Bottomonium first results from LHC experiments

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for the LHC Collaborations

Hadron2011
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introduction
• LHC
• motivations

di-lepton signals
• $\mu\mu, ee$ spectra
• detector resolution

pp @ 7TeV
• data-driven efficiency
• cross section
• prospects

PbPb @ 2.76 TeV
• $R_{AA}$, cross section
• $\gamma'$ suppression
LHC luminosity

pp@\(7\) TeV

2011 (2010)  
ATLAS, CMS: \(L \sim 1k\) (40) pb\(^{-1}\)  
LHCb: \(L \sim 300\) (40) pb\(^{-1}\)  
ALICE: \(L \sim 2\) (<1) pb\(^{-1}\)

L\(_{pp}\) \(\approx 10^{30} - 10^{33}\) cm\(^{-2}\) s\(^{-1}\)

pp@\(2.76\) TeV

ATLAS, CMS: \(L \sim 241\) nb\(^{-1}\)  
LHCb: \(L \sim 67\) pb\(^{-1}\)  
ALICE: \(L < 1\) pb\(^{-1}\)

PbPb@\(2.76\) TeV

ALICE, ATLAS, CMS: \(L \sim 9\) \(\mu\)b\(^{-1}\)  
LHCb: n/a

L\(_{PbPb}\) \(\approx 10^{25} - 10^{27}\) cm\(^{-2}\) s\(^{-1}\)
ALICE, ATLAS, CMS, LHCb
LHC experiments (cont’d)

- all four detectors have the capability to study bottomonia
- complementary phase space and physics coverage
  - e.g. central vs forward rapidities, pp vs heavy-ion environments
- based on different: B field, detector technologies, DAQ capabilities, emphasis on hermeticity or particle ID
then... & now

Fermilab, Summer 1977

CERN, Summer 2010

... a spectroscopists delight!
large set of results

BaBar: $\Upsilon(3S) \to \eta_b(1S) \gamma$

Belle: $\Upsilon(5S) \to \Upsilon(2S) \pi\pi$

(Bottomonium-like exotica: 2 charged states just above open beauty $B^*B$, $B^*B^*$ thresholds)

CESR- 1980/90s CUSB, CLEO

PEP-II/KEKB-2000s BaBar, Belle

Tevatron-2000s CDF, D0

D0
1.3 fb$^{-1}$

CDF
2.9 fb$^{-1}$

$Z_b \to \Upsilon(nS) \pi^\pm$

$\sigma(e^+e^- \to \eta_b(1S))$
bottomonium spectroscopy

**direct production**

\[ pp \to b\bar{b} + X \]

\[ \Upsilon(1S) + X \]

**indirect production**

contribution from feed down transitions from heavier bottomonia

\[ pp \to b\bar{b} + X \]

\[ \Upsilon_b \to \Upsilon(1S) + \gamma \]

\[ \Upsilon(n'S) \to \Upsilon(1S) + X \]

\[ \rightarrow 30-50\% \text{ of full } \Upsilon(1S) \text{ productions} \]

no contribution from long-lived states

\[ \Gamma(\Upsilon(nS)) \sim 20-50 \text{ KeV} \]

\[ \text{BR}(\Upsilon(1S)\to\mu\mu) = (2.48\pm0.05)\% \]

\[ \text{BR}(\Upsilon(2S)\to\mu\mu) = (1.93\pm0.17)\% \]

\[ \text{BR}(\Upsilon(3S)\to\mu\mu) = (2.18\pm0.21)\% \]
phenomenology

- heavy quarkonia constitute an ideal laboratory for testing interplay between perturbative and non-perturbative QCD
- bottomonium (and in general, quarkonium) production not satisfactorily understood
  ‣ theoretically and experimentally puzzling
- no theory has simultaneously explained Tevatron measurements of both cross section and polarization
  ‣ non-relativistic QCD (incl. color octet), color singlet model, color evaporation model, etc

(notes: drastic change of CSM predicted polarization from LO to NLO/NNLO*)

(note: NNLO* is not a complete NNLO, possibility of large uncanceled logs)
bottomonía at the LHC?

