Associated quarkonium production at ATLAS

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The associated production of a vector boson with quarkonia is a key new observable for understanding the quarkonium production mechanisms, including the separation of single and double parton scattering components. Using the 2011 ATLAS dataset of 4.5 fb^{-1} of $\sqrt{s}=7 \text{ TeV}$ pp collisions at the LHC, the first observations were made of the production of $W^\pm + \text{prompt } J/\psi$ events in hadronic collisions, and using 20.3 fb^{-1} of data collected with the ATLAS experiment, in pp collisions at $\sqrt{s}=8 \text{ TeV}$, the first measurements of associated $Z + J/\psi$ production were made for both prompt and non-prompt J/ψ production mechanisms. The cross section ratio of prompt J/ψ production in association with a vector boson ($W^\pm$ and Z^0) to the inclusive vector boson production is measured, and the double parton scattering contribution to the cross section is estimated for both analyses. Normalised differential production cross-section ratios are also determined as functions of J/ψ transverse momentum.

Keywords: Quarkonium; Associated production; ATLAS; LHC.

1. Introduction

Quarkonium is formed from a quark-antiquark pair of the same flavor and should represent one of the simplest systems described by QCD theory. However, the mechanisms responsible for the production of quarkonia in hadronic collisions are not fully understood. Study of the production of a prompt J/ψ meson in association with a vector boson offers new tests of Quantum Chromodynamics (QCD) at the perturbative/non-perturbative boundary, offers tests to try to separate single and double parton scattering components, and also helps develop the framework for future probes of the Higgs sector and beyond-the-standard-model searches in such final states. The ATLAS experiment¹ at the Large Hadron Collider (LHC) aims to investigate the above mentioned points using a quarkonium system as a probe.

2. Production of prompt J/Ψ mesons in association with a $W^\pm$ boson

Using the 2011 ATLAS dataset of 4.5 fb^{-1} of $\sqrt{s} = 7 \text{ TeV}$ pp collisions at the LHC, the first observation is made of the production of $W^\pm + \text{prompt } J/\psi$ events in hadronic collisions, using $W^\pm \rightarrow \mu\nu_\mu$ and $J/\psi \rightarrow \mu^+\mu^-$ channels².

To be considered for this analysis, events are required to have at least three identified muons. One pair of oppositely charged muons is required to form a J/ψ candidate, while an additional muon must combine with the event's missing transverse momentum E_T^{miss} to form a $W^\pm$ candidate.

In the Standard Model, a single parton-parton interaction can produce a J/ψ meson in association with a vector boson either through a “prompt” QCD subprocess, or through the production of a vector boson with a b -quark and its subsequent decay into a J/ψ (“non-prompt” production).

Fig. 1. Projections in (a) invariant mass and (b) pseudo-proper time of the two-dimensional mass-pseudo-proper time fit used to extract the prompt J/ψ candidates².

Prompt J/ψ candidates are distinguished from those originating from b -hadron decays through the spatial separation of the primary collision vertex and the J/ψ decay vertex. For this the pseudo-proper time

$$\tau \equiv \frac{\vec{L} \cdot \vec{p}_T^{J/\psi}}{p_T^{J/\psi}} \cdot \frac{m_{\mu^+\mu^-}}{p_T^{J/\psi}}, \quad (1)$$

is used, where $\vec{L}$ is the separation vector from the primary vertex to the J/ψ decay vertex and $m_{\mu^+\mu^-}$ is the invariant mass of the J/ψ candidate. Prompt J/ψ decays have a pseudo-proper time consistent with zero within resolution. Non-prompt J/ψ decay vertices are displaced from the primary vertex and have positive pseudo-proper time on average apart from resolution effects.

An unbinned maximum likelihood fit in J/ψ candidate invariant mass and pseudo-proper time is applied to obtain yields (using the sPlot procedure⁴) of prompt J/ψ , non-prompt J/ψ , and prompt/non-prompt combinatoric backgrounds, see Figure 1.

It is possible for the $W^\pm$ and J/ψ to originate from two different parton interactions in the same proton-proton collision, in a double parton scattering (DPS) process. The standard ansatz⁵ is adopted that, for a collision in which a hard process occurs, the probability of an additional process is parameterized as

$$P_{J/\psi|W^\pm} = \frac{\sigma_{J/\psi}}{\sigma_{\text{eff}}}. \quad (2)$$

The effective area parameter σ_{eff} accounts for the geometric size of the proton and transverse parton correlations, and is assumed to be independent of the scattering process. It is taken to be 15 ± 3 (stat.) $^{+5}_{-3}$ (syst.) mb as measured using $W^\pm \rightarrow l\nu_l + 2 \text{ jet}$ events¹¹.

Fig. 2. The sPlot-weighted azimuthal angle between the $W^\pm$ and the J/ψ is shown for $W^\pm + \text{prompt } J/\psi$ candidates².

A uniform distribution in the azimuthal angle between the $W^\pm$ and J/ψ

momenta is expected from DPS, under the assumption that the two interactions are independent. For the Single Parton Scattering (SPS) contribution simulations in both the colour-singlet and colour-octet models predict a distribution strongly peaked near $\Delta\phi = \pi$. The sPlot-weighted distribution of this variable for the data has a peak near π and a tail extending towards zero, as shown in Figure 2. This suggests that the observed $W^\pm + \text{prompt } J/\psi$ candidates include both SPS and DPS events.

Fig. 3. (a) Fiducial, inclusive and DPS-subtracted cross-section ratio of $W^\pm + \text{prompt } J/\psi$ to inclusive $W^\pm$ production; (b) The inclusive (SPS+DPS) cross-section ratio $dR_{J/\psi}^{\text{incl}}/dp_T$ as a function of J/ψ transverse momentum².

