HEAVY ION PHYSICS WITH FLOW IN LARGE AND SMALL SYSTEMS

MÁTÉ CSANÁD, EÖTVÖS UNIVERSITY, BUDAPEST, HUNGARY

ICNFP 2019, AUGUST 21-29, CRETE, GREECE

PHoenix
CONTENT OF THIS TALK

• INTRODUCTION
  • The Big Bang and the Little Bangs in the lab
  • Experimental control parameters
  • RHIC and PHENIX

• BASIC OBSERVATIONS
  • Nuclear modification, flow, thermal photons, heavy flavor, HBT, fluctuations

• FLOW IN SMALL SYSTEMS
  • d+Au energy scan, p+Pb and p+p at the LHC
  • p/d/³He geometry scan
  • Smallest droplets of QGP
BIG BANG IN THE LAB

- Ages of the Universe:
  - Stars & Galaxies
  - Atoms
  - Nuclei
  - Nucleosynthesis
  - Elementary particles
  - …?

- How to investigate?
  - Create little bangs
  - Collisions of heavy ions
  - Record outcoming particles
TIMELINE OF A HEAVY ION COLLISION

- Pre-thermalization stage: ~1 fm/c
- Quark-hadron transition: ~7-10 fm/c
- Chemical + kinetic freeze-out
• Initial stage:
  • Hard scattering
  • Jet formation

• Leptons, photons:
  • ”shine through”

• Hadrons:
  • Dissociation and coalescence
  • ”Final” hadrons created at freeze-out

• How do we know if sQGP was there or not?
EXPERIMENTAL CONTROL PARAMETERS

• Collision energy: controls initial temperature, initial $\mu_B$
• Collision system & centrality: controls available volume
• Event geometry: reaction plane, event plane, fluctuations
• Important parameters: $N_{\text{part}}$ (system size), $N_{\text{coll}}$ (x-sect)

Central Au+Au $N_{\text{part}} \sim 300$
Peripheral Au+Au $N_{\text{part}} \sim 50$
$\text{d}+\text{Au}$
$p+p$

Reaction Plane
FACILITIES: LARGE HADRON COLLIDER (+SPS)

- LHC collisions: p+p, p+Pb and Pb+Pb
- Energies: from 2.76 TeV/nucleon to 13 TeV (p+p only)
- Experiments: ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL, TOTEM
- Phase diagram related studies: SPS (NA61/SHINE, previously NA49)
THE RELATIVISTIC HEAVY ION COLLIDER

- At the Brookhaven National Laboratory, Long Island, New York, USA
- Collisions of: \( \bar{p}, d, ^3\text{He}, Al, Cu, Au, U \)
- Accelerator energies: 7.7-200 GeV/nucleon, even 0.5\,\text{TeV} for \( \bar{p} \)
- Experiments: STAR; future: sPHENIX; past: BRAHMS & PHOBOS & PHENIX
PHENIX AND sPHENIX

- PHENIX: versatile detector identifying many different particles, recording large amount of collisions. Dismantled in 2016, to give way to sPHENIX
- sPHENIX: to take data in ~2023
  - Jets, jet correlations, Upsilon states
  - EM+Hadronic calorimetry, high resolution tracking, fast (~100 kHz) data acquisition
THE RHIC BEAM ENERGY/SPECIES SCAN

- Collision experiments: acceptance independent of energy
- **BES-I**: 7.7-200 GeV; **BES-II**: 7.7-19.9 GeV, increased luminosity
- **Small system scan**: x+Au, 19.6-200 GeV
- **STAR fixed target mode**: down to 3 GeV

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<td>19.6</td>
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<td>d+Au</td>
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</table>
QGP SIGNATURES EXPECTATIONS, 1996

- Critical energy density: $\epsilon_c \approx 1 \text{ GeV/fm}^3$, temperature $T_c \approx 170 \text{ MeV}$
- Some observed, some not…

NUCLEAR MODIFICATION: TOMOGRAPHY!

