Heavy Flavour Physics at CMS and ATLAS
Moriond QCD and High Energy Interactions

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on behalf of the CMS and ATLAS collaborations

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Motivation

- At $\sqrt{s} = 10/14$ TeV expected $b\bar{b}$ cross section: $\sigma_{b\bar{b}} \approx 500 \mu b$
- CMS and ATLAS detectors are well suited for $B$ physics:
  - excellent tracking and muon systems and robust triggers for muons
- Known $b$ and onia decays provide good calibration
- Measurement right from startup up to high integrated $\mathcal{L}$:
  - Quarkonia ($J/\psi$ and $\Upsilon$) measurements
  - $b\bar{b}$ production cross section and correlations
  - Lifetime and properties of $b$ Hadrons: $B^+, B_d, B_s, B_c, \ldots$
  - $B_s$ oscillations and CP violation
  - Rare decays: $B_s \rightarrow \mu\mu, \ldots$

Details on CMS & ATLAS detectors: see talks on Sunday
Quarkonia studies
Quarkonia cross section measurement

**Motivation:**
- $J/\psi$ and $\Upsilon$ production mechanism not fully understood yet
- distinguish between prompt $J/\psi$ and $b \to J/\psi$ (BG for other channels)
- important for detector calibration and alignment

**Selection:**
- dimuon trigger:
  - CMS: 3+3GeV/c + inv. mass cut
  - ATLAS: 6+4GeV/c
- offline:
  - muons from common vertex
  - inv. mass cut
  - ATLAS: pseudo proper decay length cut

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**CMS Preliminary**

- $3\text{pb}^{-1}$
- $\sigma \sim 30\text{MeV}/c^2$

**ATLAS**

- $10\text{pb}^{-1}$
- no vertex and proper time cuts
- $\sigma \sim 53\text{MeV}$
- $\sigma \sim 161\text{MeV}$
extract $N(J/\psi)$ from the mass spectrum in each $p_T$ bin

determine prompt and non-prompt fraction with likelihood fit on pseudo proper decay length:

probe cross section beyond 20 GeV/c after 3pb$^{-1}$ for the first time:
better understanding of $J/\psi$ production
Quarkonia spin correlation @ ATLAS

- different predictions for polarisation $\alpha$ depending on production model
- polarisation can be determined with $\theta^*$:
  \[
  \frac{dN}{d\cos\theta^*} \propto \left( 1 + \alpha \cos^2 \theta^* \right)
  \]
- $\theta^*$ acceptance highly depends on trigger
- error on $\alpha$ for $10\text{pb}^{-1}$, $p_T = 12-21\text{GeV}/c$:
  - $J/\psi$: 0.02 - 0.06
  - $\Upsilon$: 0.2

<table>
<thead>
<tr>
<th>Sample</th>
<th>$p_T$, GeV</th>
<th>9 − 12</th>
<th>12 − 13</th>
<th>13 − 15</th>
<th>15 − 17</th>
<th>17 − 21</th>
<th>&gt; 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$, $\alpha_{\text{gen}} = 0$</td>
<td>$\alpha$</td>
<td>0.156</td>
<td>−0.006</td>
<td>0.004</td>
<td>−0.003</td>
<td>−0.039</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td>$\sigma, \text{nb}$</td>
<td>±0.166</td>
<td>±0.032</td>
<td>±0.029</td>
<td>±0.037</td>
<td>±0.038</td>
<td>±0.057</td>
</tr>
<tr>
<td>$J/\psi$, $\alpha_{\text{gen}} = +1$</td>
<td>$\alpha$</td>
<td>1.268</td>
<td>0.998</td>
<td>1.008</td>
<td>0.9964</td>
<td>0.9320</td>
<td>1.0217</td>
</tr>
<tr>
<td></td>
<td>$\sigma, \text{nb}$</td>
<td>±0.290</td>
<td>±0.049</td>
<td>±0.044</td>
<td>±0.054</td>
<td>±0.056</td>
<td>±0.088</td>
</tr>
<tr>
<td>$J/\psi$, $\alpha_{\text{gen}} = -1$</td>
<td>$\alpha$</td>
<td>−0.978</td>
<td>1.003</td>
<td>−1.000</td>
<td>1.001</td>
<td>−1.007</td>
<td>−0.996</td>
</tr>
<tr>
<td></td>
<td>$\sigma, \text{nb}$</td>
<td>±0.027</td>
<td>±0.010</td>
<td>±0.010</td>
<td>±0.013</td>
<td>±0.014</td>
<td>±0.018</td>
</tr>
<tr>
<td>$\Upsilon$, $\alpha_{\text{gen}} = 0$</td>
<td>$\alpha$</td>
<td>−0.42</td>
<td>−0.38</td>
<td>−0.20</td>
<td>0.08</td>
<td>−0.15</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>$\sigma, \text{nb}$</td>
<td>±0.17</td>
<td>±0.22</td>
<td>±0.20</td>
<td>±0.04</td>
<td>±0.18</td>
<td>±0.22</td>
</tr>
</tbody>
</table>

