Happy Birthday Reinhardt!
Thank you for your Enthusiasm and your Guidance!
Heavy Ion Physics at RHIC

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Outline

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II Accelerator facilities and experiments

III Selected physics results :
   1. Direct photons
   2. Collectivity, flow, vorticity, strangeness
   3. Quarkonia suppression
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   6. Future perspectives

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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 $T_c \approx 154 \pm 9$ 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).

Zero net baryon density

The transition from quarks and gluons to hadrons is believed to have taken 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 $T_{\text{critical}}$ is about 200 MeV.
Reach of accelerators in terms of initial Temperature

BNL, RHIC (2000-)
BNL, AGS (1986-)
CERN, SPS (1988-)
CERN, LHC (2009-)

U. Heinz, 0009170.pdf
The expected QCD phase diagram

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).

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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 Tc $\rightarrow$ e_{init}(crit), sqrt(s)(“crit”)
Multiquark states from QGP (Greiner et al) $\rightarrow$ ‘small QGP-lumps’
Critical fluctuations near the critical point, Tc $\rightarrow$ K/pi, <pT>, etc
Hadronic mass/width changes (Pisarski 1982) $\rightarrow$ rho etc
Charmonia suppression (Satz, Matsui 1987) $\rightarrow$ T(dissociation) of ccbar, bbbar
Jet quenching (J D Bjorken 1982) $\rightarrow$ medium density

$\rightarrow$ Goal is to achieve a combination of many signatures
But: discovery of "signatures" is not that simple
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.
Evidence for QGP at CERN, till 2000:

- ccbar suppression
- Strangeness enhancement
- $T_{\text{chem. freee out}} \sim T_{\text{critical}}$
- 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 ~2.4 GeV/fm$^3$ on
* J/Psi suppression occurs mainly at low pT

CERN press release 2000
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:

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

\( N_{\text{coll}} \): 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)

Historical result: Discovery of jet quenching at RHIC (2003)

Discovery of strongly interacting QGP:
RHIC white papers for the 4 RHIC experiments: 2005


Dihadron correlations for $p_T^{\text{trig}}=(4,6 \text{ GeV})$ and $p_T^{\text{associated}}=(2 \text{ GeV},p_T^{\text{trig}})$
Strangeness Enhancement as QGP signature

Initial idea introduced by J Rafelski:
First mentioned in:
J Rafelski, R Hagedorn, Ref TH.2969-CERN, 1980:
Strangeness enhancement and Strange Antibaryons are discussed as signature for Quark Gluon Plasma formation


Strangeness enhancement in QGP is expected due to
* The dominance of the gluonic production channel for strangeness in the QGP
* High gluon density in the QGP
* To the mass of the s quark being similar to the critical temperature T for the QCD phase transition
* Strangeness in QGP reach equilibrium values
* Effect expected to be more pronounced for strange antibaryons
Historical result: Observation of ssbar enhancement in SPS at CERN

Historical result: Observation of $s\bar{s}$ enhancement in SPS at CERN

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:
\[ \sqrt{s_{NN}} = 62, 130, 200 \text{ GeV} \]
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 $\sqrt{s_{NN}}$
- Pb+Pb 5.02, 8.16 TeV
- Xe+Xe
Current Experiments with Heavy Ion program

CMS  LHC  LHCb  STAR at RHIC

ATLAS  ALICE  PHENIX at RHIC

NA61/SHINE at SPS
III Selected physics results:

1. Direct photons
RHIC PHENIX: Direct photon excess in min bias Au+Au at 200 GeV

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 --> $T(\text{init})$ from hydrodynamic models : 300-600 MeV, depending on thermalization time

Critical d+Au check : No exponential excess in d+Au

Direct thermal photons were firmly established for the first time at RHIC
Different method: Measuring gammas via external conversions in detector material

