Hard Probes in Heavy-Ion Physics

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Introduction
- the physics we're ultimately after

Elastic and radiative processes
- how partons interact with a medium

Single hadron observables
- the concept of medium induced energy loss

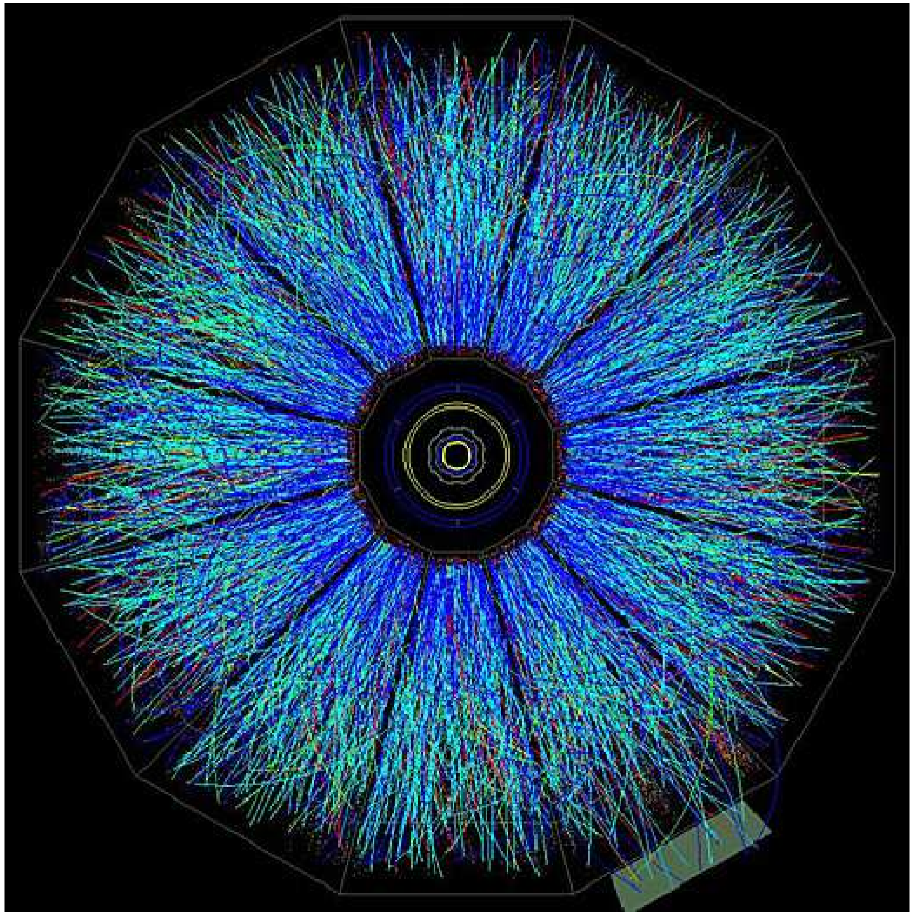
Hard correlations

In-medium Jets

Medium recoil from hard probes
- where lost energy reappears

Summary and outlook

Part I: Introduction



What is the motivation to study collisions with O(10.000) produced particles?

Central 200 AGeV Au-Au event in the STAR TPC

Exploring QCD

Aim: Explore Quantum Chromodynamics (QCD) in different limits

⇒ write the chapter on '**Collectivity and Thermodynamics**' in the QCD textbook

$$\mathcal{L}_{QCD} = \mathcal{L}_q + \mathcal{L}_{\mathcal{G}} = \overline{\Psi}(i\gamma_\mu D^\mu - \mathbf{m})\Psi - \frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu}$$

with

$$\mathcal{G}_{\mu\nu} = (\partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A_{\mu,b} A_{\nu,c}) t_a \quad \text{and} \quad D_\mu = \partial_\mu - i g t_a A^a_\mu$$

- high p_T dynamics of parton scattering and gluon radiation
- low p_T soft scattering dynamics
- rich vacuum structure: $\langle \overline{q} q \rangle$, gluon condensate, instanton configurations. . .
- running coupling, (de-)confinement and the structure of hadrons
- thermodynamics of strongly interacting matter and a phase transition
- transport properties of strongly interacting matter, viscosity,. . .

What is our toolkit to explore all this?

Two paradigms

- reductionism:

> The nature of complex things is reduced to the nature of sums of simpler or more fundamental things.

$\longrightarrow$ the way one usually thinks about high energy physics

- holism:

> There are properties of a given system which cannot be determined or explained by the sum of its component parts alone. Instead, the system as a whole determines in an important way how the parts behave.

$\longrightarrow$ the way one needs to think in heavy-ion physics

$\Rightarrow$ comprehensive modelling, one cannot e.g. separate high p_T and low p_T dynamics

In *principle*, knowing the QCD Lagrangean means we understand QCD.
In *practice*, it does not - far from it.

Probing hot QCD matter

If we are after '**Collectivity and Thermodynamics**' in QCD, do we really probe properties of hot QCD matter in heavy-ion collisions at collider energies?

We have O(10.000) particles in the final state, clearly there is massive production of secondary particles, clearly the dynamics is predominantly given by QCD — but does this qualify already for the claim that we see 'hot matter'?

More specifically:

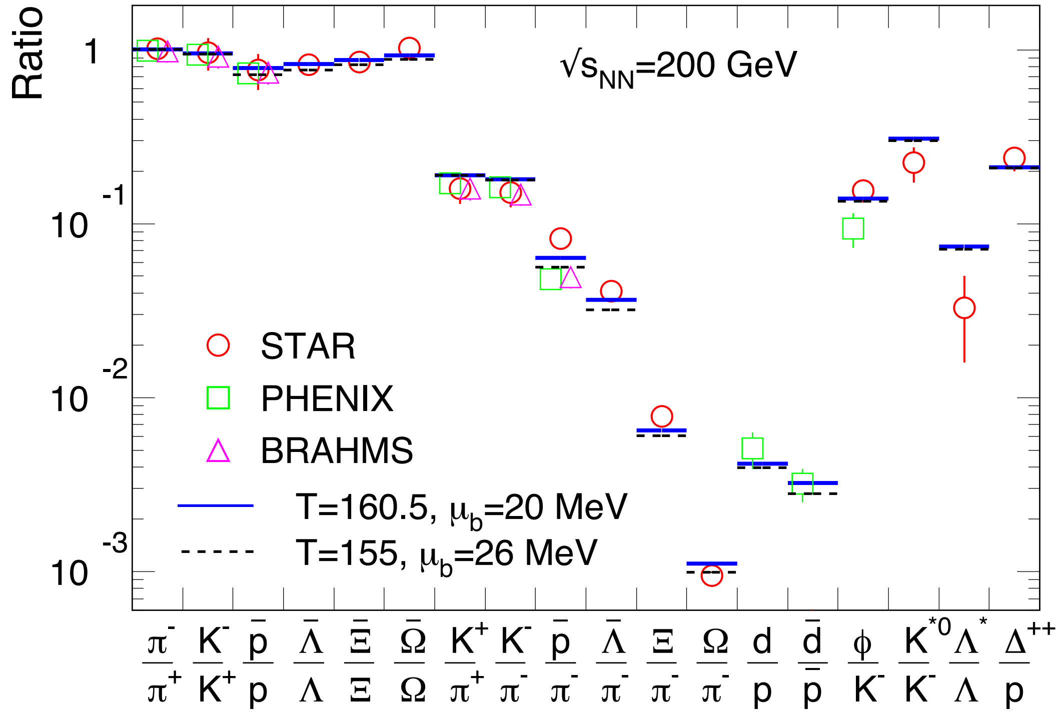
• Is what is created in the collision thermalized?
$\longrightarrow$ are phase space distributions of observed particles in equilibrium?

• Can what is created in the collision be called 'matter'?
$\longrightarrow$ is there enough final state interaction for collectivity?
$\longrightarrow$ does the system evolve differently from elementary collisions?

Let's see some evidence for both claims. . .

Evidence for thermal distribution

- simple statistical ansatz for hadron yields $n_i = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T] \pm 1}$
- for all hadrons and resonances, integrate over resonance widths
- calculate resonance decays
- depends on just two parameters, T and μ_b



$\Rightarrow$ almost perfect description of hadron yield ratios

A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **772** (2006) 167

Evidence for thermal distribution

Well... maybe this is just phase space dominance? Maybe the yield in a single event is not thermal, but as we average over many, we tend to fill the available phase space uniformly.

• note that the fit gets multistrange hadron ratios like Ω/π right!
$\Rightarrow$ the implicit model assumption $n_s \sim n_u \sim n_d$ works!

• this is very different for $p - p$ collisions at the same energy
$\rightarrow$ u and d quarks can come from the valence distribution
$\rightarrow$ s must come from sea or $q\overline{q} \rightarrow s\overline{s}$ or $gg \rightarrow s\overline{s}$

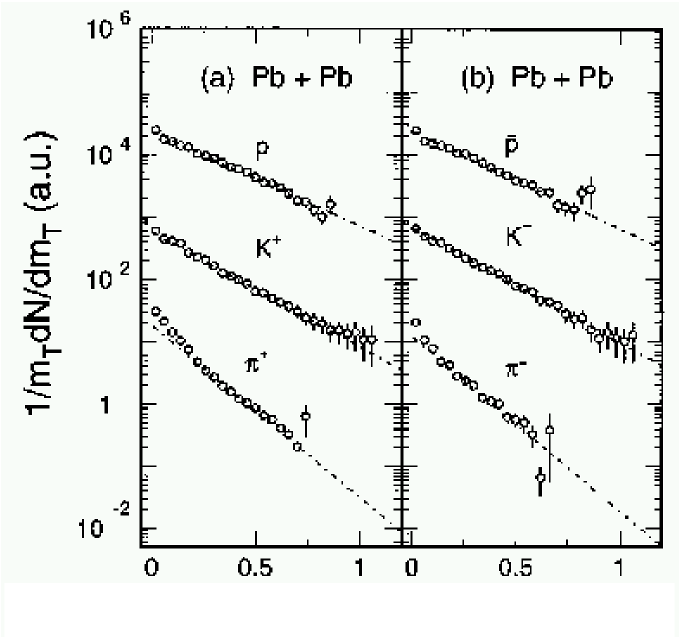
$\Rightarrow$ evidence for secondary production of s with thermal abundance

• moreover, in p-p collisions strangeness must be conserved **locally**
$\rightarrow$ strong suppression factor as compared to Grand Canonical ansatz

$\Rightarrow$ strangeness propagates freely across large distances — deconfinement?

Is there better and more evidence for collectivity?

Flow and mass scaling of $m_\perp$ spectra



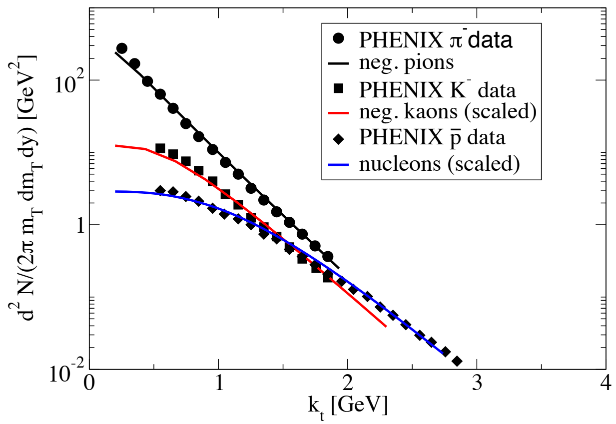
SPS 17.3 AGeV Pb-Pb collisions:

- mass ordering of transverse momentum spectra
- empirical formula:

$\frac{1}{m_T}\frac{dN}{dm_T} \sim \exp[-m_T/T^*]$ with $m_T = \sqrt{p_t^2 + m^2}$

- effective temperature $T^* = T + m\langle v_T\rangle^2$

$\Rightarrow$ thermal and collective motion



RHIC 200 AGeV Au-Au collisions:

- model bulk-medium as fluid
- fluid locally thermalized $\rightarrow$ EOS of QCD
- fluid pressure drives expansion
- at freeze-out conversion to hadrons

$\Rightarrow$ good description of data

I. G. Bearden *et al.* [NA44 Collaboration], Phys. Rev. Lett. **78** (1997) 2080; T. R., Phys. Rev. C **70** (2004) 021903.

Relativistic viscous fluid dynamics

The basics of relativistic fluid dynamics:

- energy-momentum and current conservation:

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu j_i^\mu = 0$$

- energy-momentum tensor for zero mean free path (ideal hydrodynamics):

$$T_{id}^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu}$$

- for small mean free path: additional terms (viscous hydrodynamics):

$$T^{\mu\nu} = T_{id}^{\mu\nu} + \Pi^{\mu\nu}$$

where $\Pi^{\mu\nu}$ contains various gradients, e.g. shear from velocity gradients

$\Pi^{\mu\nu} = \pi^{\mu\nu} + \Delta^{\mu\nu}\Pi$ and $\pi^{\mu\nu} = \eta\nabla^{\langle\mu}u^{\nu\rangle} - \tau_\pi \left[\Delta^\mu_\alpha \Delta^\nu_\beta u^\lambda \partial_\lambda \pi^{\alpha\beta} + \frac{4}{3}\pi^{\mu\nu}(\nabla_\alpha u^\alpha)\right] + \ldots$

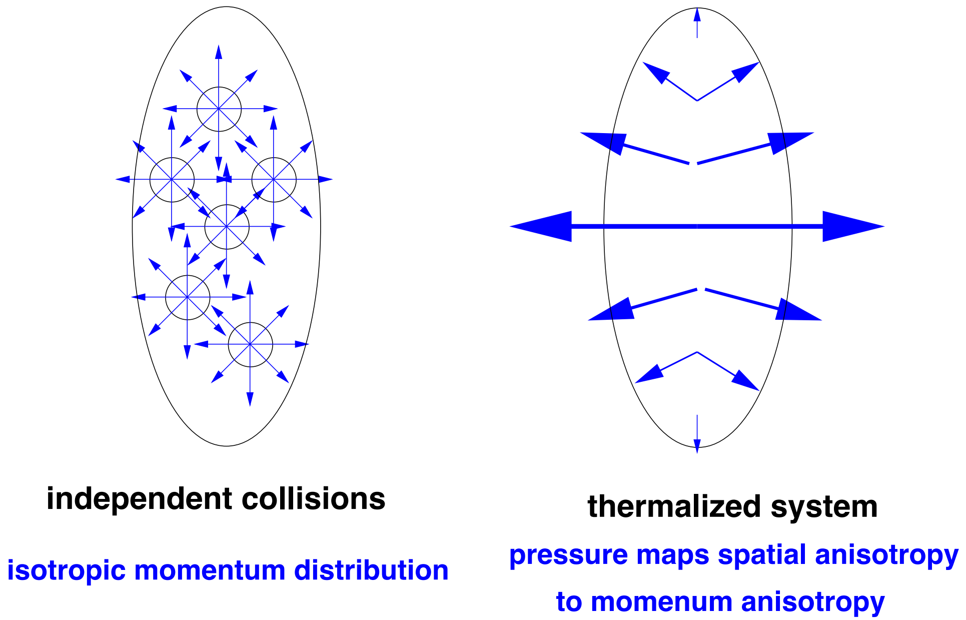
needs to include up to 2nd order gradients for stable, causal result!

- breakthrough in numerical treatment

Romatschke and Romatschke 2007, Dusling and Teaney 2007, Song and Heinz 2008, Molnar and Huovinen 2008

Elliptic flow

Further important consequence of fluid picture: elliptic flow in non-central collisions

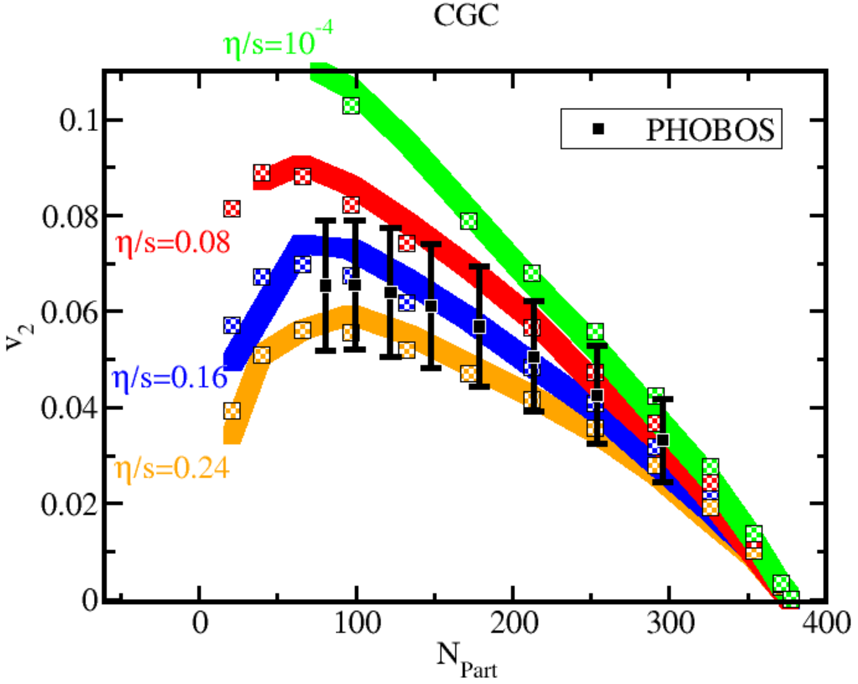


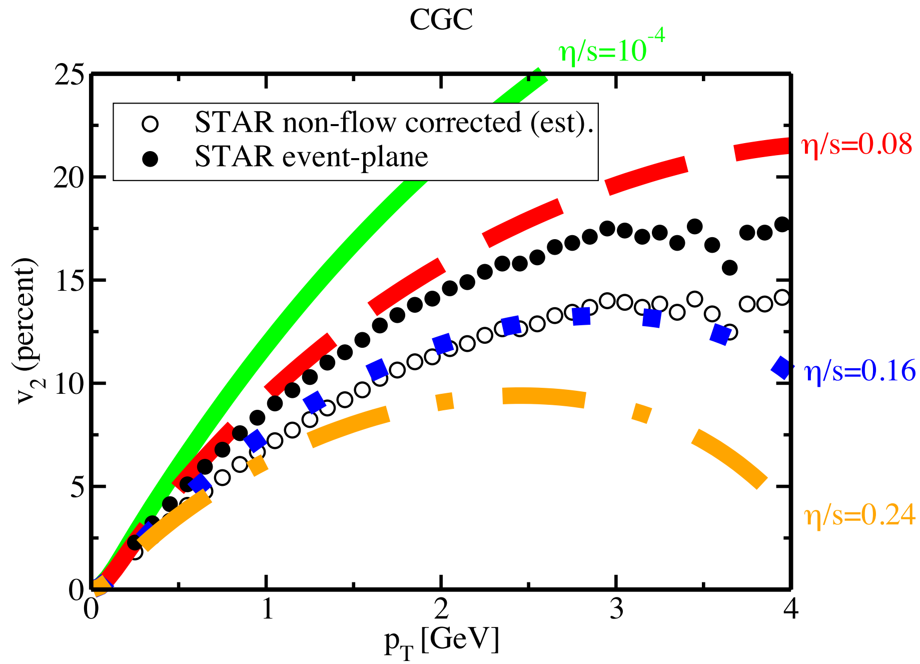
- pressure maps spatial anisotropy into momentum anisotropy
- angular distribution of hadrons: $\frac{dN}{d\phi} = \frac{1}{2\pi}[1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots]$
- the second harmonic coefficient v_2 measures this effect

Fluid dynamics should describe $v_2(p_T, N_{part}, \ldots)$!

The (almost) ideal fluid

It does — but with almost vanishing viscosity/entropy density η/s:





- superfluid Helium has $\eta/s \sim 10$ times larger!
- mean free path is *very* small, strong collectivity

⇒ origin of the 'near-perfect liquid' picture

M. Luzum and P. Romatschke, Phys. Rev. C **78** (2008) 034915

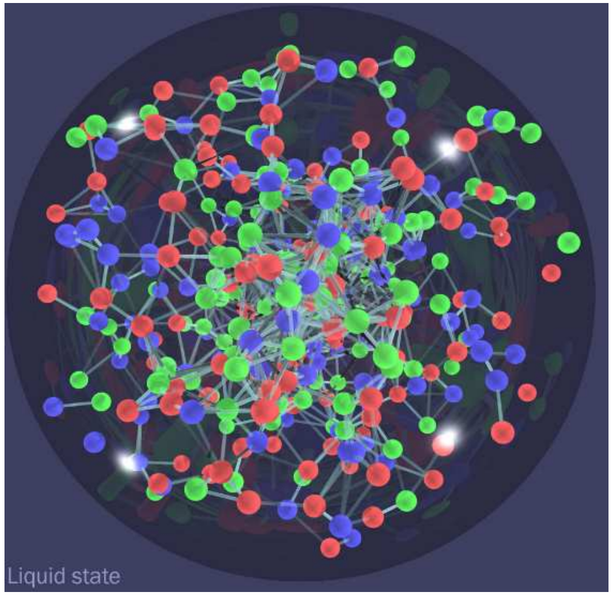
Breakdown of fluid picture

Are all observed particles thermalized? Clearly not:

• spectator nucleons → go down the beampipe

• photons and leptons couple via QED
⇒ mean free path a factor ~ 100 larger, escape without rescattering

• at high p_T, spectral shape is not thermal but pQCD



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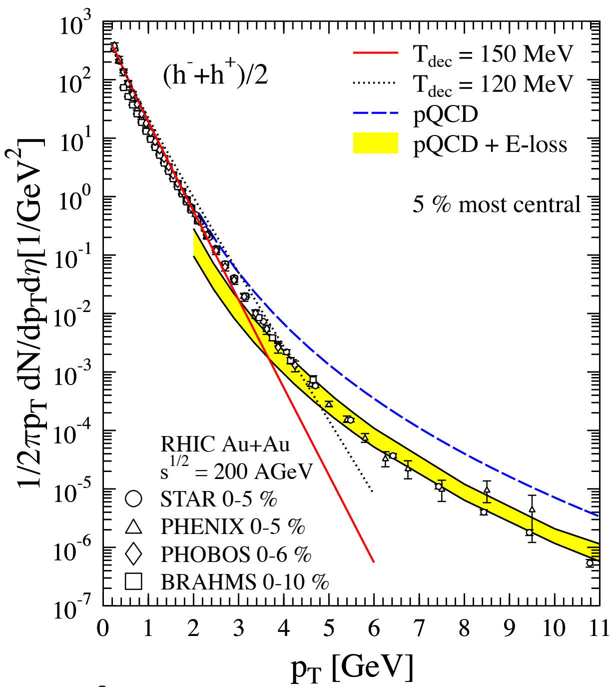
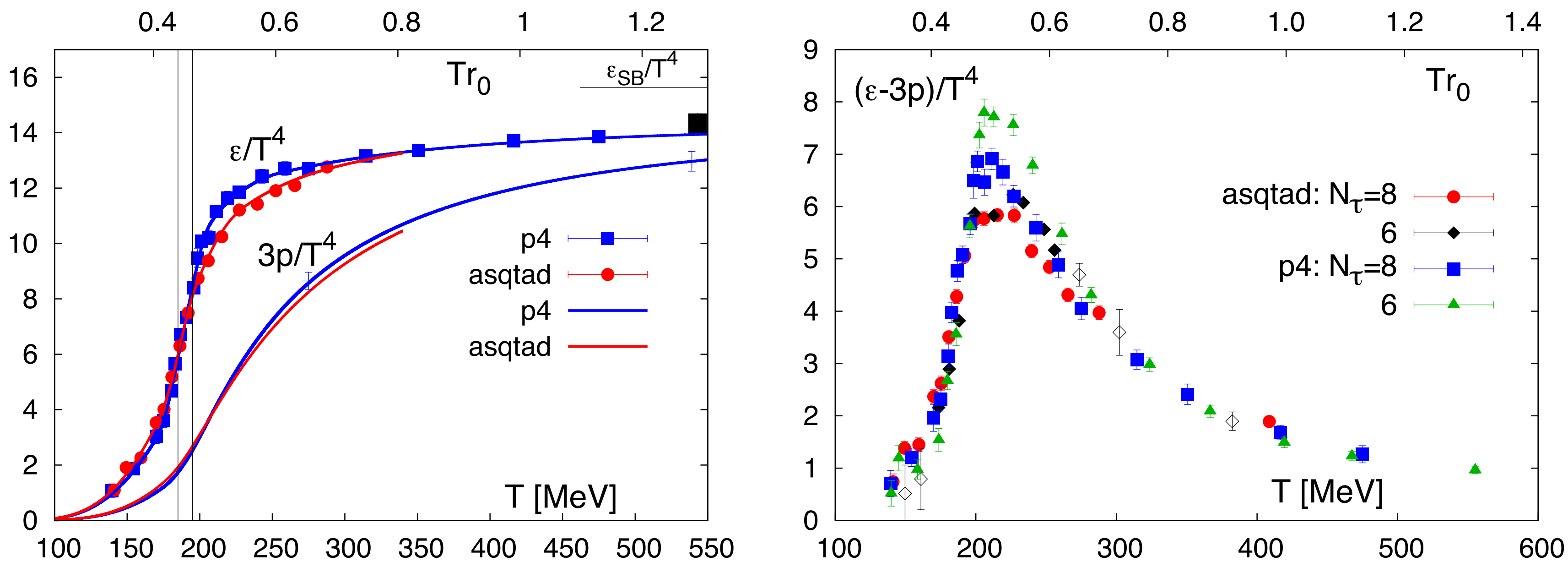


