Two and three particle azimuthal correlations

and Mach shocks

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Introduction
- why Mach cones?

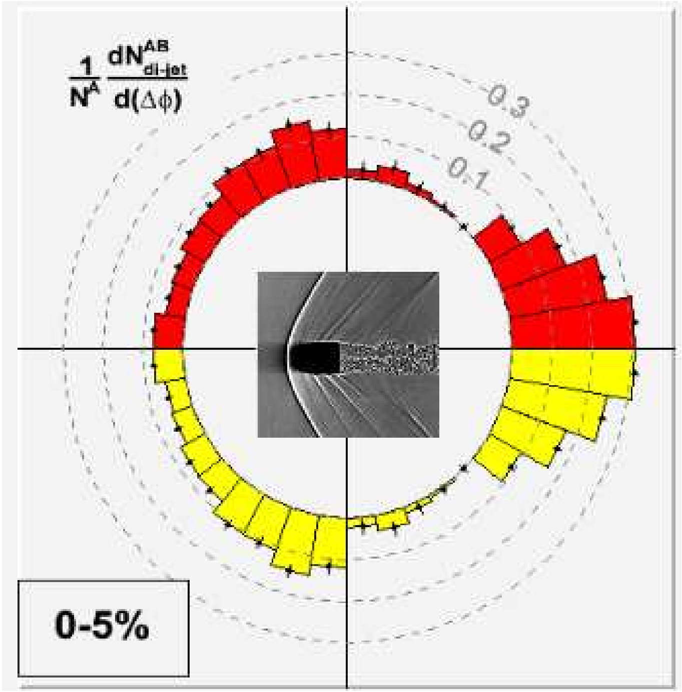
Modelling Correlations
- the trigger bias
- flow effects
- 3-particle correlations

Cone and ridge
- dihadron triggers

Conclusions

Introduction

When I first saw this, to me it looked like a shockwave:



To other people apparently not:

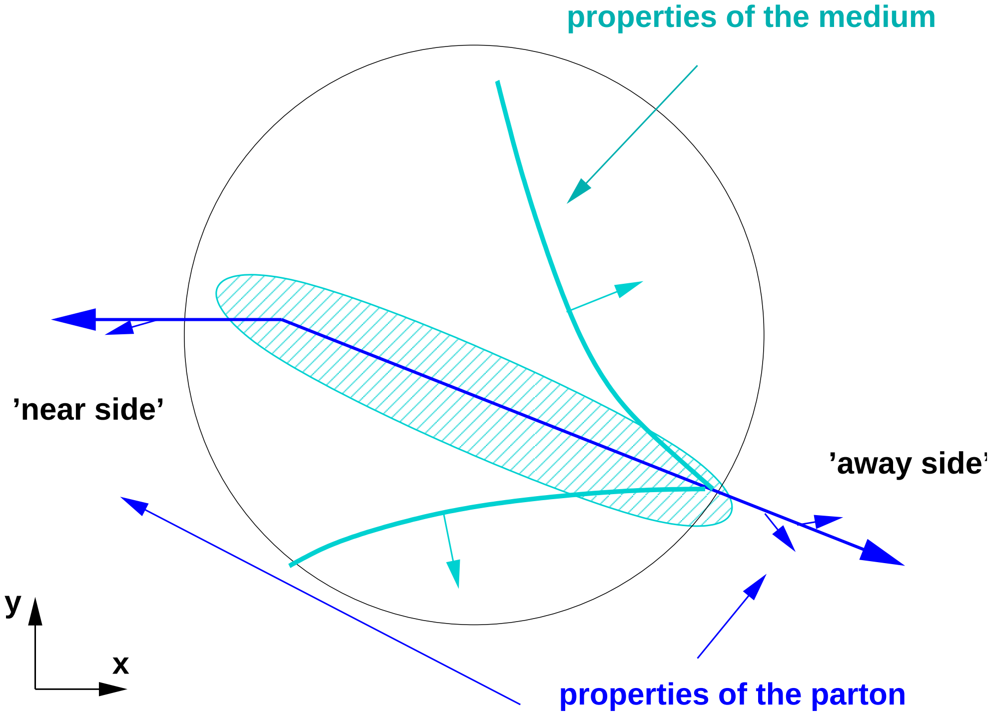
"There's only one collaboration at RHIC which believes in Mach cones."
(R. Bellwied)

"I am very sceptical about these Mach cones."
(J. Rak)

The model

hydrodynamics works $\leftrightarrow$ existence of shockwaves

energy lost from a hard parton $\leftrightarrow$ energy of the shockwave



Follow flow of energy and momentum:
$\Rightarrow$ dispersion relation
$E = c_s p$ with $c_s^2 = \partial p(T)/\partial\epsilon(T)$
Thus: $\phi = \arccos \frac{\int_{\tau_E}^{\tau} c_s(\tau) d\tau}{(\tau - \tau_E)}$
propagating in moving fluid

- 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

$\Rightarrow$ interplay between hydrodynamical processes and hard processes

Implications

Based on this picture, a number of qualitative predictions were made:

'trivial' expectations:

• correlation angle (approx.) independent of trigger or associate momentum
• correlation hadrochemistry equals bulk modulo a boost
$\rightarrow$ enhancement of p/π ratio
• without energy loss, the large angle correlation is absent

'non-trivial' expectations:

• correlation signal observable at large y for trigger at $y = 0$
$\rightarrow$ massive elongation in rapidity
• visible but weak off-diagonal peaks in 3-particle correlations

These expectations were published *before* relevant data came out!

Everything has been confirmed since, so we may have the right scenario.

T. R. and J. Ruppert, Phys. Rev. C **73** (2006) 011901; T. R. and J. Ruppert, Phys. Lett. B **646** (2007) 19; T. R., Eur. Phys. J. C **49** (2007) 13.

Trigger bias

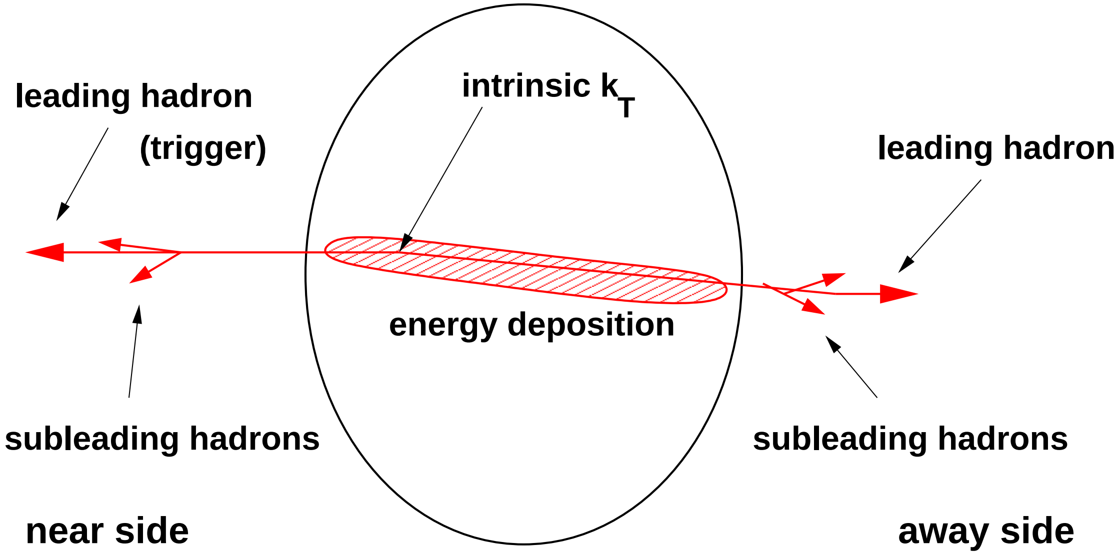
or:

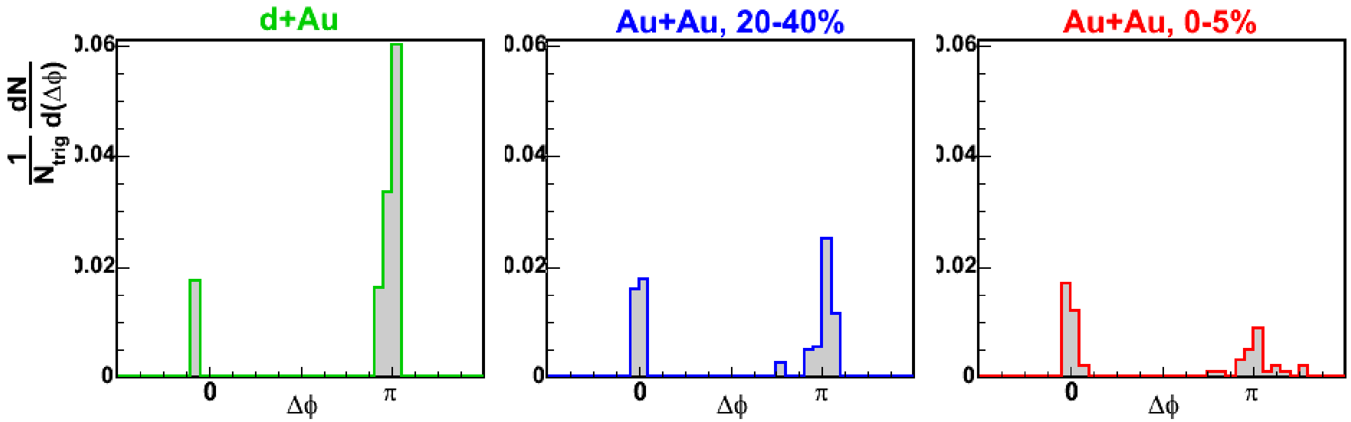
Why shockwaves come from peculiar regions

- understanding truly hard back-to-back correlations
- when does energy appear in the medium?

THE TRIGGER BIAS

Do we understand the purely hard part where only punchthrough is seen?





Monte Carlo model

Near side:

- hard parton energy (and type)

⇒ parton spectra from LO pQCD
⇒ vertex sampling from nuclear overlap
⇒ probabilistic ΔE for in-medium path
→ fragment and check against near side trigger threshold

Away side:

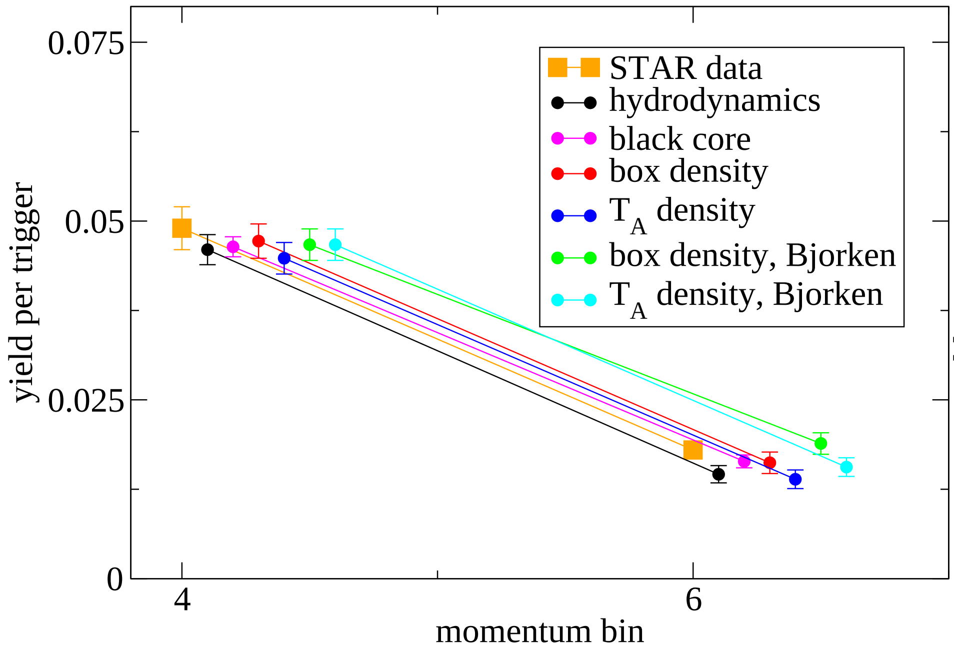
- intrinsic k_T

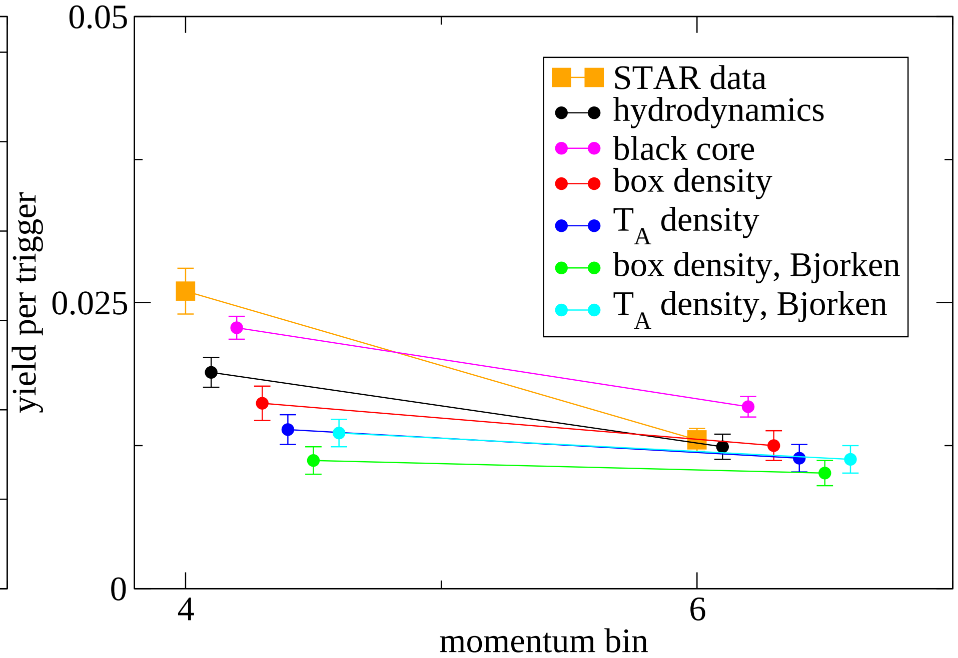
⇒ chosen such that d-Au width of far side peak is reproduced
⇒ away side probabilistic ΔE from in-medium path
⇒ near and away side (N)LO fragmentation
→ count emerging hadrons above associate threshold

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

Dihadron correlations

Yes, we understand the hard correlations (same is true for γ-h)!





Near side: Calculations agree well with data

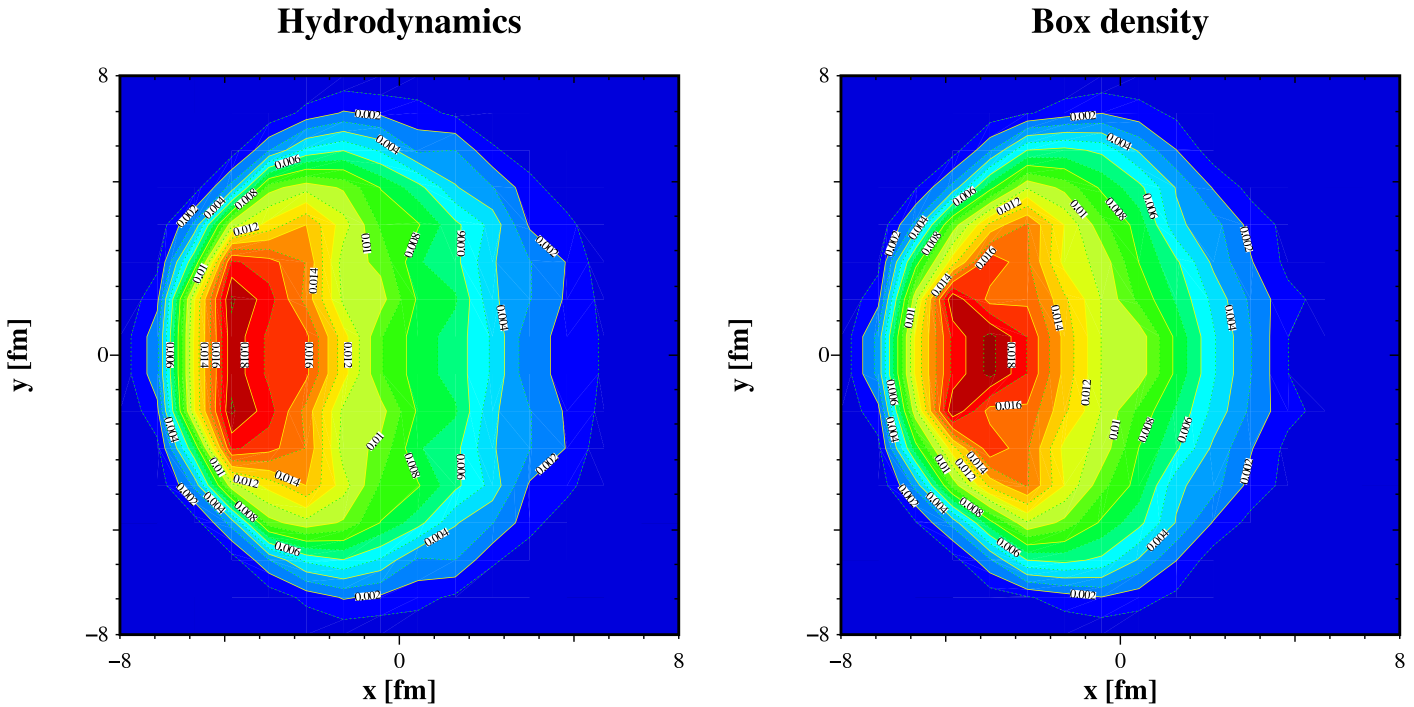
Away side: Deviations in the 4-6 GeV momentum bin → recombination

