OUTLOOK:

\( J/\psi, \psi(2S) \) and \( \Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \)

in p-Pb \( \leftrightarrow \) collisions

(and Pb-Pb \( \leftrightarrow \) collisions)
Sequential melting depending on the binding energies of the quarkonium states

\[ T < T_c \quad \psi(2S) \quad J/\psi \quad \Upsilon(1S) \]
\[ T \approx T_c \quad J/\psi \quad \Upsilon(1S) \]
\[ T \approx 3T_c \quad \Upsilon(1S) \]
\[ T >> T_c \]

(Re)combination
Increasing the collision energy the c\bar{c} pair multiplicity increases

→ enhanced quarkonium production via (re)combination at hadronization or during QGP stage

<table>
<thead>
<tr>
<th>Most central AA collisions</th>
<th>SPS 20 GeV</th>
<th>RHIC 200 GeV</th>
<th>LHC 2.76 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{c\bar{c}baryon} / \text{event} )</td>
<td>( \sim 0.2 )</td>
<td>( \sim 10 )</td>
<td>( \sim 75 )</td>
</tr>
</tbody>
</table>

On top of these mechanisms related to hot matter:

- cold matter effects (CNM)
  - nuclear parton shadowing
  - energy loss
  - $c\bar{c}$ in medium break-up

investigated through \textbf{p-A collisions}

\textbf{p-A collisions at low $\sqrt{s}$}

- Quarkonium significantly affected by CNM effects with strong kinematic dependence

- $J/\psi$ and $\psi(2S)$ behaviour in p-A collisions strongly influenced by break-up mechanism depending on charmonia crossing and formation time

E866 Collab., PRL 84 (2000) 3256
On top of these mechanisms related to hot matter:

cold matter effects (CNM):

- nuclear parton shadowing
- energy loss
- $c\bar{c}$ in medium break-up

investigated through **p-A collisions**

**A-A collisions at low $\sqrt{s}$**

Quarkonium suppression in AA collisions observed already at SPS and RHIC:

- similar patterns if CNM effects are taken into account

$\rightarrow$ Compensation of suppression/recombination effects?
With respect to lower energy experiments, at LHC we have:

- **higher energies**
  - stronger quarkonium suppression?

- **more charm**
  - larger (re)combination?

- **more bottom**
  - $\Upsilon$ can be investigated

**Complementary quarkonium results from LHC experiments!**
QUARKONIUM AT LHC: Pb–Pb RESULTS

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV
$\gamma(1, 2, 3S)$

$L_{\text{int}}$ (PbPb) = $147 \mu$b$^{-1}$

Events/(GeV/c$^2$)

$\rho, \omega, \phi$

$J/\psi$

$\psi(2S)$

$Z$

$p_T^{\mu} > 4$ GeV/c

$m_{\mu\mu}$ (GeV/c$^2$)
ALICE results show weaker centrality dependence and smaller suppression for central events with respect to PHENIX

→ behaviour expected in a (re)combination scenario
QUARKONIUM AT LHC: Pb-Pb RESULTS

- Improved agreement between ALICE and CMS data (new pp CMS reference)
- Large statistics and systematic uncertainties prevent a firm conclusion on the $\psi$(2S) trend vs centrality
First clear observation of sequential $\Upsilon(nS)$ suppression

$\Upsilon(1S)$ suppression consistent with melting of excited states ($\sim50\%$ feed-down)

Suppression of $\Upsilon(1S)$ stronger than at RHIC
**p-Pb: ROLE OF CNM EFFECTS ON J/ψ**

- **CNM effects investigated through the nuclear modification factor** $R_{pA}$

$$R_{pA}^{J/ψ} = \frac{Y_{pA}^{J/ψ}}{\langle T_{pA} \rangle \sigma_{pp}^{J/ψ}}$$

- **J/ψ behaviour strongly $y$ dependent**
  - strong $J/ψ$ suppression at forward-$y$
  - no suppression in the backward region