⇒ we can distinguish **remnants, bulk** and **probe**

K. J. Eskola, H. Honkanen, H. Niemi, P. V. Ruuskanen and S. S. Rasanen, Phys. Rev. C **72** (2005) 044904

The bulk

• thermalized matter at momentum scales $O(100)$ MeV (95% of particles)
→ realizes QCD thermodynamics and collective phenomena

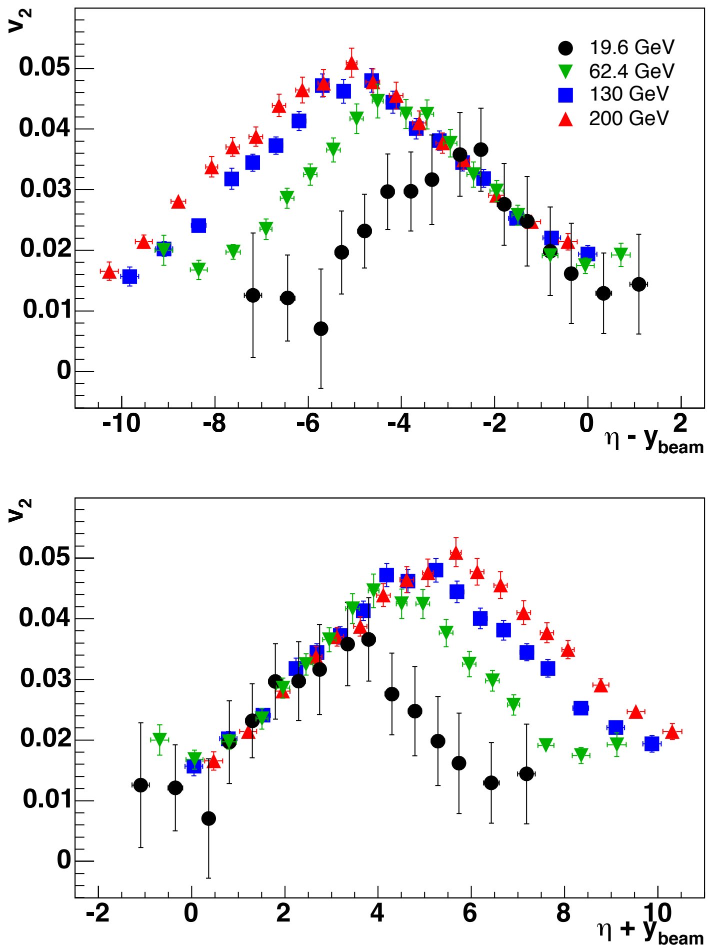


• from lattice QCD: phase transition, no ideal gas behaviour
→ above T_C partonic DOF, Quark-Gluon-Plasma (QGP)
→ below T_C hadronic DOF, hadron resonance gas (HRG)
• expect to see deconfinement and chiral restoration at some point

A. Bazavov *et al.*,0903.4379 [hep-lat]

The role of LHC

Why is a 5.5 ATeV Pb-Pb collision interesting for phenomena at $O(100)$ MeV?



- scaling of $v_2(\eta)$ with beam rapidity
$\longrightarrow$ 'slow' change with $\sqrt{s}$

- does this persist at LHC?
$\longrightarrow$ *not* expected by hydrodynamics

- (dis-)agreement with predictions reveals dynamics
$\longrightarrow$ only visible with large kinematic lever-arm

Crucial information in the excitation function of collective phenomena!

B. B. Back *et al.* [PHOBOS Collaboration], Phys. Rev. Lett. **94** (2005) 122303

The probes

- probes — particles not in thermal equilibrium

- several auto-generated probes

$\rightarrow$ γ, e^+e^-: negligible final state interaction, view into the medium
$\rightarrow$ high p_T quarks and gluons: interactions with the medium
$\rightarrow$ charmonia, heavy bound states: color screening in the medium

- are usually **rare**, either due to e.m. coupling or due to a large scale

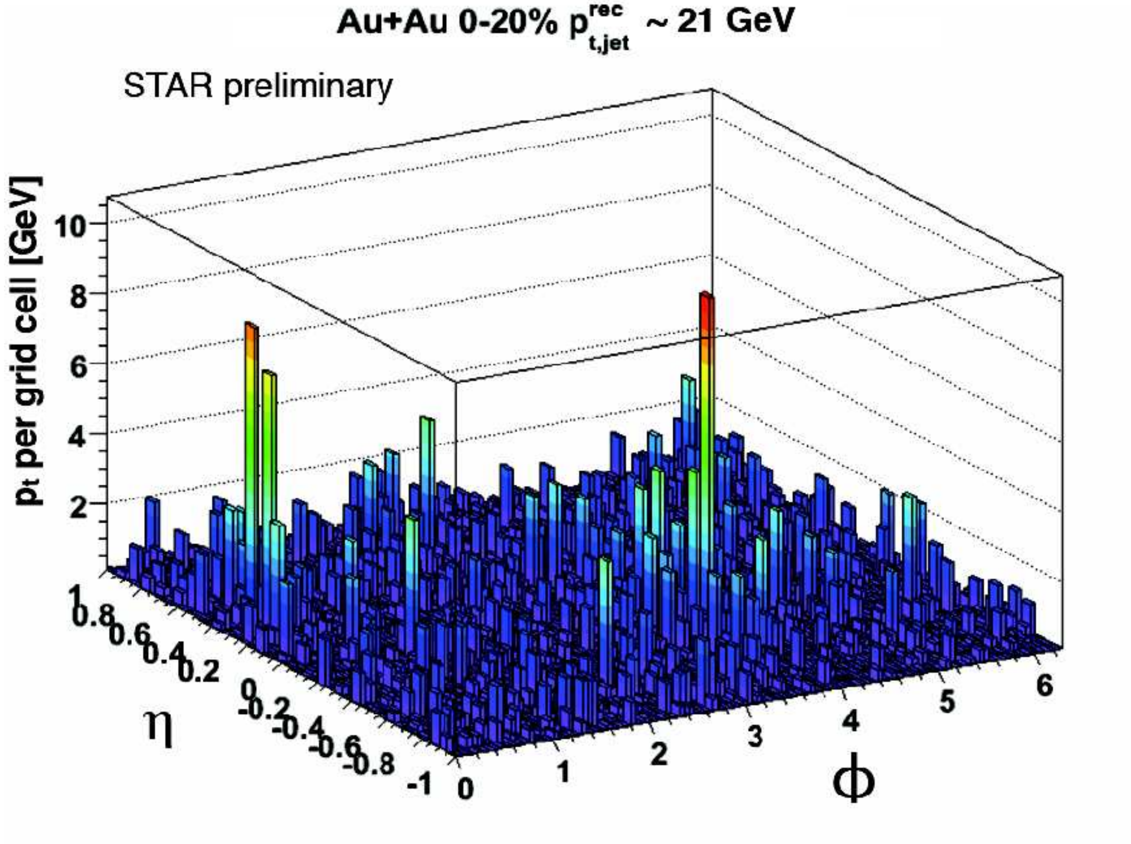
- but production process can be factorized from the bulk due to the same reasons

- particle with known production, interacting with the medium

$\Rightarrow$ probe *of* the medium, access to medium properties

Jet tomography

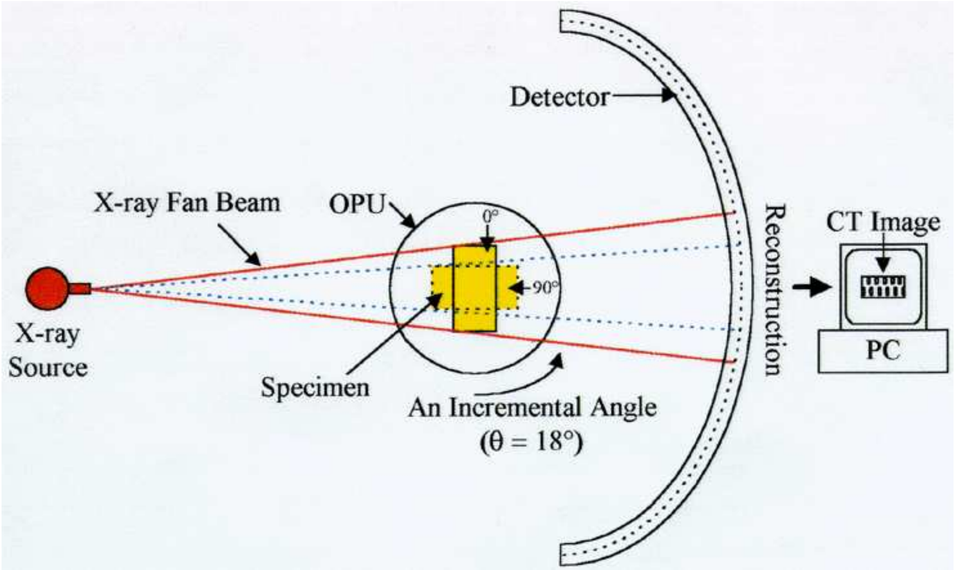
Jets and hard processes are the domain of colliders, but. . .

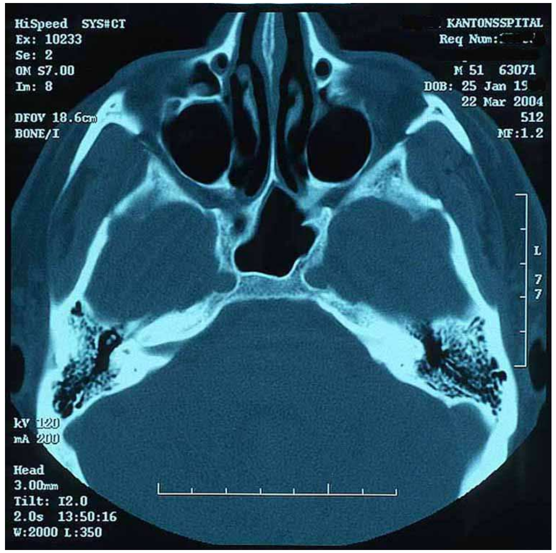


20 GeV jet event in STAR

. . . jets in heavy-ion collisions do **not** equal jets in p-p collisions
Can we exploit that to measure medium properties?

Tomography





Tomography: Tool to measure density distributions

- use known source
- let it propagate through the medium
- study the change induced by the medium

⇒ invert the problem to reconstruct the medium density

We can't shine a 'beam' of something through transient hot QCD matter — but we have hard processes in the collision available

Hard Probes

• fluid picture applies for $P_T \sim$ few T where $T \sim 100 - 300$ MeV (bulk matter)
$\Rightarrow$ what if $P_T \gg T$? (rare process)

By uncertainty principle arguments, for typical RHIC or LHC kinematics:

• initial hard process probes length scales at which the medium is irrelevant
$\Rightarrow$ expect production of high p_T partons to be unmodified

• QCD evolution of a parton shower probes length scales $\sim$ medium size
$\Rightarrow$ expect medium-modified shower evolution

• hadronization probes scales $\gg$ medium size
$\Rightarrow$ expect hadronization to be unmodified by medium

Known production of a probe which is subsequently modified by the medium, modifications are predominantly partonic physics and hence likely to be calculable in pQCD.

Tomography Comparison

Medical imaging	Heavy-Ion collisions
external probe	internal probe
clean probe/medium separation	scale separation between hard probe and soft medium
source position known	hard vertex position probability distribution known
monochromatic source	source distributed with pQCD parton spectrum
static target	evolving medium
full acceptance	limited detector acceptance

The situation in heavy-ion collisions is much more difficult!

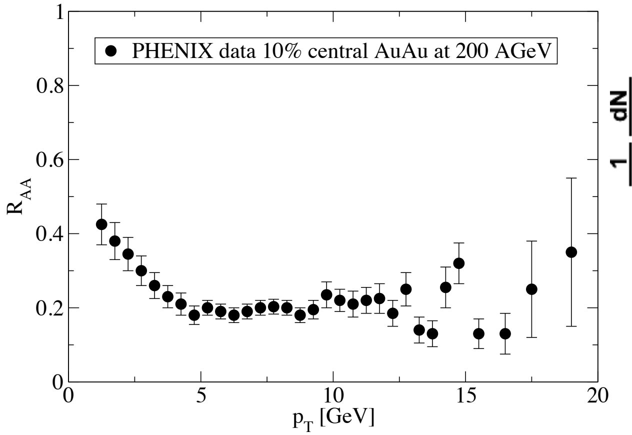
Nevertheless, the basic principle is sound: The medium attenuates hard partons:

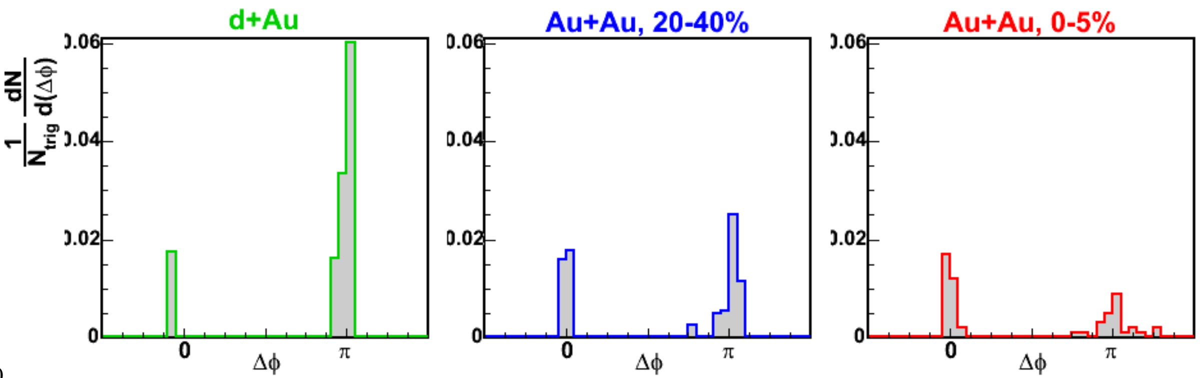
Nuclear suppression

- suppression of single inclusive high P_T hadrons

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

- 'monojet' phenomena, disappearance of back-to-back correlations





4 of 5 high P_T hadrons are modified by the medium

$\Rightarrow$ suggests picture of parton energy loss in the medium

Tomography goals

What can we hope to learn?

Three different conceptual areas influence the result:

• 1) production of a hard probe
$\longrightarrow$ well enough under theoretical control

• 2) interaction of hard probe and medium
$\longrightarrow$ this carries information about the medium DOF

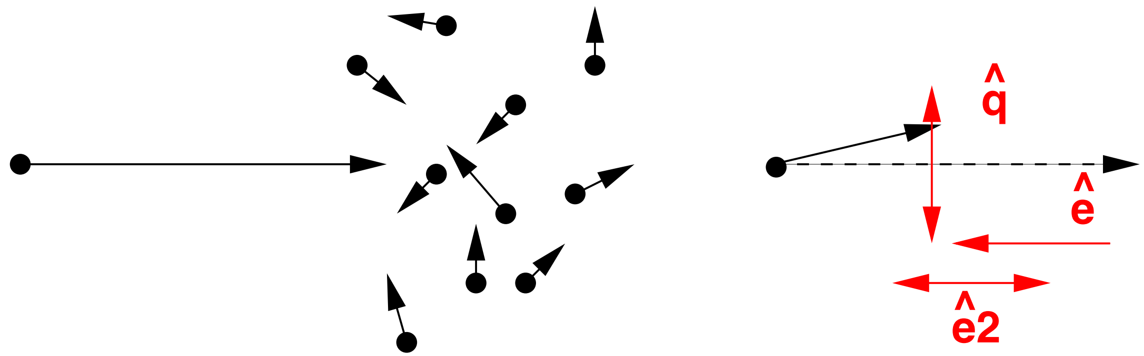
• 3) time evolution of the medium while the hard probe passes through
$\longrightarrow$ this carries information about the density evolution of the bulk

In medical imaging, one knows 1) and 2) and measures 3). Here, both 2) and 3) are unknown. Thus, we cannot expect precise informations, but rather constraints which must be used together with constraints from other measurements (remember the holistic nature of the problem?).

Transport coefficients

A generic way to characterize the effect of a medium on a hard parton:

- passage of a hard parton through a medium of thermal scattering centers



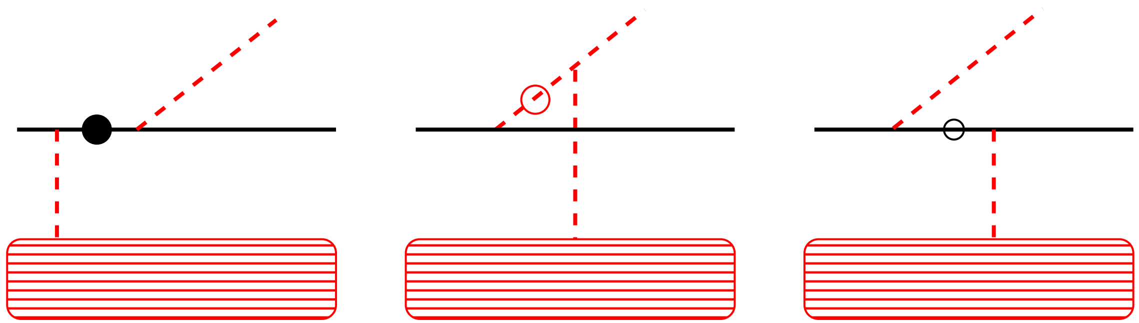
- loss of momentum along the original parton momentum vector: $\hat{e}$
- variance in fluctuation around $\hat{e}$: $\hat{e_2}$
- variance in transverse momentum fluctuation: $\hat{q}$

These transport coefficients depend on microscopical properties of the medium. Therefore, measuring them means obtaining parts of the tomographical information.

Drag vs. induced radiation

On first glance, it would seem that drag ($\hat{e}$) corresponds to energy loss. However, that is not necessarily the case since partons can be scattered off-shell:

- off-shell partons imply gluon radiation
- typical diagrams:



- medium-induced radiation can take a large fraction of the original parton energy
- including this mechanism, all transport coefficients are potentially important

The medium degrees of freedom

model 1: gas of quasi-free quarks and gluons with thermal distributions

- large $\hat{e}$ from 2-2 pQCD processes (qg $\rightarrow$ qg,. . .) where scattering partner recoils
- easy to model, but isn't a quantum liquid

$\rightarrow$ not in agreement with almost vanishing viscosity

- result (elastic recoil) depends on mass of scattering centers

$\rightarrow$ thermal field theory gives quasiparticle masses $O(gT)$

Underlying picture: the system is a collection of weakly coupled quasiparticles where the collective effects are chiefly absorbed into thermal masses and thermal screening of the coupling — more a gas than a liquid.

The medium degrees of freedom

model 2: heavy static scattering centers

- $\hat{e}, \hat{e_2} = 0$ since scattering centers never recoil
$\longrightarrow$ only medium-induced radiation as cause of energy loss

- rather drastic limit of large thermal masses/ correlated regions

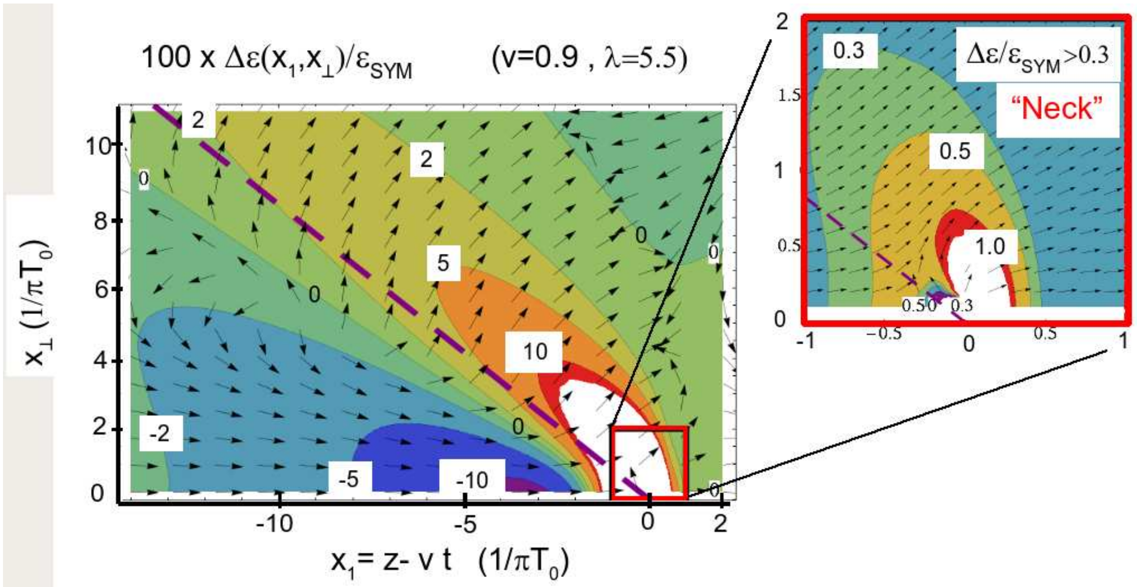
- somewhat *ad hoc* assumption

Underlying picture: the system is a collection of randomly distributed strongly correlated regions which each can be represented by a static colour dipole charge. Since the regions are 'large', they cannot take much recoil energy.

The medium degrees of freedom

model 3: strongly coupled system

- no well-defined quasiparticles
- possibly tractable using gauge/gravity dual



- strong drag, lost energy excites soundwaves

Connecting with observations

Transport coefficients are not directly observable: Unlike in CT imaging, we do not usually know parton kinematics *before* the interaction with the medium. We even don't know parton kinematic *after* interaction with the medium — all we observe is hadrons.