Simply just more?  
A+A = many p+p?

\[ R_{AA} = \frac{\text{High } p_T \text{ particle yield in } A+A}{\text{High } p_T \text{ particle yield in } p+p \times \text{Number of } p+p \text{ collisions}} \]
SUPPRESSION AS A FUNCTION OF CENTRALITY

- No suppression in d+Au or peripheral Au+Au; strong suppression in central!

**Graph: PHENIX**

- $\pi^0$ 0-5% Ce
- d+Au


Enhanced

Suppressed
SUPPRESSION OF THE AWAY SIDE JET

- Angular correlation of high energy hadrons
- Outgoing jet: similar in p+p, d+Au, Au+Au
- Inward going (away side) jet: missing in central Au+Au
HOW DO OTHER PARTICLES BEHAVE?

- All hadrons suppressed, direct photons „shine through”
- Suppression dependent of system size (controlled by centrality or $N_{\text{part}}$)

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**PHENIX Au+Au $\sqrt{s_{NN}}=200$ GeV**

**Phys.Rev.Lett. 94 (2005) 232301**

- **$R_{AA}$**
  - **$p_T > 6.0$ GeV/c**
  - **$N_{\text{participant}}$**

**Data Sources:**
- Direct $\gamma$ (PRL109, 152302)
- $J/\psi$ 0-20% cent. (PRL98, 232301)
- $\pi^0$ (PRL101, 232301)
- $\omega$ 0-20% cent. (PRC84, 044902)
- $\eta$ (PRC82, 011902)
- $e^{+}\pi^{-}$ (PRC84, 044902)
- $\bar{p}$ (PRC83, 064903)
- $p$ (PRC83, 064903)
Spatial anisotropy creates momentum-space anisotropy!

Quantified via anisotropy parameters

\[
f(\phi) = 1 + 2 \sum_{n} v_n \cos n\phi
\]
ELLIP Tic FLOW SCALING

- Hydro predicts scaling ($v_2$ versus $w \sim E_K/T_{eff}$)

- Coalescence predicts quark number scaling
  
  $E_{K{hadron}} = n_q E_{K{quark}}$

  $v_n^{hadron}(E_{K{hadron}}) \cong n_q v_n^{quark}(E_{K{quark}})$

- Flow develops in pre-hadronic stage!

**References**

- Csanád, Csörgő, Lörstad, Ster et al. (EPJA38:363-368,2008)

**Graphs**

THERMAL PHOTONS

- Soft component in direct photon spectrum compared to p+p extrapolation
- These are thermal photons!
- Large initial temperature, 3-600 MeV!
ELLIPTIC FLOW IN D+AU AT RHIC

- Deuteron-gold energy scan (19.6-200 GeV), PHENIX, PRC96, 064905 (2017)
- superSONIC in good agreement at 62.4 GeV and 200 GeV
- Underpredicts data at 19.6 GeV and 39 GeV
- Data still contains nonflow effects: AMPT(EventPlane) w/ nonflow matches
ELLIPTIC FLOW IN P+PB AT THE LHC

- Identified particle elliptic flow, ALICE pPb @ 5.02 TeV, from pions to Λ’s
- Quark number scaling works well; LHC pPb not so small system though…

V. Pacik (ALICE), Quark Matter 2018

p-Pb $\sqrt{s_{NN}} = 5.02$ TeV
$|\eta| < 0.8$

$0.25$
$0.2$
$0.15$
$0.1$
$0.05$
$0.02$
$0$

$0$
$1$
$2$
$3$
$4$
$5$
$6$
$7$

$p_T$ (GeV/c)

$0$
$0.5$
$1$
$1.5$
$2$
$2.5$
$3$
$3.5$

$(m_T - m_0) / n_q$ (GeV/c)
FLOW IN 13 TEV P+P AT CMS

- No mass ordering in low multiplicity p+p ($v_2$ due to jets)
- Mass ordering, quark number scaling in high multiplicity pp


- Note: initial energy density may reach 1 GeV/fm$^3$ already around $N_{ch}=10$

Csanád et al., Universe 3 (2017) no.1, 9
ORIGIN OF FINAL STATE COLLECTIVITY?

