Initial stages of a HI collision: where are we?

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An Experimentalist's View
What relevant things can we measure?

- EM probes
  Can we learn about early time dynamics?

- System dependence of hydro behavior
  What’s happening in small systems?

- High $p_T$ probes in QGP
  Parton interactions with dense media

- Heavy Quarks
  Production cross sections: gluon density
  Energy loss in QGP: interaction mechanism
  Quarkonia in p/d+A: these + CNM breakup
Do data have room for pre-equilibrium or thermal dileptons, if there is $\rho$ broadening and charm $\sigma$ is right?
At modest and high $p_T$, insufficient statistics to say much.
Low $p_T$ photons

There are “extra” photons with $p_T < 4$ GeV/c, with $v_2 \neq 0$

*Interpreted as late emission, but maybe we should rethink*
A drop of QGP even in p/d+A?

p/d + A show same trend as A + A hydrodynamics in small systems?!
Collective flow in small systems?

Significant $v_N$ (n=2 to 5) with “familiar” ordering + shape in $p_T$

- Collectivity in tiny system?
- Initial non-Abelian quantum fields behave incoherently?
- Correlations between particles produced in initial state?
- Radial flow an artefact of constant temperature freezeout surface?

Multi-particle correlations ($v2\{4\} \approx v2\{6\} \approx v2\{8\} \approx v2\{LYZ\}$)
$v_n$ sensitivity to fluctuation scale

$\lambda$ (fm)

$\mathcal{O}(10)$

Macro

$\mathcal{O}(1)$

Meso

$\mathcal{O}(0.1)$

Micro

$\ell_{\text{macro}} \sim R_{Pb}$

$\ell_{\text{meso}} \sim 1/\Lambda_{\text{QCD}}$

$\ell_{\text{micro}} \sim \tau_\pi = \frac{5 \eta}{T_\beta}$

$\sim 1/Q_\beta$

Hydrodynamics

$\Delta v_{2n}$

$\Delta v_{3n}$

$\Delta v_{4n}$

$\Delta v_{5n}$

$\text{PbPb } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$

$\text{mckln } 0-5\%$

$\text{mckln } 20-30\%$

- $v_n$ in Pb+Pb not sensitive to fluctuations smaller than $\sim 0.5$ fm

Different story in p+Pb

- Compare p+Pb and Pb+Pb at same multiplicity
  System size is different
- Viscous effects larger in p+Pb
  are we in the regime where hydro is fully applicable?
Position-momentum correlations? HBT!

More evidence for hydro 
same Npart: same emission duration but smaller system

How could so little matter approach isotropy so fast? 
What gluon structure does the system equilibrated FROM?
Mechanism of fast isotropization

- Hard to measure directly!

- Try, instead, to pin down mechanisms of QCD in hot dense matter
  
  *How are jets quenched?*
  
  *How is deposited energy transported?*
  
  *Heavy vs. light quark probes*
Jet fragmentation softens in matter

**ATLAS** Preliminary

Pb+Pb 0-10%

Jet $p_T > 100$ GeV

R=0.4

**CMS** PLB 730 (2014) 243

CMS PbPb, $\sqrt{s_{NN}} = 2.76$ TeV

L dt = 150 $\mu$b$^{-1}$

anti-$k_T$ jets: R = 0.3

0-10%

$p_T^{jet} > 100$ GeV/c

$0.3 < |\eta^{jet}| < 2$

$p_T^{track} > 1$ GeV/c

\[ \rho(r) = \frac{1}{\delta r N_{jets}} \frac{1}{N_{jets} \Sigma_{tracks \in (\eta, \phi)}} \frac{\sum_{tracks \in (\eta, \phi)} p_T^{track}}{p_T^{jet}} \]
Softer and broader in $\gamma$-h at RHIC

- Enhanced production of jet-correlated soft particles at large angles for soft $\gamma$ triggers
- Parton energy jet dependence?
Angular distribution of soft fragments

Dijet balance recovered at low $p_T$ and large angle

But see a similar effect of balance recovery in $p+p$

Depends on jet definition???

Matt Nguyen, QM15

Missing $p_T^{||}$: pp vs. PbPb

- Familiar shift of energy to lower $p_T$ “fragments”
- No large angular redistribution of total energy flow w.r.t. to pp
How does energy flow to large angle?

