ATLAS results on Heavy Flavour production and decay - including rare processes -

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On behalf on the ATLAS Collaboration

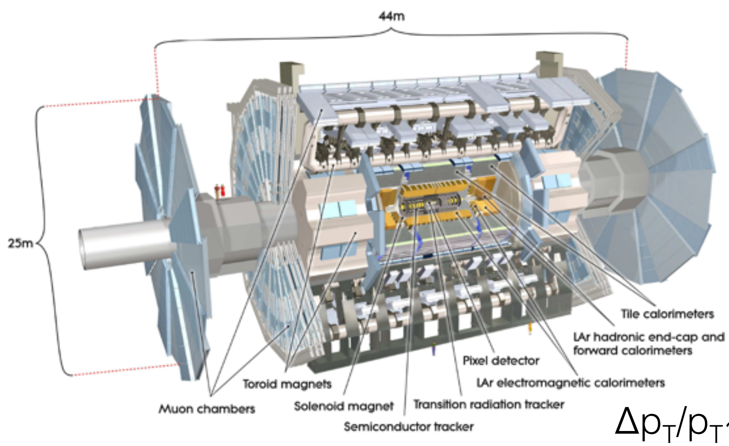
Outline

- Introduction
  - General features on Heavy Flavor Physics with ATLAS
- Quarkonia production
  - Associated production of J/ψ and $W^{\pm}$
- Open Beauty
  - Relative B_c/B^+ production measurement
- Rare decays
  - $B^0_{(s)} \rightarrow \mu^+\mu^-$

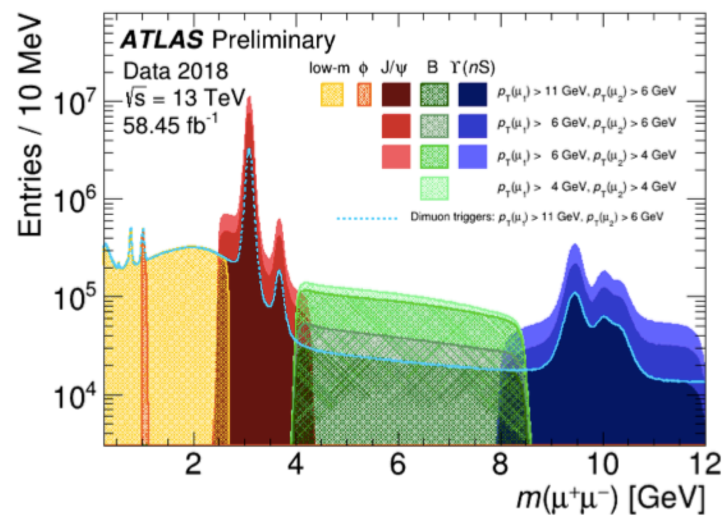
Selected recent results among the many published by the Collaborations

Quarkonia and Heavy Flavour at ATLAS

- Based on low p_T muon trigger and track reconstruction in the Inner Detector
- Wide regions in rapidity and p_T
- pp, pA; AA collisions
- Wide $\sqrt{s}$ range: 5.02, 7, 8, 13 TeV



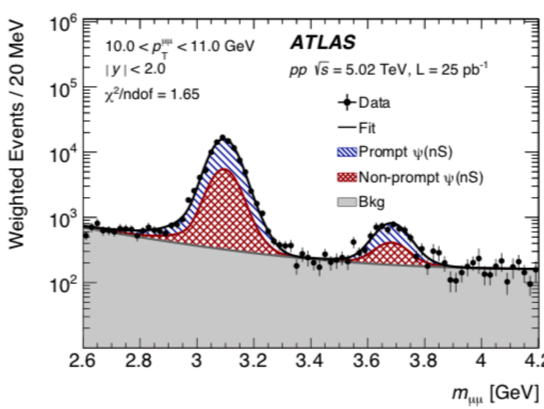
Di-μ invariant mass spectrum

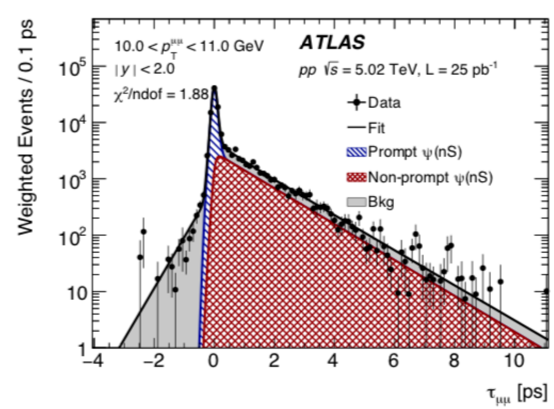


$\Delta p_T/p_T$~O(1-5%) for low-momentum tracks

- HF: main variables of 2μ pair
  - $m(\mu^+\mu^-)$
  - $\tau(\mu^+\mu^-)$

  → Prompt vs Non-Prompt (B decays in flight) separation



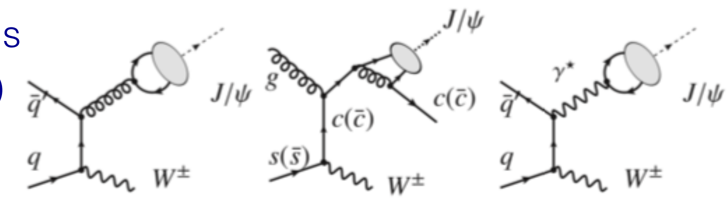


Quarkonia associated production

J/ψ W± Associated production at 8 TeV

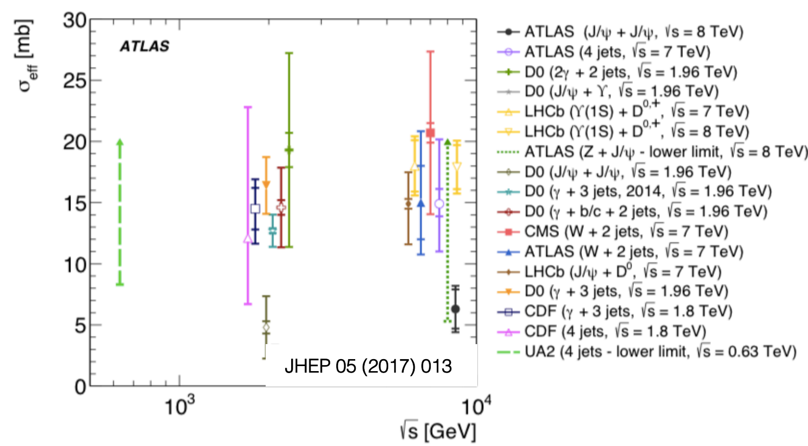
JHEP 01 (2020) 095

- Investigation of processes not well known/described
  - Production mechanism of charmonium in hadron collisions
  - Relative contribution of Color Singlet (CS) and Octet (CO)
  - Contribution of Single Parton (SPS) vs Double Parton Scattering (DPS). Cross-section sensitive to spatial distribution of gluons in the proton
  - DPS vs SPS undistinguishable on event-by-event basis.
    Discriminating angular correlation: Δy and Δϕ



arXiv:1903.09185

Many ATLAS studies on quarkonia associated production. Here: new result on prompt J/ψ+W± at 8 TeV



