

Lessons from RHIC and Potential Discoveries at LHC with Ions

recent reviews:

M. Gyulassy and L. McLerran, Nucl. Phys. A750 (2005) 30

pbm and J. Stachel, Nature 448 (2007) 302

pbm and J. Wambach, Rev. Mod. Phys. (2008, to appear)
arXiv:0801.4256

see also: Heavy Ion Collisions at the LHC – Last Call for Predictions
J. Phys. G35 (2008) 054001, arXiv:0711.0974

SPC meeting, Dec. 9, 2008

selective synopsis of RHIC results

this is not a comprehensive review of all RHIC results

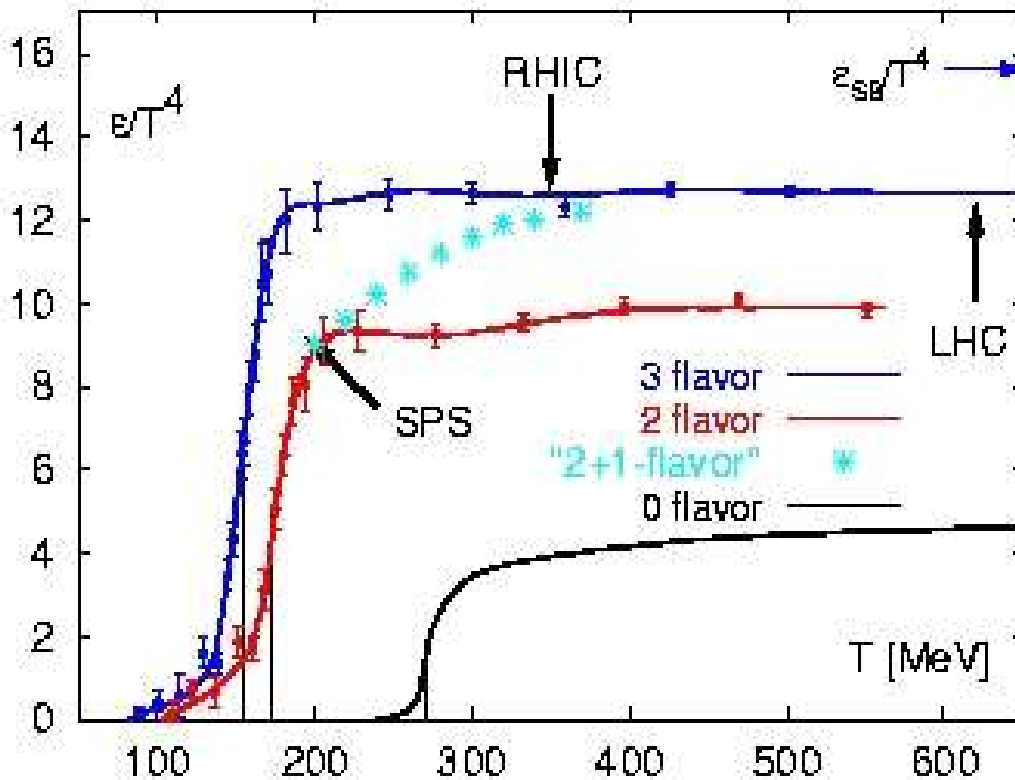
focus is on:

1. particle multiplicity
2. hadron production mechanism
3. hydrodynamic flow results
4. jet quenching
5. charmonium physics

not covered:

particle correlations, photons, dileptons,
charm and beauty production, ultraperipheral collisions, ...

Critical energy density and critical temperature



Lattice QCD calculations for $\mu_B = 0$
Karsch et al, hep-lat/0305025

$$T_c = 173 \pm 12 \text{ MeV}$$

$$\varepsilon_c = 700 \pm 200 \text{ MeV/fm}^3$$

for the (2 + 1) flavor case:

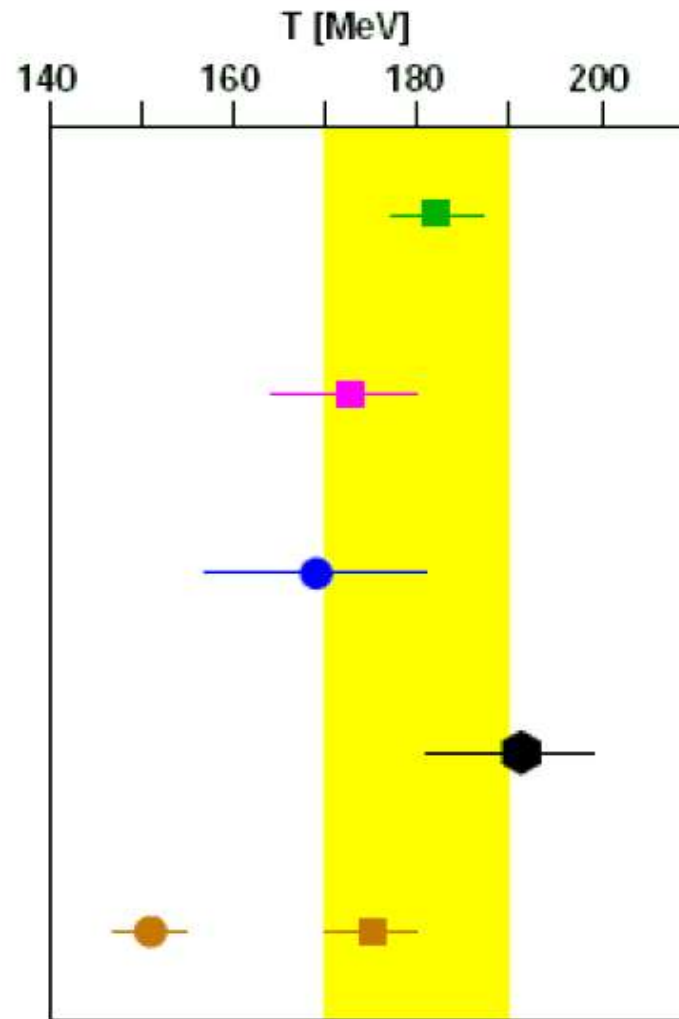
the phase transition to the QGP
and its parameters are quantitative
predictions of QCD.

The order of the transition is not
yet definitively determined,
see also:

Aoki, Y., G. Endrodi, Z. Fodor, S. D. Katz, and K. K. Szabo, 2006a, *Nature* **443**, 675.

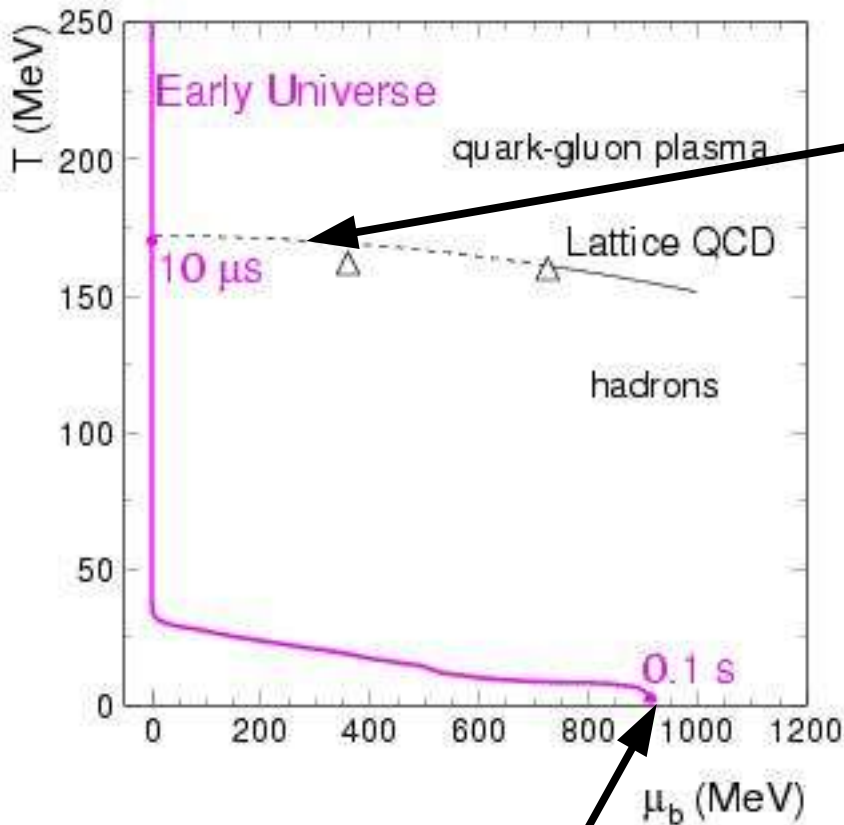
Aoki, Y., Z. Fodor, S. D. Katz, and K. K. Szabo, 2006b, *Phys. Lett.* **B643**, 46.

current status of lattice QCD calculations -- critical temperature



F. Karsch, Erice Workshop, Sept. 2008

Evolution of the Early Universe



QCD Phase Boundary

Homogeneous Universe in Equilibrium, this matter can only be investigated in nuclear collisions

- Charge neutrality
- Net lepton number = net baryon number
- Constant entropy/baryon

neutrinos decouple and light nuclei begin to be formed

characterizing QGP matter at LHC

equation of state
number of degrees of freedom
transport coefficients (viscosity etc)
velocity of sound
parton energy loss and opacity
susceptibilities
deconfinement

but also, look for the unexpected

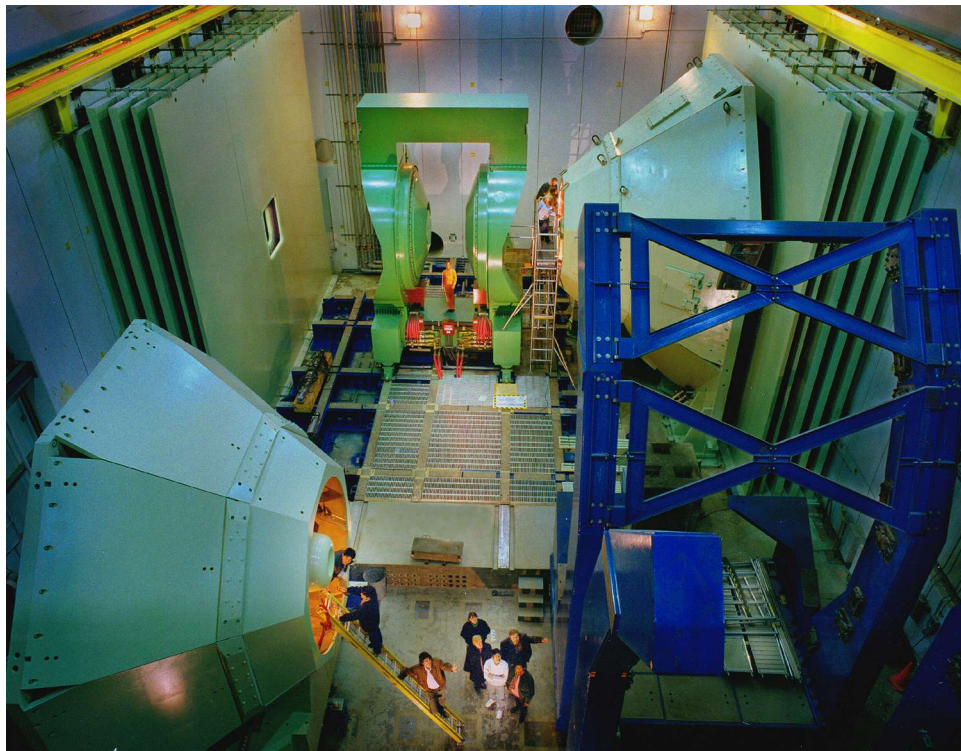
Accelerators where ultra-relativistic nuclei collide

	fixed target		collider	
	AGS	SPS	RHIC	LHC
	1987-2000		since 2000	from 2009
beam momentum	$29 \cdot Z \text{ GeV}/c$	$450 \cdot Z \text{ GeV}/c$	$ea250 \cdot Z \text{ GeV}/c$	$ea7000 \cdot Z \text{ GeV}/c$
projectile	p...Au	p...Pb	p...Au	p...Pb
energy available in c.m. system	Au+Au 600 GeV	Pb+Pb 3200 GeV	Au+Au 40 TeV	Pb+Pb 1150 TeV
hadrons produced per collision	900	2400	7500	40000?

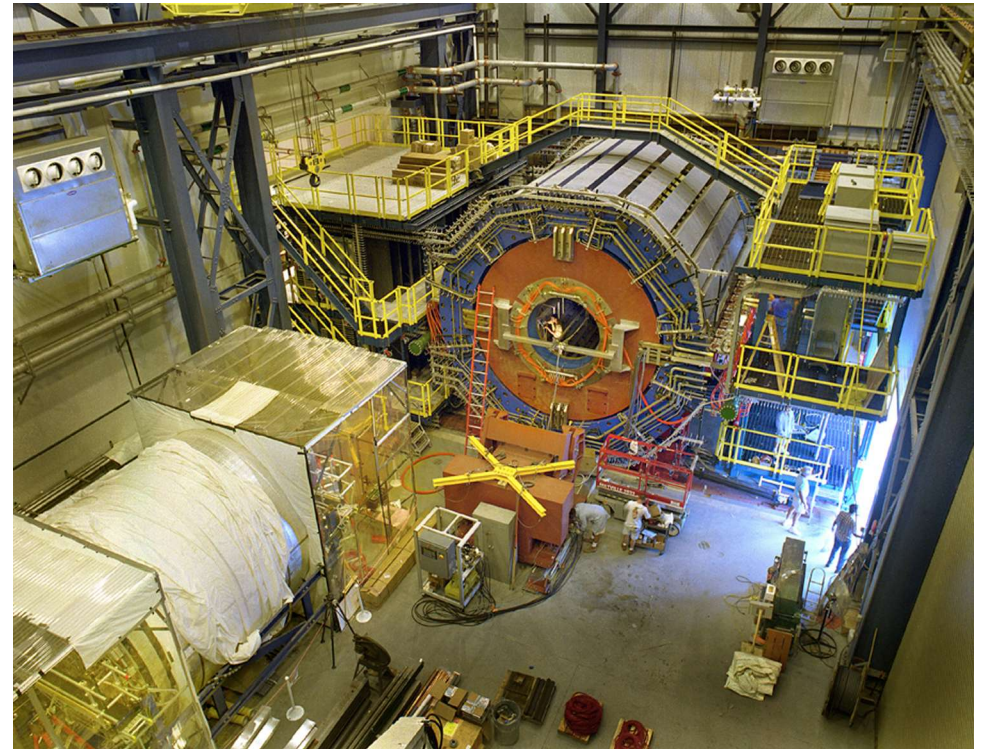
compilation: J. Stachel

RHIC experiments: 2 large and 2 small

PHENIX: central 2 arm spectrometer
plus forward/backward muon arms



STAR: large TPC at central rapidity

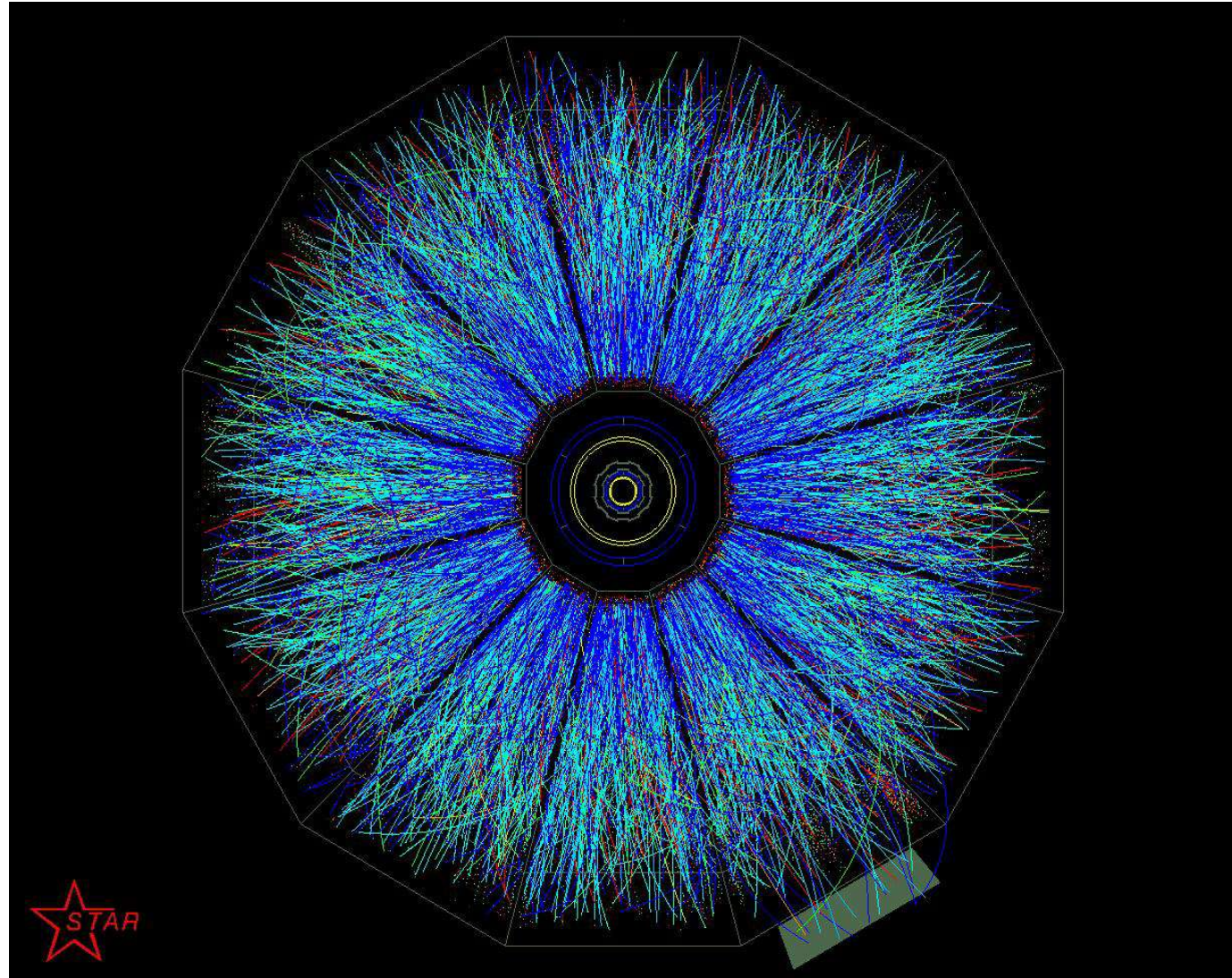


as well as **PHOBOS** and **BRAHMS** (both completed)

