# HIGH $p_T$ DIHADRON VS. SINGLE HADRON SUPPRESSION

— what is different?


Thorsten Renk

in collaboration with J. Ruppert and Kari J. Eskola

UNIVERSITY OF JYVÄSKYLÄ

HELSINKI INSTITUTE OF PHYSICS


INTRODUCTION

What information is in $R_{AA}$ at RHIC?

TOMOGRAPHY USING $R_{AA}$

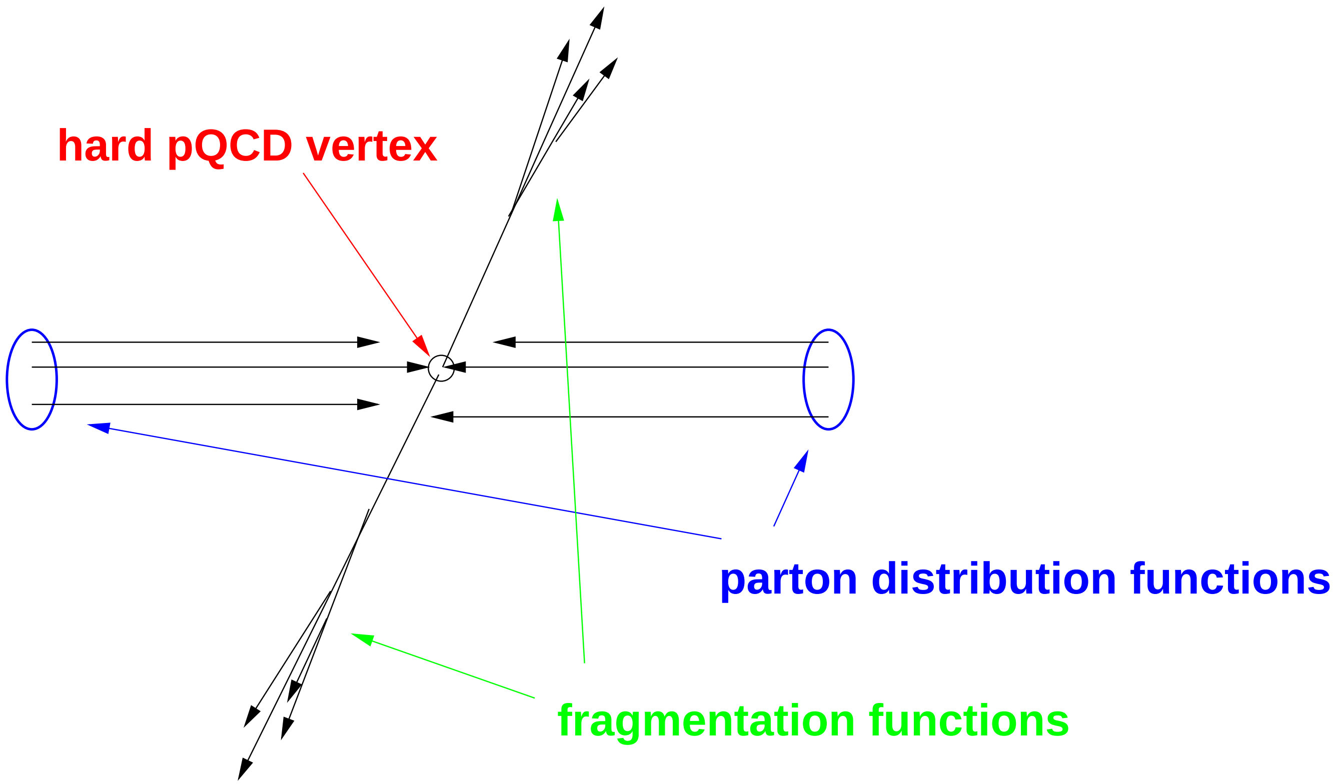
- opening the kinematic window

TOMOGRAPHY BEYOND $R_{AA}$

- $\gamma$-hadron correlations
- $R_{AA}$ vs. reaction plane
- dihadron correlations

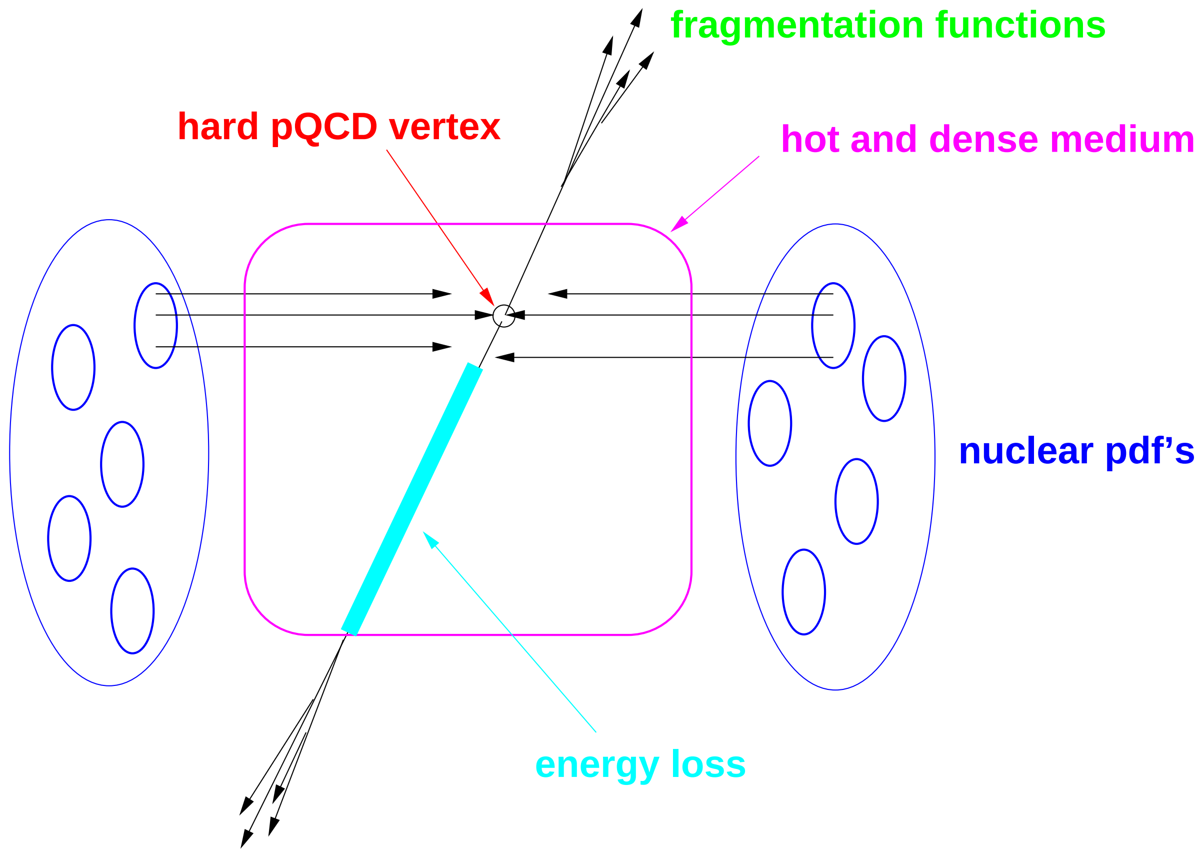
CONCLUSIONS

# 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




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

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

# What is medium tomography?

Idea of jet tomography:

- use a (comparatively) well-known calculable process in vacuum
- embed it into a medium

⇒ infer medium properties from the changes

New ingredients from p-p to A-A collisions:

- $f_{i/N}(x_1, Q^2) \rightarrow f_{i/A}(x_1, Q^2)$ (can be studied in p-A collisions)
- vertex-averaged energy loss probability $\langle P_f(\Delta E, E) \rangle_{T_{AA}}$

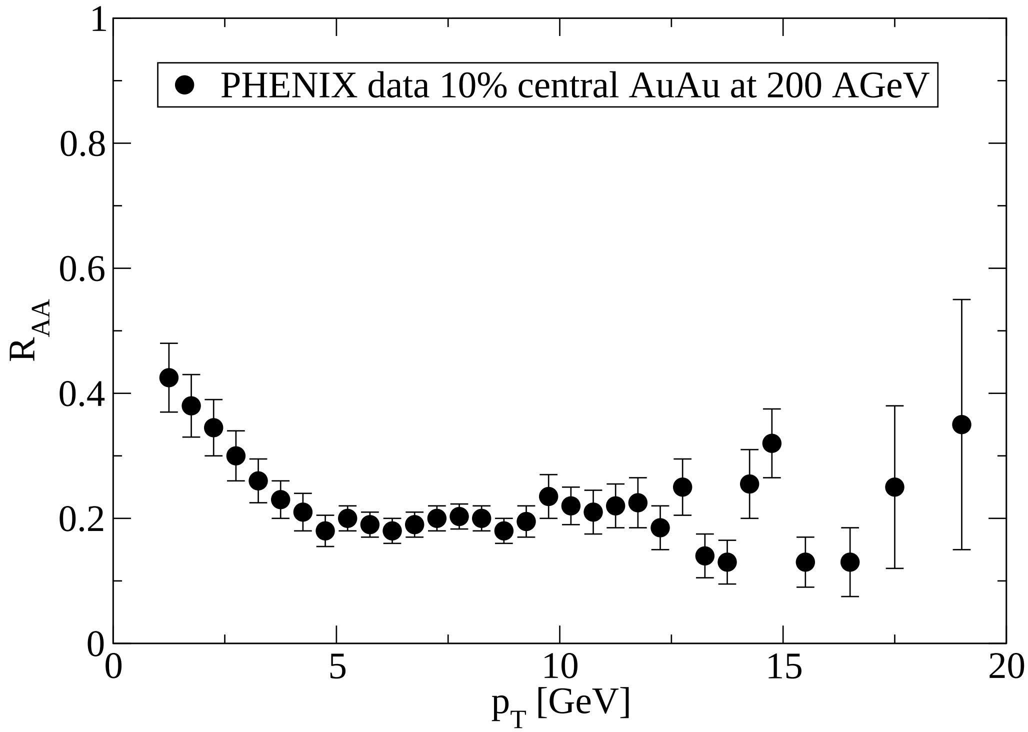
⇒ medium-modified hard processes ⇔ access to averages of energy-loss probabilities

$\langle P(\Delta E, E) \rangle$ depends on:
(1) interaction of medium and hard parton
(2) spacetime distribution of medium density relative to hard vertices

To study (2), this must be disentangled from (1)!

