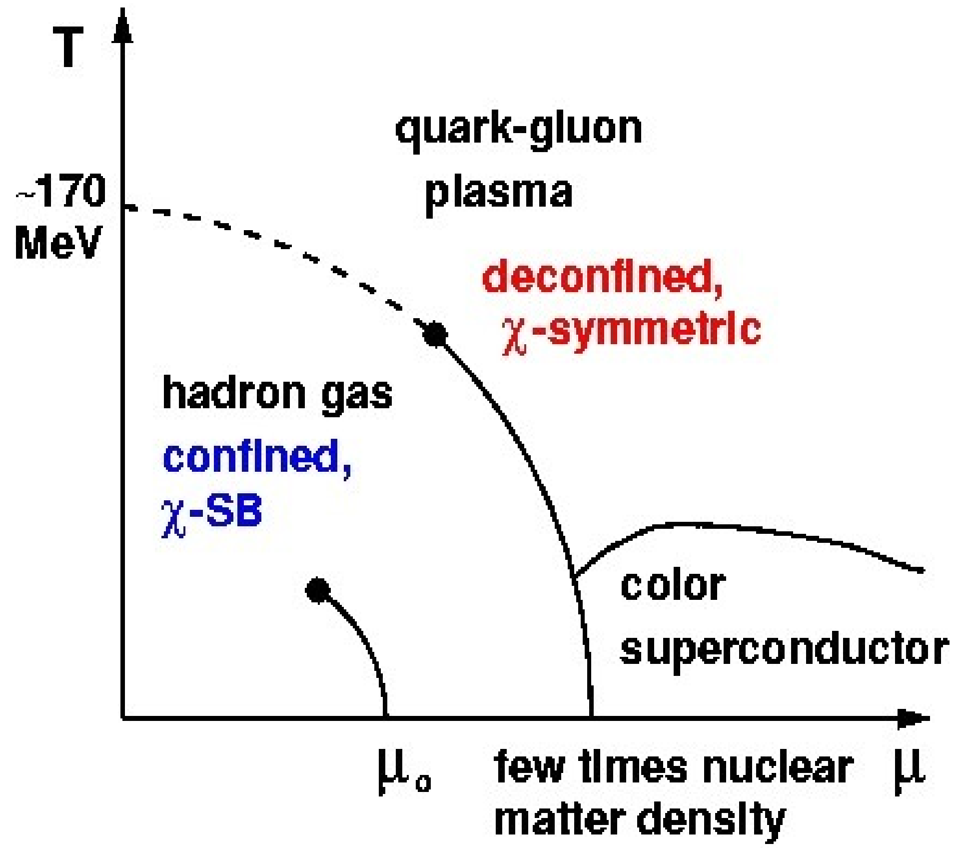
Mapping the Properties of the Quark-Gluon Plasma and the QCD Phase Boundary

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



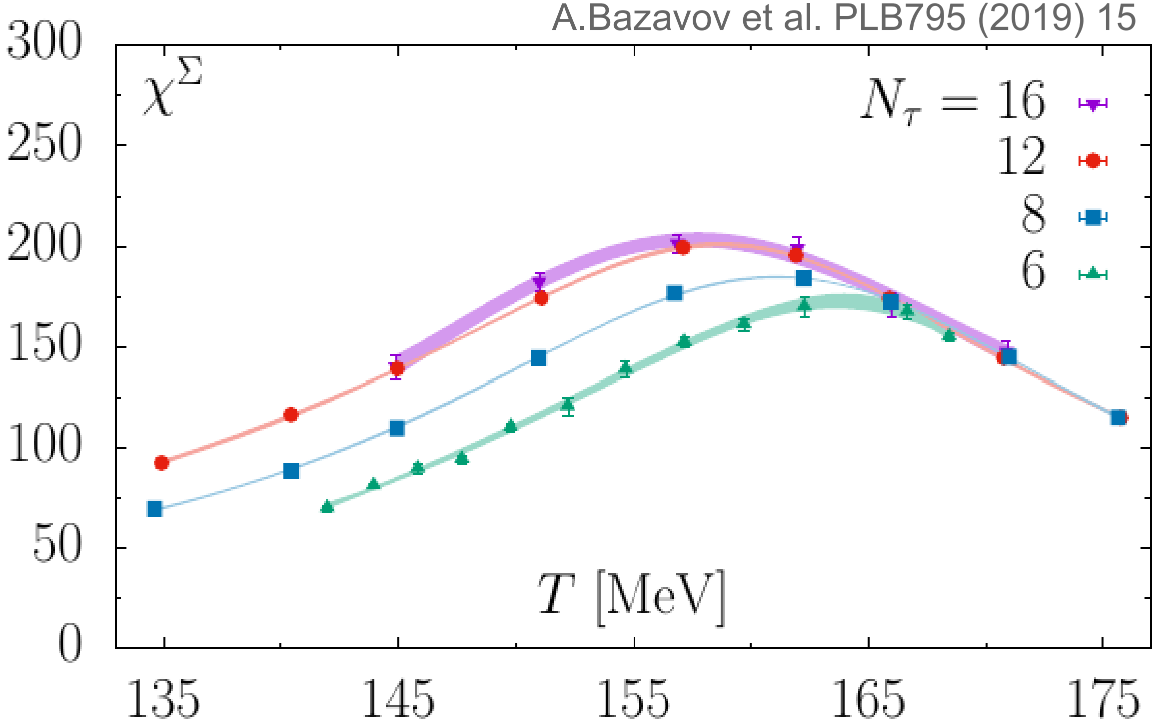
Johanna Stachel, Phys. Inst., Univ. Heidelberg
Colloquium GSI – April 30, 2024

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

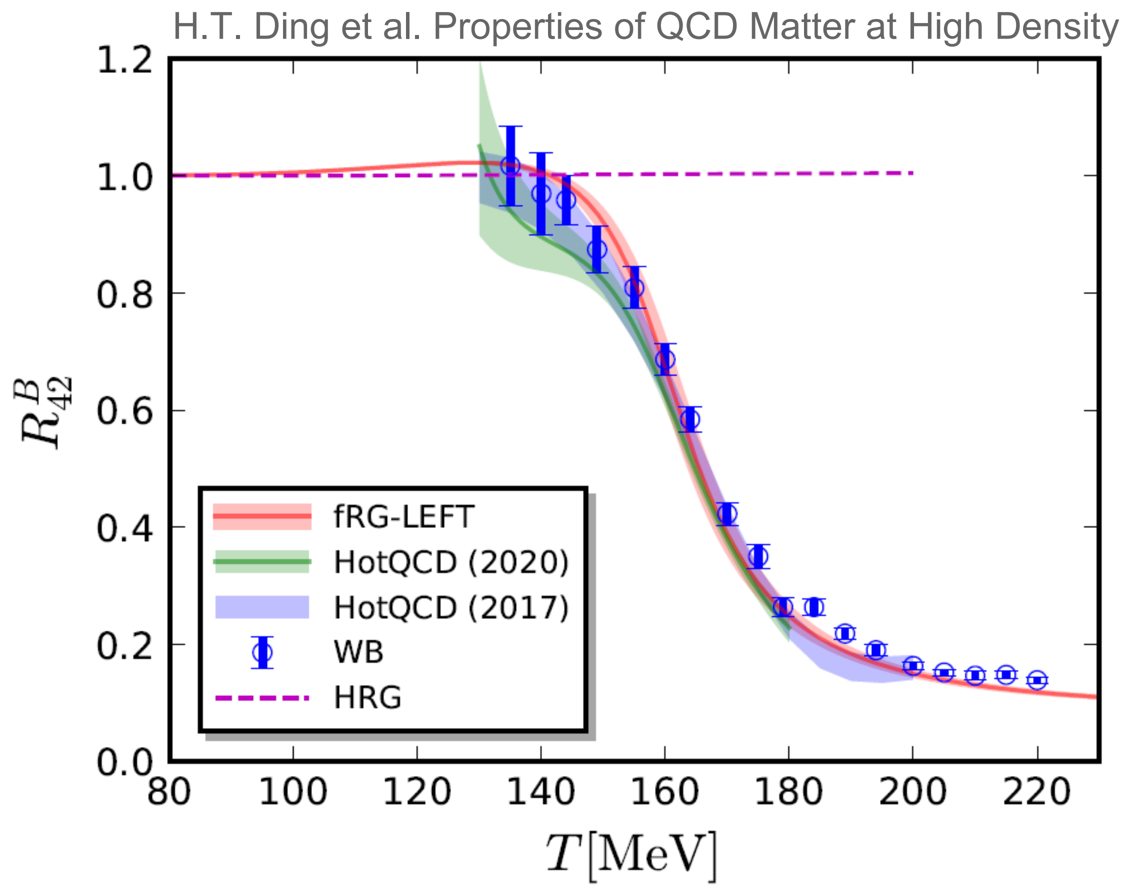
HotQCD Coll. PLB 795 (2019) 15
(comparing different measures)
T_{pc} = 156.5 +- 1.5 MeV

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

Measure of deconfinement in lQCD

ratio of quark number susceptibilities

$$R_{42}^{B} = \chi_4^B / \chi_2^B \propto \text{baryon number}^2 \qquad \chi_n^{\mathrm{B}} = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}$$



confined: 1

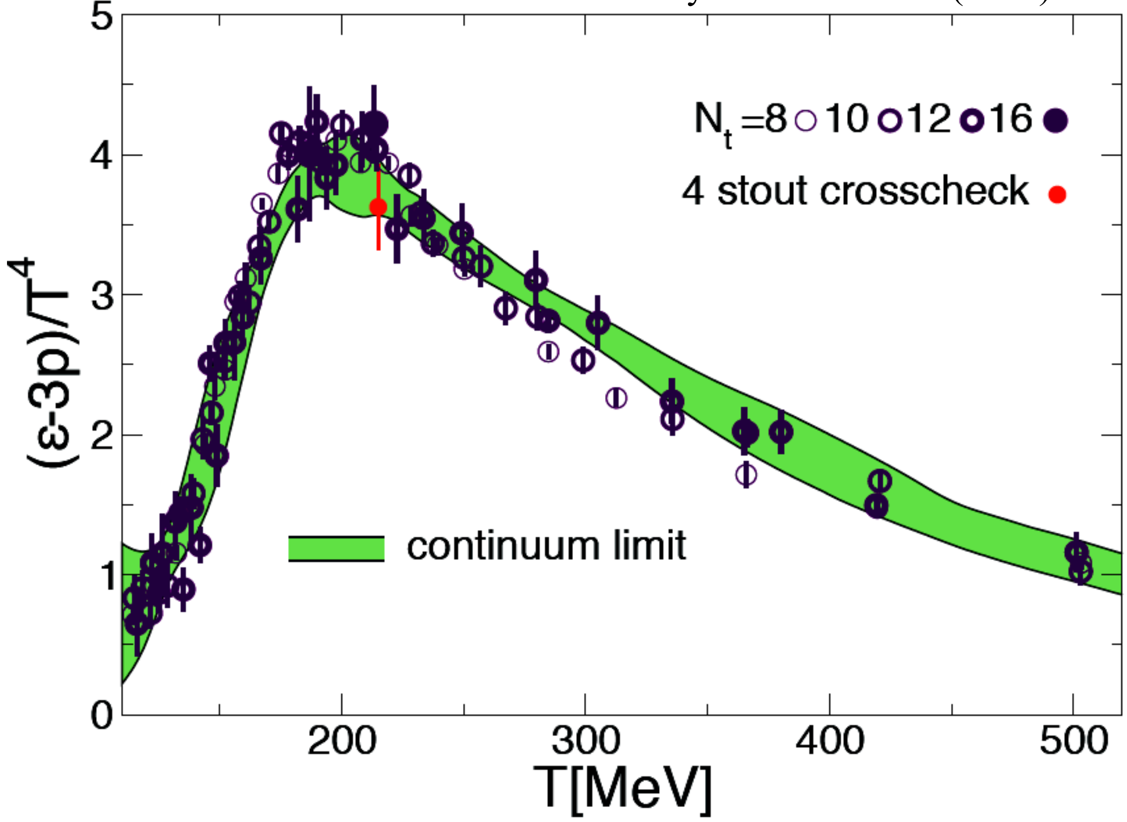
deconfined: $6/9\pi^2$

measure suggested by Ejiri, Karsch, Redlich (2006)

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

Equation of state of hot QCD matter from lQCD

S. Borsanyi et al. PLB 730 (2014) 99



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

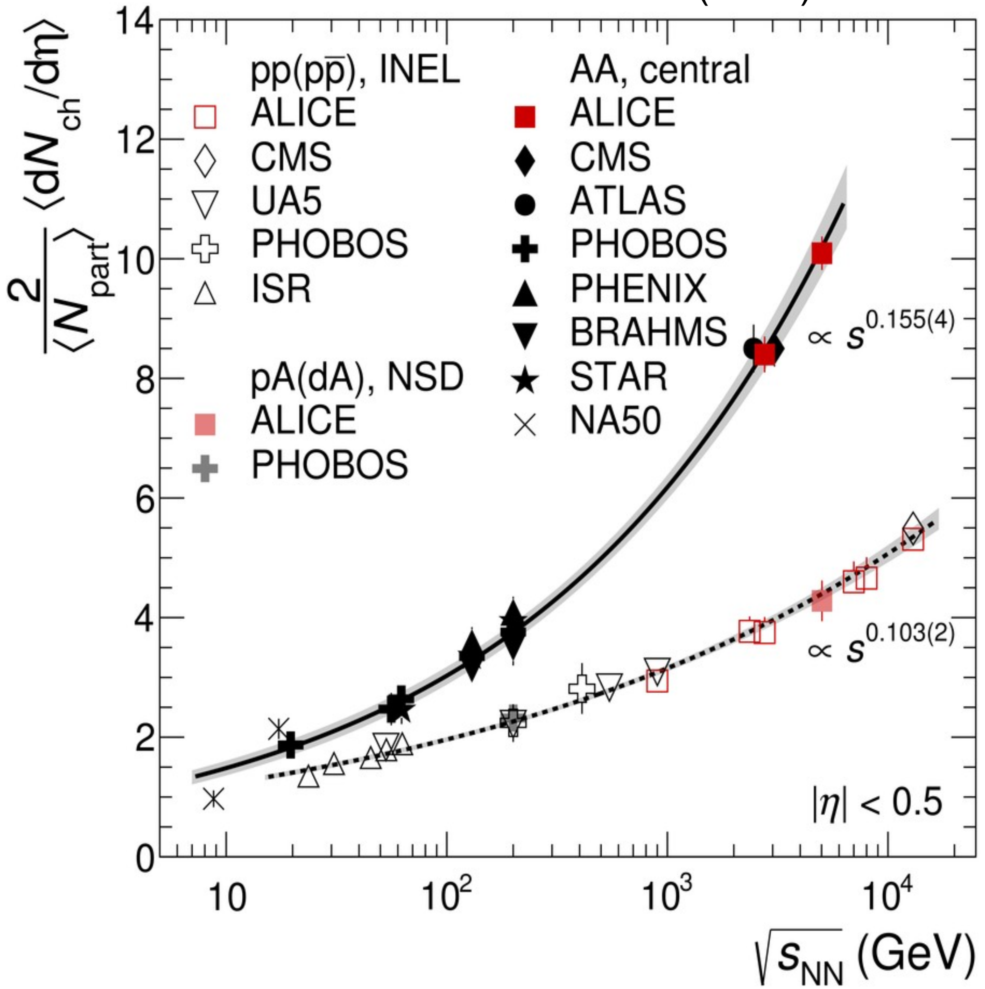
Experimental program

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	3.0 – 200 GeV	4
LHC	since 2010	2.76 – 5.02 TeV	3 (4)

Charged particle production

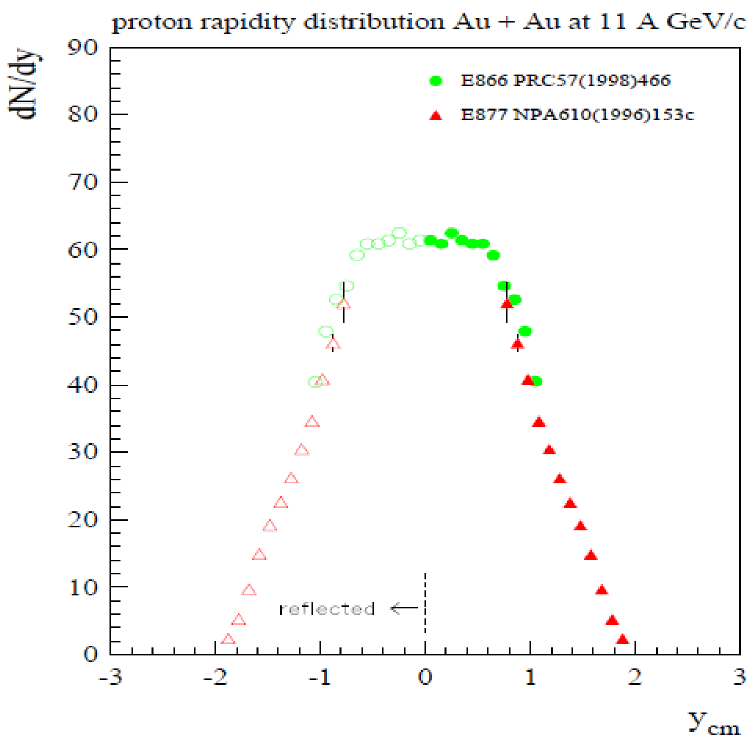
ALICE Coll. PRL116 (2016) 222302



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

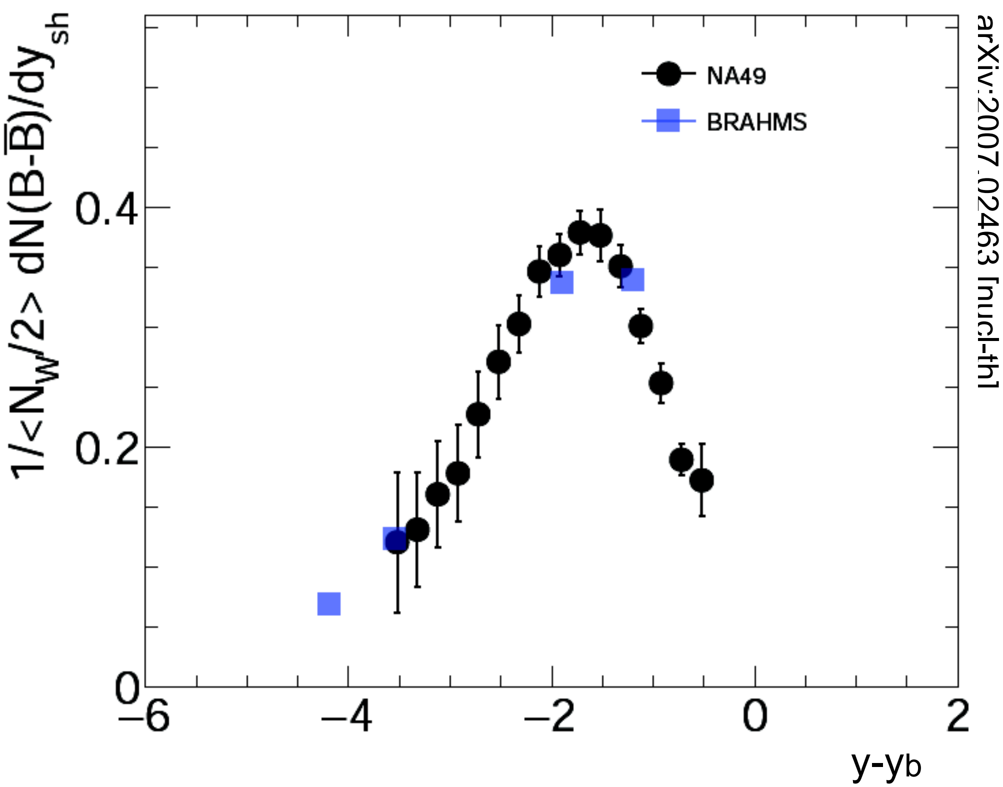
→ larger fractional energy loss in nuclear collision

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

$$\epsilon_0 = \frac{dE_t}{dy}\frac{1}{A_t}\frac{dy}{dz} = \langle m_t \rangle \frac{1.5 dN_{ch}}{dy}\frac{1}{A_t}\frac{dy}{dz}$$

Bjorken formula using Jacobian dy/dz=1/τ_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)

Upgrade to ALICE2

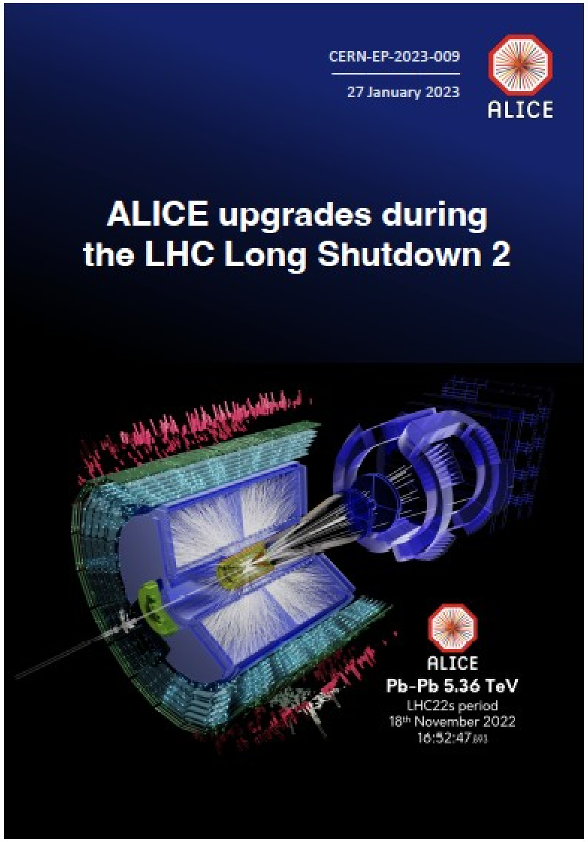
during LHC Long Shutdown 2 from 2019 to 2022
extensive upgrade program to enable PbPb data taking at 50 kHz and pp at MHz rates

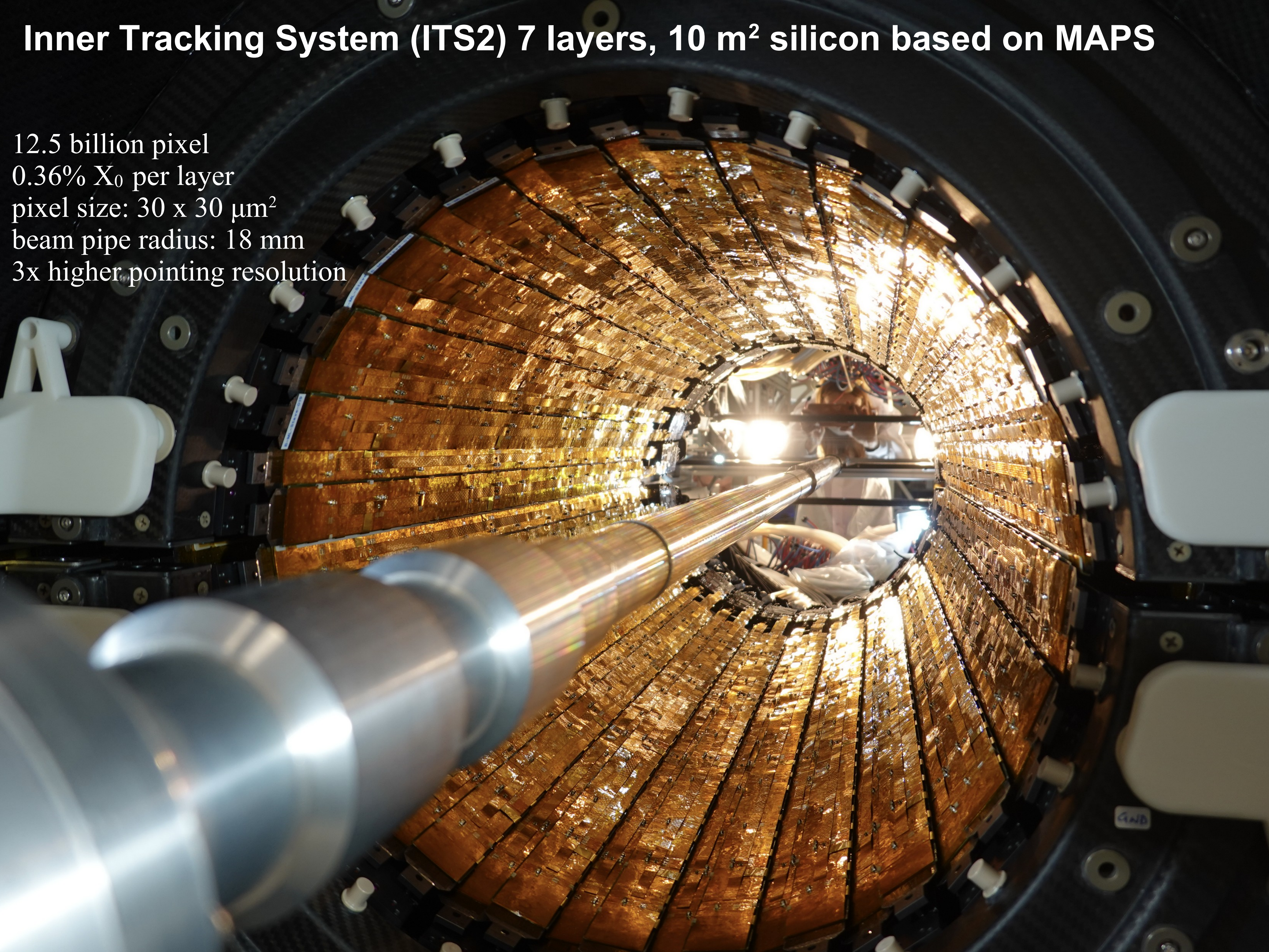
triggerless, continuous read-out

successfully completed in first half of 2022

start of LHC Run 3 in July 2022

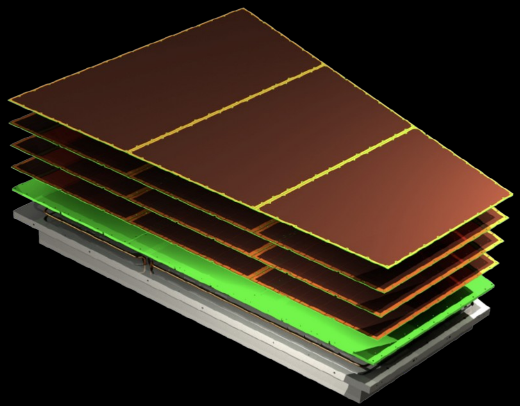
data taking with ALICE2 in Runs 3 and 4 2022 - 2032

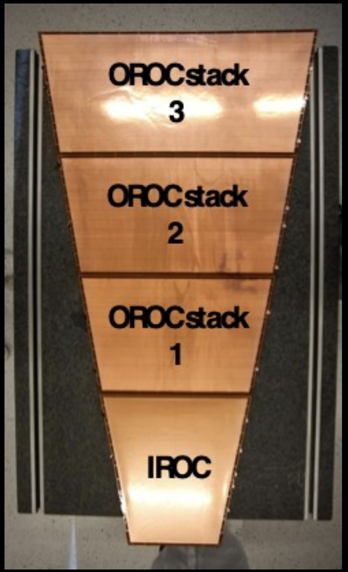


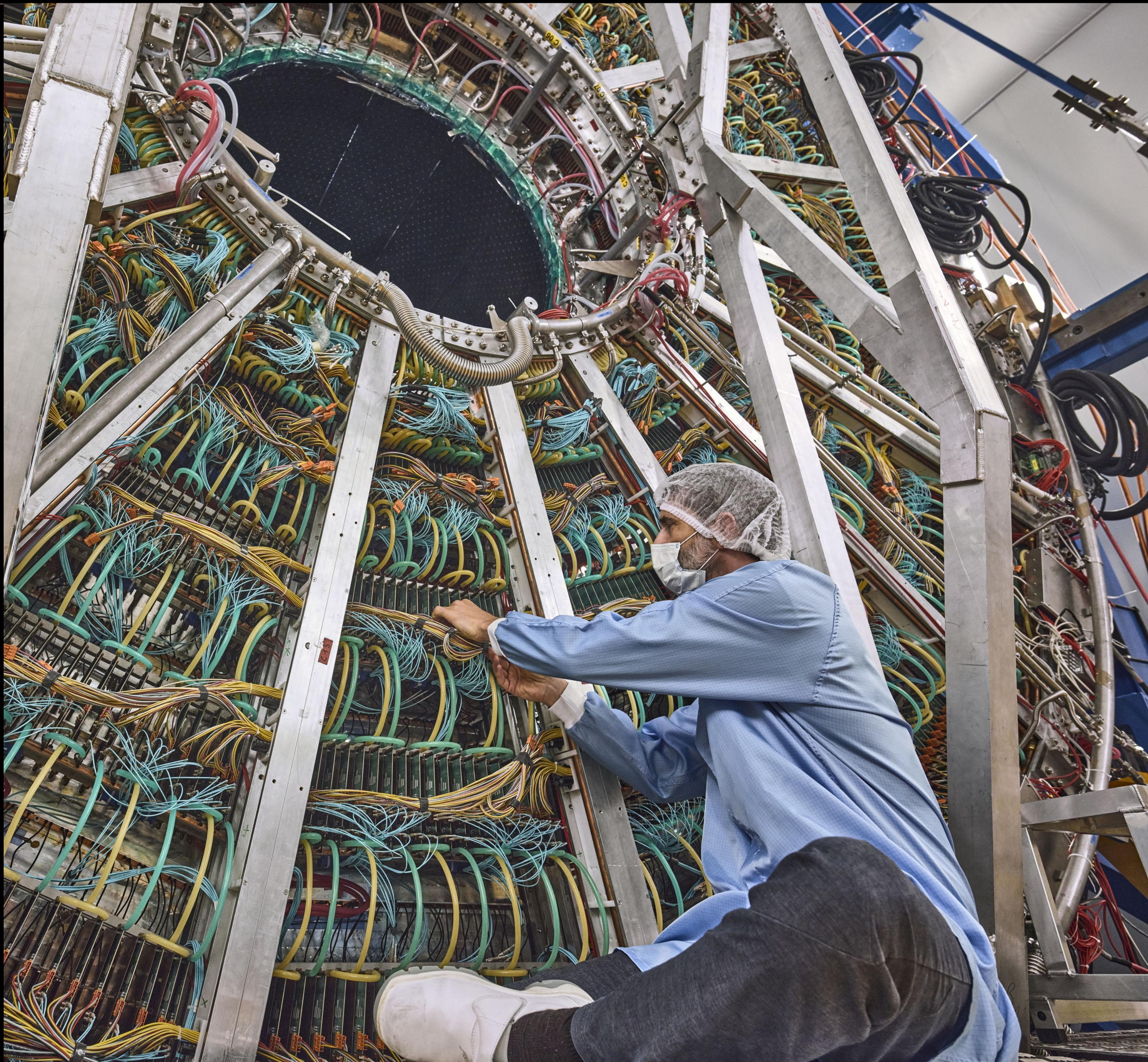

Inner Tracking System (ITS2) 7 layers, 10 m² silicon based on MAPS
12.5 billion pixel
0.36% X_0 per layer
pixel size: 30 x 30 μm²
beam pipe radius: 18 mm
3x higher pointing resolution

Time Projection Chamber – upgrade to GEM read-out chambers

- amplification in quadruple GEM stack
- continuous read-out
- 50 kHz = 100 x faster
- 3.4 TB/s

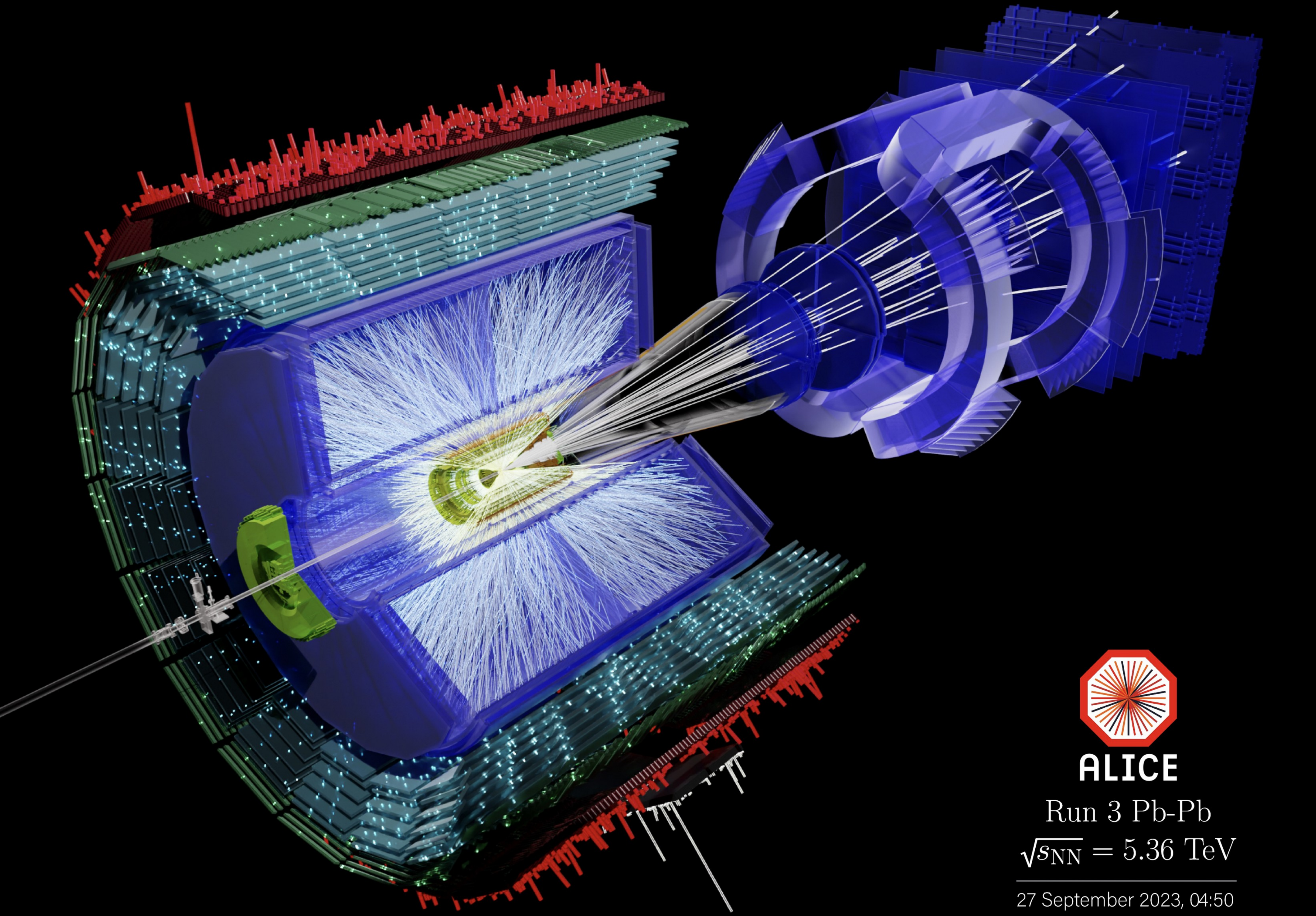






ALICE Computing at Point2: 3.6 TB/s raw data → up to 170 GB/s to disk

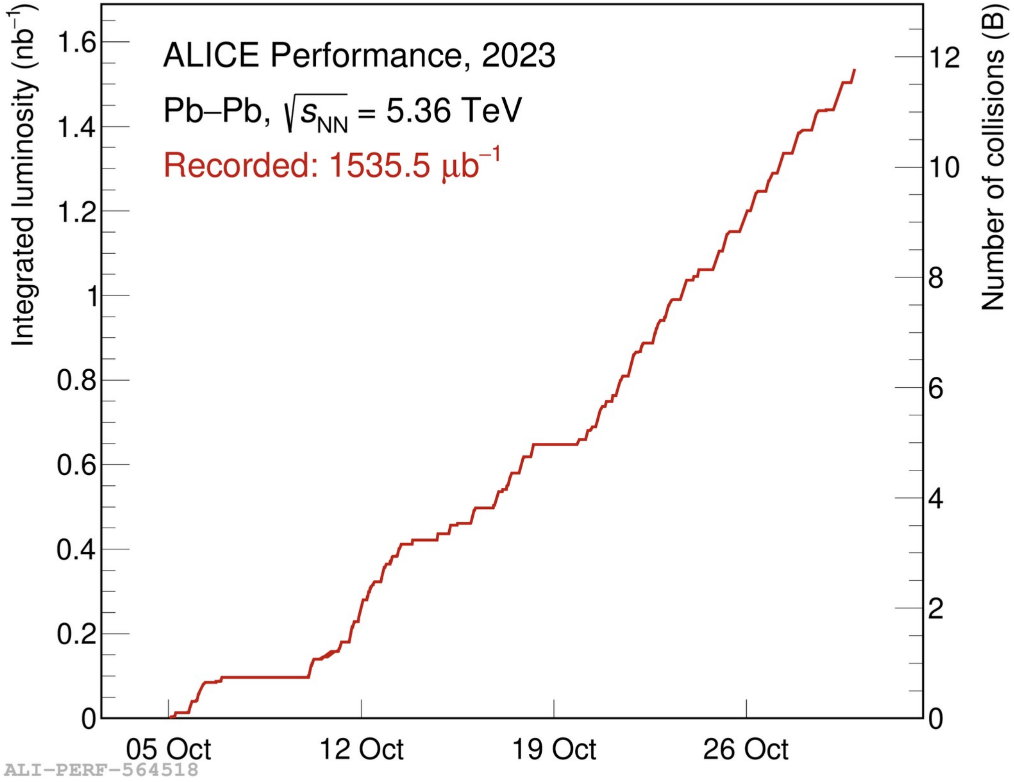
350 Servers
50k CPUs
2800 AMD GPUs
130 PetaBytes disk


ALICE
Run 3 Pb-Pb
$\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV
27 September 2023, 04:50

very successful start into Run3

Runs 1 + 2 (2009 - 2018)
pp : 0.032/pb minimum bias collisions
$2\ 10^9$ events
Pb-Pb : $3.15\ 10^8$ minimum bias collisions
$1.49\ 10^8$ 0-10% central collisions

2022 pp: 19.3/pb or
10^{12} minimum bias collisions
2023 pp: 9.7/pb or
$5\ 10^{11}$ minimum bias collisions
2023 Pb-Pb: 1.5 /nb or
$1.2\ 10^{10}$ minimum bias collisions
40x minimum bias and
7x central wrt Runs 1 + 2

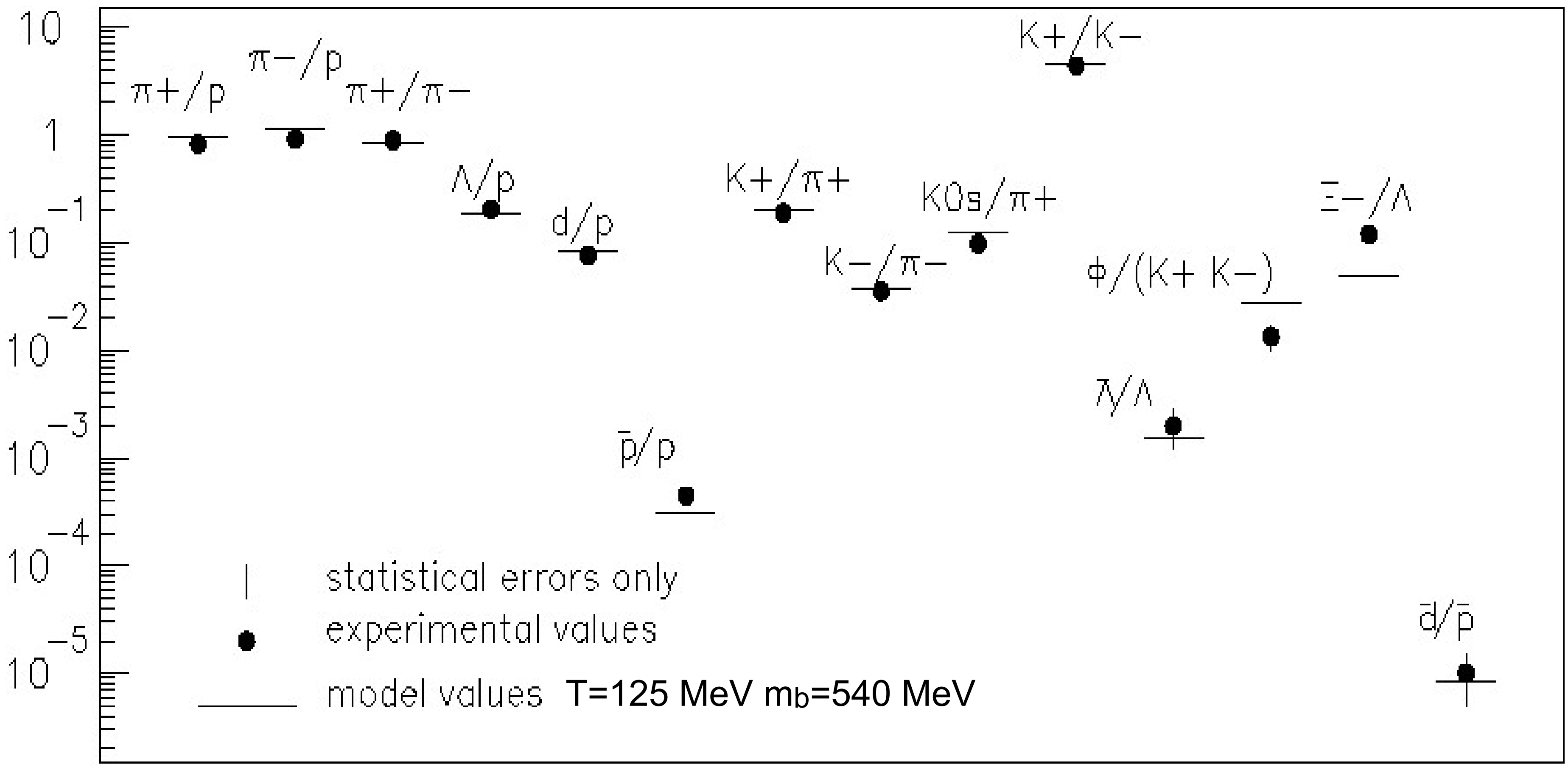


Hadronization of the fireball

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

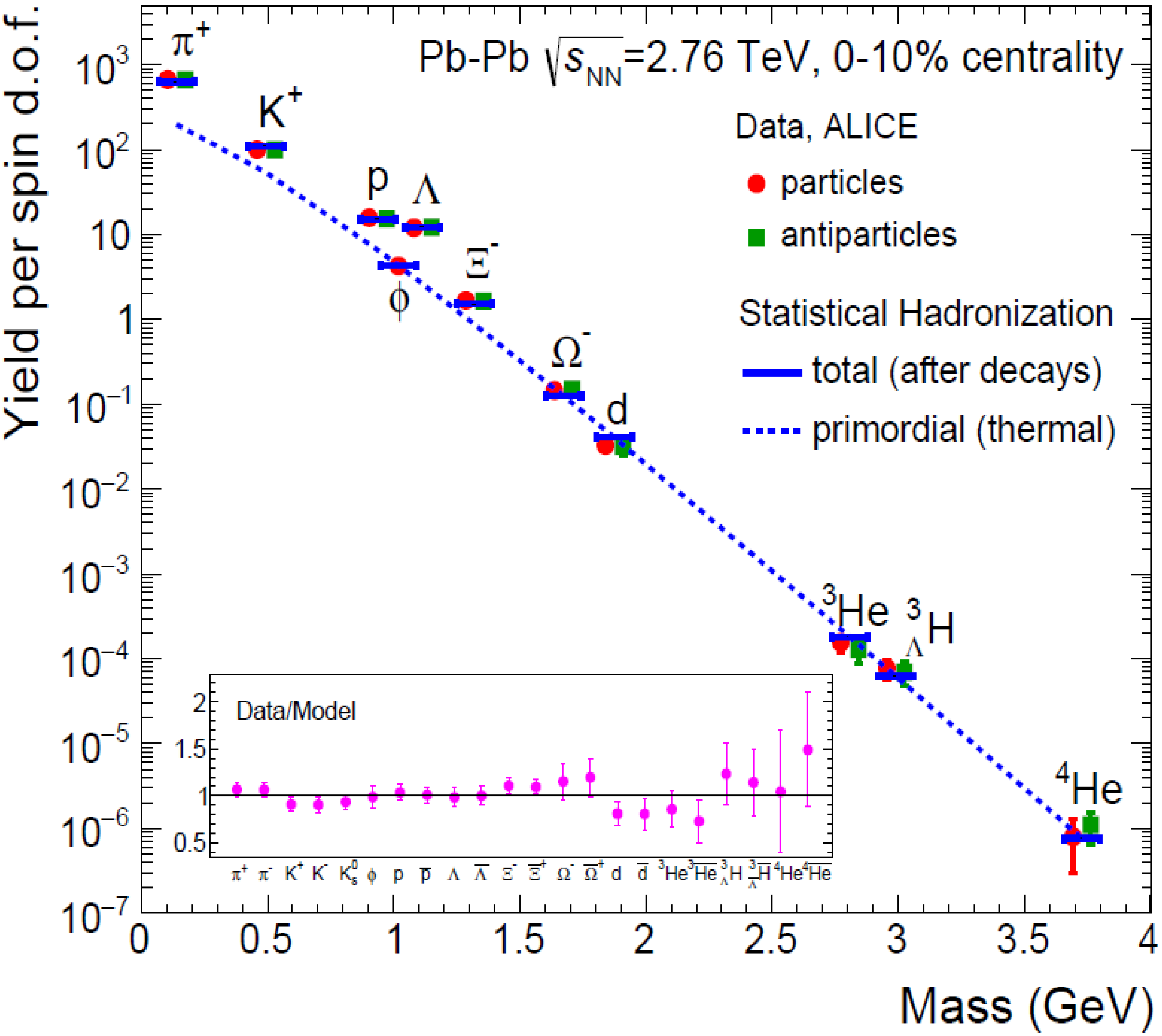
1 free parameter: temperature T

T = 156.5 ± 1.5 MeV

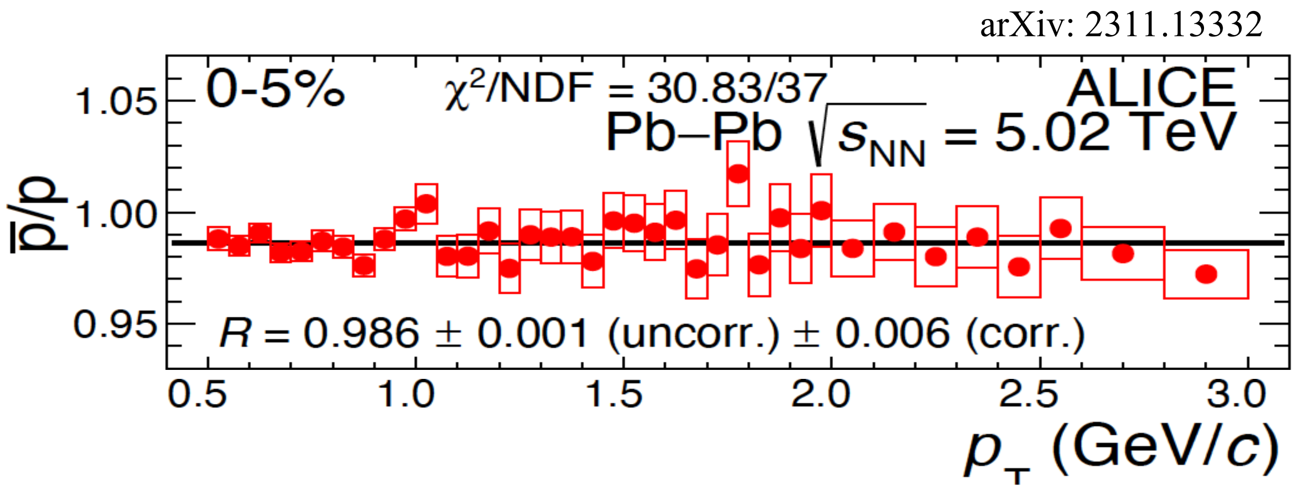
agreement over 9 orders of magnitude with QCD statistical operator prediction
(- strong decays need to be added)