Largely insensitive to *details* of the medium density evolution.

T. R. and K. J. Eskola, Phys. Rev. C **75** (2007) 054910.

Sufrace bias

Probability density of triggered event vertices 8 GeV$< p_T <$15 GeV (near side $\equiv -x$):



$\Rightarrow$ Away side energy deposition and shockwave excitation happens

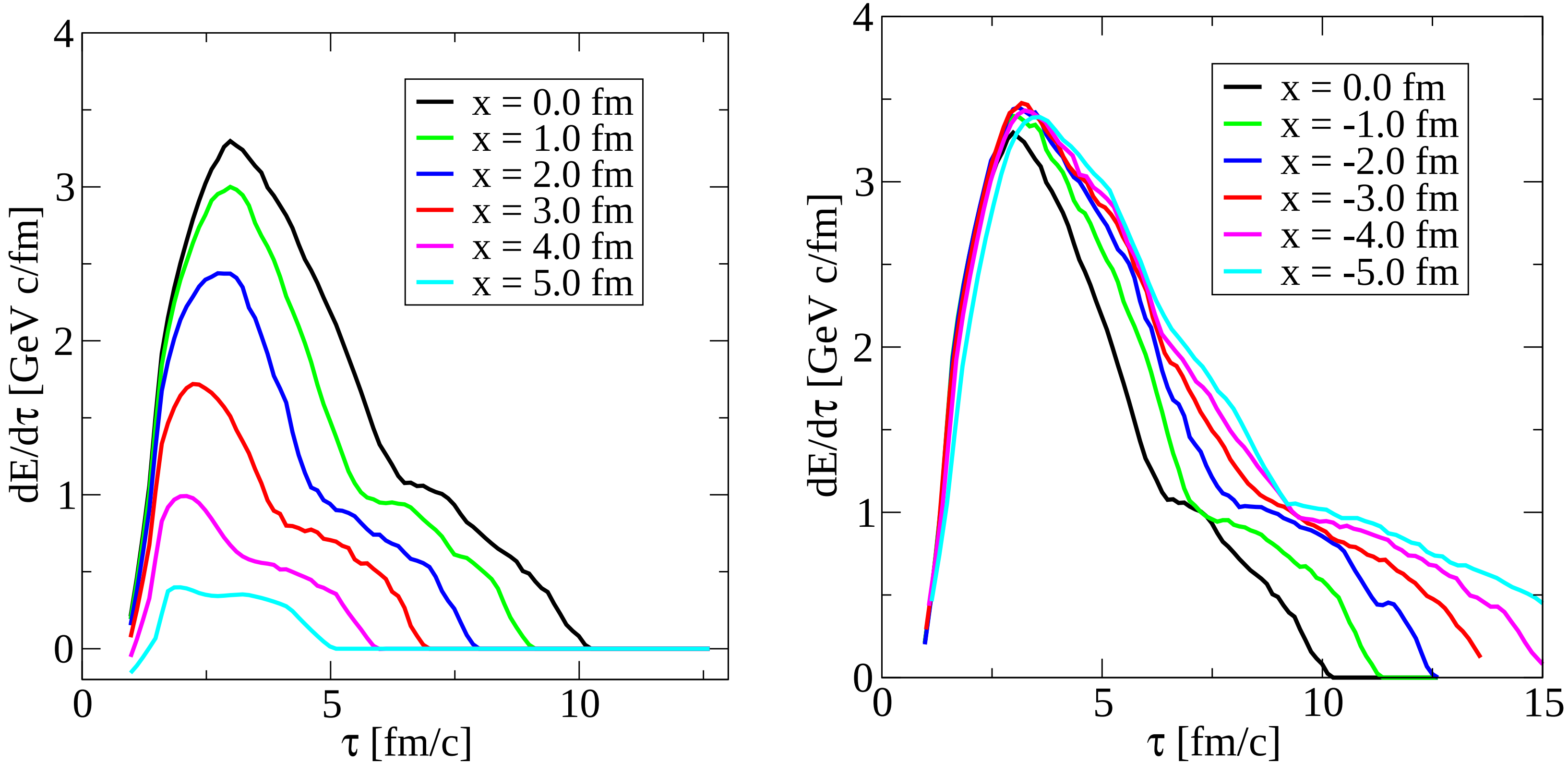
- in special density regime
- with a special orientation with respect to transverse flow

Needs to be accounted for *before* any data comparison!

T. R. and K. J. Eskola, Phys. Rev. C **75** (2007) 054910.

Surface bias

Time dependence of mean energy loss (quark jet for different vertex positions):



