10 trigger x15 Run 1 statistics
- Intermediate: MU6MU10 trigger x60 Run 1 statistics
- High yield: 2MU6 trigger x75 Run 1 statistics

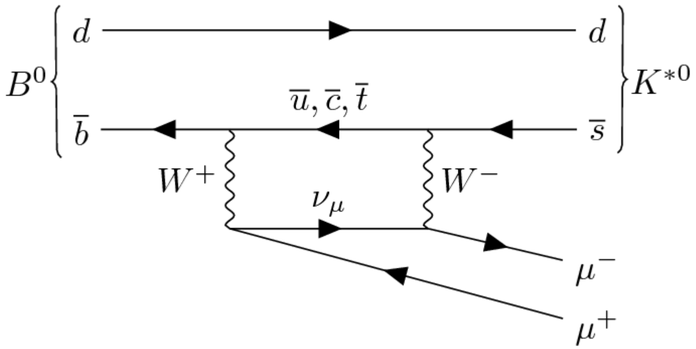


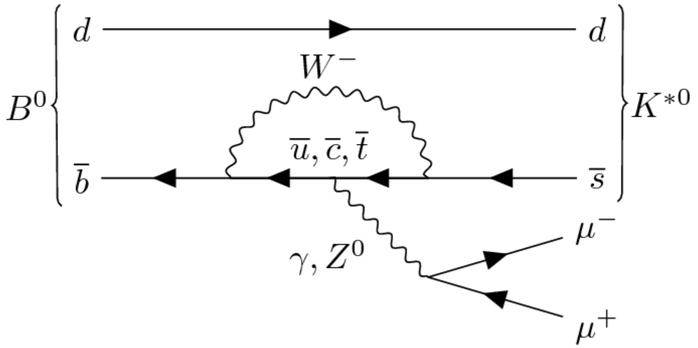


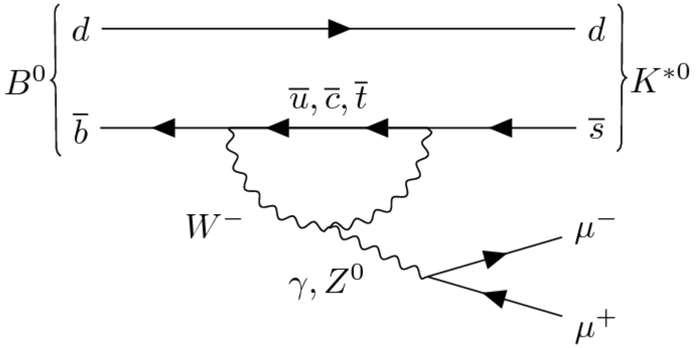


ATL PHYS PUB 2018-005

ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$







JHEP 10(2018) 047

ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

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

$$\mathcal{L} = \frac{\mathrm{e}^{-n}}{N!}\prod_{k=1}^{N}\sum_{l} n_l P_{kl}(m_{K\pi\mu\mu}, \cos\theta_K, \cos\theta_L, \phi; \widehat{p}, \widehat{\theta}),$$

JHEP 10(2018) 047

ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

$S_i \to P_j^{(\prime)}$ transformations

$$P_1 = \frac{2S_3}{1 - F_L}$$

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

Trigonometric folding scheme

$$F_L, S_3, S_4, P'_4 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_L > \frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2}, \end{cases}$$

$$F_L, S_3, S_5, P'_5 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2}, \end{cases}$$

$$F_L, S_3, S_7, P'_6 : \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \frac{\pi}{2} \\ \phi \to -\pi - \phi & \text{for } \phi < -\frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2}, \end{cases}$$

$$F_L, S_3, S_8, P'_8 : \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \frac{\pi}{2} \\ \phi \to -\pi - \phi & \text{for } \phi < -\frac{\pi}{2} \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2} \\ \theta_K \to \pi - \theta_K & \text{for } \theta_L > \frac{\pi}{2}. \end{cases}$$

