heavy ion collisions and hydrodynamics

for $T > 200$ MeV in 2-flavor QGP $n_{parton} > 4/\mathrm{fm}^3$ and with typical perturbative cross sections $\lambda < 0.8$ fm
rescattering between particles formed in primary collisions may lead to local thermal equilibrium rapidly
treat system as particle fluid using language and tools of hydrodynamics

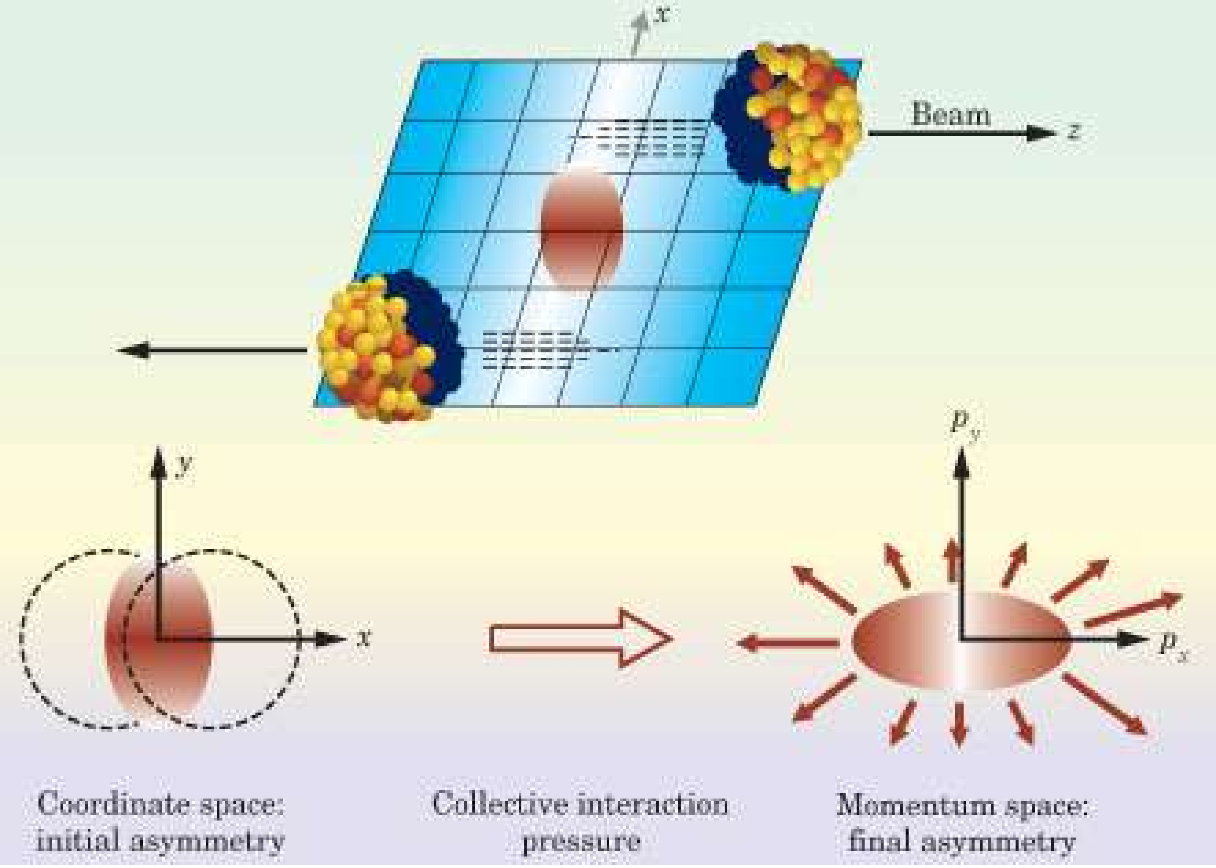
$\partial_\mu T^{\mu\nu} = 0 \quad \partial_\mu j = 0$ with energy-mom tensor $T^{\mu\nu}$ and 4-current of cons. charge j

for ideal fluid: $T^{\mu\nu} = (\varepsilon+p)u\ u - pg$ and $j_i^{\mu} = n_i u^{\mu}$

ε: energy density p: pressure u^μ: flow 4 velocity
generally all fields functions of x

generally only EoS and initial condition needed to calculate evolution
EoS: $p = p(\varepsilon, n_1, \ldots, n_n)$ connection pressure – densities
initial cond.: in ideal fluid expansion isentropic, final state multiplicity gives initial entropy, pick volume $\rightarrow$ system completely determined

Azimuthal Anisotropy Parameter v_2



Fourier decomposition of momentum distributions rel to reaction plane:

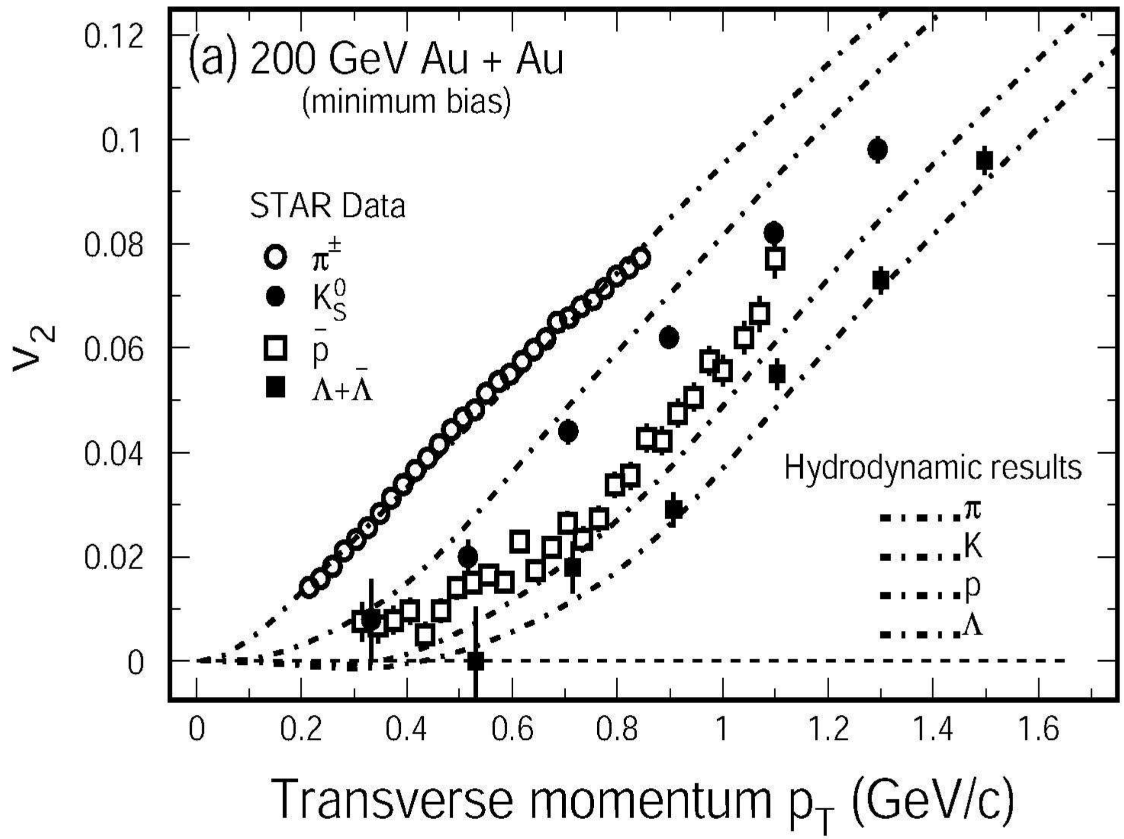
$$\frac{dN}{dp_t\,dy\,d\phi} = N_0 \cdot \left[1 + \sum_{i=1} 2\,v_i(y, p_t)\cos(i\phi)\right]$$

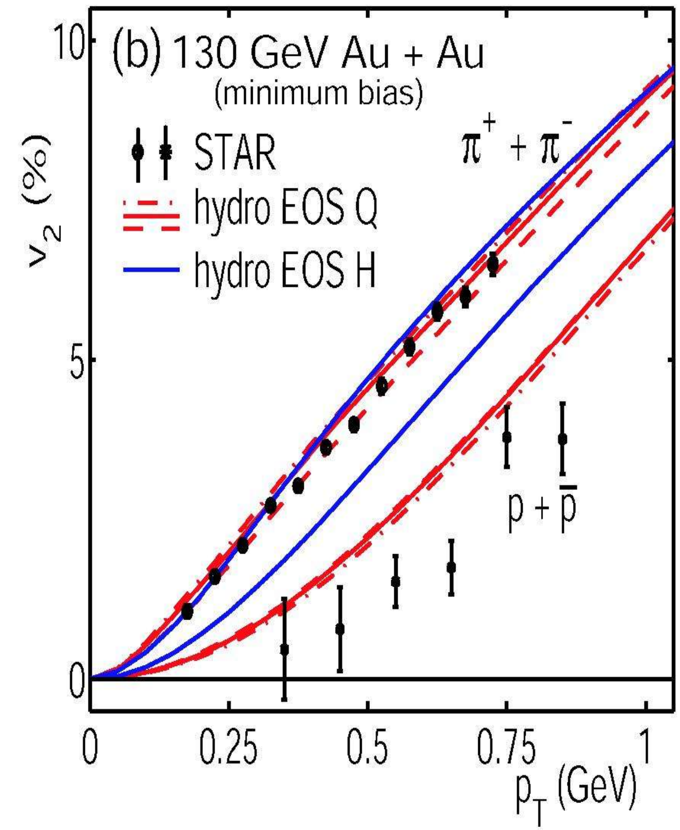
quadrupole component v_2

"elliptic flow"

