Perspectives of Charmonium Production at CMS

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1st April, University of Virginia (USA)
Outline

• Introduction to LHC, CMS and motivations
• Muon and di-muon trigger
• Muon and di-muon reconstruction
• Inclusive J/ψ cross-section measurement
• B fraction fit
• Misalignment effect in early data
• Systematic uncertainties
• Expected results at 3pb⁻¹
• Muon performance with cosmic muons (real data)
• Summary
The Large Hadron Collider (LHC)

- LHC: the world’s largest particle accelerator at CERN, Geneva

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>26658 m</td>
</tr>
<tr>
<td>Momentum at collision</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Design luminosity</td>
<td>$10^{34}$ cm$^2$s$^{-1}$</td>
</tr>
<tr>
<td>Protons per bunch</td>
<td>$1.15 \times 10^{11}$</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
</tr>
<tr>
<td>Collision rate</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>1.9 K</td>
</tr>
</tbody>
</table>

Some of the LHC parameters for $pp$ operation.

- LHC experiments: ALICE, ATLAS, CMS, LHCb, LHCf and TOTEM
The Compact Muon Solenoid (CMS)

More than 2000 scientists, from 155 institutes in 37 countries

SUPERCONDUCTING COIL

CALORIMETERS

ECAL
Scintillating PbWO4 crystals

HCAL
scintillator/brass sandwich

IRON YOKE

TRACKER
Silicon Microstrips
Pixels

MUON BARREL
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)

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

Total weight: 12,500 t
Overall diameter: 15 m
Overall length: 21.6 m
Magnetic field: 4 Tesla
Interactions in the CMS detector
Motivations

- The $J/\psi$ production is dominated by:
  - prompt $J/\psi$:
    - direct $J/\psi$ production
    - indirect from prompt $\chi_{c0}$, $\chi_{c1}$, $\chi_{c2}$...
  - non-prompt $J/\psi$: from B hadrons decay

- Prompt puzzle: no satisfactory models fit x-section and polarization simultaneously, for example:
  - CSM (Color Singlet Model): LO, NLO, NNLO
    - can not explain the cross section
  - COM (Color Octet Mechanism): NRQCD
    - COM means polarization

- Motivations:
  - Quarkonia production and polarization for theoretical interest
  - $J/\psi$ and $Y$ are crucial to understand the detector performance:
    - alignment and calibration
    - muon efficiency
  - Can be done with first data, $\leq 10\text{pb}^{-1}$
CMS Detector for Quarkonia

Muon system:
- Drift Tubes (DT) in central barrel region
- Cathode Strip Chambers (CSC) in endcap region
- Resistive Plate Chambers (RPC) in barrel and endcap

Tracker system:
- Silicon pixel layers (3 in barrel, 2 in endcap)
- Silicon strips layers (10 in barrel, 12 in endcap)

- Excellent coverage: ~5 units of rapidity and $2\pi$ of $\phi$
- Strongest magnetic field: 4 T, 2 T (return yoke)
- Tag from muon stations, momentum resolution from Silicon tracker: ~2% of momentum resolution for tracks with $p_T < 100$ GeV
- Ecal+Hcal+Coil – absorbs hadrons

precise measurement of position (momentum)
fast info for LVL-1 trigger
Charmonium generation

- **Prompt $J/\psi$ production**: NRQCD COM+CSM processes in Pythia (see backup slides) with NRQCD matrix elements from: hep-ph/0003142
  - CSM values extracted from potential models (hep-ph/9503356)
  - COM values from CDF data
  - Total $0.3846\text{ mb}$ at 14 TeV

- **B hadrons production**: MSEL=1 in Pythia and decay with EvtGen
  - gluon fusion ($50\mu\text{b}$)
  - gluon splitting ($190\mu\text{b}$)
  - flavor excitation ($220\mu\text{b}$)

- **Prediction of the differential cross-section of prompt $J/\psi$ and B-decay $J/\psi$ at LHC, 14TeV** (right).
The L1 and HLT muon trigger
CMS muon trigger

