HI possibilities at forward rapidity (in fsPHENIX)

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What stated here is solely my thought, and not an official sPHENIX perspective.

My goal is to draw your attention to interesting physics that can be performed at forward / backward rapidity at RHIC
  ◦ I’ll focus on A+A case

I’m not presenting full feasibility of this physics in the currently planned sPHENIX / fsPHENIX detector complex
HI collision dynamics

- Gold ions pass through each other
  - High-\(x\) partons fly away
  - Low-\(x\) gluons remain in the mid-rapidity (\(y=0\)), and create “gluon matter” (CGC?)

- CGC → Gluon Plasma → QGP → Mixed phase → Hadronization + expansion
  - Transition temperature (quark to hadron) : \(T_{\text{chem}} \approx 180\text{MeV}\)

Parameters
At Hadronization: \(T_{\text{chem}}, \mu_b\)
At Expansion: \(T_{\text{kin}}, \beta\)
HI collision dynamics question (I)

- Is this picture correct?

- How the Quark Gluon Plasma develops from the initial A+A collisions to the freezeout?
  - Time evolution of the Quark Gluon Plasma
  - Initial condition, etc.

Parameters
At Hadronization: $T_{\text{chem}}$, $\mu_b$
At Expansion: $T_{\text{kin}}$, $\beta$

Gluon Plasma  QGP phase  Mixed phase  Hadronization + Expansion
HI collision dynamics question

- The system expands longitudinally (beam direction) as well as transversely (normal to beam direction)
- Question is whether the expansion is isotropic (and uniform)?
HI collision dynamics question

- The system expands longitudinally (beam direction) as well as transversely (normal to beam direction)
- Question is whether the expansion is isotropic (and uniform)?

These questions can be answered by looking at observables at forward/backward rapidities
Selected results at mid-rapidity
1. Particle flow

- In non-central collisions, the collision area is not isotropic
  - Different pressure gradient produces momentum anisotropy of particles
  - 2nd order Fourier coefficient shows the elliptic flow

- Fluctuation of nucleon position yields higher order anisotropy
  - Higher order flow ($v_3$, $v_4$, ... $v_n$) are sensitive to the properties of the matter
  - e.g. Shear viscosity ($\eta$) to Entropy density ($s$) ratio ($\eta/s$)

\[
\frac{dN}{d(\phi - \Psi_n)} = N_0 [1 + 2 \sum_{n=1}^{\infty} v_n \cos{n(\phi - \Phi_n)}]
\]

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

$\Phi_n$: Event Plane
$v_n$ results with hydrodynamics model

- PHENIX (RHIC) and ATLAS (LHC) $v_n$ with a hydrodynamics model
  - QGP as fluid consisting of partons

- The model reproduces the higher order flow at RHIC, LHC very well
  - Almost perfect fluid is realized at RHIC ($\eta/s$ from quantum limit: $\sim 1/4\pi$)

B. Schenke, S. Jeon and C. Gale, PRC 85, 024901 (2012)

C. Gale et al., PRL 110, 012302 (2013)
2. Jet energy loss

- High $p_T$ hadrons ($\pi^0$ etc.) are leading particles from jets (hard scattered partons)
  - A large fraction of jet momentum are carried
- Energy loss is turned into the yield suppression of high $p_T$ hadrons

Energy loss = Yield suppress

$\pi^0$ without energy loss
$\pi^0$ with energy loss

Gamma

Energy loss = Yield suppress

$0 \leq p_T \leq 20$ GeV/c

Yield suppression of leading particles

- Nuclear Modification Factor \( (R_{AA}) \)
  - \( (\text{Yield in A+A collision})/(\text{Yield in p+p collision } \times \text{Ncoll}) \)
  - \( R_{AA} = 1 \): No nuclear effect
  - \( R_{AA} < 1 \): Suppression due to energy loss, etc.

\[
R_{AA} = \frac{N_{\text{coll}} \left( \frac{d^3N}{dp^3} \right)_{AA}}{\sigma_{\text{inel}} \left( \frac{d^3\sigma}{dp^3} \right)_{pp}}
\]

\( \pi^0 \) and \( \eta \), PHENIX, PRC82, 011902(R) (2010)

\( \pi^0 \), PRL 101, 232301(2008)

Au+Au Minimum Bias \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

PHENIX
3. Temperature was high (photons)

- $$T_{\text{ave}} = 239 \pm 25\, \text{(stat)} \pm 7\, \text{(syst)} \, \text{MeV (0-20\%)}$$
- c.f. LHC, Pb+Pb 2.76 TeV: $$T_{\text{ave}} = 304 \pm 51\, \text{(stat+syst)} \, \text{MeV (0-40\%)}$$

*Phase transition would occur at $$T \sim 180 \, \text{MeV}$$

Direct photon spectra

- Virtual photon

PRC91, 064904 (2015)

