# Cosmic matter, quark matter, and high energy nuclear collisions: a journey to the beginnings

HELMHOLTZ GEMEINSCHAFT

- introduction and perspective
- the quark-gluon plasma and the early universe
- the ALICE experiment and a brief synopsis of very selected results
- hadron production, Lattice QCD and the QCD phase boundary
- charmonia and deconfinement
- outlook

FIAS Frankfurt Institute for Advanced Studies

EMMI

HUAZHONG UNIVERSITY

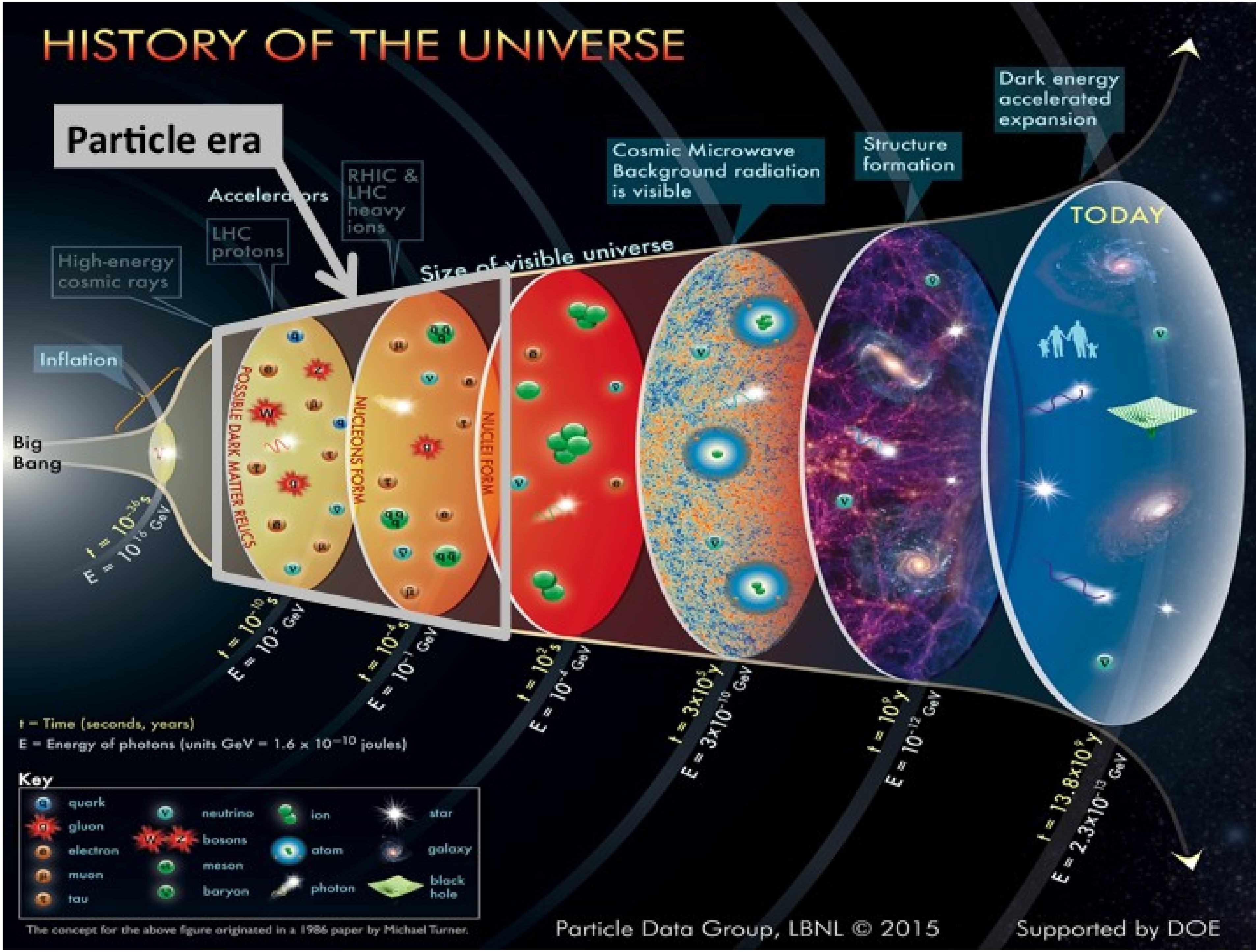
GSI colloquium
Nov. 3, 2015

GSI

TECHNISCHE UNIVERSITÄT DARMSTADT

Peter Braun-Munzinger

much of the phenomenology work shown here was worked out with
Anton Andronic,
Krzysztof Redlich, and Johanna Stachel


HISTORY OF THE UNIVERSE
Particle era
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Big Bang
Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion
TODAY
Size of visible universe
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

## time line and matter in the early universe

- inflation up to $10^{-32}$ s
- $10^{-32}$ to $10^{-12}$ s: cosmic matter consists of **massless** particles and fields quarks, leptons, neutrinos, photons, Z, $W^{\pm}$, H ??? lots of speculations
- $10^{-12}$ s: electroweak phase transition, T $\approx$ 100 GeV
- $10^{-12} - 10^{-5}$ s quark-gluon plasma phase
  particles acquire mass through Higgs mechanism, QGP consists of:
  $\overline{q}q\bar{l}l\gamma ZW^{\pm}H$, all in equilibrium
- $10^{-5}$ s QCD phase transition, T = 155 MeV
- $10^{-5}$ s to 1 s annihilation phase, T(1 s) $\approx$ 1 MeV
  cosmic matter converts into protons, neutrons, leptons, neutrinos, photons
- t > 1 s: leptons annihilate and reheat universe, neutrinos decouple, light element production commences

# QGP in the early universe

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho$$ cosmological scale factor $a(t)$

Hubble parameter $H(t)$ $$\dot{\rho} = -3H\,(\rho + p)$$

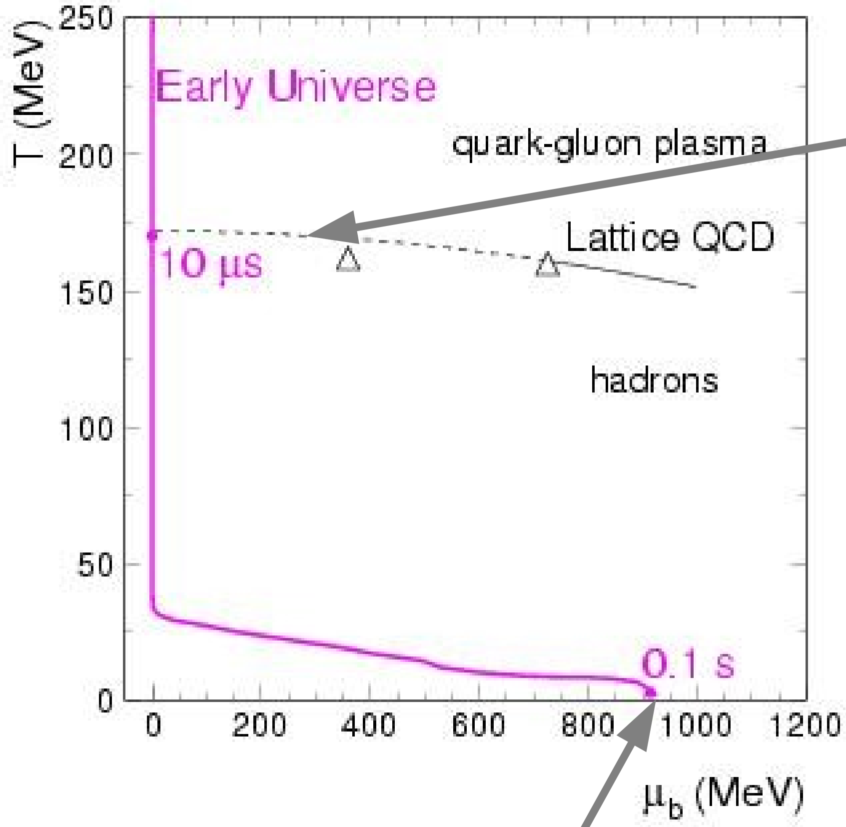
| Temperature | New Particles | $4N(T)$ |
|---|---|---|
| $T < m_e$ | $\gamma$'s + $\nu$'s | 29 |
| $m_e < T < m_\mu$ | $e^\pm$ | 43 |
| $m_\mu < T < m_\pi$ | $\mu^\pm$ | 57 |
| $m_\pi < T < T_c{}^\dagger$ | $\pi$'s | 69 |
| $T_c < T < m_{\rm strange}$ | $\pi$'s + $u, \bar{u}, d, \bar{d}$ + gluons | 205 |
| $m_s < T < m_{\rm charm}$ | $s, \bar{s}$ | 247 |
| $m_c < T < m_\tau$ | $c, \bar{c}$ | 289 |
| $m_\tau < T < m_{\rm bottom}$ | $\tau^\pm$ | 303 |
| $m_b < T < m_{\rm W,Z}$ | $b, \bar{b}$ | 345 |
| $m_{\rm W,Z} < T < m_{\rm Higgs}$ | $W^\pm, Z$ | 381 |
| $m_H < T < m_{\rm top}$ | $H^0$ | 385 |
| $m_t < T$ | $t, \bar{t}$ | 427 |

source: RPP 2014

$$\rho = \left(\sum_B g_B + \frac{7}{8}\sum_F g_F\right)\frac{\pi^2}{30}T^4 \equiv \frac{\pi^2}{30}N(T)\,T^4 = \frac{\pi^2}{30}g_T T^4$$

$$t_{[s]} = \frac{2.42}{\sqrt{g_T}(T_{[\rm MeV]})^2}$$

# evolution of the early universe and the QCD phase diagram



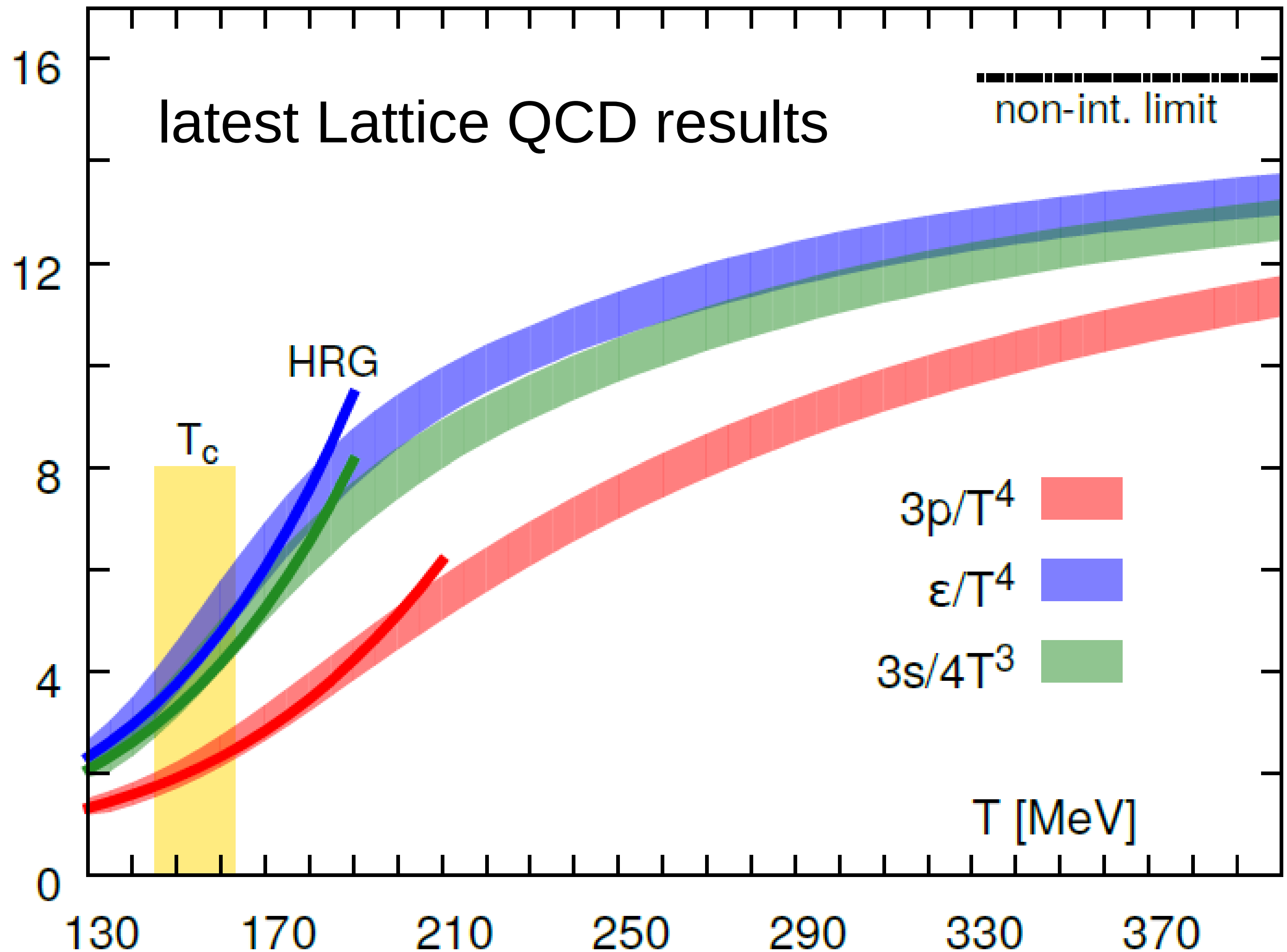

QCD phase boundary

homogeneous Universe in equilibrium, this matter can only be investigated in nuclear collisions

- charge neutrality
- net lepton number = net baryon number
- constant entropy/baryon

neutrinos decouple and light nuclei begin to be formed

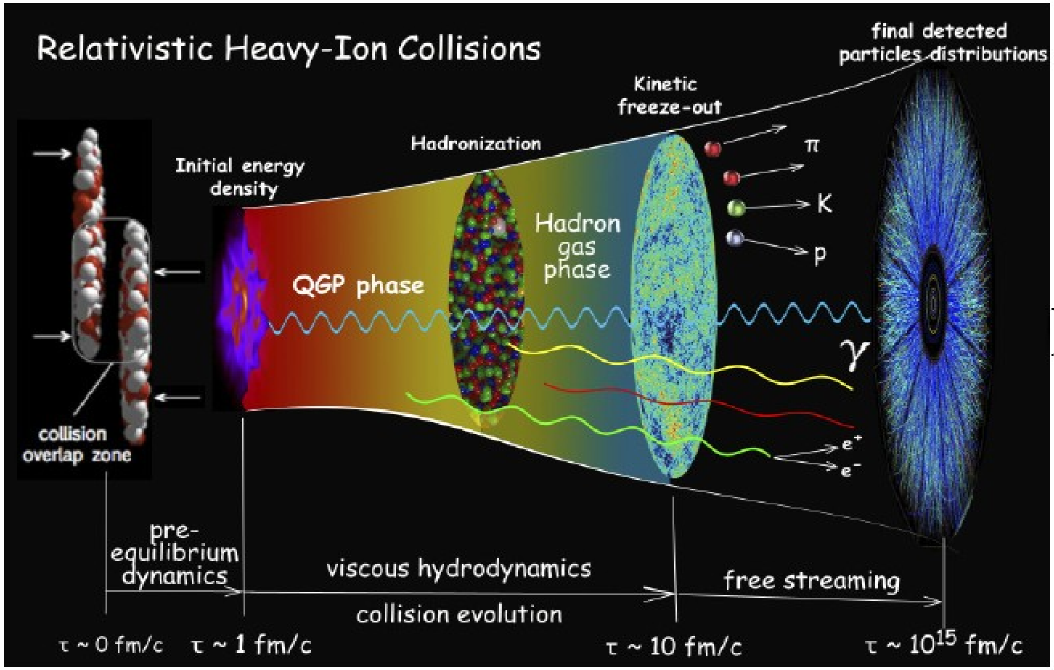
# the equation of state of hot QCD matter – a chiral (cross over) phase transition between hadron gas and the QGP

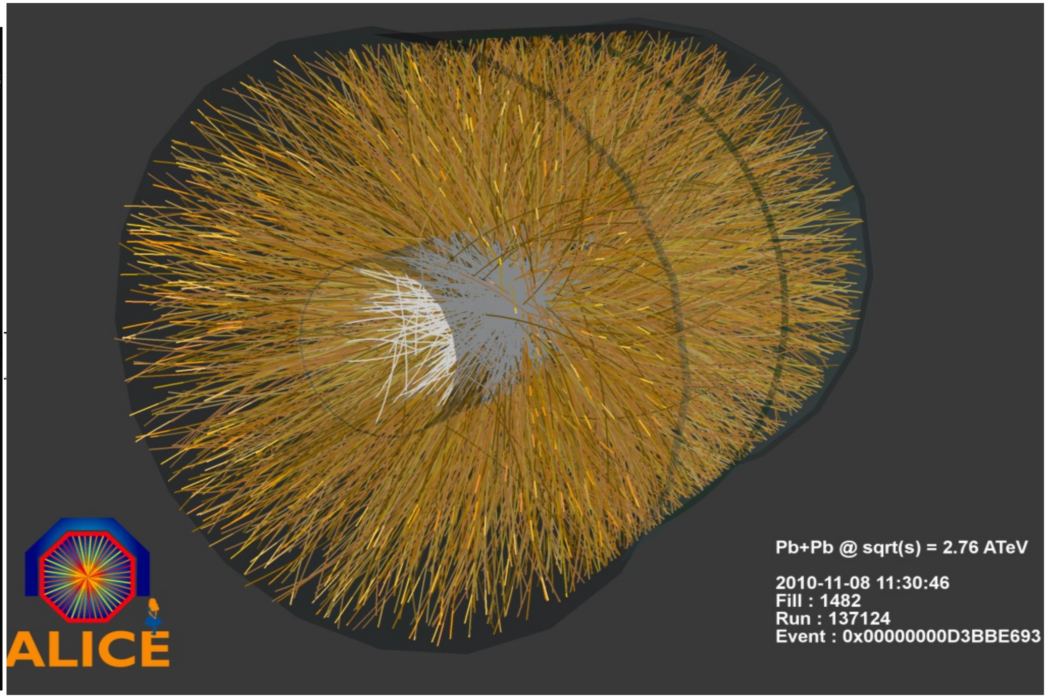



critical region: $T_c = (154 \pm 9)$ MeV $\varepsilon_{crit} = (340 \pm 45)$ MeV/fm$^3$

HOTQCD coll., Phys.Rev. D90 (2014) 9, 094503

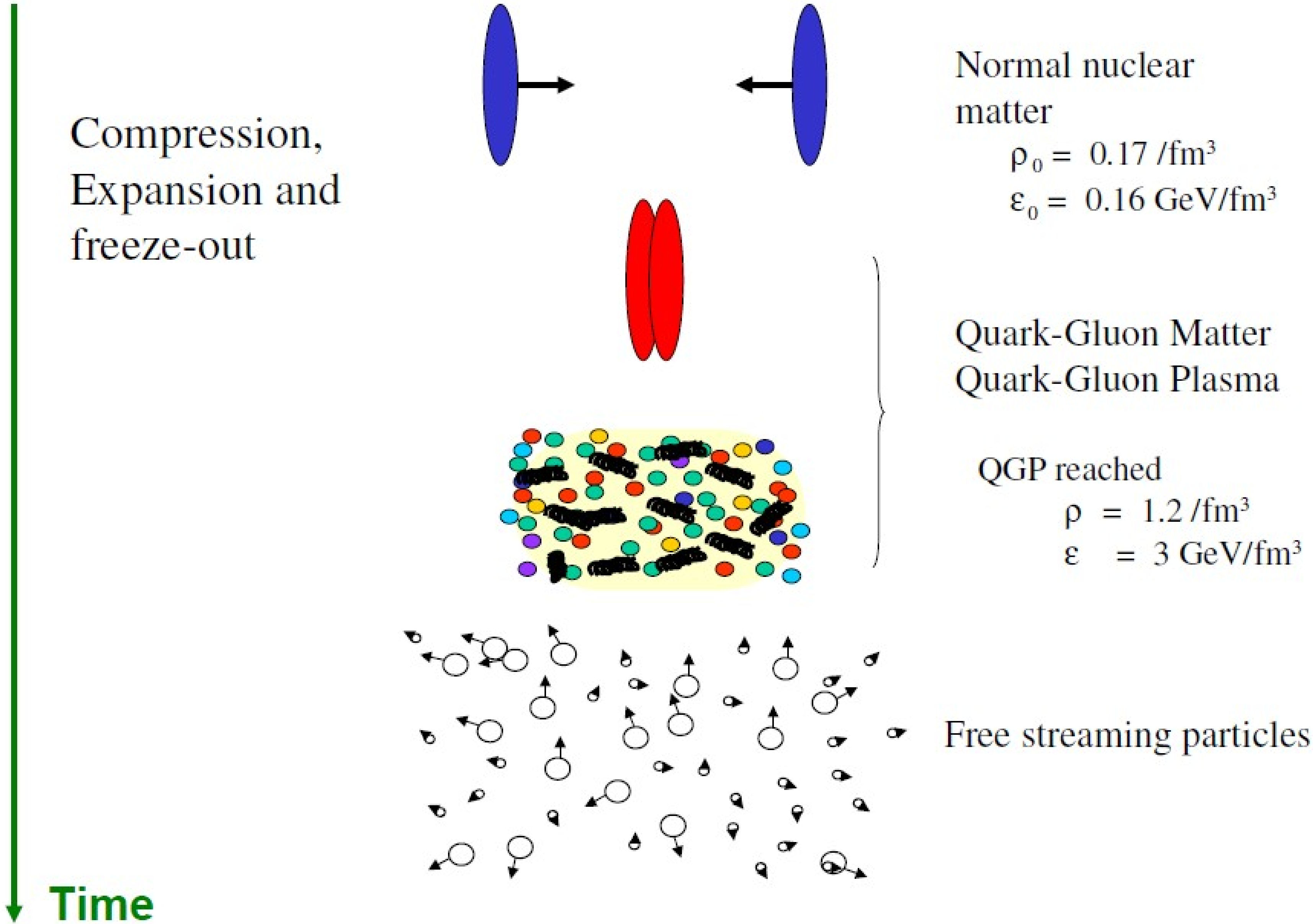
# the Quark-Gluon Plasma formed in nuclear collisions at very high energy




Paul Sorensen and Chun Shen

# how to create QGP in the laboratory?



# The Large Hadron Collider (LHC)

27 km long, 8 sectors

**1232 dipole** magnets (15m, 30 tonnes each) to bend the beams

Cooled with **120 tonnes of He at 1.9 K**

pp: 2808 bunches/ring, each $1.15 \times 10^{11}$ protons (8 min filling time)

Design luminosity: **$10^{34}$ cm$^{-2}$s$^{-1}$**

PbPb: 592 bunches/ring, each $7 \times 10^{7}$ Pb ions

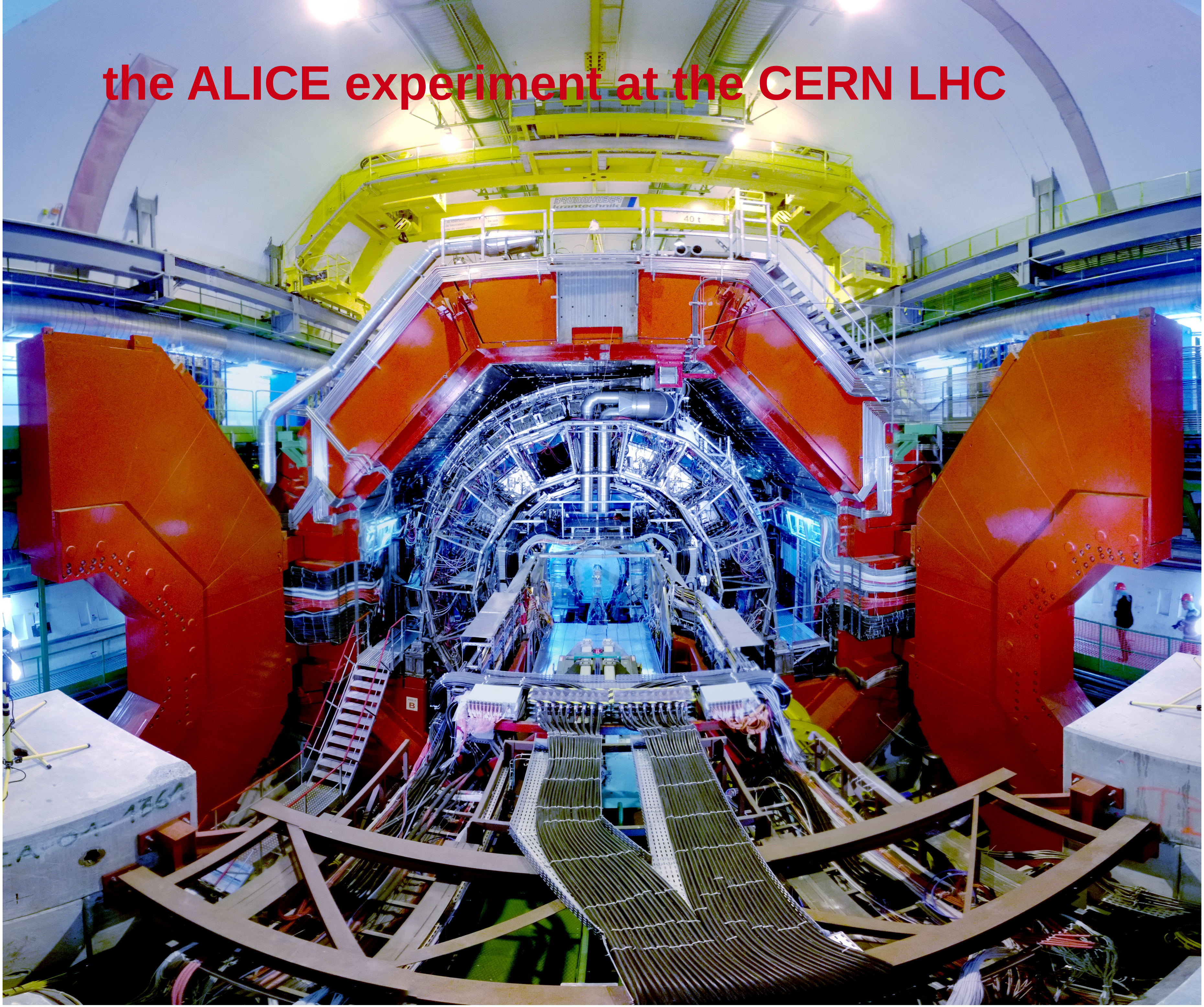
Design luminosity: $10^{27}$ cm$^{-2}$s$^{-1}$

