Outline

• Introduction

• \( \bar{Q}Q \) in Small Systems → Large Systems
  • Focus on medium interactions

• Exotic hadrons containing \( \bar{Q}Q \)
  • \( X(3872) \) in the QCD medium

• Brief look to the future
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• Brief look to the future
Heavy $Q\bar{Q}$ states in vacuum

Solve Schrodinger equation with the potential

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3} \frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2} \delta_\sigma(r) \vec{S}_c \cdot \vec{S}_{\bar{c}}$$

Heavy $Q\bar{Q}$ states in vacuum

Solve Schrödinger equation with the potential

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3} \frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2} \delta_\sigma(r) \hat{S}_c \cdot \hat{S}_\bar{c}$$

Heavy $Q\bar{Q}$ states in vacuum

The most recently discovered charmonium state: $\psi_3(1^3D_3)$

Measured mass: $3842.71 \pm 0.16 \pm 0.12$ MeV
Predicted mass: 3849 MeV

Incredibly rich structure, accessible theoretically and experimentally
Heavy $Q\bar{Q}$ states in the QCD medium

Diffuse medium $\xrightarrow{\text{Increasing } T, N_{\text{ch}}}$ Dense medium

Dissociation via interactions with comoving particles
Heavy $Q\bar{Q}$ states in the QCD medium

Diffuse medium  Increasing $T, N_{\text{ch}}$  Dense medium

Dissociation via interactions with comoving particles

Hydrodynamic flow induced by pressure gradients (initial state?)
Heavy $Q\bar{Q}$ states in the QCD medium

Diffuse medium \[ \rightarrow \text{Increasing } T, N_{\text{ch}} \rightarrow \text{Dense medium} \]

- Dissociation via interactions with comoving particles
- Hydrodynamic flow induced by pressure gradients (initial state?)
- Suppression via color screening

Matt Durham - Hard Probes 2020
Heavy $Q\bar{Q}$ states in the QCD medium

Diffuse medium

- Dissociation via interactions with comoving particles

Increasing $T$, $N_{\text{ch}}$

Hydrodynamic flow induced by pressure gradients (initial state?)

Dense medium

- Suppression via color screening

- Production via coalescence
Heavy $Q\bar{Q}$ states in the QCD medium

*Additional initial state effects from modified nPDF and energy loss can also be significant in collisions with nuclei.

Experimentally, we use different collision systems/kinematic regions to prepare environments where different effects dominate for different probes.
Every experiment contributes to quarkonia physics

Taken together:
- $-5 < y < 5$
- $0 < p_T < \text{several hundred GeV}$
- $\sim 0 < T < \text{hundreds of MeV}$
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Charmonium in $pp$ vs. multiplicity

New ALICE results on $J/\psi$ production in $13$ TeV $pp$ shows faster-than-linear growth with multiplicity: various CGC calculations match data.
New ALICE results on J/⟨ψ⟩ production in 13 TeV pp shows faster-than-linear growth with multiplicity: various CGC calculations match data.

Hints that ⟨ψ⟩ production does now grow as fast as J/⟨ψ⟩ with multiplicity – initial state models should give similar trend for both. Final state effect suppressing ⟨ψ⟩ in pp?
New ALICE results on $J/\psi$ production in 13 TeV pp shows faster-than-linear growth with multiplicity: various CGC calculations match data.

Hints that $\psi(2S)$ production does now grow as fast as $J/\psi$ with multiplicity – initial state models should give similar trend for both. Final state effect suppressing $\psi(2S)$ in pp?
Midrapidity STAR data shows little $J/\psi$ modification at intermediate $p_T$:

- Consistent with nPDF calculations
- Consistent with PHENIX d+Au data
- CNM not dominant effect in AA in this range
**J/ψ in small systems at RHIC**

Sanghoon Lim, Tues 11:20

1910.14487

![Graph showing inclusive J/ψ production in various reactions: p+Al, p+Au, and 3He+Au at √s_{NN}=200 GeV.](image)

