Comparison of Jet Energy-Loss Schemes in a 3D Hydrodynamic Medium

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- a model for the medium: 3D-RFD
- jet energy-loss schemes
- azimuthally dependent jet energy-loss

collaborators:
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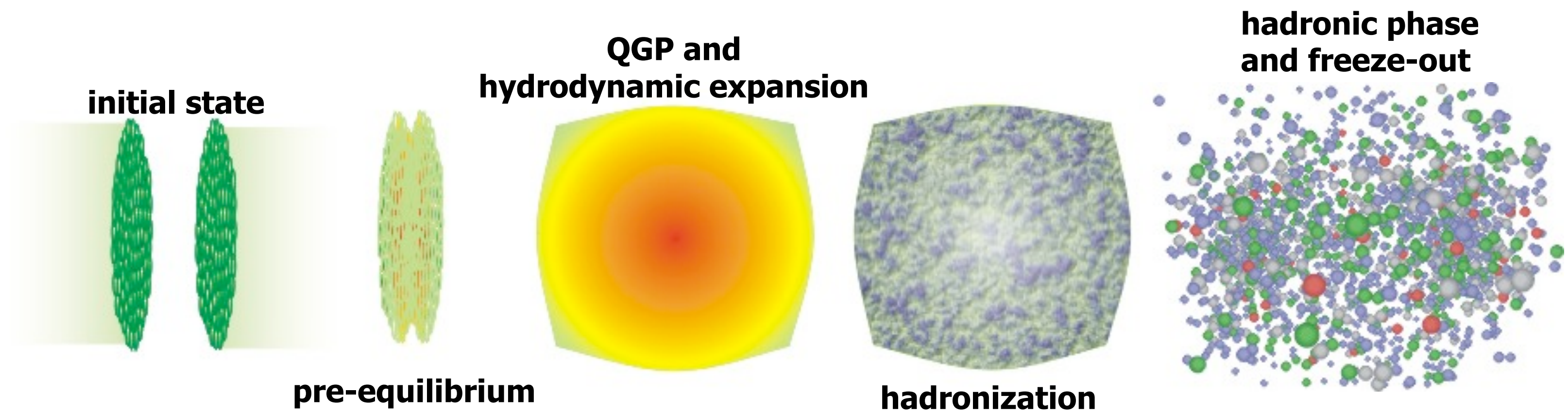
- T. Renk
- G.Y. Qin
- C. Nonaka
- A. Majumder
- C. Gale

Exploring QCD Matter at RHIC and LHC



Lattice-Gauge Theory:
- rigorous calculation of QCD quantities
- works in the infinite size / equilibrium limit

Experiments:
- observe the final state + penetrating probes
- rely on QGP signatures predicted by Theory

Phenomenology & Transport Theory:
- connect QGP state to observables
- provide link between LGT and data

The Medium:
3D Relativistic Fluid Dynamics

C. Nonaka & S.A. Bass, Phys. Rev. **C75** 014902 (2007)

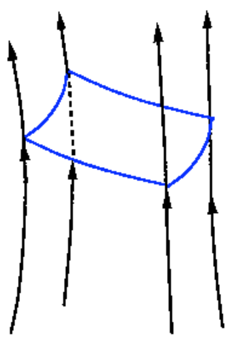
Relativistic Fluid Dynamics

- transport of macroscopic degrees of freedom
- based on conservation laws: $\partial_\mu T^{\mu\nu}=0$ $\partial_\mu j^\mu=0$
- for ideal fluid: $T^{\mu\nu}= (\varepsilon+p)\, u^\mu u^\nu - p\, g^{\mu\nu}$ and $j_i^\mu = \rho_i u^\mu$
- **Equation of State** needed to close system of PDE's: $p=p(T,\rho_i)$
- ➢ connection to Lattice QCD calculation of EoS

- initial conditions (i.e. thermalized QGP) required for calculation
- Hydro assumes local thermal equilibrium, vanishing mean free path

This particular implementation:

- ➢ fully 3+1 dimensional, using (τ,x,y,η) coordinates
- ➢ Lagrangian Hydrodynamics
  - ➢ coordinates move with entropy-density & baryon-number currents
  - ➢ trace adiabatic path of each volume element



3D-Hydro: Parameters

Initial Conditions:

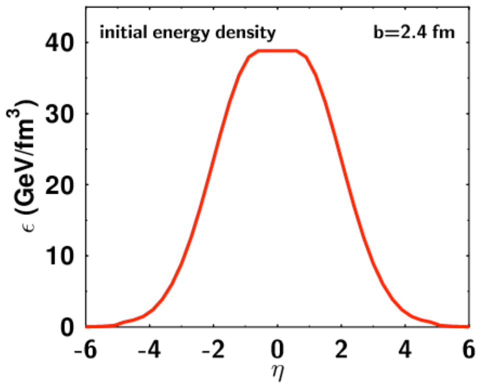
- Energy Density:

$$\epsilon(x,y,\eta) = \epsilon_{\max} W(x,y;b) H(\eta)$$

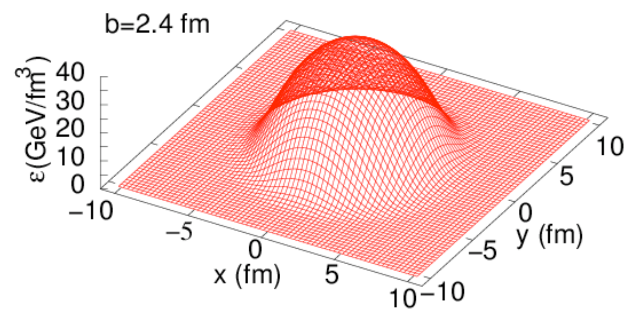
- Baryon Number Density:

$$n_B(x,y,\eta) = n_{B\max} W(x,y;b) H(\eta)$$

longitudinal profile:



transverse profile:

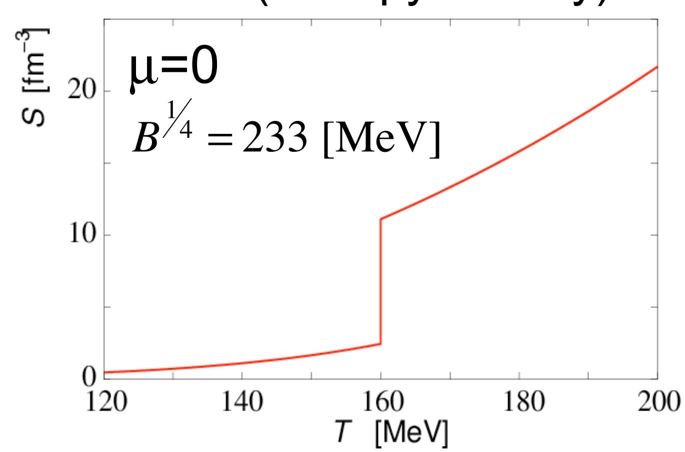


Parameters:

- τ_0=0.6 fm/c
- ε_{max}=55 GeV/fm^3, n_{Bmax}=0.15 fm^{-3}
- η_0=0.5 σ_η=1.5

- Initial Flow: $v_L=\eta$ (Bjorken's solution); v_T=0

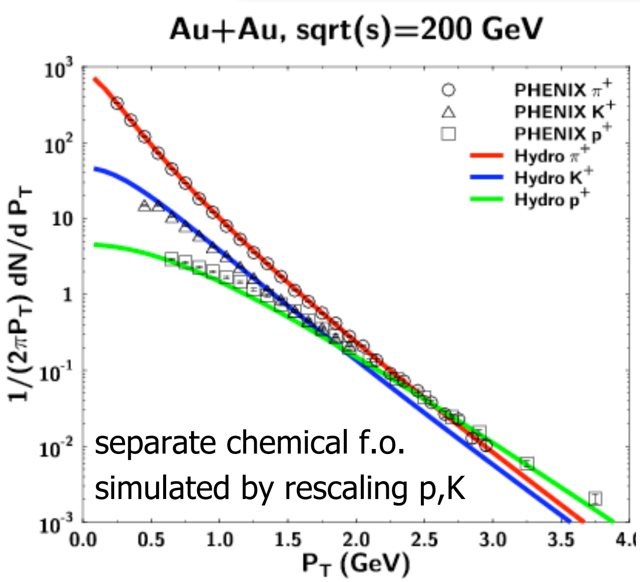
EOS (entropy density)

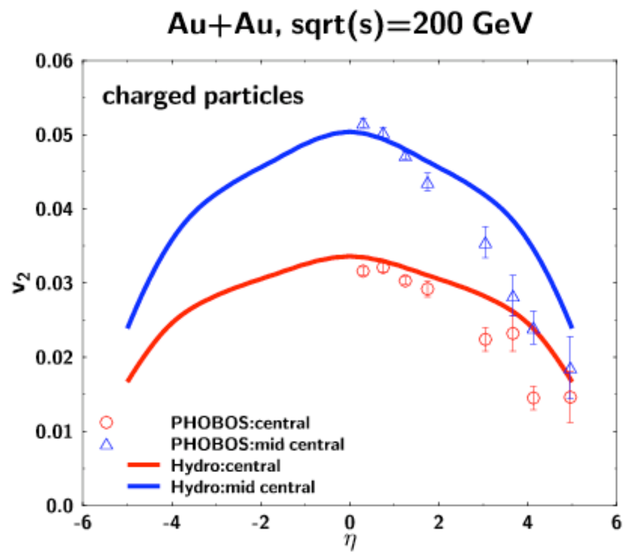


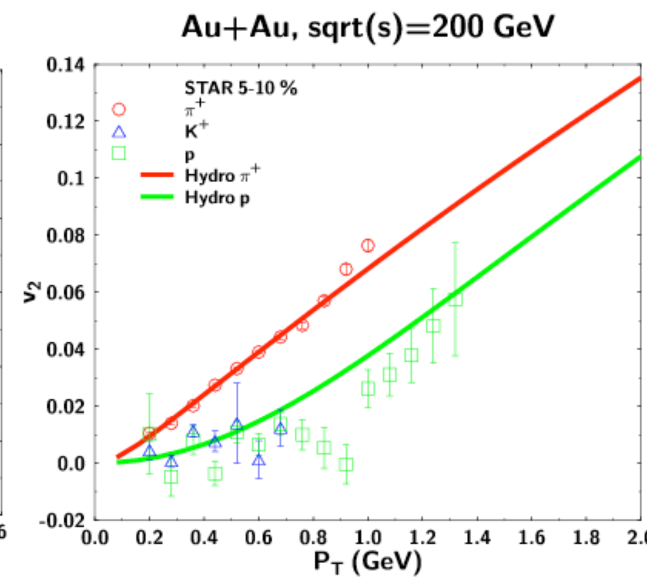
Equation of State:

- Bag Model + excluded volume
- 1st order phase transition (to be replaced by Lattice EoS)

