Quarkonia at the LHC: open questions

E. Scomparin (INFN-Torino)

- A short introduction
  - Lessons from the past
- Our present knowledge
  - Have LHC results improved our understanding of quarkonium vs QGP?
- Open points and prospects
  - Future measurements at the LHC

Tomography of the Quark-Gluon Plasma with Heavy Quarks

Workshop: 10 - 14 October 2016, Leiden, the Netherlands
A short historical timeline

- Lessons from the past
  - '80s: The original “promise” of quarkonium as a QGP signature → a simple and model-independent observable
  - '90s: high statistics data from the SPS, progress in phenomenology → the “QGP” vs “comovers” saga
  - '00s: Enter RHIC, the QGP does not melt the J/ψ → suppression vs recombination

- Have LHC results improved our understanding of quarkonium vs QGP?
  - '10s: “precision” data from the experiments → the bottomonium “revolution”: back to the original vision?
  - → regeneration of charmonia: a new/different probe of QGP?
  - '15s: LHC hits the top → can we expecting anything new?

- Future measurements at the LHC
  - '20s: LHC run-3, run-4,... → can we access more rare probes?
1986-1987: The Matsui-Satz prediction and the first results...

Quark Matter 87, NA38 Collaboration

- Fall 1986
- Oxygen-Uranium collisions at the CERN SPS
- 200 GeV/nucleon (lab system! $\sqrt{s_{NN}}=19.4$ GeV)

First evidence for J/ψ suppression in nuclear collisions!

Abstract. The dimuon production in 200 GeV/nucleon oxygen-uranium interactions is studied by the NA38 Collaboration. The production of $J/\Psi$, correlated with the transverse energy $ET$, is investigated and compared to the continuum, as a function of the dimuon mass $M$ and transverse momentum $PT$. A value of $0.64 \pm 0.06$ is found for the ratio ($\Psi$/Continuum at high $ET$)/($\Psi$/Continuum at low $ET$), from which the $J/\Psi$ relative suppression can be extracted. This suppression is enhanced at low $PT$. 
...which got immediate attention from the (newborn) HI community...

- QM87, from the summary talk of M. Gyulassy

The most provocative observation, reported by NA 38 [13], was that $J/\psi$ production seems to be suppressed by $\sim 30\%$ in high $E_T$ events. The second provocative

3 Puzzles

3.1 $J$/Psi suppression

$$\frac{N_{\psi}}{N_c} = \begin{cases} 9.3 \pm 0.6 & \text{for } E_T < 28 \text{ GeV} \\ 5.9 \pm 0.4 & \text{for } E_T > 50 \text{ GeV.} \end{cases}$$ (10)

This 30% reduction of $\psi$ production caused the most controversy at Quark Matter ’87.

There are naturally several caveats that need further consideration. First, there is the problem of prov-

Competing sources of suppression involving hadronic final state interactions Dissociation reactions with $\sigma_{\text{diss}} \sim 1\text{-}2 \text{ mb}$ could reproduce the observation

A signature of deconfinement, or just a generic signature for ultra-dense matter formation?
...which looked for alternative explanations/mechanisms...

...which included a significant contribution from J/ψ interactions with nucleons (nowadays Cold Nuclear Matter effects, CNM)

Triggered an experimental program at SPS energy (with inputs from the FNAL fixed target program too!) on the study of p-A collisions, used as a reference for A-A results
...including “recombination” processes

Q3. Could $J/\psi$ suppression be compensated at the hadronization stage?

- This is very unlikely from our consideration on the charm production mechanism. One should check, however, both experimentally and theoretically whether there is no anomalous enhancement in the charm production cross section which could lead to large recombination probability of $c\bar{c}$ into $J/\psi$ during the hadronization stage.

- T. Matsui, QM87 proceedings

First hint for the possibility of a charmonium enhancing mechanism (?)
Evolution of the field

- From this brief flash of very first achievements, one may conclude that the seeds of future progress were there since the (very) beginning.

- At the same time technical improvements were steadily introduced.

- On theory side:
  - Lattice calculations
  - Effective models of charmonium in a high-T medium
  - Realistic treatment of the fireball evolution

- None of the above represents an easy task!
  → Example: after 30 yrs the connection between the temperature of the medium and the survival of the resonance is (at best!) qualitatively known.
  → Will the “dream of the QGP thermometer” become eventually a reality?

A. Adare et al. (PHENIX), arXiv:1404.2246

E. Scomparin, Quarkonia at the LHC: open questions, Leiden, October 2016
Evolution of the field

- Similarly, on the experimental side, enormous progress has been carried out, but a (very) good margin for improvement remains.

- Limiting the discussion to charmonia at the LHC.

- High statistics charmonia $\rightarrow$ multi-dimensional analyses
  - But only for the ground state
  - The $\psi(2S)$ is still elusive
  - The $\chi_C$ remains unknown

- Some non-$R_{AA}$ analyses for the $J/\psi$ were carried out $\rightarrow v_2$
  - But at a still qualitative level

- Other observables are missing (correlation studies, etc...)

- Lots of p-A data exist (or will be taken shortly!)
  - But their use in the context of Pb-Pb results remain speculative.
Evolution of the field

- On the bottomonium side (experiment)
- Real “quantum step” in the quarkonium saga → quality of 1S results at least as good as for J/ψ at RHIC

- Level of “competitiveness” of RHIC experiments still much lower (at least until sPHENIX)
  → Not necessarily a good news

- Still an enormous potential for improvement
- In particular
  → γ(3S) still not seen
  → non-RAA analyses still not accessible
  → Multi-dimensional analyses hardly possible
The legacy of SPS/RHIC

- Several landmarks were firmly (?) established
  - $J/\psi$ suppression beyond CNM effects at SPS
  - Much stronger $\psi(2S)$ suppression relative to $J/\psi$ at SPS
  - Strong $y$-dependence of $J/\psi$ suppression at RHIC (not an evidence of recombination per se)

R. Arnaldi et al. (NA60) NPA830 (2009) 345c
All the four experiments have investigated quarkonium production

- Pb-Pb → mainly ALICE + CMS, p-Pb → all the 4 experiments

Complementary kinematic ranges → excellent phase space coverage

- ALICE → forward-\(y\) (\(2.5<y<4\), dimuons) and mid-\(y\) (\(|y|<0.9\), electrons)
- LHCb → forward-\(y\) (\(2<y<4.5\), dimuons)
- CMS → mid-\(y\) (\(|y|<2.4\), dimuons)
- ATLAS → mid-\(y\) (\(|y|<2.25\), dimuons)

(N.B.: \(y\)-range refers to symmetric collisions → rapidity shift in p-Pb!)

