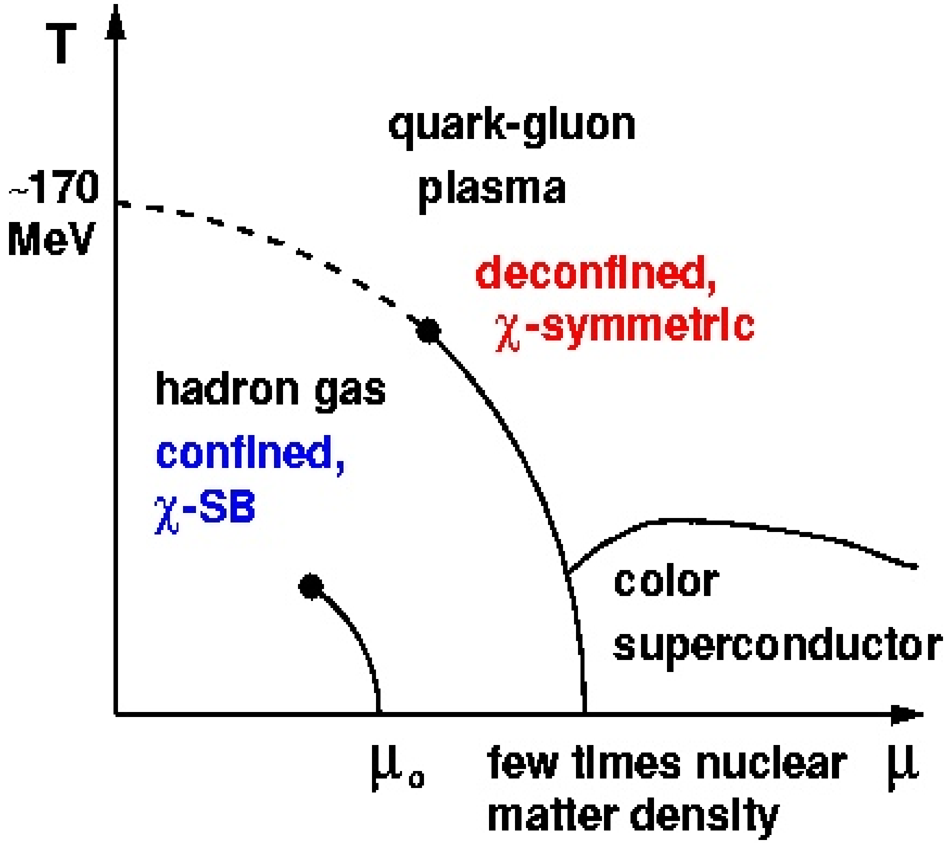
30 years of Quark-Gluon Plasma Studies – lessons and perspectives

from a wealth of experimental results
  my personal view of
  - highlights
  - physics insights
  - perspectives

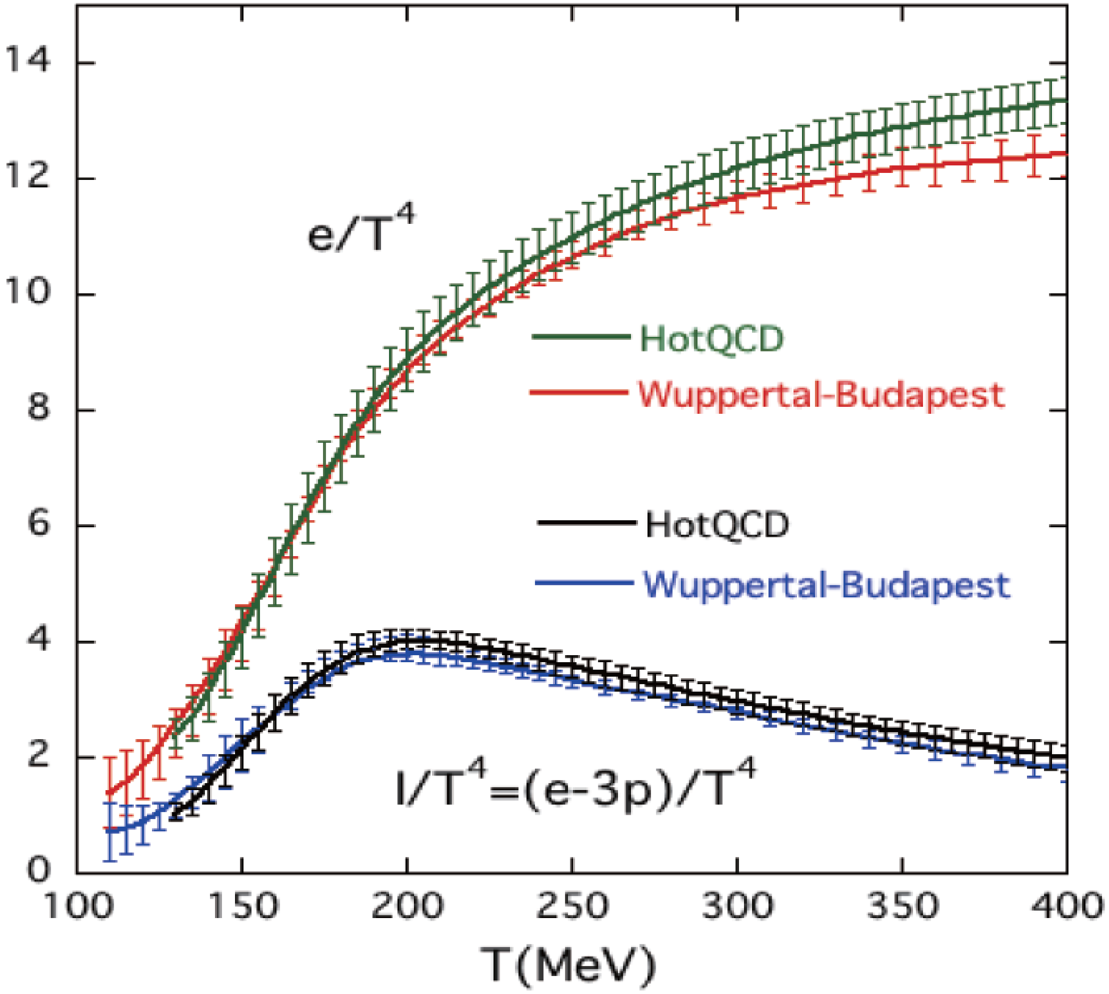


Johanna Stachel – Universität Heidelberg
the 21st Particles & Nuclei International Conference, Sept 1-5, 2017

Equation of state of hot QCD matter in lattice QCD

computation of QCD EoS one of the major goals in lQCD community since 1980

A.Ukawa, arXiv:1501.04215



consolidated results on EoS from different groups, extrapolated to continuum and chiral limit

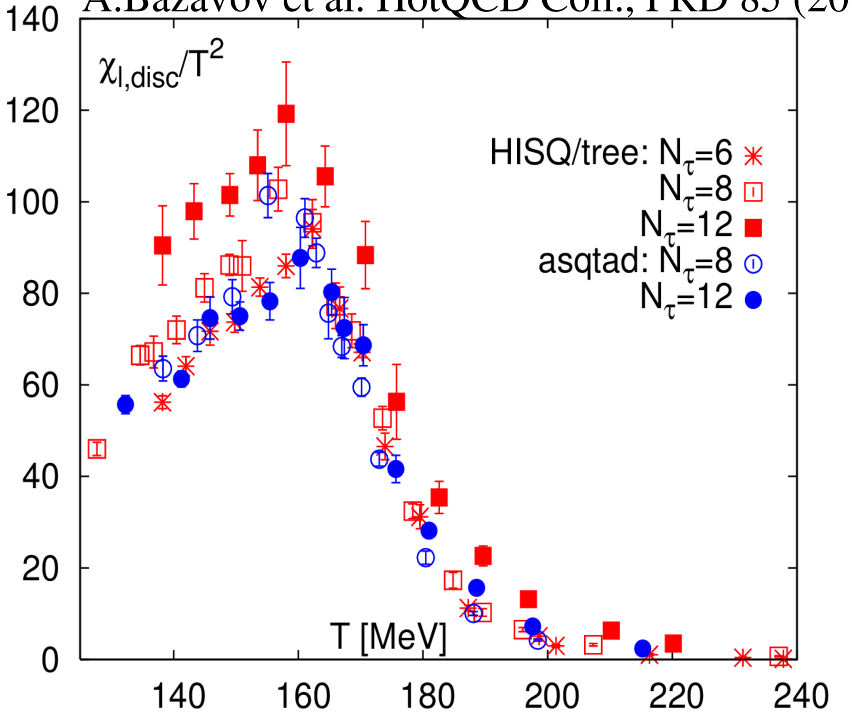
rapid rise of energy density (normalized to T^4 rise for relativistic gas)

- signals rapid increase in degrees of freedom due to transition from hadrons to quarks and gluons
- lQCD points to continuous cross over transition

Measure for chiral symmetry restoration in lQCD

order parameter: chiral condensate, its susceptibility peaks at T_c

S.Borsayi et al. Wuppertal-Budapest Coll., JHEP 1009 (2010) 073
A.Bazavov et al. HotQCD Coll., PRD 85 (2012) 054503



$$\langle \bar{\Psi}\Psi \rangle = \frac{T}{V}\frac{\partial \ln Z}{\partial m}$$

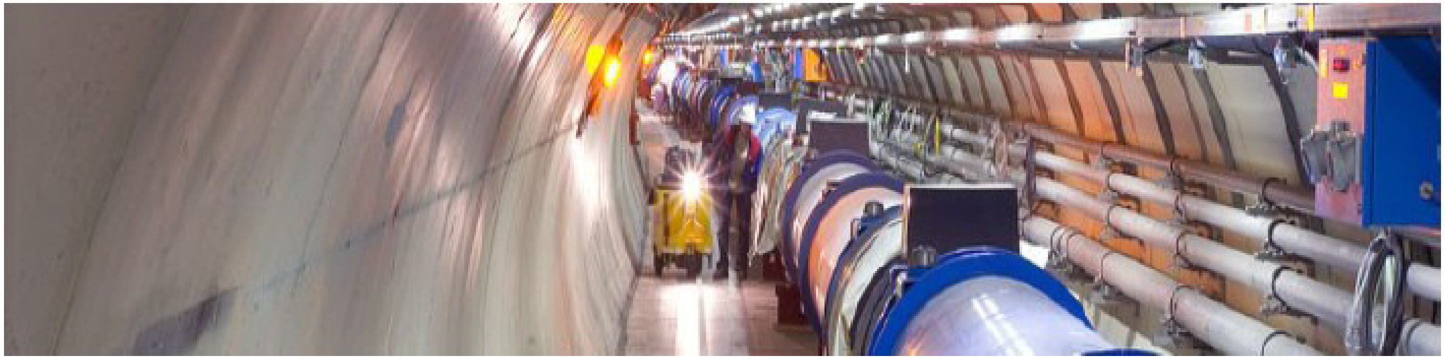
$$\chi_{\bar{\Psi}\Psi} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial m^2}$$

comparing different measures and different fermion actions, consensus:
T_c = 150 – 160 MeV for chiral restoration

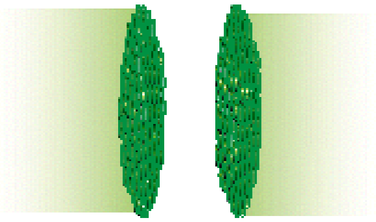
Experimental program

QGP and phase diagram studied in high energy collisions of nuclei

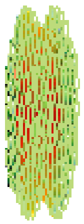
accelerator	years	$\sqrt{s_{NN}}$	large exp.
AGS	1986 - 2002	2.7 - 4.8 GeV	5
SPS	since 1986	6.2 - 19.3 GeV	7
RHIC	since 2000	7.0 – 200 GeV	4
LHC	since 2009	2.76 – 5.02 TeV	3 (4)



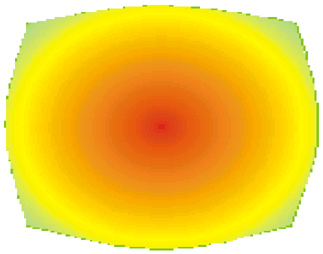
Space-time evolution of a relativistic nuclear collision at LHC energy



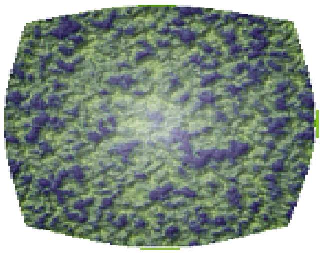
CGC



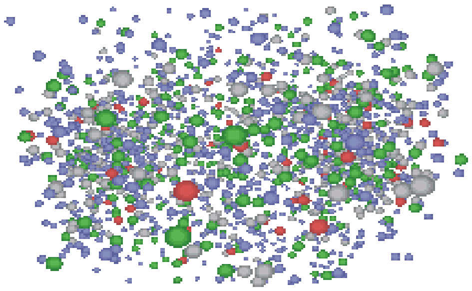
Initial Singularity



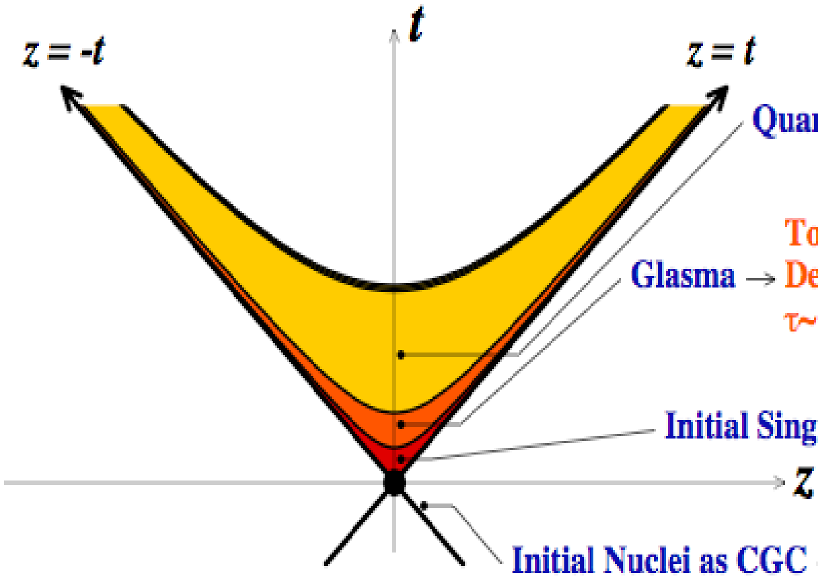
Glasma



sQGP



Hadron Gas



Quark Gluon Plasma → Perfect Fluid
Hadronization
τ~ 1 - 10 fm/c

Glasma → Topological Excitations
Density Fluctuations, Thermalization
τ~ 0.1 - 1 fm/c

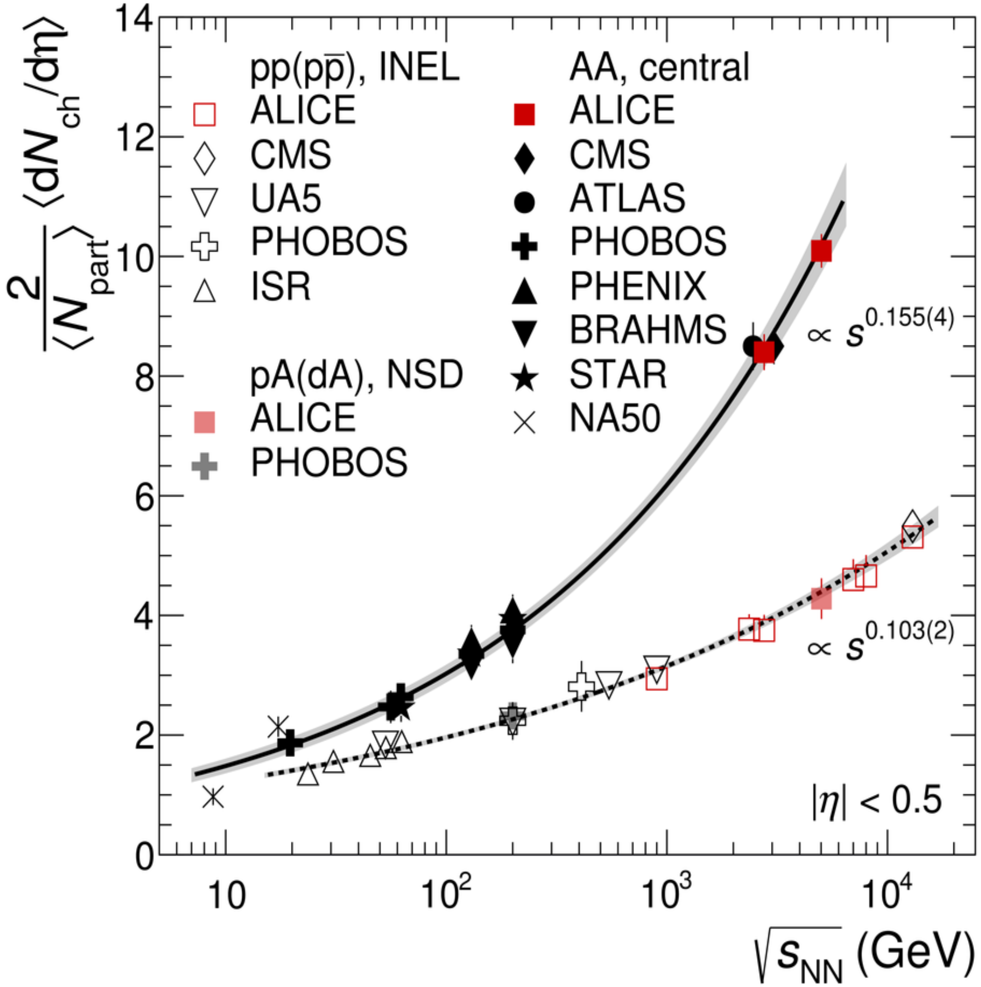
Initial Singularity → Event Horizon
Quantum Fluctuations
τ~ 0 - 0.1 fm/c

Initial Nuclei as CGC → Coherent, High-density Gluons

similar to early universe, fluctuations observed in the much later phase may allow to deduce early singularities

one possible view (courtesy L. McLerran)

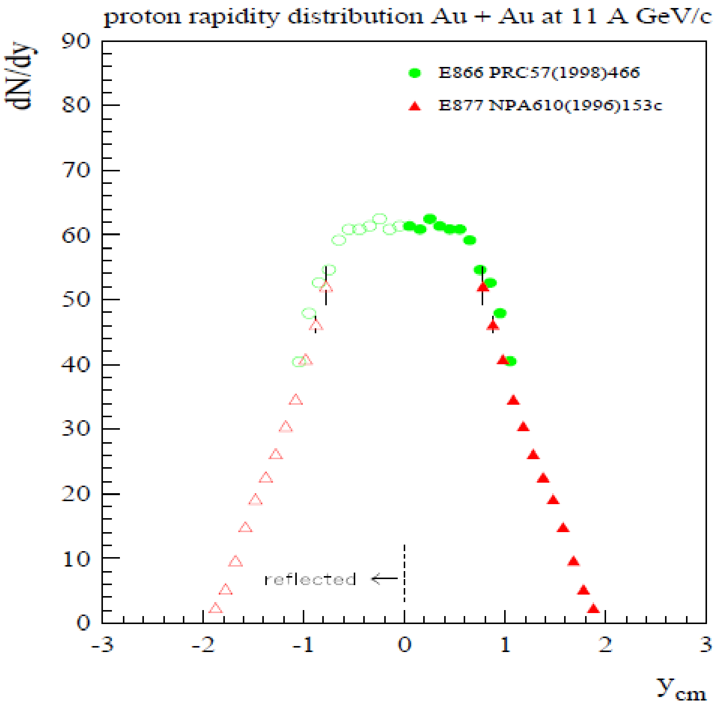
Charged particle production



increase in nuclear collisions much faster with √s than in pp

→ larger fractional energy loss in nuclear collision

Nuclear stopping power



AGS: nuclei stop each other completely $\Delta y = 1.7$

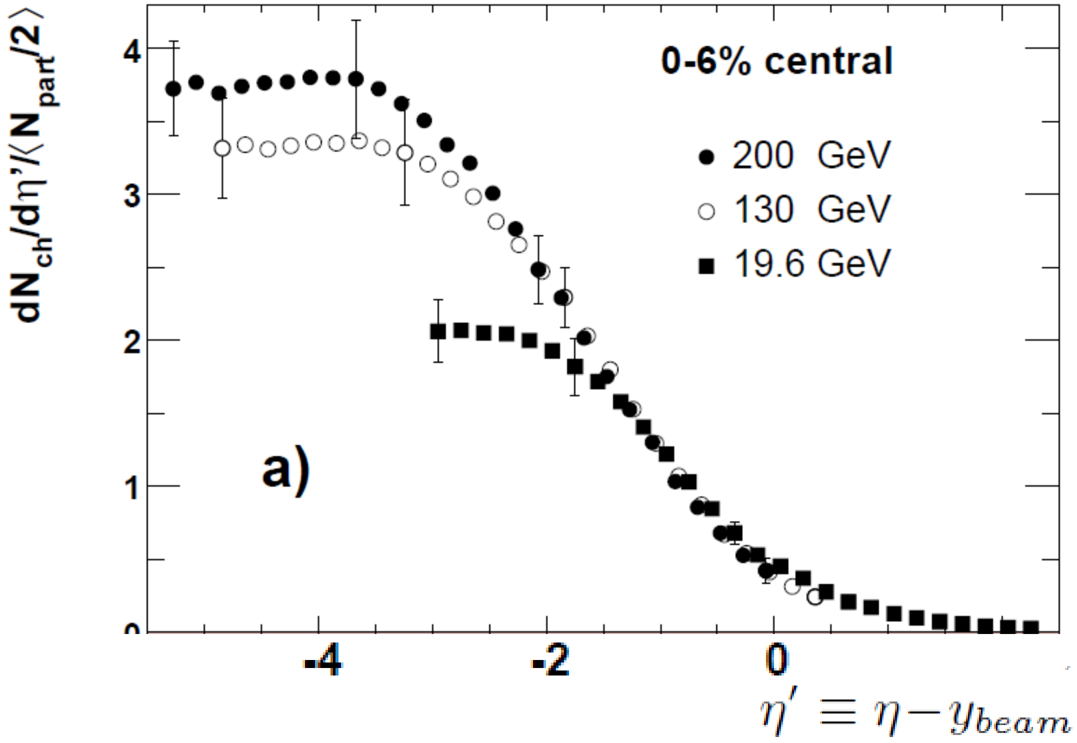
SPS: slight onset of transparency $\Delta y = 2.0$

RHIC: 'limiting fragmentation' $\Delta y = 2.0$

implying fraction $1-\exp(-\Delta y) = 86\%\ E_{loss}$

energy deposit in central fireball

in pp (Fermilab data): $\Delta y = 0.95 \mathrel{\widehat{=}} 60\%\ E_{loss}$



PHOBOS nucl-ex/0210015

Initial Energy Density

$$\epsilon_0 = \mathrm{dE_t/dy/A_t \times dy/dz} = \langle \mathrm{m_t} \rangle \mathrm{1.5dN_{ch}/dy/A_t \times dy/dz}$$

Bjorken formula[*] using Jacobian $dy/dz=1/\tau_0$

typically evaluated at $\tau_0 = 1$ fm/c

	$\sqrt{s_{NN}}$ (GeV)	dE_t/dy (GeV)	ε_0 (GeV/fm^3)	T (GeV)
AGS	4.8	200	1.4	0.17
SPS	17.2	450	3.0	0.21
RHIC	200	600	5.5	0.30
at $\tau_0 = 1/p_{sat} = 0.14$ fm/c			40	0.49
LHC	2760	1755	11.7	0.36
at $\tau_0 = 1/p_{sat} = 0.08$ fm/c			146	0.68

all above lQCD result for pseudo-critical energy density and temperature

---

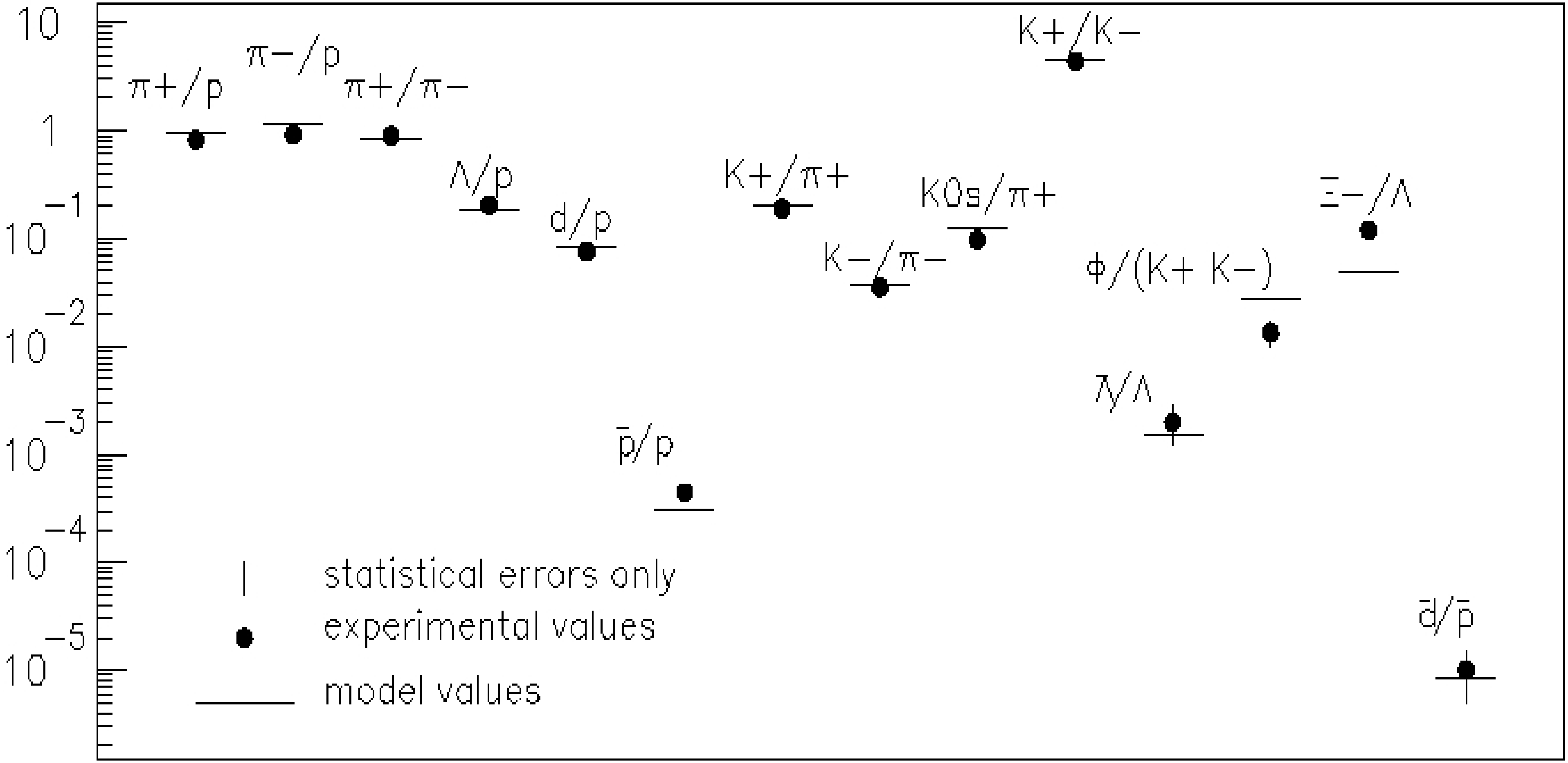
[*] this is lower bound; if during expansion work is done (pdV) initial energy density higher (indications from hydrodynamics at LHC: factor 3)

Hadronization of the fireball

hadro-chemical freeze-out at phase boundary between QGP and hadronic matter

first measurement of a comprehensive set of hadrons at BNL AGS by 1993

14.6 A GeV/c central Si + Au collisions – combined data by E802, E810, E814



first successful application of statistical hadronization model (grand canonical ensemble) -2 fit parameters dynamic range: 9 orders of magnitude! no deviation

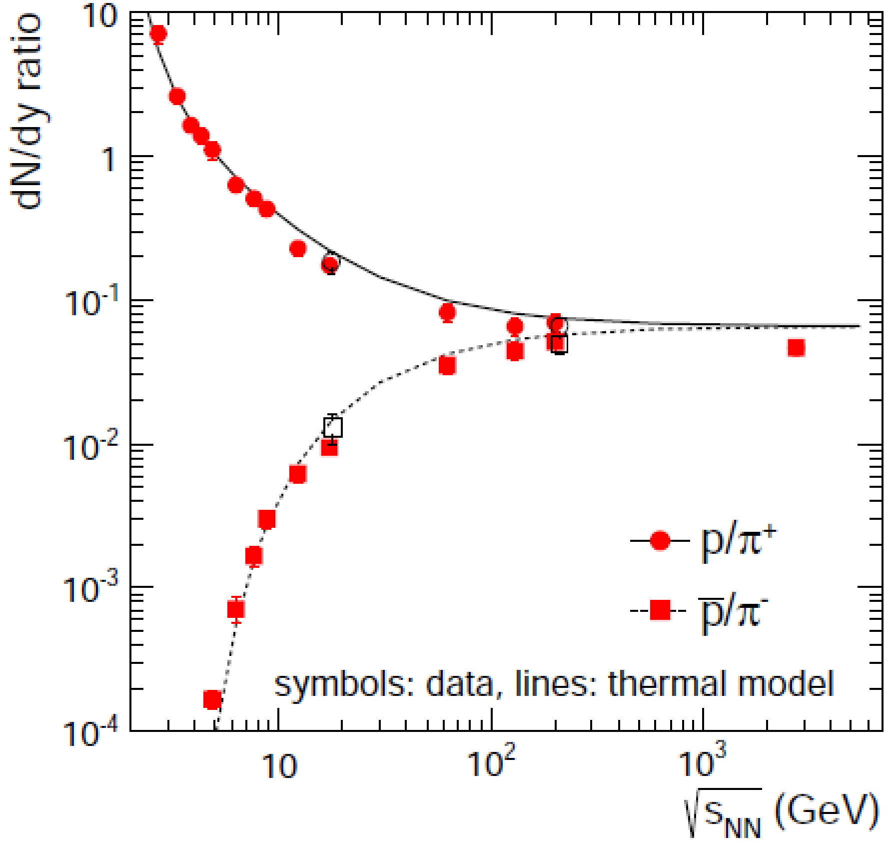
P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, PLB344 (1995) 43

