introduction and perspective
heavy quark production from pp to AA collisions
quarkonia and deconfinement
a note on Debye screening
summary and outlook
Why open heavy flavor?

- transport coefficient for heavy quarks

  energy loss of heavy quark (radiative energy loss should be suppressed due to large mass (1.2 GeV);

  in-medium gluon radiation into angles $< m_q/E_q$ suppressed (Dokshitzer and Kharzeev)

  Casimir factor $C_q = 4/3$ vs $C_{\text{gluon}} = 3$

- need total charm cross section for understanding of charmonia (ccbar states)

- in pp and pA charm physics interesting on it's own right, tests pQCD and parton distribution functions as well as nuclear effects
Open heavy flavor production and the QGP

1. \( m_q \gg \Lambda_{\text{QCD}} \) charm quark production is independent of the medium formed in the collision (see above)

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 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

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

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
Glue radiation by a quark traversing a medium


we get for the probability of radiation of a gluon with energy by a quark with mass M and energy E

$$dP = \frac{\alpha_s}{\pi} \frac{C_F}{\omega} \frac{d\omega}{\omega} \frac{k_\perp^2 \, dk_\perp^2}{(k_\perp^2 + \omega^2 \theta_0^2)^2}, \quad \theta_0 \equiv \frac{M}{E}$$

$$k_\perp^2 \approx \sqrt{\hat{q} \, \omega} \quad \hat{q} \equiv \rho \int \frac{d\sigma}{dq^2} \, q^2 \, dq^2 \quad C_F = \frac{N_c^2 - 1}{2N_c}$$

Here the density of scatterers in the medium is encoded in $q^\perp$.
'dead cone' effect for charm quarks

expect significant in-medium enhancement in $R_{AA}$ for D mesons relative to pions for $5 < p_T < 10$ GeV

not observed, see later

Figure 1: Ratio of gluon emission spectra off charm and light quarks for quark momenta $p_\perp = 10$ GeV (solid line) and $p_\perp = 100$ GeV (dashed); $x = \omega/p_\perp$. 
Production in hadronic collisions

because of large quark mass, pQCD should be applicable at all values of p_t
Production in hadronic collisions

reality is even more complicated, with ISR and FSR and fragmentation functions

picture from A. Beraudo, QM2014
Heavy ion data from the LHC

PbPb at $\sqrt{s_{NN}} = 2.76$ TeV ALICE, ATLAS, CMS

- 2010 about 9 $\mu$b$^{-1}$
- 2011 about 150 $\mu$b$^{-1}$ $\approx 10^9$ collisions

pPb at $\sqrt{s_{NN}} = 5.02$ TeV ALICE, ATLAS, CMS, LHCb

- 2013 about 30 nb$^{-1}$ $\approx 5 \cdot 10^{10}$ collisions

total of about 12 weeks in 3 years of running

pp reference at $\sqrt{s}=7$ TeV ALICE

- 2010 about 5 nb$^{-1}$ min bias and 16.5 nb$^{-1}$ muon trigger

pp ref. at $\sqrt{s}=2.76$ TeV ALICE

- 2011 about 1.1 nb$^{-1}$ min bias and 19 nb$^{-1}$ muon trigger
Charm production in pp and pQCD ALICE data

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

Mid-y cross sections:

\[ \frac{d\sigma^{D^0}}{dy} = 516 \pm 41 \text{(stat.)}^{+69}_{-175} \text{(syst.)} \pm 18 \text{(lumi.)} \pm 7 \text{(BR)}^{+120}_{-37} \text{(extr.)} \mu b, \]

\[ \frac{d\sigma^{D^+}}{dy} = 248 \pm 30 \text{(stat.)}^{+52}_{-92} \text{(syst.)} \pm 9 \text{(lumi.)} \pm 5 \text{(BR)}^{+57}_{-18} \text{(extr.)} \mu b, \]

\[ \frac{d\sigma^{D^{*+}}}{dy} = 247 \pm 27 \text{(stat.)}^{+36}_{-81} \text{(syst.)} \pm 9 \text{(lumi.)} \pm 4 \text{(BR)}^{+57}_{-16} \text{(extr.)} \mu b. \]
Charm production in pp and pQCD
LHCb data

for a recent summary of data and pQCD predictions see:
Beraudo, 1509.04530
Guzzi, Geiser, Rizatdinova, 1509.04582
Energy dependence of total open charm cross section

