7$^{\text{th}}$ General Meeting of the LHC EFT Working Group
CERN
23–24 April 2024

B-Physics EFT in ATLAS

Pavel Řezníček (Charles University) for the ATLAS Collaboration
24$^{\text{th}}$ April 2024

FORTE
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MINISTRY OF EDUCATION, YOUTH AND SPORTS

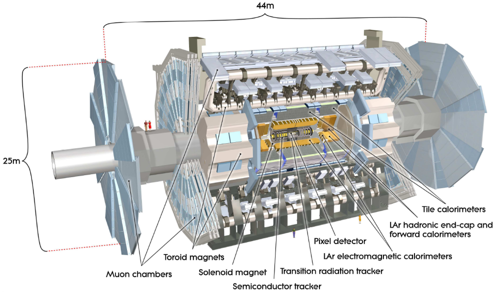
B-Physics at ATLAS

- LHC@ATLAS producing 2.5 M $b\bar{b}$ pairs/second, B_s, B_c, Λ_b, etc. available
- Program focused mostly on muonic final states (trigger), fully reconstructable by the inner tracker (combinatorial background suppression)
- Typical trigger: low-p_T di-muons at low invariant mass, using information from tracker and muon detectors
- Exceptions: di-electron triggers introduced in 2018; analyses with soft γ or neutrino in the final state

New Physics Searches

- Observables with precise SM prediction, experimentally accessible and potentially deviating from SM
- Precision measurements: CP violation, oscillations
- FCNC rare decays

- Other program: HF production, spectroscopy, exotic states



$B^0_{(s)} \to \mu\mu$ BR and lifetime measurement

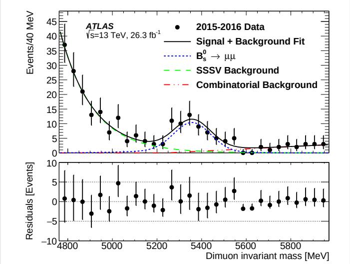
JHEP 04 (2019) 098 JHEP 09 (2023) 199

Very rare decay, FCNC & helicity suppressed

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 $\mathcal{B}(B^\pm \to J/\psi K^\pm)$
- BDT based background suppression, trained on sidebands data
- Yields $N_{d(s)}$ and $N_{J/\psi K^\pm}$ obtained from UML fits to the mass spectra
  - Along with combinatorial background incorporates also partially reconstructed b-hadron decays and 2-prong hadronic decays
- Relative reconstruction efficiencies estimated from MC (corrected for data-MC differences)
- Known branching ratios from PDG, $f_u/f_{d(s)}$ from HFLAV
- Lifetime extracted using SPLOT technique and fitting MC lifetime templates (χ^2 minimization)



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

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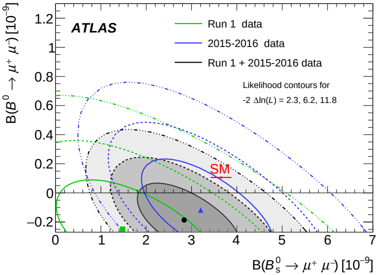
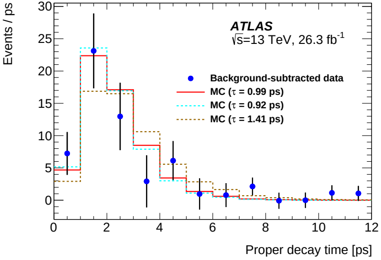
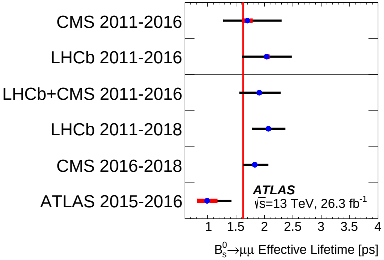


- Combined Run 1 + 2015 + 2016 data result:
  $\mathcal{B}(B^0_s \to \mu\mu) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$
  $\mathcal{B}(B^0 \to \mu\mu) < 2.1 \times 10^{-10}$ at 95% CL
- Compatible with SM at 2.4 σ
- Stat. uncertainty dominates, largest systematics from di-muon mass fit procedure