<table>
<thead>
<tr>
<th>HLT path</th>
<th>L1 seeds</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT_Mu3</td>
<td>L1_SingleMu3</td>
<td>one L3 muon pT&gt;3 GeV/c,</td>
</tr>
<tr>
<td>HLT_Mu5</td>
<td>L1_SingleMu3</td>
<td>one L3 muon pT&gt;5 GeV/c,</td>
</tr>
<tr>
<td>HLT_Mu9</td>
<td>L1_SingleMu7</td>
<td>one L3 muon pT&gt;9 GeV/c,</td>
</tr>
<tr>
<td>HLT_DoubleMu3</td>
<td>L1_DoubleMu3</td>
<td>two L3 muon pT&gt;0 GeV/c,</td>
</tr>
<tr>
<td>HLT_JPsiMuMu</td>
<td>L1_DoubleMu3</td>
<td>two L3 muon pT&gt;0 GeV/c,</td>
</tr>
<tr>
<td>HLT_UpsilonMuMu</td>
<td>L1_DoubleMu3</td>
<td>two L3 muon pT&gt;0 GeV/c,</td>
</tr>
</tbody>
</table>

For example, the CMS dimuon trigger:

- **L1 filter:** hardware-based
  - DT’s range |η|<1.2; CSC 0.9<|η|<2.4; RPC |η|<2.1
  - Two L1 muons p_T>3GeV/c, |η|<2.5
- **HLT L2 filter:** on-line reconstructed L2 muons from the muon system (DT, CSC)
  - Two L2 muons p_T>3GeV/c, |η|<2.5
- **HLT L3 filter:** using L2 muons as input and constrain to the interaction region in the silicon tracker.
  - Two L3-μ p_T>3GeV/c, |η|<2.5
J/ψ HLT trigger efficiency

**eff. vs. p_T**

**eff. vs. η**
The pre-scale factors and trigger rates

The pre-scale factors and unprescaled trigger rates at luminosity = $8\times10^{29}$ cm$^{-2}$s$^{-1}$.

<table>
<thead>
<tr>
<th>HLT path</th>
<th>Prescale</th>
<th>Prompt J/ψ</th>
<th>B-decay J/ψ</th>
<th>background</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT_Mu3</td>
<td>1</td>
<td>0.256 Hz</td>
<td>0.0838 Hz</td>
<td>15.6 Hz</td>
<td>15.9 Hz</td>
</tr>
<tr>
<td>HLT_Mu5</td>
<td>1</td>
<td>0.107</td>
<td>0.0472</td>
<td>6.23</td>
<td>6.38</td>
</tr>
<tr>
<td>HLT_Mu9</td>
<td>1</td>
<td>0.0116</td>
<td>0.00886</td>
<td>0.814</td>
<td>0.834</td>
</tr>
<tr>
<td>HLT_DoubleMu3</td>
<td>1</td>
<td>0.0120</td>
<td>0.00793</td>
<td>0.122</td>
<td>0.142</td>
</tr>
<tr>
<td>HLT_JPsiMuMu</td>
<td>1</td>
<td>0.0117</td>
<td>0.00630</td>
<td>0.00294</td>
<td>0.0209</td>
</tr>
</tbody>
</table>

The pre-scale factors and unprescaled trigger rates at luminosity = $1\times10^{31}$ cm$^{-2}$s$^{-1}$.

<table>
<thead>
<tr>
<th>HLT path</th>
<th>Prescale</th>
<th>Prompt J/ψ</th>
<th>B-decay J/ψ</th>
<th>background</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT_Mu3</td>
<td>infinity</td>
<td>3.20 Hz</td>
<td>1.05 Hz</td>
<td>195 Hz</td>
<td>None</td>
</tr>
<tr>
<td>HLT_Mu5</td>
<td>25</td>
<td>1.34</td>
<td>0.590</td>
<td>77.4</td>
<td>79.8 Hz</td>
</tr>
<tr>
<td>HLT_Mu9</td>
<td>1</td>
<td>0.145</td>
<td>0.111</td>
<td>10.2</td>
<td>10.5</td>
</tr>
<tr>
<td>HLT_DoubleMu3</td>
<td>1</td>
<td>0.150</td>
<td>0.099</td>
<td>1.53</td>
<td>1.78</td>
</tr>
<tr>
<td>HLT_JPsiMuMu</td>
<td>1</td>
<td>0.146</td>
<td>0.079</td>
<td>0.037</td>
<td>0.261</td>
</tr>
</tbody>
</table>
In the first run of 2009-2010, the total integral luminosity is about 200 pb⁻¹.