Thermal photon spectra

- $$239 \pm 25\, \text{(stat)} \pm 7\, \text{(syst)} \, \text{MeV}/c$$

$$0-20\%$$
Going forward
fsPHENIX

GEM tracking stations

Restacked PbSc EM Calorimeter from PHENIX (1.4<\(\eta\)<3.3)

PbW (reuse of PHENIX MPC) 3.3<\(\eta\)<4.0

New PbSc Hadronic Calorimeter (1.2<\(\eta\)<4.0)
fsPHENIX (w HI-wish detector)

GEM tracking stations

PbW (reuse of PHENIX MPC)
3.3<\(\eta\)<4.0

New PbSc Hadronic Calorimeter (1.2<\(\eta\)<4.0)

Time-Of-flight for PID (and pre-shower?)

Restacked PbSc EM Calorimeter from PHENIX (1.4<\(\eta\)<3.3)
Detectors for forward HI physics

- Maybe peripheral to semi-central collisions are the targets
  - Central is impossible because of multiplicity

- Instrumentation both forward and backward, ideally
  - In order to perform wide-rapidity correlation measurement
  - We can do forward-central correlation, too

- EMCal with good position/energy resolution
  - Higher granularity; $\pi^0$ and/or $\eta$, single photon separation is needed

- Good tracking in high multiplicity environment

- A device to separate $\pi/K/p$ (if possible)
  - $K/p$ separation may be enough, assuming $\pi^0$ is well identified down to low $p_T$ in EMCal
  - A candidate device is time-of-flight?
Inclusive measurement
3D scan of QGP

- Mid- and forward rapidity have different $\mu_b$
  - Possibility of exploring different path in phase diagram
    - BRAHMS, PRL90, 102301 (2003)

- There are $p_T$ spectra for $\pi/K/p$ in Au+Au, Cu+Cu @200GeV
  - Particle ratios (related to $T_{chem}$ and $\mu_b$), $T_{kin}$ and $\beta$ scale with $N_{part}$ (dN/dy)
    - BRAHMS, PRC94, 014907(2016)

- How about the temperature at forward rapidity?

![Diagram showing 3D scan of QGP with different y values and $\mu_b$ values](image)
Jet suppression tells size of the matter

- Degree of the suppression can tell how much matter that the hard scattered partons passed through

- Interesting to see more continuously over rapidity
  - Need large statistics

Flow tells “liquidity” of the system

- State-of-art hydrodynamical calculations were compared with $v_2$ measurement by PHOBOS
- Without changing shear viscosity as a function of temperature (assumed), the data is not reproduced
  - Shear viscosity = “liquidity”
- More differential measurement help determine spatial structure
  - Higher order flow, and their fluctuation, etc.

G. Denicol, A. Monnai, and B. Schenke, PRL116, 212301(2016)
Rapidity correlation measurement
Before QGP = CGC?

- The collision area is full of gluons in the very initial stage
  - Gluon plasma $\rightarrow$ q-qbar $\rightarrow$ QGP

- At very high energy, the small $x$ gluons increasing exponentially, which eventually violates unitarity
  - Small $x$ gluons have to merge and turn into higher $x$ gluons

- **Color Glass Condensate (CGC)**
  - In highly non-linear state and has strong correlation

- Hadron yield will be reduced in low $p_T$ at forward (backward) rapidity
  - Small $x$ region

\[ E^z = ig[\alpha_1^i, \alpha_2^j] \]
\[ B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j]. \]
CGC explains the p+A flow?

- Strong correlation from the initial high density gluonic state (CGC) may have survived until final state

- Part of the $v_2$ measured in p+Pb collisions at LHC can be explained, but not perfect
  - No quantitative calculation is shown for RHIC

A. Dumitru et al, PLB697 (2011)21
K. Dusling and R. Venugopalan, PRD87, 094034(2013)
Rapidity correlation is important!

- It is said that the correlation of particles with large rapidity gap comes from the initial state of the collisions
  - Simple causality argument (e.g. arXiv:1412.0471)

- Using this fact, one can dial the time in the system evolution
  - e.g. CGC, pre-equilibrium state
Using A+A and p+A

One can dial the time in the system evolution

Both particles in very forward rapidity: tuning to very initial stage: CGC

\[ z_T = \frac{p_{Ta}}{p_{Tt}} \]
\[ \xi = \ln\left(\frac{1}{z_T}\right) \]

\( h^{+/−} \): e.g. \( \pi^0 \)
Using A+A and p+A

- One can dial the time in the system evolution

Both particles in mid rapidity: tuning more into later stage: CGC+QGP

\[ z_T = \frac{p_{Ta}}{p_{Tt}} \]
\[ \xi = \ln(\frac{1}{z_T}) \]