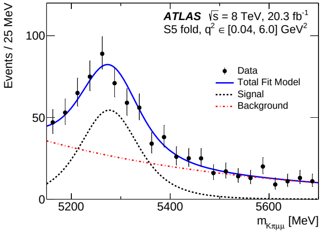
- Effective lifetime:
  $0.99^{+0.42}_{-0.07}\,(\text{stat.}) \pm 0.17\,(\text{syst.})$ ps
- Consistent with SM
- Dominant syst. from data-MC discrepancies



NP potentially strong enough to modify the differential decay rate

Measurement

- Extended unbinned maximum likelihood fit in decay angles and $m(\mu\mu K\pi)$ (sequential mass $\to$ angles)
- Folded angular distributions to cope with small statistics
- Potential backgrounds from radiative resonant decays and other semileptonic rare decays treated in systematics
- No K/π separation in ATLAS $\implies$ 11% wrong tag of B-flavour

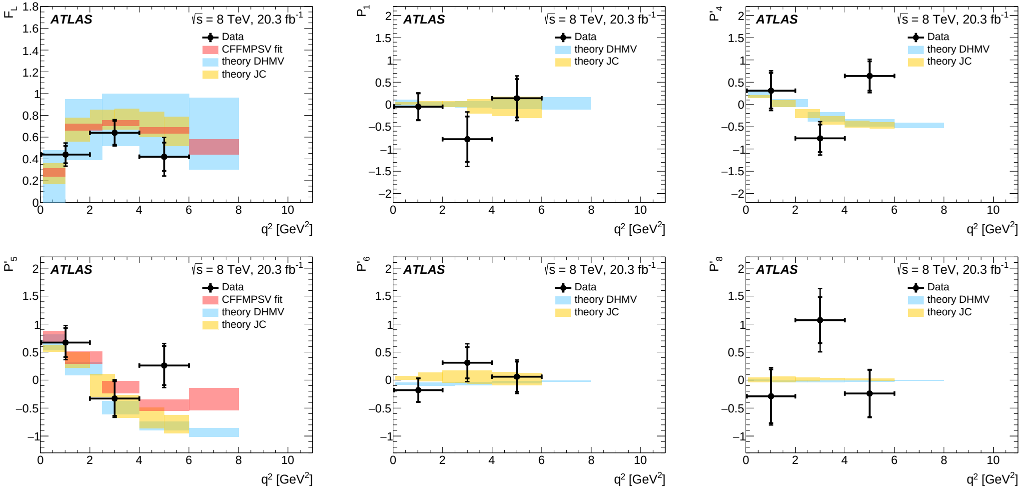


q^2 [GeV^2]	n_{signal}	$n_{\text{background}}$
[0.04, 2.0]	128 ± 22	122 ± 22
[2.0, 4.0]	106 ± 23	113 ± 23
[4.0, 6.0]	114 ± 24	204 ± 26
[0.04, 4.0]	236 ± 31	233 ± 32
[1.1, 6.0]	275 ± 35	363 ± 36
[0.04, 6.0]	342 ± 39	445 ± 40

$B^0 \to K^{*0}\mu\mu$ Results

JHEP 10 (2018) 047

- 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



CPV in $B_s^0 \to J/\psi\phi$ and the measurement

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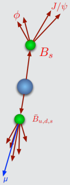
CPV due to interference of direct decay and decay with mixing, CPV phase $\phi_s \simeq -2\beta_s$

Measurement: time-dependent angular analysis

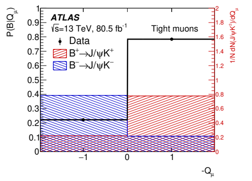
- Initial B_s^0 flavour: opposite-side flavour tagging using $b(\bar{b}) \to l^{-(+)}$ transitions
- Unbinned maximum likelihood fit including $m(\mu\mu KK)$, per-candidate detector resolution and tag prob.
- Δm_s fixed to PDG, direct CP λ to unity
- Detector acceptance & time efficiency modeled by MC

