Parton propagation in a colored parton liquid

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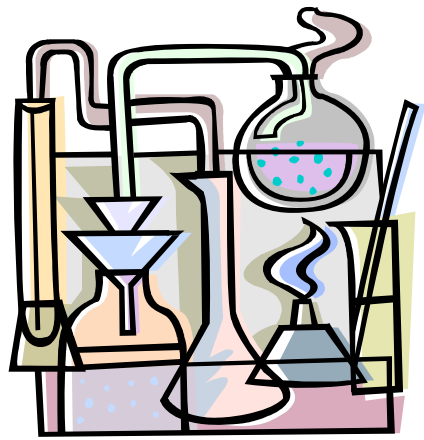
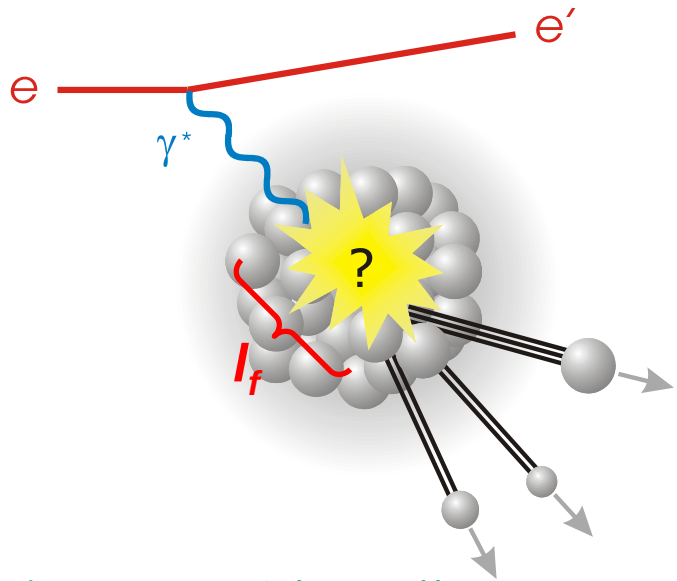


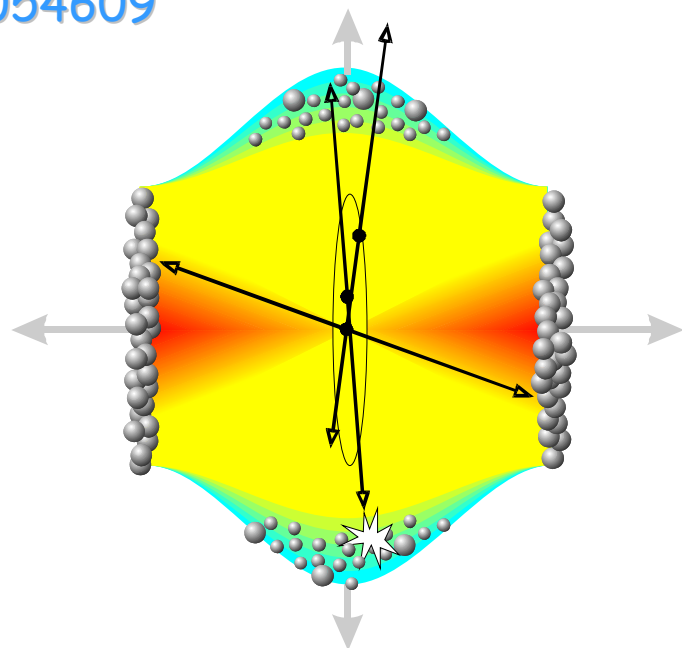
- *eA* reactions at HERMES
  - interactions with (cold) nuclear medium during t_f



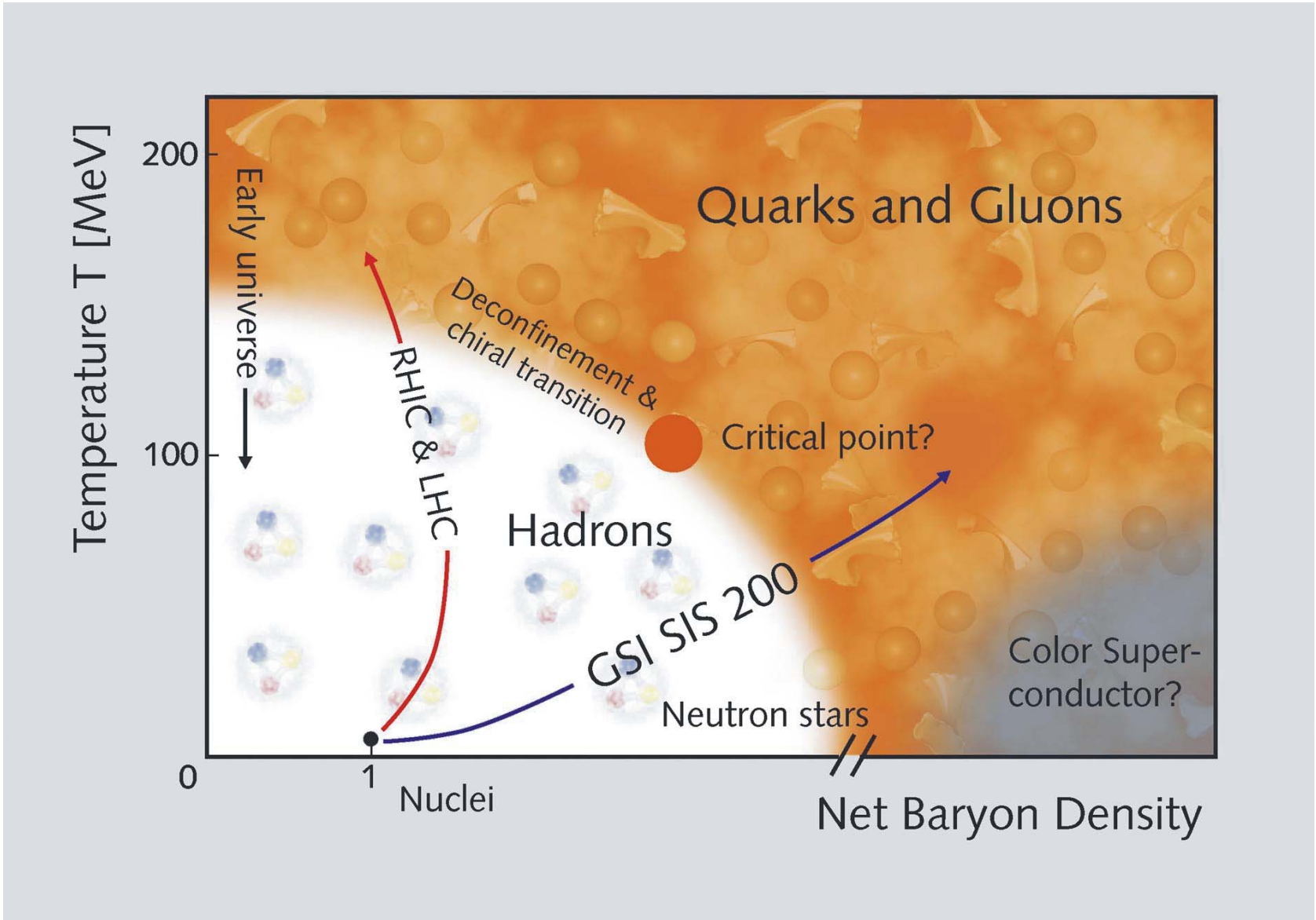
→ **space-time picture of hadronization & prehadronic interactions**

String model + prehadronic interactions work reasonably well
→talks by T. Falter, K. Gallmeister
PLB 594 (2004) 61; PRC 70 (2004) 054609

- **Similar dynamics for more complex heavy-ion collisions?**
  - jet suppression at RHIC
    - partonic energy loss in QGP
    - (pre-)hadronic FSI



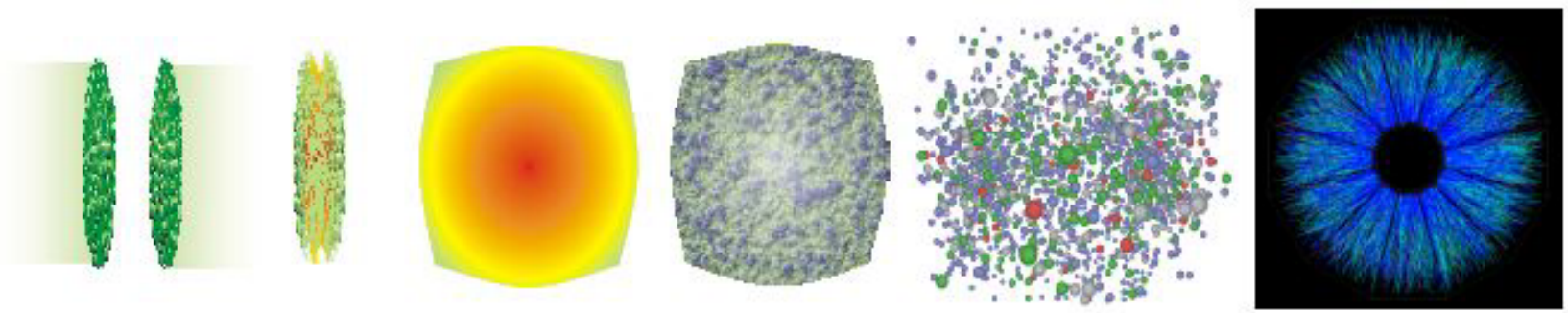
Schematic phase diagram of QCD



Transport studies of relativistic many-body systems

Transport theory: off-shell Kadanoff-Baym equations
for the Green-functions $G^<_h(x,p)$ in phase-space representation

Actual solutions:
Monte Carlo simulations with a large number of test-particles



Scetch of an ultrarelativistic nucleus-nucleus collision (S. A. Bass)

