Recent Heavy Flavour results from ATLAS and CMS

Leonid Gladilin (MSU / JINR)
on behalf of the ATLAS and CMS Collaborations

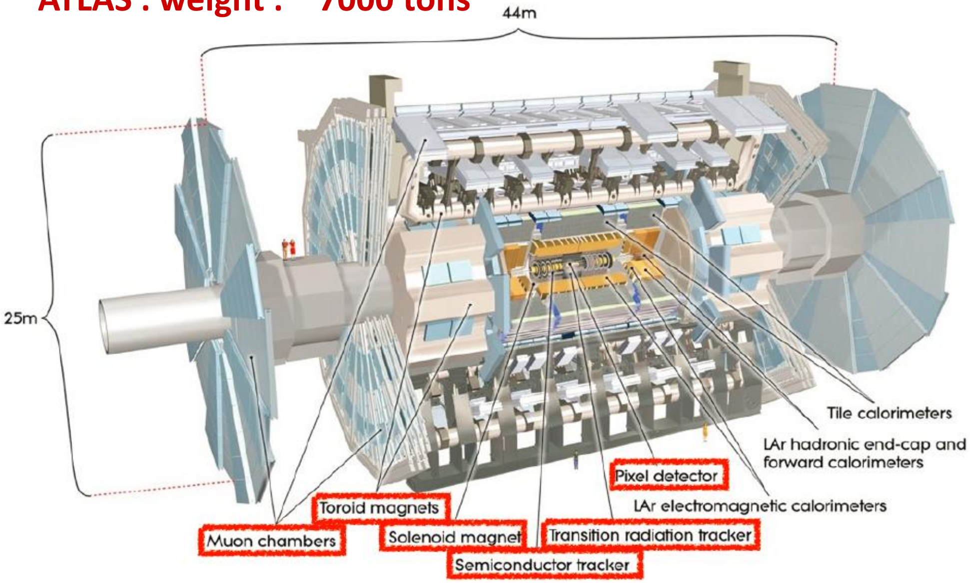
ICPPA 2022, 29.11-02.12 2022, MEPhI

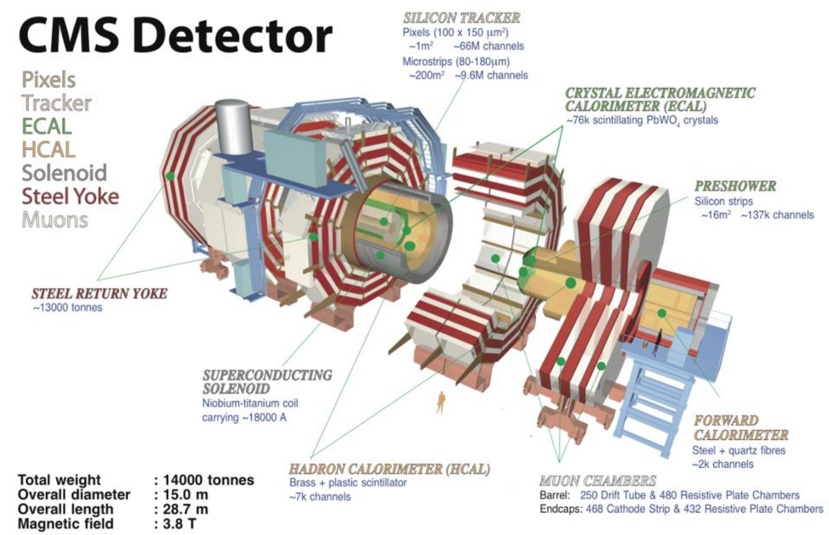
Selected recent results

Outline : **ATLAS + CMS @ LHC**
- **Di-charmonia resonances** **(ATLAS-CONF-2022-040, CMS PAS BPH-21-003)**
- **Triple J/ψ production** **(arXiv:2111.05370 accepted by Nature Physics)**
- **B_c^+ production and decays** **(PRD 104(2021), JHEP 08(2022)87)**
- **$B_{(s)}^0 \to \mu^+\mu^-$ decays (FCNC)** **(CMS PAS BPH-21-006)**
- ***b* quark fragmentation** **(JHEP 12 (2021) 131)**
- **$B^0_{(s)} \to \psi(2S)K^0_S\ (X)$ decays** **(EPJC 82 (2022) 499)**
- **Prospects & Summary**

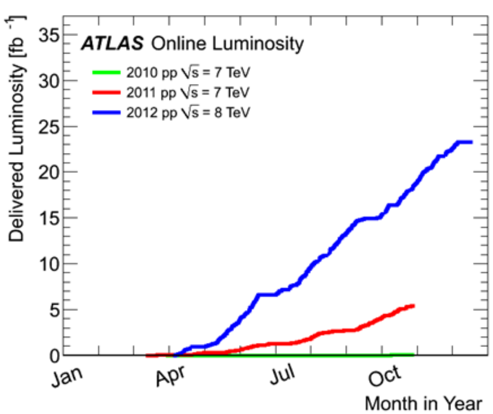
ATLAS+CMS @ LHC

ATLAS : weight : ~ 7000 tons



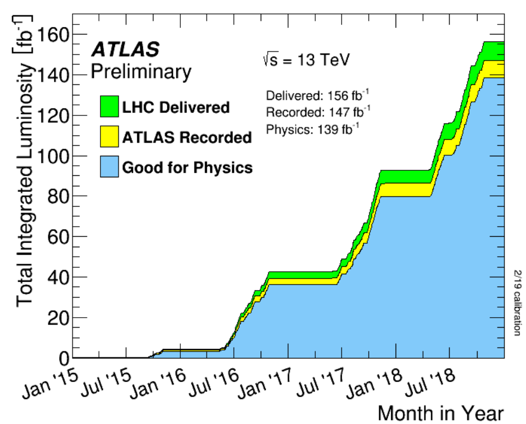


Run I : 2010 - 2012

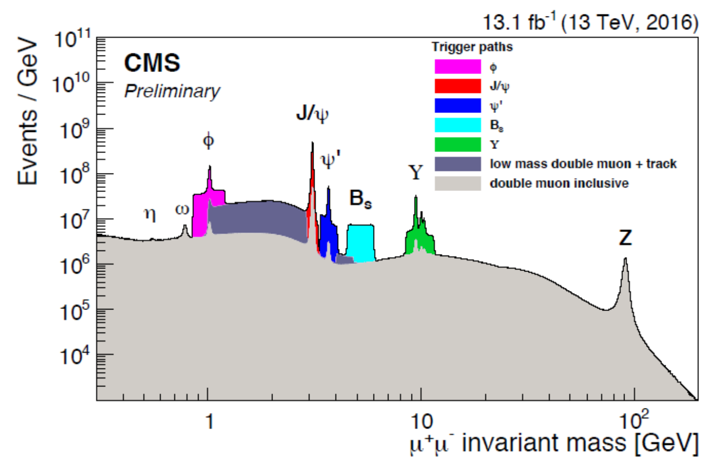


$L_{max} = 6.76 \times 10^{33}\ cm^{-2}\ s^{-1}$

Run II : 2015 - 2018



$L_{max} = 20.9 \times 10^{33}\ cm^{-2}\ s^{-1}$



Dimuon triggers

Di-charmonia tetraquarks ($c\bar{c}c\bar{c}$)

ATLAS-CONF-2022-040

J/ψJ/ψ and J/ψ+ψ(2S) in 4μ final state studied at ATLAS using 139 fb^{-1} of pp at √s = 13 TeV

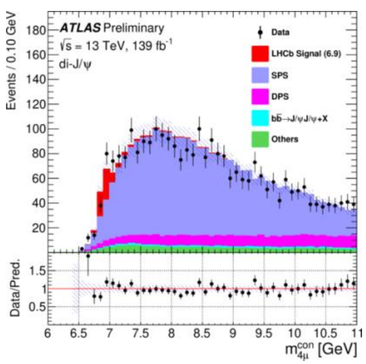
Blind analysis

Di-charmonium Process	Generator	PDF	Parton shower	Tune
SPS	Pythia 8.244	NNPDF23LO	Pythia 8.244+NNPDF23LO	A14
DPS	Pythia 8.244	NNPDF23LO		A14
Non-prompt	Pythia 8.244	NNPDF23LO		A14
X(6900)	JHU	CTEQ6L1		A14

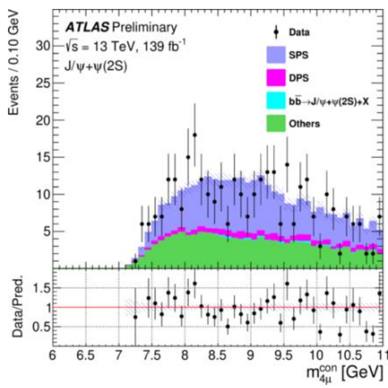
Event selection, reconstruction and definition of signal and control regions

Signal region	SPS/DPS control region	non-prompt region
Di-muon or tri-muon triggers, Opposite charged muons from the same J/ψ or $\psi(2S)$ vertex, Loose muon ID, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons $m_{J/\psi} \in \{2.94, 3.25\}$ GeV, or $m_{\psi(2S)} \in \{3.56, 3.80\}$ GeV, Loose vertex cuts $\chi^2_{4\mu}/N < 40$ and $\chi^2_{\text{di-}\mu}/N < 100$,		
Vertex $\chi^2_{4\mu}/N < 3$, $L^{4\mu}_{xy} < 0.2$ mm, $\lvert L^{\text{di-}\mu}_{xy}\rvert < 0.3$ mm,		Vertex $\chi^2_{4\mu}/N > 6$,
$m_{4\mu} < 7.5$ GeV, $\Delta R < 0.25$ between charmonia	7.5 GeV$< m_{4\mu} <$ 12.0 GeV (SPS) 14.0 GeV$< m_{4\mu} <$ 25.0 GeV (DPS)	$\lvert L^{\text{di-}\mu}_{xy}\rvert > 0.4$ mm

ΔR > 0.25



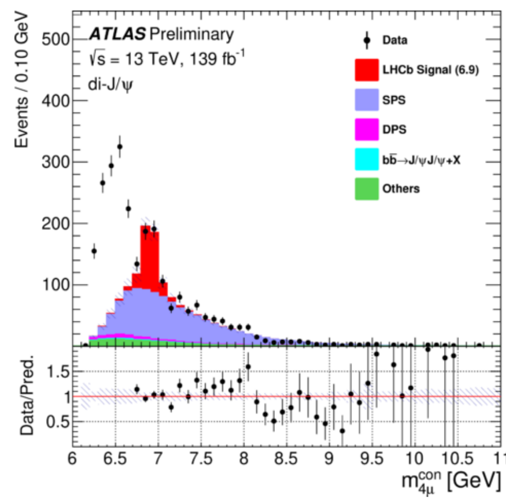
m(J/ψ J/ψ)



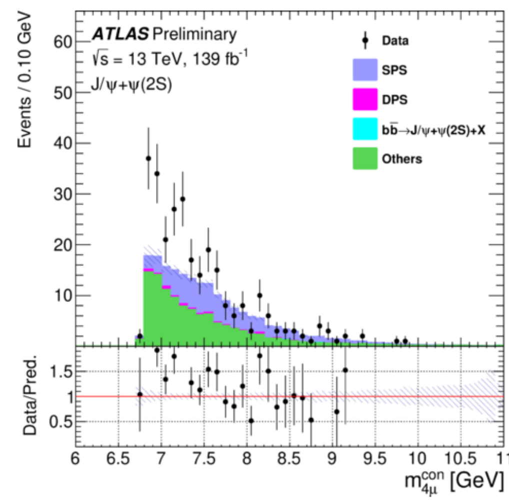
m(J/ψ ψ(2S))

ΔR < 0.25

Wow effect after unblinding



m(J/ψ J/ψ)



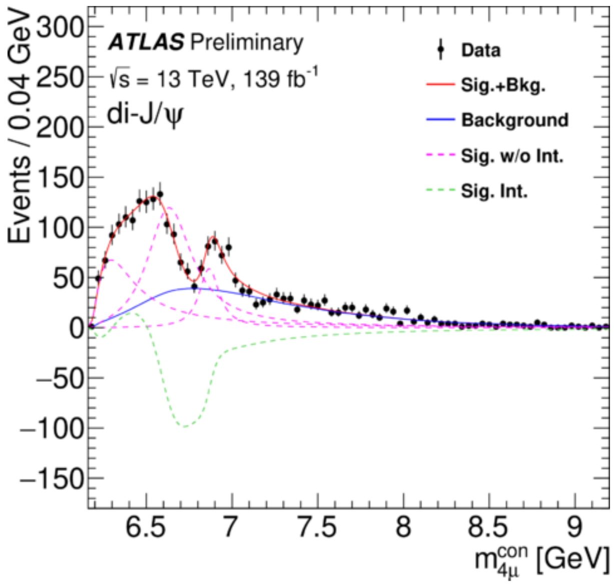
m(J/ψ ψ(2S))

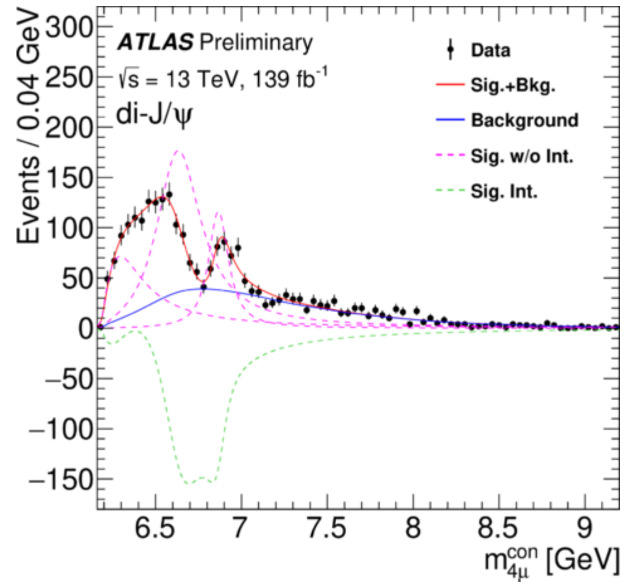
Di-charmonia tetraquarks ($c\bar{c}c\bar{c}$)

ATLAS-CONF-2022-040

J/ψJ/ψ: best fit obtained with 3 interfering BWs, 70% worse fit quality for 2-resonance fit

6.9 GeV resonance confirmed, consistent with LHCb

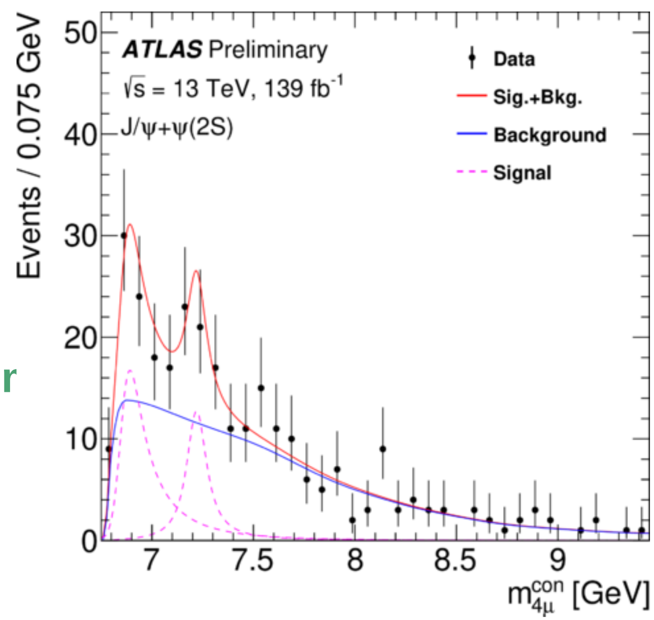


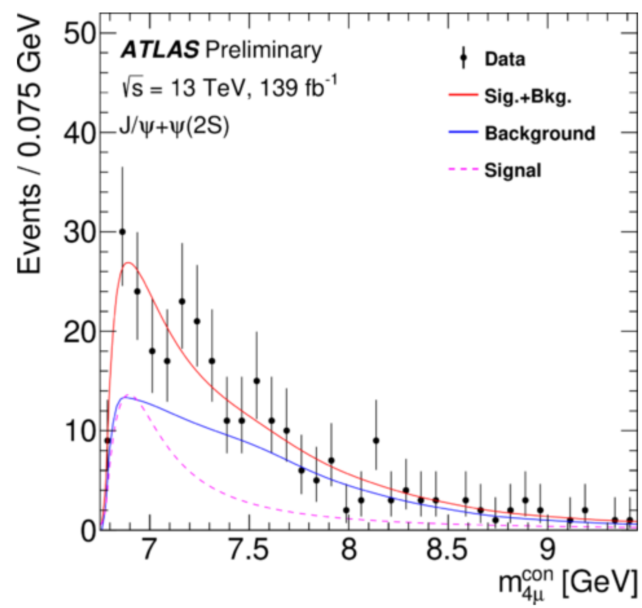


Fit on J/ψψ(2S) mass spectrum, significance:

- ● Model A: 4.6σ
- ○ X(7200): 3.2σ
- ● Model B: 4.3σ

Evidence for an enhancer at 6.9 GeV and 7.2 GeV





Di-J/ψ tetraquarks ($c\bar{c}c\bar{c}$)

CMS PAS BPH-21-003

J/ψJ/ψ (→ 4μ) spectrum studied at CMS using 135 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV (2016-2018)

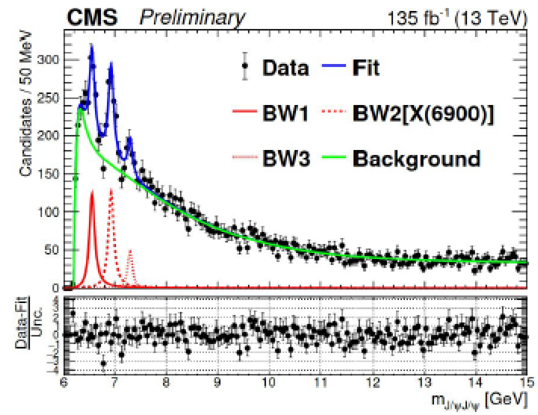
Event selection and reconstruction:

- **3-μ trigger**: $\mu^+\mu^-$ from J/ψ + third muon (on muons from J/ψ: $p_T(\mu^+\mu^-) > 3.5$ GeV in 2017-2018)
- **blinded signal region m(J/ψJ/ψ) in [6.2, 7.8] GeV** (from preliminary investigation on 2011-2012 data)
- $p_T(\mu) > 2.0$ GeV; $|\eta(\mu)| < 2.4$; loose muon identification
- $m(\mu^+\mu^-)$ in [2.95, 3.25] GeV; $p_T(\mu^+\mu^-) > 3.5$ GeV $P_{vtx}(\mu^+\mu^-) > 0.5\%$
- common vertex fit: $P_{vtx}(4\mu) > 0.5\%$
- Arbitration of multiple candidates:
  - Select best combination of same 4μ (from MC: 0.2%)
  - Keep all candidates arising from more than four muons (from MC: 0.2%)

$$\chi^2_m = \left(\frac{m_1(\mu^+\mu^-)-M_{J/\psi}}{\sigma_{m_1}}\right)^2 + \left(\frac{m_2(\mu^+\mu^-)-M_{J/\psi}}{\sigma_{m_2}}\right)^2$$

Background model:

- **NRSPS**: threshold function * pol2 * exponential
- **NRDPS**: threshold function * pol2 * exponential
- **BW0**: Relativistic Breit-Wigner near J/ψJ/ψ threshold
  - inadequacy of NRSPS near threshold
  - feed-down of partially reconstructed higher mass states
  - possible coupled-channel interactions, pomeron-exchange processes, etc.



χ^2-Prob = 79% in [6.2, 15] GeV

No interference assumed

Di-J/ψ tetraquarks ($c\bar{c}c\bar{c}$)

CMS PAS BPH-21-003

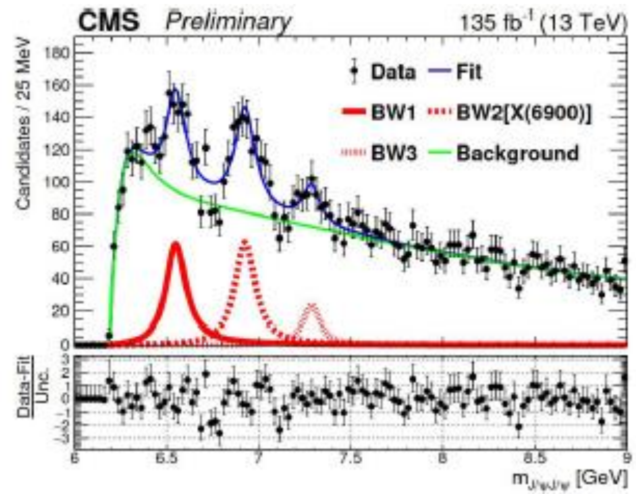
CMS signal + background model

Three Relativistic Breit-Wigner ($J^P = 0^+$) are considered

	Mass (MeV)	Width (MeV)	Local stat. signif.
BW1	6552 ± 10 ± 12	124 ± 29 ± 34	> 5.7σ
BW2	6927 ± 9 ± 5	122 ± 22 ± 19	> 9.4σ
BW3	7287 ± 19 ± 5	95 ± 46 ± 20	> 4.1σ

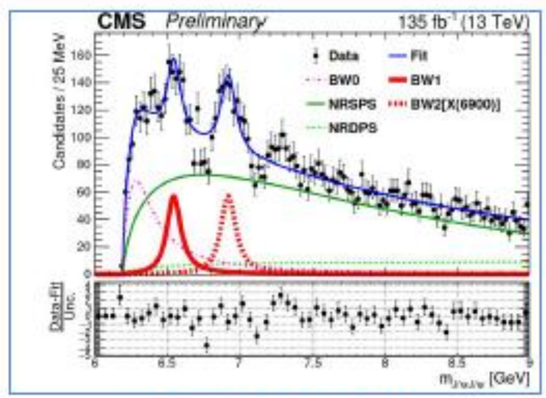
first error is statistic, second is systematic error

X(6900) confirmed at CMS
Values consistent with LHCb

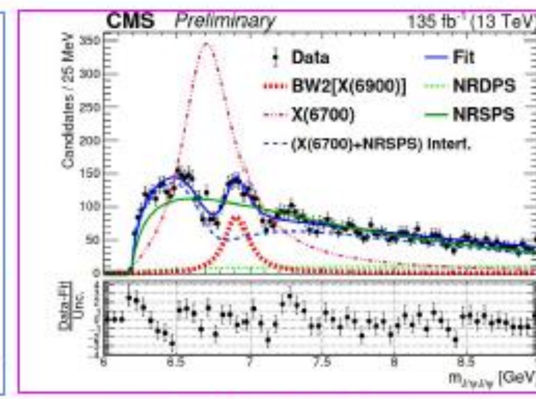


LHCb signal models + CMS background

- **Model 1:**
  - X(6900) parameters in agreement
  - but dip at 6.7 not well described
- **Model 2:**
  - Larger X(6700) amplitude
  - X(7200) region not well described



χ^2-Prob = 10^{-4} in [6.2, 7.8] GeV



χ^2-Prob = 10^{-4} in [6.2, 7.8] GeV

LHCb non-interference model I

LHCb interference model II

Di-charmonia tetraquarks ($c\bar{c}c\bar{c}$)

ATLAS

(GeV)	m_0	Γ_0	m_1	Γ_1
di-J/ψ	$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
	m_2	Γ_2	—	
	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	
(GeV)		m_3	Γ_3	
J/ψ+$\psi(2S)$	model A	$7.22 \pm 0.03^{+0.02}_{-0.03}$	$0.10^{+0.13+0.06}_{-0.07-0.05}$	—
	model B	$6.78 \pm 0.36^{+0.35}_{-0.54}$	$0.39 \pm 0.11^{+0.11}_{-0.07}$	—

CMS

	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56

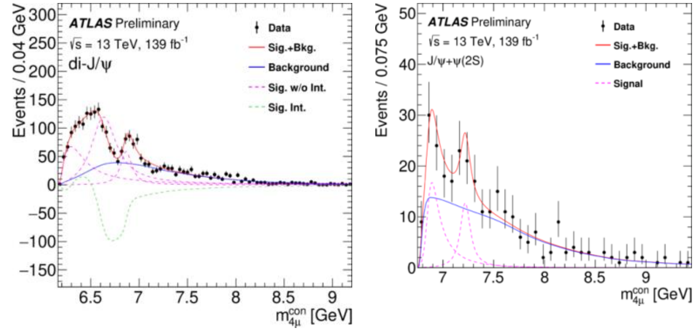
X(6900) well seen by all 3 experiments

Signatures for a bump at 7.2-7.3 GeV
In all 3 experiments

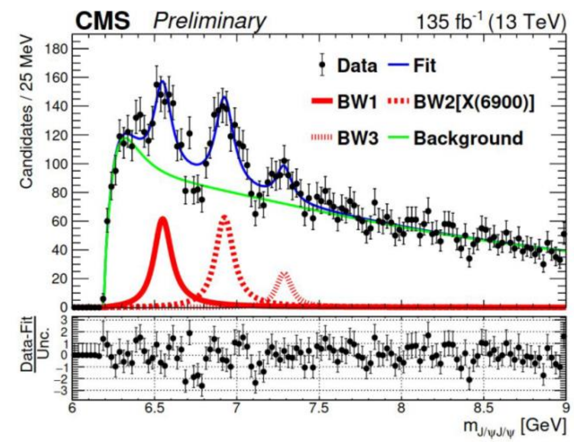
Nature of the low-mass bump to be clarified

Role of reflections from decays to $J/\psi+\psi(2S)$, $J/\psi+\chi_c$ to be studied

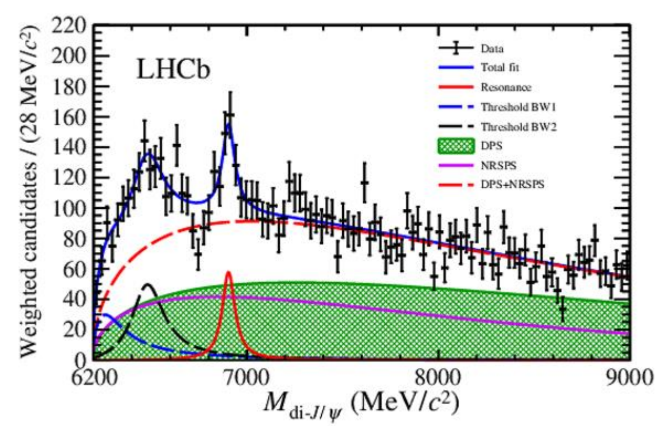
ATLAS-CONF-2022-040



CMS PAS BPH-21-003



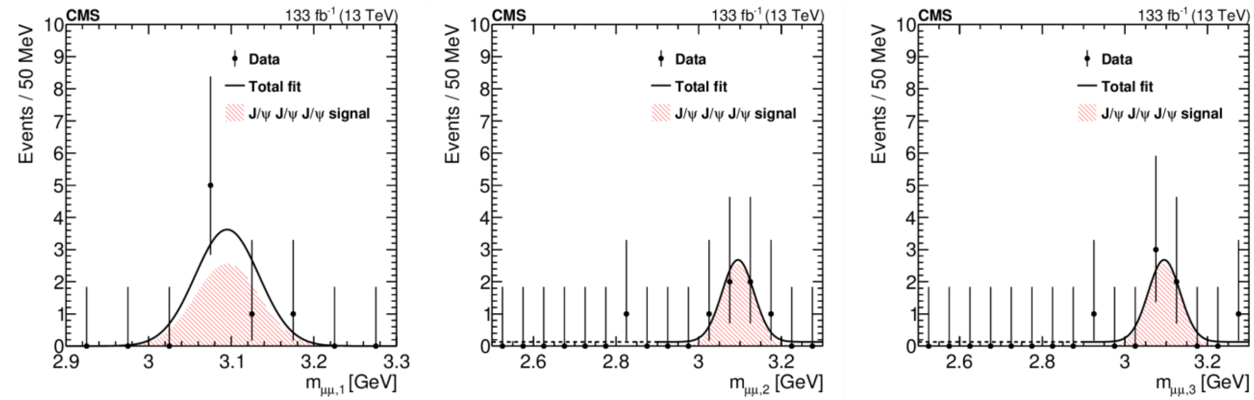
Sci.Bull. 65 (2020) 1983



Observation of triple J/ψ meson production

CMS, arXiv:2111.05370 accepted by Nature Physics

For all muons	$p_T > 3.5$ GeV for $\|\eta\| < 1.2$ $p_T > 2.5$ GeV for $1.2 < \|\eta\| < 2.4$
For all J/ψ mesons	$p_T > 6$ GeV and $\|y\| < 2.4$ $2.9 < m_{\mu^+\mu^-} < 3.3$ GeV

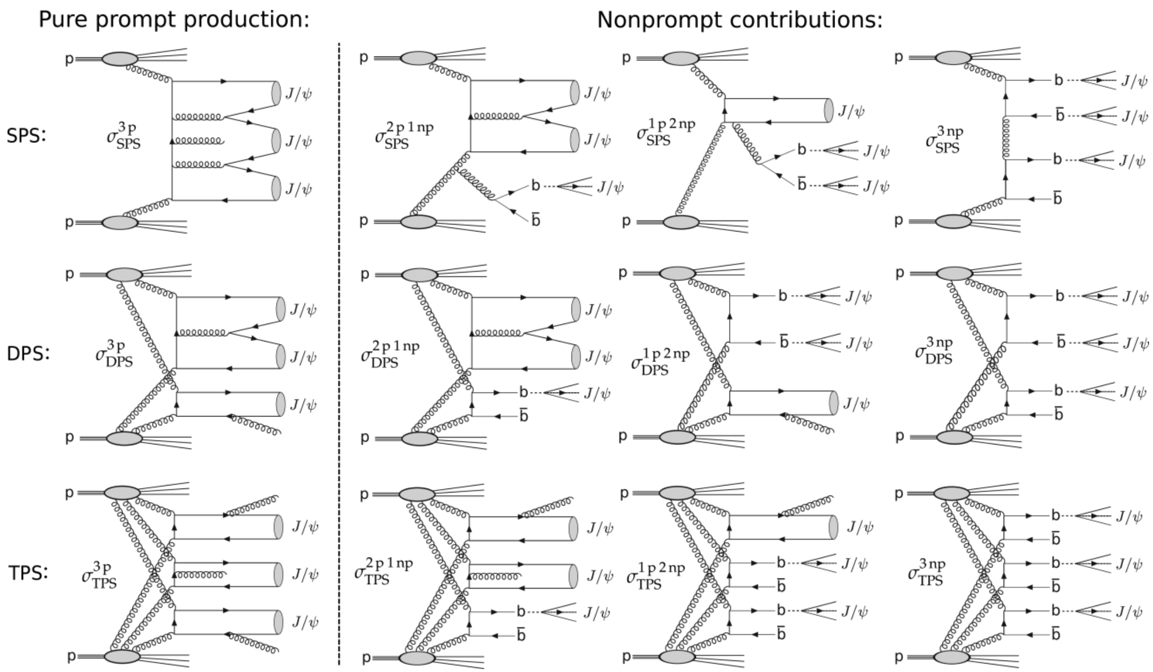


$$N_{\mathrm{sig}}^{3\mathrm{J}/\psi} = 5.0^{+2.6}_{-1.9}$$

5.5 σ (MC toys)

