SIGNATURES OF MACH SHOCKS AT RHIC

(. . . and whatever else is in the angular high p_T correlations)

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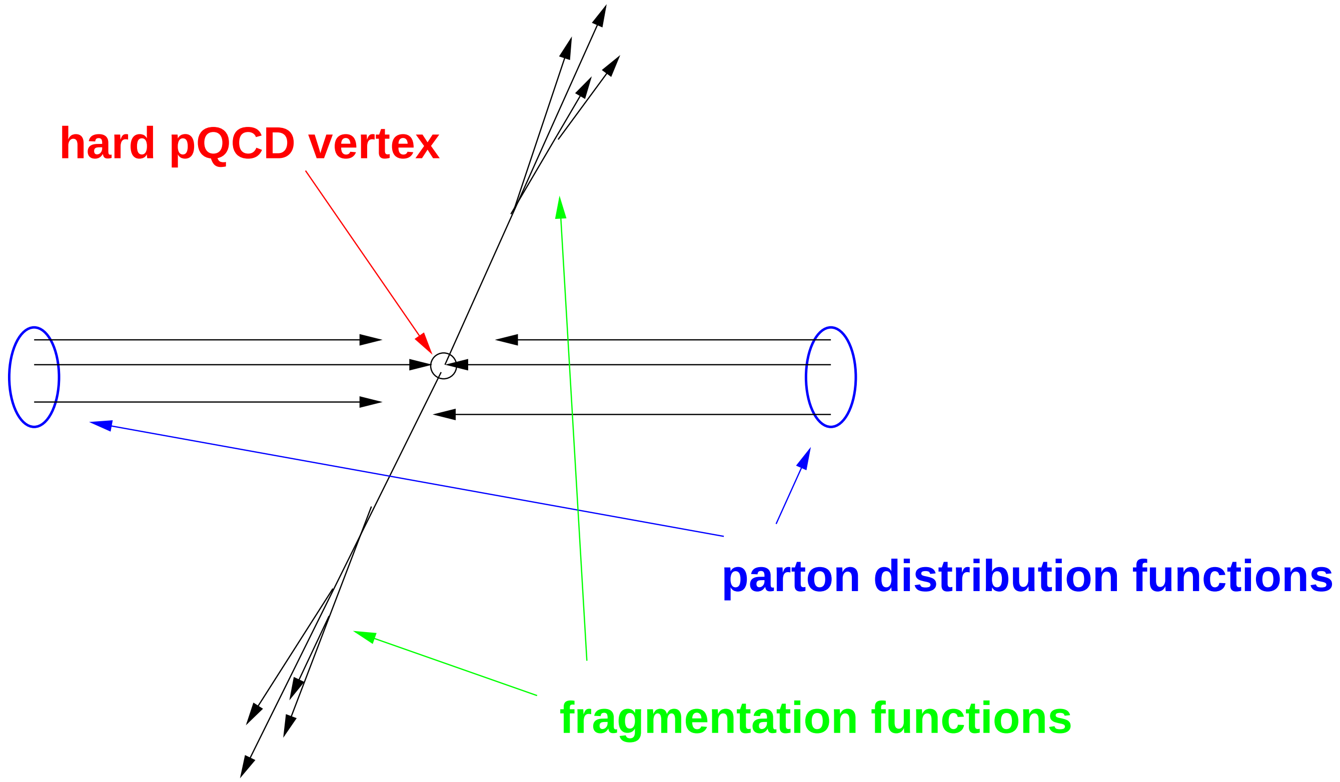
INTRODUCTION
- Jets in p-p collisions. . .
- . . . and their dis- (re-)appearance in A-A