Concepts: HSD & UrQMD

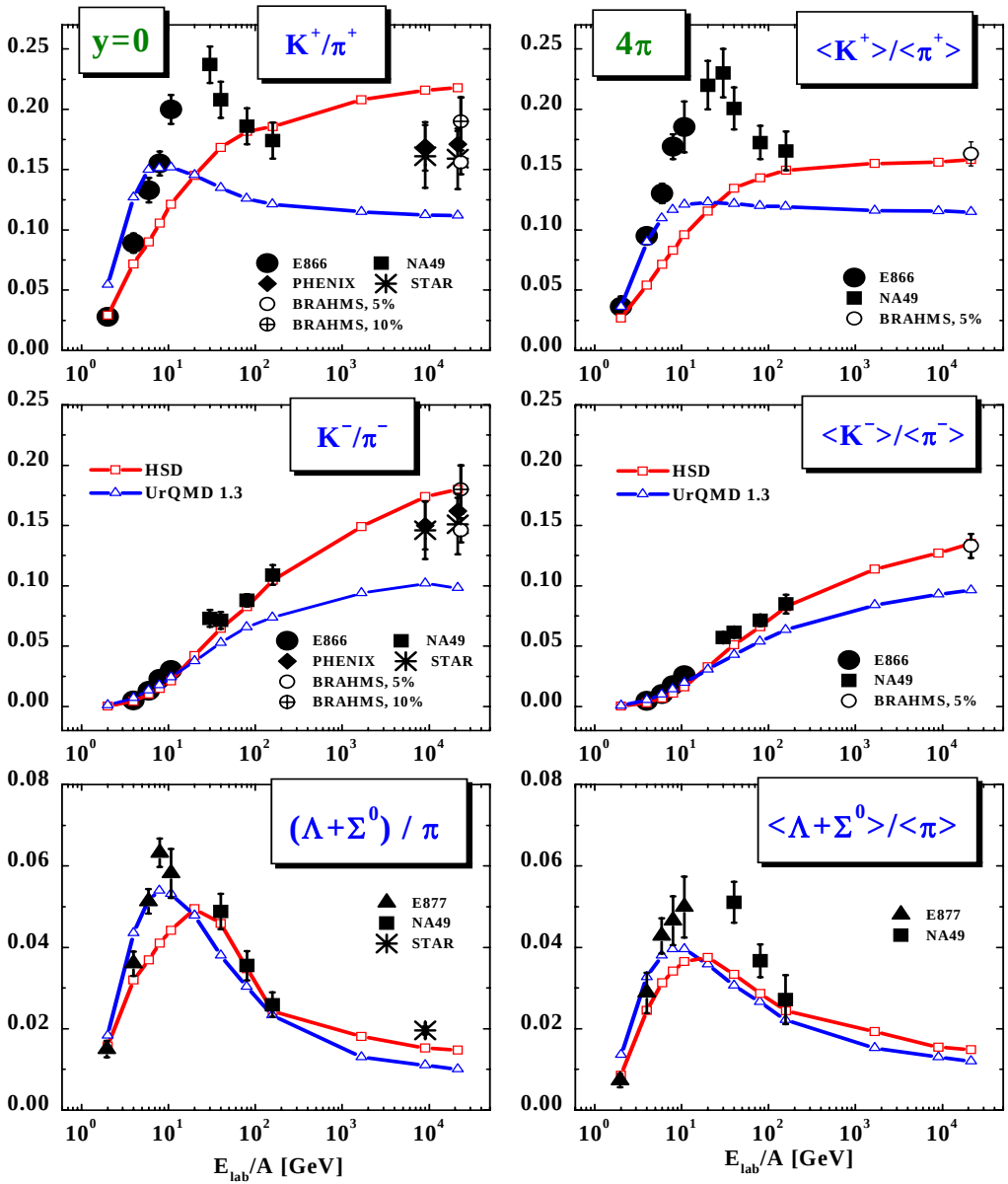
- Solution of the transport equations with collision terms describing:
  - elastic and inelastic hadronic reactions
  - formation and decay of baryonic and mesonic resonances
  - string formation and decay

- Implementation of detailed balance on the level of 1<->2 and 2<->2 reactions
  (+ 2<->n multi-meson fusion reactions in HSD/PHSD)

- Degrees of freedom:
  strings, q, qbar, (qq), (qbar qbar) (+gluons in PHSD)
  baryons + mesons including excited states

Hadron-String Dynamics Ultra-relativistic Quantum-Molecular Dynamics

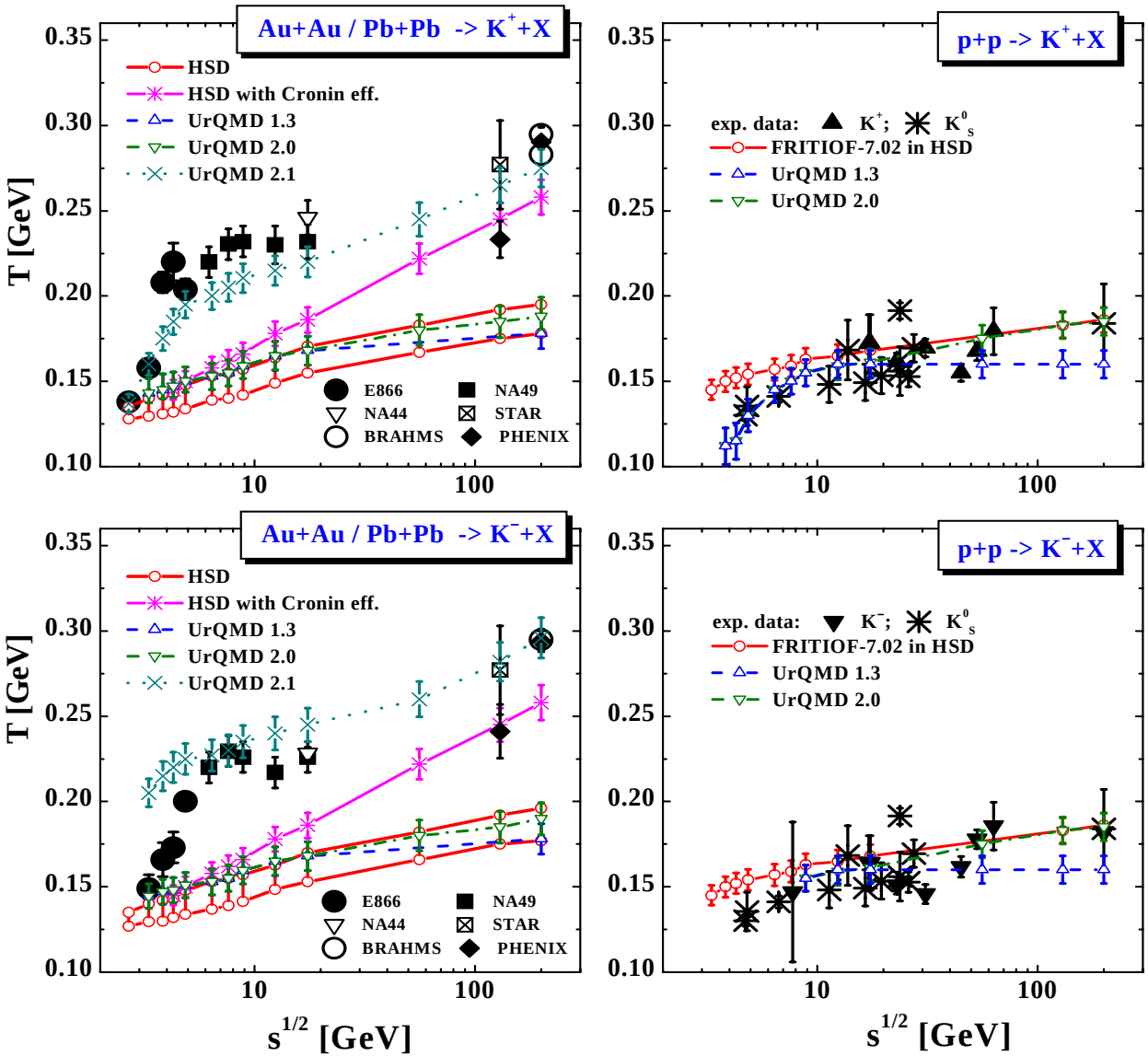
Excitation function of K^+/π^+, K^-/π^-, $(\Lambda+\Sigma^0)/\pi$ ratios



- Experimental K^+/π^+ ratios show a peak at ~30 A GeV ('horn'), which is not reproduced by the transport approaches HSD and UrQMD !

PRC 69 (2004) 054907

Inverse slopes T for K^+ and K^-



- In UrQMD and HSD hadronic rescattering has only a small impact on the kaon slope
- The hadron-string picture fails?
- New degrees of freedom (colored partons : q^c, g^a) are missing ?

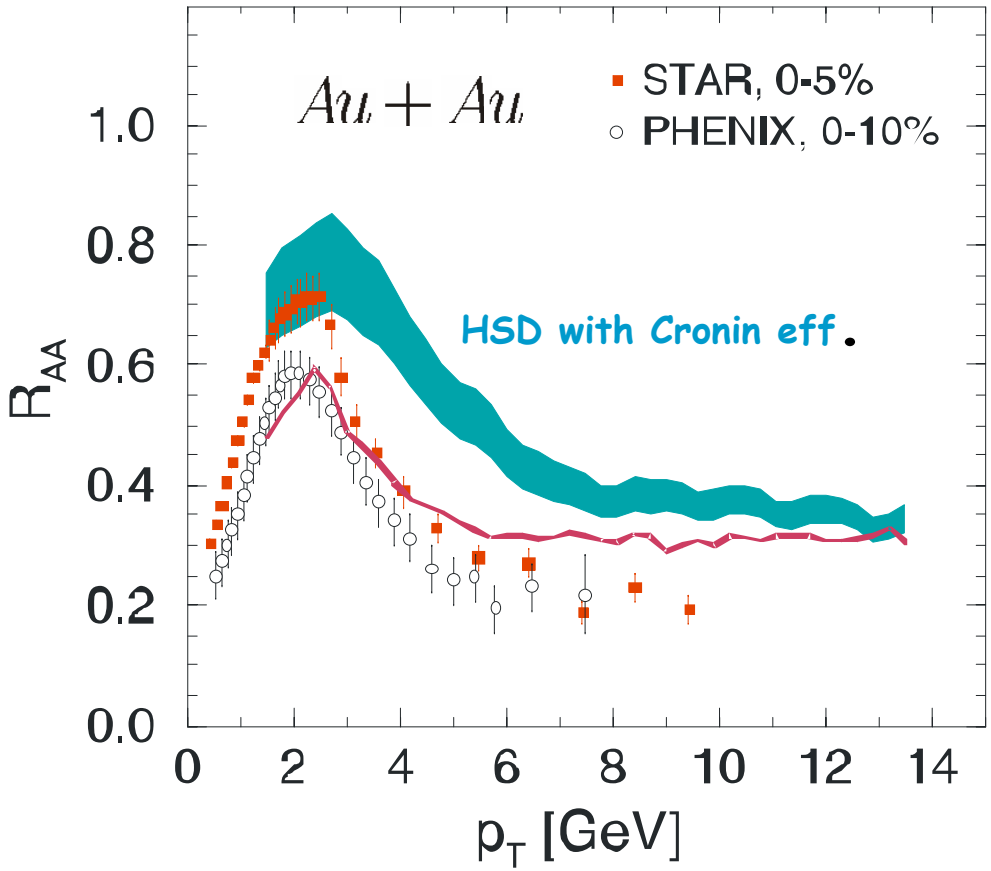
PRC 69 (2004) 054907
PRL 72 (2004) 032302

Hadron suppression in central Au+Au at RHIC (HSD)

$$R_{AA}(p_T) = \frac{1/N_{AA}^{event} \cdot d^2N_{AA}/dydp_T}{< N_{coll} > /\sigma_{pp}^{inelas} \cdot d\sigma_{pp}/dydp_T}$$

