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Jet Propagation and Mach Cone Formation in (3+1)dimensional Ideal Hydrodynamics

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and

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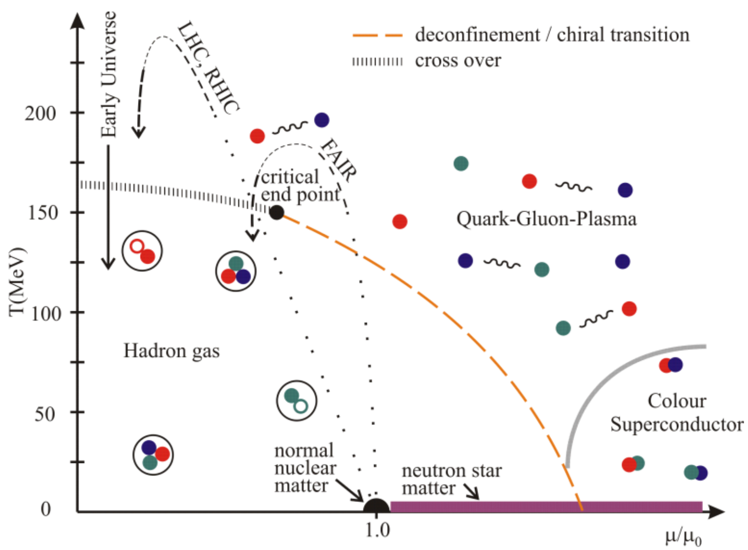
Giorgio Torrieri

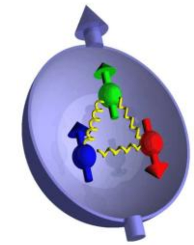
Phys. Rev. C **79**, 034902 (2009), Phys. Lett. B **675**, 340 (2009),
Nucl. Phys. A **830**, 777c (2009), arXiv:1005.5461

Explore The Matter in a HIC

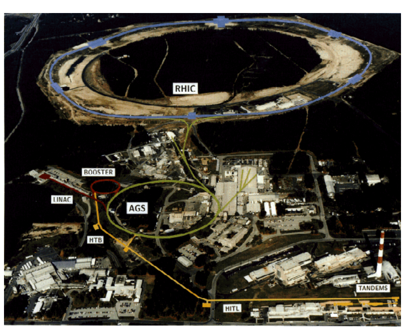
- Why do we want to study jets & Mach cones?
- Why do we use hydrodynamics?



- Insights into theory of strong interactions (QCD)



- Medium created in heavy-ion (HIC) collisions similar to the one created after Big Bang
- Explore the phase diagram of QCD with HIC



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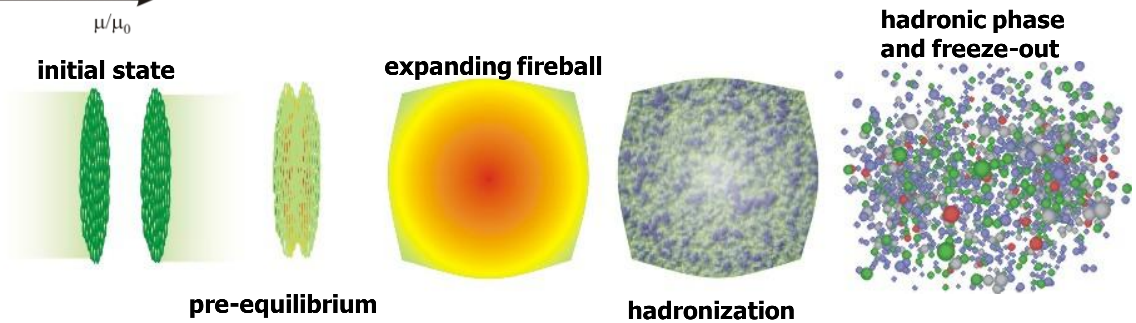

S. Bass, Talk Quark Matter 2001

RHIC Results

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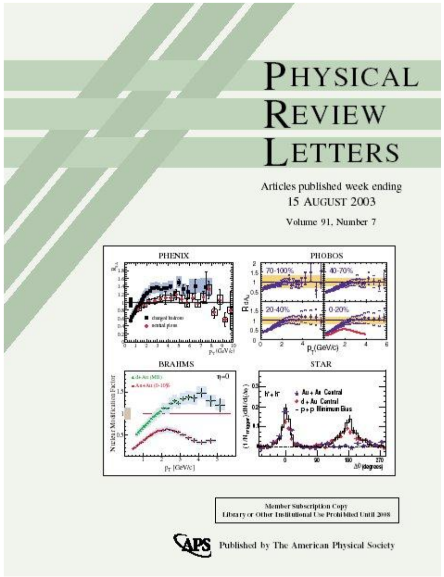

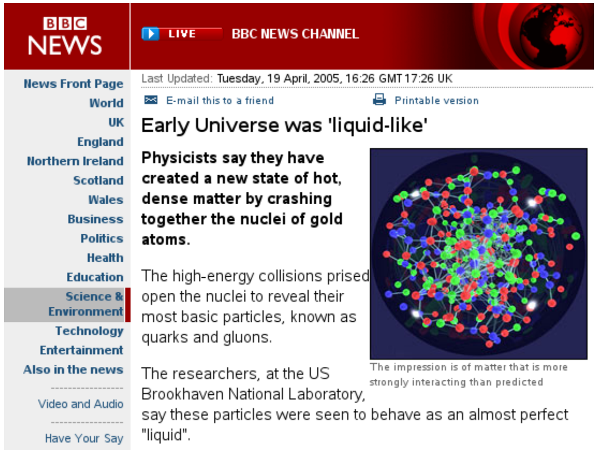

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Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The impression is of matter that is more strongly interacting than predicted

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

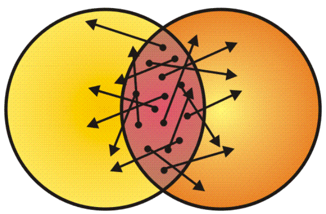
- Jets are suppressed

→ System is dense and opaque

- Medium behaves like a fluid

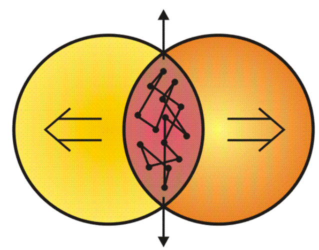
The Expanding Medium

From first principles, it is unclear if medium is …



„dust“

Particles don't interact, expansion independent of initial shape

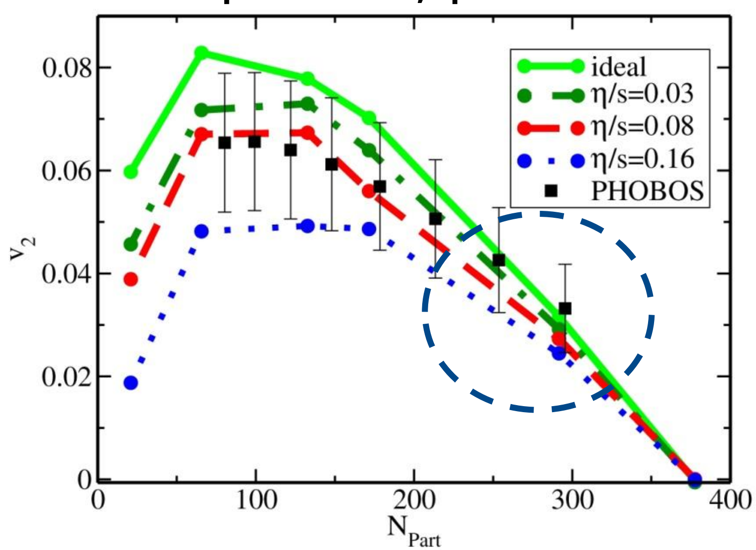


fluid

Particles interact, expansion determined by density gradient

Hydrodynamics: azimuthal anisotropy of emitted particles, parametrized by v_2

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi)\right]$$



- Data described by hydrodynamics
- Small η/s

→ Medium behaves like an almost ideal fluid

P. Romatschke and U. Romatschke, Phys. Rev. Lett. **99**,172301 (2007)

Hydrodynamics

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→ Medium created in a HIC can be described using hydrodynamics

- Hydrodynamics represents (local) conservation of

  energy-momentum $\partial_\mu T^{\mu\nu} = 0, \quad \mu, \nu = 0, ..., 3$

  (local) charge $\partial_\mu N_i^\mu = 0, \quad i = 1, ..., n$

- For ideal hydrodynamics in local thermodynamical equilibrium

$$T^{\mu\nu} = (\varepsilon + p) u^\mu u^\nu - p\, g^{\mu\nu}, \qquad g^{\mu\nu} = \mathrm{diag}(+, -, -, -)$$

$$N_i^\mu = n_i u^\mu, \qquad u^\mu = \gamma(1, \vec{v}), \qquad \gamma = (1 - v^2)^{-1/2}$$

- Equation of State $p = p(\varepsilon, n_i)$
- Viscous hydrodynamics will not be considered in our calculations

Jet - Studies in HIC I

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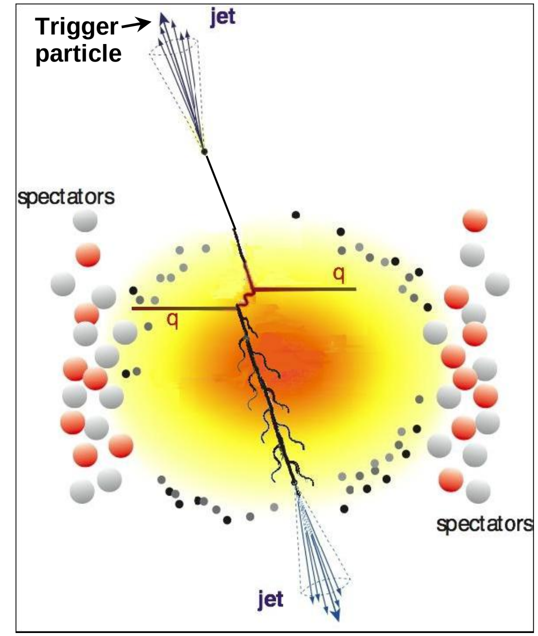
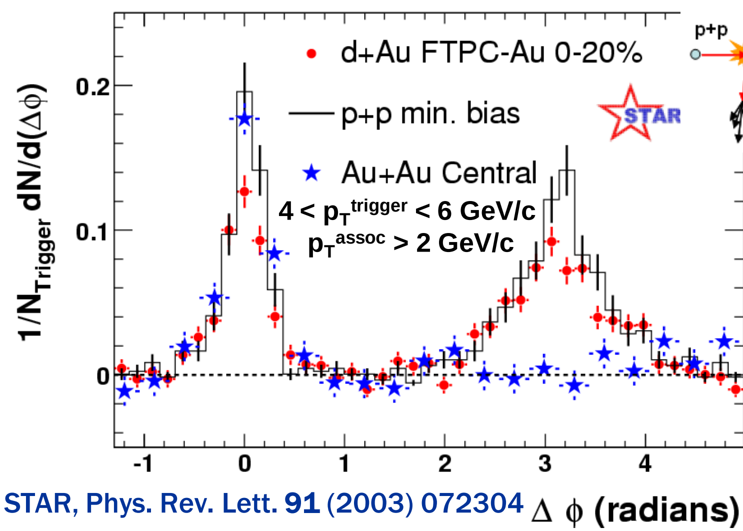
- Jet moving through dense matter, depositing its energy

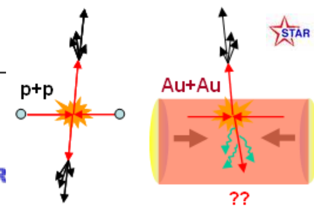
→ should eventually disappear

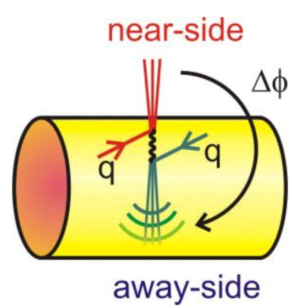
- Jet suppression: signal for creation of opaque matter (Quark-Gluon Plasma)





STAR, Phys. Rev. Lett. **91** (2003) 072304





→ Can energy lost by jets tell us something about medium properties?

Jet - Studies in HIC II

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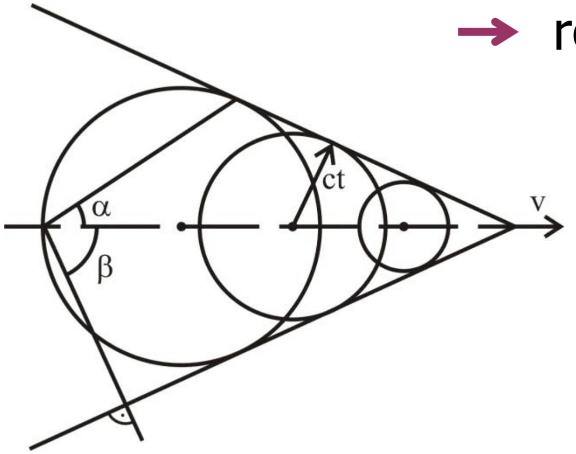
Can energy lost by jets tell us something about medium properties?

→ Idea: Propagation of fast parton generates a Mach cone pattern

H. Stöcker, Nucl. Phys. A **750**, **121** (2005), J. Casalderrey-Solana et al. Nucl. Phys. A **774**, 577 (2006)



→ reflect interaction of jet with medium

Mach cone angle sensitive to EoS

$$\cos\phi_M = \cos\beta = c_s/v_{\text{jet}}$$

By observation:

- Confirm fast thermalization
- Study EoS of the fluid

Jet - Studies in HIC III

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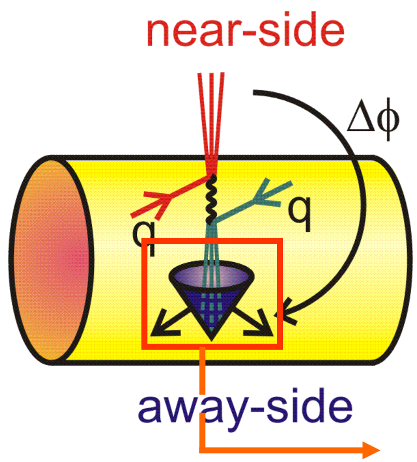
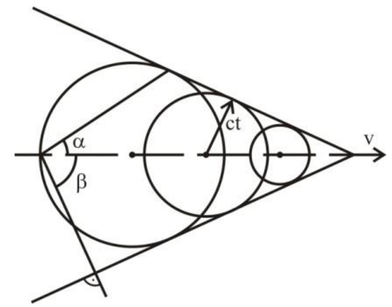
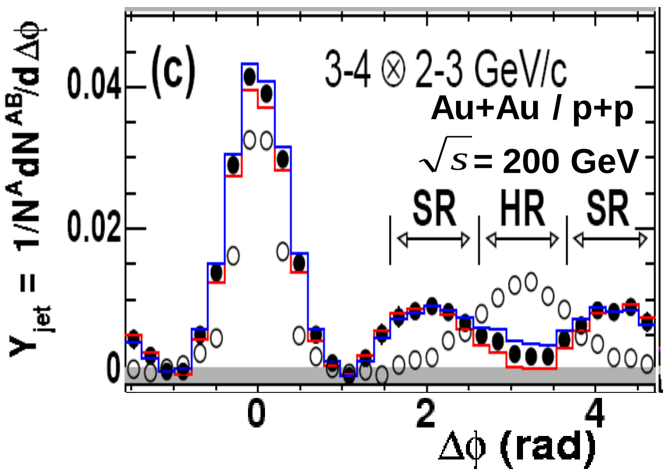
- Generation of Mach cone pattern

→ Redistribution of energy to lower p_T-particles

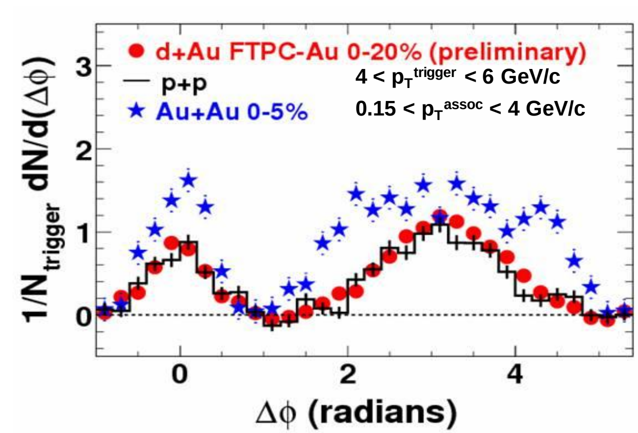
- Re-appearance of the away-side for low and intermediate p_T^{assoc}







