Mach cones and dijets

- jet quenching and fireball expansion dynamics

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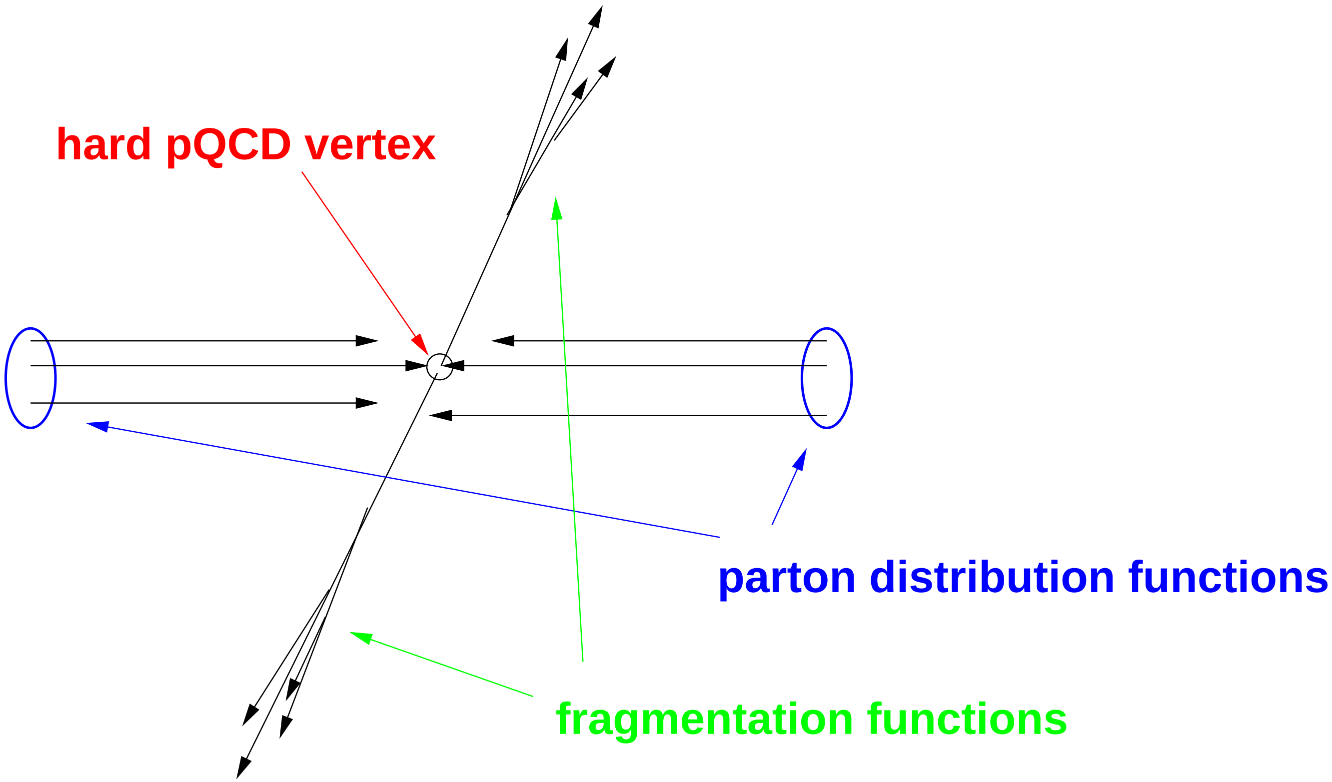
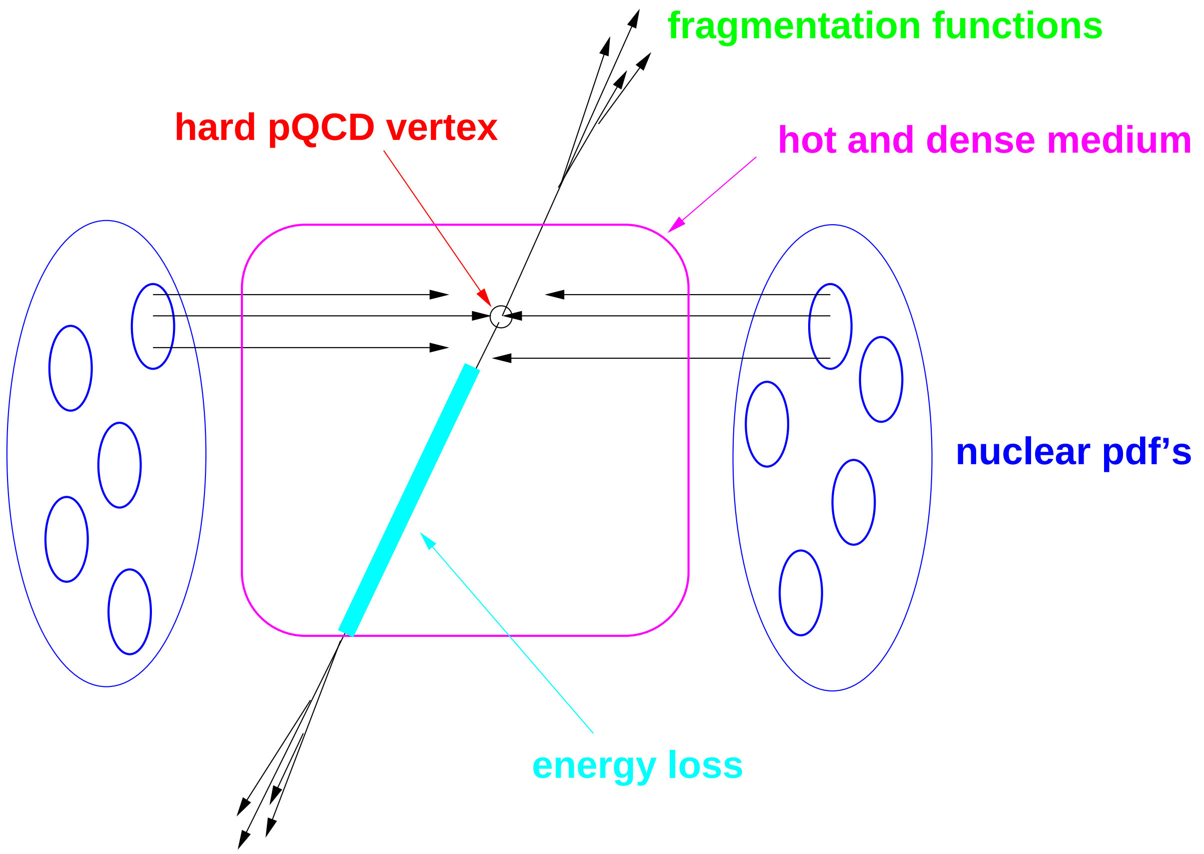
Introduction
What information is in R_{AA}?
Semi-hard correlations
- Mach cones, Cherenkov radiation or . . . ?
Towards the hard trigger
- the question of excitation functions
Hard physics
- jets punching through the medium
Conclusions

Hard p-p collisions



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

Hard Au-Au collisions



$$d\sigma_{med}^{AA\to\pi+X} = \sum_{f} d\sigma_{vac}^{AA\to f+X} \otimes P_f(\Delta E) \otimes D_{f\to\pi}^{vac}(z,\mu_F^2)$$

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

What information is in R_{AA}?

