Effects of jet quenching on hydrodynamical evolution of Quark-Gluon Plasma

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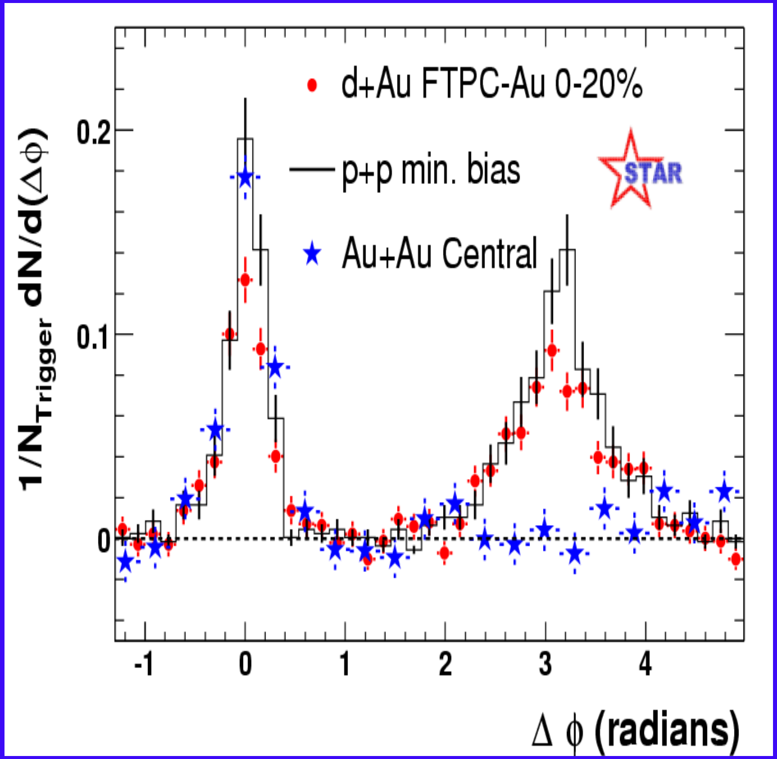
Three important new results in Au+Au collisions at RHIC:

(i) disappearance of away side jet

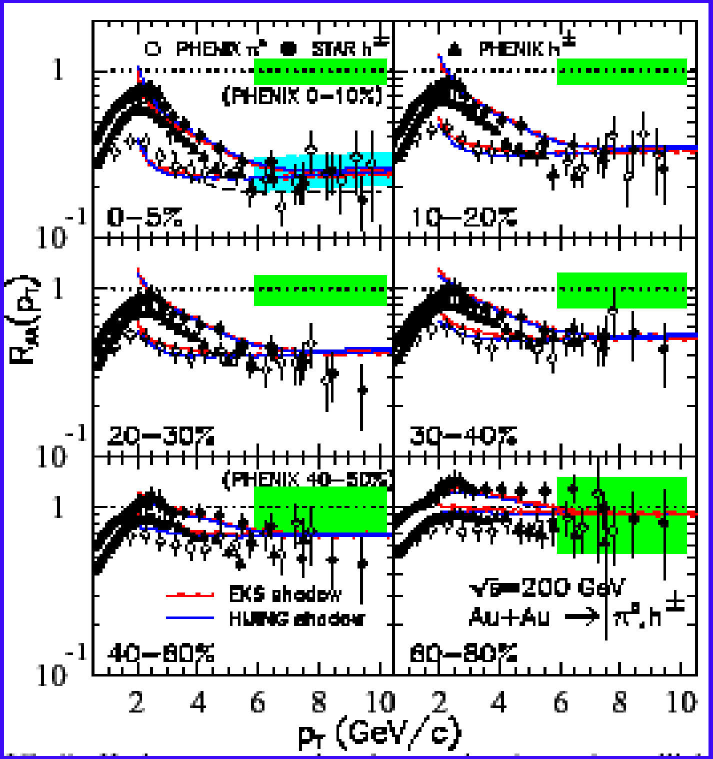
(ii) high P_T suppression=> jet quenching model

(iii)large elliptic flow

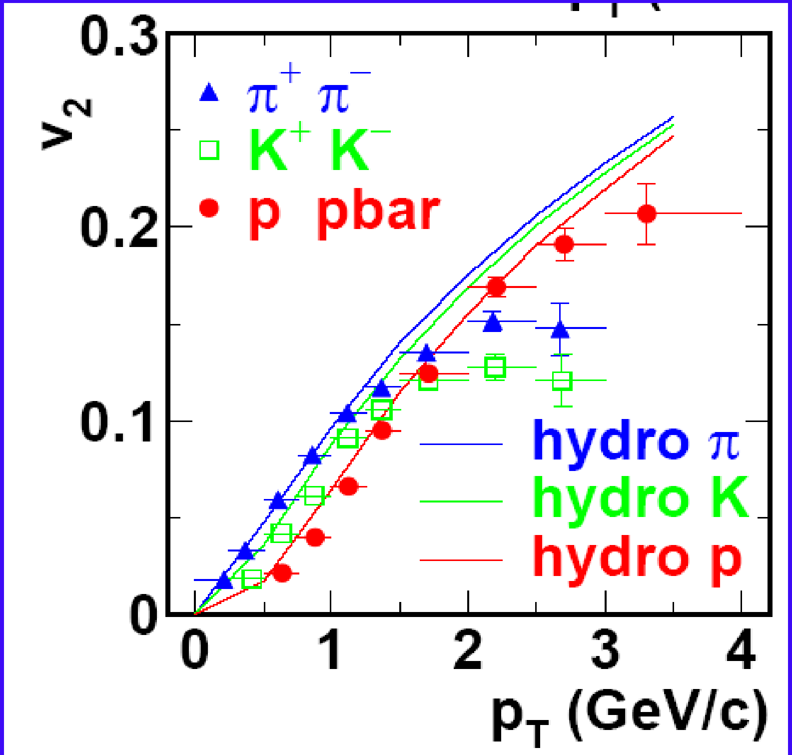
disappearance of away side jet

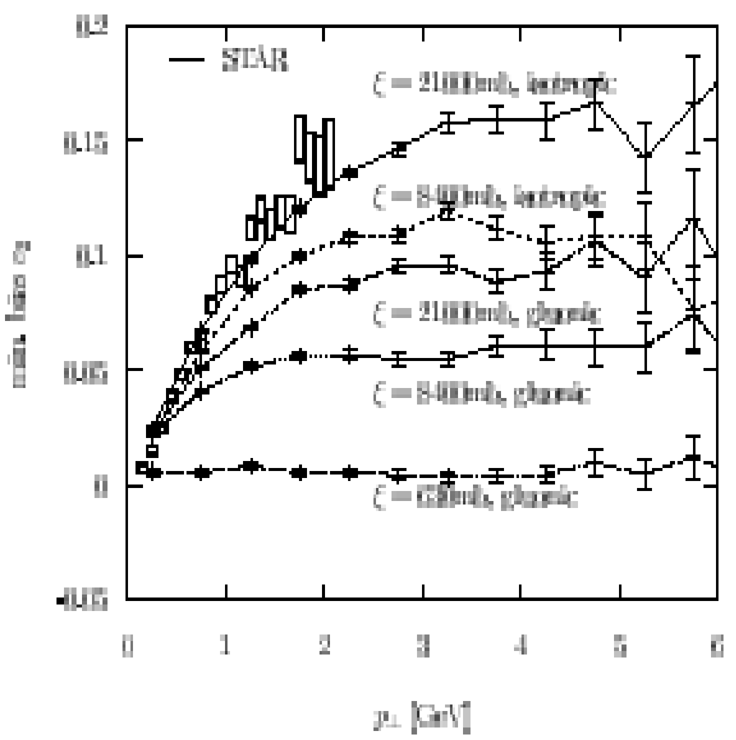


high p_T suppression



experimental observations are explained in jet quenching model, where partons lose energy in a deconfined matter (Wang,Gyulassy,PRL68).





ideal hydrodynamics explain elliptic flow, and a host of other data (Heinz, Kolb, nucl th/0305084).

parton cascade model require rather large cross-section (Molnar, Gyulassy NPA697).