elliptic flow for different particle species and p_t

$v_2 = \langle \cos(2\phi) \rangle$ where angle ϕ is relativ to reaction plane



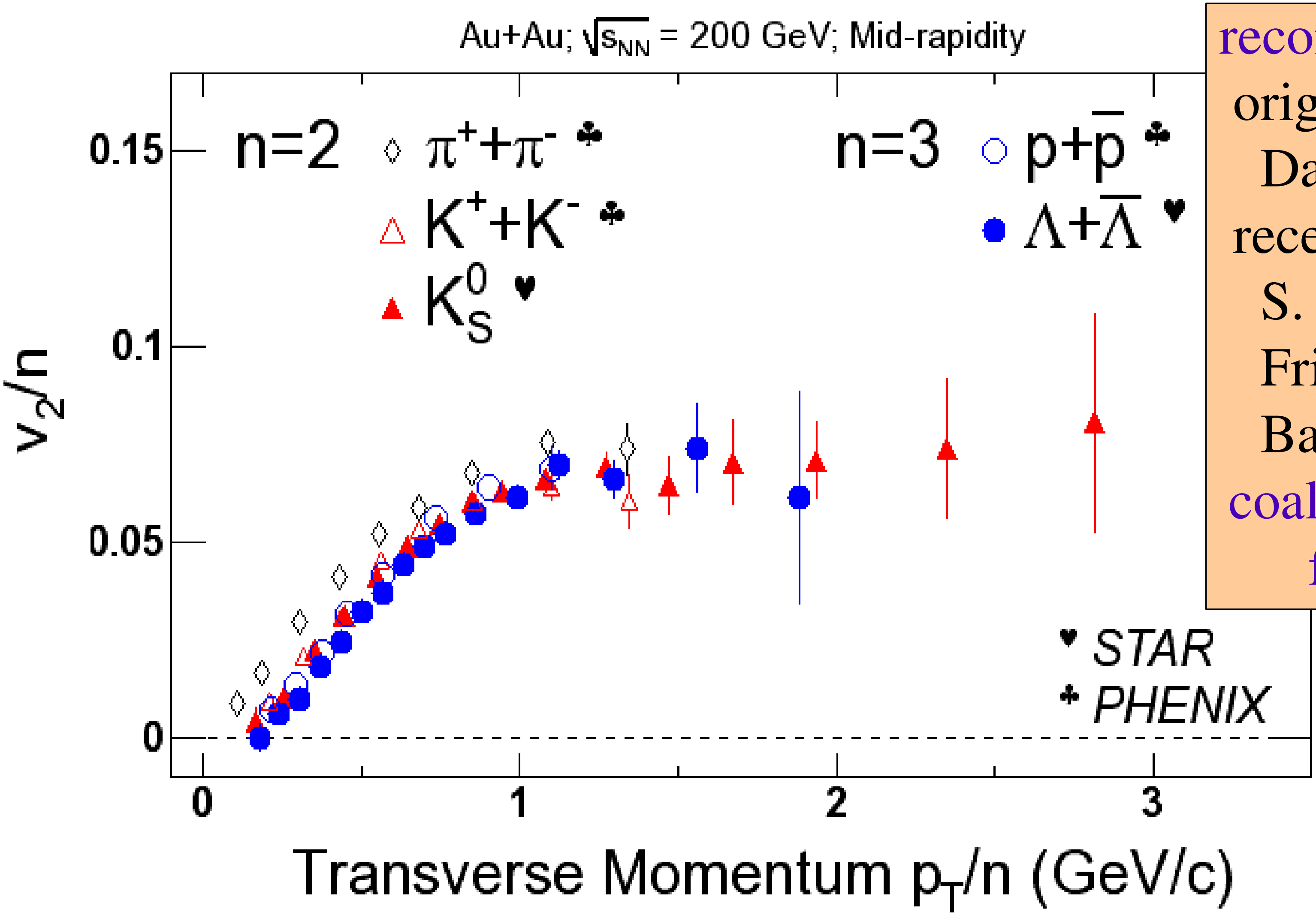


QGP
hadron gas

data: STAR PRL92 (2004) 052302
and PRL 87 (2001) 182301
hydro: P. Huovinen et al. PL B503 (2001) 58
and priv. comm.

well described by hydrodynamics
sensitivity to EOS

valence quark scaling of elliptic flow



recombination of quarks:

original idea:

Das & Hwa 1977

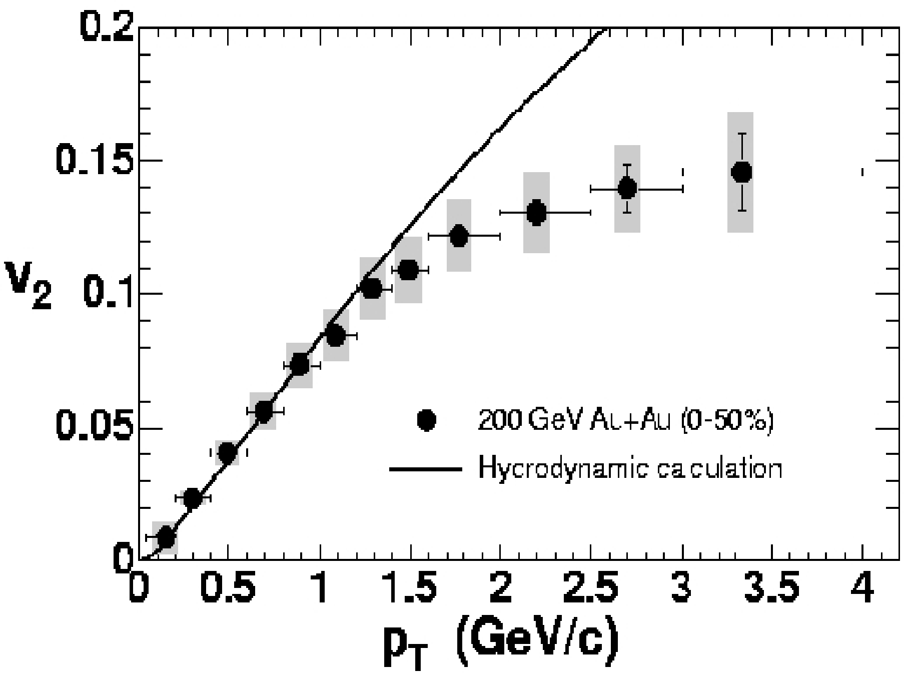
recent connection to data:

S. Voloshin 2003

Fries, Müller, Nonaka, Bass 2003

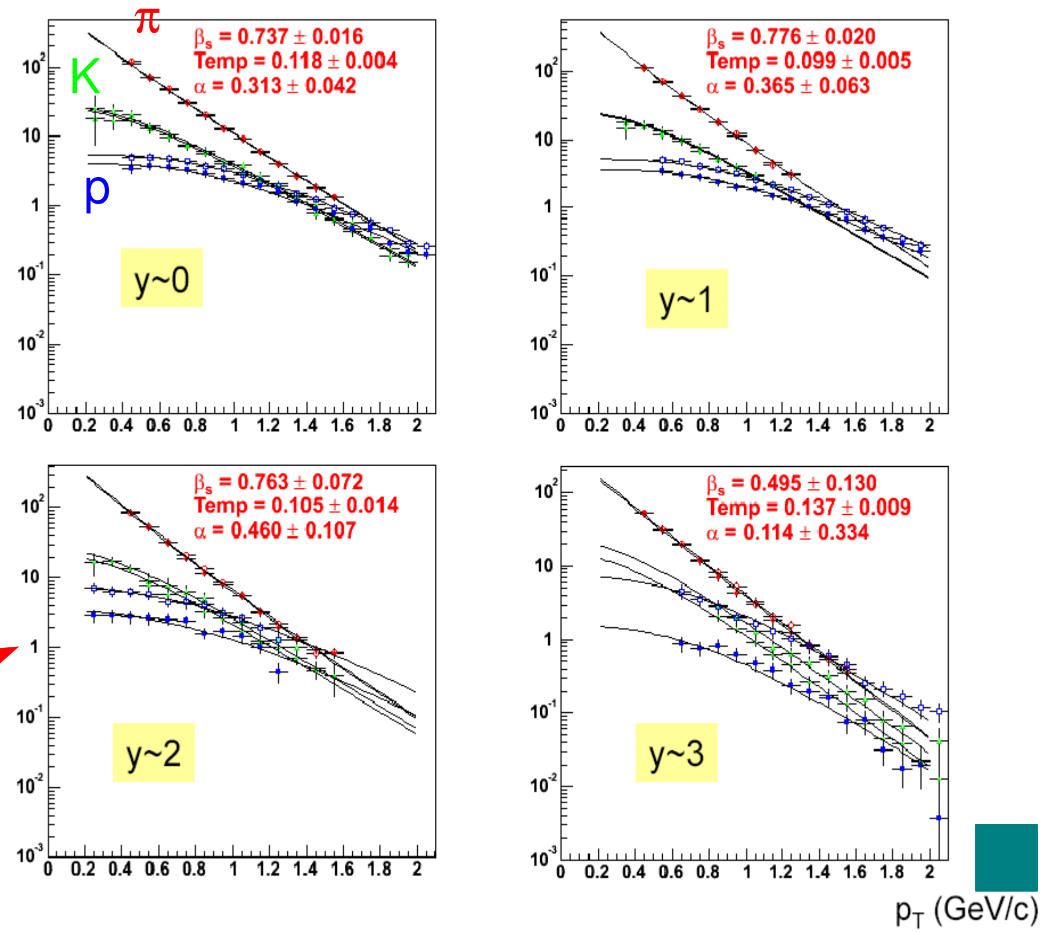
coalescence model works for $p_t > 2\text{-}3$ GeV/c

typical data: p_t spectra and elliptic flow



PHOBOS, nucl-ex/0410022

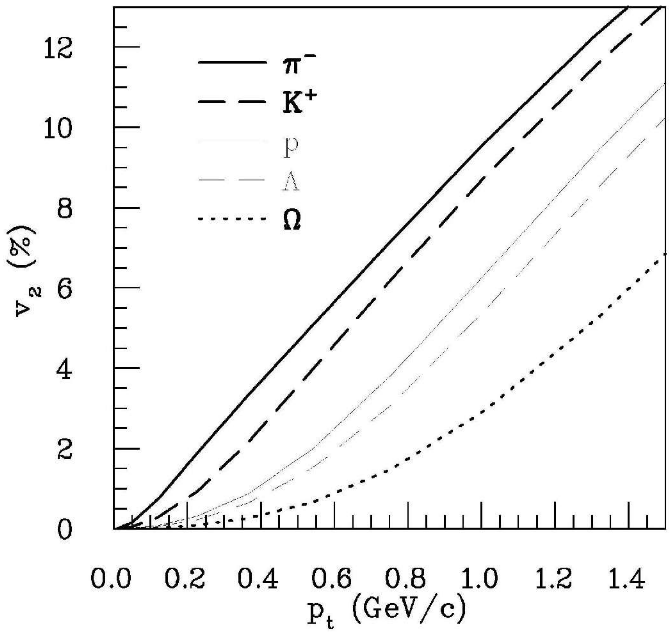
inv. slope constant grows with mass – typical for expanding fireball (Hubble expansion)