Data samples

- Run 1

\[
\begin{align*}
\text{Pb-Pb}, \sqrt{s_{\text{NN}}} &= 2.76 \text{ TeV}, 2010 (9.7 \mu\text{b}^{-1}) + 2011 (184 \mu\text{b}^{-1}) \\
\text{p-Pb}, \sqrt{s_{\text{NN}}} &= 5.02 \text{ TeV}, 2013 (36 \text{ nb}^{-1}) \\
\text{ref. p-p}, \sqrt{s} &= 2.76 \text{ TeV}, 2011 (250 \text{ nb}^{-1}) + 2013 (5.6 \text{ pb}^{-1})
\end{align*}
\]
Low-$p_T$ $J/\psi$: ALICE (vs PHENIX)

- Compare $J/\psi$ suppression, RHIC ($\sqrt{s_{NN}}=0.2$ TeV) vs LHC ($\sqrt{s_{NN}}=2.76$ TeV)
- Results vs centrality dominated by low-$p_T$ $J/\psi$
  - Systematically larger $R_{AA}$ values for central events at LHC energy
  - $R_{AA}$ increases at low $p_T$ at LHC energy

Possible interpretation:

- RHIC energy $\rightarrow$ suppression effects dominate
- LHC energy $\rightarrow$ suppression + regeneration
- Pb-Pb collisions @ $\sqrt{s_{NN}}=5.02\text{TeV}$
- High statistics Run-2 allows the $R_{AA}$ evaluation in narrow centrality bins

- Similar centrality dependence at the two energies, with an increasing suppression up to $N_{\text{part}} \sim 100$, followed by a plateau

- $R_{AA}$ @ 5.02TeV is $\sim15\%$ higher than the one at 2.76TeV, even if within uncertainties
Comparison with models

- Theoretical and experimental uncertainties reduced in the $R_{AA}$ double ratio
- Centrality dependence of the $R_{AA}$ ratio is rather flat

$R_{AA}$ increases at low $p_T$, at both energies, as expected in a regeneration scenario
- Hint for an increase of $R_{AA}$ at 5.02 TeV, in $2<p_T<6$ GeV/c

→ Also $\sqrt{s_{NN}}=5.02$ TeV results support a picture where a combination of $J/\psi$ suppression and (re)combination occurs in the QGP
Low-$p_T$ $J/\psi$: open questions

- Reasonably good set of data → fundamental to investigate re-combination issues
- Quantitative interpretation made difficult by the significant spread in crucial quantities of the models, such as ($\sqrt{s}=5$ TeV):
  
  \[
  (d\sigma/dy)_{cc} = \begin{cases} 
  0.42 \text{ mb (Statistical, Andronic)} \\
  0.57 \text{ mb (Transport, Du/Rapp)} \\
  0.82 \text{ mb (Transport, Zhou et al.)} \\
  0.45-0.70 \text{ mb (Comover, Ferreiro)} 
  \end{cases}
  \]

- Recent LHCb estimates (LHCB-CONF-2016-003) suggest values on the low-side of this range (caveat, extrapolation, to be updated with their $\sqrt{s}=5$ TeV data
- Starting from their $\sigma_{D0}(p_T<8 \text{ GeV}/c, 2.5<y<4) = 713 \pm 95(\text{LHCb}) \pm 47(\text{interp.}) \mu b$
  one gets
  \[
  (d\sigma/dy)_{cc} = 0.44 \pm 6(\text{LHCb}) \pm 3(\text{interp.}) \pm 2(\text{FF}) \text{ mb} = 0.44\pm0.07 \text{ mb}
  \]
Low-$p_T J/\psi$: open questions

- Precise measurements of open charm cross section are mandatory

- Best results available today (ALICE, LHCb) have uncertainties of about 20%

- If there is no space for a significant improvement, model uncertainties are not getting smaller

- Theorists, please, agree on using the same input values!

- CNM (shadowing) is the other main source of uncertainty (see later)
High-$p_T$ $J/\psi$: CMS (+ATLAS)

- Maximum $J/\psi$ suppression, then increase beyond $p_T=20$ GeV/c
- Similar behavior as for hadrons?
- Is a model description in terms of energy loss needed?
- Compatibility ATLAS vs CMS: factor~2 more suppression for ATLAS
- Could it be an effect of the different $\sqrt{s}$? Wait for CMS run-2 results
Maximum $J/\psi$ suppression, then increase beyond $p_T=20$ GeV/c

Similar behavior as for hadrons?

Is a model description in terms of energy loss needed?

Compatibility ATLAS vs CMS: factor~2 more suppression for ATLAS

Could it be an effect of the different $\sqrt{s}$? Wait for CMS run-2 results
CMS: final results for high-$p_T$ $J/\psi$

- Strong high-$p_T$ suppression: compatibility ALICE vs CMS OK

- Fine centrality binning
- Striking difference with respect to low-$p_T$
- Continuously increasing suppression vs saturation
Non-zero $v_2$ for J/$\psi$ at the LHC

- The contribution of J/$\psi$ from (re)combination could lead to a significant elliptic flow signal at LHC energy $\rightarrow$ observed!

- A significant $v_2$ signal is observed at LHC but not at RHIC
- $v_2$ remains significant even in the region where the contribution of (re)generation should be negligible $\rightarrow$ Likely due to path length dependence of energy loss

E. Abbas et al. (ALICE), PRL111(2013) 162301, CMS-HIN-12-001
L. Adamczyk et al. (STAR), PRL 111,052301 (2013)
Comparing $R_{AA}$ and $v_2$ for closed/open charm

- CMS final results from HP2016
- Striking similarity for $R_{AA}$, $v_2$ systematically lower for J/$\psi$
- Interesting but not trivial comparison (same-$p_T$ comparison can probe different HQ kinematics, ...)
- Need a solid theory support

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Feed-down

- Cannot be addressed precisely until today!

