γ production: an example of heavy-ion physics with the extracted 2.76 TeV lead LHC beam

Jean-Philippe Lansberg

Probing the Strong Interaction at A Fixed Target Experiment with the LHC beams Ecole de Physique des Houches, 12-17 January 2014
Use LHC beams on fixed target:

• LHC 7 TeV proton beam
  \( \sqrt{s} \sim 115 \text{ GeV} \): \( pp, pd, pA \)

• LHC 2.76 TeV lead beam
  \( \sqrt{s} \sim 72 \text{ GeV} \): \( \text{Pb--p}, \text{PbA} \)
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Spin physics
PDF and nPDF at large \( x_b \)
heavy quarkonium prod.
Cold Nuclear Matter effects
W, Z prod. near threshold

UPC
QGP studies, high precision heavy quarkonium observatory, jets
diffractive physics
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- benefit from the typical advantages of a fixed target experiment
  - high luminosity, high boost \((y_{\text{lab}} = 4.84 \text{ @ } 115 \text{ GeV}), \text{ target versatility}\)
Use LHC beams on fixed target:

- **LHC 7 TeV proton beam**
  \[ \sqrt{s} \approx 115 \text{ GeV}: pp, pd, pA \]
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  between SPS and top AA RHIC energies

- benefit from the typical advantages of a fixed target experiment
  - high luminosity, high boost \( \gamma_{\text{lab}} = 4.84 \) at 115 GeV, target versatility
  - multipurpose experiment, modern detection techniques
More details

- on the website: [after.in2p3.fr](http://after.in2p3.fr)
- in Physics Reports:

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J.P. Lansberg

Les Houches, January 17, 2014
Energy density and temperature

Energy density vs time @ RHIC

\begin{align*}
T_{\text{initial}} &\quad 370 - 450 \text{ MeV} \\
T_{\text{avg}} &\quad = 221 \pm 19 \text{ (stat)} \pm 19 \text{ (syst)} \text{ MeV (0-20\% AuAu)}
\end{align*}

\[ T_c \sim 150 - 175 \text{ MeV} \]

\[ \varepsilon = 15 \text{ GeV/fm}^3 \]

\[ \varepsilon = 5.4 \text{ GeV/fm}^3 \]

\[ 2N_c = \text{Earliest Validity of Bjorken Formula} \]

\[ \text{Formation Time } T_{\text{From}} \]

\[ \text{Range of } \varepsilon \text{ from hydrodynamics} \]

\[ \text{Possible EOS} \]

\[ \text{Threshold for QGP Formation} \]

\[ 10^1 \quad 10^2 \quad 10^3 \]

\[ \text{Time (fm/c)} \]

\[ 1 \quad 10^{-1} \]

\[ \text{Energy Density (GeV/fm}^3) \]

\[ [ \text{PHENIX White paper, nucl-ex/0410003} ] \]

\[ [ \text{Strickland et al., NPA 879 (2012) 25-58} ] \]

\[ [ \text{Turbide et al., PRC 69 (2004) 014903} ] \]

\[ [ \text{PHENIX, PRL. 104 (2010) 132301} ] \]


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AFTER in PbA

\[ \sqrt{s} = 72 \text{ GeV} \]
Energy density and temperature

Energy density vs time @ RHIC

Energy density, max. collision energy, and temperature

$T_{\text{initial}}$ = 370 - 450 MeV

$T_{\text{avg}} = 221 \pm 19 \text{ (stat)} \pm 19 \text{ (syst)}$ MeV (0-20% AuAu)

$T_c \sim 150 - 175$ MeV

$\sqrt{s} = 72$ GeV

J.P. Lansberg

Les Houches, January 17, 2014
Sequential melting in QGP

Dissociation temperatures from lattice QCD (+hydro)

\[ T_{d}/T_{c} \]

1.2 \( \Upsilon(2S) \)
1.4 \( \Upsilon(3S) \)
1.1 \( \chi_{b}(2P) \)
?? \( \chi_{b}(3P) \) ??

\( T_{c} \sim 150 - 175 \text{ MeV} \)

Sequential melting in QGP

Dissociation temperatures from lattice QCD (+hydro)

Energy density ($\propto T^4$)

melting of the excited states which feed-down the 1S

$T_d/T_c$

1.2

$J/\psi(1S)$

$\Upsilon(1S)$

$\Upsilon(2S)$

$\Upsilon(3S)$

$\chi_b(1P)$

$\chi_c(1P)$

$\psi(2S)$

$\chi_b(2P)$

$\chi_b(3P)$

$T_c \sim 150 - 175$ MeV

Sequential melting in QGP

Bottomonium family: richer, broader range in $T$ (compared to charmonium)
- Less necessary to measure the $\chi_b(nP)$


Bottomonium sequential suppression @ LHC

Serious candidate for a « textbook-like » plot at the recent Hard Probes 2013 conference

[ CMS, PRL 109 (2012) 222301 ]

J.P. Lansberg

Les Houches, January 17, 2014
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- necessary ingredients:
  - high inv. mass resolution in pp and PbPb + background under control

- Sequential suppression seen:
  - 3S completely melted?
  - 2S very suppressed
  - direct 1S not affected?

