Jet and Electromagnetic Tomography of High-energy Heavy-ion Collisions

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Two questions we ask:

- What is the phase structure of QCD
- What are the properties of nuclear matter in extreme conditions?
\[ W_{\mu \nu}(q) = \frac{1}{4\pi} \int d^4 x e^{i q \cdot x} \left\langle A \left| j_{\mu}^{em}(0) j_{\nu}^{em}(x) \right| A \right\rangle = -e_T^{uv} F_1(x_B) + e_L^{uv} F_2(x_B) \]

\[ x_B = \frac{Q^2}{2p \cdot q} \]

Probing Nuclear Matter
Jet in $e^+e^-$ Annihilation

**LEP (\(\sqrt{s} = 90 - 205\) GeV)**

**TASSO**

- 4 tracks
  - 4.1 GeV
- 5 tracks
  - 4.3 GeV
- 6 tracks
  - 7.8 GeV
Jets in pp collisions at LHC !!!

CMS preliminary, 60 nb⁻¹

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ \frac{d^2\sigma}{dy dp_T^2} \text{ (pb/GeV)} \]

- \( |y| < 0.5 \times 1024 \)
- \( 0.5 \leq |y| < 1.0 \times 256 \)
- \( 1.0 \leq |y| < 1.5 \times 64 \)
- \( 1.5 \leq |y| < 2.0 \times 16 \)
- \( 2.0 \leq |y| < 2.5 \times 4 \)
- \( 2.5 \leq |y| < 3.0 \times 1 \)

- NLO pQCD+NP
- Exp. uncertainty
- Anti-\( k_T \) R=0.5 PF

\[ x_T = p_T/\sqrt{s} = 0.005 \]
Jets at RHIC
Jet quenching

\[ \Delta D(z, k_{\perp}) \quad k_T \text{ broadening} \]

\[ \frac{dE}{dx} \quad \hat{q} \]
Jet Transport in Medium

Classical Lorentz force:

\[ \frac{d\vec{p}_\perp}{d\tau} = g\vec{F}_{\perp\mu}v^\mu \]

\[ \vec{W}_\perp(y^-, \vec{y}_\perp) \equiv i\vec{D}_\perp(y) + g \int_{-\infty}^{y^-} d\xi^- \vec{F}_{+\perp}(\xi^-, y_\perp) \]

Jet Transport Operator

\[ f_A^q(x, \vec{k}_\perp) = \int \frac{dy^-}{4\pi} e^{ix^+y^-} \langle A|\bar{\psi}(0)\gamma^+ \exp[\vec{W}_\perp(y^-) \cdot \nabla_{\vec{k}_\perp}]\psi(y^-)|A\rangle \delta^{(2)}(\vec{k}_\perp) \]

Liang, XNW & Zhou (2008)
Momentum Broadening

\[ \langle W_{\perp}^{2n} \rangle_A \sim \left[ \int dy \frac{\rho_A(y)}{2p^+} \langle N | F_{+\perp} F_{+\perp} | N \rangle \right]^n \sim \left[ \int dy \rho_A(y) x G_N(x) \right]^n \]

2-gluon correlation approximation

\[ \Delta = \langle \Delta k_{\perp}^2 \rangle = \int d\xi_N \hat{q}(\xi_N) \frac{1}{\Delta} \left[ \frac{(\vec{k}_{\perp} - \vec{q}_{\perp})^2}{\Delta} \right] f^q_A(x, \vec{k}_{\perp}) \]

\[ \hat{q}(\xi_N) = \frac{4\pi^2\alpha_s C_F}{N_c^2 - 1} \rho_A(\xi_N) x G_N(x) \bigg|_{x=0} \]

Jet transport parameter

Liang, XNW & Zhou’08
Majumder & Muller’07
Kovner & Wiedemann’01
BDMPS’96
Jet Acoplanarity

