Experimental Overview of Quarkonia

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Excellence Cluster “Universe” - TUM

Strangeness in Quark Matter 2016
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Charmonia
J/ψ in pp vs N_{ch}

• Faster than linear rise of self-normalised J/ψ yield with multiplicity
  ‣ was seen already at the LHC (open and closed HF)
  ‣ now also at RHIC

• Sign of fundamental process, such as MPI
J/ψ in p-Pb $\sqrt{s_{NN}} = 5$ TeV

- $R_{pA}$ at forward and backward rapidity
  - no pp data at 5 TeV at the time, reference from interpolation (updates soon?)
  - ALICE and LHCb roughly agree
  - strong suppression at forward
    - agreement with shadowing only, but also with models that include parton energy loss
  - no strong suppression/enhancement in the backward region

ALICE, JHEP 02 (2014) 073
LHCb, JHEP 02 (2014) 072
High-\(p_T\) J/\(\psi\) in p-Pb

- No significant CNM effects at high \(p_T\) (none expected)
  - discrepancy between ATLAS and CMS at intermediate \(p_T\) (<10 GeV)?
- \(R_{pPb}\) based on interpolation with large uncertainties
  - wait for update based on pp measurement at proper energy
• **Backward:** suppression of $\psi(2S)$, none for $J/\psi$
  ‣ $J/\psi$ maybe enhanced in central p-Pb

• **Forward:** suppression of $\psi(2S)$ and $J/\psi$ almost the same

• Comover interaction model qualitatively describes patterns

ALICE, arXiv:1603.02816
also see: LHCb, JHEP 03 (2016) 133
Quarkonia: $\psi'$ at forward/backward in central collision

- $\psi'$ broken up

- Qualitatively agrees with the comover dissociation model.

- Comparison with the QGP model: work in progress.

- Similar relative suppression of $\psi'$ at backward rapidity, but larger relative suppression of $\psi'$ at forward rapidity at LHC.

RHIC: d+Au, p+Au, p+Al

LHC: p+Pb

$R = \frac{\psi(2S)/J/\psi(2S)/J/\psi}{pA/\psi(2S)/J/\psi}$

- Relative $\psi(2S)$ suppression observed in p-A from 200 GeV to 5 TeV
  - $A = $ Al, Au, Pb
  - hints for stronger suppression at backward rapidity, comover dissociation?
At high $p_T$ and midrapidity: hint of opposite behavior of $\psi (2S)$ to $J/\psi$ double ratio in peripheral p-Pb collisions

- disappears in central collisions
J/ψ in A-A from RHIC to the LHC

- STAR: new, independent measurement at |y|<0.5 via muon channel
- Confirms existing picture:
  - Low-\(p_T\) J/ψ at the LHC are less suppressed than at RHIC, extra source
  - High-\(p_T\) J/ψ at the LHC are more suppressed than at RHIC, more dissociation
J/ψ in A-A from RHIC to the LHC

- First time that J/ψ are less suppressed at low $p_T$ than high $p_T$
- Also visible in $r_{AA} = \langle p_T \rangle_{AA}/\langle p_T \rangle_{pp}$
- Models including regeneration component describe data well
Sequential Melting vs. Regeneration

- Always change of J/ψ yield relative to total charm not to pp
- Sequential Melting: naively expect plateaus and steps as $\sqrt{s_{NN}}$ increases
- Regeneration: at high enough $\sqrt{s_{NN}}$, $R_{AA}$ should increase with centrality
  - from 2.76 TeV to 5 TeV, charm cross section expected to increase by factor 1.5
  - really need a measurement of the charm cross section in AA

A. Andronic et al., PLB 652 (2007) 259
J/ψ in Pb-Pb $\sqrt{s_{\text{NN}}} = 5.02$ TeV

$R_{\text{AA}}$: assumes binary scaling of charm cross section

ALICE, exclusive J/ψ → $\mu^+\mu^-$

2.5 < $y$ < 4, $p_T < 8$ GeV/c

• Centrality independent increase from 2.76 TeV to 5.02 TeV (<1σ)
  ‣ present also in peripheral collision: LHCb?
• No change at low $p_T$ (phase space? $dN/dp_T$ peaks around 1–2 GeV)
• Increase for $p_T$>2 GeV, recombination + radial flow effects?
• Extends to $p_T$~6 GeV: ATLAS, CMS…?
• Do we need an FCC to see/rule out an increase of $R_{\text{AA}}$ (or $y=0$ at LHC)?
J/ψ in Pb-Pb √s_{NN} = 5.02 TeV