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

is (in the fragmentation region) uniquely determied by

$$p_{out} = p_{in} \otimes \langle P(\Delta E, E) \rangle \otimes D^{vac}_{f \to \pi}(z, \mu_F^2)$$

$\langle P(\Delta E, E) \rangle$: energy loss probability averaged over unobserved quantities
$\Rightarrow$ vertex position, parton direction, path length, bulk matter model

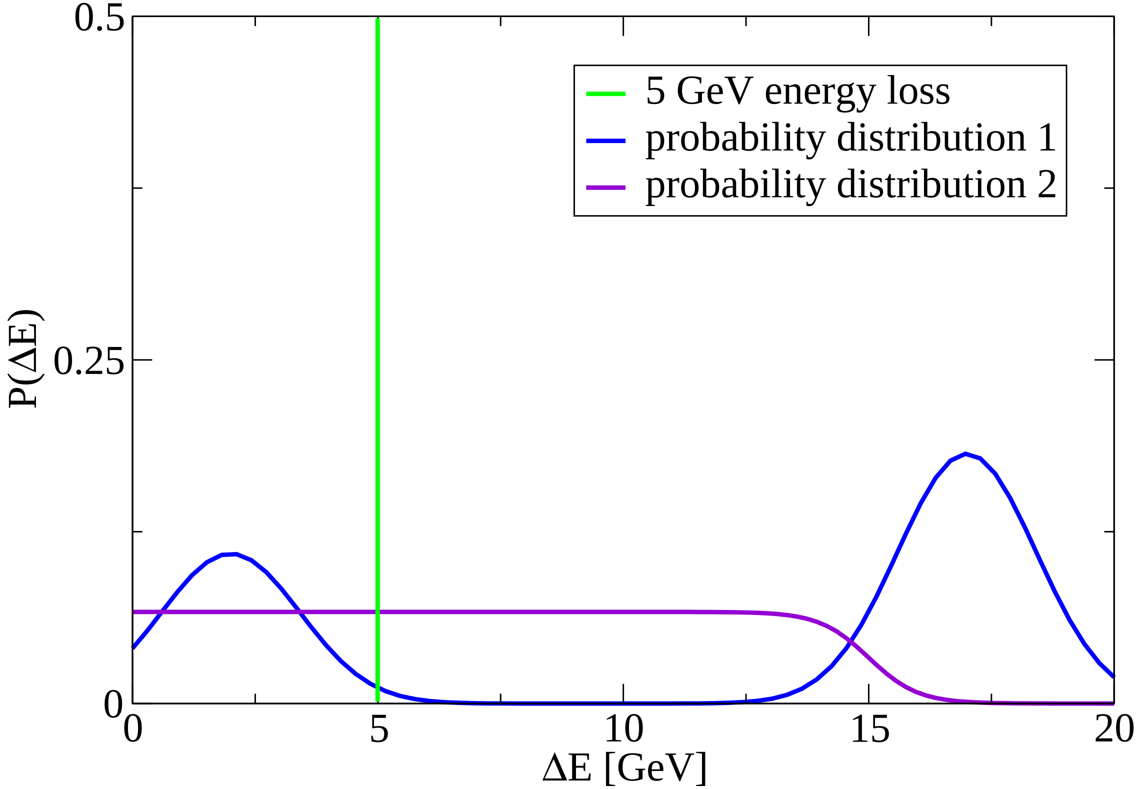
- calculable for any framework by $\langle$energy loss mechanism $\otimes$ medium model$\rangle$
- measurable for quarks

$\rightarrow$ photon tagged jets from $qg \rightarrow q\gamma$ to fix p_{in}
$\rightarrow$ unfolding with $D^{vac}_{q \to \pi}(z, \mu_F^2)$ yield $\langle P(\Delta E, E) \rangle$

R_{AA} constrains averged energy loss probability distributions!

How well does R_{AA} in constraining $\langle P(\Delta E, E)\rangle$?

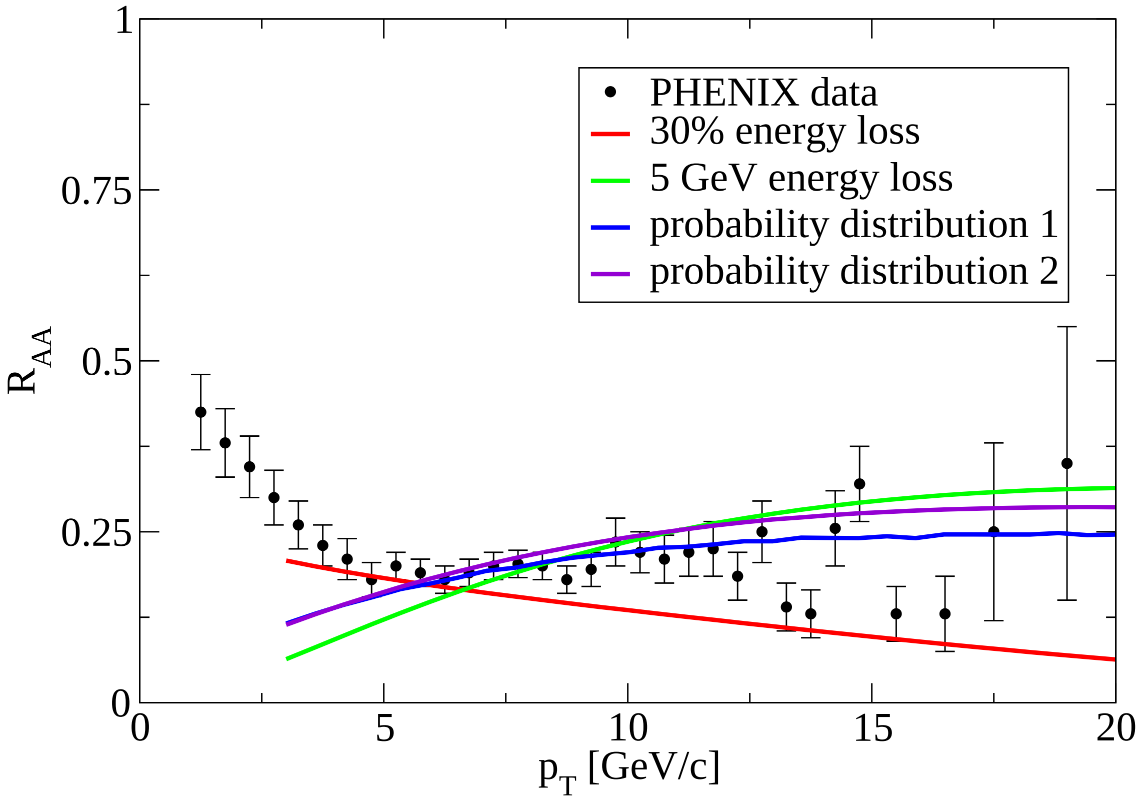
Consider some very different energy loss probabilities:



(with the understanding that a parton with less than 500 MeV energy is absorbed into the medium)

How well does R_{AA} in constraining $\langle P(\Delta E, E)\rangle$?

R_{AA} does not strongly constrain the energy loss probability distribution:



usually 1-parameter tuning brings a trial $\langle P(\Delta E, E)\rangle$ distribution to the data:

but: quenching has to be substantial!

How large is the quenching?

- Dynamical evolution $\Leftrightarrow$ transport coefficient $\hat{q}$ is different at each spacetime point
- pQCD does not predict $\hat{q}$ (only relation between ϵ and $\hat{q}$)

$\Rightarrow$ can't characterize scenario by a single value of $\hat{q}$

K-factor: $\hat{q}(\eta, r, \phi, \tau) = K \cdot 2 \cdot \epsilon^{3/4}(\eta, r, \phi, \tau)$

as a measure for the discrepancy from pQCD expectations

For reasonable models, the $K-$factor can vary a factor 5 (from about 1 to 5) dependent on detailed assumptions about flow and α_s!