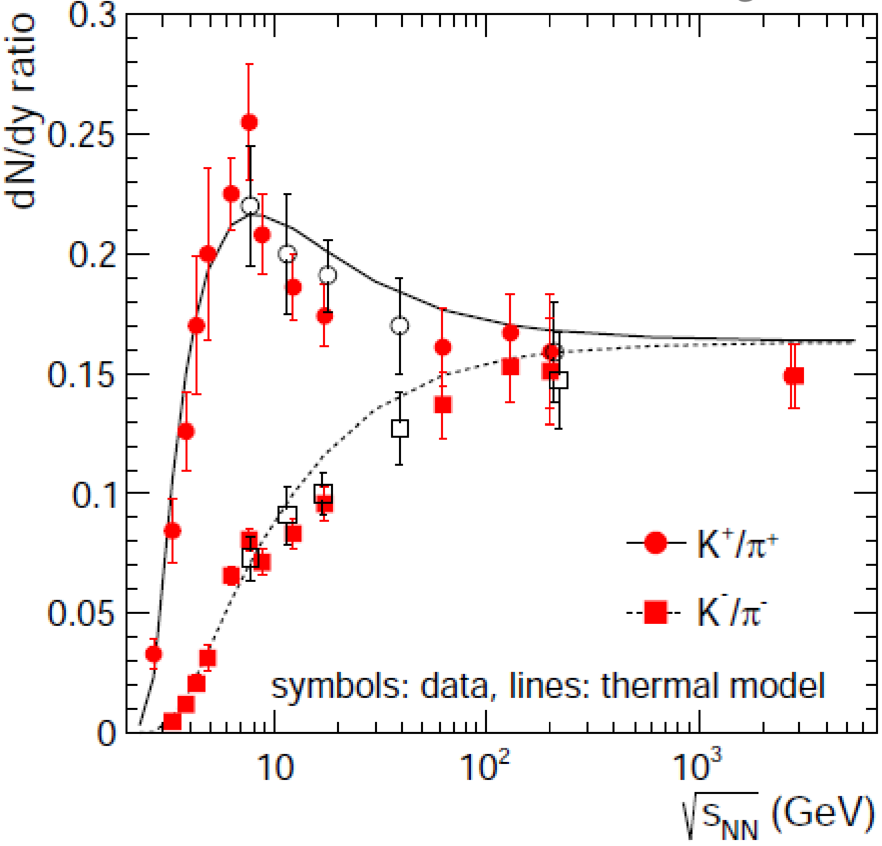
Beam energy dependence of hadron yields in AuAu and PbPb collisions from AGS to LHC

fits work equally well at higher beam energies

following the obtained T and μ_b evolution, features of proton/pion and kaon/pion ratios reproduced in detail

A. Andronic, P. Braun-Munzinger, J.S.

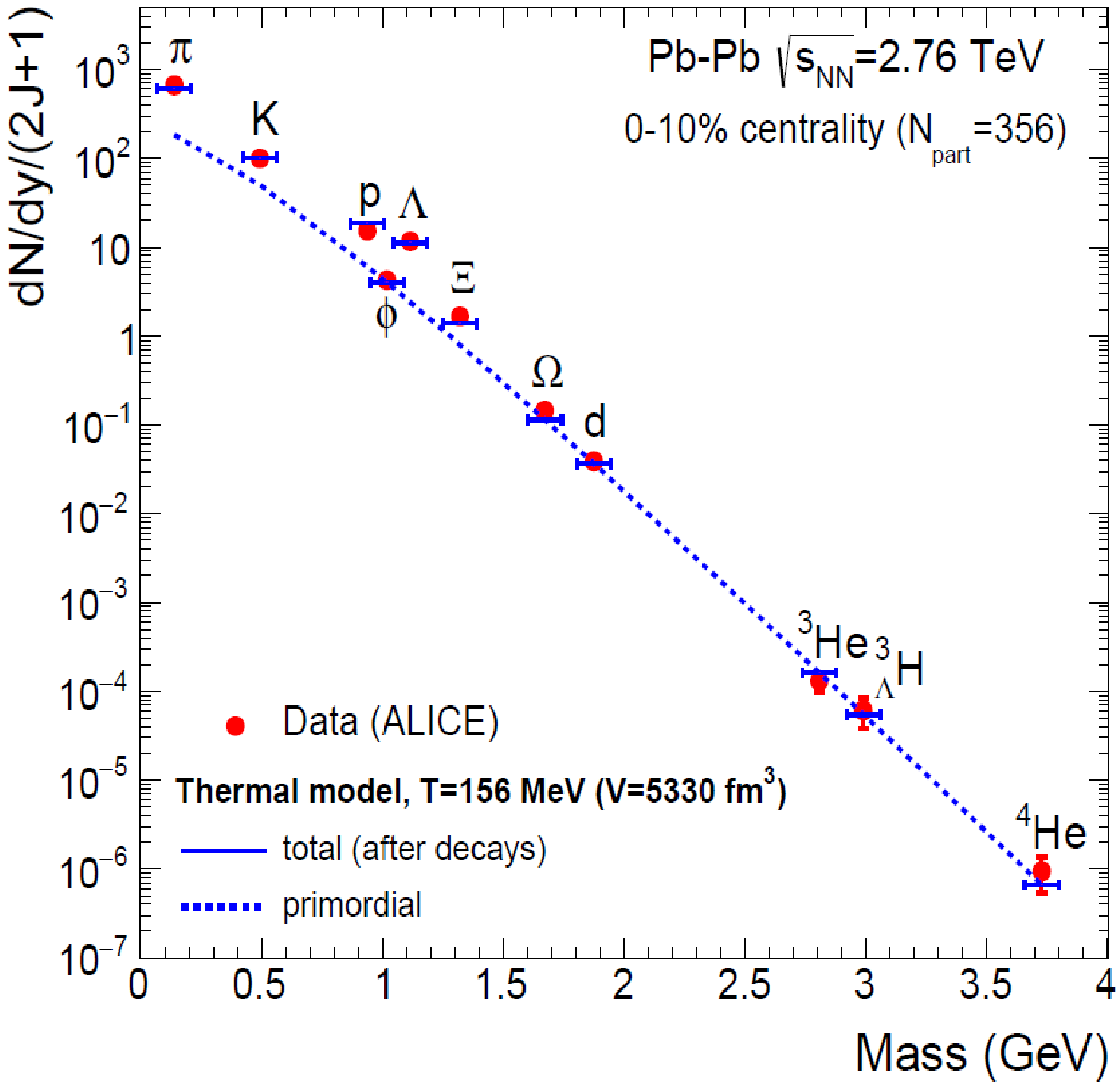




Statistical model (grand canonical) describes production of hadrons and (anti-)nuclei at LHC

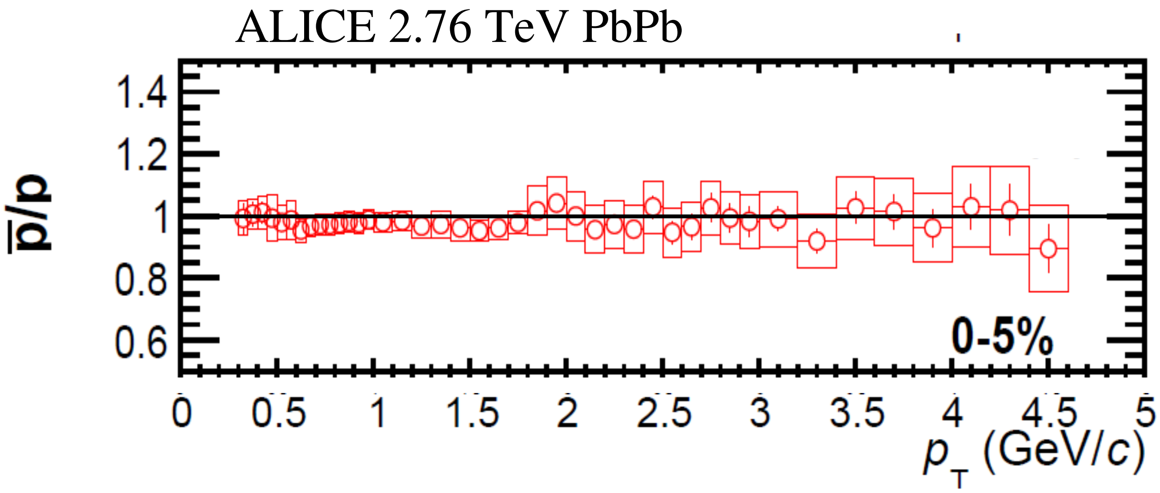
1 free parameter: temperature T

agreement over 9 orders of magnitude with QCD statistical operator prediction
(- strong decays need to be added)

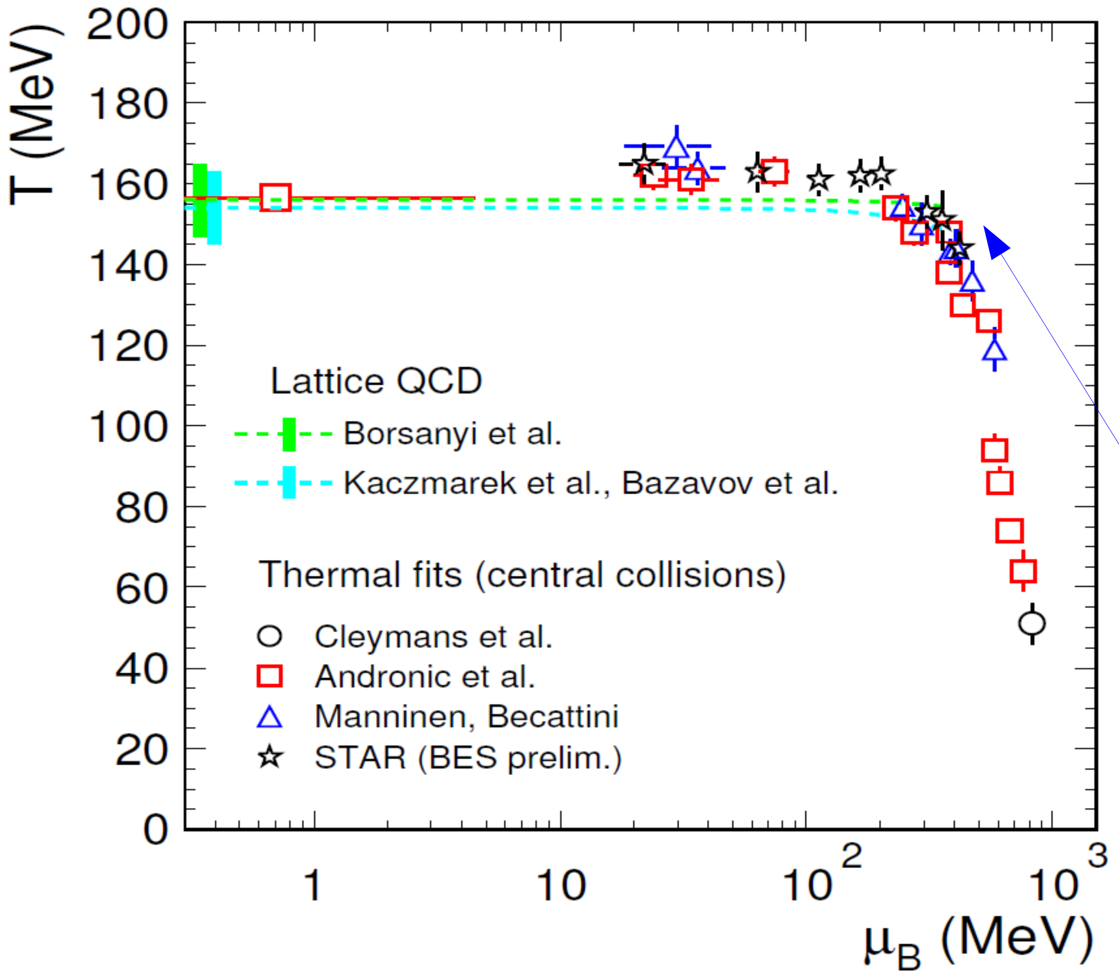


Biggest difference LHC compared to lower energies

- matter and anti-matter produced in equal proportions at LHC
- consistent with net-baryon free central region, (μ_b < 1 MeV) similar to early universe



Energy dependence of temperature and baryochem pot.



hadron yields for Pb-Pb central collisions from LHC down to RHIC, SPS, AGS and even SIS energies well described by a statistical ensemble

- there is a limiting temperature for a hadronic system

$T_{lim} = 159 \pm 3$ MeV

reached for $\sqrt{s_{NN}} \geq 10$ GeV

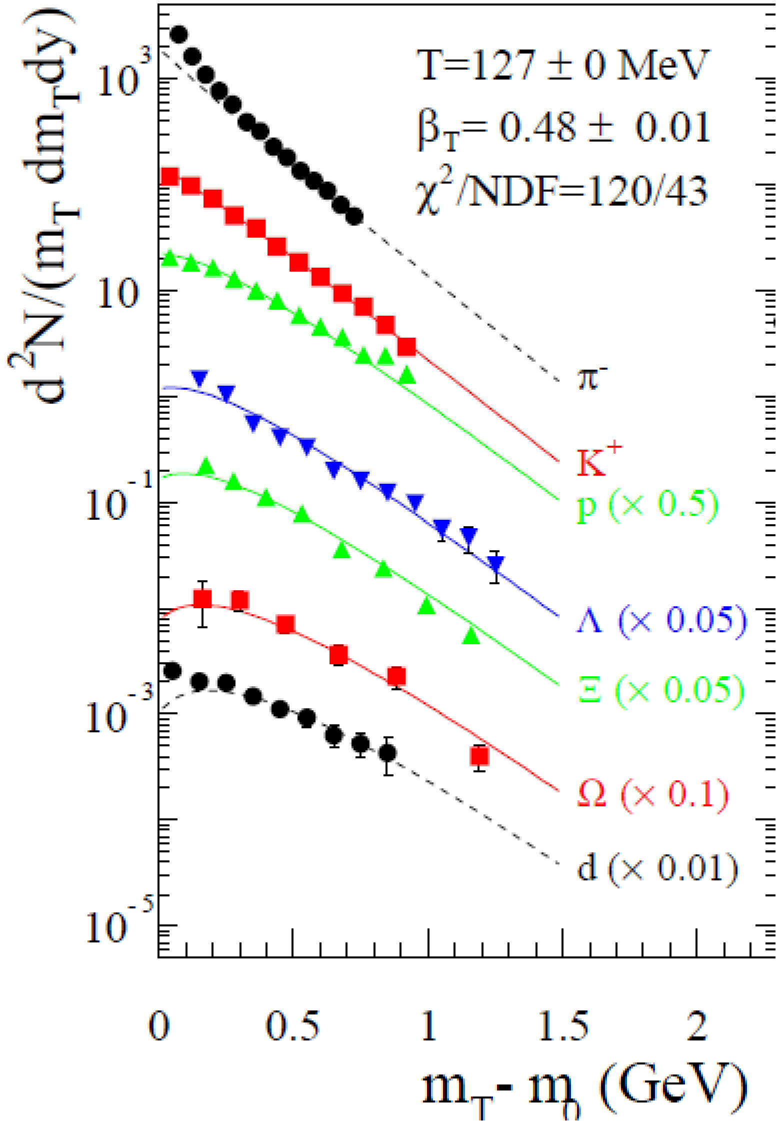
- T_{lim} in agreement with the pseudo-critical temperature $T_c = 154 \pm 9$ MeV from lQCD

Hadron spectra and correlations

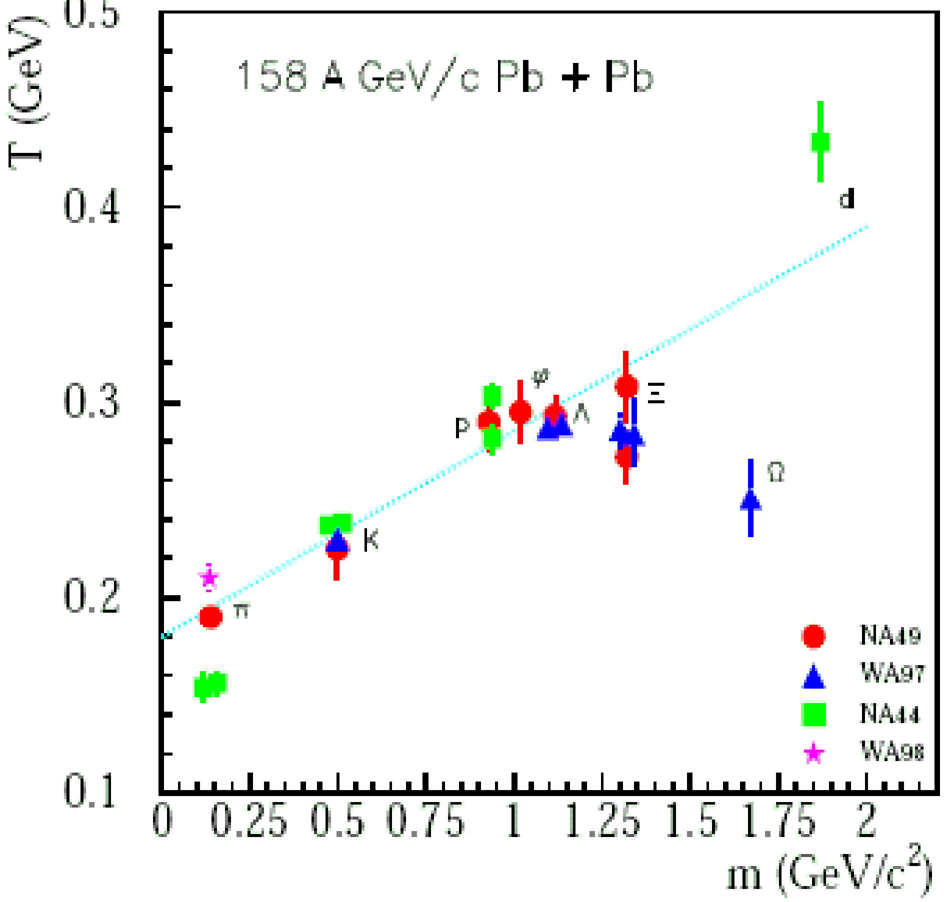
- reveal in addition to kinetic freeze-out temperature strong collective expansion
- survival of early fluctuations

Spectra of identified hadrons at SPS

158 GeV/c PbPb NA49 at SPS



mass dependence of inverse slopes



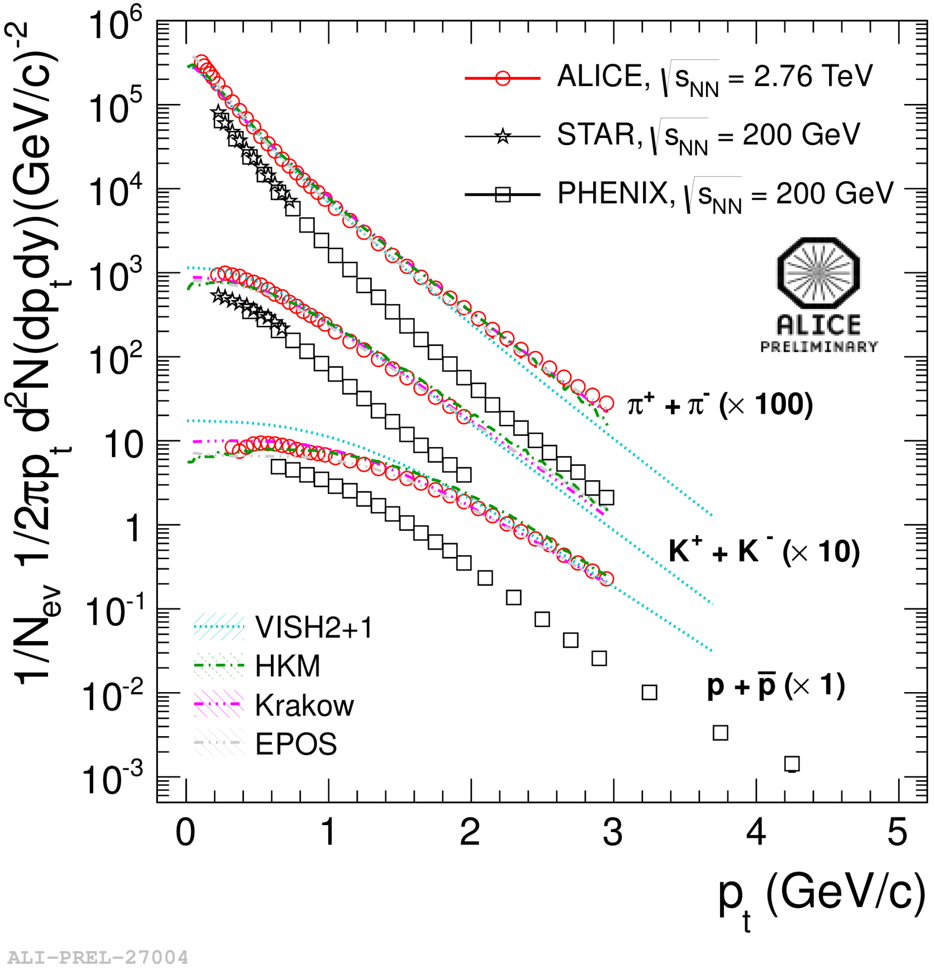
with flow

no flow

strong (linear) mass dependence of spectral slopes: superposition of random thermal motion and ordered collective expansion (flow) - $\beta_T \approx 0.5$

Spectra of identified hadrons at RHIC and LHC

central AuAu and PbPb at RHIC and LHC



spectral shapes even stronger mass dependence - characteristic for hydrodynamic expansion

indicate at LHC significantly larger expansion velocity than at RHIC

models with hydrodynamic expansion that reproduce HBT (see below) also describe spectra very well (HKM, Krakow)

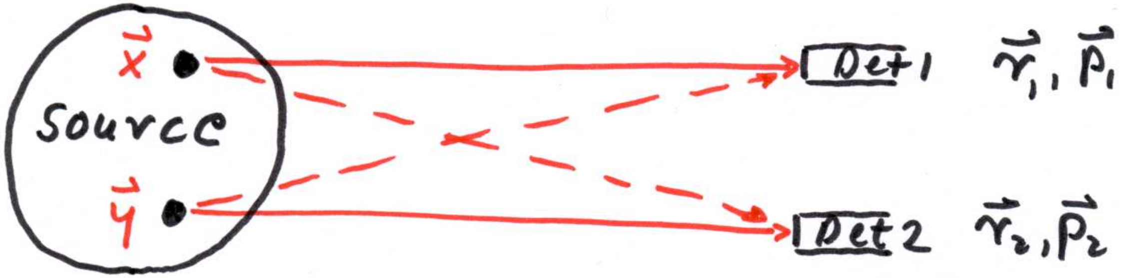
expansion velocity at surface: ¾ c

Bose-Einstein correlations and space-time extent of fireball

stochastic emission from extended source

consider 2 identical bosons (photons, pions, …)

2 detectors in locations r_1, r_2 observe identical bosons of momenta p_1 and p_2



cannot distinguish solid and dashed paths because of identical particles

for plane waves, the probability amplitude for detection of the pair is

$$A_{12} = \frac{1}{\sqrt{2}}[e^{ip_1(r_1-x)}e^{ip_2(r_2-y)} + e^{ip_1(r_1-y)}e^{ip_2(r_2-x)}]$$

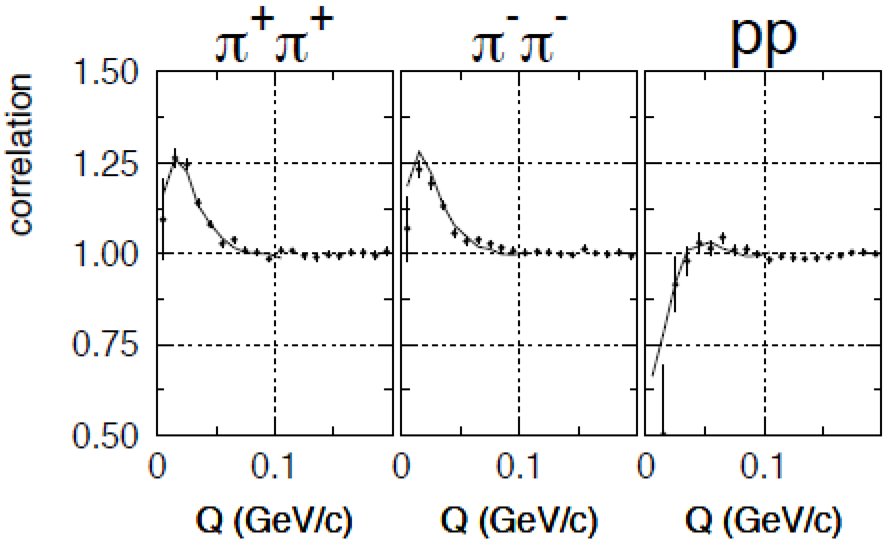
with 4-vectors p,r,x,y (to be general for nonstatic source)

square of amplitude: intensity → “intensity interferometry”

technique of intensity interferometry developed by Hanbury-Brown and Twiss in astrophysics as a means to determine size of distant objects

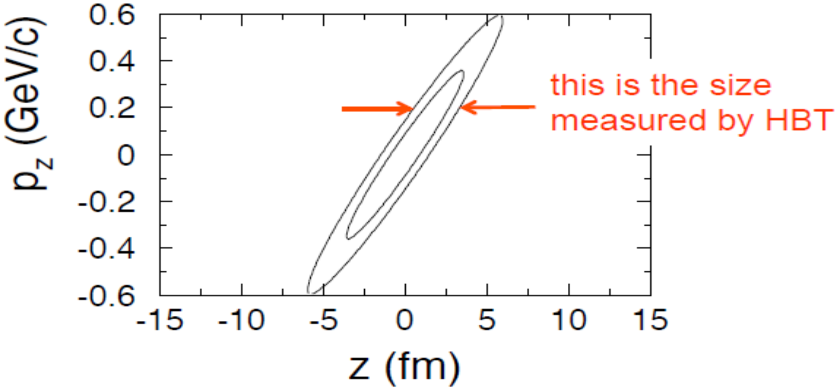
Hanbury-Brown/Twiss correlations to measure the space-time extent of the fireball

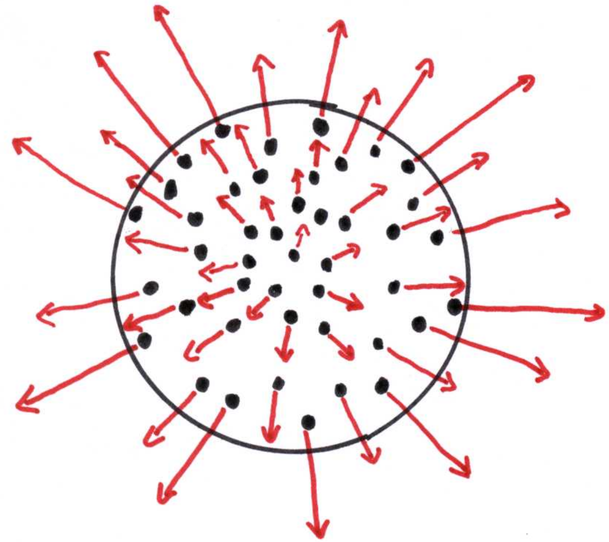
Au + Au at 10.8 A GeV
E877 data compared to RQMD



first a puzzle: small apparent radii (2 fm/c)
then a discovery: are due to collective expansion of fireball

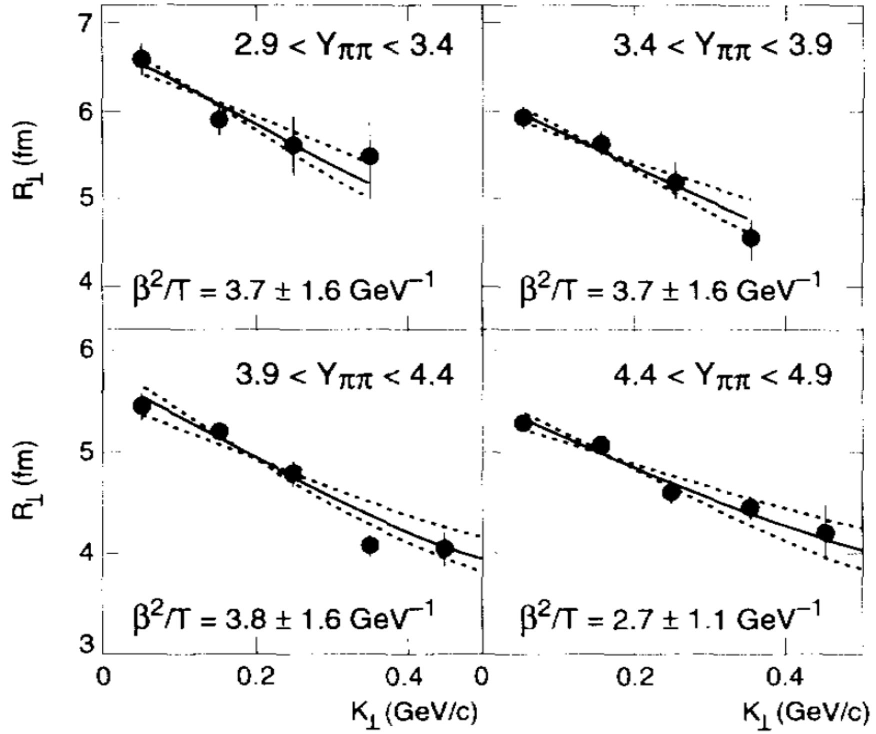
space – momentum correlations → only part of the source is 'visible'
predicted by Mahklin/Sinyukov





2-Pion Hanbury-Brown/Twiss correlations → Radius Parameters as Function of Pair Transverse Momentum