Initially: decoherence time Finally: dropping density

For most situations, energy will enter the medium between 2 and 4 fm/c

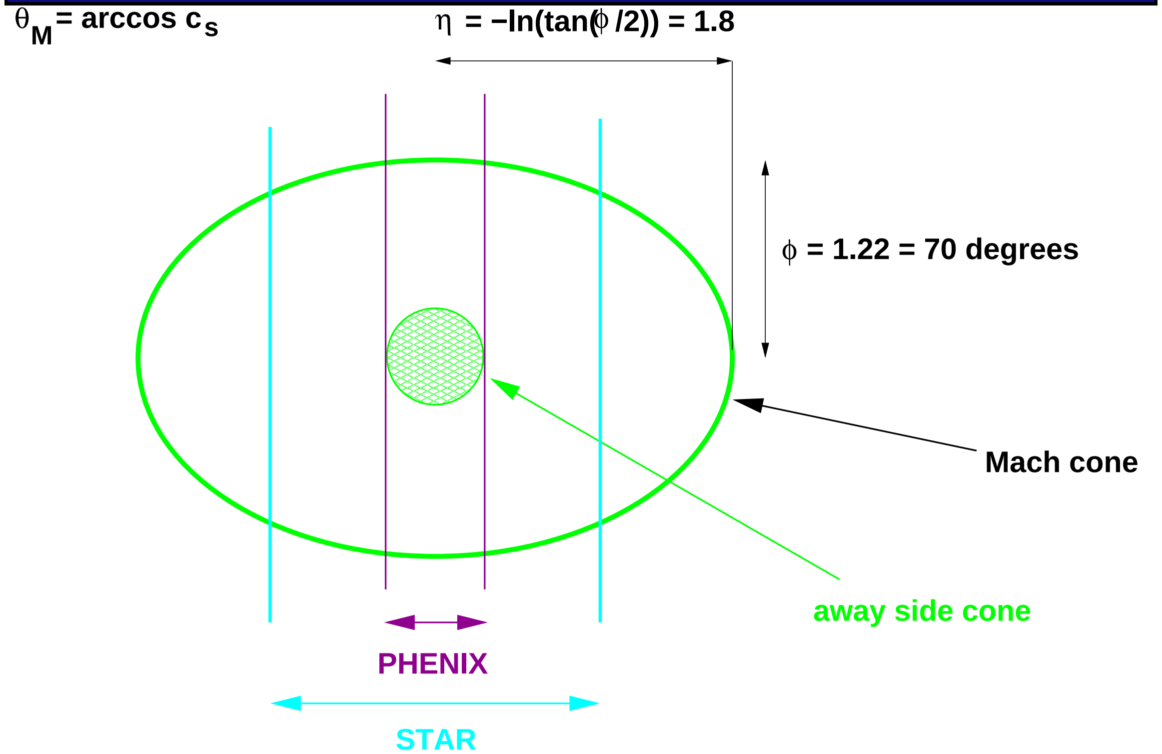
Flow effects

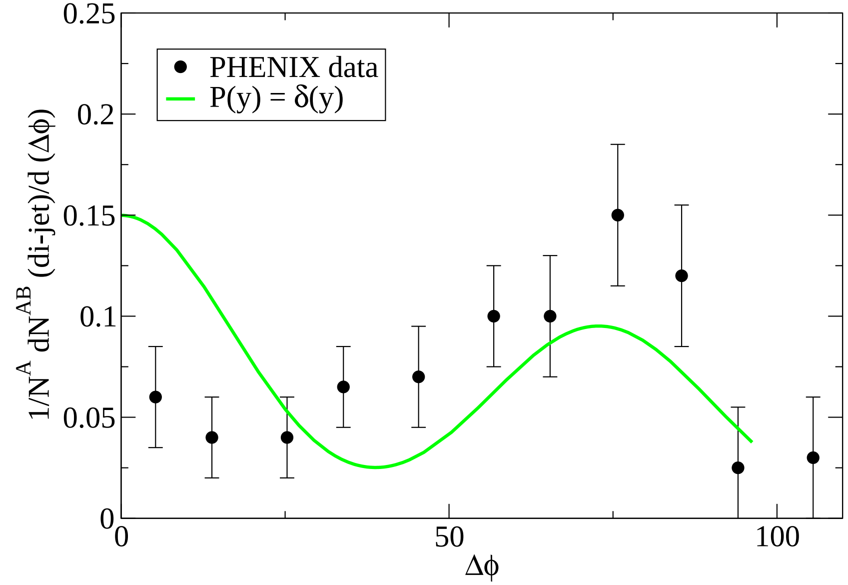
or:

The difficulty of observing a large angle signal *at all*

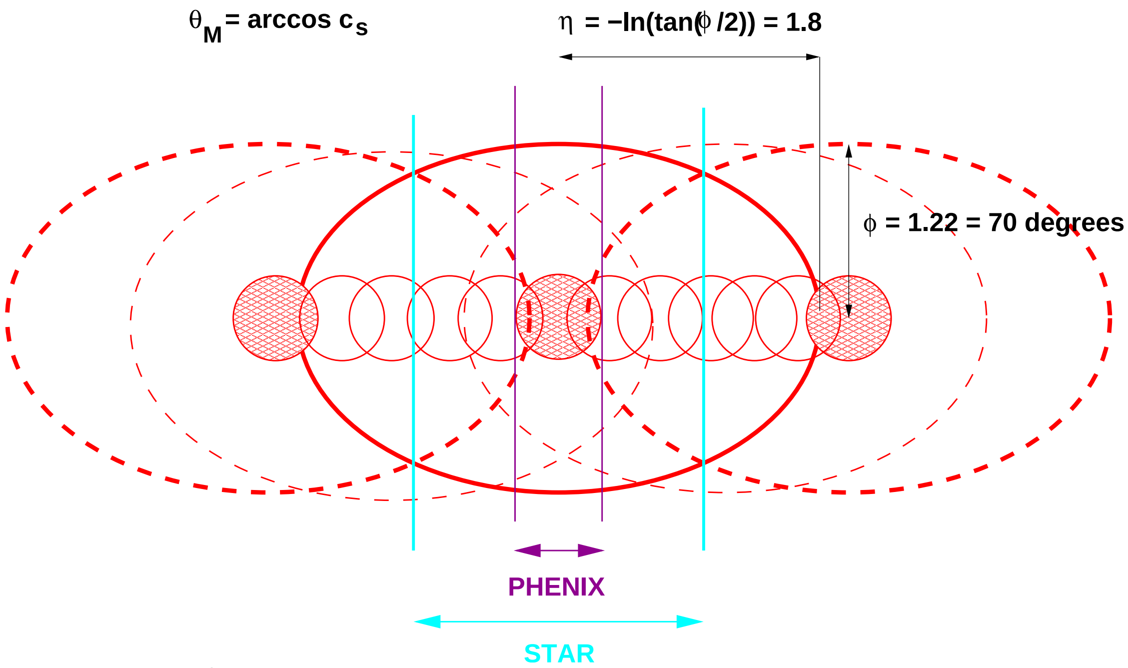
- rapidity of the away side parton
- longitudinal flow effects
- transverse flow effects