- If $\psi(2S)$ and $\chi_c$ were precisely measured in Pb-Pb their contribution could be subtracted out and obtain direct $J/\psi$

- Explicitly done (only ?) by NA50, for $\psi(2S)$ when comparing p-A and S-U data

- We are still very far at the LHC! Needed for a quantitative understanding
CMS preliminary results

- Larger $\psi(2S)$ suppression confirmed at high $p_T$
- Has the anomalous bump seen at 2.76 TeV disappeared?
- Or is this one of the few observables sensitive to the LHC energy increase?
- ATLAS confirms suppression in the high-$p_T$ region
CMS preliminary results

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$\psi(2S)$: 5.02 vs 2.76 TeV
ψ(2S): 5.02 vs 2.76 TeV

- ψ(2S) regeneration occurring at higher $p_T$ due to larger flow push
- Smart ad-hoc explanation for the enhancement at 2.76 TeV, still needed? Debate still open!
- Quality of ALICE results should improve in run-2 in order to give valuable input
Photonuclear production: LHC

- A new source of $J/\psi$ in hadronic Pb-Pb collision
  - Low $p_T$ “excess” (huge $R_{PbPb}$ values for $p_T<0.3$ GeV/c)

- Likely due to photoproduction in events with $b>2R$
  (recently observed at RHIC too!)

- $\sim 75\%$ of the signal expected for $p_T<0.3$ GeV/c

- ALICE peripheral $R_{AA}$ lowers by max 20% when photoproduction removed

- At the same time
  - A “background” for hadronic $R_{PbPb}$ studies (anyway concentrated in peripheral events, where theory calculations are less reliable)
  - A “signal” of a known process in a “non-standard” environment

If under theory control, could it be used as a probe of hot matter?
Cold nuclear matter: the J/ψ

- Originally studied, in the frame of our field, as a mean to calibrate cold nuclear matter effects for hot matter studies (in particular for quarkonia!)

- Gradually emerged as a field of its own

- Older descriptions in terms of nuclear matter absorption, parametrized through a single effective parameter $\sigma_{\psi N}$, refined adding more and more effects

- SPS energy $\rightarrow$ nuclear absorption (effective)
- RHIC energy $\rightarrow$ nuclear absorption + shadowing
- LHC energy $\rightarrow$ nuclear absorption + shadowing/CGC + energy loss + comovers + ....

Reasonable set of results available (more to come soon) $\rightarrow$ Enough to go beyond the qualitative comparison data/models?
LHC results: low $p_T$

- p-Pb collisions, $\sqrt{s_{NN}}=5.02$ TeV, $R_{pPb}$ vs $p_T$

  ![Graphs showing $R_{pPb}$ vs $p_T$ for different y regions](image)

- On one hand: **CNM effects strong**, clearly impact on Pb-Pb interpretation
- On the other hand: considerable uncertainties at the theory level
  - Shadowing: prospect for reducing nPDF uncertainties? Can the data be used to reduce nPDF uncertainties?

- Can the forthcoming **8 TeV results** give a handle to discriminate between models which for the moment are all doing a fair job?
- Are theory uncertainties expected to decrease in e.g. the ratio of $R_{pPb}$?

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E. Scomparin, Quarkonia at the LHC: open questions, Leiden, October 2016
J/$\psi$ $R_{pPb}$: ATLAS “vs” ALICE “vs” LHCb

- $R_{pPb}$ vs $p_T$ at $y \sim 0$ → fair agreement ALICE vs ATLAS (extends to high $p_T$)
  ALICE, JHEP 1506 (2015) 055

- $R_{pPb}$ vs $y$ → fair agreement ALICE vs LHCb, ATLAS refers to $p_T > 10$ GeV/c
  LHCb, JHEP 02 (2014) 72, ALICE, JHEP 02 (2014) 73
Comparing $R_{FB}$ from ALICE and CMS

- Good compatibility at forward $y$ (slightly more forward for ALICE)
- Check shadowing ($y$-effect or different calculation?)
- $R_{FB}$ pros/cons: reduced uncertainties vs less sensitivity to models
CNM effects: from p-Pb to Pb-Pb

- x-values in Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV, $2.5<y_{\text{cms}}<4$
  \[2.10^{-5} < x < 9.10^{-5}, \quad 1.10^{-2} < x < 6.10^{-2}\]

- x-values in p-Pb $\sqrt{s_{NN}}=5.02$ TeV, $2.03 < y_{\text{cms}} < 3.53$ \[2.10^{-5} < x < 8.10^{-5}\]
- x-values in p-Pb $\sqrt{s_{NN}}=5.02$ TeV, $-4.46 < y_{\text{cms}} < -2.96$ \[1.10^{-2} < x < 5.10^{-2}\]

→ Partial compensation between $\sqrt{s_{NN}}$ shift and y-shift

- If CNM effects are dominated by shadowing
  - $R_{PbPb}^{\text{CNM}} = R_{pPb} \times R_{Pbp} = 0.75 \pm 0.10 \pm 0.12$
  - $R_{PbPb}^{\text{meas}} = 0.57 \pm 0.01 \pm 0.09$

- Same kind of “agreement” in the energy loss approach (Arleo)
  ...which does not exclude hot matter effects which partly compensate each other

F. Arleo and S. Peigne, arXiv:1407.5054
Can we consider this as something more than a cautious exercise?  
Are other approaches feasible/in sight?
**Cold nuclear matter: the $\psi(2S)$**

- In principle should be affected by CNM in the same way as the $J/\psi$
- Formation times should prevent any “nuclear absorption”
- Shadowing/energy loss cancel, at least at first order

Results show a (much) stronger $\psi(2S)$ suppression

Not a “real” surprise, already seen by PHENIX even if with large uncertainties

Very strong rapidity dependence, compatible with an effect related with the hadronic activity (not so strange, seen the weak binding)
Cold nuclear matter: the $\psi(2S)$

- In principle should be affected by CNM in the same way as the $J/\psi$
- Formation times should prevent any “nuclear absorption”
- Shadowing/energy loss cancel, at least at first order

Nicely confirmed by LHCb!
ATLAS on $\psi(2S)$ in p-Pb

- High $p_T$, rather large uncertainties
- Hints for strong enhancement, concentrated in peripheral events

- Possible tension with ALICE results (sees $R_{pPb} < 1$ at forward-$y$ up to $p_T = 8$ GeV/c), even if it is difficult to conclude

- Issues with the centrality assignment?