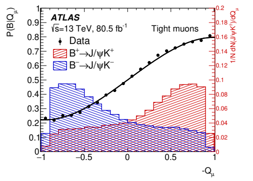
B_s^0 tagging performance

ϵ_x = tag efficiency, d = 1 - 2× wrong-tag fraction, $t_x = \epsilon_x d^2$ = tagging power



Tag method	ϵ_x [%]	D_x [%]	T_x [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	12.04 ± 0.02	16.6 ± 0.1	0.334 ± 0.006
Total	21.23 ± 0.03	28.7 ± 0.1	1.75 ± 0.01





$B_s^0 \to J/\psi\phi$: Results

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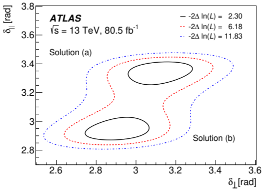
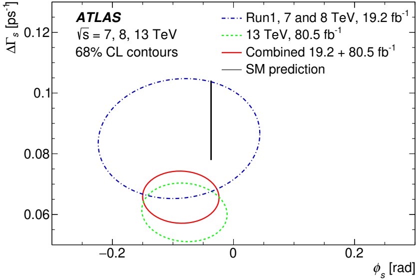
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\|A_\parallel(0)\|^2$	0.2213	0.0019	0.0023
$\|A_0(0)\|^2$	0.5131	0.0013	0.0038
$\|A_S(0)\|^2$	0.0321	0.0033	0.0046
$\delta_\perp - \delta_S$ [rad]	-0.25	0.05	0.04
Solution (a)			
$\delta_\perp$ [rad]	3.12	0.11	0.06
$\delta_\parallel$ [rad]	3.35	0.05	0.09
Solution (b)			
$\delta_\perp$ [rad]	2.91	0.11	0.06
$\delta_\parallel$ [rad]	2.94	0.05	0.09

- Two solutions in $\delta_\parallel - \delta_\perp$ plane, with negligible impact on other parameters



- Statistical (BLUE) combination with Run 1 result

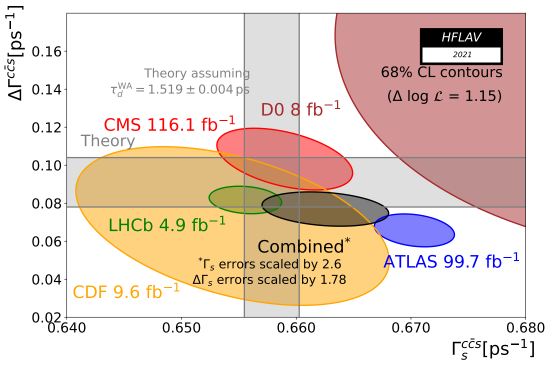


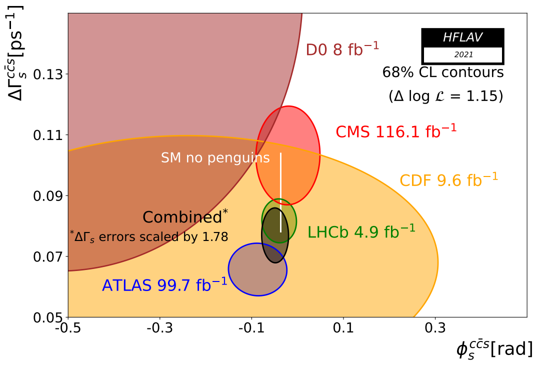
- Almost 500 k signal candidates
- Weak phase ϕ_s as well as decay width difference $\Delta\Gamma_s$ compatible with Standard Model
- Dominant systematics on ϕ_s measurement from tagging
  - Accounting for pile-up dependence, calibration curves model and MC precision, "Punzi" PDFs variations, difference between $B^\pm$ and B_s^0 kinematics

