UNCE Seminar
IPNP

Rare B decays at ATLAS experiment

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- $B \to ll$ and $B \to s(d)ll$ suppressed at tree level in the SM
  - Further suppression by CKM and helicity
- For pure leptonic decays BR is predicted within SM with small uncertainties

Bobeth et al., PRL 112 (2014) 101801

$\mathcal{B}(B_s^0 \to ee) = (8.54 \pm 0.55) \times 10^{-14}$ $\mathcal{B}(B^0 \to ee) = (2.48 \pm 0.21) \times 10^{-15}$

$\mathcal{B}(B_s^0 \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$ $\mathcal{B}(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$

$\mathcal{B}(B_s^0 \to \tau\tau) = (7.73 \pm 0.49) \times 10^{-7}$ $\mathcal{B}(B^0 \to \tau\tau) = (2.22 \pm 0.19) \times 10^{-8}$

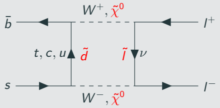
Beneke et al., JHEP 10 (2019) 232

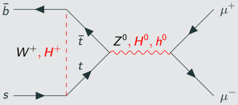
$\mathcal{B}(B_s^0 \to \mu\mu) = (3.66 \pm 0.14) \times 10^{-9}$

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

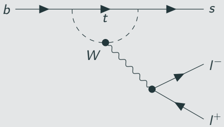
New physics contributions

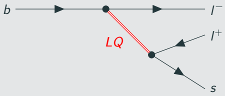
- ... could suppress or enhance decay rates





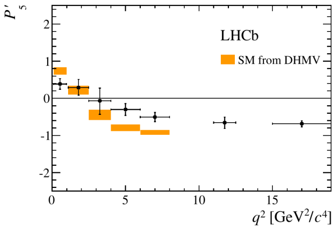
- ... could affect angular distributions in $b \to sll$

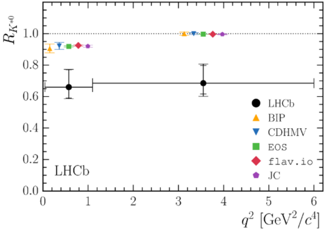


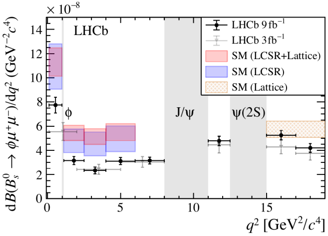


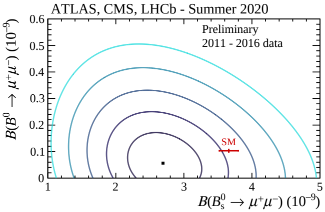
- Lepton Flavour Universality tests

- Long-standing tension w.r.t. SM in rare b-hadron decays

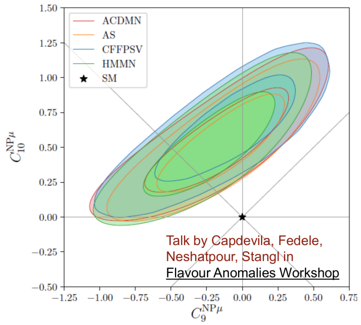




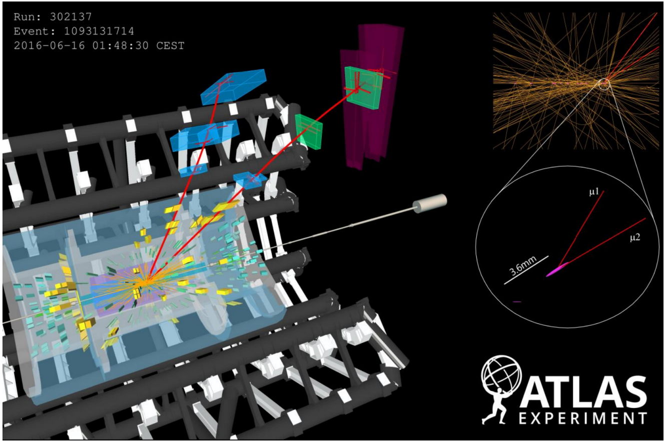




Interpreted in Effective Field Theories



- **Branching ratio of $B^0_{(s)} \to \mu\mu$**
- **Angular analysis of $B^0 \to K^{*0}\mu\mu$**
- In progress: lifetime of $B^0_s \to \mu\mu$
- In progress: $R(K^*)$
- Potentially $R(K^+)$, $R(D^{(*+)})$, other $b \to sll$ decays

