Prospects of $J/\psi \rightarrow \mu^+\mu^-$ measurements in CMS

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on behalf of the CMS collaboration

“Quarkonium production at the LHC” workshop
CERN – 19 Feb 2010
Outline

• The CMS detector
• Cross-section measurement prospects in CMS
  – 2007 MC-based analysis (14 TeV)
  – Results for yields and non-prompt J/ψ fraction
• Analysis improvements:
  – Muon reconstruction and selection
  – Triggers for low luminosity
• Perspectives in first data:
  – 2009 MC-based analysis (0.9 and 2.36 TeV)
  – Search in December ‘09 data
  – Other possible analyses
• Conclusions
The CMS detector

SOLENOID
3.8 T B-field

CALORIMETERS
HCAL Plastic scintillator/brass sandwich

ECAL
Crystals

Silicon Strips
Pixels

Drift Tubes (DT)

Resistive Plate Chambers (RPC)

Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

Tracker

MUON BARREL

MUON ENDCAPS

The CMS detector

Quarkonium production workshop

Roberto Covarelli
The \( J/\psi \) \textit{x-section formula}

\[
\frac{d\sigma}{dp_T}(J/\psi) \cdot Br(J/\psi \rightarrow \mu^+\mu^-) = \frac{N_{J/\psi}^{\text{fit}}}{\int L dt \cdot A \cdot \lambda_{\text{trigger}}^{\text{corr}} \cdot \lambda_{\text{reco}}^{\text{corr}} \cdot \Delta p_T}
\]

- \( N_{J/\psi}^{\text{fit}} = (1 - f_B)N_{J/\psi}^{\text{tot}} \) (prompt) or \( f_B N_{J/\psi}^{\text{tot}} \) (non-prompt) *
- \( \int L dt \) = integrated luminosity
- \( A \) = signal acceptance/efficiency (from MC modeling) *
- \( \lambda_{\text{trigger}}^{\text{corr}} \cdot \lambda_{\text{reco}}^{\text{corr}} \) = trigger/reconstruction efficiency MC/data correction (to be determined with “tag-and-probe” method) *
- \( \Delta p_T \) = \( p_T \) bin size *

Differential \textit{x-section in rapidity} can be considered, depending on available statistics \( \leftarrow \) separation of barrel/endcap implies simpler \textit{mass description} (see next slides)

\(* = \text{function of } p_T\)
**MC event generation**

- **Signal** \( p_T^\mu > 2.5 \text{ GeV}/c, |\eta^\mu| < 2.4 \)
  - **Prompt** \( J/\psi \rightarrow \text{PYTHIA6} \)
    - Color Singlet + Color Octet model
    - COM non-perturbative factors \( \langle O_n^{(2S+1)L_J} \rangle \) fitted from CDF results
    - Cross-section reweighting with \( p_{T0}^2 \) cut-off
    - Fragmentation parameters set to obtain “high” soft-gluon radiation (details in Aafke’s talk)
    - Uniform polarization
  - **Non-prompt** \( J/\psi \rightarrow \text{PYTHIA6} \) (no EvtGen!)

- **Background** \( p_T^\mu > 2.5 \text{ GeV}/c, |\eta^\mu| < 2.4 \)
  - **Muon-enriched QCD events** \( \rightarrow \text{PYTHIA6} \)
    Main sources of background from MC-truth information:
    - D and B meson decays
    - Decay in flight of \( \pi \) and K
    - Hadron punch-through
Muon reconstruction in CMS

- Large rapidity coverage:
  - $|\eta| < 2.4$

- Excellent muon momentum resolution:
  - matching between $\mu$-chambers and in the silicon tracker (only using the latter for momentum determination at low $p_T$)
  - strong solenoidal magnetic field (3.8 T)
  - Because of the increasing material thickness traversed and the different lever arm, the resolution changes with pseudo-rapidity
**J/ψ yields (N_{J/ψ \text{tot}})**

