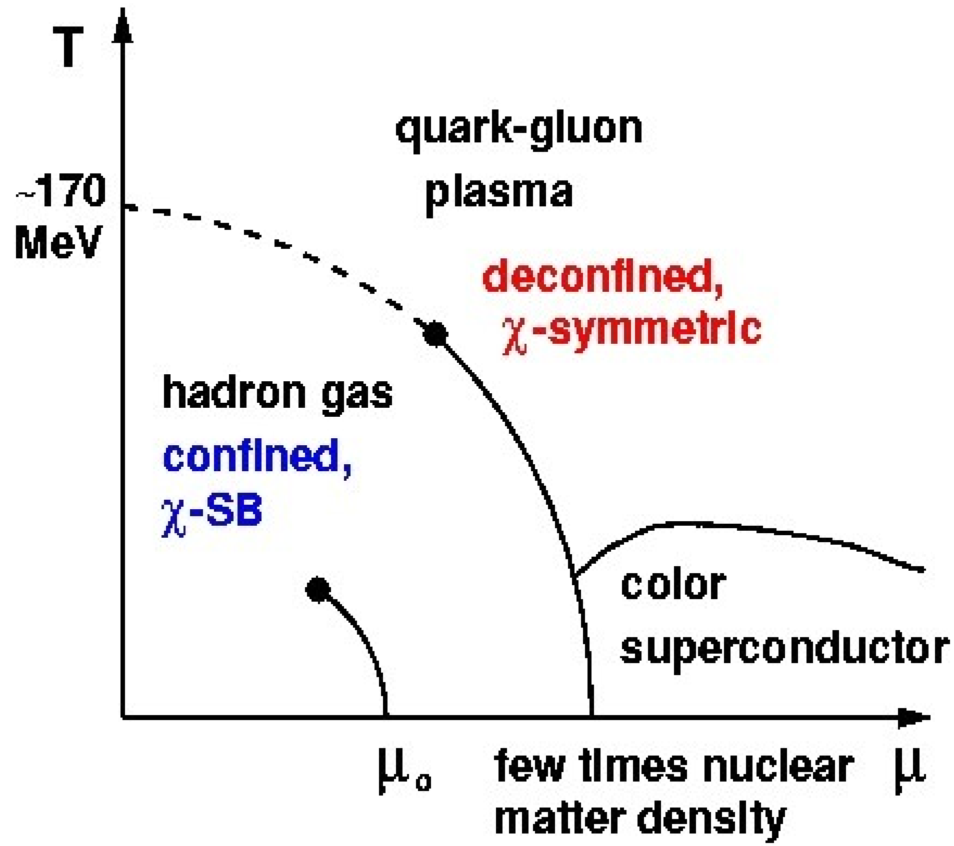
Exploring the Phase Diagram of Strongly Interacting Matter

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



Johanna Stachel, Phys. Inst., Univ. Heidelberg

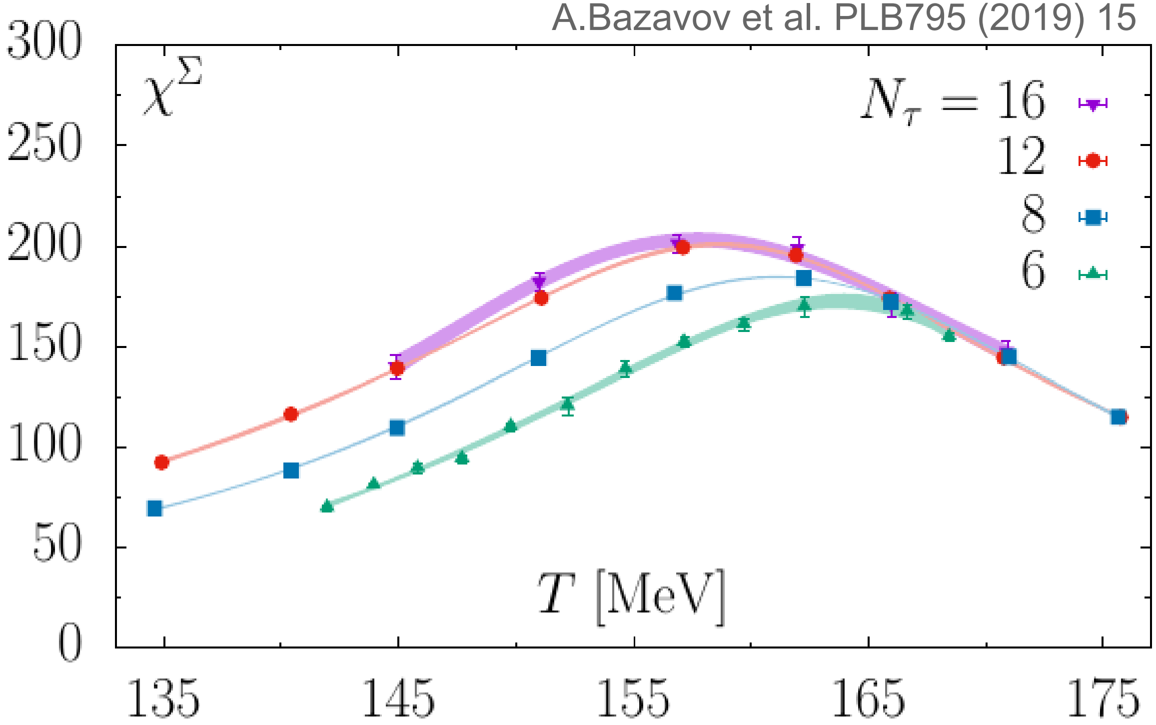
QNP2022, 9th Int. Conf. on Quarks and Nuclear Physics
Florida State Univ., Tallahassee, USA - Sept. 5, 2022

Measure for chiral symmetry restoration in lQCD

order parameter: chiral condensate, its susceptibility peaks at T_c

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

A.Bazavov et al. PLB795 (2019) 15

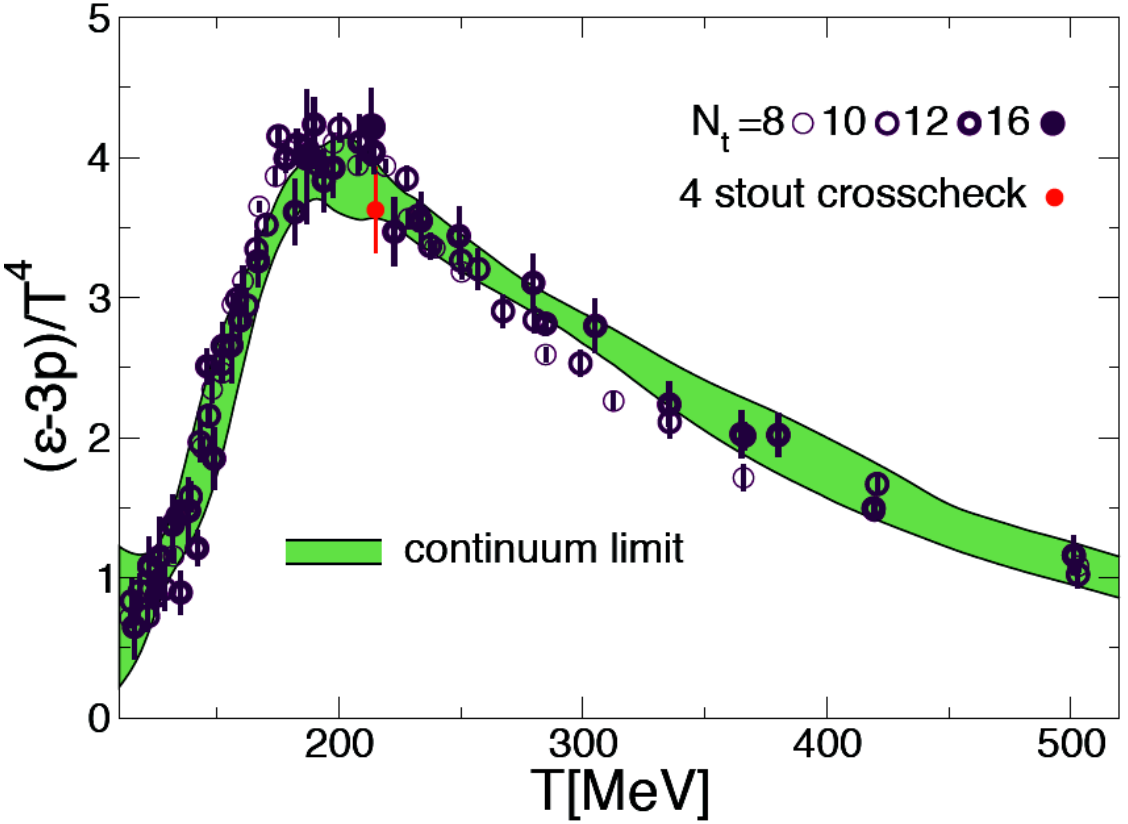


most recent results on pseudo-critical temperature for chiral phase transition

HotQCD Coll. PLB 795 (2019) 15
(comparing different measures)
T_{pc} = 156.5 +- 1.5 MeV

Wuppertal-Budapest Coll.
PRL 125 (2020) 052001
T_{pc} = 158.0 +- 0.6 MeV

Equation of state of hot QCD matter from lQCD



interaction measure or
trace anomaly
(normalized to T^4) shows:
QCD still in
strongly coupled regime

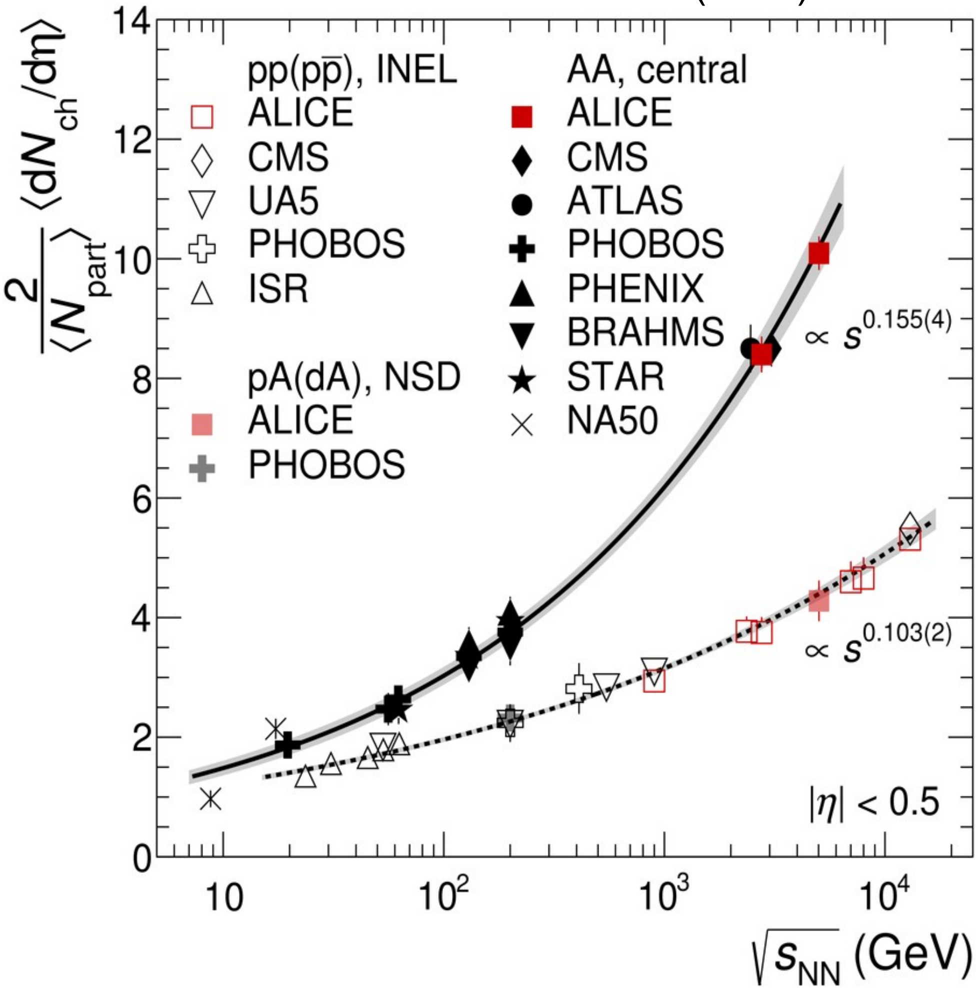
Experimental program

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 2010	2.76 – 5.02 TeV	3 (4)