- 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 $2 \pm 0.5$ above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL
Beauty cross section in pp and ppbar collisions

rapidity density of beauty cross section in excellent agreement with pQCD

total bbar cross section
\[ \sigma_{b\bar{b}} = 280 \pm 23 \text{(stat)} \pm 81 \text{(sys)} \pm 7 \text{(extr)} \pm 10 \text{(BR)} \text{ \mu b} \]

well consistent with ALICE measurement of J/psi from displaced secondary vertices

\[ \sigma_{b\bar{b}} = 282 \pm 74 \text{(stat)} \pm 58 \text{(sys)} \pm 8 \text{(extr)} \text{ \mu b} \]

compared to FONLL

\[ \sigma_{b\bar{b}} = 259 \pm 120 \text{ \mu b} \]
Now on to Pb-Pb collisions
reminder of parton energy loss in the hot medium
collisions of pPb as baseline for PbPb

p Pb data consistent with unity

strong suppression in nuclear collision is final state (QGP) effect

now on to charm quarks

n.b. Baseline for PbPb is min. bias pPb
A surprize?

The energy loss of g, u, d, s partons is very similar to that of c quarks. Where is the dead cone effect?
comparison of $c$ and $b$-quark energy loss with theory

above 6.5 GeV/c in PbPb collisions, $b$-quark suppression established by CMS via $J/\psi$ from B-decay

non-prompt $J/\psi$ less suppressed than $D$ in line with expectation $\Delta E_c > \Delta E_b$

mean $p_t$ of $D$ and contributing $B$ mesons as well as rapidity range are similar

pQCD based calculation of energy loss in QGP reproduces data well (M. Djordjevic PLB 734 (2014) 286)

other calculations (TAMU, BAMPS, WHDG, MC@sHQ+EPOS2) give similar trends

reality is more complicated than 'simple' dead cone effect
Comparison of ALICE and CMS data on non-prompt J/psi with various model predictions
fireball expands collectively like an ideal fluid

\[
dN/d\phi = 1 + 2 V_2 \cos 2(\phi - \psi) + \ldots
\]

hydrodynamic flow characterized by azimuthal anisotropy coefficient \( V_2 \)
+ higher orders

do charm quarks participate in the flow?
large flow effects seen in D meson production
...and in leptons from heavy flavor decays

[Graphs showing charged particle yields and v2 distributions for heavy flavor decays in Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV for 10-20% and 20-40% centrality classes.]
comparison of $R_{AA}$ and $v_2$ data to model predictions

simultaneous description still a challenge for many models
can yield of charmed hadrons be described in a thermal approach?
can this work also for D mesons?

charm quarks are not in chemical equilibrium but:

previous results have provided a good basis for thermal equilibration

assuming all charm quarks are produced in initial hard collisions but equilibrate thermally (pbm, J. Stachel, Phys. Lett. B490 (2000) 196) the yield of all charmed hadrons can be predicted
Comparison of D-meson yields among experiments and to models

canonical statistical model (SHM) with $T=164$ MeV, $V=30\pm10$ fm$^3$, strangeness fugacity $0.60\pm0.04$

Andronic, Beutler, Braun-Munzinger, Redlich, Stachel, PLB 678 (2009) 350

pp and e+e- collisions only up to now, PbPb results should come from LHC Run2

- very similar number LHCb in B-sector: $f_s/f_d = 0.267+0.021-0.020$
- within current errors no evidence for lifting of strangeness suppression at LHC energy
summary I: open heavy flavor

• heavy quark production in pp collisions at LHC energy: pQCD rules

• min bias pPb collisions: no medium effects in $R_{ppb}$

• $R_{AA}$ for D mesons $= R_{AA}$ for pions within uncertainties

• $R_{AA}$ for B $> R_{AA}$ for D consistent with some model predictions but not 'simple dead cone' effect

• charm quarks follow the hydro flow of pions

• first evidence for thermal equilibration of charm quarks – are there any hints in the b sector

significant advances expected in LHC Run2 currently running
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

production probability scales with $N(\text{ccbar})^2$

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

n.b. at collider energies there is a complete separation of time scales $t_{\text{coll}} \ll t_{\text{QGP}} < t_{\text{Jpsi}}$

implanting charmonia into QGP is an inappropriate notion

this issue was already anticipated by Blaizot and Ollitrault in 1988

See also: Heavy quark bound states in a quark-gluon plasma: dissociation and recombination

