• introductory remarks and context
• a few words on open heavy flavor production
• the charmonium story – deconfinement and color screening
  • SPS and RHIC energies
  • LHC results
• remarks on Y production
• the Debye screening radius and LQCD
• summary

ECT* workshop on heavy flavor
March 16-20, 2015
Open heavy flavor production and the QGP

1. $m_q \gg \Lambda_{QCD}$, charm quark production is independent of the medium formed in the collision.

2. Propagation of heavy quarks in the medium can be used to diagnose it.

   - Energy loss – thermalization – hydrodynamic flow

interaction with the hot/dense QCD medium

- Energy loss
  - Dependence on medium density and volume
  - Color charge dependent (Casimir factor) $\Rightarrow \Delta E_{\text{gluon}} > \Delta E_{\text{quark}}$
  - Parton mass dependent (dead cone effect: Dokshitzer & Kharzeev, PLB 519(2001)199) $\Rightarrow \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

- Thermalization
  - Dependence on transport properties of the medium
Formation time of quarkonia

heavy quark velocity in charmonium rest frame:

\[ v = 0.55 \text{ for } J/\psi \quad \text{see, e.g. G.T. Bodwin et al., hep-ph/0611002} \]

minimum formation time: \[ t = \frac{\text{radius}}{v} = 0.45 \text{ fm} \]


formation time of order 1 fm

formation time is not short compared to plasma formation time especially at high energy
formation time of open charm hadrons not well understood

presumably similar to charmonia

separation of time scales for initial hard process and late hadronization/hadron formation is called „factorization“

rigorously proven for deep inelastic scattering
charm conservation equation

$$\sigma_{c\bar{c}} = \frac{1}{2} \left[ \sigma_{D^+} + \sigma_{D^-} + \sigma_{D^0} + \sigma_{\bar{D}^0} + \sigma_{\Lambda_c} + \sigma_{\bar{\Lambda}_c} \ldots \right]$$

no medium effect

Medium effects on charmed hadrons affect redistribution of charm, but not overall cross section.

It is not consistent with the charm conservation equation to reduce all charmed hadron masses in the medium for an enhanced cross section.
total ccbar cross section in pp at LHC energy

- good agreement between ALICE, ATLAS and LHCb
- syst. error due to extrapolation to low pt,
- data about factor 2 above central value of FONLL
- beam energy dependence follows well FONLL prediction
- significant improvement of accuracy expected in LHC Run2
how to quantify the effect of the medium?

\[ R_{AA} = \frac{\text{yield}(AA)}{(N_{\text{coll}} \text{ yield}(pp))} \]

\[ R_{AA} = \text{medium/vacuum} \]

\[ R_{AA} = 1 \text{ if no dense medium is formed} \]

\[ \text{or} \]

\[ \text{if one looks at electro-weak probes} \]
suppression of charm at LHC energy

comparison to EPS09 shadowing: suppression not an initial state effect will be measured directly in pPb collisions

energy loss of charm quarks only slightly less than that for light quark → thermalization
no charm modification in p-Pb collisions
charm Quarks also Exhibit Elliptic Flow

non-zero elliptic flow for $3 \sigma$ 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)
2b) the quarkonium story

- some historical remarks
- the statistical hadronization model
- comparison to results from RHIC
- charmonium production at LHC energy
- the color screening length in the QGP
- remarks on bottomonium
Charmonium as a probe for the properties of the QGP

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

new insight (pbm, Stachel 2000) QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfined, thermalized charm quarks

recent reviews:  L. Kluberg and H. Satz, arXiv:0901.3831

pbm and J. Stachel, arXiv:0901.2500

both published in Landoldt-Boernstein Review, R. Stock, editor, Springer 2010
related approaches

alternative to statistical hadronization: implementation of screening into space-time evolution of the fireball – continuous destruction and (re)generation


for a very recent new approach see Blaizot et al, arXiv:1503.03857.
**time scales**

For the original Matsui/Satz picture to hold, the following time sequence is needed:

1) charmonium formation  
2) quark-gluon plasma (QGP) formation  
3) melting of charmonium in the QGP  
4) decay of remaining charmonia and detection

**questions:**

a) beam energy dependence of time scales  
b) what happens with the (many) charm quarks at hadronization, i.e. at the phase boundary?

