Heavy Quarks in CMS

Gerd J. Kunde
Heavy Quarks in CMS

- Detector
- Heavy Ion Program
  - LHC Performance
  - First Plots
- Proton-Proton Program
  - LHC Performance
  - Results
    - J/ψ
    - Upsilon
- Future
The Compact Muon Solenoid Detector

EM Calorimeter (ECAL)

Hadron Calorimeter (HCAL)

Tracker (Pixels and Strips)

Beam Scintillator Counters (BSC)

Forward Calorimeter (HF)

MUON (Barrel)

MUON (Endcaps)

The conceptual design of the CMS experiment dates back to 1992. The construction of the gigantic detector (15 m diameter by nearly 29 m long with a weight of 14000 tonnes) took 16 years of effort from one of the largest international scientific collaborations ever assembled: more than 3100 scientists and engineers from 169 institutions and research laboratories distributed in 39 countries all over the world.
Muon Detection: Drift Tubes – Cathode Strips – Resistive Plate Chambers
Muon Reconstruction cont.

- 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 magnetic field (3.8 T)

Two muon identifications:

- Global muon (outside-in):
  - High purity
  - Low efficiency for low momentum muon

- Tracker muon (inside-out):
  - Fake muon level high
  - Higher efficiency low momentum muon
Proton-Proton Dimuon Spectra

CMS Preliminary, $\sqrt{s} = 7$ TeV

$L_{\text{int}} = 280$ nb$^{-1}$

$\rho, \omega, \phi$, $\psi'$, $Y(1,2,3S)$

$\mu^+\mu^-$ mass (GeV/c$^2$)

$\mu^+\mu^-$ mass (GeV/c$^2$)

$\sqrt{s} = 7$ TeV, $L_{\text{int}} = 3.1$ pb$^{-1}$

electrons!
The Heavy Ion Run

CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173
Heavy Ion Data Taking with CMS

GREAT thanks to LHC Team

$7.36 \mu b^{-1} = 56.3 \text{ M}$
Heavy Ion Triggering on Collisions

- Maximize efficiency for high $p_T$ probes
  - Muons
  - Jets
  - Photons/Electrons

- Record large Minimum Bias sample

- Additional triggers
  - Ultra Peripheral Collisions
  - Background monitoring

- Minimize backgrounds
HI Event Selection

• Level 1 trigger
  – Coincidence of two scintillator counters OR
  – Coincidence of two HF towers
  – Muons

• High Level Trigger
  – Jets
  – Muons
  – Photons

• Offline
  – Veto on scintillator beam halo
  – At least 3 HF towers on each side above threshold (E > 3 GeV)
  – Reconstructed pixel vertex with two or more tracks
  – Beam-scraping removal with pixel cluster vertex compatibility
HI Minimum Bias Event Sample

CMS Preliminary

Non collision A

Non collision B

Sum HF energy (TeV)

# of 1st layer pixel hits
HI  Dileptons: Past and Future

Quarkonia should melt in the Quark Gluon Plasma...

• J/ψ suppression has been seen at SPS and RHIC
  – Details are not completely understood, interplay of cold and hot effects
  – Regeneration of J/ψ from the (large) number of uncorrelated cc pairs would be a golden probe at LHC

• Only order 100 Upsilon seen at RHIC
  – Successive melting of the three bound states could act as a thermometer

• Weak bosons have not been observed at RHIC
  – Test of nuclear PDFs
  – Standard candle for other processes
  – Future Z-tagging (high luminosity)

• CMS will be able to study all of the above in detail
HI: High $p_T$ $J/\psi \rightarrow \mu^+\mu^-$

![Graph showing the distribution of dimuon masses with high $p_T$.](image)

- **CMS Preliminary**
- **PbPb at $\sqrt{s_{NN}} = 2.76$ TeV**

**Global-Global**
- $|y| < 2.4$
- $p_T^{\text{Dimuon}}$ (GeV/c) [6.5, 30.0]

- **Opposite Charge**
- **Same Charge**
- $N_{J/\psi} \approx 200$
HI: High $p_T \ Upsilon \rightarrow \mu^+ \mu^-$

CMS Preliminary
PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

- $|y| < 2.4$
- $p_T^\mu > 4$ GeV

Events/(200 MeV/c^2)

Global-Global
- Opposite Charge
- Same Charge

$N_\Upsilon \approx 50$

Dimuon mass (GeV/c^2)
**HI: First Z⁰ → µ⁺µ⁻ Candidate**

CMS Experiment at LHC, CERN
Data recorded: Tue Nov 9 23:51:56 2010 CEST
Run/Event: 150590 / 776435
Lumi section: 183

