Mini Review on Open Heavy Flavor and Quarkonia in Heavy Ion Collisions

Sonia Kabana, University of Nantes and SUBATECH, France

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Outline

I  Introduction
II  Accelerator facilities and experiments
III  Open heavy flavor
IV  Quarkonia
V  Conclusions and outlook
I Introduction
The QCD phase transition

QCD on the lattice predicts a cross over at zero net baryon density with critical temperature $T_c \approx 154 \pm 9$ MeV (2014), critical energy density $\approx 0.6$ GeV/fm$^3$


The transition from quarks and gluons to hadrons is believed that took place few 10-6 sec after the Big Bang

Zero net baryon density

Quarkonia suppression as QGP signature

Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

Many effects play a role like

dissociation in QGP,

cold matter interaction,

recombination/coalescence from c, cbar,

feeding, eg B mesons carry 10-25% of charmonia yields
Open Heavy Flavor crucial observable for QGP physics

- Produced in hard scattering processes in the initial stage of the collision
- Calculated by pQCD
- Can test jet quenching
- Can test thermalization
- Help understand quarkonia

“The nuclear modification factor” $R_{AA}$ compares A+A to expectations from p+p:

$$R_{AA}(p_T) = \frac{\text{Yield}(A + A)}{\text{Yield}(p + p) \times \langle N_{\text{coll}} \rangle}$$

$N_{\text{coll}}$: Average number of NN collisions in AA collision

Suppression of jets in AuAu: $R_{AA} < 1$

Quarks are expected to exhibit different radiative energy loss depending on their mass (D.Kharzeev et al. Phys Letter B. 519:1999)

Partons interact with the medium and loose energy through eg gluon radiation

Collisional “elastic” energy loss: elastic interaction with the medium

Radiative energy loss: parton radiation due to interaction with the medium
Test collective behaviour with Flow coefficients $v_n$, n=1,2,3..

Matter in the overlap area of two colliding nuclei gets compressed and heated.

Initial anisotropy gets transferred into the momentum space via pressure gradients.

\[ \frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)] \]

\[ v_n = \langle \cos[n(\phi - \Phi_n)] \rangle \]

Higher harmonics

$v$ : flow coefficients
(v1: directed flow, v2: elliptic flow, ...)

\[ \Phi_2, \Phi_3, \Phi_4 \]
II Accelerator facilities and experiments today
RHIC has been exploring nuclear matter at extreme conditions over the last 18 years, since 2000

4 experiments initially:
STAR PHENIX
BRAHMS PHOBOS

Still running: STAR

Still analysing data: PHENIX

Main colliding systems:
- p+p, p+A, d+Au, Cu+Cu, Au+Au
- Cu+Au, U+U, Zr+Zr, Ru+Ru

Main energies A+A:
- $\sqrt{s_{NN}} = 62, 130, 200$ GeV
- and low energy scan
- 7.7, 11.5, 19.6, 22.4, 27, 39, 54 GeV
- + Fixed target
Large Hadron Collider (LHC) at CERN

run-1 (2009-13): p+p $\sqrt{s_{NN}} = 0.9, 2.76, 7, 8$ TeV, $=2.76$ TeV
run-2 (2015-18): p+p $\sqrt{s_{NN}} = 5.02, 13$ TeV $=5.02$ TeV

p+Pb $\sqrt{s_{NN}} = 5.02$ TeV, Pb+Pb at $\sqrt{s_{NN}}$

Xe+Xe
Current Experiments with Heavy Ion program

- CMS
- LHC
- LHCb
- STAR at RHIC
- ATLAS
- ALICE
- PHENIX at RHIC
- NA61/SHINE at SPS

Sonia Kabana, Open Heavy Flavor and Quarkonia in Heavy Ion Collisions, DAE 2018, Chennai, India
Open Heavy Flavor results
D meson $p_T$ distribution different energies vs FONLL

Deepa Thomas, Hard Probes 2018

Sonia Kabana, Open Heavy Flavor and Quarkonia in Heavy Ion Collisions, DAE 2018, Chennai, India
Left, pPb at high mult: $v_2/n_q$ of strange particles tend to lie on a universal curve below 1.5 GeV, while $D^0$ fall below indicating weaker collective behaviour for charm quarks.

