$J/\psi \rightarrow \mu\mu$ Cross Section Measurement
A Feasibility Study in Early Data

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On behalf of CMS collaboration

Workshop on Physics Opportunities with the First LHC Data
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Outline

1 Motivations
2 Monte Carlo Samples
3 $J/\psi$ Trigger and Reconstruction
4 Cross Section Measurement Strategy
5 Non-prompt Fraction Measurement
6 Sources of Systematic Uncertainties
7 Results and Summary
# Production Types of $J/\psi$

<table>
<thead>
<tr>
<th>1st step</th>
<th>2nd step</th>
<th>3rd step</th>
<th>Prod. type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\bar{p} \rightarrow c\bar{c} + X$</td>
<td>$c\bar{c} \rightarrow J/\psi$</td>
<td>$\chi_c \rightarrow J/\psi + \gamma$</td>
<td>Prompt, Direct</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow bc + X$</td>
<td>$c\bar{c} \rightarrow \psi'$</td>
<td>$\psi' \rightarrow J/\psi + X$</td>
<td>Prompt, Indirect</td>
</tr>
<tr>
<td>$\bar{b}c \rightarrow \bar{c}c + l^- + \nu_l$</td>
<td>$c\bar{c} \rightarrow J/\psi$</td>
<td>$\chi_c \rightarrow J/\psi + \gamma$</td>
<td>Non-prompt</td>
</tr>
</tbody>
</table>

**Branching ratio:** $J/\psi \rightarrow \mu\mu = 5.88\%$

$J^{PC} = 0^{--} \quad 1^{--} \quad 0^{++} \quad 1^{++} \quad 1^{+-} \quad 2^{++}$
Measurements at Hadron Colliders

Color Octet Model of Non-relativistic QCD fits CDF cross-section measurement well

Non-relativistic QCD predictions are in disagreement with the CDF polarization measurement


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Motivations

1. Production mechanism of $J/\psi$ is not well understood
   - LHC with high luminosity and large $p_T$ $J/\psi$s has the potential to discriminate between the theoretical models

2. Large cross section of $J/\psi$ production allows its measurement in early data at a new energy scale of 10TeV

3. $J/\psi$s are important for calibration and alignment of the detector
Monte Carlo Samples, $\sqrt{s} = 14\text{GeV}$

**Signal Samples:**
- Prompt $J/\psi$
  - Leading Order, Color Singlet and Octet Mechanisms
  - No polarization
  - 2 muons with $p_T > 2.0\text{GeV}$ and $|\eta| < 2.5$ gen. filter
- Non-prompt $J/\psi$
  - QCD $2 \rightarrow 2$, B-hadron decays
  - 2 muons with $p_T > 2.0\text{GeV}$ and $|\eta| < 2.5$ gen. filter

**Background Samples:**
- Muon enriched QCD
  - QCD $2 \rightarrow 2$, heavy flavor quark decays
  - Decays in flight
  - 1 muon with $p_T > 2.5\text{GeV}$ and $|\eta| < 2.5$ gen. filter
- Drell-Yan
  - 2 muons with $p_T > 2.0\text{GeV}$ and $|\eta| < 2.5$ gen. filter

Full GEANT simulation, CMSSW reconstruction software
J/ψ Trigger

- **Level1 Trigger (L1):**
  - L1 muon objects are based on muon chamber information only
  - requires 2 L1 muons with $p_T > 3$GeV

- **High Level Trigger (HLT):**
  - HLT muon objects confirm L1 muons and add silicon tracker information to improve $p_T$ resolution
  - requires 2 HLT muons with $p_T > 3$GeV
  - opposite charge
  - and $2.8$GeV < invariant mass < $3.4$GeV

- Rates assume *instantaneous luminosity of $10^{32}$cm$^{-2}$s$^{-1}$*
- Number of events normalized to 3pb$^{-1}$ of data

<table>
<thead>
<tr>
<th></th>
<th>Trigger rate (Hz)</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt J/ψ</td>
<td>1.92</td>
<td>58K</td>
</tr>
<tr>
<td>B-decay J/ψ</td>
<td>0.85</td>
<td>26K</td>
</tr>
<tr>
<td>QCD background</td>
<td>0.40</td>
<td>12K</td>
</tr>
</tbody>
</table>
Muon Reconstruction

