Associated J/ψ Production Measurements at ATLAS
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Benjamin Weinert
Indiana University
(on behalf of the ATLAS Collaboration)
Outline

- Double Parton Scattering (DPS):
  - Interest
  - Definition

- Review of associated production of J/ψ with a vector boson.

- Prompt pair production of J/ψ (ATLAS-CONF-2016-047):
  - Differential cross-section.
  - Data-driven DPS and SPS model.
  - Effective cross-section of DPS.
Interest in DPS

- **Single Parton Scattering (SPS):**
  - Importance/effects of feed-down from decays of excited charmonium.

- Double Parton Scattering can be a significant contributor to associated charmonium.

- **Double Parton Scattering (DPS):**
  - Larger role at high energies (arXiv:1504.06491 )
  - Background to Higgs searches, SUSY and exotics searches (arXiv:0909.1586).
  - Better understanding of Non-perturbative QCD.
  - Effective cross-section measured for multiple final states: γ+3-jets, 4-jets, W+2-jets, Z+J/ψ, etc.
    - Process dependent?
    - Dependent on initial partons (gluons or quarks)?
    - Deeper insight into the structure of the proton.

\[ \sigma_{\text{SPS}} \sim (\text{parton density})^2 \]
\[ \sigma_{\text{DPS}} \sim (\text{parton density})^4 \]
Double Parton Scattering (DPS)

- Large c.m. energies and low values of incoming fractional momenta (x).
- DPS cross section can be written as: \( \sigma_{DPS} = \frac{m}{2} \frac{\sigma_A \sigma_B}{\sigma_{eff}} \).
  - m is a symmetrization parameter.
  - \( \sigma_{eff} \) measures the size in impact parameter space of the incident hadron’s partonic core.
  - \( \sim \) Transverse distance between partons.

- If equal to the inelastic cross section, it would imply uncorrelated scatterings.
  - Assumptions lead to process and energy independence.

- A constant value of \( \sigma_{eff} \) has been able to describe results in different kinematical regions. CDF (PRL.79.584) tested the dependence of \( \sigma_{eff} \) on x and had compatible results with being independent of x.
Results: Vector Boson + J/ψ

- $\sigma_{\text{eff}} = 15\pm3(\text{stat})^{+5}_{-3}(\text{sys})$ mb taken from ATLAS W+2j results (arXiv:1301.6872[hep-ex]) is used for the DPS estimates.

- DPS is found to be, $f_{\text{DPS}} \sim 37\%$.

- NLO Color Octet contributions are an order of magnitude smaller than LO Color Singlet contributions.

  - LO: arXiv:1303.5327
  - NLO: arXiv:1012.3798

- Z+J/ψ: $f_{\text{DPS}} = (29\pm9)\%$ prompt, $(8\pm2)\%$ non-prompt.

- Theory underestimates SPS production, does not include feed-down.

- $\sigma_{\text{eff}} > 5.3$ mb $(3.7$ mb) at 68% (95%) CL.

  - LO Theory: arXiv:1210.2430
  - NLO Theory: arXiv:1102.0398
First look at prompt J/ψ pair production using ATLAS 8 TeV data with decay mode $J/\psi \rightarrow \mu^+\mu^-$. 

- Muon kinematic requirements:
  - $|y| < 2.3$ and $p_T > 2.5$ GeV.
  - One $J/\psi$ must have both muons with $p_T > 4$ GeV.

- $J/\psi$ kinematic requirements:
  - $2.8$ GeV $\leq m_{\mu\mu} \leq 3.4$ GeV for each $J/\psi$ candidate.
  - $p_T > 8.5$ GeV and $|y_{J/\psi}| < 2.1$. 

![Graphs showing kinematic distributions for central and forward regions.](image)
First look at prompt $J/\psi$ pair production using ATLAS 8 TeV data with decay mode $J/\psi \rightarrow \mu^+\mu^-$. 

**Backgrounds:**
- Non-$J/\psi$ background
- Non-prompt background (non-prompt $J/\psi$)
- Pile-up events
Extracting DPS

- DPS is modeled using re-sampled randomized $J/\psi$ pairs from different di-$J/\psi$ events.
  - Assumption/approximation is made of independent kinematics.