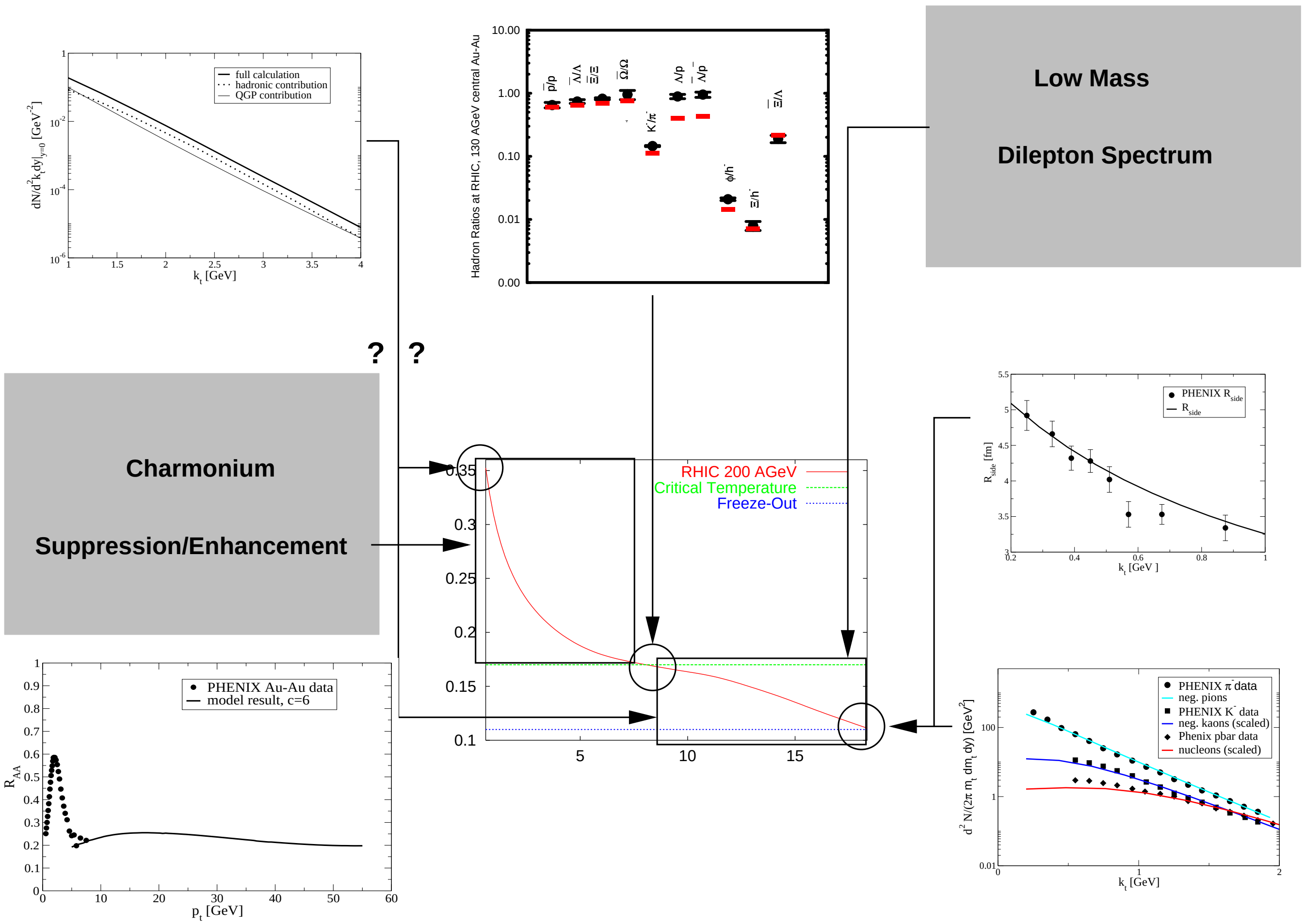
T.R. and J. Ruppert,Phys.Rev.C72:044901,2005

Constraining the model and more differential observables are crucial!

In this talk: Parametrized fireball evolution $(K = 1.5, \alpha_s = 0.45)$ and hydrodynamics $(K = 3.3, \alpha_s = 0.45)$, K adjusted to describe R_{AA}

Part I

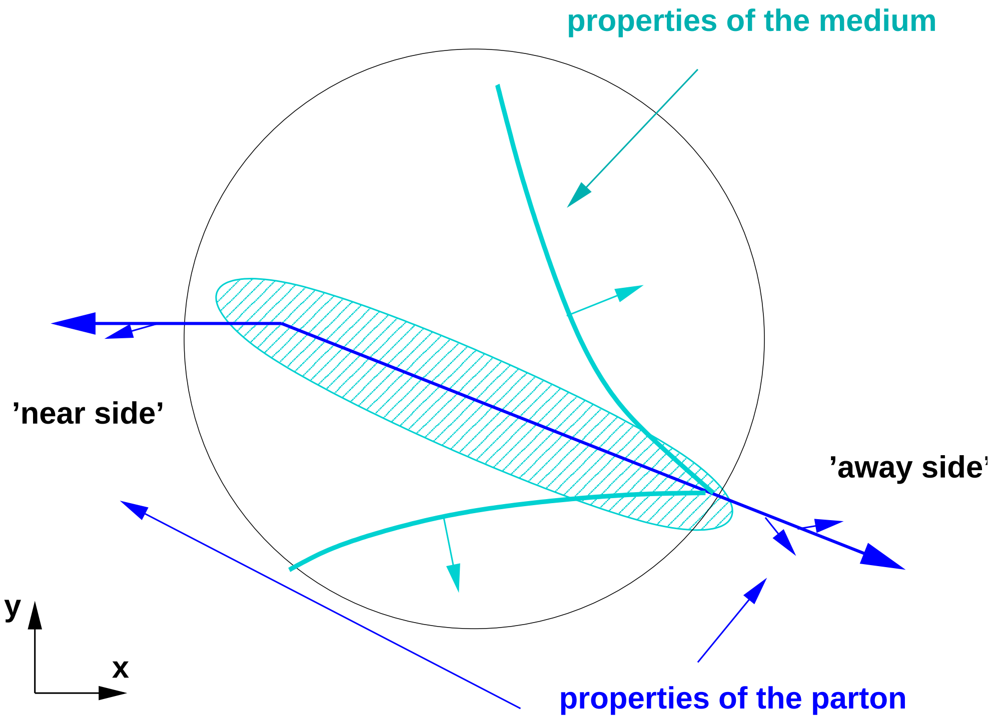
The model



THE MODEL

Energy can't be 'lost' - it must reappear somewhere:

Assume a large fraction of lost parton energy excites a shockwave in the medium



- 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

The model

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

$$E = c_s p \quad \text{with} \quad c_s^2 = \partial p(T)/\partial \epsilon(T) \quad \text{from EOS} \quad \Rightarrow \qquad \phi = \arccos \frac{\int_{\tau_E}^\tau c_s(\tau) d\tau}{(\tau - \tau_E)}$$

Sound propagates in the (locally moving) fluid

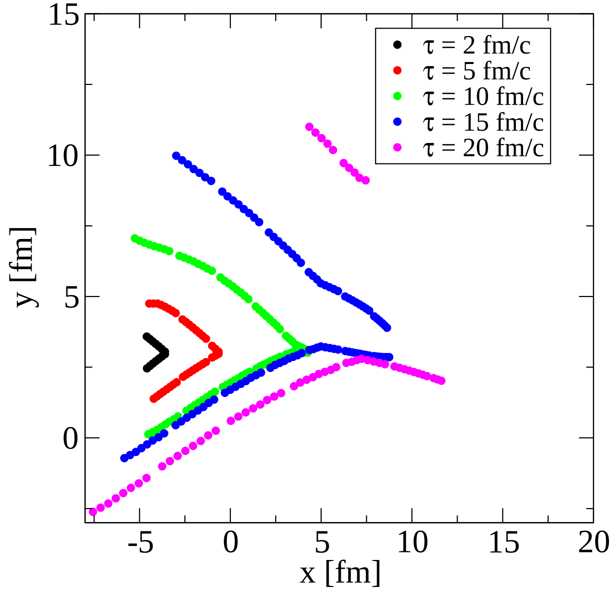
$\Rightarrow$ boost with local flow rapidity

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

The model

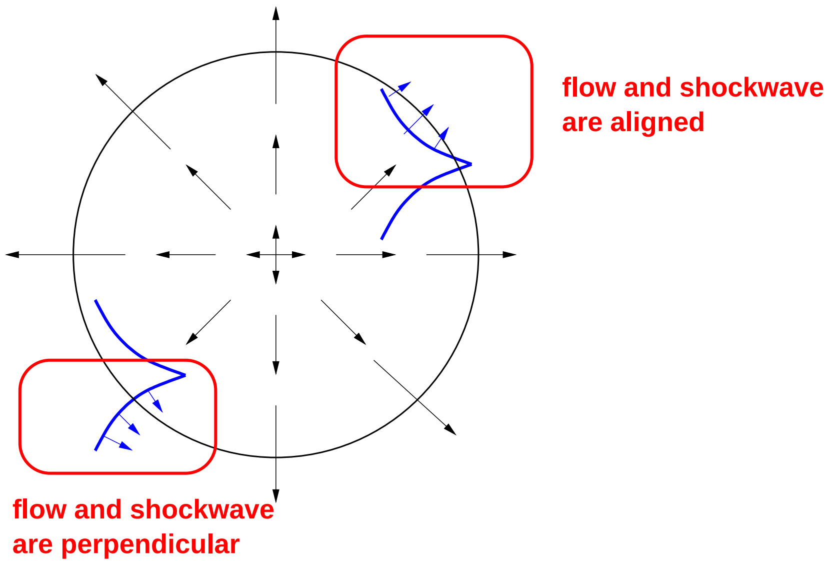
Shockwave ⇔ additional boost for hadrons at freeze-out

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)

The model

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

→ track lost energy (shockwave) and/or emerging parton (dijets)

