Recent results from Heavy-Ion Physics at RHIC and LHC

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RHIC :
Brookhaven Lab, Long Island
New York, USA

LHC :
CERN, Geneva,
Switzerland
Outline

I Introduction

II Accelerator facilities and experiments

III Selected physics results from RHIC and LHC:
   1. Direct photons
   2. Collectivity, flow
   3. Jet quenching
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IV Conclusions and Perspectives
I Introduction
The QCD phase transition between hadronic and partonic phase

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

(Nuclear Density: $\rho = 0.15$ GeV/fm$^3$
Density inside Nucleon: $\rho = 0.5$ GeV/fm$^3$)

The order of the transition depends on the parton masses.
A cross over is expected by Lattice QCD for the physical point (for the physical $u,d,s$ masses).

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).
The expected QCD phase diagram

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The transition from quarks and gluons to hadrons is believed that took place few 10-6 sec after the Big Bang. The QCD phase transition is the only phase transition of the early universe that can be reproduced in the Lab today since $T_{critical}$ is about 200 MeV.
Signatures of the Quark Gluon Plasma

Direct photons from QGP $\rightarrow$ $T(QGP)$

Strangeness enhancement (Mueller, Rafelski 1981) $\rightarrow$ $K/\pi$

$U,d,s$ yields for $T$ (freeze out) or $pT$ slopes (Van Hove, H Stoecker et al) $\rightarrow$ plateau vs energy at $T_c$ $\rightarrow$ $e_{\text{init}}(\text{crit}), \sqrt{s}(\text{"crit"})$

Multiquark states from QGP (Greiner et al) $\rightarrow$ ‘small QGP-lumps’

Critical fluctuations near the critical point, $T_c$ $\rightarrow$ $K/\pi, <p_T>$, etc

Hadronic mass/width changes (Pisarski 1982) $\rightarrow$ rho etc

Charmonia suppression (Satz, Matsui 1987) $\rightarrow$ $T$ (dissociation) of $c\bar{c}, b\bar{b}$

Jet quenching (J D Bjorken 1982) $\rightarrow$ medium density

$\rightarrow$ Goal is to achieve a combination of many signatures
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 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.
Jet quenching as QGP signature

**p+p Collision**

**Au+Au Collision**

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
Jet quenching

“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 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)

Flow coefficients \( v_n, n=1,2,3, \ldots \)

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

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

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

\( v \): flow coefficients
- \( v_1 \): directed flow
- \( v_2 \): elliptic flow

Higher harmonics
History of the search for QGP

First signature found: Strangeness enhancement

Streamer chamber picture, NA35 exp. CERN


1986 CERN SPS A+A sqrt(s)=20 GeV and later Pb+Pb sqrt(s)=17 GeV
1989 : BNL AGS A+A around sqrt(s)=<8 GeV
1986-2000: Discovery of a new state of matter at CERN

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

CERN press release 2000
2000-2003: Discovery of strongly interacting QGP and of jet quenching at RHIC

RHIC white papers for the 4 RHIC experiments: 2005


Dihadron correlations for pT(trig)=(4,6 GeV) and pT(associated)=(2 GeV,pT(trig))
2009: first p+p collisions at LHC
2010: first Pb+Pb collisions at LHC

LHC Pb+Pb, p+Pb, p+p: Jet quenching studied in great detail

LHC + RHIC: Y states suppression

RHIC + SPS: Low energy beam scans
II Accelerator facilities and experiments today
RHIC has been exploring nuclear matter at extreme conditions over the last 15 years 2000-2015

4 experiments initially: STAR PHENIX BRAHMS PHOBOS

Still running: STAR and PHENIX

Colliding systems:
p+p, d+Au, Cu+Cu, Au+Au
Cu+Au, U+U

Energies A+A:
\[ \sqrt{s_{NN}} = 62, 130, 200 \text{ GeV} \]
and low energy scan
7.7, 11.5, 19.6, 22.4, 27, 39 GeV
+ Fixed target
Large Hadron Collider (LHC) at CERN

