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Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s} = 8\,\text{TeV}$ with the ATLAS detector

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The associated production of a vector boson with heavy quarkonia is a key observable for understanding the quarkonium production mechanisms. In this poster the observation of the production of the Z boson in association with a prompt or with a non-prompt J/ψ meson with the ATLAS detector at LHC is presented and its production rate is measured in comparison of the inclusive Z production. Relative contributions to the signal from single and double parton scattering are estimated. Single parton scattering cross-sections are compared to cutting-edge theoretical calculations in the colour singlet and colour octet formalisms. Finally, a lower limit in the double parton scattering effective cross section is extracted.

The European Physical Society Conference on High Energy Physics
22–29 July 2015
Vienna, Austria

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PoS(EPS-HEP2015)588

1. Introduction

The associated production of vector boson ($\mathscr{V}$) with heavy quarkonia ($\mathscr{Q}$) is a subject of interest from both the experimental [1, 2] and the theoretical point of view [3 – 5]. These final states do not only provide constraints on the contributions from colour-singlet and colour-octet production processes, and their properties [6], but can also be used to study heavy flavour production (non-prompt $\mathscr{Q}$ originating from a b-hadron) in association with a $\mathscr{V}$. Finally, since the $\mathscr{V}+\mathscr{Q}$ can be produced either from a single parton interaction (SPS) or from the interaction of two different pairs of partons (DPS), it can be used for modelling multi-parton interactions in pp collisions.

The ATLAS Collaboration observed the production of prompt $J/\psi(\to\mu\mu)$ mesons in association with $W(\to\mu\nu)$ bosons [2], using $4.5\,\text{fb}^{-1}$ of $\sqrt{s}=7\,\text{TeV}$ pp collisions at the LHC. Here the observation of the associated production of prompt and non-prompt $J/\psi(\to\mu\mu)$ mesons with $Z(\to\ell\ell)$ bosons ($\ell=\mu,e$) is presented, using $20.3\,\text{fb}^{-1}$ of $\sqrt{s}=8\,\text{TeV}$ pp collisions [7].

2. The ATLAS detector and event selection

The ATLAS detector [8] is a general purpose detector with cylindrical geometry[1] and forward-backward symmetric coverage in pseudorapidity (η). The detector consists of inner tracking detectors (ID), calorimeters, the muon spectrometer (MS) and has a three-level trigger system. The ID directly surrounds the beam pipe and is immersed in a 2 T axial magnetic field generated by a superconducting solenoid.

For the search of the associated production of $Z+J/\psi$, events with two opposite-charged lepton pairs are selected, with at least one lepton having $p_{\text{T}}>24\,\text{GeV}$. Each pair is fitted in a common vertex, and only events where the invariant mass of the first pair is between $2.6-3.6\,\text{GeV}$ (J/ψ) and the second between $81.2-101.2\,\text{GeV}$ (Z) are considered. Additionally, the J/ψ candidate must have $p_{\text{T}}^{J/\psi}>8.5\,\text{GeV}$ and $|y_{J/\psi}|<2.1$. In order to reduce contamination from pileup (Z and J/ψ produced from two independent inelastic collisions), the Z and J/ψ vertices are required to be closer than 10 mm in the z-direction.

Muons from Z boson decay are required to have $p_{\text{T}}>15\,\text{GeV}$ and $|\eta|<2.5$ and electrons to have $p_{\text{T}}>15\,\text{GeV}$, $|\eta|<2.47$ and satisfy isolation requirements based on tracking information (scalar sum of p_{T} inside an $\eta-\phi$ cone of size $\Delta R=0.2$ around the lepton to be less than 15% of the lepton p_{T}). One of the Z boson leptons must be matched with the lepton that fired the trigger and that lepton must have $p_{\text{T}}>25\,\text{GeV}$ and $|\eta|<2.4$. For the J/ψ muons, at least one of them must have $p_{\text{T}}>4\,\text{GeV}$ and an additional requirement of $p_{\text{T}}>2.5(3.5)\,\text{GeV}$ is applied for those with $|\eta|>1.3(<1.3)$. After all selections are applied a total of 290 events are found (139 with $Z\to\mu\mu$ and 151 with $Z\to ee$).

