Associated quarkonium production at ATLAS

Tamar Zakareishvili (HEPI TSU),
On behalf of the ATLAS Collaboration

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Introduction

• Quarkonia are formed from a quark 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, are not fully understood in hadron collisions.

• Motivation to study the production of a prompt J/ψ meson in association with a vector boson offers:
  - Tests of Quantum Chromodynamics (QCD) at the perturbative/non-perturbative boundary;
  - Useful information on the Double Parton Scattering (DPS) process along with Single Parton Scattering (SPS) process;
  - Developing the framework for future probes of the Higgs sector;
  - Beyond-the-standard-model searches in such final states.
Colour-Singlet (CS) and Colour-Octet (CO) states

Perturbative calculations of heavy quarkonium production in hadronic collisions distinguish between terms that produce a heavy quark system (Q̄Q) in a colour-singlet (CS) or a colour-octet (CO) state.
SPS and DPS

The production of two objects in the same pp collision can be due to:

**Single-Parton Scattering (SPS):**
the two objects are produced via a subprocess in a single interaction of two partons.

**Double-Parton Scattering (DPS):**
simultaneous interaction of two pairs of partons, each producing one of the two objects, assumed to be uncorrelated.
Prompt $J/\psi + W^\pm$

Measurement of the production cross section of prompt $J/\psi$ mesons in association with a $W^\pm$ boson in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *JHEP 04 (2014) 172;*

Production channel in the analysis:

$W^\pm (\rightarrow \mu^\pm \nu_\mu) + J/\psi (\rightarrow \mu^+ \mu^-)$

Trigger: single muon, $p_T > 18$ GeV

Fiducial phase space: $8.5 < p_T^{J/\psi} < 30$ GeV, $|y_{J/\psi}| < 2.1$;

- $p_T^\mu > 3.5$ GeV, $|\eta^\mu| < 1.3$, $|\eta^{W}| < 2.5$ at least one $p_T^\mu > 4$ GeV
- $p_T^\mu > 2.5$ GeV, $|\eta^\mu| > 1.3$
- $p_T^{W} > 25$ GeV, $|\eta^{W}| < 2.4$

In a later analysis [*Phys.Lett. B781 (2018) 485-491*] the authors found some evidence of DPS in this measurement.
Signal extraction

Prompt production: $J/\psi$ produced in the hard scattering process.

Non-prompt production: $J/\psi$ produced in the decay of a $B$ hadron, decay vertex separated from the primary vertex.

$$\tau \equiv \frac{\mathbf{L} \cdot \mathbf{p}_{T}^{J/\psi}}{p_{T}^{J/\psi}} \cdot \frac{m_{\mu^{+}\mu^{-}}}{p_{T}^{J/\psi}}$$

An unbinned maximum likelihood fit in $J/\psi$ candidate invariant mass and pseudo-proper time.

sPlot procedure (Nucl.Instrum.Meth.A555:356-369,2005) used to obtain yields for prompt $J/\psi$, non-prompt $J/\psi$, and background.
Double Parton Scattering - DPS


\[ P_{J/\psi | W^\pm} = \frac{\sigma_{J/\psi}}{\sigma_{\text{eff}}}. \]

\( \sigma_{\text{eff}} \) - the geometric size of the proton and transverse parton correlations - assumed to be independent of the scattering process.

From DPS - a uniform distribution in the azimuthal angle between the \( W^\pm \) and \( J/\psi \) momenta.

From SPS - a distribution strongly peaked near \( \Delta \phi = \pi \).

Observed \( W + \text{prompt } J/\psi \) candidates include both SPS and DPS events.
Results

W^+ ± prompt J/ψ:
- **Fiducial** - W production cross-section ratio in the J/ψ fiducial region;
- **Inclusive** - after correction for J/ψ acceptance;
- **DPS-subtracted** - after subtraction of the double parton scattering component.

The inclusive (SPS+DPS) cross-section ratio as a function of prompt J/ψ transverse momenta.

CS prediction being consistent with the measured DPS-subtracted rate within the current experimental and theoretical uncertainties. This emphasizes that this process appears to be dominated by CS production.