- 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

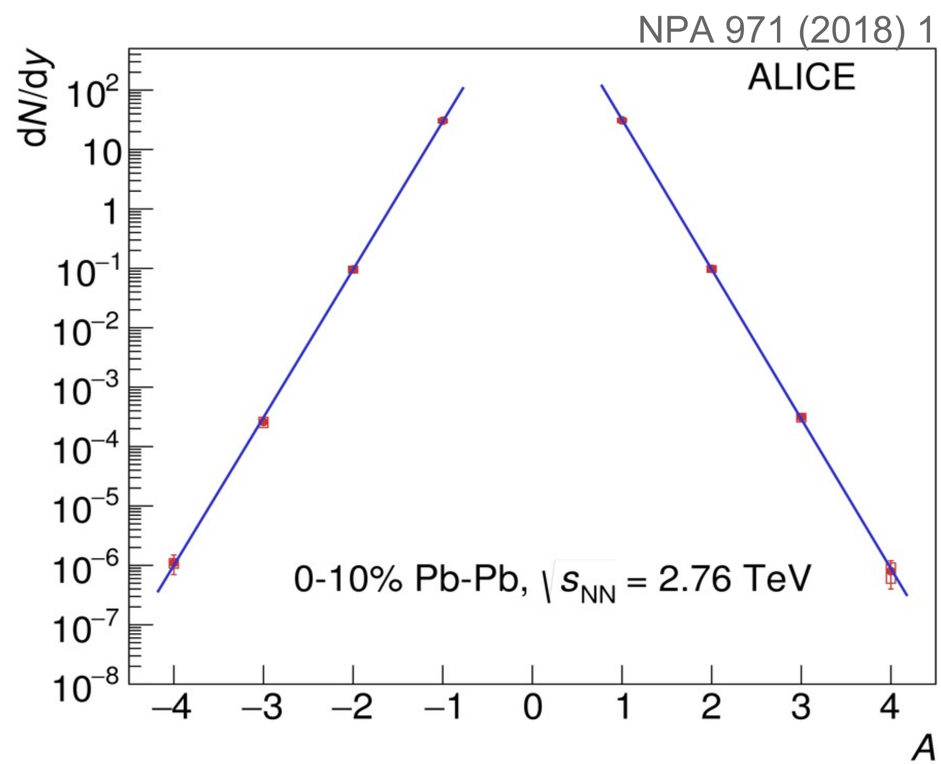


- matter and anti-matter produced in equal proportions at LHC
- consistent with net-baryon-free central region
  μ_b = 0.90 ± 0.43 MeV

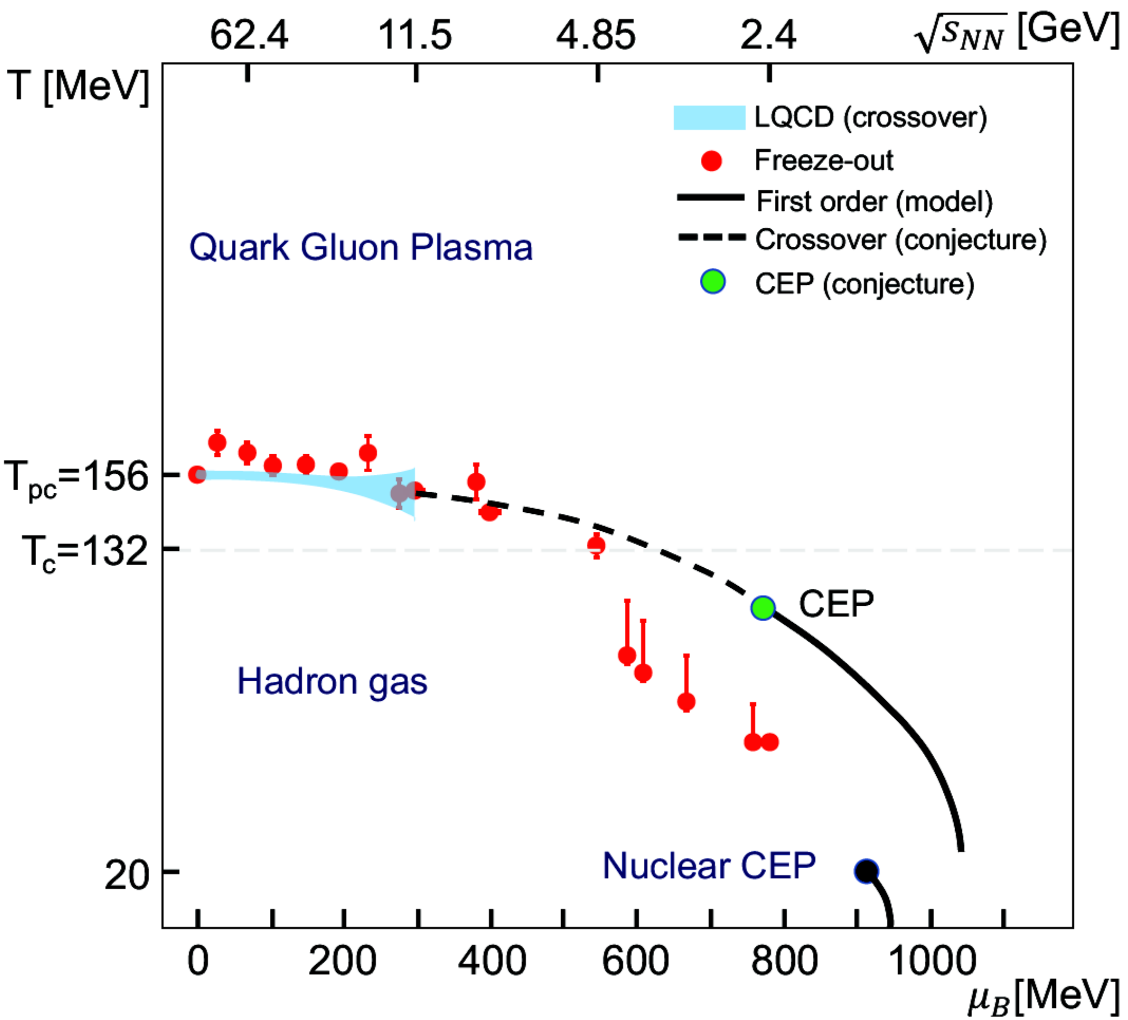
similar to early universe

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 MeV 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

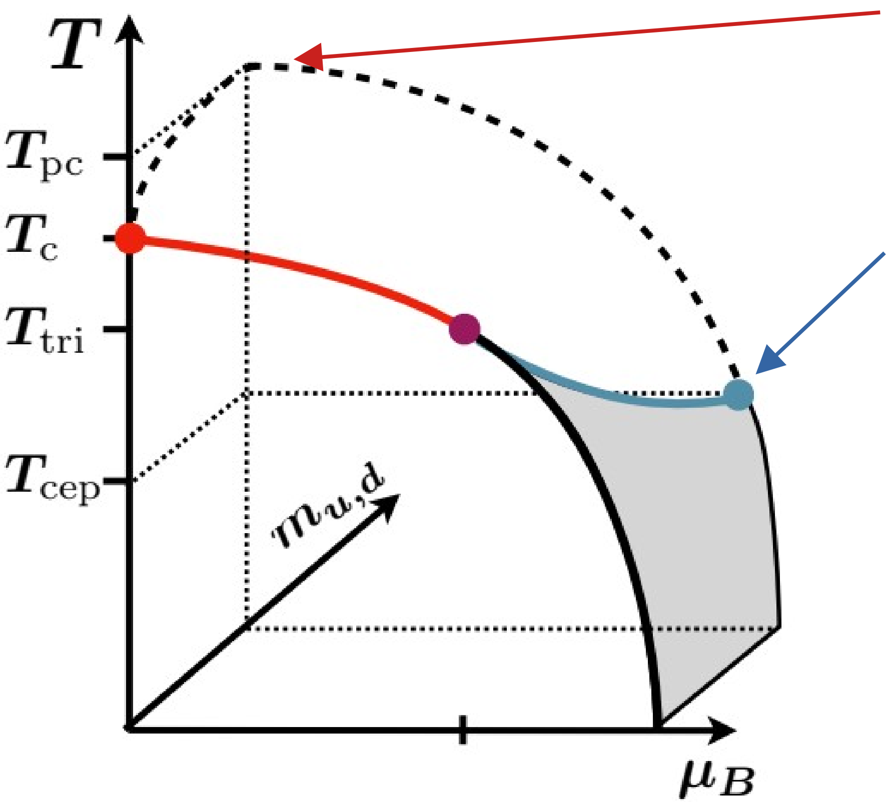
A. Bazavov et al. PLB 795 (2019) 15
S. Borsanyi et al. PRL 125 (2020) 052001

- 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)

What about higher moments?

if the first moments frozen in at the phase boundary, maybe also
higher moments determined by the characteristics of the chiral phase transition



due to smallness of u,d quark masses:

the pseudo-critical point can still carry traces of the O(4) characteristics of the 2nd order chiral phase transition at T_c at $m_{u,d} = 0$

the critical endpoint, if it exists, could still show the characteristics of the tri-critical point at T_{tri} and $m_{u,d} = 0$

Fluctuations of conserved charges

yields of hadrons in local equilibrium at cross over transition at
T=156.5 MeV and $\mu_B = 0$
described by QCD statistical operator

it makes sense to study fluctuations of these quantities and to compare to fluctuation measure in lQCD (the quark number susceptibilities)

$$\chi_n^{\mathrm{B}} = \frac{\partial^n (P/T^4)}{\partial \hat{\mu}_B^n} = \frac{\kappa_n}{VT^3} \Longleftrightarrow$$

κ_n cumulants of net baryon distribution

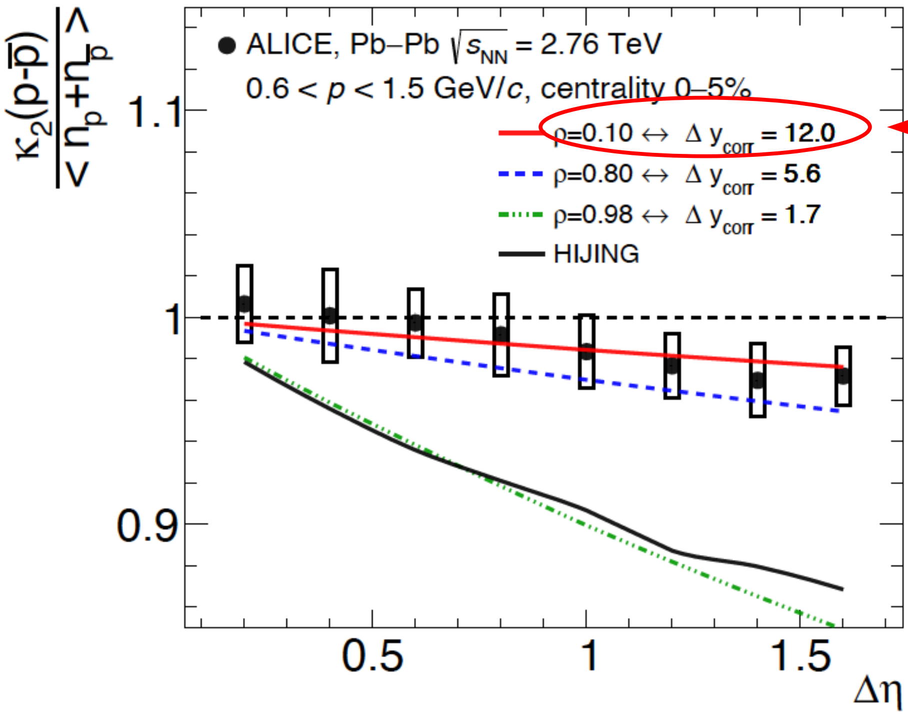
- insight into the nature of the chiral phase transition
- charge conservation and correlation length

2^{nd} order cumulants and baryon correlation length

in statistical mechanics, fluctuations of conserved charges predicted within Grand Canonical Ensemble (HRG)
in particular $\kappa_2(B - \bar{B}) = \langle n_B + n_{\bar{B}} \rangle$

syst. deviation from equality seen in ALICE data can be linked to baryon number conservation → can be computed within Canonical Ensemble

P. Braun-Munzinger, K. Redlich, A. Rustamov, J. Stachel arXiv: 2312.15534



sample p and pbar rapidity distributions and introduce correlations, using Metropolis method

obtain corr. coeff. $\rho = \frac{Cov(y_p, y_{\bar{p}})}{\sigma_p \sigma_{\bar{p}}} = 0.1$

corresponding to Δy_{corr} = 12.0

correlation length at LHC close to entire rapidity gap, i.e. global conservation calls into question baryon formation by string fragmentation with Δy_{corr} = 1.7

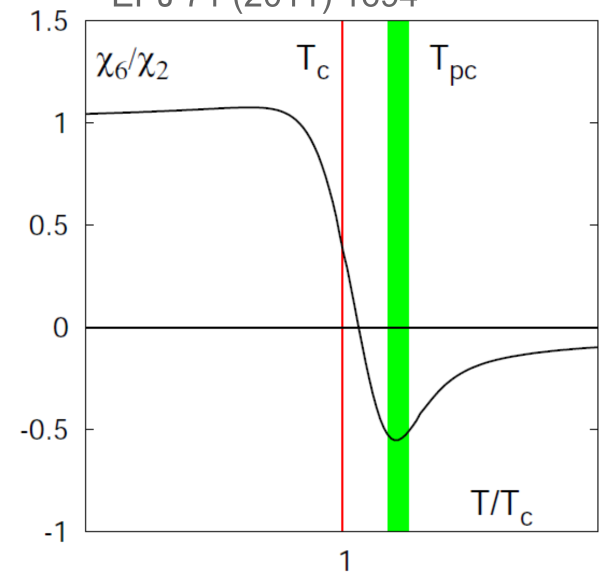
Opportunity to probe nature of chiral phase transition

based on O(4) scaling functions: χ_6^B near T_{pc} negative due to singular term in pressure

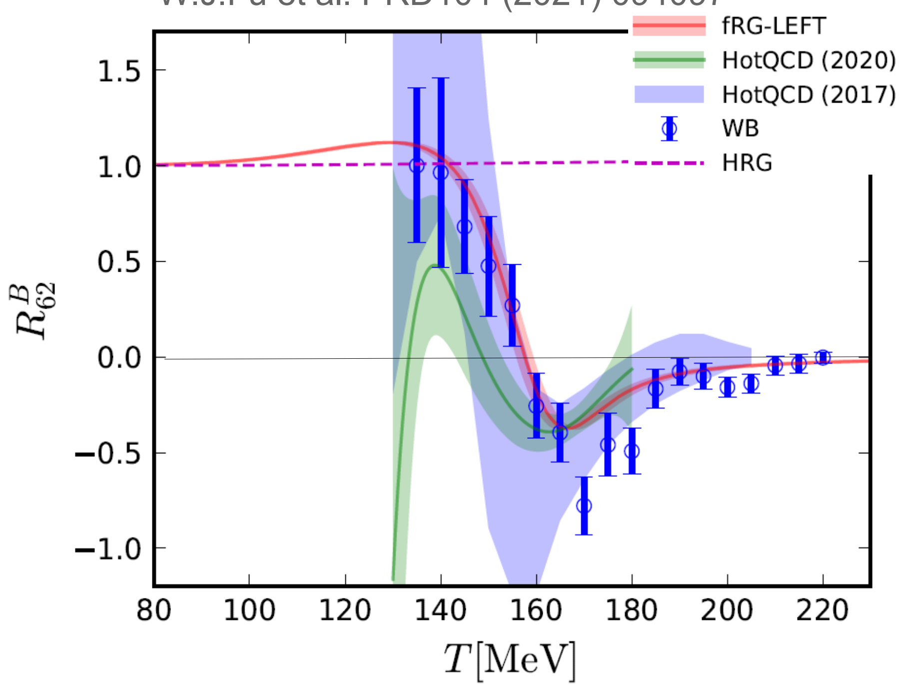
lQCD: remnant of O(4) criticality at physical light quark masses

Bazavov et al., PRD101 (2020)074502
Borsanyi et al., JHEP10 (2018) 205

Friman, Karsch, Redlich, Skokov
EPJ 71 (2011) 1694



W.J.Fu et al. PRD104 (2021) 094097



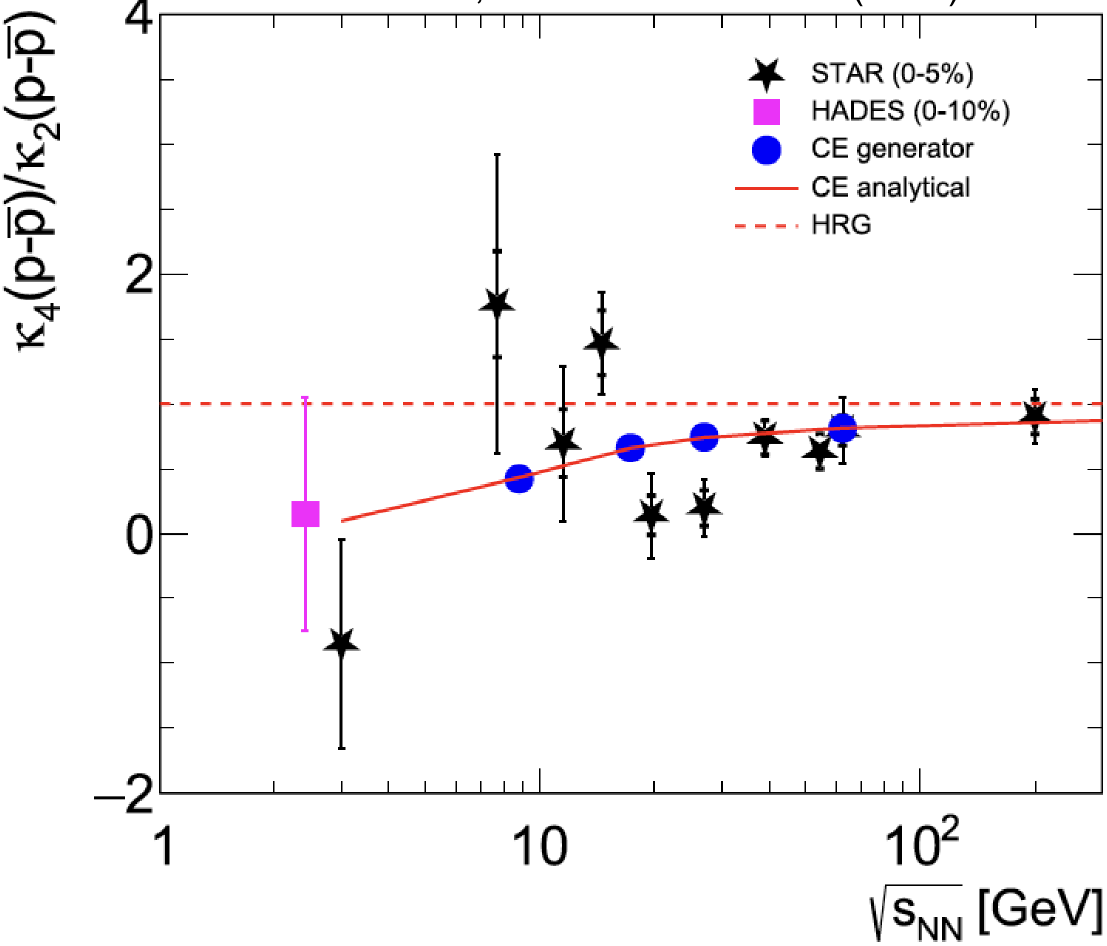
ALICE Run 2:
κ_4(p-$\bar{p}$) and $\kappa_4(\Lambda$-$\bar{\Lambda})$
already significant reduction (30%) in full QCD due to nonperturbative dynamics
Run 3,4: κ_6(p-$\bar{p}$)

ALICE 3: extension into charm sector
κ_2(D-$\bar{D}$) charm-anticharm correlation length

Sensitivity to critical endpoint

expect charge number susceptibilities to diverge at all orders near CEP
but for smaller systems at lower cm energies conservation laws increasingly important

P. Braun-Munzinger, B. Friman, K. Redlich,
A. Rustamov, J. Stachel NPA 1008 (2021) 122141

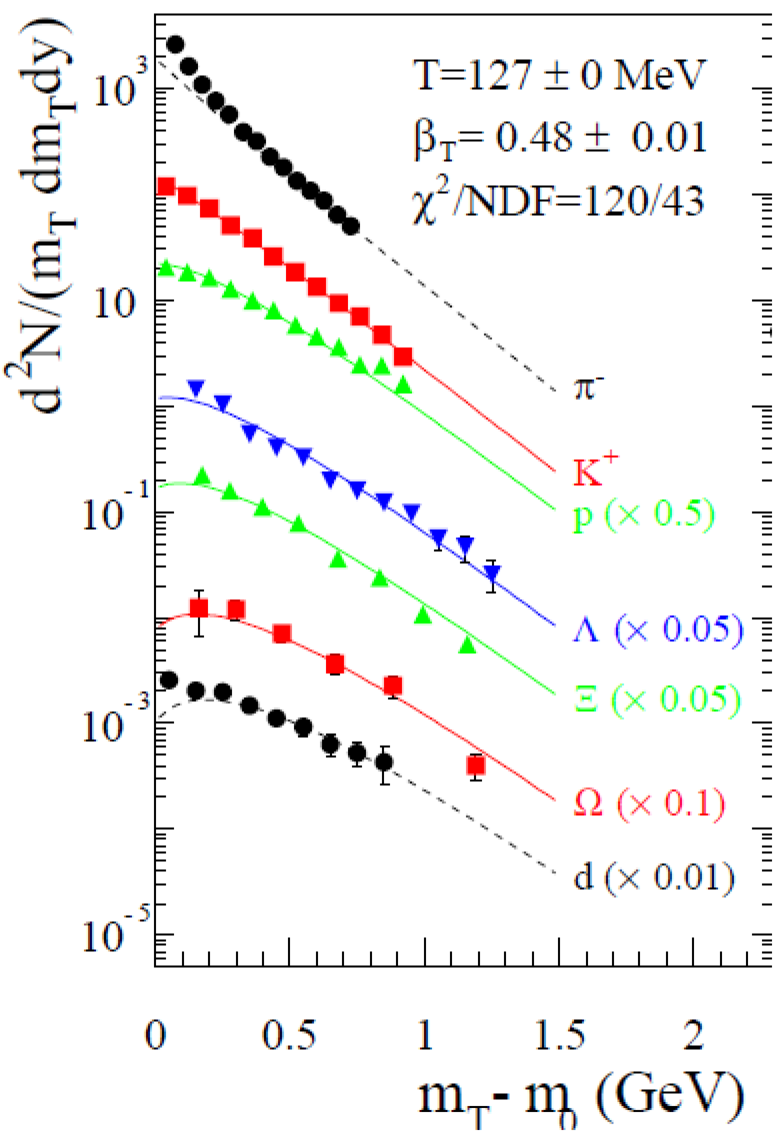


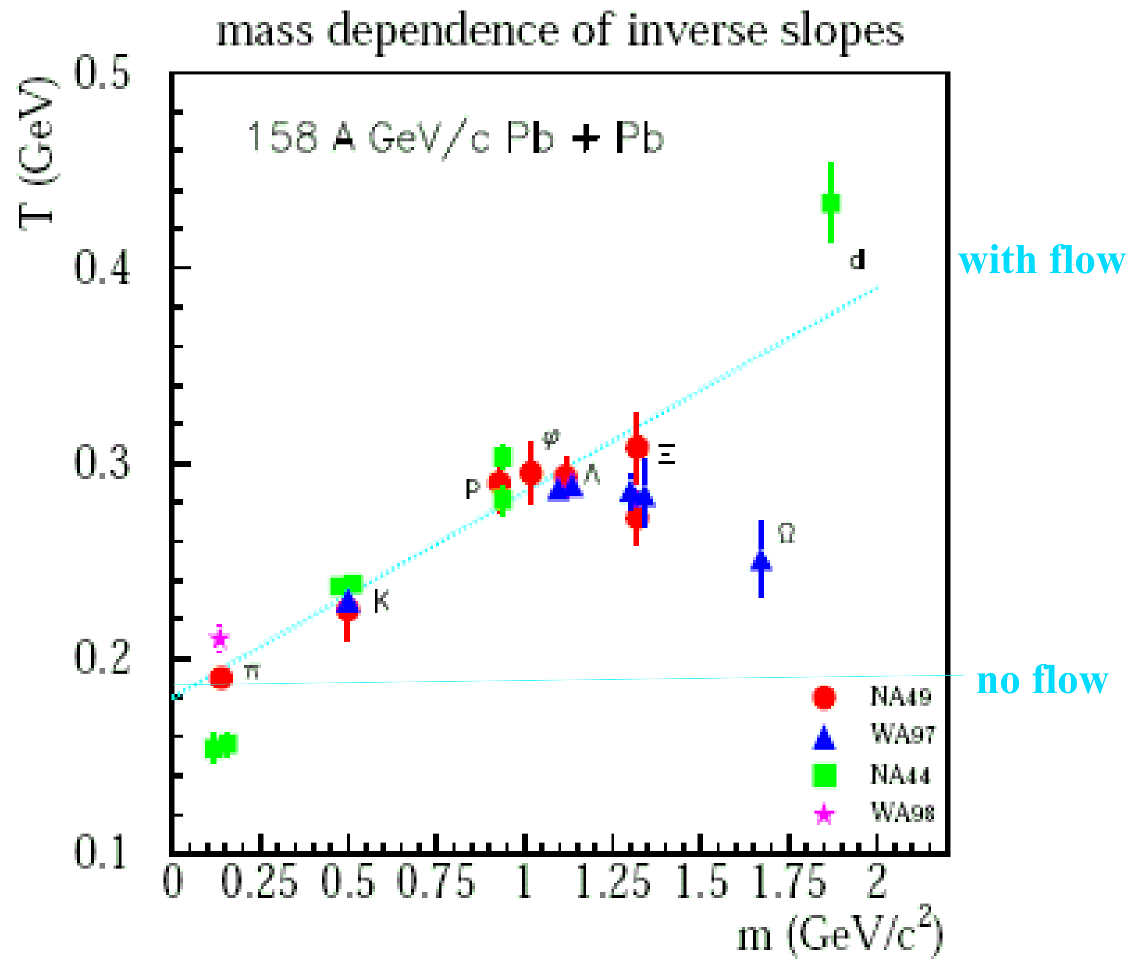
so far up to 4th order no significant deviations from suppression due to baryon number conservation

Hadron spectra and azimuthal correlations

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

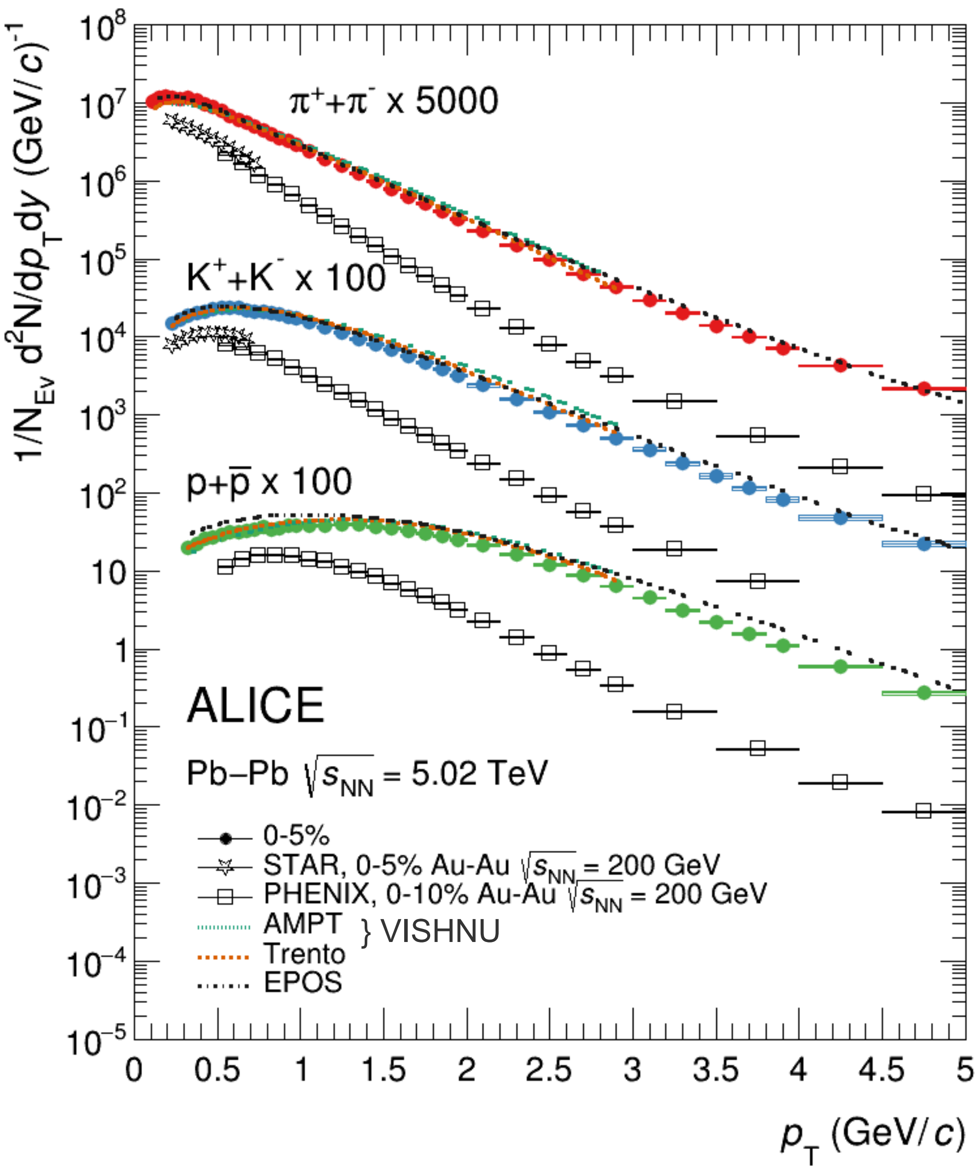
Spectra of identified hadrons at SPS





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

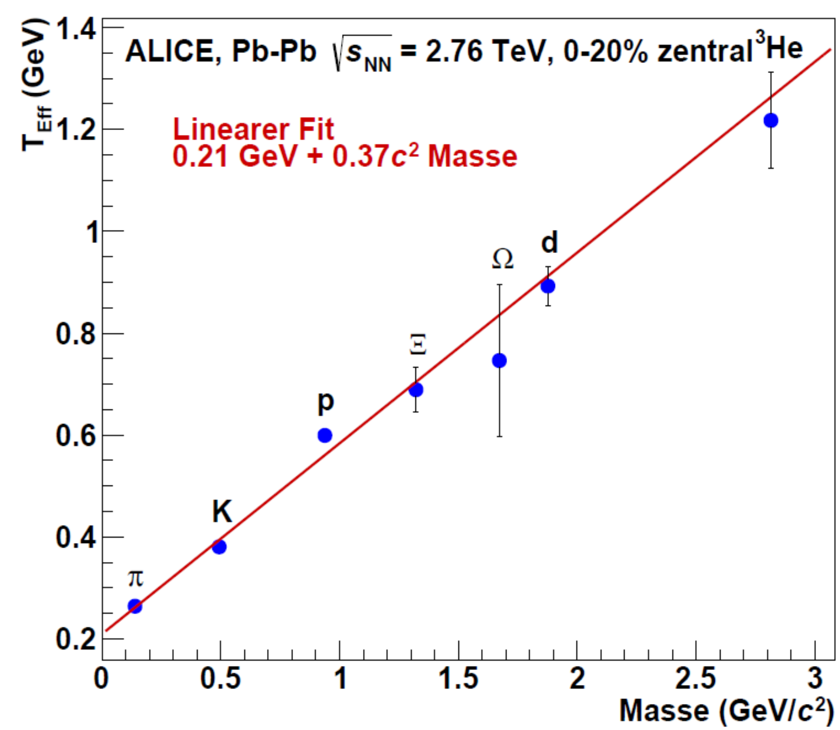
Spectra of identified hadrons at RHIC and LHC



spectral shapes exhibit even stronger mass dependence
- characteristic for hydrodynamic exp.

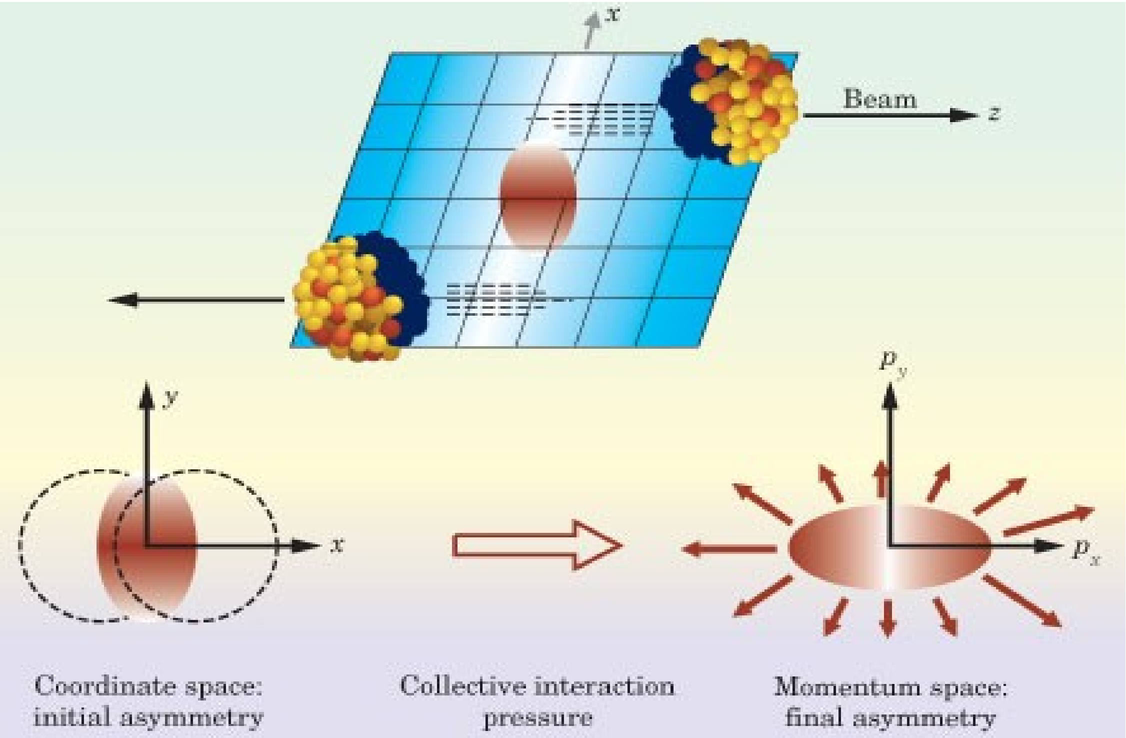
indicate at LHC significantly larger expansion velocity than at RHIC

captured well by hydrodynamic modelling - velocity at surface: ¾ c



courtesy B. Doenigus

Azimuthal anisotropy of transverse spectra



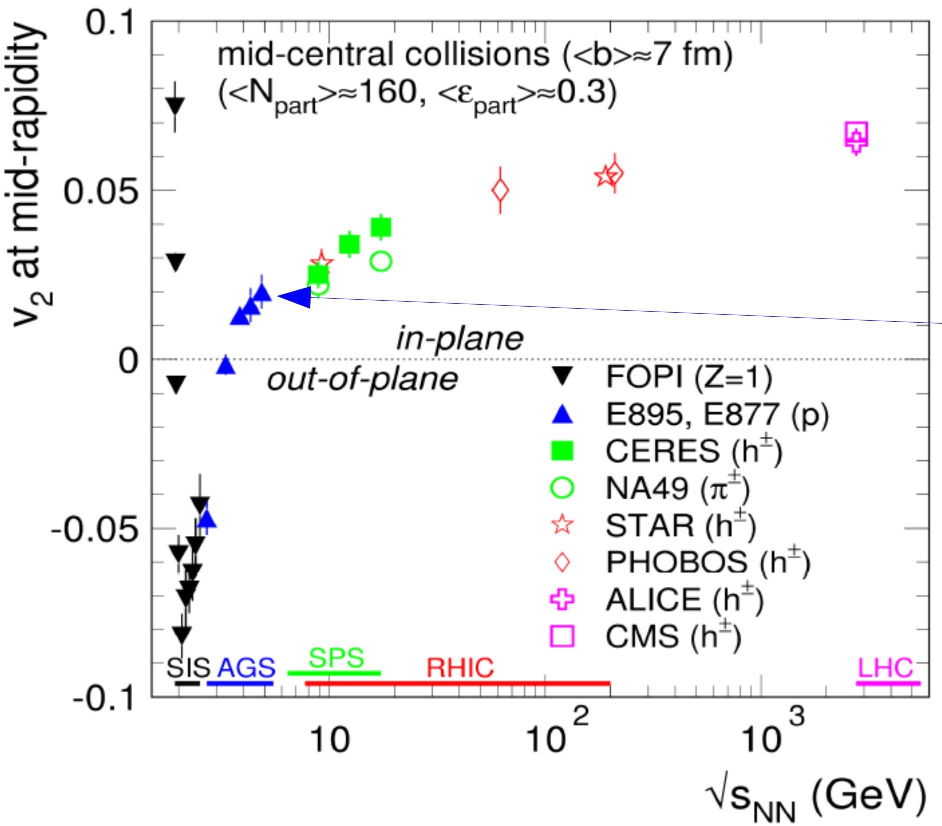
Fourier decomposition of momentum distributions rel. to reaction plane:

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

quadrupole component v_2
“elliptic flow”

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

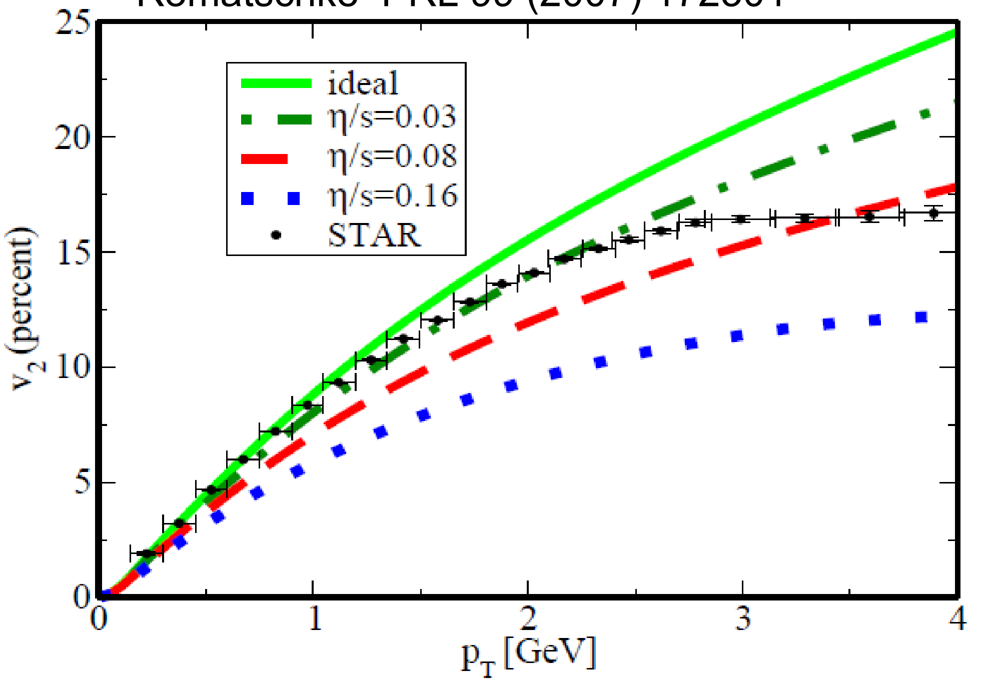
Elliptic flow as function of collision energy



- effect of expansion (positive v2) seen from top AGS energy upwards
- at lower energy: shadowing by fragments

first discovered as tiny 2% effect by E877 in 1993

Romatschke PRL 99 (2007) 172301

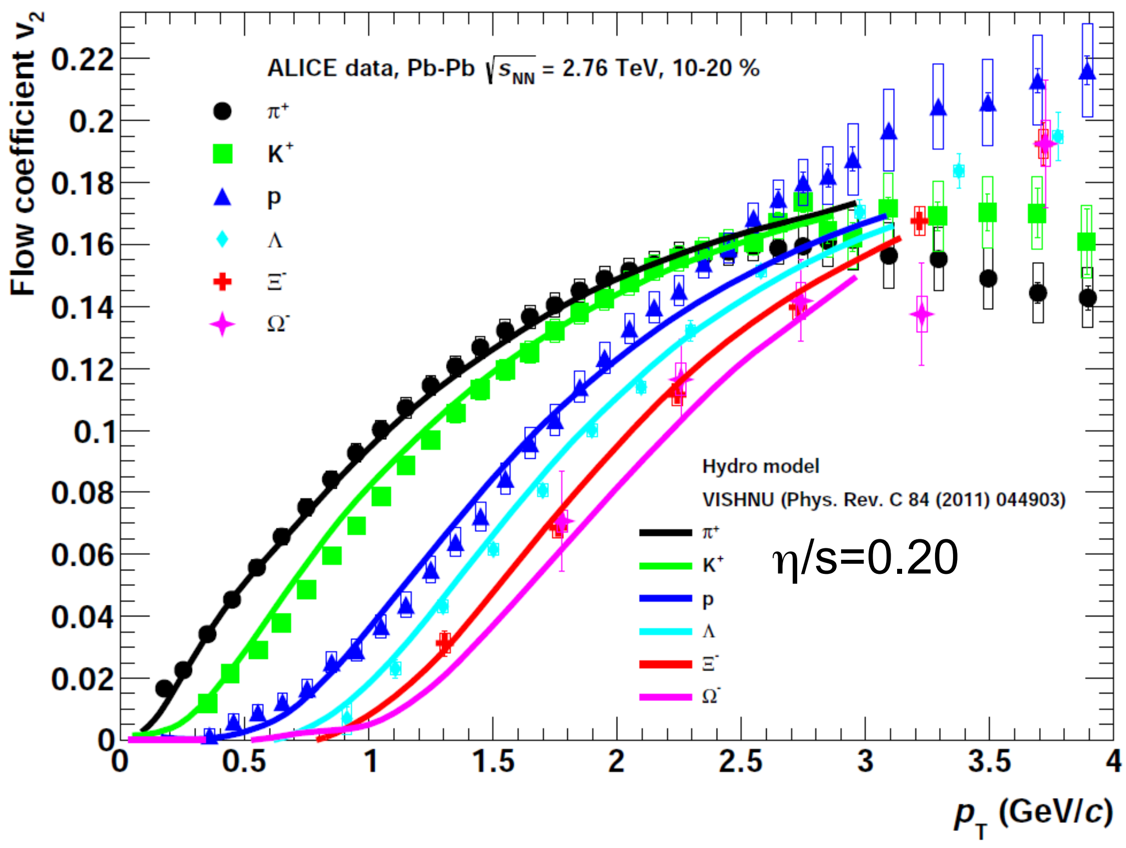


RHIC: paradigm of QGP as perfect liquid reflecting the strong coupling regime

$$\eta/(\epsilon + \mathrm{P}) = \eta/(\mathrm{Ts})$$

- very small ratio of shear viscosity to entropy density η/s describes data
- values of v2 driven by initial conditions and properties of the liquid

