CKM 2021

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Rare B Decays at ATLAS and CMS

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Introduction

- $B \to ll$ 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

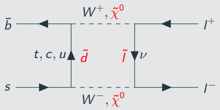
$\mathcal{B}(B_s^0 \to ee) = (8.54 \pm 0.55) \times 10^{-14}$ $\mathcal{B}(B^0 \to ee) = (2.48 \pm 0.21) \times 10^{-15}$
$\mathcal{B}(B_s^0 \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$ $\mathcal{B}(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$
$\mathcal{B}(B_s^0 \to \tau\tau) = (7.73 \pm 0.49) \times 10^{-7}$ $\mathcal{B}(B^0 \to \tau\tau) = (2.22 \pm 0.19) \times 10^{-8}$

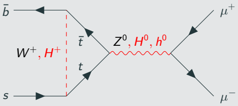
Beneke et al., JHEP 10 (2019) 232

$\mathcal{B}(B_s^0 \to \mu\mu) = (3.66 \pm 0.14) \times 10^{-9}$
$\mathcal{B}(B^0 \to \mu\mu) = (1.03 \pm 0.05) \times 10^{-10}$

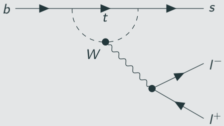
New physics contributions

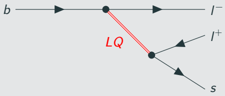
- ... could suppress or enhance BR





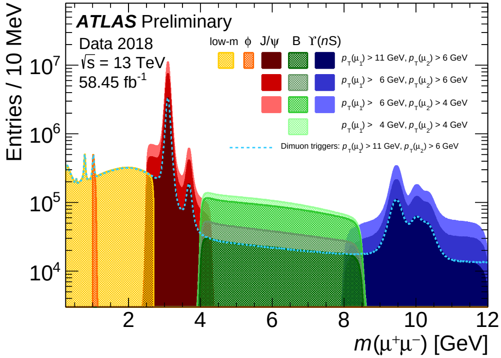
- ... could affect angular distributions in $b \to sll$

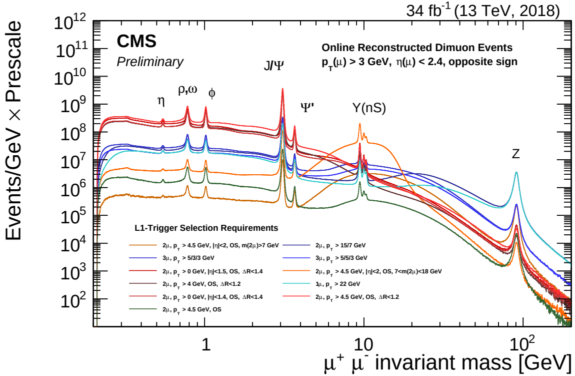




- Direct probing of potential LFU effects in progress too (not discussed)

- Data: Run 2 $\sim$140 fb^{-1} pp collisions at $\sqrt{s} = 13$ TeV (2015-18), Run 1 $\sim$25 fb^{-1} at 7/8 TeV (2011-12)
- Producing 2.5 M $b\bar{b}$ pairs/second, B_s, B_c, Λ_b, etc. available
- Program focused mostly on muonic final states, fully reconstructable; exceptions exist:
  - CMS B-parking Run 2 data collecting huge unbiased ($\sim 10^{10}$) b-hadron events
  - Di-electron triggers in Run 2 at ATLAS





Rare B decays results from ATLAS & CMS

Purely leptonic decays

- Branching ratio of $B^0_{(s)} \to \mu\mu$ and $B^0_s \to \mu\mu$ effective lifetime in *pp* collisions with 2011-2016 data (CMS)
  JHEP 04 (2020) 188, PRL 111 (2013) 101804, Nature 522 (2015) 68
- Branching ratio of $B^0_{(s)} \to \mu\mu$ in *pp* collisions during LHC Run 1 and 2015 and 2016 data (ATLAS)
  JHEP 04 (2019) 098, EPJC 76 (2016) 513

Semileptonic decays (all using *pp* collisions data at $\sqrt{s} = 8$ TeV)

- Angular analysis of $B^\pm \to K^\pm\mu\mu$ (CMS) PRD 98 (2018) 112011
- Angular analysis of $B^\pm \to K^{*\pm}\mu\mu$ (CMS) JHEP 04 (2021) 124
- Angular analysis of $B^0 \to K^{*0}\mu\mu$ (CMS) PLB 781 (2018) 517 (P_1, P'_5), PLB 753 (2016) 424 (A_{FB}, F_L)
- Angular analysis of $B^0 \to K^{*0}\mu\mu$ (ATLAS) JHEP 10 (2018) 047