JHEP 10(2018) 047

ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

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

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

JHEP 10(2018) 047

ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

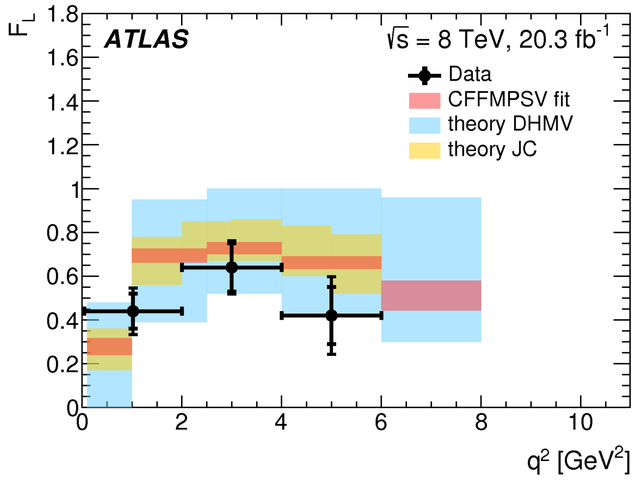
q^2 [GeV^2]	n_{signal}	$n_{\text{background}}$
[0.04, 2.0]	128 ± 22	122 ± 22
[2.0, 4.0]	106 ± 23	113 ± 23
[4.0, 6.0]	114 ± 24	204 ± 26
[0.04, 4.0]	236 ± 31	233 ± 32
[1.1, 6.0]	275 ± 35	363 ± 36
[0.04, 6.0]	342 ± 39	445 ± 40

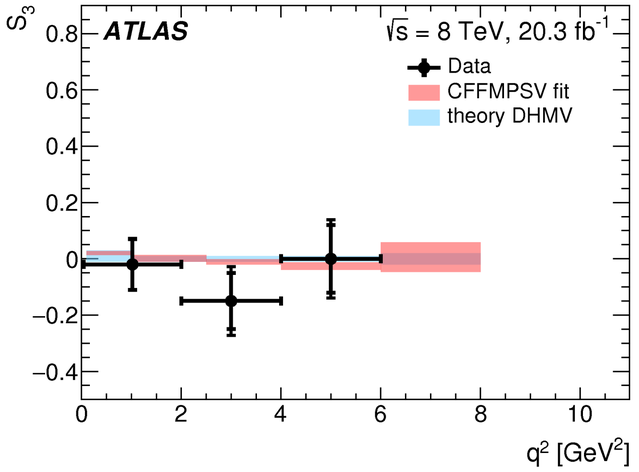
Source	F_L	S_3	S_4	S_5	S_7	S_8
Combinatoric $K\pi$ (fake K^*) background	0.03	0.03	0.05	0.04	0.06	0.16
D and B^+ veto	0.11	0.04	0.05	0.04	0.01	0.06
Background pdf shape	0.04	0.04	0.03	0.03	0.03	0.01
Acceptance function	0.01	0.01	0.07	0.01	0.01	0.01
Partially reconstructed decay background	0.03	0.05	0.02	0.08	0.05	0.06
Alignment and B field calibration	0.02	0.04	0.05	0.04	0.04	0.04
Fit bias	0.01	0.01	0.02	0.03	0.01	0.05
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	0.03
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

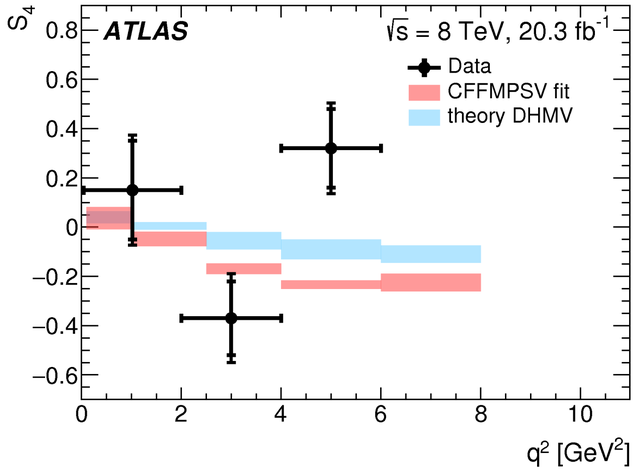
JHEP 10(2018) 047

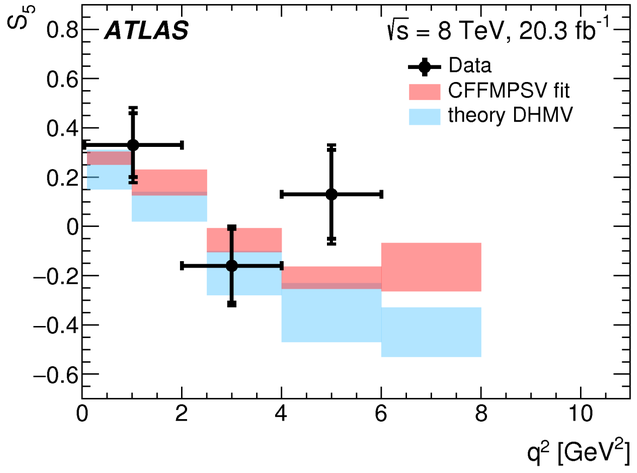
ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

