What can we learn from $R_{AA}$ vs high $p_T$ flow observables in heavy-ion collisions?

Rosi’s 1st generation "jets"+hydro

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Santa Fe Jets and Heavy Flavor Workshop
Jan 30th 2018
Modeling of Heavy-Ion Collisions

**Initial Conditions**
Quantum fluctuations in the position of nucleons/QCD fields

**Hydrodynamics** (for heavy-ions collisions) in a nutshell

**Hydrodynamics** viscosity and thermodynamics

**Hard Probes**
Produced early, lose energy in medium

**τ₀** initial time to switch on hydro

**T_{sw}** temperature at which the Quark Gluon Plasma switches to hadrons

**Hadron Gas**: number of hadrons, decays, interactions etc

Pressure, energy, entropy

*Initial Conditions*
Quantum fluctuations in the position of nucleons/QCD fields
“Event-by-Event” Holding the number of partons (density) constant for the same types of collisions, different shapes can be formed.

For the same 5 participants

Ellipsoid = Large eccentricity ($\varepsilon_2$)

Circle = Small eccentricity ($\varepsilon_2$)

Triangles, squares etc can even appear...
Perfect fluidity leads to elliptical flow
Perfect fluidity leads to elliptical flow

Shape quantified by eccentricities $\varepsilon_n$ where $n=2$ (ellipse), $n=3$ (triangle), $n=4$ (square) ...

Pressure gradients push outwards

Initial Condition

Final State

$V_n \propto \varepsilon_n$
Azimuthal anisotropies

The distribution of particles can be written as a Fourier series

\[
E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left[ 1 + \sum_n 2v_n \cos [n(\phi - \psi_n)] \right]
\]

- Flow Harmonics at mid-rapidity

\[
v_n(p_T) = \frac{\int_0^{2\pi} d\phi \frac{dN}{p_T dp_T d\phi} \cos [n(\phi - \psi_n)]}{\int_0^{2\pi} d\phi \frac{dN}{p_T dp_T d\phi}}
\]

where \( \psi_n = \frac{1}{n} \arctan \frac{\langle \sin[(n\phi)] \rangle}{\langle \cos[(n\phi)] \rangle} \)

\[\begin{align*}
  n = 2 & \quad \text{\textbf{}} & \\
  n = 3 & \quad \text{\textbf{}} & \\
  n = 4 & \quad \text{\textbf{}} & \\
  n = 5 & \quad \text{\textbf{}} & \\
  n = 6 & \quad \text{\textbf{}} & 
\end{align*}\]
High $p_T$ flow harmonics

Correlate 1 high $p_T$ particle with 1(+) soft particles

- More high $p_T$ particles are emitted aligned with the event plane
- High $p_T$ particles sensitive to the path length (initial state)

First suggested in early 2000’s

Learn from soft to understand hard physics

\[ v_2(2) \]

- **ALICE+CMS**
- **Hydrodynamics**
- **Intermediate \( p_T \)**
- **Hydrodynamics + energy loss**

PbPb 5.02 TeV
What properties do we want to learn?

- Initial Conditions
- Energy Loss
- Identified Particles (mass differences)
- Viscosity
- Hadronization
- Critical Point
- Chiral Magnetic Effect
- Vorticity

How do we disentangle them?
Life is complicated—guidance from the soft sector

Overview

Initial Conditions

Energy Loss

Heavy Flavor

SHEE

Outlook

**Initial Conditions**

Viscosity

Energy Loss

**Overview**

**Initial Conditions**

**Energy Loss**

**Heavy Flavor**

**SHEE**

**Outlook**

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[Image of graph showing viscosity and energy loss with references]

- JNH et al, Phys.Rev. C95 (2017) no.4, 044901
Too many initial conditions on the market

- Wounded Nucleons
- Color Glass Condensate
- Hadronic Cascades
  + Glauber
  + MCKLN
  + Gluon Saturation
  + IP-Glasma
  + Partonic Strings
- NeXuS/EPOS
- UrQMD
- Initial Flow
- 3D (longitudinal)
- EKRT
- BAMPS
- DIPSY
- Trento, supersonic
Can we first eliminate certain initial conditions from the soft sector?