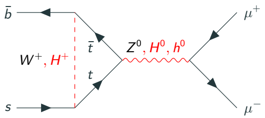


Study of the rare decays of B_s^0 and B^0 mesons into muon pairs using data collected during 2015 and 2016 with the ATLAS detector

JHEP 04 (2019) 098

Analysis of rare $B^0_{(s)} \to \mu\mu$ decays

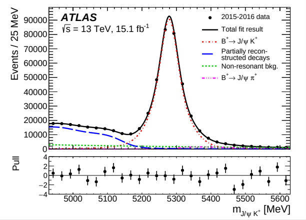
- FCNC in the SM proceeding via loop and box diagrams, and helicity suppressed $\implies \mathcal{B} \sim 10^{-9}$
- BSM can significantly contribute, modifying the branching ratio



Measurement

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N_{d(s)} \cdot \frac{\mathcal{B}(B^\pm \to J/\psi K^\pm) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)}{N_{J/\psi K^\pm} \cdot \frac{\epsilon_{\mu^+\mu^-}}{\epsilon_{J/\psi K^\pm}}} \cdot \frac{f_u}{f_{d(s)}}$$

- $\mathcal{B}(B^0_{(s)} \to \mu\mu)$ measurement relative to $\mathcal{B}(B^\pm \to J/\psi K^\pm)$, $B^0_s \to J/\psi\phi$ as control channel
- Blinded signal di-muon invariant mass region $[5166, 5526]$ MeV
- BDT based background suppresion, trained on sidebands data
- Yields $N_{d(s)}$ and $N_{J/\psi K^\pm}$ obtained from UML fits to the mass spectra
- Relative reconstruction efficiencies estimated from MC (corrected for data-MC differences): $\epsilon_{\mu^+\mu^-}/\epsilon_{J/\psi K^\pm} = 0.1176 \pm 0.0009_{\text{stat.}} \pm 0.0047_{\text{syst.}}$
- Known branching ratios from PDG, $f_u/f_{d(s)}$ from HFLAV

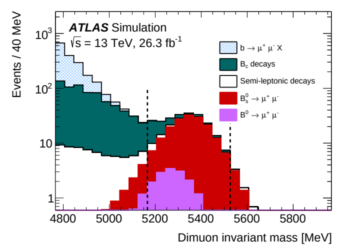


- $B^\pm \to J/\psi K^\pm$ yield: $33435 \pm 0.3\%_{\text{stat.}} \pm 4.8\%_{\text{syst.}}$

Backgrounds

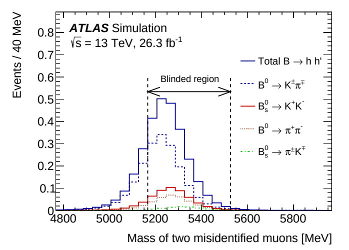
Partially reconstructed *b*-hadron decays

- Mostly in the low di-muon mass region
- Shape free in the mass fit



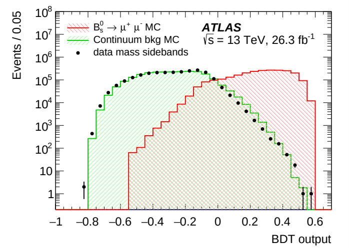
Peaking backgrounds

- Hadronic B_s^0 decays where hadrons are misidentified as muons
- Simulated and fixed in the mass fit



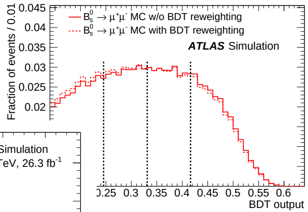
Continuum background

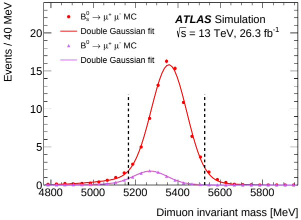
- Combinatorics of μ and uncorrelated hadron decays
- Reduced by BDT
- Linear shape constrained in the mass fit across BDT bins
- Systematics due to $B_c^\pm \to J/\psi\mu\nu$ and $B_{(s)}^0/\Lambda_b^0 \to h\mu\nu$ decays