σ(pp→ J/ψ J/ψ J/ψ X) =

272^{+141}_{-104}(stat)±17(syst) fb



f_{SPS} = 6%

f_{DPS} = 74%

f_{TPS} = 20%

Observation of triple J/ψ meson production

CMS, arXiv:2111.05370 accepted by Nature Physics

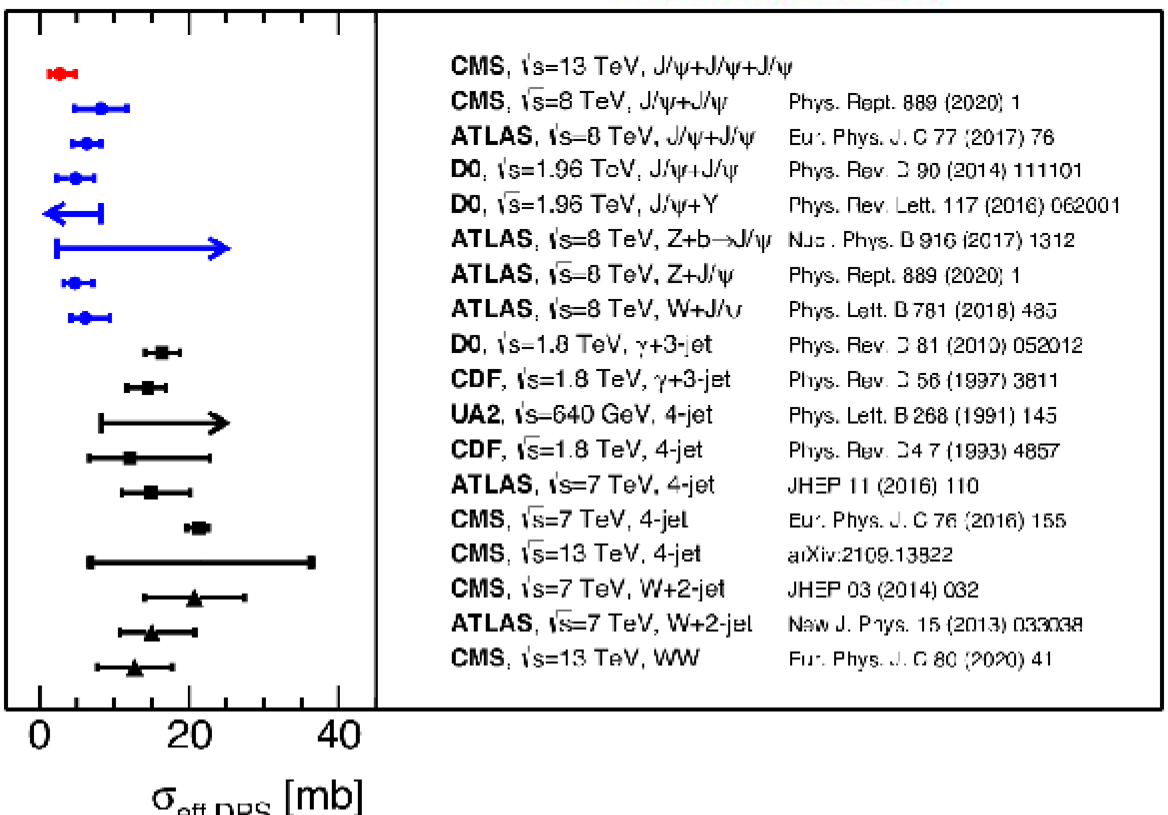
$$\sigma_{\mathrm{DPS}}^{\mathrm{PP}\to\psi_1\psi_2+\mathrm{X}} = \left(\frac{m}{2}\right)\frac{\sigma_{\mathrm{SPS}}^{\mathrm{PP}\to\psi_1+\mathrm{X}}\,\sigma_{\mathrm{SPS}}^{\mathrm{PP}\to\psi_2+\mathrm{X}}}{\sigma_{\mathrm{eff,DPS}}} \qquad \begin{array}{ll}\psi_1 \neq \psi_2: & m=1\\ \psi_1 = \psi_2: & m=2\end{array}$$

$$\sigma_{\mathrm{TPS}}^{\mathrm{PP}\to\psi_1\psi_2\psi_3+\mathrm{X}} = \left(\frac{m}{3!}\right)\frac{\sigma_{\mathrm{SPS}}^{\mathrm{PP}\to\psi_1+\mathrm{X}}\,\sigma_{\mathrm{SPS}}^{\mathrm{PP}\to\psi_2+\mathrm{X}}\,\sigma_{\mathrm{SPS}}^{\mathrm{PP}\to\psi_3+\mathrm{X}}}{\sigma_{\mathrm{eff,TPS}}^2}$$

$$\sigma_{eff,TPS} = \kappa\,\sigma_{eff,DPS} \qquad \kappa = 0.82 \pm 0.11$$

from PRL 118 (2017) 122001

$$\sigma_{eff,DPS} = 2.7^{+1.4}_{-1.0}(exp)^{+1.5}_{-1.0}(theo)\,mb$$



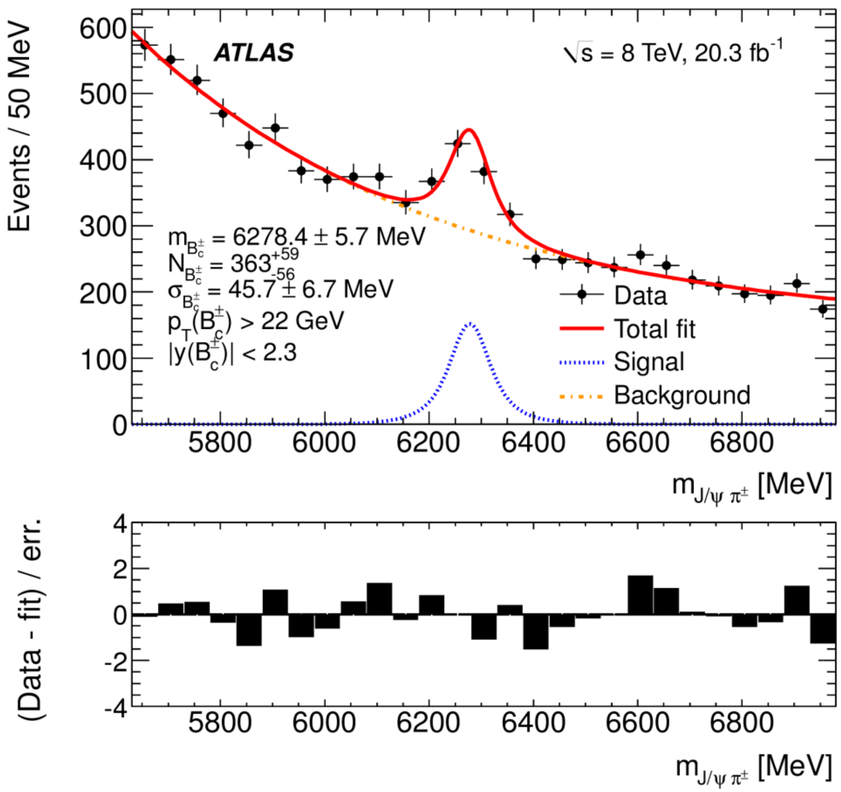
Consistent with measurements from di-onia production

Smaller than those from jets/photon/W-based measurements

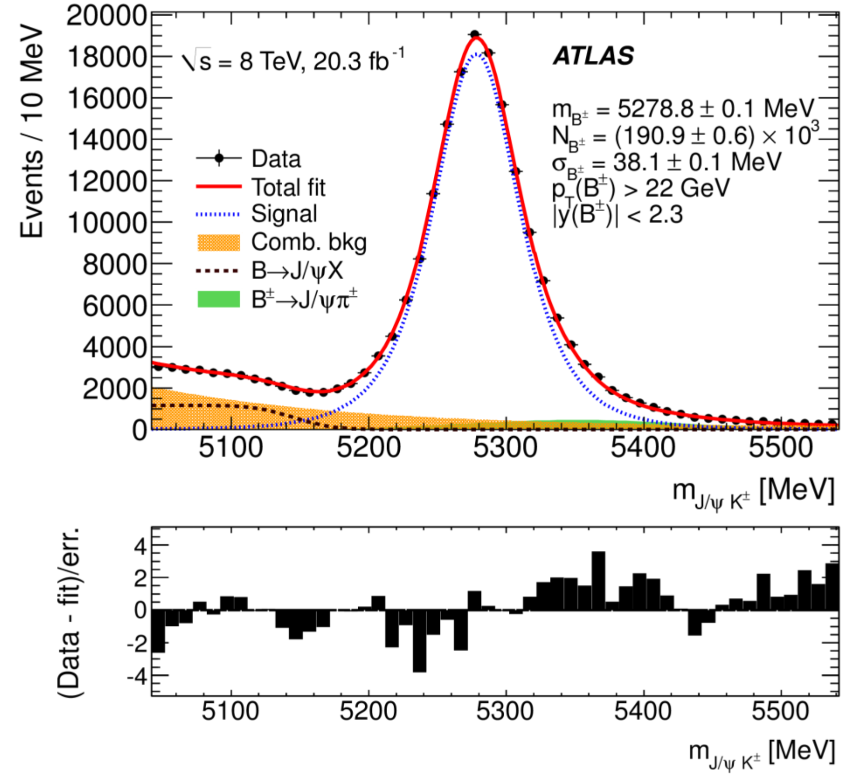
Measurement of the relative $B_c^{\pm}/B^{\pm}$ production cross section with the ATLAS detector at $\sqrt{s} = 8$ TeV

PHYSICAL REVIEW D **104**, 012010 (2021)

$B_c^+ \rightarrow J/\psi\ \pi^+$



$B^+ \rightarrow J/\psi\ K^+$



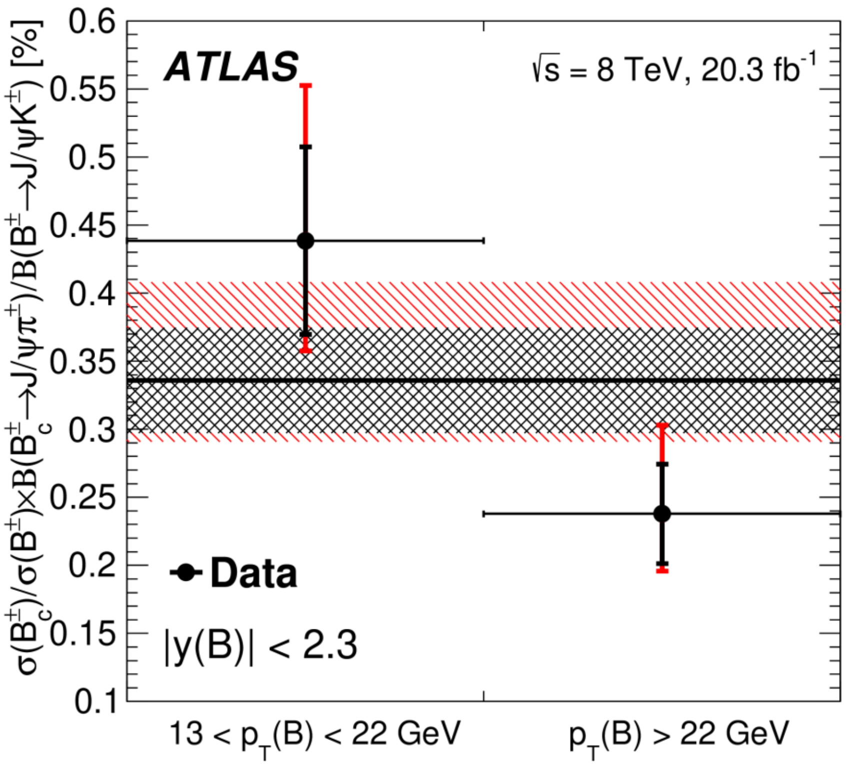
B_c^+ and B^+ yields measured using di-muon trigger

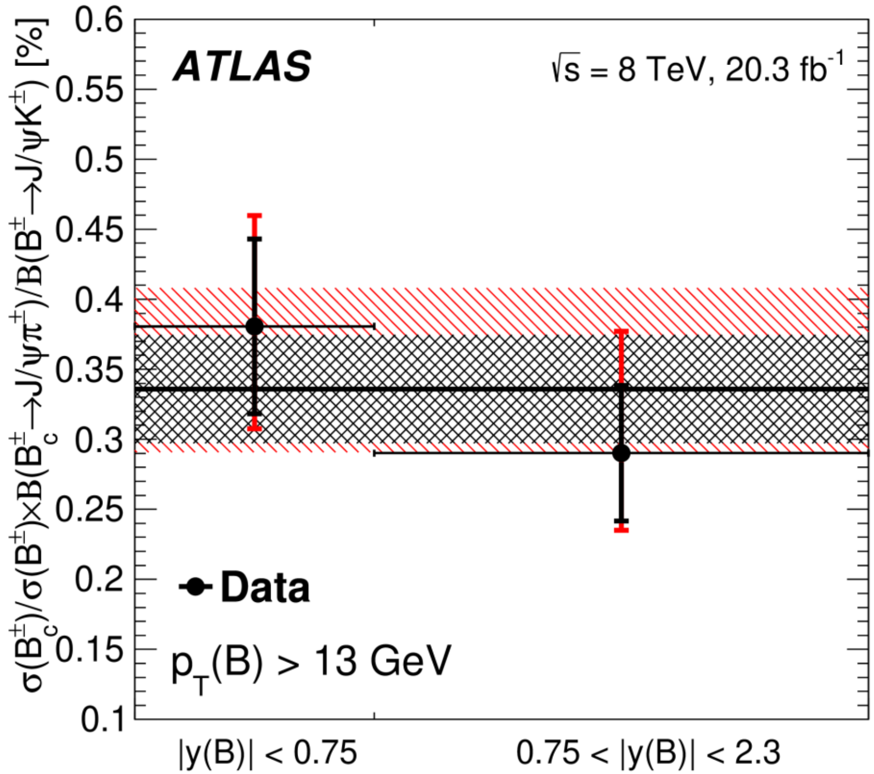
Their ratios, corrected for acceptances and efficiencies, measured in two p_T bins (13-22 GeV, >22 GeV) and two |y| bins (<0.75, 0.75-2.3)

B_c^+ / B^+ x-section ratios at 8 TeV

$$\frac{\sigma(B_c^\pm)\cdot\mathcal{B}(B_c^\pm\to J/\psi\pi^\pm)}{\sigma(B^\pm)\cdot\mathcal{B}(B^\pm\to J/\psi K^\pm)} = (0.34\pm0.04_{\text{stat}}\,{}^{+0.06}_{-0.02}{}_{\text{syst}}\pm0.01_{\text{lifetime}})\%$$

Compatible with CMS/LHCb





The ratio decreases with p_T

No significant |y| dependence

Differences in production?

hadronization?

B_c^+ / B^+ x-section ratios at LHC

$$\frac{\sigma(B_c^\pm)\cdot\mathcal{B}(B_c^\pm \to J/\psi\pi^\pm)}{\sigma(B^\pm)\cdot\mathcal{B}(B^\pm \to J/\psi K^\pm)} =$$

0.683 ± 0.018 ± 0.009 **pT < 20 GeV**, 2.0 < |y| < 4.5 LHCb at 8 TeV

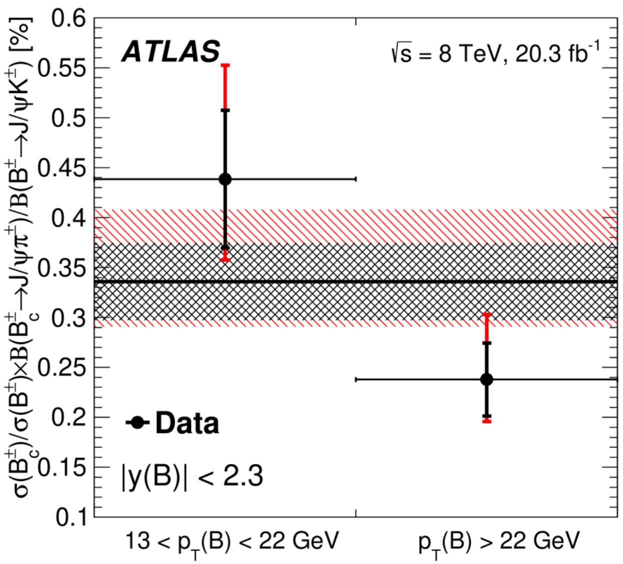
0.48 ± 0.05 ± 0.03 ± 0.05 **pT > 15 GeV**, |y| < 1.6 CMS at 7 TeV

0.44 ± 0.07 $^{+0.09}_{-0.04}$ ± 0.01 **13 < pT** < 22 GeV, |y| < 2.3 ATLAS at 8 TeV

0.24 ± 0.04 $^{+0.05}_{-0.01}$ ± 0.01 **pT > 22 GeV**, |y| < 2.3 ATLAS at 8 TeV

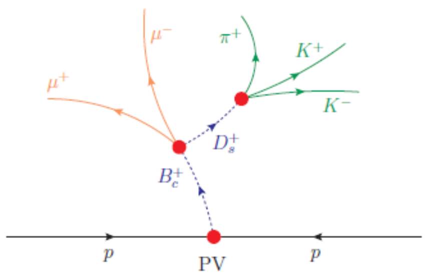
The ratio decreases with p_T

Differences in production?
hadronization?



Measurement of $B_c^+ \longrightarrow J/\psi\ D_s^{(*)+}$

ATLAS, JHEP 08(2022)87



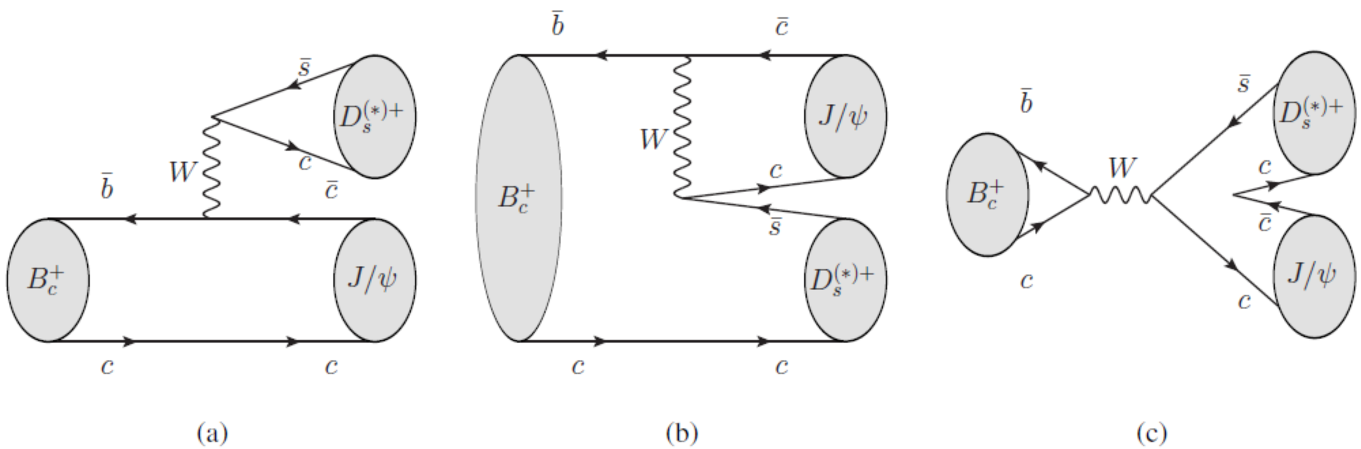


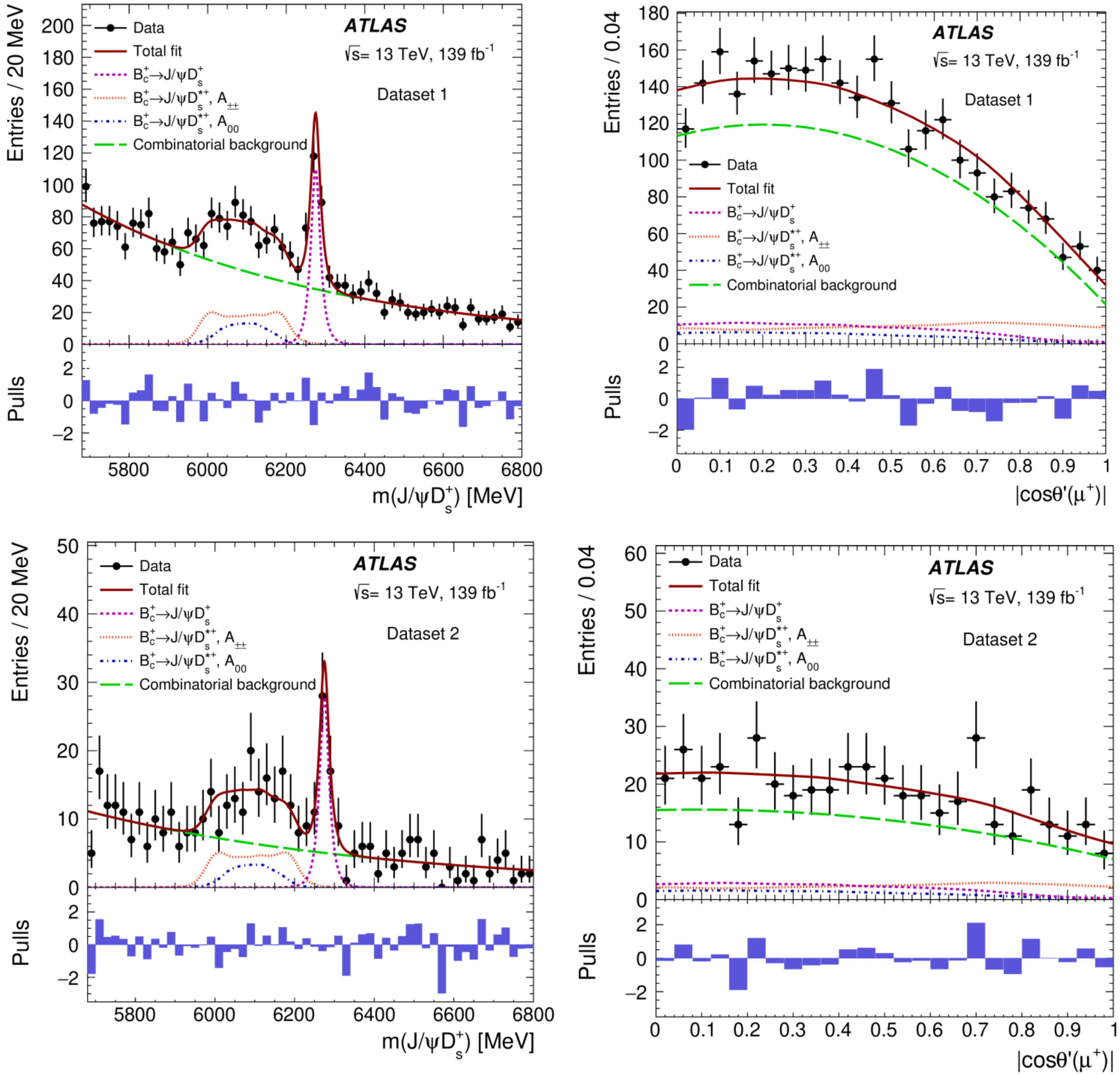
Figure 1: Feynman diagrams for $B_c^+ \to J/\psi D_s^{(*)+}$ decays: (a) colour-favoured spectator, (b) colour-suppressed spectator, and (c) annihilation topology.

Normalization mode: $B_c^+ \longrightarrow J/\psi\ \pi^+$

Run-I measurements: LHCb Phys. Rev. D **87** (2013) 112012,

ATLAS Eur. Phys. J. C **76** (2016) 4,

2D unbinned fit of two subsets simultaneously



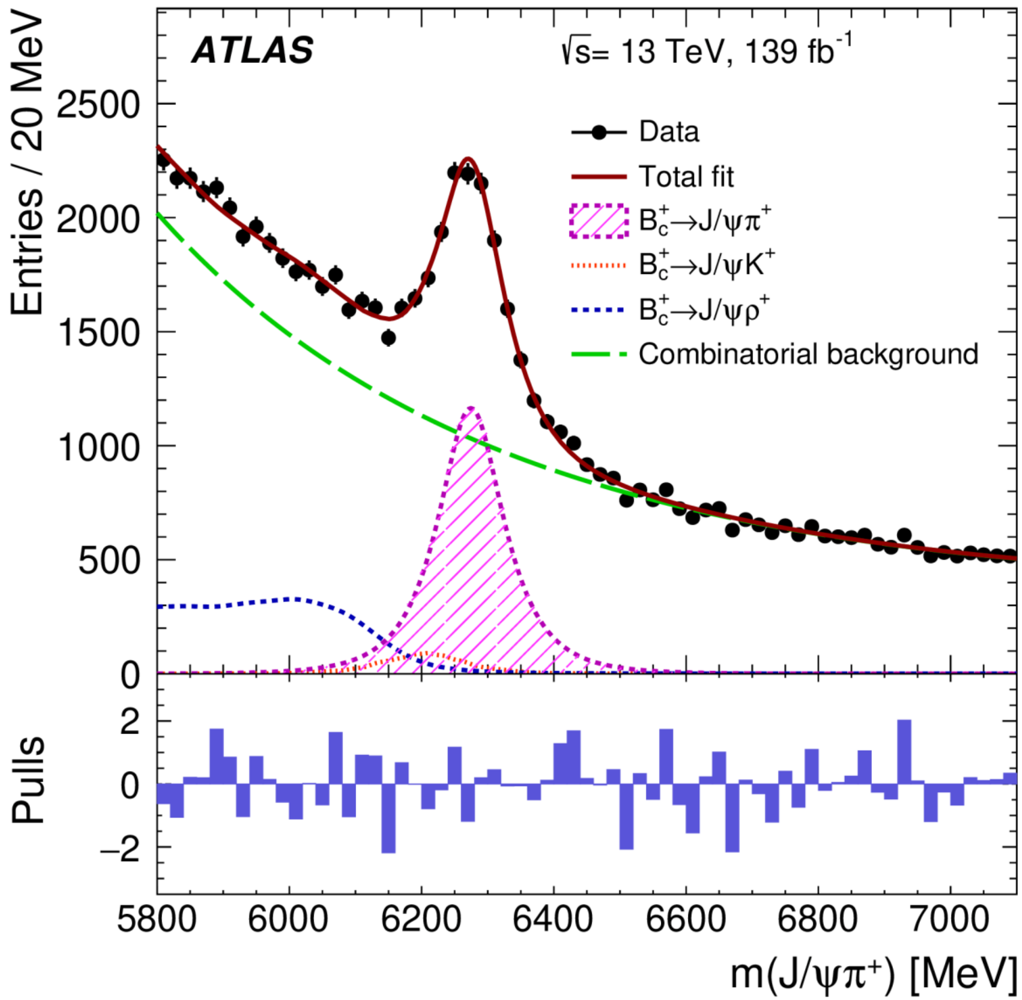
di-muon and tri-muon triggers

$B_s^0 \to \mu^+\mu^-\phi$ triggers

helicity angle θ′ : between μ^+ and D_s^+ in $\mu^+\mu^-$ rest frame

Normalization mode: $B_c^+ \rightarrow J/\psi\, \pi^+$

- $\chi^2(B_c^+)/N_{\text{dof}} < 1.8$ ($N_{\text{dof}} = 4$ in the $B_c^+ \to J/\psi\pi^+$ vertex fit),
- $L_{xy}(B_c^+) > 0.3$ mm,
- $|d_0^{\text{PV}}(B_c^+)/\sigma_{d_0^{\text{PV}}}(B_c^+)| < 3$ and $|z_0^{\text{PV}}(B_c^+)/\sigma z_0^{\text{PV}}(B_c^+)| < 3$,
- $p_{\text{T}}(B_c^+)/\sum p_{\text{T}}(\text{trk}) > 0.10$,



Parameter	Value
$m_{B_c^+}$ [MeV]	6274.5 ± 1.5
$\sigma_{B_c^+}$ [MeV]	47.5 ± 2.5
$N_{B_c^+ \to J/\psi\pi^+}$	8440^{+550}_{-470}

BCVEGPY 2.2
interfaced to PYTHIA 8.244

Mode	$\epsilon^{\text{DS1}}_{B_c^+\to J/\psi X}$ [%]	$\epsilon^{\text{DS1\&2}}_{B_c^+\to J/\psi X}$ [%]
$B_c^+ \to J/\psi D_s^+$	0.971 ± 0.012	1.163 ± 0.013
$B_c^+ \to J/\psi D_s^{*+}$, A_{00}	0.916 ± 0.012	1.088 ± 0.012
$B_c^+ \to J/\psi D_s^{*+}$, $A_{\pm\pm}$	0.868 ± 0.010	1.049 ± 0.011
$B_c^+ \to J/\psi\pi^+$	2.169 ± 0.018	–

