Diagnosing a new state of matter in collisions of atomic nuclei at very high energy

recent reviews:

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

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

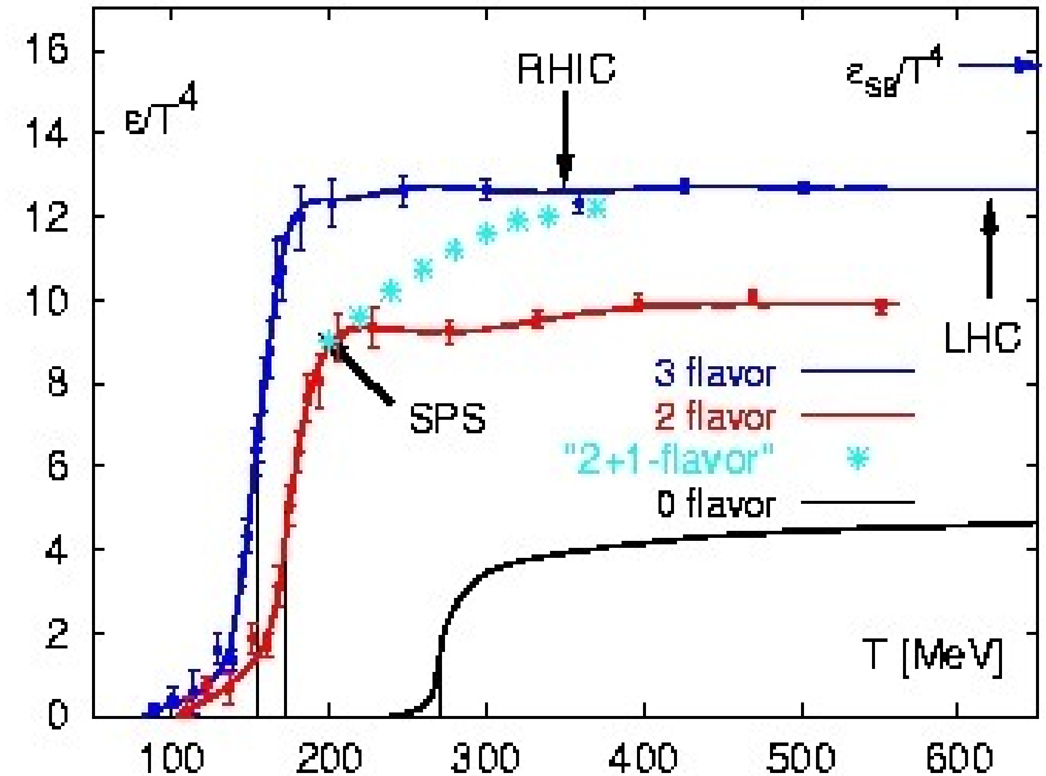
pbm and J. Wambach, Rev. Mod. Phys. (2009) in print
arXiv:0801.4256

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

Minerva symposium, Berlin, Oct. 13, 2009

Peter Braun-Munzinger

Critical energy density and critical temperature



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

$T_c = 173 \pm 12$ MeV

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

for the (2 + 1) flavor case:

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

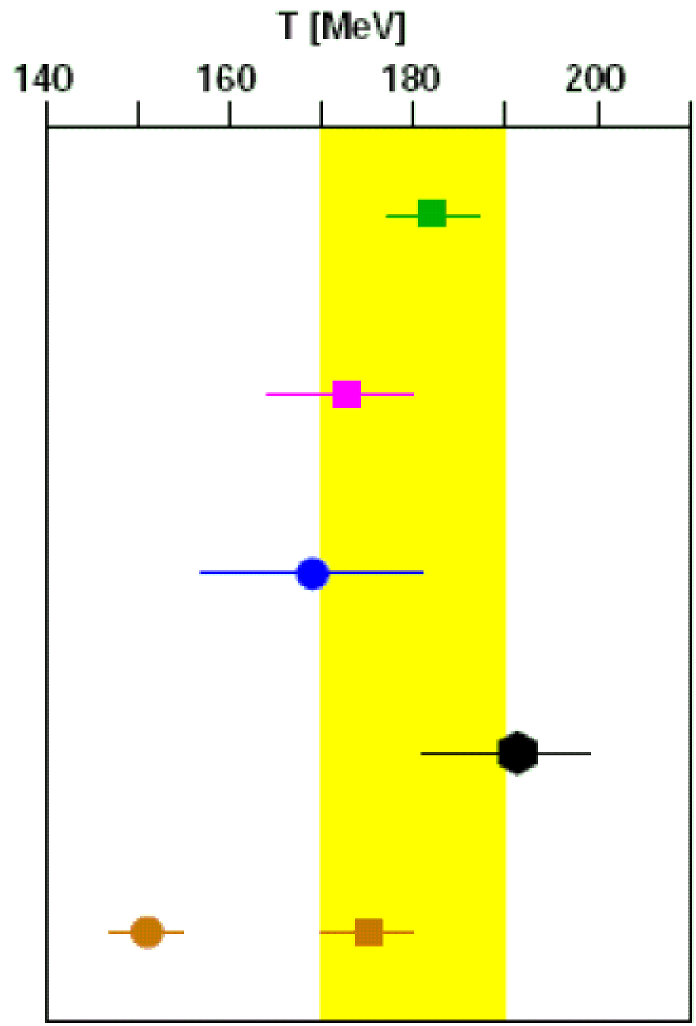
The order of the transition is not yet definitively determined, see also:

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.

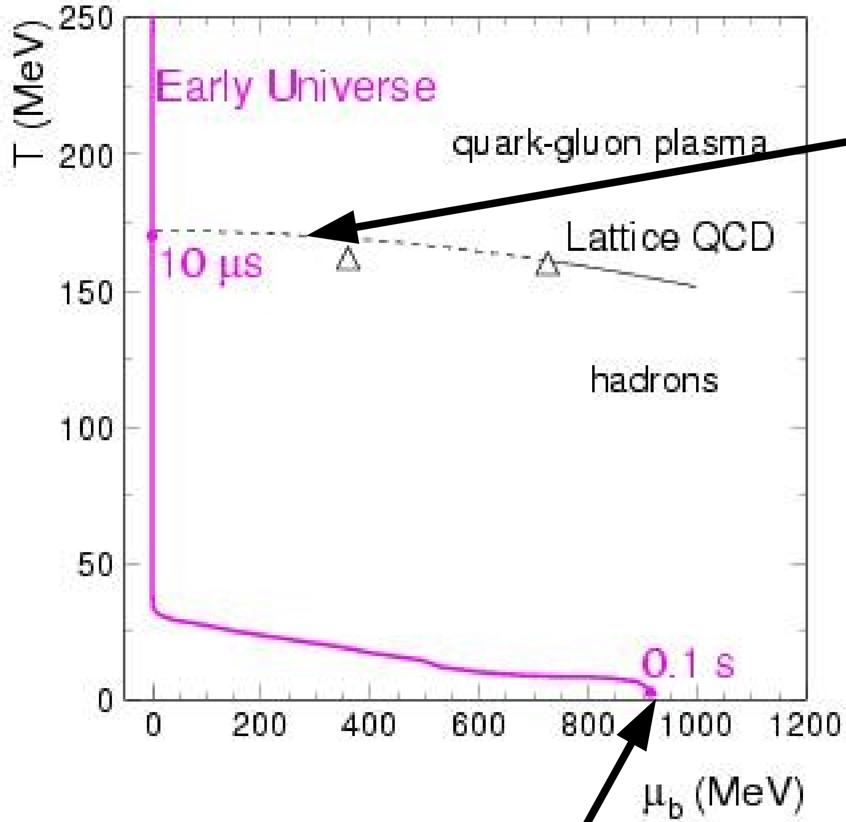
current status of lattice QCD calculations -- critical temperature

most rcent result from Riken-BNL-Bielefeld group (lattice 2009) T_c ~ 165 MeV



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 with nuclear collisions

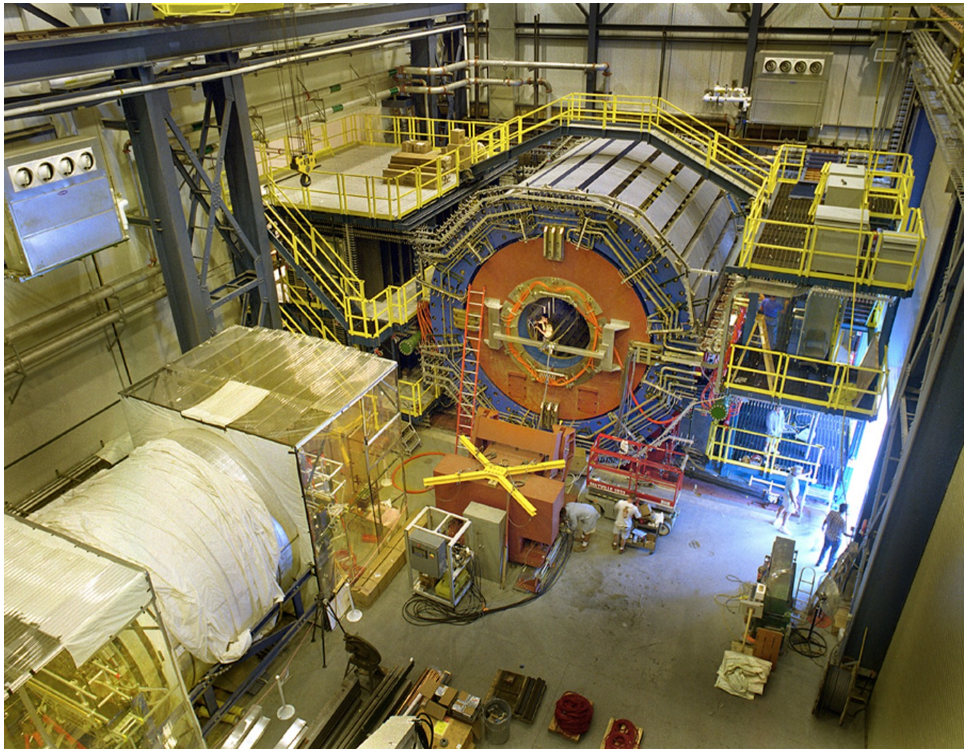
equation of state
number of degrees of freedom
transport coefficients (viscosity etc)
velocity of sound
parton energy loss and opacity
susceptibilities
deconfinement

but also, at LHC, to start soon, look for the unexpected

RHIC experiments: 2 large and 2 small

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

STAR: large TPC at central rapidity

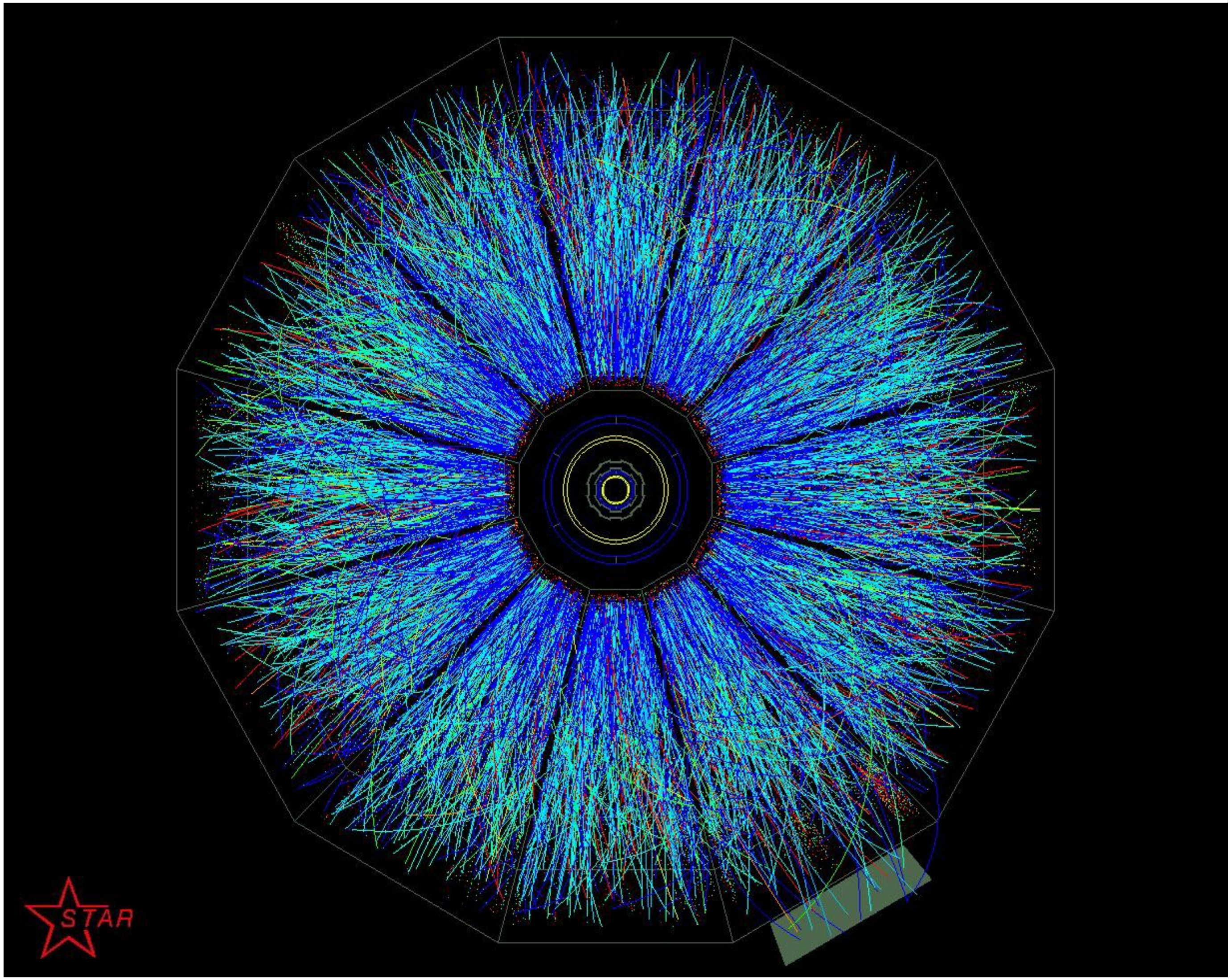


as well as PHOBOS and BRAHMS (both completed)