R_{AA}: assumes binary scaling of charm cross section

ALICE, Pb–Pb, inclusive J/ψ → µ⁺µ⁻
2.5 < y < 4, 0.3 < p_T < 8 GeV/c

- Centrality independent increase from 2.76 TeV to 5.02 TeV (<1σ)
  - present also in peripheral collision: LHCb?
- No change at low p_T (phase space? dN/dp_T peaks around 1–2 GeV)
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ALICE, CERN-EP-2016-162 (submitted for publication)

R_{AA}(5.02 TeV)/R_{AA}(2.76 TeV)

ALICE, inclusive J/ψ → µ⁺µ⁻
2.5 < y < 4

Transport \sqrt{s_{NN}} = 5.02 TeV (TM1, Du and Rapp)
Pb–Pb \sqrt{s_{NN}} = 5.02 TeV, 0-20%
Pb–Pb \sqrt{s_{NN}} = 2.76 TeV, 0-20%
Low-$p_T$ J/$\psi$ in Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV

- **LHCb** measured inclusive J/$\psi$ with $p_T>0$ in two centrality bins:
  - 70–90%
  - 50–70%

- $R_{CP} = ?$
  - uncharted territory for the VELO
  - need to understand (strong) centrality dependence of efficiency

\( \psi(2S) \) in Pb-Pb \( \sqrt{s_{NN}} = 2.76 \) TeV

- Puzzling results from CMS
  - high p\( _T \) and midrapidity: as expected
  - more forward rapidity and p\( _T > 3 \) GeV: hint of relative enhancement
  - Data not precise enough to conclude yet
- ALICE data not precise enough either to confirm or rule out
- What will happen at 5 TeV?
- Regeneration in hadronic phase would favor \( \psi(2S) \):
  - PBM and K. Redlich, EPJ C16 (2000) 519
  - Xiaoqian Du and R. Rapp, NPA 943 (2015) 147

CMS PbPb & pp \( \sqrt{s_{NN}} = 2.76 \) TeV

- 3 < p\( _T \) < 30 GeV/c, 1.6 < |y| < 2.4
- 6.5 < p\( _T \) < 30 GeV/c, |y| < 1.6

95% CL
**ψ(2S) in Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV**

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Bottomomonia
Y yield & polarization vs multiplicity

- No significant change of $\Upsilon$ polarization with multiplicity
  - no change of production mechanism at high $p_T$
  - but multiplicity dependence was measured at low $p_T$

- Yield vs $N_{ch}$ at high $p_T$?
\( \Upsilon \) in p-Pb

- Observed suppressions consistent with shadowing
- LHCb and ALICE results seem to give different message but agree within uncertainties
 Measure event activity at

- Forward rapidity ($4<|\eta_{\text{lab}}|<5.2$)
  - $\sum E_T$ in Hadronic Forward Calorimeter
  - weak dependence
  - independent sets consistent with flat

Single Ratios corrected for acceptance and efficiency
Measure event activity at:

- **Forward rapidity** \( (4 < |\eta_{\text{lab}}| < 5.2) \)
  - \( \sum E_T \) in Hadronic Forward Calorimeter
  - weak dependence
  - independent sets consistent with flat

- **Midrapidity** \( (|\eta_{\text{lab}}| < 2.4)) \)
  - \( N_{\text{tracks}} \): multiplicity in silicon tracker
  - significant decrease with multiplicity

- **Two options to explain results at midrapidity:**
  - \( \Upsilon \) affects multiplicity
    - ground states comes with 2 tracks more than excited state
  - multiplicity affects \( \Upsilon \)
    - activity around the \( \Upsilon \) breaks the state (comovers?)

- **Consequences for PbPb?!**
**Y(nS)/Y(1S) Double Ratio in p-Pb**

CMS, JHEP 04 (2014) 103

- **Pb-Pb: PRL 109 (2012)**
  - slightly different rapidity (|y_{CM}|<2.4)
  - 2011 pp dataset

- Double ratios in p-Pb larger than in Pb-Pb
  - suggests further final state effects in Pb-Pb
  - but: model dependent extrapolation from pPb to PbPb

- p-Pb vs pp:
  - double ratio less than unity (significance <3σ)
  - if multiplicity integrated double ratio indeed less unity: it's not the Y that affects the multiplicity → comovers?
**Y(nS)/Y(1S) Single Ratios**

- **CMS:**
  - midrapidity: slightly smaller values in pPb than pp (|y|<1.93)

- **LHCb:**
  - backward rapidity: Y(2S) consistent with pp (-5<y<-2.5)
  - forward rapidity: Y(2S) large uncertainties but slightly lower than pp (1.5<y<4)
  - Y(3S): too large uncertainties to discriminate

- **STAR**
  - excited states accessible in muon channel
  - hint of less suppression of excited states, consistent with Y(1S) R_{AA}

