CP violation and rare decays processes with beauty mesons at ATLAS

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on behalf of the
ATLAS collaboration

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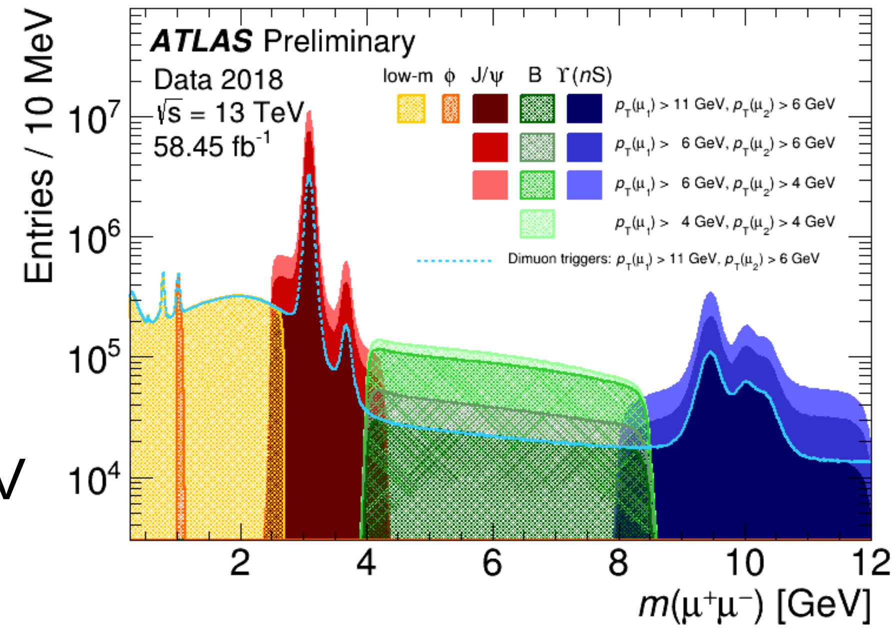
B physics in ATLAS

- ATLAS has collected 25 fb^{-1} of data in Run 1, and 139 fb^{-1} in Run 2
- Has access to B, B_s, B_c, Λ_b, etc.
- Focus mostly on final states with muons
  - Typical trigger: di-muons with p_T thresholds at 4, 6 and 11 GeV



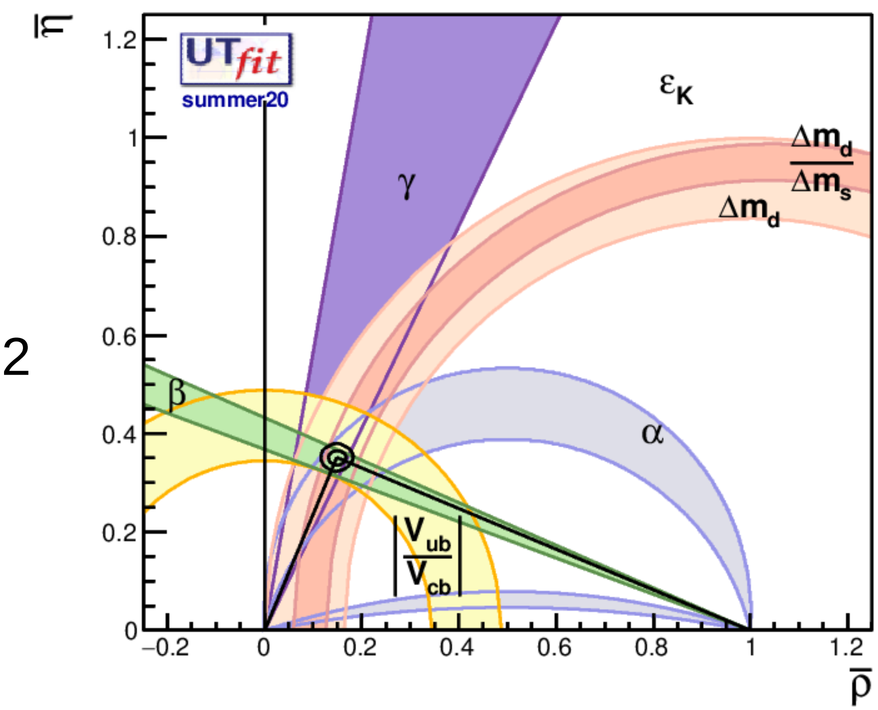
- **Rare and semi-rare decays: state of the art at ATLAS**
  - B to K*μμ angular analysis in Run 1 *[JHEP 10 (2018) 047]*
  - $B_{(s)}$ to μμ in 2015-2016 Run 2 *[JHEP 04 (2019) 098]*
    - LHC combination $B_{(s)}$ to μμ for Summer 2020, partial Run 2 *[ATLAS-CONF-2020-049]*

- **CP Violation in B_s system: most recent result at ATLAS**
  - CP violating phase φ_s in $B_s^0 \rightarrow J/\psi\varphi$ angular analysis in 2015-2017 Run 2 *[Eur. Phys. J. C 81 (2021) 342]*

CP violation in the SM and NP:

- $B_{(s)}$ systems are giving us a rather precise picture
  - However there is some space for NP
  - Could appear as new contributions in ΔF=2 loop processes

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

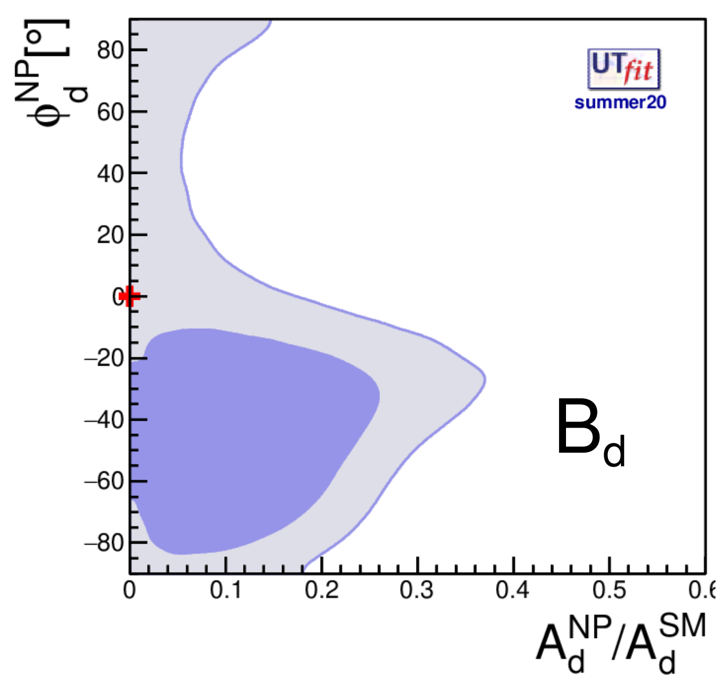


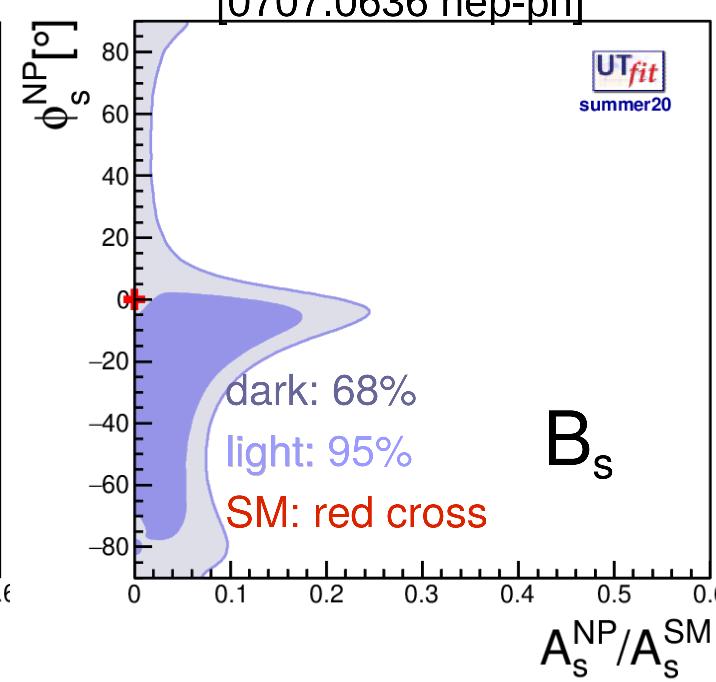
The ratio of NP/SM amplitudes need to be:

< 26% @68% prob. (37% @95%) in B_d mixing

< 18% @68% prob. (25% @95%) in B_s mixing

[0707.0636 hep-ph]





Angular analysis on $B \rightarrow K^{*}\mu\mu$

Run1 result:

JHEP 10 (2018) 047, arXiv:1805.04000

HL-LHC prospects:

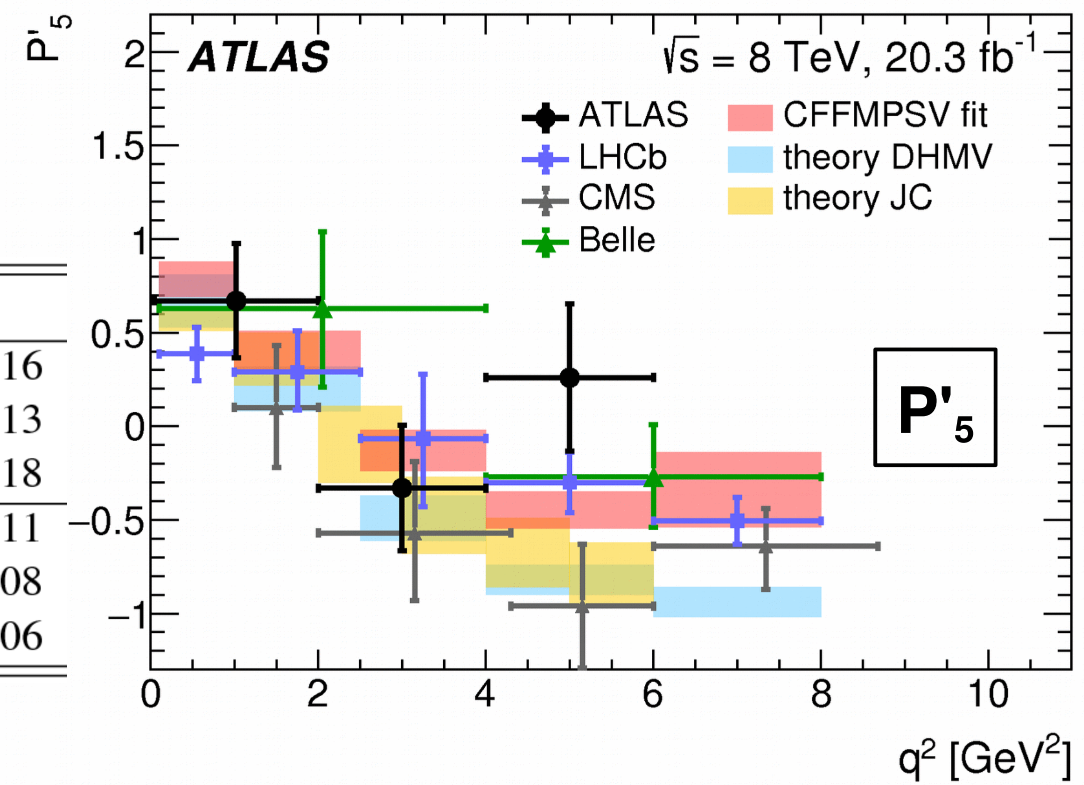
ATL-PHYS-PUB-2019-003

K*μμ angular analysis

JHEP 10 (2018) 047, arXiv:1805.04000

- Data collected in 2012 at 8 TeV with 20.3 fb^{-1} Run 1 data
- fold the angular distribution via trigonometric relations to reduce the number of free parameters
- Results are compatible with theoretical calculations & fits
- P(P‘) parameters have reduced dependence on hadronic form factors.
- ATLAS gets deviations of about 2.5σ (2.7σ) from DHMV in P'_4(P'_5) in [4,6] GeV^2

q^2 [GeV^2]	P'_4	P'_5
[0.04, 2.0]	$0.31 \pm 0.40 \pm 0.20$	$0.67 \pm 0.26 \pm 0.16$
[2.0, 4.0]	$-0.76 \pm 0.31 \pm 0.21$	$-0.33 \pm 0.31 \pm 0.13$
[4.0, 6.0]	$0.64 \pm 0.33 \pm 0.18$	$0.26 \pm 0.35 \pm 0.18$
[0.04, 4.0]	$-0.30 \pm 0.24 \pm 0.17$	$0.32 \pm 0.21 \pm 0.11$
[1.1, 6.0]	$0.05 \pm 0.22 \pm 0.14$	$0.01 \pm 0.21 \pm 0.08$
[0.04, 6.0]	$0.05 \pm 0.20 \pm 0.14$	$0.27 \pm 0.19 \pm 0.06$

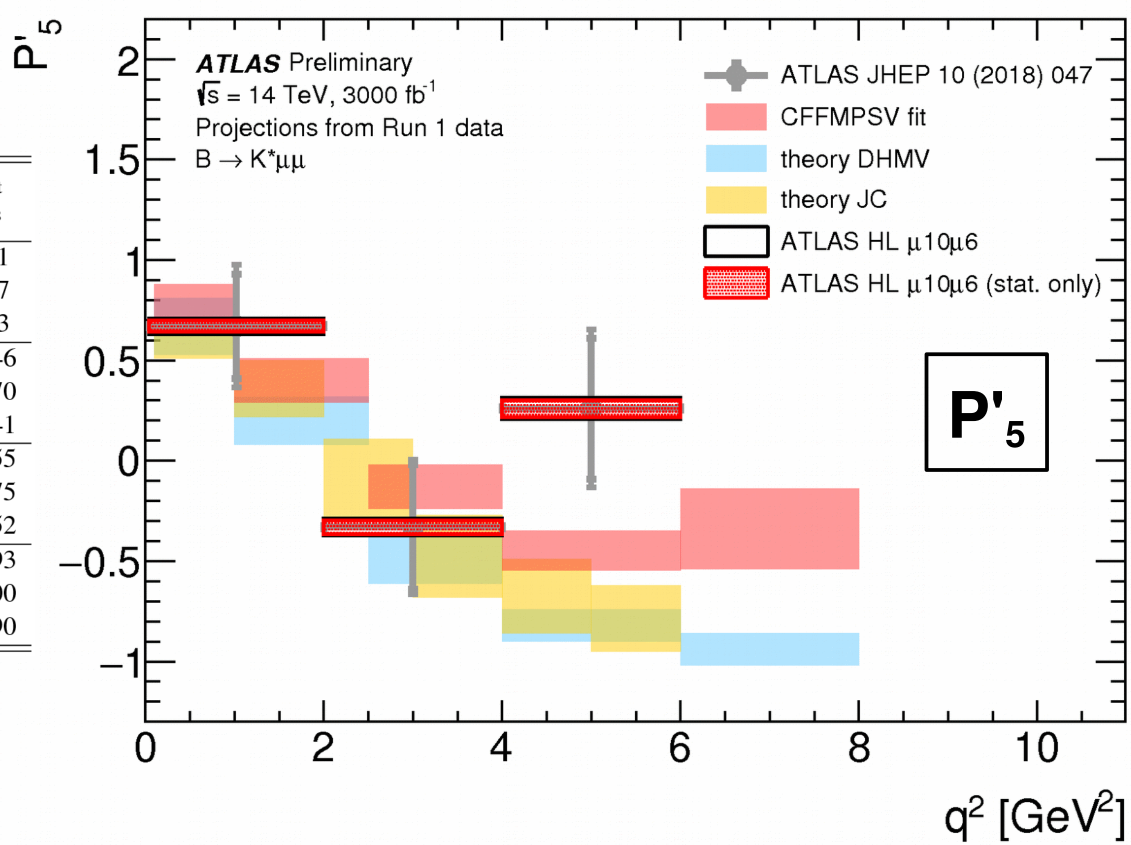


OPE and LHCb data fit: CFFMPSV: Ciuchini et al.; JHEP 06 (2016) 116.
QCD factorisation: DMVH: Decotes-Genon et al.; JHEP 12 (2014) 125.
JC: Jäger-Camalich; Phys. Rev. D93 (2016) 014028.

