# 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. (2009) in print
arXiv:0801.4256

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

Warsaw, May 18, 2009

Peter Braun-Munzinger

# selective synopsis of RHIC results

this is not a comprehensive review of all RHIC results

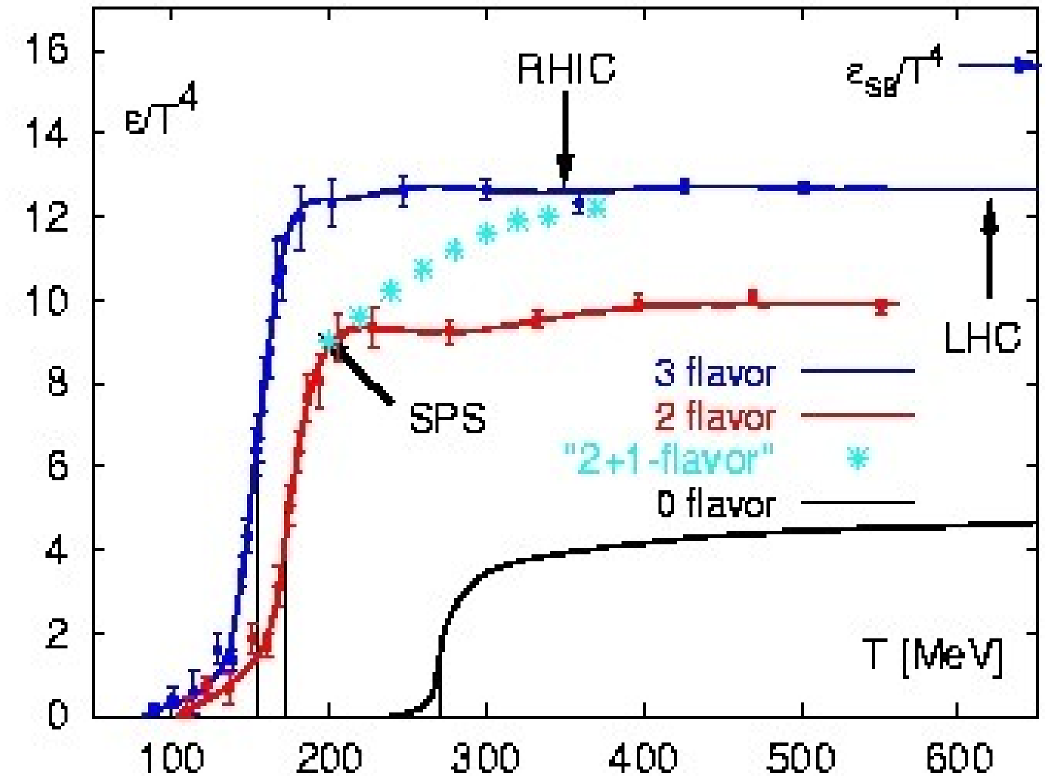
focus is on:

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 ± 12 MeV

$\varepsilon_c$ = 700 ± 200 MeV/fm$^3$

for the (2 + 1) flavor case:

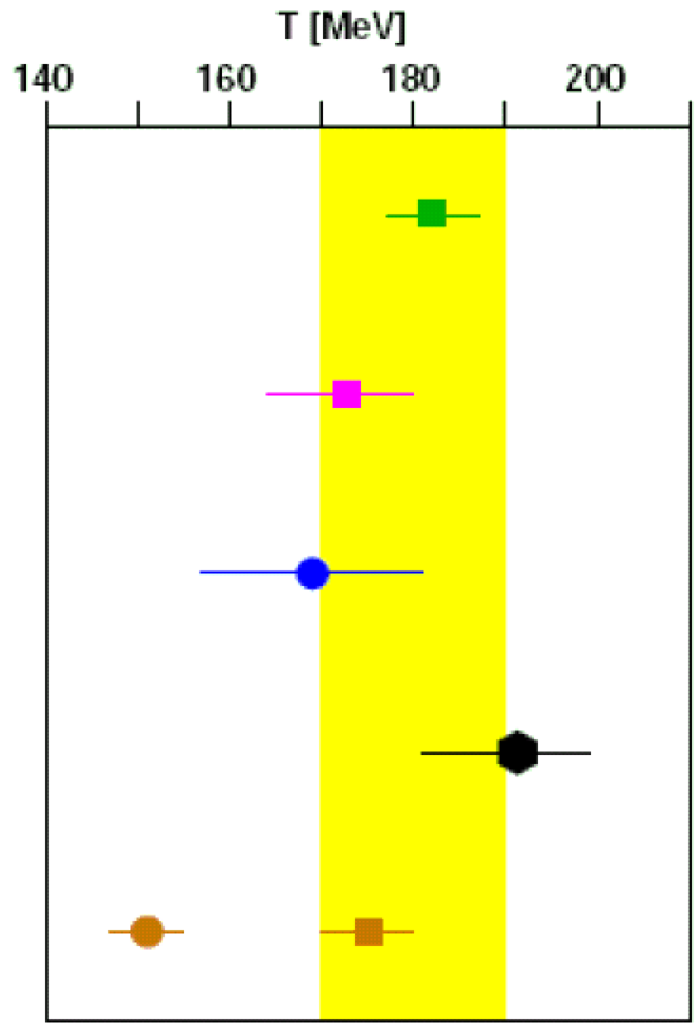
the phase transition to the QGP and its parameters are quantitative predictions of QCD.

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.

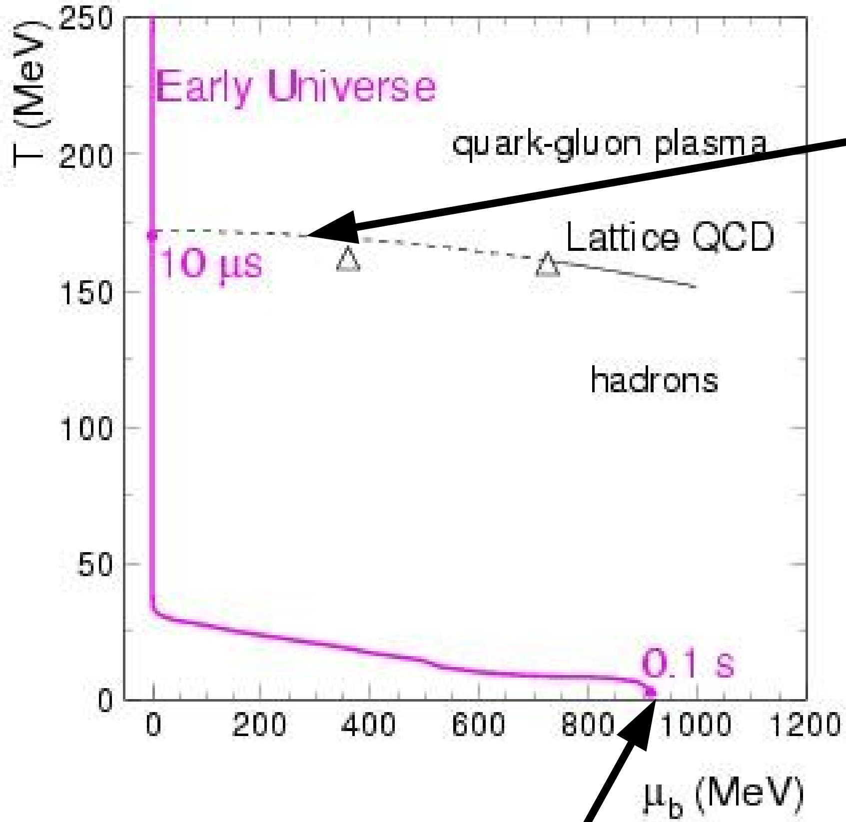
Aoki, Y., Z. Fodor, S. D. Katz, and K. K. Szabo, 2006b, Phys. Lett. **B643**, 46.

# 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

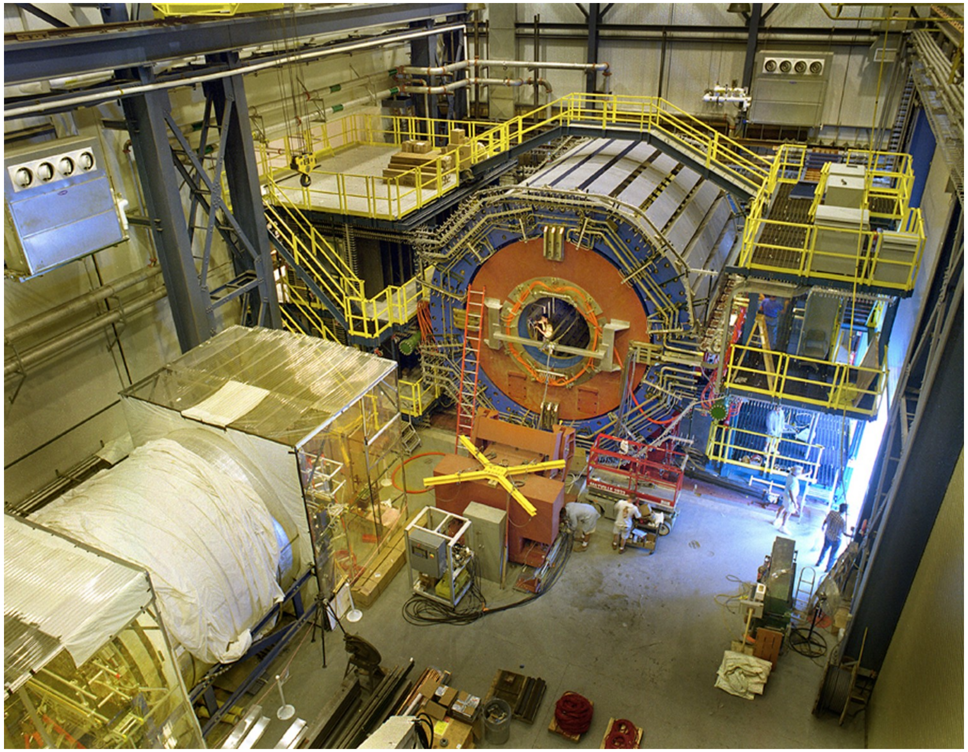
| | fixed target AGS | fixed target SPS | collider RHIC | collider LHC |
|---|---|---|---|---|
| | 1987-2000 | 1987-2000 | since 2000 | from 2009 |
| beam momentum | 29 ·Z GeV/c | 450 ·Z GeV/c | ea250 ·Z GeV/c | ea7000 ·Z GeV/c |
| projectile | p...Au | p...Pb | p...Au | p...Pb |
| energy available in 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

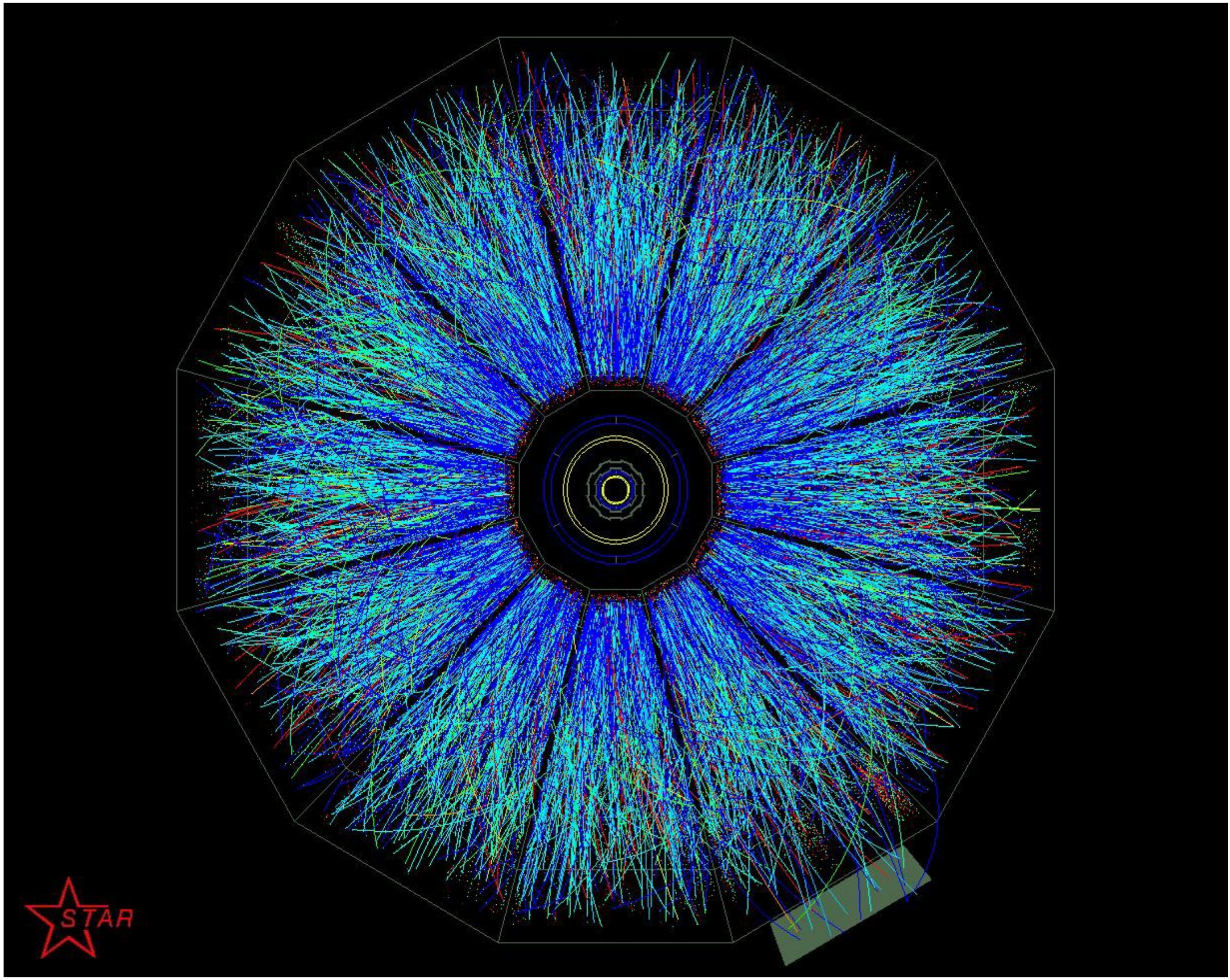


as well as PHOBOS and BRAHMS (both completed)

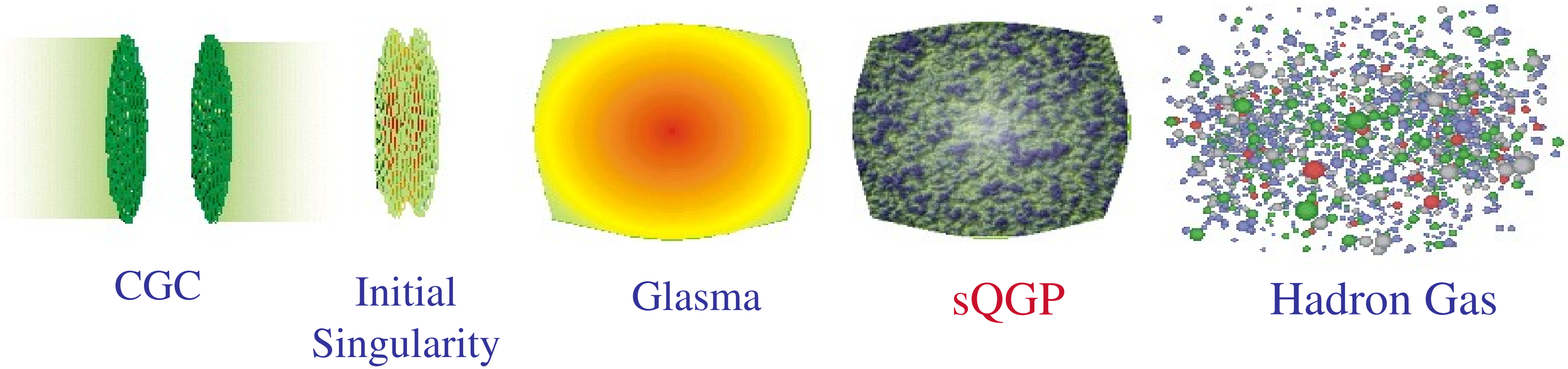
# STAR event display

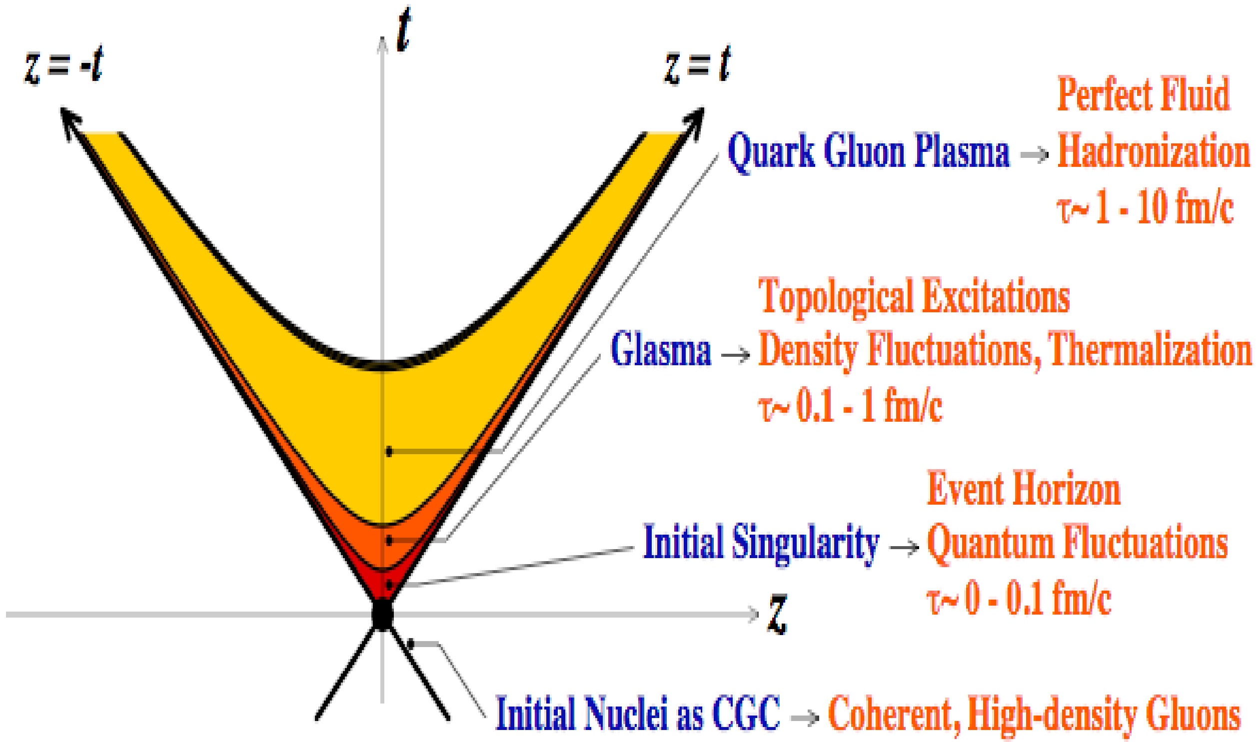
in central AuAu collsions
at RHIC √s = 200 GeV
about 7500 hadrons
produced (BRAHMS)