Elliptic flow for identified particles at LHC



mass ordering as function of p_t characteristic for hydrodynamic expansion
- reproduced quantitatively by viscous hydrodynamic modeling

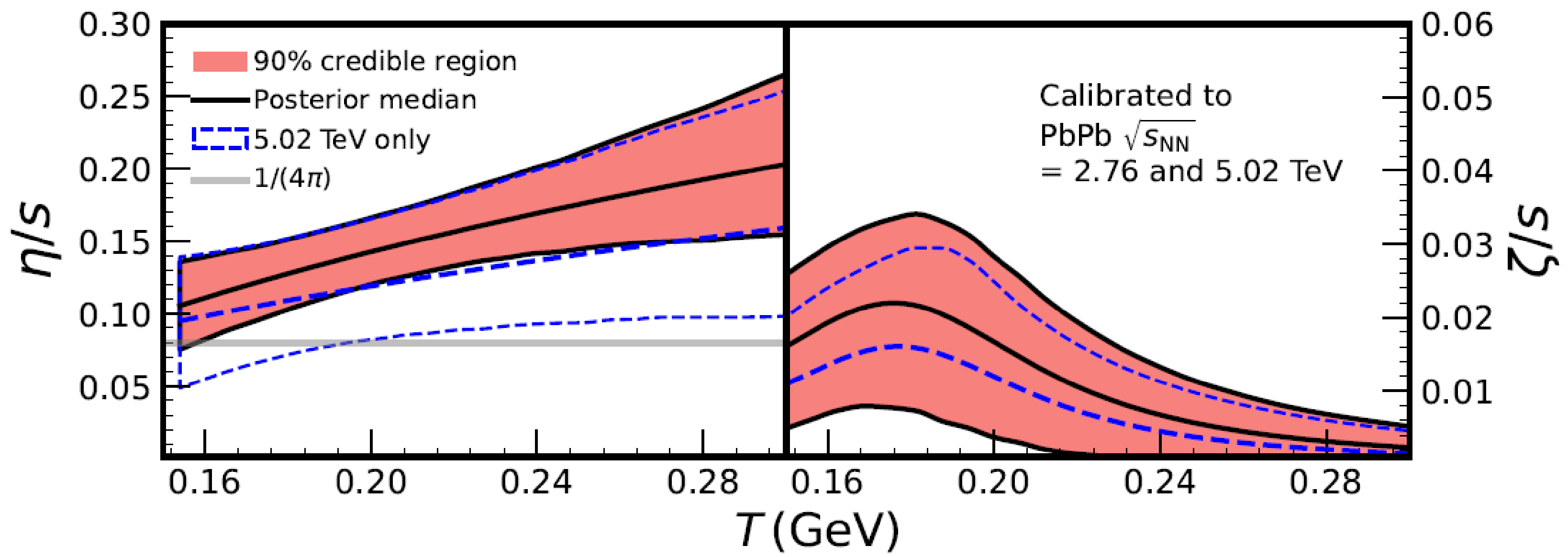
Constraining initial condition and QGP medium properties

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

see e.g. 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

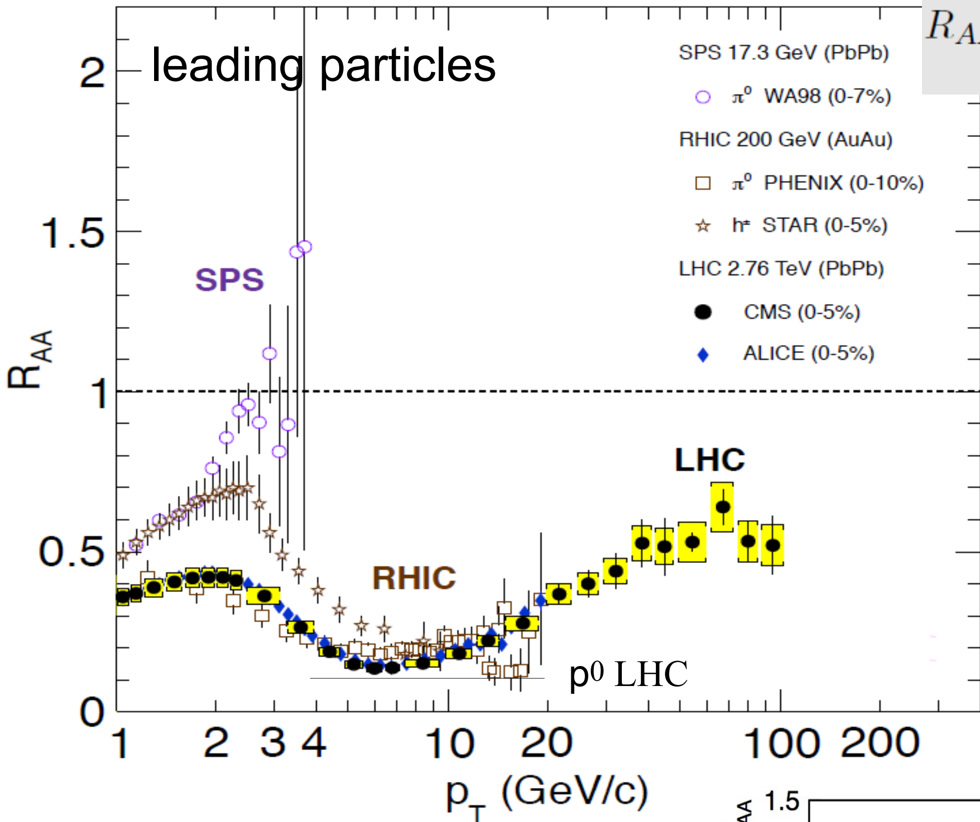
J. Parkkila et al., arXiv: 2111.08145



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

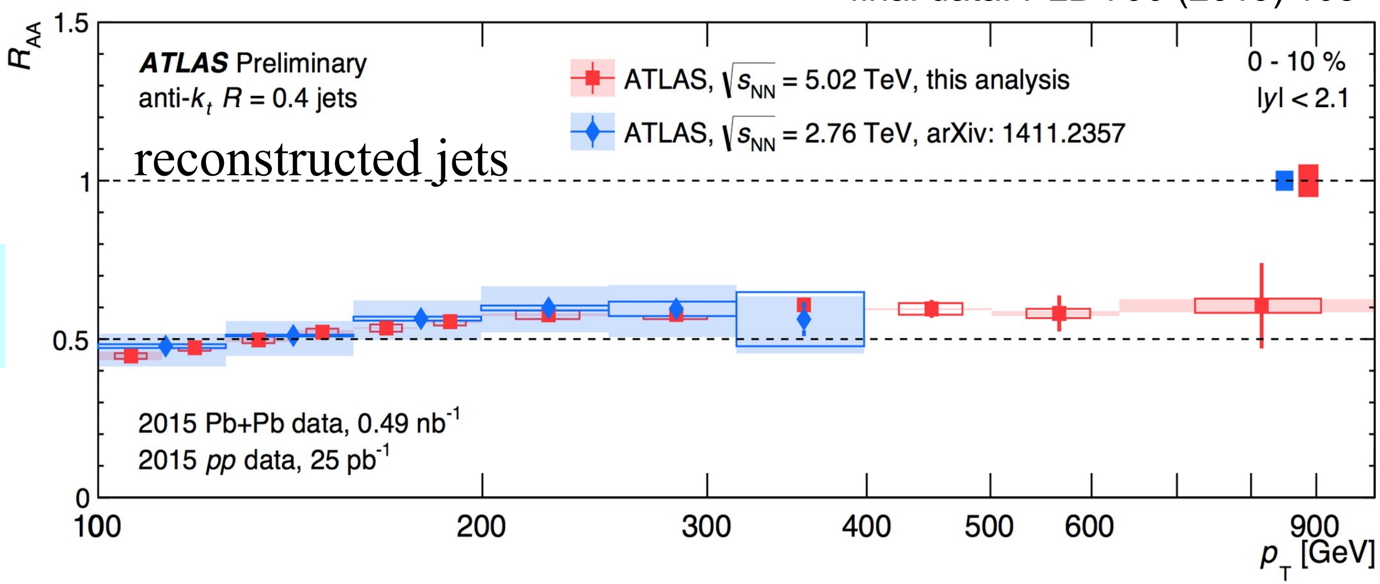
Jet quenching – parton energy loss in QGP

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



- 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

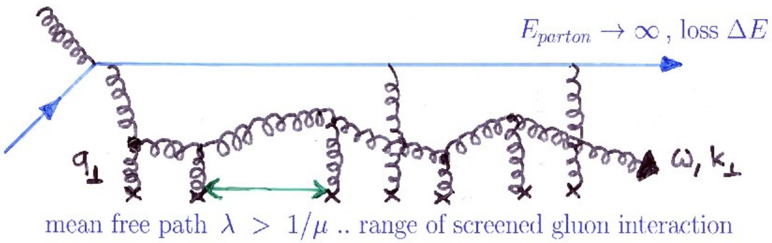
Extracting the jet quenching parameter

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

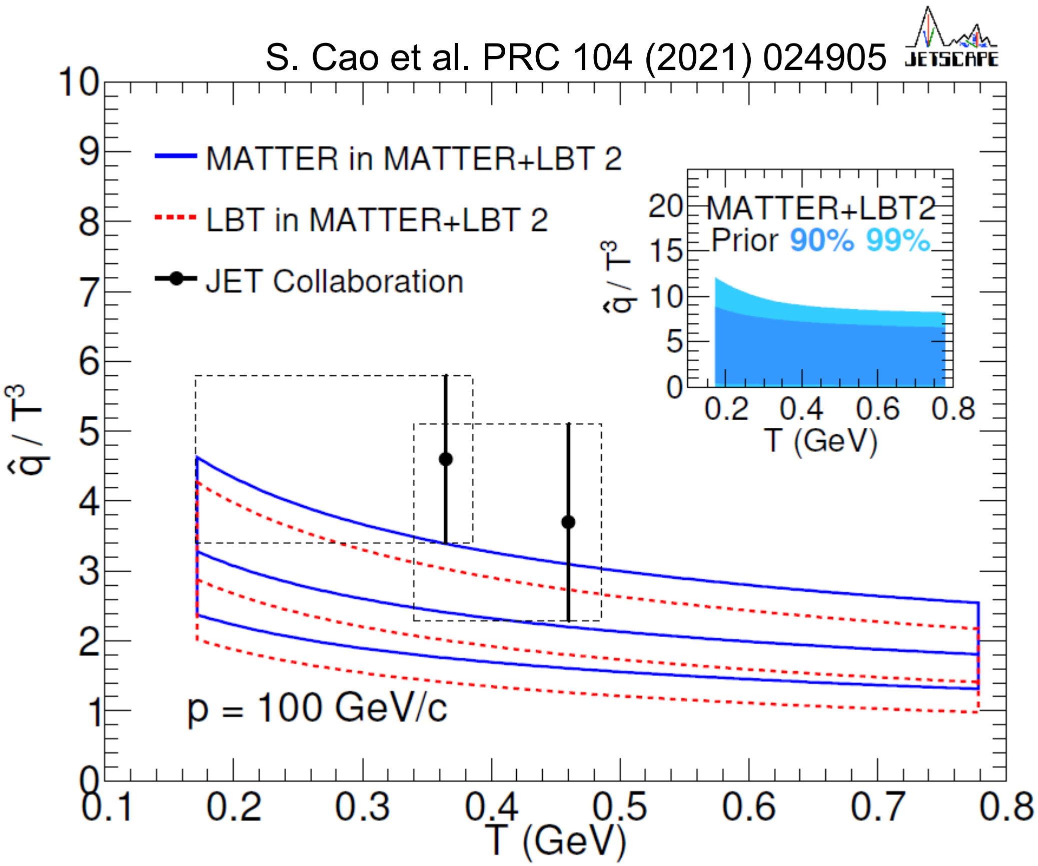
$$dE/dx \propto \rho\, \sigma \langle k_t^2 \rangle\, L$$

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

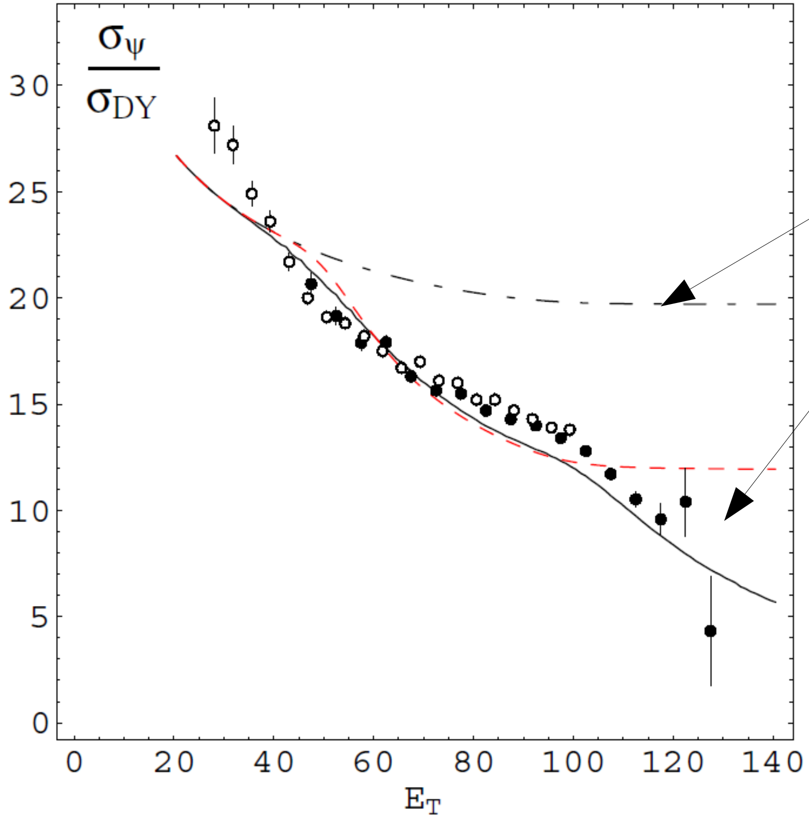
T. Matsui and H. Satz PLB 178 (1986) 416

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 all 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

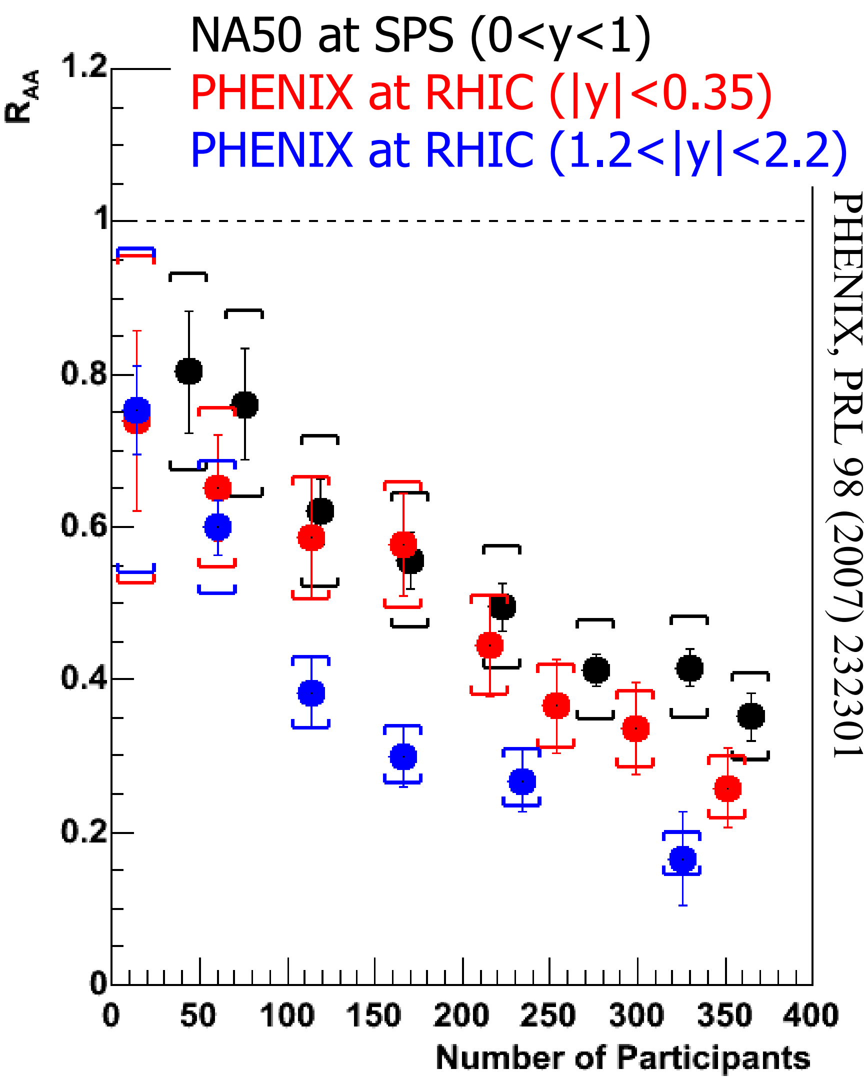
technically:

- 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"?

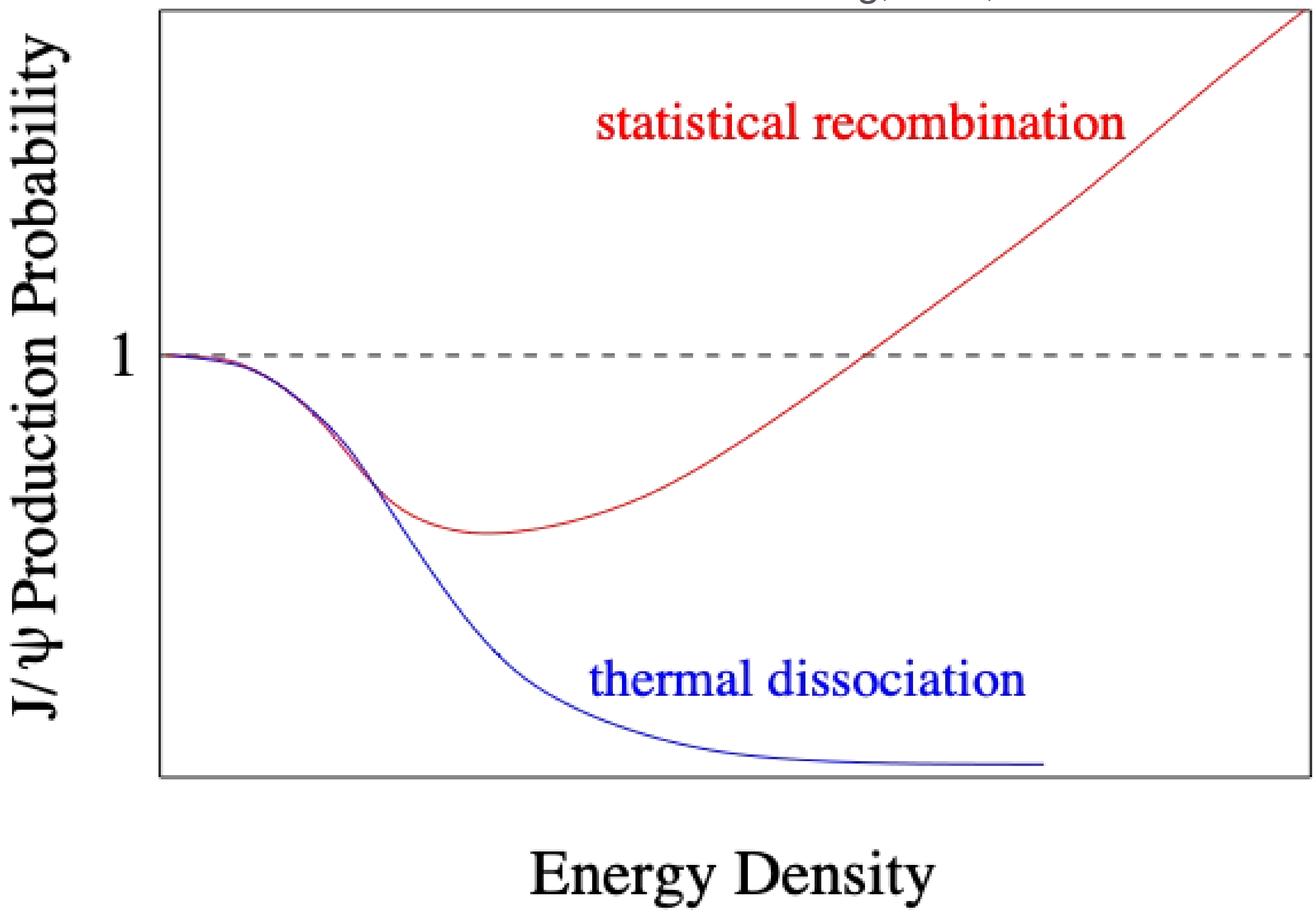
data could be indeed described by statistical hadronization using pQCD charm cross section

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

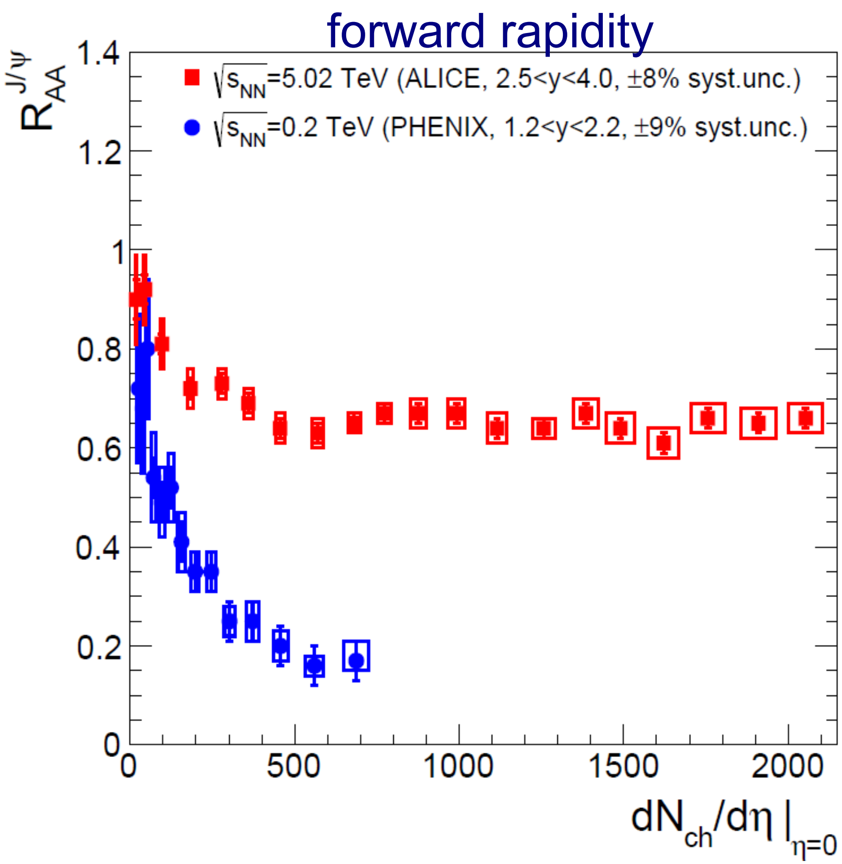
Expectations for LHC

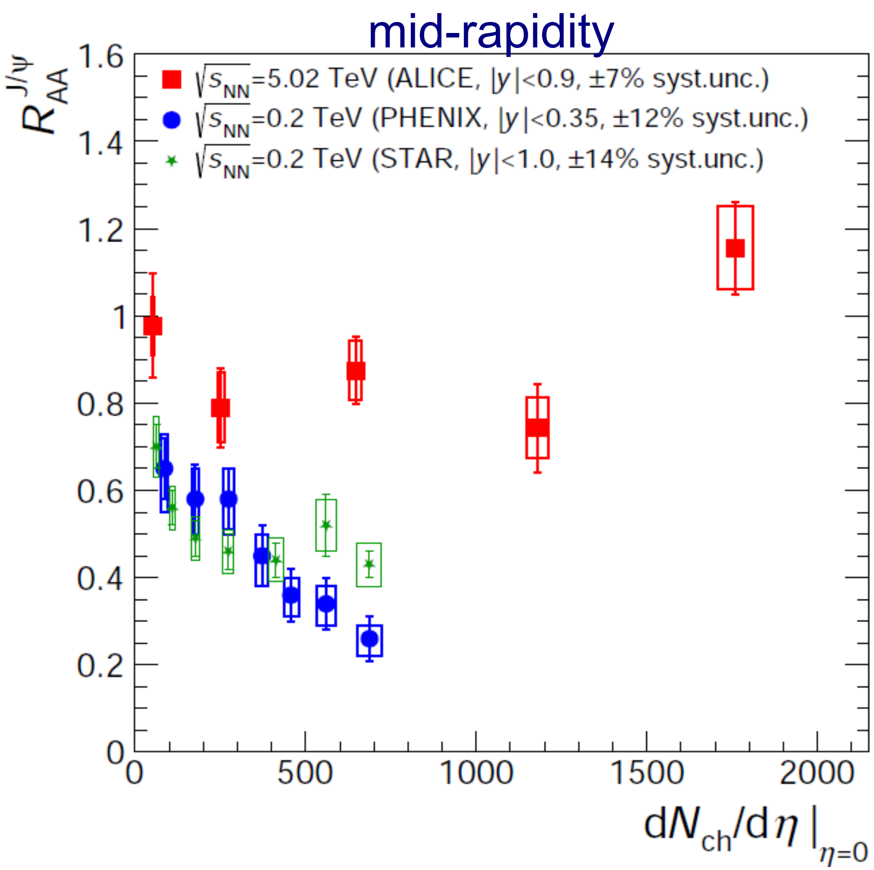
2 possibilities:

Kluberg, Satz, arXiv:0901.3831



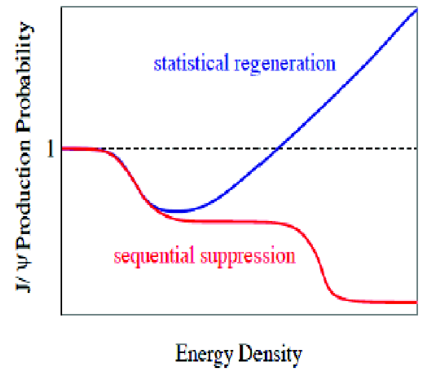
J/ψ production in PbPb collisions: LHC relative to RHIC





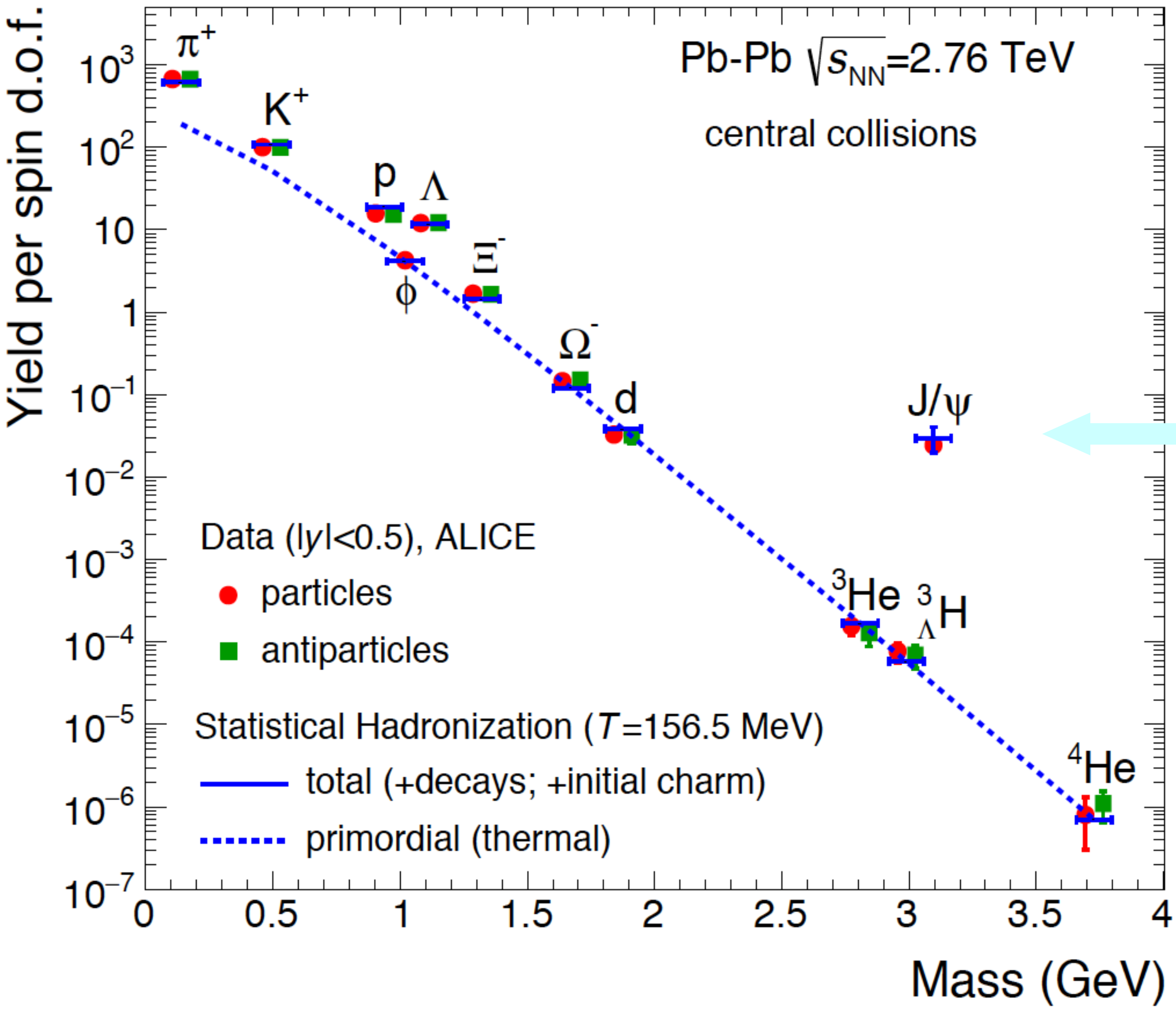
energy density →

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

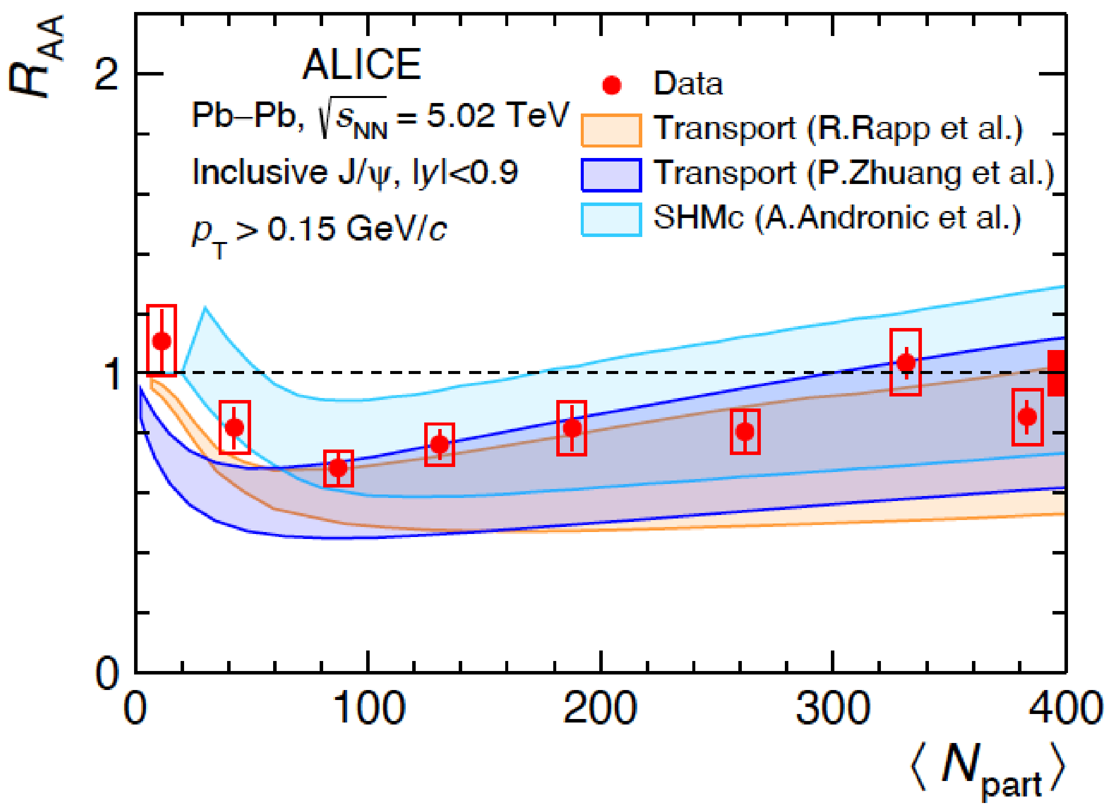
A.Andronic et al., PLB 797 (2019) 134836

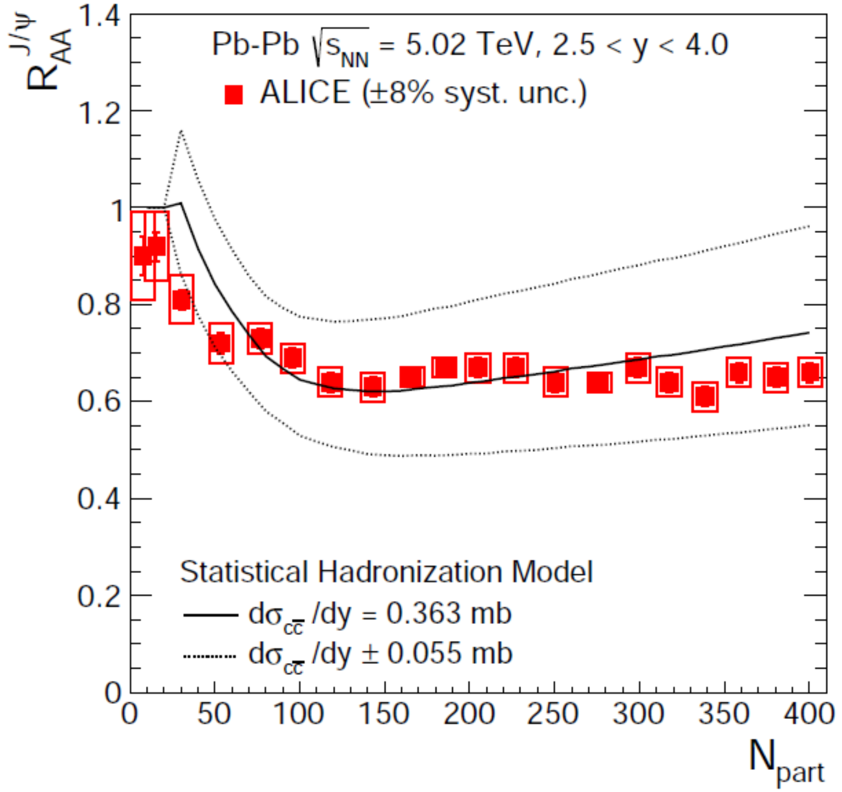


J/ψ enhanced compared to other M = 3 GeV hadrons by factor g_c^2 = 900 relative to purely thermal yield
quantitative agreement with hadronization of deconfined thermalized charm quarks

J/ψ and statistical hadronization

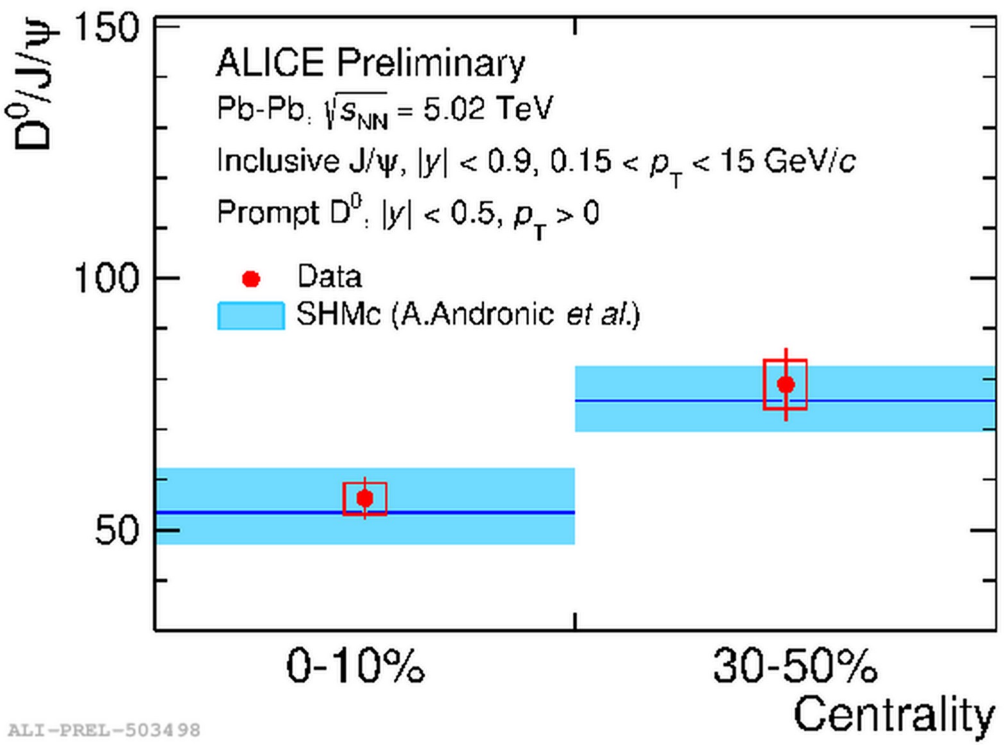
arXiv: 2303.13361





production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
main uncertainty: open charm cross section

Towards a meaningful normalization of charmonia

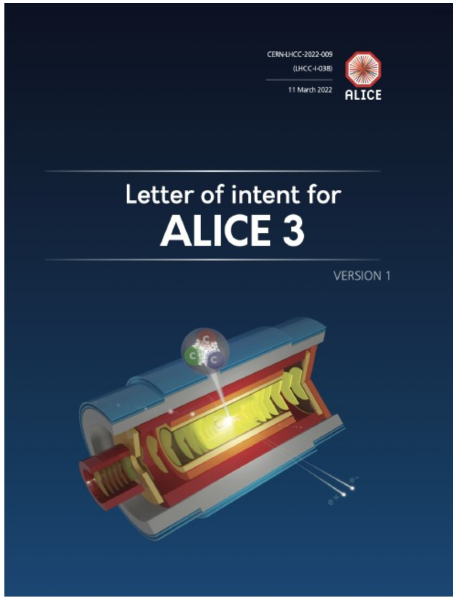


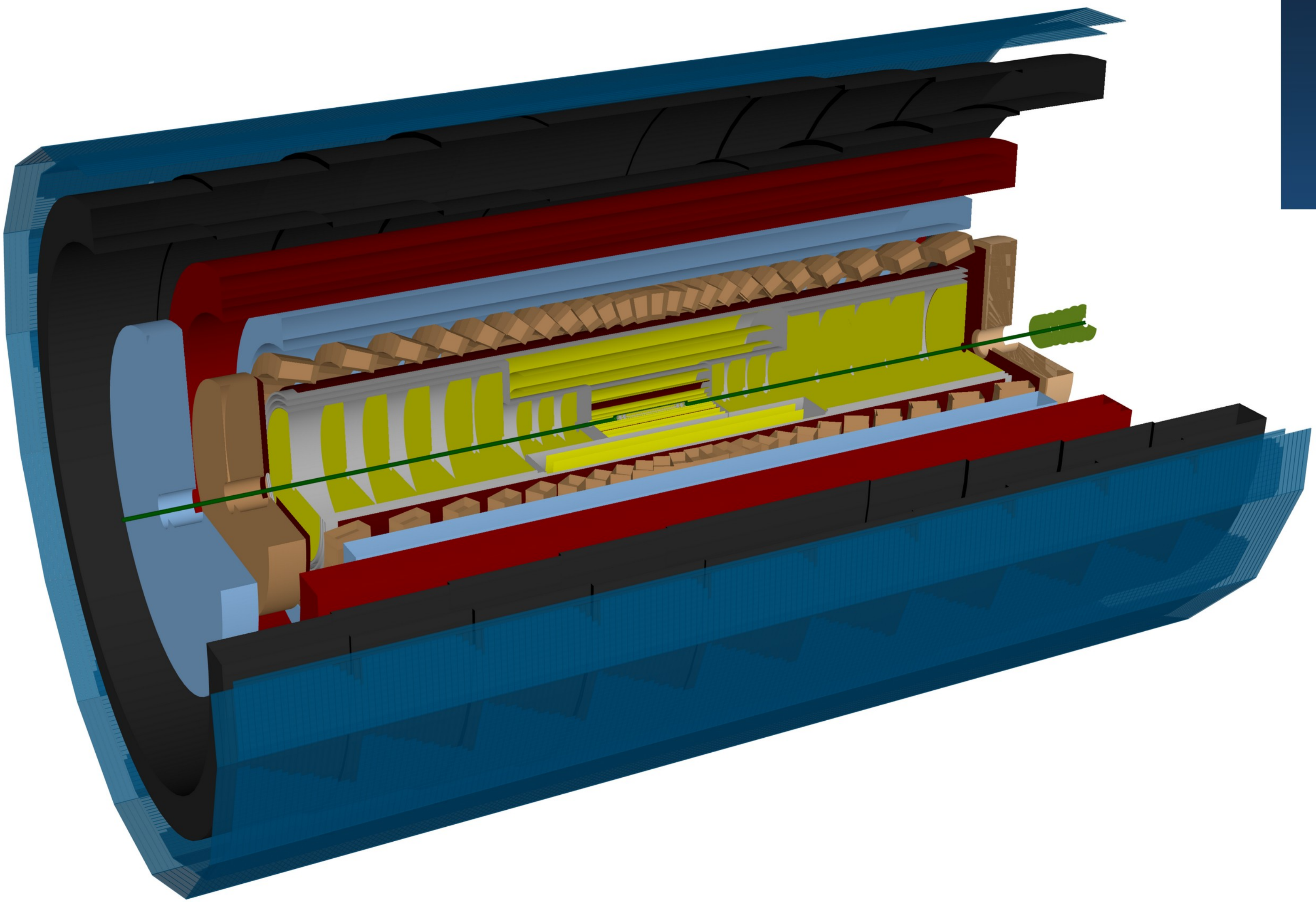
open charm yield would be natural normalization
real breakthrough in data:
can base charm cross section on measured dN/dy of D^0 in PbPb

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

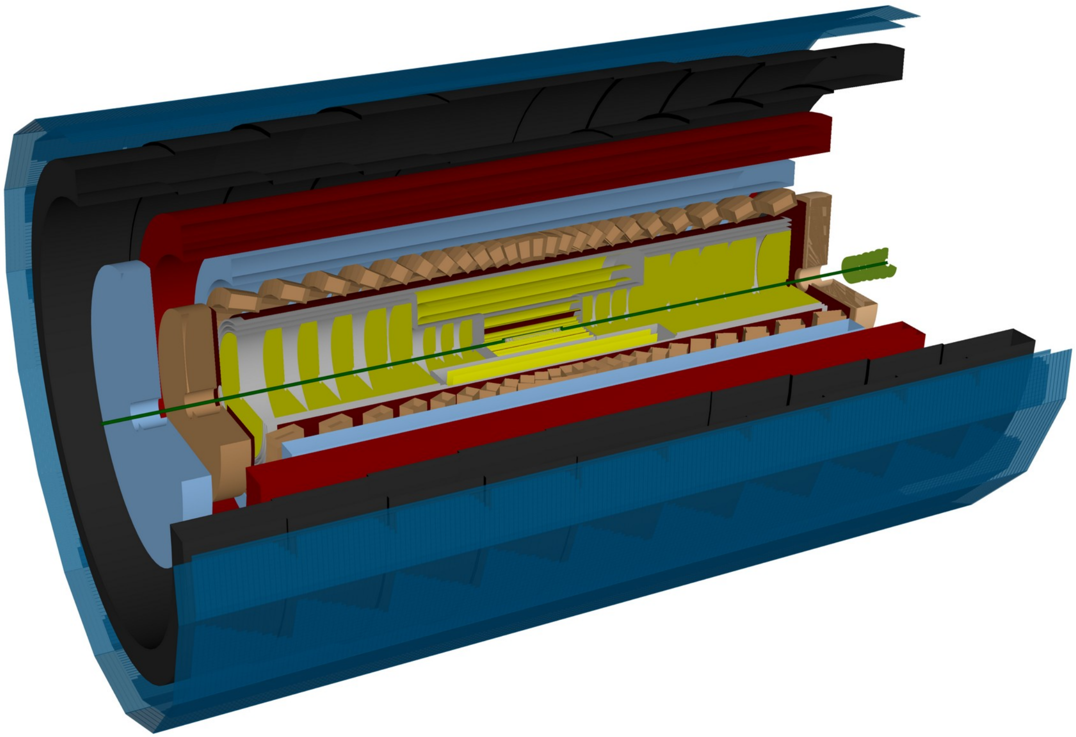
ALICE3 – a (nearly) all silicon experiment