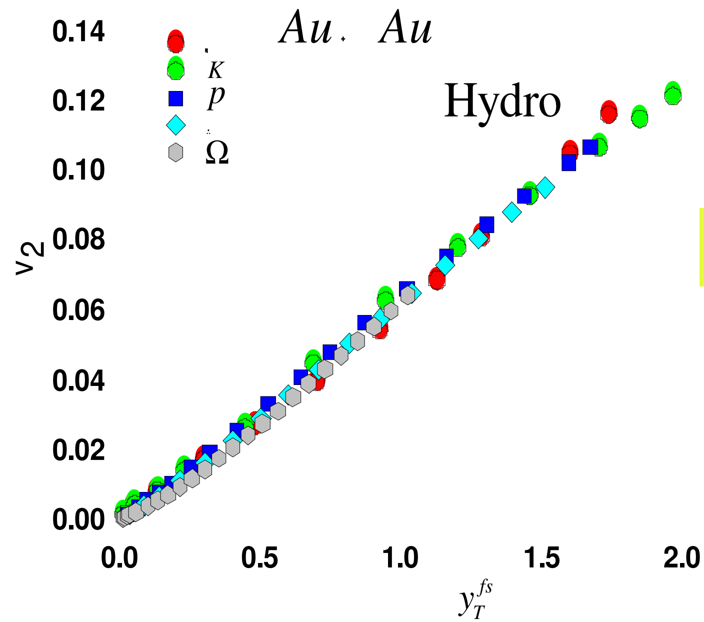


R. Debbe, BRAHMS, Proc. ICPAQGP 2005, Kolkata

particular scaling of hydrodynamics with mass – observed in hydrodynamic models as well as data

P. Huovinen, P.F. Kolb .. Phys. Lett. B503:58 (2001)

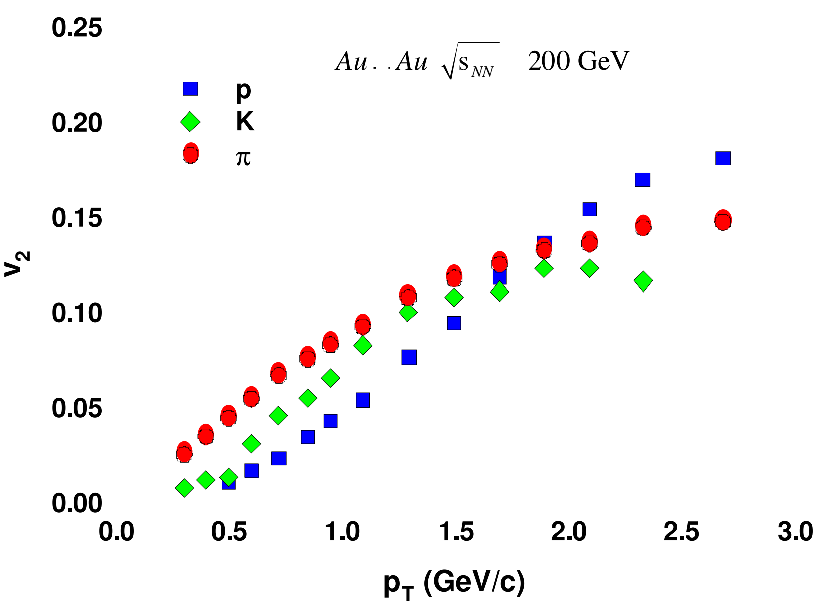


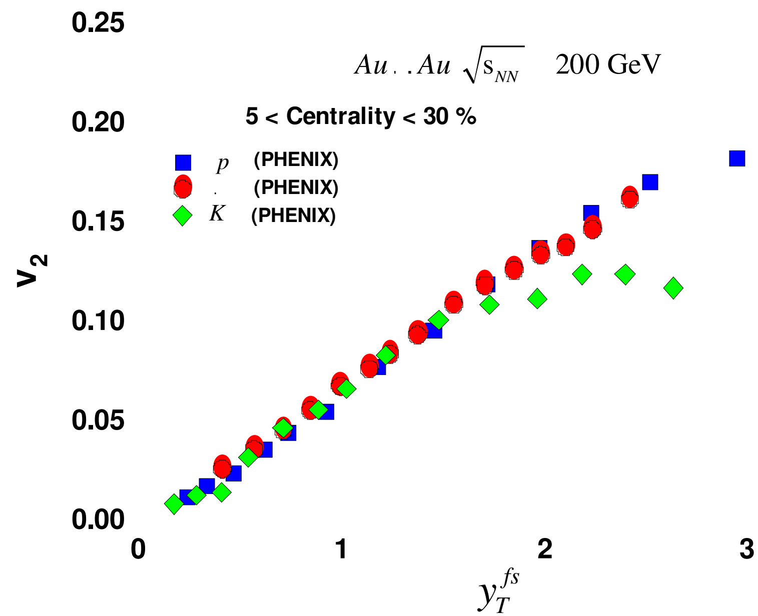


hydro scaling realized: Csörgö et al., PRC67 (2003)034904

$$p_T \rightarrow y_T = \sinh^{-1}(p_T/m)$$

application to model and data: R.Lacey and A.Taranenko nucl-ex/0506019



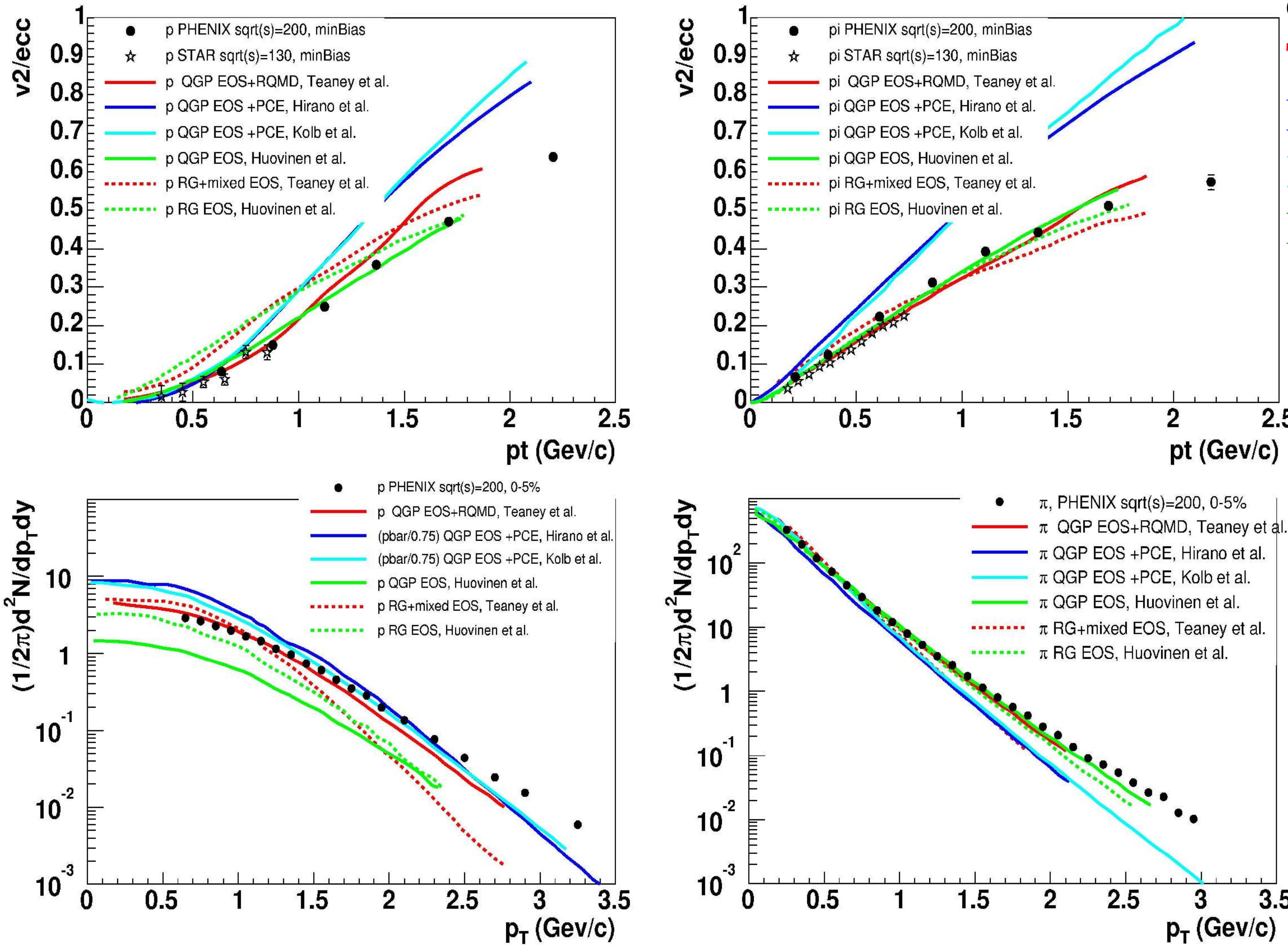


HELMHOLTZ GEMEINSCHAFT

TECHNISCHE UNIVERSITÄT DARMSTADT

ideal hydrodynamics describes spectra and elliptic flow

proton pion

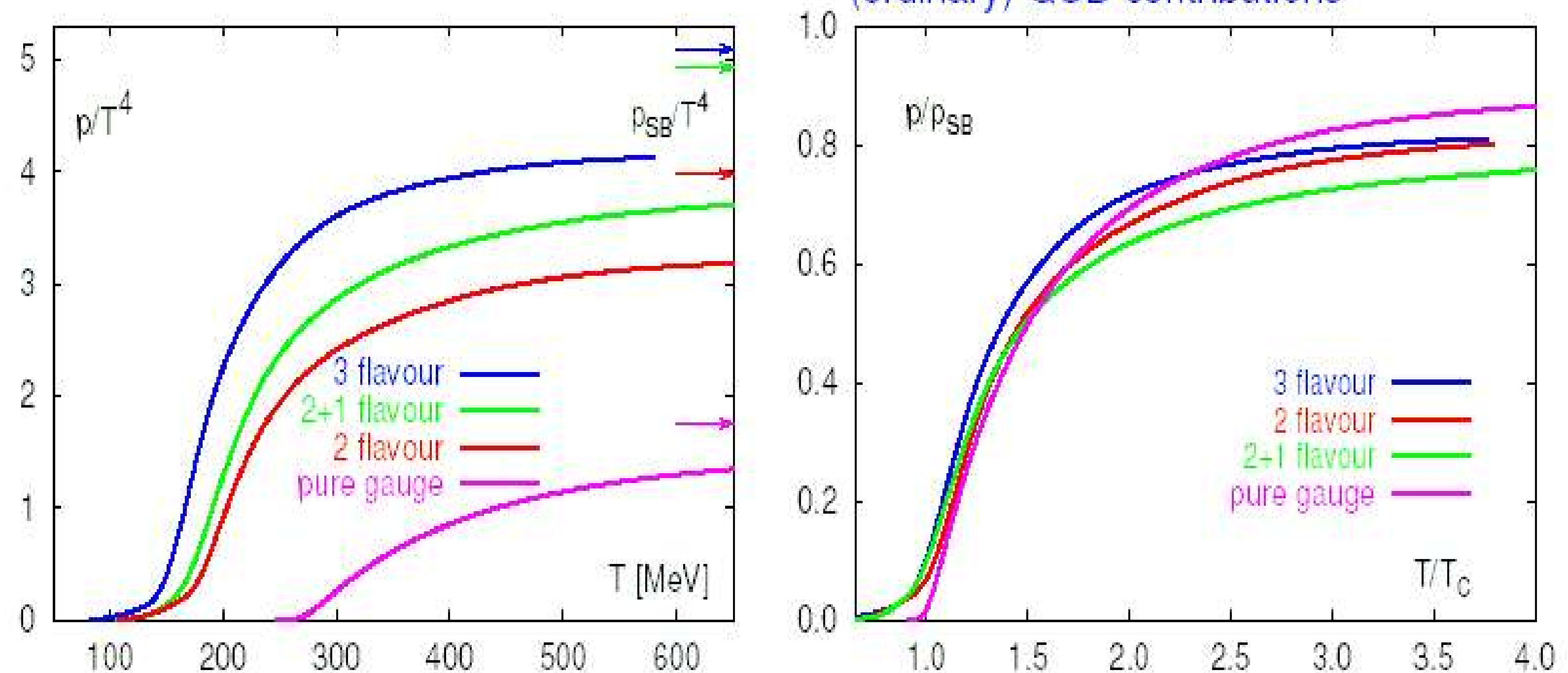


different hydrodyn. models:
Teaney *(w/ & w/o RQMD)*
Hirano *(3d)*
Kolb
Huovinen *(w/& w/oQGP)*

works up to about 2 GeV/c
„requires strong interactions at short times“
(role of CGC?)

