Role of QCD Monopoles in Jet Quenching

Based on: AR and E. Shuryak, arXiv:1708.04254, PRD 97 (in production)

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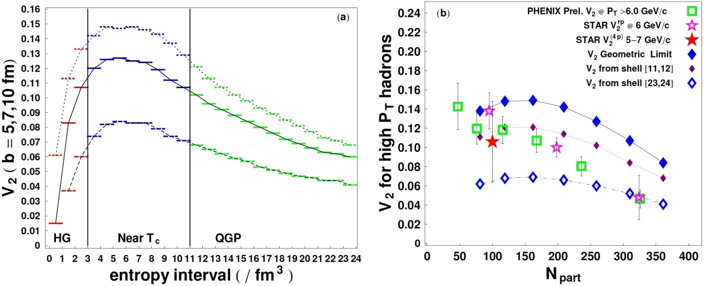
$R_{\mathrm{AA}} \oplus v_2$ "puzzle"

- First RHIC data on the nuclear modification factor and azimuthal anisotropy in early/mid 2000s
  - Jet quenching models of the time under-predicted azimuthal anisotropy by approximately a factor of 2
- Improvements on jet quenching models to try to fix this discrepancy
  - Coupling of jets to flow Betz, Gyulassy (2014)
  - Event-by-event fluctuations Noronha-Hostler, Betz, Noronha, Gyulassy (2016)
  - Non-perturbative effects Liao, Shuryak (2008), Xu, Liao, Gyulassy (2015, 2016)
  - ...

$R_{AA} \oplus v_2$ “puzzle”

Shuryak (2007), Liao and Shuryak (2008)



Near T_c enhancement of jet quenching could explain large v_2

Magnetic Scenario of QCD

Dual Superconductivity Model of the QCD Vacuum

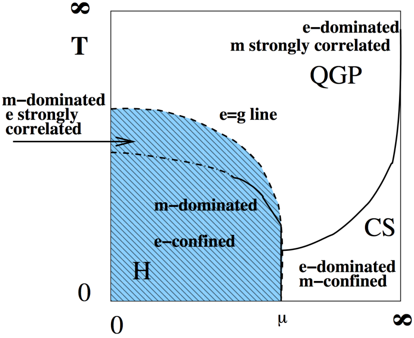
Nambu (1974), Mandelstam (1976), ‘t Hooft (1981)

- Electric quasiparticles (quarks and gluons) and magnetic quasiparticles (monopoles, etc.)
- Confinement is due to the Bose-Einstein condensation (BEC) of magnetic quasiparticles
- Lattice studies have identified electric flux-tubes, monopole currents, and gauge-invariant magnetic field correlated with monopoles

  Koma, et al. (2003), Bornyakov, et al. (2003)

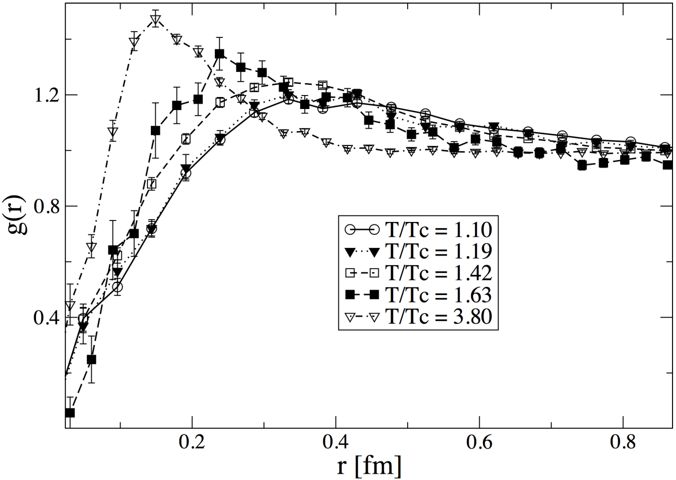
Magnetic Scenario of QCD

- Condition for making Dirac strings invisible: $\frac{eg}{4\pi} = \text{integer}$
  Dirac (1931)
  - $\alpha_s = e^2/4\pi$ in QCD runs with T and μ
  - $\alpha_m = g^2/4\pi$ runs oppositely