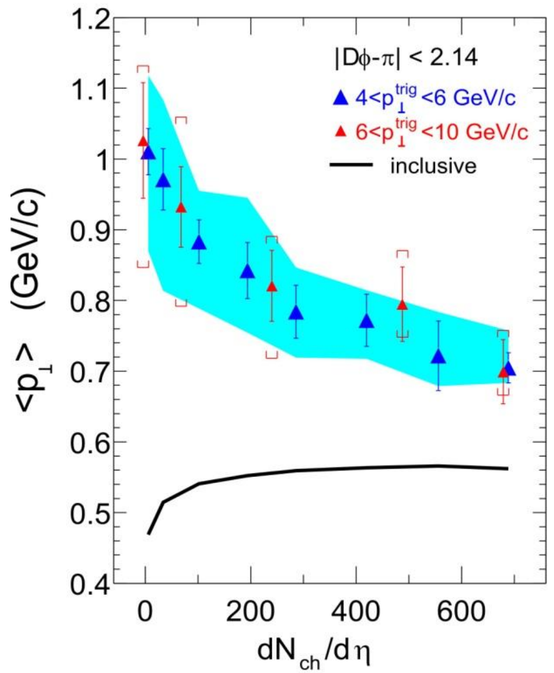
PHENIX, Phys. Rev. C **77**, 011901 (2008)



STAR, Nucl. Phys. A **774**, 129 (2006)

The Theory

Modelling of Jets

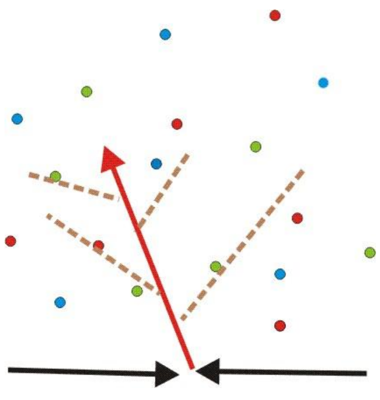


STAR, Phys. Rev. Lett. **95**, 152301 (2005)

Jets can be modelled using (ideal) hydrodynamics:

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

residue of energy and momentum given by the jet



- Different jet deposition mechanisms
  - GLV, BDMPS, ASW, AMY, Higher Twist

The Freeze-out Prescription

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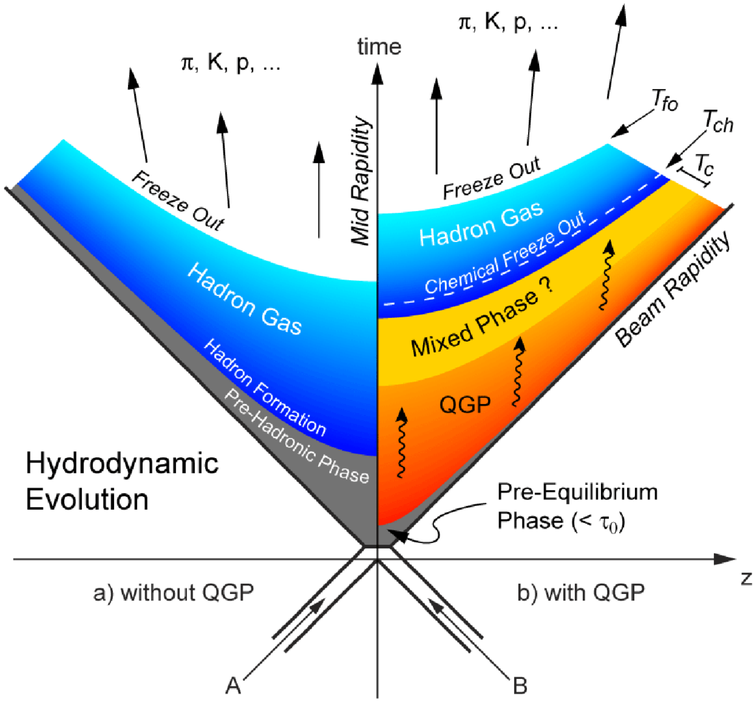
Cooper-Frye Freeze-out:

$$\frac{dN}{p_T dp_T d\phi} = C \int dV \exp[-\gamma(E - p_i v^i)/T]$$

$\rightarrow e^{+\vec{p}\cdot\vec{v}}$

→ mainly flow driven

- Assumption of isochronous/isothermal freeze-out
- No interaction afterwards



http://www.rnc.blb.gov/ssalur/www/Research3.html

The Static Medium

Stopped Jet I

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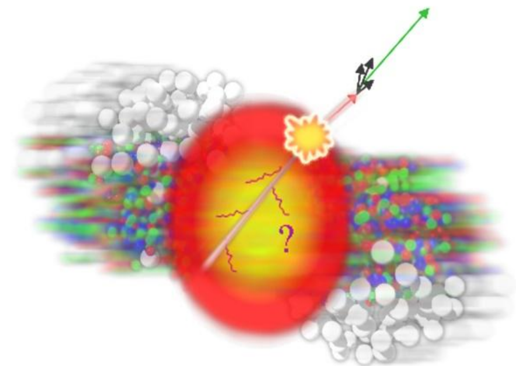
Applying a static medium and an ideal Gas EoS for massless gluons

→ Maximal fluid response

Assume: Near-side jet is not modified by medium



$$S^\nu = \int_{\tau_i}^{\tau_f} \frac{dM^\nu}{d\tau} \delta^{(4)} \left[x^\mu - x^\mu_{\rm jet}(\tau) \right] d\tau$$

$$dM^\nu/d\tau = (dE/d\tau, d\vec{M}/d\tau) \quad x^\mu_{\rm jet} = x^\mu_0 + u^\mu_{\rm jet}\tau$$

Jet decelerating from v=0.999
according to Bethe-Bloch formalism

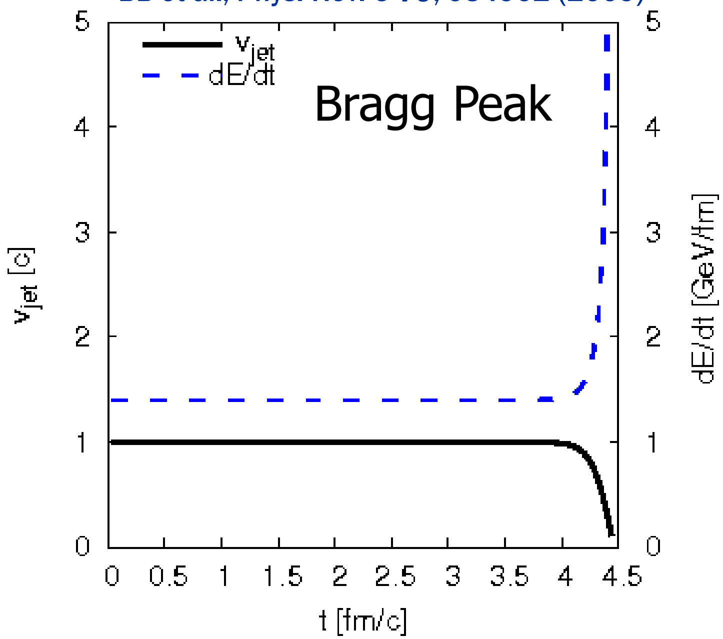
$$\frac{dE}{dt}(t) = a \frac{1}{v_{\rm jet}(t)}$$

a=-1.36 GeV/fm

adjusts path length

Simplest back-reaction from the medium

BB et al., Phys. Rev. C **79**, 034902 (2009)



Stopped Jet II

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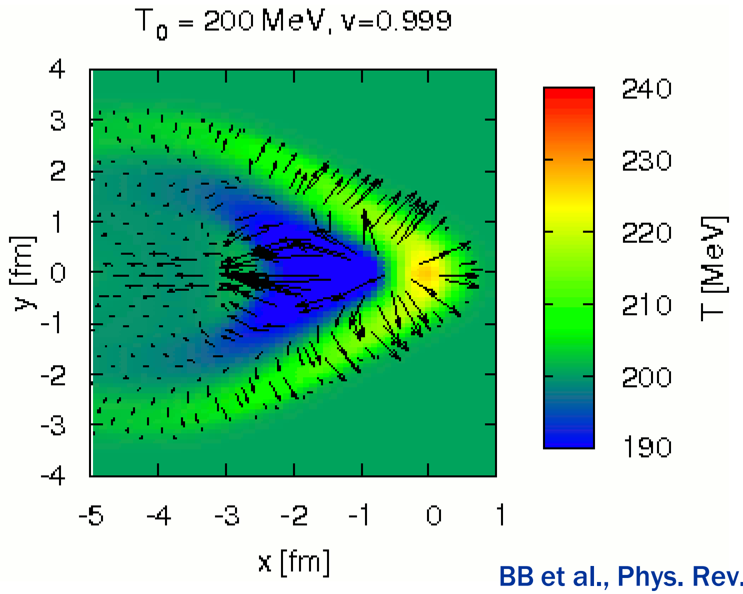
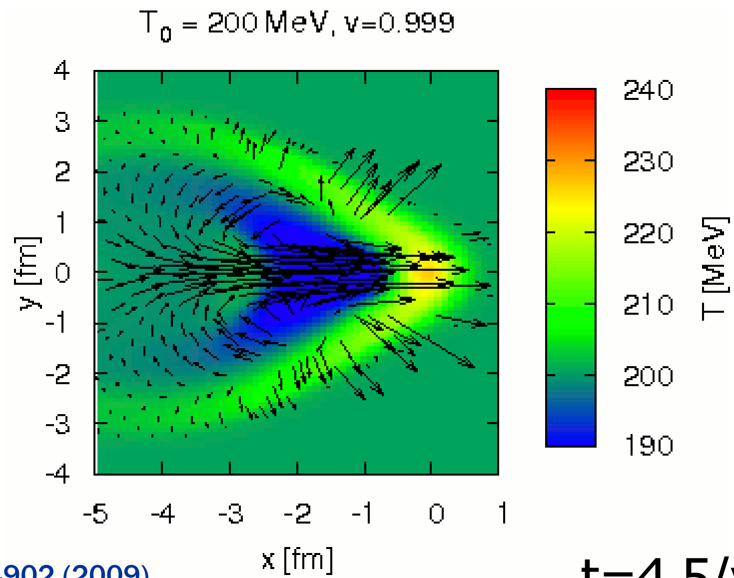


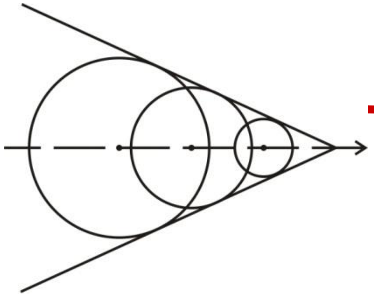


BB et al., Phys. Rev. C **79**, 034902 (2009)

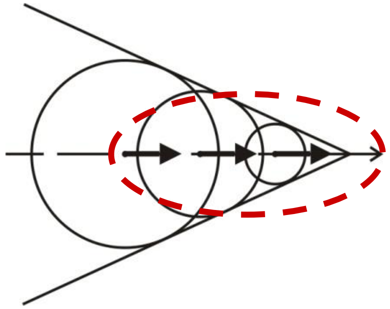
t=4.5/v fm

$$\frac{dE}{dt}(0) = 1.5\frac{GeV}{fm} \quad \frac{dM}{dt}(0) = 0\frac{GeV}{fm}$$

$$\frac{dE}{dt}(0) = v\frac{dM}{dt}(0) = 1.5\frac{GeV}{fm}$$



→ Mach cone for sound waves



→ Diffusion wake

Stopped Jet III

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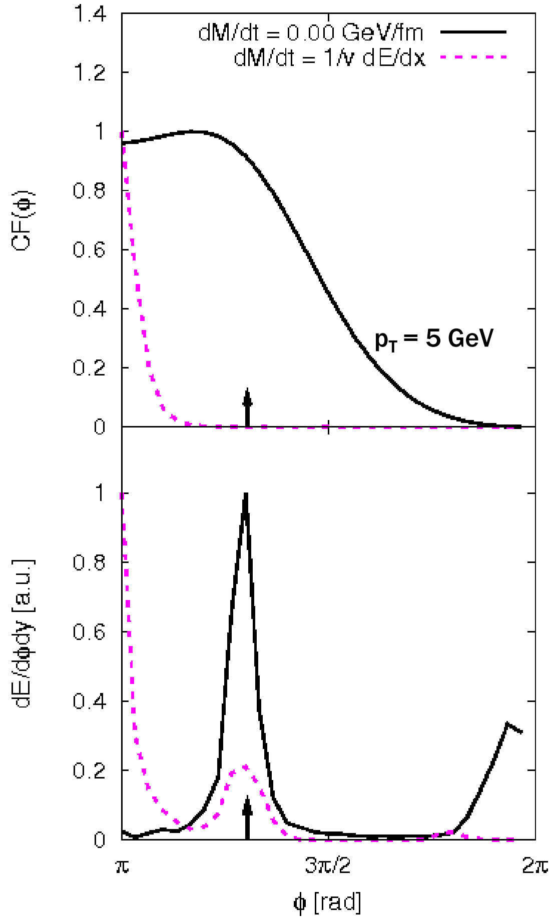
BB et al., Phys. Rev. C **79**, 034902 (2009)



Diffusion wake causes peak in jet direction

Normalized, background-subtracted isochronous Cooper-Frye at mid-rapidity

$$\left.\frac{dN}{p_T dp_T dy d\phi}\right|_{y=0} = \int_\Sigma d\Sigma_\mu p^\mu \left[f_{\mathrm{Boltzmann}}(u \cdot p/T) - f_{\mathrm{eq}}\right]$$

Energy Flow Distribution

$$\left.\frac{dE}{d\phi dy}\right|_{y=0} = \int d^3\vec{x} E(\vec{x}) \delta[\phi - \Phi(\vec{x})]$$

$$\Phi(\vec{x}) = \tan^{-1}\left[\frac{M_y(\vec{x})}{M_x(\vec{x})}\right]$$

Assuming: Particles in subvolume will be emitted into the same direction

Stopped Jet IV

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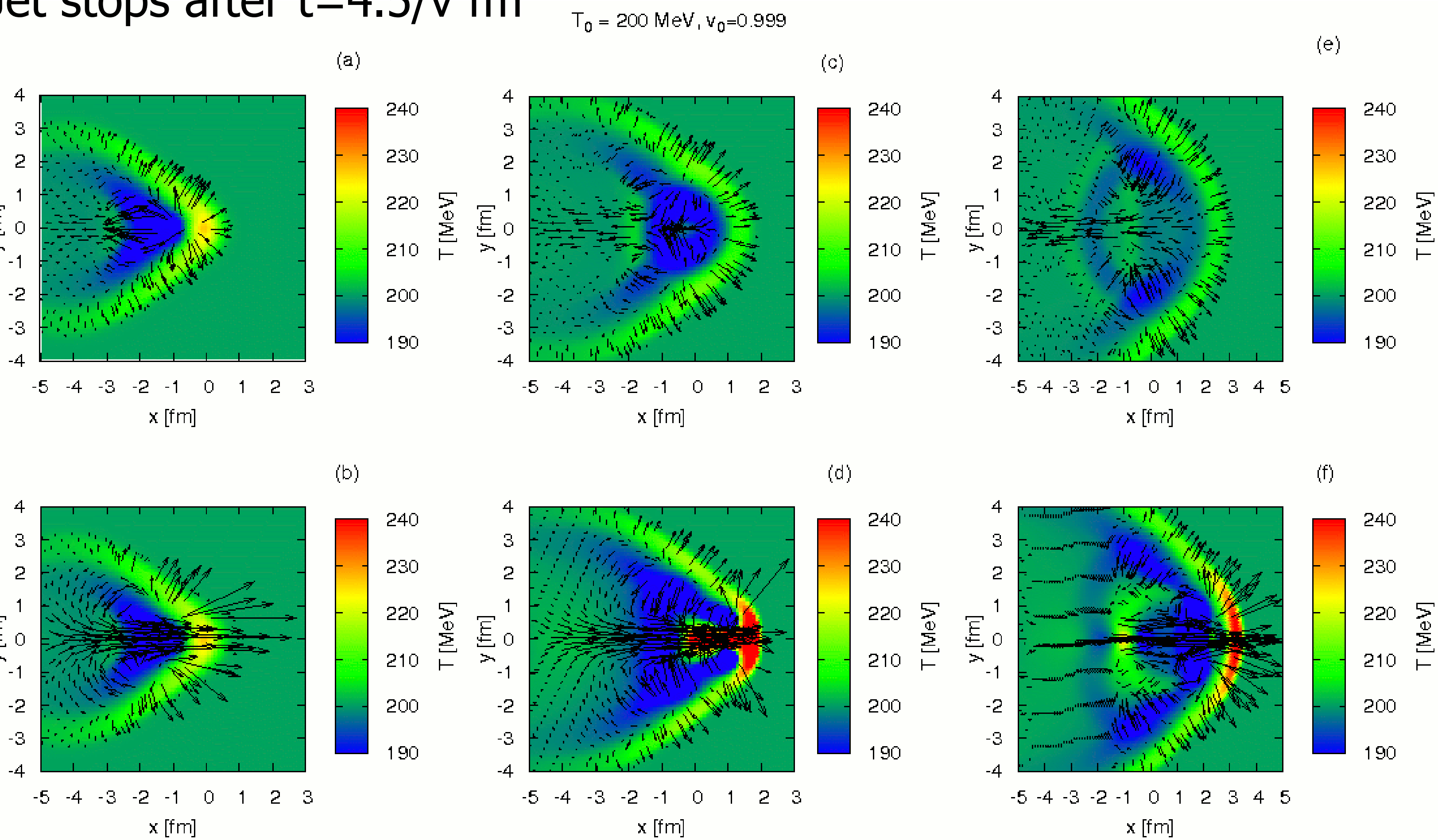
- Jet stops after t=4.5/v fm

