Charmonium and the Quark-Gluon Plasma at the LHC

Motivation
Open charm – thermalization of heavy quarks
Charmonium – a probe of deconfinement
Outlook

a Tribute to Gerald E. Brown – Stony Brook November 24-26, 2013
prologue

30 years of a very close friendship
and ... 
1 joint paper

Pions from resonance decay
in Brookhaven relativistic heavy-ion collisions ⋆

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Received 21 September 1990

which Gerry dubbed 'cool pions from hot nucleons'

Johanna Stachel
Charm (and Beauty) quarks in QGP – impurities in matter of mostly gluons and also light quarks (u,d,s)

- ccbar formed in hard scattering event in early stage of the collision (t = 1/2m_c = 0.08 fm)
- medium with high density of color charges screens strong interaction (Debye screening, Satz/Matsui 1986)
- charm quarks diffuse, loose energy, thermalize – see D-meson R_{AA} and v_2
- once T_c is reached, system hadronizes and D-mesons and maybe ccbar bound states form
interest 2-fold:
- do charm quarks thermalize in a QGP?
  transport coefficient for heavy quarks?
  energy loss of heavy quark (radiative energy loss should be suppressed due to large mass (1.2 GeV); in vacuum gluon radiation into angles suppressed (Dokshitzer and Kharzeev)
  and Casimir factor $C_q = 4/3$ vs $C_{\text{gluon}} = 3$

- need total charm cross section for understanding of charmonia
Measurement of open charm cross section at the LHC

all LHC experiments contribute:

- ALICE at $p_t > 2$ GeV/c and $0 < y < 4$
- ATLAS and CMS at $p_t > 6$ GeV/c and $0 < y < 2.5$
- LHCb at $p_t > 2$ GeV/c and $2.5 < y < 4$

all detectors employ sophisticated Si vertex detectors

measurement technique:
- reconstruction of hadronic decays of D-mesons (ALICE)
- semi-leptonic decays into electrons (ATLAS, ALICE)
- “into muons (ATLAS, ALICE)
for $10^9$ events, expect to measure open charm for $p_t = 0.5 - 15$ GeV/c
Measurements agree well with state of the art pQCD calculations

\[ J^2, \text{pp } \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 5 \text{ nb}^{-1} \]

\[ D^0, \text{pp } \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 5 \text{ nb}^{-1} \]

\[ D^-, \text{pp } \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 5 \text{ nb}^{-1} \]

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Data are compared to perturbative QCD calculations with reasonable agreement:
- At upper end of FONLL and at lower end of GM-VFNS
- Measure 80% of charm cross section for $|y| < 0.5$

FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439
a first try at the total ccbar cross section in pp collisions

- good agreement between ALICE, ATLAS and LHCb
- large syst. error due to extrapolation to low pt, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL
D meson signals in Pb Pb collisions

data: ALICE JHEP 1209 (1012)112
Suppression of charm at LHC energy

\[ R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}}{dp_t} \left/ \frac{d\sigma_{pp}}{dp_t} \right. \]

yield in PbPb/(number binary collisions times yield in pp)

energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - suppr. factor 4 for 6-12 GeV/c
Suppression of charm at LHC energy

comparison to EPS09 shadowing: suppression not an initial state effect

energy loss of charm quarks only little less than that for light quarks/gluons → thermalization
Charm Quarks also Exhibit Elliptic Flow

Non-zero elliptic flow $5.7\sigma$ effect for $D^0$ 2-6 GeV/c within errors charmed hadron $v_2$ equal to that of all charged hadrons

2 centrality classes event plane from TPC corrected for B-feed down (FONLL)
both are determined by transport properties of the medium (QGP) simultaneous description still a challenge for models
Charmonia as a probe of Deconfinement

Charmonia: bound states of charm and anticharm quarks, e.g. $J/\psi$ 1s state of $c\bar{c}$

mass 3.1 GeV
radius 0.45 fm

the original idea (Matsui and Satz 1986): implant charmonia into the QGP and observe their modification (Debye screening of QCD) in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – sequential melting

new insight (Braun-Munzinger, J.S. 2000): QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfinement
charmonium enhancement as fingerprint of deconfinement at LHC energy
only free parameter: open charm cross section in nuclear collision
Decision on Regeneration vs. Sequential Suppression from LHC Data

![Graph showing statistical regeneration and sequential suppression with energy density on the x-axis and $J/\psi$ production probability on the y-axis.]

