Recent results on quarkonium production

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Disclaimer: only a selection of the results could be shown (time limit)

QNP, 10 July 2024, Barcelona (Spain)
Heavy quarks are produced in initial hard scatterings with large $Q^2 \rightarrow$ calculable with pQCD.

Large masses $m_b > m_c \gg \Lambda_{QCD} \rightarrow$ short formation time (<QGP lifetime) $\rightarrow$ experience whole medium evolution

Interactions with the medium don’t change the flavour, but can modify the phase-space distribution. Thermal production rate in the QGP is expected to be ‘small’.

$\rightarrow$ destruction or creation in the medium is difficult
Why heavy flavours?

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Quarkonia in medium
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- Quarkonia are bound states of heavy quarks

vacuum like
Quarkonia in medium

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• Color screening [JPG 32 R25 (2006)]: melting of quarkonium states is expected to follow a sequential pattern (QGP thermometer?)
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- **Color screening** [JPG 32 R25 (2006)]: melting of quarkonium states is expected to follow a sequential pattern (QGP thermometer?)
- **Regeneration**: if the initial number of $Q\bar{Q}$ pairs is large and heavy quarks thermalise in the QGP, quarkonia can form at the phase boundary by **statistical hadronization** [PLB 490 (2000) 196] or during the **QGP evolution** [PRC 63 (2001) 054905] by heavy quark **recombination**
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- Regeneration is a competing phenomena w.r.t. quarkonium suppression, possibly compensate or even exceed it
Quarkonia in medium

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Energy and system size dependence of J/ψ $R_{AA}$

- **J/ψ suppression** ($R_{AA} < 1$) in central heavy-ion collisions observed at RHIC and LHC energies
- Strong rise of the J/ψ $R_{AA}$ from RHIC to LHC energies $\rightarrow$ evidence for **charmonium regeneration** at the LHC
- STAR: No strong collision system size dependence of the J/ψ $R_{AA}$
- Suppression at $\sqrt{s_{NN}} = 200$ GeV in AuAu beyond expectation from CNM
• $J/\psi$ production in central PbPb collisions described by an **interplay between dissociation, regeneration and energy loss**

• Stronger regeneration at midrapidity w.r.t forward rapidity
- J/\psi/D^0 ratio interesting to further constrain models (similar initial state). Increasing ratio with centrality well described by SHMc at \( \sqrt{s_{NN}} = 5.02 \) TeV (ratio related to charm fugacity)
- Fixed Target@LHC: No evidence of anomalous J/\psi suppression in central PbNe collisions at \( \sqrt{s_{NN}} = 68.5 \) GeV
\( \psi(2S) \) and \( \psi(2S)/J/\psi \) ratio

- Golden probe at low \( p_T \) to disentangle among regeneration models
- **Larger suppression of \( \psi(2S) \)** w.r.t. \( J/\psi \) in a wide \( p_T \) interval
- Transport model reproduces better the \( \psi(2S) \) \( R_{AA} \) in central PbPb events
- Suggesting **sequential suppression of charmonia**

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$Y(nS) R_{AA}$

![Graph of $Y(nS) R_{AA}$ vs. $<N_{part}>$ showing data points for different $Y$ states.](boundinc.github.io/hinRPlot)
Observation of $\Upsilon(3S)$ by CMS in PbPb collisions

Sequential suppression of $\Upsilon(nS)$ states at the LHC energies

$R_{AA} (\Upsilon(3S)) \approx R_{AA} (\Upsilon(2S)) < R_{AA} (\Upsilon(1S))$
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$R_{AA}(\Upsilon(3S)) \lesssim R_{AA}(\Upsilon(2S)) < R_{AA}(\Upsilon(1S))$

Similar $\Upsilon(1S)$ suppression at RHIC($\uparrow$) and at the LHC($\bullet$): favouring a negligible melting of direct $\Upsilon(1S)$ production. Suppression of excited states only + CNM effects.

Hint that $\Upsilon(2S)$ might be less suppressed at RHIC in peripheral events than at the LHC?
Picturing the PbPb $v_2$ results in a nutshell

- **Positive $v_2$** of heavy flavours in mid-central PbPb collisions
  → Evidence of **strong collective effects**

- **Exhibit a mass hierarchy** at low and intermediate $p_T$ ($\lesssim 8$ GeV/c)
  $v_2 (J/\psi) < v_2 (D) < v_2 (\pi)$
  similar curve at high $p_T$.