BB et al., Phys. Rev. C **79**, 034902 (2009)

$$\frac{dE}{dt}(0) = 1.5\,\frac{GeV}{fm} \qquad \frac{dM}{dt}(0) = 0\,\frac{GeV}{fm}$$

$$\frac{dE}{dt}(0) = 1.5\,\frac{GeV}{fm} \qquad v\frac{dM}{dt}(0) = 1.5\,\frac{GeV}{fm}$$



t_{FO}=4.5/v fm t_{FO}=6.5/v fm t_{FO}=8.5/v fm

Diffusion wake still present → Vorticity conservation

Different Jet-Energy Loss Modells

Modelling Jets using …

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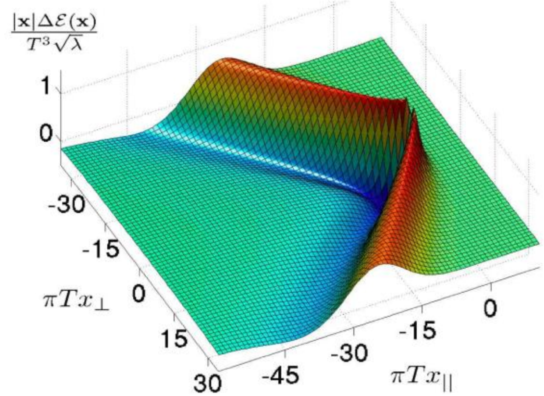
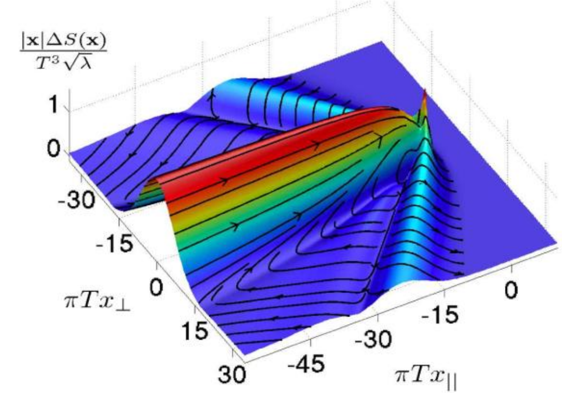
Strongly-coupled theory

AdS/CFT

Energy density perturbation



Pointing vector perturbation



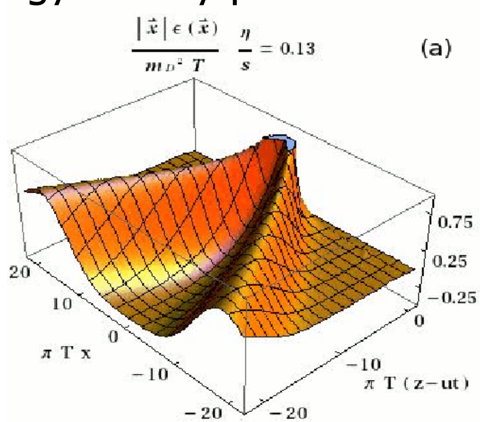
v=0.75

P. Chesler and L. Yaffe, Phys. Rev. D **78**, 045013 (2008)

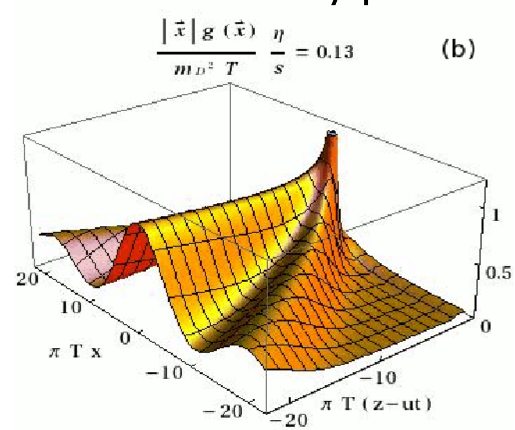
Weakly-coupled theory

pQCD

Energy density perturbation



Momentum density perturbation

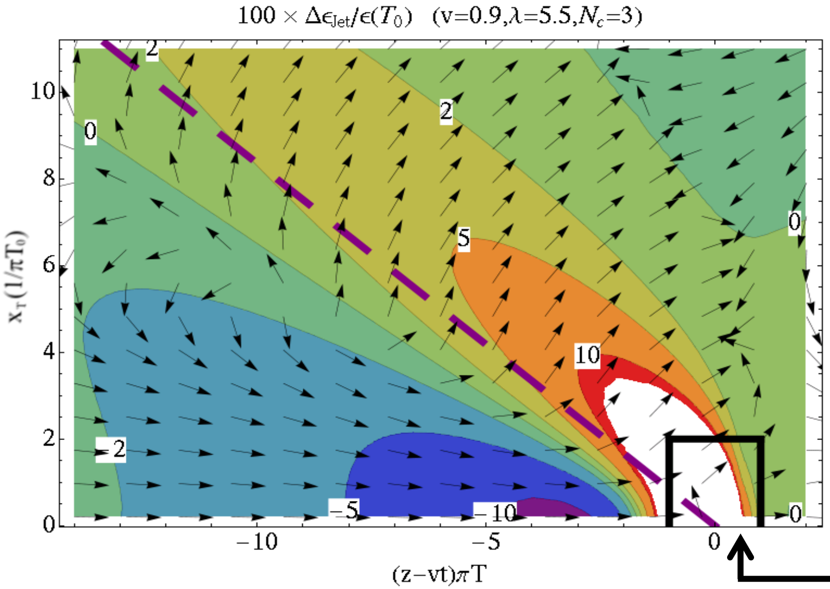


R. Neufeld et al, Phys. Rev. C **78**, 041901 (2008)

v=0.99955

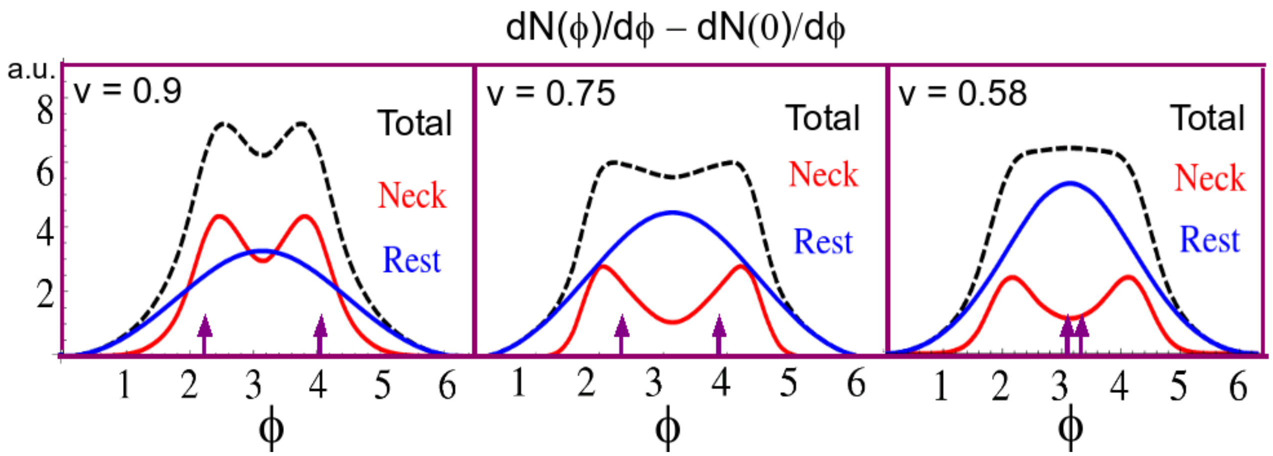
→ Conclusion about Mach cones?

Jets in AdS/CFT



Non-Mach correlations caused by Neck region

J. Noronha et al., Phys. Rev. Lett. **102**, 102301 (2009)



$$\cos \phi_M = c_s / v_{\text{jet}}$$

Heavy Quark Jets

Heavy Quark Jets

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Compare weakly and strongly coupled models using heavy punch-through jet

Static medium and isochronous freeze-out needed for comparison

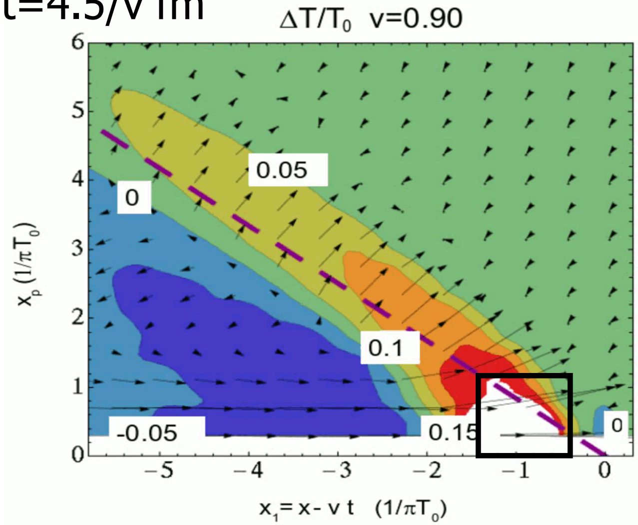
pQCD: Neufeld et al. source for a heavy quark

R. Neufeld et al, Phys. Rev. C **78**, 041901 (2008)

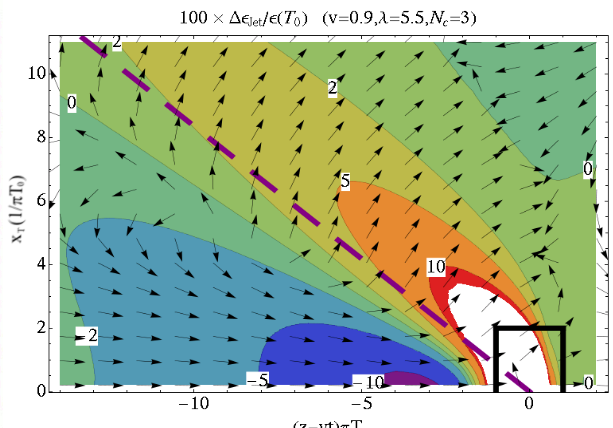
AdS/CFT: Stress tables with $\eta/s=1/(4\pi)$

S. Gubser et al, Phys. Rev. Lett. **100**, 012301 (2008)

t=4.5/v fm

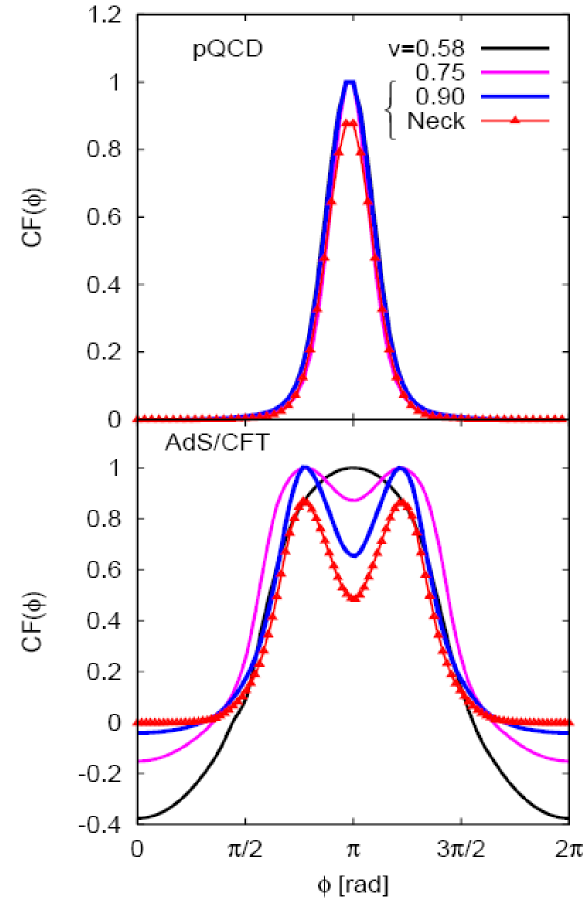


BB et al., Phys. Lett. B **675**, 340 (2009)



J. Noronha et al., Phys. Rev. Lett. **102**, 102301 (2009)

BB et al., Phys. Lett. B **675**, 340 (2009)



p_T = 3.14 GeV

→ No Mach-like peaks: $\cos\phi_M = c_s/v_{\rm jet}$

AdS/CFT: Strong influence of the Neck region

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The Expanding Medium

Expanding Medium I

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- Consequences of expansion?

  Radial flow, Elliptic flow

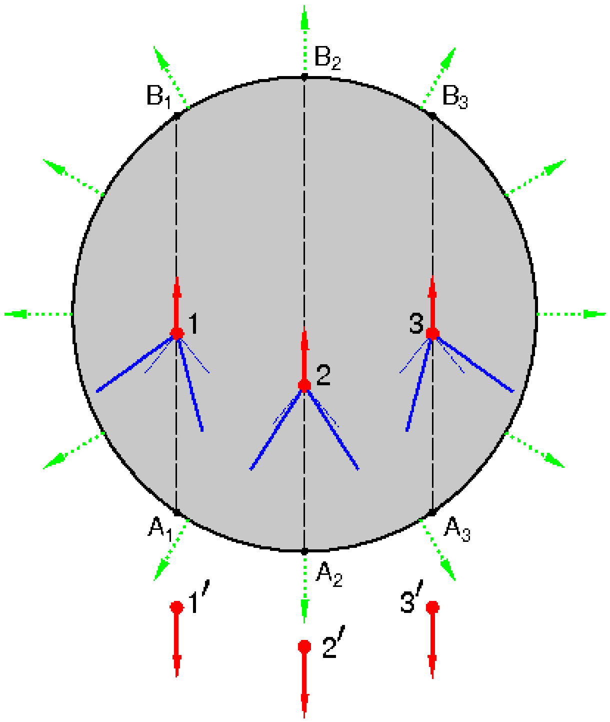
- Predictions:

  Transverse flow causes distortion

  Expansion broadens Mach cone angle

→ Mach cones are sensitive to the background flow

- Qualitative, model-independent effect



Satarov et al, PLB 627:64 (2005)

Expanding Medium II

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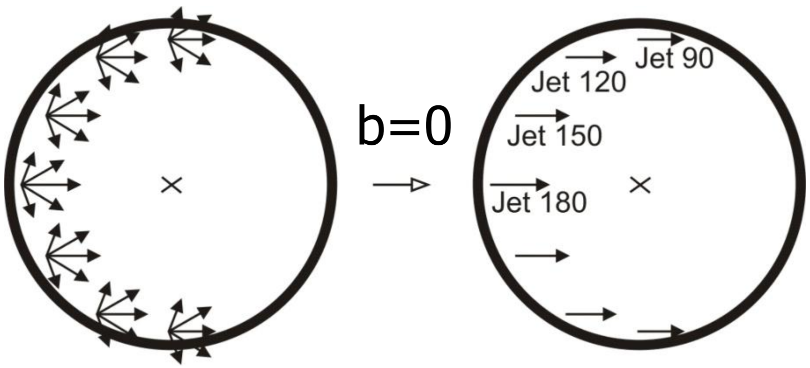


Experimental results based on many events

Consider different jet paths

A. K. Chaudhuri, Phys. Rev. C **75**, 057902 (2007) ,
A. K. Chaudhuri, Phys. Rev. C **77**, 027901 (2008)

- Apply Glauber initial conditions and an ideal Gas EoS for massless gluons
- Focus on radial flow contribution

$$S^\nu = \int_{\tau_i}^{\tau_f} \frac{dM^\nu}{d\tau}\bigg|_o \left[\frac{T(\tau)}{T_{\max}}\right]^3 \delta^{(4)}[x^\mu - x^\mu_{\rm jet}(\tau)]d\tau$$