# Tomography in Jet Suppression?

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




is (in the fragmentation region) uniquely determied by

$$p_{had} = p_{part} \otimes \langle P(\Delta E, E)\rangle_{T_{AA}} \otimes D^{vac}_{f\to\pi}(z, \mu_F^2)$$

Can we invert this relation to infer $\langle P(\Delta E, E)\rangle_{T_{AA}}$ from $R_{AA}$?

# Defining $\langle P(\Delta E, E)\rangle_{T_{AA}}$

Hard vertices for impact parameter **b** have a probability distribution given by

$$P(x_0, y_0) = \frac{T_A(\mathbf{r_0} + \mathbf{b/2})T_A(\mathbf{r_0} - \mathbf{b/2})}{T_{AA}(\mathbf{b})},$$

where $T_A(\mathbf{r}) = \int dz \rho_A(\mathbf{r}, z)$.

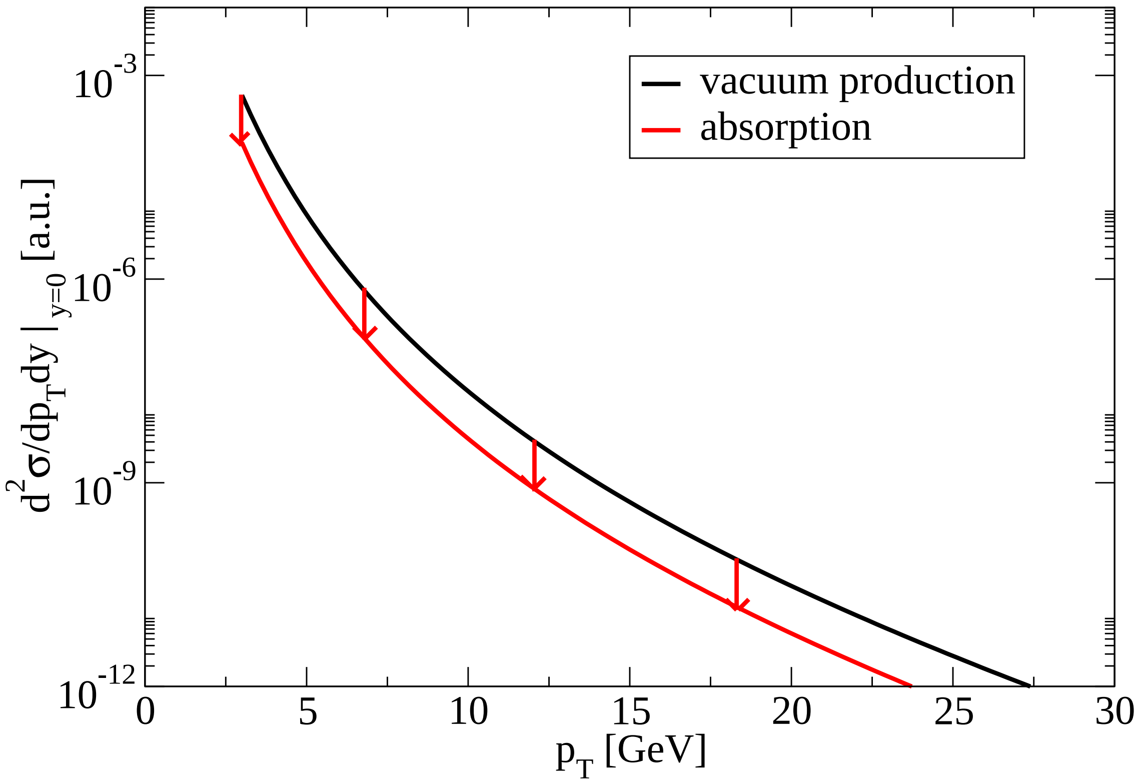
If the probability of energy loss along a given path (determined by medium, vertex $\mathbf{r_0} = (x_0, y_0)$, rapidity $y$ and transverse angle $\phi$ is $P(\Delta E, E)_{path}$ we can define:

$$\langle P(\Delta E, E)\rangle_{T_{AA}} = \frac{1}{2\pi}\int_0^{2\pi} d\phi \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 P(x_0, y_0) P(\Delta E, E)_{path}.$$

The medium information is now in details of $P(\Delta E, E)_{path}$. For $R_{AA}$, this is averaged over the overlap geometry.

# Tomography in Jet Suppression?

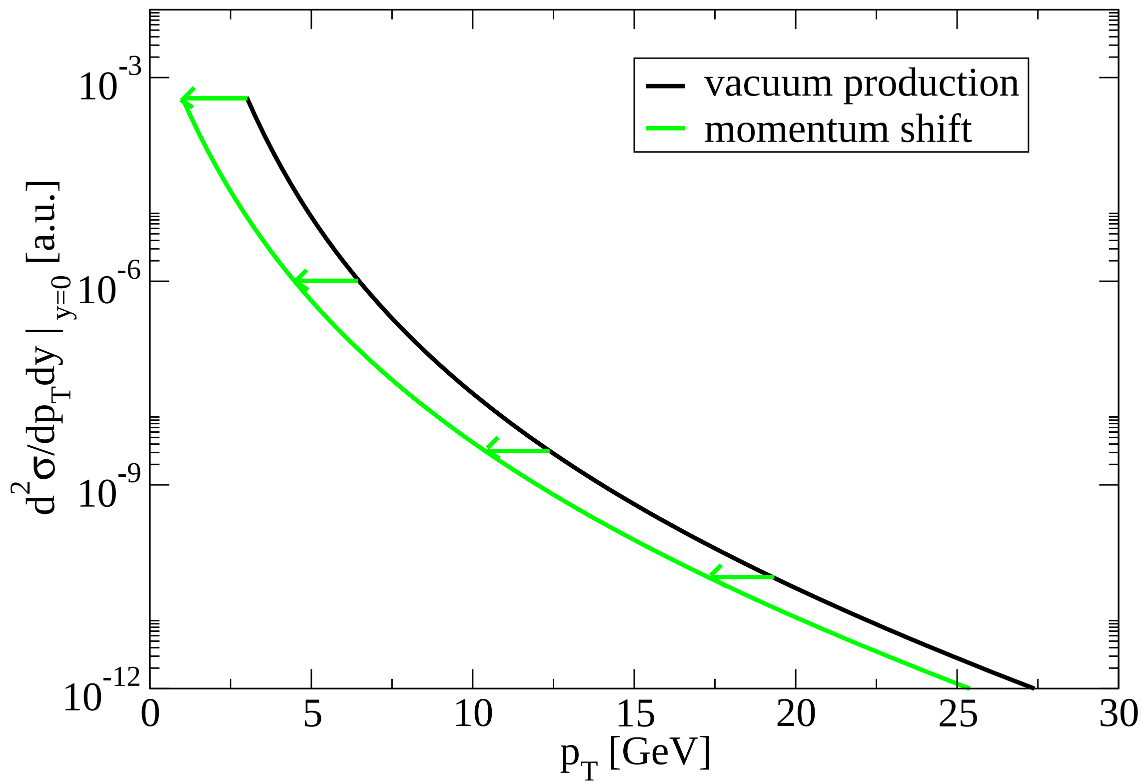
Is the observed $R_{AA}$ due to absorption of 80% of all partons while the rest escapes unmodified?




$$P(\Delta E, E) = 0.2\delta(\Delta E) + 0.8\delta(\Delta E - E) \quad \text{(downward shift)}$$