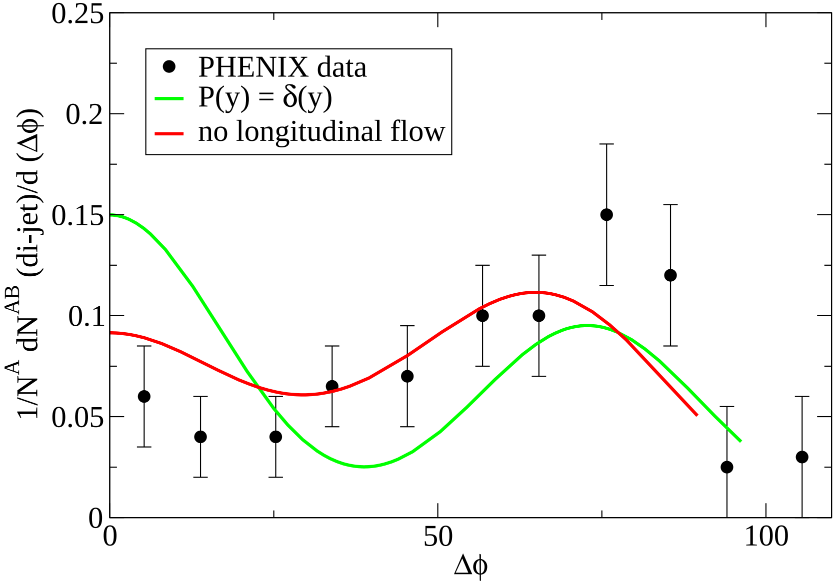
Away side parton at midrapidity



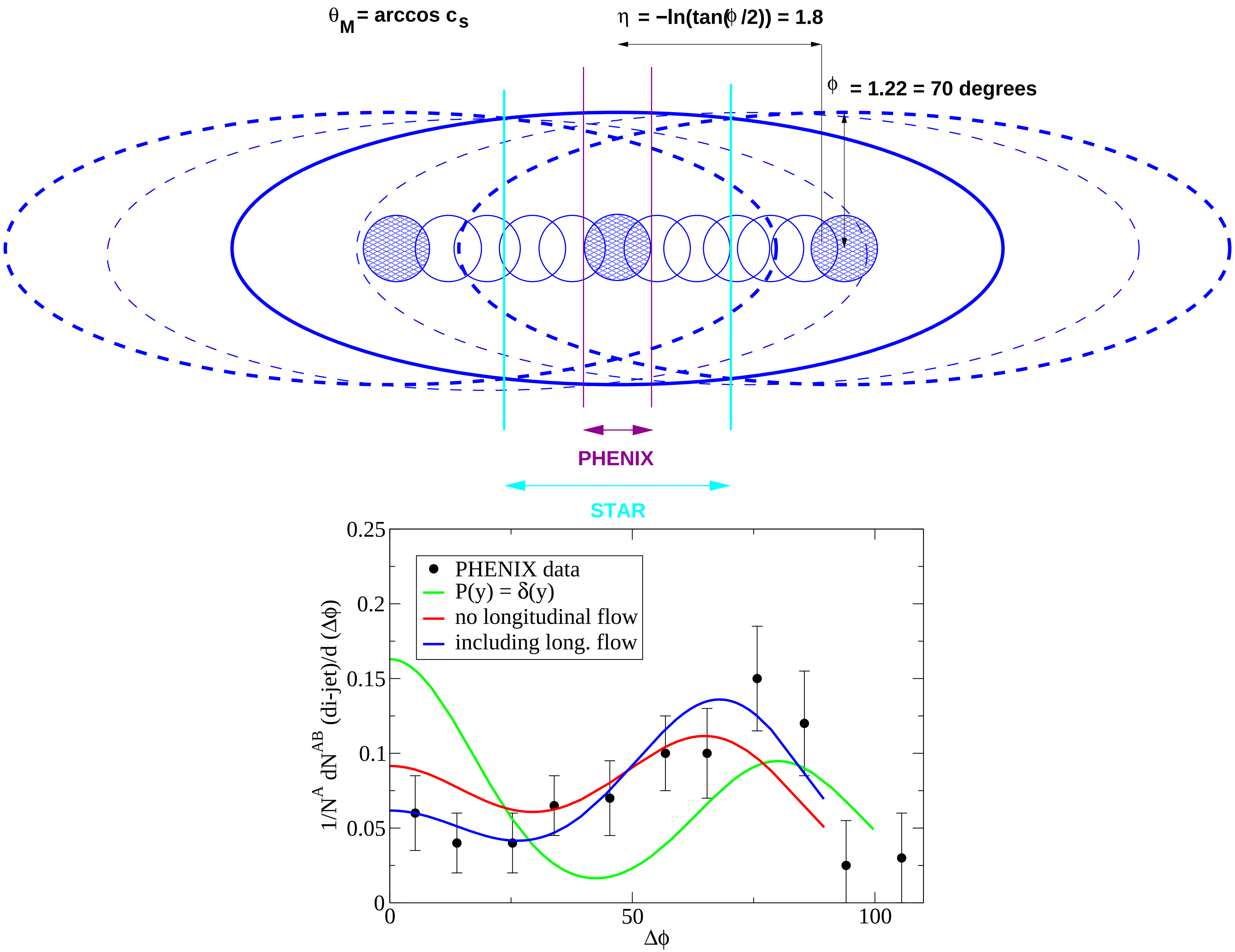


Rapidity-averaged away side parton





Including longitudinal flow

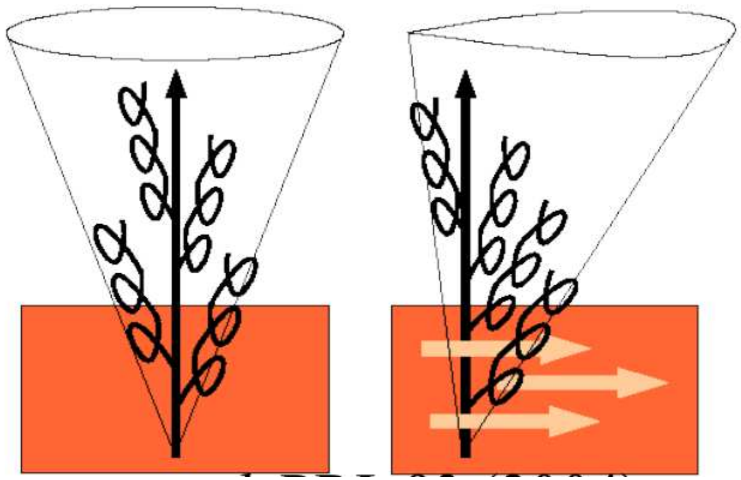


Longitudinal flow effects

Longitudinal elongation:

- *absolutely crucial* for observed large angle
- predicts *same* correlation angle at large y for trigger at $y = 0$

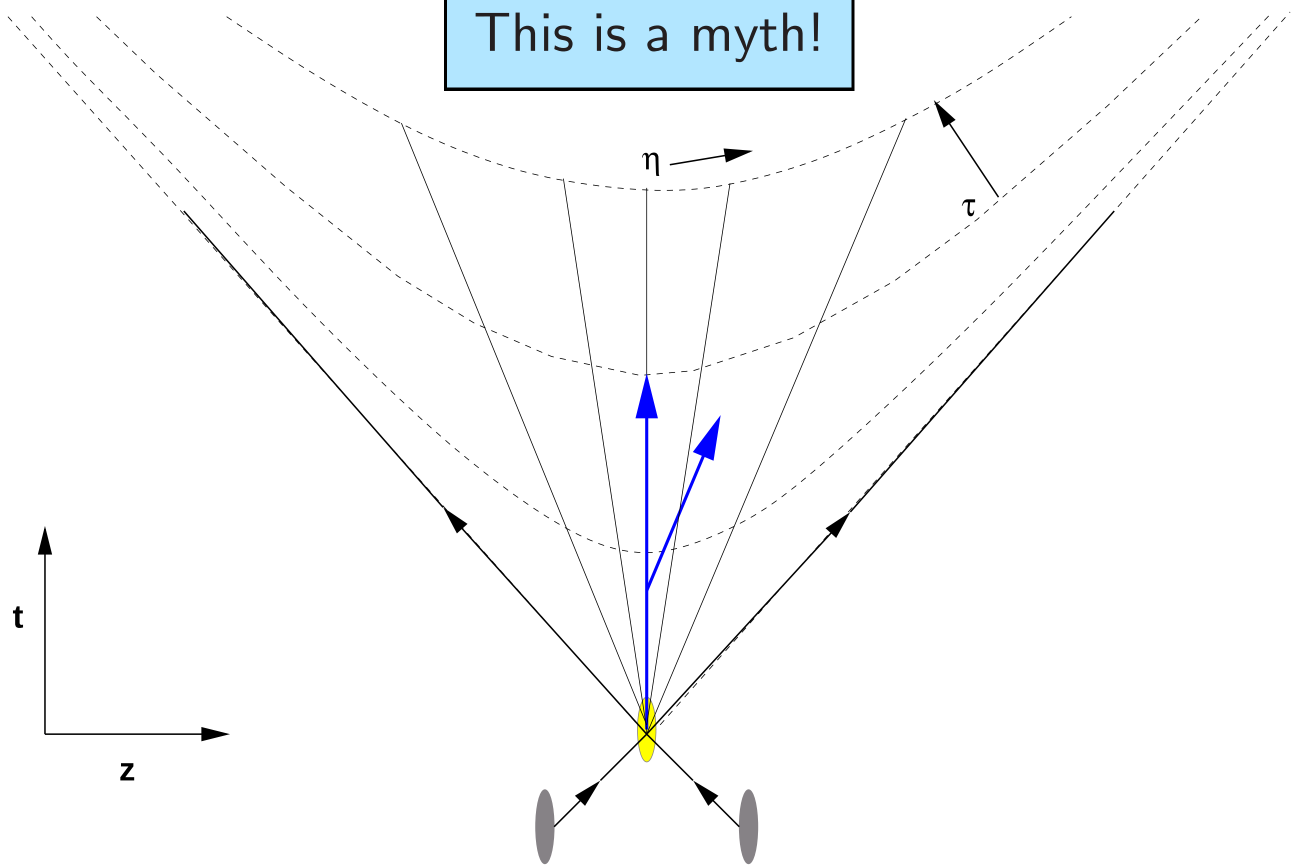
Intuitive picture: longitudinal flow drags radiated quanta to higher rapidity



Would work for Cherenkov radiation, medium modified jets. . .

Longitudinal flow effects

This is a myth!



position on hyperbola ↔ spacetime rapidity
line slope ↔ momentum rapidity

For any emission after initial collision, local Bjorken flow is *slower* than emitted quanta

⇒ *collimation* in rapidity, not widening

ONLY SHOCKWAVES GO WITH THE FLOW

This is not so for shockwaves:

Shockwaves propagate with c_s *relative to the local medium*

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

$\Rightarrow$ longitudinal flow field at z_{final} determines boost in momentum space

$\rightarrow$ this leads to propagation in rapidity space

Elongation *only* for excitation propagating *relative to the medium*!