The same requirements described above, applied to the Z boson, are also applied for the inclusive Z candidate selection. Estimates of the background in the inclusive Z sample are obtained

[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined in terms of the polar angle θ as $\eta=-\ln\tan(\theta/2)$ and the transverse momentum p_{T} is defined as $p_{\text{T}}=p\sin\theta$. The rapidity is defined as $y=0.5\ln\left((E+p_z)/(E-p_z)\right)$, where E and p_z refer to energy and longitudinal momentum, respectively. The η–ϕ distance between two particles is defined as $\Delta R=\sqrt{(\Delta\eta)^2+(\Delta\phi)^2}$.

using both MC simulation and data-driven techniques. The total number of inclusive Z candidates, after background subtraction (which was found to be $0.4 \pm 0.4\%$) is 16.15 million (8.20 million with $Z \to \mu\mu$ and 7.95 million $Z \to ee$).

3. Signal extraction

The $Z + J/\psi$ candidates might originate from pileup, be fake particles mimicking the Z boson or the J/ψ meson and the J/ψ may originate either from prompt QCD interactions or by a b-hadron decay. First step in selecting true $Z + J/\psi$ events is to distinguish prompt and non-prompt J/ψ from fake J/ψ mesons. Prompt J/ψ mesons are separated from non-prompt using a two-dimensional unbinned maximum likelihood fit in the J/ψ invariant mass and pseudo-proper time (see figure 1). Due to the small statistics of the $Z + J/\psi$ associated production sample and to improve the stability of the fit process, the pseudo-proper time and invariant mass of the associated production J/ψ candidates are fitted simultaneously with a high statistics inclusive J/ψ sample, selected with the same criteria as the $Z + J/\psi$ sample.

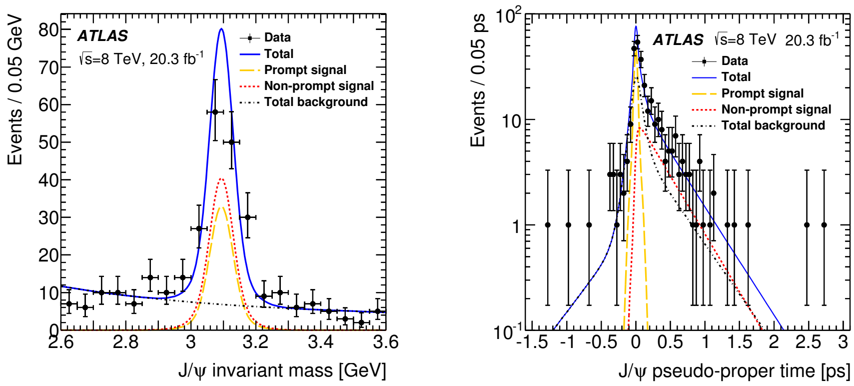

Figure 1: Projection of the unbinned mass (left) and pseudo-proper time (right) maximum-likelihood fit [7].

Performing the fit to the $Z + J/\psi$ sample, 56 ± 10 prompt and 95 ± 12 non-prompt J/ψ mesons are found to be produced in association with a Z boson candidate. After the fit is performed, the sPlot tool [9] is used in order to extract per-event weights for each of the four yield components of the fit (prompt J/ψ, non-prompt J/ψ, prompt background and non-prompt background). Applying the weights coming from the prompt J/ψ and non-prompt J/ψ to the invariant mass distribution of Z boson candidates (see figure 2), the contamination of background to the Z candidates associated with prompt and non-prompt J/ψ mesons can be evaluated. For this, signal and multi-jet templates, extracted from the Powheg MC generator [10] and data respectively, are compared with the sPlot weighted distributions. The number of background events was found to be $0 \pm 4 (1 \pm 4)$ and $1 \pm 5 (0 \pm 5)$ for the $Z \to ee(\mu\mu)$ candidates, produced in association with prompt and non-prompt J/ψ mesons.

