Quarkonium studies in p+p and Pb+Pb collisions with CMS

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Why to study Quarkonia at the LHC?

In Pb+Pb collisions:
• Debye screening in deconfined phase leads to melting of quarkonia when screening length exceeds binding radius
• Binding energy depends on quarkonium state and feed down from higher states lead to sequential suppression of J/ψ and Υ with increasing temperature
• It is important to measure quarkonium yields in Pb+Pb collisions as function of p_T and collision centrality

In p+p collisions:
• Base line for heavy ion collisions
• Cross section measurements
• Polarization

\[ T < T_c \]

\[ \psi' \]

\[ \chi_c \]

\[ (2S) \quad (1P) \quad (1S) \]

\[ \varepsilon(2S) \quad \varepsilon(1P) \quad \varepsilon(1S) \]

\[ \chi_b(2P) \quad Y(3S) \quad Y(2S) \quad Y(1S) \]

\[ \chi_b(1P) \]

\[ Y \text{ suppression pattern} \]

S.Digal et al., PRD64,094015
Quarkonia production at the LHC

The LHC will provide p+p and Pb+Pb collisions at high energies and luminosities:

• Early times should be with p+p collisions at 10 TeV with instantaneous luminosities between $10^{30}$ and $10^{31}$ cm$^{-2}$s$^{-1}$

• Depending on the machine performance, at some moment the energy will be increased to 14 TeV and the luminosity to $2 \times 10^{33}$ (low lumi) and $10^{34}$ cm$^{-2}$s$^{-1}$ (high lumi)

• The Pb+Pb runs will occur at 5.5 TeV per NN collision, with $4 \times 10^{26}$ cm$^{-2}$s$^{-1}$ Pb+Pb instantaneous luminosity

⇒ Quarkonium states will be produced at very high rates
A transverse slice of the CMS barrel

Si Tracker
Silicon micro-stripes and pixels

Calorimeters
- ECAL PbWO$_4$
- HCAL Plastic Sci/Steel sandwich

Muon Barrel
- Drift Tube Chambers (DT)
- Resistive Plate Chambers (RPC)
CMS phase-space coverage

- CMS: full $\phi$ and almost full $\eta$ acceptance at the LHC
- charged tracks and muons: $|\eta| < 2.4$
- electrons and photons: $|\eta| < 3$
- jets, energy flow: $|\eta| < 6.7$ (plus $|\eta| > 8.3$ for neutrals, with the ZDC)

- excellent granularity and resolution
- very powerful High-Level-Trigger
CMS is ideal to measure quarkonia in the dimuon decay channel:
- large rapidity coverage (|\eta|<2.4)
- excellent dimuon mass resolution

Good muon momentum resolution:
- matching between the tracks in the muon chambers and in the silicon tracker
- strong solenoidal magnetic field (4 T)

Because of the increasing material thickness traversed by the muons, the dimuon mass resolution changes with pseudo-rapidity, from ~15 MeV at \( \eta \sim 0 \) to ~40 MeV at \( \eta \sim 2.2 \)
Inclusive differential J/ψ cross sections in p+p collisions

- The observed J/ψ yield results from:
  - direct production
  - decays from ψ’ and χ_c states
  - decays from B hadrons (non-prompt)

- CMS will measure the inclusive, prompt, and non-prompt production cross sections

- CMS will collect ~ 25 000 J/ψ events in 1 or 2 days at 10^{31} cm^{-2}s^{-1} (\int L dt = 1 \text{ pb}^{-1})

- The J/ψ yield is extracted by fitting the dimuon mass distribution, separating the signal peak from the underlying background continuum
Inclusive differential $J/\psi$ cross sections

$$\frac{d\sigma}{dp_T^{J/\psi}} \cdot Br(J/\psi \rightarrow \mu^+ \mu^-) = \int L dt \cdot \Delta p_T^{J/\psi} \cdot A \cdot \lambda_{corr}$$

$A$ : convolution between the detector acceptance and the trigger and reconstruction efficiencies, which depend on the assumed polarization

$\lambda_{corr}$ : needed if MC description of trigger and offline efficiencies does not match “reality”

Competitive with Tevatron results after only 3 pb$^{-1}$
Quarkonium production in Pb+Pb collisions

\[ \Upsilon \rightarrow \mu^+ \mu^- \]

\[ \frac{dN_{\text{ch}}}{d\eta} = 3500 \]
\[ \Upsilon \rightarrow \mu^+ \mu^- : \text{acceptance and mass resolution} \]

- CMS has a very good acceptance for dimuons in the Upsilon mass region.