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.022

- Statistical (BLUE) combination

Comparison with other experiments

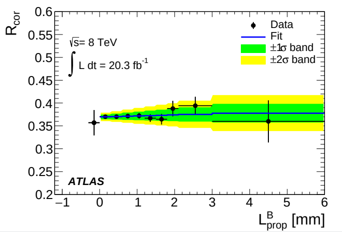




- Dominant systematics on ϕ_s measurement from tagging
  - Accounting for pile-up dependence, calibration curves model and MC precision, "Punzi" PDFs variations, difference between $B^{\pm}$ and B_s^0 kinematics

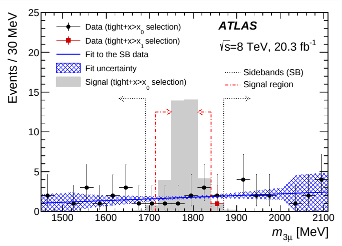
$\Delta\Gamma_d/\Gamma_d$ measurement

- Extracted from comparing decay time (L_{prop}) distributions of $B_d^0 \to J/\psi K^{*0}$ and $B_d^0 \to J/\psi K_s^0$ decays
  - $\Gamma[t, J/\psi K^{*0}] \sim e^{-\Gamma_d t}\left[\cosh \frac{\Delta\Gamma_d t}{2}\right]$
  - $\Gamma[t, J/\psi K_s^0] \sim e^{-\Gamma_d t}\left[\cosh \frac{\Delta\Gamma_d t}{2} + \cos(2\beta)\sinh \frac{\Delta\Gamma_d t}{2} - A_p \sin(2\beta)\sin \Delta m_d t\right]$
- $\mathbf{\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1\,(stat.) \pm 0.9\,(syst.)) \times 10^{-2}}$



$\tau \to \mu\mu\mu$ search

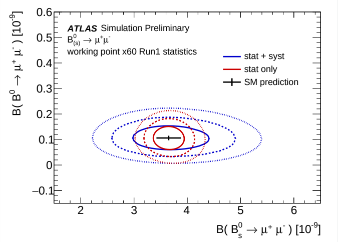
- Tau leptons from $W \to \tau\nu$ decays
- BDT based selection
- $\mathcal{B}(\tau \to 3\mu) < 3.76 \times 10^{-7}$ **at 90% CL**



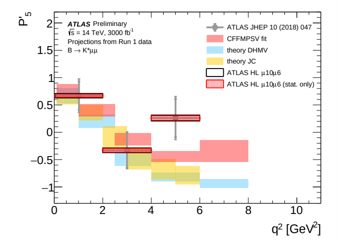
Summary

- ATLAS searches for NP in B-physics in number of channels
  - No significant deviation from SM found yet though...
- Others in progress: updates with full Run 2 data (139 fb^{-1}), LFV & LFU measurements
- Limits mainly at the trigger (low-p_T signatures, high background rates) $\Longrightarrow$ complicated trig. signatures
- Program continuation in Run 3 and HL-LHC
  - HL-LHC projections CERN Yellow Report Monograph 7 (2019), p.867-1158: Opportunities in flavour physics at HL/HE-LHC

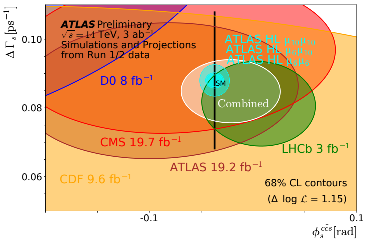
$B_s^0 \to \mu\mu$ projections



$B_d^0 \to K^{*0}\mu^+\mu^-$ projections



$B_s^0 \to J/\psi\phi$ projections



Thank you

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Name of the project: Fundamental constituents of matter through frontier technologies (FORTE)
Registration number: CZ.02.01.01/00/22_008/0004591

