Joint theory and experimental session on quarkonia at the LHC

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on behalf of the ALICE, ATLAS, CMS and LHCb Collaborations
Quarkonium: What and Where from?

- **What?**
  - a bound state of two heavy quarks (c or b)
- **Where from?**
  - prompt hadroproduction
  - decays of higher resonances (feed-down)
  - production in b-hadron decays / non-prompt (charmonium only)

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Quarkonium production: Current status

- **Existing challenges**: *
  - simultaneous description of $J/\psi$ production and polarization – “polarization puzzle”
  - simultaneous description of $\eta_c$ and $J/\psi$ together with $J/\psi$ photoproduction - “HQSS puzzle”
  - negative contribution in the cross-section
  - tension with $J/\psi+Z$ production
  - CEM does not describe P-waves production
  - …

  *Please, check WG4 sessions for more details

- **New sources of input**: *
  - Study of $\eta_q$ and $\chi_q$ states
  - Associated quarkonia production
  - Production in heavy-ion collisions
  - Non-conventional quarkonium
  - …

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No consensus on the quarkonium production mechanism

Nearly all approaches assume factorisation between the $Q\bar{Q}$ formation and its hadronization into a meson.

Three common models with the different description of the hadronization:

- Colour evaporation model (CEM): application of quark-hadron duality; only the invariant mass matters;
- Colour-singlet model (CS): intermediate $Q\bar{Q}$ state is colourless and has the same $J^{PC}$ as the final-state quarkonium;
- Colour-octet model (CO) (encapsulated in NRQCD): all viable colours and $J^{PC}$ allowed for the intermediate $Q\bar{Q}$ state;

NRQCD is found to be the most used, because it is based on an EFT and can be improved systematically.

"Quarkonium production: Models"

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NRQCD: Theory vs Experiment

- Two scales of production: hard process of \( Q\bar{Q} \) formation and soft scale hadronization of \( Q\bar{Q} \)
- **Factorization?**
  \[ d\sigma_{A+B\rightarrow H+X} = \sum_n d\sigma_{A+B\rightarrow Q\bar{Q}(n)+X} \times <\Omega^H(n)> \]
  - **Short distance**: perturbative cross-sections + pdf for the production of a \( Q\bar{Q} \) pair
  - **Long distance matrix elements (LDMEs)**: non-perturbative part
  - Both CS and CO states are allowed with varying probabilities
    => LDMEs from experimental data: \( p_T \)-differential production, feed-down...

- **Universality?**
  - same LDMEs for different \( \sqrt{s} \), prompt production and production in b-decays
    => production at all possible \( \sqrt{s} \), associated production, separate prompt and b-decays...

- **Heavy-Quark Spin-Symmetry?**
  - links between CS and CO LDMEs of different quarkonium states
    => simultaneous studies of several states...

\[
\begin{align*}
\left< \mathcal{O}_{1,8}^c \left(^1 S_0 \right) \right> &= \frac{1}{3} \left< \mathcal{O}_{1,8}^{J/\psi} \left(^3 S_1 \right) \right> \\
\left< \mathcal{O}_{8}^c \left(^3 S_1 \right) \right> &= \left< \mathcal{O}_{8}^{J/\psi} \left(^1 S_0 \right) \right> \\
\left< \mathcal{O}_{8}^c \left(^1 P_1 \right) \right> &= 3 \left< \mathcal{O}_{8}^{J/\psi} \left(^3 P_0 \right) \right>
\end{align*}
\]

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LHC detectors hunting for quarkonium

• ATLAS and CMS: mid-rapidity region, with muons in final state

• LHCb: forward-rapidity region, with muons and hadrons in final state

• ALICE: both mid- and forward-rapidity regions, with muons and electrons in final state

Experiments provide complementary measurements
Final states:
- hadrons or γγ
- μ⁺μ⁻/e⁺e⁻ or hadrons
- ³S₁γ, ³S₁π⁺π⁻ or hadrons
- ¹S₀γ or hadrons