- The dimuon mass resolution allows us to separate the three Upsilon states:
  - \( \sim 54 \text{ MeV} \) within the barrel and
  - \( \sim 86 \text{ MeV} \) when including the endcaps.
\[ J/\psi \rightarrow \mu^+\mu^- : \text{acceptance and mass resolution} \]

- The material between the silicon tracker and the muon chambers (ECAL, HCAL, magnet’s iron) prevents hadrons from giving a muon tag but impose a minimum muon momentum of 3.5–4.0 GeV/c:
  - No acceptance problem for \( \Upsilon \) due to high mass
  - but for \( J/\psi \)'s this sets a relatively high threshold on the \( p_T \)

- The low \( p_T \) \( J/\psi \) acceptance is better at forward rapidities

\[
\begin{array}{c|c|c}
\text{J/ψ} & \text{Acceptance} & \text{\( p_T \) (GeV/c)} \\
\hline
\text{barrel + endcaps} & \text{\( \sigma_{\text{J/ψ}} = 35 \text{ MeV/c} \)} & \\
\text{barrel} & & \\
\end{array}
\]

\[
\frac{dN_{\text{ch}}}{d\eta}|_{\eta=0} = 2500
\]

\[ J/\psi \text{ barrel + endcaps} \quad (|\eta|<2.4) \]

\[ \sigma_{J/\psi} = 35 \text{ MeV/c}^2 \]
The High Level Trigger

• CMS High Level Trigger:
  12 000 CPUs of 1.8 GHz ~ 50 Tflops!
• Executes “offline-like” algorithms

• p+p design luminosity L1 trigger rate: 100kHz
• Pb+Pb collision rate: 3 kHz (peak = 8 kHz)
  ⇒ p+p L1 trigger rate > Pb+Pb collision rate
  ⇒ run HLT codes on all Pb+Pb events

• Pb+Pb event size: ~2.5 MB (up to ~9 MB)
• Data storage bandwidth: 225 MB/s
  ⇒ 10–100 Pb+Pb events / second
• HLT reduction factor: 3000 Hz → 100 Hz
• Average HLT time budget per event: ~4 s

• Using the HLT, the event samples of hard processes are statistically enhanced by considerable factors

Pb+Pb at 5.5 TeV design luminosity

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$p_T$ reach of quarkonia measurements

0.5 nb$^{-1}$ : 1 month at $4 \times 10^{26}$ cm$^{-2}$s$^{-1}$

Expected rec. quarkonia yields:

$J/\psi : \sim 180 000$  \  $\Upsilon : \sim 26 000$

Statistical accuracy (with HLT) of $\Upsilon' / \Upsilon$ ratio vs. $p_T$ should be good enough to rule out some models
Summary

• CMS has a high granularity silicon tracker, a state-of-the-art ECAL, large muon stations, powerful DAQ and HLT systems, etc.
  ⇒ excellent capabilities to study quarkonium production, in p+p and Pb+Pb
• Dimuon mass resolutions: ~30 MeV for the J/ψ; ~90 MeV for the Υ, over |η|<2.4
  ⇒ Good S/B and separation of Υ(1S), Υ(2S) and Υ(3S)
• Expected p+p rates:
  25 000 J/ψ and 7 000 Υ per pb⁻¹ (1 or 2 days at 10³¹ cm⁻²s⁻¹)
  ⇒ J/ψ and Υ dimuons up to pₜ ~ 40 GeV/c in a few days
• Expected Pb+Pb rates:
  180 000 J/ψ and 25 000 Υ(1S) per 0.5 nb⁻¹ (one month)
  ⇒ Studies of Upsilon suppression as signal of QGP formation
• J/ψ and Υ polarization, and χₖ → J/ψ + γ studies require larger samples

Further information can be found in:
http://cms.cern.ch/iCMS/ (“B-physics” and “Heavy-Ions” Physics Analysis Groups)
CMS recorded several splash events when the proton beam was steered onto the collimators; halo muons were observed once beam started passing through CMS detectors.looded by few hundred thousand muons resulting from $10^9$ protons (one bunch) simultaneous hitting a collimator.

Correlation between the energies collected in the HCAL and ECAL calorimeters from several “beam-collimator collisions”
Cosmic Muons in CMS

CMS recorded almost 300 million cosmic muons in one month of 24/7 running at full magnetic field and with all detectors operational.