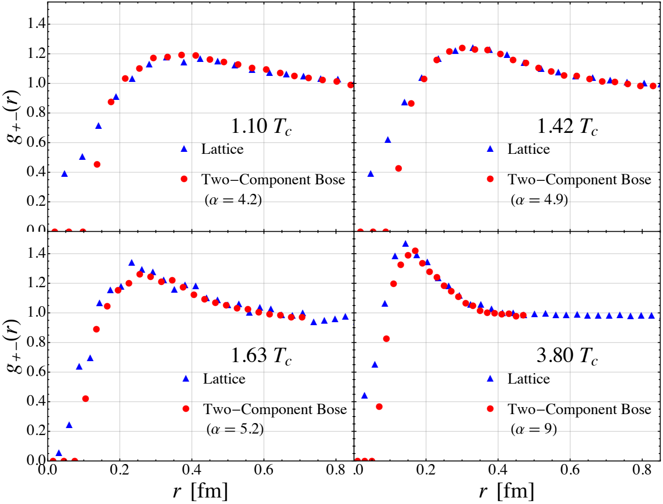
Liao and Shuryak (2007)

Monopoles on the Lattice: SU(2)



D'Alessandro and D'Elia (2007)

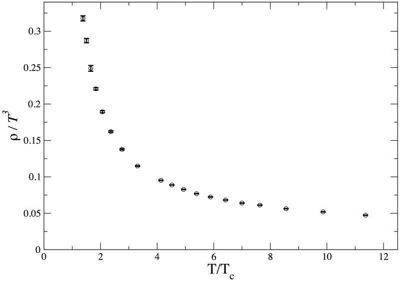
Matching Radial Distribution Functions



AR, E. Shuryak (2017)

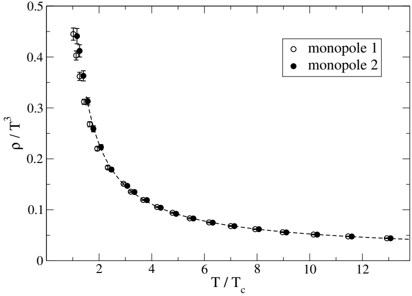
Monopoles on the Lattice

Density: $\rho_m/T^3 \sim \log(T)^{-3} \rightarrow$ Monopoles important near T_c



SU(2)

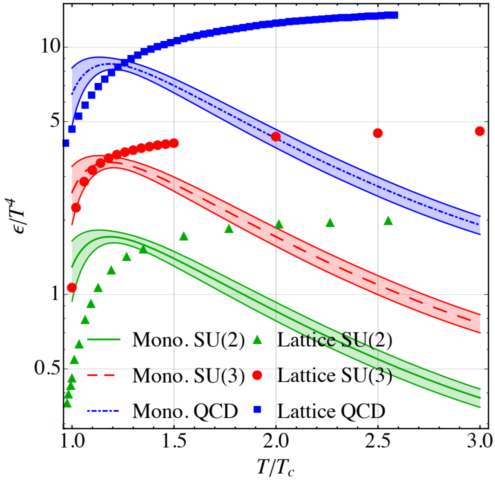
D'Alessandro and D'Elia (2007)



SU(3)

Bonati and D'Elia (2013)

Lattice Equation of State



AR, E. Shuryak (2017)

Goals

Introduce monopoles into the BDMPS jet quenching framework
→ jet observables

- Study the effects of different monopole density parameterizations
- Study the effects of different background evolutions
- Study the energy dependence of jet quenching parameters/observables

BDMPS

Baier, Dokshitzer, Mueller, Peigne, Schiff (1997, 1998)

- Energy loss:

$$-\frac{dE}{dz} \propto \hat{q}z$$

$$\hat{q}(z) \approx \rho(z) \int_0^{1/b^2} \mathrm{d}^2\vec{q}_\perp \vec{q}_\perp^2 \frac{\mathrm{d}\sigma}{\mathrm{d}\vec{q}_\perp^2}(\vec{q}_\perp^2, z)\,,$$

  where $\rho(z)$ is the density of scatterers.