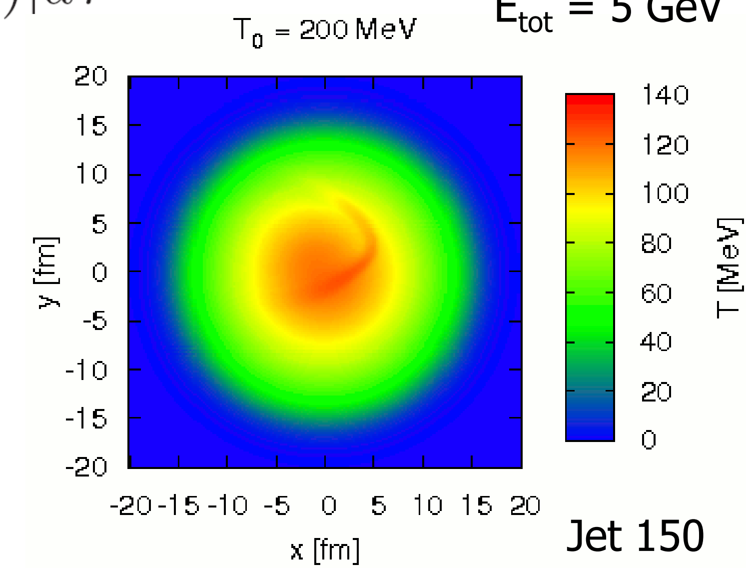
- Two-particle correlation ($T_{\text{freeze-out}} < T_{\text{crit}} = 130$ MeV):

$$N(\phi) = A(\phi) + \int_0^{2\pi} d\phi^\star N(\phi - \phi^\star) f(\phi^\star)$$

$$\langle CF(\phi)\rangle = \frac{\langle N\rangle(\phi) - \langle N_{\rm back}\rangle(\phi)}{\int_0^{2\pi}\langle N_{\rm back}\rangle(\phi)d\phi}$$

near-side jet

E_{tot} = 5 GeV



Expanding Medium III

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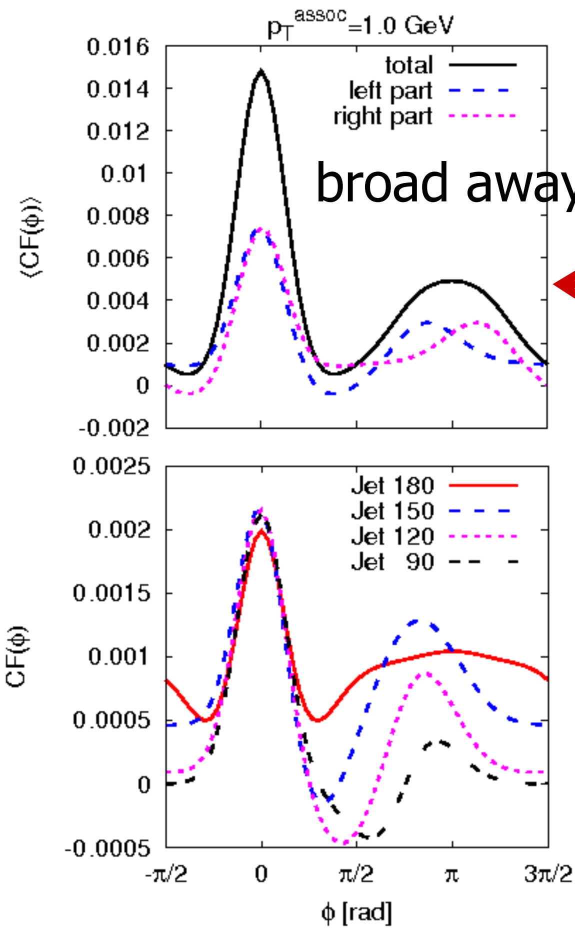
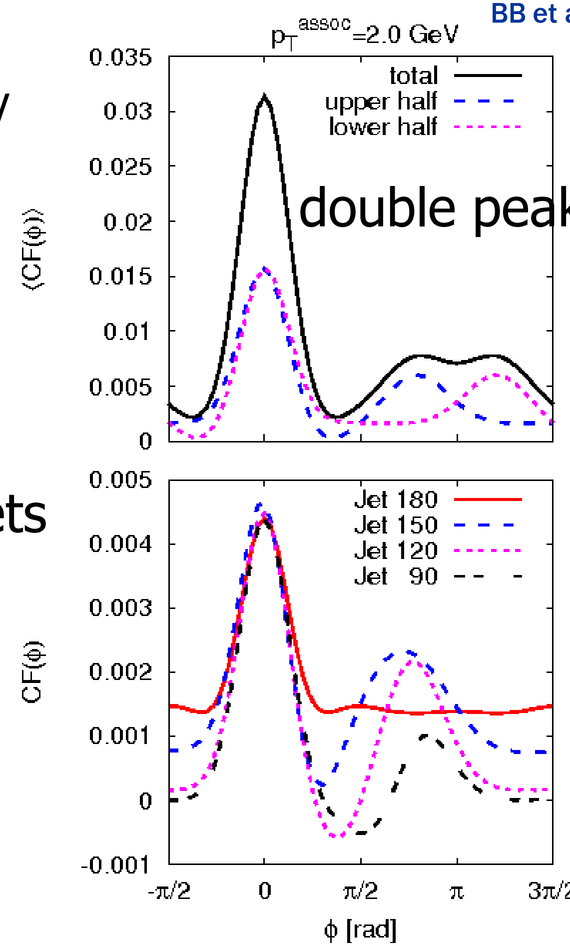
BB et al., arXiv: 1005.5461

E_{tot} = 5 GeV

p_T^{trig} = 3.5 GeV

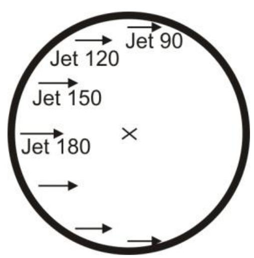


broad away-side peak

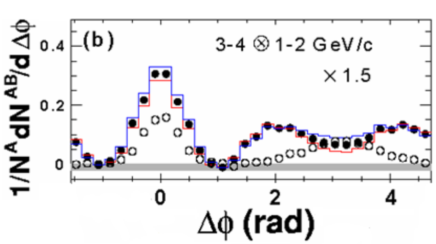


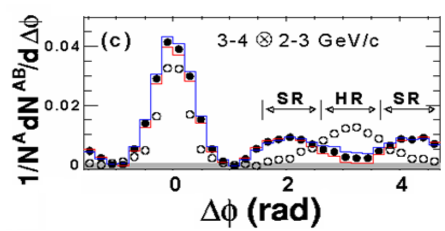
double peaked structure

due to non-central jets



v_{jet} =0.999





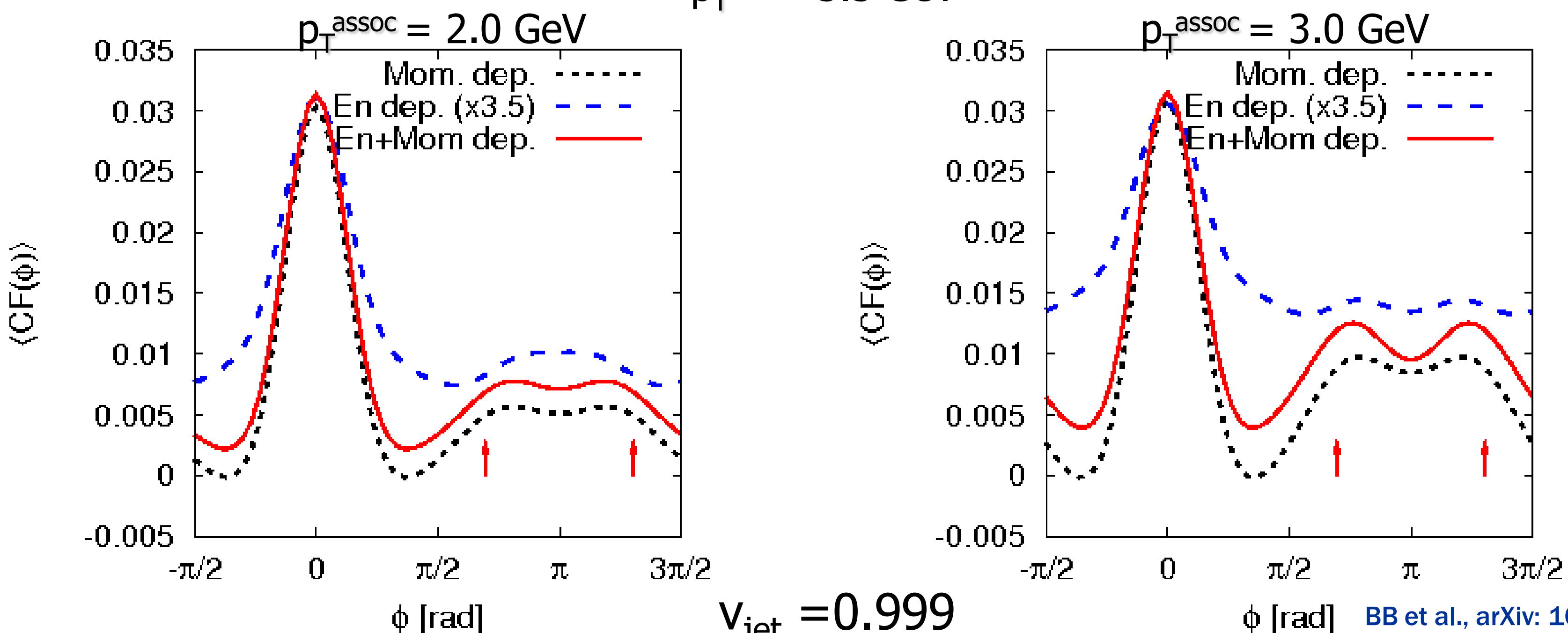
PHENIX, Phys. Rev. C 77, 011901 (2008)

Expanding Medium IV

Comparing different deposition scenarios, one sees that

→ „cone" angle approximately the same for different deposition scenarios

p_T^{trig} = 3.5 GeV



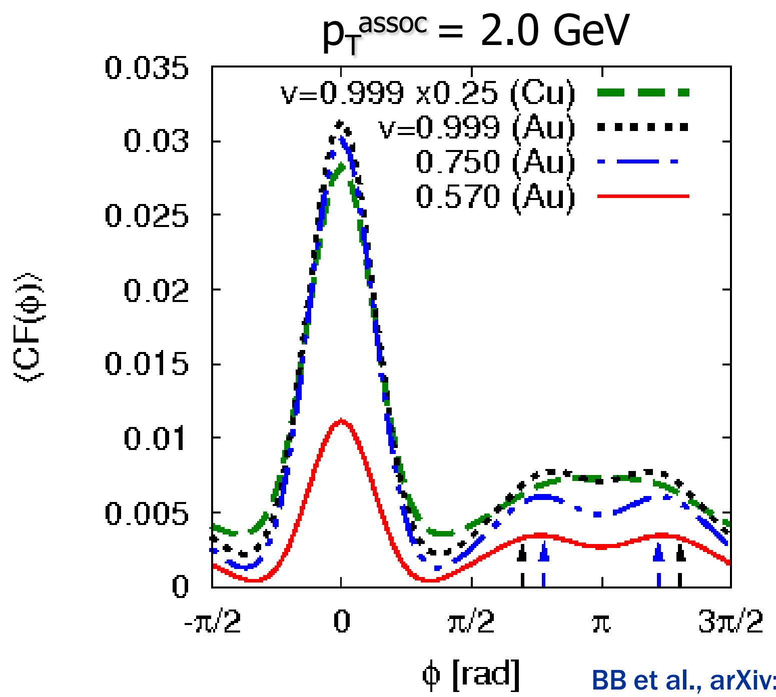
v_{jet} =0.999

BB et al., arXiv: 1005.5461

→ p_T^{assoc} = 2.0 GeV: No double-peaked structure for pure energy deposition scenario due to thermal smearking

Expanding Medium V

Considering a bottom quark (M=4.5 GeV), propagating at $v_{jet} < c_s$ (on-shell energy-momentum deposition scenario)



BB et al., arXiv: 1005.5461

→ Conical emission angle also appears for subsonic jets ⇒ Not a Mach cone

→ Cu+Cu: Similar away-side shoulder width,
double-peak structure reappars for p_T^{assoc} = 3 GeV

Summary

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- Investigation of jet-medium interactions using (3+1)d ideal hydrodynamics for different energy and momentum loss scenarios (schematic source term, pQCD, AdS/CFT)
- Diffusion wake is always created if dM/dx > threshold
- Different impacts of pQCD and AdS/CFT source terms
- „Conical" signal can be created:

  → by averaging over wakes created by jets in different events.

  → There is a deflection of particles emitted due to collective transverse flow.

  → Quite insensitive to deposition mechanism, jet velocity (even for *subsonic* jets), and system size

⇒ Structure unrelated to EoS

⇒ Can be tested experimentally comparing hard-soft correlations induced by heavy-flavor tagged jets.

Backup

Punch – Through Jet I

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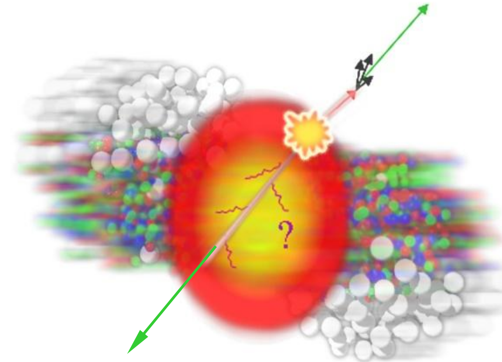
Applying a static medium and an ideal Gas EoS for massless gluons

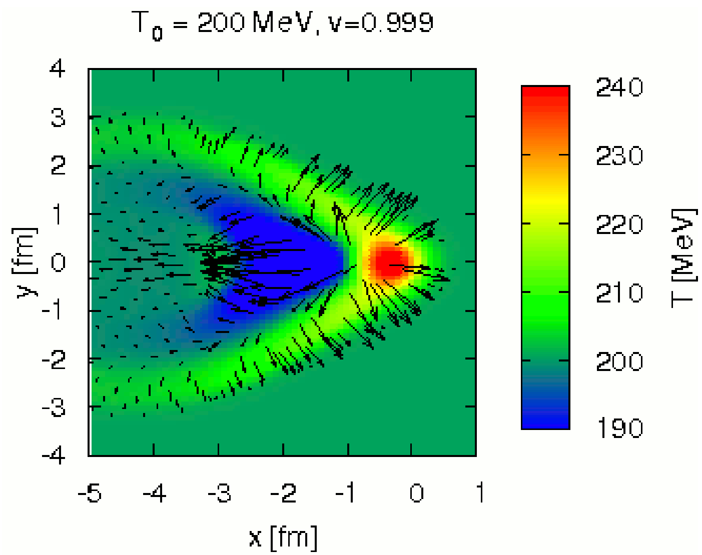
→ Maximal fluid response

Assume: Near-side jet is not modified by medium

$$S^{\nu} = \int_{\tau_i}^{\tau_f} \frac{dM^{\nu}}{d\tau} \delta^{(4)} \left[x^{\mu} - x^{\mu}_{\text{jet}}(\tau) \right] d\tau$$