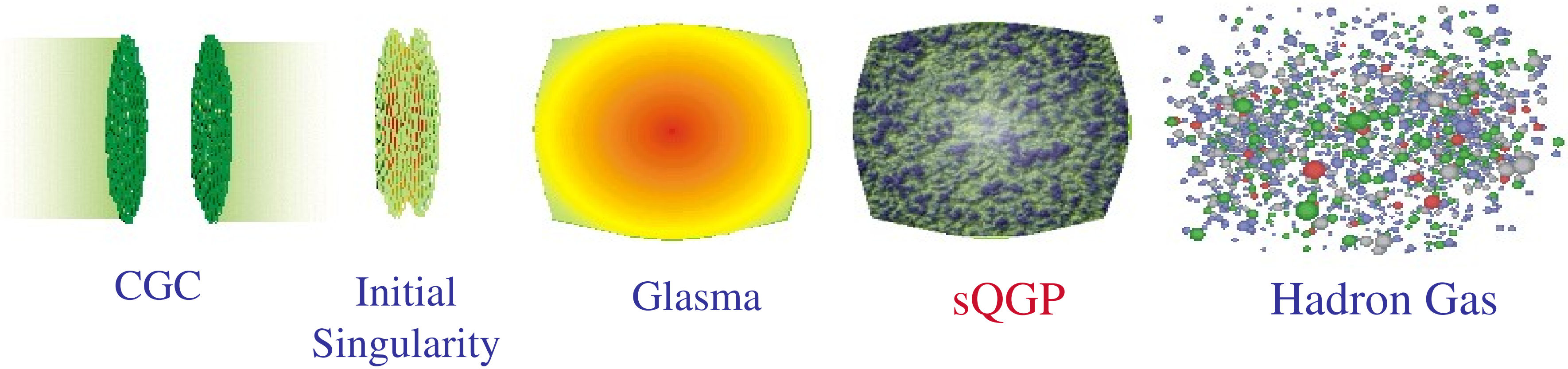
STAR event display

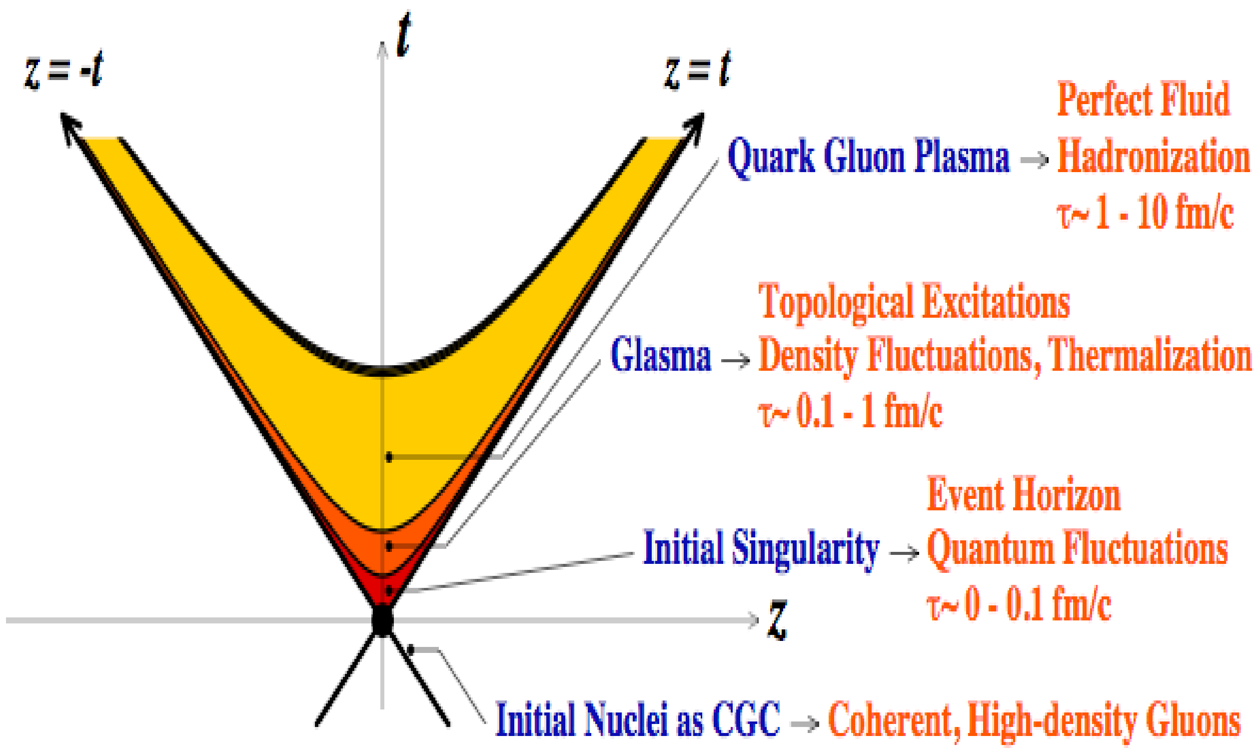
in central AuAu collsions at RHIC √s = 200 GeV about 7500 hadrons produced (BRAHMS)

about three times as much as at CERN SPS



The Space-Time Evolution of a Relativistic Nuclear Collision



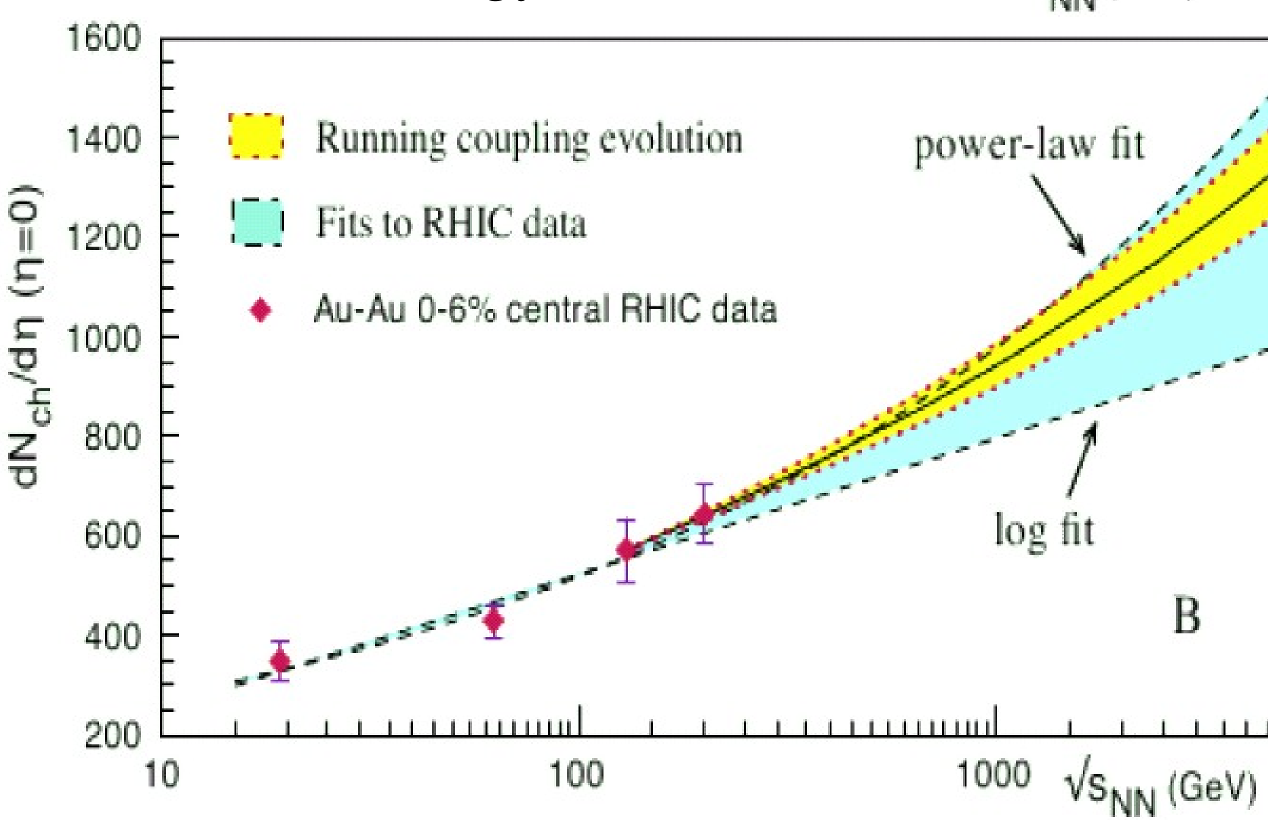


one possible view
(courtesy
Larry McLerran)

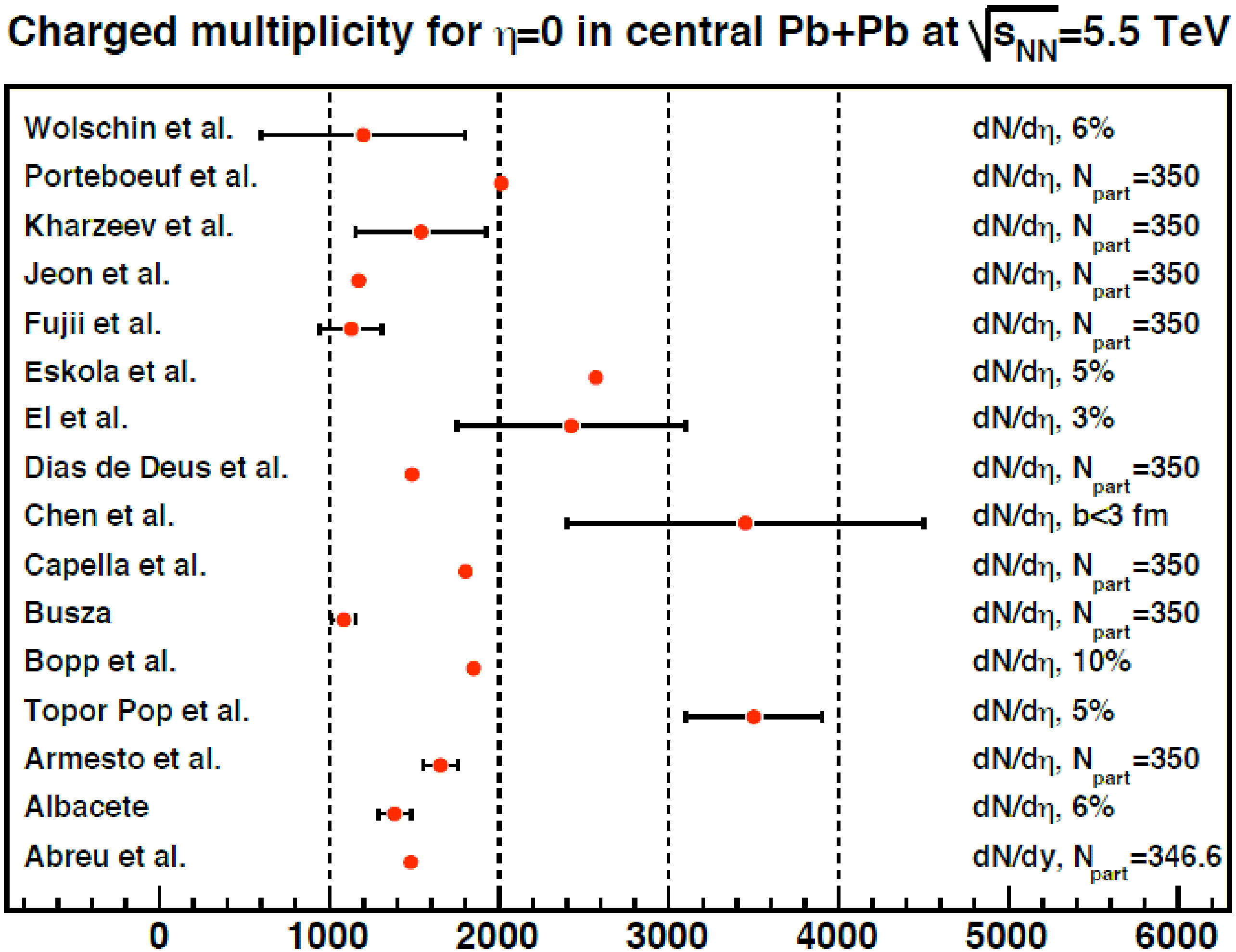
fireball measurements – charged particle multiplicity

thousends of particles (mesons, baryons) are produced in one collision!

Extrapolation to LHC energy??



differing predictions for multiplicity density



compilation from: arXiv:0711.0974

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

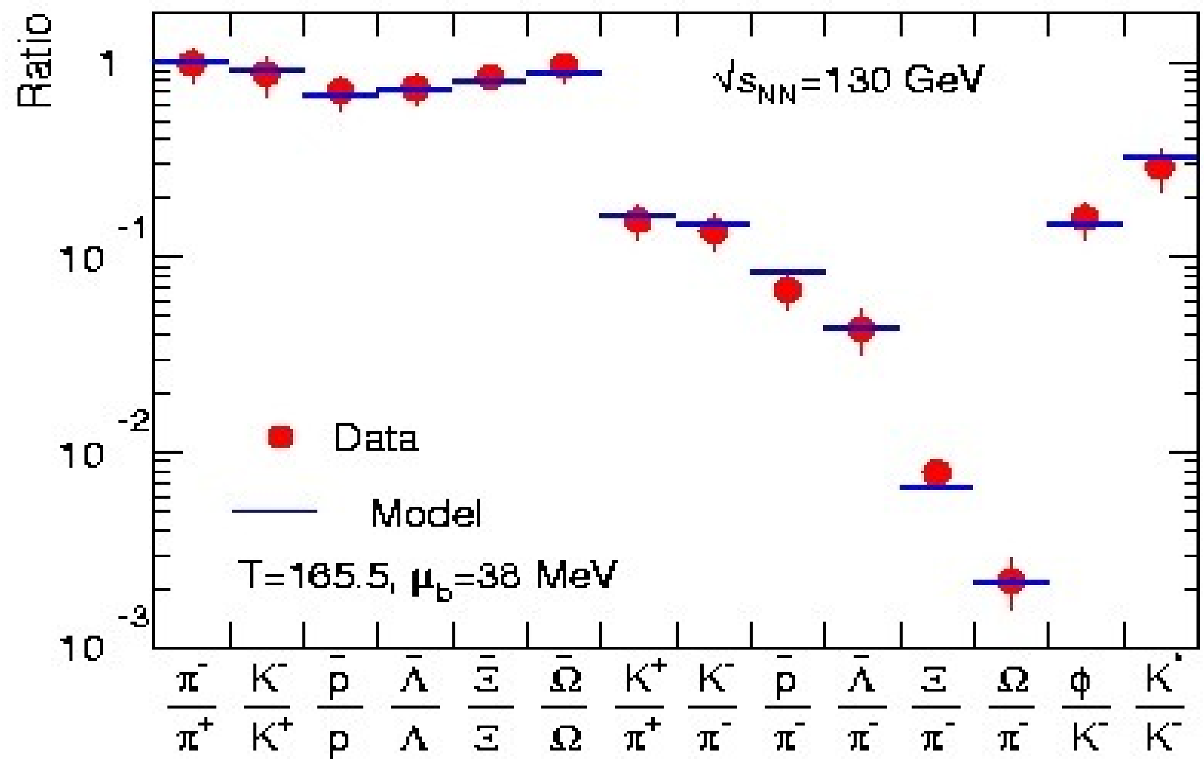
Hadro-chemistry at RHIC

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



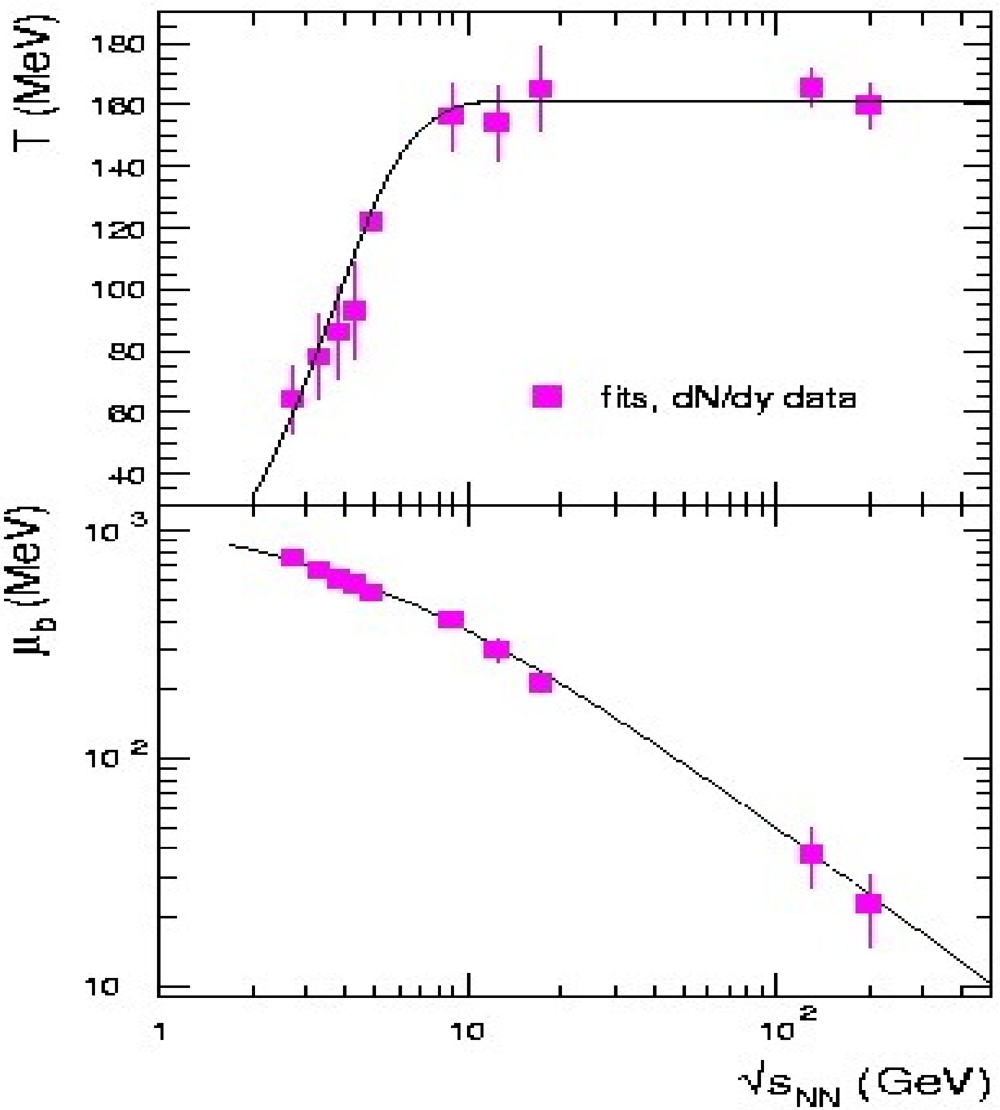
pbm, Magestro, Stachel, Redlich, Phys. Lett. B518 (2001) 41;
see also Xu et al., Nucl. Phys. A698(2002) 306;
Becattini, J. Phys. G28 (2002) 1553;
Broniowski et al., nucl-th/0212052.