• infer information from changes in statistical averages of hadron distributions (R_{AA})
$\longrightarrow$ best statistics
$\longrightarrow$ very averaged process, no detaild tomographical information

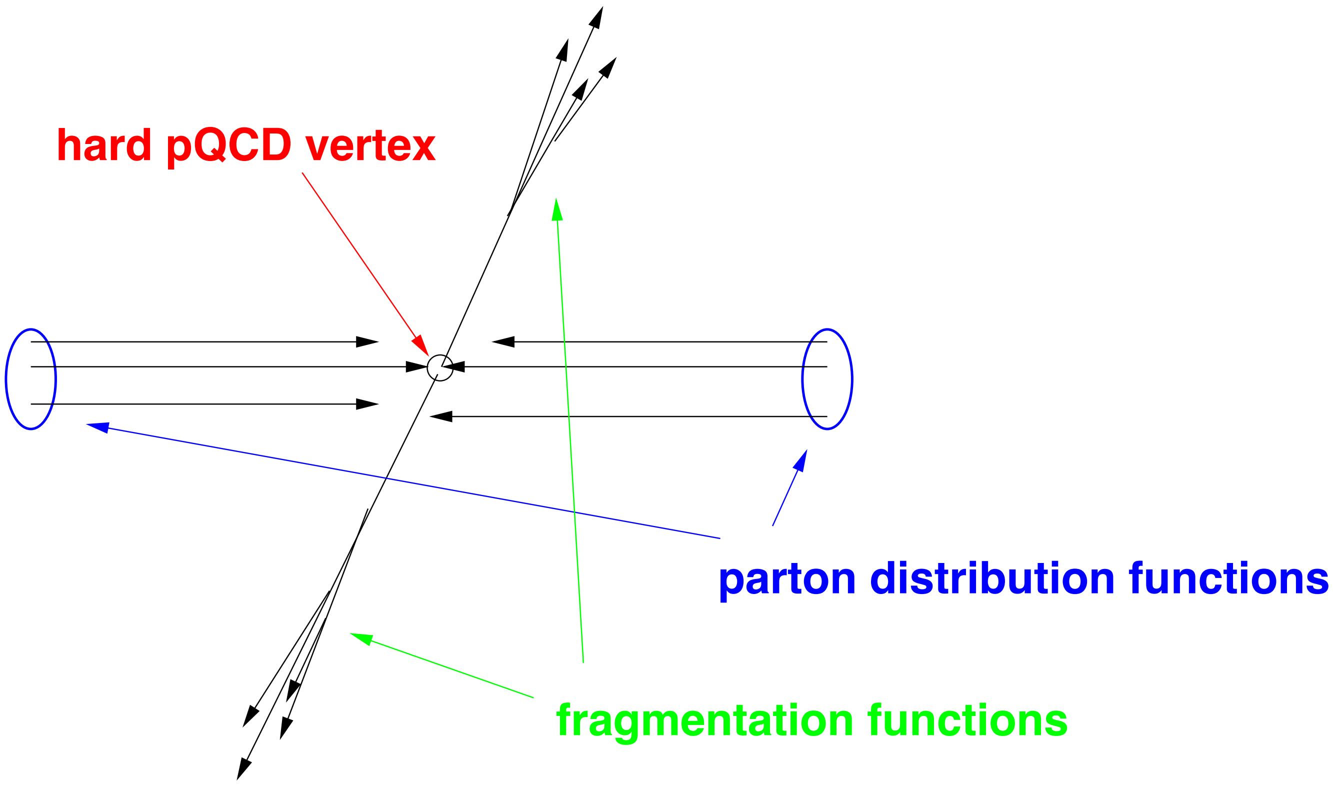
• hard back-to-back hadron correlations (I_{AA})
$\longrightarrow$ worse statistics
$\longrightarrow$ more differential information

• hard γ-hadron correlations (I_{AA})
$\longrightarrow$ almost complete access to parton kinematics before medium interaction
$\longrightarrow$ suppressed by α_{em}/α_s, very poor statistics

• full jet reconstruction
$\longrightarrow$ difficult to do in heavy-ion background
$\longrightarrow$ in principle complete information on medium-induced flow of energy/momentum

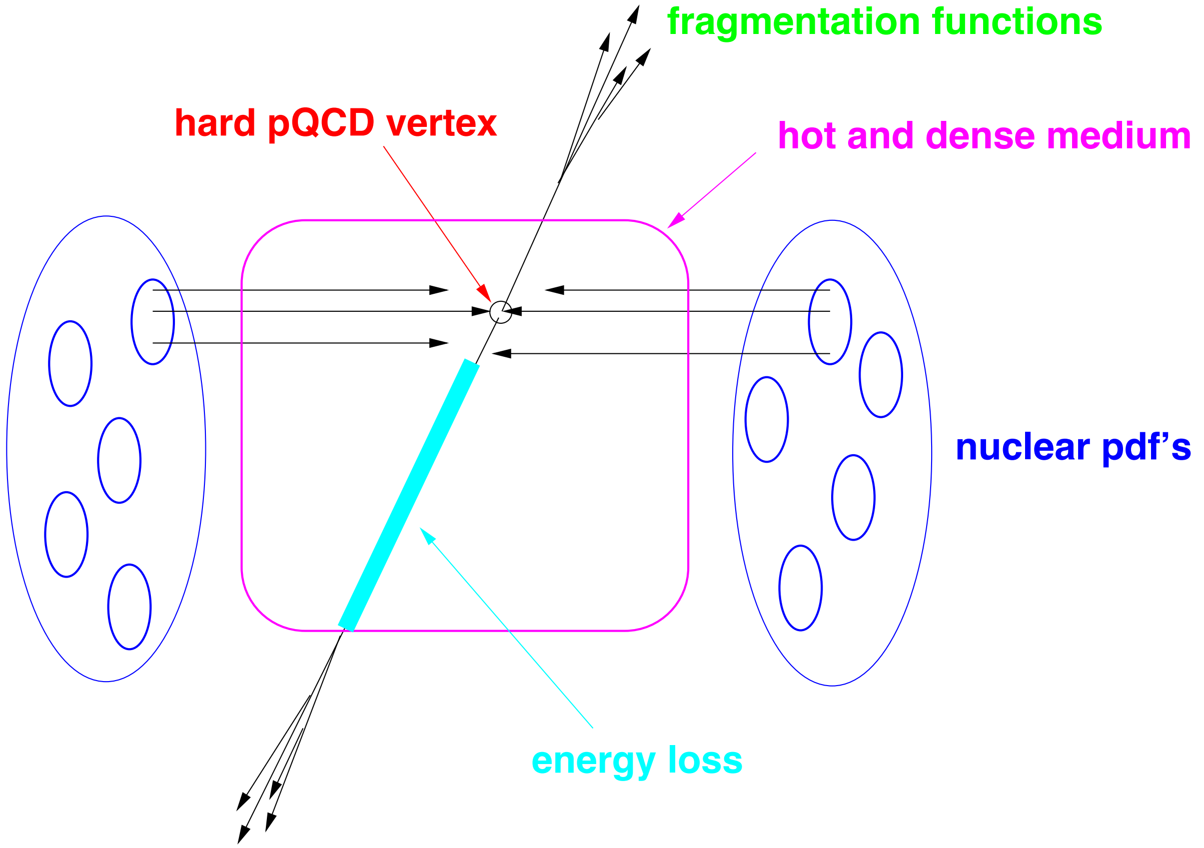
So, what is it we have to calculate, knowing the probability for energy loss $P(\Delta E)$?

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



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

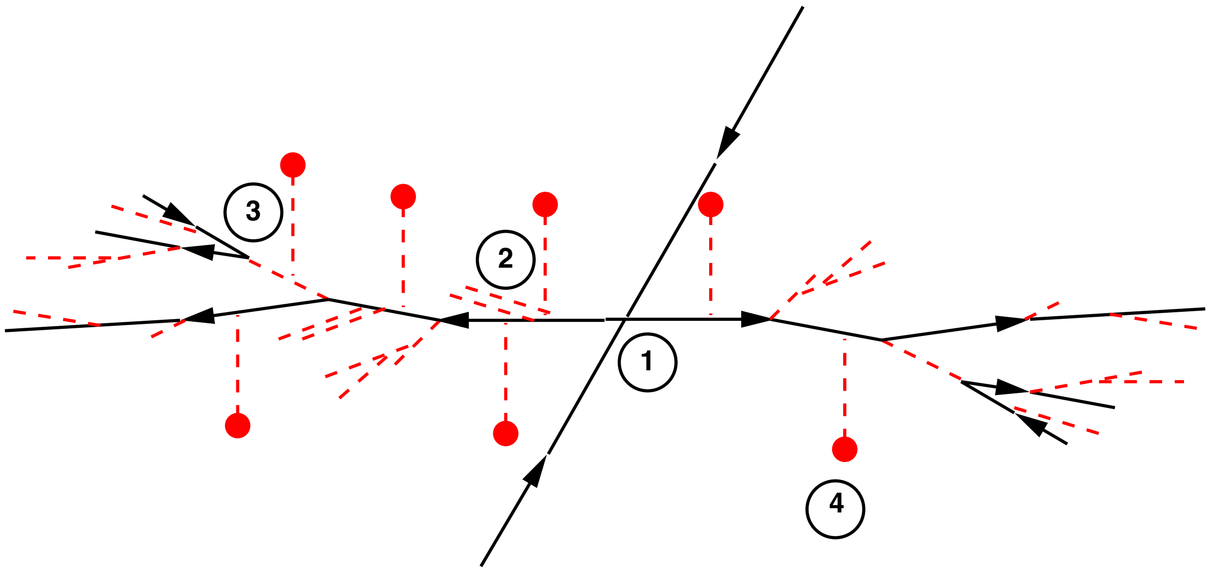
$$d\sigma_{vac}^{AA\to f+X} = \sum_{ijk} f_{i/A}(x_1,Q^2) \otimes f_{j/A}(x_2,Q^2) \otimes \hat{\sigma}_{ij\to f+k}$$

Summary

To take away from this chapter:

- aim of heavy-ion physics: to address **collectivity** in **QCD**
- requires modelling a **complex system** where parts can seldom be isolated
- experimental evidence for **thermalization** and **collectivity**, i.e. **bulk matter**
- bulk matter behaves like an **almost ideal fluid**
- non-thermal particles can act as probes of bulk properties — this is **tomography**
- particles from initial **hard processes** can act as tomographic probes
- experimental findings leds to the concept of **partonic energy loss**
- transport coefficients $\hat{q}$, $\hat{e}$ and $\hat{e_2}$ can classify models for the medium DOF
- energy loss is one building block in a long pQCD calculation

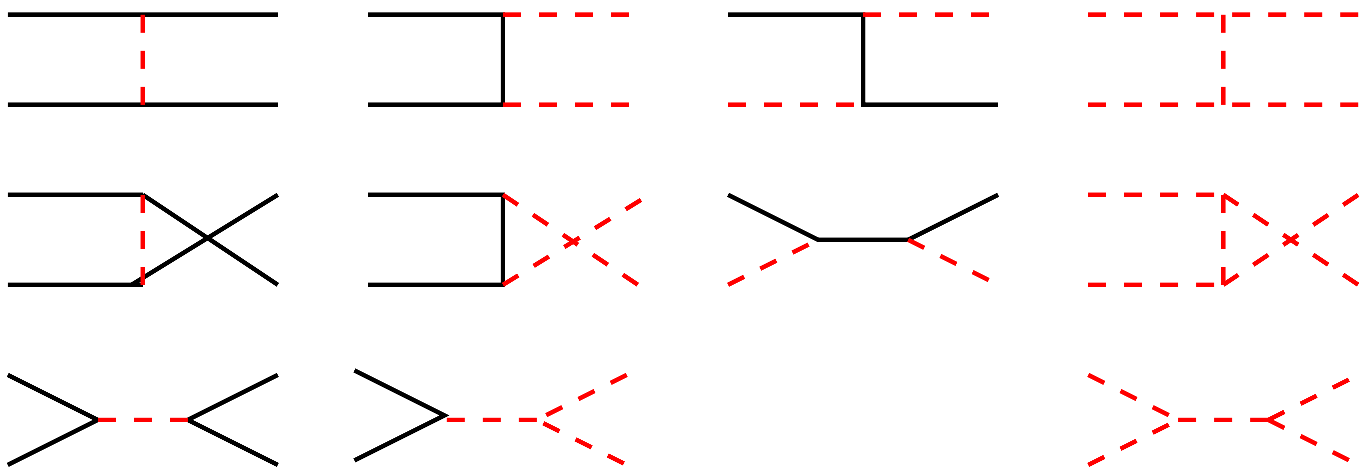
Part II: QCD parton-medium interaction



How do we obtain $\langle P(\Delta E) \rangle$?

QCD ELASTIC ENERGY LOSS

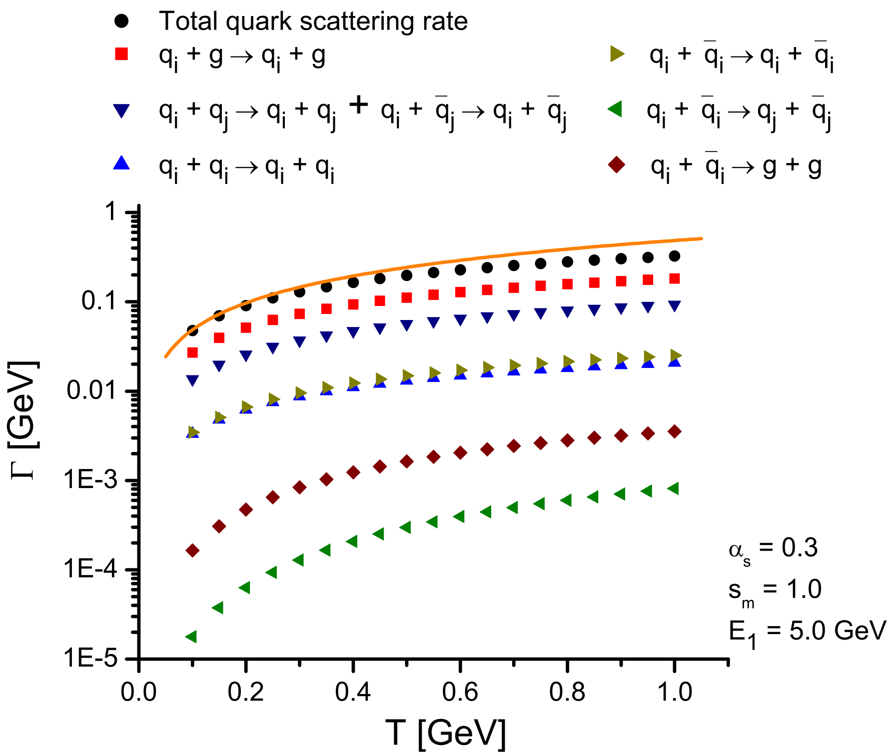
- assuming a gas of quasi-free partons
$\longrightarrow$ variety of 2$\rightarrow$2 diagrams in QCD
- one incoming parton is hard, the other is thermal
- thermal Debye masses $\sim gT$ screen singularities

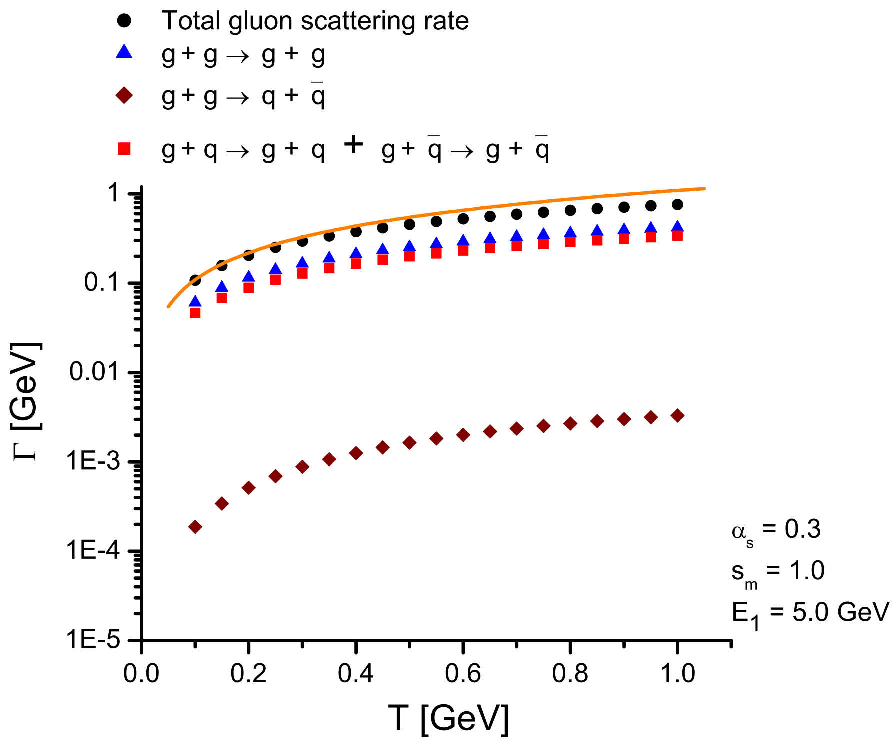


- the hard parton may have a different identity after scattering
- elastic processes with c and b quarks are therefore very different

QCD ELASTIC ENERGY LOSS

• relative importance depends on availablility of thermal scattering partners
$\longrightarrow$ gluon reactions dominate



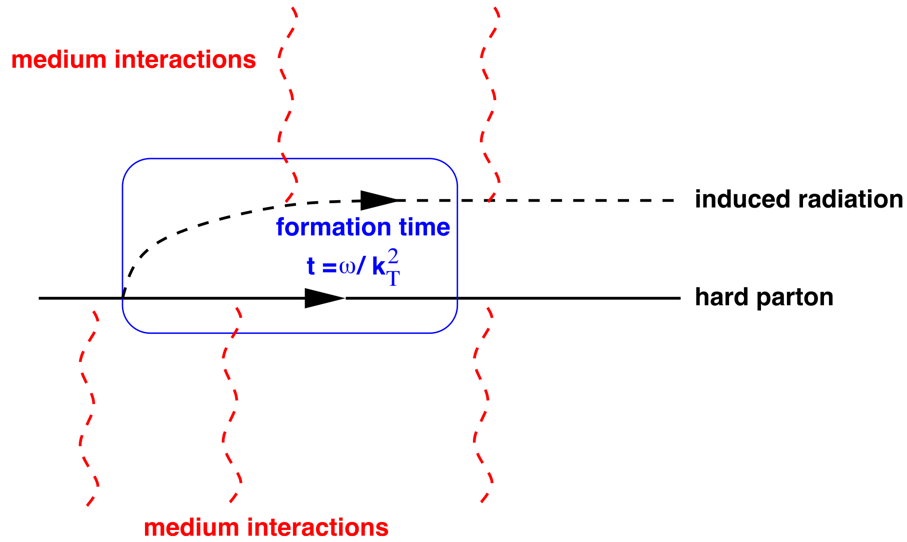


• 'lost' energy is carried by recoil of partner
$\longrightarrow$ transport cross section rather than cross section determines energy loss

J. Auvinen, K. J. Eskola and T. R., 0912.2265 [hep-ph].

QCD RADIATIVE ENERGY LOSS

- assume a medium characteried by a constant value of $\hat{q}$



- time to radiate a gluon: $\tau \sim \omega/Q^2 \sim L$
- virtuality picked up during that time: $Q^2 \sim \hat{q}L \sim \hat{q}\omega/Q^2$
- typical radiated energy $\omega_c = Q^4/\hat{q} = \hat{q}^2L^2/\hat{q} = \hat{q}L^2$
- gluon energy spectrum per unit pathlength for single emitted gluon ($\omega < \omega_c$):

$$\omega\frac{dI}{d\omega dz} \sim \frac{\lambda}{\tau_{coh}}\omega\frac{dI_{1scatt}}{d\omega dz} \sim \frac{\alpha_s}{\tau_{coh}} \sim \alpha_s\sqrt{\frac{\hat{q}}{\omega}}; \quad \text{incl. phase space} \sim \sqrt{\frac{\omega_c}{\omega}}$$

QCD radiative energy loss

- this yields quadratic pathlength dependence for constant $\hat{q}$

$$\langle \Delta E \rangle = \int_0^\infty d\omega \omega \frac{dI}{d\omega} \sim \int_0^{\omega_c} d\omega \sqrt{\frac{\omega_c}{\omega}} \sim \omega_c \sim \frac{\hat{q}}{2} L^2$$

Thus, if a single elastic reaction causes the average energy loss $\langle \Delta E_{el} \rangle$ then

- $\langle E_{el}^{tot} \rangle = L \frac{1}{\lambda} \langle \Delta E_{el} \rangle$, i.e. linear pathlength dependence
- $\langle E_{rad}^{tot} \rangle = L^2 \hat{q}$, i.e. quadratic pathlength dependence

$\Rightarrow$ radiative energy loss parametrically dominates for long pathlengths

- strongly coupled AdS/CFT results can generate even an L^3 dependence

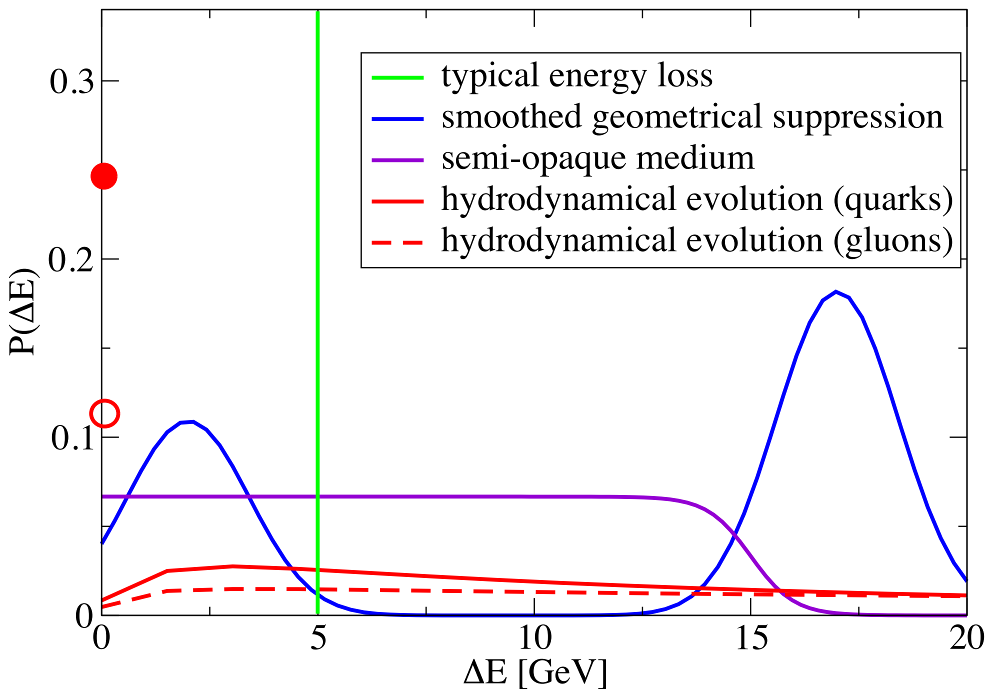
Thus, can we use this to estimate the parton spectrum by a power law and calculate

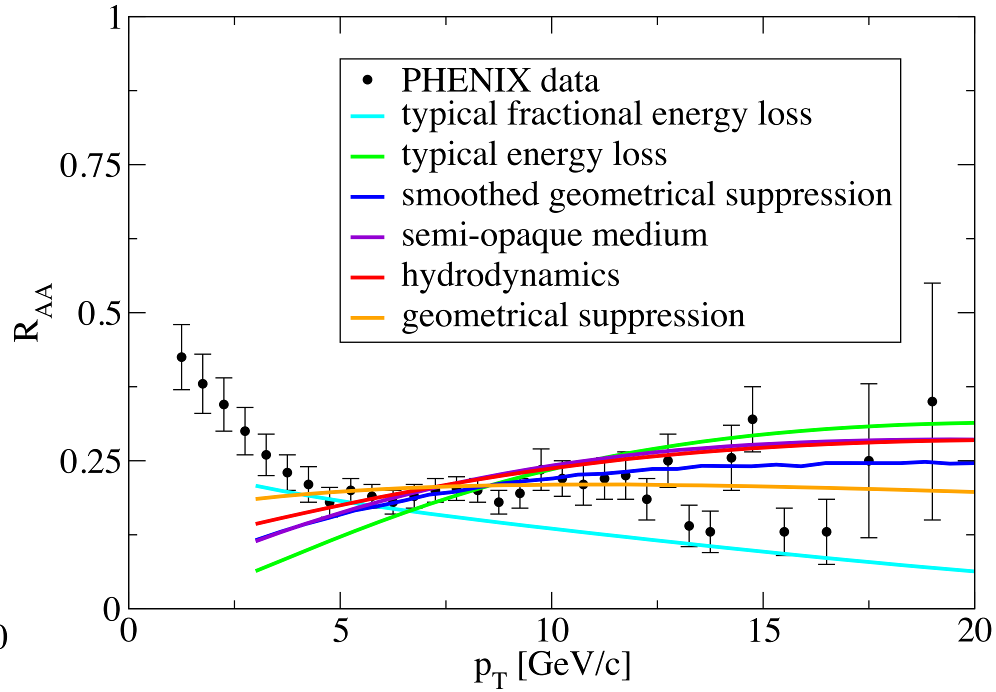
$R_{AA}(p_T) \approx \left(\frac{p_T}{p_T + \langle \Delta E \rangle} \right)^n = \left(1 - \frac{\langle \Delta E \rangle}{p_T + \langle \Delta E \rangle} \right)^n$

No! Absolutely not!

Probabilistic treatment matters!