ANGULAR CORRELATIONS IN THE MODEL
- low p_T Mach cones
- high p_T punchthrough

CONCLUSIONS

HARD P-P COLLISIONS



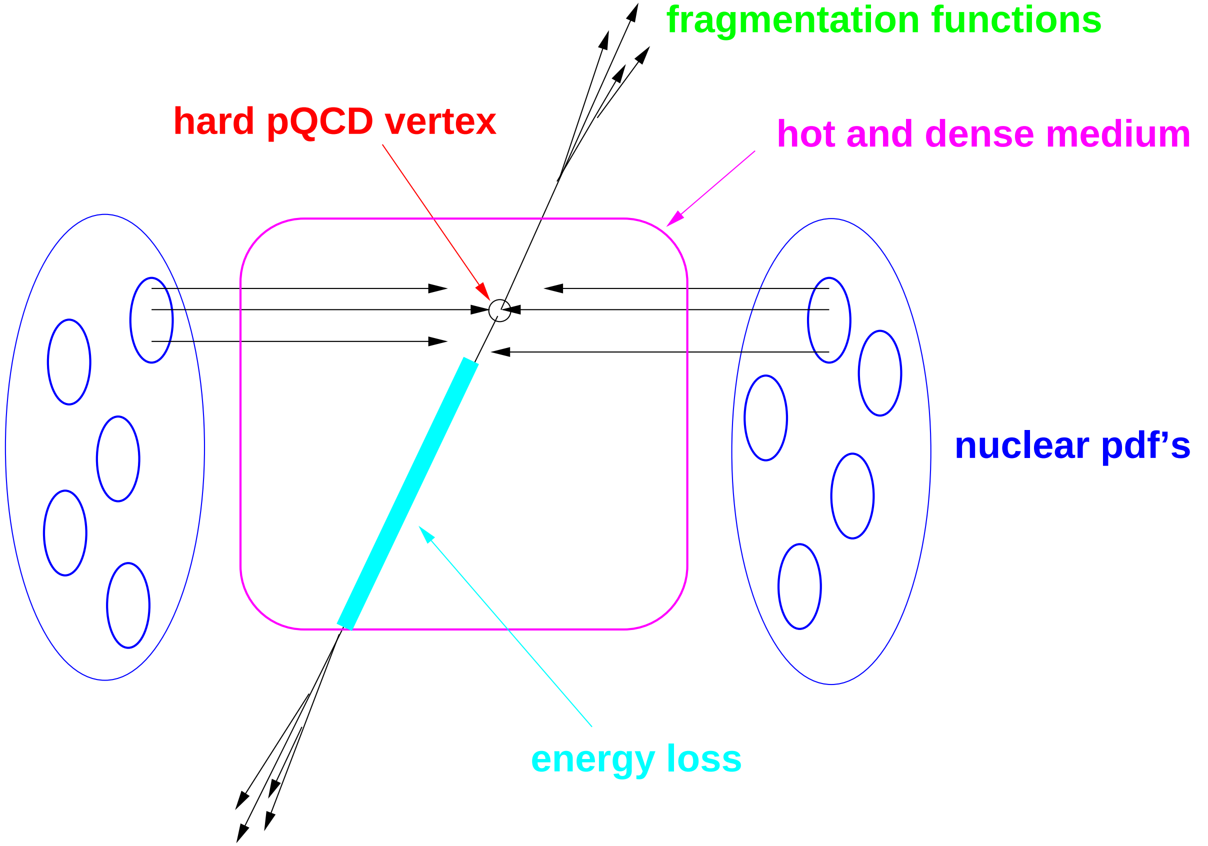
hard pQCD vertex

parton distribution functions

fragmentation functions

$$d\sigma^{NN\rightarrow h+X} = \sum_{fijk} f_{i/N}(x_1,Q^2)\otimes f_{j/N}(x_2,Q^2)\otimes \hat{\sigma}_{ij\rightarrow f+k}\otimes D^{vac}_{f\rightarrow h}(z,\mu_f^2)$$

HARD AU-AU COLLISIONS

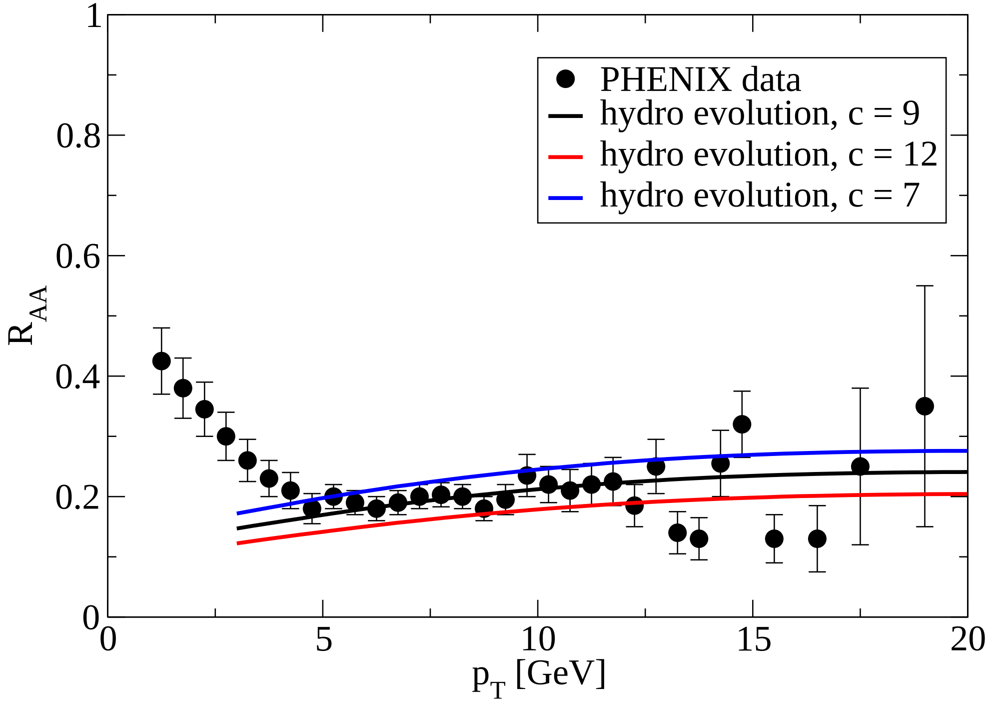


$$d\sigma^{AA\to\pi+X}_{med} = \sum_f d\sigma^{AA\to f+X}_{vac} \otimes P_f(\Delta E) \otimes D^{vac}_{f\to\pi}(z,\mu_F^2)$$

$$d\sigma^{AA\to f+X}_{vac} = \sum_{ijk} f_{i/A}(x_1,Q^2) \otimes f_{j/A}(x_2,Q^2) \otimes \hat{\sigma}_{ij\to f+k}$$