- Go from the angular ordering seen in vacuum fragmentation
- To a medium-induced cascade $\rightarrow$ time-ordered

High energy jets fragment mostly outside the plasma radiate gluons as they transit plasma, producing secondary showers with enhanced splitting

Softer jets resolved by medium; fragment inside?

Y. Mehtar-Tani: 1602.01047

In-medium cascade

Fundamentally different from the vacuum cascade

- **No collinear divergence** due to rescatterings \( k_\perp^2 \sim \hat{q} t \)
- **Probabilistic picture**: evolution variable \( t \sim L \)
- **Incoherent large angle gluon radiation** (with the leading parton)

  Turbulent transport of energy to large angles

  ↓

  Might explain missing \( p_T \) in dijet events (CMS 2011-2014)

**Initial state @ small x is dense: similar effects?!**
Insights from heavy quarks
Charm quarks lose energy, too!

* As much energy loss as light quarks!
* Less phase space for gluon radiation, so collisional energy loss must be important

\[ \Delta E_{\text{collision}} \sim L \quad \Delta E_{\text{radiative}} \sim L^2 \text{ (maybe also } L \ldots) \]
Energy loss and medium density

- In dilute medium
  Independent processes: bremsstrahlung & scattering
  Calculate probabilities and add them up
  Independent radiations follow Bethe-Heitler

- In dense medium
  Mean free path is short: $\lambda = \sigma/\rho$
  Formation time of radiated gluon: $\tau = \omega/k_T^2$
  Transverse momentum of radiated gluon: $k_T^2 = n\mu^2$
  # of collisions $n = L/\lambda$, $\mu =$ typical $p_T$ transfer in 1 scattering
  $\lambda, \mu$ are properties of the medium, combine to $q = \sqrt{\mu^2/\lambda}$

- Non-factorization in the dense medium!
  Next scattering takes place faster than gluon formation
  Add amplitudes for all multiple scatterings
  In QCD this increases the energy loss!

*see evidence also in cold matter!*
Triple differential $J/\psi$ data in $d+\Lambda$

- $p_T$ broadening
  - $\Rightarrow$ multiple scattering

- $p_T$, $y$, centrality dependence not reproduced by various models

- Global Scale Uncertainty 8.3%
  - Kopeliovich et al.
  - Lansberg et al.
  - $nDSg \sigma_{abs} = 4.2 \text{ mb}$

- Global Scale Uncertainty 7.8%
  - Kopeliovich et al.
  - Lansberg et al.
  - $nDSg \sigma_{abs} = 4.2 \text{ mb}$

- Global Scale Uncertainty 8.2%
  - Kopeliovich et al.
  - Lansberg et al.
  - $nDSg \sigma_{abs} = 4.2 \text{ mb}$

PRC87, 034911 (2013)
coherent parton energy loss and $p_T$ broadening from multiple scattering in the nucleus is consistent with data!

$\hat{q}_0 = 0.075 \text{ GeV}^2/\text{fm}$

\textit{Dynamics of the probe & structure of the medium mix!!}
Why worry about “parton dynamics”?

- Nuclear pdf’s aren’t the whole story!

- In p/d+A you probe cold nuclear matter with a parton, not a photon.
  - It can lose energy before the hard scattering
  - It can lose energy after the hard scattering
  - It can experience multiple scattering

- No factorization!!!!

- These are effects upon the probe, not part of the structure of cold nuclear matter!

- How to sort this out?
• Probe is a gluon
• Probe has structure!
• Dynamics of the probe mixed up with structure of the nucleus
Use ions in an electron-ion collider
Conclusions

- Flow signals in small systems are numerous
  Perhaps still ambiguous?
- In-medium jet modification indicates modified cascade
  Initial stage is cold, but also dense medium
  Take insights from jets in QGP to calculation early
time dynamics
- Radiation vs. collisions not settled yet
- We see non-factorization of eloss & hard scattering
  Initial/final state radiation can interfere
  Shouldn’t include p+A in nPDF fits??
  *Sort out using electron-ion collisions!*
● Backup
Probe nucleons & nuclei with electrons

- How many gluons are there?
  Measure $e+p$, $e+A \rightarrow e$

- How are they distributed?
  In space? In momentum?
  Measure $e+p$, $e+A \rightarrow e + \text{hadrons, } e + \gamma$
  or $J/\psi$

- How are they correlated inside nucleus?
  Measure $e+p$, $e+A \rightarrow e + \geq 2 \text{ hadrons}$

- What's gluon range inside a nucleus?
  Measure hadron production
nPDFs:

\[ R = \frac{f_i/A}{Af_i/p} \approx \text{measured} \]
\[ \approx \text{expected if no nuclear effects} \]

- Lack of data ⇒ models give vastly different results for small scales and \( x \) in benchmark HIC.