- folding of parton spectrum with different $P(\Delta E)$





- $\langle \Delta E \rangle$ ranging from 4 GeV to 120 GeV lead to very similar results

$\longrightarrow$ what is seen is the probability of having no or small energy loss

$\longrightarrow$ mean energy loss is not probed

- cannot use simple average of single reaction n times

T. R., Phys. Rev. C **74** (2006) 034906

Iterating in-medium diagrams

To get a fully probabilistic picture, allow any number of elementary reactions

- assuming independent recations: Poissonization

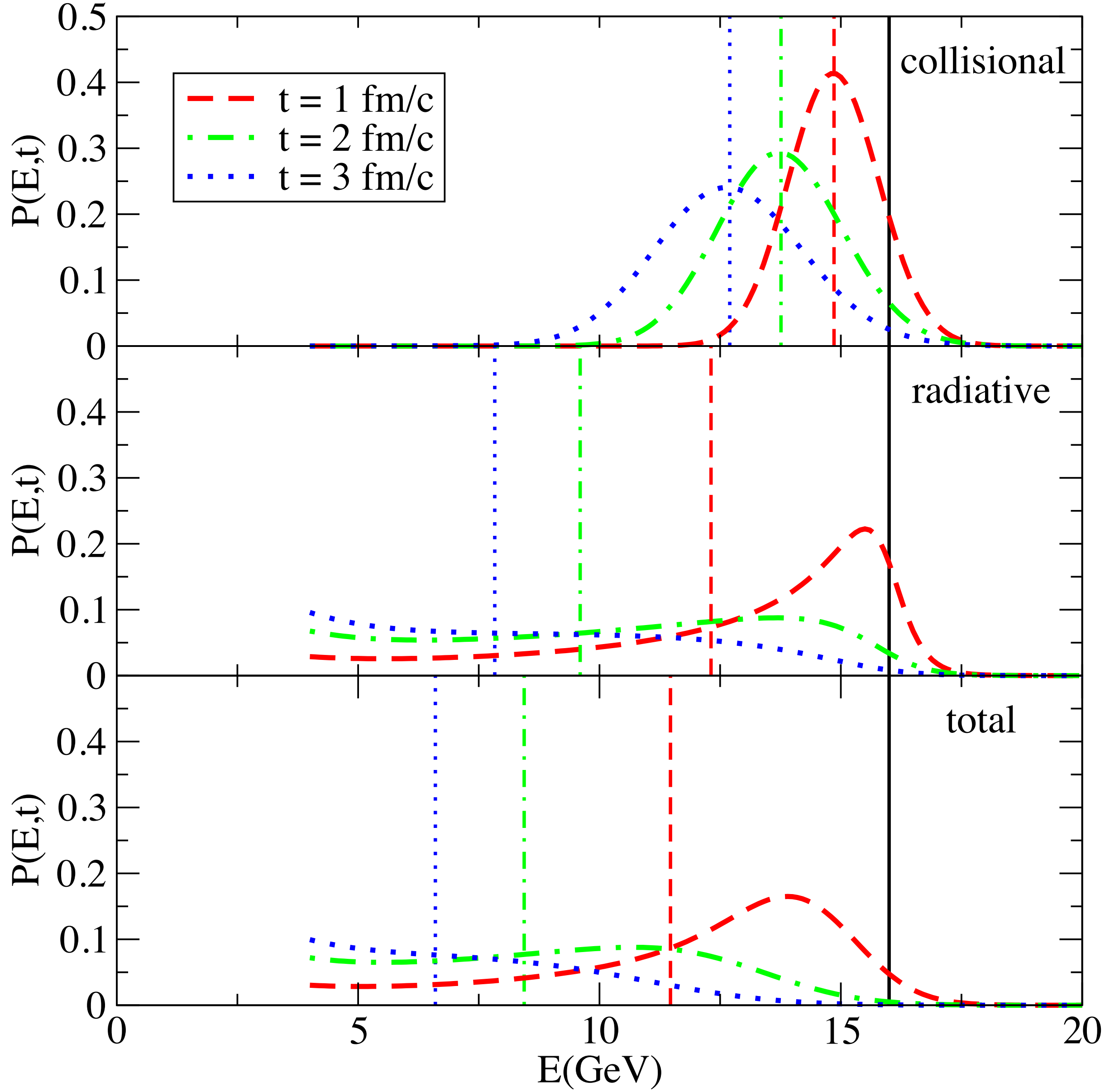
$$P(\Delta E)_{path} = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta \left(\Delta E - \sum_{i=1}^{n} \omega_i \right) \exp \left[- \int d\omega \frac{dI}{d\omega} \right]$$

→ not strictly consistent with formation time and finite medium length
→ but 'good enough', as we are interested in the limit of few reactions

- assuming correlated reactions: rate equations or Monte-Carlo codes

→ take into account energy degradation or full transverse kinematics

Iterating in-medium diagrams



G. Y. Qin, J. Ruppert, C. Gale, S. Jeon, G. D. Moore and M. G. Mustafa, Phys. Rev. Lett. **100** (2008) 072301

Space-time averaging

Are we done? No - we just computed the result for a single parton path, now we need to average over all possible parton paths:

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 ϕ is $P(\Delta E)_{path}$ we can define:

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

Intermediate summary

model of medium DOF $\Rightarrow$ **elementary energy loss process**

$\Downarrow$

ΔE

correlations between reactions $\Rightarrow$ **iteration of elementary process**

$\Downarrow$

$P(\Delta E)$

model of medium geometry $\Rightarrow$ **space-time averaging**

$\Downarrow$

$\langle P(\Delta E) \rangle$

folding with pQCD spectrum and fragmentation function

$\Downarrow$

observables, R_{AA}

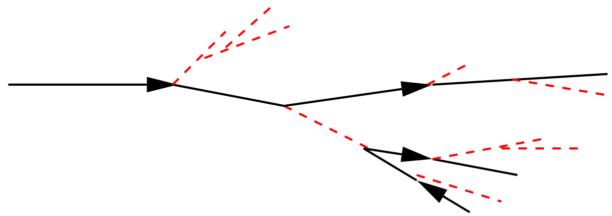
- non-trivial to invert the problem and extract medium DOF or geometry evolution
- and still an approximation, since. . .

The fragmentation function

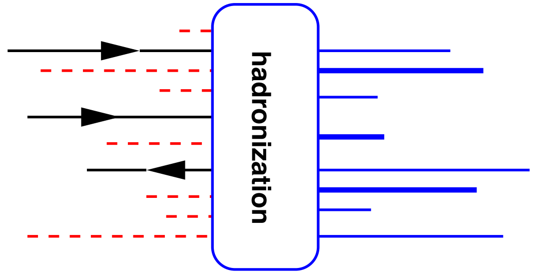
Conceptual issue: partons produced in a hard process are *not* on-shell

• fragmentation function $D^{vac}_{f\to h}(z,\mu_f^2)$ encodes the following physics:

• radiation from the highly virtual initial parton via $q \to qg, g \to gg$ and $g \to q\overline{q}$ (perturbatively calculable for $Q \simeq 1$ GeV)



• hadronization (non-perturbative)



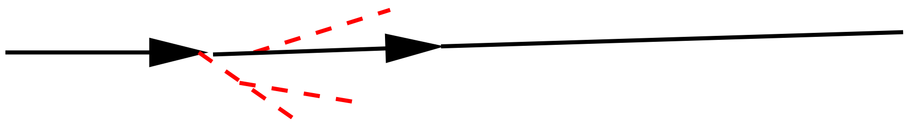
• virtual parton formation time $\tau \sim E/Q^2$, hadron formation time $\tau_h \sim E_h/m_h^2$
$\to$ part of the shower evolution takes place in medium

• Why would it be correct to compute for a single hard on-shell parton?

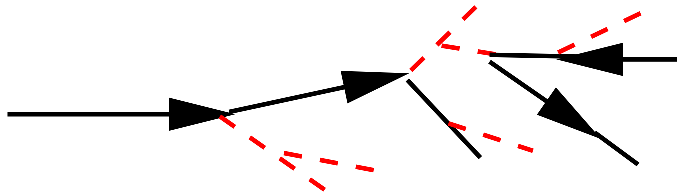
ENERGY LOSS VS. IN-MEDIUM SHOWER

Single inclusive hard hadron production:

• dominated by showers in which a single parton carries most of the momentum



• unbiased hard jet events — multiple low p_T hadron production



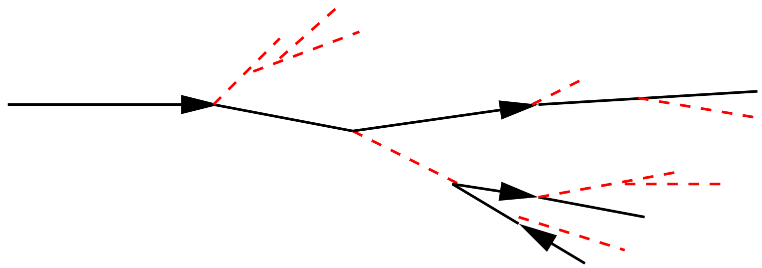
For single inclusive hard hadron production:

$\Rightarrow$ fragmentation function $\approx$ hadronization of leading parton
$\Rightarrow$ medium effect $\approx$ reduction of leading parton energy
$\Rightarrow$ if hadronization happens outside the medium, the two factorize!

$\Rightarrow$ Medium-induced energy loss good concept to describe *leading* hadron only

$\Rightarrow$ use full medium-modified fragmentation function otherwise

QCD SHOWER EVOLUTION IN VACUUM



- in MC picture, tree of splittings $a \to b, c$
- evolution variables $t = \ln Q^2/\Lambda_{QCD}$ and z
- differential branching probability at scale t:

$$I_{a\to bc}(t) = \int_{z_-(t)}^{z_+(t)} dz \frac{\alpha_s}{2\pi} P_{a\to bc}(z)$$

with kinematic limits $z_\pm$ dependent on parent and daughter virtualities M_{abc} and

$$P_{q\to qg}(z) = \frac{4}{3}\frac{1+z^2}{1-z} \quad P_{g\to gg}(z) = 3\frac{(1-z(1-z))^2}{z(1-z)} \quad P_{g\to q\bar{q}}(z) = \frac{N_F}{2}(z^2+(1-z)^2)$$

- probability density for branching of a occuring at t_m when coming down from t_{in}:

$$\frac{dP_a}{dt_m} = \left[\sum_{b,c} I_{a\to bc}(t_m)\right] \exp\left[-\int_{t_{in}}^{t_m} dt' \sum_{b,c} I_{a\to bc}(t')\right].$$

$\Rightarrow$ realized as MC code in PYSHOW, HERWIG,. . .

Shower evolution in position space

jet evolution equations $\Leftrightarrow$ momentum space
medium description $\Leftrightarrow$ position space

- model average time for a parton b to branch from parent a as

$$\langle \tau_b \rangle = \frac{E_b}{Q_b^2} - \frac{E_b}{Q_a^2}$$

- actual branching time in given event from probability distribution

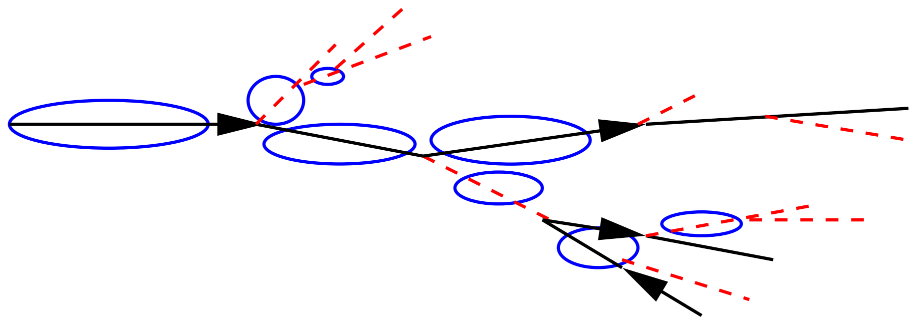
$$P(\tau_b) = \exp\left[-\frac{\tau_b}{\langle \tau_b \rangle}\right]$$

- assume all partons are on eikonal trajectory determined by the shower initiator

$\Rightarrow$ position of all branchings in spacetime known and connected with medium model

Medium-modified branching

- change parton kinematics during propagation



∗ multiple soft scattering leads to medium-induced virtuality (RAD)

$$\Delta Q_a^2 = \int_{\tau_a^0}^{\tau_a^0+\tau_a} d\zeta \hat{q}(\zeta)$$

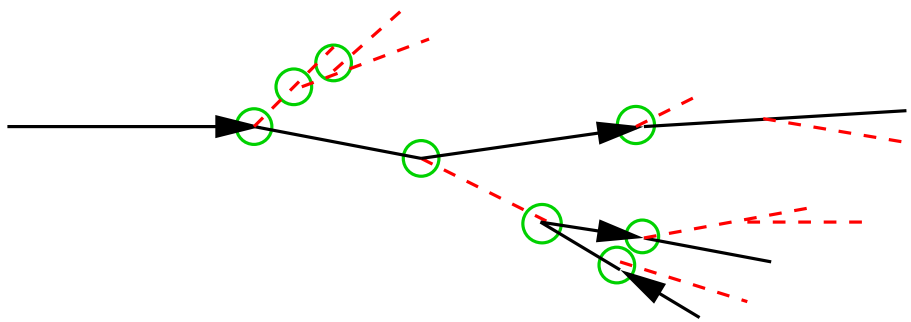
∗ in a strongly coupled medium, a drag force appears (DRAG)

$$\Delta E_a = \int_{\tau_a^0}^{\tau_a^0+\tau_a} d\zeta D\rho(\zeta)$$

T. R., Phys. Rev. C **78** (2008) 034908

Medium-modified branching

- change splitting probability in Kernel



∗ enchance singular part of splitting kernel by $(1 + f_{med})$ (FMED), e.g.

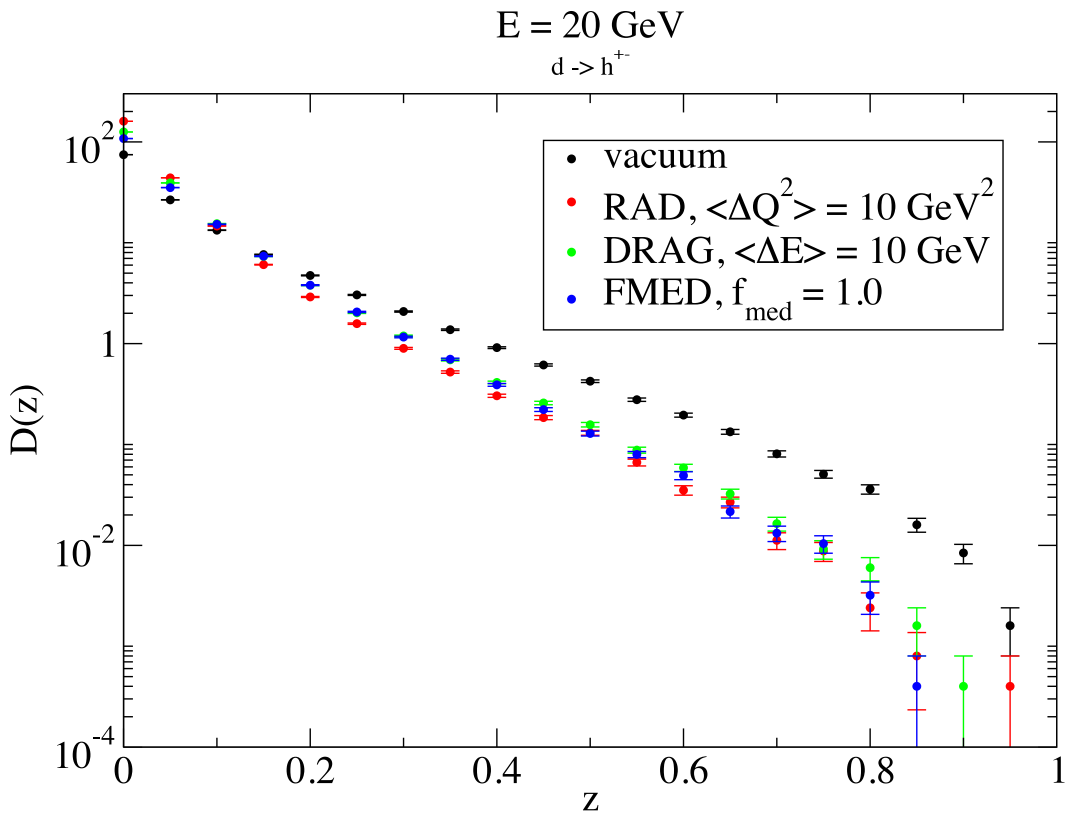
$$P_{q\to qg}(z) = \frac{4}{3}\frac{1+z^2}{1-z} \Rightarrow \frac{4}{3}\left(\frac{2(1+f_{med})}{1-z} - (1+z)\right)$$

$\Rightarrow$ assume $f_{med} \sim \int d\zeta \rho(\zeta)$ to link with spacetime evolution

N. Borghini and U. A. Wiedemann, hep-ph/0506218; K. Zapp, G. Ingelman, J. Rathsman, J. Stachel and U. A. Wiedemann, 0804.3568 [hep-ph].

Modified shower comparison

Comparison between energy loss and medium-modified FF:

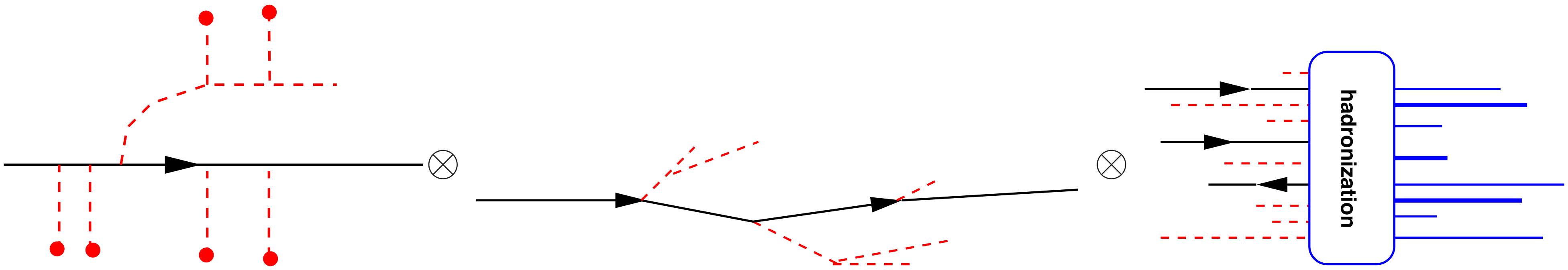


- medium-modified FF: depletion at high $z \longrightarrow$ 'energy loss'
- enhancement at low z: 'lost' energy appears as soft hadron production
- hadronization mainly probes $z \sim 0.7$, MMFF and eloss 'similar'

T.R., Phys. Rev. C **79** (2009) 054906

Energy loss vs. in-medium shower

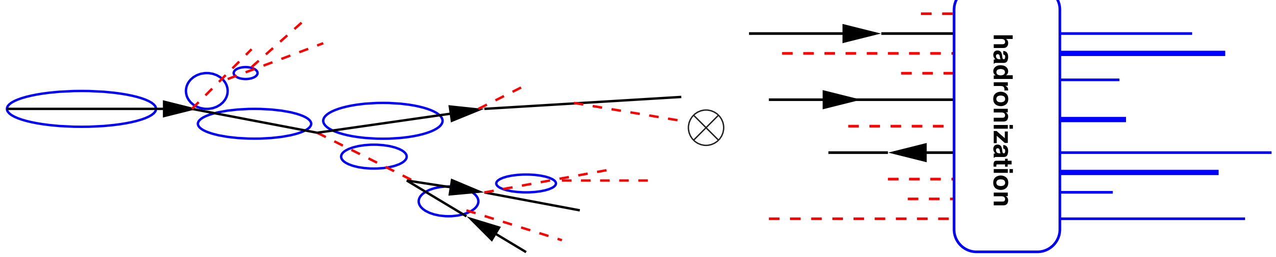
1) medium-induced energy loss for the leading parton, then vacuum fragmentation



$$P(E, \Delta E) \otimes D_{vac}(z, Q_i \to Q_h) \otimes D_{vac}(z, Q_h)$$

(BDMPS, ASW, (D)GLV, AMY, some HT results)

2) in-medium shower, followed by hadronization in vacuum



$$D_{med}(z, Q_i \to Q_h) \otimes D_{vac}(z, Q_h)$$

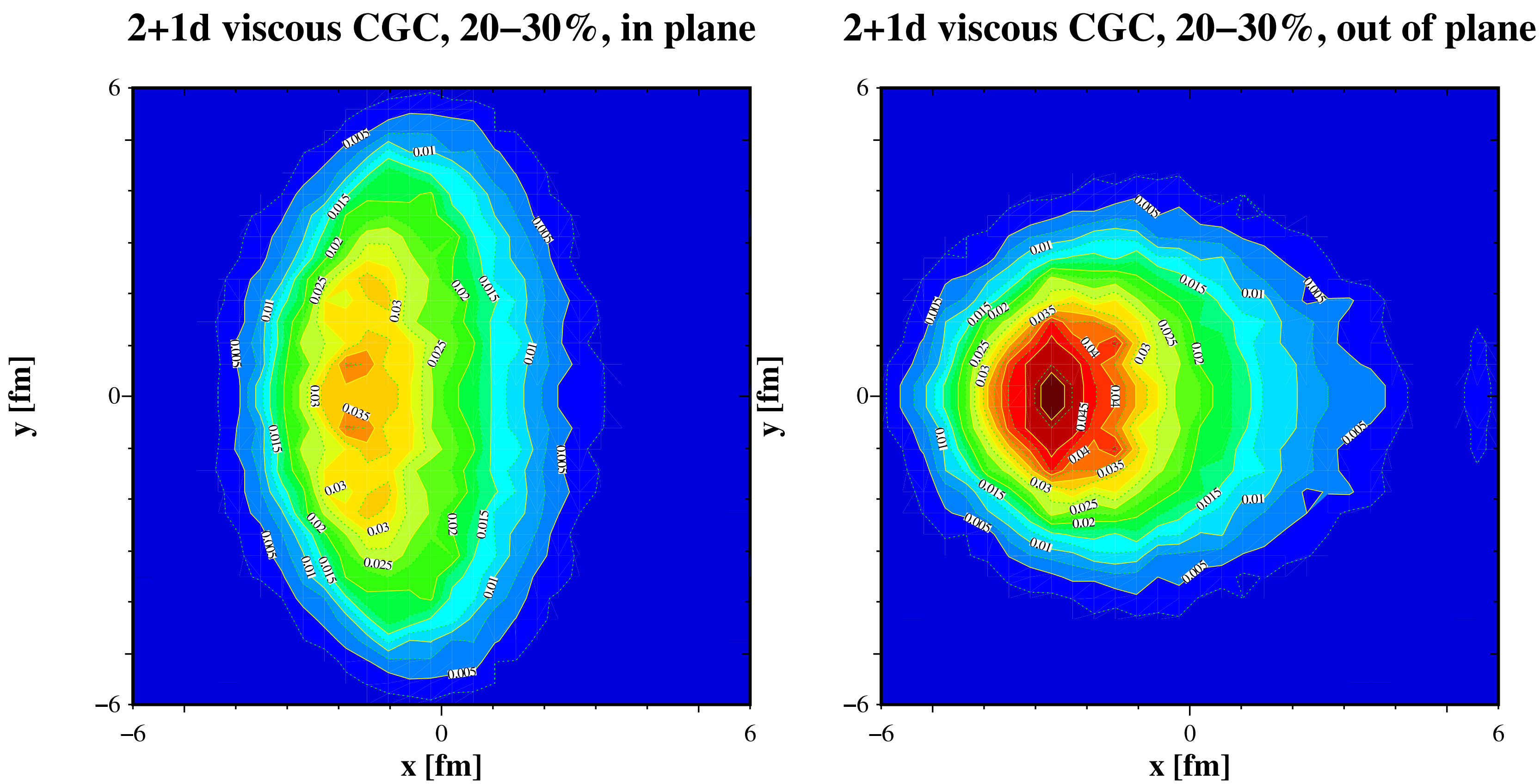
(recent HT, JEWEL, YaJEM, Q-PYTHIA, Q-HERWIG)

Summary

To take away from this chapter:

- basic QCD parton-medium interactions are elastic $2 \to 2$ and radiative $2 \to 3$
- **pathlength dependence** of energy loss is a decisive criterion
- **average** energy loss does not work, a **probabilistic framework** is needed
- need to keep track of **position space** as well as **momentum space**
- all observable quantities contain some degree of **averaging** in position space
- **energy loss** is an **approximation** for leading hadrons from a shower
- full in-medium shower MC codes exist, but are much more complicated

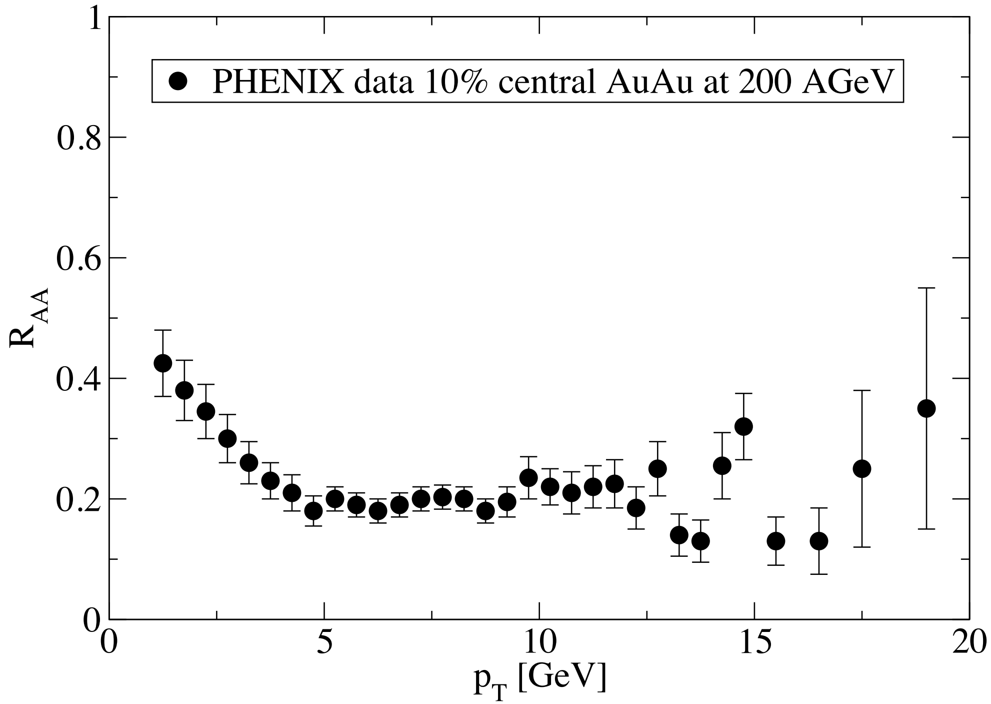
Part III: Single hadron observables



What physics causes the suppression in single hadron spectra?