$\Upsilon$ polarisation at the Tevatron

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Heavy Flavour Physics at CMS and ATLAS
χ reconstruction @ ATLAS

- 30 - 40% of $J/\psi$ ($\Upsilon$) expected to come from $\chi_c \rightarrow J/\psi \gamma$ ($\chi_b \rightarrow \Upsilon \gamma$)

- $\chi_c \rightarrow J/\psi \gamma$:
  - reconstruct $\gamma$ in the event
  - angle between $J/\psi$ and $\gamma$ small
  - mass difference $\mu\mu\gamma - \mu\mu$ shows peak
  - $\epsilon(\text{reco}) \approx 4\%$

- $\chi_b \rightarrow \Upsilon \gamma$:
  - photon softer, more difficult to detect
  - $\epsilon(\text{reco}) \approx 0.03\%$

- $\chi_b \rightarrow J/\psi J/\psi$:
  - needs much more luminosity, at least $10fb^{-1}$
  - select two pairs of muons with $m(\mu\mu) \approx m(J/\psi)$
  - $\epsilon(\text{reco}) \approx 0.8\%$
$b$-production studies
Inclusive $b$ production @ CMS

**Motivation**
- large cross section
- different contributions to productions not fully clear (pair production, flavour excitation, gluon splitting)
- background to many other physics channels

**Selection**
- **trigger**: $\mu +$ jet trigger
- **offline**:
  - highest $p_T$ $b$-jet in event
  - $\mu$ associated to jet
  - use $p_T(\text{rel})$ to distinguish between $b$, $c$ and light quark jets

![Graph showing expected uncertainties on cross section]
**Motivation**
- clear event topology
- reference channel for rare decays
- allows detector performance studies

**Selection**
- **trigger:**
  - single muon trigger with 6 GeV/c
- **offline**
  - 2 muons with $p_T > 3(6)$ GeV/c
  - cuts on common vertex
  - $m_{\text{inv}}(\mu\mu) \approx m(J/\psi)$
  - additional track displaced from primary vertex ($K^+$)
  - cuts on $\mu\muK^+$ vertex
  - measurement in different bins of $p_T$
Study of $b\bar{b}$ correlations with $J/\psi$ and muons @ CMS

New and for $\sqrt{s} = 10$ TeV

**Motivation**
- muons easy to reconstruct at startup
- no dependence on b-tagging, calorimeter...

**Selection**
- dimuon trigger with $p_T > 3$ GeV/c
- offline
  - pair muons to $J/\psi$ candidate
  - 3rd muon required
  - signal extraction with unbinned likelihood on $M_{\mu\mu}$, $L_{xy}$ and $d_{xy}$
  - determine azimuthal angle between $J/\psi$ and $\mu$
  - unfold $\Delta\phi(J/\psi\mu)$ distribution to $\Delta\phi(b\bar{b})$ distribution

![Graph showing the distribution of events and unfolded $\Delta\phi$ for $b\bar{b}$ and $J/\psi\mu$]
$b$-decay studies
Motivation
- clear event topology
- $B_s \rightarrow J/\psi \phi$ very promising for LHC

Selection
- trigger:
  - dimuon trigger with $6 + 4$ GeV/c
  - offline
- 2 muons with $p_T > 6(4)$ GeV/c
- cuts on common vertex quality
- $m_{\text{inv}}(\mu \mu) \approx m(J/\psi)$
- two tracks to form $K^*$ ($\phi$)
- $m_{\text{inv}}(2\text{tracks}) \approx m(K^*)(m(\phi))$
- cuts on vertex and $p_T$ of $B_d$ ($B_s$)
- no cuts on decay length applied
- simultaneous fit on mass and lifetime
Motivation

- very clean signal channel
- measurement still not very precise

Selection

- dedicated trigger:
  - 2 muons
  - full decay reconstruction
- offline:
  - full decay reconstruction
  - kinematic vertex fit
  - angular analysis to extract $\Delta \Gamma_s$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>stat. error</th>
<th>sys. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_s$</td>
<td>0.0080 ps$^{-1}$</td>
<td>0.0227 ps$^{-1}$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$</td>
<td>0.0255 ps$^{-1}$</td>
<td>0.0113 ps$^{-1}$</td>
</tr>
</tbody>
</table>

Non SM $\phi_S$ measurable as well
Prospects for the measurement of $\Delta m_s$ @ ATLAS

- Use two fully hadronic decay modes:
  - $B_s \rightarrow D_s^- \pi^+ \rightarrow \phi(K^+K^-)\pi^-\pi^+$
  - $B_s \rightarrow D_s^- a_1^+ \rightarrow \phi(K^+K^-)\pi^-\rho(\pi^+\pi^-)\pi^+$

- Selection
  - single muon trigger + dedicated trigger for the hadronic $B_s$ decays
  - opposite side lepton flavor tag
  - amplitude scan

