Dijets and Mach cones

angular correlations as a probe of early medium evolution

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Introduction

What information is in R_{AA}?

Correlations beyond R_{AA}

- hard-hard correlations: dijets
- hard-soft correlations: Mach cones

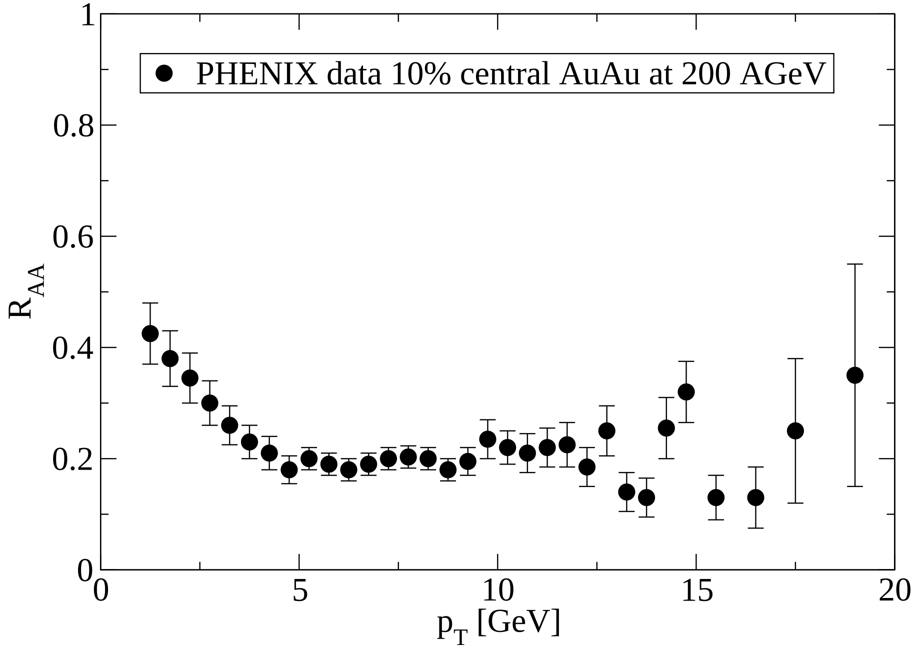
Other methods

- R_{AA} vs. reaction plane

Conclusions

TOMOGRAPHY IN JET SUPPRESSION?

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



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

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

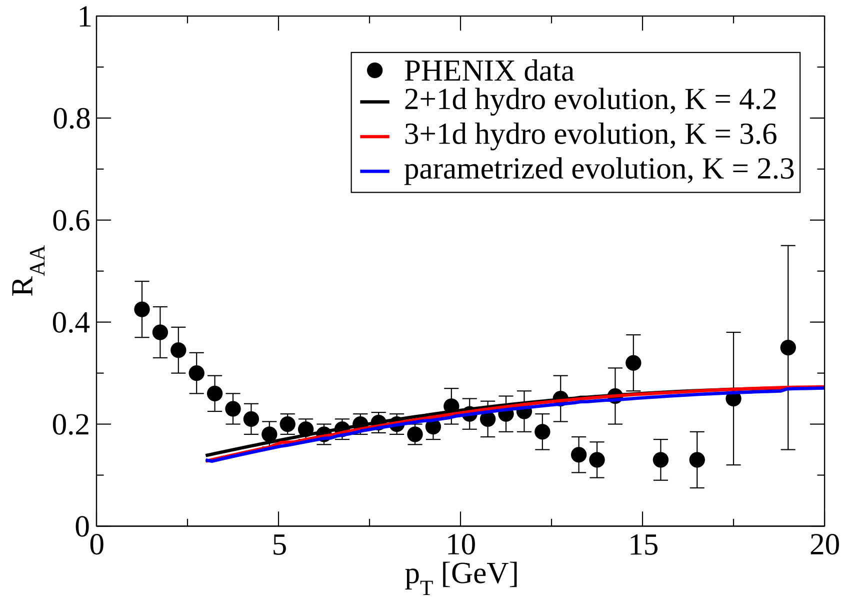
Tomography in Jet Suppression?

Assuming BDMPS energy loss: Scale ω_c of $\langle P(\Delta E, E)\rangle$: $\omega_c \sim 2 \cdot K\alpha_s\epsilon^{3/4}$

with $K = 1$ where pQCD is strictly applicable.

- If you believe you know α_s and that pQCD is strictly applicable:
$\rightarrow R_{AA}$ determines ϵ (or dN_g/dy)

- If you have a model for ϵ (i.e. a hydro evolution):
$\rightarrow R_{AA}$ determines strength of α_s or deviations from pQCD ($K \neq 1$)



Virtually no dependence on evolution beyond the scale information!

K. J. Eskola *et al.*, Phys. Rev. C **72** 044904 (2005); C. Nonaka and S. A. Bass, nucl-th/0607018.

Beyond R_{AA}

Sophisticated models for medium/pathlength distribution:
$\rightarrow$ determine scale of energy loss, $2 < K < 5$ for $\alpha_s = 0.45$

Can write

$$\langle P(\Delta E)\rangle = T\delta(\Delta E) + S \cdot P(\Delta E) + A \cdot \delta(\Delta E - E)$$

- T: 'transmission', no energy loss
- S: 'shift', parton emerges after finite energy loss, 'sideward shift' of spectrum
- A: 'absorption', parton thermalizes, 'downward shift' of spectrum

- How important are fluctuations around the typical scale? How does R_{AA} arise from T,S and A?