Charged particle production

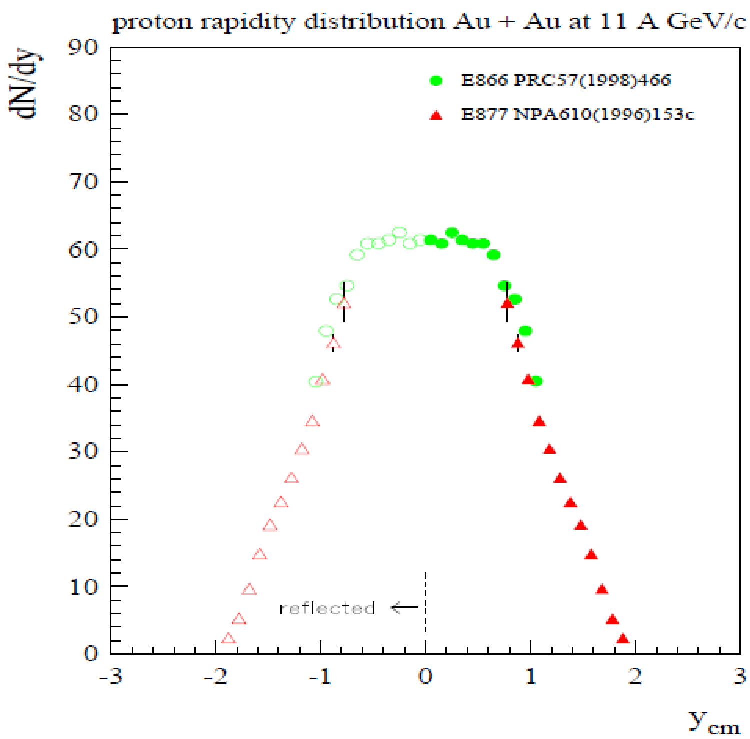
ALICE Coll. PRL116 (2016) 222302



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

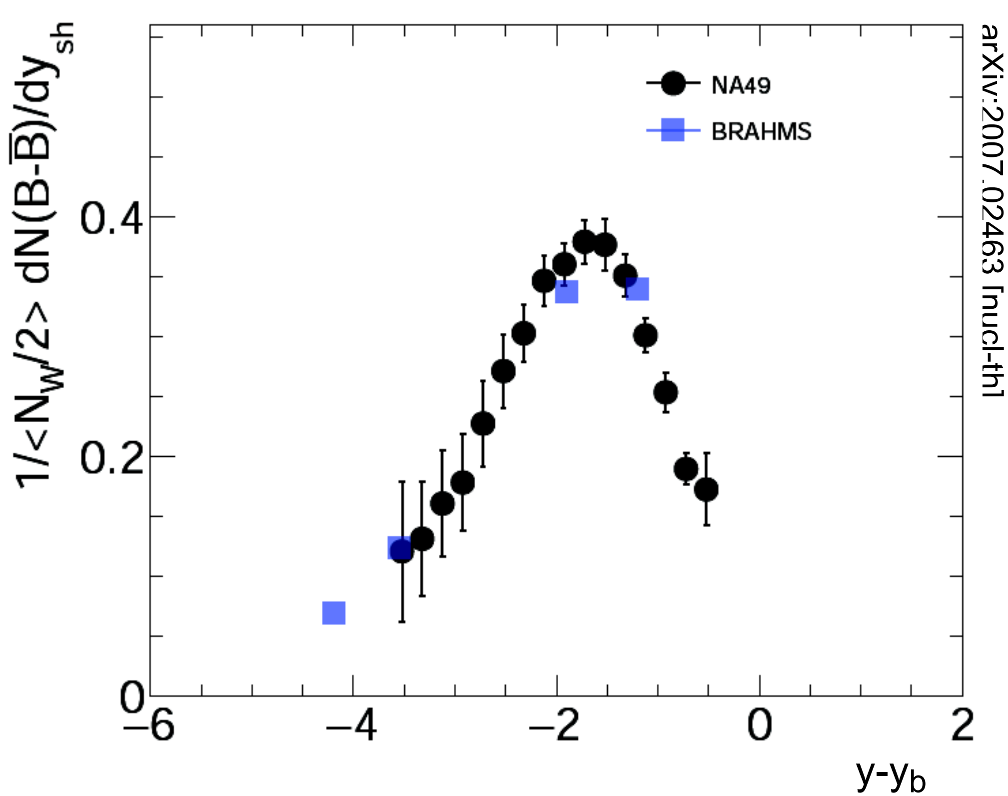
→ larger fractional energy loss in nuclear collision

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(-Δy) ≙ 86% E_{loss}
energy deposit in central fireball
in pp (Fermilab data): $\Delta y = 0.95$ ≙ 60% E_{loss}



Initial Energy Density

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

Bjorken formula using Jacobian $dy/dz=1/\tau_0$
typically evaluated at τ_0 = 1 fm/c

	$\sqrt{s_{NN}}$ [GeV]	$dE_t/d\eta$ [GeV]	ϵ_{BJ} * [GeV/fm^3]	T [GeV]
AGS	4.8	200	1.9	0.180
SPS	17.2	400	3.5	0.212
RHIC	200	600	5.5	0.239
LHC	2760	2000	14.5	0.307

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

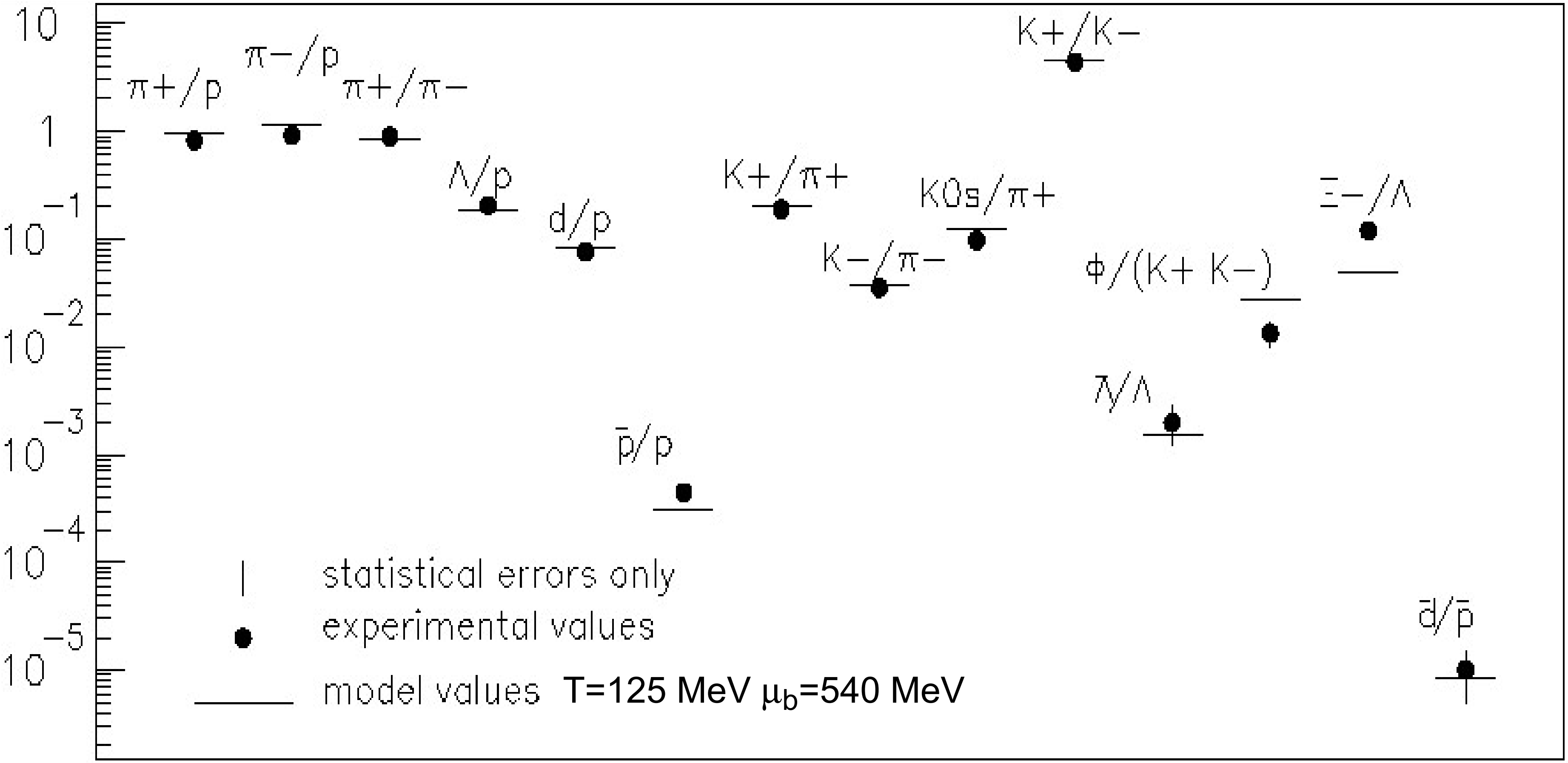
* these are lower bounds; if during expansion work is done (pdV) initial energy density higher (indications from hydrodynamics at LHC: factor 3)