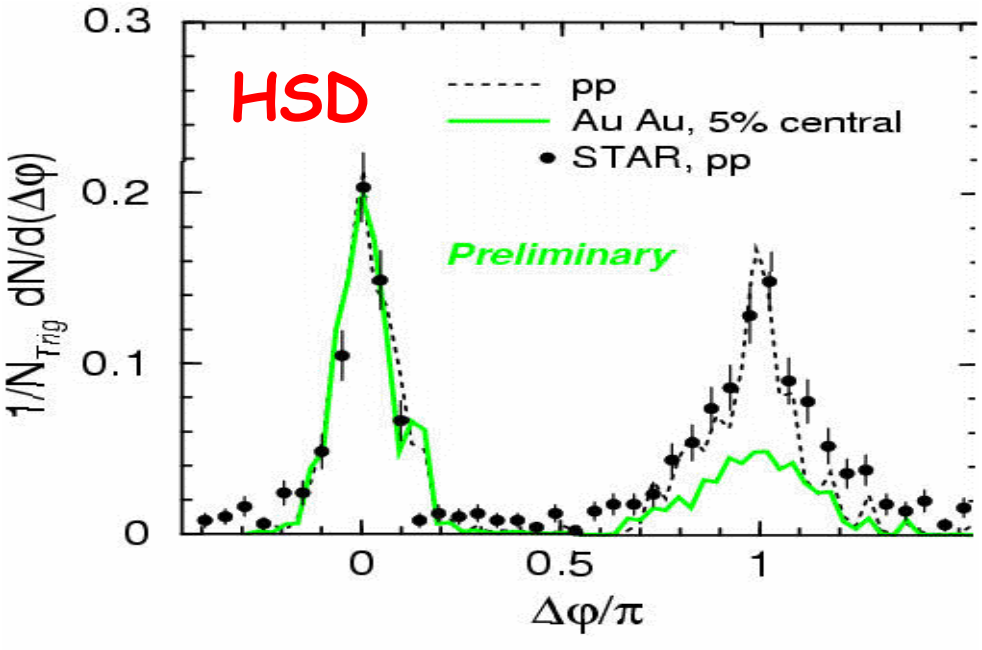
- Hadron-string model doesn't provide enough high p_T suppression for central Au+Au

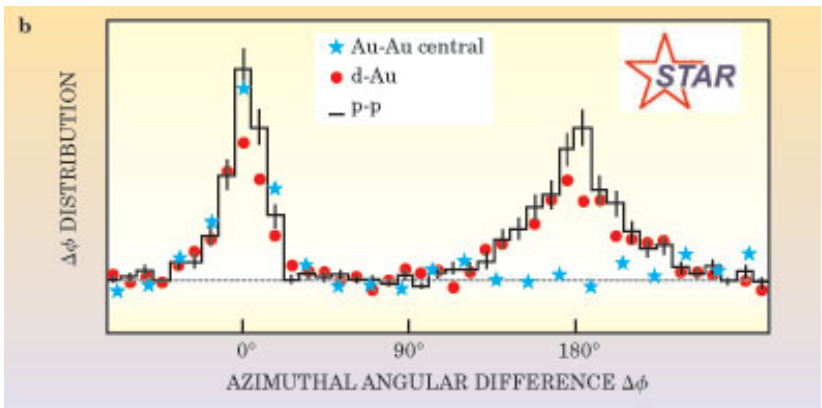
-> Extra suppression – from new phase ?!



NPA 735 (2004) 277

Jet suppression: dN/dφ (HSD)



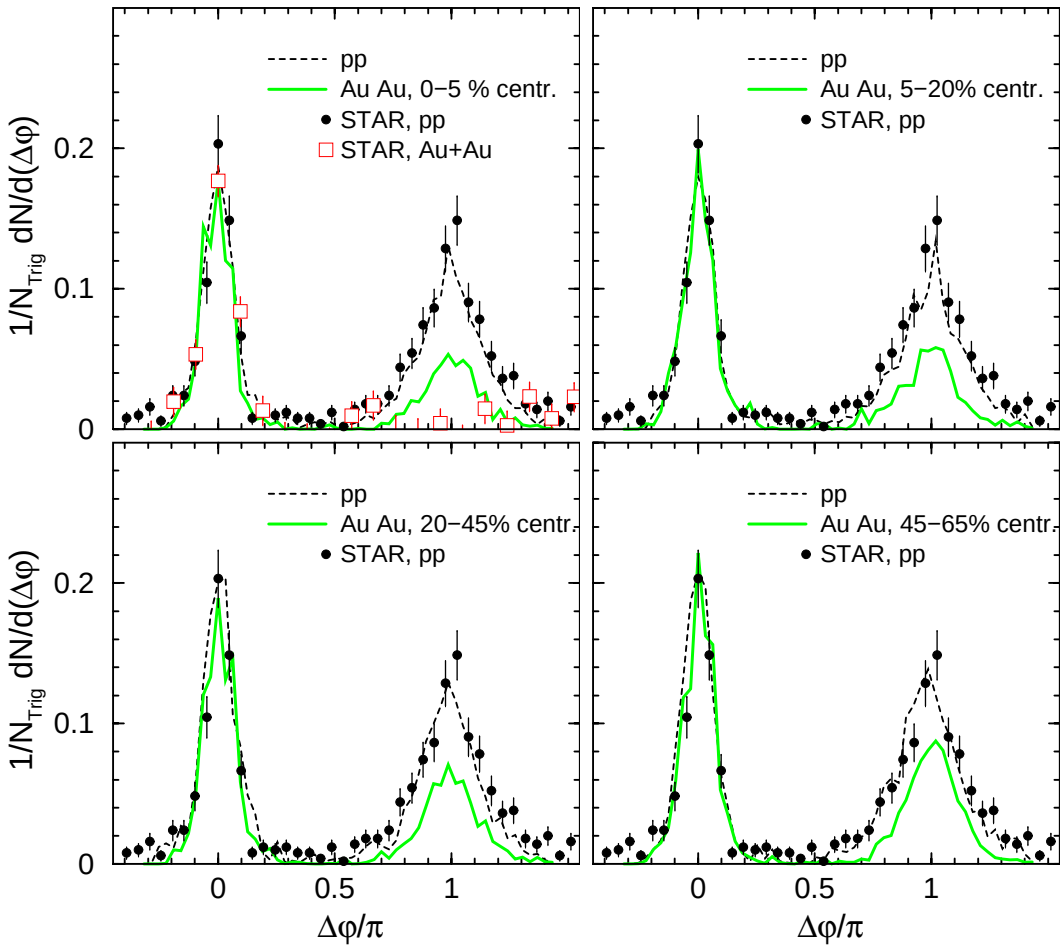


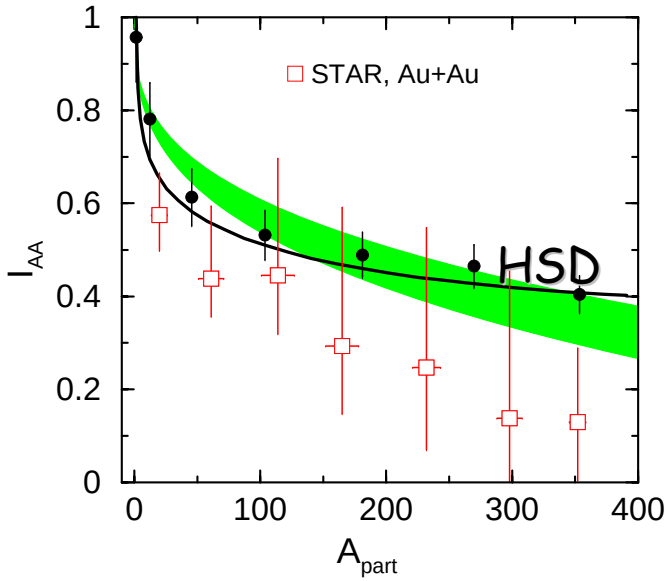
Δ ϕ (radians)

- The jet angular correlations for pp are fine !
- The near-side jet angular correlation for central Au+Au is well described, but the suppression of the far-side jet is too low !!

W. Cassing, K. Gallmeister and C. Greiner, J. Phys. G30 (04) S801, NPA 748 (05) 241

Centrality dependence of angular correlations





Missing suppression of far-side jet in central reactions!

Near-side jet is unchanged for all centralities

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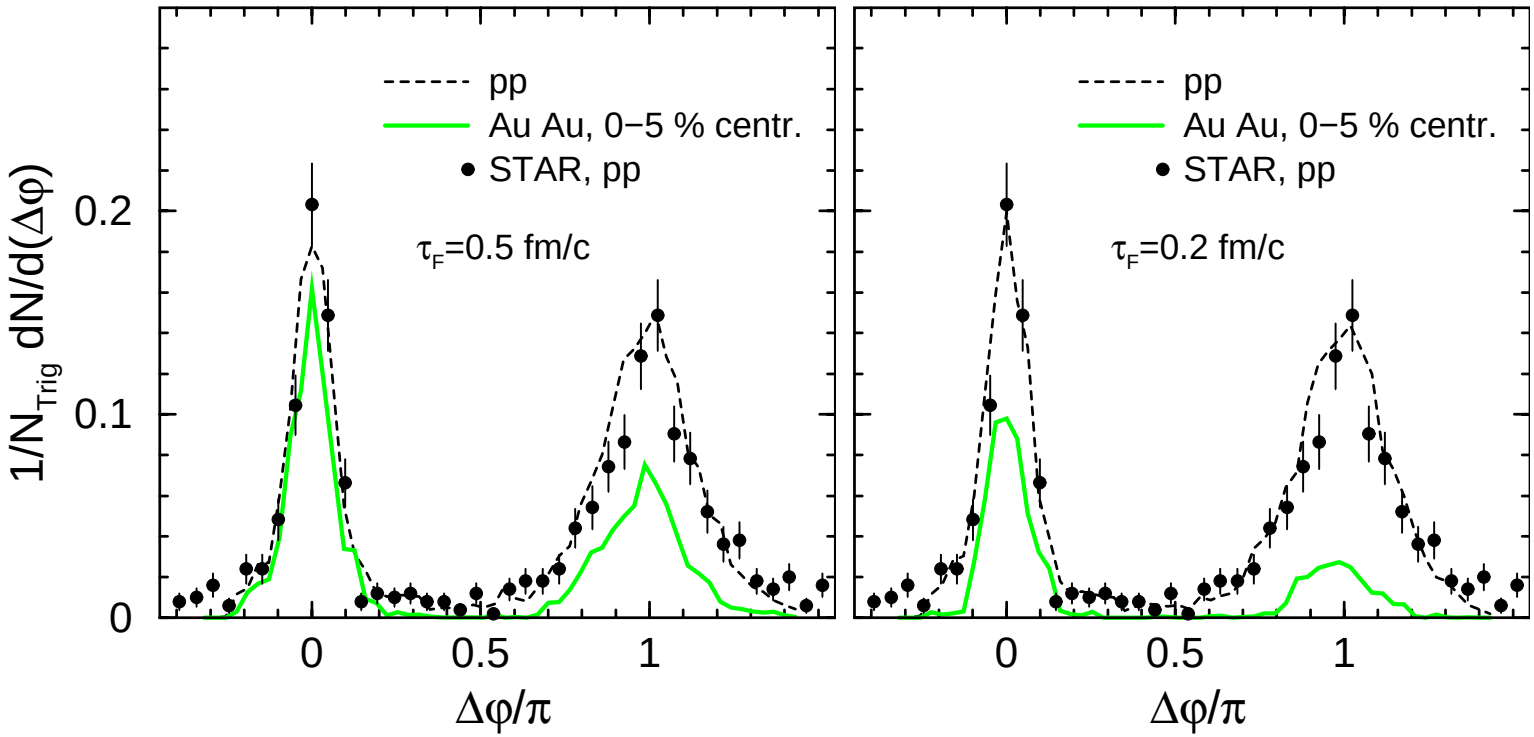
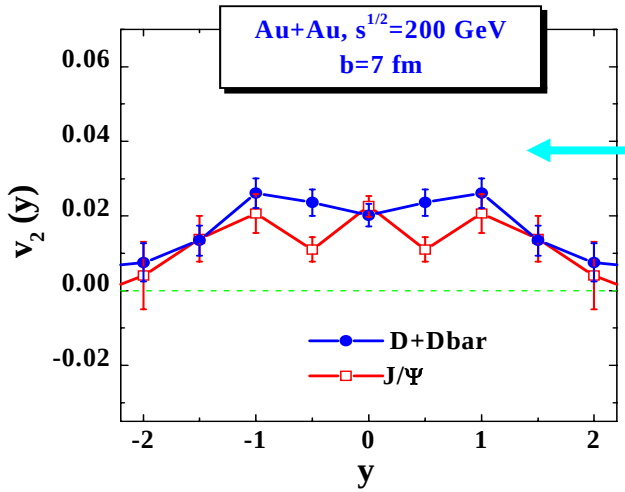
Constraints on hadron formation time