- **Low/intermediate $p_T$**:
  later thermalization of charm quarks
  (vs. light quarks) and/or
  recombination of charm quarks

- **High $p_T$**:
  path-length dependent energy loss

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ALICE, JHEP 09 (2018) 006
ALICE, JHEP 10 (2020) 141
Quarkonium collectivity in heavy-ion collisions

$v_2$ of $J/\psi$ at the LHC

$v_2$ of $J/\psi$ at RHIC
Quarkonium collectivity in heavy-ion collisions

- Significant $J/\psi$ $v_2$ at low $p_T$ and the LHC energies $\rightarrow$ Sign of charmonium regeneration
Quarkonium collectivity in heavy-ion collisions

- Significant $\psi$ v$_2$ at low p$_T$ and the LHC energies → Sign of charmonium regeneration
- Hint for $\psi$(2S) v$_2$ larger than J/$\psi$ v$_2$ for p$_T$ > 6.5 GeV/c?
  Larger contribution from recombination for $\psi$(2S)? Interesting to extend with Run 3 and down to lower p$_T$
Quarkonium collectivity in heavy-ion collisions

- Significant $J/\psi$ $v_2$ at low $p_T$ and the LHC energies → Sign of charmonium regeneration
- Hint for $\psi(2S) v_2$ larger than $J/\psi v_2$ for $p_T > 6.5$ GeV/c? Larger contribution from recombination for $\psi(2S)$? Interesting to extend with Run 3 and down to lower $p_T$
- $\Upsilon(1S) v_2$ compatible with zero → no evidence for regeneration within uncertainties Would be interesting to look at $v_2$ of excited states if doable
Significant $J/\psi$ $v_2$ at intermediate $p_T$ in pPb collisions at high multiplicity, not explained by transport models (negligible path-length dependence and regeneration).

No hint of collective behaviour observed for $J/\psi$ in pp data at high multiplicity.

Possibly a common mechanism at the origin of collective behaviour in both pPb and PbPb?

$\Upsilon(1S)$ $v_2$ consistent with zero $\rightarrow$ No significant dependence of b-quark modification on in-medium path length.
Measurements vs. charged-particle multiplicity

- Simplified picture…
Measurements vs. charged-particle multiplicity

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Measurements vs. charged-particle multiplicity

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\[ \frac{dN_i/dy}{\langle dN_i/dy \rangle} \]

Hard process scales with the mean multiplicity (naive MPI scenario)

Production independent of underlying event

\[ x = y \]

\[ \frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle} \]
Measurements vs. charged-particle multiplicity

- Simplified picture…

\[ \frac{dN_i}{dy} / \langle dN_i/dy \rangle \]

Hadronization, saturation, probe hardness… result in a more complex correlation

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Charm yields vs. charged-particle multiplicity in pp

- **Rapid increase with charged-particle multiplicity at mid-rapidity** (D, D_s, J/Ψ, non-prompt J/Ψ, c/b → l)
  - suggesting common origin,
  - trend described by models including some ‘sort of’ **multiple-parton interactions**
  - all models show a departure from linearity;
  - described by initial state model with modified gluon distribution or percolation models;
  - PYTHIA and EPOS do not reproduce quantitatively the trend.

![Graph showing charm yields vs. charged-particle multiplicity](image)
Charm yields vs. charged-particle multiplicity in pp

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ALICE, PLB 810 (2020) 135758

**Prompt $J/\psi$**
- $J/\psi$, $|y| < 0.9$, $p_T$ integrated
- SPD event selection
- Data
- PYTHIA 8.2
- CPP
- EPOS3 (no hydro)
- 3-Pomeron CGC
- Percolation
- CGC

**Inclusive $J/\psi$, $|y| < 0.9$, $p_T$ integrated**
- Initial state model with modified gluon distribution or percolation models;
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Quarkonium yields vs. charged-particle multiplicity in pp

- Rapid increase with charged-particle multiplicity at midrapidity (D, Ds, J/Ψ, non-prompt J/Ψ)
  - suggesting common origin,
  - trend described by models including some ‘sort of’ multiple-parton interactions

- But J/Ψ and Υ results at forward-y suggest a slower increase (than midrapidity ones)
- hadronisation?
  D-meson measurements disfavour this hypothesis
- fragmentation?
  Study particle species (kinematic dep.), also particle production in jets / isolated.
- associated production? underlying event?
  Multi-differential studies: yields at different y, vs multiplicity at different y, in sphericity intervals or vs angle (event classifier).
  - final state effects?
Excited-to-ground state ratios provide information on final state effects, as most of the initial state effects cancel in the ratio, and the higher mass states are characterized by a lower binding energy.