AuAu at low pT: nearly exponential shape $T(\text{eff})$ 240 MeV $> T_c$

AuAu follows nr of collision scaling above pT 4 GeV like p+p

Wenqing Fan, ICNFP2017

Sonia Kabana, Heavy Ion Physics at RHIC, Frankfurt on Main 1st Nov 2018, Germany
Direct photons also flow

Example: viscous hydro + thermal emission

Thermal direct photons with large flow $v_2$, $v_3$: challenge for models

*PHENIX: Phys. Rev. C 91 064904 (2015) and 1405.3940*
Direct photon elliptic flow in ALICE and QM2018

- Non-zero $v_2^{\gamma,\text{dir}}$ observed for low momenta direct photons and of similar magnitude as at RHIC.

- Flow signal is close to the expected flow for decay photons.

- $1.4\sigma$ significance for hypothesis $v_2^{\gamma,\text{dir}} = 0$ for $0.9 < p_T < 2.1$ GeV/c.

- Transport and hydrodynamic models predict a smaller direct photon flow, but are consistent with the data.
ALICE direct photons

ALICE: different centralities

T(dir. phot.) at RHIC and LHC is > than critical $T_{crit} \approx 154$ MeV

The real initial $T$ of the source is higher than the measured $T$
RHIC
Theory on direct photons

C. Gale et al, 1308.2440

The 3rd dimension in these plots is cross section of photons

\[ \frac{dN^\gamma}{dy} \]

\[ \frac{dN^\gamma}{dydTd\tau} \]
LHC

Theory on direct photons

C. Gale et al, 1308.2440
* 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 $T_{\text{init}}$
Results from RHIC Beam Energy Scan: direct photons

PHENIX, Dheepali Sharma
QM2017
2. Collectivity, Flow, Strangeness
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)
v2 of D0 in Au+Au follows Number-of-Constiuent-Quarks scaling of other hadrons
-> Evidence for thermalization of u,d,s,c mesons
Small Systems
Left, pPb at high mult: $v_2/n_q$ 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.

Right, PbPb semiperiph.: $v_2/n_q$ 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.
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 $p_T$ 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?
Number of quark scaling in \(^3\)He+Au

The familiar behavior of number of quark scaling observed in Au+Au collisions is also seen in the small \(^3\)He+Au system.
Strangeness enhancement
Strange particle enhancement in AuAu 200 GeV STAR (AA) / (pp or pBe)


STAR (solid marks) vs SPS PbPb sqrt(s)=17.3 GeV (open marks)
Strangeness enhancement gets smaller as collision energy increases here from SPS 17 GeV -> RHIC 200 GeV -> LHC 2.76 TeV
**ALICE strangeness**

PbPb 2.76 TeV, p+p 7 TeV, p+Pb 5.02 TeV

The novel measurement of ALICE: consistent strangeness enhancement in pp, pPb and PbPb collisions which depends on strangeness content and cannot be reproduced by models at same time as p/π ratio.

Adds to previous measurements showing QGP signatures in small systems. These new measurements at LHC point towards possible formation of QGP matter at high Temperature and density also in small collisions systems.

Comment from ALICE paper:

"The remarkable similarity of strange particle production in pp, p–Pb and Pb–Pb collisions adds to previous measurements in pp, which also exhibit characteristic features known from high-energy heavy-ion collisions and are understood to be connected to the formation of a deconfined QCD phase at high temperature and energy density.

QGP formation also in small systems?"
Strangeness in Xe+Xe ALICE

ALICE Collab. QM2018

Same picture with new data from Xe+Xe 5.44 TeV and p+p sqrt(s)=13 TeV

p+Pb 5.02 TeV
Pb+Pb=5.02 TeV
Xe+Xe 5.44 TeV
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 definition 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?