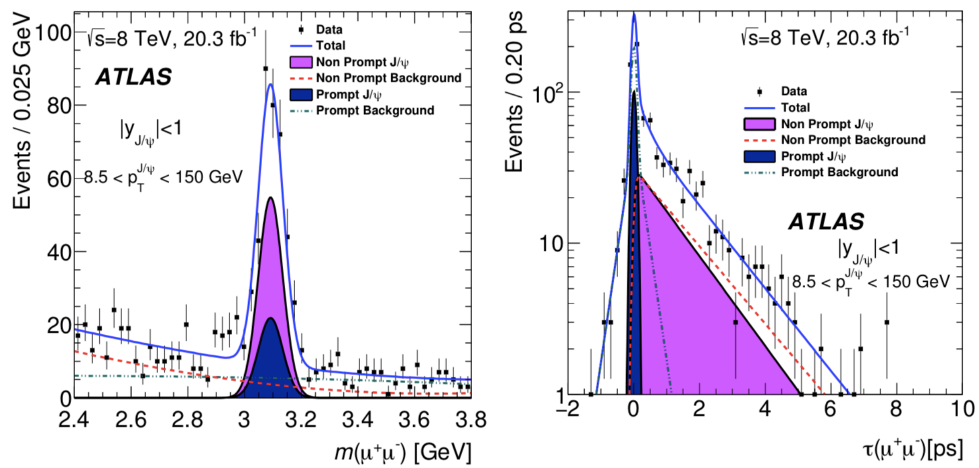
Summary of old experimental results
σ_{eff} generally lower from prompt di-J/ψ and di-Y wrt final states with vector bosons

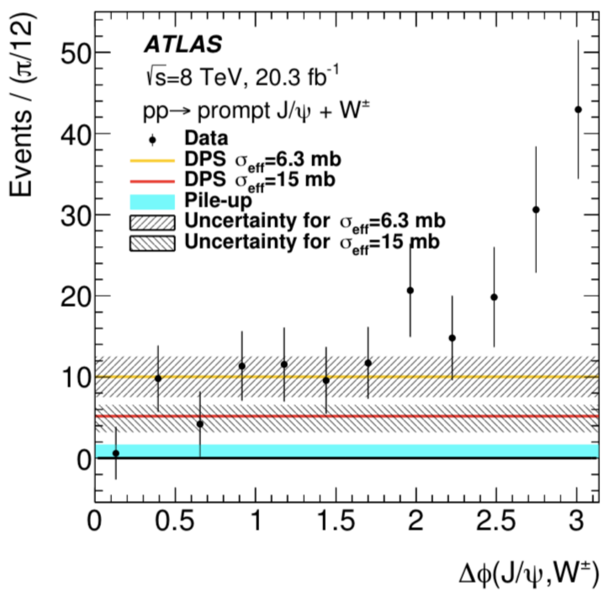
- Probability: $P_{W+J/\psi} = \sigma_{J/\psi}/\sigma_{eff}$
- Value of σ_{eff} unknown → use values from previous ATLAS measurements
  - $\sigma_{eff} = 15 \pm 3\ (stat)^{+5}_{-3}(syst)\ mb$ from W+2jets
  - $\sigma_{eff} = 6.3 \pm 1.6\ (stat) \pm 1.0\ (syst)\ mb$ from prompt 2-J/ψ

J/ψ W± Associated production at 8 TeV

- Dataset: 20.3 fb^{-1} @ 8 TeV
  - Single high-pT trigger
  - $J/\psi \rightarrow \mu^+\mu^-$ and $W^\pm \rightarrow \mu^\pm \nu_\mu$
  - Two pseudo-rapidity intervals
  - Fit to m(μμ) and τ(μμ) → prompt J/ψ
  - Systematic uncertainty dominated by vertex separation between J/ψ and W
- Prompt signal yields:
  - 93±14(stat) for |y(J/ψ)|<1
  - 102±17(stat) for 1<|y(J/ψ)|< 2.1

Di-μ invariant mass and pseudo-proper decay time



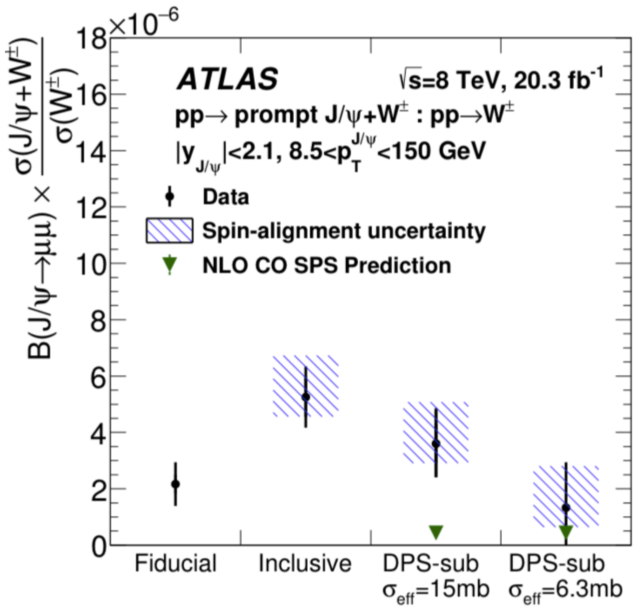


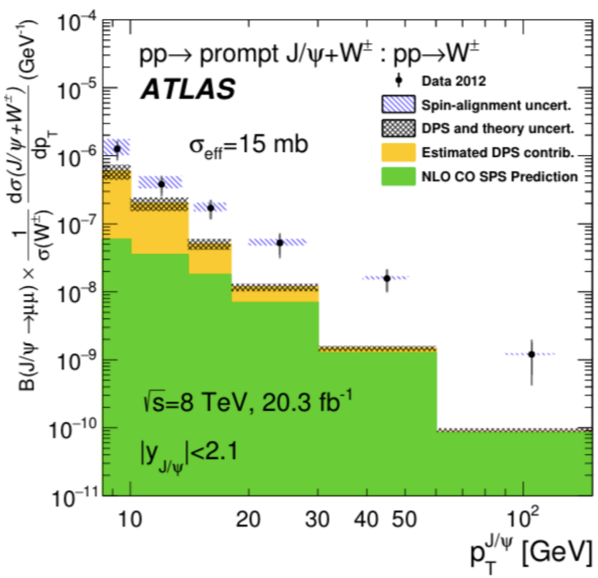
- Contribution from both DPS and SPS (peak at Δφ=π)
- DPS contribution to inclusive signal yield
  - $(31^{+9}_{-12})\%$ (σ_{eff} = 15 mb)
  - (75±23)% (σ_{eff} = 6.3 mb)
- Both values of σ_{eff} consistent with data at low Δφ