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

Production of hadrons and (anti-)nuclei at LHC

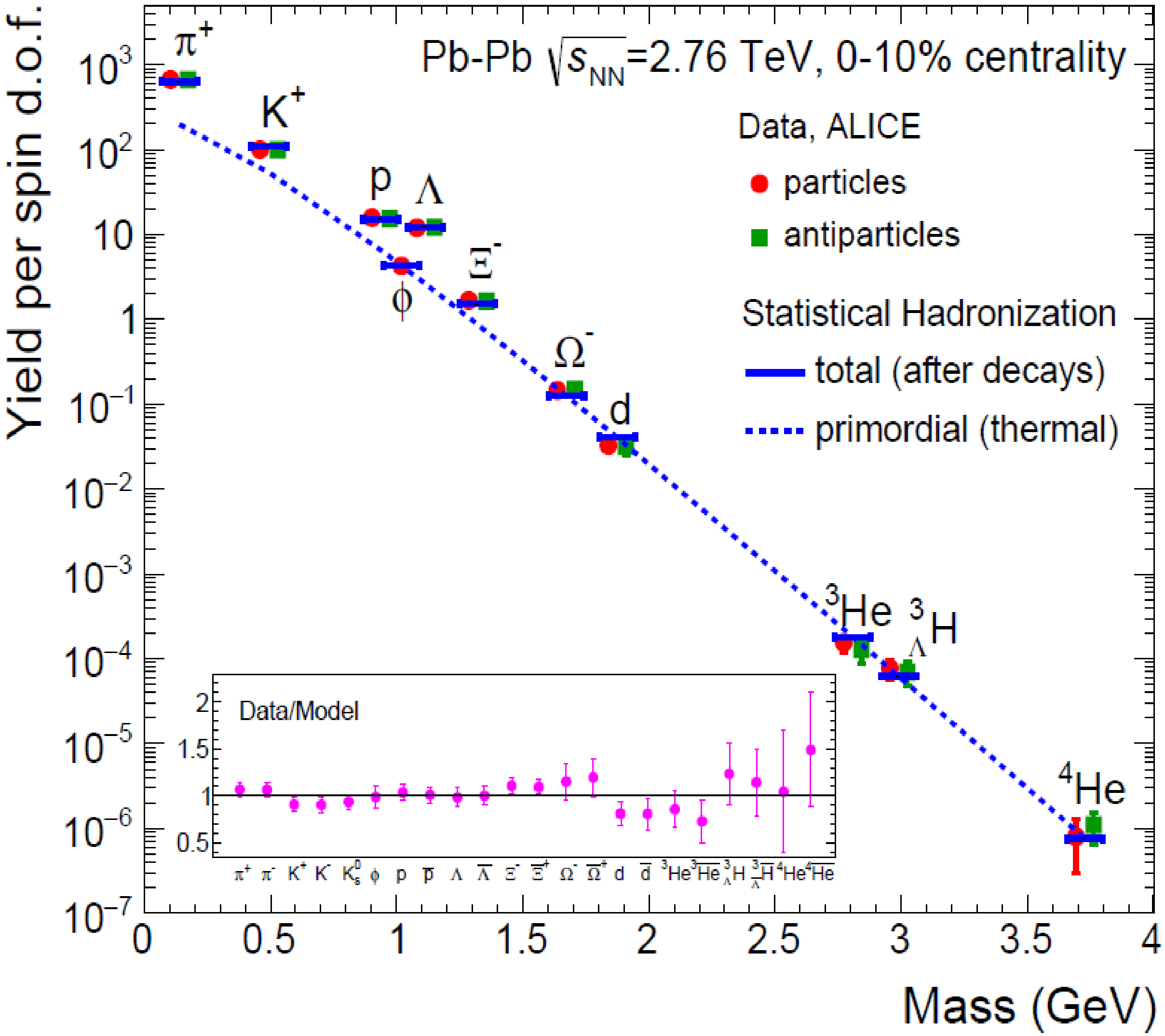
1 free parameter: temperature T

T = 156.5 ± 1.5 MeV

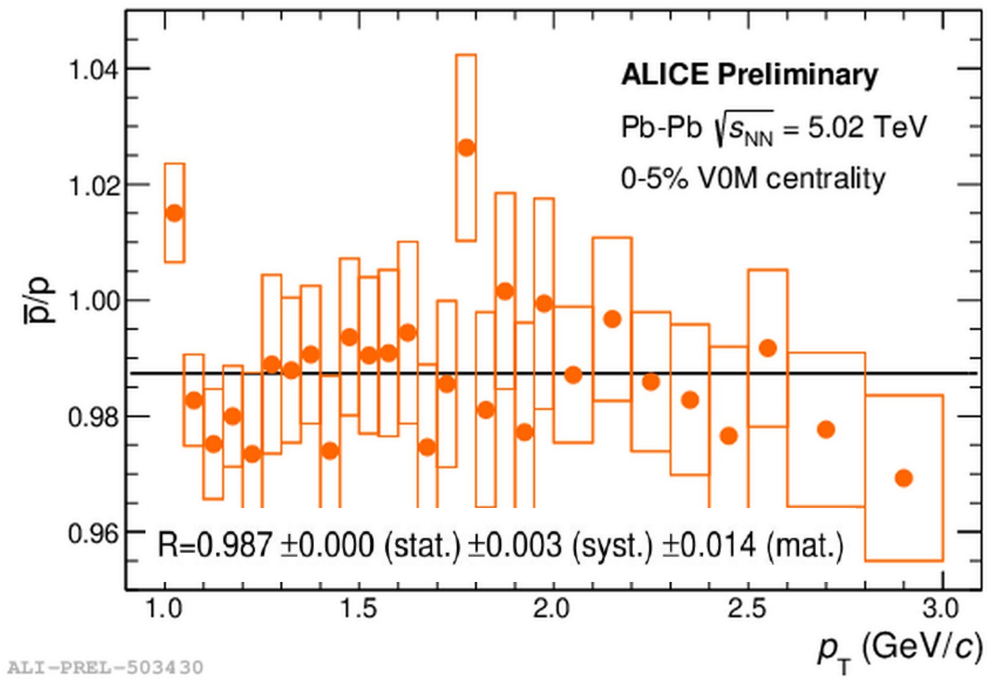
agreement over 9 orders of magnitude with QCD statistical operator prediction
(- strong decays need to be added)

- matter and antimatter are formed in equal portions at LHC
- even large very fragile hypernuclei follow the same systematics

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) 321

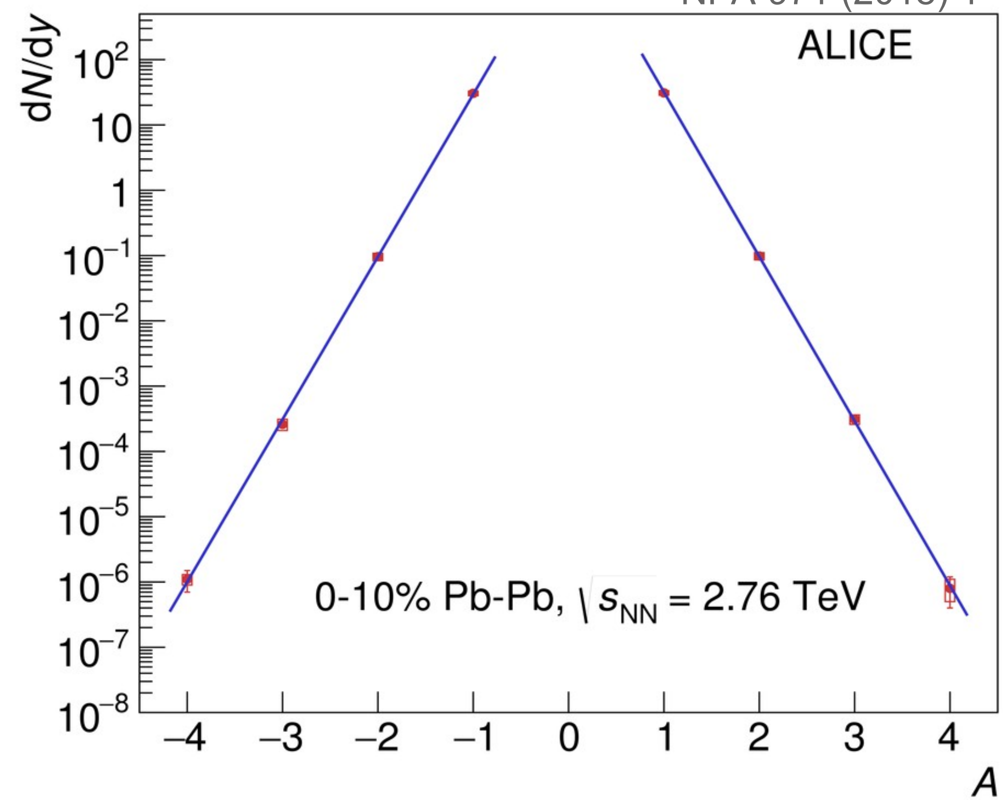


Benefit and curse of nuclear transparency at LHC



- matter and anti-matter produced in equal proportions at LHC
- consistent with net-baryon-free central region, (μ_b = 0.6 ± 0.1 MeV) similar to early universe

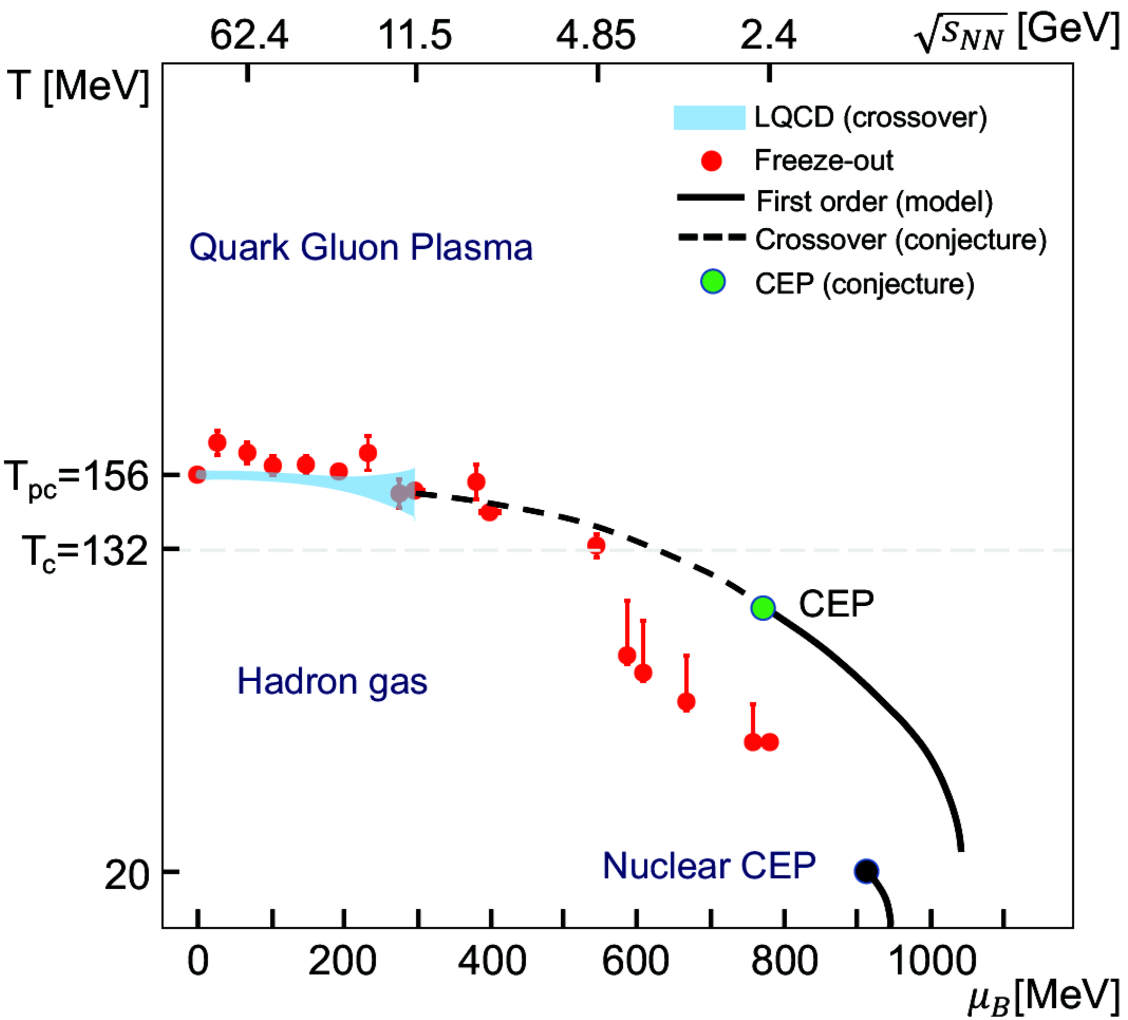
NPA 971 (2018) 1



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

compared to 24 for nuclei
and 140 000 for anti-nuclei
at top AGS energy with
μ_b = 537 and T=124 MeV

Energy dependence of temperature and baryochem potential



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

- limiting temperature hadronic system, reached for $\sqrt{s_{NN}} \geq 12$ GeV

- T_{CF} at LHC in exact agreement with the pseudo-critical temperature T_{pc} from lQCD

A. Bazavov et al. PLB 795 (2019) 15
S. Borsanyi et al. PRL 125 (2020) 052001

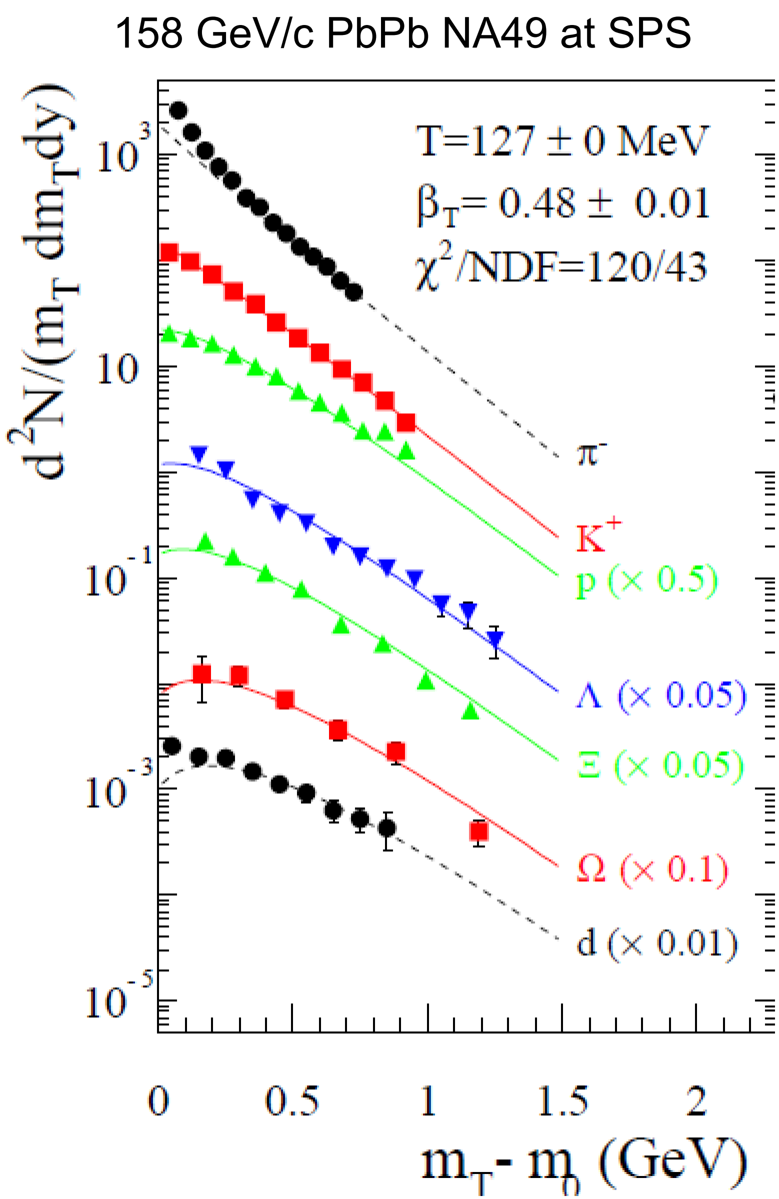
- why chemical freeze-out very close to T_{pc}? close to T_{pc} rate for multi-particle reactions explodes (critical opalescence)