Maximum of strangeness suppression factor

Maximum of $\lambda s$ occurs at or below initial energy density of 1 GeV/fm$^3$ (red points)

The maximum is not seen in $p+p\bar{p}$ and $e^+e^-$ collisions

Historical plot: Energy dependence of s/q
The "Horn"


"Horn" proposed as signature for the QCD phase transition occurring nearby!
Maximum seen in the K/π collision energy dependence

V Sagun et al, EPJA (2018) 54; 100
The maximum disappears at \( \mu_B = 0 \)

After extrapolating all points to \( \mu_B = 0 \) the maximum of \( \lambda \)s disappear.

This suggests that the maximum is entirely due to the finite values of \( \mu_B \).

After eliminating the effect of having different \( \mu_B \) for each point, small and large systems universally agree and depend only on initial Bjorken energy density reached in the collision.

The onset of saturation reveals the onset of the QCD phase transition (Van Hove's signature).

Dissapearance of "maximum " at µB=0 in A+A

Mu_b non-zero

Mu_b zero


Temperature and baryochemical potential collision energy dependence in A+A

STAR

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

Universal Strangeness Production

results from F. Becattini et al

P. Castorina, S. Plumari, H. Satz, 1709.02706

$s_0$ initial entropy density calculated using the Bjorken relation

\[
s_0 \tau_0 \simeq \frac{1.5A^x}{\pi R_x^2} \left( \frac{dN}{dy} \right)_{y=0}^x, \text{ with } x \sim pp, pA, AA,
\]

Gamma_s factor depends in universal way from $s_0$ for small and big systems
They calculate the initial entropy density using a parametrization of data from above figure and the Bjorken formula.
Strangeness suppression is happening only below $T_c$.

Gamma_s becomes 1 near $T_c$.

P. Castorina, S Plumari, H Satz, 1709.02706
5. Quarkonia suppression
Suppression in Au+Au Collisions

Sequential melting observed at both RHIC and LHC energies

Li Yi (STAR coll.) Santa Fe 2018
Hierarchy of quarkonia suppression has been observed at RHIC and LHC

STAR, Z. Ye, QM2017

In central collisions $Y(2S+3S)$ more suppressed than $Y(1S)$
Combined results from $Y \rightarrow e^+e^-$ and $Y \rightarrow \mu^+\mu^-$ improve precision of $Y$ measurements.

$Y \rightarrow \mu^+\mu^-$ 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)

$Y(1S) R_{AA}: 0.50 \pm 0.06 \text{ (stat.)} \pm 0.05 \text{ (sys.)}$

$Y(2S+3S) R_{AA}: 0.17 \pm 0.09 \text{ (stat.)} \pm 0.06 \text{ (sys.)}$
Upsilon Y(1S): STAR vs LHC vs models

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>

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 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: $Y(2S+3S) R_{AA}: 0.35 \pm 0.08$ (stat.) $\pm 0.10$ (sys.) ($0 < p_T < 10$ GeV/c, 0-60%)
  CMS: $Y(2S) R_{AA}: 0.08 \pm 0.05$ (stat.) $\pm 0.03$ (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)]
$p_T$ dependence of J/Psi suppression in Au+Au, Cu+Cu 200 GeV

- 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
J/ψ Suppression in Au+Au Collisions

Low $p_T$ J/ψ in central collisions:

High $p_T$ J/ψ in all centralities:

$R_{AA}(200 \text{ GeV}) < R_{AA}(2.76 \text{ TeV}) \sim R_{AA}(5.02 \text{ TeV})$

$R_{AA}(200 \text{ GeV}) > R_{AA}(2.76 \text{ TeV}) \sim R_{AA}(5.02 \text{ TeV})$

Li Yi (STAR coll.) Santa Fe 2018

J/Ψ recombination at LHC?
What is the right normalization for quarkonia?