Matt Durham - Hard Probes 2020
J/ψ in small systems at RHIC


Forward rapidity (p or 3He-going direction):
• Data generally in agreement with nPDF calculations
Backward rapidity (A-going direction):
• Data from Au nucleus is **inconsistent with nPDF calculation**:
  • Additional effects *required* to explain data

Significantly improved precision in state-of-the-art nPDF calculations, which include D, J/ψ, and Y(1S) LHC data
**J/ψ in small systems at RHIC**

![Diagram]

**Forward rapidity (p or 3He-going direction):**
- Data generally in agreement with nPDF calculations

**Backward rapidity (A-going direction):**
- Data from Au nucleus is **inconsistent with nPDF calculation:**
  - Additional effects required to explain data

Significantly improved precision in state-of-the-art nPDF calculations, which include D, J/ψ, and Y(1S) LHC data
At both forward and backward rapidity, $J/\psi$ well described by nPDF calculations: initial state dominates

- **Marked difference from PHENIX data, where additional effects are required to match backwards $J/\psi$ data**
- $J/\psi$ breakup smaller at LHC - smaller crossing time

Backwards $\psi(2S)$ data shows inconsistency with nPDF
At both forward and backward rapidity, J/\(\psi\) well described by nPDF calculations: initial state dominates

- **Marked difference from PHENIX data, where additional effects are required to match backwards J/\(\psi\) data**
- **J/\(\psi\) breakup smaller at LHC - smaller crossing time**

Backwards \(\psi(2S)\) data shows inconsistency with nPDF

- **Tension eases when final state comover breakup is included, small effect for forward.**

Similar effects previously observed by PHENIX, ALICE, LHCb

Similar sequential suppression of \(Y(nS)\) also observed in pPb
At both forward and backward rapidity, J/ψ well described by nPDF calculations: initial state dominates

- Marked difference from PHENIX data, where additional effects are required to match backwards J/ψ data
- J/ψ breakup smaller at LHC - smaller crossing time

Backwards ψ(2S) data shows inconsistency with nPDF

- Tension eases when final state comover breakup is included, small effect for forward.

Similar effects previously observed by PHENIX, ALICE, LHCb

Similar sequential suppression of Υ(nS) also observed in pPb
J/$\psi$ flow

Data on J/$\psi$ production is consistent with nPDF, however: Significant J/$\psi$ $v_2$ observed in pPb collisions
J/ψ flow

Data on J/ψ production is consistent with nPDF, however: Significant J/ψ v₂ observed in pPb collisions

- Similar to PbPb; some differences observed at high pt, typically attributed to L dependent energy loss, not present in pPb
J/ψ flow

Data on J/ψ production is consistent with nPDF, however: Significant J/ψ $v_2$ observed in pPb collisions

Yousen Zhang, Mon 11:20

- Similar to PbPb; some differences observed at high $p_T$, typically attributed to $L$ dependent energy loss, not present in pPb
- Transport model with short lived plasma phase in pPb does not give large $v_2$ in pPb (does describe low $p_T$ PbPb)
Data on $J/\psi$ production is consistent with nPDF, however: Significant $J/\psi$ $v_2$ observed in pPb collisions

**MAJOR OPEN QUESTION**

- Similar to PbPb; some differences observed at high $p_T$, typically attributed to $L$ dependent energy loss, not present in pPb
- **Transport model with short lived plasma phase in pPb does not give large $v_2$ in pPb (does describe low $p_T$ PbPb)**
- CGC calculation describes part of pPb $v_2$; however CGC has mixed results describing light sector $v_2$

---

**J/$\psi$ flow**

Yousen Zhang, Mon 11:20

Florian Damas, Mon 1:35
J/ψ flow

Data on J/ψ production is consistent with nPDF, however: Significant J/ψ $v_2$ observed in pPb collisions

- CGC calculation gives very similar $v_2$ for Upsilon states on pPb: next challenge for experiments
\( \Upsilon(nS) \) in PbPb

