High Energy Frontier – Recent Results from the LHC: Heavy Ions IV

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Ruprecht-Karls-University, Heidelberg
Pb+Pb @ \sqrt{s} = 2.76 ATeV

2010-11-08 11:30:46
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Outline

- lecture 1 (22.11.): introduction
  - basics of relativistic heavy-ion collisions
- lecture 2 (29.11.): soft probes
  - hadron yields & spectra
  - hydrodynamics & collective motion
- lecture 3 (13.12.): hard probes
  - jets
  - heavy-flavor hadrons
- lecture 4 (20.12.): quarkonia & el.magn. probes
  - quest for $J/\psi$ suppression/enhancement
  - direct & thermal photons
  - dileptons
Heavy quarkonia

- charmonium and bottomonium
  - basics and discovery
- quarkonia as probes for the QGP
  - basic idea
  - complications
  - (measurements at the SPS)
- quarkonia at RHIC
- quarkonia at the LHC
Particle production in $e^+e^-$

$$R = \frac{\sigma(e^+e^- \rightarrow \text{Hadronen})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = N_{\text{Flavour}} \cdot \sum_{\text{Flavour}} q^2$$

![Graph showing particle production in $e^+e^-$ with various peaks and labels for $J/\psi$, $\psi(2S)$, $\Upsilon$, $\rho$, $\omega$, $\phi$, $Z$.](image)
A chance missed

Observation of Muon Pairs in High-Energy Hadron Collisions*

J. H. Christenson, † G. S. Hicks, † L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027
and Brookhaven National Laboratory, Upton, New York 11973

E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 30 March 1973)

Muon pairs with effective masses between 1 GeV/c^2 and 6.5 GeV/c^2 have been observed in the collisions of 30-GeV protons with a uranium target. The production cross section was seen to vary smoothly with mass exhibiting no resonant structure.

The real dimuon spectra (...) amounted to some 4% of the in-time data sample. The real effect varied with dimuon mass from 2% at 1.5 GeV/c^2 to 40% at 5 GeV/c^2.

Of course, with such a small signal-to-noise ratio, the data were extremely sensitive to systematical effects that would distort the subtraction procedure.

p-U → μμ at 29.5 GeV
Charmonium: $J/\psi$

- 1974: $J/\psi$ discovery

- Interpretation: bound state of heavy quarks: $c\bar{c}$
- Quantum numbers as the photon: $J^P = 1^-$
- $J/\psi$ mass: 3.1 GeV
- $c$ mass: $\sim$1.3 GeV
- Binding energy $\sim$600 MeV
- Width: 93 keV (life time: $10^{-20}$s)
- Quark motion is non-relativistic
Bottomonium: Y

- Bottomonium: bound bb states
  - p + A @ 400 GeV → μ⁺μ⁻
- Discovery: L. Lederman et al. (lesson learned!)

Production mechanism

- production in hadron-hadron collisions mainly via gluon fusion in early, hard parton scattering processes
- resonance „lives“ only after formation time \( \tau \)
- formation time increases with the momentum of the resonance (time dilatation)
Charmonium production rate

- heavy quark-antiquark pair yield in central A+A collisions

<table>
<thead>
<tr>
<th></th>
<th>SPS</th>
<th>RHIC</th>
<th>LHC</th>
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</thead>
<tbody>
<tr>
<td>charm</td>
<td>0.2</td>
<td>10</td>
<td>130</td>
</tr>
<tr>
<td>bottom</td>
<td>---</td>
<td>0.05</td>
<td>5</td>
</tr>
</tbody>
</table>

- only a fraction (~ 2%) of the pairs end up in quarkonia. Most heavy quarks fragment into D(B) mesons.
Charmonium spectroscopy

- spectroscopy $\rightarrow$ information about the QCD potential (analogue to positronium in QED)
Quark potential

- Charmonium spectroscopy

\[ V(r) = -\frac{4}{3} \frac{\alpha_s(r) \hat{h} c}{r} + kr \]

Coulomb part (1-gluon exchange) dominant for small \( r \)