The new plan is to measure the cross section at 3 pb⁻¹ by using HLT_Mu3 path.
Muon and $J/\psi$ reconstruction
Figure 7: The $\eta$ and $p_T$ 2D distributions of muon and prompt $J/\psi$ for reconstructed $J/\psi$-events.
Muon Acceptance

• We calculated the efficiency by matching the global reconstructed muon with MC truth: (1) same charge, (2) $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$, (3) $\Delta p_T/p_T < 0.2$
Muon reconstruction performance

<table>
<thead>
<tr>
<th></th>
<th>barrel</th>
<th>transition</th>
<th>end-cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(1/p_T)$</td>
<td>0.6~1.0%</td>
<td>1.1~1.5%</td>
<td>1.5~2.3%</td>
</tr>
<tr>
<td>$\sigma(\eta)$</td>
<td>0.0003~0.0016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma(\phi)$</td>
<td>0.0002~0.0016</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
J/ψ selection

- We selected reconstructed global muon pairs by requiring:
  1. HLT_DoubleMu3 trigger
  2. Opposite charge.
  3. Each muon $p_T > 3\text{GeV/c}$, $|\eta| < 2.4$.
  4. Dimuon invariant mass between $2.8$ to $3.4\text{GeV/c}^2$.
  5. Two muons come from a common vertex.

Offline selection criteria will depend on the trigger selection.

3 pb$^{-1}$
$\sigma \sim 30\text{MeV}$
J/ψ mass distribution

- We divided J/ψ into $p_T$ and $\eta$ bins and fit the mass distribution in each bin with a single Gaussian:

- $0.0 < |\eta| < 0.2$
  - Mean = 3.098 GeV/$c^2$
  - $\sigma$ = 16.8 MeV/$c^2$

- $1.0 < |\eta| < 1.2$
  - Mean = 3.098 GeV/$c^2$
  - $\sigma$ = 27.1 MeV/$c^2$

- $2.0 < |\eta| < 2.2$
  - Mean = 3.103 GeV/$c^2$
  - $\sigma$ = 39.7 MeV/$c^2$
J/ψ mass resolution

$E(m)$ vs. $p_T$

$\sigma(m)$ vs. $p_T$

$E(m)$ vs. $\eta$

$\sigma(m)$ vs. $\eta$
Inclusive J/ψ cross-section
Measurement of Cross-section

Following the CDF measurement, the inclusive $J/\psi$ cross-section is determined by

$$\frac{d\sigma}{dp_T}(J/\psi) \cdot Br(J/\psi \rightarrow \mu^+\mu^-) = \frac{N_{\text{sig}}^{J/\psi}}{\int Ldt \cdot A \cdot \lambda_{\text{corr}}^{\text{trigger}} \cdot \lambda_{\text{corr}}^{\text{reco}} \cdot \Delta p_T}$$

1. $\int Ldt$: the integral luminosity
2. $\Delta p_T$: the size of the pT bin. We divided into 15 bins from 5 to 40 GeV/c
3. $N_{\text{sig}}$: the number of reconstructed $J/\psi$s from fitting
4. $A$: the total efficiency determined from MC simulation
5. $\lambda_{\text{corr}}^{\text{trigger}}$ and $\lambda_{\text{corr}}^{\text{reco}}$: correction factors to the trigger and offline efficiencies, as measured in data compared to the MC.
Figure 18: Mass distribution fit with linear background and signal peak of a single Gaussian (a) or double Gaussian (b) in pT range 9\,GeV/c < p_T < 10\,GeV/c.
Total selection efficiency

\[ A(p_T^{J/\psi}, \eta^{J/\psi}) = \frac{N_{J/\psi}^{\text{rec}}(p_T^{J/\psi}, \eta^{J/\psi})}{N_{J/\psi}^{\text{gen}}(p_T^{J/\psi}, \eta^{J/\psi})} \]

Total efficiency includes:
- detector acceptance
- trigger efficiency
- offline efficiency

\[ I(\cos \theta) = \frac{3}{2(\alpha + 3)} \left(1 + \alpha \cos^2 \theta\right) \]

