Quarkonia as probes of deconfinement at the LHC - experimental data and phenomenology

- introduction
- charmonium data
  (run1 completely analyzed, first run2 results)
- pPb data
- bottomonium

Johanna Stachel, Universität Heidelberg
Seminar on Physics of the Quark-Gluon Plasma
Heidelberg, July 6, 2016
charmonia as a probe of deconfinement

- 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

- new insight (Braun-Munzinger, J.S. 2000): QGP screens all charmonia (as proposed by Matsui and Satz), but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfinement

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

what happens to deconfined charm quarks as beam energy increases at colliders?

as more and more charm quarks produced, probability for $c$ and $\bar{c}$ to hadronize into $J/\psi$ grows quadratically

low energy: few $c$-quarks per collision  $\rightarrow$ suppression of $J/\psi$

high energy: many $``$  $``$  $\rightarrow$ enhancement $``$

reversal unambiguous signature for QGP!
needed input for statistical hadronization and for transport approach: total charm cross section

standard approach: reconstruct charmed hadrons from their weak decay products, try to cover spectral range down to 0, obtain charm cross section assuming some known fragmentation functions

difficulties:
- reach to very low $p_t$ - to a lesser extent, rapidity coverage, extrapolation leads to systematic errors
- modifications in PbPb vs pp due to different parton distributions, use min. bias pPb as intermediate step, proxy for cold nuclear medium, largest contribution to syst.
- modifications due to QGP medium (thermal charm), still minor contr.

no medium effect

classic charm conservation equation

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

medium effects on charmed hadrons affect redistribution of charm (among hadrons and in momentum), but not overall cross section
First measurements of open charm down to $p_t = 0$ at $y=0$

very hard struggle to deal with (irreducible) combinatorial background, very recently successful in pp and pPb
charm production in pp and pQCD at forward rapidity
LHCb data

for a recent summary of data and pQCD predictions see:
Guzzi, Geiser, Rizatdinova, 1509.04582 and Beraudo, 1509.04530
additional constraint of gluon PDF in particular at low x (down to 5 10^{-6})
Currently best measurement of the total ccbar cross section in pp at LHC

- good agreement between ALICE, ATLAS and LHCb
- ALICE and LHCb at 7 TeV measurement down to zero $p_t$,
much reduced syst. error
- data at upper edge of NLO pQCD band but well within uncertainty
- beam energy dependence follows well NLO pQCD

arXiv: 1605.07569
Consequences of charm cross section for $J/\psi$ production at LHC energies

Open charm is natural and essential normalization precision measurement needed.

LHC 2.76 TeV including shadowing (more below)

Beauty cross section in pp and ppbar collisions

rapidity density of beauty cross section in excellent agreement with pQCD

total bbar cross section
\[ \sigma_{b\bar{b}} = 280 \pm 23 \text{(stat)}^{+81}_{-79} \text{(sys)}^{+7}_{-8} \text{(extr)} \pm 10 \text{(BR)} \mu b \]

well consistent with ALICE measurement of J/$\psi$ from displaced secondary vertices
\[ \sigma_{b\bar{b}} = 282 \pm 74 \text{(stat)}^{+58}_{-68} \text{(sys)}^{+8}_{-7} \text{(extr)} \mu b \]

compared to FONLL
\[ \sigma_{b\bar{b}} = 259^{+120}_{-96} \mu b \]
Expectation for LHC data on decision of regeneration vs. sequential suppression

Picture:
H. Satz 2009
photoproduction in ultra-peripheral PbPb collisions – excellent signal to background
very good understanding of line shape
(probes nuclear gluon shadowing, not discussed here)
most challenging: central PbPb collisions in spite of formidable combinatorial background (true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible
Johanna Stachel

melting scenario not observed
rather: enhancement with increasing energy density!
(from RHIC to LHC and from forward to mid-rapidity)
J/ψ and statistical hadronization production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties. Transport models also in line with $R_{AA}$ but different open charm cross section used (0.5-0.75 mb TAMU and 0.65-0.8 mb Tsinghua vs. 0.3-0.4 mb SHM) more below. Main uncertainties for models: open charm cross section, shadowing in Pb.
Rapidity dependence of $R_{AA}$

yield in PbPb peaks at mid-$y$ where energy density is largest

for statistical hadronization $J/\psi$ yield proportional to $N_c^2$ - higher yield at mid-rapidity predicted in line with observation (at RHIC and LHC)
$p_t$ dependence of $R_{AA}$ supports dominance of new production mechanism at LHC at small $p_t$