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

2. Jpsi AA/pA : \( R_{pA} \)
   \( (J/\Psi \text{ AA measured})/(\text{expected from } pA) \) (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 drawn depending on normalization.
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/Ψ compared to open charm - LHC

"Low Pt (2-5 GeV)"\[R_{AA}\]

High Pt > 6.5 GeV\[R_{AA}\]

H. Satz, arXiv 1303.3493

J/Ψ 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

CMS

Supplementary

J/$\psi$ suppression similar to D$^0$ suppression
Jet quenching for charmonia?
First study of J/Psi/D0 suppression versus $\varepsilon$(init,Bjorken):
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$^3$ instead of 2.3 GeV/fm$^3$ and coincides with strangeness saturation onset

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

First comparison of J/Psi/D suppression and ssbar enhancement versus $\epsilon$\,(init,Bjorken):

When J/Psi suppression is quantified by J/Psi/(open charm) onset of J/Psi suppression is 1 GeV/fm$^3$, and coincides with the onset of strangeness enhancement.


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
First measurement on $R_{pAu}$ of $J/\psi$ at RHIC

- $R_{pAu}$ 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
First measurement of the Vorticity of QGP
First Vorticity measurement in AuAu 200 GeV 20-50% centrality

Average vorticity points towards the direction of the angular momentum $J(\text{sys})$ of the collision.

\[
\frac{dN}{d\cos \theta^*} = \frac{1}{2} \left( 1 + \alpha_H |\vec{P}_H| \cos \theta^* \right).
\]

$H$: Lambda/Anti-Lambda

**$P_H$: Lambda/AntiL polarization vector in the hyperon rest frame**

Average projection of the Polarization on $J(\text{sys})$ is extracted:

\[
\overline{P}_H \equiv \langle \vec{P}_H \cdot \hat{J}_{\text{sys}} \rangle = \frac{8}{\pi \alpha_H} \frac{\left\langle \cos \left( \phi^*_p - \phi \hat{J}_{\text{sys}} \right) \right\rangle}{R^{(1)}_{\text{EP}}}.
\]

Decay parameter $\alpha_{\Lambda} = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$

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sQGP vorticity measured to be maximal


Measurement of vorticity in Au+Au collisions with 20-50% centrality via the average polarization of Lambda and Antilambda.

Fluid vorticity can be calculated using the hydrodynamic relation (Becatini et al 1610.02506.)

\[ \omega = k_B T \left( \overline{P}_\Lambda + \overline{P}_{\Lambda'} \right) / \hbar, \]

With T the temperature. The vorticity found is omega = (9+1) \times 10^{-21} \text{ s}^{-1} with an additional systematic error of a factor of 2 which by far surpasses the vorticity of all known fluids.

For example solar subsurface flow has omega = 10^{-7} \text{ s}^{-1} and superfluid nanodroplets omega = 10^{-7} \text{ s}^{-1}

* The Quark Gluon Plasma produced in heavy ion collisions is
- hotter
- least viscous
- and has larger vorticity,
from all fluids ever produced in the laboratory!

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First observation of fluid vortices formed by heavy-ion collisions

PAGES 34 & 35

SUBATOMIC SWIRLS
New STAR results on global polarization of Lambda, Antilambda in Au+Au at 200 GeV

High precision measurement of a finite Lambda and Antilambda global polarization of the level of 0.1-0.5% (depending on centrality) in Au +Au at 200 GeV

Global polarization increases with decreasing collision energy
4. Jet quenching
Single hadrons
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
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 pT>2 GeV/c
$D^0$ $R_{AA}$ suppression in Au+Au collisions at 200 GeV

Using the STAR HFT silicon detector

$D^0$ at low $p_T$ is suppressed without exhibiting significant centrality dependence.