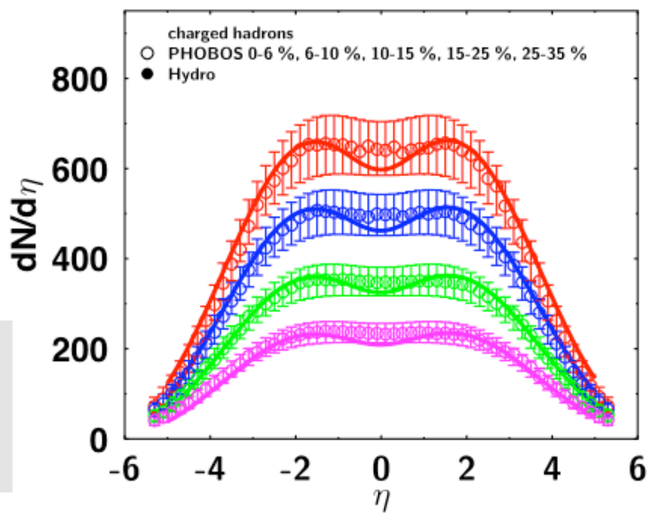
3D-Hydro: Comparison to RHIC

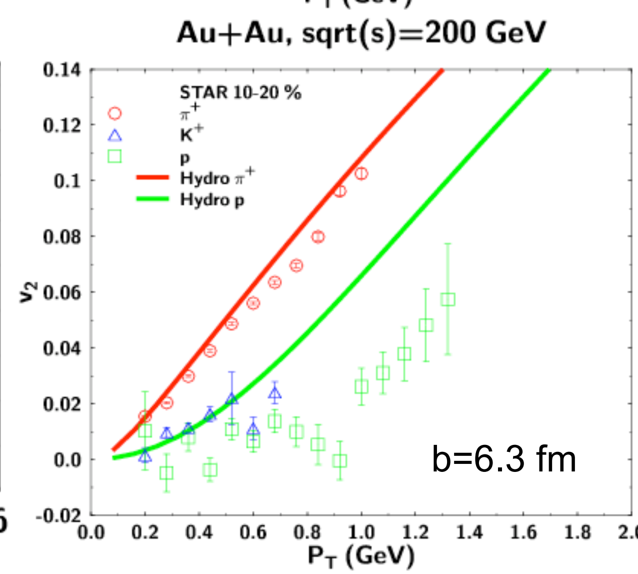






- address all data in the soft sector with one consistent calculation





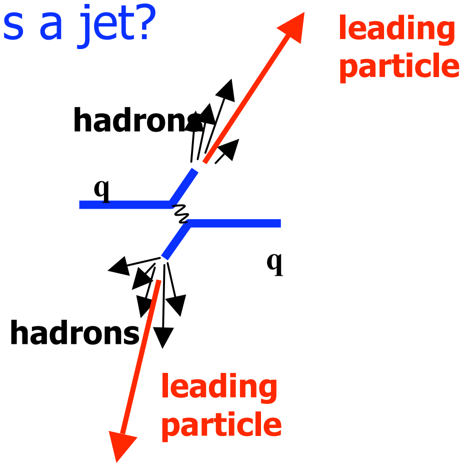
Nonaka & Bass:
PRC75, 014902 (2007)
See also Hirano; Kodama et al.

Jet-Medium Correlations:
Azimuthally Dependent Jet-Quenching

Renk, Ruppert, Nonaka & Bass: Phys. Rev. **C75** (2007) 031902
Majumder, Nonaka & Bass: Phys. Rev. **C76** (2007) 041902
Qin, Ruppert, Turbide, Gale, Nonaka & Bass: Phys. Rev. **C76** (2007) 064907

Jet-Quenching: Basic Idea

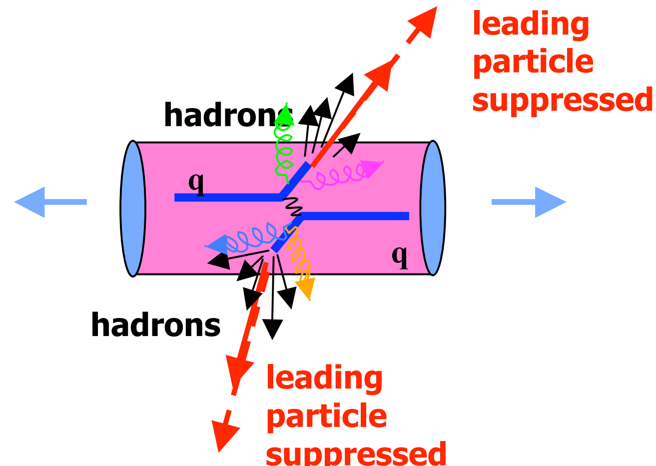
What is a jet?



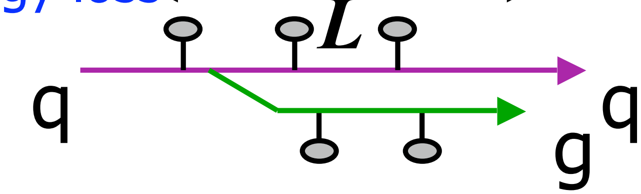
- fragmentation of hard scattered partons into collimated "jets" of hadrons

➢ p+p reactions provide a calibrated probe, well described by pQCD

what happens if partons traverse a high energy density colored medium?



- partons lose energy and/or fragment differently than in the vacuum: radiative energy loss



$$\hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2} \equiv \rho\sigma \left\langle k_T^2 \right\rangle = \frac{\mu^2}{\lambda_f}$$

➢ transport coefficient q is sensitive to density of (colored) charges

Jet Energy-Loss Schemes

Armesto, Salgado, Wiedemann (ASW):

- medium of heavy static scattering centers w/ Yukawa-like potentials
- parton pics up transverse kicks $\sim\mu^2$
- path integral over multiple scatterings in the medium

Arnold, Moore, Yaffe (AMY):

- thermalized partonic medium in HTL approx. ($T\rightarrow\infty$ and $g\rightarrow 0$)
- hard parton comes on-shell, receives hits of $\mu \sim gT$
- resummation over multiple scatterings and absorptions

Higher Twist (HT):