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

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

Part II

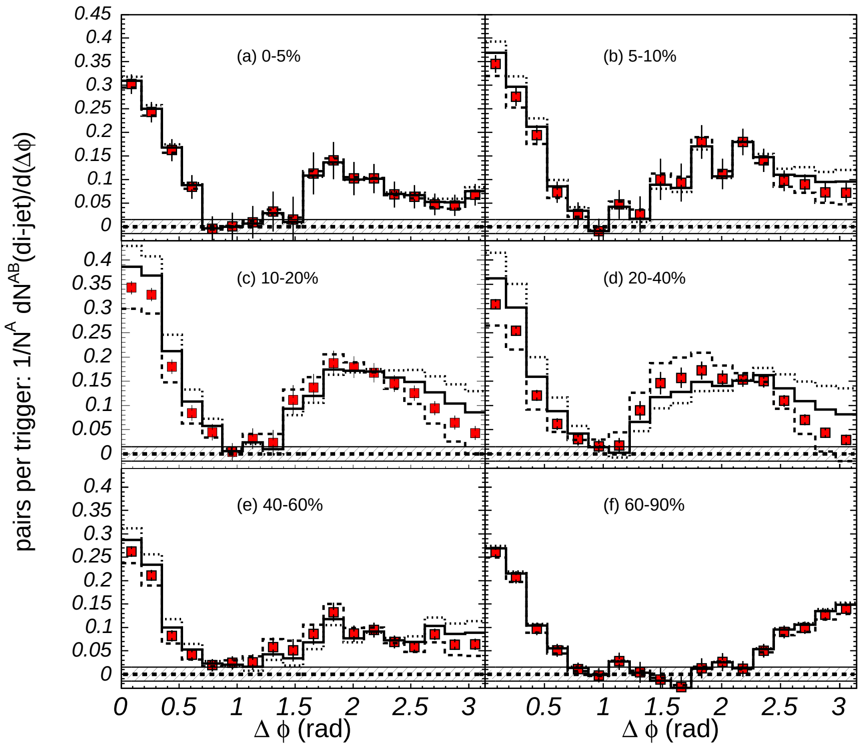
Semi-hard trigger and semi-hard associate hadrons - Mach shocks, Cherenkov radiation or something completely different?

"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 EVIDENCE

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

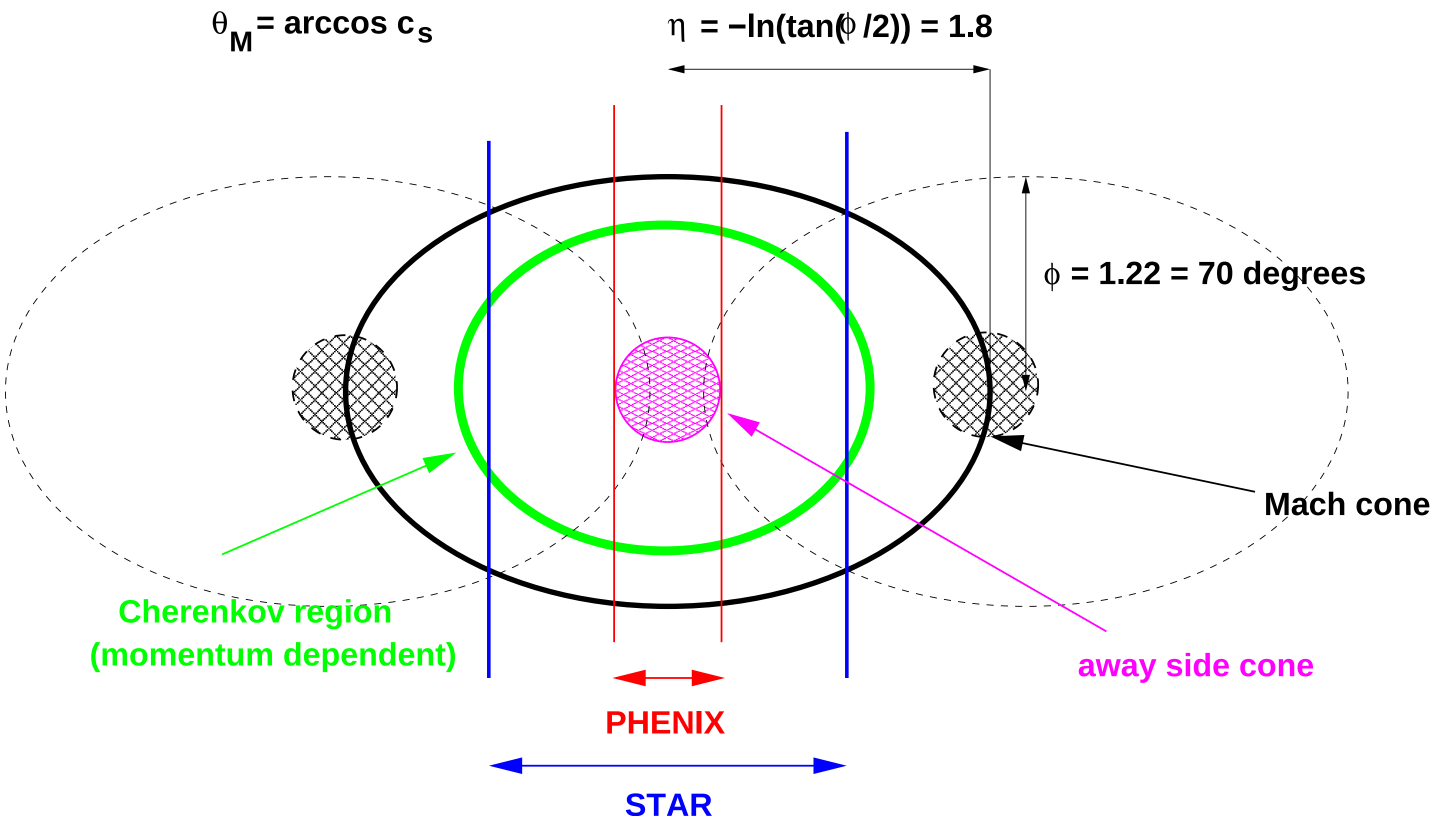


- central collisions: dip at expected position of away side jet
- position of correlation maximum consistent with Mach shock

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

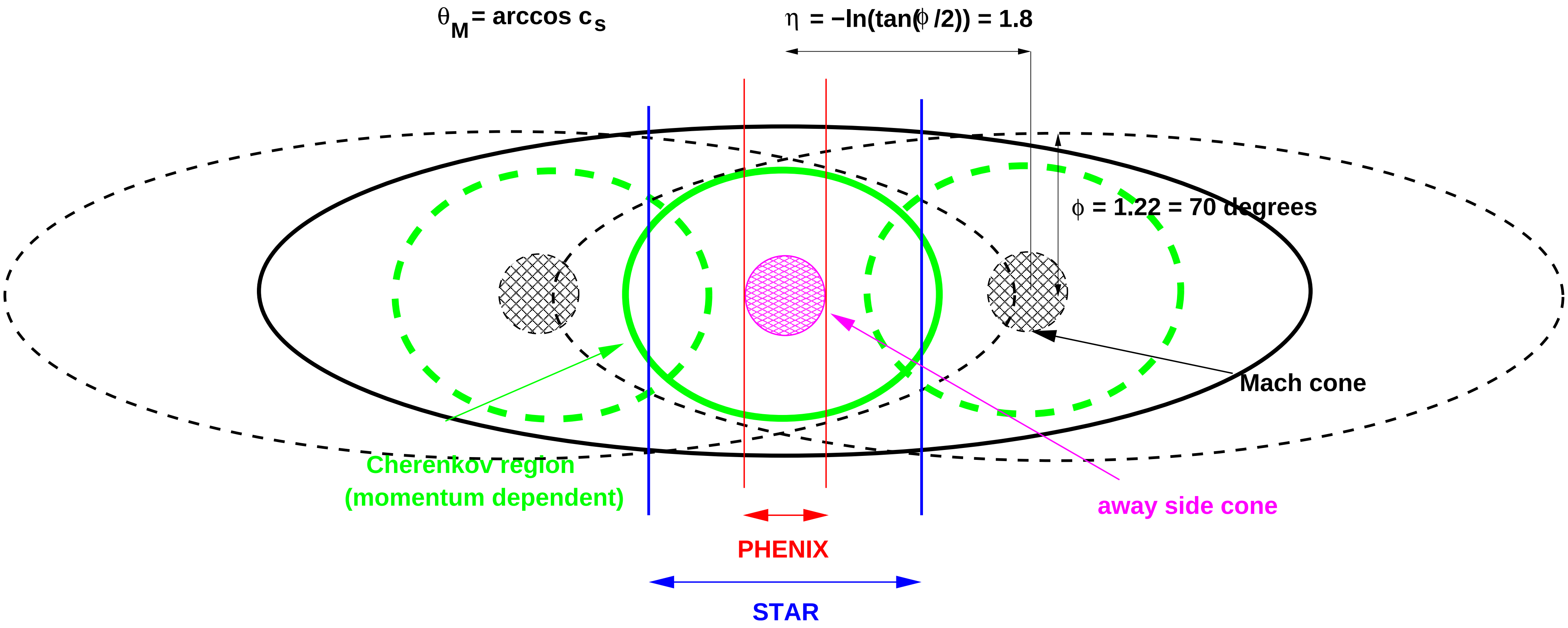
Why should there be a dip at all?