Existing measurements:
- ηᶜ production
- ηᶜ(2S) production in b-decays
- J/ψ, ψ(2S) and Y(nS) production and polarization
- J/ψ+J/ψ/jet/Z/W⁺, J/ψ+J/ψ+J/ψ and Y(1S)+Y(1S) production
- χᶜ production and polarization
- χᵇ production

Hadronic final states allow to study different quarkonium states simultaneously
J/ψ: Differential production cross-sections

- **ATLAS** prompt and from-b @ 13 TeV
  \[ 60 < p_T < 360 \text{ GeV/c}, |y| < 2.0 \]

- Data compared with lower-\(p_T\) CMS results

- **LHCb** prompt and from-b @ 5.02 TeV
  \[ 0 < p_T < 20 \text{ GeV/c}, 2.5 < y < 4.0 \]

- **ALICE** prompt and from-b @ 5.02 and 13 TeV
  \[ p_T > 2(1) \text{ GeV/c}, |y| < 0.9 \]

- Reasonable agreement between NRQCD and data

- ICEM shows good agreement with data

- Good agreement between data and FONLL at low-\(p_T\), with theory exceeding prediction at high-\(p_T\)

Single J/ψ hadroproduction has been studied in all possible configurations

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J/ψ: Polarization

polarization @ 8 TeV
2 < p_T < 15 GeV/c, 2.5 < y < 4.0

ALICE

• Measured via angular distributions of muons in quarkonium rest frame
• Two different polarization frames are used: Helicity and Collins- Soper
• Good agreement between ALICE and LHCb measurements at √s = 7 TeV
• No significant J/ψ polarization observed
• Tension between existing NRQCD prediction and data
• Better agreement for NRQCD+CGC [JHEP 1812(2018)057]; however tensions still present

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ψ(2S): Differential production cross-sections

- **ATLAS**
  - Prompt and from-b @ 13 TeV
    - $60 < p_T < 360$ GeV/c, $|y| < 20$
  - Prompt and from-b @ 7 and 13 TeV
    - $p_T < 20$ GeV/c, $2.0 < y < 4.5$
  - Inclusive @ 5.02 TeV
    - $p_T < 12$ GeV/c, $25 < y < 4.0$

- Reasonable agreement between NRQCD and data in a limited $p_T$ range ($p_T > 7$ GeV/c)

- Another mechanism is needed at low-$p_T$

- ICEM shows good agreement with data

- Good agreement with FONLL for production in b-decays for all experiments

Same situation as for single J/ψ hadroproduction

Joint TH and EXP session on quarkonia at the LHC
Y(nS): Differential production cross-sections

- $p_T$- and $y$-differential cross-sections @ 5.02 TeV
  $p_T < 20 \text{ GeV}/c, 2.0 < y < 4.5$

- $p_T$- and $y$-differential cross-sections @ 5.02 TeV
  $p_T < 15 \text{ GeV}/c, 2.5 < y < 4.0$

- Ratios computed between different states and different energies

- Reasonable agreement between NRQCD and data

- Both ICEM and CEM describe data within uncertainties

Same situation as for single J/$\psi$ hadroproduction

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\( \eta_c(1S) \): Differential production cross-section

- **Relative** \( \eta_c/J/\psi \) and **absolute** \( \eta_c \)  
  \( p_T \)-differential production **cross-sections** @ 13 TeV

- \( \eta_c(1S) \) production:
  - \( 6.5 < p_T < 14.0 \text{ GeV}/c, 2.0 < y < 4.5 \)
  - \( \sigma_{\eta_c}^{\text{prompt}} = 1.26 \pm 0.11_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.14_{/\psi} \mu b \)
  - \( \mathcal{B}_{b \to \eta_c X} = (5.51 \pm 0.32_{\text{stat}} \pm 0.29_{\text{syst}} \pm 0.77_{/\psi}) \times 10^{-3} \)

- Results may **provide important link** between \( J/\psi \) production and **polarization**

- \( \eta_c(1S) \) production can be described by **CS contribution** only; measurement in extended \( p_T \) is required: **larger slope** would indicate possible **CO contribution**

**Interpretation of \( \eta_c(2S)/\psi(2S) \)** much cleaner than for \( \eta_c(1S)/J/\psi \) due to absence of feed-down
**$\eta_c(2S)$: Production in $b$-decays**

- **Production @7 and 8 TeV via decays to $\phi\phi$**: True $\phi\phi$ combinations extracted using 2D fit technique.