about three times as
much as at CERN SPS



# The Space-Time Evolution of a Relativistic Nuclear Collision

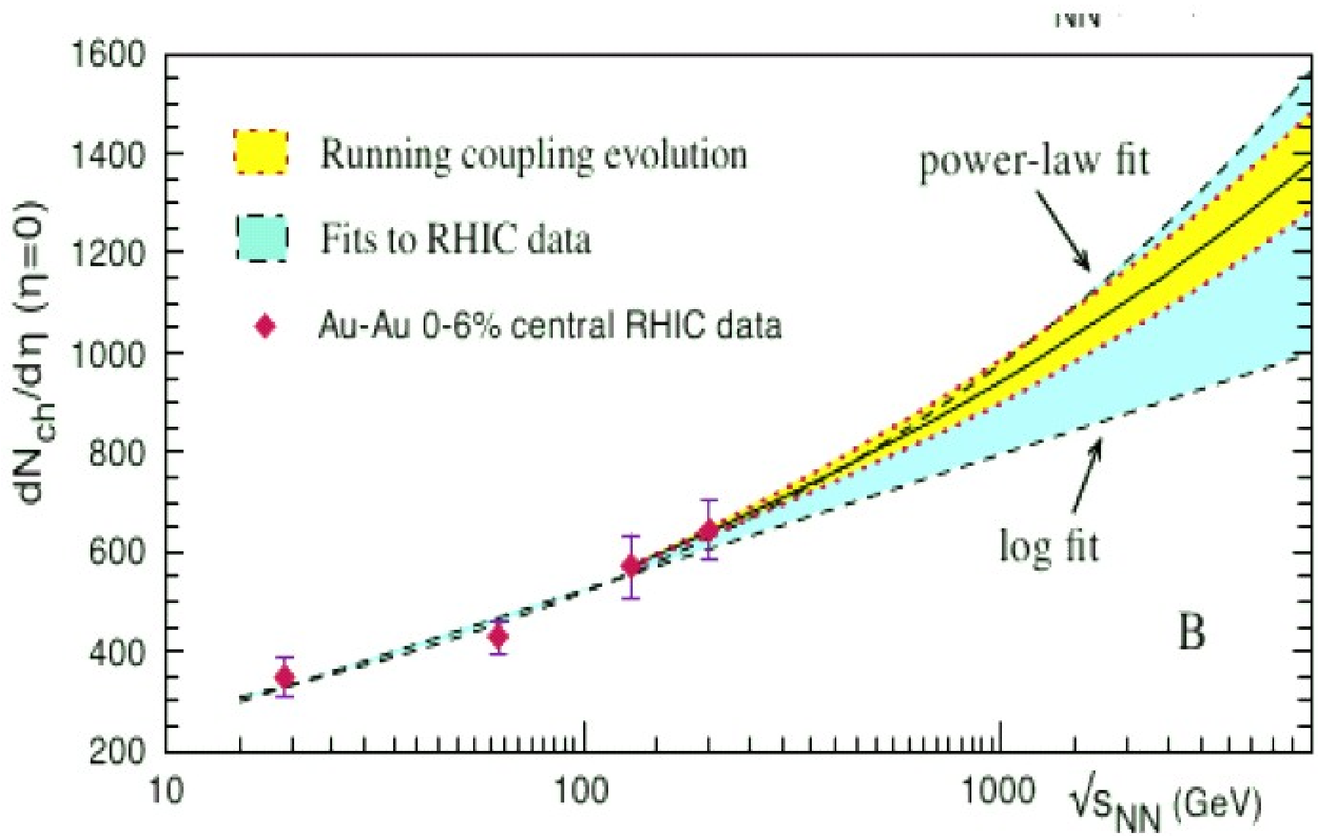


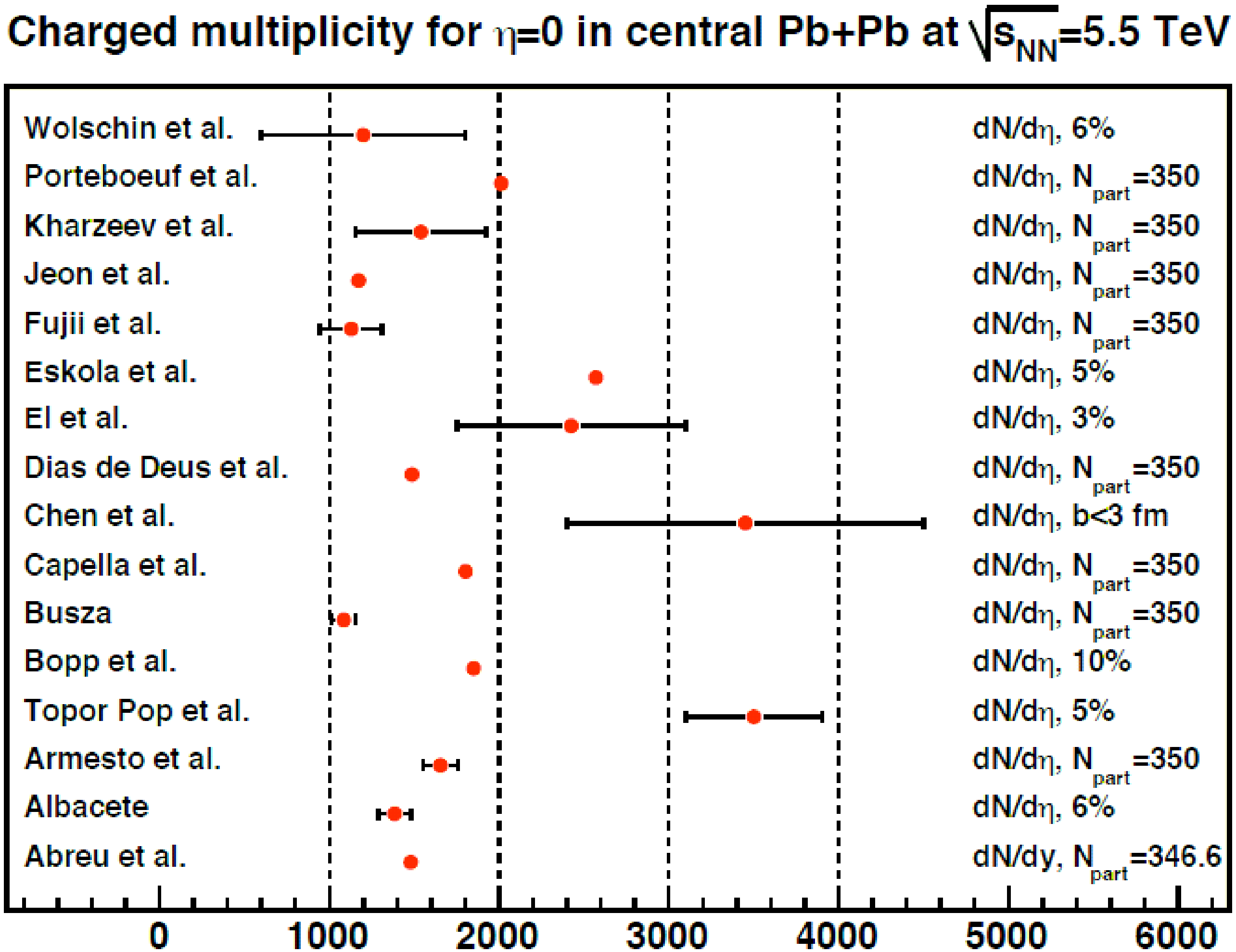

one possible view
( courtesy
Larry McLerran)

# 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




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 fron 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

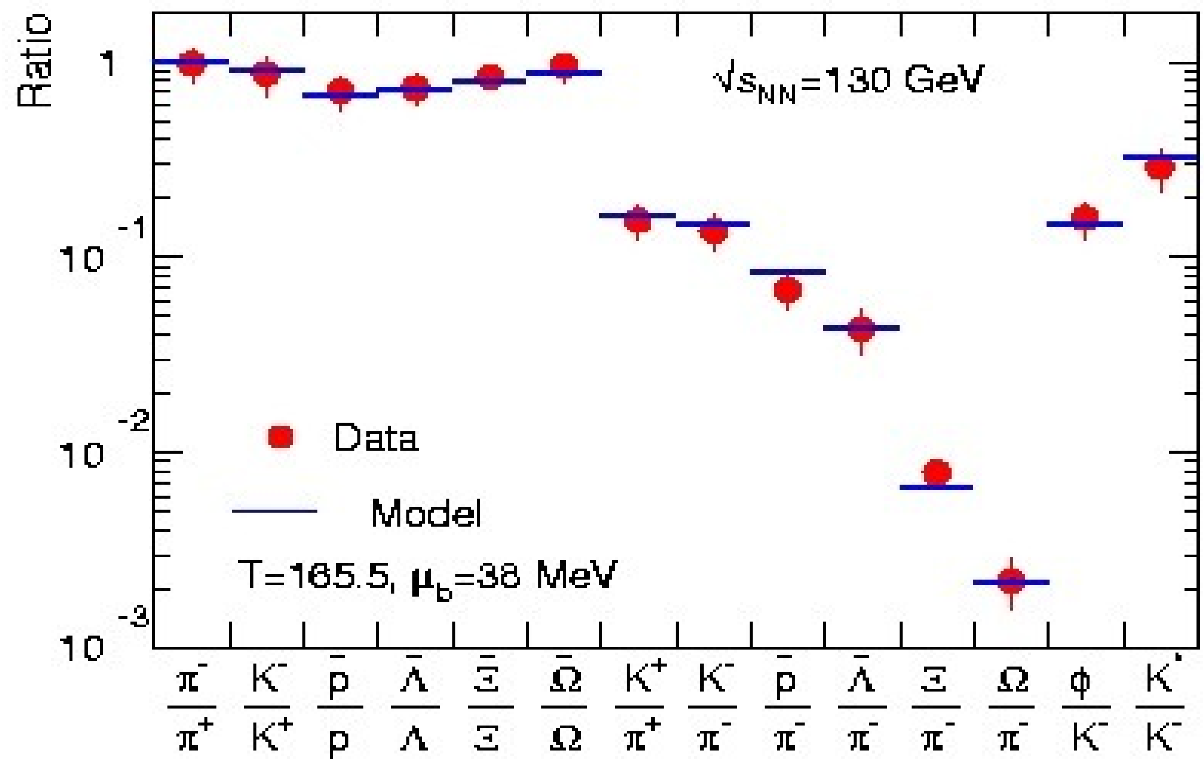
# Hadro-chemistry at RHIC

All data in excellent agreement with thermal model predictions

chemical freeze-out at: T = 165 ± 8 MeV

fit uses vacuum masses

most recent analysis: A. Andronic, pbm, J. Stachel, nucl-th/0511071 Nucl. Phys. A772(2006) 167



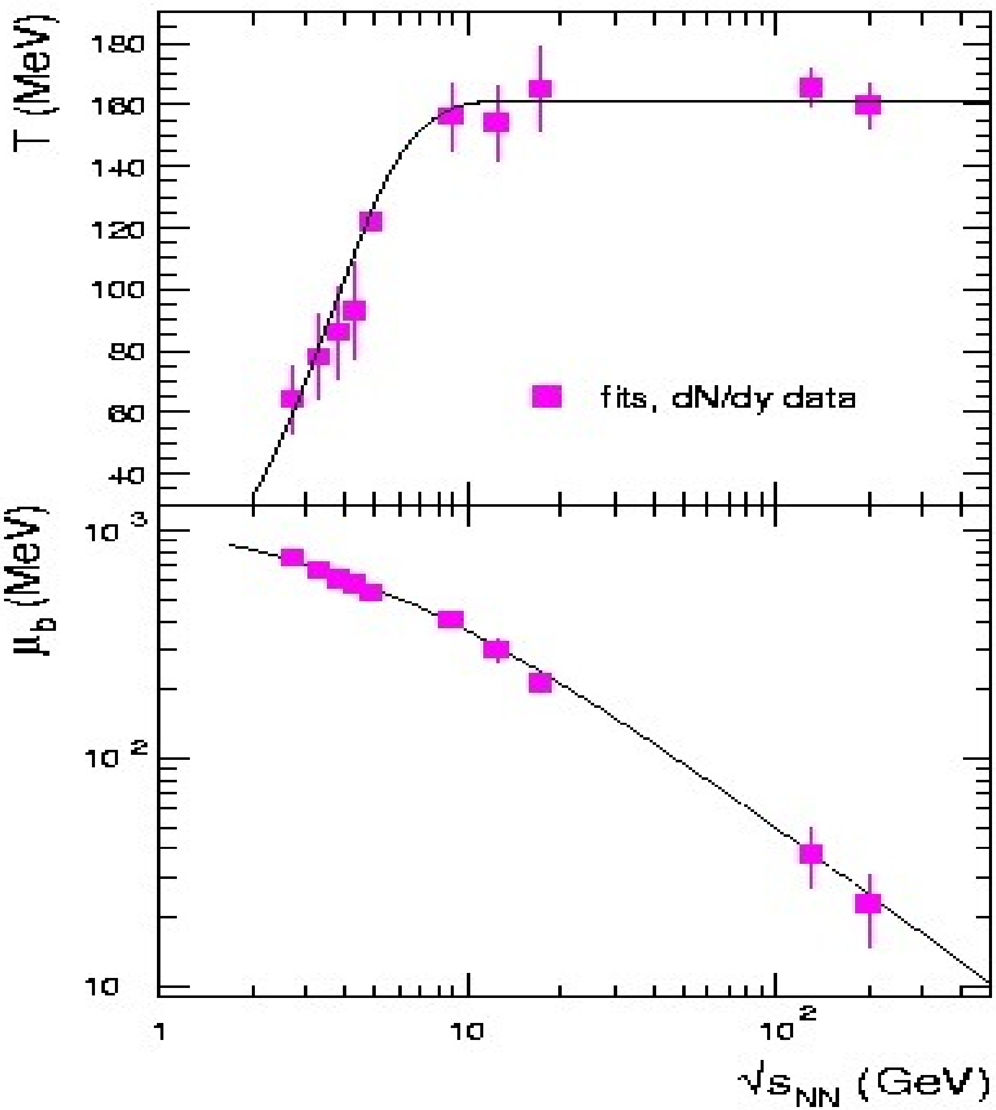

pbm, Magestro, Stachel, Redlich, Phys. Lett. B518 (2001) 41;
see also Xu et al., Nucl. Phys. A698(2002) 306;
Becattini, J. Phys. G28 (2002) 1553;
Broniowski et al., nucl-th/0212052.