Linear rise (Confinement) dominant for large \( r \)
<table>
<thead>
<tr>
<th></th>
<th>mass [GeV]</th>
<th>radius [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/ψ</td>
<td>3.1</td>
<td>0.50</td>
</tr>
<tr>
<td>χ</td>
<td>3.5</td>
<td>0.70</td>
</tr>
<tr>
<td>ψ'</td>
<td>3.7</td>
<td>0.88</td>
</tr>
<tr>
<td>Y</td>
<td>9.5</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Quark potential for $T > 0$

- Modification of quark potential in medium

\[ V(r) = -\frac{4}{3} \alpha_s kr \rightarrow V(r, T) = -\frac{4}{3} \alpha_s e^{-r/r_D(T)} + kr_D(T) \left(1 - e^{-r/r_D(T)}\right) \]

- With Debye screening length $r_D$

\[ r_D(T) \sim \frac{1}{g(T) \cdot T}, \quad \alpha_s = \frac{g^2}{4\pi}, \quad g(T) \approx \frac{24 \pi^2}{(33 - 2n_f) \ln(T/\Lambda)} \]

$\Rightarrow r > r_D$: Quark interaction strongly reduced
Quark potential from lattice QCD
J/ψ suppression as QGP signature

- charmonium should not be bound in QGP at high enough temperature
- THE publication:
  
  from the abstract
  
  If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents cc binding in the deconfined interior of the interaction region .../... It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation

- J/ψ suppression was regarded as THE „smoking gun“ signature of QGP formation
Dissociation temperatures of charmonia

careful: model dependence!
Heavy quarkonia in HI collisions

- heavy quarkonia as probes for the QGP in heavy-ion collisions
  - large quark masses $\rightarrow$ (dominant) production via hard scattering of partons in the early phase of the collision
  - strongly bound (small radius) and weakly coupled to light mesons
  - sensitive to the formation of a QGP via color screening and/or (re)generation

<table>
<thead>
<tr>
<th></th>
<th>mass</th>
<th>radius</th>
<th>$T_{\text{diss.}}$</th>
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<tbody>
<tr>
<td>$J/\psi$</td>
<td>3.1 GeV</td>
<td>0.50 fm</td>
<td>1.2 $T_c$ ?</td>
</tr>
<tr>
<td>$Y$</td>
<td>9.5 GeV</td>
<td>0.28 fm</td>
<td>2 $T_c$ ?</td>
</tr>
</tbody>
</table>

Color Screening
At a glance: \( J/\psi \) at SPS

- absorption in cold nuclear matter ("normal nuclear abs.")
  - good description of p+A, S+U, and peripheral In+In and Pb+Pb collisions
  - \( \sigma_{\text{abs}} = 4.18 \pm 0.35 \text{ mb} \)
- additional “anomalous suppression” in more central In+In and Pb+Pb collisions
  - sets in at \( N_{\text{part}} \sim 80 \)

\[ B_{\mu\mu} \frac{\sigma(J/\psi)}{\sigma(DY)_{2.9-4.5}} \]

- at SPS, \( J/\psi \) shows features expected for the predicted golden QGP signature

\( \sigma_{\text{abs}} = 4.18 \pm 0.35 \text{ mb} \)
Life is more complicated!

Data – SPS, PHENIX, STAR, LHC…
Need high statistical & systematic accuracy

PHENIX $J/\psi$ Suppression:
- like SPS at mid-rapidity
- stronger at forward rapidity with forw/mid ~0.6 saturation
- $<p_T^2>$ centrality indep.

Regeneration & destruction
less suppression at mid-rapidity
narrowing of $p_T$ & $y$
$J/\psi$ flow

Regeneration (in medium?)

large charm cross section
Charm dE/dx & flow

Sequential screening
$\chi_c, \psi'$ 1st, $J/\psi$ later

large gluon density destroys $J/\psi$'s

lattice & dynamical screening
$J/\psi$ not destroyed?

comovers
more mid-rapidity suppression

absorption
d+Au constraint?

shadowing
or coherence

configuration of ccbar state

CGC - less charm at forward rapidity

~40% feedown from $\chi_c, \psi'$
(uncertain fraction)
Heavy quarkonia in HI collisions

- caveats
  - production mechanism, even in p+p, not well understood
  - production/survival altered in the presence of nuclear matter by many effects
  - not straightforward to extrapolate these cold nuclear matter effects and subtract from what is measured in A+A