Transverse r.m.s beam size: **16 μm**, r.m.s. bunch length: 7.5 cm

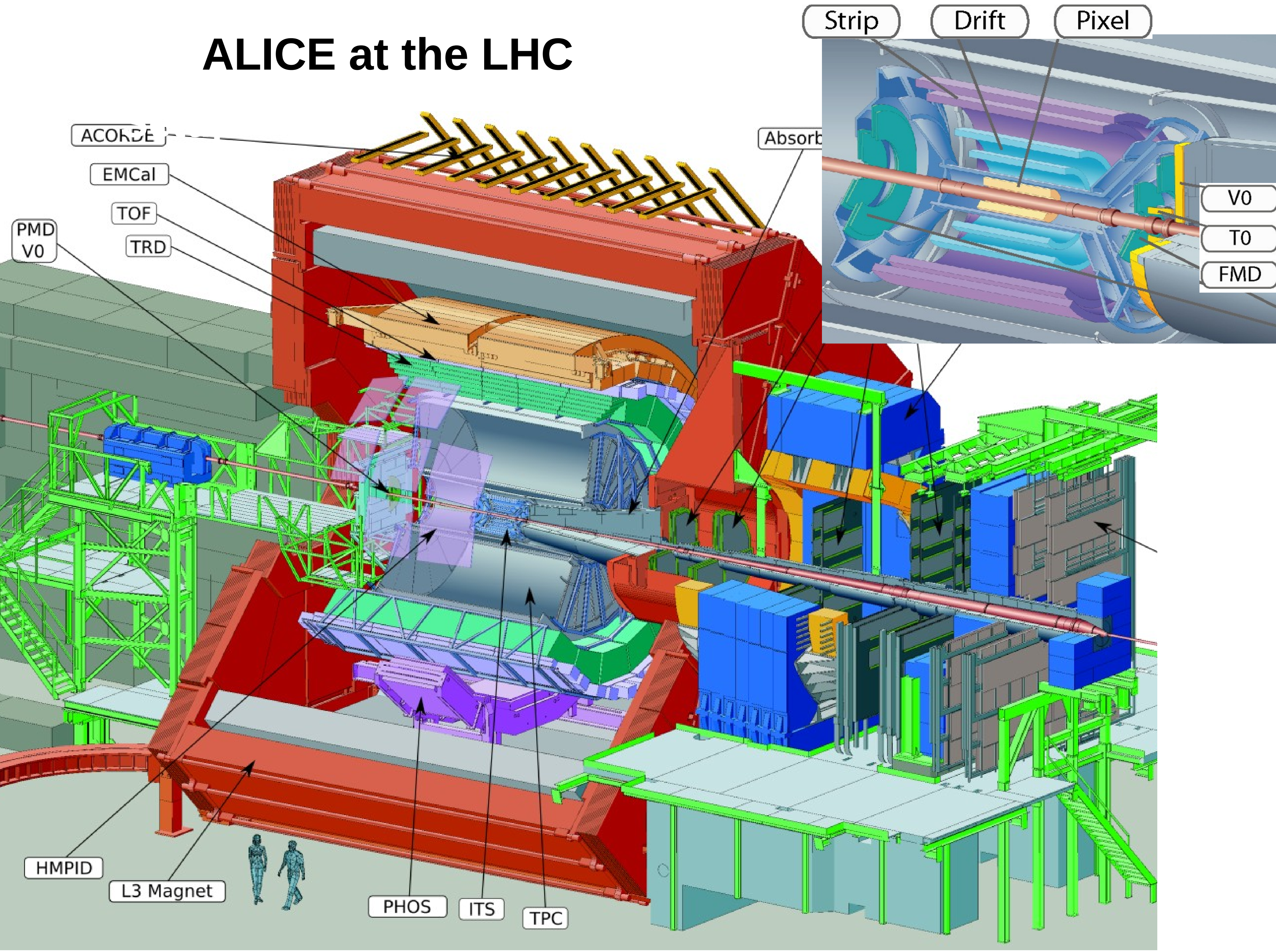
Beam kinetic energy: 362 MJ per beam (1 MJ melts 2 kg copper)

Total stored electromagnetic energy: **8.5 GJ** (dipole magnets only)

# the ALICE experiment at the CERN LHC



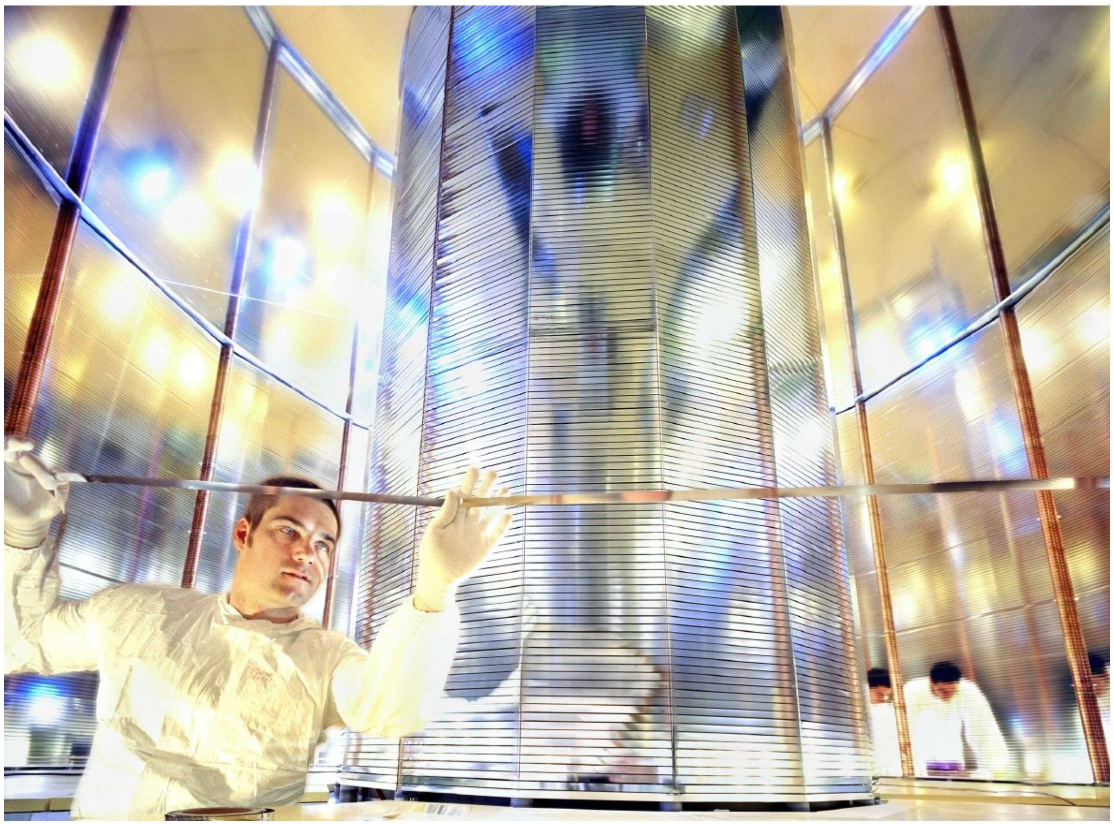
# ALICE at the LHC



# the TPC (Time Projection Chamber) - 3D reconstruction of up to 15 000 tracks of charged particles per event

ALICE

with 95 $m^3$ the largest TPC ever



**560 million read-out pixels!**

precision better than 500 μm in all 3 dim.

180 space and charge points per track

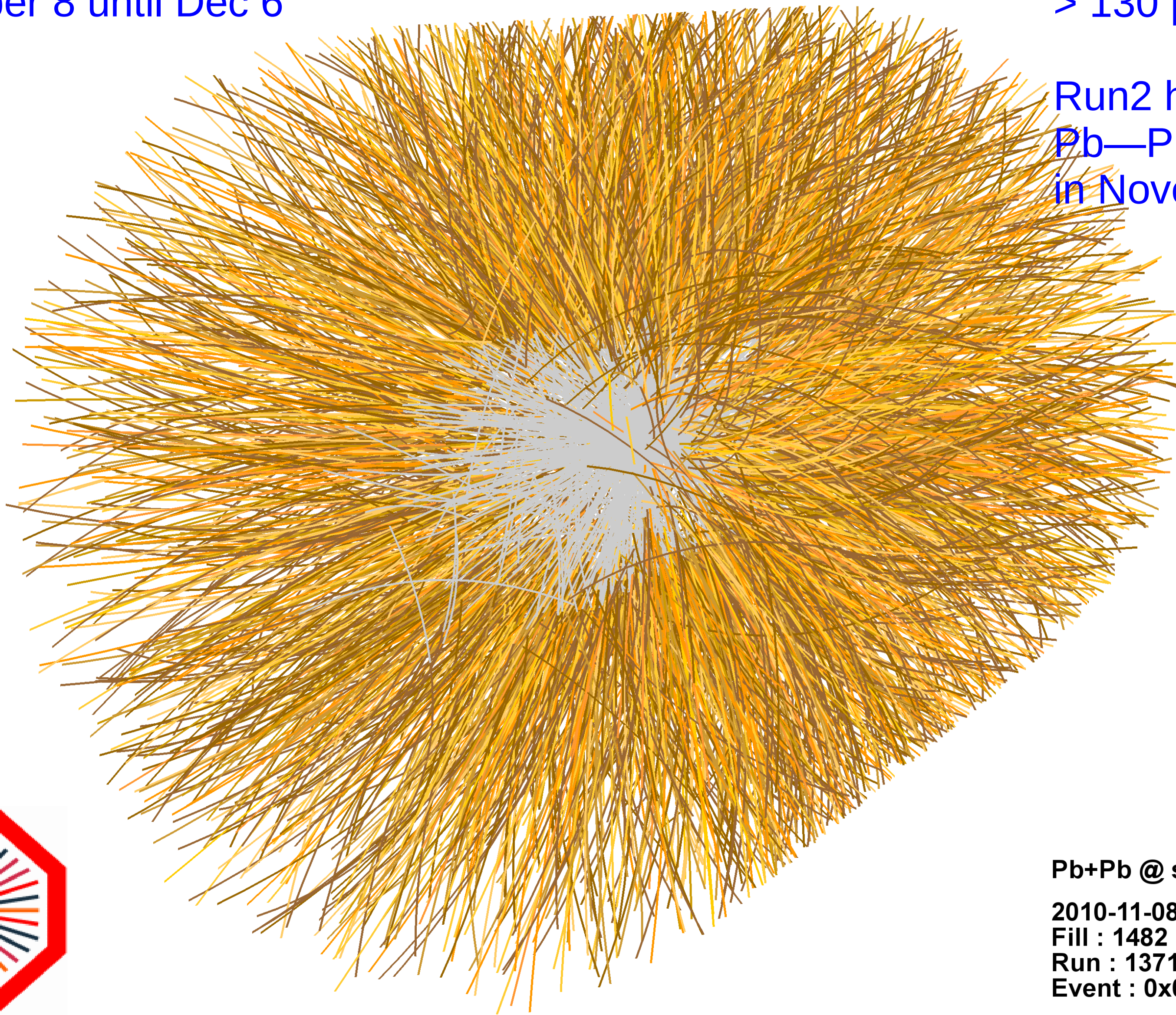

the interior of the TPC, 2004

# first PbPb collisions at LHC at √s = 2.76 A TeV

setup for ion collisions: November 4
first collisions with stable beams:
November 8 until Dec 6

Run1: 3 data taking campaigns
pp, pPb, Pb—Pb
> 130 publications

Run2 has started with 13 TeV pp
Pb—Pb run starting
in November 2015



Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

ALICE

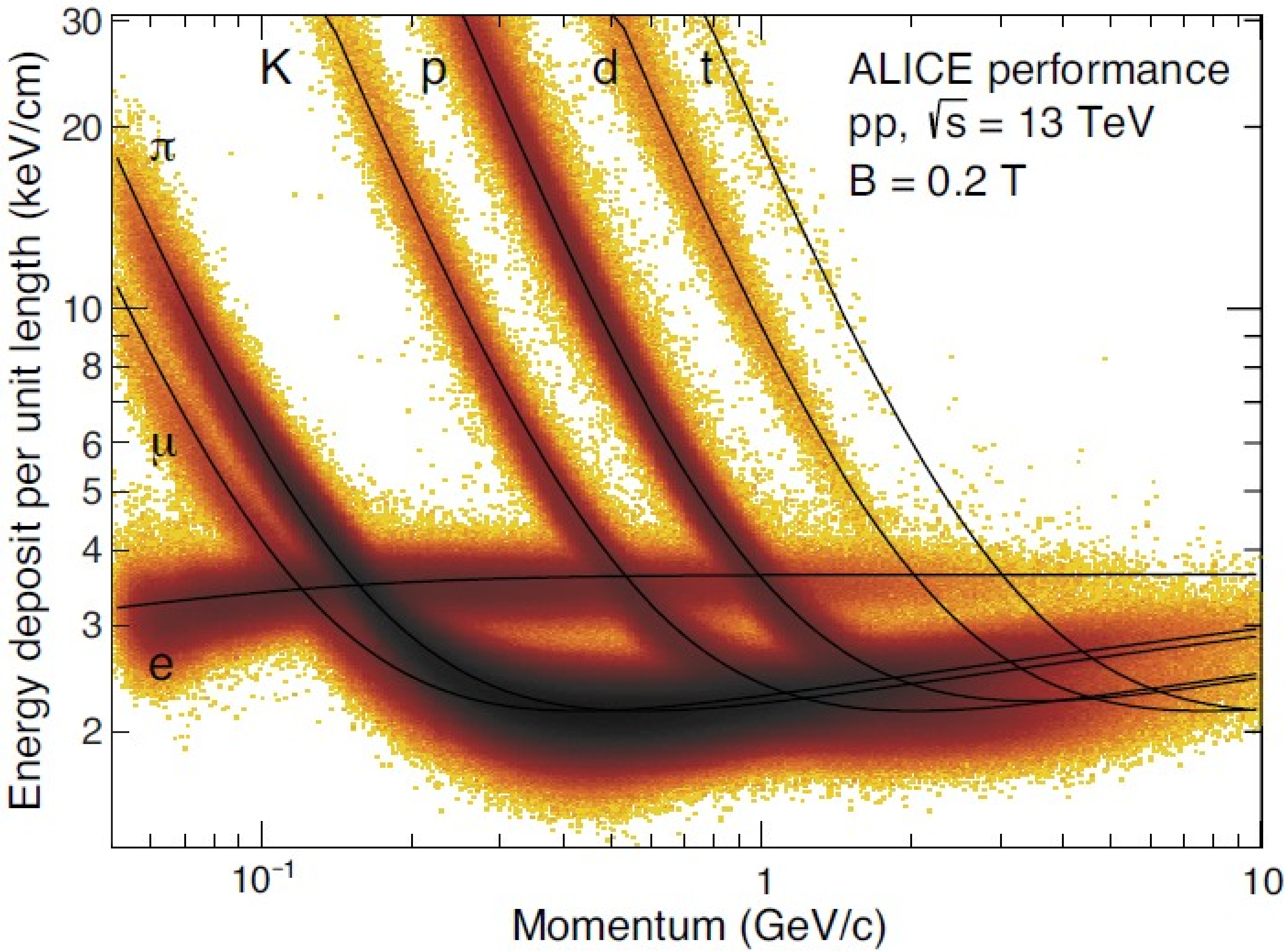
**and the fun started**

# ALICE TRD Detector complete Nov. 26, 2014

first fully operational barrel TRD
project coordination: Heidelberg

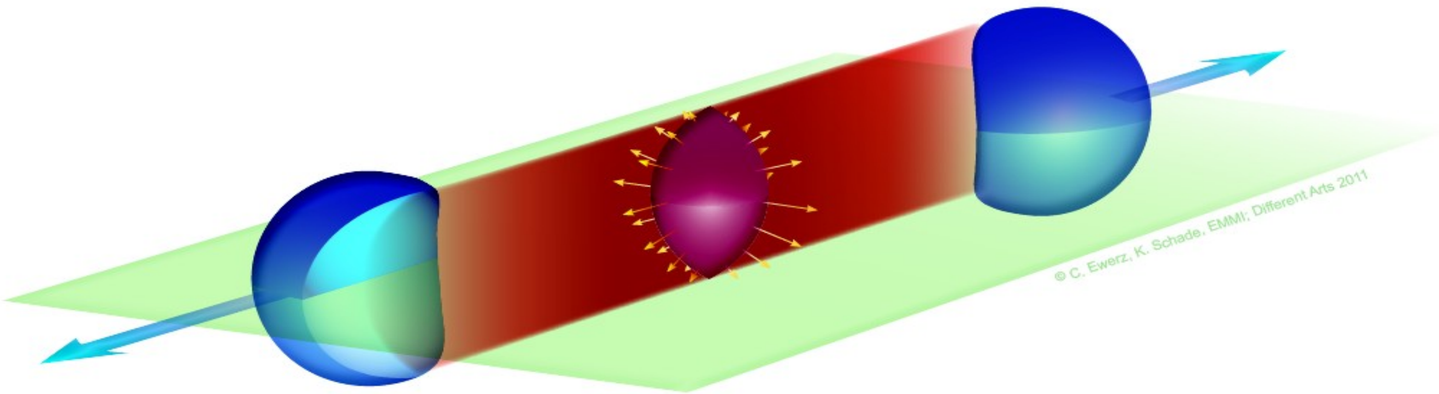
# a synopsis of very selected results

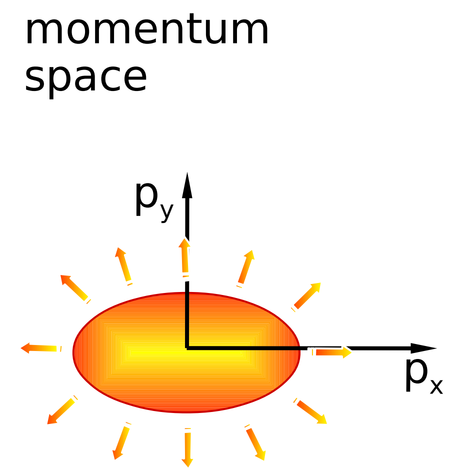
particle identification with the ALICE TPC
from 50 MeV to 50 GeV



# hydrodynamic expansion of fireball

# fireball expands collectively like an ideal fluid



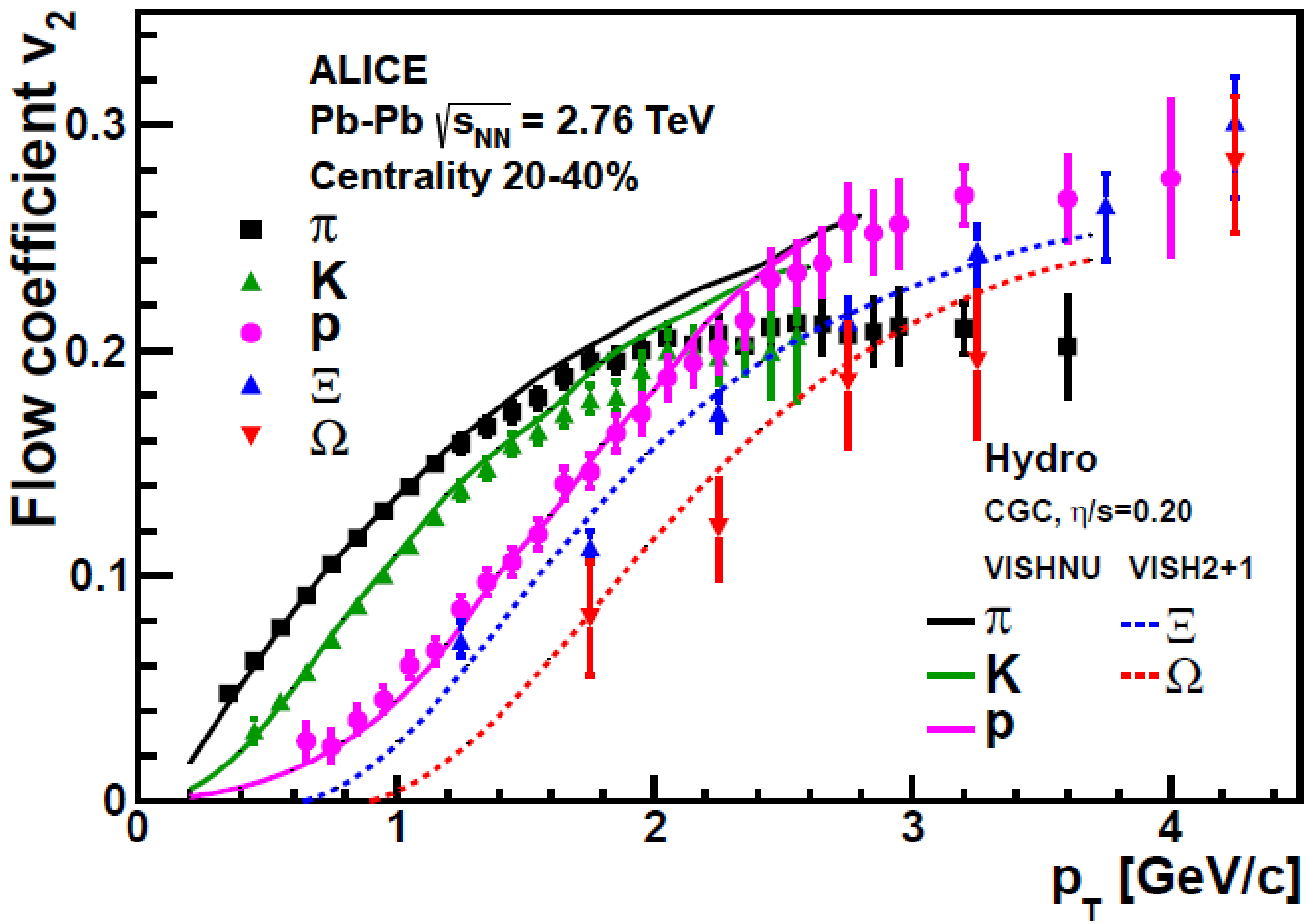




$$dN/d\phi = 1 + 2\,V_2 \cos 2\,(\phi - \psi) + \ldots$$

hydrodynamic flow characterized by azimuthal anisotropy coeffient $v_2$

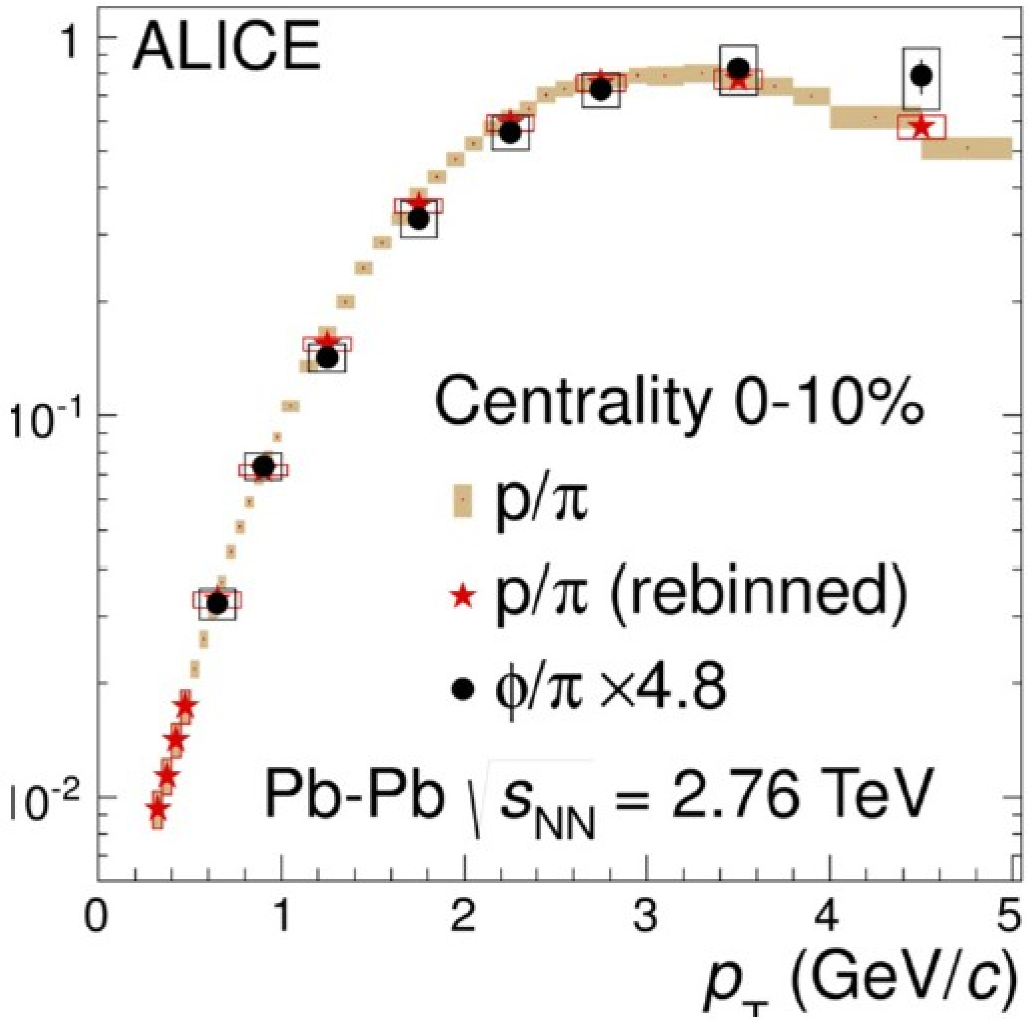
+ higher orders

# elliptic flow in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV




rapidly rising $v_2$ with $p_t$ and mass ordering are typical features of hydrodynamic expansion
nearly ideal (non-dissipative) hydrodynamics reproduces data, system fairly strongly coupled arXiv:1405.4632, JHEP 1506 (2015) 190, ALICE coll.

# phi meson and proton transverse momentum spectra

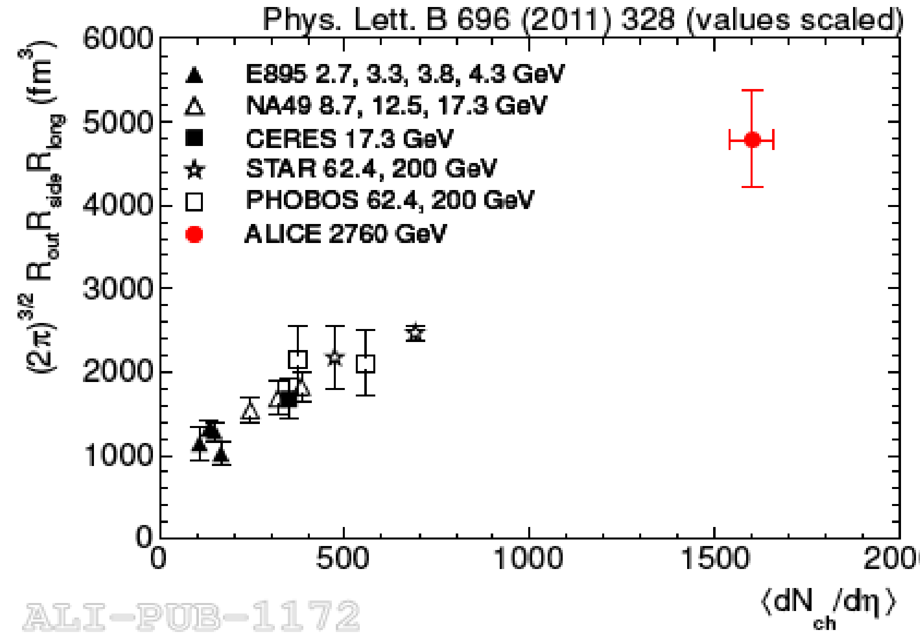


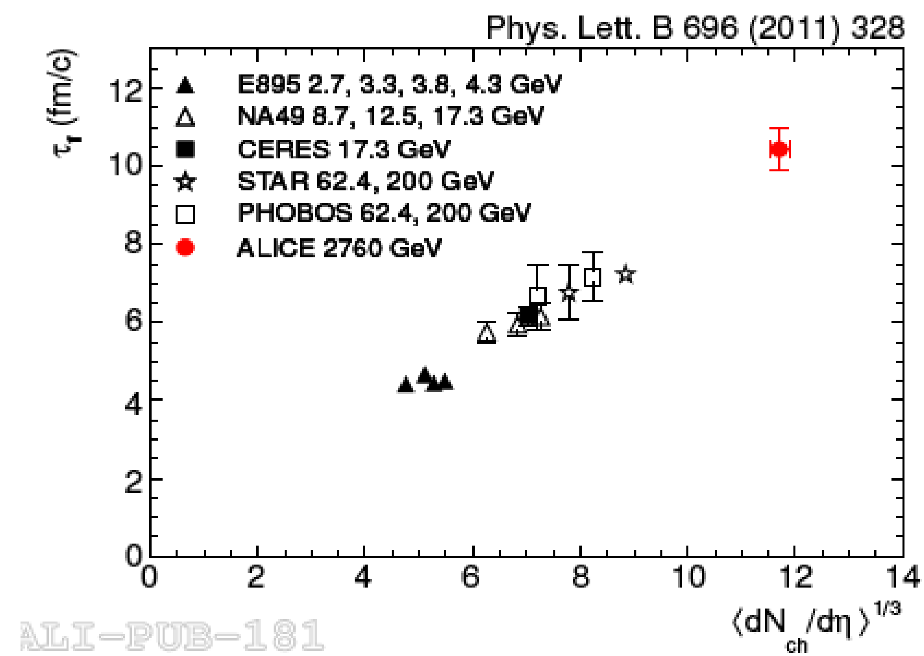

… depend only on particle mass, not quark content. strong sign of hydrodynamic flow. **'constituent quark scaling' is not observed** (in any case, this scaling would not be consistent with hydrodynamics ...)