- **First measurement of $\eta_c(2S)$ production in $b$-decays**: First evidence for $\eta_c(2S) \rightarrow \phi\phi$

$$\frac{B(b \rightarrow \eta_c(2S)X)}{B(b \rightarrow \eta_c(1S)X)} \times \frac{B(\eta_c(2S) \rightarrow \phi\phi)}{B(\eta_c(1S) \rightarrow \phi\phi)} = 0.040 \pm 0.011 \pm 0.004$$

**Important to measure $\eta_c(2S)$ hadroproduction**:
- Theory prediction ⇒
- Dedicated LHCb trigger in 2018

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**Joint TH and EXP session on quarkonia at the LHC**
$\chi_c$: Production in $b$-decays

- **Production** @7 and 8 TeV via **decays to $\phi\phi$**; true $\phi\phi$ combinations extracted using 2D fit technique

- **First measurement of $\chi_{c0}$ production in $b$-decays:**
  \[ B(b \to \chi_{c0}X) = (3.02 \pm 0.47_{\text{stat}} \pm 0.23_{\text{syst}} \pm 0.94_B) \times 10^{-3} \]

- **Most precise measurements** of $\chi_{c1}$ and $\chi_{c2}$ production in $b$-decays, consistent with B-factories

- **Promising channel to study $\chi_c$ polarization** [Phys.Rev.D 103 (2021) 9, 096006]

Joint TH and EXP session on quarkonia at the LHC
\( \chi_{c1,2} \): Production using \( \chi_{c1,2} \rightarrow J/\psi \gamma \)

- Relative \( \chi_{c2} / \chi_{c1} \) prompt \( p_T \)-differential production cross-section:

\[
R_p = \frac{\sigma(pp \rightarrow \chi_{c2}X) \times \mathcal{B}(\chi_{c2} \rightarrow J/\psi \gamma)}{\sigma(pp \rightarrow \chi_{c1}X) \times \mathcal{B}(\chi_{c1} \rightarrow J/\psi \gamma)}
\]

- Relative \( \chi_{c2} / \chi_{c1} \) and \( \chi_{c0} / \chi_{c2} \) prompt \( p_T \)-differential production cross-section

- \( \chi_{c0} \) relative production measured with 4\( \sigma \) significance:

\[
\frac{\sigma_{\chi_{c0}}}{\sigma_{\chi_{c2}}} = 1.19 \pm 0.27_{\text{stat}} \pm 0.29_{\text{syst}} \pm 0.16_{\text{\(p_T\) model}} \pm 0.09_{\mathcal{B}}
\]

- \( \chi_{c2} \) production is enhanced at low-\( p_T \)

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\( \chi_{c1,2}: \text{Production using } \chi_{c1,2} \rightarrow J/\psi \)

- **ATLAS** \( \chi_{c1} \) and \( \chi_{c2} \) \( p_T \)-differential production cross-section @ 7 TeV

- Prompt and b-decays production measured separately

- Estimated \( J/\psi \) fraction from \( \chi_c \) decays: result in agreement with LHCb measurement [PLB 714 (2012) 215]

- Results compared with theoretical predictions: good agreement with NRQCD
**$\chi_{c1,2}$: Production using $\chi_{c1,2} \rightarrow J/\psi\gamma$**

- Combined study of $\chi_c$ states

- NRQCD fit for production cross-section
  - absolute $\Rightarrow$ ATLAS
  - relative $\Rightarrow$ LHCb, CMS

- CO LDME for $\chi_c$ is obtained from fit to data

- More precise when looking for ratio

Small $p_T$ region has to be explored
**$\chi_{c1,2}$: Production using $\chi_{c1,2} \rightarrow J/\psi \mu^+\mu^-$**

- First observation of $\chi_{c1,2} \rightarrow J/\psi \mu^+\mu^-$ decay modes
- Extremely clean signals
- $\chi_{c1,2}$ resonance parameters measured with world average precision