Projections: arXiv:1812.07638 (resp. CERN Yellow Rep. Monogr. 7 (2019) pp. 1-1418)

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

Datasets

- ATLAS data: 2015+2016 data analysis, combined with Run 1 result
- CMS data: Run 1 + 2016 data analysis

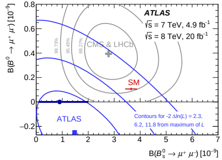
- $\mathcal{B}(B^0_{(s)} \to \mu\mu)$ measurement relative to $\mathcal{B}(B^\pm \to J/\psi K^\pm)$, $B^0_s \to J/\psi\phi$ as control channel

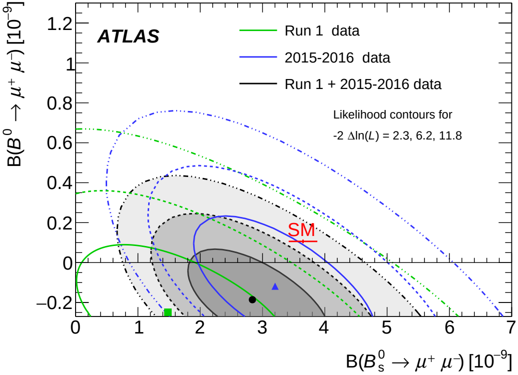
$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N_{d(s)} \cdot \frac{\mathcal{B}(B^\pm \to J/\psi K^\pm) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)}{N_{J/\psi K^\pm} \cdot \frac{\epsilon_{\mu^+\mu^-}}{\epsilon_{J/\psi K^\pm}}} \cdot \frac{f_u}{f_{d(s)}}$$

- Blinded signal di-muon invariant mass region
- Backgrounds
  - Combinatorial background suppressed by BDT, trained on data sidebands
    - ATLAS: 4 BDT bins with equal signal efficiency, 15 variables on kinematics, isolation and B-vertex separation from PV
    - CMS: 14 BDT categories (barrel/endcap, year datasets), 10-15 pile-up independent variables
  - Peaking backgrounds (mostly mis-id) and partially reconstructed B-decays from simulations
- Yields $N_{d(s)}$ and $N_{J/\psi K^\pm}$ obtained from UML fits to the mass spectra
- Relative reconstruction efficiencies and acceptances from simulation (corrected for data-MC differences)
- Known branching ratios from PDG, $f_u/f_{d(s)}$ from HFLAV

$B^0_{(s)} \to \mu\mu$: ATLAS results

In Run 1 ATLAS measurement lower in both $B^0_s \to \mu\mu$ and $B^0 \to \mu\mu$ BR compared to combined CMS+LHCb; tension in B^0_d reduced with the Run 2 LHCb measurement (PRL 118 (2017) 191801)





ATLAS 2015 + 2016 data

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

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

ATLAS Run 1 + 2015 + 2016 data

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

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

- Contours obtained using Neyman construction
- Compatible with SM at 2.4 σ
- Statistic uncertainties dominate

$B^0_{(s)} \to \mu\mu$: CMS results

CMS 2011 + 2012 + 2016 data

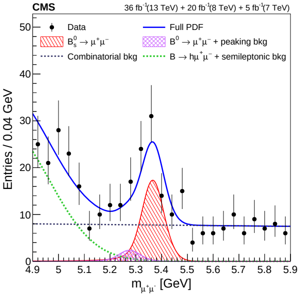
Multi-bin BDT fit

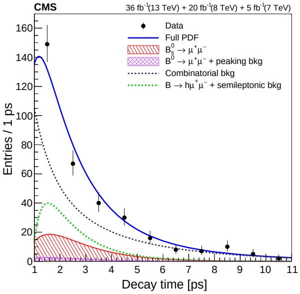
$\mathcal{B}(B^0_s \to \mu\mu) = (2.9 \pm 0.7_{\text{exp}} \pm 0.2_{\text{frag}}) \times 10^{-9}$