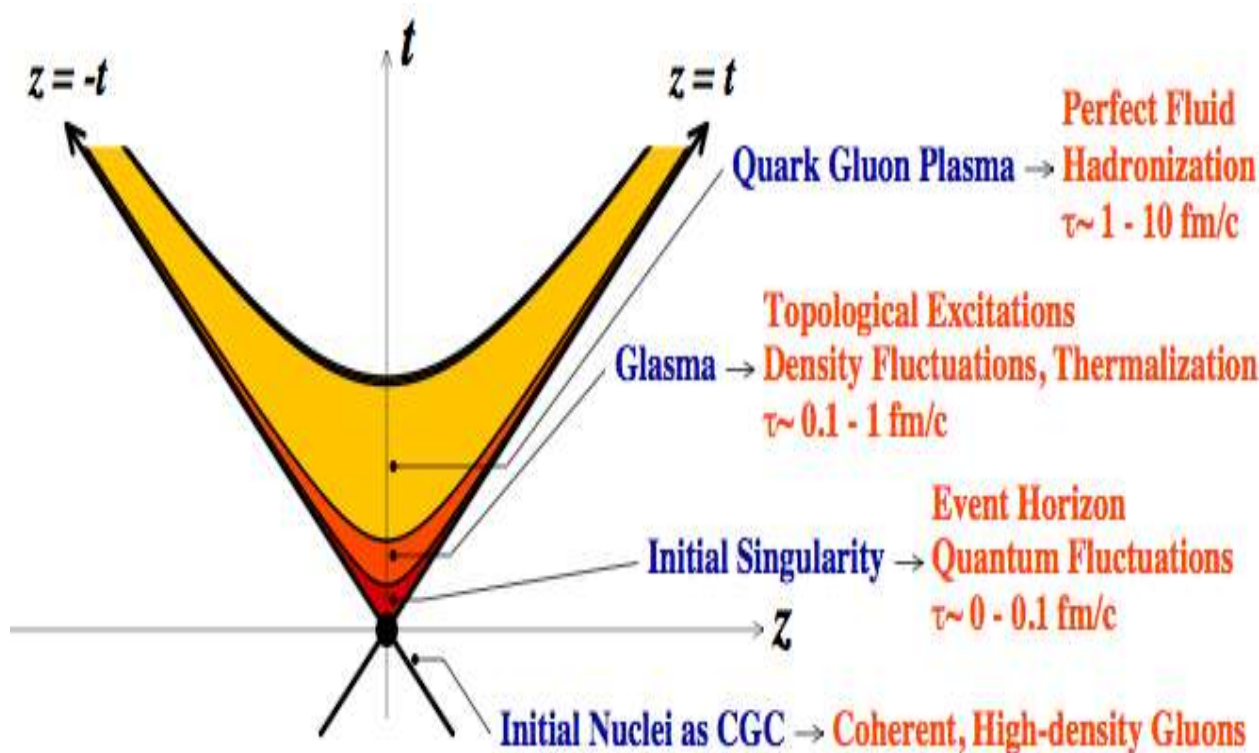
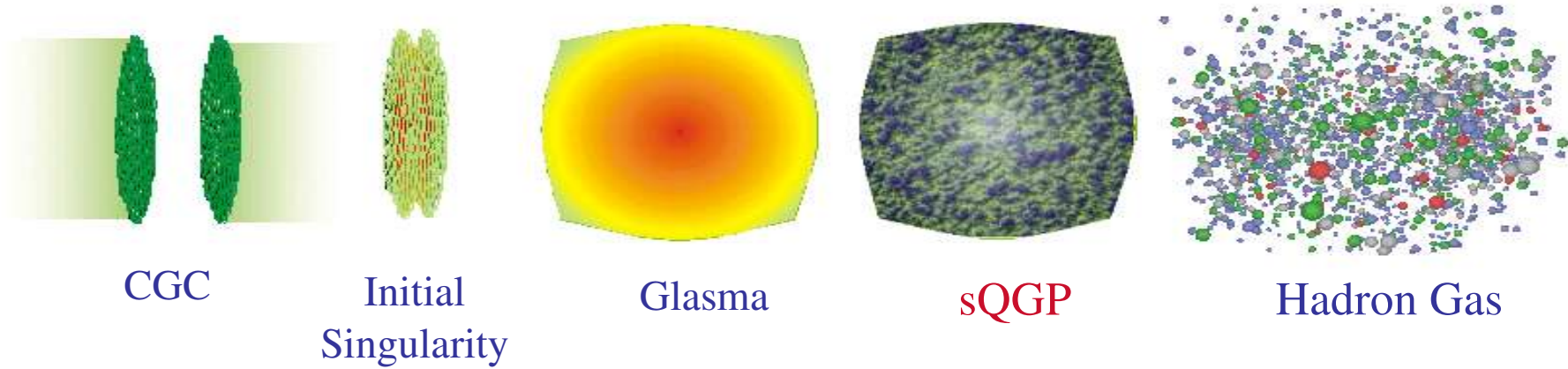
STAR event display

in central AuAu collisions
at RHIC $\sqrt{s} = 200$ GeV
about 7500 hadrons
produced (BRAHMS)

about three times as
much as at CERN SPS



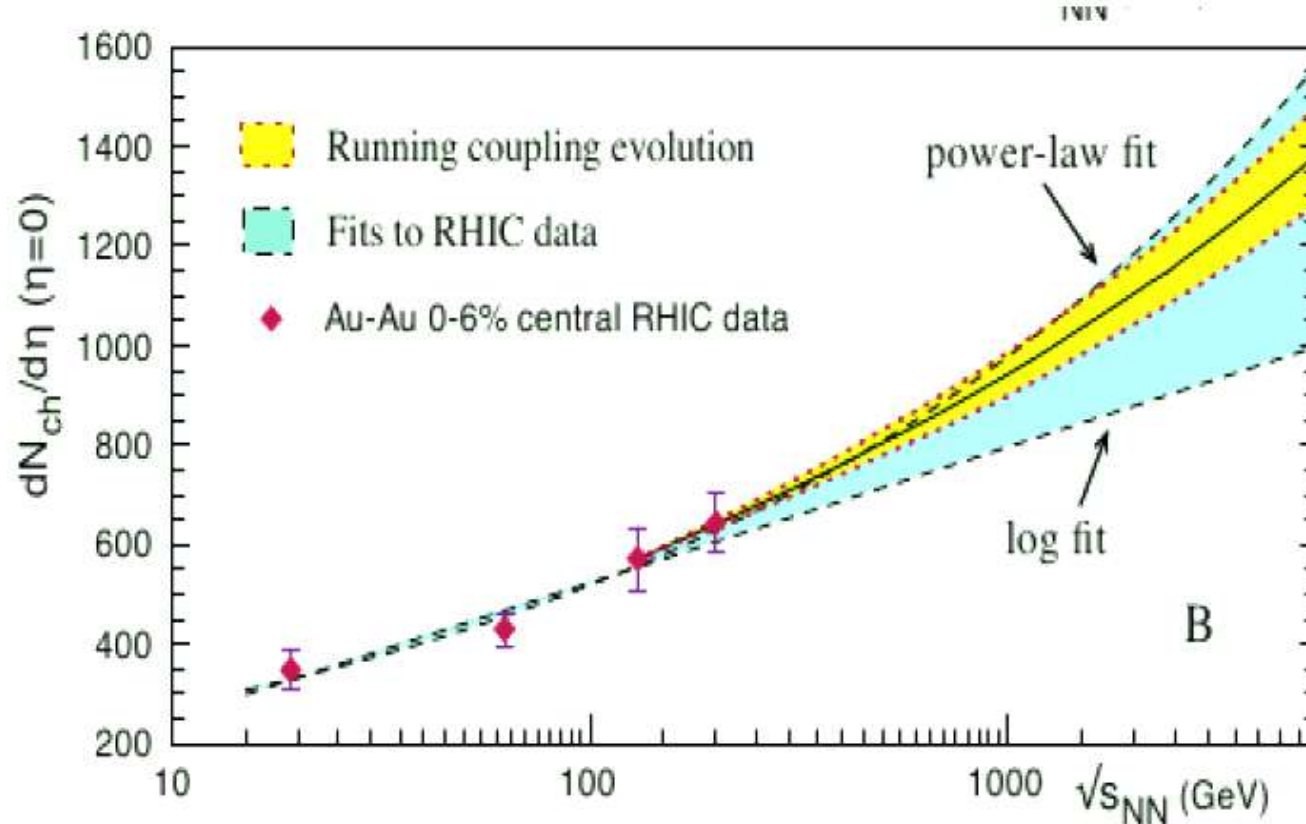
The Space-Time Evolution of a Relativistic Nuclear Collision



one possible view
(courtesy
Larry McLerran)

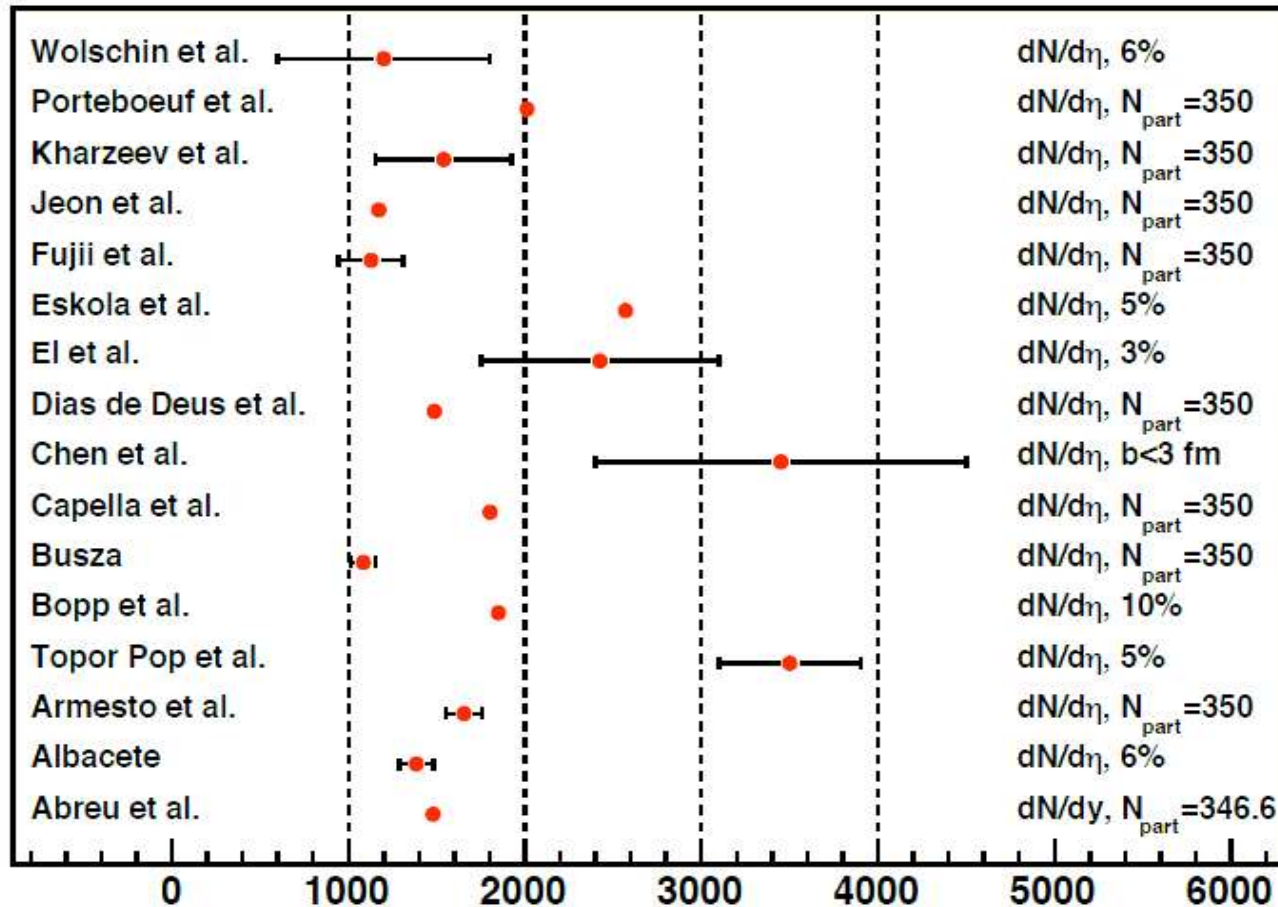
Day 1 Measurements – charged particle multiplicity

RHIC energy too low for safe extrapolation, many differing models - strongly sensitive to initial condition at LHC



differing predictions for multiplicity density

Charged multiplicity for $\eta=0$ in central Pb+Pb at $\sqrt{s_{NN}}=5.5$ TeV



compilation from: arXiv:0711.0974

Summary on particle multiplicity

**day 1 results from LHC will define the
„particle production landscape“ -> insight into
initial conditions and crucial test of different
theoretical approaches
(color glass cond., saturation, shadowing, ...)**

The fireball emits hadrons from an equilibrium state

- From AGS energy on, all hadron yields in central PbPb collisions reflect grand-canonical equilibration
- Strangeness suppression observed in elementary collisions is lifted

For a recent review see:

pbm, Stachel, Redlich,
QGP3, R. Hwa, editor,
Singapore 2004,
nucl-th/0304013

Hadro-chemistry at RHIC

All data in excellent
agreement with
thermal model
predictions

chemical freeze-out
at: $T = 165 \pm 8$ MeV

fit uses vacuum
masses

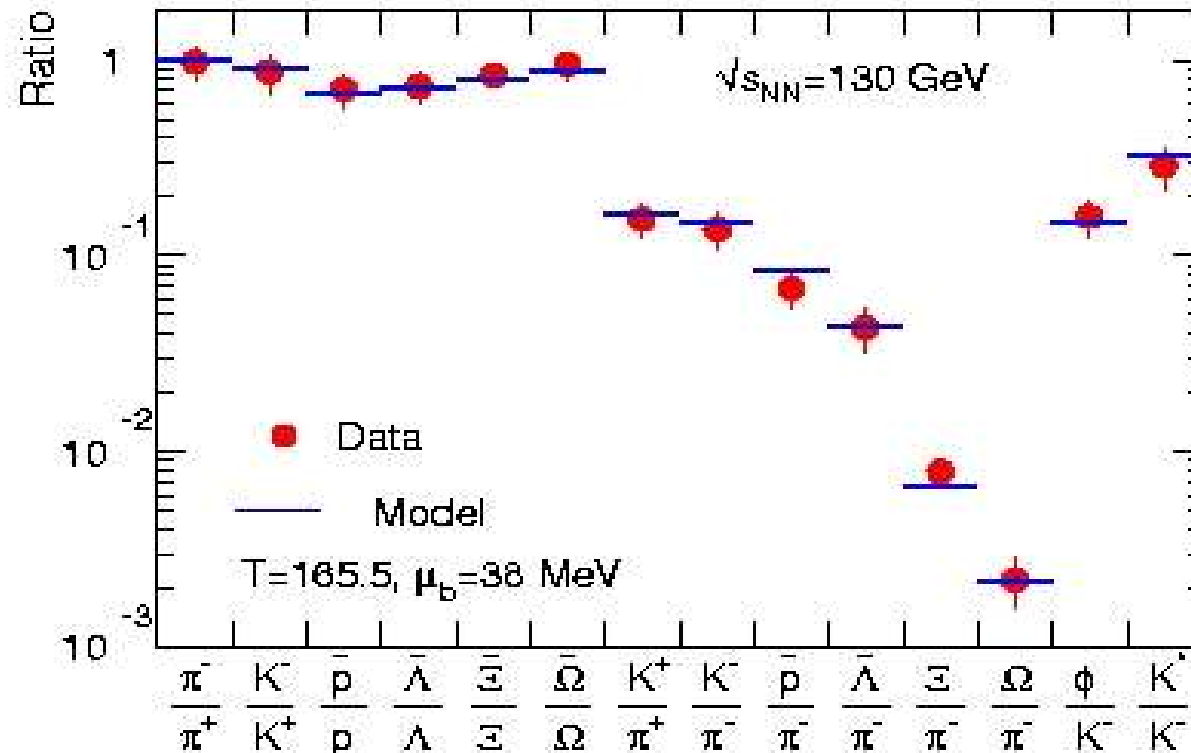
most recent analysis:

A. Andronic, pbm, J.
Stachel,

nucl-th/0511071

Nucl. Phys. A772

(2006) 167



pbm, Magestro, Stachel, Redlich, Phys. Lett. B518 (2001) 41;
see also Xu et al., Nucl. Phys. A698(2002) 306;
Becattini, J. Phys. G28 (2002) 1553;
Broniowski et al., nucl-th/0212052.