the pressure indicates non-ideal behavior

$T \gtrsim (2\text{-}3)T_c$: deviations from ideal gas understood in terms of non-perturbative (ordinary) QCD contributions

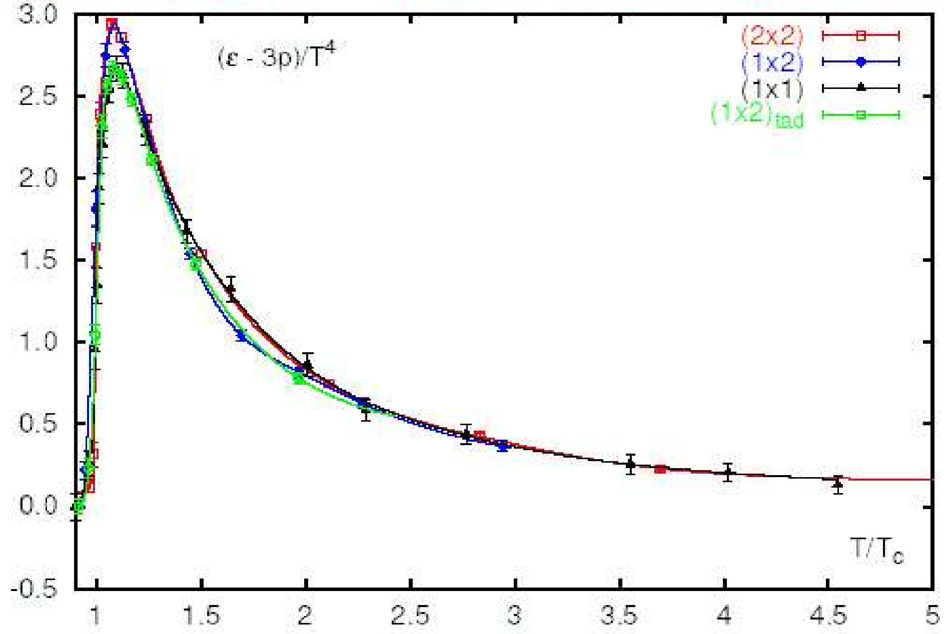


FK, E. Laermann and A. Peikert, Phys. Lett. B478 (2000) 447.

strong interactions near T_c

Deviation from ideal gas (pure gauge)
– suggests strong interactions –

evidence for significant deviations from ideal gas behavior;
at least up to $T \simeq (2-3)\,T_c$; i.e. in the regime accessible to RHIC



colored bound states above T_c ??

hydro-summary

- success of hydrodynamic description – short mfp
- from lattice: QGP is strongly coupled near T_c
- but: ideal liquid interpretation is a guess
- no computation of viscosity from LQCD yet
- no computation of viscosity in hadron gas
- no systematic study of viscous hydrodynamics for RHIC data

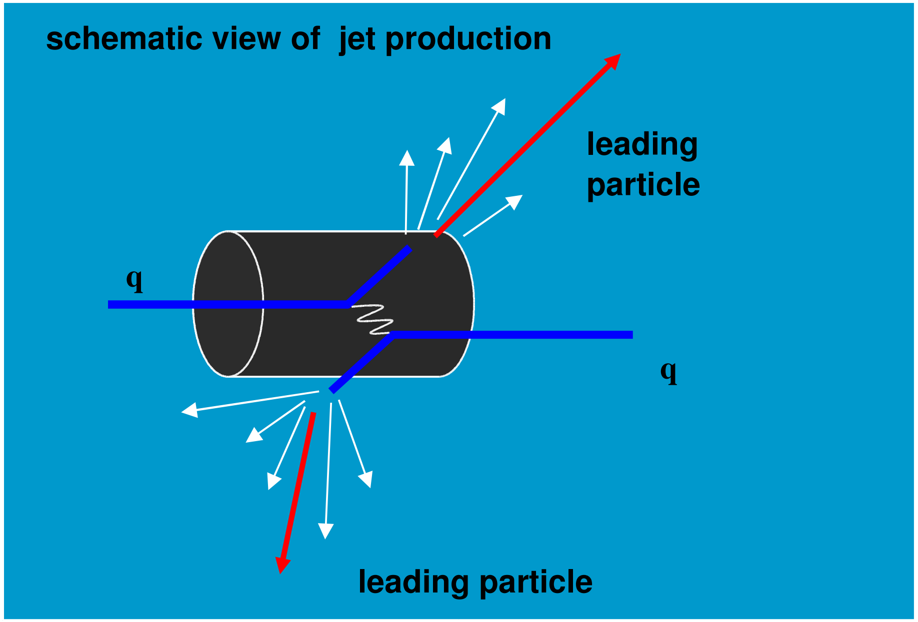
many open questions

Jet quenching

- suppression of high p_t particles in AA relative to pp collisions
- disappearance of jet-like correlations
- connected to large gluon density in hot (QGP) fireball

Jets of hard partons as probe of the hot medium

- Hard parton scattering observed via leading particles
- Expect strong $\Delta\phi=\pi$ azimuthal correlations



However, the scattered partons may loose energy (~ several GeV/fm) in the colored medium

→ momentum reduction (fewer high p_T particles in jet)

→ no jet partner on other side

Jet Quenching

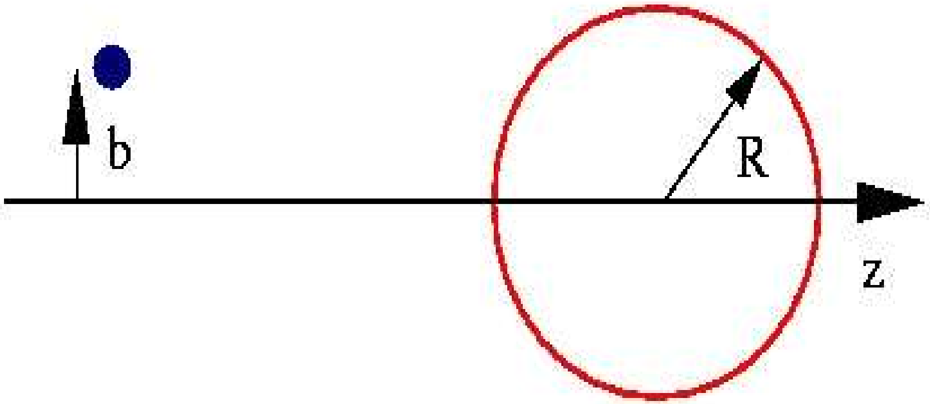
From pp to AA collisions

all valid for hard scattering only

start with normalized nuclear density, $\rho(b, z)$

$$\int \rho(b, z)\,\mathrm{d}z\,\mathrm{d}b \cdot 2\pi b = A$$

$$R = r_0 A^{1/3}$$



Thickness function:

- pA collisions:

$$T_A(b) = \int_{-\infty}^{+\infty} \mathrm{d}z\, \rho(b, z)$$

with $\int \mathrm{d}^2 b T_A(b) = \int_0^\infty 2\pi b \mathrm{d}b T_A(b) = A$

Note: $\sigma_{NN} \cdot T_A(b) = \langle N^{pA}_{coll}(b) \rangle$

sharp spheres: $T_A(0) = \frac{3}{2} \frac{A}{\pi R_A^2}$

Thickness function continued

- AB collisions:

$$T_{AB}(b) = \int \mathrm{d}^2 b_1 \mathrm{d}^2 b_2 \delta^{(2)}(\vec{b} - \vec{b_1} - \vec{b_2}) T_A(b_1) T_B(b_2)$$

with $\int \mathrm{d}^2 b T_A(b) = A \cdot B$

$$\sigma_{NN} \cdot T_{AB}(b) = \langle N_{coll}^{AB}(b) \rangle$$

sharp spheres: $T_{AB}(0) = \frac{9}{8} \frac{A^2}{\pi R_A^2}$

Thickness function continued

Implications:

$$\frac{\mathrm{d}\sigma^{AB}}{\mathrm{d}y}(\Delta b = b_2 - b_1) = \frac{\mathrm{d}\sigma^{NN}}{\mathrm{d}y} \int_{b_1}^{b_2} \mathrm{d}^2 b T_{AB}(b)$$

for minimum bias ($b = [0, R_A + R_B]$):

$$\frac{\mathrm{d}\sigma^{AB}}{\mathrm{d}y} = \frac{\mathrm{d}\sigma^{NN}}{\mathrm{d}y} \cdot A \cdot B$$

also:

$$\frac{\mathrm{d}N^{AB}}{\mathrm{d}y} = \frac{\mathrm{d}N^{NN}}{\mathrm{d}y} \cdot \sigma^{NN}_{inelastic} \cdot \frac{\int_{b_1}^{b_2} \mathrm{d}^2 b T_{AB}(b)}{\pi(b_2^2 - b_1^2)}$$