# Tomography in Jet Suppression?

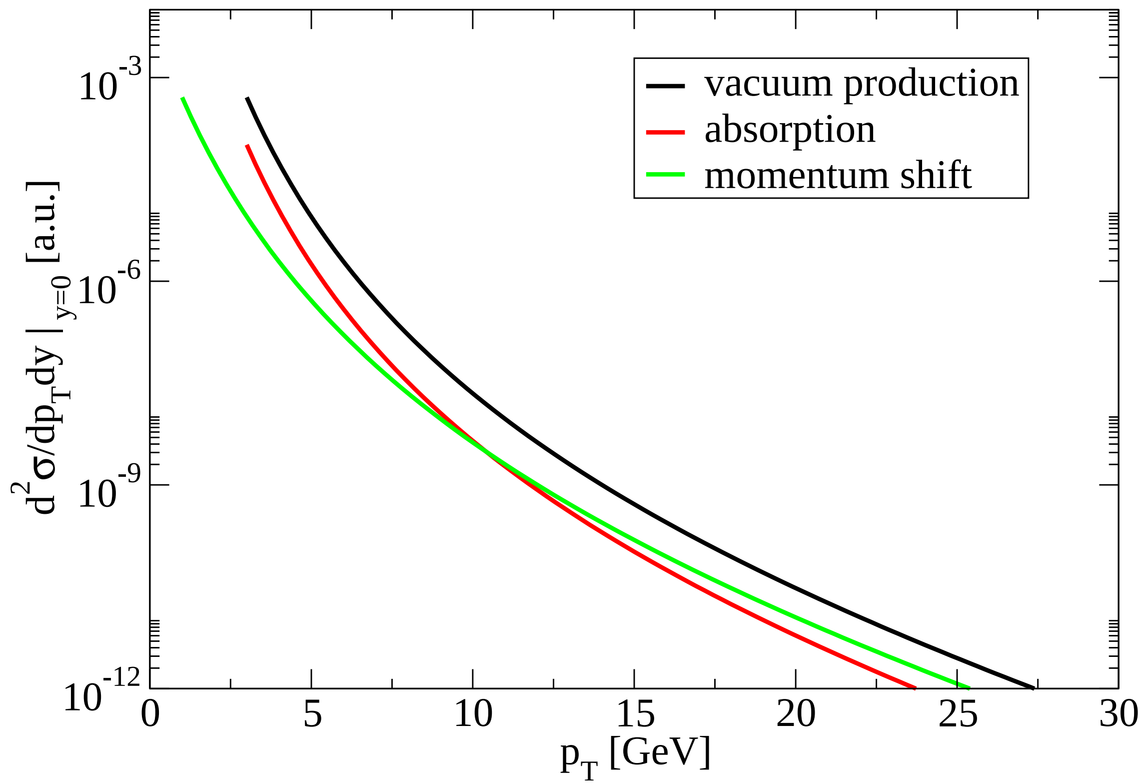
Or is the observed $R_{AA}$ due a small shift of the energy of all partons?




$$P(\Delta E, E) = \delta(\Delta E - 2\,\text{GeV}) \quad \text{(sideward shift)}$$

# Tomography in Jet Suppression?

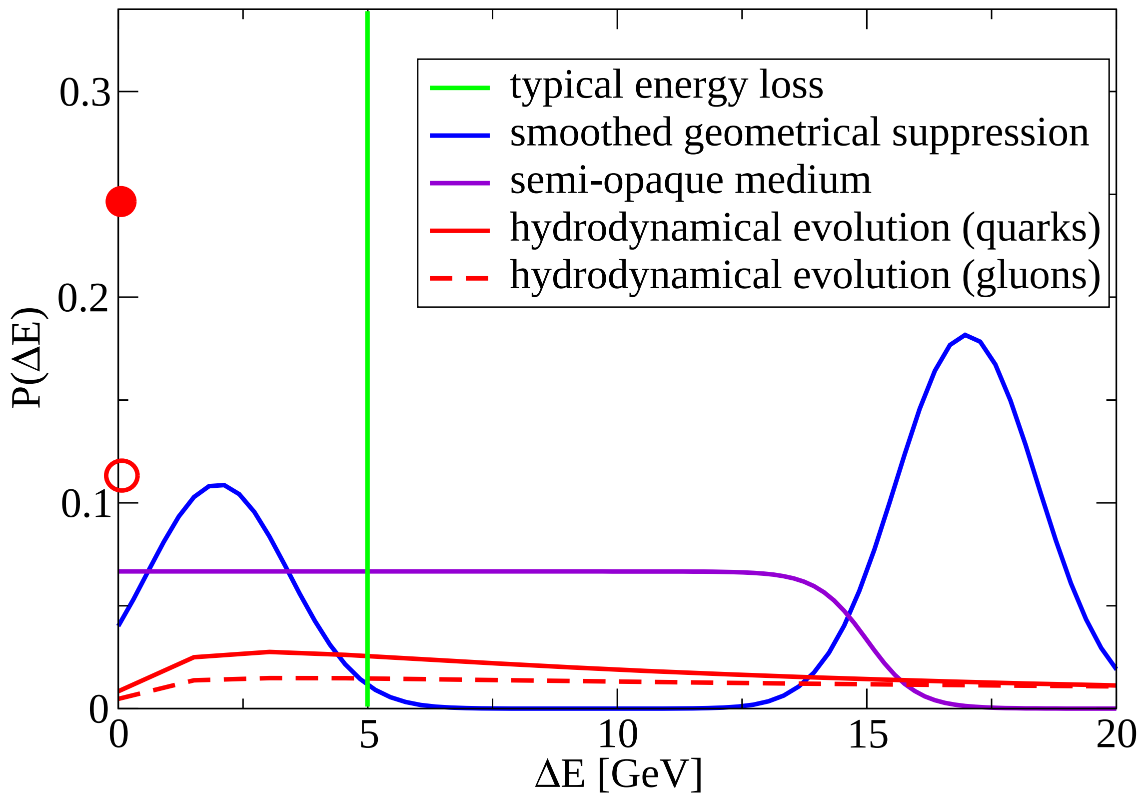
Difficult to distinguish in a limited kinematic range:




In general, any combination of downward and sideward shift might occur!

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

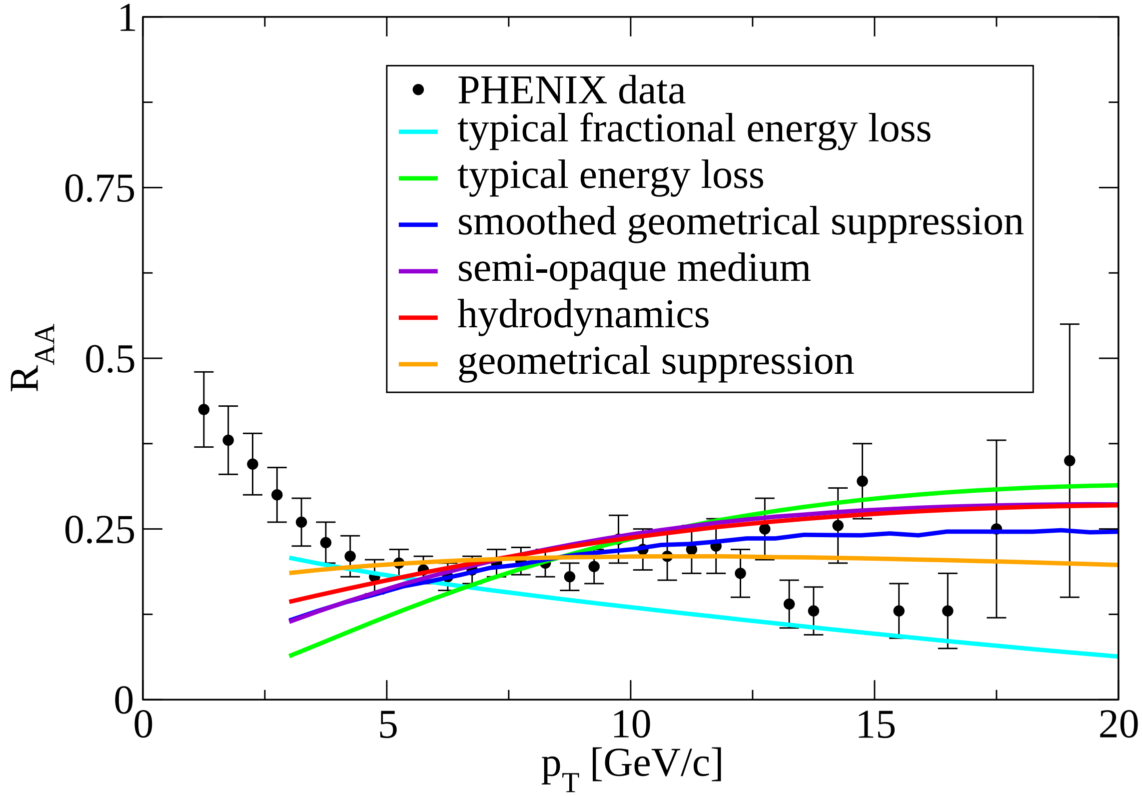
Consider some very different $T_{AA}$ averaged trial energy loss probabilities:




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

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

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




usually 1-parameter tuning brings a trial $\langle P(\Delta E, E)\rangle_{T_{AA}}$ distribution to the data:

Quenching has to be substantial, but we don't really measure even $\langle P(\Delta E, E)\rangle_{T_{AA}}$!

# Differences in detail

Strong explicit depenence of on initial energy $E$ seems to be ruled out.

To first order:

- all probability distributions yield flat lines

$\Rightarrow$ why?