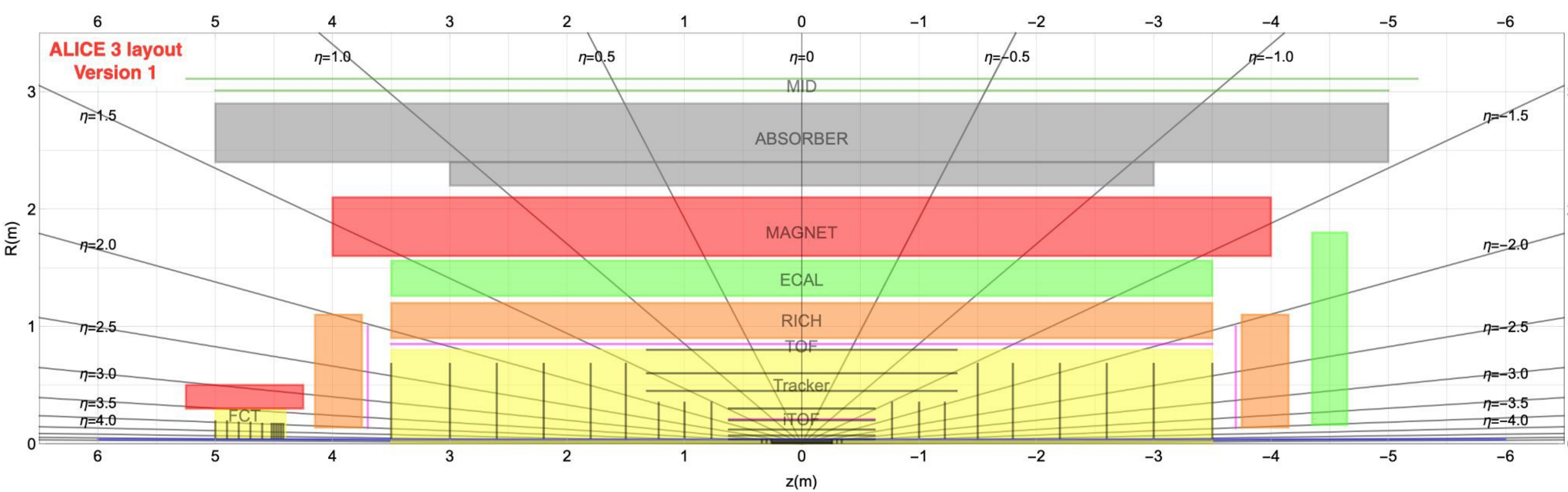
Letter of Intent submitted to LHCC in 2022
positively reviewed and recommended to continue to next step



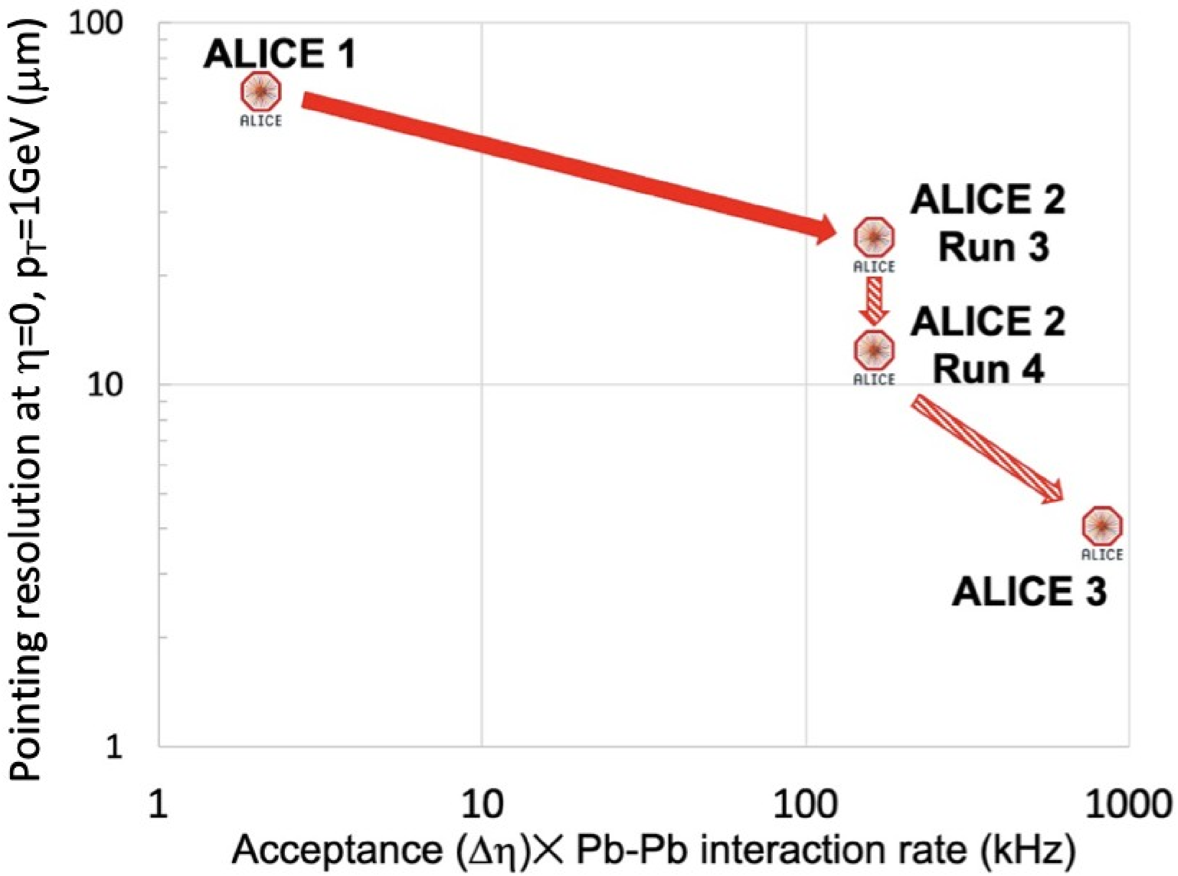


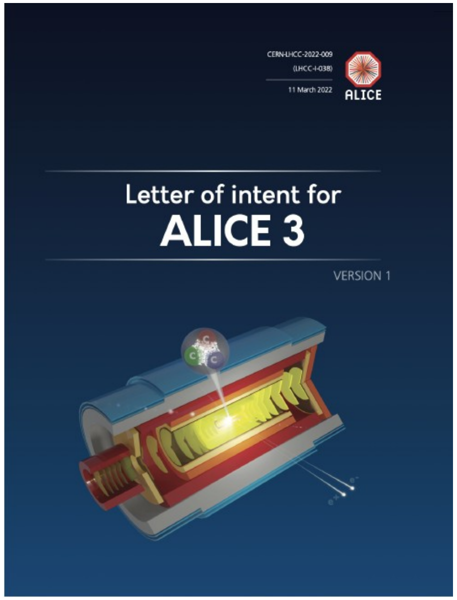
ALICE3 layout



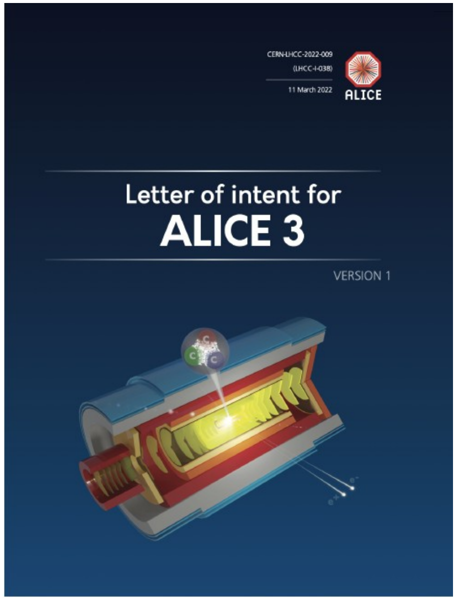


ALICE3 – a (nearly) all silicon experiment





ALICE3 – a (nearly) all silicon experiment



high-efficiency for heavy-quark identification
open heavy flavor hadrons and quarkonia
and reconstruction of low-mass dielectrons
e.g. **chiral symmetry restoration**

heavy anti-nuclei and anti-hyper-nuclei

vertexing close to the beam with unprecedentedly low material budget

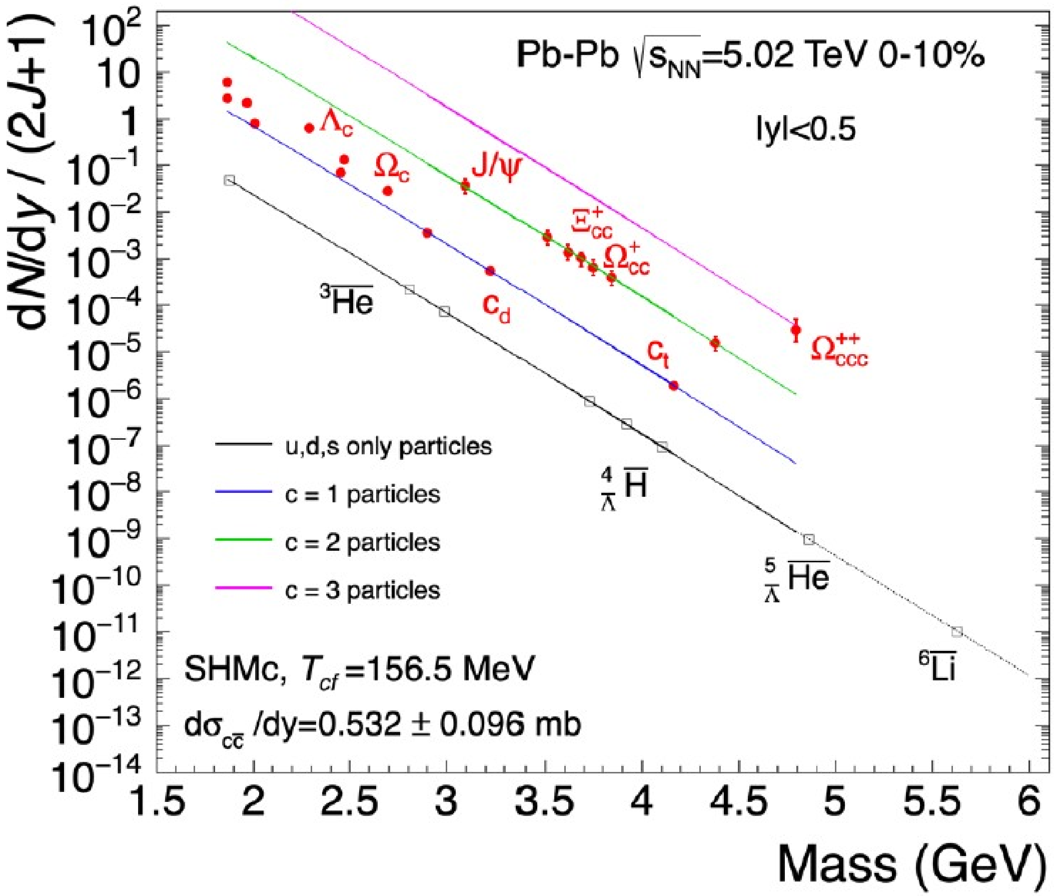
large acceptance with excellent coverage down to low p_T
excellent particle ID (muons, electrons, photons, hadrons)

Vertexing precision x 3: 10μm at p_T = 200 MeV/c
Acceptance x 4.5: $|\eta| < 4$ (with particle ID)
A-A rate x 5 (**pp x 25**)

Forward conversion tracker (FCT) : **ultrasoft photons, test fundamental, controlled low momentum divergence of QFTs**

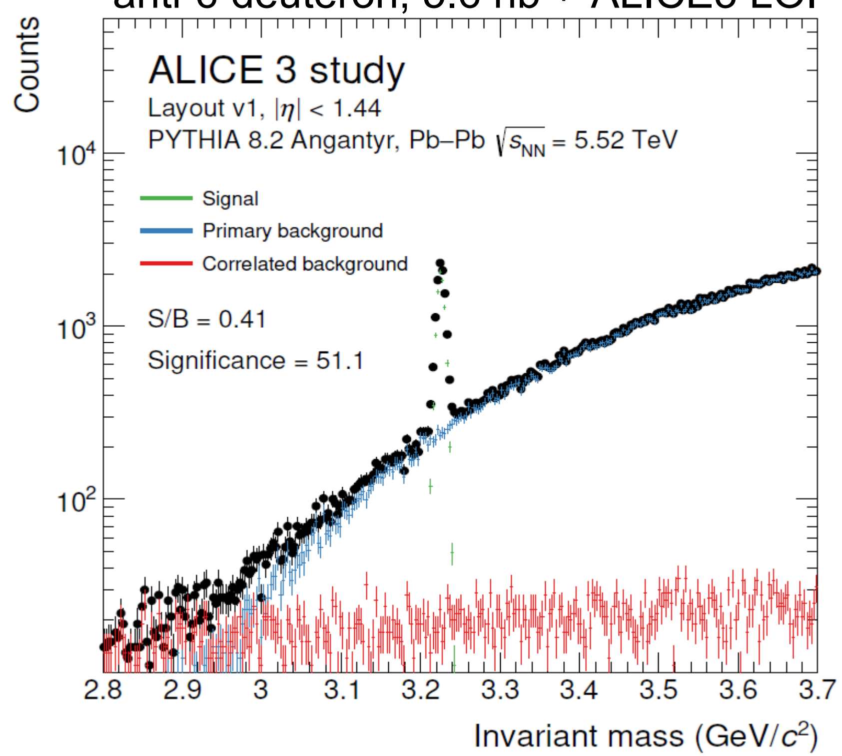
novel technologies relevant for future HEP and NP programs

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

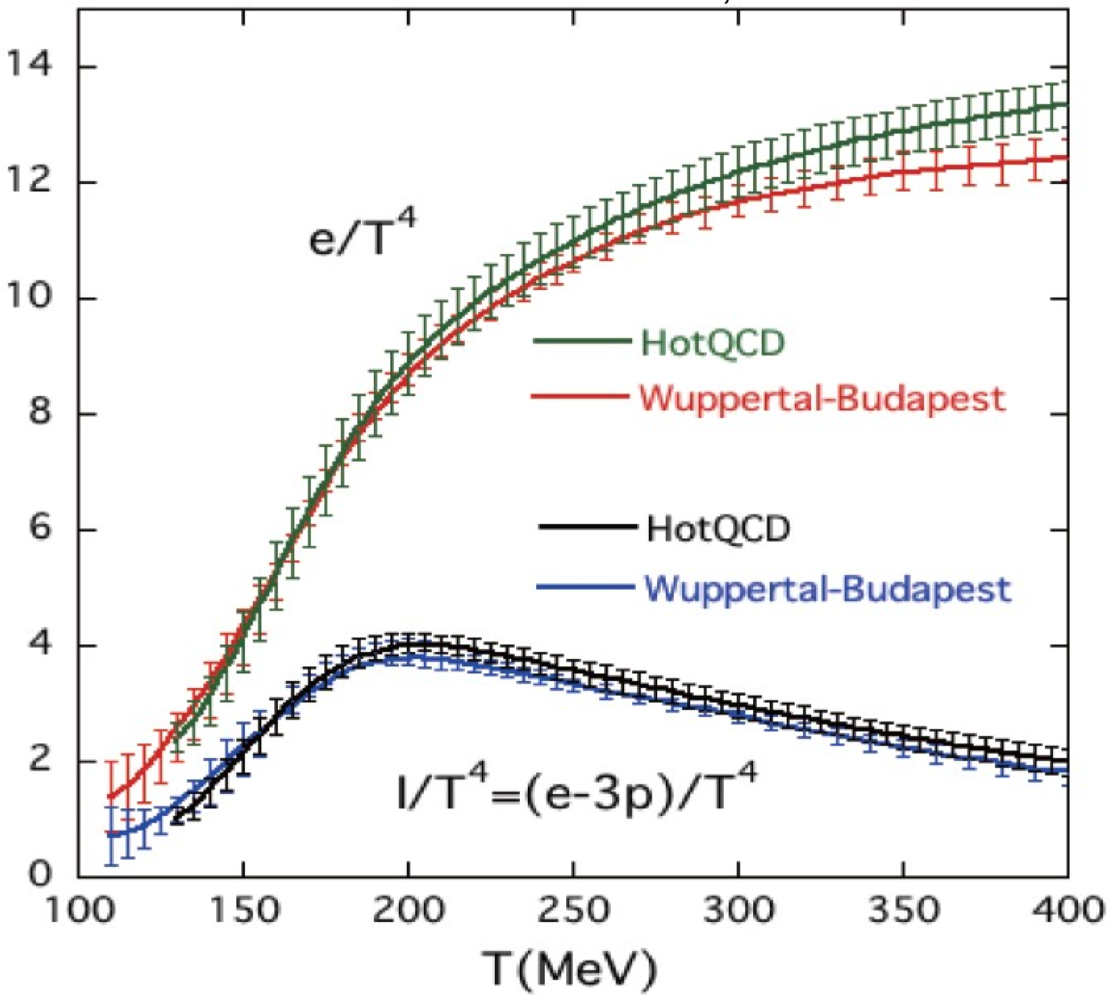
- LHC runs3,4 qualitatively new regime of statistics, heavy flavor, real & virtual photons, nature of phase transition
  sPHENIX high p_t and heavy flavor sector
  ALICE3 as next generation experiment in runs 5,6 of LHC
- sofar no evidence for a critical endpoint in phase diagram, could be around top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

backup

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

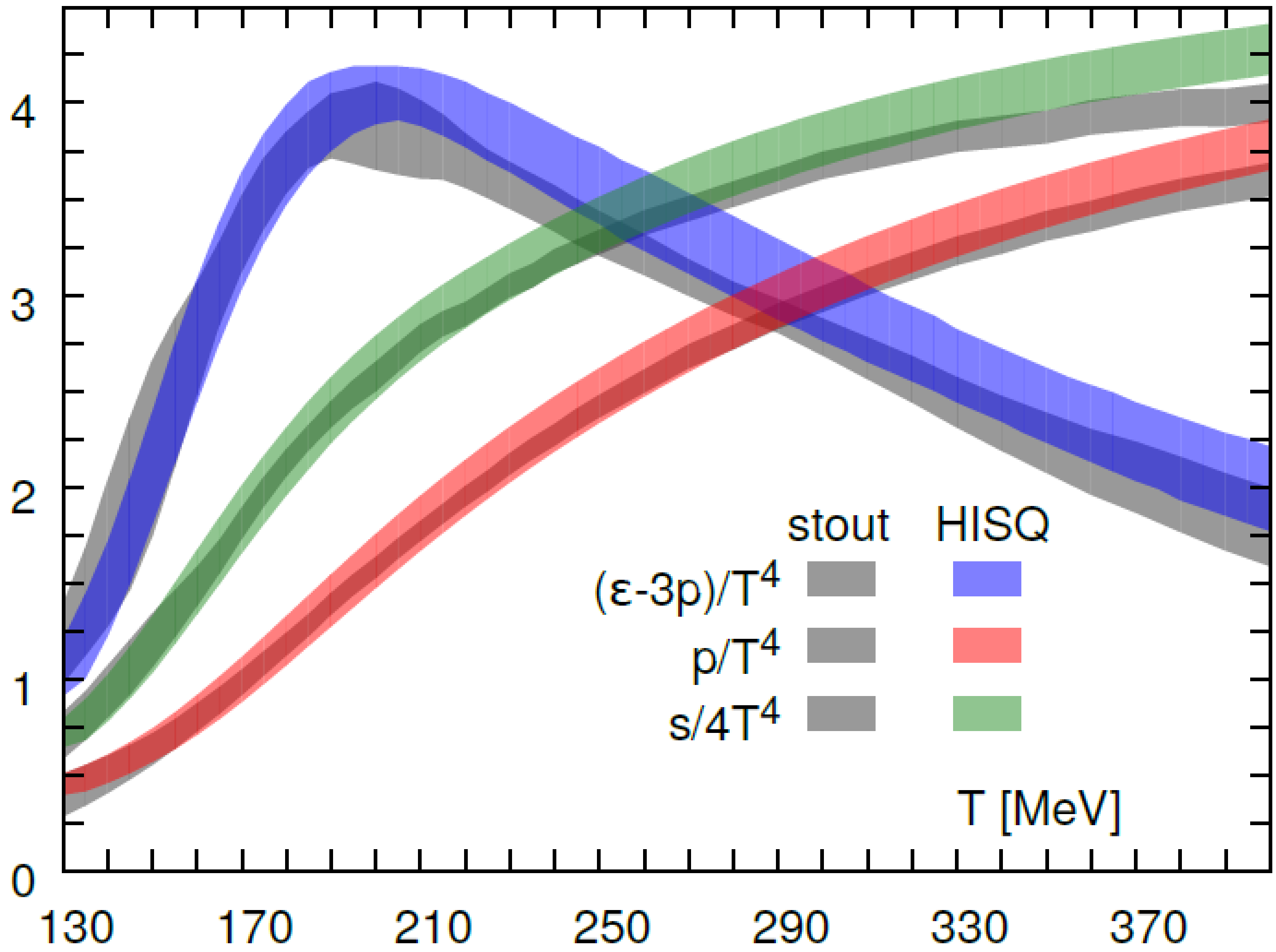


consolidated results on EoS from different groups, extrapolated to continuum and chiral limit

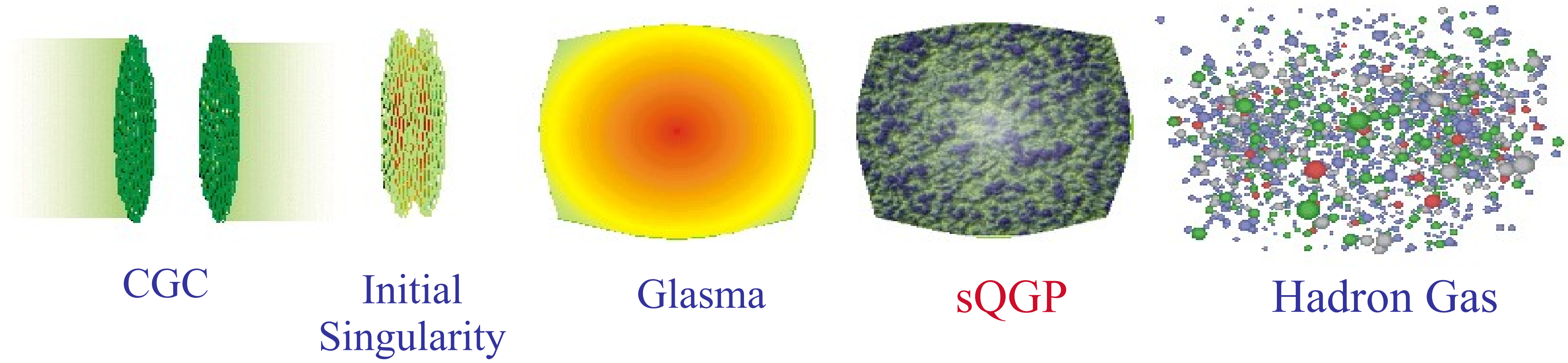
rapid rise of energy density (normalized to T^4 rise for relativistic gas)
- signals rapid increase in degrees of freedom due to transition from hadrons to quarks and gluons
- lQCD points to continuous cross over transition

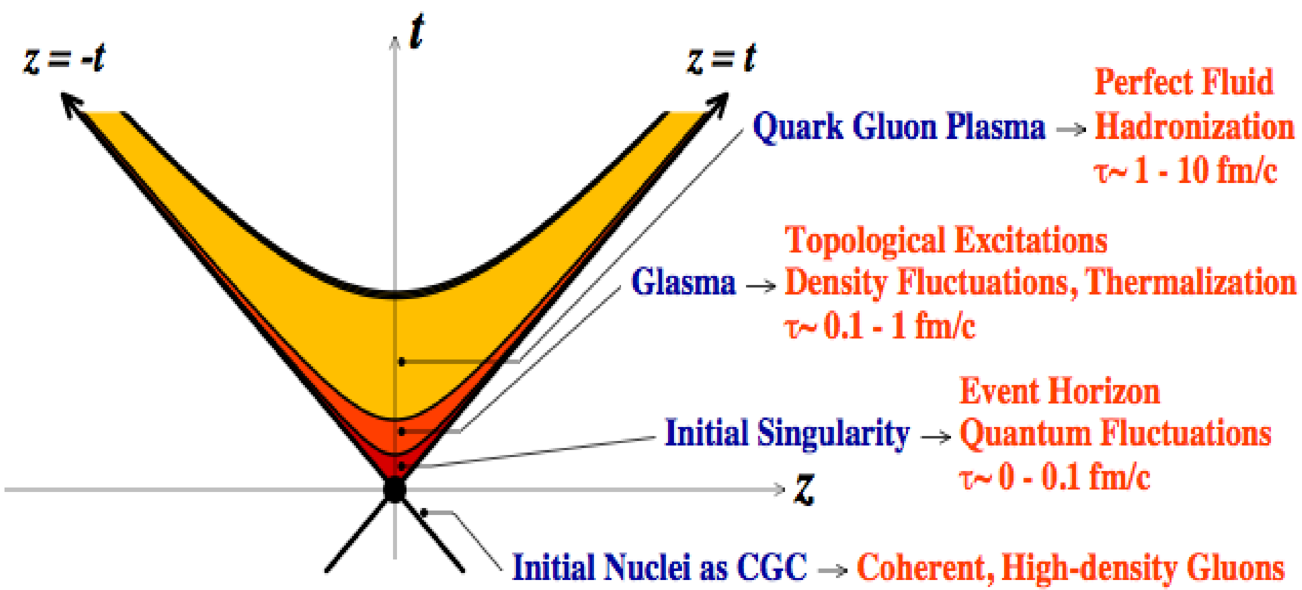
Alternative for lattice QCD EoS

from Bazavov arXiv: 1407.6387



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





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

one possible view (courtesy L. McLerran)

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

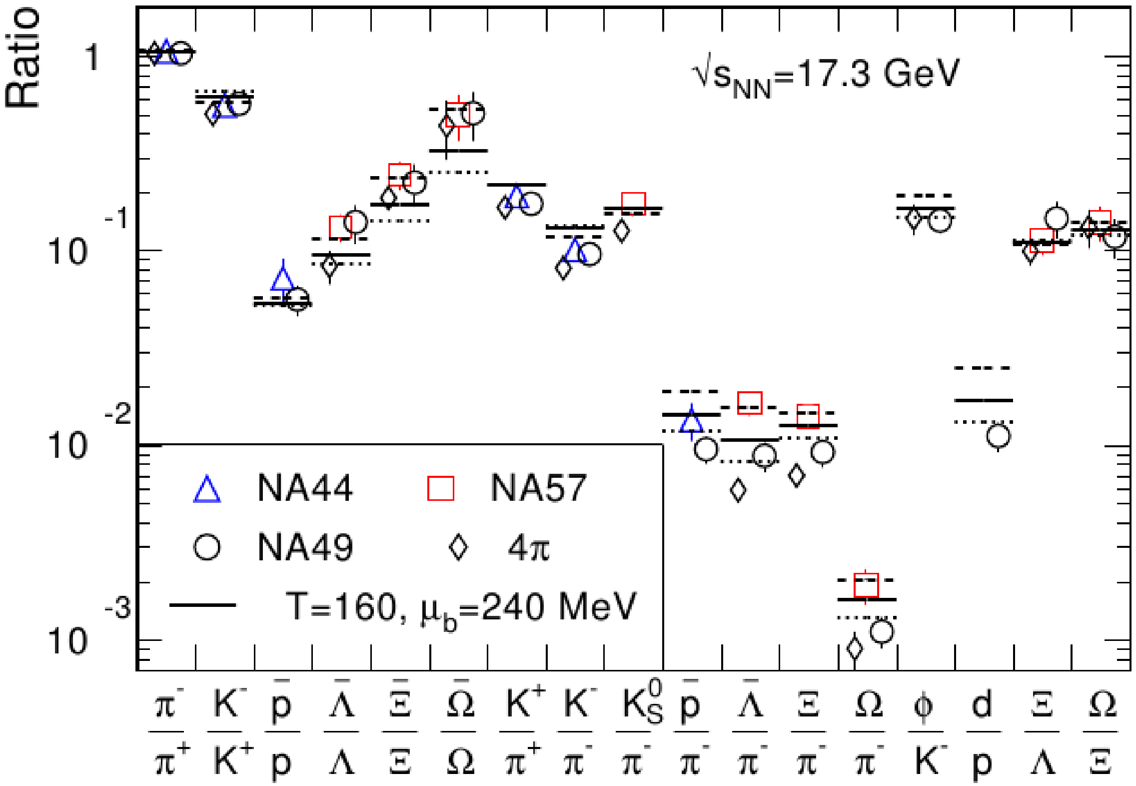
for every conserved quantum number there is a chemical potential:

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

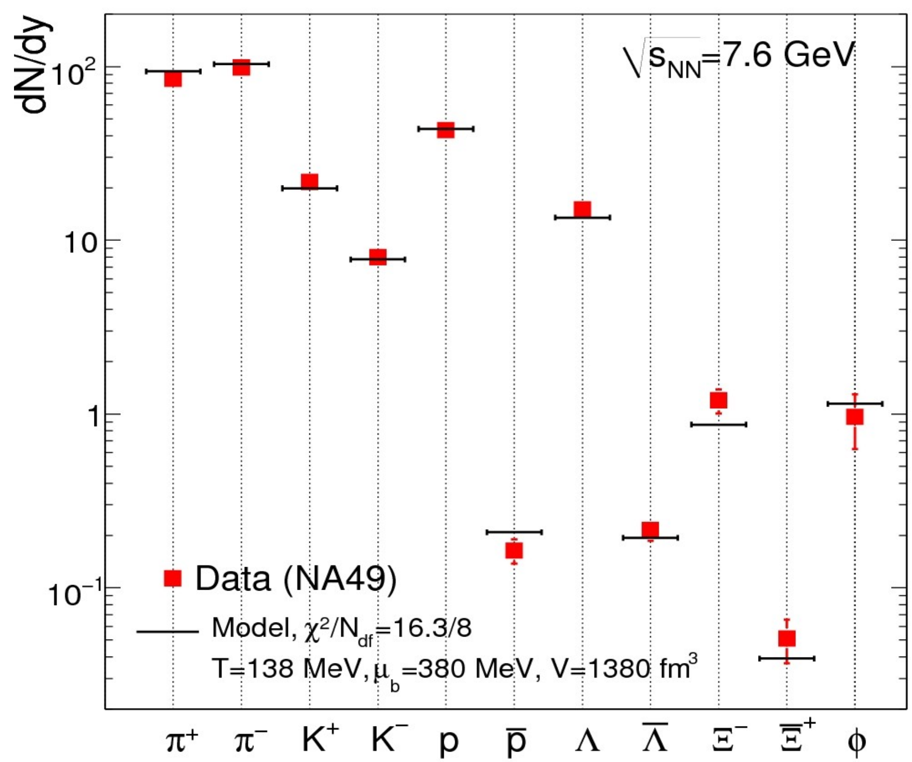
but can use conservation laws to constrain V, μ_S, μ_{I_3}

→ **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

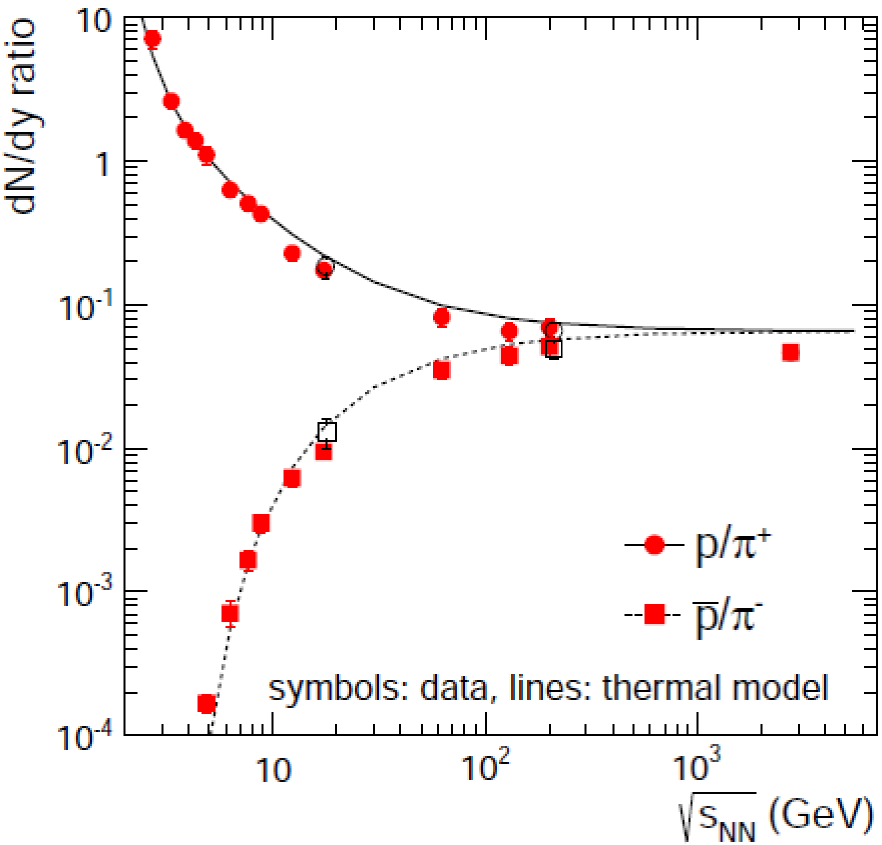


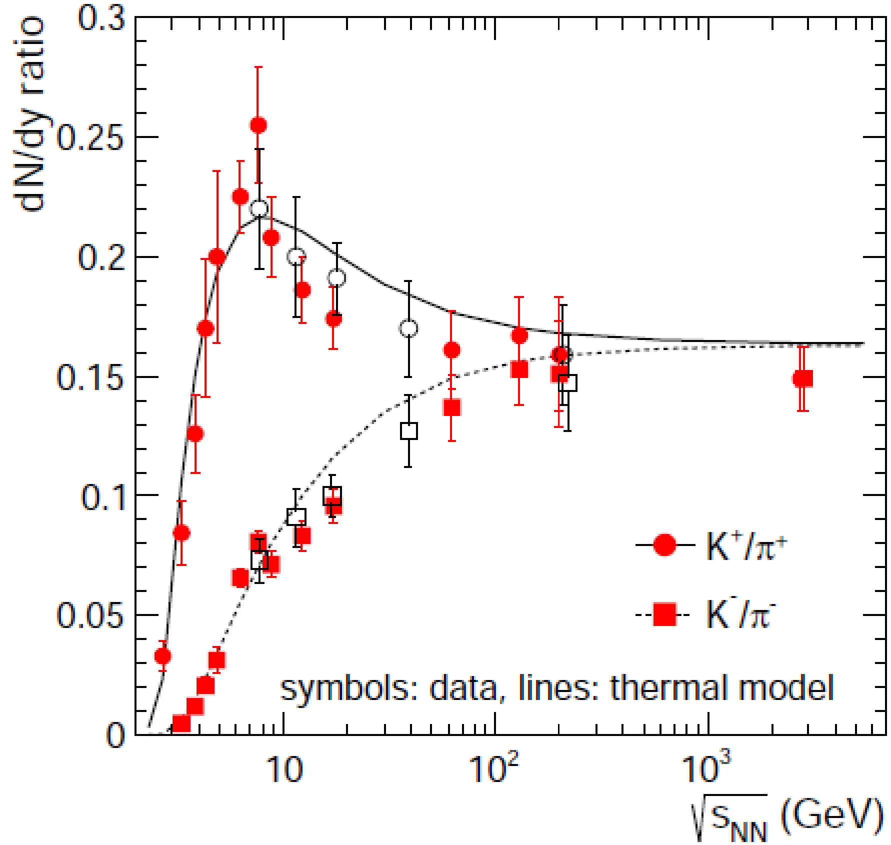
figures from A. Andronic, P. Braun-Munzinger, J.S. Nucl. Phys. A772 (2006) 167

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

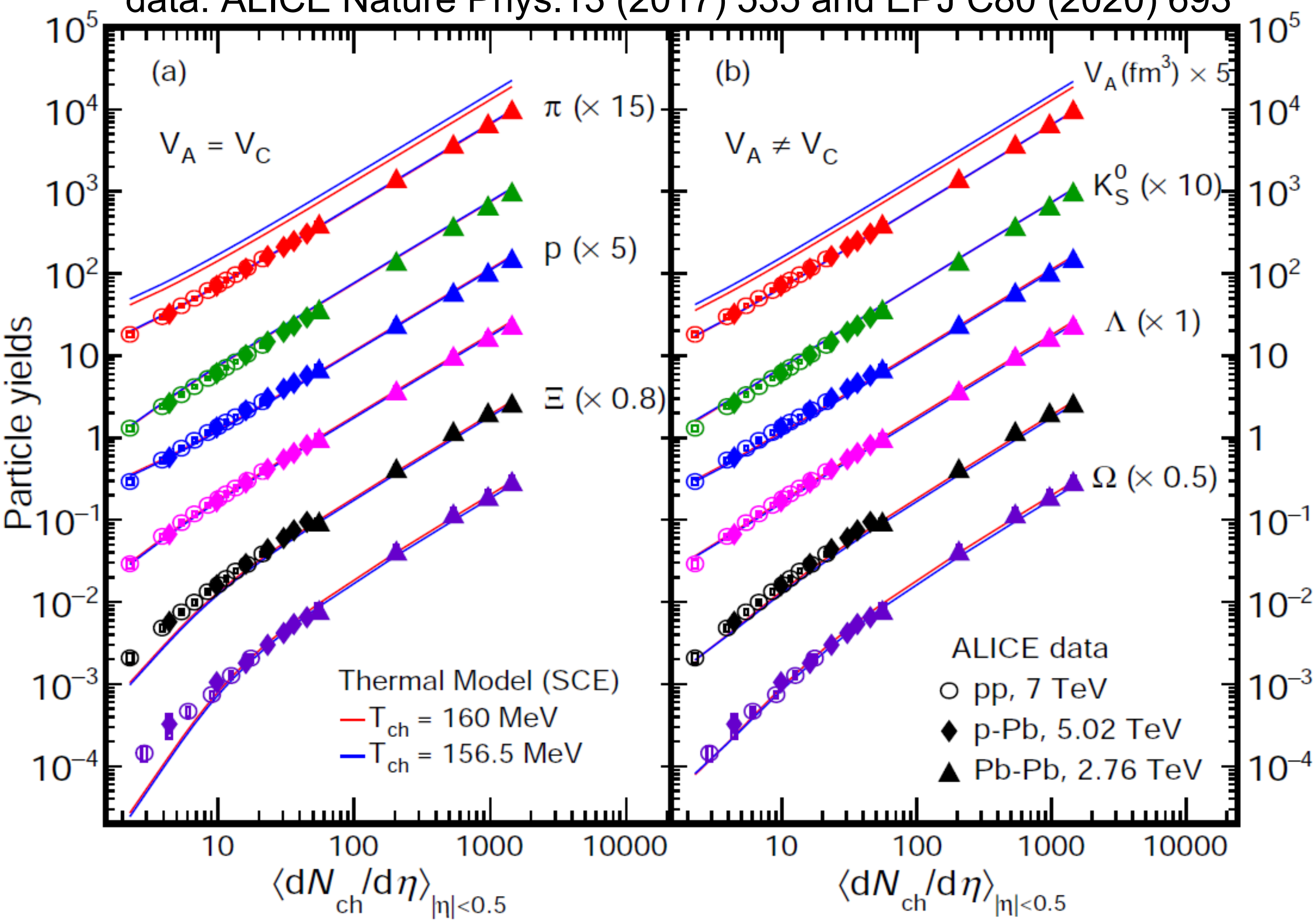
A. Andronic, P. Braun-Munzinger, J.Stachel, PLB 673 (2009) 142





from pp to Pb-Pb collisions: smooth evolution with system size

data: ALICE Nature Phys.13 (2017) 535 and EPJ C80 (2020) 693

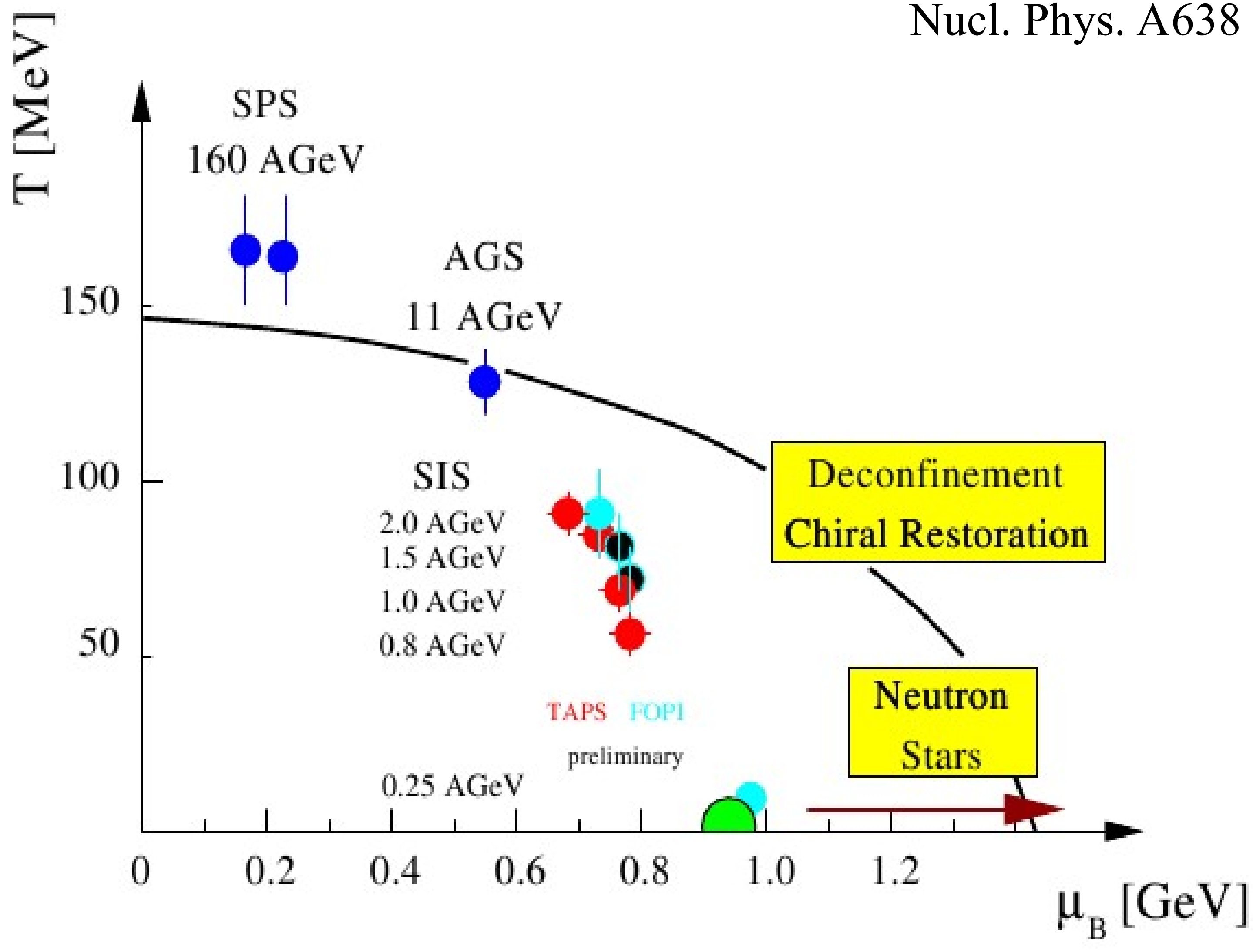


universal hadronization can be described with few parameters in addition to T and μB → transition from canonical to grand-canonical thermodynamics