**Goal**

Search for observables where $\varepsilon_n$ can be reasonable substitutes for $\nu_n$ while at the same time constraining initial state models

**Stick to $\nu_2$ and $\nu_3$**

- $\nu_4$ and above have non-linear effects so extracting their initial eccentricities is complicated. Many works e.g. ATLAS, Teaney, Denicol, Niemi, Ollitrault, Gardim, Luzum, Grassi, JNH etc

- $\nu_1$ also has many non-linear effects

Note: assumes initial flow/shear stress tensor etc is negligible.
Elliptical Flow distribution

\[ v_2\{4\}/v_2\{2\} \text{ large for small fluctuations, small for large fluctuations} \]

- Generated from initial conditions
Elliptical flow fluctuations $\nu_n{4}/\nu_n{2}$


No $\eta/s$ or EoS dependence Niemi, Eskola, Paatelainen PRC93(2016)no.2024907; Alba, Mantovani, Noronha, JNH, Parotto, Portillo, Ratti, arXiv:1711.08499
MCGLauber fails $v_2\{4\}/v_2\{2\}$ in PbPb

Differential flow harmonics

\[ v_2^2 \]

ALICE+CMS

Hydrodynamics

Intermediate \( p_T \)

Hydrodynamics + energy loss

0–5%
**Event-by-Event hydro+jet tomography [3]**

**v-USPhydro [1]**

- **ATLAS**
  - $\eta/s = 0.11$
  - $\sqrt{s} = 2.76 \text{ TeV}$
- $v_2(2)$
- $v_3(2)$
- mckln

- **ALICE**
  - $\eta/s = 0.05$
  - $\eta/s = 0.12$
  - $\sqrt{s} = 5.02 \text{ TeV}$
- $v_2(2)$
- $v_3(2)$

**BBMG [2]**

- $dE/dL \sim L$ “pQCD-like”
  - (radiative energy loss)
- $dE/dL \sim L^2$ “AdS/CFT-like”
- Full hydrodynamical backgrounds incorporated on an event-by-event basis

**References**

$R_{AA}$ of all charged particles for $p_T > 10$ GeV

$v_n\{SP\}(p_T) = \frac{\langle v_n^{soft} v_n^{hard}(p_T) \cos (n [\psi_n^{soft} - \psi_n^{hard}(p_T)]) \rangle}{\sqrt{\langle (v_n^{soft})^2 \rangle}}$

Global analysis needed to determine $dE/dL$, one centrality=misleading

$v_2(p_T)$ for $p_T > 10$ GeV

$v_3(p_T)$ for $p_T > 10$ GeV

Only using event-by-event fluctuations!

Does $v_n\{2\} \rightarrow v_n\{SP\}(p_T)$ for $p_T > 10$ GeV?

Soft $v_n$ a very good predictor for $v_n(p_T > 10\text{GeV})^*$

Must first match $v_n\{2\}$ soft before studying $dE/dL$!!

mckln+v-USPhydro+BBMG Phys.Rev. C95 (2017) no.4, 044901

*Complications arise for $n > 2$ Jia PRC87,no. 6,061901(2013)
Differential multiparticle cumulants are complicated

Correlate 1 high $p_T$ particles with n-1 soft particles.

$$\frac{v_n\{4\}(p_T)}{v_n\{2\}(p_T)} = \frac{v_n\{4\}}{v_n\{2\}} \left[ 1 + \left( \frac{v_n\{2\}}{v_n\{4\}} \right)^4 \left( \frac{\langle v_n^4 \rangle}{\langle v_n^2 \rangle^2} - \frac{\langle v_n^2 V_n V_n^*(p_T) \rangle}{\langle v_n^2 \rangle \langle V_n V_n^*(p_T) \rangle} \right) \right]$$

soft–hard fluctuations

(1)

If there’s no hard physics,

$$\frac{v_n\{4\}(p_T)}{v_n\{2\}(p_T)} = \frac{v_n\{4\}}{v_n\{2\}}$$

JNH et al Phys.Rev. C95 (2017) no.4, 044901
If $v_2^{\{4\}}(p_T)/v_2^{\{2\}}(p_T) \rightarrow 1$, there are still fluctuations!