# fireball at LHC energy has much larger size and lives longer than at lower energies

volume and lifetime
from Hanbury-Brown/Twiss
analysis

fireball volume at (thermal)
freeze-out is about 5 x larger
than volume of a Pb nucleus

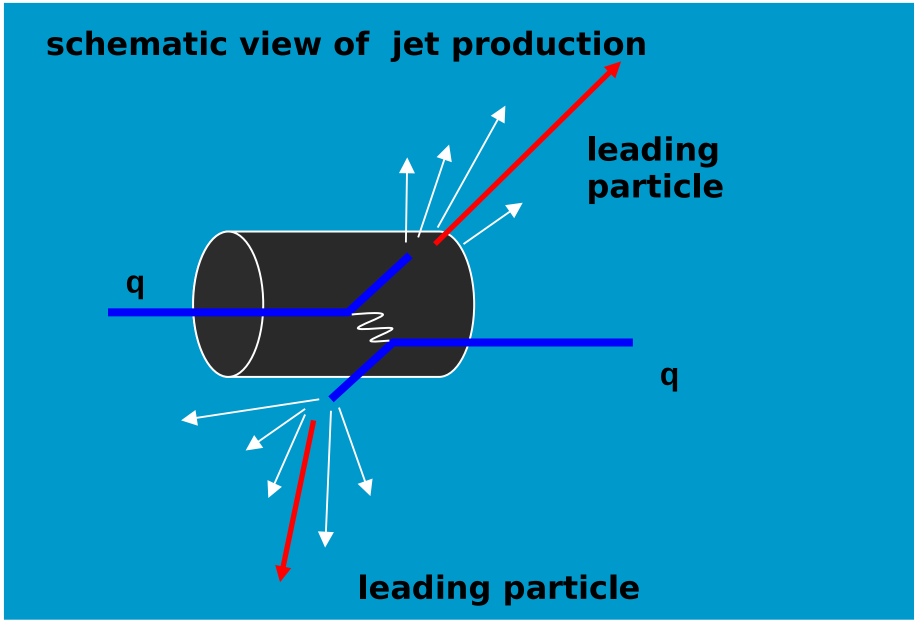


# the fireball is opaque to high energy partons (quarks and gluons)

# jets of hard partons as probe of the hot medium

- hard parton scattering observed via leading particles
- expect strong $\Delta\varphi=\pi$ azimuthal correlations




however, the scattered partons may loose energy (~ several GeV/fm) in the colored medium

→ momentum reduction (fewer high $p_T$ particles in jet)
→ no jet partner on other side

jet quenching

# the nuclear modification factor R_AA

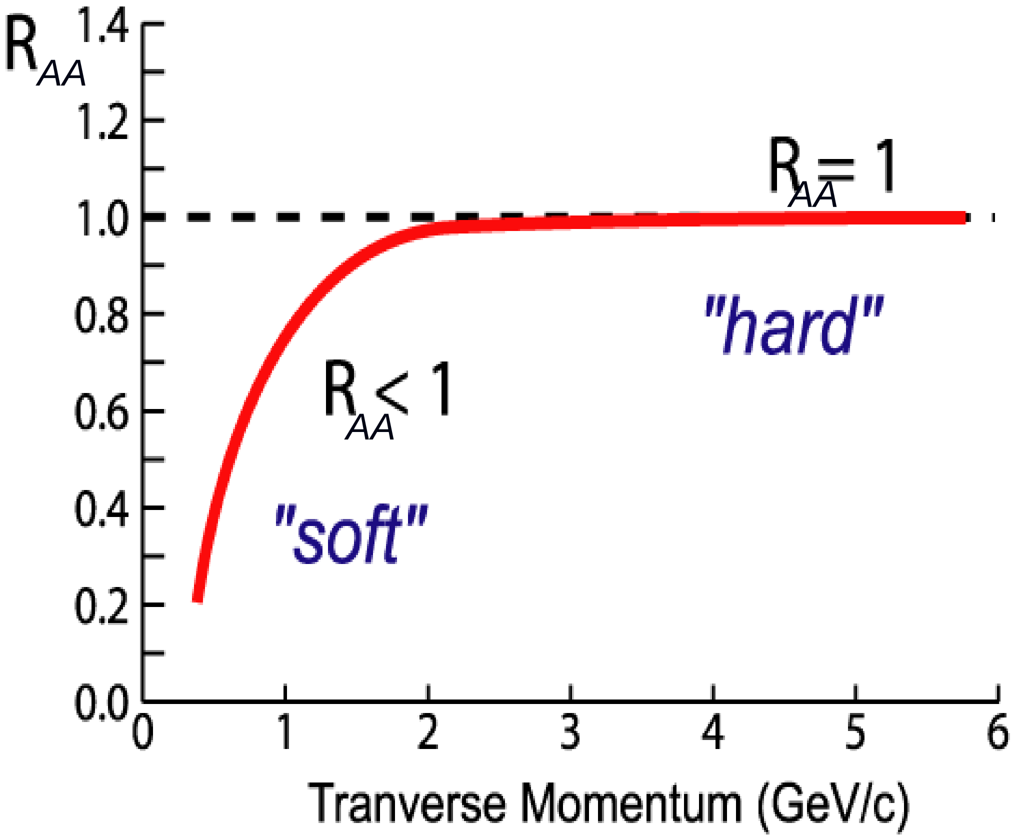
The $R_{AA}$ function:

$$R_{AA}(b) = \frac{\frac{\mathrm{d}^2 N^{AA}}{\mathrm{d}p_t^2 \mathrm{d}y}}{N_{coll}^{AA}(b) \cdot \frac{\mathrm{d}^2 N^{NN}}{\mathrm{d}p_t^2 \mathrm{d}y}}$$

if hard scattering only:

$$R_{AA}(b) = 1$$

# qualitative expectations




no medium effects:

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

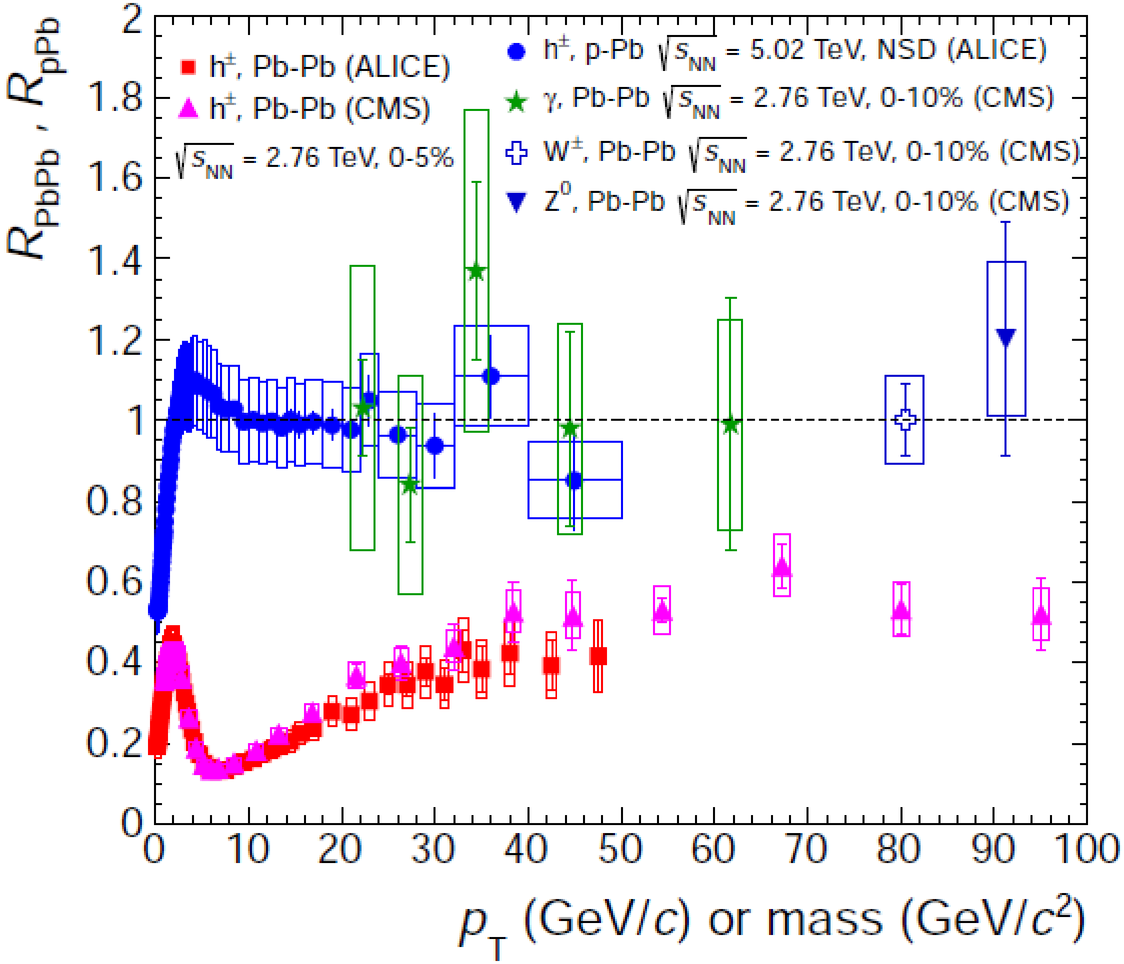
$R_{AA}$ = 1 at high-$p_T$ where hard scattering dominates

Suppression:

$R_{AA}$ << 1 at high-$p_T$

# synopsis of energy loss measurements for hard probes

no suppression in pPb, QGP opaque for high energy partons




Alice coll.,

arXiv:1405.2737

photons, Z and W scale with number of binary collisions in PbPb – not affected by medium

→ demonstrates that charged particle suppression is medium effect: energy loss in QGP

# hadron production and the QCD phase boundary

# quark-gluon plasma and hadron yields in central nuclear collisions

QCD implies duality between (quarks and gluons) – hadrons

hadron gas is equilibrated state of all known hadrons

QGP is equilibrated state of deconfined quarks and gluons

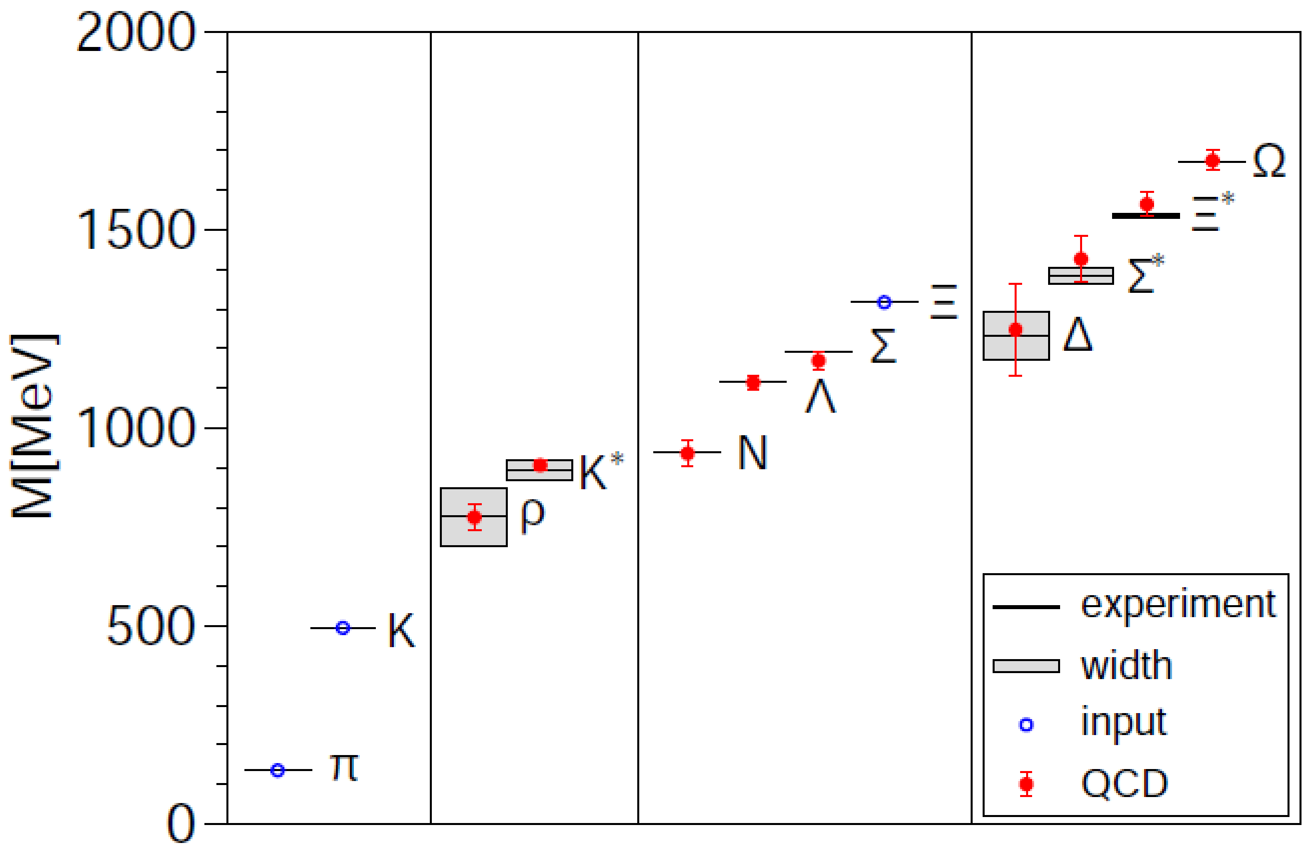
at a critical temperature $T_c$ a hadronic system converts to QGP

consequence:

QGP in central nuclear collisions if:

1. all hadrons in equilibrium state at common temperature T
2. as function of cm energy the hadron state must reach a limiting temperature $T_{lim}$
3. all hadron yields must agree with predictions using the full QCD partition function at the QCD critical temperature $T_c = T_{lim}$

# the hadron mass spectrum and lattice QCD




S. Duerr et al., Science 322 (2008) 1224-1227

# equilibration at the phase boundary

- Statistical model analysis of (u,d,s) hadron production: an important test of equilibration of quark matter near the phase boundary, **no equilibrium → no QGP matter**
- No (strangeness) equilibration in hadronic phase
- Present understanding: multi-hadron collisions near phase boundary bring hadrons close to equilibrium – supported by success of statistical model analysis
- This implies little energy dependence above RHIC energy
- Analysis of hadron production → determination of $T_c$

pbm, Stachel, Wetterich,
Phys.Lett. B596 (2004) 61-69

At what energy is phase boundary reached?

# thermal model of particle production and QCD

partition function Z(T,V) contains sum over the full hadronic mass spectrum and is fully calculable in QCD

for each particle i, the statistical operator is:

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

particle densities are then calculated according to:

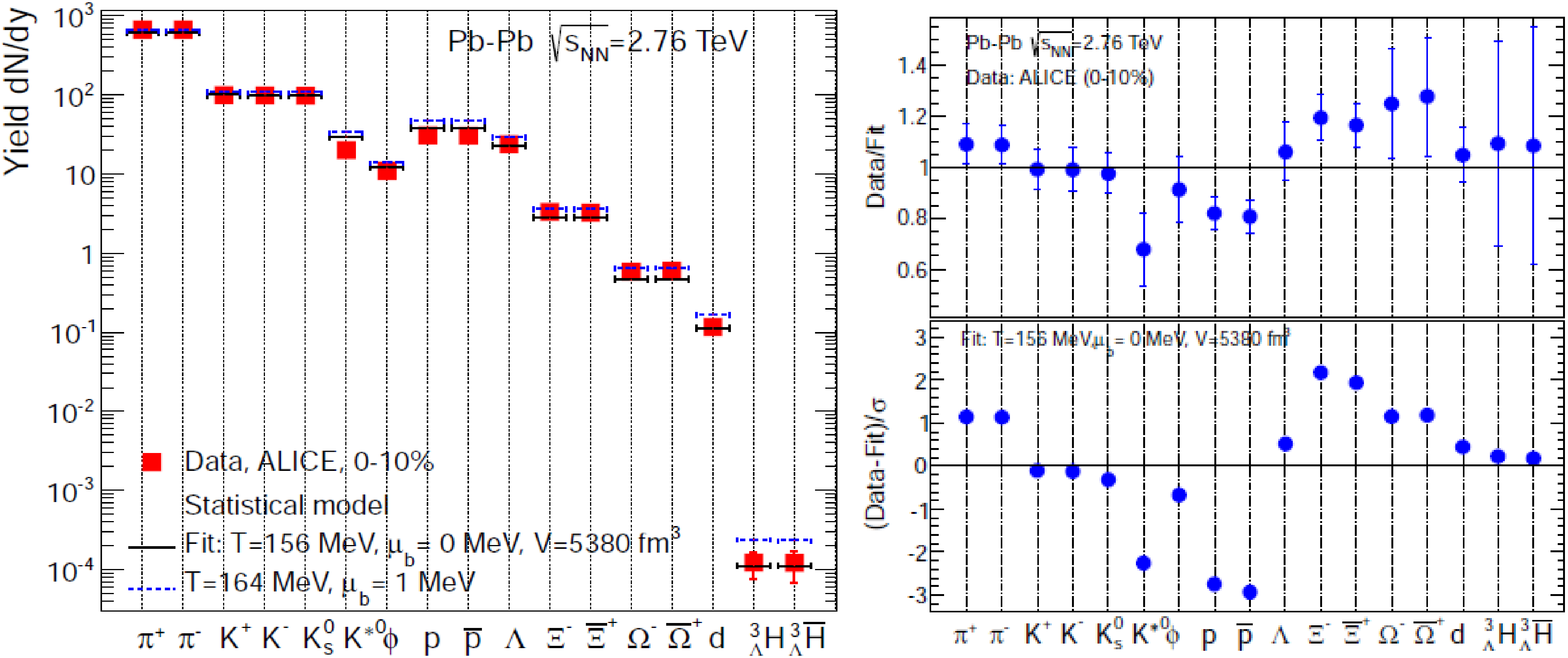
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}$$

from analysis of all available nuclear collision data we now know the energy dependence of the parameters T, mu_b, and V over an energy range from threshold to LHC energy and can confidently extrapolate to even higher energies

in practice, we use the full experimental hadronic mass spectrum from the PDG compilation (vacuum masses) to compute the 'primordial yield'

comparison with measured hadron yields needs evaluation of all strong decays

# Excellent description of LHC data

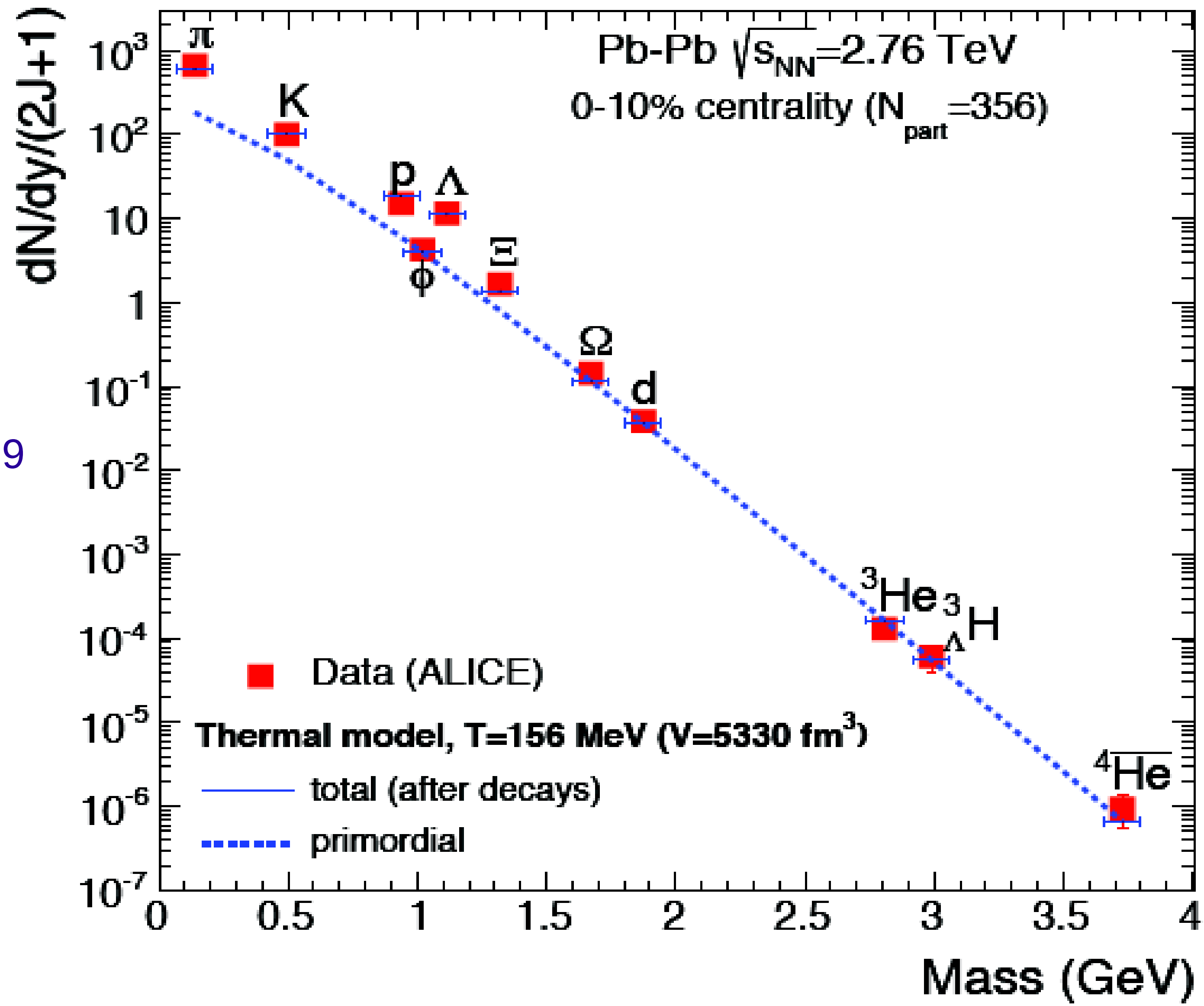



proton discrepancy 2.8 sigma

fit includes loosely bound systems such as deuteron and hypertriton
hypertriton is bound-state of (Λ,p,n), Λ separation energy about 130 keV
size about 10 fm, the **ultimate halo nucleus,**
produced at T=156 MeV. close to an Efimov state

# excellent agreement over 9 orders of magnitude

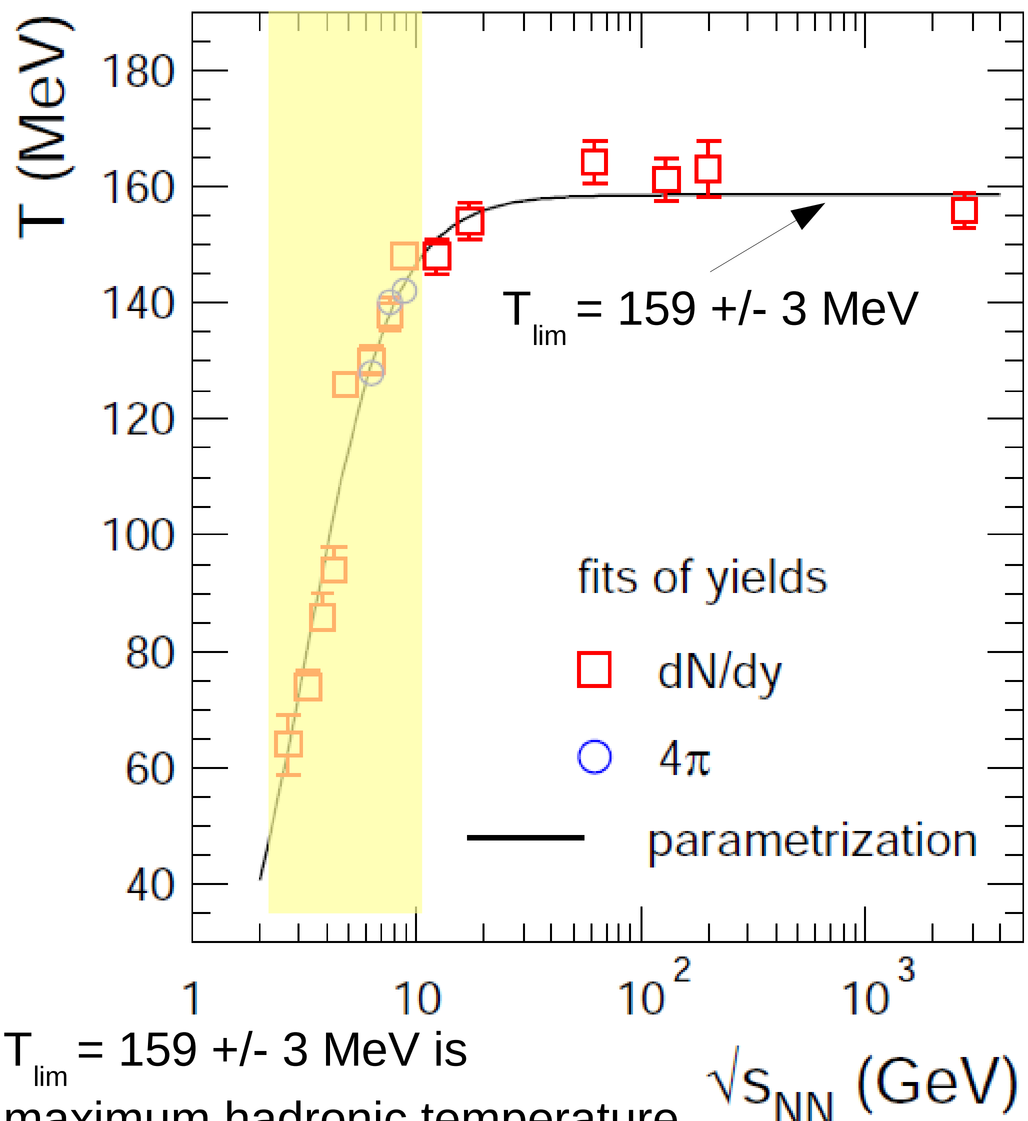
agreement over 9 orders of magnitude with QCD statistical operator prediction




yield of light nuclei predicted in: pbm, J. Stachel, J.Phys. G28 (2002) 1971-1976,
J.Phys. G21 (1995) L17-L20