Thickness function continued

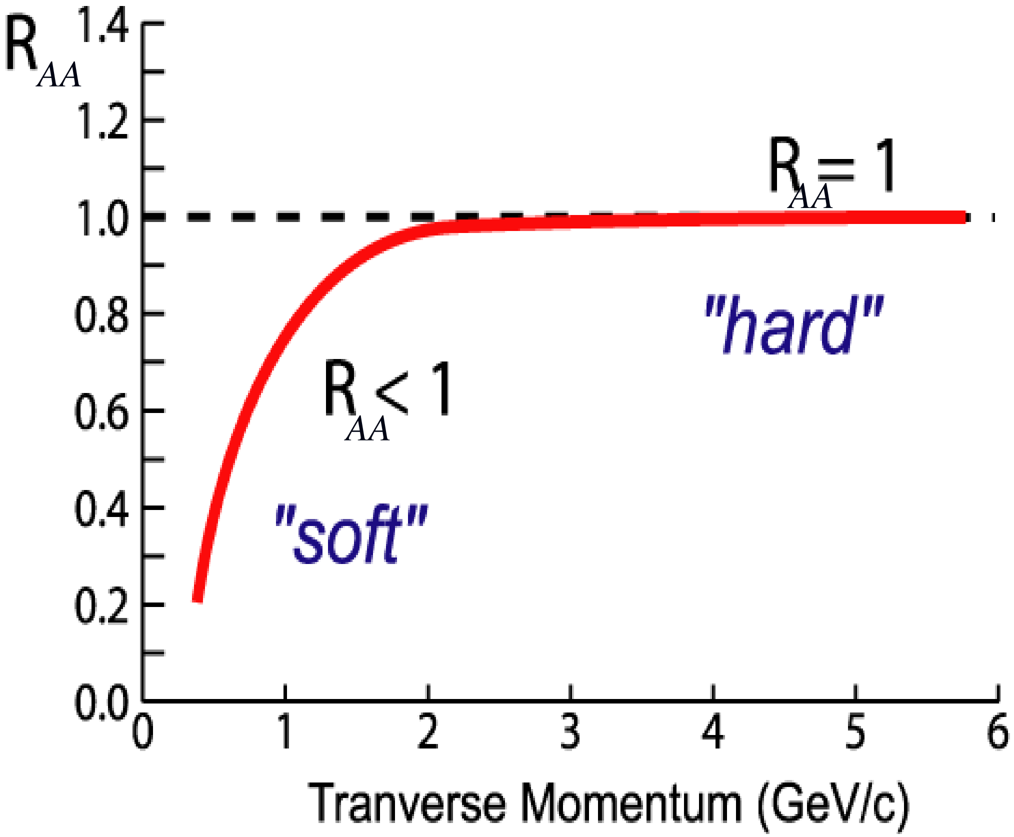
The R_{AA} function:

$$R_{AA}(b) = \frac{\frac{\mathrm{d}^2 N^{AA}}{\mathrm{d}p_t^2 \mathrm{d}y}}{N_{coll}^{AA}(b) \cdot \frac{\mathrm{d}^2 N^{NN}}{\mathrm{d}p_t^2 \mathrm{d}y}}$$

if hard scattering only:

$$R_{AA}(b) = 1$$

Qualitative expectations



no medium effects:

$R_{AA} < 1$ in regime of soft physics

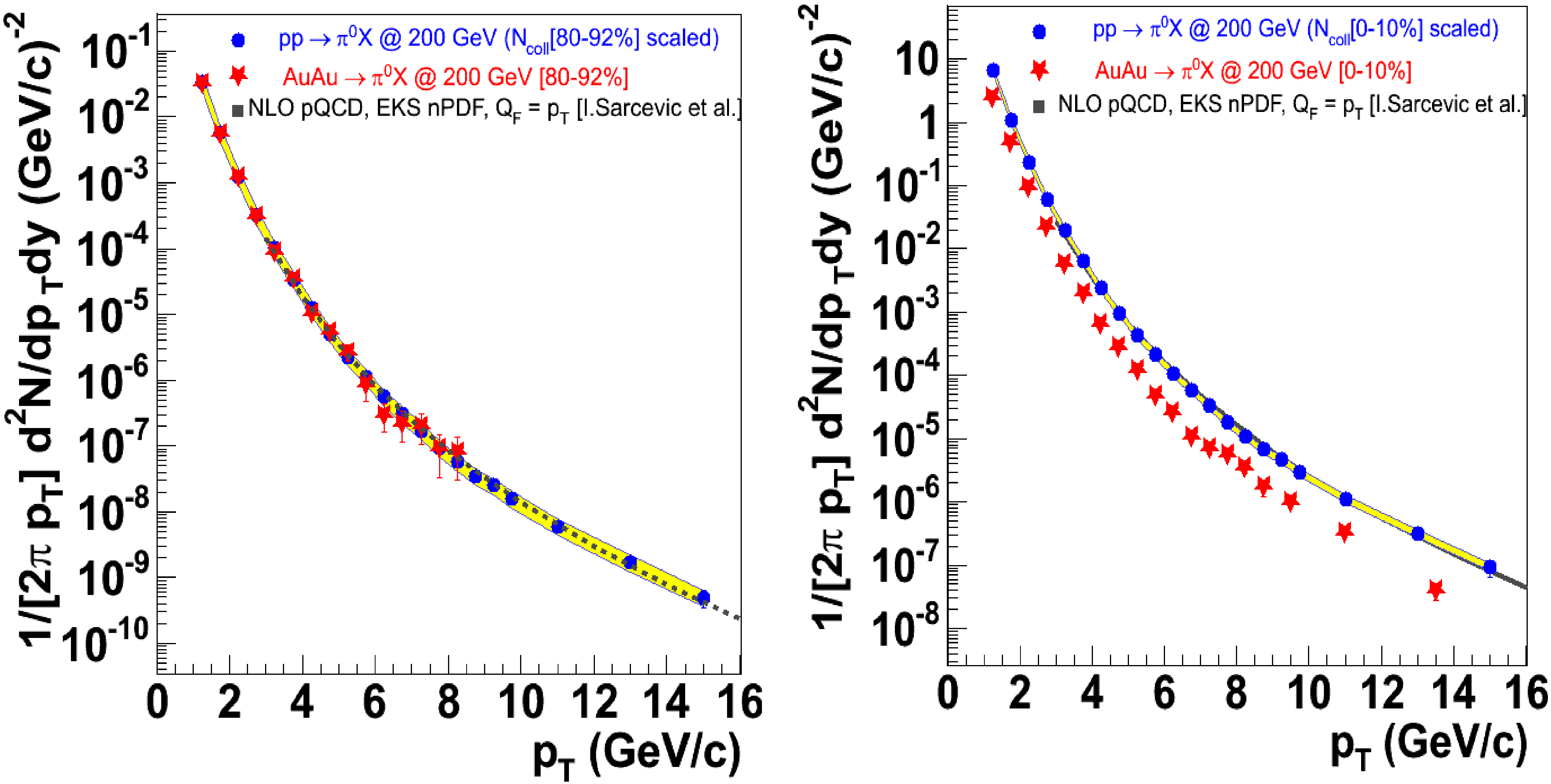
$R_{AA} = 1$ at high-p_T where hard scattering dominates

Suppression:

$R_{AA} \ll 1$ at high-p_T

spectra suppressed at high p_t in AuAu relative to pp

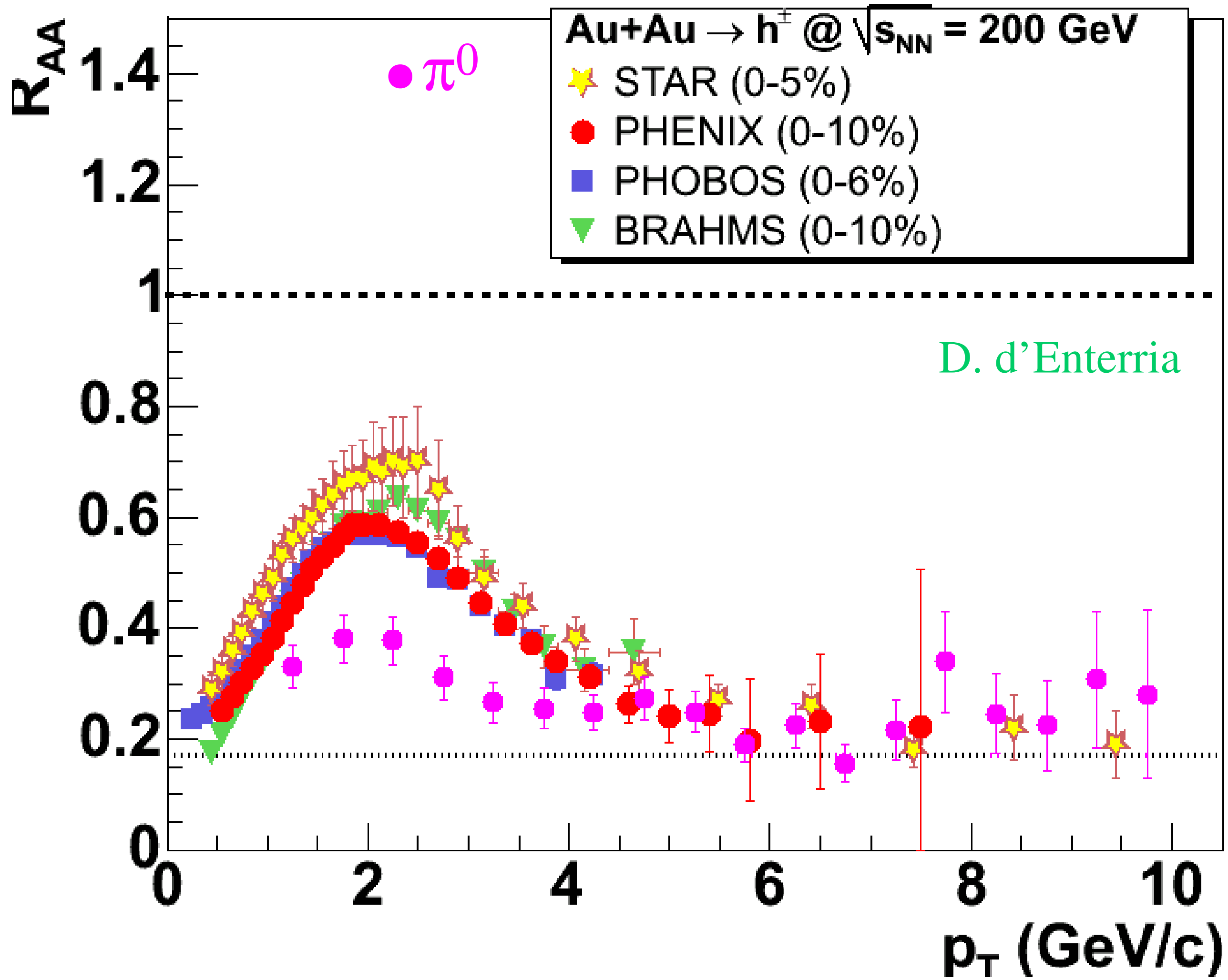
proton data scaled to AuAu with appropriate number of binary collisions



PHENIX PRL 91 (2003) 072305 and 241803

high p_t suppression seen by all experiments

R_{AA}=yield(AuAu)/N_{coll} yield(pp)