Right, PbPb semiperiph.: $v_2/n_q$ of strange particles and $D^0$ tend to lie on a universal curve below 1.0 GeV, indicating strong collective behaviour of $D^0$, similar to the bulk of QGP medium.
Baryon/meson enhancement tests coalescence

The Lambda_c to D0 ratio suggests production via coalescence
RAA compared to models for energy loss allows for an estimate of gluon density $dN/dy(gluon)$

Here as an example we get (GLV model):

- $dN/dy(g)=400$ for SPS
- $dN/dy(g)=1400$ for RHIC
- $dN/dy(g)=2000-4000$ for LHC

To estimate with confidence $dN/dy(g)$, we should understand the mechanism of jet quenching via studies of its dependence from $p_T$, energy, event plane, path length, centrality, quark mass etc.

Sonia Kabana, Open Heavy Flavor and Quarkonia in Heavy Ion Collisions, DAE 2018, Chennai, India
D0 nuclear modification factor in Au+Au 200 GeV from HFT

Suppression of D0 at high pT
Enhancement of D0 at pT<2 GeV/c
Comparison RHIC to LHC

RAA of D0 mesons is similar in RHIC and LHC at pT>2 GeV/c
D mesons pT distribution
ALICE

arXiv:1804.09083
RAA of open charm and beauty at the LHC

ALICE, QM2015

Pb+Pb ALICE, CMS:

RAA of D mesons is much smaller than RAA of non-prompt J/Ψ representing open beauty (B→J/Ψ X) (but pT range different)

RAA of pions and D mesons is consistent (pT range is the same)
CMS: non prompt D⁰ from b hadron

Non-prompt D⁰ and J/ψ less suppressed than D⁰ and charged hadrons
RAA of Charm and Beauty in min. bias Au+Au at 200 GeV

RAA of \( b \rightarrow e \) is less suppressed than RAA of \( c \rightarrow e \) in \( p_T=3-4 \text{ GeV/c} \)

STAR Beauty vs Charm in Au+Au 200 GeV 0-80%, mass hierarchy of energy loss

* Using the new STAR HFT silicon tracker with excellent resolution
* Electrons from B quark are less suppressed than electrons from D

Li Yi, STAR coll. Santa Fe work. Jan 2018
PHENIX $B \rightarrow J/\psi$ in Cu+Au collisions

Prompt $J/\psi$ in Cu+Au is suppressed

$B \rightarrow J/\psi$, (displaced $J/\psi$) is not suppressed

New PHENIX results: ccbar and bbar production mechanisms in p+p at 200 GeV

- Measurement of angular correlations of e-e, e-mu, mu-mu pairs from ccbar and bbar decays

Data are consistent with Pythia Tune A

(PC= Pair creation, FE= Flavor excitation, GS=Gluon Splitting)

In p+p collisions at 200 GeV the data indicate that
- ccbar production is dominated by the NLO flavor excitation
- bbar production is dominated by the Leading Order pair production
5. Quarkonia suppression
Sequential Psi prime and J/Psi suppression has been observed at CERN SPS Pb+Pb 158 A GeV


\[ \varepsilon_{Bj} (\tau) = \frac{1}{A_T} \frac{dE_T (\tau)}{dy}, \]

* Psi prime is suppressed from 1.23 GeV/fm^3 on
* J/Psi is suppressed from \sim 2.4 GeV/fm^3 on
* J/Psi suppression occurs mainly at low p_T

CERN press release 2000

A Kurepin, 18th Nucl Phys Div Conf of EPS, Aug 23-29, 2004
$p_T$ dependence of J/Psi suppression in Au+Au, Cu+Cu 200 GeV

- J/Psi not suppressed at high $p_T$'s in non-central collisions
- J/Psi suppressed at all $p_T$'s for most central events
- $R_{AA}$ of J/Psi is systematically larger for higher $p_T$. Low $p_T$ J/Psi is more suppressed

Liu et al, PLB 678 (2009) 72
Zhao et al, PRC 82 (2010) 064905
J/ψ Suppression in Au+Au Collisions

Low $p_T$ J/ψ in central collisions:

High $p_T$ J/ψ in all centralities:

R$_{AA}$(200 GeV) < R$_{AA}$(2.76 TeV) ~ R$_{AA}$(5.02 TeV)
Less regeneration at RHIC

R$_{AA}$(200 GeV) > R$_{AA}$(2.76 TeV) ~ R$_{AA}$(5.02 TeV)
Less color screening at RHIC