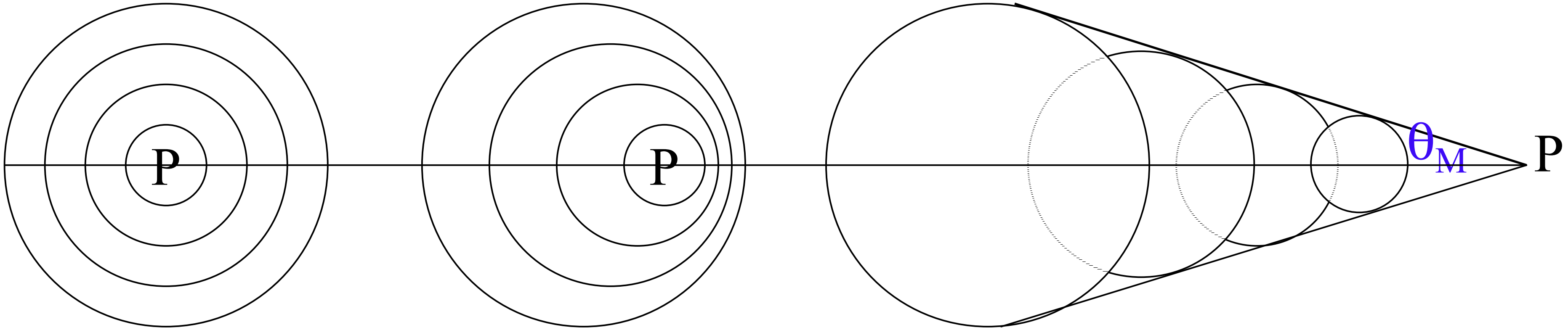
QGP is a fluid with small viscosity.

Absence of collective flow ==> No QGP formation,

presence of collective flow==> not necessarily QGP formation.

Shock wave formation

Static medium **moving medium**



Disturbance created at P propagate with speed c. At time t, 2t, 3t... disturbance will reach points which lie on concentric spheres of radius ct, 2ct, 3ct...

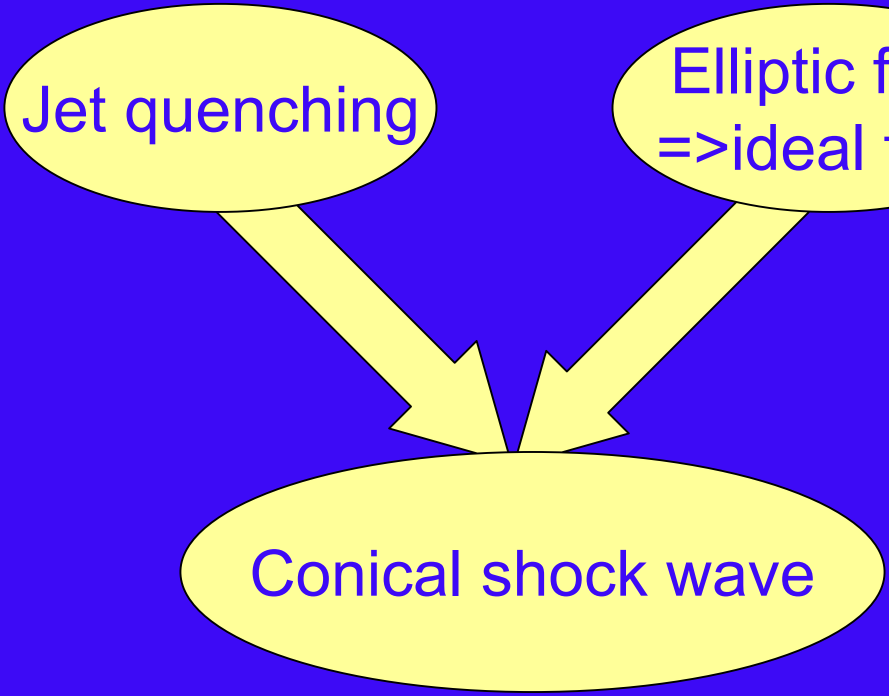
Medium moves with velocity v from right to left. Disturbance at time nt will lie on a sphere of radius nct, with centre at a distance of nvt from P. v<c, spheres do not intersect. Disturbance will reach any pre-assigned point of space.

for v>c, disturbance can not reach points outside a cone (Mach) whose vertex is P. Cone angle $2\theta_M$.

$\sin(\theta_M)=c/v$

θ_M= Mach angle.

New phenomena at RHIC:



Jet quenching

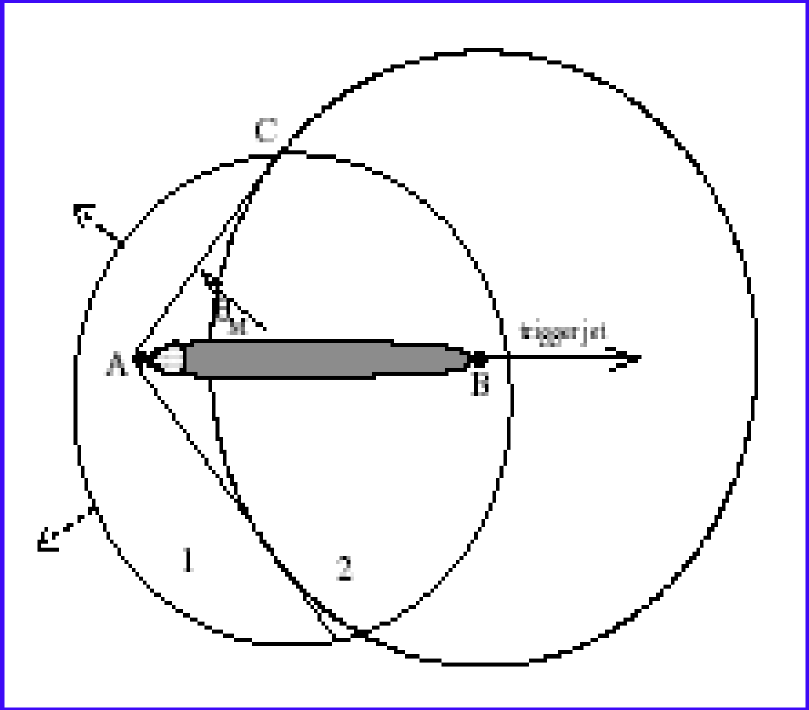
Elliptic flow
=>ideal fluid

Conical shock wave

Casalderrey-Solana,Shuryak,Teaney:J.Phys.Conf.Series:27

Jet moves at, speed of light >> speed of sound==>Shock wave.

QGP: nearly ideal fluid. Shock waves will not be damped due to viscosity.