Parameterization of all freeze-out points

note: discovery of the limiting temperature

T_{lim} = 160 MeV

provides connection to QCD phase boundary



Boiling point of hadronic matter – implies phase transition to QGP

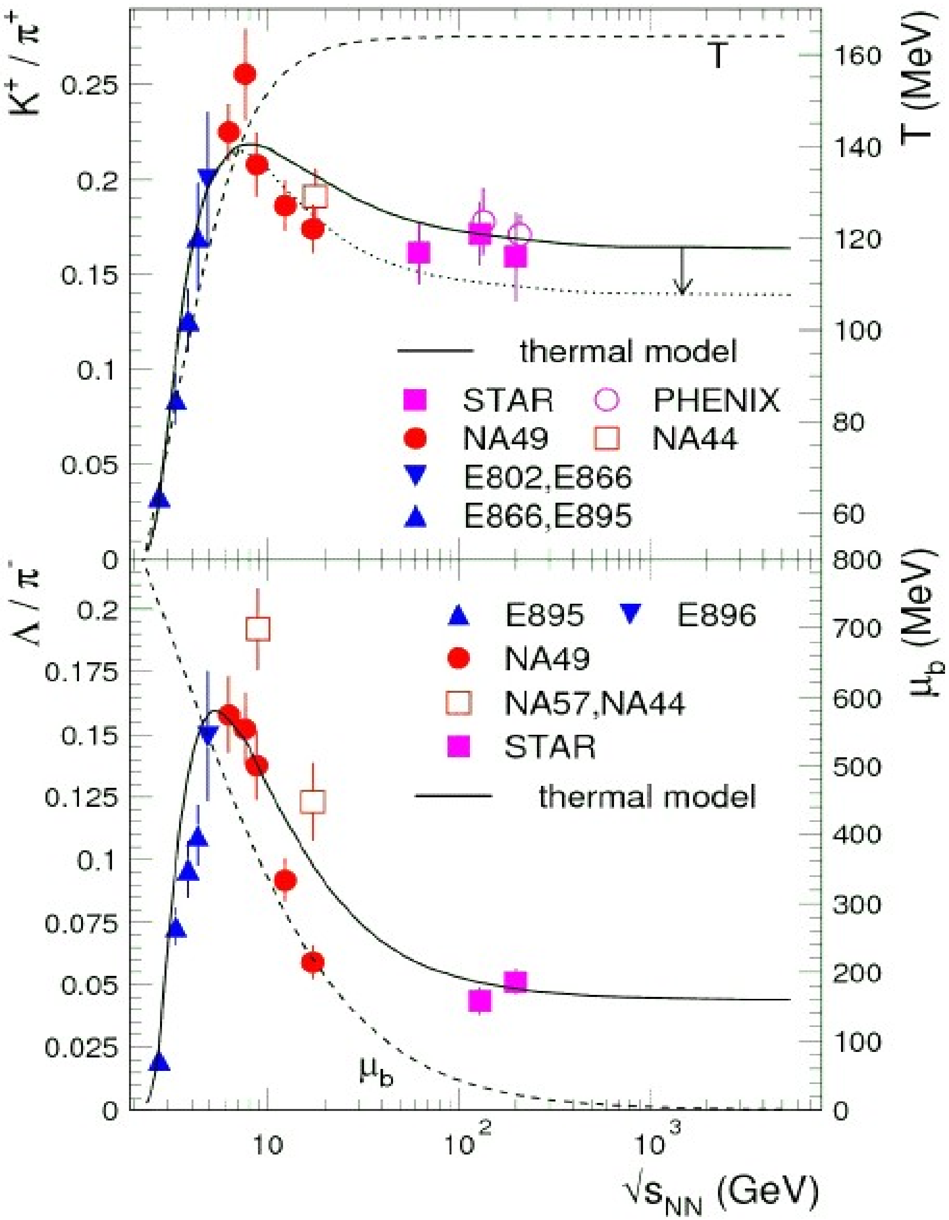
Horn structure well described

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



GSI

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Summary of statistical model interpretation

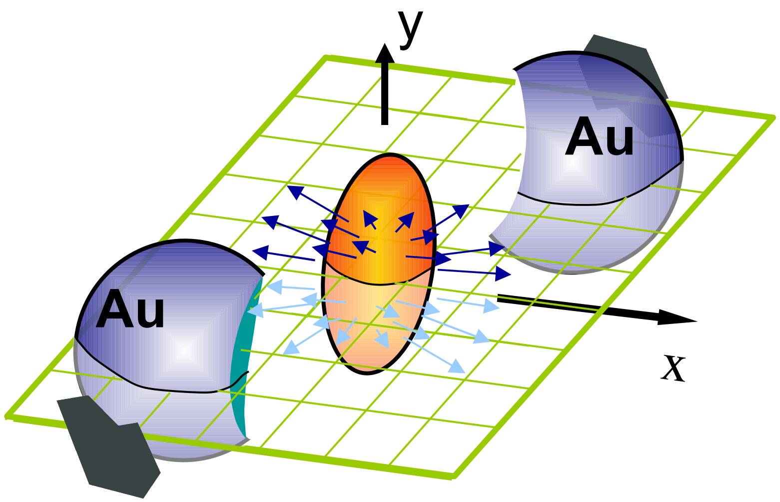
- hadron yields quantitatively described at all energies by 3 parameters: T, mu_b, V
- local equilibrium neat T_c
- limiting temperature established
- connection to QCD phase boundary

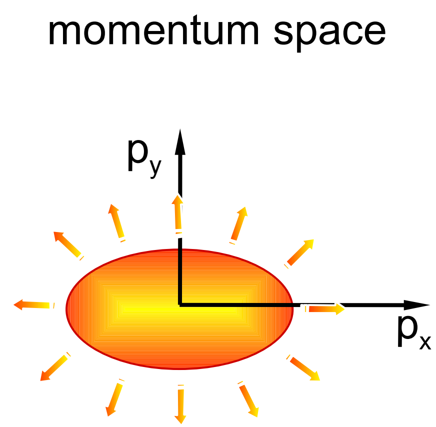
- first data from LHC will provide a crucial test of this picture: does limiting temperature picture survive a 20 fold increase in cm energy?

anything else would be a major surprize

already day 1 data from LHC will be decisive

The fireball expands collectively like an ideal fluid

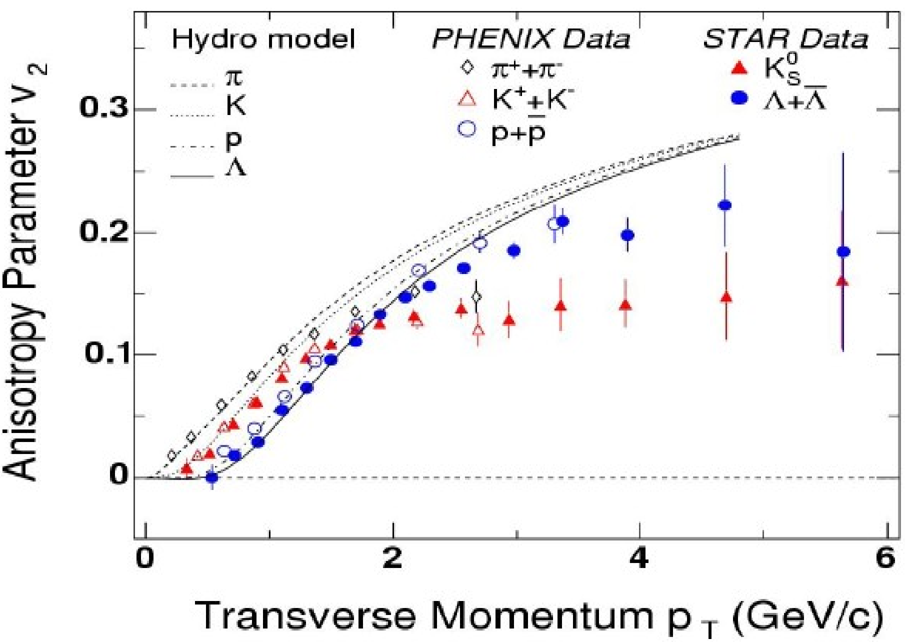


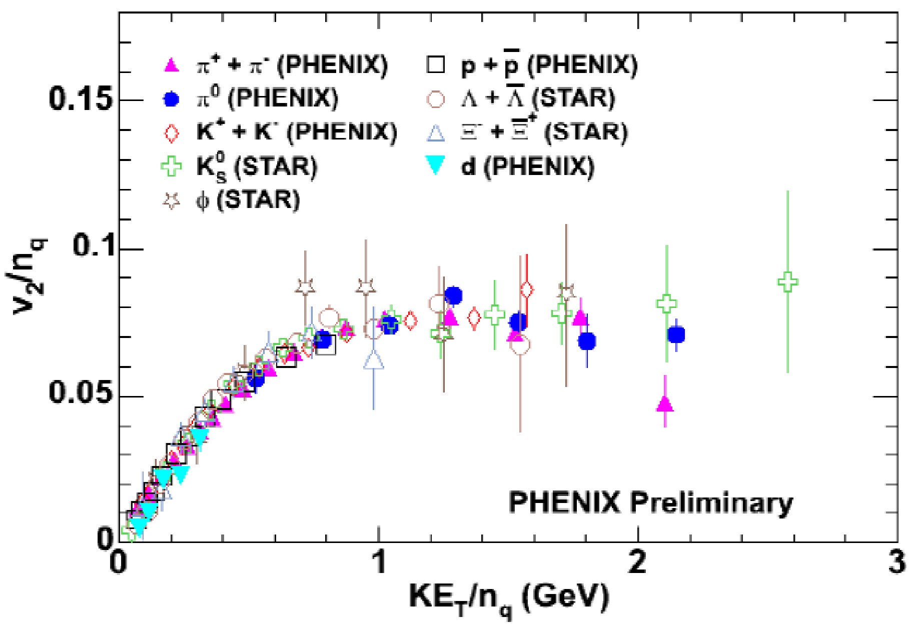


$dN/d\phi = 1 + 2\, V_2 \cos 2\,(\phi - \psi) + \ldots$

hydrodynamic flow characterized by azimuthal anisotropy coeffient v_2

Elliptic Flow Results from RHIC



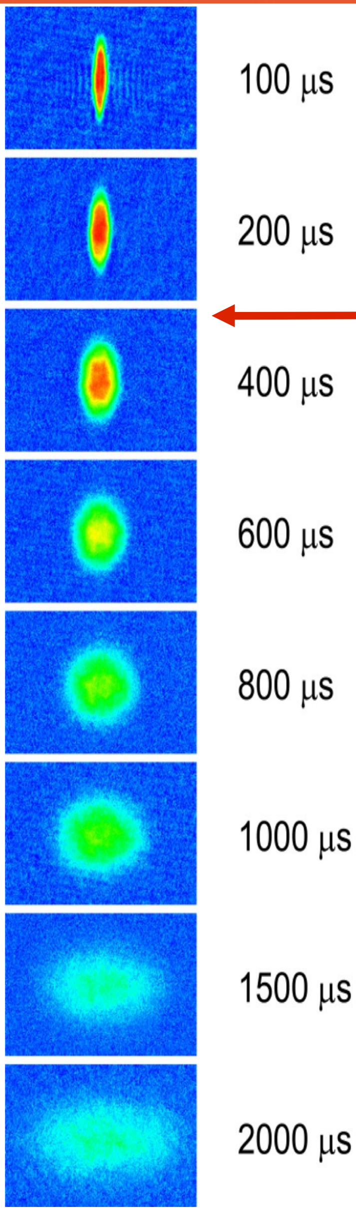


note the peculiar quark scaling!