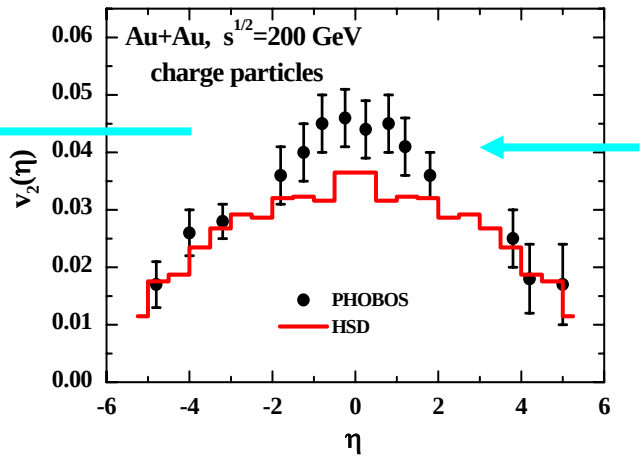


Near-side jet becomes suppressed
if hadron formation time gets too short !

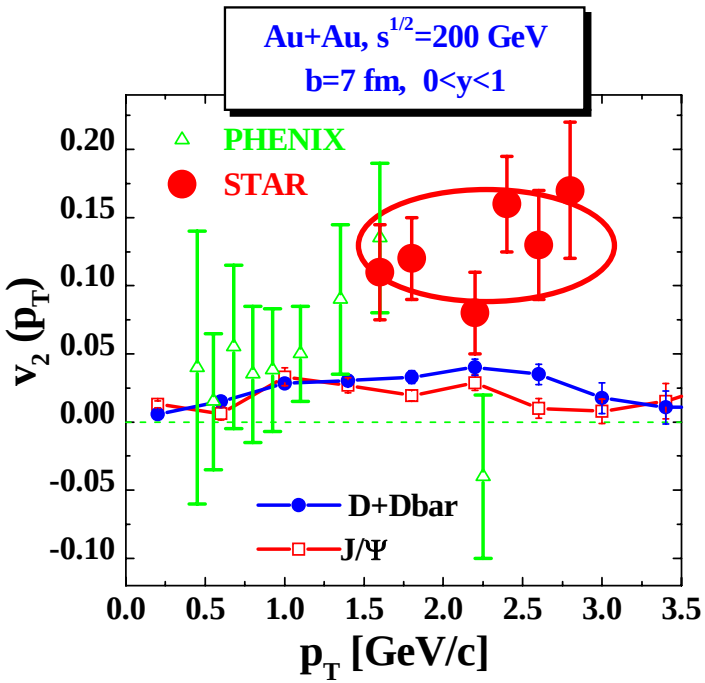
NPA 748 (2005) 241

Collective flow: v_2 of D+Dbar and J/Ψ from Au+Au versus p_T and y at RHIC





Collective flow from hadronic interactions is too low at midrapidity !



- **HSD:**
  D-mesons and J/Ψ : small v_2 < 3%

- **STAR data show very large collective flow of D-mesons v_2~10-15%!**

=> strong initial flow of non-hadronic nature!

PRC 67 (2003) 054905, PRC 71 (2005) 044901

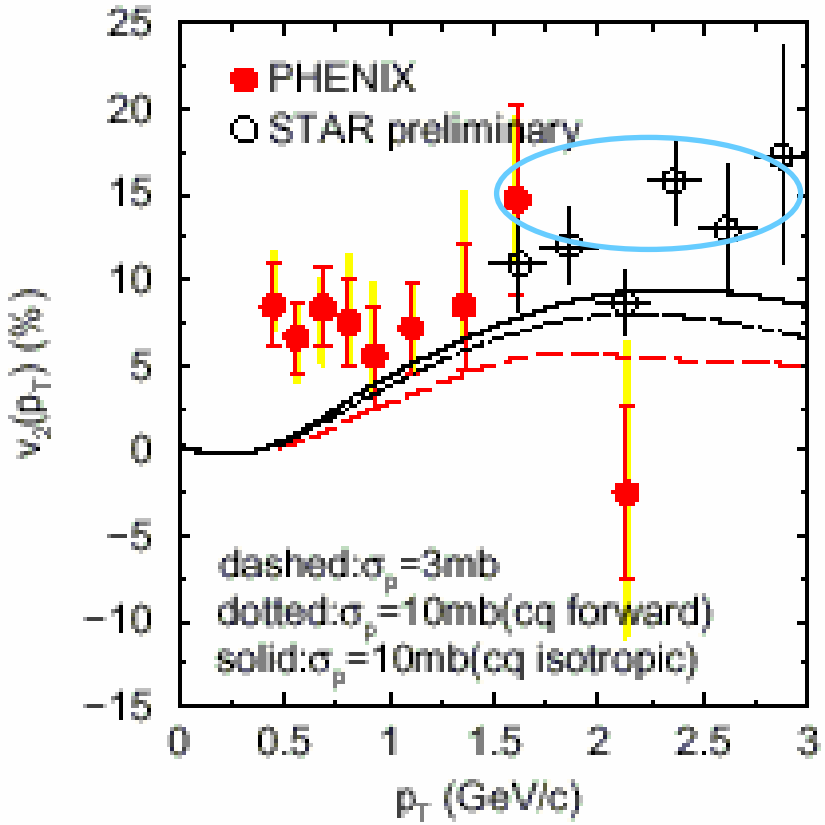
AMPT model: v_2 of D+Dbar from Au+Au versus p_T at RHIC

- **AMPT multi-phase transport model:**
  (B. Zhang, L.-W. Chen and C.-M. Ko)

Minijet partons from hard proceses (ZPC- Zang's parton cascade) + strings from soft processes (HIJING)

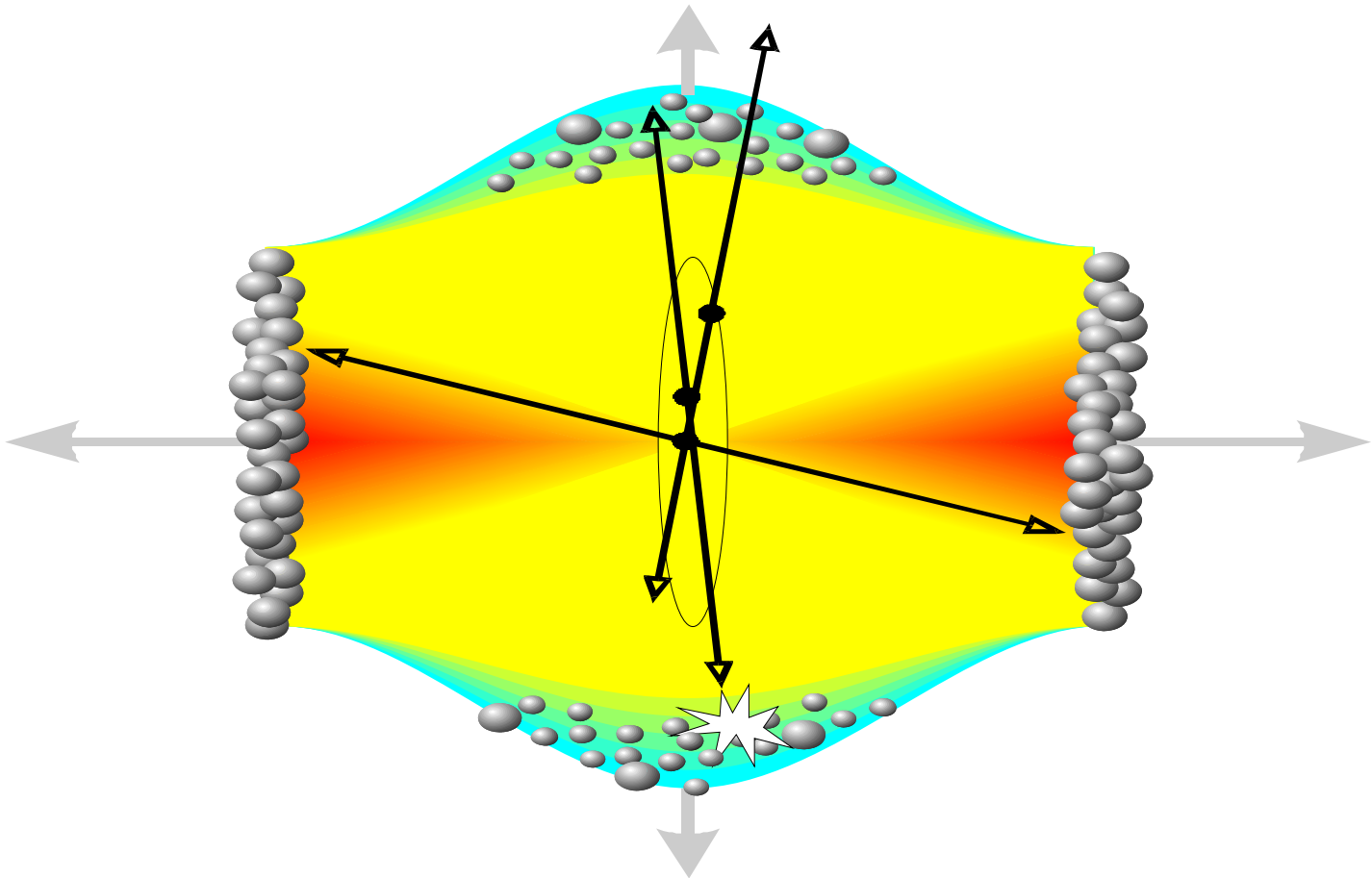
- **Parton (q, qbar) scattering cross sections (3-10 mb)**

„To describe the large electron elliptic flow observed in available experimental data requires a charm quark scattering cross section that is much larger than given by perturbative QCD"
[nucl-th/0502056]



QGP is NOT a weakly interacting gas as described by pQCD!