# Parameterization of all freeze-out points

note: discovery of the limiting temperature

**$T_{lim}$ = 160 MeV**

**provides connection to QCD phase boundary**




can use parameterization to predict particle ratios at all energies

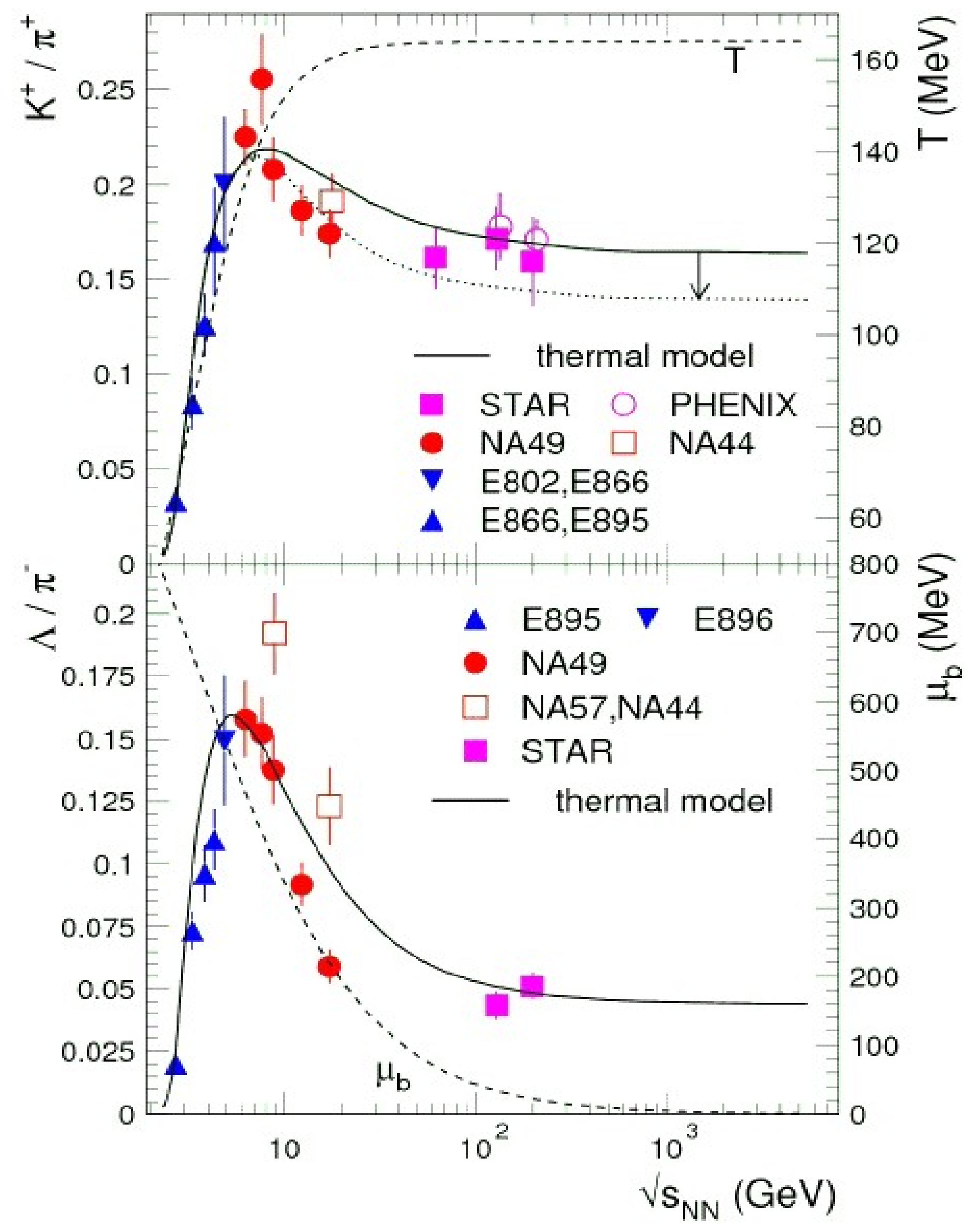
# Horn structure well described

rapid saturation of contributions from higher resonances in conjunction with additional pions from the sigma describes horn structure well

crucial input is saturation of T due to the phase boundary

solid prediction for LHC energy

Andronic, pbm, Stachel
ArXiv:0812.1186 [nucl-th]
Phys. Lett. B673 (2009) 142



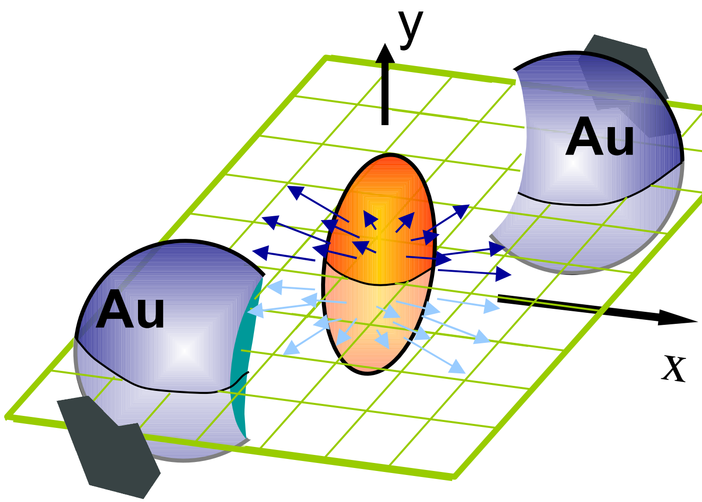
# Summary of statistical model interpretation

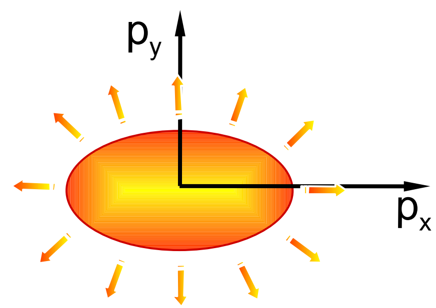
- hadron yields quantitatively described at all energies by 3 parameters: T, mu_b, V
- limiting temperature established
- connection to QCD phase boundary

- 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

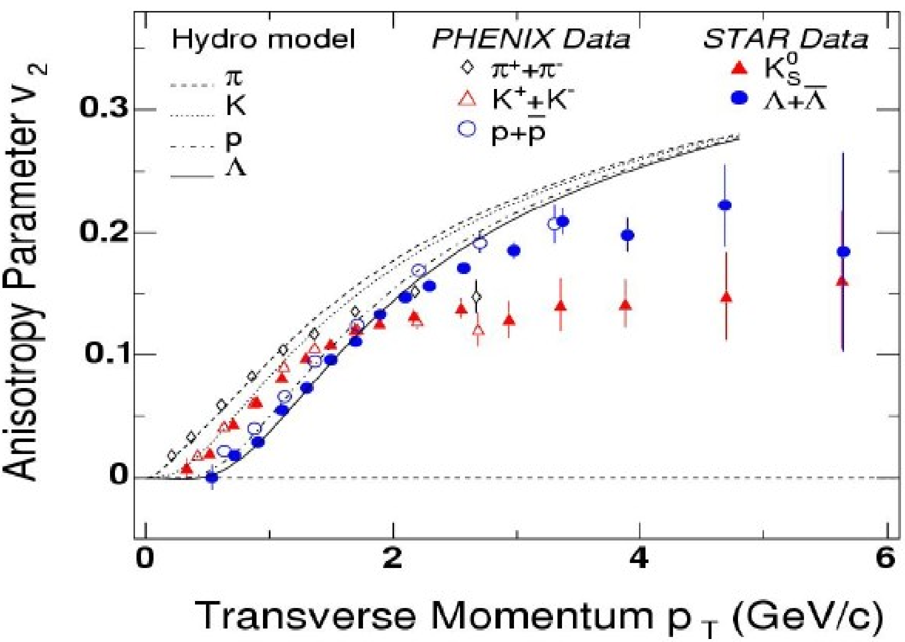


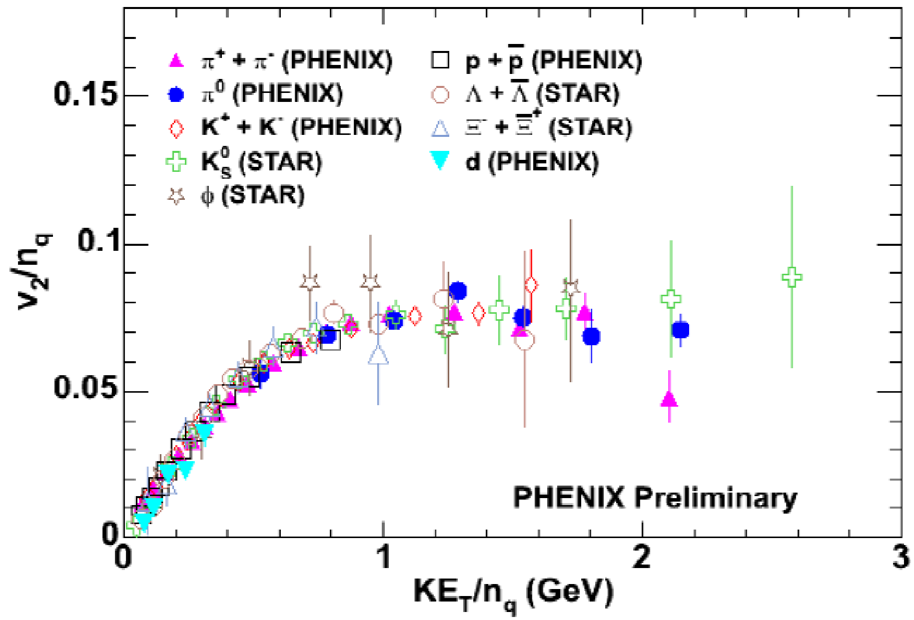




$$dN/d\phi = 1 + 2\,V_2 \cos 2(\phi - \psi) + \ldots$$

hydrodynamic flow characterized by azimuthal anisotropy coeffient $v_2$

# Elliptic Flow Results from RHIC

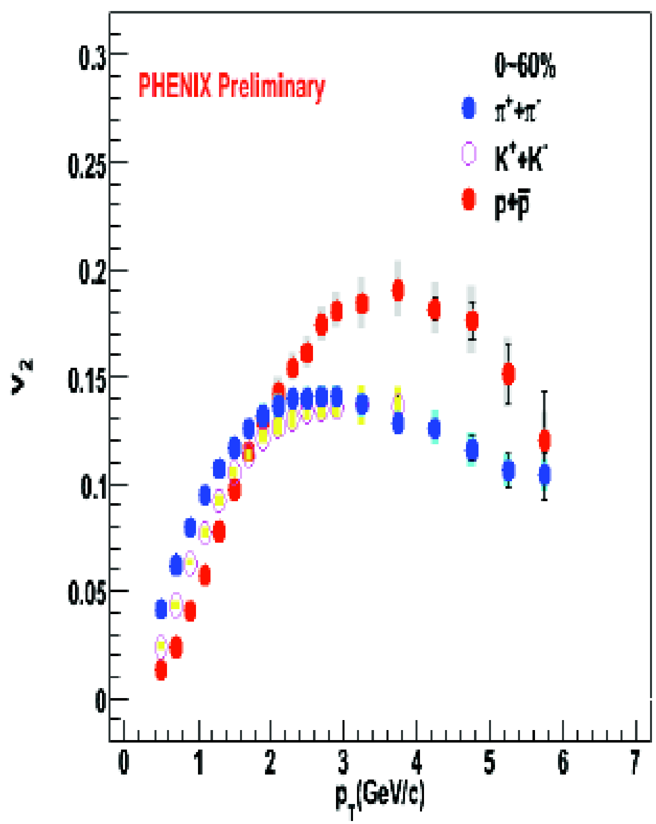

shear viscosity/entropy close to theoretical (AdS/CFT) limit eta/s = 1/(4π)

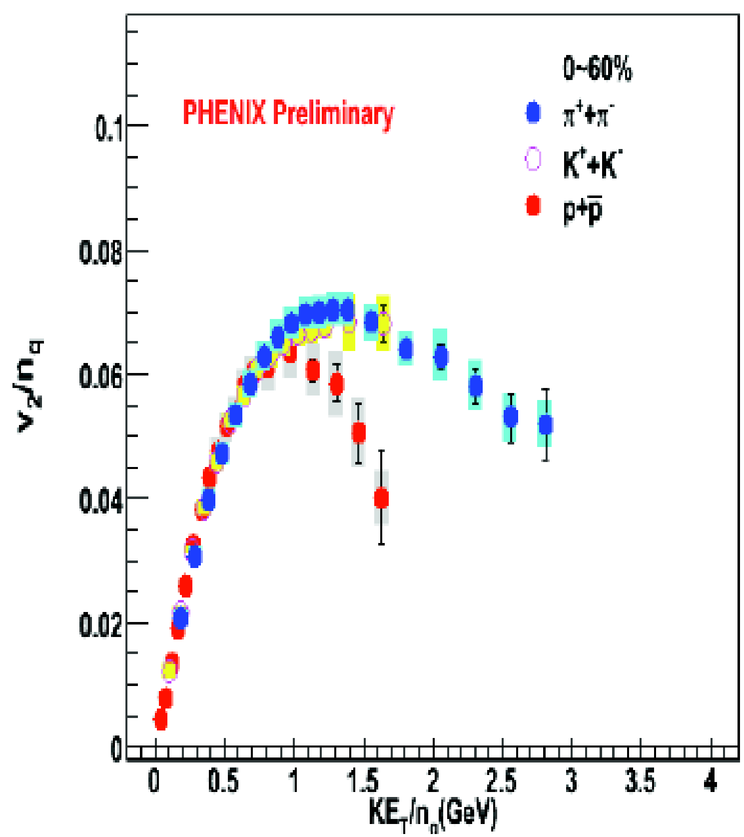
note the peculiar quark scaling!

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

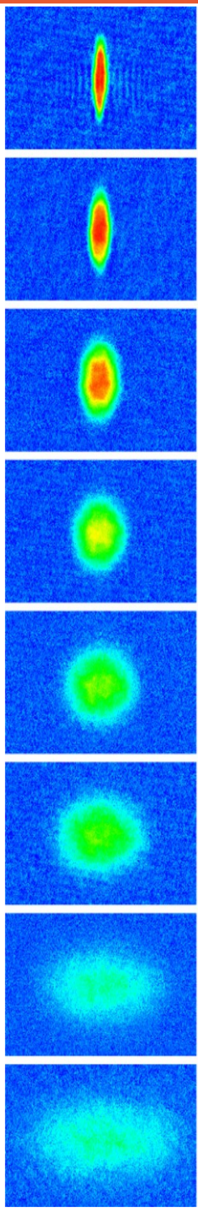
# Quark number scaling violations

What will come from LHC measurements?
1st data will tell!