Projections for K*μμ angular analysis at HL-LHC

- Extrapolation from signal/background yields in Run 1 and toy-MC simulations
- Accounting for improved performance of the ATLAS Upgraded tracking system
- Three trigger scenarios: high-yield, intermediate and low-statistics for signal.
- The precision on, for example, the P′5 parameter expected to improve by factors of ~9×, ~8×, ~5× (for the three trigger scenarios) relative to Run 1

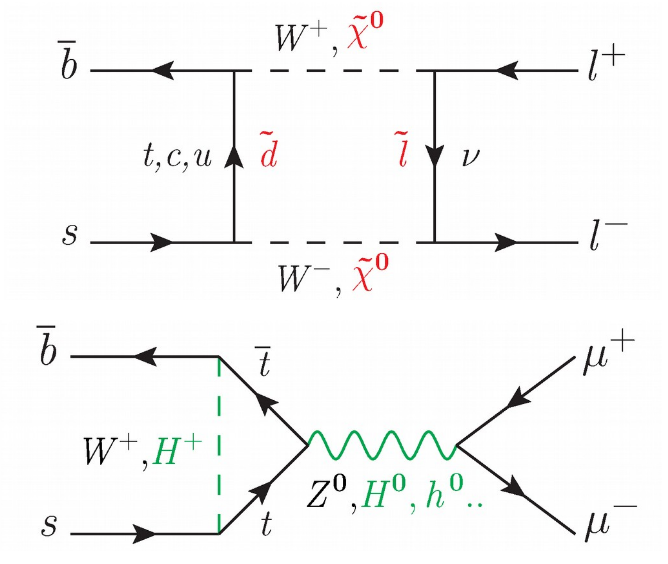
LHC phase	q^2 [GeV^2]	$\delta^{tot}_{F_L}$	$\delta^{tot}_{P_1}$	$\delta^{tot}_{P'_4}$	$\delta^{tot}_{P'_5}$	$\delta^{tot}_{P'_6}$	$\delta^{tot}_{P'_8}$
Run 1	[0.04, 2.0]	0.11	0.31	0.45	0.31	0.21	0.51
	[2.0, 4.0]	0.12	0.61	0.37	0.34	0.34	0.57
	[4.0, 6.0]	0.18	0.50	0.38	0.39	0.30	0.43
HL-LHC μ6μ6	[0.04, 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 $B_{(s)} \rightarrow \mu^+\mu^-$

Run1 result:
    EPJ C76 (2016) 513, arXiv:1604.04263
Run2 result on 2015-2016 data:
    JHEP 04 (2019) 098, arXiv:1812.03017
LHC combination:
    ATLAS-CONF-2020-049
HL-LHC prospects:
    ATL-PHYS-PUB-2018-005



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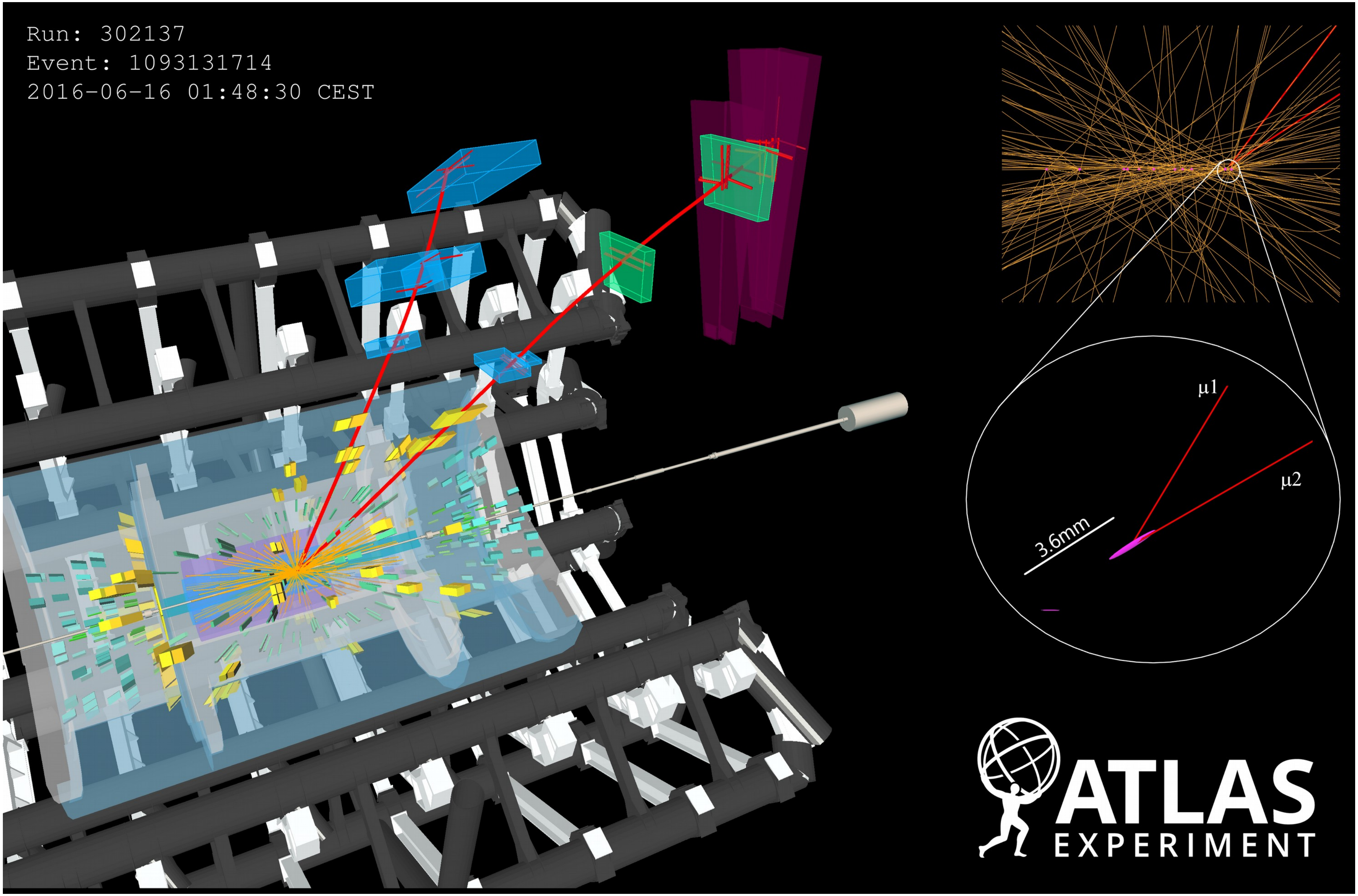


Motivations

- Flavour Changing Neutral Currents (FCNC), CKM and helicity suppressed.
- SM prediction with small theoretical uncertainties of order 6-8%
- Perfect for indirect new physics searches: virtual new particles in the loop
  - both enhancement and suppression effects are possible

ATLAS analysis on 2015-2016 Run 2 data

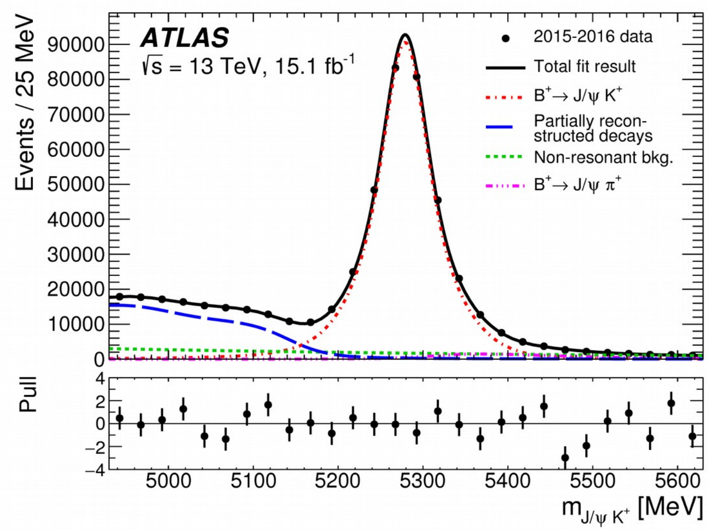
- 36.2 fb^{-1} dataset of 2015-2016 data taking:
  - effectively 26.3 fb^{-1} for $B \to \mu\mu$
- Trigger: higher thresholds [4-6 GeV] than in Run 1,
  - $L_{xy} > 0$ request at trigger level

JHEP 04 (2019) 098
arXiv:1812.03017

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

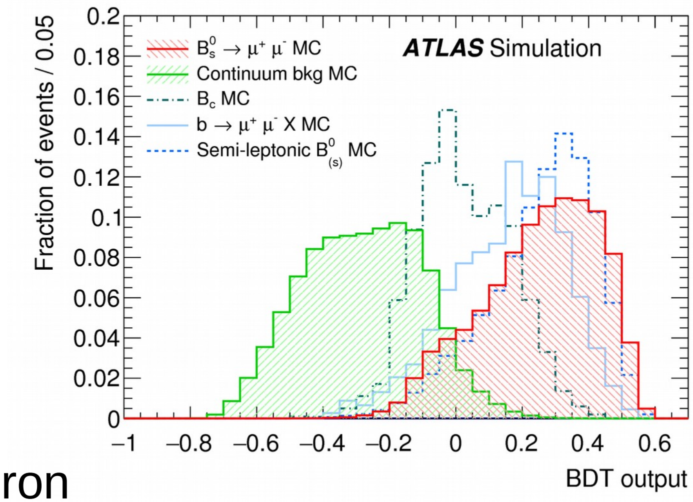
Normalisation B yield extraction

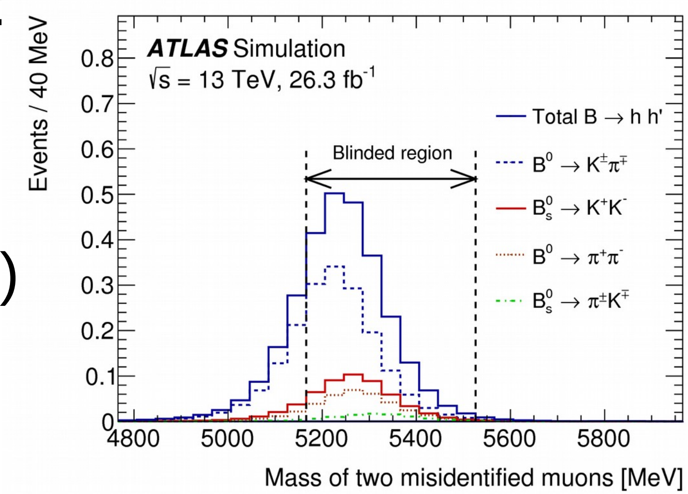
- unbinned maximum likelihood fit of the invariant mass $m_{J/\psi K} \to m_{\mu\mu K}$



Backgrounds and control samples

- combinatorial background: μ's from other b quarks
  - BDT classifier with 15 variables
- partially reconstructed B decays:
  - Same Vertex (SV): B → μμX decays
  - Same Side (SS): b → cμν → s(d)μμνν
  - B_c decays: like B_c → J/ψ μν
- semileptonic B and B_S decays: μ and charged hadron
- peaking background from hadronic $B_{(S)}$ decays:
  - B decays to two hadrons h (K/π): $B^0_{(S)}$ → hh'





Tight muon-ID against hadron misID

- negligible misidentification of protons (< 0.01%)
- misidentification is 0.08% (0.10%) for K (π).

peaking-background events: 2.7±1.3

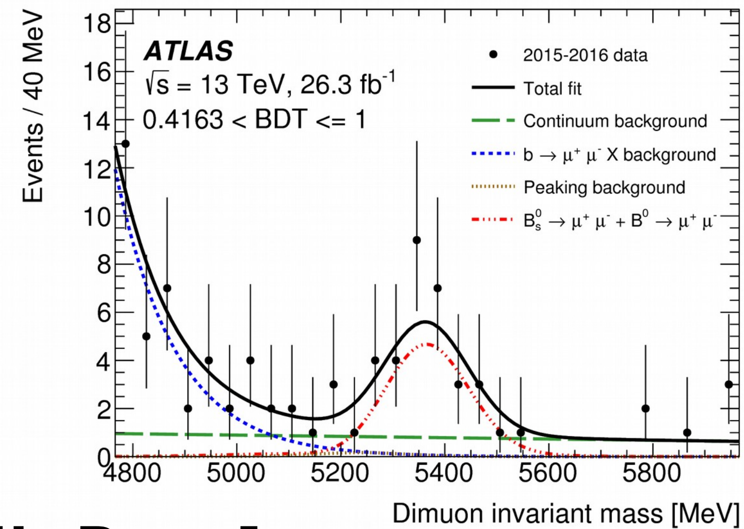
Efficiency ratio $\varepsilon_{\mu\mu}/\varepsilon_{J/\psi K}$

- from MC and systematic from data-MC discrepancies
- For B^0_S: 2.7% correction for lifetime difference of the B^0_S mass eigenstates

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 yield extraction

- unbinned maximum likelihood fit to the dimuon mass simultaneously in 4 BDT bins
  - 18% signal efficiency each bin
  - signals, B to hh: 3 double Gaussians
  - continuum: first order polynomial
  - partially reconstructed B: exponential
  - semi-leptonic: exponential



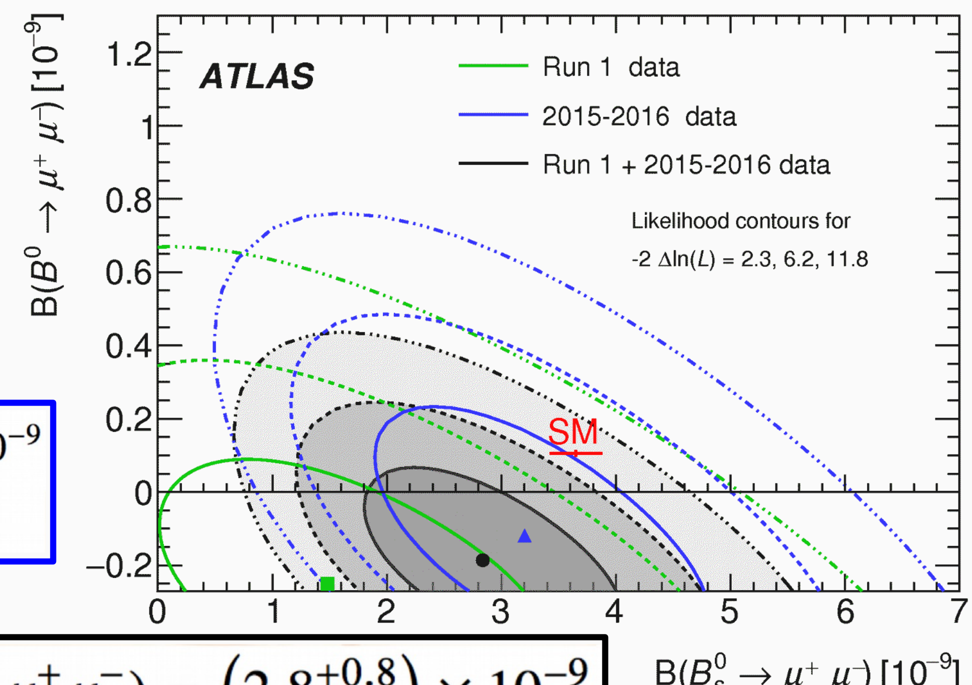
Run 2 results and combinations with Run 1

- yields unconstrained:
  - N_S = 80 ± 22 and N_d = -12 ± 20
  - expected from the SM:
    - N_S = 91 ± and N_d = 10

Neyman Contours for Run 2:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.21^{+0.96+0.49}_{-0.91-0.30}\right) \times 10^{-9} = \left(3.2^{+1.1}_{-1.0}\right) \times 10^{-9}$$

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



Run 1 + Run 2 (2015+2016):
Compatible with SM at 2.4σ

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

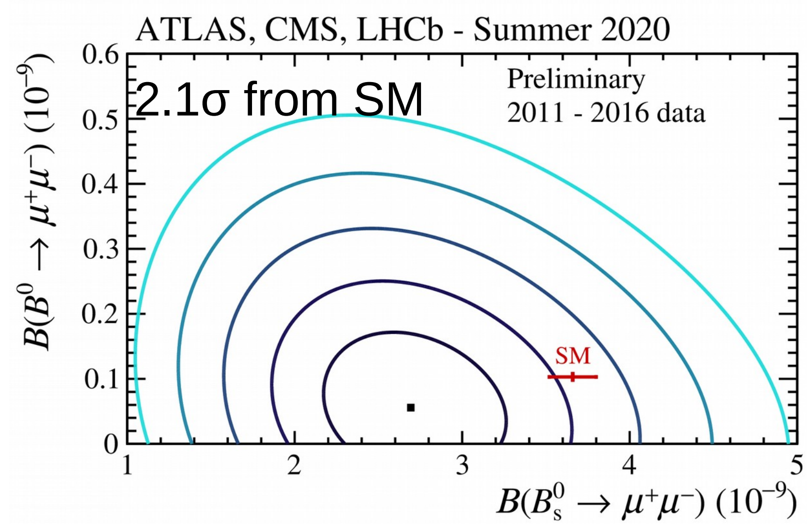
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$$

LHC combination from Summer 2020

- Combination from binned two-dimensional profile likelihoods
- Independent systematics, except for ratio of fragmentation fractions f_d/f_s,
  - f_d/f_s profiled separately and its uncertainty included in one likelihood.

