a wealth of results from run1 at the LHC (see recent Quark Matter Conference in Darmstadt)
where do we go from here? LHC run2 and run3
a very personal selection of just a few observables*
- azimuthal correlations
- open heavy flavor
- quarkonia
- photons and di-leptons

* due to time constraint mostly focused on ALICE
Azimuthal Anisotropy of Transverse Spectra

Fourier decomposition of momentum distributions rel. to reaction plane:

\[
\frac{dN}{dp_t \, dy \, d\phi} = N_0 \cdot \left( 1 + \sum_{i=1}^{n} 2v_i(y, p_t) \cos(i\phi) \right)
\]

quadrupole component \(v_2\)

“elliptic flow”

effect of expansion (positive \(v_2\) seen from top AGS energy upwards

the \(v_n\) are the equivalent of the power spectrum of cosmic microwave rad.
Elliptic Flow of Charged Particles at LHC

Elliptic flow ($v_2$) as function of $p_t$:
- excellent agreement between all 3 LHC experiments
- same for $v_3$

Hydrodynamic regime:
- $v_2$ driven by pressure gradient

Jet fragmentation regime:
- $v_2$ driven by energy loss

Figure modified from B. Muller, J. Schukraft, B. Wyslouch, arXiv:1202.3233v1
Elliptic flow of identified pions, kaons, protons

the quest to extract the ratio of shear viscosity over entropy density \( \eta/s \)

note: minimum value of \( 1/4\pi \approx 0.08 \) predicted with AdS/CFT correspondence

data: ALICE
calculations: (2+1)-D hydro plus UrQMD (VISHNU)


mass dependence is a genuine prediction of hydrodynamics

calculations with shear viscosity to entropy density \( \eta/s = 0.20 \) reproduce data very well

but: uncertainty due to initial condition

color glass initial condition ↔ Glauber

\( \eta/s = 0.20 ↔ 0.08 \)
very well reproduced by viscous hydrodynamics (MUSIC) with fluctuating IP Glasma initial condition (including initial quantum fluctuations of gluon fields) for LHC $\eta/s = 0.20$ for RHIC $\eta/s = 0.12$ indication of temperature dependence of $\eta/s$?
Sensitivity of temperature dependence of $\eta/s$


$3+1$-D viscous hydro, initial cond fixed to $dN/d\eta$, freeze-out to spectra, EOS from lattice QCD

while RHIC data show no sensitivity to QGP $\eta/s$
at LHC there is sensitivity, but less to hadron gas

on the other hand, can always rescale $\eta/s$ to reproduce data at one energy and centrality

**recipe: multi-differential measurements**

$v_2, v_4$, as function of rapidity and $p_t$

fix hadron gas $\eta/s(T)$ with RHIC data

then proceed to extract $\eta/s(T)$ for QGP with LHC data as well as minimal value
2 different methods:
- reconstruction of D-mesons
- e or μ from semileptonic D-decays

all LHC experiments contribute for published data:
ALICE at \( p_t > 2 \) GeV/c and \( 0 < y < 4 \)
ATLAS and CMS at \( p_t > 6 \) GeV/c \( 0 < y < 2.5 \)
LHCb at \( p_t > 2 \) GeV/c and \( 2.5 < y < 4 \)

all detectors employ sophisticated Si vertex detectors
a first try at the total ccbar cross section in pp at LHC

- 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
- soon more accurate $4\pi$ extrapolation at 7 TeV
- aim for 10% syst error with run3 data
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.

elliptic flow for charm – participation in coll. flow
Models constrained by simultaneous fit of $R_{AA}$ and $v_2$
new high performance ITS plus rate increase (TPC upgrade)
Charmonia as a probe of Deconfinement

charmonia: bound states of charm and anticharm quarks, e.g. 

J/ψ 1s state of ccbar
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

"If high energy heavy-ion collisions lead to the formation of a hot quark-gluon-plasma, then color screening prevents c̅c 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."

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


- mid-y LHC 2.76 TeV including shadowing
- forward-y LHC 2.76 TeV including shadowing
J/ψ production in PbPb collisions: LHC relative to RHIC

\[ R_{AA}(p_T) = \frac{(1/N_{\text{evt}}^{AA})d^2N_{\text{ch}}^{AA}/d\eta dp_T}{\langle N_{\text{coll}} \rangle (1/N_{\text{evt}}^{PP})d^2N_{\text{ch}}^{PP}/d\eta dp_T} \]

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)

transport codes that produce and destroy charmonia in the QCG also reproduce data, albeit with about twice the charm cross section
Progress in the charmonium sector: excited charmonia

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

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

expected ALICE performance muon arm run2 and run3
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

consistent with excited state suppression (50% feed-down)
the Upsilon could also come from statistical hadronization

SHM/thermal model: Andronic, Braun-Munzinger, Redlich, J.S.

in this picture the entire Upsilon family is formed at hadronization

but: need to know first – do b-quark thermalize at all?