To second order:

- systematic differences at high $p_T$

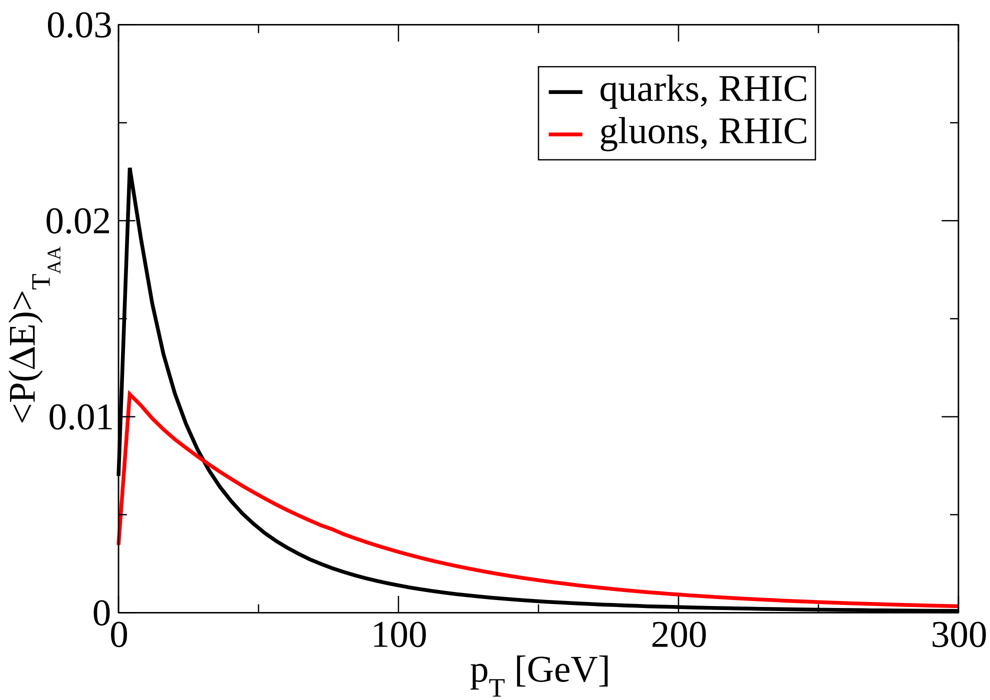
$\Rightarrow$ reflect the presence or absence of a scale in $\langle P(\Delta E, E)\rangle_{T_{AA}}$

What properties of $\langle P(\Delta E, E)\rangle_{T_{AA}}$ cause this?

$$\langle P(\Delta E)\rangle_{T_{AA}} = T\delta(\Delta E) + S \cdot P(\Delta E) + A \cdot \delta(\Delta E - E)$$

- 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

# $\langle P(\Delta E, E)\rangle_{T_{AA}}$ CALCULATED




- 'shift' or 'absorption' depends on the scale at which this is probed
- large fluctuations, large discrete escape probability
- RHIC medium is so dense $\Rightarrow O(100)$ GeV quark to guarantee punchthrough

$\Rightarrow$ in accessible $p_T$-range: (almost) either absorption or transmission

- but: different quenching properties for quarks and gluons

Can this be exploited?

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

# Experimental evidence

Generically, gluons have stronger interaction with the medium (different color factor)

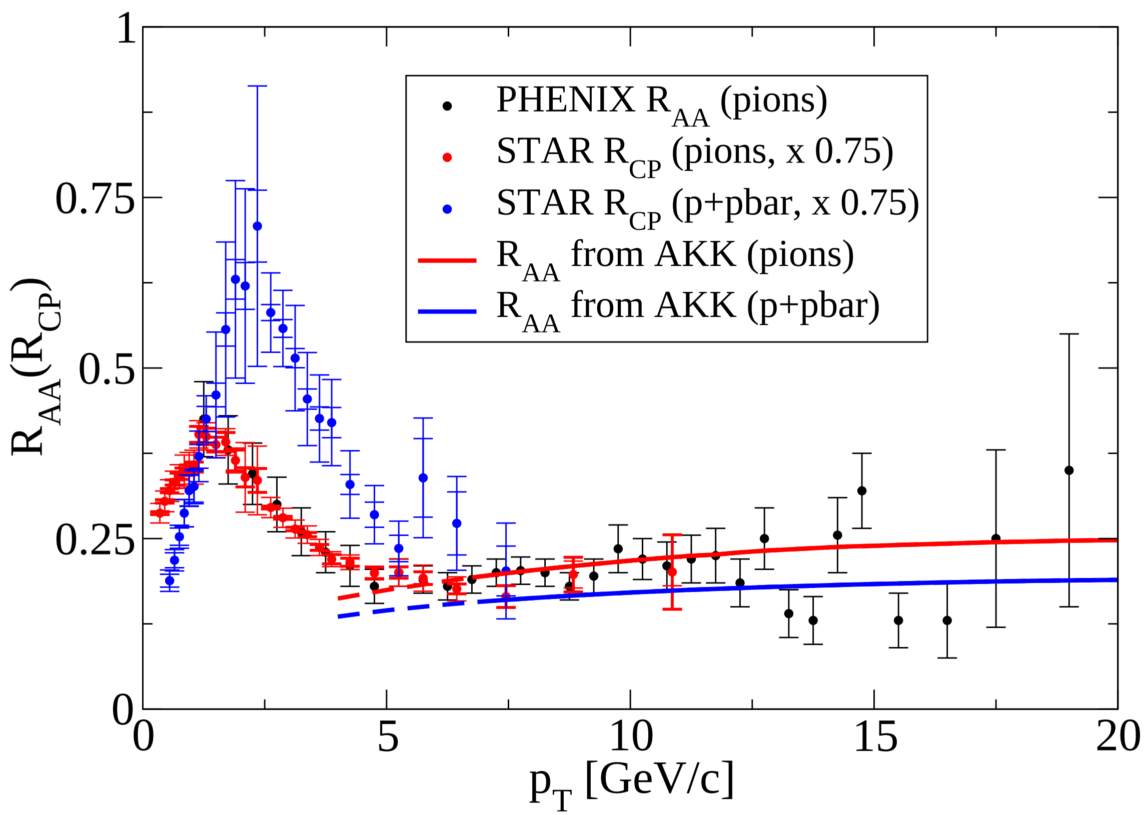
Idea: find probes which are dominated by

- quark fragmentation (D- and B-meson production, not topic of this talk)
- both quark and gluon fragmentation (pions)
- gluon fragmentation (protons, according to AKK fragmentation function)

If the medium is very dilute. . .
. . . energy loss happens throughout the medium inducing *shift*
⇒ the probes should show different suppression

If the medium is very dense. . .
. . . a completely absorbing core is surrounded by a transmitting halo, suface bis
⇒ the probes should show the same suppression

# Experimental evidence




Experimentally, pion and proton suppression seems similar

$\Rightarrow$in agreement with strong absorption, no evidence for shift

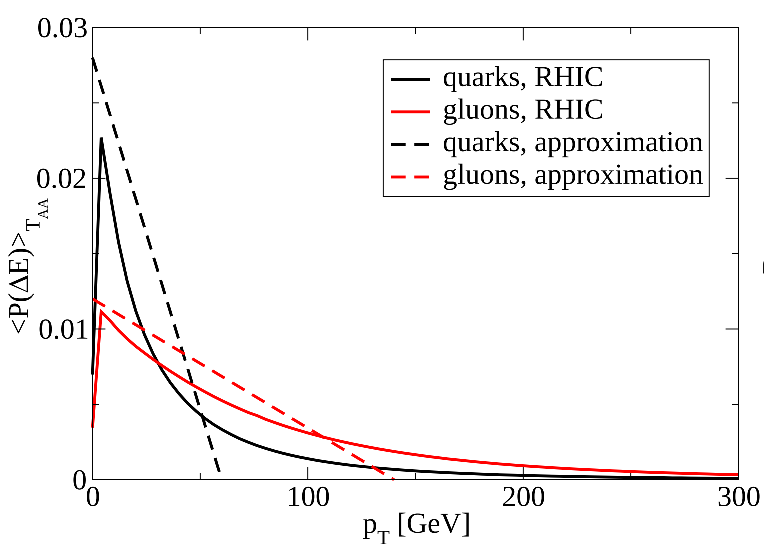
# A simple model

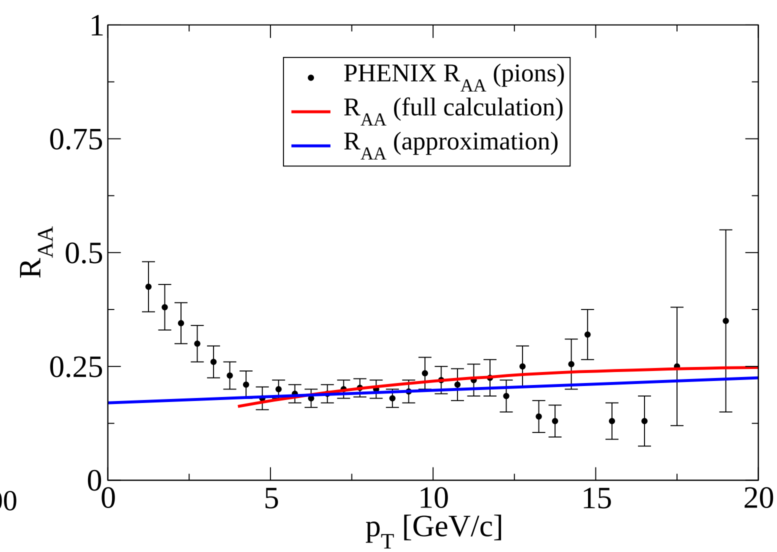
- assume a power-law spectrum $\sim 1/p_T^n$ ($n \approx 7, 8$ at RHIC)
- for massless partons, energy loss $\Delta E$ changes the spectrum to $1/(p_T + \Delta E)^n$, thus

$$R_{AA} \approx \int d\Delta E \langle P(\Delta E) \rangle_{T_{AA}} 1/(1 + \frac{\Delta E}{p_T})^n$$