- all expts. see large suppression in AuAu
- π^0 lower than $h^{\pm}$
- no suppression in dAu rather Cronin enhancement → medium effect, not incoming partons

- reasonable agreement between 4 experiments

Suppression predicted due to energy loss of partons in hot matter "jet quenching"

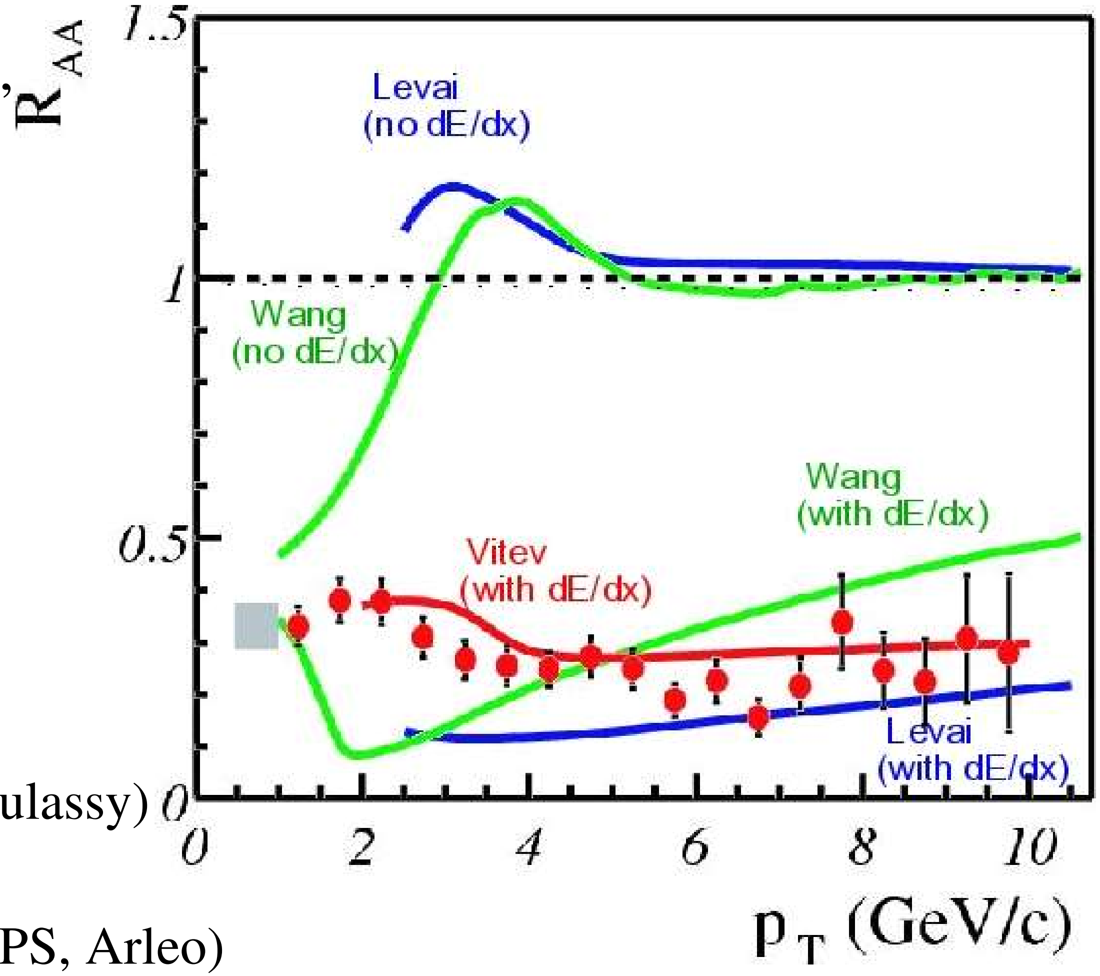
H. Baier, Y.L. Dokshitzer, A.H. Mueller, S. Peigne, D. Schiff, Nucl. Phys. B483 (1997) 291 and 484 (1997) 265

energy loss of high energy parton traversing color charged medium ->

medium induced gluon radiation

in high energy limit

$\Delta E \approx \alpha_s \mu^2 L^2/\lambda \, (1 + O(1/N))$



implemented in models in different ways:

high initial densities $dN_g/dy=1100$ (Vitev/Gyulassy)

large opacities $<n> = L/\lambda \approx 3\text{-}4$ (Levai et al.)

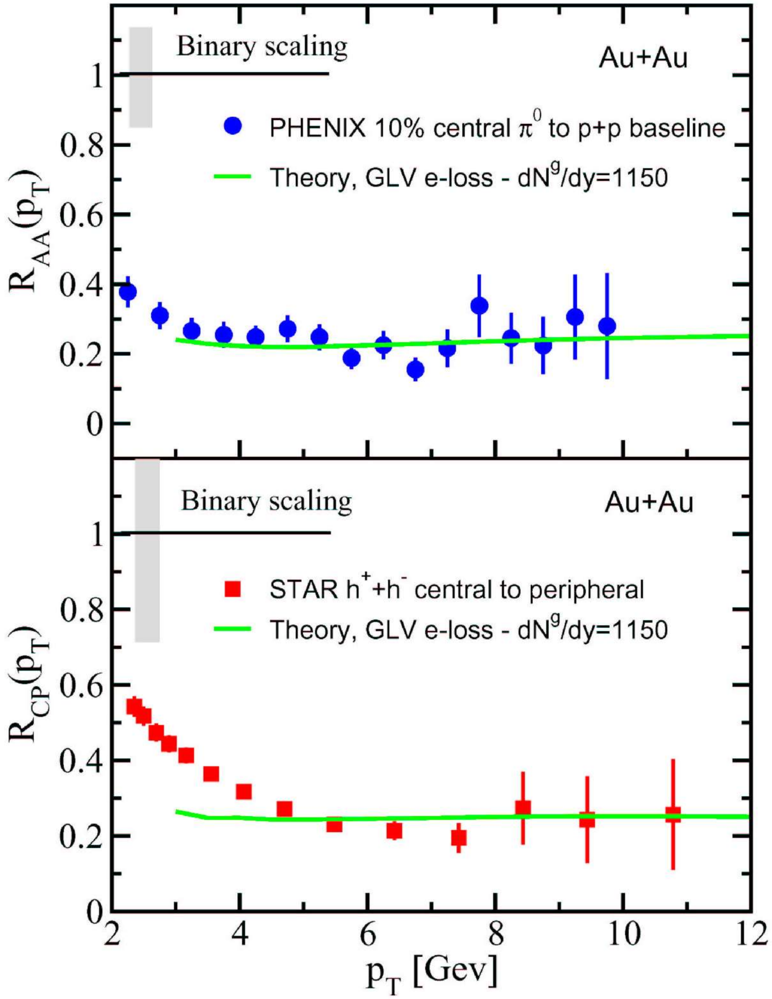
transport coefficients $q_0=3.5$ GeV/fm^2 (BDMPS, Arleo)

plasma temperature T = 400 MeV (G. Moore)

medium induced ratiative energy loss

dE/dx(expanding)=0.25 GeV/fm or dE/dx(static source)=14 GeV/fm (S.N.Wang)

suppression of hadron yields at high p_t in central AuAu collisions

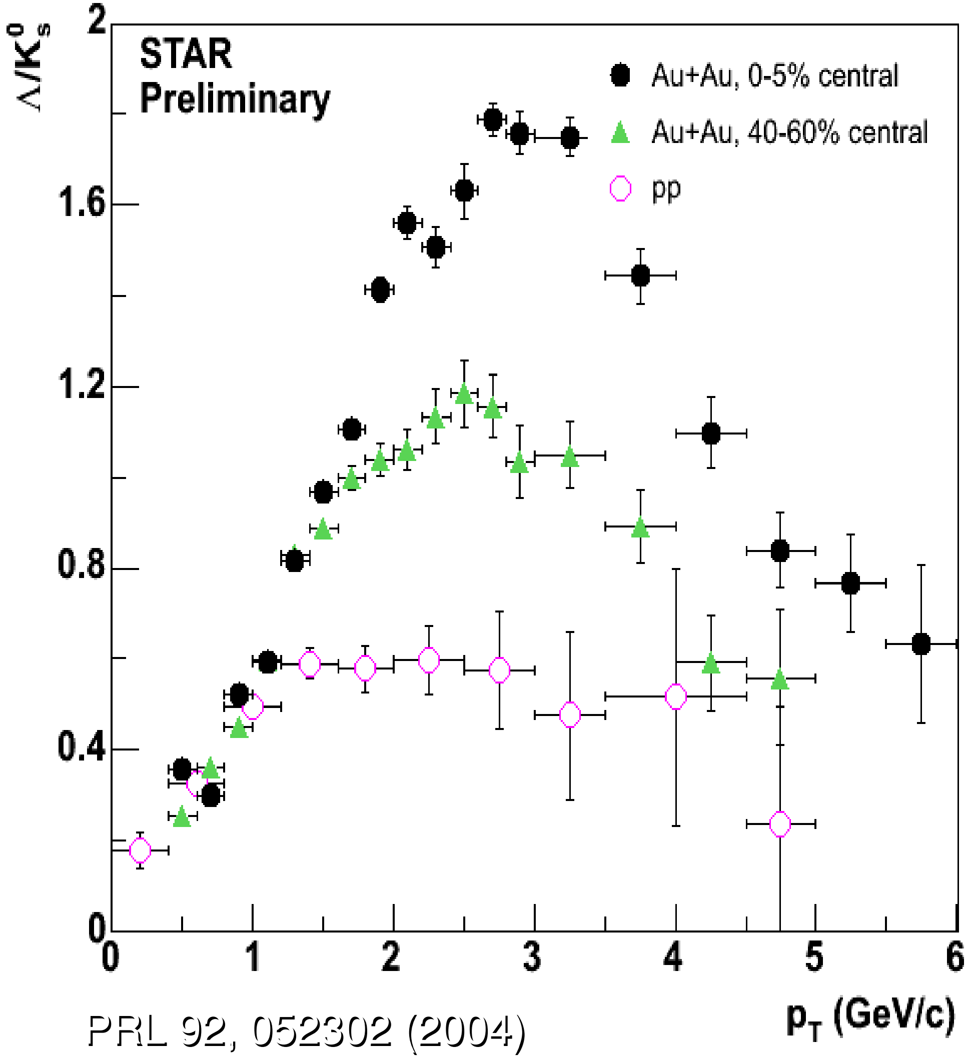


AuAu compared to pp scaled with number of binary collisions

AuAu central collisions compared to peripheral collisions scaled with number of binary collisions

in central collisions hadron yields suppressed indicative of jet quenching due to parton energy loss due to high gluon density