$p_t$ dependence at LHC opposite to RHIC and SPS supports argument: thermalized deconfined charm quarks hadronize into $J/\psi$
p_t dependence of $R_{AA}$

what effects to expect?
- statistical hadronization in p_t range where charm quarks are reasonably thermal
- modification of spectrum relative to pp due to radial flow
- suppression in $R_{AA}$ due to charm quark energy loss (see D mesons)
$p_T$ dependence of $R_{AA}$

is high $p_T$ part indicative of the same charm quark energy loss seen for D's out to what $p_T$ is statistical hadronization/regeneration relevant?
charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

- 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

first observation of $J/\psi$ $v_2$

in line with expectation from statistical hadronization
J/ψ flow compared to models including (re-) generation


$v_2$ of J/ψ consistent with hydrodynamic flow of charm quarks in QGP and statistical (re-)generation
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

\[ L_{\text{int}} = 52 \mu\text{b}^{-1} \]
at low $p_T$ yield in nuclear collisions above pPb collisions

$J/\psi$ production **enhanced** in nuclear collisions **over mere shadowing effect**
use these data to extract relevant shadowing for J/ψ production in PbPb:
for mid-y suppression by 0.56 ± 0.20
(all data + consult R.Vogt)
for y = 2.5-4.0 " 0.71 ± 0.10
(forward/backward data + consult R.Vogt)
crucial input for both statistical hadronization model and transport models for destruction and regeneration of charmonia

sofar, no measurement of the cross section for PbPb

proxy: take pp cross section at 7 TeV and scale to 2.76 TeV using FONLL $\sqrt{s}$ dependence

apply shadowing correction derived from pPb data


\[
\begin{align*}
y&=2.0-4.5 \text{ and 7 TeV } \quad \frac{d\sigma}{dy}(c\bar{c}) &= 0.568 \pm 0.054 \text{ mb} \\
e&xtrapolate \text{ to } 2.76 \text{ TeV and } y=2.4-4.0 \quad \frac{d\sigma}{dy}(c\bar{c}) &= 0.290 \pm 0.028 \text{ mb} \\
&\text{apply shadowing } (x 0.71 \pm 0.10) \quad \frac{d\sigma}{dy}(c\bar{c}) &= 0.206 \pm 0.035 \text{ mb}
\end{align*}
\]

baseline for PbPb

ALICE: arXiv:1605.07569, D-measurement down to pt=0

\[
\begin{align*}
|y| &\leq 0.5 \text{ and 7 TeV } \quad \frac{d\sigma}{dy}(c\bar{c}) &= 0.988 + 0.150 - 0.221 \text{ mb} \\
&\text{extrapolate to } 2.76 \text{ TeV } \quad \frac{d\sigma}{dy}(c\bar{c}) &= 0.588 + 0.089 - 0.132 \text{ mb} \\
&\text{apply shadowing } (x 0.56 \pm 0.20) \quad \frac{d\sigma}{dy}(c\bar{c}) &= 0.329 + 0.128 - 0.138 \text{ mb}
\end{align*}
\]

baseline for PbPb
newest results with updated charm cross section

Pb-Pb, \( \sqrt{s_{NN}} = 2.76 \text{ TeV}, 2.5 < y < 4.0 \)
- ALICE (±15% syst. unc.)

Pb-Pb, \( \sqrt{s_{NN}} = 5.02 \text{ TeV}, 2.5 < y < 4.0 \)

Statistical Hadronization Model
- \( d\sigma_{cc}/dy = 0.206 \text{ mb} \)
- \( d\sigma_{cc}/dy \pm 0.045 \text{ mb} \)

Statistical Hadronization Model
- \( d\sigma_{cc}/dy = 0.322 \text{ mb} \)
- \( d\sigma_{cc}/dy \pm 0.070 \text{ mb} \)

prediction for run2

to constrain models more: need precise ccbar cross section for PbPb
for \( \sqrt{s_{NN}} = 5 \text{ TeV} \) expect increase for central collisions by about 10-15%
transport models should use this same ccbar cross section