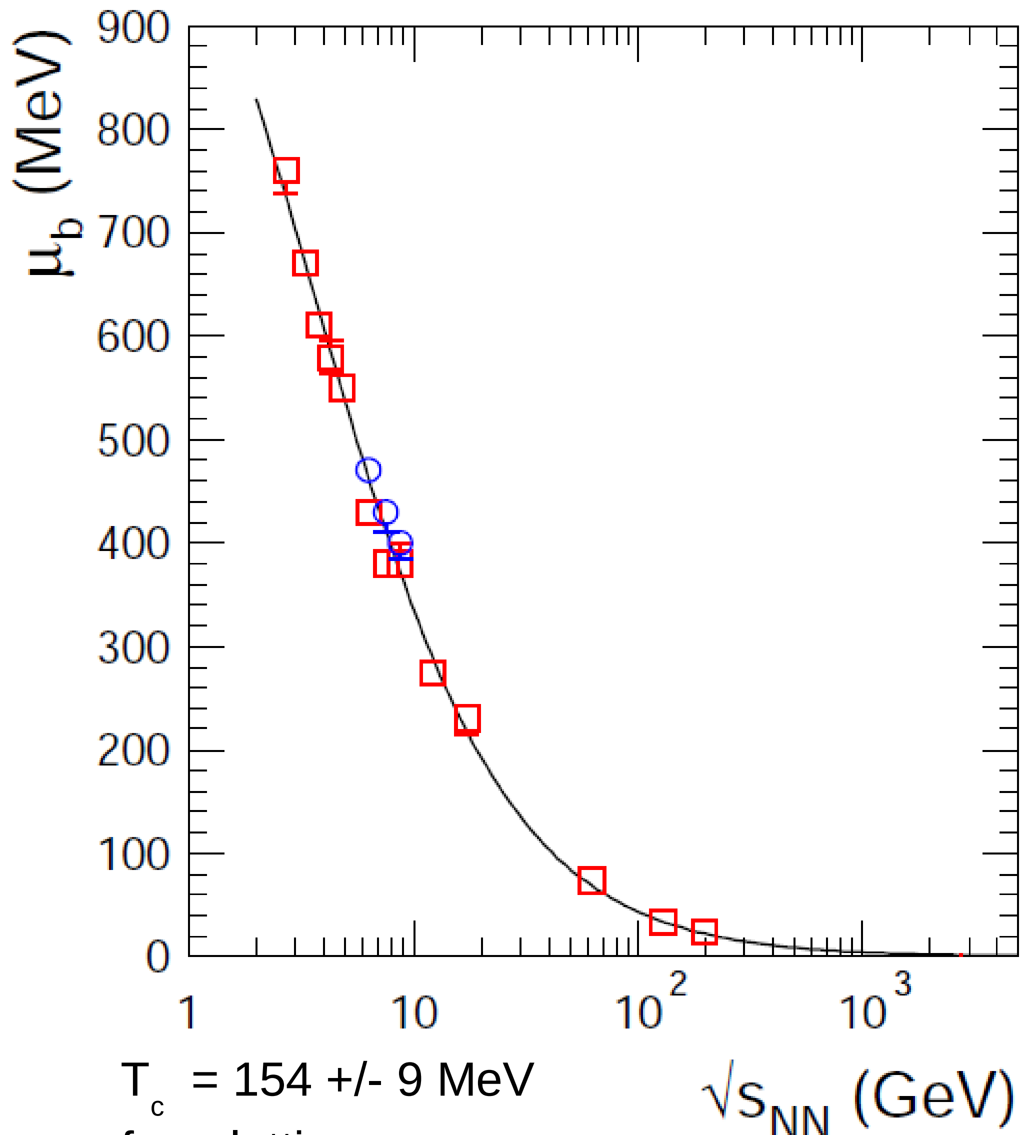
# energy dependence of temperature and baryo-chemical potential

energy range from SPS down to threshold



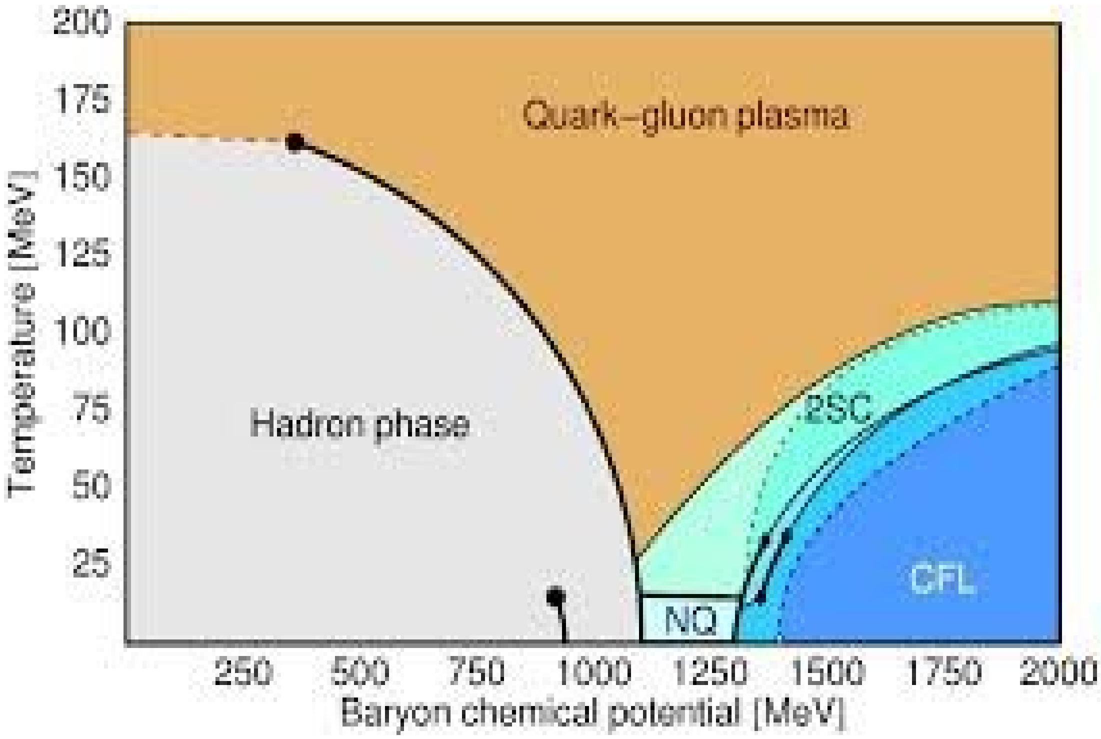

$T_{lim}$ = 159 +/- 3 MeV is
maximum hadronic temperature

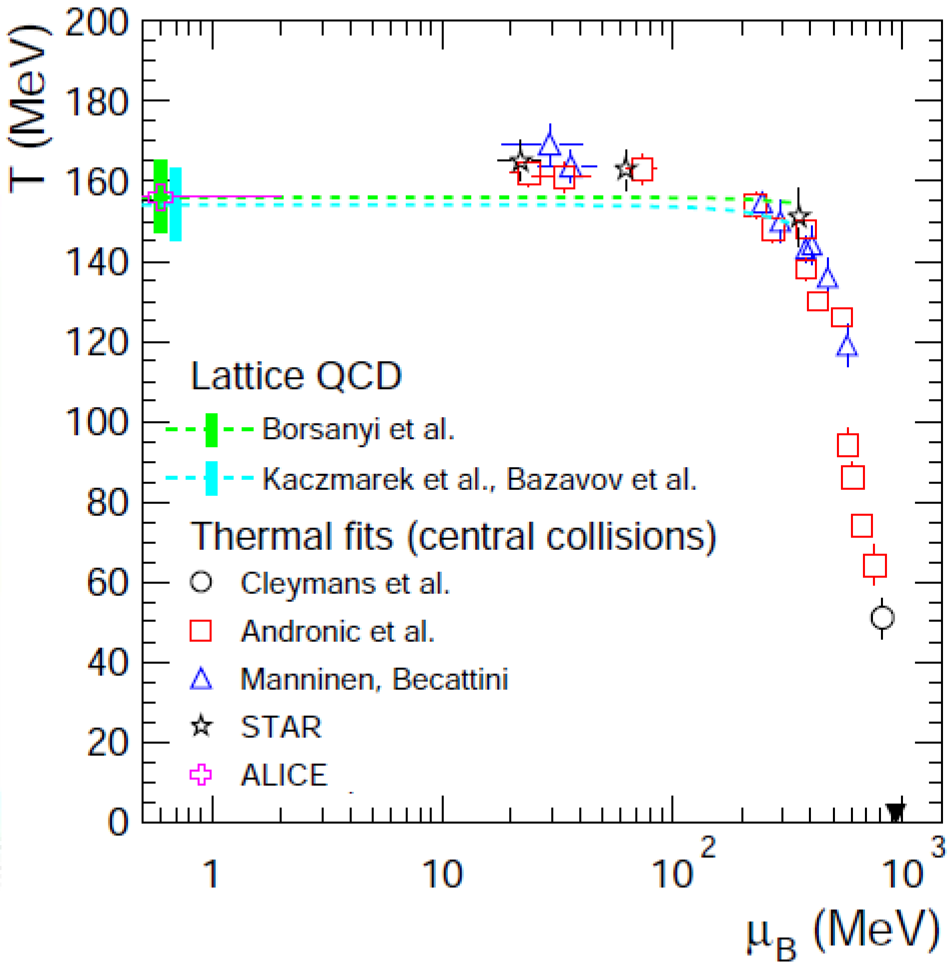
is phase boundary ever reached
for $\sqrt{s_{NN}}$ < 10 GeV?




$T_c$ = 154 +/- 9 MeV
from lattice

# the QGP phase diagram, LQCD, and hadron production data



# lattice QCD, net 'charges', susceptibilities, and ALICE data

main idea: at LHC energy, $\mu_b = 0$, no sign problem, LQCD approach reliable

in a thermal medium, fluctuations or correlations of net 'charges' N are expressed in terms of susceptibilities as:

$$\hat{\chi}_N \equiv \frac{\chi_N}{T^2} = \frac{\partial^2 \hat{P}}{\partial \hat{\mu}_N^2} \qquad \hat{\chi}_{NM} \equiv \frac{\chi_{NM}}{T^2} = \frac{\partial^2 \hat{P}}{\partial \hat{\mu}_N \partial \hat{\mu}_M}$$

here, the reduced pressure and chemical potential are, with N,M =(B,S,Q):

$$\hat{P} = P/T^4 \qquad \hat{\mu}_N = \mu_N/T$$

thermodynamically, the susceptibility for the conserved charge N is related to its variance via:

$$\hat{\chi}_N = \frac{1}{VT^3}(\langle N^2 \rangle - \langle N \rangle^2)$$

work based on arXiv:1412.8614, Phys. Lett. B747 (2015) 292,
pbm, A. Kalweit, K. Redlich, J. Stachel

for the special case of uncorrelated emission (Skellam distribution) and net baryon number N = B, the susceptibility is related to the total mean number of baryons + anti-baryons via

$$\frac{\chi_N}{T^2} = \frac{1}{VT^3}(\langle N_q \rangle + \langle N_{-q} \rangle)$$

in this limit, we can make a direct comparison between the susceptibility from LQCD, and the experimentally measured total mean number of baryons and anti-baryons.

for N = strangeness S or charge Q, similar expressions, with |q| = (1,2) and |q| = (1,2,3) hold:

$$\frac{\chi_N}{T^2} = \frac{1}{VT^3}\sum_{n=1}^{|q|} n^2(\langle N_n \rangle + \langle N_{-n} \rangle)$$

within this approach, a direct link between ALICE LHC data and LQCD predictions can be established

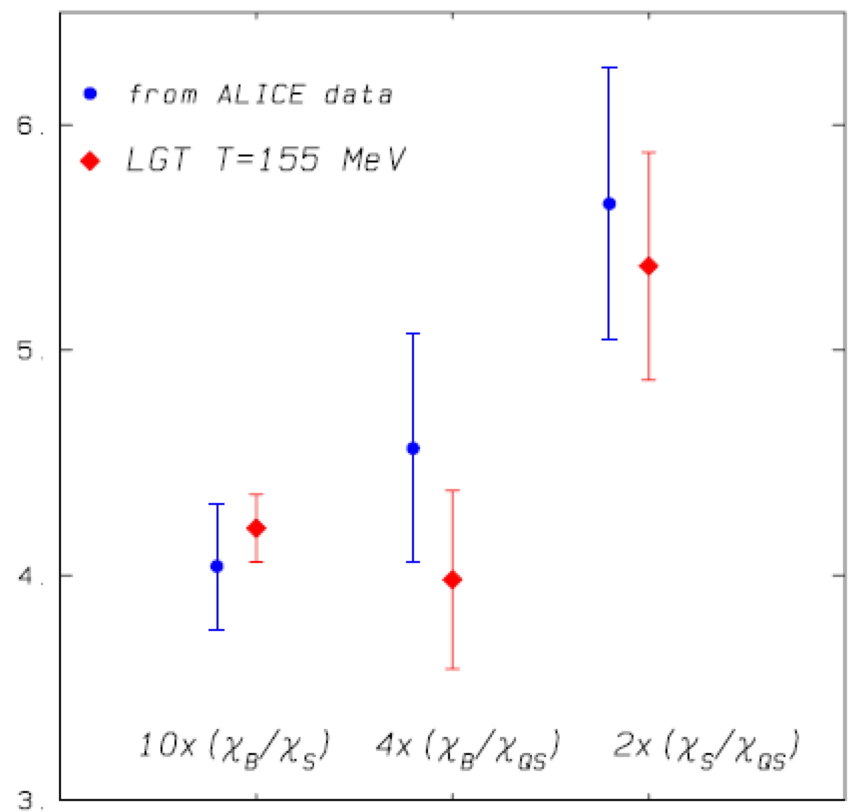
LQCD predictions from:

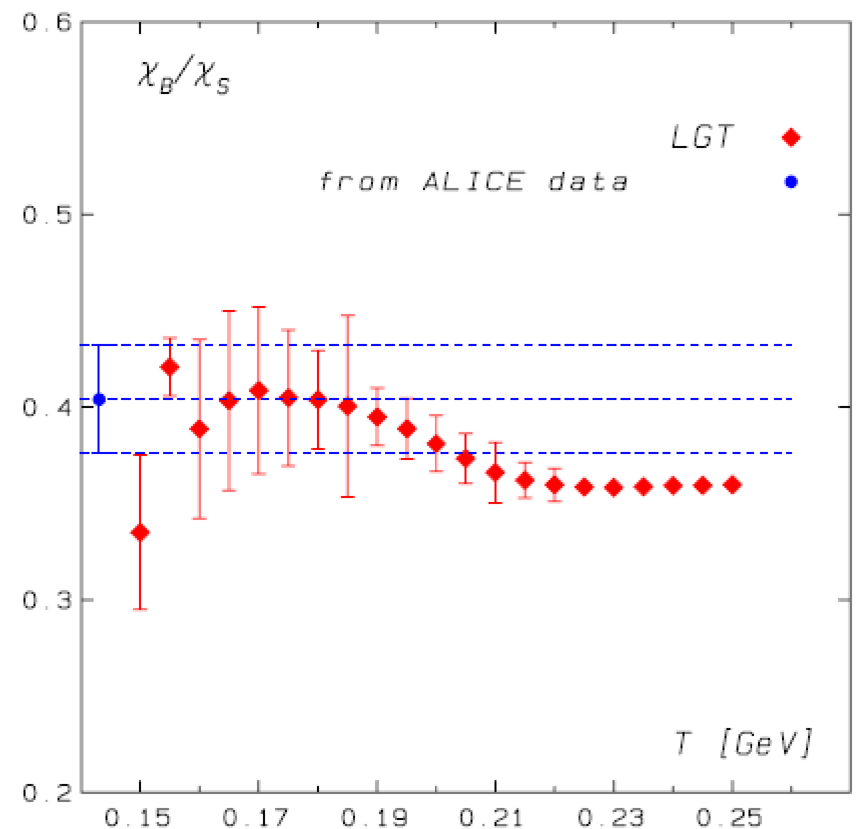
A. Bazavov *et al.* [HotQCD Collaboration], Phys. Rev. D **86**, 034509 (2012).
A. Bazavov, H.-T. Ding, P. Hegde, O. Kaczmarek, F. Karsch, E. Laermann, Y. Maezawa and S. Mukherjee, Phys. Rev. Lett. **113**, 072001 (2014).

expressed in terms of measurable quantities:

$$\frac{\chi_B}{T^2} = \frac{1}{VT^3}[\langle p\rangle + \langle N\rangle + \langle \Lambda + \Sigma^0\rangle + \langle \Sigma^+\rangle + \langle \Sigma^-\rangle + \langle \Xi^-\rangle + \langle \Xi^0\rangle + \langle \Omega^-\rangle + \text{antiparticles}],$$

$$\frac{\chi_S}{T^2} \simeq \frac{1}{VT^3}[(\langle K^+\rangle + \langle K^0\rangle + \langle \Lambda + \Sigma^0\rangle + \langle \Sigma^+\rangle + \langle \Sigma^-\rangle + 4\langle \Xi^-\rangle + 4\langle \Xi^0\rangle + 9\langle \Omega^-\rangle + \text{antiparticles}) - (\Gamma_{\phi\to K^+} + \Gamma_{\phi\to K^-} + \Gamma_{\phi\to K^0} + \Gamma_{\phi\to \bar{K}^0})\langle\phi\rangle]. \quad (9)$$



from the above figures, one concludes that LQCD predictions and data agree for (pseudo-)critical temperatures T > 150 MeV.

however, as shown in F. Karsch, Acta Phys. Polon. Supp. **7**, no. 1, 117 (2014)

LQCD results cannot be described by hadronic degrees of freedom for T > 163 MeV.

hence we conclude that

**150 < T < 163 MeV**

from the comparison of ALICE hadron yields with LQCD predictions, completely consistent with the chemical freeze-out analysis

# summary I

overall the LHC data provide strong support for chemical freeze-out driven by the phase transition at $T_c$ = 156 MeV

the full QCD statistical operator is encoded in the nuclear collision data on hadron multiplicities

energy dependence of hadron yields provides strong connection to fundamental QCD prediction of hadronic and quark-gluon matter at high temperature

success to describe also yields of loosely bound states provides strong evidence for isentropic expansion after chemical freeze-out

**connection between LQCD and data**

# charmonium as a probe for the properties of the QGP

the original idea: (Matsui and Satz 1986) implant charmonia into the QGP and observe their modification, in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – sequential melting

n.b. at collider energies there is a complete separation of time scales

$t_{coll} << t_{QGP} < t_{Jpsi}$

new insight (pbm, Stachel 2000) QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfined, thermalized charm quarks production probability scales with $N(_{ccbar})^2$

implanting charmonia into QGP is an inappropriate notion

this issue was already anticipated by Blaizot and Ollitrault in 1988

recent reviews: L. Kluberg and H. Satz, arXiv:0901.3831

pbm and J. Stachel, arXiv:0901.2500

both published in Landoldt-Boernstein Review, R. Stock, editor, Springer 2010

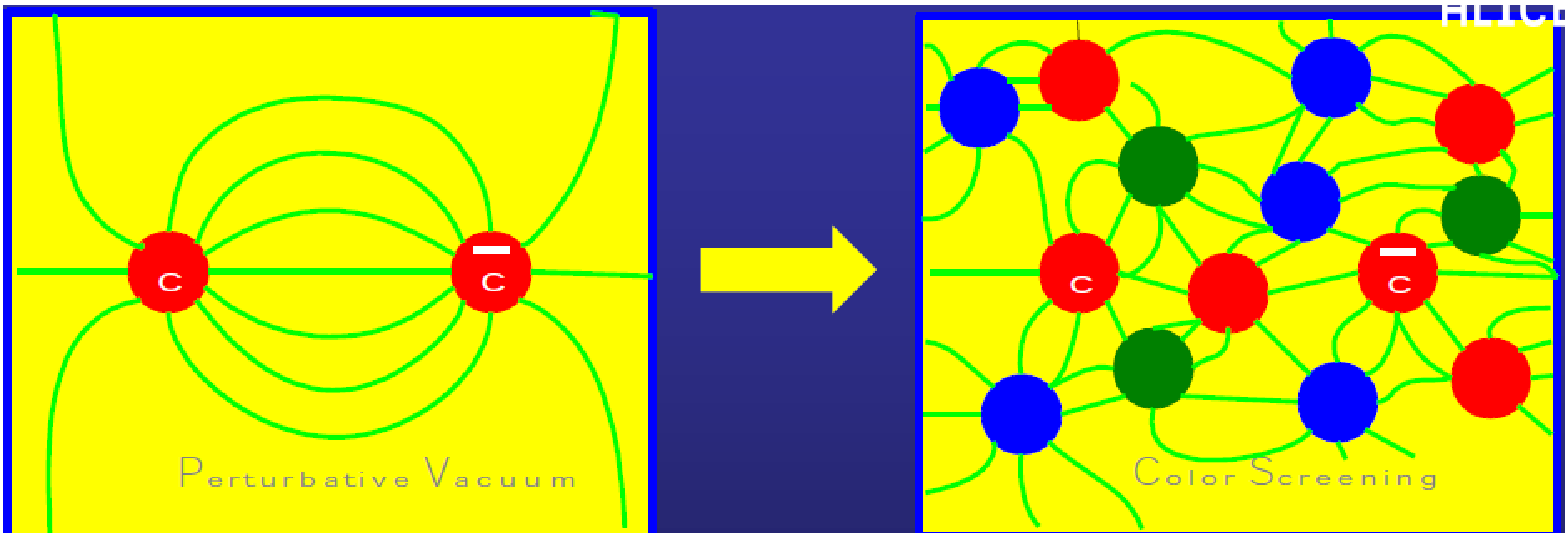
See also: Heavy quark bound states in a quark-gluon plasma: dissociation and recombination

Jean-Paul Blaizot, Davide De Boni, Pietro Faccioli, Giovanni Garberoglio

arXiv:1503.03857 [nucl-th]

# color screening removes bound states

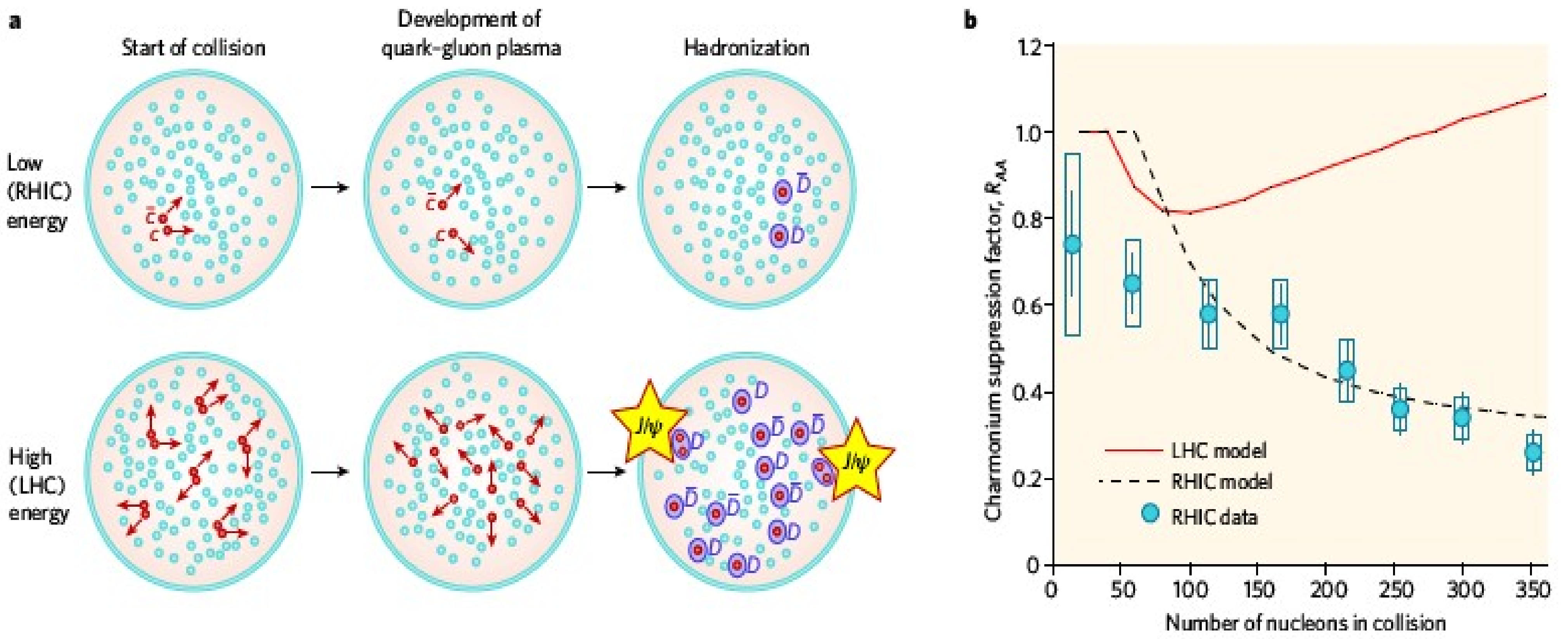
vacuum QGP




will this happen at $T_c$ or only when deep inside the QGP?

# quarkonium as a probe for deconfinement at the LHC
# the statistical (re-)generation picture

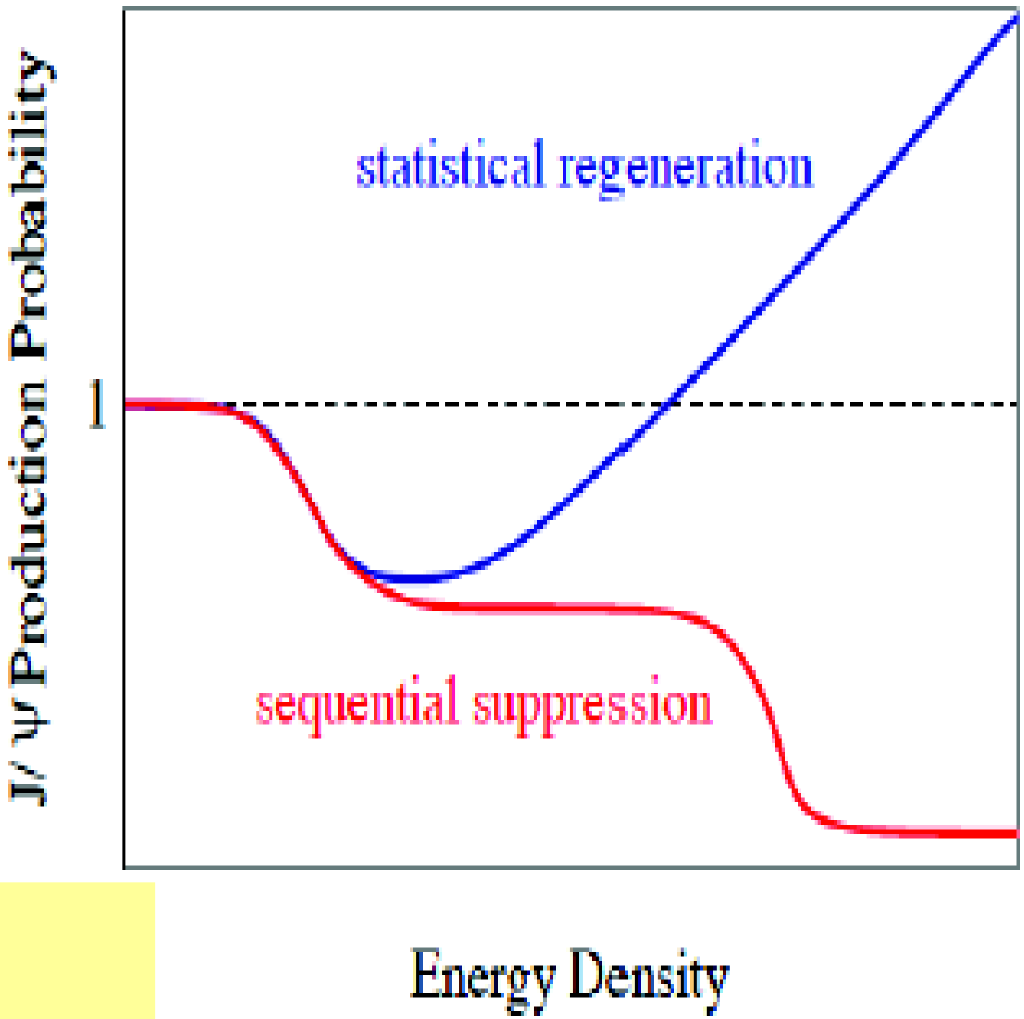
P. Braun-Munzinger, J. Stachel, The Quest for the Quark-Gluon Plasma,
Nature **448** Issue 7151, (2007) 302-309.




charmonium enhancement as fingerprint of color screening and deconfinement at LHC energy

pbm, Stachel, Phys. Lett. B490 (2000) 196
Andronic, pbm, Redlich, Stachel, Phys. Lett. B652 (2007) 659

