Analysis of charmonium production at fixed-target experiments

J. Spengler, DESY, Hamburg

This analysis was performed by F. Maltoni + several members of the HERA-B collaboration

Outline:

1. Motivation
2. J/ψ cross section measured at HERA-B
3. Compilation of all pA J/ψ and Ψ(2S) cross sections
4. The NRQCD approach
5. Fit results
1. Motivation:

Expt. view: HERA-B uses a dilepton trigger $B \rightarrow J/\Psi, \chi_c \rightarrow J/\Psi, \Psi(2S) \rightarrow J/\Psi$ are normalized to $J/\Psi \rightarrow$ dileptons to reduce sys. errors. Thus a precise $J/\Psi$ cross section is required:

a) Measure $J/\Psi$ in minimum bias data

b) Global fit to all $J/\Psi$ cross section measurements

Theo. view: test universality of non-perturbative matrix elements of quarkonia
2. J/$\Psi$ cross section at HERA-B:

- Interactions of 920 GeV protons on C, Ti and W targets (180M events)
- Minimum bias trigger with >97% efficiency
- $pA \rightarrow J/\Psi \ X$ with $J/\Psi \rightarrow e^+e^- \ or \ \mu^+\mu^-$
- Visible fraction of total cross section = 63%
- Expect low sys. error; result dominated by stat. error despite huge statistics
$100\pm12 \ J/\Psi \rightarrow \mu^+\mu^-$

$57+13 \ J/\Psi \rightarrow e^+e^-$
1. Combine both final states for each target
2. Determine pA cross sections for A = C, Ti, W
3. Determine pN cross section by fitting

\[ \sigma_{pN} = \sigma_{pA} \cdot A^\alpha \]

using \( \alpha = 0.96 \pm 0.01 \) at \( x_F \approx 0 \) (E866 result). Most precise measurement available.

Final result: \( \sigma_{pN} = 663 \pm 74 \pm 46 \) nb/nucleon

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Updates applied to all data:

a) Assume the same target mass dependence $A^\alpha$
b) Assume symmetric $x_F$ dependence
c) Update for PDG04 branching ratios
d) Combine different targets of same experiment
e) Assume that sys. error quoted includes all contributions (Br, A-dependence)
Mid-rapidity and total cross sections in pN reactions:

Several measurements are not compatible.

Detailed tables can be found in the paper.

HQQW06 at BNL     J. Spengler
4. The NRQCD approach:
NRQCD expresses the cross section for a quarkonium state in pp interactions in NLO as product of short-distance coefficient * long-distance matrix element. Here we need the direct production $\sigma^D$ of $J/\psi$, $\chi_{cJ}$ and $\psi(2S)$.

$$\sigma(\Psi(2S)) = \sigma^D(\Psi(2S))$$

$$\sigma(J / \Psi) = \sigma^D(J / \Psi) + \sum_{J=0}^{2} Br(\chi_{cJ} \rightarrow J / \Psi\gamma) \cdot \sigma^D(\chi_{cJ}) + Br(\Psi(2S) \rightarrow J / \Psi X) \cdot \sigma^D(\Psi(2S))$$

$$R_\Psi = \sigma(J / \Psi) / \sigma(\Psi(2S))$$
Choices to be made:

1. Scale parameter: $\mu_0 = 2m_c$ with $m_c = 1.5$ GeV
   $\mu_0 = \mu_F(\text{factorization}) = \mu_R(\text{renormalization})$

2. PDF sets: MRST2002nlo and CTEQ6m

3. Color-singlet matrix elements from potential model calculations

4. Color-octet matrix elements extracted from CDF data (based on LO calculations only)

Introduce free scaling parameters for S-wave color-octet ME
$\lambda_{J/\Psi}$ and $\lambda_{\Psi(2S)}$
= fraction of color-octet contribution required relative to CDF results
Matrix elements used for fit:

<table>
<thead>
<tr>
<th>H</th>
<th>$\langle \mathcal{O}_{1}^{H} \rangle$</th>
<th>$\langle \mathcal{O}<em>{8}^{H(3S</em>{1})} \rangle$</th>
<th>$\langle \mathcal{O}<em>{8}^{H(1S</em>{0})} \rangle$</th>
<th>$\langle \mathcal{O}<em>{8}^{(3P</em>{0})} \rangle / m_{c}^{2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\Psi$</td>
<td>1.16 GeV$^{3}$</td>
<td>$1.19 \cdot 10^{-2}$ GeV$^{3}$ · $\lambda_{J/\Psi}$</td>
<td>$1.0 \cdot 10^{-2}$ GeV$^{3}$ · $\lambda_{J/\Psi}$</td>
<td>$1.0 \cdot 10^{-2}$ GeV$^{3}$</td>
</tr>
<tr>
<td>$\Psi(2S)$</td>
<td>0.76 GeV$^{3}$</td>
<td>$0.50 \cdot 10^{-2}$ GeV$^{3}$ · $\lambda_{\Psi(2S)}$</td>
<td>$0.42 \cdot 10^{-2}$ GeV$^{3}$ · $\lambda_{\Psi(2S)}$</td>
<td>$0.42 \cdot 10^{-2}$ GeV$^{3}$</td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>0.11 GeV$^{5}$</td>
<td>$0.31 \cdot 10^{-2}$ GeV$^{3}$</td>
<td>-</td>
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</table>

$\langle \mathcal{O}_{8}^{\Psi}(3P_{J}) \rangle = (2J + 1) \langle \mathcal{O}_{8}^{\Psi}(3P_{0}) \rangle$

$\langle \mathcal{O}_{8}^{\chi_{cJ}(3S_{1})} \rangle = (2J + 1) \langle \mathcal{O}_{8}^{\chi_{c0}(3S_{1})} \rangle$

$\langle \mathcal{O}_{8}^{\chi_{cJ}(3P_{J})} \rangle = (2J + 1) \langle \mathcal{O}_{8}^{\chi_{c0}(3P_{0})} \rangle$
5. Fit results:

Data available: 21 results on $J/\psi$, 3 on $\psi(2S)$ and 5 on $R_\psi$.

1. step: fit scale factor “x” common to all states

$\mu_F = \mu_R = x \cdot \mu_0$ for both PDF sets

2. step: fit $\lambda_{J/\psi}$ and $\lambda_{\psi(2S)}$ for both PDF sets

<table>
<thead>
<tr>
<th></th>
<th>MRST2002nlo</th>
<th>CTEQ6m</th>
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<tbody>
<tr>
<td>$\mu_F = \mu_R$</td>
<td>1.5 $\mu_0$</td>
<td>2.6 $\mu_0$</td>
</tr>
<tr>
<td>$\chi^2$/dof</td>
<td>114 / 27</td>
<td>170 / 27</td>
</tr>
<tr>
<td>$\lambda_{J/\psi}$</td>
<td>0.089±0.013</td>
<td>0.211±0.027</td>
</tr>
<tr>
<td>$\lambda_{\psi(2S)}$</td>
<td>0.061±0.012</td>
<td>0.112±0.017</td>
</tr>
</tbody>
</table>
Comments:

- Large $\chi^2$/dof $\rightarrow$ error on $\lambda$ scaled (PDG)
- Differences in $\lambda$ due to different scaling factors
- Stability of fits was tested by
  - Excluding results with bad partial $\chi^2$
  - Changing the cms-energy range
  - Excluding targets with $A>14$

  $\Rightarrow$ Fit results very stable. Only significant changes in $\lambda$ due to PDF and scaling factors

- Select MRST2002nlo as baseline (smaller $\chi^2$)
NRQCD “prediction” of $d\sigma/dy$ at $y=0$:

12 (out of 23) data points partially correlated with previous fits
Conclusions:

For both PDF’s and all fits we obtain:

\[ 0.01 < \lambda_{J/\Psi} < 0.31 \] and \[ 0.02 < \lambda_{\psi(2S)} < 0.14 \]

Required color-octet contribution about 10% of that for Tevatron data. Supports HERA ep data which do not need large octet contributions.

- Difference too large to be due to LO calc. for Tevatron analysis
- Missing NLO calc. of short-distance coeff. for color-singlet production can decrease octet contri. as observed in photoproduction