• Here we take existing measurements as default (CDF for prompt, BaBar for non-prompt), uncertainty in systematic error analysis.
• Polarization measurement at CMS will be done too.
• The $J/\psi$ reconstruction efficiency can be expressed by:

$$\varepsilon_{\text{offline}}^{J/\psi}(p_T, \eta_{J/\psi}, \theta_{J/\psi}) = \varepsilon_1(p_T, \eta_1) \times \varepsilon_2(p_T, \eta_2),$$

• Muon reconstruction efficiency can be measured from data by Tag&probe method. Tag&probe can be used both on MC events or real data. Thus the correction factor is:

$$\lambda_{\text{reco}}^{corr}(p_T, \eta) = \frac{\varepsilon_{\text{data}}(p_T, \eta)}{\varepsilon_{\text{MC}}(p_T, \eta)}$$

• $\lambda_{\text{reco}}^{corr}(p_T, \eta)$ is ideal to be 1 if the MC simulation is perfect.
• Absolute muon efficiency is difficult to obtain at low $p_T$.

• Correction factors to the $J/\psi$ trigger efficiency can be determined in a similar way.
B fraction fit
To distinguish $b \rightarrow J/\psi$ from prompt $J/\psi$, we use the pseudo-proper decay length:

$$
\ell_{xy} = \frac{L_{xy}^{J/\psi} \cdot M_{J/\psi}}{P_T^{J/\psi}}
$$

$L_{xy}^{J/\psi}$ is the transverse component of decay length in lab system.

1. **Prompt $J/\psi$:** decays at the primary vertex (red), described with resolution function: double Gaussian + double-sided exponential,

   $$
   F_p(\ell_{xy}) = R(\ell_{xy}, \sigma)
   $$

2. **Non-prompt $J/\psi$:** $B$-hadrons have long lifetimes:

   $$
   F_B(\ell_{xy}) = R(\ell_{xy} - \ell_{xy}', \sigma) \otimes X_{mc}(\ell_{xy}')
   $$

$X_{mc}(\ell_{xy}')$ is the $b \rightarrow J/\psi$ lifetime distribution, an exponential function convoluted with a Gaussian.
B fraction fit (2)

- **Unbinned Maximum Likelihood** fit is used.
  - Both pseudo-proper decay length and invariant mass distributions are used.
  - Likelihood of mass signal and side-band events are minimized simultaneously.

- The likelihood function is:

\[
\ln L = \sum_{i=1}^{N} \ln F(\ell_{xy}, m_{\mu\mu})
\]

\[
F(\ell_{xy}, m_{\mu\mu}) = f_{\text{sig}} F_{\text{sig}}(\ell_{xy}) M_{\text{sig}}(m_{\mu\mu}) + (1 - f_{\text{sig}}) F_{\text{bkg}}(\ell_{xy}) M_{\text{bkg}}(m_{\mu\mu})
\]

\[
F_{\text{sig}}(\ell_{xy}) = (1 - f_{B}) F_{\text{p}}(\ell_{xy}) + f_{B} F_{\text{B}}(\ell_{xy})
\]

B fraction: what we want

\[
R(\ell_{xy}, \sigma) \quad R(\ell_{xy} - \ell'_{xy}, \sigma) \otimes X_{mc}(\ell'_{xy})
\]

Example of B fraction fit in J/ψ
pT bin 9-10 GeV/c
The fit result is very well compared to the MC truth.

Figure 25: (a) B fraction from fitting (dot) and the MC truth (triangle) (b) the deviation of B fraction from MC truth. The unbinned maximize likelihood fitting provides the correct results, within the range of three $\sigma$. 
The figure shows the results of other fits divided by the standard fitting, and the differences are considered as systematic uncertainties (see slide 35).

Systematic uncertainties in B fraction fit seem small.
Misalignment
Mass resolution

• Plots of $J/\psi$ invariant mass distribution in 10pb$^{-1}$, 100pb$^{-1}$ and ideal conditions. And table 5 gives the numbers of the mass resolutions.

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

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

- Left: Misalignment effects on the pseudo-proper decay length distribution.
- Right: We fitted the B fraction in 10pb⁻¹ sample and compared with MC and result in ideal.