158 A GeV PbPb – NA49 – Nucl. Phys. A638 (1998) 91c

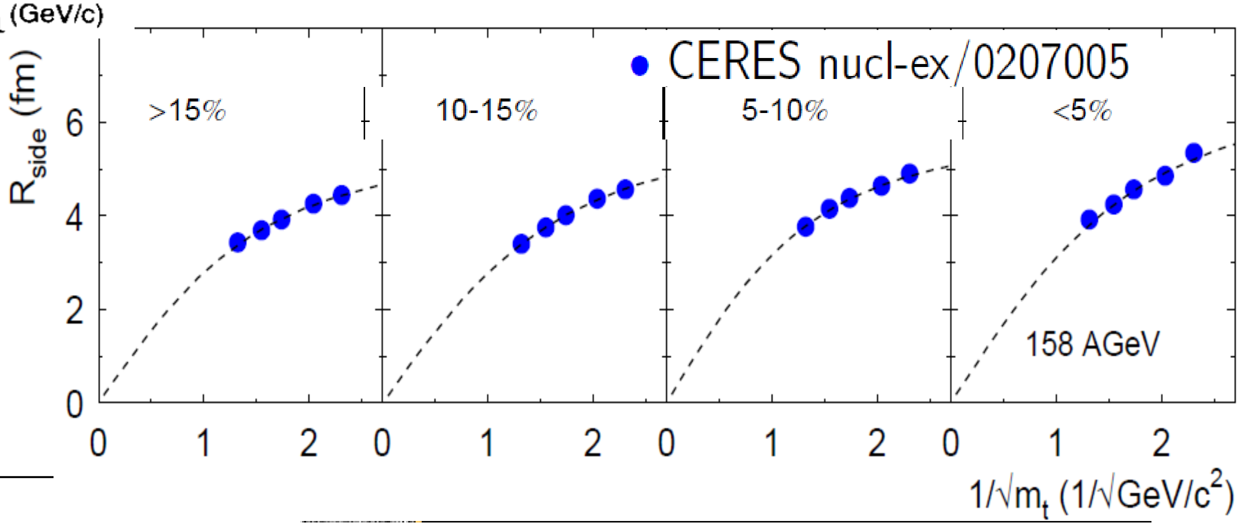


transverse mom. dependence shows typical shape for hydrodynamically expanding source

$$R_{\rm side} \approx R_{\rm geo}/(1 + m_t \cdot F(T_f, \beta_t))^{\frac{1}{2}}$$

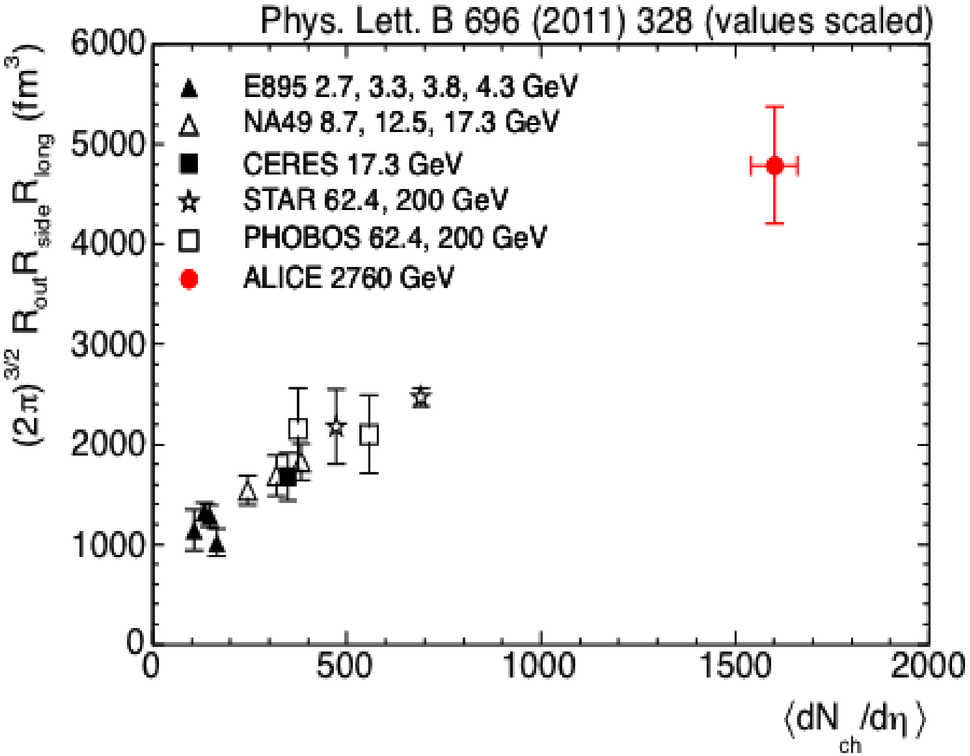
U. Heinz *et al.*

$\beta_t \approx 0.55$ for $T_f = 120$ MeV



Freeze-out volume and duration of expansion

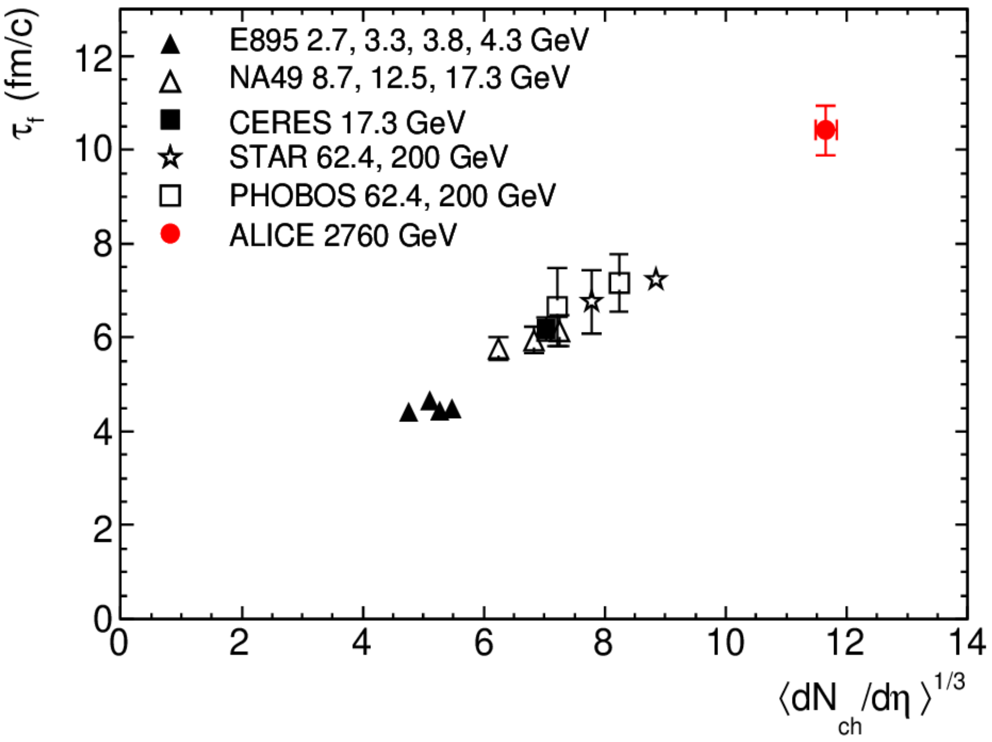
coherence volume $V = (2\pi)^{3/2} R_{side}^2 R_{long}$



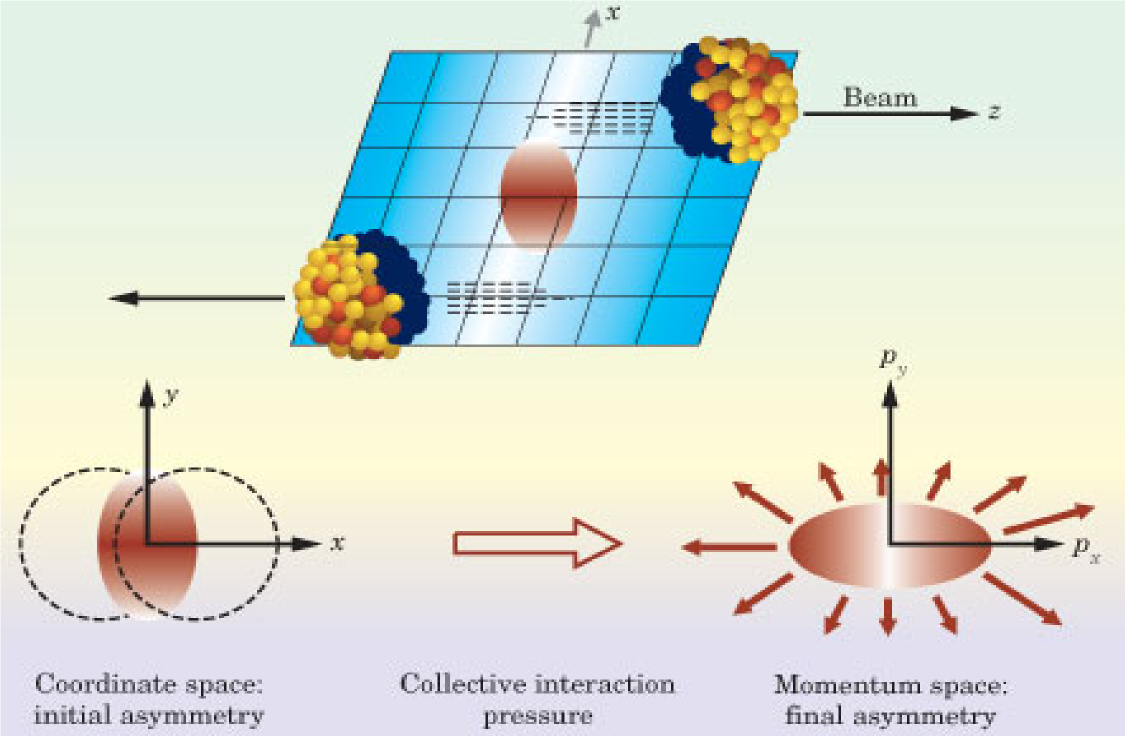
huge growth with √s - at all energies larger than overlap volume – reflects strong expansion of fireball at surface at LHC velocity ¾ c

from R_{long}: duration of expansion
4.5 fm/c at AGS to 10 fm/c at LHC

$$R_{long} = \tau_f \sqrt{T/m_t}$$



Azimuthal anisotropy of transverse spectra



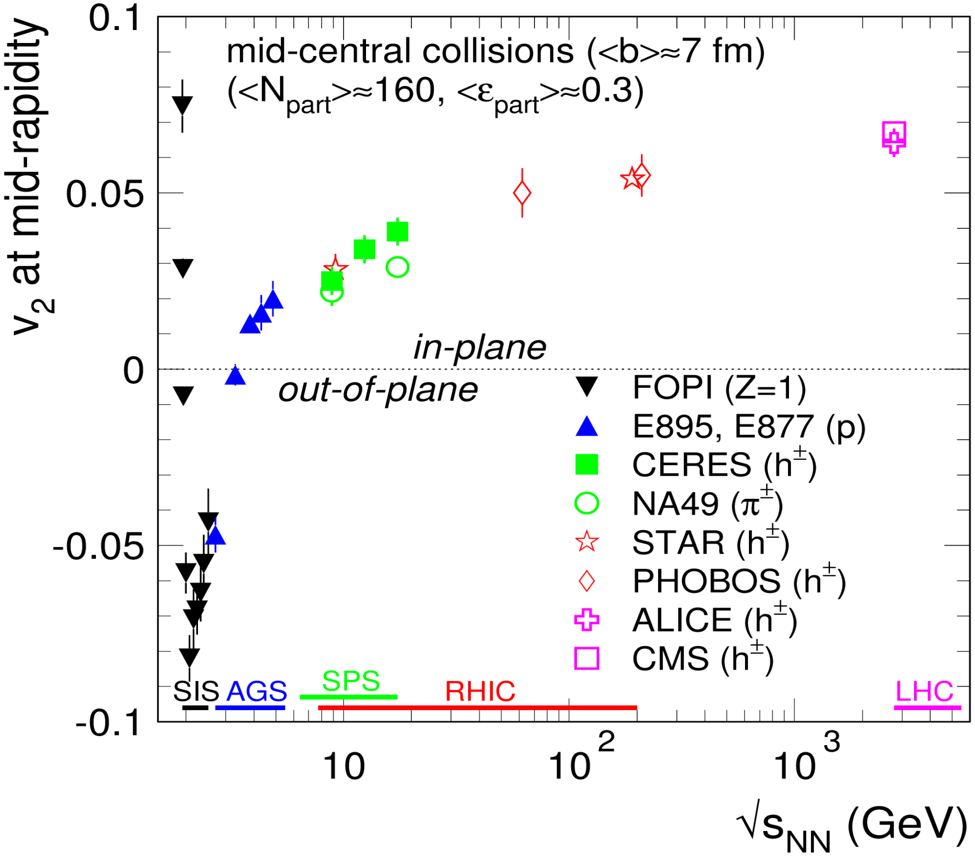
Fourier decomposition of momentum distributions rel. to reaction plane:

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

quadrupole component v_2
"elliptic flow"

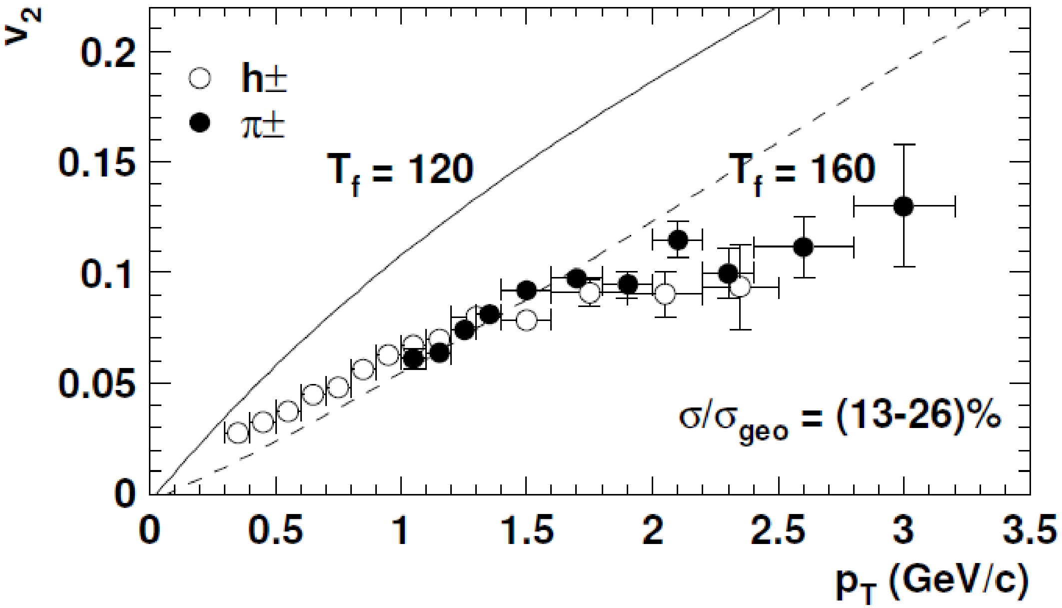
the v_n are the equivalent of the power spectrum of cosmic microwave rad.

Elliptic flow as function of collision energy



- effect of expansion (positive v_2) seen from top AGS energy upwards
- at lower energy: shadowing by fragments
- first discovered as tiny 2% effect by E877 in 1993

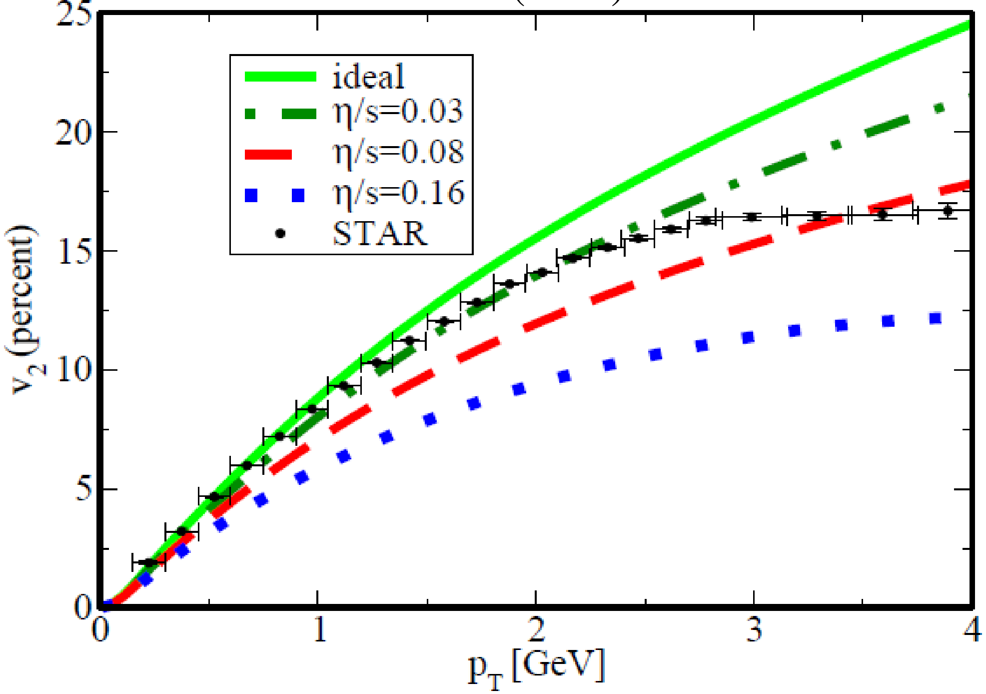
158 A GeV PbAu – CERES PRL 92 (2004) 032301



at top SPS energy, modelling with ideal relativistic hydrodynamics close to exp. data

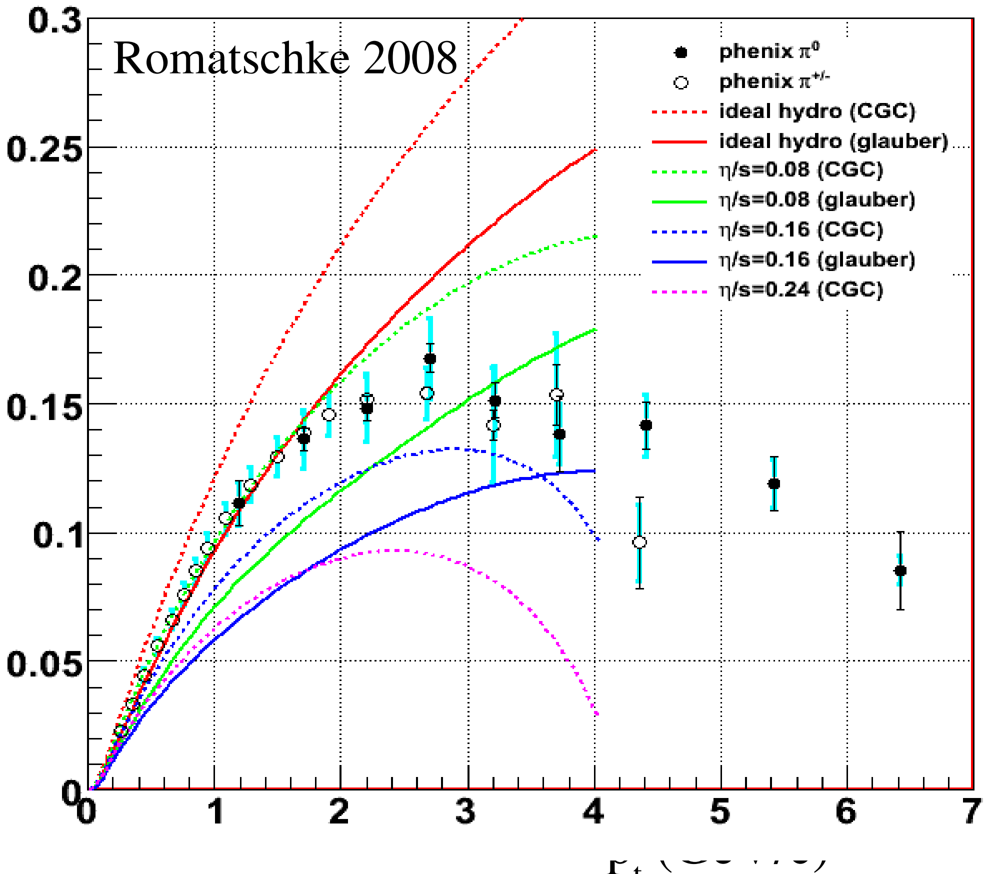
Discovery of RHIC: paradigm of QGP as near ideal liquid

Romatschke PRL 99 (2007) 172301



how perfect is the fluid observed at RHIC?
very small ratio of shear viscosity to entropy density η/s describes data

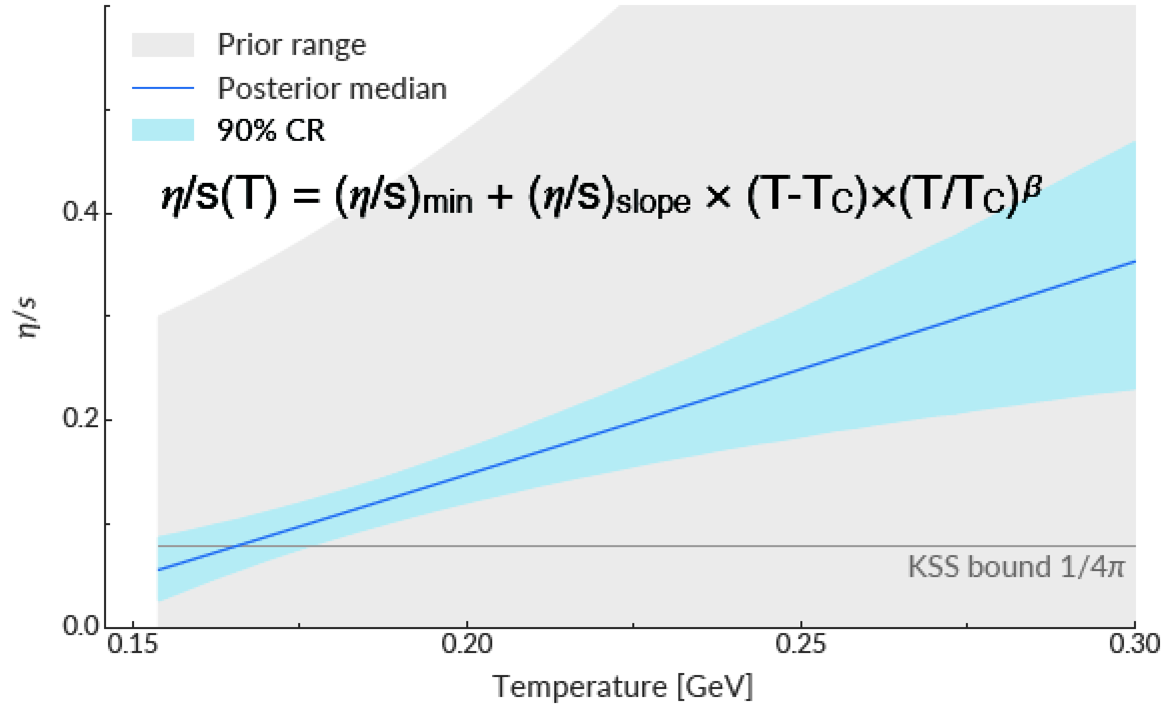
in hydro regime v_2 driven by
initial condition and
properties of the liquid
→ ratio of viscosity to entropy density η/s

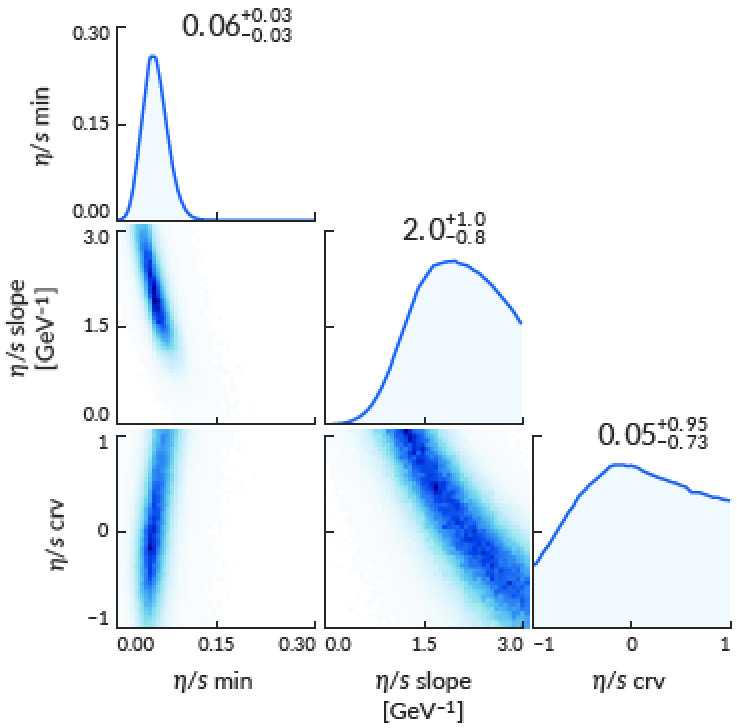


Constraining initial condition and QGP medium properties simultaneously

global Bayesian analysis of ALICE v2, v3, v4, π, K, p yields and $<p_t>$, charged particle yields in PbPb at 2.76 and 5.02 TeV, use of Gaussian process emulators

S. Bass et al., QM2017, arXiv:1704.04462

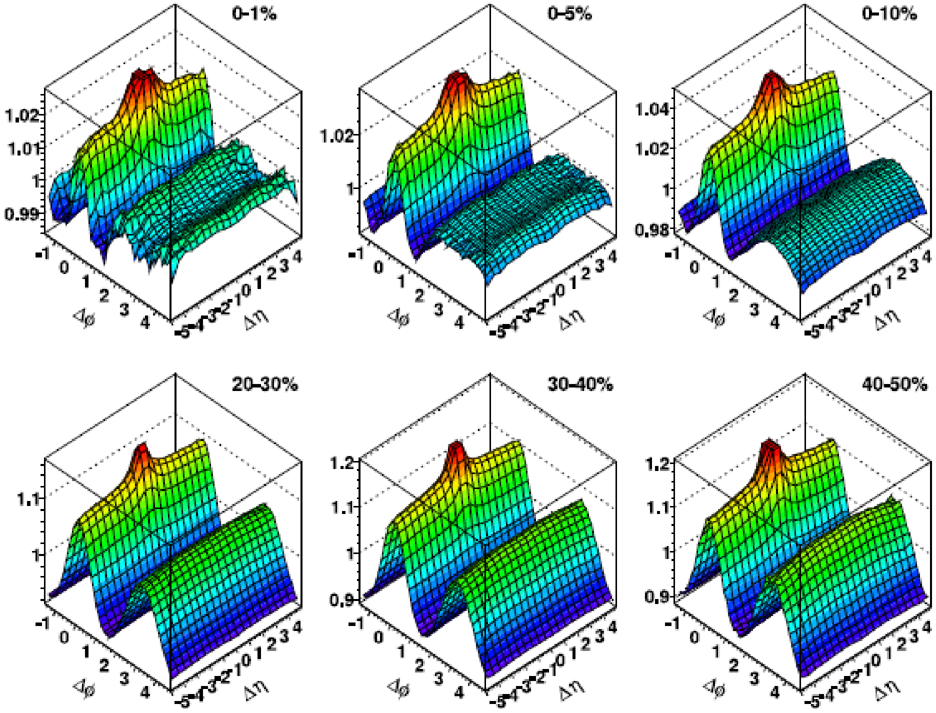


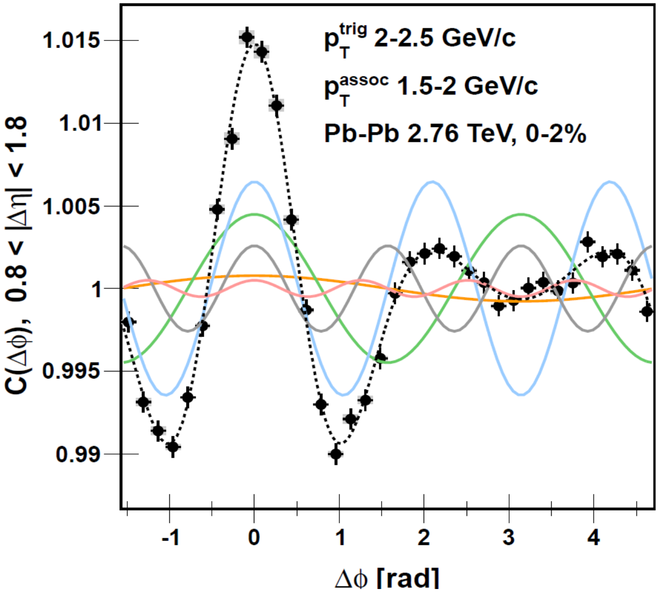


near T_c, shear viscosity/entropy density close to AdS/CFT lower bound $1/4\pi$ rising with temperature in QGP