<table>
<thead>
<tr>
<th>Quantity</th>
<th>LHCb measurement</th>
<th>Best previous measurement</th>
<th>World average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m(\chi_{c1})$</td>
<td>3510.71 ± 0.10</td>
<td>3510.72 ± 0.05</td>
<td>3510.66 ± 0.07</td>
</tr>
<tr>
<td>$m(\chi_{c2})$</td>
<td>3556.10 ± 0.13</td>
<td>3556.16 ± 0.12</td>
<td>3556.20 ± 0.09</td>
</tr>
<tr>
<td>$\Gamma(\chi_{c2})$</td>
<td>2.10 ± 0.20</td>
<td>1.92 ± 0.19</td>
<td>1.93 ± 0.11</td>
</tr>
</tbody>
</table>

- New channel for production measurement
- Similar studies can be done at CMS?

**Promising channel for $\chi_c$ hadroproduction at low-$p_T$**
$\chi_{c1}$ vs $\chi_{c2}$: Polarization

- First measurement of $P$-wave quarkonium polarization @8 TeV $\chi_{c2}/\chi_{c1}$ ratios as a function of $|\cos\theta^{HX}|$ and $\phi^{HX}$

- Unpolarized scenario and large part of the physically allowed region (red rectangle) excluded at 99.7% CL

→ at least one state is strongly polarized
The production of two particles in the same pp collision can be due to:

**Single-Parton Scattering (SPS):**
- the two particles are produced a single interaction of two partons
- expected to be “back-to-back” in transverse plane

**Double-Parton Scattering (DPS):**
- simultaneous interaction of two pairs of partons, assumed to be uncorrelated
- DPS “Pocket formula”:

\[
\sigma_{DPS}^{pp\to\psi_1\psi_2} = \frac{m}{2} \frac{\sigma_{SPS}^{pp\to\psi_1X} \sigma_{SPS}^{pp\to\psi_2X}}{\sigma_{eff,DPS}}
\]

- **Di-J/ψ production:**
  - expected small SPS CO contribution
  - DPS contribution is important at large J/ψ Δγ
  - feed-down contribution depends on the production mechanism
Di-J/ψ: Production

- Di-J/ψ production was measured in different kinematical regions

\[ \sigma_{\text{eff}} = 6.3 \pm 1.6_{\text{stat}} \pm 1.0_{\text{syst}} \text{ mb} \]

- Measurement shows:
  \[ p_T > 8.5 \text{ GeV}/c, |y| < 2.1 \]

- Measurement shows:
  \[ p_T < 10 \text{ GeV}/c, 2.0 < y < 4.5 \]

\[ \sigma_{\text{eff}} \text{ from } 8.8 \pm 5.6 \text{ mb to } 12.5 \pm 4.1 \text{ mb} \]

- LHCb result shows lower \( \sigma_{\text{eff}} \) than the other LHCb measurements, but higher than ATLAS and CMS results

- An improvement in the precision for SPS predictions is needed for a better discrimination between theory approaches

- Feed-down contribution can amount up to 40% of SPS contribution and has to be accounted for
**Di-J/ψ: Search for resonances**

- **First observation of fully heavy tetraquark candidate X(6900)**

- **Observes similar structure + two more candidates X(6600) and X(7300)**

- **Threshold structure with a few possible interpretations:**
  - One BW, combination of two BWs, feed-down...

- **Additional study together with spin-parity measurement required to explain nature of threshold structure**

**More studies of J/ψ+quarkonium will arrive soon**

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Di-Y(1S): Production and search for resonances

- **DPS process** can provide information on partons $p_T$, their correlations inside proton and can help understanding various backgrounds.

