Associated quarkonia production:

- $J/\psi$ and $W^\pm$ boson at $\sqrt{s} = 7$ TeV – JHEP 1404 (2014) 172
- $\psi(2S)$ and $X(3872)$ production at $\sqrt{s} = 8$ TeV – JHEP 1701 (2017) 117
Motivation:

- Probes the production mechanisms of quarkonium (is not fully understood in hadron collisions)
- New tests of QCD at the perturbative/non-perturbative boundary;
- Further constraints on the contributions from colour-singlet (CS) and colour-octet (CO) production processes, and their properties;
- Two principal possibilities to produce two objects in a pp collision:
  - 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.
The first observation of the production of prompt $J/\psi + W^\pm$ events in hadronic collisions:

- Use 4.5 fb$^{-1}$ @ 7 TeV data;
- $J/\psi \rightarrow \mu^+\mu^-$ and $W^\pm \rightarrow \mu^\pm\nu\mu^-$ at least three identified muons;
- Additional muon must combine with the events missing transverse momentum ($E_T^{miss}$);
- The $W^\pm$ boson transverse mass $m_T = \sqrt{2p_T(\mu)E_T^{miss}(1 - \cos(\phi_\mu - \phi_\nu))}$
- $27.4^{+7.5}_{-6.5}$ prompt $J/\psi + W^\pm$ events were observed with a statistical significance of $5.1\sigma$.

<table>
<thead>
<tr>
<th>Yields from two-dimensional fit</th>
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<tbody>
<tr>
<td>Process</td>
</tr>
<tr>
<td>Prompt $J/\psi$</td>
</tr>
<tr>
<td>Non-prompt $J/\psi$</td>
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<tr>
<td>Prompt background</td>
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<tr>
<td>Non-prompt background</td>
</tr>
<tr>
<td>$p$-value</td>
</tr>
</tbody>
</table>

(*) of which 1.8 ± 0.2 originate from pileup
Associated production of $J/\psi + W^\pm$: double parton scattering:

- $J/\psi$ and $W^\pm$ candidates originate from two different parton interactions in the same $pp$ collision.
- The probability is $P_{J/\psi|W^\pm} = \sigma_{J/\psi}/\sigma_{\text{eff}}$
  - $\sigma_{\text{eff}}$ is assumed to be universal across processes and energy scales.
  - $\sigma_{\text{eff}} = 15 \pm 3(\text{stat.})_{-3}^{+5}(\text{syst.}) \text{ mb} - \text{New J. Phys. 15 (2013) 033038}$
- The total number of DPS events in the signal yield is estimated to be $10.8 \pm 4.2$ events.
- A uniform distribution in the azimuthal angle between the $W^\pm$ and $J/\psi$ momenta is expected from DPS, under the assumption that the two interactions are independent.
- Peak near $\pi$ and a tail extending towards zero in data distribution $\implies$ SPS and DPS events are present;
Associated production of $J/\psi + W^{\pm}$: cross-section ratios

Fiducial – production cross-section ratio in the $J/\psi$ fiducial region
\[ R_{J/\psi}^{\text{fid}} = (51 \pm 13 \pm 4) \times 10^{-8} \]

Inclusive – after correction for $J/\psi$ acceptance
\[ R_{J/\psi}^{\text{incl}} = (126 \pm 32 \pm 9^{+11}_{-25}) \times 10^{-8} \]

DPS-subtracted – after subtraction of the double parton scattering component
\[ R_{J/\psi}^{\text{DPS sub}} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8} \]

Predictions – LO CS: $(10 - 32) \times 10^{-8}$, LO CO: $(4.6 - 6.2) \times 10^{-8}$

$SPS$ is dominant at low $J/\psi$ transverse momenta

$DPS$ estimate accounts for a large fraction of the observed signal ($\sim 40\%$)