$p+p, s^{1/2} = 200$ GeV

$E_T^a = 10$ GeV

$q^2 \sim 1-2$ GeV$^2$/fm
Splitting functions in medium

\[
\Delta \gamma(z, \ell_{\perp}^2) = C_A \frac{1 + z^2}{(1 - z) + \ell_{\perp}^4} \int d\xi^- \hat{q}(\xi) \left[ 1 - \cos(x_{LP}^+ \xi^-) \right]
\]

Parton Energy Loss

\[
\frac{\Delta E}{E} = C_A \frac{\alpha_s}{2\pi} \int \frac{d\ell_T^2}{\ell_T^4} \int dz \left[ 1 + (1 - z)^2 \right] \int d\xi^- \hat{q}(\xi) 4 \sin^2(x_{LP}^+ \xi^- / 2)
\]
Jet Quenching phenomena at RHIC

STAR Preliminary

Au+Au (central collisions):
- Direct $\gamma$ (PHENIX Preliminary)
- Inclusive $h^\gamma$ (STAR)
- $\pi^0$ (PHENIX Preliminary)
- GLV parton energy loss ($dN/dy = 1100$)

$R_{AA}$ vs $p_T$ (GeV/c)

$1/N_{\text{Trigger}} dN/d(\Delta \phi)$

$1_{cp}$ of direct $\gamma$ and $\pi^0$

STAR Preliminary
Jet Quenching at LHC
Jet quenching phenomenology

Bass et al, 2008
Jet & Electromagnetic Tomography

- Go beyond soft and collinear approximation
  - parton recombination, heavy quark
- Realistic space-time evolution of bulk matter
  - viscous hydro, parton and hadron cascade
- Develop new and powerful Monte Carlo
  - include interaction of jet and dynamic medium
- Systematic phenomenological studies
  - quantitative tomography of dynamic medium
Approaches to parton energy loss

• **Armesto, Salgado, Wiedemann (ASW)**
  - Static scattering center medium with Yukawa like potentials
  - Path integral over multiple scatterings in the medium

• **Gyulassy, Levai, Vitev (GLV/DGLV/WHDG)**
  - Medium of heavy (static) scattering centers with Yukawa like potentials
  - Calculate order by order in number of scatterings per emission

• **Arnold, Moore, Yaffe (AMY)**
  - Thermalized partonic medium at $T \to \infty$, $g \to 0$, HTL plasma
  - Multiple scattering resummation on near on-shell parton

• **Higher Twist (HT)**
  - Arbitrary medium, no model (soft scattering assumed)
  - An expansion in $1/Q^2$ of multiple scattering on a hard parton
Systematic comparisons of different approaches:

N. Armesto et al. arXiv:1106.1106

Single gluon emission

Sensitivity to maximum angle cut-off for gluon emission
Collinear approximation & NLO pQCD

collinear $k^2_\perp < \mu^2$

large angle $k^2_\perp > \mu^2$

single jet -- LO

two jets -- NLO
Example: LT photon radiation

\[ F_T(z, x_B, y, \vec{L}_T) = \frac{4A(1 - z)Q^2}{(2\pi)^3 \pi x_B \Delta_2} \int e^{-k_T^2/\Delta_2} f_{q/N}(x) \bigg|_{x=x_B} \left[ 1 + \frac{(zk_T + l_T)^2}{z(1-z)Q^2} \right] \times \right. \\
\left. \left\{ \frac{1 + (1 - z)^2}{(zk_T + l_T)^2} - \frac{(zk_T + l_T)^2}{[z(1-z)Q^2 + (zk_T + l_T)^2]^2} \right. \\
+ 2(1 - z) \left. \frac{6z^2(1 - z)^2Q^2}{[z(1-z)Q^2 + (zk_T + l_T)^2]^2} \right\} d^2k_T, \right. \\
\]
Survival under the LHC sea