- **Good agreement between ALICE and LHCb results**

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**Michael Winn - Friday**
**p-Pb: Role of CNM Effects on J/ψ**

CNM effects investigated through the nuclear modification factor $R_{pA}$

$$R_{pA}^{J/ψ} = \frac{Y_{pA}^{J/ψ}}{\langle T_{pA} \rangle \sigma_{pp}^{J/ψ}}$$

- J/ψ behaviour strongly $y$ dependent
  - strong J/ψ suppression at forward and mid-$y$
  - no suppression in the backward region

Fair agreements with models based on shadowing + energy loss
**p-Pb: Role of CNM Effects on J/ψ**

**backward-γ**

ALICE Preliminary
p-Pb \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \), inclusive J/ψ \( \rightarrow \mu^+\mu^- \)
4.46 < \( y_{	ext{cms}} < 2.96 \), \( L_{\text{int}} = 5.8 \text{ nb}^{-1} \)

**forward-γ**

ALICE Preliminary
p-Pb \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \), inclusive J/ψ \( \rightarrow \mu^+\mu^- \)
2.63 < \( y_{	ext{cms}} < 3.53 \), \( L_{\text{int}} = 5.0 \text{ nb}^{-1} \)

**mid-γ**

ALICE Preliminary
p-Pb \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \), inclusive J/ψ \( \rightarrow e^+e^- \)
-1.37 < \( y_{	ext{cms}} < 0.43 \)

**Fair Agreements with Models**

Based on shadowing + energy loss except at forward-γ and low \( p_T \).
\( Q_{pA} \): nuclear modification factor potentially influenced by a bias in the event activity estimator.

\[
Q_{pA} = \frac{Y_{J/\psi}^{pA}}{\langle T_{pA} \rangle \sigma_{pp}^{J/\psi}}
\]

**forward-\( y \):** strong \( J/\psi \) \( Q_{pA} \) decrease from low to high event activity.

**backward-\( y \):** \( Q_{pA} \) consistent with unity, with a feeble event activity dependence.
**CNM EFFECTS FROM p-Pb TO Pb-Pb**

- CNM effects evaluated from p-Pb data

**Hypothesis:**
- 2→1 kinematics for $J/\psi$ production
- CNM effects (dominated by shadowing) factorize in p-A
- CNM evaluated as $R_{pA} \times R_{Ap} (R_{pA}^2)$, similar x-coverage as Pb-Pb

![Graph showing kinematics for $J/\psi$ production and CNM effects](image)

- Sizeable $p_T$ dependent suppression still visible
  → CNM effects not enough to explain AA data at high $p_T$
CNM EFFECTS FROM p-Pb TO Pb-Pb

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Sizeable $p_T$ dependent suppression still visible
- CNM effects not enough to explain AA data at high $p_T$
- From enhancement to suppression increasing $p_T$
- Hint for recombination
A strong decrease of the $\psi(2S)$ production in p-Pb, relative to $J/\psi$, is observed with respect to the pp measurement ($2.5<y_{\text{cms}}<4$, $\sqrt{s}=7\text{TeV}$)

Double ratio allows a direct comparison of the $J/\psi$ and $\psi(2S)$ production yields between experiments

Similar effect seen by PHENIX in d-Au collisions, at mid-$y$, at $\sqrt{s_{\text{NN}}}=200\text{ GeV}$

$[\psi(2S)/J/\psi]_{\text{pp}}$ variation between ($\sqrt{s}=7\text{TeV}$, $2.5<y<4$) and ($\sqrt{s}=5.02\text{TeV}$, $2.03<y<3.53$ or $-4.46<y<-2.96$) based on CDF and LHCb data (\sim8% included in the systematic uncertainty)
\( \psi(2S) \) suppression stronger than the \( J/\psi \) one, reaching a factor \( \sim 2 \) wrt pp

same initial state CNM effects (shadowing & coherent energy loss) for both \( J/\psi \) and \( \psi(2S) \)

theoretical predictions in disagreement with \( \psi(2S) \) result
\( \psi(2S) \) \( R_{pA} \) VS RAPIDITY