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**CMS, JHEP 04 (2014) 103**

**LHCb, JHEP 07 (2014) 094**

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**SHM prediction:** Y(2S)/Y(1S) = 0.032
Andronic, NPA 931 (2014) 135
**Y(nS)/Y(1S) Single Ratios**

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**Graph:**
- p+p (world-wide)
- CMS Pb+Pb@2.76 TeV (0-100%)
- STAR Au+Au@200 GeV (μμ) (0-80%)

**SHM prediction:** Y(2S)/Y(1S) = 0.032
Andronic, NPA 931 (2014) 135
Y(1S) in Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

- At the LHC, Y(1S) already suppressed in semi-peripheral collisions
  - at RHIC only in central collisions
- Y(1S) suppression in most central collisions might be larger than just lack of feed-down
  - feed-down fraction 30–40% but large uncertainties
- More suppression at forward than at midrapidity
  - beware of uncertainties
  - same story as charmonia at RHIC?
  - recombination also for bottomonia
  - ~2 bb pairs per event but 10x smaller closed/open ratio than charm
\( \Upsilon(1S) \) in Pb-Pb \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

- ALICE finds similar suppression to the one at 2.76 TeV
  - Increase less than 0.5\( \sigma \)
    - centrality integrated: 1.3±0.2±0.2

- Yet, so far quarkonia \( R_{AA} \) went only up with \( \sqrt{s_{NN}} \)
  - excited states? CMS...?

- Need feed-down measurements!
  - split “opinions” on signs of direct \( \Upsilon(1S) \) suppression
**$\Upsilon(1S)$ in Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV**

- ALICE finds similar suppression to the one at 2.76 TeV
  - Increase less than 0.5$\sigma$
    - centrality integrated: 1.3±0.2±0.2

- Yet, so far quarkonia $R_{AA}$ went only up with $\sqrt{s_{NN}}$
  - excited states? CMS...?

- Need feed-down measurements!
  - split “opinions” on signs of direct $\Upsilon(1S)$ suppression

![Graph showing suppression](image)
Fixed Target Experiments at the LHC

- Using SMOG to inject noble gas
  - He, Ne, Ar
- Moves LHCb detector to “midrapidity” in center of mass
  - $\Delta y = 4.5$
- Moves LHC to RHIC energy domain: $\sqrt{s_{NN}} = 87$ GeV
Summary

p-A:
- quarkonium data point towards some kind of comover effects

A-A:
- some form of regeneration seems to be present for J/ψ (unless charm cross section scales faster then $N_{\text{coll}}$)
- precise measurements of excited states crucial to kill models
- $Y(1S)$ looks more and more like the new J/ψ
  - with all its problems (competing hot and cold processes)

SMOG:
- turns LHCb into a fixed-target experiments at back-/midrapidity with p-gas and Pb-gas collisions in RHIC energy range
Quarkonium Talks at SQM

• ALICE
  ‣ Javier Castillo, Mon at 9h
  ‣ Hugo Pereira Da Costa, Tue at 16h
  ‣ Biswarup Paul, Tue at 17h
  ‣ Orlando Baillie, Thu at 11h
  ‣ Antoine Lardeux, Thu at 11h20

• ATLAS
  ‣ Qipeng Hu, Mon at 10h
  ‣ William Brooks, Thu at 12h20

• CMS
  ‣ Wei Xie, Mon at 9h30
  ‣ Songkyo Lee, Tue at 16h40
  ‣ Chad Steven Flores, Thu at 11h40

• LHCb
  ‣ Michael Schmelling, Mon at 12h

• PHENIX
  ‣ Rachid Nouicer, Mon at 11h30

• STAR
  ‣ Zhenyu Ye, Mon at 11h
  ‣ Wangmei Zha, Tue at 16h20
  ‣ Takahito Todorok, Tue at 17h40

• The full HF summary:
  ‣ Rongrong Ma, Fri at 14h
Backup
ALICE: $\psi(2S)$ in p-Pb

ALICE, p-Pb $\sqrt{s_{NN}} = 5.02$ TeV

Inclusive $J/\psi$, $\psi(2S) \rightarrow \mu^+\mu^-$

$2.03 < y_{\text{cms}} < 3.53$
- centrality-analysis
- $p_T$-analysis (JHEP 06(2015)55)

$\langle \tau_c \rangle$ (fm/c)

ALI-PUB-105839
Prompt $\psi(2S)$ in p-Pb

$LHCb, JHEP 03 (2016) 133$
High-\(p_T\) \(\psi(2S)\) in p-Pb

**ATLAS Preliminary**

\(10 < p_T < 30\) GeV

\(p+Pb\) \(\sqrt{s_{NN}} = 5.02\) TeV

**Data**

- Data
- Data (No Bias Correction)