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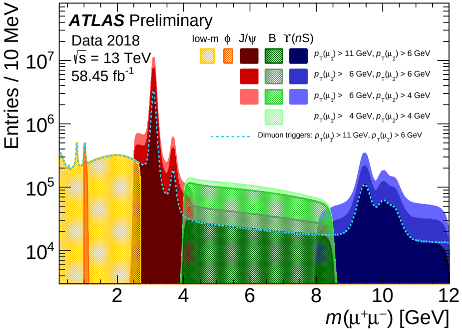
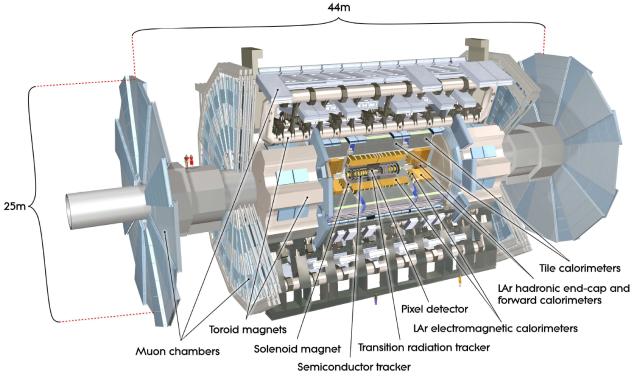
Backup

B-Physics at ATLAS

- 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
- Typical trigger: low-p_T di-muons at low invariant mass, using information from tracker and muon detectors
- B-physics trigger rate up to $\sim$ 200 Hz





Measurement of the CP-violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ decays in ATLAS at 13 TeV

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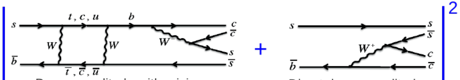
CPV in $B_s^0 \to J/\psi\phi$ and the measurement

- Interference of direct decay and decay with mixing into the same final state of $B_s^0 \to J/\psi\phi$ gives rise to time-dependent CP violation

Decay rate ~



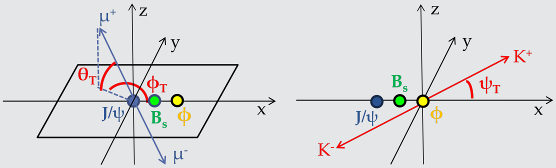
Decay amplitude with mixing — Direct decay amplitude

- In the Standard Model (SM) the ϕ_s is small: $\phi_s \simeq -2\beta_s = -0.03696^{+0.00072}_{-0.00082}$ rad
- New Physics (NP) could contributed to the mixing box diagrams, potentially enlarging ϕ_s

- Whole system described by:
  - weak phase ϕ_s and direct-CPV parameter λ
  - CP-state amplitudes (and their phases)
  - the mixing parameters Δm_s, $\Delta\Gamma_s$, Γ_s

Measurement

- Final state: admixture of CP-odd $(L = 1)$ and CP-even $(L = 0, 2)$ states
- Distinguishable through time-dependent angular analysis: $\frac{\mathrm{d}^4\Gamma}{\mathrm{d}t\ \mathrm{d}\Omega} = \sum_{k=1}^{10} \mathcal{O}^{(k)}(t) g^{(k)}(\theta_T, \psi_T, \phi_T)$
- Analyzing signal final state $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
- S-wave decay $B_s^0 \to J/\psi K^+K^-$ contribution included in the differential decay rate

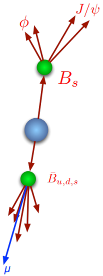


Opposite-side flavour tagging

- Use $b - \bar{b}$ correlation $\implies$ initial B_s^0 flavour
  - $b(\bar{b}) \to l^{-(+)}$ transition
  - diluted by oscillations and $b \to c \to l$
- Key variables: charge of p_T-weighted tracks in cone $\Delta R(\phi, \eta)$ around the opposite side lepton

$$Q_x = \frac{\sum_i^{N \text{ tracks}} q_i \cdot (p_{\mathrm{T}i})^{\kappa}}{\sum_i^{N \text{ tracks}} (p_{\mathrm{T}i})^{\kappa}}$$

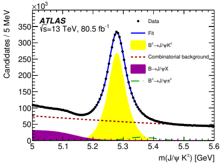
- Building per-candidate tag probability $P(B|Q)$



Four taggers

- **Muon**: tight-ID or low-p_T, $\kappa = 1.1$, $\Delta R = 0.5$
- **Electron**: $p_T(e) > 0.5$ GeV, $\kappa = 1.0$, $\Delta R = 0.5$
- **Jet**: b-tagged jets, $\kappa = 1.1$, $\Delta R = 0.5$
- Search order based on best purity