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



⇒ Why would there be any angular structure visible?

Because a shockwave goes with the flow!

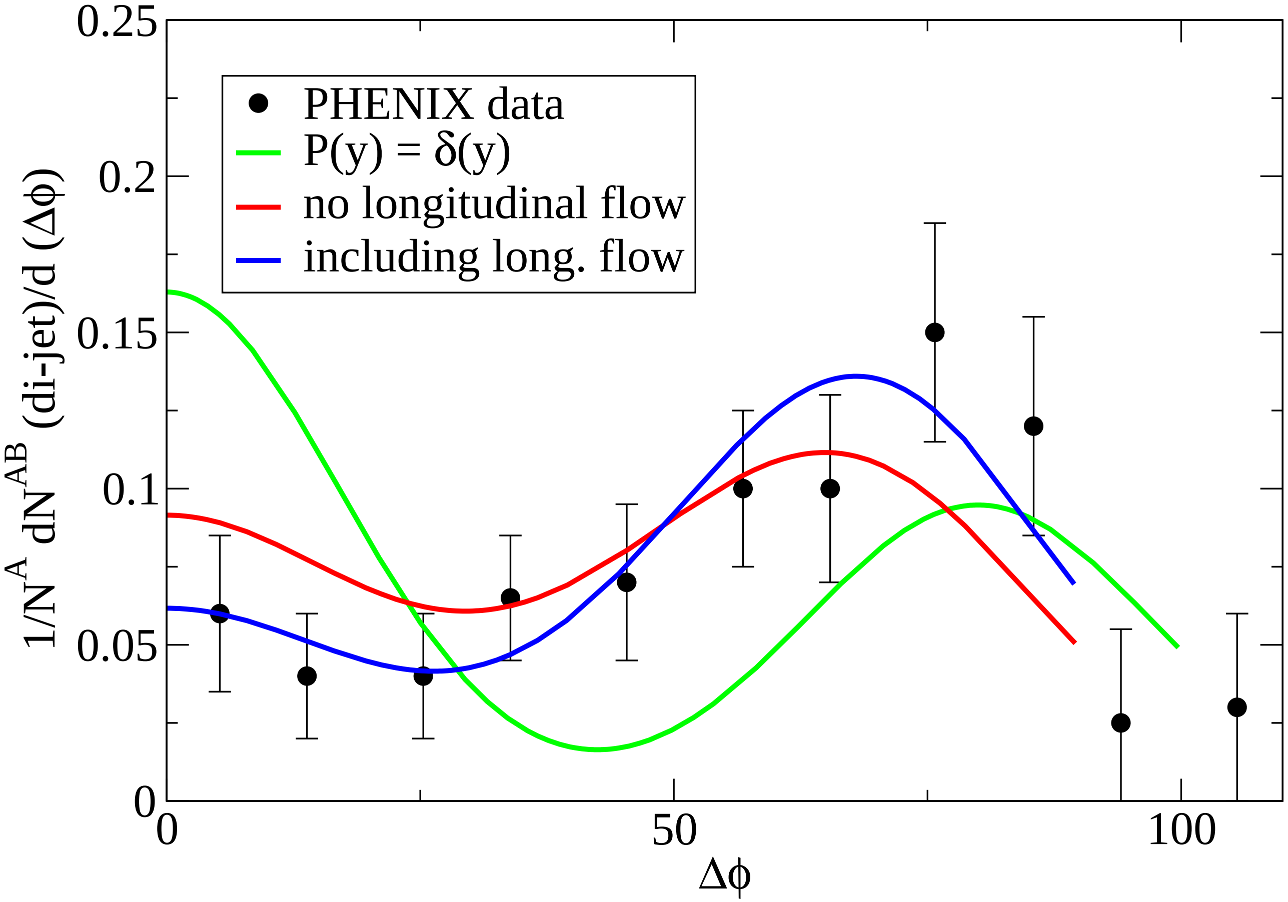


$$\frac{dz}{dt} = \left. \frac{u(z,R,t) + c_s(T(z,R,t))}{1 + u(z,R,t)c_s(T(z,R,t))} \right|_{z=z(t)}$$

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

Elongation only for excitation propagating relative to the medium!

Model results



- $P(y)$ shifts the correlation peak to smaller angles
- the elongation by flow is crucial to avoid this effect

⇒ If not a Mach cone, it should still better go with the flow!

Other good evidence for flow elongation, cf. 'ridge-correlation' on near side!

PART III

Hard trigger and semi-hard associate hadrons - a question of excitation functions.

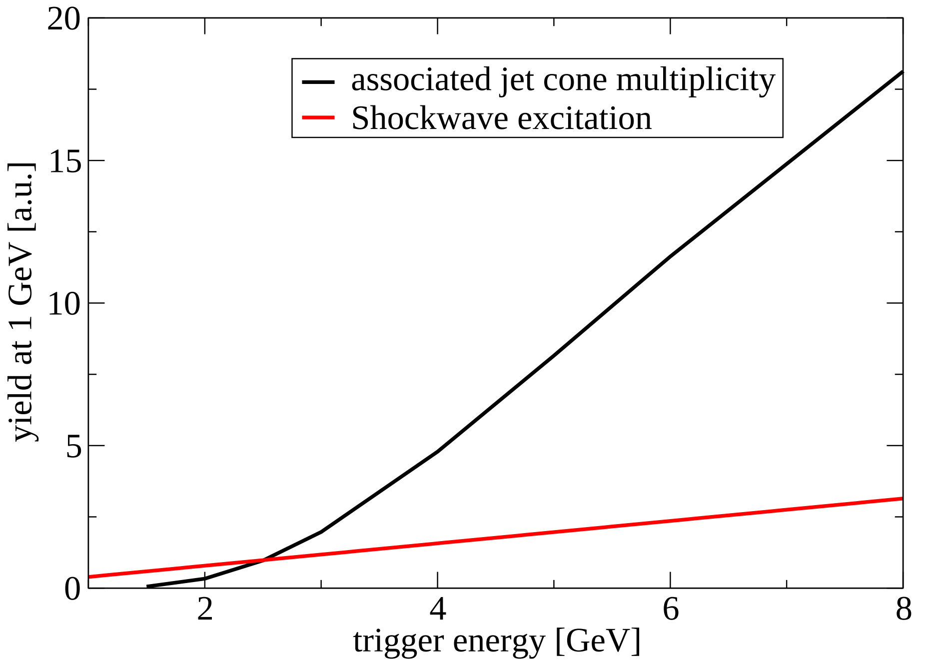
"Therefore, one expects to see the Cherenkov cone become smaller and the cone will eventually disappear for high-energy [associate] gluons."
(A. Majumder and X.-N. Wang)