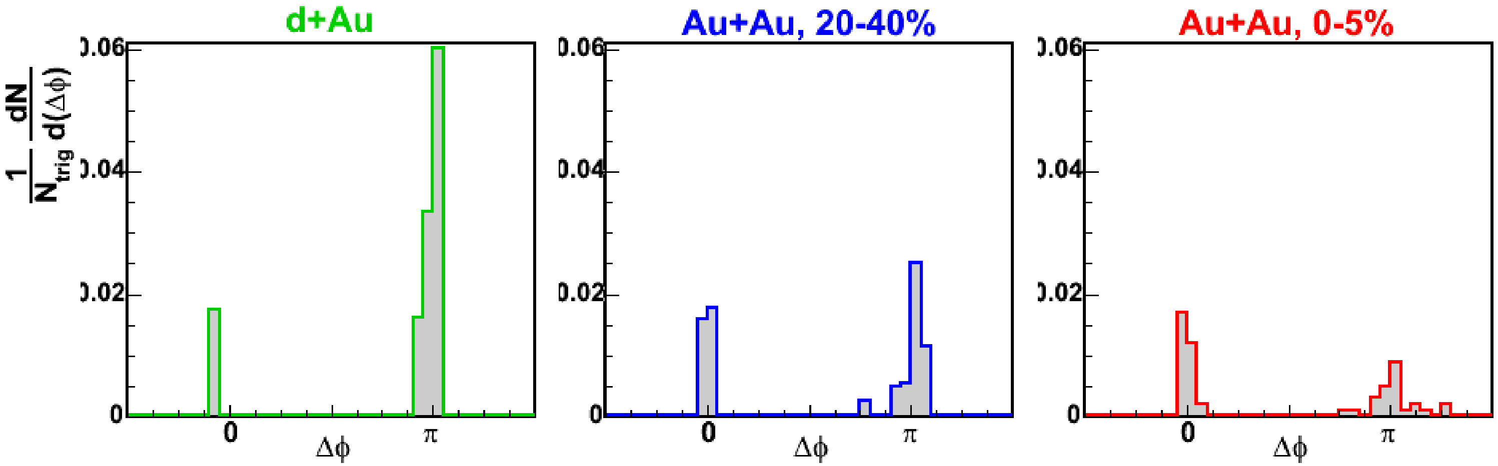
- Where does the energy go?

- Where do we have to look in order to see the medium evolution?

Use information from 2- and 3-particle correlations

Hard dihadron correlations

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



- clear jet cones with vacuum width
- jet quenching: change in the yield per trigger of the away side peak
- no visible broadening of away side peak

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

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:

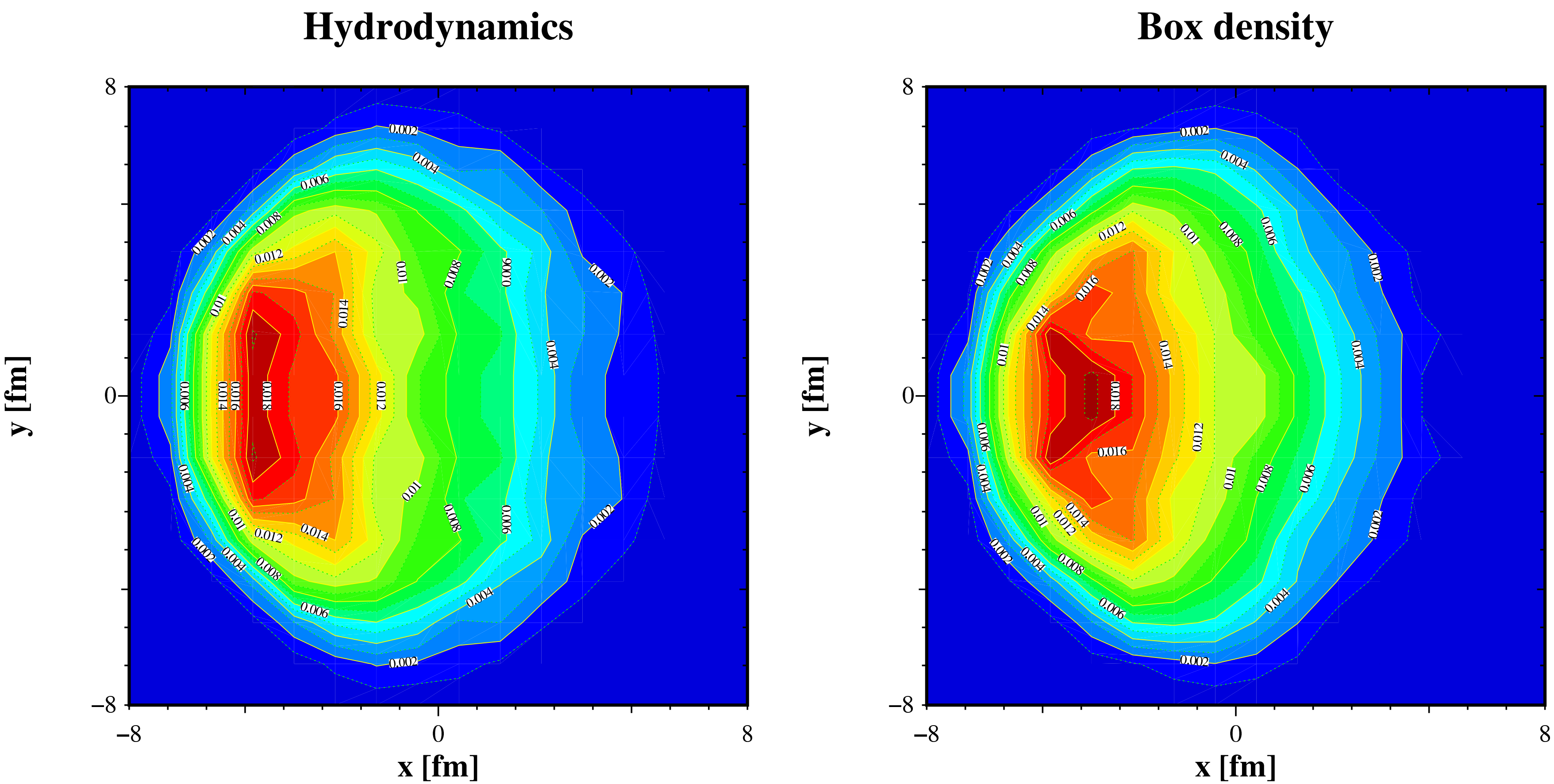
- intrinsic k_T

⇒ 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)L fragmentation
→ count emerging hadrons above associate threshold