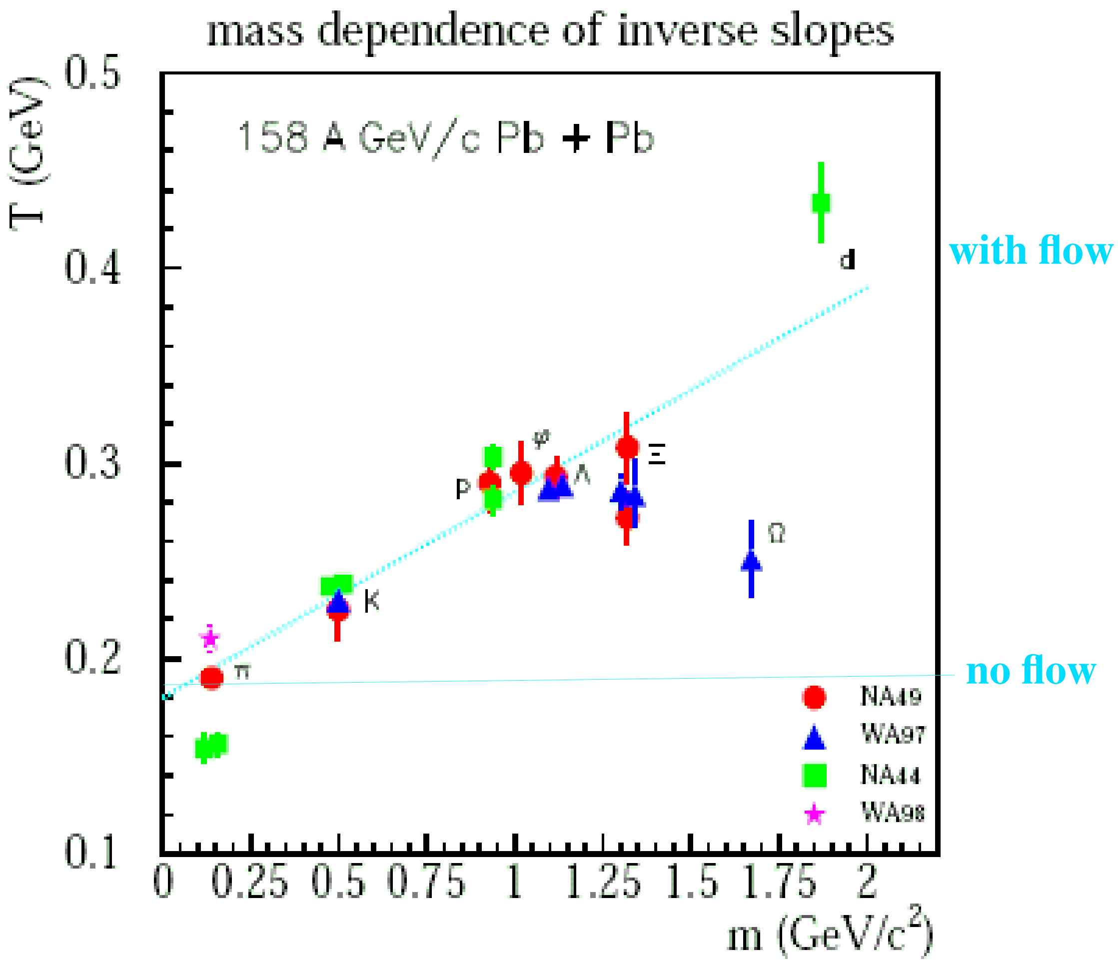
P. Braun-Munzinger, JS, C. Wetterich (2004)

Hadron spectra and correlations

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

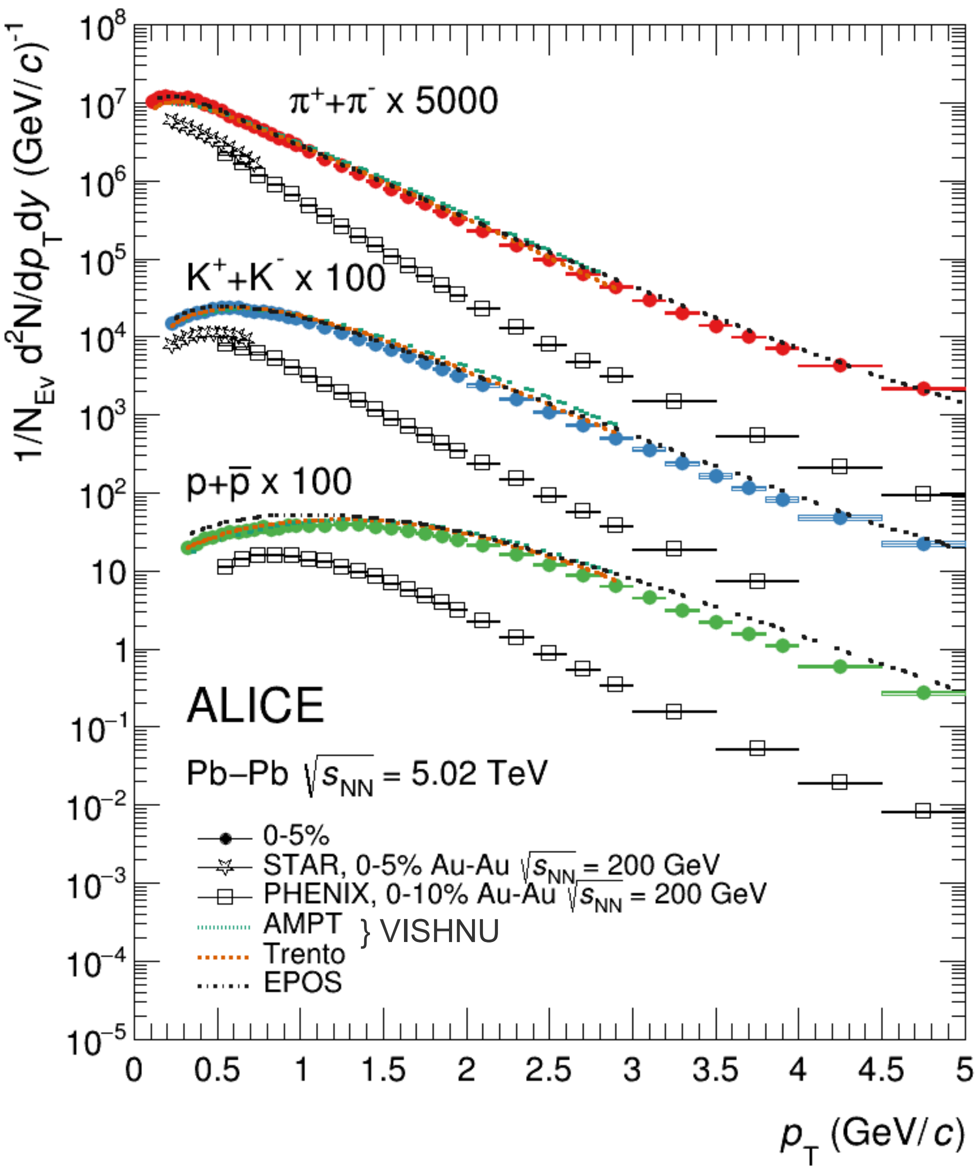
Spectra of identified hadrons at SPS





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

Spectra of identified hadrons at RHIC and LHC



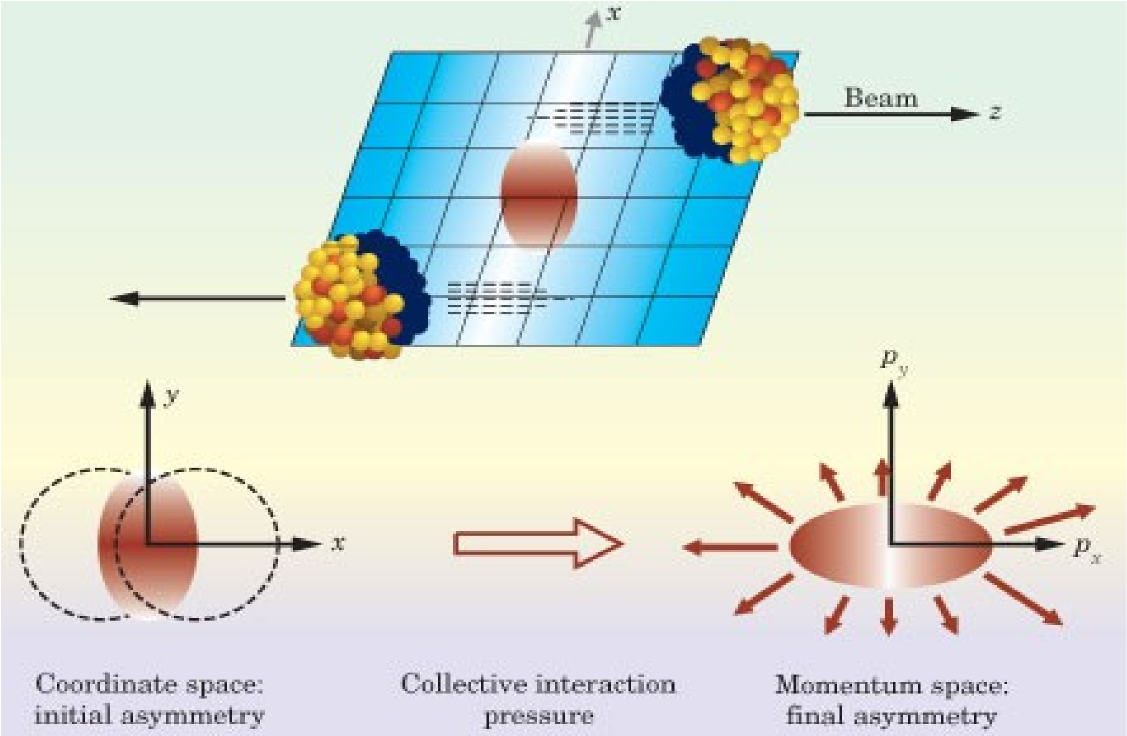
spectral shapes exhibit even stronger mass dependence
- characteristic for hydrodynamic expansion

indicate at LHC significantly larger expansion velocity than at RHIC

captured well by hydrodynamic expansion
(EPOS, K. Werner et al. Subatech)

expansion velocity at surface: ¾ c

Azimuthal anisotropy of transverse spectra



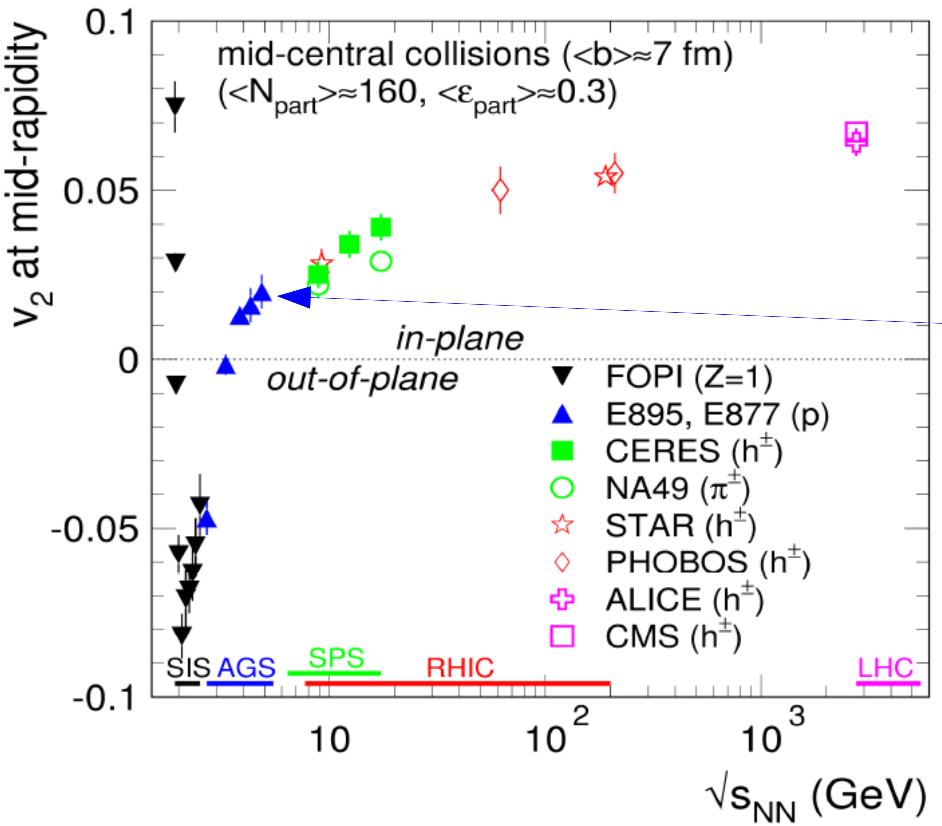
Fourier decomposition of momentum distributions rel. to reaction plane:

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

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

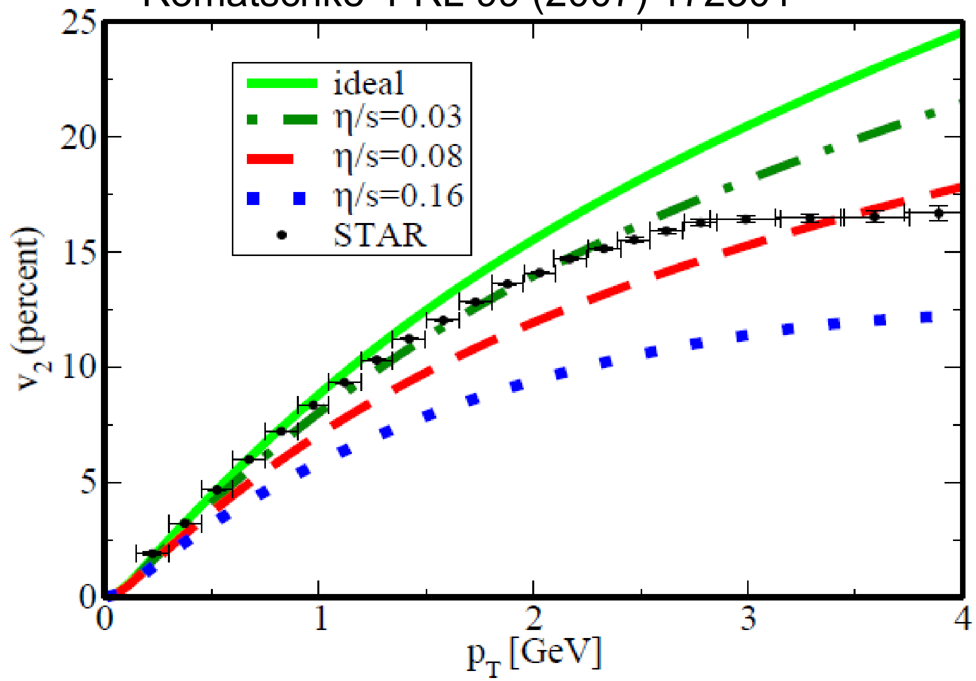
first discovered as tiny 2% effect by E877 in 1993

RHIC: paradigm of QGP as perfect liquid reflecting the strong coupling regime

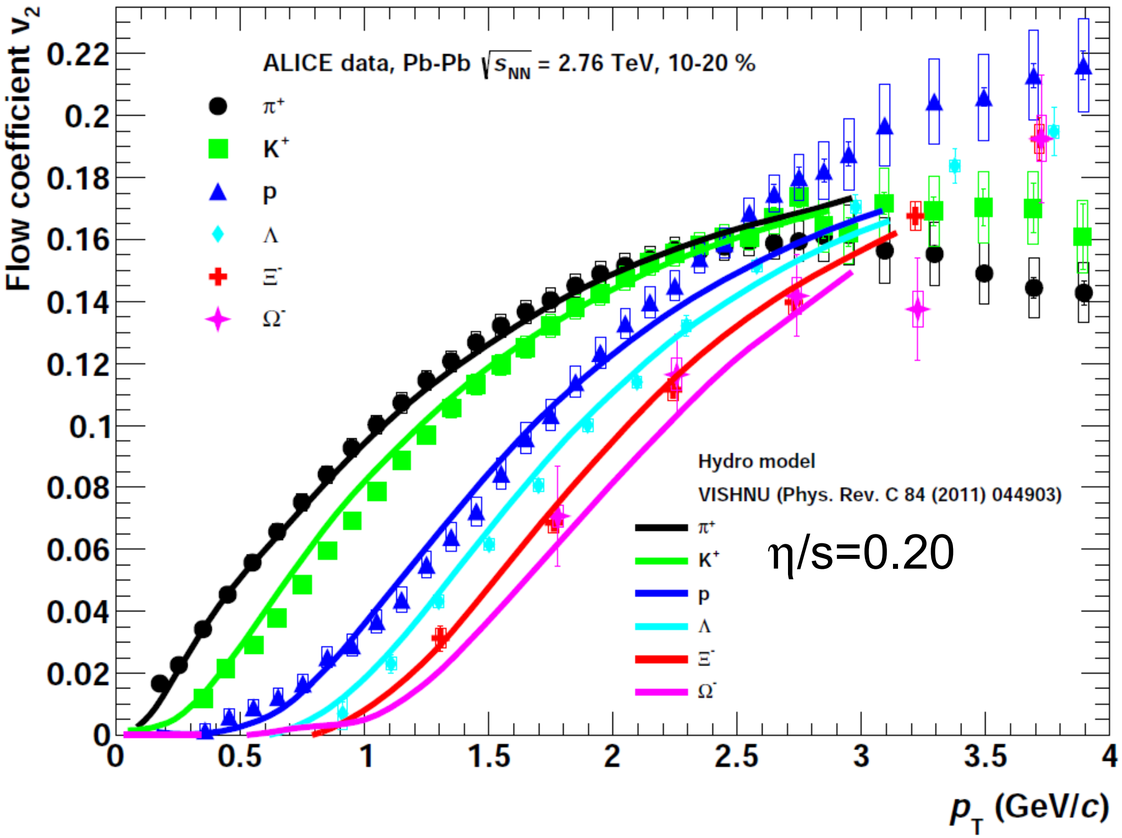
$$\eta/(\epsilon + P) = \eta/(Ts)$$

- very small ratio of shear viscosity to entropy density η/s describes data
- values of v_2 driven by initial conditions and properties of the liquid

Romatschke PRL 99 (2007) 172301



Elliptic flow for identified particles at LHC



mass ordering as function of p_t characteristic for hydrodynamic expansion
- reproduced quantitatively by viscous hydrodyn. modelling

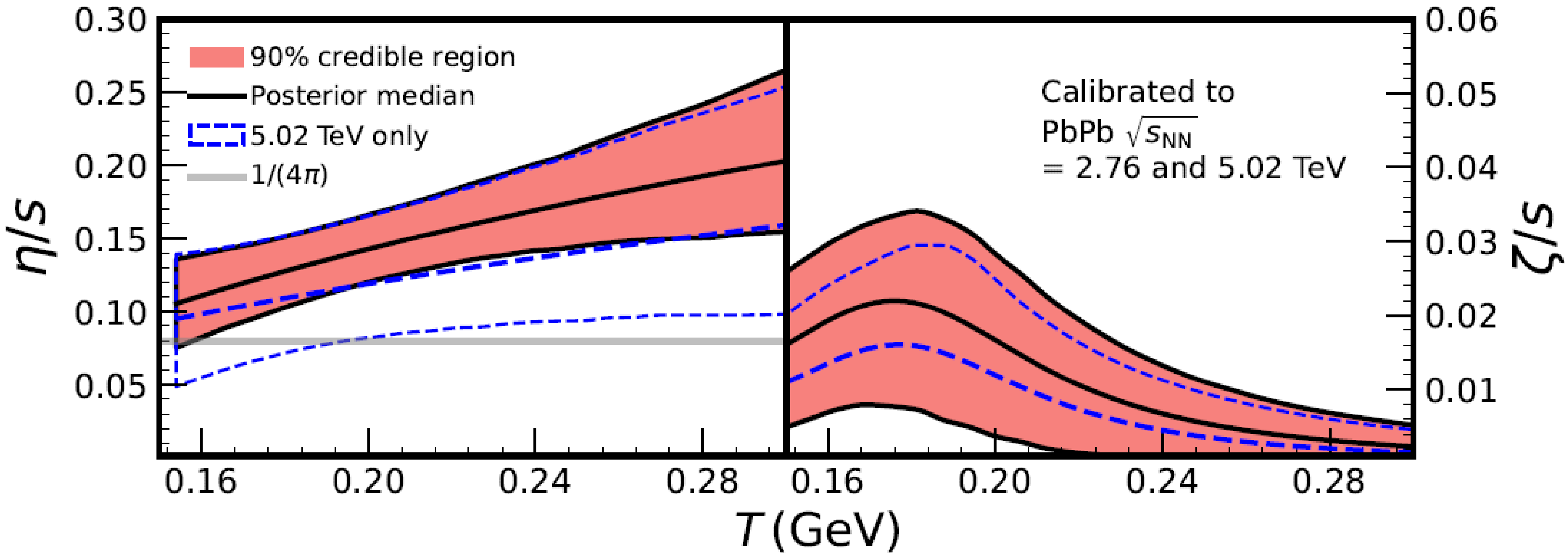
Constraining initial condition and QGP medium properties

much higher precision can be obtained from cumulants defined in terms of multiparticle azimuthal correlations

N. Borghini, P.M. Dinh, J.Y. Ollitrault, PRC 64 (2001) 054901

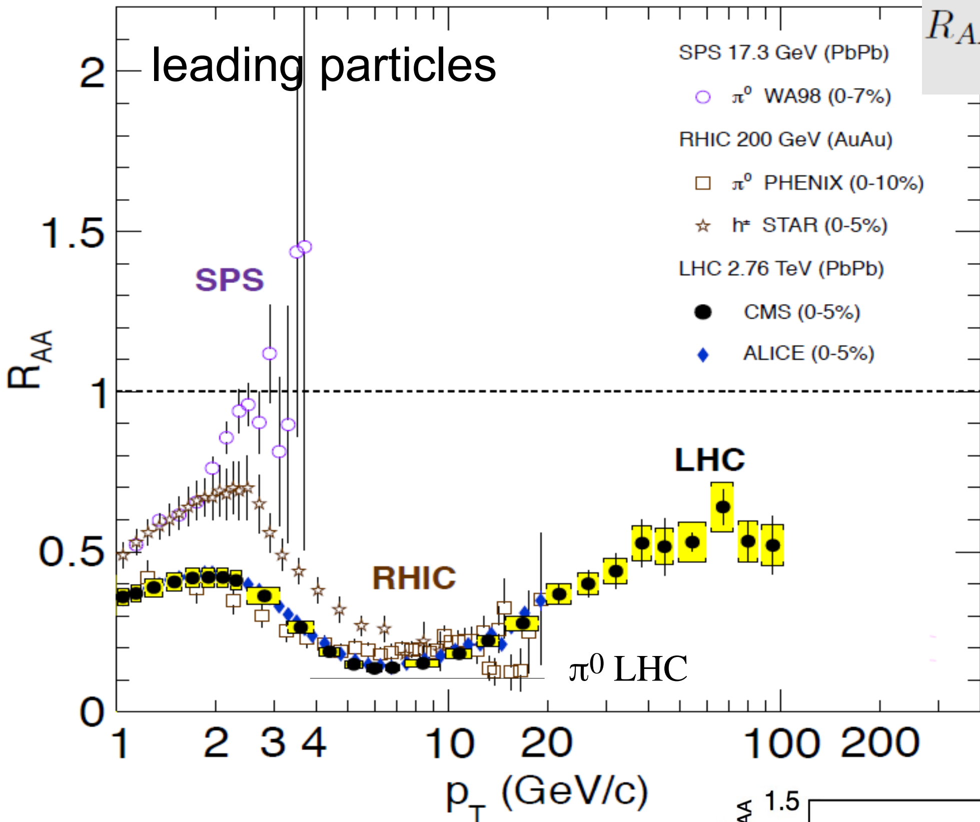
LHC: global Bayesian analysis of such new collective flow observables in PbPb from ALICE