Evidence I: Nuclear Suppression Factor

$$R_{AA}(p_T, y) = \frac{d^2N^{AA}/dp_T dy}{T_{AA}(0) d^2\sigma^{NN}/dp_T dy}$$



T. R. and J. Ruppert, Phys. Rev. C **72** (2005) 044901

Suppression by:

- downward shift

(some partons absorbed)

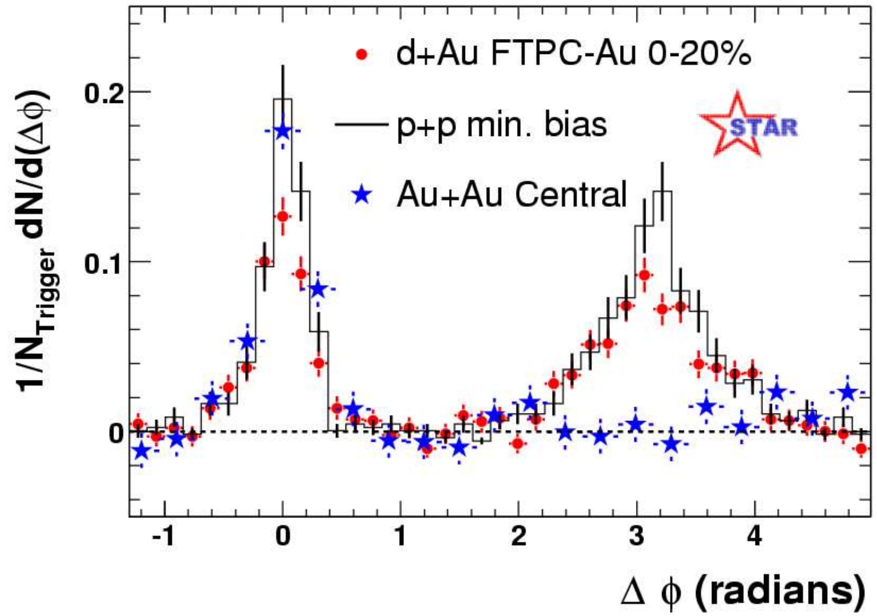
- sideward shift

(all partons lose some ΔE)

$\Rightarrow R_{AA}$ can't distinguish well

EVIDENCE II: ANGULAR CORRELATIONS

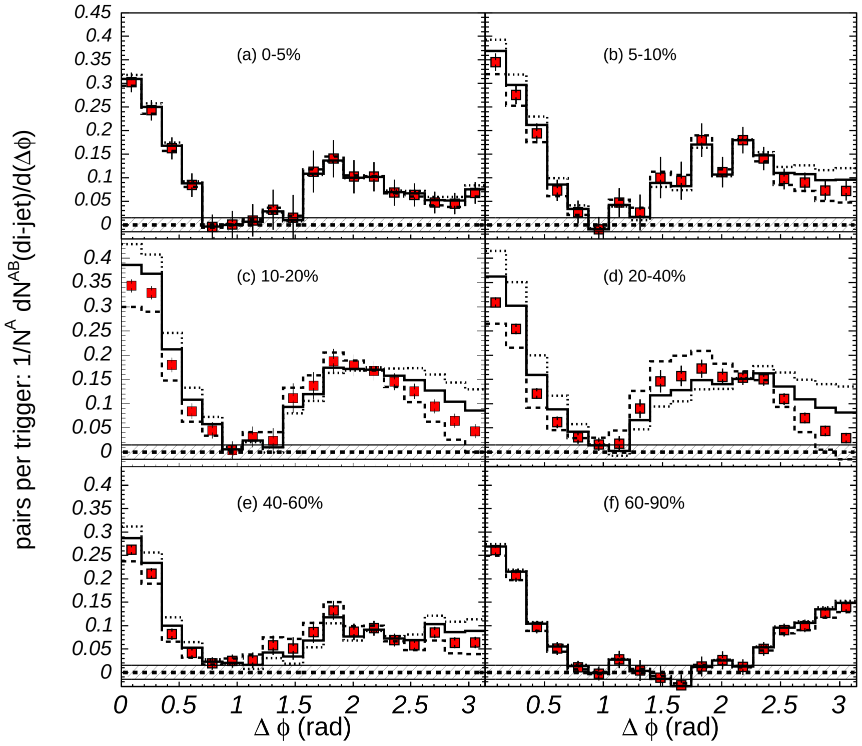
For hard > 6 GeV trigger and semi-hard ~ 1 GeV associate hadrons:



- NLO fragmentation builds near side jet cone
- acoplanarity (intrinsic k_T/NLO pQCD) widens away side cone in p-p and p-A
- energy loss causes away side cone to disappear in A-A

EVIDENCE III: ANGULAR CORRELATIONS

For semi-hard ~ 2.5 GeV trigger and semi-hard ~ 1 GeV associate hadrons:

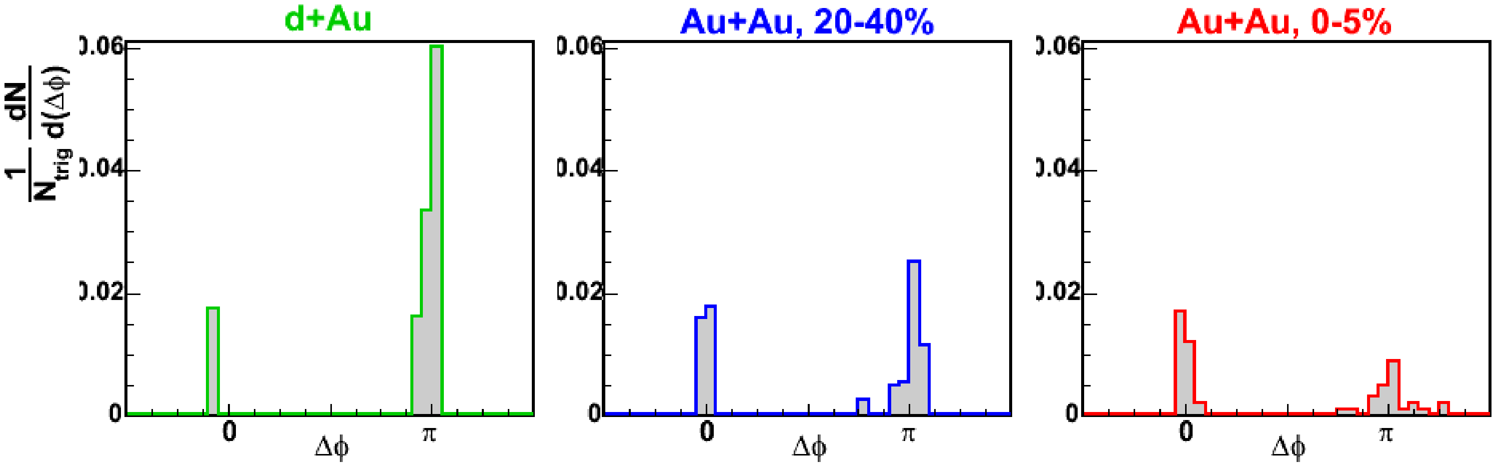


- NLO fragmentation builds near side jet cone
- central collisions: dip at expected position of away side jet
- position of correlation maximum consistent with Mach shock

S. S. Adler *et al.* [PHENIX Collaboration], nucl-ex/0507004

EVIDENCE IV: ANGULAR CORRELATIONS

For hard > 8 GeV trigger and hard > 4 GeV associate hadrons:

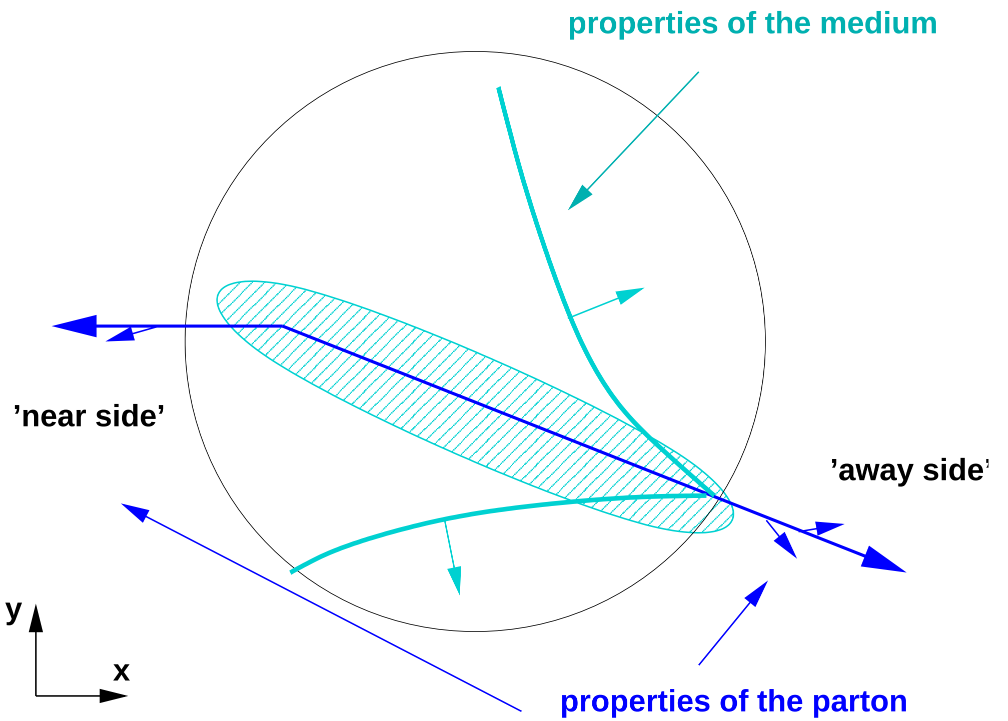


- clear jet cones with vacuum width
- near side LO fragmentation: → trigger
- away side LO fragmentation: → signal
- jet quenching: change in the yield per trigger of the away side peak

How can we understand this pattern?

J. Adams [STAR Collaboration], nucl-ex/0604018.

A TENTATIVE PICTURE



- strength and angle of Mach correlations: property of the bulk (fluid) medium
- strength and angle of near side, dijet: property of the hard parton + fragmentation
- different scaling with $p_{trigger}$ ($\Rightarrow$ apparent absence of cones for hard trigger)

Mach structures cannot be seen beyond the validity of the hydro description, regardless of trigger energy.

THEORY: ENERGY LOSS INTO THE MEDIUM

Energy loss probability (Wiedemann/Salgado): $P(\Delta_E) = P(\omega_c, (\hat{q}L))$

$$\omega_c(\mathbf{r_0}, \phi) = \int_0^{\tau} d\xi \xi \hat{q}(\xi) \quad \text{and} \quad (\hat{q}L)(\mathbf{r_0}, \phi) = \int_0^{\tau} d\xi \hat{q}(\xi)$$

$$\hat{q} = c\tilde{\epsilon}^{3/4} \left(p(\epsilon) + [\epsilon + p(\epsilon)] \frac{\beta_\perp^2}{1 - \beta_\perp^2} \right) \quad \text{and} \quad \langle \Delta E \rangle = \int_0^{\infty} P(\Delta E) \Delta E d\Delta E$$

Assume fraction f of lost energy $\langle \Delta E \rangle$ excites shockwave with dispersion relation

$$E = c_s p \quad \text{with} \quad c_s = \partial p(T)/\partial \epsilon(T) \quad \text{from EOS} \quad \Rightarrow \qquad \phi = \arccos \frac{\int_{\tau_E}^{\tau} c_s(\tau) d\tau}{(\tau - \tau_E)}$$

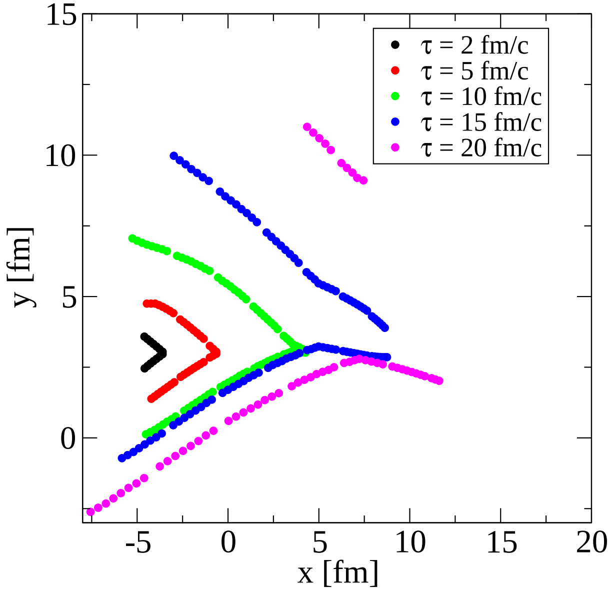
Sound propagates in the (locally moving) fluid

⇒ boost with local flow rapidity

C. A. Salgado and U. A. Wiedemann, Phys. Rev. D **68**, 014008 (2003)

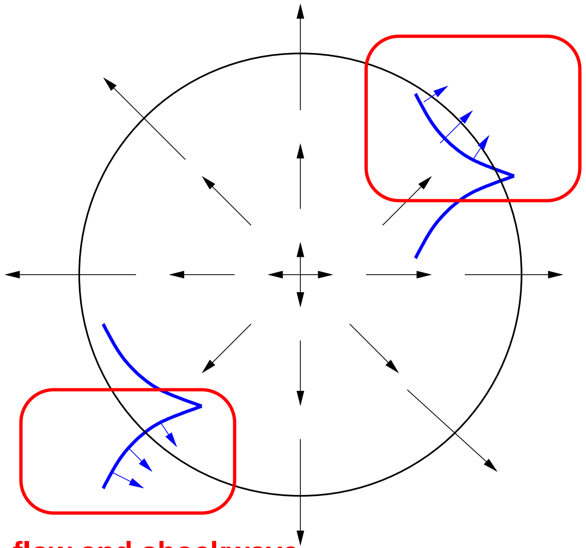
TRANSVERSE FLOW

Strong distortion in position space:



Measurement is made in momentum space:

$$E\frac{d^3N}{d^3p} = \frac{g}{(2\pi)^3}\int d\sigma_\mu p^\mu \exp\left[\frac{p^\mu u_\mu - \mu_i}{T_f}\right]$$



flow and shockwave are aligned

flow and shockwave are perpendicular

At 1 GeV, a Mach signal only appears if shockwave and flow are aligned

T. R. and J. Ruppert, Phys. Rev. C **73**, 011901 (2006)

MONTE CARLO SAMPLING OF TRIGGER CONDITIONS

Near side:

- hard parton energy (and type)

⇒ parton spectra from VNI/BMS PCM (semi-hard trigger) or pQCD (hard trigger)

⇒ vertex sampling from nuclear overlap

⇒ probabilistic ΔE dependent on in-medium path

→ check against near side trigger threshold

Away side:

- intrinsic k_T

⇒ chosen such that d-Au width of far side peak is reproduced

⇒ far side probabilistic ΔE dependent on in-medium path

⇒ near and far side (N)LO fragmentation

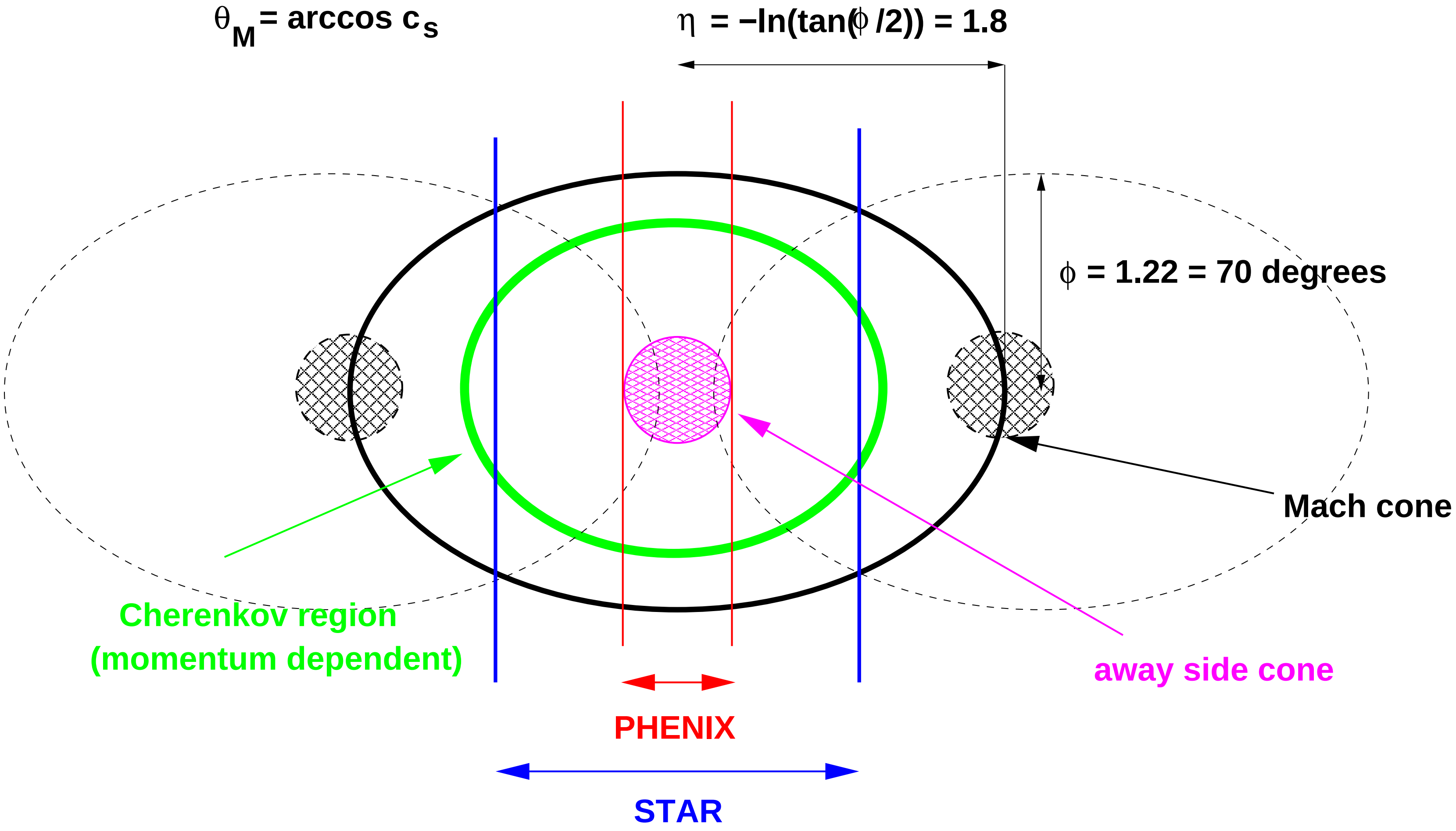
→ good description of hard dihadron yields (alas, another talk. . .)