Mach angle: $$\theta_M = \cos^{-1}\frac{c_s}{c_{jet}}$$

Enhanced particles at: $= \pi + \theta_M$ **and** $\pi \quad \theta_M$

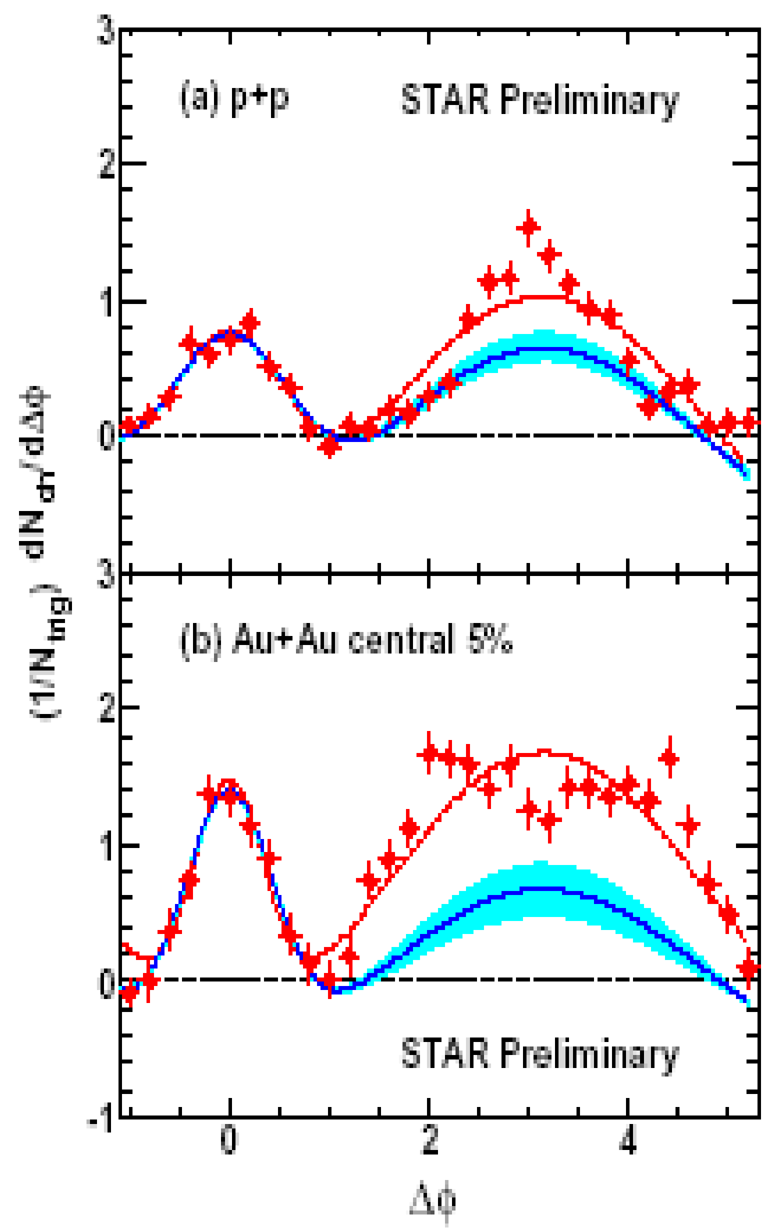
Resonance hadron gas: **$c_s^2 \approx 0.2$: $\theta_M \approx 1.11$**
and Mach peaks at **$\Phi \approx 2, 4.2$**

Star preliminary data on dN/dΔΦ vs. ΔΦ (angular interval between trigger and the particle detected).

For pp collision: away side looks like jet, but not in Au+Au collisions.

Away side show peak like structure at appropriate positions.

Are these peak are from Mach shock wave?



Model: We assume quenching jet acts as a current source.

$$\partial_\mu T^{\mu\nu} = J^\nu$$

The current

$$J^\nu(x) = J(x)(1,-1,0,0);$$

$$J(x) = \frac{dE}{dx}\frac{dx_{jet}}{dt}\delta^3(x - x_{jet})$$

$$\frac{dE}{dx} = \frac{s(x)}{s_0}\left.\frac{dE}{dx}\right|_0$$

s(x):local entropy density; reference entropy density s_0=140 fm^{-3}.
dE/dx$|_0$=14 GeV/fm for high P_T suppression at RHIC.

We work in (τ,x,y,η) co-ordinate frame and assume boost-invariance.

$$\partial_\tau \tilde{T}^{\tau\tau} + \partial_x(\tilde{v}_x \tilde{T}^{\tau\tau}) + \partial_y(\tilde{v}_y \tilde{T}^{\tau\tau}) = -\tilde{p} + \tilde{J}$$

$$\partial_\tau \tilde{T}^{\tau x} + \partial_x(\bar{v}_x \tilde{T}^{\tau x}) + \partial_y(\bar{v}_y \tilde{T}^{\tau x}) = -\partial_x \tilde{p} - \tilde{J}$$

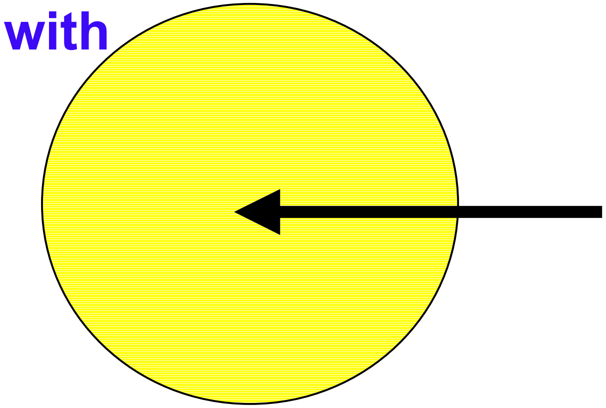
$$\partial_\tau \tilde{T}^{\tau y} + \partial_x(\bar{v}_x \tilde{T}^{\tau y}) + \partial_y(\bar{v}_y \tilde{T}^{\tau y}) = -\partial_y \tilde{p} - \tilde{J}$$

In the last equation delta functions are replaced by Gaussians of width σ.

$$\delta^3(\vec{r} - \vec{r}_{jet}) \rightarrow \frac{1}{\tau} \frac{e^{-(x-x_{jet})^2/\sigma^2}}{\sqrt{2\pi\sigma^2}} \frac{e^{-(y-y_{jet})^2/\sigma^2}}{\sqrt{2\pi\sigma^2}}$$

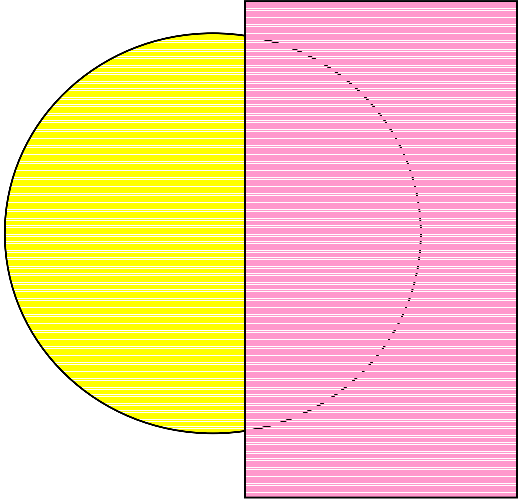
Some implications of assumed boost invariance.

Jets are three dimensional objects, with small angular width. Can be approximated by a 'point-like source'.
Trajectory of jet is then a 'line'.



pushing a needle =>conical flow

With boost-invariance jets are infinitely extended in rapidity co-ordinate.
The trajectory of the jet is then, instead of a line, a plane.



Cutting the fluid with rapidity knife. =>wedge flow

Boost invariance maximizes the effect of jet quenching.
=> upper limit .

Full 3D study is very important!

Initial conditions:

Fluid: At initial time τ_i=0.6 fm, energy density corresponds to transverse density of wounded nucleons in Au+Au collisions at impact parameter b=0, with central energy density **30 GeV/fm^3.**

Initial energy density is azimuthally symmetric.

Initial velocity V_x=V_y=0

Jet: formed at τ_i=0.6 fm, at x=6.4 fm, y=0 fm.

Equation of state: QGP phase:bag model.
hadronic phase: resonance hadron gas.