J. Cleymans, P.M. Lo, K. Redlich, N. Sharma, PRC 103 (2021) 014904

First phase diagram with experimental points

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



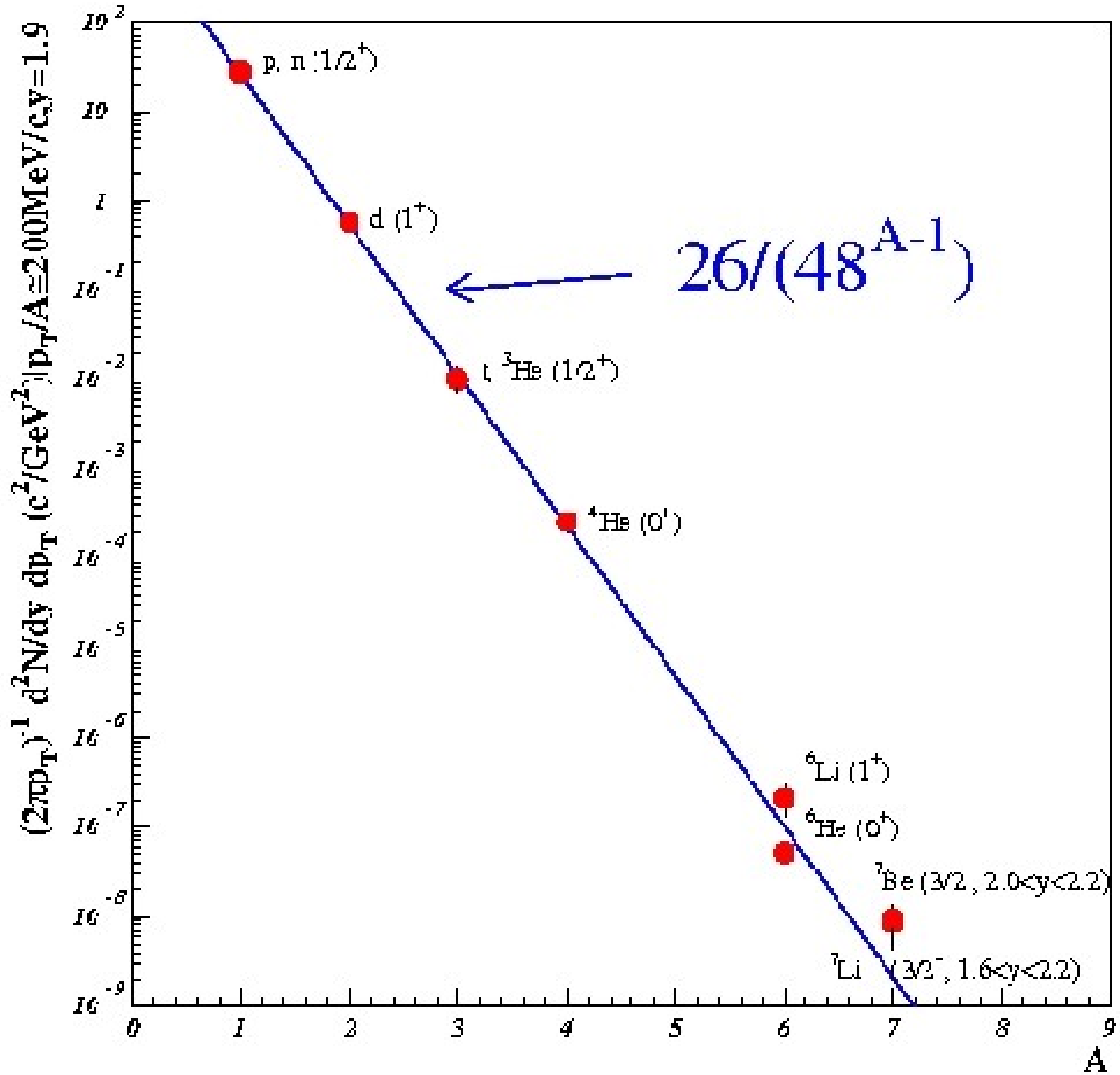
Production of light nuclei and antinuclei at the AGS

<u>data cover 10 oom!</u>
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
-> $R_p = 26$

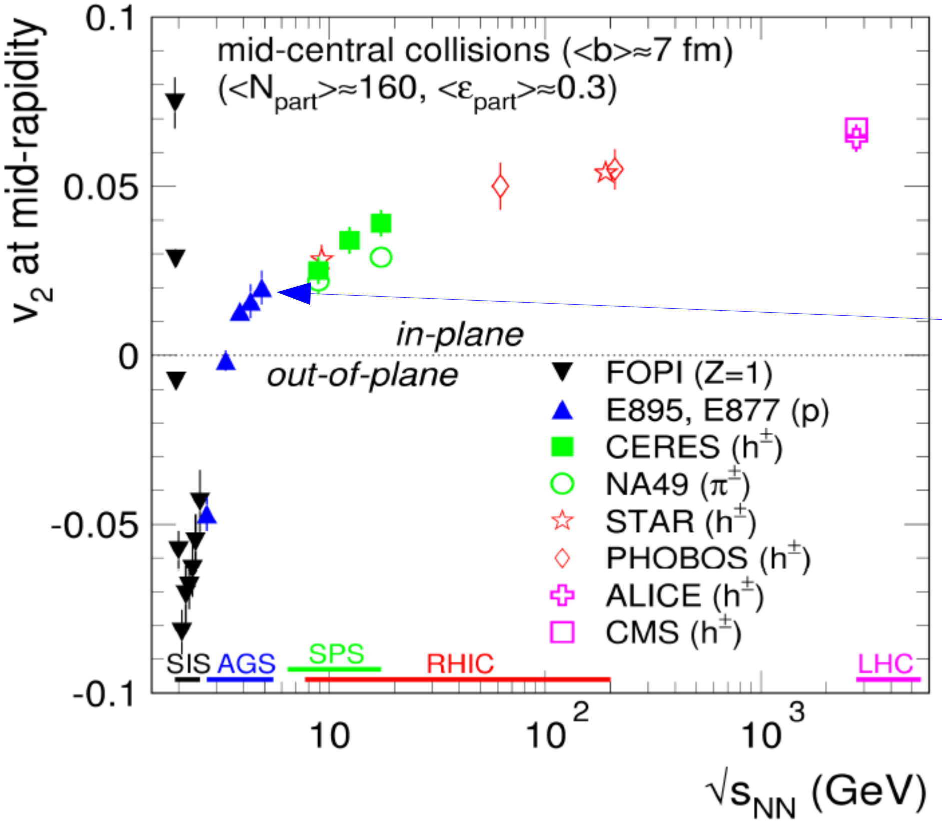
<u>GC statistical model:</u>
$$R_p \approx \exp[(m_n \pm \mu_b)/T]$$
for T=124 MeV and μ_b= 537 MeV
$R_p = 24$ good agreement
also good for **antideuterons**:
data: $R_p = 2 \pm 1 \cdot 10^5$ SM: $1.3 \cdot 10^5$

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

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



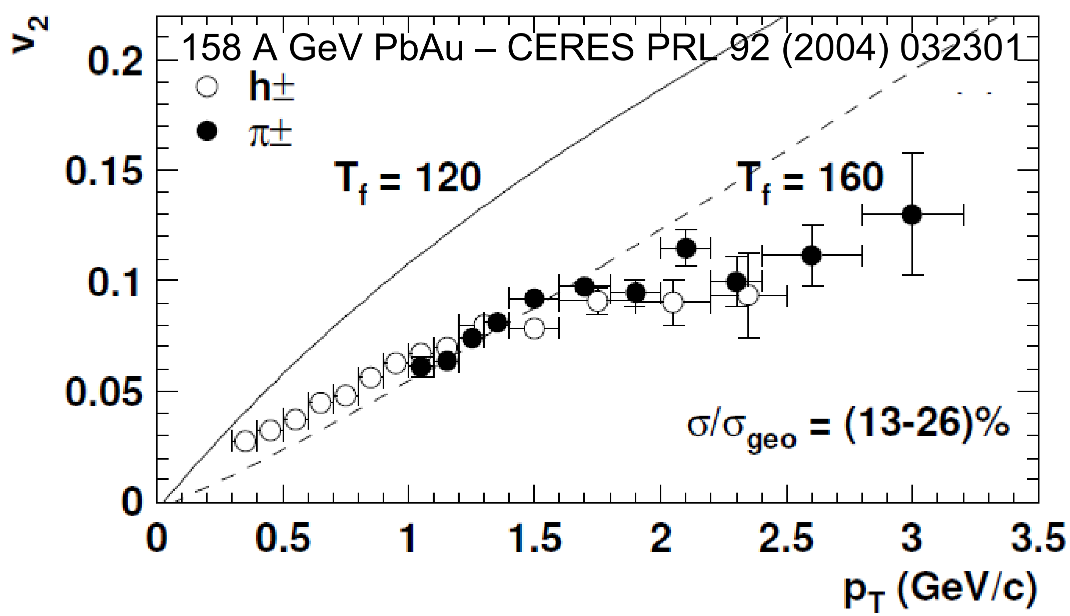
Elliptic flow as function of collision energy



- effect of expansion (positive v_2) seen from top AGS energy upwards
- at lower energy: shadowing by fragments

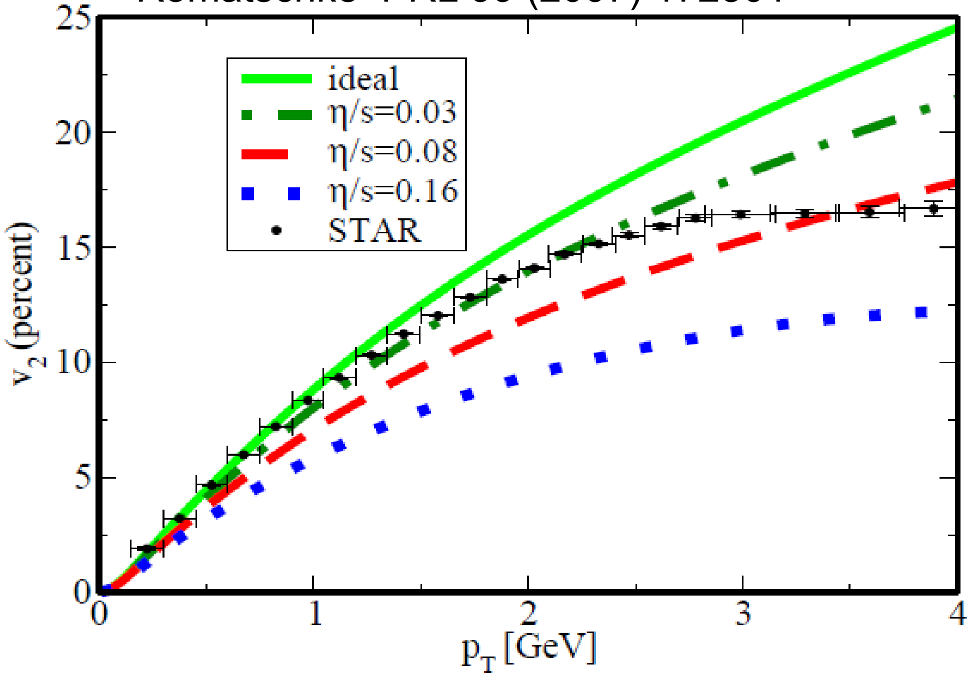
first discovered as tiny 2% effect by E877 in 1993

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



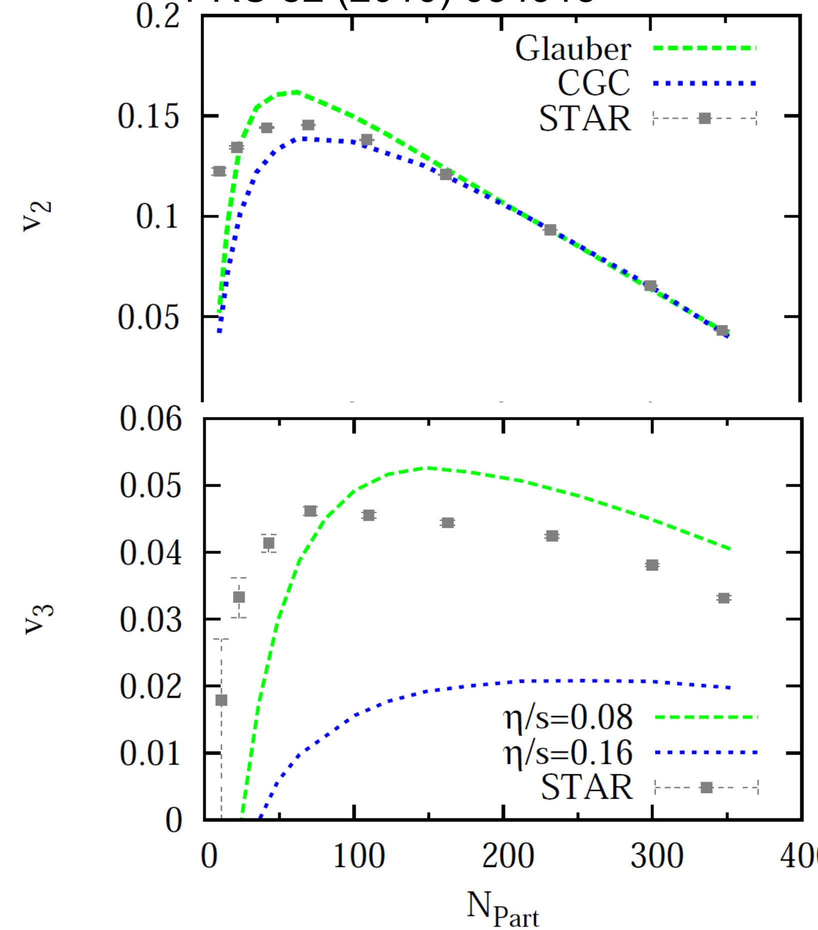
Discovery of RHIC: paradigm of QGP as near ideal liquid

Romatschke PRL 99 (2007) 172301



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

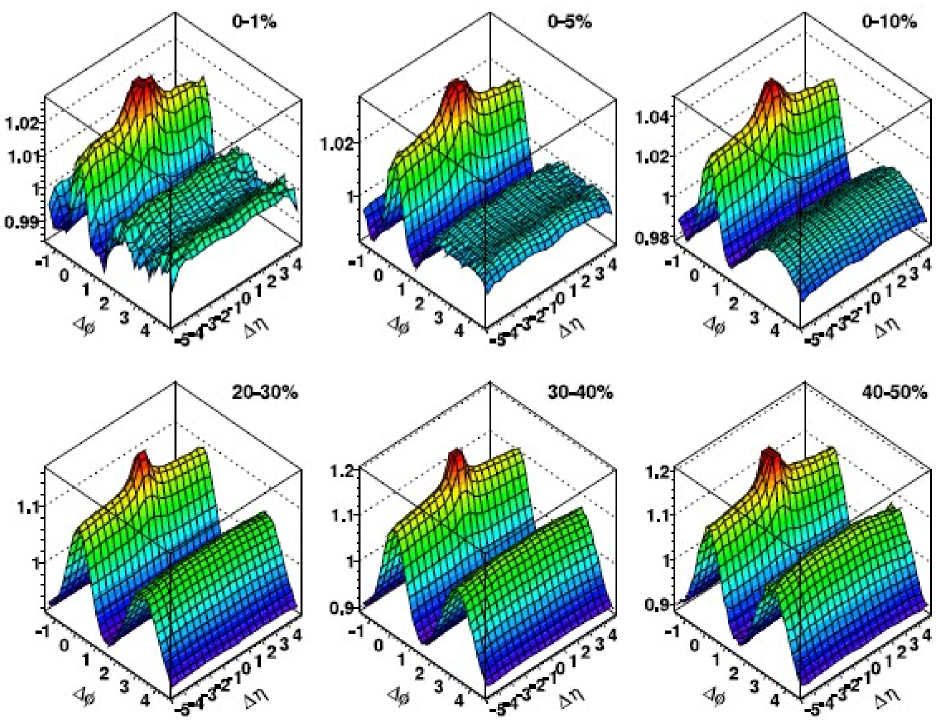
Alver, Gumbeaud, Luzum, Ollitrault, PRC 82 (2010) 034913



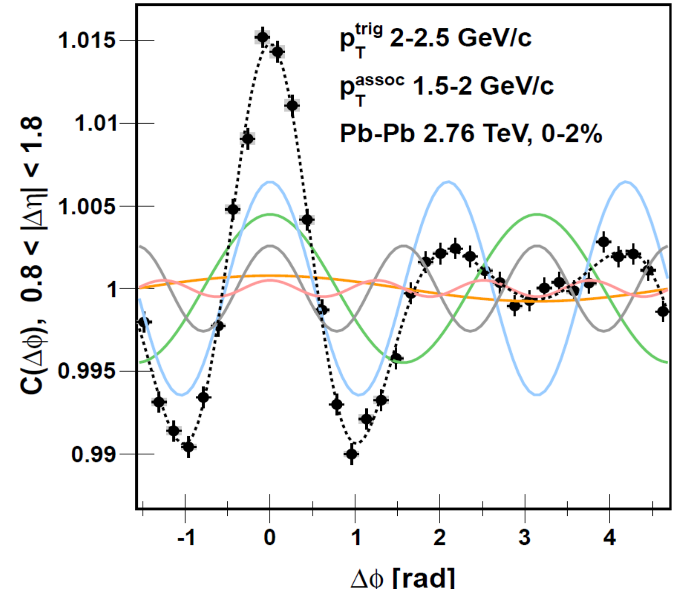
in hydro regime v2 driven by
- initial condition and
properties of the liquid as η/s
→ ambiguity between the two can be resolved by correlating observables

Propagation of sound in the quark-gluon plasma

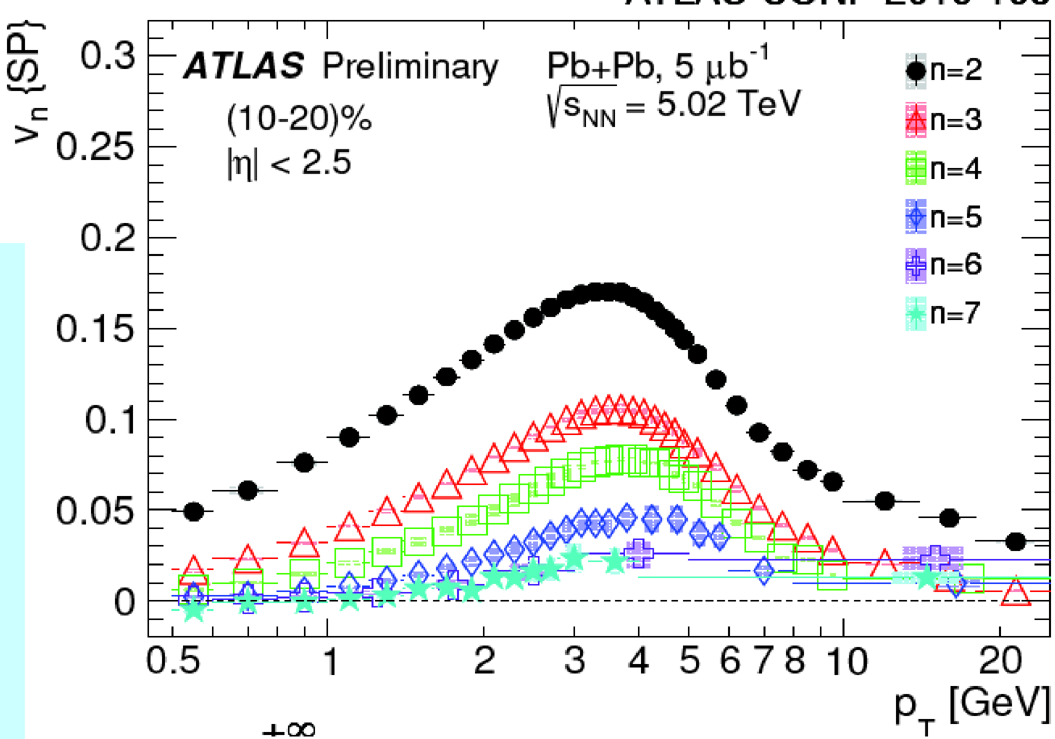
ATLAS-CONF-2011-074



ALICE, PLB 708 (2012)249



ATLAS-CONF-2016-105



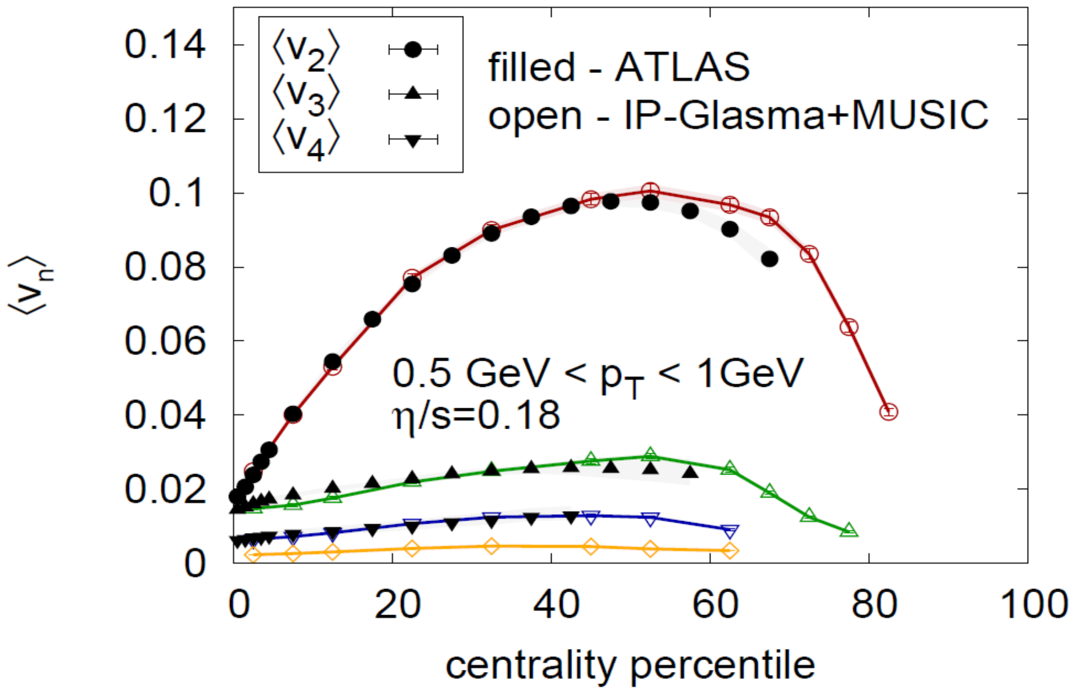
long-range rapidity correlations

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

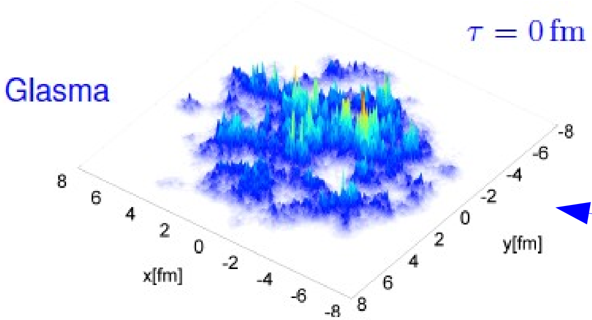
M. Luzum PLB 696 (2011) 499

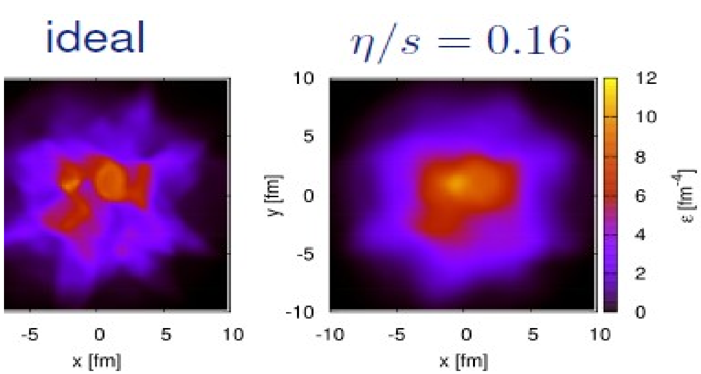
Higher flow harmonics and their fluctuations

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



ratios of v2/vn and their fluctuations depend on initial condition

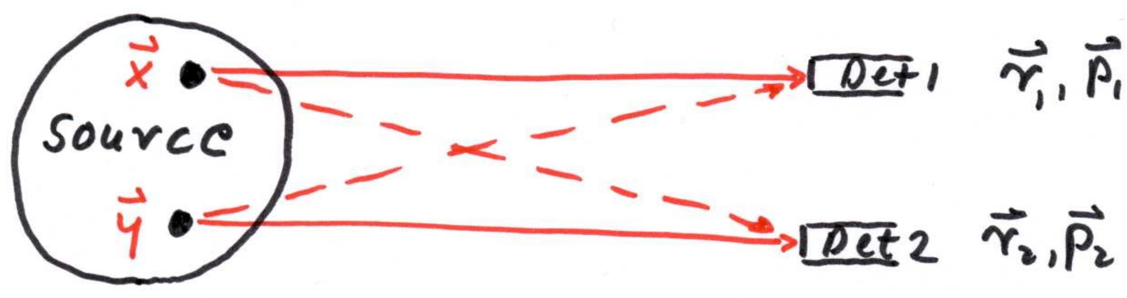




very well reproduced by viscous hydrodynamics (MUSIC) with fluctuating IP Glasma initial condition (including initial quantum fluctuations of gluon fields)
for LHC $\eta/s = 0.18$ for RHIC $\eta/s = 0.12$
indication of temperature dependence of η/s?

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

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

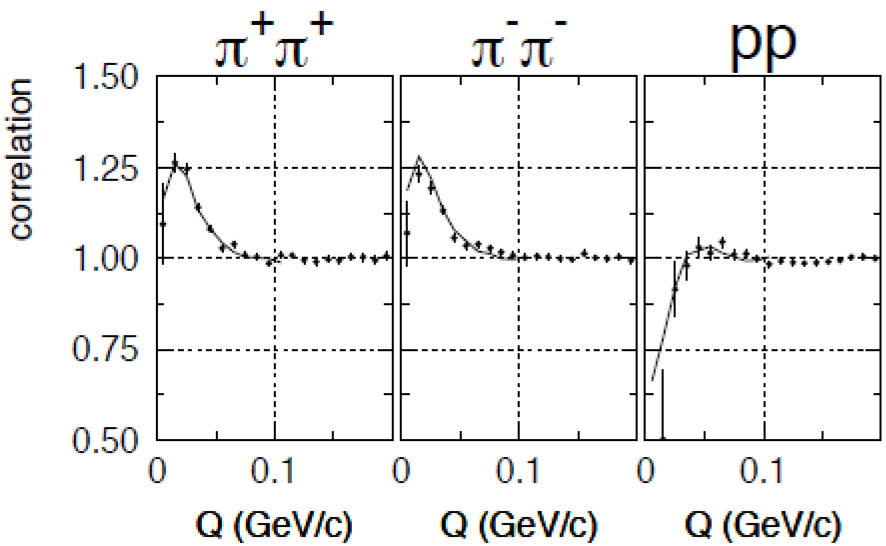
with 4-vectors p,r,x,y (to be general for nonstatic source)

square of amplitude: intensity → "intensity interferometry"

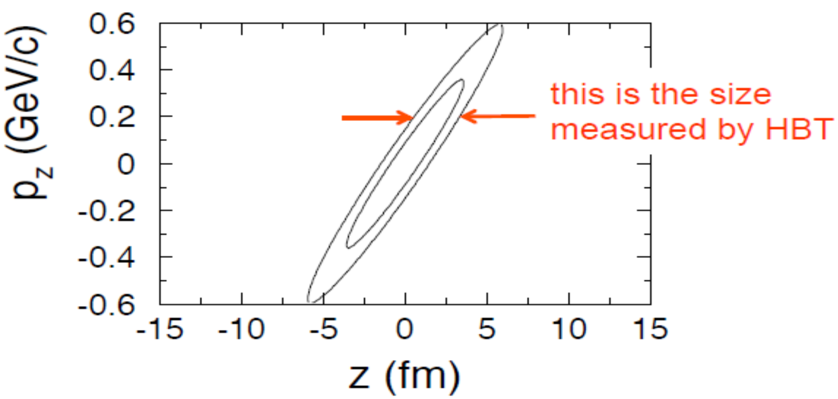
technique of intensity interferometry developed by Hanbury-Brown and Twiss in astrophysics as a means to determine size of distant objects

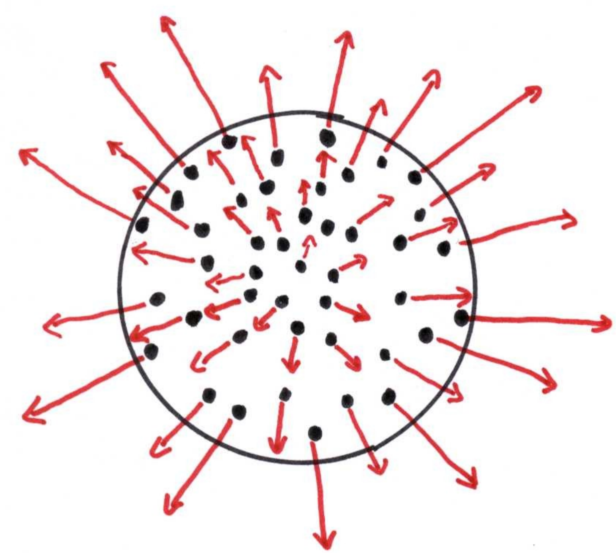
Hanbury-Brown/Twiss correlations to measure the space-time extent of the fireball

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



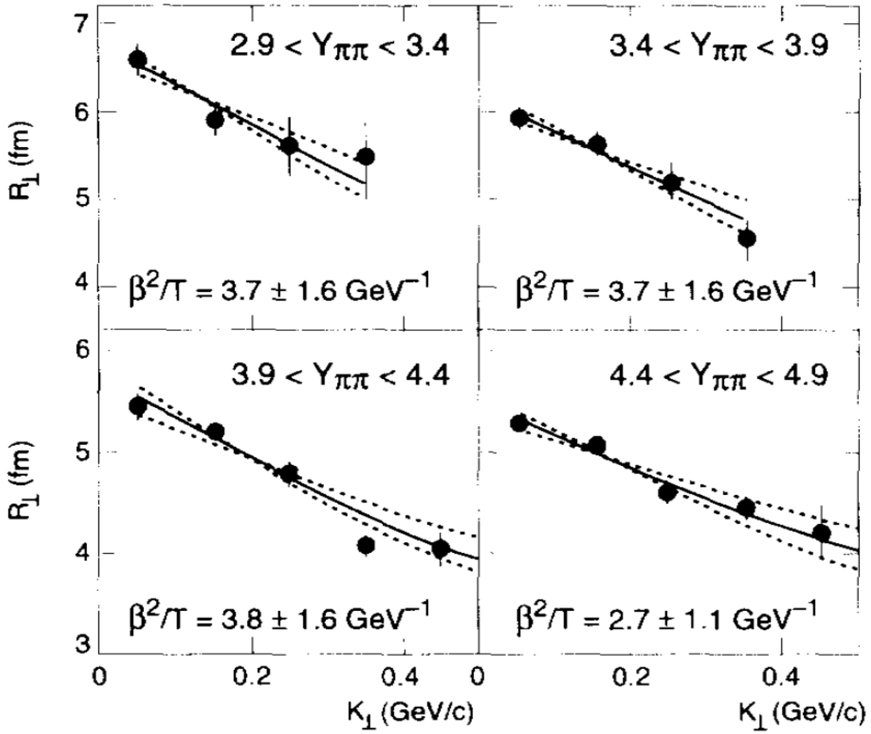
first a puzzle: small apparent radii (2 fm/c)
then a discovery: are due to collective expansion of fireball
space – momentum correlations → only part of the source is 'visible'
predicted by Mahklin/Sinyukov





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

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

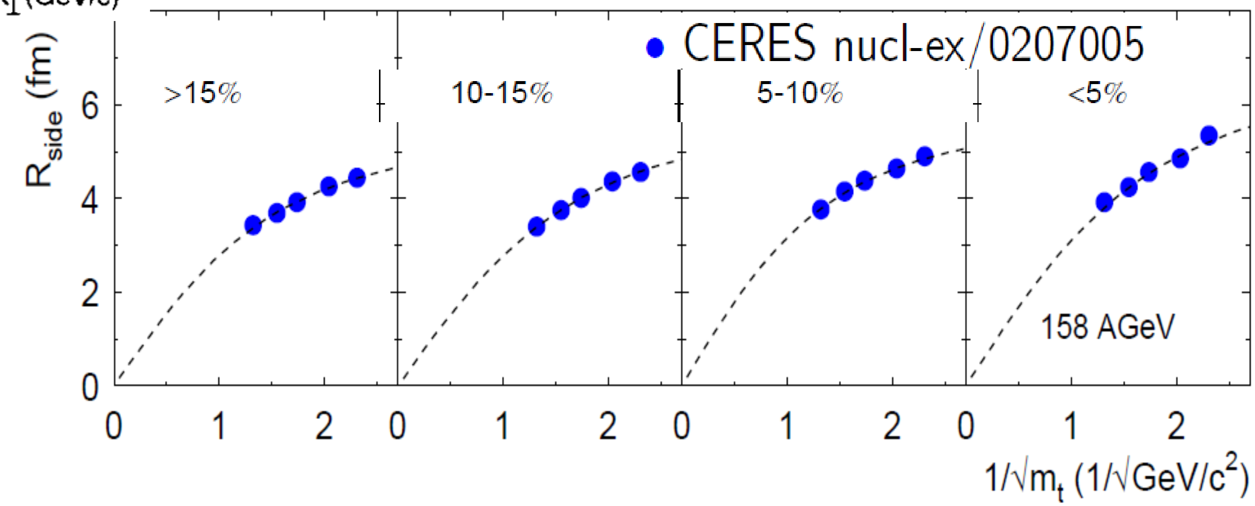


transverse mom. dependence shows typical shape for hydrodynamically expanding source

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

U. Heinz *et al.*

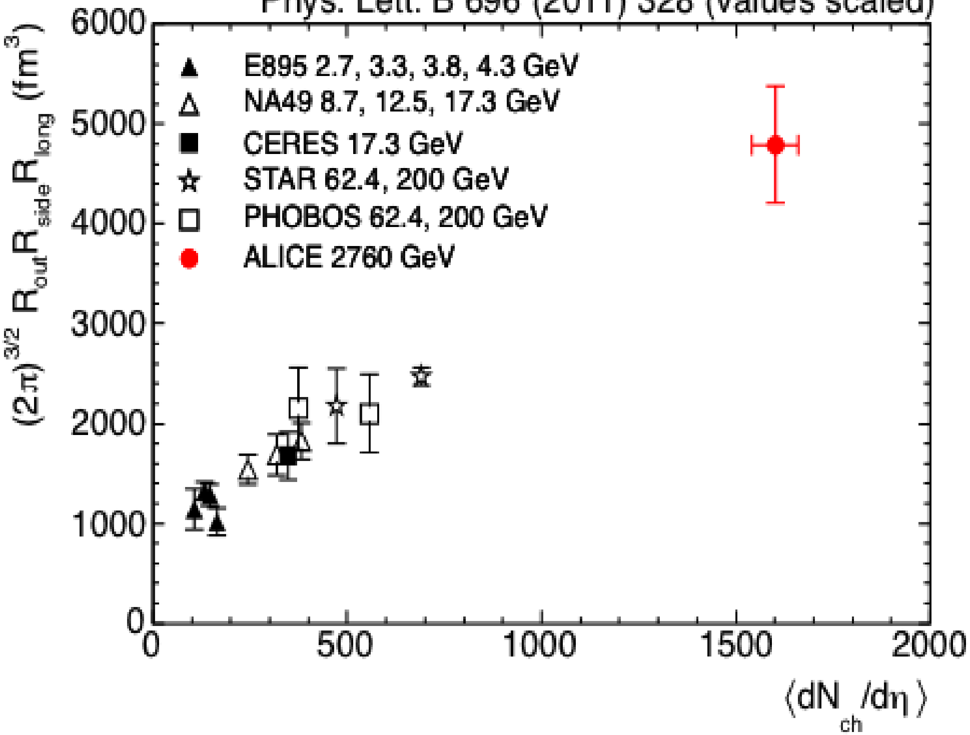
$\beta_t \approx 0.55$ for $T_f = 120$ MeV



Freeze-out volume and duration of expansion

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

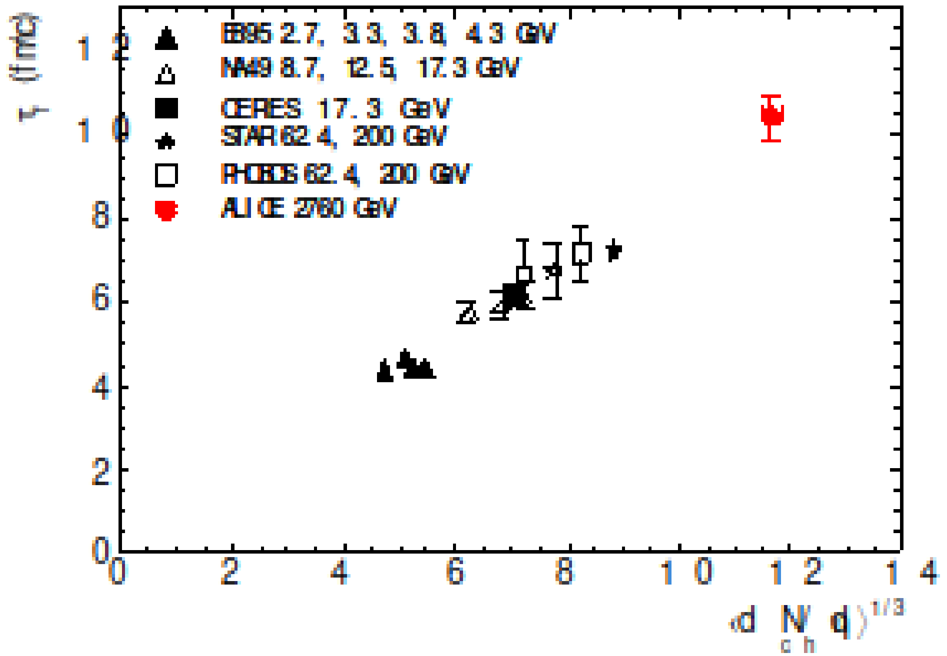
Phys. Lett. B 696 (2011) 328 (values scaled)



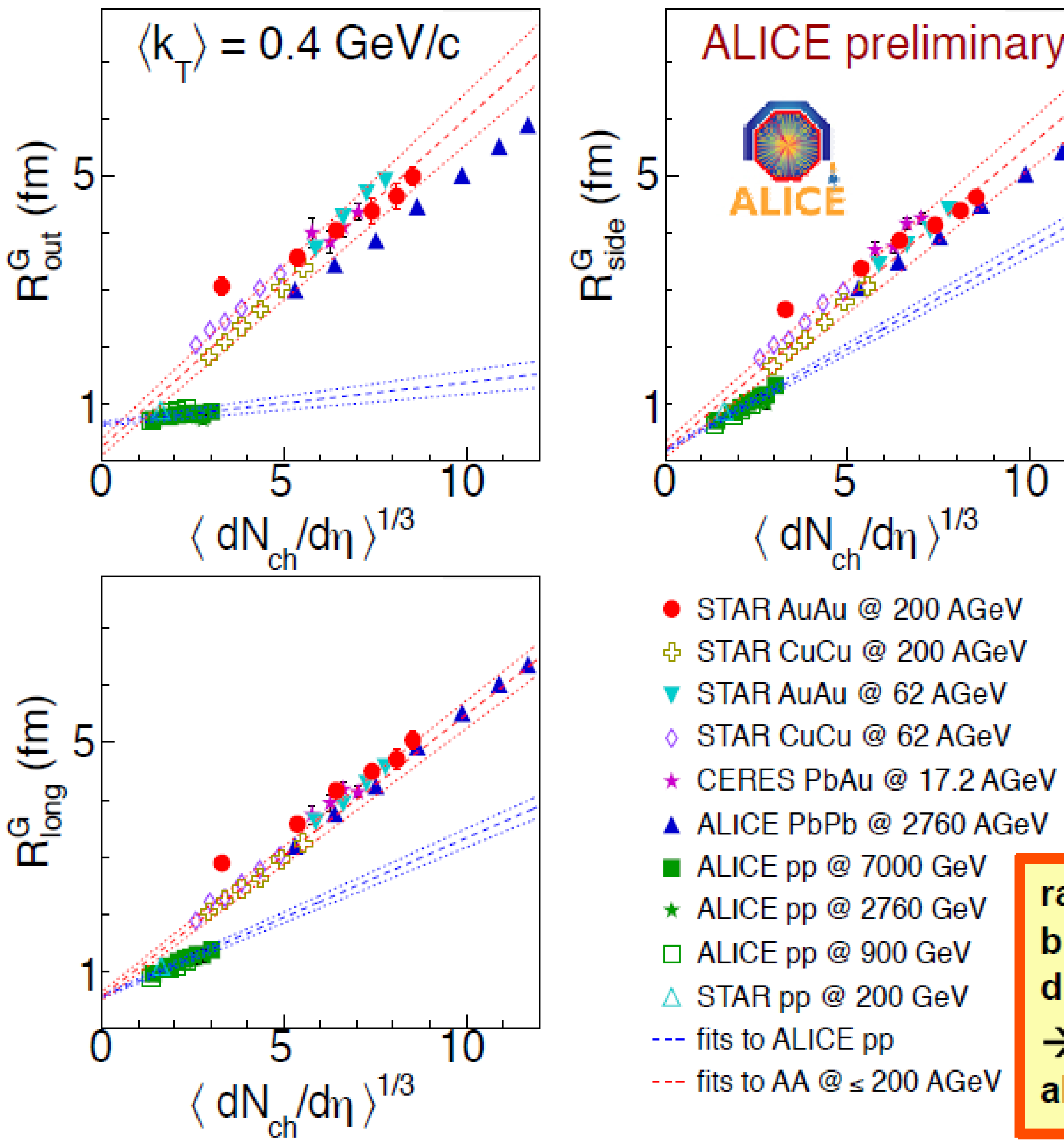
huge growth with √s at all energies
larger than overlap volume – reflects
strong expansion of fireball
at surface at LHC velocity ¾ c