• phenomenology
  ‣ large $b$-quark mass $\Rightarrow$ non-relativistic effective approaches better realized
  ‣ no feed-down from long-lived $b$-hadrons

• unprecedented energy regime
  ‣ extended reach, eg probe $p_T > 20$GeV, best discriminate between models
  ‣ high cross section (and luminosity) $\Rightarrow$ bottomonía produced copiously
  ‣ allow new era of bottomonium precision measurements

• heavy ion
  ‣ 1 month per year dedicated to heavy-ion physics run
  ‣ cross sections $\sim 50$ times larger, energy density $\sim 3$ times higher than at RHIC $\Rightarrow$ will allow first significant measurements of the $\Upsilon$ resonance family
  ‣ improve overall understanding of the cold and hot nuclear matter effects
  ‣ LHC calls for precision studies of bottomonía at high temperature
di-lepton signals
LHCb Preliminary

\begin{align*}
\sqrt{s} &= 7 \text{ TeV} \\
\int L &= 32.4 \text{ pb}^{-1} \\
N_\Upsilon &\approx 48k
\end{align*}
$N\Upsilon \approx 23k$
CMS Preliminary, $\sqrt{s} = 7$ TeV

$N_\gamma \approx 138k$ ($|\eta| < 2.4$)

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

CMS Preliminary 2010

$\sqrt{s} = 7$ TeV, $L_{\text{int}} = 35$ pb$^{-1}$

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

$N_{\text{1S}} = 23,390 \pm 194$

$N_{\text{1S}} = 7,298 \pm 133$

$N_{\text{1S}} = 3,999 \pm 113$

$PbPb@2.76\text{TeV}$

$P_{T>4.0}$ GeV/c

$N_{\Upsilon} = 138k$ ($|\eta| < 2.4$)
momentum/mass resolution

$\sigma \sim 94\text{MeV}$

$\sigma \sim 46\text{MeV}$ (up to 110 MeV at higher rapidities)

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$\sigma \sim 94\text{MeV}$

$\sigma \sim 46\text{MeV}$ (up to 110 MeV at higher rapidities)

$\sigma \sim 21\text{MeV}$ (up to 50 MeV at higher rapidities)

$\sigma \sim 13\text{ MeV}$

LHCb

LHCb

LHCb

CMS

CMS

CMS

CMS

CMS

CMS

CMS

CMS

CMS

CMS

CMS

CMS

CMS

CMS

CMS
prior expectations (before LHC startup)

ALICE simulation

CMS simulation

ATLAS simulation

LHCb simulation

\[ \sigma = 54 \text{ MeV}/c^2 \]

Resolution ~ 37 MeV
PP @ 7TeV

- LHCb-CONF-2011-016, 32pb⁻¹
- CMS-BPH-10-003 (arXiv:1012.5545,PRD), 3pb⁻¹

▶ see also talks by B.Akgun and G.Sabatino on Tuesday parallel session Quarkonia/3
Cross-section ingredients

\[ \frac{d^2\sigma}{dp_Tdy} \cdot B(Y(nS) \rightarrow \mu^+\mu^-) = \frac{N_{Y(nS)}^{fit}(A_\epsilon)}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y} \]

Acceptance

CMS

LHCb

Efficiency

CMS

LHCb

Signal yields

Polarization:
$\Upsilon(nS)$ differential cross sections

LHCb

$\sigma(pp \rightarrow \Upsilon(1S) X; 0 < p_T < 15 \text{ GeV/c}, 2 < y < 4.5) = 108.3 \pm 0.7^{+30.9}_{-25.8} \text{ nb}$

CMS (unpolarized case)

$\langle |y| < 2 \rangle$

$\sigma(pp \rightarrow \Upsilon(1S) X) \cdot B(\Upsilon(1S) \rightarrow \mu^+ \mu^-) = 7.37 \pm 0.13 \text{ (stat.)}^{+0.61}_{-0.42} \text{ (syst.)} \pm 0.81 \text{ (lumi.)} \text{ nb}$

$\sigma(pp \rightarrow \Upsilon(2S) X) \cdot B(\Upsilon(2S) \rightarrow \mu^+ \mu^-) = 1.90 \pm 0.09 \text{ (stat.)}^{+0.20}_{-0.14} \text{ (syst.)} \pm 0.24 \text{ (lumi.)} \text{ nb}$

$\sigma(pp \rightarrow \Upsilon(3S) X) \cdot B(\Upsilon(3S) \rightarrow \mu^+ \mu^-) = 1.02 \pm 0.07 \text{ (stat.)}^{+0.11}_{-0.08} \text{ (syst.)} \pm 0.11 \text{ (lumi.)} \text{ nb}$