- Calibrated on self-tagged $B^{\pm} \to J/\psi K^{\pm}$ data



tagging performance

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Tag method	ϵ_x [%]	D_x [%]	T_x [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
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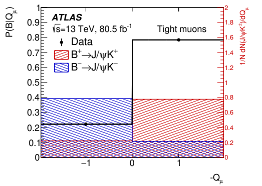
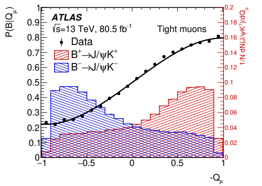




Unbinned maximum likelihood fit

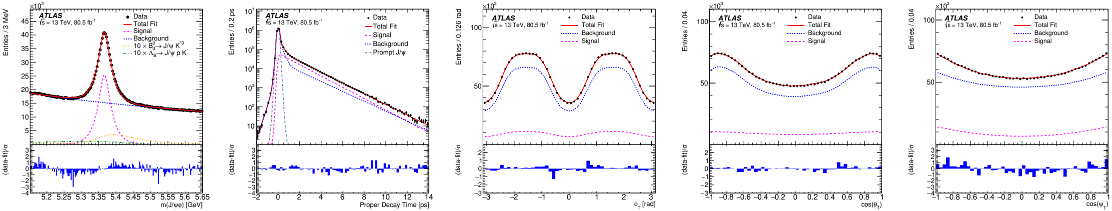
- An unbinned maximum likelihood (UML) fit performed in 10 D space

$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_\mathrm{s}\mathcal{F}_\mathrm{s} + f_\mathrm{s} f_{B^0}\mathcal{F}_{B^0} + f_\mathrm{s} f_{\Lambda_b}\mathcal{F}_{\Lambda_b} + (1 - f_\mathrm{s}(1 + f_{B^0} + f_{\Lambda_b}))\mathcal{F}_\mathrm{bkg}) \}$$

Observables

$\mathcal{F}_x(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}(p_{\mathrm{T}_i}),$
$\theta_T, \psi_T, \phi_T, P(B|Q_i))$

- Base B_s^0 decay observables: mass, time, angles
  - Conditional observables: per-candidate tagging Q_x and mass/time resolutions ($p_\mathrm{T}(B)$ dependent)
- Full time-angular PDF including S-wave
- Fixed parameters: Δm_s = PDG, direct CP $\lambda = 1$
- Trigger causing decay time inefficiency, modeled in MC



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

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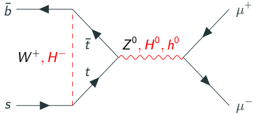
Analysis of rare $B^0_{(s)} \to \mu\mu$ decays

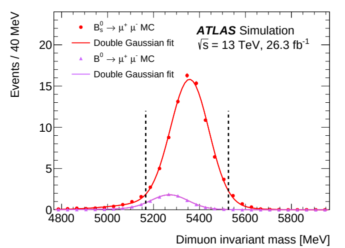
- FCNC in the SM proceeding via loop and box diagrams, and helicity suppressed $\implies \mathcal{B} \sim 10^{-9}$
- BSM can significantly contribute, modifying the branching ratio



Measurement

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

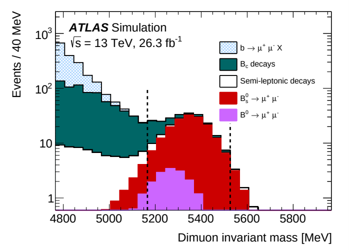
- $\mathcal{B}(B^0_{(s)} \to \mu\mu)$ measurement relative to $\mathcal{B}(B^\pm \to J/\psi K^\pm)$, $B^0_s \to J/\psi\phi$ as control channel
- Blinded signal di-muon invariant mass region
- BDT based background suppresion, trained on sidebands data
- Yields $N_{d(s)}$ and $N_{J/\psi K^\pm}$ obtained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