J. Parkkila et al., arXiv: 2111.08145



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

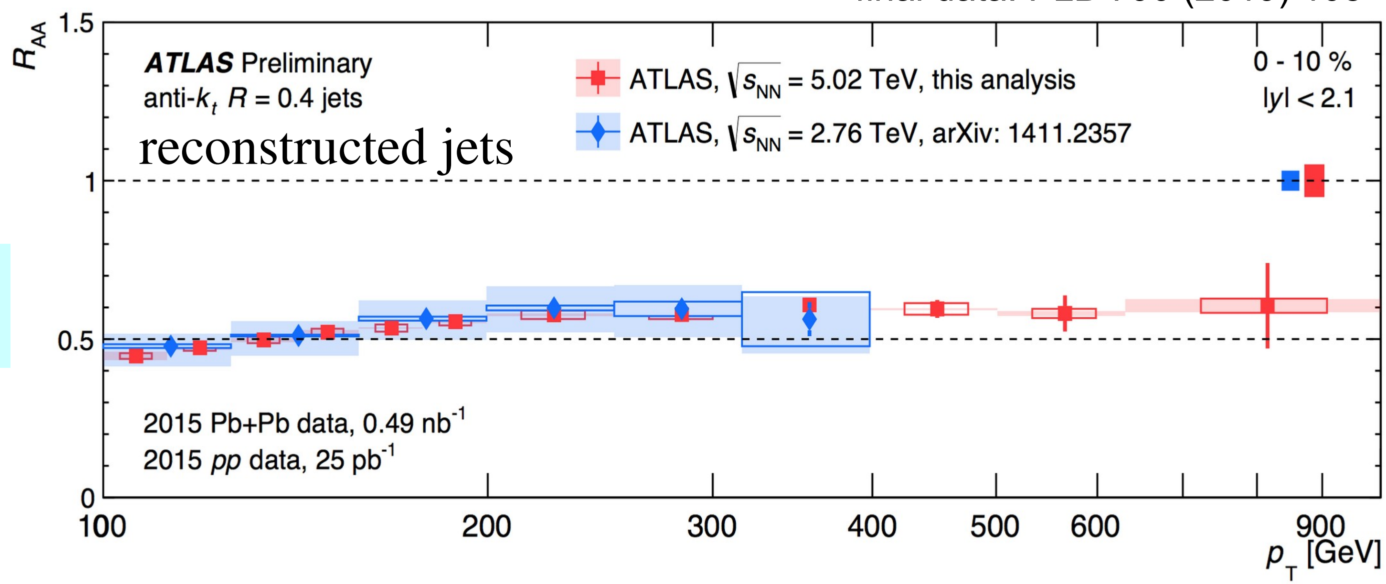
Jet quenching – parton energy loss in QGP



$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N_{pp}/\mathrm{d}y}$$

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

final data: PLB 790 (2019) 108



jet suppression at level 0.6 out to 1 TeV

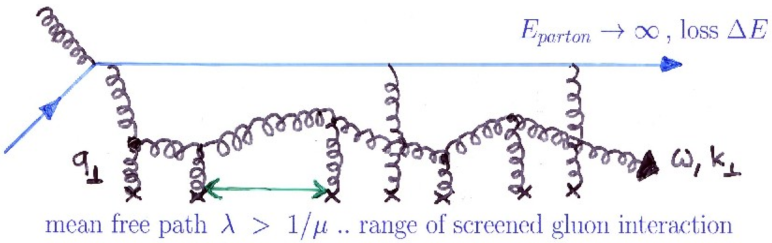
Extracting the jet quenching parameter

prediction: H. Baier, Y.L. Dokshitzer, A.H. Mueller, S. Peigne, D. Schiff, NPB 483 (1997) 291 and 484 (1997) 265

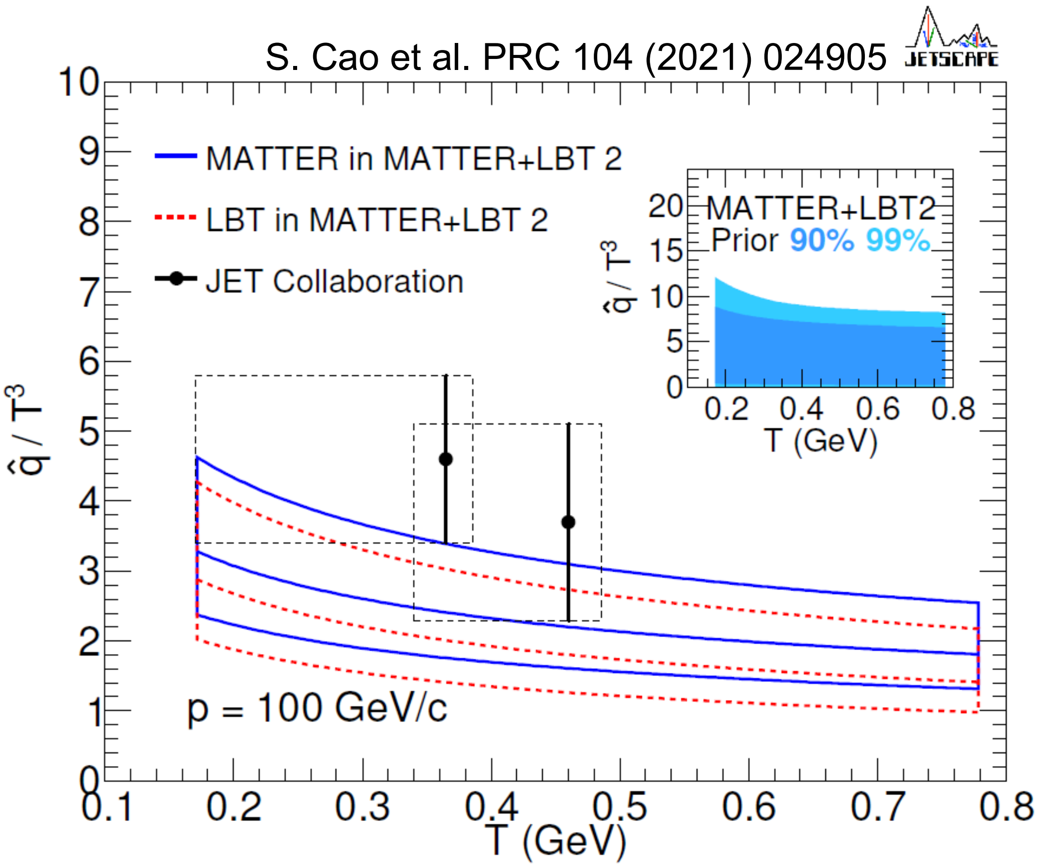
$$dE/dx \propto \rho\, \sigma \langle k_t^2 \rangle\, L$$

density of color charge carriers

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



S. Cao et al. PRC 104 (2021) 024905



determine transport coefficient from comparing a combined model of splitting of high virtuality partons (MATTER) and scattering between jet partons and a thermal QGP (LBT) to inclusive hadron R_{AA} data for RHIC and LHC (Bayesian parameter estimation)

obtain

$\hat{q}$ = 0.7±0.3 GeV^2/fm at T = 400 MeV

factor 20-40 larger than in cold nuclear matter (from DIS) !

Charmonia as a probe of deconfinement

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

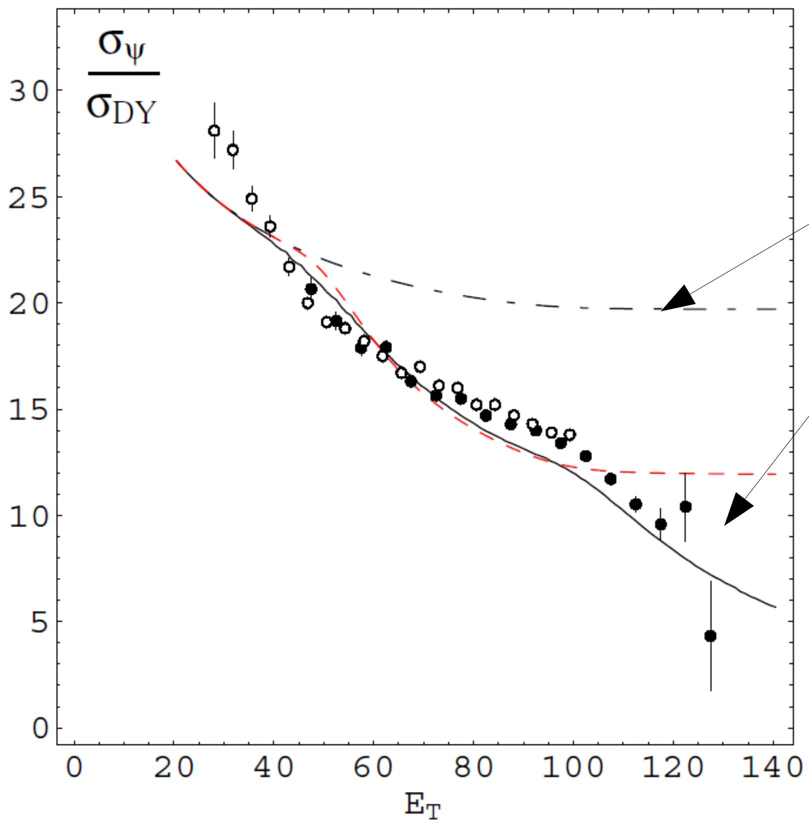
T. Matsui and H. Satz PLB 178 (1986) 416

First J/ψ suppression in nuclear collisions at SPS

key measurements by NA38 find suppression for O and S induced collisions
QM 1991 conf.: data on photon, hadron, and nucleus-nucleus coll. described by nuclear absorption

C. Gerschel and J. Hűfner, Z.Physik C56 (1992) 171

data: NA50 Phys. Lett. B447 (2000) 28



finally observations NA50:
- in pp, pA and light nuclei, 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:
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

P. Braun-Munzinger, J. Stachel, PLB 490 (2000) 196

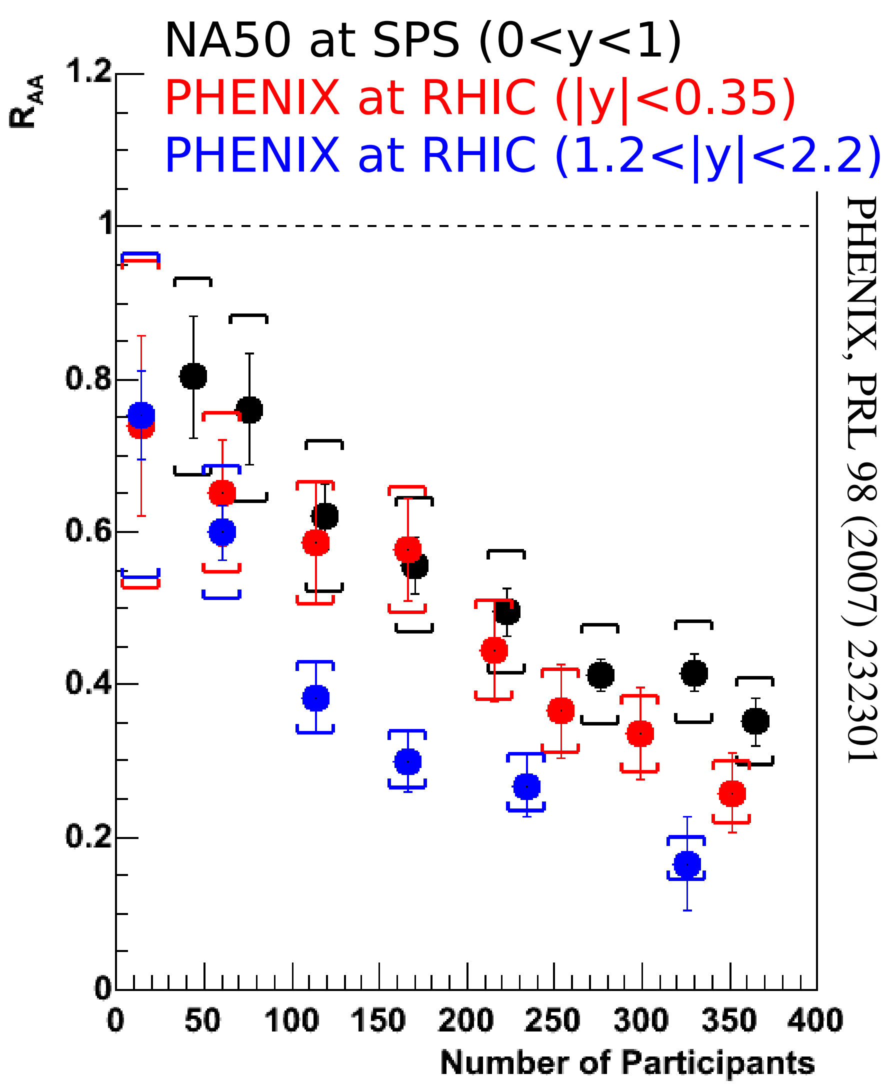
technically:

- 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 (no free parameter)

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

J/ψ suppression at RHIC – 200 A GeV AuAu



PHENIX 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”?