- advantages
  - heavy quarkonia = resonances
    - “easy” to measure, in contrast to other hard probes (jets, photons, open heavy flavor)
Quarkonia in PHENIX

- PHENIX: optimized to measure leptons
  - high rate capability
  - emphasis on mass resolution & particle ID
  - first level e&μ triggers

- mid rapidity: J/ψ, Y → e⁺e⁻
  - |η|<0.35, Δφ=2xπ/2, p>0.2 GeV
- drift and pad chamber tracking
- electron ID: Cerenkov detector (RICH) and calorimetry (EMCAL)

- forward rapidity: J/ψ, Y → μ⁺μ⁻
  - 1.2<|η|<2.2, Δφ=2π, p>2 GeV
- cathode strip chamber tracking
- muon ID: layered absorbers and larioce tubes
Quarkonia in STAR

• STAR: optimized to measure hadrons

- emphasis on tracking and particle ID over a large acceptance
- moderate rate capability
- high level quarkonia triggers

- central rapidity: \( J/\psi, \ Y \rightarrow e^+e^- \)
- \(|\eta|<1, \ \Delta\phi=2\pi\)
- TPC tracking
- electron ID: \( dE/dx \) in TPC, ToF, calorimetry
J/ψ production in p+p collisions

- baseline for d+A and A+A collisions
J/ψ rapidity distribution

- 2006 data versus published 2003 data

- Excellent agreement
- Higher statistics and better control over systematics

\[ \sqrt{s_{NN}} = 200 \text{ GeV } p+p \]

\[ \text{dN/dy} \times 10^6 \]

- PHENIX preliminary
- PRL98:232002
- RHIC 2006 y ∈ [-0.35,0.35]
- RHIC 2006 y ∈ [-2.2,-1.2]
- RHIC 2006 y ∈ [1.2,2.2]

± 10.1% Global Scale Uncertainty

⇒ Better model constraints are possible
J/ψ pₜ distributions

- good agreement of J/ψ pₜ spectra between PHENIX and STAR
- excellent agreement of J/ψ spectra for forward and backward rapidity

- STAR strength: high pₜ
- PHENIX strength: rapidity coverage & precision

- pₜ spectrum harder at y~0 than at |y|>0
J/ψ production mechanism

• several models available

• main difference: how is the c̅c pair formed in the initial hard parton scattering color-neutralized to form the J/ψ?
  – Color Singlet Model (CSM)
    – at LO, a hard gluon is used to neutralize the c̅c pair
  – Color Octet Model (COM) or NRQCD
    – the c̅c pair can be produce in an octet state. Neutralization is realized non-perturbatively via exchange of soft gluons (which do not affect the initial c̅c kinematics)
  – Color Evaporation Model (CEM)
    – heavy quarkonia production is simply considered proportional to the c̅c cross section, with a proportionality factor fitted to data (independent of pT and y)
**p_T spectra vs. models**

- J/ψ p_T spectra vs. early versions of CSM and COM calculations
- Adding higher orders to CSM calculations
- "ad-hoc" removal of feed down from data
- Agreement improved

- CSM: low; COM: OK
- Additional handle
  - J/ψ polarization

```
global errors = 10%
√s = 200 GeV |y| < 0.35
p + p → J/ψ

PHENIX PRELIMINARY

NNLO*
NLO
LO
```

Other CSM developments

- **s-channel cut:** allow the $c\bar{c}$ to be off shell before interaction with the $3^{rd}$ hard gluon

  ![Diagram](https://via.placeholder.com/150)

  H. Haberzettl, J.P. Lansberg, PRL 100(2008)032006

- accounting for $J/\psi$ production from intrinsic charm (from an incoming nucleon)

  ![Diagram](https://via.placeholder.com/150)

  S.J. Brodsky, J.P. Lansberg, PRD 81(2010)051502
Data vs. CSM+s-channel cut model
- model absolutely normalized

- CSM+s-channel cut model tuned to CDF data
- good agreement with PHENIX data
- concern: magnitude of contribution
  (P. Artoisenet, E. Braaten, PRD 80(2009)034018)
J/ψ production in d+Au collisions