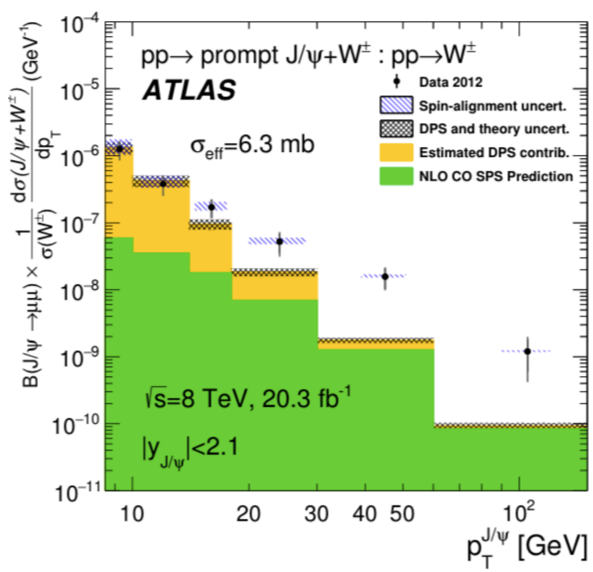
J/ψ W± Associated production at 8 TeV

- Production cross-section ratio
  - In the J/ψ fiducial region
  - Inclusive, after correction for J/ψ acceptance
  - DPS-subtracted, can be compared with CO only theoretical predictions
    → agreement when lower σ_{eff} is used

$$R^{\mathrm{fid}}_{J/\psi} = \frac{\sigma_{\mathrm{fid}}(pp \to J/\psi + W^\pm)}{\sigma(pp \to W^\pm)} \cdot \mathcal{B}(J/\psi \to \mu\mu)$$







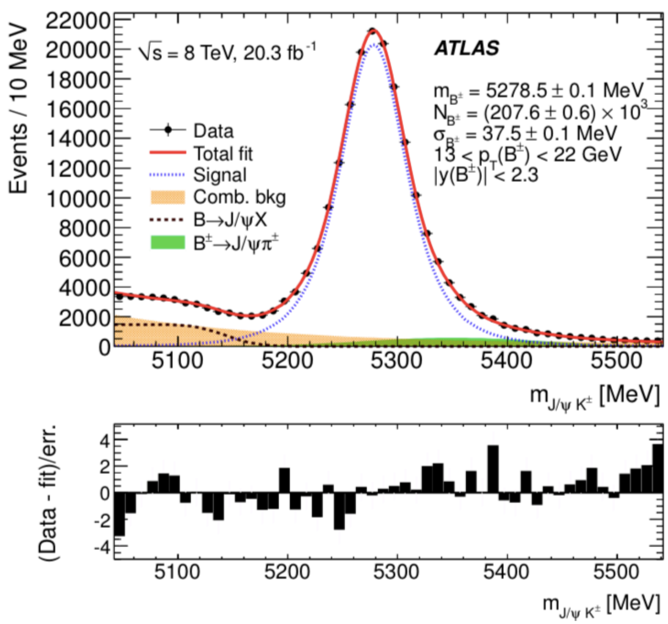
Neither value of σ_{eff} correctly models the J/ψ p_T dependence
probably due to the lack of CS contributions

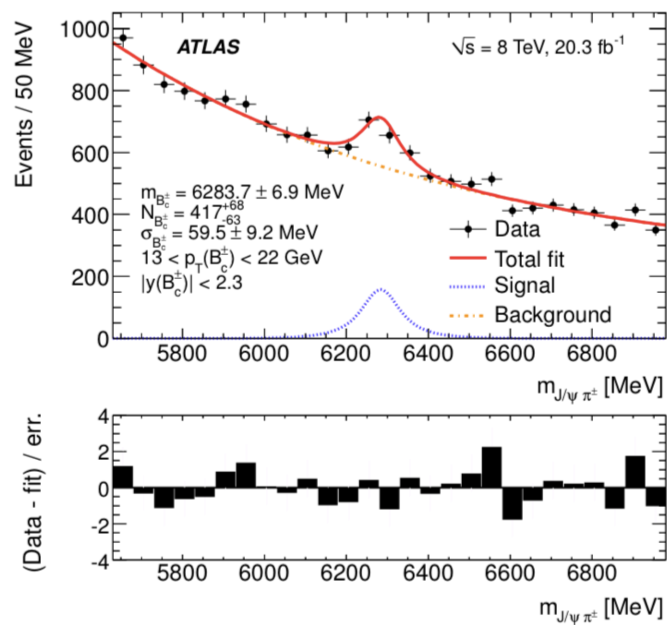
Heavy Flavor: Open Beauty

CERN-EP-2019-194 Submitted to PRD

Relative B_c/B^+ production measurement

- B_c weakly decaying particle made of two heavy quarks
  - Unique probe for heavy quark dynamics
- Measure the ratio: $$\frac{\sigma(B_c)\cdot\mathcal{B}(B_c\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)}$$
  - common systematic uncertainties mostly cancels out





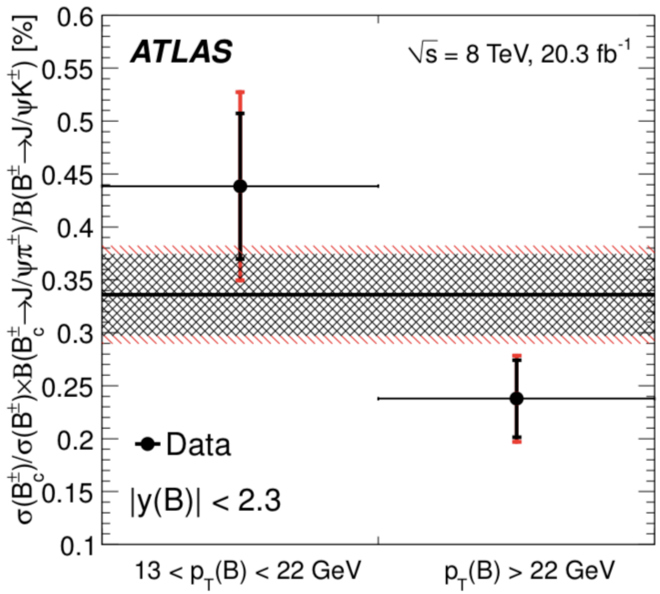
- Dataset: 20.3 fb^{-1} (2012) @ 8 TeV p-p collisions
- 2x2 ($p_T(B)$,$|y(B)|$) analysis bins