- few medium assumptions: short color correlation length
- calculates modification of n-hadron FF due to mult. scattering in medium
- scattering encoded as HT gluon-gluon field strength: can be expanded twist-by-twist or resummed for multiple scattering

Gyulassy, Levai, Vitev (GLV):

- medium of heavy static scattering centers w/ Yukawa-like potentials
- parton picks up transverse kicks $\sim\mu^2$
- operator formalism that sums order by order in opacity $n=L/\lambda_g$

The Soft/Hard Disconnect

- Heavy-ion collisions at RHIC have produced a state of matter which behaves similar to an ideal fluid
- ➢ (3+1)D Relativistic Fluid Dynamics and hybrid macro+micro models are highly successful in describing the dynamics of bulk QCD matter

- Jet energy-loss calculations have reached a high level of technical sophistication (BDMPS, GLV, higher twist…), yet they employ only very simple/primitive models for the evolution of the underlying deconfined medium…
- all conclusions to be drawn from jet energy-loss calculations are necessarily with respect to the nature of the medium assumed in the calculation

- ➢ need to overcome this disconnect and treat medium and hard probes consistently and at same level of sophistication!

Connecting high-p_t partons with the dynamics of an expanding QGP

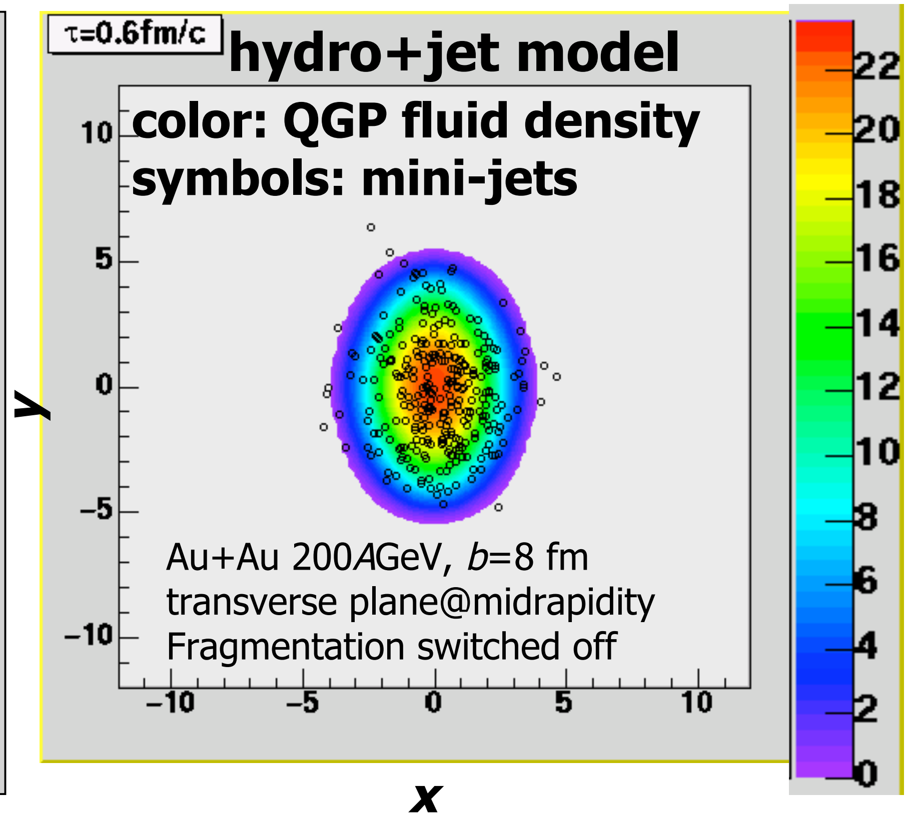
Hydro+Jet model

T.Hirano. & Y.Nara: Phys.Rev.**C66** 041901, 2002

➤ use GLV 1st order formula for parton energy loss (M.Gyulassy et al. '00)

$$\Delta E = C \int_{\tau_0} d\tau (\tau - \tau_0) \times \rho\left(\tau, \mathbf{x}(\tau)\right) \ln \left(\frac{2 p_0^{\mu} u_{\mu}}{\mu^2 L} \right)$$

➤take Parton density $\rho(x)$ from full 3D hydrodynamic calculation



- 1st work combining realistic hydro and jet energy-loss
- good description of single-inclusive spectra and R_{AA}

Energy-Loss Implementation in 3D RFD

3D hydrodynamic evolution provides ε, T, γ and Γ_{QGP} as function of (τ,x,y,η)

BDMPS/ASW:

- define local transport coefficient along trajectory ξ (K as parameter to fix opacity of medium): $\hat{q}(\xi) = K \cdot 2 \cdot \varepsilon^{\frac{3}{4}}(\xi)$