What are the properties of the new medium?



Ask lattice QCD !

From lattice QCD to quasiparticle properties

quasiparticle entropy:

$$s^{dqp} = -d_g \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} \frac{\partial n}{\partial T} \left(\mathrm{Im} \ln(-\Delta^{-1}) + \mathrm{Im}\Pi \, \mathrm{Re}\Delta \right)$$

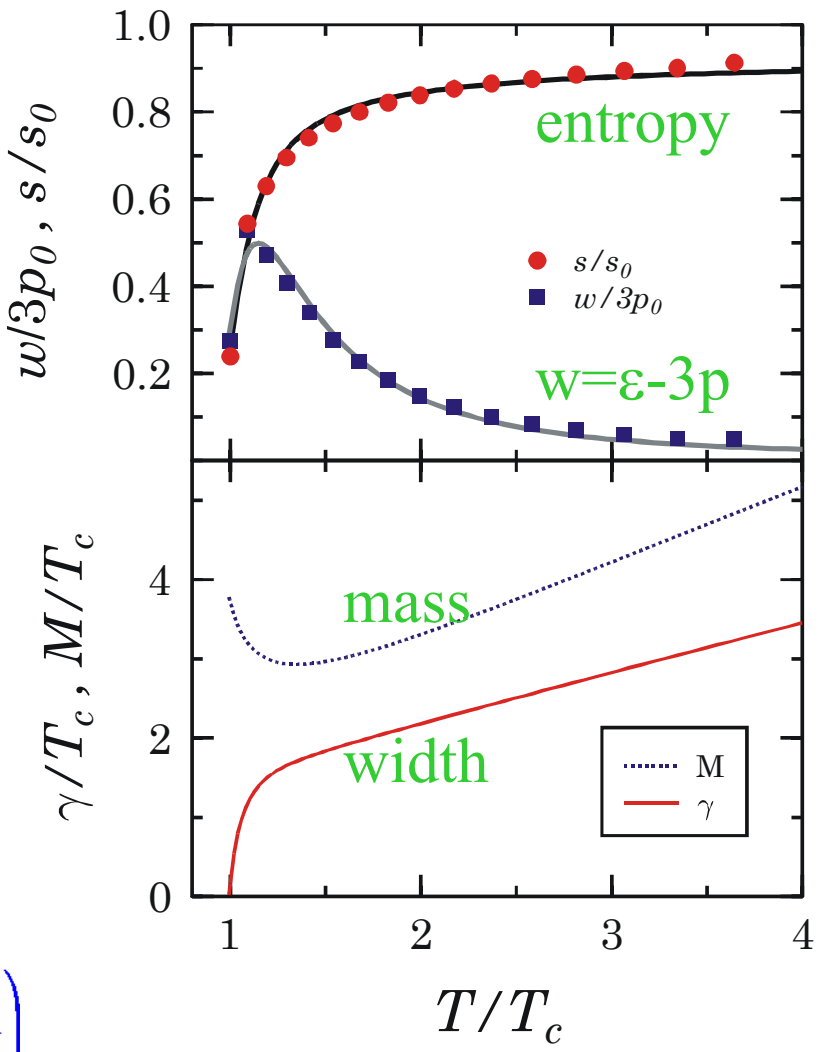
mass: $M^2 = \frac{N_c}{6} g^2 T^2$

width: $\gamma = \frac{3}{4\pi} \frac{M^2}{T^2} T \ln \frac{c}{(M/T)^2}$

coupling: $g^2(T) = \frac{48\pi^2}{11 N_c \ln(\lambda(T - T_s)/T_c)^2}$

spectral function:

$$\rho(\omega) = \frac{\gamma}{E} \left(\frac{1}{(\omega - E)^2 + \gamma^2} - \frac{1}{(\omega + E)^2 + \gamma^2} \right)$$



Andre Peshier, PRD 70 (2004) 034016

Quasiparticles of the QGP

T = 1.053 T_c **T = 1.35 T_c** **T = 3 T_c**

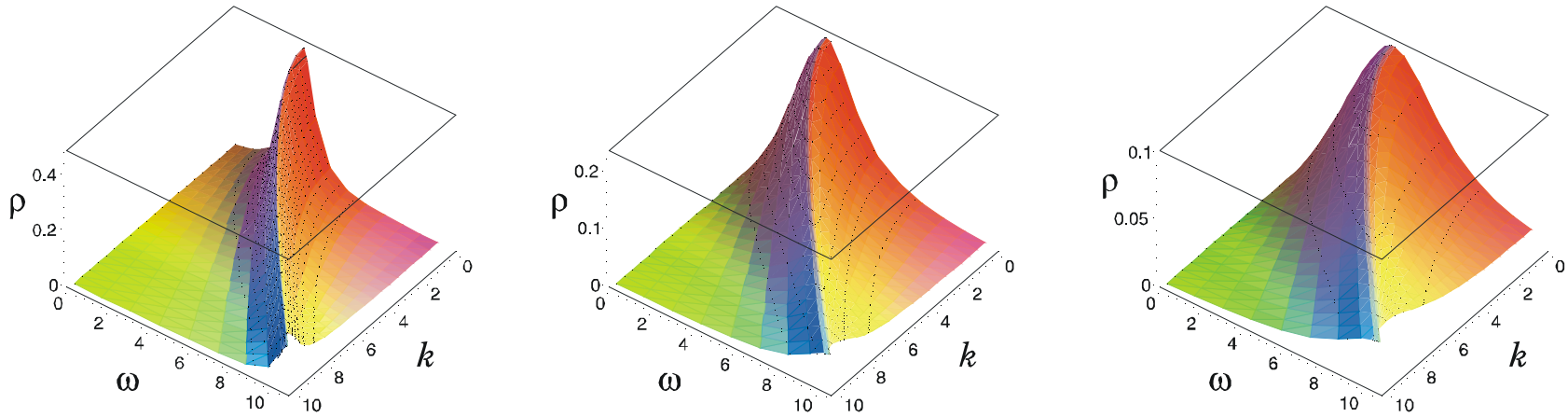


FIG. 12: The Lorentzian gluon spectral function from Fit 3 for $T/T_c = 1.03,\ 1.35,\ 3$ (ω, k and ρ are in units of T). Shown here is the full phase space although the present approach can make statements only for hard momenta, of the order of T or larger.

Andre Peshier, PRD 70 (2004) 034016

average cross section:

$$\frac{dN_{coll}}{dV\,dt} = \tilde{\mathrm{Tr}}_{P_1}\tilde{\mathrm{Tr}}_{P_2}\, 2\sqrt{\lambda(s,P_1^2,P_2^2)}\;\sigma_{tot}(P_1,P_2)$$
$$= \langle\sigma\rangle\,\tilde{\mathrm{Tr}}_{P_1}\tilde{\mathrm{Tr}}_{P_2}\, 2\sqrt{\lambda(s,P_1^2,P_2^2)} =: \langle\sigma\rangle\, I_2$$

$$\tilde{\mathrm{Tr}}_P \cdots = d_g \int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\, 2\omega\,\rho(\omega)\,\Theta(\omega)\Theta(P^2)\,n(\omega)\cdots$$

percolation parameter: $\kappa = \langle\sigma\rangle N_+^{2/3}$

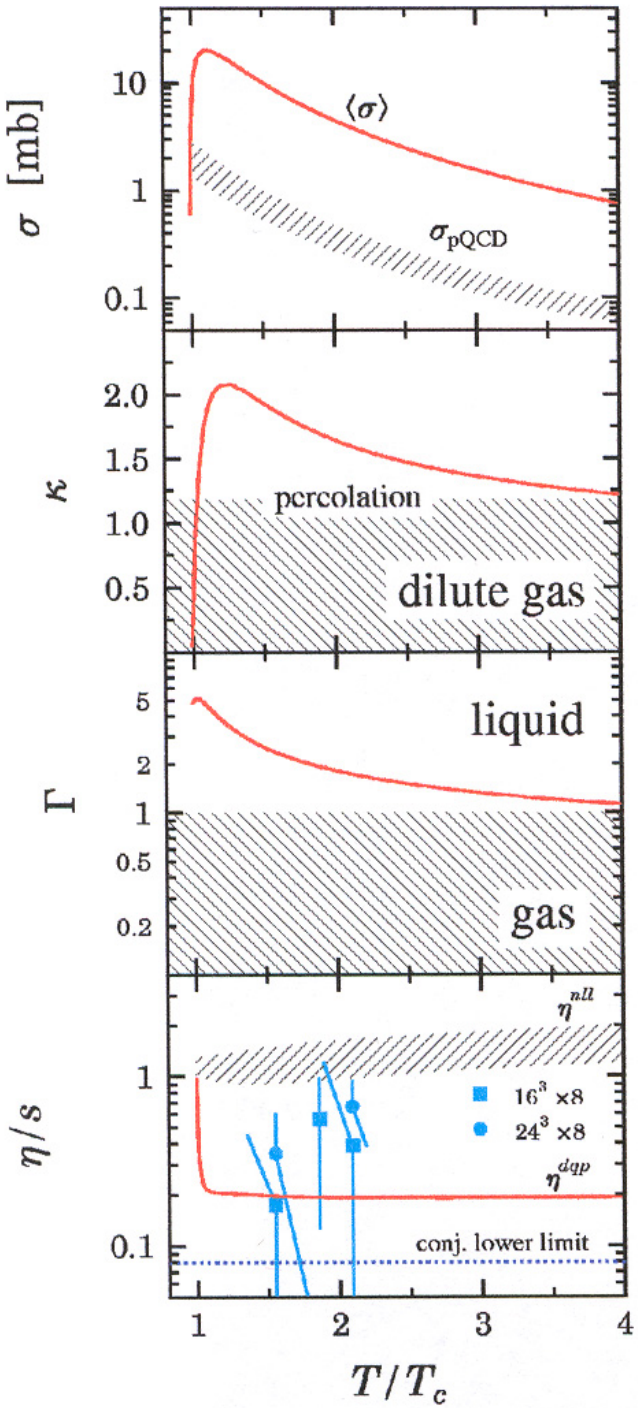
plasma parameter: $\Gamma = C_R\, g^2 N_+^{1/3}/\langle T_{kin}\rangle$

$$\langle T_{kin}\rangle = N_+^{-1}\,\tilde{\mathrm{Tr}}\left(\omega - \sqrt{p^2}\right)$$

shear viscosity:

$$\eta^{dqp} = -\frac{d_g}{60}\int\frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\frac{\partial n}{\partial\omega}\,\rho^2(\omega)\left[7\omega^4 - 10\omega^2\boldsymbol{p}^2 + 7\boldsymbol{p}^4\right]$$

=> The QGP is an almost ideal liquid !