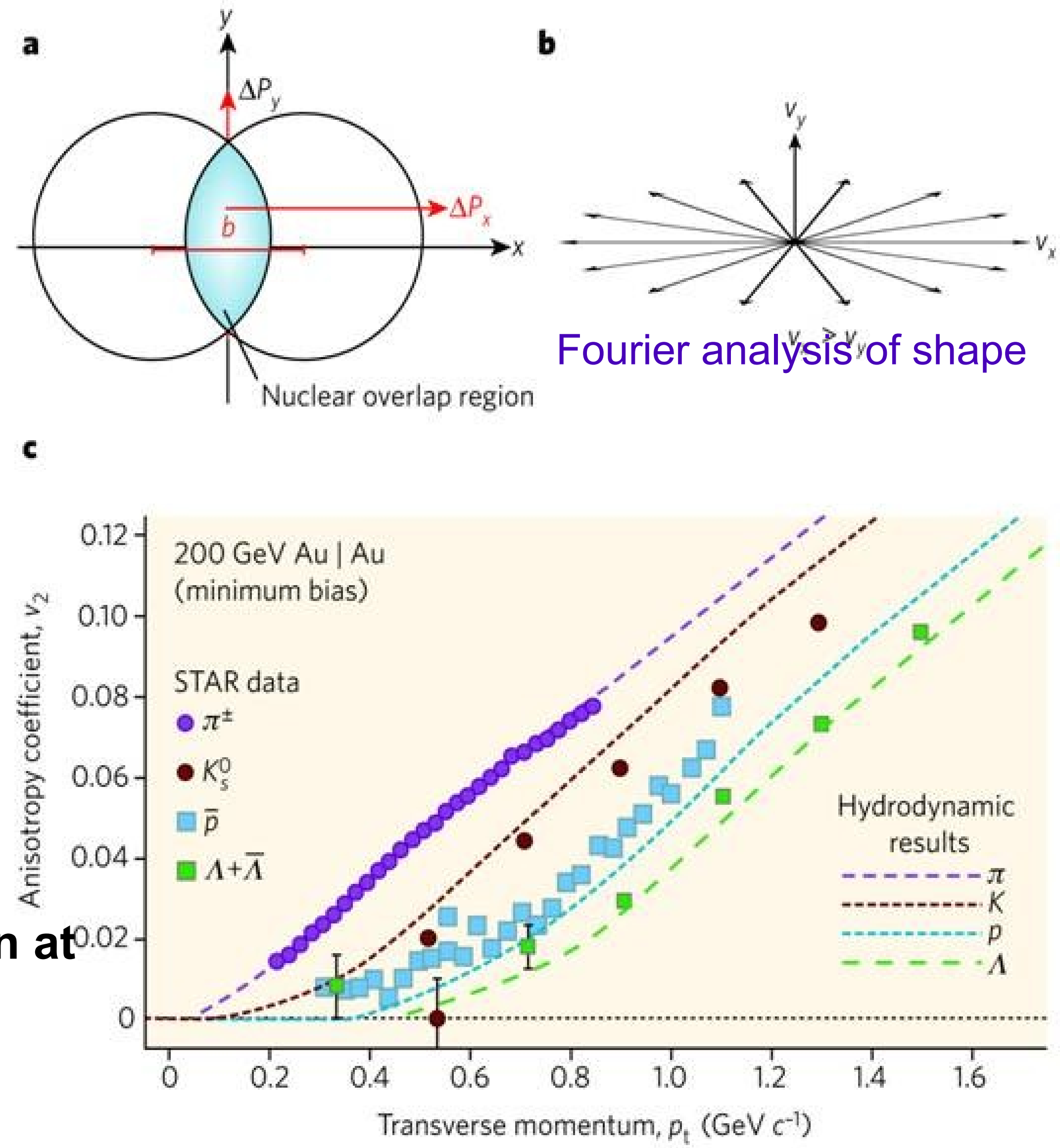
# QGP and Ultra-cold Quantum Gases




ultra-cold $^{6}$Li
10 nK
~$10^{-12}$ eV

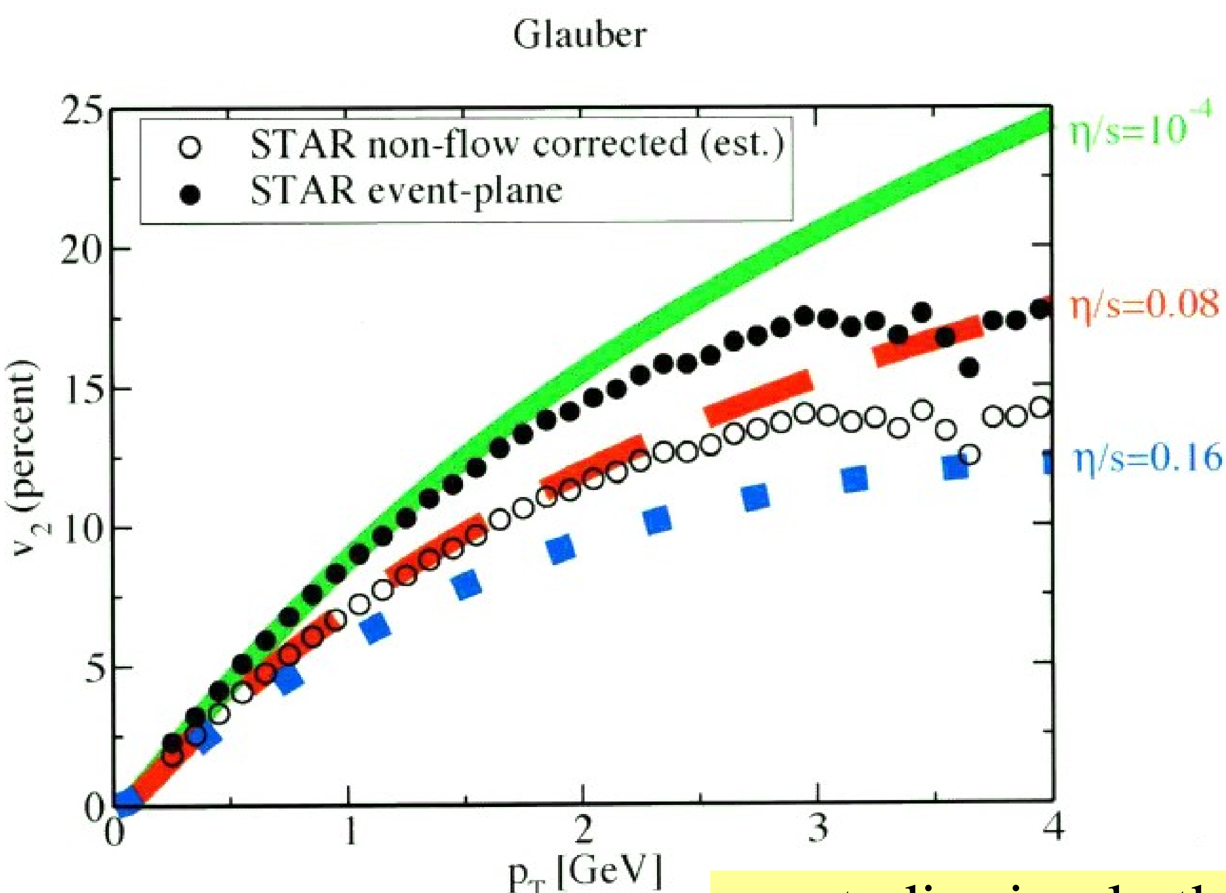
QGP
2.1 TK
~$10^{8}$ eV

**collective expansion at strong coupling**




Fourier analysis of shape

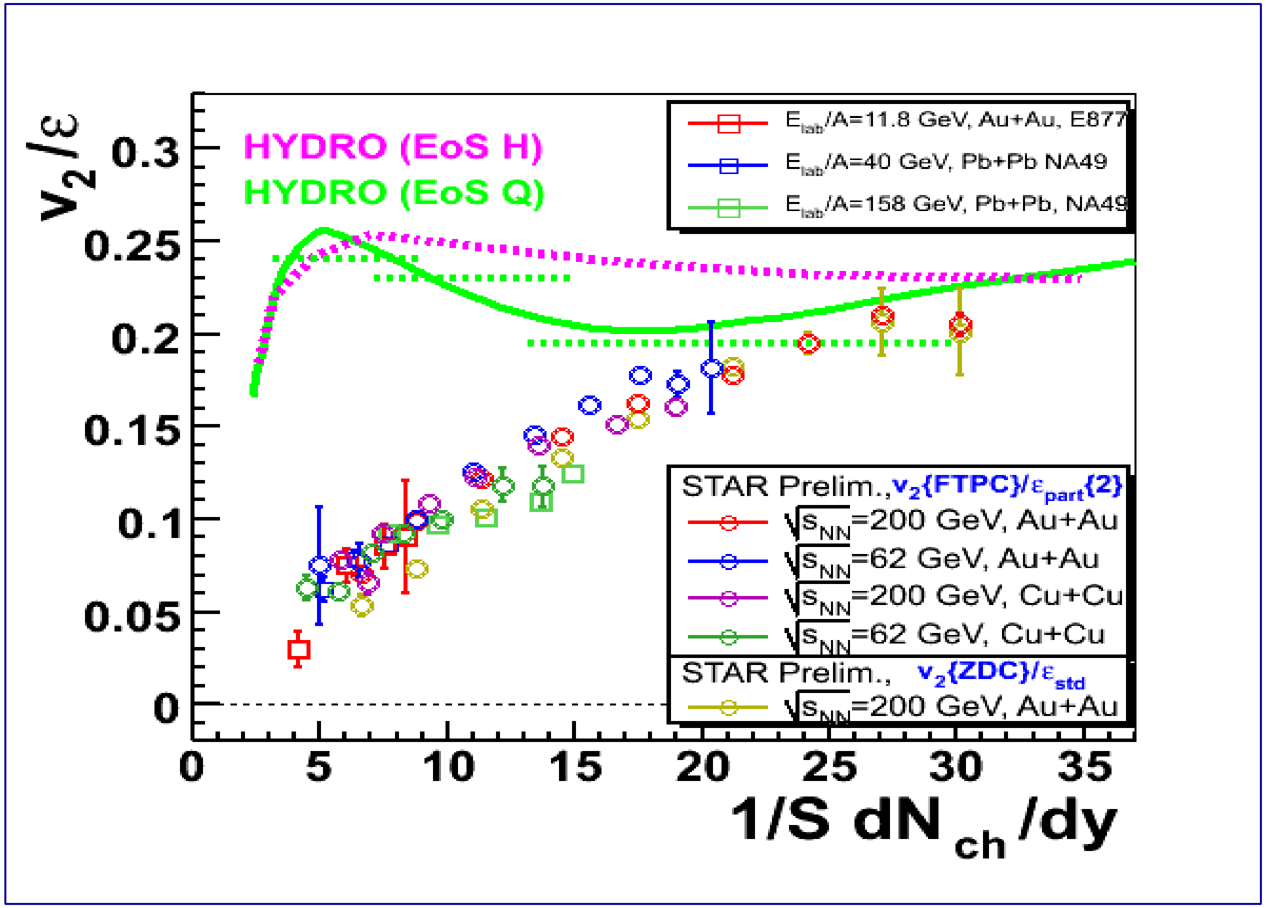
# exploring the importance of viscous effects

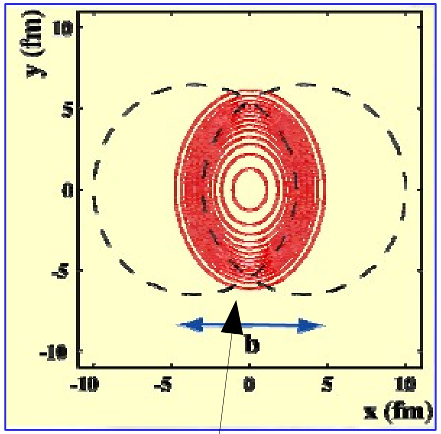



calculations by Paul Romatschke

studies imply that
eta/s > (2•AdS/CFT limit)
not compatible with data

# summary of all existing data

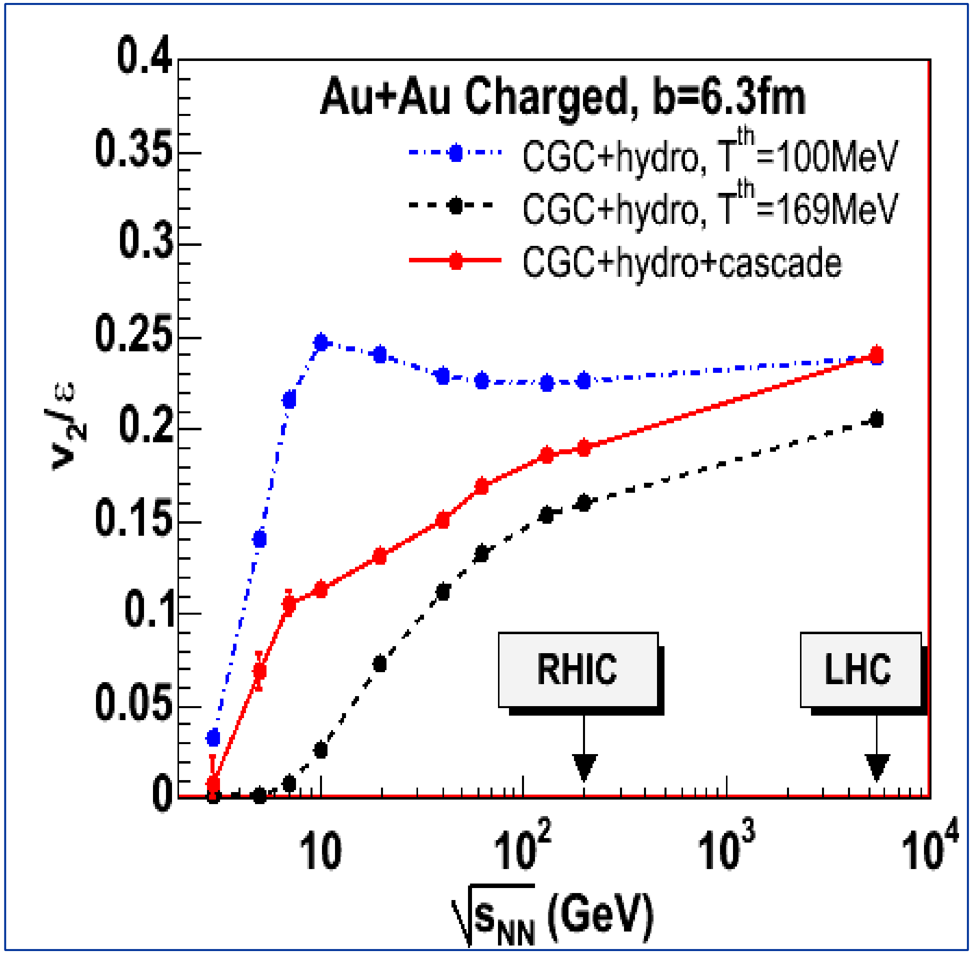


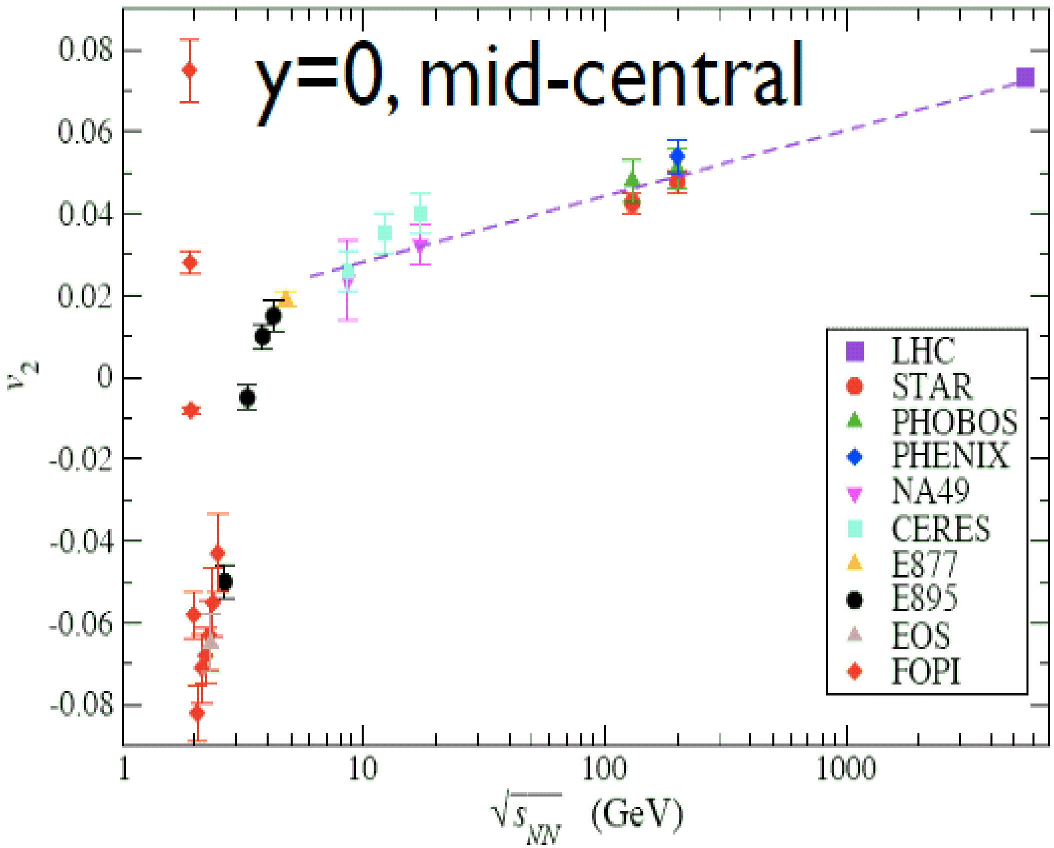




note: the initial eccentricity must be computed in a model

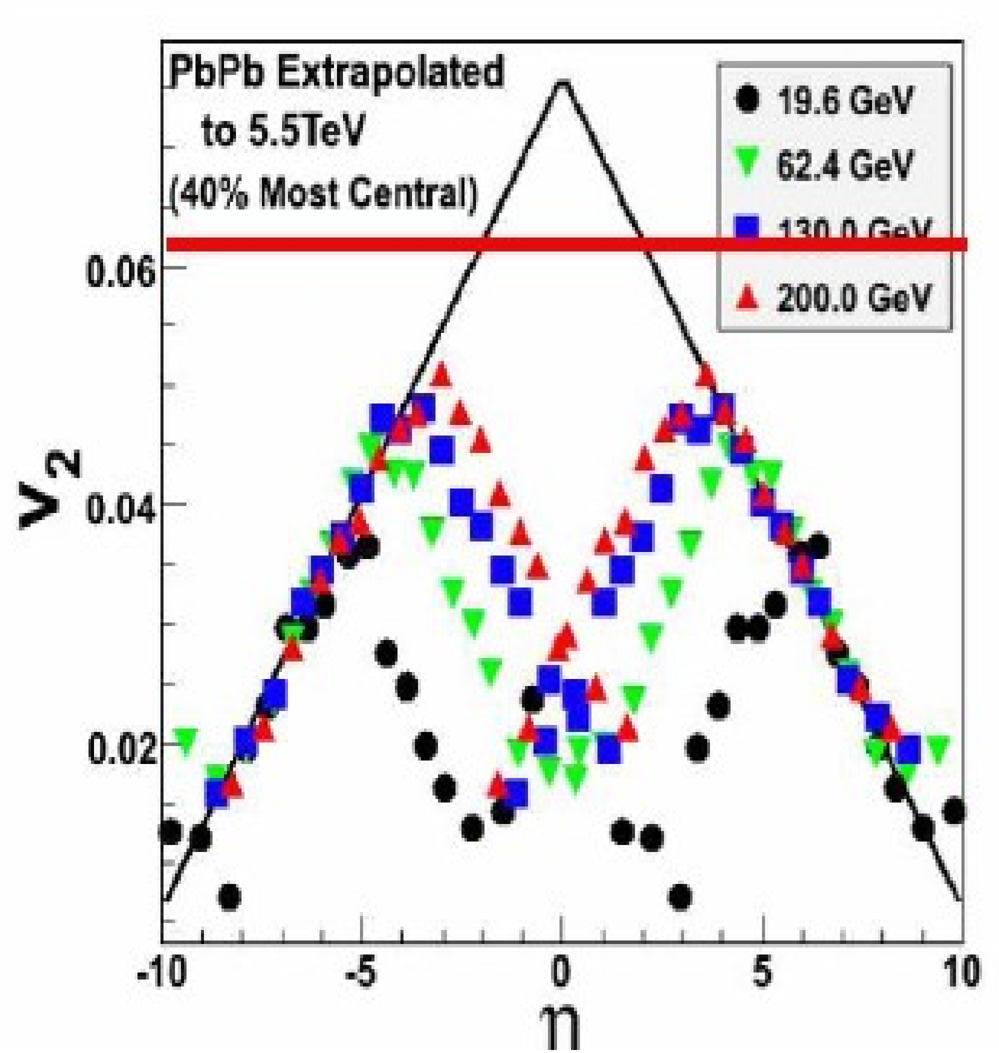
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