At LHC energy, clean separation of time scales

collision time $<<$ QGP formation time $<$ charmonium formation time
are charmonia (and charmed hadrons) produced thermally?

ratios of charmed and beauty hadrons exhibit thermal features (Becattini 1997) but: psi'/psi ratio is far from thermal in pp collisions see also Sorge&Shuryak, Phys. Rev. Lett. 79 (1997) 2775, where it is further noted that the psi'/psi ratio reaches a thermal value (T=170 MeV) in central PbPb collisions at SPS energy further analysis by Gorenstein and Gazdzicki, Phys. Rev. Lett. 83 (1999) 4003 result: (J/psi)/pi is approximately constant at SPS energy for PbPb

However, thermal production of charm quarks is appreciable only at very high temperatures (T > 800 MeV, pbm&Redlich, Eur. Phys. J. C16 (2000) 519).

solution: charm quarks produced in hard collisions, then statistical hadronization at the phase boundary.
quarkonium as a probe for deconfinement at the LHC
the statistical (re-)generation picture


charm\textit{a}sium enhancement as fingerprint of color screening and deconfinement at LHC energy

dependence of enhancement on charm cross section

open charm is natural and essential normalization precision measurement needed

Statistical hadronization in one page

Thermal model calculation (grand canonical) $T, \mu_B: \rightarrow n^t_{\chi}$

$N_{c\bar{c}}^{\text{dir}} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th})$

$N_{c\bar{c}} \ll 1 \rightarrow \text{Canonical: J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137}$

$N_{c\bar{c}}^{\text{dir}} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \rightarrow g_c$

Outcome: $N_D = g_c V n_{D}^{th} I_1 / I_0$, $N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

Inputs: $T$, $\mu_B$, $V = N_{ch}^{exp} / n_{ch}^{th}$, $N_{c\bar{c}}^{\text{dir}}$ (pQCD)
decision on regeneration vs sequential suppression from LHC data

Picture: H. Satz 2009
ingredients for prediction of quarkonium and open charm cross sections

- energy dependence of temperature and baryo-chemical potential (from hadron production analysis)
- open charm (open bottom) cross section in pp or better AA collisions
- quarkonium production cross section in pp collisions (for corona part)

result: quarkonium and open charm cross sections as function of energy, centrality, rapidity, and transverse momentum
now brief survey of SPS and RHIC results
results for SPS energy

only moderately enhanced \((2 \times pQCD)\) cc\_bar cross section needed

\(\psi'/\psi\) ratio is expected from a thermal scenario
a brief look at RHIC data
Centrality dependence of nuclear modification factor

data well described by our regeneration model without any new parameters
Comparison of model predictions to RHIC data: rapidity dependence

suppression is smallest at mid-rapidity (90 deg. emission)
a clear indication for regeneration at the phase boundary
summary of lower energy (SPS, RHIC) results

first indications for (re-)generation picture

interpretation not unique
now to LHC data

attempt full measurement of open charm and open beauty in pp, pPb, PbPb as function of centrality, rapidity and transverse momentum

attempt full measurement including polarization of all quarkonia in pp, pPb, PbPb as function of centrality, rapidity and transverse momentum

...we are on the way
J/ψ line shape in ultra-peripheral Pb—Pb collisions

resolution: about 23 MeV for J/ψ, precision determination of tail due to internal and external bremsstrahlung.
J/psi in e+e- needs electron ID in both TPC and TRD

most challenging: PbPb collisions
in spite of significant combinatorial background
(true electrons, not from J/y decay but e.g. D- or B-mesons) resonance well visible
in Pb—Pb collisions charm quarks are suppressed relative to pp collisions

in the pt range $3 < pt < 10$ GeV there are much fewer charm quarks compared to expectations from pp collisions

→ charm quarks in PbPb are at low pt!

expect that charmonia are suppressed in the pt $> 3$GeV range

measurements at low pt are absolutely essential for the charmonium story

solution: normalization of $J/\psi$ to the open charm cross section in PbPb collisions

first step: $(J/\psi)/D$ ratio in PbPb collisions to come soon from ALICE
pp @ 2.76 TeV reference for the nuclear modification factor $R_{AA}$ in Pb-Pb collisions

$$R_{AA}^i = \frac{Y_{J/\psi}^i(\Delta p_T, \Delta y)}{\langle T_{AA}^i \rangle} \times \sigma_{pp}^{J/\psi}(\Delta p_T, \Delta y)$$