Results:

$$R_{D_s^{(*)+}/\pi^+} = \frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{(*)+})}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = \frac{N^{\mathrm{DS1}}_{B_c^+ \to J/\psi D_s^{(*)+}}}{N_{B_c^+ \to J/\psi \pi^+}} \times \frac{\epsilon_{B_c^+ \to J/\psi \pi^+}}{\epsilon^{\mathrm{DS1}}_{B_c^+ \to J/\psi D_s^{(*)+}}} \times \frac{1}{\mathcal{B}(D_s^+ \to \phi(K^+K^-)\pi^+)}$$

$$R_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \to J/\psi D_s^+)} = \frac{N^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}}}{N^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^+}} \times \frac{\epsilon^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^+}}{\epsilon^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}}} = r_{D_s^{*+}/D_s^+} \times \frac{\epsilon^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^+}}{\epsilon^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}}}$$

$$\Gamma_{\pm\pm}/\Gamma = f_{\pm\pm} \times \frac{\epsilon^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}}}{\epsilon^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}, A_{\pm\pm}}}$$

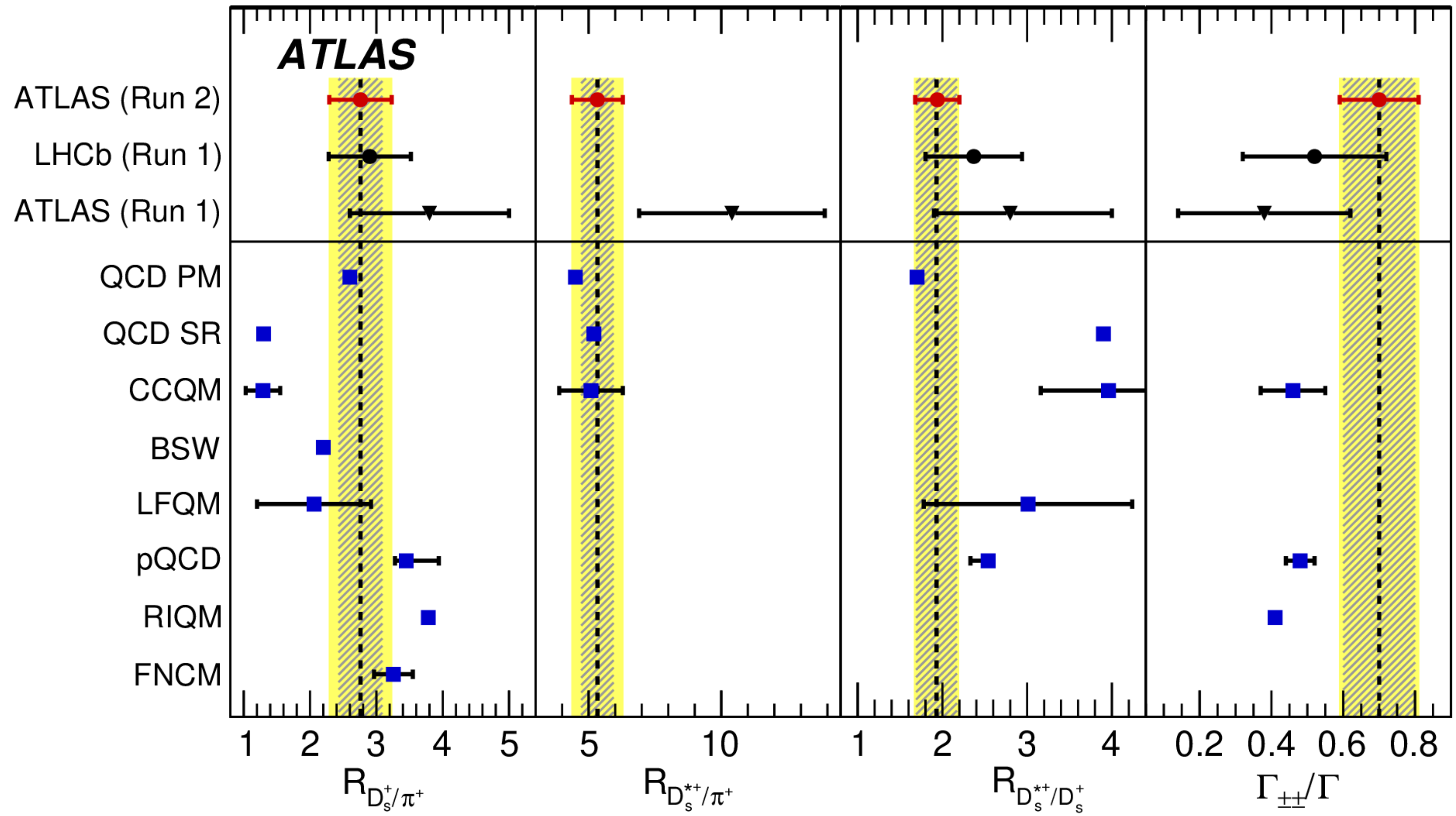
$$R_{D_s^+/\pi^+} = 2.76 \pm 0.33 \pm 0.30 \pm 0.16$$

$$R_{D_s^{*+}/\pi^+} = 5.33 \pm 0.61 \pm 0.67 \pm 0.32$$

$$R_{D_s^{*+}/D_s^+} = 1.93 \pm 0.24 \pm 0.10$$

$$\Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10 \pm 0.04$$

Comparison with previous results and models



QCD PM (Colangelo, De Fazio) – good agreement, no uncertainties, no prediction for $\Gamma_{\pm\pm}/\Gamma$

CCQM (M.Ivanov et al) – agrees only for $R_{D_s^{*+}/\pi^+}$

Predictions for $\Gamma_{\pm\pm}/\Gamma$ are below or around 0.5 while data agree with naïve spin counting 2/3

Comparison with other B-meson decays

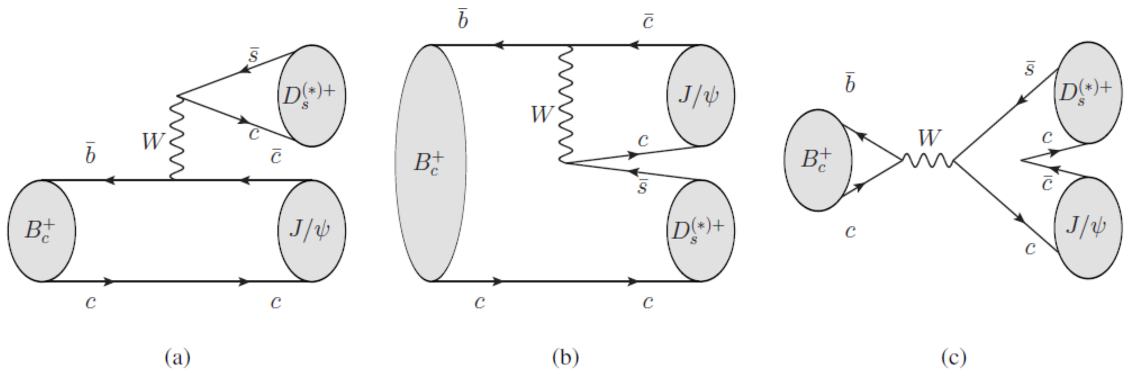


Figure 1: Feynman diagrams for $B_c^+ \to J/\psi D_s^{(*)+}$ decays: (a) colour-favoured spectator, (b) colour-suppressed spectator, and (c) annihilation topology.

$$R_{D_s^+/\pi^+} \approx \frac{\Gamma(B \to \bar{D}^* D_s^+)}{\Gamma(B \to \bar{D}^* \pi^+)},$$

$$R_{D_s^{*+}/\pi^+} \approx \frac{\Gamma(B \to \bar{D}^* D_s^{*+})}{\Gamma(B \to \bar{D}^* \pi^+)}$$

$$R_{D_s^{*+}/D_s^+} \approx \frac{\Gamma(B \to \bar{D}^* D_s^{*+})}{\Gamma(B \to \bar{D}^* D_s^+)}$$

Assuming that the colour-favoured spectator diagram dominates the decay amplitudes

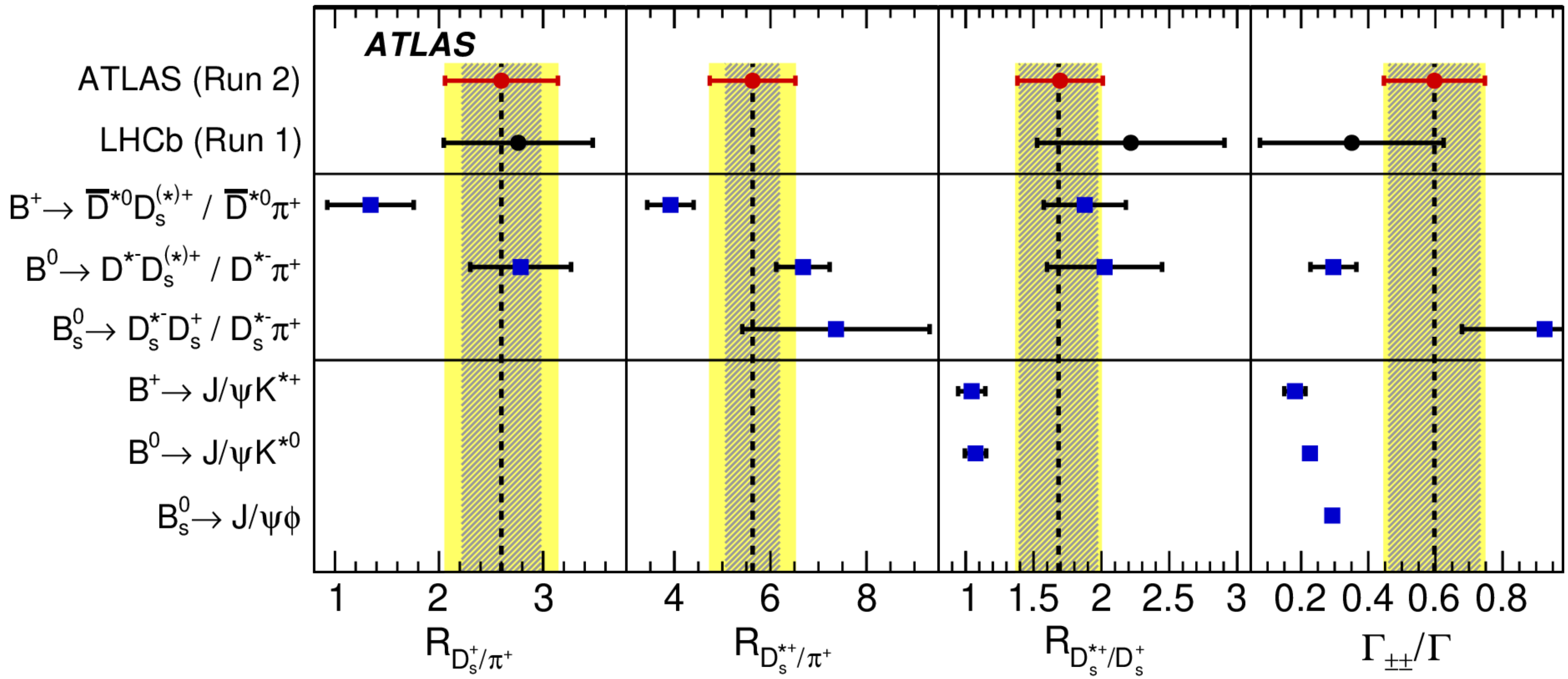
$$R_{D_s^{*+}/D_s^+} \sim \frac{\Gamma(B \to J/\psi K^*)}{\Gamma(B \to J/\psi K)}$$

Assuming that the colour-supressed spectator diagram dominates the decay amplitudes

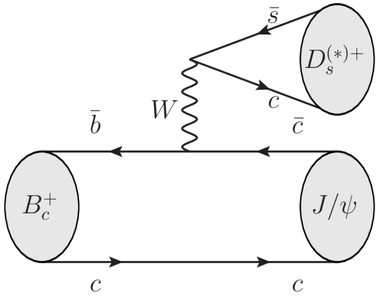
$$\Gamma_{\pm\pm}/\Gamma$$

Can be also compared to $B_s^0 \to J/\psi \phi$

Comparison with ligher B-meson decays



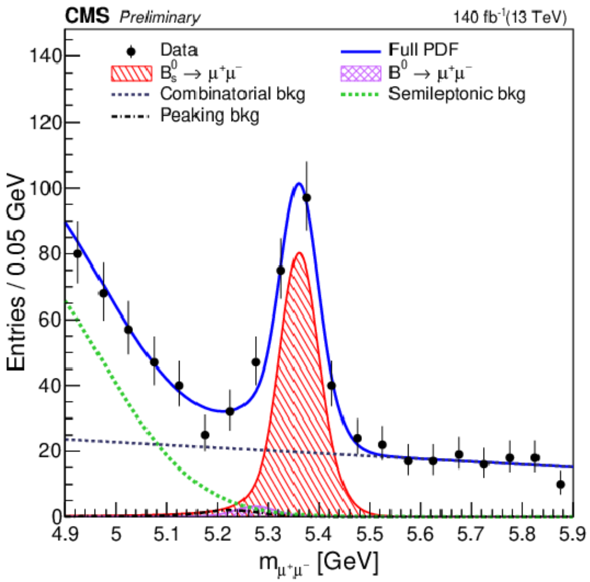
Supports the assumtion that the colour-favoured spectator diagram dominates the decay amplitudes



$B_{(s)}^0 \longrightarrow \mu^+\mu^-$ (FCNC, CKM and helicity suppressed)

CMS PAS BPH-21-006

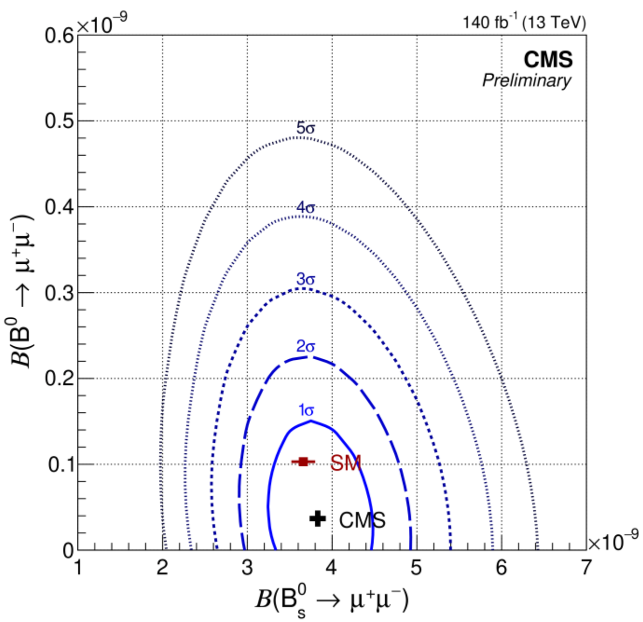
Released for ICHEP 2022



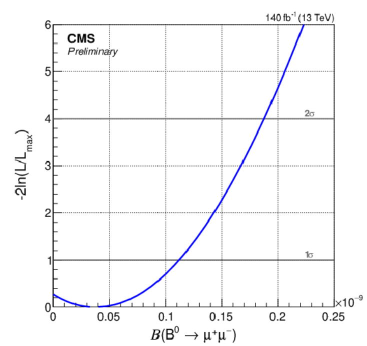
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+)\frac{N_{B_s^0\to\mu^+\mu^-}}{N_{B^+\to J/\psi K^+}}\frac{\varepsilon_{B^+\to J/\psi K^+}}{\varepsilon_{B_s^0\to\mu^+\mu^-}}\frac{f_u}{f_s},$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B_s^0 \to J/\psi\phi)\frac{N_{B_s^0\to\mu^+\mu^-}}{N_{B_s^0\to J/\psi\phi}}\frac{\varepsilon_{B_s^0\to J/\psi\phi}}{\varepsilon_{B_s^0\to\mu^+\mu^-}},$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+)\frac{N_{B^0\to\mu^+\mu^-}}{N_{B^+\to J/\psi K^+}}\frac{\varepsilon_{B^+\to J/\psi K^+}}{\varepsilon_{B^0\to\mu^+\mu^-}}\frac{f_u}{f_d},$$



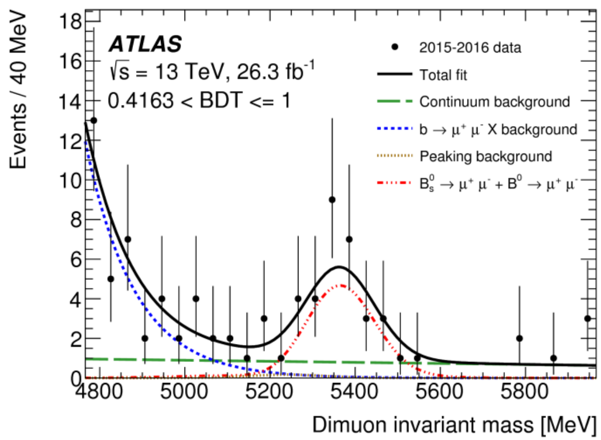
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\ (\text{stat})\ ^{+0.19}_{-0.16}\,(\text{syst})\ ^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\ (\text{stat})\ ^{+0.08}_{-0.09}\,(\text{syst})\right] \times 10^{-10}.$$



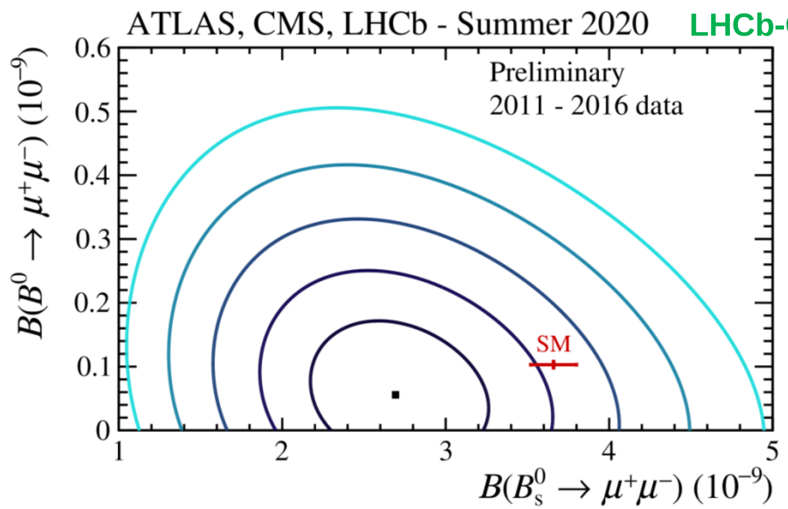
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.5 \times 10^{-10} \text{ at 90\% CL},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at 95\% CL},$$

$B_{(s)}^0 \longrightarrow \mu^+\mu^-$ (FCNC, CKM and helicity suppressed)

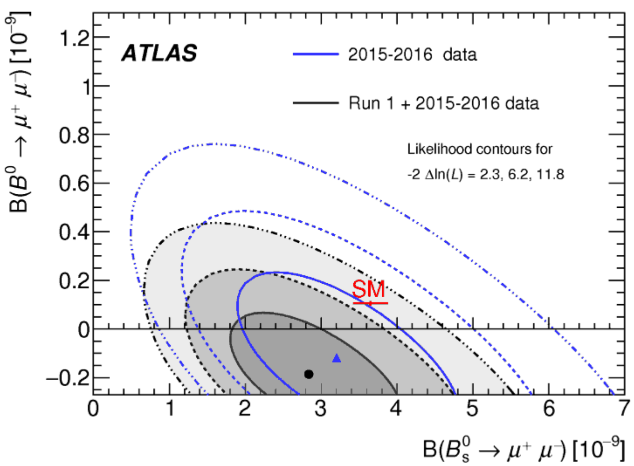
ATLAS, JHEP 04(2019)098



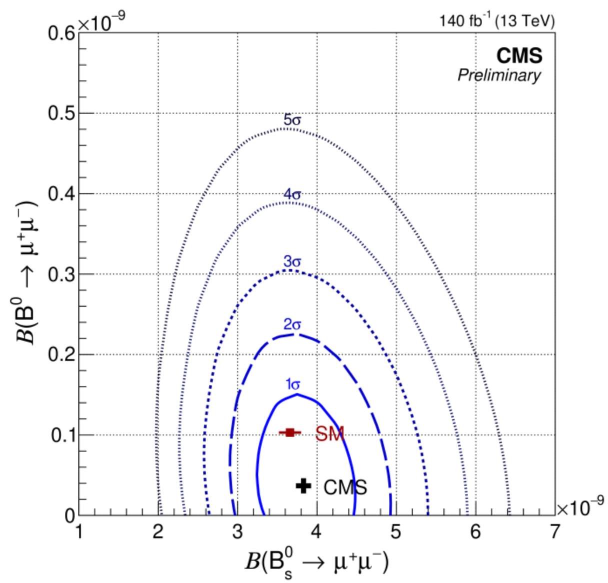
ATLAS-CONF-2020-049
CMS PAS BPH-20-003
LHCb-CONF-2020-002



agreement with sm: 2.1 σ



agreement with SM: 2.4 σ



CMS PAS BPH-21-006

Released for ICHEP 2022

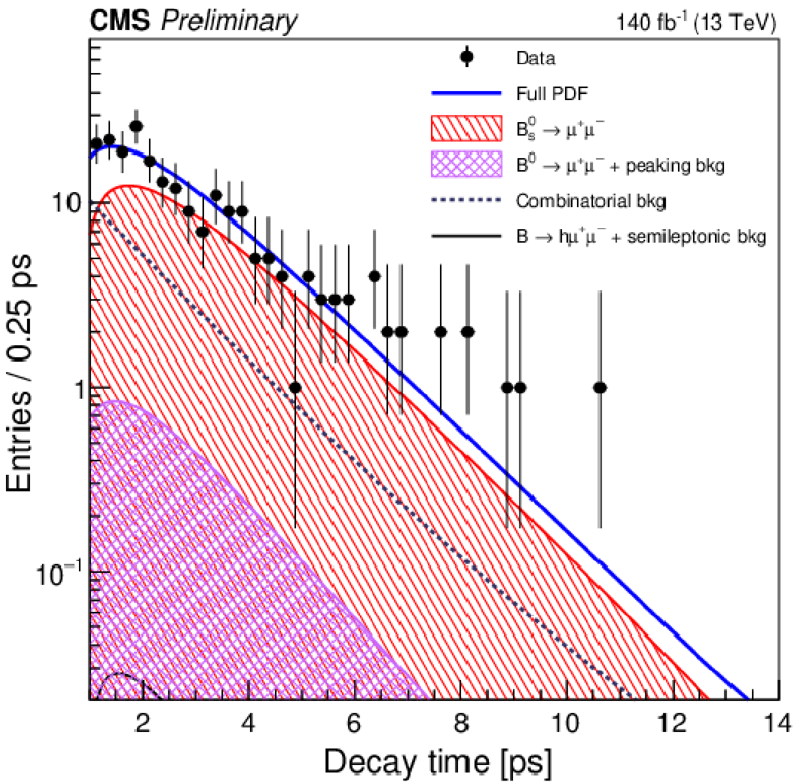
Perfect agreement!

Not an anomaly anymore

$B_{(s)}^0 \longrightarrow \mu^+\mu^-$ (FCNC, CKM and helicity suppressed)

CMS PAS BPH-21-006

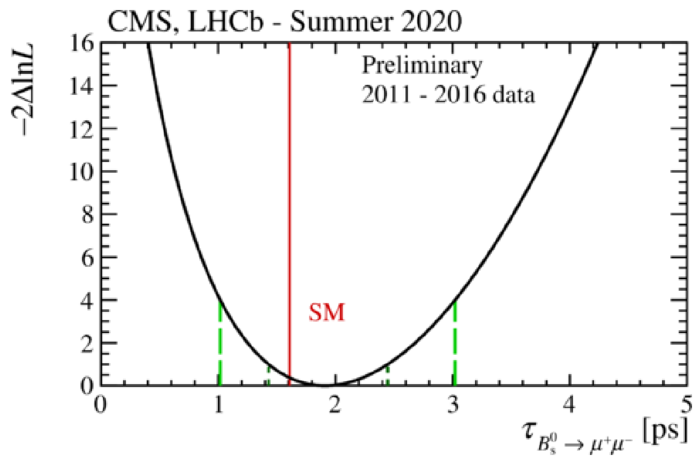
Released for ICHEP 2022



The effective lifetime for the $B_s^0 \to \mu^+\mu^-$ decay

$$\tau = 1.83\,^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})\text{ ps}$$

ATLAS-CONF-2020-049
CMS PAS BPH-20-003
LHCb-CONF-2020-002



SM-based expectation

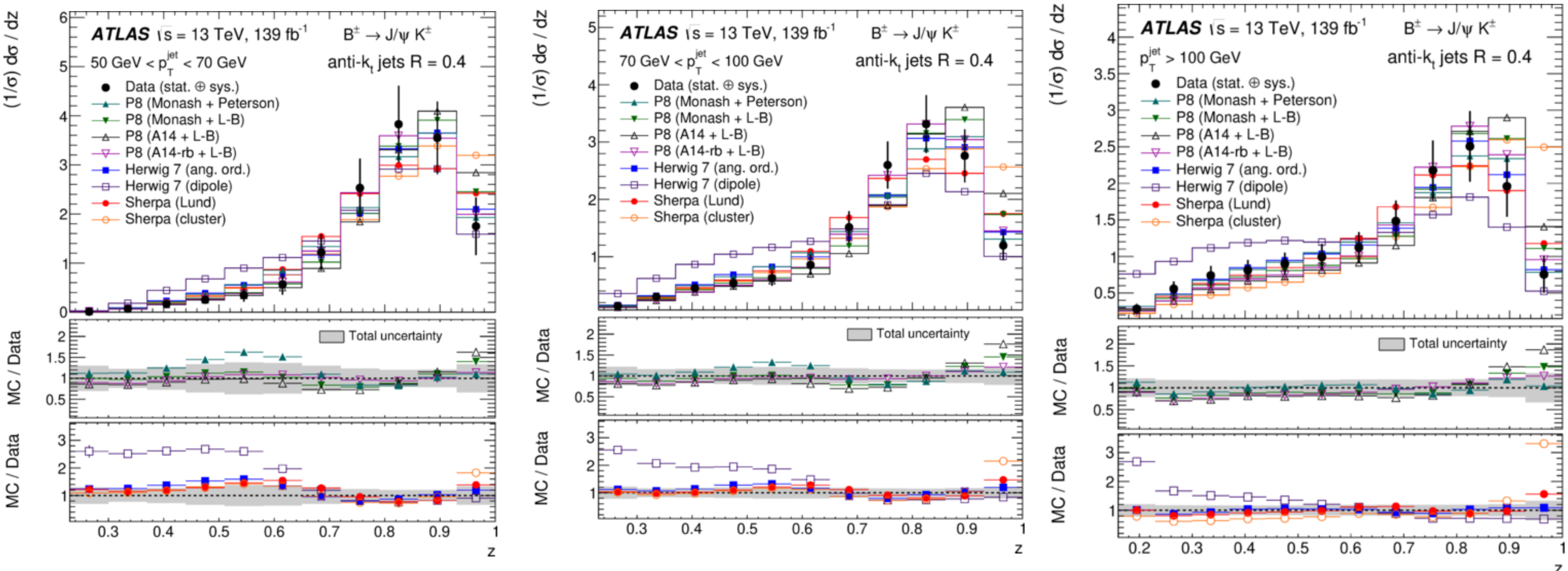
$$\tau_{B_s^0 \to \mu^+\mu^-} = 1.609 \pm 0.010\,\text{ps}$$

Good agreement

$$\tau_{B_s^0 \to \mu^+\mu^-} = 1.91^{+0.37}_{-0.35}\,\text{ps}$$

Measurement of b-quark fragmentation properties in jets using the decay $B^{\pm} \to J/\psi K^{\pm}$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS, JHEP 12 (2021) 131

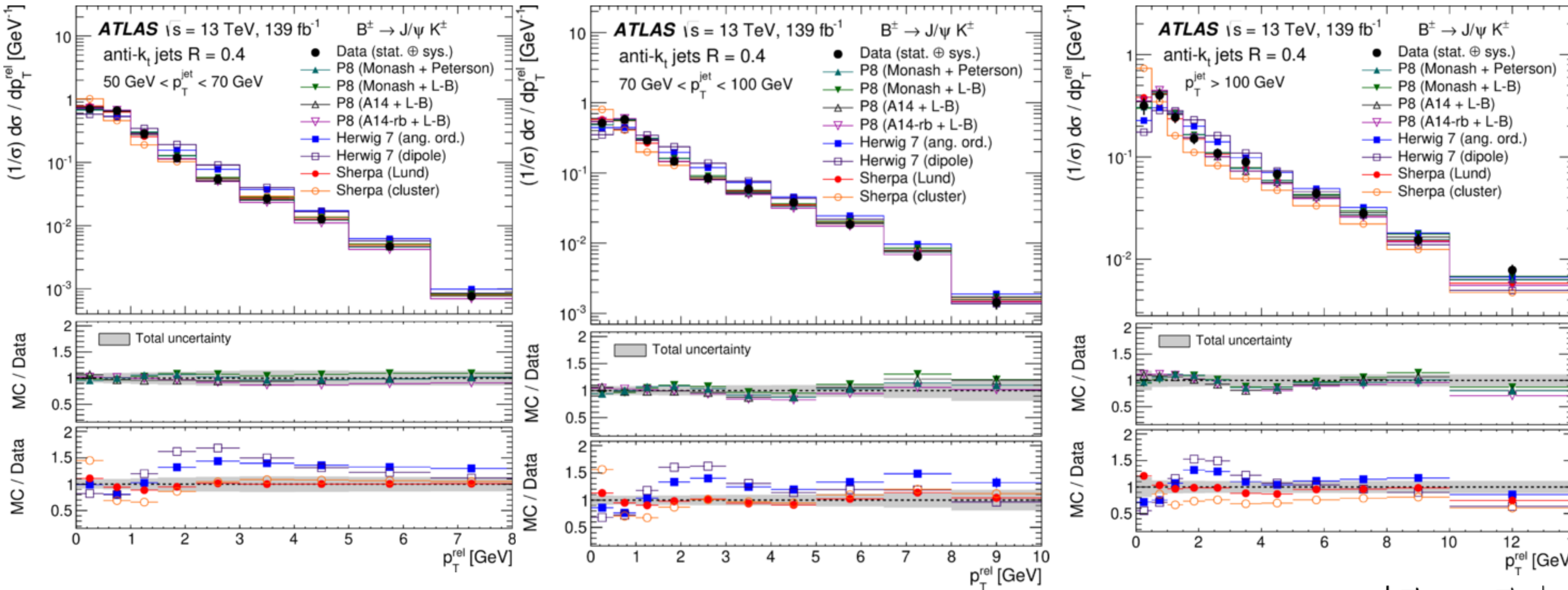


$$z = \frac{\vec{p}_J \cdot \vec{p}_B}{|\vec{p}_J|^2}$$

- All Pythia fragmentation models give a decent description.
- Herwig7 with dipole parton shower overestimates the low z tail at low p_T
  - larger fraction of jets arising from gluon splittings
- Sherpa (mainly cluster hadronisation model) differs for very high z