- Global Muons combine Stand Alone Muons in the muon system with matched Tracker Tracks in the tracking system
- Reconstruction efficiency for $p_T > 7\text{GeV}$ and $|\eta| < 2.4$ is about 95%
- Momentum resolution is at percent level
Dimuon Spectrum

- Event Selection:
  - Two Global Muons with $p_T > 3\,\text{GeV}$ and opposite charge
  - Muons required to come from a common vertex
  - Drell-Yan is less than 1% of QCD background (omitted)
  - Two fake muon background is estimated to be $\sim 10\%$ of QCD background (systematic uncertainty)

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Figure 10: Dimuon invariant mass distribution normalized to 3 pb$^{-1}$ (light grey), blue (black) and red (dark grey) areas are the prompt, non-prompt and QCD background contributions, respectively.

Figure 11: Left: mass distribution fit of background and signal fitted with a linear function and a single Gaussian in the $p_{J/\psi}$ range of $9\,\text{GeV/c} < p_{J/\psi} < 20\,\text{GeV/c}$. Right: the same, but with the signal fitted to a double Gaussian.

Figure 12: Left: mass distribution fit of background and signal fitted with a linear function and a single Gaussian in the $p_{J/\psi}$ range of $17\,\text{GeV/c} < p_{J/\psi} < 20\,\text{GeV/c}$. Right: the same, but with the signal fitted to a double Gaussian.
Differential Cross Section Measurement

\[
\frac{d\sigma (J/\psi)}{dp_T} \bigg|_{|\eta|<2.4} \quad Br \left( J/\psi \rightarrow \mu^+ \mu^- \right) = \frac{N_{J/\psi}^{fit}}{\int L dt \cdot A \cdot \lambda_{trig}^{corr} \cdot \lambda_{reco}^{corr} \cdot \Delta p_T}
\]

- \(N_{J/\psi}^{fit}\) – Number of reconstructed \(J/\psi\)s in a given \(p_T\) bin as obtained from the mass fit using double Gaussian signal and linear background
- \(A(p_T^{J/\psi})\) – Total efficiency of triggering and reconstructing \(J/\psi\) events including finite acceptance of the detector, measured in MC
- \(\lambda^{corr}\) – correction factors to the trigger and reconstruction efficiencies measured using Tag and Probe method in data and MC
- \(\int L dt\) – integrated luminosity
- \(\Delta p_T\) – \(J/\psi\) \(p_T\) bin size
Total reconstruction efficiency combines
- Detector acceptance
- Trigger efficiency
- Reconstruction efficiency

Detector acceptance depends on polarization (systematics)

The difference is about 10% at high $p_T$ and 20% in the low $p_T$ region. Indeed, at low $p_{J/\psi}$, the polarization effect is stronger, since there is a muon $p_T$ reconstruction threshold. Once the polarization parameter $\alpha$ is measured, the total reconstruction efficiency can be computed by a weighted sum of the total efficiencies from transversely and longitudinally polarized $J/\psi$ production:

$$A_{\alpha} = (1 - \eta_{\alpha}) \cdot A_T + \eta_{\alpha} \cdot A_L.$$ 

The measurement of the $J/\psi$ polarization is currently under study and a separate analysis note is in preparation. For this cross section measurement we will make use of the polarization measured in other experiments and evaluate the effects of this assumption as a systematic error.

![Graph showing total efficiency as a function of $p_T$ for unpolarized, transverse, and longitudinal polarization.](image)
Based on pseudo-proper decay time of B-hadrons $l_{xy} = \frac{L_{xy}^J M_{J/\psi}}{p_{T}^{J/\psi}}$

Unbinned maximum likelihood fit simultaneously to mass and pseudo-proper decay time in each $p_{T}^{J/\psi}$ bin

Signal PDFs from MC convoluted with a resolution function

**Figure 23:** Left: The inclusive differential cross section, as a function of $p_{T}^{J/\psi}$ in the range of $9 \text{ GeV/c} < p_{T}^{J/\psi} < 10 \text{ GeV/c}$ for prompt (top left), $B$-decay (top right) and combined (bottom center) $J/\psi$ events.