Contains all information on trigger bias, pathlength distribution, nuclear density. . .

cf. T. R., hep-ph/0602045

RAPIDITY STRUCTURE OF THE CONE

Problem: If trigger is at midrapidity, $P(y)$ on the away side extends from -2 to 2



$\Rightarrow$ Why would there be any angular structure left?

RAPIDITY STRUCTURE OF THE CONE

- shock wave propagates with $c_s(T)$ relative to the medium

⇒ spatial position as solution of

$$\frac{dz}{dt} = \left.\frac{u(z,R,t) + c_s(T(z,R,t))}{1 + u(z,R,t)c_s(T(z,R,t))}\right|_{z=z(t)}$$

⇒ longitudinal flow field at z_{final} determines boost in momentum space

Significant elongation of the ring (→ ellipse) in rapidity space

- measurement detects momentum transverse to the beam axis

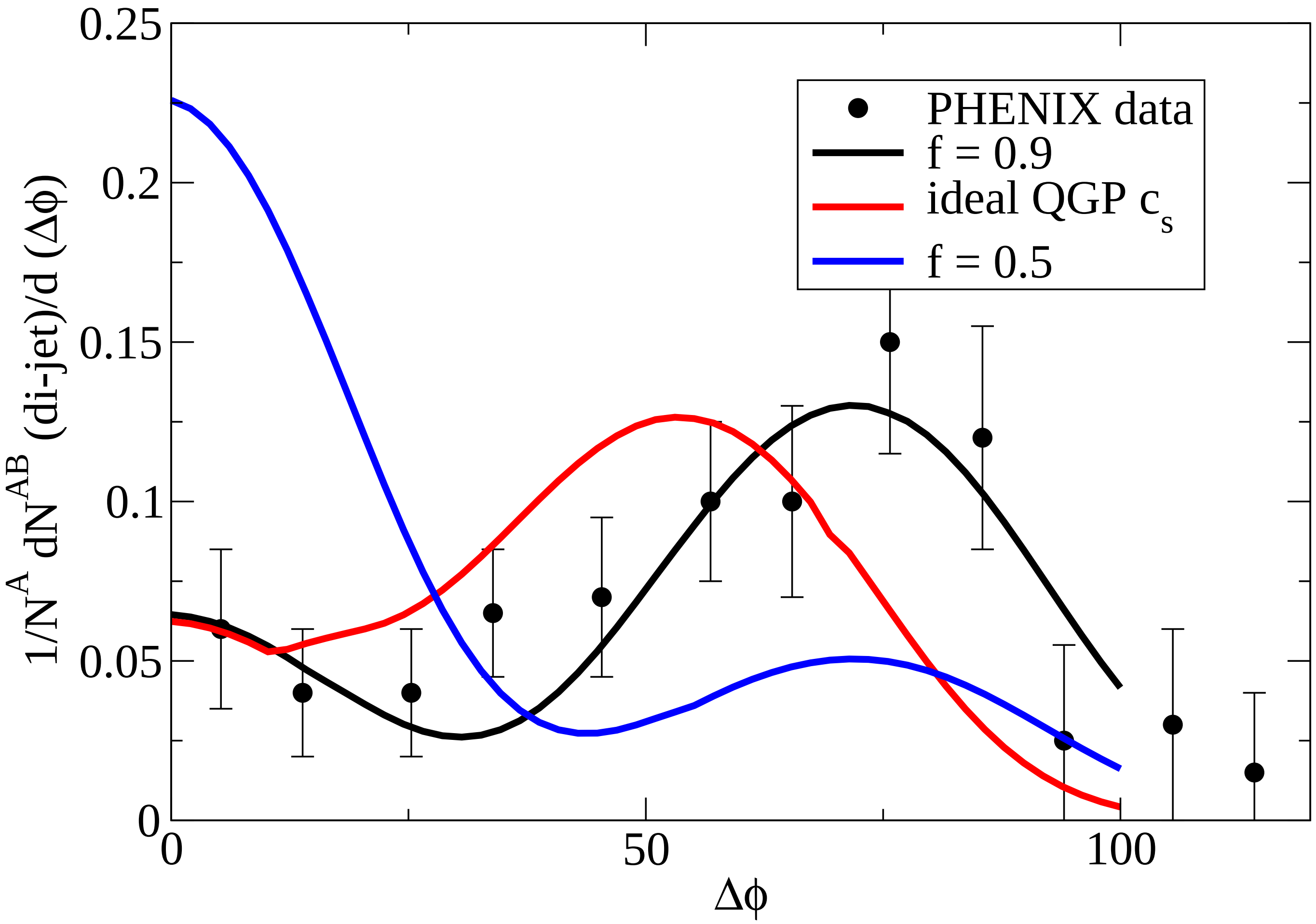
⇒ no contribution for the longitudinal component of the shockwave ring

⇒ The Mach angle remains observable under these conditions

Not so if signal doesn't propagate in the medium!
Serious problem for jet bending, Cherenkov emission. . . !

