$\gamma$ production measurements in $pp$, $p$-$Pb$ and $Pb$-$Pb$ collisions with ALICE

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Outline

• **Physics Motivation @ LHC energies**

• **Experimental Setup**

• **Results**
  – pp collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV
  – Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  – p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

• **Summary**
Motivation

• Quark Matter at extreme energy-density and formation of Quark Gluon Plasma (QGP)

• Quarkonium (c\bar{c} and b\bar{b}) suppression due to color screening [Matsui, Satz; PLB 178 (1986) 416]

• Sequential suppression [Digal, Satz, Vogt; PRC 85, (2012) 034906]

• Regeneration
  – The Q\bar{Q} production increases strongly with energy

<table>
<thead>
<tr>
<th>In most central collisions [0-10%]</th>
<th>RHIC 200 GeV</th>
<th>LHC 2.76 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{ccbar}/event</td>
<td>13</td>
<td>115</td>
</tr>
<tr>
<td>N_{bbbar}/event</td>
<td>0.1</td>
<td>3</td>
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Different sources of medium effects

- **Nuclear modification factor** $R_{AA}$:
  
  Ratio of the quarkonium yield in A-A ($Y_{AA}$) and the pp cross section, scaled by the nuclear overlap function $T_{AA}$ (from Glauber model)

  $$R_{AA} = \frac{Y_{AA}}{\langle T_{AA} \rangle \sigma_{pp}}$$

  If yield scales with the number of binary collisions
  
  $\rightarrow R_{AA} = 1$

  Medium effects will increase or decrease $R_{AA}$

  **Hot Medium effects:**
  - Quarkonium suppression ($R_{AA} \downarrow$)
  - Enhancement due to regeneration ($R_{AA} \uparrow$)

  **Cold Nuclear Matter effects (CNM):**
  - Nuclear parton shadowing/gluon saturation
  - Parton energy loss
  - Nuclear break-up

  **pp collisions:**
  
  Reference for p-Pb and Pb-Pb studies
  
  Constrain on theoretical models

  p-A collisions are used to study the CNM effects since the QGP is not expected
ALICE setup

VZERO is composed of two sets of detectors, VZERO-C (-3.7 < η < -1.7) whose pseudo-rapidity coverage overlaps with Muon Spectrometer and VZERO-A (2.8 < η < 5.1)

ALICE measures bottomonium resonances down to $p_T \sim 0$ at forward rapidity in the dimuon channel

Also see related presentations
Pereira Da Costa: Charmonium production in Pb-Pb collisions with ALICE at the LHC (29th Sept, Quarkonia II)
Leoncino: J/ψ and ψ(2S) production in p-Pb collisions with ALICE at the LHC (28th Sept, Quarkonia I)
Martinez-Garcia: Observation of a J/ψ yield enhancement at very low $p_T$ in Pb-Pb collisions at 2.76 TeV (30th Sept, Quarkonia IV)
pp results at $\sqrt{s} = 7$ TeV


- Quarkonium measurements in pp collisions allow one to test the production models
- NRQCD and CSM (better for NNLO at high $p_T$) models are in agreement with the data within uncertainties [Phys. Rev. D 84, 114001 (2011) and Nucl. Phys. A 470, 910 (2013)]

- CSM: On-shell perturbative production of $Q$ and $\bar{Q}$
- NRQCD: Systematic expansion of $Q\bar{Q}$ wavefunction in strong coupling constant and the relative velocity of $Q\bar{Q}$.

![Graphs showing measurements in pp collisions at $\sqrt{s} = 7$ TeV]
**pp results at $\sqrt{s} = 8$ TeV**


- First measurement of $\Upsilon(3S)$ with ALICE
- ALICE measurements are in agreement with LHCb [arXiv:1509.02372] as function of $p_T$ and $y$ (in both cases the difference do not exceed 1.5$\sigma$).

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28-Sep-15
Y measurements with ALICE, QM-15, I. Das
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A strong suppression has been observed in the inclusive measurement of $\Upsilon(1S)$ state in heavy-ion collision at forward rapidity (2.5<$y$<4.0)

Note the feed-down to $\Upsilon(1S)$ is approximately 30% from higher mass bottomonia [LHCb : Eur.Phys.J. C74 (2014) 3092].
\( \gamma(1S) \) \( R_{AA} \) in \( \text{Pb-Pb} \) collisions

The recent preliminary results by CMS indicate a stronger suppression compared to earlier measurement and are now is in closer agreement with ALICE results.
$\Upsilon(1S)$ $R_{AA}$ in Pb-Pb collisions: model comparison


M. Strickland, [arXiv:1207.5327]

- Thermal suppression of bottomonium states
- Anisotropic hydrodynamic model
- Two temperature rapidity profiles:
  - Boost invariant or Gaussian
- Three shear viscosities
- Feed down from higher mass states included
- No CNM included
- No regeneration included

Model underestimates the $\Upsilon(1S)$ suppression at forward rapidity
γ(1S) $R_{AA}$ in Pb-Pb collisions: model comparison


Updated calculations show a softer rapidity trend. The remaining difference at forward rapidity could be explained by CNM effects missing in the model.