- Is it due to the appearance of the sQGP (i.e. a strongly coupled fluid)?
  - If yes, how much time is needed to spend in QGP phase?
  - Test: d+Au collisions from 20 to 200 GeV
- Is it due to initial geometry and hydro?
  - Hydrodynamics: initial spatial correlations
  - Alternative: initial momentum correlations
  - Test: p+Au, d+Au, \(^3\)He+Au
  - How do \(v_2\) and \(v_3\) evolve with initial state geom.?
INITIAL STATE AND HYDRO EVOLUTION

• Evolution from SONIC

• Initial stage:

\[
\epsilon_2^{p+Au} < \epsilon_2^{d+Au} \approx \epsilon_2^{^3He+Au} \\
\epsilon_3^{p+Au} \approx \epsilon_3^{d+Au} < \epsilon_3^{^3He+Au}
\]

\[\langle \epsilon_2 \rangle \quad \langle \epsilon_3 \rangle\]
Flow ordered similarly as initial state:

\[ v_2^{p+Au} < v_2^{d+Au} \approx v_2^{3\text{He}+Au} \]

\[ v_3^{p+Au} \approx v_3^{d+Au} < v_3^{3\text{He}+Au} \]
COMPARISON TO HYDRO CALCULATIONS

- Hydro calculations
- Both 2+1D, $\eta/s = 0.08$, MCGlauber initial cond.
- Different hadronic rescattering

\[ v_2 \text{ Data} \]
\[ v_3 \text{ Data} \]
\[ v_n \text{ SONIC} \quad \text{(Eur. Phys. J. C 75, 15 (2015))} \]
\[ v_n \text{ iEBE-VISHNU} \quad \text{PRC 95, 014906 (2017)} \]
IS THERE AN ALTERNATIVE EXPLANATION?

- Hydro: initial state spatial correlations a.k.a. geometry

- Alternative: initial state momentum correlations
ALTERNATIVE MODEL VS DATA

- MVST postdiction (Mace, Skokov, Tribedy, Venugopalan, PRL121, 052301)
- Before erratum: reasonable $v_2$ description, misses $v_3$ ordering
ALL MODELS VS DATA

- Hydro description much better already ,,by eye”
- Tools for discrimination: confidence level
- MVST: multiplicity dependence; test $v_2$ at same $dN/d\eta$

$\sqrt{s_{NN}} = 200$ GeV 0-5%  

PHENIX

$\nu_2$ Data  
$\nu_3$ Data
$\nu_n$ SONIC  
$\nu_n$ iEBE-VISHNU  
$\nu_2$ MSTV  
$\nu_3$ MSTV

arXiv:1805.02973
SUMMARY

• Clear consensus on a list of QGP signs found in nucleus-nucleus collisions
  • Suppression, flow, thermal photons

• Strong evidence for QGP droplets in small systems
  • Quark number scaling works in p+Pb, mass ordering already in pp
  • Hydro works well in p/d/³He+Au

M. Csanád (Eötvös U) @ ICNFP 2019
THANK YOU FOR YOUR ATTENTION

If you are interested in these subjects, come to our Zimányi School 2019
December 2-6., Budapest, Hungary

http://zimanyischool.kfki.hu/19
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BACKUP SLIDES
HOW TO INVESTIGATE THESE LITTLE BANGS?
COLLISIONS OF DIFFERENT CENTRALITY

Peripheral --> Central
FACILITIES: LARGE HADRON COLLIDER (+SPS)

