ATLAS measurements of production, decays and spectroscopy of heavy flavour hadrons

Radek Novotný on behalf of the ATLAS collaboration

ICPPA 2020, Moscow October 7, 2020





This talk will be devoted to the recent results from the ATLAS experiment on production, decays and spectroscopy of heavy flavour hadrons:

- Measurement of the CP-violating phase ϕ_s in $B_s^0 \rightarrow J/\psi\phi$ decay at 13 TeV arXiv:2001.07115, submitted to EPJC
- J/ψ and ψ(2S) production cross-section at 13 TeV ATLAS-CONF-2019-047
- Measurement of associated J/ ψ production JHEP 01 (2020) 095
- Study of $J/\psi p$ resonances in the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays in pp collisions at 7 and 8 TeV ATLAS-CONF-2019-048
- Measurement of the relative B_c^{\pm}/B^{\pm} production cross section arXiv:1912.02672, submitted to PRD



CP-Violation measurement in $B_s^0 \rightarrow J/\psi\phi$ arXiv:2001.07115. submitted to EPJC

- $B_s^0 \rightarrow J/\psi \phi$ is used to measure CP-violation phase ϕ_s potentially sensitive to New Physics
- In SM ϕ_s is related to the CKM elements and predicted with high precision $\phi_s \simeq 2 \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)] = -0.0363^{+0.0016}_{-0.0015}$ rad
- Other quantities in B_s^0 mixing are $\Delta \Gamma_s = \Gamma_s^L \Gamma_s^H$, where Γ_s^L and Γ_s^H are the decay widths of the different mass eigenstates, and $\Gamma_s = (\Gamma_s^L + \Gamma_s^H)/2$ their average.
- The opposite side tagging uses $b \bar{b}$ pair correlation to determine initial signal flavour from the other B meson



 B_s

 $ar{B}_{u,d,s}$



CP-Violation measurement in $B_s^0 \rightarrow J/\psi \phi$

arXiv:2001.07115, submitted to EPJC

- Analysis was performed on *pp* collisions at 13 TeV collected between years 2015 and 2017 with integrated luminosity of 80.5 fb⁻¹
- Final state: admixture of *CP*-odd (L = 1) and *CP*-even (L = 0, 2) states distinguishable through time-dependent angular analysis

• Including MC derived models for dedicated backgrounds $B^0_d \rightarrow J/\psi K^*$,

• We perform unbinned maximum likelihood fit to extract parameters describing $B_s \rightarrow J/\psi\phi$ and S-wave: $\phi_s, \Delta\Gamma_s, \Gamma_s, |A_0(0)|^2, |A_{||}(0)|^2, |A_S(0)|^2, \delta_{||}, \delta_{\perp} and \delta_S$











CP-Violation measurement in $B^0_s ightarrow J/\psi \phi$

arXiv:2001.07115, submitted to EPJC

- In Run2 for the strong-phases δ_\perp and δ_\parallel two well separated local maxima of the likelihood are found
- Their difference in likelihood values is minimal
- The current results were combined with those from the previous analysis in Run1
- Consistent with SM prediction and other LHC experiments with only small tensions

	Solution (a)			Solution (b)		
Parameter	Value	Statistical	Systematic	Value	Statistical	Systematic
		uncertainty	uncertainty		uncertainty	uncertainty
ϕ_s [rad]	-0.087	0.036	0.019	-0.088	0.036	0.019
$\Delta\Gamma_s \ [\text{ps}^{-1}]$	0.0641	0.0043	0.0024	0.0640	0.0043	0.0024
$\Gamma_s [\mathrm{ps}^{-1}]$	0.6697	0.0014	0.0015	0.6698	0.0014	0.0015
$ A_{\parallel}(0) ^2$	0.2221	0.0017	0.0022	0.2218	0.0017	0.0022
$ A_0(0) ^2$	0.5149	0.0012	0.0031	0.5149	0.0012	0.0031
$ A_{S} ^{2}$	0.0343	0.0031	0.0044	0.0348	0.0031	0.0044
δ_{\perp} [rad]	3.22	0.10	0.05	3.03	0.10	0.05
δ_{\parallel} [rad]	3.36	0.05	0.08	2.95	0.05	0.08
$\delta_{\perp} - \delta_S$ [rad]	-0.24	0.05	0.04	-0.24	0.05	0.04







J/ψ and $\psi(2S)$ production cross-section at 13 TeV ATLAS-CONF-2019-047

- Differential cross section measurement of quarkonia states provides insight into QCD near the boundary of perturbative and non-perturbative regimes
- ATLAS collected huge sample of J/ψ → μ⁺μ⁻ and ψ(2S) → μ⁺μ⁻ decays allowing for thorough test of QCD calculation predictions in bins of η and ρ_Γ, and reaching very high p_Γ regions (→ 360 GeV)
- Prompt (NRQCD) and non-prompt (FONLL), directly or from feed-down







J/ψ and $\psi(2S)$ production cross-section at 13 TeV ATLAS-CONF-2019-047

- In this latest measurement, the comparison to FONLL¹ calculation describing non-prompt J/ψ was performed
- The comparison gives good agreement at the lower $p_{\rm T}$, but with FONLL predicting somewhat higher cross-sections at high- $p_{\rm T}$





¹ FONLL Heavy Quark Production Matteo Cacciari, http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html, Accessed: 2019-09-03



