Higher Harmonic Jet Tomography as a Probe of Fluctuating Initial Condition Geometries in A+A

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arXiv:1102.5416 [nucl-th]
Motivation

→ Two basic questions:
  • Is the medium weakly-coupled (pQCD) or strongly-coupled (AdS/CFT)?
  • What are the initial conditions (Glauber or CGC)?

→ Two observables characterizing the medium:
  • jet quenching: signal for creation of opaque matter (QGP)
    defined via: \[ R_{AA}(p_T) = \frac{1/\sigma_{A+A} d\sigma_{A+A}/dp_T}{\langle N_{coll}/\sigma_{p+p} d\sigma_{p+p}/dp_T} \]
  • elliptic flow: signal for creation of a (nearly) perfect fluid
    defined via: \[ \frac{dN}{d\phi} = \frac{N}{2\pi} \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n\phi) \right] \]
The Connection

• Glauber Model and CGC differ by:
  – initial temperature gradients
  – initial high-\(p_T\) parton distribution
  – distance travelled by each parton leading to a different opacity estimate

• Elliptic flow is sensitive to the path length dependence of energy loss, scaling as \(dE/dx \sim l^z\):
  
  \[ z=1 : \text{pQCD} \]
  
  \[ z=2 : \text{AdS/CFT (on-shell partons)} \]
  
  \[ z>2 : \text{AdS/CFT (off-shell partons)} \]

\[ M. \text{Gyulassy et. al., PRL 85 (2000), 5535} \]
\[ S. \text{Gubser et. al., JHEP 0810 (2008), 052; P. Chesler et.al., PRD 79 (2009) 125015} \]
Energy-Loss Mechanisms

- First investigation of $R_{AA}(N_{\text{part}})$ and $v_2(N_{\text{part}})$ for $p_T > 5$ GeV hadrons is based on

  J. Jia et. al., PRC 82 (2010), 024902

  \[ R_{AA}(N_{\text{part}}) = \langle e^{-\kappa I_m} \rangle \]

  \[ I_m = \int_0^\infty dl l^{m-1} \rho(\vec{r} + l\hat{b}), \quad m = 1, 2, \ldots \]

  \[ v_2 = \langle e^{-\kappa I} \cos 2(\phi - \Psi_{\text{part}}) \rangle \]

  → simple jet absorption model

- Once $R_{AA}(N_{\text{part}}=350) \sim 0.18$ for 0-5% $\pi^0$ data
  - pQCD-like energy loss fails to reproduce $v_2(N_{\text{part}})$
  - AdS/CFT-like energy loss describes data for CGC initial conditions

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  $v_2 = \langle e^{-\kappa I} \cos 2(\phi - \Psi_{\text{part}}) \rangle$

  $I_m = \int_0^\infty dl \, l^{m-1} \rho(r + lv), m = 1, 2, \ldots$

  → simple jet absorption model

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  $R_{AA}(N_{\text{part}}) = \langle e^{-\kappa I_m} \rangle$

  $I_m = \int_0^\infty dl l^{m-1} \rho(\vec{r} + l\hat{\nu}), m = 1, 2, ...$

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\[ A. \text{ Adare et al}, \text{Phys. Rev. Lett. 105, 142301 (2010)} \]
Choosing an ansatz for the energy loss

\[
\frac{dE}{dx}(\vec{x}_0, \phi, \tau) = -\kappa P^a T^{z-a+2} [\vec{x}_0 + \hat{n}(\phi) \tau, \tau]
\]

P: momentum of the jet(s)

a, z: parameters controlling the jet-energy and path-length dependence

\(\kappa\): being fixed thus that \(R_{AA}(N_{part}=350) \sim 0.18\) for most central data

and considering Bjorken expansion via

\[
T(\vec{x}, \tau) = T_0(\vec{x}) \left( \frac{\tau_0}{\tau} \right)^{1/3}
\]

\(\tau_0 = 1\text{fm}\), one can determine the \(R_{AA}(N_{part}) \& v_n(N_{part})\)
$R_{AA}$ and $v_2$