$\Upsilon(2S)/\Upsilon(1S): 0.26 \pm 0.02 \pm 0.04$

$\Upsilon(3S)/\Upsilon(1S): 0.14 \pm 0.01 \pm 0.02$
comparison: theory


P. Artoisenet et al., PRL101, 152001, 2008


N. Leonardo HADRON’2011 bottomonia@LHC, 20
**Comparison: Experiment**

- CMS 3.1 pb⁻¹
- LHCb 32.4 pb⁻¹

**BR(Ψ(1S) → μ⁺μ⁻)**

\[ \frac{dN}{d\phi_{T}} \propto \left[ 1 + \frac{\phi_{T}}{\langle \phi_{T} \rangle} \right]^n \]

\( \sqrt{s} = 7 \text{ TeV} \)

**Γ(1S)**

- **LHC**

**LHC vs. Tevatron**

- CMS, |y| < 2, \( \sqrt{s} = 7 \text{ TeV} \)
- DØ, |y| < 1.8, \( \sqrt{s} = 1.96 \text{ TeV} \)
- CDF, |y| < 0.4, \( \sqrt{s} = 1.8 \text{ TeV} \)

**Γ(2S)**

- CMS, |y| < 2, \( \sqrt{s} = 7 \text{ TeV} \)
- CDF, |y| < 0.4, \( \sqrt{s} = 1.8 \text{ TeV} \)

**Γ(3S)**

- CMS, |y| < 2, \( \sqrt{s} = 7 \text{ TeV} \)
- CDF, |y| < 0.4, \( \sqrt{s} = 1.8 \text{ TeV} \)

**LHC Preliminary**

\( \sqrt{s} = 7 \text{ TeV} \)

**LHCb**

- Data (p_T < 15 GeV/c)
- CMS 3 pb⁻¹ (p_T < 30 GeV/c)

**HADRON'2011**
polarization

- detector acceptance sensitive to unknown polarization \( \sigma(\Upsilon) \) variations of about 20%
- measure full angular distribution of leptons
  \[
  \frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin 2\theta \cos \phi + \lambda_\phi \sin^2 \theta \cos 2\phi
  \]
- in complementary reference frames
- also frame independent
  \[
  \bar{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}
  \]
- results binned in \( p_T \) and rapidity
- measurements being currently finalized

Acceptance test \( \bar{\lambda} \)'s
other measurements, prospects

- prompt bottomonium reconstruction includes feeddown from higher states
  - eg 40-50% of \( \Upsilon(1S) \) production from decays of excited 2S,2P,3S states [CDF, PRL84 (2000) 2094]
  - desirable to separate direct production
  - eg reconstruct \( \chi_b \rightarrow \Upsilon \gamma \) decays
    - (plots show examples already achieved for charmonia)
- search for exotica, bottomonia-like states?
-⇒ more data required
PbPb @ 2.76 TeV

- CMS-PAS-HIN-10-006

aka. Upsilon suppression.
**bottomonia as QGP probe**

- at high temperatures, strongly interacting matter becomes a plasma of quarks and gluons
- suppression of quarkonia is a classical prediction of QGP signature
  ‣ color screening of the binding potential \[ T.Matsui, H.Satz PLB178, 416 (1986) \]
  ‣ suppression pattern indicates the medium temperature (‘QGP thermometer’)
  ‣ role of cold nuclear matter effects also emphasized at SPS and RHIC
- bottomonium measurements at LHC help characterize the dense matter produced in heavy-ion collisions beyond the SPS and RHIC charmonium results
  ‣ the \( \Upsilon \) family of states is an expected powerful probe
  ‣ \( \Upsilon(1S) \) is the most tightly bound state \( \triangleright \) last to melt down
  ‣ provide 3 different states/handles for probing the hot medium
- quantitative bottomonium measurements accessible for first time
  ‣ large production rates \( \triangleright \) sizable datasets
  ‣ exploit excellent mass resolution

- \[ \frac{T}{T_C} \]

\[ \frac{1}{\langle r \rangle} [\text{fm}^{-1}] \]

<table>
<thead>
<tr>
<th>State</th>
<th>( \Upsilon(1S) )</th>
<th>( \chi_b(1P) )</th>
<th>( \Upsilon'(2S) )</th>
<th>( \chi_b'(2P) )</th>
<th>( \Upsilon''(3S) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m ) (GeV/c^2)</td>
<td>9.46</td>
<td>9.99</td>
<td>10.02</td>
<td>10.26</td>
<td>10.36</td>
</tr>
<tr>
<td>( r_0 ) (fm)</td>
<td>0.28</td>
<td>0.44</td>
<td>0.56</td>
<td>0.68</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Sequential melting

\[ T_C \sim 150-170 \text{MeV} \]
PbPb run 2010 @2.76 TeV (7.28 μb^-1)  