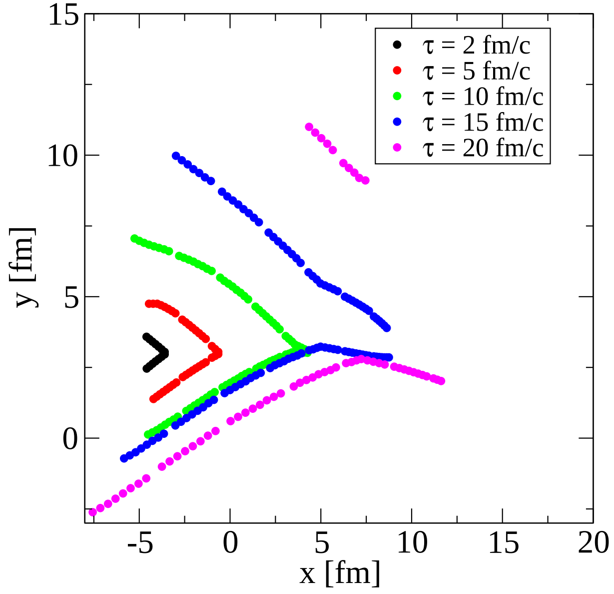
- no longitudinal elongation for modified jets
- no longitudinal elongation for Cherenkov radiation

(also rules out most explanations for near side ridge)

Transverse flow

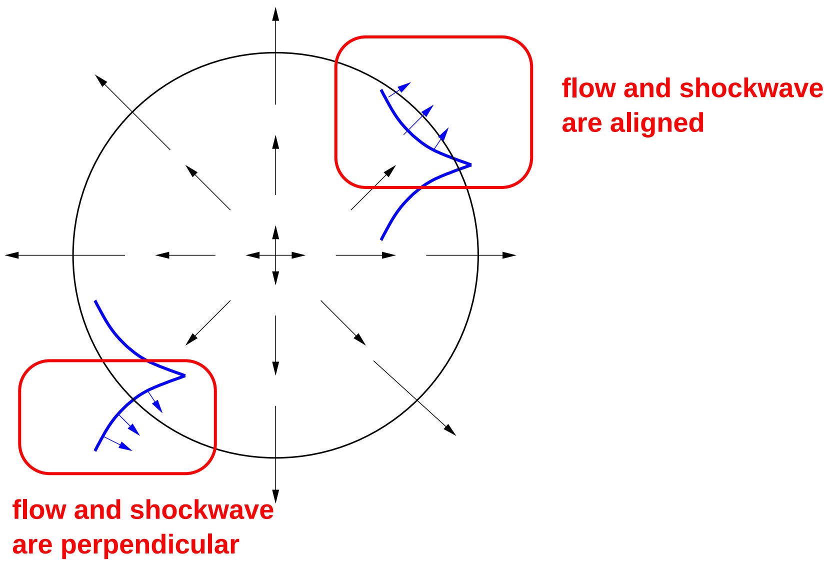
shockwave ⇔ additional boost for hadrons at freeze-out

Position space:



Momentum space:

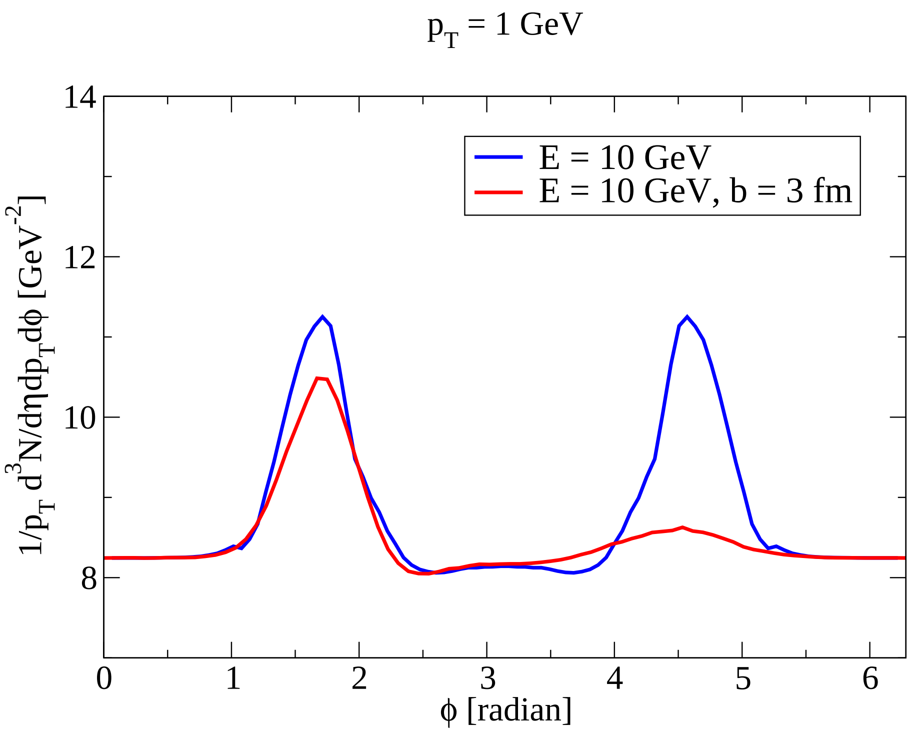
$$E\frac{d^3N}{d^3p} = \frac{g}{(2\pi)^3}\int d\sigma_\mu p^\mu \exp\left[\frac{p^\mu(u_\mu^{flow}+u_\mu^{shock})-\mu_i}{T_f}\right]$$

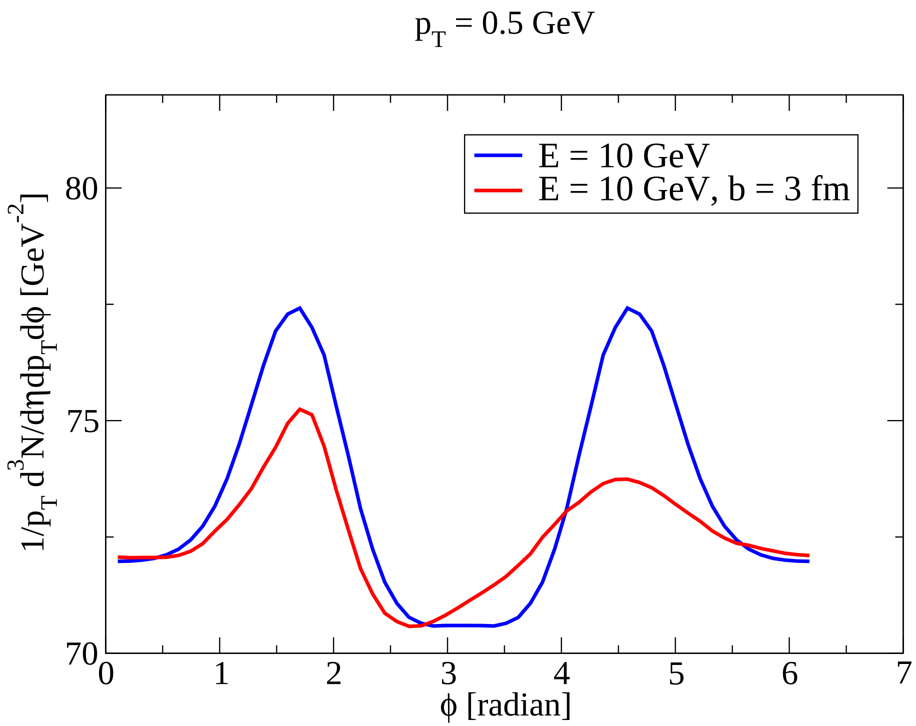


At 1 GeV, a Mach signal only appears if shockwave and flow are aligned

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

Transverse flow





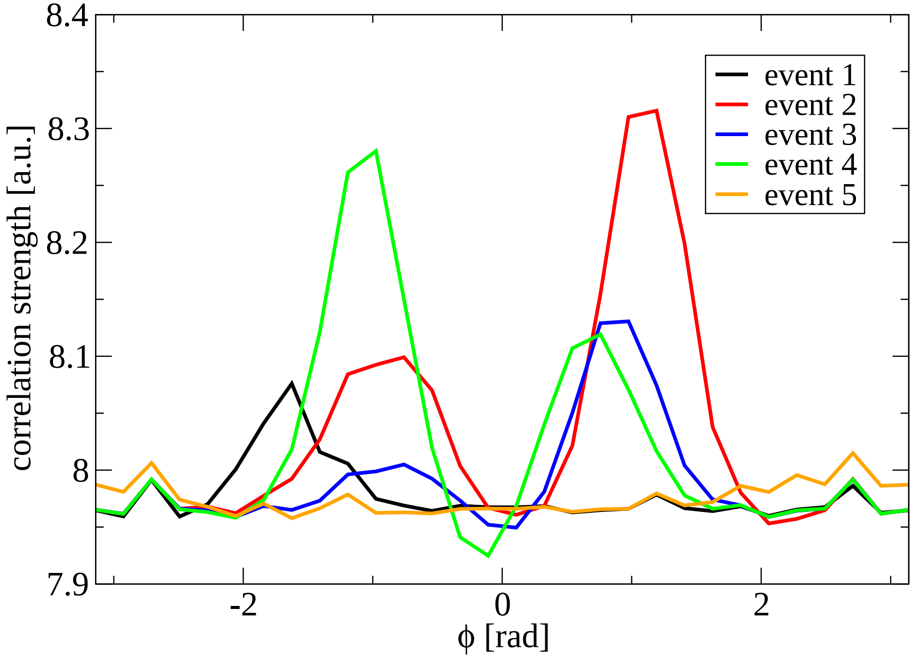
- at high p_T, if flow and shockwave are not aligned one of the wings vanishes
- due to momentum conservation, it reappears (broadened) at lower p_T