Latest LHCb result not included

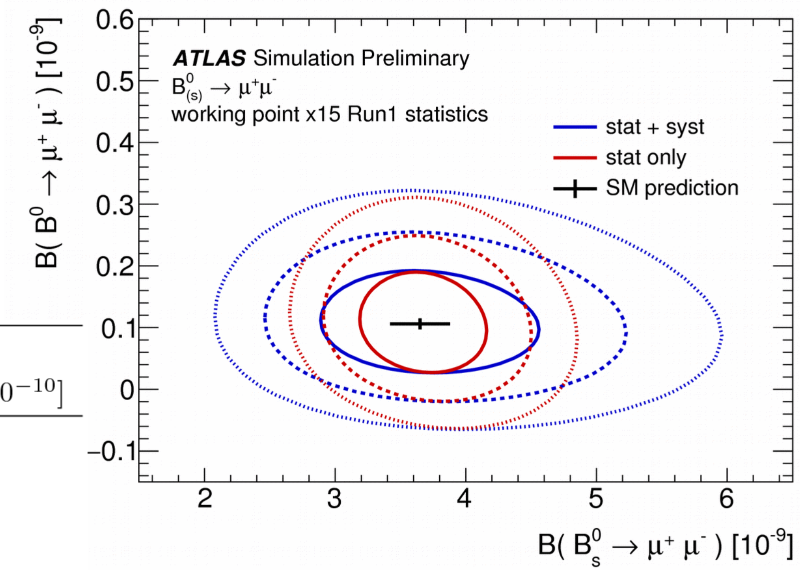
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.69\,^{+\,0.37}_{-\,0.35}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) \;<\; 1.9 \times 10^{-10} \text{ at } 95\% \text{ CL.}$$



Prospect on $B_{(s)} \to \mu^+\mu^-$ at ATLAS

- HL-LHC → 3 trigger scenarios: with thresholds ($p^{\mu 1}_T$, $p^{\mu 2}_T$):
  - Conservative: (10 GeV, 10 GeV) → ×15 Run 1
  - Intermediate: (6 GeV, 10 GeV) → ×60 Run 1
  - High-yield: (6 GeV, 6 GeV) → ×75 Run 1

	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$		$\mathcal{B}(B^0 \to \mu^+\mu^-)$	
	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

CP violation parameters from time-dependent angular analysis on $B_s \to J/\psi\phi$

Run1 result:

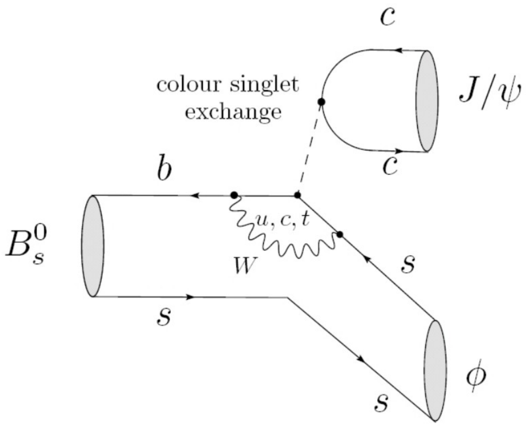
JHEP 08 (2016) 147, arXiv:1601.03297

Run2 result with 2015-2017 data:

Eur. Phys. J. C 81 (2021) 342, arXiv:2001.07115

HL-LHC prospects:

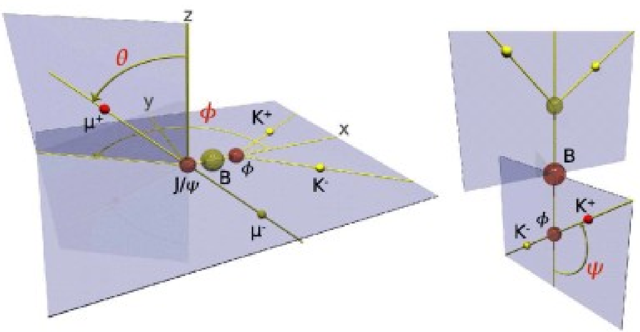
ATL-PHYS-PUB-2018-041



Time-dependent angular analysis of $B_s \to J/\psi\phi$

- Parameters of the B_s system:
  - Decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_S = 0.087 \pm 0.021\ ps^{-1}$ (SM) [*arXiv:1102.4274*]
  - CPV phase $\varphi_s \to$ *weak phase between mixing and b → ccs decay*
    - $\varphi_s = -2\beta_s = 0.0370 \pm 0.0010$ (SM) *[Utfit18]* with $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$
  - **Golden mode: penguin diagrams contribute either with the same weak phase (λ^2) or they are CKM suppressed (λ^4)**

- Pseudoscalar to vector–vector decay → mixed CP-odd and CP-even (L = 0, 1 or 2).
  - Also K^+K^- pairs in S-wave → CP-odd.
- Angular analysis: differential decay rate depends on amplitudes A_0, $A_{||}$, $A_\perp$, A_S (and interferences) and angles θ_T, ψ_T, φ_T.



ATLAS Run-2 result

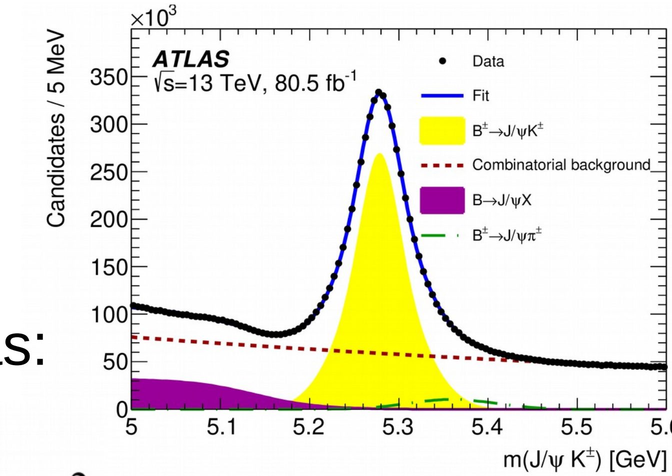
- 80.5 fb^{-1} of 13 TeV data (Run 2, 2015-2017)
- J/ψ trigger with muon p_T of 4 or 6 GeV
- Measurement of the proper decay time $t = L_{xy}\, m_B / p_T^B$
- Flavour tagging to identify the flavour of the b quark

ATLAS $B_s \to J/\psi\phi$ analysis: flavour tagging

- Flavour tagging to identify the flavour of the b quark:
  - opposite-side tagging (OST) using p_T-weighted charge of tracks in cone around muons / electrons / b jets

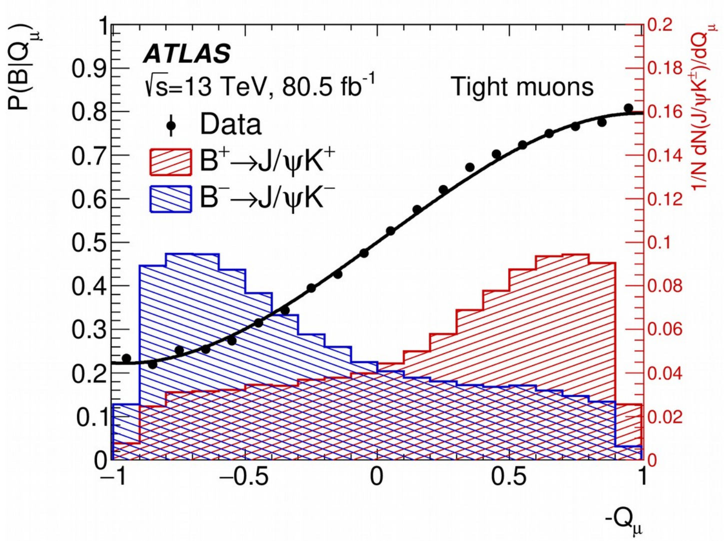
$$Q_x = \frac{\sum_i^{N\ \text{tracks}} q_i \cdot (p_{\text{T}i})^\kappa}{\sum_i^{N\ \text{tracks}} (p_{\text{T}i})^\kappa}$$

  - Calibrated on self-tagged $B^\pm \to J/\psi K^\pm$ events



  - Tag probabilities included in the B_s fit
  - Dilution $D(Q_x)$ and tagging power T_x defined as:

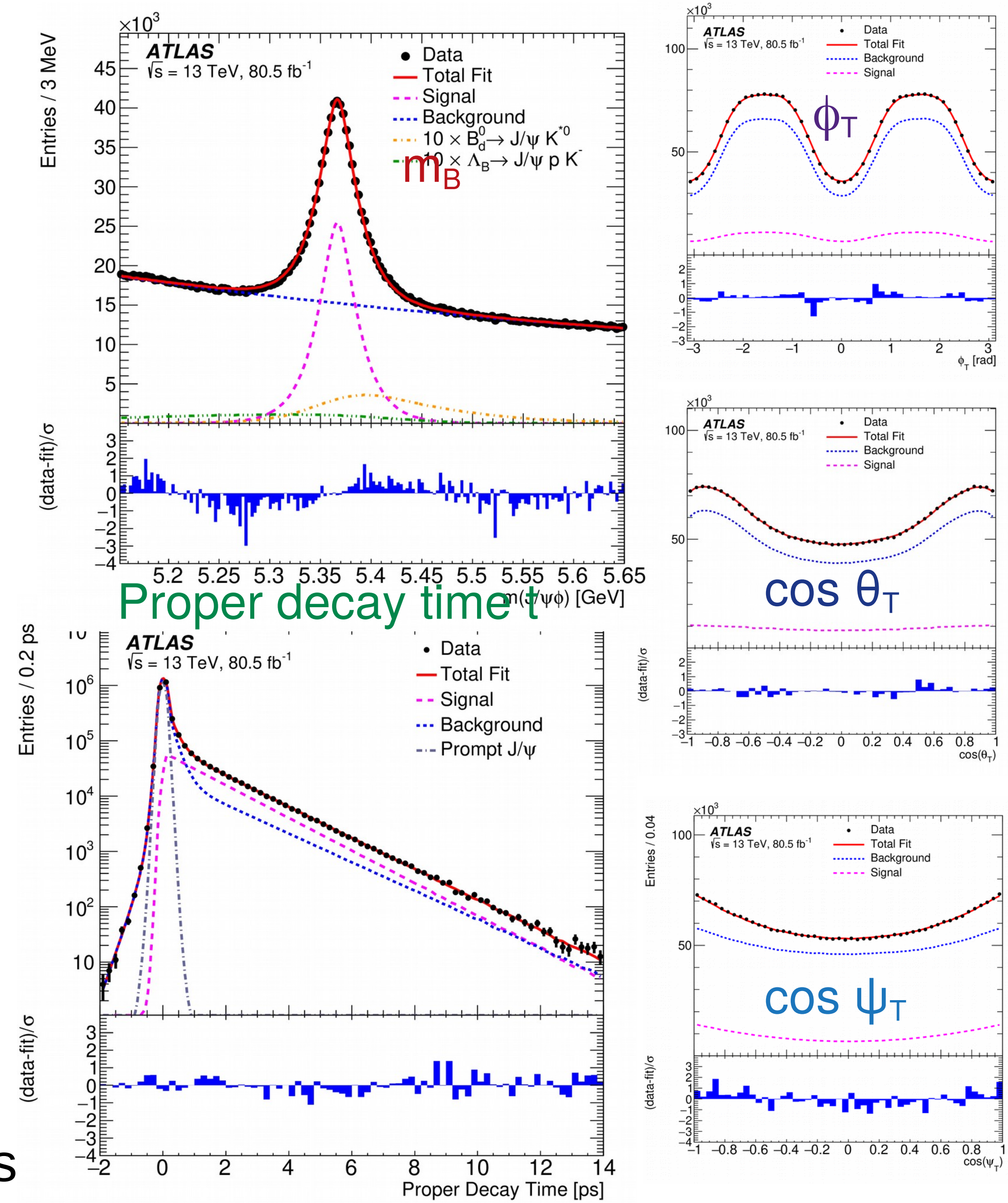
$$\mathcal{D}(Q_x) = 2P(B|Q_x) - 1$$
$$T_x = \sum_i \epsilon_{x\,i} \cdot (2P(B|Q_{x\,i}) - 1)^2$$



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

ATLAS $B_s \to J/\psi\phi$ analysis: ML fit

- Unbinned maximum-likelihood fit
  - *B_s properties*: mass m_B, proper decay time t, proper decay time error σ_t, tagging probability $P(B|Q_x)$
  - *Transversity angles*: $\Omega(\theta_T, \psi_T, \phi_T)$
  - *Physical parameters*: **$\Delta\Gamma_s$, φ_s, Γ_s, $|A_0(0)|^2$, $|A_{||}(0)|^2$, $\delta_{||}$, $\delta_{\perp}$, $|A_s(0)|^2$ and δ_s**
- Systematics:
  - *Lifetime model*: varying p_T bins and signal fraction
  - *Backgrounds*: B_d / Λ_b / angular models varied / p_T bins varied
  - *Tagging*: variation of the parameterisation / recalibration from MC samples / pile-up effects