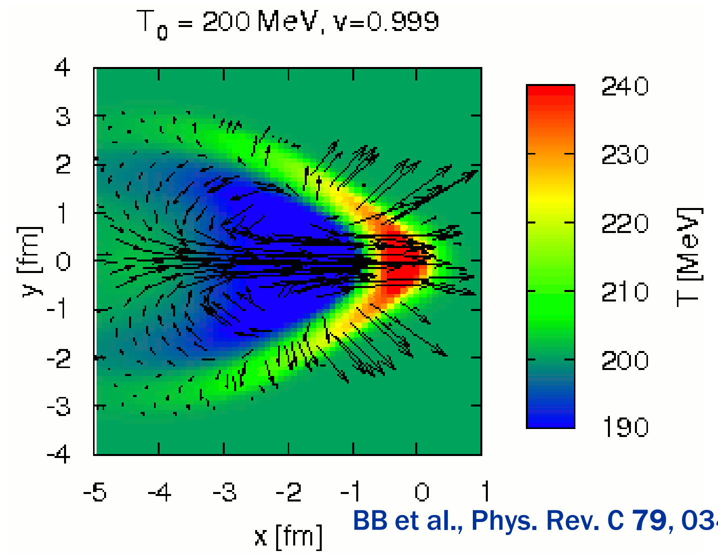
$$dM^{\nu}/d\tau = (dE/d\tau, d\vec{M}/d\tau) \quad x^{\mu}_{\text{jet}} = x^{\mu}_0 + u^{\mu}_{\text{jet}} \tau$$





$$\frac{dE}{dt} = 1.5 \frac{GeV}{fm}, \quad \frac{dM}{dt} = 0 \frac{GeV}{fm}$$

v=0.999



BB et al., Phys. Rev. C **79**, 034902 (2009)

$$\frac{dM}{dt} = \frac{dE}{dt} = 1.5 \frac{GeV}{fm}$$

t=4.5/v fm

Punch – Through Jet II

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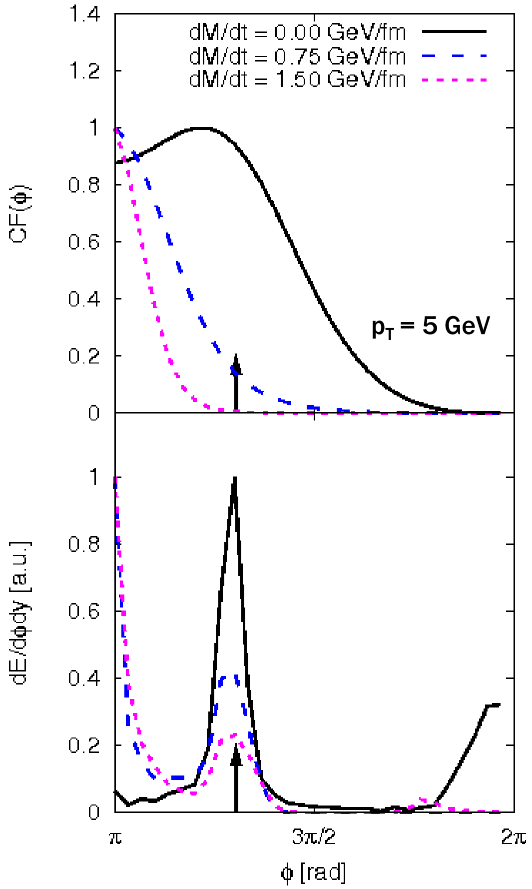
BB et al., Phys. Rev. C **79**, 034902 (2009)



Normalized, background-subtracted isochronous Cooper-Frye at mid-rapidity

$$\left.\frac{dN}{p_T dp_T dy d\phi}\right|_{y=0} = \int_\Sigma d\Sigma_\mu p^\mu \left[f_{\text{Boltzmann}}(u \cdot p/T) - f_{\text{eq}}\right]$$

Energy Flow Distribution

$$\left.\frac{dE}{d\phi dy}\right|_{y=0} = \int d^3\vec{x} E(\vec{x}) \delta[\phi - \Phi(\vec{x})]$$

$$\Phi(\vec{x}) = \tan^{-1}\left[\frac{M_y(\vec{x})}{M_x(\vec{x})}\right]$$

Diffusion wake causes peak in jet direction

Assuming: Particles in subvolume will be emitted into the same direction

Punch – Through Jet III

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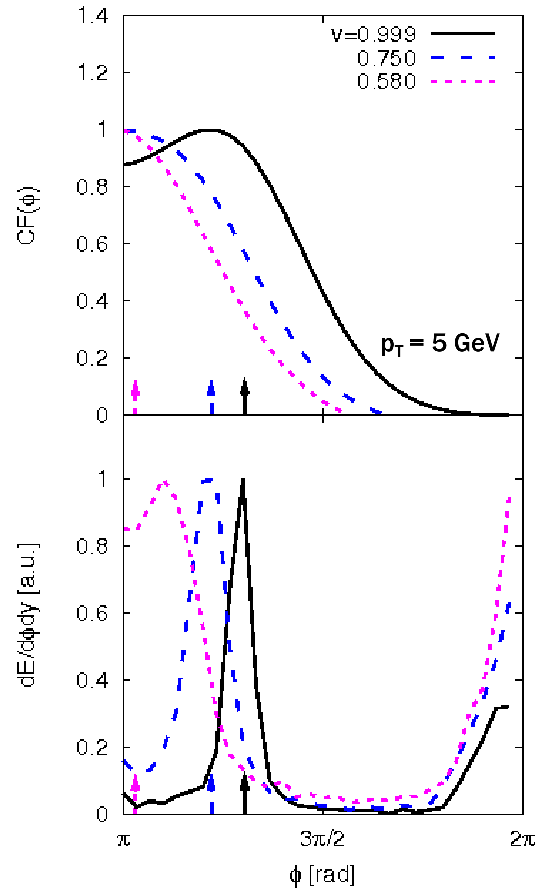
BB et al., Phys. Rev. C **79**, 034902 (2009)

Does the jet-pattern reproduce the features of a Mach cone?

$$\cos\phi_M = c_s/v_{\text{jet}}$$

→ Velocity dependence of the emission angle



Creation of Bow Shock for smaller v strengthens peak in jet direction

Punch – Through Jet IV

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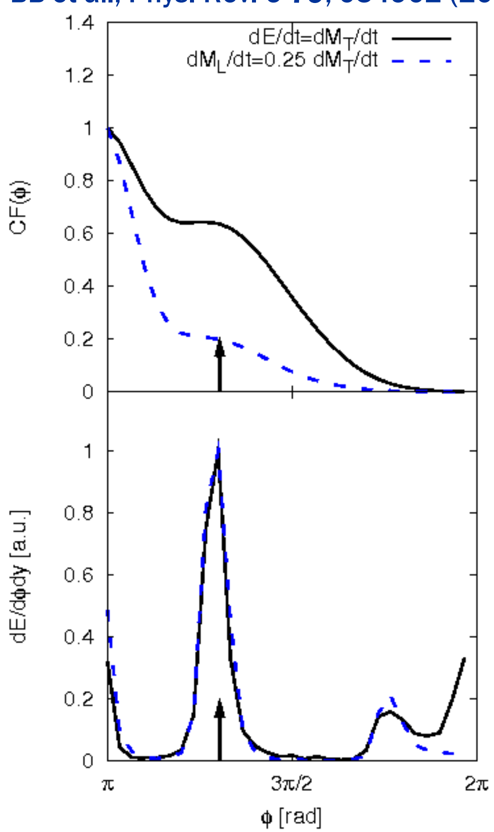
- Transverse momentum deposition:

$$S^{\nu} = \frac{1}{(\sqrt{2\pi}\sigma)^3} \exp\left[-\frac{(\vec{r}-\vec{x})^2}{2\sigma^2}\right] \left(\frac{dE}{dt}, \frac{dM_L}{dt}, \frac{dM_T}{dt}\cos\theta, \frac{dM_T}{dt}\sin\theta\right)$$

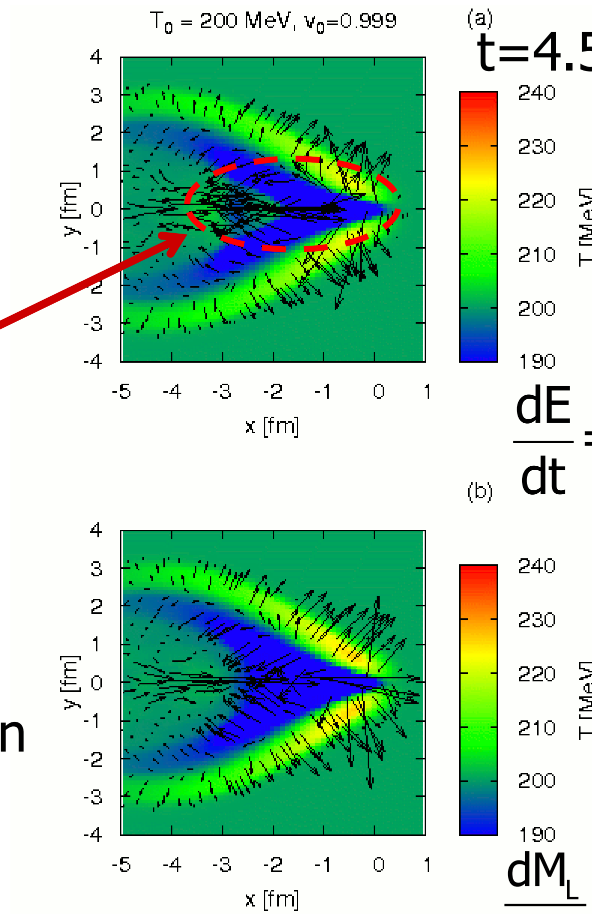
BB et al., Phys. Rev. C **79**, 034902 (2009)



→ Still influence of diffusion wake

from explosion of matter

→ Vorticity conservation



t=4.5/v fm

$$\frac{dE}{dt} = \frac{dM_T}{dt}$$

$$\frac{dM_L}{dt} = \frac{1}{4}\frac{dM_T}{dt}$$

Punch – Through vs Stopped

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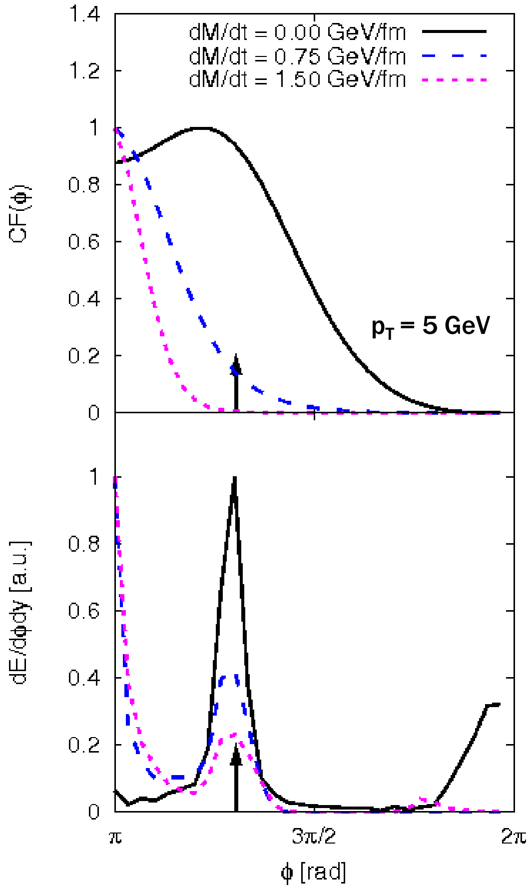
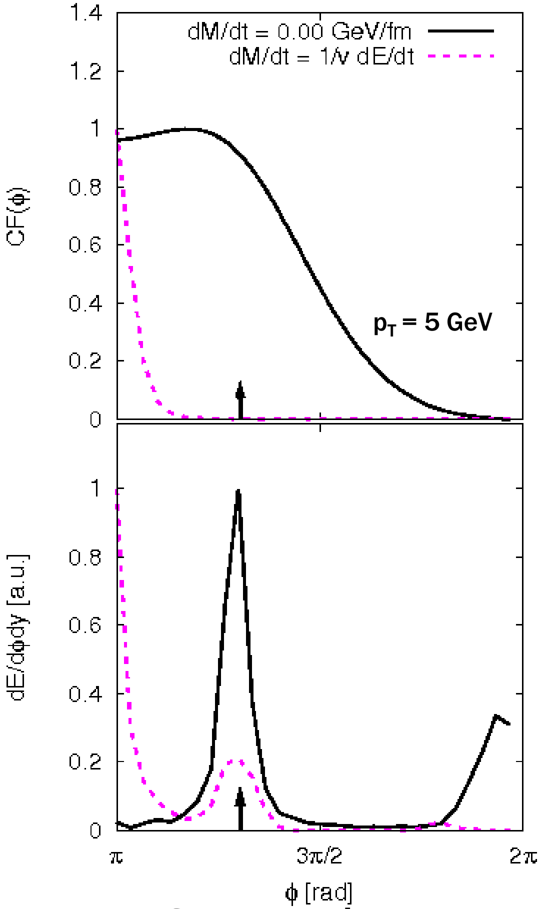
BB et al., Phys. Rev. C **79**, 034902 (2009)



Punch-Through Jet



Stopped Jet

→ Similar freeze-out patterns

Punch – Through Jet: Velocity Scan

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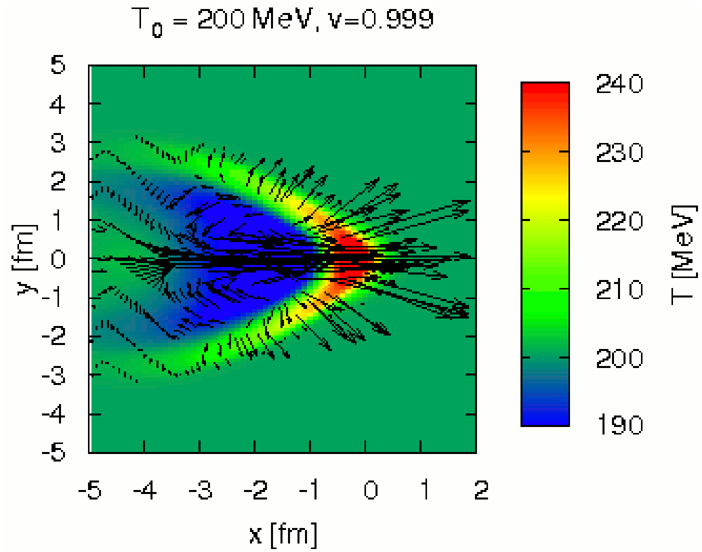

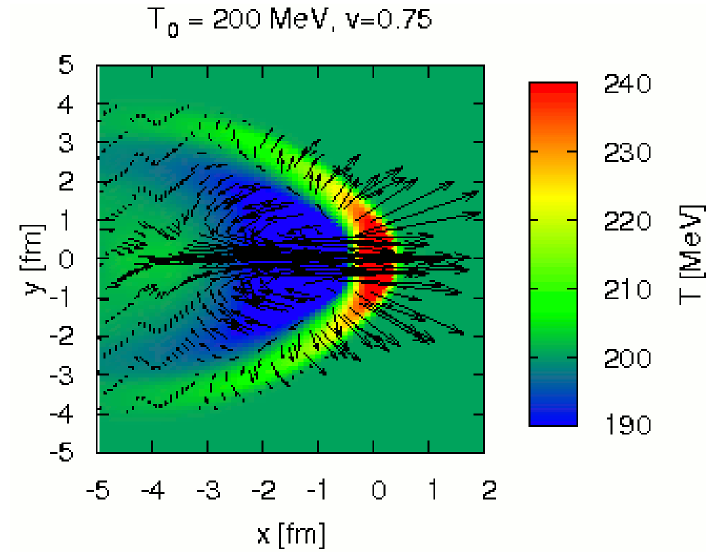

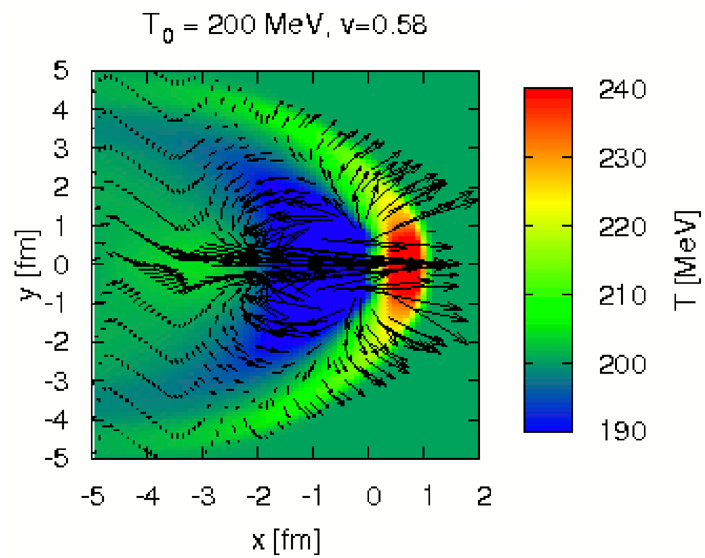

t=4.5/v fm

Why linearized Hydro is not so good

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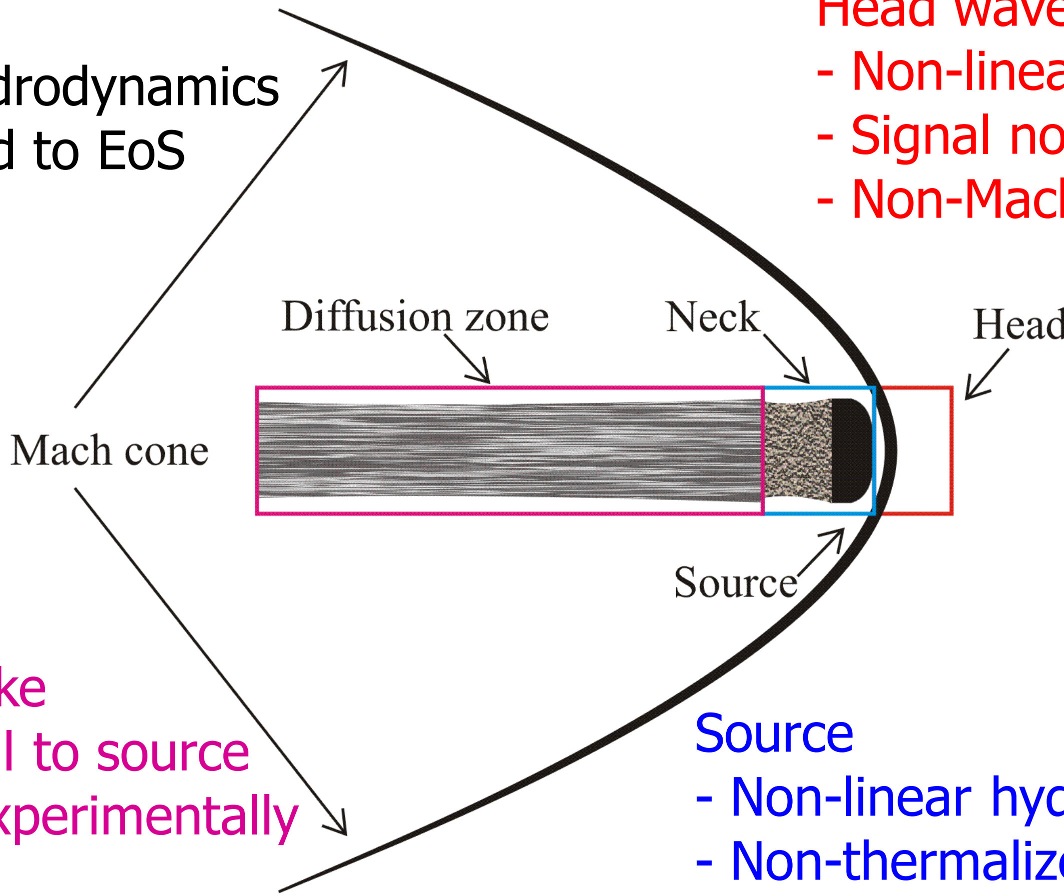
Mach Cone
- Linear hydrodynamics
- Connected to EoS