The fiducial cross-section ratio of $W^\pm + \text{prompt } J/\psi$ production to inclusive $W^\pm$ production in the fiducial region was measured. Then, after correcting for J/ψ acceptance, the inclusive cross-section ratio was calculated, and after subtracting the double parton scattering component, the DPS-subtracted cross-section ratio was obtained (Figure 3(a)). The differential cross-section ratio $dR_{J/\psi}^{\text{incl}}/dp_T$ as a function of $p_T^{J/\psi}$ was also determined (Figure 3(b)), with an estimate of the differential DPS contribution. The data suggest that SPS is the dominant contribution to the total rate at low J/ψ transverse momenta. The distribution of the azimuthal angle between the produced $W^\pm$ and J/ψ suggests the presence of both SPS and DPS contributions, while the DPS estimate accounts for a large fraction of the observed signal. The predictions from both LO CS⁸ and NLO CO⁹ theoretical models lie below the measured values.

3. Production of prompt J/ψ mesons in association with a Z^0 boson

Using 20.3 fb^{-1} of data collected by the ATLAS experiment at the LHC in pp collisions at $\sqrt{s} = 8 \text{ TeV}$, the first measurement of associated $Z + J/\psi$ production was carried out for both prompt and non-prompt mechanisms of J/ψ production¹⁰.

The final state of this measurement is $Z(\rightarrow l^+l^-) + J/\psi(\rightarrow \mu^+\mu^-)$, where $l = \mu, e$, and therefore candidate events are required to have two pairs of leptons with opposite charges. Each pair of leptons is then fitted to a common vertex, with the invariant mass of the first pair required to be close to the Z boson mass and that of the second pair to be near the J/ψ mass.

Again, the $J/\psi \rightarrow \mu^+\mu^-$ candidates originating from prompt and non-prompt production sources, as well as continuum background, are separated with the help of a simultaneous maximum likelihood fit of the J/ψ invariant mass and pseudo-proper time (Eq. 1) distribution. The sPlot tool⁴ is used to extract yields for prompt signal, non-prompt signal, and various backgrounds (Figure 4).

Fig. 4. Projections of the unbinned mass and pseudo-proper time maximum-likelihood fit in (a) invariant mass and (b) pseudo-proper time of the associated-production sample. The fit is used to extract the prompt and non-prompt signal fractions¹⁰.

Figure 5 shows the distribution in the azimuthal angle $\Delta\phi$ between the Z boson and the J/ψ momentum vectors.

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Fig. 5. Azimuthal angle between the Z boson and the J/ψ meson after the application of the sPlot weights to separate the prompt (left) and non-prompt (right) yield from background contributions¹⁰.

By conservatively assuming that all observed signal in the first bin is due to DPS, the data uncertainties and uncertainties inherent in the DPS estimate allow a lower limit $\sigma_{\text{eff}} > 5.3 \text{ mb}$ (3.7 mb) at 68% (95%) confidence level to be extracted from the $Z + \text{prompt } J/\psi$ data.

Fig. 6. Production cross-section ratios of J/ψ in association with a Z boson, relative to inclusive Z production, for prompt and non-prompt J/ψ production¹⁰.

The fiducial cross-section ratio of $Z^0 + \text{prompt } J/\psi$ production to inclusive Z^0 production was measured, without applying corrections for the incomplete geometric acceptance for the J/ψ decay muons, nor for the Z boson acceptance. The acceptance-corrected inclusive production cross-section ratio was also calculated, and finally the DPS-subtracted production cross-section ratio was obtained (Figure 6).

The differential cross-section ratio $dR_{J/\psi}^{\text{incl}}/dp_T$ as a function of $p_T^{J/\psi}$ was also determined (Figure 7), with an estimate of the differential DPS contribution. Theory predicts that colour-octet contributions exceed the production rate from color-singlet processes, with colour-octet processes becoming increasingly dominant for higher p_T of the J/ψ . The combination of DPS and NLO NRQCD contributions tends to underestimate the production rate observed in data, with the discrepancy increasing with transverse momentum and reaching a factor of 4 – 5 for $p_T^{J/\psi} > 18 \text{ GeV}$.

Fig. 7. Production cross-section of J/ψ in association with a Z boson as a function of the p_T of prompt J/ψ , and non-prompt J/ψ , normalised to the inclusive Z cross-section¹⁰.

4. Summary and conclusions

The ATLAS Collaboration has observed $W^\pm + \text{prompt } J/\psi$ production at 5.1σ significance in 4.5 fb^{-1} of $\sqrt{s} = 7 \text{ TeV}$ pp collisions at the LHC. $W + \text{prompt } J/\psi$ candidates include both SPS and DPS events. SPS is the dominant contribution to the total rate at low p_T of the J/ψ . The ATLAS Collaboration has also observed $Z^0 + \text{prompt } J/\psi$ production at

5σ significance and Z^0 + non-prompt J/ψ production at 9σ significance in 20.3 fb^{-1} of $\sqrt{s} = 8 \text{ TeV}$ pp collisions at the LHC. Z^0 + prompt J/ψ candidates include both SPS and DPS events. A lower limit has been set on $\sigma_{\text{eff}}(> 5.3 \text{ mb})$. A higher production rate is predicted through CO transitions than through CS processes. The expected production rate from the sum of singlet and octet contributions is lower than the data by a factor of 2 to 5.

In a J/ψ pair production study¹⁵, the effective cross-section of DPS is measured to be $\sigma_{\text{eff}} = 6.3 \pm 1.6 \text{ (stat.)} \pm 1.0 \text{ (syst.) mb}$, which is lower than for other final states¹⁶, but is in agreement with the lower limit shown above.

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