Picture: H. Satz 2009
J/ψ spectrum and cross section in pp collisions


- Good agreement between experiments
- Complementary in acceptance:
  - Only ALICE has acceptance below 6 GeV at mid-rapidity
- Measured both at 7 and 2.76 TeV
- Open issues: statistics at mid-rapidity, polarization (biggest source of syst error)
most challenging: PbPb collisions in spite of significant irreducible combinatorial background (true electrons, not from $J/\psi$ decay but from D- or B-mesons) resonance well visible
J/ψ production in PbPb collisions: LHC relative to RHIC

forward rapidity

mid-rapidity

energy density -->

melting scenario not observed
rather: enhancement with increasing energy density!
(from RHIC to LHC and from forward to mid-rapidity)
production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties

main uncertainties for models: open charm cross section, shadowing in Pb

(see next)
in transport models (Rapp et al. & P.Zhuang, N.Xu et al.) J/psi generated both in QGP and at hadronization

- transport models also in line with $R_{AA}$
- part of J/psi from direct hard production, part dynamically generated in QG

what I do not understand: how can error band be narrower than ours? Error open charm ...
for statistical hadronization $J/\psi$ yield proportional to $N_c^2$
higher yield at mid-rapidity predicted in line with observation

comparison to shadowing calculations:
- at mid-rapidity suppression could be explained by shadowing only
- at forward rapidity there seems to be additional suppression
- need to measure shadowing
The $p_T$ dependence of $R_{AA}$ shows relative yield larger at low $p_T$ in nuclear collisions. There is good agreement with CMS at high $p_T$. 

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

- ALICE $J/\psi \rightarrow \mu^+ \mu^-$, $2.5 < y < 4$, centrality 0\% - 90\%
  global syst. = ± 8\%

- CMS $J/\psi \rightarrow \mu^+ \mu^-$, $1.6 < |y| < 2.4$, centrality 0\% - 100\%
  global syst. = ± 8.3\%
Softening of J/ψ $p_t$ distributions for central PbPb coll.

At LHC for central collisions softening relative to peripheral collisions and relative to pp (opposite trend to RHIC) - consistent with formation of J/ψ from thermalized c-quarks
Softening of J/psi $p_t$ distributions for central PbPb coll.

P.Zhuang et al. regeneration of J/psi
90% at mid-$y$, > 60% at forward $y$
Modification of charm production in nuclei: pA collisions

Dimuons: dedicated trigger

\[ L_{\text{int}} = 5.0 \text{ nb}^{-1} \text{ (forward)} \]

\[ L_{\text{int}} = 5.8 \text{ nb}^{-1} \text{ (backward)} \]

Dielectrons: Minimum Bias

\[ L_{\text{int}} = 52 \text{ \mu b}^{-1} \]
J/psi rapidity distribution in pPb compared to pp

ALICE forward/backward  arXiv:1308.6726
good agreement with LHCb arXiv:1308.6729
ALICE mid-y    hard probes 2013

\[ R_{pPb} \mid s_{NN} = 5.02 \text{ TeV} \]

\[ L_{pt} \mid -4.46 < y_{\text{cms}} < -2.96 \] = 5.8 nb⁻¹, \[ L_{pt} \mid 2.03 < y_{\text{cms}} < 3.53 \] = 5.0 nb⁻¹
ALICE Preliminary: inclusive J/ψ → e⁺e⁻, p_T > 0 GeV/c
\[ L_{pt} \mid -1.37 < y_{\text{cms}} < 0.43 \] = 52 µb⁻¹

uncorr. systematic uncertainty
part. corr. systematic uncertainty
common \( T_{pt} \) uncertainty
J/ψ rapidity distribution in pPb compared to pp

ALICE forward/backward arXiv:1308.6726
good agreement with LHCb arXiv:1308.6729
ALICE mid-y hard probes 2013

good agreement with EPS09 shadowing wo absorption (Ferreiro)
also consistent w energy loss models wo shadowing (Arleo)
CGC calculation disfavored (Fuji)
J/psi vs pt in PbPb collisions relative to pPb collisions at low pt yield in nuclear collisions above pPb collisions  
J/psi production enhanced in nuclear collisions over mere shadowing effect
charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