Jean-Paul Blaizot, Davide De Boni, Pietro Faccioli, Giovanni Garberoglio

color screening removes bound states

will this happen at $T_c$ or only when deep inside the QGP?
quarkonium as a probe for deconfinement at the LHC
the statistical (re-)generation picture


charmonium enhancement as fingerprint of color screening and deconfinement at LHC energy

decision on regeneration vs sequential suppression from LHC data

Picture:
H. Satz 2009
less suppression when increasing the energy density

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
rapidity dependence

note: energy density largest at y = 0
statistical hadronization model
all J/psi production at the phase boundary

ALICE data and evolution from RHIC to LHC energy described quantitatively
comparison of transverse momentum spectra at RHIC and LHC

dramatic and qualitative difference between RHIC and LHC results
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
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
In the QGP, the screening radius $r_{\text{Debye}}(T)$ decreases with increasing $T$. If $r_{\text{Debye}}(T) < r_{\text{charmonium}}$ the system becomes unbound $\rightarrow$ suppression compared to charmonium production without QGP. The screening radius can be computed using potential models or solving QCD on the lattice.
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:

\[ \frac{m_{\text{Debye}}}{T} > 3.3 \]

at $T = 0.15$ GeV

J/psi data on color screening at the phase boundary are close to predictions from Lattice QCD
the bottomonium puzzle (I)

New results from LHCb: feeding into $Y(1s)$ only about 30% → $Y(1s)$ for pp 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

+ $R_{AA} (Y(1S)) = 0.30 \pm 0.05 \pm 0.04$
(at forward rapidity)

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

New results from LHCb: feeding into $Y(1s)$ only about 30% → $Y(1s)$ for pp 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 Debye screening suppression scenarios.

Measurements at large rapidity (ALICE muon arm) are crucial!
the bottomonium puzzle (III): $R_{AA}$ constant as function of $p_T$ up to 20 GeV

**γ production in PbPb**

New data with 20 times more pp data

- Centrality integrated results: $γ$ states suppressed sequentially (0-100%)
  
  $R_{AA}[γ(1S)] = 0.425 \pm 0.029 \pm 0.070$
  
  $R_{AA}[γ(2S)] = 0.116 \pm 0.028 \pm 0.022$
  
  $R_{AA}[γ(3S)] < 0.14$ at 95% CL

- $γ$ suppression does not strongly depend on kinematics.
the bottomonium puzzle (IV):

\[ R_{AA} \ Y(2s) << R_{AA} \ J/psi \]

at mid-rapidity and for central collisions:

\[ R_{AA} \ Y(2s) < 0.16 \]

\[ R_{AA} \ J/psi > 0.65 \]

but radius and binding energy of \( Y(2s) \)
and \( J/psi \) are very similar

the observed suppression pattern is inconsistent with Debye screening
summary II

- 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 $T_c$
  charm quarks deconfined in QGP

cartoon Helmut Satz, 2009

SPS  RHIC  LHC
outlook

Run2 at the LHC has started in June 2015

LHC close to full design energy $\sqrt{s} = 13$ TeV for pp
$\sqrt{s_{NN}} = 5.1$ TeV for Pb—Pb

Pb-Pb interaction rate up to 20 kHz (factor 4 increase compared to Run1 and factor 3 beyond design luminosity)

ALICE detector adapted to new running conditions

plan for order of magnitude increase in data at higher energy and significantly improved precision
Run 3: upgrade overview

- The ALICE upgrade strategy is outlined in the Letter Of Intent
  - CERN-LHCC-2012-012 ; LHCC-I-022
  - http://cds.cern.ch/record/1475243

- Operate ALICE at high luminosity ($\mathcal{L}=6\times10^{-27}$ cm$^{-2}$s$^{-1}$) and record all minimum bias events
  - 50 kHz in Pb-Pb collisions $\rightarrow$ 100 x larger than the current read-out rate
  - 5 overlapping events in TPC drift volume $\rightarrow$ TPC can not run in triggered mode

- The TPC upgrade is described in a Technical Design Report
Upgrade of the Time Projection Chamber
Technical Design Report