- \(-1.5 < y^* < 1.5\)
- \(10 < p_T < 30\) GeV

**Prompt \(\psi(2S)\)**

\(-1.5 < y^* < 1.5\)

\(\sigma\omega\) Glauber (\(\omega_n = 0\))

\(p+Pb\) \(\sqrt{s_{NN}} = 5.02\) TeV

\(\langle N_{\text{part}} \rangle\)
High-\(p_T\) \(\psi(2S)\) in p-Pb

\[R_{pPb}\] as a function of \(p_T\) and \(y^*\) for \(p+Pb\) at \(\sqrt{s_{NN}} = 5.02\) TeV.
Open vs. Hidden HF in AA

- A brief reminder: Sequential melting a la Satz:
  - less closed than open HF
  - not: less closed HF in AA than in pp
- At RHIC: open charm scales with $N_{\text{coll}} \rightarrow R_{AA}(J/\psi) = J/\psi / D$ in PbPb
  - ignoring the large uncertainties on open charm

The ALICE Collaboration

\begin{align*}
\text{Inclusive } J/\psi \\
\text{ALICE Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV} \\
\end{align*}

- $J/\psi \rightarrow e^+e^-, |y| < 0.8, p_T > 0 \text{ GeV/c}$
- $J/\psi \rightarrow \mu^+\mu^-, 2.5 < y < 4, 0 < p_T < 8 \text{ GeV/c}$

\begin{align*}
\text{global syst.} &\pm 13\% \\
\text{global syst.} &\pm 15\%
\end{align*}

no low $p_T$ open HF data at LHC yet!
Open vs. Hidden HF in AA: high $p_T$

- But how to compare open and closed HF with $p_T$ cuts?
  - not trivial to select kinematic region of interest: same quark $p_T$, same hadron $p_T$,...?
- Similar suppression for “high-$p_T$” $D$ and $J/\psi$
  (energy loss rather than screening?)
**Y(nS) in Pb-Pb**

**Figure 7.12**: PbPb nuclear modification factor $R_{AA}$ as a function of the number of participants $N_{\text{Part}}$ for $\sqrt{s_{NN}} = 2.76$ TeV. The CMS Preliminary data shows a suppression of yield compared to the NN case.

**Figure 7.13**: Comparison of the suppression of $Y(1S)$ and $Y(2S)$ in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 200$ GeV. The CMS Preliminary data indicates a stronger suppression at higher energies.

**Figure 7.14**: Study of the $p_T$ dependence of the suppression of $Y(1S)$ and $Y(2S)$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The CMS Preliminary data shows a decrease in suppression with increasing $p_T$.

**Figure 7.15**: Comparison of the $y$ dependence of the suppression of $Y(1S)$ and $Y(2S)$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The CMS Preliminary data indicates a different suppression pattern compared to the NN case.

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It is interesting to see that recently, this AuAu data has been supplemented by reports of $Y(nS)$ production at RHIC energies. Indeed, this is at variance with the status of excited state suppression at RHIC. Since the onset of the QGP-induced suppression with higher energy densities, and should be investigated further: for example, additional $dAu$ data at RHIC would help to clarify the evolution of the QGP-induced suppression with higher energy densities, and should be extended to higher charmonium families. The CMS Preliminary result as a function of $s_{NN}$ seems to behave very differently at low $s_{NN}$ energies.

The CMS Preliminary data of the present analysis can be compared to RHIC data in a similar rapidity range: the STAR Collaboration has published in [132] a AuAu measurement of $R_{AA}$ for both $Y(1S)$, $|y| < 2.4$ and $|y| < 1$. The CMS Preliminary data shows a larger suppression compared to RHIC data at $\sqrt{s_{NN}} = 200$ GeV, exhibiting a lesser suppression at equivalent $|y|$. The CMS Preliminary data also shows a smaller suppression at $\sqrt{s_{NN}} = 2.76$ TeV for $|y| > 1/2$. The CMS Preliminary data is in good agreement with the ALICE data of [152].

The CMS Preliminary data indicates a sizeable difference in the suppression of $Y(1S)$ and $Y(2S)$ compared to the CMS Preliminary data from [78], as a function of $y$.
Low-$p_T$ J/$\psi$ in Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

ALICE Coll. PRL116, 222301 (2016)
LHCb: Prospects with SMOG

- **System for Monitoring the Overlap with Gas**
- Injection of noble gas in interaction region
- Provides Pb-gas and p-gas collisions with $\sqrt{s_{NN}}$ in RHIC energy regime

2015 pNe fixed target run at $\sqrt{s_{NN}} = 110$ GeV

2013 PbNe fixed target run at $\sqrt{s_{NN}} = 54$ GeV

Y. Zhang, Moriond (QCD) 2016