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\( \Upsilon: \) the success and the problems

- Probably the most spectacular result from quarkonia at the LHC

Very recent CMS results at \( \sqrt{s} = 5 \) TeV confirm the \( \Upsilon(2S,3S) \) suppression!

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\( \Upsilon(2S) \) relative suppression

- (As usual) no big surprises when moving from 2.76 to 5.02 TeV
- New CMS results better approach the peripheral collisions
- “Almost perfect” alignment of the point hardly compatible with error size
\( \Upsilon(1S) \) ALICE result is even more striking...

- Tendency to LESS suppression for the \( \Upsilon(1S) \) when increasing energy?

- \( R_{AA} \) (5.02 TeV, 0-90\%) = 0.40 ± 0.03 (stat) ± 0.04 (syst)

- \( R_{AA} \) (2.76 TeV, 0-90\%) = 0.30 ± 0.05 (stat) ± 0.04 (syst)

- Still compatible, but also the \( y \)-shape reminds recombination patterns

- Can CNM effects play a different role at the two energies?
Also the $y$-dependence of both $\Upsilon(1S)$ and $\Upsilon(2S)$ “seriously” remind a recombination pattern? Could it be there, according to models?

N.B., also here we are still at the level of consistency within uncertainties.
Strickland’s approach: model early time dynamics, complex potential,..
Catches the main features of the results but misses $y$-dependence
$R_{AA}$ at 5 TeV compatible with the model, but the tendency is opposite
Are we missing some relevant physics here?
CNM effects: the $\Upsilon$ family

- Clear effect seen by CMS on $\Upsilon(2S)$
- Not contradicted by ALICE (larger uncertainties)

- Another clear indication for final state effects on quarkonia at LHC, although much smaller than for $\psi(2S)$

- $\Upsilon(2S)$ binding energy similar to $J/\psi$
  - Should final state effects be included also in $J/\psi$ calculations?
Improvements in the data are mandatory $\rightarrow$ run-2
No real tension between ALICE and LHCb but the range of “allowed” values is clearly too large for drawing a conclusion
CNM effect generally smaller than for charmonia, but not negligible
The comovers are back again

- A subject of “epic” battles in the ‘90s (comovers vs QGP!)
- Entered a “dormant” state in RHIC years, now re-proposed for the γ
- Old survival probability formula

$$S_Q^{co}(b,s,y) = \exp\left\{ -\sigma_{co-Q}^{co}(b,s,y) \ln\left[ \frac{\rho_{co}(b,s,y)}{\rho_{pp}(y)} \right] \right\}$$

which gave fair results at SPS with $\sigma^{co-J/\psi}=0.65$ mb and $\sigma^{co-\psi(2S)}=6$ mb

- Also does well at RHIC and LHC (2S/1S ratio), same parameters (?!)

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The comovers are back again

- Refining the comover cross section (and fixing parameters on CMS double ratios for pPb)

\[ \sigma^{co-Q_{bb}} = \sigma_{geom} \left( 1 - \frac{E_{Binding}}{E_{co}} \right)^n \]

- (Surprisingly), a qualitative agreement is found
- Is the physics of bottomonia simply “driven” by dN/d\(\eta\) ??
Feed-down

- Systematic measurements by LHC pp experiments have **enormously improved the situation**

Recent news

- Feed-down to \( \Upsilon(1S) \) is **smaller** than believed (~50% → ~30%)
- Feed-down to \( \Upsilon(3S) \) (unseen in PbPb!) is **very strong** (~40%)

<table>
<thead>
<tr>
<th>low ( P_T )</th>
<th>( \Upsilon )</th>
<th>( \Upsilon' )</th>
<th>( \Upsilon'' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>direct</td>
<td>~70%</td>
<td>~63%</td>
<td>~60%</td>
</tr>
<tr>
<td>from ( \chi_b )</td>
<td>~15%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>from ( \Upsilon' )</td>
<td>~8%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>from ( \chi_b' )</td>
<td>~5%</td>
<td>~30%</td>
<td>~4%</td>
</tr>
<tr>
<td>from ( \Upsilon'' )</td>
<td>~1%</td>
<td>~3%</td>
<td>~40%</td>
</tr>
</tbody>
</table>

Can CMS “correct” at least for \( \Upsilon(2S) \) feeddown?

(HP2016, Lansberg)
More accurate data allowed more stringent conclusions...

1994-2000: really “heavy” ions in the SPS (Pb-Pb collisions)
February 2000 → “New state of matter created at CERN” press release

- Clear suppression beyond CNM effects measured by NA50
- 1) Sharp onset of suppression
- 2) “Conventional” models found to disagree with data
...leaving a well-traced path for the following collider studies...

<table>
<thead>
<tr>
<th>Collider</th>
<th>Experiment</th>
<th>System</th>
<th>$\sqrt{s}_{\text{NN}}$ (GeV)</th>
<th>Data</th>
</tr>
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<tbody>
<tr>
<td>RHIC</td>
<td>PHENIX</td>
<td>Au-Au, Cu-Cu, Au, U-U</td>
<td>200, 62, 39</td>
<td>2000-</td>
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<td></td>
<td>STAR</td>
<td>p-A, d-Au</td>
<td>200</td>
<td></td>
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<td></td>
<td></td>
<td>pp</td>
<td>200-500</td>
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<tr>
<td>LHC</td>
<td>ALICE</td>
<td>Pb-Pb</td>
<td>2760, 5020</td>
<td>2010/2011</td>
</tr>
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<td></td>
<td>ATLAS</td>
<td>p-Pb</td>
<td>5020</td>
<td>2013</td>
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<tr>
<td></td>
<td>CMS</td>
<td>pp</td>
<td>2760, 7000, 8000, 13000</td>
<td>2010-</td>
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<tr>
<td></td>
<td>LHCb</td>
<td>pp</td>
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</tbody>
</table>

...that continue up to now
Quarkonia in 2016: from color screening...