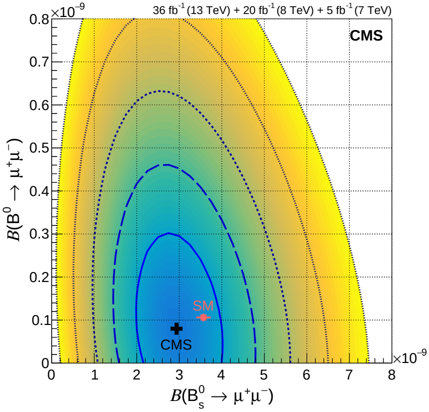
- 5.6σ observed, 6.5σ expected

$\mathcal{B}(B^0 \to \mu\mu) < 3.6 \times 10^{-10}$ at 95% CL

- resp. $\mathcal{B}(B^0 \to \mu\mu) = 0.8^{+1.4}_{-1.3} \times 10^{-10}$ (0.6σ)



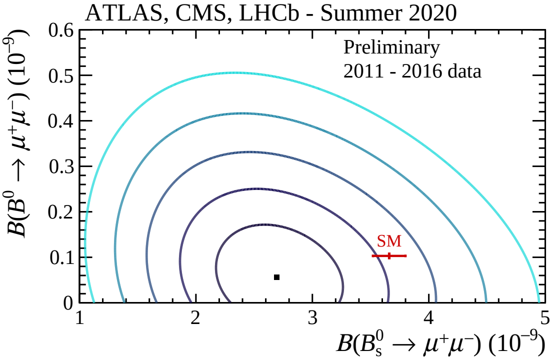




Lifetime measurement

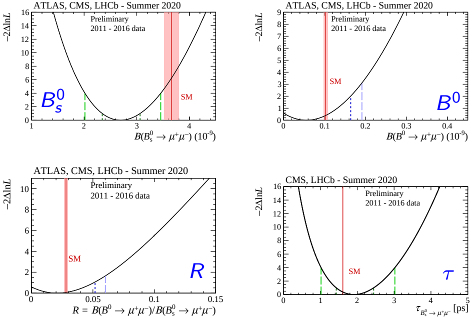
Single BDT category; fit range [1, 11] ps

$\tau_{\mu^+\mu^-} = (1.70^{+0.64}_{-0.44})$ ps



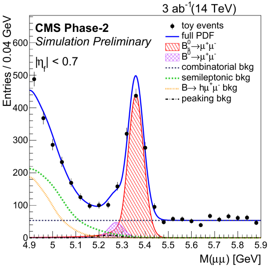
- Combining binned 2D profile likelihoods, systematics treated as independent, except for f_s/f_d which is the only source of correlation between experiments

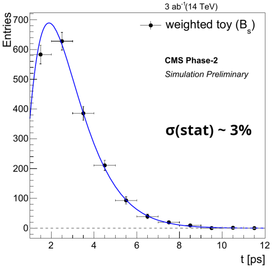
	LHC	SM
$\mathcal{B}(B^0_s \to \mu\mu) \times 10^{-9}$	$2.69^{+0.37}_{-0.35}$	3.66 ± 0.14
$\mathcal{B}(B^0 \to \mu\mu) \times 10^{-10}$	< 1.9 at 95% CL	1.03 ± 0.05
Ratio of above	< 0.052 at 95% CL	0.0281 ± 0.0016
$\tau_{B^0_s \to \mu\mu}$ [ps] (LHCb+CMS)	$1.91^{+0.37}_{-0.35}$	1.609 ± 0.010

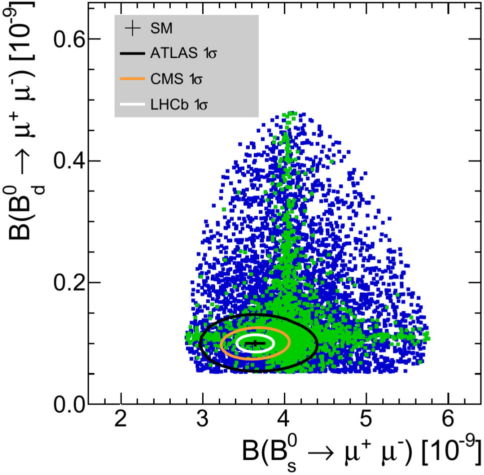


$B^0_{(s)} \to \mu\mu$: HL-LHC projections

- 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





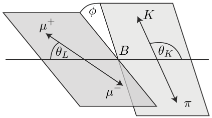


- Computations in SUSY unified models (PRD 91 (2015) no.9, 095011)
- Subset consistent with other measurements

Semimuonic rare B decays

Analyses of decay angles distributions, based on unbinned maximum likelihood fit to the data in rough $q = m(\mu\mu)^2$ bins (due to low yields)