→ Having fixed $\kappa$ for $R_{AA}(N_{\text{part}}=350) \sim 0.18$

$R_{AA}(N_{\text{part}})$ can be reproduced

→ $z=1$: CGC in. cond.
  close to data

$z=2$: CGC in. cond.
  still describe data,
  Glauber in. cond.
  getting closer

→ NO striking big difference between pQCD and AdS/CFT

B.Betz et al.,
arXiv:1102.5416 [nucl-th]
Having fixed $\kappa$ for $R_{AA}(N_{part}=350) \sim 0.18$ $R_{AA}(N_{part})$ can be reproduced

$z=1$: CGC in. cond. close to data
$z=2$: CGC in. cond. still describe data, Glauber in. cond. getting closer

Similar results for event-by-event and averaged scenarios!
Differences

pQCD-like

AdS/CFT-like


B.Betz et al., arXiv:1102.5416 [nucl-th]
Initial time

- We chose $\tau_0 = 1\text{fm}$.
  H. Song et al., arXiv:1011.2783[nucl-th]

- Jia’s model has $\tau_0 = 0\text{fm}$.

$\Rightarrow$ A smaller $\tau_0$ reduces the $v_2(N_{\text{part}})$ for both pQCD-like and AdS/CFT-like energy loss and increases the difference between the pQCD and AdS/CFT results
The role of $\tau_0$

$\tau_0 = 1\text{fm} \rightarrow \text{Assumption: NO energy loss within 1fm}$

- pQCD does not give excuse for this ansatz,
  $\tau_0 = 0\text{fm} \text{ most natural assumption}$

- describes formation time of hydrodynamics
  $\rightarrow$ no pressure at early times, everything is free flow

$\tau_0 = 1\text{fm} \rightarrow \text{essentially equivalent to AdS/CFT}$

  energy loss suppression of early times

- AdS/CFT: $dE/dx \sim l^2$ accounts for absence of energy loss $< 1\text{fm}$.

$\Rightarrow v_2(\text{high- } p_T) \text{ not sensitive to long distance } dE/dx \sim l^1$

  vs. $dE/dx \sim l^2$, but to short distance properties $< 1\text{fm}$!

$\Rightarrow \text{Only the corona is seen!}$
Higher Harmonics

$v_3$ and $v_4$ similar for Glauber and KLN initial conditions

→ Not suitable to distinguish between Glauber and CGC initial conditions

→ Higher harmonics are more sensitive to local gradients, but also to event-by-event fluctuations → larger $v_{3,4}$ fluctuations

B.Betz et al., arXiv:1102.5416 [nucl-th]
Fragmentation

Nuclear modification factor

\[ R_{AA}^{\pi}(p_\pi) = \frac{\sum_{\alpha=q,g} \int_{z_{min}}^{1} \frac{dz}{z} \ d\sigma_\alpha \left( \frac{p_\pi}{z} \right) R_{AA}^{\alpha} \left( \frac{p_\pi}{z} \right) D_{\alpha \rightarrow \pi} \left( z, \frac{p_\pi}{z} \right)}{\sum_{\alpha=q,g} \int_{z_{min}}^{1} \frac{dz}{z} \ d\sigma_\alpha \left( \frac{p_\pi}{z} \right) D_{\alpha \rightarrow \pi} \left( z, \frac{p_\pi}{z} \right)} \]

- \( z \) : momentum of the observed pion
- \( p_\pi \) : fractional momentum of the quarks and gluons
- \( d\sigma_\alpha \left( \frac{p_\pi}{z} \right) \) : fitted pQCD cross-sections for quarks and gluons
- \( D_{\alpha \rightarrow \pi} \left( z, \frac{p_\pi}{z} \right) \) : fragmentation functions for quarks and gluons
$R_{AA}$ and $v_2$ for $\pi$'s

$R_{AA}(N_{\text{part}})$ can be described

$z=1$: CGC in. cond. close to data, Glauber fails to describe $v_2$ data

A smaller $\tau_0$ reduces the $v_2(N_{\text{part}})$

For $\tau_0=1\text{fm}$ and CGC initial conditions, pQCD and AdS/CFT-like energy loss close to the data
LHC conditions for π's