Double-muon trigger with \( p_T > 3 \text{ GeV/c} \)

3 pb\(^{-1}\) integrated luminosity (14 TeV)

<table>
<thead>
<tr>
<th>( p_T^{J/\psi} ) bin (GeV/c)</th>
<th>Yield ( N_{\text{sig}} )</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5-6</td>
<td>2591±52</td>
<td></td>
</tr>
<tr>
<td>6-7</td>
<td>11098±109</td>
<td></td>
</tr>
<tr>
<td>7-8</td>
<td>17565±137</td>
<td></td>
</tr>
<tr>
<td>8-9</td>
<td>20007±147</td>
<td></td>
</tr>
<tr>
<td>9-10</td>
<td>18856±141</td>
<td></td>
</tr>
<tr>
<td>10-11</td>
<td>16601±132</td>
<td></td>
</tr>
<tr>
<td>11-12</td>
<td>13685±119</td>
<td></td>
</tr>
<tr>
<td>12-13</td>
<td>10659±106</td>
<td></td>
</tr>
<tr>
<td>13-14</td>
<td>8304±93</td>
<td></td>
</tr>
<tr>
<td>14-15</td>
<td>6513±82</td>
<td></td>
</tr>
<tr>
<td>15-17</td>
<td>8923±96</td>
<td></td>
</tr>
<tr>
<td>17-20</td>
<td>7420±88</td>
<td></td>
</tr>
<tr>
<td>20-24</td>
<td>4480±68</td>
<td></td>
</tr>
<tr>
<td>24-30</td>
<td>2617±52</td>
<td></td>
</tr>
<tr>
<td>30-40</td>
<td>1287±36</td>
<td></td>
</tr>
</tbody>
</table>

**Total** 150 600 ± 380

- 2-Gaussian shape due to non-optimal muon momentum scale in endcaps → now fixed in MC
- Momentum scale must then be extracted from data
**$B$-fraction ($f_B$)**

- Using a 2D-fit to *invariant mass* and *proper decay length* distributions:
  - Proper decay length calculated from decay length in the lab frame
  - Secondary vertex from a *Kalman vertex fit* to the two muon tracks

\[
\ell_{J/\psi} = \frac{L_{x,y}^{J/\psi} \cdot M_{J/\psi}}{p_T^{J/\psi}}
\]

- For **prompt events**, expected to be a simple $\delta$-function
- For **non-prompt events**, it has an *exponential shape* with $\lambda_B^{\text{eff}}$ [but smearing effects must be considered since in this case we are using the “pseudo”-proper decay length, i.e. $(M/p_T)_{J/\psi}$ instead of $(M/p_T)_B$]
- For **background events** a generic superposition of different contributions (symmetric + asymmetric with effective lifetimes) is adopted

*Convoluted with 2-Gauss resolution*
**\( B\)-fraction (\( f_B \))**

- From 14 TeV result (2007):
  - global-global combinations only
  - 3 \( \text{pb}^{-1} \) equivalent luminosity
  - 15 bins: \( 5 < p_T < 40 \text{ GeV}/c \)
  - 1 bin: \(|\eta| < 2.4\)

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\[ \sigma_{\text{stat}}(N_{J/\psi}^{\text{prompt}}) = 1.8\% - 5\% \]

\[ \sigma_{\text{stat}}(N_{J/\psi}^{\text{non-prompt}}) = 2\% - 10\% \]
Acceptance calculation ($A$)

- Geometrical acceptance and reconstruction efficiency for the signal is first estimated from MonteCarlo
- Main contribution to systematics expected from unknown $J/\psi$ spin alignment
  - In the 2007 work, estimated using differences in acceptance between the unpolarized case and the extreme polarization values in the helicity frame (all longitudinal, all transverse)
  - A more reliable procedure was outlined recently considering both helicity and Collins-Soper frames (details in Pietro’s talk)
Efficiency corrections ($\lambda$)

