Partons and waves

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Seminal work

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Regular Article - Theoretical Physics

Fine structure in the azimuthal transverse momentum correlations at $\sqrt{s_{NN}} = 200$ GeV using the event shape analysis

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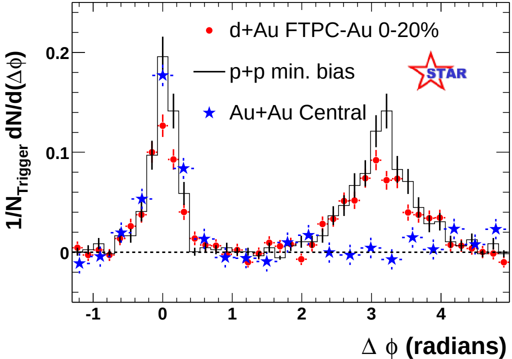
Outline

1. Azimuthal angular correlations
2. Mach cones?
3. Head shock vs. Mach cones
4. $2 \to 3$ vs. $2 \to 2$ processes
5. Small viscosity Hydro: energy-momentum deposited in medium
6. Cooper-Frye: parton distribution from energy-momentum deposited in medium
7. Correlations
8. Conclusions

Azimuthal angular correlations from RHIC (STAR)



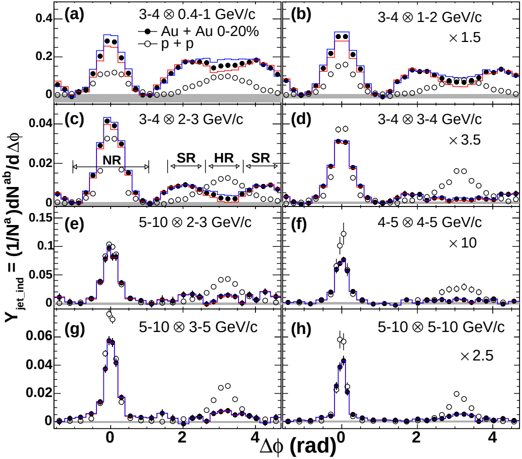
$$C(\Delta\Phi) = \frac{1}{N_{trigger}} \int d\Delta\eta \frac{dN}{d\Delta\Phi d\Delta\eta}$$

Peak suppressed at $\Delta\phi = \pm\pi$ rad

Away-side parton absorbed by medium due to energy loss

∗ *Nucl. Phys. A* **757**, *102-183 (2005) [STAR].*

Azimuthal angular correlations from RHIC (PHENIX)

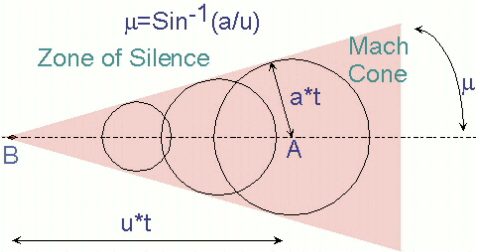


As the p_T difference between leading and associate particles increases

Excess of particles at $\Delta\phi \approx 2\pi/3$ y $\Delta\phi \approx 4\pi/3$ rad

∗ *Phys. Rev. C* **78**, *014901 (2008) [PHENIX].*

Mach cones?



Difficult to produce by a fast moving parton

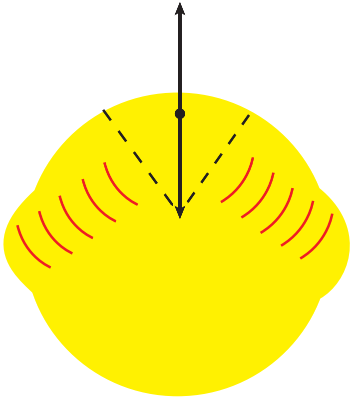
for the conditions in HIC (low viscosity, large parton velocity.

∗ *I. Bouras, A. El, O. Fochler, F. Reining, F. Senzel, J. Uphoff, C. Wes, Z. Xu, C. Greiner,*
arXiv:1207.0755v1 [hep-ph]

Head shock (wakes) vs. Mach cones (shock waves)

A fast moving parton produces a wake rather than a shock wave for small η/s.

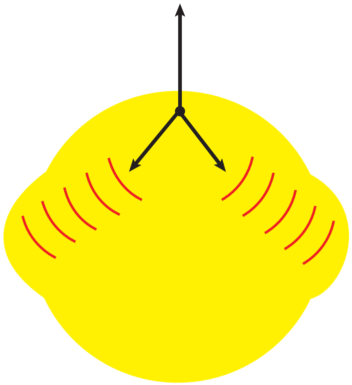
$2 \rightarrow 2$ processes: **double hump only through shock waves**



Single parton moving in plasma with momentum p_T

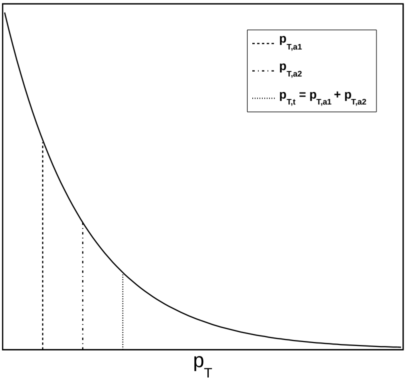
deposits energy as a shock wave.