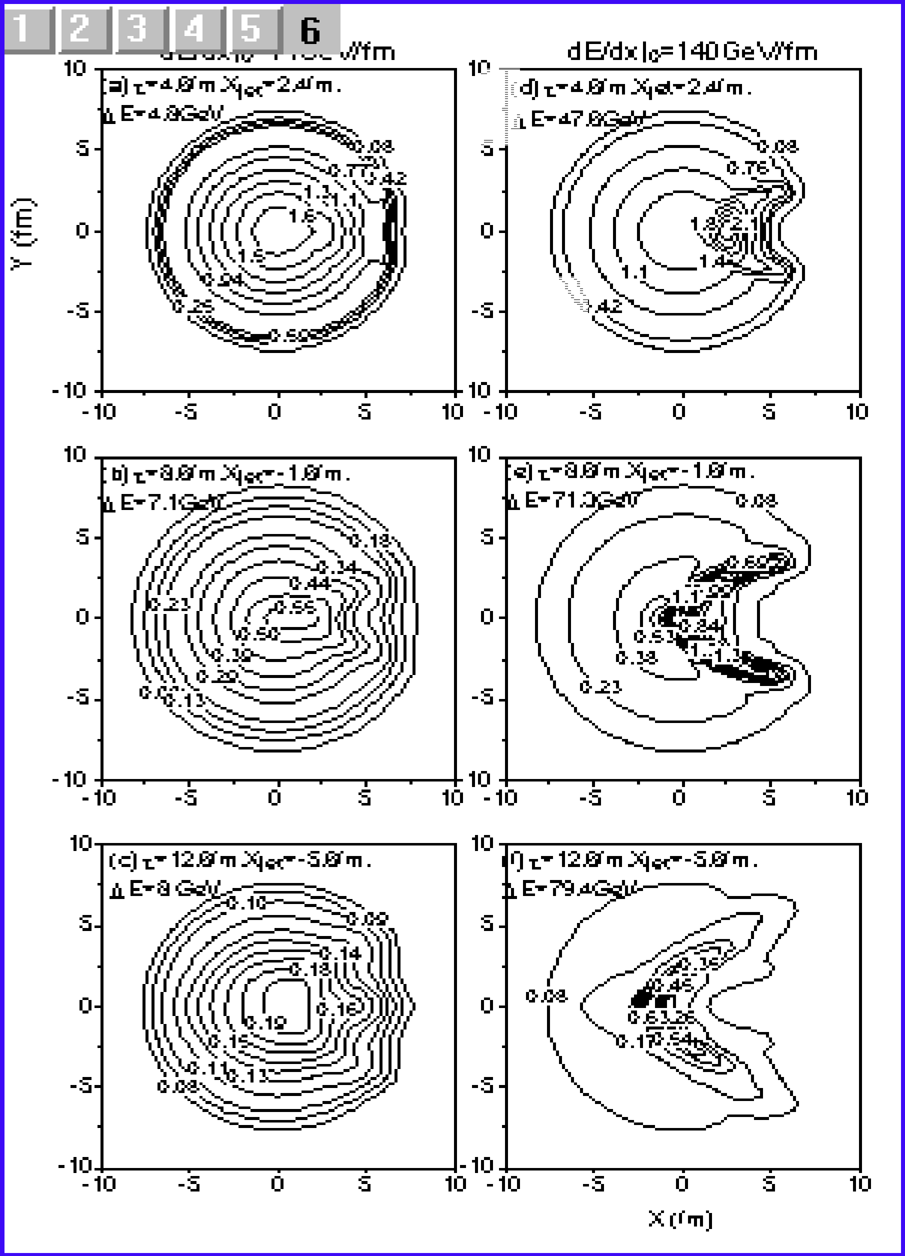
hydro+jet[PRL97]

Constant energy density contours:

Left panel: dE/dx|$_0$=14 GeV/fm:

modulation of contours due to quenching jet is small. Mach like regions are barely visible.

right panel:dE/dx|$_0$=140 GeV/fm For higher partonic energy loss, Mach like regions are visible.

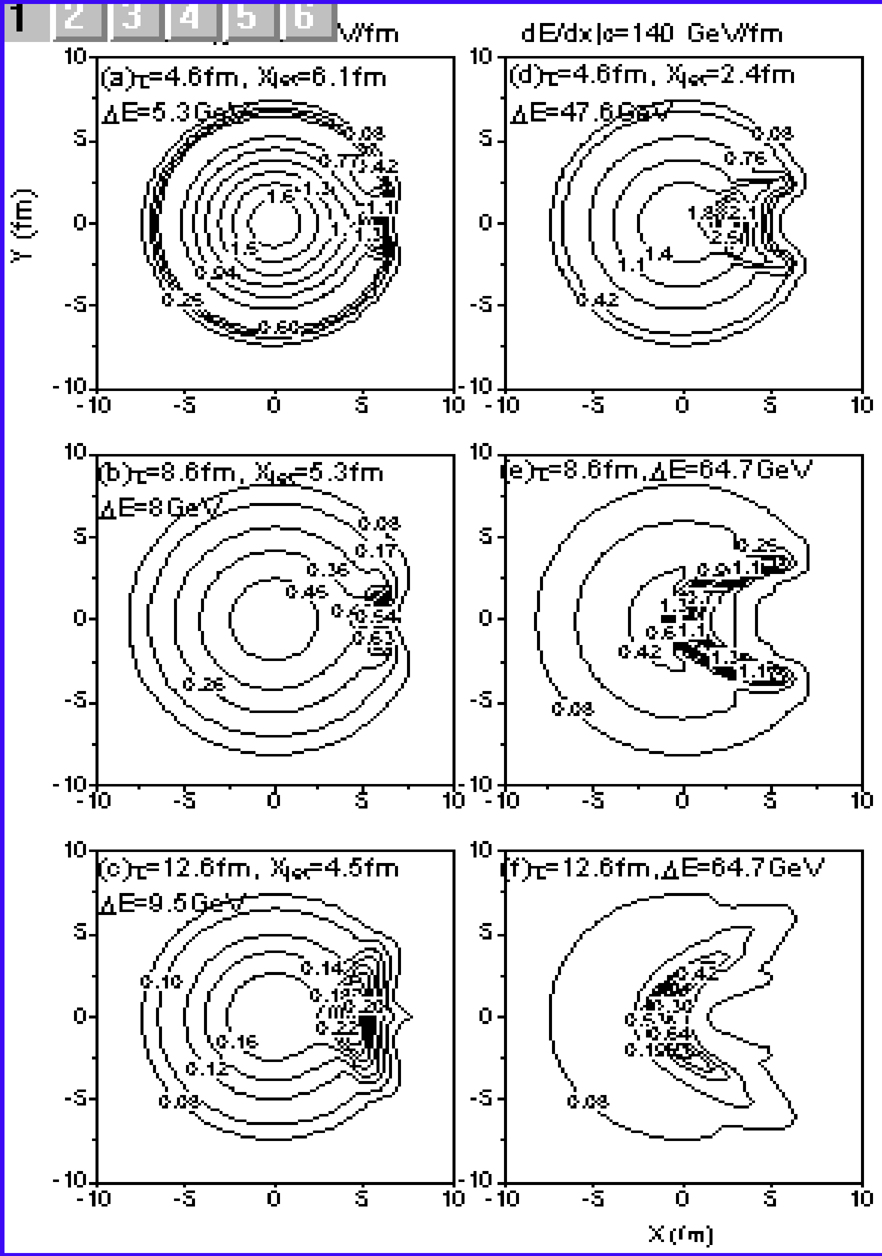


hydro+jet[PRL97]

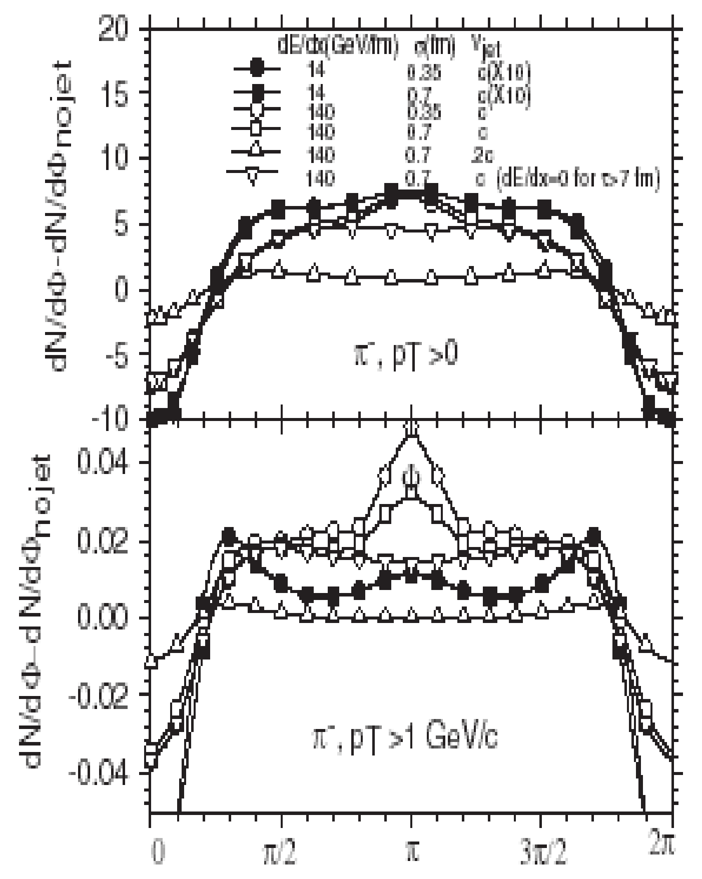
$dE/dx|_0$=140 GeV/fm

Left panel: jet velocity=0.2c, accumulation of energy around the jet.