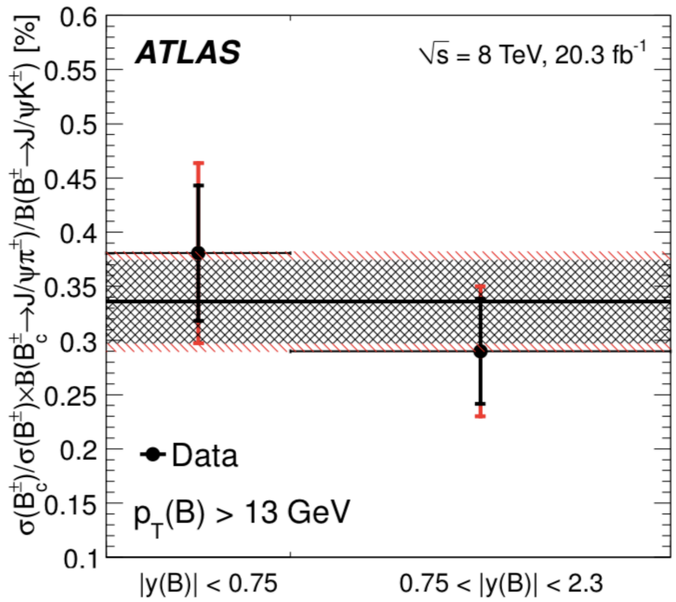
CERN-EP-2019-194 Submitted to PRD

Relative B_c/B^+ production measurement

- Results

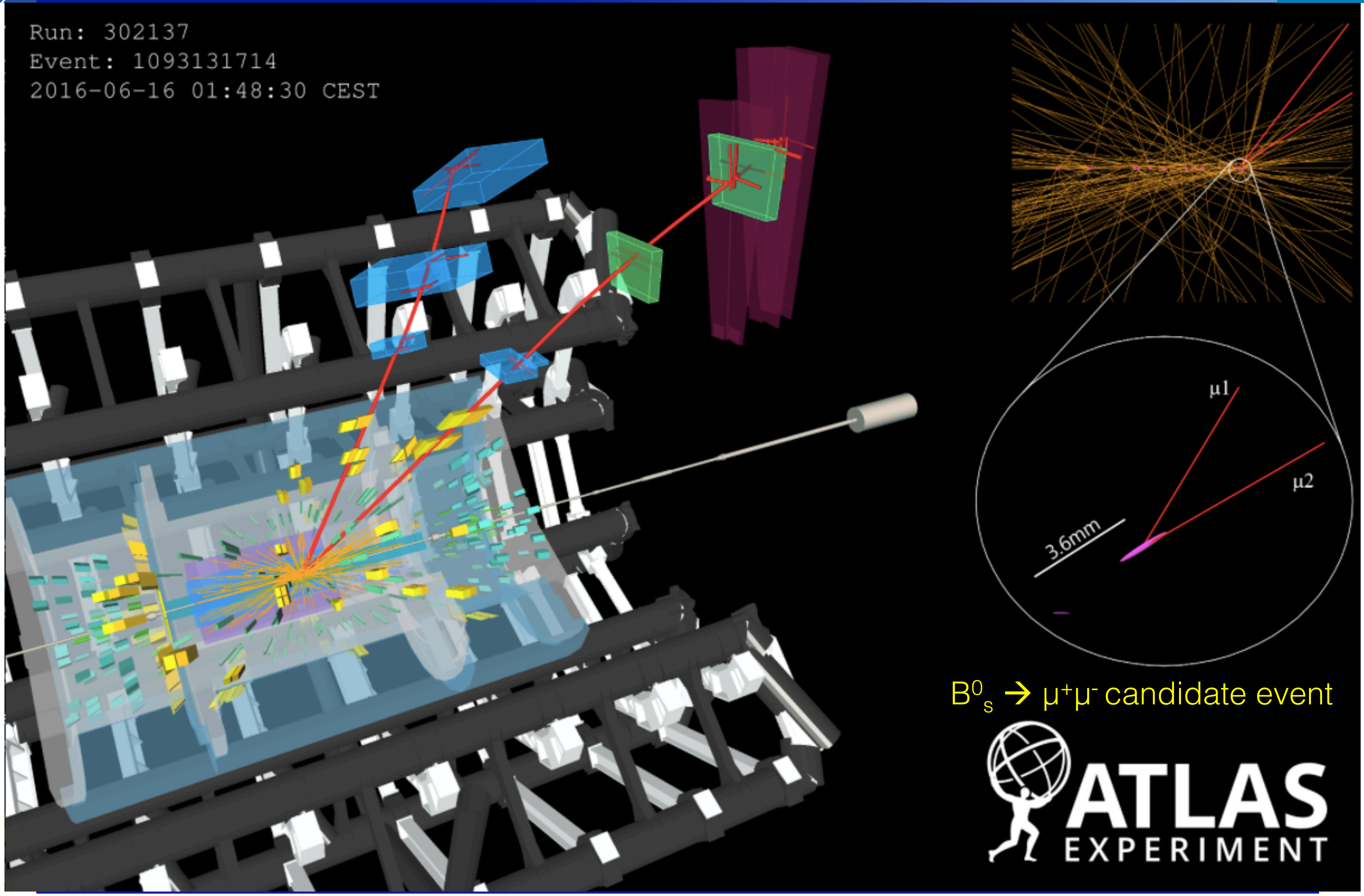
Analysis bin	$\sigma(B_c^\pm)/\sigma(B^\pm) \times \mathcal{B}(B_c^\pm \to J/\psi\pi^\pm)/\mathcal{B}(B^\pm \to J/\psi K^\pm)$
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 2.3$	$(0.34 \pm 0.04_{stat} \pm 0.02_{syst} \pm 0.01_{lifetime})\%$
$13 < p_T(B) < 22$ GeV, $\lvert y(B)\rvert < 2.3$	$(0.44 \pm 0.07_{stat} \pm 0.04_{syst} \pm 0.01_{lifetime})\%$
$p_T(B) > 22$ GeV, $\lvert y(B)\rvert < 2.3$	$(0.24 \pm 0.04_{stat} \pm 0.01_{syst} \pm 0.01_{lifetime})\%$
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 0.75$	$(0.38 \pm 0.06_{stat} \pm 0.04_{syst} \pm 0.01_{lifetime})\%$
$p_T(B) > 13$ GeV, $0.75 < \lvert y(B)\rvert < 2.3$	$(0.29 \pm 0.05_{stat} \pm 0.02_{syst} \pm 0.01_{lifetime})\%$





- Production ratio (in fiducial region): $(0.34 \pm 0.04^{stst} \pm 0.02^{syst} \pm 0.01^{lifetime})\%$
  - Lower than the LHCb result (more forward and lower-p_T fiducial phase-space)
  - Consistent with the CMS result in a similar (but not identical) phase-space
- Production decreases faster with p_T for B_c than B^+; No evident rapidity dependence

Rare $B^0_{(s)} \rightarrow \mu^+\mu^-$ decay



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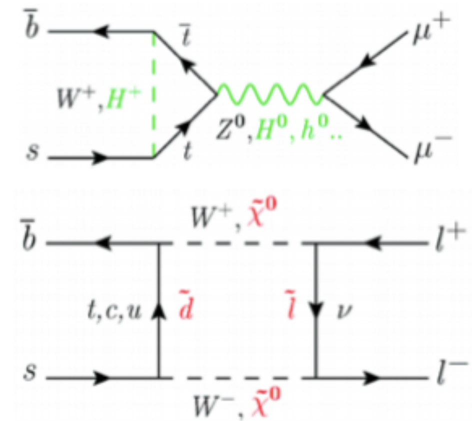
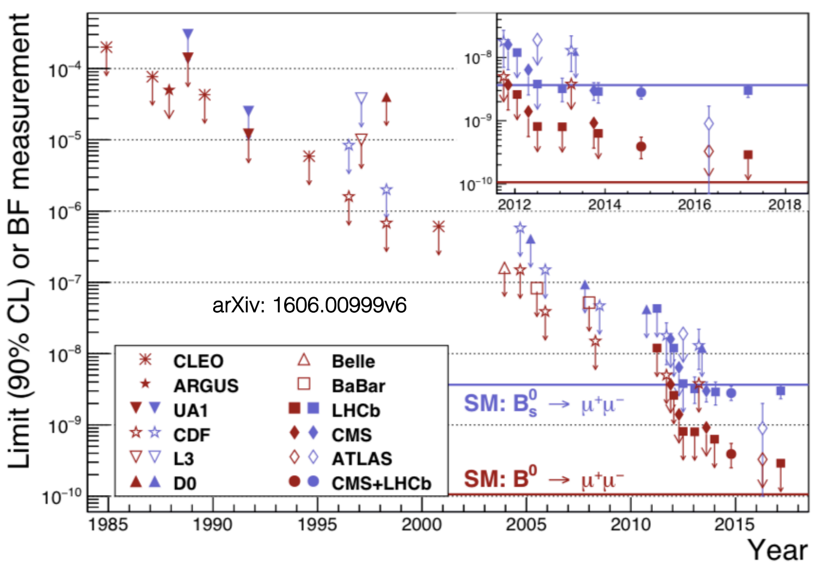
$B^0_{(s)} \rightarrow \mu^+\mu^-$