- LHC collisions: p+p, p+Pb and Pb+Pb
- Energies: from 2.76 TeV/nucleon to 13 TeV (p+p only)
- Experiments: ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL, TOTEM
- Phase diagram related studies: SPS (NA61/SHINE, previously NA49)
EXPLORING THE PHASE MAP OF QCD

• Phase map: temperature versus matter excess (baryochem. pot. $\mu_B$)

• Control parameters:
  • Collision energy, system
  • Collision geometry

• Crossover at low $\mu_B$ and $T \approx 170$ MeV

• Probably 1st order quark-hadron p.t. at high $\mu_B$ (NJL, bag model, etc)

• Critical End Point (CEP) in between?

• High $\mu_B$: nuclear matter, neutron stars, color superconductors…

• Phase transition importance: even in core-collapse supernovae!
• With Blast-Wave fits
• Predictions for not fitted particles agree well
• Flow in all systems!

STAR Collaboration, PRC93, 014907 (2016)
SUPPRESSION IN THE BEAM ENERGY SCAN

- \( R_{CP} \) analyzed here instead of \( R_{AA} \), transition to above one with coll. energy
- Hadron enhancement: Cronin-effect, radial flow, coalescence domination
- Competing effects, HIJING reproduces enhancement w/o jet quenching
- Identified particles: less suppression for kaons, enhancement for protons

SEARCH FOR THE CRITICAL POINT POSSIBLE?

- Effects of the CEP in a broad region (via an effective potential $\sim N_f=2$ QCD)

- Hydro evolution attracted to the critical point
STAR: UPGRADES AND FIXED TARGET PROGRAM

- Large acceptance, great PID capabilities: great for identified hadrons
- Upgrades for BES-II
  - innerTPC: better dE/dx (PID) and momentum resolution, by 2019
  - Event Plane Detector: replace BBC, better triggering & EP resolution, by 2018
  - Endcap TOF: extended fwd PID, by 2019
- Fixed target program: 1 cm wide, 1mm thick target at 2.1 m
- At the lowest energies: out to $\mu_B > 700$ MeV
• Reach down to 3 GeV in center of mass energy!

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<th>Fixed Target Coll. Energy</th>
<th>Single Beam C.M. Energy</th>
<th>Rapidity</th>
<th>$\mu_B$(MeV)</th>
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Energies unreachable in collider mode
FUTURE FACILITIES: NICA, FAIR, J-PARC HI

- New facilities planned/built
- NICA: 2020, MPD&BM@N
- FAIR: 2022, CBM
- J-PARC HI: 2025, JHITS
(FUTURE) FACILITIES COMPARISON

- Many future facilities and experiments, SPS and RHIC already running
- RHIC, NICA: Collider and fixed target
- SPS, FAIR, J-PARC: fixed target
- Energy ranges from 2 to 20 GeV in $\sqrt{s_{NN}}$

Compilation from Daniel Cebra and Olga Evkidomiv:

<table>
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<tr>
<th>Facility</th>
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<td>10 MHz</td>
<td>10-100 MHz</td>
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HEAVY FLAVOR SUPPRESSION & REGENERATION

- Timeline: quarkonium ($q\bar{q}$) formation $\rightarrow$ QGP evolution $\rightarrow$ $q\bar{q}$ decay
- Quarkonia experience the whole QGP evolution, competing processes
- Suppression due to color-screening: temperature and size/mass dependence

- Statistical regeneration in time:

Images from J Castillo, SQM17 and A Mócsy, HardProbes2009
CONTROL EXPERIMENT: D+AU COLLISIONS

- Suppression in Au+Au collisions: 1st milestone
- Lack of suppression in d+Au: 2nd milestone
- Two PRL covers

Zajc, Riordan, Scientific American
RHIC recorded runs and luminosity

RHIC energies, species combinations and luminosities (Run-1 to 17)

Center-of-mass energy $\sqrt{s_{NN}}$ [GeV] (scale not linear)