Textbook example of color screening

- Three well defined state observable in \( \mu^+\mu^- \)
- Bottom density relatively low – expect minimal effects from recombination
\( \Upsilon(nS) \) in PbPb

- Three well defined state observable in \( \mu^+\mu^- \)
- Bottom density relatively low – expect minimal effects from recombination

Textbook example of color screening
Well described by models
\[ \gamma(nS) \text{ in PbPb} \]

Textbook example of color screening
Well described by models

**ATLAS** Preliminary

\[ pp, \sqrt{s} = 5.02 \text{ TeV}, L = 0.26 \text{ fb}^{-1} \]

\[ \text{Pb+Pb}, \sqrt{s_{NN}} = 5.02 \text{ TeV}, L = 1.38 \text{ nb}^{-1} \]

\[ \gamma(1S) \text{ CMS, } p_T < 30 \text{ GeV, } |y|<2.4 \]

\[ \gamma(1S) \text{ ATLAS, } p_T < 30 \text{ GeV, } |y|<1.5 \]

Generally good agreement between ATLAS and CMS
$Q\bar{Q}$ flow in PbPb

In contrast to $J/\psi$, no significant $v_2$ is observed for $\Upsilon(1S)$ by ALICE or CMS. Little or no recombination due to relative low $b$ density in QGP, as expected from models.
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Hard Probes 1-9: 0 talks devoted to $X(3872)$

Hard Probes 10: 4 talks!
  2 experiment, 2 theory
Exotic $Q \bar{Q}$ states: XYZ

Matt Durham - Hard Probes 2020
Exotic $Q\bar{Q}$ states: XYZ

Dozens of states containing $c\bar{c}$ and $b\bar{b}$ have been discovered that are not predicted by any $Q\bar{Q}$ potential model.

Compact tetraquark

Hadronic molecule

Thousands of theory papers exploring possible structures, but no consensus on even the first exotic, $X(3872)$

Primarily measured as products of $b$ decays in vacuum.

Matt Durham - Hard Probes 2020

Rev. Mod. Phys. 90, 015003 (2018)
Exotic $Q\bar{Q}$ states: XYZ

Dozens of states containing $c\bar{c}$ and $b\bar{b}$ have been discovered that are not predicted by any $Q\bar{Q}$ potential model.

**Compact tetraquark**

**Hadronic molecule**

Interactions in QCD medium are dependent on binding energy/structure.

Production of multiquark exotics is especially sensitive to recombination/coalescence effects that are expected in heavy ion collisions.

Rev. Mod. Phys. 90, 015003 (2018)
Exotic $X(3872)$ in diffuse medium (8 TeV $pp$)

LHCb-CONF-2019-005

- Prompt $X(3872)/\psi(2S)$ decreases with activity
- $X(3872)$ suppressed more than $\psi(2S)$

Cameron Dean, Wed 12:25
Exotic X(3872) in diffuse medium (8 TeV pp)

LHCb-CONF-2019-005

• Prompt X(3872)/ψ(2S) decreases with activity
  • X(3872) suppressed more than ψ(2S)
• B-decay component consistent with constant
  • Production in vacuum unaffected

Cameron Dean, Wed 12:25
Exotic X(3872) in diffuse medium (8 TeV \( pp \))

LHCb-CONF-2019-005

- Prompt X(3872)/\( \psi(2S) \) decreases with activity
  - X(3872) suppressed more than \( \psi(2S) \)
- \( B \)-decay component consistent with constant
  - Production in vacuum unaffected

\[
\sigma^{co-Q}(E^{co}) = \sigma^Q_{geo} \times \left(1 - \frac{E^{Q}_{thr}}{E^{co}}\right)^n
\]

Directly probes size \( \sigma_{geom} \) and binding energy

Data clearly favors compact tetraquark interpretation

Elena Ferreiro, Wed 1:05
Exotic X(3872) in dense medium (PbPb)

Prompt $X(3872)/\psi(2S) = 1.10 \pm 0.51 \pm 0.53$ in PbPb at 5 TeV

Prompt $X(3872)/\psi(2S) \approx 0.1$ in pp at 8 TeV

Recombination of $X(3872)$ at $p_T > 15$ GeV?
Exotic X(3872) in dense medium (PbPb)