<table>
<thead>
<tr>
<th>L [fb$^{-1}$]</th>
<th>$5\sigma$ limit [ps$^{-1}$]</th>
<th>95% C.L. sensitivity [ps$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>14.5</td>
<td>25.0</td>
</tr>
<tr>
<td>5</td>
<td>17.0</td>
<td>27.0</td>
</tr>
<tr>
<td>10</td>
<td>20.5</td>
<td>29.6</td>
</tr>
<tr>
<td>20</td>
<td>23.7</td>
<td>32.0</td>
</tr>
<tr>
<td>30</td>
<td>25.3</td>
<td>33.2</td>
</tr>
<tr>
<td>40</td>
<td>26.4</td>
<td>34.1</td>
</tr>
</tbody>
</table>

$95\%$ CL sensitivity = 29.6 ps$^{-1}$
Measurement of the rare decay $B_s \to \mu\mu$

Motivation
- highly suppressed in SM: $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$
- sensitive to BSM through loop diagrams

Selection
- dimuon trigger
- offline
  - 2 muons
  - cuts on muon separation, isolation, decay length, $m_{\text{inv}}$

Event yields for 10fb$^{-1}$:

<table>
<thead>
<tr>
<th></th>
<th>signal</th>
<th>BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>5.7</td>
<td>$14^{+13}_{-10}$</td>
</tr>
<tr>
<td>CMS</td>
<td>6.1</td>
<td>$13.8^{+22.0}_{-13.8}$</td>
</tr>
</tbody>
</table>

Upper limit at 90% C.L.:
$\mathcal{B}(B_s \to \mu\mu) \leq 1.4 \cdot 10^{-8}$
Summary and Outlook

Summary

- ATLAS and CMS well prepared for heavy flavor analyses
- Analyses cover full luminosity range
- Most analyses based on robust muon detection and excellent tracking system
- SM tests with very first data

Outlook

- More topics studied
- Waiting for first collision data
Backup Slides
Backup: $J/\psi$ differential cross section @ CMS

Prompt $J/\psi$ cross section

CMS Preliminary

Prompt $J/\psi$: $\sqrt{s}=14\text{TeV}$, $|\eta|<2.4$

$\frac{d\sigma}{dp_T} \cdot \text{Br}(J/\psi \rightarrow \mu\mu)$ (nb/GeV/c)

- Fit result
- Monte Carlo

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Heavy Flavour Physics at CMS and ATLAS
quarkonium with the \( \mu 10 \) trigger

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>Events / 50 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>0</td>
</tr>
<tr>
<td>2.6</td>
<td>0</td>
</tr>
<tr>
<td>2.8</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>3.2</td>
<td>0</td>
</tr>
<tr>
<td>3.4</td>
<td>0</td>
</tr>
<tr>
<td>3.6</td>
<td>0</td>
</tr>
<tr>
<td>3.8</td>
<td>0</td>
</tr>
</tbody>
</table>

\( \Delta M = 3 \pm 3 \text{ MeV} \)
\( \sigma = 56 \pm 3 \text{ MeV} \)
\( p_T(J/\psi) > 9 \text{ GeV} \)

\( \Delta M = 3 \pm 5 \text{ MeV} \)
\( \sigma = 54 \pm 5 \text{ MeV} \)
\( p_T(J/\psi) > 17 \text{ GeV} \)
Acceptance for $\theta^*$

![Graph showing acceptance for $\theta^*$ with ATLAS, $\mu_6\mu_4$, and $\mu_{10}$]

MC truth: $\alpha=0$ (flat)
Backup: $\chi$ reconstruction @ ATLAS

$p_T$ of $\gamma$ in prompt $J/\psi$ events

opening angle

opening angle between photon and $J/\psi$ momentum
Backup: Inclusive $b$ production @ CMS

$p_T^{(rel)}$ spectrum

Number of events

Muon-BTagJet $p_T$ (GeV/c)
$B^+ \rightarrow J/\psi K^+$ production and properties @ ATLAS

(a) $10 \leq p_T < 18$ GeV

(b) $18 \leq p_T < 26$ GeV

(c) $26 \leq p_T < 34$ GeV

(d) $34 \leq p_T < 42$ GeV

ATLAS ATLAS
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Heavy Flavour Physics at CMS and ATLAS
Backup: $B_c \rightarrow J/\psi \pi$ @ CMS

Motivation
- ground state of $\bar{b}c$
- first observation in 1998 (CDF)
- still large uncertainties on lifetime

Selection
- 2 muons with $p_T > 4$ GeV/c
- cuts on common vertex quality
- $m_{\text{inv}}(\mu\mu) \approx m(J/\psi)$
- additional track as $\pi$
- cut on opening angle and decay length

Uncertainty on mass:
$\pm 25.0 \text{(stat)} \pm 14.9 \text{(sys)} \text{MeV}/c^2$

Uncertainty on lifetime:
$\pm 0.044 \text{(stat)} \pm 0.010 \text{(sys)} \text{ps}$