<p>| B fraction: $\sqrt{s}=14\text{TeV}$, $|\eta|&lt;2.4$ |
|-------------------------------------------------|</p>
<table>
<thead>
<tr>
<th>$p_{T}^{J/\psi}$ (GeV/c)</th>
<th>B fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>10</td>
<td>0.3</td>
</tr>
<tr>
<td>15</td>
<td>0.4</td>
</tr>
<tr>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td>25</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**Monte Carlo**

**Fit result**
Effects of Misalignment

- Samples are reconstructed with different alignment scenarios
- Relative difference in B-hadron fractions is 4% (plot)
- $J/\psi$ mass resolution averaged over all $p_T^{J/\psi}$ range is shown in table

### Table 5: $J/\psi$ mass resolution in different misalignment scenarios

<table>
<thead>
<tr>
<th></th>
<th>10 pb$^{-1}$</th>
<th>100 pb$^{-1}$</th>
<th>ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$ mass resolution (MeV)</td>
<td>34.2 MeV</td>
<td>30.5 MeV</td>
<td>29.5 MeV</td>
</tr>
</tbody>
</table>

Alignment after $J/\psi$ mass resolution

<table>
<thead>
<tr>
<th></th>
<th>$J/\psi$ mass resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>10pb$^{-1}$</td>
<td>34.2 MeV</td>
</tr>
<tr>
<td>100pb$^{-1}$</td>
<td>30.5 MeV</td>
</tr>
<tr>
<td>ideal</td>
<td>29.5 MeV</td>
</tr>
</tbody>
</table>
# Sources of Systematic Uncertainties

<table>
<thead>
<tr>
<th>Parameter affected</th>
<th>Source</th>
<th>$\Delta \sigma/\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>Luminosity</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Number of $J/\psi$</td>
<td>$J/\psi$ mass fit</td>
<td>1.0 - 6.3%</td>
</tr>
<tr>
<td>Number of $J/\psi$</td>
<td>Momentum scale</td>
<td>$\sim 1%$</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>$J/\psi$ polarization</td>
<td>1.8 - 7.0%</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>$p_T^{J/\psi}$ binning</td>
<td>0.1 - 10%</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>MC statistics</td>
<td>0.5 - 1.7%</td>
</tr>
<tr>
<td>$\lambda_{reco}$</td>
<td>Non-perfect detector simulation</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>$\lambda_{trig}$</td>
<td>Non-perfect detector simulation</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>B fraction</td>
<td>$l_{xy}$ resolution model</td>
<td>0 - 1.9%</td>
</tr>
<tr>
<td>B fraction</td>
<td>B-hadron lifetime model</td>
<td>0.01 - 0.05%</td>
</tr>
<tr>
<td>B fraction</td>
<td>Background</td>
<td>0.1 - 3.0%</td>
</tr>
<tr>
<td>B fraction</td>
<td>Misalignment</td>
<td>0.7 - 3.5%</td>
</tr>
<tr>
<td>Total systematics</td>
<td>$p_T^{J/\psi} \in (5, 6)\text{GeV}$</td>
<td>13%</td>
</tr>
<tr>
<td>Total systematics</td>
<td>$p_T^{J/\psi} &gt; 20\text{GeV}$</td>
<td>19%</td>
</tr>
</tbody>
</table>

Uncertainties evaluated in each $p_T^{J/\psi}$ bin
Results of inclusive and prompt cross section measurement
Include systematic and statistical uncertainties
Integrated luminosity of $3 \text{ pb}^{-1}$

Figure 23: Left: The inclusive $J/\psi$ differential cross section, $\frac{d\sigma}{dp_T} \cdot \text{Br}(J/\psi \rightarrow \mu^+\mu^-)$, as a function of $p_T$. Right: The same, but the prompt $J/\psi$ differential cross section.

Figure 24: The fitted fraction of $J/\psi$'s from B-hadron decays, integrated over the pseudorapidity range $|\eta| < 2.4$, corresponding to an integrated luminosity of $3 \text{ pb}^{-1}$, as a function of $p_T$. 
We studied the feasibility of the $J/\psi$ cross section measurement at CMS.

Prompt and non-prompt components are separated making use of large B-hadron lifetime.

Measurement with $3\text{pb}^{-1}$ of data is dominated by systematic uncertainties ($\sim 15\%$).

Measurement is feasible in early LHC data!