Backgrounds

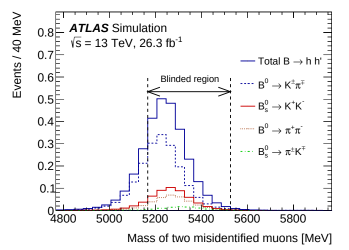
Partially reconstructed *b*-hadron decays

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



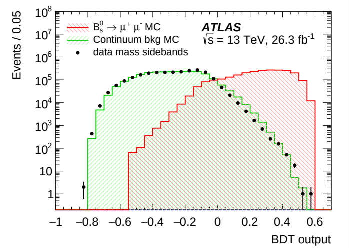
Peaking backgrounds

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



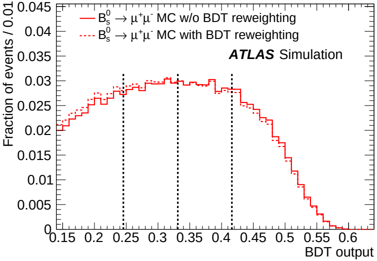
Continuum background

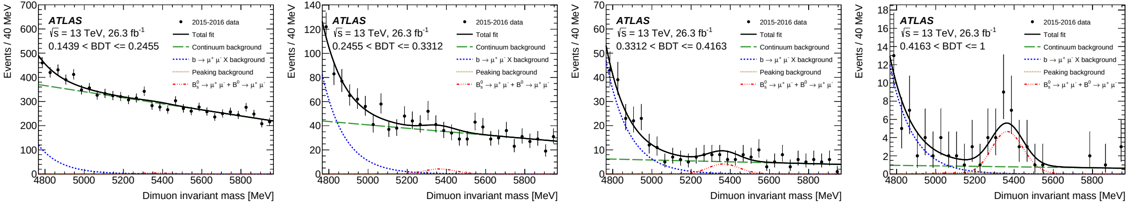
- Combinatorics of μ and uncorrelated hadron decays
- Reduced by BDT
- Linear shape constrained in the mass fit across BDT bins
- Systematics due to $B_c^{\pm} \to J/\psi\mu\nu$ and $B^0_{(s)}/\Lambda^0_b \to h\mu\nu$ decays



BDT and signal yield extraction

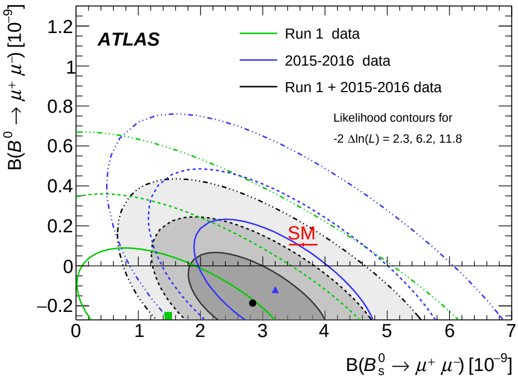
- BDT formed from 15 variables
  - kinematics, isolation, B-vertex separation from PV
- BDT output validated on reference $B^{\pm} \to J/\psi K^{\pm}$ and control $B_s^0 \to J/\psi\phi$ channels, observed difference applied as a correction to signal channel
- Signal region divided into four BDT bins 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

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

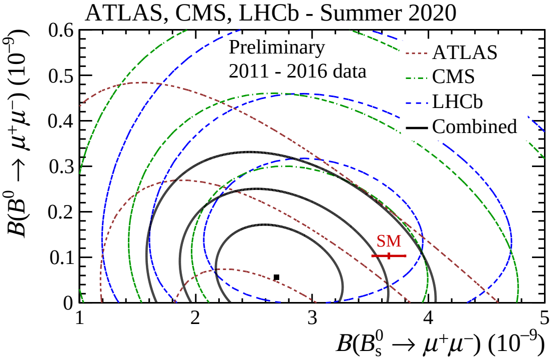
ATLAS 2015 + 2016 data

$\mathcal{B}(B_s^0 \to \mu\mu) = (3.2^{+1.1}_{-1.0}) \times 10^{-9}$
$\mathcal{B}(B^0 \to \mu\mu) < 4.3 \times 10^{-10}$ at 95% CL