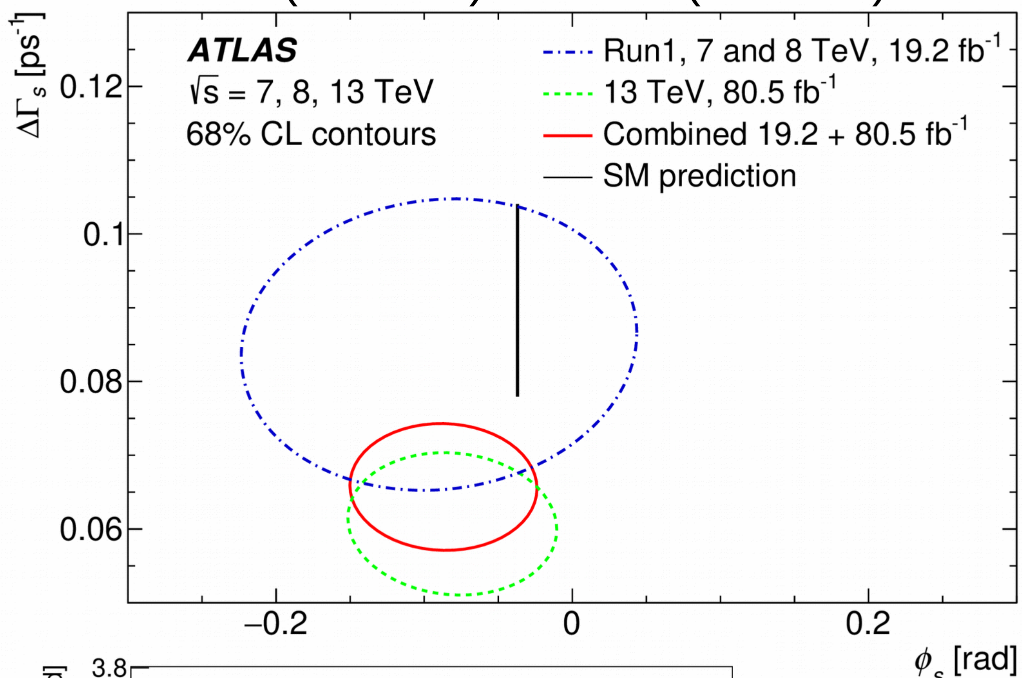
ATLAS $B_s \to J/\psi\phi$ analysis: Run-2 results

ATLAS Run-2 result on 80.5 fb^{-1} of 2015-2017 data

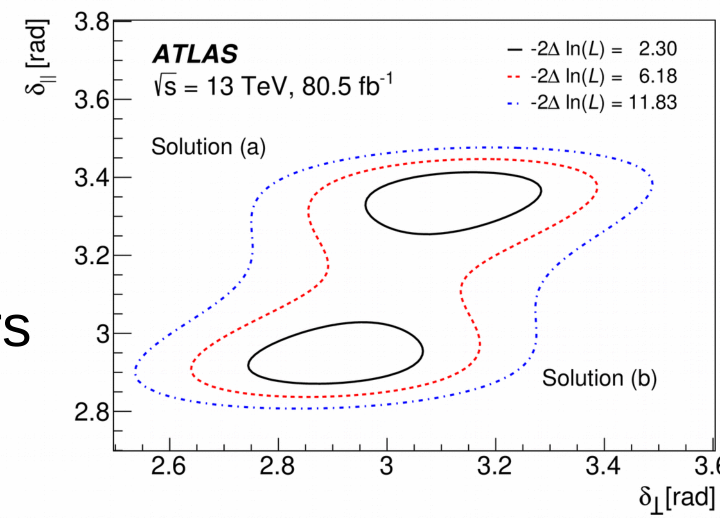
Run 2 only (80.5 fb^{-1}):

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

Run 1 (19.2 fb^{-1}) & Run 2 (80.5 fb^{-1}):



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

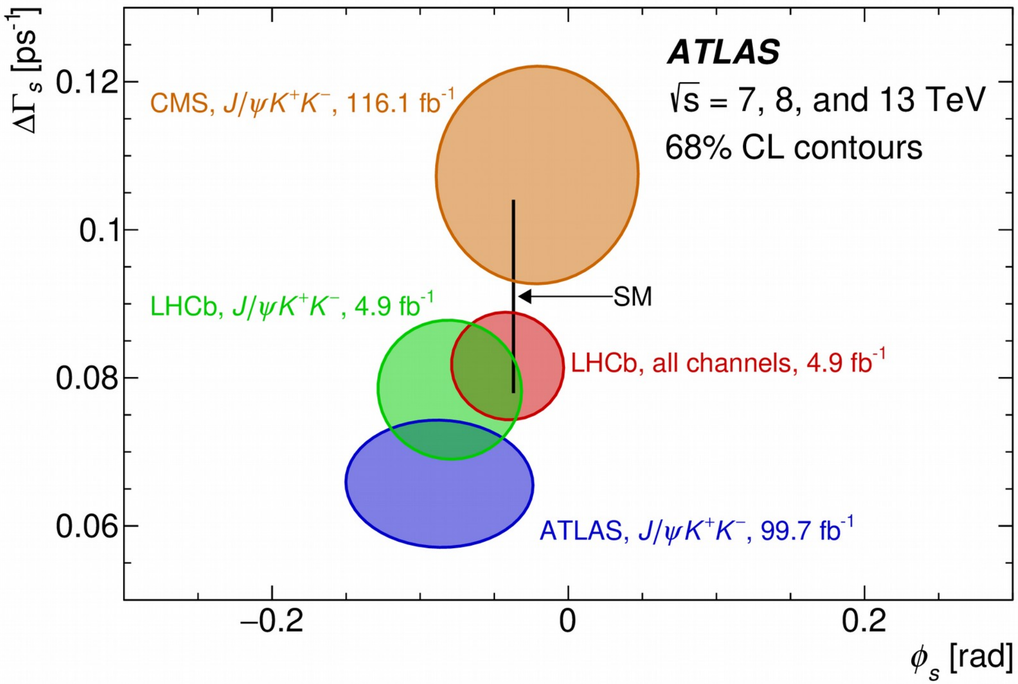


ATLAS $B_s \to J/\psi\phi$ analysis: Run1+2 combination

ATLAS Run 1 & Run 2 combined
(19.2 fb^{-1} + 80.5 fb^{-1})

Parameter	Solution (a) Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.021
$\Delta\Gamma_s$ [ps^{-1}]	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018
$\lvert A_\parallel(0)\rvert^2$	0.2220	0.0017	0.0021
$\lvert A_0(0)\rvert^2$	0.5152	0.0012	0.0034
$\lvert A_S\rvert^2$	0.0343	0.0031	0.0045
$\delta_\perp$ [rad]	3.22	0.10	0.05
$\delta_\parallel$ [rad]	3.36	0.05	0.09
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.04

Comparison with CMS & LHCb:



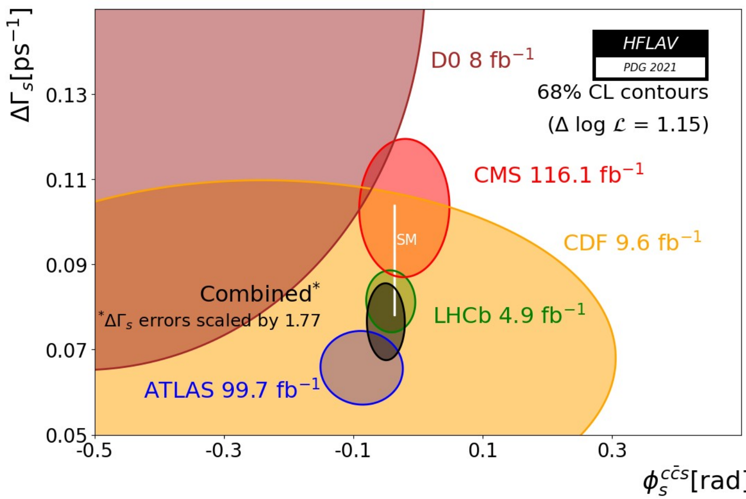
ϕ_s = -0.087 ± 0.036 (stat) ± 0.021 (syst) rad
$\Delta\Gamma_s$ = 0.0657 ± 0.0043 (stat) ± 0.0037 (syst) ps^{-1}

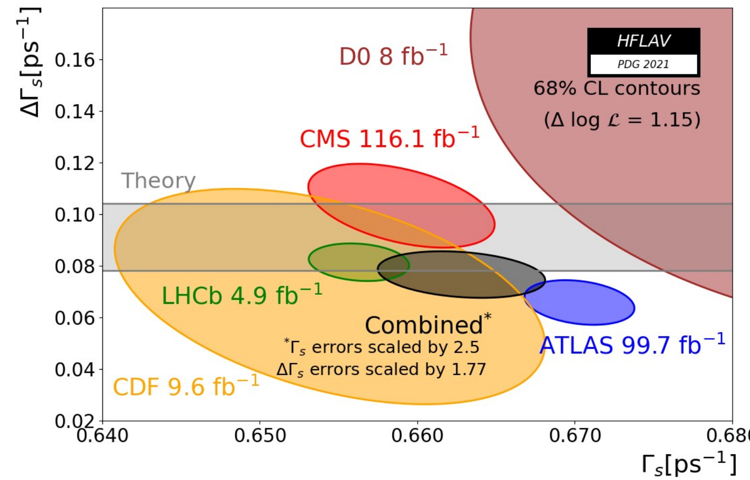
- ϕ_s result consistent with results from CMS, LHCb and SM
- Competitive single measurement of $\Delta\Gamma_s$, Γ_s and helicity parameters
- Still to add 60 fb^{-1} of 2018 data

$B_s \rightarrow J/\psi\phi$ results: HFLAV average

HFLAV average for PDG21:
ϕ_s = -0.050 ± 0.019 rad

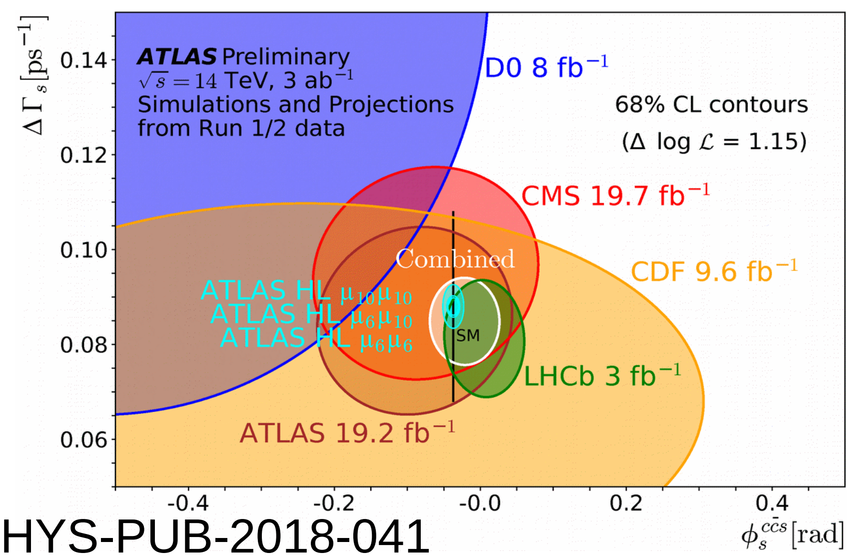
Because of tensions, errors on Γ_s and $\Delta\Gamma_s$ scaled by 2.5 and 1.77





ATLAS $B_s \rightarrow J/\psi\phi$ results: HI-LHC projections

- Updated tracking (ITk): proper decay time resolution improved by 21% w.r.t. Run 2
- Three trigger scenarios for thresholds
- Improvements w.r.t. Run 1:
  - ϕ_s stat: better by ~9x to 20x
    - uncertainty on ϕ_s at least as the theory error
  - $\Delta\Gamma_s$ stat: better by ~4x to 10x



ATL-PHYS-PUB-2018-041

Summary and Conclusions

- **Results on FCNC b to s transitions:**
  - B to K*μμ angular analysis and $B_{(s)}$ to μμ
- **Recent results on CP Violation in B_s system:**
  - CP violating phase in $B_s^0 \rightarrow J/\psi\varphi$ angular analysis

- ATLAS is competitive in B physics
  - Thanks to accumulated statistical samples
  - Thanks to some detector performance (tracking)
  - Perfect example the angular analysis of the golden mode $B_s \rightarrow J/\psi\phi$
  - **Working on the updates of all the above to full Run-2 statistics**

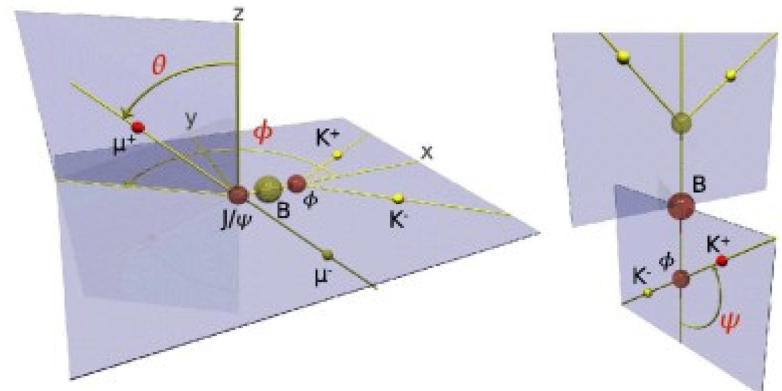
back-up slides

Time-dependent angular analysis of $B_s \to J/\psi\phi$

- Systematics:
  - *Lifetime model*: varying p_T bins and signal fraction
  - *Backgrounds*: B_d / Λ_b / angular models varied / p_T bins varied
  - *Tagging*: variation of the parameterisation / recalibration from MC samples / pile-up effects

	ϕ_s [10^{-3} rad]	$\Delta\Gamma_s$ [10^{-3} ps^{-1}]	Γ_s [10^{-3} ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$ [10^{-3}]	$\lvert A_0(0)\rvert^2$ [10^{-3}]	$\lvert A_S(0)\rvert^2$ [10^{-3}]	$\delta_\perp$ [10^{-3} rad]	$\delta_\parallel$ [10^{-3} rad]	$\delta_\perp - \delta_S$ [10^{-3} rad]
Tagging	19	0.4	0.3	0.2	0.2	1.1	17	19	2.3
ID alignment	0.8	0.2	0.5	< 0.1	< 0.1	< 0.1	11	7.2	< 0.1
Acceptance	0.5	0.3	< 0.1	1.0	0.9	2.9	37	64	8.6
Time efficiency	0.2	0.2	0.5	< 0.1	< 0.1	0.1	3.0	5.7	0.5
Best candidate selection	0.4	1.6	1.3	0.1	1.0	0.5	2.3	7.0	7.4
Background angles model:									
Choice of fit function	2.5	< 0.1	0.3	1.1	< 0.1	0.6	12	0.9	1.1
Choice of p_T bins	1.3	0.5	< 0.1	0.4	0.5	1.2	1.5	7.2	1.0
Choice of mass window	9.3	3.3	0.2	0.4	0.8	0.9	17	8.6	6.0
Choice of sidebands intervals	0.4	0.1	0.1	0.3	0.3	1.3	4.4	7.4	2.3
Dedicated backgrounds:									
B_d^0	2.6	1.1	< 0.1	0.2	3.1	1.5	10	23	2.1
Λ_b	1.6	0.3	0.2	0.5	1.2	1.8	14	30	0.8
Alternate Δm_s	1.0	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	15	4.0	< 0.1
Fit model:									
Time res. sig frac	1.4	1.1	0.5	0.5	0.6	0.8	12	30	0.4
Time res. p_T bins	0.7	0.5	0.8	0.1	0.1	0.1	2.2	14	0.7
S-wave phase	0.3	< 0.1	< 0.1	< 0.1	< 0.1	0.2	8.0	15	37
Fit bias	5.7	1.3	1.2	1.3	0.4	1.1	3.3	19	0.3
Total	22	4.3	2.2	2.3	3.8	4.6	55	88	39