Screening of strong interactions in a QGP

T. Matsui and H. Satz, PLB178 (1986) 416

- Screening stronger at high $T$
- $\lambda_D \rightarrow$ maximum size of a bound state, decreases when $T$ increases
- Different states, different sizes

Resonance melting

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...to regeneration

At sufficiently high energy, the cc pair multiplicity becomes large

<table>
<thead>
<tr>
<th>Central AA collisions</th>
<th>SPS 20 GeV</th>
<th>RHIC 200 GeV</th>
<th>LHC 2.76TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{cc\bar{c}b}/\text{event}$</td>
<td>$\sim0.2$</td>
<td>$\sim10$</td>
<td>$\sim85$</td>
</tr>
</tbody>
</table>

Statistical approach:
- Charmonium **fully melted** in QGP
- Charmonium **produced**, together with all other hadrons, at **chemical freeze-out**, according to statistical weights

Kinetic recombination:
- Continuous **dissociation/regeneration** over QGP lifetime

Contrary to the color screening scenario this mechanism can lead to a charmonium **enhancement**

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Still a bit of history....

- The possibility of an enhancement of charmonium production in nuclear collisions was considered from the very beginning!

From T.Matsui QM87 proceedings

Q3. Could $J/\psi$ suppression be compensated at the hadronization stage?

- This is very unlikely from our consideration on the charm production mechanism. One should check, however, both experimentally and theoretically whether there is no anomalous enhancement in the charm production cross section which could lead to large recombination probability of $c\bar{c}$ into $J/\psi$ during the hadronization stage.

(even if, at that time, correctly discarded because of the small open charm cross section at the energies then available)
Implementing a realistic quarkonium production in a realistic medium is a considerably difficult task.

Some open points
- In high-energy heavy-ion collisions the QGP thermalization times are very short (~1 fm/c)
  - One should deal with in-medium formation of quarkonium rather than with suppression of already formed states
  - Heavy quark diffusion is relevant for quarkonium production

Need to determine $T_D$, $M_\psi(T)$, $\Gamma_\psi(T)$ from QCD calculations (using spectral functions from EFT/LQCD)
Need to know the fireball evolution from microscopic calculations
A precise determination of the total open charm cross section is still lacking

Impressive advances on theory side but the availability of data for various colliding systems and energy remains a must!
Various systems, various effects

- **p-A**
  - Cold nuclear matter effects (CNM)
  - Warm/hot matter effects?

- **p-p**
  - “Vacuum” reference, production mechanisms

- **A-A**
  - Hot matter effects

- **CNM**: nuclear shadowing, color glass condensate, parton energy loss, resonance break-up (RHIC energy)
- **Hot matter effects**: suppression vs re-generation
- “**Warm**” matter effects: hadronic resonance gas
Various systems, various effects

- cold nuclear matter effects (CNM)
- warm/hot matter effects?
- hot matter effects

Quantify the yield modifications via the nuclear modification factor $R_{AA}$

$$R_{AA} = \frac{dN_{AA}^{p}}{\langle N_{\text{coll}} \rangle dN_{pp}^{p}}$$

- $R_{AA} < 1$ suppression
- $R_{AA} > 1$ enhancement

E. Scomparin, Quarkonia at the LHC: open questions, Leiden, October 2016
Sources of heavy quarkonia

Quarkonium production can proceed:
- directly in the interaction of the initial partons
- via the decay of heavier hadrons (feed-down)

For J/ψ (at CDF/LHC energies) the contributing mechanisms are:

- **Direct production**
- Feed-down from higher charmonium states:
  - ~ 8% from ψ(2S), ~25% from χc
- **B decay**
  - contribution is pT dependent
  - ~10% at pT~1.5GeV/c

B-decay component “easier” to separate → displaced production

E. Scomparin, Quarkonia at the LHC: open questions, Leiden, October 2016
Quarkonium at RHIC

- Kinematic coverage
  - PHENIX $1.2 < |y| < 2.2$ ($\mu^+\mu^-$), $|y| < 0.35$ ($e^+e^-$)
  - STAR $|y| < 1$ ($e^+e^-$) (recently $|y| < 0.5$ $\mu^+\mu^-$)

$L = L_{NN} / (197)^2$
Quarkonium at RHIC

- Kinematic coverage
  - PHENIX $1.2 < |y| < 2.2$ ($\mu^+\mu^-$), $|y| < 0.35$ ($e^+e^-$)
  - STAR $|y| < 1$ ($e^+e^-$) (recently $|y| < 0.5$ $\mu^+\mu^-$)

MTD → trigger on and identify muons (2014) behind magnet
- Precise timing measurement ($\sigma \sim 100$ ps)

FVTX → improve $\mu\mu$ mass resolution by measuring opening angle before absorber (from 2012)

$L = L_{NN} / (197)^2$
Charmonium results ($J/\psi$, $\psi(2S)$)
PHENIX, $\sqrt{s_{NN}} = 200$ GeV

A. Adare et al. (PHENIX) PRC84(2011) 054912

- Suppression, with strong rapidity dependence, in Au-Au at $\sqrt{s} = 200$ GeV
- Qualitatively, but not quantitatively in agreement with models
Selected RHIC results

STAR, $\sqrt{s_{NN}} = 200$ GeV

Adamczyk et al. (STAR), PRC90 (2014) 024906
Adamczyk et al. (STAR), PRL111 (2013) 052301

Good coverage from low to high $p_T$
$R_{AA}$ increases with $p_T$
No significant $J/\psi$ elliptic flow

Re-generation expected to enhance low-$p_T$ production
Re-generated $J/\psi$ should inherit charm quark flow

not seen

E. Scomparin, Quarkonia at the LHC: open questions, Leiden, October 2016
LHC results: ALICE

- Systematically larger $R_{AA}$ values for central events at LHC energy
- $R_{AA}$ increases at low $p_T$ at LHC energy

Compare $J/\psi$ suppression, RHIC ($\sqrt{s_{NN}}=0.2$ TeV) vs LHC ($\sqrt{s_{NN}}=2.76$ TeV)

Results dominated by low-$p_T$ $J/\psi$
- Systematically larger $R_{AA}$ values for central events at LHC energy
- $R_{AA}$ increases at low $p_T$ at LHC energy

Possible interpretation:
- RHIC energy $\rightarrow$ suppression effects dominate
- LHC energy $\rightarrow$ suppression + regeneration
Striking **difference** with respect to “ALICE vs PHENIX”

- No saturation of the suppression vs centrality
- High-\(p_T\) RHIC results show **weaker** suppression
- No significant \(p_T\) dependence from 6.5 GeV/c onwards
- (Re)generation processes expected to be negligible
CNM effects are not negligible!