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

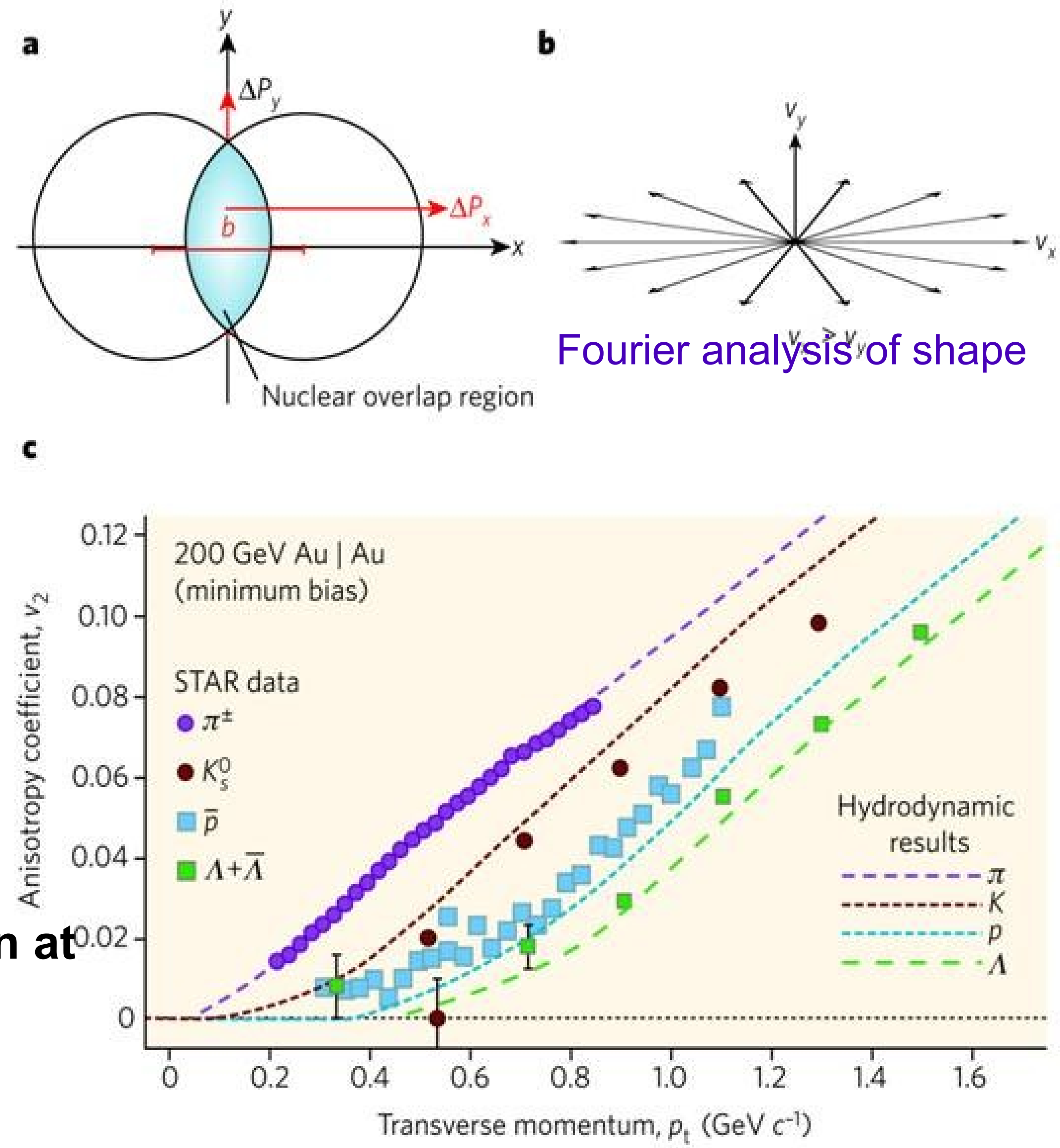
ideal hydro calculations reproduce also the observed mass ordering but fail in detail

QGP and Ultra-cold Quantum Gases



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

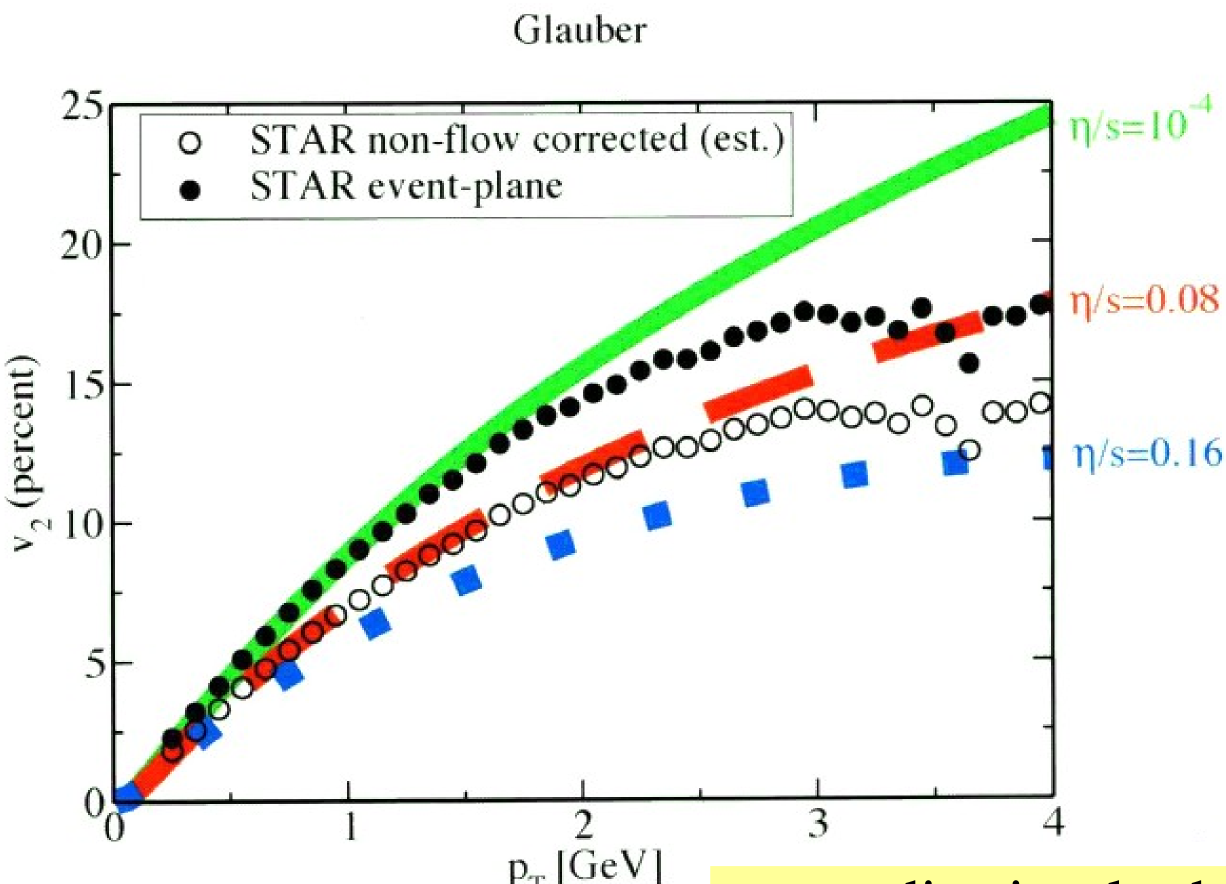
QGP
2.1 TK
~10^{8} eV



Fourier analysis of shape

collective expansion at strong coupling

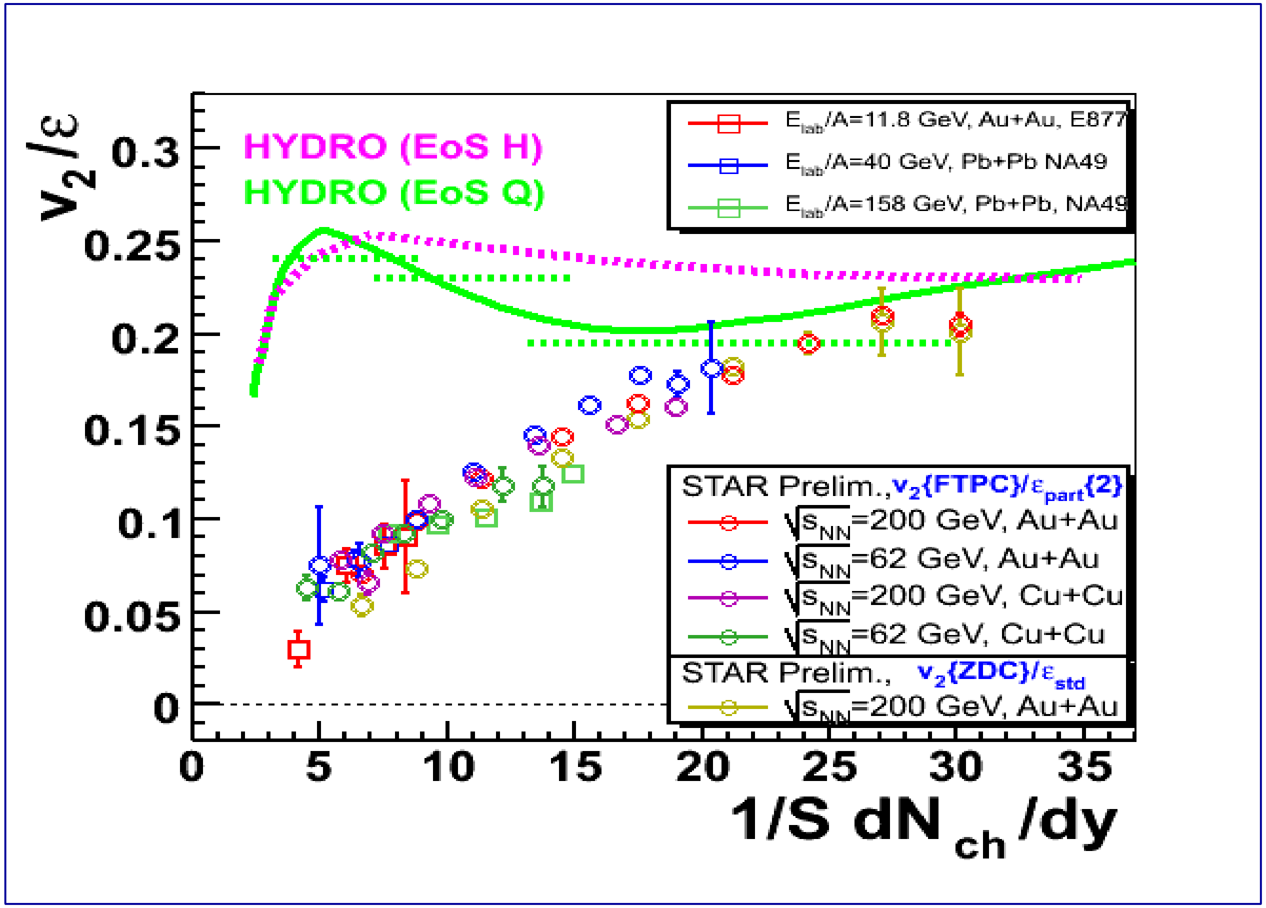
exploring the importance of viscous effects