Head wave pile-up
- Non-linear hydrodynamics
- Signal not well understood
- Non-Mach cone angle



Diffusion Wake
- Proportional to source
- Not seen experimentally

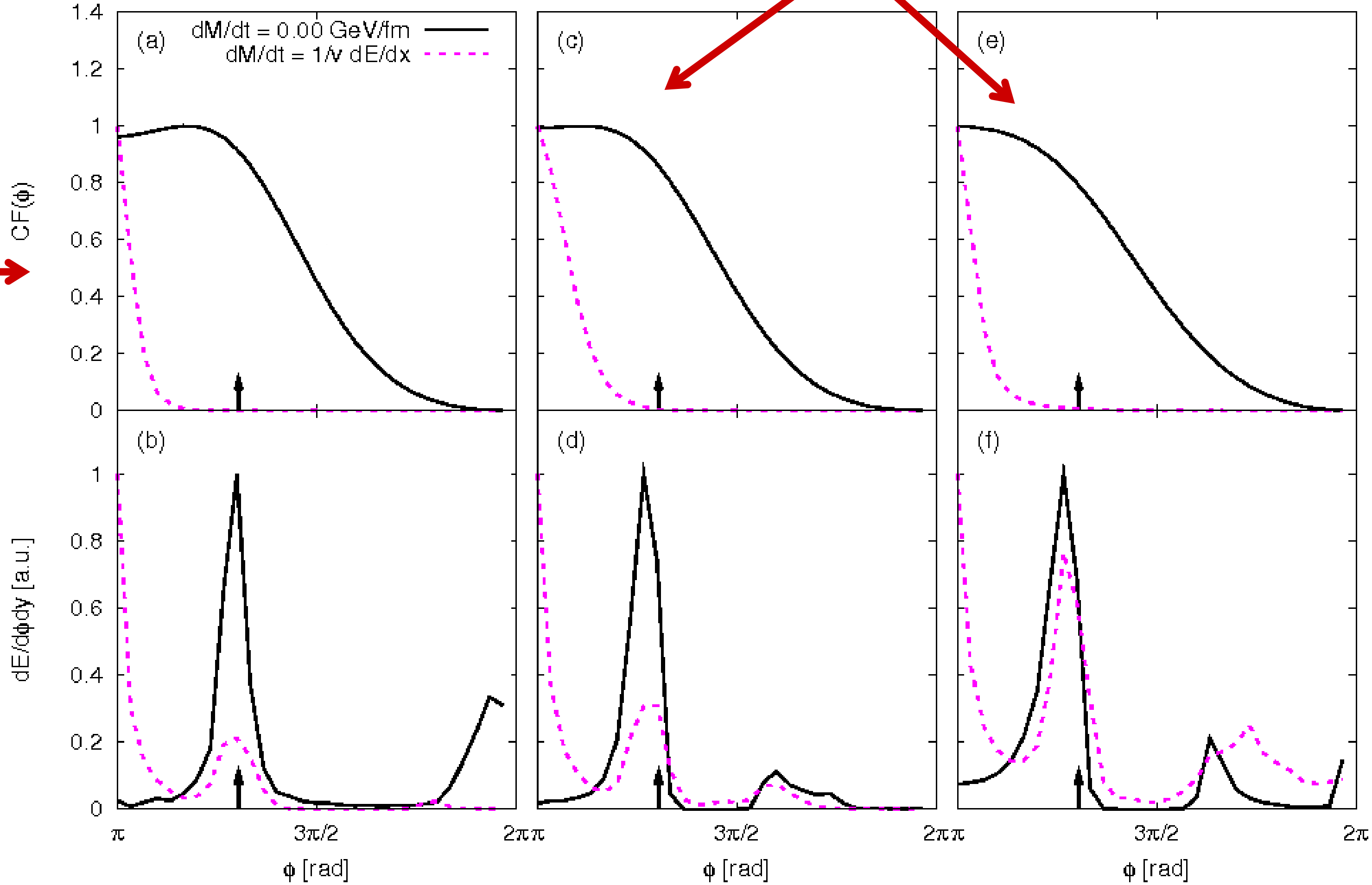
Source
- Non-linear hydrodynamics
- Non-thermalized

Stopped Jet

Diffusion wake causes peak in jet direction

Larger impact of thermal smearing

BB et al., Phys. Rev. C **79**, 034902 (2009)



t_{FO}=4.5/v fm t_{FO}=6.5/v fm t_{FO}=8.5/v fm

Jets in pQCD I

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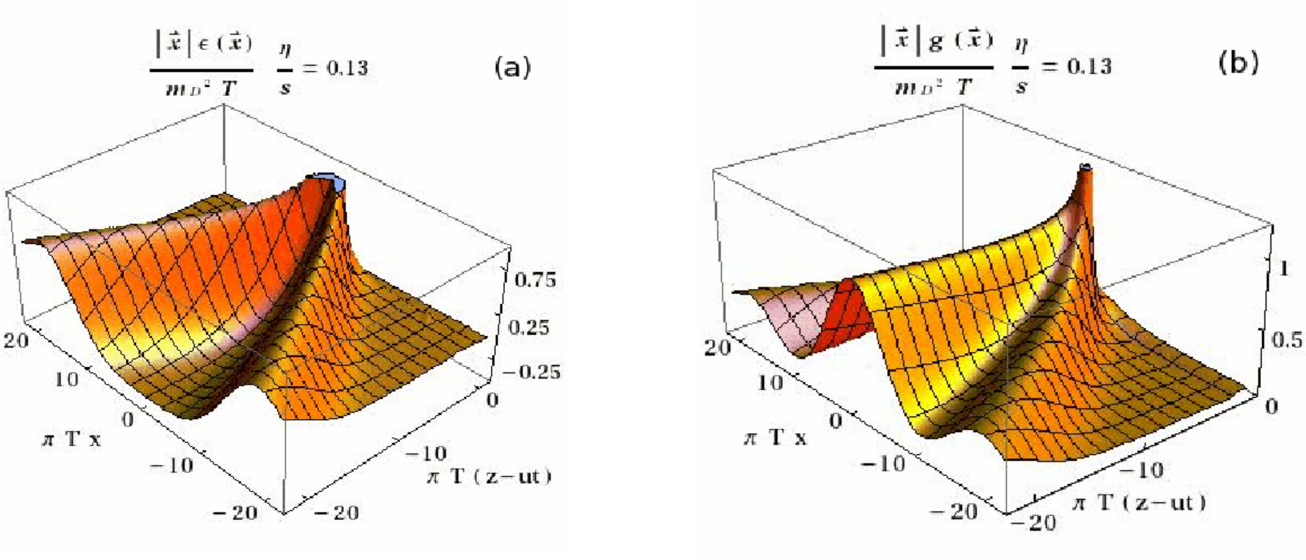
Considering a static medium and linearized hydrodynamics for a punch-though jet

R. Neufeld et al, Phys. Rev. C **78**, 041901 (2008)



→ Mach cone signal & Diffusion Wake

Jets in pQCD II

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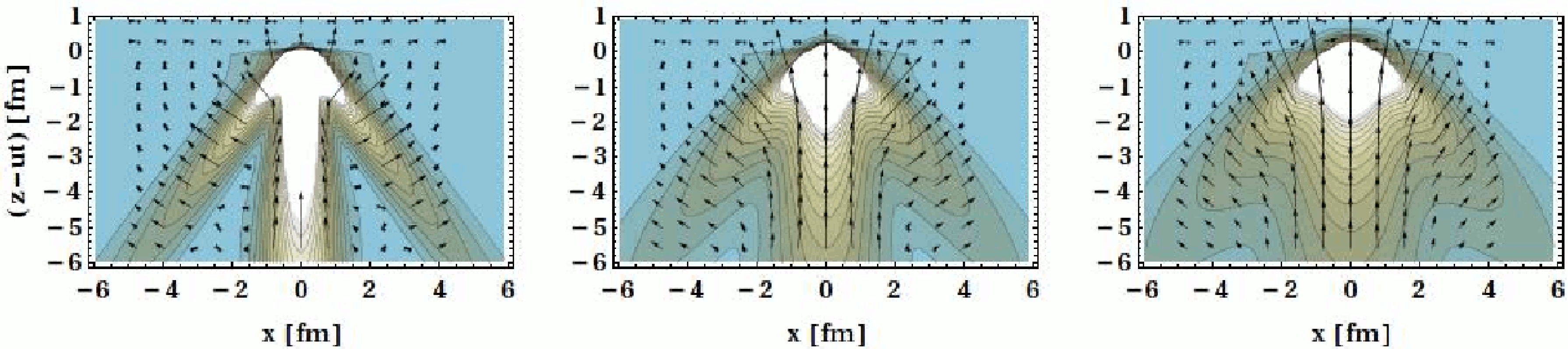
Contour plots of magnitude of perturbed momentum density

R. Neufeld et al., Phys. Rev. C **79**, 054909 (2009)



$$\frac{\eta}{s} = \frac{1}{4\pi} \qquad \frac{\eta}{s} = \frac{3}{4\pi} \qquad \frac{\eta}{s} = \frac{6}{4\pi}$$

→ Strong flow in jet-direction → $\frac{dM}{dt}(t) > \frac{dE}{dt}(t)$

Expanding Medium

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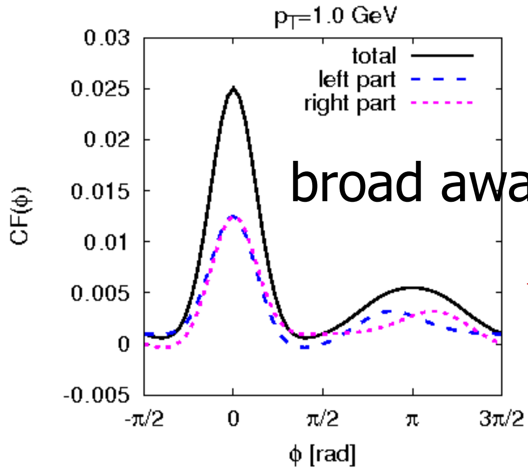
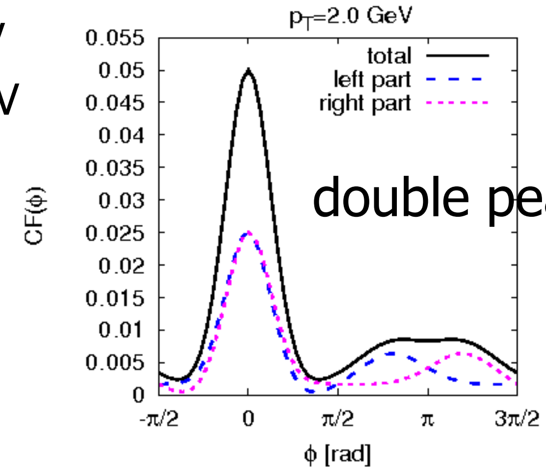
E_{tot} = 10 GeV
p_T^{trig} = 7.5 GeV

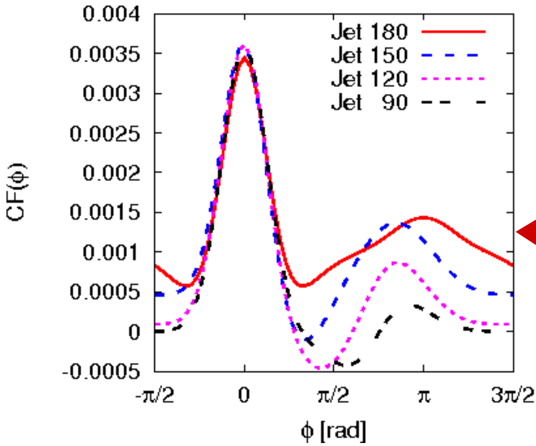


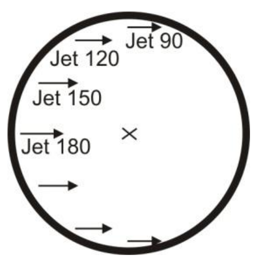
broad away-side peak

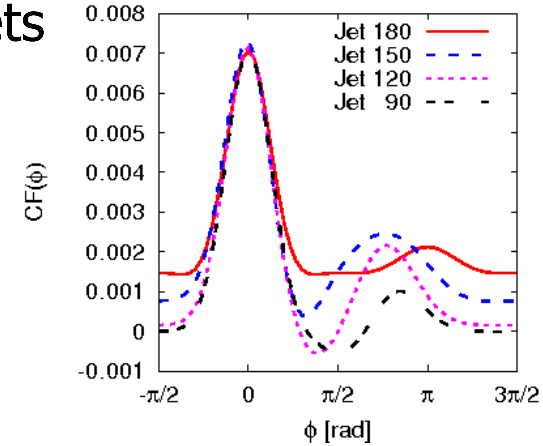


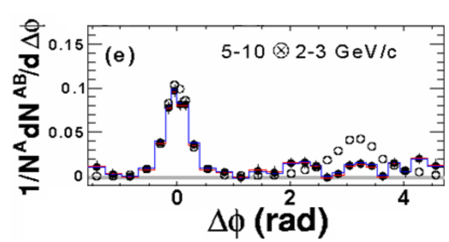
double peaked structure

due to
non-central jets









Strong impact of the Diffusion wake

→ Causes smaller dip for p_T=2 GeV

PHENIX, Phys. Rev. C **77**, 011901 (2008)