**ALICE data analysis** in 4 centrality bins


<table>
<thead>
<tr>
<th>Centrality</th>
<th>( \langle N_{\text{part}} \rangle )</th>
<th>EP resolution ± (stat.) ± (syst.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%–20%</td>
<td>283 ± 4</td>
<td>0.548 ± 0.003 ± 0.009</td>
</tr>
<tr>
<td>20%–40%</td>
<td>157 ± 3</td>
<td>0.610 ± 0.002 ± 0.008</td>
</tr>
<tr>
<td>40%–60%</td>
<td>69 ± 2</td>
<td>0.451 ± 0.003 ± 0.008</td>
</tr>
<tr>
<td>60%–90%</td>
<td>15 ± 1</td>
<td>0.185 ± 0.005 ± 0.013</td>
</tr>
<tr>
<td>20%–60%</td>
<td>113 ± 3</td>
<td>0.576 ± 0.002 ± 0.008</td>
</tr>
</tbody>
</table>

analyze opposite sign muon pairs relative to the V0 event plane as function of mass and for each pt bin

- fit distribution with

\[
v_2(m_{\mu\mu}) = v_2^{\text{sig}} \alpha(m_{\mu\mu}) + v_2^{\text{bkg}}(m_{\mu\mu})[1 - \alpha(m_{\mu\mu})]
\]

where \( \alpha(m_{\mu\mu}) = S / (S+B) \) fitted to the mass spectrum
Elliptic Flow of J/ψ vs $p_t$

- expect build-up with $p_t$ as observed for $\pi$, p, K, $\Lambda$, … and vanishing signal for high $p_t$ region where J/$\psi$ not from hadronization of thermalized quarks
- observed
J/psi flow compared to models including (re-) generation

\[ v_2 \] of J/\( \psi \) consistent with hydrodynamic flow of charm quarks in QGP and statistical (re-)generation

arXiv:1303.5880
Charm and beauty and J/ψ cross section and spectra in pp in good agreement with pQCD predictions (baseline)

- Open charm
  - spectra and elliptic flow indicate: charm quarks thermalize in QGP

J/ψ
- completely new picture at LHC compared to RHIC: $R_{AA}$, spectra, and elliptic flow indicate we are well on the way towards proof of deconfinement:
  - thermalized c-quarks form charmonia at hadronization
Gerry, we will always miss you!

Aug 1995 Great Wall - China

Nov 1995 Conscience Circle

1990 Cemetery Lane
backup
Production of charm quarks and charmonia in hadronic collisions

- Charm and beauty quarks are produced in early hard scattering processes.
- Most important Feynman diagram: gluon fusion.
- Formation of quarkonia: with about 1% probability the $c$ and $\bar{c}$ form $^31S$ state = $J/\psi$.
- Requires transition to a color singlet state.
- Not pure perturbative QCD anymore, some modelling required.

CEM Color Evaporation Model
CSM Color Singlet Model

Now reasonably successful.
Charm and beauty via semi-leptonic decays

Inclusive electron spectrum from 2 PID methods: TPC-TOF-TRD and TPC-EMCAL

subtract hadronic decay cocktail using measurements where possible ($\pi^0$, $\eta$, $m_t$ scaling for other mesons, $J/\psi$), direct $\gamma$ from pQCD
Charm and beauty electrons compared to pQCD

- ALICE data complimentary to ATLAS measurement at higher pt (somewhat larger y-interval)
- good agreement with pQCD
- at upper end of FONLL range for $p_t < 3$ GeV/c where charm dominates

arXiv:1205.5423
ATLAS: PLB707 (2012) 438
FONLL: Cacciari et al., arXiv:1205.6344
Beauty cross section in pp and ppbar collisions
Suppression only for Strongly Interacting Hard Probes

photons, Z and W scale with number of binary collisions in PbPb – not affected by medium → demonstrates that charged particle suppression is medium effect: energy loss in QGP
J/ψ in PbPb collisions relative to pp

\[ R_{AA}(p_T) = \frac{(1/N^{AA}_{evl}) \frac{d^2N^{AA}_{ch}}{d\eta d\rho_T}}{\langle N_{coll} \rangle (1/N^{pp}_{evl}) \frac{d^2N^{pp}_{ch}}{d\eta d\rho_T}} \]