Li Yi (STAR coll.) Santa Fe 2018
**Y in p+p p+Au**

- Yields consistent with NLO model
- $R_{pA}$ quantifies CNM effects

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F. Arleo, S. Peigne, JHEP 1303(2013) 121
Hierarchy of quarkonia suppression has been observed at RHIC and LHC

STAR, Z. Ye, QM2017

In central collisions $Y(2S+3S)$ more suppressed than $Y(1S)$
Y Suppression in Au+Au Collisions

Sequential melting observed at both RHIC and LHC energies

Li Yi (STAR coll.) Santa Fe 2018
Combined results from Y-> e^+e^- and Y-> μ^+μ^- improve precision of Y measurements

Y-> μ^+μ^- with the Muon Telescope Detector (MTD):
Less Bremstrahlung allows to separate the Y(1S) from Y(2S+3S)

Y(2S+3S) more suppressed than Y(1S) in the most central Au+Au collisions (0-10% centrality)
Upsilon Y(1S): STAR vs LHC vs models

STAR data on Y(1S) are consistent with LHC data
KSU and TAMU models are consistent with data on Y(1S) from RHIC (STAR) and LHC (CMS)

KSU model: use a lattice-vetted heavy-quark potential
TAMU model: use in-medium binding energies predicted by thermodynamic T-matrix calculations using internal-energy potentials, from lattice QCD

<table>
<thead>
<tr>
<th>$T_0^{QGP}$ (MeV)</th>
<th>RHIC (0.2 TeV)</th>
<th>LHC (2.76 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KSU</td>
<td>440</td>
<td>546</td>
</tr>
<tr>
<td>TAMU</td>
<td>310</td>
<td>555</td>
</tr>
</tbody>
</table>
KSU and TAMU models are consistent with data on Y(2S+3S) in central and semi-central collisions from RHIC (STAR) and LHC (CMS).

STAR Y data in central A+A collisions are consistent with "sequential melting" in QGP.

Y(2S+3S):
- Indication of less suppression at RHIC than at LHC
  - STAR: Y(2S+3S) $R_{AA}$: 0.35 ± 0.08 (stat.) ± 0.10 (sys.) (0 < $p_T$ < 10 GeV/c, 0-60%)
  - CMS: Y(2S) $R_{AA}$: 0.08 ± 0.05 (stat.) ± 0.03 (sys.) (0 < $p_T$ < 5 GeV/c, 0-100%)

[CMS: PLB 770, 357 (2017)]
[X. Du, M. He, and R. Rapp: PRC 96, 054901 (2017)]
Quarkonia at 5 TeV PbPb

CMS, J. J. Lee, QM2017

Y(1S) and Y(2S)

**Y(1S) PbPb at 2.76 and 5 TeV**

- Indication of larger suppression at 5 TeV
- Consistent with predictions from a hotter and denser medium

**PbPb at 5 TeV**

- Highest precision measurement
- Upsilon sequential suppression at 5 TeV
- Still no sign of Y(3S) with high statistics data

Sonia Kabana, Open Heavy Flavor and Quarkonia in Heavy Ion Collisions, DAE 2018, Chennai, India
J/Psi recombination at LHC?

Low pT: RAA(ALICE) > RHIC

High pT: RAA at LHC more similar to RHIC

STAR, Z. Miller, WWND2017

RAA of J/Psi in Pb+Pb at LHC is below 1

RAA of J/Psi is less suppressed at low pT, in central collisions ->

Indication of J/Psi regeneration at LHC at low pT
J/Psi compared to open charm - RHIC

High pT

Low pT

* J/Psi seems to be **neither suppressed nor enhanced** with respect to open charm at all centralities at high pT (However pT range is not exactly the same)

* J/Psi seems to be **significantly suppressed** with respect to open charm at low pT in central Au+Au events (same acceptance here)

STAR : RAA(D0) shows no suppression for peripheral collisions
J/Psi compared to open charm - LHC

"Low Pt" (2-5 GeV) vs High Pt > 6.5 GeV

H. Satz, arXiv 1303.3493

J/Psi seems to be neither suppressed nor enhanced with respect to open charm at all centralities, at intermediate (pT=2-5 GeV) and high pT>6.5 GeV

However experiments should compare more precisely within exactly same acceptance (here different y) and at low pT too
PbPb: prompt $J/\psi$ suppression

$R_{AA}$

Hidden charm
Prompt $J/\psi$

- $1.8 < |y| < 2.4$
- $|y| < 2.4$

Open charm
$D^0$ HIN-16-001

$|y| < 1$

CMS

Supplementary

Cent. 0-100%

$p_T$ (GeV/c)