- Screened Coulomb scattering centers:

$$V(q_\perp^2) = \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}^2\vec{q}_\perp}(\vec{q}_\perp) = \frac{\mu^2}{\pi(q_\perp^2 + \mu^2(z))^2}$$

Cross Sections

Generic form of $\mathrm{d}\sigma/\mathrm{d}q_\perp^2$ is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_\perp^2} = \frac{C}{(q_\perp^2 + \mu^2)^2}\,.$$

$$\frac{\mathrm{d}\sigma_{qq}}{\mathrm{d}q_\perp^2} = \frac{(4/3)^2\pi\alpha_s^2(q_\perp^2)}{(q_\perp^2 + \mu_E^2)^2}$$

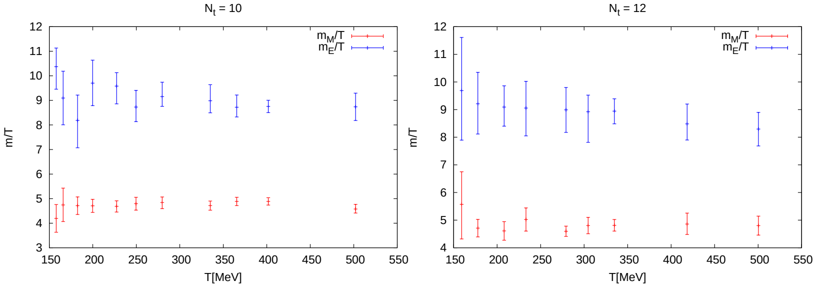
$$\frac{\mathrm{d}\sigma_{qg}}{\mathrm{d}q_\perp^2} = \frac{4\pi\alpha_s^2(q_\perp^2)}{(q_\perp^2 + \mu_E^2)^2}$$

$$\frac{\mathrm{d}\sigma_{gg}}{\mathrm{d}q_\perp^2} = \frac{9\pi\alpha_s^2(q^2)}{(q^2 + \mu_E^2)^2}$$

$$\frac{\mathrm{d}\sigma_{qm}}{\mathrm{d}q_\perp^2} = \frac{(4/3)\pi}{(q_\perp^2 + \mu_M^2)^2}$$

$$\frac{\mathrm{d}\sigma_{gm}}{\mathrm{d}q_\perp^2} = \frac{3\pi}{(q_\perp^2 + \mu_M^2)^2}$$

Screening Masses



$$m_E/T = 7.31$$
$$m_M/T = 4.48$$

Borsányi, Fodor, Katz, Pásztor, Szabó, Török (2015)

Monopole Density

- Two forms of monopole density
  - Direct lattice measurement: Bonati, D'Elia (2013)

$$\frac{\rho_m}{T^3} = \frac{3.66}{\log((1/0.163)T/T_c)^3}$$

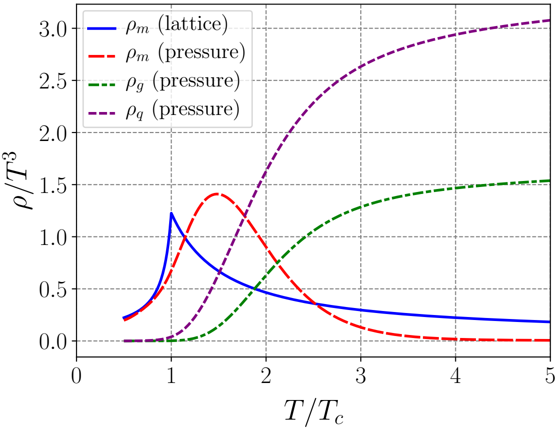
  - Polyakov line with EoS: Xu, Liao, Gyulassy (2015)