The pp reference is also the main source of systematic uncertainty in the $R_{AA}$ computation:

$J/\Psi (2.5 < y < 4)$, total syst. uncertainty of 9%

$J/\Psi (|y| < 0.9)$, total syst. uncertainty of 26%
less suppression when increasing the energy density

from here to here more than factor of 2 increase in energy density, but $R_{AA}$ increases by more than a factor of 3

2007 prediction impressively confirmed by LHC data
Comparison to Statistical Hadronization Model Prediction

- ALICE \((2.5<y<4.0, \pm 15\% \text{ syst.}), \sqrt{s_{NN}}=2.76 \text{ TeV}\)
- PHENIX \((1.2<y<2.2, \pm 9\% \text{ syst.}), \sqrt{s_{NN}}=0.2 \text{ TeV}\)
- lines: Statistical Hadronization Model

- ALICE \((|y|<0.8, \pm 13\% \text{ syst.}), \sqrt{s_{NN}}=2.76 \text{ TeV}\)
- PHENIX \((|y|<0.35, \pm 12\% \text{ syst.}), \sqrt{s_{NN}}=0.2 \text{ TeV}\)

- \(R_{AA}^{J/\psi}\)

- Forward rapidity: \(d\sigma/dy_{cc} = 0.15 \text{ mb}\)
- Midrapidity: \(d\sigma/dy_{cc} = 0.3 \text{ mb}\)
- Statistical Hadronization Model

- \(-0.25 \text{ mb}\)
- \(-0.4 \text{ mb}\)
Rapidity dependence

Note: energy density largest at $y = 0$
back to J/psi data – what about spectra and hydrodynamic flow of charm and charmonia?

if charmonia are produced via statistical hadronization of charm quarks at the phase boundary, then:

- charm quarks should be in thermal equilibrium
  - low pt enhancement
  - flow of charm quarks
  - flow of charmonia
Comparison of transverse momentum spectra at RHIC and LHC

drastic and qualitative difference between RHIC and LHC results
Comparison Pb-Pb to pPb

J/psi production in Pb-Pb is enhanced beyond shadowing
comparison with (re-)generation models

good agreement lends further strong support to the 'full color screening and late J/psi production' picture
analysis of transverse momentum spectra


Zhou, Xu, Zhuang

at LHC energy, mostly (re-) generation of charmonium, p_t distribution exhibits features of strong energy loss and approach to thermalization for charm quarks
J/psi flow compared to models including (re-) generation

hydrodynamic flow of J/psi consistent with (re-)generation
Comparison R_AA for D-mesons, charged particles, and J/psi

what is the role of energy loss of charmonium production? Is (re-)combination important at p_t = 10 GeV?
Charmonium production at LHC energy: deconfinement, and color screening

- Charmonia formed at the phase boundary $\rightarrow$ full color screening at $T_c$

- Debye screening length $< 0.4$ fm near $T_c$

- Combination of uncorrelated charm quarks into J/psi $\rightarrow$ deconfinement

Statistical hadronization picture of charmonium production provides most direct way towards information on the degree of deconfinement reached as well as on color screening and the question of bound states in the QGP
Debye mass, LQCD, and $J/\psi$ data

Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi T$ ($3\pi T$), where $\mu$ is the renormalization point. (Right) Flavor dependence of the Debye screening masses. We assume the pseudo-critical temperature for $2 + 1$-flavor QCD as $T_c \sim 190$ MeV.


from $J/\psi$ data and statistical hadronization analysis: $m_{\text{Debye}}/T > 3.3$

at $T = 0.15$ GeV
Are there hadronic bound states in the QGP?