J/$\psi$ suppression similar to $D^0$ suppression
Jet quenching for charmonia?
Y(1S) in PbPb seem less suppressed than open beauty in PbPb (needs better stat) if so -> no Y(1S) suppression

Y(2S), Y(3S) in PbPb seem more suppressed than open beauty in PbPb -> compatible with Y(2S) and Y(3S) suppression
LHCb fixed target run

$D^0$ and $J/\psi$ production in $p$He fixed target: first cross sections

$\sqrt{s}=69$ GeV

**LHCb-PAPER-2018-022, in preparation.**
First measurement on $R_{pAu}$ of $J/\psi$ at RHC

- $R_{pAu}$ is consistent with $R_{dAu}$ within uncertainty
  - There seems to be tension at $3 < p_T < 5$ GeV/c with $1.4\sigma$ significance
- Suggests similar CNM effects in these collision systems
- Model calculations with only shadowing effect can touch the upper limit of data within uncertainties
- Additional nuclear absorption is favored by data
ATLAS: Flow of prompt and non-prompt J/Ψ

- Prompt and non-prompt J/Ψ mesons have non-zero elliptic flow
- No observed dependence on rapidity or centrality

ATLAS Coll. QM2018
6. Future
Energy scans with Heavy Ions
Future: BESII, NICA, FAIR, J-PARC

T. Sakaguchi, QM2017
STAR future plans

Beam Energy Scan (BES) II 2019-2020
Will continue the BES I program
"Hot" QCD, search for a possible critical point and discontinuities in the energy dependence of QGP signatures
-> FAIR and NICA

STAR forward rapidity program (2.5-eta-4): Hcal, Ecal, tracking (Silicon and sTGCs)
"Cold" QCD, Proton TMDs, gluon saturation
Test Electron Ion Colider (EIC) detector technologies
Milestone: 2021 p+p run and sPHENIX data taking 2022+
-> EIC
## STAR goals

<table>
<thead>
<tr>
<th>Beam Energy (GeV/nucleon)</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>$\mu_B$ (MeV)</th>
<th>Run Time</th>
<th>Number Events</th>
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<tr>
<td>9.8</td>
<td>19.6</td>
<td>205</td>
<td>4.5 weeks</td>
<td>400M</td>
</tr>
<tr>
<td>7.3</td>
<td>14.5</td>
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<td>5.5 weeks</td>
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<td>5.75</td>
<td>11.5</td>
<td>315</td>
<td>5 weeks</td>
<td>230M</td>
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<td>7.7 (FXT)</td>
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<td>6.2 (FXT)</td>
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<td>2 days</td>
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<tr>
<td>9.8</td>
<td>4.5 (FXT)</td>
<td>589</td>
<td>2 days</td>
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<td>7.3</td>
<td>3.9 (FXT)</td>
<td>633</td>
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<tr>
<td>5.75</td>
<td>3.5 (FXT)</td>
<td>666</td>
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<td>100M</td>
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<tr>
<td>4.55</td>
<td>3.2 (FXT)</td>
<td>699</td>
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<td>3.85</td>
<td>3.0 (FXT)</td>
<td>721</td>
<td>2 days</td>
<td>100M</td>
</tr>
</tbody>
</table>
* New detector project at RHIC: sPHENIX

sPHENIX: start data taking 2022

Extended Calorimetry precision vertexing and tracking for jet quenching, charm, beauty

M. Connors,

Sonia Kabana, Open Heavy Flavor and Quarkonia in Heavy Ion Collisions, DAE 2018, Chennai, India
LHC experimental upgrades
ALICE upgrades for run-3

MFT: will provide secondary vertex reconstruction in forward rapidity
ITS: low pT reach and improved accuracy
High rate

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A view into the far Future: FCC

plot from M. Koratzinos, ICNFP2017
FCC: The Vision

~100 km tunnel, 16 T magnets
sqrt(s)= 100 TeV pp collisions

FCC-hh
FCC-ee
FCC-he

Possible first steps
*FCC-ee, E_CM=90-400 GeV
*HE-LHC 16T 28 TeV
in LEP/LHC tunnel

FCC-AA : sqrt(s)NN=40 TeV
FCC quarkonia

- p+p at $\sqrt{s}=100$ TeV, Pb+Pb at $\sqrt{s}=39$ TeV

D. d Enterria, QM2017

- FCC-AA ($T_0 \sim 1$GeV) can probe $Y(1S)$ “melting” expected by latt-QCD at $T=4–5 \, T_c$

[G. Aarts et al, JHEP 07 (2014) 097]

- Density of $b\bar{b}$ pairs large enough for $Y(1S)$ recombination?