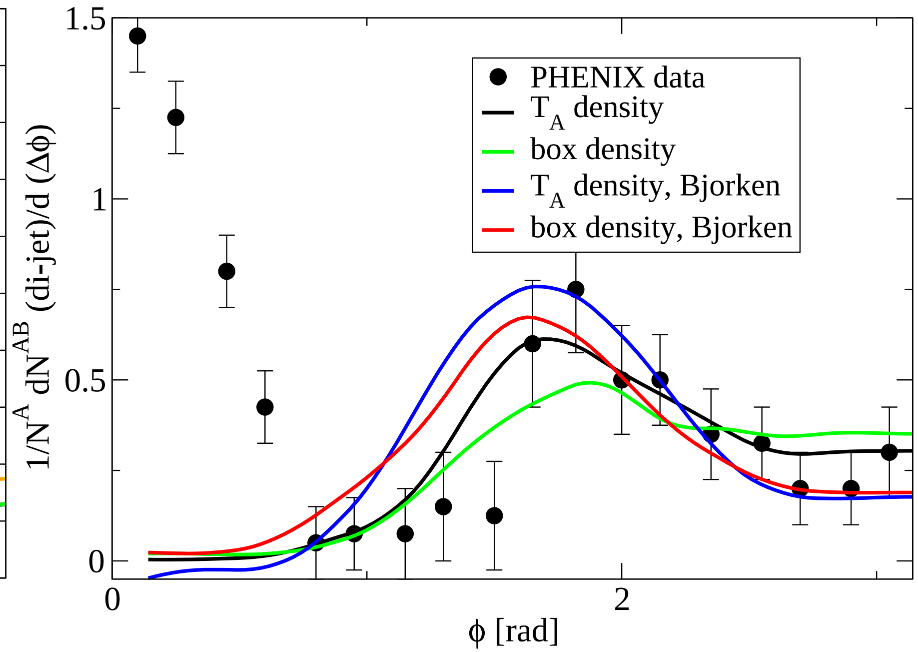
Strong bias towards events in which flow and shockwave are aligned

The combined bias

We find *surface bias* in position space and *alignment bias* in momentum space
→ but in hydrodynamics, position and flow are correlated!

⇒ wild event by event fluctuations, strong dependence on hydro background



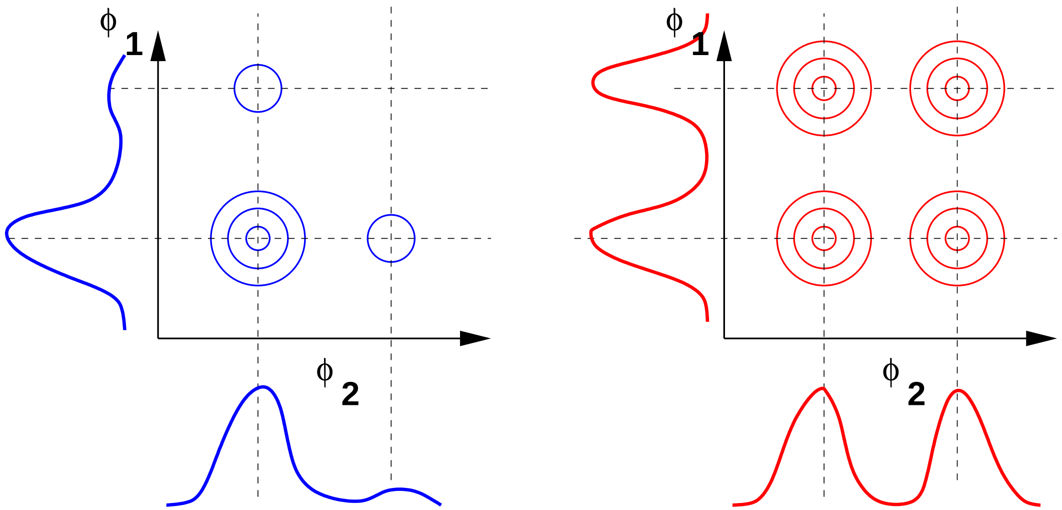


Don't even think of extracting c_s by simply inverting the angle!

→ requires self-consistent treatment of wave propagation and hydro background

3-PARTICLE CORRELATIONS

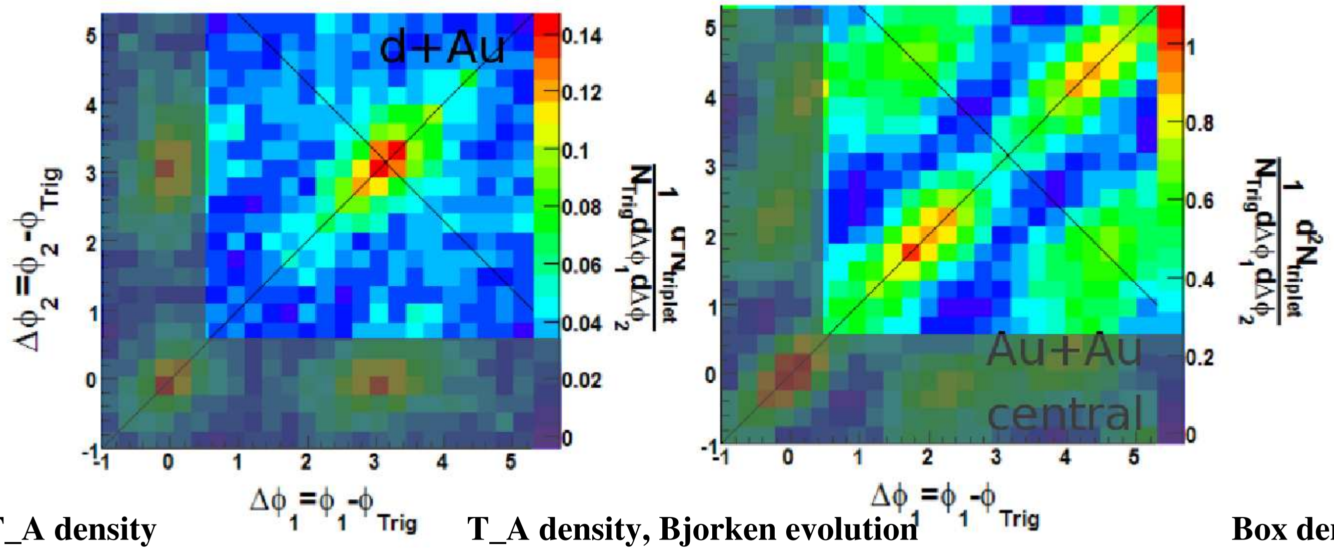
Calculated as factorized 2-particle correlations (no true 3-particle correlations)