We conclude that there is no bias in neither of the two scenarios and take 50% of the difference as a systematic error.
Systematic uncertainties.
Summary of systematic errors

Table 6: Summary of possible systematic uncertainties in the $J/\psi$ cross-section measurement in CMS early data. All the uncertainties are $p_T$-depended, except the uncertainty from luminosity. The total uncertainty is about 10% in the region $p_T > 20\text{GeV}/c$ and 16% at the first $p_T$ bin 5-6$\text{GeV}/c$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Source</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>Luminosity</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Number of $J/\psi$</td>
<td>Mass PDF</td>
<td>1.6 - 9.5%</td>
</tr>
<tr>
<td>Number of $J/\psi$</td>
<td>Momentum scale</td>
<td>$\sim 1%$</td>
</tr>
<tr>
<td>Acceptance</td>
<td>$J/\psi$ polarization</td>
<td>1.8 - 7.0%</td>
</tr>
<tr>
<td>Acceptance</td>
<td>$p_T$ spectrum</td>
<td>0.1 - 10%</td>
</tr>
<tr>
<td>Acceptance</td>
<td>MC statistics</td>
<td>0.53 - 1.7%</td>
</tr>
<tr>
<td>$\epsilon_{\text{reconstruction}}$</td>
<td>Determine in tag-and-probe</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>$\epsilon_{\text{trigger}}$</td>
<td>Determine in tag-and-probe</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>B fraction</td>
<td>Resolution model</td>
<td>0. - 2.6%</td>
</tr>
<tr>
<td>B fraction</td>
<td>B-decay J/psi model</td>
<td>0.01 - 0.05%</td>
</tr>
<tr>
<td>B fraction</td>
<td>Background</td>
<td>$\sim 1.5%$</td>
</tr>
<tr>
<td>B fraction</td>
<td>Misalignment</td>
<td>0.7 - 3.5%</td>
</tr>
<tr>
<td><strong>total 10% - 16%</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The total uncertainties is about 10\% in $p_T$ above 20$\text{GeV}$, and 16\% at the first $p_T$ bin
- The most important uncertainties will be shown, and others are in backup slides.
Uncertainties: $J/\psi$ polarization

- **What we used:**
  - Prompt $J/\psi$:
  - $B$-decay $J/\psi$: $\alpha_B = -0.13 \pm 0.01$

- **We used the mean value and varied it by $\pm \sigma$:**
  - $\alpha = \mu$, $\alpha_+ = \mu + 3\sigma$, $\alpha_- = \mu - 3\sigma$
  - With $\alpha$, $\alpha_+$, $\alpha_-$, we have acceptances: $A$, $A_+$, $A_-$
    - $A_+ < A < A_-$
  - $\Delta \sigma / \sigma_{sys} = 1.8 \sim 7.0\%$
The $J/\psi$ $p_T$ spectrum is the subject of this analysis.

The Acceptance from MC in each $p_T$ bin depends on the generated spectrum.

In order to estimate this systematic, we take the difference between the flat spectrum and the generated one:
- For each $p_T$ bin, we divided into 4 smaller bins of equal $p_T$ size:
- Calculate each small bin’s acceptance:

$$\Delta A = \sum_{i=1}^{4} A_i - \frac{\sum_{i=1}^{4} A_i N_i}{\sum_{i=1}^{4} N_i}$$

$\Delta A/A$ gives a uncertainty from 0.1 to 10%.
Uncertainties: others

- Mass fit: we split each $p_T$ bin into three separate $|\eta|$ regions (0. – 0.8 – 1.6 – 2.4) and fit each region with a single Gaussian. The difference with respect to a single $\eta$ bin and double Gaussian is taken as systematics.
  - 1.6 – 9.5%

- Residual misalignment effect: the B fraction fitting result in 10pb$^{-1}$ and ideal alignment is shown in slide 29. We conclude that there is no bias in neither of the two scenarios and take 50% of the difference as a systematic error.
  - 0.7 – 3.5%

- The luminosity uncertainty is supposed to be 5%, and the errors from Tag&Probe are also considered as 5%.