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**First Z bosons detected by CMS in heavy-ion collisions**

November 18th 2010

Z bosons produced in collisions of heavy ions have been observed for the first time by the CMS experiment at CERN's Large Hadron Collider (LHC). CMS observed 10 events containing a distinctive candidate Z boson reconstructed from a pair of electrons or a pair of muons (see figures 1 and 2 respectively), whose invariant mass is consistent with the Z boson mass.
HI: $Z^0 \rightarrow \mu^+\mu^-$

CMS Preliminary
PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

Events/(2 GeV/c²)

Global-Global
$|y| < 2.4$

Opposite Charge

Same Charge

$N_{Z^0} = 27$

Dimuon mass (GeV/c²)
Proton-Proton Results

- LHC performance and mass spectrum
- $J/\psi$
  - Trigger selection
  - Efficiency, acceptance
  - Cross-sections
  - Non-prompt
- Upsilon
  - Data sample
  - Efficiency, acceptance
  - Cross-sections
p-p Dimuon Mass Spectrum

μ+μ- invariant mass

CMS Preliminary

$\sqrt{s} = 7$ TeV, $L_{\text{int}} = 40$ pb$^{-1}$

Used for the analyses shown here:
Submitted to EPJC
arXiv:1011.4193
Analysis with full 2010 statistics in progress.
p-p  Muon triggers

• Two trigger levels

  L1: hardware
  muon system and calorimeters only

  HLT: software
  Matching of different sub-detectors.
  Fast local track reconstruction for muons

Trigger requirements changing with increasing luminosity:

– Single muons:
  \( p_T > 3 \text{ GeV} \) threshold at the startup
  Gradually increasing (\( p_T > 7 \text{ GeV} \) at \( L \sim 10^{31} \text{ Hz cm}^{-2} \))

– Double muons:
  L1 requirements only at the startup, no \( p_T \) threshold

  allows to go down to zero quarkonium \( p_T \) in the forward region

At \( L \sim 10^{31} \text{ Hz cm}^{-2} \) new strategies adopted for quarkonia (combination of L1 and HLT muons, or HLT muon and track in specific invariant mass regions… etc.)
p-p J/$\psi$ Selection and Yields

- Selections:
  - Muons in acceptance window
  - Track quality ($n_{\text{hits}}$, $n_{\text{hits}}$ in pixels, $\chi^2$, $|d_{xy}|$, $|d_z|$)
  - Muon quality (global fit $\chi^2$, track-muon segment angular matching)
  - Di-muon vertex probability

- ~27000 events selected
CMS already reached a similar quality after 6 months of data taking and “debugging”

In a couple of weeks, with ~40 pb\(^{-1}\) on tape, CMS will be able to do the physics analyses with around **2.5 million** J/\(\psi\) dimuons, **after** offline quality selection cuts
p-p $J/\psi$ Acceptance

- Acceptance is determined from MC:
  
  $$A(p_T, y, \lambda_\theta) = \frac{N_{\text{det}}(p_T, y, \lambda_\theta)}{N_{\text{gen}}(p_T, y, \lambda_\theta)}$$

- Strongly dependent on polarization assumptions for the prompt component (polarization not well known)
- Agreement to give result in 5 scenarios:
  - Isotropic
  - Extreme values of $\lambda_\theta (= \pm 1)$ in the helicity frame (along the QQ momentum)
  - Extreme values of $\lambda_\theta (= \pm 1)$ in the Collins-Soper frame (along the collision axis)

- Main systematic uncertainties coming from:
  - $p_T$ smearing and calibration
  - Uncertainty on final state radiation spectrum

J/$\psi$ acceptance in isotropic scenario
Muon efficiency from data: the “tag-and-probe” method:
- Require one well-identified muon in the event (“tag”)
- Another candidate muon, with looser criteria, is paired to it (“probe”)
- Compare resonance yields for all tag-probe pairs and for pairs where the probes pass a given selection.
p-p  Inclusive J/ψ Cross-section

\[ \frac{d^2\sigma}{dp_T\,dy} \times B(J/\psi \rightarrow \mu\mu) = \frac{N_{\text{fit}} \left\langle \frac{1}{A \cdot \varepsilon} \right\rangle}{\int Ldt \cdot \Delta p_T \cdot \Delta y} \]

\[ \left\langle A \cdot \varepsilon \right\rangle = \text{average signal acceptance/efficiency in bin} \]