$$\rho_E(T) \propto c_q L(T) + c_g L^2(T)$$

$$\rho_M(T) \propto 1 - \rho_E(T)$$

Monopole Density

- Two forms of monopole density

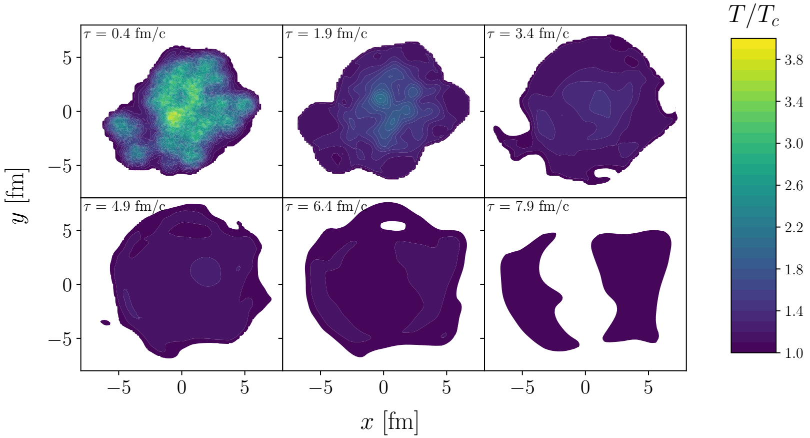


Background Medium

- Focus on 20-30% centrality AA collisions
- Different expanding-medium backgrounds:
  - Glauber-like smooth initial conditions with Bjorken (1+1)D expansion
  - Glauber-like smooth initial conditions with (2+1)D expansion with and without bulk viscosity
  - IP-Glasma initial conditions with (2+1)D expansion with and without bulk viscosity

Background Medium

Example of the hydrodynamic evolution



Numerical Simulation

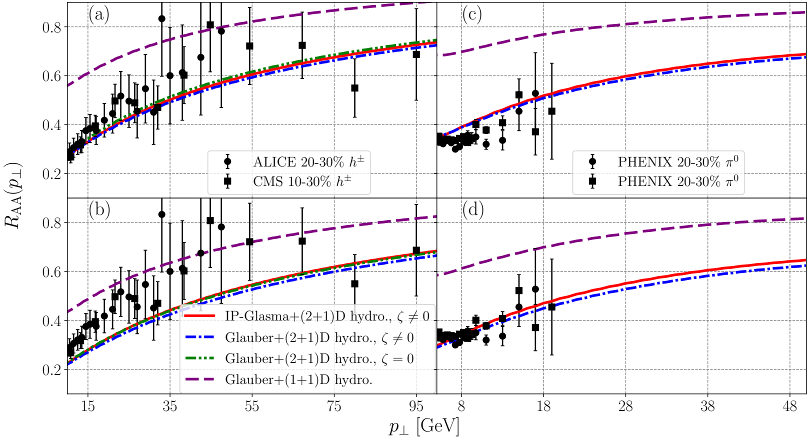
1. Jets created at $\tau = 0$ in the medium with probability proportional to energy density
2. Randomly oriented in azimuthal angle ϕ
3. Initial energy is sampled from power law spectra for quarks and gluons
4. Jet parton then traverses the (evolving) medium and loses energy
5. Fragmentation into pions / charged hadrons

Numerical Simulation

Energy loss given by

$$\begin{aligned}
-\mathrm{d}E &= z\mathrm{d}z\frac{\alpha_s N_c}{12}\hat{q}(z,E) \\
&= z\mathrm{d}z\frac{\alpha_s N_c \pi C_p}{12}\left(\rho_q(z)\int_0^{q^2_{\mathsf{max}}}\mathrm{d}q^2\frac{(4/3)\alpha_s^2(q^2)}{(q^2+\mu_E^2(z))^2}\right. \\
&\quad +\rho_g(z)\int_0^{q^2_{\mathsf{max}}}\mathrm{d}q^2\frac{3\alpha_s^2(q^2)}{(q^2+\mu_E^2(z))^2} \\
&\quad \left.+\rho_m(z)C_{\mathsf{corr}}\int_0^{q^2_{\mathsf{max}}}\mathrm{d}q^2\frac{1}{(q^2+\mu_M^2(z))^2}\right)
\end{aligned}$$