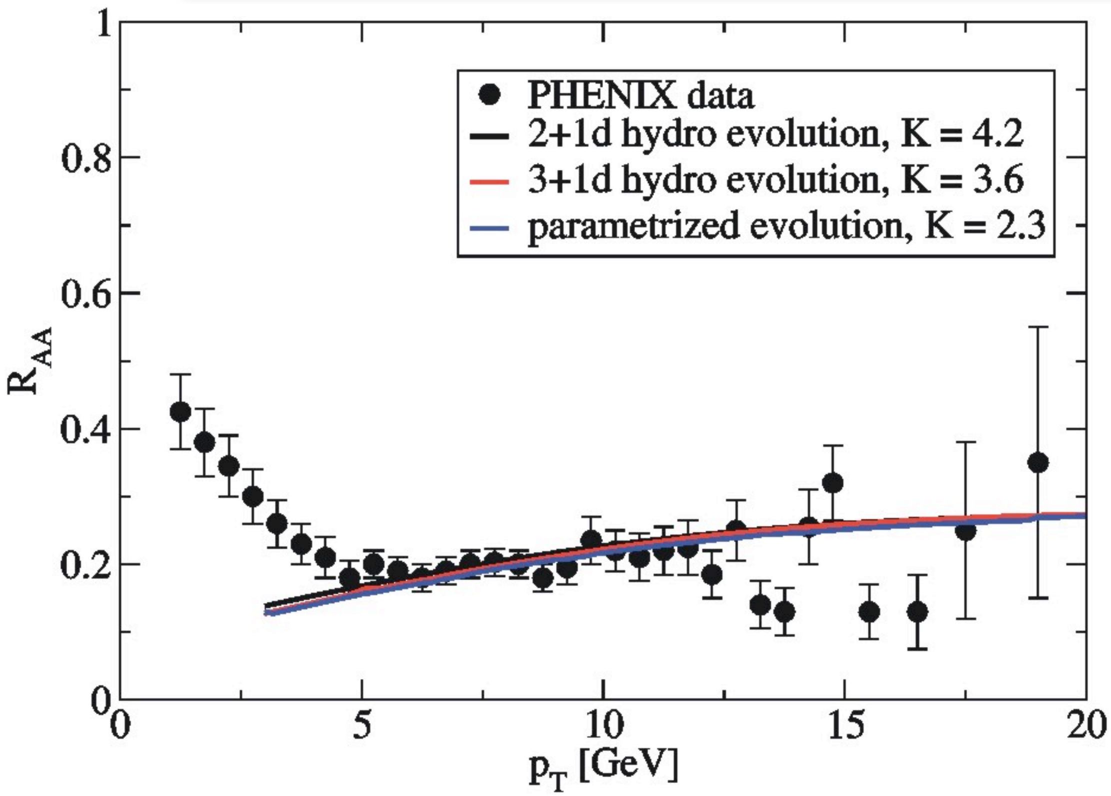
Higher Twist:

- fix starting value of q; hadronic phase can be taken into account via coefficient c_{HG}: $\hat{q}(\vec{r},\tau) = \hat{q}_0 \frac{\gamma(\vec{r},\tau) T^3(\vec{r},\tau)}{T_0^3} \left[\Gamma_{QGP}(\vec{r},\tau) + c_{HG} \left(1 - \Gamma_{QGP}(\vec{r},\tau) \right) \right]$

AMY:

•evolution of jet-momentum distribution is obtained by solving set of coupled rate eqns, with transition rates depending on the coupling constant α_s, local temperature T and flow velocity γ

Jet-Tomography: Medium Dependence



BDMPS/ASW jet energy loss calc.

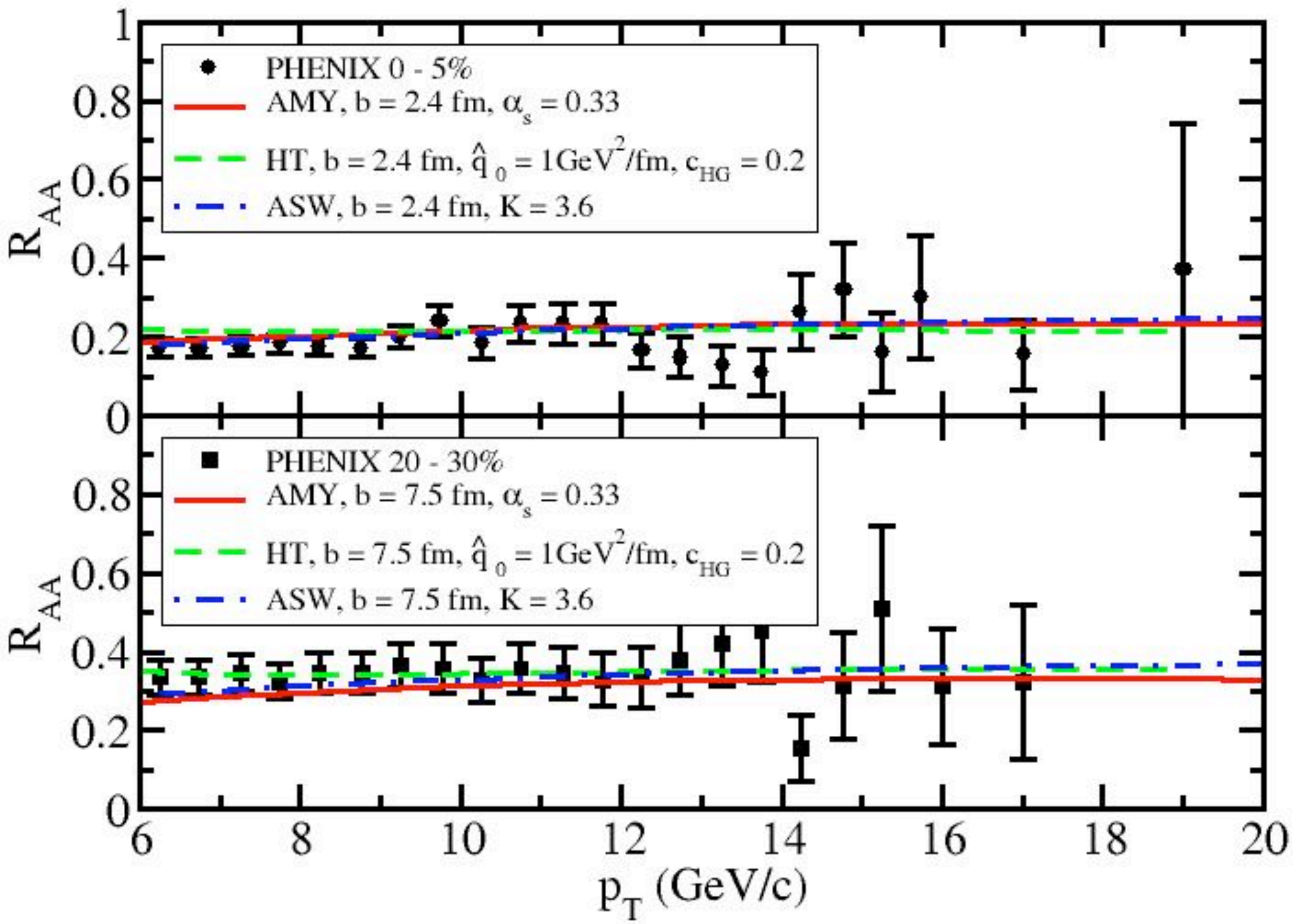
medium modeled via:

1. 2+1D Hydro (Eskola et al.)
2. parameterized evolution (Renk)
3. 3+1D Hydro (Nonaka & Bass)

- ± 50% spread in values for K

- large systematic error in tomography analysis due to varying medium descriptions
- need standard model for medium to gain predictive and discriminative power

Discriminative Power of R_{AA}



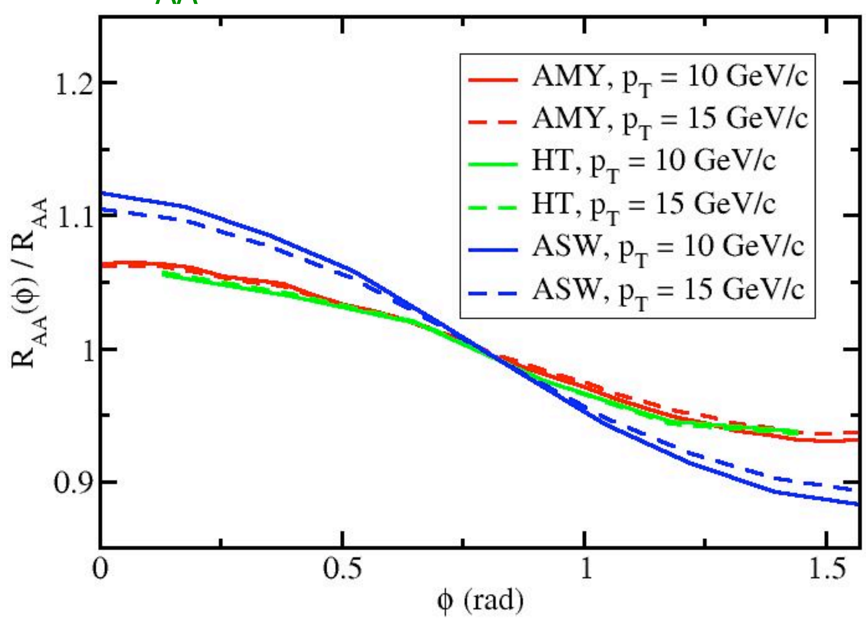
ASW	HT	AMY
K=3.6	q_0=1.5	α_s=0.33

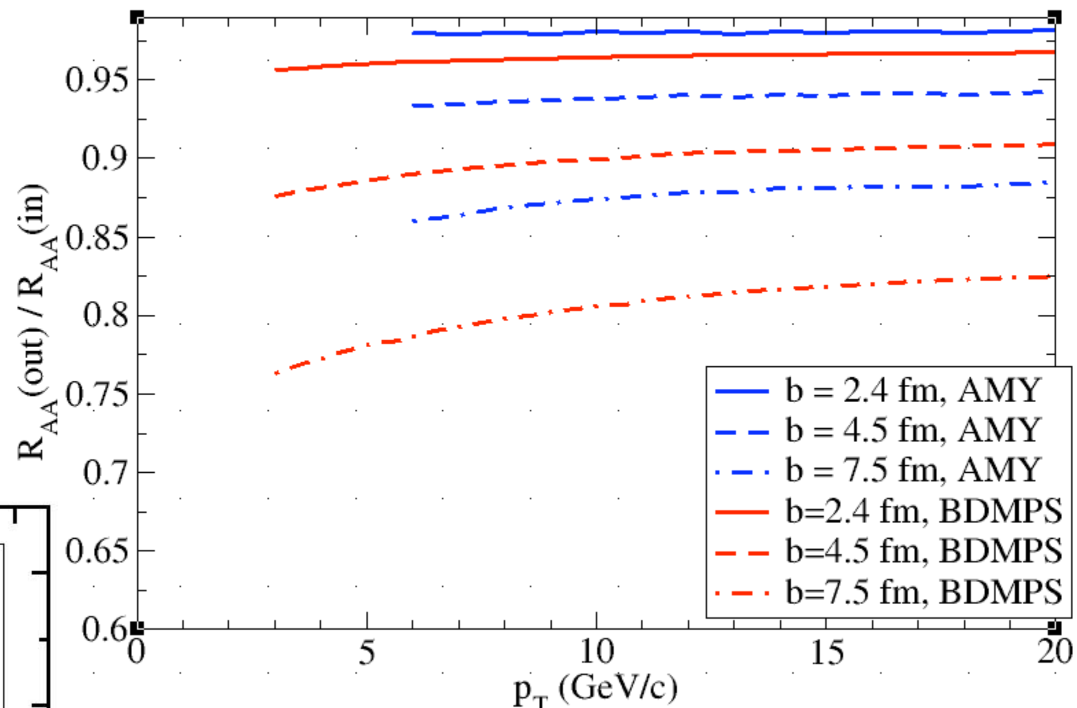
- R_{AA} in (semi-)central collisions is well described by all jet energy-loss schemes
- parameters reflect tuning of medium structure hard-wired into schemes
- do differing medium assumptions have impact on analysis?

➢ more sophisticated analysis/observables needed!

