Quarkonium production in 2.76 TeV PbPb collisions in CMS

– Guillermo Breto Rangel –
UC Davis
(for the CMS collaboration)

Winter Workshop on Nuclear Dynamics
April 11\textsuperscript{th}, 2012
1. Quarkonia are very “unusual” hadrons
   heavy quark (QQ) bound states stable under strong decay
   • heavy: $m_c \approx 1.2 - 1.4$ GeV, $m_b \approx 4.6 - 4.9$ GeV
   • stable: $M_{cc} - 2M_B \ll 0$ and $M_{bb} - 2M_D \ll 0$

What is “usual”?
   • light quark (q\bar{q}) constituents
   • loosely bound, $M_\rho - 2M_\pi \gg 0$, $M_\Phi - 2M_K \approx 0$
   • hadronic size $\sim 1/\lambda_{QCD} \approx 1$ fm, independent of mass

(At T = 0 Cornell potential gives full spectroscopy)
Sequential Melting

- Sequential Melting due to the Debye screening.
- Helps quantify medium properties (temperature)

Guillermo Breto Rangel - WWND 2012
The Compact Muon Solenoid

CMS DETECTOR

- Pixels Tracker
- ECAL
- HCAL
- Solenoid
- Steel Yoke
- Muons

**SILICON TRACKER**
- Pixels (100 x 150 µm²)
  - ~1m² ~66M channels
- Microstrips (80-180µm)
  - ~200m² ~9.6M channels

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
- ~76k scintillating PbWO₄ crystals

**PRESHOWER**
- Silicon strips
  - ~16m² ~137k channels

**SUPERCONDUCTING SOLENOID**
- Niobium-titanium coil carrying ~18000 A

**STEEL RETURN YOKE**
- ~13000 tonnes

**HADRÓN CALORIMETER (HCAL)**
- Brass + plastic scintillator
  - ~7k channels

**MUON CHAMBERS**
- Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

Total weight: 14000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T

Guillermo Breto Rangel - WWND 2102
• Global muons reconstructed with information from tracker and muon stations

• Muons need to overcome the magnetic field and energy loss in the absorber → need a minimum momentum of $p \approx 3–5$ GeV/c to reach the muon stations

• Further muon ID based on track quality ($\chi^2$, # hits,...)
$\Upsilon$ candidate in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

CMS Experiment at the LHC, CERN

Data recorded: 2010-Nov-12 03:55:57.236106 GMT (04:55:57 CEST)
Run / Event: 150887 / 1792020

$e^+e^-$ pair: mass: 9.46 GeV/c$^2$
$p_T$: 0.06 GeV/c
$p_T^{+}$: 4.74 GeV/c
$p_T^{-}$: 4.70 GeV/c

Hardware L1 Trigger + HLT
Dimuon trigger rate $\sim$ 30 Hertz

Trigger must be:
- Fast
- Flexible
- Efficient (95%)
- Redundant
Muon pairs in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV
J/ψ and Υ(1S) suppression in PbPb at 2.76 TeV

- Detailed paper based on 2010 data
- First measurements of Nuclear modification factor (R_{AA}) for:
  - non-prompt J/ψ (from B decays)
  - prompt J/ψ
  - Υ(1S)
- R_{AA} as a function of:
  - centrality: non-prompt J/ψ, prompt J/ψ, Υ(1S)
  - p_T: prompt J/ψ, Υ(1S)
  - rapidity: prompt J/ψ, Υ(1S)

\[
R_{AA} = \frac{L_{pp} \cdot N_{PbPb}(J/\psi)}{T_{AA} \cdot N_{MB} \cdot N_{pp}(J/\psi) \cdot \varepsilon_{pp} \cdot \varepsilon_{PbPb(cent)}}
\]
J/ψ in pp at $\sqrt{s} = 2.76$ TeV

- Reconstruct $\mu^+\mu^-$ vertex
- Simultaneous fit of $\mu^+\mu^-$ mass and pseudo-proper decay length

$$\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$
Prompt vs. non-prompt $J/\psi$ in PbPb

- First time that prompt and non-prompt $J/\psi$ have been separated in heavy ion collisions

arXiv:1201.5069
(submitted to JHEP)
Prompt $J/\psi$ $R_{AA}$ vs. $p_T$ and $y$

- CMS: $p_T > 6.5$ GeV/c
  - Factor 3 suppression for $p_T > 6.5$ GeV/c and at $y = 0$
  - Trend to less suppression at forward rapidity

$$R_{AA} = \frac{L_{pp}}{T_{AA}N_{MB}} \frac{N_{PbPb}(J/\psi)}{N_{pp}(J/\psi)} \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}(\text{cent})}$$

Global uncertainty from $L_{pp}$ and $T_{aa}$
Prompt $J/\psi$ $R_{AA}$ vs. $p_T$ and $y$

- CMS: $p_T > 6.5$ GeV/c
  - Factor 3 suppression for $p_T > 6.5$ GeV/c and at $y = 0$
  - Trend to less suppression at forward rapidity
- STAR: no suppression at high $p_T$
- PHENIX: lower $p_T$
  - opposite rapidity dependence


\[ R_{AA} \]

![Graph showing $R_{AA}$ vs. $p_T$ and $y$ for CMS, PHENIX, and STAR collaborations.]