Measurement of b-quark fragmentation properties in jets using the decay $B^\pm \to J/\psi K^\pm$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS, JHEP 12 (2021) 131

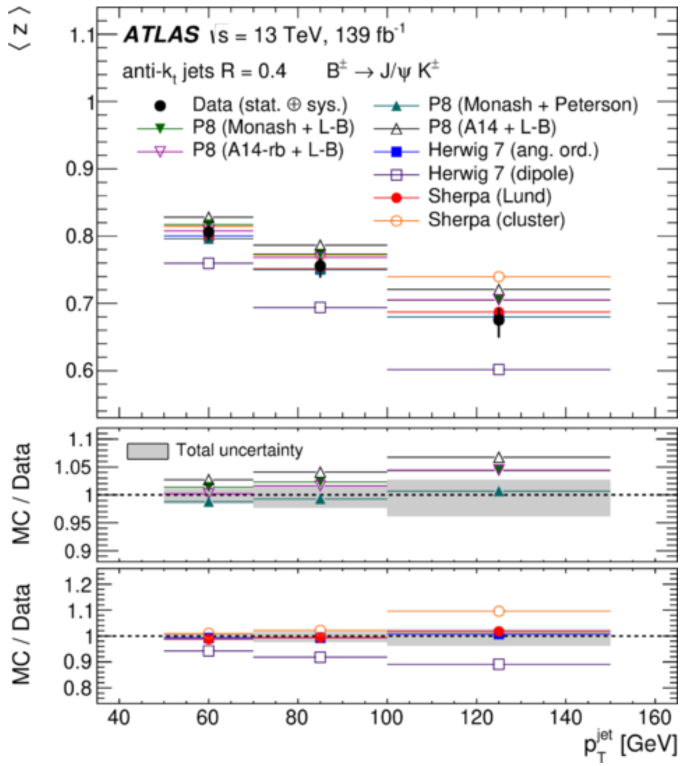


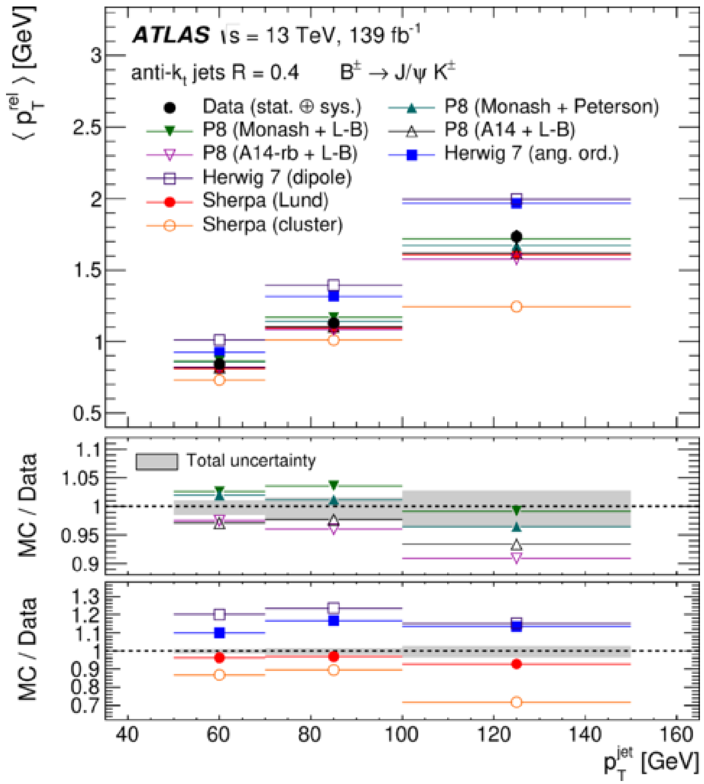
$$p_T^{\rm rel} = \frac{|\vec{p}_J \times \vec{p}_B|}{|\vec{p}_J|}$$

- All Pythia fragmentation models give a decent description.
- Herwig7 with dipole PS overestimates for p_T^{rel} in [1.5, 4.0] GeV at low p_T
- Sherpa (mainly cluster HM) discrepant for low values of p_T^{rel}, gets worse for higher jet p_T.

Measurement of b-quark fragmentation properties in jets using the decay $B^{\pm} \to J/\psi K^{\pm}$ in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

ATLAS, JHEP 12 (2021) 131

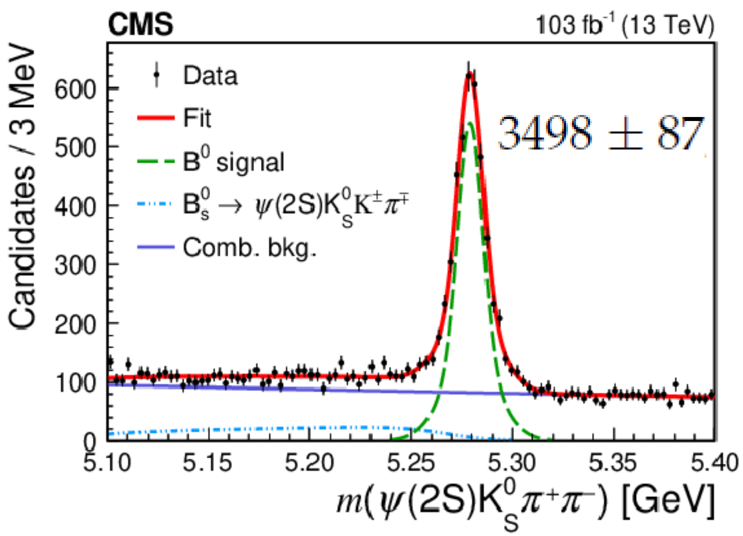




- Pythia (A14*) predicts slightly larger <z> and slightly lower $\langle p_T^{rel} \rangle$
- Both Herwig7 discrepant at 15-20% level in $\langle p_T^{rel} \rangle$ profile
- Sherpa (cluster) disagreeing at 10% to 25% for $\langle p_T^{rel} \rangle$

Observation of $B^0 \to \psi(2S) K^0_S \pi^+ \pi^-$ and $B^0_s \to \psi(2S) K^0_S$ decays

EPJC 82 (2022) 499

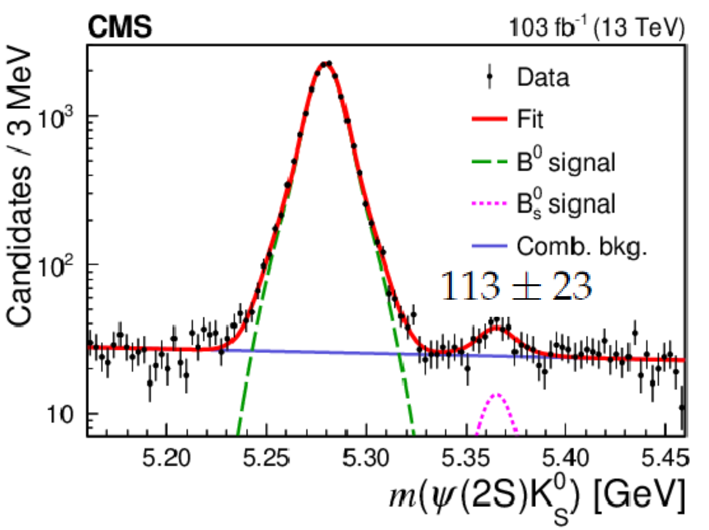


$$R_{\pi^+\pi^-} = \frac{\mathcal{B}(B^0 \to \psi(2S) K^0_S \pi^+ \pi^-)}{\mathcal{B}(B^0 \to \psi(2S) K^0_S)} =$$

$$0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst})$$

$$\mathcal{B}(B^0 \to \psi(2S) K^0_S \pi^+ \pi^-) =$$

$$(13.9 \pm 0.4\,(\text{stat}) \pm 0.9\,(\text{syst}) \pm 1.2\,(\mathcal{B})) \times 10^{-5},$$



$$R_s = \frac{\mathcal{B}(B^0_s \to \psi(2S) K^0_S)}{\mathcal{B}(B^0 \to \psi(2S) K^0_S)} =$$

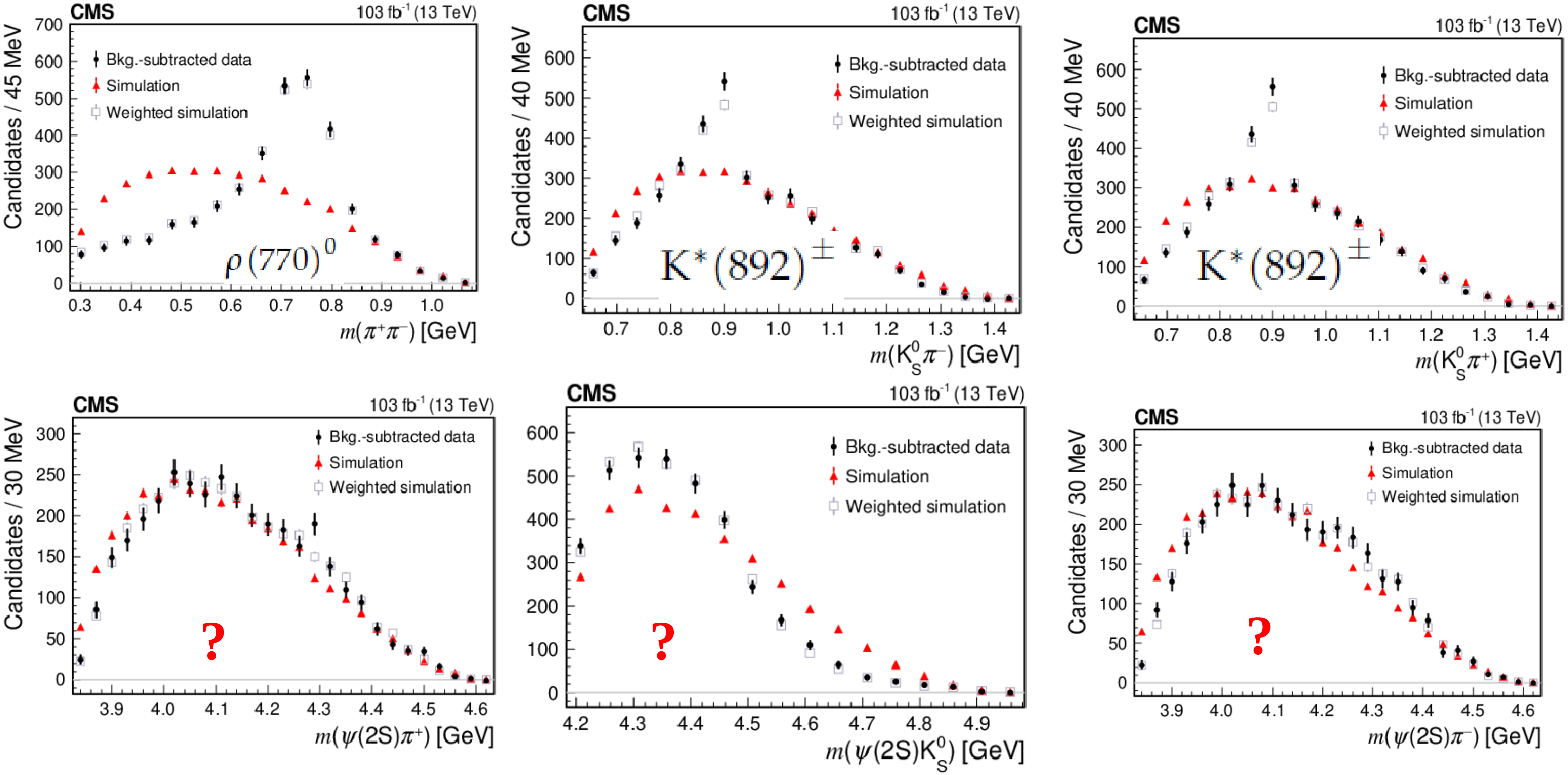
$$(3.33 \pm 0.69\,(\text{stat}) \pm 0.11\,(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2}$$

$$\mathcal{B}(B^0_s \to \psi(2S) K^0_S) =$$

$$(0.97 \pm 0.20\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.22\,(f_s/f_d) \pm 0.08\,(\mathcal{B})) \times 10^{-5}$$

Observation of $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_S$ decays

EPJC 82 (2022) 499



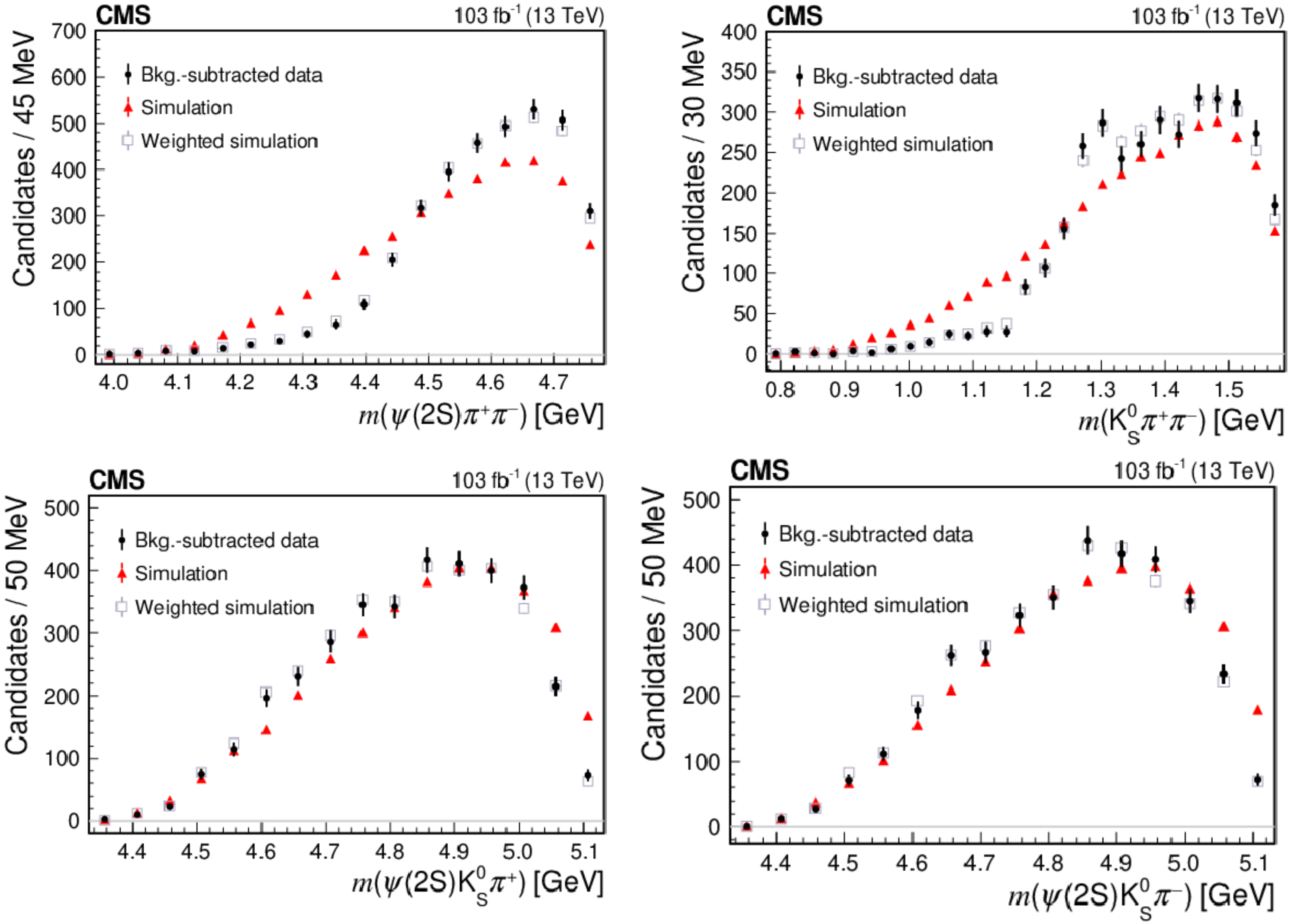
Iterative 1D reweightings done over 2- and 3-body invariant mass distributions

No significant exotic narrow structures

More data are needed?

Observation of $B^0 \to \psi(2S) K^0_S \pi^+ \pi^-$ and $B^0_s \to \psi(2S) K^0_S$ decays

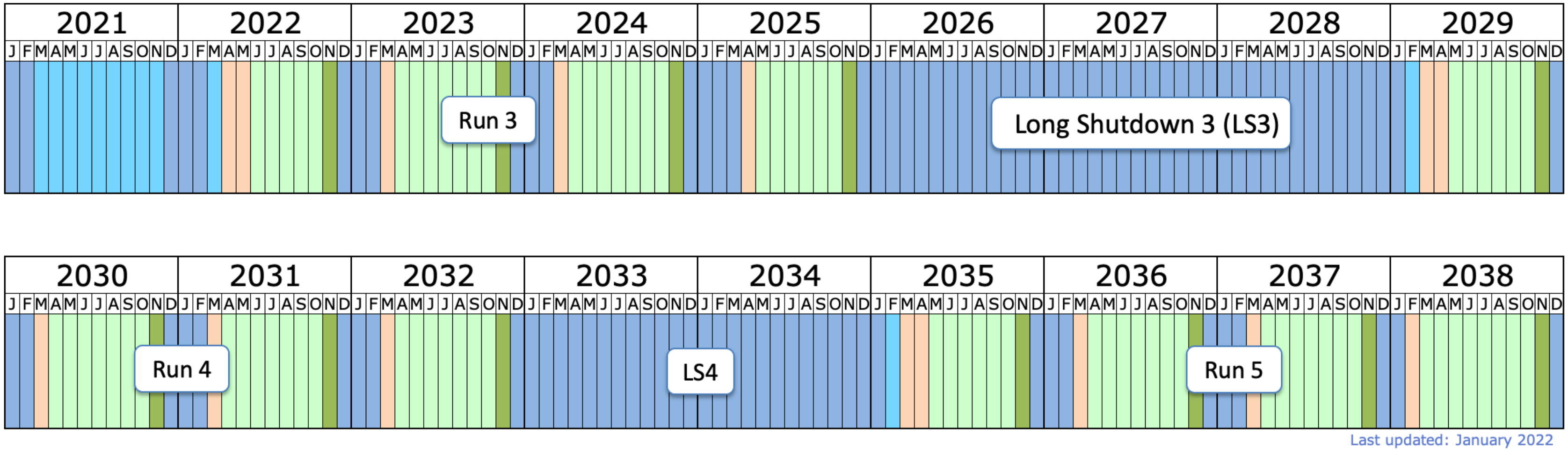
EPJC 82 (2022) 499

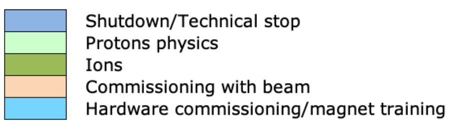


No significant exotic narrow structures

More data are needed?

Prospects

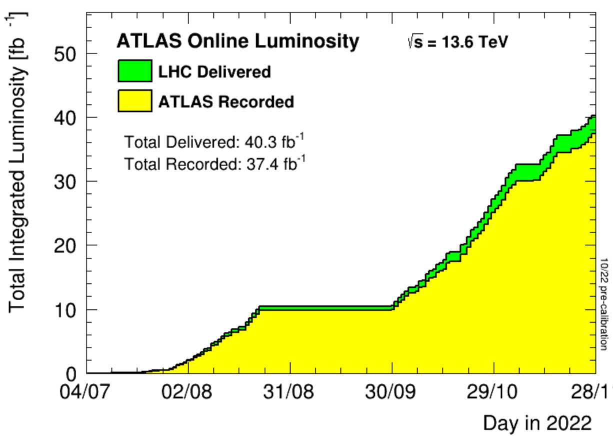


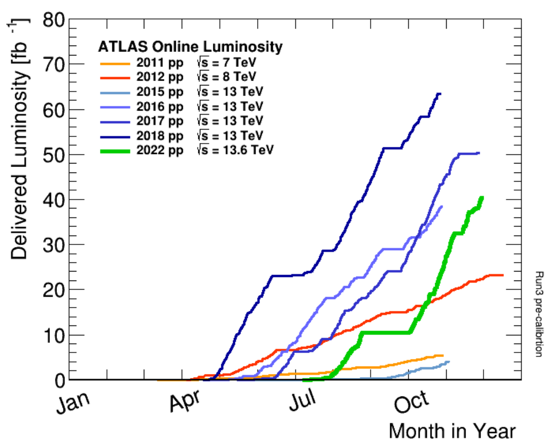


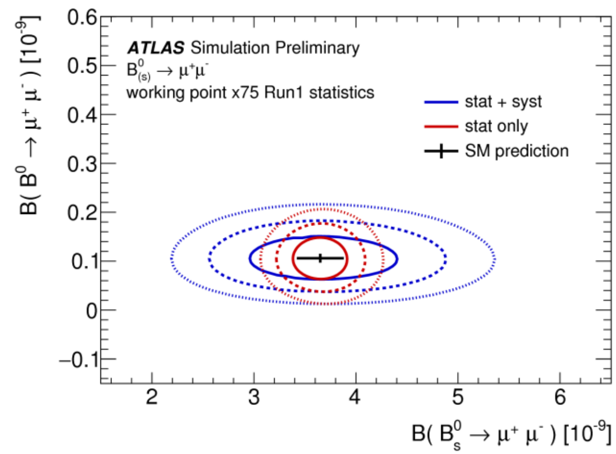
Run 3: ~300 fb-1

HL-LHC: ~3000 fb-1

HL-LHC projection







L_{max} = 25.3 x 10^{33} cm^{-2} s^{-1}

Summary : main messages

Exciting results on di-charmonia resonances from ATLAS. CMS and LHCb
2-4 $c\bar{c}c\bar{c}$ tetraquark candidates
actual states and their spin-parities to be clarified

First results on triple J/ψ meson production
supporting small $\sigma_{eff,DPS}$ value for di-onia production

Precision measurements of B_c^+ production and decays
the B_c^+ / B^+ ratio decreases with p_T
challenging for theory results on $B_c^+ \to J/\psi\, D_s^{(*)+}$

$B_{(s)}^0 \to \mu^+\mu^-$ measurement with full Run-II statistics
good agreement with SM - not an anomaly anymore

b quark fragmentation properties with B^+ in jets
PYTHIA fragmentation gives a decent description

Observation of $B^0 \to \psi(2S) K^0_S \pi^+\pi^-$ and $B^0_s \to \psi(2S) K^0_S$ decays
no significant exotic narrow structures – more data are needed?

New results with full Run-II and first Run-III data
for spring/summer conferences

Backup

J/ψJ/ψ (→ 4μ) spectrum studied at LHCb using 9 fb^{-1} of pp collisions at √s = 7, 8, 13 TeV Sci.Bull. 65 (2020), 23

Two structures are reported:

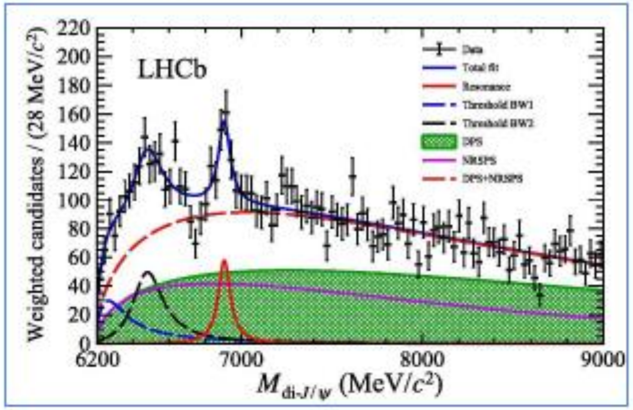
- **A narrow resonance, X(6900)**, renamed $T_{\psi\psi}(6900)$
- A broad structure near the di-J/ψ mass threshold

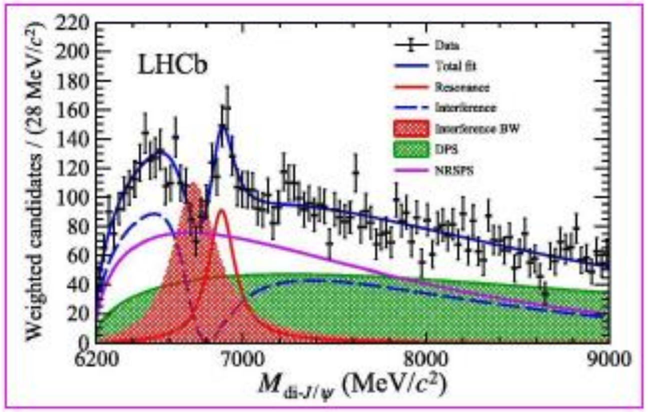
Background contribution for J/ψ pair production:

- Non-Resonant Single Parton Scattering (NRSPS)
- Non-Resonant Double Parton Scattering (DPS)

Two signal + background fit models are considered:

- **Model 1 (top)** - poor description of the "dip" at 6.7 GeV
  - background
  - Breit-Wigner for X(6900)
  - two auxiliary Breit-Wigner (near threshold)
- **Model 2 (bottom)**
  - a "virtual" X(6700) to interfere with NRSPS is added



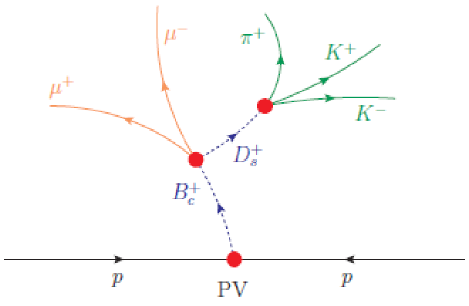


Preselection:

- $\chi^2(B_c^+)/N_{\rm dof} < 2$, where $\chi^2(B_c^+)$ is the quality of the B_c^+ cascade vertex fit and $N_{\rm dof} = 8$.
- $L_{xy}(B_c^+) > 0.3$ mm, where $L_{xy}(B_c^+)$ is the transverse distance between the primary vertex (PV) and the B_c^+ candidate vertex projected onto the direction of the B_c^+ transverse momentum. The PV is chosen as the one giving the smallest three-dimensional impact parameter of the B_c^+ candidate. To avoid biasing L_{xy}, the PV position is recalculated after removing any tracks used in the reconstruction of the B_c^+ meson candidate. To remove poorly reconstructed candidates, $L_{xy}(B_c^+)$ is also required to not exceed 10 mm.
- $L_{xy}(D_s^+) > 0$ mm, where $L_{xy}(D_s^+)$ is the transverse distance between the B_c^+ vertex and the D_s^+ vertex projected onto the direction of the D_s^+ transverse momentum. To remove poorly reconstructed candidates, $L_{xy}(D_s^+)$ is also required to not exceed 10 mm.
- $|d_0^{\rm PV}(B_c^+)/\sigma_{d_0^{\rm PV}}(B_c^+)| < 5$ and $|z_0^{\rm PV}(B_c^+)/\sigma_{z_0^{\rm PV}}(B_c^+)| < 5$, where $d_0^{\rm PV}$ and $z_0^{\rm PV}$ are the transverse and longitudinal impact parameters with respect to the PV, and $\sigma_{d_0^{\rm PV}}(B_c^+)$ and $\sigma_{z_0^{\rm PV}}(B_c^+)$ are their respective uncertainties. The uncertainties are calculated from the covariance matrix of the PV and the covariance matrix of the B_c^+ pseudo-track extracted from the cascade vertex fit. These two requirements are used to ensure that the B_c^+ candidate points back to the PV.
- $p_{\rm T}(B_c^+)/\sum p_{\rm T}({\rm trk}) > 0.10$, where the sum is taken over all tracks originating from the selected PV, including the tracks of the B_c^+ candidate. Due to the characteristic hard fragmentation of b-quarks, this requirement removes a sizeable fraction of the combinatorial background while having almost no effect on the signal.