- total b-cross section in PbPb

future measurements in run2 and run3
Direct photon excess and elliptic flow at low $p_T$ at RHIC

models underpredict photon yield and even more the photon $v_2$
Much improved measurements: the puzzle remains

S. Mizuno, PHENIX, QM2014

measurements using photon conversions extend data to significantly lower pt
confirm earlier measurements, different systematics
the challenge for theories remains
direct photons in PbPb collisions at the LHC

a hot photon (300 MeV) source, the QGP
- or are they blueshifted photons from a later stage?
elliptic flow of photons a puzzle, $v_2$ measurement very good, but significance of direct photon signal at low $p_T$?
measurements in run2 and run3:
- reduction of systematic error
- measurement of complementary observable: virtual photon to $e^+e^-$
Direct photons at LHC (and RHIC) challenge models

Spectra and elliptic flow high as compared to models – a real challenge but: systematic errors largely correlated and error in $v_2$ dominated by error in direct photon yield

R. Chatterjee, D.K. Srivastava, T. Renk
arXiv:1401.7464
it helps to introduce fluctuating initial conditions, but barely enough
Electron pairs of low and intermediate mass
- experimentally very difficult – so far not addresses in PbPb at LHC

- new ITS allows suppression of Dalitz, conversion and charm contributions
- continuous TPC read-out with 50 kHz in run3 increases event rate by a factor 100
- allows detailed investigation of thermal radiation from hadronic phase and QGP
outlook

results for PbPb collisions from run1 at the LHC:
zeroing in on the properties of the Quark-Gluon Plasma
- transport coefficients
- deconfinement

while we celebrate 60 years of CERN, we are looking forward to the next 10 years of studying the QGP at the LHC
backup
RHIC data show no sensitivity to shear viscosity of QGP
J/psi and transport models (and stat hadronization)

transport models also in line with $R_{AA}$

- part of J/psi from direct hard production, part dynamically generated in QGP
- 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)
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
$p_t$ dependence of $R_{AA}$

Relative yield larger at low $p_t$ in nuclear collisions

Good agreement with CMS at high $p_t$

Argument: thermalized deconfined charm quarks hadronize into $J/\psi$
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 $y$
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
J/ψ vs $p_t$ in PbPb collisions relative to pPb collisions

at low $p_T$ yield in nuclear collisions above pPb collisions

J/ψ production *enhanced* in nuclear collisions over mere shadowing effect
Elliptic Flow of J/ψ vs pt

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

- expect build-up with \( p_t \) as observed for \( \pi, p, K, \Lambda, \ldots \) and vanishing signal for high \( p_t \) region where J/ψ not from hadronization of thermalized quarks

First observation of J/ψ \( v_2 \) in line with expectation from statistical hadronization

Johanna Stachel
J/ψ from thermalized charm quarks should exhibit collective flow

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

future statistical errors

muon arm central barrel
Situation even more dramatic for P-states

\[ R_{\chi^c} \]

\[ \sqrt{s_{NN}} \text{ (GeV)} \]

Data
- \( \pi A \)
- \( pA(\bar{p}) \)

Data average

Statistical model

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

Transport model (Rapp)


Johanna Stachel
## Physics reach after ALICE upgrade

<table>
<thead>
<tr>
<th>Topic</th>
<th>Observable</th>
<th>Approved (1/nb delivered, 0.1/nb m.b.)</th>
<th>Upgrade (10/nb delivered, 10/nb m.b.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy flavour</td>
<td>D meson RAA</td>
<td>pT&gt;1, 10%</td>
<td>pT&gt;0, 0.3%</td>
</tr>
<tr>
<td></td>
<td>D from B RAA</td>
<td>pT&gt;3, 30%</td>
<td>pT&gt;2, 1%</td>
</tr>
<tr>
<td></td>
<td>D meson elliptic flow (for v2=0.2)</td>
<td>pT&gt;1, 50%</td>
<td>pT&gt;0, 2.5%</td>
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<tr>
<td></td>
<td>D from B elliptic flow (for v2=0.1)</td>
<td>not accessible</td>
<td>pT&gt;2, 20%</td>
</tr>
<tr>
<td></td>
<td>Charm baryon/meson ratio (Δc/D)</td>
<td>not accessible</td>
<td>pT&gt;2, 15%</td>
</tr>
<tr>
<td></td>
<td>Ds RAA</td>
<td>pT&gt;4, 15%</td>
<td>pT&gt;1, 1%</td>
</tr>
<tr>
<td>Charmonia</td>
<td>J/ψ RAA (forward y)</td>
<td>pT&gt;0, 1%</td>
<td>pT&gt;0, 0.3%</td>
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<tr>
<td></td>
<td>J/ψ RAA (central y)</td>
<td>pT&gt;0, 5%</td>
<td>pT&gt;0, 0.5%</td>
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<tr>
<td></td>
<td>J/ψ elliptic flow (forward y, for v2 =0.1)</td>
<td>pT&gt;0, 15%</td>
<td>pT&gt;0, 5%</td>
</tr>
<tr>
<td></td>
<td>ψ'</td>
<td>pT&gt;0, 30%</td>
<td>pT&gt;0, 10%</td>
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<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 v2=0.1)</td>
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<td>10%</td>
</tr>
<tr>
<td></td>
<td>Low-mass vector spectral function</td>
<td>not accessible</td>
<td>pT&gt;0.3, 20%</td>
</tr>
<tr>
<td>Heavy nuclei</td>
<td>hyper(anti)nuclei, H-dibaryon</td>
<td>35% (4ΔH)</td>
<td>3.5% (4ΔH)</td>
</tr>
</tbody>
</table>

\[\text{stat. error at min pt}\]