- \( \psi(2S)/J/\psi \) ratio as a function of multiplicity in pp collisions:
  - inclusive ratio consistent with unity,
  - decreasing trend of the prompt component, consistent with model calculations.
Excited-to-ground state ratios: possible final state effects?

- **Decrease of** \( \Upsilon(nS)/\Upsilon(1S) \) **ratios as a function of multiplicity**, consistently across system size.
- **The** \( \Upsilon(nS)/\Upsilon(1S) \) **ratios are multiplicity independent for jet-like events.**

CMS, JHEP 04 (2014) 103

CMS, JHEP 11 (2020) 001
Associated production and double parton scattering in pp

- In the **collinear factorisation** approach, \( \sigma_{1,2}^{\text{DPS}} = \frac{m}{2 \sigma_{\text{eff}}^{\text{SPS}}} \sigma_{1}^{\text{SPS}} \sigma_{2}^{\text{SPS}} \)
m=1 if 1=2, and 2 otherwise. The **effective cross section** is a (universal) constant related to the transverse overlap function between the partons of the proton.

- **Double particle production exploited to study DPS.**

- Effective cross section results:
  - \( J/\psi + C \) in agreement with multi-jet and double W,
  - double quarkonium or quarkonium+W/Z are a bit lower.
  - Possibly originated from the parton flavour (gluon vs. light-quark) probed and/or by parton correlations.

- Note: experimentally challenging to separate SPS-DPS (go to large \( \Delta \eta \)?)
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\[ \sigma_{eff} (mb) \]

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- Single Parton Scattering
- Double Parton Scattering

QNP 2024

Z. Conesa del Valle
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• Effective cross section results:
  • $J/\psi+C$ in agreement with multi-jet and double $W$,
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  • Possibly originated from the parton flavour (gluon vs. light-quark) probed and/or by parton correlations.

• Note: experimentally challenging to separate SPS-DPS (go to large $\Delta\eta$?)
Double parton scattering in pA/AA collisions

\[ \sigma_{AA \to ab}^{\text{DPS,1}} = A^2 \cdot \sigma_{NN \to ab}^{\text{DPS}} \]

\[ \sigma_{AA \to ab}^{\text{DPS,2}} = 2 \sigma_{NN \to ab}^{\text{DPS}} \cdot \sigma_{\text{eff,pp}} \cdot (A - 1) \cdot T_{AA}(0) \]

\[ \sigma_{AA \to ab}^{\text{DPS,3}} \approx \sigma_{NN \to ab}^{\text{DPS}} \cdot \sigma_{\text{eff,pp}} \cdot A^2/2 \cdot T_{AA}(0) \]
• Three contributions to the DPS cross section in AA collisions.
  Alternative to extract the effective cross section.
Double parton scattering in pA/AA collisions

- Three contributions to the DPS cross section in AA collisions. **Alternative to extract the effective cross section.**
- **First observation of DPS in pPb** collisions by LHCb!
- DPS contribution enhanced in pPb by a factor of 3 with respect to pp.
- Interpretation challenged by the dominant contribution of scatterings among partons from different nucleons, in addition to the genuine DPS, where interactions take place among partons within a nucleon.
• **First observation of double J/ψ in pPb collisions by CMS!**

• Interpretation challenged by the dominant contribution of scatterings among partons from different nucleons, in addition to the genuine DPS, where interactions take place among partons within a nucleon.

**Z. Conesa del Valle**
Take home message

• Sequential dissociation of charmonia and bottomonia in heavy-ion collisions.
• Positive $v_2$ of $J/\psi$ in PbPb and pPb collisions at high multiplicity.
• Interpreted as interplay of dissociation, regeneration and energy loss.
• The origin of the collective motion in small systems is still under debate. Important role of initial state effects and/or influence of final state effects?
• Non-negligible influence of multiparton interactions.

• Crucial to better quantify yields and collective motion of charmonia and bottomonia excited states across collision systems!
Big thank you to the organisers!

Special thanks to E. Ferreiro, L. Massacrier
for fruitful discussions and suggestions
Additional material
Zooming on $v_2$ across system size

- Heavy flavour $v_2$ follows **a smooth evolution with charged-particle multiplicity**
  - non-zero values for charm in pp and pPb collisions
  - important role of initial state effects and/or influence of final state effects?
- Crucial to quantify beauty $v_2$ in small systems

### Graphs

- **ATLAS, pp 13 TeV**
  - $c \rightarrow \mu$
  - $b \rightarrow \mu$
- **ATLAS, PbPb 5.02 TeV**
  - $c \rightarrow \mu$
  - $b \rightarrow \mu$