Available DGLAP analysis at NLO shows large uncertainties at small scales and \( x \).

Is mixing \( eA \) and \( pA \) in nPDFs wise?

Mixes structure with parton probe dynamics.
Hot, dense gluonic matter is surprising
Are cold dense gluons weird too?

- Look deep in a nucleus: gluons are numerous

- At high density what then?

- This is our initial state in heavy ion collisions!

\[
\frac{1}{Q_s^2} \quad \text{Greater gluon density Grows}
\]

\[
Q_s^2 \sim A^{1/3} \frac{1}{x^{0.3}}
\]

\[
\text{Increasing probe energy} \rightarrow
\]

Probe with e+A
Parton-medium interaction: energy flow

- If AdS/CFT is right, don’t produce any gluons!
- If gluon radiation/splitting is enhanced by QGP:

  extra gluons at small angles (in/near jet cone)

  
  radiated gluons thermalize in medium (i.e. they’re gone!)

  remain correlated with leading parton, but broaden/change jet
Consider two subsequent splittings in medium (antenna radiation pattern).

In-Medium Interactions suppress color coherence of the two charges system freeing extra in-cone soft radiation.

SOFT RADIATION OFF A HARD ANTENNA

\[ t_{f1} \ll L \ll t_{f2} \]

Decoherence parameter

\[ \Delta_{med} \equiv 1 - e^{-r_{\perp}Q_s^2} \]

Coherence: unresolved jet, decoherence: resolved substructure.
Triple differential $J/\psi$ data in d+Au collisions

$R_{dAu}$ (60-88%)

$R_{dAu}$ (0-20%)

$R_{CP}$

$d+Au \rightarrow J/\psi$ from PHENIX

Forward + y  
Backward - y  
d-going  
Au-going

Centrality 0-20%  
Global Scale Uncertainty ±8.5%

Centrality 60-88%  
Global Scale Uncertainty ±10%

Global Scale Uncertainty ±8.2%
Interactions with plasma?

- radiation (bremsstrahlung)
- collisional energy loss

In plasma: interactions among charges of multiple particles
charge is spread, screened in characteristic (Debye) length, $\lambda_D$
also the case for strong, rather than EM force ... Effect on collisions?

- $\alpha_s$ is not small so coupling is strong!
- In AdS/CFT: QGP field is modeled as $\infty$ strongly coupled
  q & g interact with this QGP as with a tiny black hole
  No particles to hit, none can survive inside. Eloss $\rightarrow$ collective excitations

S. Gubser

Figure 2: Left: a screened attraction between static quark arises from a string dipping into AdS$_5$-Schwarzschild. Right: a drag force arises from a string tailing behind a moving quark.
See hints at RHIC for saturation of gluons

\[ \text{Dilute parton system (deuteron)} \]

\[ \text{P_T is balanced by many gluons} \]

\[ \text{Dense gluon field (Au)} \]

Saturated gluon field is easier to equilibrate???

QCD Compton scattering to find out \((q+g \to q+\gamma)\):

no final state effects on \(\gamma\)!

Being measured now...

But – incoming parton dynamics are still confusing (the probe loses energy)
Heavy Quarks stop, too!
In the longer term

An electron-ion collider probe structure directly

Enhance $Q_s$ with $A$, not energy
Jet Fragmentation function

\[ D(z) = \frac{1}{N_{\text{jet}}} \frac{dN(z)}{dz}; \quad z = \frac{p_{\text{had}}}{p_{\text{jet}}} \]

Measure: count partners per trigger as fraction of trigger momentum

\[ z_T = \frac{p_{T\text{a}}}{p_{T\text{t}}} \sim z \quad \text{for } \gamma \text{ trigger} \]

\[ \xi = \ln(1/z_T) \]

Modification factor similar to \( R_{AA} \):

\[ I_{AA} \equiv \frac{(1/N_{\text{trig}} dN/d\xi)_{AA}}{(1/N_{\text{trig}} dN/d\xi)_{pp}} \]

FFn experimental challenge:
measure the parton \( p \)

Use trigger \( \gamma \) or jet