- approximate expressions for shift term $P(\Delta E)$

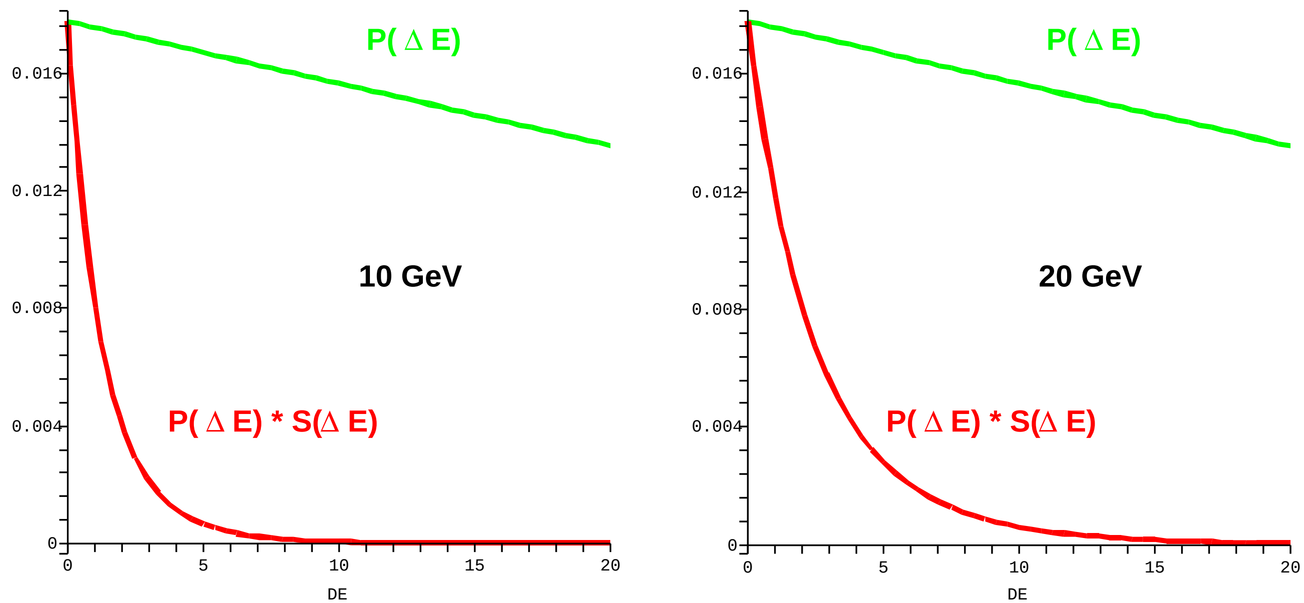
$\Rightarrow$ decent description of $R_{AA}$



# A SIMPLE MODEL

- suppression by $\Delta E \Leftrightarrow$ penalty factor $S(\Delta E) = 1/(1 + \frac{\Delta E}{p_T})^n$
- at a scale $p_T$, we observe $\langle P(\Delta E)\rangle_{T_{AA}}$ through this filter




$\Rightarrow$ shift becomes unobservable long before $\Delta E \approx E$

$\Rightarrow$ at RHIC, $p_T$ can never be enough to observe more than the onset of $\langle P(\Delta E)\rangle_{T_{AA}}$

$\Rightarrow$ on the other hand, parametrically a rise of $R_{AA}$ with $p_T$ is unavoidable

$\Rightarrow$ This seems to be the fundamental reason for the observed flatness of $R_{AA}$

# What can LHC do?

When going to higher energies

• the medium density grows like $\sim \log(\sqrt{s})$ (PHOBOS) or $\sim \sqrt{(s)}^{0.574}$ (EKRT)
• the kinematically accessible region grows like $\sim \sqrt{s}/2$

$\Rightarrow$ the kinematical window will always win out

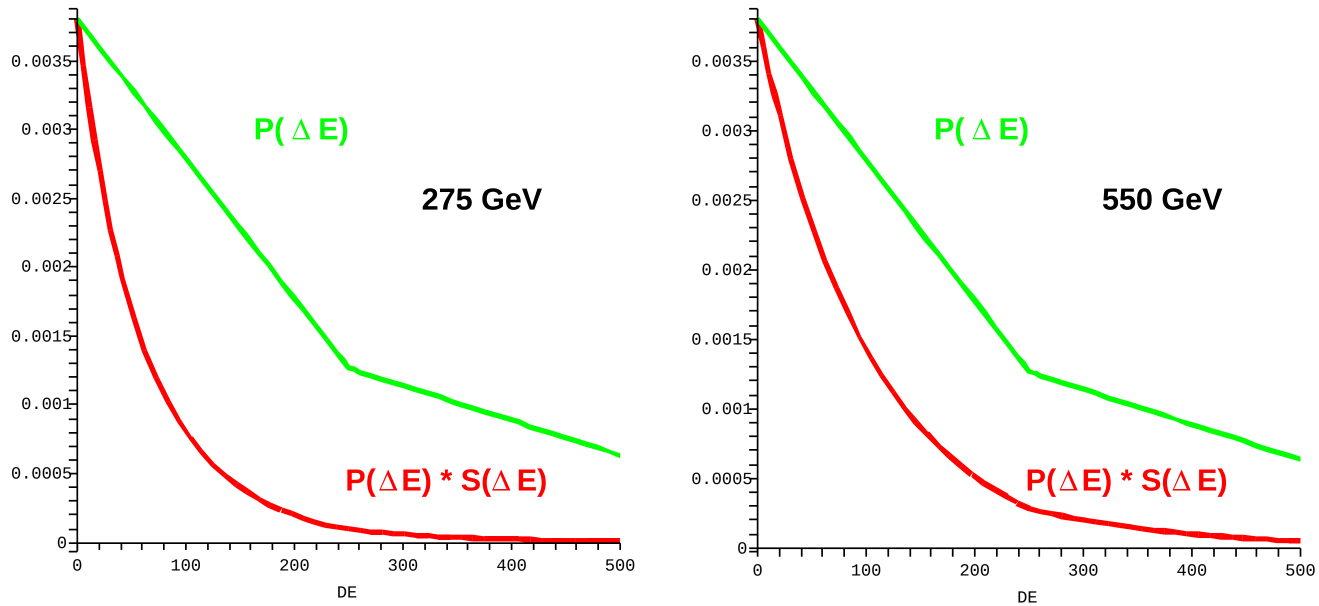
$\Rightarrow$ quite generic expectation for a rise of $R_{AA}$ in the $p_T$ range of LHC

since the reason for the rise is the shift term becoming more and more visible

Magnitude and shape of the rise will reflect the shape of the underlying energy loss probability distribution - needs high statistics and large $p_T$ range

# SIMPLE MODEL FOR LHC

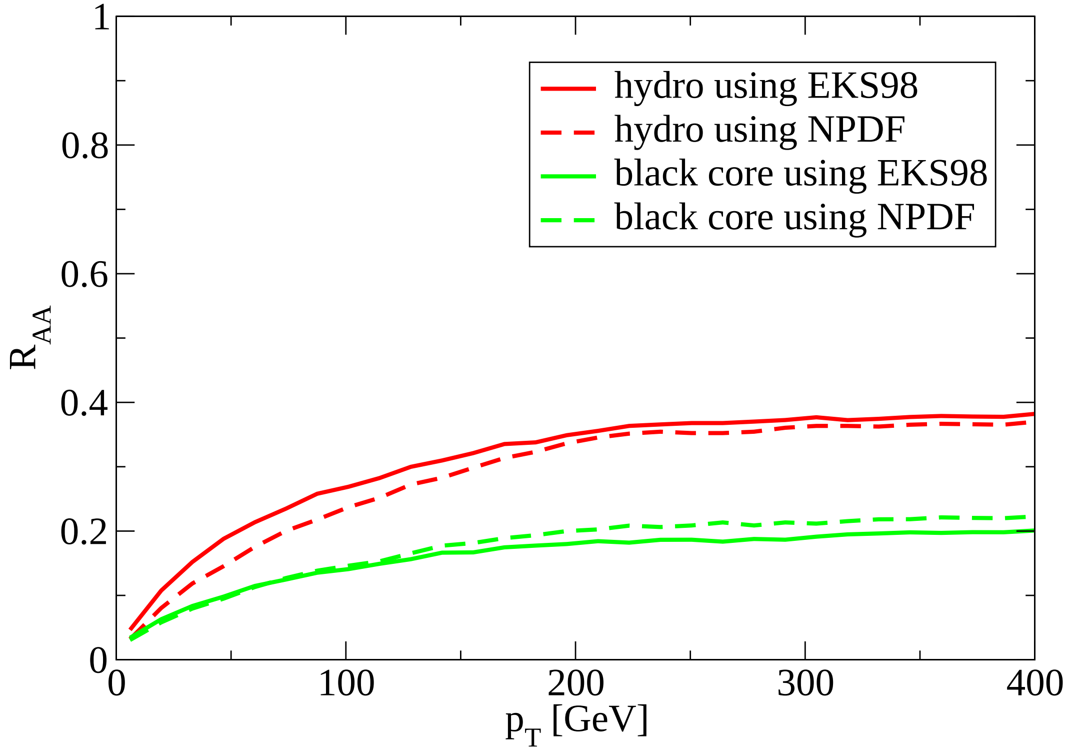
- choose $\langle \Delta E \rangle_{LHC} = 6 \langle \Delta E \rangle_{RHIC}$ (EKRT)
- LHC spectrum is harder, $n \approx 4$




For $p_T$ at same fraction of $\sqrt{s}$ from RHIC to LHC, much more of the shift is seen!