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

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



pion HBT

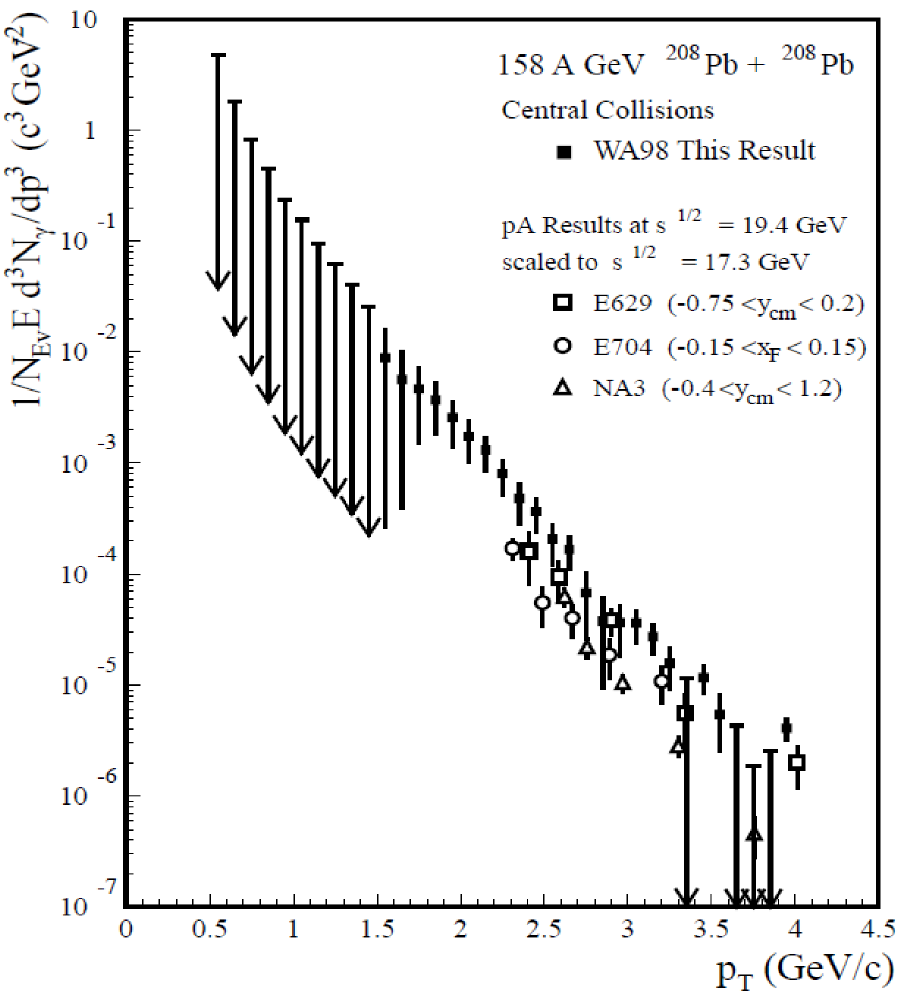


radii increase with multiplicity both in pp and Pb-Pb but with different slopes

→ not only final multiplicity but also initial geometry matters

Direct photons: give access to entire time evolution

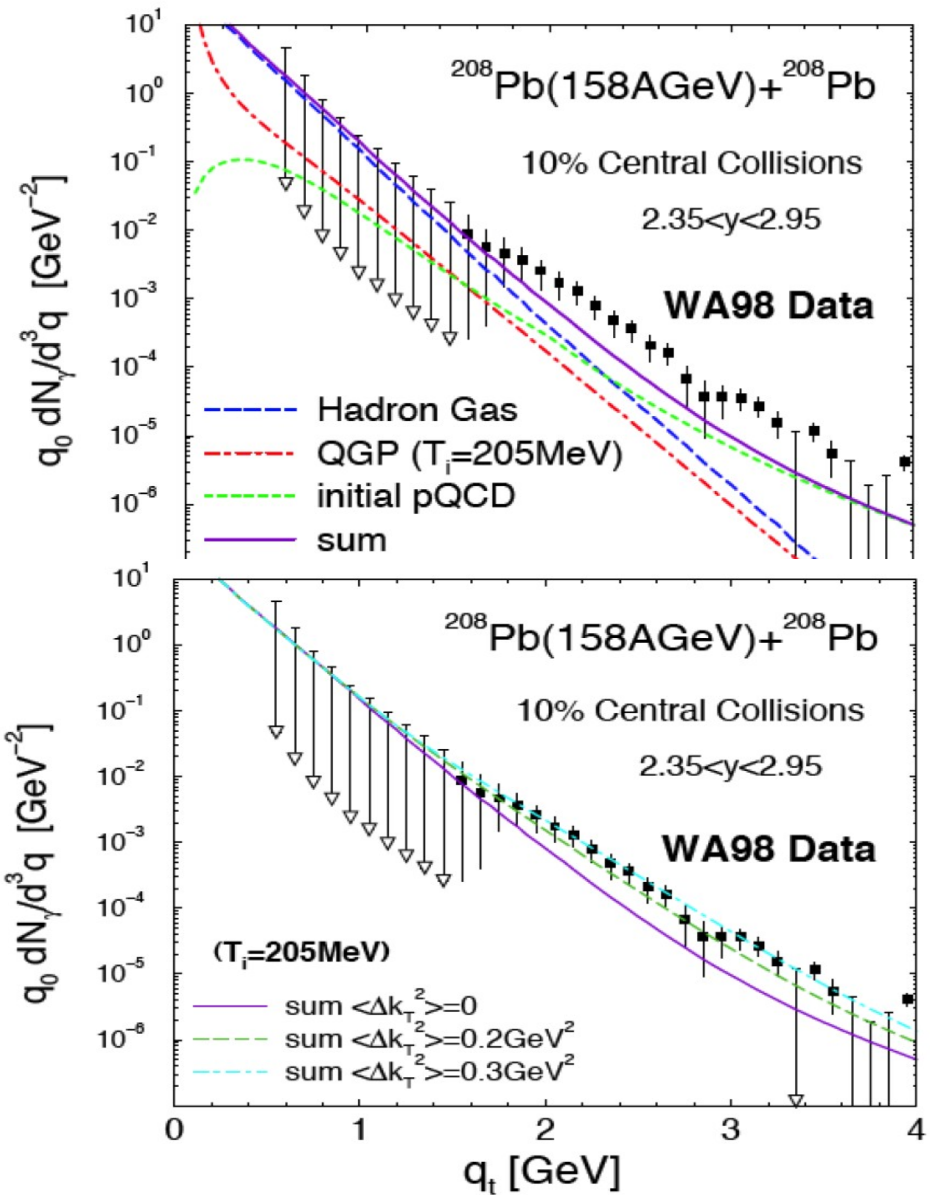
WA98



$\lambda_{mfp} \gg$ medium

$\rightarrow$ access to early QGP-phase

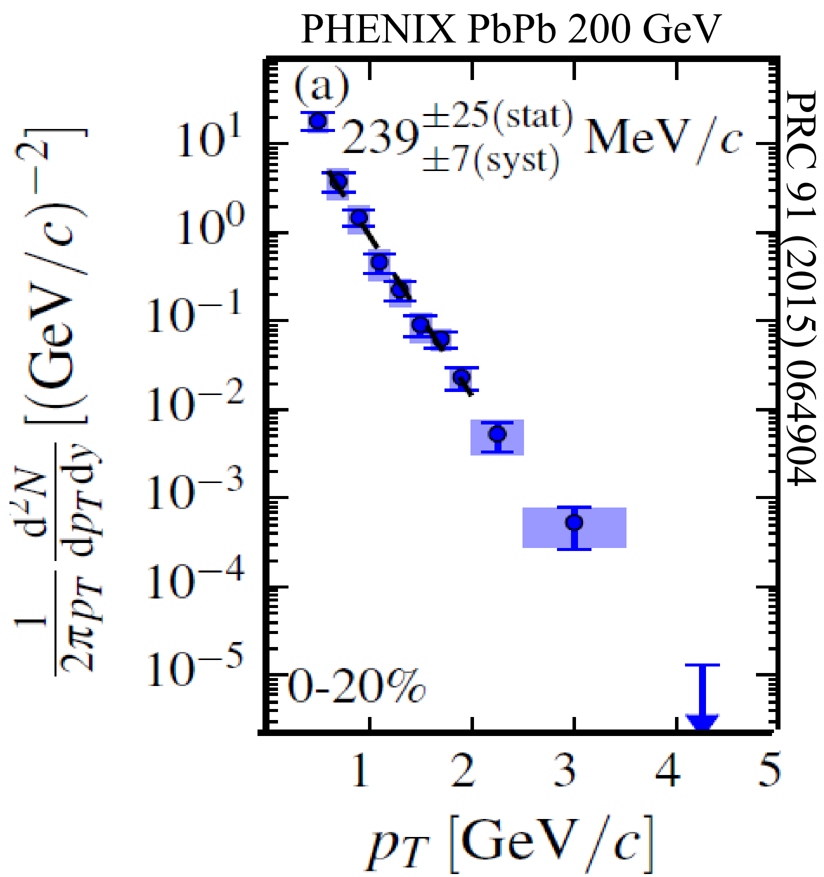
Direct photons: give access to entire time evolution

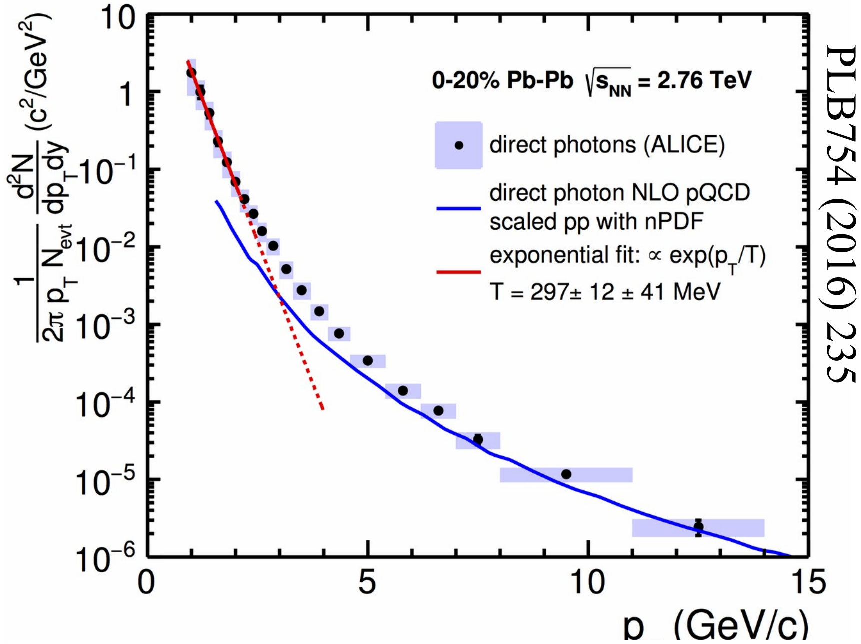


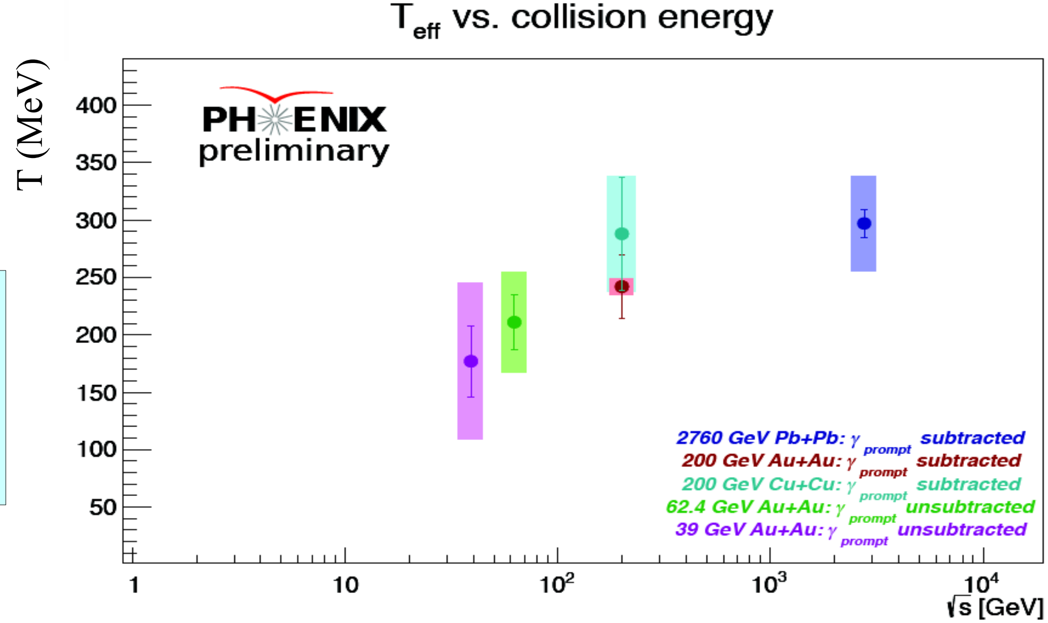
$\lambda_{mfp} \gg$ medium
$\rightarrow$ access to early QGP-phase

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





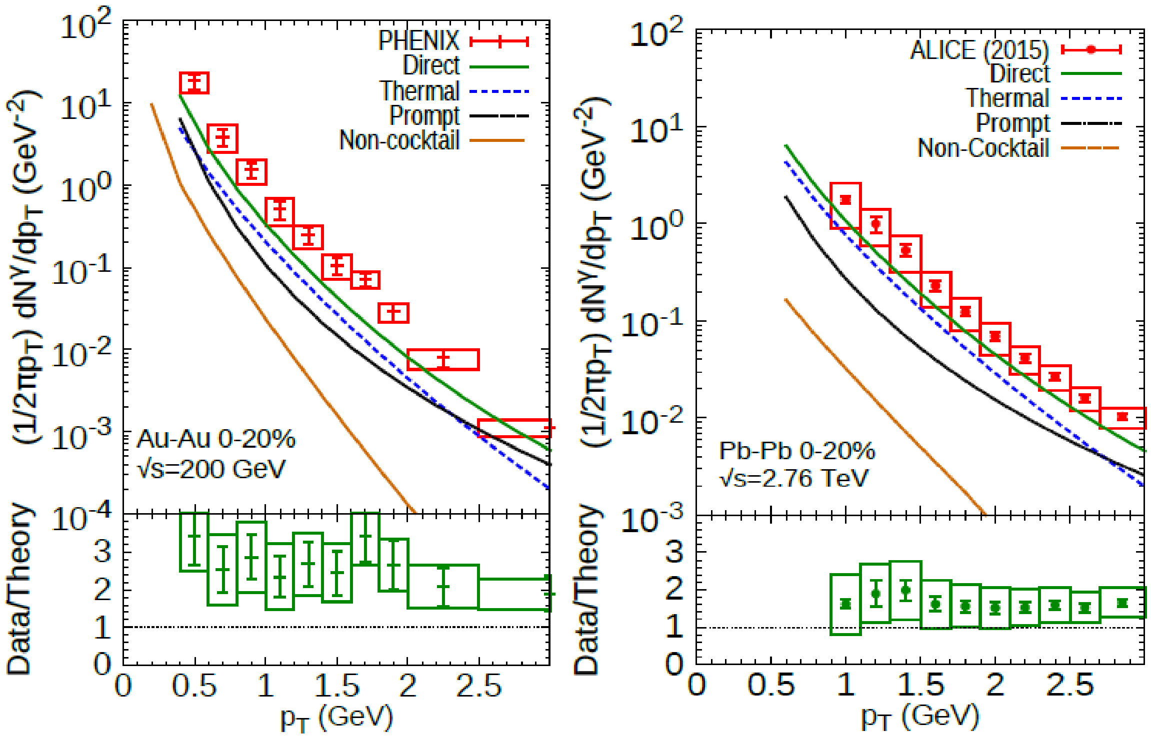


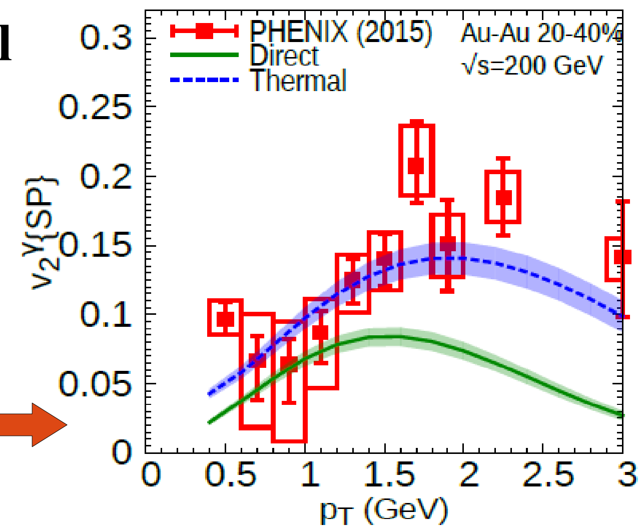
direct photons of fireball exhibit higher apparent temperatures with increasing √s

Direct photons at RHIC & LHC exhibit strong elliptic flow

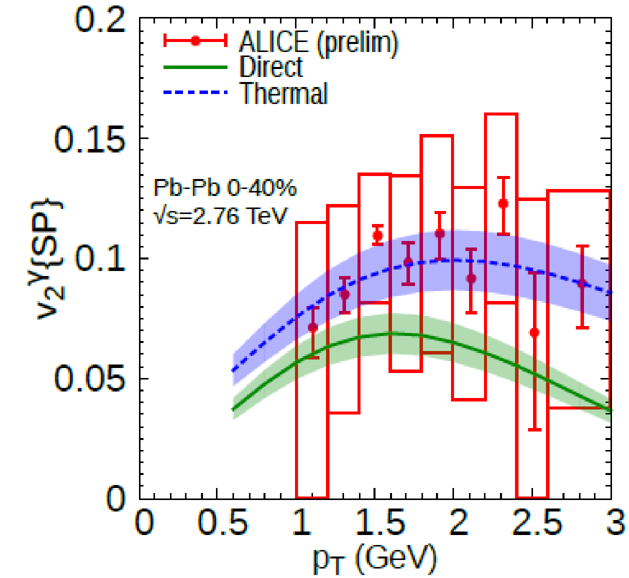
photon radiation of hydrodynamically expanding fireball

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





PRC94 (2016) 064901

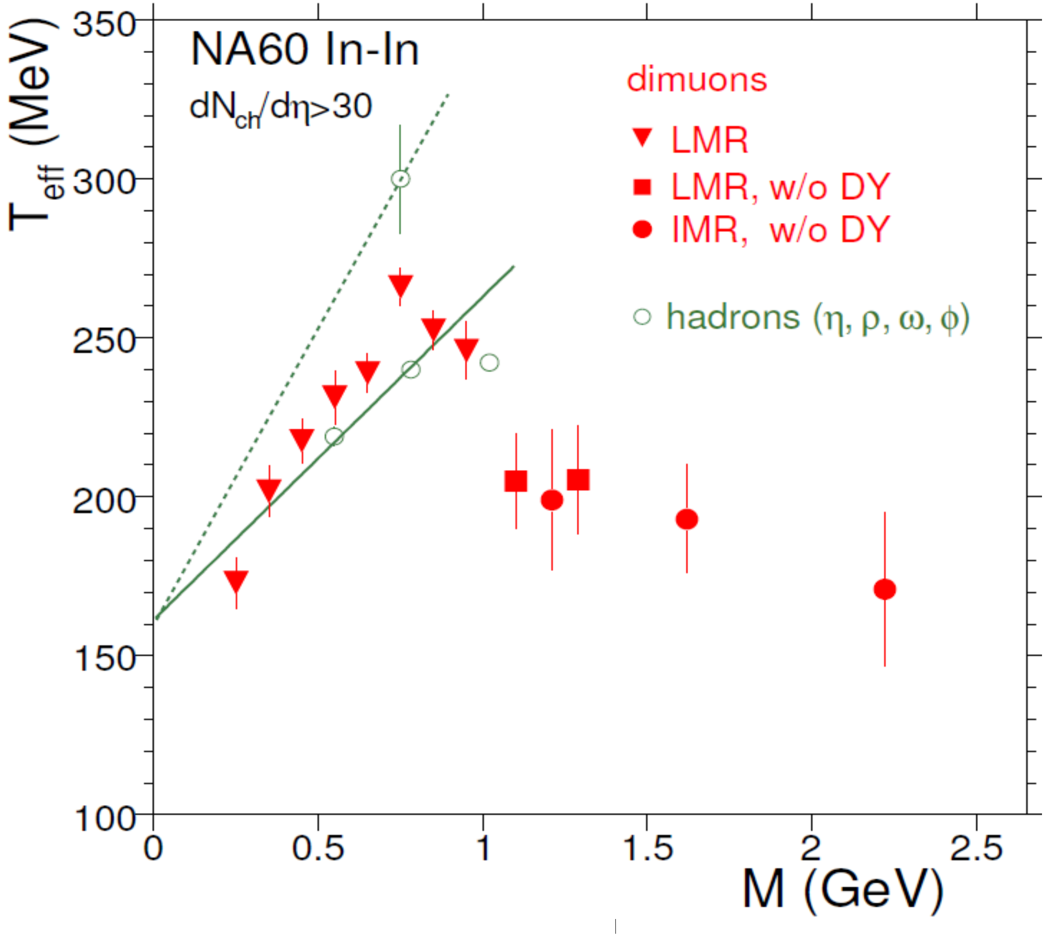


PLB754 (2016) 235

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

rate ∝ T^2 - but flow takes time to evolve

Low and intermediate mass lepton pairs

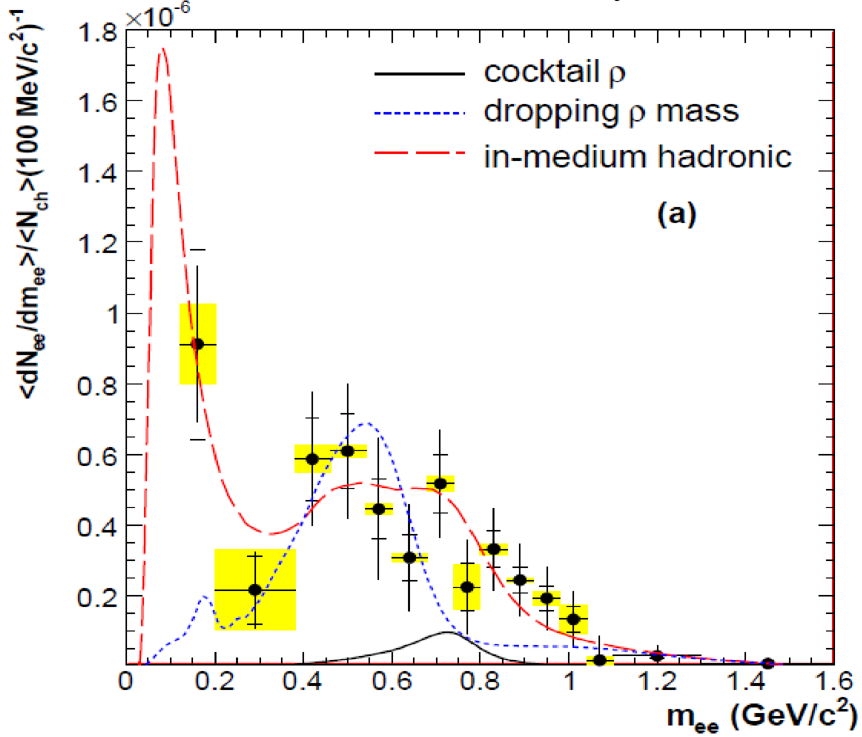


EPJ C61 (2009) 711

- 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

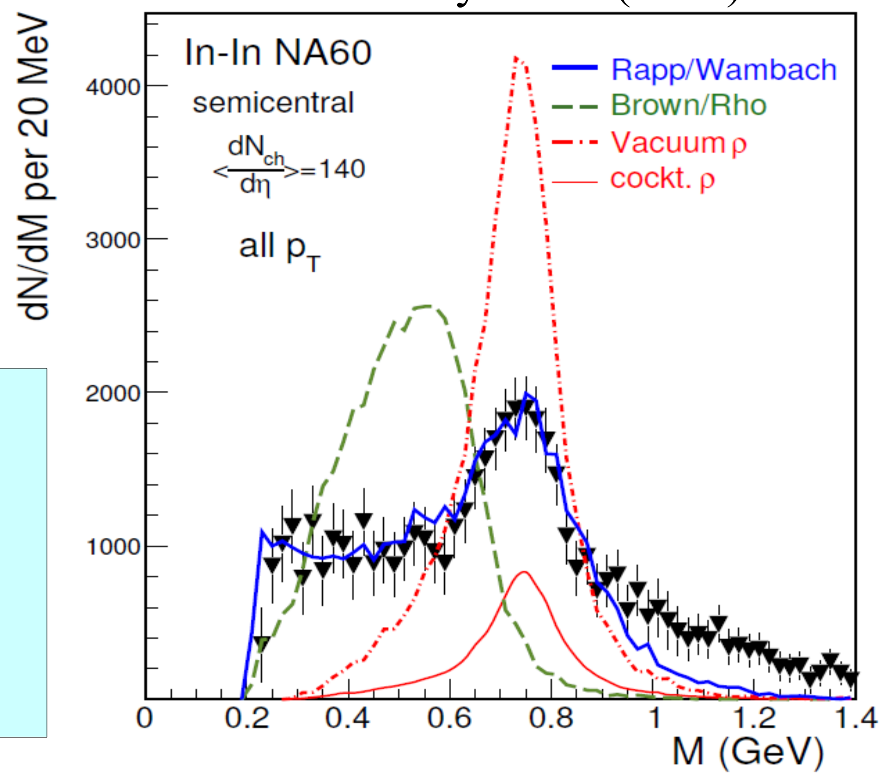
Low and intermediate mass lepton pairs

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



r meson spectral function provides access to **restoration of chiral symmetry**
at Tc degeneracy with chiral partner a1

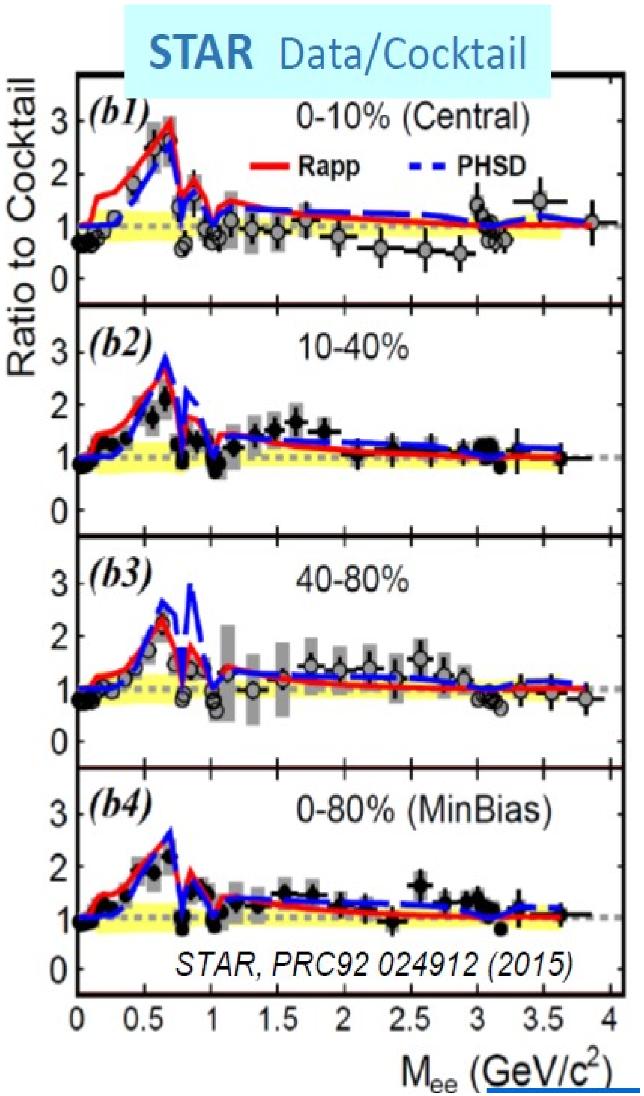
Eur. J. Phys. C61 (2009) 711



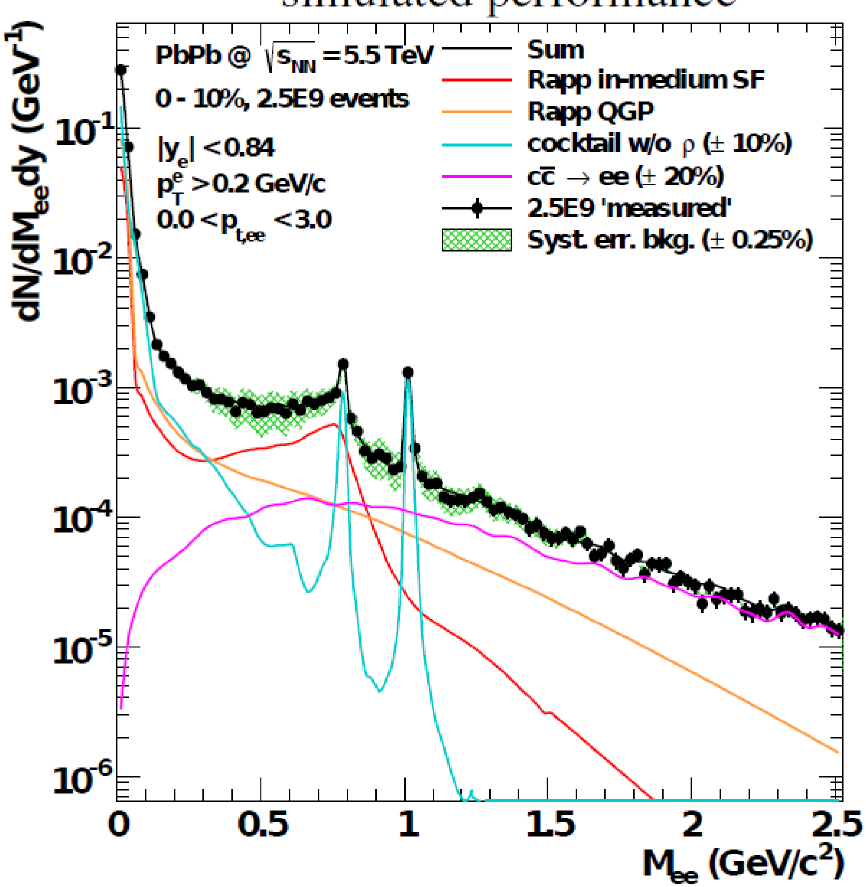
exp data of e+e- in central PbPb and of m+m- in semi-central InIn after subtraction of all hadronic contributions except ρ: theories need significant broadening of spectral function of ρ at high T

theory R. Rapp

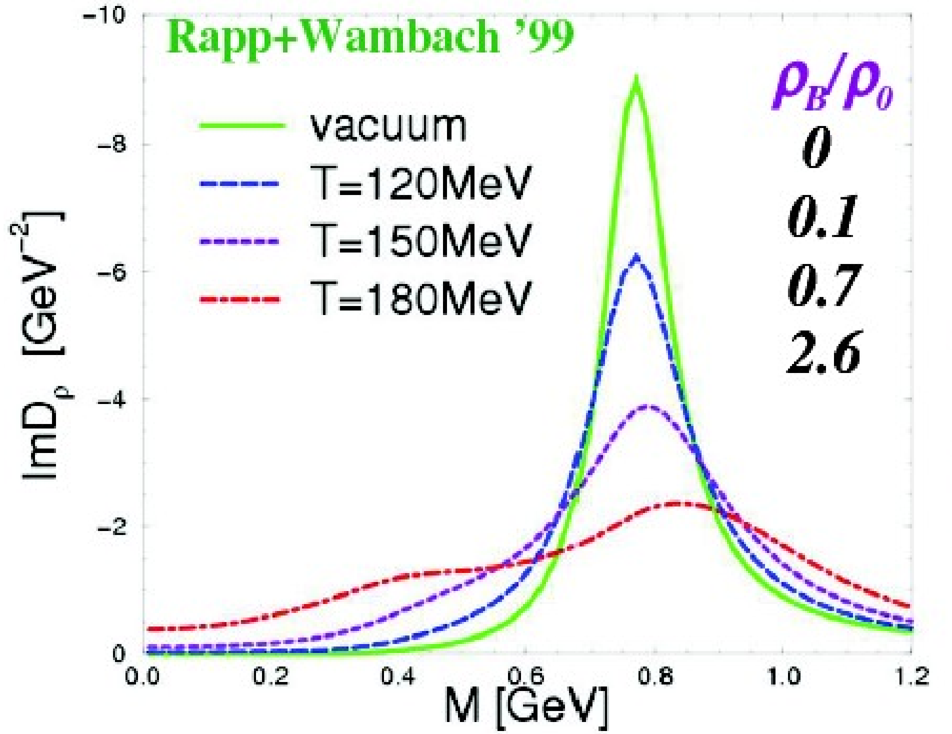
Low and intermediate mass lepton pairs at colliders



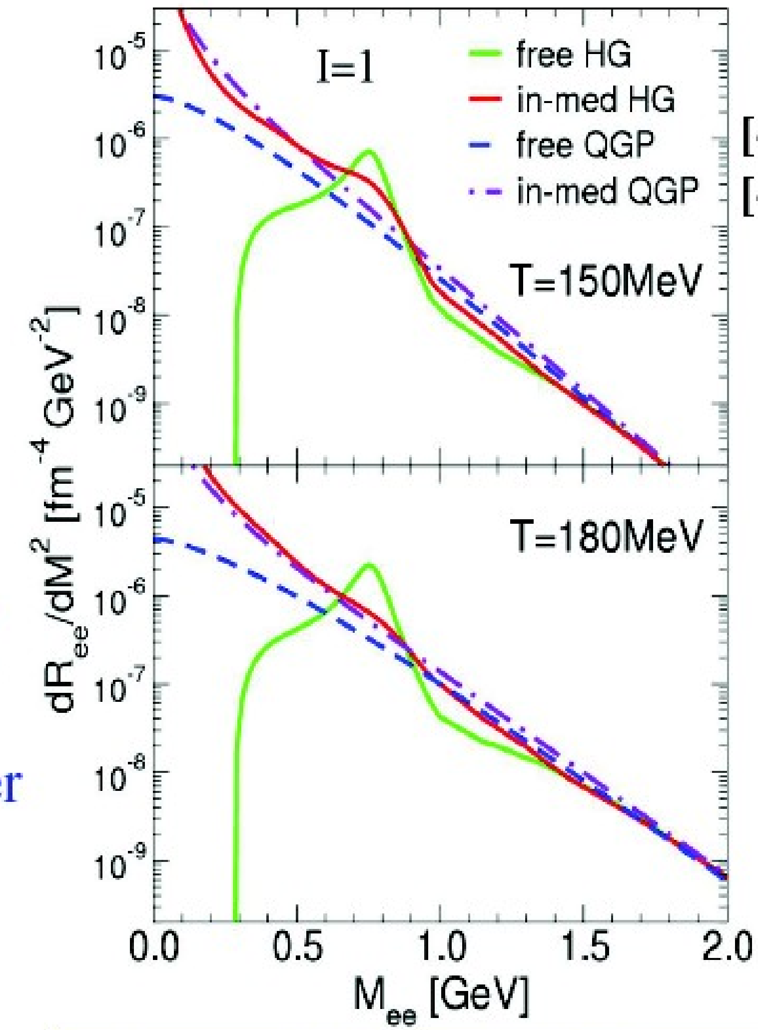
- at colliders much more difficult
- at RHIC after 15 years consolidated results between STAR and PHENIX described well by the same models as SPS data
- for ALICE very challenging project for Run3/Run4



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



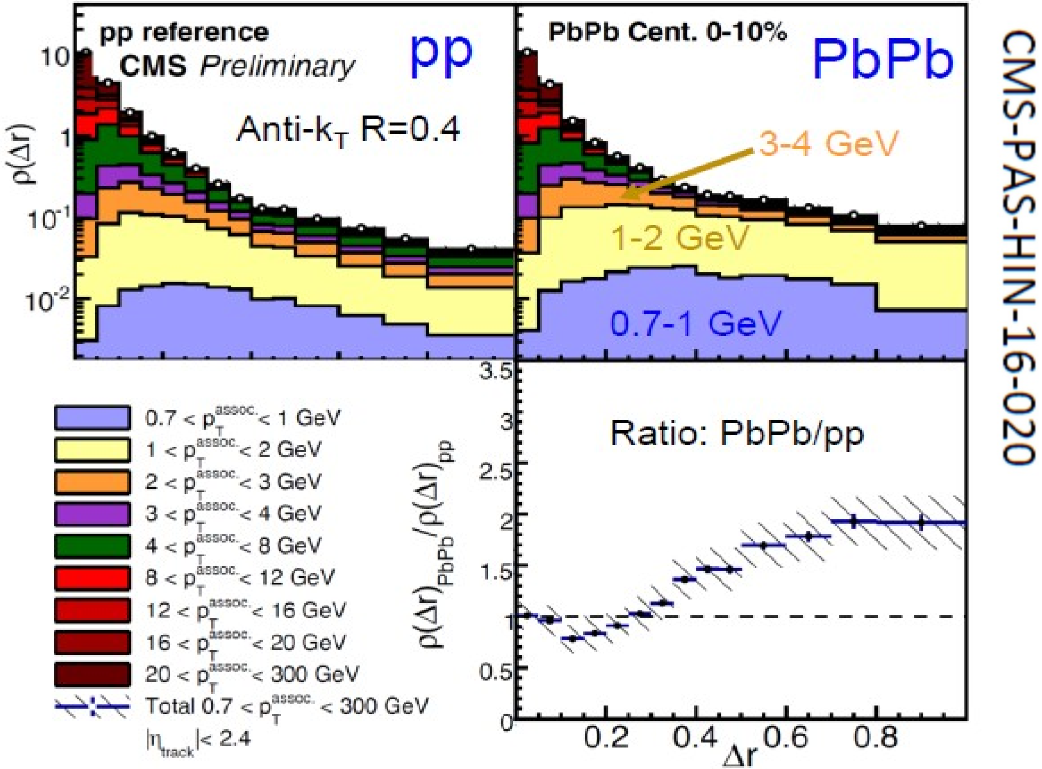
ρ-meson "**melts**" in hot and dense matter



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

Where does lost energy go?

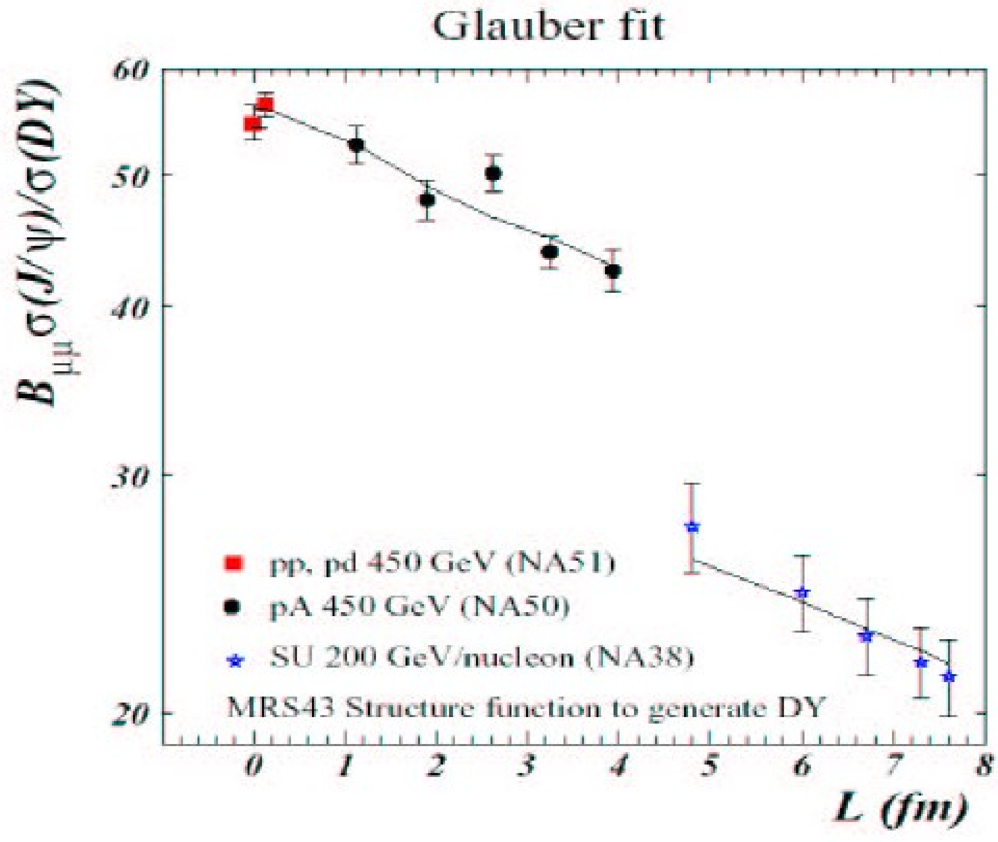
Jet-hadron correlations in pp and PbPb collisions at 5.02 TeV



low momentum particles
and at larger distance from jet core

J/ψ Suppression in pA Collisions

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



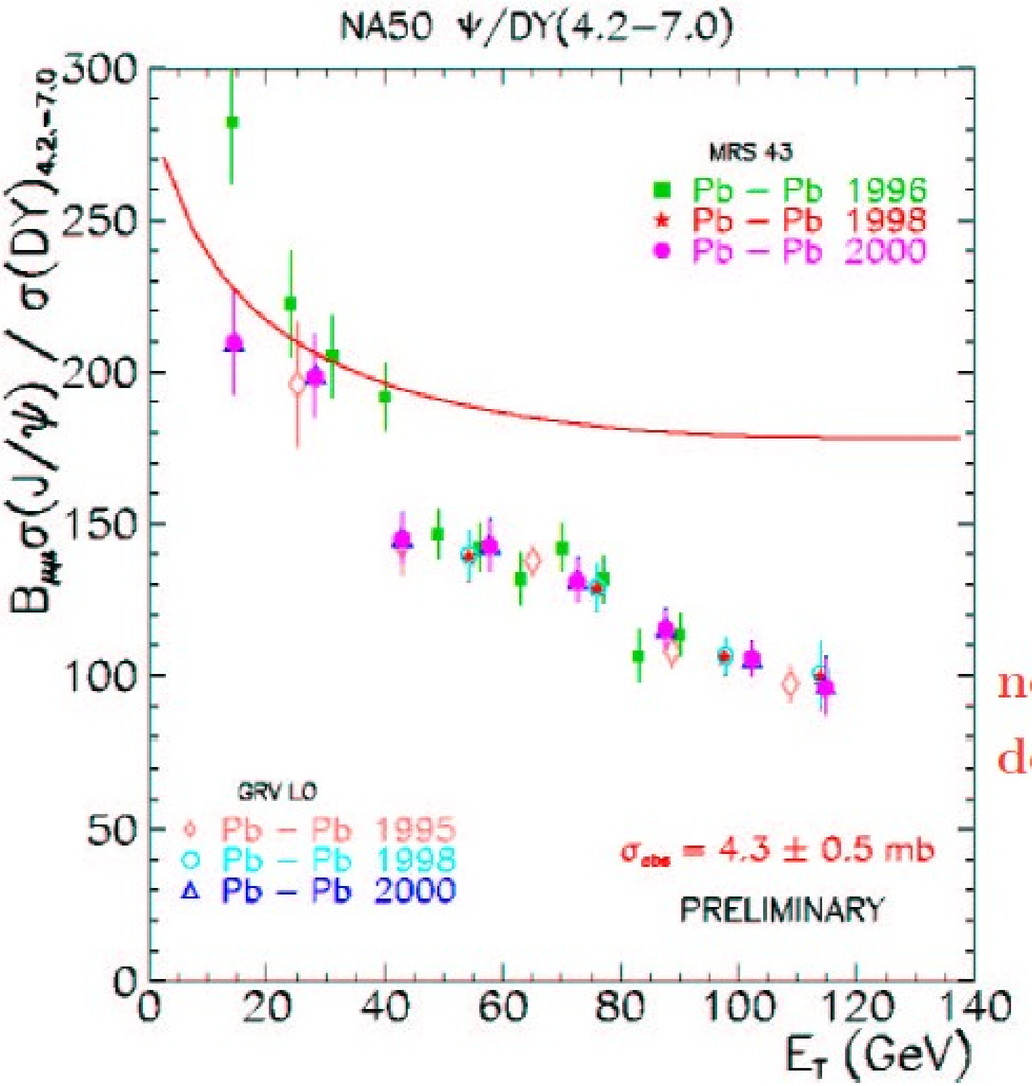
NA50,Phys.Lett.B553(2003)167

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

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

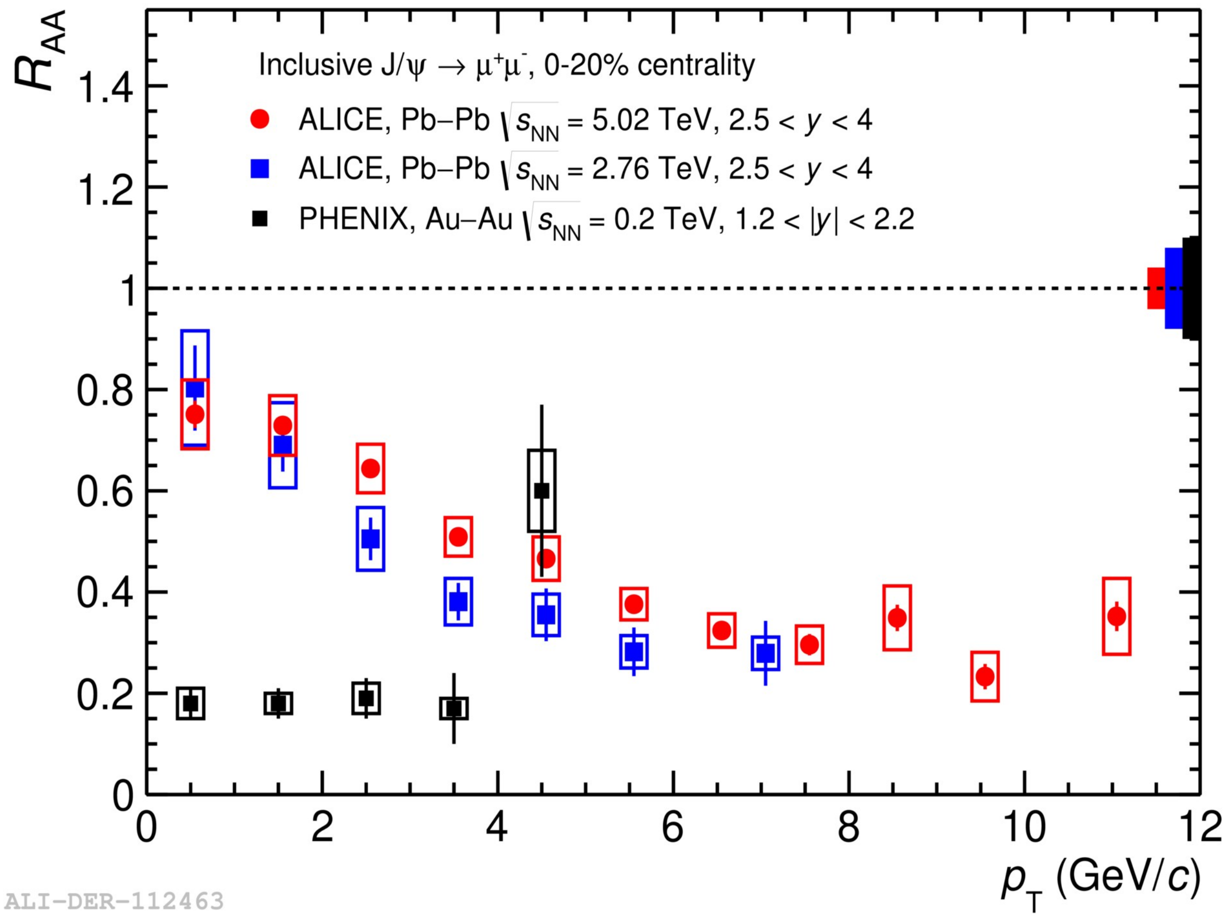
Anomalous J/ψ Suppression in PbPb Collisions