- **run-1**: p+p $\sqrt{s_{NN}} = 0.9, 2.76, 7, 8$ TeV, p+Pb $\sqrt{s_{NN}} = 5.02$ TeV, Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV
- **run-2**: p+p $\sqrt{s_{NN}} = 13$ TeV
- Dec 2015: Pb+Pb at $\sqrt{s_{NN}} = 5.1$ TeV
- 2016: p+Pb 5 and 8 TeV + fixed target (LHCb)
Current Experiments with Heavy Ion program

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

Sonia Kabana, Heavy Ion Physics at RHIC and LHC, HEP 2017, Ioannina, 6-9 April 2017
III Selected physics results:
1. Direct photons
Direct thermal photons were firmly established for the first time at RHIC

Direct photons in p+p described by NLO
Direct photon excess in min. bias Au+Au at 200 GeV over p+p at 200 GeV below pT ~2.5 GeV
Exponential spectrum in Au+Au - consistent with thermal below pT ~2.5 GeV with inverse slope \(220 \pm 20\) MeV --> T(init) from hydrodynamic models : 300-600 MeV, depending on thermalization time
Critical d+Au check : No exponential excess in d+Au
ALICE direct photons 2015
ALICE:1509.07324

ALICE: different centralities

ALICE vs PHENIX

T(dir. photons) at RHIC and LHC is > than critical $T_{crit}\sim154$ MeV

The real initial $T$ of the source is higher than the measured $T$
Photons as a thermometer

* Most photons at RHIC and LHC are emitted from time near $T_c$
* Their effective temperature is enhanced by strong radial flow (effective temperature of hadrons decaying into photons are above $T_c$ due to mass dependence of radial flow).
* However a very high temperature early initial collision stage is required to generate this radial flow

Conclusions:
* Photons can be used as a thermometer
* $T > T_c$ is reached
* More model calculations needed to fit the data and extract the $T(\text{init})$

C. Gale et al, 1308.2440
Direct photons flow too

J. F. Paquet et al, 1509.06738

Difficult for models to describe both cross section and $v_2$ flow of direct photons

Hydrodynamic model describes approx. the $v_2$ data at RHIC and LHC.

Suggests that excess of direct photons is due to thermal photons
Latest results from RHIC Beam Energy Scan: direct photons

effective $T$ (from direct photons)

PHENIX, Dheepali Sharma
QM2017
3. Collectivity, Flow
Flow and shear viscosity

- 2003: discovery at RHIC of large flow and first extraction of shear viscosity -> RHIC white papers

- QGP : a perfect liquid

- strongly interacting QGP

PHENIX

Schenke, Jeon, and Gale, PRC (2012)
New D0 v2 from STAR Heavy Flavor Tracker

1701.06060, STAR

v2 of D0 in Au+Au follows Number-of-Constituent-Quarks scaling of other hadrons

-> Evidence for thermalization of charmed mesons
v2, v3 observed also in small systems:

PHENIX, d+Au

PHENIX, J. Velkovska, QM2017
Large flow observed in p+Pb collisions at sqrt(s)=5.02 TeV

Results from ATLAS 1409.1792

After applying scale factor of 1.25 accounting for the difference in mean pT of pPb and PbPb as proposed by Basar and Teaney:

The shape of the v_n distributions in pPb and PbPb are found to be similar

Evidence for collectivity in p+Pb?
Do small QGP droplet form in p+p, p+A?

Till few years ago, p+p, p+A in the heavy ion community were assumed to be QGP-free systems by definiton to which people compared A+A to find the QGP.

New data on collectivity seen in p+A, p+p prompt the idea that QGP may form in p+p, p+A ?