# extrapolations to LHC



# 'Busza' extrapolation – too much for hydro?

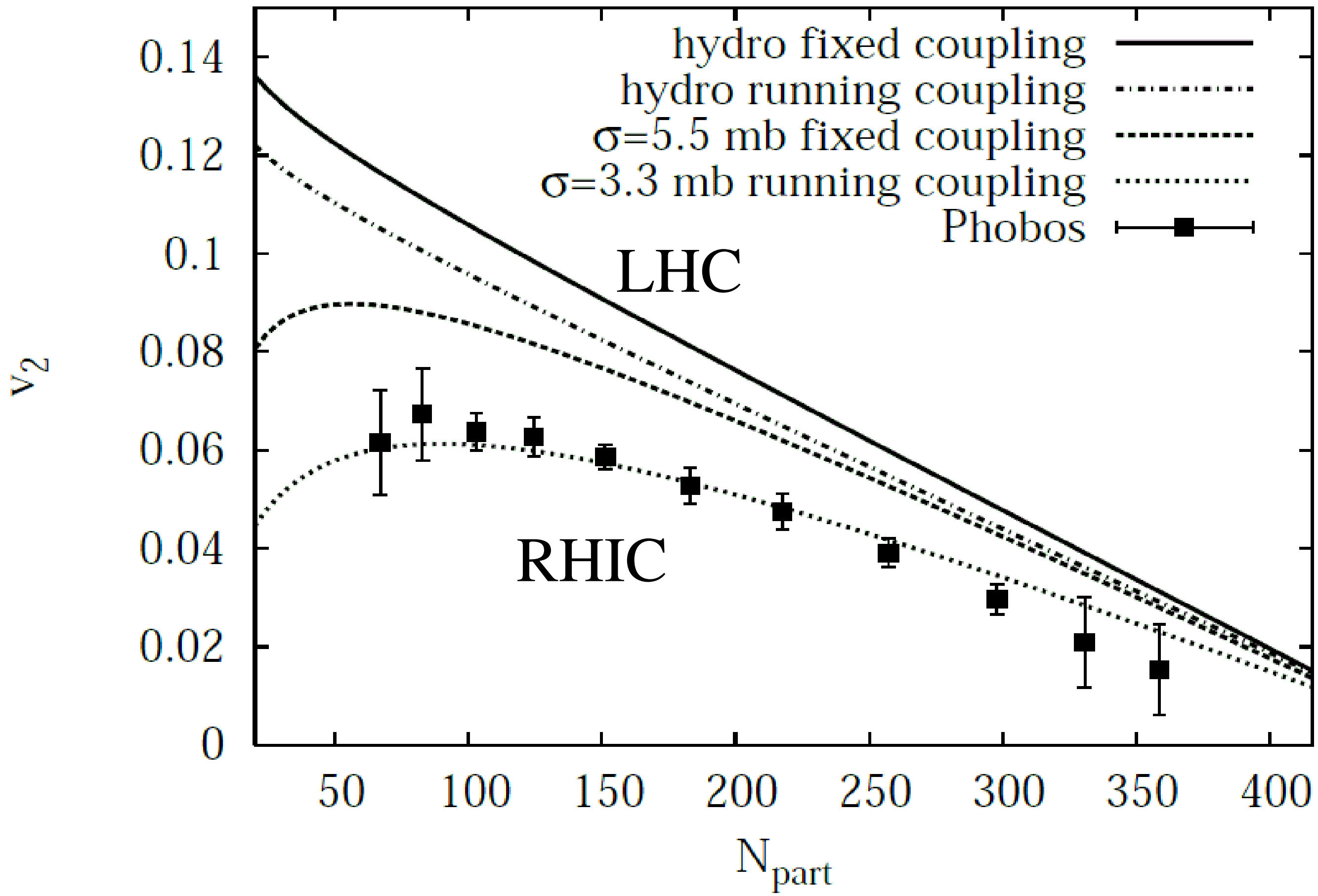


# evolution of flow in a simple scaling model

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

J.Y. Ollitrault et al, arXiv:0711.0974

$$v_2 = \frac{h\varepsilon}{1 + K/0.7} \qquad \frac{1}{K} = \frac{\sigma}{S}\frac{dN}{dy}\frac{1}{\sqrt{3}}$$




K(RHIC) =0.55

expect:

K(LHC) < 0.3

important test of ideal fluid scenario and temperature dependent shear viscosity

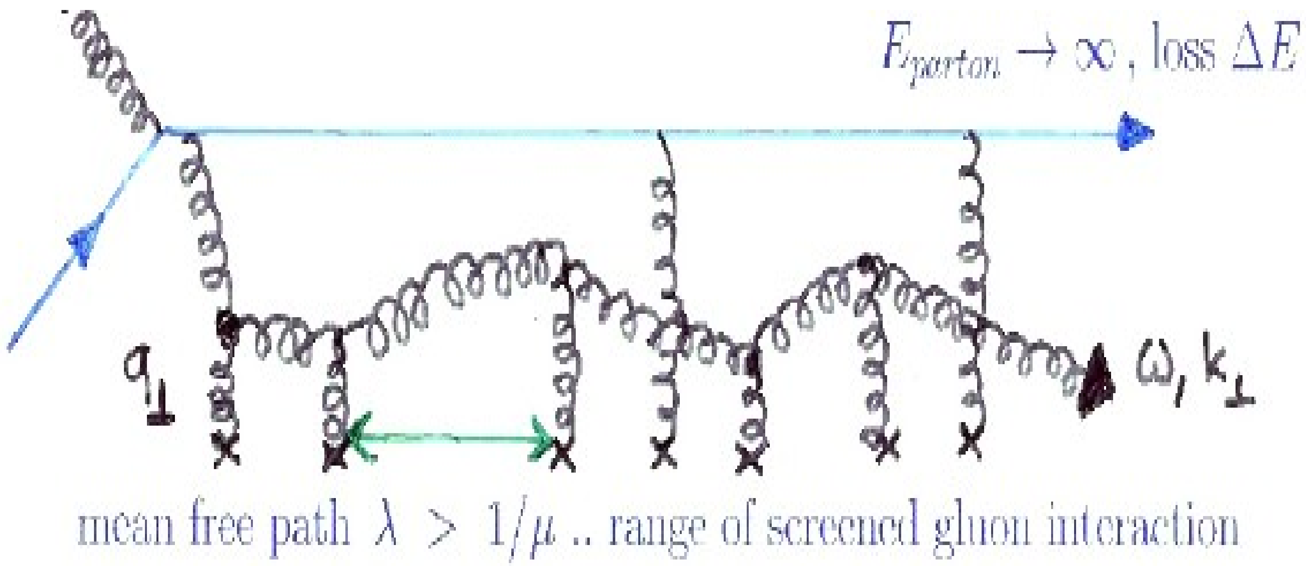
# Summary of RHIC Hydro Results

- 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

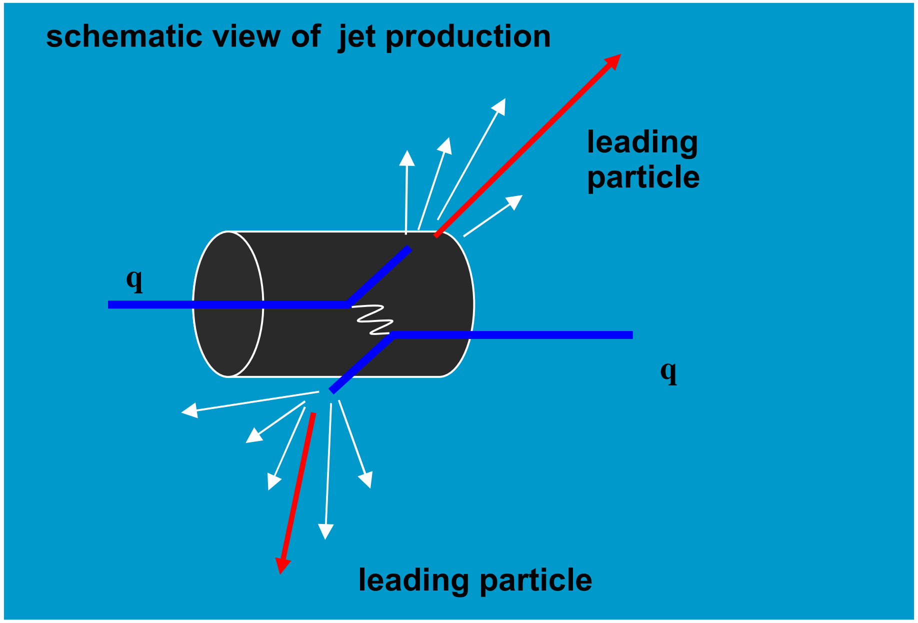
- suppression of high $p_t$ particles in AA relative to pp collisions
- disappearance of jet-like correlations
- connected to large gluon density in hot (QGP) fireball




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

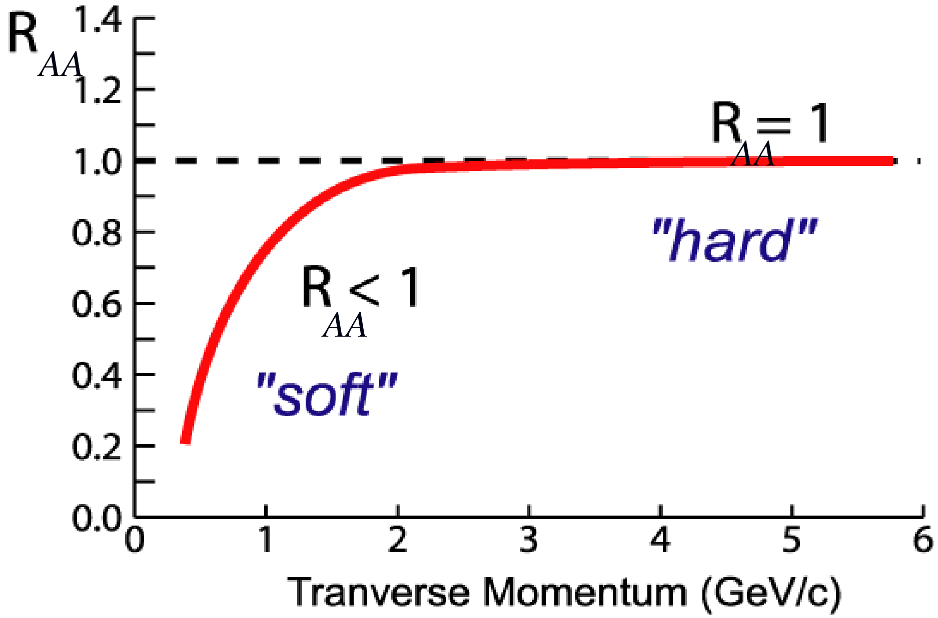
Jet Quenching

# Definition of $R_{AA}$

$R_{AA}$ = medium/vacuum

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

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




no medium effects:

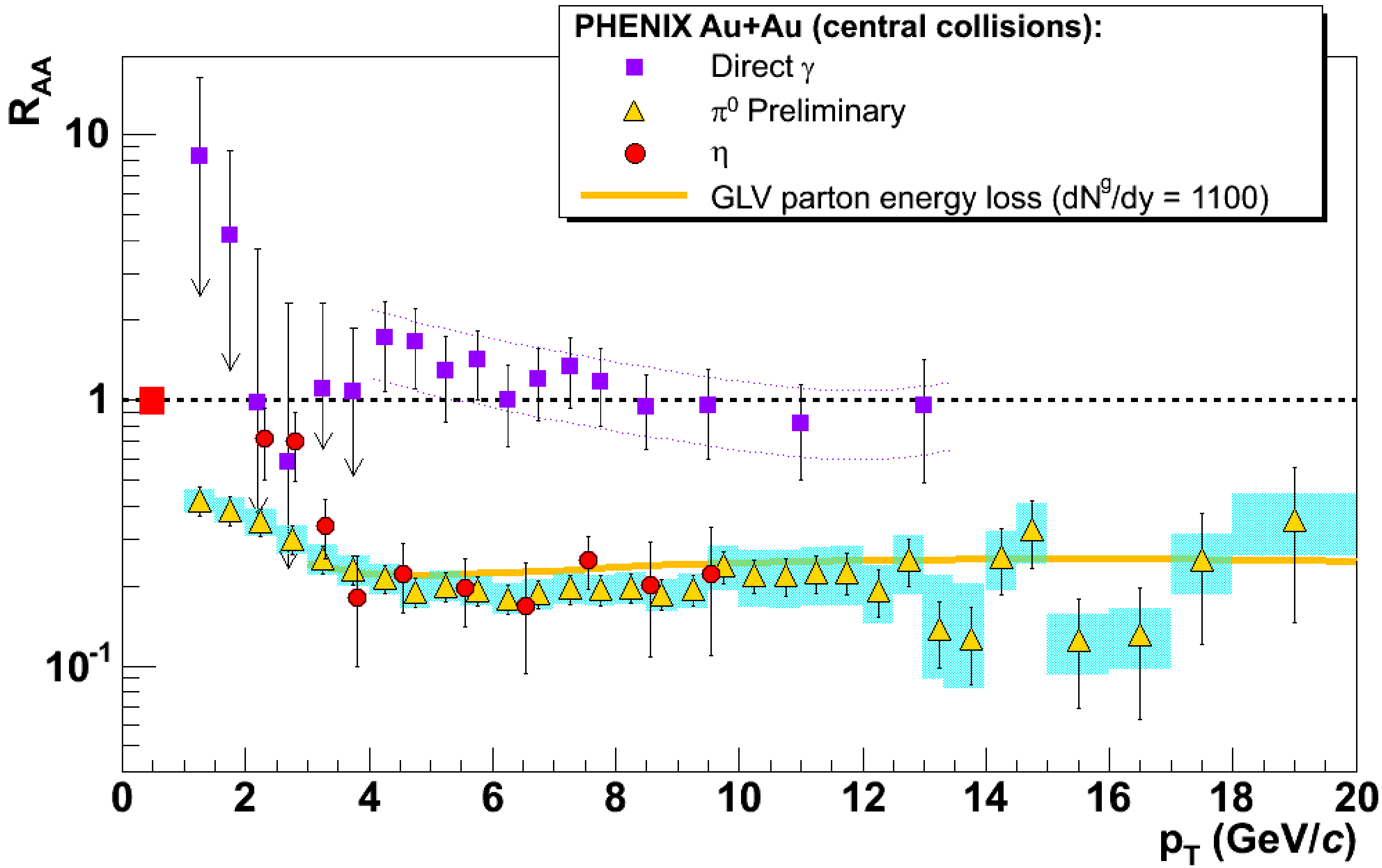
$R_{AA} < 1$ in regime of soft physics

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

Suppression:

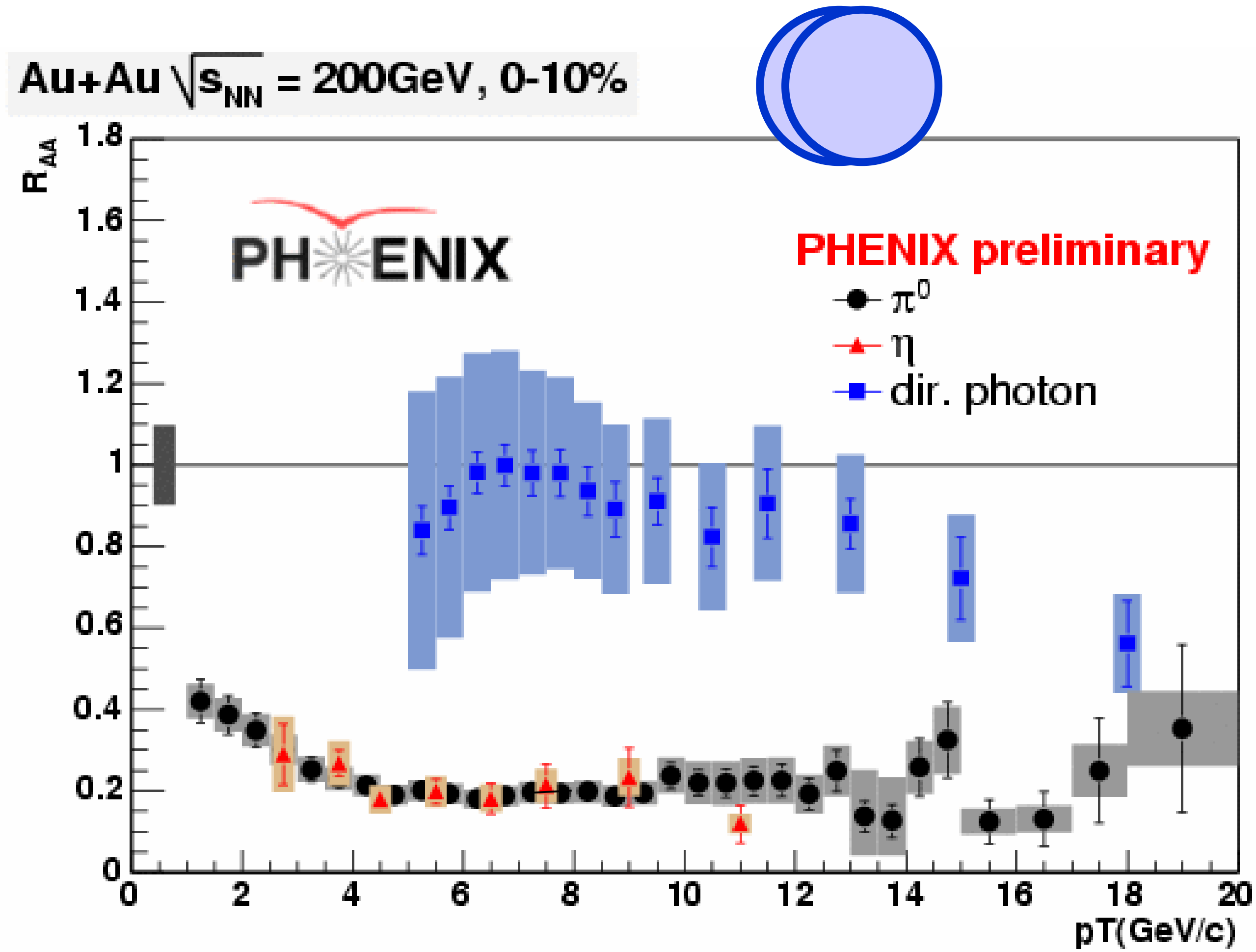
$R_{AA} \ll 1$ at high-$p_T$

# Leading hadrons and hard photons




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

but what about photons at very large $p_t$?