- p-Pb collisions, $\sqrt{s_{NN}}=5.02$ TeV, $R_{pPb}$ vs $p_T$

  - (Rough) extrapolation of CNM effects to Pb-Pb
  - $R_{PbPb}^{\text{cold}} = R_{pPb} \times R_{Pbp}$

  → Evidence for hot matter effects!

Fair agreement with models (shadowing/CGC + energy loss)

ALICE, JHEP 1506 (2015) 055

E. Scomparin, Quarkonia at the LHC: open questions, Leiden, October 2016
Significant CNM effects also at RHIC energy.

Contrary to LHC results, $J/\psi$ data allow (need) a contribution from $J/\psi$ breakup in nuclear matter ($\sigma_{J/\psi-N} \sim 4$ mb).

Transverse momentum dependence more difficult to reproduce.

PHENIX, PRL107 (2011) 142301

E. Scomparin, Quarkonia at the LHC: open questions, Leiden, October 2016
$\psi(2S)$ in p-Pb collisions

- $\psi(2S)$ suppression is stronger than the $J/\psi$ one at RHIC and LHC
  - shadowing and energy loss, almost identical for $J/\psi$ and $\psi(2S)$, do not account for the different suppression
  - Only QGP+hadron resonance gas (Rapp) or comovers (Ferreiro) models describe the strong $\psi(2S)$ suppression at LHC

- Accurate Pb-Pb results still missing!
Recent RHIC results: U-U!

(re)combination/suppression role investigated comparing U-U and AuAu in central U-U wrt Pb-Pb

1) stronger suppression due to color screening 
   $\varepsilon_{AuAu} \sim 80-85\% \varepsilon_{UU}$

2) $J/\psi$ recombination favoured by 25% larger $N_{coll}$ in UU
   $N^{stat}_{J/\psi} \sim N_c^2 \sim N_{coll}^2$

results slightly favour $N_{coll}^2$ scaling $\rightarrow$ (re)combination wins over suppression when going from central U-U to Au-Au collisions

quantitative comparison depends on the choice of the uranium Woods-Saxon parametrizations

PHENIX, arXiv:1509.05380
Bottomonium ($\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$)
\( \Upsilon \) suppression in Pb-Pb collisions

- Relatively low beauty cross section \( \rightarrow \) weak regeneration effects
- Kinematic coverage down to \( p_T = 0 \) for all LHC experiments

Strong relative suppression of more loosely bound states

\[
\begin{align*}
R_{AA}(\Upsilon(1S)) &= 0.43 \pm 0.03 \pm 0.07 \\
R_{AA}(\Upsilon(2S)) &= 0.13 \pm 0.03 \pm 0.02 \\
R_{AA}(\Upsilon(3S)) &< 0.14 \text{ at 95\% CL}
\end{align*}
\]

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 gypsum 

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- Strong $\gamma(1S)$ suppression
- Feed-down from excited states seems not enough to explain it!
- Similar suppression at RHIC and LHC energy, a priori unexpected

- $\gamma(2S)$ binding energy similar to that of the $J/\psi$, but bottomonium suppression much larger $\Rightarrow$ recombination effects negligible
R_{AA} vs p_T and y, comparison with models

- No significant p_T dependence of R_{AA}
- Hints for a decrease of R_{AA} at large y (comparison ALICE – CMS)
- Could suggest the presence of sizeable recombination effects at mid-rapidity (?)
Recent results with the STAR MTD on the ratio excited/ground state

Mutual agreement between experiments but still large stat+syst uncertainties

→ Need upgraded detectors and higher luminosity

Recent results with the STAR MTD on the ratio excited/ground state

Consistent with dielectron measurement within large uncertainties

Factor 7 more statistics on this measurement with full Run14+ Run16 data
Weak CNM effects for bottomonium

- $R_{pPb}$ close to 1 and with no significant dependence on $y$, $p_T$ and centrality

- Fair agreement ALICE vs LHCb (within large uncertainties)

ALICE, PLB 740 (2015) 105
ATLAS-CONF-2015-050
LHCb, JHEP 07(2014)094

E. Scomparin, Quarkonia at the LHC: open questions, Leiden, October 2016
Prospects
Run 1

- Integrated luminosity → more than a factor 3 delivered by the LHC with respect to run 1 (2011 Pb-Pb)

- Short pp run at $\sqrt{s} = 5.02$ TeV at the beginning of the HI period $\rightarrow L_{\text{int}} = 30$ pb$^{-1}$, good reference for BOTH Pb-Pb and p-Pb results

- Data analysis quickly progressing

Run 2

CMS Integrated Luminosity, PbPb, 2015, $\sqrt{s} = 5.02$ TeV/nucleon

Data included from 2015-11-25 09:59 to 2015-12-13 12:09 UTC

LHC Delivered: 0.60 nb$^{-1}$
CMS Recorded: 0.56 nb$^{-1}$

Preliminary Offline Luminosity

LHC run-2: Pb-Pb at $\sqrt{s}_{NN}=5$ TeV

E. Scomparin, Quarkonia at the LHC: open questions, Leiden, October 2016
First spectra from run-2

Charmonia/bottomonia signals well visible!
Expect first results very soon!

LHCb:
first Pb-Pb run and p-A beam-gas collisions ($\sqrt{s_{NN}}=110$ GeV)

E. Scomparin, Quarkonia at the LHC: open questions, Leiden, October 2016
The future of RHIC - sPHENIX

- BaBar 1.5 T superconducting solenoid
- Full em/hadronic calorimetry
- Precision tracking/vertexing

Physics program
→ Light and HF jets, photons, upsilons and their correlations

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Summary/conclusions

- **J/ψ** (quarkonium) suppression was proposed 30 years ago as an unambiguous signature of QGP formation in HI collisions.

- From the very beginning (**SPS experiments**) it received a lot of attention both in theory and experiment.

- Although a clear effect was seen from the very first measurements (**NA38/NA50 experiments**), its quantitative interpretation was (is) far from being trivial.