Possible resolution of a fundamental question:
can there be bound states of colorless hadrons in the QGP or
are all hadrons formed at the phase boundary?

measurement of psi'/psi and chi_c/psi ratio will settle the issue → ALICE upgrade

transport model:
X. Zhao, R. Rapp,
NPA 859 (2011) 114

statistical model:
A. Andronic et al.,
PLB 678 (2009) 350
hadronization of heavy quarks in $e^+e^-$ collisions

Comparison of stat. model calcs. with data


charmonium cannot be described at all in this approach

But: all charm quarks hadronize at 170 MeV
First results on $\psi'/\psi$ ratio

Possible enhancement in CMS data not found by ALICE measurements but errors still very large.
The bottomonium puzzle (I)

New results from LHCb: feeding into $Y(1s)$ only about 30% → $Y(1s)$ suppression not due to reduced feeding in Pb—Pb collisions

$R_{AA}(Y(1S)) = 0.56 \pm 0.08 \pm 0.07$
$R_{AA}(Y(2S)) = 0.12 \pm 0.04 \pm 0.02$
$R_{AA}(Y(3S)) < 0.10$ @ 95% CL

(at forward rapidity)

CMS, PRL109 (2012) 222301
ALICE, PLB738 (2014) 361

New results from LHCb: feeding into $Y(1s)$ only about 30% → $Y(1s)$ suppression not due to reduced feeding in Pb—Pb collisions
Rapidity distribution of RAA for $Y(1s)$ is peaked at $y=0$, not consistent with suppression scenarios.

Measurements at large rapidity (ALICE muon arm) are crucial!
transverse momentum distributions for Y states

if picture of Debye screening and (re-)generation also applies to Y states, expect similar $p_t$ pattern as for charmonia

needs approach to thermalization for b quarks!

predictions by Zhou, Xu, Zhuang
arXiv:1309.7520 [nucl-th]
Upsilon production and statistical hadronization

SHM/thermal model: Andronic et al.

are b quarks thermalized?
no connection to color screening with equilibrium!
summary 1 – quarkonium production

- spectacular difference between results from RHIC and LHC
- $J/\psi$ production is consistent with complete Debye screening and (re-)generation at the QCD phase boundary
- charm quarks are thermalized and deconfined
- $Y$ production: also suppressed but unclear relation to color screening
  - are $b$ quarks and/or $Y$ thermalized?
summary 2

- charmonium production – a fingerprint for deconfined quarks and gluons
- evidence for energy loss and flow of charm quarks -> thermalization
- charmonium generation at the phase boundary – a new process
- first indications for this from psi'/(J/psi) SPS and J/psi RHIC data
- evolution from RHIC to LHC described quantitatively
- charmonium enhancement at LHC – J/psi color-screened at T_c, deconfined QGP

![Cartoon](image)

cartoon Helmut Satz, 2009  
SPS  RHIC  LHC
extra slides
Evolution of J/psi transverse momentum spectra – evidence for thermalization and charm quark coalescence at the phase boundary

- Inclusive J/$\psi$
  - ALICE, pp $s=2.76$ TeV, $2.5<y<4$
  - ALICE, Pb-Pb $s_{NN}=2.76$ TeV, $2.5<y<4$
  - PHENIX, pp $s=200$ GeV, $1.2<|y|<2.2$
  - PHENIX, Au-Au $s_{NN}=200$ GeV, $1.2<|y|<2.2$
  - PHENIX, Cu-Cu $s_{NN}=200$ GeV, $1.2<|y|<2.2$

\[
\langle p_T \rangle \text{ (GeV/c)}
\]

\[
\langle N_{\text{part}} \rangle
\]
Evolution of J/$\psi$ transverse momentum spectra – evidence for thermalization and charm quark coalescence at the phase boundary

Inclusive J/$\psi$

- $\text{ALICE, pp } \sqrt{s}=2.76 \text{ TeV, } 2.5<y<4$
- $\text{ALICE, Pb-Pb } \sqrt{s_{NN}}=2.76 \text{ TeV, } 2.5<y<4$
- $\text{PHENIX, pp } \sqrt{s}=200 \text{ GeV, } 1.2<|y|<2.2$
- $\text{PHENIX, Au-Au } \sqrt{s_{NN}}=200 \text{ GeV, } 1.2<|y|<2.2$
- $\text{NA60, p-A } \sqrt{s}=17.3 \text{ GeV, } 0<y<1$
- $\text{NA50, Pb-Pb } \sqrt{s_{NN}}=17.3 \text{ GeV, } 0<y<1$