- Testing prediction of QCD, in particular color singlet (CS) and color octet (CO) processes contributions
- Requiring an associated object (eg. W^{\pm} , Z^{0} , J/ψ) filters the possible CS/CO diagrams

Measurement of the prompt $J/\psi + W^{\pm}$ yield:

- This includes contributions from Single Parton Scattering (SPS) and Double Parton Scattering (DPS) processes
- The azimuthal opening angle Δφ(J/ψ, W[±]) is sensitive to the contributions of SPS and DPS
- Exact shape of SPS is unknown but it is expected to peak at $\Delta \phi \approx \pi$ due to momentum conservation
- The DPS component should not have a preferred $\Delta \phi$ value, but the effective cross section σ_{eff} is unknown so choice between two values from previous ATLAS measurements:
 - $\sigma_{eff} = 15 \pm 3(\text{stat.})^{+5}_{-3}(\text{syst.}) \text{ mb from } W^{\pm}+2\text{-jet}$
 - $\sigma_{\it eff} = 6.3 \pm 1.6 {\rm (stat.)} \pm 1.0 {\rm (syst.)}$ mb from prompt J/ψ pair





Measurement of associated J/ ψ production JHEP 01 (2020) 095



- $W + J/\psi$: models underestimate data for both σ_{eff}
- · Possibly because color-singlet processes are not included in the prediction



Study of
$$J/\psi p$$
 resonances in the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays
ATLAS-CONF-2019-048

- In 2015 LHCb observed 2 structures in the $J/\psi p$ mass spectrum of $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay (Phys.Rev.Lett. 115 (2015) 072001)
- Interpreted as the pentaquark states $P_c(4380)^+$ and $P_c(4450)^+$
- Later LHCb resolved $P_c(4450)^+$ into two states $(P_c(4440)^+$ and $P_c(4457)^+)$ and discovered a new $P_c(4312)^+$





- ATLAS searched for pentaquarks in 7 TeV and 8 TeV data with integrated luminosities of 4.9 fb⁻¹ and 20.6 fb⁻¹, respectively
- As ATLAS has no particle-ID in, we need to consider all $H_b \rightarrow J/\psi h_1 h_2$ candidates
- signal region: 5.59 GeV $< M(J/\psi, p, K) < 5.65$ GeV

THE UNIVERSITY OF NEW MEXICO. Study of $J/\psi p$ resonances in the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays ATLAS-CONF-2019-048

- The results of the χ² fits of the M(J/ψ, p) distribution support the hypothesis with two pentaquarks with spin-parity 3/2⁻ and 5/2⁺ for lighter and heavier pentaquark candidates, respectively
- The narrow pentaquarks reported recently by LHCb cannot be distinguished
- To verify four pentaquark hypothesis, the fit with fixed masses, widths and relative yields of the narrow pentaquarks to LHCb values is performed
- The data supports this hypothesis as well $(\chi^2/N_{dof} = 37.1/42 \text{ four pentaquarks wrt. } \chi^2/N_{dof} = 37.1/39 \text{ two pentaquarks})$



THE UNIVERSITY OF Study of $J/\psi p$ resonances in the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays ATLAS-CONF-2019-048

- There was a study testing the hypothesis without pentaquarks
- The fit with default Λ^* yields $\chi^2/N_{dof} = 69.2/37$ corresponding to a p-value of 1.0×10^{-3} (left)
- The best data description is obtained using the extended $\Lambda_b^0 \rightarrow J/\psi \Lambda^{*0}$ decay model yielding to $\chi^2/N_{dof} = 42.0/23$ corresponding to a p-value of 9.1×10^{-3} (right)



 Although the data prefer the model with two or more pentaquark states, the model without pentaquarks is not excluded



6400

1600

1400

Data - fit) / err.

ATI AS

5800 6000

5800



- Measurements of the relative production cross section can provide unique insight into heavy-guark hadronization
- Unique probe for heavy quark dynamics

s = 8 TeV, 20.3 fb





arXiv:1912.02672, submitted to PRD

Relative B_c^{\pm}/B^{\pm} production cross section

- Common systematic uncertainties mostly cancel out
- Dataset: 20.3 fb⁻¹ (2012) at 8 TeV pp collisions
- Results given in:
 - 2 $p_{\rm T}(B)$ analysis bins
 - 2|y(B)| analysis bins
 - and for the full range: $p_T > 13 \text{ GeV}$ and |y| < 2.3

m_{J/w **} [MeV]

ATLAS production and spectroscopy of heavy flavour hadrons. October 7, 2020

0033

6800 6600

m the at [MeV]

6800



Relative B_c^{\pm}/B^{\pm} production cross section

arXiv:1912.02672, submitted to PRD

- Production decreases faster with p_T for B_c than B⁺
- No evident rapidity dependence



- 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

PRL 114 (2015) 132001 JHEP 01 (2015) 063



- ATLAS has a rich heavy-flavour program involving:
 - Precise measurement of CP-violation parameters in $B_s^0
 ightarrow J/\psi \phi$
 - Inclusive and associated production cross section of J/ψ candidates
 - Test of QCD predictions in b-quark / hadrons production and in spectroscopy
- Run2/3 prospects:
 - Many analyses still to be updated to the full Run2 dataset, gaining from IBL and L1-Topo
 - Majority of the current public results limited by statistics \rightarrow will improve
 - New triggers allowing to probe $B \rightarrow eeX$ decays



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Thanks for your attention!