$p_T$ dependence of $v_2^{\{4\}}/v_2^{\{2\}}$ from soft vs. hard fluctuations
DABMOD- parameterized energy loss model

- Sample charm quarks inside medium with initial momentum distribution from pqcd fonll calculations
- Decoupling temperature $T_d = 120 - 160$ MeV
- Hadronization: Peterson fragmentation function
- Quark Coalescence being implemented (Roland Katz).

Caio Prado, JNH, Katz, Suaide, Noronha, Munhoz, Constantino, Phys.Rev. C96 (2017) no.6, 064903
Muon PbPb 5.02 TeV predictions: ATLAS-CONF-2015-053

Prado, Katz, JNH, Suaide, Noronha, Munhoz, Constantino to appear shortly
Common origin of $v_2^{soft}$ and $v_2^{hard}$

Going from Theory to Experiment

- $v_2^{soft}$ creates multiple $v_2^{hard}$

$\{v_2^{hard}\}(p_T)$ vs. $v_2^{soft}$ differentiates $dE/dL$

Possible to measure experimentally

- Bin by $v_2^{soft}\{2\}$, calculate $v_2^{hard}\{SP\}$

Reference

Soft Hard/Heavy Event Engineering (SHEE)

Fluctuations measured to $p_T \sim 15\text{GeV}$

ALICE currently working on heavy flavor analog

References

Energy loss plays a larger role than fluctuations at PbPb run2

D^0 meson, 30–50% PbPb, \( \sqrt{s_{NN}} = 2.76 \) TeV

\[ T_d = 120 \text{ MeV} \]

\[ -\frac{dE}{dx} = \lambda \Gamma_{\text{flow}} \]
Rescaling SHEE

Universal consequence of linear response

Once SHEE is rescaled by $v_2 \{2\} \rightarrow$ universal scaling

If experimentalists measure something else, indication of different energy loss fluctuations by mass!
Limited statistics diminishes correlation between $v_2^{soft}$ vs. $v_2^{heavy}$.
Stop removing non-flow?

Makes the theorist’s life complicated...

P. Tribedy Initial Stages 2017, Adamczyk et al (STAR Collaboration) 1701.06496
Jets coupled to the medium (see also Xin-Nian’s talk)

\[ \partial_\mu T^{\mu\nu}_{\text{QGP}}(x) = J^\nu(x) \]

\[ \rho_{\text{jet}} = \frac{1}{N_{\text{jet}}} \sum \left[ \frac{1}{p_T^{\text{jet}}} \sum_{\text{trk} \in (r-\delta r/2, r+\delta r/2)} \frac{p_{T}^{\text{trk}}}{\delta r} \right] \]

"We call for an agreement between theorists and experimentalists on the appropriate treatment of the background, Monte Carlo generators that enable experimental algorithms to be applied to theoretical calculations, and a clear understanding of which observables are most sensitive to the properties of the medium, even in the presence of background. " Connors, Nattrass, Reed, and Salur arxiv:1705.01974, Accepted in Reviews of Modern Physics

References

Tachibana et al, Phys.Rev. C95 (2017) no.4, 044909 ; Pang et al, PRC86(2012)024911; HYDJET++ (many papers); LBT (many papers); Andrade et al, PRC90(2014)no.2,024914; Schule and Tomasik PRC90(2014)no.6,064910
Conclusions