$p_T(B_c) > 15$ GeV $|\eta(B_c)| < 2$

2-vertex cascade fit with 2 mass constraints (J/ψ and D_s)



$m(K^+K^-)$ within ±7 MeV of $m(\varphi)_{\rm PDG}$

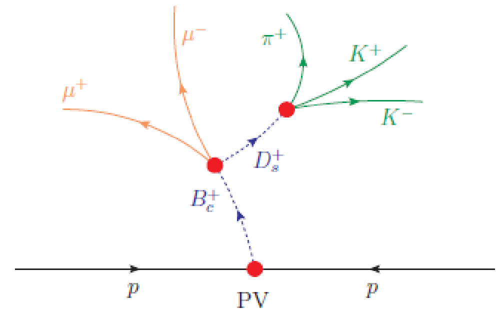
in case of $D_s^* \to D_s\, \pi^0/\gamma$: π^0/γ escapes detection

3 helicity amplitudes for PS ⟶ V + V decay: A_{00}, A_{++}, A_{--}

BDT selection:

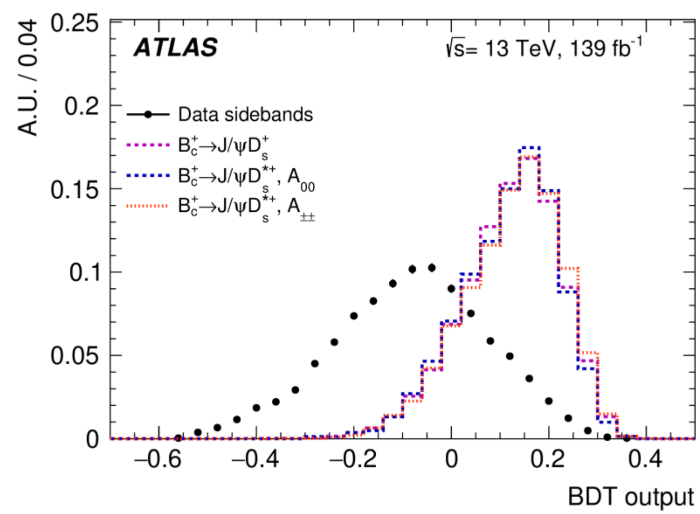
p_{T} of the D_s^+ meson candidate, the $L_{xy}(D_s^+)$ variable, and four angular variables:

- $\cos\theta^*(\pi^+)$, where $\theta^*(\pi^+)$ is the angle between the pion momentum in the $K^+K^-\pi^+$ rest frame and the $K^+K^-\pi^+$ combined momentum in the laboratory frame. The signal distribution of $\cos\theta^*(\pi^+)$ is flat before kinematic selection because the pseudoscalar D_s^+ meson decays isotropically, but it increases as $\cos\theta^*(\pi^+)$ approaches +1 for the background events.
- $|\cos^3\theta'(K^+)|$, where $\theta'(K^+)$ is the angle between one of the kaons and the pion in the K^+K^- rest frame. The decay of the pseudoscalar D_s^+ meson to the ϕ (vector) plus π^+ (pseudoscalar) final state results in the spin of the ϕ meson being aligned perpendicularly to the direction of motion of the ϕ relative to the D_s^+. Consequently, the distribution of $\cos\theta'(K)$ follows a $\cos^2\theta'(K)$ shape, implying a uniform distribution for $\cos^3\theta'(K)$. In contrast, the $\cos\theta'(K)$ distribution of the combinatorial background is approximately uniform and its $\cos^3\theta'(K)$ distribution peaks at zero.
- $\cos\theta^*(D_s^+)$, where $\theta^*(D_s^+)$ is the angle between the D_s^+ momentum in the B_c^+ rest frame and the B_c^+ flight direction in the laboratory frame. The distribution of $\cos\theta^*(D_s^+)$ is uniform for the decays of pseudoscalar B_c^+ mesons before kinematic selection, while it tends to increase towards negative values for the background.
- $\cos\theta'(\pi^+)$, where $\theta'(\pi^+)$ is the angle between the J/ψ momentum and the pion momentum in the $K^+K^-\pi^+$ rest frame. Its distribution is nearly uniform for the signal processes but peaks towards −1 and +1 for the background.



$$S/\sqrt{S+B}$$

efficiency of 81%



2D unbinned fit of two subsets simultaneously : results

Parameter	Value	
$m_{B_c^+}$ [MeV]	6274.8 ± 1.4	agree with PDG
$\sigma_{B_c^+}$ [MeV]	11.5 ± 1.5	agree with MC
$r_{D_s^{*+}/D_s^+}$	1.76 ± 0.22	
$f_{\pm\pm}$	0.70 ± 0.10	
$N^{\mathrm{DS1}}_{B_c^+ \to J/\psi D_s^+}$	193 ± 20	
$N^{\mathrm{DS2}}_{B_c^+ \to J/\psi D_s^+}$	49 ± 10	
$N^{\mathrm{DS1}}_{B_c^+ \to J/\psi D_s^{*+}}$	338 ± 32	
$N^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^+}$	241 ± 28	
$N^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}}$	424 ± 46	

Systematic uncertainties

Source	Uncertainty [%] $R_{D_s^+/\pi^+}$	$R_{D_s^{*+}/\pi^+}$	$R_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$
Simulated $p_T(B_c^+)$ spectrum	1.5	1.9	0.4	0.1
Simulated $\lvert\eta(B_c^+)\rvert$ spectrum	0.7	0.7	0.1	0.2
B_c^+ lifetime	0.1	< 0.1	–	–
D_s^+ lifetime	0.4	0.4	–	–
Tracking efficiency	1.0	1.0	< 0.1	< 0.1
Pile-up effects	1.0	1.0	–	–
χ^2/N_{dof} cut efficiency	3.2	3.2	–	–
Impact parameter cuts efficiency	0.2	0.2	–	–
BDT cut efficiency	1.3	1.3	–	–
Trigger efficiency	0.6	0.6	–	–
Other D_s^+ decay modes	1.6	1.6	–	–
$B_c^+ \to J/\psi D_s^{(*)+}$ signal fit:				
D_s^+ signal mass modelling	1.8	0.5	1.3	0.8
D_s^{*+} signal mass modelling	0.6	1.2	1.7	2.7
Signal angular modelling	0.4	< 0.1	0.4	0.6
Background mass modelling	6.0	9.0	3.2	1.0
Background angular modelling	0.9	1.3	2.1	2.4
$B_s^0 \to \mu^+\mu^-\phi$ triggers	0.8	0.5	1.3	4.0
D_s^{*+} branching fractions	< 0.1	< 0.1	< 0.1	0.7
$B_c^+ \to J/\psi \pi^+$ signal fit:				
Signal modelling	4.2	4.2	–	–
PRD/comb. background modelling	5.8	5.8	–	–
CKM-suppr. background modelling	1.0	1.0	–	–
MC statistics	1.5	1.5	1.7	1.5
Total	10.8	12.6	5.0	5.9
$\mathcal{B}(D_s^+ \to \phi(K^+K^-)\pi^+)$	5.9	5.9	–	–

Comparison with previous results, models and lighter B-meson decays

$R_{D_s^+/\pi^+}$	$R_{D_s^{*+}/\pi^+}$	$R_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$	Reference
2.76 ± 0.47	5.33 ± 0.96	1.93 ± 0.26	0.70 ± 0.11	ATLAS Run 2
2.90 ± 0.62	–	2.37 ± 0.57	0.52 ± 0.20	LHCb Run 1
3.8 ± 1.2	10.4 ± 3.5	$2.8^{+1.2}_{-0.9}$	0.38 ± 0.24	ATLAS Run 1
2.6	4.5	1.7	–	QCD potential model
1.3	5.2	3.9	–	QCD sum rules
1.29 ± 0.26	5.09 ± 1.02	3.96 ± 0.80	0.46 ± 0.09	CCQM
2.2	–	–	–	BSW
2.06 ± 0.86	–	3.01 ± 1.23	–	LFQM
$3.45^{+0.49}_{-0.17}$	–	$2.54^{+0.07}_{-0.21}$	0.48 ± 0.04	pQCD
3.7832	–	–	0.410	RIQM
3.257 ± 0.293	–	–	–	FNCM
1.67 ± 0.36	3.49 ± 0.52	2.09 ± 0.52	–	$B^+ \to \bar{D}^{*0} D_s^{(*)+} / \bar{D}^{*0}\pi^+$
2.92 ± 0.42	6.46 ± 0.60	2.21 ± 0.35	0.48 ± 0.05	$B^0 \to D^{*-} D_s^{(*)+} / D^{*-}\pi^+$
–	7.2 ± 2.1	–	0.94 ± 0.18	$B_s^0 \to D_s^{*-} D_s^+ / D_s^{*-}\pi^+$
–	–	1.402 ± 0.083	0.396 ± 0.023	$B^+ \to J/\psi K^{(*)+}$
–	–	1.425 ± 0.065	0.429 ± 0.007	$B^0 \to J/\psi K^{(*)0}$
–	–	–	0.4774 ± 0.0034	$B_s^0 \to J/\psi \phi$

Modified Gaussian

$$G_{\text{mod}} \propto \exp\left(-0.5 \times t^{1+1/(1+t/2)}\right)$$

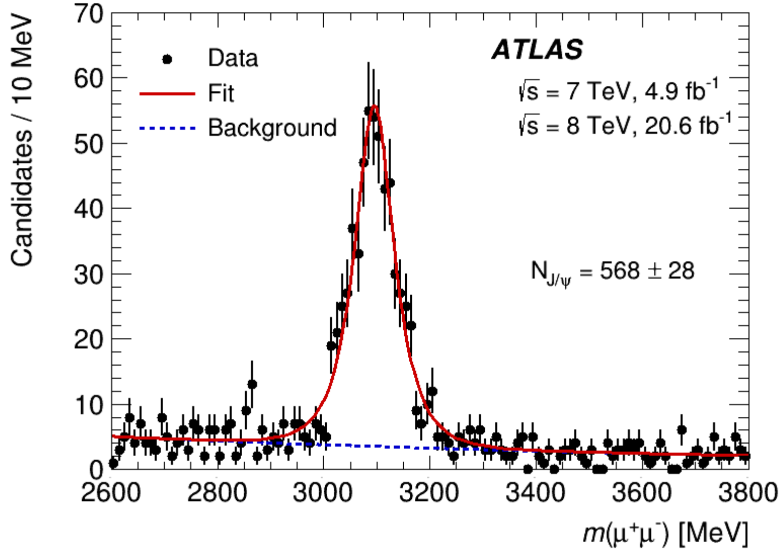
where $t = |m(J/\psi D_s^+) - m_{B_c^+}|/\sigma_{B_c^+}$

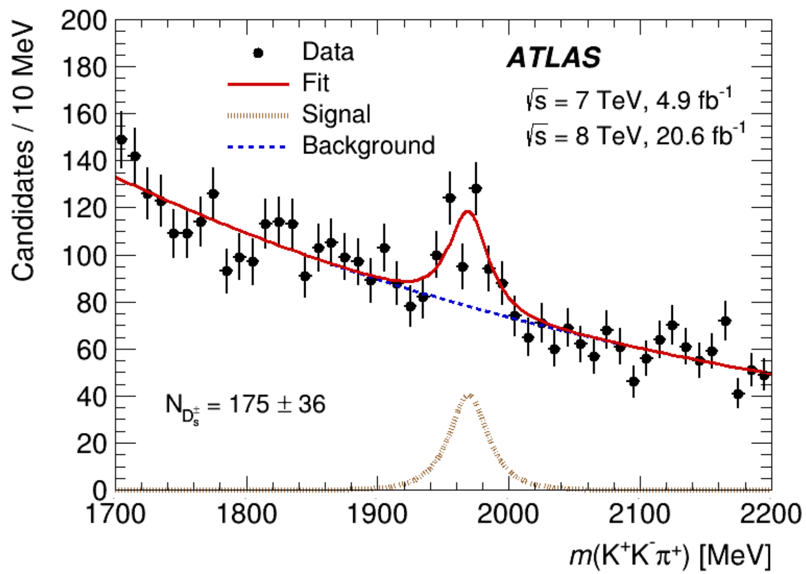
$B_c^+ \to J/\psi D_s^+$ *signal mass shape modelling* effects are tested with alternative models for the $B_c^+ \to J/\psi D_s^+$ signal $m(J/\psi D_s^+)$ distribution: a double-Gaussian function and a double-sided Crystal Ball function [34–36], fixing the tail parameters to the values extracted from simulation.

Is it really $B_c^+ \to J/\psi\ D_s^{(*)+}$?

EPJ C 75 (2016) 1

(not $B_c^+ \to \mu^+\mu^- \varphi\ \pi^+$, $\mu^+\mu^- D_s^+$, $J/\psi\ \varphi\ \pi^+$)





Cascade fit w/o mass constraints

events with 5.9 < m(J/ψ D_s^+) < 6.4 GeV

N(J/ψ) = 568 ± 28

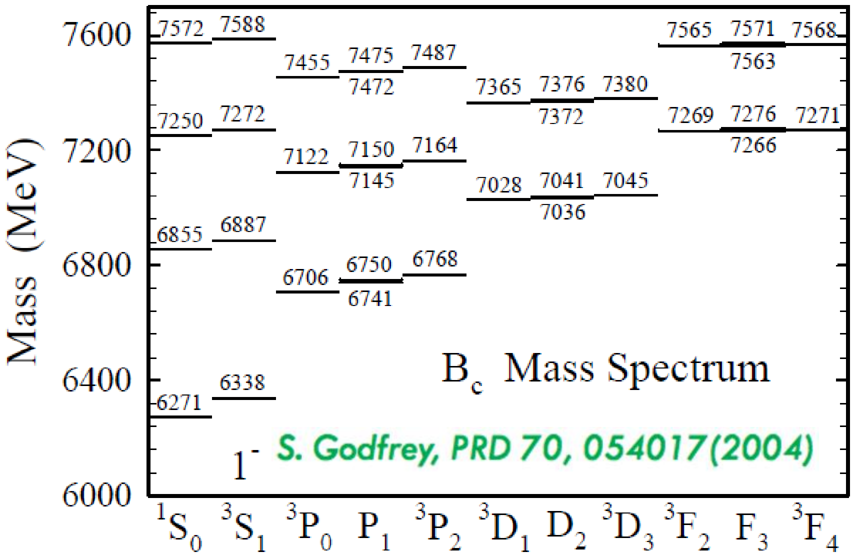
a lot of J/ψ in background

N(D_s^+) = 175 ± 36

non-significantly above
N($B_c^+ \to J/\psi\ D_s^+$) + N($B_c^+ \to J/\psi\ D_s^{*+}$)

Observation of excited B_c ($\to B_c\pi^+\pi^-$)

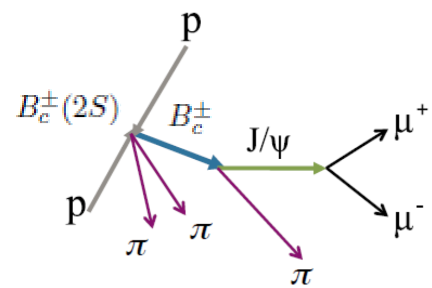
ATLAS, PRL 113 (2014) 212004



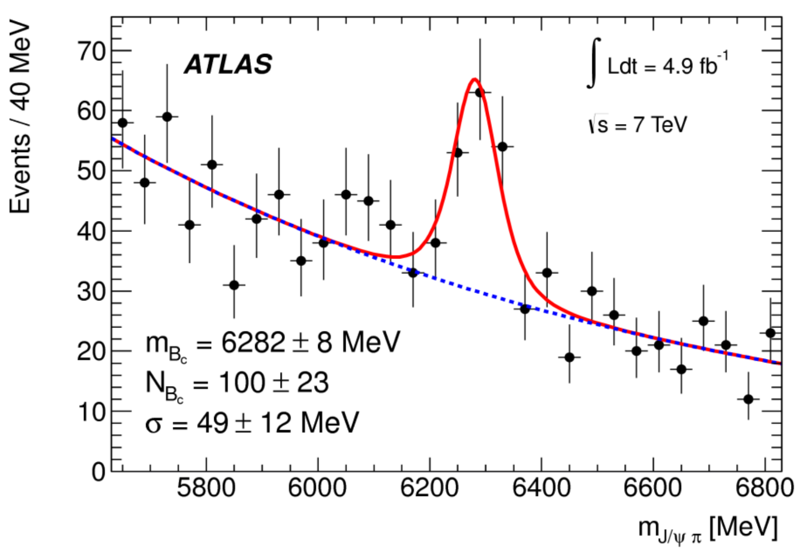
Large B_c family is expected although only ground state has been known until today

$B_c^{\pm}(2S)$ 6835–6917 MeV

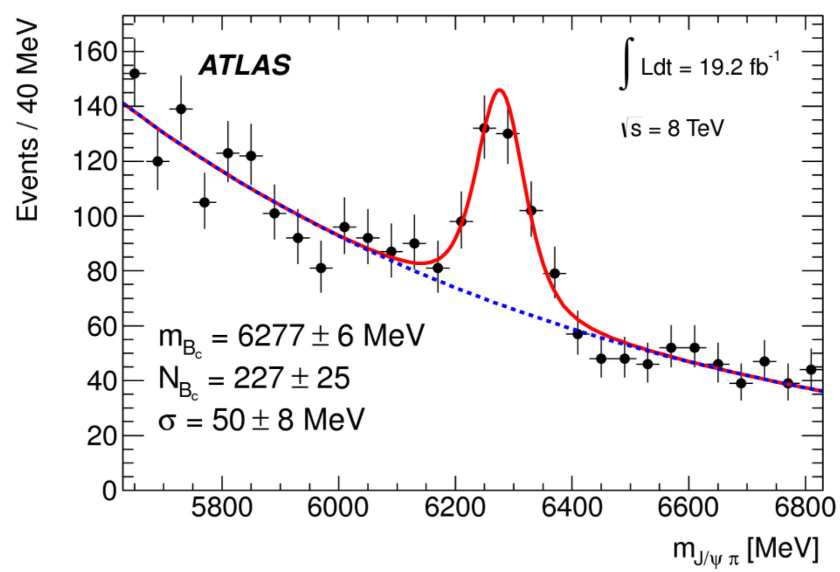
$2S/1S \simeq 0.6 \qquad 2^1S_0 \to 1^1S_0 + \pi\pi$



$p_T(\pi)$ > 4 GeV, $m(J/\psi)$ constrained to PDG



$p_T(B_c)$ > 15 GeV

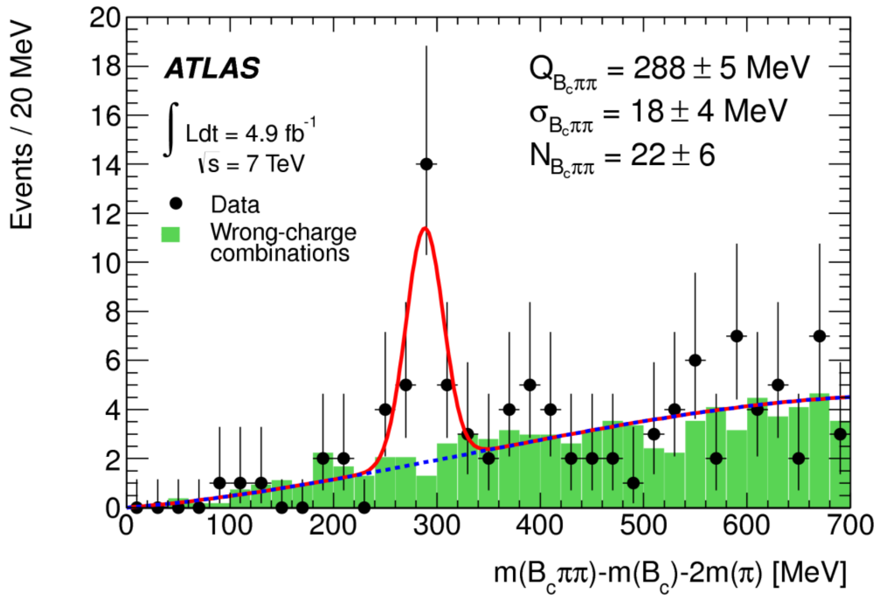


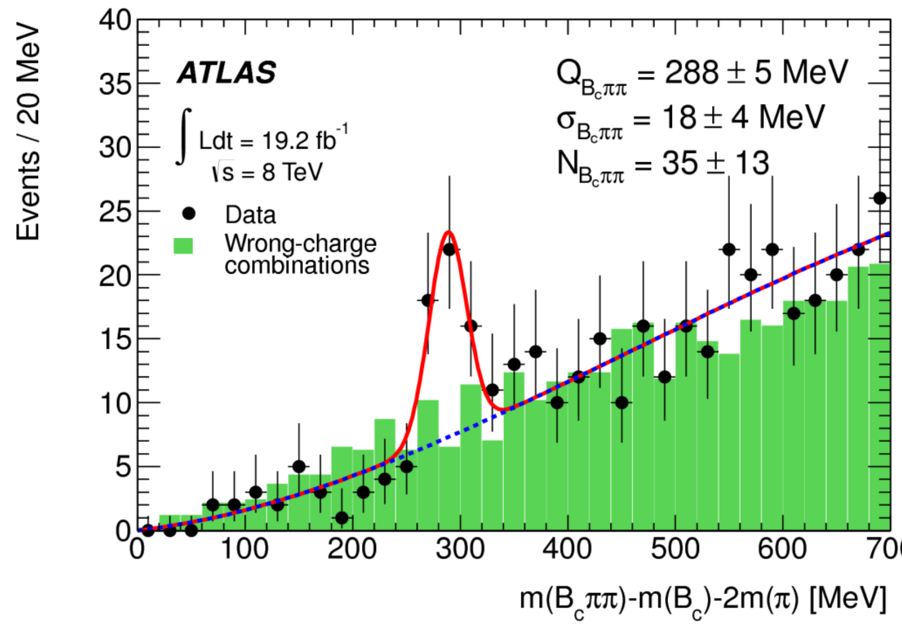
$p_T(B_c)$ > 18 GeV

Observation of excited B_c ($\longrightarrow B_c \pi^+\pi^-$)

ATLAS, PRL 113 (2014) 212004

$p_T(\pi^\pm)$ > 400 MeV, $m(J/\psi)$ constrained to PDG

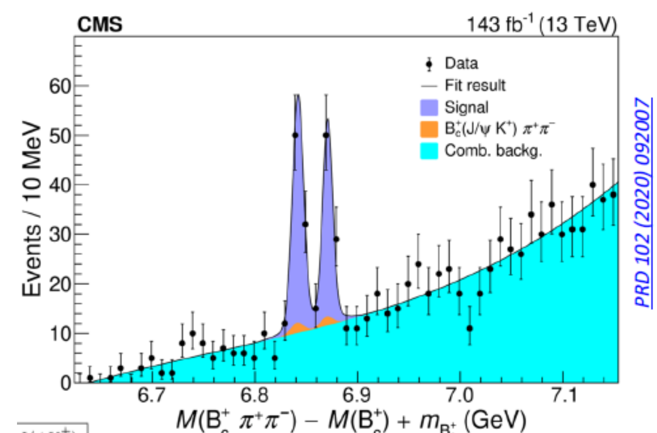




Significance from $\Delta\ln L$ of pseudo-experiments: 5.4 σ (local)
5.2 σ (“look elsewhere”)

$Q = 288.3 \pm 3.5 \pm 4.1$ MeV
$M = 6842 \pm 4 \pm 5$ MeV

Both mass value and decay mode agree with expectations for $B_c^{\pm}(2S)$

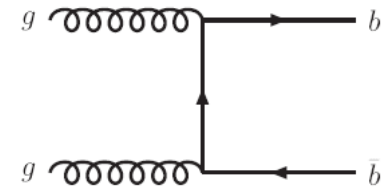


Charmonium production

Non-prompt (from B decays) – probes open b quark production, fragmentation and B-decay kinematics

FONLL, matched NLO+NLL ("massive" NLO + resummation)

GM-VFNS ("massless" NLO + mass-dependent terms)



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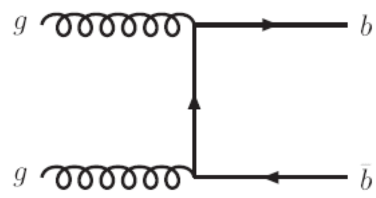
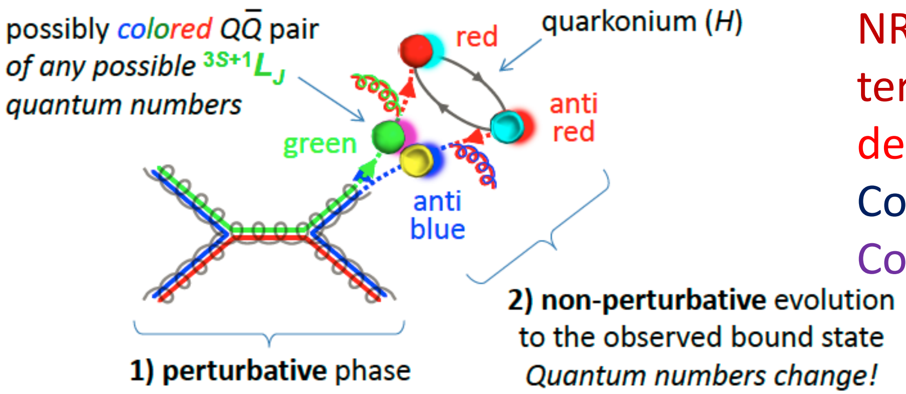


Prompt (not from B decays) – probes specific mechanisms of $Q\bar{Q}$ system production and transformation to a meson



NRQCD: Color Singlet (CS) and Color Octet (CO) terms. Long-distance matrix elements (LDME) determined from experimental data.

Color Singlet Model (CSM) – only CS diagrams.

Color Evaporation Model (CEM) – only one LDME.

Charmonium production

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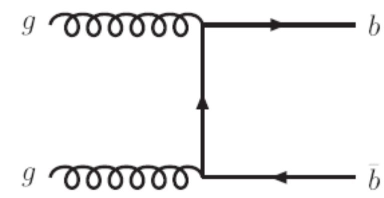
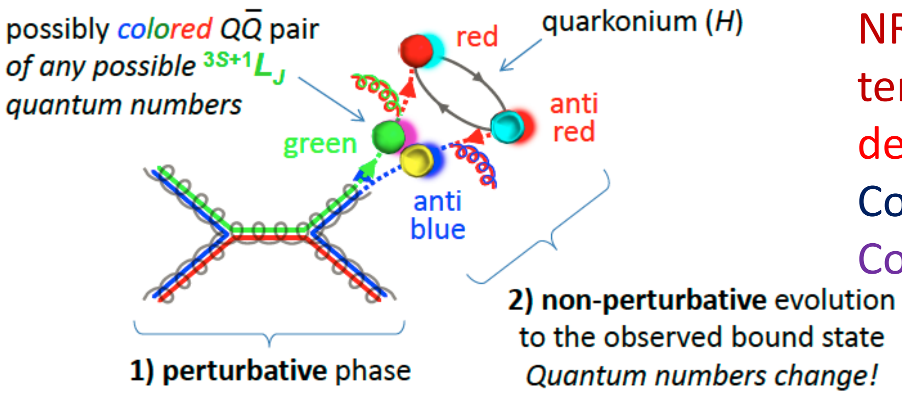


Prompt (not from B decays) – probes specific mechanisms of $Q\bar{Q}$ system production and transformation to a meson



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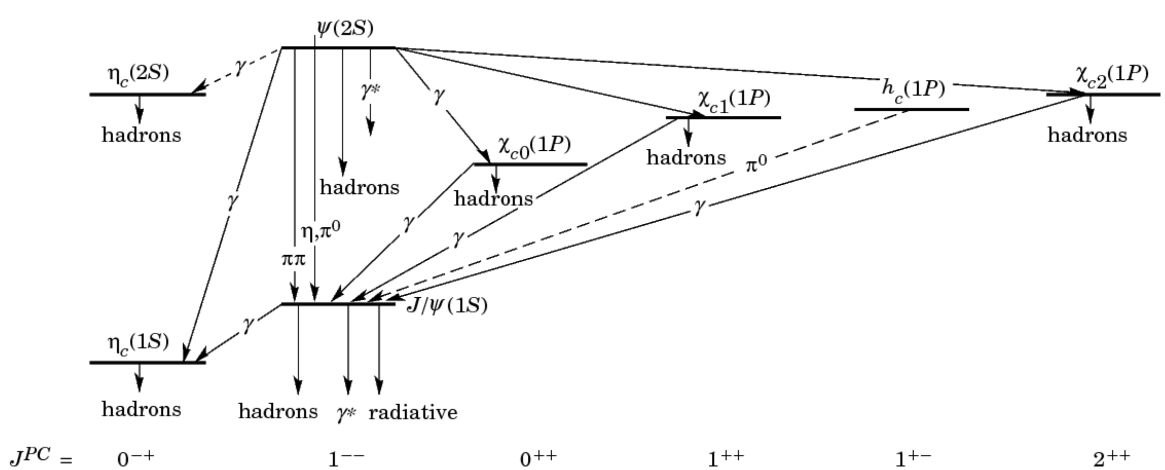


$\Psi(2S)$ – nearly feed-down free

J/ψ – feed-downs ~35%

Charmonium production at 13 TeV with 139 fb^{-1}

ATLAS-CONF-2019-047

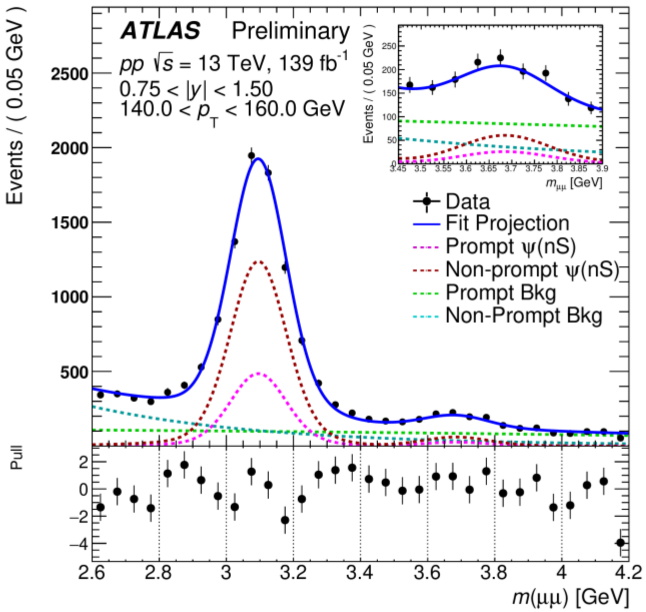
Uses a single-muon trigger, with threshold at 50 GeV, un-prescaled on the full integrated luminosity of Run II, 139 fb^{-1}