Expanding Medium

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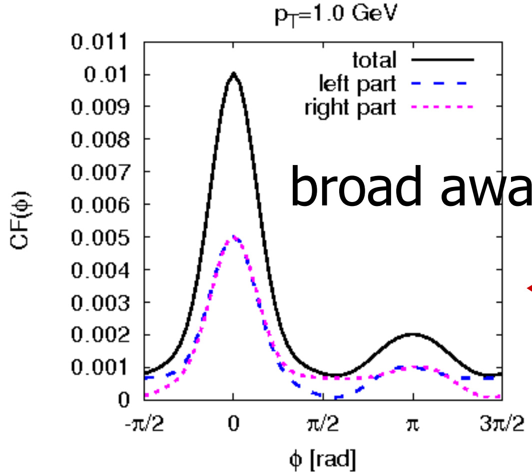
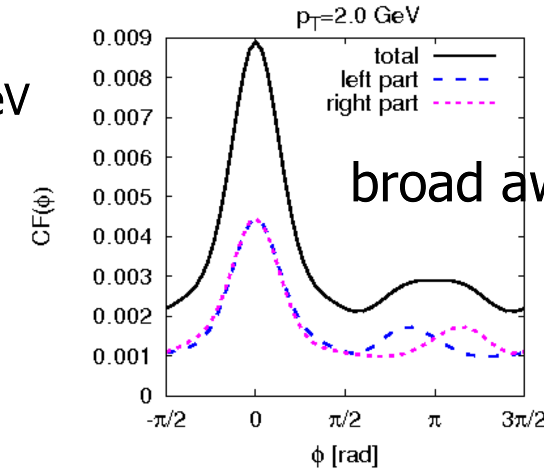
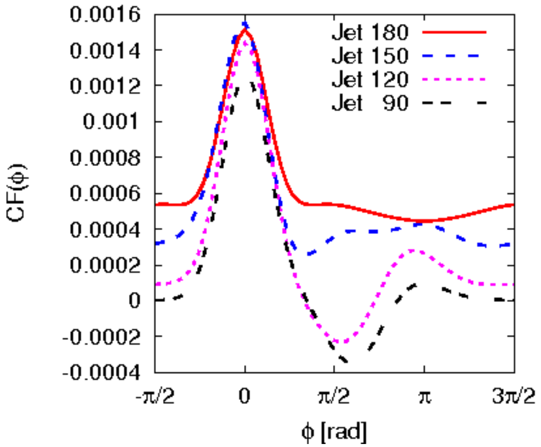
E_{tot} = 5 GeV
p_T^{trig} = 3.5 GeV

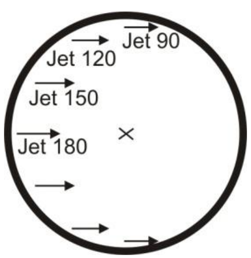


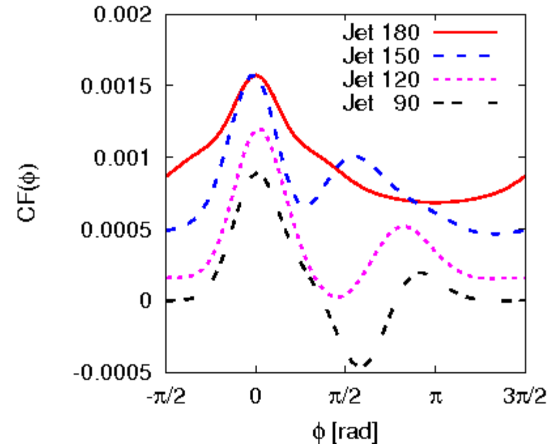
broad away-side peak



broad away-side peak







Pure energy deposition → No conical distribution in expanding medium for p_T=1 GeV and p_T=2 GeV

→ Jet 180: No peaks on away-side

Expanding Medium

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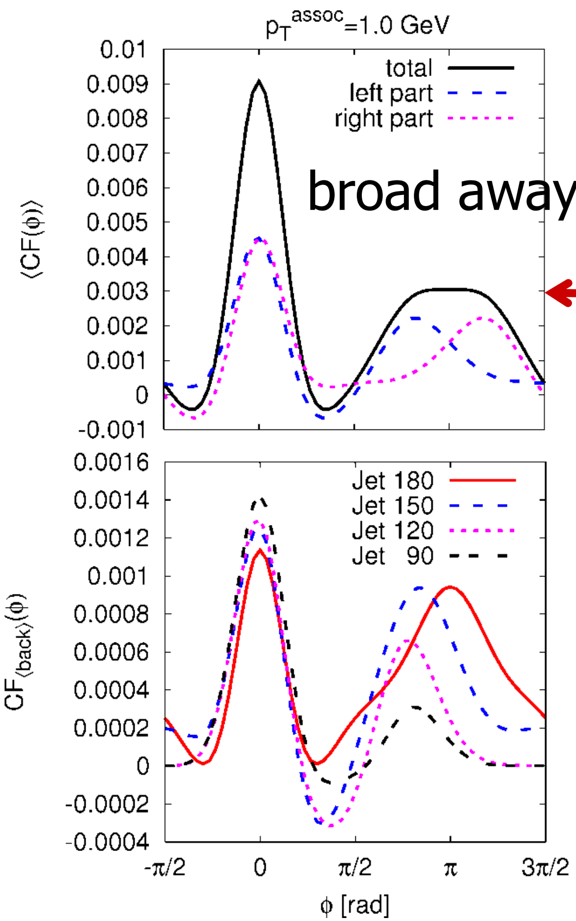
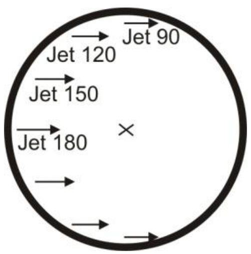
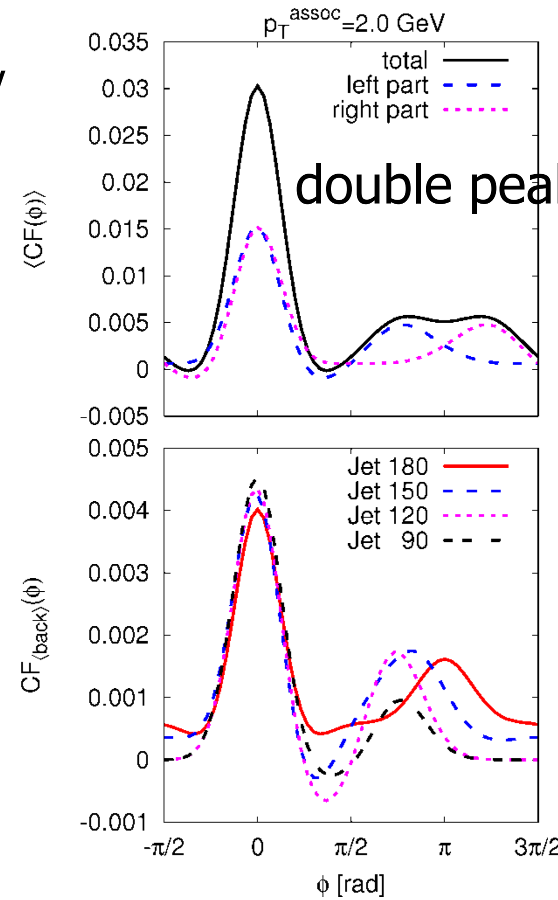
E_{tot} = 5 GeV
p_T^{trig} = 3.5 GeV



broad away-side peak





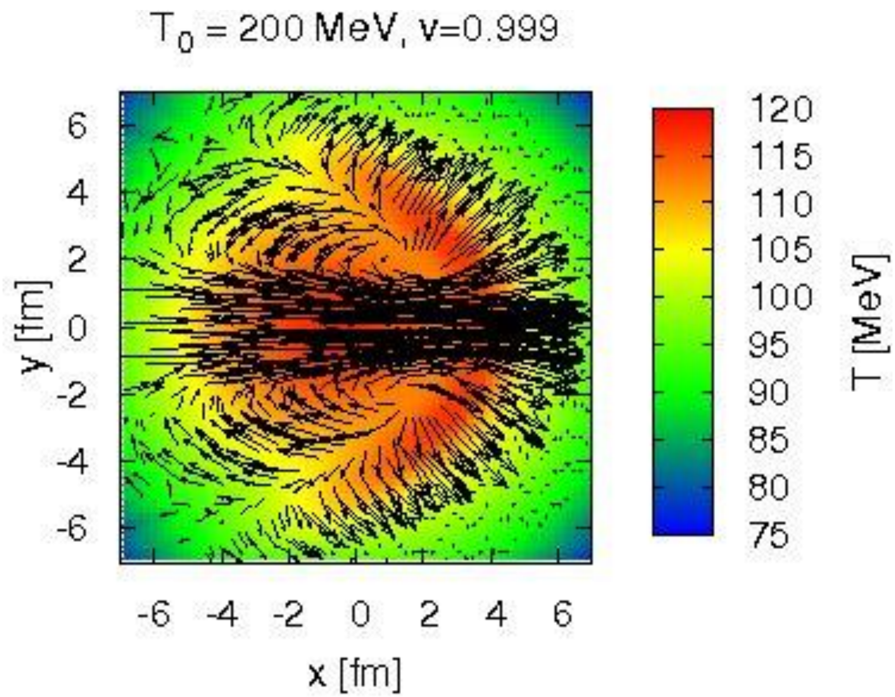
double peaked structure

Pure momentum deposition

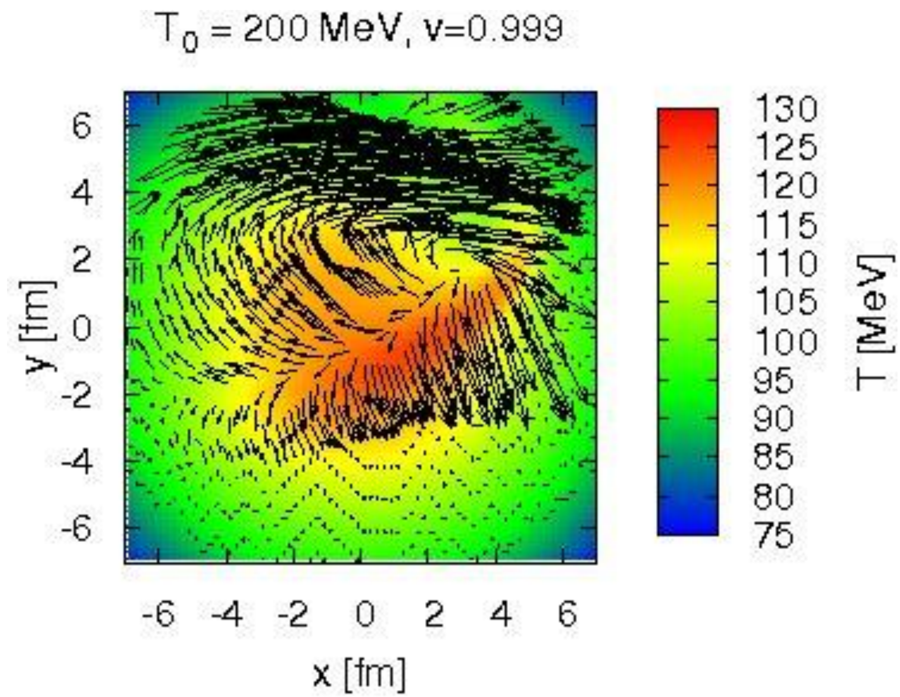
→ The same p_T-dependence as for energy and momentum deposition

Expanding Medium

Flow profile at freeze-out after background subtraction



Jet 180



Jet 150

The Caveat

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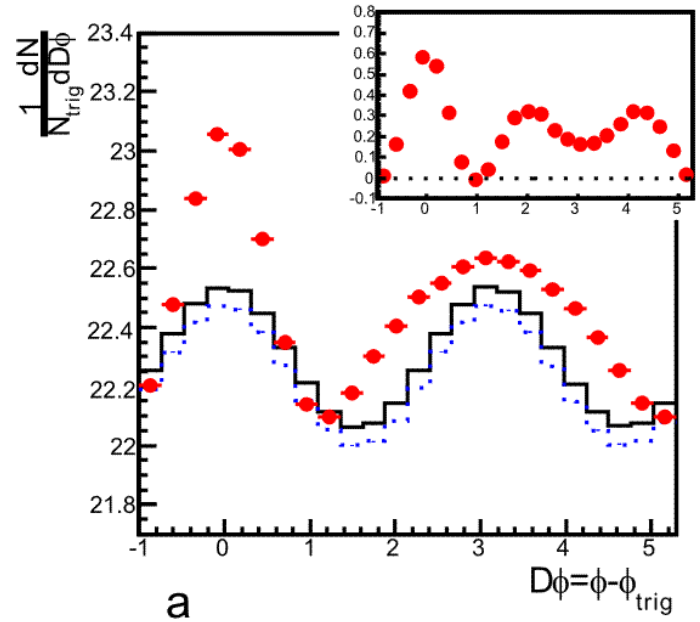
- Assumption :
Correlations from flow anisotropy and jets are uncorrelated

ZYAM (Zero Yield At Minimum)

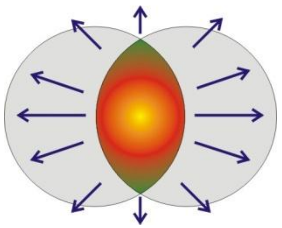
- Subtraction of:
estimated elliptic flow modulated background

- can leads to:
double peaked structure



J. Ulery [STAR], PoS **LHC07**, 036 (2007)

Background:
Particle correlation from elliptic flow



Two-source model:

$$C_2(\Delta\phi) = C_{2,\mathrm{jet}}(\Delta\phi) + b\left[1 + 2\langle v_2^T\rangle\langle v_2^A\rangle cos(2\Delta\phi)\right]$$

3-Particle Correlations

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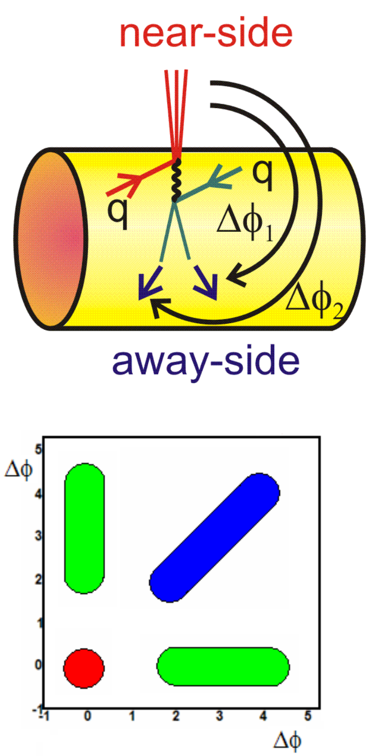
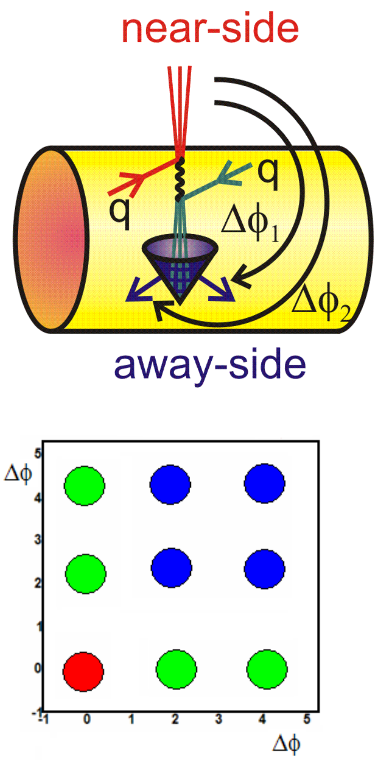
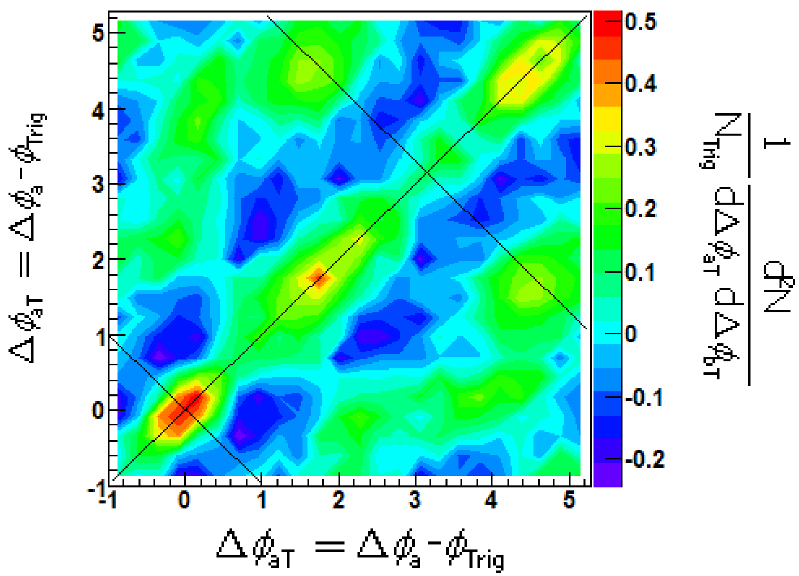
3-Particle Correlations seem to corroborate the Mach Cone picture



Deflected jet



Mach Cone



STAR Int. J. Mod. Phys. E **16** (2007)