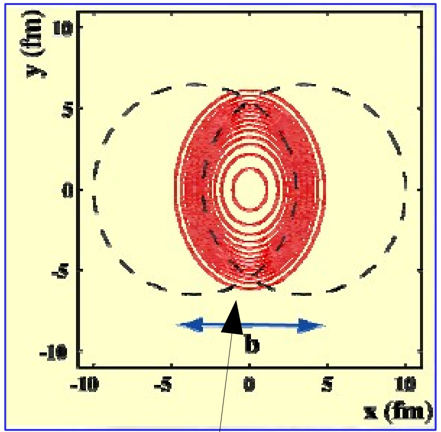


calculations by Paul Romatschke

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

summary of all existing data

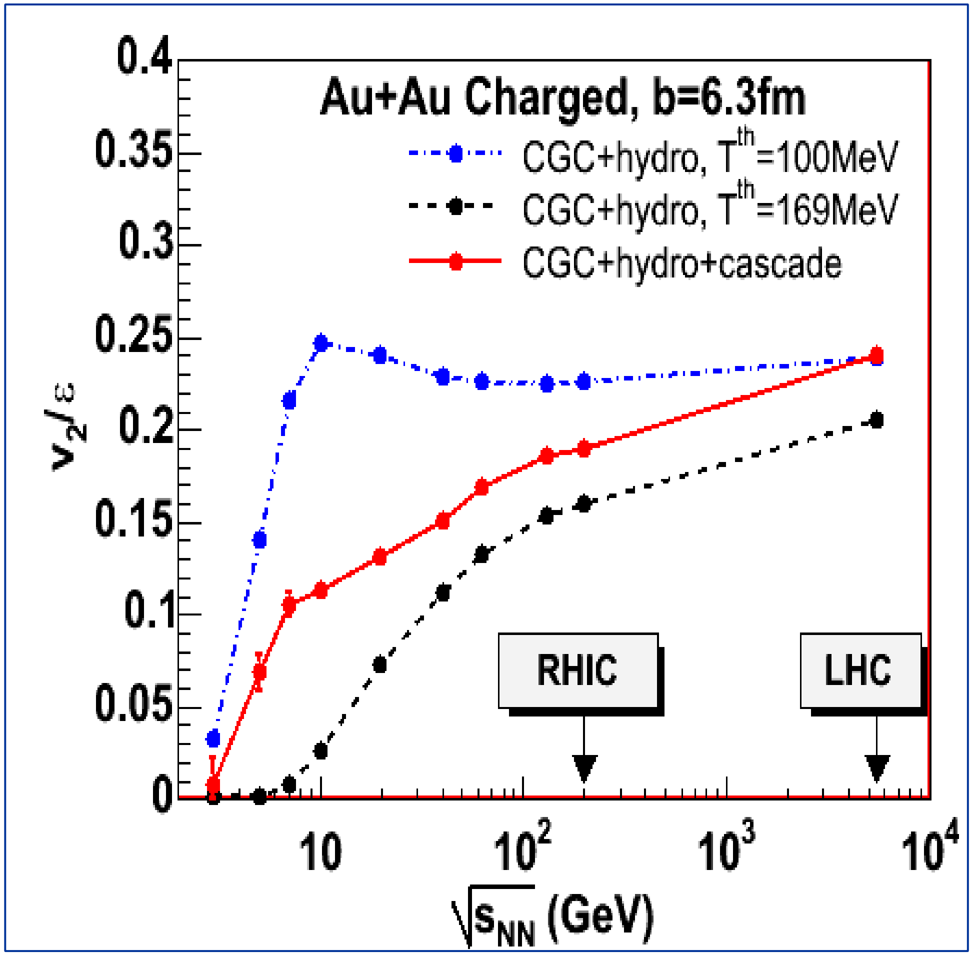


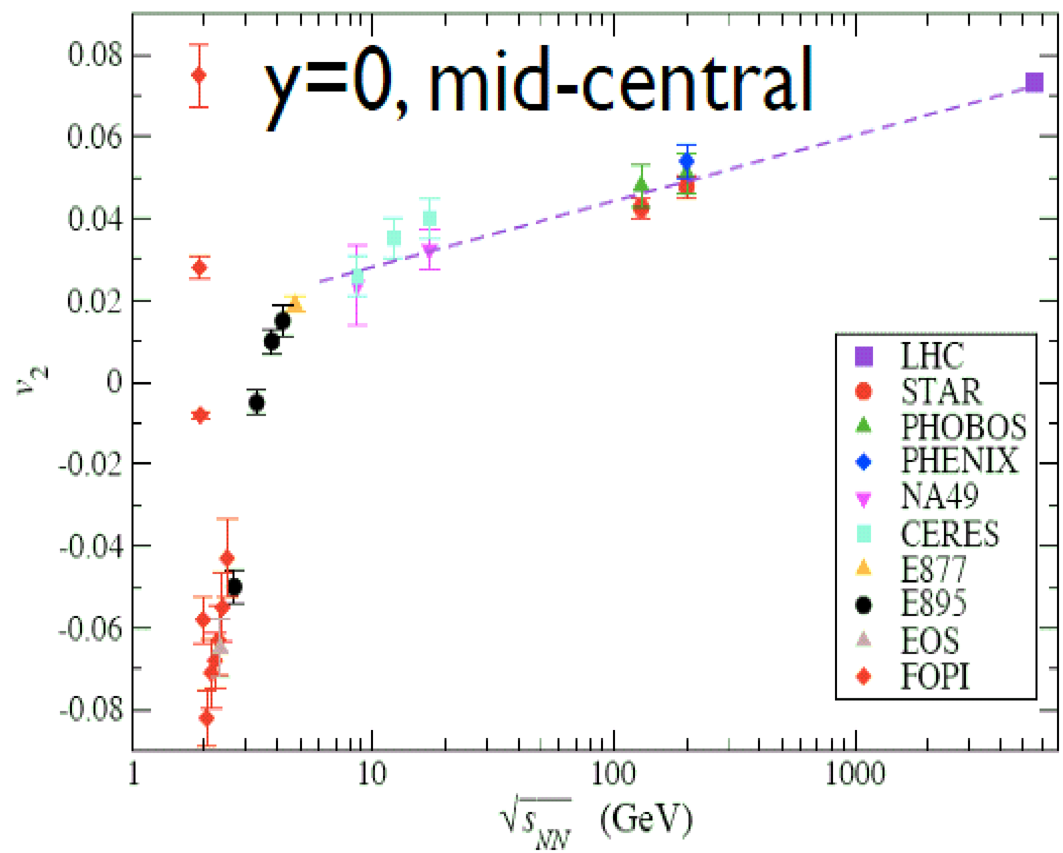


note: the initial eccentricity must be computed in a model

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

extrapolations to LHC





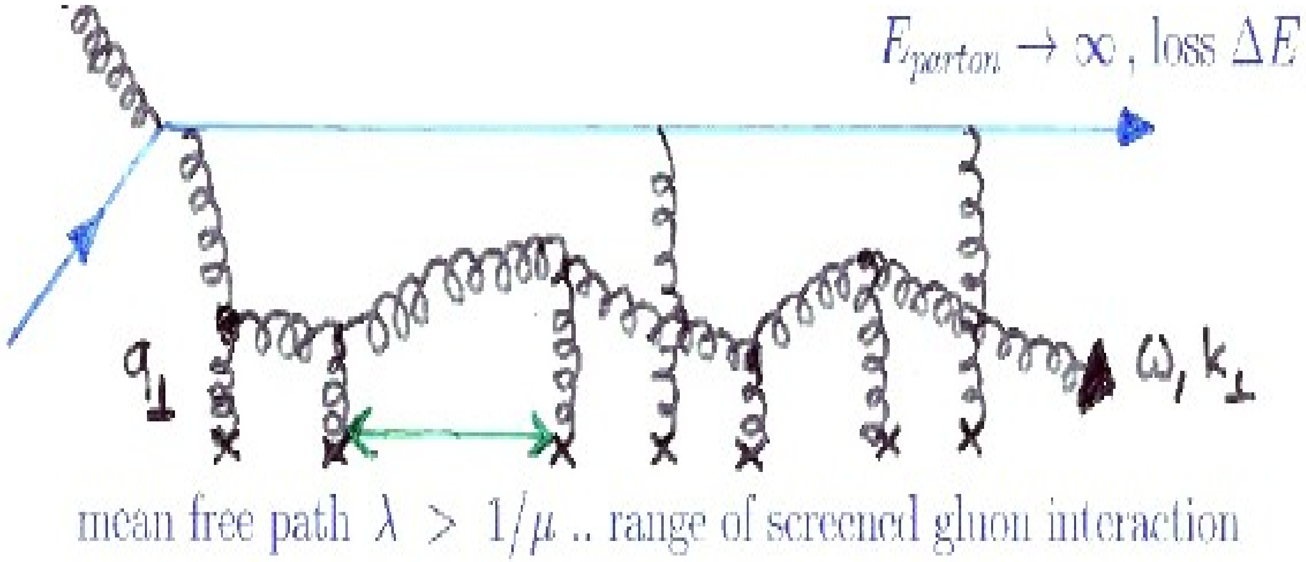
Summary of RHIC Hydro Results

- 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

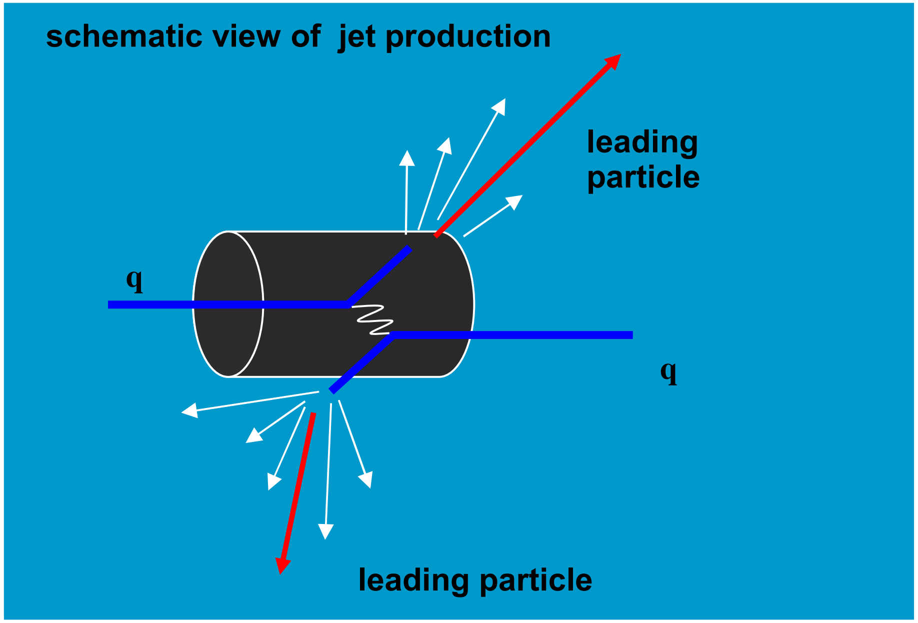
- suppression of high p_t particles in AA relative to pp collisions
- disappearance of jet-like correlations
- connected to large gluon density in hot (QGP) fireball



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

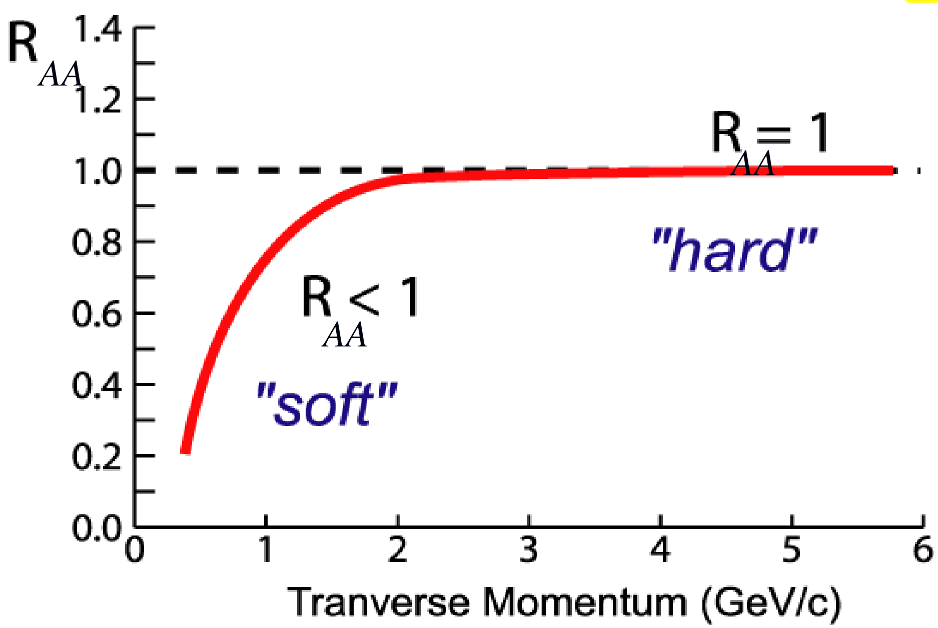
Jet Quenching

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:

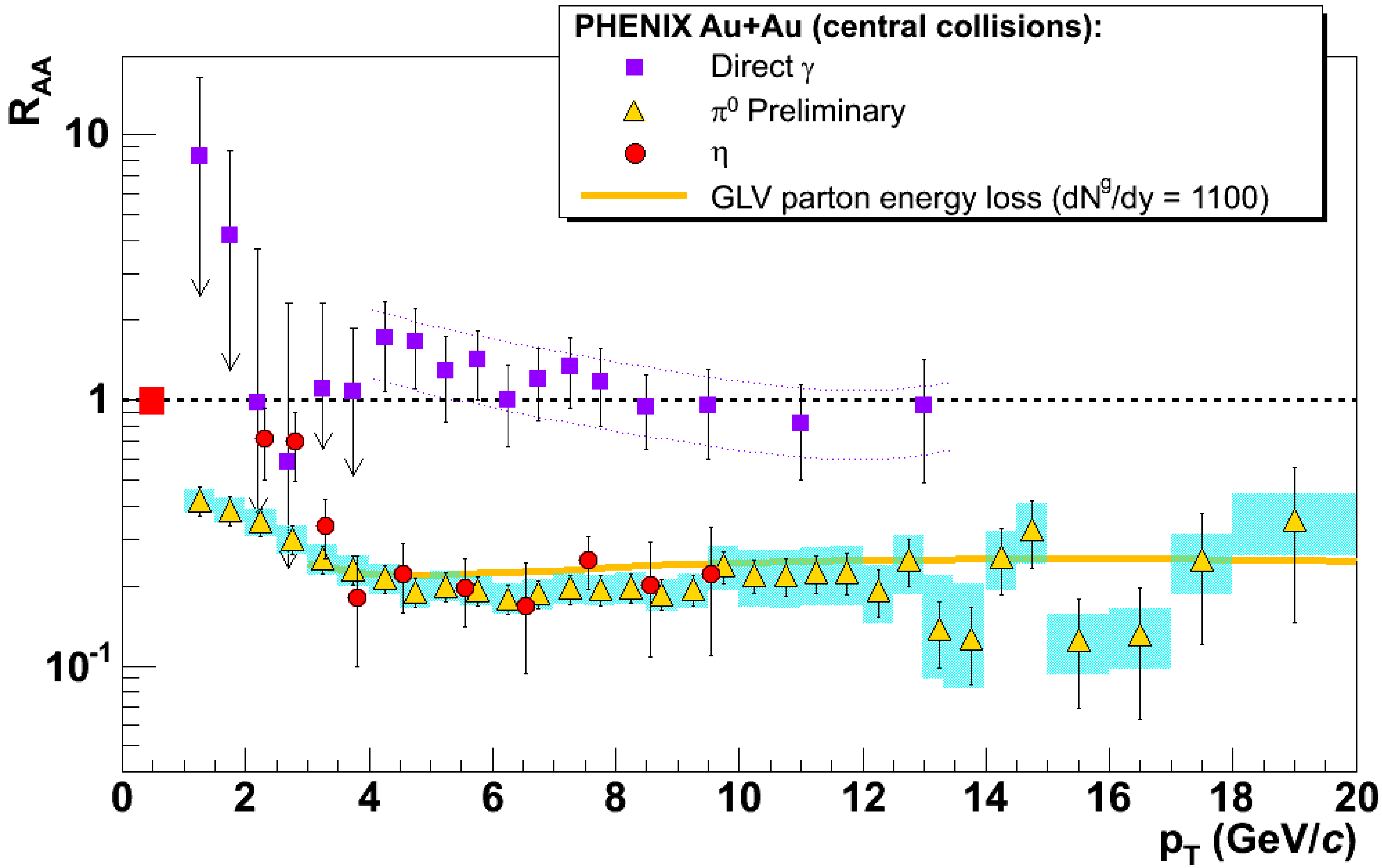
$R_{AA} < 1$ in regime of soft physics

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

Suppression:

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

Leading hadrons and hard photons

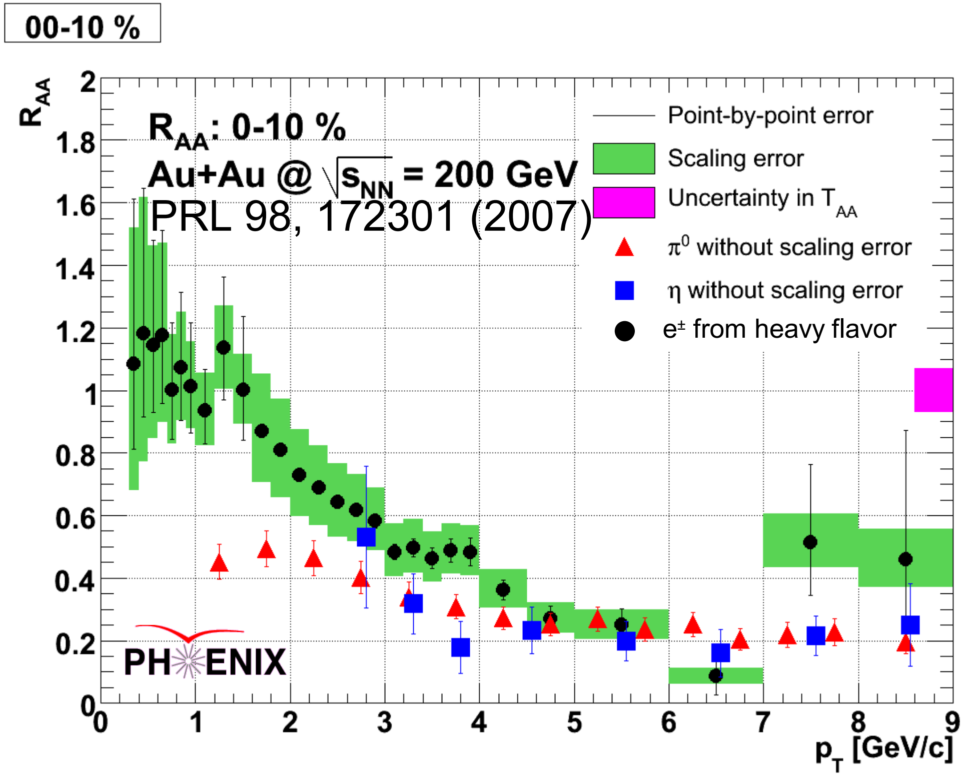


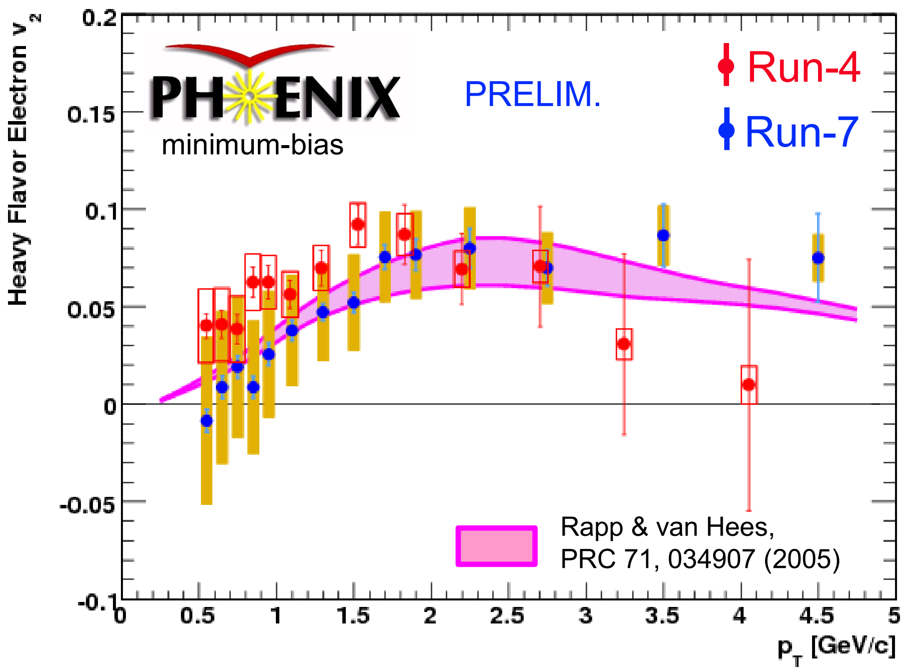
- Direct photons are not suppressed, follow pQCD predictions.
- Common suppression for π^0 and η.
- $\varepsilon > 15$ GeV/fm^3; $dN_g/dy > 1100$