elucidation is LHC territory

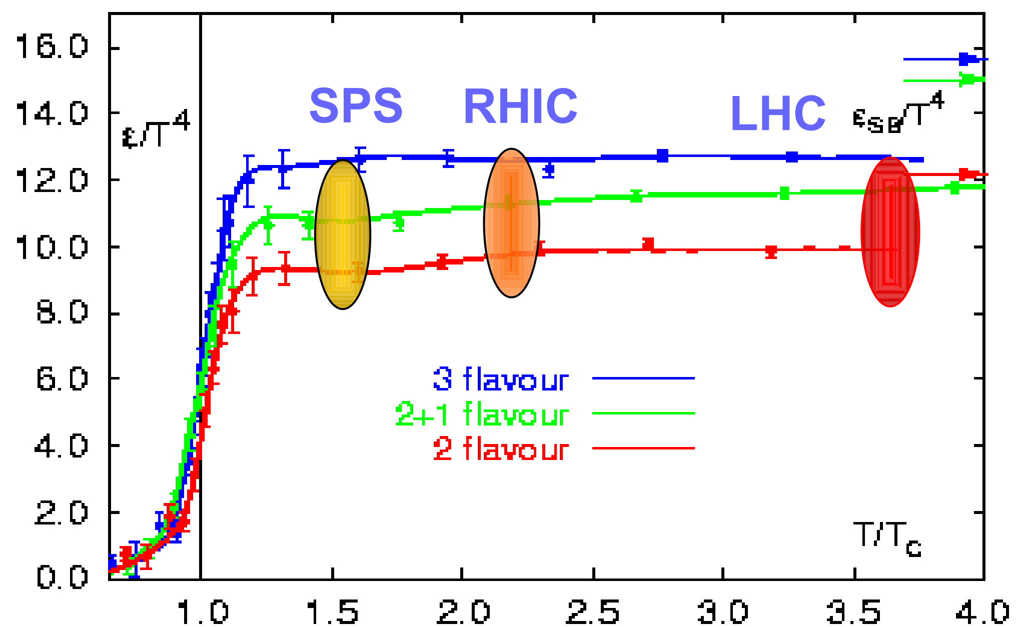
$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d\eta}{T_{AA} d^2 \sigma^{NN} / dp_T d\eta}$$

# jet quenching indicative of gluon rapidity density

| | $\tau_0[fm]$ | $T[MeV]$ | $\varepsilon[GeV/fm^3]$ | $\tau_{tot}[fm]$ | $dN^g/dy$ |
|---|---|---|---|---|---|
| **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

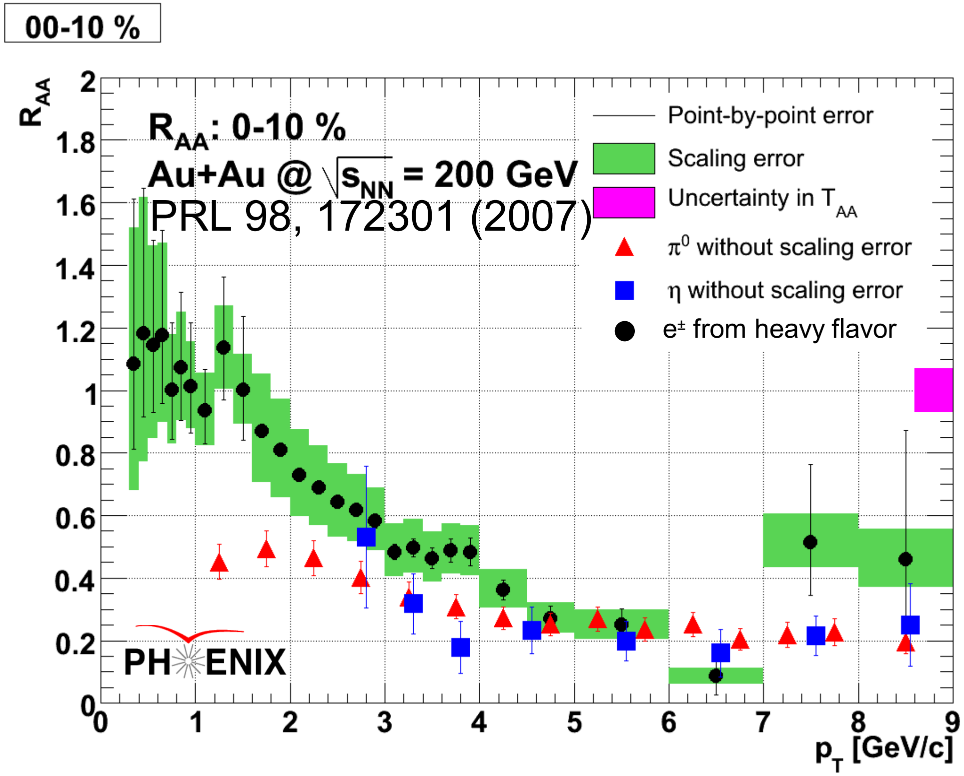
- **Estimates consistent with hydrodynamic analysis**