[A. Andronic, et al., JPG38 (2011) 124081]
IV Conclusions

- **QGP signatures** observed in central Au+Au and Pb +Pb collisions at RHIC and LHC as well as at SPS.

- Open Heavy Flavor and Quarkonia give insights into QGP formation and characteristics

  Sequenctial quarkonia suppression observed
  -> inferred QGP temperatues of 400-550 MeV

- Flavor dependence of jet quenching observed in B and D
IV Conclusions

Further studies are needed to study in detail and understand jet quenching, quarkonia suppression and other phenomena.

- RHIC BESII (2019-2020), sPHENIX (2020+)
- LHC with future upgrades
- NICA in Dubna, Russia and
- FAIR in GSI, Germany and
- J-PARC in Japan,

Center of mass energy (sqrt(s)NN):
FAIR: 2-6 (10) GeV, NICA: 4-11 GeV, RHIC: 7 (2.5) - 200 GeV
LHC: 2.76, 5 TeV
J-PARC: 1-10 GeV
FCC (100 km circular ring, p+p at sqrt(s)=100 TeV, Pb +Pb at sqrt(s)=39 TeV)
Thank you very much for your attention
J/ψ production in p+p 200 GeV

- Inclusive J/ψ cross section is measured in $0 < p_T < 14 \text{ GeV/c}$

- CGC+NRQCD & NLO NRQCD (prompt J/ψ) model calculations can describe data in the full $p_T$ range

- Improved CEM model (direct J/ψ) describes data well at low $p_T$
  - Data are above ICEM calculation at $3.5 < p_T < 12 \text{ GeV/c}$

iTPC: inner sector of TPC. Extends pseudorapidity acceptance from 1 to 1.5. Improves dE/dx

Endcap TOF: particle identification 0.9-eta-1.5

Event Plane Detector: will provide better and independent determination of centrality and event plane
STAR forward rapidity program

3 Silicon discs

4 Small-strip Thin Gap Chambers

ECal: use upgraded PHENIX PbSc calorimeter

HCal: Iron-scintillator
### LHCb upgrades: unique opportunities

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<th>Year</th>
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</table>

- **Phase I**: $\rightarrow \approx 5 \times L_{\text{inst}}(\text{Run II})$
  - extent ion-ion capabilities
  - increase pA luminosity for low-$x$ sector

- **Phase II** in design phase: $\approx 50 \times L_{\text{inst}}(\text{Run II})$
  - dream detector for heavy-ion physics
LHCb detector upgrades phase I

- replace full tracker for 5 times higher pile-up in $pp$
- inspect 30 MHz rate in software trigger in $pp$
- magnet stations for low-$p_T$ tracks & TOF for low momentum PID in consideration for Phase I consolidation or Phase II
LHCb fixed target upgrade phase I: higher luminosity & more targets

- storage cell upstream: allow also for non-noble gas targets
- target with 10-100 × larger instantaneous luminosity per unit length
Backup slides
A view into the far Future: FCC

plot from M. Koratzinos, ICNFP2017
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MFT: will provide secondary vertex reconstruction in forward rapidity
ITS: low pT reach and improved accuracy
High rate
# Beam Energy Scan Phase II

<table>
<thead>
<tr>
<th>Collision Energies (GeV)</th>
<th>7.7</th>
<th>9.1</th>
<th>11.5</th>
<th>14.5</th>
<th>19.6</th>
<th>Related to</th>
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<tr>
<td>Chemical Potential (MeV)</td>
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<td>370</td>
<td>315</td>
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<tr>
<td>$R_{cp}$ up to $p_T$ 5 GeV</td>
<td>N/A</td>
<td>N/A</td>
<td>160</td>
<td>125</td>
<td>92</td>
<td>Turn-off of QGP signature</td>
</tr>
<tr>
<td>Elliptic Flow of $\phi$ meson ($v_2$)</td>
<td>100</td>
<td>150</td>
<td>200</td>
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<td>Directed Flow studies($v_1$)</td>
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<td>75</td>
<td>100</td>
<td>100</td>
<td>200</td>
<td>1st order phase transition</td>
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<td>asHBT (proton-proton)</td>
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<td>40</td>
<td>50</td>
<td>65</td>
<td>80</td>
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<td>Net-proton kurtosis</td>
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<td>100</td>
<td>120</td>
<td>200</td>
<td>300</td>
<td>Critical point</td>
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<td>Dileptons</td>
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<td>160</td>
<td>230</td>
<td>300</td>
<td>400</td>
<td>Chiral</td>
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<tr>
<td>Proposed Event Goals</td>
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<td>230</td>
<td>300</td>
<td>400</td>
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<tr>
<td>BES I Event</td>
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<td>N/A</td>
<td>12</td>
<td>20</td>
<td>36</td>
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</table>