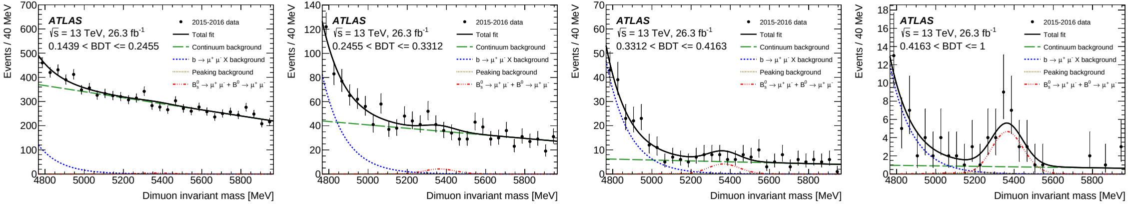


BDT and signal yield extraction

- BDT formed from 15 variables
  - kinematics, isolation, B-vertex separation from PV
- BDT output validated on reference $B^{\pm} \to J/\psi K^{\pm}$ and control $B_s^0 \to J/\psi \phi$ channels, observed difference applied as a correction to signal channel
- Signal region divided into four BDT bins with constant signal efficiency
- Simultaneous extraction of $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$ yields from unbinned maximum likelihood fit to di-muon mass distributions in the four BDT bins

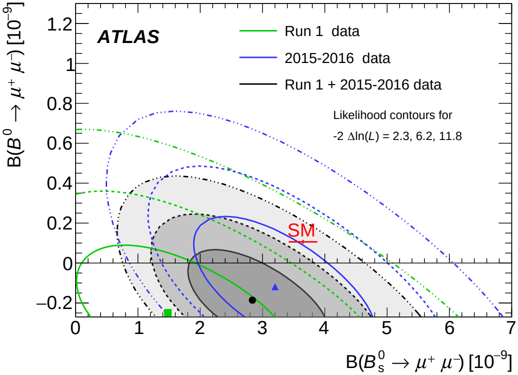






Results

- Contours obtained using Neyman construction



Standard Model

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

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

ATLAS 2015 + 2016 data

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

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

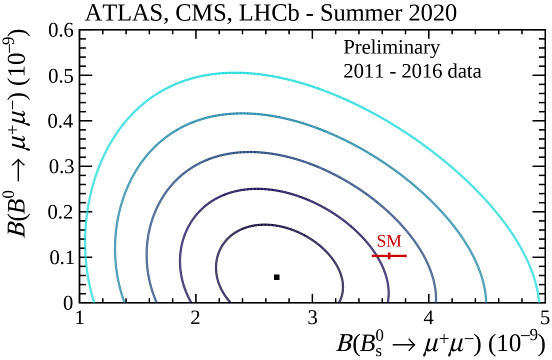
ATLAS Run 1 + 2015 + 2016 data

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

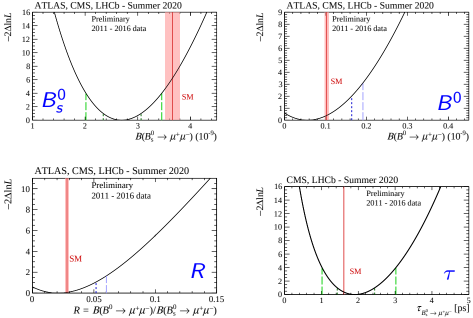
$\mathcal{B}(B^0 \to \mu\mu) < 2.1 \times 10^{-10}$ at 95% CL

- Combined measurement compatible with SM at 2.4 σ
- Statistic uncertainties dominate
- Largest systematics contribution from di-muon mass fit procedure

$B^0_{(s)} \to \mu\mu$: LHC combination



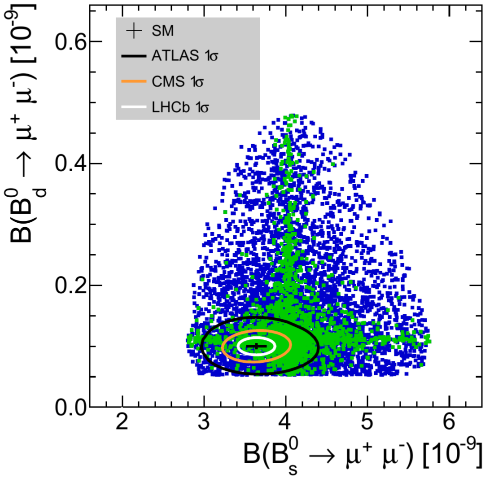
- Combining binned 2D profile likelihoods, systematics treated as independent, except for f_s/f_d which is the only source of correlation between experiments