PRL 94 (2005) 172301

Transport description of the partonic phase

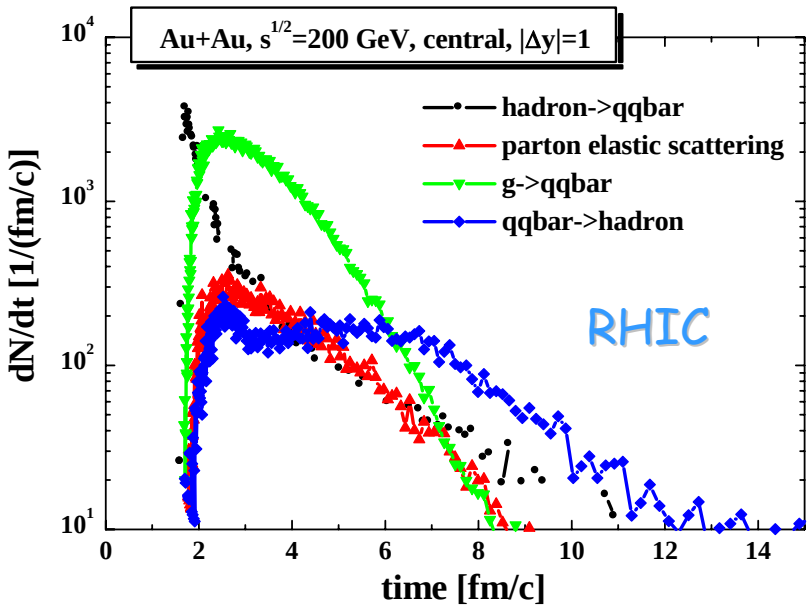
Parton-Hadron-String Dynamics

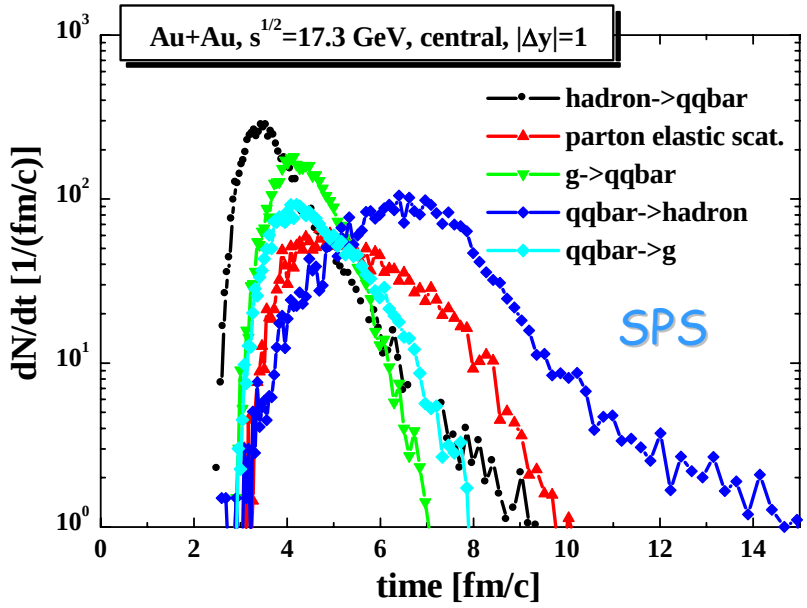
1. Dissolve all new produced secondary hadrons to partons (and attribute a random color c) using the spectral functions from the QP approximation to QCD
2. Include parton-parton elastic scattering using the effective cross sections from the QP approximation to QCD
3. quark+antiquark (flavor neutral) <-> gluon (colored)
4. gluon + gluon <-> gluon (possible due to large spectral width)
5. quark + antiquark (color neutral) <-> hadron resonances

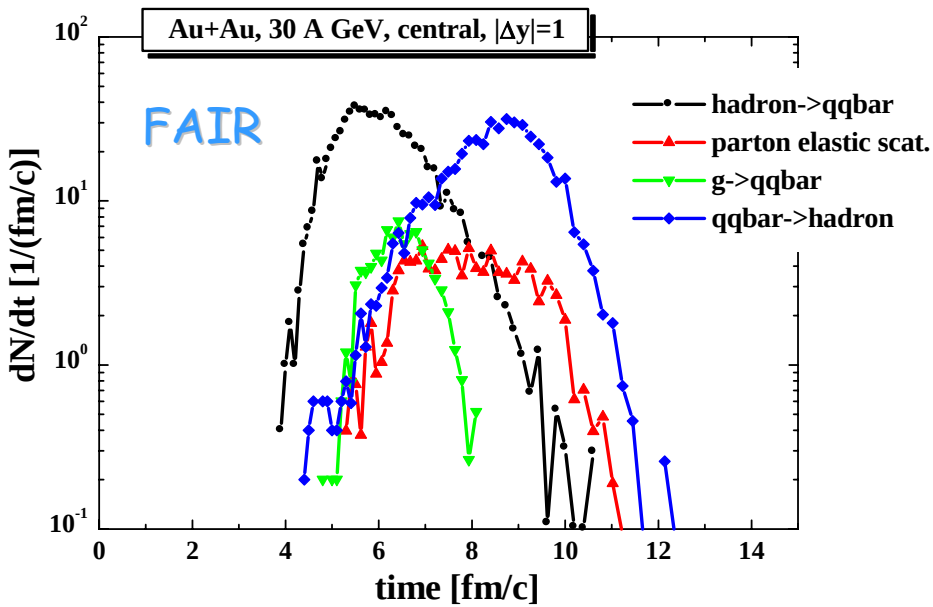
All partonic interactions are constraint to energy densities above 1 GeV/fm !

Note: Reactions 3.-5. are Breit-Wigner cross sections determined by the spectral properties of constituents !

Parton interaction rates in central Au+Au







Partonic interactions persist for about 4 fm/c at all these energies !

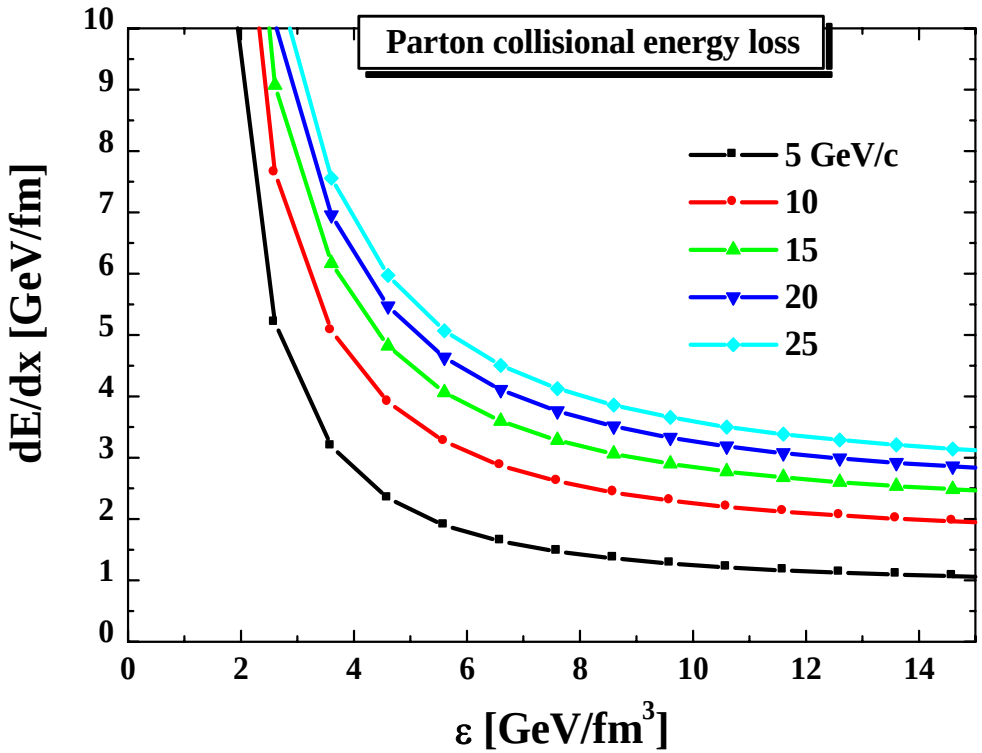
Energy loss of energetic partons

Collisional energy loss (early results):

$dE/dx = 0.12\ (4\pi)^2\ \alpha_s^2(T^2)\ T^2\ \ln[\ (3\ E\ T)^{0.5}\ /M_D(T)\ ]$