Shockwave properties and experimental cuts

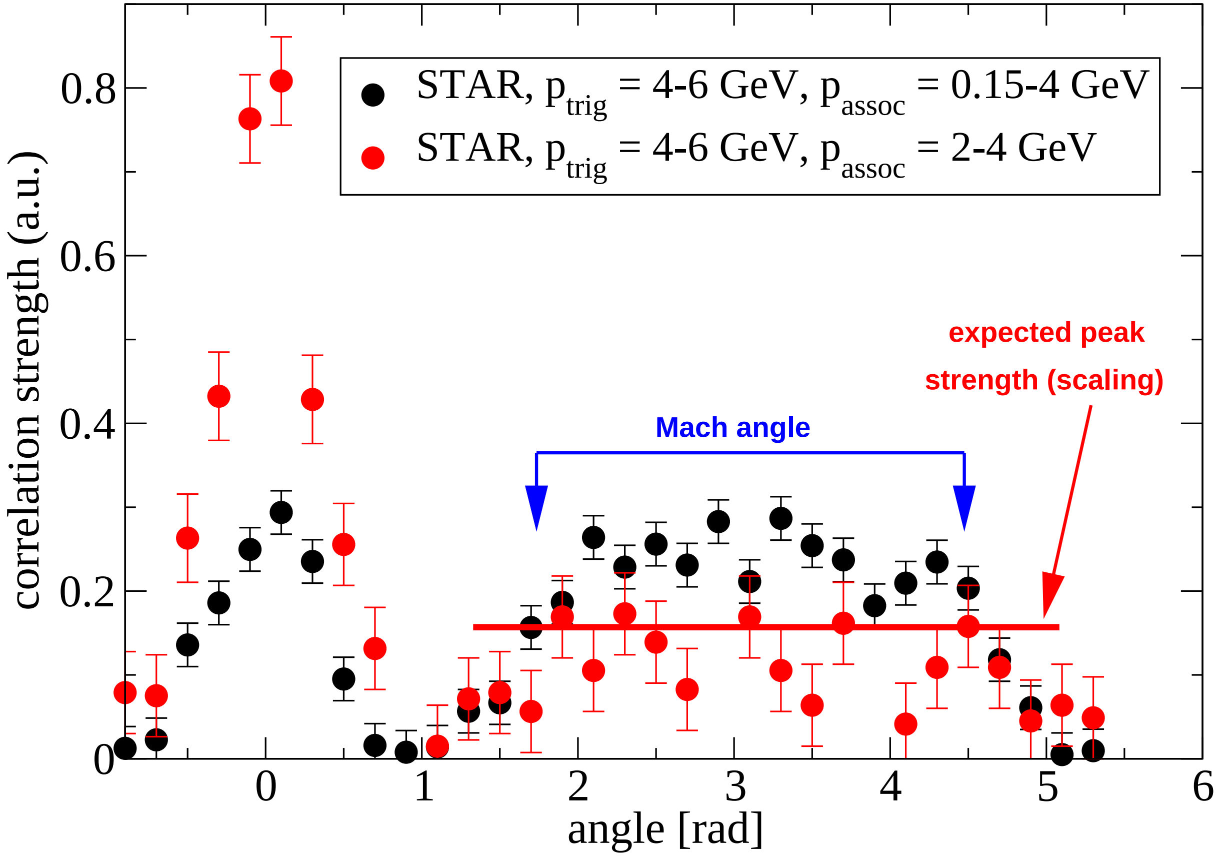
• shockwave position determined by c_s
⇒ property of the bulk medium, independent of trigger or associate momentum

• shockwave peak width partially determined by freeze-out conditions
⇒ independent of trigger momentum, thermal width determined by associate cut
(slight narrowing for increasing associate cut)

• shockwave strength (relative to near side)
⇒ dependent on availability of bulk matter (quick decrease with associate cut)
⇒ decrease with increasing trigger momentum:



Evidence



- no apparent change in angle as a function of p_{assoc}
- no apparent change in angle as a function of p_{trig}
- scaling law describes relative peak strength as a function of p_{trig}
- disappearance of dip (punchthrough?)

J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **95** (2005) 152301

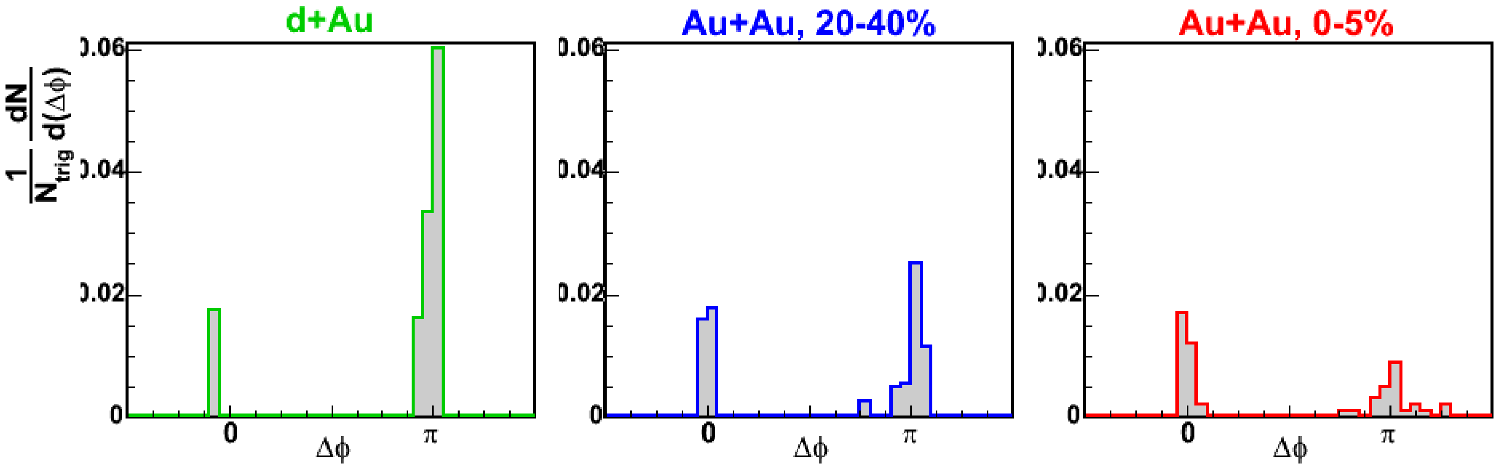
PART VI

Hard trigger and hard associate hadrons - dijets as a probe of the medium core.

"Thus, even for the highest experimentally accessible transverse momentum at the LHC and in contrast to jets, the measurement of leading partons via leading hadrons is not a penetrating probe of the dense matter."
(K. Eskola, H. Honkanen, C. Salgado and U. Wiedemann)

EVIDENCE

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



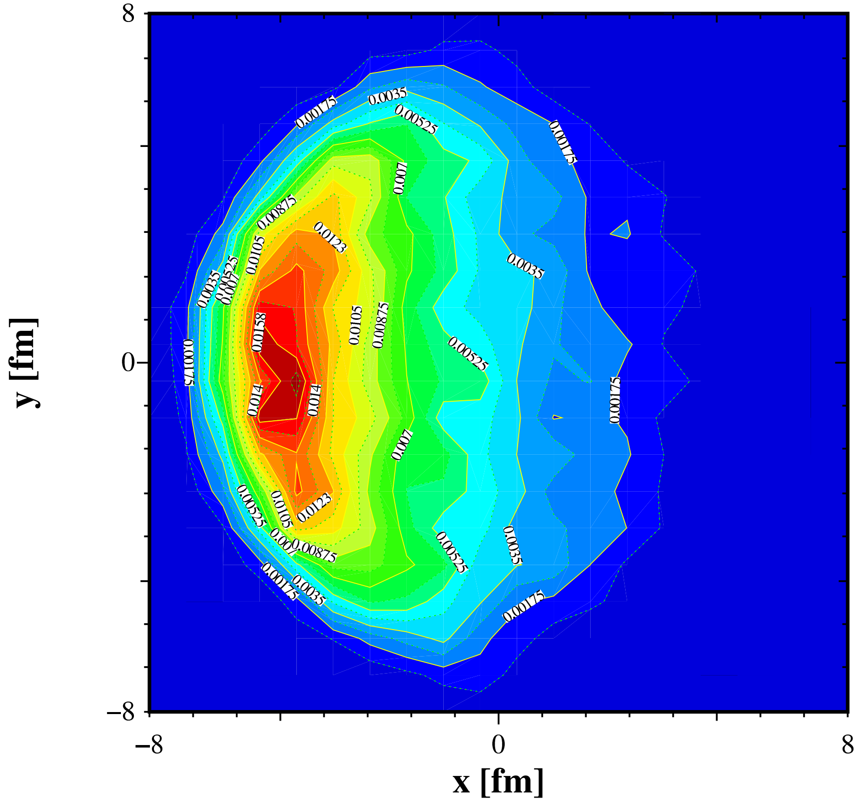
- clear jet cones with vacuum width
- near side LO fragmentation: $\longrightarrow$ trigger
- away side LO fragmentation: $\longrightarrow$ signal
- jet quenching: change in the yield per trigger of the away side peak
- no visible remnant of shockwaves