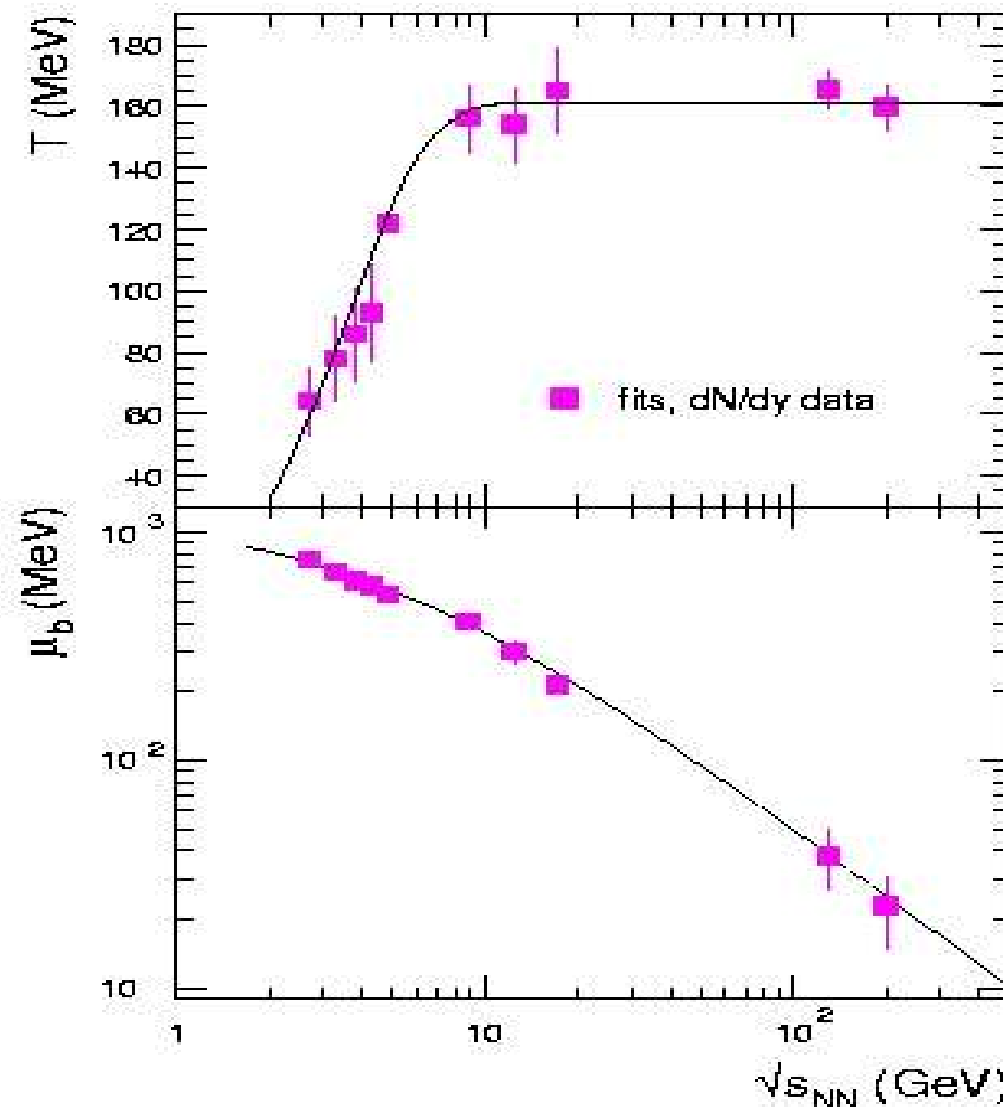
Parameterization of all freeze-out points

note: discovery of the limiting temperature

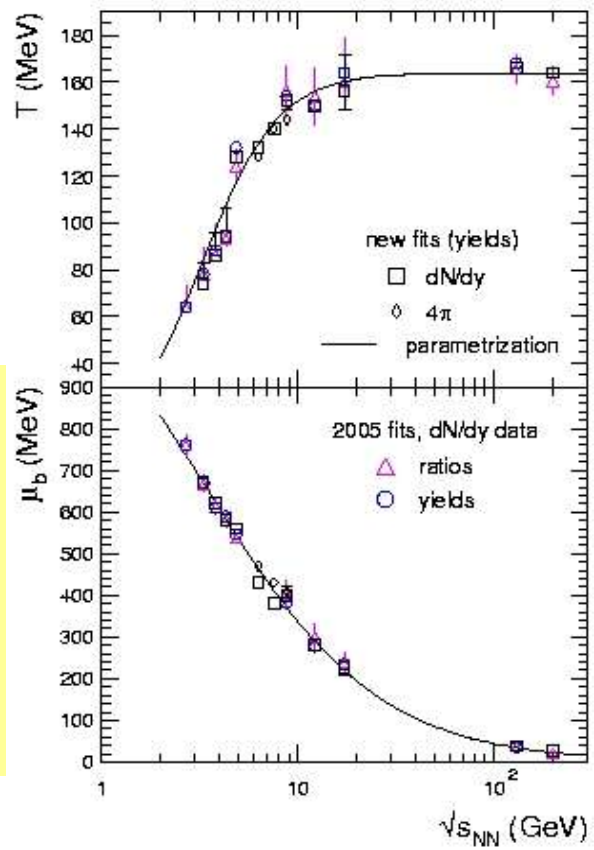
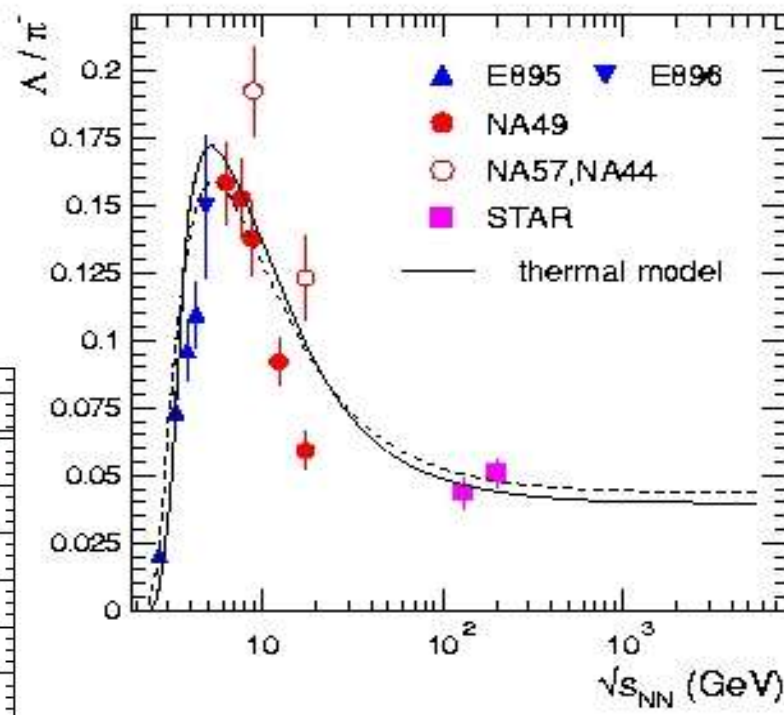
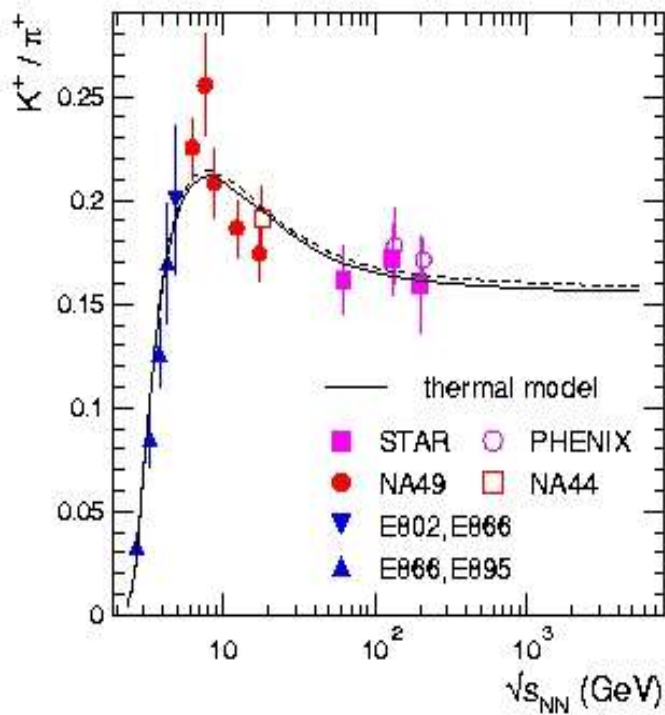
$$T_{\text{lim}} = 160 \text{ MeV}$$

provides connection to QCD phase boundary

can use parameterization to predict particle ratios at all energies



newest results: also energy dependence of 'anomalous' particle ratios (like K/pi) is reproduced



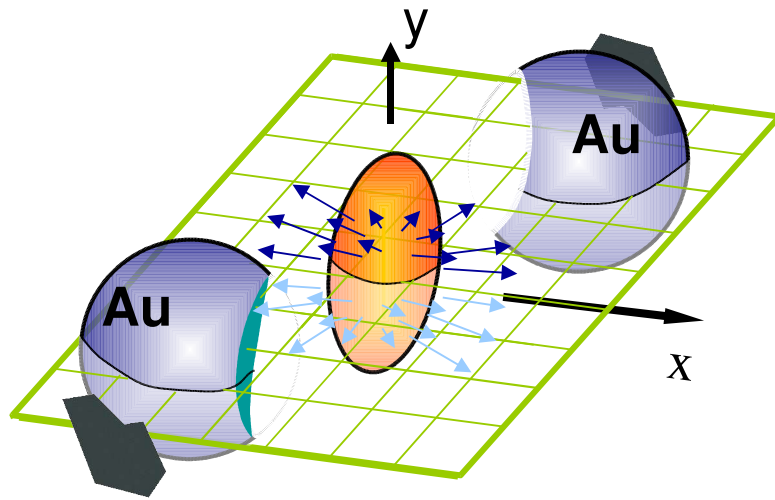
A. Andronic, pbm, J. Stachel
arXiv:0812.1186

- hadron yields quantitatively described at all energies by 3 parameters: T , μ_b , V
- limiting temperature established
- connection to QCD phase boundary

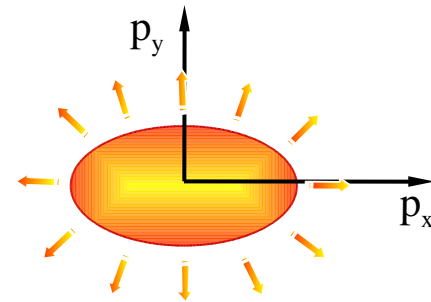
- first data from LHC will provide a crucial test of this picture: does limiting temperature picture survive a 20 fold increase in cm energy?

anything else would be a major surprize
already day 1 data from LHC will be decisive

The fireball expands collectively like an ideal fluid



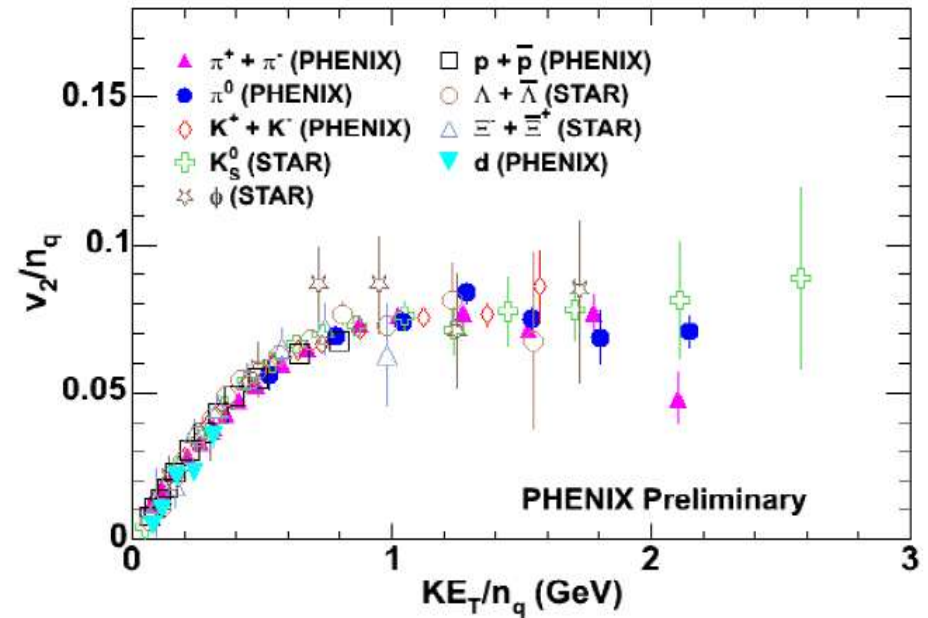
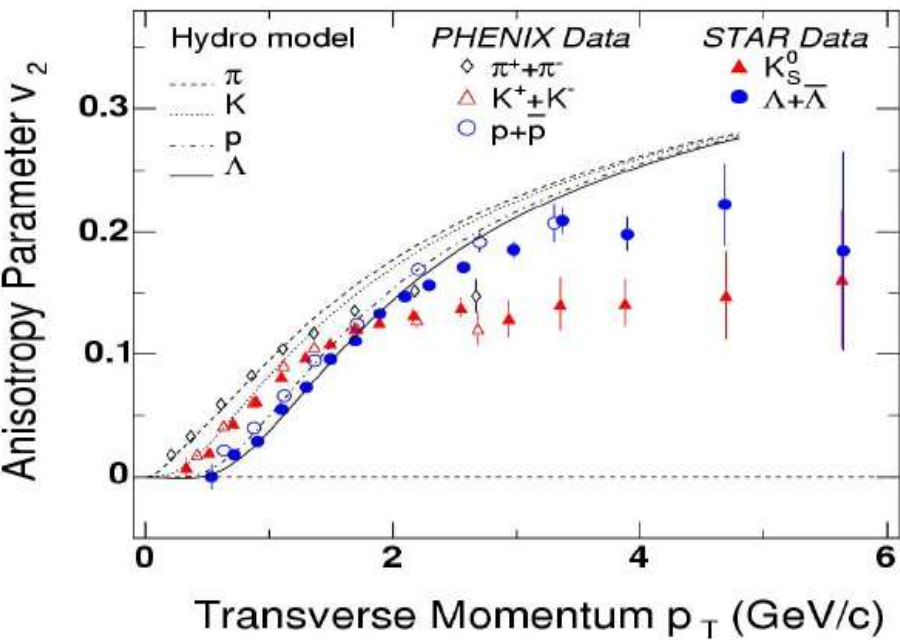
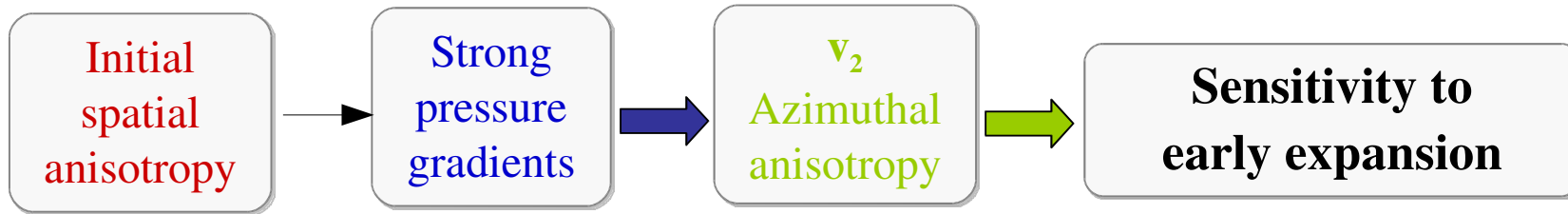
momentum space



$$dN/d\phi = 1 + 2 V_2 \cos 2 (\phi - \psi) + \dots$$

hydrodynamic flow characterized by azimuthal anisotropy coefficient v_2

Elliptic Flow Results from RHIC

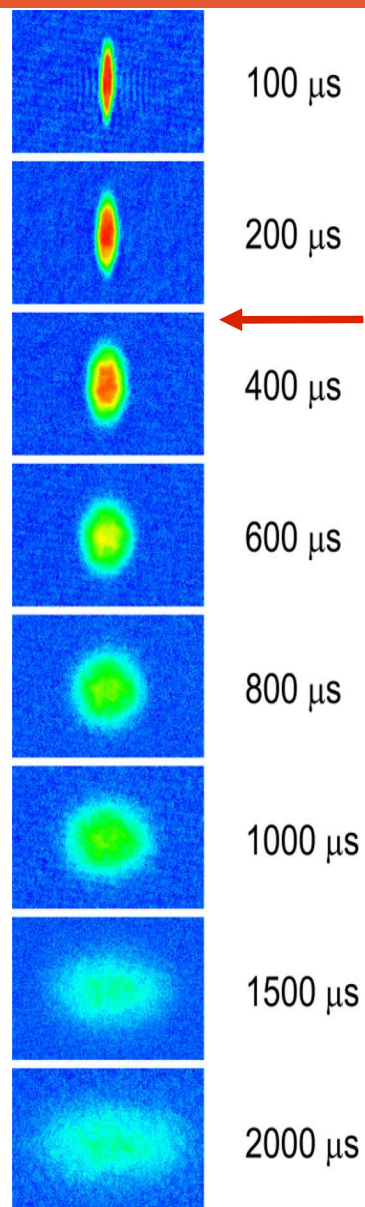


shear viscosity/entropy
close to theoretical
(AdS/CFT) limit
 $\eta/s = 1/(4\pi)$

note the peculiar quark scaling!

ideal hydro calculations
reproduce also the
observed mass ordering
but fail in detail