Only part of physics topics in BES II are shown here!
Electron Ion Collider EIC
eRHIC at BNL / JLEIC at JLAB

Start of construction estimated: 2022-2023

E. Aschenauer, ICNFP2017
Lepton-Proton Scattering Facilities

CMS Energy (GeV)

Luminosity \(10^{30} \text{ cm}^{-2} \text{s}^{-1}\)

- HERA and CERN
- Fixed Target
- EIC Projects

- LTFC
- MESA
- Jlab 6+12
- SLAC
- LEIC
- COMPASS
- BCDMS
- HERMES
- NMC
- HERA
- LHeC
- FCC–ep

E. Aschenauer, ICNF2017
Example of results II:

**EoS of QGP Matter**

Example: determine the EoS of QGP matter from experimental measurements

- what equation of state would the physics model choose to best describe the experimental data?
  - create set of QCD Equations of State (aka the prior)
  - run physics model with each EoS
  - use comparison with RHIC/LHC data to determine which Equations of State are consistent with data (i.e. the posterior)
    - posterior is very similar to Lattice EoS!!

![Constraining Eq. of State with RHIC/LHC Data (MADA1 Collab.)](image)

Lattice: Hot QCD / BW
upper/lower ranges (arXiv:1407.6387)

<table>
<thead>
<tr>
<th>T (MeV)</th>
<th>c_s^2 (speed of sound squared)</th>
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<tr>
<td>150</td>
<td>0.1</td>
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<tr>
<td>200</td>
<td>0.2</td>
</tr>
<tr>
<td>250</td>
<td>0.3</td>
</tr>
</tbody>
</table>


Sonia Kabana, Open Heavy Flavor and Quarkonia in Heavy Ion Collisions, DAE 2018, Chennai, India
1986-2000: Discovery of a new state of matter at CERN

Evidence:
- ccbar suppression
- Strangeness enhancement
- $T_{\text{chem. free out}} \sim T_{\text{critical}}$
- Direct gammas consistent with $T > T_{\text{critical}}$
- and other results

Sequential Psi prime and J/Psi suppression has been observed at CERN SPS Pb+Pb 158 A GeV

* Psi prime is suppressed from 1.23 GeV/fm$^3$ on
* J/Psi is suppressed from $\sim$2.4 GeV/fm$^3$ on
* J/Psi suppression occurs mainly at low pT

CERN press release 2000

A. Kurepin, 18th Nucl Phys Div Conf of EPS, Aug 23-29, 2004
pPb at high mult: $v_2/n_\text{q}$ of strange particles tend to lie on a universal curve below 1.5 GeV, while D0 fall below indicating weaker collective behaviour for charm quarks.

PbPb semiperiph.: $v_2/n_\text{q}$ of strange particles and D0 tend to lie on a universal curve below 1.0 GeV, indicating strong collective behaviour of D0 similar to the bulk of QGP medium.
LHCb $p+Ar$ at $\sqrt{s}=110$ GeV fixed target mode SMOG
Phases of QCD Matter
Areas of different net baryon densities and temperatures can be probed using different collision energies and nuclei.

The order of the transition is expected to change with the net baryon density.

Goal: explore experimentally the QCD phase diagram (order of transition, critical point, properties of the QGP).
Direct photons flow too
J. F. Paquet et al, 1509.06738

Difficult for models to describe both cross section and v2 flow of direct photons

Hydrodynamic model describes approx. the v2 data at RHIC and LHC.