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

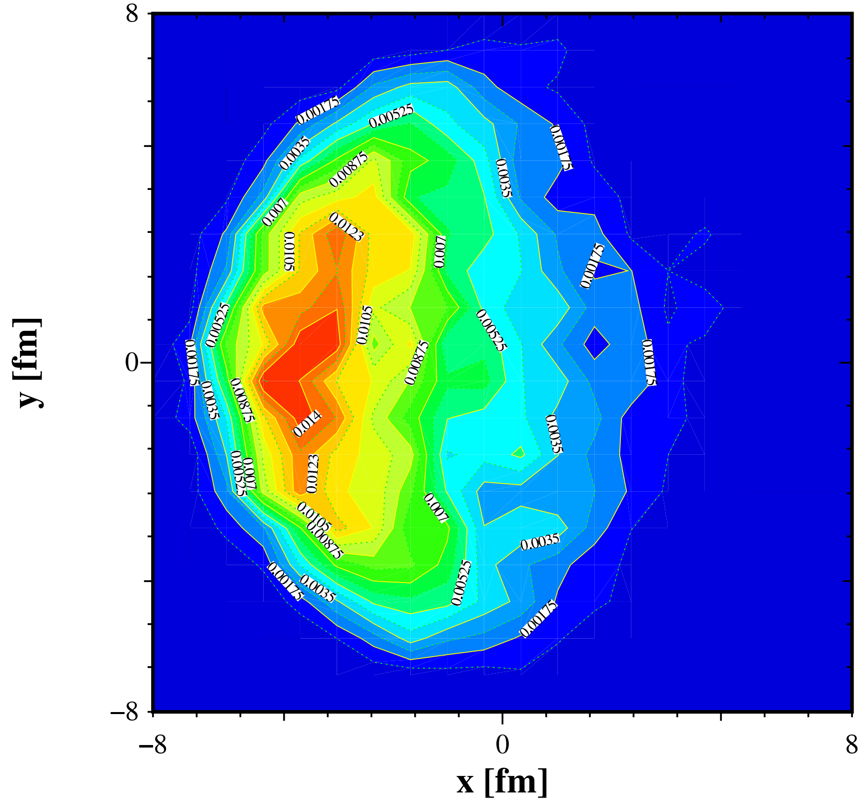
Surface bias

Probability density of vertices for triggered events (near side $\equiv -x$):

Triggered vertex distribution – hydrodynamics



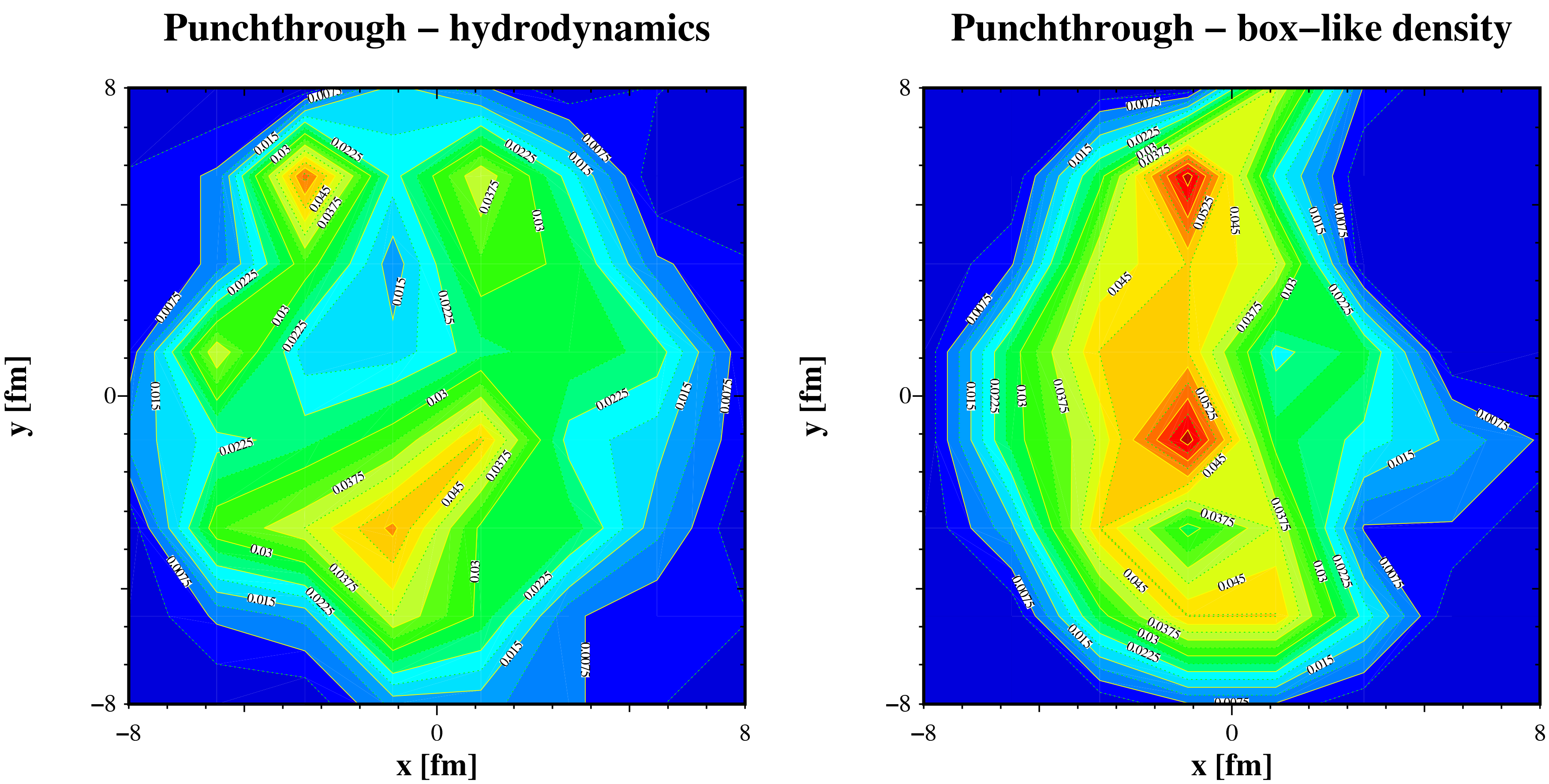
Triggered vertex distribution – box–like density



Degree of surface bias is model-dependent, some contribution from the core!

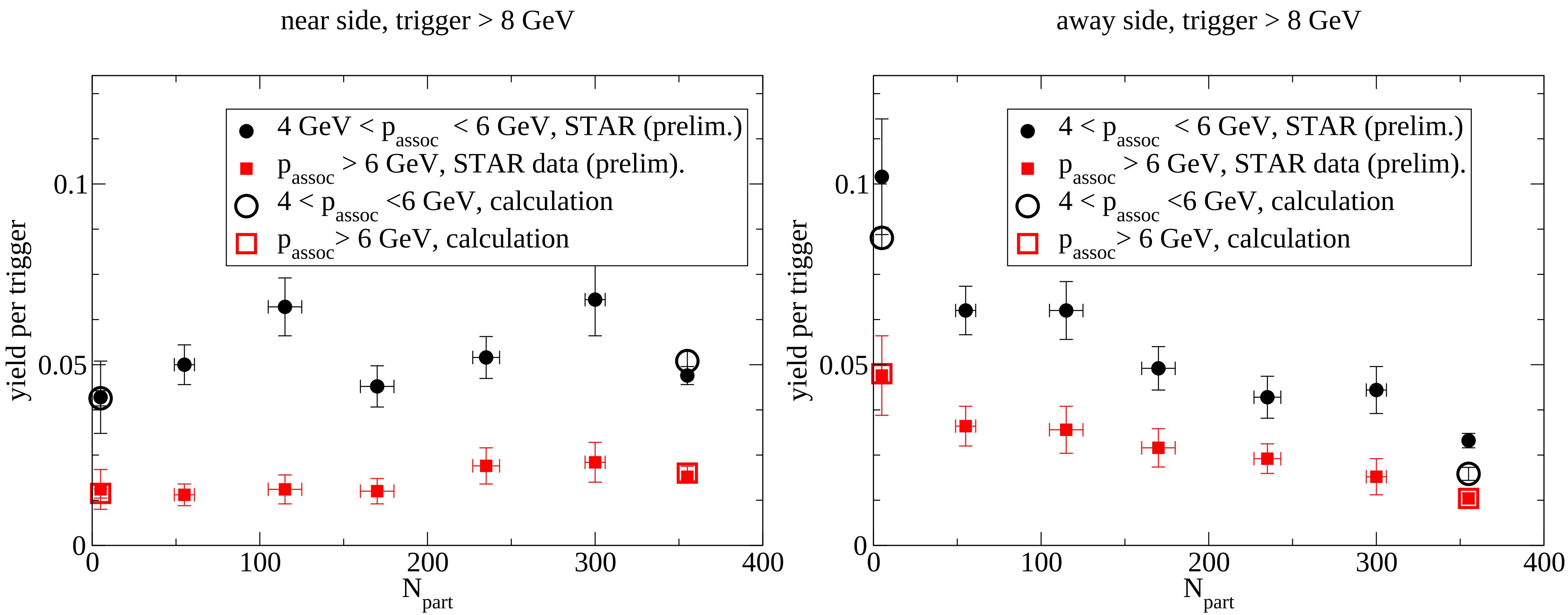
Punchthrough

Probability density of vertices leading to dihadron counts:



Region is very model-dependent, but jets penetrate the core → expansion!