- A 2-D template of $|\Delta\phi|$ vs. $|\Delta y|$ is created to extract the DPS distribution.
  - Define a DPS dominated region: $|\Delta y| \geq 1.8$ and $0 \leq |\Delta\phi| \leq \pi/2$.

- By subtracting the DPS distribution, the SPS distribution is obtained.
Inclusive cross-section assuming unpolarized $J/\psi$ mesons:
- Central Region: $\sigma = 82.2 \pm 8.3\text{(stat)} \pm 6.3\text{(syst)} \pm 0.9\text{(BF)} \pm 2.3\text{(lumi)} \text{pb for } |y(J/\psi)|< 1.05$.
- Forward Region: $\sigma = 78.3 \pm 9.2\text{(stat)} \pm 6.6\text{(syst)} \pm 0.9\text{(BF)} \pm 2.2\text{(lumi)} \text{pb for } 1.05 \leq |y(J/\psi)|< 2.1$.

DPS-enriched distributions from the data-driven method.
DPS: $\Delta y$ and $\Delta \phi$

- Total data and the data-driven DPS distributions in the fiducial volume.


- Data-driven DPS estimates and the theory predictions agree quite well.

- Disagreement between the NLO SPS predictions and data at large $\Delta y$.
  - Theory assumes constant feed-down, ~40% of SPS.

- The two-peak structure of the $\Delta \phi$: back-to-back production (LO, $\Delta \phi \sim \pi$) and gluon back-to-back with the di-$J/\psi$ system (NLO, $\Delta \phi \sim 0$).
DPS : $M(J/\psi J/\psi)$ and $p_T(J/\psi J/\psi)$

- Total data and the data-driven DPS distributions in the fiducial volume.
- Data-driven DPS estimates and theory predictions agree quite well.
- Disagreement of the data and the NLO SPS predictions at large mass.
- The NLO SPS theory under-predicts the low-$p_T$ peak near zero.
  - Assumption of a constant feed-down contribution.
  - Increased $k_T$ smearing is another possibility.
A requirement is placed on $\Delta y \geq 1.8$.
- The same binning is used as in the previous plots.
- Distributions are in the fiducial volume.

Excess at large mass is correlated to the excess at large $\Delta y$.

Both the $\Delta \phi$ and di-$J/\psi$ $p_T$ distributions, indicate the presence of back-to-back SPS production.

Feed-down can have a similar $\Delta y$ and di-$J/\psi$ mass tail to that of DPS production (arXiv:1606.06767).

Similar excess is observed in CMS.
Effective Cross-section

\[ \sigma_{\text{eff}} = \frac{1}{2} \frac{\sigma_{J/\psi J/\psi}}{\sigma_{\text{DPS}}} = \frac{1}{2} \frac{\sigma_{J/\psi J/\psi}}{\sigma_{\text{DPS}} \cdot \sigma_{J/\psi J/\psi}} \]

\[ = 8.7 \pm 1.1 \text{ (stat)} \pm 1.4 \text{ (syst)} \pm 0.1 \text{ (BF)} \pm 0.3 \text{ (lumi)} \text{ mb.} \]

- ATLAS and D0 analyses provide a hint that the effective cross-section measured from the di-$J/\psi$ final state could be lower than that measured for the other final states.

- Interesting to note that the production of the di-$J/\psi$, $J/\psi + \gamma$, and 4-jets final states are dominated by gluon interactions.
  - Should be able to directly probe the gluon spatial distribution in the proton.
Effective Cross-section vs. $\sqrt{s}$

- Effective cross-section as a function of the center-of-mass energy, $\sqrt{s}$.

- Measurements of identical center-of-mass energies are offset in $\sqrt{s}$.

- Assumptions in $\sigma_{\text{eff}}$ definition lead to process and energy independence.

- No proof of the factorization and therefore experimental evidence is needed as a test.
DPS studies are now possible using charmonium production and will become increasingly important at larger c.m. energies.