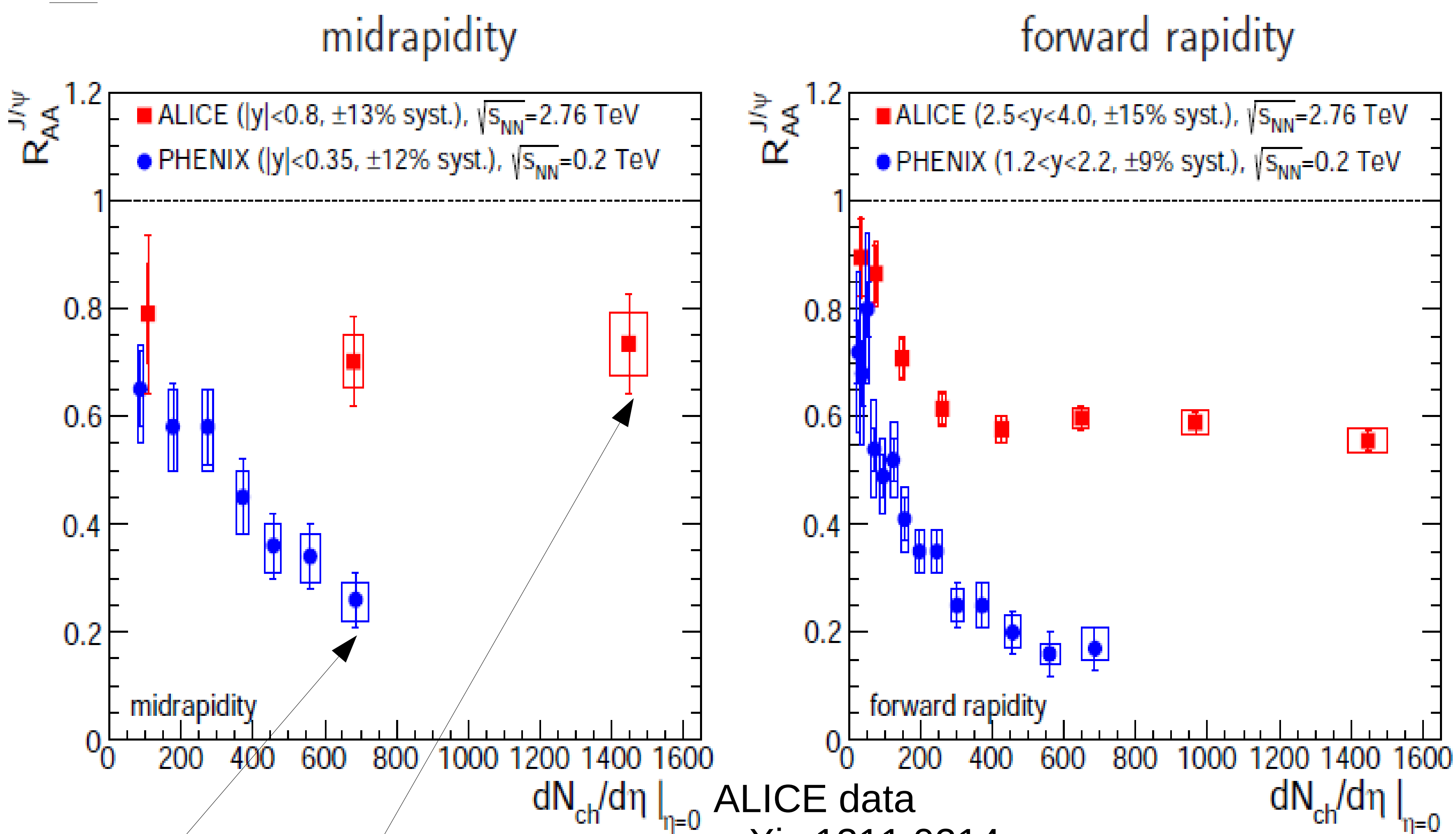
# decision on regeneration vs sequential suppression from LHC data




SPS RHIC LHC

Picture:
H. Satz 2009

# less suppression when increasing the energy density

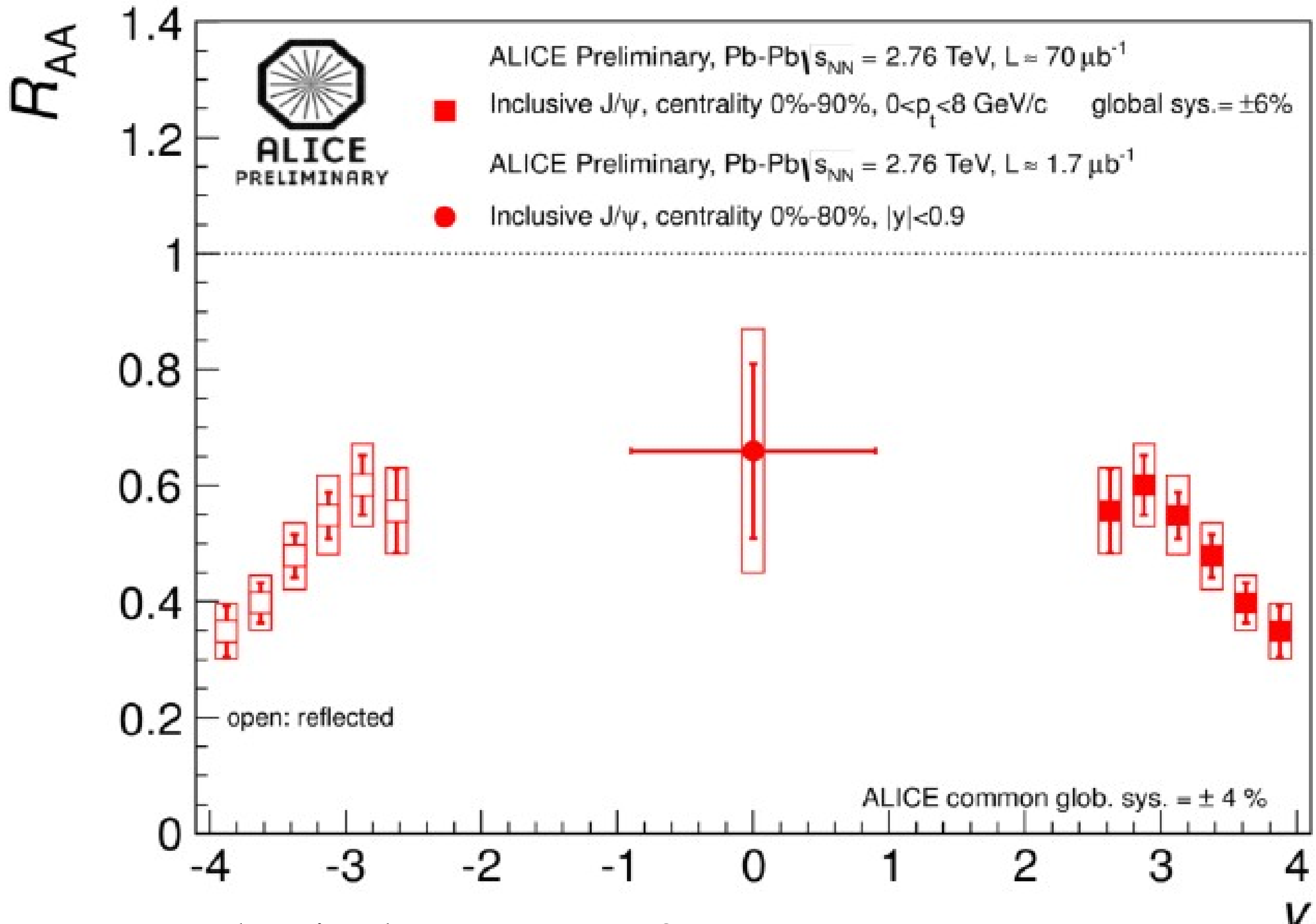



ALICE data
arXiv:1311.0214
PLB, in print

from here to here more than factor of 2 increase in energy density, but $R_{AA}$ increases by more than a factor of 3

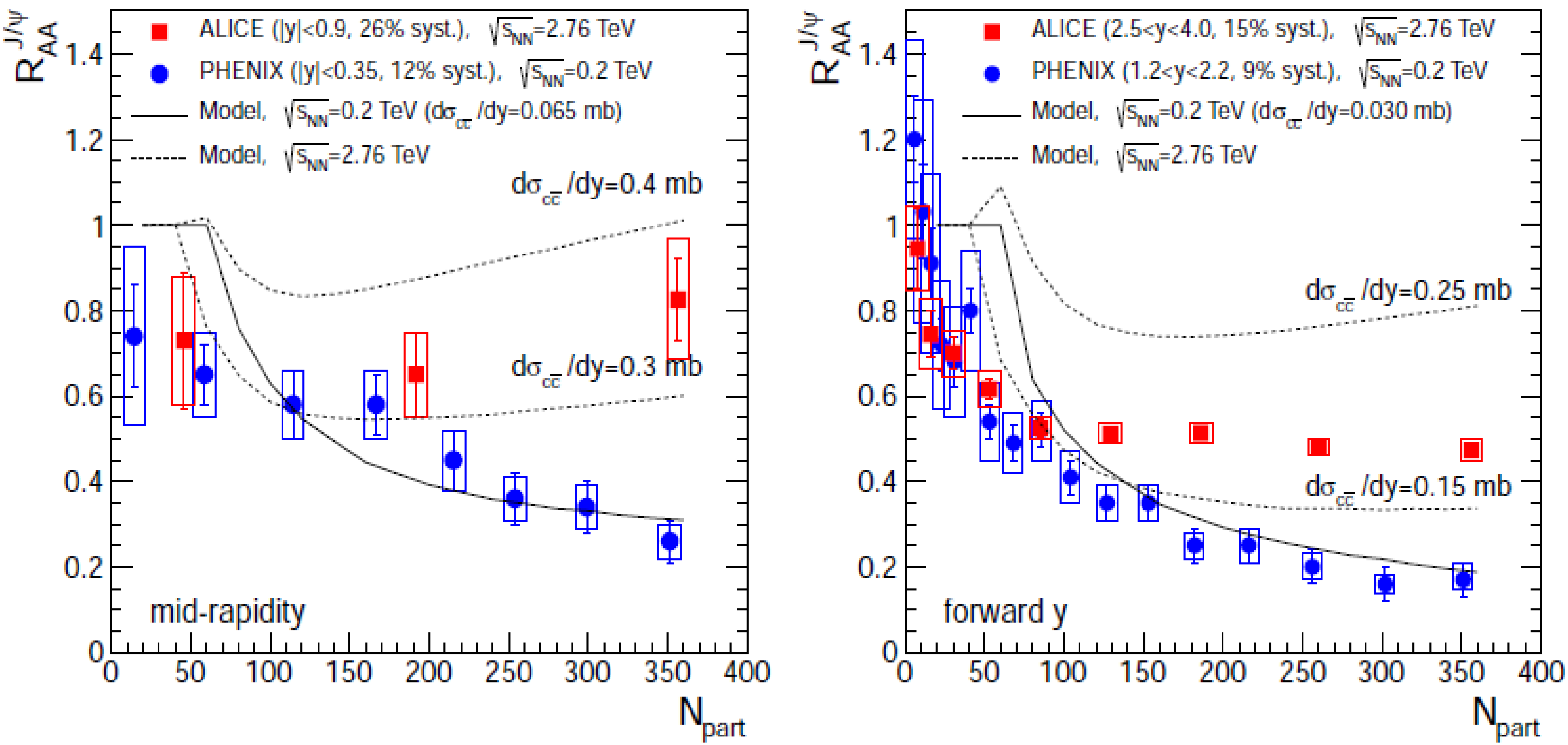
2007 prediction impressively confirmed by LHC data

# rapidity dependence



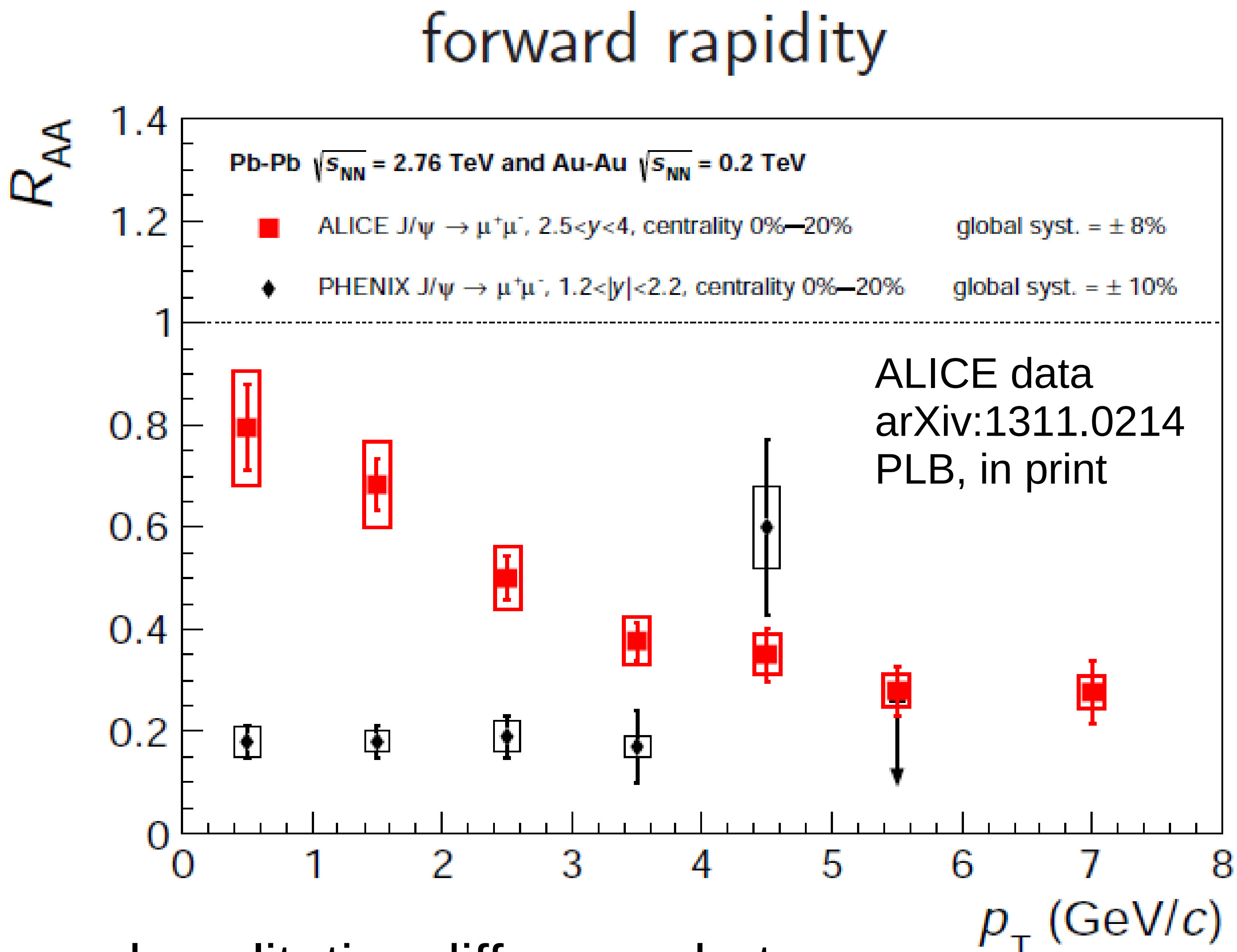

note: energy density largest at y = 0

# statistical hadronization model
# all J/psi production at the phase boundary




ALICE data and evolution from RHIC to LHC energy
described quantitatively

# comparison of transverse momentum spectra at RHIC and LHC




dramatic and qualitative difference between RHIC and LHC results

# charmonium production at LHC energy: deconfinement,and color screening

- charmonia formed at the phase boundary → full color screening at $T_c$

- Debye screening length < 0.4 fm near $T_c$

- combination of uncorrelated charm quarks into J/psi → deconfinement

**statistical hadronization picture of charmonium production provides most direct way towards information on the degree of deconfinement reached as well as on color screening and the question of bound states in the QGP**

# Debye mass, LQCD, and J/psi data

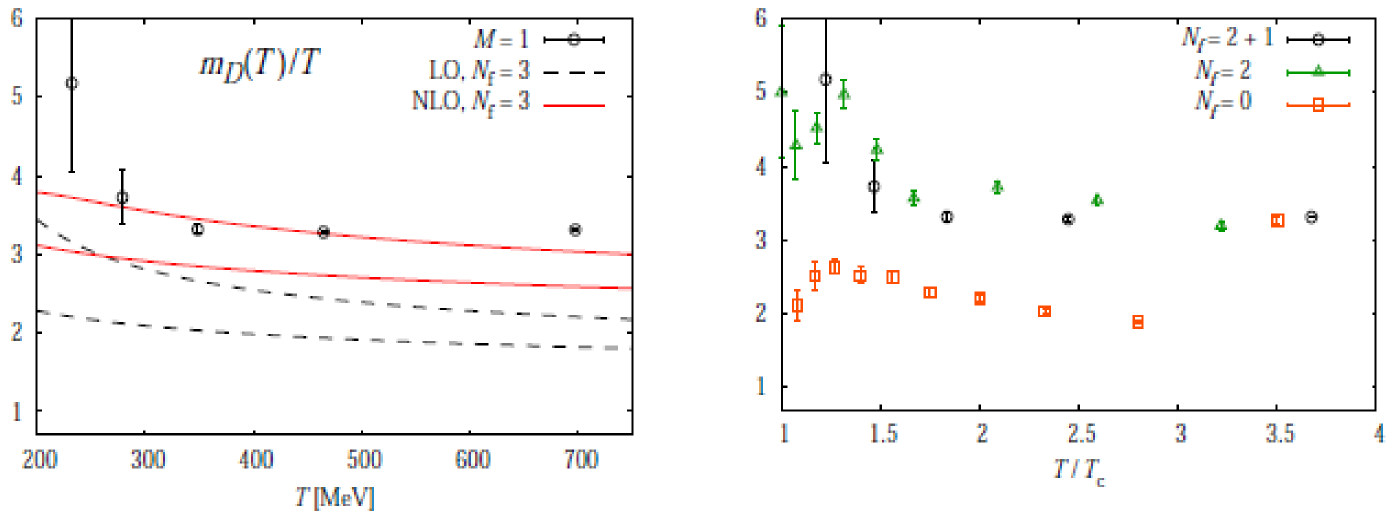



Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi T$ ($3\pi T$), where $\mu$ is the renormalization point. (Right) Flavor dependence of the Debye screening masses. We assume the pseudo-critical temperature for $2+1$-flavor QCD as $T_c \sim 190$ MeV.

arXiv:1112.2756 WHOT-QCD Coll.

from J/psi data and statistical hadronization analysis:

$m_{Debye}/T > 3.3$

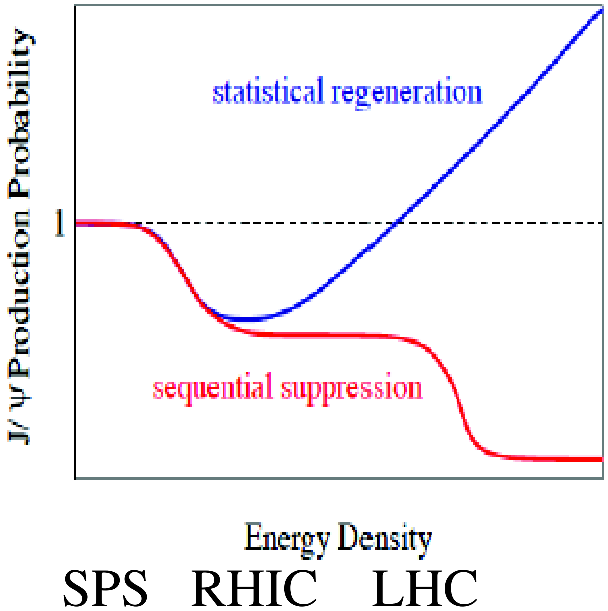
at T = 0.15 GeV

**J/psi data on color screening at the phase boundary are close to predictions from Lattice QCD**

# summary II

- charmonium production – a fingerprint for deconfined quarks and gluons

- evidence for energy loss and flow of charm quarks --> thermalization
- charmonium generation at the phase boundary – a new process
- first indications for this from psi'/(J/psi) SPS and J/psi RHIC data
- evolution from RHIC to LHC described quantitatively
- charmonium enhancement at LHC – J/psi color-screened at $T_c$
  charm quarks deconfined in QGP




cartoon Helmut Satz, 2009

# outlook

Run2 at the LHC has started in June 2015

LHC close to full design energy $\sqrt{s} =$ 13 TeV for pp
$\sqrt{s_{NN}} = 5.1$ TeV for Pb—Pb

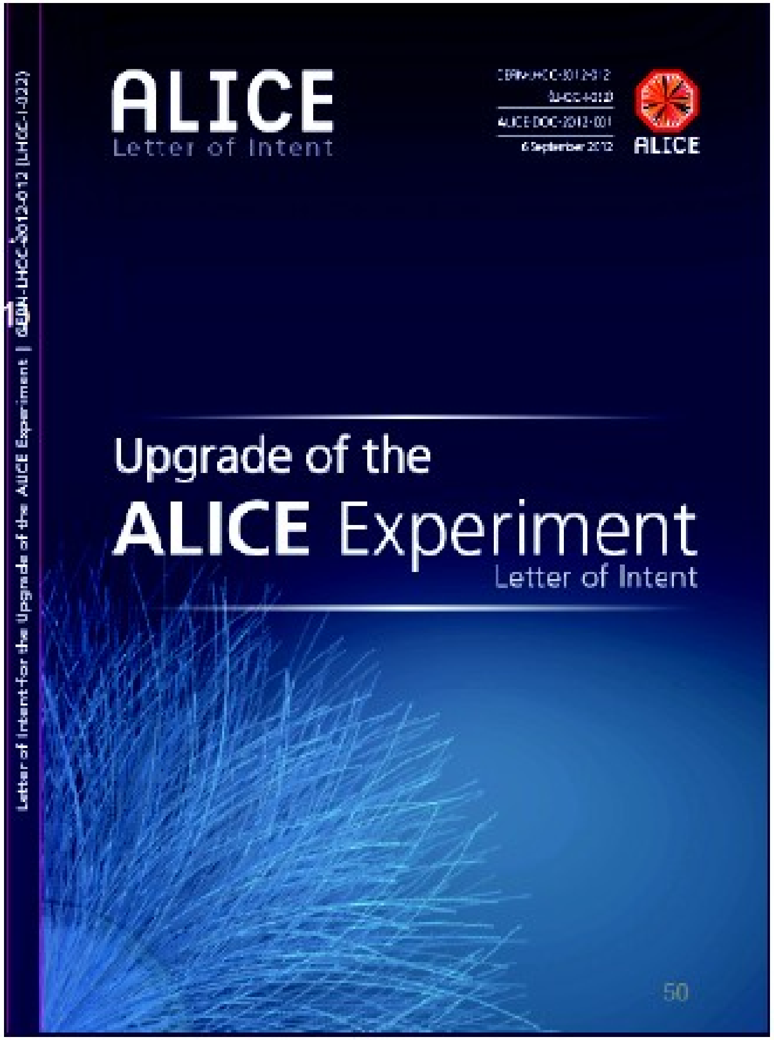
Pb-Pb interaction rate up to 20 kHz (factor 4 increase compared to Run1 and factor 3 beyond design luminosity)

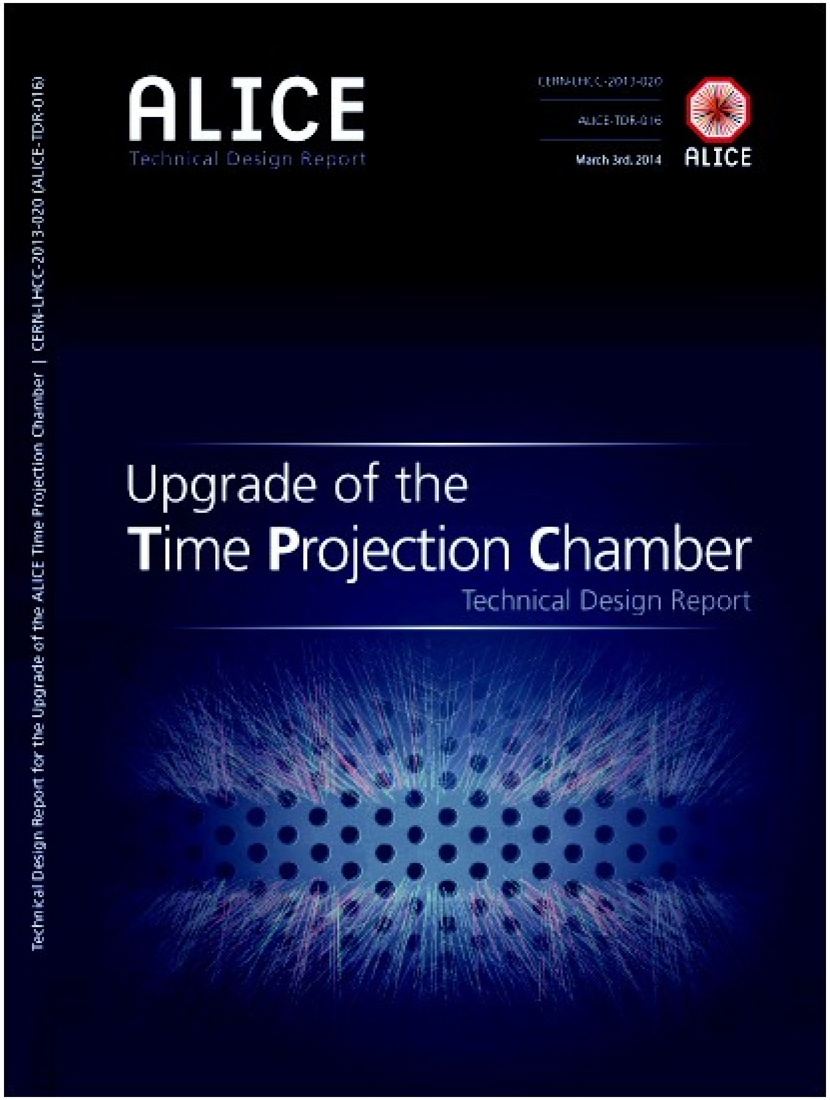
ALICE detector adapted to new running conditions

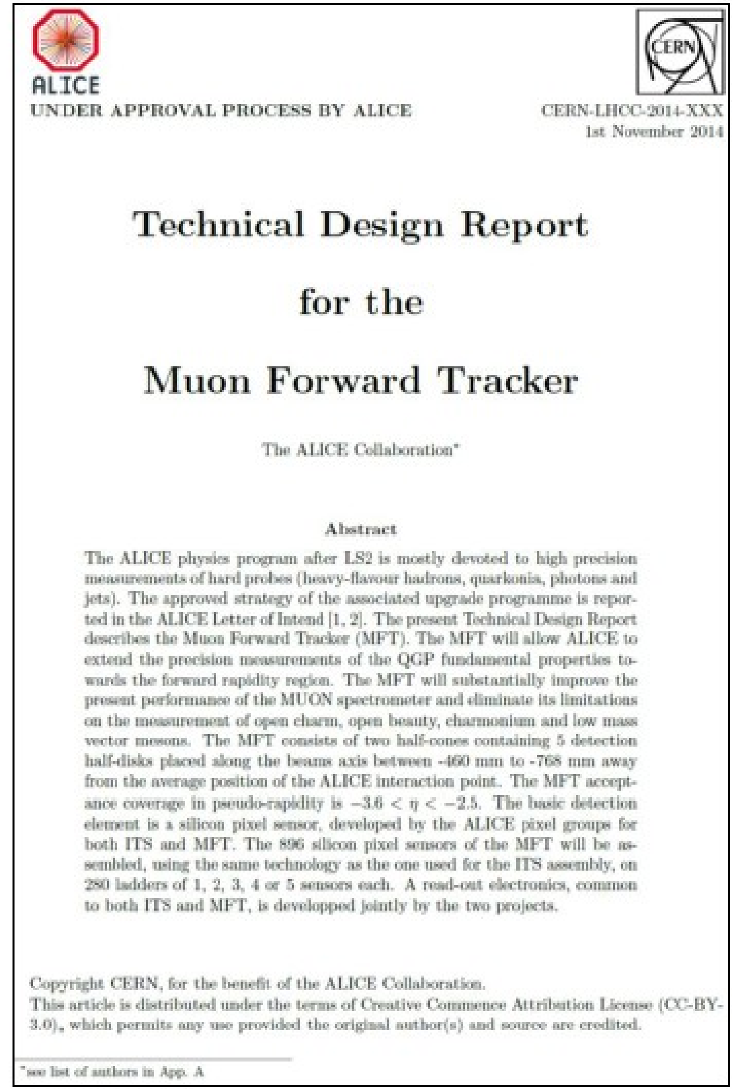
plan for order of magnitude increase in data at higher energy and significantly improved precision