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

Surface bias

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

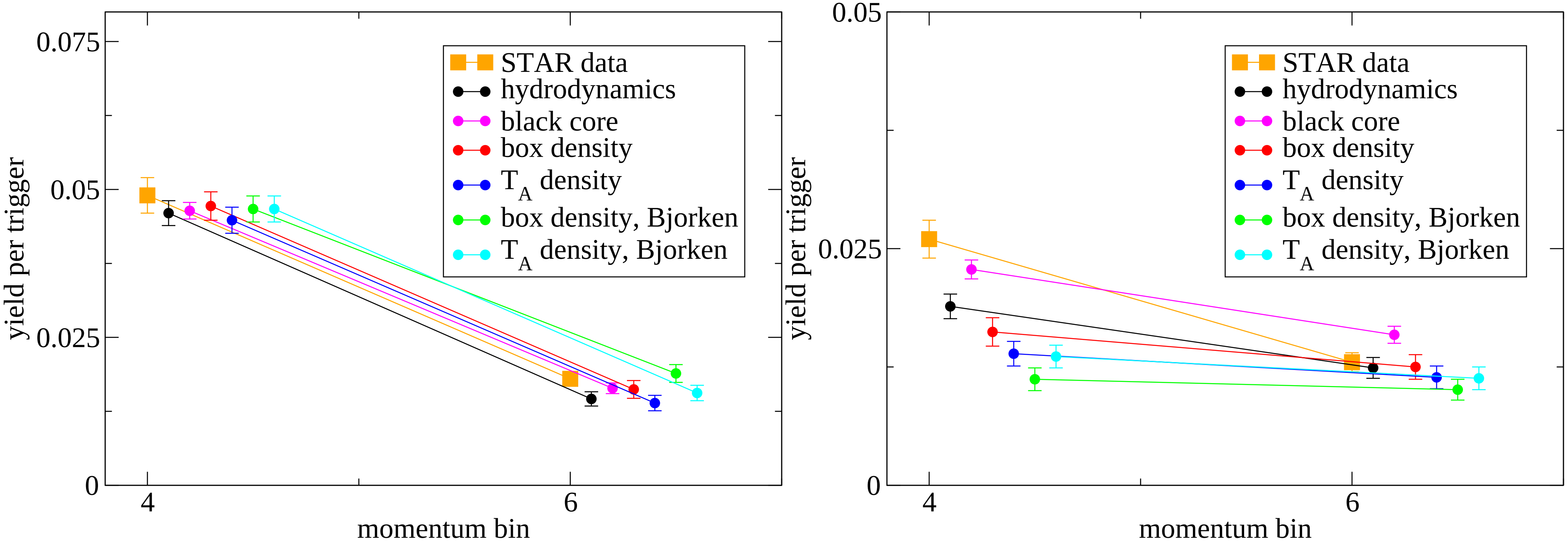


The away side yield must be averaged over this distribution rather than $\frac{[T_A(\mathbf{r_0})]^2}{T_{AA}(0)}$

T. Renk and K. J. Eskola, hep-ph/0610059

Dihadron correlations

Massive additional suppression (yield per trigger factor 4 smaller than for $\langle L_n \rangle = \langle L_a \rangle$)



Near side: Calculations agree well with data (dominance of $T\delta(\Delta E)$)

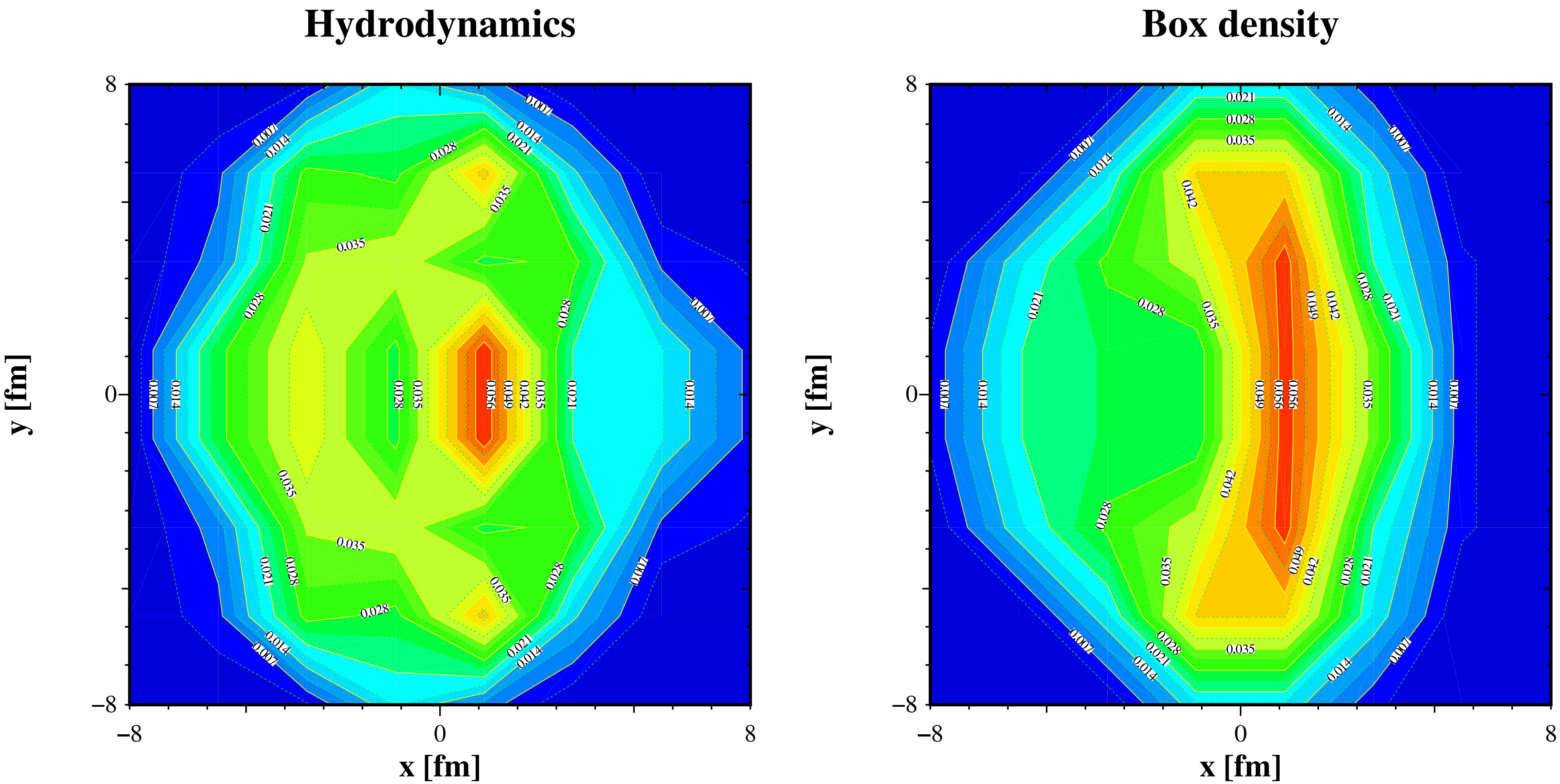
Away side: Deviations in the 4-6 GeV momentum bin → recombination
discrimination between models with *almost identical* R_{AA}