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



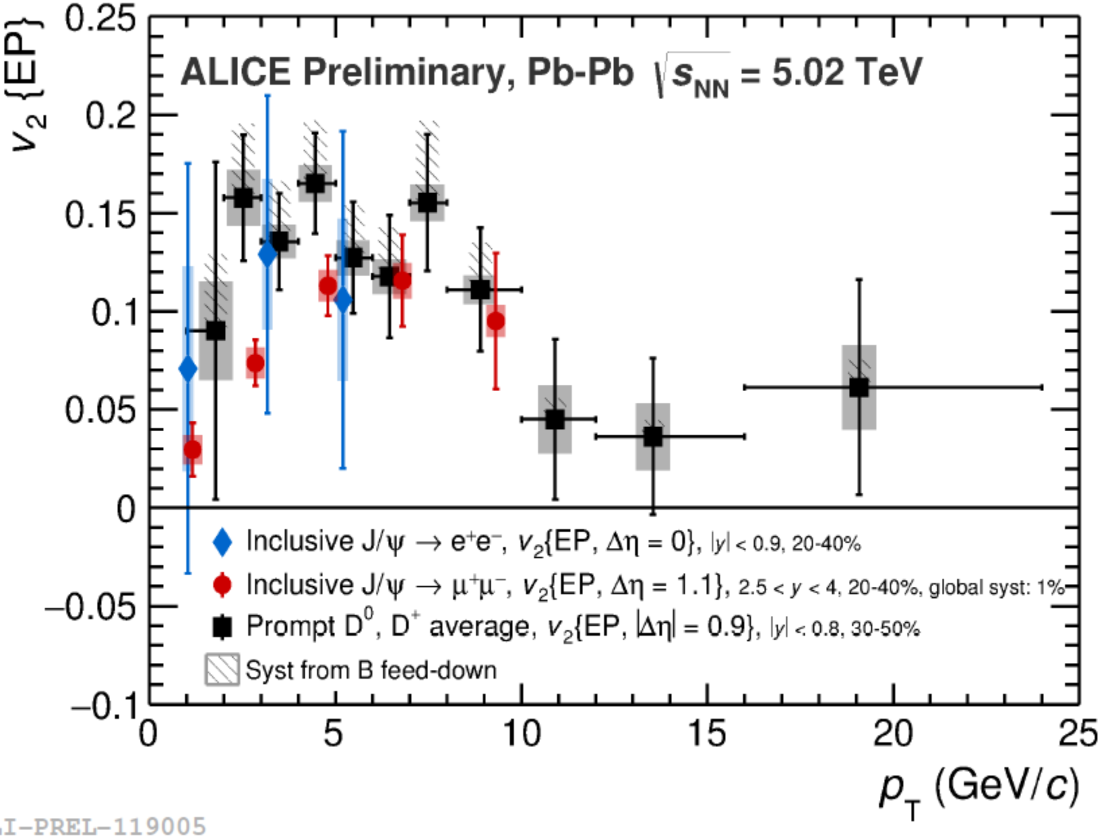
softer in PbPb as compared to pp

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



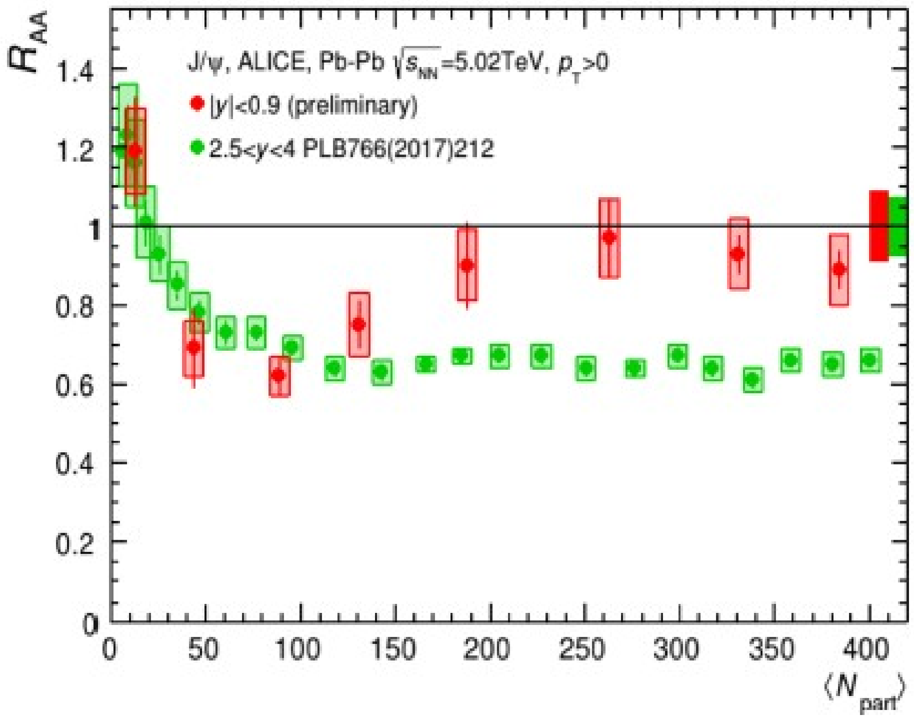
charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

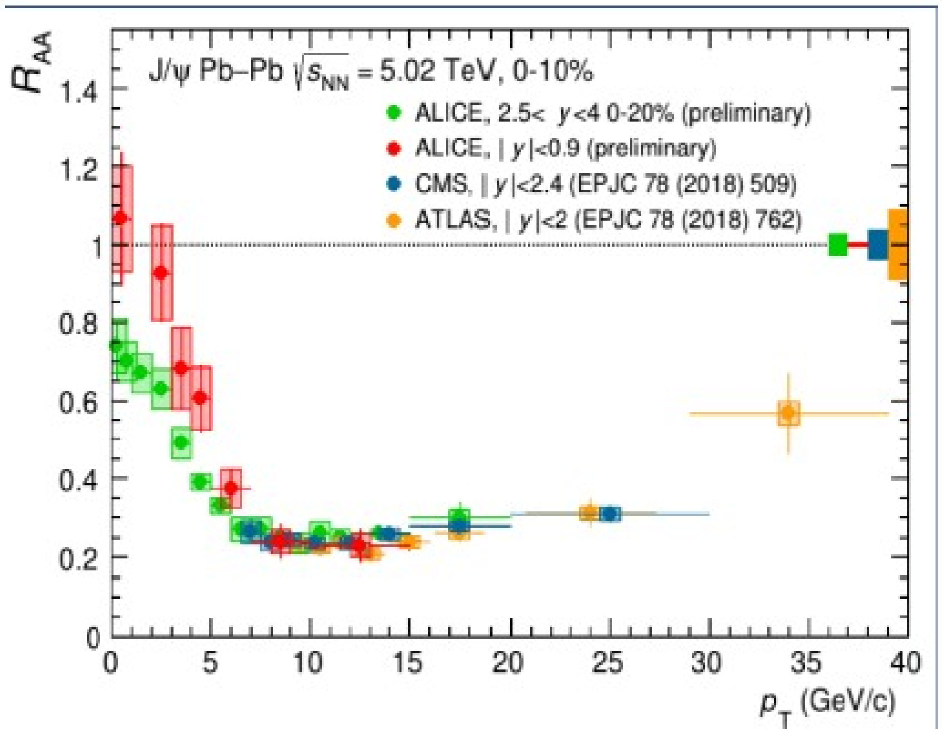
- expect build-up with p_t as observed for p, p. K, L, … and vanishing signal for high p_t region where J/y not from hadronization of thermalized quarks

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

Charmonium at LHC: peaks at mid-y and strong enhancement at low transverse momentum

nuclear modification factor: $$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}\rangle dN^{pp}/dp_T}$$

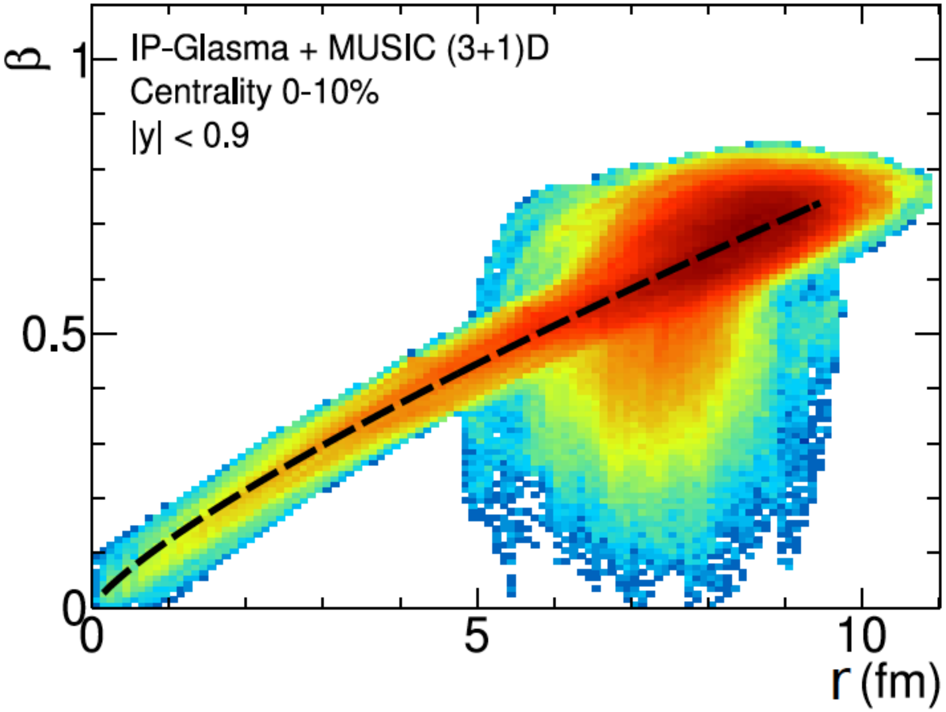




Beyond yields: transverse momentum distributions

assume thermalization of charm quarks in QGP, charm quarks follow collective flow
use hydro velocity profile at pseudocritical temperature from MUSIC (3+1) D
tuned to light flavor observables

A. Andronic, P. Braun-Munzinger, M. Koehler, K. Redlich,
J. Stachel, PLB 797 (2019) 134836 arXiv:1901.09200



$$\frac{d^2N}{p_T dp_T dy} \propto \int_0^R r dr \Big\{ m_T \cosh\rho \, K_1\left(\frac{m_T\cosh\rho}{T}\right) I_0\left(\frac{p_T\sinh\rho}{T}\right) - p_T\sinh\rho \, K_0\left(\frac{m_T\cosh\rho}{T}\right) I_1\left(\frac{p_T\sinh\rho}{T}\right)\Big\}$$

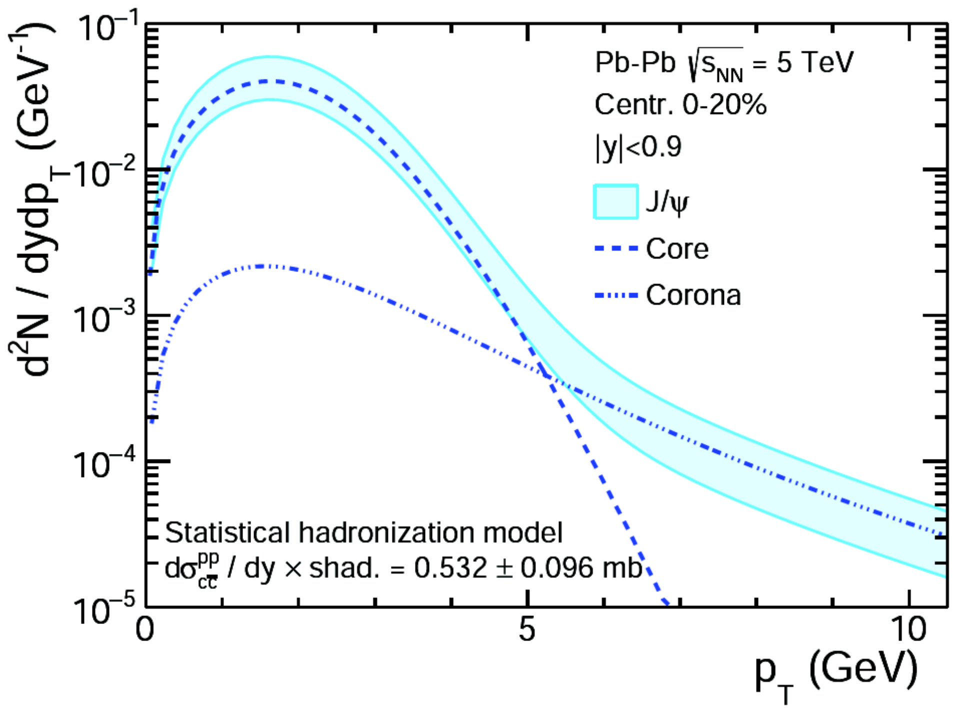
$$\rho = \operatorname{atanh}(\beta_T^s (r/R)^n)$$

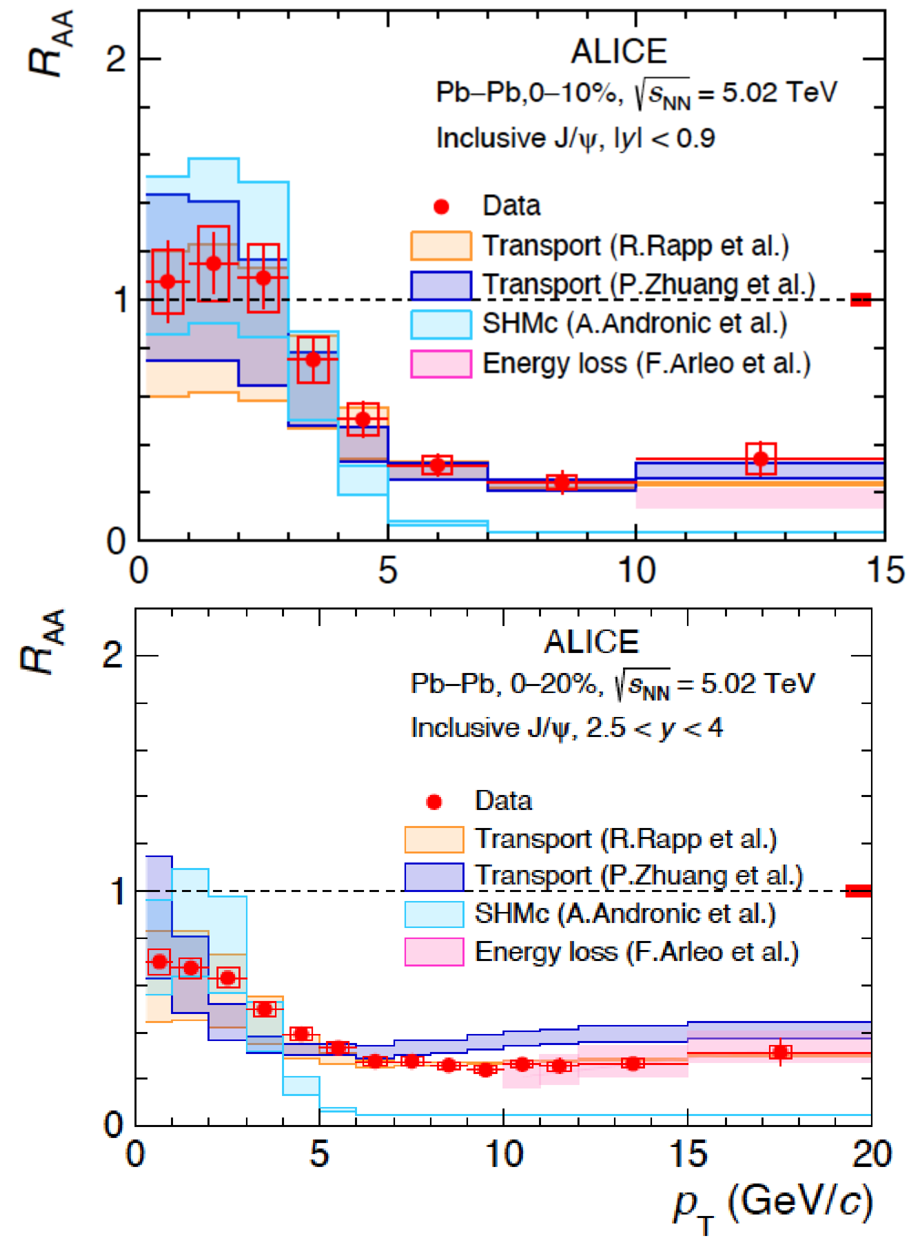
'blast wave parametrization' of spectral shape with T = 156.5 MeV and
parameters from MUSIC: n = 0.85 and $\beta_{max} = \beta^s{}_T = 0.62$

J/ψ spectra from SHMc and parametrization of hydro freeze-out hypersurface

arXiv:2303.13361

A. Andronic, P. Braun-Munzinger, M. Koehler, K. Redlich, J. Stachel, PLB 797 (2019) 134836 arXiv:1901.09200

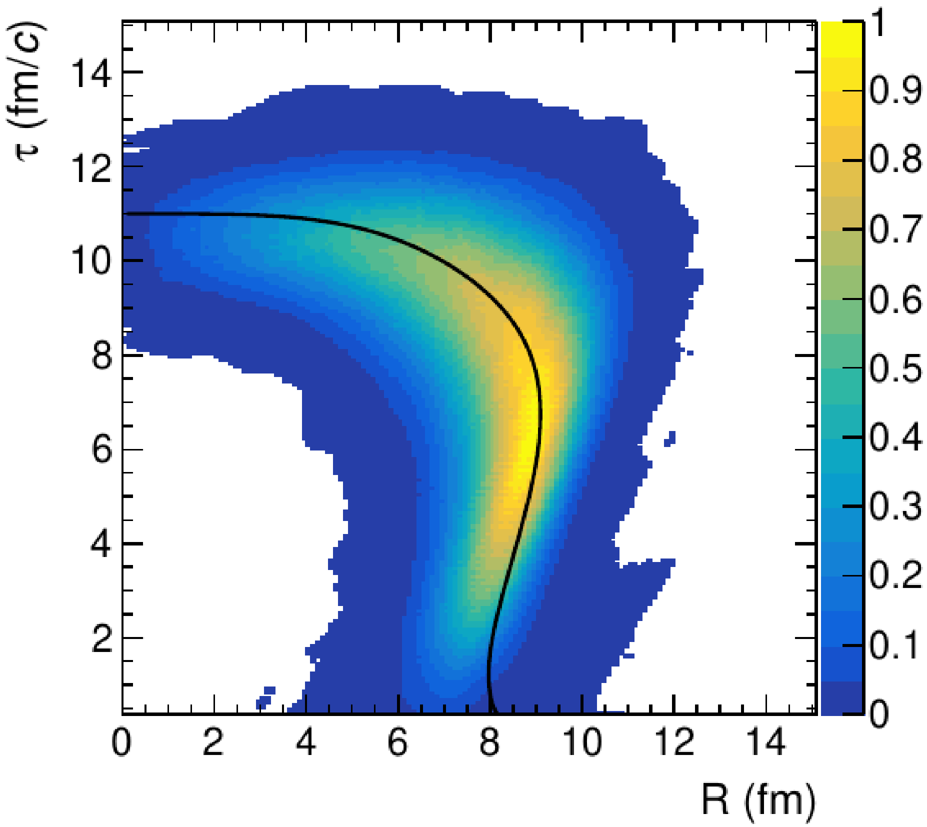




- at low and intermediate p_t very good description of data
- beyond 5 GeV there is additional source beyond statistical hadronization e.g. nonthermalized component

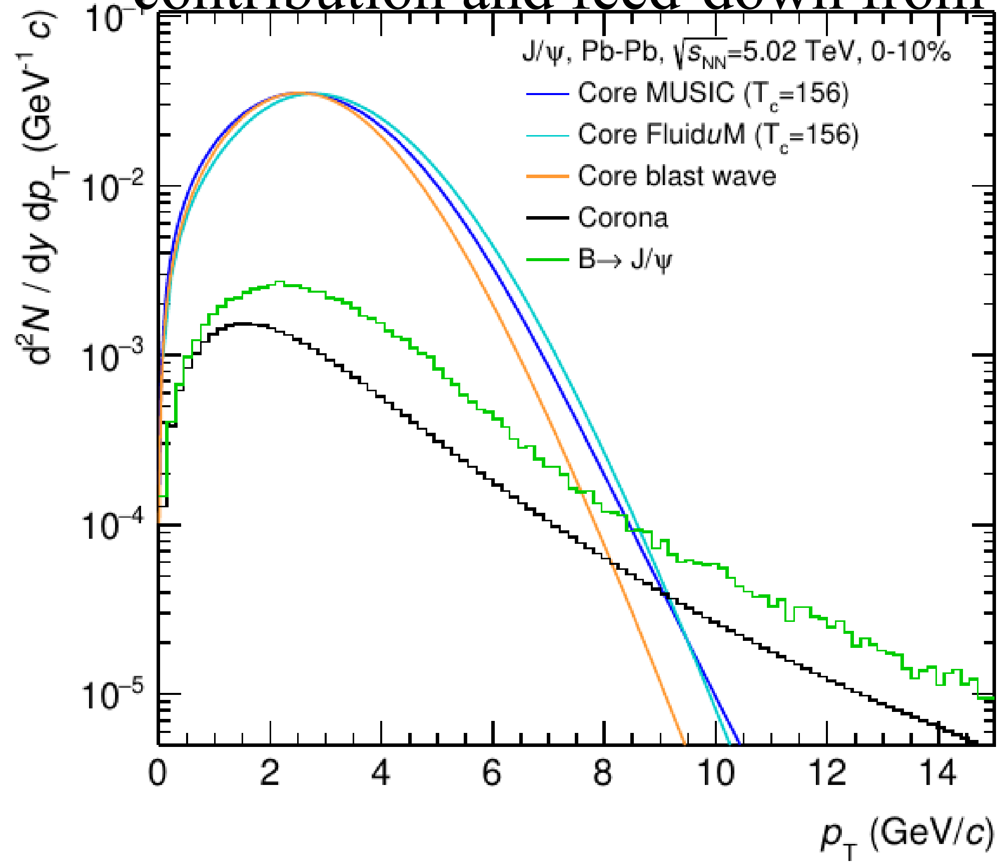
new approach to spectra and v_2: use Cooper-Frye freeze-out of hydrodynamics codes directly

A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821



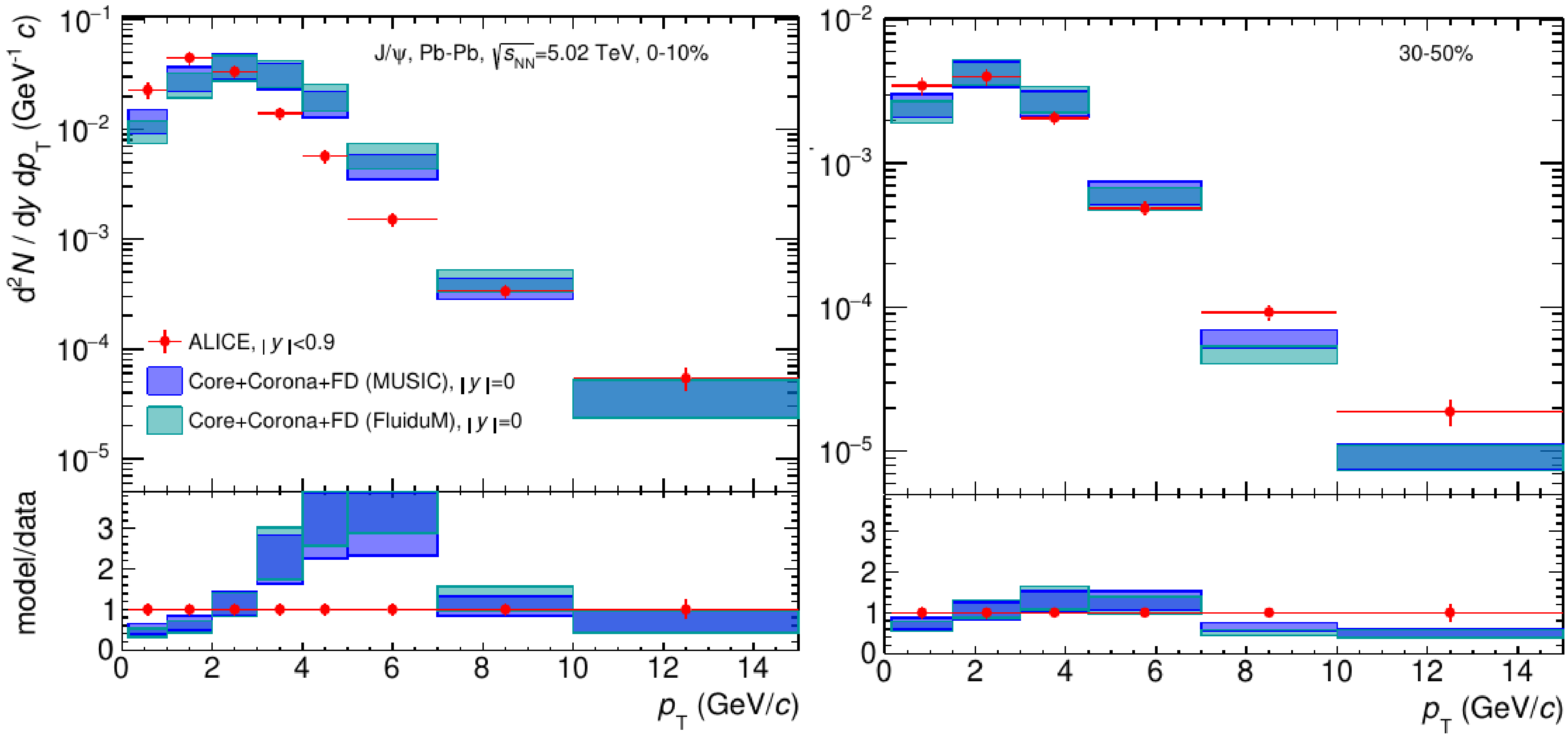
freeze-out hyper surface elements at T=156.5 MeV from MUSIC
solid line: FluiduM

resulting J/ψ spectra including corona contribution and feed-down from B



J/ψ spectra new approach

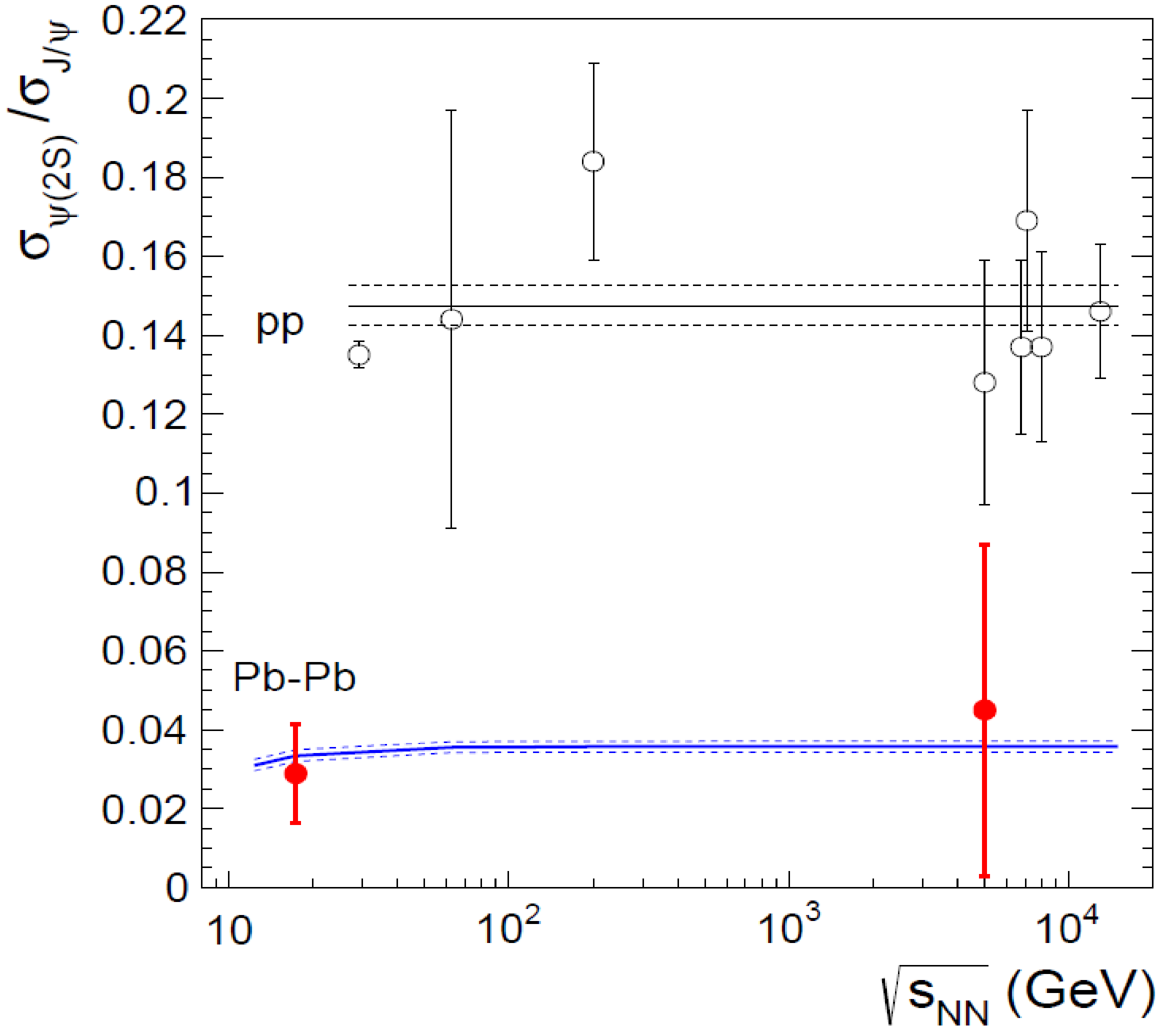
A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821



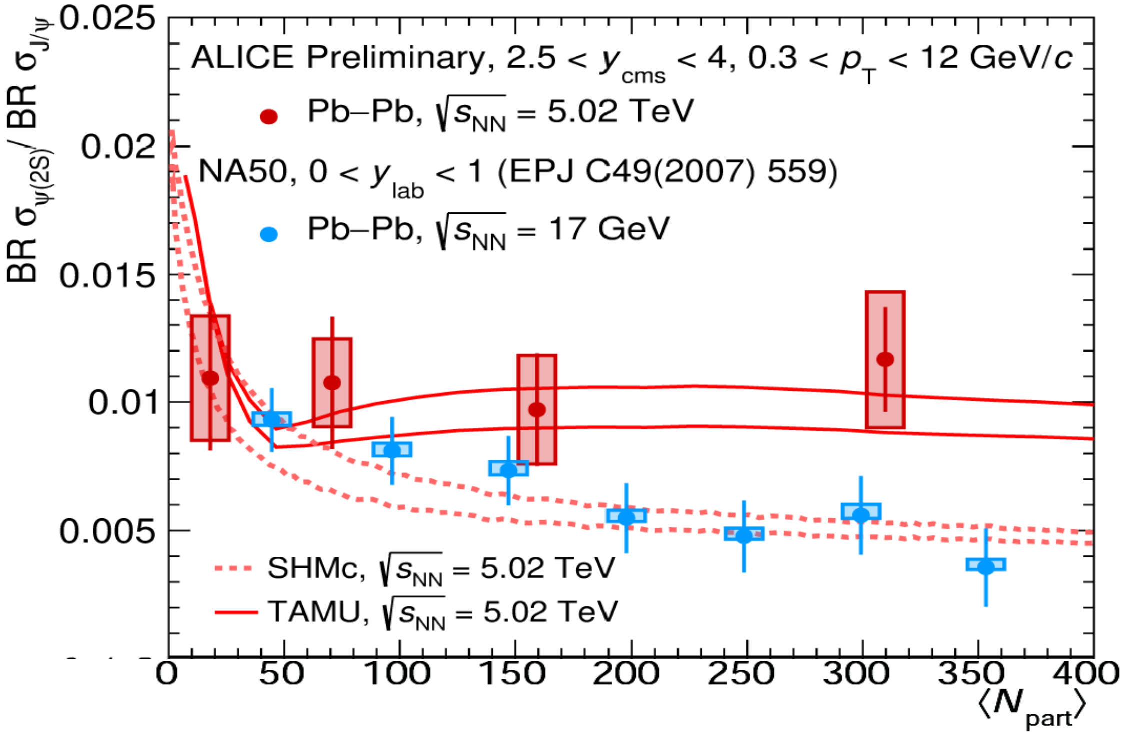
- spectra harder by about 1 GeV, in hydro many fluid cells at large velocities not accounted for by simple blast wave parametrization
- for central collisions somewhat too much flow – are charm quarks reaching the very outer front of the expanding fireball?

ψ(2S)

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



What about ψ(2S)?



excited state population suppressed by Boltzmann factor
- first measurement in PbPb down to p_t=0
- data 1.8 σ above SHMc for most central bin

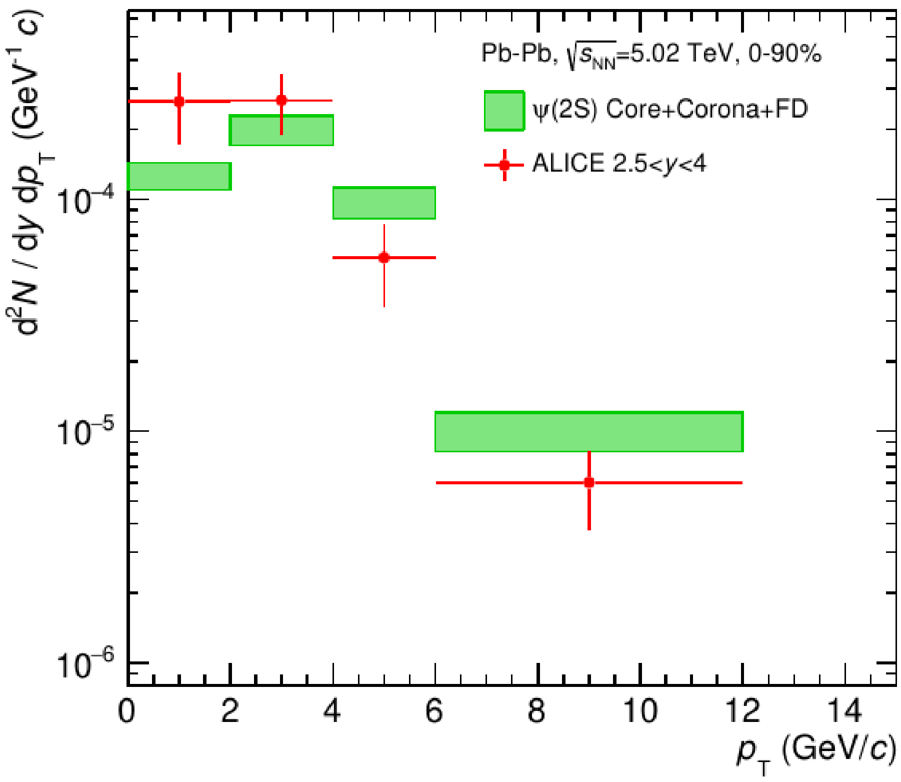
within stat. hadronization approach, an unexpected result
→ little room to accommodate in a likely physical scenario
larger common freeze-out temperature ☹
larger freeze-out temperature for ψ(2S) vs J/ψ ☹

future opportunity:
higher precision y(2S), also mid-y
χ_c maybe only in ALICE3?

} deconfinement temperature from charmonium spectrum

ψ(2S) spectrum

A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821

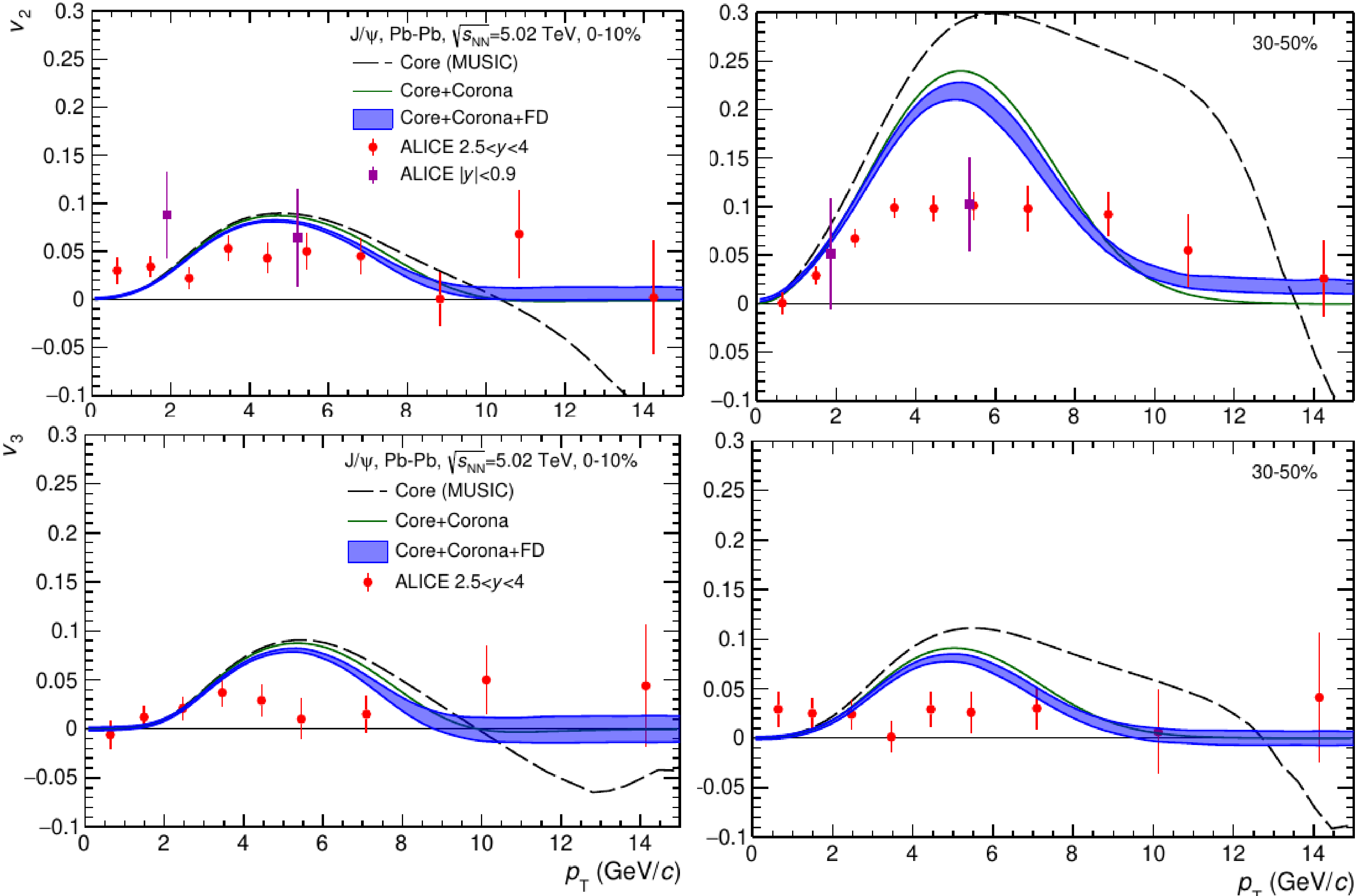


- for parameter free calculation pretty good agreement
- tendency towards somewhat too hard spectrum from model

-> needs more data

first calculation of J/ψ flow in SHMc plus hydro approach

A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821



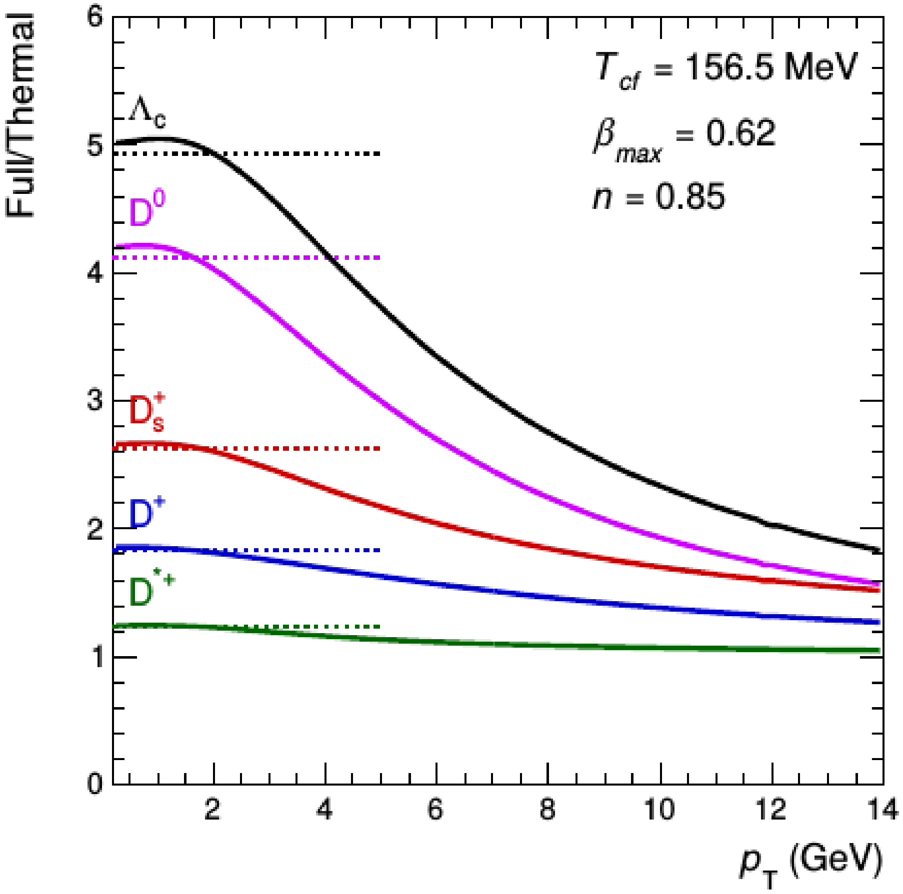
- significant flow arises over large pt range, difficult for other models
- for semi central collisions magnitude of flow over predicted

Spectra of D mesons and Λ_c baryons

for open heavy flavor hadrons strong contribution from resonance decays
- include all known charm hadron states as of PDG2020 in SHMc
- compute decay spectra with FastReso: 76 2-body and 10 3-body decays

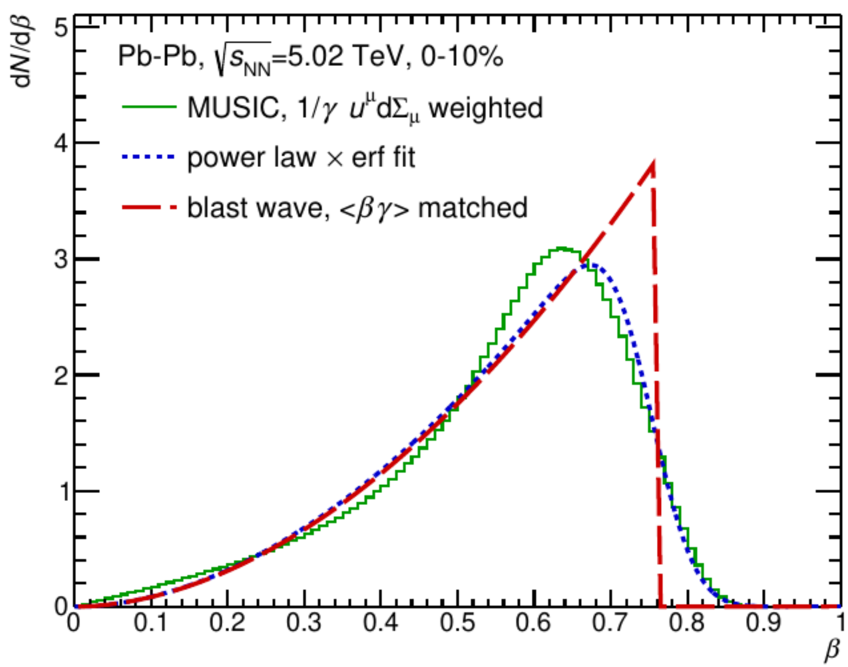
(A. Mazeliauskas, S. Floerchinger, E. Grossi, D. Teaney, EPJ C79 (2019) 284)