\textbf{arXiv:1201.5069 (submitted to JHEP)}
Prompt $J/\psi$ $R_{AA}$ vs. centrality

- Prompt $J/\psi$:
  - 0-10% suppressed by factor 5 with respect to pp
  - 50-100% suppressed by factor $\sim 1.6$
- Similar suppression seen by PHENIX
  - though at lower $p_T$

[Graph showing $R_{AA}$ vs. $N_{\text{part}}$ for PbPb and AuAu collisions]

[arXiv:1201.5069 (submitted to JHEP)]
Prompt $J/\psi$ $R_{AA}$ vs. centrality

- STAR measures less suppression at high $p_T$

---

Guillermo Breto Rangel - WWND 2012
Prompt $J/\psi$ $R_{AA}$ vs. centrality

- ALICE: inclusive $J/\psi$, $p_T > 0$ GeV/c,
- Centrality 0–80%
  - $R_{AA} = 0.49 \pm 0.03 \pm 0.11$ (Pillot, QM2011)
- Careful when comparing $R_{AA}$ of prompt $J/\psi$ (CMS) and inclusive $J/\psi$ (ALICE)
  - In pp at low $p_T$: $\sim 10\%$ b-fraction
  - From RHIC we know that open charm cross section is unmodified (can assume the same for open bottom)
  - non-prompt $J/\psi$ could shift $R_{AA}$ by $10\%$

\[ PbPb \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

|y| < 2.4
6.5 < $p_T$ < 30 GeV/c

\[ R_{AA} \]

\[ N_{\text{part}} \]

```
\text{CMS: prompt } J/\psi \quad \text{ALICE: inclusive } J/\psi
\text{2.5 < } y < 4.0
\text{(arXiv:1202.1383)}
```

Guillermo Breto Rangel - WWND 2012

arXiv:1201.5069
(submitted to JHEP)
Prompt $J/\psi$ $R_{AA}$ vs. centrality

- Prompt $J/\psi$:
  - 0-10% suppressed by factor 5 with respect to pp
  - 50-100% suppressed by factor $\sim$1.6

- Kinetic Rate Equation Approach
  - Incorporates various effects.
  - Assumes strong binding scenario
  - Recombination negligible for $p_T$ > 6.5 GeV/c
  - Predict large suppression of primordial charmonia ($\sim$10 for central Pb-Pb collisions)

Zhao & Rapp, NPA 859 (2011) 114
Promp t J/ψ : Cold Nuclear Matter effects?

- Work in progress to estimate (anti)shadowing contributions
  - Two different nuclear parton distribution functions.
  - Traditional 2 -> 2 calculations include kT smearing.
  - Suppression beyond the reach of CNM effects.

Ferreiro et al. (preliminary)
• Suppression of non-prompt $J/\psi$ observed in min. bias and central PbPb collisions
  ‣ First indications of high-\(p_T\) b-quark quenching!

\textit{arXiv:1201.5069} (submitted to JHEP)
$\Upsilon(nS)$ in pp at $\sqrt{s} = 2.76$ TeV

- Signal shape: sum of three Crystal Ball functions
- Background: 2$^{nd}$ order polynomial
- Free parameters:
  - $\Upsilon(1S)$ mass
  - $\Upsilon(1S)$ yield
  - $\Upsilon(2S)/\Upsilon(1S)$ yield ratio
  - $\Upsilon(2S)/\Upsilon(1S)$ yield ratio
- Mass ratios of higher states fixed to PDG
- $\Upsilon(1S)$ resolution fixed from MC: 92 MeV/c$^2$
  - Consistent with fits when leaving resolution free (both in pp and PbPb)
- Resolution of higher states fixed to scale with mass ratio $\sigma_{2S} = m_{2S}/m_{1S}$ $\sigma_{1S}$
  - Crystal Ball radiative tail fixed to MC

$\mathcal{N}_{\Upsilon(1S)} = 101 \pm 12$

$\mathcal{R}(2S + 3S)/\mathcal{R}(1S)|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$
$\Upsilon(nS)$ in PbPb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