- Inclusive backgrounds data driven, few peaking background contributions (simulated)
- 8 TeV collision data ($\sim 20\text{fb}^{-1}$)



$B^\pm \to K^\pm \mu\mu$ at CMS

- Muon-kaon angle in the $\mu\mu$ rest frame: θ_l
- Forward-backward asymmetry A_{FB}
- Pseudo-scalar/tensor contribution F_H
- Measured also differential BR
- $\sim$ 2300 signal events

$$\frac{1}{\Gamma_\ell}\frac{\mathrm{d}\Gamma_\ell}{\mathrm{d}\cos\theta_\ell} = \frac{3}{4}(1-F_{\mathrm{H}})(1-\cos^2\theta_\ell) + \frac{1}{2}F_{\mathrm{H}} + A_{\mathrm{FB}}\cos\theta_\ell$$

$B^0 \to K^{*0}\mu\mu$ at CMS and ATLAS

- Richer angular structure
- Folding in ϕ and θ_l to reduce number of fit-parameters
- CMS: $\sim$ 1400 signal events across $q^2 = (0-20)\,\text{GeV}^2$
- ATLAS: $\sim$ 350 signal events across $q^2 = (0-6)\,\text{GeV}^2$
- No K/π identification; $min|m_{K\pi} - m_{K*}|$ to tag B-flavor; (12 – 14)% mis-ID

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

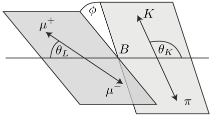
$B^\pm \to K^{*\pm}\mu\mu$ at CMS

- Similar fit structure to $B^0 \to K^{*0}\mu\mu$
- $\sim$ 90 signal events across full q^2 range

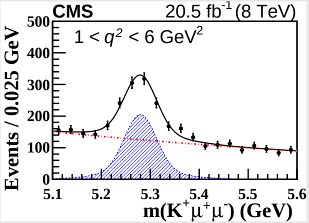
$$\begin{aligned}\frac{1}{\Gamma}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_K\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}q^2} = \frac{9}{16}\Big\{&\frac{2}{3}\left[F_S + 2A_S\cos\theta_K\right](1-\cos^2\theta_\ell) \\ &+ (1-F_S)\Big[2F_L\cos^2\theta_K(1-\cos^2\theta_\ell) \\ &+ \frac{1}{2}(1-F_L)(1-\cos^2\theta_K)(1+\cos^2\theta_\ell) \\ &+ \frac{4}{3}A_{\mathrm{FB}}(1-\cos^2\theta_K)\cos\theta_\ell\Big]\Big\}\end{aligned}$$

Analyses of decay angles distributions, based on unbinned maximum likelihood fit to the data in rough $q = m(\mu\mu)^2$ bins (due to low yields)

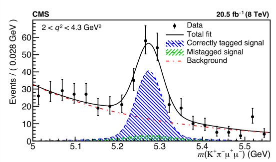
- Inclusive backgrounds data driven, few peaking background contributions (simulated)
- 8 TeV collision data ($\sim 20\text{fb}^{-1}$)

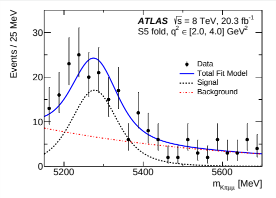


$B^{\pm} \to K^{\pm}\mu\mu$ at CMS

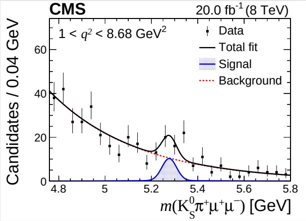


$B^0 \to K^{*0}\mu\mu$ at CMS and ATLAS



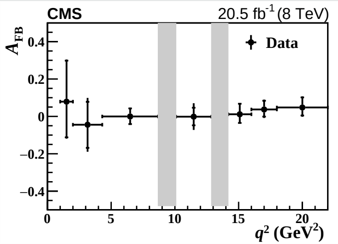


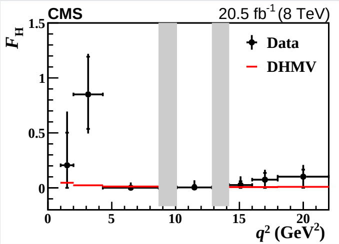
$B^{\pm} \to K^{*\pm}\mu\mu$ at CMS



$B^\pm \to K^\pm\mu\mu$, $B^\pm \to K^{*\pm}\mu\mu$: Results (CMS)