- Cold Nuclear Matter (CNM) effects
**J/ψ in d+Au**

- **nuclear modification factor from 2003 data**

\[ R_{dA} = \frac{N^{AuAu}_{J/\psi}}{N^{pp}_{J/\psi}} / \langle N^{AuAu}_{coll} \rangle \]

- **R_{CP} from 2008 data**

\[ R_{CP} = \frac{\frac{N^{dAu}_{J/\psi}, 0-20 \%}{N^{dAu}_{coll}}}{\frac{N^{dAu}_{J/\psi}, 60-88 \%}{N^{dAu}_{coll}}} \]

- **factor 40 increase in statistics**
  - 4 centrality bins
  - 9 rapidity bins

- **y < 0**
  - \( R_{CP} \approx 1 \)

- **y > 0**
  - \( R_{CP} < 1 \), decreasing with centrality

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**PHENIX preliminary**

- RHIC 2008
- d+Au, \( \frac{p_T}{N_{NN}} = 200 \) GeV
- ±11% Global Scale Uncertainty
- 40-60%

- ±8.27% Global Scale Uncertainty
- 20-40%

- ±5.05% Global Scale Uncertainty
- 0-20%
Cold Nuclear Matter effects

- CNM = modification of heavy quarkonia production in collisions involving heavy nuclei with respect to p+p collisions in absence of a quark-gluon plasma

- initial state effects
  - modification of the parton distribution function in nuclei (npdf)
  - energy loss of the incoming parton
  - gluon saturation

- final state effects
  - breakup of the J/$\psi$ or the precursor c$\bar{c}$ state in hadronic matter
Nuclear modification of PDF

- parton distribution (as function of $x_{Bj}$) inside a nucleon different for free nucleons and nucleons bound in nuclei
  - gluon nuclear PDF poorly known, in particular at low $x$
  - various parameterizations
    - small shadowing (HKN07, nDS, nDSg)
    - medium shadowing (EKS98, EPS09)
    - large shadowing (EPS08)
npdf + $\sigma_{\text{breakup}}$

- extraction of a hadronic breakup cross section $\sigma_{\text{breakup}}$
  - pick a npdf scenario (here: EKS)
  - add J/$\psi$ (or pre-cursor) breakup cross section $\sigma_{\text{breakup}}$
  - fit $\sigma_{\text{breakup}}$ to data (taking correlated and uncorrelated uncertainties properly into account)

- here: no rapidity dependence of $\sigma_{\text{breakup}}$
Energy dependence of $\sigma_{\text{breakup}}$

- global trend: decrease of $\sigma_{\text{breakup}}$ with $\sqrt{s_{\text{NN}}}$


EKS98

$J/\psi$

$\sigma_{\text{abs}}(y_{\text{cms}} = 0)$ [mb]

$E_{\text{lab}} = 158$ GeV
$0.28 < y < 0.78$

$E_{\text{lab}} = 400$ GeV
$-0.17 < y < 0.33$

power-law

PHENIX
$|y| < 0.35$

NA3
NA50-400
NA50-450
E866
HERA-B

\( \text{npdf} + \sigma_{\text{breakup}} \) versus data

- npdf with small and medium shadowing do not describe data at large rapidity
- npdf with large shadowing (EPS08) has difficulties for lower energy data
Effective $\sigma_{\text{breakup}}$ vs. rapidity

- Observed rapidity dependence of $R_{dA}$ not explained in scenarios with shadowing and fixed $\sigma_{\text{breakup}}$
- Extract effective $\sigma_{\text{breakup}}$ as function of rapidity from d+Au data
- Same trends observed by E866 at mid and forward rapidity and HERA-B at mid rapidity

$\rightarrow$ CNM effects not fully understood!
J/ψ production in A+A

- anomalous suppression in hot matter?
**J/ψ at RHIC** (Au+Au @ $\sqrt{s}_{NN} = 200$ GeV)

- PHENIX measures J/ψ production at RHIC
  - $J/ψ \rightarrow e^+e^-$ at $|y|<0.35$
  - $J/ψ \rightarrow \mu^+\mu^-$ at $1.2<|y|<2.2$