→ $R_{AA}(N_{\text{part}})$ decreases as a function of energy

→ CGC in. cond. lead to larger $v_2$

→ CGC-$v_2$ flattens for smaller $N_{\text{part}}$

B.Betz et al., in preparation
LHC conditions for $\pi$'s

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LHC conditions for π's

ALICE:
R. Snellings, $v_2\{SP\}$, p.17
H. Appelshäuser, $\pi^{+/-}$, p.24

ATLAS:
J. Jia, $h^{+/-}$, p.10

CMS:
J. Velkovska, $v_2\{EP\}$, p.8
Y.-J. Lee, $h^{+/-}$, p.26

$p_T \sim 9.5\text{GeV}$

$\tau_0=1.00\text{fm}$
$\tau_0=0.01\text{fm}$

B.Betz et.al., in preparation
LHC conditions for $\pi$'s

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R. Snellings, $v_2${SP}, p.17
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Y.-J. Lee, $h^{+/-}$, p.26
$p_T=9.5$GeV

$\Rightarrow$ Puzzle: Density dependence energy loss fails to describe $R_{AA}$ (WHHDG/DGLV)

$p_T=10$GeV

AdS/CFT-like, $z=2$

B.Betz et al., in preparation

Talk W. Horowitz, QM 2011
W. Horowitz et. al., arXiv:1104.4958[hep-ph]
Conclusions

- Introduced a generic energy loss model, exploring $dE/dx \sim P^a$ and $l^z$ with a dimensionless coupling $\kappa$

- Gets close to the $v_2(N_{\text{part}})$ data in the pQCD-case for KLN initial conditions for $\tau_0=1\text{fm}$ at RHIC energies, even after fragmentation

- Discussed the role of the initial time $\tau_0$
  - $v_2(\text{high- } \pT)$ @ RHIC is sensitive to short distance properties $< 1\text{fm}$,
  - suggesting that either weak coupling + $\tau_0 \sim 1\text{fm}$ or strong coupling features energy loss suppression at early times
  - Only the corona is seen (RHIC)

- Puzzle: Density dependence energy loss fails to describe $R_{\text{AA}}$ @LHC
Backup
Generic Energy Loss Model

Nuclear modification factor

\[ R_{AA}(\vec{x}_0, \phi, N_{part}) = \exp[-\chi(\vec{x}_0, \phi, P_f)] \]

with

\[ \chi(\vec{x}_0, \phi, P_f) = \left( \frac{1 + a - n}{1 - a} \right) \ln \left[ 1 - \frac{K}{P_0^{1-a}} I(a, z, \phi, \vec{x}_0) \right] \]

\[ I(a, z, \phi, \vec{x}_0) = \int_{\tau_0}^{\infty} \tau^z T^{-a+2} \left[ \vec{x}_0 + \hat{n}(\phi) \tau, \tau \right] d\tau \]

\( n \approx 6: \) spectral index

\( K = \kappa (1-a) \)

\[ R_{AA}(N_{part}) = \frac{\int R_{AA}(\vec{x}_0, \phi) T_{AA}(\vec{x}_0) d\vec{x}_0 d\phi / (2\pi)}{\int T_{AA}(\vec{x}_0) d\vec{x}_0} \]

\( T_{AA} : \) Glauber

\( T_{AA} = \rho^2 / P_0^2 : \) CGC

H. Drescher et. al., PRC 76 (2007) 024905
Having fixed $\kappa$, the harmonics can be calculated

$$v_n(N_{\text{part}}) = \frac{\int d\phi \cos \{ n [\phi - \psi_n] \} R_{AA}(\phi)}{\int d\phi R_{AA}(\phi)}$$

determining the angle with the reaction plane

$$\psi_n(t) = \frac{1}{n} \tan^{-1} \frac{\langle r \sin(n\phi) \rangle}{\langle r \cos(n\phi) \rangle}$$

and the Fourier density components are given by

$$e_n(t) = \sqrt{\langle r^2 \cos(n\phi) \rangle^2 + \langle r^2 \sin(n\phi) \rangle^2}$$

\[\langle r^2 \rangle\]
$R_{AA}$ and $v_2$

→ Having fixed $\kappa$ for $R_{AA}(N_{part}=350) \sim 0.18$
   $R_{AA}(N_{part})$ can be reproduced
→ $z=1$: CGC in. cond.
   close to data
→ $z=2$: Glauber in. cond.
   getting closer
→ Small fluctuations for $R_{AA}(N_{part})$
   large fluctuations for $v_2(N_{part})$
→ Not straightforward to distinguish between initial conditions