Propagation of sound in the quark-gluon plasma

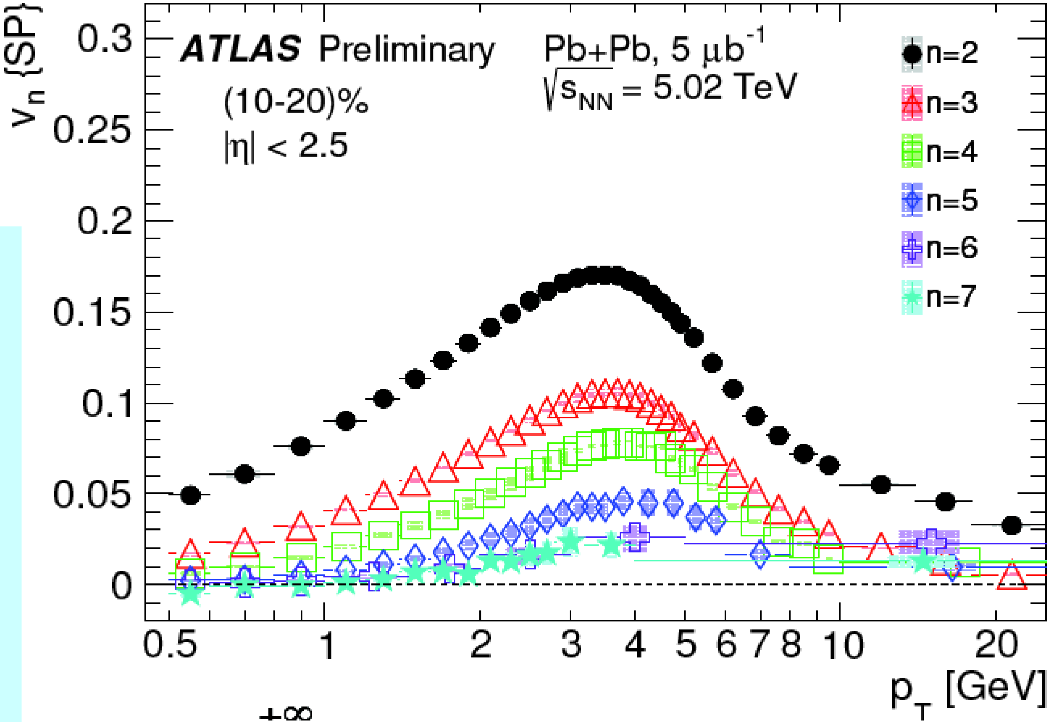
ATLAS-CONF-2011-074





ALICE, PLB 708 (2012)249

ATLAS-CONF-2016-105



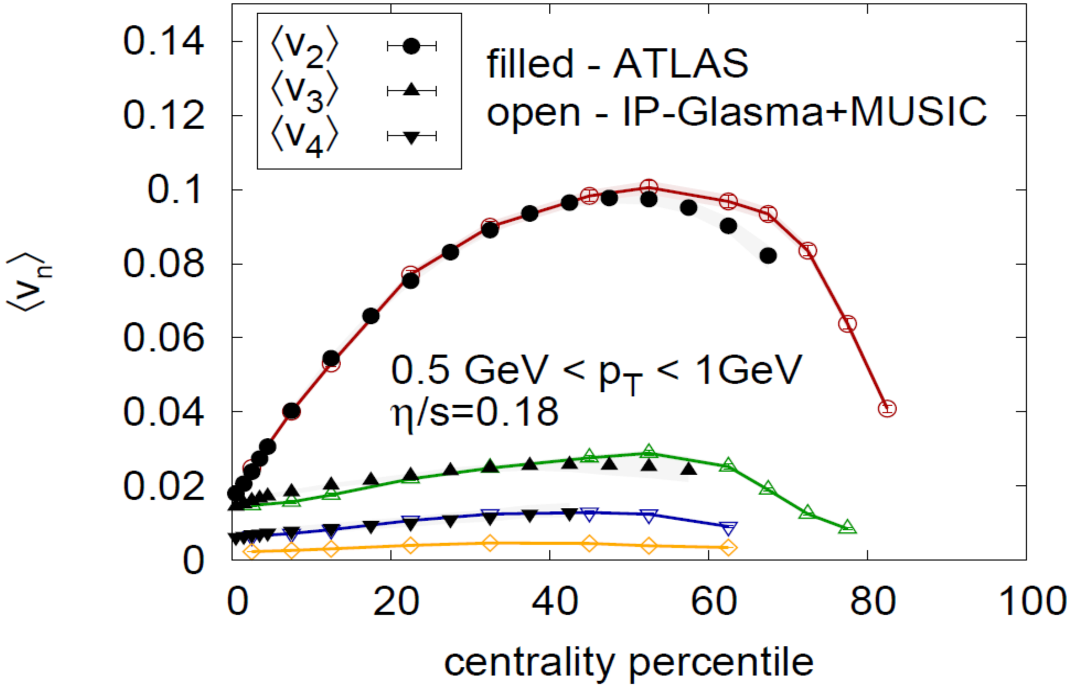
long-range rapidity correlations

understanding: higher harmonics (3,4,5,...) are due to initial inhomogeneities caused by granularity of binary parton-parton collisions survive the 10 fm/c hydrodynamic expansion phase

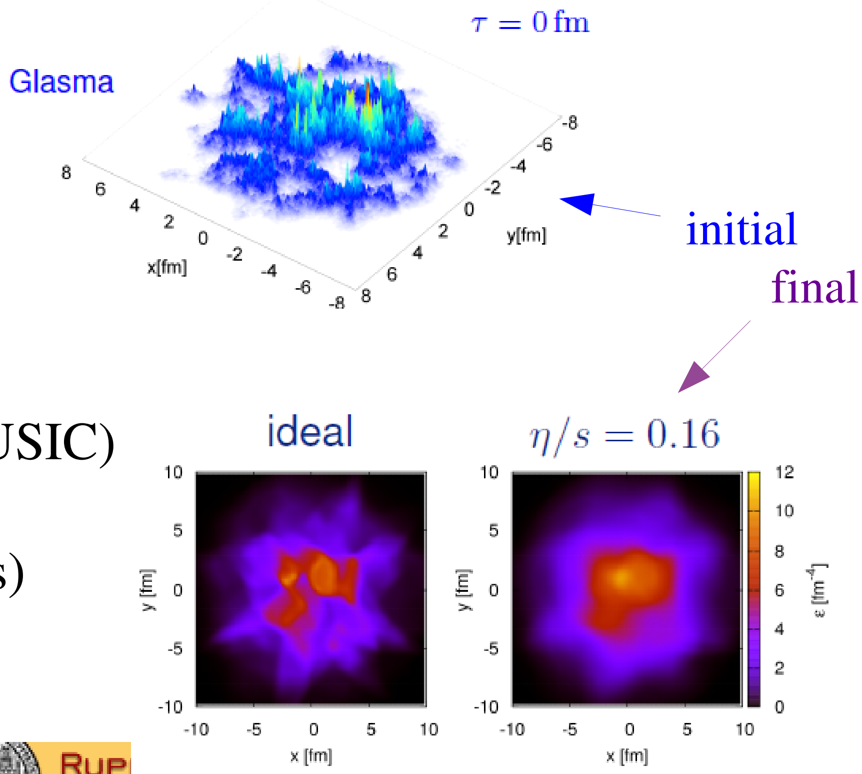
M. Luzum PLB 696 (2011) 499

Higher flow harmonics and their fluctuations

data: ATLAS JHEP 1311 (2013) 183
calc: B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113 (2014) 102301



ratios of v_2/v_n and their fluctuations depend on initial condition

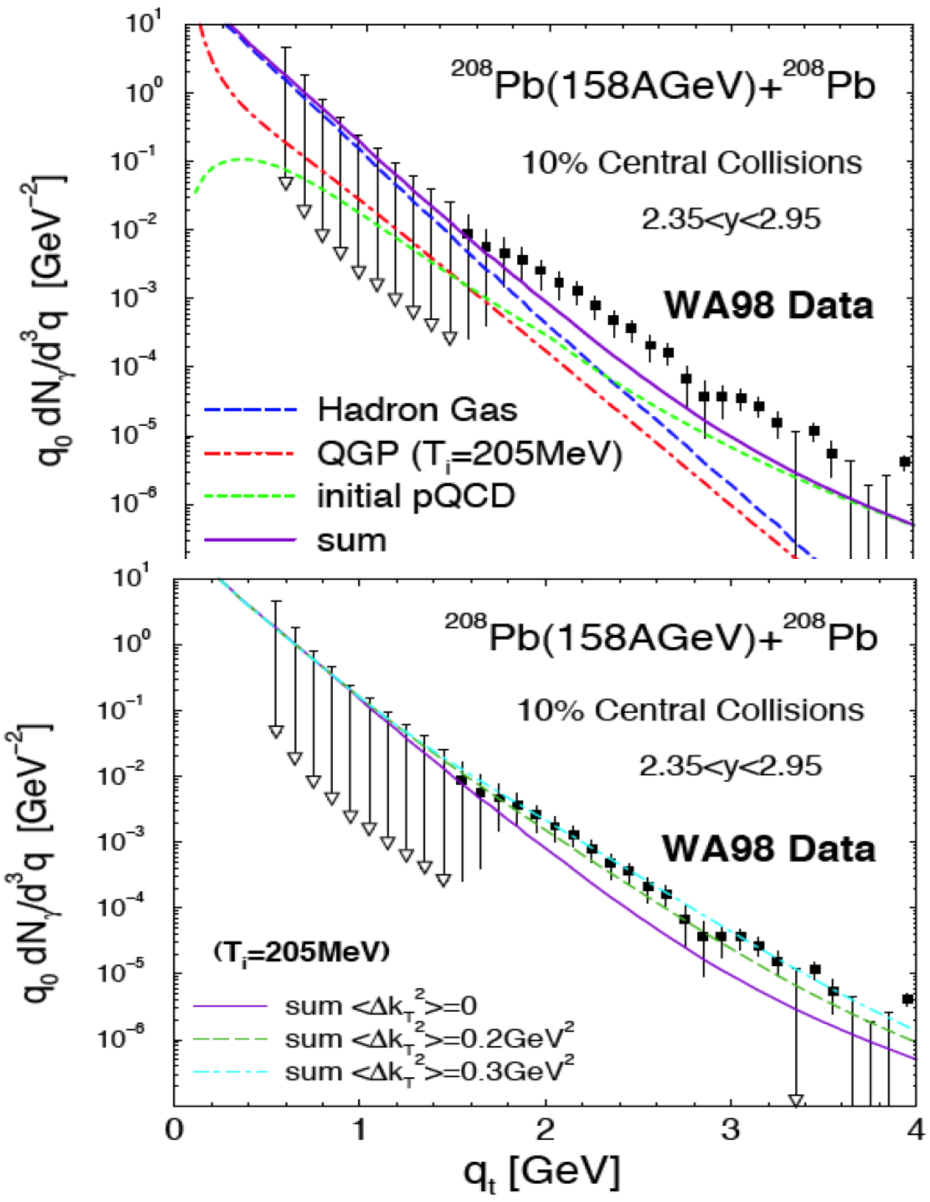


very well reproduced by viscous hydrodynamics (MUSIC) with fluctuating IP Glasma initial condition (including initial quantum fluctuations of gluon fields)

for LHC $\eta/s = 0.18$ for RHIC $\eta/s = 0.12$

indication of temperature dependence of η/s?

Direct photons: give access to entire time evolution

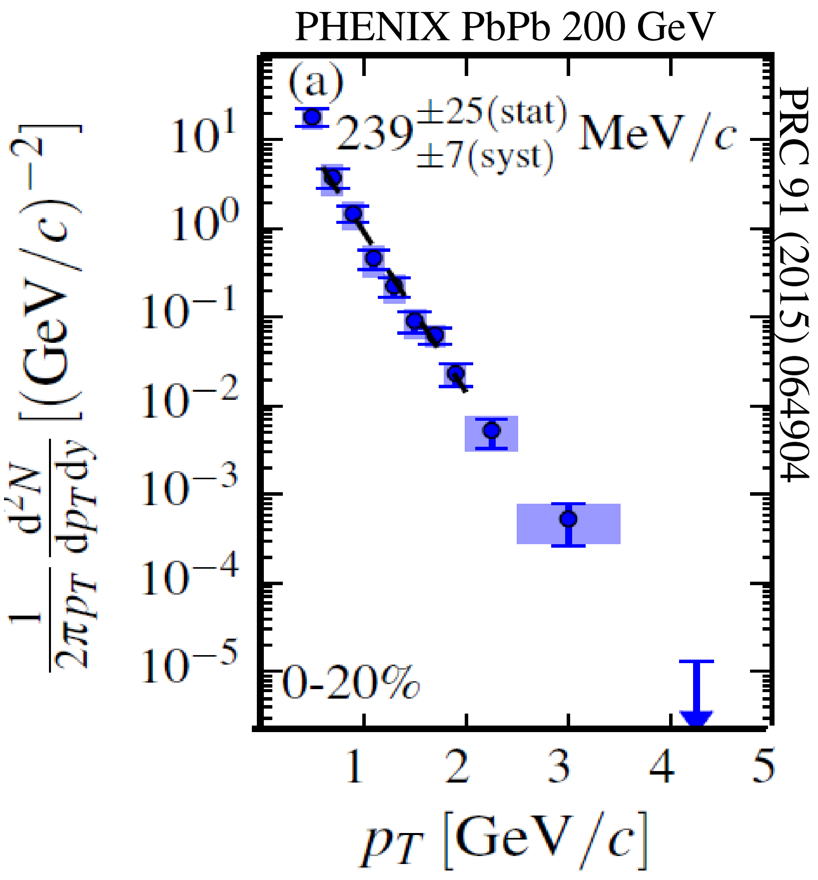


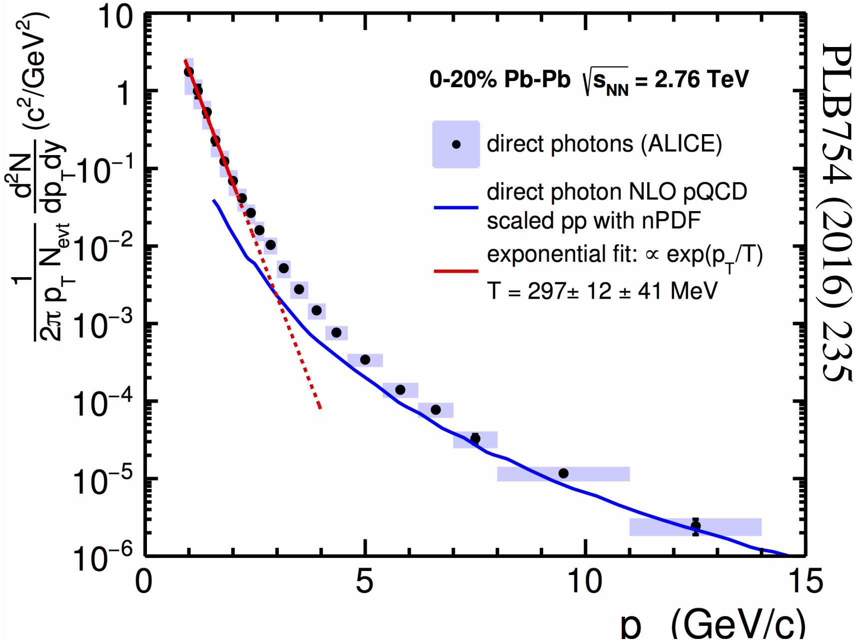
$\lambda_{mfp} \gg$ medium
$\rightarrow$ access to early QGP-phase

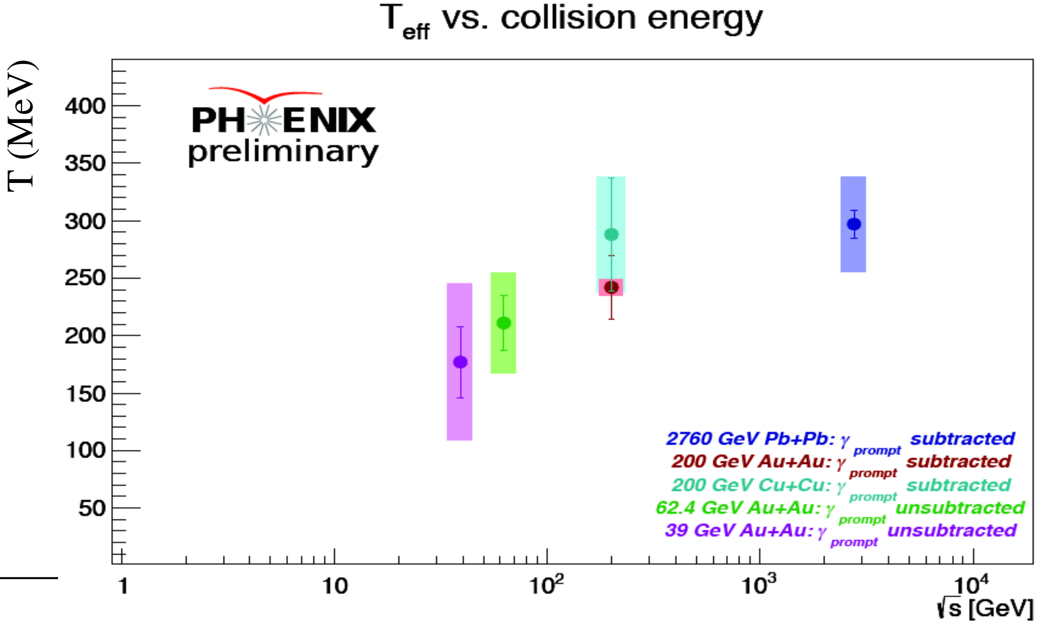
first significant measurement in PbPb collisions: WA98 at SPS

- data consistent with QGP formation (T_i = 200-270 MeV)
- but also purely hadronic scenario w. Cronin enhancement accounts for data

Direct photons at RHIC and LHC





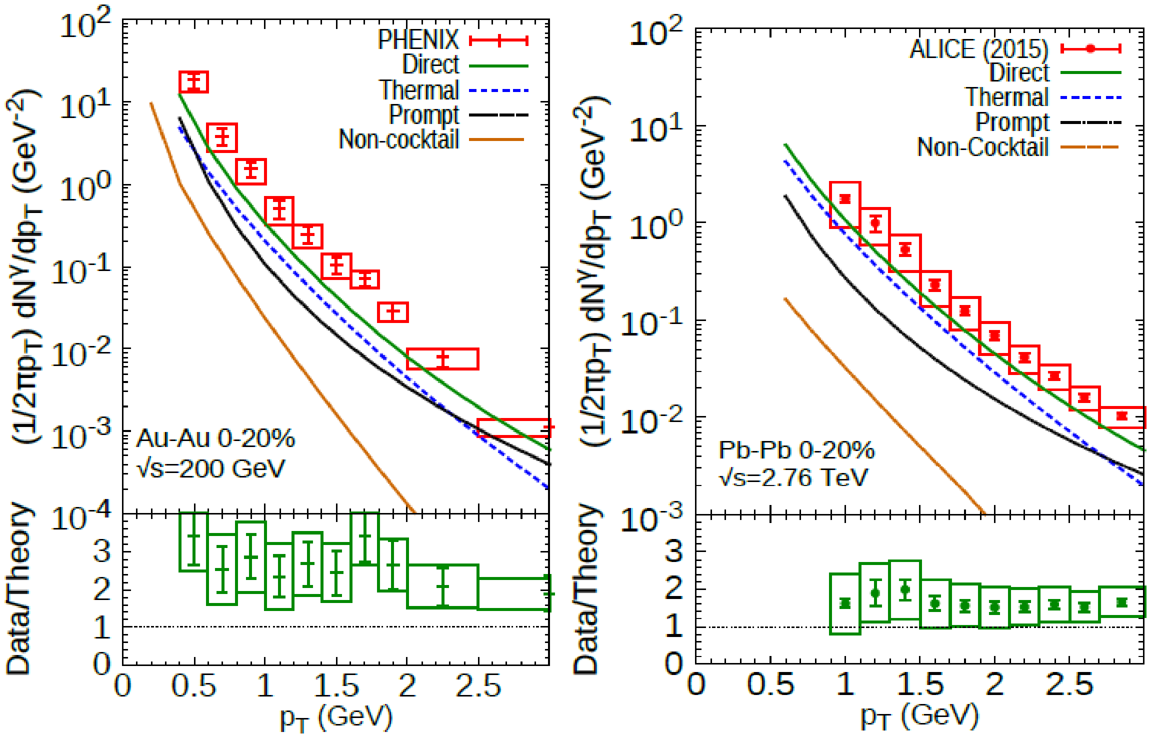


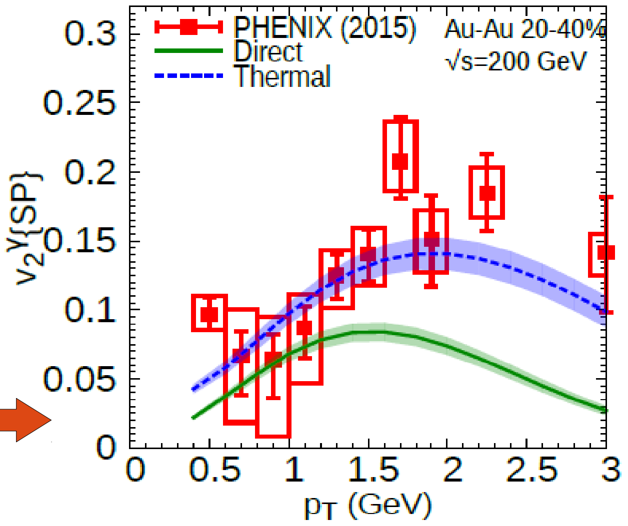
direct photons of fireball exhibit higher apparent temperatures with increasing √s

Direct photons at RHIC & LHC exhibit strong elliptic flow

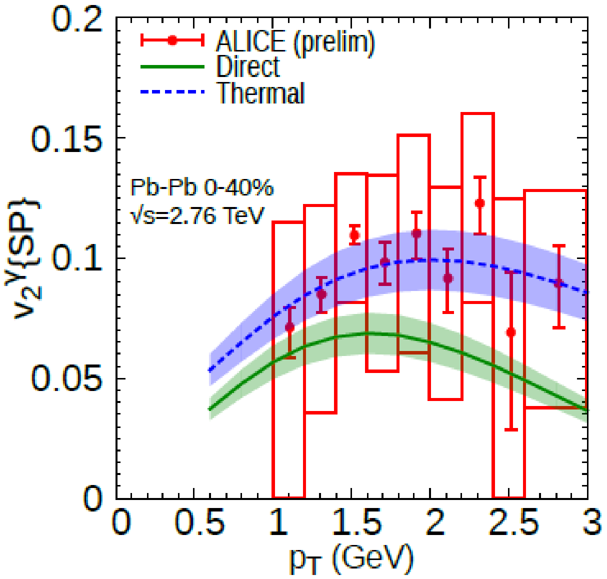
photon radiation of hydrodynamically expanding fireball

theory: J.F. Paquet et al., PRC93 (2016) 044906





PRC94 (2016) 064901

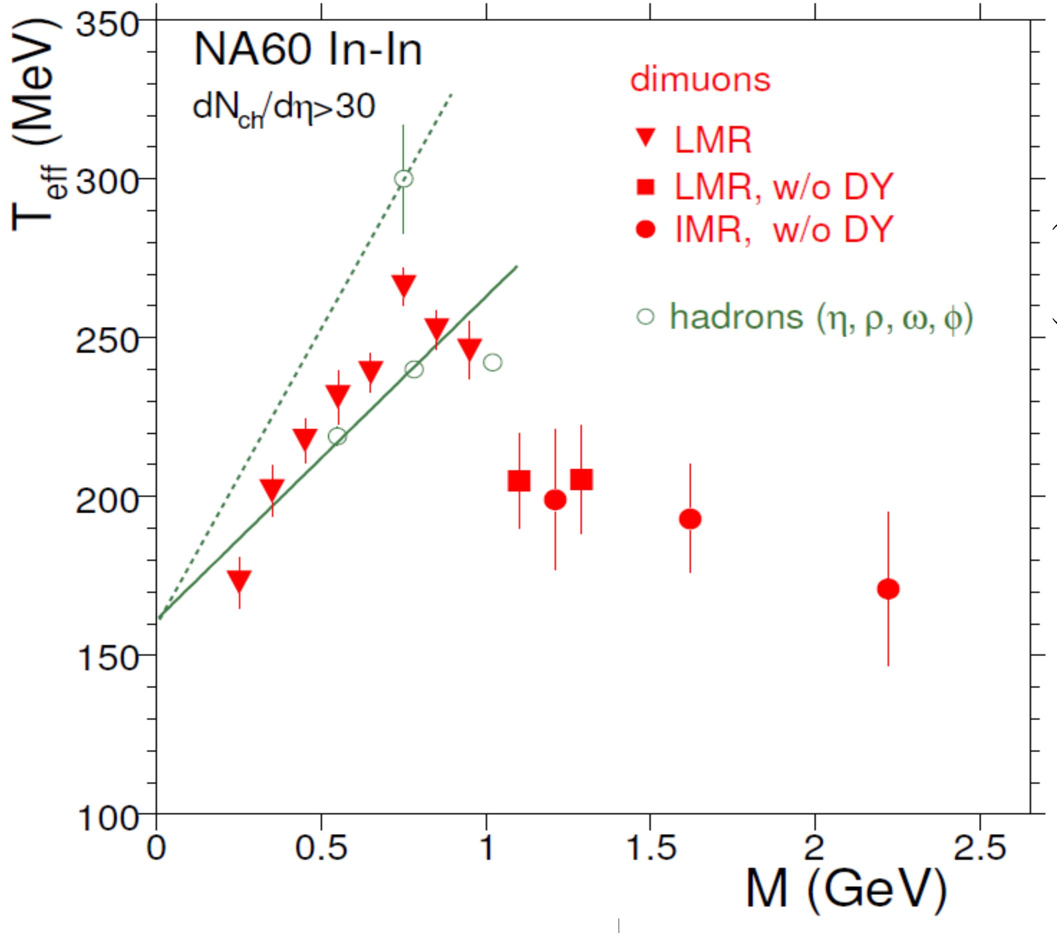


PLB754 (2016) 235

direct-photon puzzle: challenge of simultaneous description of spectra and v_2

rate µ T^2 – but flow takes time to evolve

Low and intermediate mass lepton pairs

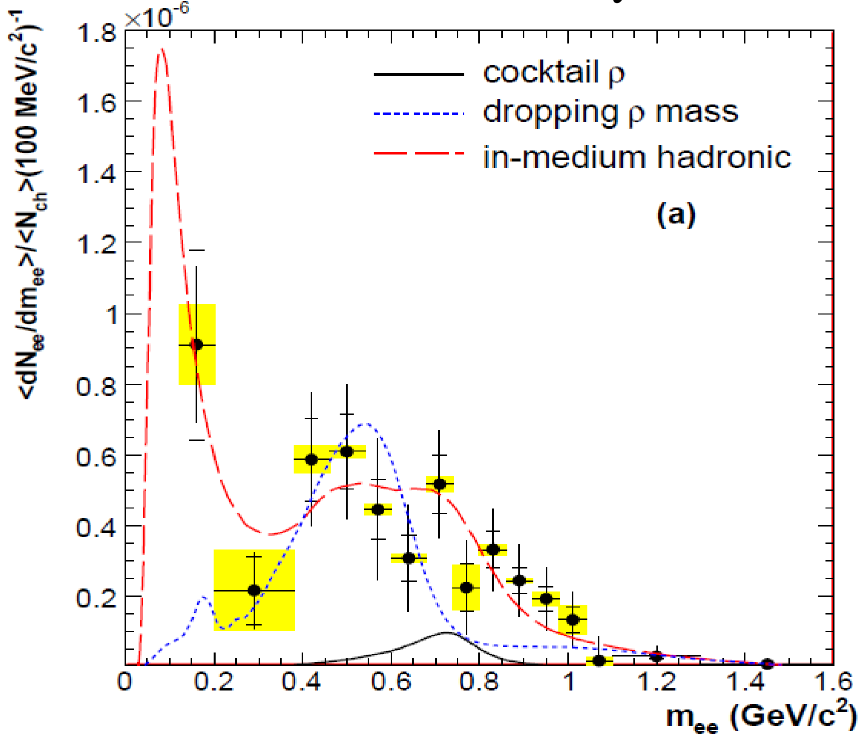


EPJ C61 (2009) 711

- up to mass ≈1.0 GeV: radial flow of a hadron-like di-lepton source
- above: thermal component with T = 205±12 MeV
- virtual photons vs real photons above

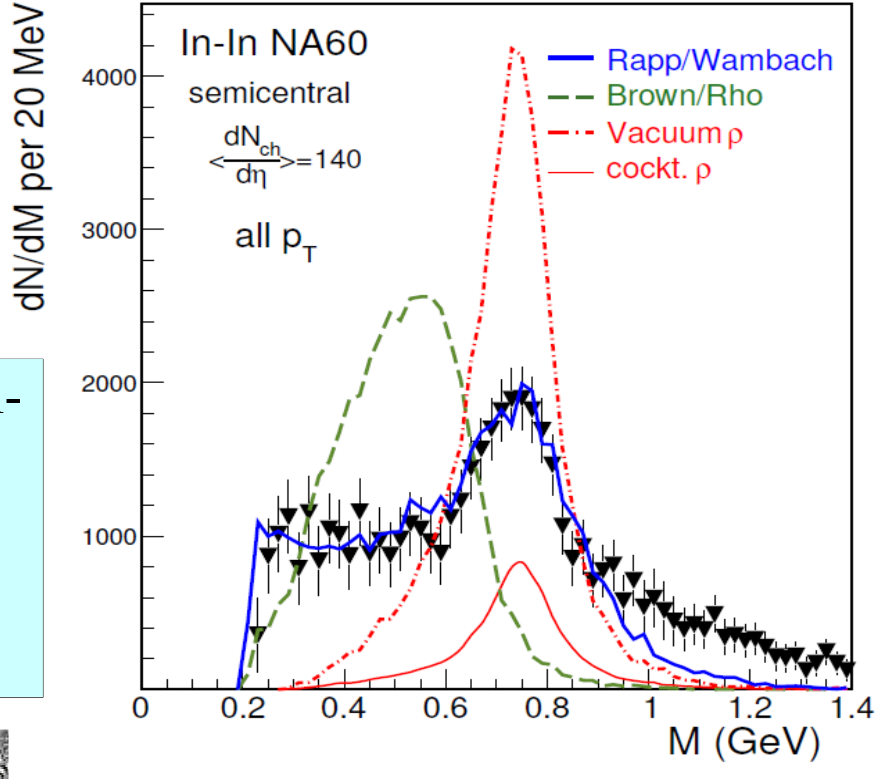
Low and intermediate mass lepton pairs

158 A GeV AuPb – CERES – Phys. Lett. B666 (2008) 425



ρ meson spectral function provides access to **restoration of chiral symmetry** at T_c degeneracy with chiral partner a_1