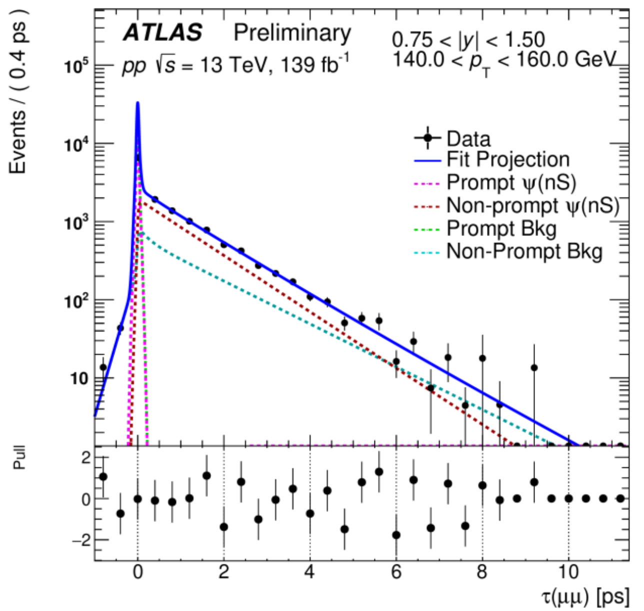
p_T range covered: 60-360 GeV for J/ψ in 11 bins
(60-140 GeV for ψ(2S))

Rapidity range |y| < 2 covered in three bins

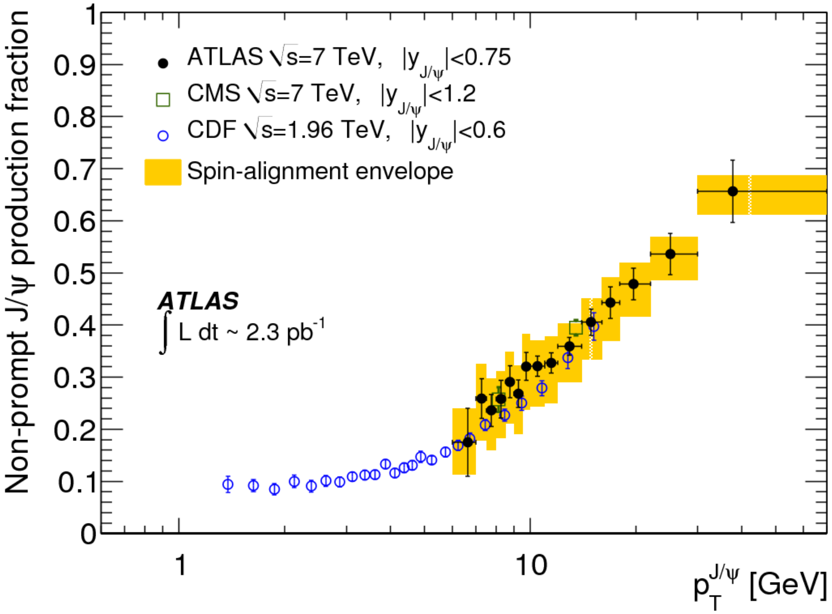
Yields for J/ψ and ψ(2S), prompt and non-prompt (from B decays), determined using 2D fit (mass and "pseudo-proper" lifetime)

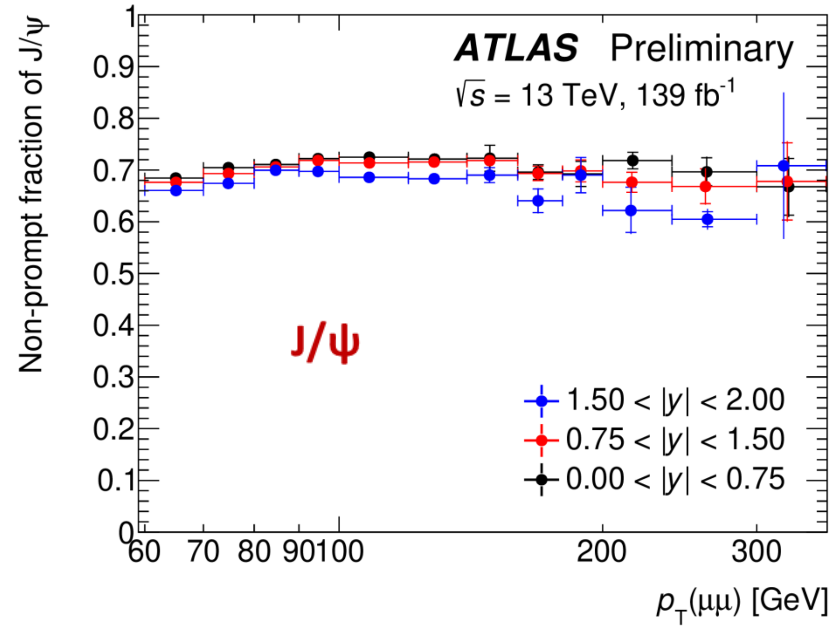
$$\tau = \frac{m\, L_{xy}}{c\, P_T}$$





Charmonium non-prompt fractions



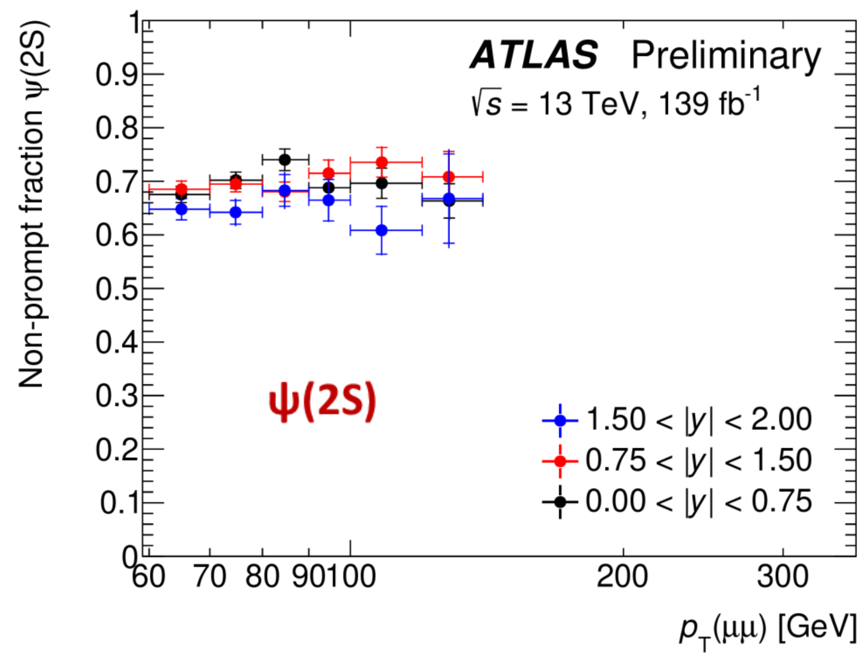


Plateau ~0.7 for p_T >~ 40 GeV

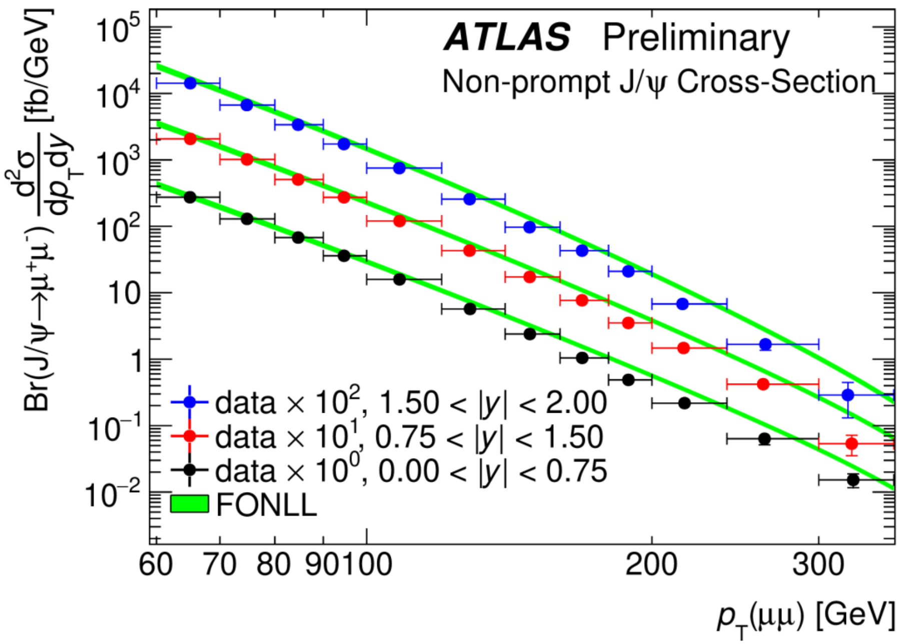
Similar behavior in pp and p$\bar{p}$ collisions for √s from 1.96 TeV till 13 TeV

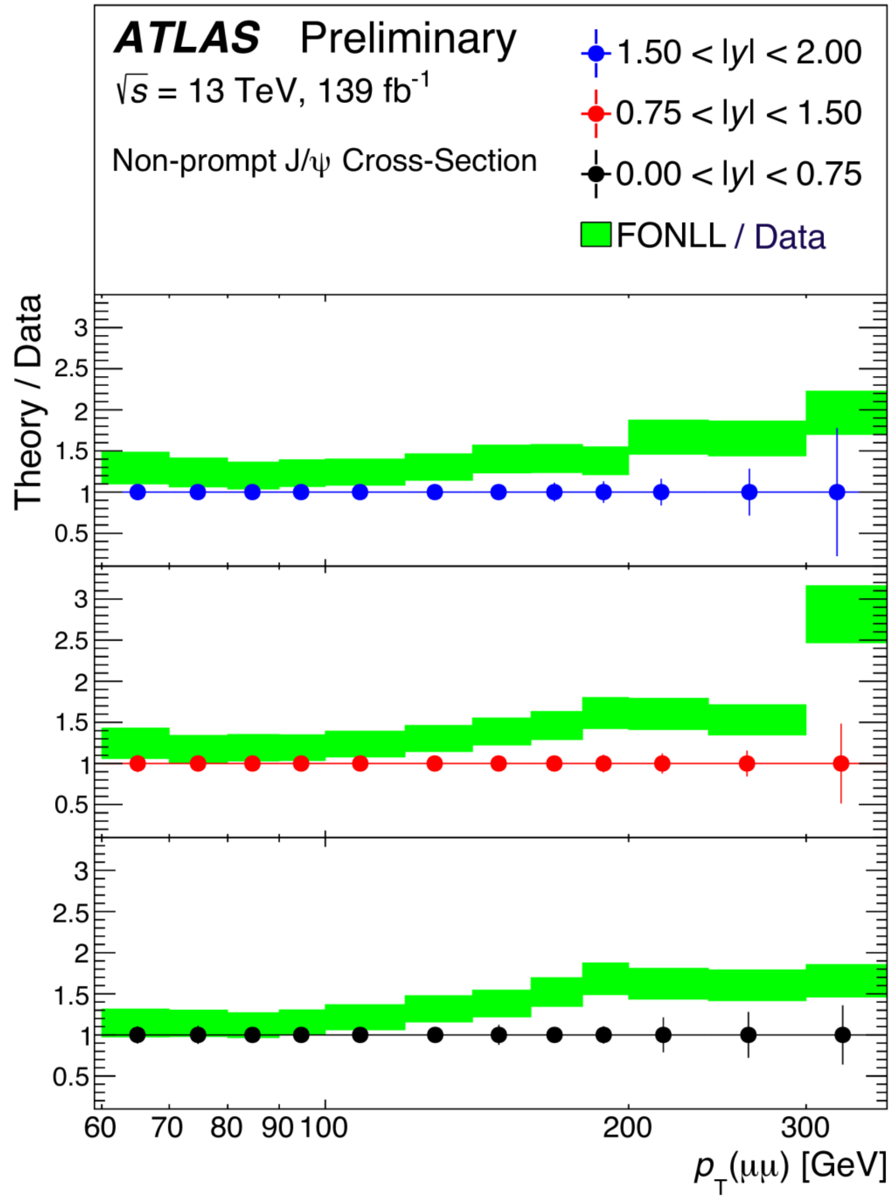
No strong dependence from rapidity

Similar for J/ψ and ψ(2S)



Charmonium non-prompt x-sections





FONLL predictions in general agreement, too high at high p_T

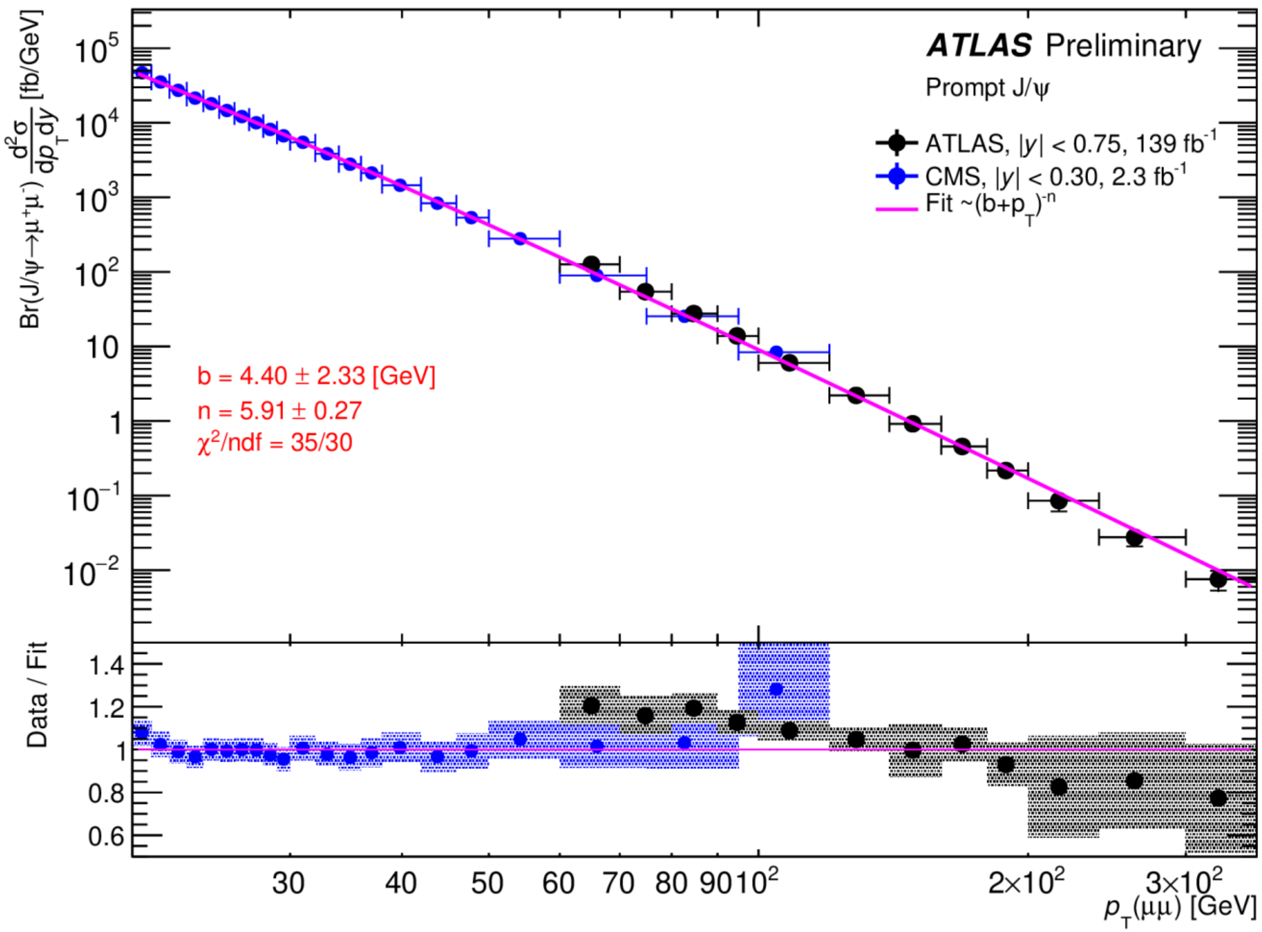
Deviations from data up to ~2

NNLO?

New fragmentation tuning?

Fixing of technical FONLL problems at high p_T?

Charmonium prompt x-sections



ATLAS and CMS agree in the range of overlap

Can be described by simple parametrization

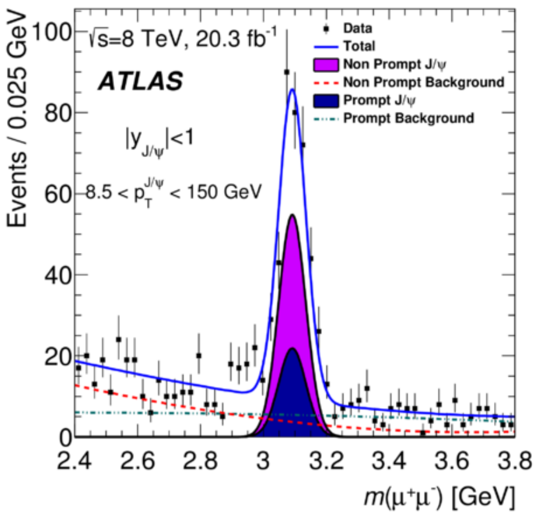
$$\sim(b+p_T)^{-n}$$

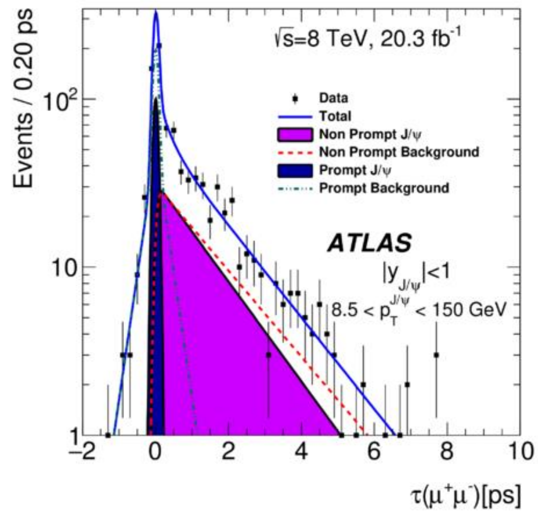
with b=4.4 and n=6

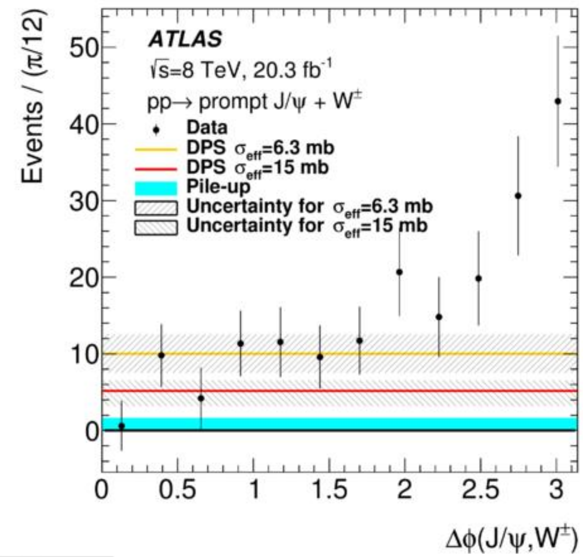
Waiting NRQCD predictions for high-p_T charmonium production

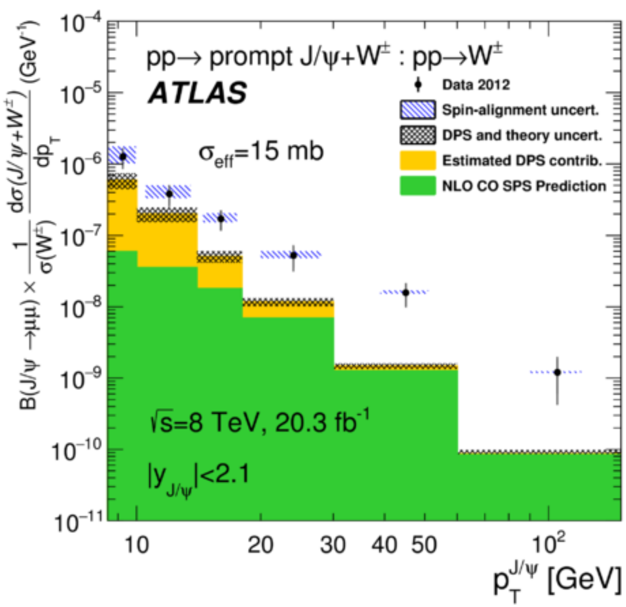
Measurement of J/ψ production in association with a $W^{\pm}$ boson with pp data at 8 TeV

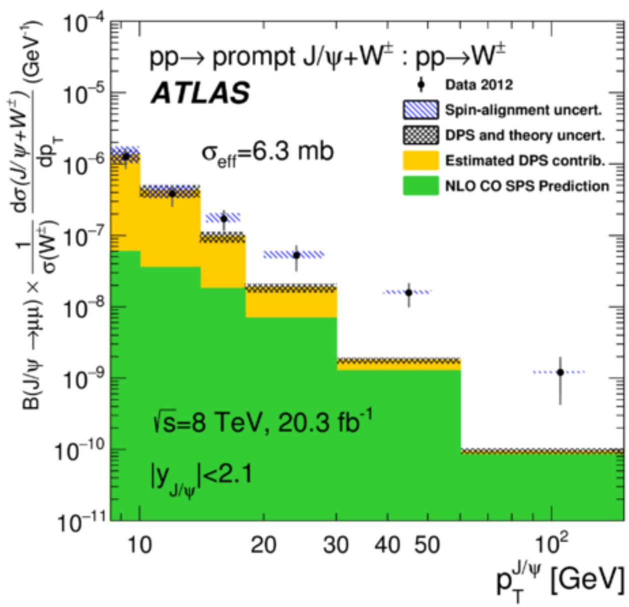
ATLAS, JHEP 01 (2020) 95











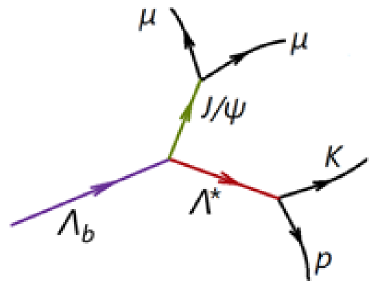
Missing CS SPS?

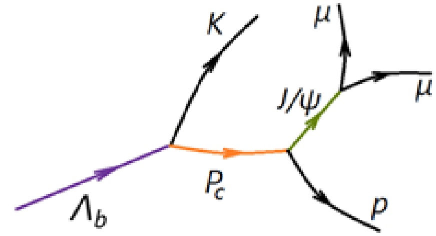
Results for 13 TeV in preparation

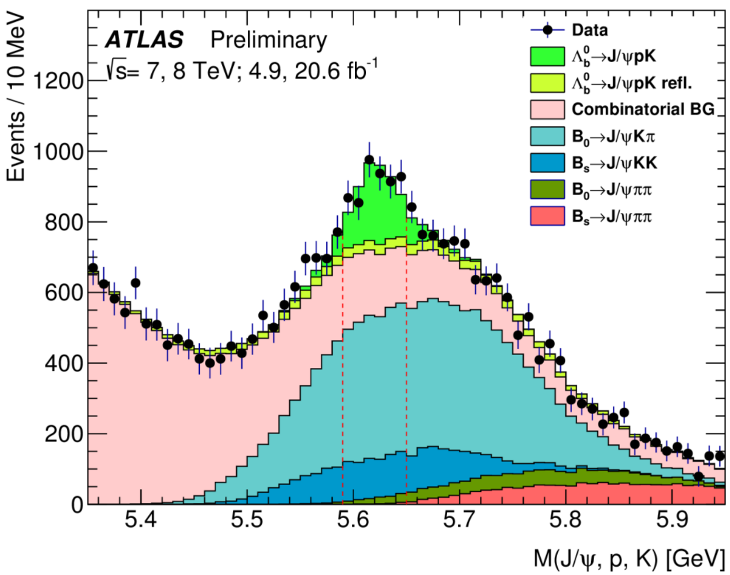
Pentaquarks with hidden charm ($c\bar{c}uud$) at 7 - 8 TeV with 25 fb^{-1}

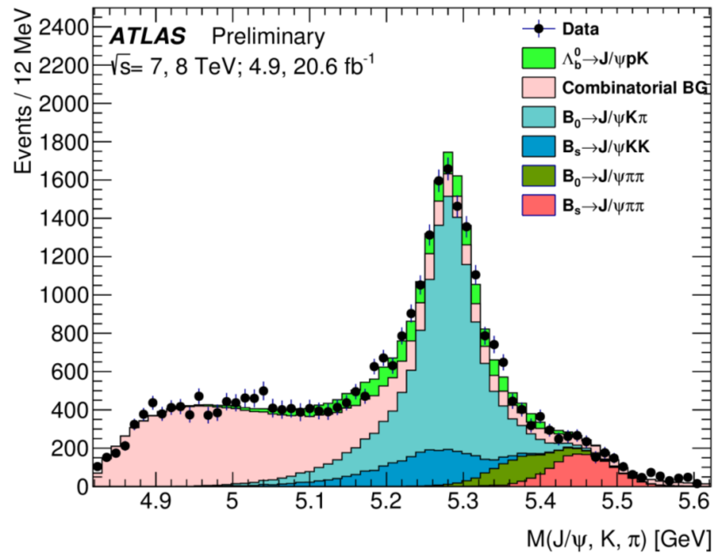
ATLAS-CONF-2019-048

m(Kπ) > 1.55 && m(πK) > 1.55 → m(pK) > 2.0 GeV





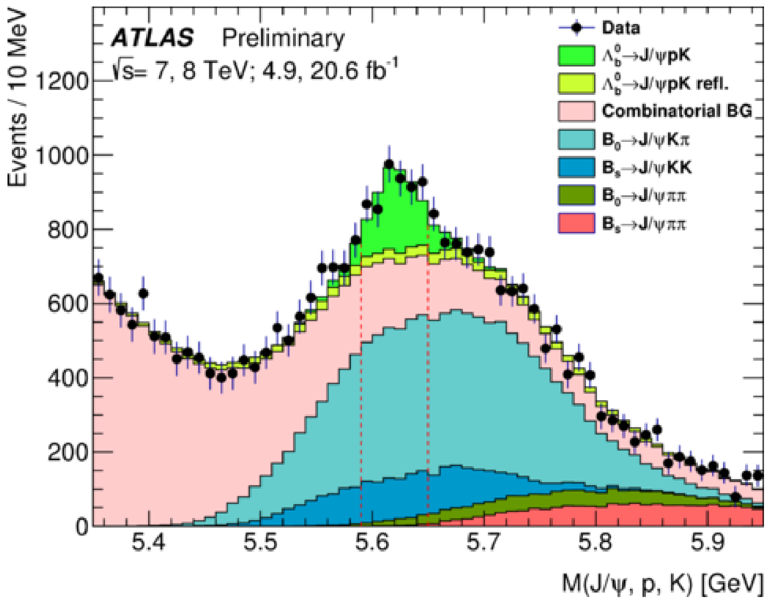




$\Lambda_b \to J/\psi\ p\ K^-$ signal is seen on the top of

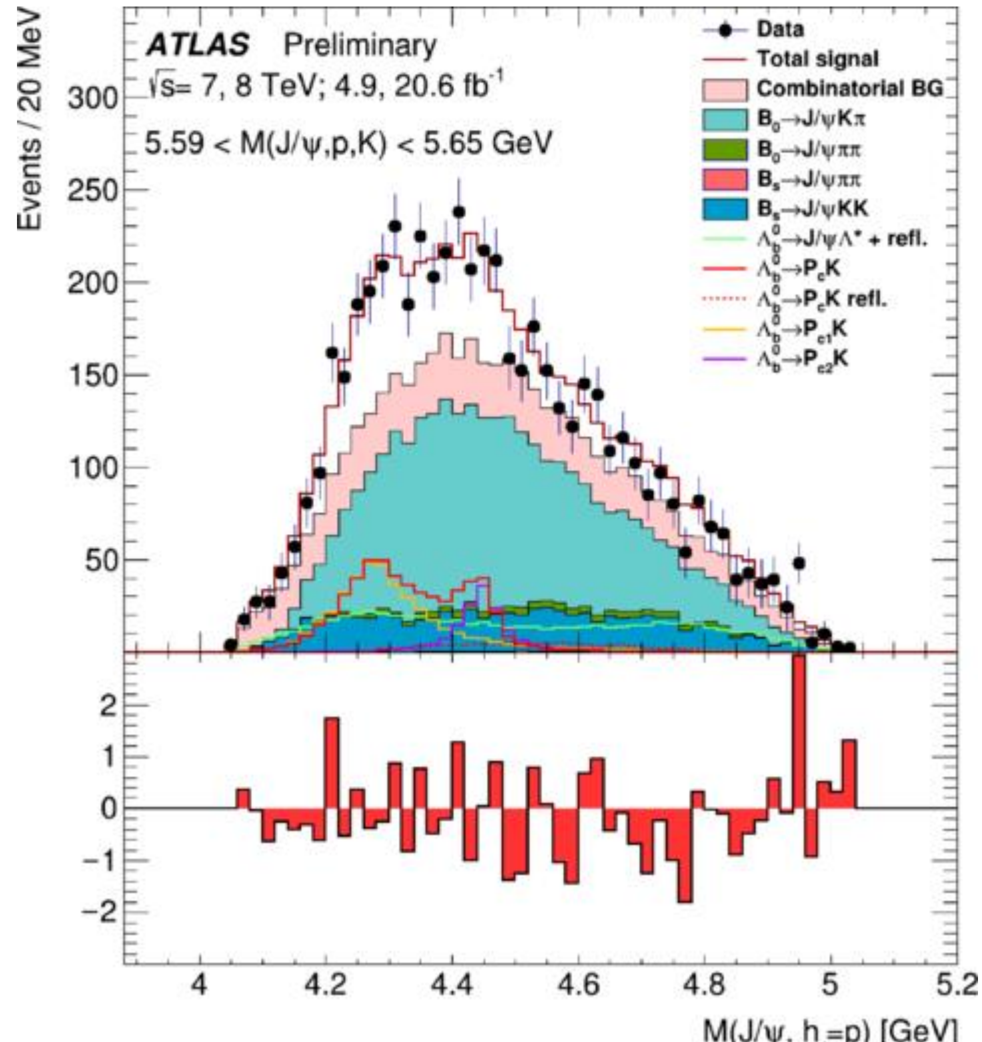
- **large combinatorial background**
- **very large $B \to J/\psi\ K^+ \pi^-$ contribution**
- **large $B_s \to J/\psi\ K^+ K^-$ contribution**
- **tails from small $B \to J/\psi\ \pi^+ \pi^-$ and $B_s \to J/\psi\ \pi^+ \pi^-$ contributions**