\( \psi(2S) \) suppression stronger than the \( J/\psi \) one, reaching a factor \(~2\) wrt pp

Can the stronger \( \psi(2S) \) suppression be due to break-up of the fully formed resonance in CNM? Possible if formation \((\tau_f)\) < crossing time \((\tau_c)\) 
\[ \tau_f \sim 0.05 - 0.15 \text{fm/c} \]

\[ \tau_c = \frac{\langle L \rangle}{\beta z \gamma} \]

forward-\( y \): \( \tau_c \sim 10^{-4} \text{ fm/c} \)
backward-\( y \): \( \tau_c \sim 10^{-1} \text{ fm/c} \)

forward-\( y \): break-up effects excluded

backward-\( y \): \( \tau_f \sim \tau_c \), hence break-up in CNM hardly explains the strong \( J/\psi \) and \( \psi(2S) \) difference

**Graph:**
- ALICE, p-Pb \( \sqrt{s_{NN}} = 5.02 \text{ TeV}, \) inclusive \( J/\psi, \psi(2S) \rightarrow \mu^+\mu^- \)
- \( \text{arXiv:1405.3796} \)
- Forward-\( y \): break-up effects excluded
- Backward-\( y \): \( \tau_f \sim \tau_c \), hence break-up in CNM hardly explains the strong \( J/\psi \) and \( \psi(2S) \) difference
Final state effects related to the (hadronic) medium created in the p-Pb collisions?

Charmonium interaction with comoving particles:

- Comovers dissociation affects more strongly the loosely bound $\psi(2S)$ than the $J/\psi$
- Comovers density larger at backward rapidity

$\psi(2S) R_{pA} \text{ vs RAPIDITY: COMOVERS?}$

E. Ferreiro arXiv:1411.0594
**J/ψ and ψ(2S) Q_{pPb} vs Event Activity**

### Inclusive J/ψ, ψ(2S) → μ⁺μ⁻

- **p-Pb \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)**
  - 2.03 < \( y_{\text{cms}} \) < 3.53 (p-going direction)

**Forward-\( y \):** J/ψ and ψ(2S) show a similar decreasing pattern vs event activity.

**Backward-\( y \):** the J/ψ and ψ(2S) behaviour is different, with the ψ(2S) significantly more suppressed for largest event activity classes.

→ Another hint for ψ(2S) suppression in the (hadronic) medium?
\( \Upsilon(1S) \) production in p-Pb

\( \Upsilon(1S) \) measured at mid-\( y \) by CMS and at forward-\( y \) by both ALICE and LHCb

\( R_{pA} \) results within uncertainties (but LHCb systematically higher)

Hint for stronger suppression at forward-\( y \) (similarly to J/\( \psi \))

Theoretical calculations based on initial state effects seem not to describe simultaneously forward and backward \( y \)

ALICE: arXiv:1410.2234, accepted by PLB
LHCb: JHEP 07(2014)094

Massimiliano Marchisone - Friday 22
\( \Upsilon(nS)/\Upsilon(1S) \) PRODUCTION IN p-Pb

Initial state effects similar for the three \( \Upsilon \) states

p-Pb vs pp @mid-y: different/stronger final states effects in p-Pb affecting the excited states

p-Pb vs PbPb @mid-y: even stronger suppression of excited states in PbPb


ALICE (and LHCb) observes:

\( \Upsilon(2S)/\Upsilon(1S) \) (ALICE)

2.03 < \( y \) < 3.53: \( 0.27 \pm 0.08 \pm 0.04 \)

-4.46 < \( y \) < -2.96: \( 0.26 \pm 0.09 \pm 0.04 \)

Compatible with pp results 0.26±0.08 (ALICE, pp@7TeV)

CMS analyses the double ratio \([\Upsilon(2S)/\Upsilon(1S)]/[\Upsilon(nS)/\Upsilon(1S)]_{pp}\) and finds

0.83±0.05±0.05
Weaker dependence when the activity estimator is in a different kinematic region with respect to the $\gamma$.