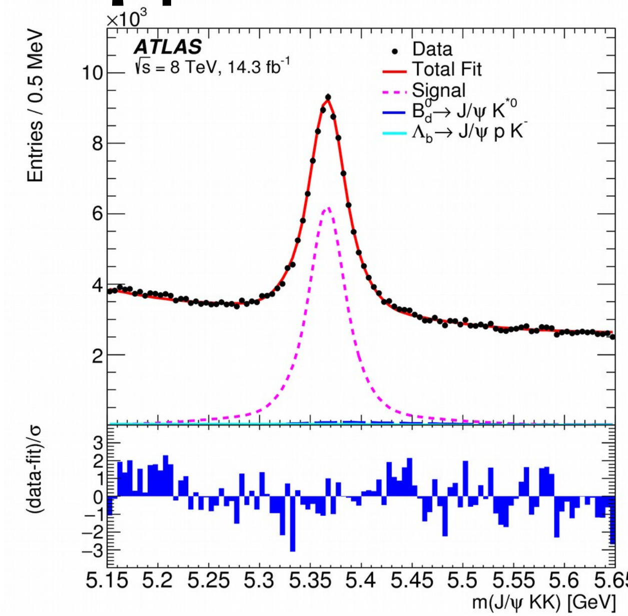
Time-dependent angular analysis of $B_s \rightarrow J/\psi\phi$



$$\frac{d^4\Gamma}{dt\, d\Omega} = \sum_{k=1}^{10} O^{(k)}(t) g^{(k)}(\theta_T, \psi_T, \phi_T),$$

k	$O^{(k)}(t)$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2}\lvert A_0(0)\rvert^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}\lvert A_\parallel(0)\rvert^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$
3	$\frac{1}{2}\lvert A_\perp(0)\rvert^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T\sin^2\theta_T$
4	$\frac{1}{2}\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert\cos\delta_\parallel$ $\left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$
5	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\cos(\delta_\perp-\delta_\parallel)\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp-\delta_\parallel)\cos\phi_s\sin(\Delta m_s t))]$	$-\sin^2\psi_T\sin 2\theta_T\sin\phi_T$
6	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\cos\delta_\perp\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin\delta_\perp\cos(\Delta m_s t) - \cos\delta_\perp\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\phi_T$
7	$\frac{1}{2}\lvert A_S(0)\rvert^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{2}{3}\left(1-\sin^2\theta_T\cos^2\phi_T\right)$
8	$\alpha\lvert A_S(0)\rvert\lvert A_\parallel(0)\rvert[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\sin(\delta_\parallel-\delta_S)\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos(\delta_\parallel-\delta_S)\cos(\Delta m_s t) - \sin(\delta_\parallel-\delta_S)\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$
9	$\frac{1}{2}\alpha\lvert A_S(0)\rvert\lvert A_\perp(0)\rvert\sin(\delta_\perp-\delta_S)$ $\left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$
10	$\alpha\lvert A_0(0)\rvert\lvert A_S(0)\rvert[\frac{1}{2}(e^{-\Gamma_H^{(s)}t} - e^{-\Gamma_L^{(s)}t})\sin\delta_S\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos\delta_S\cos(\Delta m_s t) + \sin\delta_S\cos\phi_s\sin(\Delta m_s t))]$	$\frac{4}{3}\sqrt{3}\cos\psi_T\left(1-\sin^2\theta_T\cos^2\phi_T\right)$

TD angular analysis of $B_s \to J/\psi\phi$



ATLAS Run-1 result:

- 14.3 fb^{-1} of ATLAS data from 2012 at 8 TeV
- Results:

ϕ_s = -0.090 ± 0.078 (stat) ± 0.041 (syst) rad

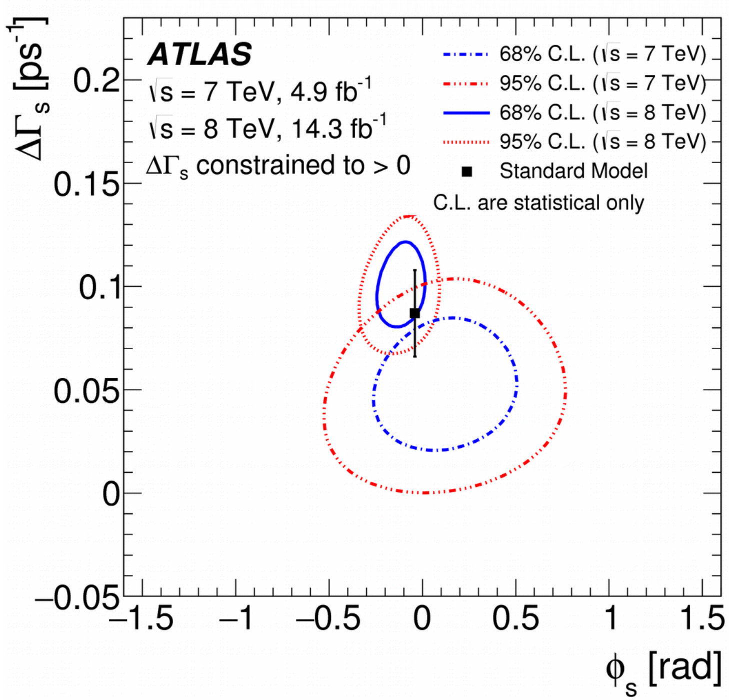
$\Delta\Gamma_s$ = 0.085 ± 0.011 (stat) ± 0.007 (syst) ps^{-1}

[JHEP 08 (2016) 147]

- Agrees with SM
- Consistent with other experiments
- Consistent with previous analysis, using 2011 data at 7 TeV

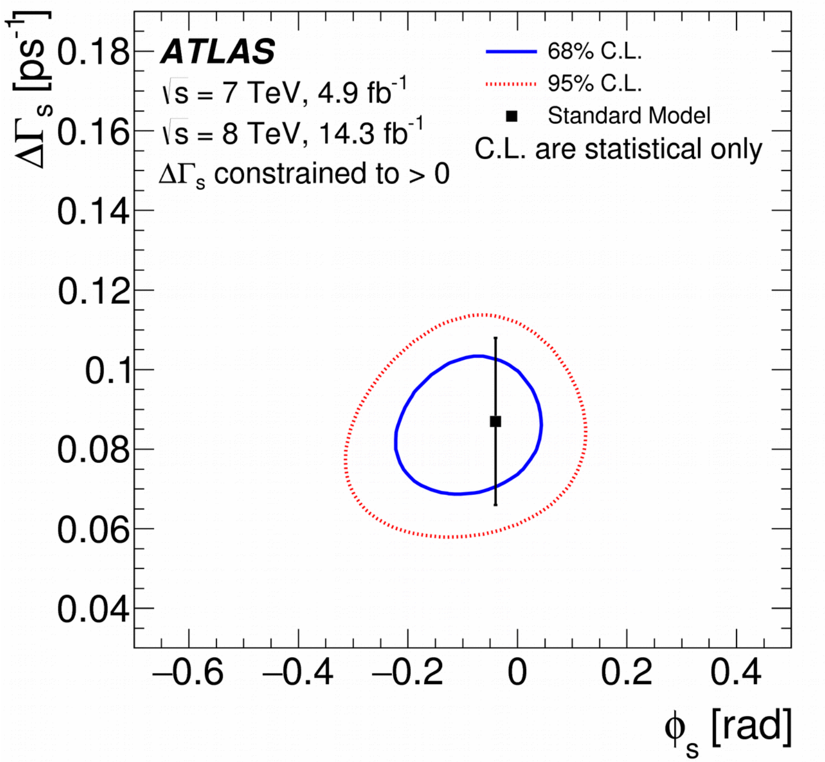
[Phys. Rev. D 90, 052007 (2014)]

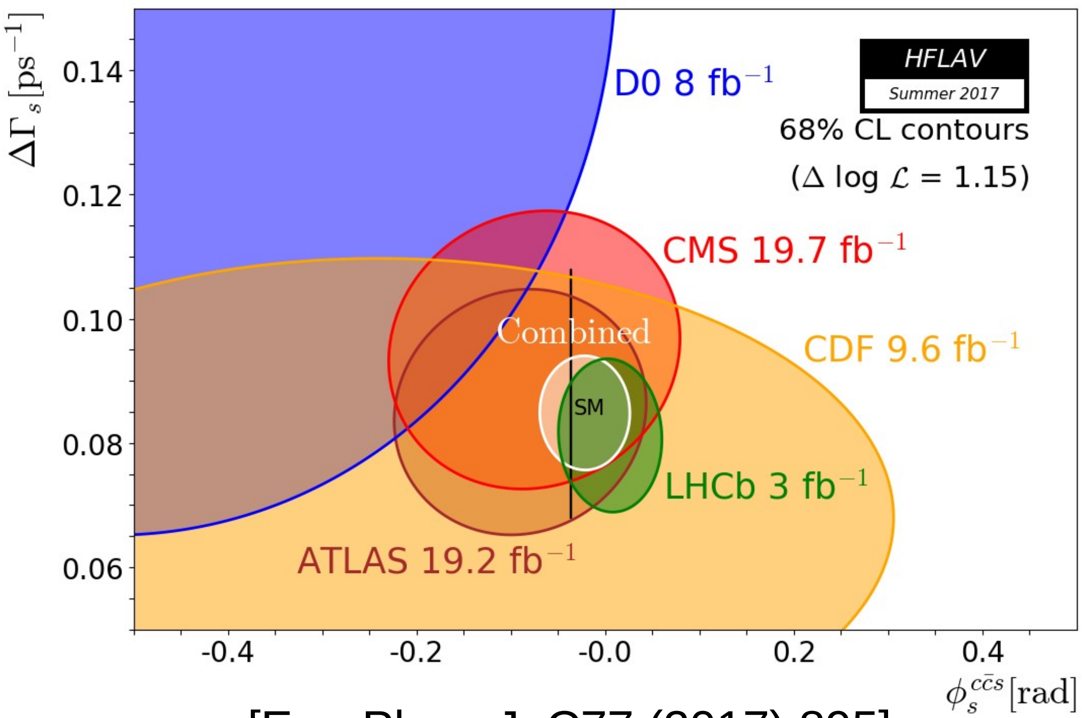
- A Best Linear Unbiased Estimate (BLUE) combination used to combine 7 and 8 TeV measurements



Time-dependent angular analysis of $B_s \to J/\psi\phi$

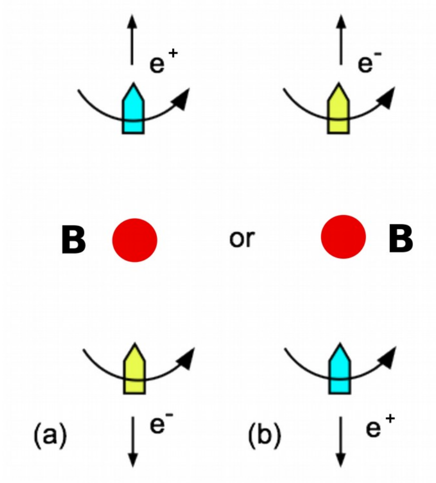
ATLAS combined Run-1 result:





[Eur. Phys. J. C77 (2017) 895]

Motivations and predictions

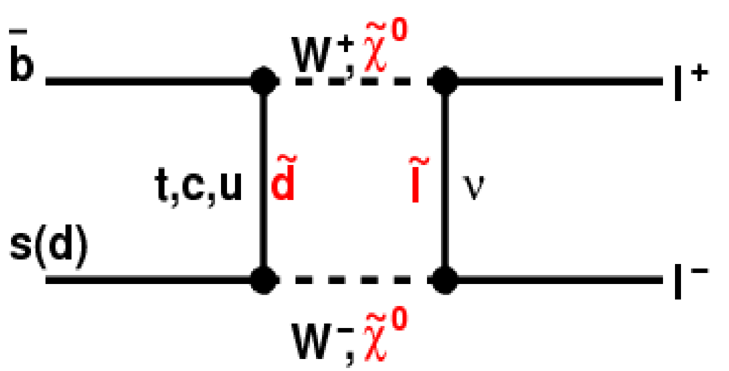


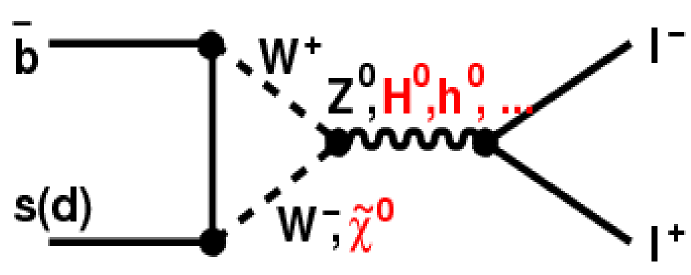
- Decays of B^0 and B^0_s into two leptons have to proceed through Flavour Changing Neutral Currents (FCNC)
  → forbidden at tree level in the SM
- In addition, they are CKM and helicity suppressed.
- Within the SM, they can be calculated with small theoretical uncertainties of order 6-8%

meson type	Lepton type e	μ	τ
B^0	$(2.48 \pm 0.21)10^{-15}$	$(1.06 \pm 0.09)10^{-10}$	$(2.22 \pm 0.19)10^{-8}$
B^0_s	$(8.54 \pm 0.55)10^{-14}$	$(3.65 \pm 0.23)10^{-9}$	$(7.73 \pm 0.49)10^{-7}$

Bobeth et al., PRL 112 (2104) 101801 [includes NLO EM and NNLO QCD corrections]

- Perfect ground for indirect new physics searches:
  - virtual new particles can contribute to the loop
  - both enhancement and suppression effects are possible





ATLAS analysis on 2015-2016 Run 2 data

JHEP 04 (2019) 098, arXiv:1812.03017

- 36.2/fb dataset of 2015-2016 data taking:
  - effectively 26.3/fb for B → μμ
  - 15.1/fb for B → J/ψΦ and B → J/ψK
- Trigger: higher thresholds [4-6 GeV] than in Run1,
  - Lxy > 0 request at trigger level

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

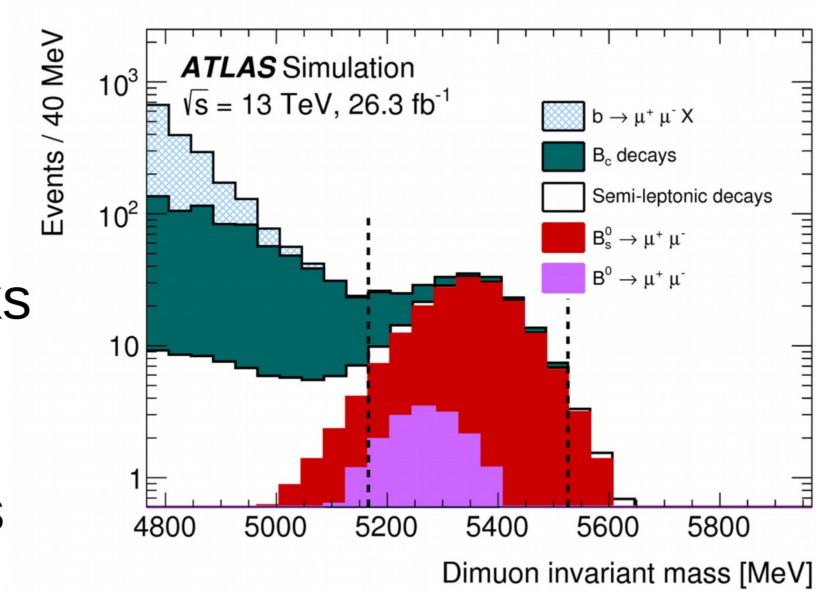
- correction for the different hadronisation probabilities for B^0_S and B^0 vs $B^{\pm}$
- include the $B^{\pm}$ and J/y branching fractions
- correction for the efficiencies of the two channels
- normalisation yield and efficiency ratio define the factor:

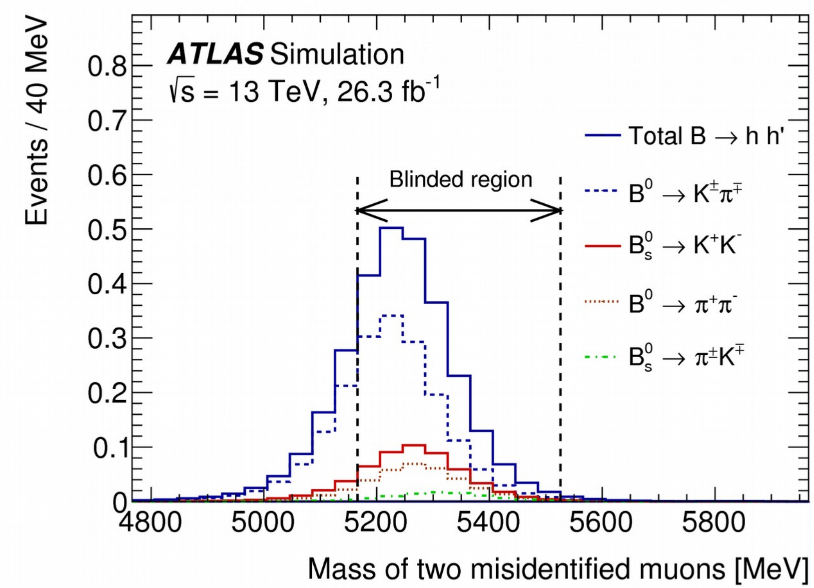
$$\mathcal{D}_{\text{norm}} = N_{J/\psi K^+} \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^+}} \right)$$