# Run 3: upgrade overview

- The ALICE upgrade strategy is outlined in the Letter Of Intent
  - CERN-LHCC-2012-012 ; LHCC-I-022
  - http://cds.cern.ch/record/1475243
- Operate ALICE at high luminosity ($\mathcal{L}=6\mathrm{x}10^{-27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$) and record all minimum bias events
  - 50 kHz in Pb-Pb collisions → 100 x larger than the current read-out rate
  - 5 overlapping events in TPC drift volume → TPC can not run in triggered mode
- The TPC upgrade is described in a Technical Design Report





ALICE

UNDER APPROVAL PROCESS BY ALICE

CERN-LHCC-2014-XXX
1st November 2014

# Technical Design Report for the Muon Forward Tracker

The ALICE Collaboration*

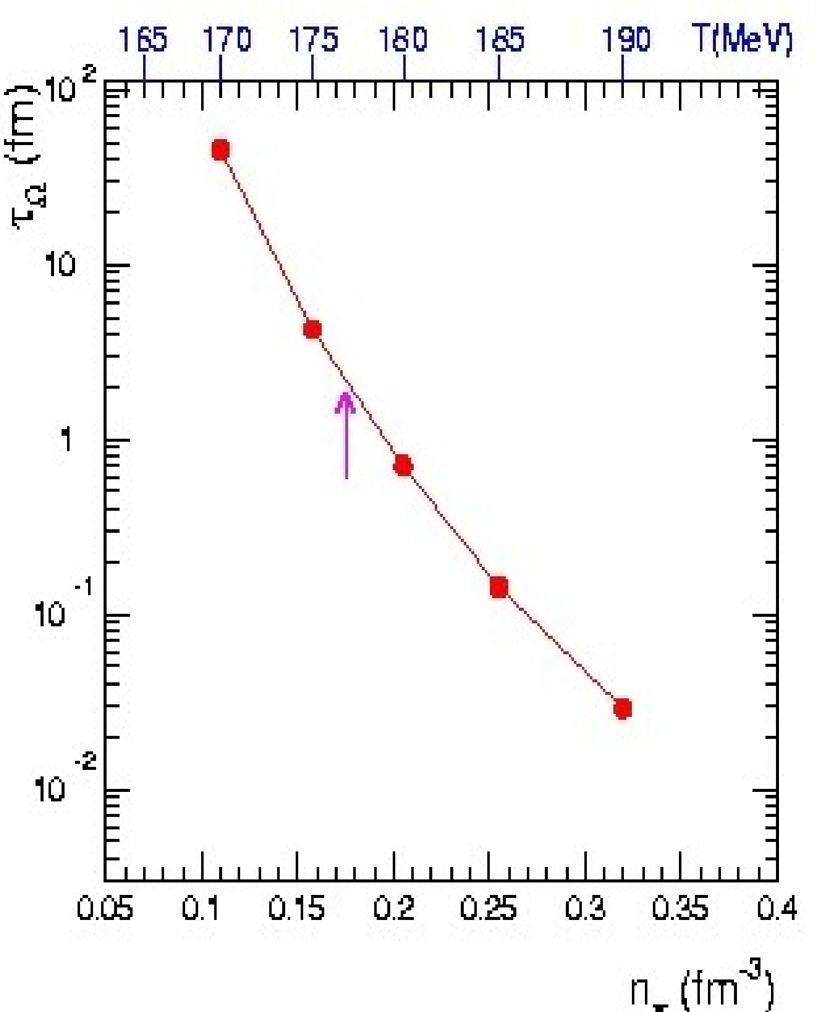
**Abstract**

The ALICE physics program after LS2 is mostly devoted to high precision measurements of hard probes (heavy-flavour hadrons, quarkonia, photons and jets). The approved strategy of the associated upgrade programme is reported in the ALICE Letter of Intend [1, 2]. The present Technical Design Report describes the Muon Forward Tracker (MFT). The MFT will allow ALICE to extend the precision measurements of the QGP fundamental properties towards the forward rapidity region. The MFT will substantially improve the present performance of the MUON spectrometer and eliminate its limitations on the measurement of open charm, open beauty, charmonium and low mass vector mesons. The MFT consists of two half-cones containing 5 detection half-disks placed along the beams axis between -460 mm to -768 mm away from the average position of the ALICE interaction point. The MFT acceptance coverage in pseudo-rapidity is $-3.6 < \eta < -2.5$. The basic detection element is a silicon pixel sensor, developed by the ALICE pixel groups for both ITS and MFT. The 896 silicon pixel sensors of the MFT will be assembled, using the same technology as the one used for the ITS assembly, on 280 ladders of 1, 2, 3, 4 or 5 sensors each. A read-out electronics, common to both ITS and MFT, is developped jointly by the two projects.



*see list of authors in App. A

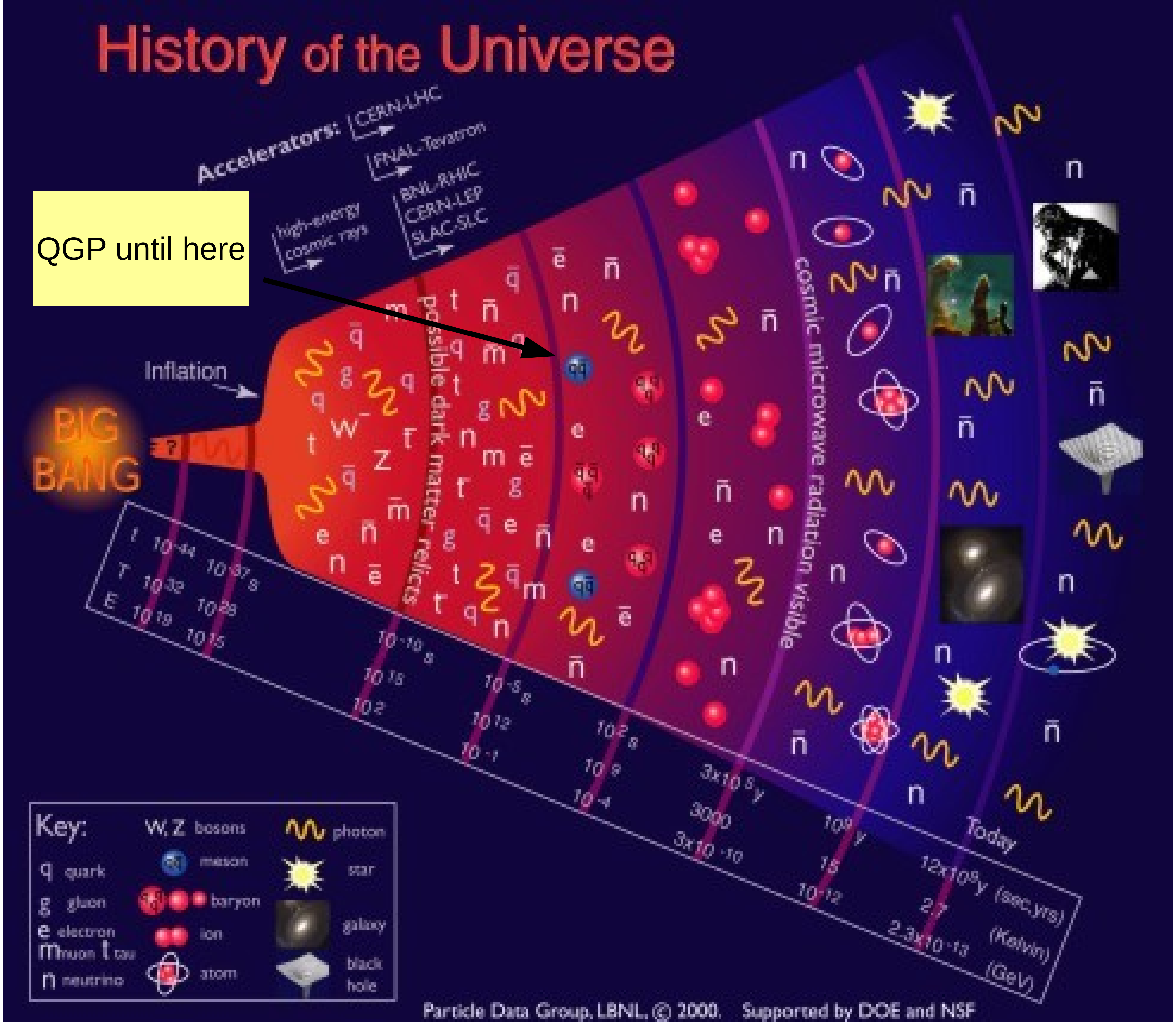
# The QGP phase transition drives chemical equilibration for small $\mu_b$



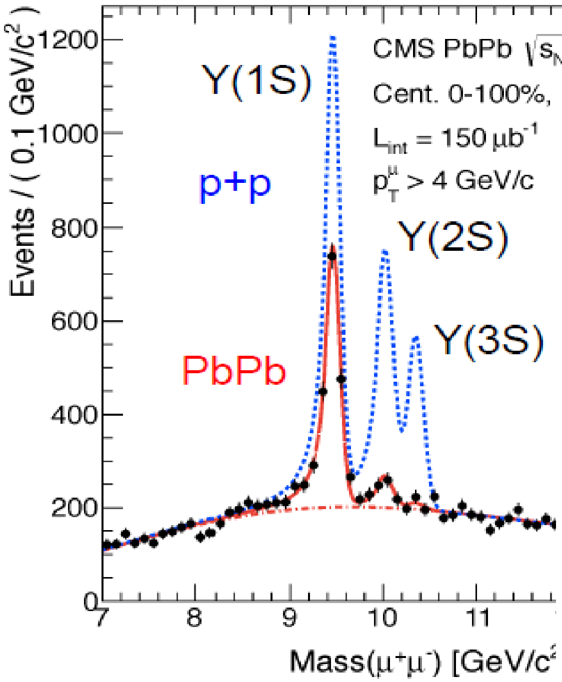

- Near phase transition particle density varies rapidly with T.
- For small $\mu_b$, reactions such as $KKK\pi\pi \rightarrow \Omega N_{bar}$ bring multi-strange baryons close to equilibrium.
- Equilibration time $\tau \propto T^{-60}$ !
- All particles freeze out within the same very narrow temperature window.

are there similar mechanisms for large $\mu_b$?

pbm, J. Stachel, C. Wetterich
Phys. Lett. B596 (2004) 61
nucl-th/0311005


History of the Universe
QGP until here
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

# the bottomonium puzzle (I)

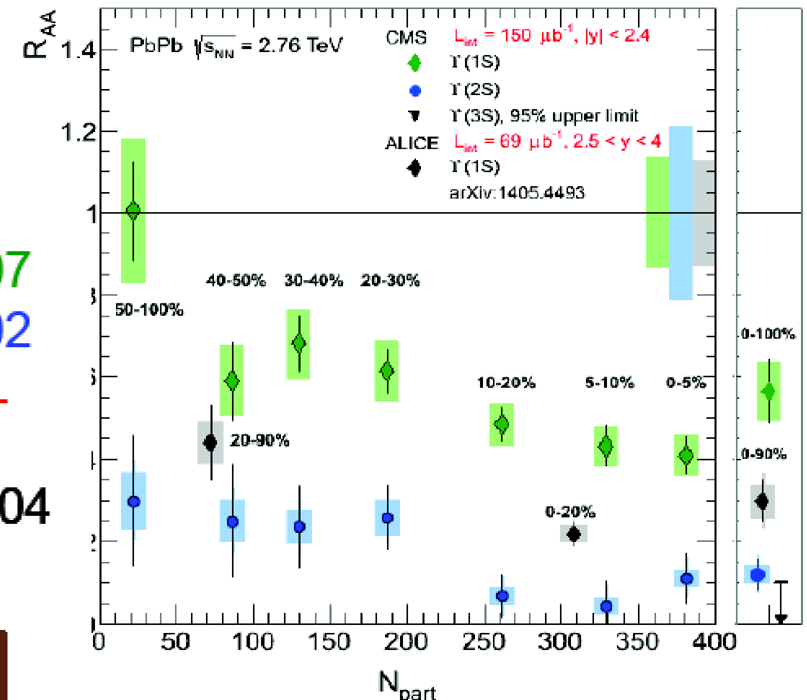



$R_{AA}$ (Υ(1S)) = 0.56 ± 0.08 ± 0.07

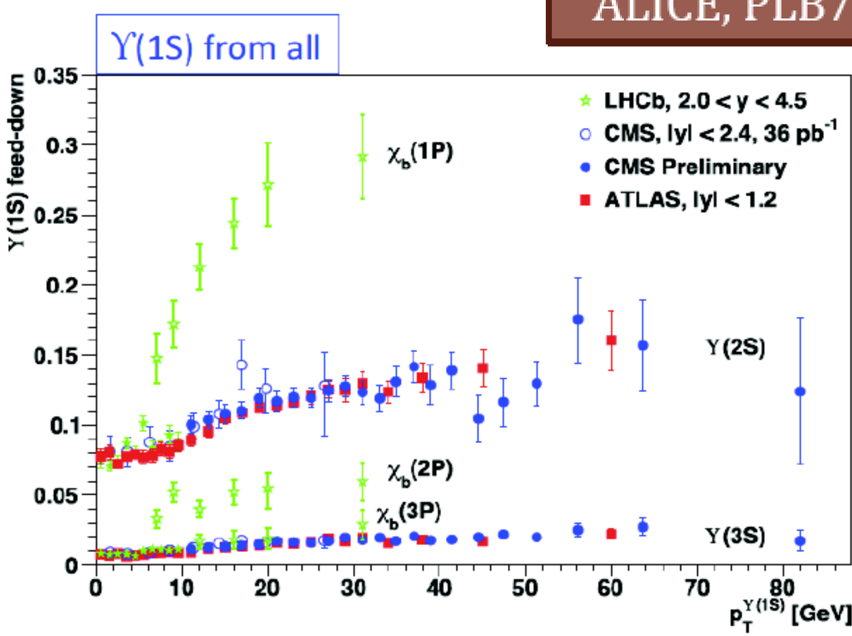
$R_{AA}$ (Υ(2S)) = 0.12 ± 0.04 ± 0.02

$R_{AA}$ (Υ(3S)) < 0.10 @ 95% CL

+ $R_{AA}$ (Υ(1S)) = 0.30 ± 0.05 ± 0.04 (at forward rapidity)

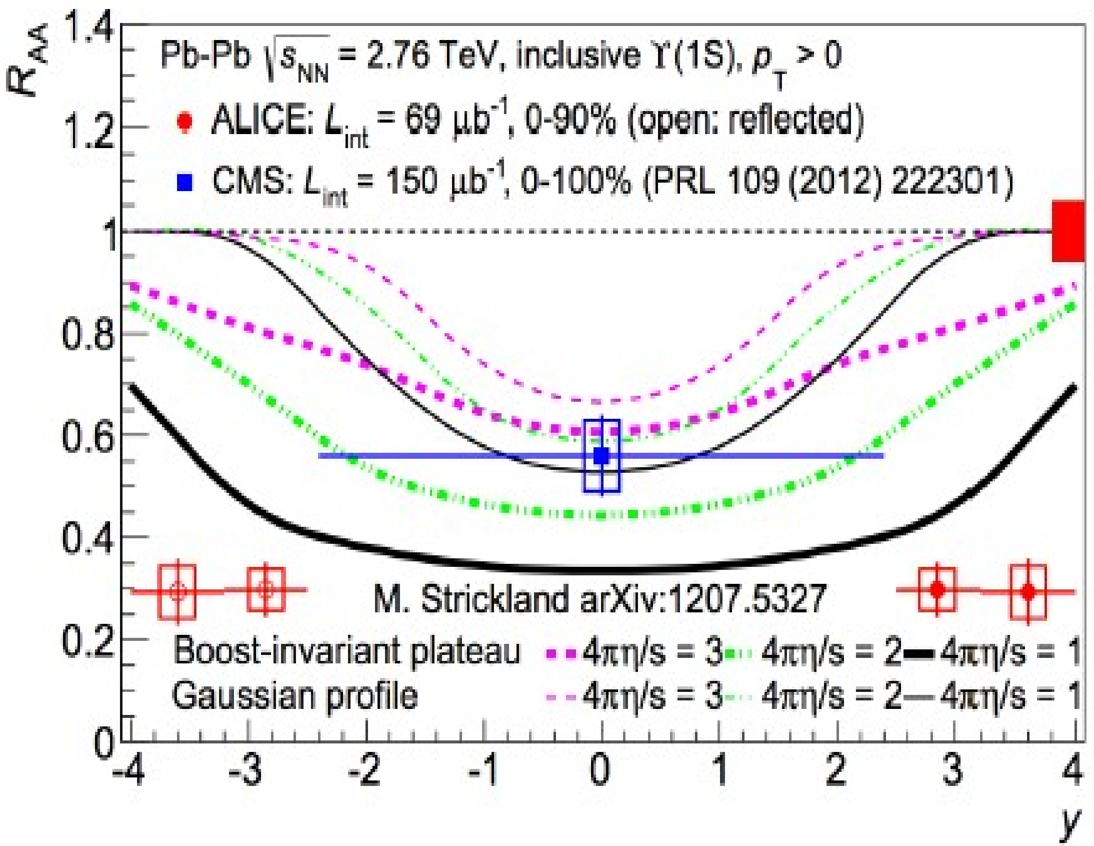



CMS, PRL109 (2012) 222301
ALICE, PLB738 (2014) 361




New results from LHCb: feeding into Υ(1s) only about 30% → Υ(1s) for pp suppression not due to reduced feeding in Pb—Pb collisions

# the bottomonium puzzle (II)




Rapidity distribution of RAA for Y(1s) is peaked at y=0, not consistent with suppression scenarios

**Measurements at large rapidity ( ALICE muon arm) are crucial!**

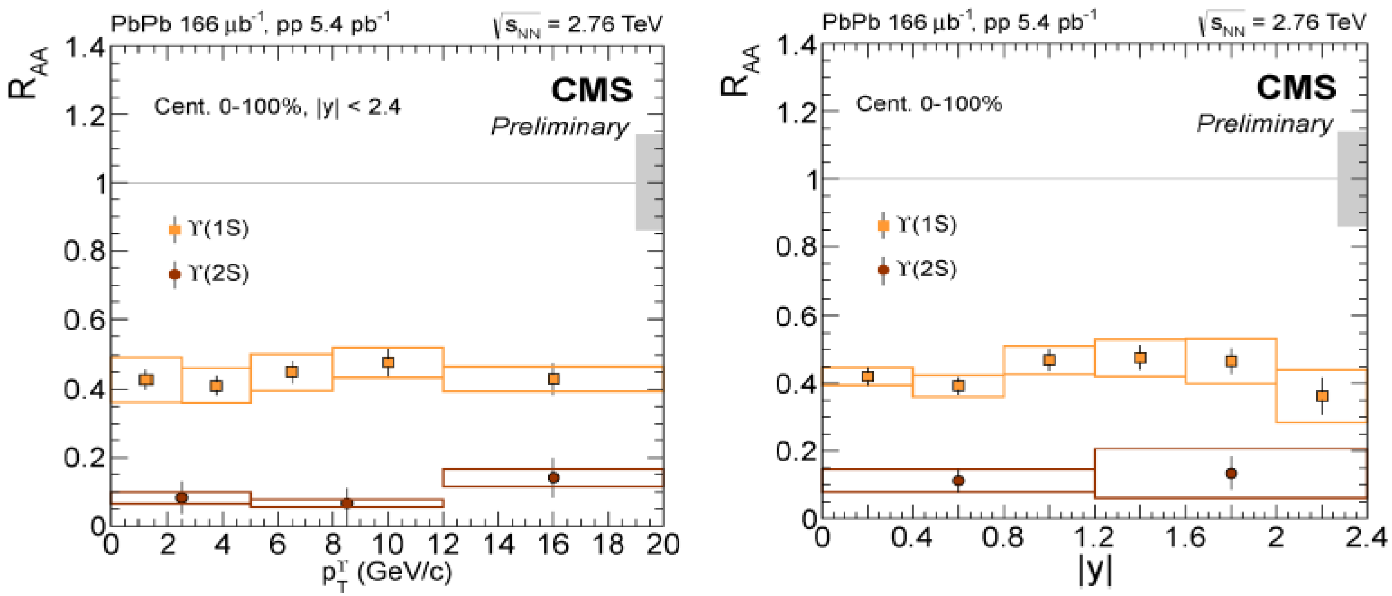
# the bottomonium puzzle (III): $R_{AA}$ constant as function of $p_T$ up to 20 GeV

## Υ production in PbPb

New data with 20 times more pp data

M. Jo

CMS-HIN-15-001




- Centrality integrated results: $\Upsilon$ states suppressed sequentially (0-100%)

$$R_{AA}[\Upsilon(1S)] = 0.425 \pm 0.029 \pm 0.070$$
$$R_{AA}[\Upsilon(2S)] = 0.116 \pm 0.028 \pm 0.022$$
$$R_{AA}[\Upsilon(3S)] < 0.14 \text{ at } 95\% \text{ CL}$$

- $\Upsilon$ suppression does not strongly depend on kinematics.

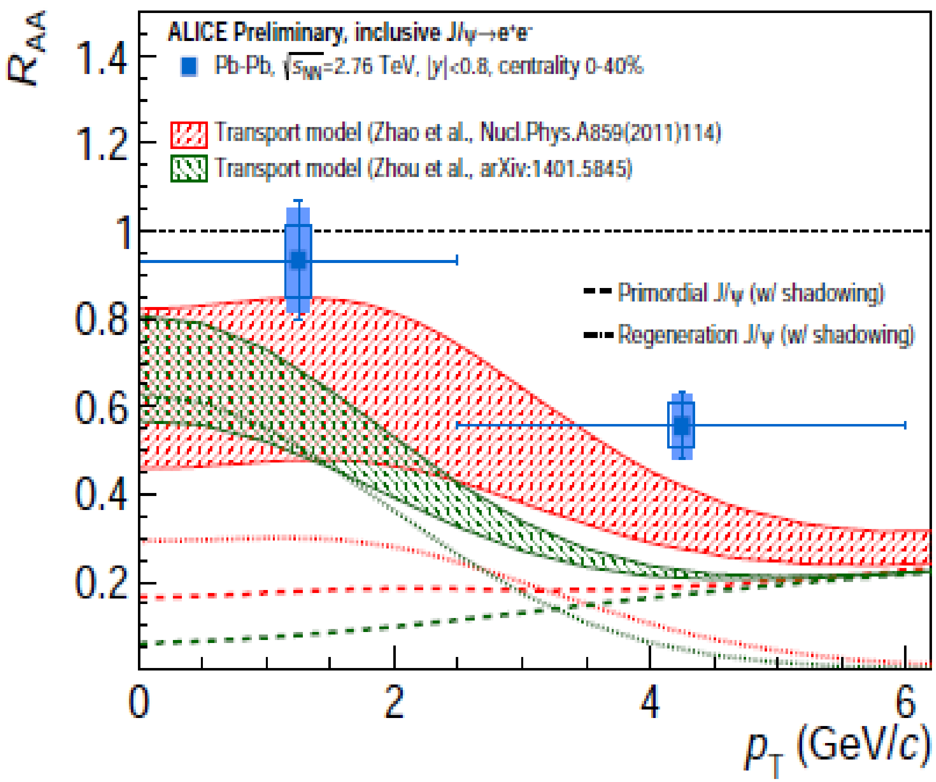
# back to J/psi data – what about spectra and hydrodynamic flow of charm and charmonia?

if charmonia are produced via statistical hadronization of charm quarks at the phase boundary, then:

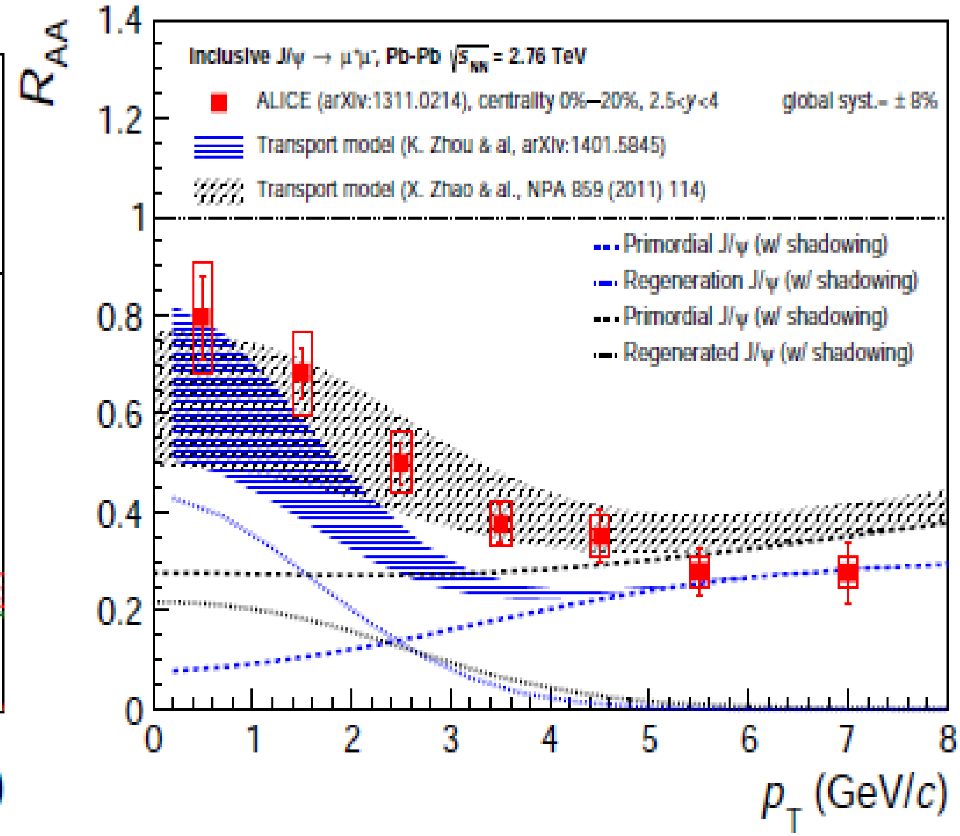
- charm quarks should be in thermal equilibrium
    - low pt enhancement
    - flow of charm quarks
    - flow of charmonia

# comparison with (re-)generation models

midrapidity




forward rapidity



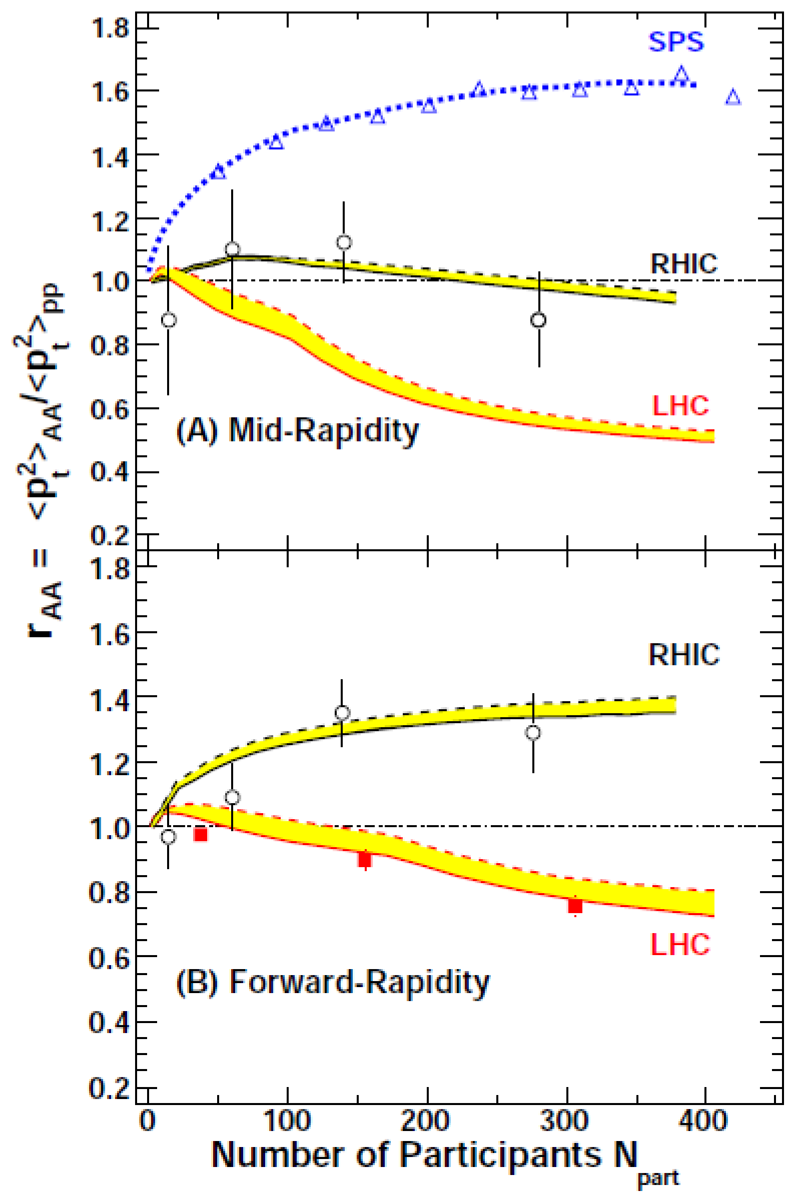

good agreement lends further strong support to the
'full color screening and late J/psi production' picture