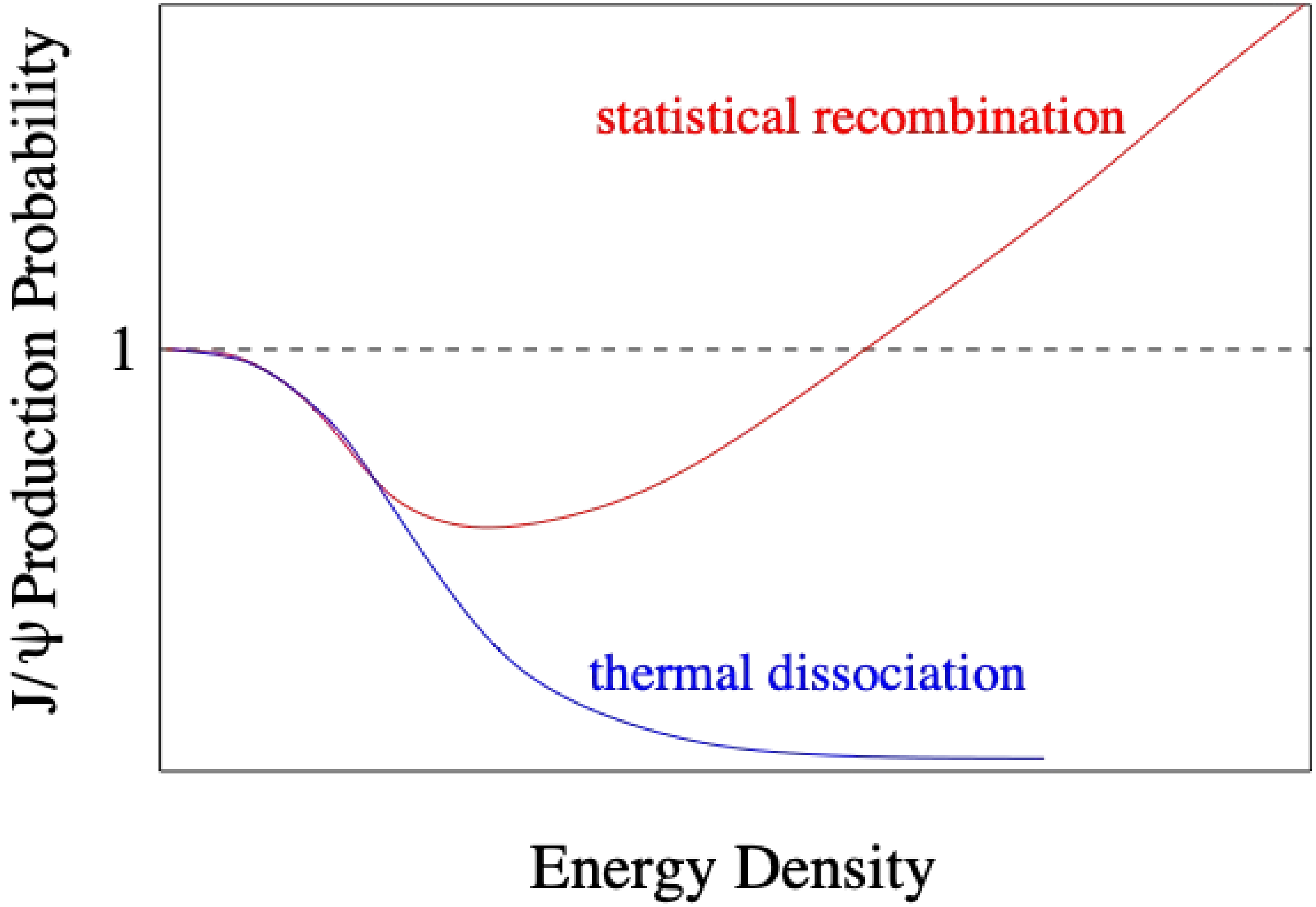
data could be indeed described by statistical hadronization using pQCD charm cross section

A.Andronic, P.Braun-Munzinger, K.Redlich, J.Stachel, PLB 652 (2007)259

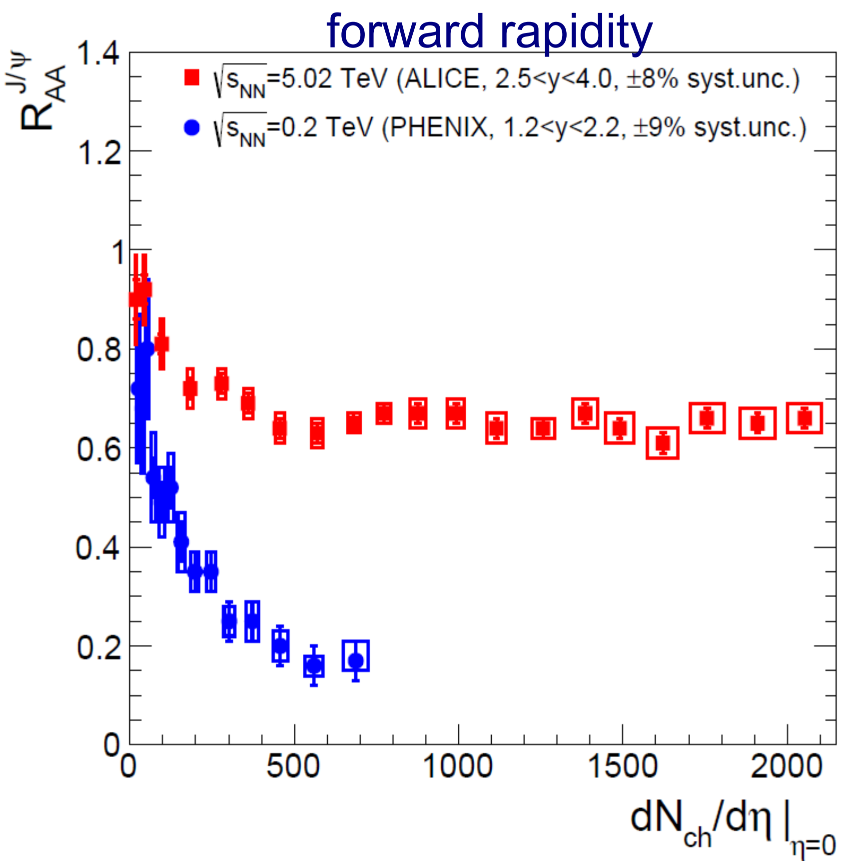
Expectations for LHC

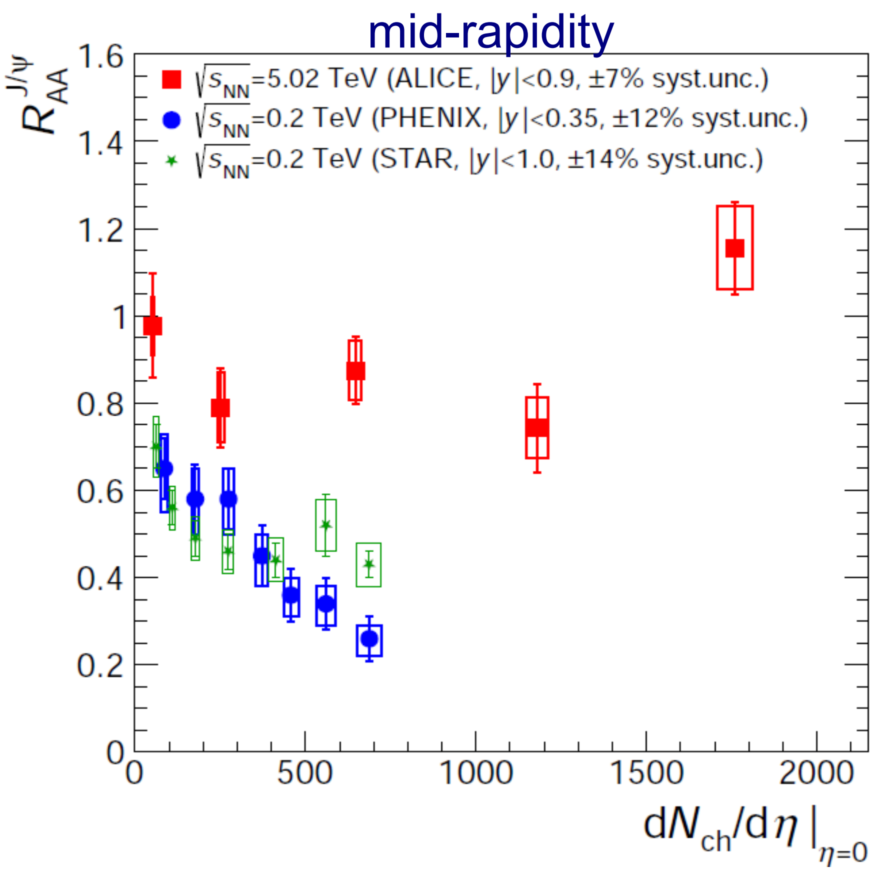
2 possibilities:

Kluberg, Satz, arXiv:0901.3831



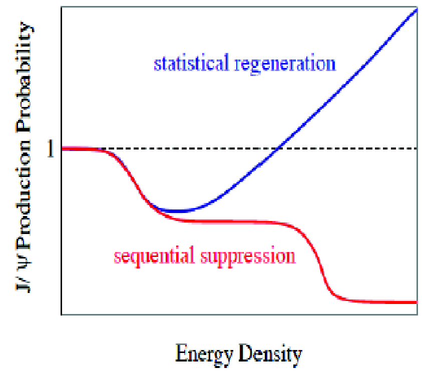
J/ψ production in PbPb collisions: LHC relative to RHIC