	LHC	SM
$\mathcal{B}(B^0_s \to \mu\mu) \times 10^{-9}$	$2.69^{+0.37}_{-0.35}$	3.66 ± 0.14
$\mathcal{B}(B^0 \to \mu\mu) \times 10^{-10}$	< 1.9 at 95% CL	1.03 ± 0.05
Ratio of above	< 0.052 at 95% CL	0.0281 ± 0.0016
$\tau_{B^0_s \to \mu\mu}$ [ps] (LHCb+CMS)	$1.91^{+0.37}_{-0.35}$	1.609 ± 0.010

$B^0_{(s)} \to \mu\mu$: HL-LHC projections

- Theory prediction limited by $|V_{cb}|$
- Experimental uncertainty on B^0_s dominated by f_s/f_d
- Mass resolution improvements will help distinguishing the B^0_s and B^0_d peaks
- Additional information from effective lifetime and *CP* asymmetry
  - Distinguish RH and LH contributions
  - Inclusion of $B^0_s \to \mu\mu\gamma$ studies to probe vector coupling



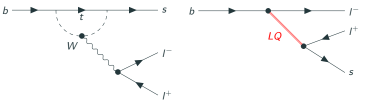
- Computations in SUSY unified models (PRD 91 (2015) no.9, 095011)
- Subset consistent with other measurements

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays in *pp* collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector (Run 1 data)

JHEP 10 (2018) 047

Analysis of rare $B^0 \to K^{*0}\mu\mu$ decays

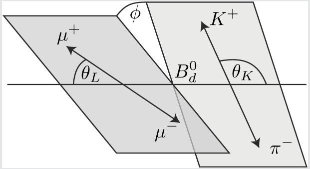
- FCNC in the SM proceeding via loop and box diagrams
- BSM can significantly contribute, modifying the differential decay rate



Measurement

$$\mathcal{L} = \frac{e^{-N}}{n!}\prod_{i=1}^{n}\sum_{j} n_j P_{ij}(m_{K\pi\mu\mu}, \cos\theta_K, \cos\theta_L, \phi; \hat{p}, \hat{\theta})$$

- Extended unbinned maximum likelihood fit of the 3D decay angles distribution (and B-candidate mass)
  - Dependent on di-muon invariant mass[2] q^2 (ignored range above $c\bar{c}$)
- Blinded fit results
- Study of number of potential backgrounds from radiate resonant decays and other semileptonic rare decays
  - Treated in systematics, no need to include in default fit
- Detector acceptance (sculpting of the angular distributions) from MC
- No K/π separation in ATLAS $\implies$ 11% wrong tag of B-flavor



Fit simplifications

Low statistics ($\sim$ 340 signal events) does not allow full fit $\Longrightarrow$ simplifications:

Angular distribution folding

- Full angular distribution $\rightarrow$ four simplier distributions
- Lost sensitivity to S_6 and S_9

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

$\Downarrow$

$$F_L, S_3, S_5, P_5' : \begin{cases}\phi \rightarrow -\phi & \text{for } \phi < 0\\ \theta_L \rightarrow \pi - \theta_L & \text{for } \theta_L > \frac{\pi}{2}\end{cases} \Longrightarrow$$

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{8\pi}\Bigg[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_\ell$$
$$-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_5\sin 2\theta_K\sin\theta_\ell\cos\phi\Bigg]$$

Fit simplifications

Low statistics ($\sim$ 340 signal events) does not allow full fit $\Longrightarrow$ simplifications:

Angular distribution folding

- Full angular distribution $\rightarrow$ four simplier distributions
- Lost sensitivity to S_6 and S_9