- At **RHIC** ($\sqrt{s_{\text{NN}}}$ up to 0.2 TeV) and **LHC** ($\sqrt{s_{\text{NN}}}$=2.76 TeV, now 5 TeV) large samples of data now exist for both bottomonia and charmonia.
Summary/conclusions

- In the **bottomonium** sector
  - CNM effects are present but not strong
  - At LHC, a very strong suppression of \( \Upsilon(2S) \) and \( \Upsilon(3S) \) states wrt pp was observed, while the tightly bound \( \Upsilon(1S) \) yield is reduced by \(~50\%\)
  - Compatible with **sequential suppression** of the states in a QGP
  - Quantitative description still needs refinements
  - **RHIC upgrades** will bring high quality data also at lower energies

- In the **charmonium** sector
  - The **re-generation mechanism** has been predicted to be sizeable at both RHIC and LHC
  - Hints for its presence were singled out at RHIC \( (R_{AA} \ vs \ \Upsilon, \ UU \ vs \ PbPb) \)
  - **Re-generation** clearly present at **LHC energy** \( (R_{AA} \ vs \ p_T, \ flow) \)
  - Models qualitatively describe the data, but still large uncertainty on some key parameters \( \rightarrow \) open charm cross section
  - **CNM**, dominated by **shadowing/CGC**, are stronger than in the \( \Upsilon \) sector
More info
Anisotropic transverse flow

- In collisions with $b \neq 0$ (non central) the fireball has a geometric anisotropy, with the overlap region being an ellipsoid.

- Macroscopically (hydrodynamic description)
  - The pressure gradients, i.e. the forces "pushing" the particles are anisotropic ($\varphi$-dependent), and larger in the $x$-$z$ plane.
  - $\varphi$-dependent velocity $\rightarrow$ anisotropic azimuthal distribution of particles.

- Microscopically
  - Interactions between produced particles (if strong enough!) can convert the initial geometric anisotropy in an anisotropy in the momentum distributions of particles, which can be measured.
Anisotropic transverse flow

- Starting from the azimuthal distributions of the produced particles with respect to the reaction plane $\Psi_{RP}$, one can use a Fourier decomposition and write

$$\frac{dN}{d(\varphi - \Psi_{RP})} = \frac{N_0}{2\pi} (1 + 2v_1 \cos(\varphi - \Psi_{RP}) + 2v_2 \cos(2(\varphi - \Psi_{RP})) + \ldots)$$

- The terms in $\sin(\varphi - \Psi_{RP})$ are not present since the particle distributions need to be symmetric with respect to $\Psi_{RP}$.
- The coefficients of the various harmonics describe the deviations with respect to an isotropic distribution.
- From the properties of Fourier’s series one has

$$v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$
On feed-down fractions

- Usually they are not supposed to vary strongly with \( \sqrt{s} \) (or \( y \))
- New LHCb pp results could alter the picture inherited by CDF (relative to \( p_T > 8 \) GeV/c)

<table>
<thead>
<tr>
<th>( p_T^\gamma ) (GeV/c)</th>
<th>( \mathcal{R}^{\chi_b(1P)}_Y(nS) )</th>
<th>( \mathcal{R}^{\chi_b(2P)}_Y(nS) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Y(1S) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6–8</td>
<td>14.8 ± 1.2 ± 1.3</td>
<td>3.3 ± 0.6 ± 0.2</td>
</tr>
<tr>
<td>8–10</td>
<td>17.2 ± 1.0 ± 1.4</td>
<td>5.2 ± 0.6 ± 0.3</td>
</tr>
<tr>
<td>10–14</td>
<td><strong>21.3 ± 0.8 ± 1.4</strong></td>
<td><strong>4.0 ± 0.5 ± 0.3</strong></td>
</tr>
<tr>
<td>14–18</td>
<td>24.4 ± 1.3 ± 1.2</td>
<td>5.2 ± 0.8 ± 0.4</td>
</tr>
<tr>
<td>18–22</td>
<td>27.2 ± 2.1 ± 2.1</td>
<td>5.5 ± 1.0 ± 0.4</td>
</tr>
<tr>
<td>22–40</td>
<td>29.2 ± 2.5 ± 1.7</td>
<td>6.0 ± 1.2 ± 0.4</td>
</tr>
</tbody>
</table>

- At the limit of uncertainties or do we have a problem here?
- Difficult to reach 50% including 2S and 3S

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Can we take CNM into account?

- Apply the simple $R_{pPb} \times R_{Pbp}$ recipe on ALICE pPb
- Would give $0.78 \times 0.86 = 0.67$ for $3.25 < y < 4$
  $0.91 \times 0.66 = 0.60$ for $2.5 < y < 3.25$
  (but see also LHCb result)

- No results from CMS (for the moment?)
- Assuming a “smooth” $y$-interpolation of CNM

$\sim 0.5$ “anomalous” suppression at forward-$y$

$\sim 0.8-0.9$ “anomalous” suppression at central-$y$
The regeneration of $\psi'$ mesons occurs significantly later than for $J/\psi$'s. Despite a smaller total number of regenerated $\psi'$, the stronger radial flow at their time of production induces a marked enhancement of their $R_{AA}$ relative to $J/\psi$'s in a momentum range $p_t \approx 3$-6 GeV/c.
*E. Scomparin, Quarkonia at the LHC: open questions, Leiden, October 2016*

- **$J/\psi$ $R_{pPb}$: centrality dependence**

  - **backward-$y$**
  - **mid-$y$**
  - **forward-$y$**

  **ALICE:**
  - mid and fw-$y$: suppression increases with centrality
  - backward-$y$: hint for increasing $Q_{pA}$ with centrality
  - Shadowing and coherent energy loss models in fair agreement with data

  **ATLAS**
  - Flat centrality dependence in the high $p_T$ range

---

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Dependence of suppression on \( \tau_C \)

Forward-\( y \): \( \tau_C << \tau_f \)
interaction with nuclear matter cannot play a role

Backward-\( y \): \( \tau_C \lesssim \tau_f \)
indication of effects related to break-up in the nucleus?