Prompt $J/\psi + Z^0$


Production channel in the analysis:

$Z^0 \left( -\mu^+\mu^-/e^+e^- \right) + J/\psi \left( -\mu^+\mu^- \right)$

Trigger: single muon or electron, $p_T > 24$ GeV

- Fiducial phase space $8.5 < p_T^{J/\psi} < 100$ GeV  $|y^{J/\psi}| < 2.1$
- $p_T^{\mu} > 3.5$ GeV  $|\eta^{\mu}| < 1.3$  $|\eta^{\mu}| < 2.5$
- $p_T^{\mu} > 2.5$ GeV  $|\eta^{\mu}| > 1.3$  at least one  $p_T^{\mu} > 4$ GeV
- $p_T^{\mu(Z)} > 15$ GeV  $|\eta^{\mu(Z)}| < 2.5$
- $p_T^{e(Z)} > 15$ GeV  $|\eta^{e(Z)}| < 2.47$
Signal extraction

2D fit of $J/\psi$ candidate invariant mass and pseudo-proper time. 

sPlot procedure (arXiv:physics/0402083) used to obtain yields for:

- prompt $J/\psi$;
- non-prompt $J/\psi$;
- background.
**Double Parton Scattering – DPS / Yields**

Total yield for prompt $J/\psi$ production is $56\pm10$ events.

Total yield for non-prompt $J/\psi$ production is $95\pm12$ events.

In the yields:

- estimated pile up: $5.2^{+1.8}_{-1.3}$ and $2.7^{+0.9}_{-0.6}$ for prompt and non-prompt samples respectively;
- estimated DPS: $11.1^{+5.7}_{-5.0}$ and $5.8^{+2.8}_{-2.6}$ for prompt and non-prompt samples respectively,

assuming: $\sigma_{\text{eff}} = 15 \pm 3 \text{ (stat)} \pm 3 \text{ (syst)} \text{ mb}$, New J. Phys. 15 (2013) 033038

$\sigma_{J/\psi}$ from Nucl. Phys. B 850 (2011) 387-444

If all signal in the first $\Delta\phi$ bin is due to DPS, a lower limit is set: $\sigma_{\text{eff}} > 5.3 \text{ mb}$
Results

The cross-section ratio of $Z^0 + \text{prompt } J/\psi$ to inclusive $Z^0$ production in the $J/\psi$ fiducial region (Fiducial), after correction for $J/\psi$ acceptance (Inclusive), and after subtraction of the double parton scattering component (DPS-subtracted).

The inclusive (SPS+DPS) cross-section ratio is shown as a function of $J/\psi$ transverse momentum.

- A higher production rate is predicted through colour-octet transitions than through colour-singlet 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 the $J/\psi$ $p_T$ range studied.
Summary

- ATLAS Collaboration has observed:
  - $W^\pm$ + prompt $J/\psi$ production at 5.1\(\sigma\) significance in 4.5 \(fb^{-1}\) of \(\sqrt{s} = 7\) TeV pp collisions at the LHC:
    - $W^\pm$ + prompt $J/\psi$ candidates include both SPS and DPS events;
    - SPS is the dominant contribution to the total rate at low $J/\psi$ $p_T$;
    - This process appears to be dominated by CS production.
  - $Z^0$ + prompt $J/\psi$ production at 5\(\sigma\) significance and $Z^0$ + non-prompt $J/\psi$ production at 9\(\sigma\) significance in 20.3 \(fb^{-1}\) of \(\sqrt{s} = 8\) TeV pp collisions at the LHC:
    - $Z^0$ + prompt $J/\psi$ candidates include both SPS and DPS events;
    - Lower limit has been set on $\sigma_{eff}$ (> 5.3 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.

- The effective cross-section of double parton scattering is measured to be $\sigma_{eff} = 6.3 \pm 1.6(\text{stat}) \pm 1.0(\text{syst})$ mb [Eur. Phys. J. C77 (2017) 76], which is lower than from other final states.

- Some measured SPS contributions are well above theoretical predictions.

- Theoretical predictions of the dependence of $\sigma_{eff}$ on the process and energy are needed.
Triggers, fiducial cuts, integrated luminosities

Trigger: single muon, $p_T > 18$ GeV

$\sqrt{s} = 7$ TeV
$\mathcal{L} = 4.51$ fb$^{-1}$
$J/\psi \to \mu^+ \mu^-$
$W^\pm \to \mu \nu_\mu$

fiducial phase space $8.5 < p_T^{J/\psi} < 30$ GeV $|y^{J/\psi}| < 2.1$

$p_T^{\mu} > 3.5$ GeV $|\eta^{\mu}| < 1.3$ $|\eta^{\mu}| < 2.5$

$p_T^{\mu} > 2.5$ GeV $|\eta^{\mu}| > 1.3$

$p_T^{(W)} > 25$ GeV $|\eta^{(W)}| < 2.4$

at least one $p_T^{(W)} > 4$ GeV

Trigger: single muon or electron, $p_T > 24$ GeV

$\sqrt{s} = 8$ TeV
$\mathcal{L} = 20.3$ fb$^{-1}$
$J/\psi \to \mu^+ \mu^-$
$Z \to l l, l = \mu, e$