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

electrons from heavy flavor mesons

strong energy loss | hydrodynamic flow

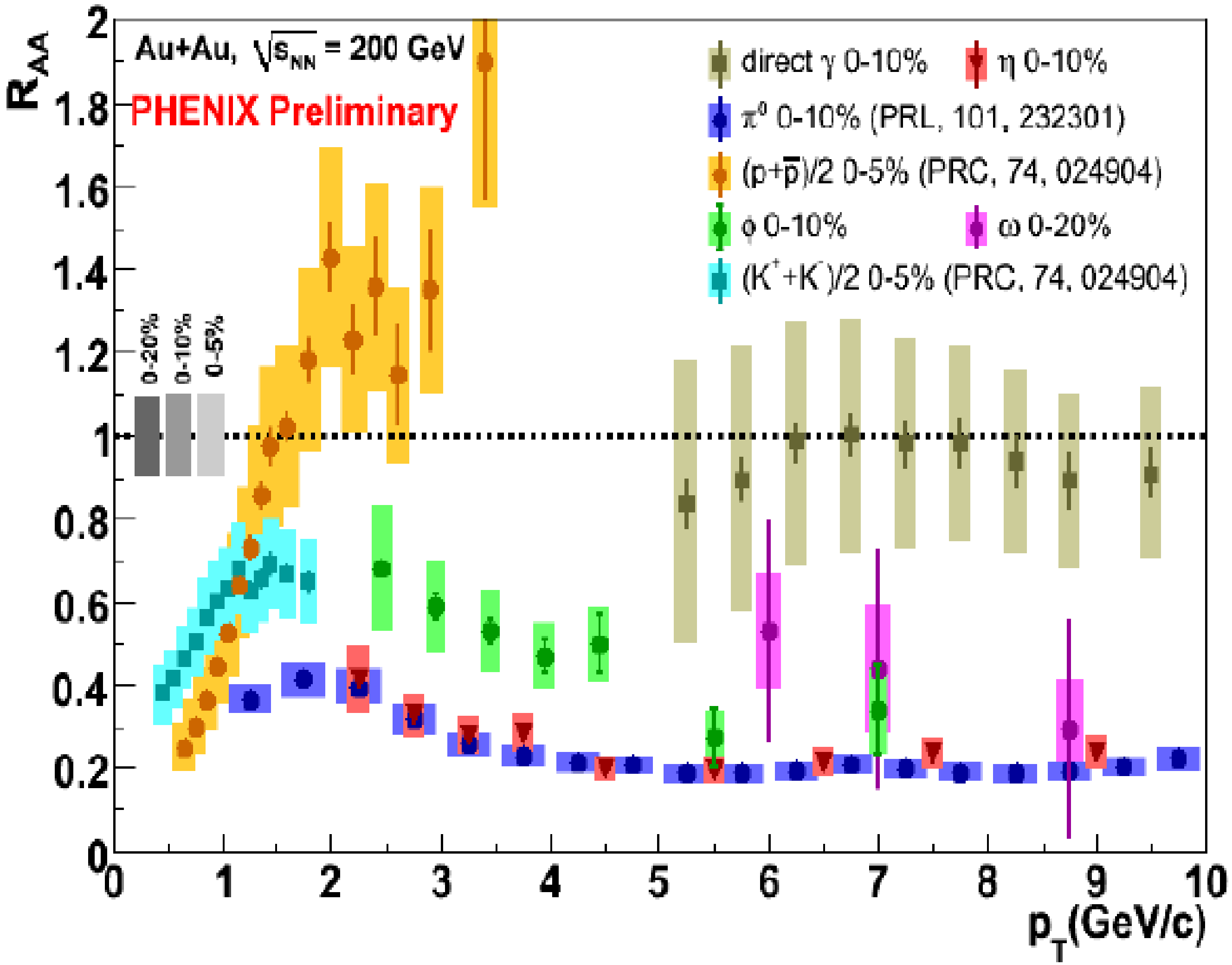




these data are not well explained, measure heavy quarks „directly“ at LHC

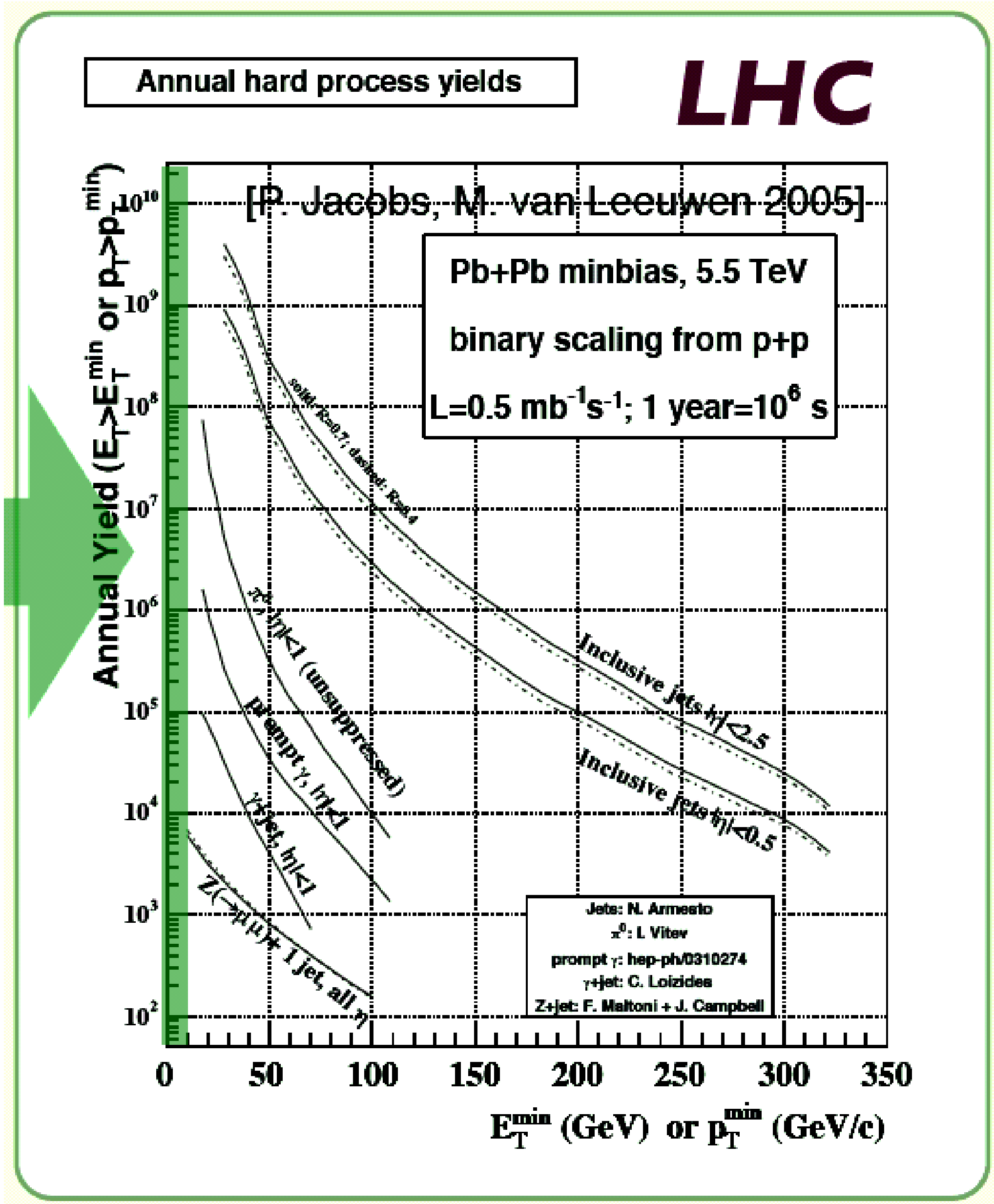
Complex suppression pattern – mesons vs baryons J/psi?

RAA (pT > 6 GeV/c)	
π	0.25±0.05
ρ	0.25±0.1
ω	0.3±0.2
η	0.25±0.05
k	0.4±0.1
ϕ	0.25±0.1
p	0.6±0.2
D/B (via e)	0.25±0.1
J/ψ	1.4±0.4



the ultimate hard probes machine

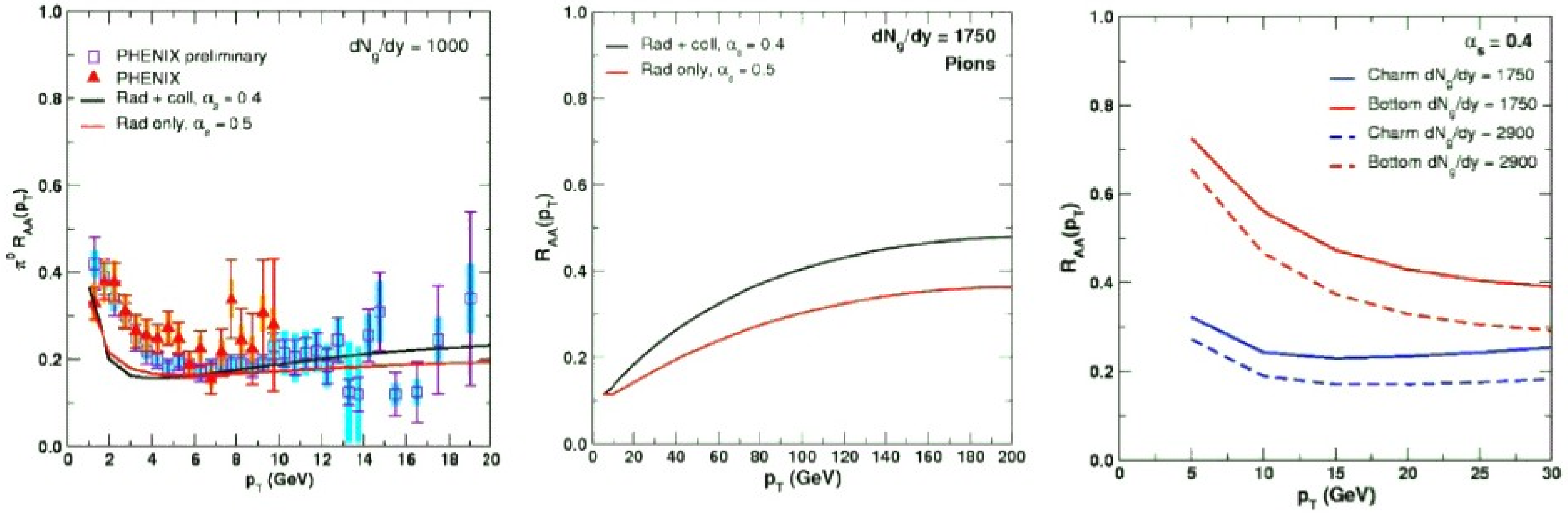
covered
at RHIC



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

Predictions for jet quenching at LHC

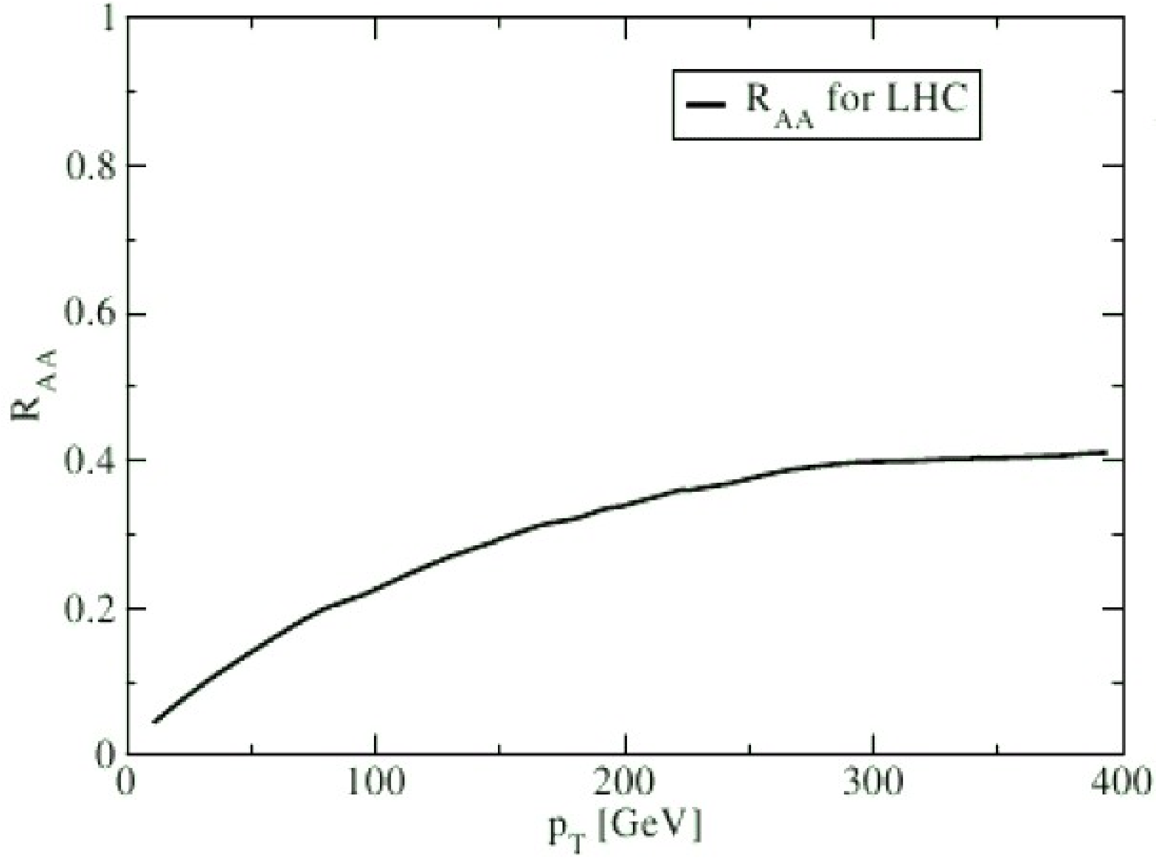
S. Wicks and M. Gyulassy



more predictions...

Renk and Eskola

connection
to AdS/CFT
considerations?



important: perturbative QCD regime may never be reached!

