PROCEEDINGS OF SCIENCE

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

Stefanos Leontsinis*
on behalf of the ATLAS Collaboration
National Technical University of Athens, Brookhaven National Laboratory
E-mail: stefanos.leontsinis@cern.ch

A key observable for understanding the quarkonium production mechanism is the associated production of a vector boson with heavy quarkonia. ATLAS Collaboration at LHC observed the associated production of prompt and non-prompt J/ψ mesons with Z boson with 5σ and 9σ signifance, respectively. In this poster the measurement of the production rate of $Z+J/\psi$ over inclusive Z is discussed. Additionally, contributions from single and double parton interactions are evaluated and the results are compared to latest theoretical calculations in the colour singlet and colour octet formalisms. Finally, a lower limit of the double parton scattering effective cross section is extracted.

XXVII International Symposium on Lepton Photon Interactions at High Energies
17-22 August 2015
Ljubljana, Slovenia

*Speaker.

PoS(LeptonPhoton2015)084

1. Introduction

A process that ignited the interest of both the theoretical [1 – 3] and experimental communities is the associated production of vector boson ($\mathscr{V}$) with heavy quarkonia ($\mathscr{Q}$). Such processes are particularly interesting, enabling the study of the contributions from colour-singlet (CS) and colour-octet (CO) models [4], the heavy flavour production (non-prompt $\mathscr{Q}$ originating from a b-hadron) in association with a $\mathscr{V}$ and finally, the multi-parton interactions in hadronic collisions (since the two final state particles can be produced either from a single parton interaction, SPS, or from the interaction of two different pairs of partons, DPS).

The ATLAS Collaboration contributed in the study of the $\mathscr{V}+\mathscr{Q}$ processes, observing the production of prompt $J/\psi(\to\mu\mu)$ mesons in association with $W(\to\mu\nu)$ bosons [5], using $4.5\,\mathrm{fb}^{-1}$ of $\sqrt{s}=7\,\mathrm{TeV}$ pp collisions at the LHC and the associated production of prompt and non-prompt $J/\psi(\to\mu\mu)$ mesons with $Z(\to\ell\ell)$ bosons ($\ell=\mu,e$) [6]. The latter analysis used $20.3\,\mathrm{fb}^{-1}$ of $\sqrt{s}=8\,\mathrm{TeV}$ pp collisions and is the process discussed here.

2. Event selection and reconstruction

The ATLAS detector [7] 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.

Both Z and J/ψ particles are reconstructed in their di-lepton decay mode ($Z\to\ell\ell$, $\ell=\mu,e$ and $J/\psi\to\mu\mu$). Events with two opposite-charged lepton pairs are selected, with at least one lepton having $p_{\mathrm{T}}>24\,\mathrm{GeV}$. Each lepton pair is then fitted in a common vertex, and only events where the invariant mass of the first pair is between $2.6-3.6\,\mathrm{GeV}$ (J/ψ) and the second between $81.2-101.2\,\mathrm{GeV}$ (Z) are selected for the analysis. Additional requirements of the J/ψ candidate are $p_{\mathrm{T}}^{J/\psi}>8.5\,\mathrm{GeV}$ and rapidity[2] $|y_{J/\psi}|<2.1$. 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.

Selection requirements to muons from Z boson decay are $p_{\mathrm{T}}>15\,\mathrm{GeV}$ and $|\eta|<2.5$ and electrons are required to have $p_{\mathrm{T}}>15\,\mathrm{GeV}$, $|\eta|<2.47$ and must 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 leptons originating from the Z boson must be matched with the lepton that fired the trigger and must have $p_{\mathrm{T}}>25\,\mathrm{GeV}$ and $|\eta|<2.4$. For the J/ψ muons, at least one of them must have $p_{\mathrm{T}}>4\,\mathrm{GeV}$ and an additional requirement of $p_{\mathrm{T}}>2.5(3.5)\,\mathrm{GeV}$ is applied for those with $|\eta|>1.3(<1.3)$. A total of 290 events are found (139 with $Z\to\mu\mu$ and 151 with $Z\to ee$) after all selections are applied.

Since this analysis measures the $Z+J/\psi$ production ratio over inclusive Z, the same requirements described above, applied to the Z boson, are also applied for the inclusive Z candidate selection. Both MC simulation and data-driven techniques are employed to estimate background contributions in the inclusive Z sample. After background subtraction, which was found to be $0.4\pm0.4\%$, the total number of inclusive Z candidates is 16.15 million (8.20 million with $Z\to\mu\mu$ and 7.95 million $Z\to ee$).

3. Signal extraction

Possible sources of $Z+J/\psi$ candidates are pileup, fake particles that mimic the Z boson or the J/ψ meson and that the J/ψ may originate either from prompt QCD interactions or by a b-hadron decay. This analysis first selects true $Z+J/\psi$ events by distinguishing prompt and non-prompt J/ψ from fake

[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 $p_{\mathrm{T}}=p\sin\theta$. The η–ϕ distance between two particles is defined as $\Delta R=\sqrt{(\Delta\eta)^2+(\Delta\phi)^2}$.

[2] 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.

J/ψ mesons. This is realised with a two-dimensional unbinned maximum likelihood fit in the J/ψ invariant mass and pseudo-proper time (see figure 1), since non-prompt J/ψ mesons are expected to have longer pseudo-proper times. The shape related parameters of the fit to the $Z+J/\psi$ sample are driven from a high statistics inclusive J/ψ sample, which is fitted simultaneously with the $Z+J/\psi$ sample. This prevents instabilities that may occur from the low statistics of the $Z+J/\psi$ sample.