Abstract
The ALICE physics program after LHC is mostly devoted to high precision measurements of hard probes (heavy-flavour hadrons, quarkonia, photons and jets). The approved strategy of the associated upgrade programme is reported in the ALICE Letter of Intent [1, 2]. The present Technical Design Report describes the Muon Forward Tracker (MFT). The MFT will allow ALICE to extend the precision measurements of the QGP fundamental properties towards the forward rapidity region. The MFT will substantially improve the present performance of the MUON spectrometer and eliminate its limitations on the measurement of open charm, open beauty, charmonium and low mass vector mesons. The MFT consists of two half-cylinders containing 5 detection half-disks placed along the beam axis between −460 mm to −768 mm away from the average position of the ALICE interaction point. The MFT acceptance coverage in pseudo-rapidity is −36 < η < −2.5. The basic detection element is a silicon pixel sensor, developed by the ALICE pixel groups for both ITS and MFT. The 806 silicon pixel sensors of the MFT will be assembled, using the same technology as the one used for the ITS assembly, on 280 ladders of 1, 2, 3, 4 or 5 sensors each. A read-out electronics, common to both ITS and MFT, is developed jointly by the two projects.

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The QGP phase transition drives chemical equilibration for small $\mu_b$

- Near phase transition particle density varies rapidly with $T$.
- For small $\mu_b$, reactions such as $\text{KKK}\pi\pi \rightarrow \Omega N_{\text{bar}}$ bring multi-strange baryons close to equilibrium.
- Equilibration time $\tau \propto T^{-60}$!
- All particles freeze out within the same very narrow temperature window.

are there similar mechanisms for large $\mu_b$?

pbm, J. Stachel, C. Wetterich
nucl-th/0311005
The thermal model and loosely bound, fragile objects

successful description of production yields for d, d_bar, 3He hypertriton, ...
implies no entropy production after chemical freeze-out

hypertriton binding energy is 130 keV << T_chem = 156 MeV

use relativistic nuclear collision data and thermal model predictions to search for exotic objects


see also Pal and Greiner, Phys. Rev. C87 (2013) 034608
The thermal model and loosely bound, fragile objects

successful description of production yields for $d$, $d_{\bar{b}}$, $3He$ hypertriton, …
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see also Pal and Greiner, Phys. Rev. C87 (2013) 034608
Some historical context on cluster production in relativistic nuclear collisions


here the provocative statement was made that cluster formation probability is determined by the entropy of the fireball in its compressed state, i.e. for example:
entropy/baryon is proportional to -\ln(d/p)

ENTROPY AND CLUSTER PRODUCTION IN NUCLEAR COLLISIONS

László P. CSERNAI* and Joseph I. KAPUSTA


Very concise summary, including an elucidation of the relation between thermal fireball model and coalescence model
In conclusion, the fireball model based on thermal and chemical equilibrium describes cluster formation well, where measured. It gives results similar in magnitude to the predictions of the coalescence model developed recently [6] to estimate production probabilities for light nuclear fragments (p, d, t, α ...) and for strange hadronic clusters (such as the H dibaryon) in Au-Au collisions at the AGS. Predicted yields for production of strange matter with baryon number larger than 10 are well below current experimental sensitivities.
Thermal vs coalescence model predictions for the production of loosely bound objects in central Au—Au collisions

<table>
<thead>
<tr>
<th>Particles</th>
<th>Thermal Model</th>
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<td>$^{20}\text{St}^{−16}$</td>
<td>$9.6 \cdot 10^{-31}$</td>
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deuterons and anti-deuterons also well described at AGS energy

14.6 A GeV/c central Si + Au collisions and GC statistical model

dynamic range: 9 orders of magnitude! No deviation
Thermal model and production of light nuclei at AGS energy

data cover 10 oom!
addition of every nucleon
-> penalty factor $R_p = 48$
but data are at very low pt
use m-dependent slopes following systematics up to deuteron
-> $R_p = 26$

GC statistical model:
$R_p \approx \exp[(m_n \pm \mu_b)/T]$
for $T=124$ MeV and $\mu_b = 537$ MeV
$R_p = 24$ good agreement
also good for antideuterons:
data: $R_p = 2 \pm 1 \cdot 10^5$ SM: $1.3 \cdot 10^5$
Production of light anti-nuclei at LHC energy

penalty factor $\exp\{-m/T\} \approx 330$
Cluster production and entropy

$$S = s \ V = -\text{const} \ \ln(d/p)$$

Interacting hadron resonance gas meets lattice QCD

arXiv:1201.0693

A. Andronic\textsuperscript{a,b}, P. Braun-Munzinger\textsuperscript{a,c,d,e}, J. Stachel\textsuperscript{f}, M. Winn\textsuperscript{f}
energy dependence of d/p ratio and thermal model prediction

agreement between thermal model calculations and data from Bevalac/SIS18 to LHC energy
loosely bound objects are formed at chemical freeze-out very near the phase boundary

implies that chemical freeze-out is followed by an isentropic expansion

no appreciable annihilation in the hadronic phase
loosely bound objects are formed at chemical freeze-out very near the phase boundary

implies that chemical freeze-out is followed by an isentropic expansion

no appreciable annihilation in the hadronic phase
The size of loosely bound molecular objects