  - NLO CO contributions are an order of magnitude less than LO CS contributions.
  - Double parton scattering (DPS), $f_{DPS} \sim 37\%$.

  - Higher production rate via CO than CS process, but underestimates the data by a factor of 2 to 5 in $p_T$ range.
  - $f_{DPS} \sim 29\%$ for prompt J/ψ.
  - $\sigma_{eff} > 5.3 \text{ mb}(3.7 \text{ mb})$ at 68% (95%) CL.

- **J/ψ+J/ψ production:**
  - First ATLAS measurement of the prompt J/ψ pair cross-section.
  - Data-driven DPS model.
  - $f_{DPS} \sim 6.6\%$ (~20% for $\Delta y \geq 1.8$).
  - $\sigma_{eff} = 8.7 \pm 1.1 \text{ (stat)} \pm 1.4 \text{ (syst)} \pm 0.1 \text{ (BF)} \pm 0.3 \text{ (lumi)} \text{ mb}$.
  - Feed-down events (arXiv:1606.06767).
  - A low value of the effective cross-section for gluon dominated processes could indicate a smaller transverse distance between gluons in the nucleon as suggested by the pion cloud model (arXiv: 0906.3267).
Backup Slides
Selection Criteria: Vector Boson + J/ψ

\[ \mu: \ |\eta| < 2.5; \ p_T > 3.5 \ (2.5) \text{ GeV for } |\eta| < (>)1.3; \text{ within 10 mm of PV along } z \]

\[ \text{J/ψ: } |y| < 2.1, \ p_T > 8.5 \text{ GeV}; \geq 1 \ p_T > 4 \text{ GeV muon}; \geq 1 \text{ “combined” muon} \]

\[ \text{W} + \text{J/ψ} \]
- \[ p_T^{J/ψ} < 30 \text{ GeV, } 2.5 < m_{\mu\mu} < 3.5 \text{ GeV,} \]
- Single-muon trigger: \[ p_T > 18 \text{ GeV,} \]
- \[ W^\pm \text{ vertex matches trigger,} \]
- \[ Z^0 \text{ veto: } W \text{ decay and OS muons,} \]
- \[ E_T^{\text{miss}} > 20 \text{ GeV,} \]
- \[ m_T > 40 \text{ GeV.} \]

\[ \text{Z} + \text{J/ψ} \]
- \[ p_T^{J/ψ} < 100 \text{ GeV, } 2.6 < m_{\mu\mu} < 3.6 \text{ GeV,} \]
- Single muon or electron trigger: \[ p_T > 24 \text{ GeV,} \]
- At least one lepton matches trigger,
- \[ \mu: \ |\eta| < 2.5, \ p_T > 15 \text{ GeV, combined,} \]
- \[ e: \ |\eta| < 2.47, \ p_T > 15 \text{ GeV,} \]
- \[ |m(l^+l^-) - m_Z| < 10 \text{ GeV,} \]
- \[ J/ψ \text{ and } Z \text{ vertices < 10 mm in } z. \]
W+J/ψ: Extracting the Signal

- A Maximum Likelihood fit of the Di-muon invariant mass and J/ψ pseudo-proper time are used to extract prompt J/ψ events. Then $m_T(W)$ is fit to separate the QCD multijet background. The background-only hypothesis is rejected at 5.1σ.
The differential cross-section ratio for $W+J/\psi$ as a function of $p_T$ of the $J/\psi$ meson, $dR^{incl}_{J/\psi}/dp_T$.

- $R_{W+J/\psi} = BF(J/\psi \rightarrow \mu^+\mu^-) \frac{\sigma(pp \rightarrow W+J/\psi)}{\sigma(pp \rightarrow W)}$
- $R^{fid}_{W+J/\psi} = (51 \pm 13 \pm 4) \times 10^{-8}$.  