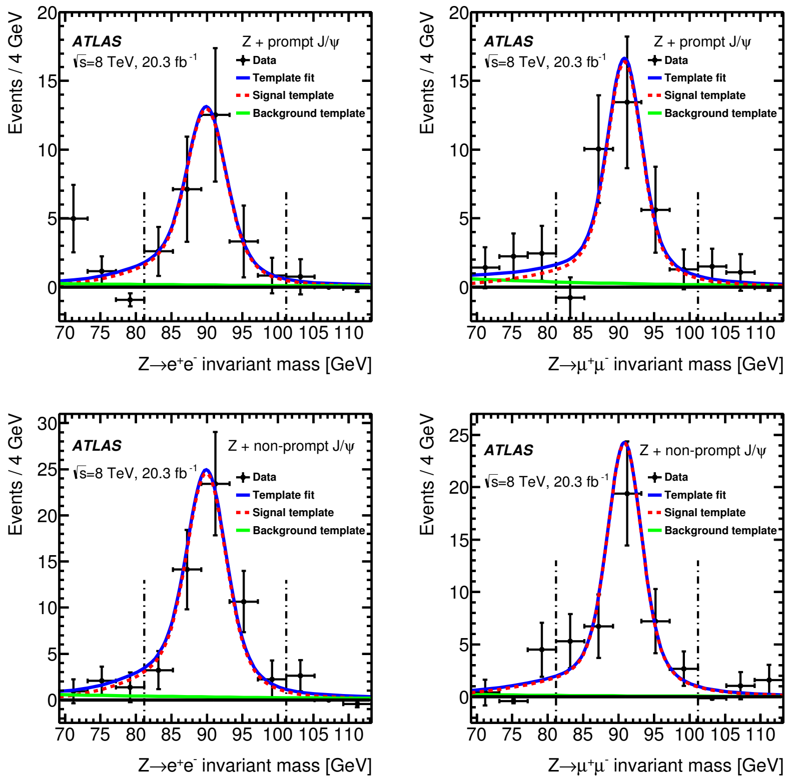

Figure 2: $Z \to ee$ (left) and $Z \to \mu\mu$ (right) mass distributions for Z bosons produced in association with prompt (top) and non-prompt (bottom) J/ψ mesons [7].

As discussed in section 2, the Z and J/ψ vertices are required to be closer than 10 mm, aiming to reduce pileup contamination. The number of pileup candidates are estimated according to the formula $N_{\text{pileup}} = N_{\text{extra}} N_Z P_{J/\psi}$, where N_{extra} is the number of additional vertices which lie within 10 mm of a vertex which produced a Z boson, N_Z is the number of inclusive Z candidates in the fiducial region and $P_{J/\psi}$ is the probability for a J/ψ to be produced at a given pileup vertex. The total number of pileup events were found to be $5.2^{+1.8}_{-1.3}$ and $2.7^{+0.9}_{-0.6}$ for the prompt and non-prompt cases respectively.

The DPS contribution to the $Z + J/\psi$ events, which is treated as part of the signal, is estimated using the assumption that the DPS effective cross-section (σ_{eff}) is process-independent and that the two hard interactions are uncorrelated. Based on that, for a collision where a Z boson is produced, the probability that a J/ψ meson will be produced in association with the Z is $P_{J/\psi|Z} = \sigma_{J/\psi}/\sigma_{\text{eff}}$. $\sigma_{J/\psi}$ is the cross-section of the J/ψ production and the value of σ_{eff} is taken to be $\sigma_{\text{eff}} = 15 \pm 3(\text{stat.})^{+5}_{-3}(\text{sys.})$ mb, based on the ATLAS measurement [11]. The estimated number of DPS events were found to be $11.1^{+5.7}_{-5.0}$ and $5.8^{+2.8}_{-2.6}$ for prompt and non-prompt J/ψ mesons produced in association with a Z boson.