A cosmic muon that traversed the barrel muon systems, the barrel calorimeters, and the silicon strip and pixel trackers.

Improved track quality in the strip tracker as the nominal design geometry is replaced by versions aligned with cosmic muons.

See http://www.cern.ch/cms-project-cmsinfo/ for more information.
Backup
Some numbers

### $B_{\mu\mu} \times \sigma_{\text{PbPb}}$ (μb)

<table>
<thead>
<tr>
<th></th>
<th>J/ψ</th>
<th>$\psi'$</th>
<th>$\Upsilon$</th>
<th>$\Upsilon'$</th>
<th>$\Upsilon''$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>48 900</td>
<td>880</td>
<td>300</td>
<td>80</td>
<td>44</td>
</tr>
</tbody>
</table>

### $dN_{\text{ch}}/d\eta|_{\eta=0}$, $\Delta \eta$

| $dN_{\text{ch}}/d\eta$ | $|\eta|< 2.4$ | $|\eta|< 0.8$ | $|\eta|< 2.4$ | $|\eta|< 0.8$ | $|\eta|< 2.4$ | $|\eta|< 0.8$ |
|--------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| S/B                      | 1.2            | 4.5            | 0.6            | 2.8            | 0.6            | 2.8            |
| N(J/ψ)                   | 184 000        | 11 600         | 146 000        | 12 600         | 146 000        | 12 600         |
| S/B                      | 0.12           | 0.97           | 0.07           | 0.52           | 0.07           | 0.52           |
| N($\Upsilon$)           | 26 000         | 6 400          | 20 300         | 6 000          | 20 300         | 6 000          |
| N($\Upsilon'$)          | 7 300          | 2 000          | 5 900          | 1 800          | 5 900          | 1 800          |
| N($\Upsilon''$)         | 4 400          | 1 200          | 3 500          | 1 100          | 3 500          | 1 100          |
Feed-down from B meson decays

An unbinned maximum likelihood fit is made, in $p_T$ bins, to determine the non-prompt fraction, $f_B$, using the dimuon mass and the pseudo proper decay length.

$$\ell_{xy} = \frac{L_{J/\psi}}{p_T} \frac{M_{J/\psi}}{P_{J/\psi}}$$

Systematic error dominated by luminosity and polarization uncertainties.
Y production in ultra-peripheral Pb+Pb collisions

- CMS will also measure Upsilon photo-production, occurring in collisions with impact parameters larger than the Pb nuclear radii
- This will allow us to study the gluon distribution function in the Pb nucleus
- Around 500 events are expected after 0.5 nb$^{-1}$, adding the e$^+e^-$ and $\mu^+\mu^-$ decay channels

Using neutron tagging in the ZDCs
Hard Probes at the LHC

- Experimentally & theoretically controlled probes of the early phase in the collision

- Very large cross sections at the LHC

- CMS is ideally suited to measure them

- Pb+Pb instant. luminosity: $10^{27}$ cm$^{-2}$s$^{-1}$
- $\int L \, dt = 0.5$ nb$^{-1}$ (1 month, 50% run eff.)
- Hard cross sections: Pb+Pb = $A^2 \times p+p$
  $\Rightarrow p+p$ equivalent $\int L \, dt = 20$ pb$^{-1}$
  $\Rightarrow$ 1 event limit at 0.05 pb (p+p equiv.)
Impact of the HLT on the $p_T$ reach of $R_{AA}$

Nuclear modification factor = AA-yield / pp-yield = “QCD medium” / “QCD vacuum”

$$R_{AA}(p_T) = \frac{d^2 N_{AA}/d^y dp_T}{\langle T_{AB}(b) \rangle \cdot d^2 \sigma_{pp}/d^y dp_T}$$

Important measurement to compare with parton energy loss models and derive the initial parton density and the medium transport coefficient
Jet $E_T$ reach and fragmentation functions

Jet spectra up to $E_T \sim 500$ GeV (Pb+Pb, 0.5 nb$^{-1}$, HLT-triggered)
⇒ Detailed studies of medium-modified (quenched) jet fragmentation functions
\( \gamma, \gamma^*, \) and \( Z \) tagging of jet production

Unique possibility to calibrate jet energy loss (and FF) with back-to-back gauge bosons (large cross sections and excellent detection capabilities).

Heavy quark dimuon (dominant) background can be rejected by a secondary vertex cut.

Resolutions: 50 mm in radius and 20 mm in \( \phi \)