$2 \to 3$ processes: **double hump possible with wakes from two away-side particles**



Two partons moving in plasma with momentum $p_{1T} + p_{2T} = p_T$

deposit energy, each as a wake, rather than a shock wave.



$2 \to 3$ **suppressed** by α_s compared to $2 \to 2$ **but**

enhanced since on average (for same deposited energy)

two partons come with lower momentum than one in the away side

Linearized, small viscosity hydro

Total energy-momentum of medium $T^{\mu\nu}$ form initial $T_0^{\mu\nu}$ perturbed by fast parton

$$T^{\mu\nu} = T_0^{\mu\nu} + \delta T^{\mu\nu}$$

Small deviations from equilibrium hydro equations

$$\begin{aligned} \partial_\mu T_0^{\mu\nu} &= 0 \\ \partial_\mu \delta T^{\mu\nu} &= J^\nu \end{aligned}$$

Relativistic (small viscosity) fluid energy-momentum tensor components in terms of energy density $\delta\epsilon$ and momentum density $\mathbf{g}$ transferred by fast parton to the medium

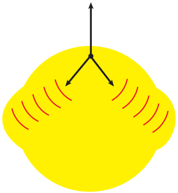
$$\begin{aligned} \delta T_0^{00} &\equiv \delta\epsilon \\ \delta T^{0i} &\equiv g^i \\ \delta T^{ij} &\equiv c_s^2 \delta\epsilon \delta^{ij} - \frac{3}{4}\Gamma_s(\partial^i g^j + \partial^j g^i - \frac{2}{3}\nabla \cdot \mathbf{g}\delta^{ij}) \end{aligned}$$

Linearized, small viscosity hydro

Speed of sound: $c_s = \sqrt{1/3}$.
Sound attenuation length: $\Gamma_s = 4\eta/3sT$.
Equations more easily solved in Fourier space

$$\begin{aligned}
\delta\epsilon &= \frac{ik\mathbf{J}_L + \mathbf{J}^0(i\omega - \Gamma_s k^2)}{\omega^2 - c_s^2 k^2 + i\Gamma_s \omega k^2} \\
\mathbf{g}_L &= \frac{i\omega\mathbf{J}_L + ic_s^2\hat{\mathbf{k}}J^0}{\omega^2 - c_s^2 k^2 + i\Gamma_s \omega k^2} \\
\mathbf{g}_T &= \frac{i\mathbf{J}_T}{\omega + \frac{3}{4}i\Gamma_s k^2} \\
\mathbf{J}_L &\equiv (\mathbf{J}\cdot\hat{\mathbf{k}})\,\hat{\mathbf{k}} \\
\mathbf{J}_T &\equiv \mathbf{J} - \mathbf{J}_L
\end{aligned}$$

Energy-momentum deposited by partons in medium



2 away-side partons in $2 \to 3$ processes absorbed by medium deposit energy and momentum. Model the current they produce by:

$$J^{\nu}(x) = \langle \frac{dE}{dx} \rangle \delta(\mathbf{x} - \mathbf{u}t) U^{\nu}$$

$U^{\nu} \equiv \gamma(1, \mathbf{u})$, $\mathbf{u}$ is the corresponding parton velocity
average energy-loss per unit length: $\langle \frac{dE}{dx} \rangle$

R. B. Neufeld, Thorsten Renk. Phys. Rev. C. **82**. *044903 (2010)*

Energy-momentum deposited by partons in medium

Density of particles produced at central rapidity (Cooper-Frye):

$$\frac{dN}{dy\,d\phi}(y=0) = \int_{p_T^i}^{p_T^f} \frac{dp_T\,p_T}{(2\pi)^3} \int d\Sigma_\mu p^\mu\ \left(f(x_\perp, p_\perp) - f_0\right)$$

Constant time freeze-out hyper surface: $d\Sigma_\mu p^\mu = d^3 r$.

Equilibrium distribution (Boltzmann): $f_0 = e^{-p_T/T_0}$.