4. Results

Using 20.3 fb^{-1} of $\sqrt{s} = 8$ TeV pp data, ATLAS Collaboration observed the prompt and non-prompt J/ψ meson production in association with a Z boson with a $5\,\sigma$ and $9\,\sigma$ significance respectively. After correcting for the J/ψ muon reconstruction efficiency, the fiducial cross-section ratio, defined as $R^{\rm fid}_{Z+J/\psi} = \sum_{p_{\rm T}\ \rm bins}[N^{\rm ec}(Z+J/\psi) - N^{\rm ec}_{\rm pileup}]/N(Z)$ is measured to be $(36.8 \pm 6.7(\text{stat.}) \pm 2.5(\text{syst.})) \times 10^{-7}$ for the prompt and $(65.8 \pm 9.2(\text{stat.}) \pm 4.2(\text{syst.})) \times 10^{-7}$ for the non-prompt $J/\psi + Z$ production. Assuming unpolarised J/ψ decays and correcting for geometric acceptance losses due to J/ψ muon $p_{\rm T}$ and η requirements, the inclusive cross-section ratio is measured to be $(63 \pm 13(\text{stat.}) \pm 5(\text{syst.}) \pm 10(\text{pol.})) \times 10^{-7}$ and $(102 \pm 15(\text{stat.}) \pm 5(\text{syst.}) \pm 3(\text{pol.})) \times 10^{-7}$ for prompt and non-prompt J/ψ production respectively.

Subtracting DPS contributions, in order to compare the SPS measurement with theoretical models, the $Z+$ prompt J/ψ production cross-section ratio was found to be $(45 \pm 13(\text{stat.}) \pm 6(\text{syst.}) \pm 10(\text{pol.})) \times 10^{-7}$ and $Z+$ non-prompt J/ψ $(94 \pm 15(\text{stat.}) \pm 5(\text{syst.}) \pm 3(\text{pol.})) \times 10^{-7}$. Leading Order (LO) colour-singlet mechanism calculations vary between $(11.6 \pm 3.2) \times 10^{-8}$ [5] and $46.2^{+6.0}_{-6.5} \times 10^{-8}$ [4] and Next to LO (NLO) NRQCD model predicts a cross-section ratio of $(45.7^{+10.5}_{-9.6}) \times 10^{-8}$ [4], underestimating ATLAS measurement, as illustrated on figure 3.

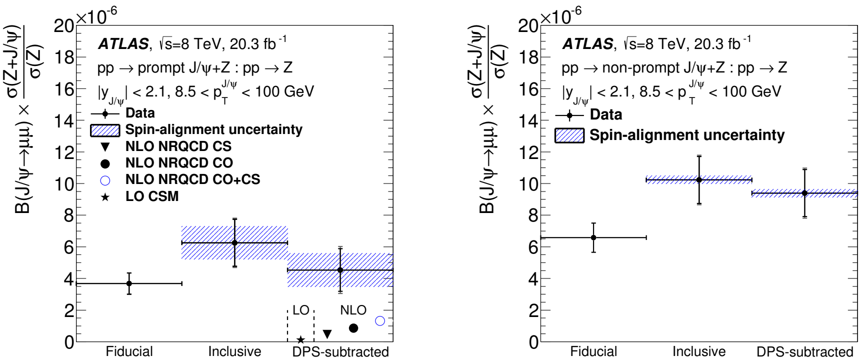

Figure 3: Production cross-section ratios of prompt (left) and non-prompt(right) J/ψ mesons produced in association with a Z boson relative to inclusive Z production [7].

5. Double Parton Scattering

Figure 4 (left) shows the azimuthal angle between the Z boson and the prompt J/ψ momentum vectors ($\Delta\phi$) after the application of sPlot weights corresponding to the prompt J/ψ signal component. The estimated DPS and pileup contribution are overlaid with yellow and cyan colours respectively. DPS events are expected to be distributed uniformly along the $\Delta\phi$ variable because the Z and J/ψ particles are produced from two independent scatters. SPS events are expected to show a back-to-back correlation $\Delta\phi = \pi$, since they originate from a single parton interaction, with a smearing due to detector effects, presence of gluons in the final state and radiation from the leptons and by the intrinsic properties of the protons.

Based on above, the low $\Delta\phi$ region which is sensitive to DPS, can be used to limit the maximum allowed DPS contribution to the observed signal, which corresponds to a lower limit on $\sigma_{\rm eff}$. Using the assumption that the first bin $\Delta\phi(Z, J/\psi) < \pi/5$ is DPS dominated, the data uncertainties and uncertainties inherent in the DPS estimate allow a lower limit $\sigma_{\rm eff} > 5.3\,\text{mb}(3.7\,\text{mb})$ at 68%(95%) confidence level to be extracted (see figure 4 right).