- **MC efficiency** is used in the 2007 analysis ($\lambda = 1$)
- **“Tag-and-probe” method:**
  - Given a cleanly identified (“tag”) muon, estimate number of other muons satisfying or not certain steps of reconstruction (“probes”) from a fit to the $J/\psi$ mass vs. $p_T$, $\eta$ of the muon $\Leftarrow$ selection independent
  - **Reconstruction:**
    - Tag: reconstructed muon with $p_T > 3$ GeV/c
    - Trigger:
      - Tag: reconstructed muon matched to a trigger object
        \[
        \varepsilon_{\text{trk}} = \frac{N_{\text{trk}+\mu C}}{N_{\mu C}} \quad \varepsilon_{\mu-ID} = \frac{N_{\text{trk}+\mu C}}{N_{\text{trk}}}
        \]
      - Limited by muon resolution in $\mu$-chambers and biased
      - Well established
  - Trigger:
    - Tag: reconstructed muon matched to a trigger object
      \[
      \varepsilon_{\text{trig}} = \frac{N_{\text{global}-\mu+\text{trig}}}{N_{\text{global}-\mu}}
      \]
- **Limitations of the method:**
  - Fit precision
  - Correlation between muons (e.g. small $\Delta R$)
# 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>$J/\psi$ $p_T$ 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>$\lambda_{reconstruction}$</td>
<td>Non-perfect detector simulation</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>$\lambda_{trigger}$</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>
</tbody>
</table>

**Total systematic uncertainty 13-19%**

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**Effects of misalignment on:**

- Lifetime
- Invariant mass

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<table>
<thead>
<tr>
<th>$J/\psi$ mass resolution (MeV/$c^2$)</th>
<th>10 pb$^{-1}$</th>
<th>100 pb$^{-1}$</th>
<th>ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$ mass resolution</td>
<td>34.2</td>
<td>30.5</td>
<td>29.5</td>
</tr>
</tbody>
</table>

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Improvements since 2007 (1)

- **MC Generators:**
  - EvtGen / PHOTOS have now been introduced in CMS and used to simulate properly $B \rightarrow J/\psi \ X$ decays / generate FSR

- **Muon trigger and reconstruction:**
  - A reconstructed muon ("global" muon) in CMS is defined as a $\mu$-chamber “seed”, then matched to a track in the tracking devices:
    - In order to compute a rough momentum estimate and thus fire the Level-1 trigger, hits must be in at least two stations
    - Curvature due to the $B$-field and material crossed limit the $p_T$ acceptance
Improvements since 2007 (2)

• The idea of “tracker muons”:
  – Perform the reconstruction inside-out, starting from a silicon track and searching for any possible compatible muon signal in the chambers (even in one station)
  – Tight selections on track-segment matching are required to keep hadron background under control
    • Calorimeters can be also exploited to check compatibility with MIP energy deposits
  – Efficiency is enhanced by a large factor, especially at low $p_T$

• Problem:
  – This procedure cannot be done at trigger level due to processing-time limitations

but…
Improvements since 2007 (3)

- ... trigger strategies can evolve/be optimized to LHC luminosity

  - Write on tape all minimum-bias triggers (maximum advantage from all types of muons)

  - Use single-muon triggers

  - Use ad-hoc intermediate solutions:
    - Example 1: combining a single-muon trigger with other information, profiting from the CMS High-Level Trigger versatility

  - Use only double-muon triggers (2007 analysis, almost no benefit from tracker muons)
MC analysis at 0.9-2.36 TeV

• Event selection:
  – All tracks:
    • $N_{\text{hits}}$ (pixels + strips) > 12
    • $|d_0| < 5$ cm, $|d_z| < 20$ cm
  – “Global” muons: normalized global $\chi^2 < 20$
  – “Tracker” muons:
    • normalized track $\chi^2 < 5$
    • tight angular compatibility between track and muon segment directions
  – Probability of the di-muon vertex > 0.001