$M_D(T) = 2.7\ \gamma_{glue}(T)$ from LQCD

$\alpha_s^2(T^2)$ from QP approach to QCD

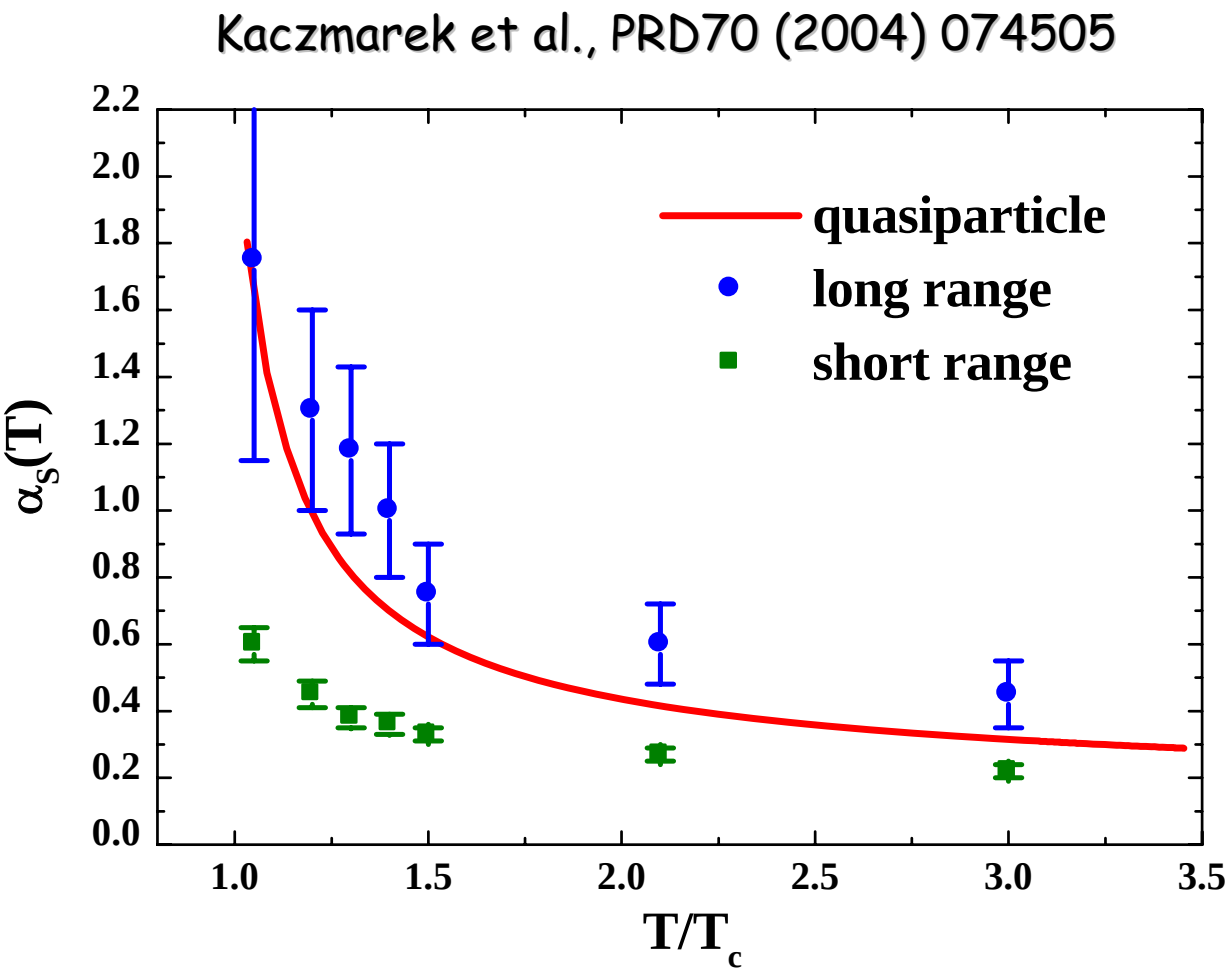


Huge energy loss of energetic partons !

$\alpha_s^2(T^2)$ too large ?

M. Thoma, M. Gyulassy

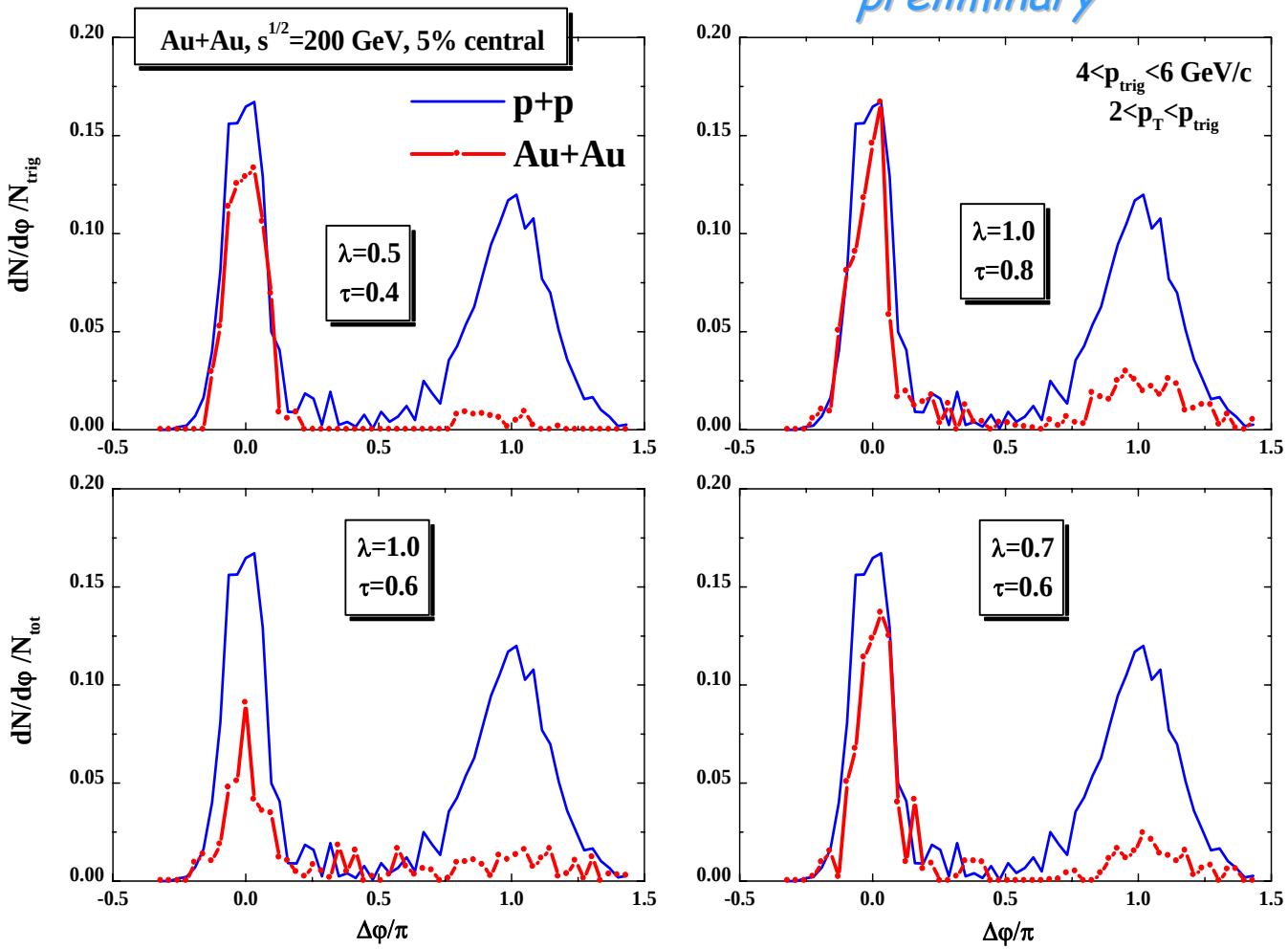
Comparing α_s with LQCD



There is some room to scale α_s with some parameter λ !

Jet suppression in PHSD

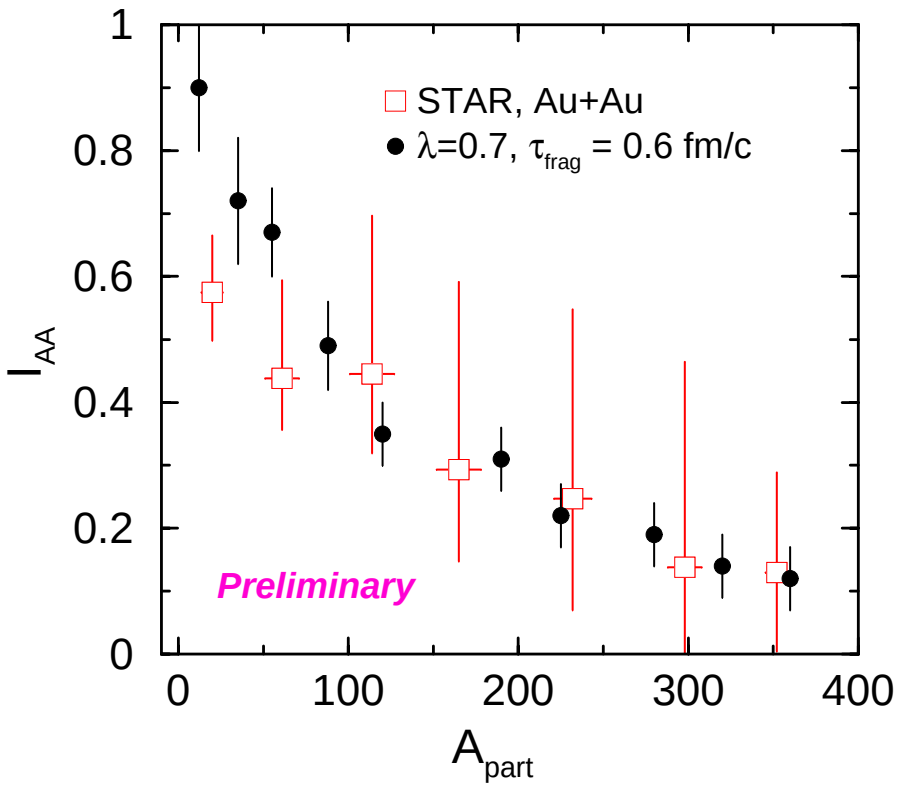
preliminary



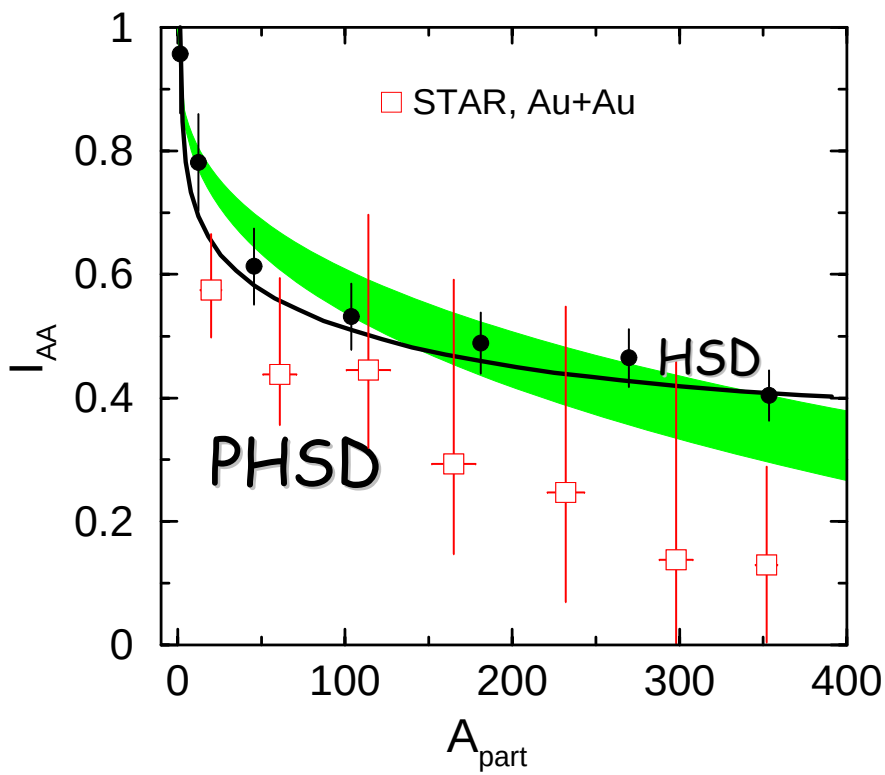
is sensitive to the strength λ and the coherence/fragmentation time τ