Johanna Stachel
J/ψ in PbPb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

$R_{AA}^{0-90\%}(5.02 \text{ TeV}) / R_{AA}^{0-90\%}(2.76 \text{ TeV}) = 1.13 \pm 0.02(\text{stat}) \pm 0.18(\text{syst})$

increase of J/ψ $R_{AA}$ for all centralities and over large range of $p_t$ (but within 1 $\sigma$)
J/ψ $R_{AA}$ at $\sqrt{s_{NN}} = 5.02$ TeV compared to stat. hadronization and transport models.
excited charmonia crucial to distinguish between models

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

for statistical hadronization need to see suppression by Boltzmann factor $\chi_c$ even bigger difference

expected ALICE performance muon arm run2 and run3
suppression of Upsilon states

\[ R_{AA}(Y(1S)) = 0.425 \pm 0.029 \pm 0.070 \]
\[ R_{AA}(Y(2S)) = 0.116 \pm 0.028 \pm 0.022 \]
\[ R_{AA}(Y(3S)) < 0.14 \text{ at 95\% CL} \]

\[ R_{AA}(Y(1S)) = 0.30 \pm 0.05 \pm 0.04 \text{ (at forward rapidity)} \]

another puzzle: radius of Upsilon(2S) similar to radius J/ψ, but at mid-\( y \) \( R_{AA} = 0.12 \) vs 0.70

not consistent with just excited state suppression (LHCb data: only 25% feed-down in pp at LHC)
the Upsilon could also come from statistical hadronization

SHM/thermal model: Andronic et al.

in this picture, the entire Upsilon family is formed at hadronization but: need to know first – do b-quark thermalize at all? spectra of B - total b-cross section in PbPb
Upsilon $R_{AA}$ rapidity dependence

CMS 20 times more statistics in pp than previously published

M. Jo, CMS-HIN-15-001

$R_{AA}$ still peaked at mid-$y$ like for $J/\psi$
not in line with collisional damping in expanding medium (Strickland)
First look at Upsilon at $\sqrt{s_{NN}} = 5.02$ TeV

\[ R_{AA}^{0-90\%}(5.02 \text{ TeV}) / R_{AA}^{0-90\%}(2.76 \text{ TeV}) = 1.3 \pm 0.2(\text{stat}) \pm 0.2(\text{syst}) \]
J/ψ formation via statistical hadronization at $T_c$ implies experimental determination of Debye length (mass) and temperature $\lambda_D < 0.4 \text{ fm at } T = 156 \text{ MeV}$ or $\omega_D/T > 3.3$

can compare to theory:

quite ok

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 $T_c \sim 190 \text{ MeV}$. 

- lots of new experimental data
- clear indication of new production mechanism for charmonia at LHC supported by yields, spectra, rapidity distribution, v2
- data consistent with statistical hadronization model and transport model approaches
- limitation in interpretation:
  - precision measurement of open charm cross section in PbPb statistics of charmonium observables
- bottomonium data not in line with simple screening picture statistical hadronization as well? Does beauty thermalize in QGP?

- expect significant progress from run2 and run3 LHC data from all experiments
backup
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.
heavy quark velocity in charmonium rest frame:
\[ v = 0.55 \text{ for J}/\psi \] see, e.g. G.T. Bodwin et al., hep-ph/0611002

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

see also:

**formation time of order 1 fm**

formation time is not short compared to QGP formation time

\[ \rightarrow \text{if J}/\psi \text{ forms at all, it does so in QGP} \]

\[ \rightarrow \text{if high color density QGP screens interaction, J}/\psi \text{ never forms until screening seizes} \]
quarkonium as a probe for deconfinement at the LHC
the statistical hadronization picture

charmonium enhancement as fingerprint of deconfinement at LHC energy
only free parameter: open charm cross section in nuclear collision
extension of statistical model to include charmed hadrons