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J/ψ at very low p_{T} 

- **Strong R_{AA} enhancement** in peripheral collisions for 0<p_{T}<0.3 GeV/c

- Significance of the excess is 5.4 (3.4)σ in 70-90% (50-70%)

- Behaviour not predicted by transport models

- Excess might be due to coherent J/ψ photoproduction in PbPb (as measured also in UPC)

If excess is “removed” requiring p_{T}^{J/ψ}>0.3GeV/c
→ ALICE R_{AA} lowers by 20% at maximum (in the most peripheral bin)

E. Scomparin, Quarkonia at the LHC: open questions, Leiden,
Models provide a fair description of the data, even if with different balance of primordial/regeneration components

Still rather large theory uncertainties: models will benefit from precise measurement of $\sigma_{cc}$ and CNM effects

Opposite trend with respect to lower energy experiments
Building a reference $\sigma_{pp} \rightarrow$ interpolation

- Simple empirical approach adopted by ALICE, ATLAS and LHCb

\[
\sigma_{\text{incl}} = 5.28 \pm 0.40_{\text{exp}} \pm 0.10_{\text{inter}} \pm 0.05_{\text{theo}} \, \mu b = 5.28 \pm 0.42 \, \mu b.
\]

- $\psi(2S) \rightarrow$ interpolation difficult, small statistics at $\sqrt{s}=2.76$ TeV
- Ratio $\psi(2S) / J/\psi \rightarrow$ ALICE uses $\sqrt{s}=7$ TeV pp values (weak $\sqrt{s}$-dependence)

\[
R_{pA}^{\psi(2S)} = R_{pA}^{J/\psi} \times \frac{\sigma_{p\psi(2S)}}{\sigma_{p\psi}} \times \frac{\sigma_{J/\psi}}{\sigma_{pp}} \times \frac{\sigma_{pp}}{\sigma_{pA}}
\]

ALICE estimate (conservative) $ightarrow$ 8% syst. unc. due to different $\sqrt{s}$ (using CDF/ALICE/LHCb results)
ψ(2S) in Pb-Pb: ALICE "vs" CMS

- ψ(2S) production modified in Pb-Pb with a strong kinematic dependence
- CMS → suppression at high $p_T$, enhancement at intermediate $p_T$

Possible interpretation (Rapp et al.) → Re-generation for ψ(2S) occurs at later times wrt $J/\psi$, when a significant radial flow has built up, pushing the re-generated ψ(2S) at a relatively larger $p_T$

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Small tension, between ALICE and CMS, for central events?

Du and Rapp arXiv:1504.00670

CMS, PRL113 (2014) 262301
ALICE, arXiv:1506.08804
**J/ψ R_{pPb}: ATLAS “vs” ALICE “vs” LHCb**

- **R_{pPb} vs p_T around midrapidity → fair agreement ATLAS vs ALICE**
  - ALICE, JHEP 1506 (2015) 055
  - ATLAS-CONF-2015-023

- **R_{pPb} vs y → fair agreement ALICE vs LHCb, ATLAS refers to p_T>10 GeV/c**
  - LHCb, JHEP 02 (2014) 72, ALICE, JHEP 02 (2014) 73
ψ(2S) in p-Pb: $p_T$ dependence

- **ALICE (low $p_T$)**: rather strong suppression, possibly vanishing at backward $y$ and $p_T > 5$ GeV/c
- **ATLAS (high $p_T$)**: larger uncertainties, hints for strong enhancement, concentrated in peripheral events

Possible tension between ALICE and ATLAS results? Wait for final results

ALICE, JHEP 12 (2014) 073

ATLAS, JHEP 12 (2014) 073
High $p_T$ $\Upsilon$: model comparison

- High $p_T$ $\Upsilon$ suppression
- Propagation effects through QGP
  - Quenching of the color octet component
  - Collisional dissociation model
- Approximation: initial wave function of the quarkonia well approximated by vacuum wavefunctions in the short period before dissociation
- CNM effects accounted for (shadowing + Cronin)

Some J/ψ predictions for run-2

- First predictions for (both statistical and transport models) indicate a moderate increase in $R_{AA}$ when comparing $\sqrt{s_{NN}}=5.02$ and 2.76 TeV

- Theoretical uncertainties are larger than the predicted increase
  → Provide quantities where at least partial cancellation of uncertainties takes place (double ratios of $R_{AA}$)

PBM, Andronic, Redlich and Stachel
From run-1 ro run-2

- **Charmonium highlight** → evidence for a new mechanism which enhances the \( J/\psi \) yield, in particular at low \( p_T \), with respect to low-energy experiments.

- In addition
  - Indications for \( J/\psi \) azimuthal anisotropy (non-zero \( v_2 \))
  - Significant final state effects on \( \psi(2S) \) in \( p-Pb \), likely related to the (hadronic) medium created in the collision.

- **Bottomonium highlight** → evidence for a stronger suppression of 2S and 3S states compared to 1S. Effect not related to CNM and compatible with sequential suppression of “bottomonium” states.

- In addition
  - 1S is also suppressed (\( \sim 50\%-60\% \)). *Feed-down* effect only?
  - \( y \)-dependence of 1S suppression to be understood.
From run-1 to run-2

- Prospects for run-2
  - Collect a \( \sim 1 \) order of magnitude larger integrated luminosity

- High-statistics \( J/\psi \) sample
  - Comparison with run-1 AND with theoretical predictions crucial to confirm/quantify our understanding in terms of regeneration
  - more precise \( v_2 \) results also needed

- Significant \( \psi(2S) \) sample
  - Crucial: run-1 results “exploratory” (and interpretation not clear)

- High-statistics \( \Upsilon(1S) \) sample
  - A significant increase in 1S suppression with respect to run-1 might imply that a high-T QGP is formed (“threshold” scenario)

- Differential \( \Upsilon(2S) \) and \( \Upsilon(3S) \) results from run-1 are limited by statistics
  - Centrality and \( p_T \)-dependent studies important to assess details of sequential suppression
Suppression vs $\sqrt{s_{NN}}$ (RHIC)

- At RHIC 39 GeV, 62 GeV, 200 GeV all show similar suppression
Yield ratios for bottomonium in p-Pb

CMS

- **Excited states suppressed** with respect to $\Upsilon(1S)$
- Initial state effects similar for the various $\Upsilon(ns)$ states
  - Final states effects at play?

ATLAS

- no strong $y$ (and $p_T$) dependence
- agreement with CMS within uncertainties
Self-normalized $\Upsilon$ cross sections

- All the ratios increase with increasing forward transverse energy.
- When Pb nuclei are involved → Increase partly due to larger number of N-N collisions.
- Increase observed also in pp collisions → multiple partonic interactions?

Similar behaviour observed for $J/\psi$ (ALICE) (PLB712 (2012) 165-175)

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In the beginning...

...there was a definite and clear prediction

ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the $J/\psi$ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined.

We conclude that $J/\psi$ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.