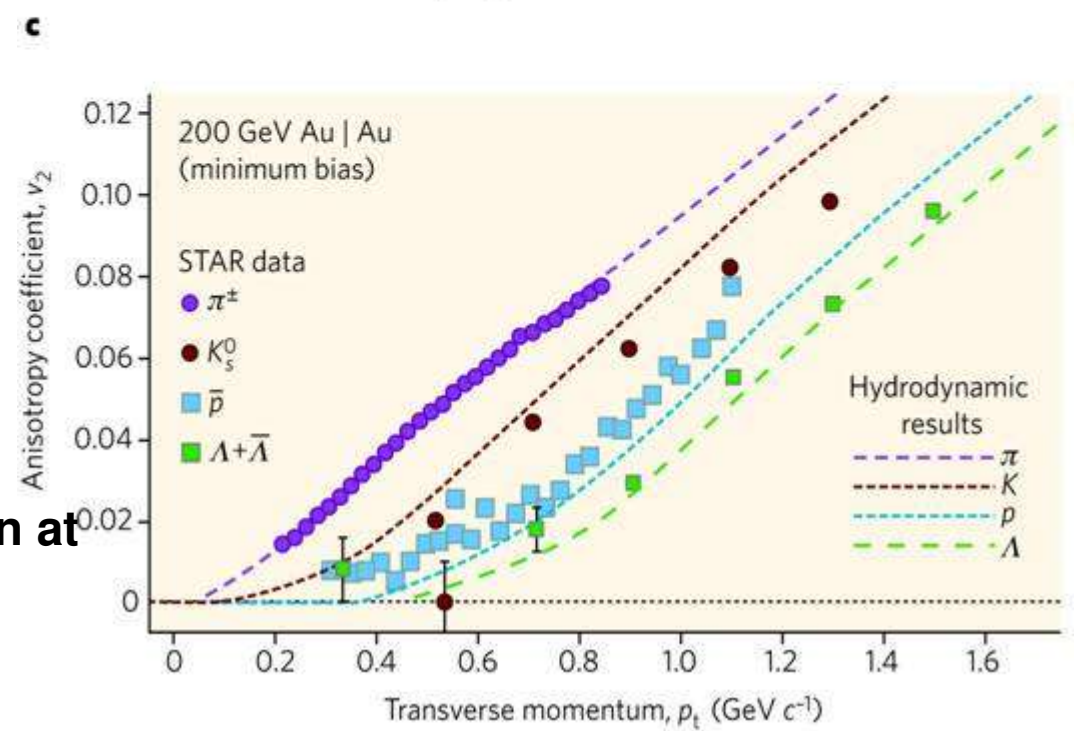
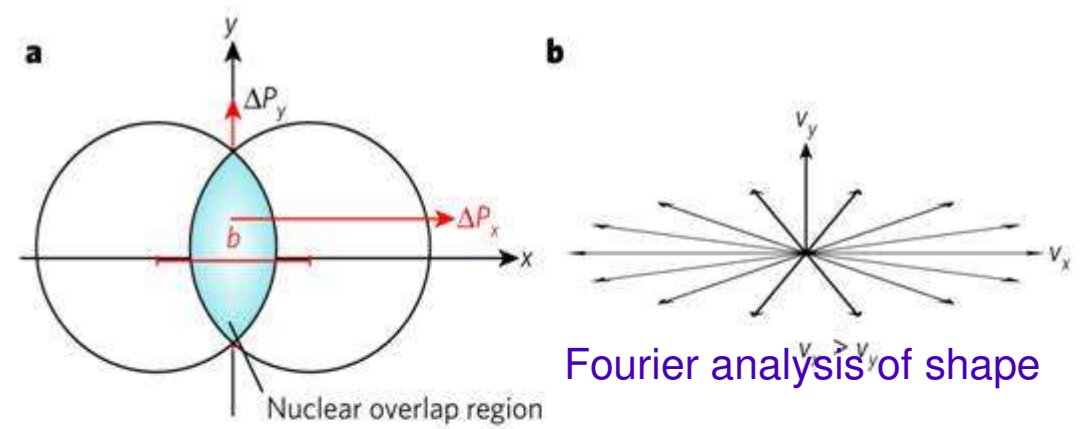
QGP and Ultra-cold Quantum Gases



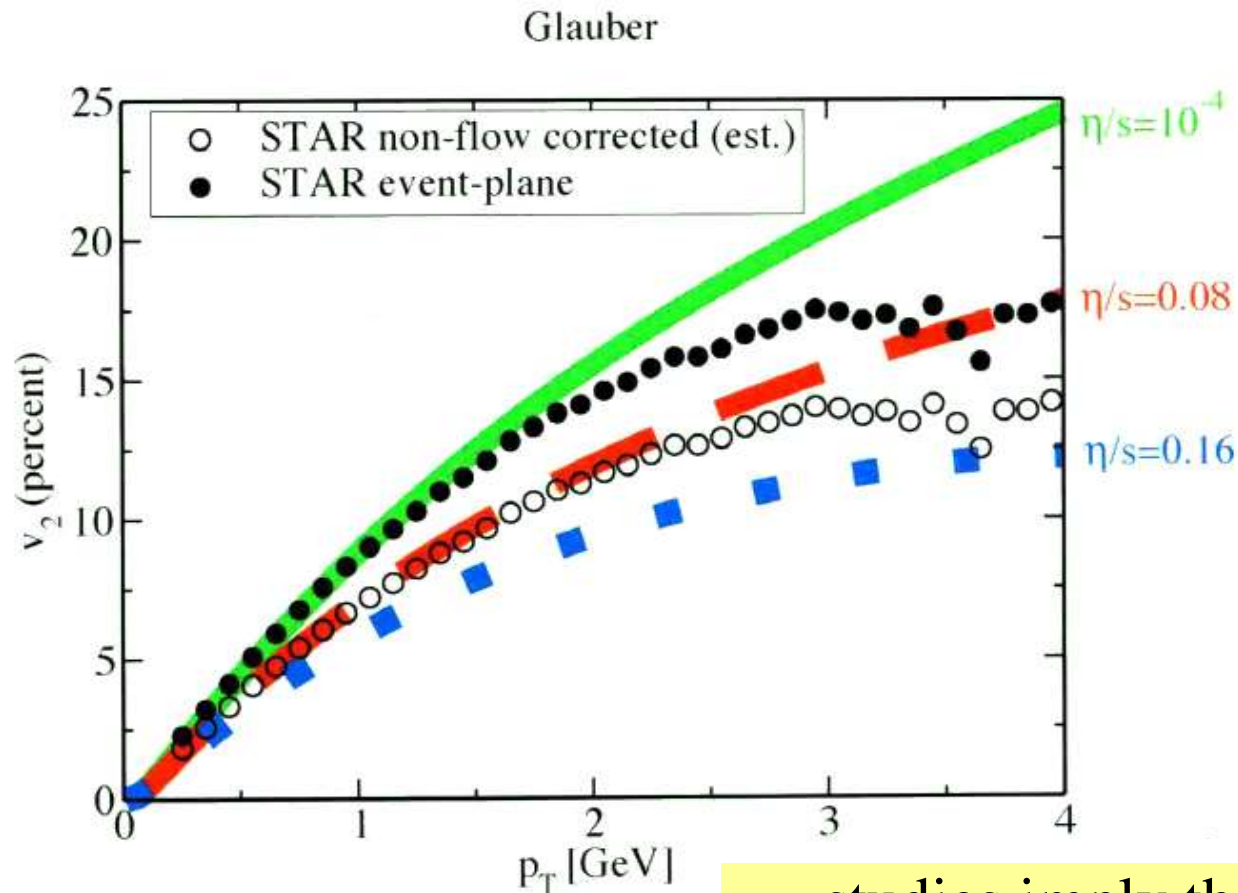
ultra-cold ${}^6\text{Li}$
10 nK
 $\sim 10^{-12}$ eV

QGP
2.1 TK
 $\sim 10^8$ eV

collective expansion at
strong coupling



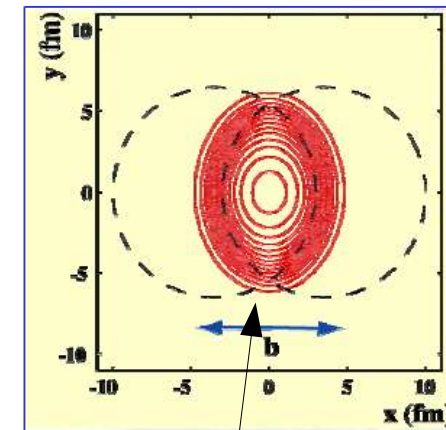
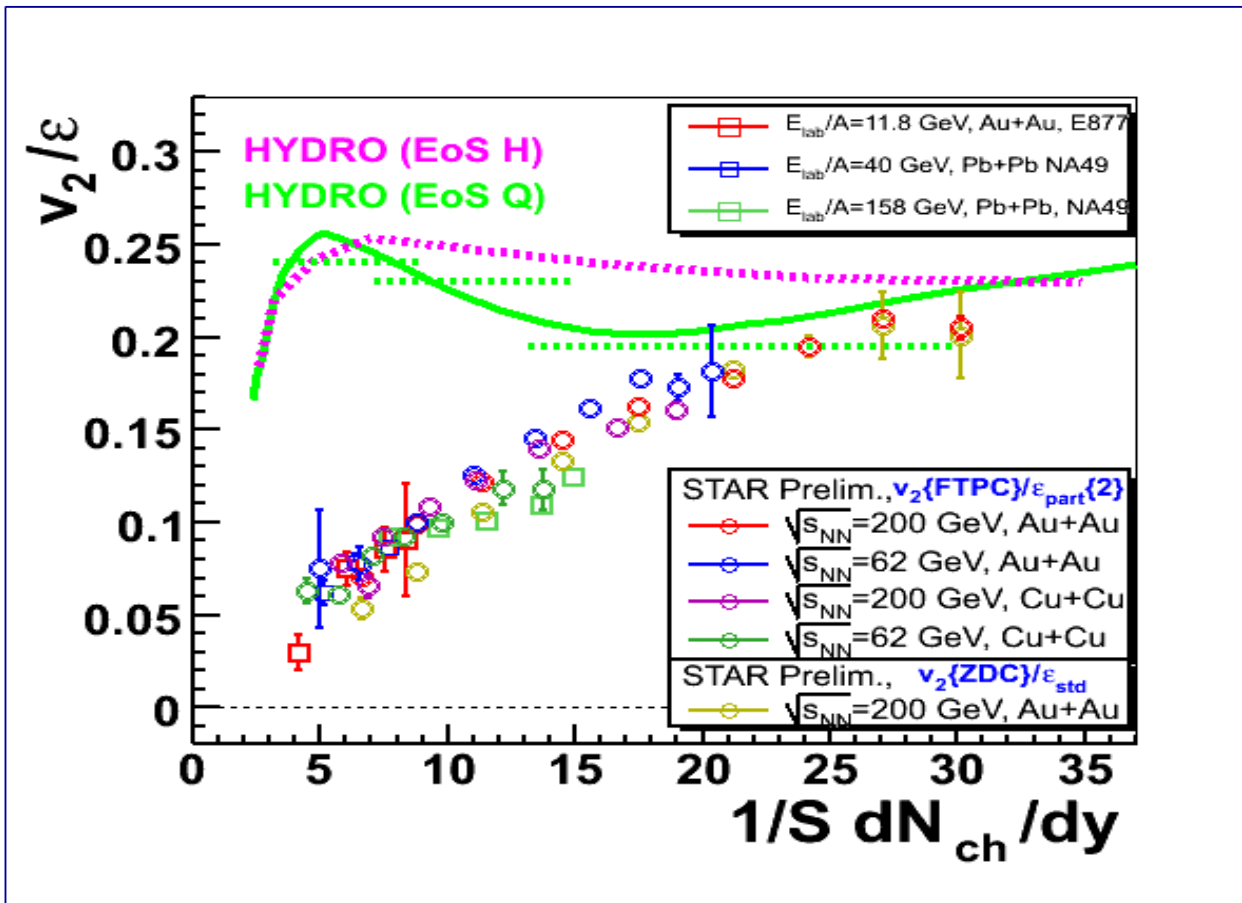
exploring the importance of viscous effects



calculations by Paul Romatschke

studies imply that
 $\eta/s > (2 \cdot \text{AdS/CFT limit})$
not compatible with data

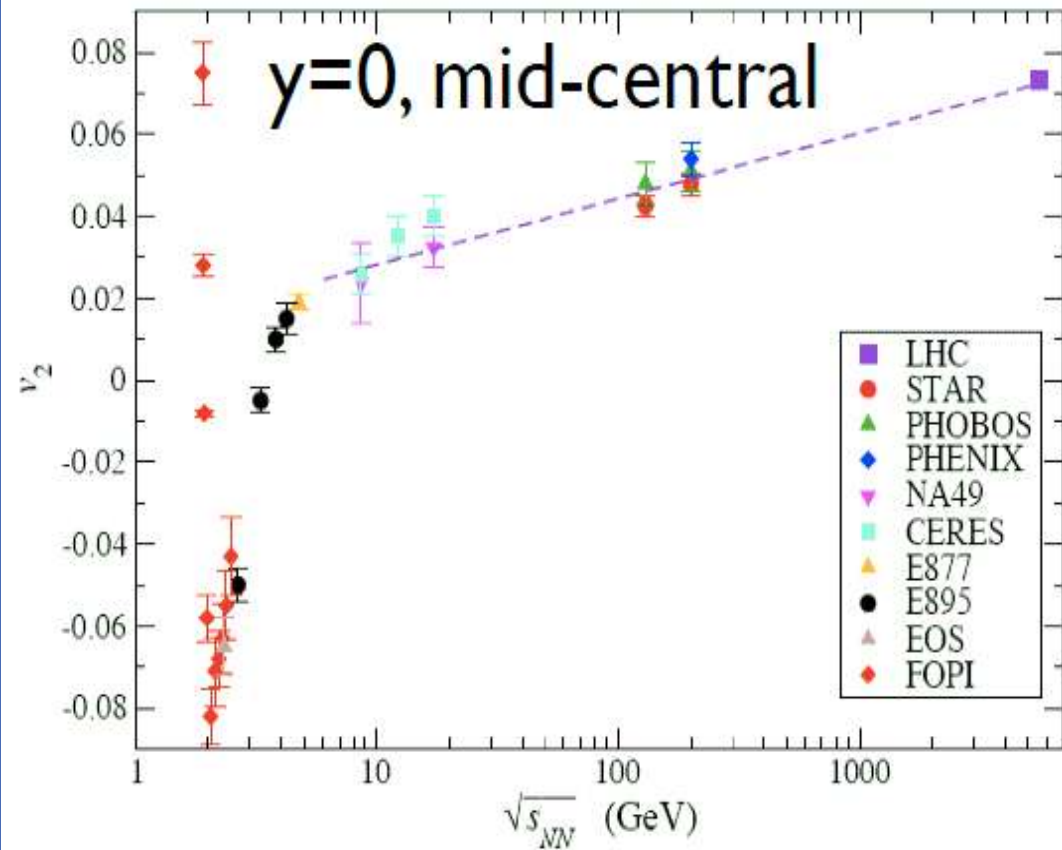
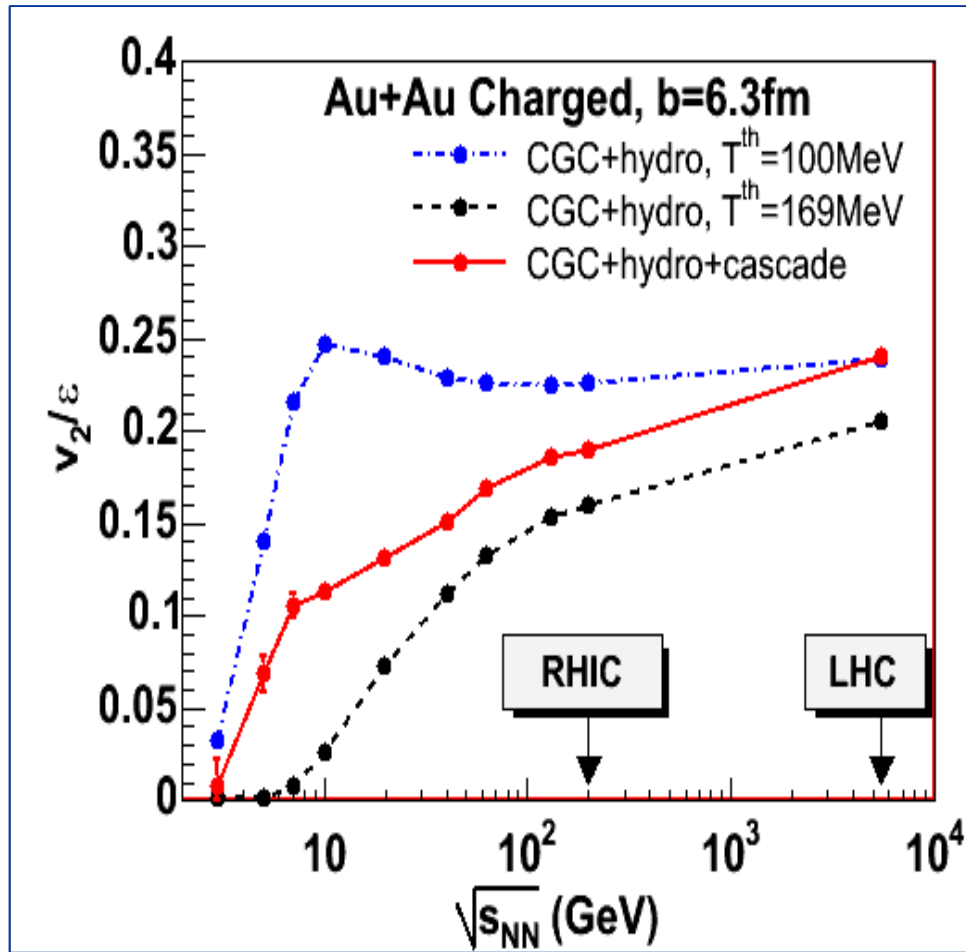
summary of all existing data