- Signal shape: sum of three Crystal Ball functions
- Background: 2$^{\text{nd}}$ order polynomial
- Free parameters:
  - $\Upsilon(1S)$ mass
  - $\Upsilon(1S)$ yield
  - $\Upsilon(2S+3S)/\Upsilon(1S)$ yield ratio
  - $\Upsilon(2S)/\Upsilon(1S)$ yield ratio
- Mass ratios of higher states fixed to PDG
- $\Upsilon(1S)$ resolution fixed from MC: 92 MeV/$c^2$
  - Consistent with fits when leaving resolution free (both in pp and PbPb)
- Resolution of higher states fixed to scale with mass ratio $\sigma_{2S} = m_{2S}/m_{1S}$ $\sigma_{1S}$
  - Crystal Ball radiative tail fixed to MC

$N_{\Upsilon(1S)} = 86 \pm 12$

$\Upsilon(2S + 3S)/\Upsilon(1S)|_{\text{PbPb}} = 0.24^{+0.13}_{-0.12} \pm 0.02$
$\Upsilon(2S+3S)$ Suppression

- Measure $\Upsilon(2S+3S)$ production relative to $\Upsilon(1S)$ production

- Simultaneous fit to pp and PbPb data at 2.76 TeV

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)}{\Upsilon(2S+3S)/\Upsilon(1S)}_{|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)}{\Upsilon(2S+3S)/\Upsilon(1S)}_{|_{PbPb}} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

---

PRL 107 (2011) 052302

Guillermo Breto Rangel - WWND 2012
Could background fluctuation produce a result as extreme as observed in data?

- Generate pseudo-experiments following the *null-hypothesis* (i.e. no suppression)
- Fit pseudo-data samples with nominal fit
- Count fraction of occurrences for which the ratio (taken as test statistic) is same or lower than observed:
  - $p$-value: 0.9%
  - $2.4\sigma$ (1-sided Gaussian test)
• \(\Upsilon(1S)\) suppressed at low \(p_T\)
• No obvious rapidity dependence
• CMS: \(\Upsilon(1S)\)
  ‣ suppressed by factor \(\sim 2.2\) in \(0–10\%\)
• Large feed down contribution from excited states (\(\chi_b, \Upsilon(2S), \Upsilon(3S)\))
  ‣ Observed \(\Upsilon(1S)\) suppression consistent with melting of excited states only

\[
R_{AA} = \frac{L_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}(\Upsilon(1S))}{N_{pp}(\Upsilon(1S))} \frac{\varepsilon_{pp}}{\varepsilon_{PbPb(cen)}}
\]

\[\text{arXiv:1201.5069}
\]

(submitted to JHEP)
Guillermo Breto Rangel - WWND 2012
• $\Upsilon(1S)$ suppressed at low $p_T$

• No obvious rapidity dependence

• CMS: $\Upsilon(1S)$
  ‣ suppressed by factor $\sim 2.2$ in 0–10%

• STAR measures
  ‣ for CMS (0–100%):

$$R_{AA}(\Upsilon(1S + 2S + 3S)) = 0.56 \pm 0.21^{+0.08}_{-0.16} \quad (\text{arXiv:1109.3891})$$

$$R_{AA}(\Upsilon(1S + 2S + 3S)) = R_{AA}(\Upsilon(1S)) \times \frac{1 + \Upsilon(2S + 3S)/\Upsilon(1S)|_{\text{PbPb}}}{1 + \Upsilon(2S + 3S)/\Upsilon(1S)|_{\text{pp}}}$$

$$= 0.63 \times \frac{1 + 0.24}{1 + 0.78} \approx 0.44 \quad (\text{arXiv:1201.5069})$$

(submitted to JHEP)
\( \Upsilon(1S) \) \( R_{AA} \)

- \( \Upsilon(1S) \) suppressed at low \( p_T \)
- No obvious rapidity dependence
- A lot of activity on the theory side
Summary

- In PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
- Prompt $J/\psi$ suppressed
- $\Upsilon(2S+3S)$ suppressed relative to $\Upsilon(1S)$
  - Observed $\Upsilon(1S)$ suppression consistent with melting of excited states only
- $J/\psi$ from B decays suppressed
Outlook

- Recorded 150 \( \mu b^{-1} \) in 2011
  - including a double muon trigger without \( p_T \) cut
    (muon \( p_T \) reach limited only by acceptance)
- Will be able to study quarkonia in PbPb collisions in much more detail
  - Double differential measurements of prompt \( J/\psi \) \( R_{AA} \)
  - Precise measurement of excited \( \Upsilon \) states double ratio
  - \( R_{AA} \) of \( \Upsilon(nS) \) states
  - Map centrality and \( p_T \) dependence of b-quark energy loss with non-prompt \( J/\psi \)
Backup
Tag & Probe