- More details in the backup slides.
Results
Table 8: The prompt and B-decay $J/\psi$ differential cross sections as a function of $p_T$ with statistical and systematic uncertainties. The cross section in each $p_T$ bin is integrated over the $\eta$ range $|\eta| < 2.4$. The Monte Carlo input values are listed in the last 2 columns.

<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
<th>$d\sigma/dp_T \cdot Br(n b/(G e V/c))$</th>
<th>MC input values (nb/(GeV/c))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>prompt $J/\psi$</td>
<td>B-decay $J/\psi$</td>
</tr>
<tr>
<td>5-6</td>
<td>$220\pm5(stat)\pm41(syst)$</td>
<td>$47.8\pm3.2(stat)\pm8.9(syst)$</td>
</tr>
<tr>
<td>6-7</td>
<td>$130\pm2\pm18$</td>
<td>$30.2\pm1.0\pm4.1$</td>
</tr>
<tr>
<td>7-8</td>
<td>$74.9\pm0.7\pm10.2$</td>
<td>$22.2\pm0.5\pm3.0$</td>
</tr>
<tr>
<td>8-9</td>
<td>$44.5\pm0.4\pm6.3$</td>
<td>$15.4\pm0.3\pm2.2$</td>
</tr>
<tr>
<td>9-10</td>
<td>$26.9\pm0.3\pm4.0$</td>
<td>$11.4\pm0.2\pm1.7$</td>
</tr>
<tr>
<td>10-11</td>
<td>$16.6\pm0.2\pm2.4$</td>
<td>$7.91\pm0.13\pm1.14$</td>
</tr>
<tr>
<td>11-12</td>
<td>$11.1\pm0.2\pm1.6$</td>
<td>$5.53\pm0.10\pm0.81$</td>
</tr>
<tr>
<td>12-13</td>
<td>$6.97\pm0.10\pm1.06$</td>
<td>$4.19\pm0.08\pm0.64$</td>
</tr>
<tr>
<td>13-14</td>
<td>$4.80\pm0.07\pm0.72$</td>
<td>$2.87\pm0.06\pm0.43$</td>
</tr>
<tr>
<td>14-15</td>
<td>$3.39\pm0.06\pm0.54$</td>
<td>$2.16\pm0.05\pm0.35$</td>
</tr>
<tr>
<td>15-17</td>
<td>$2.03\pm0.03\pm0.35$</td>
<td>$1.45\pm0.03\pm0.25$</td>
</tr>
<tr>
<td>17-20</td>
<td>$0.942\pm0.016\pm0.158$</td>
<td>$0.745\pm0.015\pm0.12$</td>
</tr>
<tr>
<td>20-24</td>
<td>$0.379\pm0.009\pm0.067$</td>
<td>$0.320\pm0.008\pm0.057$</td>
</tr>
<tr>
<td>24-30</td>
<td>$0.131\pm0.004\pm0.024$</td>
<td>$0.122\pm0.004\pm0.022$</td>
</tr>
<tr>
<td>30-40</td>
<td>$0.0347\pm0.0015\pm0.0071$</td>
<td>$0.0347\pm0.0015\pm0.0071$</td>
</tr>
</tbody>
</table>
Inclusive J/ψ cross section and B fraction

- The inclusive J/ψ differential cross-section as a function of $p_T$, integrated over the pseudorapidity range $|\eta|<2.4$, corresponding to an integral luminosity of 3pb$^{-1}$.
- Results of B fraction fit.
The prompt and non-prompt $J/\psi$ differential cross-section as a function of $p_T$, integrated over the pseudorapidity range $|\eta|<2.4$, corresponding to a integral luminosity of $3\text{pb}^{-1}$.

This study is expected to be the first physics paper with real collision data in CMS.
Cosmic Muon Study
Cosmic muon reconstruction

- The normal cosmic muon reconstruction contains one-leg track and two standalone muons.
- It can also be reconstructed as two splitted global muons:
  - two tracks and two standalone muons
  - up muon’s outer position $y>0$
  - down muon’s outer position $y<0$

Cosmic muon selection:
1. Good runs with B field on (3.8 T)
2. Events with 2 tracks in opposite hemispheres
3. Each track: $|d0|<10$ and $|dz|<40$

- Total 85 K events after selection

- Plot $\Delta p_T/p_T$, $\Delta \eta$, and $\Delta \phi$ of the two splitted tracks in bins of the one-leg muon’s $p_T$, $\eta$, $\phi$ and number of valid hits.
Muon resolution vs. $p_T$

\[ \frac{\Delta p_T}{p_T} \]

- Gaussian width of $p_T(\mu_{\text{up}}) - p_T(\mu_{\text{down}})$ divided by the center value and rescaled by $1/\sqrt{2}$ for single prong resolution.
  - the same to $\Delta \eta$ and $\Delta \phi$.