Examples: deuteron, hypertriton, XYZ 'charmonium states, molecules near Feshbach resonances in cold quantum gases

Quantum mechanics predicts that a bound state that is sufficiently close to a 2-body threshold and that couples to that threshold through a short-range S-wave interaction has universal properties that depend only on its binding energy. Such a bound state is necessarily a loosely-bound molecule in which the constituents are almost always separated by more than the range. One of the universal predictions is that the root-mean-square (rms) separation of the constituents is \((4\mu E_X)^{-1/2}\), where \(E_X\) is the binding energy of the resonance and \(\mu\) is the reduced mass of the two constituents. As the binding energy is tuned to zero, the size of the molecule increases without bound. A classic example of a loosely-bound S-wave molecule is the deuteron, which is a bound state of the proton and neutron with binding energy 2.2 MeV. The proton and neutron are correctly predicted to have a large rms separation of about 3.1 fm.

Artoisenet and Braaten,
arXiv:1007.2868
The deuteron as a loosely bound object

Mass = 1875 MeV
B.E. = 2.23 MeV
rms radius = 3 fm > range of potential

$R = 2.1 \text{ fm}$
$V_0 = 35 \text{ MeV}$
The Hypertriton

mass = 2.990 MeV

B.E. = 0.13 MeV

molecular structure: \((p+n) + \Lambda\)  

2-body threshold: \((p+p+n) + \pi^- = {}^3\text{He} + \pi^-\)

\[\text{rms radius} = (4 \text{ B.E. } M_{\text{red}})^{-1/2} = 10.3 \text{ fm}\]

\(\text{rms separation between } d \text{ and } \Lambda\)

in that sense: hypertriton = \((p \ n \ \Lambda)\)

= \((d \ \Lambda)\) is the ultimate halo state

yet production yield is fixed at 156 MeV

temperature \((\text{about } 1000 \times \text{E.B.})\)
The X(3872)

mass is below threshold of $(D^{*0} D^0_{\text{bar}})$ by $(0.42 \pm 0.39)$ MeV

$rms\ separation = 3.5 - 18.3\ fm$  structure:

$$D^{*0} \bar{D}^0 + D^0 \bar{D}^{*0}$$

should be able to predict the X(3872) production probability in pp collisions at LHC energy with an accuracy of about 30%, uncertainty is due to not very precisely known number of charm quarks

result ready shortly
where are we?

since QM2012, discrepancy between protons and thermal fit went from 7 sigma to 2.9 (2.7) sigma

T went from 152 to 156.5 MeV

fit without protons yields slightly higher T = 158 MeV, driven by hyperons
where are we?

since QM2012, discrepancy between protons and thermal fit went from 7 sigma to 2.9 (2.7) sigma

T went from 152 to 156.5 MeV

fit without protons yields slightly higher $T = 158$ MeV, driven by hyperons
important note: corrections for weak decays

All ALICE data do not contain hadrons from weak decays of hyperons and strange mesons – correction done in hardware via ITS inner tracker.

The RHIC data contain varying degrees of such weak decay hadrons. This was on average corrected for in previous analyses.

In light of high precision LHC data the corrections done at RHIC may need to be revisited.
treatment of weak decays

fraction of yield from weak decays

biggest correction for protons
done in hardware (vertex cut) at ALICE
software corrections at all lower energies
Re-evaluation of fits at RHIC energies – special emphasis on corrections for weak decays

Note: corrections for protons and pions from weak decays of hyperons depend in detail on experimental conditions

RHIC hadron data all measured without application of Si vertex detectors

In the following, corrections were applied as specified by the different RHIC experiments
Au+Au central at 200 GeV, all experiments combined

T = 162 MeV

Data:
- STAR
- PHENIX
- BRAHMS

Thermal model fit, $\chi^2/N_{\text{df}} = 35.8/12$
$T = 162\text{ MeV}$, $v_b = 24\text{ MeV}$, $V = 2100\text{ fm}^3$

Peter Braun-Munzinger
could it be weak decays from charm?

weak decays from charmed hadrons are included in the ALICE data sample

at LHC energy, cross sections for charm hadrons is increased by more than an order of magnitude compared to RHC

first results including charm and beauty hadrons indicate changes of less than 3%, mostly for kaons

not likely an explanation
could it be incomplete hadron resonance spectrum?