suppression pattern depends on hadronic species



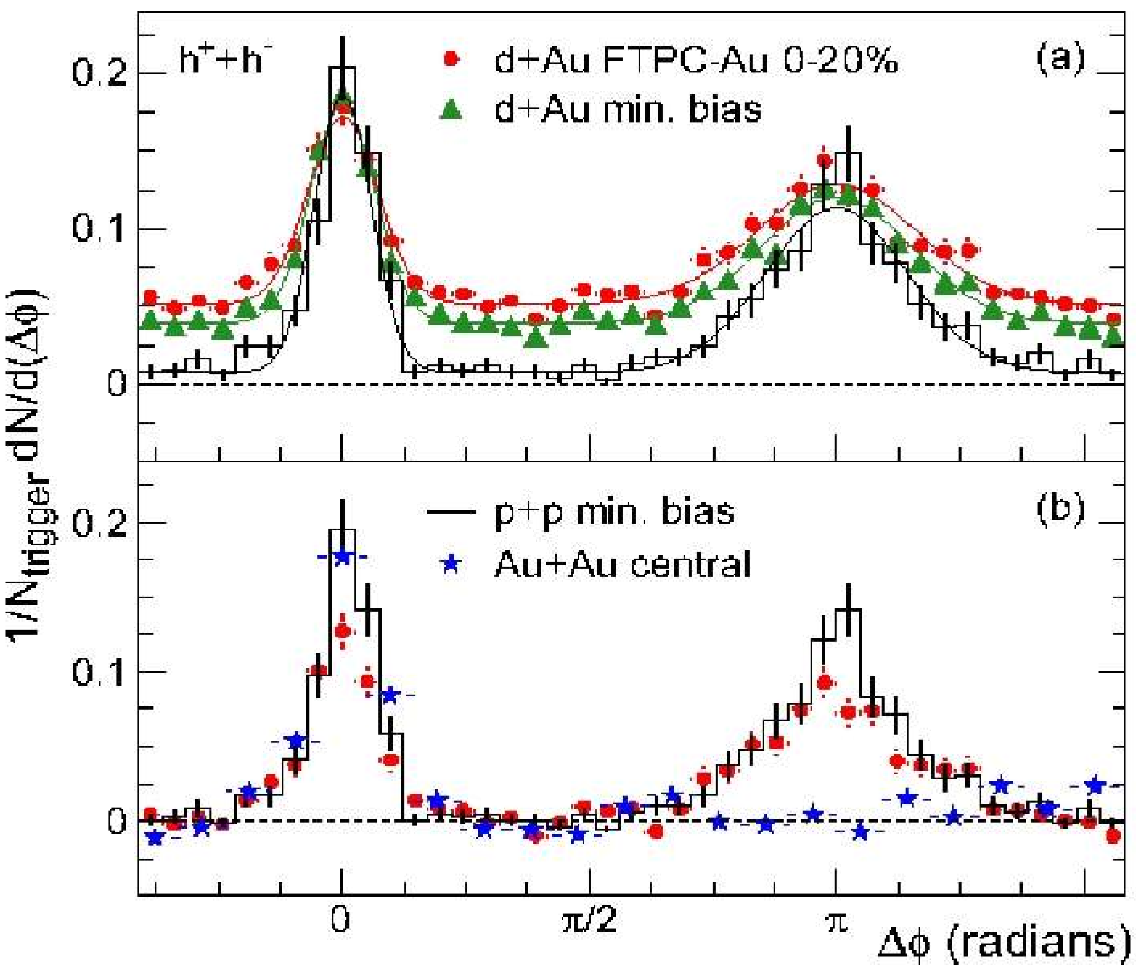
PRL 92, 052302 (2004)
J.Phys. G30, S963 (2004)

observed early on: protons exceed number of pions at 2 GeV/c

general feature for all baryons?

very cleanly shown recently for Λ as compared to $K^0{}_s$
while pp shows normal fragmentation
coalescence of valence quarks? 3:2
Duke model...