- same online+offline selection applied to both datasets  
- muon selection: quality cuts,  
\[ p_T > 4 \text{ GeV/c}, \ |\eta| < 2.4 \]  

pp run 2011 @2.76 TeV (225 nb^-1)
invariant yields
$\Upsilon(1S)$ invariant yields in PbPb

- **Systematic uncertainties**
  - yield extraction: 8-14%
  - acceptance: 1-5%
  - efficiency: 14%
  - $T_{AA}$: 4.3-15%
- **Statistical uncertainties**: 5-20%
nuclear modification factor, $R_{AA}$

$$R_{AA} = \frac{\mathcal{L}_{pp}^{int}}{T_{AA} N_{MB}} \frac{N_{PbPb}^{PpPb}}{N_{pp}^{PpPp}} \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}(cent)}$$

- $N_{PbPb} = 86 \pm 12^{[\text{stat}]} \pm 3^{[\text{syst}]}$
- $N_{pp} = 101 \pm 12^{[\text{stat}]} \pm 3^{[\text{syst}]}$
- $T_{AA} = 5.66 \text{ mb}^{-1}$
- $N_{MB} = 55.7 \text{M MB PbPb collisions}$
- $L_{pp} = 225 \text{ nb}^{-1}$

- $R_{AA}(1S)$ in 20% most central bin
  - $0.60 \pm 0.12^{\text{stat.}} \pm 0.10^{\text{syst.}}$

- 1S yields affected by large feeddown
- suppression might be due to melting of excited states (2S, 2P, 3S)
• 1S inclusive (minimum bias) $R_{AA}$
  ‣ $0.62 \pm 0.11_{\text{stat.}} \pm 0.10_{\text{syst.}}$

• no clear dependency on rapidity or centrality; high $p_T$ not as suppressed?

• will be answered with more data
  ‣ also separate 2S, 3S measurements
$\Upsilon(2S+3S) \text{ vs } \Upsilon(1S)$

- measure fraction of excited states $\Upsilon(2S+3S)$ relative to $\Upsilon(1S)$
- extracted directly from fit to PbPb and pp data samples

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

$\frac{\Upsilon(2S+3S)}{\Upsilon(1S)}_{\text{pp}} = 0.78^{+0.16}_{-0.14} \pm 0.02$
• extract double ratio directly from simultaneous fit to both samples

\[ \chi = \frac{\gamma(2S+3S)/\gamma(1S)}{\gamma(2S+3S)/\gamma(1S)} \bigg|_{\text{PbPb}} = 0.31^{+0.19}_{-0.15} \pm 0.03 \]

• advantages of double ratio
  ‣ acceptance, efficiency, luminosity cancel
  ‣ remaining systematics 9% from fit lineshape model
  ‣ measurement is statistics dominated

first observation of suppression of excited $\Upsilon$ states
\( \Upsilon \) suppression: \( p \)-value

- ‘what is probability for a background fluctuation to mimic the observed result?’
  
  \- generate pseudo-experiments assuming the null hypothesis (ie no suppression)
  \- fit pseudo-data samples with nominal fit
  \- count fraction of occurrences for which ratio (taken as test statistic) is same or lower than observed

- \( p \)-value: 0.9\%, or

- significance 2.4\( \sigma \) (1-sided Gaus. test)

\[ \chi = \frac{[Y(2S+3S)/Y(1S)]_{\text{PbPb}}}{[Y(2S+3S)/Y(1S)]_{\text{pp}}} \]

null hypothesis: \( \chi = 1 \) (no suppression)

\( p \)-value < 1\%
Summary

• first measurements of $\Upsilon(nS)$ differential cross sections and ratios at $\sqrt{s}=7\text{TeV}$ have been performed
  ‣ very good agreement between all LHC results, contributing to an improved understanding of quarkonium production
  ‣ polarization studies being finalized, will shed further light on existing puzzles

• bottomonia also studied in PbPb collisions at $\sqrt{s_{NN}}=2.76\text{TeV}$
  ‣ first observation of relative suppression of excited $\Upsilon$ states
  ‣ 40% suppression of $\Upsilon(1S)$ $\Rightarrow$ consistent with melting of excited states only

• pp and PbPb 2011 LHC runs will allow to:
  ‣ probe high $p_T$ spectrum
  ‣ improve precision and significance of the measurements
  ‣ measure further bottomonia/-like states