Background contributions

In order of relative magnitude:

- combinatorial background:
  - two real muons from different b quarks
- partially reconstructed B decays:
  - two real muons
  - Same Vertex (SV): B → mmX decays
  - Same Side (SS): semileptonic decay cascades (b → cmn → s(d)mmnn)
  - B_c decays: like B_c → J/y mn
  - all these accumulate at low values of the dimuon invariant mass
- semileptonic B and B_S decays:
  - one real muon and a charged hadron.
- peaking background from charmless hadronic $B_{(S)}$ decays:
  - B decays into two hadrons h (kaons and pions): $B^0_{(S)}$ → hh'
  - smaller component, but overlays with the signal in dimuon invariant mass

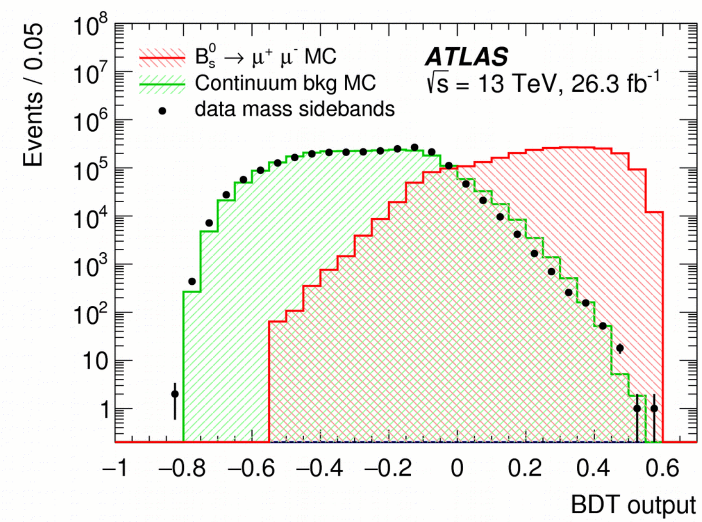




Tight muon-ID against hadron misidentification

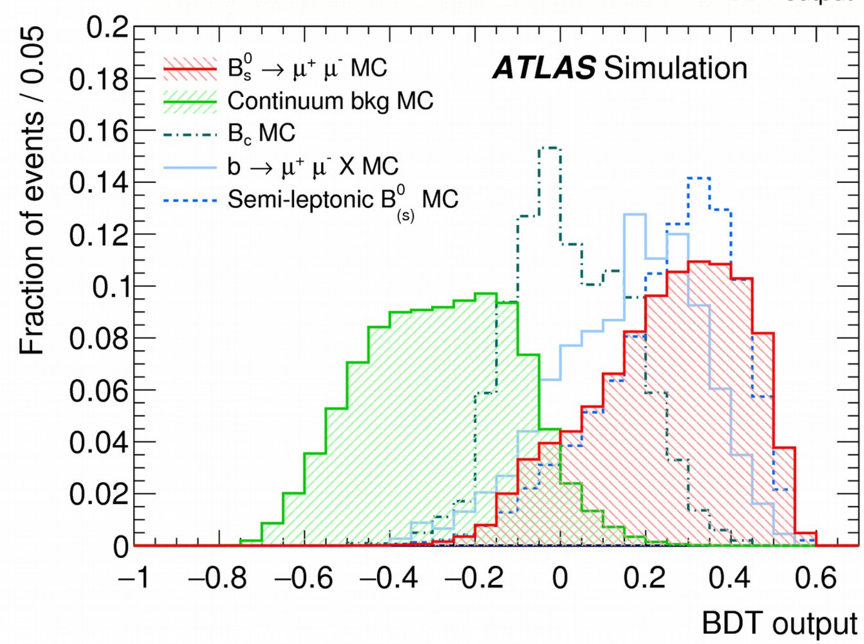
- mis-identification reduced by 0.39^2 using standard 'tight' ATLAS selections
- studied on simulated samples
- validated on control regions
- negligible misidentification of protons (< 0.01%)
- misidentification is 0.08%(0.10%) for K(p).

peaking-background events: 2.7±1.3



BDT against combinatorial bkg

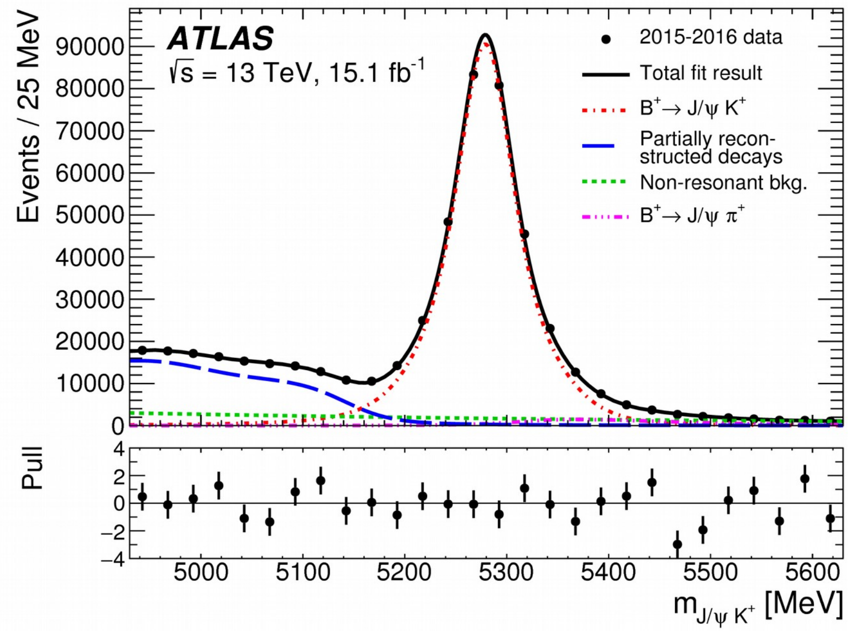
- MVA classifier to discriminate from signal
- trained and tested on mass sidebands
  - divided in 3 subsets
    - 3 independent BDTs
    - compatible performance
- 15 variables related to properties of B candidates, muons from the B decay, other tracks from the same collision and to pile-up vertices.



Normalisation B yield extraction

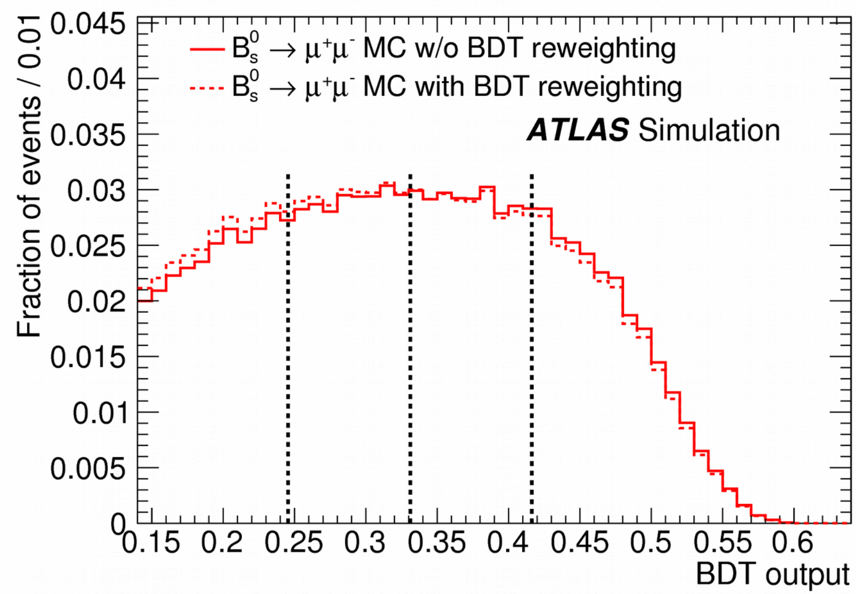
- unbinned maximum likelihood fit of the invariant mass $m_{J/yK} \rightarrow m_{mmK}$
- cross-checked with raw relative yield of J/yp over J/yK ratio
  $r_{p/K}$ = (3.71 ± 0.09)%

$$\mathcal{D}_{\text{norm}} = N_{J/\psi K^+} \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^+}} \right)$$



Efficiency ratio $\varepsilon_{\mu\mu}/\varepsilon_{J/\psi K}$

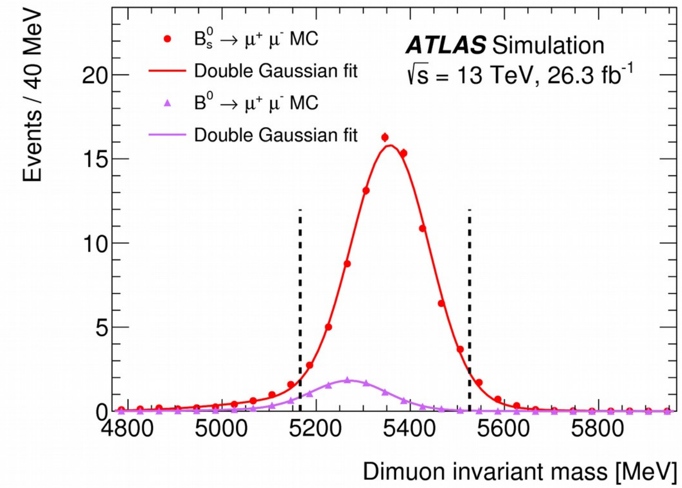
- efficiency ratio from MC
- systematic from data-MC discrepancies
- For B^0_S: 2.7% correction for lifetime difference of the B^0_S mass eigenstates

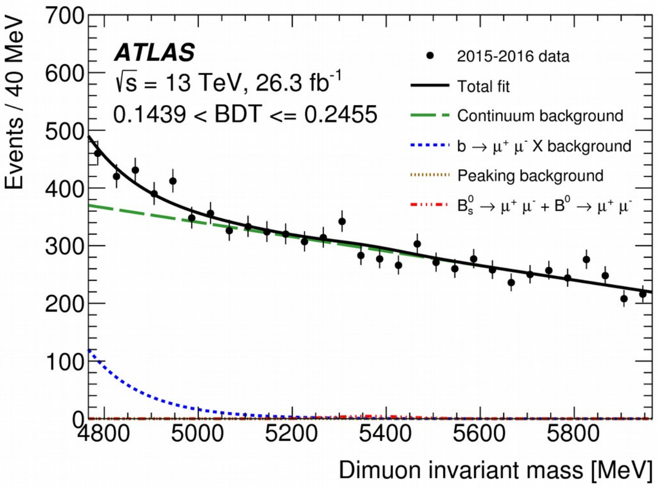


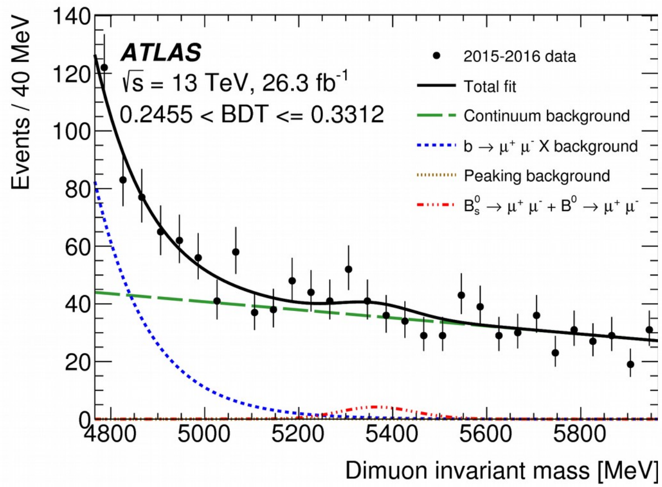
Source	Contribution (%)
Statistical	0.8
BDT Input Variables	3.2
Kaon Tracking Efficiency	1.5
Muon trigger and reconstruction	1.0
Kinematic Reweighting (DDW)	0.8
Pile-up Reweighting	0.6

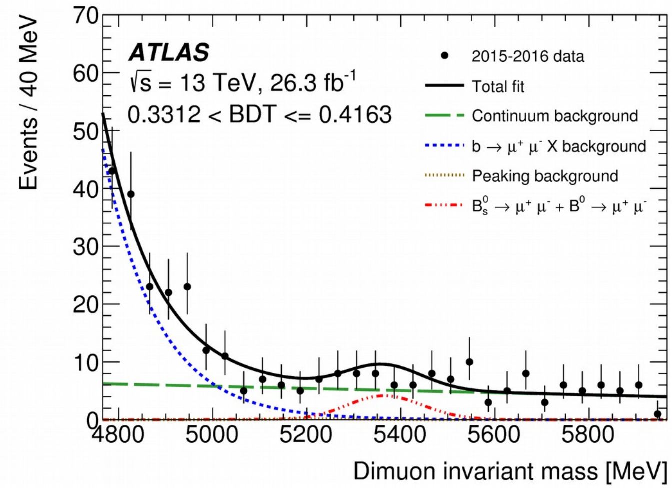
Signal yield extraction

- signal yields extracted with a unbinned maximum likelihood fit to the dimuon mass
- fit performed simultaneously in four BDT bins
  - 18% signal efficiency

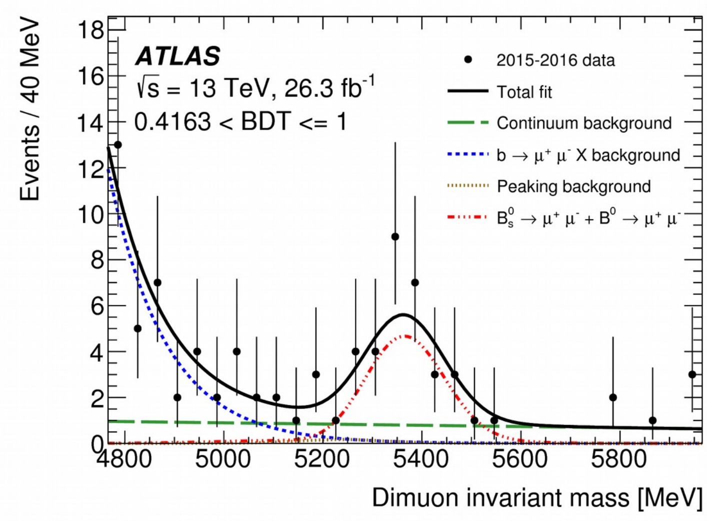






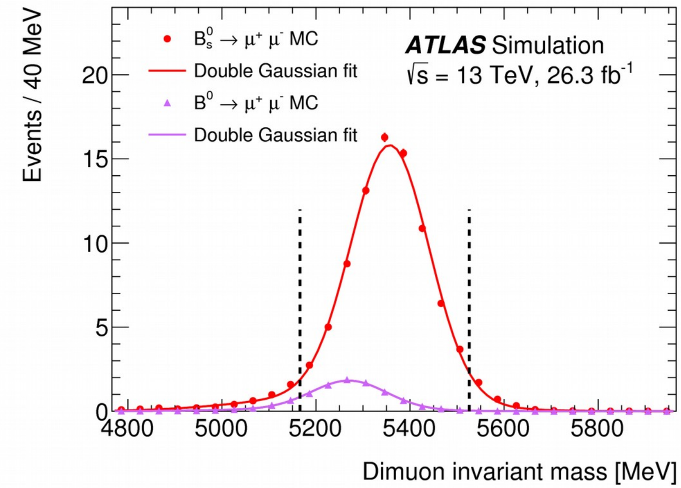


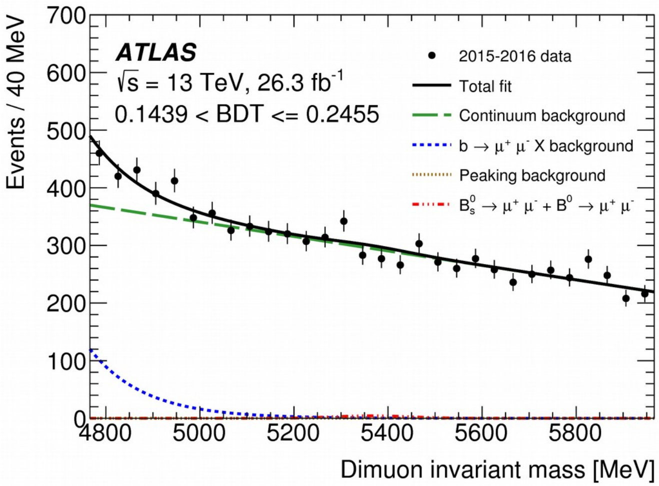
- signals, B to hh: 3 double Gaussians
- continuum: first order polynomial
- partially reconstructed B: exponential
- semi-leptonic: exponential