- $B^0_{(s)} \rightarrow \mu^+\mu^-$:
  - Loops and helicity suppressed
  - Precise theoretical predictions
  - Sensitive to NP via loop diagrams



- Experimental limits/measurements constantly improving
  Approaching SM predictions with LHC experiments



- ATLAS Run1 results
  - $BR(B^0_s \rightarrow \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$
  - $BR(B^0 \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-10}$ at 95% CL
  - Compatible with SM at ~2σ

- New ATLAS measurement based on 26.3 fb^{-1} p-p collision data at 13 TeV from Run2 (2015+2016)
  + combination with Run1

$B^0_{(s)} \rightarrow \mu^+\mu^-$

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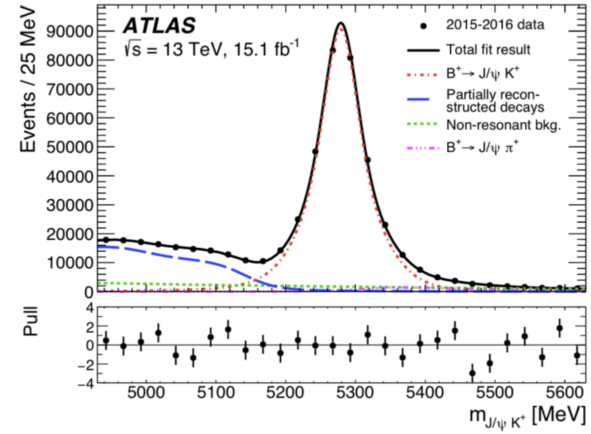
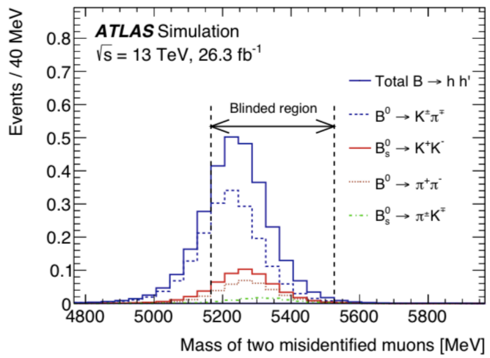
$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}} \times \left[\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right] \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_{d(s)}}$$

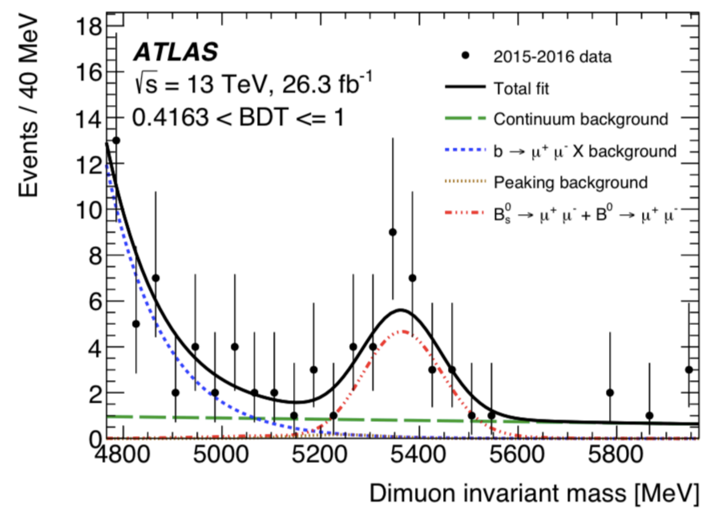


- $B^+ \rightarrow J/\psi\, K^+$ reference channel
- Blinded analyses



- BG main components
  - Combinatorial from semi-leptonic B hadrons
  - Partially-reconstructed B decays with two μ: $B \rightarrow \mu\mu h$
  - B decays to h misidentified as μ: $B \rightarrow hh$, $B \rightarrow h\nu\mu$

- Unbinned ML fit to $m_{\mu\mu}$ in 4 BDT bins
- B^0_s and B^0 peaks overlap (limited resolution) → statistically separated in the fit procedure
- Extracted yields:
  - $N(B^0_s) = 80 \pm 22$ $N(B^0) = -12 \pm 20$
- Consistent with SM expectations:
  - $N(B^0_s) = 91$ $N(B^0) = 10$



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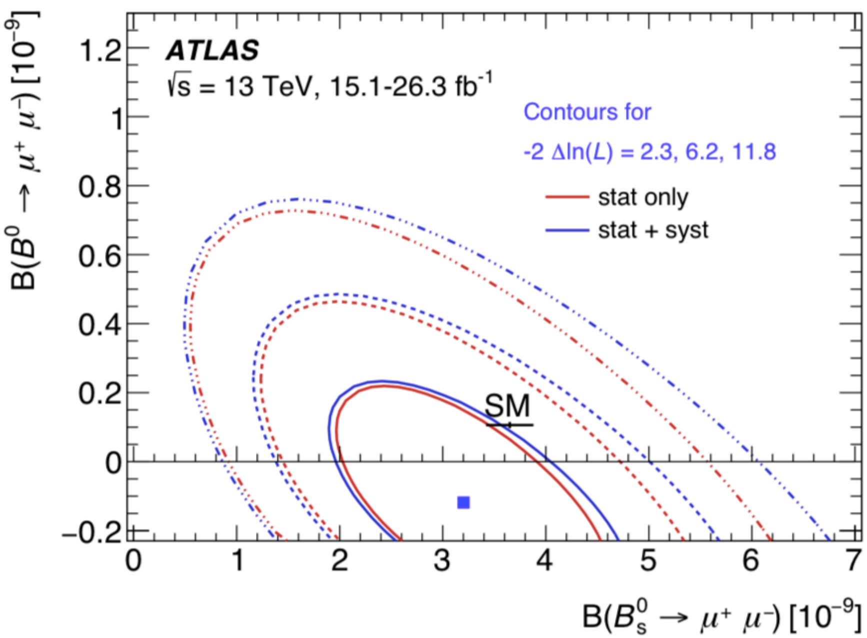
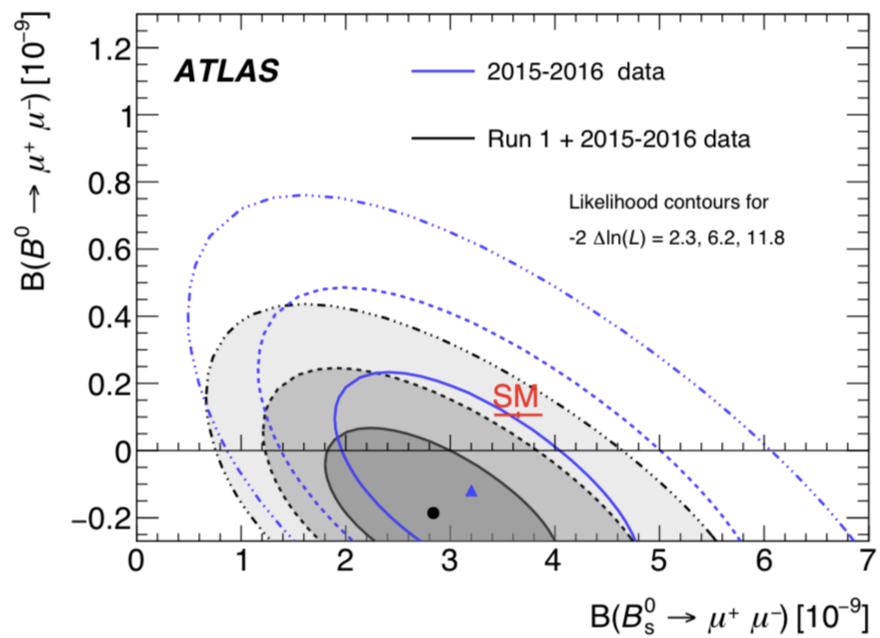
$B^0_{(s)} \rightarrow \mu^+\mu^-$: Results