Nuclear Modification Factor R_{AA}



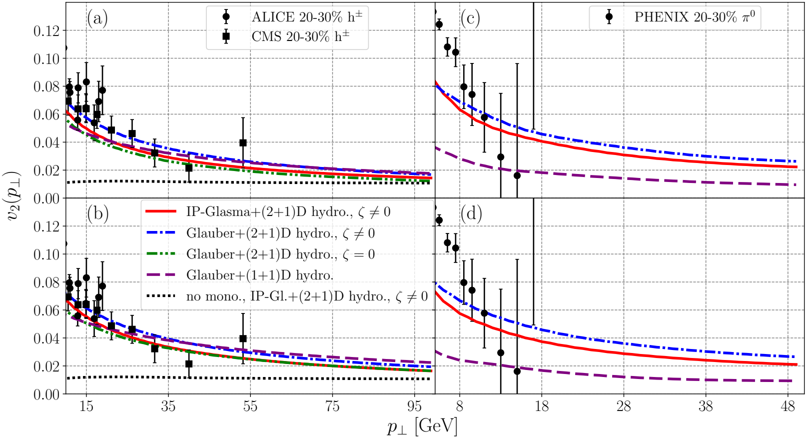
Direct

EoS

LHC 2.76 TeV Pb-Pb

RHIC 200 GeV Au-Au

Azimuthal Anisotropy v_2



Direct

EoS

LHC 2.76 TeV Pb-Pb

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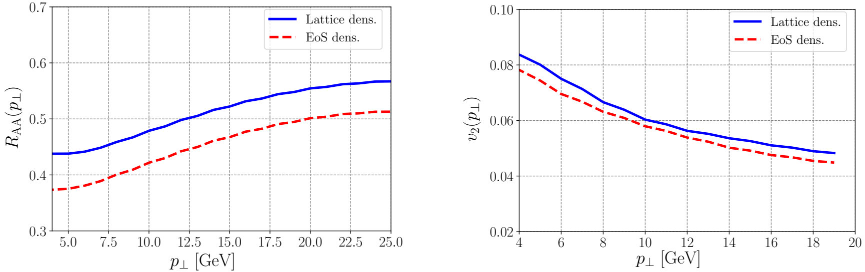
Predictions for the Beam Energy Scan

62.4 GeV Au-Au collisions, optical Glauber initial conditions



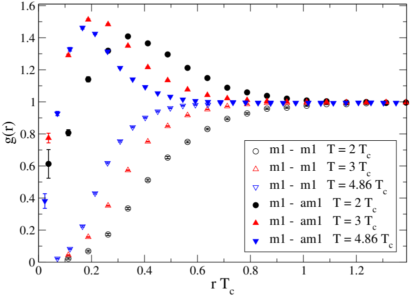
R_{AA} and v_2 of same magnitude as higher energy collisions

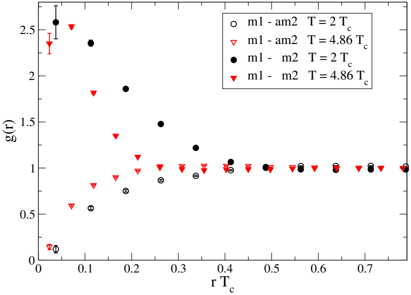
Summary

- BDMPS framework with monopoles can reproduce correct trends for experimental observables
    - Needs realistic hydrodynamic background, but event-by-event fluctuations not necessary except for dijet asymmetry
- Lower energy collisions should see similar v_2 and R_{AA} to higher energy collisions → monopole dominated
    - Can be probed in Beam Energy Scan