$D^0$ at high $p_T$ in Au+Au collisions is more suppressed in central collisions.
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/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

For 5<p_T<15 GeV

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->e) is less suppressed than RAA of (c->e) in pT=3-4 GeV/c
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
Measured open bottom hadron production via displaced J/ψ, D⁰ and electron decay channels in 200 GeV Au+Au collisions

✓ Strong suppression for B → J/ψ and B → D⁰ at high p_T
✓ Indication of less suppression for B → e than D → e (∼2σ): consistent with ΔE_c > ΔE_b
PHENIX B->J/Psi in Cu+Au collisions

New PHENIX results: \( \bar{c}c \) and \( \bar{b}b \) production mechanisms in \( p+p \) at 200 GeV

1805.04075

- Measurement of angular correlations of e-e, e-mu, mu-mu pairs from \( \bar{c}c \) and \( \bar{b}b \) 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
- \( \bar{c}c \) production is dominated by the NLO flavor excitation
- \( \bar{b}b \) production is dominated by the Leading Order pair production
ALICE p+Pb and Pb+Pb data at LHC

\[ R(pPb) \text{ for charged particles is compatible with 1 at high } p_T \]

No jet quenching in p+Pb

The jet quenching seen in Pb+Pb is not due to cold nuclear matter effects
Reconstructed jets
The jet cross section in p+p 200 GeV is described by NLO pQCD over seven orders of magnitude.
Hadron vs jet suppression

Jets are less suppressed than hadrons at RHIC, while in LHC they are suppressed the same.

Less out of cone radiation at RHIC?
Dijets
Dijet imbalance in STAR: $A_J$

STAR, PRL 119, 062301 (2017)

J. Putschke, STAR, QM14

Calculate $A_J$ with constituent $p_{T,\text{cut}}>2$ GeV/c

\[
A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}
\]

$p_T = p_{T,\text{rec}} - \rho \times A$

Calculate “matched” $|A_J|$ with constituent $p_{T,\text{cut}}>0.2$ GeV/c.
Au+Au di-jets more imbalanced than p+p for $p_T^{cut}>2$ GeV/c

J. Putschke, STAR, QM14
Au+Au di-jets more imbalanced than p+p for $p_T^{cut}>2$ GeV/c

Au+Au $A_J \sim p+p A_J$ for matched di-jets (R=0.4)

Quenched jet energy is recovered at low $p_T$ within a cone of R=0.4
Dijet imbalance with R=0.2

Sys. Uncertainties:
- tracking eff. 8%
- tower energy scale 2%

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

Matched Au+Au $A_J \neq p+p A_J$ for $R=0.2$ 
$\rightarrow$ (recoil) Jet broadening in 0.2 – 0.4

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.**

![Diagram showing dijet balance characterization](image)

Dijet balance (or imbalance) characterization:

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

Color decoherence can lead to large angle emission

N. Armesto et al, 1207.0984
K. Tywokiuk et al 1401.8293
$R_{AA}$ in central Xe-Xe collisions is similar to $R_{AA}$ in Pb-Pb collisions at similar multiplicity.

ALICE Collab., QM2018
Jet transport coefficient at RHIC and LHC
Extracting jet transport coefficient from data and models at RHIC and LHC

In last years the JET collaboration of groups using different models has made an important step forward evaluating for the first time q-hut with a fit to both RHIC and LHC and reaching a good agreement of all models while fitting the experimental data at RHIC and LHC.


Jet transport coefficient for a jet initiated by a light quark considered (10 GeV jet assumed). For the QGP medium viscous hydrodynamics (VISH2+1) is employed (Ohio State group).

Example of fit to pi0 in central 0-5% Au+Au and Pb+Pb for the Higher-Twist-Majumder (HT-M) model.

The model calculates the medium modified fragmentation function including multiple induced gluon emission.

Sonia Kabana, Heavy Ion Physics at RHIC, Frankfurt on Main 1st Nov 2018, Germany
Extracting jet transport coefficient from data and models at RHIC and LHC

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

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

Dashed boxes show expected values for $\sqrt{s}=0.063$, 0.130 and 5.5 TeV.
5. Beam Energy Scan (BES) -1
Chemical freeze out temperature vs baryochemical potential

Model used for particle ratio fits: THERMUS by J Cleymans et al

Grand canonical ensemble fits to particle ratios give consistent results for mid-central and central Au+Au collisions, unlike peripheral collisions.