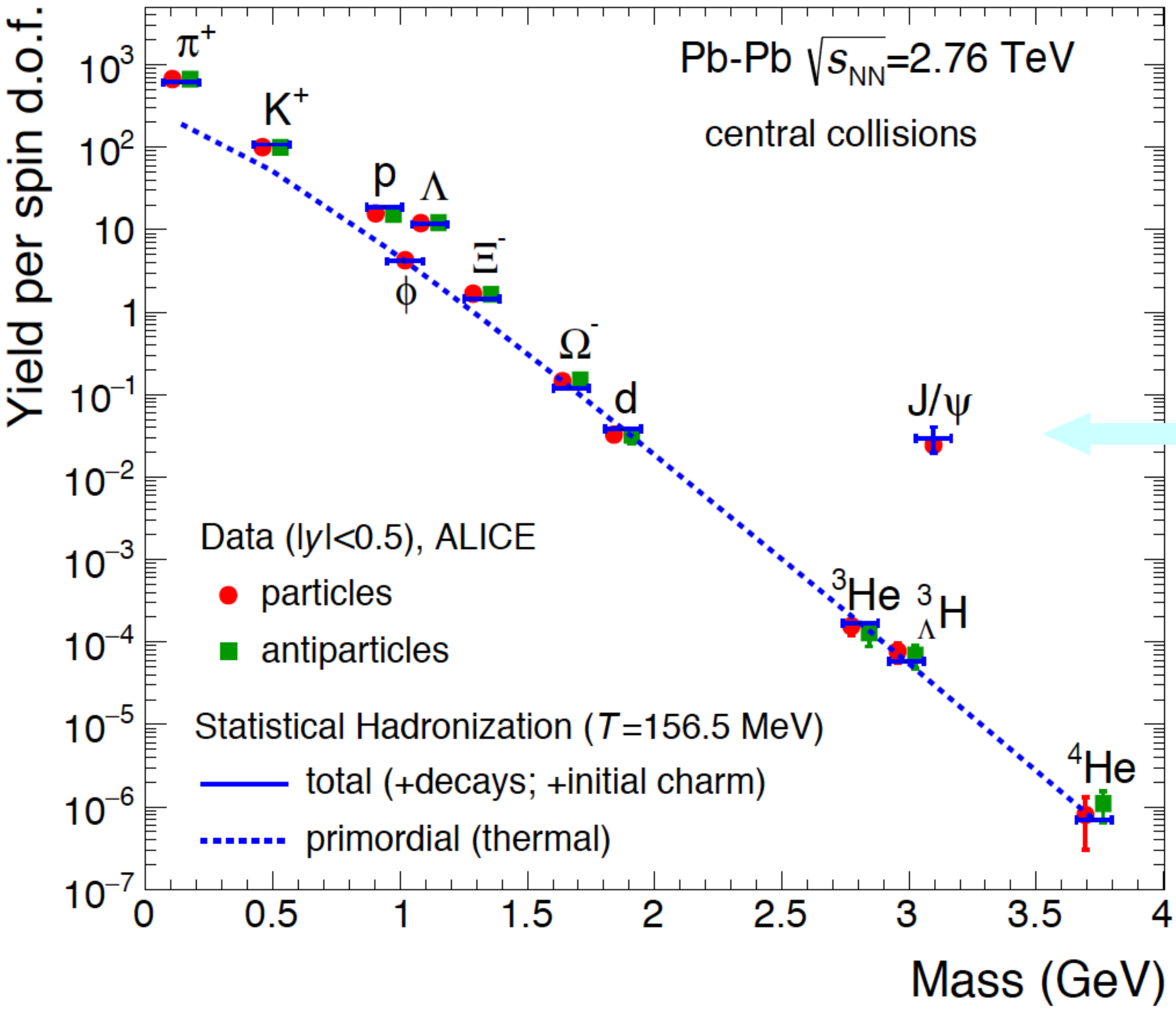
energy density →

melting scenario not observed
rather: enhancement with increasing energy density!
(from RHIC to LHC and from forward to mid-rapidity)



J/ψ overpopulation due to hard production of charm and statistical hadronization of deconfined quarks

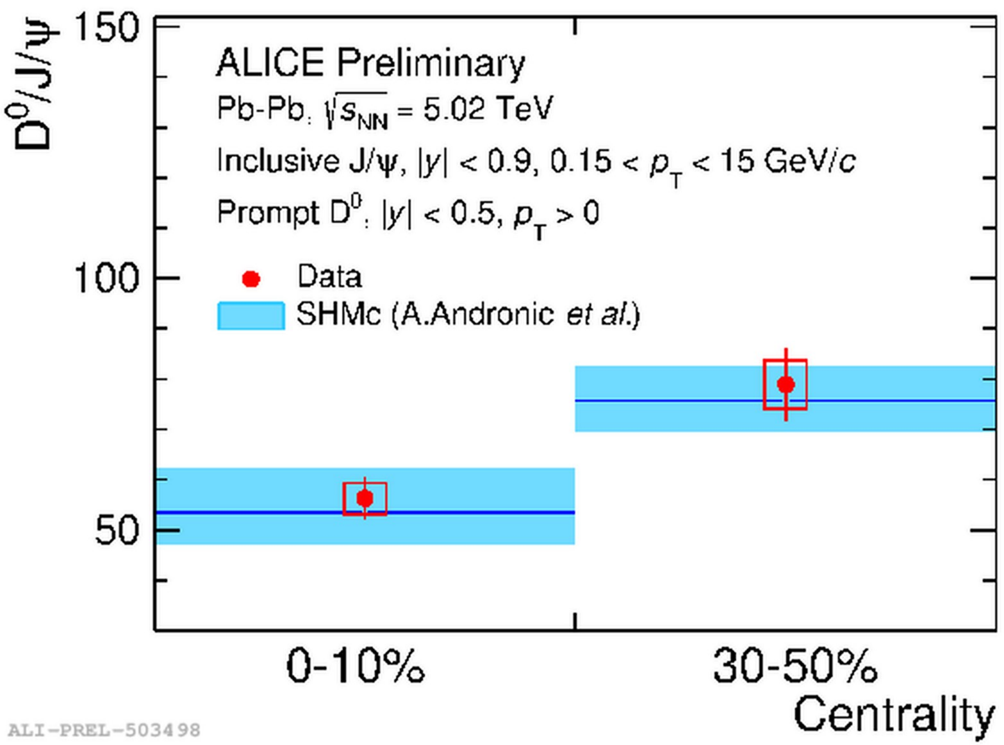
A.Andronic et al., PLB 797 (2019) 134836



J/ψ enhanced compared to other M = 3 GeV hadrons by factor g_c^2 = 900 relative to purely thermal yield

quantitative agreement with hadronization of deconfined thermalized charm quarks

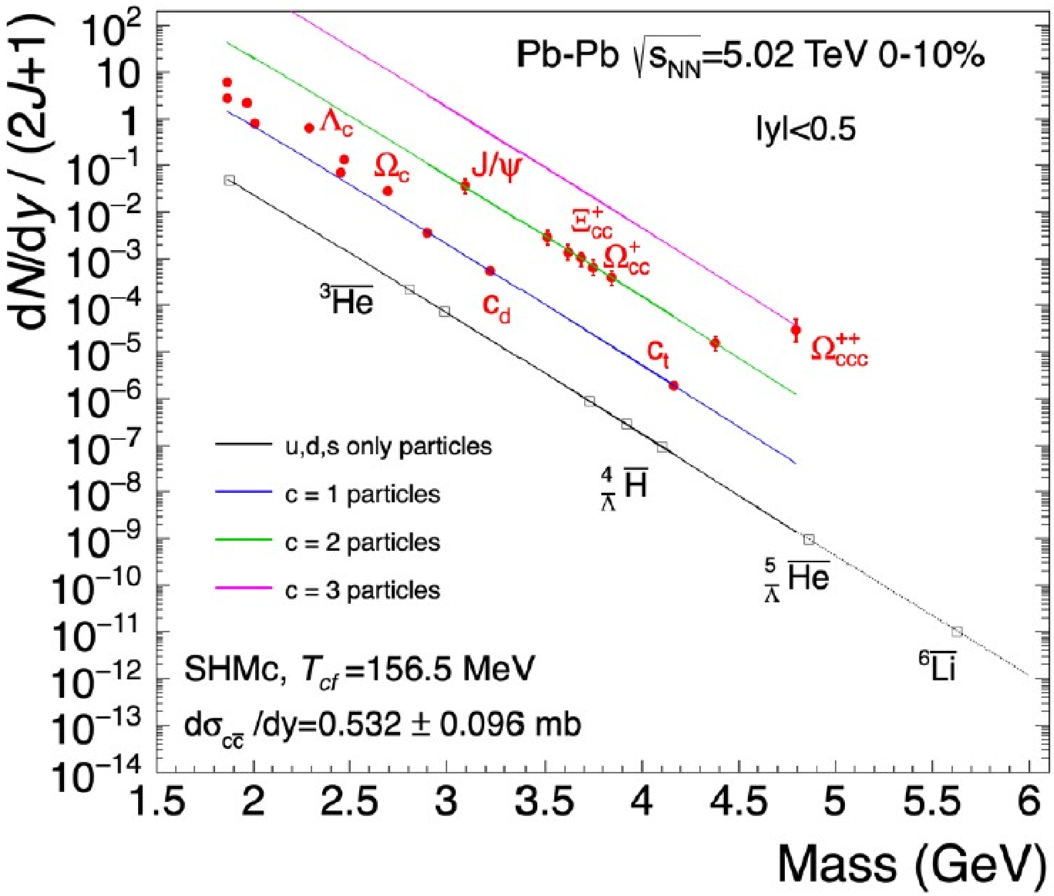
Towards a meaningful normalization of charmonia



open charm yield would be natural normalization
real breakthrough in data:
can base charm cross section on measured dN/dy of D^0 in PbPb

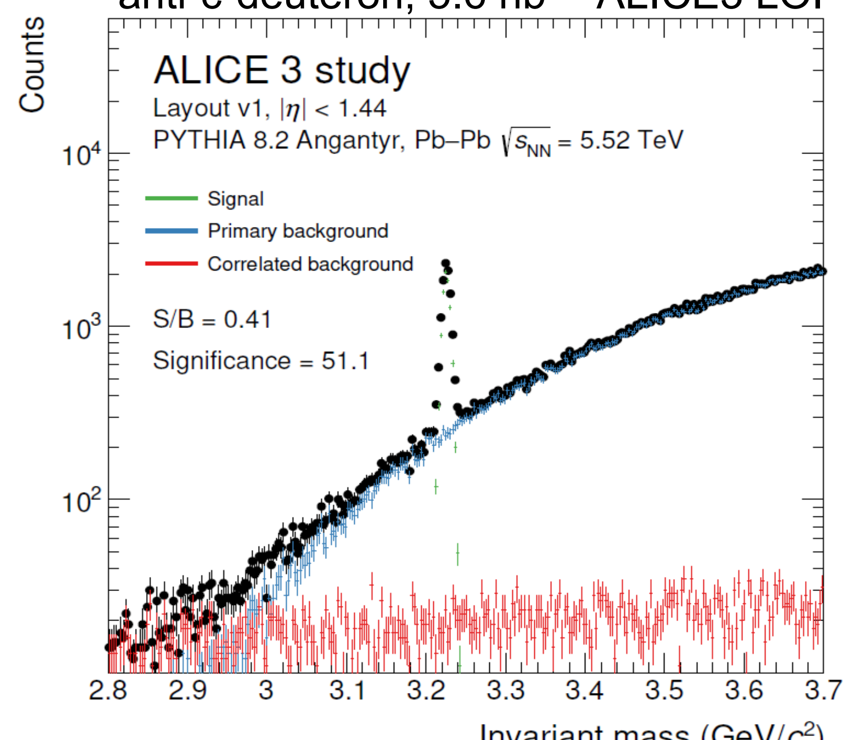
→ J/ψ relative to D^0 falls into place naturally and with much increased precision

Opportunities charmed hadrons and nuclei



a large part of what is shown here
comes into reach with ALICE3
multicharmed hadrons
exotica: $\chi_{c1}(3872)$, T_{cc}^{+}
hypernuclei
mass 6 nuclei
addresses fundamental questions
on charm hadronization

anti-c-deuteron, 5.6 nb^{-1} ALICE3 LOI



Summary and outlook

over the past 35 years significant knowledge has been gained about the nuclear phase diagram at high temperature

- knowledge of the location of the phase boundary to QGP, data and theory
- from top AGS energy to LHC most likely QGP is reached in nuclear collisions (certainly from top SPS energy)
- many common features that change only quantitatively, hadronization, collective behavior, formation of nuclei
- new features at collider energies, evidence for strongly coupled liquid, parton energy loss, determination of transport coefficients of QGP
- established at LHC: equilibration of charm quarks, partial for beauty, statistical hadronizaton of charmed hadrons from deconfined charm quarks

there is a rich physics program ahead to answer open and important physics questions

- LHC runs3,4 qualitatively new regime of statistics, heavy flavor, real & virtual photons, nature of phase transition
  sPHENIX high p_t and heavy flavor sector
  ALICE3 as next generation experiment in runs 5,6 of LHC
- sofar no evidence for a critical endpoint in phase diagram, could be around top AGS energy, RHIC beam energy scan and CBM at FAIR