Right panel: jet stops midway. Mach shock like region is seen at late time, even though the jet no longer exists. At late time, due to dilution, energy deposition is small.



hydro+jet[PRL97]

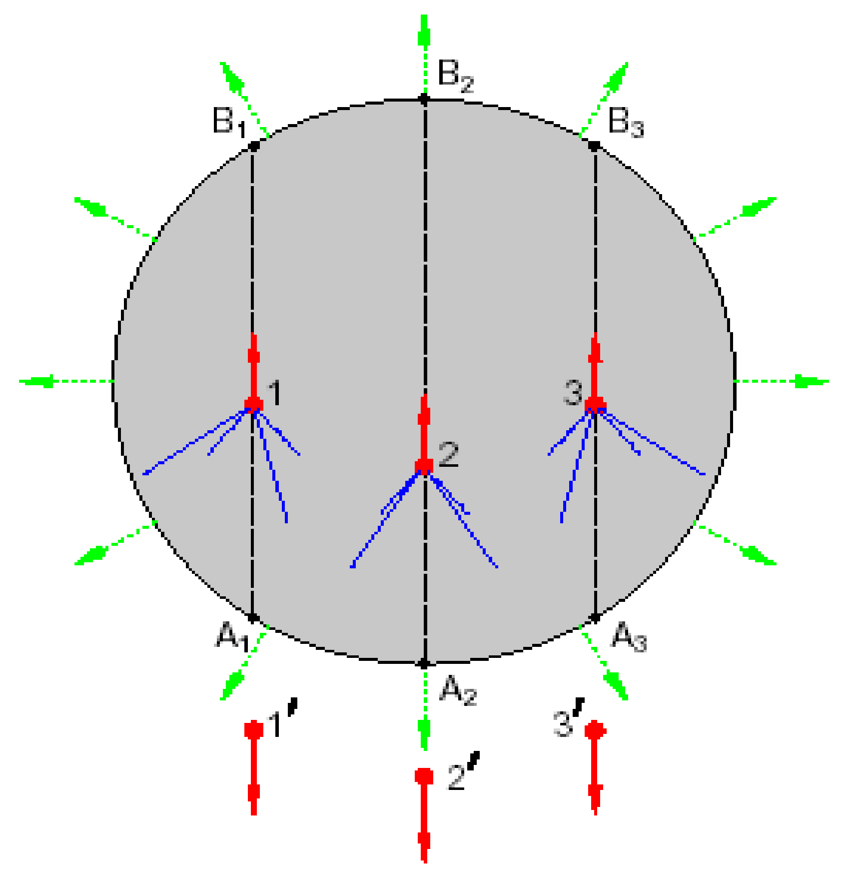


realistic parton energy loss or even for higher parton energy loss Mach peak at $\pi-\theta_M$ and $\pi+\theta_M$ associated with dip at $\Phi=\pi$, is not seen. Rather we find peak at $\Phi=\pi$ with shoulders on both sides. Peak at $\Phi=\pi$ reflect directed momentum imparted by the quenching jet. It is absent when the jet stops midway.

Shoulders exist even for subsonic speed: back splash, general bias of energy deposition towards the right side of the fire-ball etc. have strong influence of on particle production and Mach peak position. Absence of dip at $\Phi=\pi$ is very disturbing

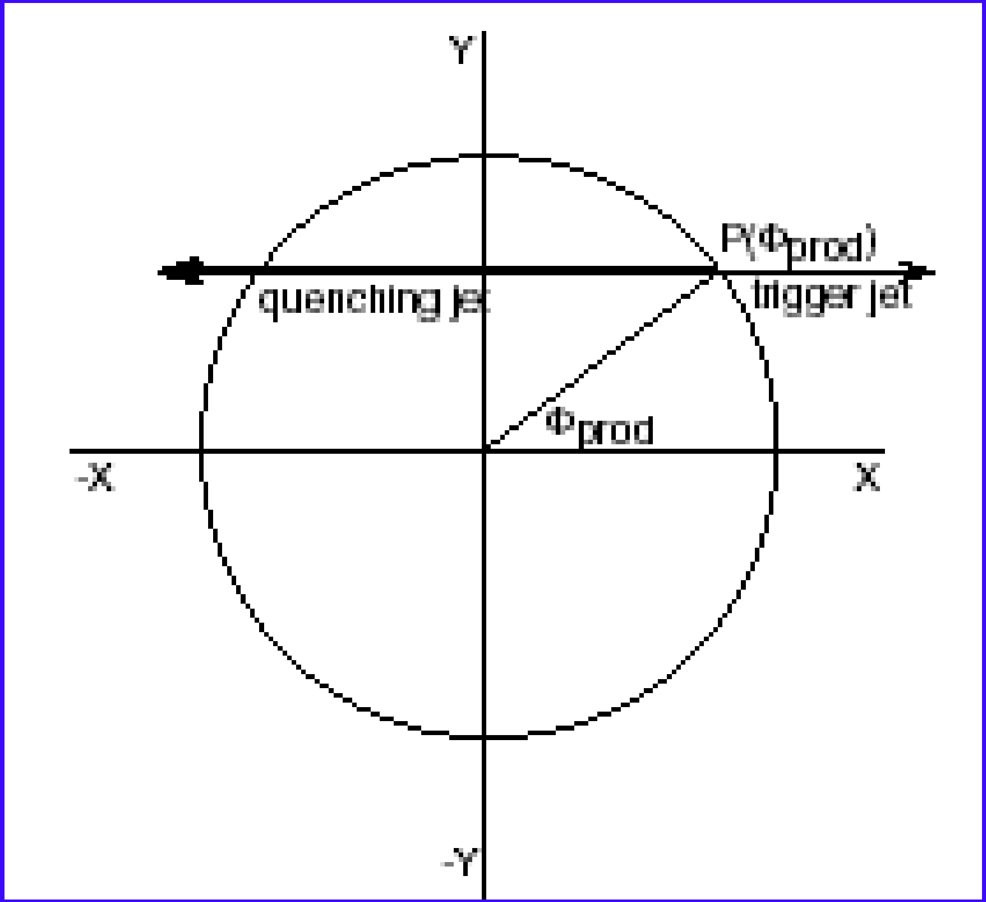
We concluded: conical flow may explain the broadening of the peak seen by STAR, but not for the sharp structure seen at $\Phi=\pi\pm1$.

Satarov, Stoecker, Mishustin: PLB627,64(2005)



Mach shock region is deformed, due to finite fluid velocity.

Off-diagonal jets, Mach region become asymmetric.



at impact parameter b collisions, parton pair is produced at P(Φ_{prod}), on the surface of ellipsoidal fireball, with major and minor axes, R-b/2 and $\sqrt{(R^2-b^2/4R^2)}$.