• Here neglecting contributions of $B \rightarrow J/\psi X$ decays, expected to be < 10% in total

<table>
<thead>
<tr>
<th></th>
<th>900 GeV</th>
<th>2.36 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>prompt $J/\psi$</td>
<td>background</td>
</tr>
<tr>
<td>global - global</td>
<td>$5.6 \pm 0.1$</td>
<td>$0.3 \pm 0.2$</td>
</tr>
<tr>
<td>global - tracker</td>
<td>$19.1 \pm 0.2$</td>
<td>$1.5 \pm 0.5$</td>
</tr>
<tr>
<td>tracker - tracker</td>
<td>$8.3 \pm 0.1$</td>
<td>$1.3 \pm 0.4$</td>
</tr>
</tbody>
</table>
MC results at 0.9-2.36 TeV

- Using simulation of CMS as close as possible to the expected initial detector conditions
Search for $J/\psi$ in data

- Minimum-bias events triggered using coincidence of beam scintillators (approximate collected luminosity: $10 \mu b^{-1}$ at 900 GeV, $400 \text{mb}^{-1}$ at 2.36 TeV)
- "Good" collision events selected based on generic criteria (tracker/muons in the data-taking, presence of at least a reconstructed primary vertex … etc.), then analysis requirements are applied
The “J/ψ” event display

Run 124120
Event 5686693

Mass = 3.04 GeV/c^2
p_T = 5.38 GeV/c
Dimuon vertex $\chi^2$ prob. = 57%
$c\tau = -17 \pm 81 \mu m$
Other on-going studies

• Wide physics program for **quarkonia in CMS:**
  - Production **cross-section measurement** (J/ψ and Y’s)
    - The expected Y-peak resolution of ~90 MeV/c^2 allows to separate the three states, at least in the muon barrel
  - **Spin alignment measurement** (J/ψ and Y’s)
    - Depending crucially on detector acceptance: detailed studies ongoing
  - **P-wave state (χ_c, χ_b) radiative decays**
    - Very useful to extract direct J/ψ / Y production, but depending on the performance of identifying low-energy photons in data
  - **Quarkonia in di-electron channel**
    - Depending on the performance of triggering/identifying low-pT electrons in data (huge amount of bremsstrahlung in the tracker material): probably adding not so much to the di-muon yields
Conclusions

- Perspectives of $\text{J}/\psi \rightarrow \mu^+\mu^-$ measurements with the CMS detector have been presented.

- The cross-section measurement prospects have been investigated:
  - with the old nominal LHC energy / luminosity / trigger strategy
  - using 15 $p_T$ bins between 5 and 40 GeV/$c$ and the full rapidity range
  - Effective separation of prompt and non-prompt contribution using proper decay length distributions
  - Total uncertainties vary with the $p_T$ bin and are of the order of 5% statistical and 15% systematic with an integrated luminosity of 3 pb$^{-1}$

- Current analysis of MC and data has large benefits from improvements on muon reconstruction and relaxed trigger criteria, both in terms of yields and lower $p_T$ reach
  - Clean “observation” possible with only 1 nb$^{-1}$ of data
  - One suitable candidate already found in December LHC data
Backup slides
CRAFT results

Currently used in CMS

Reconstruction efficiency
Cosmic data vs. simulation

HLT efficiency
Cosmic data
### 14 TeV vs. 7 TeV cross-sections

<table>
<thead>
<tr>
<th>Cross-section x BR</th>
<th>Prompt $J/\psi \rightarrow \mu \mu$</th>
<th>QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 TeV</td>
<td>21.0 $\mu$b</td>
<td>54.71 mb</td>
</tr>
<tr>
<td>10 TeV</td>
<td>15.6 $\mu$b</td>
<td>51.60 mb</td>
</tr>
<tr>
<td>7 TeV</td>
<td>12.6 $\mu$b</td>
<td>48.44 mb</td>
</tr>
</tbody>
</table>