Prompt X(3872)/\(\psi(2S)\) = 1.10 ± 0.51 ± 0.53 in PbPb at 5 TeV
Prompt X(3872)/\(\psi(2S)\) ≈ 0.1 in pp at 8 TeV

Intriguing data! Inconclusive with these uncertainties.
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Fixed target at LHCb: SMOG II

Example SMOG2 pAr at 115 GeV for one year

<table>
<thead>
<tr>
<th>Int. Lumi.</th>
<th>80 pb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sys.error of $J/\Psi$ xsection</td>
<td>~3%</td>
</tr>
<tr>
<td>$J/\Psi$ yield</td>
<td>28 M</td>
</tr>
<tr>
<td>$D^0$ yield</td>
<td>280 M</td>
</tr>
<tr>
<td>$\Lambda_c$ yield</td>
<td>2.8 M</td>
</tr>
<tr>
<td>$\Psi'$ yield</td>
<td>280 k</td>
</tr>
<tr>
<td>$Y(1S)$ yield</td>
<td>24 k</td>
</tr>
<tr>
<td>$DY\mu^+\mu^-$ yield</td>
<td>24 k</td>
</tr>
</tbody>
</table>

Upgraded SMOG system at LHCb allows greatly increased rates of beam+injected gas collisions

No centrality limitations in p+gas or Pb+gas at LHCb

Large heavy flavor samples
Access to exotic states near RHIC energies

New detector at RHIC: sPHENIX

Precision bottomonium measurements at RHIC are a major focus of sPHENIX

Rosi Reed, Fri 8:00

arXiv:1501.06197
Future facility: electron-ion collider

EIC site selection at BNL announced Jan 2020

Charm production inside the nucleus probes:
• Parton structure of nucleons
• nPDF modifications
• QCD energy loss

In the kinematic range accessed by the EIC, hadronization *inside the nucleus* becomes an important effect on observables.

E. Aschenauer, Wed 9:15

Vitev, 1912.10965

Xuan Li, Thurs 10:35
EIC site selection at BNL announced Jan 2020

Charm production inside the nucleus probes:  
• Parton structure of nucleons  
• nPDF modifications  
• QCD energy loss

E + A collisions have relatively low backgrounds – well suited for studies of higher charmonia and exotics: $P_c^+, Z_c^+, \chi_c$, ...

Xuan Li, Thurs 10:35

E. Aschenauer, Wed 9:15
Summary

• Quarkonia remains a major focus of heavy ion physics 34 years after Matsui and Satz
  • Contributions from all experimental collaborations – a wealth of data
  • Strong synergy with theory community

• The lines between small and large systems are continually becoming blurred
  • Final state suppression manifests in many systems at high multiplicity
  • Universal understanding of $J/\psi$ flow from small to large systems remains elusive

• Exotic multiquark states are becoming accessible in a QCD medium
  • Medium probes exotic properties ⇔ Exotics probe medium properties

• Exciting future programs of in-medium quarkonia studies at LHC/RHIC/EIC to come

Los Alamos is supported by the US Dept. of Energy/Office of Science/Office of Nuclear Physics
BACKUPS
We have only measured 2 charmonium states in heavy ion collisions at LHC.

We have only measured 3 bottomonium states in heavy ion collisions at LHC.
States with >3 quarks have been expected since the beginning of the quark model
Charmonium in $pp$ - RHIC

PHENIX: PRD 101 (2020) 5, 052006

Agreement with calculations across entire $p_T$ range

STAR, PRD 100 (2019) 5, 052009
Charmonium in $pp$ - LHC

Preliminary result from ATLAS:

- $J/\psi$ measured up to 360 GeV
- $\psi(2S)$ measured up to 140 GeV
Charmonium in $pp$ - LHC

Preliminary result from ATLAS:

$J/\psi$ measured up to 360 GeV
$\psi(2S)$ measured up to 140 GeV

Non-prompt component (from $b$ decays) diverges from FONLL calculations for $p_T > 100$ GeV
J/$\psi$ flow: pPb and PbPb
PHENIX PRL 21, 222301
Improved nPDF extraction

This data is already being used to constrain the gluon nPDF down to $x \sim 5 \times 10^{-6}$

Kusina, Lansberg, Schienbein, Shao,

*Gluon shadowing and antishadowing in heavy-flavor production at the LHC*

Phys. Lett. B Volume 774, 10 November 2017, Pages 159-178

[Graphs showing the $R_{pPb}$ ratio for prompt $J/\psi$ for $p_{T}$ from 0 to 10 GeV/c, comparing HELAC-Onia with EPS09LO, nCTEQ15, EPS09NLO, and CGC, and LHCb at 8.16 TeV in $pPb$ and PbPb collisions with $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$.]
At both forward and backward rapidity, $J/\psi$ and $\Upsilon(1S)$ states are well described by nPDF calculations: initial state dominates

- Marked difference from PHENIX data, where additional effects beyond nPDF were required to match backwards data.
At both forward and backward rapidity, $J/\psi$ and $\Upsilon(1S)$ states are well described by nPDF calculations: initial state dominates

**Final state effects required to explain suppression of excited states at backwards rapidity**
### $D \bar{D}^*$ Molecule

<table>
<thead>
<tr>
<th>state</th>
<th>$\eta_c$</th>
<th>$J/\psi$</th>
<th>$\chi_{c0}$</th>
<th>$\chi_{c1}$</th>
<th>$\chi_{c2}$</th>
<th>$\psi'$</th>
<th>$X(3872)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass [GeV]</td>
<td>2.98</td>
<td>3.10</td>
<td>3.42</td>
<td>3.51</td>
<td>3.56</td>
<td>3.69</td>
<td>3.872</td>
</tr>
<tr>
<td>$\Delta E$ [GeV]</td>
<td>0.75</td>
<td>0.64</td>
<td>0.32</td>
<td>0.22</td>
<td>0.18</td>
<td>0.05</td>
<td>0.00001± 0.00027</td>
</tr>
</tbody>
</table>

Exotic X(3872) in diffuse medium (8 TeV pp)

Prompt fraction of X(3872) and ψ(2S) both drop as function of event activity:
• Increasing $b$ component?
• Suppressed prompt component? i.e. final state effect in $pp$?

Cameron Dean, Wed 12:25
“No significant contribution from coalescence” at $p_T > 10$ GeV/c for charm baryons

Charm quark coalescence?

Good agreement between pp data and PYTHIA8 with color reconnection

Lack of an enhancement in PbPb: No significant contribution from coalescence
Quarkonia inside the nucleus

Fixed target p+A experiments also operated in a kinematic region where quarkonia hadronized inside the nucleus – similar to EIC

Natural explanation based on size: Larger (weakly bound) states sample a larger volume of the nucleus while passing through – larger absorption cross section

Arleo, Gossiaux, Gousset, Aichelin PRC 61 (2000) 054906

Significant differences observed between states with same quark content, but different binding energies

Matt Durham - Hard Probes 2020
ALICE Preliminary, Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV, $2.5 < y < 4$

- Inclusive $\Upsilon(1S)$ (global uncertainty 8.1%)
- Inclusive $\Upsilon(2S)$ (global uncertainty 9.6%)

Transport model (Du et al.):
- with regeneration
- without regeneration

Systematic uncertainty
Recent LHCb Discovery – $P_c$ States

Select daughters from the decay

$$\Lambda_b^0 \rightarrow J/\psi pK^-$$

Masses are close to meson+baryon thresholds – candidate for hadronic molecule
Charged Exotic – $Z_c$ State

Select daughters from the decay

$$B^0 \rightarrow \psi' K^+ \pi^-$$

Charged and contains $c\bar{c}:$ Minimal 4 quark content: $c\bar{c}q\bar{q}$

Mass is NOT close to any hadron+hadron threshold – candidate for compact tetraquark