Universality of the QCD phase transition in p+p, p+A, A+A

Key idea: extrapolate to $\mu_B=0$

Consequences:
-> Universality of onset of phase transition near $\sim 0.8$ GeV/fm$^3$
-> Universality of onset of saturation of strangeness suppression factor

Differences of AA, pp, pA disappear at high enough initial energy density and at same $\mu_B$

4. Jet quenching
Single hadrons
Jet quenching of light hadrons at RHIC

* Light hadrons are quenched
* Photons are not quenched
Jet quenching hadrons
Collision energy dependence

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

Same RAA for pions at RHIC and LHC at high $p_T$
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 pointing to charm coalescence with a flowing medium
Comparison RHIC to LHC

RAA of D0 mesons is similar in RHIC and LHC at $p_T > 2$ GeV/c
RAA of open charm and beauty at the LHC

Pb+Pb ALICE, CMS:

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

RAA of pions and D mesons is consistent (pT range is the same)
RAA of Charm and Beauty in min. bias Au+Au at 200 GeV


RAA of (b->e) is less suppressed than RAA of (c->e) in pT=3-4 GeV/c
p+Pb and Pb+Pb data at LHC

R(pPb) for charged particles is compatible with 1 at high pT

No jet quenching in p+Pb

The jet quenching seen in Pb+Pb is not due to cold nuclear matter effects
Reconstructed jets
Dijet imbalance in STAR: $A_J$

J. Putschke, STAR, QM14
STAR, Dijet imbalance Au+Au 0-20% R=0.4

J. Putschke, STAR, QM14
Quenched jet energy is recovered at low pT within a cone of R=0.4
Dijet imbalance with $R=0.2$

J. Putschke, STAR, QM14
Dijet imbalance with R=0.2, matched

At RHIC the lost energy seem to reside inside a cone of R=0.4
Comparison to LHC: first LHC results

Asymmetry parameter $A_J$ defined to characterize dijet balance (or imbalance):

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}.$$
Jet quenching via dijet imbalance

Observation of highly unbalanced dijet events in central PbPb collisions -> evidence for energy loss in medium or “jet quenching”
Where did the lost energy go?

CMS: Look at track-jet correlations

-> RHIC and LHC differ: in LHC lost energy is moved from large to small PT and from small to large angles namely outside the leading and subleading jets cones.

Dijet balance (or imbalance) characterization:

\[ A = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}} \]

CMS, PRC 84 (2011) 024906

Color decoherence can lead to large angle emission

N. Armesto et al, 1207.0984
K. Tywokiuk et al 1401.8293
New results ATLAS Pb+Pb 5 TeV

Pb+Pb at 5 TeV is consistent with 2.76 TeV
Modification in Jet fragmentation

Jet fragmentation function $D(z)$

$z$: longitudinal momentum fraction of a particle with respect to jet

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

$$R_{D(z)} = \frac{D(z)_{\text{cent}}}{D(z)_{pp}}.$$

In central Pb+Pb:
Enhancement at low $z$
Suppression at $z$ around 0.1
Enhancement at high $z$
Jet transport coefficient at RHIC and LHC
Extracting jet transport coefficient from data and models at RHIC and LHC

Scaled jet transport parameter $q_{hut}/T^3$

Results from JET collaboration agree with results from AdS/CFT correspondence shown here with the arrows named NLO SYM

Dashed boxes show expected values for $\sqrt{s}=0.063$, 0.130 and 5.5 TeV

Results from JET collaboration agree with results from AdS/CFT correspondence shown here with the arrows named NLO SYM
5. Quarkonia suppression
Hierarchy of quarkonia suppression has been observed at RHIC and LHC.

STAR, Z. Ye, QM2017

In central collisions $\Upsilon(2S+3S)$ more suppressed than $\Upsilon(1S)$
Indication for less suppression than LHC for $\Upsilon(3S)$
New: Quarkonia at 5 TeV PbPb

CMS, J. J. Lee, QM2017

- Indication of larger suppression at 5 TeV
- Consistent with predictions from a hotter and denser medium
- Highest precision measurement
- Upsilon sequential suppression at 5 TeV
- Still no sign of Y(3S) with high statistics data
J/Psi recombination at LHC?