**Acceptance:** from MC simulation  
**Efficiency:** determined with tag and probe method from J/ψ events

### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative error (%)</th>
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<tr>
<td>[y] &lt; 1.2</td>
<td>0.8 – 2.5</td>
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<tr>
<td>1.2 &lt;</td>
<td>y</td>
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<tr>
<td>1.6 &lt;</td>
<td>y</td>
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<td>(p_T) calibration and resolution</td>
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<td>Kinematical distributions</td>
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<td>b-hadron fraction and polarization</td>
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<td>Muon efficiency</td>
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<tr>
<td>(\rho) factor</td>
<td>0.5 – 0.9</td>
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<tr>
<td>Fit function</td>
<td>0.6 – 1.1</td>
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</table>

\[ \sigma(pp \rightarrow J/\psi + X) \cdot BR(J/\psi \rightarrow \mu^+\mu^-) = 97.5 \pm 1.5(\text{stat}) \pm 3.4(\text{syst}) \pm 10.7(\text{luminosity}) \text{ nb} \]

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Measurement of prompt/non-prompt component with a 2D fit to mass and “pseudo”-proper decay length

\[ \ell_{xy} = \frac{L_{xy}^{J/\psi} \cdot M_{J/\psi}^{J/\psi}}{P_{T}^{J/\psi}} \]

\[ L_{xy} = \frac{\mu^{T} \sigma^{-1} x}{u^{T} \sigma^{-1} u} \]

\( L_{xy}^{J/\psi} \) is the transverse component of most probable decay length in lab system

Decay length parameterization:
- For prompt events, δ-function
- For non-prompt events, MC templates
- For background events a generic superposition of different contributions (symmetric + asymmetric with effective lifetimes)

all convoluted with 3-Gaussian resolution

Cross check with fit with the mean B-hadron lifetime left as a free parameter and found it to be \( t_B = 1.32 \pm 0.07 \text{ ps} \), where the error is statistical only, consistent with the world average
Systematics of the non-prompt fraction:

| Source                  | $|y|<1.2$ | $1.2<|y|<1.6$ | $1.6<|y|<2.4$ |
|-------------------------|---------|---------------|---------------|
| Tracker misalignment    | 0.5 – 0.7 | 0.9 – 4.6     | 0.7 – 9.1     |
| b-lifetime model        | 0.0 – 0.1 | 0.5 – 4.8     | 0.5 – 11.2    |
| Vertex estimation       | 0.3     | 1.0 – 12.3    | 0.9 – 65.8    |
| Background fit          | 0.1 – 4.7 | 0.5 – 9.5     | 0.2 – 14.8    |
| Resolution model        | 0.8 – 2.8 | 1.3 – 13.0    | 0.4 – 30.2    |
| Efficiency              | 0.1 – 1.1 | 0.3 – 1.3     | 0.2 – 2.4     |

Very little sensitivity to rapidity and energy ($>2$ TeV)
p-p Non-prompt $J/\psi$ Fraction cont.

No sensitivity to rapidity nor energy (>2 TeV)
p-p \ J/\psi \ Theory \ Comparison

- Only with models that include feed-down decays

  - PYTHIA

  - FONLL Cascade

  - Color Evaporation Model


Comparison only with models that include feed down from higher states
p-p Upsilon Data Sample

Apr-Sep run: \( \mathcal{L} = 10^{31} \text{cm}^{-2} \text{s}^{-1}, \int \mathcal{L} \, dt = 3.1 \pm 0.3 \text{ pb}^{-1} \)

Trigger: 2 muons at Hardware level, no \( p_T \) cut

Offline muon identification:

- track extrapolation matches hits in at least one \( \mu \)-chamber
- track momentum: \( p_T^{\mu} > 3.5 \) GeV if \( |\eta| < 1.6 \), \( p_T^{\mu} > 2.5 \) GeV if \( 1.6 < |\eta| < 2.4 \)
- track quality: \( n_{\text{hits}} \geq 12, n_{\text{pixel}} \geq 1, \chi^2 < 5 \cdot \text{Ndf}, d_{xy} < 0.2 \text{ cm}, d_{z} < 25 \text{ cm} \)

U selection

- two opposite-charge muons with \( 8 \leq M_{\mu\mu} < 12 \text{ GeV} \)
- probability of common vertex > 0.1%
- distance along \( Z < 2 \text{ cm} \)
- rapidity \( |y_{\mu\mu}| < 2 \)
p-p Upsilon Efficiency Correction

- Trigger Efficiency * Tracking Efficiency * Muon Identification

\[ \epsilon_{\text{total}} = \epsilon_{\text{trig|id}} \times \epsilon_{\text{id|track}} \times \epsilon_{\text{track|accepted}} \equiv \epsilon_{\text{trig}} \times \epsilon_{\text{id}} \times \epsilon_{\text{track}} \]