M. Strickland, [New predictions arXiv:1507.03951]  
M. Strickland, [arXiv:1207.5327]
\( \Upsilon(1S) \) \( R_{AA} \) in Pb-Pb collisions: model comparison


A. Emerick et al., [EPJ A48 (2012) 72]

- Transport model
- Suppression of \( \Upsilon(1S) \) resonances by the QGP
- Small regeneration component included
- Feed down from higher mass states included
- CNM included via an “effective” \( \sigma_{abs} = 0\text{–}2 \text{ mb} \)

Model underestimates the \( \Upsilon(1S) \) suppression at forward rapidity
The recent preliminary results by CMS indicate a stronger suppression compared to earlier measurement and now is in closer agreement with ALICE results.
Results in p-Pb collisions

Forward rapidity

2.03 < \( y_{\text{cms}} \) < 3.53 \( L \sim 5.03 \text{ nb}^{-1} \)

\[ \Delta y = 0.465 \] in the direction of the proton beam

Nuclear modification factor \( R_{\text{pPb}} \):

\[ R_{\text{pPb}} = \frac{\sigma_{\text{pPb}}}{A_{\text{Pb}} \cdot \sigma_{\text{pp}}} \]

pp data at \( \sqrt{s} = 5.02 \text{ TeV} \) are not available

Reference cross section is obtained using an energy interpolation procedure [ALICE-PUBLIC-2014-002, LHCb-CONF-2014-003].
Suppression of \( \Upsilon(1S) \) at forward rapidity with respect to pp reference, while the backward rapidity measurement is compatible with no suppression.

ALICE and LHCb \( R_{pPb} \) are compatible, with LHCb results being systematically larger.
**$R_{pPb}$ of $\Upsilon(1S)$: model comparisons**


- **Ferreiro et al. [EPJC 73 (2013) 2427]**
  - 2→2 production model at LO
  - EPS09 shadowing parameterization at LO
  - Fair agreement with the measured $R_{pPb}$
    - Although slightly overestimates it in the antishadowing region

- **Fuji et al. [Nucl. Phys. A 915 (2013) 1]**
  - CGC + CEM production model
  - Slightly underestimates the $R_{pPb}$ at forward rapidity

**Model underestimates the $\Upsilon(1S)$ suppression at backward rapidity**
$R_{pPb}$ of $\gamma(1S)$: model comparisons

- **Arleo et al. [JHEP 1303 (2013) 122]**
  - Model including a contribution from coherent parton energy loss
  - With or without shadowing (EPS09)
  - Forward: better agreement with ELoss and shadowing
  - Backward: better agreement with ELoss only

  - CEM production model at NLO
  - EPS09 shadowing parameterization at NLO
  - Fair agreement with measured $R_{pPb}$ within uncertainties
    - Although it slightly overestimates the measurement
Summary

• ALICE findings in pp collisions:
  – Constrain on theoretical models
  – Consistent results with other LHC experiments

• ALICE findings in Pb-Pb collisions:
  – **Strong suppression** of $\Upsilon(1S)$ at forward rapidity.
  – The $R_{AA}$ of $\Upsilon(1S)$ shows a **stronger** suppression in **central** than **peripheral** collisions.
  – The **feed-down** of higher states **are not able to account** for the measured **suppression** of $\Upsilon(1S)$.
  – The strong suppression of $\Upsilon(1S)$ constrains the **sequential suppression models**.
  – The $\Upsilon(1S)$ suppression is **stronger at forward** than at mid-rapidity. However, recent CMS preliminary data show a better agreement with our data yielding a **softer rapidity dependence**.

• ALICE p-Pb results:
  – A **suppression** of $\Upsilon(1S)$ production is observed at **forward rapidity**.
  – At **backward rapidity** it is consistent with **unity**, suggesting small gluon anti-shadowing.
  – Pure **nuclear shadowing** and/or (coherent) **energy loss models** seem to **overestimate** the measured **nuclear modification factor**.
Thank You
The $R_{FB}$ of $\Upsilon(1S)$ is larger than the one of $J/\psi$ and compatible with unity. All available models are compatible with the measured $R_{FB}$ within the large experimental uncertainties (shown in left side figure).
• Comparison with earlier results of ALICE (results in nb)

<table>
<thead>
<tr>
<th></th>
<th>$\Upsilon(1S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(3S)$</th>
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<tbody>
<tr>
<td>7 TeV</td>
<td>$54 \pm 5 \pm 7$</td>
<td>$18 \pm 4 \pm 3$</td>
<td>-</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$68 \pm 6 \pm 7$</td>
<td>$25 \pm 5 \pm 4$</td>
<td>$9 \pm 4 \pm 1$</td>
</tr>
</tbody>
</table>