Results: Vector Boson + $J/\psi$

- $R_{Z+J/\psi} = BF(J/\psi \rightarrow \mu^+\mu^-) \frac{\sigma(pp \rightarrow Z+J/\psi)}{\sigma(pp \rightarrow Z)}$
- $R^{fid}_{Z+J/\psi} = (36.8 \pm 6.7 \pm 2.5) \times 10^{-7}$ (prompt).
- $R^{fid}_{Z+J/\psi} = (65.8 \pm 9.2 \pm 4.2) \times 10^{-7}$ (non-prompt).
Z + J/ψ: Extracting Signal

- Z→ττ, W→lν, t¯t, single top and diboson backgrounds are modeled by MC.
- Multijet and misidentified leptons are modelled by reversing isolation req.
- Pileup background events are estimated.
Z + J/ψ: Differential Cross Section Ratio

- Prompt differential cross section ratio is compared to NLO SPS predictions and DPS expectations.
- Theory predicts CO > 2*CS with CO increasing with $p_T$.
- DPS + NLO SPS predictions underestimate the data by a factor of 4-5 for $p_T^{J/ψ} > 18$ GeV.

- Significant SPS contribution to Z + non-prompt J/ψ is expected from Z + b-jet production.
- The data presents the opportunity to test Z + b-jet production at low $p_T$. 

The 2-D fit of the transverse decay length, $L_{xy}$, integrates over the $p_T$ spectrum of each $J/\psi$ meson.

Any resulting bias is corrected using a scale factor obtained from simulation using the AU2 tune, and CTEQ6L1 PDF of Pythia 8B.

The scale factors are defined as a function of the reconstructed prompt-prompt fraction, $f_{PP}$. 
Differential $f_{PP}$ Correction: $p_T(J/\psi_2)$

- Shown are the sub-leading $J/\psi$ $p_T$ distribution for the PP MC input, the original MC reconstructed distribution, and the reconstructed and corrected distribution.

- The fraction of prompt events decreases with $p_T$ and therefore the bias should increase.
  - The correction performs much better than the original at high $p_T$.

- The correction factor is also found to perform well for each of the variables considered.
\[ \frac{d\sigma}{dp_T(J/\psi J/\psi)} \text{ for Prompt di-J/\psi} \]

Central Region

\[ \sigma = 81.4\pm7.9\text{(stat)}\pm6.2\text{(syst)}\pm0.9\text{(BF)}\pm2.3\text{(lumi)} \text{ pb} \]

Forward Region

\[ \sigma = 76.8\pm8.8\text{(stat)}\pm6.5\text{(syst)}\pm0.9\text{(BF)}\pm2.2\text{(lumi)} \text{ pb} \]
\[ \frac{d\sigma}{dm(J/\psi J/\psi)} \] for Prompt di-J/\psi

Central Region

\[ \sigma = 81.0 \pm 7.9 \text{(stat)} \pm 6.2 \text{(syst)} \pm 0.9 \text{(BF)} \pm 2.3 \text{(lumi)} \text{ pb} \]

Forward Region

\[ \sigma = 74.4 \pm 8.5 \text{(stat)} \pm 6.3 \text{(syst)} \pm 0.8 \text{(BF)} \pm 2.1 \text{(lumi)} \text{ pb} \]
\[ \sigma_{DPS}^{AB} = \frac{m}{2} \sum_{ijkl} \int \Gamma_{ij}(x_1, x_2, b_1, b_1, \mu_A, \mu_B) \sigma_{i k}^A(x_1, x'_1, \mu_A) \times \Gamma_{kl}(x'_1, x'_2, b_1 - b, b_1 - b, \mu_A, \mu_B) \sigma_{j l}^B(x_2, x'_2, \mu_B) dx_1 dx_2 dx'_1 dx'_2 \, d^2 b \]

- \( m \): Symmetrization parameter.

- Double parton distribution function: \( \Gamma_{ij}(x_1, x_2, b_1, b_1, \mu_A, \mu_B) = D_{hl}^{ij}(x_1, x_2, \mu_A, \mu_B) f(b_1) f(b_2) \)

- \( \sigma_{i k}^A \): Diff. cross-section for process A via the collisions of partons \( i \) and \( k \).

The effective cross-section is related to the radius of the proton, as the partons in each proton must overlap.

- Naïve guess: \( \sigma_{\text{Eff}} \approx \pi R_p^2 \approx 50 \, \text{mb}; \ R_p \equiv \text{radius of the proton} \).