[Diagram with vectors and arrows, labeled as away-side and h^±, and an orange square.]
Taking flow ($v_2$) as an example

- If there is no hydrodynamical flow in p+A, i.e., the flow is built only by CGC (left)

\[
\Delta \eta = \eta_1 - \eta_2
\]

- If there is hydrodynamical flow in p+A, i.e., the flow is built by CGC+QGP (right)

\[
\Delta \eta = \eta_1 - \eta_2
\]
Some news from QM2017
STAR Rapidity Correlations in BES

- Two-particle correlation of pion pairs
- Charge independent new ridge structure observed at around $\sqrt{s_{NN}} = 19.6$ and 27 GeV → no ridge at higher/lower energies

Slides and data from A. Schmah (STAR) at QM17

3/10/2017  T. Sakaguchi @ RSC meeting at BNL
Consequence of longitudinal fluctuation

Event plane de-correlation

Event plane twist

(a) $N^F_{\text{part}} \neq N^B_{\text{part}}$

(b) $\varepsilon^F_2 \neq \varepsilon^B_2$

(c) $\Psi^F_2 \neq \Psi^B_2$

Event-by-Event Multiplicity
Fluctuations along $\eta$.

EbE Flow fluctuations, in magnitude and direction along $\eta$.

3-D initial condition!

ATLAS Collaboration
arXiv:1606.08170

Slides and data from S. Mohapatra (ATLAS) at QM17
De-correlation/twist measured by ATLAS

Flow Vector
\[ q_n \equiv \frac{\sum_i w_i e^{i n \phi_i}}{\sum_i w_i} \equiv q_n e^{i n \eta} \]
Correlate \( k \)th power of \( n \)th order flow-vector (\( k = 1, 2, 3 \))

\[ r_{n|n;k} = \frac{\langle q_n^{k}(-\eta)q_n^{\ast k}(\eta_{ref}) \rangle}{\langle q_n^{k} (+\eta)q_n^{\ast k}(\eta_{ref}) \rangle} \]
This correlator is sensitive to both, twist as well as magnitude decorrelation

\[ r_{n|n;k} \approx 1 - 2k F_{n;k}^{r} \eta \]
\[ F_{n;k}^{r} = F_{n;k}^{asym} + F_{n;k}^{twist} \]

\[ R_{n,n|n,n} = \frac{\langle q_n (-\eta_{ref})q_n (-\eta)q_n^{\ast} (+\eta)q_n^{\ast} (\eta_{ref}) \rangle}{\langle q_n (-\eta_{ref})q_n (+\eta)q_n^{\ast} (-\eta)q_n^{\ast} (\eta_{ref}) \rangle} \]
This correlator is sensitive only to the event-plane twist

\[ R_{n,n|n,n} \approx 1 - 4F_{n;2}^{twi} \eta \]

Slides and data from S. Mohapatra (ATLAS) at QM17

n=2 case
De-correlation/twist measured by ATLAS

Flow Vector \[ q_n = \frac{\sum_i w_i e^{i \eta_i}}{\sum_i w_i} = q_n e^{i \eta_n} \]

Correlate \( k \)-th power of \( n \)-th order flow-vector (\( k=1,2,3 \))

\[ r_{n|n;k} = \frac{\langle q_n^k(-\eta)q_n^*(\eta_{ref}) \rangle}{\langle q_n^k(+\eta)q_n^*(\eta_{ref}) \rangle} \]

This correlator is sensitive to both, twist as well as magnitude decorrelation.

r_{212.1} vs \( \eta \)

More de-correlation/twist seen in lower energy RHIC would see more drastic effect?

\[ R_{n,n|n,n} = \frac{\langle q_n(-\eta_{ref})q_n(-\eta)q_n^*(-\eta)q_n^*(\eta_{ref}) \rangle}{\langle q_n(-\eta_{ref})q_n(+\eta)q_n^*(+\eta)q_n^*(\eta_{ref}) \rangle} \]

This correlator is sensitive only to the event-plane twist

\[ R_{n,n|n,n} \approx 1 - 4F_{n;2}^{twi} \eta \]

Slides and data from S. Mohapatra (ATLAS) at QM17

3/10/2017  T. Sakaguchi @ RSC meeting at BNL
Decorrelation not seen at RHIC?

Slides and plots from H. Nakagomi (PHENIX) at QM17
Decorrelation not seen at RHIC?

Initial geometry seems to be identical between forward and backward rapidity
Why forward at RHIC even after LHC?