- nearly flat over large centrality range
- indication of rise for most central and mid-rapidity
J/ψ production in PbPb collisions: LHC relative to RHIC

melting scenario not observed
rather: enhancement with increasing energy density!
(from RHIC to LHC and from forward to mid-rapidity)
production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties

- main uncertainties for models: open charm cross section, shadowing in Pb
- shadowing from pPb collisions: forward y: $R_{AA} = 0.76(12)$ mid-y $R_{AA}$ (estim) =0.72(15)
due to displaced decay-vertices, pseudoproper decay length can be used to determine B-fraction
Fraction of $J/\psi$ from $B$-decays

$p_T$ integrated non-prompt $B$-fraction of small within current errors no significant difference in pp and PbPb collisions
J/ψ $p_t$ distributions as function of centrality

new feature: distributions get narrower (softer) for more central collisions
ALICE, Pb-Pb $s_{NN}=2.76$ TeV, $L=70$ μb$^{-1}$
- inclusive J/ψ, centrality 0%-20%, 2.5<y<4, global sys.$=\pm6\%$

PHENIX (PRC 84(2011) 054912), Au-Au $s_{NN}=0.2$ TeV
- inclusive J/ψ, centrality 0%-20%, 1.2<|y|<2.2, global sys.$=\pm10\%$
Rapidity dependence of J/psi $R_{AA}$

Least amount of suppression at mid-rapidity
J/ψ in pPb - ALICE compared to LHCb
Ppb model comparison – data in larger pt bins

\[ R_{Pb} \mid s_{NN} = 5.02 \text{ TeV} \]

ALICE arXiv:1308.6726: inclusive \( J/\psi \rightarrow \gamma \gamma \), \( 0 < p_T < 15 \text{ GeV/c} \)
\[ L_{\text{int}} (\text{abs} < 2.96) = 5.6 \text{ nb}^{-1}, \quad L_{\text{int}} (\text{abs} < 3.53) = 5.0 \text{ nb}^{-1} \]

ALICE Preliminary: \( J/\psi \rightarrow e^+e^- \), \( p_T > 0 \text{ GeV/c} \)
\[ L_{\text{int}} (\text{abs} < 0.43) = 52 \mu\text{b}^{-1} \]

\[ y_{\text{cms}} \]

- EPS09 NLO (Vogt)
- CGC (Fujii et al.)
- ELoss with \( q = 0.075 \text{ GeV}^2/\text{fm} \) (Arleo et al.)
- EPS09 NLO + ELoss with \( q = 0.055 \text{ GeV}^2/\text{fm} \) (Arleo et al.)
- EPS09 LO central set (Ferreiro et al.)
- EPS09 LO central set + \( q_{\text{abs}} = 1.5 \text{ mb} \) (Ferreiro et al.)
- EPS09 LO central set + \( q_{\text{abs}} = 2.8 \text{ mb} \) (Ferrore et al.)

ALT-DE-61374

Johanna Stachel
Kinematics for J/psi production in pPb vs PbPb

For 2 → 1 kinematics: \[ x_{1/2} = \frac{m_T}{\sqrt{s_{NN}}} \exp(-y_{\text{cms}}) \]

Values for \( p_T = 0 \) GeV/c for the analysed data samples in 2010-2013:

Dimuons:
p-Pb forward rapidity (\( \sqrt{s_{NN}} = 5.02 \) TeV) \( x_{\text{Pb}} = 1.8 - 8.1 \times 10^{-5} \)
p-Pb backward rapidity (\( \sqrt{s_{NN}} = 5.02 \) TeV) \( x_{\text{Pb}} = 1.1 - 5.3 \times 10^{-2} \)
Pb-Pb (\( \sqrt{s_{NN}} = 2.76 \) TeV) \( x_{\text{Pb1}} = 1.4 - 6.1 \times 10^{-2} \)
\( x_{\text{Pb2}} = 2.1 - 9.2 \times 10^{-5} \)