note: the initial eccentricity must be computed in a model

$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

extrapolations to LHC

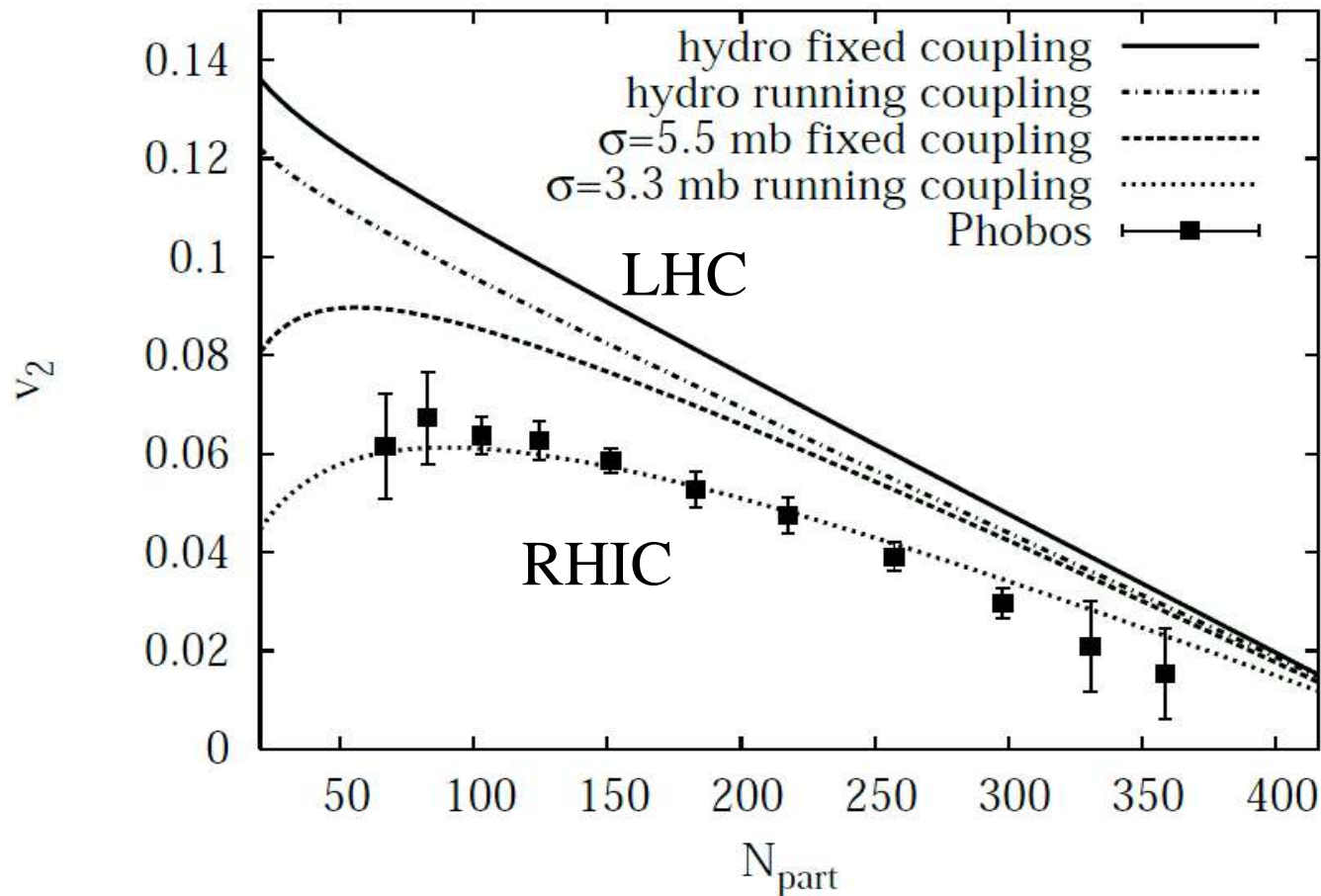


evolution of flow in a simple scaling model

v_2 scales with eccentricity ϵ , Knudsen number K describes deviation from ideal hydro, where $K=0$

J.Y. Ollitrault et al, arXiv:0711.0974

$$v_2 = \frac{h\epsilon}{1 + K/0.7}, \quad \frac{1}{K} = \frac{\sigma}{S} \frac{dN}{dy} \frac{1}{\sqrt{3}}$$



$K(\text{RHIC}) = 0.55$

expect:

$K(\text{LHC}) < 0.3$

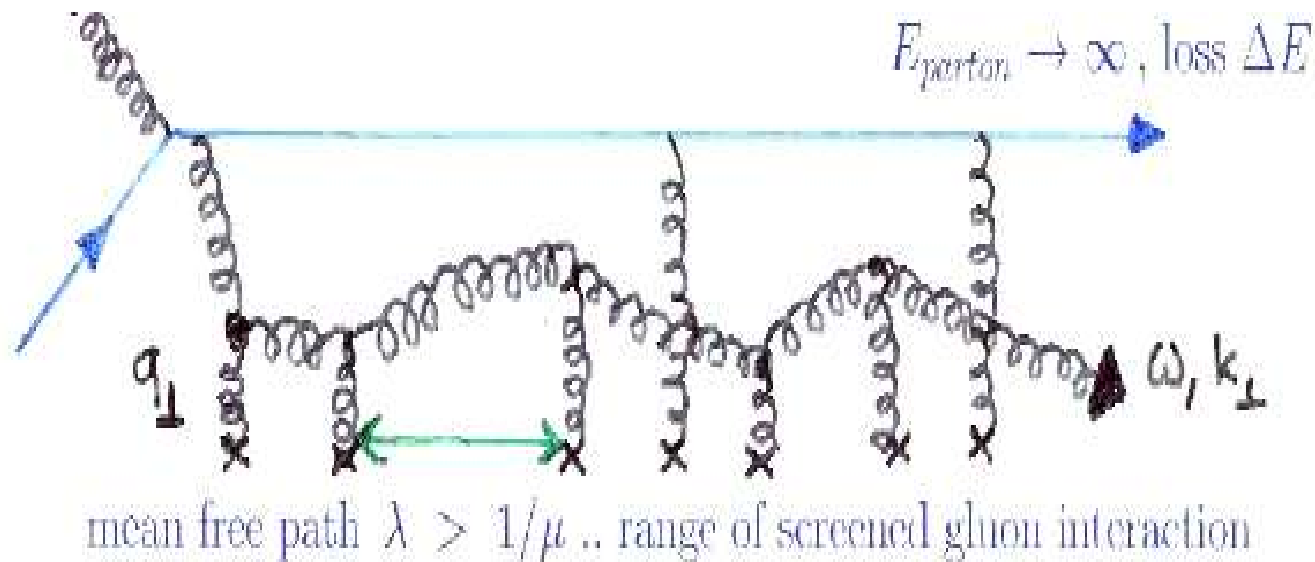
important test of ideal fluid scenario and temperature dependent shear viscosity

- spectra and flow well explained by ideal hydrodynamics calculations
- viscosity/entropy density close to AdS/CFT limit
- is hydro limit reached at RHIC, will it be „exceeded at LHC“?
- is viscosity only low near phase boundary?
- is quark scaling universal?

day 1 results from LHC will be decisive

The fireball is opaque for high momentum partons

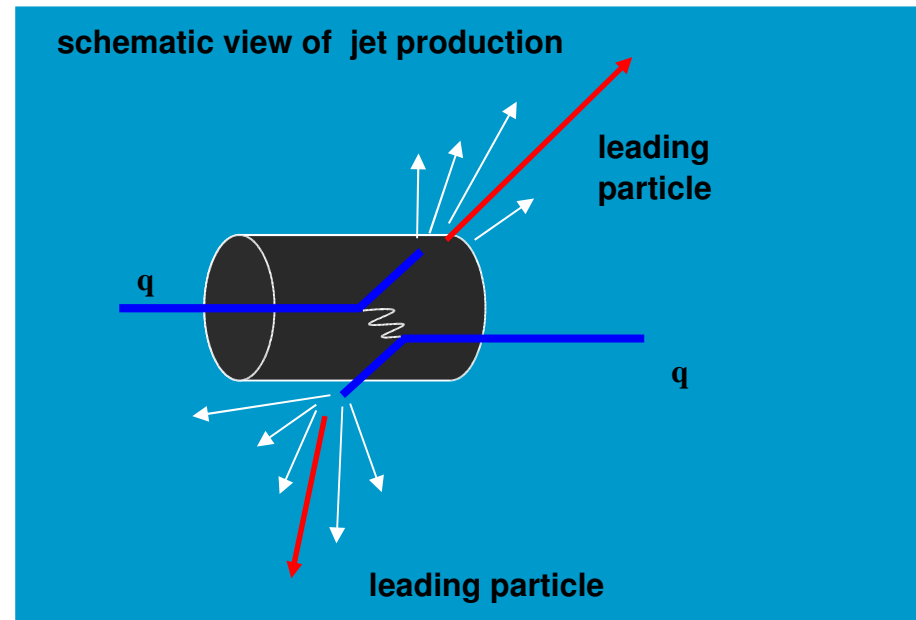
- suppression of high p_t particles in AA relative to pp collisions
- disappearance of jet-like correlations
- connected to large gluon density in hot (QGP) fireball



schematic picture of energy loss of a fast parton

Jet quenching

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



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

- momentum reduction (fewer high p_T particles in jet)
- no jet partner on other side

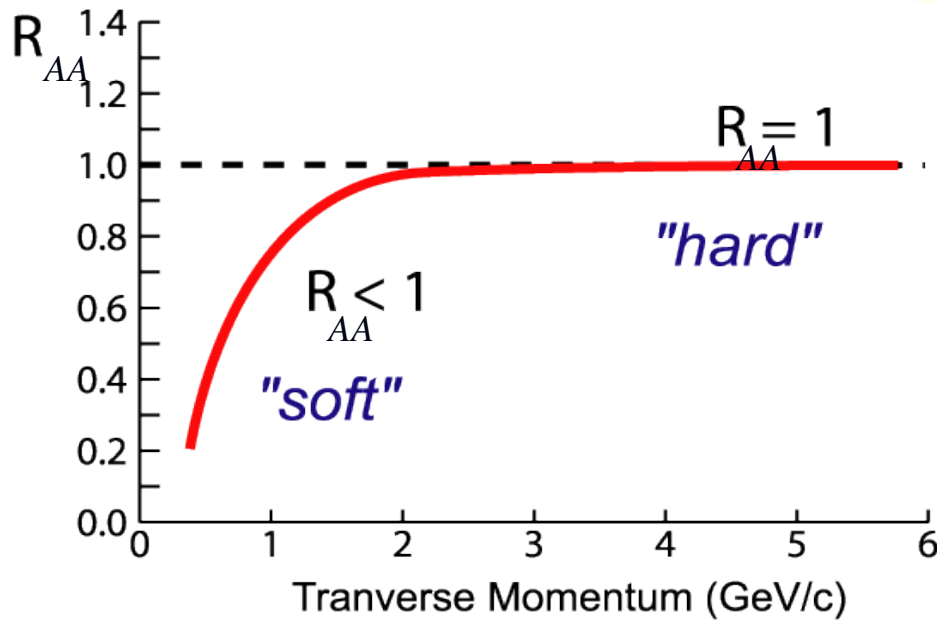
Jet Quenching

Definition of R_{AA}

$R_{AA} = \text{medium/vacuum}$

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

$$\langle N_{\text{binary}} \rangle / \sigma_{\text{inel}}^{p+p}$$



no medium effects:

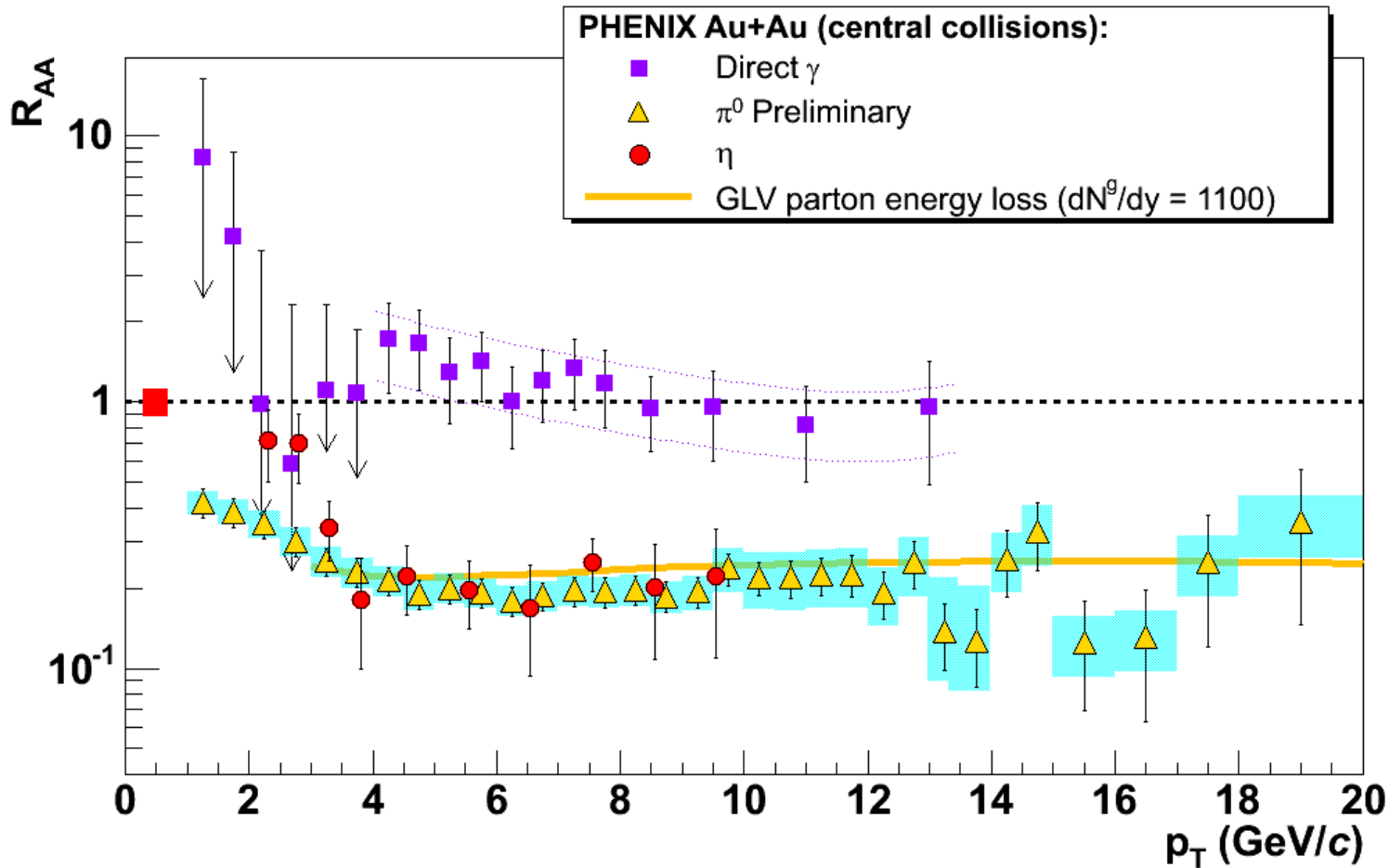
$R_{AA} < 1$ in regime of soft physics

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

Suppression:

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

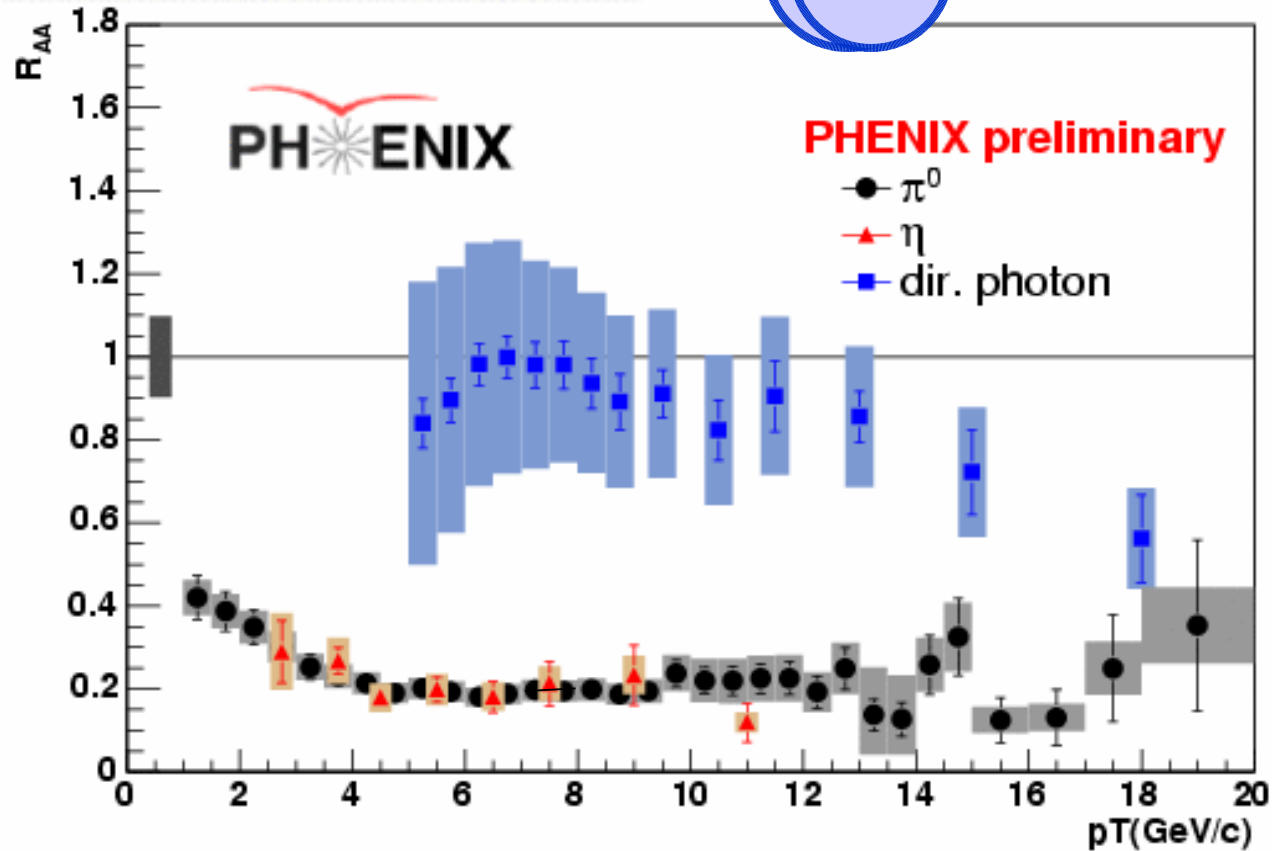
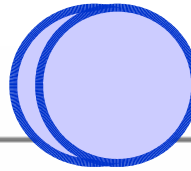
Leading hadrons and hard photons



- Direct photons are not suppressed, follow pQCD predictions.
- Common suppression for π^0 and η .
- $\varepsilon > 15 \text{ GeV}/\text{fm}^3$; $dN_g/dy > 1100$

but what about photons at very large p_t ?