$$\pi/2 \geq \Phi_{prod} \geq -\pi/2$$

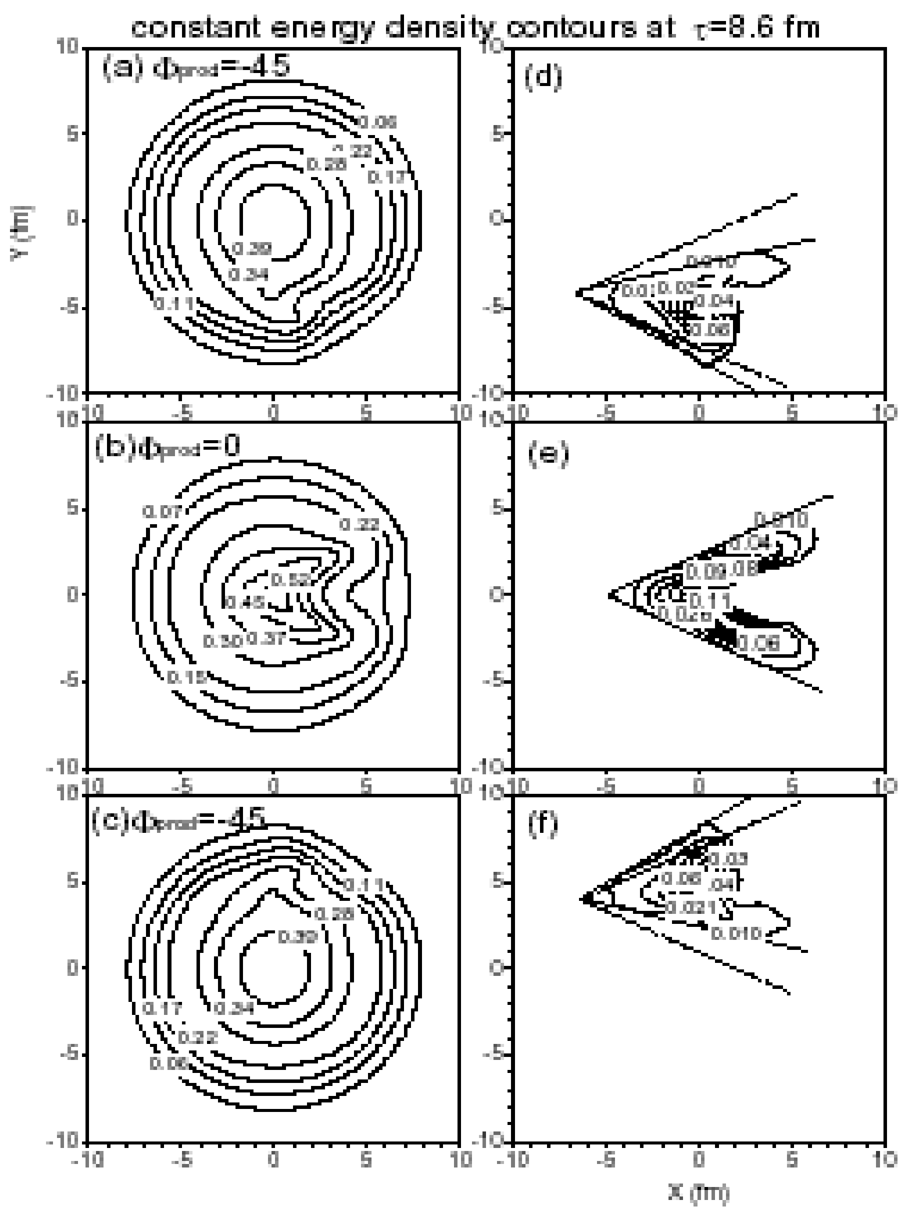
nucl-th/06010121

Au+Au@b=3 fm: Hydro+jet

left panel: constant energy density contours for Φ_{prod}=-45°,0° and 45°, after t=8.6 fm of evolution with a quenching jet. Mach shock like region is barely visible in off-diagonal trajectories.

right panel: constant “excess” energy density contours due to jet only. Mach shock like regions, for off-diagonal trajectories is clearly visible.

corroborate study by Satarov, Stoecker, Mishustin: PLB627,64(2005)



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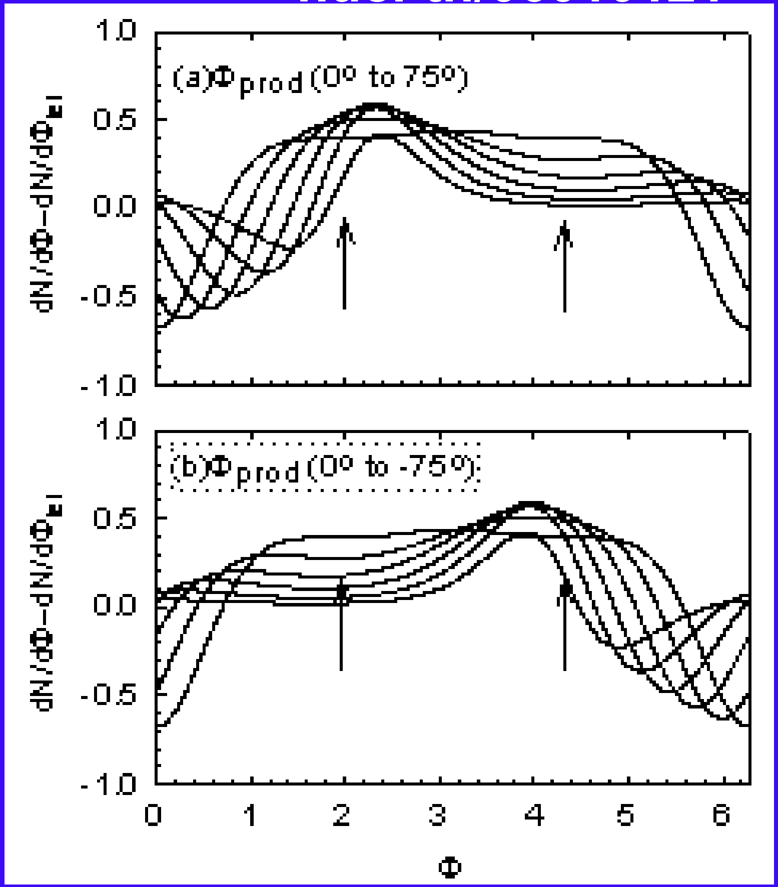

off-diagonal trajectories: only one peak, irrespective of jet position, so long the trajectories are far off from the centre. One peak, give way to a broad maxima as the jet trajectory comes closer to the centre. Depletion in production at $\Phi = \Phi_{prod}$

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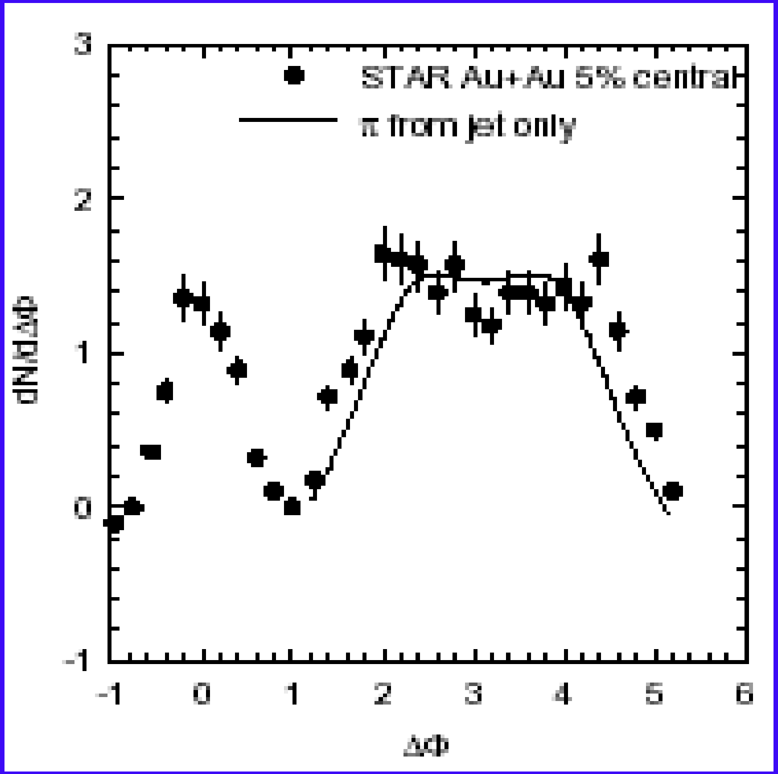


normalised **(normalising factor ~2) angular distribution of pions due to quenching jet only.**

STAR data on background subtracted secondaries are possibly due to “conical” flow generated by the partonic energy loss.

Conclusions:

(i) Partonic energy loss in the medium created in central Au+Au collisions can produce Mach shock like region. Unlike in static matter, Mach shock fronts are distorted due to finite fluid velocity. Inhomogeneity of the medium also distort the Mach region.

(ii) Jet traveling diagonally, two shock fronts are pushed in. For off-diagonal jets inside front is pushed in while the out side front is pushed out.

(iii) Angular distribution of pions due to partonic energy loss only, resemble the STAR data on the azimuthal distribution of back-ground subtracted secondaries, associated with high p_T trigger. Fine structure seen by the STAR and PHENIX in the sideward peak, mey be related to conical flow. However, better understanding of distortion of shock due to finite fluid velocity and inhomogeneity is required.

Natural language for describing flow is hydrodynamics.

$$\partial_\mu N^\mu = 0;$$
$$\partial_\mu T^{\mu\nu} = 0;$$

$$N^\mu = N u^\mu$$
$$T^{\mu\nu} = (\varepsilon + p) u^\mu u^\nu - p g^{\mu\nu}$$

5-equations and 6 unknown (i)number density (N), (ii)energy density (ε), (iii)pressure (p), (iv-vi)3 hydrodynamic velocity ($u^2=1$).