- Run2 only
  - $BR(B^0_s \rightarrow \mu^+\mu^-) = (3.2\ ^{+1.1}_{-1.0}) \times 10^{-9}$
  - $BR(B^0 \rightarrow \mu^+\mu^-) < 4.3 \times 10^{-10}$ 95% C.L.
- Combination with Run1 ATLAS results
  - $BR(B^0_s \rightarrow \mu^+\mu^-) = (2.8\ ^{+0.8}_{-0.7}) \times 10^{-9}$
  - $BR(B^0 \rightarrow \mu^+\mu^-) < 2.1 \times 10^{-10}$ 95% C.L.





- Compatible with SM at 1σ level
- Compatible with SM at 2.4σ level

Experiment	$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-)$	$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$
ATLAS	$2.8^{+0.8}_{-0.7}\times^{-9}$	$(-1.9 \pm 1.6)\times^{-10}$
CMS	$(2.9^{+0.7}_{-0.6} \pm (0.2))\times^{-9}$	$0.8^{+1.4}_{-1.3}\times^{-10}$
LHCb	$3.0^{+0.7}_{-0.6}\times^{-9}$	$1.5^{+1.1}_{-1.0}\times^{-10}$

- SM predictions (JHEP 10 (2019) 232):
  - $BR(B^0_s \rightarrow \mu^+\mu^-) = (3.44 \pm 0.14) \times 10^{-9}$
  - $BR(B^0_s \rightarrow \mu^+\mu^-) = (1.05 \pm 0.05) \times 10^{-10}$
- Combination of the 3 exp ongoing

Summary

- ATLAS has a rich physics program for studies of heavy flavour physics

Selection of recent results on:

- Associated production of J/ψ and $W^{\pm}$
  - Production cross-section ratio DPS-subtracted in agreement with NLO
  - Disagreement with models on J/ψ p_T dependence: CS contribution?
- Relative B_c/B^+ production measurement
  - Production ratio (in fiducial region): $(0.34\pm0.04^{stst}\pm0.02^{syst}\pm0.01^{lifetime})\%$
    Consistent with measurements from CMS
- $B^0_{(s)} \rightarrow \mu^+\mu^-$ rare decay new results
  - $BR(B^0_s \rightarrow \mu^+\mu^-) = (2.8\ ^{+0.8}_{-0.7}) \times 10^{-9}$
  - $BR(B^0 \rightarrow \mu^+\mu^-) < 2.1 \times 10^{-10}$ at 95% C.L.

Many more studies ongoing; more results to come in the next months

Additional Material

J/ψ $W^{\pm}$ Associated production at 8 TeV

J/ψ selection
$2.4 < m(\mu^+\mu^-) < 3.8$ GeV
$8.5 < p_T^{J/\psi} < 150$ GeV, $\lvert y_{J/\psi}\rvert < 2.1$
$p_T^{\mu_1} > 4$ GeV, $\lvert\eta^{\mu_1}\rvert < 2.5$
either $p_T^{\mu_2} > 2.5$ GeV, $1.3 \leq \lvert\eta^{\mu_2}\rvert < 2.5$ or $p_T^{\mu_2} > 3.5$ GeV, $\lvert\eta^{\mu_2}\rvert < 1.3$

Source of Uncertainty	Uncertainty [%] $\lvert y_{J/\psi}\rvert < 1$	Uncertainty [%] $1 < \lvert y_{J/\psi}\rvert < 2.1$
J/ψ mass fit	8.7	4.9
Vertex separation	12	15
$\mu_{J/\psi}$ efficiency	2.0	1.6
Pile-up	1.1	1.4
$J/\psi + Z$ and $J/\psi + W^{\pm}(\to \tau^{\pm}\nu)$	3.5	4.8
Efficiency correction	2.3	2.3

$p_T^{J/\psi}$ [GeV]	Inclusive prompt ratio [$\times 10^{-7}$/ GeV] value	± (stat)	± (syst)	± (spin)	Estimated DPS [$\times 10^{-7}$/ GeV] $\sigma_{\text{eff}} = 15^{+5.8}_{-4.2}$ mb	Estimated DPS [$\times 10^{-7}$/ GeV] $\sigma_{\text{eff}} = 6.3 \pm 1.9$ mb
(8.5, 10)	12.6	± 3.3	± 2.4	$^{+5.0}_{-2.4}$	$5.3^{+1.5}_{-2.1}$	12.7 ± 3.8
(10, 14)	3.8	± 1.0	± 0.8	$^{+1.2}_{-0.5}$	$1.64^{+0.46}_{-0.64}$	3.9 ± 1.2
(14, 18)	1.70	± 0.50	± 0.21	$^{+0.35}_{-0.17}$	$0.33^{+0.09}_{-0.13}$	0.77 ± 0.23
(18, 30)	0.52	± 0.17	± 0.12	$^{+0.08}_{-0.04}$	$0.048^{+0.013}_{-0.019}$	0.114 ± 0.034
(30, 60)	0.156	± 0.054	± 0.021	$^{+0.013}_{-0.006}$	$0.0021^{+0.0006}_{-0.0008}$	0.0049 ± 0.0015
(60, 150)	0.012	± 0.006	± 0.005	$^{+0.0005}_{-0.0002}$	$0.000032^{+0.000009}_{-0.000012}$	0.000076 ± 0.000023

Relative B_c/B^+ production measurement

Analysis bin	Fitted mass of the $B^\pm$ [MeV]	Number of the $B^\pm$ candidates	σ_m of the $B^\pm$ [MeV]
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 2.3$	5278.6 ± 0.1	$(398.3 \pm 0.8) \times 10^3$	37.5 ± 0.1
$13 < p_T(B) < 22$ GeV, $\lvert y(B)\rvert < 2.3$	5278.5 ± 0.1	$(207.6 \pm 0.6) \times 10^3$	37.5 ± 0.1
$p_T(B) > 22$ GeV, $\lvert y(B)\rvert < 2.3$	5278.8 ± 0.1	$(190.9 \pm 0.6) \times 10^3$	38.1 ± 0.1
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 0.75$	5278.4 ± 0.1	$(147.9 \pm 0.5) \times 10^3$	26.6 ± 0.1
$p_T(B) > 13$ GeV, $0.75 < \lvert y(B)\rvert < 2.3$	5279.1 ± 0.1	$(248.8 \pm 0.6) \times 10^3$	45.9 ± 0.1