Dielectrons:
p-Pb (\( \sqrt{s_{NN}} = 5.02 \) TeV) \( x_{\text{P0}} = 2.4 - 4.0 \times 10^{-3} \)
Pb-Pb (\( \sqrt{s_{NN}} = 2.76 \) TeV) \( x_{\text{P0}} = 2.5 - 5.0 \times 10^{-3} \)
Relevance of pPb results for PbPb collisions

\[
R_{pPb} = 0.70 \pm 0.01 \text{(stat.)} \pm 0.04 \text{(syst. uncorr.)} \pm 0.03 \text{(syst. part. corr.)} \pm 0.03 \text{(syst. corr.)}
\]

\[
R_{Pbp} = 1.08 \pm 0.01 \text{(stat.)} \pm 0.08 \text{(syst. uncorr.)} \pm 0.07 \text{(syst. part. corr.)} \pm 0.04 \text{(syst. corr.)}
\]

if interpreted as shadowing (consistent with model comparisons), these results can be used to calculate the “cold nuclear matter effect” due to shadowing for PbPb collisions:

the \( x_F \)-ranges probed by J/psi production in pPb and Pbp are very close to the ones for gluon fusion selected in PbPb collisions:

2.1 \( 10^{-5} \) – 9.2 \( 10^{-5} \) and 1.4 \( 10^{-2} \) – 6.1 \( 10^{-2} \) for nucleons moving away from and towards the muon spectrometer

and then

\[
R_{PbPb} = R_{pPb} \cdot R_{Pbp} = 0.76 \pm 0.07 \pm 0.10 \text{ for } y=2.5-4.0
\]

and

\[
R_{PbPb} \approx 0.72 \pm 0.15 \text{ for midrapidity}
\]
$R_{AA}$ in PbPb collisions: shadowing contribution

- **mid-y J/psi** $R_{AA}$ consistent with or slightly above shadowing estimate
- J/psi at forward $y$ below shadowing
Predictions for statistical hadronization

Predictions based on pQCD cross section for full LHC energy

in line with current pp charm cross section at $\sqrt{s_{NN}} = 2.76$ TeV and pPb shadowing
need more precise ccbar cross section measurement and full LHC energy data
\(p_t\) Dependence of \(R_{AA}\)

Statistical hadronization only expected for charm quarks thermalized in the QGP

\(p_t\) dependence in line with this prediction in CMS only suppression
Elliptic Flow of J/psi

first observation of significant J/ψ v₂

arXiv:1303.5880
$R_{AA}$

ALICE, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
$|y|<0.9$, $p_T>0$ GeV/c, $L=15 \mu$b$^{-1}$

- Shadowing, EKS98, (E.Ferreiro, priv.comm.)
- Shadowing, nDSg, (E.Ferreiro, priv.comm.)

$\langle N_{\text{part}} \rangle$

ALI-PREL-39381
p-Pb $\sqrt{s_{NN}} = 5.02$ TeV, inclusive $J/\psi \rightarrow \mu^+\mu^-$

$2.96 < y_{cm} < 3.53$, $0 < p_T < 15$ GeV/c

ALICE

EPS09 NLO
(Vogl)

EPS09 LO
(Ferreiro et al.)

nDSG LO
(Ferreiro et al.)

EPS09 NLO and E Loss, $q_s = 0.055$ GeV$^2$/fm
(Arleo et al.)

E Loss, $q_s = 0.075$ GeV$^2$/fm
(Arleo et al.)
Precision spectra of J/psi should reveal flow and direct production at high pt

predictions A. Andronic, P. Braun-Munzinger, K. Redlich, J.S.
for statistical hadronization $J/\psi$ yield proportional to $N_c^2$
higher yield at mid-rapidity predicted
in line with observation
already seen at RHIC by PHENIX

Prediction based on pQCD $d\sigma_{cc}/dy$
central value 0.64 mb
low 0.32 mb, high 1.28 mb

model: A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel

data: PHENIX nucl-ex/0611020
additional 14% syst error beyond shown
Statistical hadronization model predictions for $\psi'$

- pp and pA data factor 3 above statistical hadronization value
- only result for AA at SPS energy; very close agreement
- data at higher energies will be crucial test

in fact: here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!
Suppression of Upsilon States

Centrality integrated:

2S/1S PbPb relative to pp $0.21 \pm 0.07 \pm 0.02$

3S/1S $< 0.1$ 95% C.L.

Higher upsilon states expected to melt earlier because of larger radius

but also: statistical population much reduced beyond pp value due to Boltzmann factors

consistent with excited state suppression (50% feed-down)