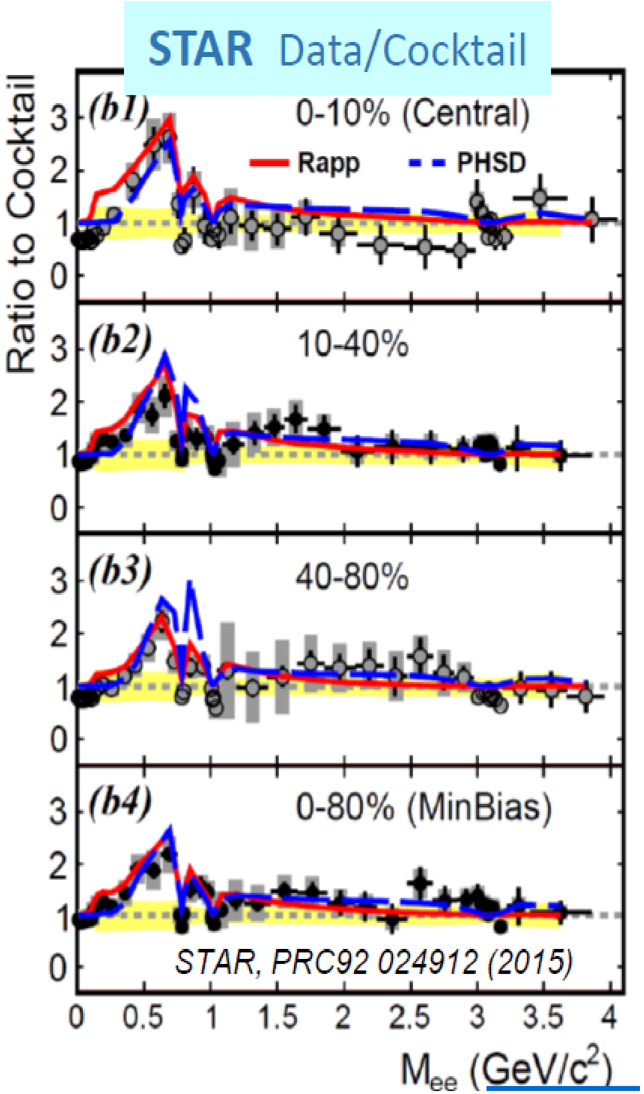
Eur. J. Phys. C61 (2009) 711



exp data of e^+e^- in central PbPb and of $\mu^+\mu^-$ in semi-central InIn after subtraction of all hadronic contributions except ρ: theories need significant broadening of spectral function of ρ at high T

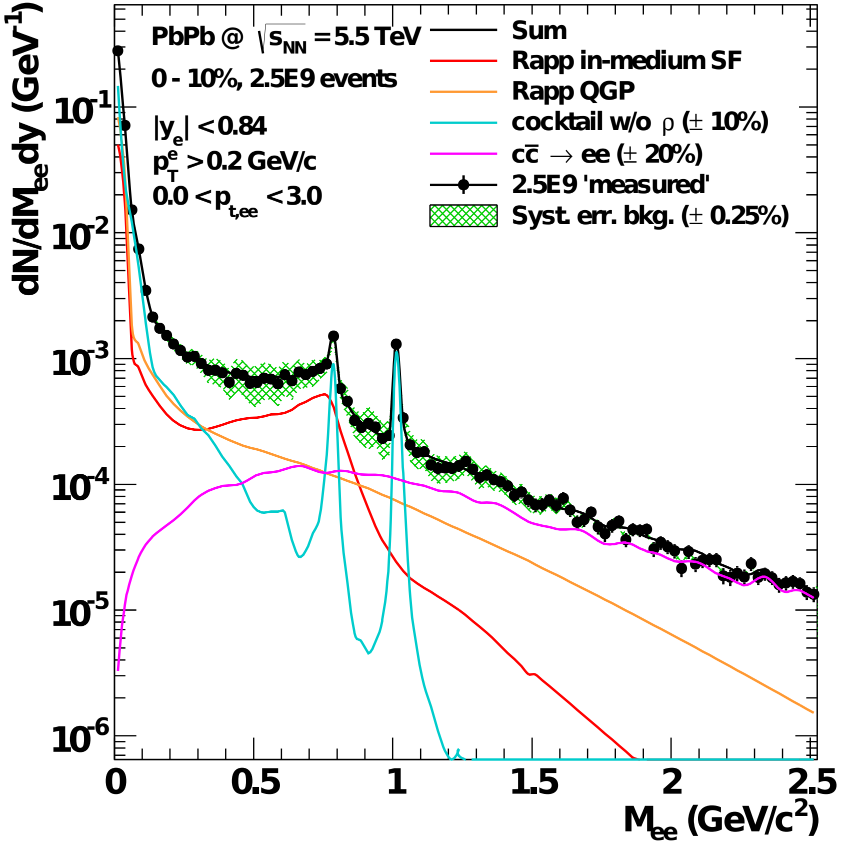
theory R. Rapp

Low and intermediate mass lepton pairs at colliders

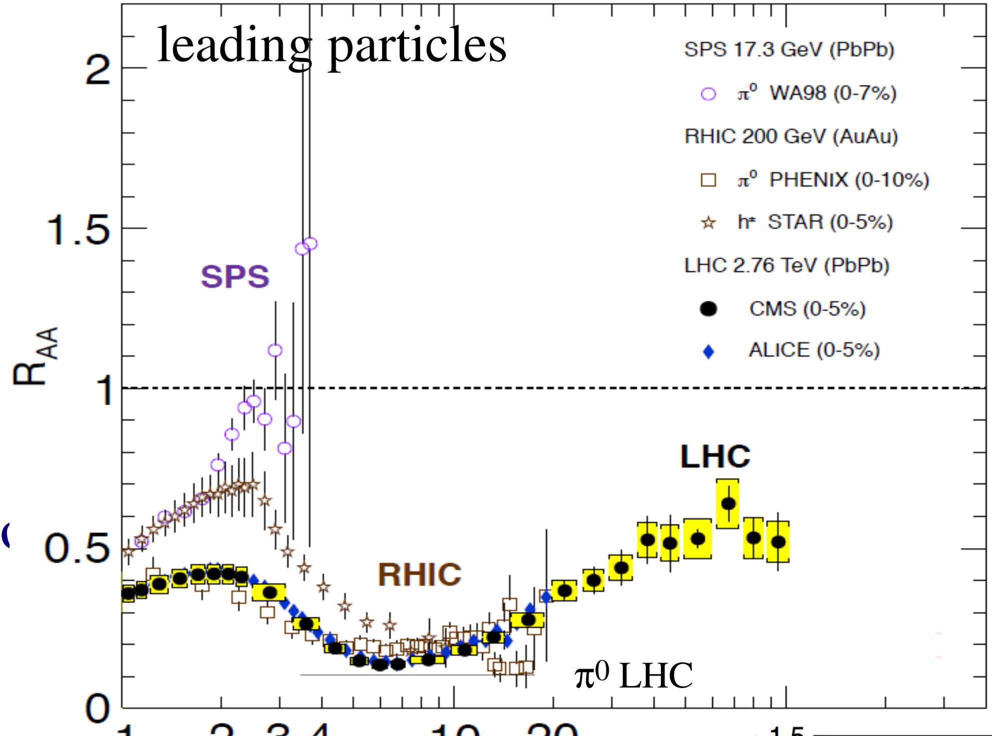


- at colliders much more difficult
- at RHIC after 15 years consolidated results between STAR and PHENIX described well by the same models as SPS data
- for ALICE very challenging project for Run3/Run4

simulated performance

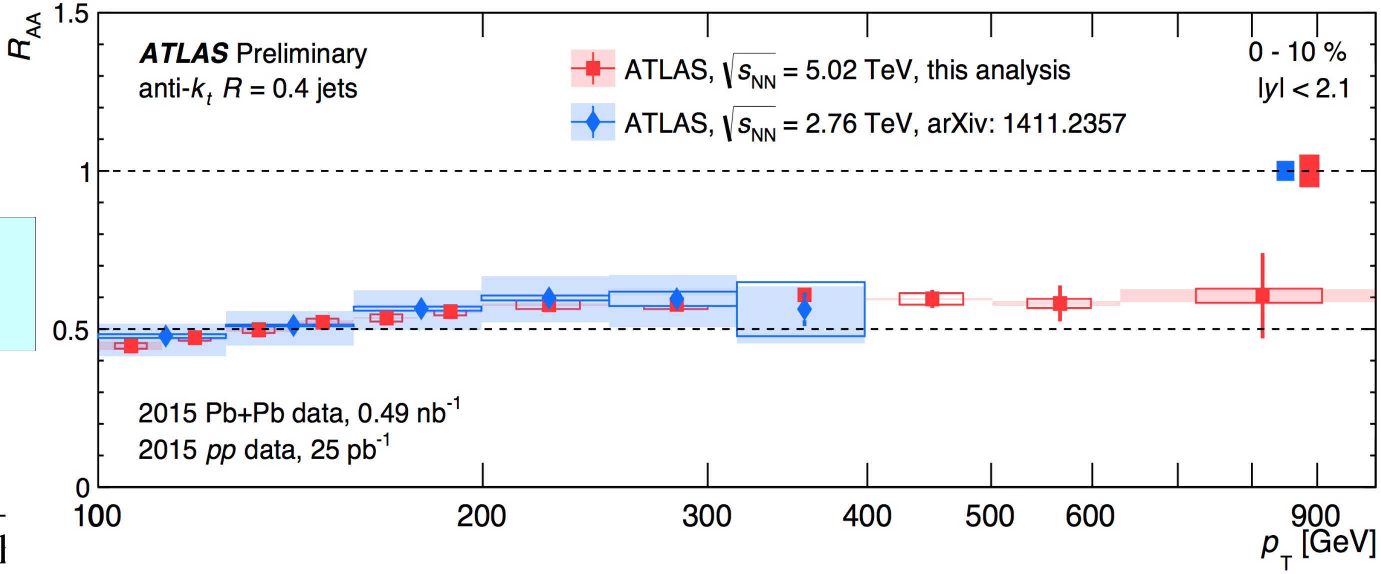


Jet quenching – parton energy loss in QGP



- suppression of leading particles first observed at RHIC
- still stronger at LHC
- upturn beyond 7 GeV new at LHC
- levels off at 0.5

reconstructed jets



out to 1 TeV suppression at level of factor 2

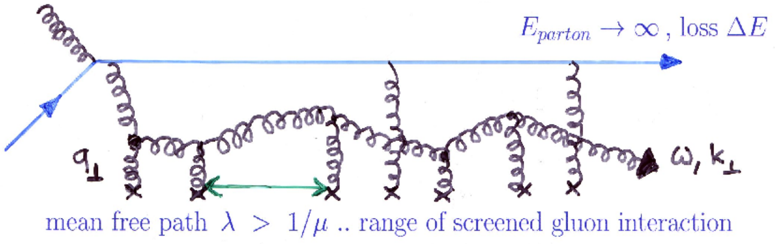
Extracting the jet quenching parameter

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

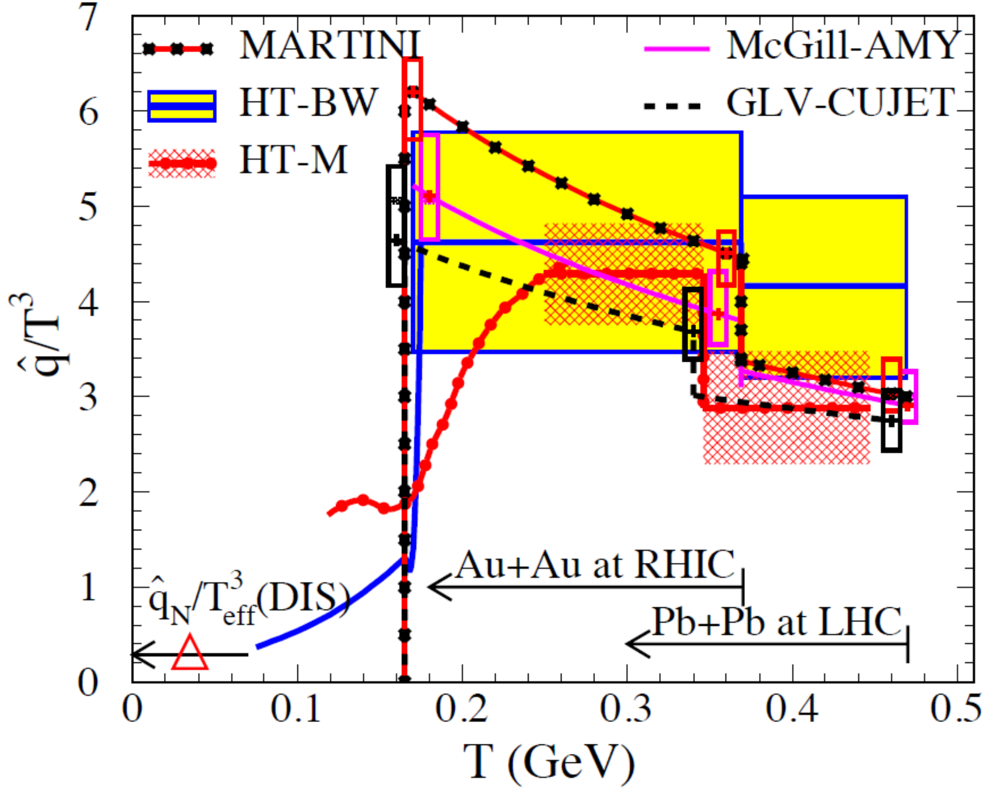
$$dE/dx \propto \rho\, \sigma \langle k_t^2 \rangle\, L$$

density of color charge carriers

transport coefficient $\hat{q} \propto \rho\, \sigma \langle k_t^2 \rangle$



JET collaboration, arXiv:1408.3519



determine transport coefficient from comparing transport model calculations to R_{AA} data

at center of nuclear fireball at τ_0=0.6 fm/c

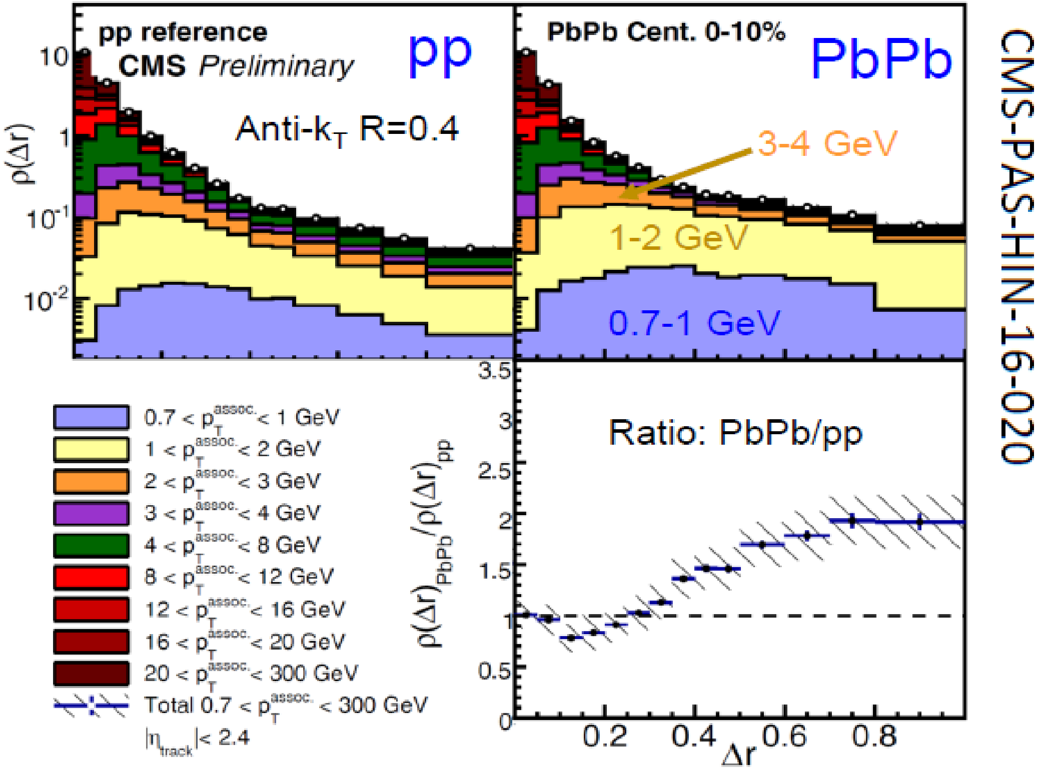
obtain for RHIC and LHC

$$\hat{q} = \begin{array}{ll} 1.2\pm0.3\ \text{GeV}^2/\text{fm} & \text{at T = 370 MeV} \\ 1.9\pm0.7\ \text{GeV}^2/\text{fm} & \text{470 MeV} \end{array}$$

2 orders of magnitude larger than in nuclear matter (from DIS)!

Where does lost energy go?

Jet-hadron correlations in pp and PbPb collisions at 5.02 TeV



low momentum particles
and at larger distance from jet core

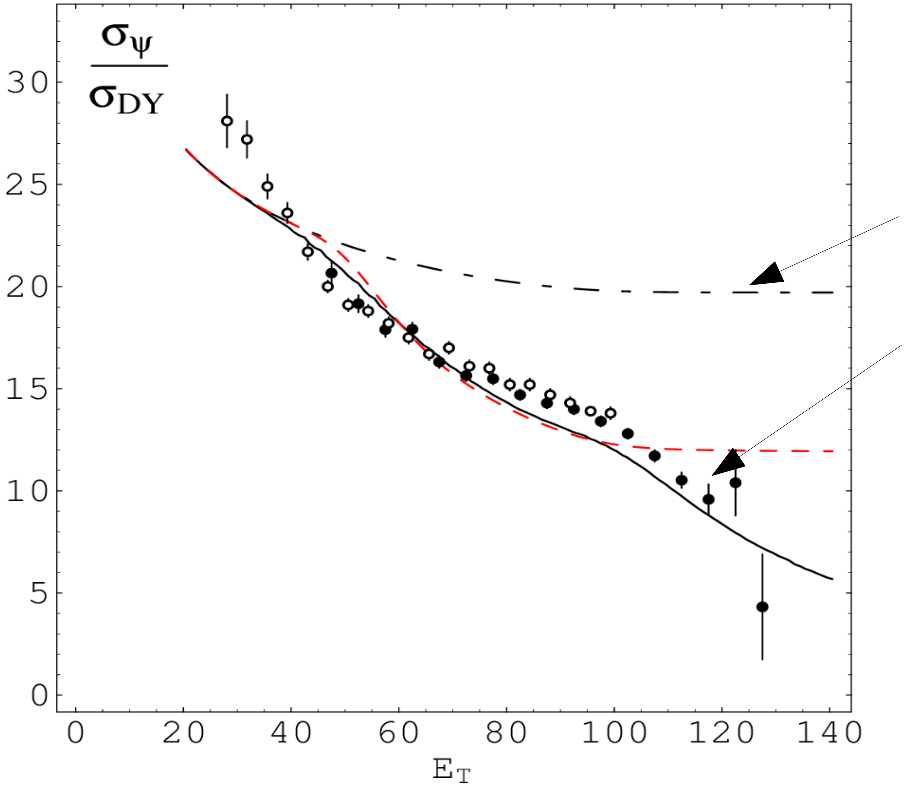
Charmonia as a probe of Deconfinement

the original idea (Matsui and Satz 1986): implant charmonia into the QGP and observe their modification (Debye screening of QCD), in terms of suppressed production in nucleus-nucleus collisions – sequential melting

"If high energy heavy-ion collisions lead to the formation of a hot quark-gluon-plasma, then color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. ... It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon-plasma formation."

First J/ψ suppression in nuclear collisions at SPS

data: Phys. Lett. B447 (2000) 28



observations NA50:

- in pp and pA collisions suppression pattern consistent with absorption on (cold) nuclear matter 4.3±0.5 mb

- in central collisions of PbPb much stronger suppression

data described by dissolution of J/ψ at critical density $n_c = 3.7/fm^2$ — — —

& including energy density fluct. ——

J.P. Blaizot, P.M. Dinh, J.Y. Ollitrault
PRL 85 (2000) 4012

Charmonium formation at hadronization: extension of statistical model to include charmed hadrons

new insight (Braun-Munzinger, J.S. 2000): QGP screens all charmonia, but charm quarks remain in the fireball

charmonium production takes place at the phase boundary

→ enhanced production at colliders – signal for deconfinement

technically:

- assume: all charm quarks are produced in initial hard scattering; number not changed in QGP

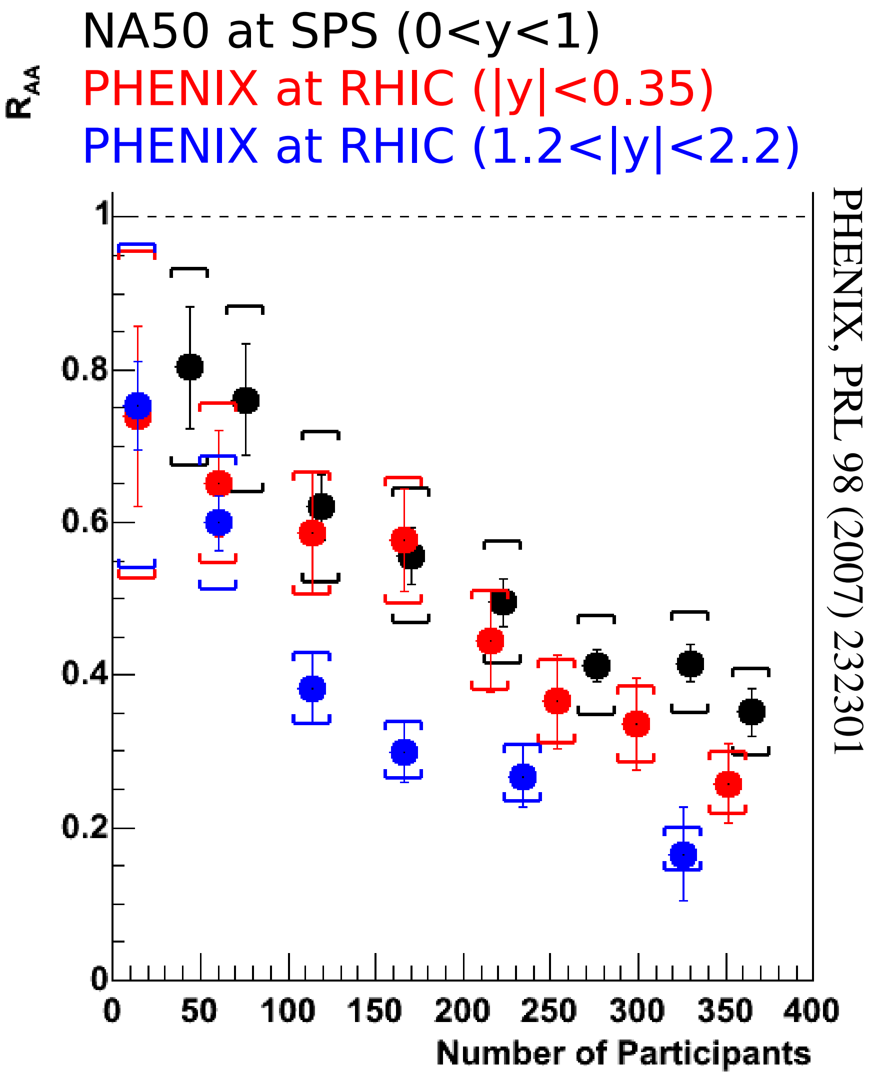
  $N_{c\bar{c}}^{direct}$ from data (total charm cross section) or from pQCD

- hadronization at T_c following grand canonical statistical model used for hadrons with light valence quarks (canonical corr. if needed)

  technically number of charm quarks fixed by a charm-balance equation containing fugacity g_c

$$N_{c\bar{c}}^{direct} = \frac{1}{2} g_c V \left(\sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm}\right) + g_c^2 V \left(\sum_i n_{\psi_i}^{therm}\right) + \ldots$$

J/ψ suppression at RHIC – 200 A GeV AuAu



PHENIX, PRL 98 (2007) 232301

PHENIX talk at QM2006:

Suppression patterns are remarkably similar at SPS and RHIC!

Cold matter suppression larger at SPS, hot matter suppression larger at RHIC, balance?

Recombination cancels additional suppression at RHIC?

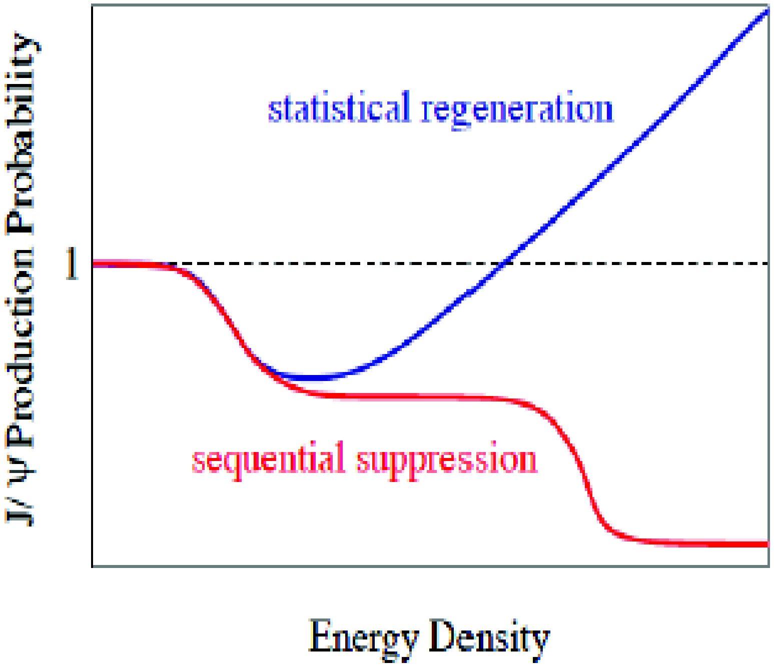
How did we get so “lucky”?

data could be indeed described by statistical hadronization using pQCD charm cross section

Andronic, Braun-Munzinger, Redlich, JS, PLB652 (2007)259

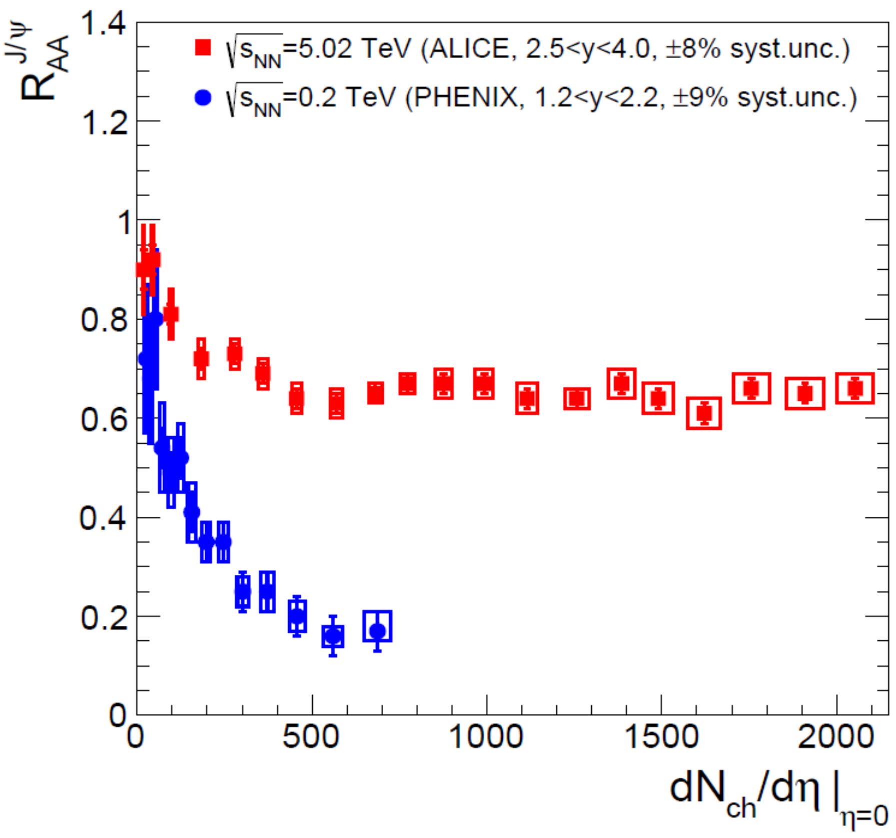
Expectations for LHC

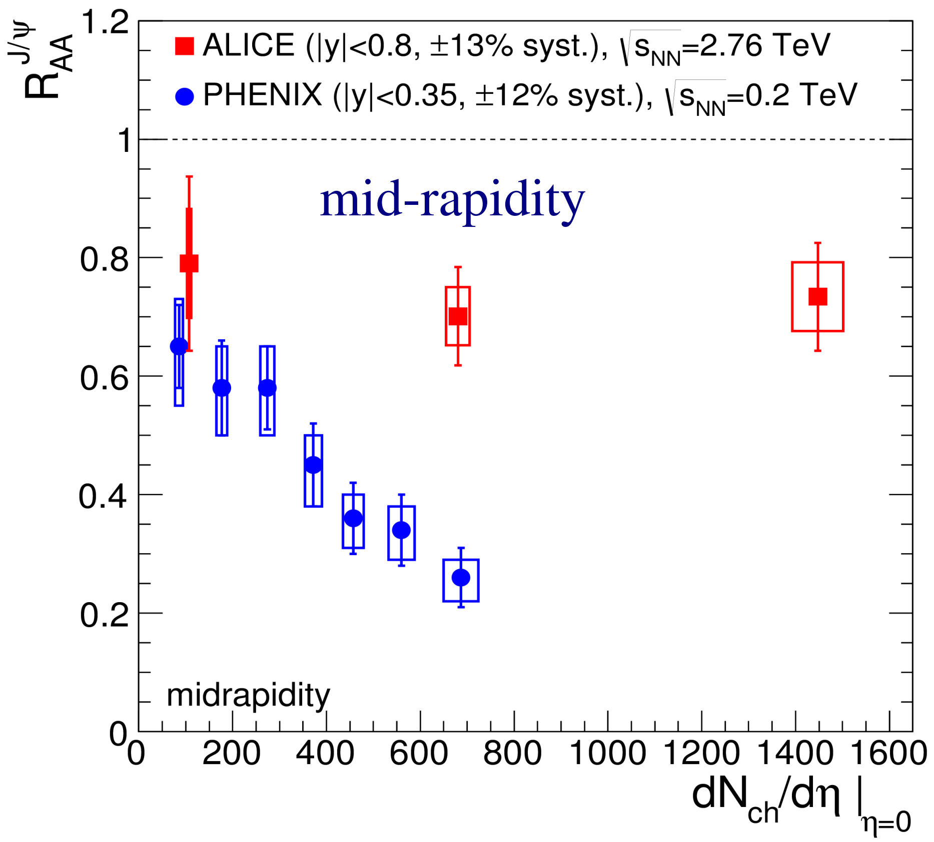
2 possibilities:



H.Satz 2009

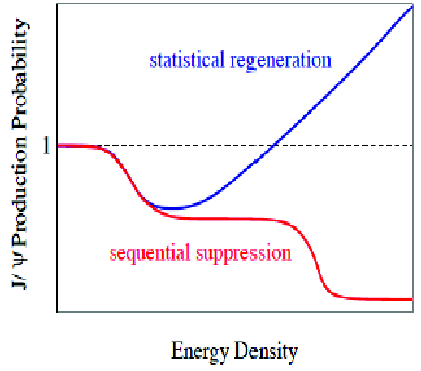
J/ψ production in PbPb collisions: LHC relative to RHIC





mid-rapidity

energy density -->

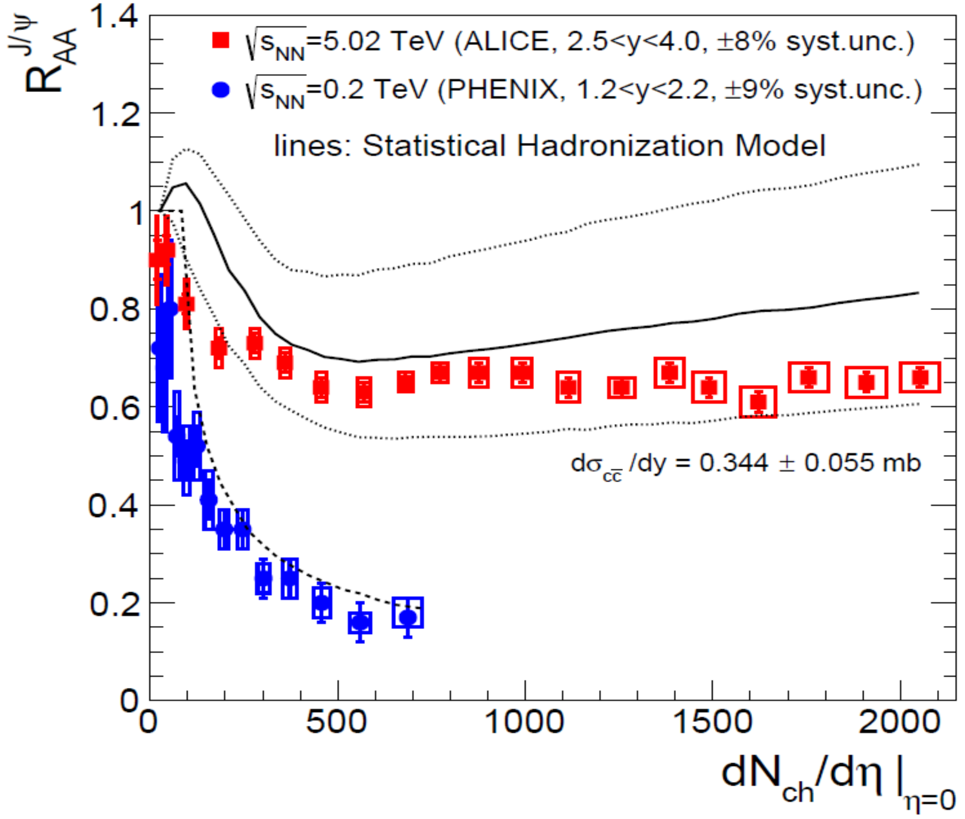


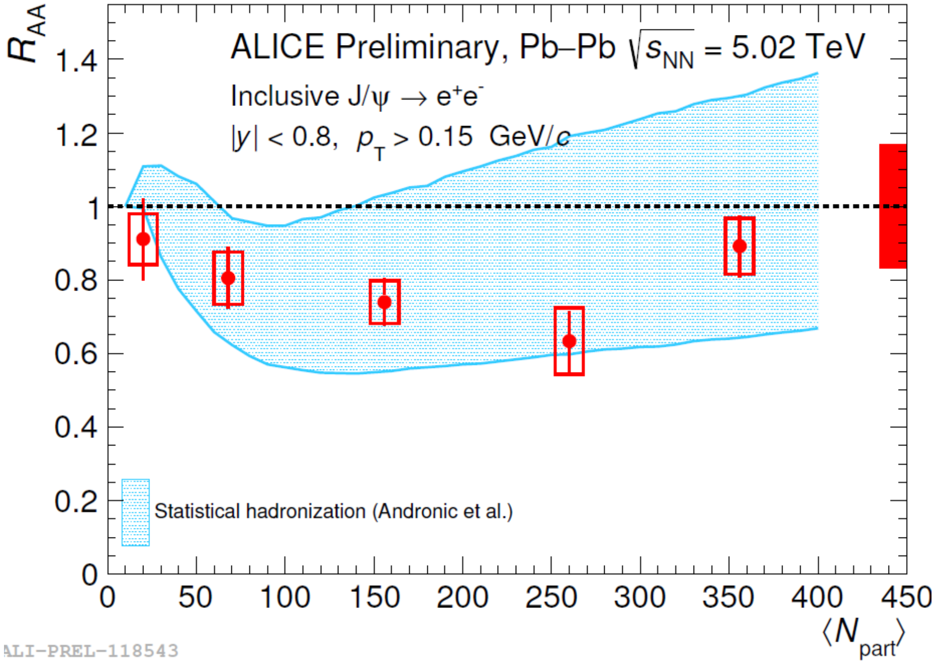
melting scenario not observed

rather: enhancement with increasing energy density!

(from RHIC to LHC and from forward to mid-rapidity)

J/ψ and statistical hadronization

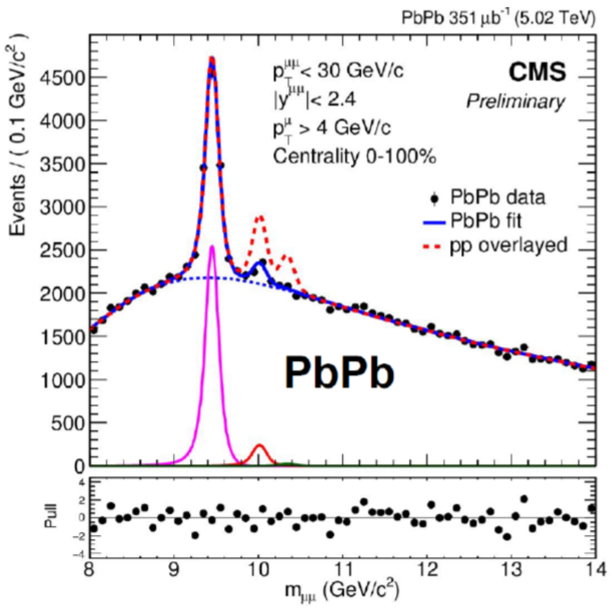


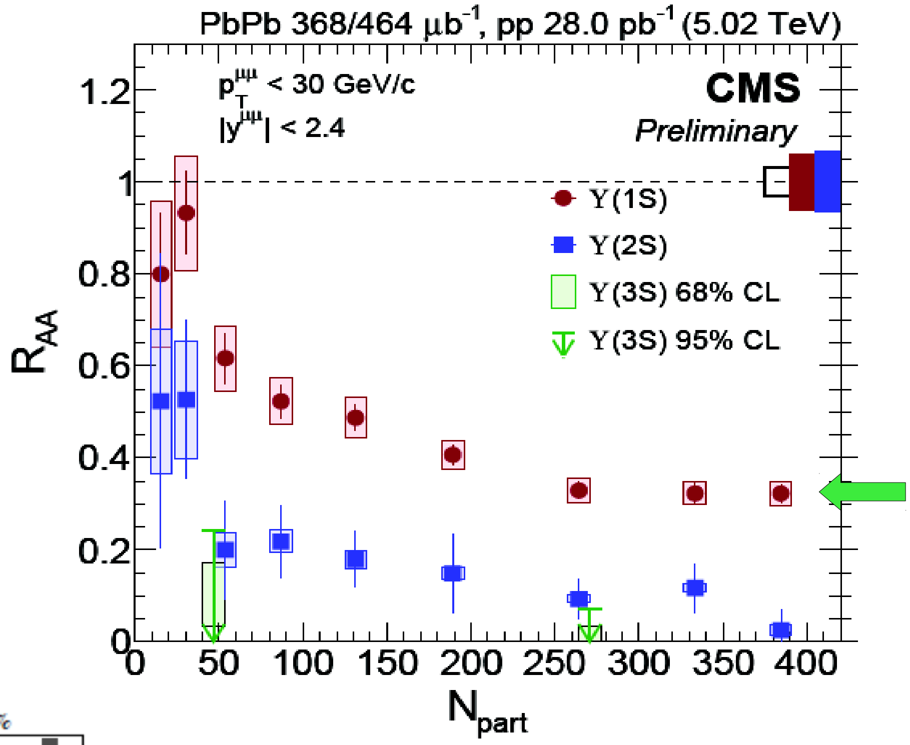


production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties

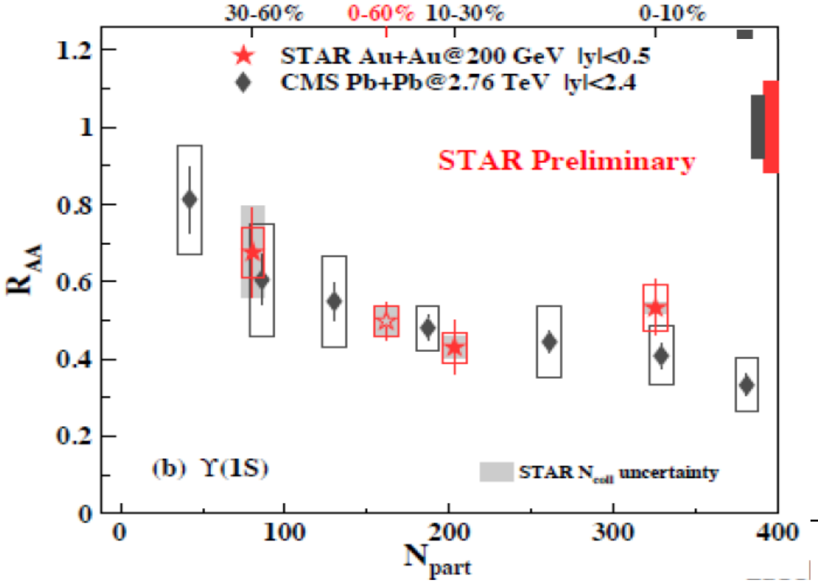
main uncertainties for models: open charm cross section, shadowing in Pb

Suppression of Upsilon states





not consistent with just excited state suppression (LHCb data: only 25 % feed-down in pp at LHC)



genuine Upsilon suppression
- real and imaginary part of potential at finite temperature play a role
- similarity of RHIC and LHC suppression reminiscent of SPS and RHIC for J/ψ
- possibility of statistical hadronization?

Outlook – an incomplete, but maybe realistic wishlist for the coming decade

Important measurements to come:

- open charm cross section in PbPb down to pt=0, baseline for J/ψ
– higher charmonium states to distinguish J/ψ formation scenarios
- to what degree does beauty thermalize in QGP, baseline for Upsilon understanding
- direct photons (real and virtual) and their azimuthal asymmetries with larger significance, thermal evolution of QGP
- low mass dilepton pairs and rho spectral function, chiral symmetry restoration
- fluctuations of conserved charges as sign of critical behavior
    - at LHC due to proximity to O(4) critical region
    - at lower energies due to possible critical endpoint in phase diagram

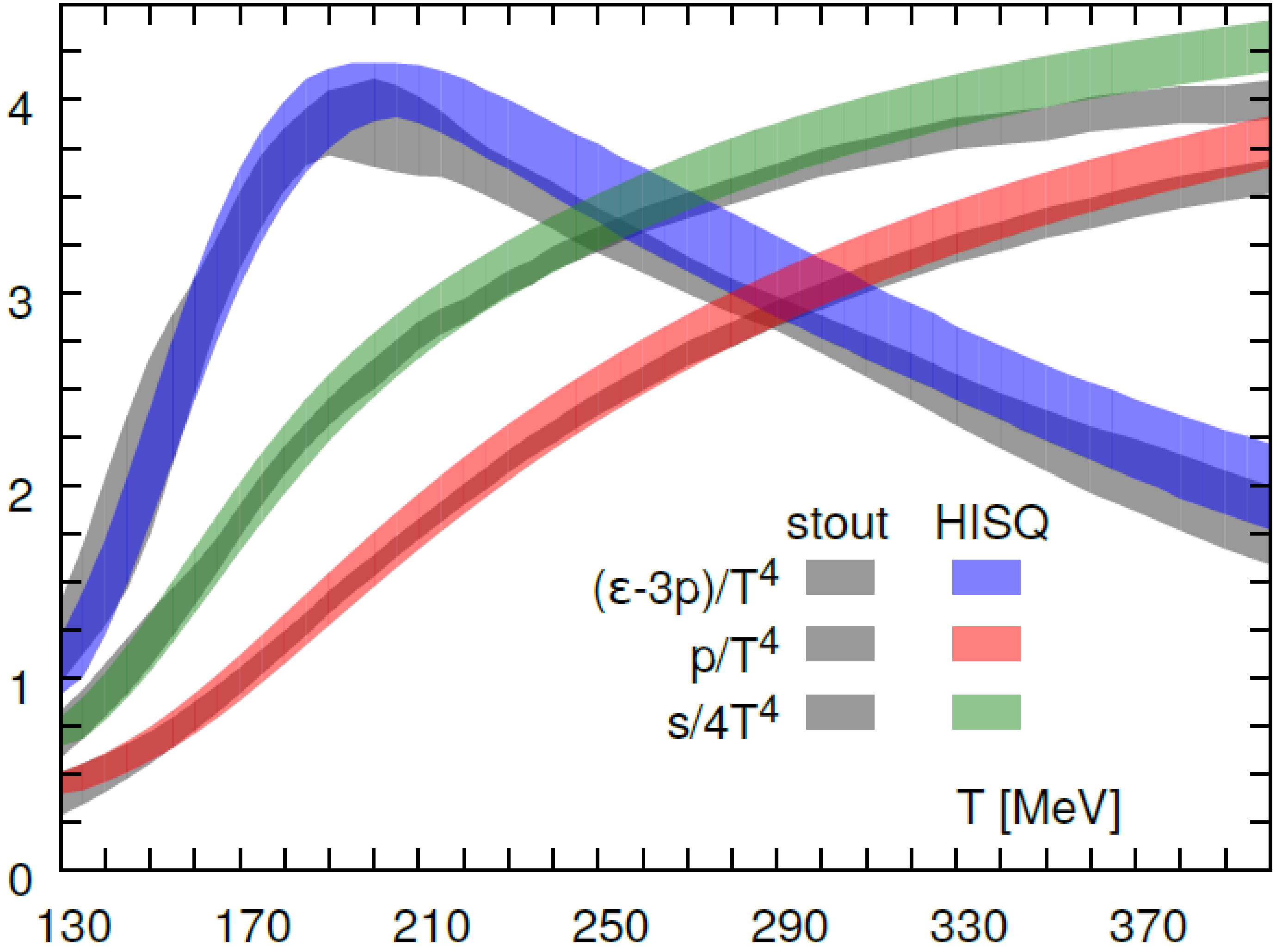
Tasks for theory:

- determination of temperature dependent transport coefficients from exp. data
- the way to thermalization: from overpopulated gluon fields to hydrodynamics to hadronization
- first priniples computation of transport coefficients

backup

Alternative for lattice QCD EoS

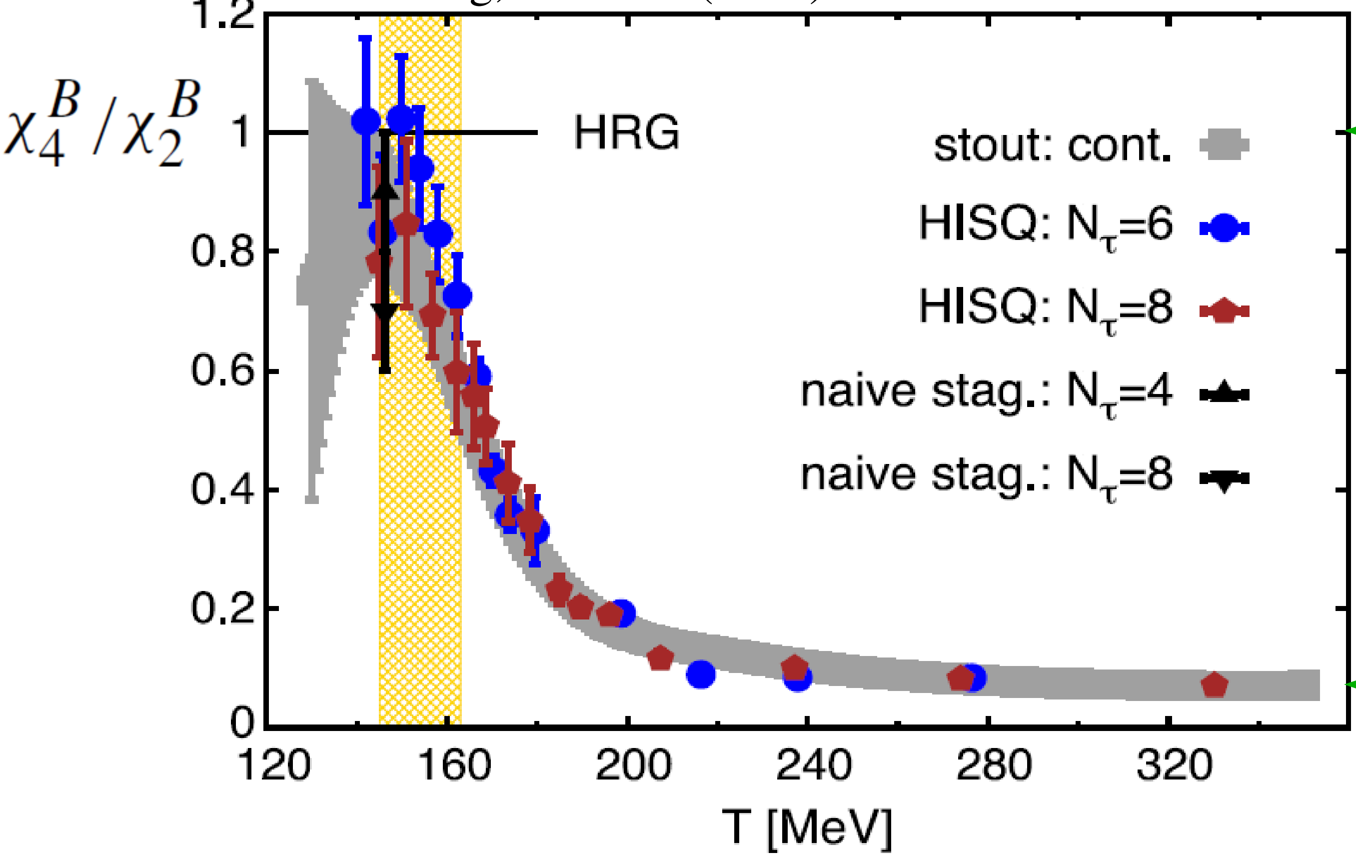
from Bazavov arXiv: 1407.6387



Measure of deconfinement in lQCD

$$\chi_4^B/\chi_2^B \propto \text{baryon number}^2$$

H.T.Ding, NPA931 (2014) 52



confined: 1

measure suggested by Ejiri, Karsch, Redlich (2006)

deconfined: $6/9\pi^2$

rapid drop suggests: chiral cross over and deconfinement appear in the same narrow temperature range

Analysis of hadron yields: the statistical model – grand canonical

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

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

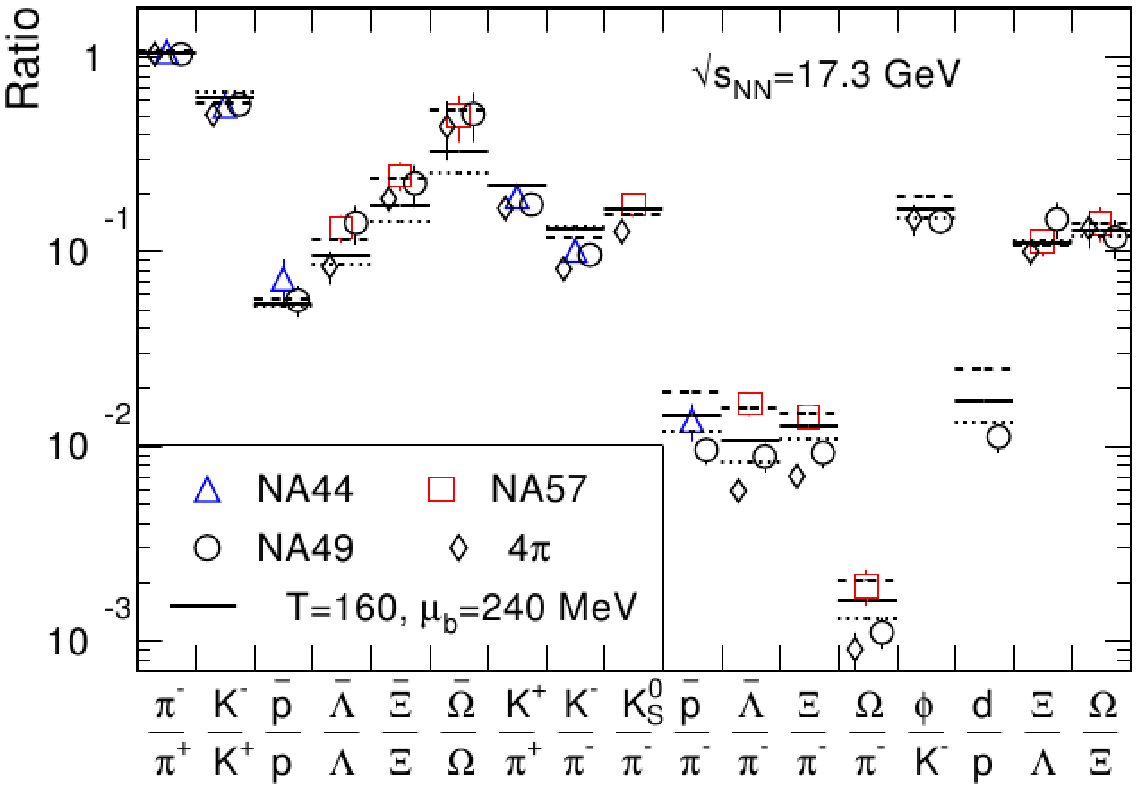
for every conserved quantum number there is a chemical potential:

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

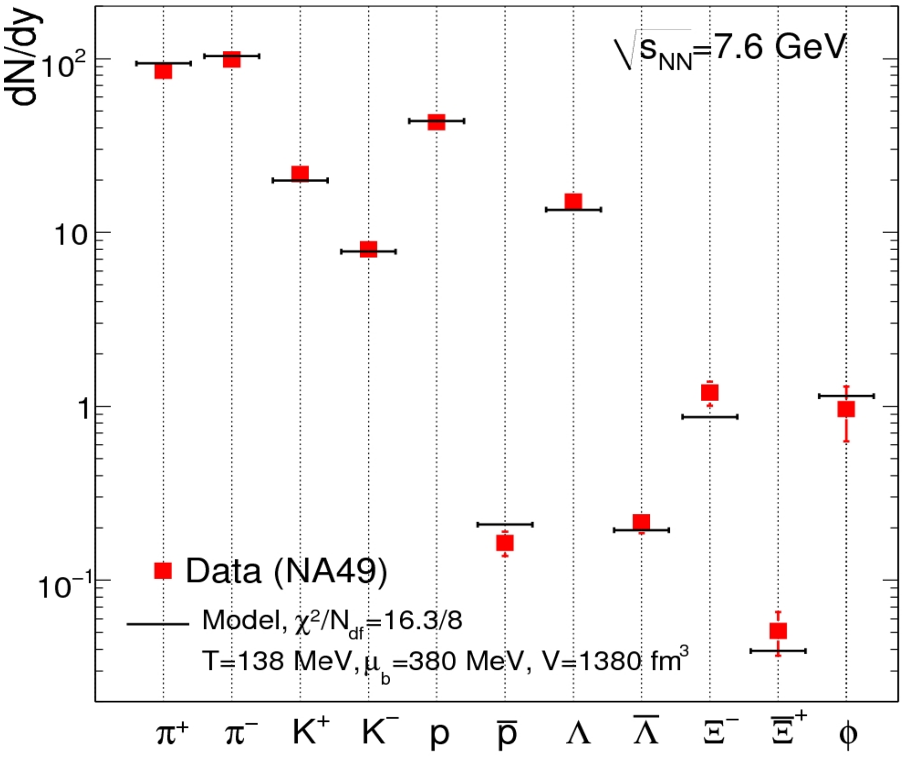
but can use conservation laws to constrain V, μ_S, μ_{I_3}

→ **Fit at a given √s provides values for T and μ_b**

SPS Pb + Pb data and thermal model



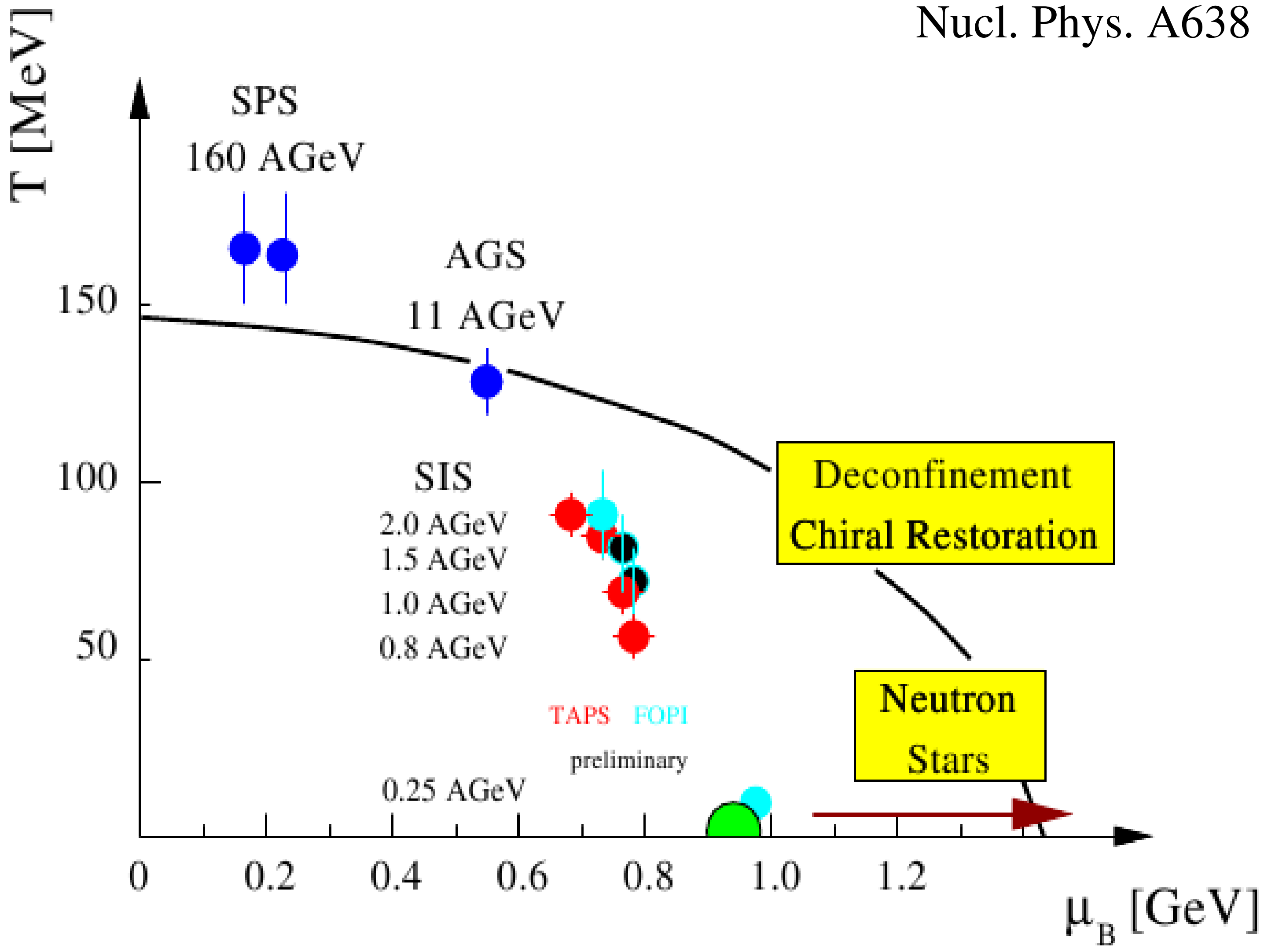
full energy – largest amount of data but also some problems in data revealed



figures from A. Andronic, P. Braun-Munzinger, J.S. Nucl. Phys. A772 (2006) 167

leading to the first phase diagram with experimental points

P.Braun-Munzinger and J. Stachel, nucl-th/9803015,
Nucl. Phys. A638 (1998) 3



Production of light nuclei and antinuclei at the AGS

data cover 10 oom!