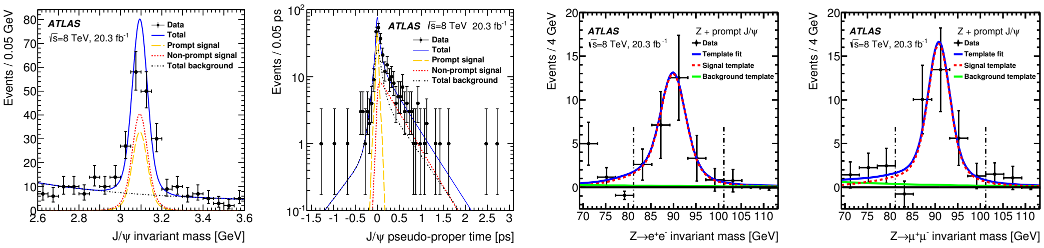

Figure 1: Projection of the unbinned mass (left) and pseudo-proper time (middle-left) maximum-likelihood fit. $Z \to ee$ and $Z \to \mu\mu$ mass distributions for Z bosons produced in association with prompt J/ψ mesons (middle-right and right) [6].

A total of 56 ± 10 prompt and 95 ± 12 non-prompt J/ψ mesons are found to be produced in association with a Z boson candidate from the fit procedure. After the fit is performed, the sPlot tool is used, so 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) can be extracted. Weights from prompt J/ψ and non-prompt J/ψ yields are further applied to the invariant mass distribution of Z boson candidates (see figure 1). From these distributions, showing the Z boson candidates produced in association with either a prompt or a non-prompt J/ψ meson, the contamination from background sources is evaluated. Signal and multi-jet templates, extracted from the Powheg MC generator and data respectively, are applied and compared with the sPlot weighted distributions. Backgrounds were estimated 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.

In order to reduce pileup contamination, the Z and J/ψ vertices are required to be closer than 10 mm in the z direction. 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. Using the formula above, 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 is not considered as a background source and, as it is treated as part to the signal, its contribution is estimated. This estimation is 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 [8]. 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

ATLAS Collaboration, using $20.3\,\text{fb}^{-1}$ of $\sqrt{s} = 8\,\text{TeV}$ pp data, observed the prompt and non-prompt J/ψ meson production in association with a Z boson with a 5σ and 9σ significance respectively. The fiducial cross-section ratio, defined as $R^{\text{fid}}_{Z+J/\psi} = \sum_{p_{\text{T}}^{J/\psi}\ \text{bins}} [N^{\text{ec}}(Z+J/\psi) - N^{\text{ec}}_{\text{pileup}}]/N(Z)$, where $N^{\text{ec}}(Z+J/\psi)$ is the yield of $Z+J/\psi$ events after correcting for J/ψ muon reconstruction efficiency, $N(Z)$ is the background-subtracted yield of inclusive Z events and $N^{\text{ec}}_{\text{pileup}}$ is the efficiency-corrected expected pileup background contribution in the fiducial J/ψ acceptance, 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_{T} and η requirements, the inclusive cross-section ratio is measured to be $(63 \pm 13(\mathrm{stat.}) \pm 5(\mathrm{syst.}) \pm 10(\mathrm{pol.})) \times 10^{-7}$ and $(102 \pm 15(\mathrm{stat.}) \pm 5(\mathrm{syst.}) \pm 3(\mathrm{pol.})) \times 10^{-7}$ for prompt and non-prompt J/ψ production respectively.

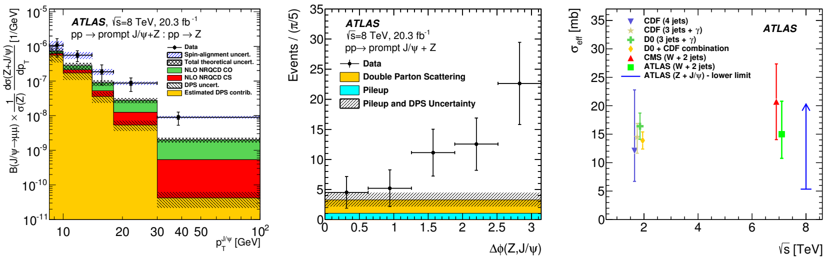

Figure 2: (Left) Production cross-section of J/ψ in association with a Z boson as a function of the prompt J/ψ p_{T}, normalised to the inclusive Z cross-section. (Middle) Azimuthal angle between the Z boson and the J/ψ meson after the application of J/ψ signal prompt sPlot weights. (Right) Measurements and limits on σ_{eff} as a function of $\sqrt{s}$ (right) (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)) [6].

The inclusive $Z+$ prompt or non-prompt J/ψ production over inclusive Z cross-section ratio is also measured as a function of the $p_{\mathrm{T}}^{J/\psi}$, as illustrated in figure 2. Together with the inclusive differential cross-section ratio, the differential DPS contribution is shown. The measurement is compared with NLO CS and CO calculations. The combination of the DPS and NLO CO+CS contributions underestimates the rate observed in data.

5. Double Parton Scattering

A sensitive variable to study DPS is the azimuthal angle between the Z boson and the prompt J/ψ momentum vectors ($\Delta\phi$). The $\Delta\phi$ distribution, after the application of sPlot weights corresponding to the prompt J/ψ signal component, is shown in figure 2 (middle). SPS events are expected to show a back-to-back correlation $\Delta\phi = \pi$, while 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.

Based on the above, the low $\Delta\phi$ region ($\Delta\phi(Z, J/\psi) < \pi/5$), which is dominated by DPS, is used to place a lower limit to the maximum allowed DPS contribution to the observed signal. The lower limit was found to be $\sigma_{\mathrm{eff}} > 5.3\,\mathrm{mb}(3.7\,\mathrm{mb})$ at $68\%(95\%)$ confidence level (see figure 2 right).

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] 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].

[2] 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)].

[3] 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].

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

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

[6] 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].

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

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