# Full calculation for LHC

- minijets and initial state saturation for initial state
- hydrodynamics with RHIC-tested parameters
- jet-quenching in this soft medium with RHIC-tested parameters




⇒ detailed calculation shows a rise compatible with the result from the simple model

⇒ details of the rise reflect $p_T$-shift vs. parton absorption

# Single hadron observables

+ value of $R_{AA}$ indicates strong quenching

+ flat $R_{AA}$ and proton $R_{AA}$ point to dominance of absorption

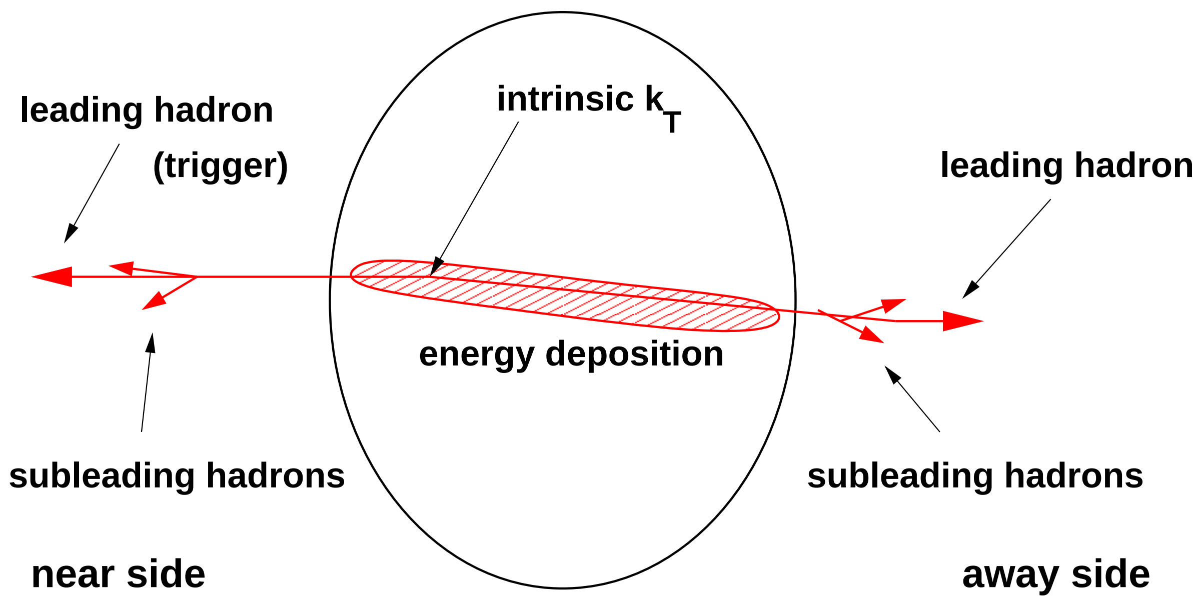
- small sensitivity to shift, hence little tomographical information

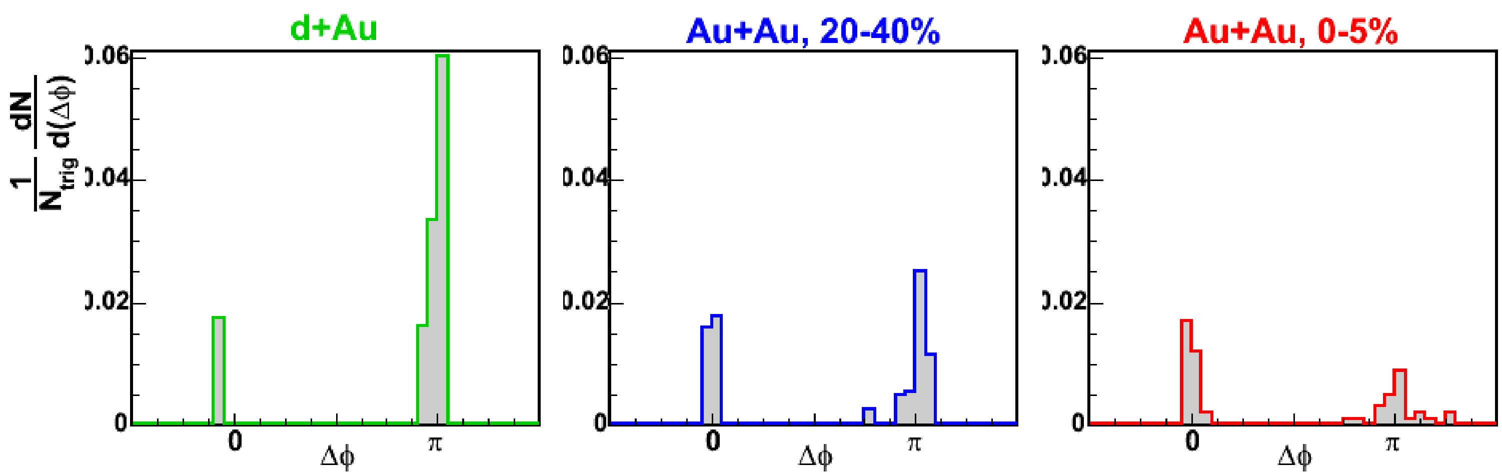
- difficult to disentangle medium geometry and energy loss

+ expected to improve at LHC

Improvements are possible: $R_{AA}$ vs. reaction plane and $R_{AA}$ for different system size provide systematic variations of pathlength

# Dihadron correlations



# Dihadron correlations

Near side:

• hard parton energy (and type)

⇒ parton spectra from LO pQCD

⇒ vertex sampling from nuclear overlap

⇒ probabilistic $\Delta E$ 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

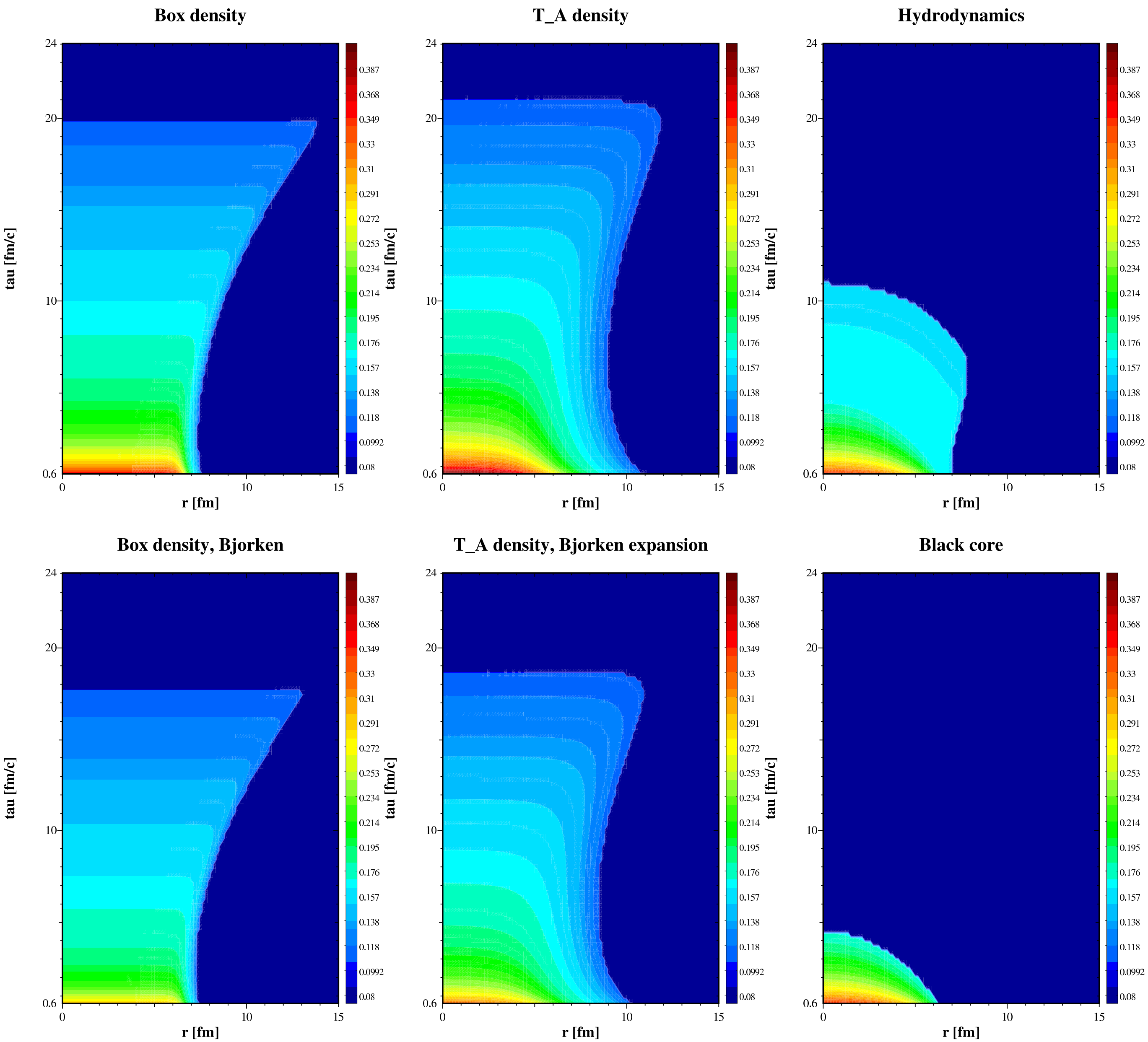
⇒ away side probabilistic $\Delta E$ from in-medium path