- \( \sigma_{\text{eff}} = \left[ \int [ \int f(b_1) f(b_1 - b) d^2 b_1 ]^2 d^2 b \right]^{-1} \), where \( \int f(b_1) f(b_1 - b) d^2 b_1 d^2 b = \int T(b) d^2 b = 1 \).

- Given that process A has occurred, \( \sigma_B / \sigma_{\text{eff}} \) is the probability that a process B will occur.
## Systematics: Di-J/ψ Cross-Section

| Source                     | $|y(J/ψ_2)|<1.05$ [%] | $1.05≤|y(J/ψ_2)|<2.1$ [%] |
|----------------------------|----------------|------------------|
| Trigger                   | ± 7.5          | ± 8.3            |
| Muon Reconstruction       | ± 1.1          | ± 1.3            |
| Kinematic Acceptance      | ± 0.3          | ± 1.1            |
| Mass Model                | ± 0.1          | ± 0.1            |
| Mass Bias                 | ± 0.2          | ± 0.2            |
| Prompt-Prompt Model       | ± 0.2          | ± 0.01           |
| Differential f$_{pp}$ Corr. | ± 0.6        | ± 0.3            |
| Pile-up                   | ± 0.03         | ± 0.4            |
| **Total**                 | ± 7.7          | ± 8.5            |
| Branching Fraction        | ± 1.1          | ± 1.1            |
| Luminosity                | ± 2.8          | ± 2.8            |
| Spin-Alignment            | +68 $\rightarrow$ -47 | +83 $\rightarrow$ -45 |
### Systematics: $\text{Di-J}/\psi \, f_{\text{DPS}}$

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<td>Trigger</td>
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<td>DPS Model</td>
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<td><strong>Total</strong></td>
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In an analysis of 2011 \( \sqrt{s}=7 \) TeV data, CMS found the prompt J/\( \psi \) pair cross-section to be \( \sigma = 1.49 \pm 0.07 \) (stat) \( \pm 0.14 \) (syst) nb.

Although this is an order of magnitude higher than our measurement, the CMS inclusive volume goes down to lower \( p_T \) where J/\( \psi \) production is enhanced. Their inclusive volume is also a function of \( p_T \), this increases the difficulty of a comparison.

Using the results in arxiv:1410.8822, we can take the ratio of the predictions for the 7 TeV CMS cross-section and the ATLAS 8 TeV cross-section as a rough estimate. The SPS predictions are scaled to account for feed-down, and the DPS predictions are scaled to our measured value of \( \sigma_{\text{eff}} \).

- Data (CMS/ATLAS) = 9.3 \( \pm 0.8 \) (stat) \( \pm 1.2 \) (syst).
- Prediction (CMS/ATLAS) = 10.1\( ^{+1.6}_{-0.9} \)
Comparison with CMS: Effective Cross-section

- The effective cross-section is measured to be $8.7 \pm 1.1 \text{ (stat)} \pm 1.4 \text{ (syst)} \pm 0.1 \text{ (BF)} \pm 0.3 \text{ (lumi)} \text{ mb}.

- In arxiv:1410.8822, the authors take the CMS prompt $J/\psi$ pair cross-section and fit for the effective cross-section using MC templates.

- There are three fits. Both use a prompt single-$J/\psi$ matrix element modelled from combined fits of data from multiple experiments for DPS. Fit 2 uses 7 TeV LHC data in the model. Fit 3 uses only data from CDF to parameterize the prompt single-$J/\psi$ matrix element.
  - $\sigma_{\text{eff}}(\text{Fit1}) = 11 \pm 2.9 \text{ mb}.$
  - $\sigma_{\text{eff}}(\text{Fit2}) = 8.2 \pm 2.2 \text{ mb}.$
  - $\sigma_{\text{eff}}(\text{Fit3}) = 5.3 \pm 1.4 \text{ mb}$

- Both fits that use LHC data are equal to the ATLAS measured central value within theoretical uncertainty. Fit 2, which uses newer data in the model, is extremely close to the measured value. Each of the predicted effective cross-sections are smaller than the values obtained from quark-dominated processes.