Single hadron observables

- 80% suppression in central 200 AGeV Au-Au collisions - what does this mean?



- problem: hydrodynamics knows T, ϵ, s, but not $\hat{q}$

$\longrightarrow$ need model like $\hat{q} = const. \cdot s, \hat{q} = const. \cdot \epsilon^{3/4}$ to connect

- thus, we have one free parameter to fit a straight line

$\longrightarrow$ this is bound to work. . .

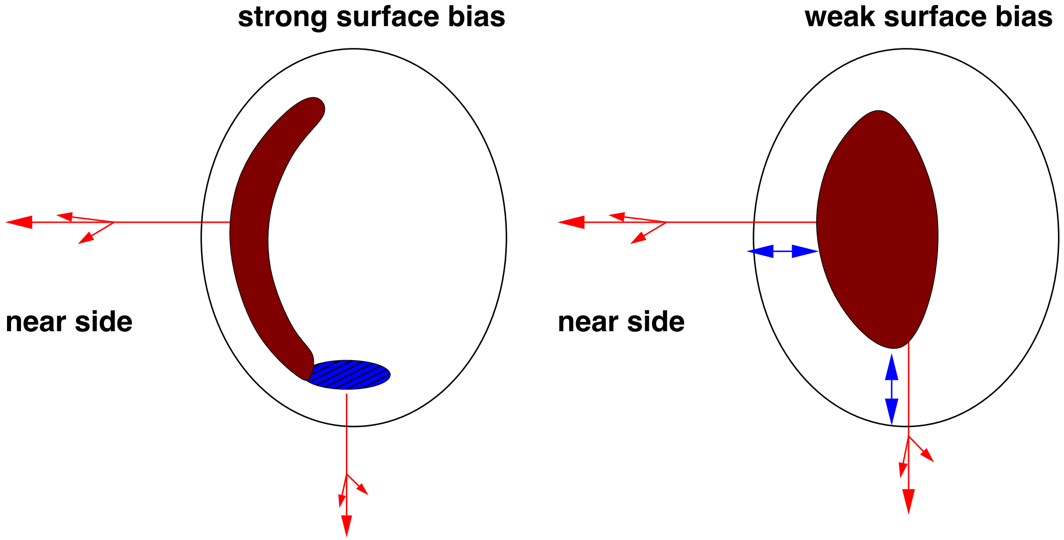
- but - we can adjust the parameter and predict non-central collisions

Pinning down pathlength

- surface bias: we see hadrons because they never crossed the medium

$\longrightarrow$ no energy loss for partons produced on the periphery

- spread in-plane vs. out of plane in $R_{AA}(\phi)$ related to



- strong surface bias (medium very opaque for large pathlength/ high density regions)

$\longrightarrow$ more emission in-plane because the emitting surface is larger

- weak surface bias (emission also from the medium core)

$\longrightarrow$ more emission in plane because $\langle x \rangle < \langle y \rangle$

$\Rightarrow$ no clear qualitative signal

Pinning down pathlength

- normalization of $R_{AA}(b)$ increases for peripheral collisions due to

- drop in average density

$\longrightarrow$ this is seen for any scenario of parton-medium interaction

- drop in average pathlength

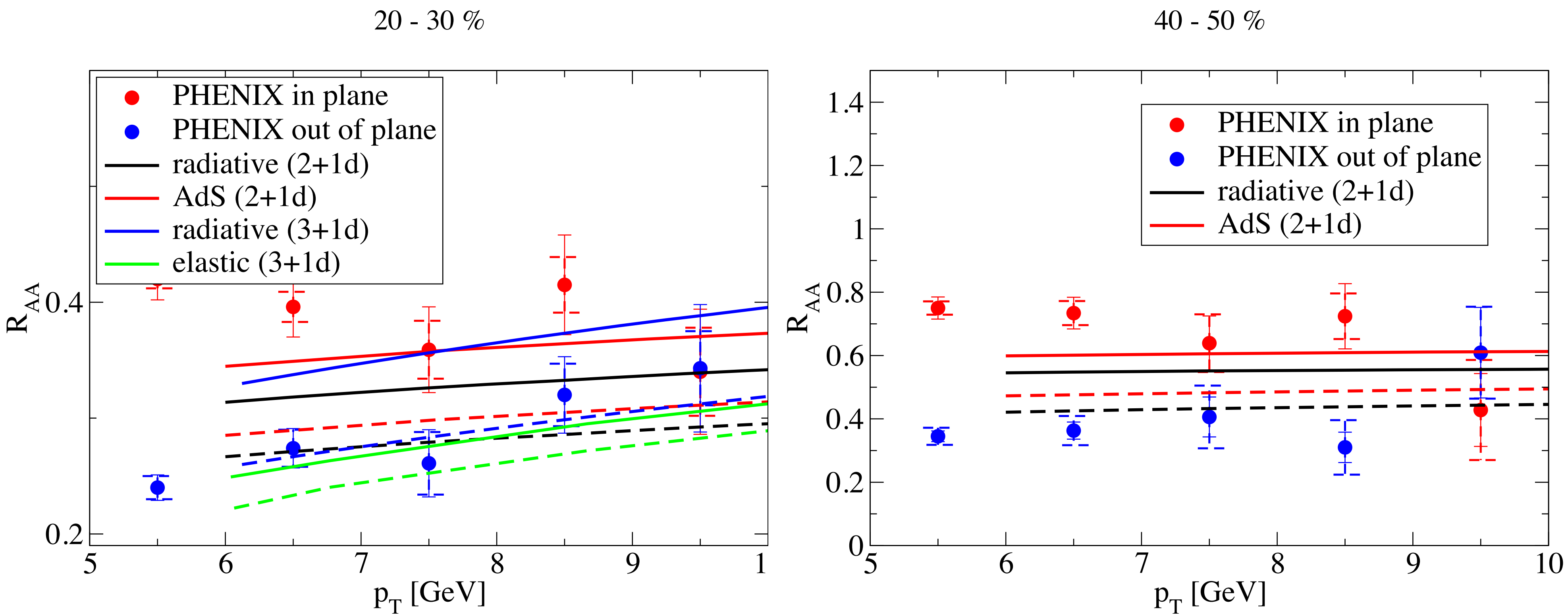
$\longrightarrow$ this probes pathlength dependence in a qualitatively characteristic way
$\Rightarrow$ expect $R_{AA}^{AdS} > R_{AA}^{rad} > R_{AA}^{el}$ for non-central collisions

For increasing b, R_{AA} rises and a spread between in-plane and out of plane emission opens:

normalization $\Leftrightarrow$ average density, average pathlength

spread $\Leftrightarrow$ hydro density profile, emission geometry, pathlength difference. . .

Pinning down pathlength



• clear dependence on hydro model (3+1d hydro causes larger spread)
⇒ need to investigate systematically

• elastic fails to reproduce spread and normalization
⇒ large component of elastic energy loss disfavoured by data

• AdS pQCD hybrid reproduces normalization best and has largest spread
⇒ indication for non-perturbative re-interaction of radiated gluons

Pinning down geometry

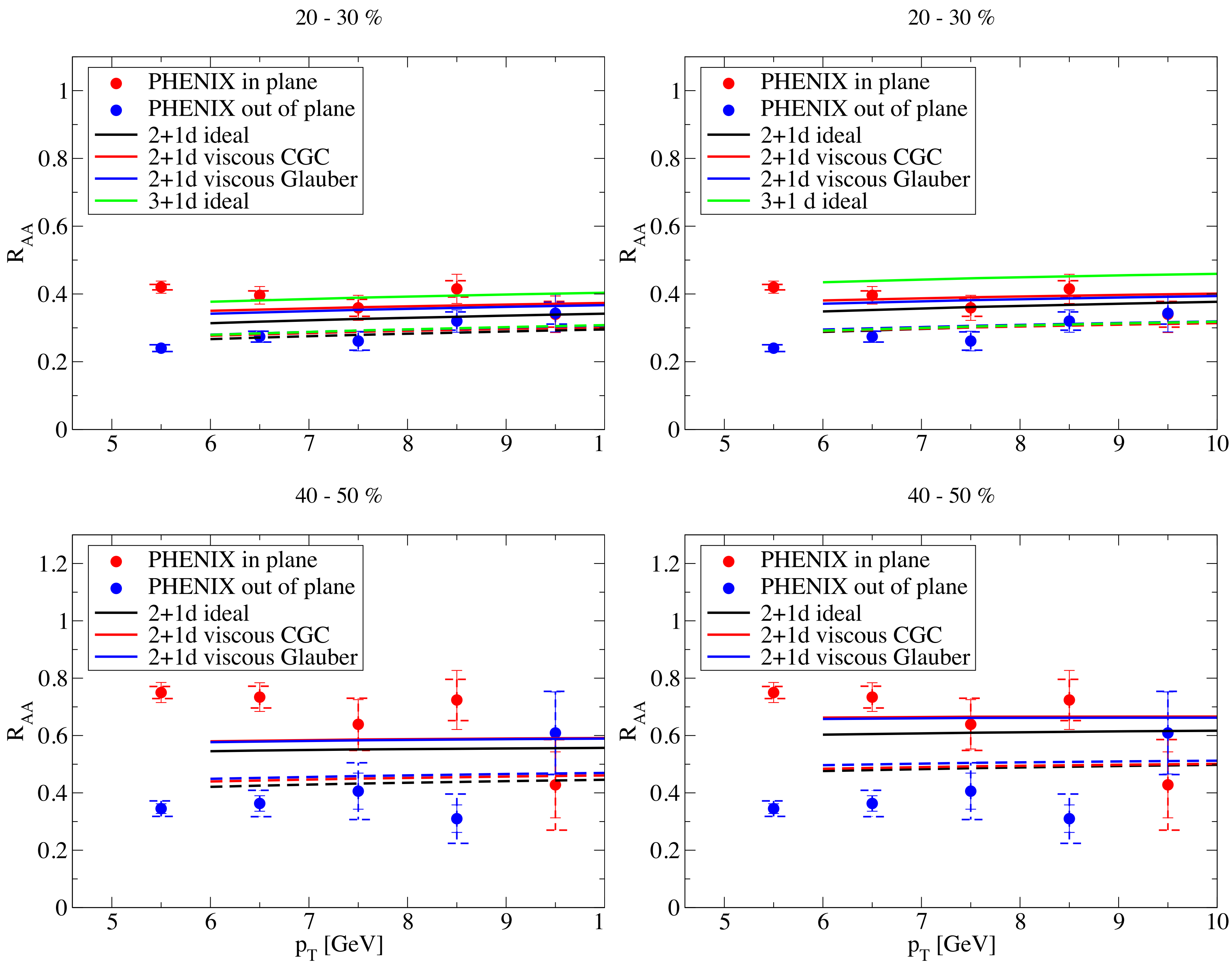
• difficult problem, what is measured is a final state in momentum space
$\longrightarrow$ probe all fluid dynamical evolutions leading to that final state
$\longrightarrow$ we don't know what that group is

• test a few contenders instead
$\longrightarrow$ CGC (sharp) initial state vs. Glauber (smooth) initial state
$\longrightarrow$ viscous (entropy production) vs. ideal (entropy from initial state)
$\longrightarrow$ 3+1d vs. 2+1d
$\longrightarrow$ low (long hadronic evolution) vs. high decoupling temperature

• try to identify generic trends

• need to run both L^2 and L^3 dependence!

Pinning down geometry



Pinning down geometry

- low decoupling temperature (long thermal evolution) favoured
- AdS/QCD hybrid L^3 dependence reproduces normalization and spread better

$\rightarrow$ however weak coupling pQCD is not out yet

- viscosity increases the spread
- initial state geometry is a small effect

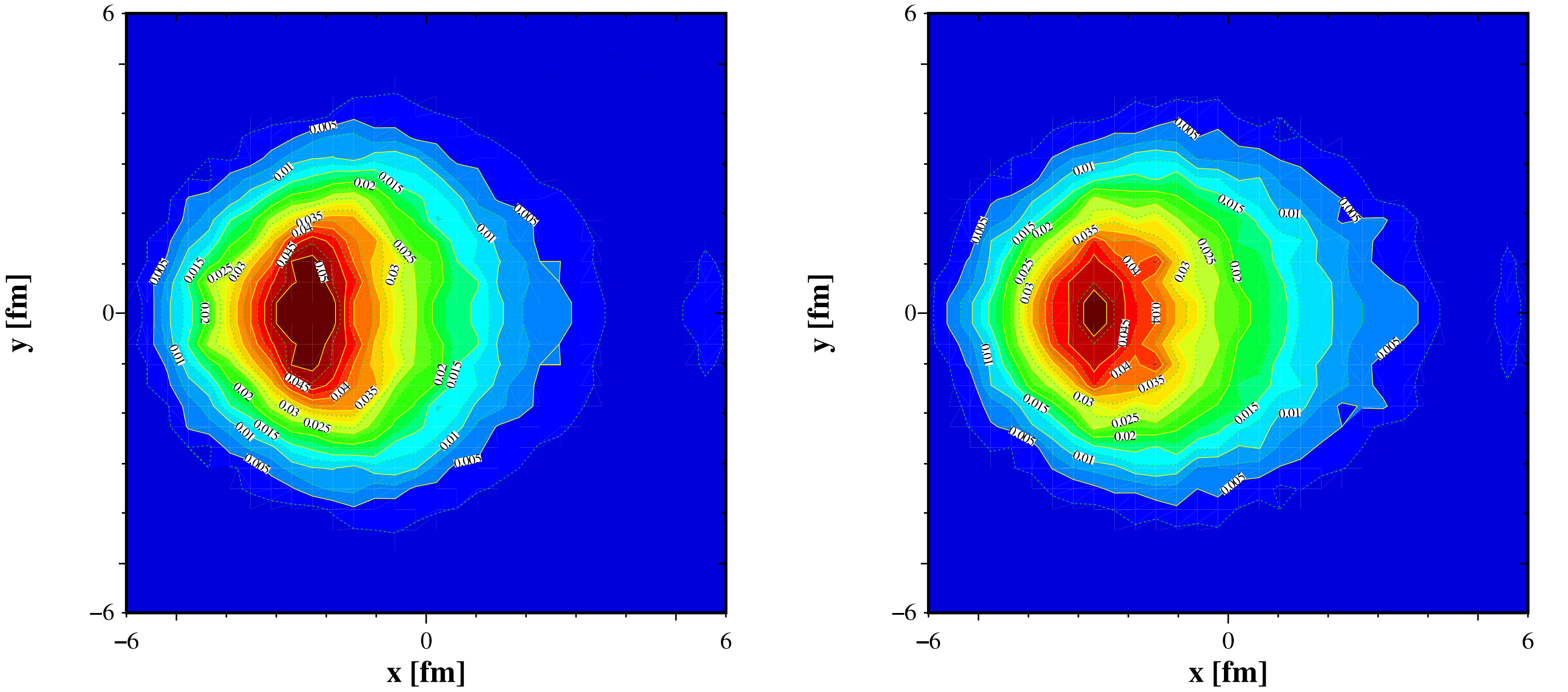
$\rightarrow$ not surprising for L^2 or L^3 weighting which suppress early times

$\Rightarrow$ some information about the density evolution is emerging

Pinning down geometry

- probability density for production vertex, given an observed hadron

2+1d viscous CGC, AdS, 20–30%, out of plane | **2+1d viscous CGC, 20–30%, out of plane**



- visually different degree of surface bis

$\longrightarrow$ yet translates into relatively small observable quantity

- can we do better?

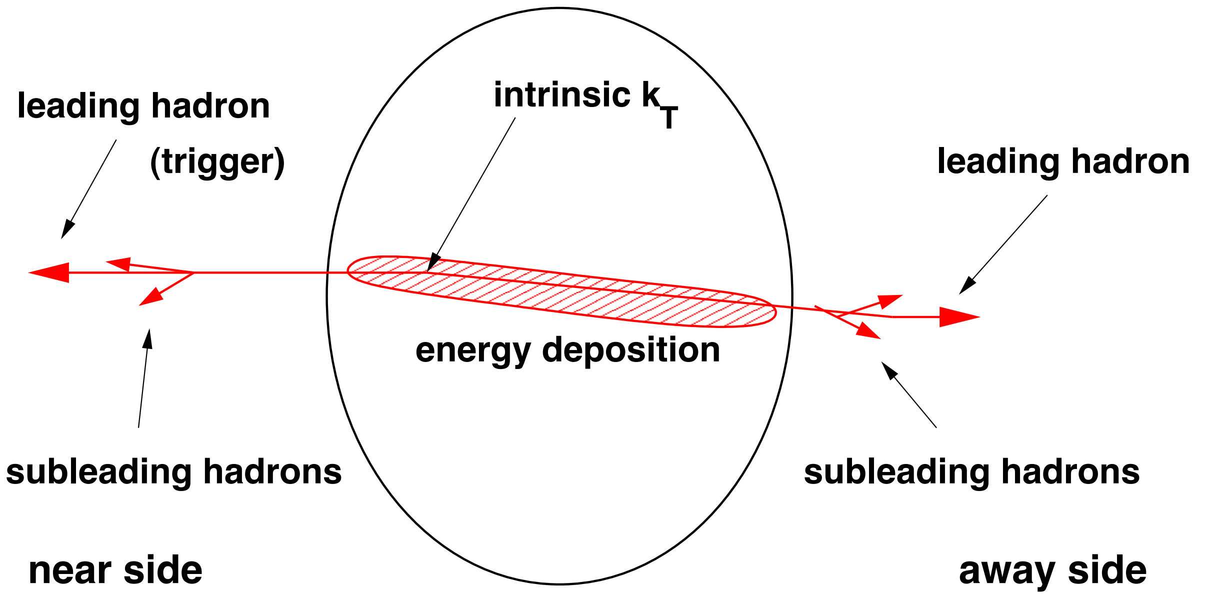
Summary

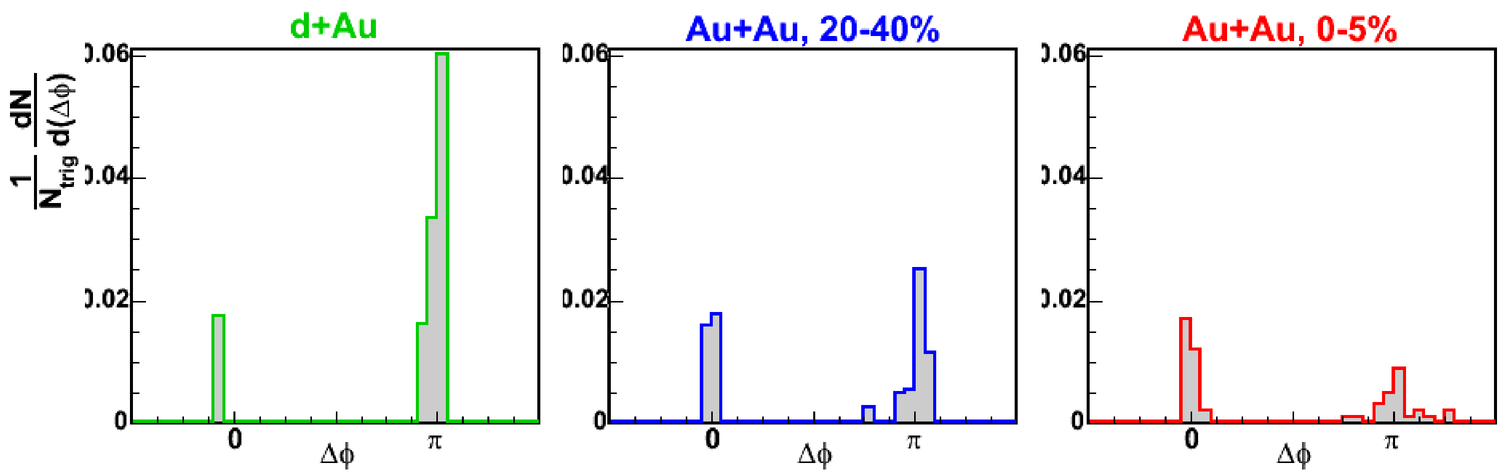
To take away from this chapter:

- there is **a free parameter** connecting thermodynamics and transport coefficients
- this parameter is determined using the single hadron suppression in central collisions
- the **extrapolation to non-central collisions** is the crucial test for models
- spread between in-plane and out-of-plane emission most interesting
- **elastic energy loss** must be **small**
- no clear decision between weak and strong coupling, but strong coupling favoured

Dihadron correlations

Part IV: Hard back-to-back correlations

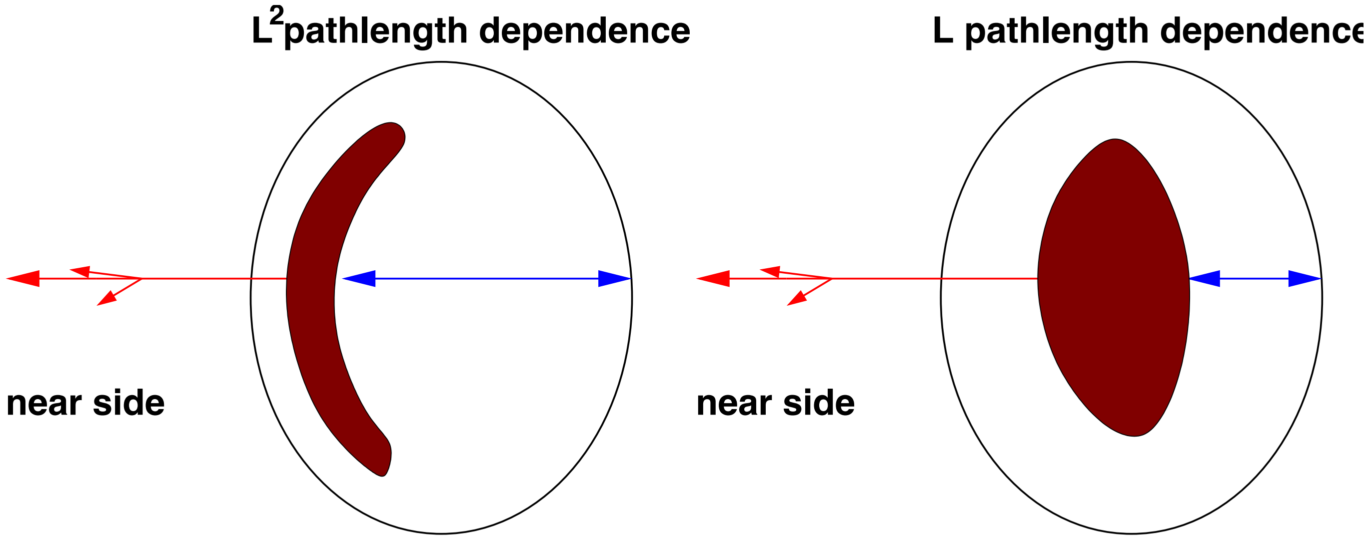




How does energy loss affect back-to-back correlations?