- $v_2\{4\}/v_2\{2\}$ best observable for constraining initial condition model in large systems
- High $p_T$ "flow" can tell about $dE/dL$ but must get the soft sector right first!
- Heavy flavor SHEE sensitive to statistics
- Universal scaling between all flow harmonics at high $p_T$? Juries still out...
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**BACKUP**
Multi-particle cumulants

Reconstructing the $v_n$ distribution with cumulants

\[
\begin{align*}
v_n\{2\}^2 &= \langle v_n^2 \rangle, \\
v_n\{4\}^4 &= 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle, \\
v_n\{6\}^6 &= \frac{1}{4} \left[ \langle v_n^6 \rangle - 9\langle v_n^2 \rangle\langle v_n^4 \rangle + 12\langle v_n^2 \rangle^3 \right], \\
v_n\{8\}^8 &= \frac{1}{33} \left[ 144\langle v_n^2 \rangle^4 - 144\langle v_n^2 \rangle^2\langle v_n^4 \rangle + 18\langle v_n^4 \rangle^2 \\
&\quad + 16\langle v_n^2 \rangle\langle v_n^6 \rangle - \langle v_n^8 \rangle \right],
\end{align*}
\]

where collectivity $\rightarrow v_n\{2\} > v_n\{4\} \sim v_n\{6\} \sim v_n\{8\}$ but there are differences between higher order cumulants!
Constraining initial condition models

- Mean shape $\langle \varepsilon_n \rangle \rightarrow \eta/s$, EOS etc..

![Graph showing event-by-event fluctuations and correlation between harmonics]

- Size of event-by-event fluctuations $\varepsilon_n\{4\}/\varepsilon_n\{2\}$

- Correlation different harmonics $SC(3, 2)$
Constraining initial condition models

- Mean shape $\langle \varepsilon_n \rangle \rightarrow \eta/s, \text{ EOS etc.}.$

- Size of event-by-event fluctuations $\varepsilon_n\{4\}/\varepsilon_n\{2\}$

- Correlation different harmonics $\text{SC}(3, 2)$
Constraining initial condition models

- Mean shape $\langle \varepsilon_n \rangle \rightarrow \eta/s, \text{EOS etc.}$

- Size of event-by-event fluctuations $\varepsilon_n\{4\}/\varepsilon_n\{2\}$

- Correlation different harmonics $SC(3,2)$
Total initial entropy profile

\[ S(p; S_A, S_B) = \left( \frac{S_A^p + S_B^p}{2} \right)^{\frac{1}{p}}, \]

where

\[ S_{A,B} = w_{A,B} \frac{1}{2\pi\sigma^2} \exp \left[ \frac{(x - x_{A,B})^2 + (y - y_{A,B})^2}{2\sigma^2} \right]. \]

normalization, \( w \), is a random number which is assigned to each participant nucleon, \( \Gamma \) probability distribution with the width \( k \).
Multiparticle cumulants at high $p_T$

**Scalar product, $v_2\{2\}(p_T) \equiv v_2\{SP\}$**

Avoids well-known problems with the event-plane method comparing between theory and experiments.

See Luzum and Ollitrault PRC87 (2013) no.4, 044907

$v_n\{2\}(p_T)$ Two particle correlation (one soft, one hard)

$$\frac{\langle v_n^{soft} v_n^{hard}(p_T) \cos \left( n \left[ \psi_n^{soft} - \psi_n^{hard}(p_T) \right] \right) \rangle}{\sqrt{\langle \left( v_n^{soft} \right)^2 \rangle}}$$

$v_2\{4\}(p_T)$ Four particle correlation (three soft, one hard)

$$\frac{2 \langle |v_n^{soft}|^2 v_n^{soft} v_n^{hard}(p_T) \cos \left[ n \left( \psi_n^{soft} - \psi_n^{hard}(p_T) \right) \right] \rangle - \langle (v_n^{soft})^3 v_n^{hard}(p_T) \cos \left[ n \left( \psi_n^{soft} - \psi_n^{hard}(p_T) \right) \right] \rangle}{(v_n^{soft}\{4\})^{3/4}}$$