- **Y(1S) pair production for unpolarized case**

  $$\sigma_{Y(1S)Y(1S)} = 79 \pm 11_{stat} \pm 6_{syst} \pm 3_{\#} pb, \ |y|<2.0$$

- Charging $\lambda_\theta$ in range $[-1, +1]$ production varies from $-60\%$ to $+25\%$

- First measurement of DPS contribution to $\sigma_{Y(1S)Y(1S)}$

  $$f_{DPS} = (39 \pm 14)\%$$

- **No excess** of events compatible with signal is observed in 4-$\mu$ invariant mass spectrum

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First observation of triple-$J/\psi$ production

Cross-section:

$$\sigma_{3J/\psi} = 272^{+141}_{-101} \text{ stat} \pm 16 \text{ syst } fb, \ |y_{J/\psi}| < 2.4$$

Contributions of DPS and TPS:

$$f_{DPS} \sim 76\% \text{ and } f_{TPS} \sim 20\%$$

Measured $\sigma_{eff} = 2.7^{+1.4}_{-1.0 \text{ stat}}^{+1.5}_{-1.0 \text{ syst}} mb$ is consistent with di-$J/\psi$ results, but lower than jet/$W/Z$ results
Prospects

• Single quarkonium production:
  • $\eta_c(2S)$, $h_c$ and $\eta_b(1S)$ production
  • $X_c$ production at low-$p_T$
  • simultaneous study of $\psi(2S)$ and $\eta_c(2S)$
    ➢ no feed-down from higher stated, clean interpretation
  • decays to $\Lambda\Lambda$, $\Lambda^*\Lambda^*$, $\Sigma\Sigma$, $\Xi\Xi$ final states
    ➢ access to new quarkonium states

• Double quarkonium production:
  • $J/\psi+\eta_c$
    ➢ NRQCD predicts suppressed yield w.r.t. $J/\psi+J/\psi$
  • $J/\psi+Y$
    ➢ dominant SPS CO
  • $J/\psi+\psi(2S)$, $\psi(2S)+\psi(2S)$
    ➢ will help to understand feed-down contribution
Summary

• Recent LHC results on quarkonium production will be useful input to understand quarkonium production mechanism in pp and heavy-ion collisions

• Comprehensive quarkonium production model is missing
  • new inputs are necessary to improve understanding: associated production, production of $\eta_c$ and $h_c$ ...

• Upcoming interesting results on single and associated quarkonium production
  • would it be possible to have new theory constraints?
  • new models?

Thanks for your attention!
$\chi_b$ resonances
$\chi_b$ PRODUCTION in LHCb at $\sqrt{s}=7$ and 8 TeV

- Search for $\chi_b(nP)$ using decay to $\Upsilon(nS)\gamma$
  \[ R_{\Upsilon(nS)} = \frac{N_{\chi_b(mP)}}{N_{\Upsilon(nS)}} \times \frac{\varepsilon_{\Upsilon(nS)}}{\varepsilon_{\chi_b(mP)}} \]
- Invariant mass fit to extract yields
  - Fraction $R_{\Upsilon(nS)}$ measured in bins of $p_T$
- $\chi_b(3S) \to \Upsilon(3S)\gamma$ observed for the first time

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**$\chi_b$ PRODUCTION in LHCb at $\sqrt{s}=7$ and 8 TeV**

- **First measurement of $\chi_b(1P)/\chi_b(1P)$ production** using decay to $Y(1S)\gamma$
  
  $$\frac{\sigma_{\chi_b(1P)}}{\sigma_{\chi_b(1P)}} = \frac{N_{\chi_b(1P)}}{N_{\chi_b(1P)}} \times \frac{\varepsilon_{\chi_b(1P)}}{\varepsilon_{\chi_b(1P)}} \times \frac{B(\chi_b(1P)\rightarrow Y(1S)\gamma)}{B(\chi_b(1P)\rightarrow Y(1S)\gamma)}$$

- **Results have reasonable agreement with CMS results and LHCb-based LO NRQCD prediction** \([\textbf{JHEP} \, 10 \, (2013) \, 115]\) at high-$p_T$
$\chi_b$ PRODUCTION in CMS at $\sqrt{s}=8$ TeV

- Precise measurement of $\chi_b^{2}(1P)/\chi_b^{1}(1P)$ production cross-section in complementary region to LHCb: $5 < p_T^\gamma < 25$ GeV/c, $|y| < 1.5$