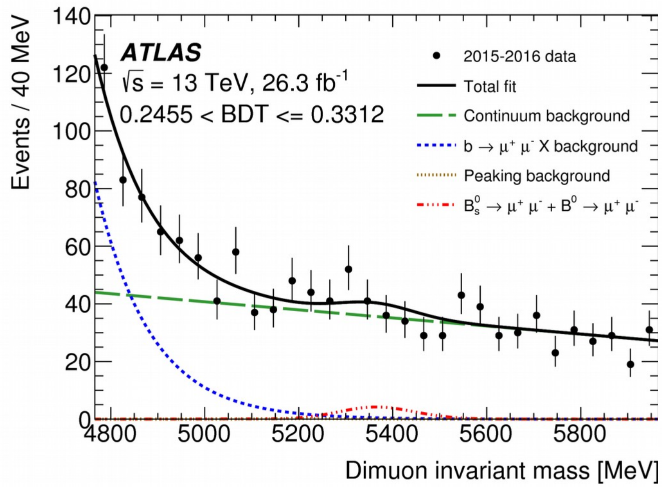


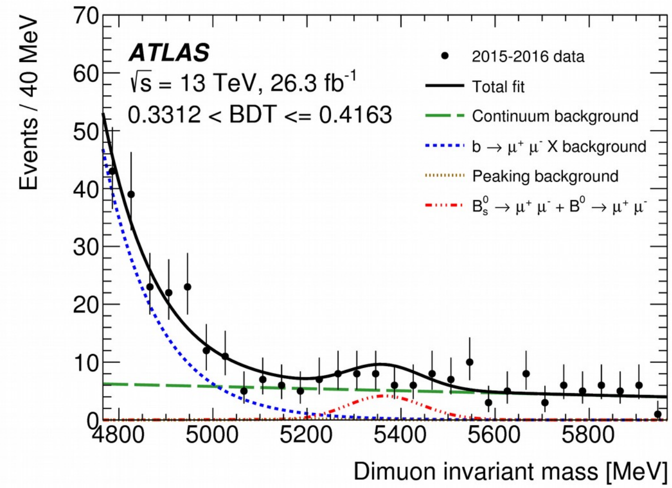
Signal yield extraction

- yields unconstrained:
  - $N_S = 80 \pm 22$ and $N_d = -12 \pm 20$
- expected from the SM:
  - $N_S = 91 \pm$ and $N_d = 10$



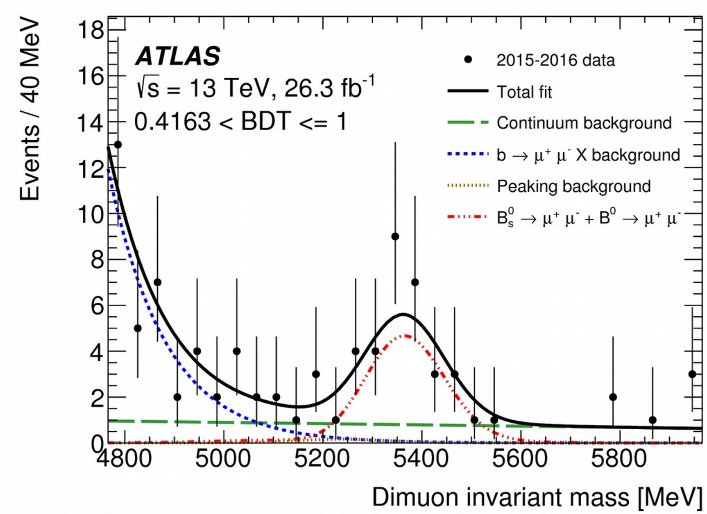






- consistent with Standard Model predictions
- likelihood maximum:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.21^{+0.90+0.48}_{-0.83-0.31}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(-1.3^{+2.2+0.7}_{-1.9-0.8}\right) \times 10^{-10}$$

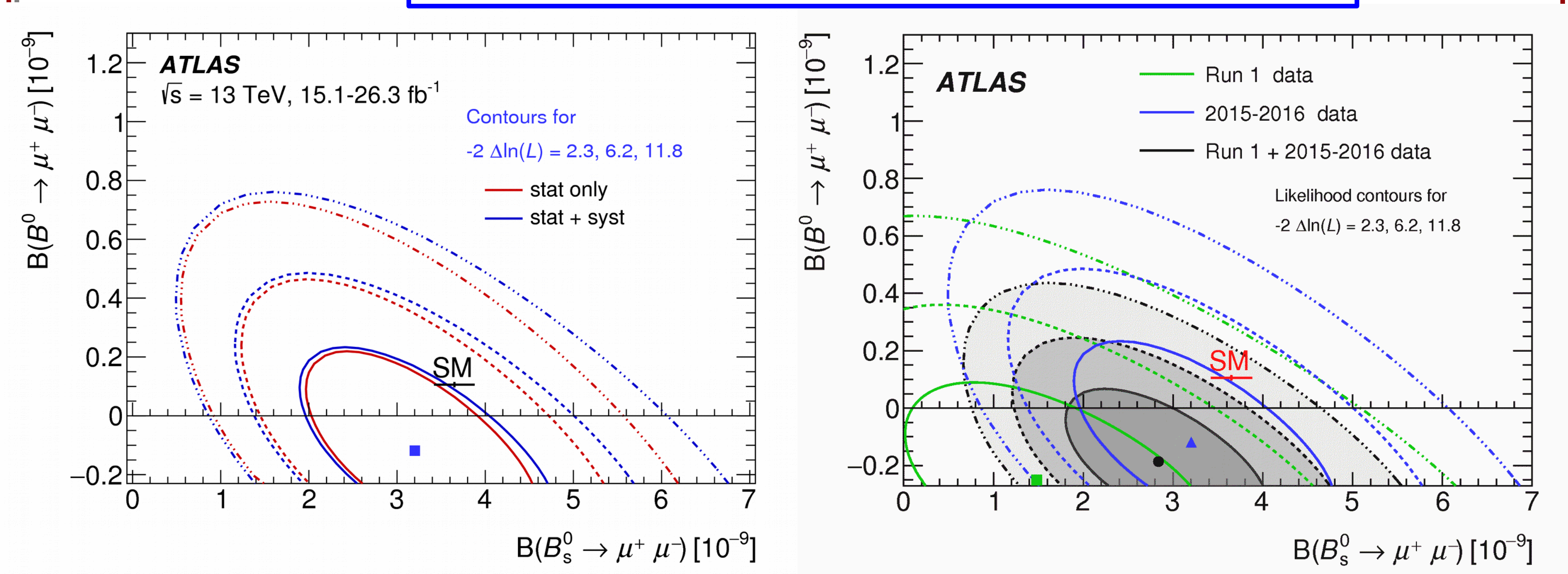


Combination of Run 1 and Run 2 results

Neyman Contours yield for Run 2:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.21^{+0.96+0.49}_{-0.91-0.30}\right) \times 10^{-9} = \left(3.2^{+1.1}_{-1.0}\right) \times 10^{-9}$$

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



Run 1 + Run 2 (2015+2016) combination:
Compatible with SM at 2.4σ

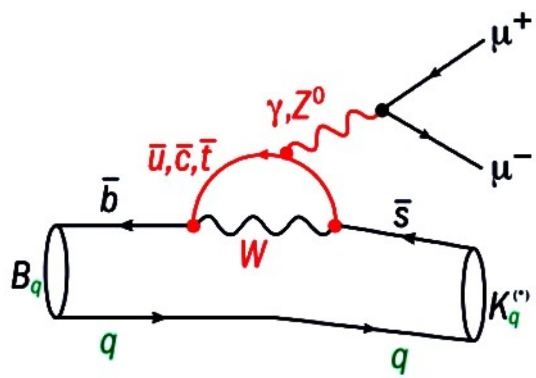
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$$

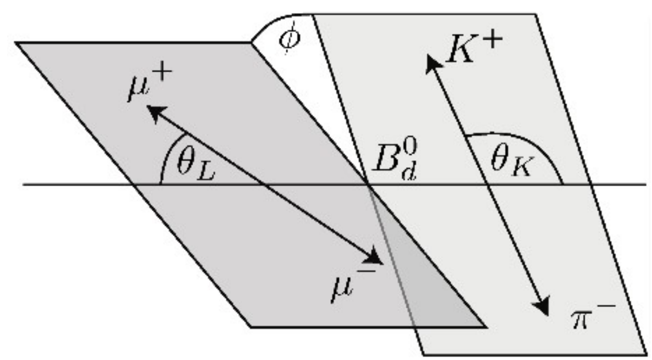
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$$

Angular analysis on B → K*μμ

JHEP 10 (2018) 047, arXiv:1805.04000

- FCNC b to s transition with a BR ~ 1.1 10^{-6}
- Angular distribution of the 4 particles in the final state sensitive to new physics for the interference of NP and SM diagrams





- Decay described by three angles (q_L, q_K, f) and the di-muon mass squared q^2 → angular distribution in bins of q^2 as function of q_L, q_K and f.

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

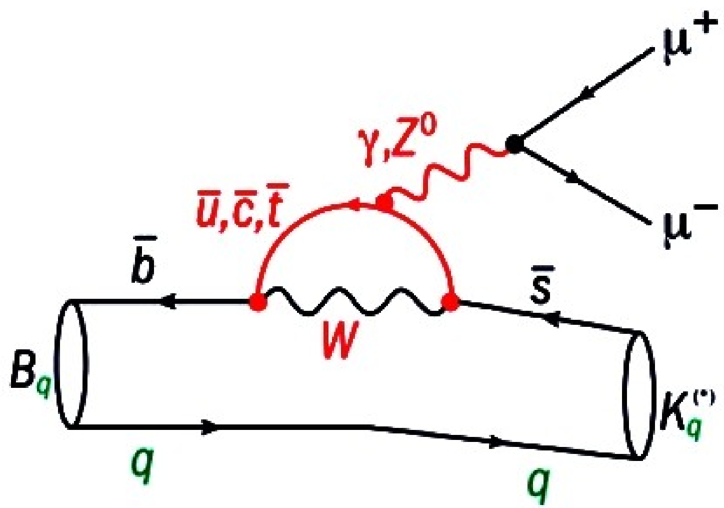
- The S parameters are translated into the $P^{(\prime)}$ parameters via

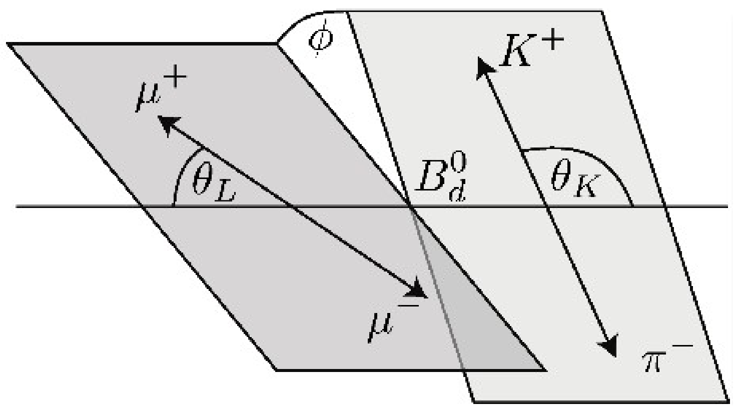
$$P_1 = \frac{2S_3}{1-F_L} \qquad P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

with reduced dependence on the hadronic form factors.

Angular analysis on $B \rightarrow K^*\mu\mu$

- another way to look at FCNC: $b \rightarrow s$ transition with a BR ~ $1.1\ 10^{-6}$
- angular distribution of the 4 particles in the final state sensitive to new physics for the interference of NP and SM diagrams
  - allows measuring a large set of angular parameters sensitive to Wilson coefficients $C^{(\prime)}_7$, $C^{(\prime)}_9$, $C^{(\prime)}_{10}$, $C^{(\prime)}_{S,P}$





- decay described by three angles (θ_L, θ_K, ϕ) and the di-muon mass squared q^2 → the angular distribution is analysed in finite bins of q^2 as a function of θ_L, θ_K and ϕ.
- LHCb reports a 3.4σ deviation from the SM.

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arXiv:1512.04442

Angular analysis on $B \to K^*\mu\mu$

- B^0 flavour eigenstate can be identified through the $K^* \to K^- \pi^+$ decay
- angular distribution given by:

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

- the S parameters are translated into the $P^{(\prime)}$ parameters via

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

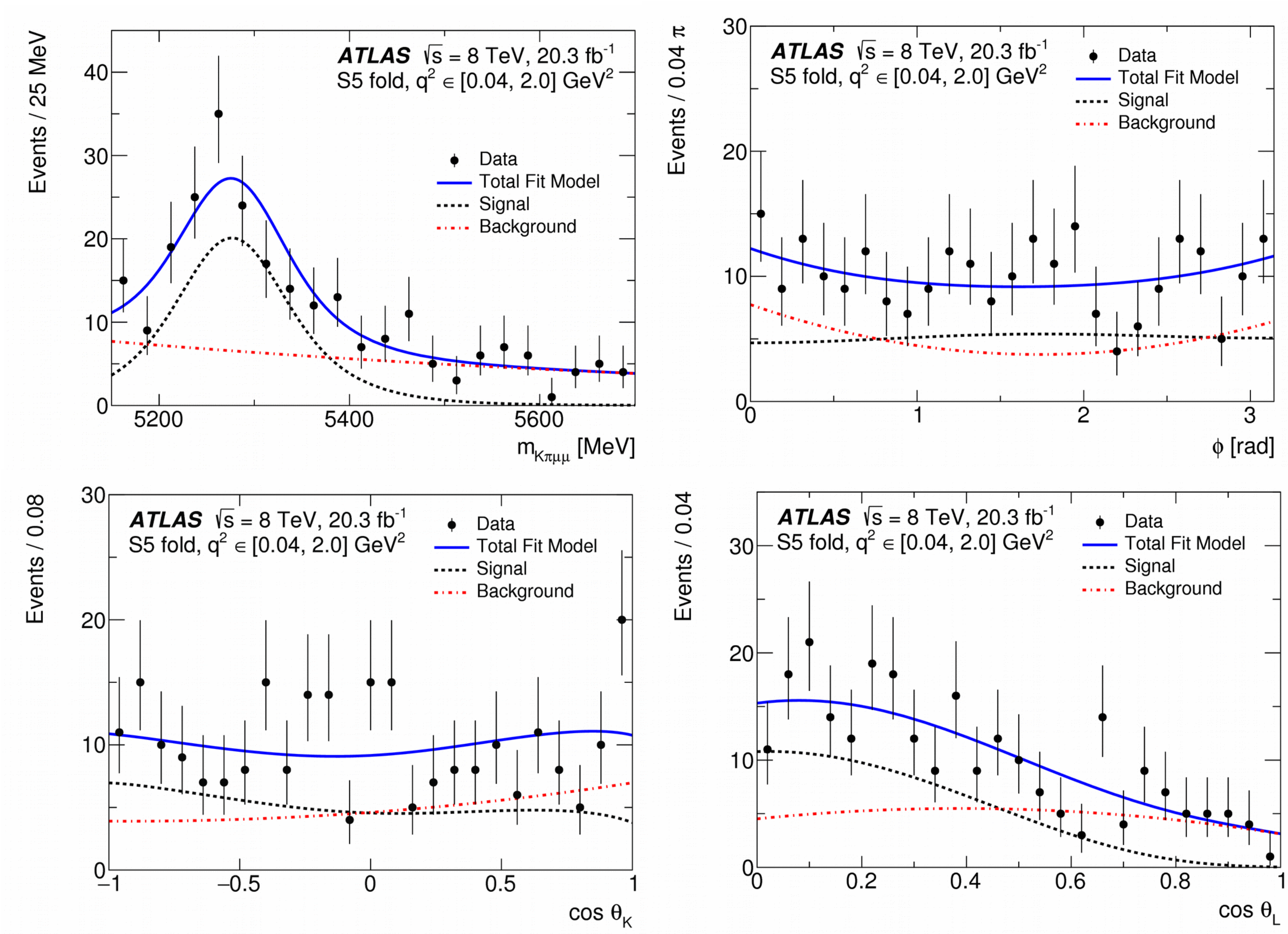
- the $P^{(\prime)}$ parameters are expected to have a reduced dependence on the hadronic form factors.
- ATLAS and CMS need to fold the angular distribution via trigonometric relations to reduce the number of free parameters