Au+Au $\sqrt{s_{NN}} = 200\text{GeV}$, 0-10%



elucidation is LHC territory

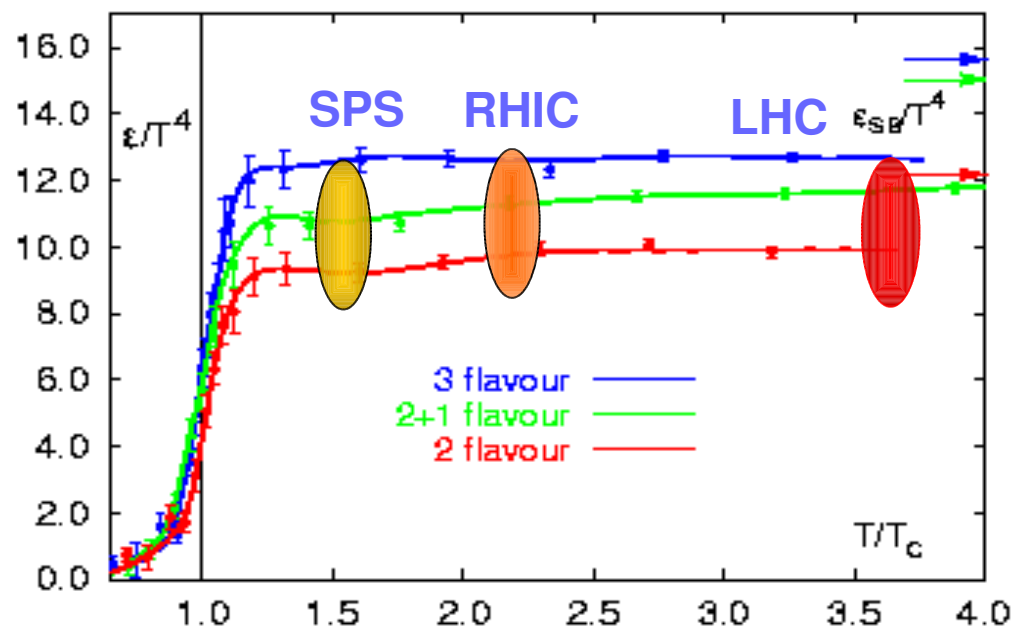
$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d\eta}{T_{AA} d^2 \sigma^{NN} / dp_T d\eta}$$

jet quenching indicative of gluon rapidity density

	$\tau_0 [fm]$	$T [MeV]$	$\epsilon [GeV / fm^3]$	$\tau_{tot} [fm]$	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

- Estimates consistent with hydrodynamic analysis

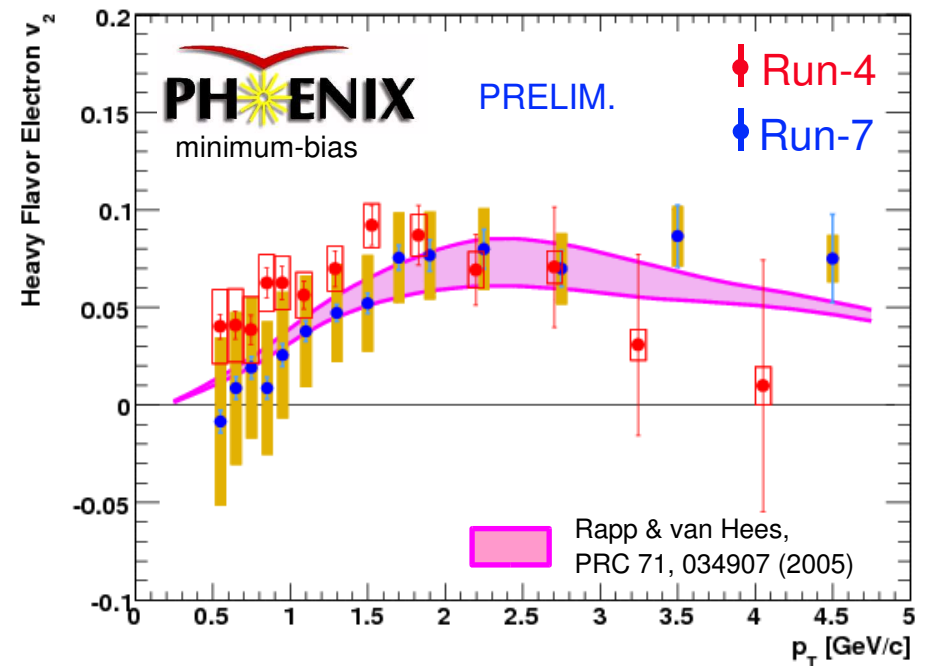
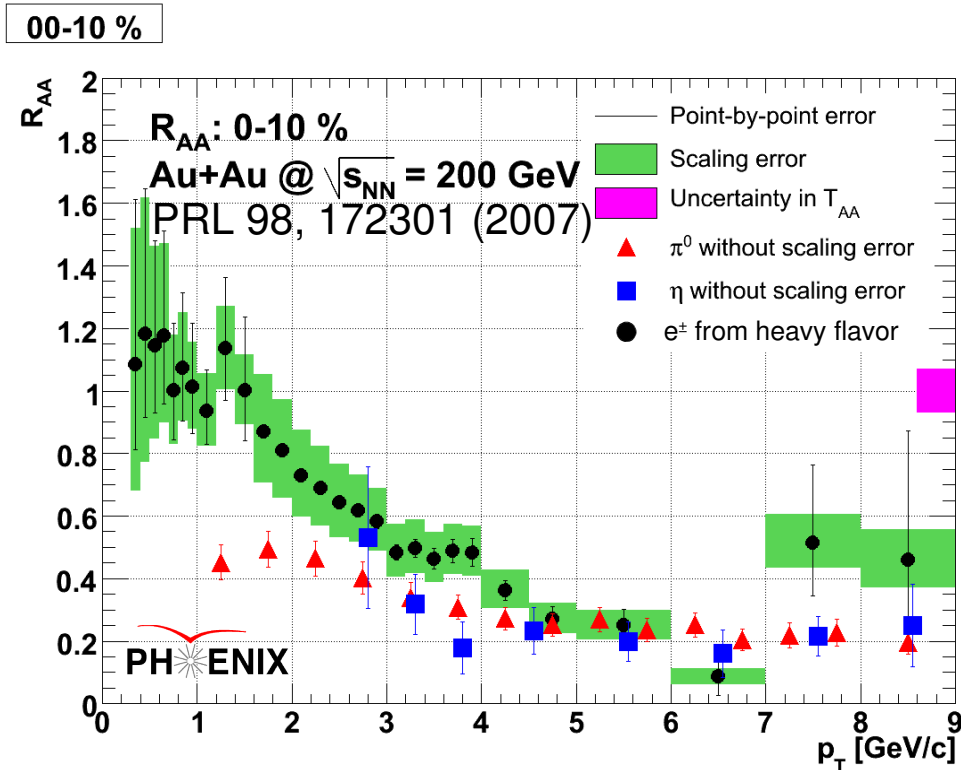


further big surprize at RHIC: strong energy loss of heavy quarks

electrons from heavy flavor mesons

strong energy loss

hydrodynamic flow

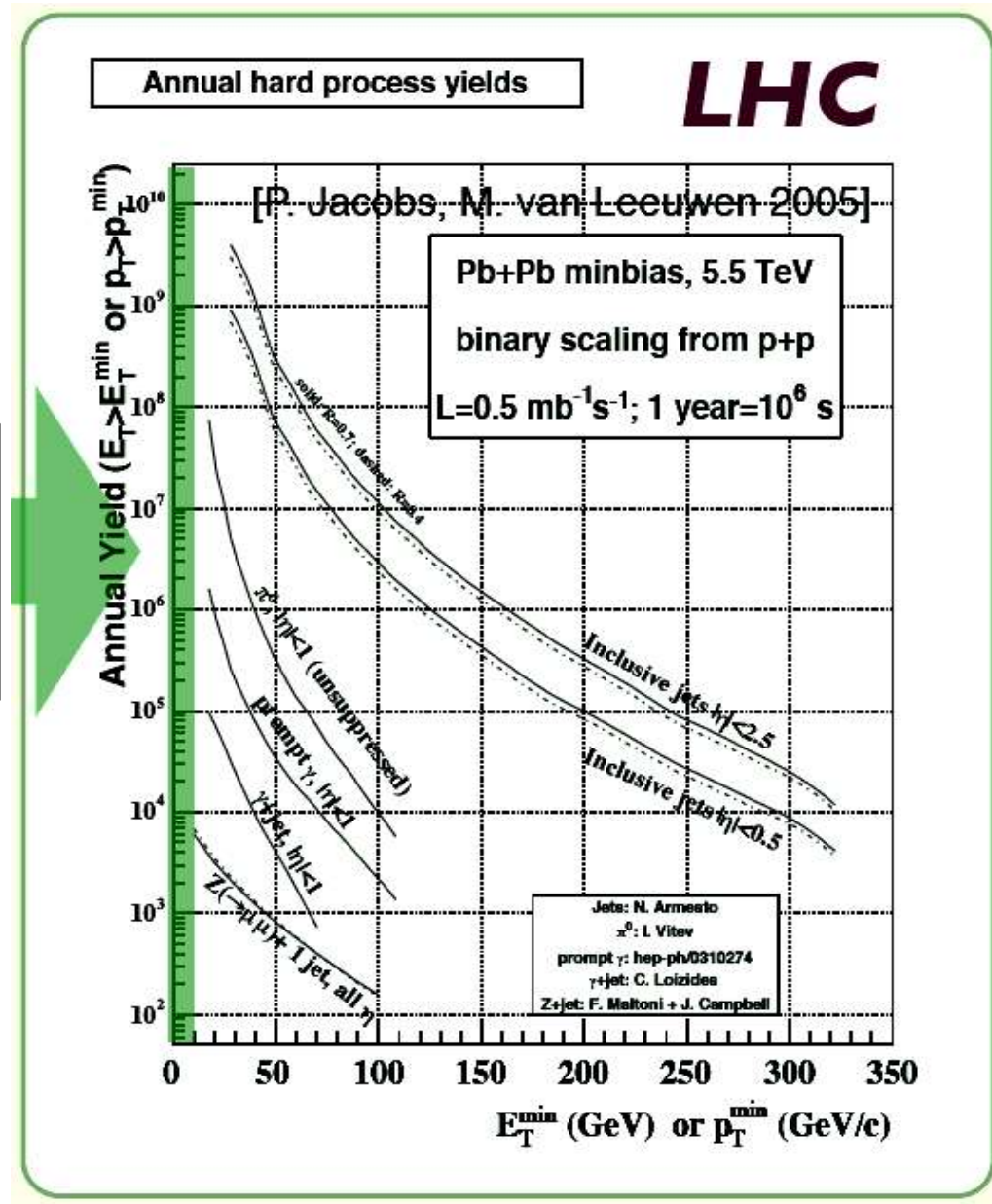


these data are not well explained, measure heavy quarks „directly“ at LHC

the ultimate hard probes machine

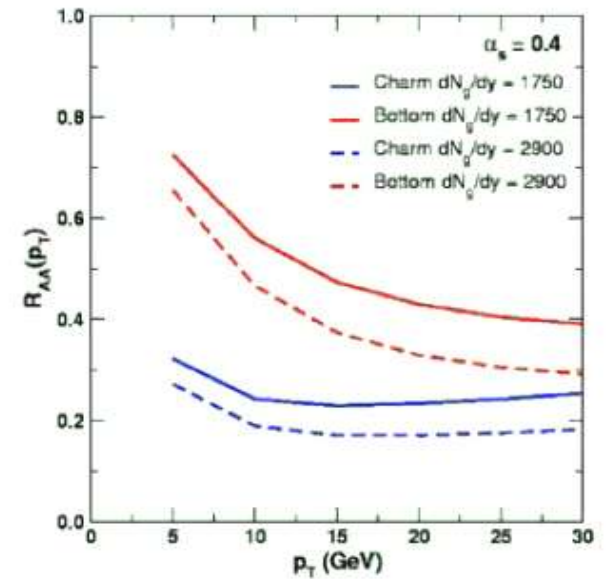
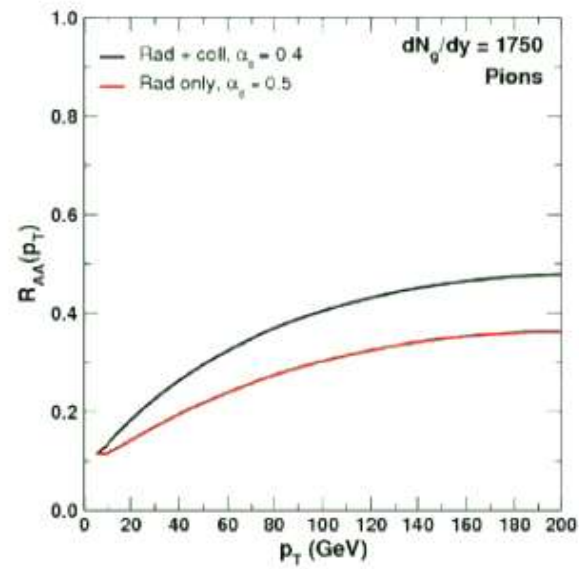
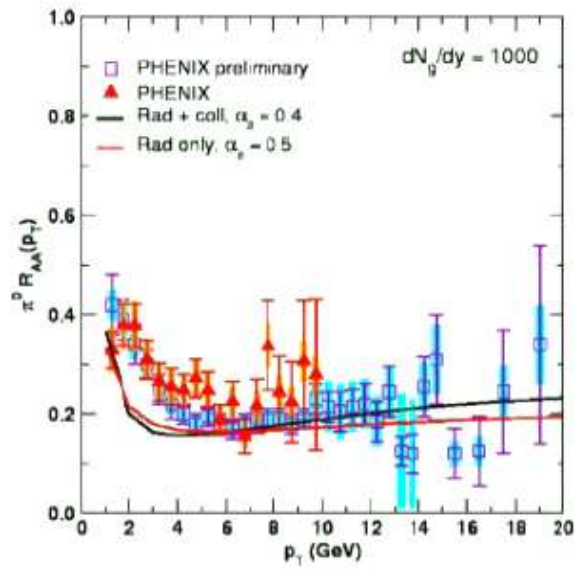
covered
at RHIC

$> 10^4$ jets with
 $E_T > 150$ GeV
in one month of
PbPb collisions at LHC



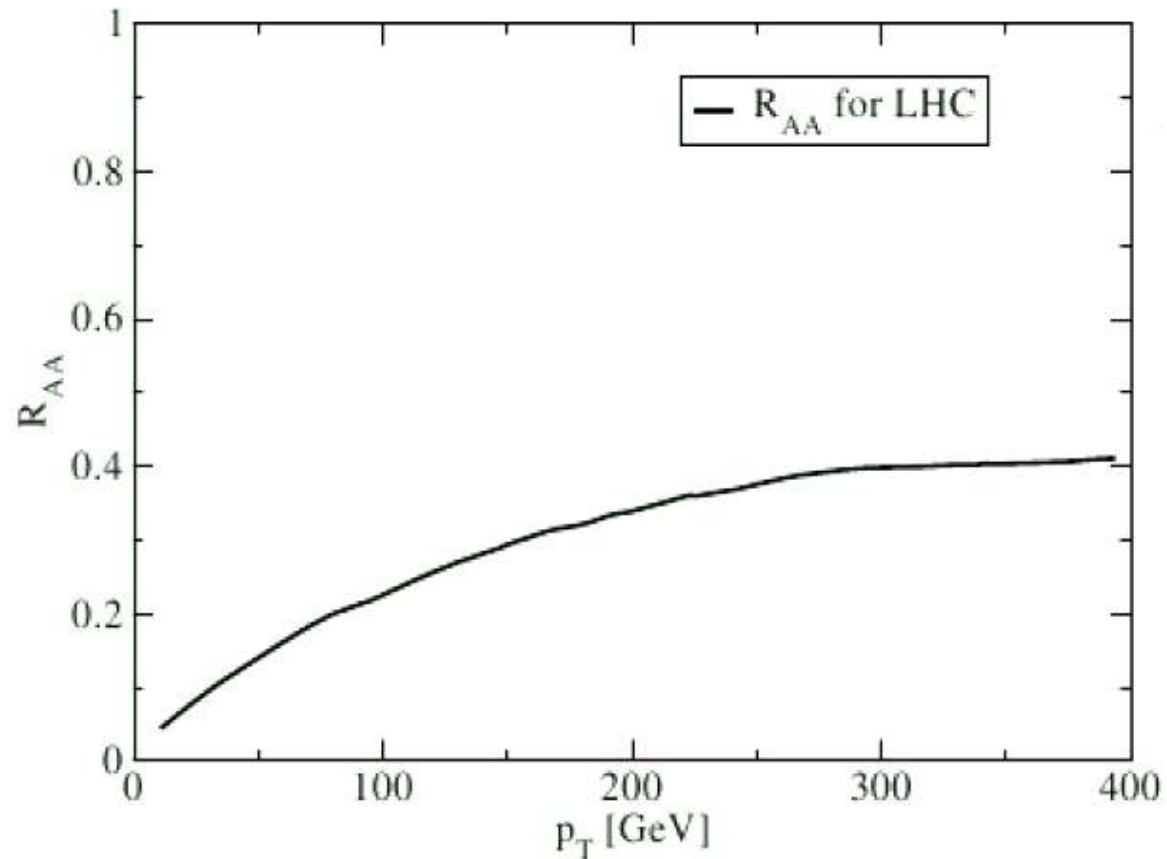
Predictions for jet quenching at LHC

S. Wicks and M. Gyulassy



more predictions...