$R_{AA}$

ALICE, charged particles, Pb-Pb
$\sqrt{s_{NN}} = 2.76$ TeV, 0-5%, $|\eta| < 0.8$

ALICE Preliminary

Horowitz and Gyulassy: arXiv:1104.4958
Majumder and Shen: arXiv:1103.0809
Chen et. al. arXiv:1102.5614
Di-Jet Asymmetry

Jet transport with HT kernel


Z0 tagged jet

\[ s^{1/2} = 4 \text{ TeV} \]
\[ |y_{\text{jet}}| < 2.5 \quad |y_{\mu\mu}| < 2.5 \]
\[ M_Z - 3 \Gamma_Z < M_{\mu\mu} < M_Z + 3 \Gamma_Z \]

jet-medium interaction in a dynamic medium

developed 3+1D viscous hydro
developed hydro/hadron cascade interface
Flow at LHC

Data: ALICE
Lines: Shen et al., arXiv:1105.3226 (VISH2+1)

ALICE preliminary, Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV
centrality 10%-20%

- $\pi^0$, $v_2$ (SP, $|\Delta \eta|>1$)
- $K^0$, $v_2$ (SP, $|\Delta \eta|>1$)
- $p$, $v_2$ (SP, $|\Delta \eta|>1$)

--hydro LHC
(CGC initial conditions)
($\eta/s=0.2$)

ALICE preliminary, Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV
centrality 40%-50%

- $\pi^0$, $v_2$ (SP, $|\Delta \eta|>1$)
- $K^0$, $v_2$ (SP, $|\Delta \eta|>1$)
- $p$, $v_2$ (SP, $|\Delta \eta|>1$)

--hydro LHC
(CGC initial conditions)
($\eta/s=0.2$)
Jet quenching in hadronic phase

\[ \hat{q}(\tau, r) = \hat{q}_0 \frac{\rho^{QGP}(\tau, r)}{\rho^{QGP}(\tau_0, 0)} (1 - f) + \hat{q}_h(\tau, r)f \]

\[ \hat{q}_h = \frac{\hat{q}_N}{\rho_N} \left[ \frac{2}{3} \sum_M \rho_M(T) + \sum_B \rho_B(T) \right] \]

\[ \hat{q}_0 = 0.9^{+0.05}_{-0.04} \text{ GeV}^2/\text{fm} \]

30% quenching from hadronic phase

Chen, Greiner, Wang, XNW, Xu (2010)

\[ \hat{q}_N = 0.02 \text{ GeV}^2/\text{fm} \]

from HERA DIS
Jet-induced medium excitation

\[ \Delta \eta < 4 \]

\[ 3 < \Delta \eta < 4 \]

\[ \Delta \eta \]

\[ 2 < \Delta \eta < 4 \]

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Goals of JET Collaboration

- Extend and improve the current framework for the study of jet-medium interaction
- Develop Monte Carlo program for jet quenching
- Coupling to realistic bulk evolution
- Systematic phenomenological study of jet quenching
Publications

(Publications are ordered chronologically according to the arXiv number)

38) A. Buzzatti and M. Gyulassy,
Jet Flavor Tomography of Quark Gluon Plasmas at RHIC and LHC,

37) Chun Shen, U. Heinz, P. Huovinen, and H. Song,
Radial and elliptic flow in Pb+Pb collisions at the Large Hadron Collider from viscous hydrodynamics,

36) W. A. Horowitz and M. Gyulassy,
The Surprising Transparency of the sQGP at LHC,

35) Z. Qiu and U. Heinz,
Event-by-event shape and flow fluctuations of relativistic heavy-ion collision fireballs,

34) Min He, Rainer J. Fries and Ralf Rapp,
Thermal Relaxation of Charm in Hadronic Matter,

33) T. Song, K. Han, and C. M. Ko,
Charmonium Production in Heavy-Ion Collisions from SPS to LHC,

32) J. Xu and C. M. Ko,
Triangular Flow in Relativistic Heavy Ion Collision,
JET Annual Summer Schools

June 14-17, 2010, LBNL
June 15-17, 2011, Duke
For the next fives