Analysis strategy for $B \to K^*\mu\mu$

- Data collected in 2012 at 8 TeV with 20.3 fb^{-1} Run 1 data
- Measured in 6 (overlapping) bins of q^2 in the range [0.04, 6] GeV^2
- 4 sets of fits for three parameters (F_L , S_3 and S_j with j=4,5,7,8)
- Selection of triggers with muon p_T thresholds starting at 4 GeV
- K* tagged by the kaon sign:
  - dilution from mistag probability included in (1-2$\langle w \rangle$):
    - $\langle w \rangle$ ~ 10.9(1)% with small dependence on q^2
- 787 events selected with $q^2 < 6$ GeV^2
- Extended unbinned maximum likelihood fits in each of the fit variants in each q^2 bin:
  - two step fit procedure: first fit the invariant mass distribution
  - then add to the fit the angular distributions to extract the F_L and S(P) parameters
- Signal shape studies from control samples K^*J/ψ and $K^*\psi(2S)$

Fit projections

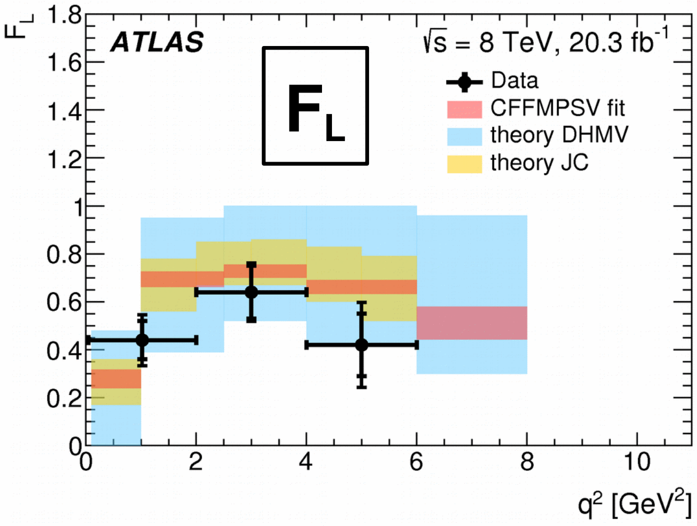
- fit m(K*μμ), $\cos\theta_L$, $\cos\theta_K$ and ϕ to isolate signal and extract parameters of interest.

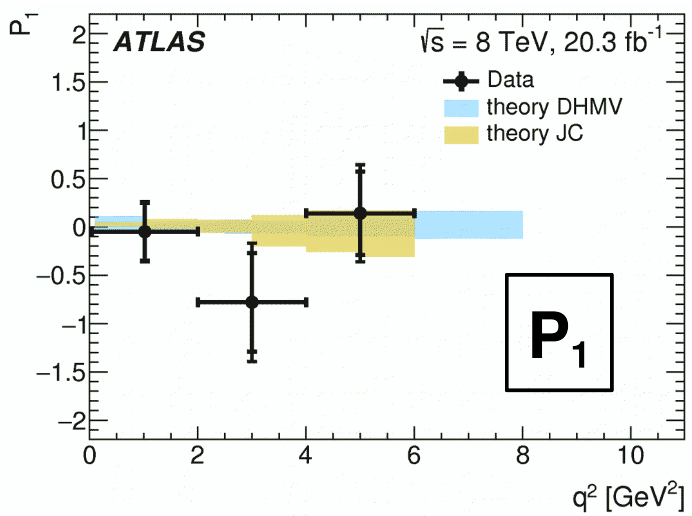


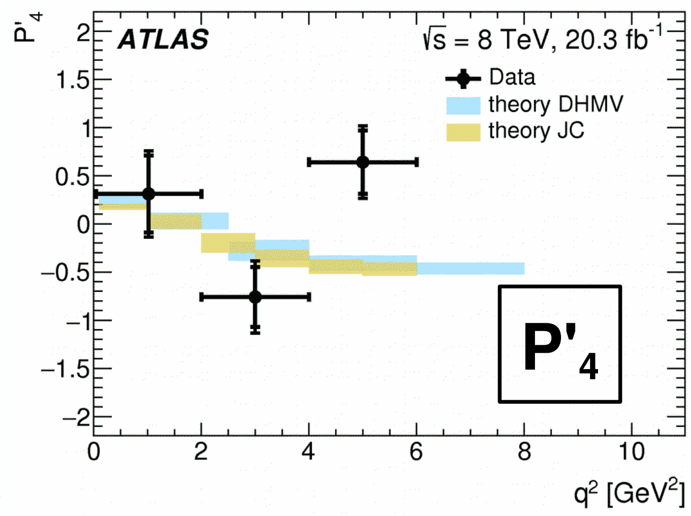
- Data shown for [0.04,2.0] GeV²
- projections for the S_5 fit.
- Approx 106-128 signal events in 2 GeV² q² bin.
- Similar results for the other q² bins and other fit variants.

Angular analysis results

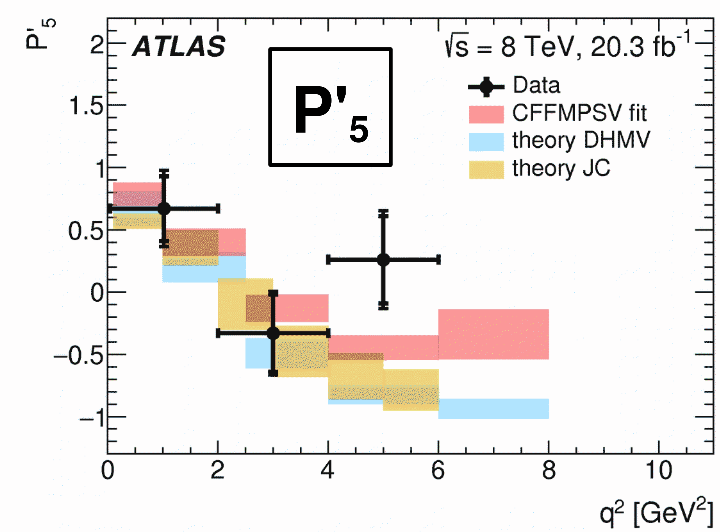
- Results are compatible with theoretical calculations & fits:







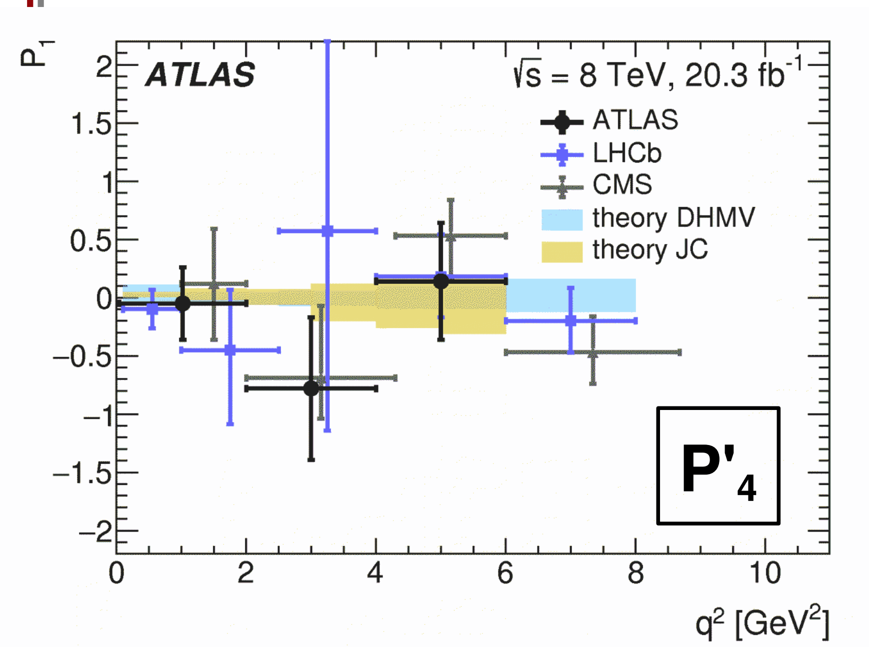
q^2 [GeV^2]	P_1	P'_4	P'_5
[0.04, 2.0]	$-0.05 \pm 0.30 \pm 0.08$	$0.31 \pm 0.40 \pm 0.20$	$0.67 \pm 0.26 \pm 0.16$
[2.0, 4.0]	$-0.78 \pm 0.51 \pm 0.34$	$-0.76 \pm 0.31 \pm 0.21$	$-0.33 \pm 0.31 \pm 0.13$
[4.0, 6.0]	$0.14 \pm 0.43 \pm 0.26$	$0.64 \pm 0.33 \pm 0.18$	$0.26 \pm 0.35 \pm 0.18$
[0.04, 4.0]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

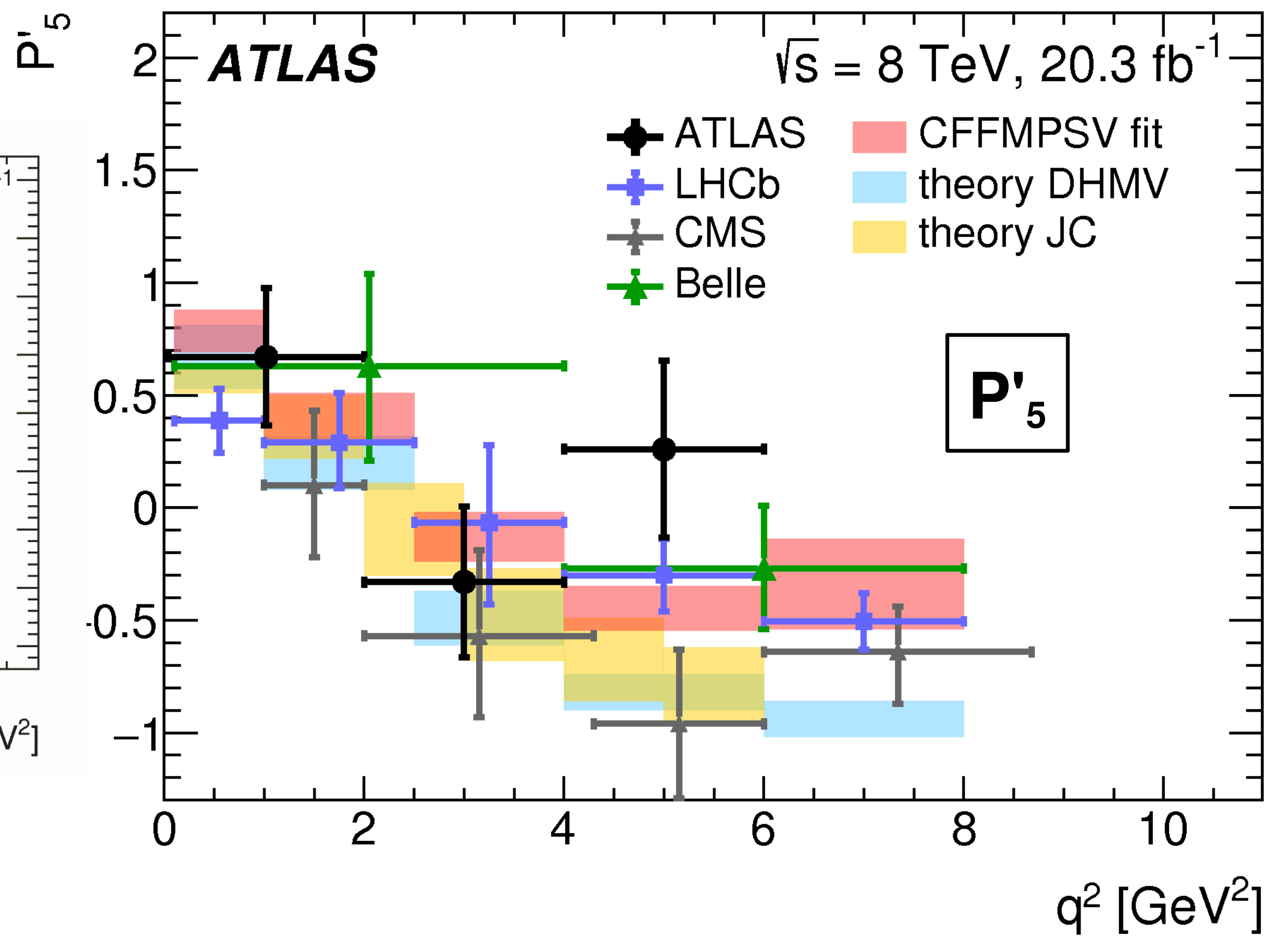


OPE and LHCb data fit: CFFMPSV: Ciuchini et al.; JHEP 06 (2016) 116.
QCD factorisation: DMVH: Decotes-Genon et al.; JHEP 12 (2014) 125.
JC: Jäger-Camalich; Phys. Rev. D93 (2016) 014028.

Angular analysis results

- ATLAS gets deviations of about 2.5σ (2.7σ) from DHMV in $P'_4(P'_5)$ in [4,6] GeV^2





CFFMPSV: Ciuchini et al.; JHEP 06 (2016) 116.
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TD angular analysis of $B_s \to J/\psi\phi$

ATL-PHYS-PUB-2018-041

Period	L_{int} [fb^{-1}]	N_{sig}	f_{sig}	Tag Power [%]	$\sigma(\tau)$ [ps]	$\delta^{\mathrm{stat}}_{\phi_s}$ [rad] measured (extrapolated)	$\delta^{\mathrm{stat}}_{\Delta\Gamma_s}$ [ps^{-1}] measured (extrapolated)
2012	14.3	73693	0.20	1.49	0.091	0.082	0.013
2011	4.9	22690	0.17	1.45	0.100	0.25 (0.22)	0.021 (0.023)
						$\delta^{\mathrm{stat}}_{\phi_s}$ [rad] extrapolated	
HL-LHC	3000						
Trigger μ6μ6		$9.72 \cdot 10^{6}$	0.17	1.49	0.048	0.004	0.0011
Trigger μ10μ6		$5.93 \cdot 10^{6}$	0.17	1.49	0.044	0.005	0.0014
Trigger μ10μ10		$1.75 \cdot 10^{6}$	0.15	1.49	0.038	0.009	0.003