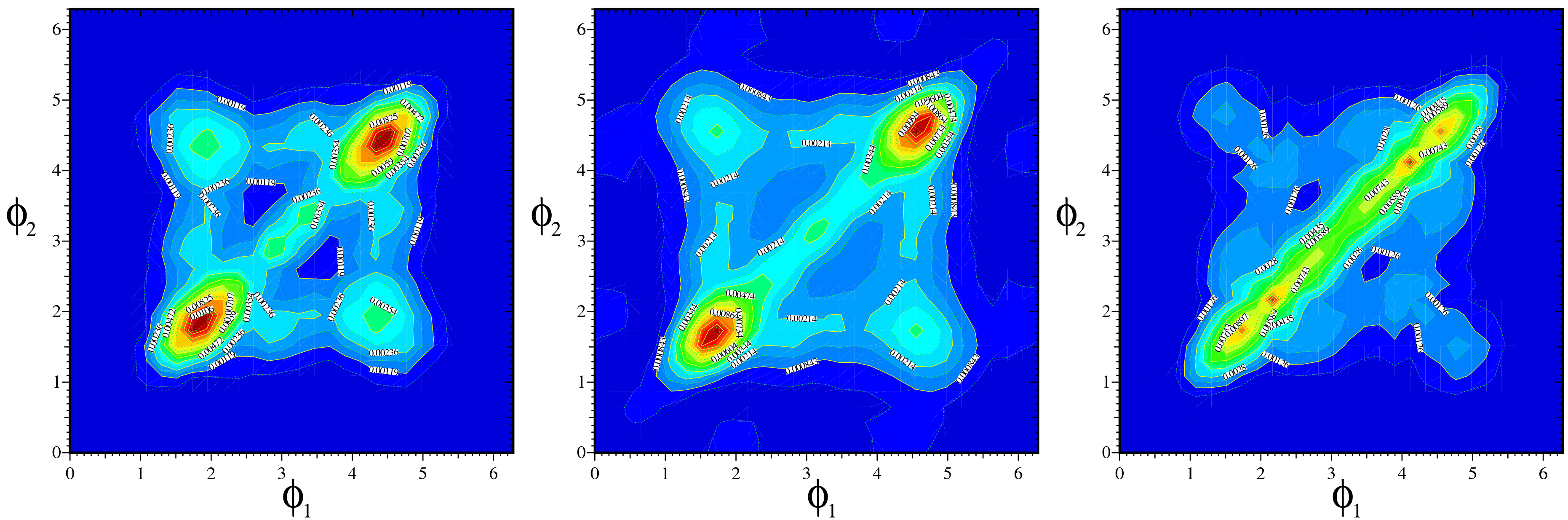
- calculated background subtracted
- each particle from shockwave is correlated with away side parton
- no correlations among particles in shockwave

(in reality: momentum conservation shared among $O(20+)$ particles)

3-PARTICLE CORRELATIONS



T_A density **T_A density, Bjorken evolution** **Box density**



T. R. and J. Ruppert, Phys. Rev. C **76** (2007) 014908.

Cone and Ridge

or:

A few things which can not cause a ridge

- connection to energy loss
- dihadron triggers

What is the ridge?

Difference between near and away side: average pathlength $\langle L \rangle$

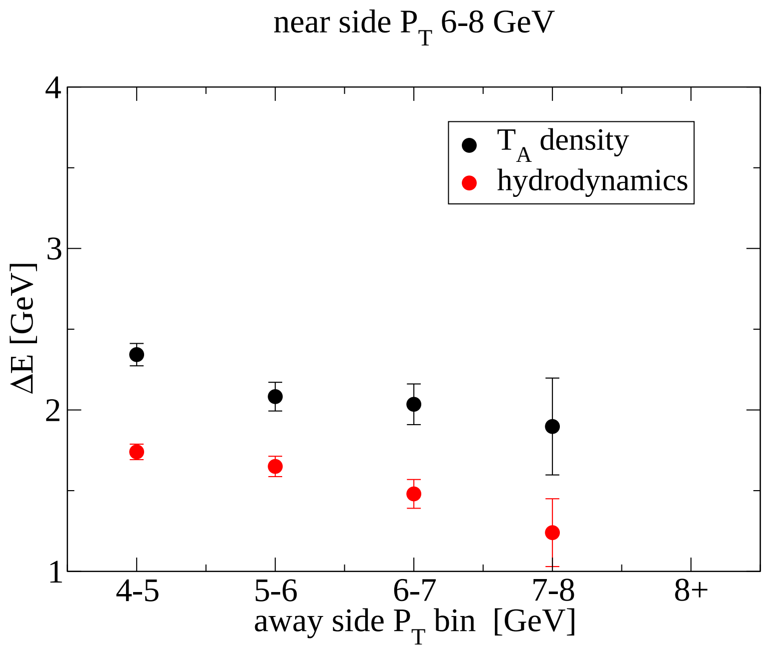
If both ridge and cone are connected to energy loss, either

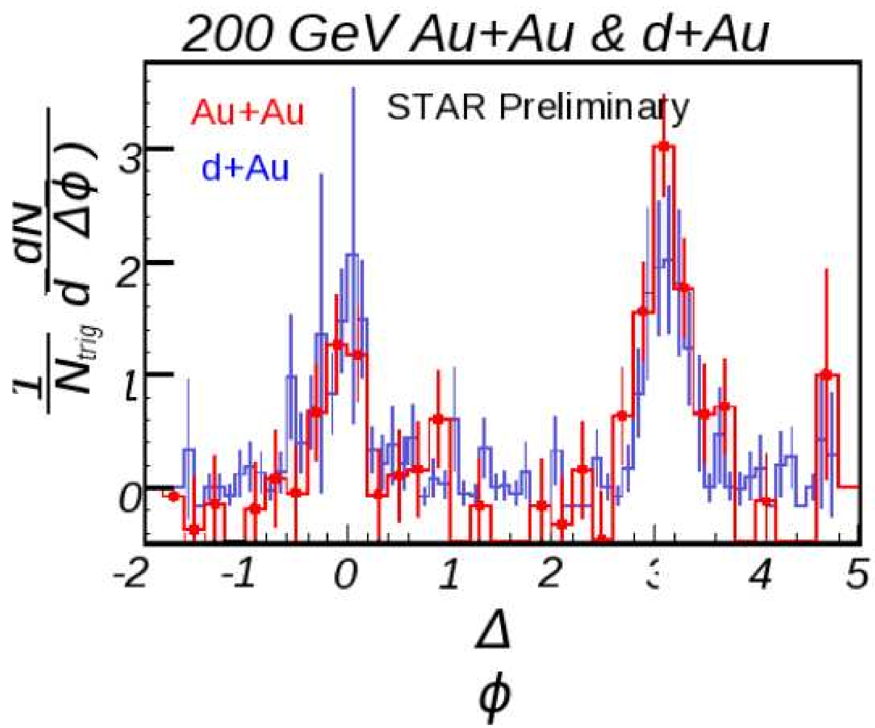
- Ridge and cone are the same phenomenon, i.e. the ridge is a cone which had too little time to develop (the bow shock). In this case, varying $\langle L \rangle$ should turn the ridge into the cone.
- Ridge and cone are separate phenomena. In this case, the ridge is hidden on the away side by the fact that the rapidity position of the away side parton is not known. In addition, there must be a minimum length $\langle L \rangle$ for the cone to develop, because it is not seen on the near side.

A back-to-back dihadron trigger can fix the rapidity of the away side parton and (for asymmetric momenta) allows to dial $\langle L \rangle$ on near and away side.

Dihadron triggers?

Shockwave strength scales with energy deposition *given the trigger*





$\longrightarrow$ this is reduced drastically ($\sim 1/6$) for a dihadron trigger

$\Rightarrow$ currently, away side NL fragmentation should dominate

T. R., Phys. Rev. C **78** (2008) 014903

Is the ridge connected with energy loss?

Connecting the ridge with energy loss faces problems:

• energy balance:
- energy in ridge: 'several GeV' $\leftrightarrow$ $\langle \Delta E \rangle$ given near side trigger: ~ 0.5 GeV
$\Rightarrow$ impossible for direct radiation, but maybe boost of matter?

• timescales:
- lost energy becomes available comparatively late (2-4 fm after medium production)
$\Rightarrow$ very difficult to get correlation to large y

• rapidity width:
- no longitudinal elongation for radiated quanta (most mechanisms assume this!)
$\Rightarrow$ how does the correlation get to large y?

At this point, cone and ridge seem to be distinct phenomena.

Ridge $\leftrightarrow$ initial state effect?

Conclusions

Qualitatively, Mach cones agree with findings

- independence of angle $\leftrightarrow$ complicated bias
- widening in rapidity predicted and seen
- qualitative agreement for three-particle correlations

$\Rightarrow$ no other model has demonstrated this so far

Quantitative calculations are *extremely* tough!

- complicated simulation of trigger bias
- same EOS for density and shockwave evolution
- multiple shockwaves from minijets?
- proper hydro source term?

$\Rightarrow$ reasonably, we can only expect quantitative answers *after* solving the nature of energy loss (and a few other things)