$CS$ mechanism is expected to be the dominant contribution to the cross section

<table>
<thead>
<tr>
<th>$y_{J/\psi} \times p_T^{J/\psi}$ Bin</th>
<th>Inclusive (SPS+DPS) ratio $dR_{J/\psi}^{\text{incl}}/dp_T$ ($\times 10^{-6}$)</th>
<th>DPS ($\times 10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(0, 2.1) \times (0, 10)$</td>
<td>$0.56 \pm 0.16 \text{ (stat)} \pm 0.04 \text{ (syst)}$</td>
<td>$0.13 \pm 0.10$</td>
</tr>
<tr>
<td>$(0, 2.1) \times (10, 14)$</td>
<td>$0.070 \pm 0.030 \text{ (stat)} \pm 0.006 \text{ (syst)}$</td>
<td>$0.04 \pm 0.03$</td>
</tr>
<tr>
<td>$(0, 2.1) \times (14, 18)$</td>
<td>$0.011 \pm 0.017 \text{ (stat)} \pm 0.001 \text{ (syst)}$</td>
<td>$0.007 \pm 0.004$</td>
</tr>
<tr>
<td>$(0, 2.1) \times (18, 30)$</td>
<td>$0.0092 \pm 0.0067 \text{ (stat)} \pm 0.0006 \text{ (syst)}$</td>
<td>$0.0009 \pm 0.0006$</td>
</tr>
</tbody>
</table>

$ICNFP$ 2019, 21-29 August 2019
Tatiana Lyubushkina JINR
**The first observation and measurement of associated $Z$ and $J/\psi$ production**

- Use 20.3 fb$^{-1}$ @ 8 TeV data;
- $J/\psi \rightarrow \mu^+\mu^-$ and $Z \rightarrow \mu^+\mu^-$, $Z \rightarrow e^+e^-$ – two pairs of leptons with opposite charge; regions

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**Table:**

| Process                  | $|y_{J/\psi}| < 1.0$ | $1.0 < |y_{J/\psi}| < 2.1$ | Total                |
|--------------------------|----------------------|-----------------------------|----------------------|
|                          | Events               | From pileup                 | Events               |
| Prompt signal            | $24 \pm 6 \pm 2$     | $32 \pm 8 \pm 5$           | $56 \pm 10 \pm 5$    |
| Non-prompt signal        | $54 \pm 9 \pm 3$     | $41 \pm 8 \pm 7$           | $95 \pm 12 \pm 8$   |
| Background               | $61 \pm 11 \pm 6$    | $77 \pm 13 \pm 7$          | $138 \pm 17 \pm 9$  |

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**Graphs:**

- ATLAS $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
- ATLAS $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
- ATLAS $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
- ATLAS $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
Associated production of $J/\psi + Z$: double parton scattering

The probability is $P_{J/\psi|Z} = \sigma_{J/\psi}/\sigma_{\text{eff}}$

- $\sigma_{\text{eff}} = 15 \pm 3(\text{stat.})^{+5}_{-3}(\text{syst.})$ mb – New J. Phys. 15 (2013) 033038
- The total number of DPS events in the signal yield is estimated to be $11.1^{+5.7}_{-5.0}$ for prompt and $5.8^{+2.8}_{-2.6}$ for non-prompt components.
- Both DPS and SPS contributions may be present in the data:
Associated production of $J/\psi + Z$: cross-section ratios


**Cross-section ratios:**

\[
p_{R_{Z+J/\psi}^{\text{fid}}} = (36.8 \pm 6.7 \pm 2.5) \times 10^{-7}
\]

\[
n_{p_{R_{Z+J/\psi}^{\text{fid}}}} = (65.8 \pm 9.2 \pm 4.2) \times 10^{-7}
\]

\[
p_{R_{Z+J/\psi}^{\text{incl}}} = (63 \pm 13 \pm 5 \pm 10) \times 10^{-7}
\]

\[
n_{p_{R_{Z+J/\psi}^{\text{incl}}}} = (102 \pm 15 \pm 5 \pm 3) \times 10^{-7}
\]

\[
p_{R_{Z+J/\psi}^{\text{DPS sub}}} = (45 \pm 13 \pm 6 \pm 10) \times 10^{-7}
\]

\[
n_{p_{R_{Z+J/\psi}^{\text{DPS sub}}}} = (94 \pm 15 \pm 5 \pm 5) \times 10^{-7}
\]