B. Betz et al., arXiv:1102.5416 [nucl-th]
$R_{AA}$ vs. $I_{AA}$, and $v_n$ vs. $v_n^{IAA}$

- Extend to dijet analysis,
  
  **but considering $\kappa_{\text{away}} = \kappa$**

- In contrast to Jia’s model, we fit the $R_{AA}$ vs. $I_{AA}$
  
  J. Jia et al., arXiv:1101.0290 [nucl-th]

- $v_n$ vs. $v_n^{IAA}$:
  - clear shift between Glauber and CGC model

- It is necessary to **always** determine the mean and the width of a correlation!

B. Betz et al., arXiv:1102.5416 [nucl-th]
Path-length dependence

- Study the path-length dependence at $b=8\text{fm}$:
  - Once $R_{AA}$ is fixed via $\kappa$,
  - sensitivity remains mostly for $v_2$ and $v_3$
  
- small saturation effect occurs for larger $z$
  
- described by AdS/CFT off-shell partons

*S. Gubser et. al., JHEP 0810 (2008), 052; P. Chesler et.al., PRD 79 (2009) 125015*
Insensitivity of higher $v_n$'s

Why are the $v_n$'s at high-$p_T$ so insensitive to initial conditions while the $v_n$'s of soft particles are?

- Viscous forces are driven by *local gradients*
- Jet absorption is driven by *global differences* in the integrated

$$\langle -\kappa P^a \tau^z T^{\tau - a + 2} \rangle$$

These two effects are different, especially event-by-event

- Glauber and CGC in. cond. are tuned to reproduce the observed multiplicites

$$\langle T \rangle$$ is *similar*, even if *local gradients* of $T$ are different

Hydrodynamics and tomography lead to very different results.
Nuclear modification factor for the generic energy loss model

\[ R_{AA} = \left\{ 1 - \frac{K}{P_0^{1-a}} \int_{\tau_0}^{\infty} \tau^z T^{z-a+2} [x_0 + \hat{n}(\phi) \tau, \tau_0] d\tau \right\}^{(n-1-a)/(1-a)} \]

K = \kappa (1-a), leads to the line integral (a=0, z=1)

\[ I = \int_{\tau_0}^{\infty} T_0^2 [x_0 + \hat{n}(\phi) \tau] d\tau = \int_{\tau_0}^{\infty} \rho_0^{2/3} [x_0 + \hat{n}(\phi) \tau] d\tau \]

Line integral according to A. Adare et al, PRL 105, 142301 (2010) → The powers matter!
Differences

KLN in cond., b=8 fm

$\tau_0=1 fm$

$\tau_0=0.01 fm$

$\tau_0=0.01 fm$, adjusted $\kappa$

change $\tau_0$

adjust $\kappa$

$R_{AA}(\phi)$ changes

$v_n(N_{part}) = \frac{\int d\phi \cos \{ n [\phi - \psi_n] \} R_{AA}(\phi)}{\int d\phi R_{AA}(\phi)}$

$\tau_0=1 fm$

$\tau_0=1 fm$, adjusted kappa

$\rho$ (Surviving Jets) [1/fm$^3$]
Initial Fluctuations I

Glauber initial conditions: 

\[ \frac{dN}{d\phi} = \frac{N}{2\pi} \left( 1 + \sum 2v_n \cos(n(\phi - \psi_R)) \right) \]

\[ v_2 = \langle \cos(2(\phi - \psi_R)) \rangle \]

\[ v_3 = 0 \]

→ due to symmetry, odd Fourier components vanish

Fluctuating initial conditions: 

\[ \frac{dN}{d\phi} = \frac{N}{2\pi} \left( 1 + \sum 2v_n \cos(n(\phi - \psi_n)) \right) \]

\[ v_2 = \langle \cos(2(\phi - \psi_2)) \rangle \]

\[ v_3 = \langle \cos(3(\phi - \psi_3)) \rangle \]

→ higher Fourier components may occur