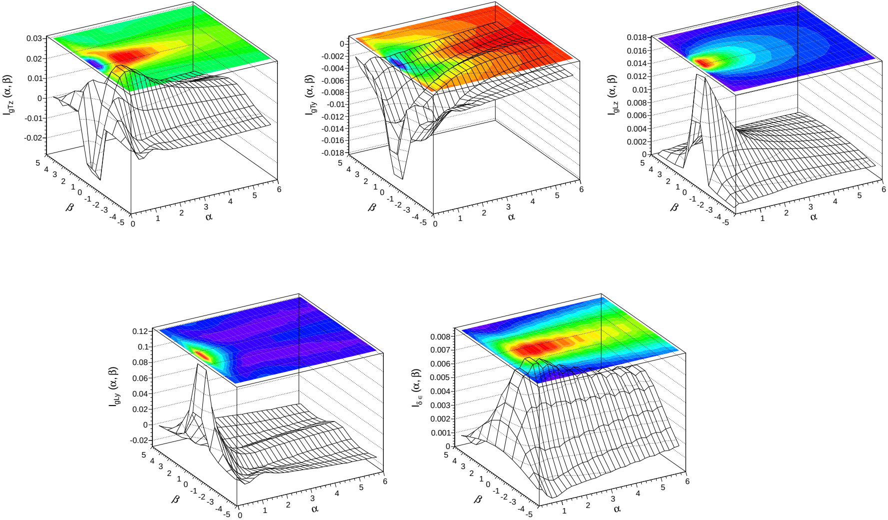
Distribution generated by deposited energy-momentum:

$$f(x_\perp, p_\perp) - f_0 \simeq \left(\frac{p_T}{T_0\epsilon_0}\right)\left(\frac{\delta\epsilon}{\epsilon_0} + \frac{g_y(x_\perp)\sin\phi + g_z(x_\perp)\cos\phi}{\epsilon_0(1+c_s^2)}\right) e^{-p_T/T_0}$$

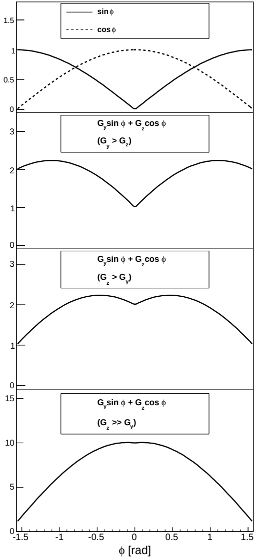
Angle between $\mathbf{g}$ and $\hat{\mathbf{z}}$: ϕ

Initial medium's energy density and temperature: $\epsilon_0,\ T_0$

Energy-momentum deposited by fast particle in medium



Particle distribution around parton direction of motion depends on the relative strength of g_y (the coefficient of $\sin\phi$) and g_z (the coefficient of $\cos\phi$)



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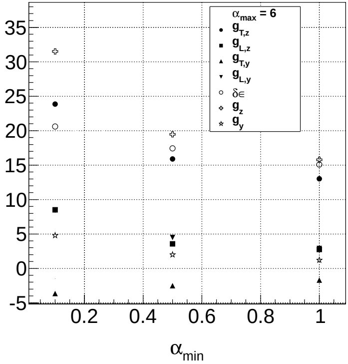
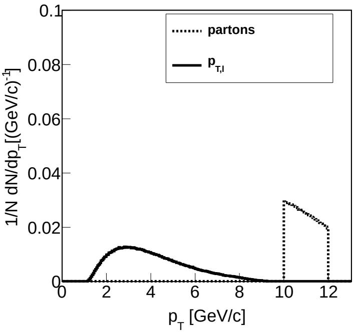
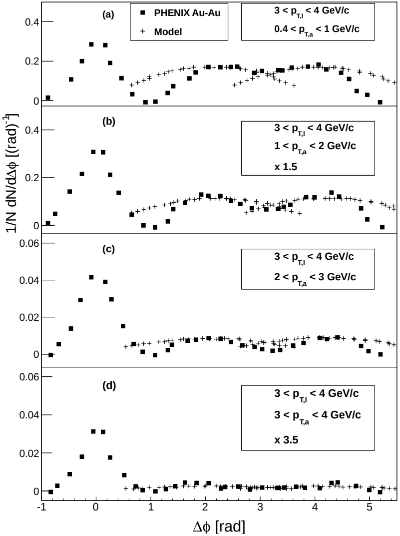


Surface emission of leading particle together with two away-side partons moving through medium ($2 \rightarrow 3$ processes)



Azimuthal correlations compared to PHENIX data. Systematics of double hump correlation signal decreasing as the momentum of the away-side hadron gets closer to the momentum of the leading hadron is well reproduced



CONCLUSIONS

- $2 \to 3$ vs. $2 \to 2$ processes in-medium.
- Lower production rate compensated by higher momentum space population.
- Energy-momentum deposited in medium described by low viscosity hydro.
- Particles produced along direction of motion of partons (Wakes instead of Mach cones).
- Surface emission of leading particle together with away side partons depositing energy momentum within medium reproduce after hadronization systematics of two hadron correlations.