Pinning down pathlength

- advantage of back-to-back correlations



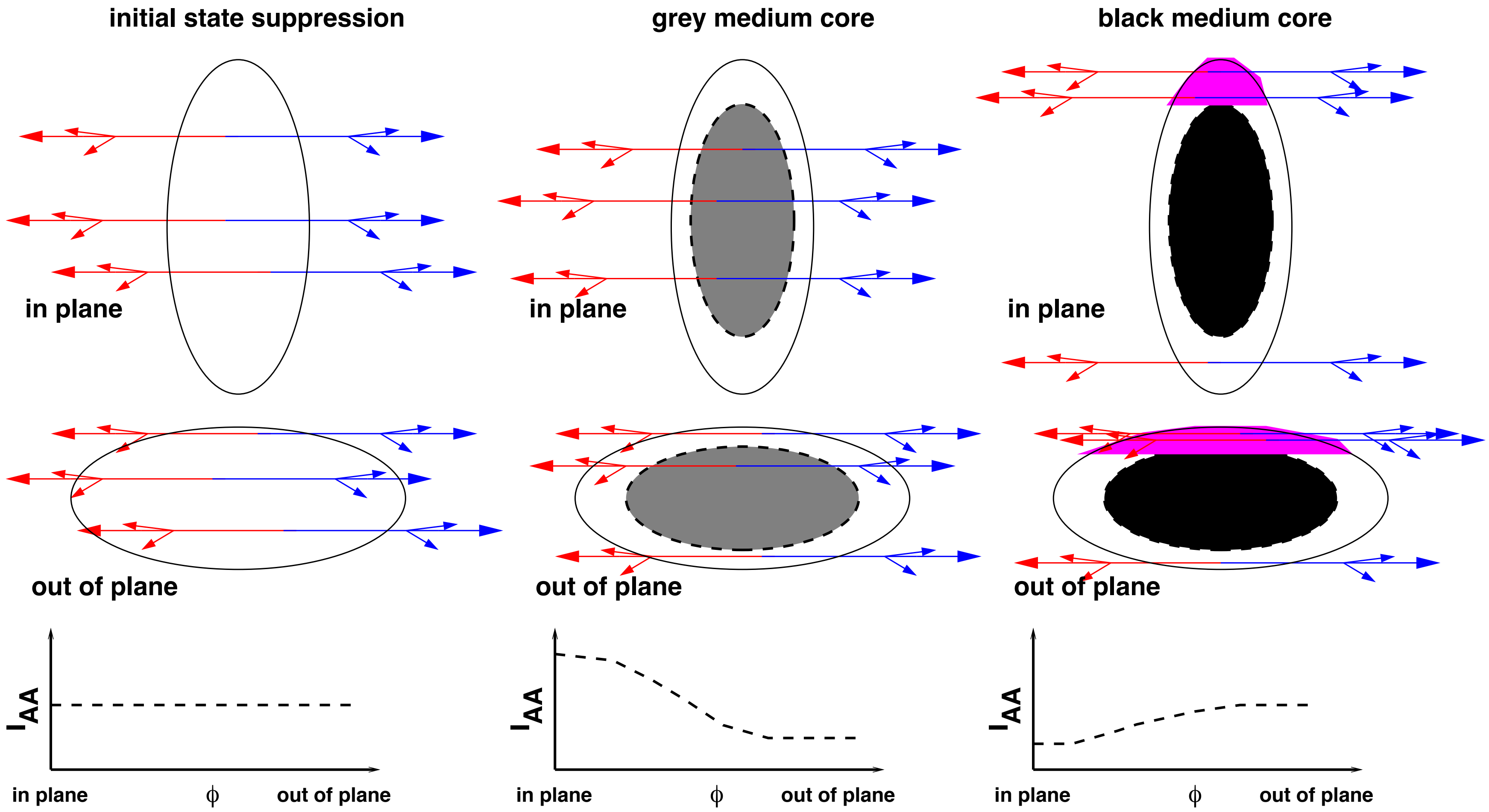
- expect (due to surface bias of trigger) $\sim$ factor 2 in away side pathlength

$\Rightarrow$ magnifies pathlength effects as compared to $R_{AA}(\phi)$

Large difference in predicted away side per-trigger yield (or I_{AA})

Pinning down geometry

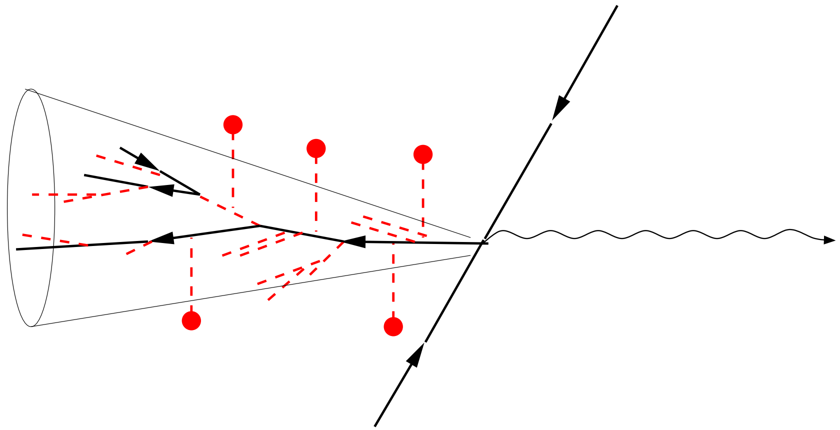
- How large is the degree of surface bias?



Qualitatively different expectations for $I_{AA}(\phi)$

γ-H CORRELATIONS

- replace one hadron by a photon



- kinematics (up to intrinsic k_T) given by photon

$\longrightarrow$ clean information on initial energy

- little bias in photon trigger

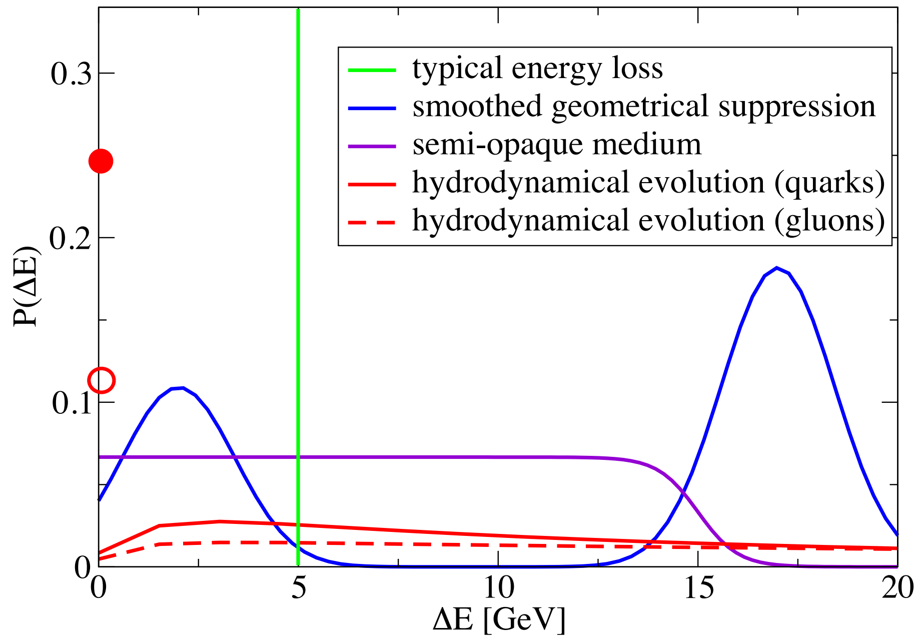
$\longrightarrow$ photons (almost) always escape
$\longrightarrow$ no bias, no matter how the parton side is modified

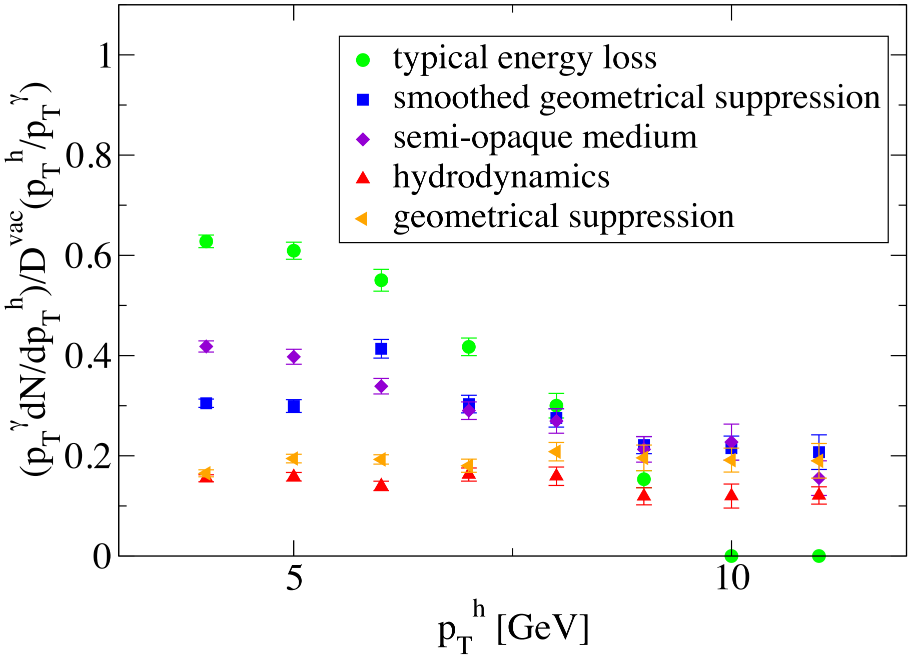
- some complications

$\longrightarrow$ fragmentation photons, parton-photon conversions. . .
$\longrightarrow$ low statistics

γ-H CORRELATIONS

• What does it buy to know the initial energy?





⇒ in principle, a lot! Resolves differences far beyond what R_{AA} can do

T. R., Phys. Rev. C **74** (2006) 034906

Computation outline

Modelling is done in a MC simulation framework:

• generate a hard back-to-back parton pair according to LO pQCD
$\longrightarrow$ take care of initial state effects (nPDFs), intrinsic k_T,. . .

• follow the path of each parton through the evolving hydrodynamical medium
$\longrightarrow$ in eikonal approximation, tests have shown that corrections are small

• compute gluon radiation from leading parton / shower evolution
$\longrightarrow$ different prescriptions, ASW, YaJEM, . . .

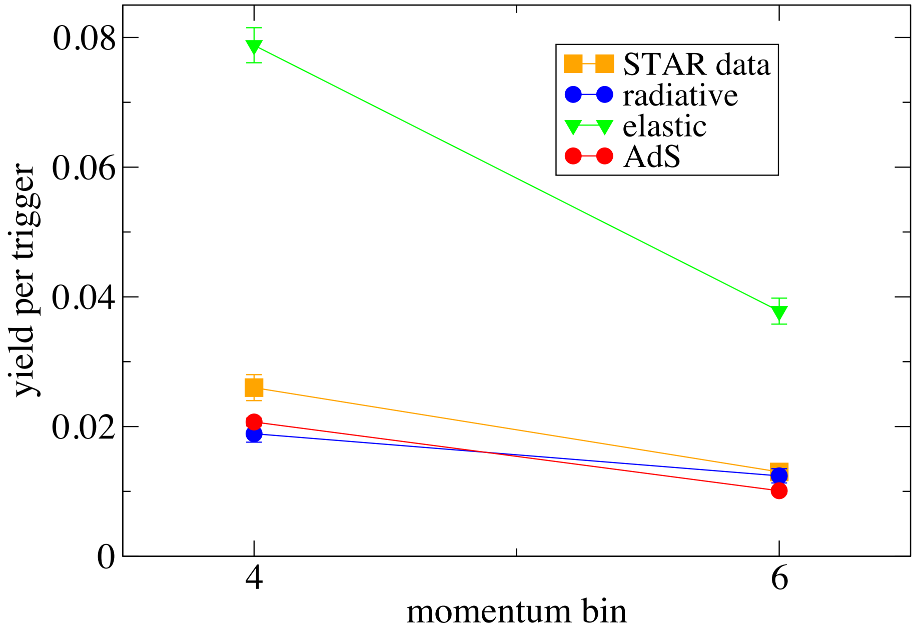
• hadronize the emerging partons, assuming it happens outside the medium
$\longrightarrow$ FFs for leading parton, Lund model for shower

• apply any experimental cuts
$\longrightarrow$ count yields of remaining hadrons

Needs substantial amount of CPU-time ($O(10.000)$ h), but is easily doable on a grid facility.

Pinning down pathlength

- per-trigger yield for an 8-15 GeV trigger hadron



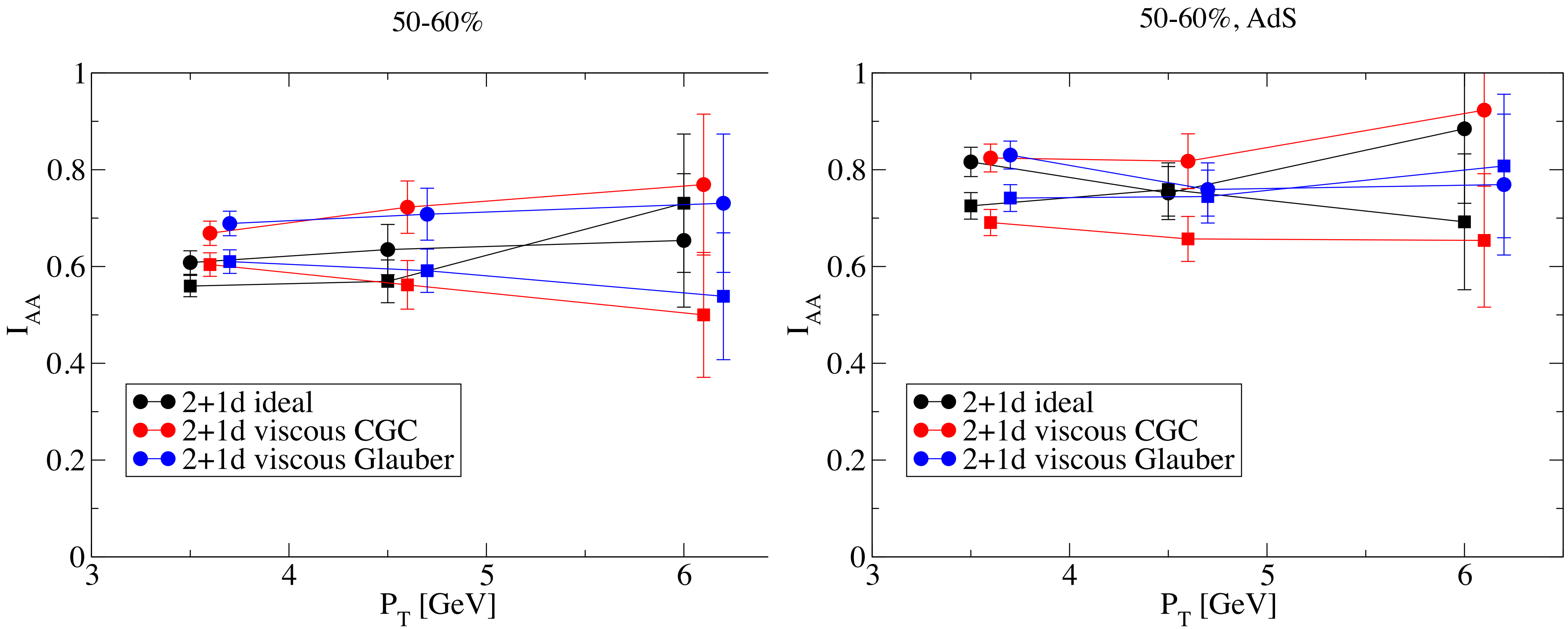
- confirms earlier conclusions with regard to pathlength dependence
- 4 GeV is not enough for a pQCD + fragmentation model to work

$\longrightarrow$ other sources of hadron production are important

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

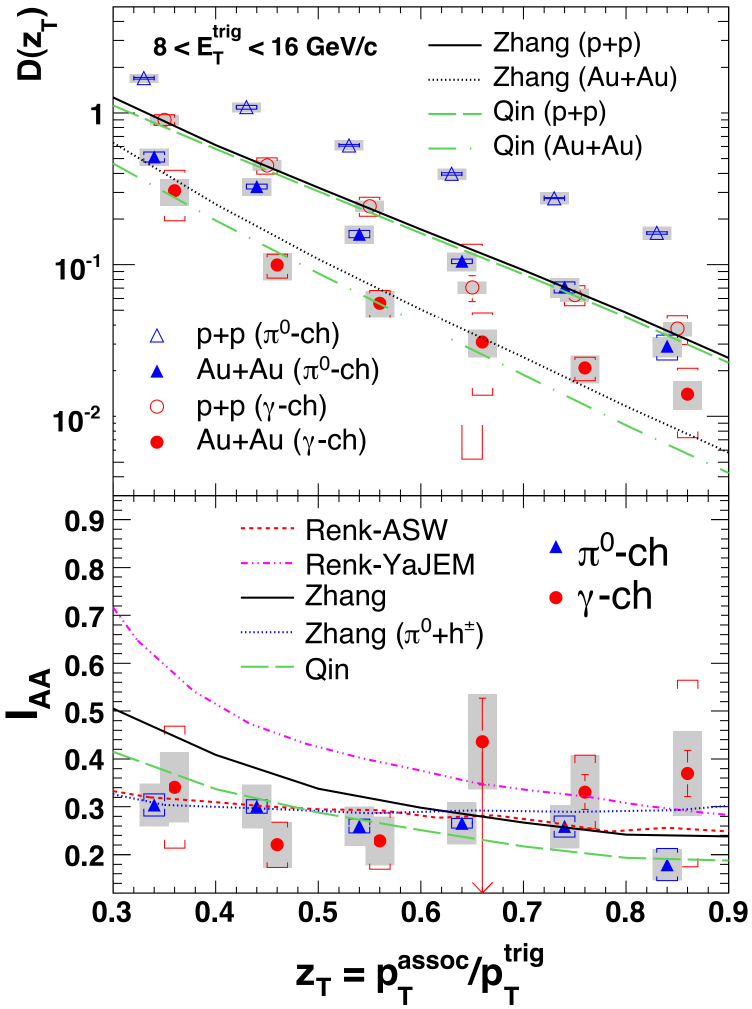
Pinning down geometry

- more systematics — look at $I_{AA}(\phi)$
- data taken, but yet unpublished



- no geometry suggests a black core
- even theory statistics-limited. . .
- trends as established already — AdS results show stronger effect for large b

γ-H CORRELATIONS



- comparable with h-h results

$\longrightarrow$ rather wider trigger range

- no low z_T enhancement!

$\longrightarrow$ implications for in-medium shower models

$\longrightarrow$ a posteriori justification of energy loss

- I_{AA} in γ-h $\approx R_{AA}$ of quarks

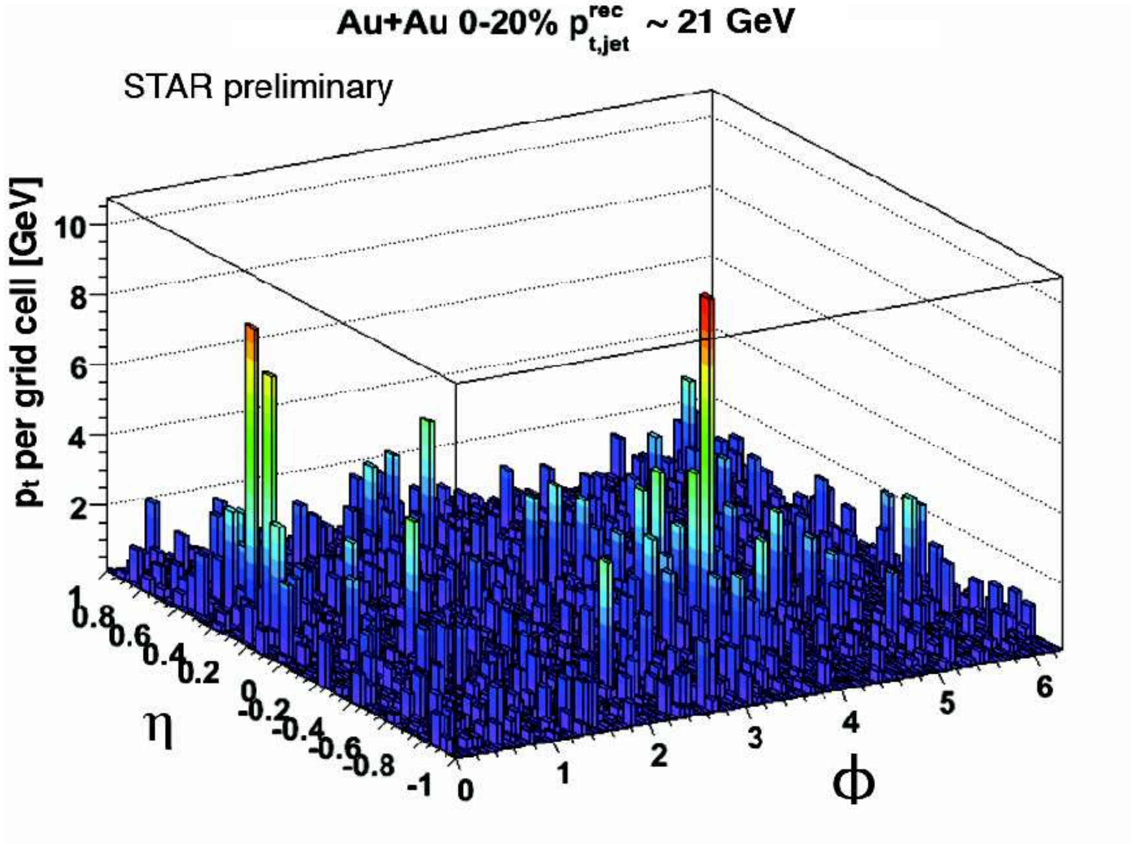
$\longrightarrow$ not much information beyond R_{AA}

Summary

To take away from this chapter:

- h-h correlations magnify pathlength effects
- h-h correlations give a qualitative signal of medium opaqueness / surface bias
- γ-**h correlations** provide the **full kinematics**
- results confirm earlier conclusions based on R_{AA}
- h-h measurements show **no signal of completely opaque core**
- γ-h show signs of **non-perturbative energy redistribution**

Part V: Medium-modified jets



Where does lost energy go?