- assume: all charm quarks are produced in initial hard scattering; number not changed in QGP
- hadronization at $T_c$ following grand canonical statistical model used for hadrons with light valence quarks (A. Andronic, P. Braun-Munzinger, J.S. or J. Cleymans, K. Redlich or F. Becattini) number of charm quarks fixed by a charm-balance equation containing fugacity $g_c$

$$N_{cc}^{direct} = \frac{1}{2} g_c V \left( \sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm} \right) + g_c^2 V \left( \sum_i n_{\psi_i}^{therm} \right) + \ldots$$

and for $N_c, \bar{c} << 1 \rightarrow$ canonical: $N_{cc}^{dir} = \frac{1}{2} g_c N_{oc}^{therm} \frac{I_1(g_c N_{oc}^{therm})}{I_0(g_c N_{oc}^{therm})}$

obtain: $N_D = N_D^{therm} \cdot g_c \cdot \frac{I_1}{I_0}$ and $N_{J/\psi} = N_{J/\psi}^{therm} \cdot g_c^2$ and same for all other charmed hadrons

additional input parameters (beyond $T, \mu_b$ fixed by fitting light flavor hadron yields:
- volume $V$ fixed by $dN_{ch}/d\eta$
- $N_{cc}^{direct}$ from pQCD as long as precision data are lacking
- causally connected region – use 1 unit $y$ (but tested a range)
- core-corona: treat overlap with the tails of nuclear density distribution as pp physics
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)
J/ψ and ψ(2S) spectrum in pp collisions


**inclusive J/ψ**

ALICE, inclusive J/ψ, 2.5<y<4
- 100 x \( \sqrt{s} = 13 \) TeV (prelim), \( L_{int} = 3.2 \text{ pb}^{-1} \pm 3.4\%
- 10 x \( \sqrt{s} = 8 \) TeV, \( L_{int} = 1.3 \text{ pb}^{-1} \pm 5\%
- 1 x \( \sqrt{s} = 7 \) TeV, \( L_{int} = 1.4 \text{ pb}^{-1} \pm 5\%
- 0.1 x \( \sqrt{s} = 5 \) TeV, \( L_{int} = 0.11 \text{ pb}^{-1} \pm 2.1\%
- 0.01 x \( \sqrt{s} = 2.76 \) TeV, \( L_{int} = 0.02 \text{ pb}^{-1} \pm 1.9\%

Systematic uncertainty
BR uncert.: 0.6 %

**inclusive ψ(2S)**

ALICE, inclusive ψ(2S), 2.5<y<4
- 1 x \( \sqrt{s} = 13 \) TeV (prelim), \( L_{int} = 3.2 \text{ pb}^{-1} \pm 3.4\%
- 0.1 x \( \sqrt{s} = 8 \) TeV, \( L_{int} = 1.3 \text{ pb}^{-1} \pm 5\%
- 0.01 x \( \sqrt{s} = 7 \) TeV, \( L_{int} = 1.4 \text{ pb}^{-1} \pm 5\%

Systematic uncertainty
BR uncert.: 11 %
Spectra of charmonia in pp collisions – data and pQCD

Johanna Stachel

Ruprecht-Karls-Universität Heidelberg
J/psi and statistical hadronization

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

\[ y = 2.4-4.0 \ \text{d} \sigma / \text{d}y = 0.206 \pm 0.035 \ \text{mb} \]

mid-y: \[ = 0.329 \pm 0.128 - 0.138 \ \text{mb} \]

Transport models should use same cross section!
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 QGP, part at hadronization, but different open charm cross section used
  (0.5-0.75mb TAMU and 0.65-0.8 mb Tsinghua vs. 0.3-0.4 mb SHM)
Charm quarks thermalize to large degree in QGP

strong energy loss of charm quarks

M. Djordjevic, arXiv:1307.4098:

equal $R_{AA}$ is a conspiracy of different fragmentation functions of light quarks, gluons, charm and different color factors in energy loss
models constrained by simultaneous fit of $R_{AA}$ and $v_2$
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
$p_t$ dependence of $R_{AA}$ supports dominance of new production mechanism at LHC at small $p_t$

$p_t$ dependence at LHC opposite to RHIC supports argument: thermalized deconfined charm quarks hadronize into $J/\psi$
comparison with (re-)generation models

good agreement lends further strong support to the 'full color screening and late J/psi production' picture
at LHC energy, mostly (re-) generation of charmonium, $p_t$ distribution exhibits features of strong energy loss and approach to thermalization for charm quarks
**Comparison of model predictions to RHIC data:**