$B^\pm \to K^\pm\mu\mu$

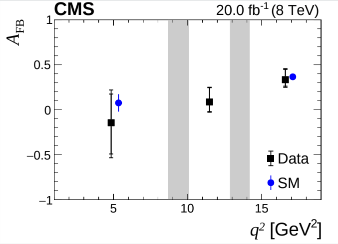


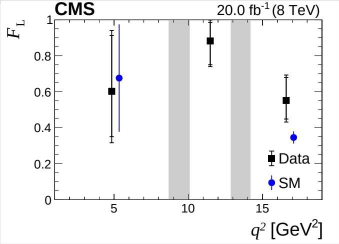


- Consistent with SM predictions (and previous results)

Systematic uncertainty	A_{FB} ($\times 10^{-2}$)	F_H ($\times 10^{-2}$)
Finite size of MC samples	0.4–1.8	0.9–5.0
Efficiency description	0.1–1.5	0.1–7.8
Simulation mismodeling	0.1–2.8	0.1–1.4
Background parametrization model	0.1–1.0	0.1–5.1
Angular resolution	0.1–1.7	0.1–3.3
Dimuon mass resolution	0.1–1.0	0.1–1.5
Fitting procedure	0.1–3.2	0.4–25
Background distribution	0.1–7.2	0.1–29
Total systematic uncertainty	1.6–7.5	4.4–39

$B^\pm \to K^{*\pm}\mu\mu$



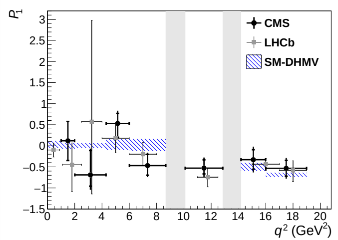


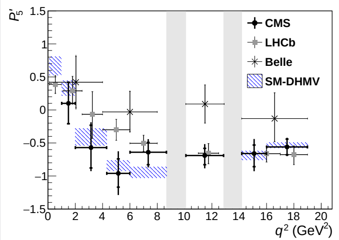
- Consistent with SM predictions

Source	A_{FB} (10^{-3})	F_L (10^{-3})
MC statistical uncertainty	12 – 29	18 – 38
Efficiency model	3 – 25	4 – 12
Background shape functional form	0 – 9	0 – 33
Background shape statistical uncertainty	16 – 73	20 – 87
Background shape sideband region	28 – 153	38 – 78
S-wave contamination	4 – 22	5 – 12
Total systematic uncertainty	42 – 174	55 – 127

$B^0 \to K^{*0}\mu\mu$: Results (CMS, ATLAS)

CMS: P_1, P_5', A_{FB}, F_L; full q^2 range

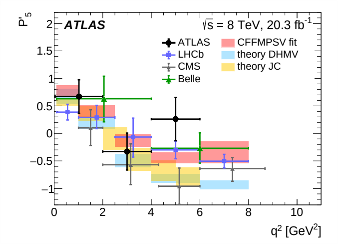


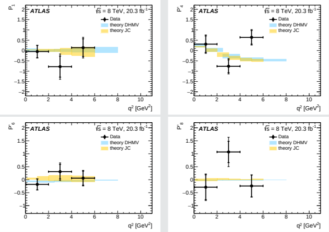


- Consistent with SM predictions

Source	$P_1(\times 10^{-3})$	$P_5'(\times 10^{-3})$
Simulation mismodeling	1–33	10–23
Fit bias	5–78	10–120
Finite size of simulated samples	29–73	31–110
Efficiency	17–100	5–65
$K\pi$ mistagging	8–110	6–66
Background distribution	12–70	10–51
Mass distribution	12	19
Feed-through background	4–12	3–24
F_L, F_S, A_S uncertainty propagation	0–210	0–210
Angular resolution	2–68	0.1–12
Total	100–230	70–250

