Measurement of $J/\psi$ production in continuum $e^+e^-$ annihilations near $\sqrt{s} = 10.6$ GeV

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on behalf of the

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BaBar™ collaboration
Scope and Motivations

- $J/\psi$ production in *continuum* (non B decays) at PEP-II
  - $e^+e^-$ collisions at or near $\sqrt{s} = 10.58$ GeV ($\Upsilon(4S)$ mass peak)
  - asymmetric collider: $\beta\gamma = 0.56$

- Provide an independent test of *QCD* predictions for heavy quarkonium production
  - no previously published measurements of $e^+e^-$ $J/\psi$ production below $Z^0$ in non-B decays
**QCD predictions: color-singlet vs. color-octet**

- **Color-singlet model** (lowest order in $\alpha_s$)
  
  Heavy quarkonia produced in short-distance processes that create QQ pairs in colorless configuration.

  It does not account for gross features of recent high $p_T$ heavy quarkonium production data in pp collisions (CDF).

- **Fragmentation + color-octet production mechanism**
  
  Based on the factorization model of Bodwin, Braaten and Lepage (NRQCD).

  High $p_T$ heavy quarkonium production dominated by fragmentation rather than by hard processes.

  Charmonium production sometimes dominated by $c\bar{c}$ produced at short-distance in a color-octet state.
Testable predictions for $J/\psi$ production in $e^+e^-$ continuum

- **Cross sections @ $\sqrt{s} \sim M_{Y(4S)}$**
  - **CS** (Cho & Leibovich, PRD 54 (1996)): $\sigma \sim 0.45 \div 0.81$ pb
  - **CO** (Schuler, Eur. Phys. J. C8 (1999)): $\sigma \sim 1.1 \div 1.6$ pb

- **$J/\psi$ angular distributions (in $e^+e^-$ CM)**
  (Braaten & Chen, PRL 76 (1996))
  $$\frac{d\sigma}{dE \ d\cos\theta^*} = S(E) \left[ 1 + A(E)\cos^2\theta^* \right]$$
  - **CS**: $A \sim -0.8$
  - **CO**: $0.6 < A < 1.0$

Both CS & CO predict $A \sim 0$ at low $p^*$ near the end point of the $J/\psi$ momentum spectrum (high $p^*$)
The BaBar detector

- 1.5T solenoid
- CsI(Tl) EMC
- Drift Chamber
- Instrumented Flux Return
- Silicon Vertex Tracker
- DIRC (PID)

- $e^\pm$ ID
- $\gamma$ reconstruction
- Bremsstrahlung recovery
- $\sigma_E/E = 2.32\% E^{-1/4} \oplus 1.85\%$

- $e^+ (3.1\text{GeV})$
- $e^- (9\text{GeV})$
- $\mu^\pm$ ID

- High quality tracking
  (fiducial volume: $0.41 < \theta < 2.54$
  $\sigma(p_T)/p_T = 0.13\% P_T + 0.45\%$
Data set (1999/2000)

<table>
<thead>
<tr>
<th>Integrated Luminosity (fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ON peak</strong></td>
</tr>
<tr>
<td><strong>OFF peak</strong></td>
</tr>
</tbody>
</table>

Below $\Upsilon(4S)$ & BB threshold

Luminosity-weighted CM energy = 10.57 GeV

ON peak
\[ \sqrt{s} = 10.58 \text{ GeV} \]

OFF peak
\[ \sqrt{s} = 10.54 \text{ GeV} \]
J/ψ reconstruction

- $J/\psi \rightarrow e^+e^-, \mu^+\mu^-$  \( (\text{BF}(J/\psi \rightarrow l^+l^-) \sim 2 \times 5.9\%) \)

- 2 high quality lepton tracks
  - at least 12 hits in the Drift Chamber
  - $|\Delta z| < 10 \text{ cm from beam spot}$
    - $R < 1.5 \text{ cm from the beam line}$
  - $p_T > 100 \text{ MeV/c}$
  - $p < 10 \text{ GeV/c}$

- To reject beam-gas and beam pipe wall interactions
  - Construct an event $\text{vtx}$
  - Require: $R^{\text{vtx}} < 5 \text{ mm from beam line}$
    - $|\Delta z^{\text{vtx}}| < 6 \text{ cm from beam spot}$

- To suppress radiative Bhabha events (with converting $\gamma$)
  - Require at least 5 tracks in the event ($e^+e^-$ only)
**J/ψ reconstruction**

- Tight lepton PID selection (high efficiency, low misID)
J/ψ in continuum: backgrounds

- For **ON-peak data**: main background is \( B \rightarrow J/\psi X \)
  - Require \( p^* > 2 \text{ GeV/c} \) (above the kinematic limit for B decays)

- **Initial State Radiation J/ψ production** (\( e^+e^- \rightarrow J/\psi \gamma \))

- \( \gamma\gamma \rightarrow \chi_{c1} \), followed by \( \chi_{c1} \rightarrow J/\psi \gamma \)
  
  Require at least 3 high quality tracks (0.41 < \( \theta \) < 2.54 rad)

- **Remaining background is mainly**:
  - ISR \( \psi(2S) \) production: \( e^+e^- \rightarrow \psi(2S) \gamma \),
    followed by \( \psi(2S) \rightarrow J/\psi \pi^+ \pi^- \)