⇒ near and away side (N)L fragmentation

→ count emerging hadrons above associate threshold

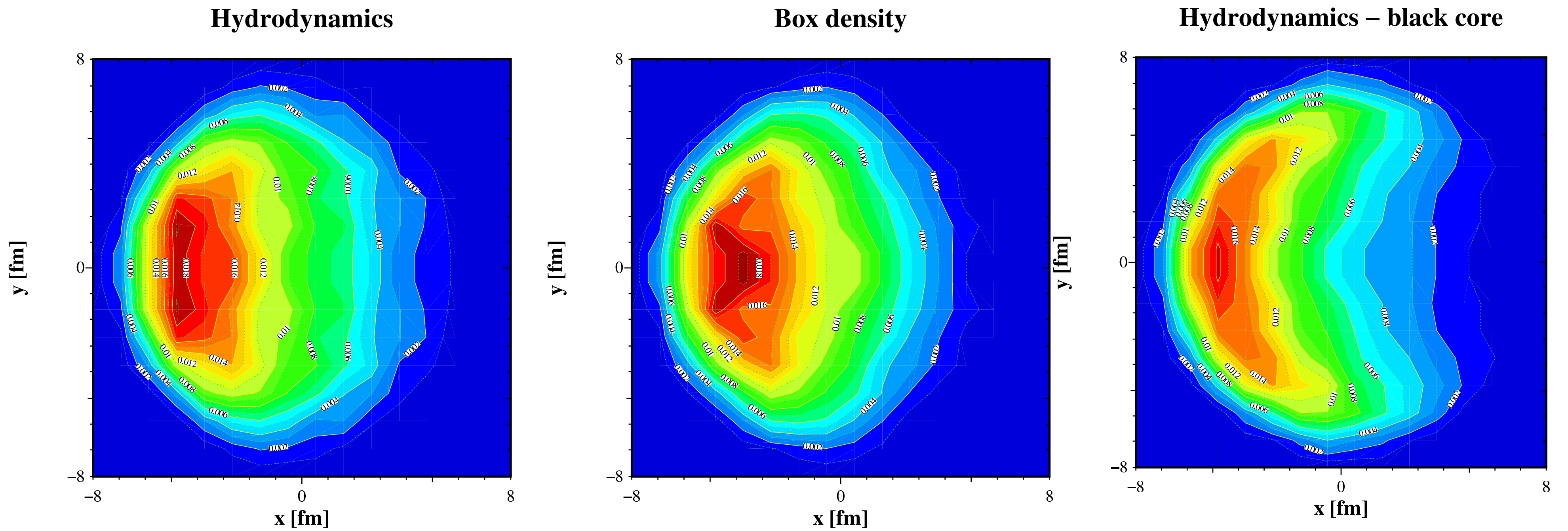
Contains all information on trigger bias, pathlength distribution, nuclear density. . .

# Density models



# SUFRACE BIAS

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



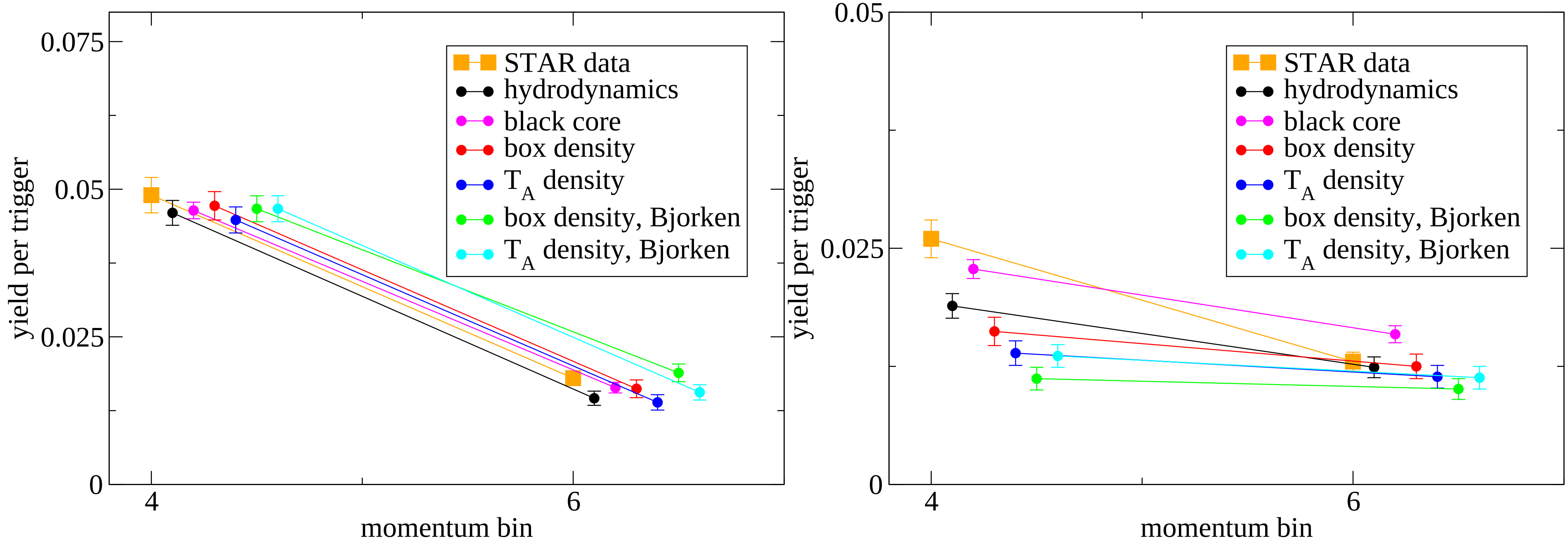

The away side yield must be averaged over this distribution rather than $\frac{[T_A(\mathbf{r_0})]^2}{T_{AA}(0)}$

$\Rightarrow$ expect different away side suppression even for identical $R_{AA}$

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

# 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 $\rightarrow$ recombination

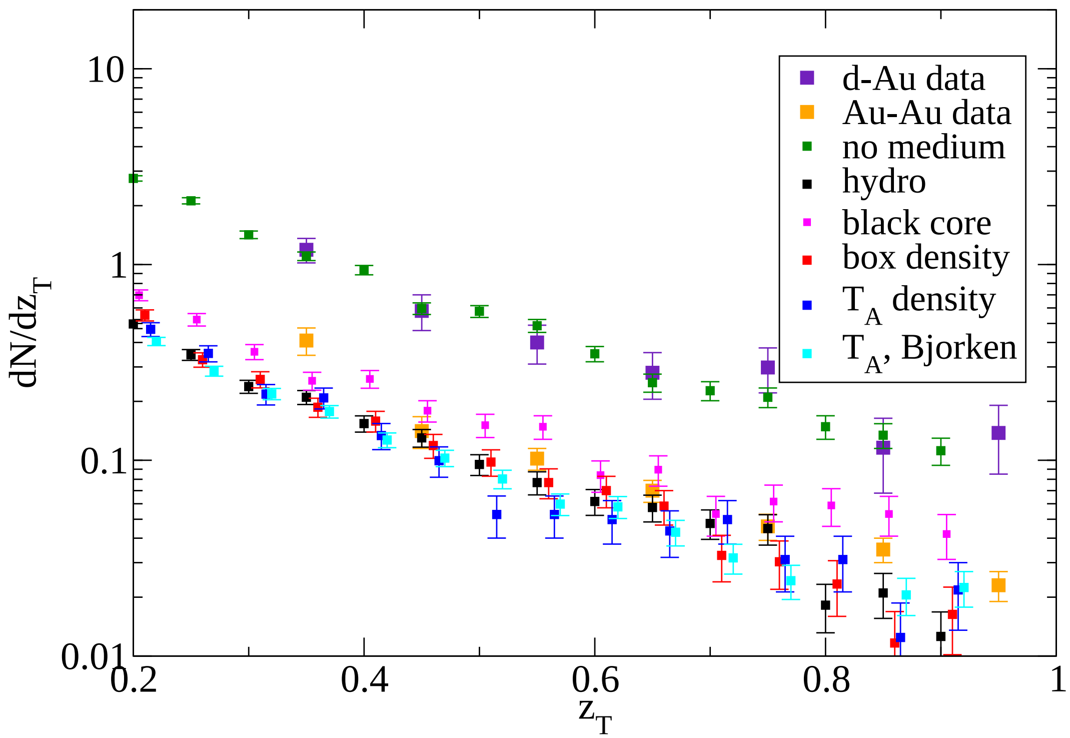
discrimination between models with *almost identical* $R_{AA}$

Some sensitivity to medium density distribution

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

# Dihadron correlations

Away side: $z_T$-distributions ($p_T^{assoc} = z_T \cdot p_T^{trig}$):

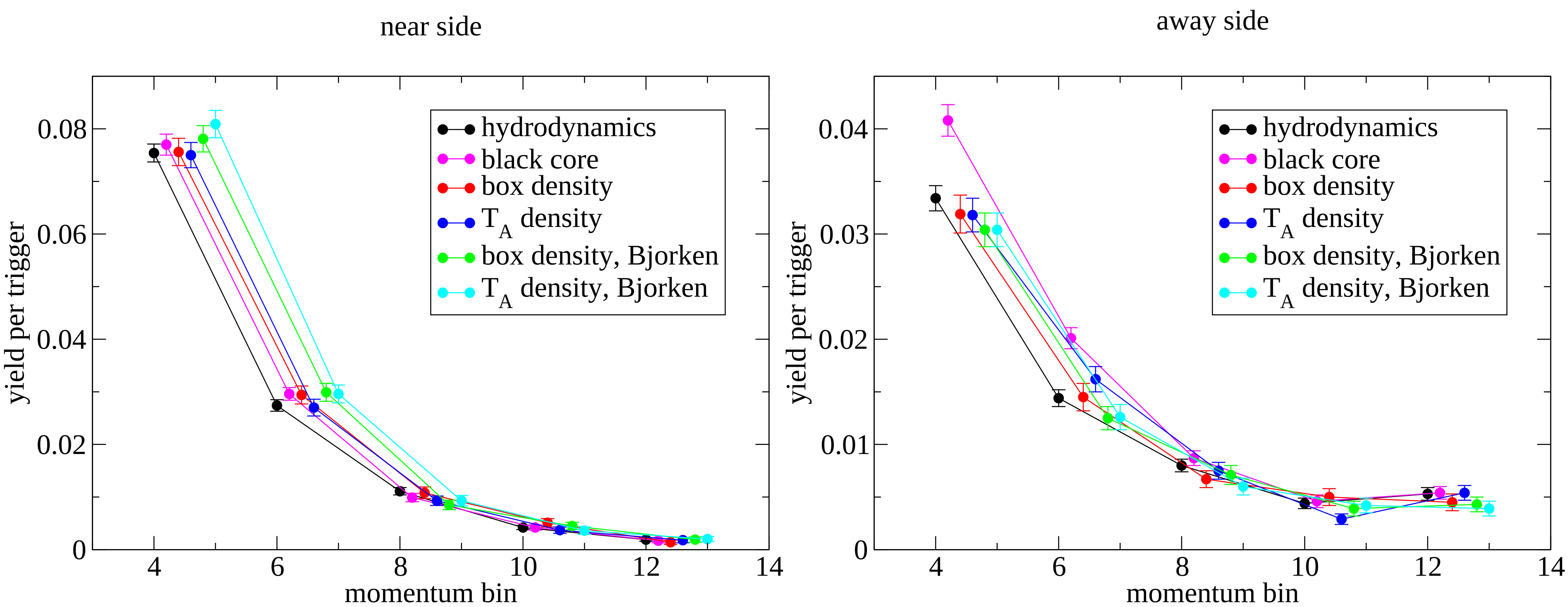



No additional information, shape consistent with all density models but black core