Analysis bin	Fitted mass of the $B_c^\pm$ [MeV]	Number of the $B_c^\pm$ candidates	σ_m of the $B_c^\pm$ [MeV]
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 2.3$	6281.0 ± 4.5	798^{+92}_{-84}	52.4 ± 5.6
$13 < p_T(B) < 22$ GeV, $\lvert y(B)\rvert < 2.3$	6283.7 ± 6.9	417^{+68}_{-63}	59.5 ± 9.2
$p_T(B) > 22$ GeV, $\lvert y(B)\rvert < 2.3$	6278.4 ± 5.7	363^{+59}_{-56}	45.7 ± 6.7
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 0.75$	6275.1 ± 1.7	319^{+57}_{-52}	31.5 ± 5.7
$p_T(B) > 13$ GeV, $0.75 < \lvert y(B)\rvert < 2.3$	6275.2 ± 9.0	454^{+71}_{-66}	67.1 ± 10.4

Source of uncertainty	Uncertainty value			
	$B_c^\pm$		$B^\pm$	
	$\lvert y\rvert < 0.75$	$0.75 < \lvert y\rvert < 2.3$	$\lvert y\rvert < 0.75$	$0.75 < \lvert y\rvert < 2.3$
Signal model of the fit	2.5%	2.8%	0.1%	0.2%
Cabibbo-suppressed decay modeling	2.4%	2.4%	0.5%	0.5%
Background model of the fit	2.8%	1.3%	0.2%	0.2%
Trigger effects and reconstruction effects	1.1%	1.0%	1.2%	1.1%
B-meson lifetime uncertainty	1.0%	0.9%	< 0.1%	< 0.1%

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

- BDT input variables

Variable	Description
p_T^B	Magnitude of the B candidate transverse momentum $\overrightarrow{p_T}^B$.
$\chi^2_{\mathrm{PV,DV}\,xy}$	Compatibility of the separation $\overrightarrow{\Delta x}$ between production (i.e. associated PV) and decay (DV) vertices in the transverse projection: $\overrightarrow{\Delta x}_T \cdot \Sigma^{-1}_{\overrightarrow{\Delta x}_T} \cdot \overrightarrow{\Delta x}_T$, where $\Sigma_{\overrightarrow{\Delta x}_T}$ is the covariance matrix.
$\Delta R_{\mathrm{flight}}$	Three-dimensional angular distance between $\overrightarrow{p}^B$ and $\overrightarrow{\Delta x}$: $\sqrt{\alpha_{2D}{}^2 + (\Delta\eta)^2}$
$\lvert\alpha_{2D}\rvert$	Absolute value of the angle in the transverse plane between $\overrightarrow{p_T}^B$ and $\overrightarrow{\Delta x}_T$.
L_{xy}	Projection of $\overrightarrow{\Delta x}_T$ along the direction of $\overrightarrow{p}^B_T$: $(\overrightarrow{\Delta x}_T \cdot \overrightarrow{p_T}^B)/\lvert\overrightarrow{p_T}^B\rvert$.
IP^{3D}_B	Three-dimensional impact parameter of the B candidate to the associated PV.
$\mathrm{DOCA}_{\mu\mu}$	Distance of closest approach (DOCA) of the two tracks forming the B candidate (three-dimensional).
$\Delta\phi_{\mu\mu}$	Azimuthal angle between the momenta of the two tracks forming the B candidate.
$\lvert d_0\rvert^{\max}$-sig.	Significance of the larger absolute value of the impact parameters to the PV of the tracks forming the B candidate, in the transverse plane.
$\lvert d_0\rvert^{\min}$-sig.	Significance of the smaller absolute value of the impact parameters to the PV of the tracks forming the B candidate, in the transverse plane.
$P^{\min}_L$	The smaller of the projected values of the muon momenta along $\overrightarrow{p_T}^B$.
$I_{0.7}$	Isolation variable defined as ratio of $\lvert\overrightarrow{p_T}^B\rvert$ to the sum of $\lvert\overrightarrow{p_T}^B\rvert$ and the transverse momenta of all additional tracks contained within a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.7$ around the B direction. Only tracks matched to the same PV as the B candidate are included in the sum.
$\mathrm{DOCA}_{\mathrm{xtrk}}$	DOCA of the closest additional track to the decay vertex of the B candidate. Only tracks matched to the same PV as the B candidate are considered.
$N^{\mathrm{close}}_{\mathrm{xtrk}}$	Number of additional tracks compatible with the decay vertex (DV) of the B candidate with $\ln(\chi^2_{\mathrm{xtrk,DV}}) < 1$. Only tracks matched to the same PV as the B candidate are considered.
$\chi^2_{\mu,\mathrm{xPV}}$	Minimum χ^2 for the compatibility of a muon in the B candidate with any PV reconstructed in the event.

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

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

Semi-rare

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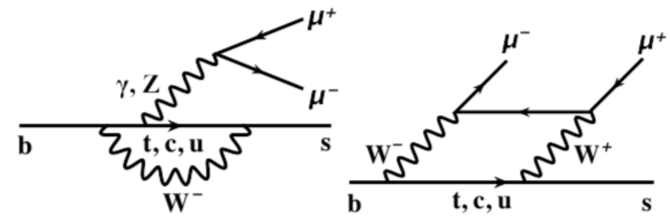
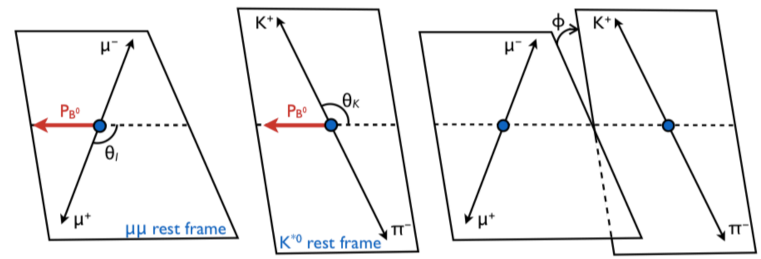
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

- $B^0 \to K^{*0}\mu^+\mu^- \to K^+\pi^-\mu^+\mu^-$ is a FCNC process fully described by the three angles (θ_L, θ_K, ϕ) and the di-μ invariant mass squared q^2.
- New physics entering the loop can be detected by looking at the angular distributions of the decay
- Angular differential decay rate expressed with S coefficients represented by helicity or transversity amplitudes





$$A_{FB} = 3S_6/4$$

$$\begin{aligned} P_1 &= \frac{2S_3}{1-F_L} \\ P_2 &= \frac{2}{3}\frac{A_{FB}}{1-F_L} \\ P_3 &= -\frac{S_9}{1-F_L} \\ P'_{j=4,5,6,8} &= \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}. \end{aligned}$$

A_{FB} = Forward-backward Asymmetry
F_L = fraction of longitudinally polarised K*
F_S = s-wave fraction

- Generally written in terms of P and P' observables as they are less sensitive to theoretical uncertainties at LO