**$R_{AA}$**: $J/\psi$ yield in AuAu / $J/\psi$ yield in pp times $N_{coll}$

- **Data**: PHENIX nucl-ex/0611020
- Additional 14% syst error beyond shown

Remark: y-dep opposite in 'normal Debye screening' picture; suppression strongest at midrapidity (largest density of color charges)
rapidity dependence of J/psi $R_{AA}$

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

Johanna Stachel
charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

ALICE data analysis in 4 centrality bins

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

- fit distribution with

\[ \nu_2(m_{\mu\mu}) = \frac{\nu_{2}^{\text{sig}}(m_{\mu\mu})}{\nu_{2}^{\text{bkg}}(m_{\mu\mu})} + \alpha(m_{\mu\mu})[1 - \alpha(m_{\mu\mu})] \]

where \( \alpha(m_{\mu\mu}) = \frac{S}{S+B} \) fitted to the mass spectrum

<table>
<thead>
<tr>
<th>Centrality</th>
<th>( \langle N_{\text{part}} \rangle )</th>
<th>EP resolution ( \pm ) (stat.) ( \pm ) (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>
$v_2$ of $J/\psi$ consistent with hydrodynamic flow of charm quarks in QGP and statistical (re-)generation

but:

CMS observes similar $v_2$ at higher $p_T$

this calls for more and better data
J/psi flow compared to models including (re-) generation

is high $p_t$ $v_2$ of the same origin? i.e. path length dependence of E-loss?
calls for more data
Feeding into Upsilon (1S)

$\Upsilon(1S)$ from all

- LHCb, $2.0 < y < 4.5$
- CMS, $|y| < 2.4$, $36 \text{ pb}^{-1}$
- CMS Preliminary
- ATLAS, $|y| < 1.2$

$\chi_b^{(1P)}$
$\chi_b^{(2P)}$
$\chi_b^{(3P)}$

$\Upsilon(2S)$
$\Upsilon(3S)$

$P_T^{\Upsilon(1S)} \text{ [GeV]}$
\( \psi(2S) \) in p-Pb

- **Backward**: suppression of \( \psi(2S) \), none for J/\( \psi \)
  - J/\( \psi \) maybe enhanced in central p-Pb
- **Forward**: suppression of \( \psi(2S) \) and J/\( \psi \) almost the same
- Comover interaction model qualitatively describes patterns

ALICE, arXiv:1603.02816
also see: LHCb, JHEP 03 (2016) 133
psi' to J/psi at LHC

- experimental errors still significant
- within errors consistent with low value in statistical model due to suppression with Boltzmann factor
- also consistent with larger values resulting from transport models
psi' to J/psi at LHC - not yet conclusive

- errors of data still large
- are we seeing a peculiar pt dependence? If so, could we see effect of collective flow of charm quarks before hadronization?
outlook – what ALICE can do in the future

LHC run1:
2 PbPb runs
- 2010 $O(10 \mu b^{-1})$
- 2011 $O(150 \mu b^{-1})$
luminosity reached $\mathcal{L}=2 \times 10^{26}$ cm$^{-2}$ s$^{-1}$ twice design lumi at this energy
1 pPb run
- 2012/2013 $O(30 \ nb^{-1})$

from 2/2013 until end of 2014 LS1: consolidation of LHC to allow full energy

LHC run2: 2015-2018 PbPb running at $\sqrt{s_{NN}} = 5.5$ TeV
to achieve approved initial goal of 1 nb$^{-1}$

late 2018 start LS2 – increase of LHC luminosity und experiment upgrade

LHC run3: 2020 onwards - expect $\mathcal{L}=6 \times 10^{27}$ cm$^{-2}$ s$^{-1}$ or PbPb interactions at 50 kHz
achieve for PbPb 10 nb$^{-1}$ corresponding to $8 \times 10^{10}$ collisions sampled
plus a low field run of 3 nb$^{-1}$ + pp reference running + pPb - a program for about 6 years
J/psi as probe of deconfinement

di-electrons statistics limited, 10 nb\(^{-1}\) will have huge effect
but also syst uncertainties will decrease with upgrade:
  will also add TRD for electron id - reduced comb background
thinner ITS reduced radiation tail
both affect signal extraction
spectral distribution is key to thermalization

at LHC shift of paradigm: more central collision → narrower momentum distribution

my interpretation: thermalization

but if charm quark thermalize, their spectral distributions should also reflect collective flow of liquid
situation even more dramatic for P-states