AMY HT & ASW: Azimuthal Spread

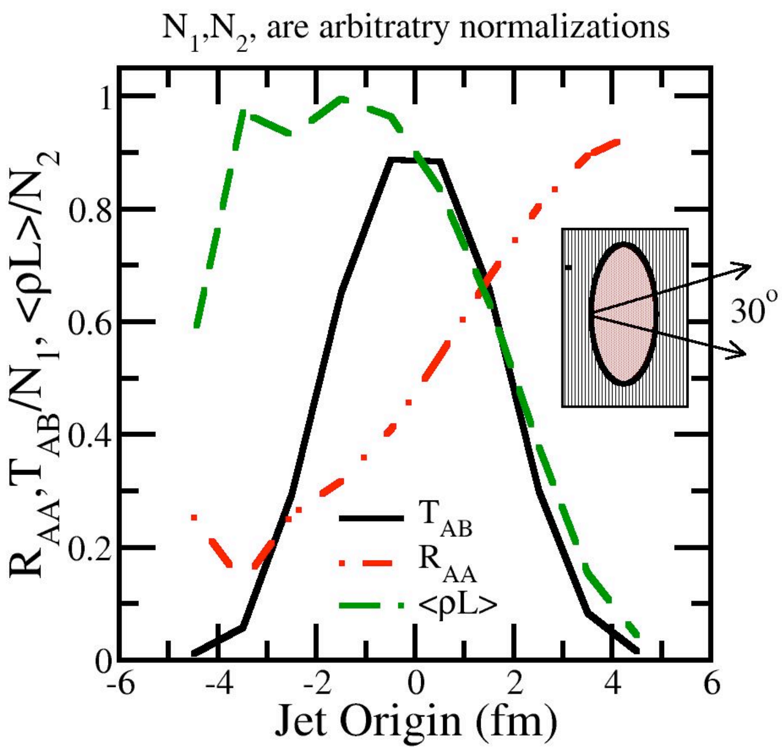
- ➢ study energy-loss as function of reaction plane and centrality:
- • ASW/BDMPS shows a significantly stronger azimuthal dependence of R_{AA} than AMY & HT





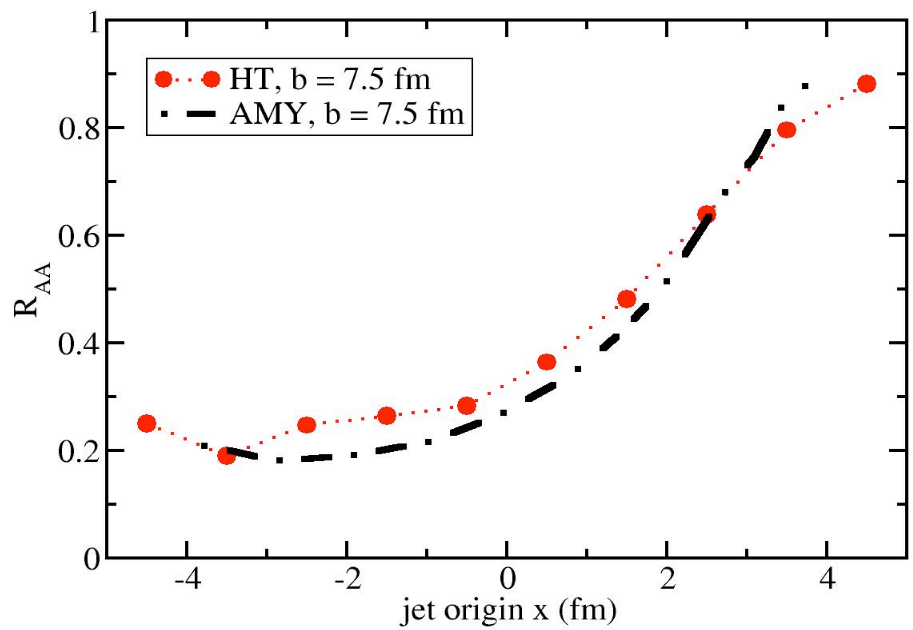
- • ratio of in-plane vs. out-plane R_{AA} shows same & can be easily evaluated as function of centrality
- ➢ investigate temporal & spatial characteristics of energy-loss in different schemes!

Jet Quenching: Differential Analysis



- R_{AA} in reaction plane
- T_{AB}: initial number of b.c.
- length integrated density: ⟨ρL⟩ ~ q-hat

- R_{AA} backside rise: tangential emission of jets
- clear anti-correlation between R_{AA} and q-hat
- near plateau for q-hat for jets originating in back-hemisphere



- comparison shows near identical trends for HT and AMY

➢ convergence of approaches allows to shift focus from formalism to physics analysis

Summary and Outlook

- Heavy-Ion collisions at RHIC have produced a state of matter which behaves similar to an ideal fluid and can be well described by RFD
- jet energy-loss has developed into a sophisticated tool to probe the properties of QCD matter produced at RHIC
- different energy-loss schemes can only be consistently tested and applied to data if the same hydrodynamic evolution is utilized to describe the underlying medium (currently: BDMPS, HT & AMY)
- azimuthal dependence of jet energy-loss improves constraints on jet-tomography schemes and parameters
- ➢ convergence of HT and AMY: formalism under control, now can focus on physics analysis
- ➢ consistent treatment of hard and soft physics crucial for progress!