ATLAS: P_1, P_4', P_5', P_6', P_8', F_L; low q^2 range only

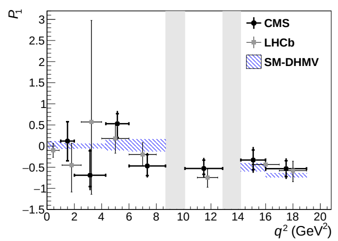


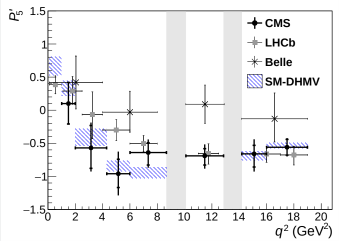


Source	F_L	S_3	S_4	S_5	S_7	S_8
Combinatoric $K\pi$ (fake K^*) background	0.03	0.03	0.05	0.04	0.06	0.16
D and B^+ veto	0.11	0.04	0.05	0.04	0.01	0.06
Background pdf shape	0.04	0.04	0.03	0.03	0.03	0.01
Acceptance function	0.01	0.01	0.07	0.01	0.01	0.01
Partially reconstructed decay background	0.03	0.05	0.02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

$B^0 \to K^{*0}\mu\mu$: Results (CMS, ATLAS)

CMS: P_1, P_5', A_{FB}, F_L; full q^2 range





- Consistent with SM predictions

Source	$P_1 (\times 10^{-3})$	$P_5' (\times 10^{-3})$
Simulation mismodeling	1–33	10–23
Fit bias	5–78	10–120
Finite size of simulated samples	29–73	31–110
Efficiency	17–100	5–65
$K\pi$ mistagging	8–110	6–66
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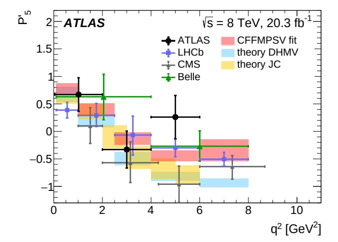
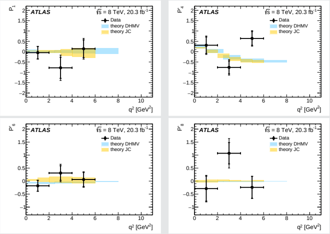
Mass distribution	12	19
Feed-through background	4–12	3–24
F_L, F_S, A_S uncertainty propagation	0–210	0–210
Angular resolution	2–68	0.1–12
Total	100–230	70–250

ATLAS: P_1, P_4', P_5', P_6', P_8', F_L; low q^2 range only





- P_5' and P_4' deviation of 2.7σ in $q^2 = (4-6)\,\mathrm{GeV}^2$ following direction of the LHCb deviation
- But still compatible with SM prediction

$B^0 \to K^{*0}\mu\mu$: 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
    - $\sim 15\times$ for CMS

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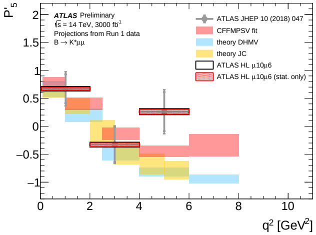
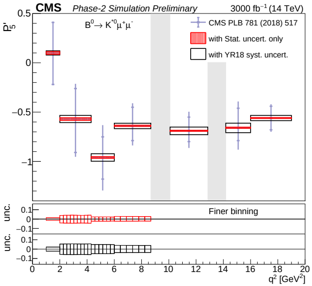
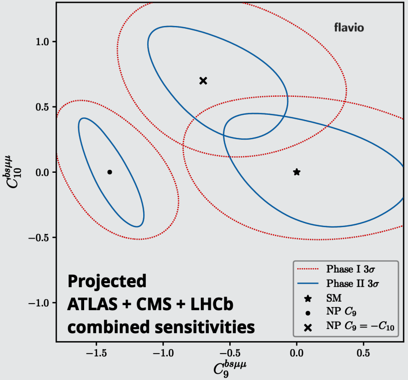


CMS-PAS-FTR-18-033



Combination of all observables will help discriminating NP scenarios

arXiv:1812.07638



Summary

ATLAS and CMS produced results mostly based on Run 1 and few based on Run 2 data

- ATLAS+CMS+LHCb results on $B^0_{(s)} \to \mu\mu$ decays using Run 1 and (2015+)2016 datasets combined; most precise measurement of effective lifetime $\tau_{\mu^+\mu^-}$ to date
- Angular analyses of $B^0 \to K^{*0}\mu\mu$, $B^\pm \to K^\pm\mu\mu$ and $B^\pm \to K^{*\pm}\mu\mu$ performed
- Results are consistent with SM prediction (within the limited experimental precision)

- **More results to come with full Run 2 data**
  - $4\times$ more integrated luminosity
  - Improved tracking precision (Insertable B-Layer for ATLAS in 2014, new pixel detector for CMS since 2017)
- **Stay tuned for more in Run 3 and with High-Luminosity LHC**