Jets in heavy-ion collisions

- not tractable using the energy loss picture

$\longrightarrow$ use an in-medium shower MC code

- results shown from YaJEM

$\longrightarrow$ vacuum baseline given by PYSHOW

- three different models for parton-medium interaction

$\longrightarrow$ RAD: induced radiation by explicit change of parton kinematics
$\longrightarrow$ DRAG: AdS/CFT type drag force causing energy loss from shower
$\longrightarrow$ FMED: induced radiation by enhancing the branching probability

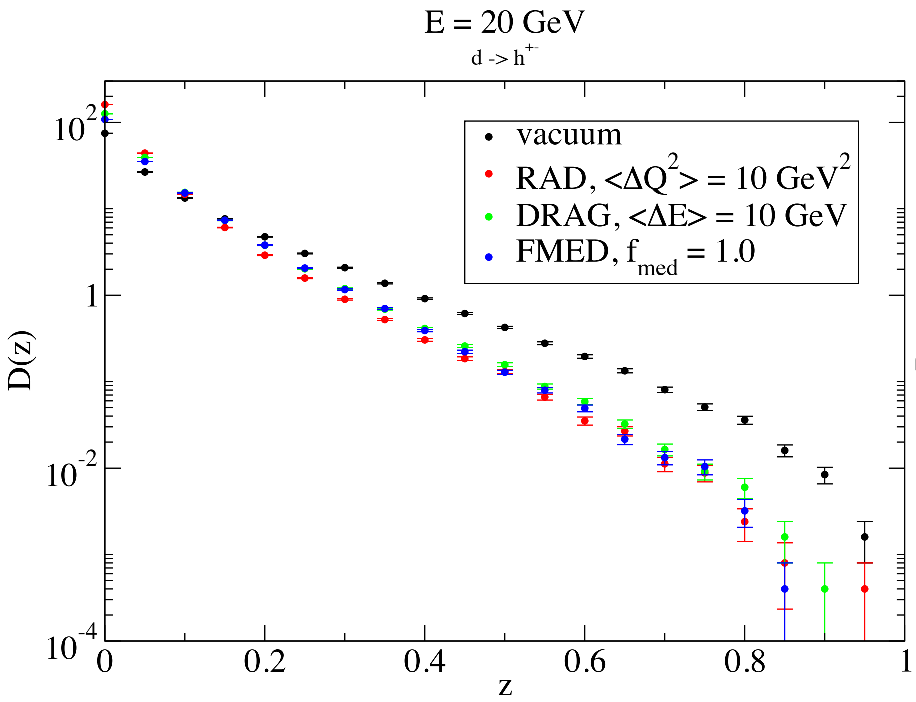
- no precise measurements yet

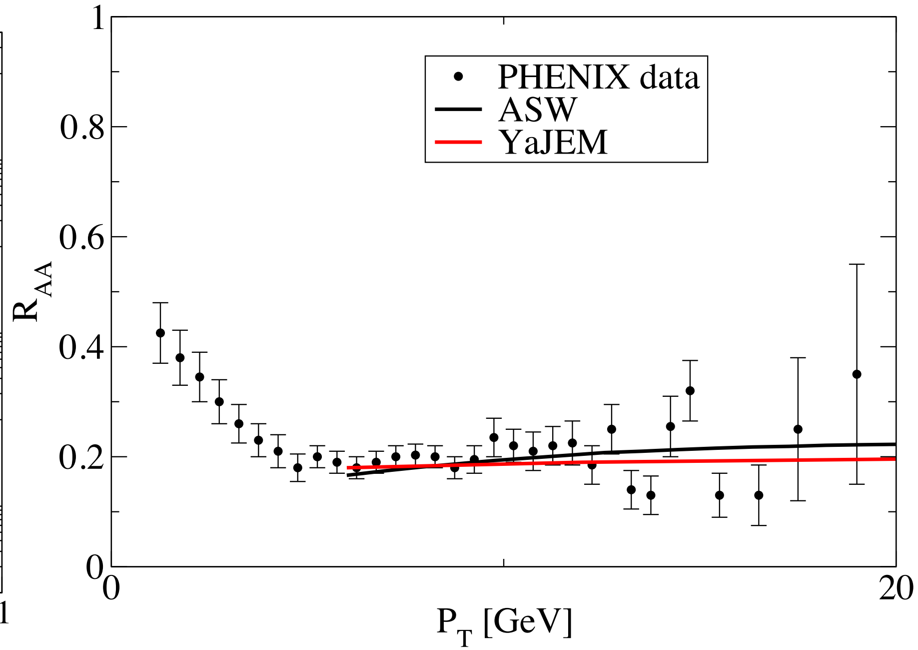
- domain of LHC kinematics

Modified shower comparison (II)

Averaged over 3-d hydrodynamical medium evolution, data comparison is possible:

- does the distortion of the FF shape matter for observables?





- results for all scenarios similar to analytical energy loss model

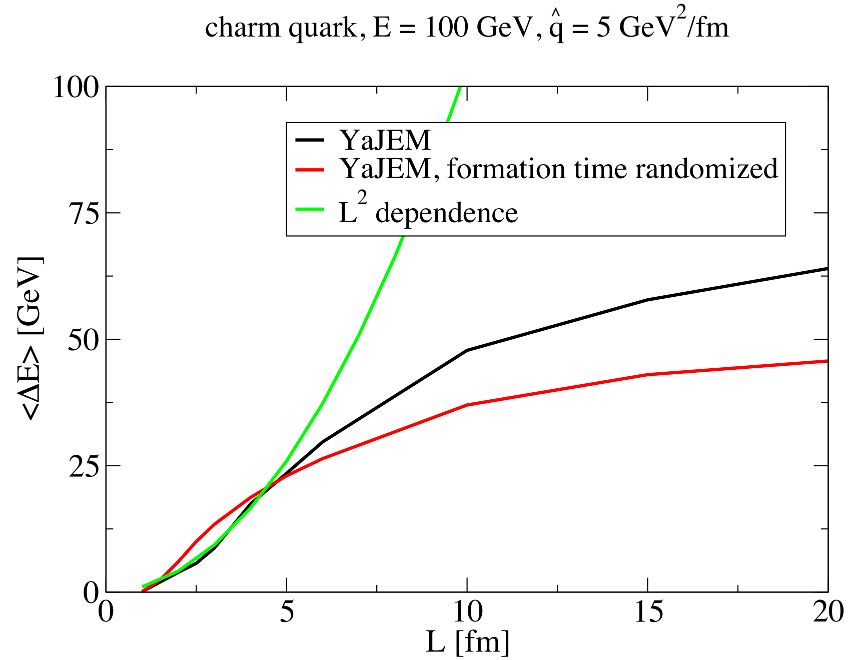
$\longrightarrow$ perhaps not a surprise, as R_{AA} is very insensitive

$\longrightarrow$ shape change in R_{AA} is insignificant

Energy loss

- pathlength dependence of the MC?

$\rightarrow$ does it cope with the quantum interference responsible for the L^2 dependence?



- $\hat{q}$ const., L increased

$\rightarrow$ if formation time not randomized: initial L^2 dependence, then finite energy limit

$\rightarrow$ if formation time randomized: L^2 dependence almost invisible

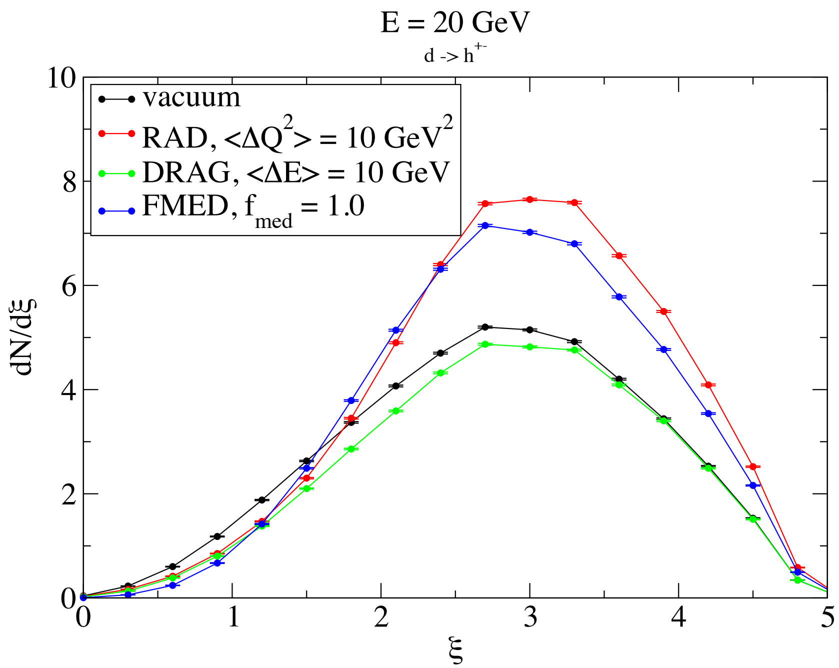
- reason for L^2 dependence:

$\rightarrow$ coherent summation of medium effect during gluon formation time in RAD scenario

$\Rightarrow$ MC framework is indeed able to deal with the relevant physics

Low p_T hadron production

• looking at $\xi = \ln[1/z]$ magnifies low z particle production:



• medium-induced radiation as in RAD or FMED enhance the hump-backed plateau

• a drag force in which energy is transferred to the medium does not

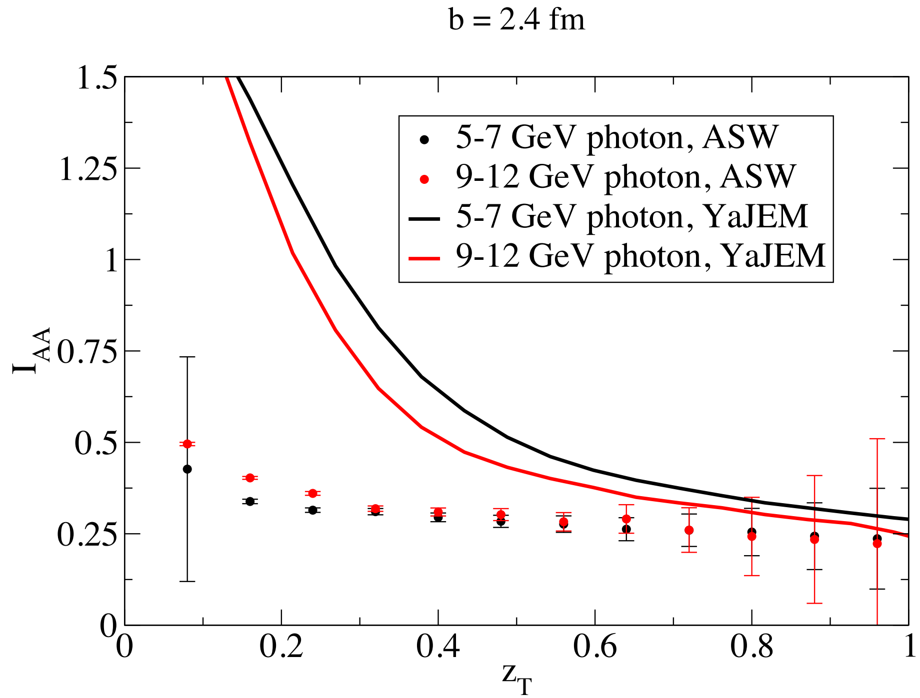
• picture of RAD and FMED: 'lost' energy reappears in low P_T hadron production
$\longrightarrow$ **perturbative** redistribution of energy in the jet cone

T.R., Phys. Rev. C **79** (2009) 054906

Conncetion to γ-h correlations

- I_{AA} correlated yield in the cone opposite to γ, normalized by p-p

$\rightarrow$ averaged over 3-d hydrodynamical medium evolution, I_{AA} in γ-h:



- assumtion: lost energy in ASW nonperturbatively distributed in medium
- perturbative low z hadron production in shower should be visible

$\Rightarrow$ $I_{AA} > 1$ not seen in either preliminary STAR or PHENIX data

$\Rightarrow$ possible hint of non-perturbative energy redistribution in medium

T. R., Phys. Rev. C **80** (2009) 014901

Towards jet observables

Problem 1: Cannot distinguish medium and jet at low P_T:

any low P_T hadron correlated with the jet axis may be correlated because. . .

- it is part of the hadronization of the perturbative shower
- it is bulk medium recoiling from the jet-medium interaction
- it is, due to a similar bias, accidentially correlated
  (e.g. unmodified jets tend to emerge $\perp$ surface — direction of radial flow!)

Problem 2: The hadronization models may not be valid at low P_T (in the medium)

- at present we can only compute reliably *above* a P_T cut

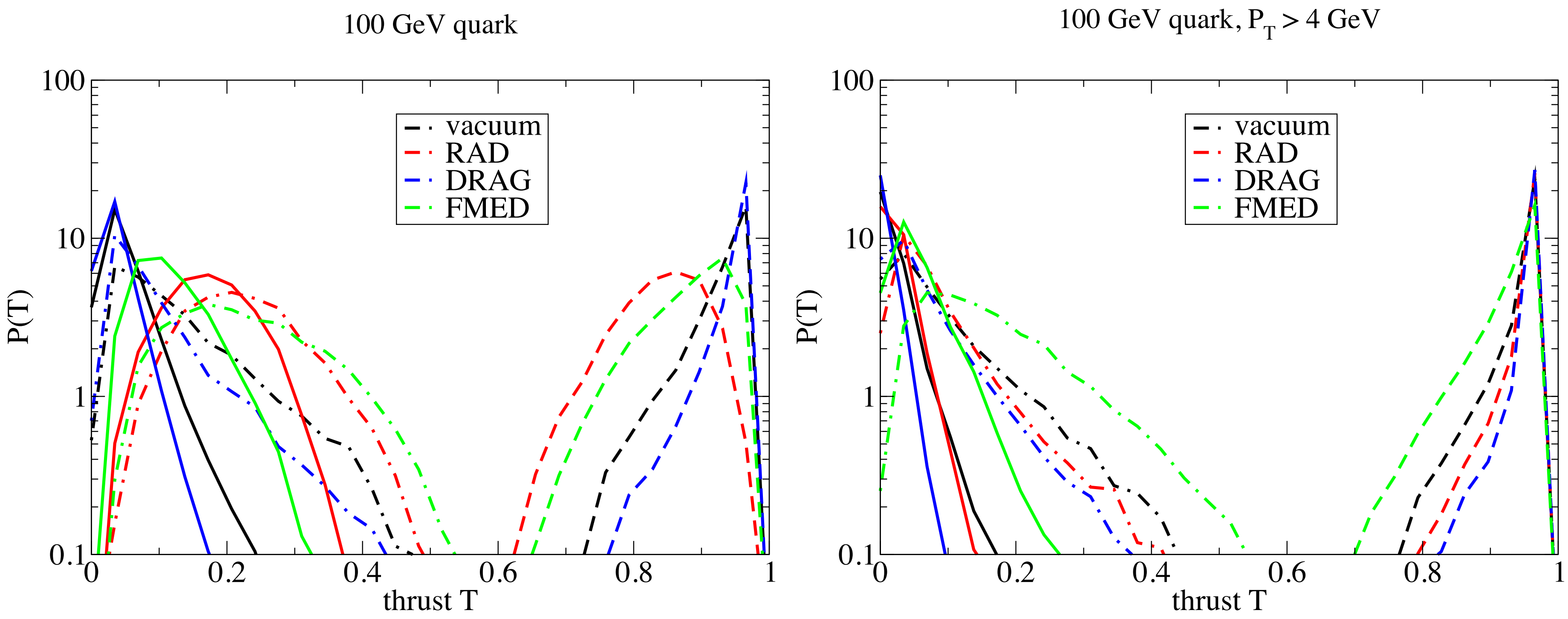
$\Rightarrow$ need to worry about bias (excluding events with lots of soft production)

LHC jet expectations are proof of principle! Real predictions will require knowledge of experimental jet finding strategy — lots of issues hidden in the small print!

Jet observables at LHC (I)

Thrust distribution for typical medium path:

$$T = \max_{\mathbf{n}_T} \frac{\sum_i |\mathbf{p}_i \cdot \mathbf{n}_T|}{\sum_i |\mathbf{p}_i|} \quad T_{maj} = \max_{\mathbf{n}_T \cdot \mathbf{n}=0} \frac{\sum_i |\mathbf{p}_i \cdot \mathbf{n}|}{\sum_i |\mathbf{p}_i|} \quad T_{min} = \frac{\sum_i |\mathbf{p}_i \cdot \mathbf{n}_{mi}|}{\sum_i |\mathbf{p}_i|}$$



- induced radiation tends to make the event more spherical
- difference between RAD and FMED for P_T cut

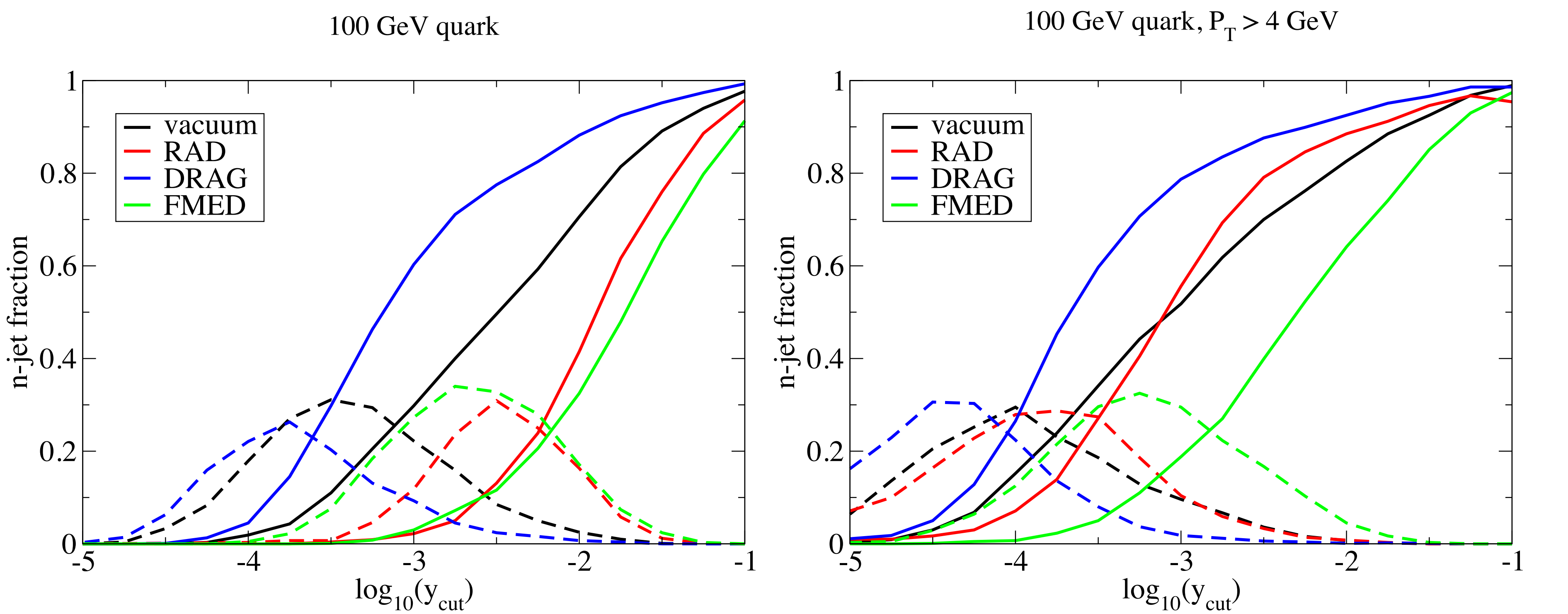
T. R., Phys. Rev. C **80** (2009) 044904

Jet observables at LHC (II)

2 and 4-jet fraction for typical in-medium path for a back-to-back pair:

Clustering with a resolution scale y_{min} based on distance measure

$$y_{ij} = 2\text{min}(E_i^2, E_j^2)(1 - \cos(\theta_{ij})/E_{\text{cm}}^2$$

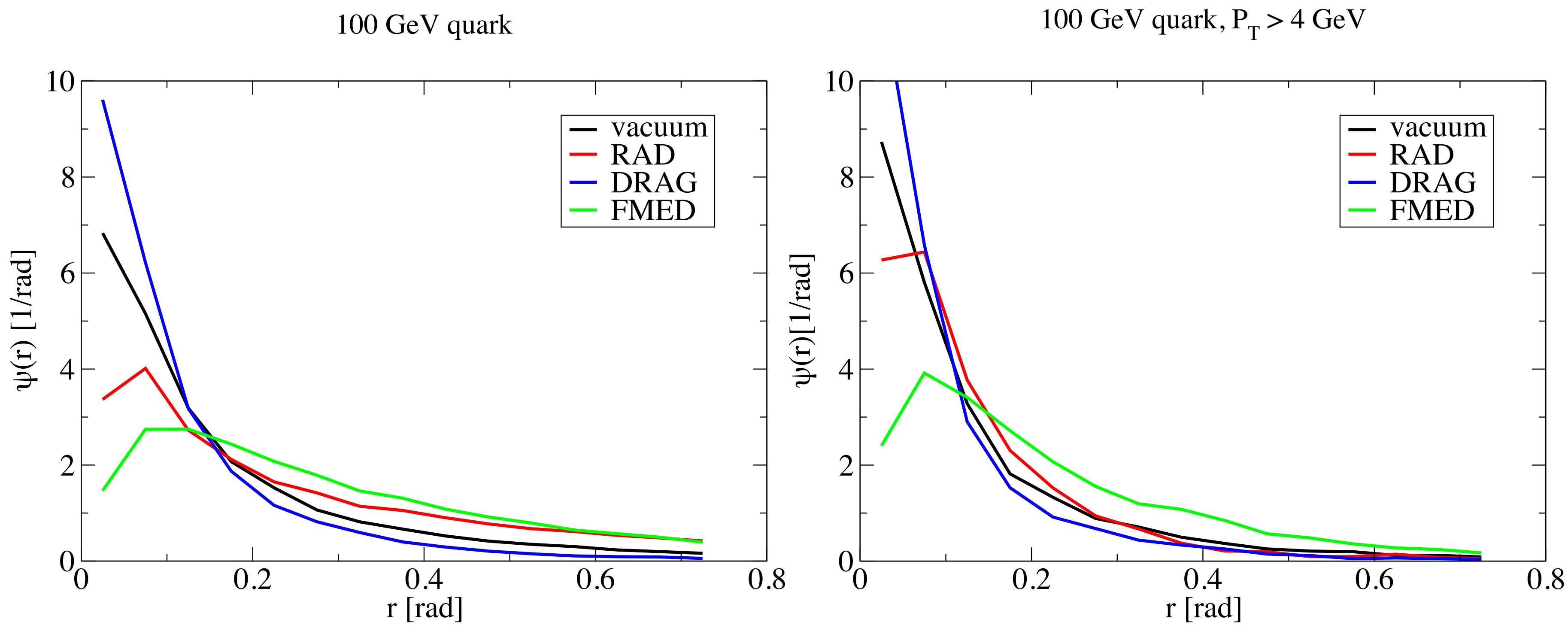


T. R., Phys. Rev. C **80** (2009) 044904

Jet observables at LHC (III)

Jet shapes for typical medium path:

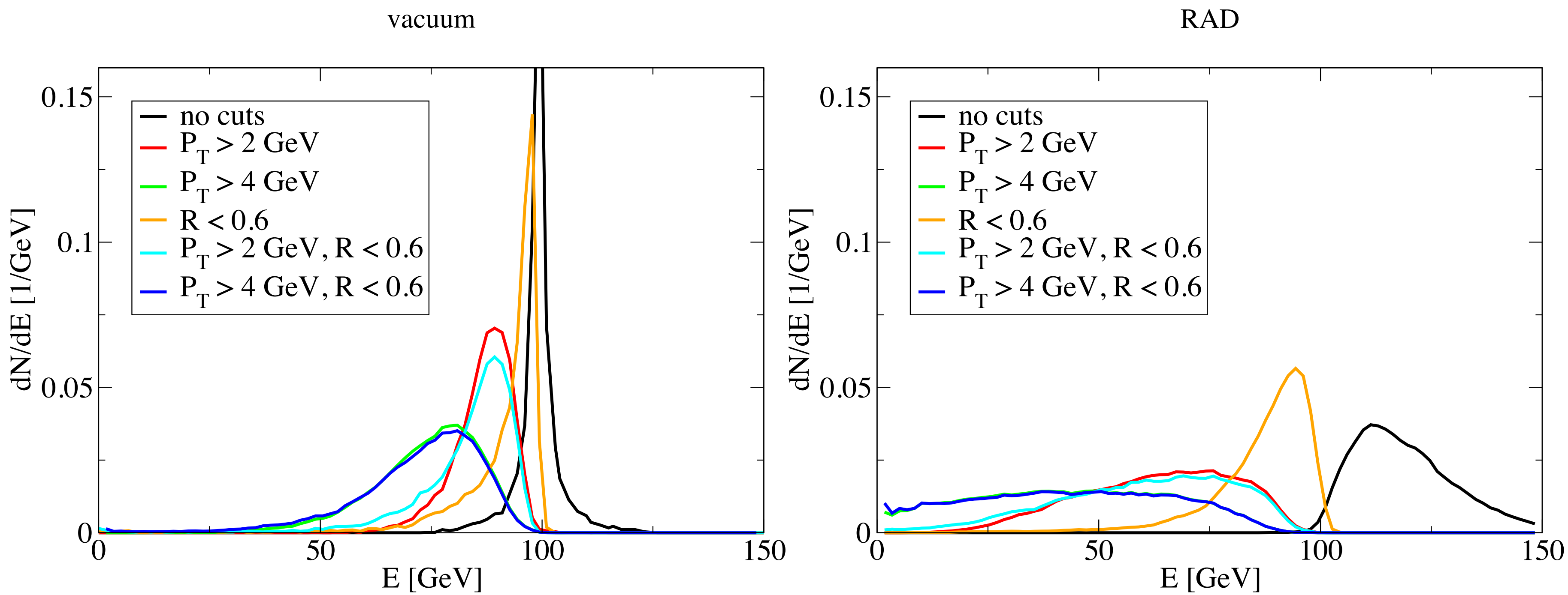
$$\Psi_{int}(r,R) = \frac{\sum_i E_i \theta(r-R_i)}{\sum_i E_i \theta(R-R_i)}$$



T. R., Phys. Rev. C **80** (2009) 044904

Jet observables at LHC — trigger bias

Given a 100 GeV quark shower initiator — what is the energy detected within typical experimental cuts (cone radius R or P_T)?