Azimuthal correlations of high p_t particles

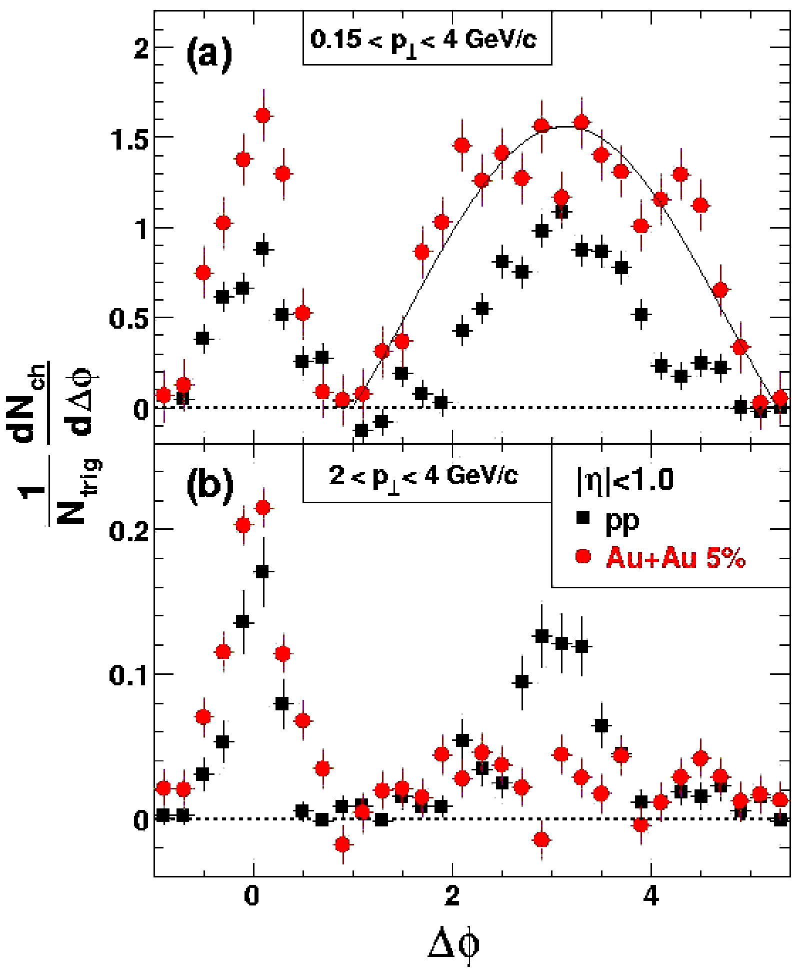


trigger particle: 4-6 GeV/c
correlated with all others
with p_t=2-4 GeV/c

STAR: PRL 91 (2003) 072304

away-side associated hadrons at lower p_t

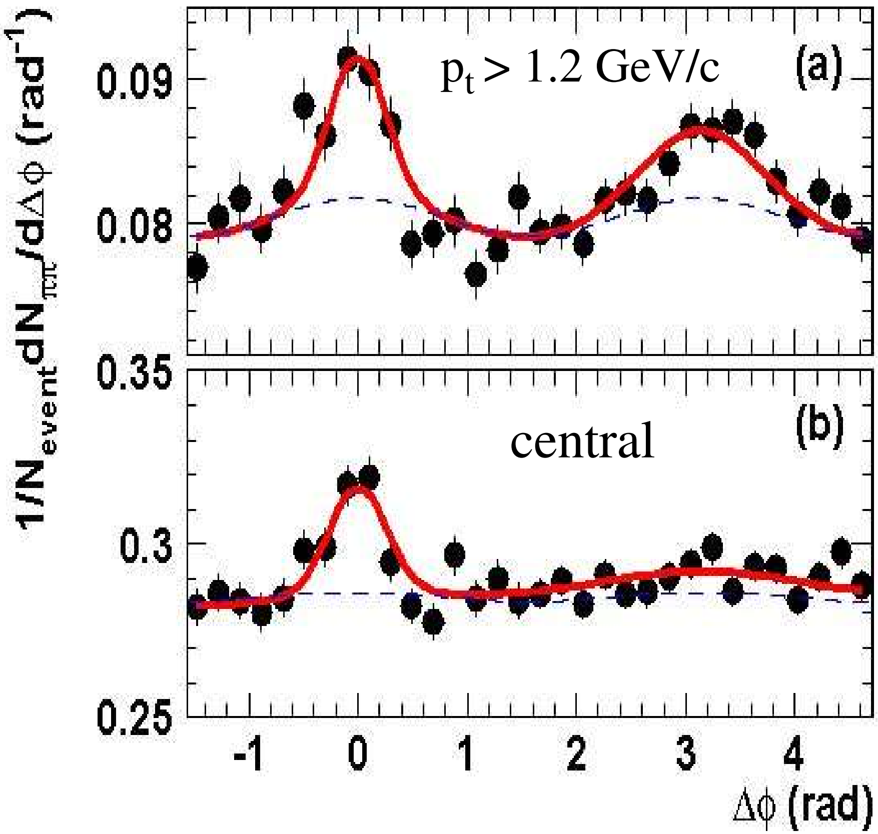
STAR 200 GeV nucl-ex/0501016



4 < p_T(trig.) < 6 GeV/c

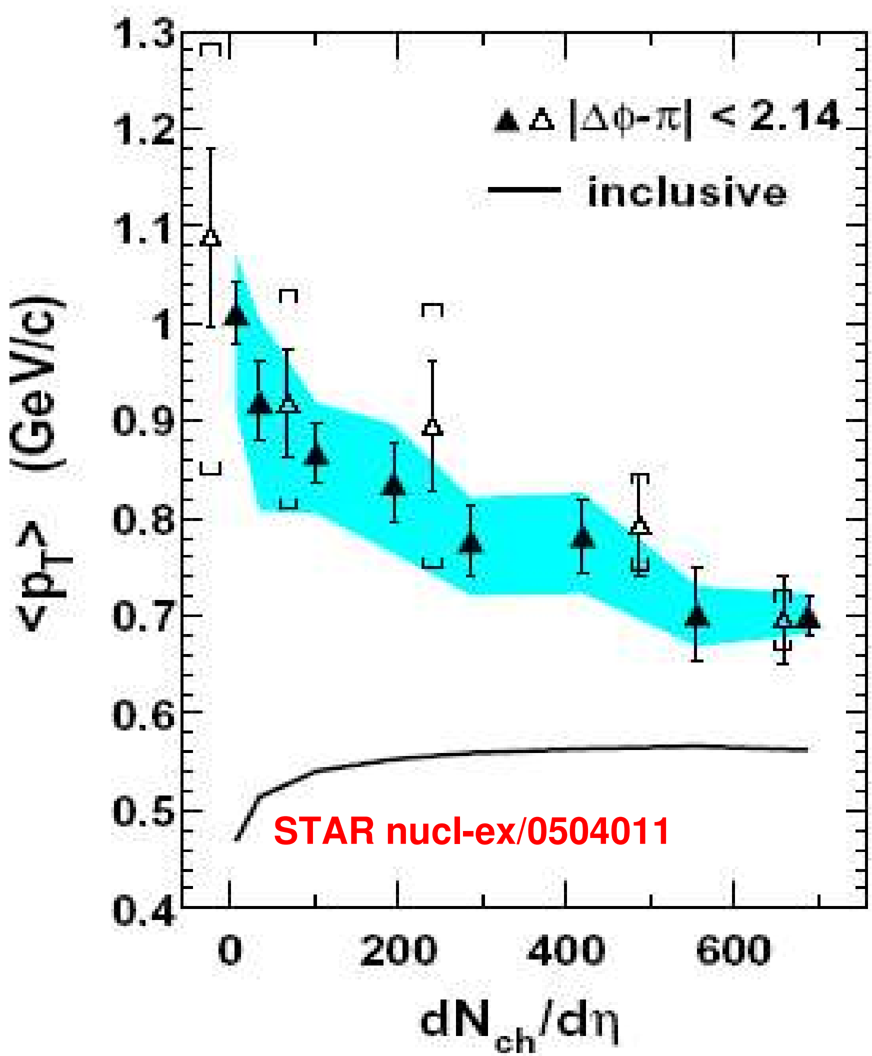
$\sqrt{s}$ = 17.2 GeV

CERES/NA45 PRL92(2004)032301



shape of away side peak changes (broadens)
momenta reduced

mean p_t in cone opposite to leading trigger particle



for central collisions mean p_t on opposite side looks nearly thermalized

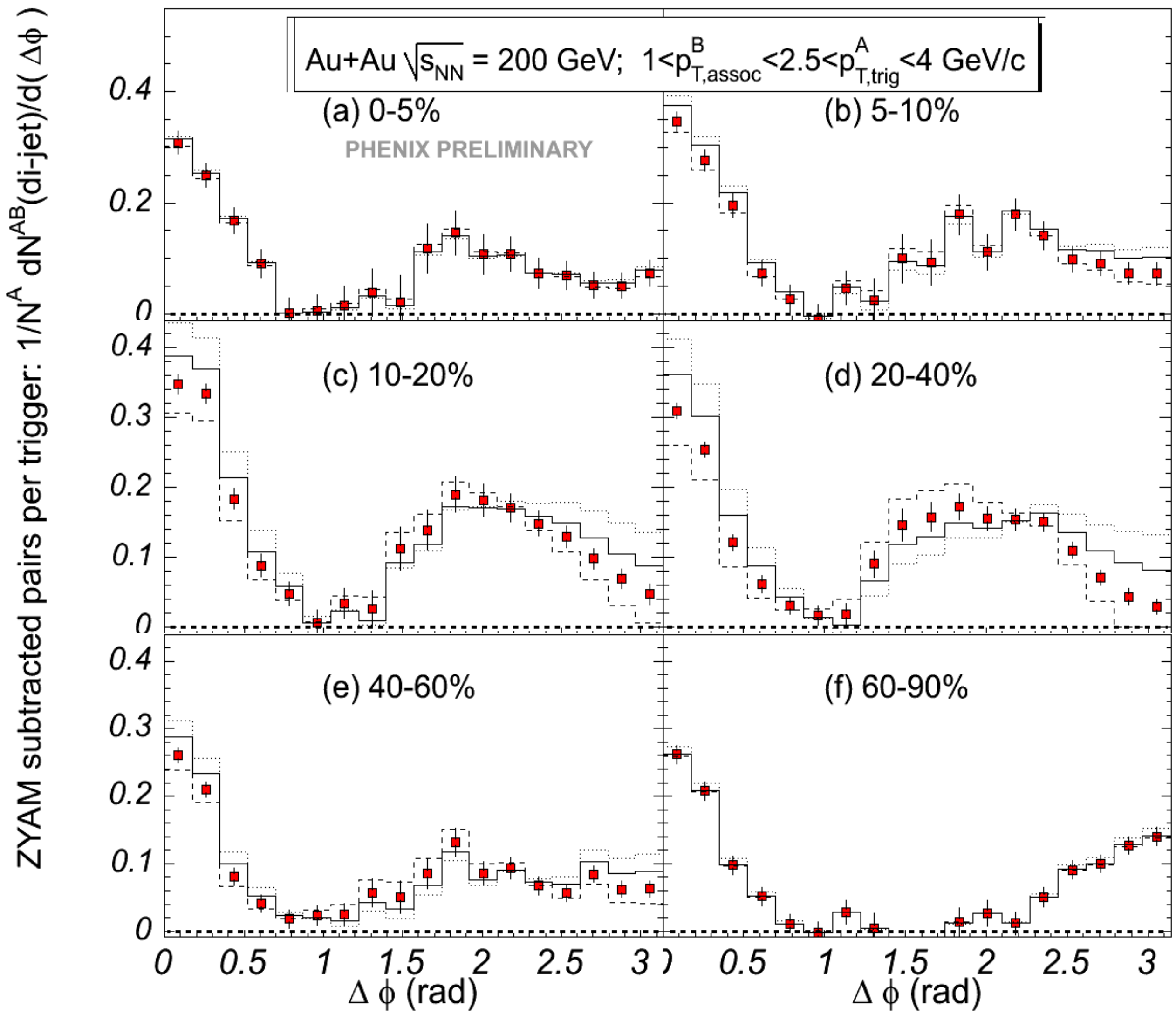
$\sqrt{s_{NN}}$ = 200 GeV Au+Au results:

Closed symbols ⇔ $4 < p_T^{trig} < 6$ GeV/c

Open symbols ⇔ $6 < p_T^{trig} < 10$ GeV/c

Assoc. particles: $0.15 < p_T < 4$ GeV/c

opening angle correlations between high p_t particles



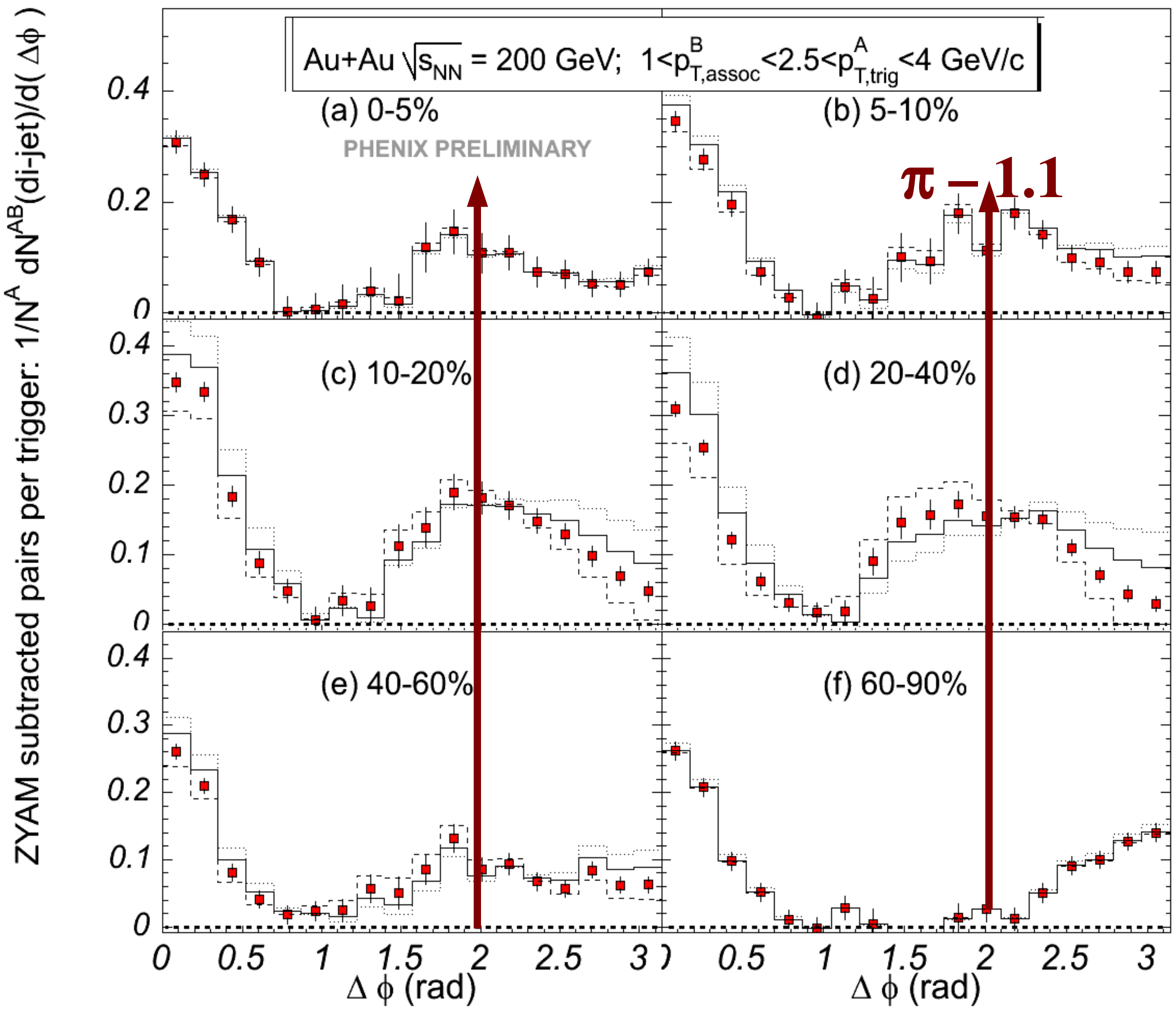
when asking for softer particle opposite hard trigger particle: dip (2 σ) at $\Delta\varphi = \pi$ except for most peripheral bin

N.N.Ajitanand, Proc. Int. Conf. Phys. & Astrophys. of QGP, Kolkata Feb. 2005

Mach cone due to sonic boom from quenched jets?

original idea:
Stöcker/Greiner 1976
for nuclear reactions;
Stöcker 2004:
60º cone for jets in QGP

J.Casalderrey-Solana,E. Shuryak, D. Teaney,hep-ph/0411315



if this can be established
far reaching consequences:
sensitivity to speed of
sound and EOS

experimental challenge:
can one see cone in 2d?
rel to reaction plane?

jet quenching indicative of gluon rapidity density

	$\tau_0[fm]$	$T[MeV]$	$\varepsilon[GeV/fm^3]$	$\tau_{tot}[fm]$	dN^g/dy
SPS	0.8	210-240	1.5-2.5	1.4-2	200-350
RHIC	0.6	380-400	14-20	6-7	800-1200
LHC	0.2	710-850	190-400	18-23	2000-3500

I. Vitev, JPG 30 (2004) S791

- **Consistent estimate with hydrodynamic analysis**