[ CMS, PRL 109 (2012) 222301 ]
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**PRL 109, 222301 (2012)**

Observation of Sequential Y Suppression in PbPb Collisions

S. Chatrchyan et al.
(CMS Collaboration)
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Sequential suppression seen:
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CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV
Cent. 0-100%, $|y| < 2.4$
$L_{int} = 150 \mu$b$^{-1}$
$p_T > 4$ GeV/c

PbPb $\sim 1K$ events
pp $\sim 0.1K$ events

PRL 109, 222301 (2012) Selected for a Viewpoint in Physics
PHYSICAL REVIEW LETTERS

Observation of Sequential Y Suppression in PbPb
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Sequential *melting* @ LHC?

- 3S completely melted?
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CMS Preliminary 
PbPb $\sqrt{s_{NN}} = 2.76$ TeV

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<tr>
<th>state</th>
<th>$R_{AA} \pm \text{stat} \pm \text{syst}$</th>
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<td>Y(1S)</td>
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Sequential *melting* @ LHC?

- 3S completely melted?
- 2S very suppressed
- (Direct) 1S not affected?

If the sequential suppression is due to QGP effects *only*, what is the temperature reached @ LHC?

- rough first estimate: $1.4 T_c (~230 \text{ MeV}) < T < 4 T_c (~600 \text{ MeV})$
- lattice QCD + hydro evolution: $T_{\text{initial}} \sim 550 \text{ MeV} > T$

Measurement (thermal photons, dominant at low $p_T$): $T_{\text{avg}} \sim 304 \pm 51 \text{ MeV}$

(0-40% PbPb)

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**Table:**

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J.P. Lansberg  
Les Houches, January 17, 2014
Lessons from SPS and RHIC

Same $J/\psi$ suppression observed at SPS & RHIC

Two widely spread interpretations:

- Melting of excited states of SPS & RHIC energies (1P & 2S)
- Induced suppression by feed-down
- **No** additional melting of the direct yield at RHIC
- Temperature between RHIC and SPS is somewhere between $1.2 \ & \ 2 \ T_c$

- Melting of excited states of SPS & RHIC energies
- **Direct** $J/\psi$’s partially melt
- This additional suppression is compensated by regeneration
- Temperature between RHIC and SPS range from $1.2 \ T_c$ up to $2 \ T_c$

Nota: The fact that the $\Upsilon(2S)$ would only be partially suppressed at LHC energies does not fit well with the hypothesis that the $J/\psi$ already partially melts at RHIC [Theory predictions (lattice, ...) sometimes disagree on this, though]
**Lessons from SPS and RHIC**

*Same J/ψ suppression observed at SPS & RHIC*

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<td>→ <strong>Temperature between RHIC and SPS</strong> is somewhere between $1.2 &amp; 2T_c$</td>
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| ꜀ Melting of **excited** states of SPS & RHIC energies |
| → **Direct** J/ψ’s **partially melt** |
| → This additional suppression is compensated by **regeneration** |
| → **Temperature between RHIC and SPS** range from $1.2T_c$ up to $s2T_c$ |

---

In both case, the temperature expected for AFTER@LHC is likely around where the 2S and 3S bb states are expected to melt

Nota: The fact that the $\Upsilon$(2S) would only be partially suppressed at LHC energies does not fit well with the hypothesis that the J/ψ already partially melts at RHIC [Theory predictions (lattice, ...) sometimes disagree on this, though]

J.P. Lansberg

Les Houches, January 17, 2014
Another hint: $\Upsilon(1S + 2S + 3S)$ suppression @ RHIC

**AuAu@200GeV** (STAR run 2007, PHENIX run 2010)

- STAR preliminary
- Invariant Mass Yields in the Region [4, 12 GeV]
- $\Upsilon$ suppression
- RHIC
- AuAu@200GeV
- STAR run 2007, PHENIX run 2010
- 500 µb$^{-1}$
- ~200 $\Upsilon$

[Reed for STAR, JPG 38 (2011) 124185]

**pp@200GeV** (run 2006)

- STAR
- $\Upsilon$ suppression
- RHIC
- pp@200GeV
- STAR run 2006
- 7.9 pb$^{-1}$
- ~60 $\Upsilon$