Some sensitivity to medium density distribution, but: dominance of transmission

T. R. and K. J. Eskola, hep-ph/0610059

Origin of dihadrons

Trigger: 8 GeV $< p_T < 15$ GeV, associate 4 GeV $< p_T <$ 6 GeV



The observed dihadrons originate from the medium center

T. R. and K. J. Eskola, hep-ph/0610059

WHAT HAVE WE LEARNED?

• dominance of $T\delta(\Delta E)$ over $S \cdot P(\Delta E)$ explains
- lack of broadening on the away side
- non-violation of x_T scaling (see Phys. Lett. B **637** (2006) 58)
- small sensitivity to medium evolution
- flatness of R_{AA}

$\Rightarrow$ fluctuations (as expected for BDMPS) are crucial to understand the data

• additional away side suppression
- completely compatible with L^2 pathlength dependence, not with L

$\Rightarrow$ points to presence coherence length effects

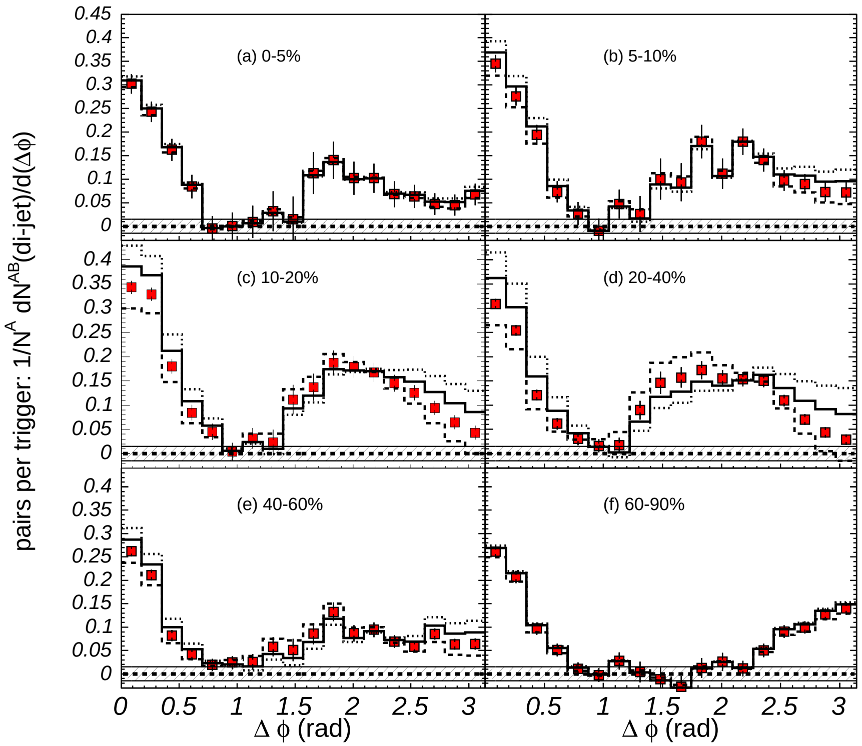
• agreement with data for $p_T > 6$ GeV
- dominance of hadronization mechanism other than fragmentation at $p_T < 6$ GeV

For shifts in the spectrum (and hence tomographical information), we need:
- larger lever-arm in p_T
- harder parton spectrum