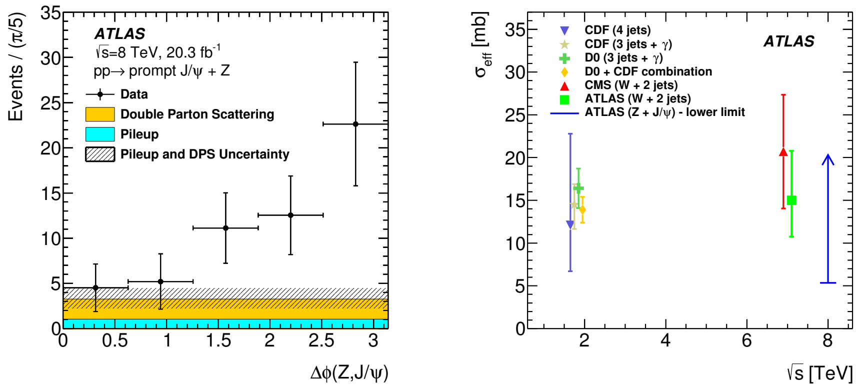

Figure 4: Left: Azimuthal angle between the Z boson and the J/ψ meson after the application of J/ψ signal prompt sPlot weights. Right: Measurements and limits on σ_{eff} as a function of $\sqrt{s}$ [7] (JHEP 03 032 (2014), New J. Phys. 15 (2013) 033038, Phys. Rev. D47 4857-4871 (1993), Phys. Rev. D56 3811-3832 (1997), Phys. Rev. D81 052012 (2010), JHEP 113 1310 (2013)).

Acknowledgments

The present work was co-funded by the European Union (European Social Fund ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) 2007-2013. ARISTEIA-1893-ATLAS MICROMEGAS.

References

[1] CDF Collaboration, T. Aaltonen et al., Search for production of an $\Upsilon(1S)$ meson in association with a W or Z boson using the full 1.96 TeV $p\bar{p}$ collision data set at CDF, Phys. Rev. **D91**, 052011 (2015), arXiv:1412.4827 [hep-ex].

[2] ATLAS Collaboration, Measurement of the production cross section of prompt J/ψ mesons in association with a $W^{\pm}$ boson in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, JHEP **04**, 172 (2014), arXiv:1401.2831 [hep-ex].

[3] T. Alexopoulos and S. Leontsinis, Estimates of Z boson and J/ψ production cross sections at the Large Hadron Collider, J. Exp. Theor. Phys. **120**, 808–812 (2015), arXiv:1309.4736 [hep-ph].

[4] S. Mao, M. Wen-Gan, L. Gang, Z. Ren-You, and G. Lei, QCD corrections to J/ψ plus Z^0-boson production at the LHC, JHEP **02**, 071 (2011), arXiv:1102.0398 [hep-ph]. [Erratum: JHEP12,010(2012)].

[5] B. Gong, J.-P. Lansberg, C. Lorce, and J. Wang, Next-to-leading-order QCD corrections to the yields and polarisations of J/ψ and Υ directly produced in association with a Z boson at the LHC, JHEP **03**, 115 (2013), arXiv:1210.2430 [hep-ph].

[6] Quarkonium Working Group Collaboration, N. Brambilla et al., Heavy quarkonium physics, arXiv:hep-ph/0412158 [hep-ph].

[7] ATLAS Collaboration, Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector, Eur. Phys. J. **C75**, 229 (2015), arXiv:1412.6428 [hep-ex].

[8] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, JINST **3**, S08003 (2008).

[9] M. Pivk and F. R. Le Diberder, SPlot: A Statistical tool to unfold data distributions, Nucl. Instrum. Meth. **A555**, 356–369 (2005), arXiv:physics/0402083 [physics.data-an].

[10] S. Alioli, P. Nason, C. Oleari, and E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, JHEP **06**, 043 (2010), arXiv:1002.2581 [hep-ph].

[11] ATLAS Collaboration, Measurement of hard double-parton interactions in $W(\rightarrow l\nu)$+ 2 jet events at $\sqrt{s}$=7 TeV with the ATLAS detector, New J. Phys. **15**, 033038 (2013), arXiv:1301.6872 [hep-ex].