Renk and Eskola

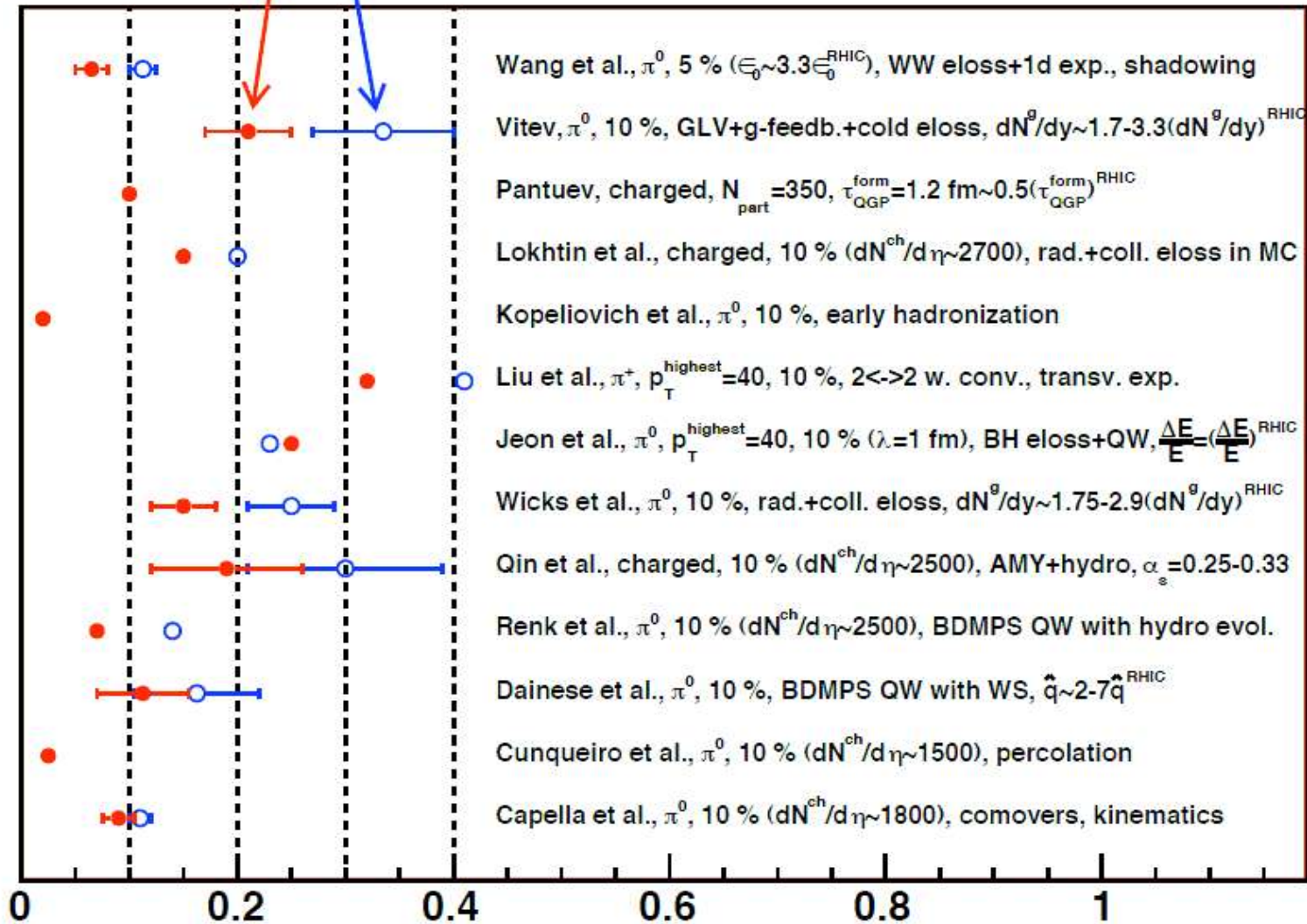


connection
to AdS/CFT
considerations?

important: perturbative QCD regime may never be reached!

synopsis of jet quenching predictions for LHC energy

$R_{PbPb}(p_T=20,50 \text{ GeV}, \eta=0)$ in central Pb+Pb at $\sqrt{s_{NN}}=5.5 \text{ TeV}$



- for $p_t > 3$ GeV hadron production is strongly suppressed compared to pQCD expectations
- only viable explanation: large energy loss of fast partons in fireball
- even heavy quarks lose large amount of energy
- both gluon radiation and collisional energy loss seem important but no unique theoretical description of RHIC data

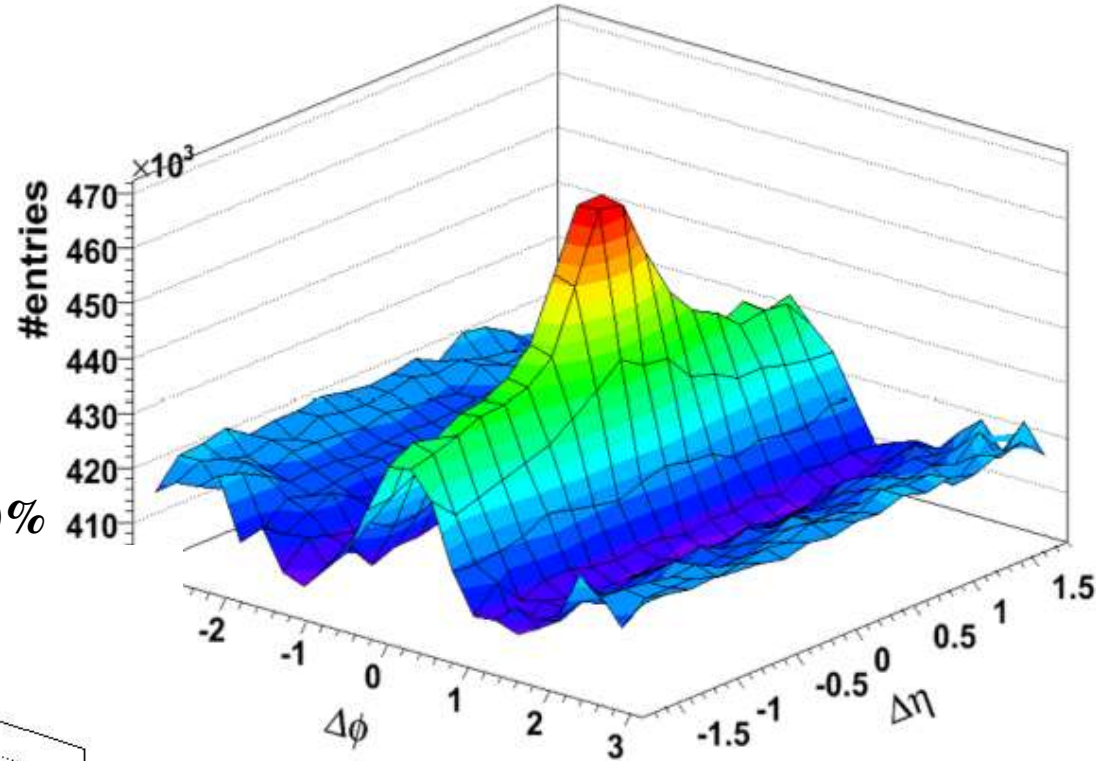
first month of LHC data with p_t reach up to 50 GeV will bring
decisive new insights

Another provocative issue: Long range rapidity correlations (the ridge)

where can correlations over >4 units of rapidity come from?

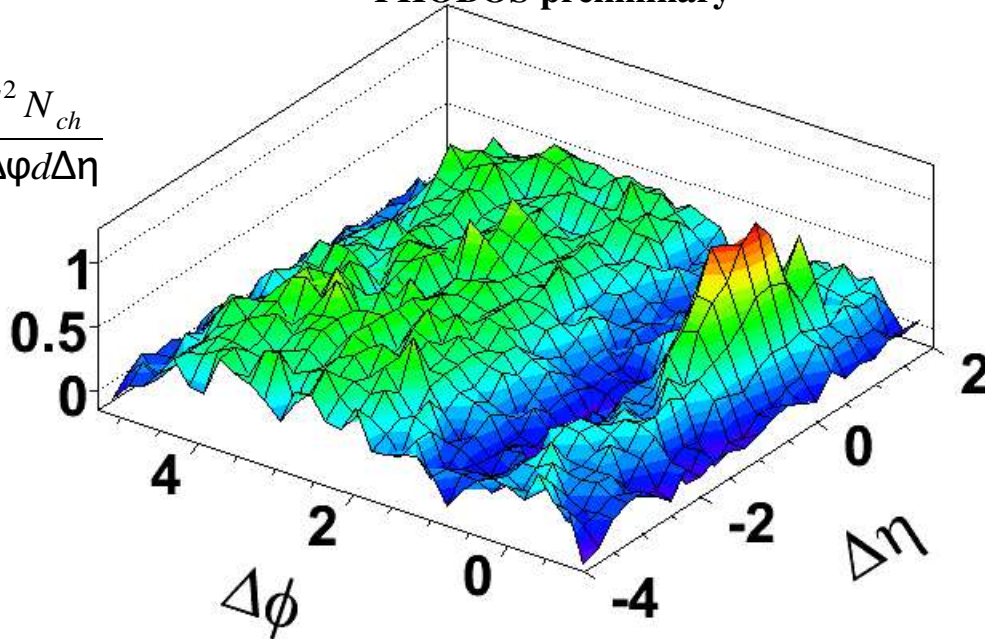
very early collision phase?
color glass?

STAR AuAu



Au+Au 200 GeV, 0 - 30%
PHOBOS preliminary

$$\frac{1}{N_{trig}} \frac{d^2 N_{ch}}{d\Delta\phi d\Delta\eta}$$



LHC to shed light on this

The fireballs modifies charmonium production

Charmonium as a probe for the properties of the QGP

the main idea: implant charmonia into the QGP and observe their modification, in terms of suppressed (or enhanced) production in nucleus-nucleus collisions with or without plasma formation

original proposal: H. Satz and T. Matsui, Phys. Lett. B178 (1986) 416

assumptions:

- **all** charmonia are produced before QGP formation
- suppression takes place in QGP
- some charmonia might survive beyond T_c

→ sequential suppression pattern due to feeding

Review of results from RHIC

new aspects compared to SPS results

- absolute normalization of yields
- rapidity dependence
- comparison to results from pp collisions

Definition of Modification of Charmonium in the Fireball

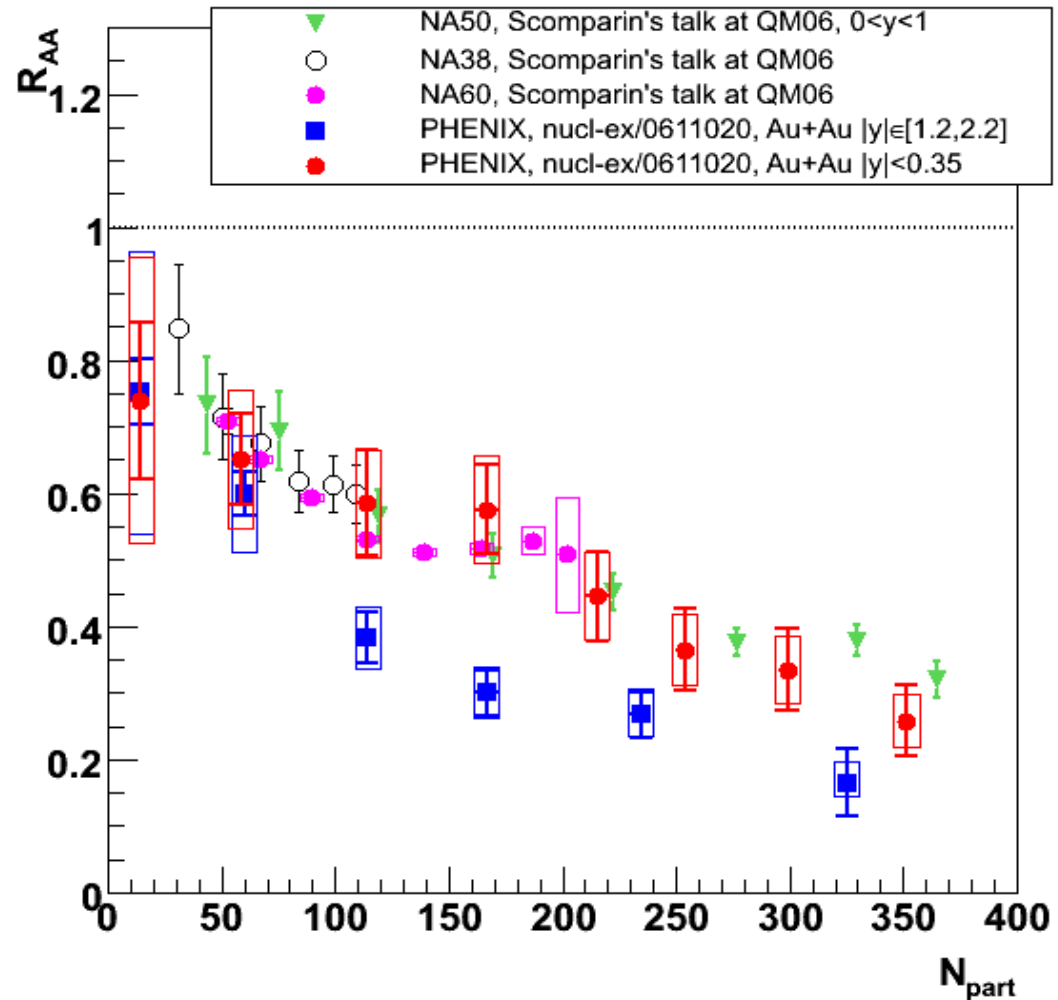
use R_{AA} to define charmonium modification experimentally
no need to normalize to Drell-Yan process

$$R_{AA}^{J/\psi} = \frac{dN_{J/\psi}^{AuAu} / dy}{N_{coll} \cdot dN_{J/\psi}^{pp} / dy}$$

if $\sigma_{\text{Drell-Yan}} \propto N_{\text{coll}}$, R_{AA} is equivalent to NA50 definition, except for 'cold nuclear matter' effects