LHCb measured a ~3σ discrepancy with model on P'_5

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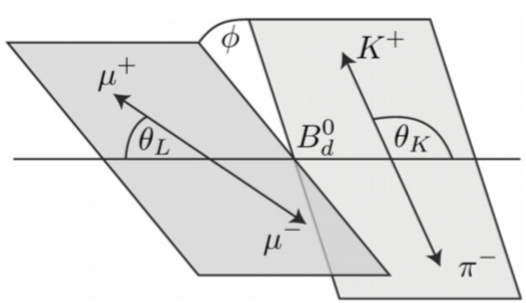
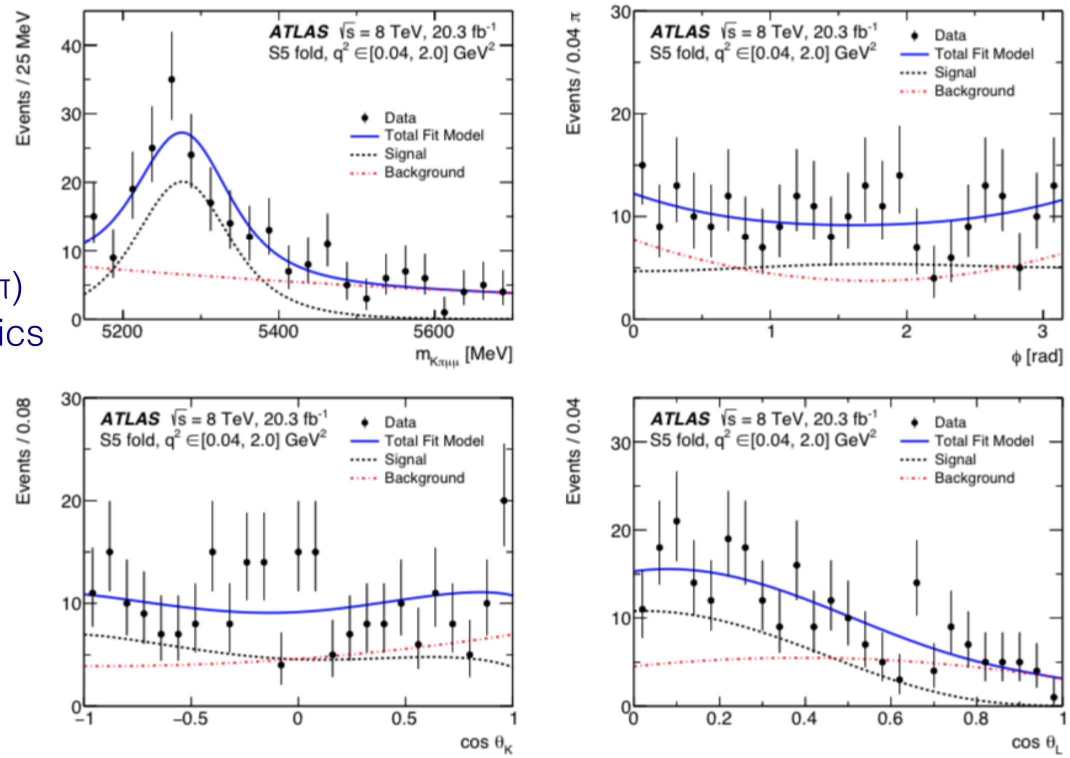
- ATLAS analysis uses ~20 fb^{-1} of 8 TeV pp data to extract P_1 and P'_i (i=4,5,6,8)

- Fit signal and background
  - Four fits, 3 free parameters each
  - FL, S3 common to each fit
  - S4, S5, S7, S8 fitted parameters
  - P1, Pi' extracted from fit parameters
  - S-wave component (non-resonant Kπ) neglected and included as systematics
  - 340 events in 3 q^2 bins
- Signal PDF folded to reduce the number of free parameters and improve fit convergence





Examples with S5 folding scheme applied

Result still statistically limited

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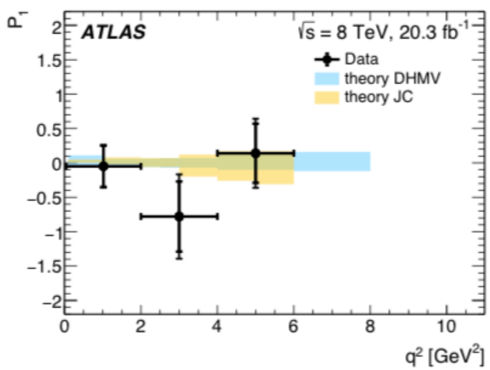
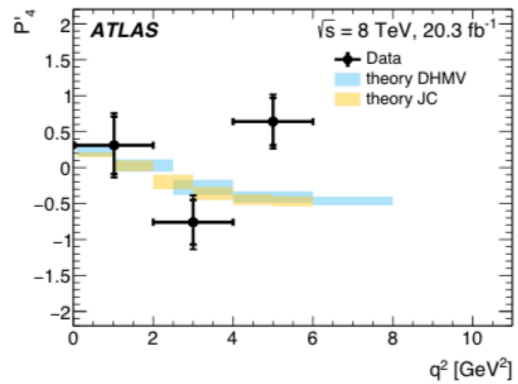
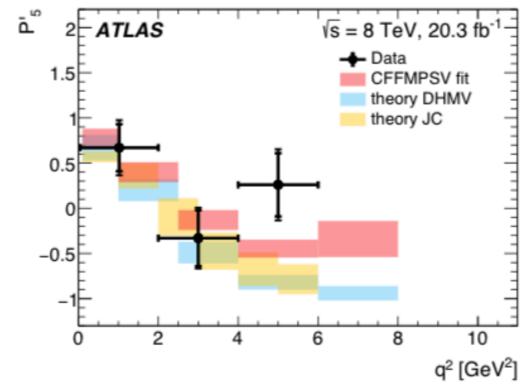
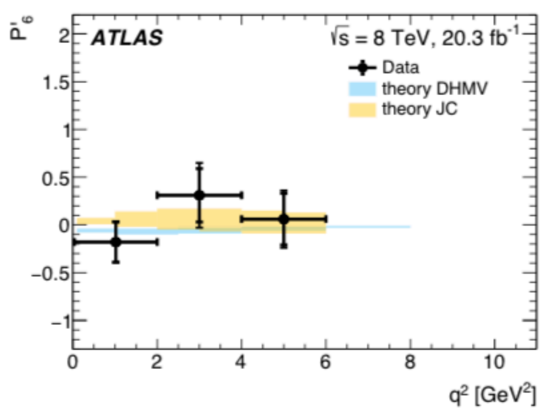
- Theory:
  - DHMV/JC: QCD factorization, hadronic uncertainties from calculations
  - HEP t/CFFMPSV t: hadronic charm contributions fitted from LHCb data

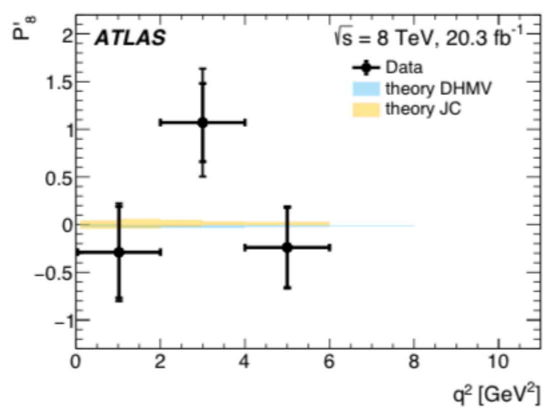
- ATLAS generally in good agreement with SM, except a ~2.5σ deviation from DHMV for P_4', P_5' in one bin











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