- $\chi_b$ relative production in integrated $p_T$-range:
  \[ \frac{\sigma_{\chi_b^{2}}}{\sigma_{\chi_b^{1}}} = 0.85 \pm 0.07_{\text{stat}}{\text{syst}} \pm 0.08_{\text{B}} \]

- Ratio does not show significant dependence on $Y(1S) p_T$

- $>2\sigma$ discrepancy with NRQCD prediction at high-$p_T$

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Di-$J/\psi$ and resonances
**Di-J/ψ production and search for resonances**

- **First observation of fully heavy tetraquark candidate**
- Threshold structure with a few possible interpretations:
  - One BW, combination of two BWs, feed-down...
  - Additional study together with spin-parity measurement required to explain nature of threshold structure
- **Peak at 6.9 GeV: X(6900), consistent with BW structure**
  - Without interference:
    \[
m_{X(6900)} = 6905 \pm 11_{\text{stat}} \pm 7_{\text{syst}} \text{ MeV/c}^2
    \]
    \[
    \Gamma_{X(6900)} = 80 \pm 19_{\text{stat}} \pm 33_{\text{syst}} \text{ MeV/c}^2
    \]
  - With interference:
    \[
m_{X(6900)} = 6886 \pm 11_{\text{stat}} \pm 11_{\text{syst}} \text{ MeV/c}^2
    \]
    \[
    \Gamma_{X(6900)} = 168 \pm 33_{\text{stat}} \pm 69_{\text{syst}} \text{ MeV/c}^2
    \]
Di-J/ψ production and search for resonances

- Three tetraquark candidates (two new)

- Three structures were observed:

<table>
<thead>
<tr>
<th></th>
<th>BW1</th>
<th>BW2</th>
<th>BW3</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>6552 ± 10 ± 12</td>
<td>6927 ± 9 ± 5</td>
<td>7287 ± 19 ± 5</td>
</tr>
<tr>
<td>Γ</td>
<td>124 ± 29 ± 34</td>
<td>122 ± 22 ± 19</td>
<td>95 ± 46 ± 20</td>
</tr>
<tr>
<td>N</td>
<td>474 ± 113</td>
<td>492 ± 75</td>
<td>156 ± 56</td>
</tr>
</tbody>
</table>

- **Peak at 6.9 GeV**: consistent with X(6900) reported by LHCb (9.4σ)
- Two new structures, provisionally named as X(6600) (5.7σ) and X(7300) (4.1σ)

- Additional study together with spin-parity measurement required to explain nature of the structures
Di-\(J/\psi\) production and search for resonances

- **ATLAS**

**Excess in \(J/\psi + J/\psi\) and \(J/\psi + \psi(2S)\) spectra**

- Three candidates in \(J/\psi + J/\psi\) and two candidates in \(J/\psi + \psi(2S)\) spectra

\[
\begin{array}{cccc}
\text{(GeV)} & m_0 & \Gamma_0 & m_1 \\
\text{di-\(J/\psi\)} & 6.22 \pm 0.05^{+0.04}_{-0.05} & 0.31 \pm 0.12^{+0.07}_{-0.08} & 6.62 \pm 0.03^{+0.02}_{-0.01} & 0.31 \pm 0.09^{+0.06}_{-0.11} \\
\text{\(J/\psi + \psi(2S)\)} & m_2 & \Gamma_2 & \\
6.87 \pm 0.03^{+0.06}_{-0.01} & 0.12 \pm 0.04^{+0.03}_{-0.01} & \\
\end{array}
\]

- Both fits have a peak consistent with \(X(6900)\) reported by LHCb
Di-Y(1S) and search for resonances in Y(1S)µ⁺µ⁻

- **Y(1S) pair production for unpolarized case**
  \[ \sigma_{Y(1S)Y(1S)} = 79 \pm 11_{\text{stat}} \pm 6_{\text{syst}} \pm 3_{\text{b}} \text{ pb}, |y|<2.0 \]

- First measurement of DPS contribution to \( \sigma_{Y(1S)Y(1S)} \)
  \[ f_{\text{DPS}} = (39 \pm 14)\% \]

- **No excess** of events compatible with signal is observed in 4-\( \mu \) invariant mass spectrum

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