fiducial phase space $8.5 < p_T^{J/\psi} < 100$ GeV $|y^{J/\psi}| < 2.1$

$p_T^{\mu} > 3.5$ GeV $|\eta^{\mu}| < 1.3$ $|\eta^{\mu}| < 2.5$

$p_T^{\mu} > 2.5$ GeV $|\eta^{\mu}| > 1.3$

at least one $p_T^{\mu} > 4$ GeV

$p_T^{\mu(Z)} > 15$ GeV $|\eta^{\mu(Z)}| < 2.5$

$p_T^{e(Z)} > 15$ GeV $|\eta^{e(Z)}| < 2.47$
2D fit model

The combined probability density function used for the fit is:

\[
p \propto N_{\text{prompt } J/\psi} \times M_{J/\psi}(m_{\mu^+\mu^-}) \times T_{\text{prompt } J/\psi}(\tau)
+ N_{\text{non-prompt } J/\psi} \times M_{J/\psi}(m_{\mu^+\mu^-}) \times T_{\text{non-prompt } J/\psi}(\tau)
+ N_{\text{prompt bkg}} \times M_{\text{prompt bkg}}(m_{\mu^+\mu^-}) \times T_{\text{prompt bkg}}(\tau)
+ N_{\text{non-prompt bkg}} \times M_{\text{non-prompt bkg}}(m_{\mu^+\mu^-}) \times T_{\text{non-prompt bkg}}(\tau).
\]

The functional forms of the probability density functions are:

\[
M_{J/\psi}(m_{\mu^+\mu^-}) = G(m_{\mu^+\mu^-}; m_{J/\psi}^{\text{PDG}}, \sigma_m)
\]

\[
T_{\text{prompt } J/\psi}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left((1 - a)\delta(\tau) + aC_0e^{-|\tau|/\tau_0}\right)
\]

\[
T_{\text{non-prompt } J/\psi}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left(C_1\theta(\tau)e^{-\tau/\tau_1}\right)
\]

\[
M_{\text{prompt bkg}}(m_{\mu^+\mu^-}) = C_2e^{-m_{\mu^+\mu^-}/k_0}
\]

\[
M_{\text{non-prompt bkg}}(m_{\mu^+\mu^-}) = C_3e^{-m_{\mu^+\mu^-}/k_1}
\]

\[
T_{\text{prompt bkg}}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left((1 - b)\delta(\tau) + bC_4e^{-|\tau|/\tau_0}\right)
\]

\[
T_{\text{non-prompt bkg}}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left(C_5\theta(\tau)e^{-\tau/\tau_2}\right).
\]
Some definitions

The cross-section ratio of \( W^\pm \) prompt \( J/\psi \) production to the inclusive \( W^\pm \) production:

\[
R_{J/\psi}^{\text{fid}} = \frac{\text{BR}(J/\psi \to \mu^+\mu^-)}{\sigma_{\text{fid}}(pp \to W^\pm)} \cdot \frac{d\sigma_{\text{fid}}(pp \to W^\pm + J/\psi)}{dy} = \frac{N^{\text{rec}}(W^\pm + J/\psi)}{N(W^\pm)} \cdot \frac{1}{\Delta y} - R_{\text{pileup}},
\]

\[
R_{J/\psi}^{\text{incl}} = \frac{\text{BR}(J/\psi \to \mu^+\mu^-)}{\sigma_{\text{fid}}(pp \to W^\pm)} \cdot \frac{d\sigma(pp \to W^\pm + J/\psi)}{dy} = \frac{N^{\text{rec}+\text{ac}}(W^\pm + J/\psi)}{N(W^\pm)} \cdot \frac{1}{\Delta y} - R_{\text{pileup}},
\]

The cross-section ratio of \( Z^0 \) prompt \( J/\psi \) production to the inclusive \( Z^0 \) production:

\[
R_{Z+J/\psi}^{\text{fid}} = \mathcal{B}(J/\psi \to \mu^+\mu^-) \frac{\sigma_{\text{fid}}(pp \to Z + J/\psi)}{\sigma_{\text{fid}}(pp \to Z)}
= \frac{1}{N(Z)} \sum_{\text{pt bins}} \left[ N^{\text{rec}}(Z + J/\psi) - N^{\text{rec}}_{\text{pileup}} \right],
\]

\[
R_{Z+J/\psi}^{\text{incl}} = \mathcal{B}(J/\psi \to \mu^+\mu^-) \frac{\sigma_{\text{incl}}(pp \to Z + J/\psi)}{\sigma_{\text{incl}}(pp \to Z)}
= \frac{1}{N(Z)} \sum_{\text{pt bins}} \left[ N^{\text{rec}+\text{ac}}(Z + J/\psi) - N^{\text{rec}+\text{ac}}_{\text{pileup}} \right],
\]
Backgrounds