**DPS contributions:**

- (29 ± 9)% for prompt production
- (8 ± 2)% for nonprompt production

**Prediction:**

LO CS $(11.6 \pm 3.2) \times 10^{-8} - (46.2^{+6.0}_{-6.5}) \times 10^{-8}$

LO CO $(25.1^{+3.3}_{-3.5}) \times 10^{-8}$, NLO CO $(86^{+20}_{-18}) \times 10^{-8}$ ⇒ CO should have a higher production rate than CS

**Data:** expected production rate from CO + CS is lower than the data by a factor of 2 to 5
 "$\psi(2S)$ and $X(3872)$ production

JHEP 01 (2017) 117

- $X(3872)$ was observed by Belle in 2003, later confirmed by others, $J^{PC} = 1^{++}$
- No clear theoretical picture yet
  - Tetraquark (diquark + diquark)
  - Loosely bound $D^0\bar{D}^*0$ molecule
  - $\chi_{c1}(2P)$ state, or the mixture with $D^0\bar{D}^*0$
- ATLAS measurement can help to answer some of the questions
  - Measure in $J/\psi\pi^+\pi^-$ mode, together with well known $\psi(2S)$ state
    - helps to reduce systematics in ratios
  - Use 11.4 fb$^{-1}$ @ 8 TeV data
    - Limit to $|y| < 0.75$ for the best mass resolution
      - $\sim 470k \psi(2S)$ and $\sim 30k X(3872)$
  - Use 4 bins of pseudo proper lifetime to extract prompt/non-prompt components
Effective $X(3872)$ lifetime hypotheses

- **Single lifetime hypothesis**
  - same lifetime for $\psi(2S)$ and $X(3872)$ in each $p_T$ bin
  - effective $X(3872)$ lifetime shorter in low-$p_T$ bins $\Rightarrow$ different production mechanism at low $p_T$
  - Measure the $X(3872)/\psi(2S)$ non-prompt production cross sections ratio
    \[ R_B = \frac{\mathcal{B}(B \to X(3872) + \text{any}) \mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-)}{\mathcal{B}(B \to \psi(2S) + \text{any}) \mathcal{B}(\psi(2S) \to J/\psi \pi^+ \pi^-)} \]
    \[ R_B^{1L} = (3.95 \pm 0.32(\text{stat.}) \pm 0.08(\text{syst.})) \times 10^{-2} \]

- **Double lifetime hypothesis**: long-lived (LL) and short-lived (SL) components
  - LL $- B^\pm, B^0, B_s, b$-barions; SL $- B_c$
  - $\tau_{LL}$ determined from $\psi(2S)$ fits, allowing for some SL contribution
  - $\tau_{SL}$ from simulation, varying $B_c$ lifetime
  - Calculate $X(3872)$ fraction from $B_c$
    \[ \frac{\sigma(pp \to B_c + \text{any}) \mathcal{B}(B_c \to X(3872) + \text{any})}{\sigma(pp \to \text{non-prompt} \ X(3872) + \text{any})} = (25 \pm 13(\text{stat.}) \pm 2(\text{syst.}) \pm 5(\text{spin}))\% \]
Prompt production described well by NRQCD
  - $X(3872)$ considered as a mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{*0}$ molecule

Non-prompt compared to FONLL calculations
  - Predictions for $\psi(2S)$ recalculated using kinematic template of $X(3872)/\psi(2S)$
  - Factor 4–8 above the data, larger discrepancy at high $p_T$

Non-prompt production fraction: no $p_T$ dependence, agreement with CMS data
A selection of ATLAS results was presented

- Associated production:
  - production of $J/\psi + W$
  - production of $J/\psi + Z$

- Exotic states: $X(3872)$ measurement

Many interesting results not covered, e.g.