[STAR, PRD 82 (2010) 012004]

J.P. Lansberg

Les Houches, January 17, 2014
Another hint: $Y(1S + 2S + 3S)$ suppression @ RHIC

**AuAu@200GeV** (STAR run 2007, PHENIX run 2010)

- Not enough stat. (and resolution) to get separate results for the 3 states

**pp@200GeV** (run 2006)

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Another hint: $\Upsilon(1S + 2S + 3S)$ suppression @ RHIC

**AuAu@200GeV** (STAR run 2007, PHENIX run 2010)

- Not enough stat. (and resolution) to get separate results for the 3 states
  - Specific $R_{AA}$ computation for PHENIX:
    - $pp \ J/\psi, \ Upsilon \ run \ 2006$
    - $AuAu \ \Upsilon \ \ run \ 2010$
    
    $$R_{AA}(\Upsilon) = \frac{[N(\Upsilon)/N(J/\psi)]_{AA}}{[N(\Upsilon)/N(J/\psi)]_{pp}} \times R_{AA}(J/\psi)$$

**pp@200GeV** (run 2006)

- Not enough stat. (and resolution) to get separate results for the 3 states

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**STAR, PRD 82 (2010) 012004**

**PHENIX, preliminary**

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**J.P. Lansberg**  Les Houches, January 17, 2014
Luminosities

Instantaneous luminosity:

\[ \mathcal{L} = N_{\text{beam}} \times N_{\text{target}} = N_{\text{beam}} \times (\rho \cdot e \cdot N_A) \]

with \( e = \text{target thickness} \)

Planned luminosity for PHENIX:

- @ 200 GeV run14pp 12 pb\(^{-1}\), run14dAu 0.15 pb\(^{-1}\)
- @ 200 GeV run15AuAu 2.8 pb\(^{-1}\) (0.13 nb\(^{-1}\) @ 62 GeV)

Nominal LHC luminosity PbPb 0.5 nb\(^{-1}\)
Luminosities

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7 TeV proton beam

\[ pp, pd, pA \text{ vs } 115 \text{ GeV} \]

<table>
<thead>
<tr>
<th>Target</th>
<th>( \rho ) (g cm(^{-3}))</th>
<th>( A )</th>
<th>( \mathcal{L} ) (( \mu b^{-1} s^{-1} ))</th>
<th>( \int \mathcal{L} ) (pb(^{-1}) yr(^{-1}))</th>
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</thead>
<tbody>
<tr>
<td>solid H</td>
<td>0.088</td>
<td>1</td>
<td>26</td>
<td>260</td>
</tr>
<tr>
<td>liquid H</td>
<td>0.068</td>
<td>1</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>liquid D</td>
<td>0.16</td>
<td>2</td>
<td>24</td>
<td>240</td>
</tr>
<tr>
<td>Be</td>
<td>1.85</td>
<td>9</td>
<td>62</td>
<td>620</td>
</tr>
<tr>
<td>Cu</td>
<td>8.96</td>
<td>64</td>
<td>42</td>
<td>420</td>
</tr>
<tr>
<td>W</td>
<td>19.1</td>
<td>185</td>
<td>31</td>
<td>310</td>
</tr>
<tr>
<td>Pb</td>
<td>11.35</td>
<td>207</td>
<td>16</td>
<td>160</td>
</tr>
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</table>

Table 1: Instantaneous and yearly luminosities obtained with an extracted beam of \( 5 \times 10^8 \text{ p}^+ / \text{s} \) with a momentum of 7 TeV for various 1 cm thick targets.

extracted beam \( N_{\text{beam}} = 5 \times 10^8 \text{ p}^+ / \text{s} \)

9 months running / year \( \Leftrightarrow 10^7 \text{ s} \)

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Table 2: Instantaneous and yearly luminosities obtained with an extracted beam of \(2 \times 10^5\) Pb/s with a momentum per nucleon of 2.76 TeV for various 1 cm thick targets

Bottomonium studies: from RHIC to AFTER

Today:

› inclusive $\Upsilon$ $R_{AA}$ vs centrality

› the most central point is compatible with a complete melting of 3S and a very strong suppression of 2S, with $T_{\text{initial}} \sim 430$ MeV in this model

From thermal photon $p_T$ spectra:

$T_{\text{avg}} = 221 \pm 19$ (stat) $\pm 19$ (syst) MeV (0-20% AuAu)
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From thermal photon \( p_T \) spectra:

\[
T_{\text{avg}} = 221 \pm 19 \text{ (stat)} \pm 19 \text{ (syst)} \text{ MeV (0-20\% AuAu)}
\]

decompose this model into each state

need more stat in AA

+ very good resolution

remind

STAR : \( \sim 200 \) \( Y \)