P_c^+ at 7 - 8 TeV



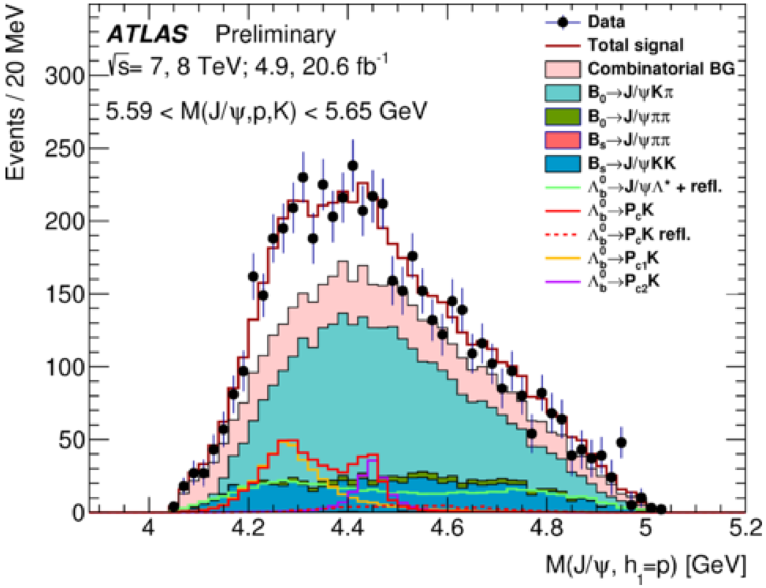
$N(\Lambda_b \to J/\psi,p,K) = 2270 \pm 300$

$N(B^0 \to J/\psi,K,\pi) = 10770,$
$N(B_s \to J/\psi,K,K) = 2290,$
$N(B^0 \to J/\psi,\pi,\pi) = 1070,$
$N(B_s \to J/\psi,\pi,\pi) = 1390;$

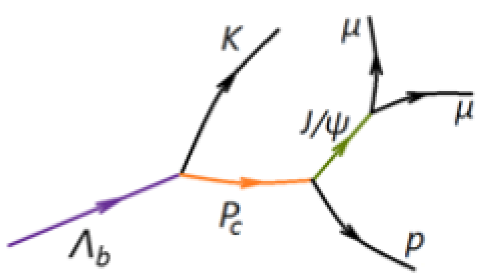


1010±140 direct $\Lambda_b \to J/\psi,p,K$

$\Lambda_b \to J/\psi, p, K$ decays analysis: 2 pentaquark hypothesis



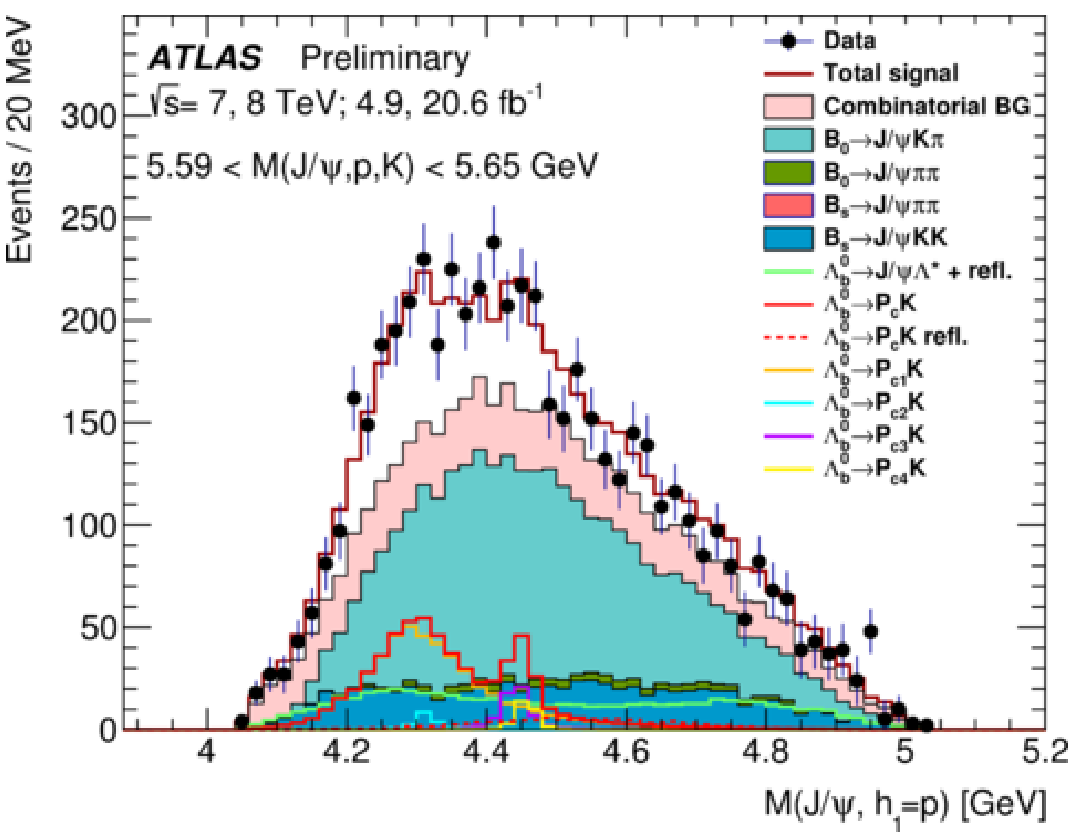
$\chi^2/N_{dof} = 49.0/43$ (p-value= 0.25)



P_c signal parameters and yields from fit:

Parameter	Value	LHCb value
$N(P_{c1})$	400^{+130}_{-140}(stat)$^{+110}_{-100}$(syst)	–
$N(P_{c2})$	150^{+170}_{-100}(stat)$^{+50}_{-90}$(syst)	–
$N(P_{c1}+P_{c2})$	540^{+80}_{-70}(stat)$^{+70}_{-80}$(syst)	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}$(stat)$^{+0.2}_{-0.1}$(syst) rad	–
$m(P_{c1})$	4282^{+33}_{-26}(stat)$^{+28}_{-7}$(syst) MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	140^{+77}_{-50} (stat)$^{+41}_{-33}$ (syst) MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	4449^{+20}_{-29} (stat)$^{+18}_{-10}$ (syst) MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat)$^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV

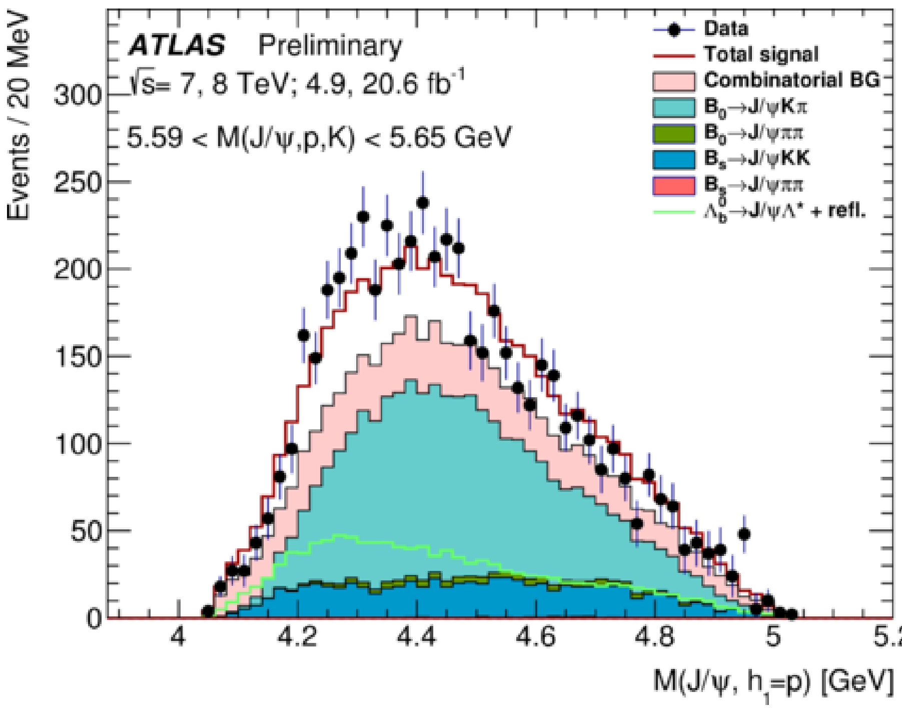
$\Lambda_b \to J/\psi,p,K$ decays analysis: 4 pentaquark hypothesis

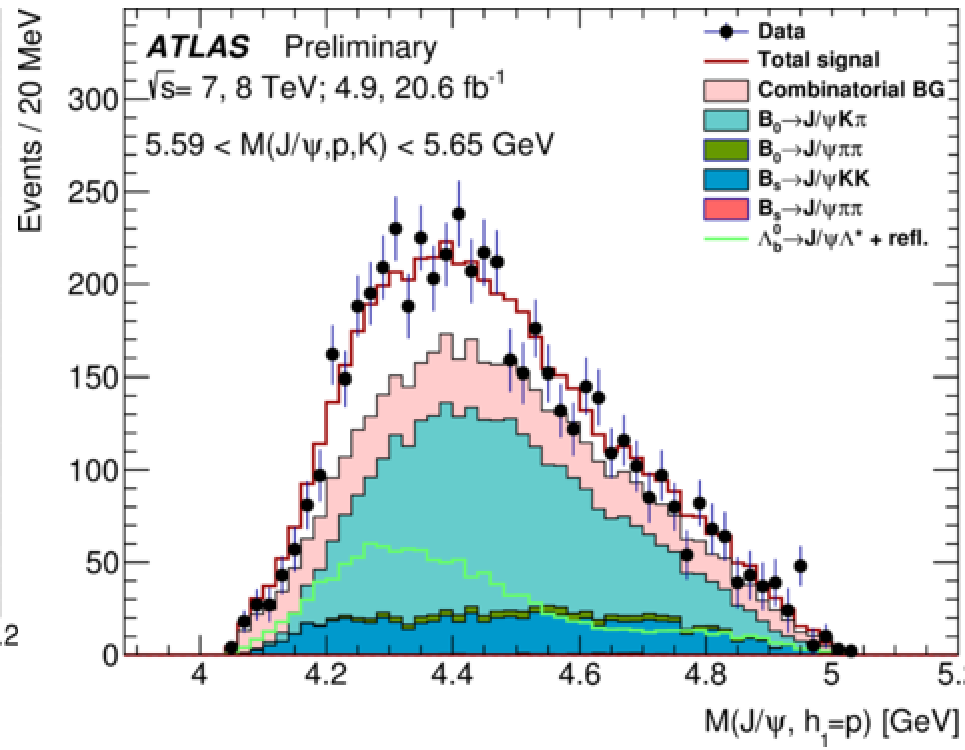


Similar fits (no interference, Breit-Wigner amplitudes) has been performed on our data with masses, widths and relative yields of narrow states fixed to LHCb values. Parameters of $P_c(4380)$ kept free.

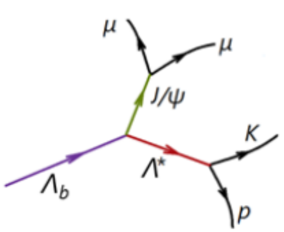
ATLAS data is consistent with LHCb Run II results.

No pentaquark fits: extended Λ^* decay model





Projection of 2D M(J/ψ,p) vs M(J/ψ,K) + 1D M(p,K) fit w/o pentaquarks using extended Λ* decay model (left)



Result of 1D χ2 M(J/ψ,p) fit with the same model (right): χ^2/NDF = 42.0/23
p-val = 9.1 x 10^{-3}

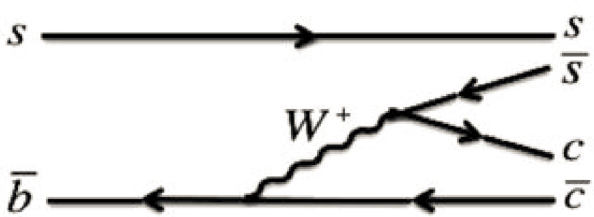
This model shows a 'border-line agreement' with data.

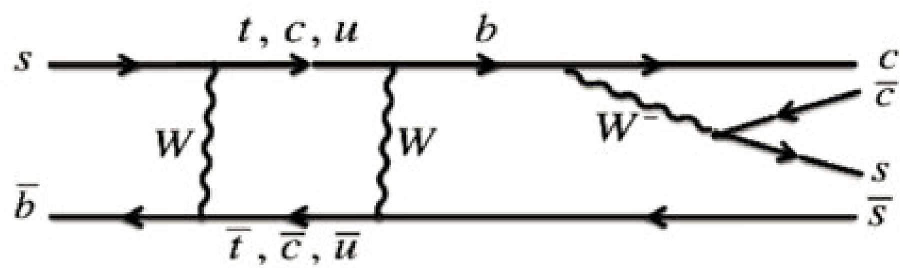
Measurements of CP violation with $B_s \to J/\psi\varphi$

The time evolution of B_s meson mixing is characterized by

- ✓ the mass difference Δm_s of the heavy (B_H) and light (B_L) mass eigenstates
- ✓ the CP-violating mixing phase φ_s
- ✓ the width difference of $\Delta\Gamma_s = \Delta\Gamma_L - \Delta\Gamma_H$

Interference between the B_s decays amplitudes to the CP eigenstates $J/\psi\varphi$ or via mixing gives rise to a measurable CP violating phase φ_s





SM:

$$\phi_s \simeq -2\beta_s = -0.0363^{+0.0016}_{-0.0015}\ \text{rad} \qquad \beta_s \doteq \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$$

$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.087 \pm 0.021\ \text{ps}^{-1}$

New Physics could modify φ_s and $\Delta\Gamma_s$ / Δm_s If new particles contributes to box diagrams

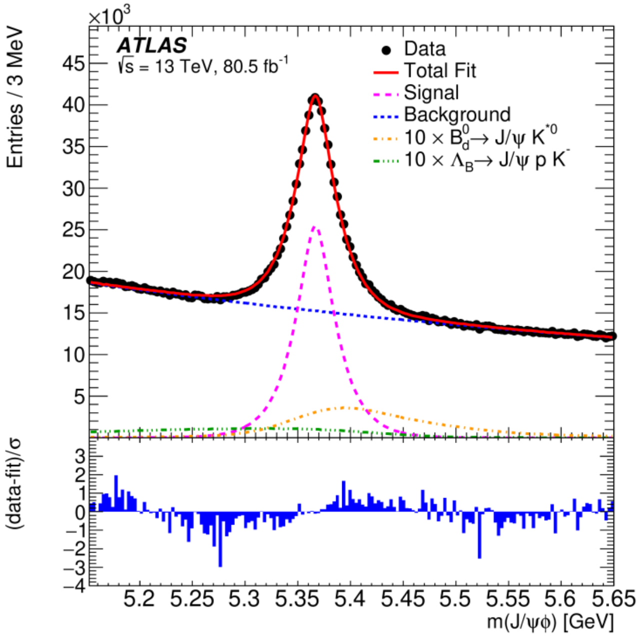
$PS \to VV$ decay gives orbital angular momentum $L = 0$, 1 or 2

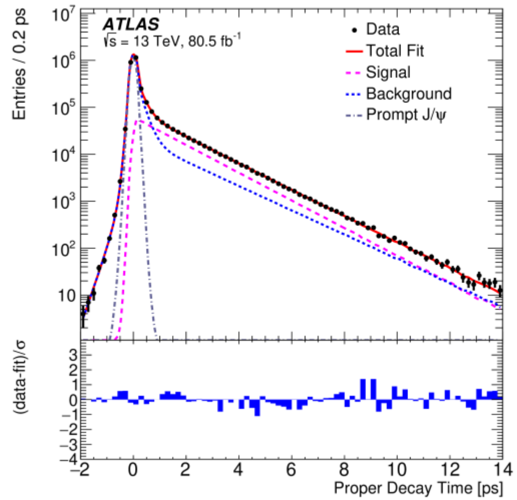
$L = 0$ or 2 are CP-even

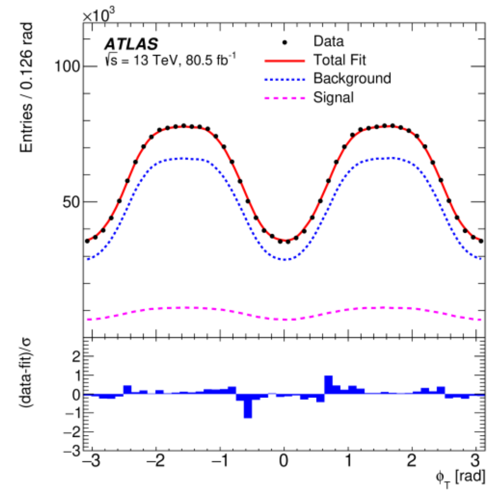
$L = 1$ is CP-odd

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

Eur. Phys. J. C 81 (2021) 342
DOI: 10.1140/epjc/s10052-021-09011-0

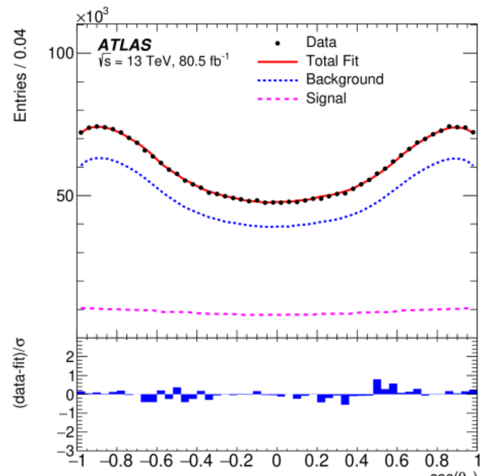


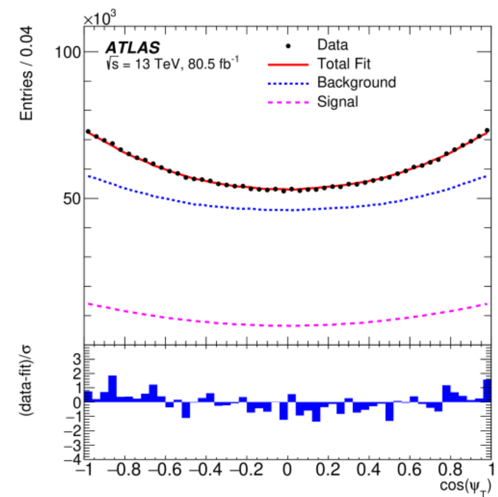


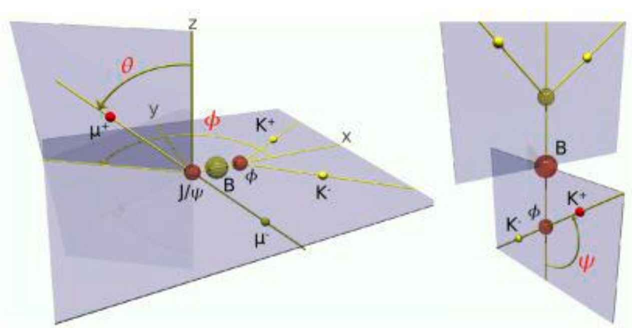


453570 ± 740

***$B_s \to J/\psi\varphi$* мезонов**

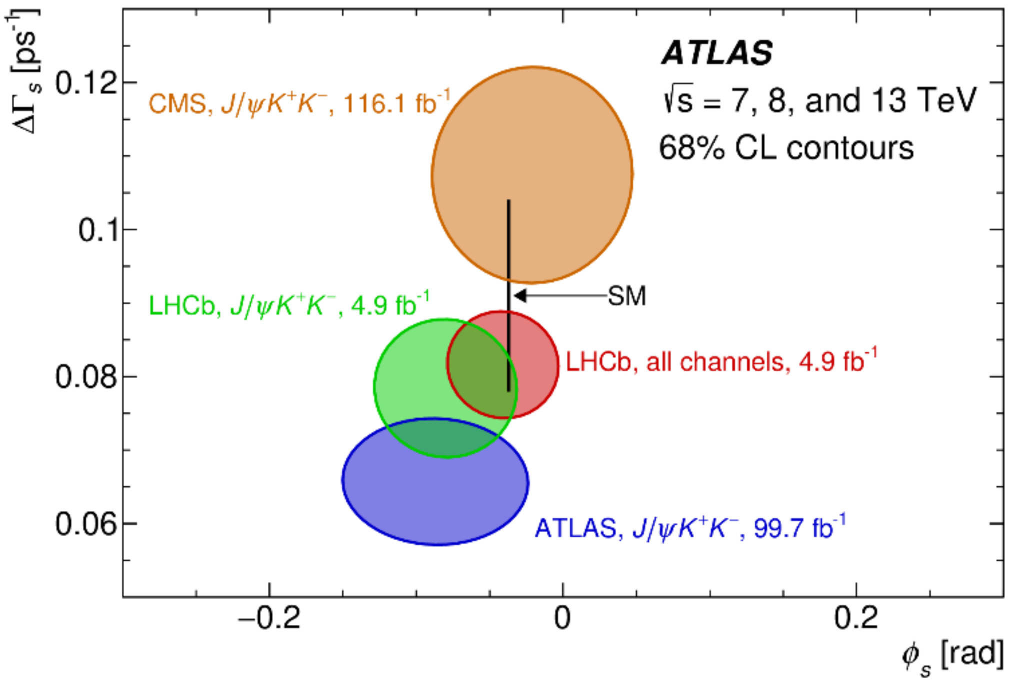






time-dependent, flavour-tagged angular analysis

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



Eur. Phys. J. C 81 (2021) 342
DOI: 10.1140/epjc/s10052-021-09011-0

$$\begin{aligned}
\phi_s &= -0.087 \pm 0.036\ (\text{stat.}) \pm 0.021\ (\text{syst.})\ \text{rad} \\
\Delta\Gamma_s &= 0.0657 \pm 0.0043\ (\text{stat.}) \pm 0.0037\ (\text{syst.})\ \text{ps}^{-1} \\
\Gamma_s &= 0.6703 \pm 0.0014\ (\text{stat.}) \pm 0.0018\ (\text{syst.})\ \text{ps}^{-1}
\end{aligned}$$

13 TeV: Data 2015 – 2017

Data 2018 to be included in next publication

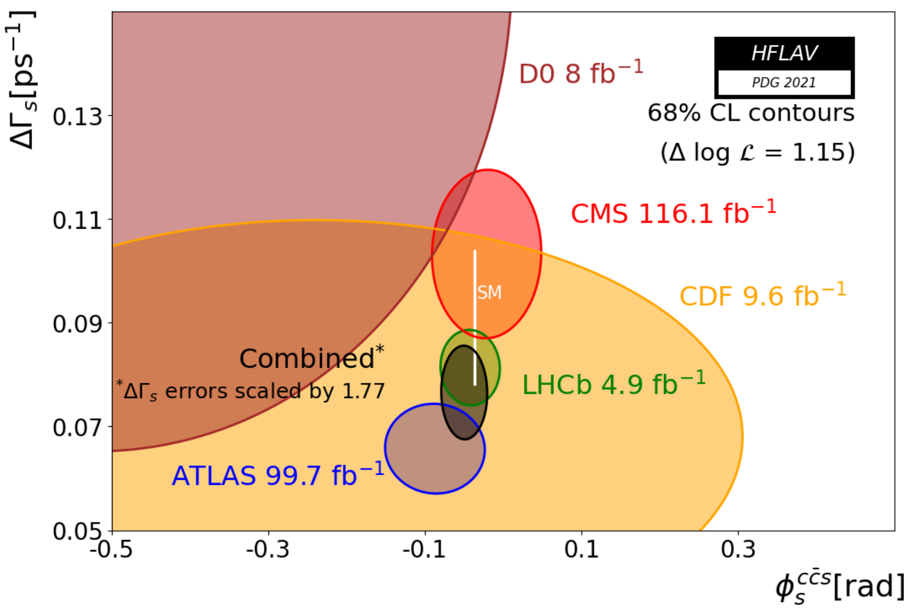
Измерение CP-нарушающей фазы φ_s и $\Delta\Gamma_s$ на 100 fb^{-1}

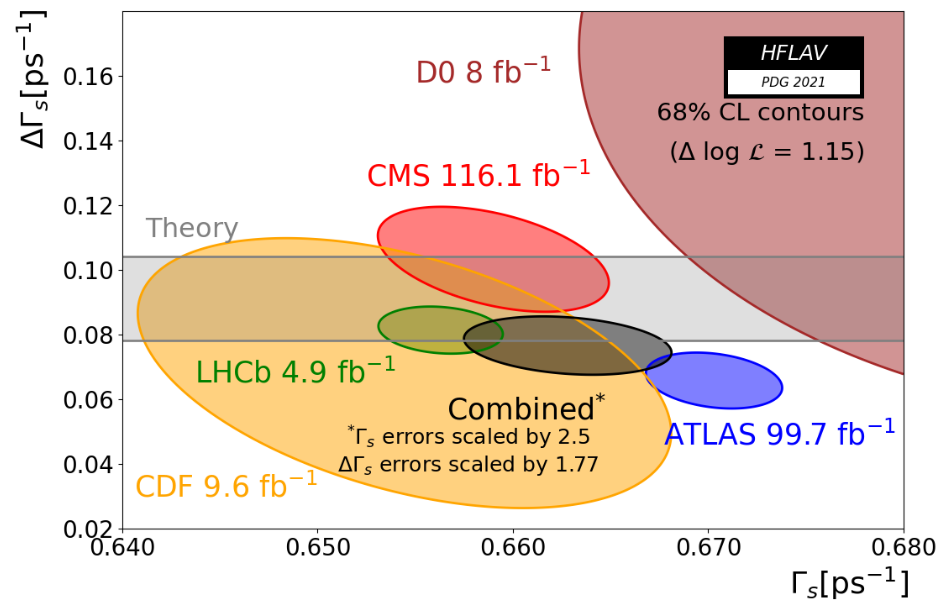
В согласии с LHCb, CMS и СМ по φ_s
рассогласование по $\Delta\Gamma_s$ и Γ_s

New combination after full Run-2 results publication

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

Eur. Phys. J. C 81 (2021) 342
DOI: 10.1140/epjc/s10052-021-09011-0





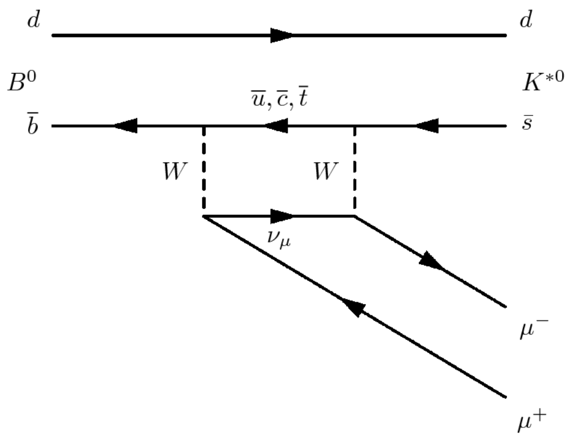
Studies of methodical differences

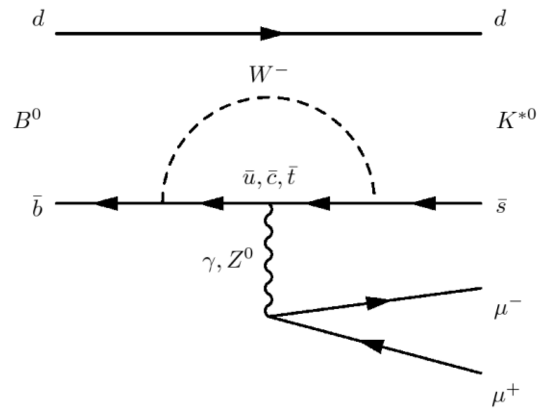
New combination after full Run-2 results publication

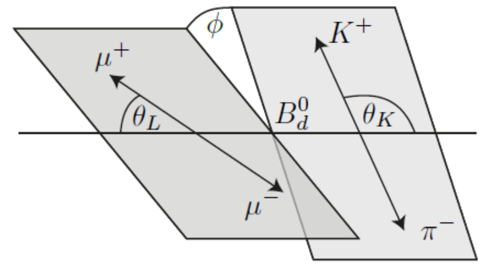
Problems with lifetime measurements?

ATLAS is working on high precision measurement of B° →J/ψK^{*0} lifetime

$B^0 \to K^{*0}\mu^+\mu^-$ (FCNC) ATLAS, JHEP 10 (2018) 047







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

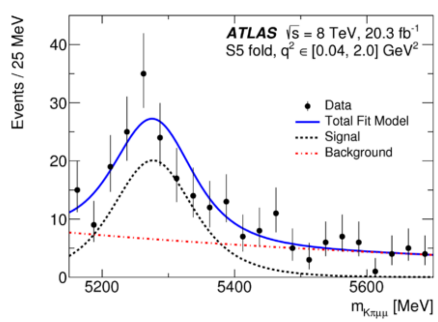
$$
\begin{aligned}
P_1 &= \frac{2S_3}{1-F_L} \\
P_2 &= \frac{2}{3}\frac{A_{\mathrm{FB}}}{1-F_L} \\
P_3 &= -\frac{S_9}{1-F_L} \\
P'_{i=4,5,6,8} &= \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.
\end{aligned}
$$

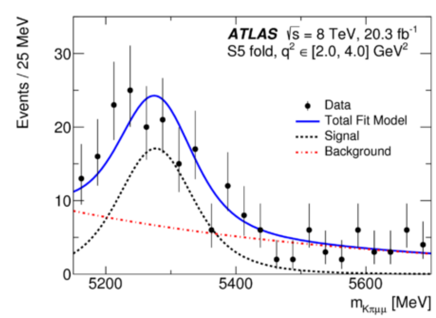
to reduce theor. uncert.