➔ Experimental data show 2 off-diagonal peaks

Jet - Studies at SPS Energies

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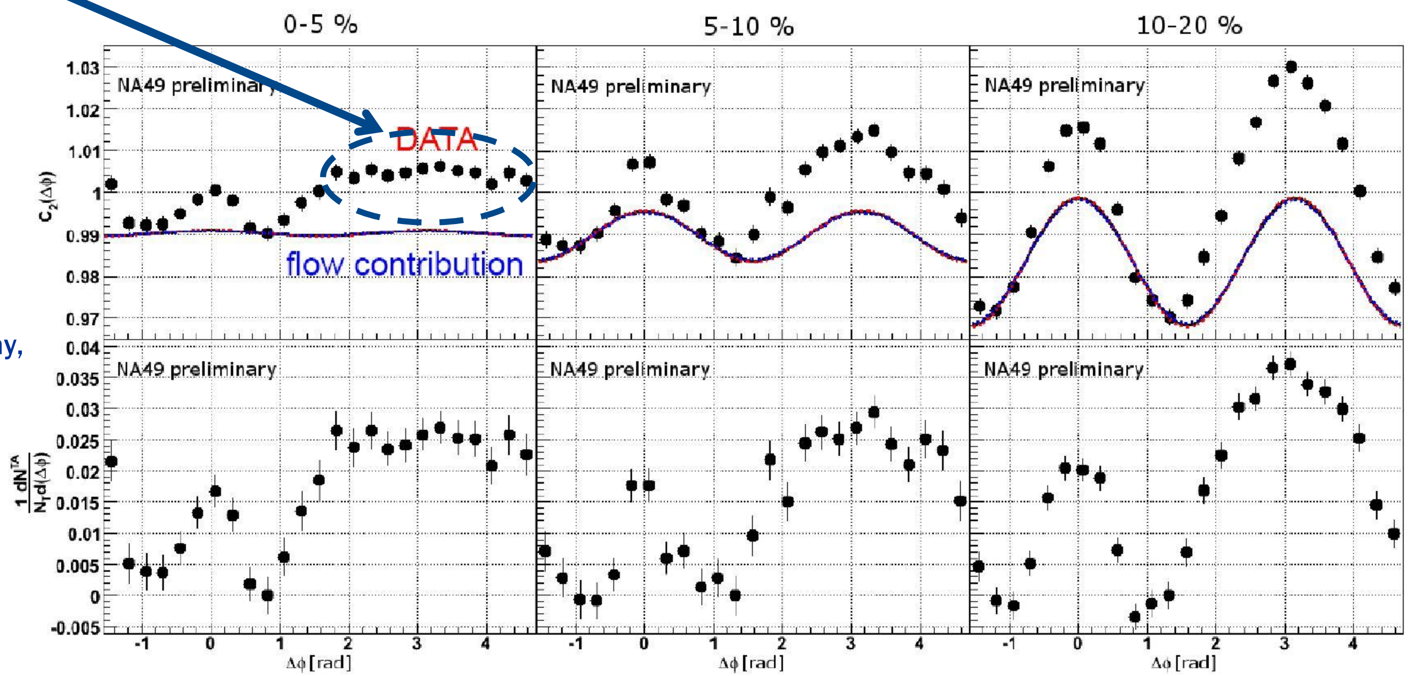
- High-p_T correlations at SPS energies show conical structure?

→ Conical structure even before subtracting the effect of elliptic flow - ZYAM

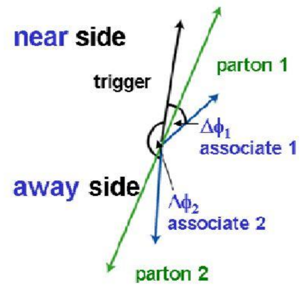
Blume, Talk at Confinement8, Mainz, Germany, 2008



Pb+Pb at 158AGeV

Correlation function:

$$C(\Delta\phi)=\frac{N^{pair}_{same}(\Delta\phi)}{N^{pair}_{mixed}(\Delta\phi)}\times\frac{\int N^{pair}_{mixed}}{\int N^{pair}_{same}}$$



Conditional yield:

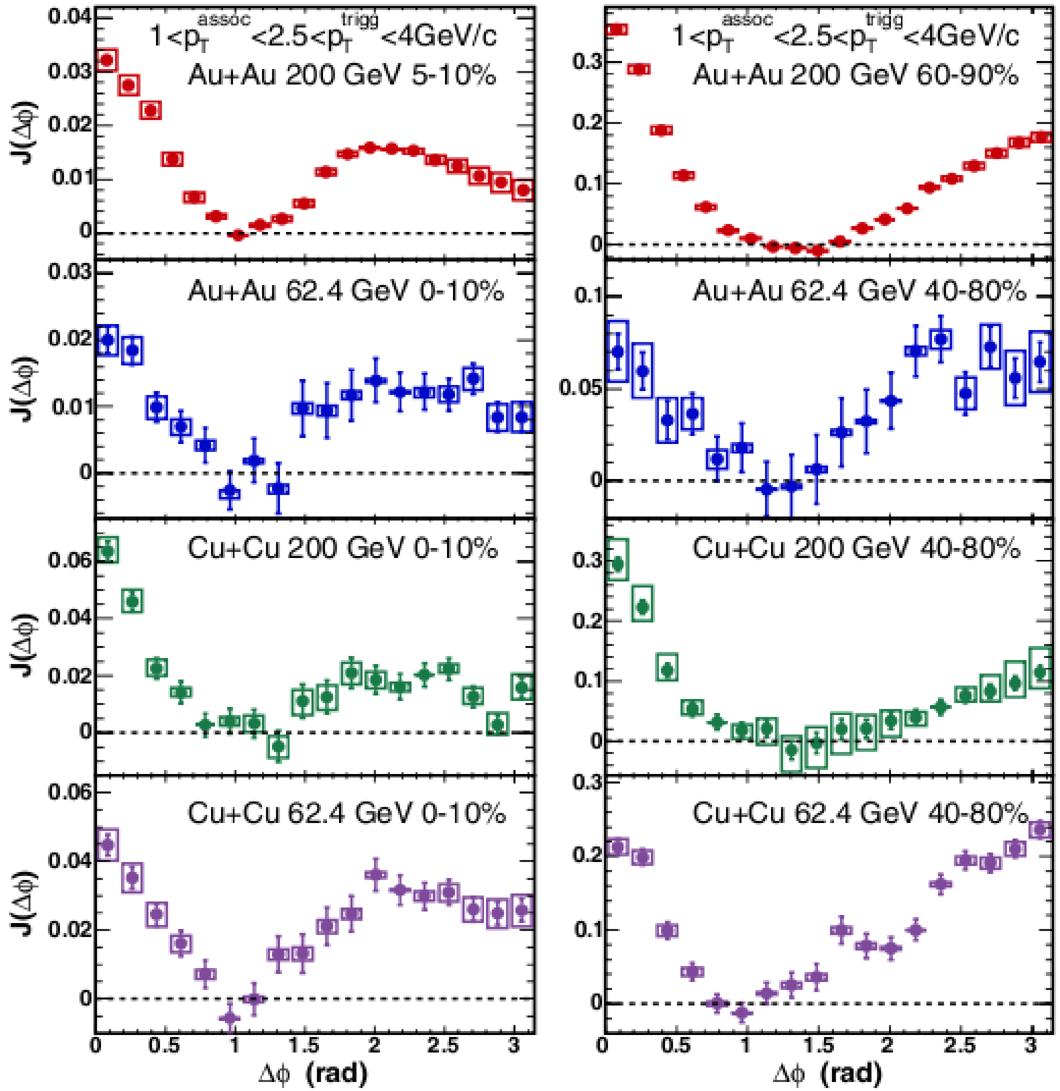
$$J_2(\Delta\phi)=\frac{1}{N^T}\frac{dN^{TA}}{d(\Delta\phi)}=\frac{C_2^{jet}(\Delta\phi)}{\int C_2(\Delta\phi')d(\Delta\phi')}\frac{N^{TA}}{N^T}$$

Flow contribution subtracted using ZYAM method

Jet - Studies in HIC

Columbia University in the City of New York

For most central collisions, the shoulder width is similar in Au+Au and Cu+Cu collisions



PHENIX, PRL**98**, 232302 (2007)

Jet-Medium Models

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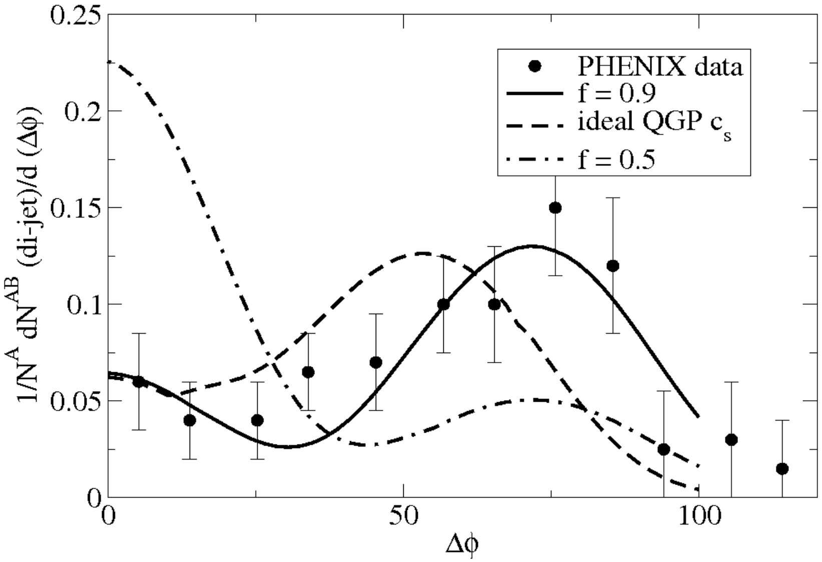
Determines angular correlation pattern

- Fireball model
- Lattice QCD EoS
- BDMPS-like energy loss



T. Renk and J. Ruppert, Phys. Rev. C **73**, 034907 (2006)

f: **„fraction ... of energy lost to the medium [that] excites a collective mode“** → sound wave

(1-f): **„remaining energy fraction ... [that] in essence heats the medium and leads to some amount of the collective drift along the jet axis...“** → diffusion

→ Mach cones only if dM/dx << dE/dx

Jet – Energy Loss Studies

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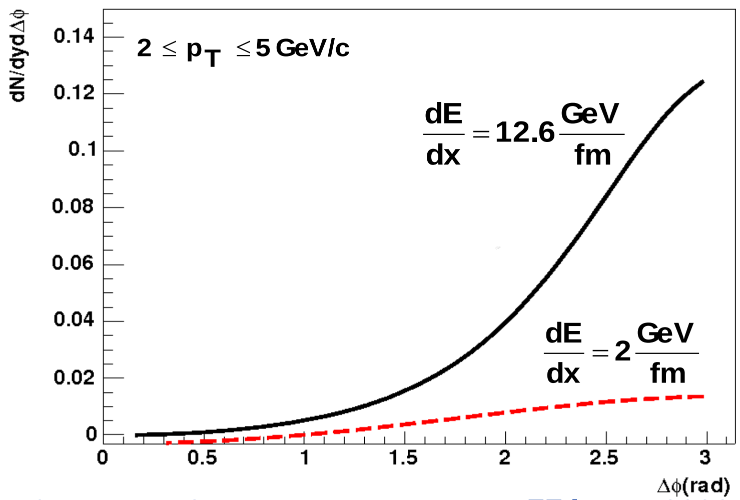
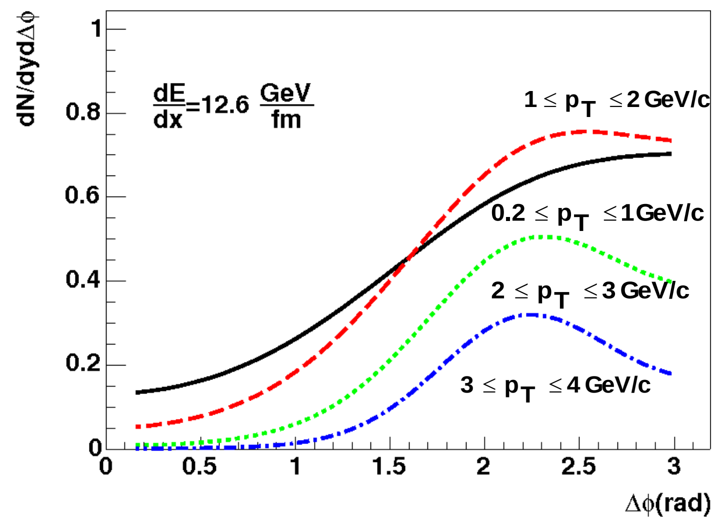
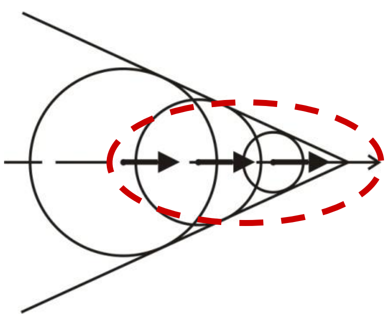
- Jet deposits energy and momentum along a trajectory
- Applying linearized hydrodynamics

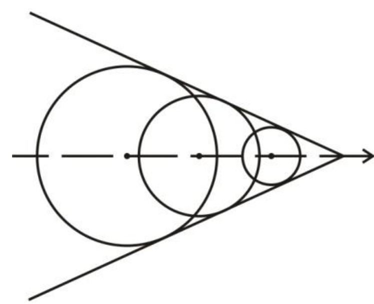


J. Casalderrey-Solana et al., Nucl. Phys. A **774**, 577 (2006)





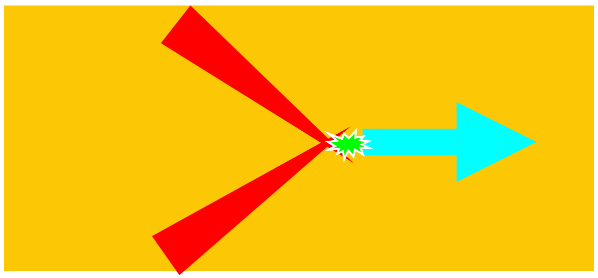
→ Diffusion wake

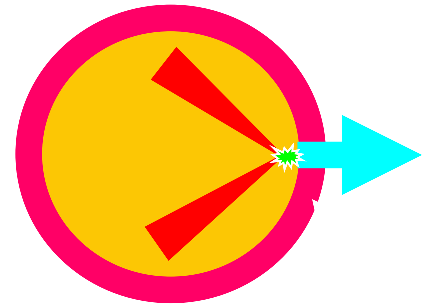


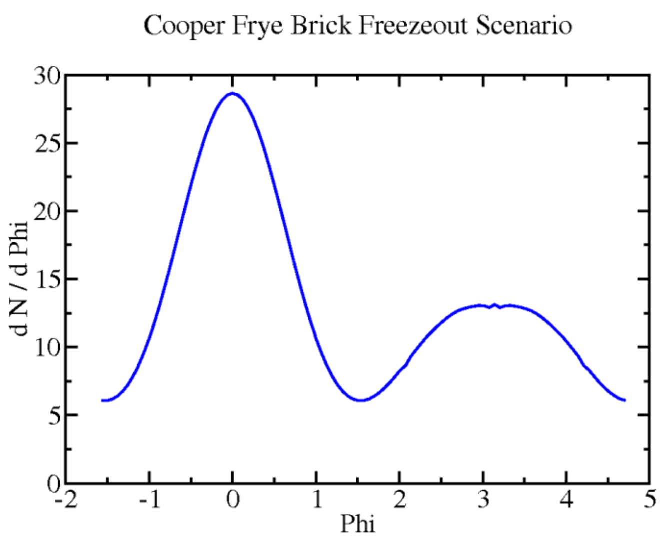
→ Mach cone for sound waves

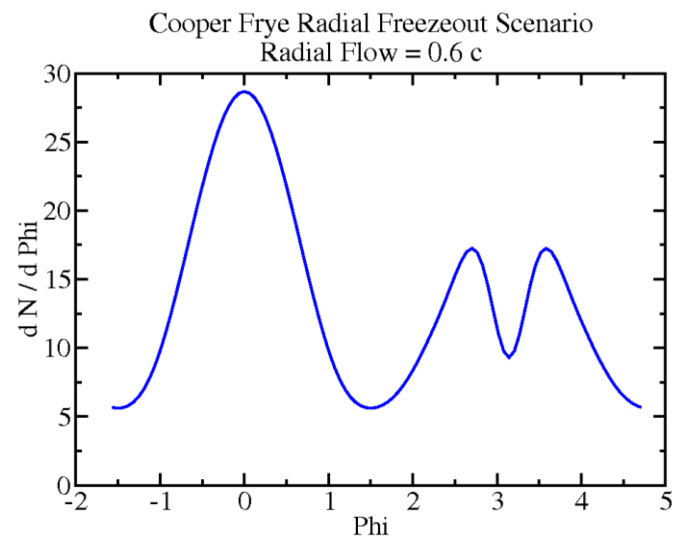
Jets in pQCD

Comparing different freeze-out scenarios, neglecting the diffusion wake:









Neufeld et al, arXiv:0810.3185 [hep-ph]

→ Is the diffusion wake really an artefact???