This is the domain of LHC

Semi-hard semi-hard correlations

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



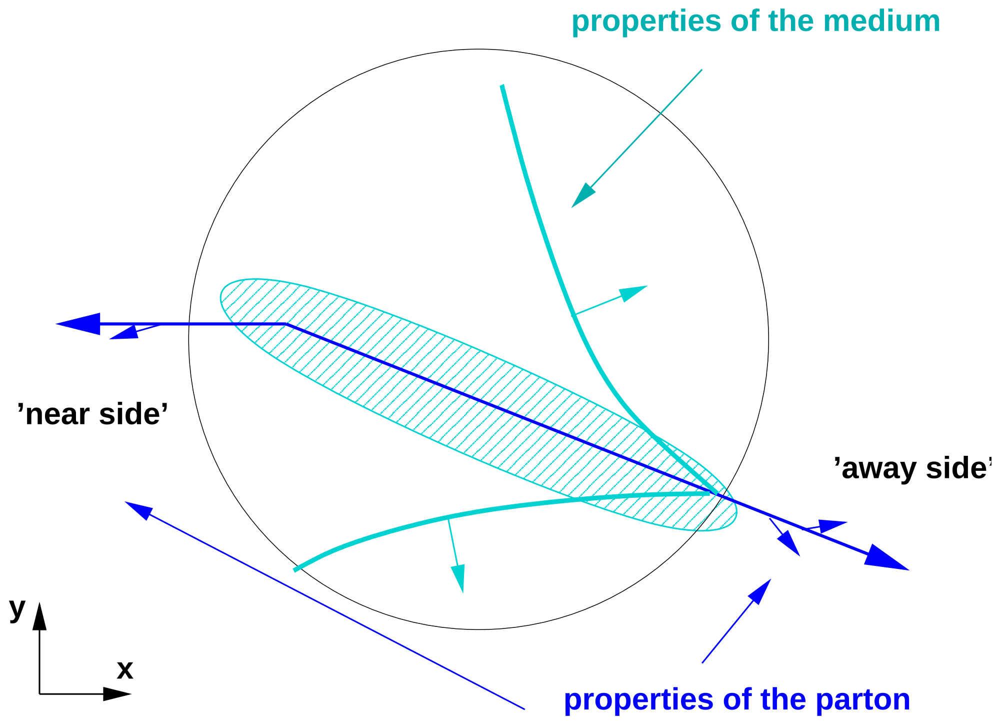
- large-angle signal
- central collisions: dip at expected position of away side jet
- position of correlation maximum consistent with Mach angle

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

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



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

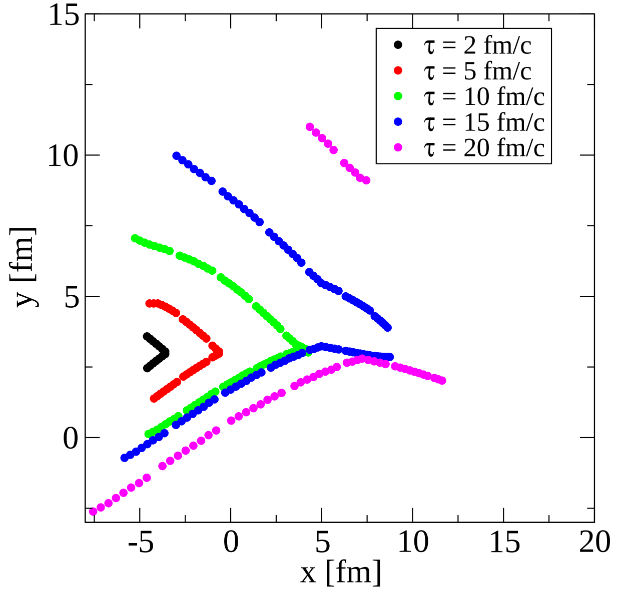
- strength and angle of Mach correlations: property of the bulk (fluid) medium
- strength and angle of near side, dijet: property of the hard parton + fragmentation

$\Rightarrow$ interplay between hydrodynamical processes and hard processes

The model

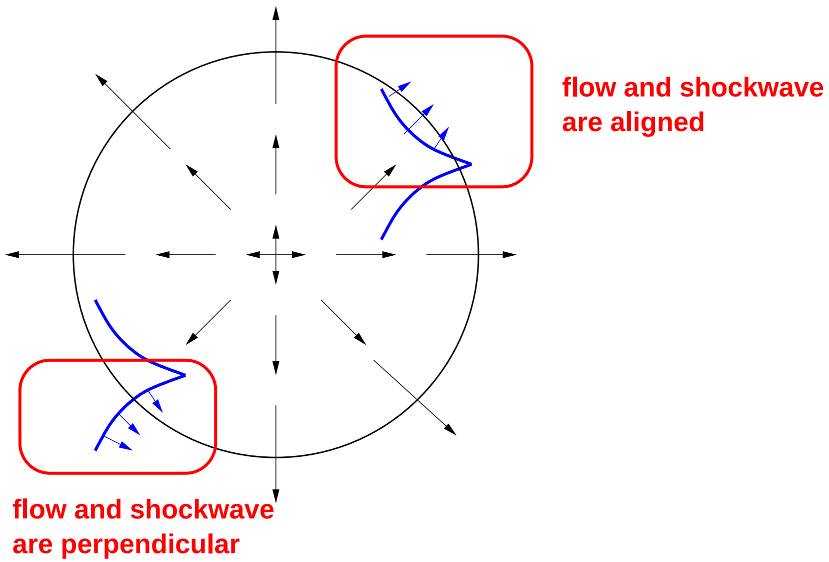
Shockwave ⇔ additional boost for hadrons at freeze-out

Position space:



Momentum space:

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

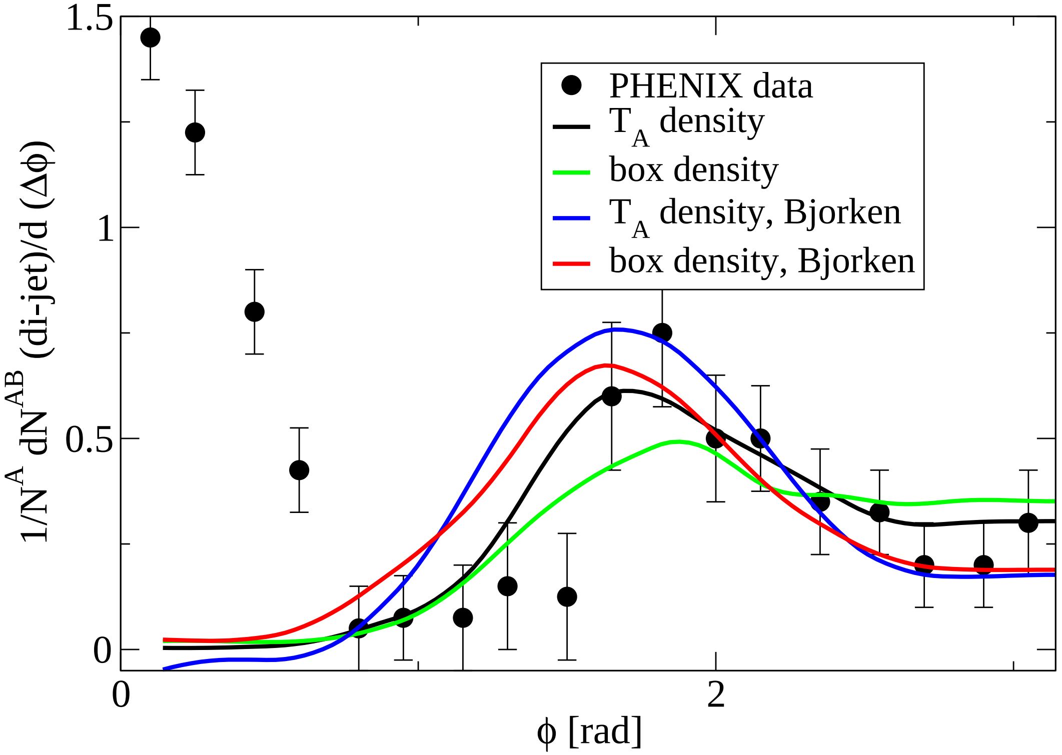


At 1 GeV, a Mach signal only appears if shockwave and flow are aligned

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

2-PARTICLE CORRELATIONS AND MEDIUM PROPERTIES

Correlation pattern at $y = 0$ (finite acceptance window reduces angle somewhat):

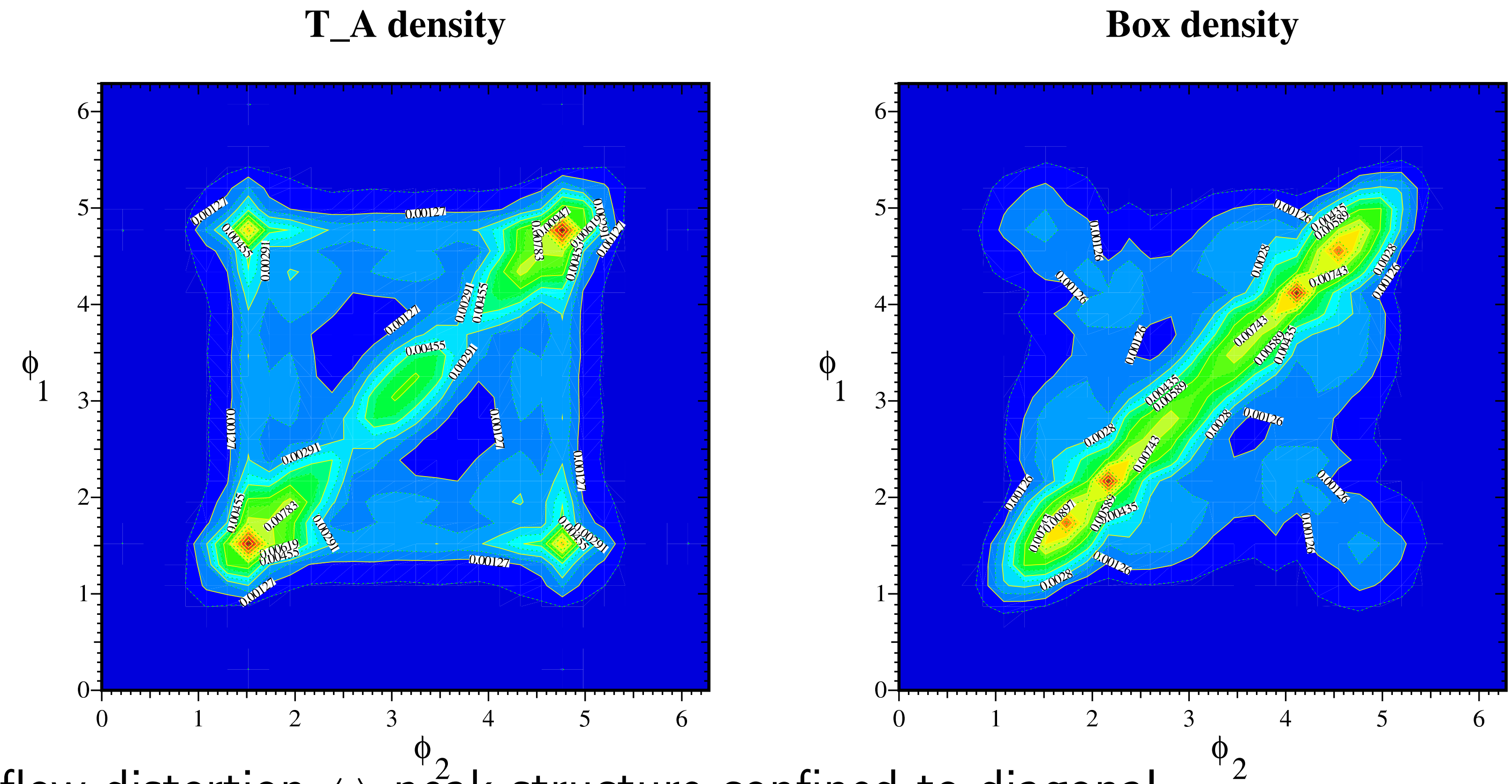


- faster evolution $\Leftrightarrow$ larger angle
- more exposure to flow $\Leftrightarrow$ peak structure washed out

A strong dip doesn't appear automatically for Mach cones!