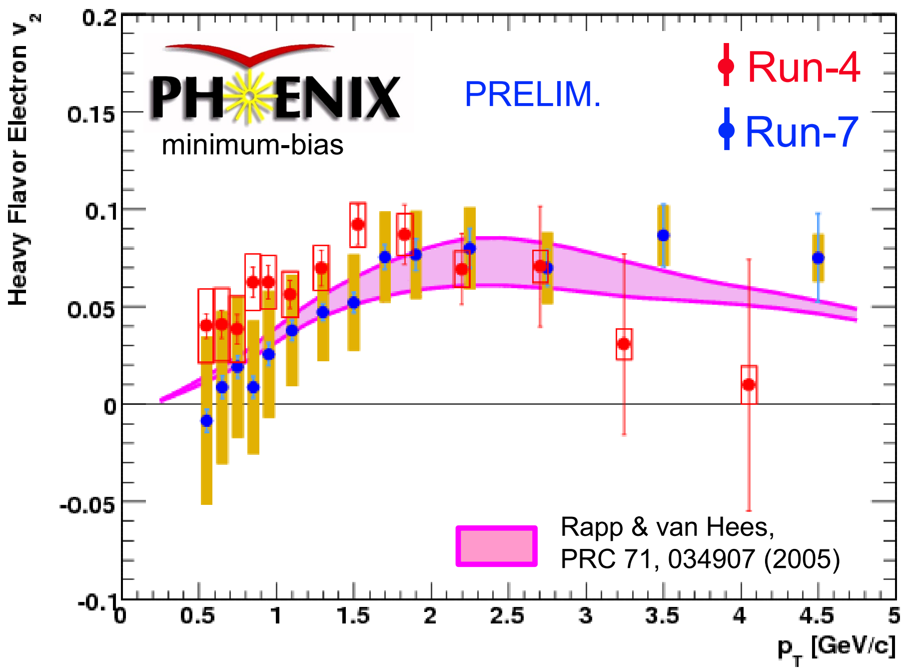


# further big surprize at RHIC: strong energy loss of heavy quarks

electrons from heavy flavor mesons

strong energy loss | hydrodynamic flow

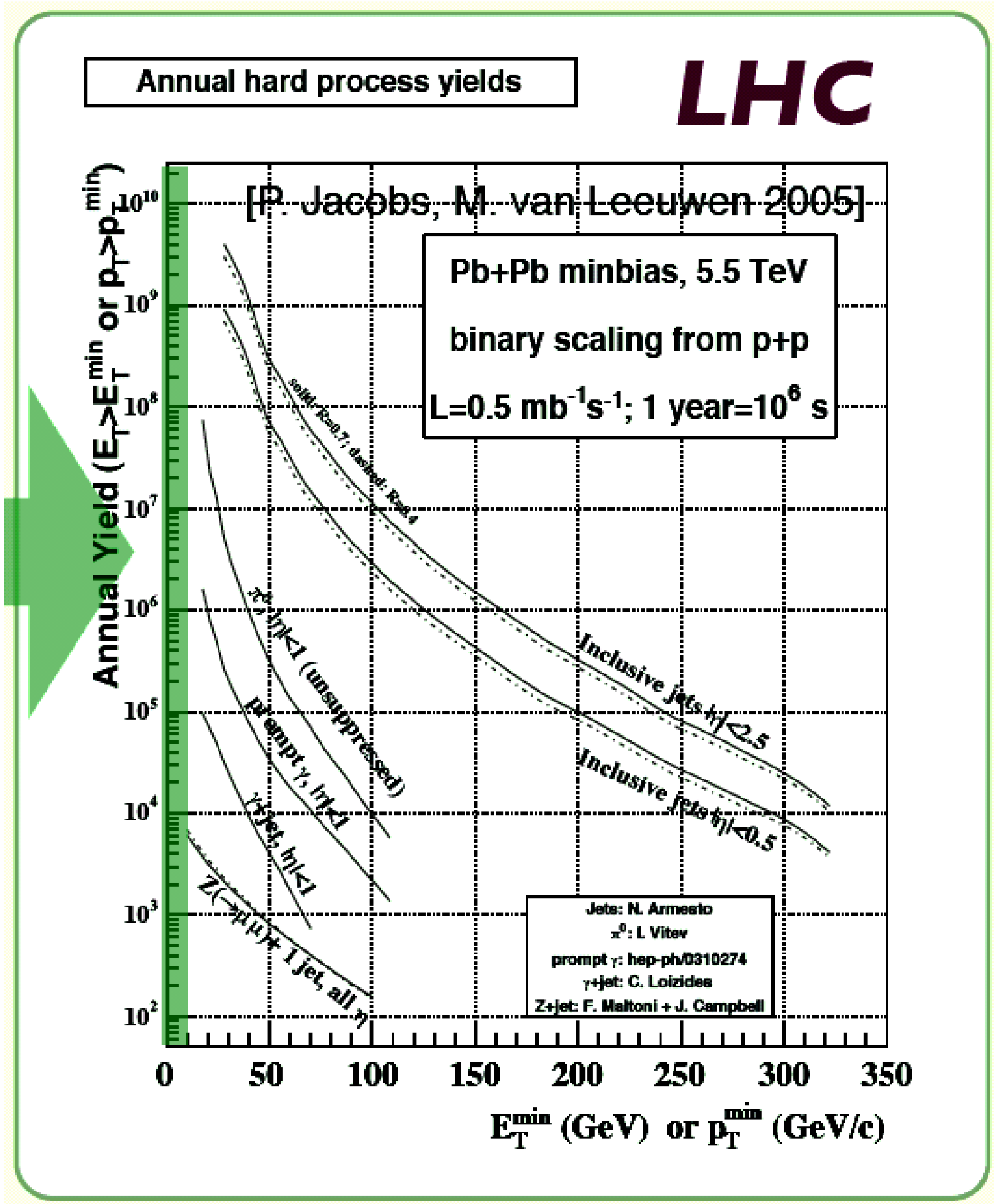



these data are not well explained, measure heavy quarks „directly“ at LHC

# the ultimate hard probes machine

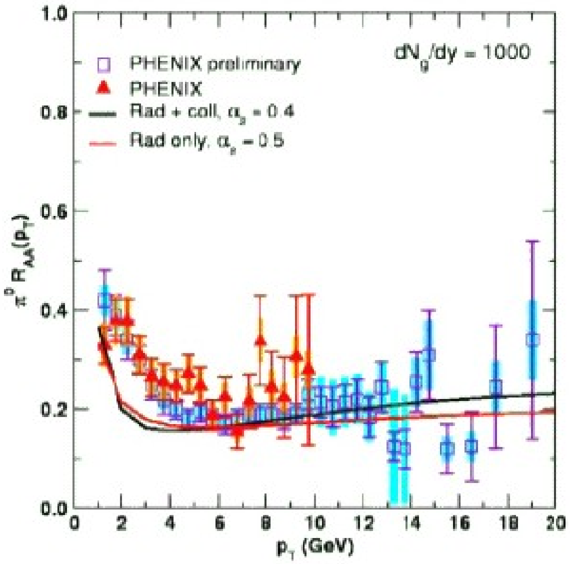
covered
at RHIC

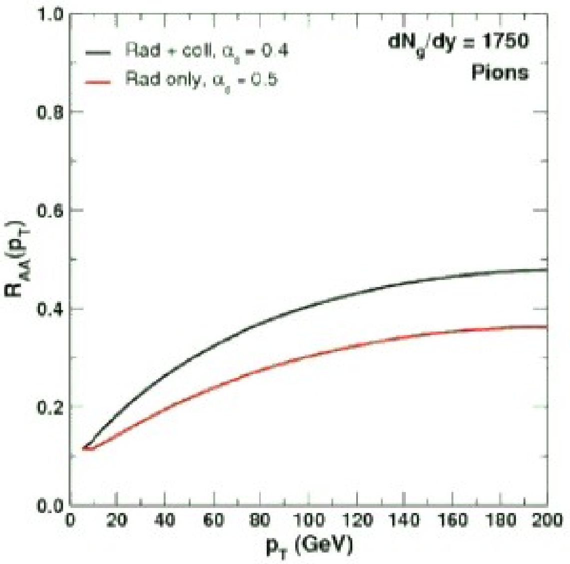


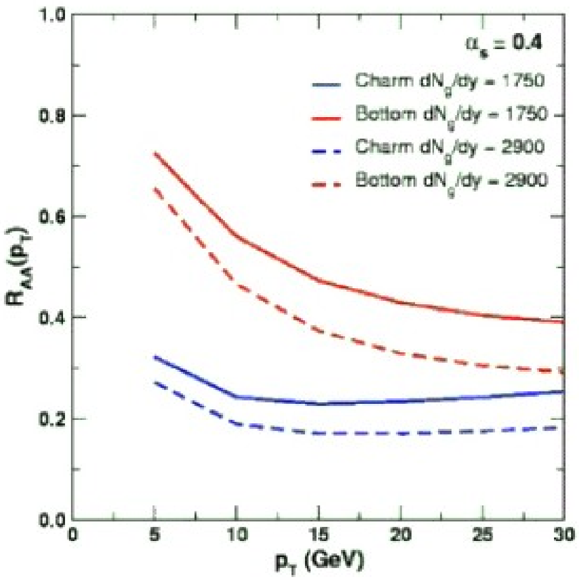

$> 10^4$ jets with
$E_T > 150$ GeV
in one month of
PbPb collisions at LHC

# Predictions for jet quenching at LHC

S. Wicks and M. Gyulassy



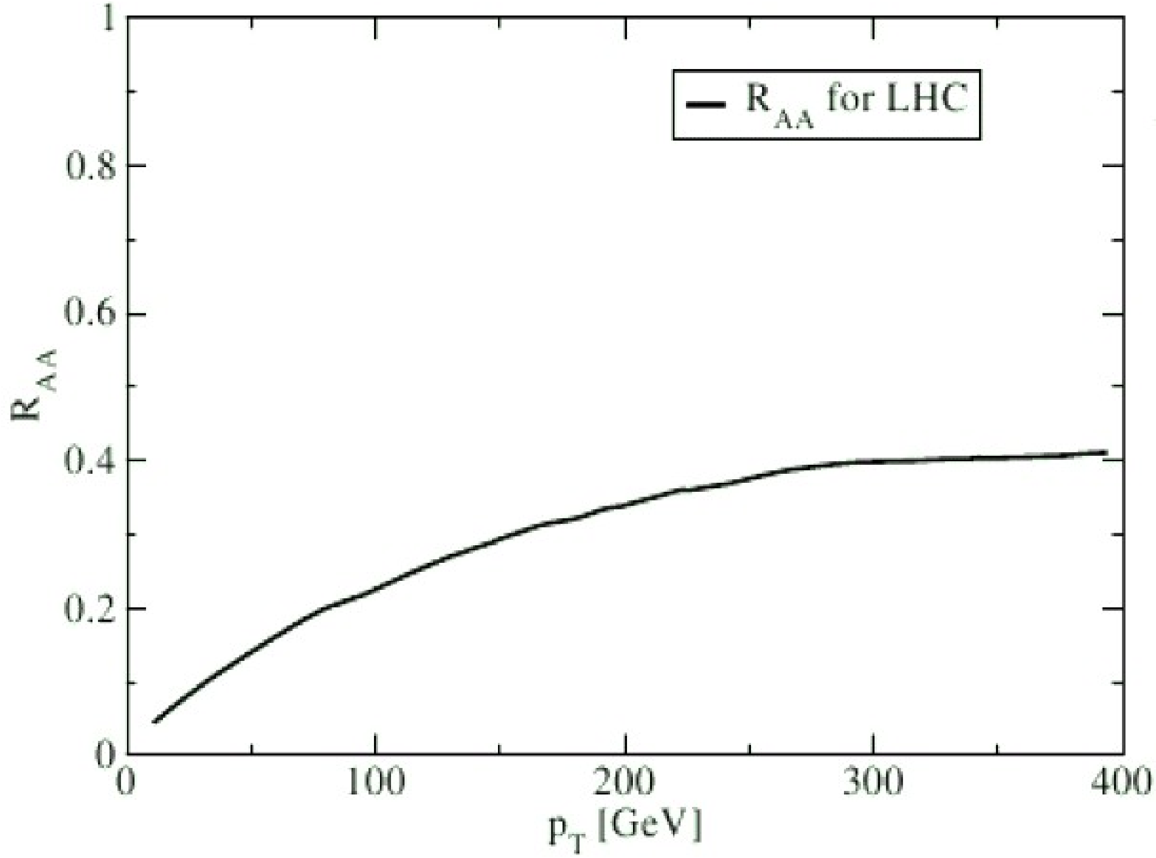



# more predictions...

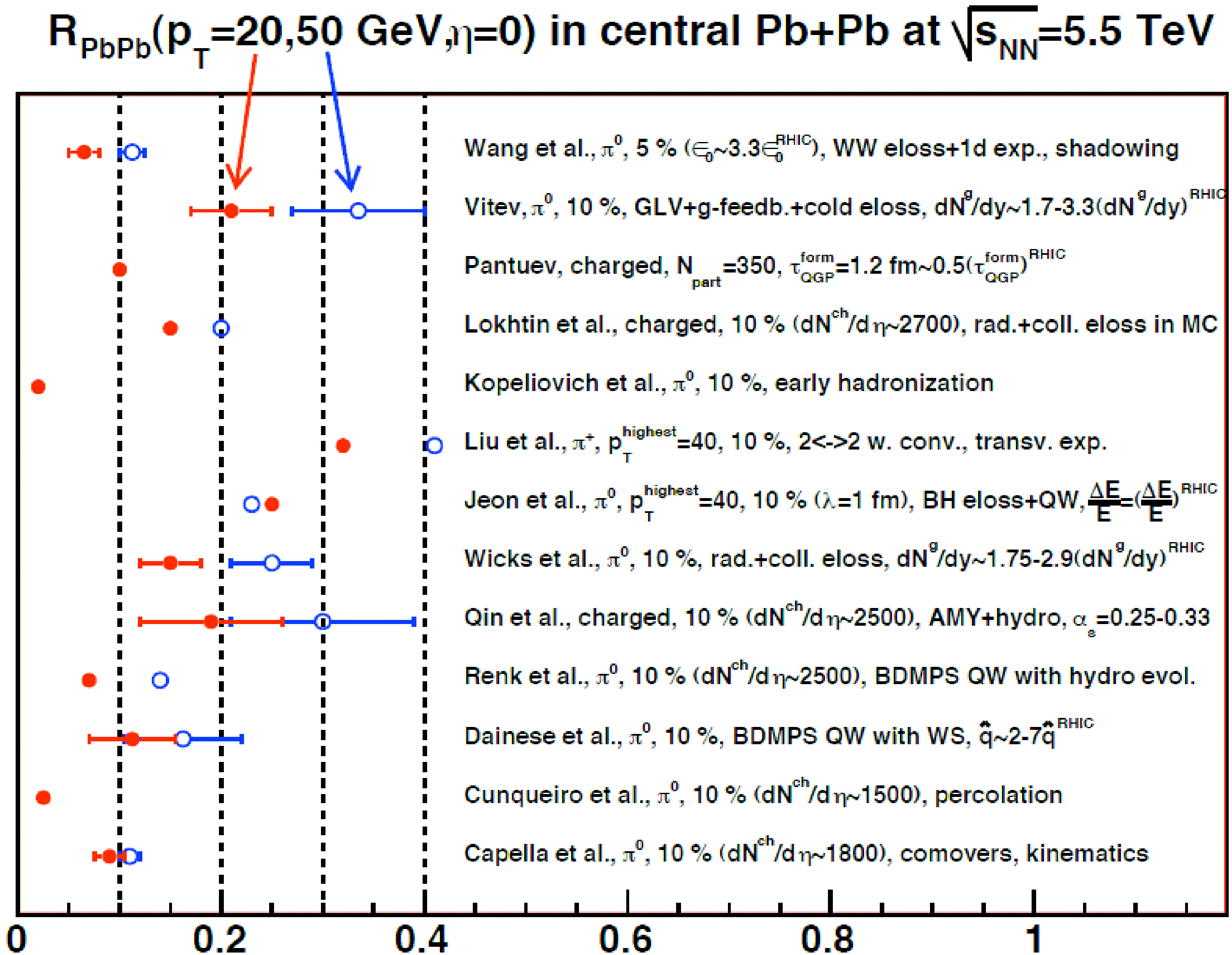
Renk and Eskola

connection
to AdS/CFT
considerations?




important: perturbative QCD regime may never be reached!

# synopsis of jet quenching predictions for LHC energy



# Summary of jet quenching results

- 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

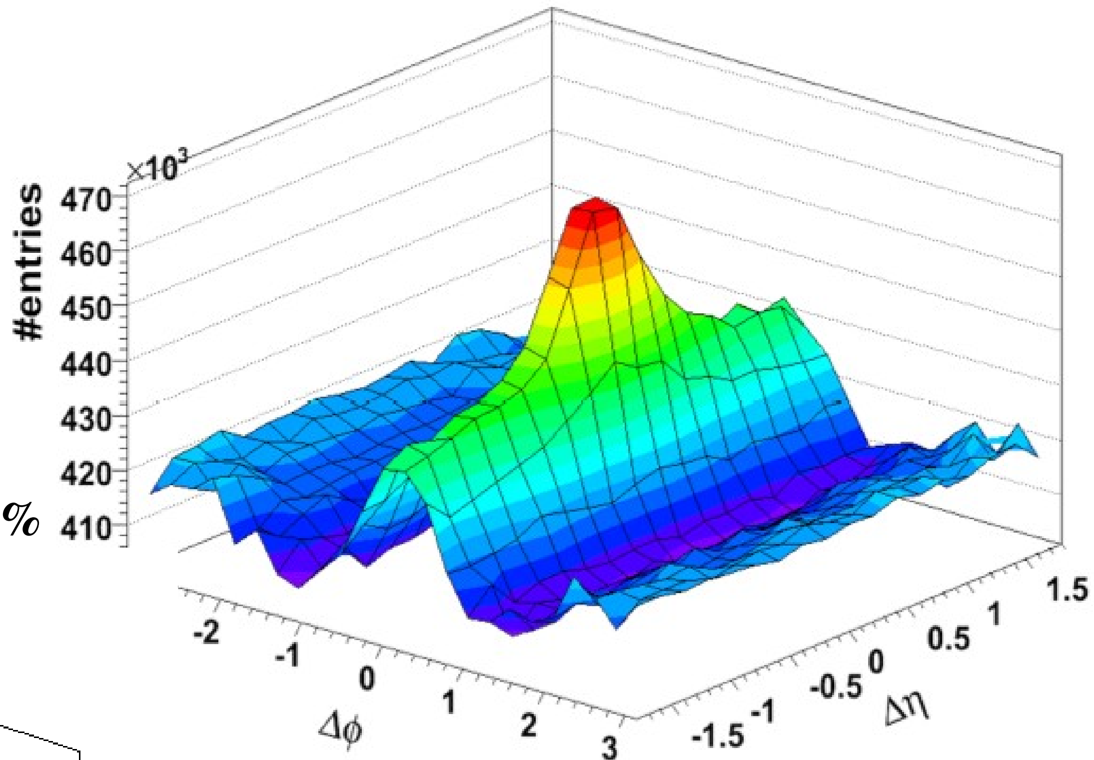
first month of LHC data with $p_t$ reach up to 50 GeV will bring decisive new insights

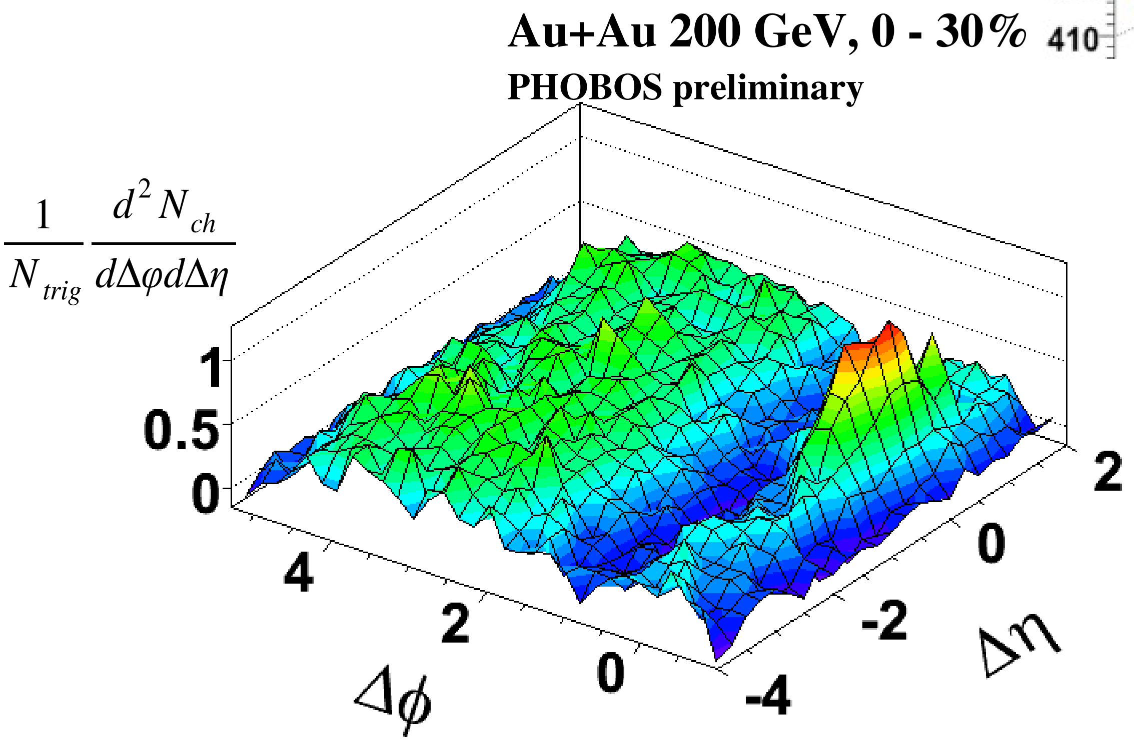
# Another provocative issue: Long range rapidity correlations (the ridge)

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

very early collision phase?
color glass?

STAR AuAu




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 $T_c$

$\rightarrow$ 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

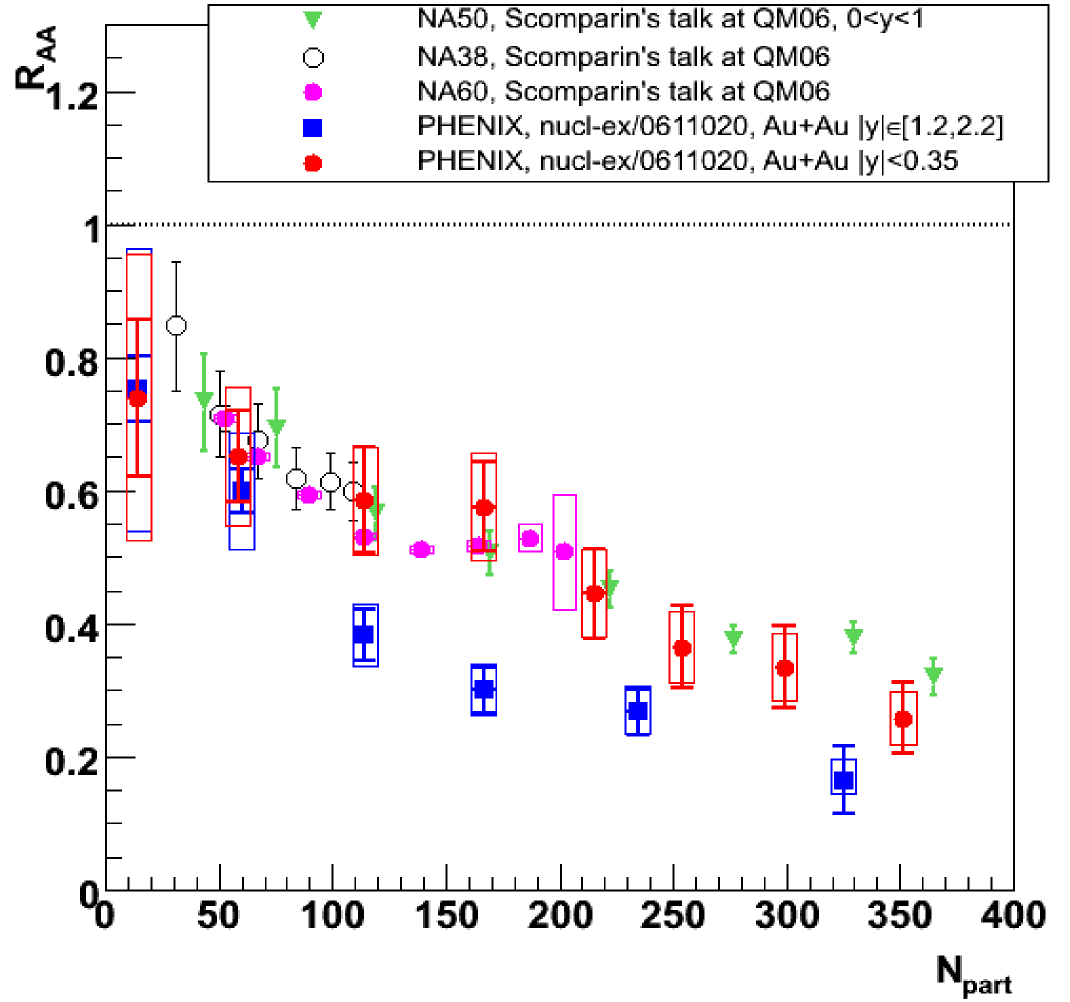
use $R_{AA}$ to define charmonium modification experimentally
no need to normalize to Drell-Yan process

$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

if $\sigma_{Drell\text{-}Yan} \propto N_{coll}$ , $R_{AA}$ 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