- Tracking efficiency:
- Tag: high quality muon
- Probe: track in the muon station
- Passing Probe:
  - Probe that is also reconstructed as global muon (i.e. with a track in the Si-tracker)
- Reconstruct J/ψ peak in passing probe-tag pairs and in failing probe-tag pairs
- Simultaneous fit to passing and failing probes allows us to measure the efficiency of the inner track reconstruction
- Agreement within stat. uncertainty of data
  → 14% systematic uncertainty on data/MC agreement
  - dominant systematic uncertainties on cross section results in PbPb
Separate prompt & non-prompt $J/\psi$

HI tracking algorithm uses vertex constraint
  - Smaller efficiency for non-prompt than for prompt $J/\psi$
  - Effect increases with $p_T$

Efficiencies from Monte Carlo
  - Simulate signal with “realistic” PYTHIA
  - Embed signal in min. bias event simulated with HYDJET (also in data)
  - Validated MC by comparing efficiencies measured with “Tag & Probe” in MC and data
Y(2S+3S) Suppression

With 2011 data:

- Confirm suppression of excited states with higher precision
- Measure double ratio as a function of centrality, $p_T$...
**Y(1S) Acceptance and Efficiency**

- **Acceptance**
  - Efficiencies from Monte Carlo
    - Validated with data driven method (Tag & Probe)
  - Acceptance to $p_T = 0$ GeV/c

- **Efficiency**

---

CMS Simulation
PYTHIA + EvtGen + PHOTOS
$pp \sqrt{s} = 2.76$ TeV

$Y(1S)$

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

- Efficiencies from Monte Carlo
  - Validated with data driven method (Tag & Probe)
- Acceptance to $p_T = 0$ GeV/c
$J/\psi$ in pp at $\sqrt{s} = 7$ TeV

- Uncorrected for acceptance
\( \psi (2S) \) in pp at \( \sqrt{s} = 7 \text{ TeV} \)

- Uncorrected for acceptance
Y(2S+3S) Suppression

• Systematic uncertainty: 9.1%
• Statistical uncertainty: 55%
• Null-hypothesis testing:
  ‣ p-value = 1%
  ‣ Significance of suppression is 2.4 \( \sigma \)
• Relative suppression of Y(2S+3S) vs. Y(1S)
  ‣ Observation consistent with melting of the excited states only?
• What about cold nuclear matter effects?
  ‣ Shadowing cancelling in the Y(2S+3S)/Y(1S) ratio
  ‣ pA run?
• \( \Upsilon(1S) \) suppressed at low \( p_T \)
• No obvious rapidity dependence
• CMS: \( \Upsilon(1S) \)
  ‣ suppressed by factor \( \sim 2.2 \) in 0–10%
• M. Strickland calculates \( \Upsilon(1S) \) and \( \chi_b \) \( R_{AA} \) (arXiv:1106.2571)
  ‣ For feed down: no explicit calculation of \( \Upsilon(nS) \) \( R_{AA} \): assume all states as suppressed as the \( \chi_b \)
  ‣ Rapidity and centrality dependence in good agreement, but misses suppression at low \( p_T \)
\( J/\psi \) in ultra-peripheral PbPb collisions

- Only two tracks in the event (the two muons), barely any energy in the calorimeters, and classified in the 2.5% most peripheral collision bin for heavy ions
Muon pairs in pp at $\sqrt{s} = 7$ TeV
• Prompt $J/\psi$ well described by NRQCD
• Open heavy-flavour:
  ․ Non-prompt $J/\psi$ fall faster at high $p_T$ than expected from FONLL

[CMS-BPH-10-014](http://example.com)
[arXiv:1111.1557](http://example.com)
(accepted by JHEP)
• Prompt $\psi(2S)$ well described by NRQCD

• Open heavy-flavour:
  
  ‣ Non-prompt $\psi(2S)$ overestimated by FONLL (however, large uncertainty on BR(B→$\psi(2S)$X))
    
    • falls faster with $p_T$ than expected from FONLL

CMS-BPH-10-014
arXiv:1111.1557
(accepted by JHEP)
$\chi_c$ in pp at $\sqrt{s} = 7$ TeV

- Measured radiative decay: $\chi_c \rightarrow J/\psi \gamma$
- Photon measured by reconstructing $e^+e^-$ conversion pairs
  - Excellent mass resolution → separating $\chi_{c1}$ and $\chi_{c2}$
  - Hint of $\chi_{c0}$

CMS DPS 2011-011
• Separation of the 3 $\Upsilon$ states with good mass resolution

• PYTHIA agrees in shape, but not in normalisation
  ‣ Total cross section overestimated by about a factor 2