The medium is strongly absorbing, but not completely surface dominated

# Dihadron correlations

More leverage in momentum: 15 – 20 GeV trigger

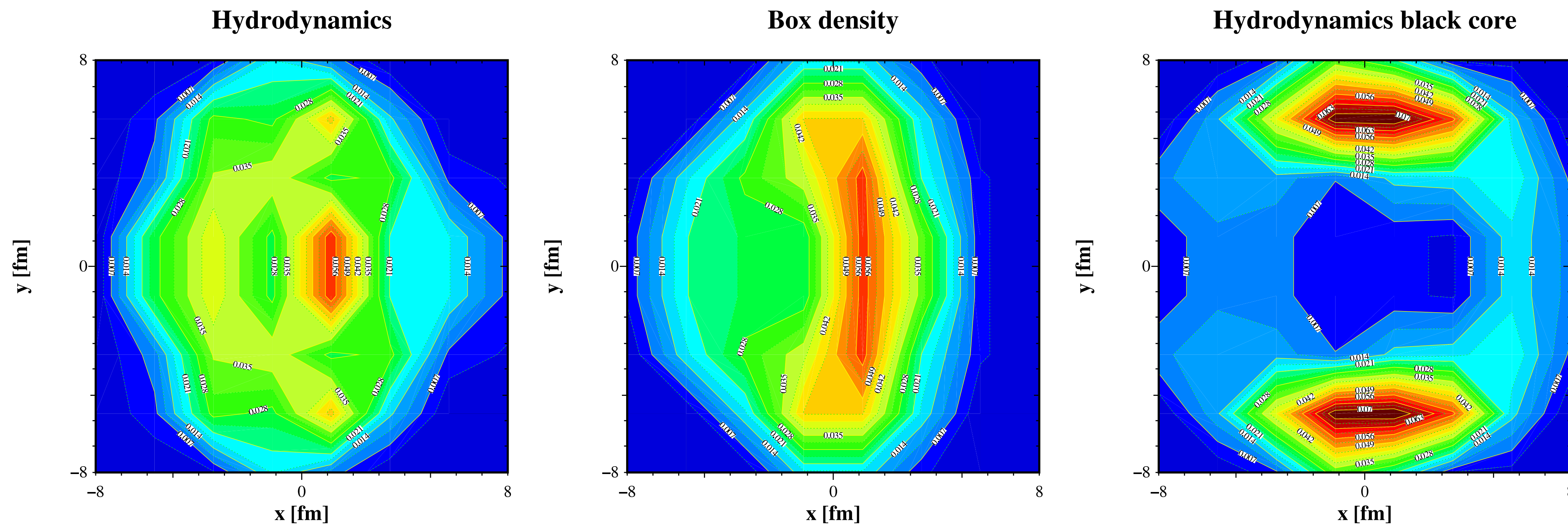



If sufficient precision can be reached, there is sensitivity to the density evolution
$\Rightarrow$ need some $p_T$ between trigger and associate to pick up momentum shift

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

# Origin of dihadrons

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

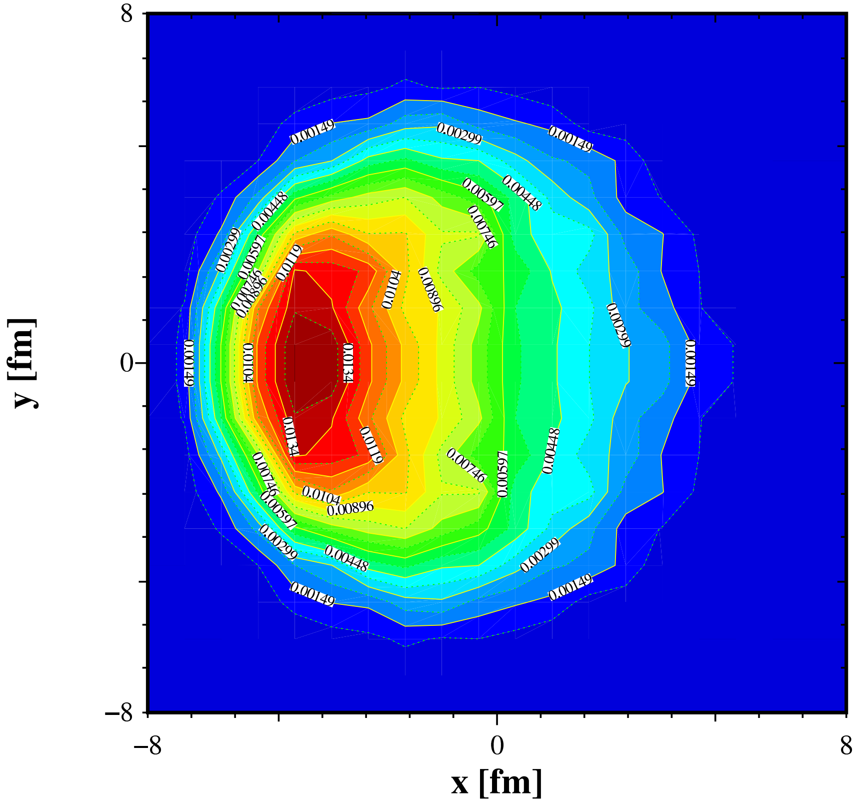



The observed dihadrons originate can from the medium center

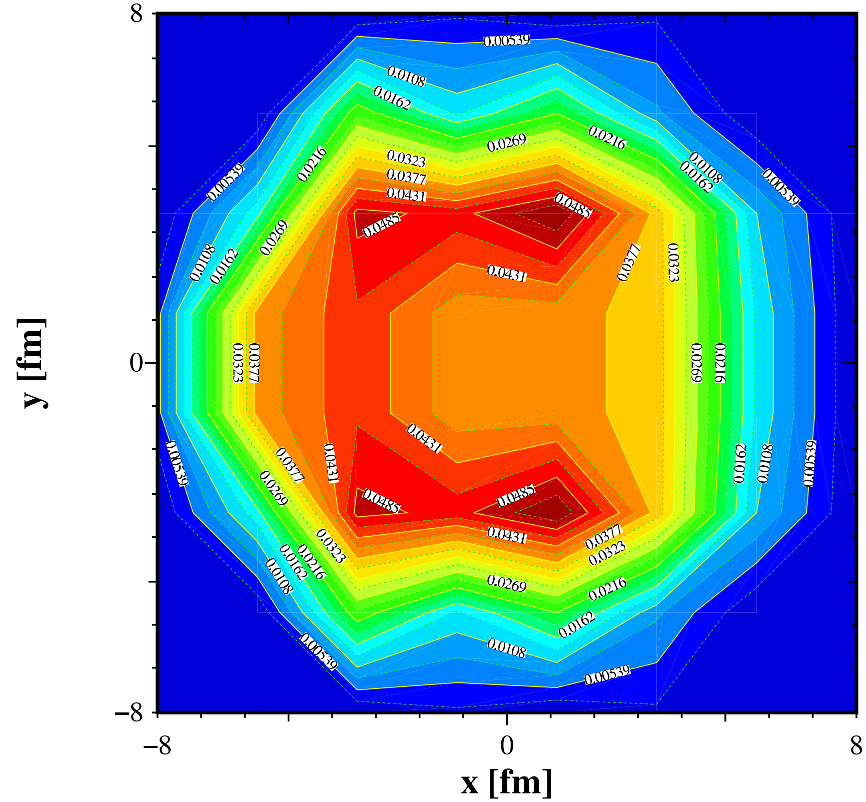
T. R. and K. J. Eskola, Phys. Rev. C **75** (2007) 054910

# Dihadrons at LHC

**Trigger 25 GeV**




**Trigger 25 GeV and associate 10 GeV**




Some degree of surface bias for lower $p_T$ at LHC

# Hard di-hadron correlations

+ tomographical information beyond $R_{AA}$
+ probes medium center
+ very suited to large momentum lever-arm at LHC
- test of a density model, not measurement of a density
- needs high precision

If sufficient precision can be reached and the parton-medium interaction can be established, information about the medium density can be inferred from this observable.

# SUMMARY

- Jet quenching is established

⇒ now we're capable of addressing quantitative questions

- $R_{AA}$ is of limited value for medium tomography

- but we have other measurements to overcome this problem:
  * $\gamma$-hadron correlations: $T_{AA}$ averaged energy loss probability
  * dihadron correlations: density distribution at medium center
  * $R_{AA}$ vs. reaction plane: early hydro evolution at edge

- we need:
  * good medium models
  * refined jet-medium interaction models
  * high precision data

Lots of exciting results still to come!