- The $p_T$ resolution is consistent with CMS PTDR (Physics Technical Design Report)!
Muon resolution vs. $N_{\text{hits}}$

The resolution as a function of $\eta$ and $\phi$ is in the back-up slides.

\[ \frac{\Delta p_T}{p_T} \]

\[ N_{\text{hits}}(\mu_{\text{up}}) + N_{\text{hits}}(\mu_{\text{down}}) \leq N_{\text{hits}}(\mu_{\text{one-leg}}) \]
Summary

- We present a feasibility study of the J/ψ cross section measurement with first data:
  1. Inclusive J/ψ cross section measurement
  2. B fraction fitting
  3. Misalignment effects are considered
  4. Systematic uncertainties are estimated.

- J/ψ in CMS:
  1. Mass resolution: $\sigma_{J/ψ} = 30$ MeV/c² ($|\eta| < 2.4$)
  2. Signal/Background: ~7 for J/ψ by requiring two muons $p_T > 3$ GeV/c
  3. Expected rates in $|\eta| < 2.4$: two muons $p_T > 3$ GeV/c, ~25K J/ψ per 1 pb⁻¹ (1.2 days @10³¹ cm⁻² s⁻¹)

- Splitted cosmic muons can be used to inspect the detector performance.
  - The tracker seems to behave very well.

The LHC will start at September 2009!
Thank you!
&Backup slides
Event Generation (1)

- COM $J/\psi$ generation were originally implemented by S. Wolf (2002, never in official release)
  - Based on NRQCD- approach
  - Singlet and octet QQ produced perturbatively, followed by shower
  - Parton showers for radiation off octet QQ

- In Pythia:
  - Code integrated (Sjöstrand): PYTHIA $\geq 6.324$
  - Possibility to dampen cross section at small PT like for $gg \rightarrow gg$ in underlying event (PYEVWT)
  - NRQCD matrix elements tuned (See Bargiotti, CERN-LHCb-2007-042)
NRQCD matrix elements

- Rates for all quarkonium processes given by NRQCD matrix elements
- Motivation of tuning: agreement MC↔data
- NRQCD matrix elements from: hep-ph/0003142
  - CSM values extracted from potential models (hep-ph/9503356)
  - COM values from CDF data
- Quark masses: $m_c = 1.5 \text{ GeV}$, $m_b = 4.88 \text{ GeV}$

See also talk by M. Bargiotti at HERA-LHC workshop 2006

| PARP(141) | $\langle O^{J/\psi}[^{3}S_1^{(1)}] \rangle$ | 1.16 |
| PARP(142) | $\langle O^{J/\psi}[^{3}S_1^{(8)}] \rangle$ | 0.0119 |
| PARP(143) | $\langle O^{J/\psi}[^{1}S_0^{(8)}] \rangle$ | 0.01 |
| PARP(144) | $\langle O^{J/\psi}[^{3}P_0^{(8)}] / m_c^2 \rangle$ | 0.01 |
| PARP(145) | $\langle O^{\chi_c 0}[^{3}P_0^{(1)}] / m_c^2 \rangle$ | 0.05 |
| PARP(146) | $\langle O^{\Upsilon}[^{3}S_1^{(1)}] \rangle$ | 9.28 |
| PARP(147) | $\langle O^{\Upsilon}[^{3}S_1^{(8)}] \rangle$ | 0.15 |
| PARP(148) | $\langle O^{\Upsilon}[^{1}S_0^{(8)}] \rangle$ | 0.02 |
| PARP(149) | $\langle O^{\Upsilon}[^{3}P_0^{(8)}] / m_b^2 \rangle$ | 0.02 |
| PARP(150) | $\langle O^{\chi_b 0}[^{3}P_0^{(1)}] / m_b^2 \rangle$ | 0.085 |
Event generation (2)

- Prediction of the differential cross-section of prompt $J/\psi$ and B decayed $J/\psi$ at LHC, 14TeV

- Prompt $J/\psi$: Use the tuned parameters and increase energy to 14TeV

- B decayed $J/\psi$: MSEL=1, QCD processes

Figure 3: Prompt and non-prompt $J/\psi$ differential cross sections in $pp$ collision at 14TeV integrated over the range $|\eta| < 2.4$. 
Update (1)

- Resolution function: to parameterize the prompt J/psi pseudo-proper decay length.