- $b$ hadron pair production at $\sqrt{s} = 8$ TeV – JHEP 1711 (2017) 062
- $J/\psi$ and $\psi(2S)$ production at $\sqrt{s} = 7, 8$ TeV – Eur. Phys. J. C 76 (2016) 283
- $D$ mesons production at $\sqrt{s} = 7$ TeV – Nucl. Phys. B 907 (2016) 717
- Search for resonances in $B_s^0\pi^\pm$ system – Phys. Rev. Lett. 120 (2018) 202007

Full Run-2 dataset is still be fully exploited – waiting for many new results!
Thank you very much!
Backup slides
ATLAS detector and trigger

Entries / 50 MeV

\[ \text{Trigger: EF}_{2\mu 4} \text{DiMu, EF}_{2\mu 4} \text{Jpsimumu, EF}_{2\mu 4} \text{Bmumu, EF}_{2\mu 4} \text{Upsimumu, EF}_{\mu 4\mu 6} \text{Jpsimumu, EF}_{\mu 4\mu 6} \text{Bmumu, EF}_{\mu 4\mu 6} \text{Upsimumu, EF}_{\mu 20} \]
\( J/\psi + W^\pm \)

\[ \tau = \frac{\vec{L} \cdot p_T^{J/\psi}}{p_T^{J/\psi}} \cdot \frac{m_{\mu^+\mu^-}}{p_T^{J/\psi}} \]

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

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

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

\( J/\psi + Z \)

\[ \tau := \frac{L_{xy} m_{J/\psi}}{p_T^{J/\psi}} \]

\( R_{Z+J/\psi}^{\text{fid}} = B(J/\psi \to \mu^+\mu^-) \frac{\frac{d\sigma_{\text{fid}}(pp \to Z + J/\psi)}{dy}}{\frac{d\sigma(pp \to Z)}{dy}} \)

\( = \frac{1}{N(Z)} \sum_{\text{pt bins}} [N^{\text{ec}}(Z + J/\psi) - N^{\text{pileup}}_{\text{ec}}], \)

\( R_{Z+J/\psi}^{\text{incl}} = B(J/\psi \to \mu^+\mu^-) \frac{\frac{d\sigma_{\text{incl}}(pp \to Z + J/\psi)}{dy}}{\frac{d\sigma(pp \to Z)}{dy}} \)

\( = \frac{1}{N(Z)} \sum_{\text{pt bins}} [N^{\text{ec}+\text{ac}}(Z + J/\psi) - N^{\text{pileup}}_{\text{ec+ac}}], \)

Fiducial phase space: 8.5 < \( p_T^{J/\psi} \) < 100 GeV, \(|y_{J/\psi}| < 2.1\)
Backgrounds

\[ J/\psi + W^\pm \]

- 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 vetoing events where a pairing of muons has an invariant mass within 10 GeV of the Z boson mass;
- Multi-jet production – the \( m_T(W^\pm) \) distribution of signal events is fit to a sum of a multi-jet template and a \( W^\pm \) boson signal template.

\[ J/\psi + Z \]

- Background estimation using MC:
  - \( Z \rightarrow \tau \tau \) or \( W \rightarrow \ell \nu \) background;
  - Top quark processes involving \( t\bar{t} \) or single top production;
  - The single-top \( Wt \) process;
  - Diboson (\( WZ, WW \) and \( ZZ \)) production.
- Background estimation using data:
  - Multi-jet production – selecting non-isolated leptons. The \( m_T(Z) \) distribution of signal events is fit to a sum of a multi-jet template and a Z boson signal template.
$X(3872)$

- Data: $-0.3 < \tau < 0.025$ ps ($w_0$) blue Fit
- Data: $0.025 < \tau < 0.3$ ps ($w_1$) red Fit  $12 < p_T < 16$ GeV
- Data: $0.3 < \tau < 1.5$ ps ($w_2$) green Fit  $|y| < 0.75$
- Data: $1.5 < \tau < 15$ ps ($w_3$) yellow Fit