B-candidate mass distribution pre-fits

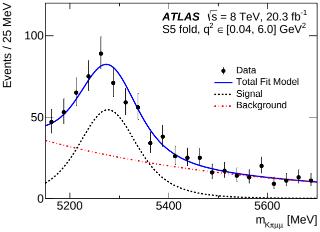
- B-candidate mass distribution pre-fitted and fixed in the angular fit
- Mass nuisance parameters extract from fits to control channels ($B^0 \rightarrow J/\psi K^*$, $B^0 \rightarrow \psi(2S)K^*$)

Rough q^2 binning

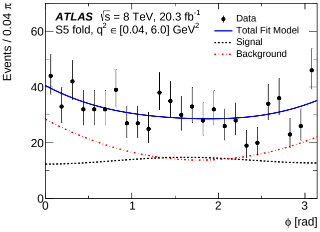
- 3 bins only in q^2 GeV]: (0.04 - 2), (2.0 - 4.0), (4.0 - 6.0)

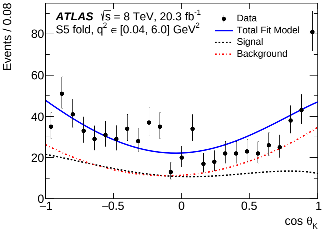
Fit projections

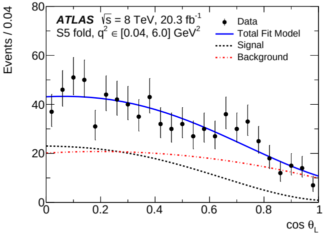
- Example of fit projections for the extraction of S_5 (resp. P_5') parameter for q^2 bin (4-6) GeV



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

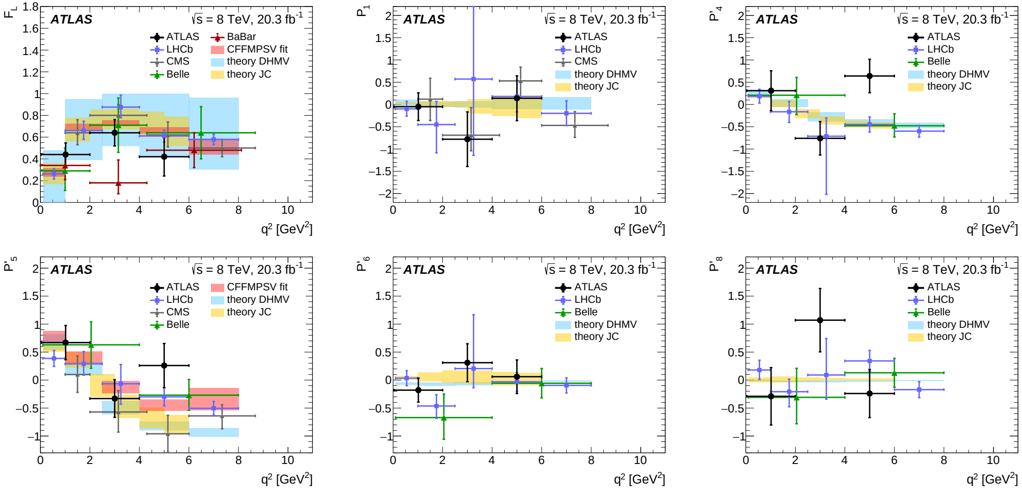






Results

- Results ∼ compatible with Standard Model predictions and with other experiments
- Largest (local) deviations of 2.7σ for P_5' and P_4', follow LHCb observation



$B^0 \to K^{*0}\mu\mu$: HL-LHC projections

- The transitions $b \to sll$ provide access to number of operators
- Statistics would allow improvement in the precision by one order
  - $\sim (5-9)\times$ for ATLAS

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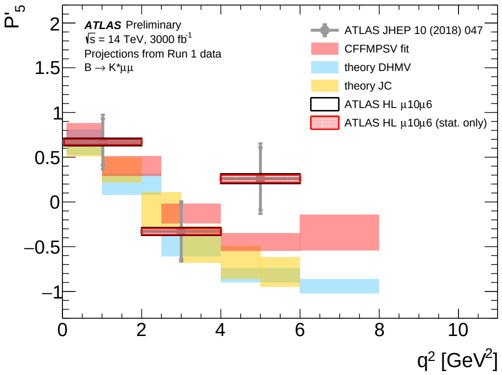

Combination of all observables will help discriminating NP scenarios

arXiv:1812.07638