- Tag&Probe and embedding for J/psi sample (statistics)
p-p  Upsilon Acceptance Correction

• Via Geant4 simulation of the CMS detector using \the upsilon “particle gun”

• Very good acceptance even at low pt
• Fit epsilon/A corrected spectra in pt/eta bins
• Float yields, background shape parameters width and position of 1S peak
• Fix relative (1S) (2S,3S) mass difference to PDG

\[ \sigma_M(\Upsilon(1S)) = 96 \pm 2 \text{ MeV} \]

\[ \Upsilon(1S) : 7825 \pm 133 \]
\[ \Upsilon(2S) : 2279 \pm 91 \]
\[ \Upsilon(3S) : 1324 \pm 84 \]
p-p Upsilon Cross-section Results

\[
\frac{d\sigma (pp \to Y(nS))}{dp_T} \Bigg|_{|y|<2} B(Y(nS) \to \mu^+\mu^-) = \frac{N_{Y(nS)}^{\text{fit}}(p_T; A, \varepsilon_{\text{track}}, \varepsilon_{\text{id}}, \varepsilon_{\text{trig}})}{\mathcal{L} \cdot \Delta p_T}
\]

\[
\begin{align*}
\sigma(pp \to Y(1S)X) \cdot B(Y(1S) \to \mu^+\mu^-) &= (7.49 \pm 0.13(\text{stat.})^{+0.67}_{-0.49}(\text{syst.}) \pm 0.82(\text{lumi.})) \text{ nb,} \\
\sigma(pp \to Y(2S)X) \cdot B(Y(2S) \to \mu^+\mu^-) &= (1.93 \pm 0.08(\text{stat.})^{+0.19}_{-0.14}(\text{syst.}) \pm 0.21(\text{lumi.})) \text{ nb,} \\
\sigma(pp \to Y(3S)X) \cdot B(Y(3S) \to \mu^+\mu^-) &= (1.04 \pm 0.07(\text{stat.})^{+0.12}_{-0.09}(\text{syst.}) \pm 0.11(\text{lumi.})) \text{ nb.}
\end{align*}
\]

• Included Uncertainties
  – Detector effects
  – Statistics of the tag&probe sample
  – Luminosity (dominating)

• NOT Included
  – Polarization effects: +-20 % effect
**p-p Upsilon $p_T$-dependent Cross-section**

### Polarization Models

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<tr>
<th>$p_T$ (GeV/c)</th>
<th>$\sigma$</th>
<th>stat. / $\sigma$</th>
<th>$\sum_{\text{stat.}} / \sigma$</th>
<th>$\Delta \sigma / \sigma$</th>
<th>HX T</th>
<th>HX L</th>
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### Y(2S)

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<th>HX L</th>
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### Y(3S)

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<td>-18</td>
<td>+16</td>
<td>-21</td>
</tr>
<tr>
<td>6 - 9</td>
<td>0.25</td>
<td>14</td>
<td>11 (9)</td>
<td>21 (20)</td>
<td>+15</td>
<td>-20</td>
<td>+10</td>
<td>-13</td>
</tr>
<tr>
<td>9 - 14</td>
<td>0.16</td>
<td>12</td>
<td>10 (8)</td>
<td>19 (18)</td>
<td>+14</td>
<td>-20</td>
<td>-1</td>
<td>+2</td>
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<tr>
<td>14 - 20</td>
<td>0.05</td>
<td>17</td>
<td>11 (9)</td>
<td>23 (22)</td>
<td>+13</td>
<td>-18</td>
<td>-4</td>
<td>+9</td>
</tr>
<tr>
<td>20 - 30</td>
<td>0.03</td>
<td>20</td>
<td>13 (10)</td>
<td>26 (25)</td>
<td>+11</td>
<td>-16</td>
<td>-4</td>
<td>+9</td>
</tr>
</tbody>
</table>
p-p Upsilon Cross-section cont.
p-p Upsilon Theory Comparisons

- PYTHIA – FONLL Cascade - Color Evaporation Model


Little sensitivity of $p_t$ spectra to center of mass energy
Future

• For 7 TeV p-p collisions CMS collected a quarkonium event sample of around 2.5 M J/ψ and 100 000 Γ(1S) (only counting dimuons)
  • J/ψ and Upsilon polarization, in several p_T and y intervals, over a broad phase space
  • χ_c over J/ψ cross section ratio, using calorimeter-seeded photons
  • χ_{c1} over χ_{c2} cross section ratio, using tracker-seeded photon conversions

• For 2.76 TeV Pb-Pb collisions analyses of J/ψ and Upsilon are in progress and the first Z^0 paper is being written … plus there is a great future at higher luminosities