3-PARTICLE CORRELATIONS AND MEDIUM PROPERTIES

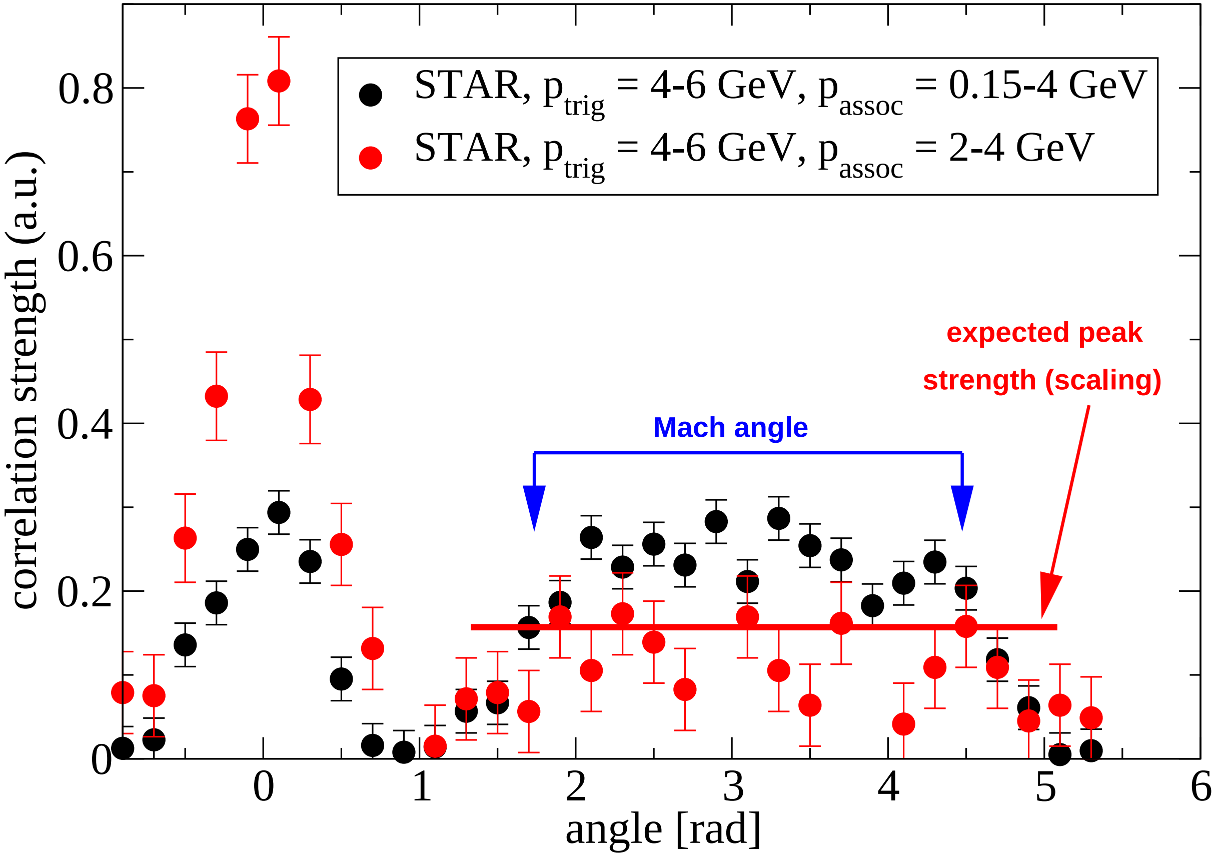
Correlation pattern at $y = 0$ (calculated as factorized 2-particle correlations):



- strong flow distortion ⇔ peak-structure confined to diagonal

Off-diagonal peaks do not appear automatically for Mach cones!

Scaling properties



- 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

What have we learned?

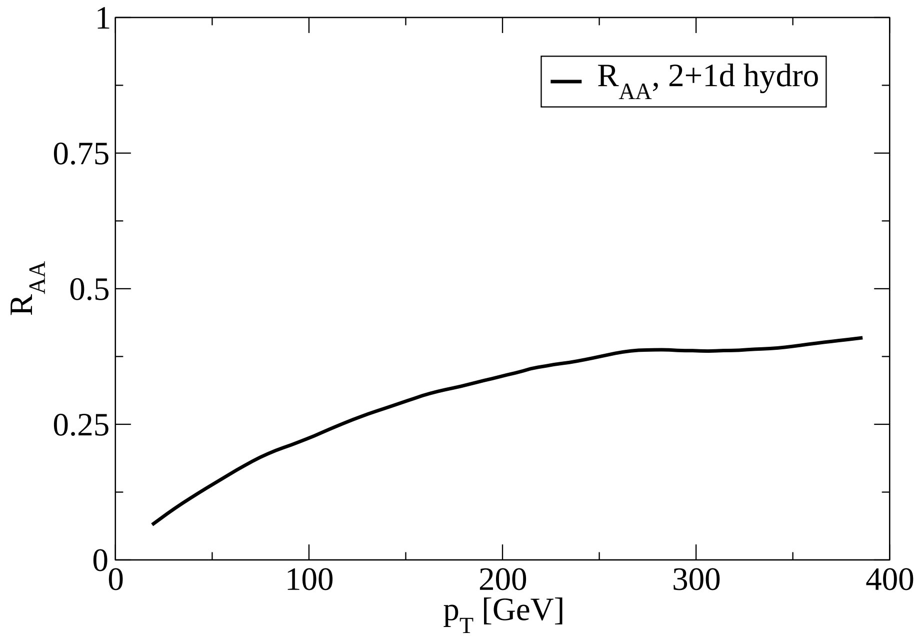
• Mach shocks redistributing lost energy explain:
- relative independence of away side correlation width with p_{trig} and p_{assoc}
- presence of a dip on the away side
- (weak) off-diagonal peaks in 3-particle correlations