Equations are closed with a Equation of state, $p=p(\varepsilon)$.

Required: initial conditions, freeze-out conditions.

Particle spectra:
(Cooper-Frey)

$$\frac{dN}{p_T dp_T d\phi dy} = \int d\sigma_\mu p^\mu f(x,p)$$

equilibrium distribution function: $f(x,p) = \dfrac{1}{\exp(u_\mu p^\mu / T) \pm 1}$

emergence of back-to-back di-jet peak!
STAR:nucl-ex/0604018

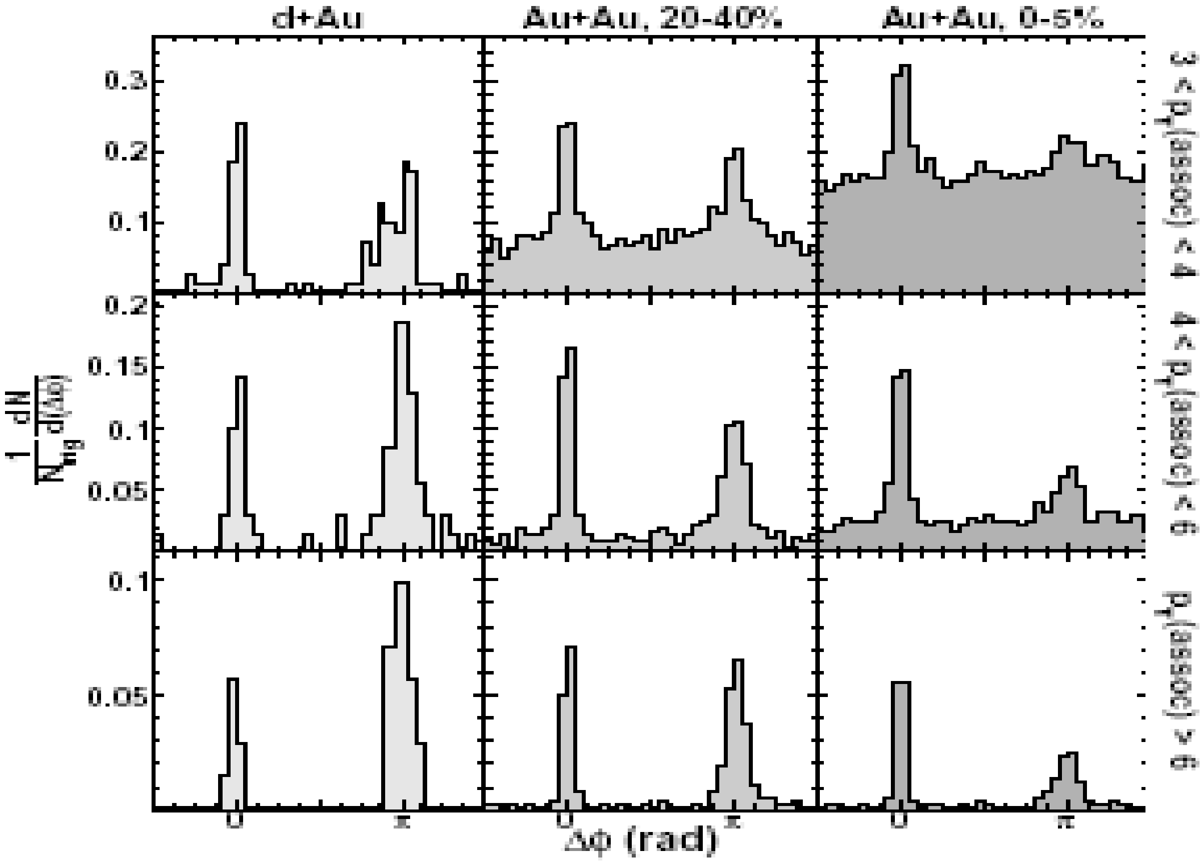
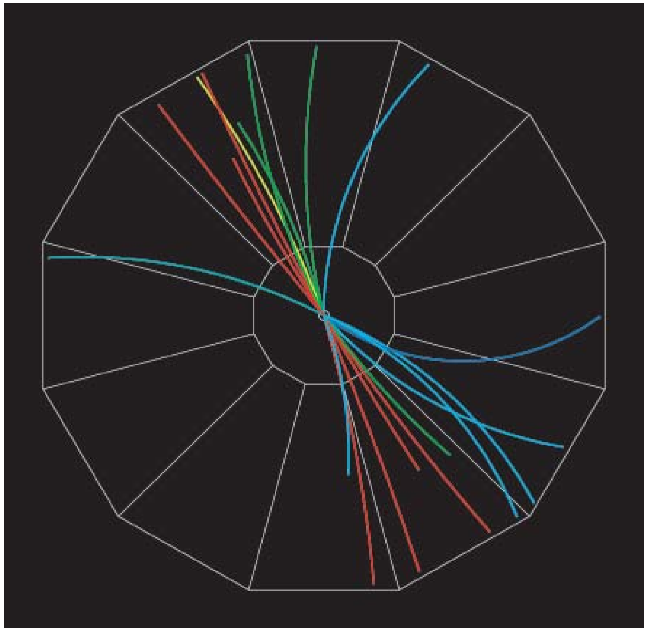


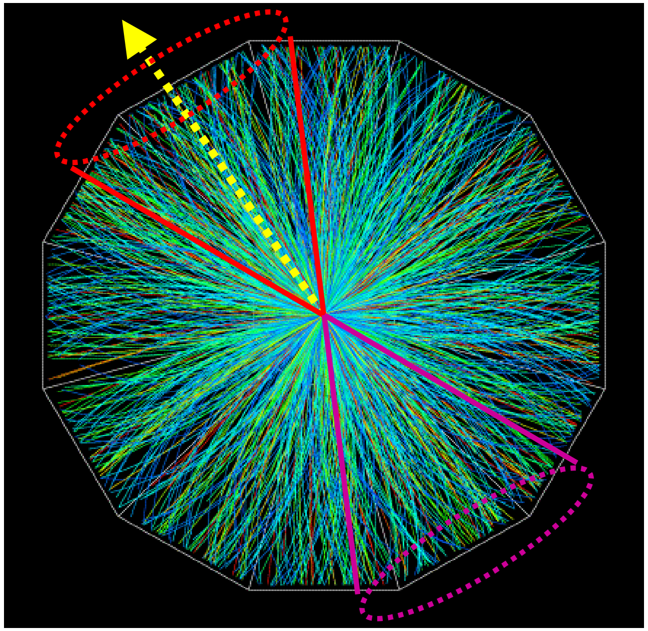
FIG. 2: Azimuthal correlation histograms of high p_T charged hadrons for $8 < p_T^{\mathrm{trig}} < 15$ GeV/c, for d+Au, 20-40% Au+Au and 0-5% Au+Au events. p_T^{assoc} increases from top to bottom.

present theories must be changed to reconcile with new data.

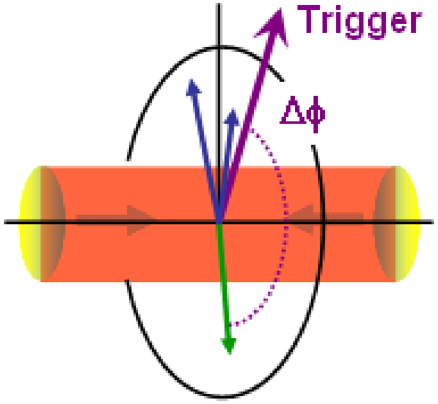
particles in pp

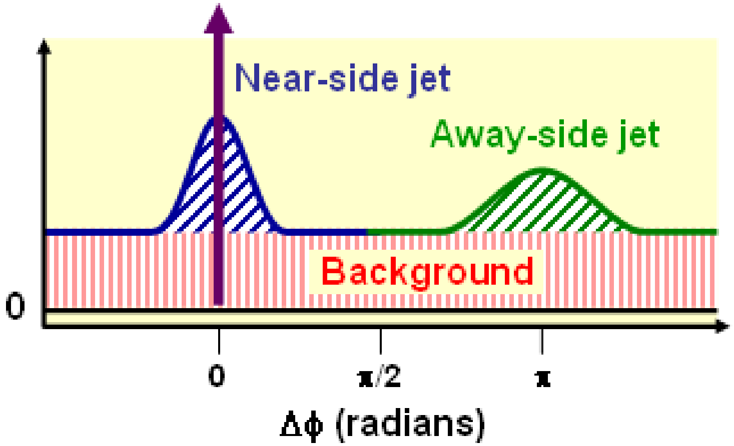


particles in Au+Au



back-to-back Azimuthal correlation method





require large background subtraction!