- **CMS, pPb 8.16 TeV**
  - prompt $D^0$
  - non-prompt $D^0$

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**References**

- STAR, PLB 844 (2023) 138071
- ATLAS, pp, PRL 124 (2020) 082301
- ATLAS, PbPb, PLB 807 (2020) 135595
- CMS, pPb, prompt $D^0$, PRL 121 (2018) 8, 082301
- CMS, pPb, non-prompt $D^0$, PRL 813 (2021) 136036
- LHCb, $D^0$, arXiv:2205.03936
Associated production and multiparton interactions in pp

- Production of multiple (two, three, …) heavy flavour particles, be it $D^0$, $J/\psi$, $\Upsilon$, …
- Single parton scattering: can be treated by pQCD
- **n-parton scattering** (double, triple, …): need to reformulate quantum field theories
  - Generalised PDFs ($x, Q^2, b$) of the proton, including the unknown energy evolution of the proton transverse profile.
  - Role of partonic correlations in the wave functions ($x, p$, flavour, spin, colour, …).
  - Constrain heavy-flavour modelling.
  - Background for other studies (e.g. BSM resonance decays of multiple heavy particles).
Brief picture of double parton scattering in pp

• In the **collinear factorisation approach**, assuming two parton GPD can be decomposed in longitudinal and transverse components, and neglecting correlations in the proton:

\[
\sigma_{1,2}^{\text{DPS}} = \frac{m}{2} \sigma_{1}^{\text{SPS}} \sigma_{2}^{\text{SPS}}
\]

\(m=1\) if \(1=2\), and \(2\) otherwise.

The **effective cross section** is a (universal) constant related to the transverse overlap function between the partons of the proton.

• **Double particle production exploited to study DPS**: double quarkonium (\(J/\psi+J/\psi\), \(J/\psi+\Upsilon\),…), electroweak boson + quarkonium, double charm, charm+quarkonium, multi-jets, \(\gamma+n\)-jet, \(W+2\)-jet,…

• Effective cross section results:
  • \(J/\psi+C\) in agreement with multi-jet and double \(W\),
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- Note: experimentally challenging to separate SPS-DPS (go to large \(\Delta\eta\)?)

\[
\sigma_{eff} (\text{mb})
\]
Brief picture of double parton scattering in pp

- In the **collinear factorisation approach**, assuming two parton GPD can be decomposed in longitudinal and transverse components, and neglecting correlations in the proton:

\[
\sigma_{\text{DPS}}^{1,2} = \frac{m}{2\sigma_{\text{eff}}} \sigma_{\text{SPS}} \sigma_{\text{SPS}}
\]

\(m=1\) if \(1=2\), and \(2\) otherwise.

The **effective cross section** is a (universal) constant related to the transverse overlap function between the partons of the proton.

- **Double particle production exploited to study DPS**: double quarkonium (J/\(\psi\)+J/\(\psi\), J/\(\psi\)+Y,...), electroweak boson + quarkonium, double charm, charm+quarkonium, multi-jets, \(\gamma+n\)-jet, W+2-jet,...

- Effective cross section results:
  - J/\(\psi\)+C in agreement with multi-jet and double W,
  - double quarkonium or quarkonium+W/Z are a bit lower.
  - Possibly originated from the parton flavour (gluon vs. light-quark) probed and/or by parton correlations.

- Note: experimentally challenging to separate SPS-DPS (go to large \(\Delta\eta\)?)
In the **collinear factorisation approach**, assuming two parton GPD can be decomposed in longitudinal and transverse components, and neglecting correlations in the proton:

\[
\sigma_{1,2}^{DPS} = \frac{m}{2 \sigma_{eff}} \sigma_{SPS}^{m} \sigma_{SPS}^{2}
\]

\(m=1\) if \(1=2\), and \(2\) otherwise.

The **effective cross section** is a (universal) constant related to the transverse overlap function between the partons of the proton.

**Double particle production exploited to study DPS**: double quarkonium (\(J/\psi+J/\psi, J/\psi+\Upsilon, \ldots\)), electroweak boson + quarkonium, double charm, charm+quarkonium, multi-jets, \(\gamma+n\)-jet, \(W+2\)-jet,…

**Effective cross section results:**
- \(J/\psi+C\) in agreement with multi-jet and double \(W\),
- double quarkonium or quarkonium+\(W/Z\) are a bit lower.
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**Note**: experimentally challenging to separate SPS-DPS (go to large \(\Delta\eta\)?)
Quarkonium yields vs. charged-particle multiplicity in pp

- Underlying event or associated particle influence?
- Faster than linear increase when overlap in rapidity between Nch and J/ψ
- Reduced increase with multiplicity for large $\Delta y$ gap between Nch and J/ψ