  - Residual \( J/\psi \) ISR production, where the ISR \( \gamma \) converts
Fighting the residual backgrounds

Require:

- $E$ (visible energy) $> 5$ GeV

**ISR kinematics ensures** $E < 5$ GeV when $p_{\gamma}$ is along the beam line

A $\gamma$ interacting with material outside the fiducial region can give rise to $E > 5$ GeV

- $R_2 \equiv \frac{H_2}{H_0} < 0.5$

$H_0, H_2 = 0$-th, 2-nd Fox Wolfram moment

Almost no signal above $R_2 = 0.5$

Continuum $J/\psi$ unlike generic $c\bar{c}$
**J/ψ mass distributions**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass (MeV/c²)</th>
<th>Error (MeV/c²)</th>
<th>OFF peak (no p* cut)</th>
<th>ON peak (p* &gt; 2 GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁺e⁻</td>
<td>121 ± 26 J/ψ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>µ⁺µ⁻</td>
<td>156 ± 25 J/ψ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e⁺e⁻</td>
<td>799 ± 62 J/ψ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>µ⁺µ⁻</td>
<td>879 ± 52 J/ψ</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
J/ψ in continuum: cross section

- Total reconstruction + signal selection efficiency
  \( \varepsilon(ee) = 37\% \), \( \varepsilon(\mu\mu) = 43\% \)
  (independent, consistent measurements, then combined)

\[
\sigma_{ee \rightarrow J/\psi X} = (2.52 \pm 0.21_{\text{stat}} \pm 0.21_{\text{syst}}) \text{ pb}
\]

<table>
<thead>
<tr>
<th>systematic errors (%)</th>
<th>ee</th>
<th>( \mu\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>total</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>Background rejection</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>5 tracks requirement</td>
<td>4.9</td>
<td>none</td>
</tr>
<tr>
<td>Tracking</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>PID</td>
<td>1.8</td>
<td>1.4</td>
</tr>
<tr>
<td>ISR background</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>
The statistical error on $\sigma$ is dominated by the uncertainty on the $p^* < 2$ GeV/c component.

Cross section for $p^* > 2$ GeV/c only:

$$\sigma_{ee \rightarrow J/\psi X} (p^* > 2 \text{ GeV/c}) = (1.87 \pm 0.10_{\text{stat}} \pm 0.15_{\text{syst}}) \text{ pb}$$
$J/\psi$ production from $Y(4S)$ decay

- No excess in the ON-peak w.r.t the OFF-peak data (both at $p^* > 2$ GeV/c)

- Upper limit set on direct $Y(4S) \rightarrow J/\psi + X$:

  $$\text{BF}(Y(4S) \rightarrow J/\psi + X) < 4.3 \times 10^{-4} (@ 90\% \text{ CL})$$

- Well below CLEO (PRL 64 (1990)):

  $$(2.2 \pm 0.6 \pm 0.4) \times 10^{-3}$$


  $$(1.0 \div 2.5) \times 10^{-4}$$
Angular distributions

Polar angle $\theta^*$ ($e^+e^-\ CM$)
Fit with: $1 + A \cos^2 \theta^*$

- $A = 0.05 \pm 0.22$ (p* < 3.5 GeV/c)
- $A = 1.5 \pm 0.6$ (p* > 3.5 GeV/c)

Favors NRQCD

Helicity angle $\theta_H$
Fit with: $3(1 + \alpha \cos^2 \theta_H) / 2(\alpha+3)$

- $\alpha = -0.46 \pm 0.21$ (p* < 3.5 GeV/c)
- $\alpha = -0.80 \pm 0.09$ (p* > 3.5 GeV/c)

$\alpha \equiv (f_T-2f_L) / (f_T+2f_L) = 0, +1, -1$
unpol., transversely pol., longit. pol.
Conclusions

- $J/\psi$ production in the continuum in the $\Upsilon(4S)$ region

$$\sigma_{ee \rightarrow J/\psi X} = (2.52 \pm 0.21_{\text{stat}} \pm 0.21_{\text{syst}}) \text{ pb}$$

$$\sigma_{ee \rightarrow J/\psi X (p^* > 2 \text{ GeV/c})} = (1.87 \pm 0.10_{\text{stat}} \pm 0.15_{\text{syst}}) \text{ pb}$$

- $\sigma$ and polar angle distribution favor NRQCD fragmentation + color-octet

- $\Upsilon(4S) \rightarrow J/\psi + X < 4.3 \times 10^{-4}$ (@ 90% CL)


SLAC-PUB-8854 and hep-ex/0106044
Backup slides
The fragmentation + color-octet mechanism provides an explanation for the high $p_T \psi(2S)$ production cross-section observed by CDF (factor 30 higher than expected by previous models)

The NRQCD formalism allows to factor the fragmentation functions for heavy quarkonium production into:

- **short-distance coefficients**
  - describe the $c\bar{c}$ production rate within a region of size $1/m_Q$
  - independent of the quarkonium final state
  - perturbatively computable in $\alpha_s(m_Q)$

- **long-distance matrix elements**
  - contain all the nonperturbative dynamics of the formation of a $Q\bar{Q}$ bound state
  - independent of the initial state
  - extracted from experimental data