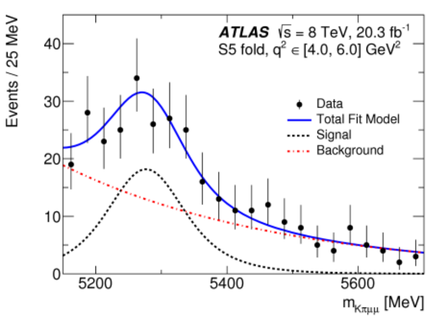
F_L – fraction of longit. polarised K*'s

S_i – angular coefficients

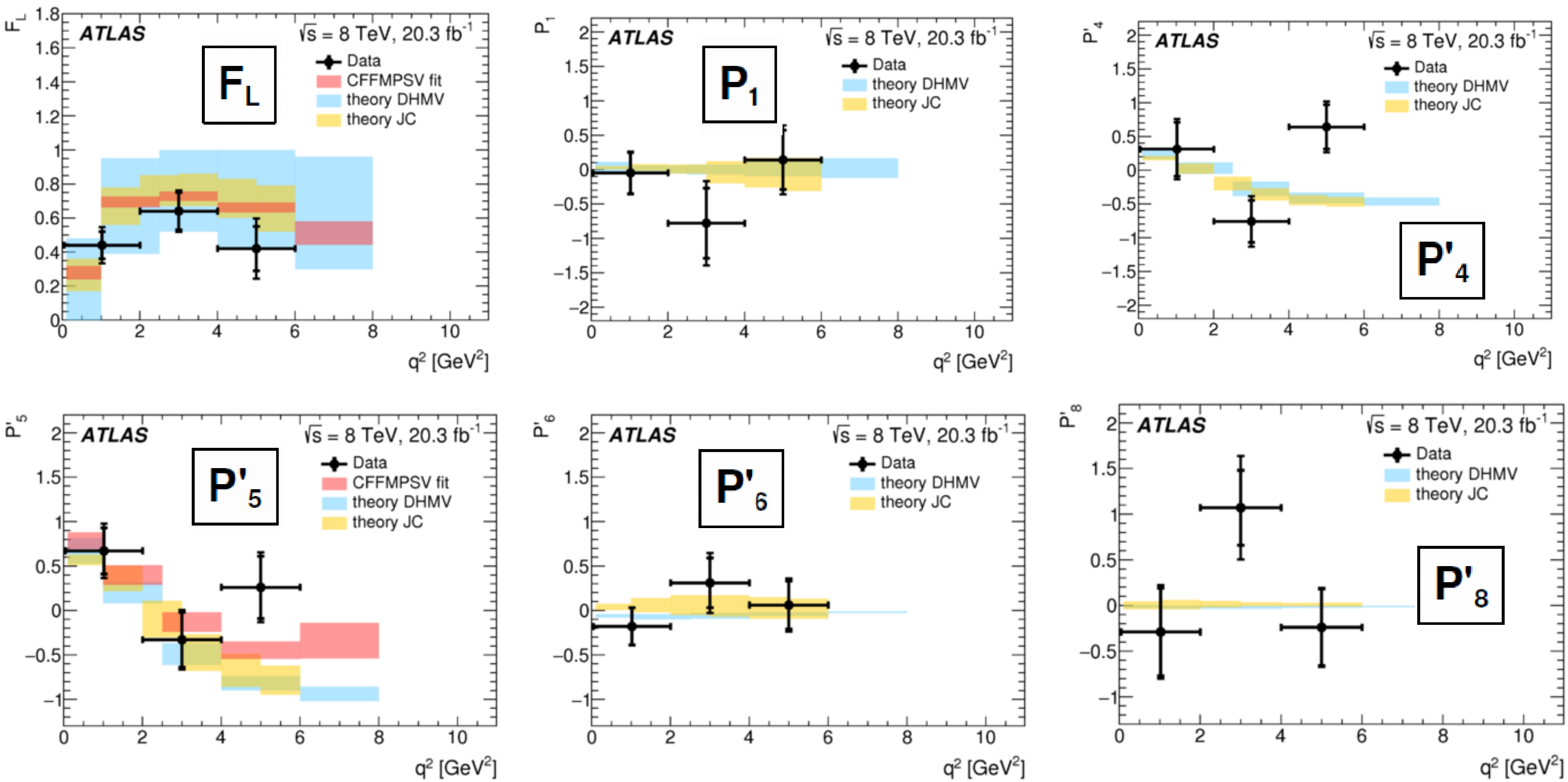
Full angular analysis Performed in bins of *$q^2 = m^2(\mu^+\mu^-)$*







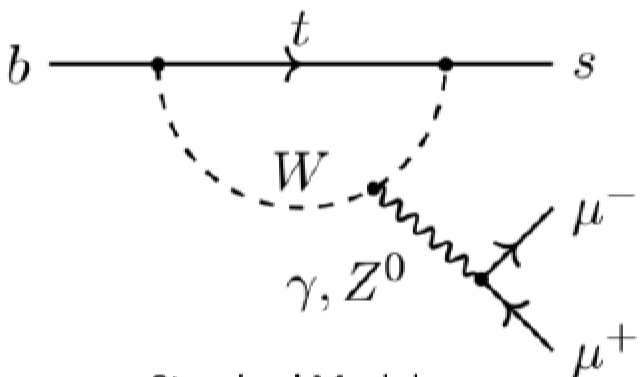
Angular analysis on B → K*μμ at 8 TeV



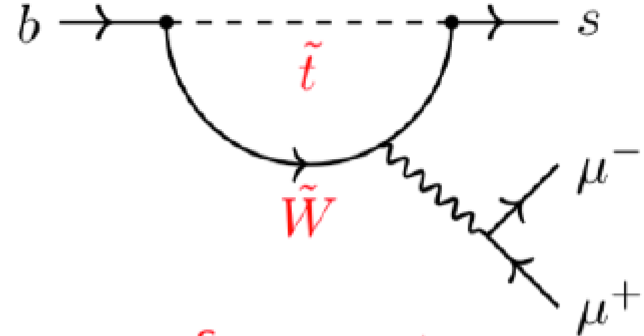
Results are compatible with theoretical calculations & fits

Deviations of about 2.5σ (2.7σ) from DHMV in P'_4(P'_5) in [4,6] GeV²

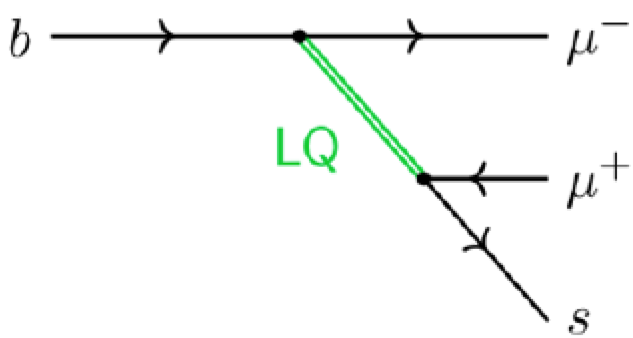
$b \to s\ell^+\ell^-$ transitions



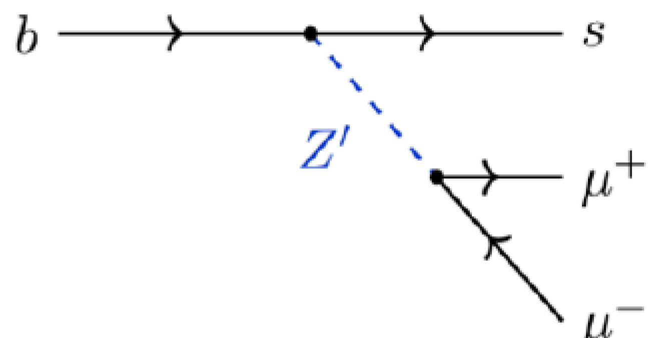
Standard Model



Supersymmetry

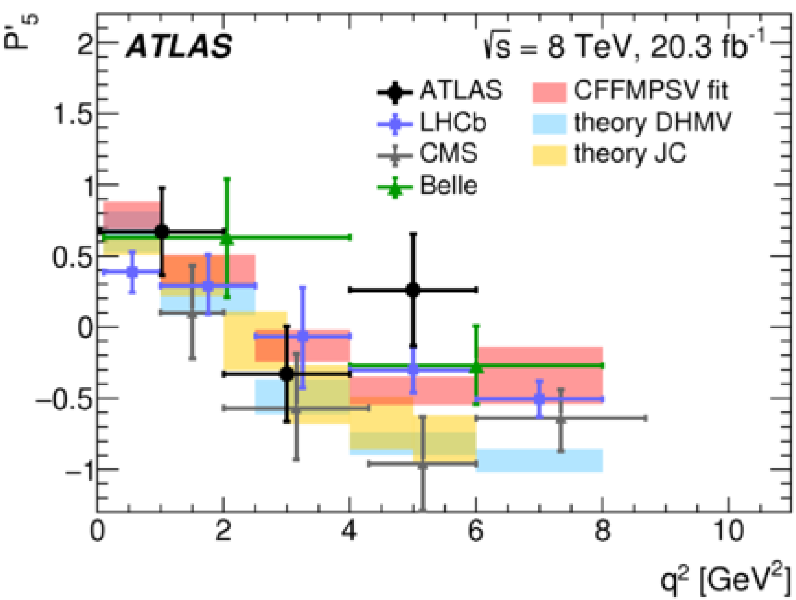


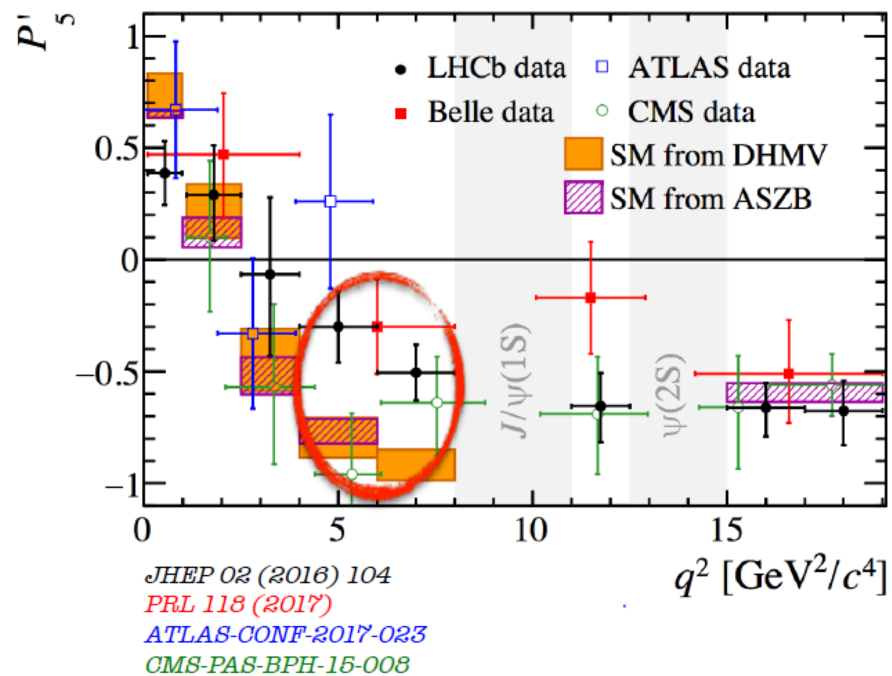
Leptoquarks



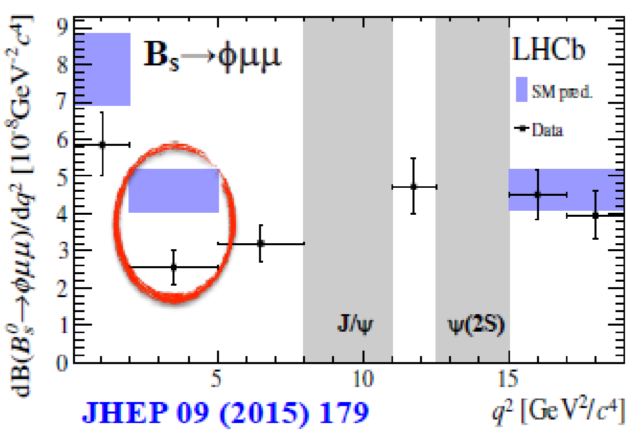
New heavy gauge bosons

$B^0 \to K^{*0} \mu^+\mu^-$ (FCNC) JHEP 10 (2018) 047





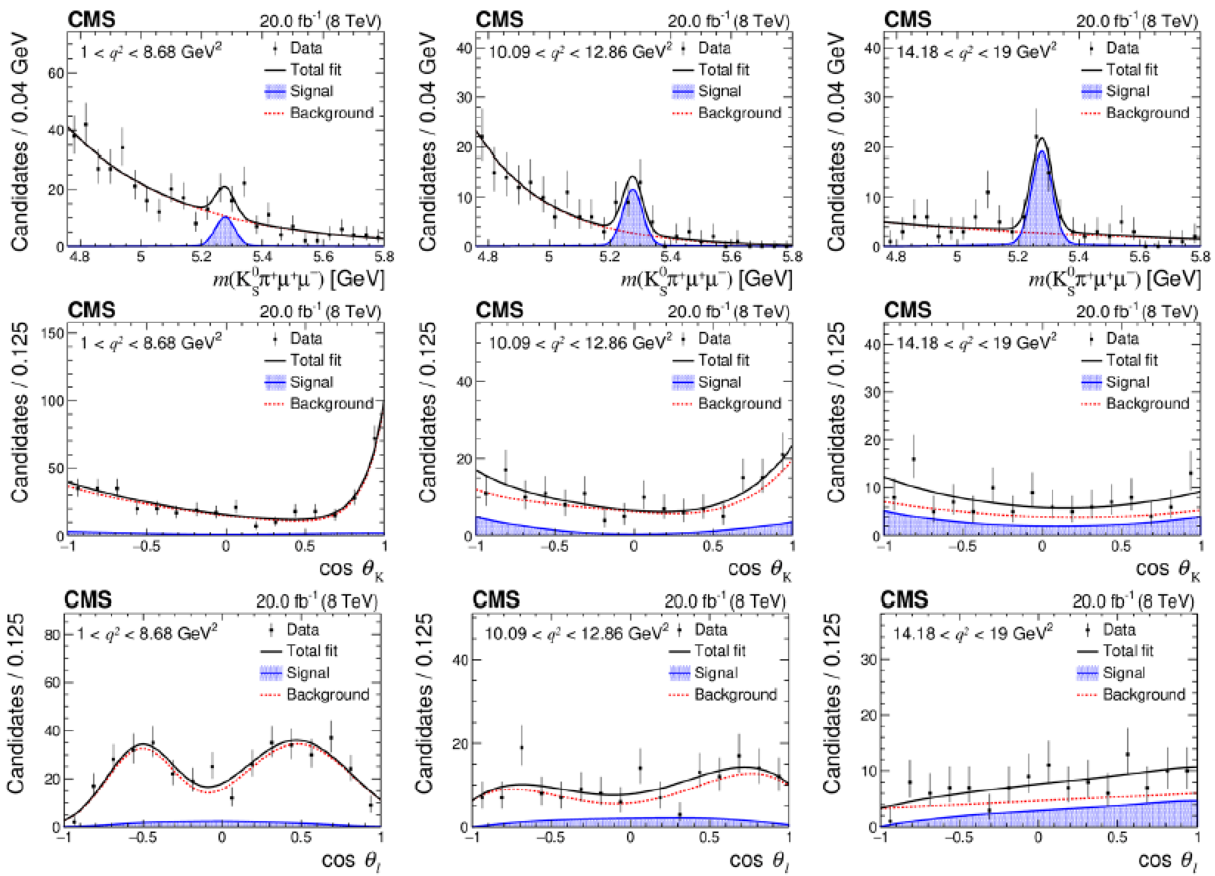
Angular observables in B->$K^*\mu\mu$ show about 3.4σ discrepancy



More data are needed!

Angular analysis of $B^+ \to K^*(892)^+ \mu^+ \mu^-$ at CMS

JHEP 04 (2021) 124



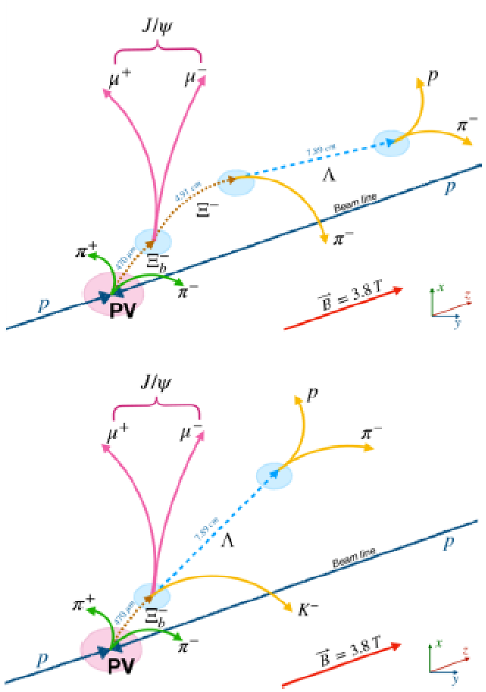
- The first angular analysis of the $B^+ \to K^*(892)^+ \mu^+ \mu^-$ decay is performed;
- In three bins of the dimuon invariant mass squared (q^2), a 3D fits are performed;
- The muon forward/backward asymmetry (A_{FB}) and $K^*(892)^+$ longitudinal fraction (F_L) are consistent with SM predictions;

q^2 (GeV^2)	Y_S	A_{FB}	F_L
1 – 8.68	22.1 ± 8.1	$-0.14^{+0.32}_{-0.35} \pm 0.17$	$0.60^{+0.31}_{-0.25} \pm 0.13$
10.09 – 12.86	25.9 ± 6.3	$0.09^{+0.16}_{-0.11} \pm 0.04$	$0.88^{+0.10}_{-0.13} \pm 0.05$
14.18 – 19	45.1 ± 8.0	$0.33^{+0.11}_{-0.07} \pm 0.05$	$0.55^{+0.13}_{-0.10} \pm 0.06$

- ATLAS earlier performed similar analysis of $B^0 \to K^* \mu^+ \mu^-$ decays

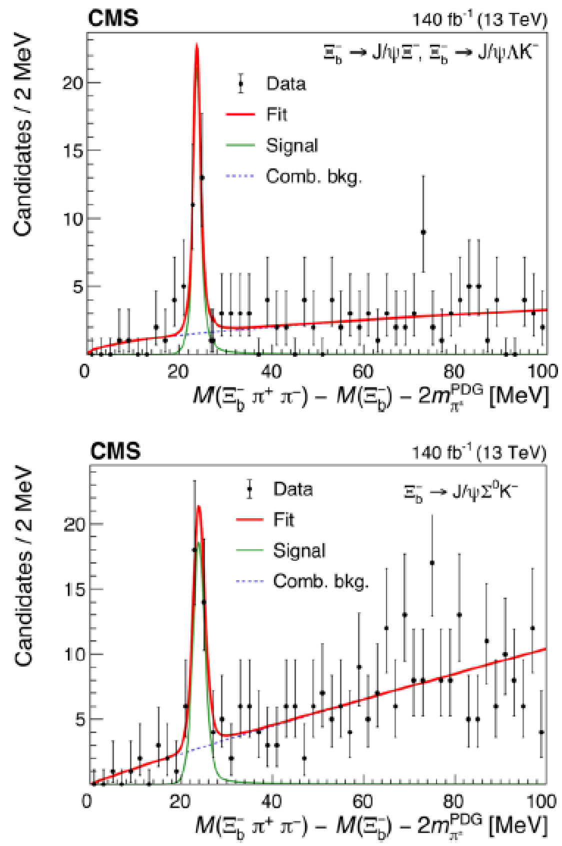
JHEP 10 (2018) 047

Observation of new bottom-strange baryon $\Xi^-_b(6100)$ in $\Xi^-_b\pi^+\pi^-$ channel at CMS



Topologies with different Ξ^-_b decay channels

Phys. Rev. Lett. 126 (2021) 252003



- A narrow resonance $\Xi^-_b(6100)$ is observed at a $\Xi^-_b\pi^+\pi^-$ invariant mass of:

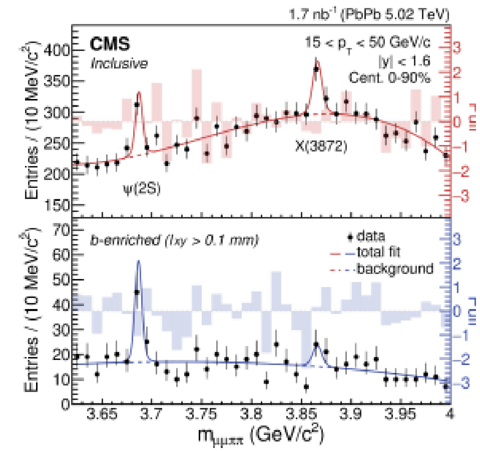
  M = 6100.3 ±0.2(stat)±0.1(syst) ±0.6(Ξ^-_b)

- Results are consistent between fully reconstructed channels and partially reconstructed channel with $\Sigma^0\to\Lambda\gamma$
- Upper limit is set 1.9MeV on a natural width of the new state (95% CL)
- New state is consistent with orbitally excited Ξ^-_b baryon with spin/parity of $3/2^-$.

X(3872) production in different collision systems

First evidence using 1.7 nb^{-1} of PbPb collisions data (2018) at CMS at $\sqrt{s_{NN}}$ = 5.02 TeV per nucleon pair PRL 128 (2022) 032001

kinematical range: $15 < p_T < 50$ GeV/c, $|y| < 1.6$



UML fit to extract signal yields for ψ(2S) and X(3872)

Final state: $J/\psi(\rightarrow \mu^+\mu^-)\,\pi^+\pi^-$

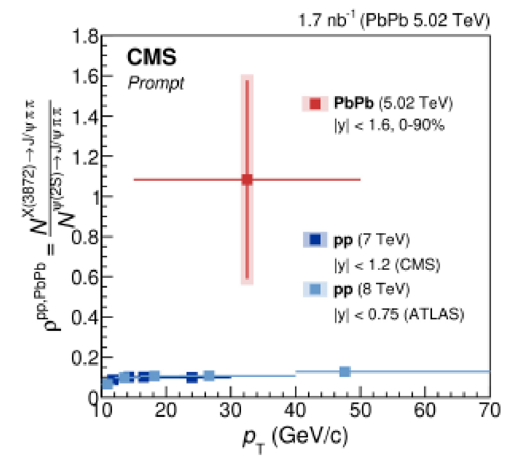
Significance for inclusive X(3872): 4.2σ

Prompt fraction estimated with MC studies

Yields corrected by acceptance and overall efficiency

Ratio of corrected yields for prompt production in PbPb collisions ρ^{pp} :

- **compatible with 1** (within 1σ)
- **compatible with ρ^{pp} = 0.1** (within 2σ)



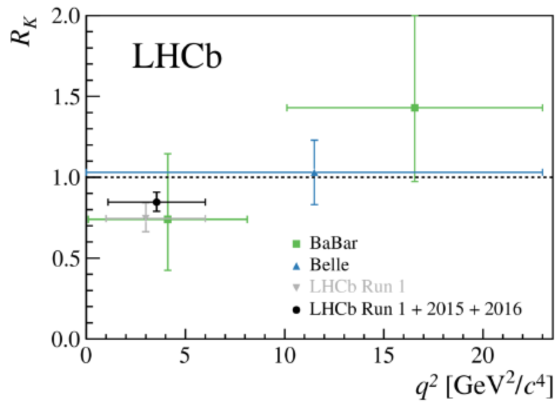
Much larger data sample expected in Run-3 at LHC in order to improve the measurement and understand the internal structure of X(3872) and the differences of its production mechanism w.r.t. ψ(2S)

Lepton Flavour Universality (Violation?)

$$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)} \qquad \mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

Phys. Rev. Lett. 122 (2019) 191801

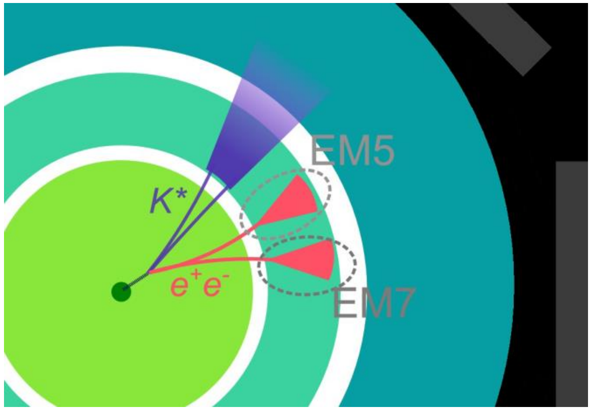
2.5σ from the SM



ATLAS potentially can do

R(K), R(ϕ), R(pK) = BR($\Lambda_b \to$ pKμμ)/BR($\Lambda_b \to$ pKee)

In 2018, a di-electron high-level trigger implemented and being analysed now



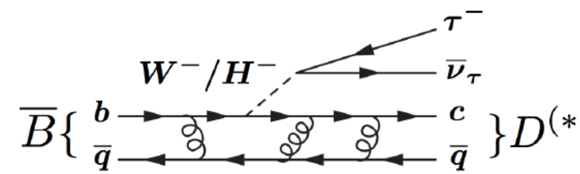
Aiming at R(K*) measurement

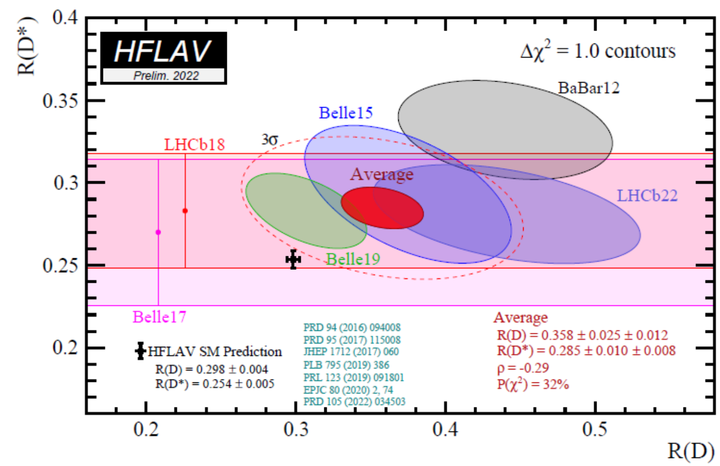
Run-3 data will add statistic

Lepton Flavour Universality (Violation?)

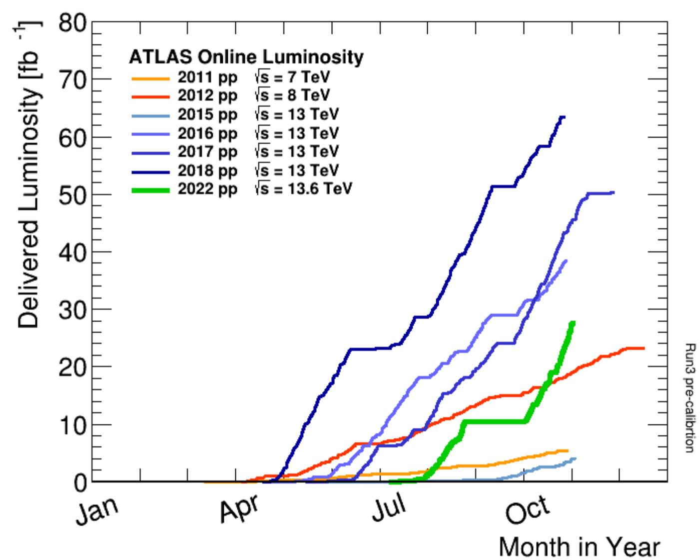
$$R_{D^*} = \frac{\Gamma(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\Gamma(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$

ATLAS added dedicated trigger branches for Run 3:

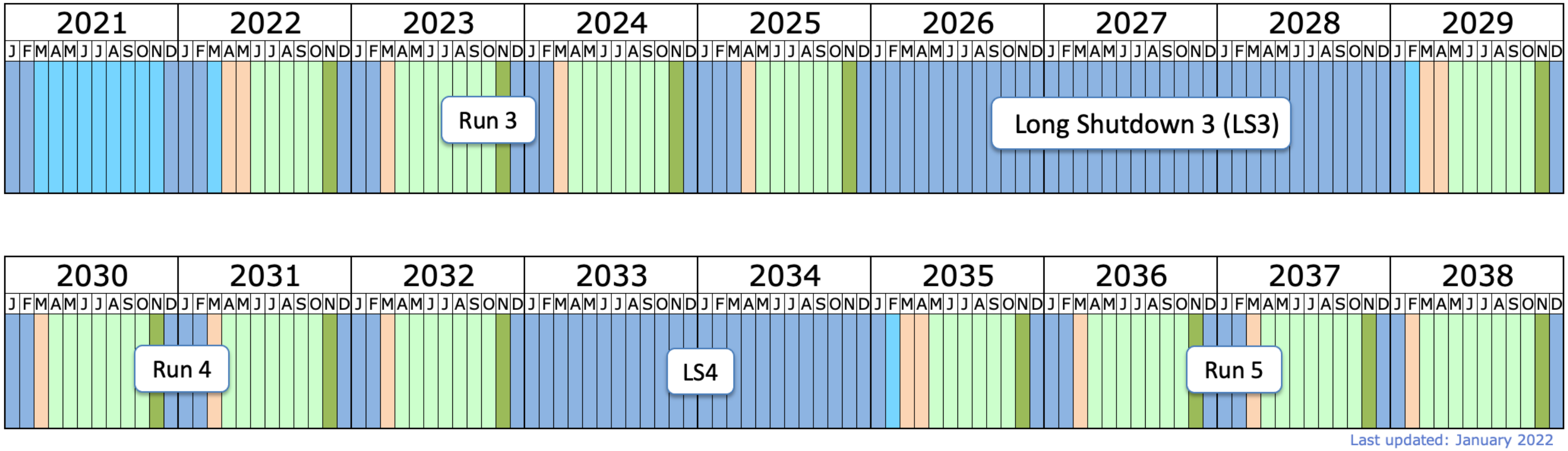


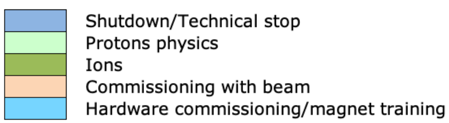


3.2 σ



Prospects





Run 3: ~300 fb-1

HL-LHC: ~3000 fb-1