addition of every nucleon

-> penalty factor $R_p = 48$

but data are at very low pt

use m-dependent slopes following systematics up to deuteron

-> $R_p = 26$

GC statistical model:

$$R_p \approx \exp[(m_n \pm \mu_b)/T]$$

for T=124 MeV and $\mu_b = 537$ MeV

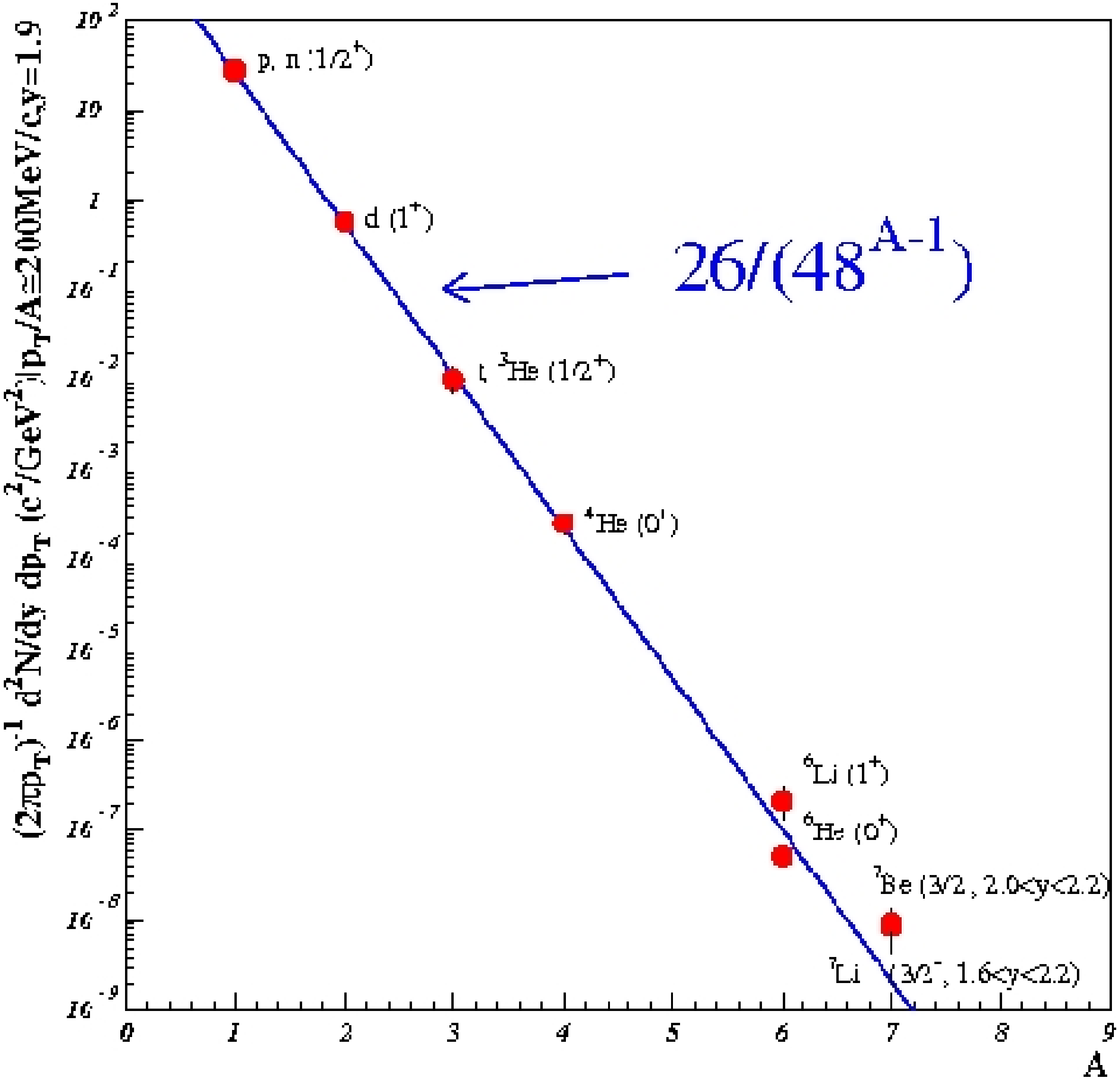
$R_p = 24$ good agreement

also good for **antideuterons**:

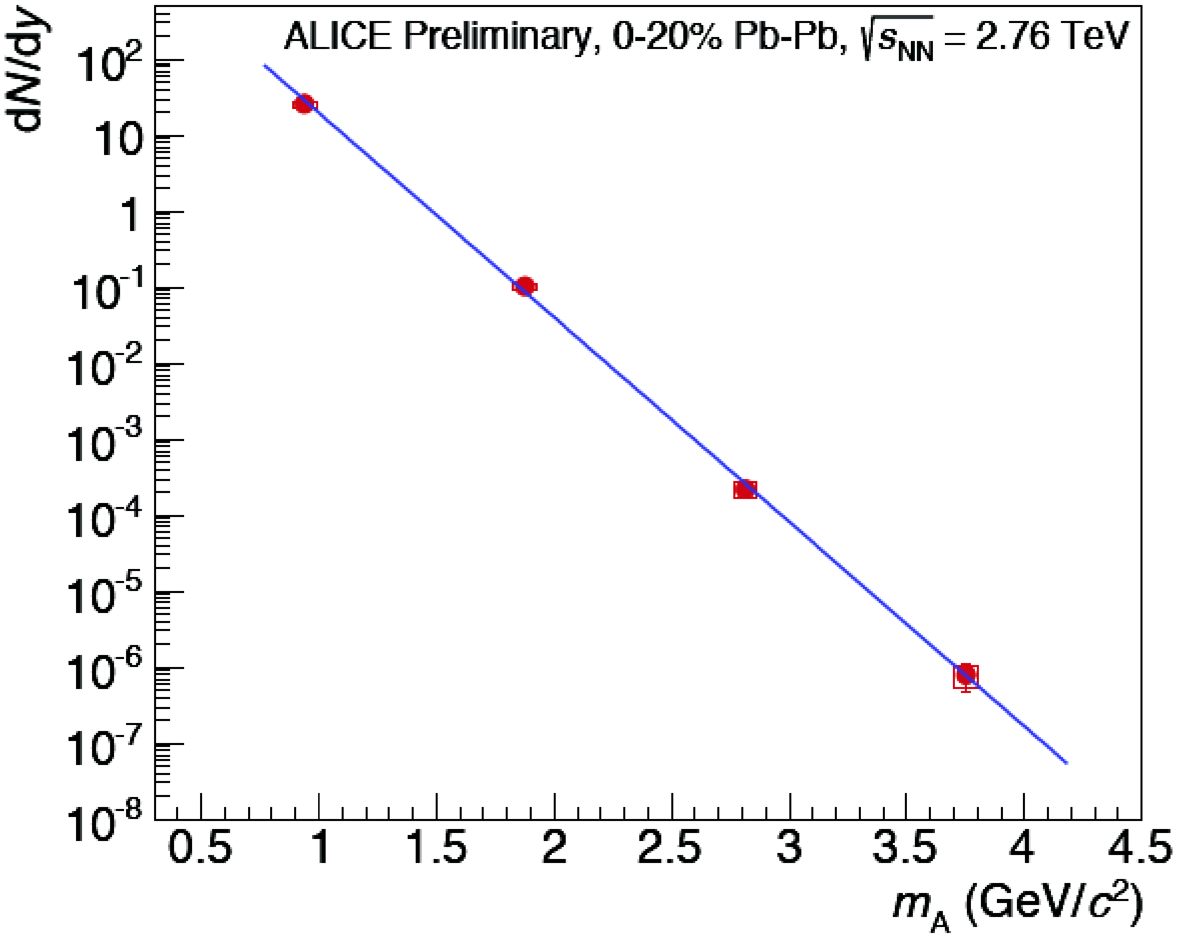
data: $R_p = 2\pm1\cdot10^5$ SM: $1.3\cdot10^5$

P. Braun-Munzinger, J. Stachel, J. Phys. G28 (2002) 1971

E864 Coll., Phys. Rev. C61 (2000) 064908



Production of light anti-nuclei at LHC energy



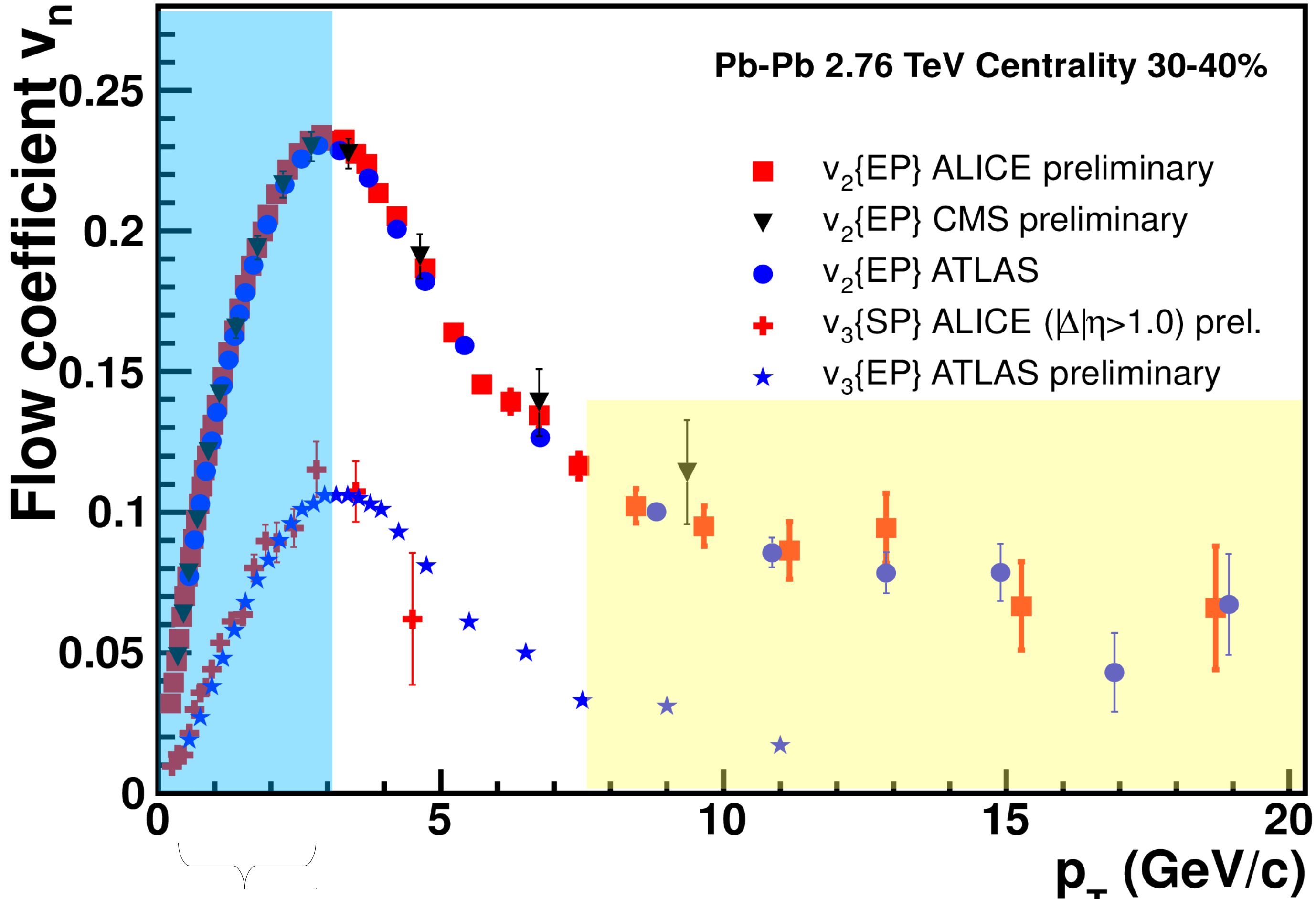
penalty factor exp(-m/T) ≈ 300 for nuclei and anti-nuclei as $\mu_b = 0$ at LHC

compared to 24 for nuclei at top AGS energy

and 140 000 for anti-nuclei with $\mu_b = 537$ and T=124 MeV

Elliptic flow of charged particles at LHC

figure modified from B. Muller, J. Schukraft, B. Wyslouch, arXiv:1202.3233v1



elliptic flow (v_2) as function of p_t :

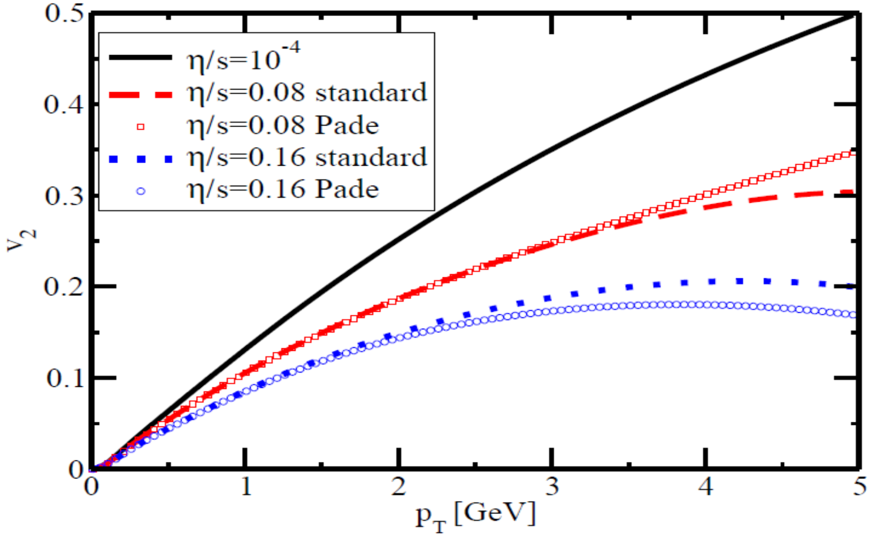
- excellent agreement between all 3 LHC experiments
- same for v_3

hydrodynamic regime
v_2 driven by pressure gradient

jet fragmentation regime
v_2 driven by energy loss

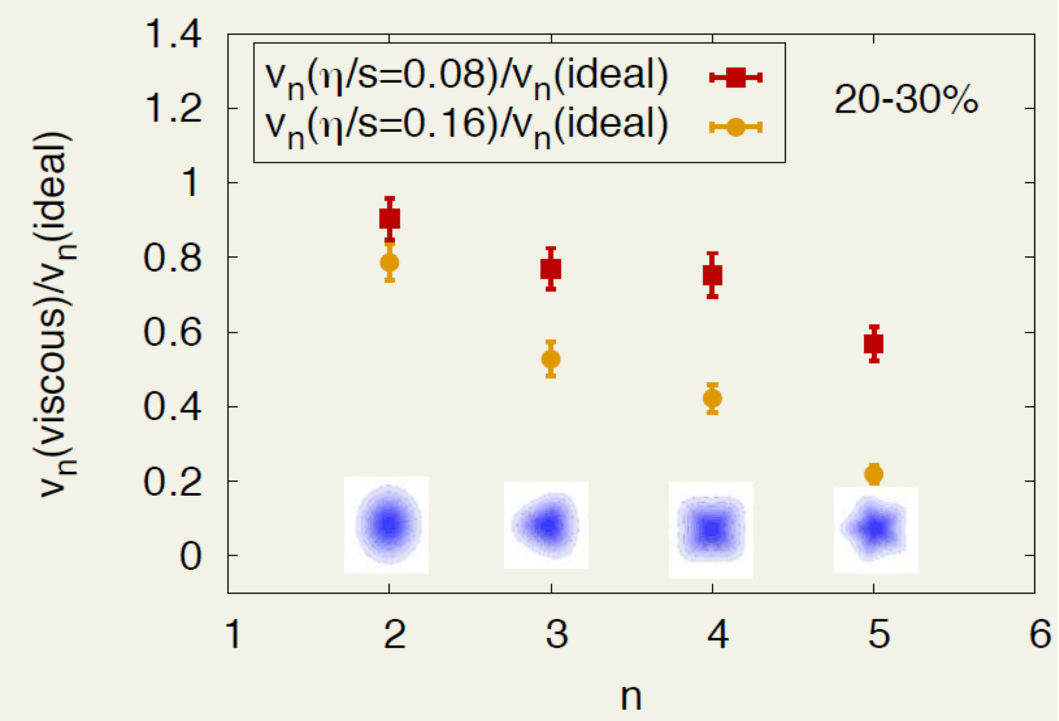
Sensitivity to viscosity of the fluid

Luzum, Romatschke PRC 78 (2008) 034915



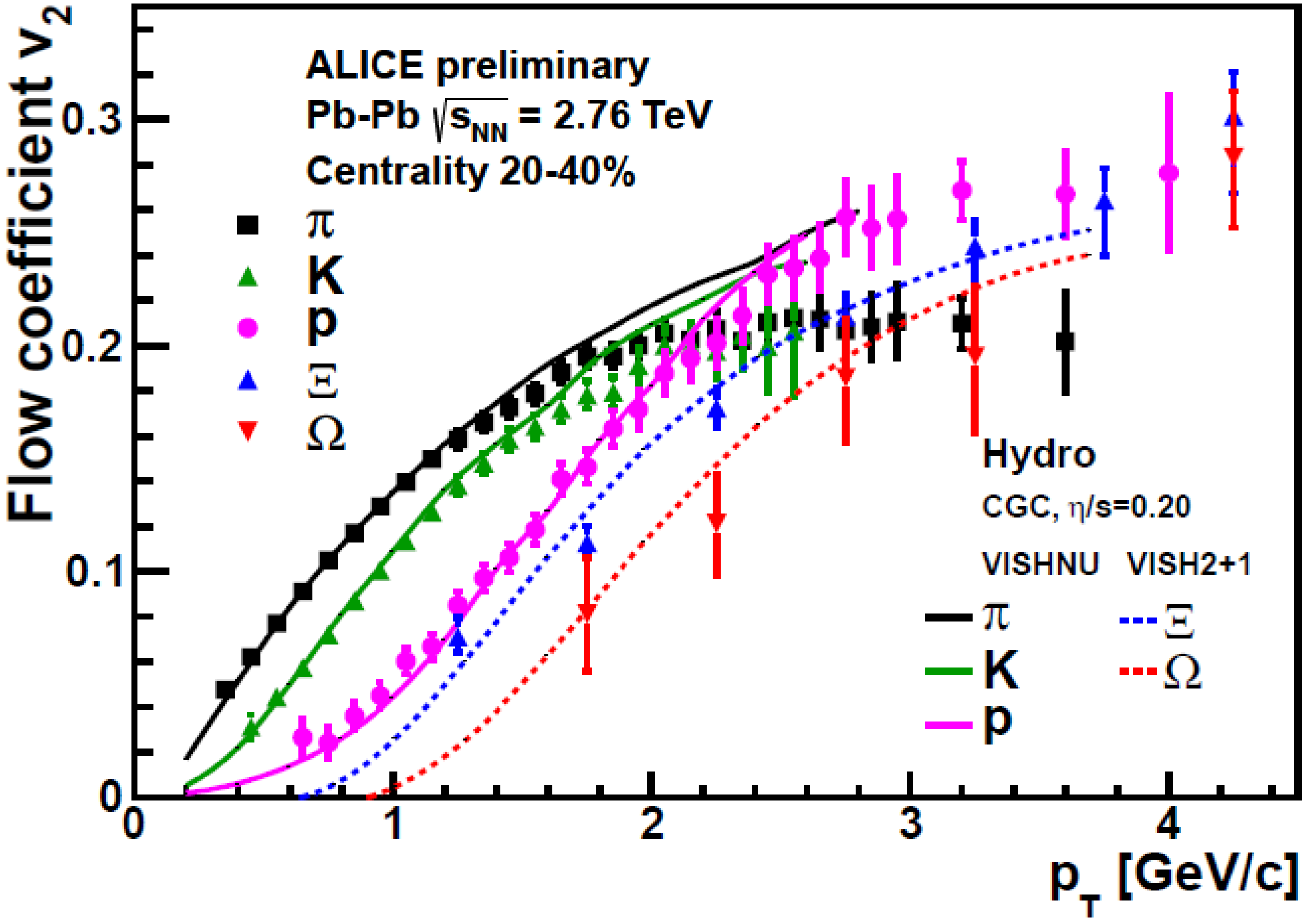
in hydro regime v_2 driven by initial condition and properties of the liquid
→ ratio of viscosity to entropy density η/s

Schenke *et al.* Phys.Rev.C85:024901,2012



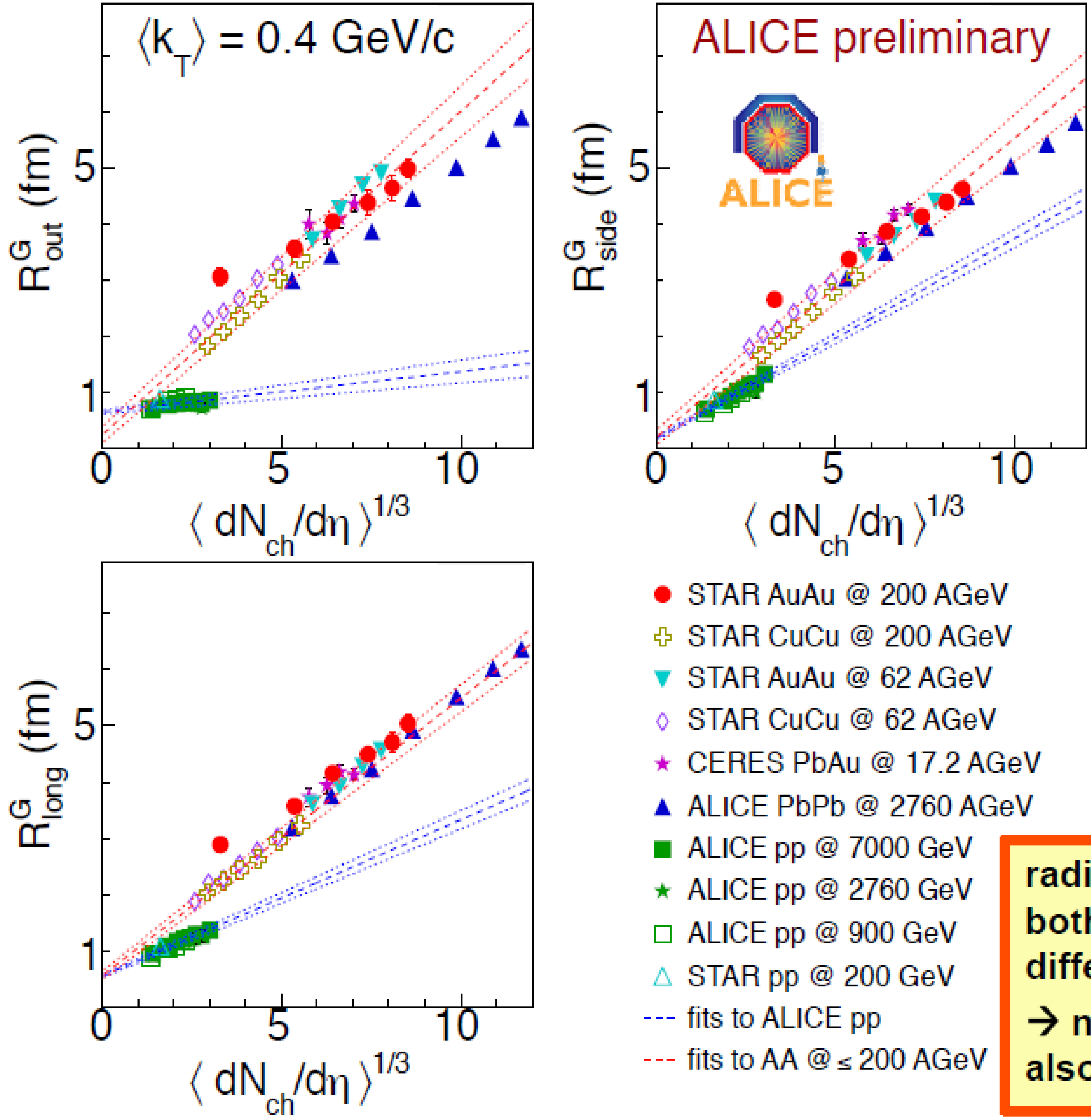
viscosity suppresses v_2
higher moment suppressed more strongly

Elliptic Flow in PbPb Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV



rapidly rising v_2 with p_t and mass ordering typical features of hydrodyn. expansion
same hydrodynamics calc. with small eta/s reproduces data

pion HBT

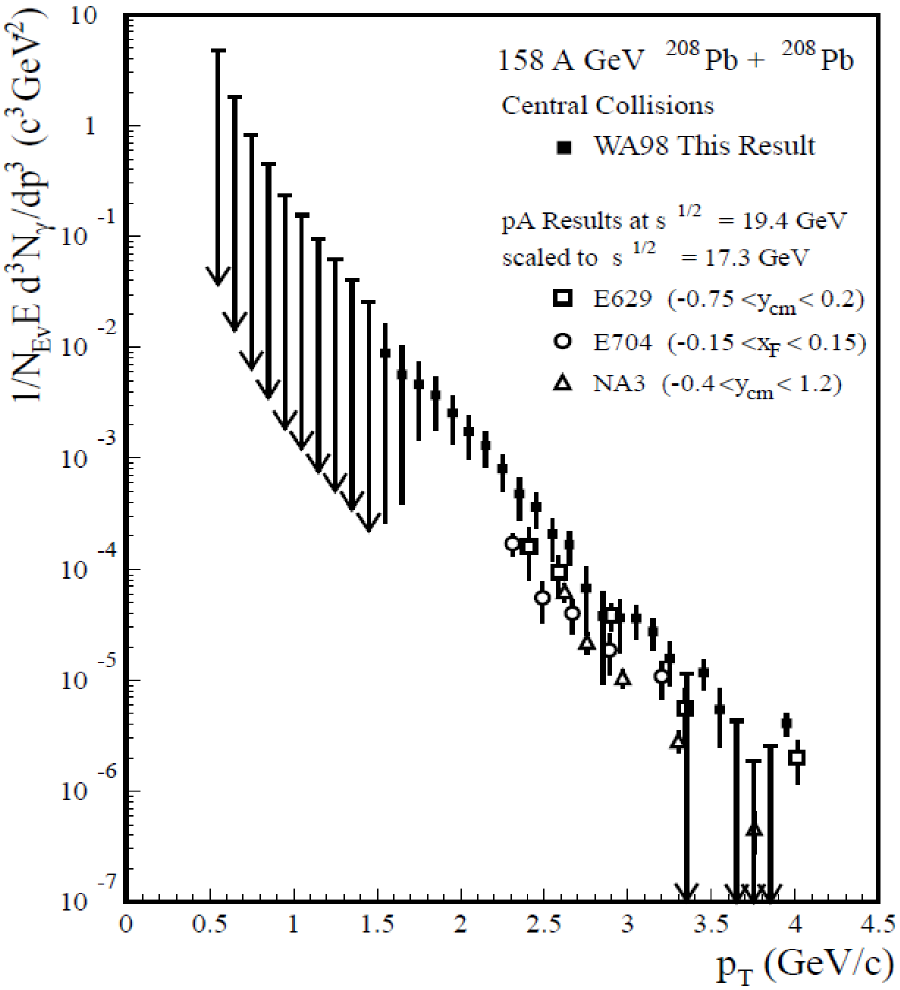


radii increase with multiplicity both in pp and Pb-Pb but with different slopes

→ not only final multiplicity but also initial geometry matters

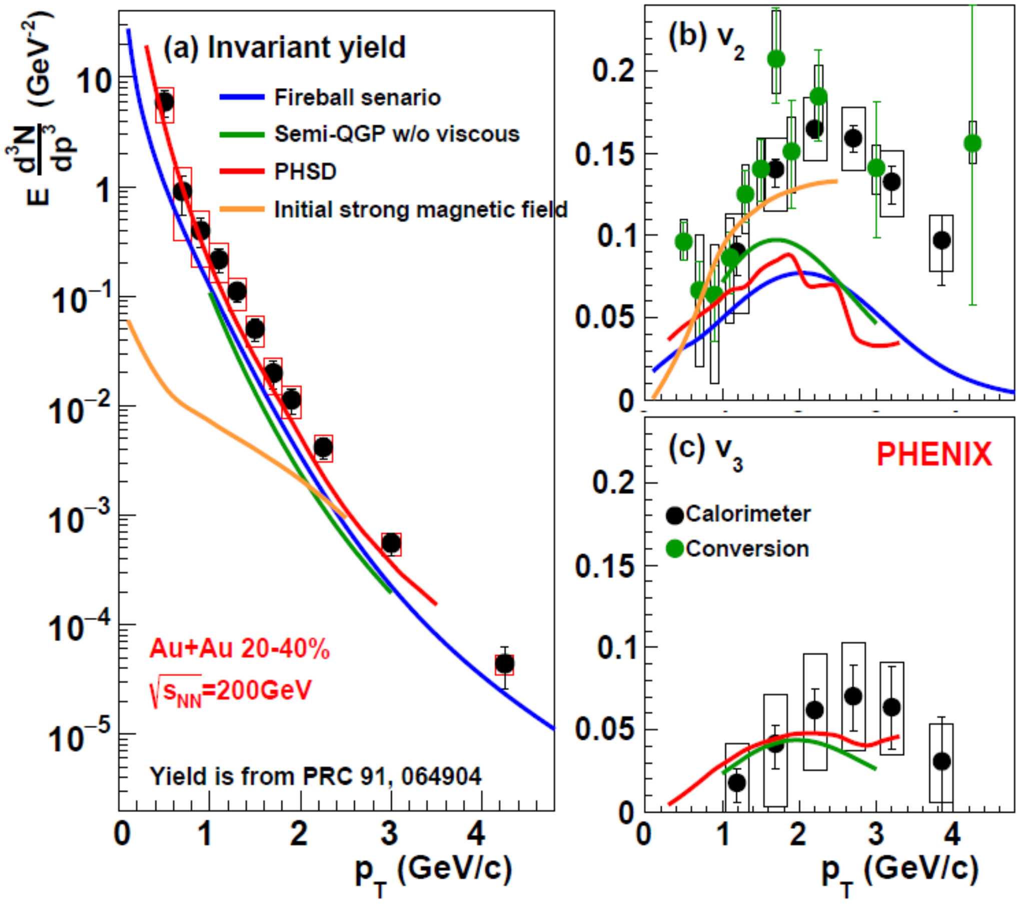
Direct photons: give access to entire time evolution