- Production of $W^\pm$ bosons in association with $b$ quarks, subsequent $b$-hadron decay to $J/\psi$ – rejected using the fit.
- Decays of $B_c \rightarrow J/\psi \mu^+ \nu \mu X$ – negligible background.
- The production of $Z$ bosons ($Z \rightarrow \mu^+ \mu^-$) – vetoing events where a pairing of muons has an invariant mass within 10 GeV of the $Z$ boson mass.
- Multi-jet production – The $m_T(W)$ distribution of signal events is fit to a sum of a multi-jet template and a $W^\pm$-boson signal template.

**Total yield** for prompt $J/\psi$ production is $29.2^{+7.5}_{-6.5}$ Events. In the yield:
- estimated pile up : $1.8 \pm 0.2$
- estimated DPS: $10.8 \pm 4.2$

assuming: $\sigma_{\text{eff}} = 15 \pm 3 \, \text{(stat)} ^{+5}_{-3} \, \text{(syst)} \, \text{mb}$  

$\sigma_{J/\psi}$ from *Nucl. Phys. B 850 (2011) 387-444*
Backgrounds

Background estimation using MC:

- \(Z\rightarrow \tau\tau\) or \(W\rightarrow \ell\nu\) background;
- Top quark processes involving \(\bar{t}t\) or single top production;
- The single-top Wt process;
- Diboson (WZ, WW and ZZ) production.

Using data:

- Multi-jet production – Selecting non-isolated leptons.

The \(m(Z)\) distribution of signal events is fit to a sum of a multi-jet template and a \(Z^0\) boson signal template.

The numbers of background events estimated in the Z signal region, defined as \(m_{Z_{PDG}} \pm 10\) GeV, for the \(Z\rightarrow e^+e^- (\mu^+\mu^-)\) candidates are:

- associated with prompt J/\(\psi\): 0±4 (1±4);
- associated with non-prompt J/\(\psi\): 1±5 (0±5).

The sample is dominated by genuine \(Z + J/\psi\) events.
Measurements and limits on the effective cross section

ATLAS
- $\sqrt{s} = 63$ GeV, 4 jets, 1986
- $\sqrt{s} = 630$ GeV, 4 jets, 1991
- CDF ($\sqrt{s} = 1.8$ TeV, 4 jets, 1993)
- CDF ($\sqrt{s} = 1.8$ TeV, γ + 3 jets, 1997)
- DØ ($\sqrt{s} = 1.96$ TeV, γ + 3 jets, 2010)
- LHCb ($\sqrt{s} = 7$ TeV, J/$\psi$Λ$_c^+$, 2012)
- LHCb ($\sqrt{s} = 7$ TeV, J/$\psi$D$_s^+$, 2012)
- LHCb ($\sqrt{s} = 7$ TeV, J/$\psi$D$^+$, 2012)
- LHCb ($\sqrt{s} = 7$ TeV, J/$\psi$D$^0$, 2012)
- ATLAS ($\sqrt{s} = 7$ TeV, W + 2 jets, 2013)
- CMS ($\sqrt{s} = 7$ TeV, W + 2 jets, 2014)
- DØ ($\sqrt{s} = 1.96$ TeV, γ + b/c + 2 jets, 2014)
- DØ ($\sqrt{s} = 1.96$ TeV, γ + 3 jets, 2014)
- DØ ($\sqrt{s} = 1.96$ TeV, J/$\psi$ + J/$\psi$, 2014)
- ATLAS ($\sqrt{s} = 8$ TeV, Z + J/$\psi$, 2015)
- LHCb ($\sqrt{s} = 7$ TeV, Υ(1S)D$^{0,+}$, 2015)
- DØ ($\sqrt{s} = 1.96$ TeV, J/$\psi$ + T, 2016)
- DØ ($\sqrt{s} = 1.96$ TeV, 2γ + 2 jets, 2016)
- ATLAS ($\sqrt{s} = 7$ TeV, 4 jets, 2016)
- ATLAS ($\sqrt{s} = 8$ TeV, J/$\psi$ + J/$\psi$, 2017)
- CMS ($\sqrt{s} = 8$ TeV, T + T, 2017)
- LHCb ($\sqrt{s} = 13$ TeV, J/$\psi$ + J/$\psi$, 2017)
- CMS ($\sqrt{s} = 8$ TeV, W$^\pm$W$^\mp$, 2018)
- ATLAS ($\sqrt{s} = 8$ TeV, 4 leptons, 2018)