# analysis of transverse momentum spectra

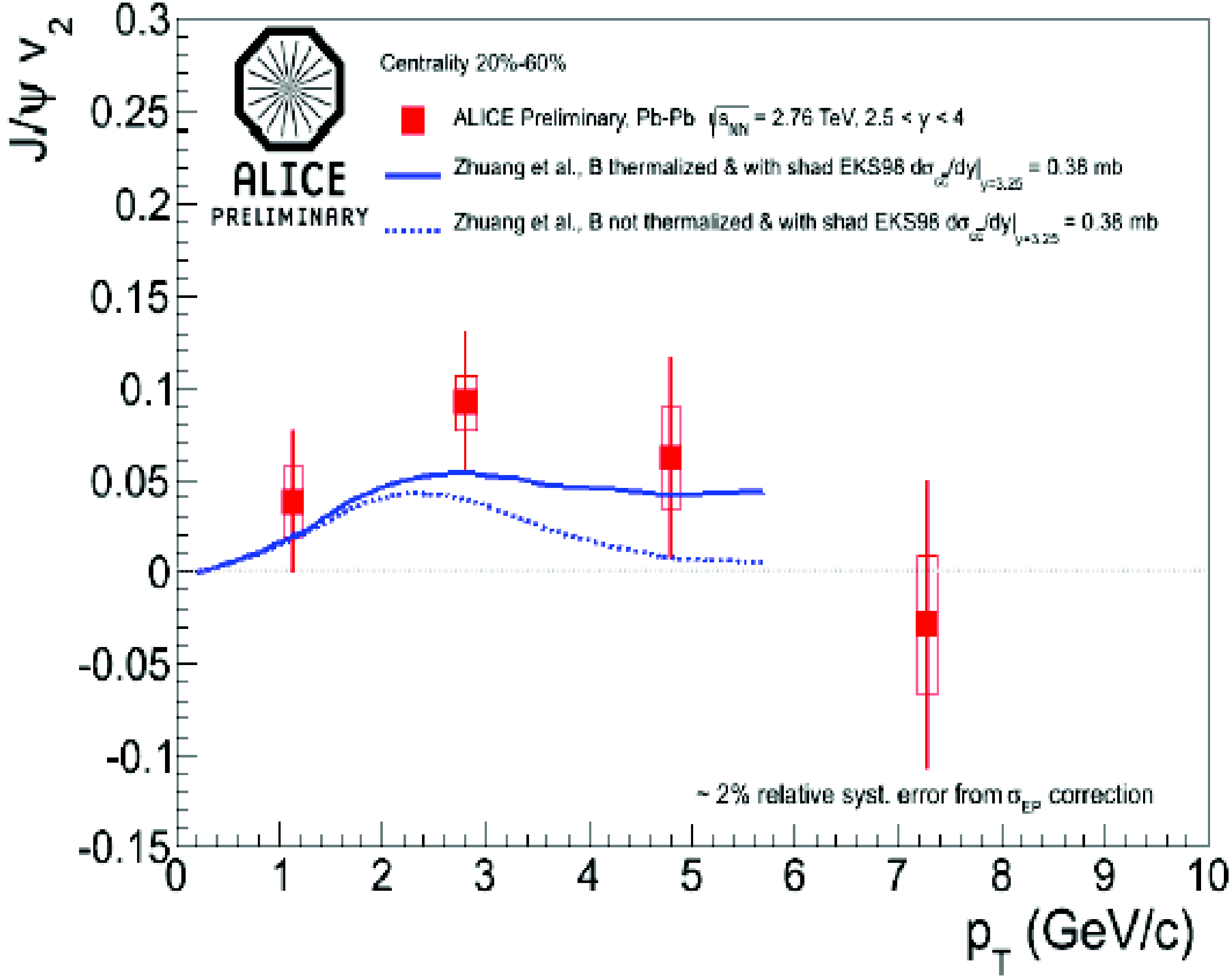
arXiv:1309.7520v1 [nucl-th] 29 Sep 2013

Zhou, Xu, Zhuang

at LHC energy, mostly (re-) generation of charmonium, $p_t$ distribution exhibits features of strong energy loss and approach to thermalization for charm quarks



# J/psi flow compared to models including (re-) generation




hydrodynamic flow of J/psi consistent with (re-)generation

# The thermal model and loosely bound, fragile objects

successful description of production yields for d, d_bar, 3He hypertriton, …
implies no entropy production after chemical freeze-out

hypertriton binding energy is 130 keV << T_chem = 156 MeV

use relativistic nuclear collision data and thermal model predictions to search for exotic objects

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoecker, Production of light nuclei, hypernuclei and their antiparticles in relativistic nuclear collisions, Phys. Lett. B697 (2011) 203, arXiv:1010.2995 [nucl-th].

see also Pal and Greiner, Phys. Rev. C87 (2013) 034608

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see also Pal and Greiner, Phys. Rev. C87 (2013) 034608

# Some historical context on cluster production in relativistic nuclear collisions

P.J. Siemens and J.I. Kapusta, Phys. Rev. Lett. 43 (1979) 1486.

here the provocative statement was made that cluster formation probability is determined by the entropy of the fireball in its compressed state, i.e. for example:
entropy/baryon is proportional to -ln(d/p)

**ENTROPY AND CLUSTER PRODUCTION IN NUCLEAR COLLISIONS**

László P. CSERNAI* and Joseph I. KAPUSTA

PHYSICS REPORTS (Review Section of Physics Letters) 131, No. 4 (1986) 223–318.

Very concise summary, including an elucidation of the relation between thermal fireball model and coalescence model

# The 'snowball in hell' story

Production of strange clusters and strange matter in nucleus-nucleus collisions at the AGS

P. Braun-Munzinger, J. Stachel (SUNY, Stony Brook). Dec 1994. 9 pp.

Published in J.Phys. G21 (1995) L17-L20

In conclusion, the fireball model based on thermal and chemical equilibrium describes cluster formation well, where measured. It gives results similar in magnitude to the predictions of the coalescence model developed recently [6] to estimate production probabilities for light nuclear fragments (p, d, t, $\alpha$ ...) and for for strange hadronic clusters (such as the H dibaryon) in Au-Au collisions at the AGS. Predicted yields for production of strange matter with baryon number larger than 10 are well below current experimental sensitivities.

Thermal vs coalescence model predictions for the production of loosely bound objects in central Au—Au collisions

A.J. Baltz, C.B. Dover, et al., Phys. Lett. B315 (1994) 7

| | Thermal Model | | |
|---|---|---|---|
| Particles | $T$=.120 GeV | $T$=.140 GeV | Coalescence Model |
| d | 15 | 19 | 11.7 |
| t+$^3$He | 1.5 | 3.0 | 0.8 |
| $\alpha$ | 0.02 | 0.067 | 0.018 |
| $H_0$ | 0.09 | 0.15 | 0.07 |
| $^5_{\Lambda\Lambda}$H | $3.5 \cdot 10^{-5}$ | $2.3 \cdot 10^{-4}$ | $4 \cdot 10^{-4}$ |
| $^6_{\Lambda\Lambda}$He | $7.2 \cdot 10^{-7}$ | $7.6 \cdot 10^{-6}$ | $1.6 \cdot 10^{-5}$ |
| $^7_{\Xi^0\Lambda\Lambda}$He | $4.0 \cdot 10^{-10}$ | $9.6 \cdot 10^{-9}$ | $4 \cdot 10^{-8}$ |
| $^{10}_{1}$St$^{-8}$ | $1.6 \cdot 10^{-14}$ | $7.3 \cdot 10^{-13}$ | |
| $^{12}_{1}$St$^{-9}$ | $1.6 \cdot 10^{-17}$ | $1.7 \cdot 10^{-15}$ | |
| $^{14}_{1}$St$^{-11}$ | $6.2 \cdot 10^{-21}$ | $1.4 \cdot 10^{-18}$ | |
| $^{16}_{2}$St$^{-13}$ | $2.4 \cdot 10^{-24}$ | $1.2 \cdot 10^{-21}$ | |
| $^{20}_{2}$St$^{-16}$ | $9.6 \cdot 10^{-31}$ | $2.3 \cdot 10^{-27}$ | |

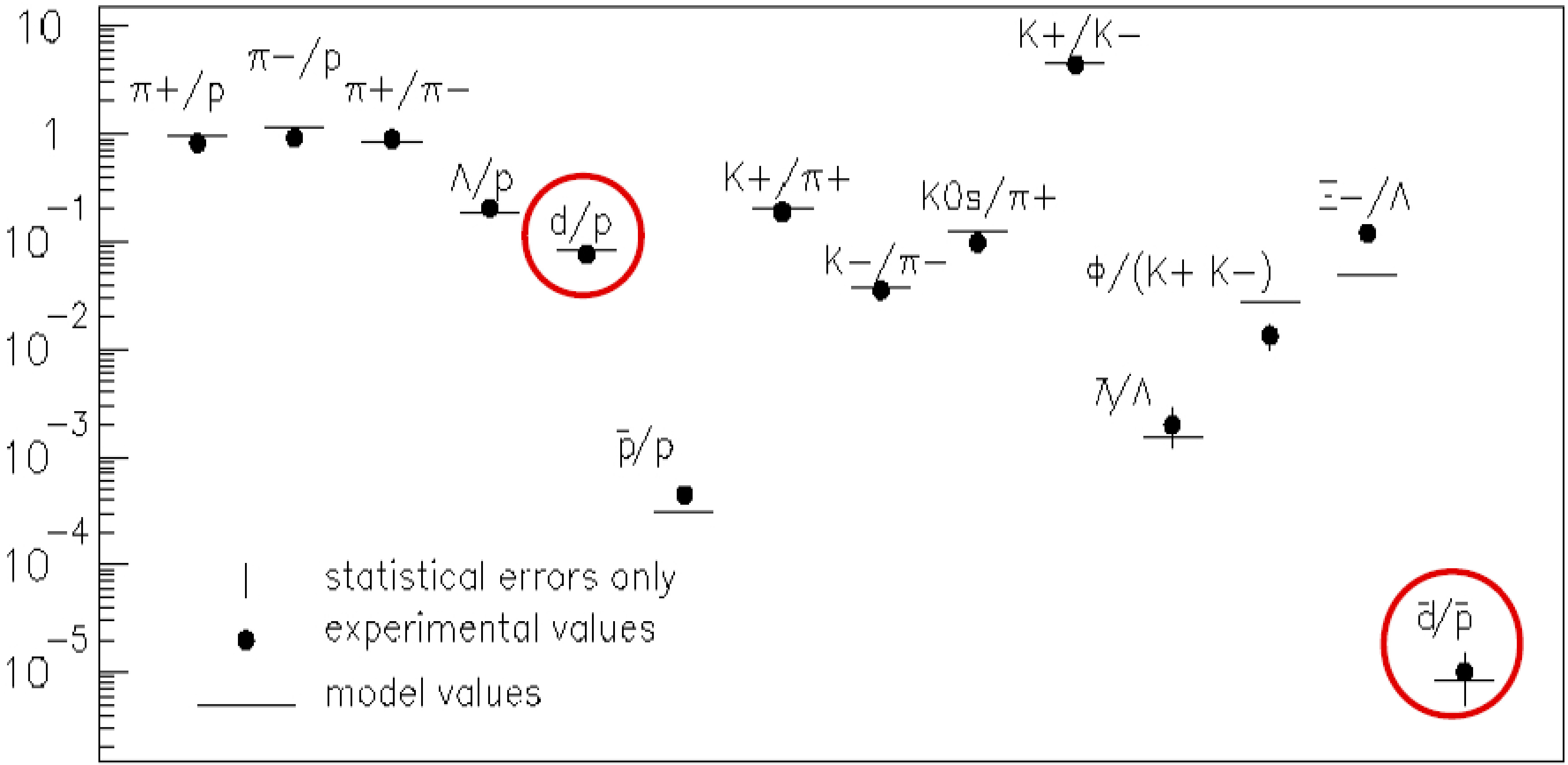
P. Braun-Munzinger, J. Stachel, J. Phys. G **28** (2002) 1971 [arXiv:nucl-th/0112051]

J.Phys. G21 (1995) L17-L20

# deuterons and anti-deuterons also well described at AGS energy

14.6 A GeV/c central Si + Au collisions and GC statistical model

P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, PLB 1994




dynamic range: 9 orders of magnitude! No deviation

# Thermal model and production of light nuclei at AGS energy

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

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:

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

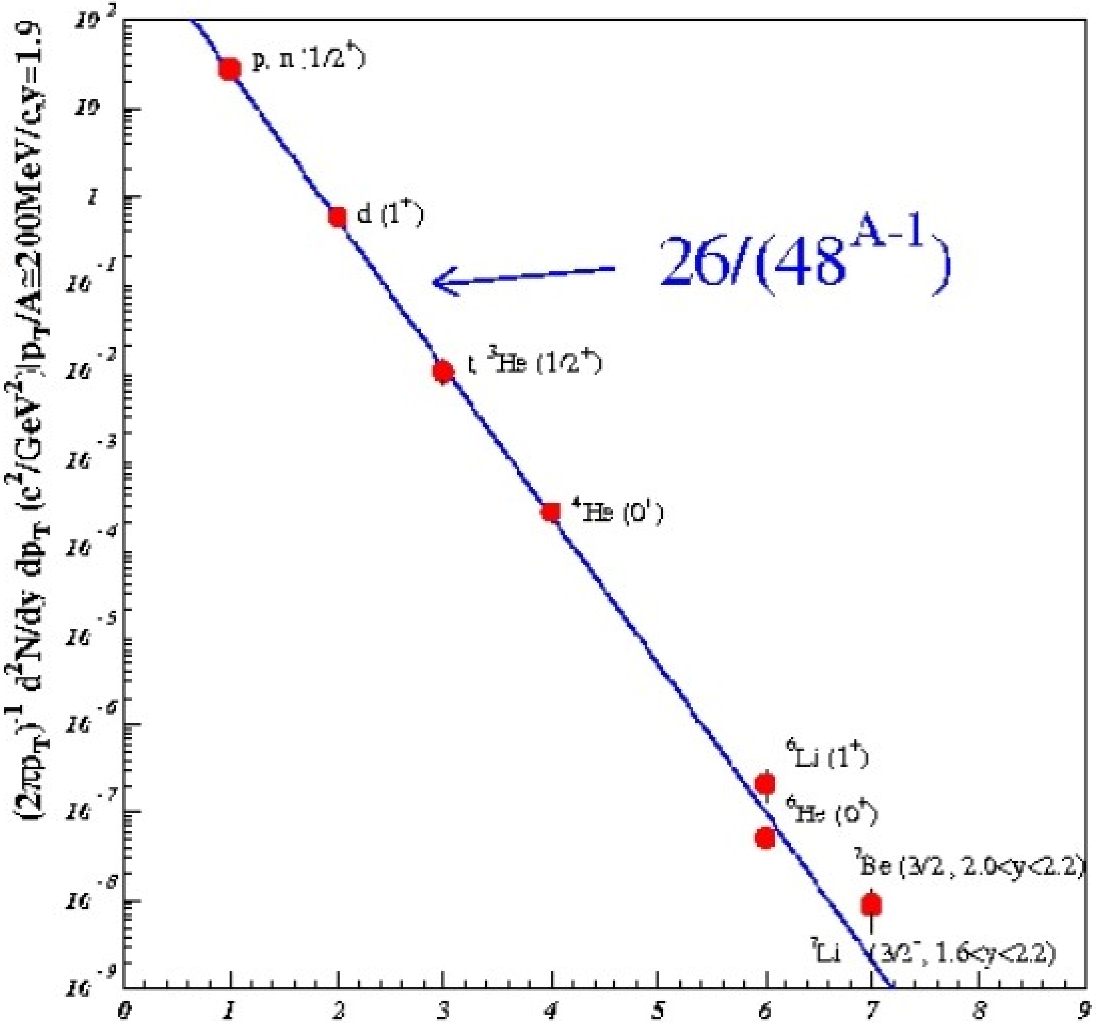
for T=124 MeV and $\mu_b$= 537 MeV

$R_p = 24$ good agreement

also good for **antideuterons**:

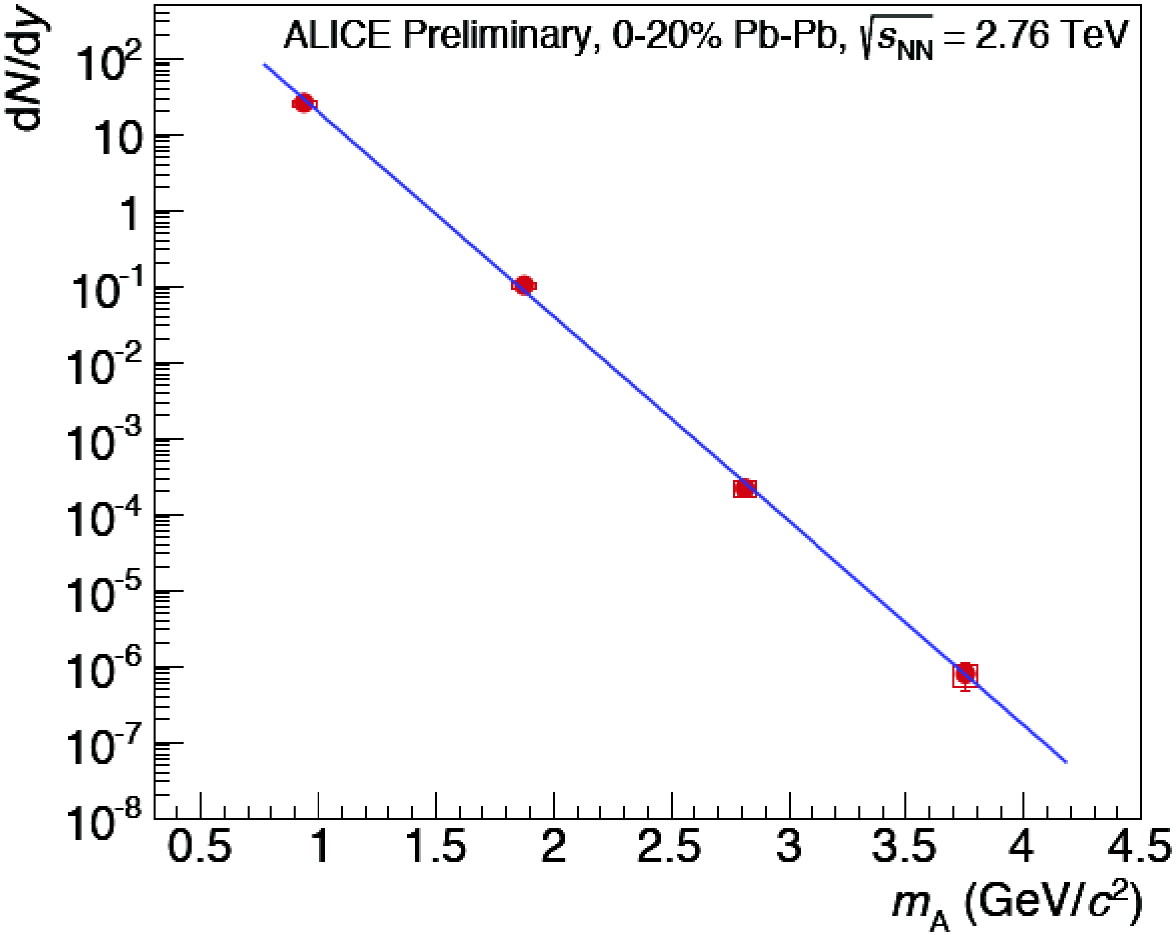
data: $R_p = 2\pm1\cdot10^5$ SM: $1.3\cdot10^5$

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




mass number A

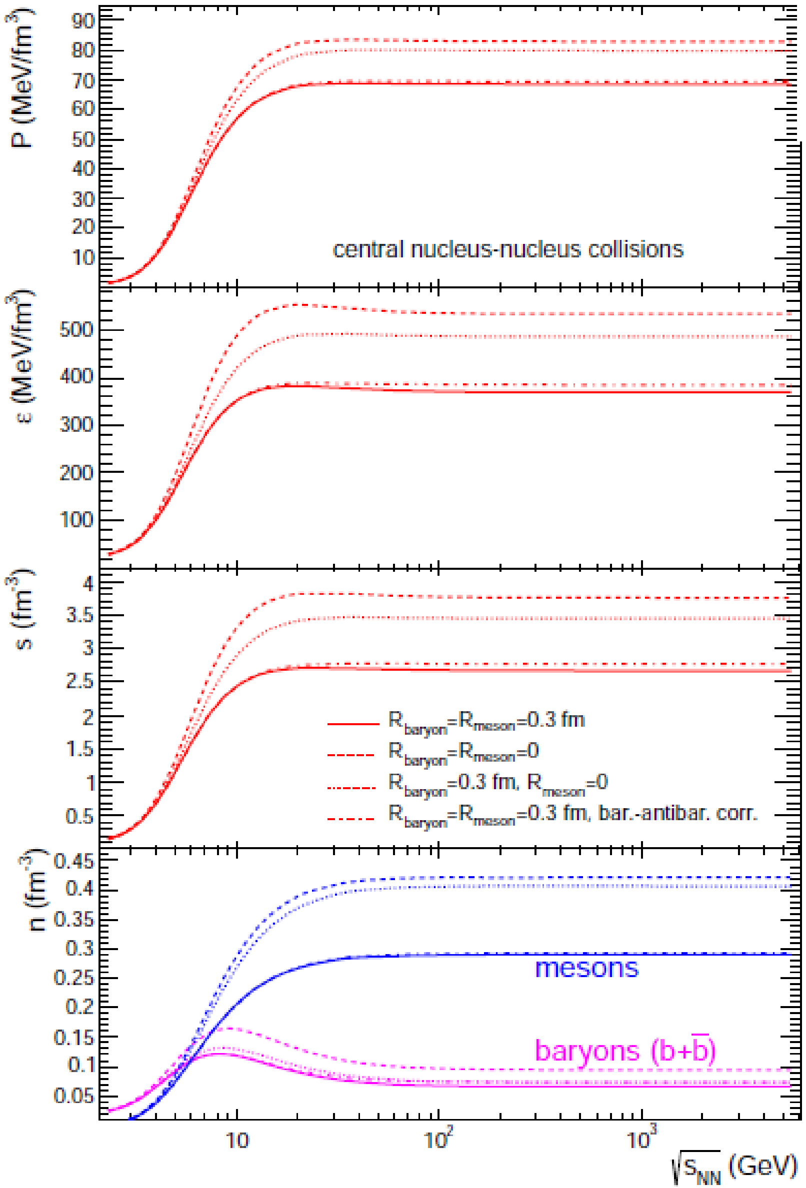
# Production of light anti-nuclei at LHC energy




penalty factor exp{-m/T} ≈ 330

# Cluster production and entropy

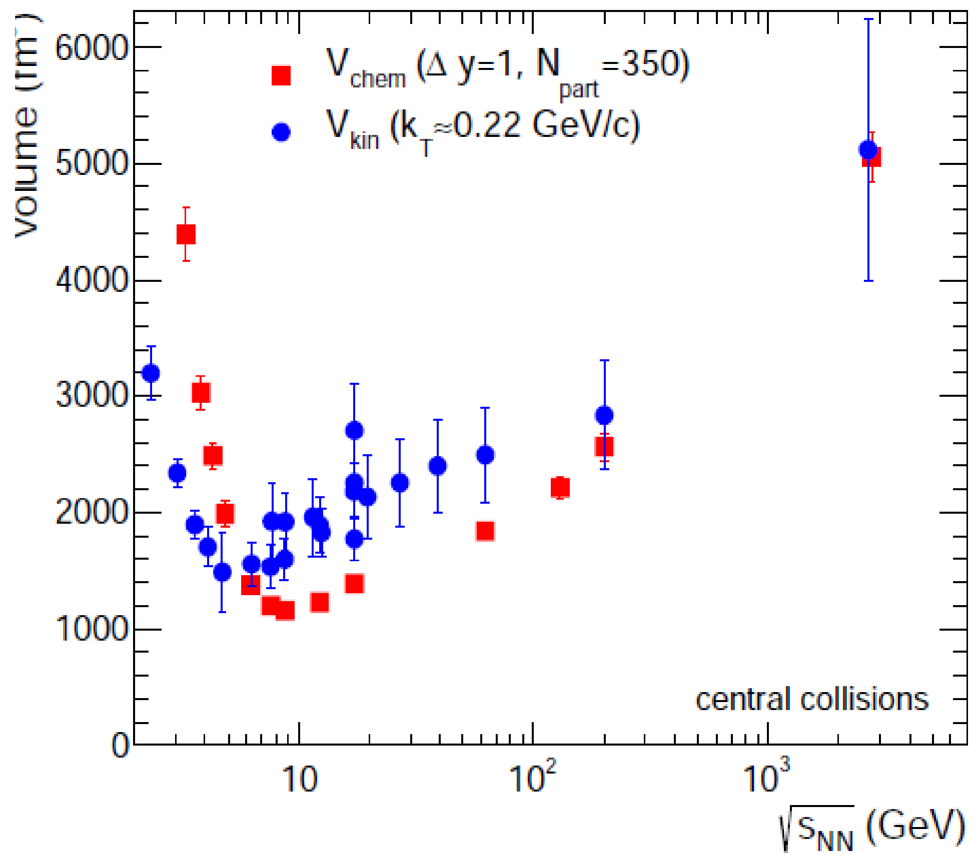
$S = s\,V = -\text{const}\,\ln(d/p)$



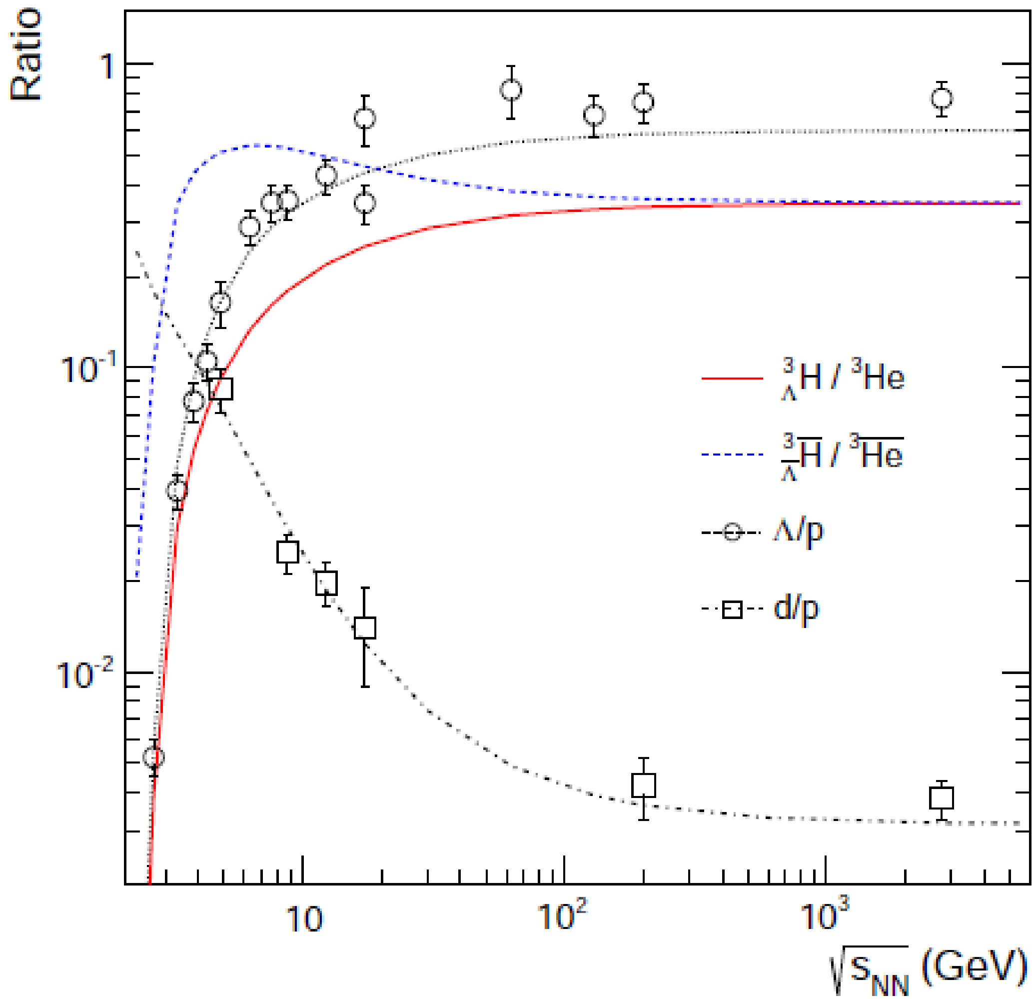

Interacting hadron resonance gas meets lattice QCD

arXiv:1201.0693


A. Andronic [a,b], P. Braun-Munzinger [a,c,d,e], J. Stachel [f], M. Winn [f]

# energy dependence of d/p ratio and thermal model prediction




agreement between thermal model calculations and data from Bevalac/SIS18 to LHC energy

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoecker, Phys. Lett. B697 (2011) 203, arXiv:1010.2995 [nucl-th].