Comparison of RHIC and SPS Results

surprize:
no energy dependence
but unexpected
rapidity dependence

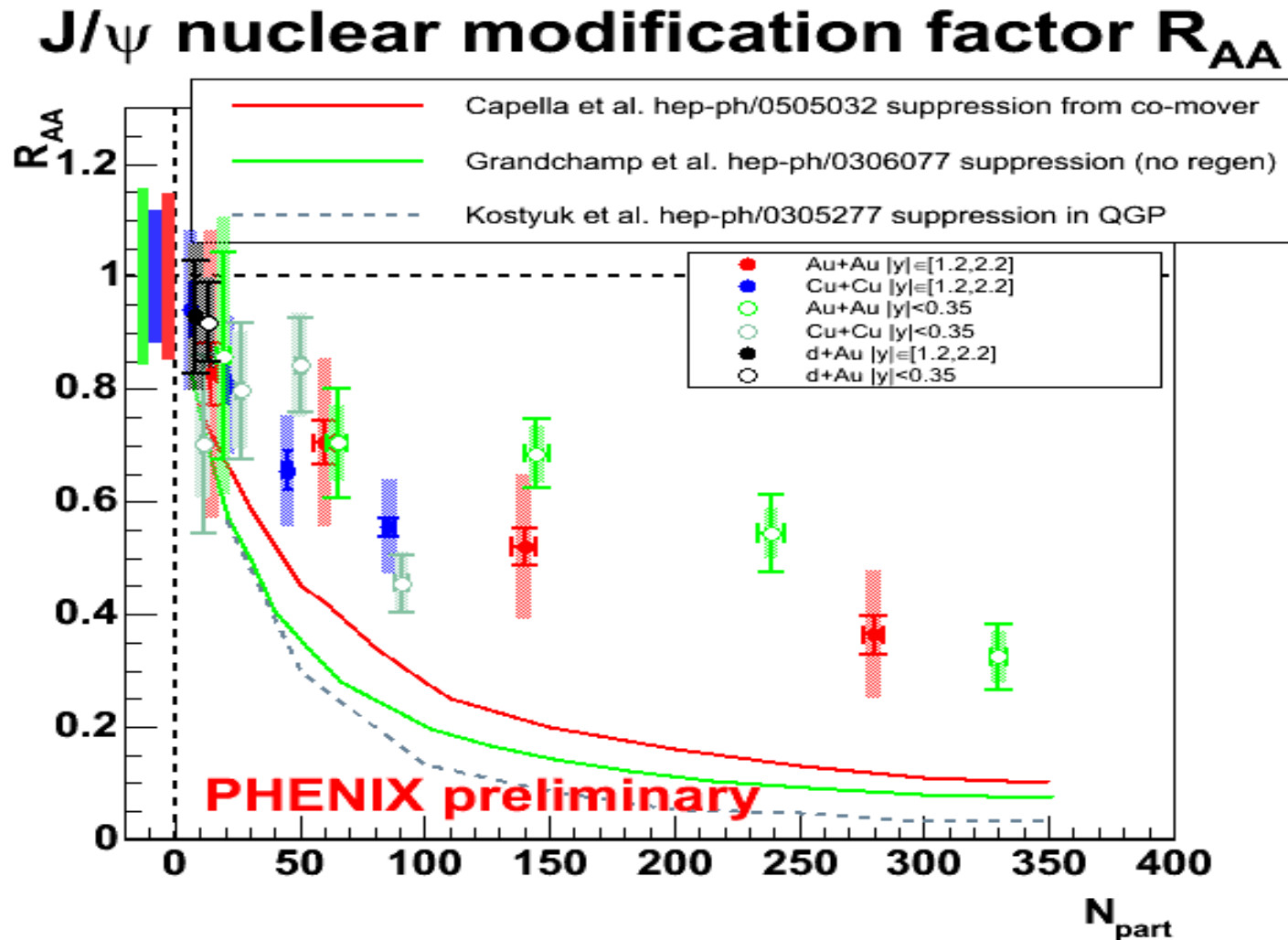


comparison produced by
R. Granier de Cassagnac

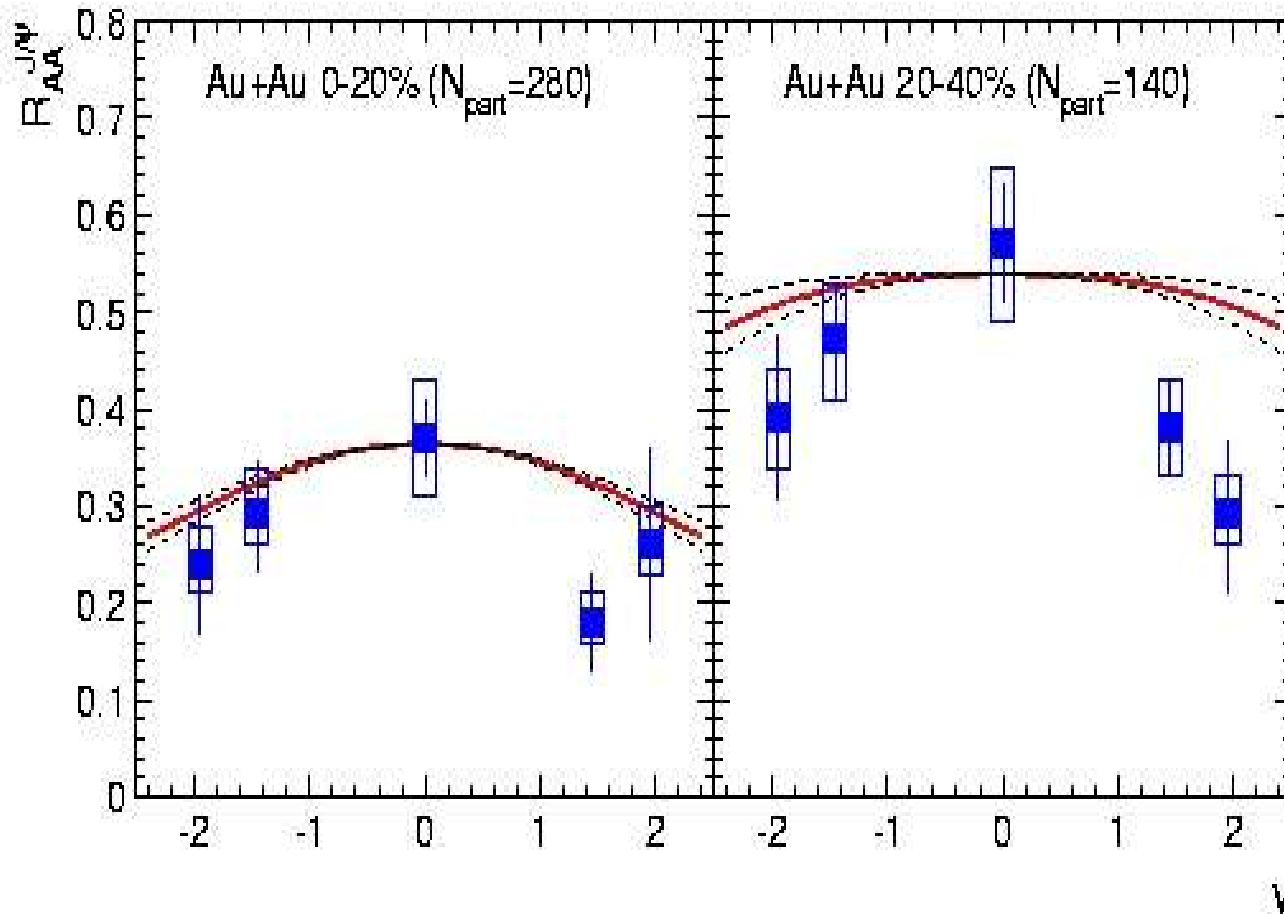
Too much suppression at RHIC in Standard QGP Scenario

standard scenario: all charmonia melt near T_c

models tuned for SPS data fail at RHIC



Comparison of model predictions to RHIC data: rapidity dependence



charmonium generation via statistical hadronization

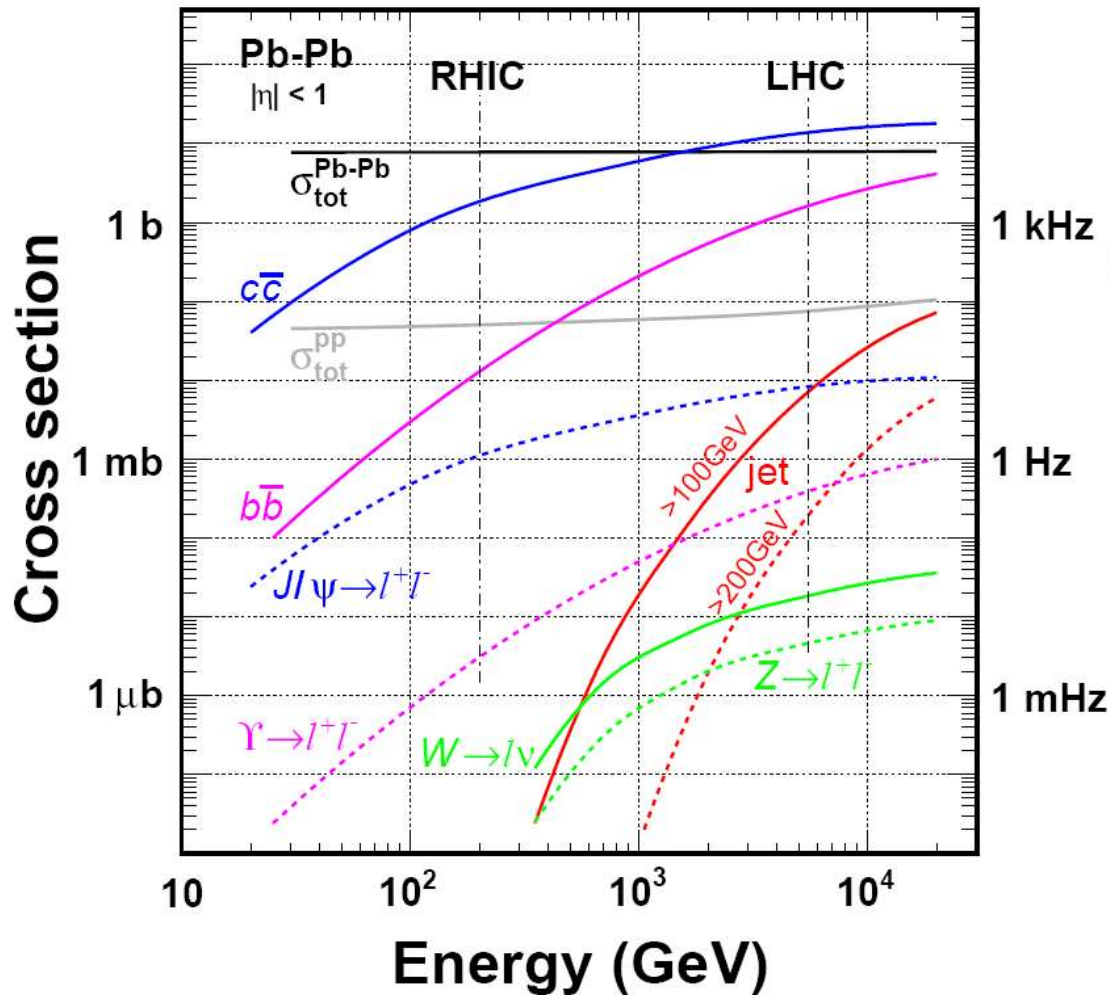
A. Andronic, pbm, K. Redlich, J. Stachel

Phys. Lett. B652 (2007) 259, nucl-th/0701079

suppression is smallest at mid-rapidity (90 deg. emission) where energy density is largest

a clear indication for charmonium generation at the phase boundary

large rates and cross sections for heavy quark production at the LHC



Cross-sections of interesting probes expected to increase by factors of

- ~ 10 (ccbar) to
- ~ 10² (bbar) to
- > 10⁵ (very high p_T jets)

Quarkonium as a probe for deconfinement at the

LHC

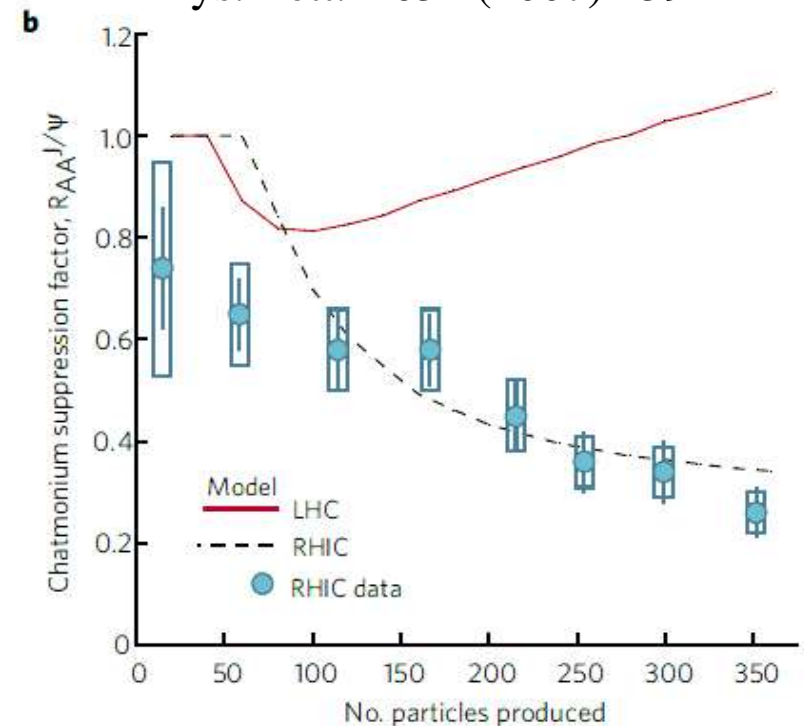
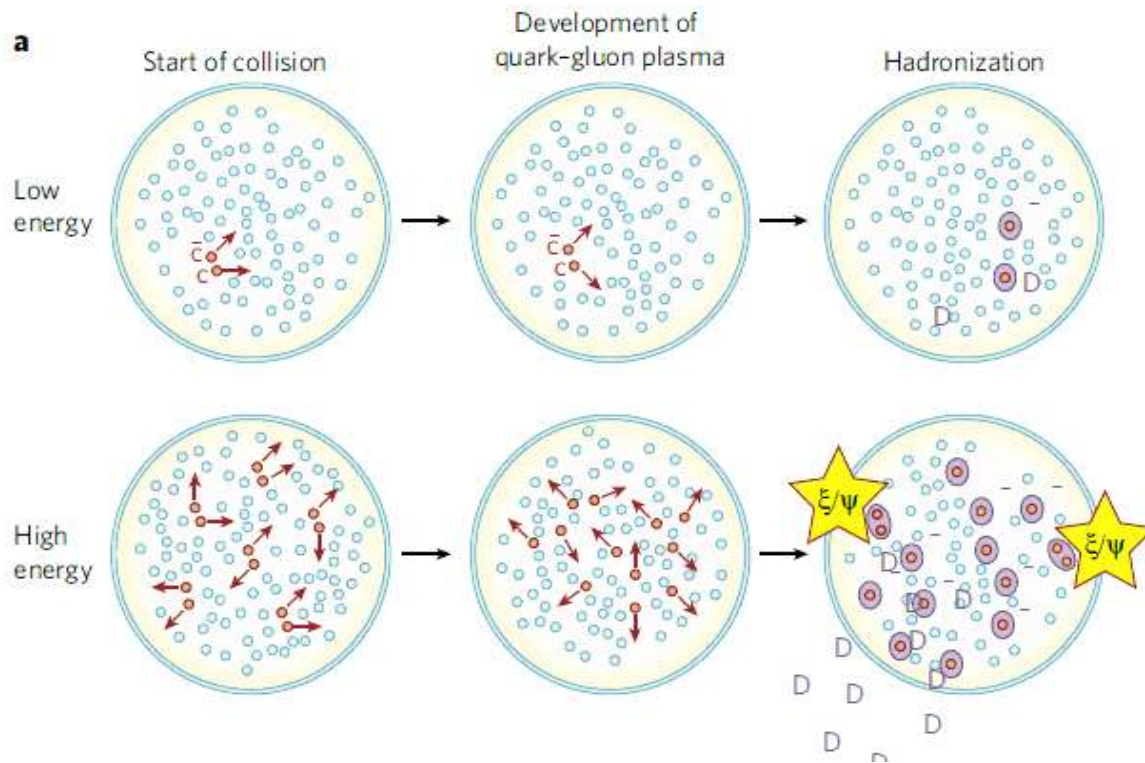
at hadronization of QGP
 J/ψ can form again
 from deconfined quarks,
 in particular if number of
 $c\bar{c}$ pairs is large

$$N_{J/\psi} \propto N_{c\bar{c}}^2$$

(P. Braun-Munzinger and
 J. Stachel, PLB490 (2000) 196)

charmonium enhancement as fingerprint of
 deconfinement at LHC energy

Andronic, pbm, Redlich, Stachel,
 Phys. Lett. B652 (2007) 259



- major surprize: suppression equal to that observed at SPS
 - major surprize: suppression is minimal at midrapidity
 - LHC: expect qualitatively new features due to very large charm quark density
-
- first month of LHC data with a few thousand charmonia will bring decisive new insights

the discoveries at RHIC, principally on

thermalization and flow --> ideal fluid scenario

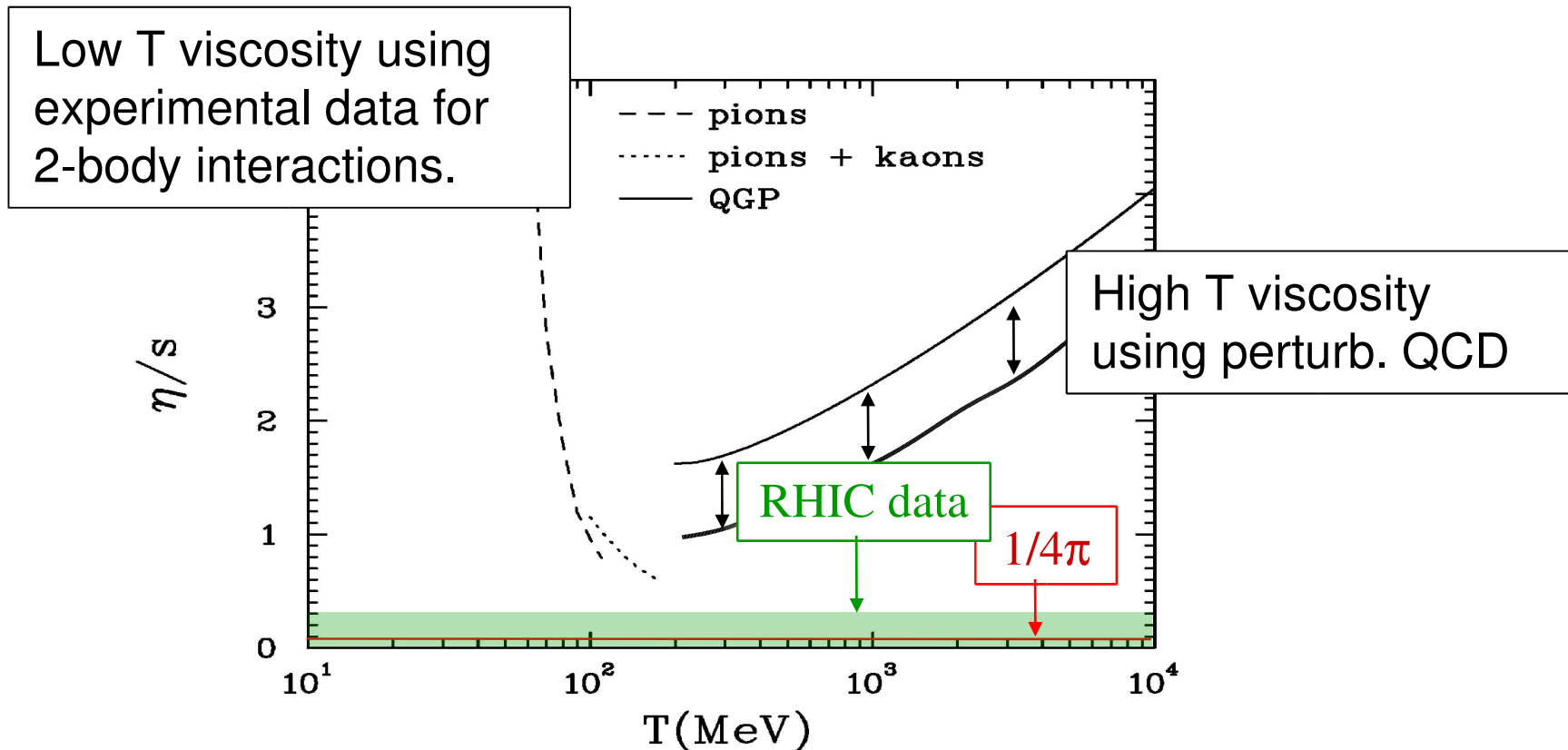
jet quenching --> parton energy loss in dense fireball

have led to major progress in our understanding of the QGP

These discoveries raise many new questions. Even a short heavy ion run in 2009 can bring fundamentally new insights. The experiments are ready.

additional slides

Viscosity of QCD matter



To the rescue: String theory and lattice QCD.

- General argument [Kovtun, Son & Starinets] based on duality between

Thermal model description of hadron yields

Grand Canonical Ensemble

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T))$$

$$n_i = N/V = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp((E_i - \mu_i)/T) \pm 1}$$

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

Fit at each
energy
provides
values for
T and μ_b

for every conserved quantum number there is a chemical potential μ
but can use conservation laws to constrain:

- Baryon number: $V \sum_i n_i B_i = Z + N \rightarrow V$
- Strangeness: $V \sum_i n_i S_i = 0 \rightarrow \mu_S$
- Charge: $V \sum_i n_i I_i^3 = \frac{Z - N}{2} \rightarrow \mu_{I_3}$

This leaves only μ_b and T as free parameter when 4π considered
for rapidity slice fix volume e.g. by dN_{ch}/dy

The QCD phase diagram and chemical freeze-out

Main result: chemical freeze-out points seem to delineate the QCD phase boundary at small baryo-chemical potential ($\mu < 400$ eV)