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

STAR, Z. Miller, WWND2017
What is the right normalization for quarkonia?

1. J/Ψ AA/pp : RAA(J/Ψ)

2. J/Ψ AA/pA : RpA
   
   \[ R_{AA}(p_T) = \frac{\text{Yield}(A + A)}{\text{Yield}(p + p) \times \langle N_{coll} \rangle} \]

   (J/Ψ AA measured)/(expected from pA) (NA50)

   to subtract Cold Nuclear Matter effects (CNM)

3. (J/Ψ AA/pp) / (open charm AA/pp) :
   
   RAA(J/Ψ) / RAA(open charm)

4. (J/Ψ AA/pA) / (open charm AA/pA):
   
   (RpA (J/Ψ)) / (RpA (open charm))

Very different conclusions can be drown depending on normalization
STAR : RAA(D0) shows no suppression for peripheral collisions

* 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)
J/Psi compared to open charm - LHC

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
Measured ratio of J/\(\Psi\) to D mesons at SPS

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

The J/\(\Psi\)/(DDbar) estimate is suppressed at 1 GeV/fm\(^3\)

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

Would be nice to get \(\chi_c\) measurements at energies at or below RHIC to disentangle screening vs other mechanisms of quarkonia suppression

LHCb SMOG program will address this at ~ top SPS energy (F Fleuret et al).

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,
Example of results I:

Review: S. Bass, QM2017,
Needed developments

Review: S. Bass, QM2017,

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 ($p+A$, $d+A$, $3\text{He}+A$, $A+B$)
  - 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
6. Beam energy scan
Model used for particle ratio fits: THERMUS by J Cleymans et al

Grand canonical ensemble and strangeness canonical ensemble fits to particle ratios give consistent results for mid-central and central Au+Au collisions and disagree for peripheral collisions.
Energy scans with Heavy Ions

Future: BESII, NICA, FAIR, J-PARC
IV Conclusions and perspectives

- Several sQGP signatures observed in central Au+Au and Pb+Pb collisions at high energy at RHIC and LHC as well as previously at SPS (2000).

- We have obtained first quantitative estimates for characteristics of sQGP, like its shear viscosity, temperature, density and energy density.

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

- RHIC BESII (2019-2020), sPHENIX (2020+), eRHIC?
- LHC with future upgrades
- Further data taking and upgrades of existing experiments at RHIC, SPS and LHC, as well as new accelerator facilities and corresponding new experiments, NICA in Dubna, Russia and FAIR in GSI, Germany and J-PARC in Japan, will allow to progress in significant way in the next decades.

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
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http://indico.cern.ch/event/icnfp2017

Main topics of the Conference

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Heavy Ion Physics, Critical phenomena
Quantum Physics, Quantum Optics, Quantum Information
Cosmology, Astrophysics, Gravity, Mathematical physics

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You are warmly invited!

Workshops and Special Sessions

Workshop on Continuous Variables and Relativistic Quantum Information
Workshop on Quantum Foundations and Quantum Information
Workshop on Exotic Hadrons
Mini-workshop on New Searches in High Energy Particle Physics
Mini-workshop: Correlations and Fluctuations in Relativistic Heavy Ion Collisions
Workshop on Physics at FAIR-NICA-SPS-BES/RHIC
Special session on QCD
Special session on Astro-Cosmo-Gravity
Special Session on Super Heavy Elements
Walter Greiner Memorial Session
Spartak Belyaev Memorial Session
Helmut Oeschler Memorial Session
Backup slides
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 (MADAI Collab.)**

- Lattice: Hot QCD / BW upper/lower ranges (arXiv:1407.6387)
- Constrained by data
- Hadron gas

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FCC quarkonia

D. d Enterria, QM2017

FCC-aa ($T_0 \sim 1\text{GeV}$) 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 bb\bar{b} pairs large enough for $Y(1S)$ recombination?

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