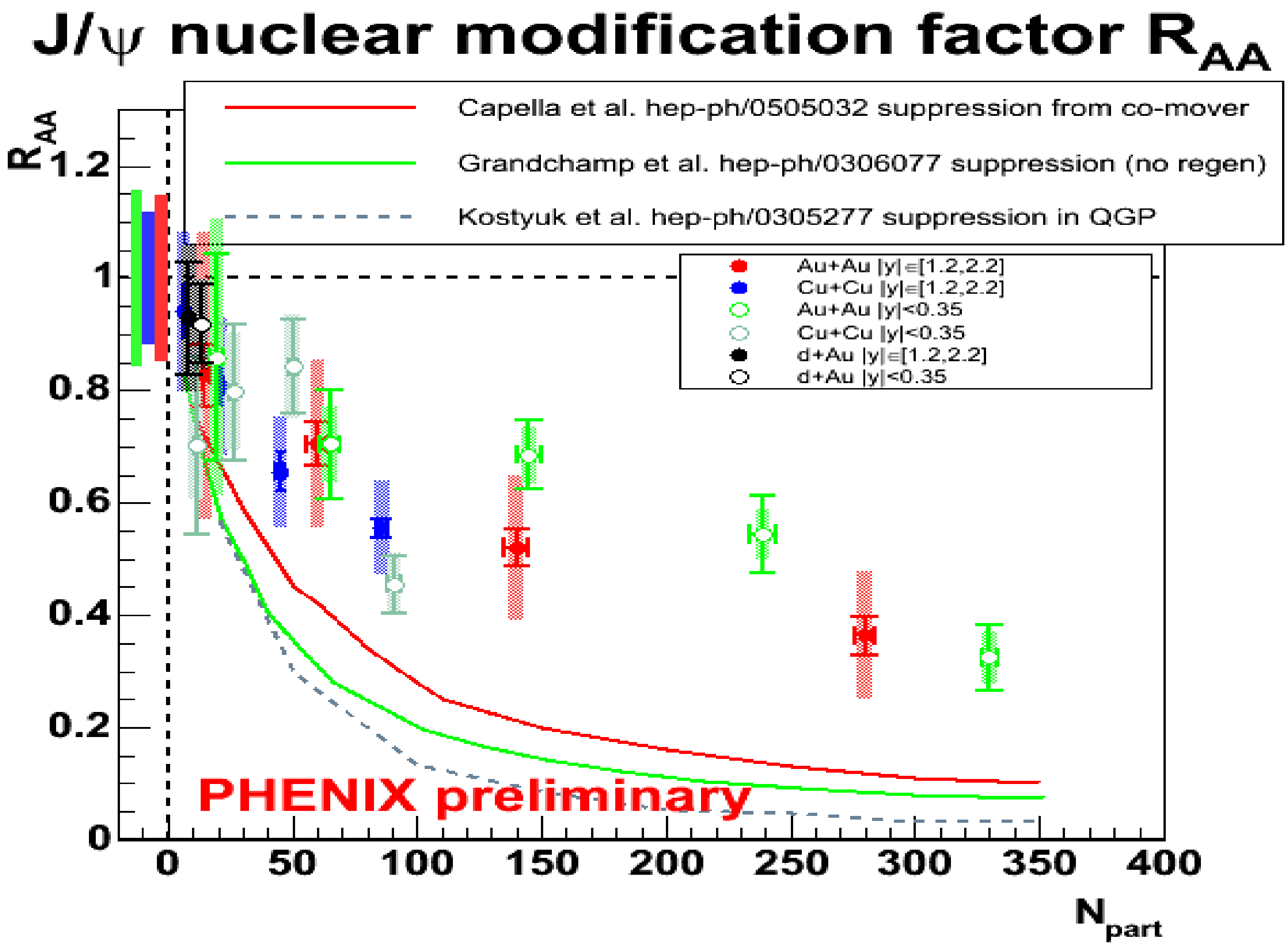



comparison produced by
R. Granier de Cassagnac

# 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



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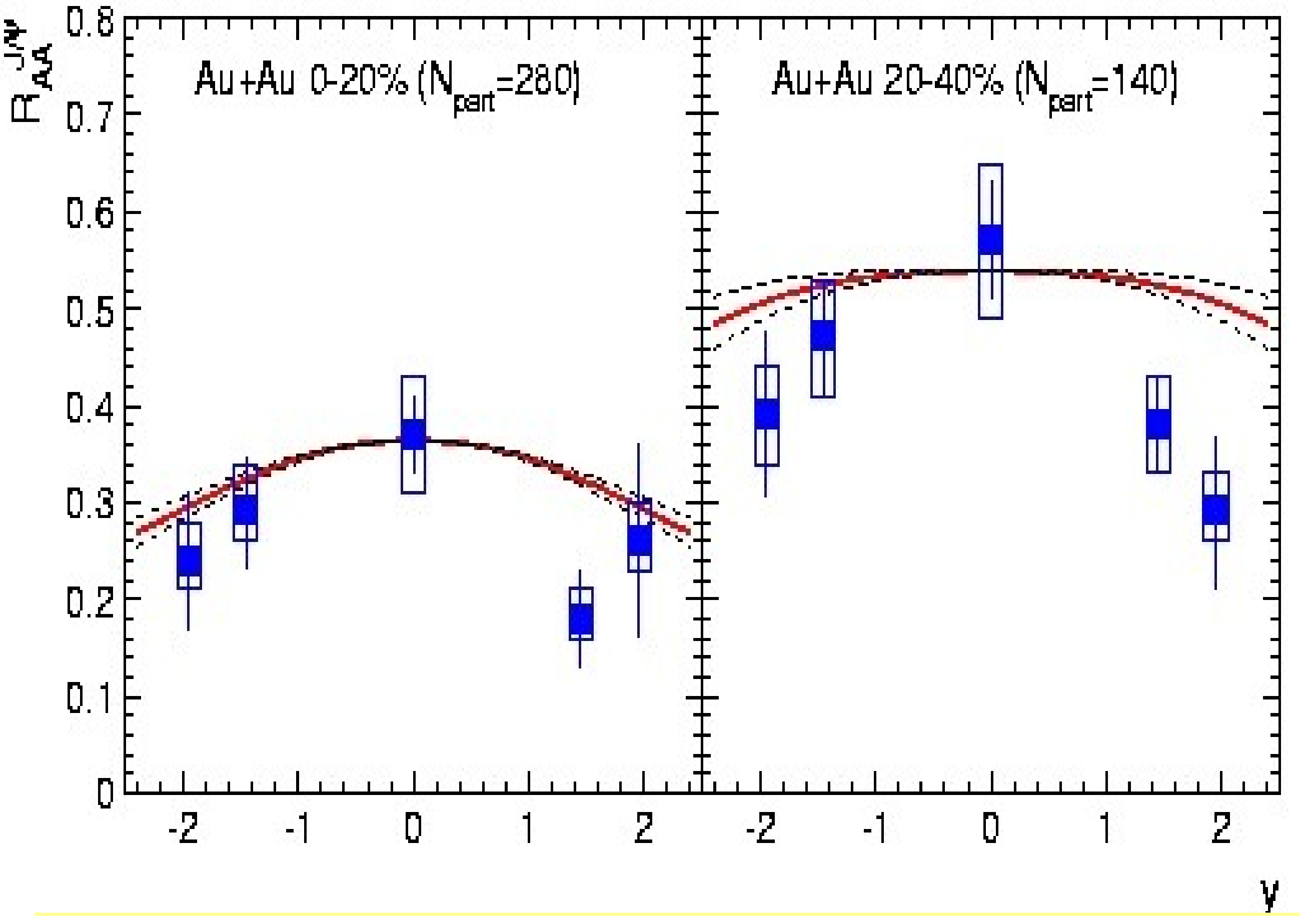
# Comparison of model predictions to RHIC data: rapidity dependence

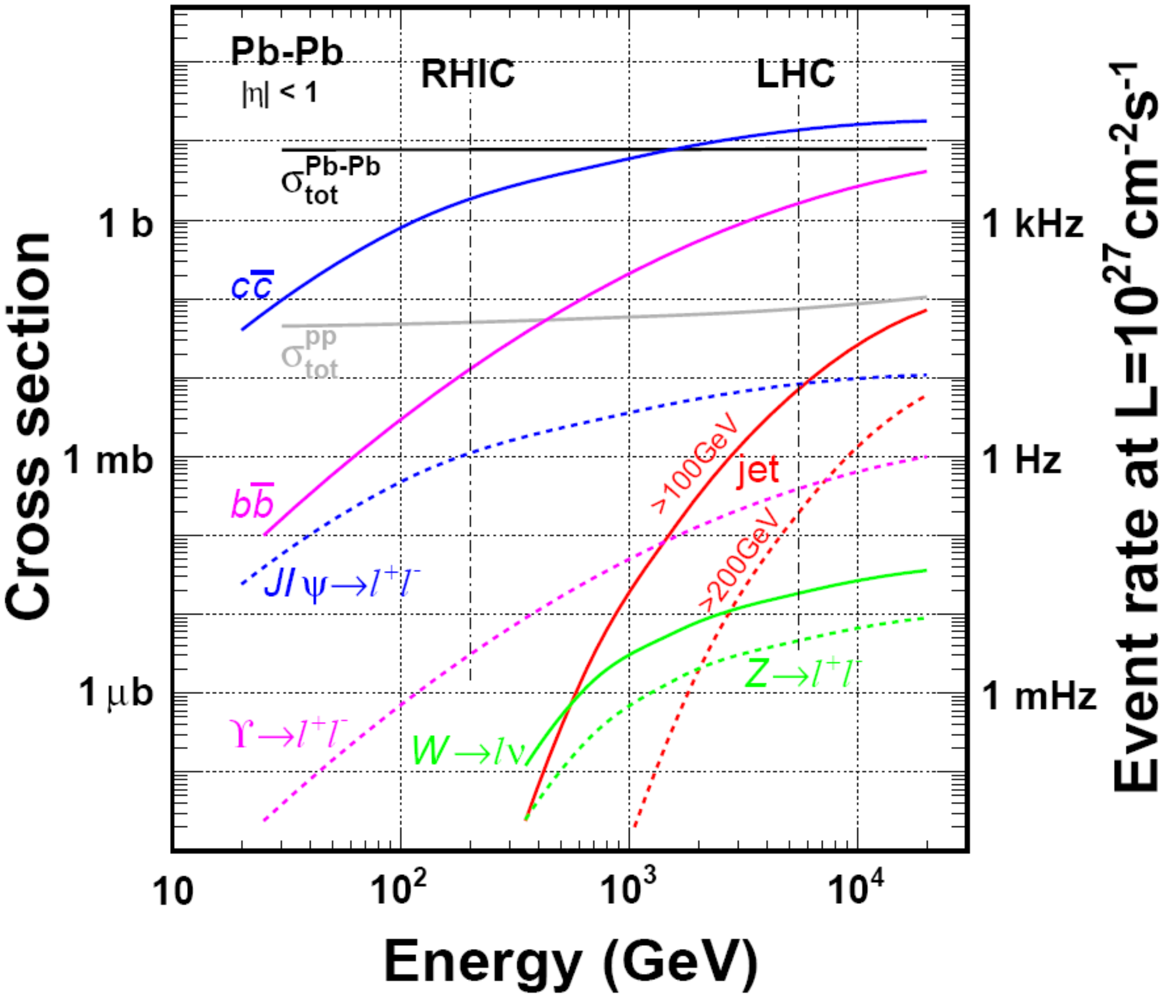



charmonium generation via statistical hadronization

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

~ $10^2$ (bbar) to

> $10^5$ (very high $p_T$ jets)

# Quarkonium as a probe for deconfinement at the LHC

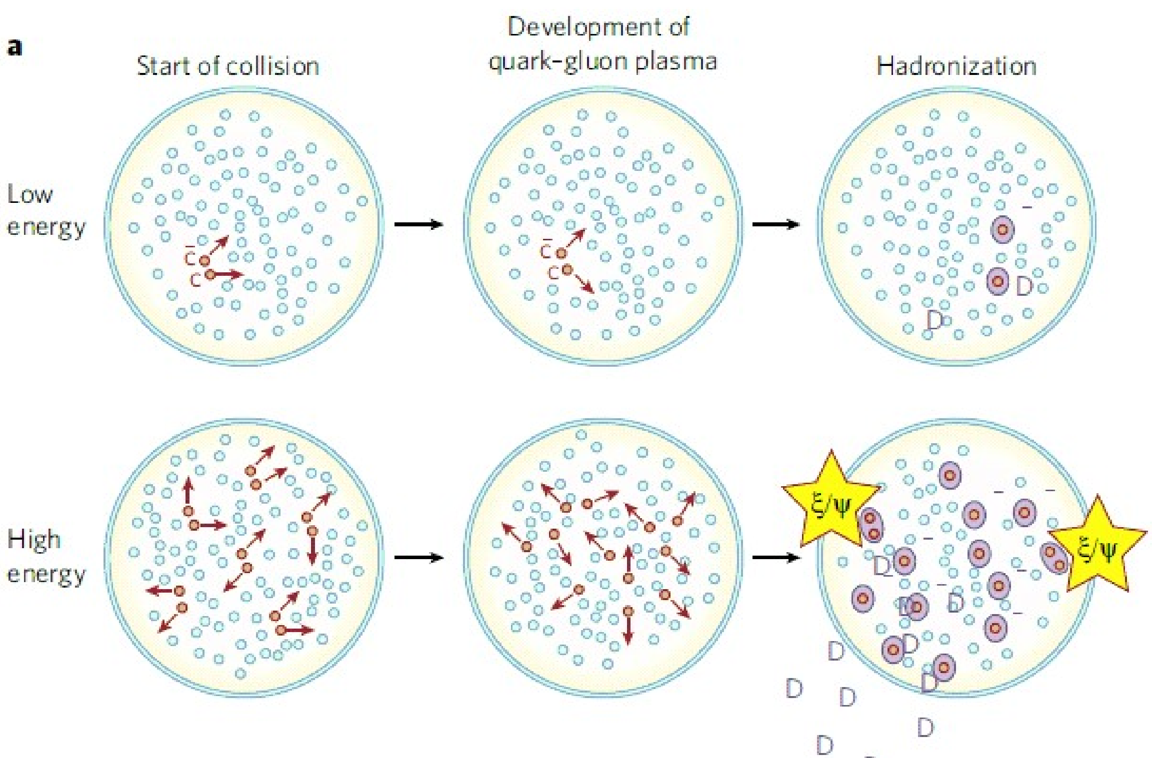
at hadronization of QGP $J/\psi$ can form again from deconfined quarks, in particular if number of ccbar pairs is large

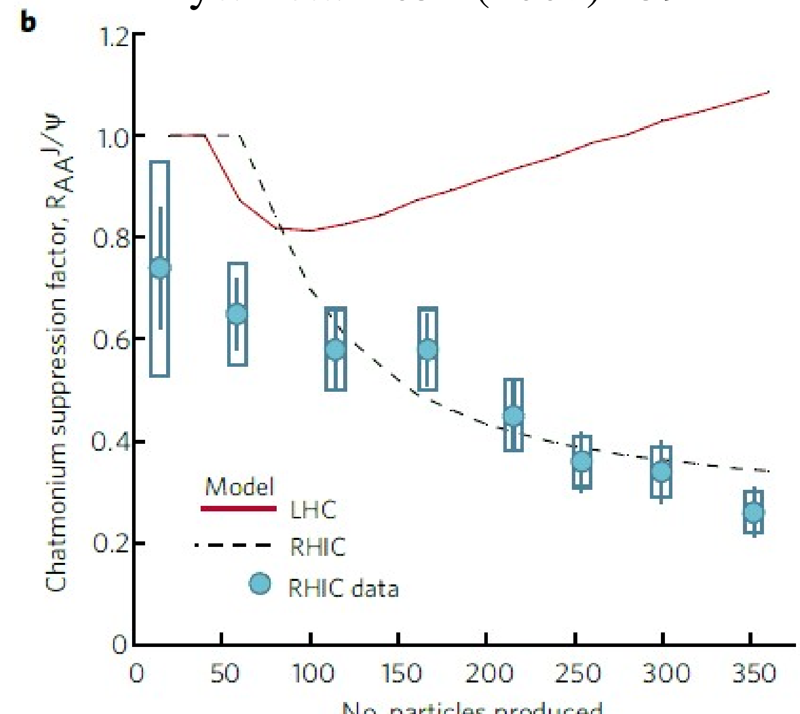
$$N_{J/\psi} \propto N_{cc}^{\;2}$$

(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



# Summary of RHIC data on charmonium production

- 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 thousend charmonia will bring decisive new insights

# final comment

the discoveries at RHIC, principally on

thermalization and flow --> ideal fluid scenario

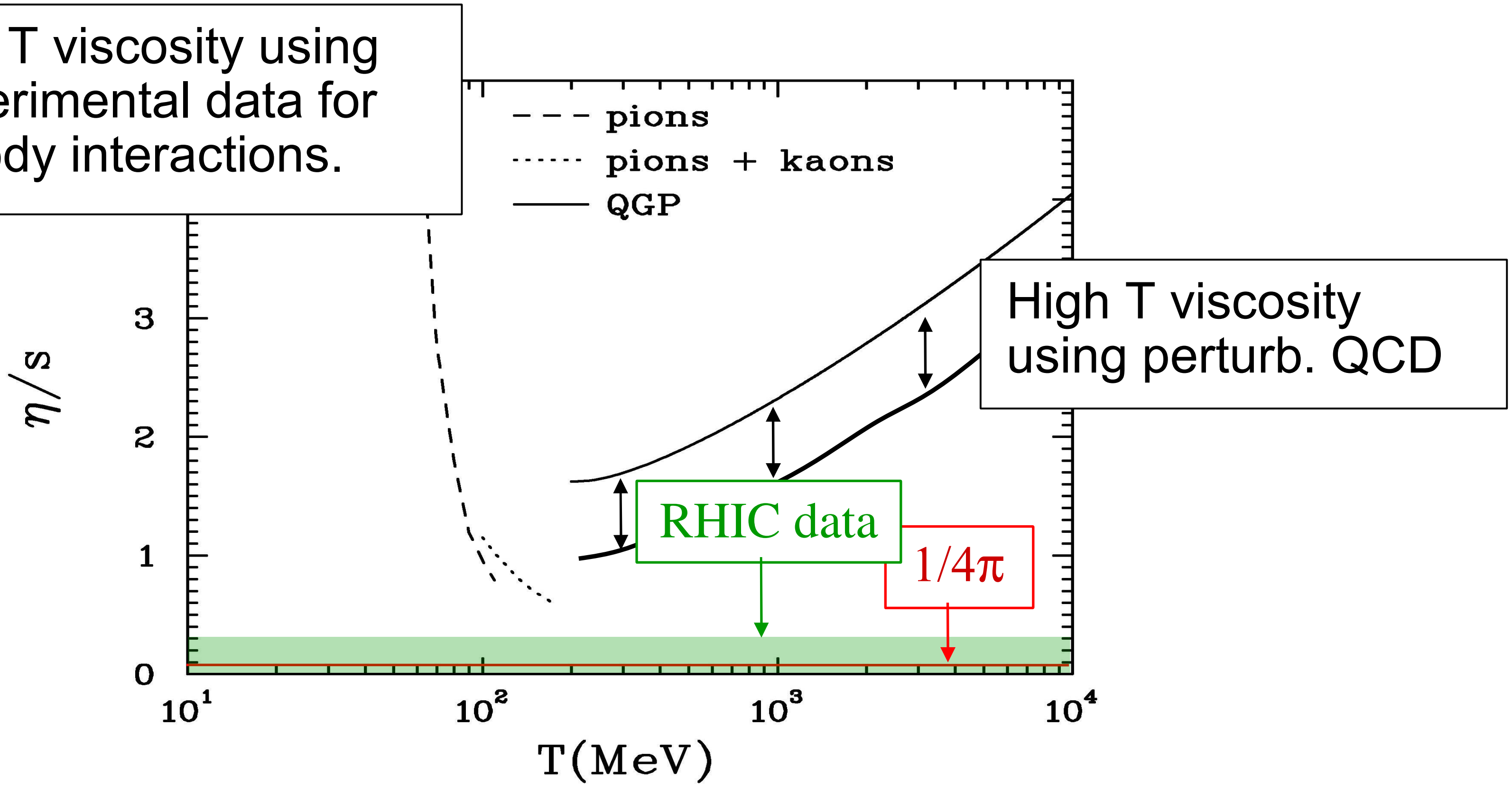
jet quenching --> parton energy loss in dense fireball

have led to major progress in our understanding of the QGP

These discoveries raise many new questions. Even a short heavy ion run in 2009/2010 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 betwe

# Thermal model description of hadron yields

Grand Canonical Ensemble

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

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

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

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

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

This leaves only $\mu_b$ and T as free parameter when $4\pi$ considered

for rapidity slice fix volume e.g. by $dN_{ch}/dy$

**Fit at each energy provides values for T and $\mu_b$**

# 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
(μ < 400 MeV)