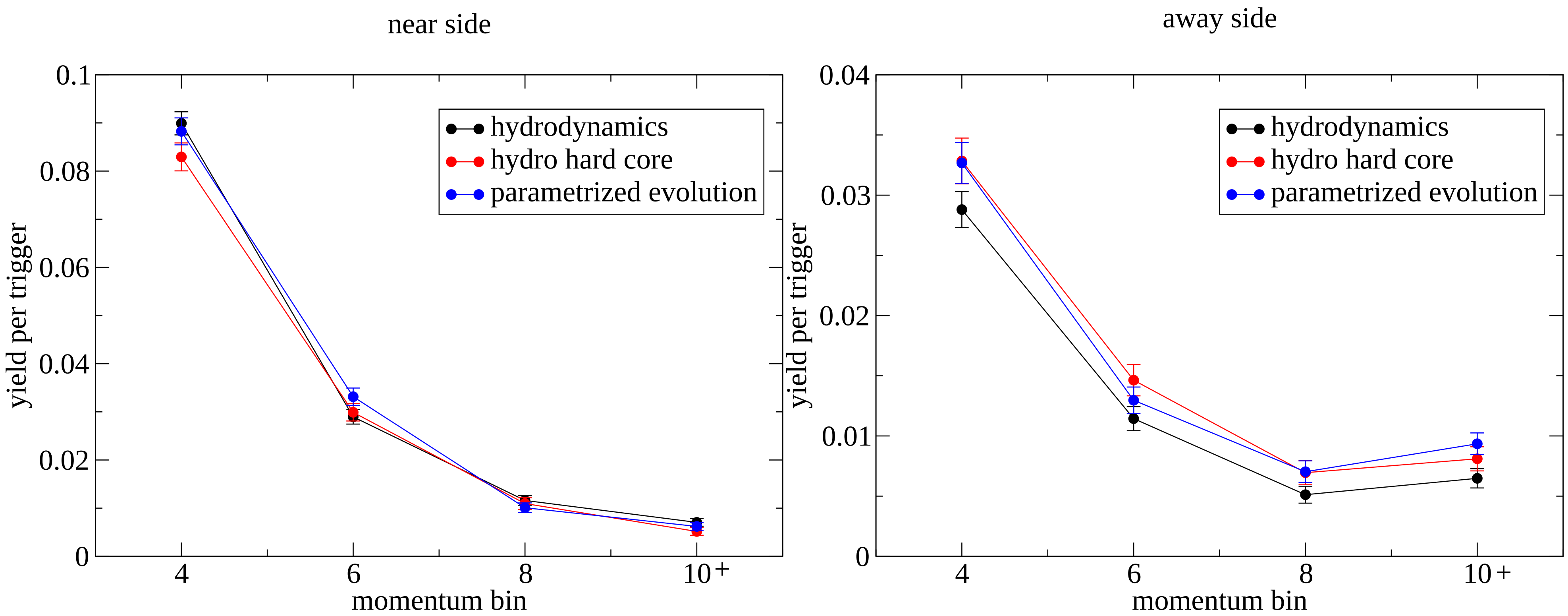
Yield per trigger



- yields are in general well described
- the 4-6 GeV associate cut away side yield is missed by $\sim 30\% \Rightarrow$ reco contribution?
- yield is described well where fragmentation is supposed to work

What can we learn?

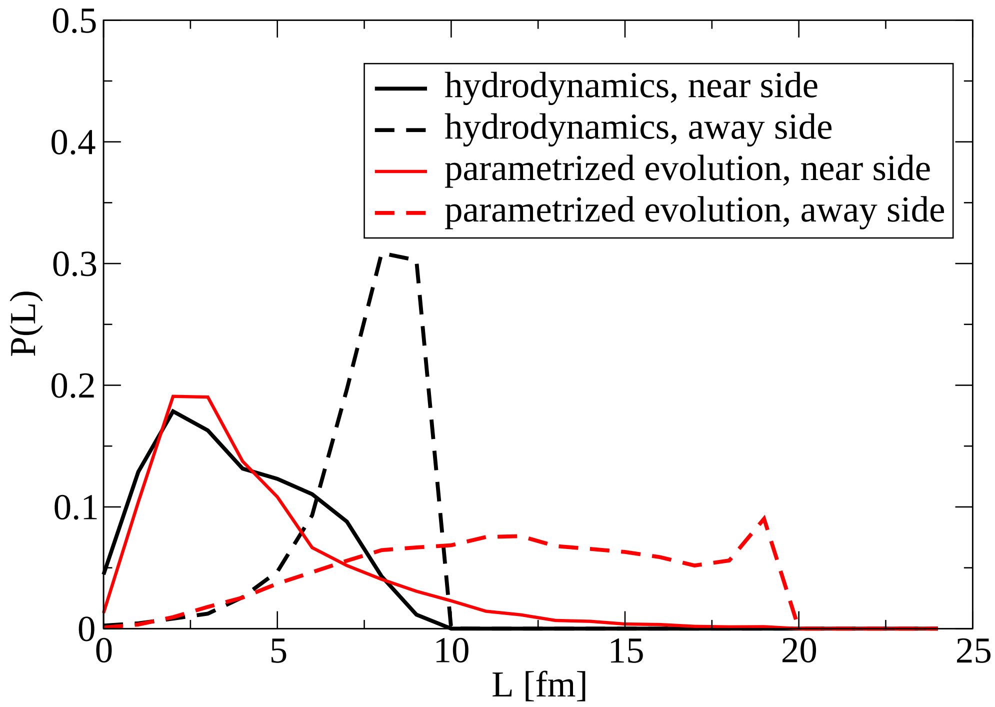
Raising the trigger energy and getting more associated p_T bins:



Why is this so similar? Is R_{AA} determining everything?

What can we learn?

But: $\Delta E_{coll} \sim \int d\xi \; \hat{q}(\xi)$ whereas $\Delta E_{rad} \sim \int d\xi \; \xi \; \hat{q}(\xi)$



- Average pathlength significantly increased on the away side

- Collisional energy loss has very different pathlength dependence

$\Rightarrow$ If collisional energy loss causes the suppression in R_{AA}, it will overestimate the dijet yield

The dihadron measurement seems to favour radiative energy loss

cf. also b-dependence of R_{AA} in radiative energy loss, A. Dainese, C. Loizides and G. Paic, Eur. Phys. J. C **38** (2005) 461

Summary

Nuclear suppression

- poses no strong constraint on energy loss probabilities
- . . . but requires 'large' suppression
- (dis-)agreement with pQCD is model-dependent

⇒ external evolution constrains and more differential constraints needed!

Semi-hard correlations

- are consistent with Mach shocks
- favour propagation with longitudinal flow
- show qualitatively the expected behaviour with p_{trig} and p_{assoc}

⇒ theory: dynamical recombination for quantitative calculations

⇒ experiment: excitation function systematics

Summary

Hard correlations

• probe medium core if the expansion is taken into account
• show no great sensitivity to evolution model — why?
• pose constraints on the parametric pathlength dependence
⇒ more p_T-bins in the clear fragmentation region would be helpful

LHC expectations

• no Mach signal beyond the hydro regime
• due to fragmentation vs. hydro excitation functions, jet cones will dominate most p_T regions
• quenched minijets may contribute a sizeable fraction of transverse flow
⇒ Let's see what happens!

Are there Mach shocks?

The strategy from here:

"It is an old maxim of mine that when you have excluded the impossible, whatever remains, however improbable, must be the truth."
(Sherlock Holmes, The Adventure of the Beryl Coronet)