**ATLAS**

$s=8$ TeV, 11.4 fb$^{-1}$

$J/\psi \pi^+\pi^-$ candidates / 3.5 MeV

$m(J/\psi \pi^+\pi^-)$ [GeV]
<table>
<thead>
<tr>
<th>Experiment (energy, final state, year)</th>
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<tbody>
<tr>
<td>ATLAS ( (\sqrt{s} = 8 \text{ TeV}, J/\psi + J/\psi, 2016) )</td>
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<tr>
<td>ATLAS ( (\sqrt{s} = 8 \text{ TeV}, Z + J/\psi, 2015) )</td>
</tr>
<tr>
<td>ATLAS ( (\sqrt{s} = 7 \text{ TeV}, W + 2 \text{ jets}, 2014) )</td>
</tr>
<tr>
<td>CDF ( (\sqrt{s} = 1.8 \text{ TeV}, W + 2 \text{ jets}, 1997) )</td>
</tr>
<tr>
<td>CDF ( (\sqrt{s} = 1.8 \text{ TeV}, \gamma + 3 \text{ jets, 1997}) )</td>
</tr>
<tr>
<td>DØ ( (\sqrt{s} = 1.96 \text{ TeV}, \gamma + 3 \text{ jets, 2014}) )</td>
</tr>
<tr>
<td>DØ ( (\sqrt{s} = 1.96 \text{ TeV}, \gamma + b/c + 2 \text{ jets, 2014}) )</td>
</tr>
<tr>
<td>DØ ( (\sqrt{s} = 1.96 \text{ TeV}, \gamma + 3 \text{ jets, 2010}) )</td>
</tr>
<tr>
<td>LHCb ( (\sqrt{s} = 7 \text{ TeV}, J/\psi + D^+ + D^0, 2012) )</td>
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<tr>
<td>LHCb ( (\sqrt{s} = 7 \text{ TeV}, J/\psi + D^+, 2012) )</td>
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<tr>
<td>LHCb ( (\sqrt{s} = 1.96 \text{ TeV}, J/\psi + \Upsilon(1S) + \Upsilon(1S), 2014) )</td>
</tr>
<tr>
<td>LHCb ( (\sqrt{s} = 13 \text{ TeV}, J/\psi + J/\psi, 2017) )</td>
</tr>
<tr>
<td>CMS + Lamberts, Shao ( (\sqrt{s} = 7 \text{ TeV}, J/\psi + J/\psi, 2014) )</td>
</tr>
<tr>
<td>CMS ( (\sqrt{s} = 8 \text{ TeV}, \Upsilon(1S) + \Upsilon(1S), 2016) )</td>
</tr>
</tbody>
</table>
Studying associated production

- Multiple possibilities to produce two objects $A$, $B$ in a $pp$ collision
  - Single Parton Scattering ($SPS$)
    - described by specific process cross-section $\sigma_{AB}^{SPS}$ – higher-order “real” associated production
  - Double Parton Scattering ($DPS$)
    - individual process cross-sections $\sigma_A$, $\sigma_B$
    - effective cross-section $\sigma_{\text{eff}}$ accounting for probability of the two processes to happen in a single $pp$ collision
      \[
      \sigma_{AB} = \sigma_{AB}^{SPS} + \sigma_{AB}^{DPS} = \sigma_{AB}^{SPS} + \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \times \frac{1}{1 + \delta_{AB}}
      \]

- DPS/SPS separation is intrinsically uncertain
  - Limited knowledge of $\sigma_{\text{eff}}$
  - Higher-order SPS contributions can undermine assumptions
  - Experimentally one can measure $N_A$, $N_B$, and $N_{AB}$, with different efficiencies, lumi etc
    \[
    f_{DPS} = \frac{\sigma_{AB}^{DPS}}{\sigma_{AB}} = \frac{\sigma_A \sigma_B}{\sigma_{AB} \sigma_{\text{eff}}} \times \frac{1}{1 + \delta_{AB}} \sim \frac{1}{\sigma_{\text{eff}}} \times \frac{N_A N_B}{N_{AB}} \times \frac{1}{1 + \delta_{AB}}
    \]