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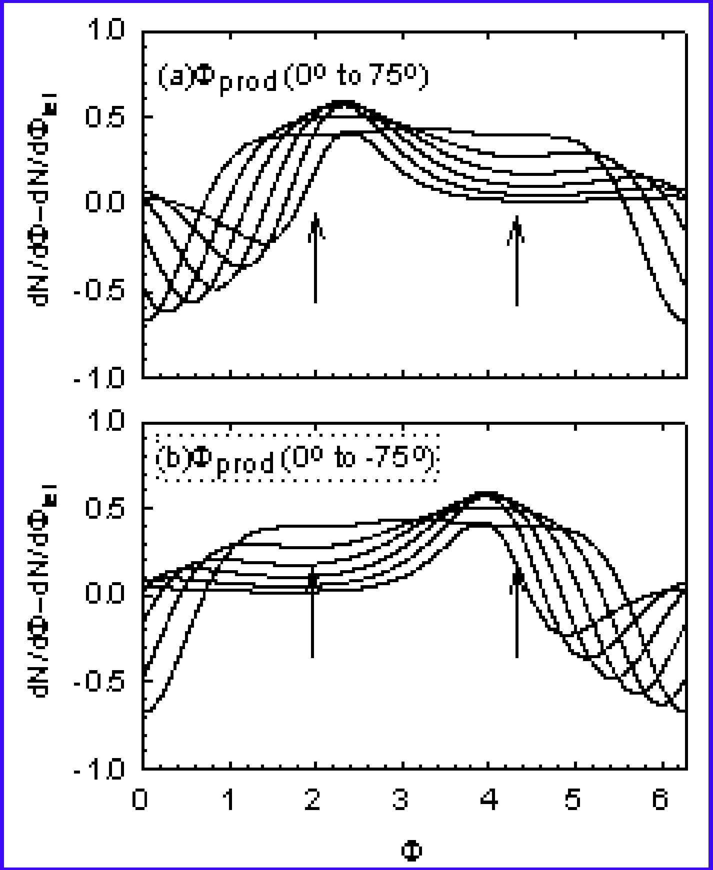
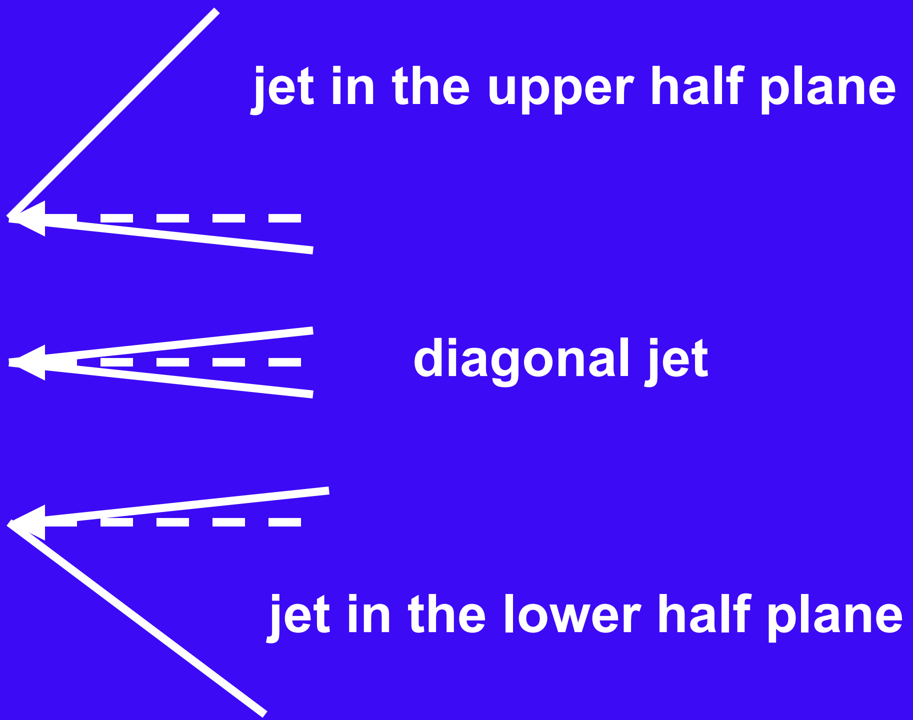
Mach shock fronts consistent with ang. dist. of pions due to jet only:

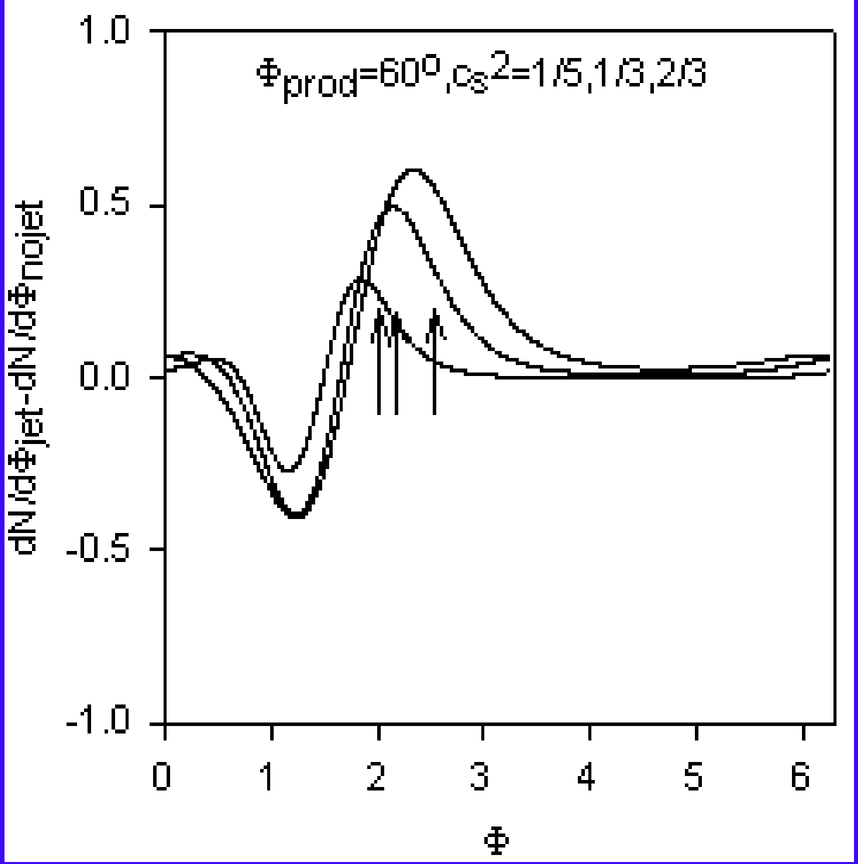



jet in the upper half plane

diagonal jet

jet in the lower half plane

From the spectra, Mach cone opening angle: $\theta_M = \mathrm{asin}(c_s/c_{jet}) \approx 0.72$;
hadron resonance gas: $c^2_s \approx 0.15$: $\theta_M \approx 0.4$
Fluid velocity effectively enhances the speed of sound:
$\theta_M \approx 0.72$ ==>; $c^2_s \approx 0.43$.



peak is related to speed of sound: Peak changes with speed of sound .

No simple relation with peak due to Mach cone in a static medium.

speed of sound =1/5=> θ_M =1.1, we get $\theta_M \approx 0.8$
1/3=> θ_M =0.95, $\theta_M \approx 1.0$
2/3=> θ_M =0.61, $\theta_M \approx 1.2$

More study is needed to understand the effect of fluid velocity and inhomogeneity of the medium.