Strong decrease with increasing charged particle multiplicity both in pp and p-Pb.

$\gamma(nS)/\gamma(1S)$ studied as a function of event activity.

$\gamma(1S)$ produced with more particles than excited states.

$\gamma$ production affects multiplicity? or multiplicity affects the $\gamma$?

Weaker dependence when the activity estimator is in a different kinematic region with respect to the $\gamma$. 

CMS pp $\sqrt{s} = 2.76$ TeV, CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV.
Large wealth of quarkonium results at LHC complementing SPS and RHIC measurements!

Very interesting observations, qualitative understanding of the main quarkonium features in A-A:

- important role of charmonium (re)generation processes at low $p_T$
- bottomonium sequential suppression observed

In p-A collisions:

- an interplay of shadowing and coherent energy loss can satisfactorily describe the $J/\psi$ results
- the loosely bound $\psi(2S)$ state is likely to be influenced by the hadronic final state
- $\Upsilon(1S)$ described within uncertainties by shadowing+energy loss
- also $\Upsilon(2S)$ and $\Upsilon(3S)$ are possibly influenced by the final state

Results from LHC Run2 eagerly awaited!
Strongly bound states have smaller sizes.

Debye screening condition $r_0 > \lambda_D$ will occur at different $T$.

Differences in the binding energies of the quarkonium states lead to a sequential melting of the states with increasing temperature.

<table>
<thead>
<tr>
<th>state</th>
<th>J/ψ</th>
<th>χc</th>
<th>ψ(2S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (GeV)</td>
<td>3.10</td>
<td>3.51</td>
<td>3.69</td>
</tr>
<tr>
<td>ΔE (GeV)</td>
<td>0.64</td>
<td>0.22</td>
<td>0.05</td>
</tr>
<tr>
<td>$r_0$ (fm)</td>
<td>0.50</td>
<td>0.72</td>
<td>0.90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>state</th>
<th>Y(1S)</th>
<th>Y(2S)</th>
<th>Y(3S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (GeV)</td>
<td>9.46</td>
<td>10.0</td>
<td>10.36</td>
</tr>
<tr>
<td>ΔE (GeV)</td>
<td>1.10</td>
<td>0.54</td>
<td>0.20</td>
</tr>
<tr>
<td>$r_0$ (fm)</td>
<td>0.28</td>
<td>0.56</td>
<td>0.78</td>
</tr>
</tbody>
</table>

(Digal, Petrecki, Satz PRD 64(2001) 0940150)
**J/ψ R_{AA} VS CENTRALITY: THEORY COMPARISON**

**Comparison to theory calculations:**

- Models including a large fraction (> 50% in central collisions) of J/ψ produced from (re)combination or models with all J/ψ produced at hadronization provide a reasonable description of ALICE results.

- Still rather large theory uncertainties: models will benefit from a precise measurement of \(\sigma_{cc}\) and from cold nuclear matter evaluation.
**J/ψ R_{AA} VS TRANSVERSE MOMENTUM**

J/ψ production via (re)combination should be more important at low transverse momentum $p_T$ region accessible by ALICE

- Different suppression for low and high $p_T$ J/ψ
- Striking difference between the PHENIX and ALICE patterns, in particular at low $p_T$ and central collisions (where PHENIX suppression is 4 times larger)
J/ψ production via (re)combination should be more important at low transverse momentum.

$p_T$ region accessible by ALICE.

Models with a large regeneration component (at low $p_T$) are in fair agreement with the data.

Multi-differential studies show that the difference low vs high $p_T$ suppression is even more important for central collisions.
Muons need to overcome the magnetic field and energy loss in the absorber: minimum momentum $p \sim 3$-5 GeV/c to reach the muon stations.

- Limits $J/\psi$ acceptance
  - mid-$y$: $p_T > 6.5$ GeV/c
  - forward $y$: $p_T > 3$ GeV/c

Opposite behavior when compared to low-$p_T$ results.