RESULTS

The average angle is sensitive to the speed of sound

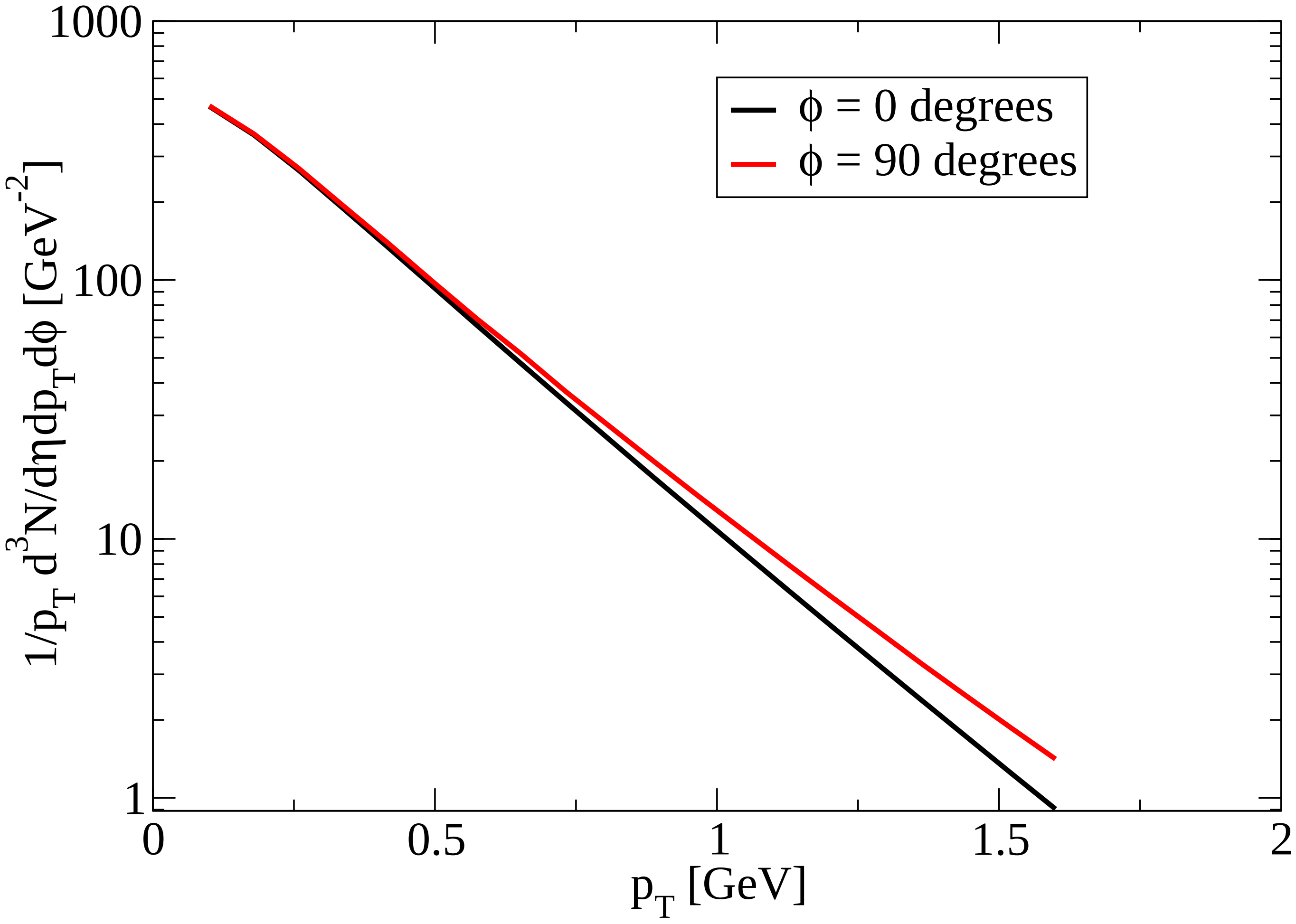


Dip at 0 degrees $\Leftrightarrow$ excitation of shock must be very efficient

T. R. and J. Ruppert, Phys. Rev. C **73**, 011901 (2006)

p_T-SPECTRA

For 5 GeV energy loss from a hard parton, spectral change as a function of angle:



Sizeable effect on the spectrum

SUMMARY

Angular hadron correlations for (semi-) hard triggers emerge naturally from

- excitation of hydrodynamical shockwaves
- hard punchthrough + fragmentation

with different excitation function for rising trigger energy!

Due to $P(y)$ of the away side parton: Large angle correlations only visible if

- signal moves relative to flowing medium

$\Rightarrow$ problem for other explanations!

Mach shocks survive challenges posed by the data so far $\Rightarrow$ direct access to c_s