- Double Gaussian $G+G$: 5

- Triple Gaussian $G+G+G$: 8

- $G+G*E$: 6

- $G+G+E+E$: 7
Update (2)

- Non-J/psi QCD background life time fitting

\[
F_{Bkg}(\ell_{xy}) = \begin{cases} 
(1 - f_+ - f_- - f_{\text{sym}}) \cdot R(\ell_{xy}, \sigma) + \frac{f_+}{\lambda_+} e^{-\frac{\ell_{xy}}{\lambda_+}} \otimes R(\ell'_{xy} - \ell_{xy}, \sigma) \\
+ \frac{f_{\text{sym}}}{2\lambda_{\text{sym}}} e^{-\frac{\ell_{xy}}{\lambda_{\text{sym}}}} \otimes R(\ell'_{xy} - \ell_{xy}, \sigma) \\
(1 - f_+ - f_- - f_{\text{sym}}) \cdot R(\ell_{xy}, \sigma) + \frac{f_-}{\lambda_-} e^{\frac{\ell_{xy}}{\lambda_-}} \otimes R(\ell'_{xy} - \ell_{xy}, \sigma) \\
+ \frac{f_{\text{sym}}}{2\lambda_{\text{sym}}} e^{\frac{\ell_{xy}}{\lambda_{\text{sym}}}} \otimes R(\ell'_{xy} - \ell_{xy}, \sigma) 
\end{cases}
\]

when $\ell_{xy} > 0$, (26)  
when $\ell_{xy} < 0$, 

Background only
• Because of the small background statistics, I didn’t split them into pT bins but put them all into one bin:
  – Each pT bin will have different background level
  – Likelihood functions of the events in mass signal and mass side-band window are minimized simultaneously.

In pT bin 5-6 GeV/c, the background level $S/B = 2.35$

<table>
<thead>
<tr>
<th></th>
<th>fit (w bkg)</th>
<th>fit (w/o bkg)</th>
<th>MC input</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_b$</td>
<td>$0.212 \pm 0.019$</td>
<td>$0.178 \pm 0.012$</td>
<td>0.180</td>
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</tbody>
</table>
In pT bin 9-10 GeV/c, the background level $S/B = 16.7$

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<th>fit (w bkg)</th>
<th>fit (w/o bkg)</th>
<th>MC input</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_b$</td>
<td>$0.296 \pm 0.0047$</td>
<td>$0.299 \pm 0.0045$</td>
<td>0.295</td>
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</tbody>
</table>
In pT bin 20-24 GeV/c, the background level $S/B = 4.36$

<table>
<thead>
<tr>
<th></th>
<th>fit (w bkg)</th>
<th>fit (w/o bkg)</th>
<th>MC input</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_b$</td>
<td>0.454 ± 0.011</td>
<td>0.458 ± 0.009</td>
<td>0.457</td>
</tr>
</tbody>
</table>
Cosmic Muons
Muon resolution vs. $\eta$

$$\frac{\Delta p_T}{p_T}$$

$p_T$ resolution vs $\eta$

$\eta$ resolution vs $\eta$

$\phi$ resolution vs $\eta$
Muon resolution vs. $\eta$
Muon resolution vs. $N_{\text{hits}}$

\[
\frac{\Delta p_T}{p_T} = p_T \text{ resolution vs } N_{\text{hits}}
\]

\[
N_{\text{hits}}(\mu_{\text{up}}) + N_{\text{hits}}(\mu_{\text{down}}) \leq N_{\text{hits}}(\mu_{\text{one-leg}})
\]

The resolution as a function of $\eta$ and $\phi$ is in the back-up slides.