CMS : \( \sim 1k \) \( Y \)

The dream measurements:

[ Strickland et al., NPA 879 (2012) 25-58 ]
High statistics $pA$ studies with AFTER: reference for nuclear effects & nPDF \textit{per se}

- A dependence thanks to target \textit{versatility}

$<N_{\text{coll}}>$ dependence vs. $A$ dependence (à la NA50, NA60)

[ PHENIX, arXiv:1204.0777 ]
High statistics $pA$ studies with AFTER: reference for nuclear effects & nPDF *per se*

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  $<N_{\text{coll}}> \text{ dependence vs. } A \text{ dependence (à la NA50, NA60)}$

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- Gluon nPDF extraction using quarkonia (+ correlations), isolated photons, photon-jet correlation

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High statistics \( pA \) studies with AFTER: reference for nuclear effects & nPDF \textit{per se}

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- Nuclear PDF from intermediate to high \( x \): antishadowing, EMC region, Fermi motion
- Gluon nPDF extraction using quarkonia (+ correlations), isolated photons, photon-jet correlation
- Strongly limited at RHIC

\[ \text{J.P. Lansberg} \]

\[ \text{Les Houches, January 17, 2014} \]
Bottomonium : a cleaner QGP probe?

• 3 states (2S & 3S not too fragile)
• Better applicability of pQCD w.r.t. $J/\psi$
• in the QGP : negligible regeneration effects

BUT
Bottomonium : a cleaner QGP probe ?

- 3 states (2S & 3S not too fragile)
- Better applicability of pQCD w.r.t. J/ψ
- in the QGP : negligible regeneration effects

**pPb vs. pp**: excited states suppressed more than the ground state in pPb compared to pp collisions (significance < 3σ ?)

**Cold effects (i.e. not QGP)**:
- ♦ non-trivial effects seen in pA collisions
- ♦ need more studies and high stat pA measurements

⇒ This is where AFTER cannot be challenged

J.P. Lansberg
Les Houches, January 17, 2014
Summary and outlooks
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Using the LHC Pb beam on a nucleus target:

\[ \sqrt{s_{NN}} \sim 72 \text{ GeV} \] between SPS and top RHIC energies
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M. Anselmino (Torino), R. Arnarldi (Torino), S.J. Brodsky (SLAC), V. Chambert (IPN), J.P. Didelez (IPN), B. Genolini (IPN), E.G. Ferreiro (USC), F. Fleuret (LLR), C. Hadjidakis (IPN), J.P. Lansberg (IPN), C. Lorcé (IPN), A. Rakotozafindrabe (CEA), P. Rosier (IPN), I. Schienbein (LPSC), E. Scomparin (Torino), U.I. Uggerhøj (Aarhus), R. Ulrich (KIT)
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Les Houches, January 17, 2014
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• RHIC experiments cannot resolve the 3 states and are limited by the luminosity (stronger limitation at 62 GeV)

• Measurement of $\chi_b$ states not required, since we could use all 3 $\Upsilon(nS)$ states, but would certainly add very interesting pieces of information.
SPARE SLIDES
Backward physics

Hadron center-of-mass system

\[ x_1 \approx x_2 \]

\[ x_1 \ll x_2 \]

Target rest frame

\[ \sim 1^\circ \]

large angle
# Energy density in heavy ion collisions

## Initial energy density:

<table>
<thead>
<tr>
<th>Facility</th>
<th>Collision Species</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>$\epsilon_B \times \tau_0$ (GeV/fm$^3 \cdot$ fm/c)</th>
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<tr>
<td>AGS (BNL)</td>
<td>Au+Au</td>
<td>5</td>
<td>1,5</td>
</tr>
<tr>
<td>SPS (CERN)</td>
<td>Pb+Pb</td>
<td>17</td>
<td>3,9</td>
</tr>
<tr>
<td>RHIC (BNL)</td>
<td>Au+Au</td>
<td>200</td>
<td>5,5</td>
</tr>
<tr>
<td>LHC (CERN)</td>
<td>Pb+Pb</td>
<td>5500</td>
<td>10</td>
</tr>
</tbody>
</table>

## Longitudinal QGP expansion:

The Bjorken formula is given by:

$$\epsilon_Bj = \frac{dE_t}{dy} \frac{1}{A_\perp \tau_0}$$

where $dE_t$ is the transverse energy, $dy$ is the rapidity interval, $A_\perp$ is the transverse area, and $\tau_0$ is the freeze-out time. 

The measured and computed $\epsilon_B$ and $\tau_0$ values are plotted in the graph. The facilities include AGS (BNL), SPS (CERN), RHIC (BNL), and LHC (CERN) with their respective collision species.