STAR, Phys.Rev. C96 (2017) no.4, 044904
Directed flow of protons BES 1

* Directed flow slope is sensitive to a 1st order transition

* STAR: $v_1$ slope changes sign from positive to negative between 7.7 and 11.5 GeV

Pions and antiprotons have always negative $v_1$ slopes.

* Net-proton $v_1$ slope shows a minimum around 11.5-19.6 GeV

UrQMD model (model without phase transition) cannot explain the data

H Stoecker et al, Nucl. Phys A 750 (2005) 121
$R_{CP}$ of charged hadrons versus energy.

$R_{CP}$ of charged hadrons becomes smaller than 1 at 39 GeV.
6. Future
Energy scans with Heavy Ions
Future: BES-2, NICA, FAIR, HIAF, J-PARC

G. Odyniec, STAR, Corfu 2018

Collision Energy $\sqrt{s_{NN}}$ (GeV)
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 BES-2

<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>
</tr>
</thead>
<tbody>
<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>
<td>260</td>
<td>5.5 weeks</td>
<td>300M</td>
</tr>
<tr>
<td>5.75</td>
<td>11.5</td>
<td>315</td>
<td>5 weeks</td>
<td>230M</td>
</tr>
<tr>
<td>4.55</td>
<td>9.1</td>
<td>370</td>
<td>9.5 weeks</td>
<td>160M</td>
</tr>
<tr>
<td>3.85</td>
<td>7.7</td>
<td>420</td>
<td>12 weeks</td>
<td>100M</td>
</tr>
<tr>
<td>31.2</td>
<td>7.7 (FXT)</td>
<td>420</td>
<td>2 days</td>
<td>100M</td>
</tr>
<tr>
<td>19.5</td>
<td>6.2 (FXT)</td>
<td>487</td>
<td>2 days</td>
<td>100M</td>
</tr>
<tr>
<td>13.5</td>
<td>5.2 (FXT)</td>
<td>541</td>
<td>2 days</td>
<td>100M</td>
</tr>
<tr>
<td>9.8</td>
<td>4.5 (FXT)</td>
<td>589</td>
<td>2 days</td>
<td>100M</td>
</tr>
<tr>
<td>7.3</td>
<td>3.9 (FXT)</td>
<td>633</td>
<td>2 days</td>
<td>100M</td>
</tr>
<tr>
<td>5.75</td>
<td>3.5 (FXT)</td>
<td>666</td>
<td>2 days</td>
<td>100M</td>
</tr>
<tr>
<td>4.55</td>
<td>3.2 (FXT)</td>
<td>699</td>
<td>2 days</td>
<td>100M</td>
</tr>
<tr>
<td>3.85</td>
<td>3.0 (FXT)</td>
<td>721</td>
<td>2 days</td>
<td>100M</td>
</tr>
</tbody>
</table>
Luminosity improvements for BES-II

- RHIC with e-cooling and long bunches ($v_z = \pm 1m$)
- Minimum projection (e-cooling only)
- BES-I performance

### Implementation:
- 2019 - $\sqrt{s_{NN}} : 15 - 20$ GeV
- 2020 - $\sqrt{s_{NN}} : 7.7 - 11.5$ GeV
- 2021 - 

Electron cooling + longer beam bunches for BES-II provide factor 4-15 improvement in luminosity compared to BES-I

Every energy available with electron cooling

G Odyniec, STAR, Corfu 2018
Readiness of BES-II

3 year BES-II program 2019-2021 just starting

First BES-II run in 2019

run19: 19 and 14.5 GeV - will start from higher energies
run 20: 11.5, 9.1, 7.7 (part of ) GeV - electron cooling available from 2020
run21: 7.7 GeV (finish)

STAR and STAR upgrades will be ready to take data on time

iTPC and eTOF installation will be completed before March 2019
EPD already installed and commissioned in 2018 run
Future of STAR at a glance:

STAR BES-2 2019-:
    Avatar of FAIR-NICA physics

STAR and forward rapidity program 2021-:
    Avatar of EIC physics (+10 years)
* New detector project at RHIC: sPHENIX

sPHENIX: start data taking 2022

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

M. Connors,
If QGP forms in all collision systems that reach above critical energy density, still some QGP signatures may not show up in small systems.