Note: because of baryon conservation, adding more baryon resonances will decrease in the model the p/\pi ratio

An \(N^*\) will decay dominantly into 1 \(N\) + a number (depending on the \(N^*\) mass) of pions

Same effect seen in \(K/\pi\) ratio because of strangeness conservation

could it be proton annihilation in the hadronic


- need to incorporate detailed balance, $5\pi \rightarrow p p_\text{bar}$
  not included in current Monte Carlo codes (RQMD)

- taking detailed balance into account reduces effect strongly, see Rapp and Shuryak 1998

  and recent reanalysis, by Pan and Pratt, arXiv:

- agreement with hyperon data would imply strongly reduced hyperon annihilation cross section with anti-baryons → no evidence for that
centrality dependence of proton/pion ratio

different centrality dependence for RHIC and LHC is a real puzzle
- does not support annihilation picture
- is it real? physics origin?
the 'proton anomaly' and production of light nuclei

can the measurement of d, t, 3He and 4He settle the issue?
what about hypertriton?

important to realize: production yield of deuterons is fixed at $T = T_{\text{chem}} = 156 \text{ MeV}$ even if $E_B(d) = 2.23 \text{ MeV}$!

entropy/baryon is proportional to $-\ln(d/p)$ and is conserved after $T_{\text{chem}}$

good agreement with LHC d and hyper-triton yield implies: there is no shortage of protons and neutrons at chemical freeze-out, inconsistent with annihilation scenario
Nuclear collisions, open and hidden charm hadrons, and QCD

Hadrons containing charm quarks can also be described provided open charm cross section is known.

Recent ALICE data imply Debye screening near $T_c$ for charmonium and deconfined heavy quarks, see talk by Johanna Stachel.

Could it be that increasing number of charm quarks changes (lowers) $T_c$? An issue for the FCC!
In the QGP, the screening radius $r_{\text{Debye}}(T)$ decreases with increasing $T$. If $r_{\text{Debye}}(T) < r_{\text{charmonium}}$ the system becomes unbound $\rightarrow$ suppression compared to charmonium production without QGP. The screening radius can be computed using potential models or solving QCD on the lattice.
Charmonium production at LHC energy: deconfinement, and color screening

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

- Debye screening length < 0.4 fm near $T_c$

- Combination of uncorrelated charm quarks into J/psi → 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: $m_{Debye}/T > 3.3$

at $T = 0.15$ GeV
energy dependence of d/p ratio and thermal model prediction

agreement between thermal model calculations and data from Bevalac/SIS18 to LHC energy
ALICE TRD Detector complete Nov. 26, 2014

first fully operational barrel TRD
project coordination: Heidelberg
Quarkonia:
\textbf{heavy} quark bound states \textbf{stable} under strong decay

\textbf{heavy}: charm \((m_c \simeq 1.3 \text{ GeV})\) or beauty \((m_b \simeq 4.7 \text{ GeV})\)

\textbf{stable}: \(M_{c\bar{c}} \leq 2M_D\) and \(M_{b\bar{b}} \leq 2M_B\)

\textbf{heavy} quarks \(\Rightarrow\) quarkonium spectroscopy via
non-relativistic potential theory

Schrödinger equation
\[
\left\{ 2m_c - \frac{1}{m_c} \nabla^2 + V(r) \right\} \Phi_i(r) = M_i \Phi_i(r)
\]

confining ("Cornell") potential \(V(r) = \sigma \ r - \frac{\alpha}{r}\)

string tension \(\sigma \simeq 0.2 \text{ GeV}^2\), gauge coupling \(\alpha \simeq \pi/12\)

\(\Rightarrow\) quarkonium masses \(M_i\) and radii \(r_i\)
Complete angular (pseudo-rapidity) distributions

complete angular distr. between 1 and 179 deg

excellent pseudo-rapidity coverage
Charged particle multiplicity in pp, pPb and central PbPb collisions


increase with beam energy significantly steeper than in pp

pPb similar to pp inelastic

can the fireball formed in central nuclear collisions be considered matter in equilibrium?
Mesonic correlation functions at finite temperature and density in the Nambu-Jona-Lasinio model with a Polyakov loop


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