Suggests that excess of direct photons is due to thermal photons
Large $v_2$ and $v_3$ of direct photons in Au+Au at 200 GeV studied vs $p_T$ and centrality
RHIC: results from 2015 p+Au run and results from 2014 3He+Au at 200 GeV


Large $v_2$, $v_3$ components in 0-5% 3He+Au, d+Au and p+Au from 2015 run
\( \Lambda/\pi \) vs. \( dN_{ch}/d\eta \)

- \( \Lambda/\pi \) ratio reaches Grand Canonical limit in Pb–Pb
- Similar multiplicity dependence in pp and p–Pb
  - Neither PYTHIA6 nor 8 reproduce data in any of the tunes tested
\[ \frac{\Xi}{\pi} \text{ and } \frac{\Omega}{\pi} \text{ vs. } dN_{ch}/d\eta \]

- ALICE strangeness

- \( \text{Pb-Pb} \)
- \( \text{p-Pb} \)
- \( \text{pp} \)

- L. Bianchi
- QM2015

- \( \frac{\Xi}{\pi} \text{ and } \frac{\Omega}{\pi} \) reach Grand Canonical limit in Pb–Pb
- Similar multiplicity dependence in pp and p–Pb
  - Neither PYTHIA6 nor 8 reproduce data in any of the tunes tested
The ratios $L/K_0s$ and $p/\pi$ do not change significantly with the charged multiplicity demonstrating that the observed enhancement of strange hadrons over pions is not due to the different hadron masses.

The models cannot reproduce simultaneously the observation of strangeness enhancement over pions as a function of multiplicity and the constant $p/\pi$ ratio versus multiplicity.

DIPSY: model that describes data best includes color ropes that cause enhanced production of strange particles and baryons.
**Quarkonia**

Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

Many effects play a role like dissociation in QGP, cold matter absorption, recombination/coalescence from c, cbar, feeding, eg B mesons carry 10-25% of charmonia yields (B->J/Psi from J/Psi-h correlation STAR measurement)

Other models: B. Kopeliovich et al, D. Kharzeev, E. Ferreiro, A. Capella, A. Kaidalov et al etc.

Multi-parameter estimates from a variety of data
Multiple parameter estimation

Important progress in estimating properties of QGP using statistical analysis methods and a multi-parameter model-to-data comparison, with many different data (flow, spectra, etc)


Review: S. Bass, QM2017,

- **diagonals**: probability distribution of each parameter, integrating out all others
- **off-diagonals**: pairwise distributions showing dependence between parameters
Example of results I:

**Temperature Dependence of Shear & Bulk Viscosities**

**temperature dependent shear viscosity:**
- analysis favors small value and shallow rise
- results do not fully constrain temperature dependence:
  - inverse correlation between $(\eta/s)_\text{slope}$ slope and intercept $(\eta/s)_\text{min}$
  - insufficient data to obtain sharply peaked likelihood distributions for $(\eta/s)_\text{slope}$ and curvature $\beta$ independently
- current analysis most sensitive to $T<0.23$ GeV
  - RHIC data may disambiguate further

**temperature dependent bulk viscosity:**
- setup of analysis allows for vanishing value of bulk viscosity
- significant non-zero value at $T_C$ favored, confirming the presence / need for bulk viscosity
- either high sharp peak or broad & shallow temperature dependence

Caveat of current analysis:
- bulk-viscous corrections are implemented using relaxation-time approximation & regulated to prevent negative particle densities

\[ \eta/s(T) = (\eta/s)_\text{min} + (\eta/s)_\text{slope} \times (T/T_C)^\beta \]

\[ \zeta/s(T) = (\zeta/s)_\text{max} / [1 + (T-T_C)^2/\Gamma^2] \]
Needed developments

current analysis focus was on the properties of bulk QCD matter and utilized only LHC data on soft hadrons. The analysis needs to be extended to:

- **include data from lower beam energies**
  - necessary for determination of the temperature and $\mu_B$ dependence of transport coefficients

- **include asymmetric collision systems (p+A, d+A, 3He+A, A+B)**
  - generate improved understanding of the initial state

- **include hard probes (jets and heavy quark observables)**
  - consistent determination of jet and heavy flavor transport coefficients

- **include other physics models**
  - analysis is model agnostic, allows for quantitative comparison among different models and verification/falsification of models/conceptual approaches
RHIC Beam Energy Scan: At which energy does J/Psi suppression turn off?