For example, volume in pp and pA at present collision energies may not be large enough for some signatures to develop (quarkonia suppression, jet quenching...)

What will be at the FCC?
IV Conclusions

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

- Some QGP signatures and collectivity are seen also in small systems p+p, p+A, small nuclei

Universality picture emerging

- Obtained quantitative estimates for characteristics of sQGP, like its shear viscosity, temperature, density and critical energy density. The sQGP has a temperature more than 100000 the T of the core of the sun, has the smallest shear viscosity and the largest vorticity measured in fluids in the Lab.
IV Conclusions

Focus of next years in many facilities:

**Energy scans**

- RHIC BESII (2019-2020), sPHENIX (2020+), CERN SPS
- 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 p+p at sqrt(s)=100 TeV, Pb+Pb at sqrt(s)=39 TeV.
Thank you very much
Happy Birthday Reinhardt!

Reaching into the future

Sonia Kabana, Heavy Ion Physics at RHIC, Frankfurt on Main 1st Nov 2018, Germany
Backup slides
Inner sectors upgrade

One sector has been installed in October 2017, data collected in 2018.

The outer pad plane have continuous tracking... while the inner pad plane is not:

- Increase the segmentation on the inner pad plane, new electronics for inner sectors
- Renew the inner sector wires which are showing signs of aging

Better momentum resolution, better dE/dx resolution, and improved acceptance at high $\eta$:

Old: $-1 < \eta < 1$  
New: $-1.5 (-1.7) < \eta < 1.5 (1.7)$
Table 8: Event statistics (in millions) needed in BES-II for various observables. This table updates estimates originally documented in Ref. [45].

<table>
<thead>
<tr>
<th>Collision Energy (GeV)</th>
<th>7.7</th>
<th>9.1</th>
<th>11.5</th>
<th>14.5</th>
<th>19.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_B$ (MeV) in 0-5% central collisions</td>
<td>420</td>
<td>370</td>
<td>315</td>
<td>260</td>
<td>205</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observables</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{CP}$ up to $p_T = 5$ GeV/c</td>
<td>-</td>
<td>160</td>
<td>125</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>Elliptic Flow ($\phi$ mesons)</td>
<td>80</td>
<td>120</td>
<td>160</td>
<td>160</td>
<td>320</td>
</tr>
<tr>
<td>Chiral Magnetic Effect</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Directed Flow (protons)</td>
<td>20</td>
<td>30</td>
<td>35</td>
<td>45</td>
<td>50</td>
</tr>
<tr>
<td>Azimuthal Femtoscopicity (protons)</td>
<td>35</td>
<td>40</td>
<td>50</td>
<td>65</td>
<td>80</td>
</tr>
<tr>
<td>Net-Proton Kurtosis</td>
<td>70</td>
<td>85</td>
<td>100</td>
<td>170</td>
<td>340</td>
</tr>
<tr>
<td>Dileptons</td>
<td>100</td>
<td>160</td>
<td>230</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>$&gt;5\sigma$ Magnetic Field Significance</td>
<td>50</td>
<td>80</td>
<td>110</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td><strong>Required Number of Events</strong></td>
<td>100</td>
<td>160</td>
<td>230</td>
<td>300</td>
<td>400</td>
</tr>
</tbody>
</table>

+100M for each FXT energy

Typically factor 20 more than for BES-I

STAR BES-II goals
STAR forward rapidity program

3 Silicon discs

4 Small-strip Thin Gap Chambers

ECal: use upgraded PHENIX PbSc calorimeter

HCal: Iron-scintillator
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