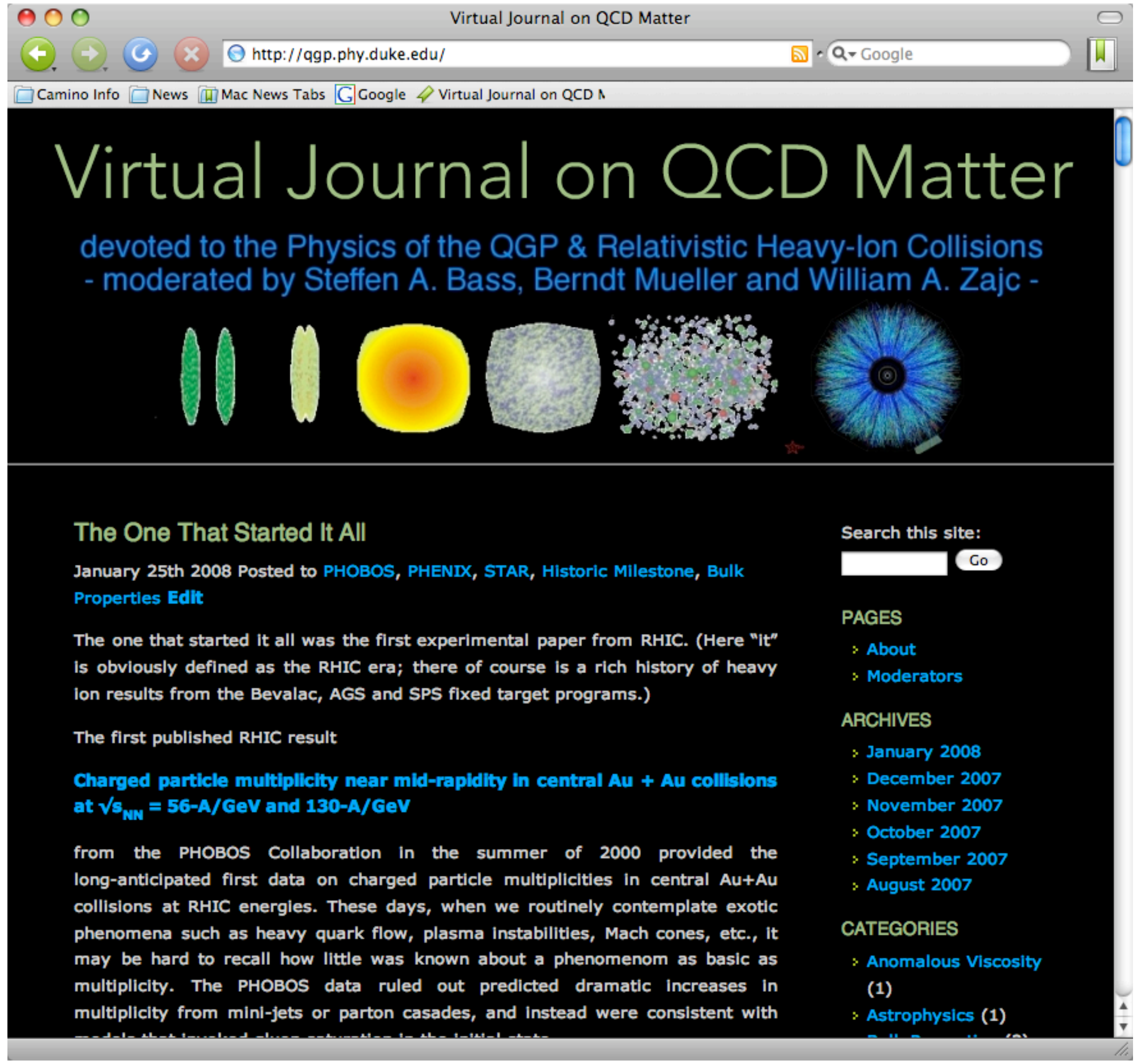
next step:

- ➢ probe dependence of results on equation of state and initial cond.
- ➢ incorporate effects of hard probes on medium

Virtual Journal on QCD Matter

- digest of preprints on
  - hot & dense QCD matter
  - the QGP
  - relat. heavy-ion collisions
- targeted at graduate students & junior postdocs
- aims to provide a bigger picture, on how individual publications shape the advancement of the field

http://qgp.phy.duke.edu/



Hot Quarks 2008

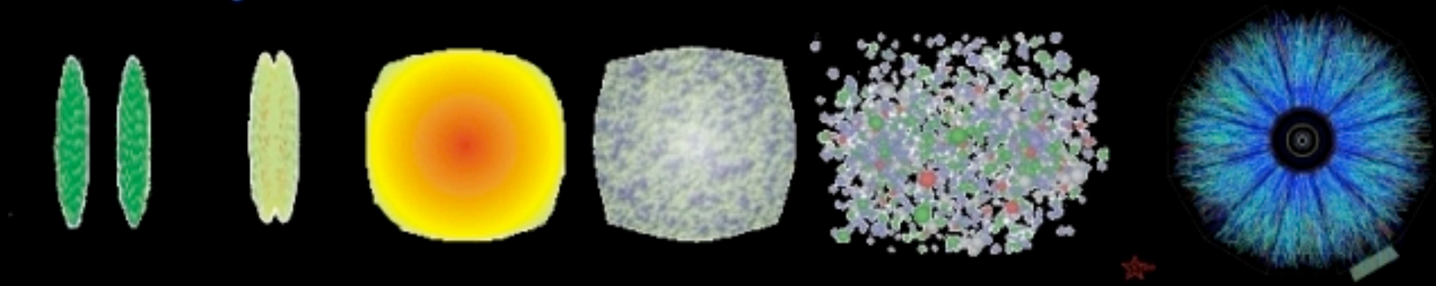
- a conference for young scientists -

- the premier conference for graduate students, postdocs & junior faculty (up to 12 years post Ph.D.)
- all areas of experimental and theoretical relativistic heavy-ion physics will be covered
- August 18 -23 2008
- Aspen Lodge at Estes Park, Colorado

The End

Virtual Journal on QCD Matter

devoted to the Physics of the QGP & Relativistic Heavy-Ion Collisions
- moderated by Steffen A. Bass, Berndt Mueller and William A. Zajc -



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Survey of Transport Approaches