- mid rapidity $R_{AuAu}$ looks surprisingly similar to $R_{PbPb}$ at SPS

- although the systems are very different:
  - different energy densities at a given $N_{part}$
  - different cold nuclear matter effects ($x_{Bjorken}, \sigma_{abs}, \ldots$)
  - different overall charm yield

$R_{AuAu}$ ($y≈0$ @ RHIC) $\approx R_{PbPb}$ (@ SPS)
J/ψ at RHIC (Au+Au @ $\sqrt{s_{NN}} = 200$ GeV)

- **J/ψ suppression at RHIC**
  - mid versus forward rapidity
  - more suppression at forward rapidity!
  - but: energy density should be LOWER at forward rapidity

$$\frac{R_{AA}(y\approx 1.7)}{R_{AA}(y\approx 0)}$$

$R_{AuAu}$ (y≈1.7) $< R_{AuAu}$ (y≈0) @ RHIC

**J/ψ** $R_{AA}$ versus $N_{\text{part}}$

- **J/ψ** nuclear modification factor as function of $N_{\text{part}}$, $p_T$, and $y$ from 2004 Au+Au data

- **2007 data**
  - higher statistics (x4)
  - preliminary $R_{AA}$ (and $v_2$)
Forward rapidity "puzzle" at RHIC, more suppression at forward rapidity!

- two possible theoretical explanations

- hot medium related
  - (re)generation of $J/\psi$ from charm (anti)quarks in a deconfined medium
    - statistical hadronization
    - coalescence
    - regeneration

- cold matter related
  - modification of initial parton distribution functions in cold nuclear matter
    - (anti)shadowing
    - saturation
many approaches

- and many others

all explain

- \( R_{AA}(y=0) > R_{AA}(y=1.7) \)
- more c quarks to recombine at \( y=0 \)

all need reliable open charm input for quantitative constraints!
Quarkonia at the LHC

Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
• invariant cross sections are measured
• ALICE uniqueness: low $p_T$ at mid-rapidity!
J/ψ: pp @ 7 TeV

- NLO NRQCD calculations agree with data
J/ψ: pp @ 7 TeV

- multiplicity dependence
- not reproduced by model (PYTHIA)

- relative J/ψ yield increases linearly with relative charged particle multiplicity
- interplay between hard and soft interactions in the context of multi-partonic interactions (MPI)
J/ψ: Pb-Pb @ 2.76 TeV

- $R_{AA}$ vs. $N_{\text{part}}$: ALICE & PHENIX

- Stronger centrality dependence at lower energy
- $R_{AA}$ systematically larger in central collisions for ALICE compared to PHENIX
- Qualitatively consistent with (re)generation
$J/\psi$: Pb-Pb @ 2.76 TeV

- $R_{AA}$ from ALICE vs. models

- Models with large fraction (>50% in central collisions) of $J/\psi$ from (re)combination or models with all $J/\psi$ produced at hadronization can describe ALICE results for central collisions in both rapidity ranges

$J/\psi$: Pb-Pb @ 2.76 TeV

- $R_{AA}$ vs. $p_T$ in centrality bins

- non-central: no strong $p_T$ dependence
- central: larger suppression (or less re-generation) towards larger $p_T$
  $\rightarrow$ consistent with (re)generation picture
J/ψ: Pb-Pb @ 2.76 TeV

- $R_{AA}$ vs. rapidity

- Suppression is stronger (or less re-generation) towards larger rapidity
  → consistent with (re)generation picture
CMS: dimuon measurement

CMS Preliminary
\( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

\( \Upsilon(1,2,3S) \)

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

\( \rho, \omega, \phi \)

\( \psi(2S) \)

\( p_T^\mu > 4 \text{ GeV/c} \)

\( m_{\mu\mu} \) (GeV/c^2)

Y: Pb-Pb @ 2.76 TeV

- sequential suppression of Y states

→ investigate in more detail
Towards a quarkonium thermometer

- clear ‘hierarchy’ of quarkonium states

→ expected in terms of binding energies
Summary

• quarkonia = one of the most interesting probes for the QGP
• in the focus of the field since suppression was proposed as QGP signature
• original idea was nice but too simple
• enormous progress at the LHC