WA98



$\lambda_{mfp} \gg$ medium

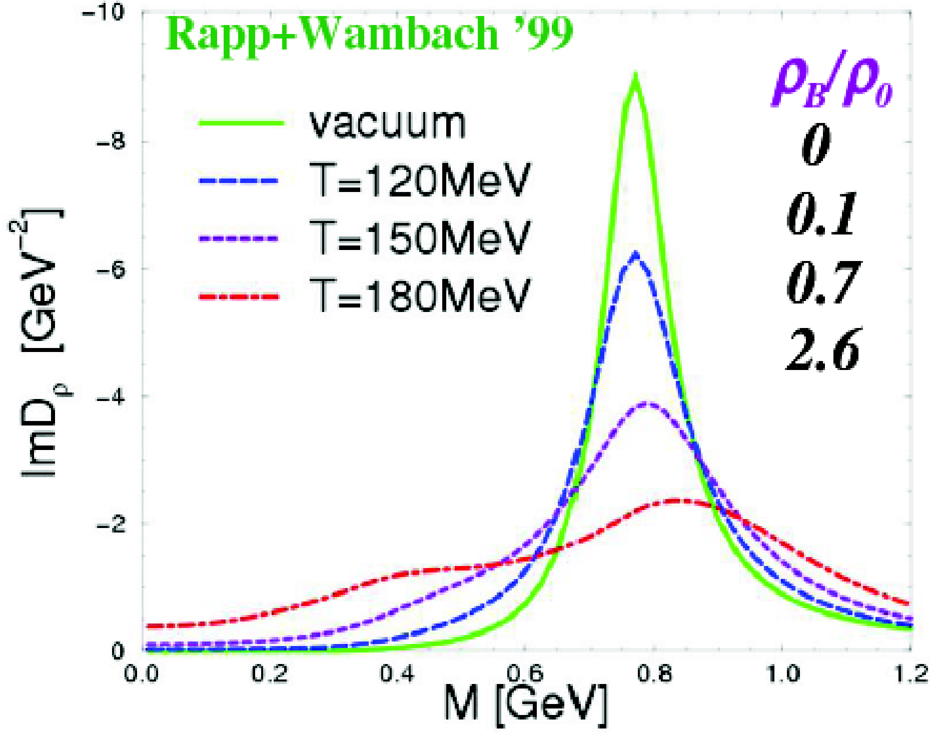
→ access to early QGP-phase



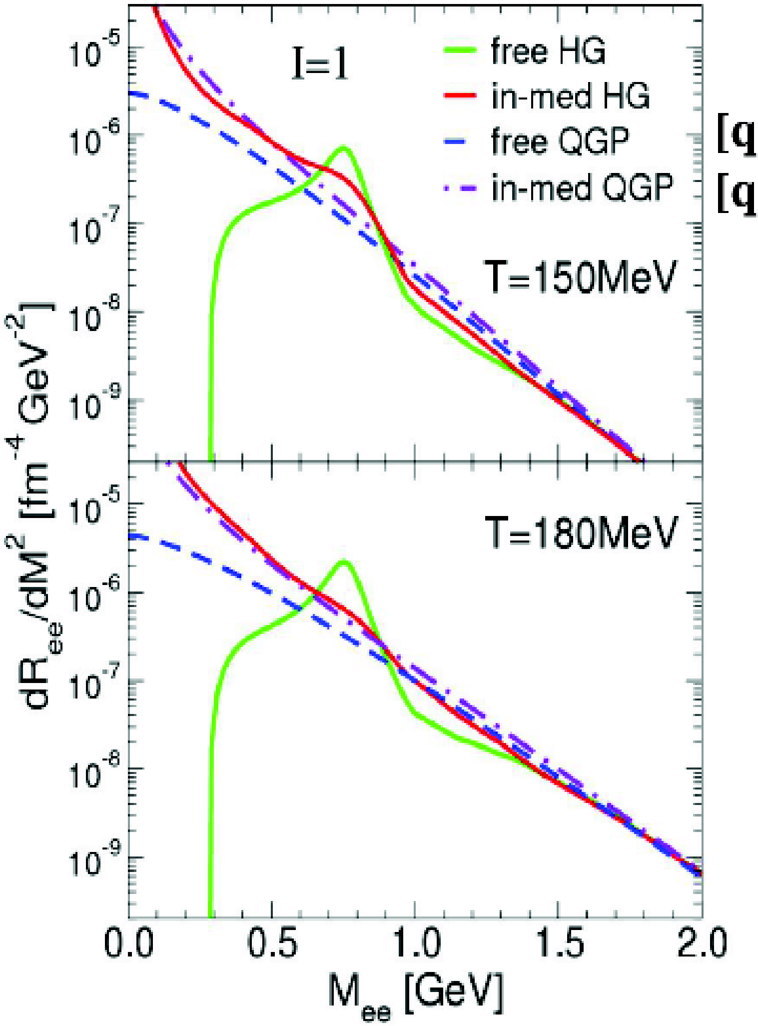
<u>direct-photon puzzle</u>

challenge: simultaneous description of spectra and v_2

How does this modified ρ look like? integrate over space-time evolution of spectral function for ee mass spectrum



ρ-meson "**melts**" in hot and dense matter



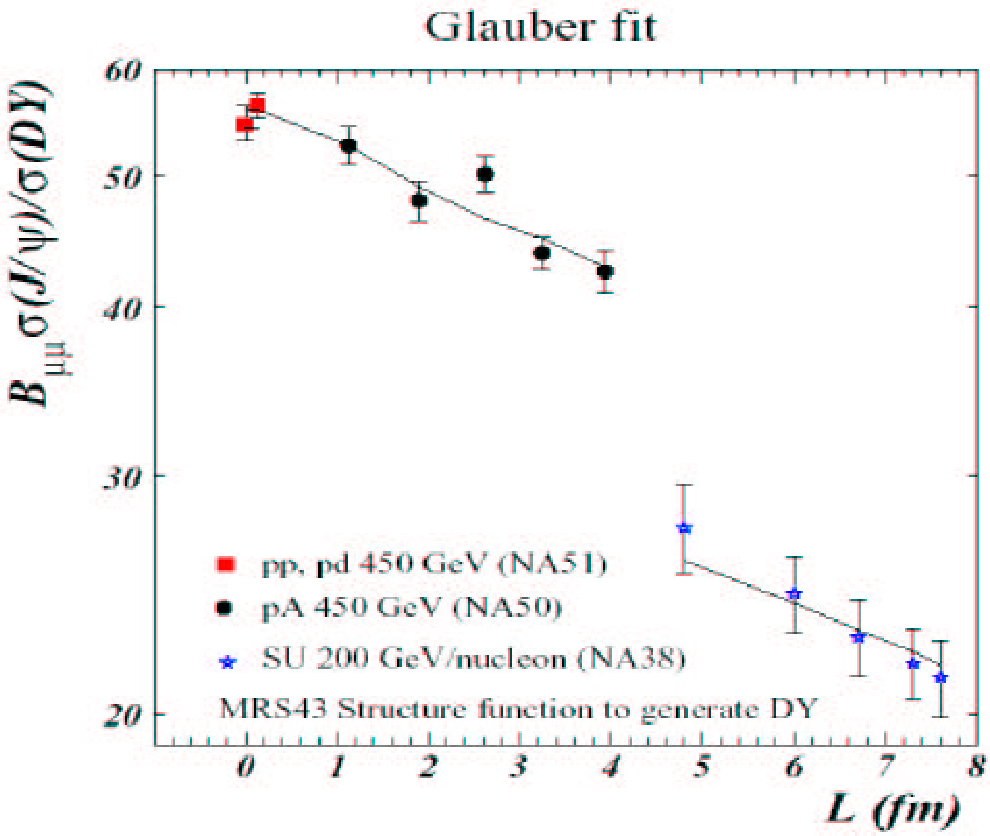
[$q\bar{q}\rightarrow ee$]

[$q\bar{q}+O(\alpha_s)$-HTL]

in-med HG and QGP match
'quark – hadron duality?'

J/ψ Suppression in pA Collisions

in pA and light nucl. coll. J/ψ production suppressed (NA38)



Glauber fit

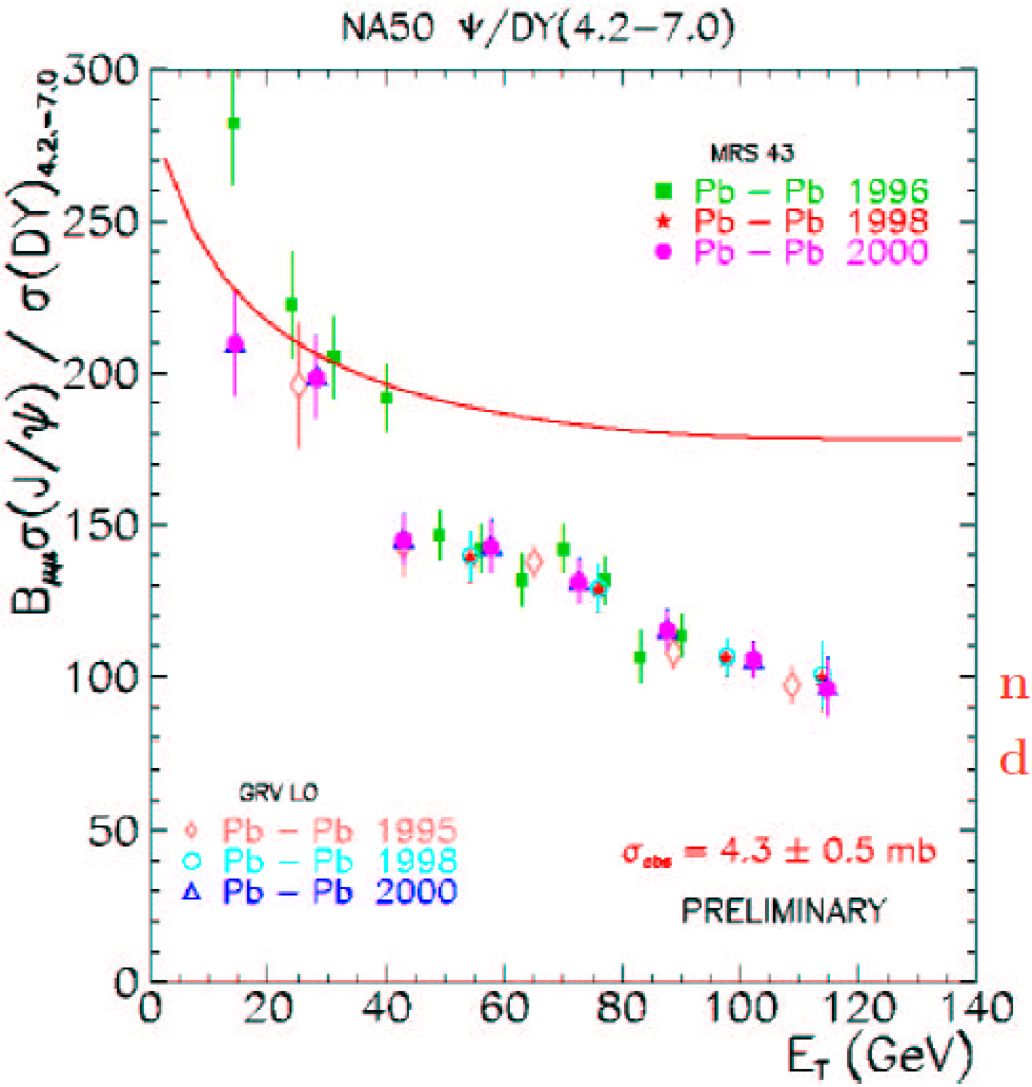
NA50,Phys.Lett.B553(2003)167

$$\sigma(J/\psi) \propto exp(-\rho\sigma_{abs}L)$$

with $\rho = 0.17/\mathrm{fm}^3$ and $\sigma_{abs} = 4.3 \pm 0.6$ mb

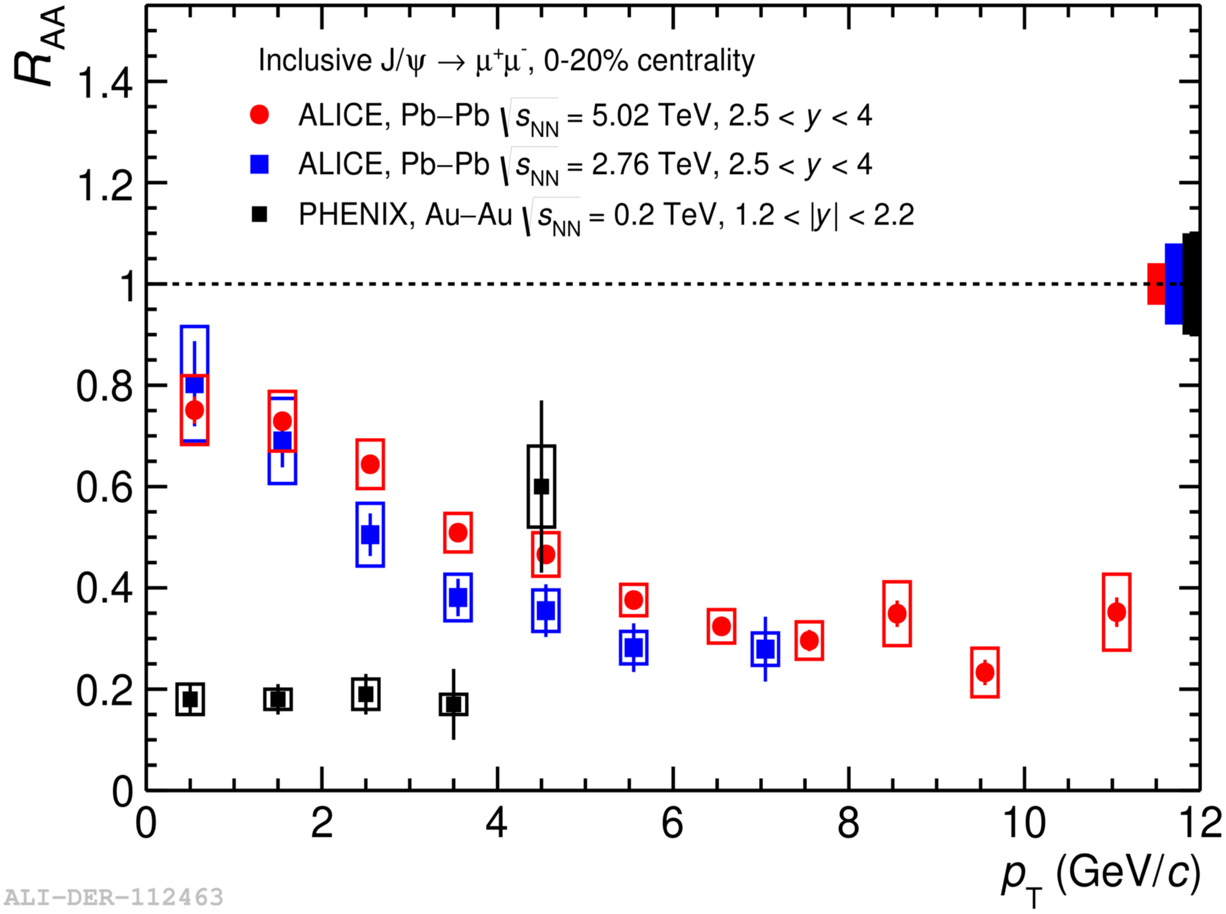
Anomalous J/ψ Suppression in PbPb Collisions

NA50, Phys. Lett. B447 (2000) 28 and Proc. Quarkmatter 2002, Nucl. Phys. A



normal suppression as in pA does not descibe the data

transverse momentum spectrum



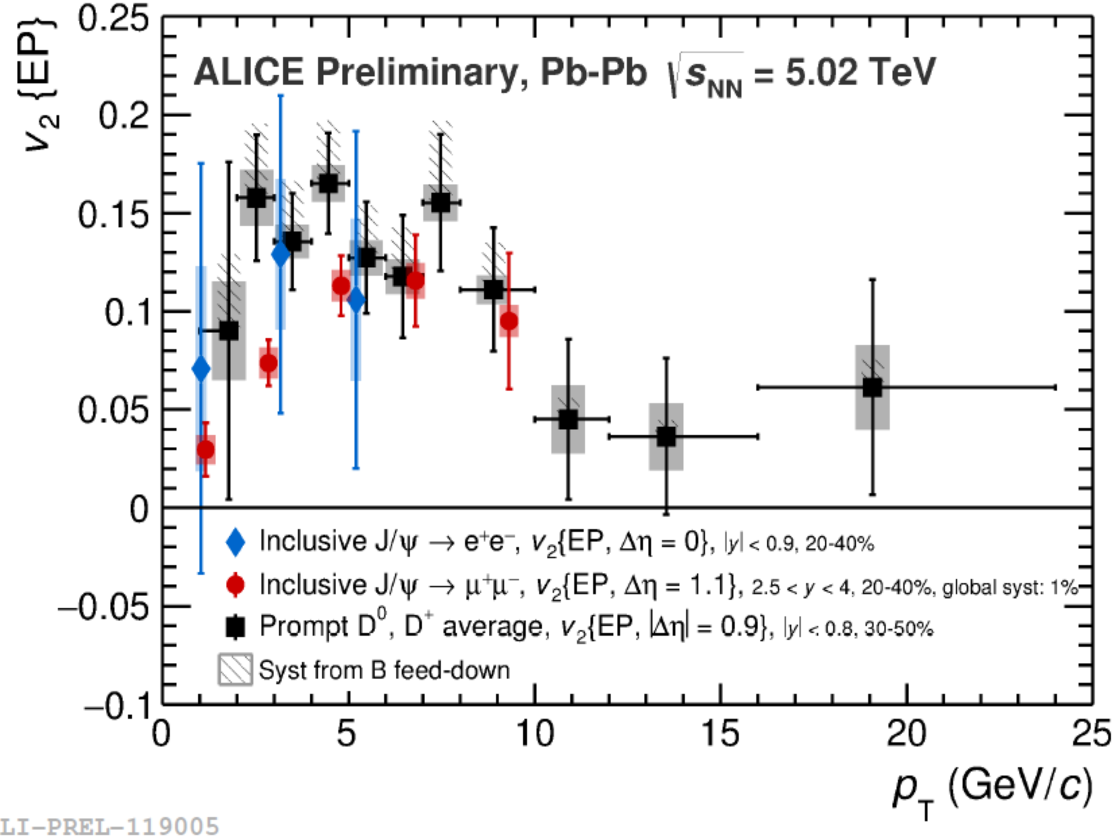
softer in PbPb as compared to pp

a qualitatively new feature as compared to RHIC where the trend is opposite

in line with thermalized charm in QGP at LHC, forming charmonia

elliptic flow of J/ψ vs p_t

arXiv:1705.05810



ALI-PREL-119005

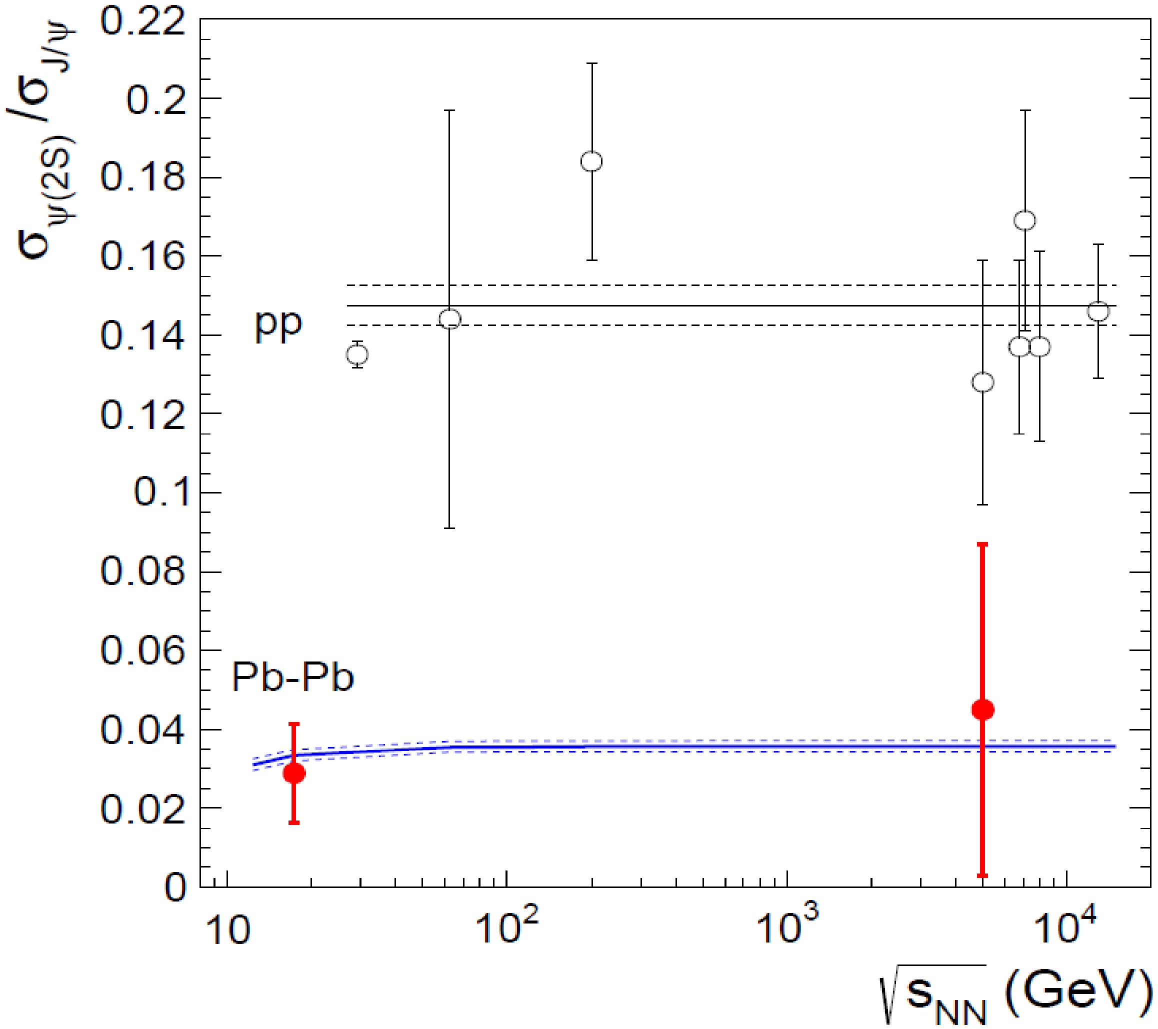
charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

- expect build-up with p_t as observed for π, p. K, Λ, … and vanishing signal for high p_t region where J/ψ not from hadronization of thermalized quarks

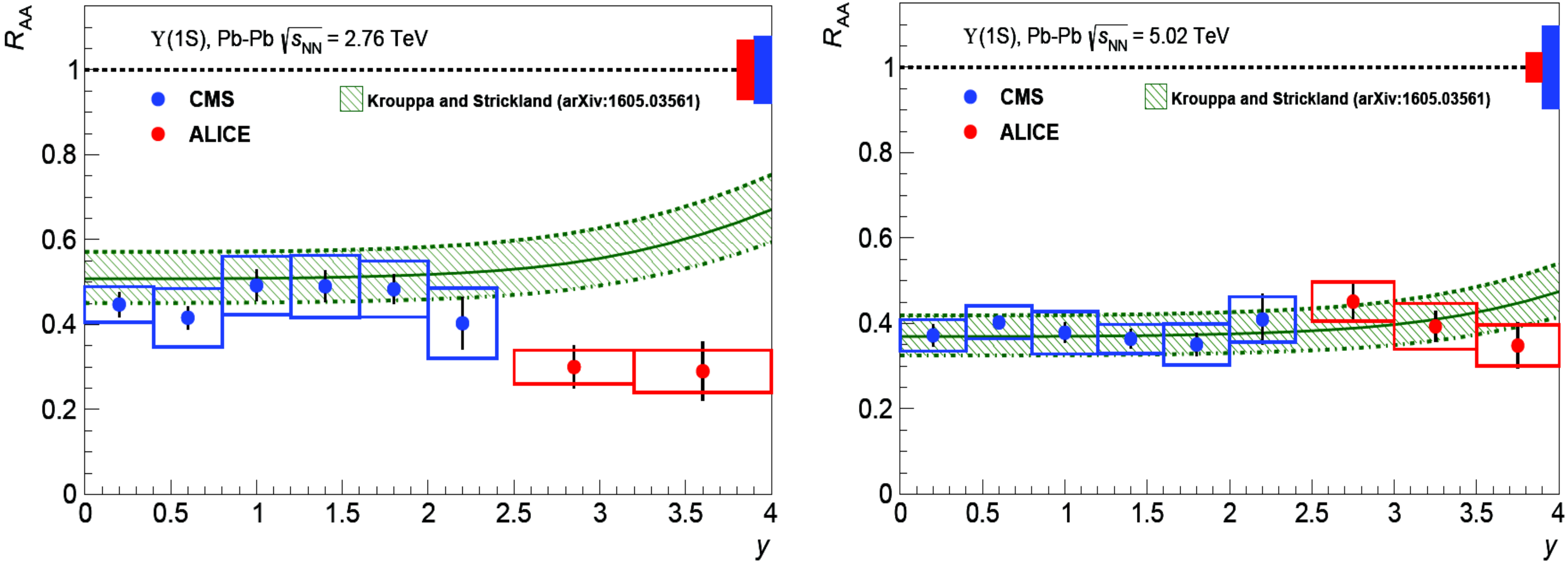
first observation of significant J/ψ v_2 in line with expectation from statistical hadronization

ψ(2S)

in picture where psi is created from deconfined quarks in QGP or at hadronization, psi(2S) is suppressed more than J/psi



Upsilon R_{AA} rapidity dependence

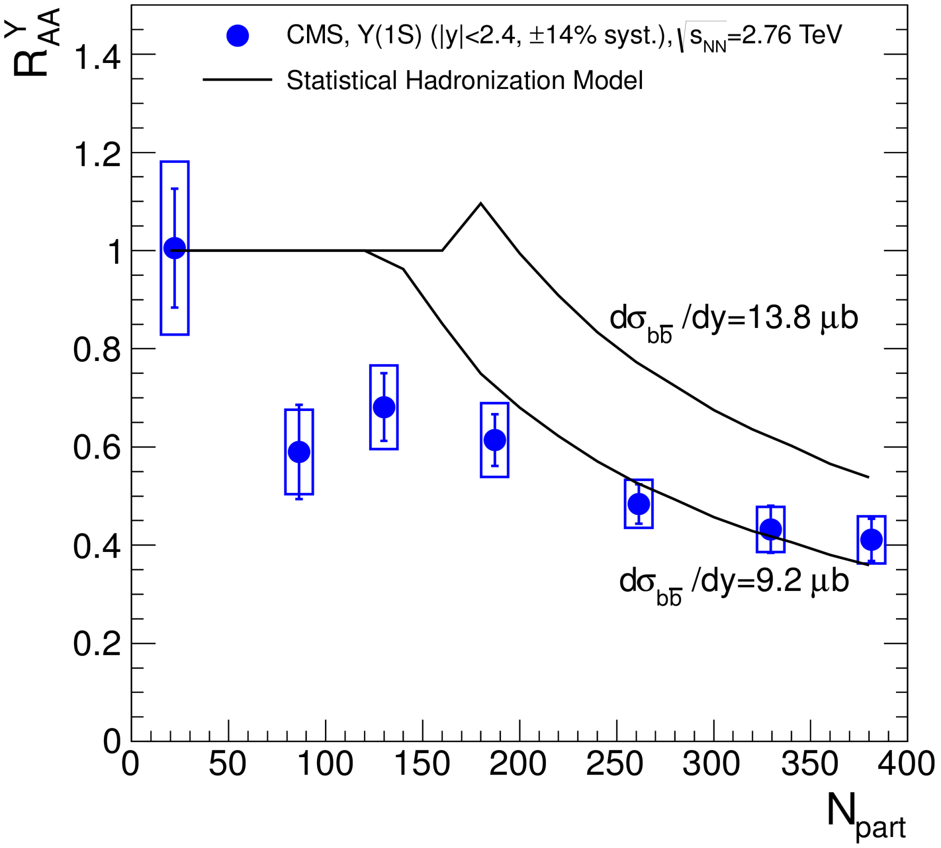


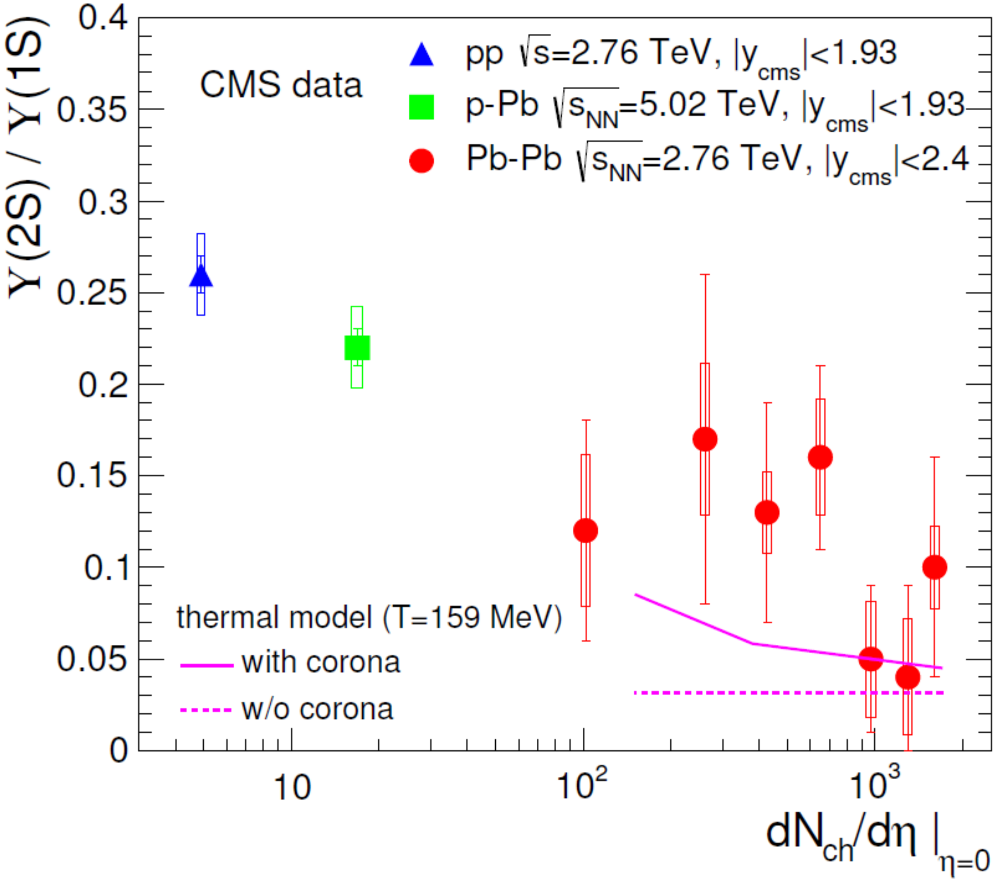
Indication: R_{AA} peaked at mid-y like for J/ψ

not in line with collisional damping in expanding medium

the Upsilon could also come from statistical hadronization

SHM/thermal model: Andronic et al.





in this picture, the entire Upsilon family is formed at hadronization
but: need to know first – do b-quark thermalize at all? spectra of B
- total b-cross section in PbPb