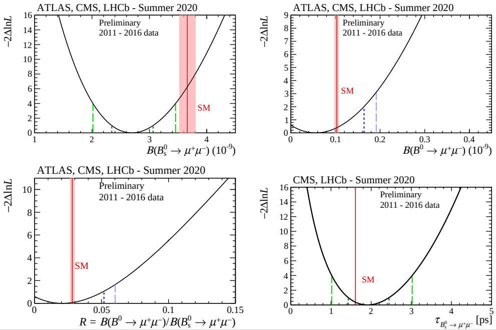
ATLAS Run 1 + 2015 + 2016 data

$\mathcal{B}(B_s^0 \to \mu\mu) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$
$\mathcal{B}(B^0 \to \mu\mu) < 2.1 \times 10^{-10}$ at 95% CL

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



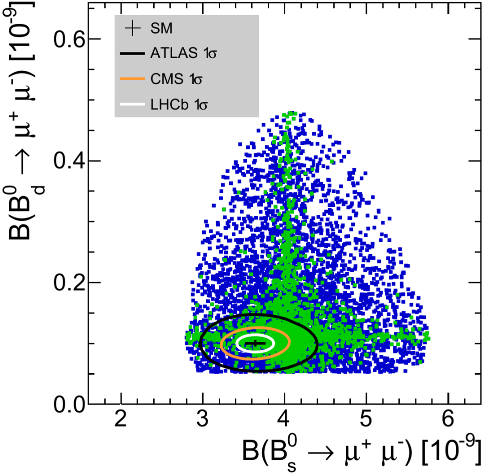
- Combining binned 2D profile likelihoods, f_s/f_d the only source of correlation between experiments



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

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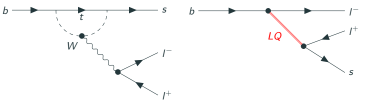
Analysis of rare $B^0 \to K^{*0}\mu\mu$ decays

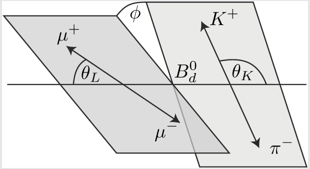
- FCNC in the SM proceeding via loop and box diagrams
- BSM can significantly contribute, modifying the differential decay rate



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

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

$\Downarrow$

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

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

Fit simplifications

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B-candidate mass distribution pre-fits

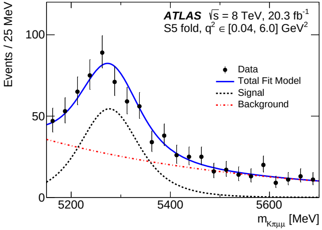
- B-candidate mass distribution pre-fitted and fixed in the angular fit
- Mass nuisance parameters extract from fits to control channels ($B^0 \rightarrow J/\psi K^*$, $B^0 \rightarrow \psi(2S)K^*$)

Rough q^2 binning

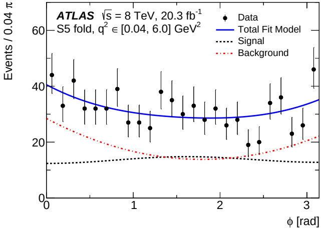
- 3 bins only in q^2 GeV]: (0.04 - 2), (2.0 - 4.0), (4.0 - 6.0)

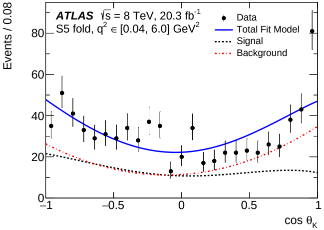
Fit projections

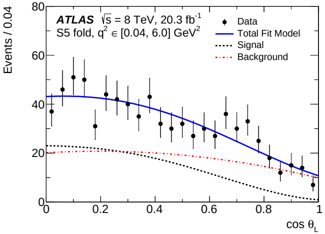
- Example of fit projections for the extraction of S_5 (resp. P'_5) parameter for q^2 bin (4-6) GeV



q^2 [GeV^2]	n_{signal}	$n_{background}$
[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