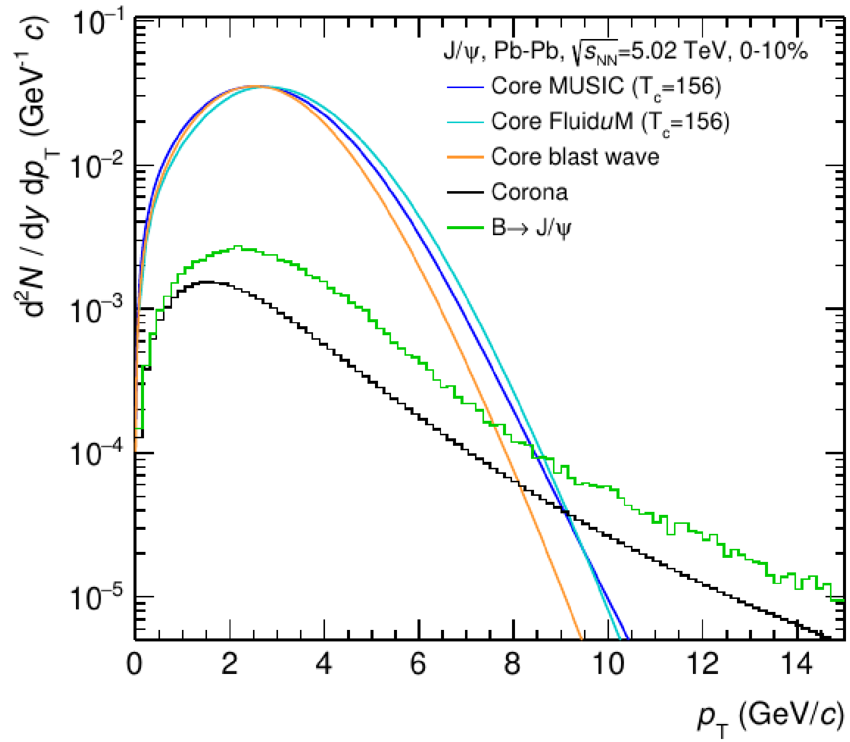
A.Andronic, P.Braun-Munzinger, M.Köhler, A.Mazeliauskas, K.Redlich, JS,V.Vislavicius JHEP 07 (2021) 035



Optimally matched blast wave parameters

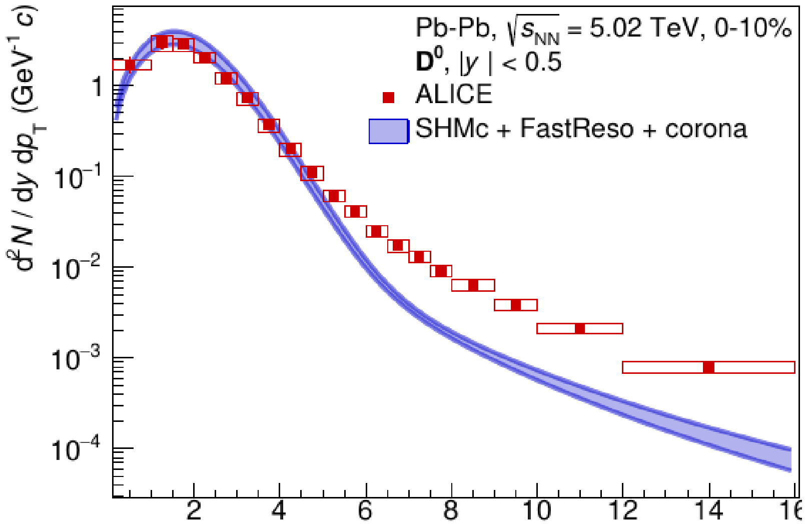
instead of inserting dozens of charmed hadrons into MUSIC, resort to blast wave parametrization again
but now we have advantage to be able to compare to 'true' hydro J/ψ spectrum
→ blastwave parameters modeled such that mean βγ of hydrodynamics is matched

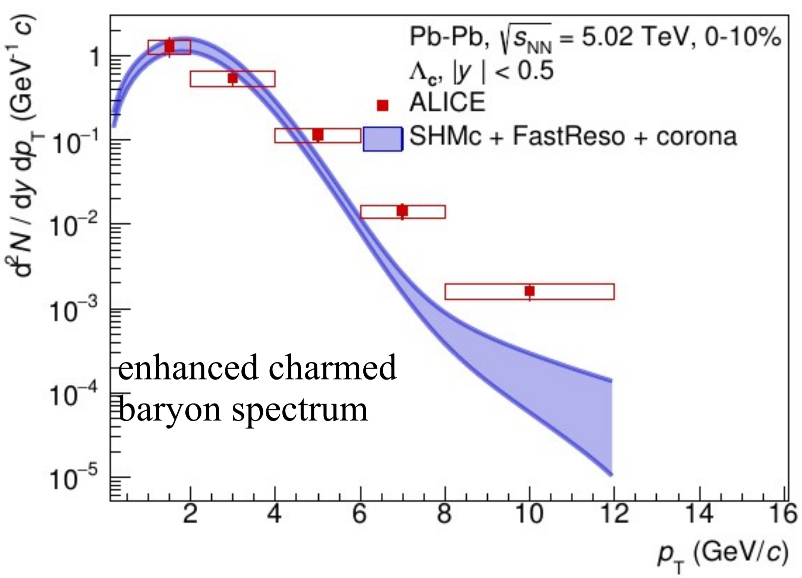




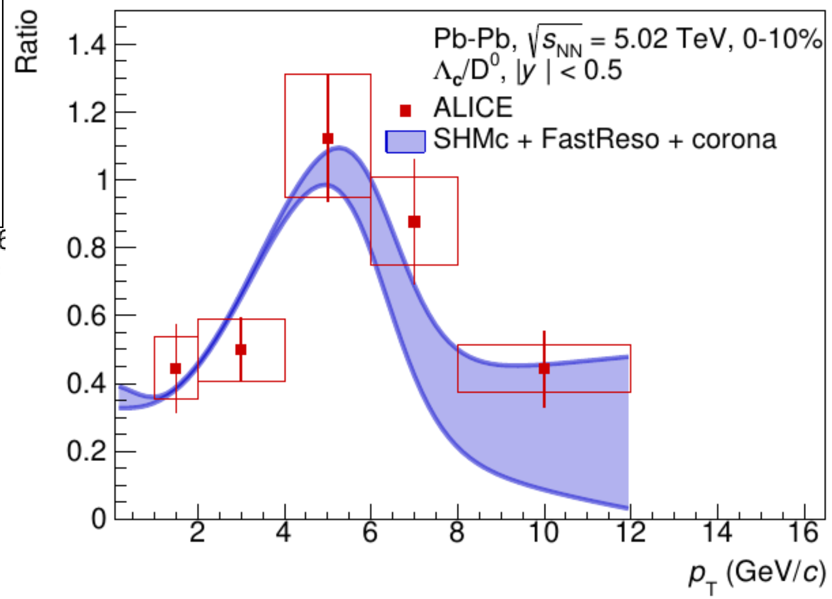
with β_{max} = 0.76 good matching can be achieved (red vs blue curves for core)

Open charm spectra – examples D^0 and Λ_c





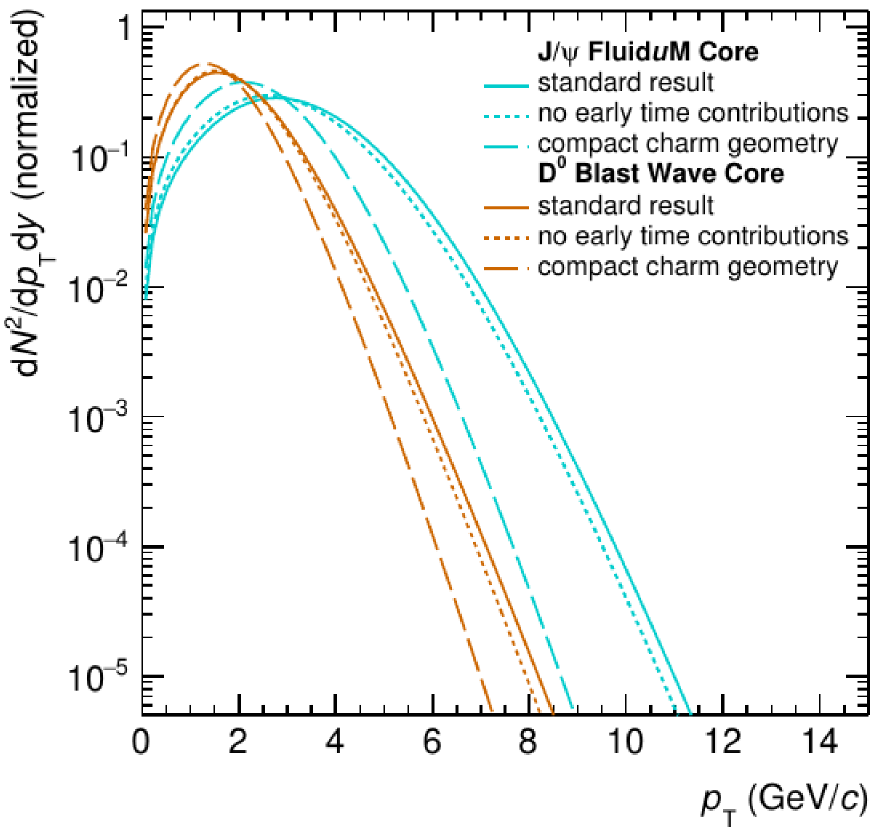
A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821



very good description of low and intermediate p_t data
maximum in ratio arises naturally from expansion

Charm quark spatial distribution at hadronization

A. Andronic, P. Braun-Munzinger, H. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821



strong indication that charm quarks are largely thermalized in terms of momenta

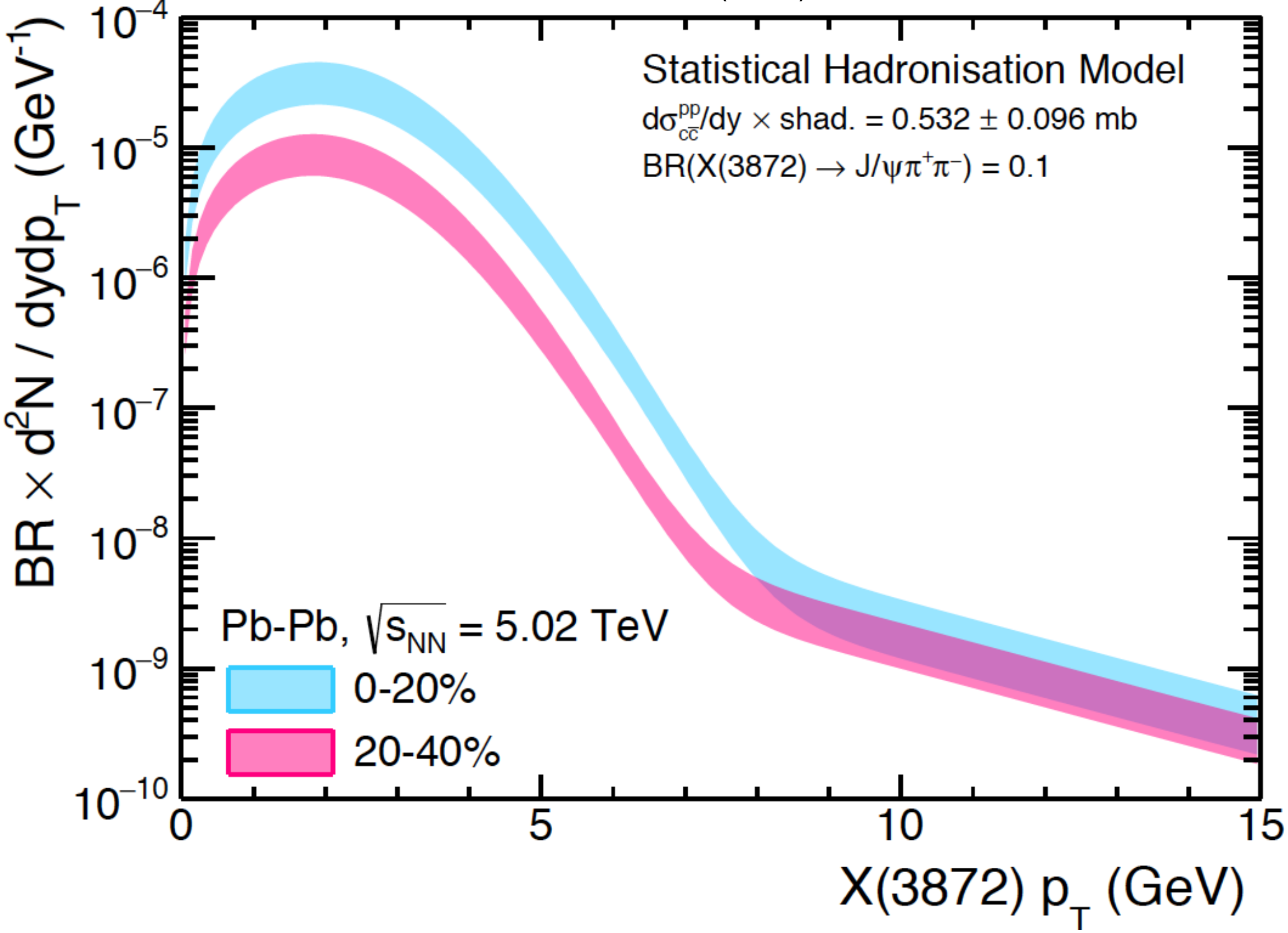
but since thermalization takes time, spatial distribution could lag behind front of expanding fireball

no experimental input
production of charm quarks very compact
(N_{coll})

test: cut off outermost 1 fm in spatial distribution (dashed line)
→ this goes in direction of matching exp. data

Future opportunities: χ_{c1}(3872)

A. Andronic, P. Braun-Munzinger, M. Koehler, K. Redlich, J. Stachel, PLB 797 (2019) 134836 arXiv:1901.09200



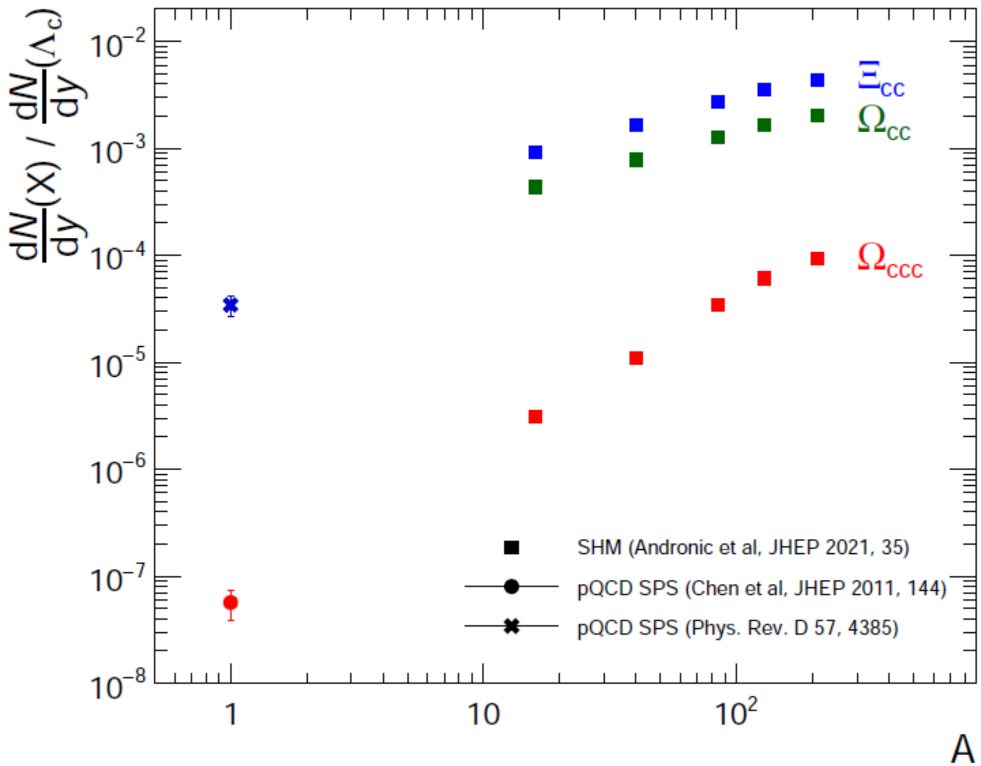
close to D^0D^{0*} threshold
- tetraquark or molecule?
- is it formed like (hyper)nuclei?

- decay into $J/\psi\ \pi^+\pi^-$
- doable in Run3/4?
- otherwise ALICE3

note: dramatic enhancement at low p_t predicted

CMS addresses only very high p_t part

Multi-charmed baryons



Letter of intent ALICE3 arXiv: 2211.02491

because of powers of g_c → strongly favored in collisions of heavy nuclei

can be addressed by ALICE3
e.g. Ξ_{cc}^{++} recently discovered by LHCb in pp collisions arXiv:1910.11316

$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$
$$\Lambda_c^+ \to p K^- \pi^+$$

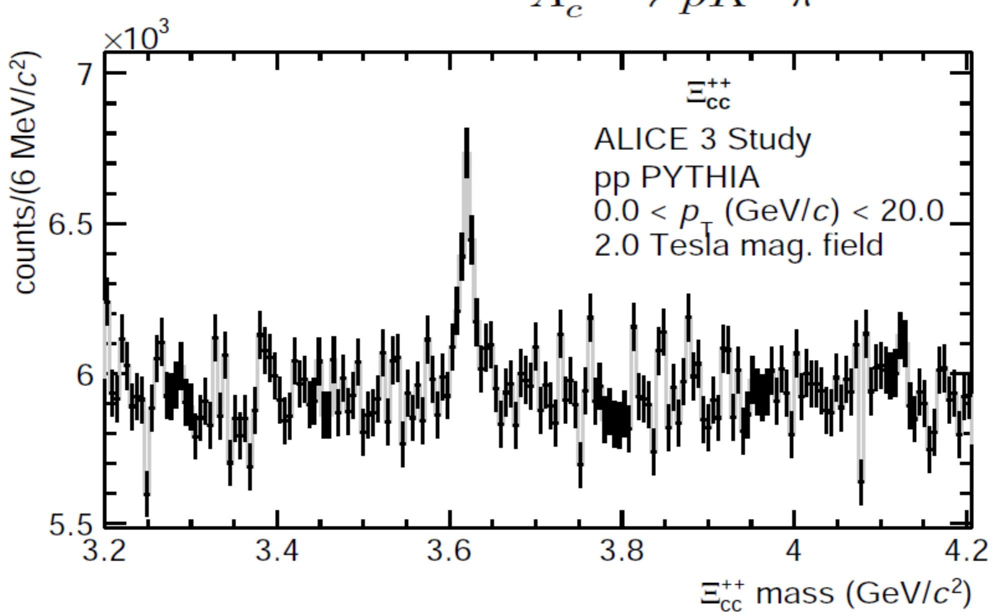


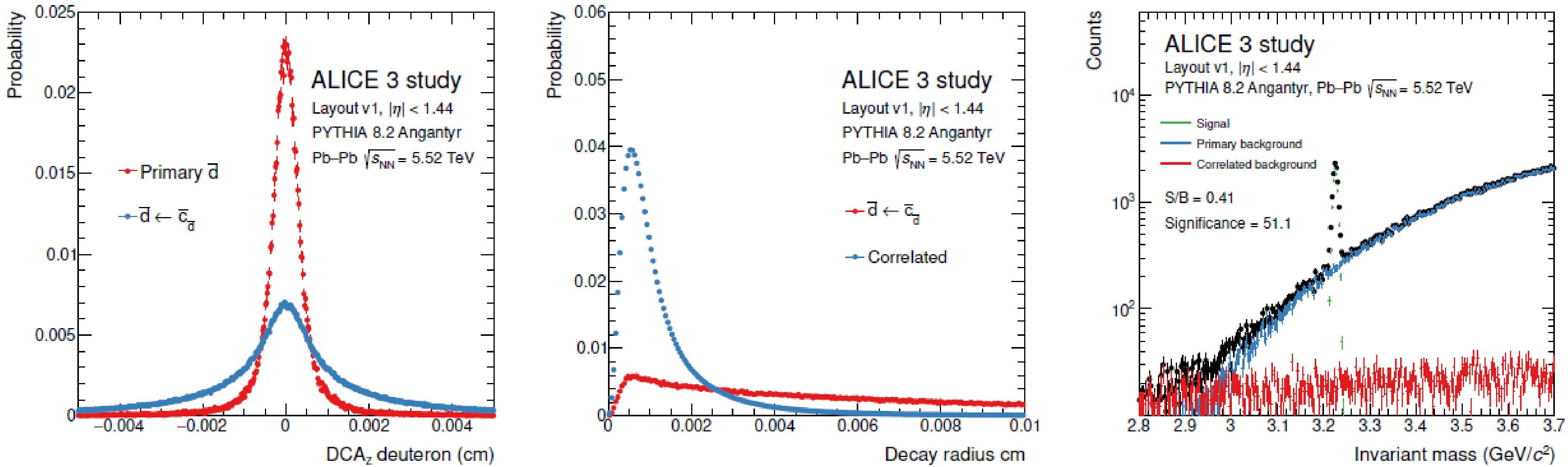
Figure 35: Expected Ξ_{cc}^{++} mass peak and background in pp collisions with $\mathscr{L}_{int} = 18\,\mathrm{fb}^{-1}$

Feasibility for c deuteron in ALICE3

is c-deuteron bound and weakly decaying? discover or put limit

$c_d \rightarrow d + K^- + \pi^+$ using $\Lambda_c \rightarrow p + K^- + \pi^+$ with 6.3 % and binding into d with coalescence model

arXiv: 2211.02491

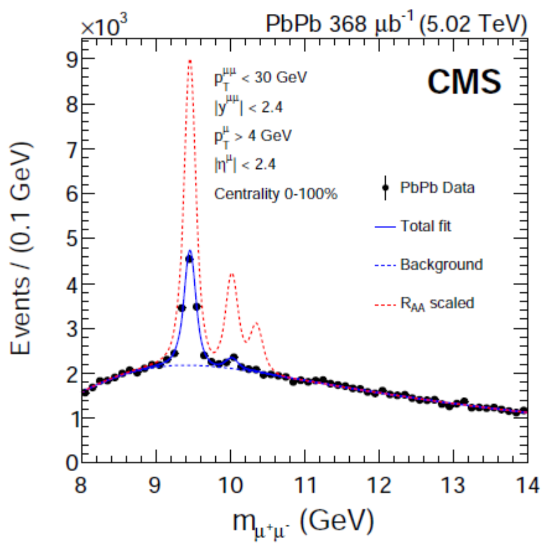


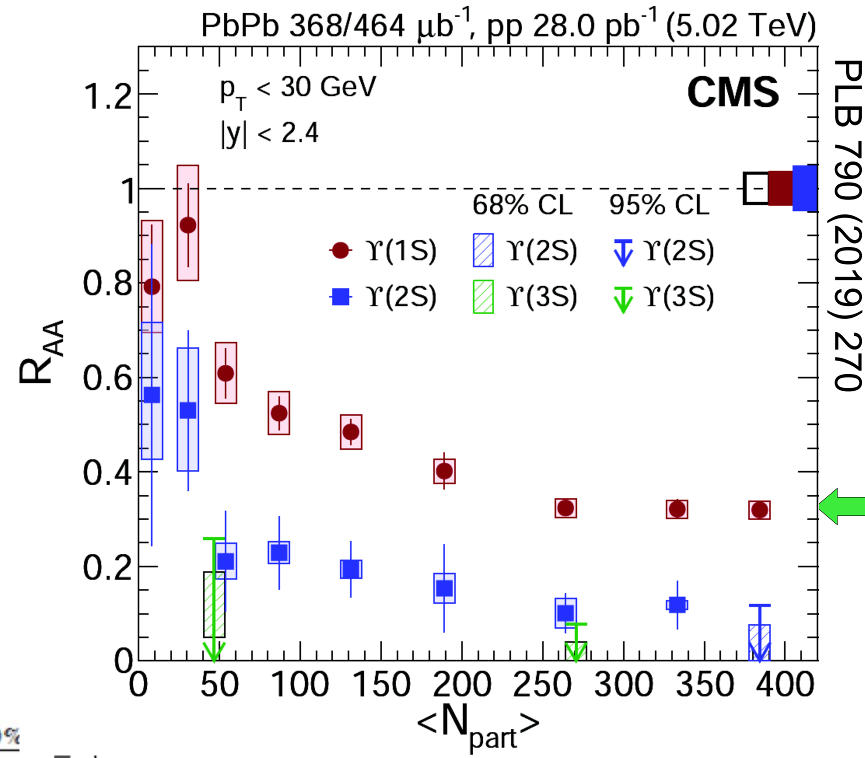
main combinatorial background from primary deuterons can be effectively suppressed due to superb vertex resolution $\rightarrow$ significance 51

1 month PbPb collisions = 5.6 nb^{-1}

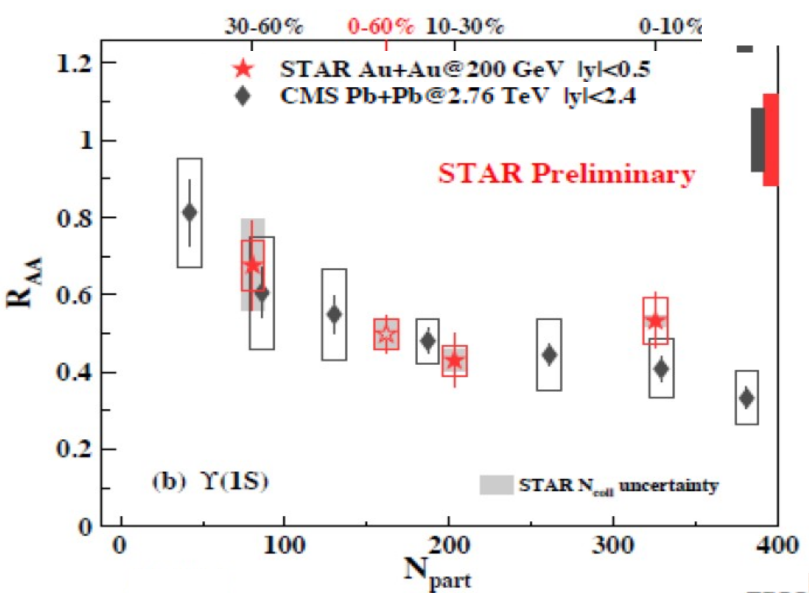
abundance c_t factor 350 less, significance factor 18 less, needs all of Run5+6 (factor 6)

Suppression of Upsilon states





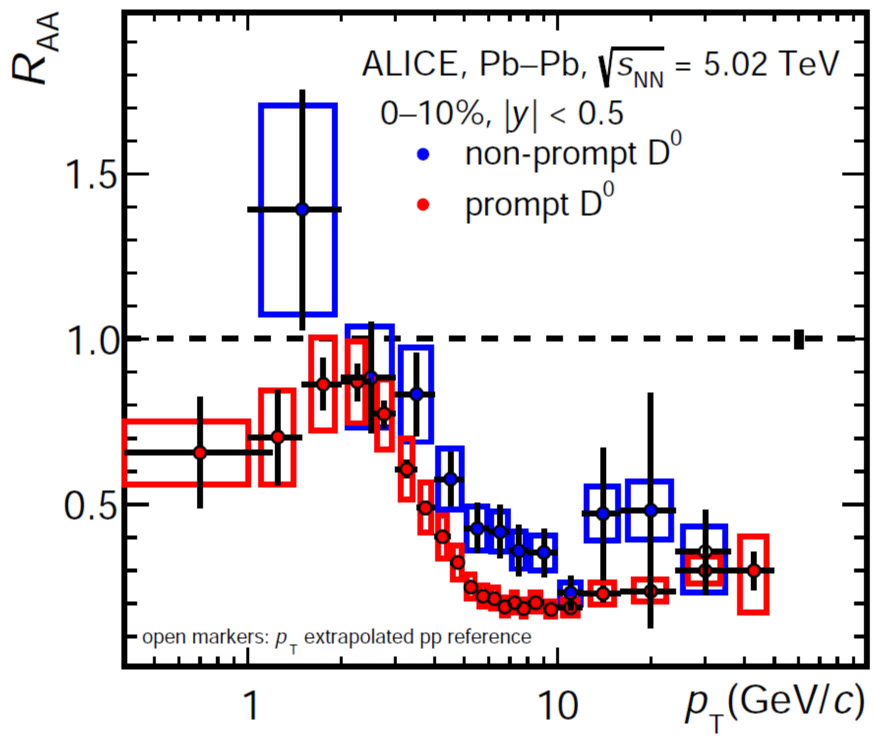
not consistent with just excited state suppression (LHCb data: only 25 % feed-down in pp at LHC)



genuine ϒ 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?

Thermalization of beauty?

arXiv: 2202.0081



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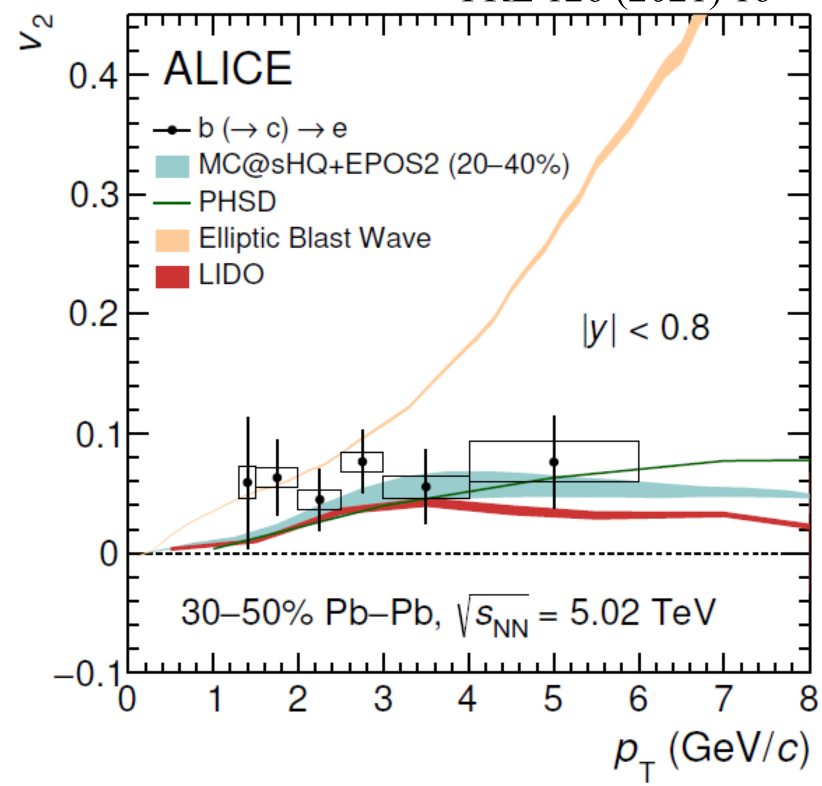
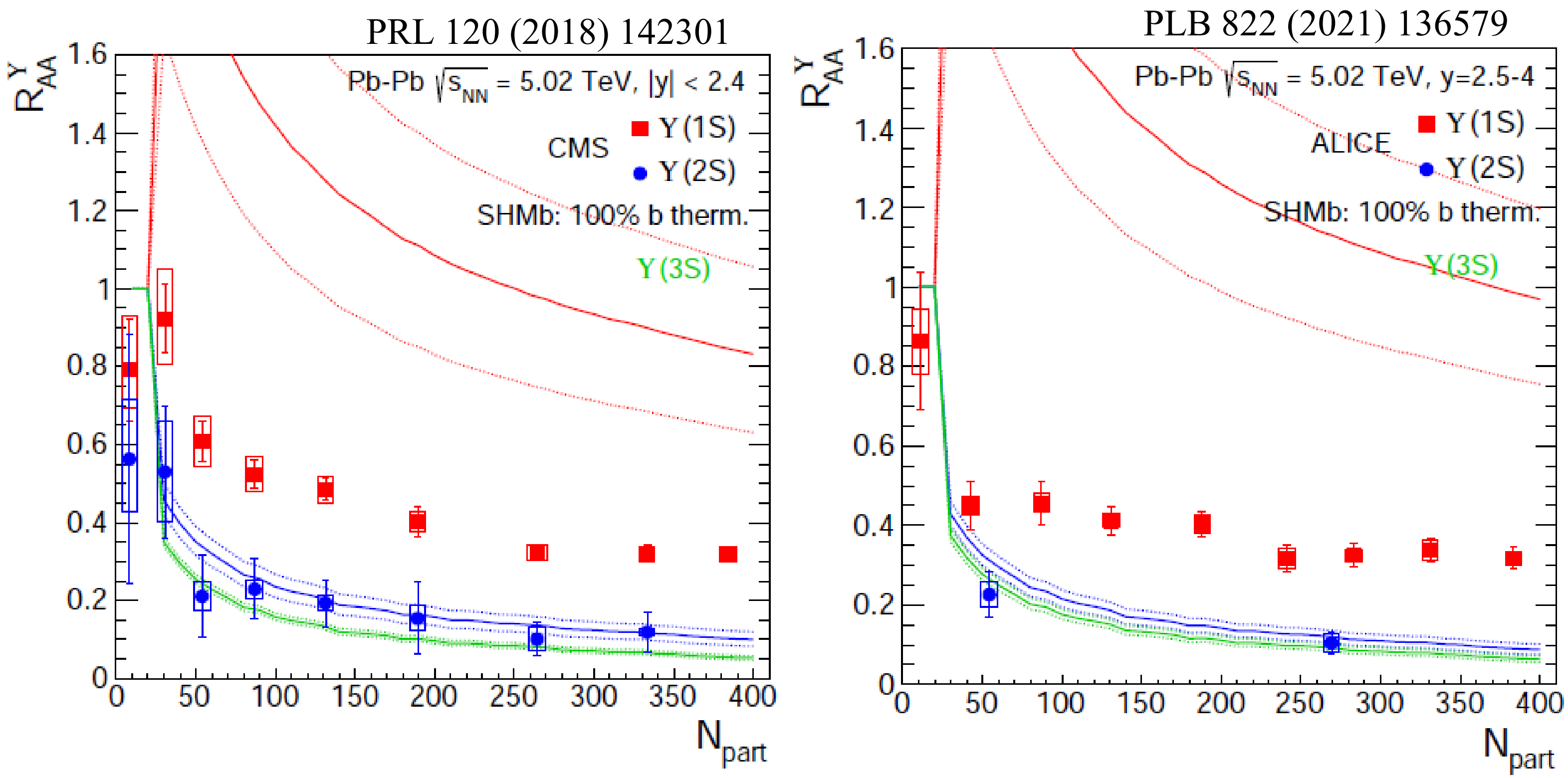


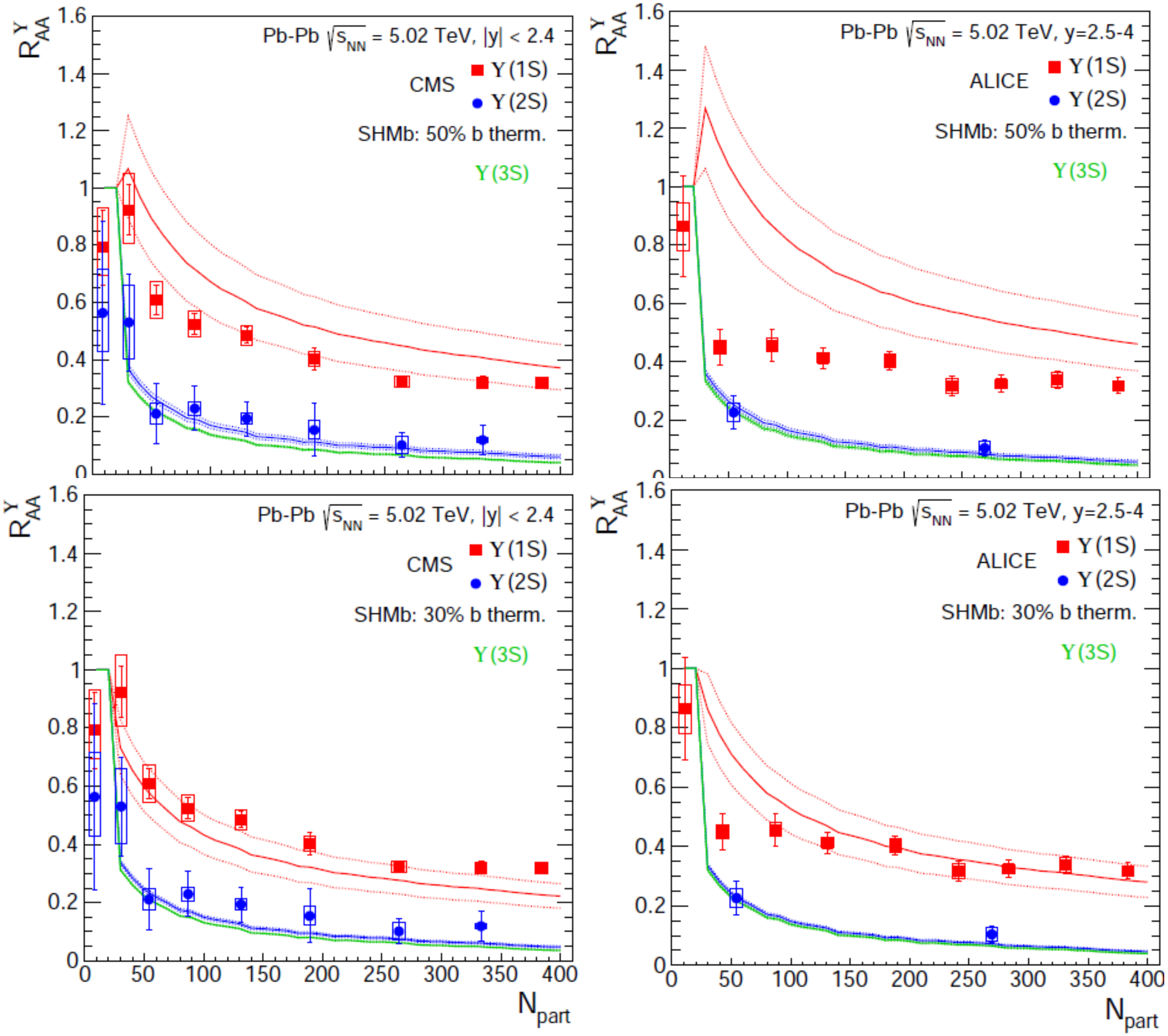
strong reduction of R_{AA} and significant v_2, but both a factor 2 less pronounced than for prompt D0 → indication that beauty quarks thermalize only partly only the thermalized fraction should hadronize statisticly

Bottomonia in SHMb assuming full thermalization



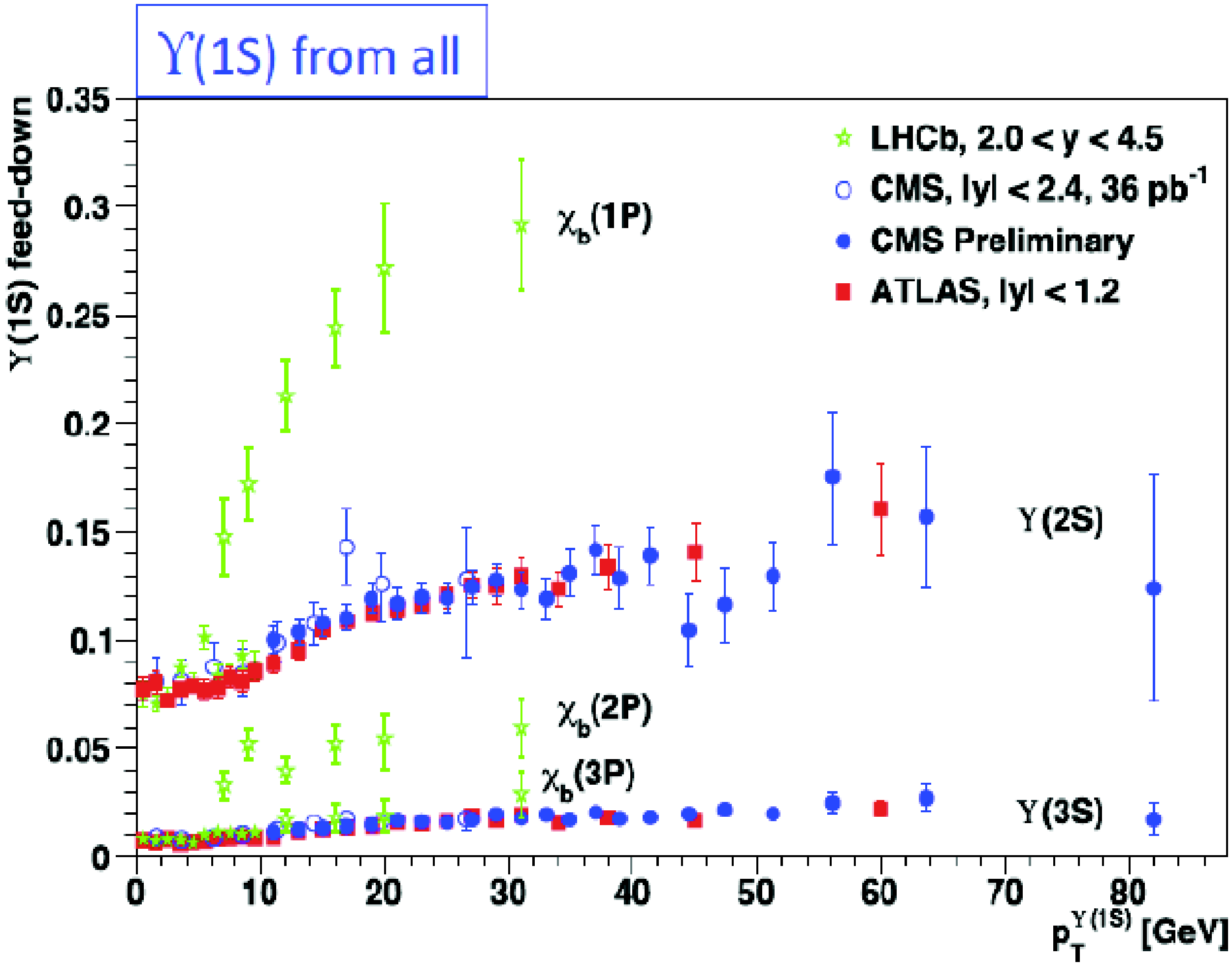
- indeed, assumption of fully thermalized b-quarks fails to reproduce Υ(1S) by factor 2-3 for central collisions
  but: $g_b = 10^9$ so Υ is scaled up from thermal yield by 10^{18}
- so, to come without any free parameter within a factor 2-3 is not a minor feat

Bottomonia assuming partial thermalization

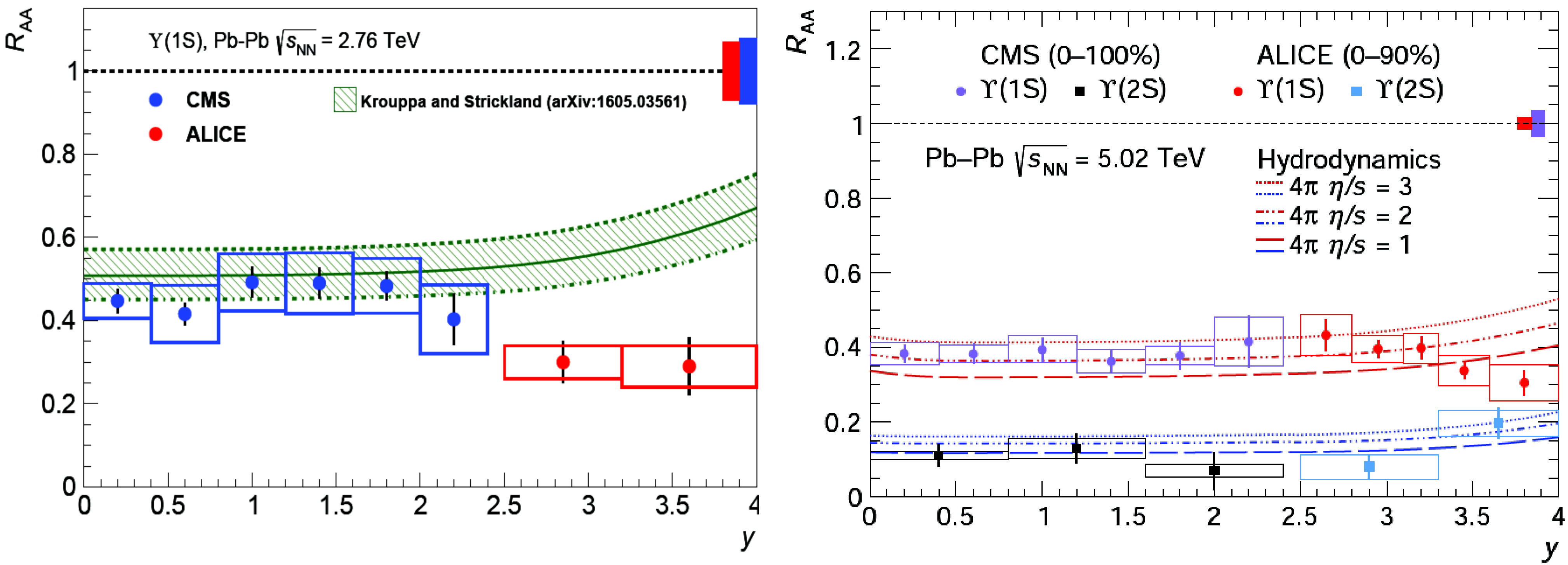


factor 2-3 reproduces
Υ yields
could be in line with open
beauty energy loss and flow

Feeding into Upsilon (1S)



Upsilon RAA rapidity dependence



Indication: RAA peaked at mid-y like for J/ψ
not in line with collisional damping in expanding medium