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

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

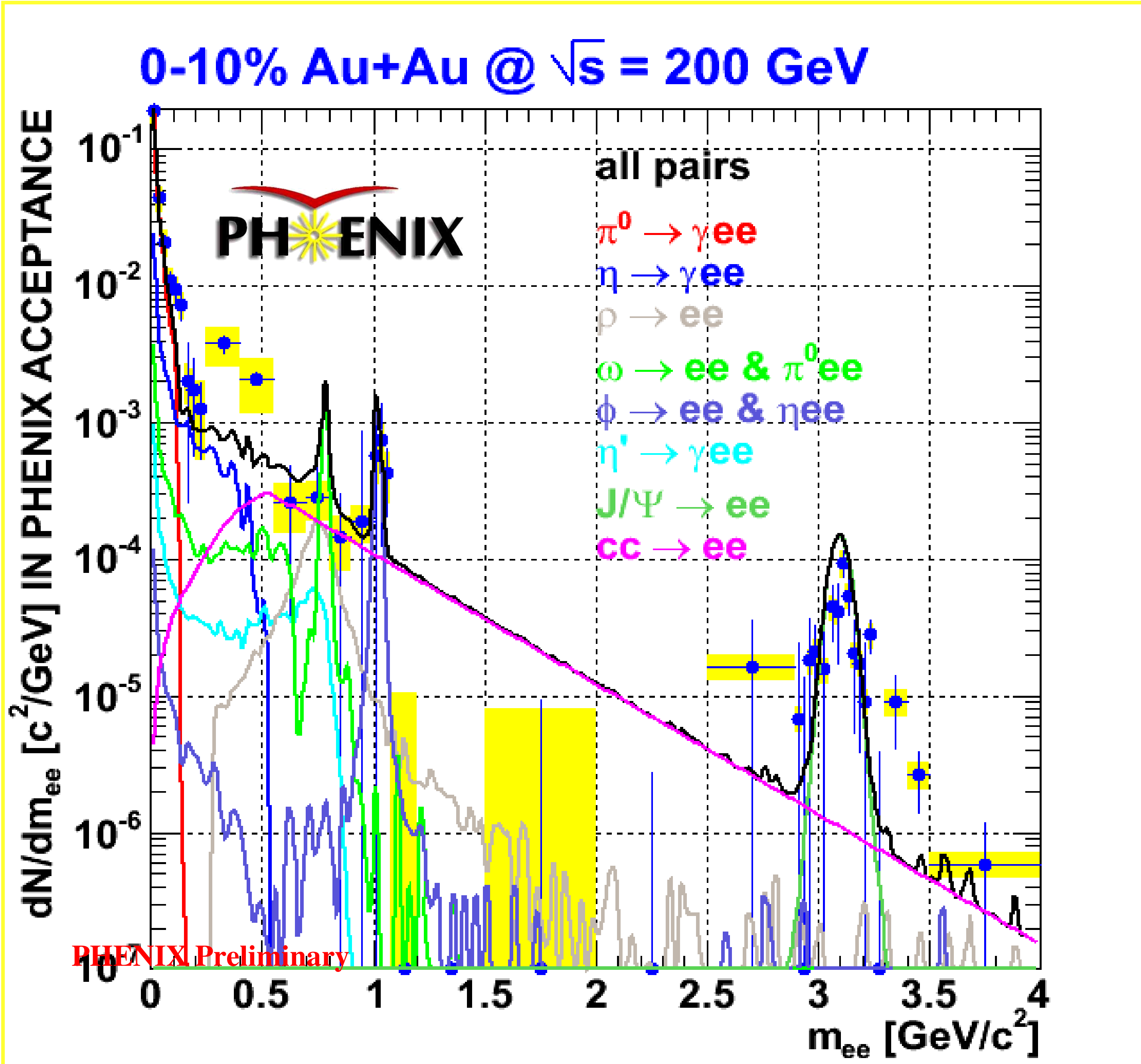
original proposal: H. Satz and T. Matsui, Phys. Lett. B178 (1986) 416

assumptions:

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

$\rightarrow$ sequential suppression pattern due to feeding

PHENIX measurements in Au-Au collisions at RHIC



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Quarkonium as a probe for deconfinement at the LHC

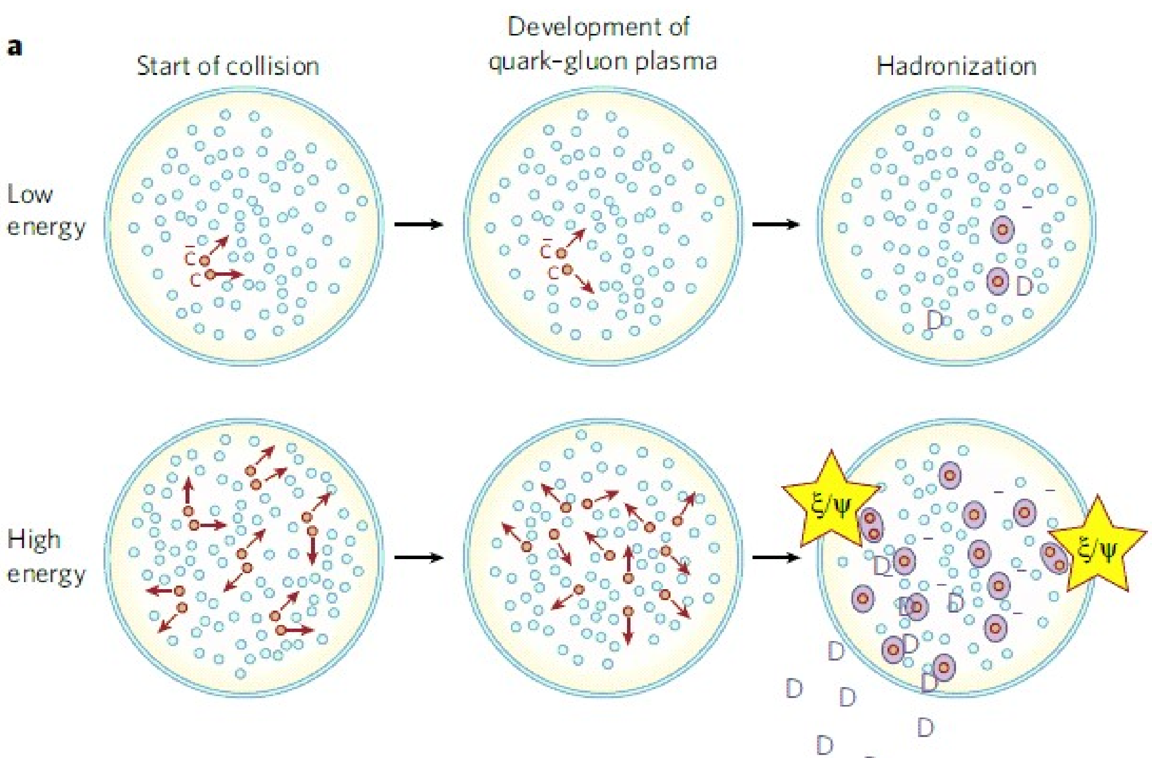
at hadronization of QGP J/ψ can form again from deconfined quarks, in particular if number of ccbar pairs is large

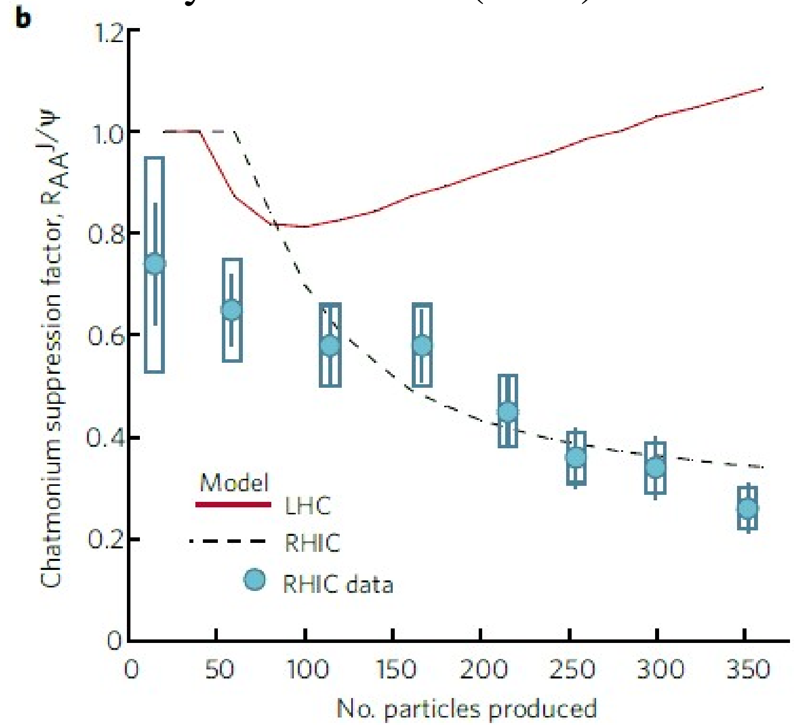
$$N_{J/\psi} \propto N_{cc}^{2}$$

(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 AGS/SPS/RHIC, principally on

local equilibrium → critical temperature

thermalization and flow --> ideal fluid scenario

jet quenching --> parton energy loss in dense fireball

have led to major progress in our understanding of QCD/QGP

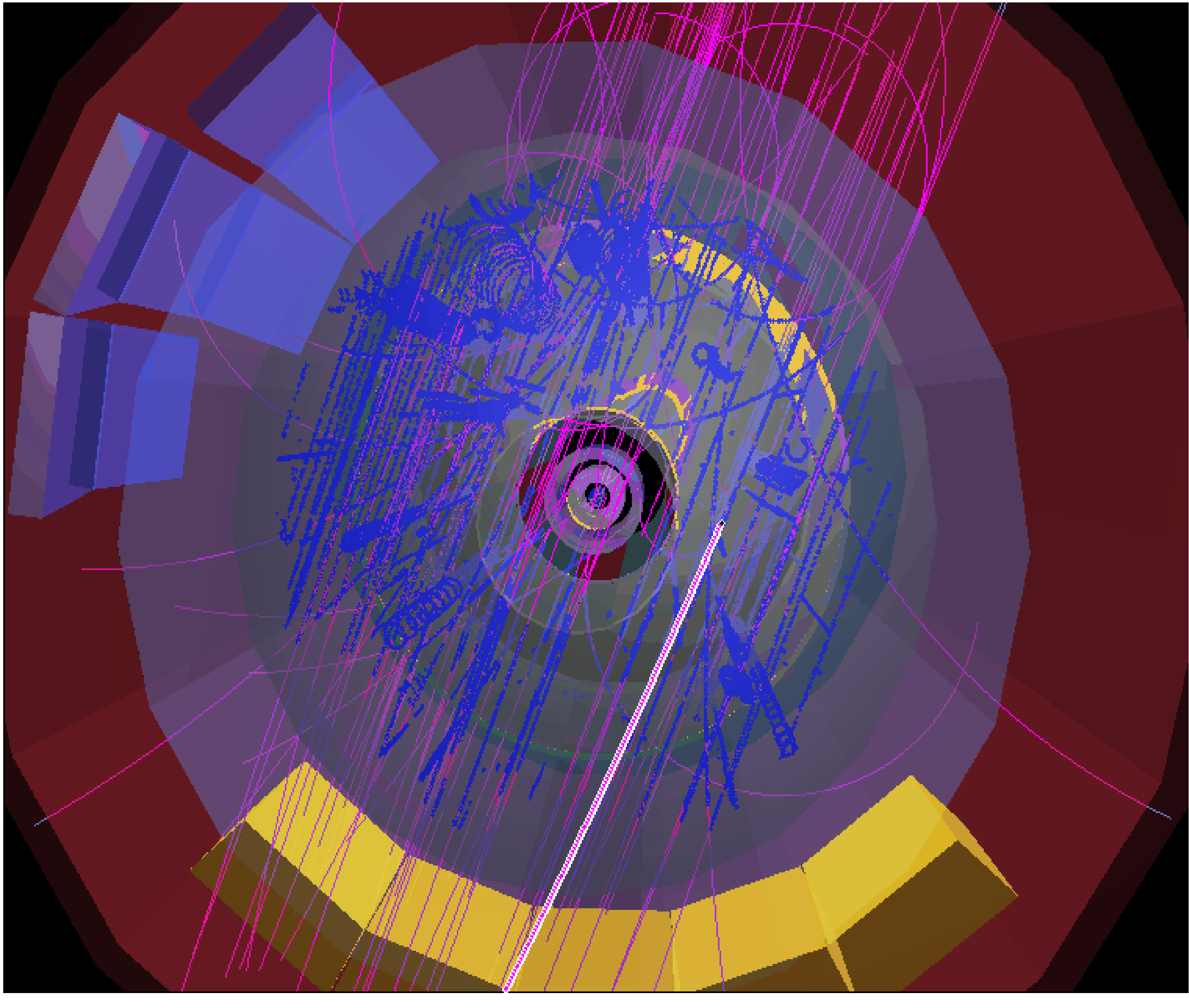
These discoveries raise many new questions. The next frontier is at the LHC! The experiments are ready.

A spectacular event with cosmic rays

ALICE has entered the Terascale

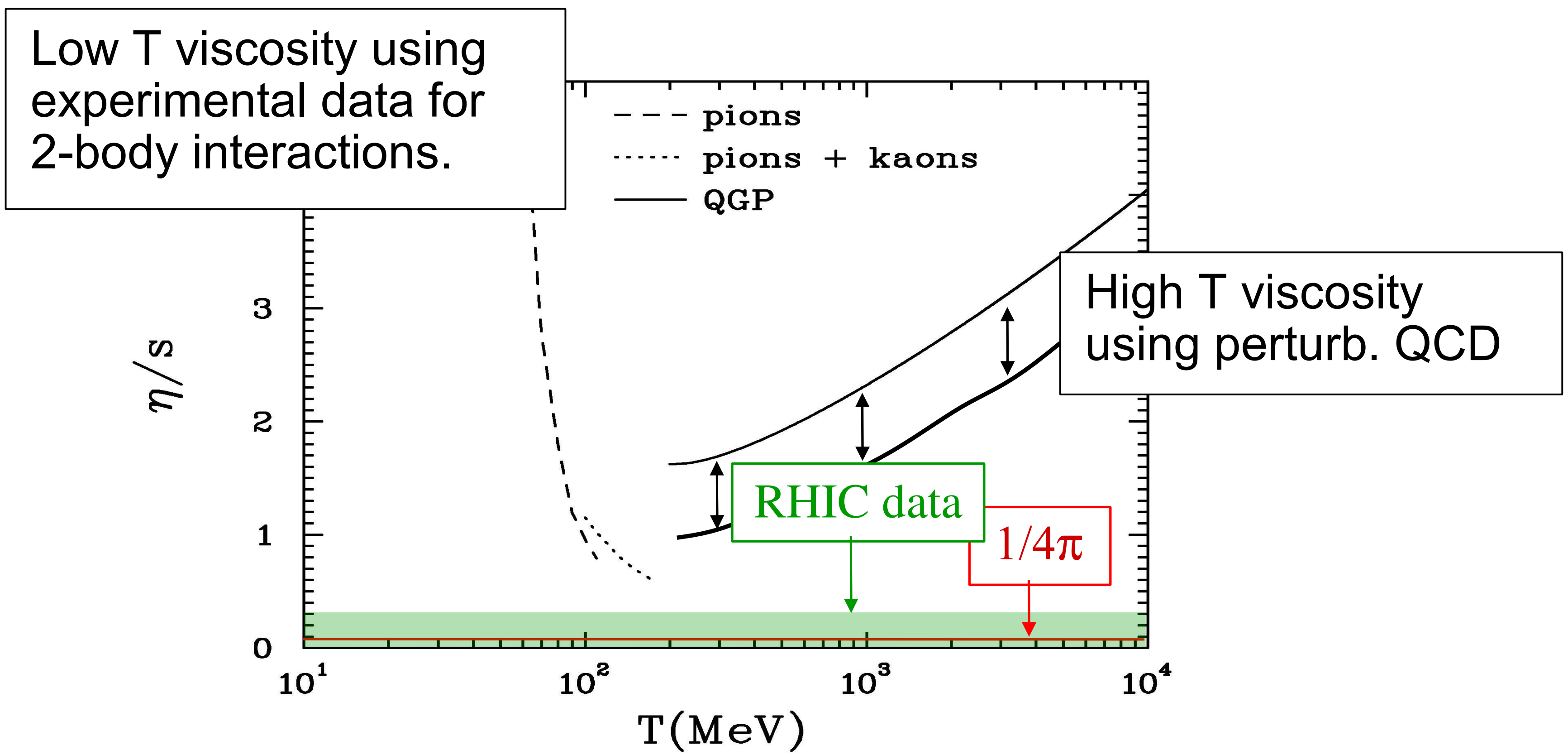
a muon bundle:

more than 30 muons,
essentially parallel,
total momentum
>1TeV



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

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

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

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

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

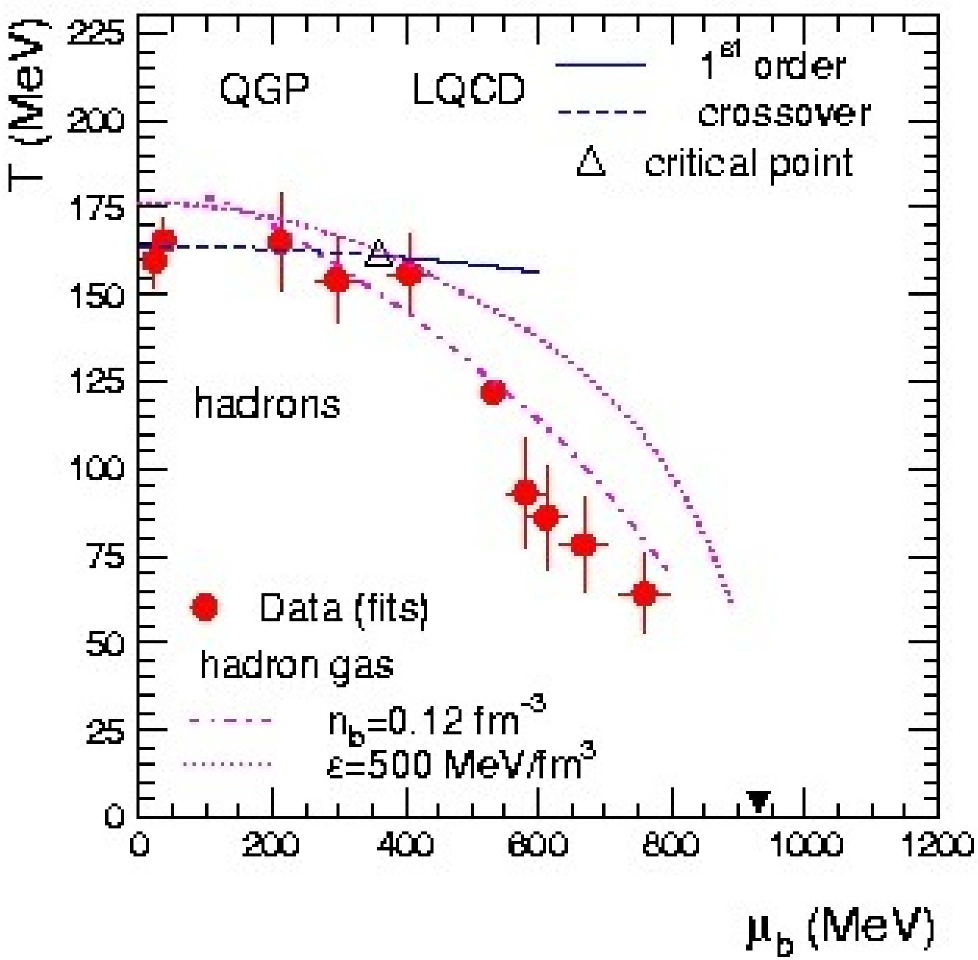
- Baryon number: $V \sum_i n_i B_i = Z + N \quad \rightarrow V$
- Strangeness: $V \sum_i n_i S_i = 0 \quad \rightarrow \mu_S$
- Charge: $V \sum_i n_i I_i^3 = \frac{Z - N}{2} \quad \rightarrow \mu_{I_3}$

This leaves only μ_b and T as free parameter when 4π considered

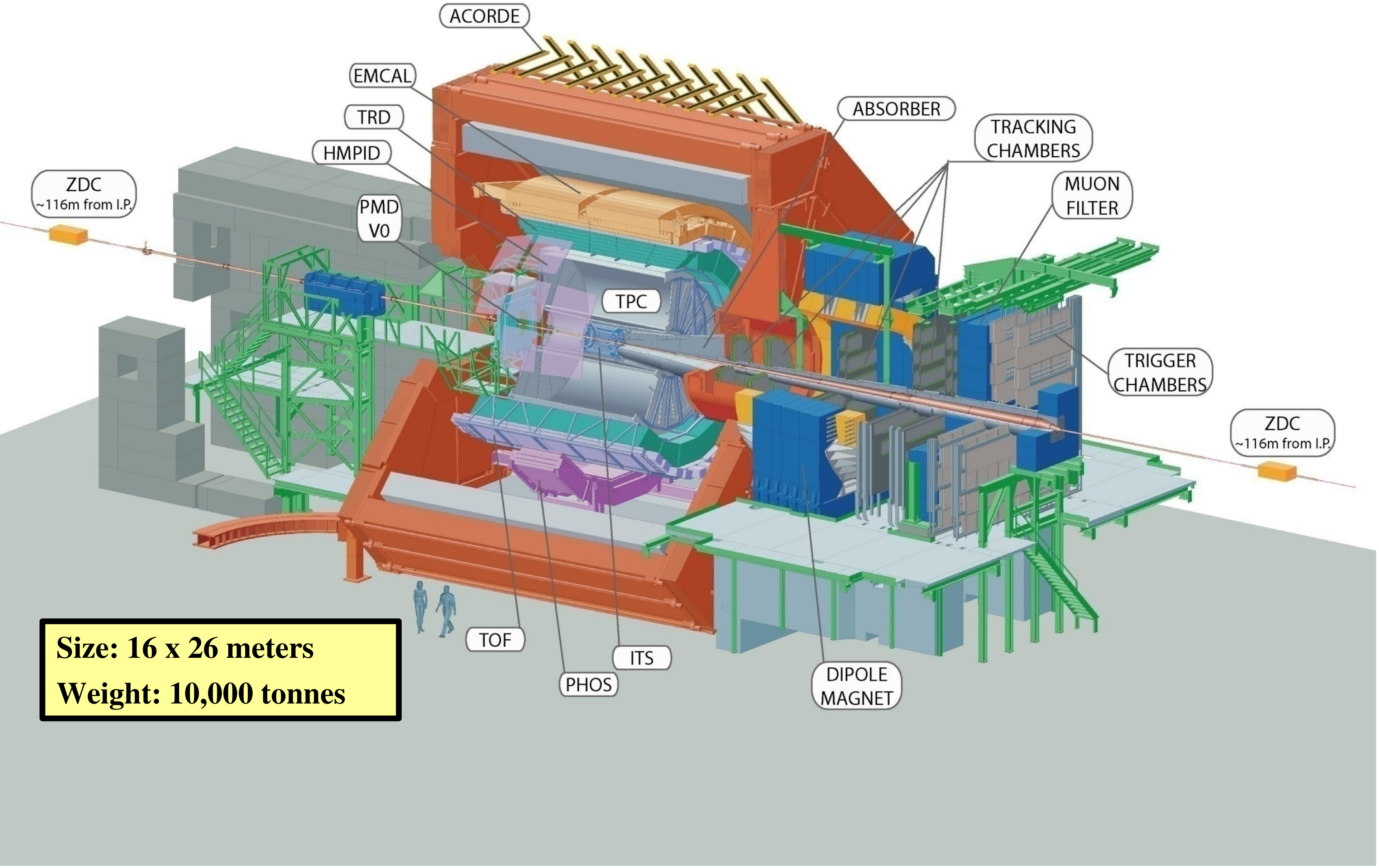
for rapidity slice fix volume e.g. by dN_{ch}/dy

Fit at each energy provides values for T and μ_b

Main result: chemical freeze-out points seem to delineate the QCD phase boundary at small baryo-chemical potential (μ < 400 MeV)

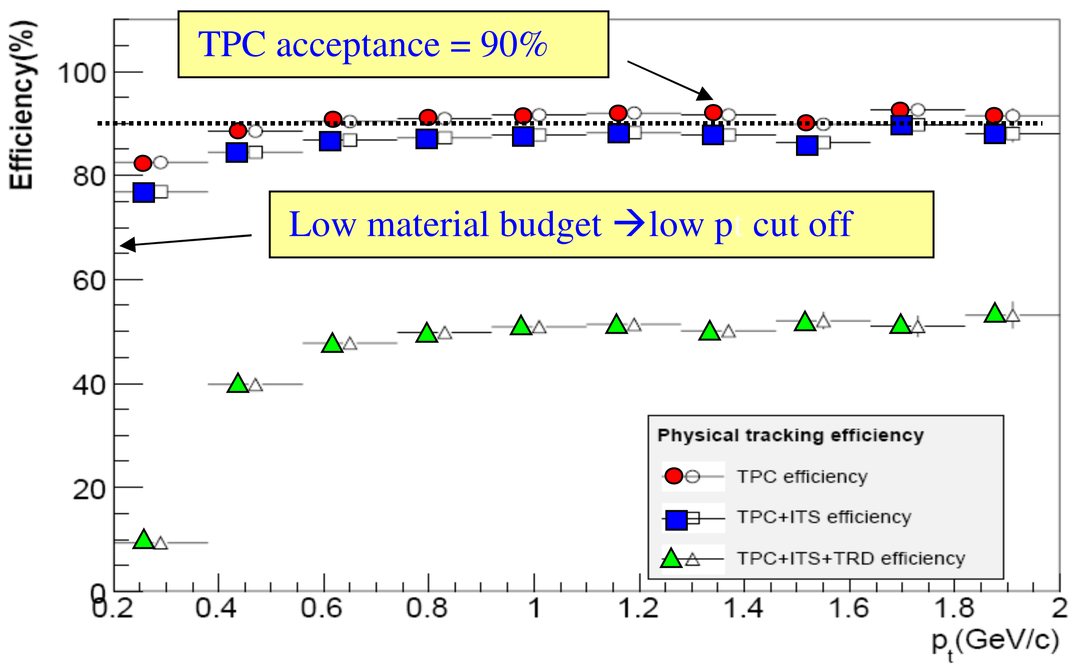


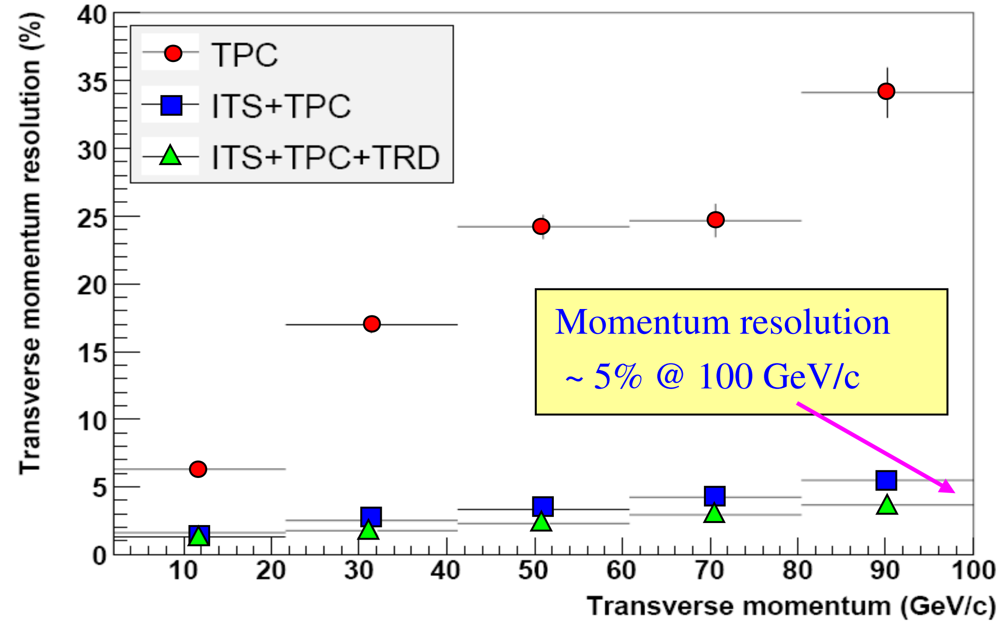
ALICE: A Large Ion Collider Experiment at CERN-LHC

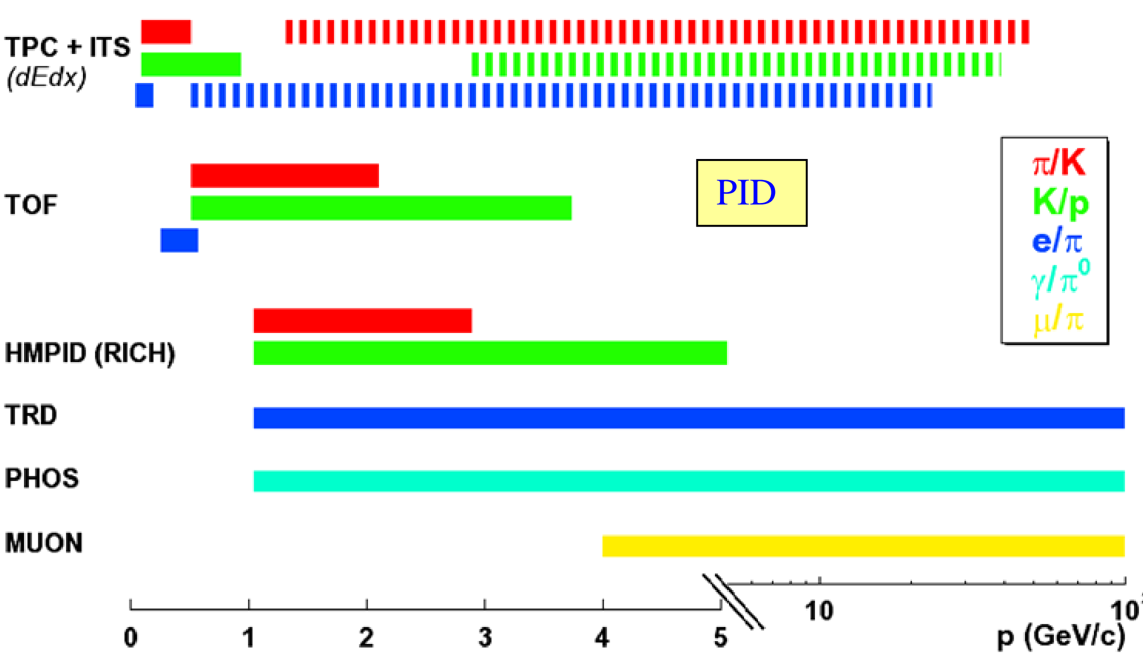


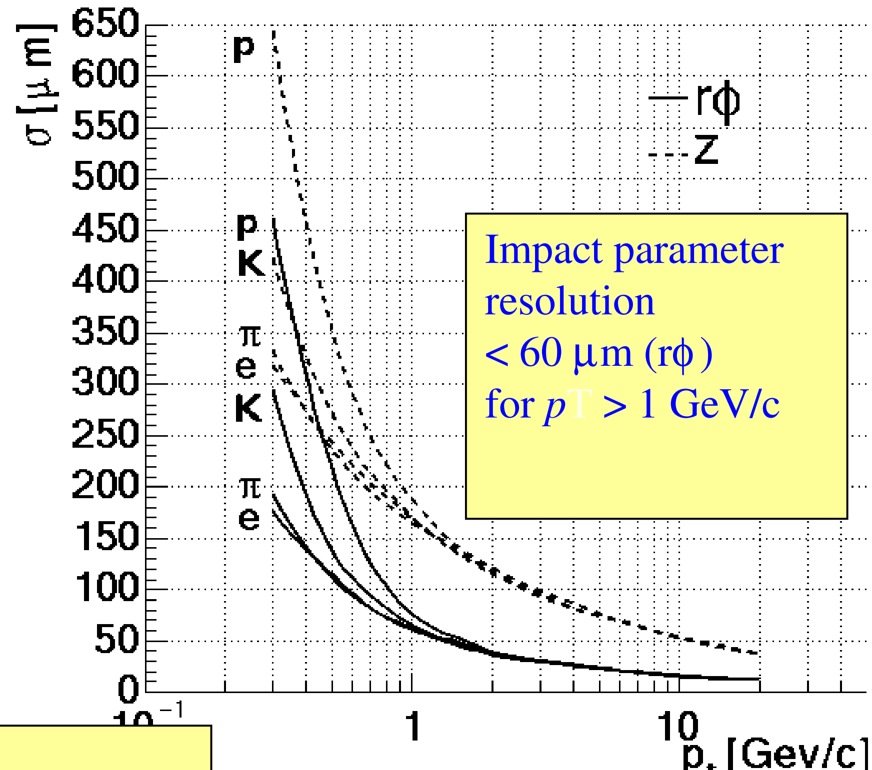
Size: 16 x 26 meters
Weight: 10,000 tonnes

ALICE Design Performance









+ decay topologies ((K0, K+, K-, Λ, ϕ, D) K and Λ beyond 10 GeV/c