Suppression of far-side peak in central Au+Au

PHSD

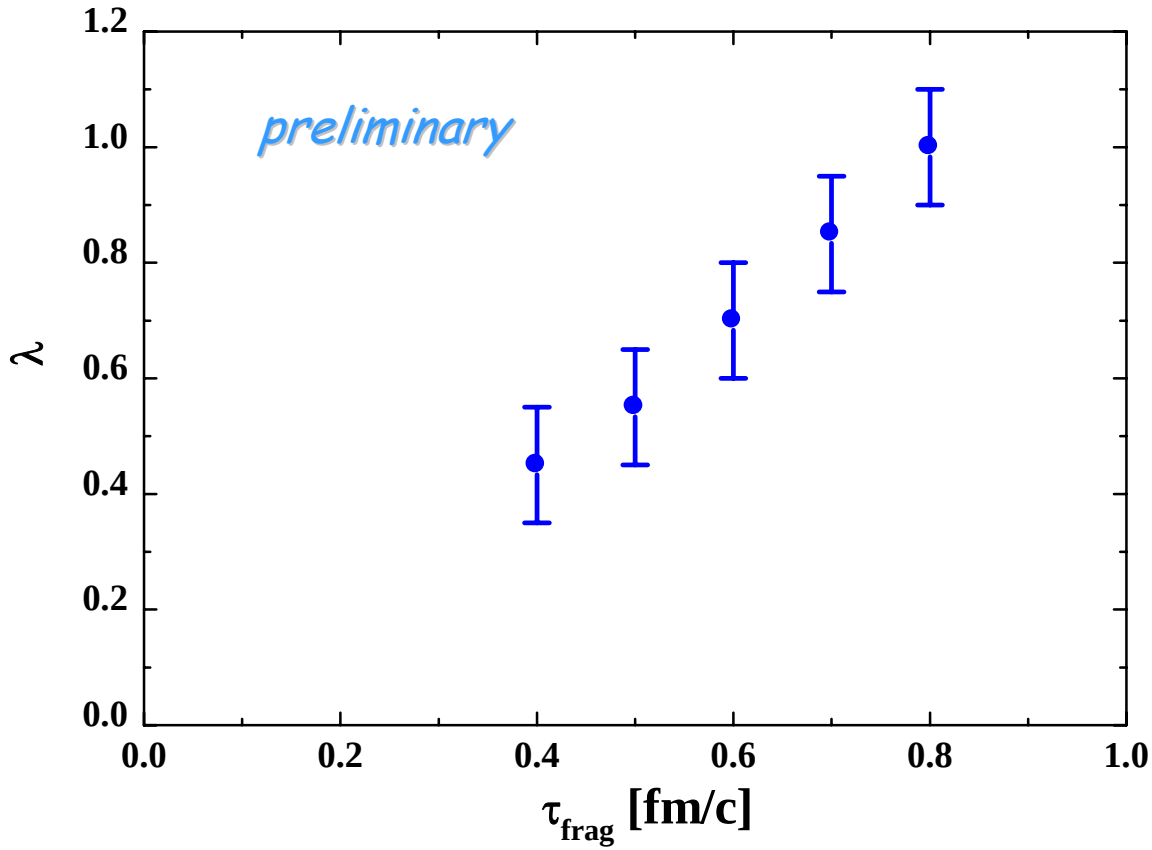


HSD



appears to be compatible with PHSD for a large delay in fragmentation or large coherence length/time !

Correlation diagram



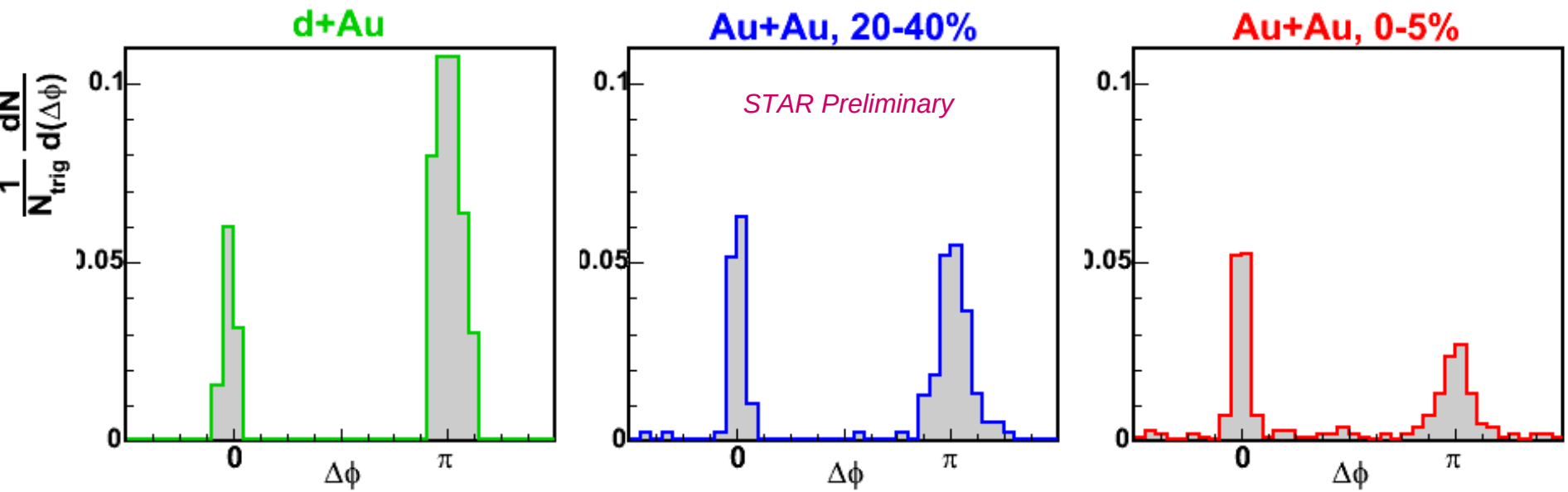
will allow to fix approximately the energy loss as well as the fragmentation time τ !

STAR: Emergence of dijets

Dunlop: QM05

$8 < p_T(\text{trig}) < 15$ GeV/c

$p_T(\text{assoc}) > 6$ GeV



For the first time: clear jet-like peaks seen on near and away side in central Au+Au collisions

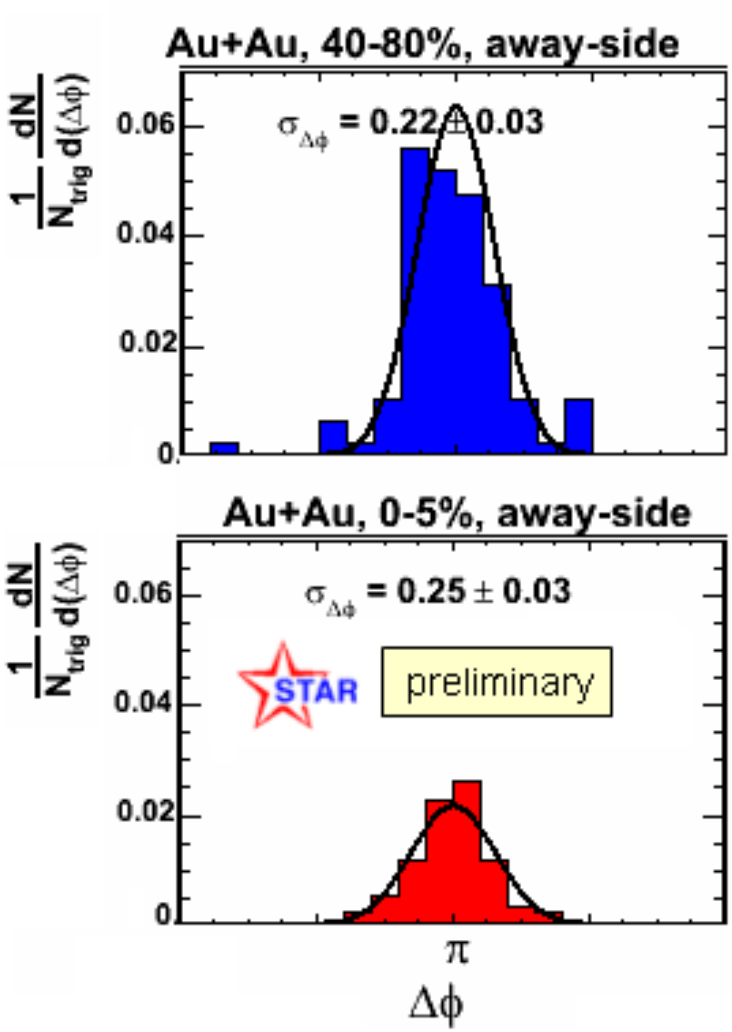
Note: near-side peak practically unchanged !

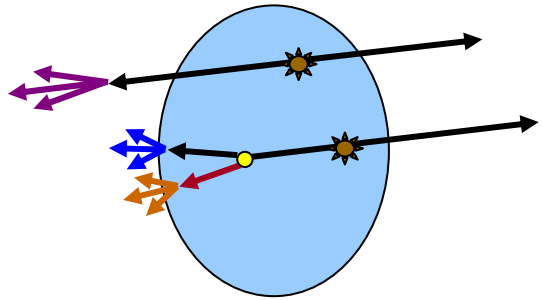
Away-side widths similar for central and peripheral

$8 < p_T(\text{trig}) < 15$ GeV/c

$p_T(\text{assoc}) > 6$ GeV

Dunlop: QM05





Widths unchanged with centrality: seeing those partons that fragment in vacuum?

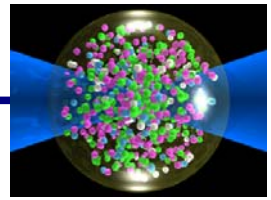
Summary I - HSD

- The elliptic flow at RHIC is larger than expected in the hadron/string approach ! ➔ The system almost behaves like an ideal fluid !
- The transverse ‚slopes' of heavy particles are significantly higher – as expected – already above 5 A GeV !
- The attenuation of high p_T-hadrons is underestimated in central Au+Au collisions at top RHIC energies !
- The suppression of the ‚far-side' jet is underestimated in central Au+Au collisions at $s^{1/2}$ = 200 GeV ! ➔ System interacts more strongly in the early phase than hadron-like matter !
- The D+Dbar fusion plays a small role at SPS, but is essential at RHIC (=> strong J/Psi regeneration !)
- At RHIC: collective flow of D-mesons is severely under-estimated by hadron/string dynamics !

Summary II - PHSD

- The quasiparticle approach to QCD reveals a strongly interacting system above T_C, which has the properties of an almost ideal parton liquid !
- The elliptic flow at RHIC increases due to large parton-parton scattering cross sections
- Strangeness approximately equilibrates due to a large reaction rate $g \rightarrow s+s_{bar}$
- The attenuation of high p_T-hadrons can be described in the partonic + hadronic picture at practically all p_T
- The suppression of the ‚far-side' and ‚near-side' jet provides severe constraints on the parton energy loss and the parton fragmentation/coherence time
- A rather large fragmentation/coherence time (> 0.5 fm/c) is mandatory to understand the lack of ‚near-side' jet suppression and the survival of energetic ‚far-side' jets

Outlook



The Quark-Gluon-Plasma is there!
But what are the properties of this phase ?!

Initial idea (1970 – 2003):
QGP is a weakly interacting gas of colored but almost massless quarks and gluons

State of the art 2005:
QGP is a strongly interacting and almost ideal „color liquid“ !

JPG 31 (2005) L7; PRL 94 (2005) 172301

Jet suppression in 2005:
much more complicated than assumed before due to delayed fragmentation !

New phase diagram of QCD