- Suppression is stronger at LHC energy (by a factor $\sim 3$ compared to RHIC for central events).

Is the suppression for central events ($R_{AA} \sim 0.2$) compatible with a full suppression of all charmonia?
The contribution of J/ψ from (re)combination should lead to a significant elliptic flow signal at LHC energy.

STAR found $v_2$ consistent with 0.

ALICE measures $v_2$ (with a significance up to $3\sigma$ for chosen kinematic/centrality selections) in agreement with transport models including (re)combination.

CMS measures a significant $v_2$ in a region where (re)combination should be negligible → due to path-length dependence of J/ψ suppression.
Separation via secondary vertex identification exploiting the ALICE ITS capabilities

Fraction of b-hadron decays obtained down to $p_T^J/\psi = 2\text{GeV}/c$

...but for the moment ALICE $R_{AA}$ results are for inclusive $J/\psi$
Comparison with CMS mid-rapidity results (PRL 109 (2012) 222301)

In most central collisions suppression seems stronger at forward rapidities

Stronger suppression at forward rapidity than at mid-rapidity
**Comparison with Theory**

- Evolving QGP described via a dynamical model including suppression of bottomonium states, but not CNM nor recombination.
- 2 different initial temperature $y$ profiles: boost invariant or Gaussian (3 tested shear viscosity).

The model underestimates the measured $\Upsilon(1S)$ suppression at forward-$y$, while it is in fair agreement with mid-$y$ data.
**Comparison with Theory**

- Transport model accounting for both regeneration and suppression
- CNM effects included via an effective absorption cross section (0-2 mb)

The measured $R_{AA}$ vs centrality is slightly overestimated by the model at forward-$y$, while it reproduces CMS results. Constant $R_{AA}$ behavior vs $y$ is not supported by the data.
ALICE p-Pb collisions

Beam energy: $\sqrt{s_{NN}} = 5.02$ TeV
Energy asymmetry of the LHC beams ($E_p = 4$ TeV, $E_{Pb} = 1.58$ A·TeV) → rapidity shift $\Delta y = 0.465$ in the proton direction

Beam configurations:
Data collected with two beam configurations: p-Pb and Pb-p

Muon analysis
$2.03 < y_{CMS} < 3.53$

Pb

Electron analysis
$-1.37 < y_{CMS} < 0.43$

Pb

Data collected with two beam configurations: p-Pb and Pb-p

$p$
The sizeable $\psi(2S)$ statistics in p-Pb collisions allows the differential study of $\psi(2S)$ production vs $p_T$.

Different $p_T$ correspond to different crossing times, with $\tau_c$ decreasing with increasing $p_T$.

backward-$y$: $\tau_c \sim 0.07$ ($p_T=0$) and $\sim 0.03$ fm/c ($p_T=8$ GeV/c).

if $\psi(2S)$ breaks up in CNM, the effect should be more important at backward-$y$ and low $p_T$.

No clear $p_T$ dependence is observed at $y<0$, within uncertainties.
• **Ferreiro et al. [EPJC 73 (2013) 2427]**
  - Generic 2→2 production model at LO
  - EPS09 shadowing parameterization at LO
  - Fair agreement with measured $R_{pPb}$
    • Although slightly overestimates it in the antishadowing region

• **Vogt [arXiv:1301.3395]**
  - CEM production model at NLO
  - EPS09 shadowing parameterization at NLO
  - Fair agreement with measured $R_{pPb}$ within uncertainties
    • Although slightly overestimates it
$\frac{\Gamma(2S)/\Gamma(1S)}{\Gamma(3S)/\Gamma(1S)}$ vs Event Activity

Weak variation as a function of the forward transverse energy

Strong decrease with increasing charged particle multiplicity
\( \Upsilon(2S)/\Upsilon(1S) \) PRODUCTION IN P-Pb

Initial state effects similar for the three \( \Upsilon \) states

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