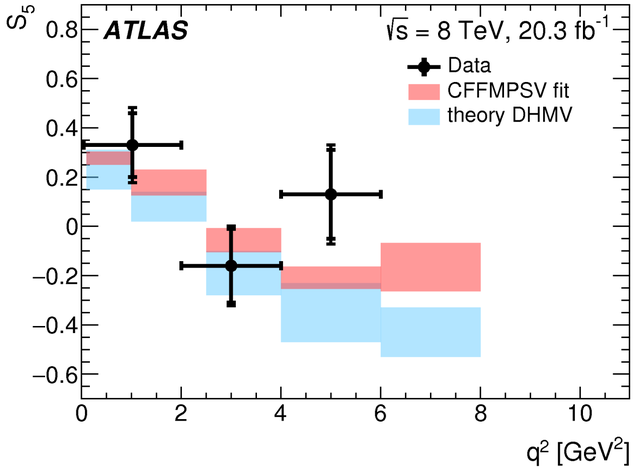
JHEP 10(2018) 047

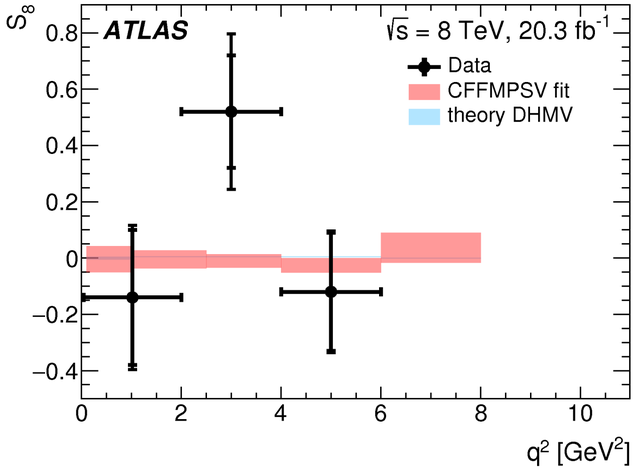






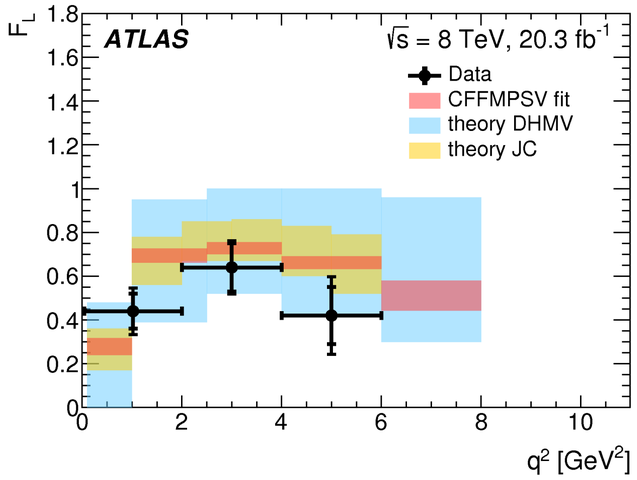


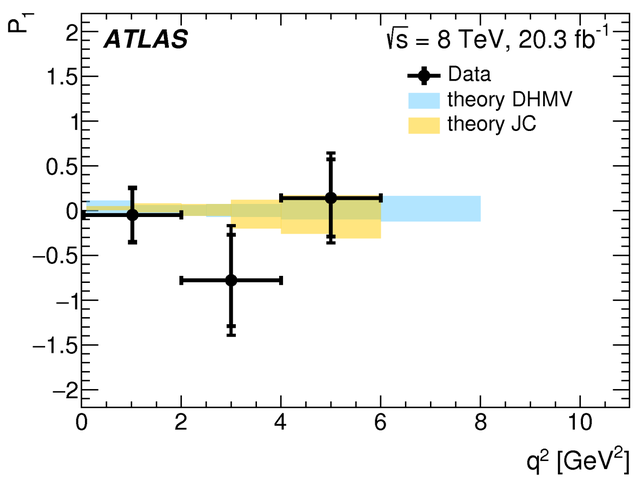


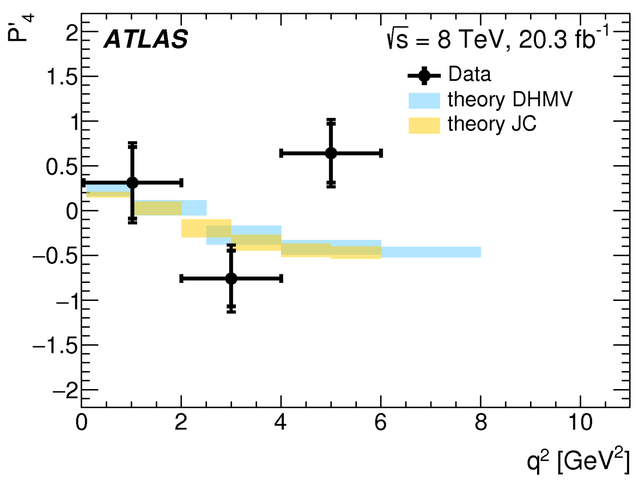


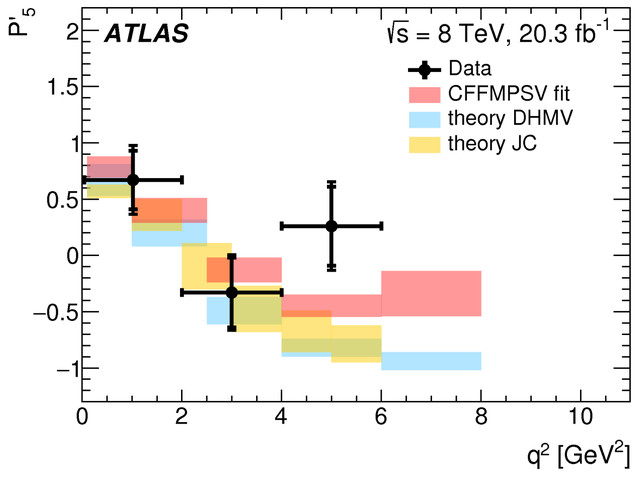
ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

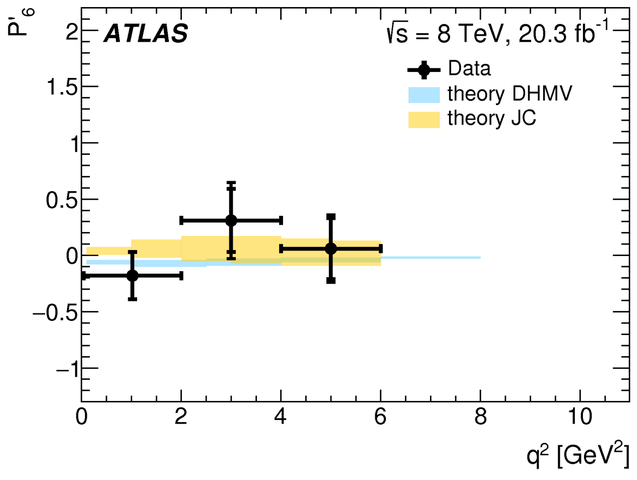
JHEP 10(2018) 047

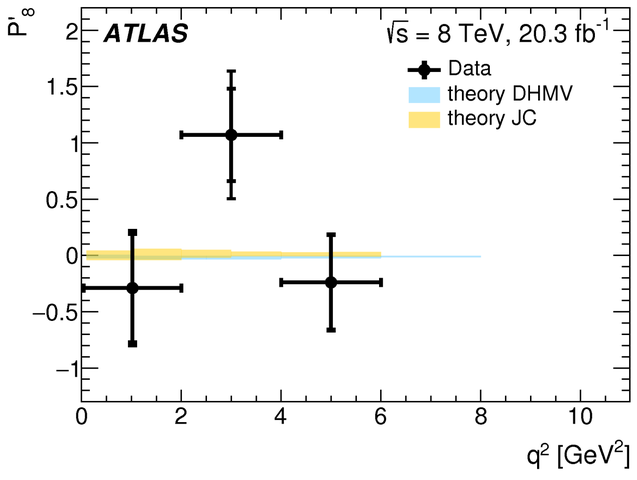












ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

HL-LHC prediction

ATL PHYS PUB 2019 003