- fsPHENIX rapidity is closer to the beam rapidity at RHIC compared to the one at LHC

- Beam rapidity for $\sqrt{s_{NN}}=2.76\text{TeV}$ collisions is $y=8.7$,
  - ATLAS measurement in $|\eta|<2.4$ (e.g. 1606.0817),
  - ALICE FOCAL upgrade: $2.5<\eta<6$
  - $\Delta y = 8.7-6 = 2.7$

- Beam rapidity for $\sqrt{s_{NN}}=200\text{GeV}$ is $y=5.5$,
  - If we instrument up to $y=3.5$, $\Delta y=2$.
  - Covering more forward rapidity compared to LHC.

- More hard scattering background at LHC as compared to RHIC
  - Soft process increases with $T = E^{1/4}$ while hard process is with $(\sqrt{s})^8$
  - RHIC is suitable place for detail investigation of QGP
To conclude

- HI measurement at forward (and backward) rapidity is definitely new and there are likely many discoveries.
  - Very little measurement so far
  - Theory community rapidly gets interested in this region

- RHIC is the suitable place to do HI physics at forward rapidity
  - PIDed flow, single measurement, correlation measurement
  - Electro-magnetic probe for accessing initial temperature
  - Full jet reconstruction may be hard

- Not necessarily have to be done in central Au+Au collisions
  - Or, we can collide lighter nuclei

- Close tag with p+A/p+p collisions is essential
  - Match the direction towards the EIC era?
HI physics field: QCD phase diagram
Another way to look at dynamics

Color Glass Condensate

QGP

Glasma

hadrons

\( \tau = \text{const} \)

\( \eta = \text{const} \)

nucleus1

nucleus2

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Several quantities for HI

- **Number of participant nucleons (N_{\text{part}})**
  - Calculable from impact parameters
  - A measure of energy density

- **Number of nucleon collisions (N_{\text{coll}})**
  - Number of nucleon collisions in an event
  - Nucleons are considered to collide individually in high energy collisions

- **Centrality**: Event class variable proportional to impact parameters
  - 0%: \( b=0 \), **Central collisions**
  - 100%: \( b=b_{\text{max}} \), **Peripheral collisions**
Shooting thermal photons

- Hadron contamination to the photon samples has been a big issue
- Smallest hadron contamination when using photons converted to electron pairs

**Internal conversions (virtual photon)**

**External conversions (real photon)**
Result improved theories

- **Large yield**
  - Emission from the early stage where temperature is high

- **Large elliptic flow ($v_2$)**
  - Emission from the late stage where the collectivity is sufficiently built up

- A big input to the time profile of the theoretical model
  - A latest calculation of hydrodynamics model did a fairly good job
    - PRL 114, 072301 (2015)

- Ingredients discovered
  - Late stage emission (near freezeout)
  - Blueshift of spectra
  - Viscosity correction is necessary

Comparison with 20-40% cent data

\[ T_e = \sqrt{\frac{1 + v}{1 - v}} T \]
Nature of sources seeding the long-range collective behavior?

\[ \frac{dN}{d\eta} \] shape reflects asymmetry in the number of forward-backward sources;

- \( dN/d\eta \) shape reflects asymmetry in the number of forward-backward sources;

\[ \eta \approx 1 + a_1 \eta \]

PRC 93, 044905 (2016)
PRC 87, 024906 (2013)
arXiv: 1606.08170

Not enough FB sources in models.

\[ \langle a_1^2 \rangle \]

\[ \langle a_1^2 \rangle \sim 10^{-1} \]

\[ \langle a_1^2 \rangle \]

\[ \langle a_1^2 \rangle \]

Not enough FB sources in models.

Slide from M. Zhou (ATLAS) at QM17

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3. Thermal photons

- Emitted from all the stages after collisions
- Penetrate the system unscathed after emission
  - Carry out thermodynamical information such as temperature
- Photons will be produced by Compton scattering or qqbar annihilation at LO

\[ E \frac{dR_\gamma}{d^3 p} = -\frac{\alpha_{em}}{\pi^2} \text{Im} \Pi_{em} (\omega, k) \frac{1}{e^{E/T} - 1} \]

\[ \Pi_{em}: \text{photon self energy} \]

\[ \text{Im} \Pi_{em} (\omega, k) \approx \ln \left( \frac{\omega T}{m_{th} (\approx g T)} \right) \]

- Product of Bose distribution and transition probability
- Slope at \( E >> T \) tells temperature (\( T \sim 200 \text{MeV} \))

A recent review: TS, Pramana 84, 845(2015)
BRAHMS also measured this

- BRAHMS published $\pi/K/p$ spectra in forward region in Cu+Cu collisions
- Particle ratios (related to $T_{\text{chem}}$ and $\mu_b$), $T_{\text{kin}}$ and $\beta$ are compared with those from Au+Au collisions
- As found in mid-rapidity before, the parameters scales with $N_{\text{part}} (dN/dy)$
  - 3D profile of Au+Au and Cu+Cu collisions look similar

BRAHMS, PRC94, 014907(2016)