Species combination:
- $p^+ + p^+$
- $p^+ + Al$
- $p^+ + Au$
- $d + Au$
- $h + Au$
- $Cu + Cu$
- $Cu + Au$
- $Au + Au$
- $U + U$

Average store luminosity $L/N [10^{30} cm^{-2} s^{-1}]$
FREEZE-OUT FROM PARTICLE YIELDS

- Chemical and kinetic freeze-out parameters via THERMUS and BlastWave
- Thermal multiplicity assumption valid
- Systematics investigated (parameter constraints, included species)
- Separation of $T_{\text{ch}}$ and $T_{\text{kin}}$ around $\sqrt{s_{NN}} = 4-5$ GeV, $T_{\text{ch}}$ flattens at $\sim 10$ GeV

\[ \sqrt{s_{NN}} = 4-5 \text{ GeV}, T_{\text{ch}} \text{ flattens at } \sim 10 \text{ GeV} \]

EVEN HEAVY FLAVOR FLOWS!

- Electrons from heavy flavor measured
- Even heavy flavor is suppressed
- Even heavy flavor flows
- Strong coupling of charm & bottom to the medium
- Small charm & bottom relaxation time in medium and small viscosity
VISCOSITY

- Viscosity/entropy density: proportional to mean free path
- Strong coupling: small $\eta/s$
- $\text{AdS}_{D+1}/\text{CFT}_D$ lower bound: $\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$
- Measurement and calculation results:
  - A. Adare et al. (PHENIX), PRL98:172301, 2007
J/ψ IN THE BEAM ENERGY SCAN

- Regeneration from c\bar{c} and feed-down from \chi_c and \psi', increases with \sqrt{S_{NN}}

- Screening and cold nucl. matt.: less primordial charmonium with increasing \sqrt{S_{NN}}

- Two effects seem to compensate for \sqrt{S_{NN}} < 200 GeV

QUARK PARTICIPANT SCALING

- Transverse energy and particle number: not constant vs Npart!
- Number of quark participants: a better estimator, quark degrees of freedom?

![Graphs showing transverse energy and particle number scaling vs Nqp for different collision energies.](image)
STATISTICAL TEST OF ALL MODELS

- QGP droplet and hydro describes data the best; MSVT close to marginal

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<th>d+Au</th>
<th>3He+Au</th>
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<td>2.67x10^{-43}</td>
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MVST PREDICTION FOR FIXED MULTIPLICITY

• Compare similar collision systems
  • d+Au 20-40% ($dN/d\eta = 12.2 \pm 0.9$)  
    PRC 96, 064905 (2017)
  • p+Au 0-5% ($dN/d\eta = 12.3 \pm 1.7$)  
    PRC 95, 034910 (2017)

• Fixed multiplicity:  
  same MVST prediction for $v_2$

• Hydro description:  
  better qualitative agreement  
  (same multiplicity scales with eccentricity)

• Note: no nonflow systematics  
  estimate in d+Au ($\leq$ than in p+Au)
FROM PP THROUGH PPB TO PbPb

- ALICE, arXiv:1903.01790
- A given hydro does not describe pp very well, still better than Pythia
DIRECT PHOTONS

- Clear direct $\gamma$ signal at lower energies
- Yield scaling from RHIC to LHC, transition from $p+p$, to $A+A$: $p+Au$, $d+Au$
- Effective photon temperature similar from 39 to 2760 GeV
- Note overlapping mechanisms: hadron gas, sQGP, jets, bremsstrahlung, hard scatt.
SUPPRESSION IN HIGHLY ASYMMETRIC SYSTEMS

- p+Au, d+Au, \(^3\)He+Au compared
- Centralities determined as for large systems
- New p+Au results show large centrality dependence
- System sizes agree at high \(p_T\)
- At moderate \(p_T\), ordering seen
- Model comparison:
  - Vitev, HIJING++ investigated
  - No full match of ordering, peak location, etc