Backup Slides

Monopoles on the Lattice: SU(3)

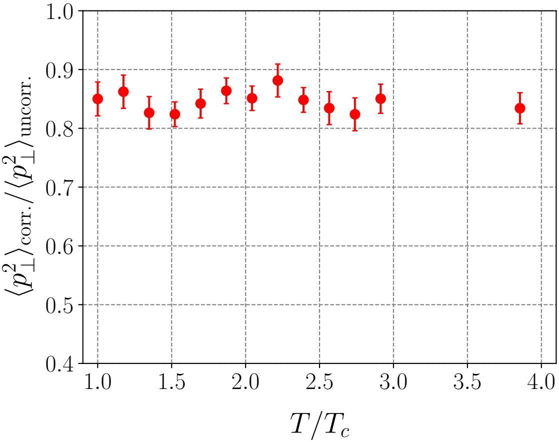




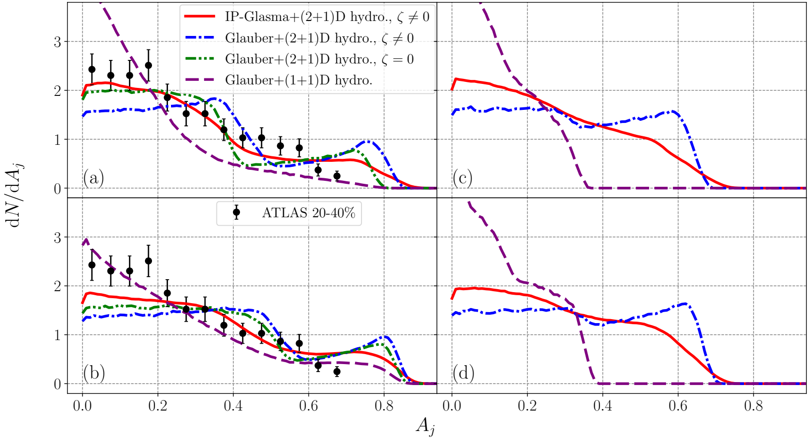
Bonati and D'Elia (2013)

Monopole Correlations

Reduction in momentum transfer due to correlated + and - charges



Dijet Asymmetry A_j



Direct

EoS

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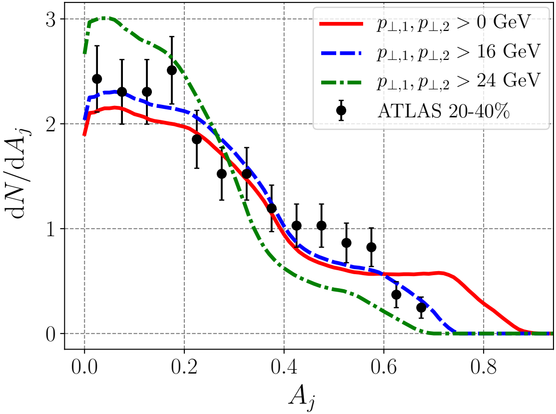
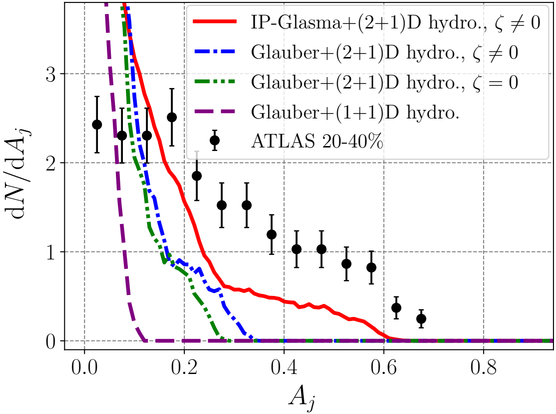


$p_\perp$ cut makes large difference in result!

Dijet Asymmetry A_j



Jets only from center give different distribution than observed