Color Evaporation Model (CEM) estimate for p+p reference used for 39, 62 GeV \( R_{AA} \) in U+U 193 GeV is consistent within errors with Au+Au 200 GeV \( R_{AA} \) of J/Psi is suppressed in similar way at 39, 62 and 200 GeV
Strangeness suppression near T_c

P. Castorina, S Plumari, H Satz, 1709.02706

Gamma_s becomes 1 near T_c
Fractional momentum loss is different at RHIC and LHC:

\[ \frac{dpt}{pt}(LHC) \sim 1.25 \frac{dpt}{pt}(RHIC) \]

Charged multiplicity:

\[ \frac{dN}{dy}(LHC) \sim 2.2 \frac{dN}{dy}(RHIC) \]

\[ \Rightarrow \text{Interaction region at LHC less opaque to hard partons than RHIC} \]

M. Tannenbaum and PHENIX collaboration

arXiv 1208.2254
Jet quenching of light hadrons at RHIC

* Light hadrons are quenched
* Photons are not quenched
STAR $R_{AA}$ of $D_0$ in Au+Au 200 GeV

$R_{AA}$ of $D_0$ at high $p_T$:
- RAA $D_0$ suppression in central Au+Au 200 GeV
- suppression at high $p_T$ similar to pions
- Enhancement at $p_T$~0.7-2 GeV (described eg by models with charm quark coalescence with light quarks)

ALICE new data on charmed baryons

* New charmed baryon measurements from ALICE
* Charmed baryon to meson ratios are not well described by event generators
LHCb J/Psi and B->J/Psi in p+Pb

At backward rapidity prompt J/Psi not well described by models
s_0 initial entropy density calculated using the Bjorken relation

\[ s_0 \tau_0 \simeq \frac{1.5 A^x}{\pi R_x^2} \left( \frac{dN}{dy} \right)_y^x, \text{ with } x \sim pp, pA, AA, \]

Gamma_s factor depends in universal way from s_0 for small and big systems  
Gamma_s becomes 1 near T_c
Upsilon vs models at RHIC

No Cold Nuclear Matter effects
T(initial)=428-443 MeV
Potential model A is based on heavy quark free energy (disfavored)
Potential model B is based on heavy quark internal energy

Y data in agreement with Y melting scenario

Model of Liu, Chen, Xu, Zhuang (Phys Lett B 697, 32 (2011))
Potential model, no Cold Nuclear Matter effects. T= 340 MeV

Cold Nuclear Matter effects included
Modification in Jet fragmentation

Jet fragmentation function $D(z)$

$$D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dz},$$

In central Pb+Pb:
- Enhancement at low $z$
- Suppression at $z$ around 0.1
- Enhancement at high $z$
Secondary vertex reconstruction of D mesons with HFT

Heavy Flavor Tracker started taking data in run-14

STAR Preliminary
Au+Au $\sqrt{s_{NN}} = 200$ GeV
RHIC Run 2014

$D^0 \rightarrow K\pi$

~ 4 orders of magnitude reduction of combinatorial background
J/Psi in p+p coll at RHIC

- CGC+NRQCD and NLO NRQCD (prompt) consistent with data (inclusive) at p+p @ 200 and 500 GeV

Li Yi (STAR coll.) Santa Fe 2018

Sonia Kabana, Open Heavy Flavor and Quarkonia in Heavy Ion Collisions, DAE 2018, Chennai, India
What is the right normalization for quarkonia?

1. J/Psi AA/pp : $R_{AA}(J/\Psi)$

$$R_{AA}(p_T) = \frac{Yield(A + A)}{Yield(p + p) \times \langle N_{coll} \rangle}$$

2. Jpsi AA/pA : $R_{pA}$
   
   $(J/Psi \ AA \ measured)/(expected \ from \ pA)$ (NA50)
   
   to subtract Cold Nuclear Matter effects (CNM)

3. (J/Psi AA/pp) / (open charm AA/pp) :

   $R_{AA}(J/\Psi) / R_{AA}(\text{open charm})$

4. (J/Psi AA/pA) / (open charm AA/pA):

   $(R_{pA} \ (J/\Psi)) / (R_{pA} \ (\text{open charm}))$

Very different conclusions can be drown depending on normalization
Measured ratio of J/ψ to D mesons at SPS

- Open charm measured by dimuons in region 1.6-2.5 GeV

The J/ψ/(D D̅) estimate is suppressed at 1 GeV/fm³ instead of 2.3 GeV/fm³ and coincides with strangeness saturation onset

Need open charm measurements at low energy to understand quarkonia onset of suppression