$pA$ and $\pi A$ data on average factor 7 above statistical model prediction

Transport model (Rapp)

outlook open heavy flavor – LHC run3

new high performance ITS plus rate increase (TPC upgrade)
## Physics Reach after ALICE Upgrade

<table>
<thead>
<tr>
<th>Topic</th>
<th>Observable</th>
<th>Approved (1/\text{nb delivered, 0.1/\text{nb m.b.}})</th>
<th>Upgrade (10/\text{nb delivered, 10/\text{nb m.b.}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy flavour</td>
<td>D meson RAA</td>
<td>$p_T &gt; 1, 10%$</td>
<td>$p_T &gt; 0, 0.3%$</td>
</tr>
<tr>
<td></td>
<td>D from B RAA</td>
<td>$p_T &gt; 3, 30%$</td>
<td>$p_T &gt; 2, 1%$</td>
</tr>
<tr>
<td></td>
<td>D meson elliptic flow (for $v_2=0.2$)</td>
<td>$p_T &gt; 1, 50%$</td>
<td>$p_T &gt; 0, 2.5%$</td>
</tr>
<tr>
<td></td>
<td>D from B elliptic flow (for $v_2=0.1$)</td>
<td>not accessible</td>
<td>$p_T &gt; 2, 20%$</td>
</tr>
<tr>
<td></td>
<td>Charm baryon/meson ratio ($\Lambda c/D$)</td>
<td>not accessible</td>
<td>$p_T &gt; 2, 15%$</td>
</tr>
<tr>
<td></td>
<td>Ds RAA</td>
<td>$p_T &gt; 4, 15%$</td>
<td>$p_T &gt; 1, 1%$</td>
</tr>
<tr>
<td>Charmonia</td>
<td>$J/\psi$ RAA (forward $y$)</td>
<td>$p_T &gt; 0, 1%$</td>
<td>$p_T &gt; 0, 0.3%$</td>
</tr>
<tr>
<td></td>
<td>$J/\psi$ RAA (central $y$)</td>
<td>$p_T &gt; 0, 5%$</td>
<td>$p_T &gt; 0, 0.5%$</td>
</tr>
<tr>
<td></td>
<td>$J/\psi$ elliptic flow (forward $y$, for $v_2=0.1$)</td>
<td>$p_T &gt; 0, 15%$</td>
<td>$p_T &gt; 0, 5%$</td>
</tr>
<tr>
<td></td>
<td>$\psi'$</td>
<td>$p_T &gt; 0, 30%$</td>
<td>$p_T &gt; 0, 10%$</td>
</tr>
<tr>
<td>Dielectrons</td>
<td>Temperature IMR</td>
<td>not accessible</td>
<td>10% on $T$</td>
</tr>
<tr>
<td></td>
<td>Elliptic flow IMR (for $v_2=0.1$)</td>
<td>not accessible</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>Low-mass vector spectral function</td>
<td>not accessible</td>
<td>$p_T &gt; 0.3, 20%$</td>
</tr>
<tr>
<td>Heavy nuclei</td>
<td>hyper(anti)nuclei, H-dibaryon</td>
<td>35% ($4\Delta H$)</td>
<td>3.5% ($4\Delta H$)</td>
</tr>
</tbody>
</table>

Stat. error at min pt
J/ψ elliptic flow

observation of flow with muon arm presently 3 sigma
needs statistics to make model comparison meaningful

future statistical errors
muon arm central barrel
heavy quark and quarkonium production 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
extension of statistical model to include charmed hadrons

core-corona effect considered: important for more peripheral collisions
“core” up to $R_A + X_c$  “corona” outside

\[ N_{\text{part}}(b) = N_{\text{core}}(b) + N_{\text{corona}}(b) \]

Collisions in corona region treated as in pp, core: medium, e.g. QGP

\[ \frac{dN_{\text{ch}}}{d\eta}/N_{\text{part}}(b) = \frac{dN_{\text{ch}}}{d\eta}/N_{\text{core}}(b) + \frac{dN_{\text{ch}}}{d\eta}/N_{\text{corona}}(b) \]

and same for $J/\psi$
core-corona effect