• If so, the measured correlations give access to:
- $\langle c_s \rangle$ (through angle)
- evolution of flow and density (through off-diagonal peak extinction)

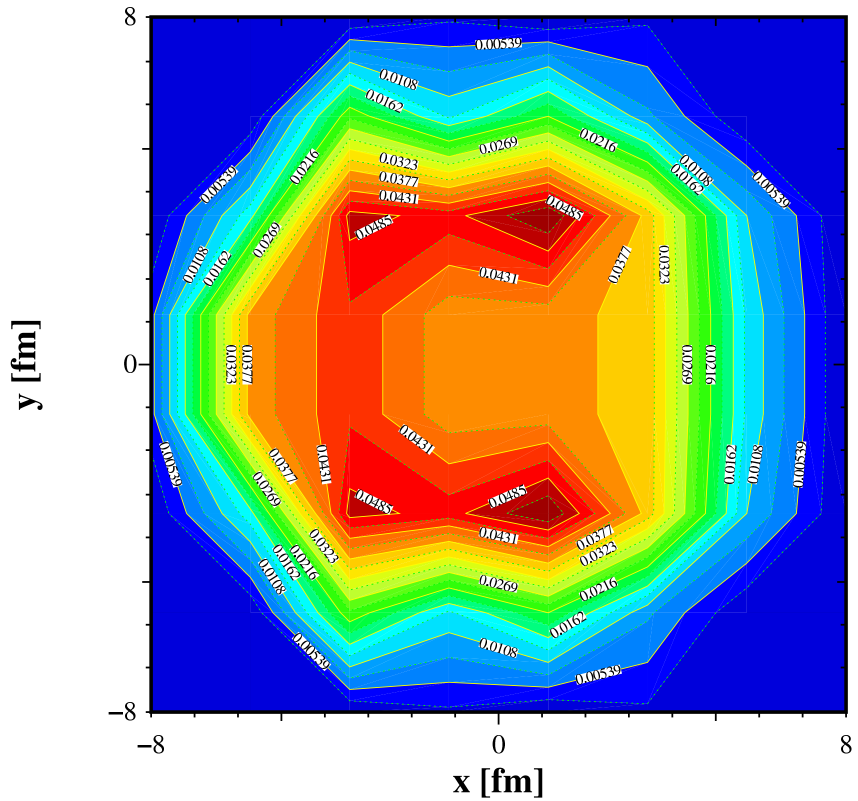
• In any case, energy lost from a hard parton appears:
- at lower p_T
- at wide angles

Outlook to LHC

R_{AA}: access to shift in parton p_T



Origin of dihadrons



Dynamical calculations suggest that jets are sensitive to the medium core

Summary

Hard-hard correlations:

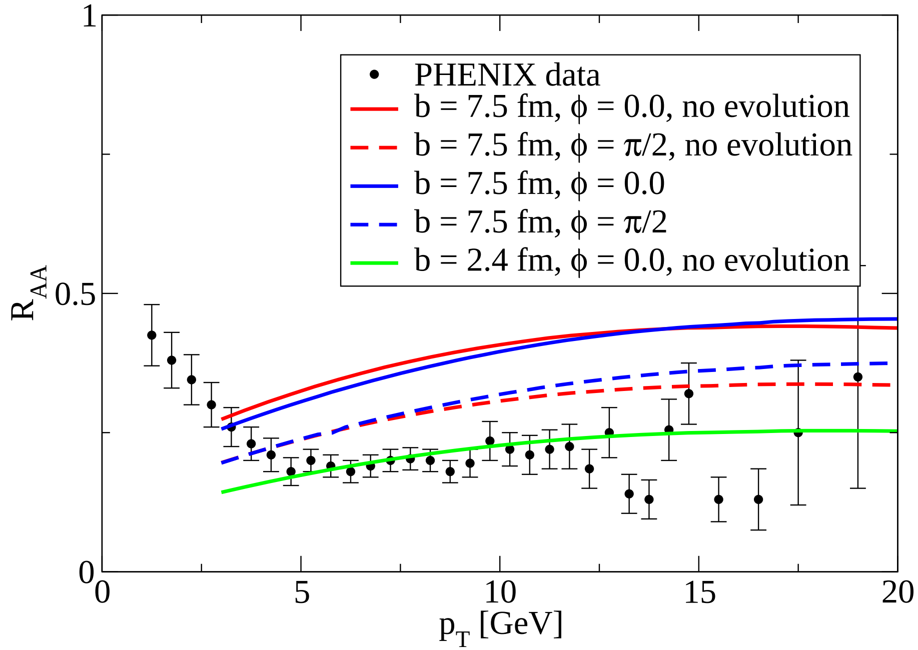
• at RHIC, dominated by balance between transmission and absorption
• in agreement with pathlength dependence expected for radiative energy loss
$\longrightarrow$ should re-investigate heavy-quark energy loss within full dynamics
• at LHC, gradually picking up shifts in parton energy
$\longrightarrow$ window for medium tomography opens up

Hard-semi-hard correlations:

• hydrodynamical modes naturally explain many properties
• sensitive to evolution details
$\longrightarrow$ needs further exploration

Correlation measurements: quantitative tools for LHC

BACKUP: R_{AA} VS. REACTION PLANE



- quenching strong for $\tau > L_{short}/c$ to see pathlength difference
- hydrodynamics removes spatial anisotropy over time τ_{iso}

$\Rightarrow$ situation is only comparable with static case if

a) $\tau_{quench} > L_{short}/c$ and

b) $\tau_{quench} < \tau_{iso}$

Probes spatial anisotropy in early hydro evolution

If anything, this points to pathlength dependence stronger than L^2!