- medium-modified jets are unlikely to be found with correct energy

T. R., Phys. Rev. C **80** (2009) 044904

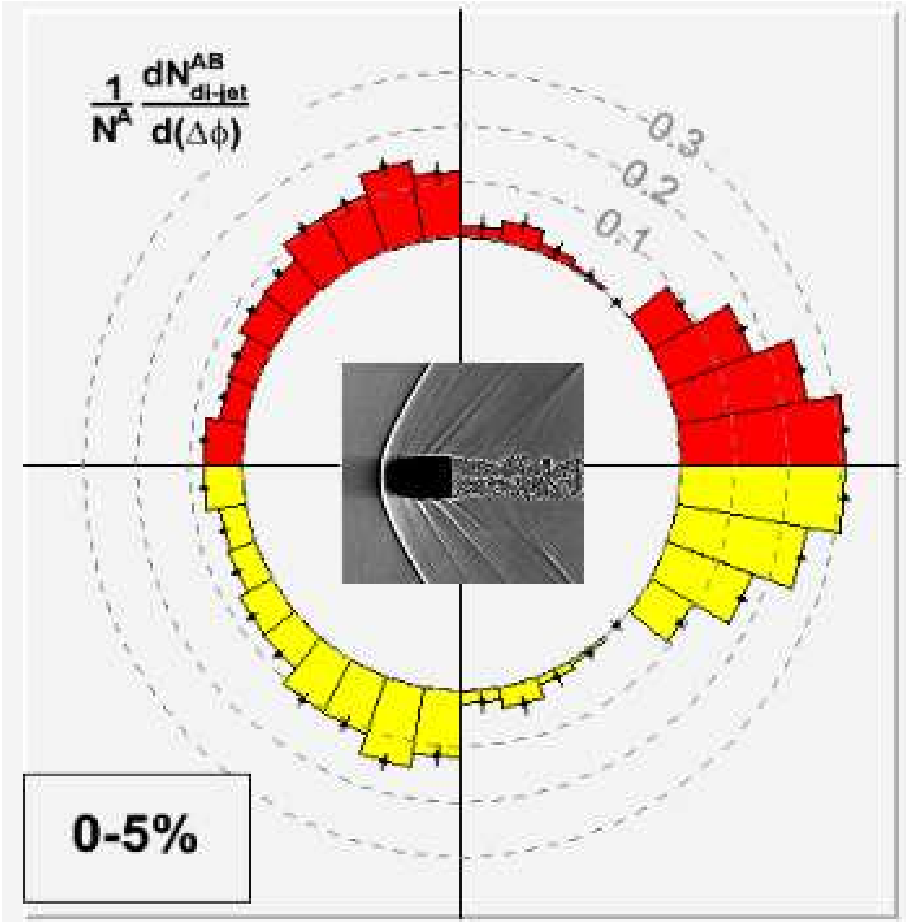
Summary

To take away from this chapter:

- jets in heavy-ion collisions are **difficult**
- jets show where energy lost from leading parton is recovered
- the medium tends to **broaden** and **soften** the jet
- at low P_T, no indication that pQCD works!
- theory is proof of concept, no more and no less

Part III

Part VI: Medium recoil



Is energy redistribution non-perturbative?

The non-perturbative frontier

There are some issues with the in-medium jet picture:

• conceptually: how to distinguish between a low p_T jet and medium parton?
→ once $q_T \sim T$, there is no criterion to tell

• kinematically: if jet is modified by the medium, so is the medium by the jet
→ energy/momentum gain and loss terms of the jet must be compensated by medium

• phenomenologicaly: low p_T enhancement of hadron production not seen in γ-h
→ flow of energy/momentum out of the jet cone

Since we propose a fluid picture for the bulk, it is natural to assume energy and momentum in the bulk are carried by fluid excitations

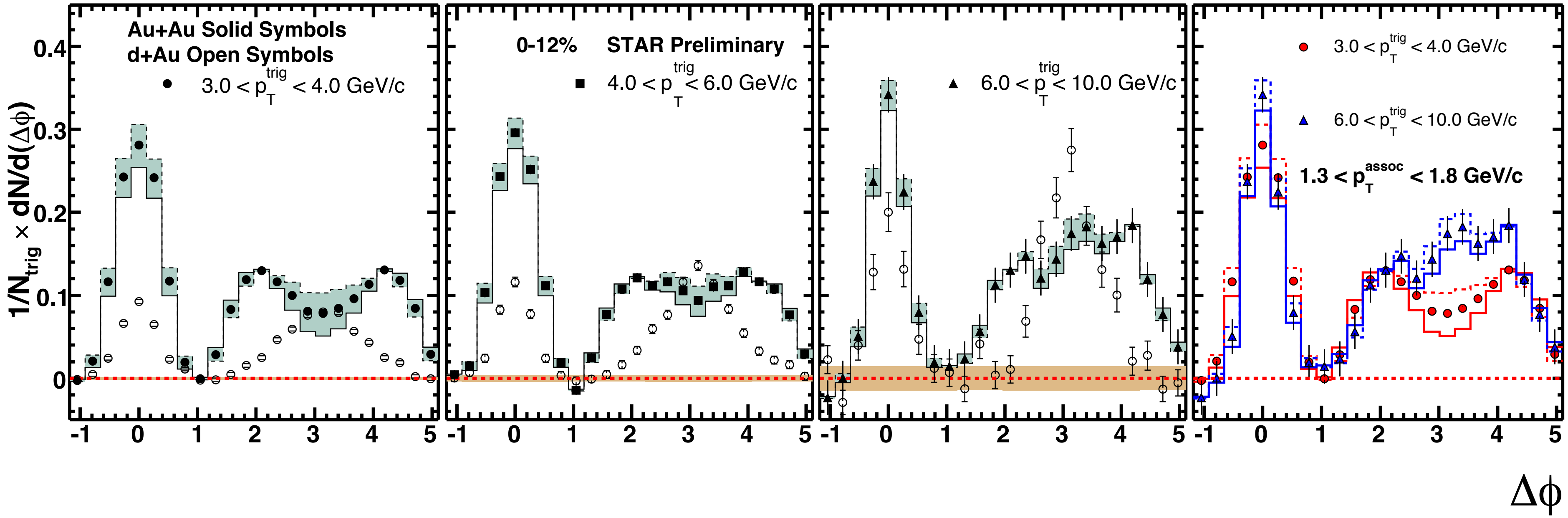
⇒ jet energy loss excites some kind of **shockwave** in the medium

• explicitly part of the strong coupling AdS/CFT QCD picture

A localized perturbation leading to a response potentially allows to measure yet other transport coefficients – such as the speed of sound c_s.

Shockwaves

- angular distribution of particles correlated with a trigger hadron



- at low P_T, medium result very different from vacuum
$\longrightarrow$ double-hump structure

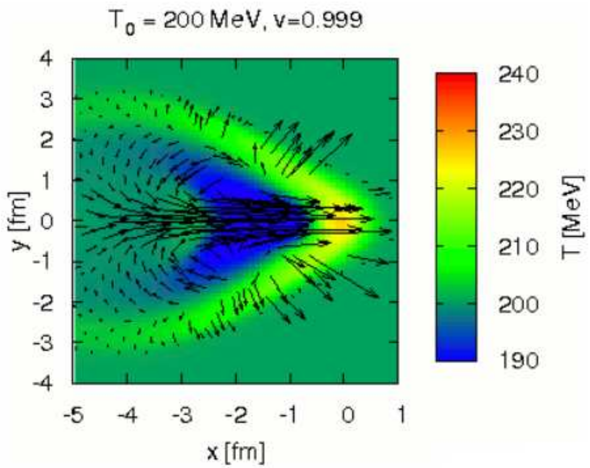
- for large trigger and large associated P_T, vacuum shape restored
$\longrightarrow$ but suppressed, cf. energy loss picture

- consistent with bulk medium recoil from the hard probe, shockwave

M. J. Horner [STAR Collaboration], J. Phys. G **34** (2007) S995

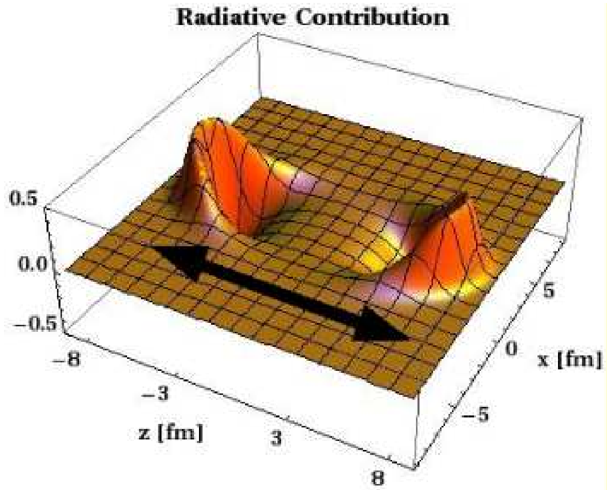
Shockwaves

- assume energy transfer into the fluid medium → shockwave excitation
- ideal hydrodynamical calculations with additional energy/momentum source terms



Bethe-Bloch source term

B. Betz *et al*, 0812.4401 [nucl-th]



HTL source term

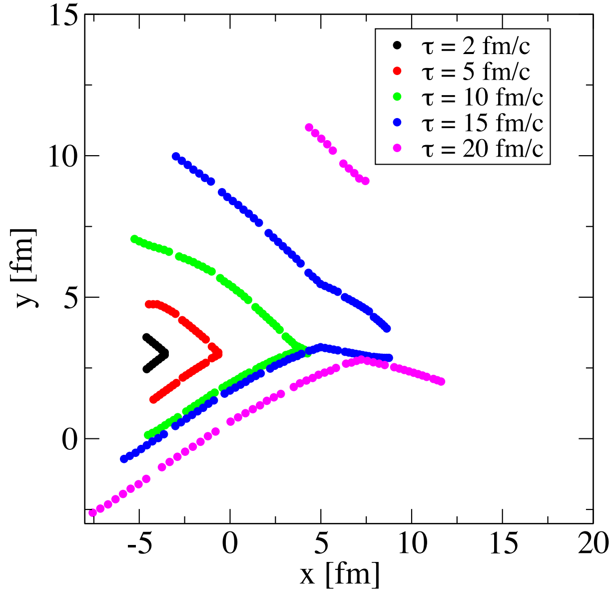
R. B. Neufeld and B. Muller,0902.2950 [nucl-th]

- proof of concept only, no proper averaging over trigger surface bias
- phenomenological hydro-inspired model including proper averaging reproduces data

Why is understanding the data complicated?

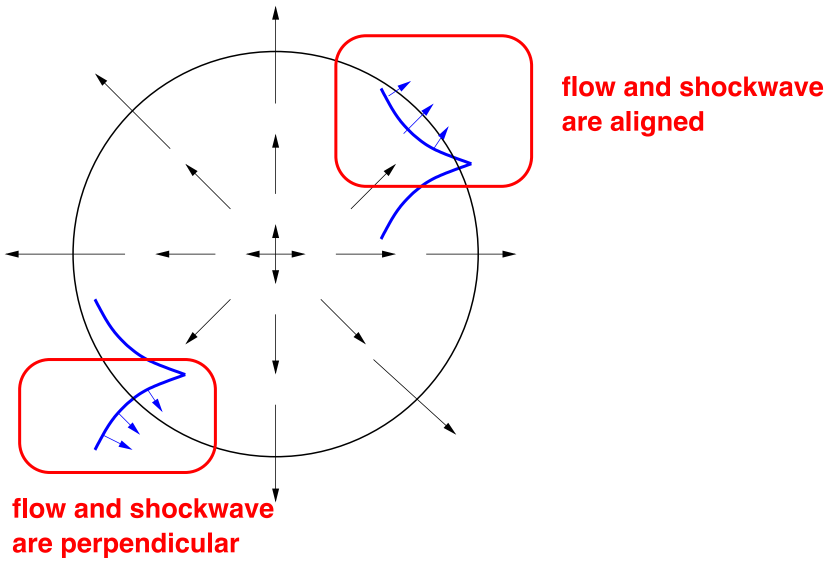
- shockwaves interact with the collective flow field

Position space:



Momentum space:

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



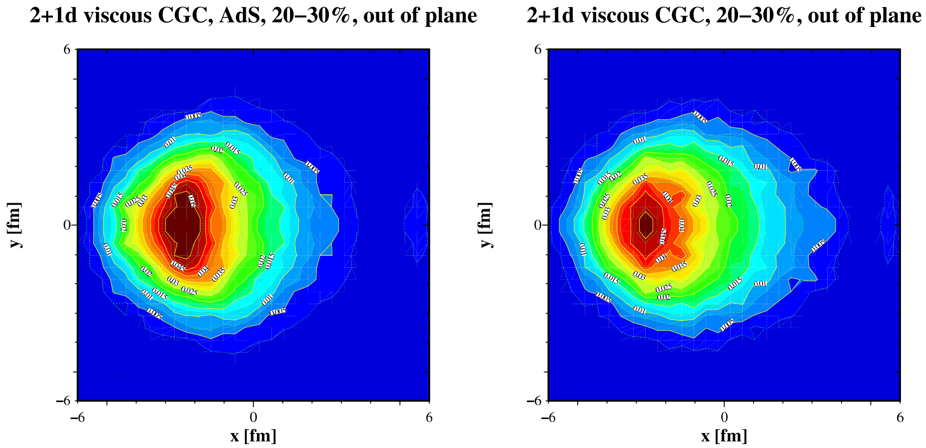
$\Rightarrow$ signal depends on the relative alignment of flow and shockwave

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

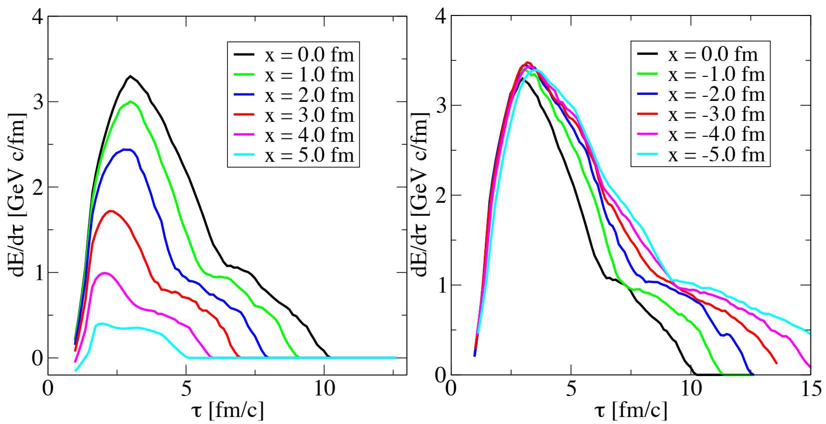
Why is understanding the data complicated?

To get the relative alignment of flow and shockwave, we need:

• the distribution of vertices of origin, given the observed trigger
⟶ we calculated this earlier, depends on geometry and parton-medium interaction



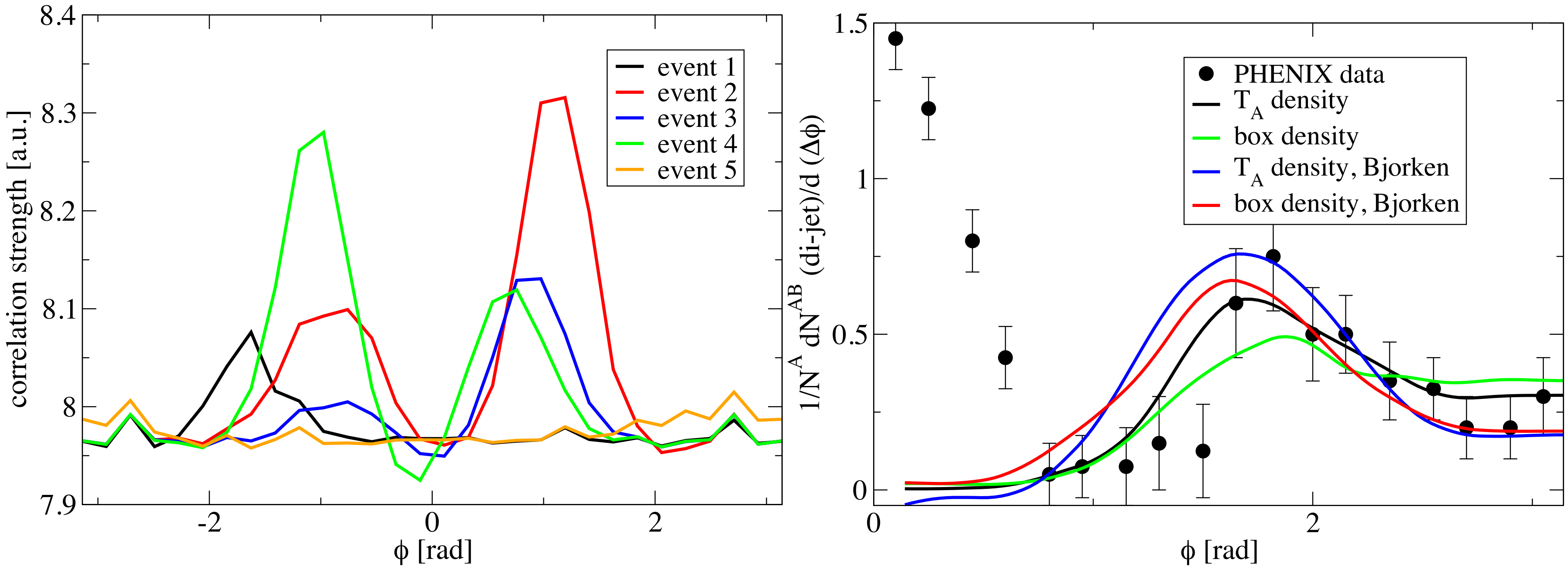
• the space-time picture of energy loss into the medium
⟶ depends on assumed parton-medium interaction



Why is understanding the data complicated?

• **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



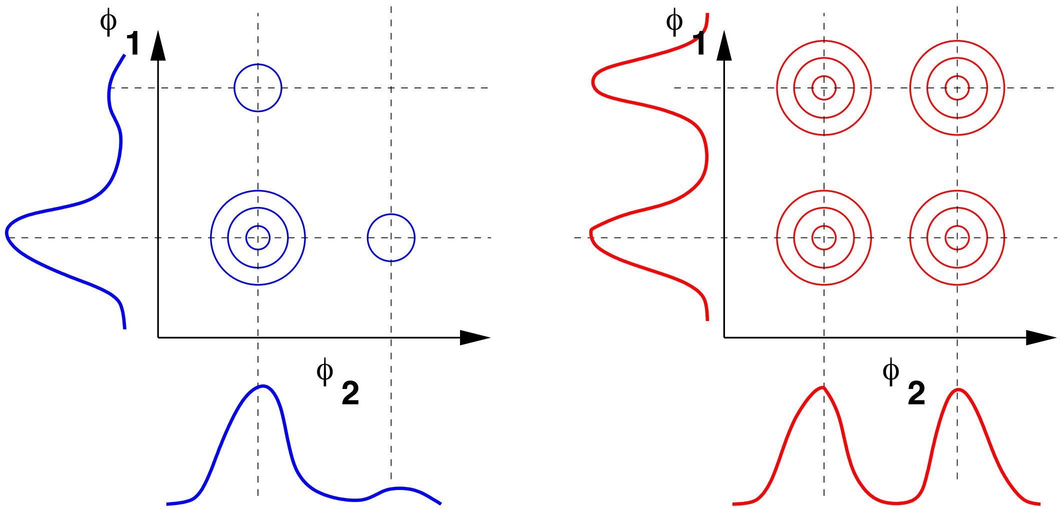
• the observed angle is driven by the combined bias, rather than c_s

• needs a lot more insight into the hard physics before quantitative conclusions!

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

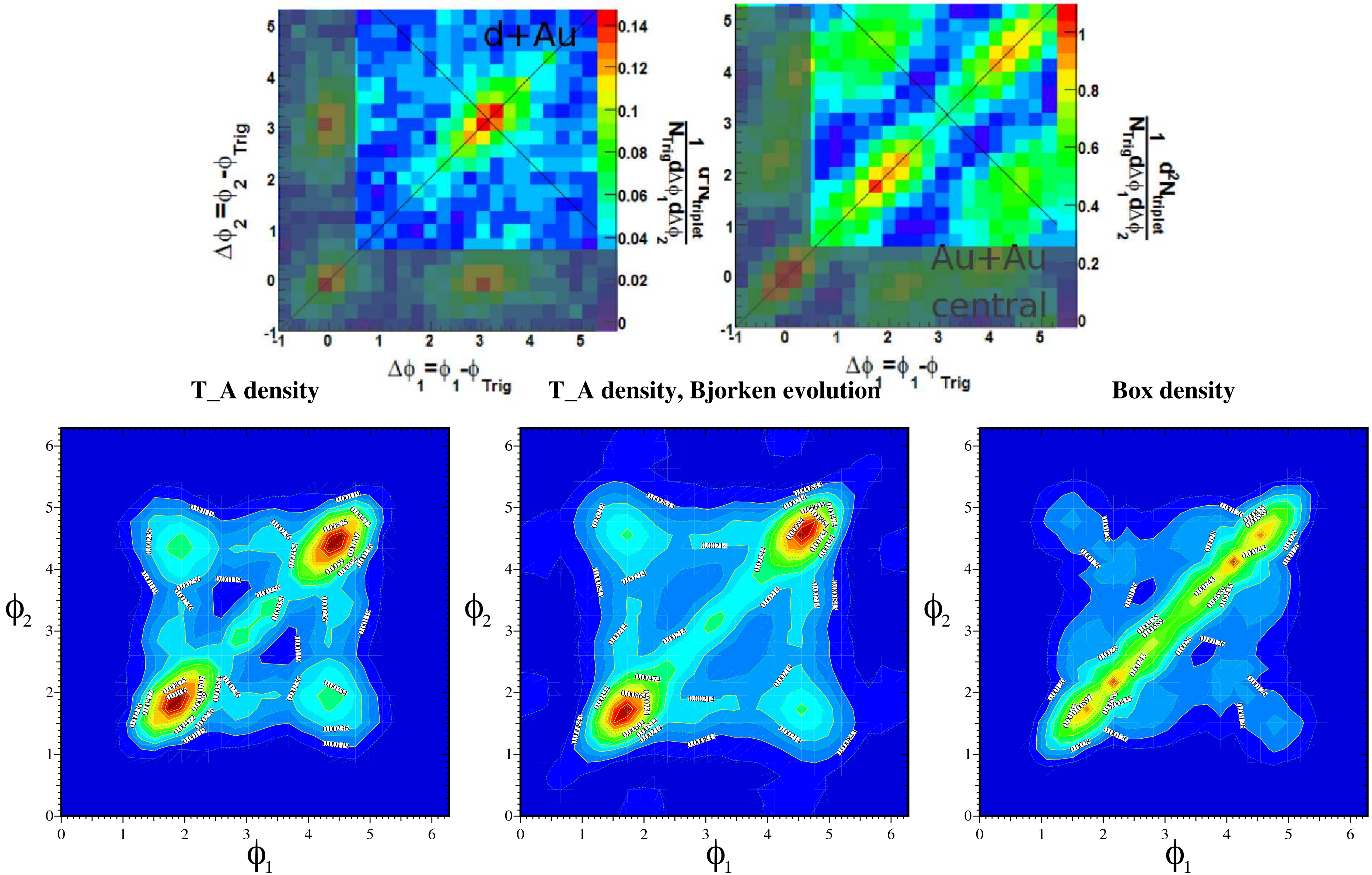
3-PARTICLE CORRELATIONS

• Is this event-by-event fluctuation even qualitatively correct?
$\longrightarrow$ observe 3-particle correlation



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

3-particle correlations

• possible to get to the data
$\longrightarrow$ qualitatively, the physics seems to be there

• **insanely sensitive** to what one assumes for medium evolution, interactions,. . .
$\longrightarrow$ basically an unconstrained problem

• experimentally, comparatively easy to get
$\longrightarrow$ but theoretically a nightmare to treat

Currently not possible to use the correlations to extract medium properties!

(don't trust claims made to that effect)

Summary

To take away from this chapter:

- there is some evidence for a **recoil** of the medium from a hard probe
- this seems to cause **large angle correlations** characteristic of a **shockwave**
- qualitatively, hydrodynamical models can show such shockwaves
- addressing the problem quantitatively is very complicated

Summary of lecture

To take away from these lectures:

• we don't really know much about QCD
$\longrightarrow$ for collectivity, even qualitative understanding is often absent

• heavy-ion physics aims to close part of that gap
$\longrightarrow$ usually the challenge is finding the right model, rather than computing corrections

• hard processes can serve as probes of collective bulk matter
$\longrightarrow$ provided careful and comprehensive modelling is done

• some tomographical information has already been obtained
$\longrightarrow$ awaiting data with LHC statistics to really get into details

The end!