# loosely bound objects are formed at chemical freeze-out very near the phase boundary

implies that chemical freeze-out is followed by an isentropic expansion

no appreciable annihilation in the hadronic phase

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implies that chemical freeze-out is followed by an isentropic expansion

no appreciable annihilation in the hadronic phase

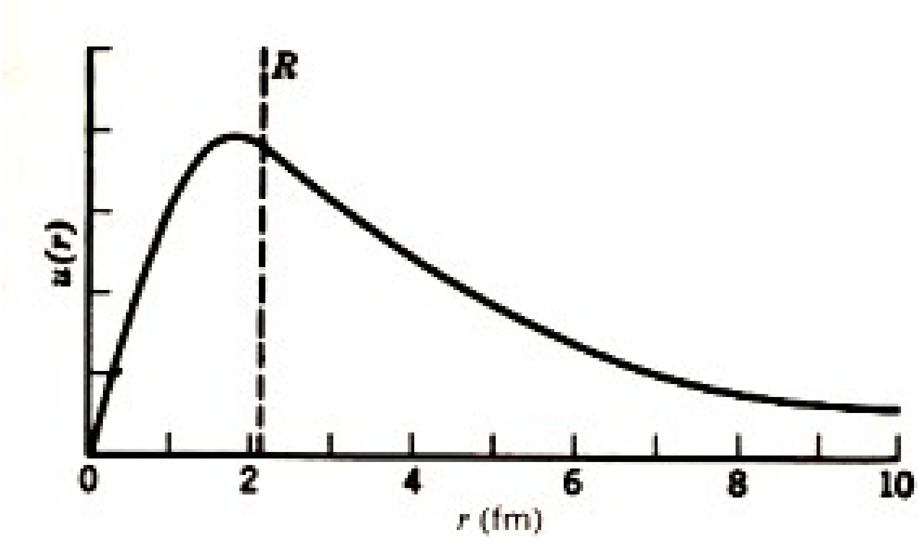
# The size of loosely bound molecular objects

Examples: deuteron, hypertriton, XYZ 'charmonium states, molecules near Feshbach resonances in cold quantum gases

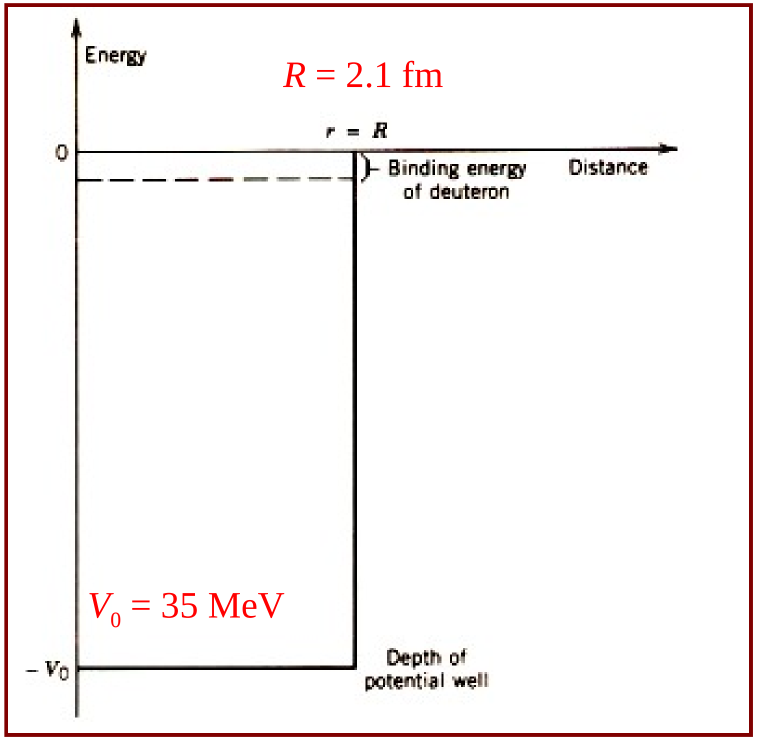
Quantum mechanics predicts that a bound state that is sufficiently close to a 2-body threshold and that couples to that threshold through a short-range S-wave interaction has universal properties that depend only on its binding energy. Such a bound state is necessarily a loosely-bound molecule in which the constituents are almost always separated by more than the range. One of the universal predictions is that the root-mean-square (rms) separation of the constituents is $(4\mu E_X)^{-1/2}$, where $E_X$ is the binding energy of the resonance and $\mu$ is the reduced mass of the two constituents. As the binding energy is tuned to zero, the size of the molecule increases without bound. A classic example of a loosely-bound S-wave molecule is the deuteron, which is a bound state of the proton and neutron with binding energy 2.2 MeV. The proton and neutron are correctly predicted to have a large rms separation of about 3.1 fm.

Artoisenet and Braaten, arXiv:1007.2868

# The deuteron as a loosely bound object




Mass = 1875 MeV
B.E. = 2.23 MeV
rms radius = 3 fm > range of potential



# The Hypertriton

mass = 2.990 MeV

B.E. = 0.13 MeV

molecular structure: (p+n) + Lambda

hypertriton is (very close to) an 'Efimov' state

2-body threshold: (p+p+n) + pi- = $^{3}$He + pi-

rms radius = (4 B.E. $M_{red}$)$^{-1/2}$ = 10.3 fm = rms separation between d and Lambda

in that sense: hypertriton = (p n Lambda) = (d Lambda) is the ultimate halo state

yet production yield is fixed at 156 MeV temperature (about 1000 x E.B.)

# The X(3872)

mass is below threshold of ($D^{*0}$ $D^{0}_{bar}$) by (0.42 +/- 0.39) MeV

$D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$

rms separation = 3.5 – 18.3 fm   structure:

should be able to predict the X(3872) production probability in pp collisions at LHC energy with an accuracy of about 30%, uncertainty is due to not very precisely known number of charm quarks

result ready shortly

# where are we?

since QM2012, discrepancy between protons and thermal fit went from 7 sigma to 2.9 (2.7) sigma

T went from 152 to 156.5 MeV

fit without protons yields slighty higher T = 158 MeV, driven by hyperons

# where are we?

since QM2012, discrepancy between protons and thermal fit went from 7 sigma to 2.9 (2.7) sigma

T went from 152 to 156.5 MeV

fit without protons yields slighty higher T = 158 MeV, driven by hyperons

# important note:  corrections for weak decays

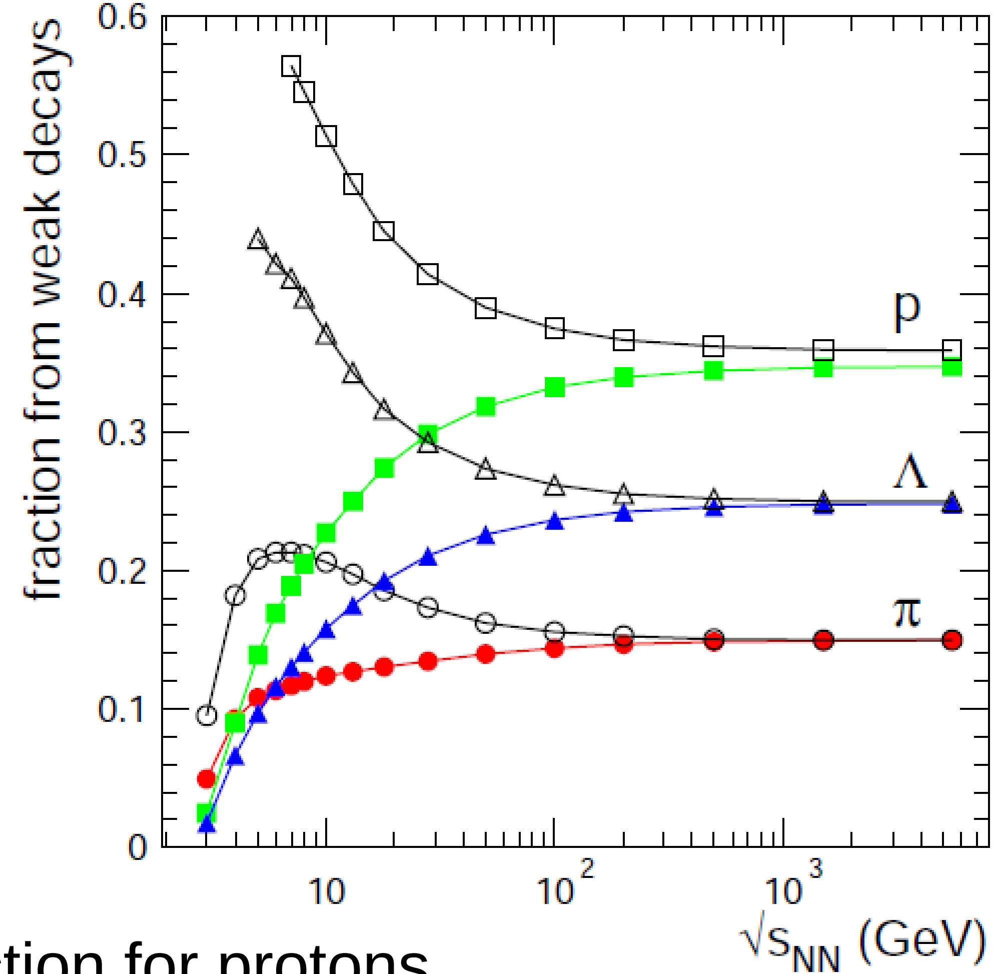
All ALICE data do not contain hadrons from weak decays of hyperons and strange mesons – correction done in hardware via ITS inner tracker

The RHIC data contain varying degrees of such weak decay hadrons. This was on average corrected for in previous analyses.

in light  of high precision LHC data the corrections done at RHIC may need to be revisited.

# treatment of weak decays

fraction of yield from weak decays




biggest correction for protons
done in hardware (vertex cut) at ALICE
software corrections at all lower energies

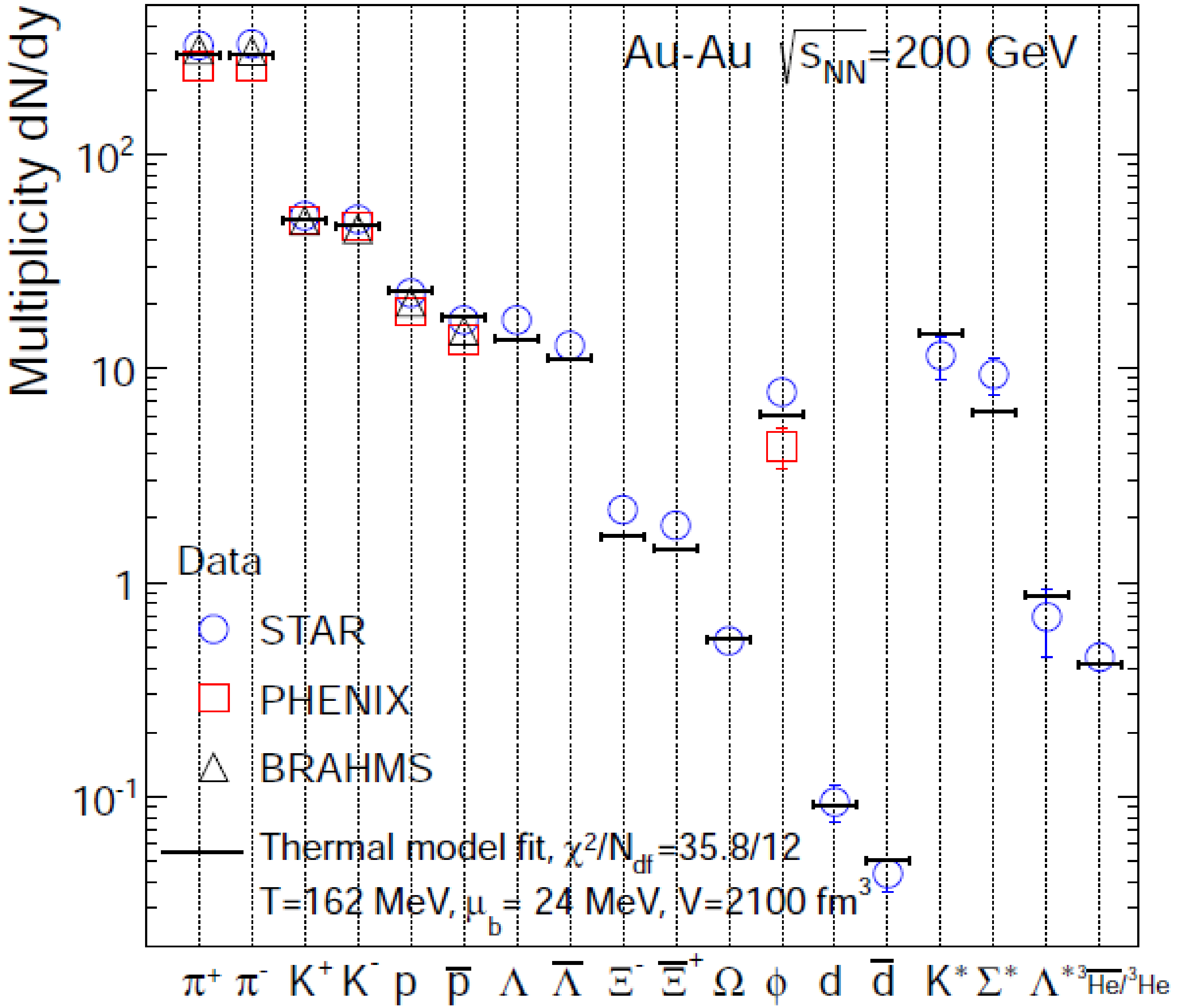
# Re-evaluation of fits at RHIC energies – special emphasis on corrections for weak decays

Note: corrections for protons and pions from weak decays of hyperons depend in detail on experimental conditions

RHIC hadron data all measured without application of Si vertex detectors

In the following, corrections were applied as specified by the different RHIC experiments

# Au+Au central at 200 GeV, all experiments combined




T = 162 Me'

# could it be weak decays from charm?

weak decays from charmed hadrons are included in the ALICE data sample

at LHC energy, cross sections for charm hadrons is increased by more than an order of magnitude compared to RHC

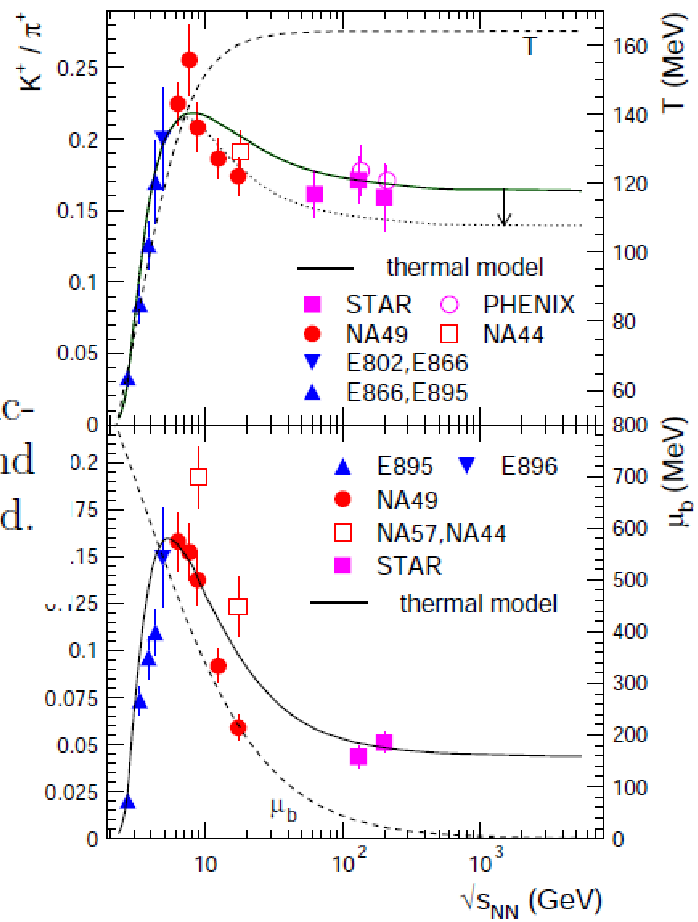
first results including charm and beauty hadrons indicate  changes of less than 3%, mostly for kaons

**not likely an explanation**

# could it be incomplete hadron resonance spectrum?

Note: because of baryon conservation, adding more baryon resonances will decrease in the model the p/pi ratio

An N* will decrease dominantly into 1 N + a number (depending on the N* mass) of pions




Same effect seen in
K/pi ratio because of strangeness conservation

A. Andronic, P. Braun-Munzinger, J. Stachel, Thermal hadron production in relativistic nuclear collisions: the sigma meson, the horn, and the QCD phase transition, Phys. Lett. **B673** (2009) 142, erratum ibid. **B678** (2009) 516, arXiv:0812.1186.

# could it be proton annihilation in the hadronic

F. Becattini et al., Phys. Rev. C85 (2012) 044921 and arXiv: 1212.2431

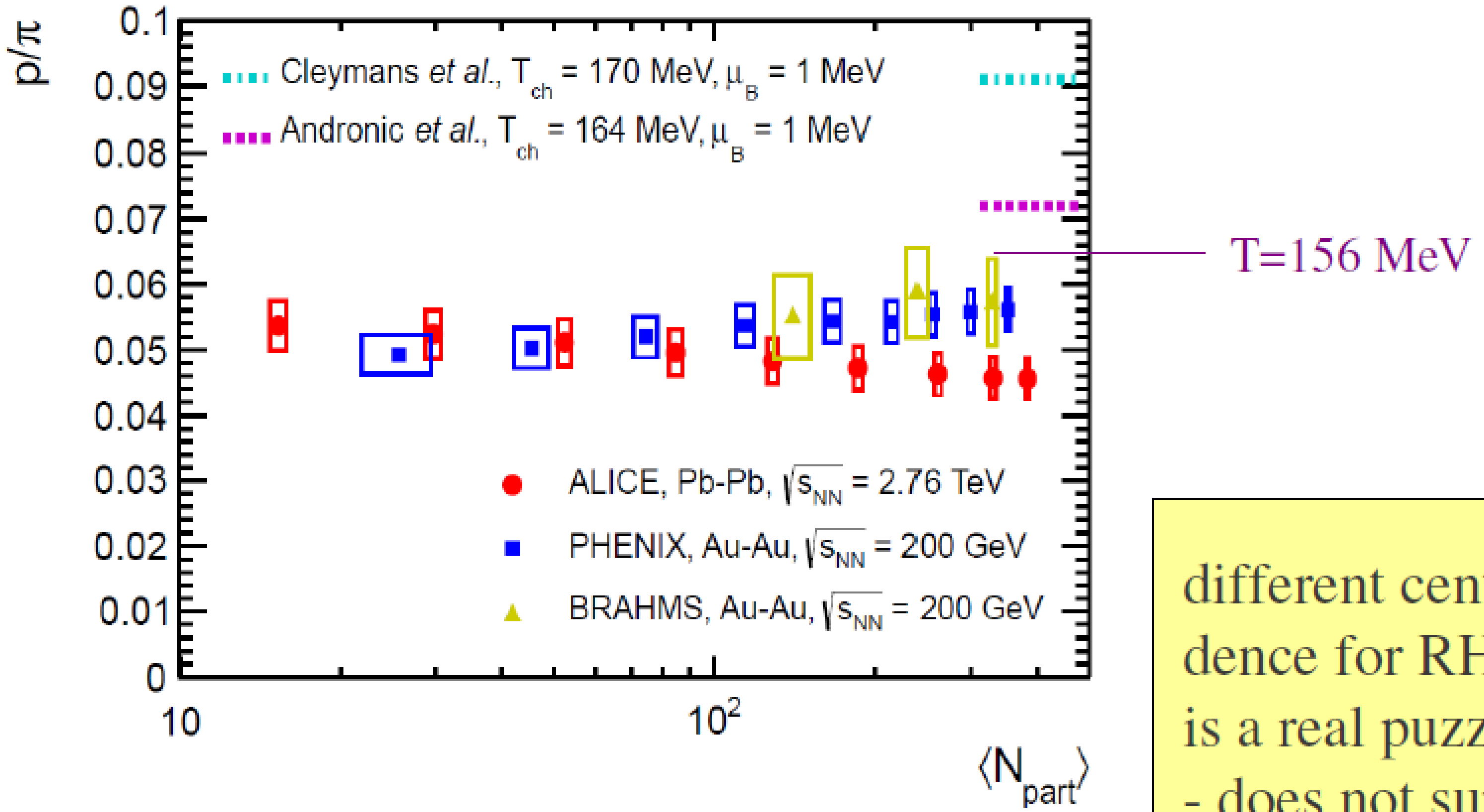
• need to incorporate detailed balance, 5pi → p p_bar not included in current Monte Carlo codes (RQMD)

• taking detailed balance into account reduces effect strongly, see Rapp and Shuryak 1998

• see also W. Cassing, Nucl. Phys. A700 (2002) 618 and recent reanalysis, by Pan and Pratt, arXiv:

• agreement with hyperon data would imply strongly reduced hyperon annihilation cross section with anti-baryons → no evidence for that

# centrality dependence of proton/pion ratio




different centrality dependence for RHIC and LHC is a real puzzle

- does not support annihilation picture
- is it real? physics origin?

# the 'proton anomaly' and production of light nuclei

can the measurement of d, t, 3He and 4He settle the issue?
what about hypertriton?

important to realize: production yield of deuterons is fixed at $T = T_{chem} = 156$ MeV even if $E_B(d) = 2.23$ MeV!

entropy/baryon is proportional to $-\ln(d/p)$ and is conserved after $T_{chem}$

good agreement with LHC d and hyper-triton yield implies: there is no shortage of protons and neutrons at chemical freeze-out, inconsistent with annihilation scenario

# Nuclear collisions, open and hidden charm hadrons, and QCD

Hadrons containing charm quarks can also be described provided open charm cross section is known

Recent ALICE data imply Debye screening near $T_c$ for charmonium and deconfined heavy quarks, see talk by Johanna Stachel

Could it be that increasing number of charm quarks changes (lowers) $T_c$? An issue for the FCC!

# Quarkonium Properties and Debye Screening

| state | $J/\psi$ | $\chi_c$ | $\psi'$ | $\Upsilon$ | $\chi_b$ | $\Upsilon'$ | $\chi_b'$ | $\Upsilon''$ |
|---|---|---|---|---|---|---|---|---|
| mass [GeV] | 3.10 | 3.53 | 3.68 | 9.46 | 9.99 | 10.02 | 10.26 | 10.36 |
| $\Delta E$ [GeV] | 0.64 | 0.20 | 0.05 | 1.10 | 0.67 | 0.54 | 0.31 | 0.20 |
| $\Delta M$ [GeV] | 0.02 | -0.03 | 0.03 | 0.06 | -0.06 | -0.06 | -0.08 | -0.07 |
| radius [fm] | 0.25 | 0.36 | 0.45 | 0.14 | 0.22 | 0.28 | 0.34 | 0.39 |

table from H. Satz, J. Phys. G32 (2006) R25

In the QGP, the screening radius $r_{Debye}(T)$ decreases with increasing T. If $r_{Debye}(T) < r_{charmonium}$ the system becomes unbound $\rightarrow$ suppression compared to charmonium production without QGP. The screening radius can be computed using potential models or solving QCD on the lattice.

# Charmonium production at LHC energy: deconfinement,and color screening

- Charmonia formed at the phase boundary → full color screening at $T_c$

- Debye screening length < 0.4 fm near $T_c$

- Combination of uncorrelated charm quarks into J/psi → deconfinement

**statistical hadronization picture of charmonium production provides most direct way towards information on the degree of deconfinement reached as well as on color screening and the question of bound states in the QGP**

# Debye mass, LQCD, and J/psi data

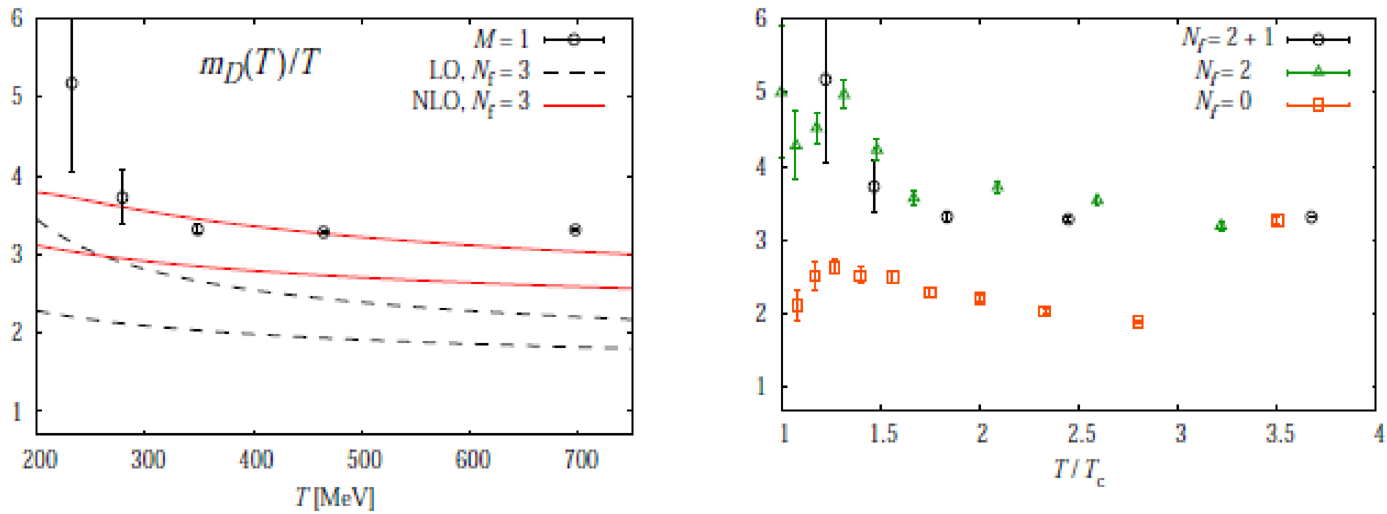



Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi T$ $(3\pi T)$, where $\mu$ is the renormalization point. (Right) Flavor dependence of the Debye screening masses. We assume the pseudo-critical temperature for $2+1$-flavor QCD as $T_c \sim 190$ MeV.

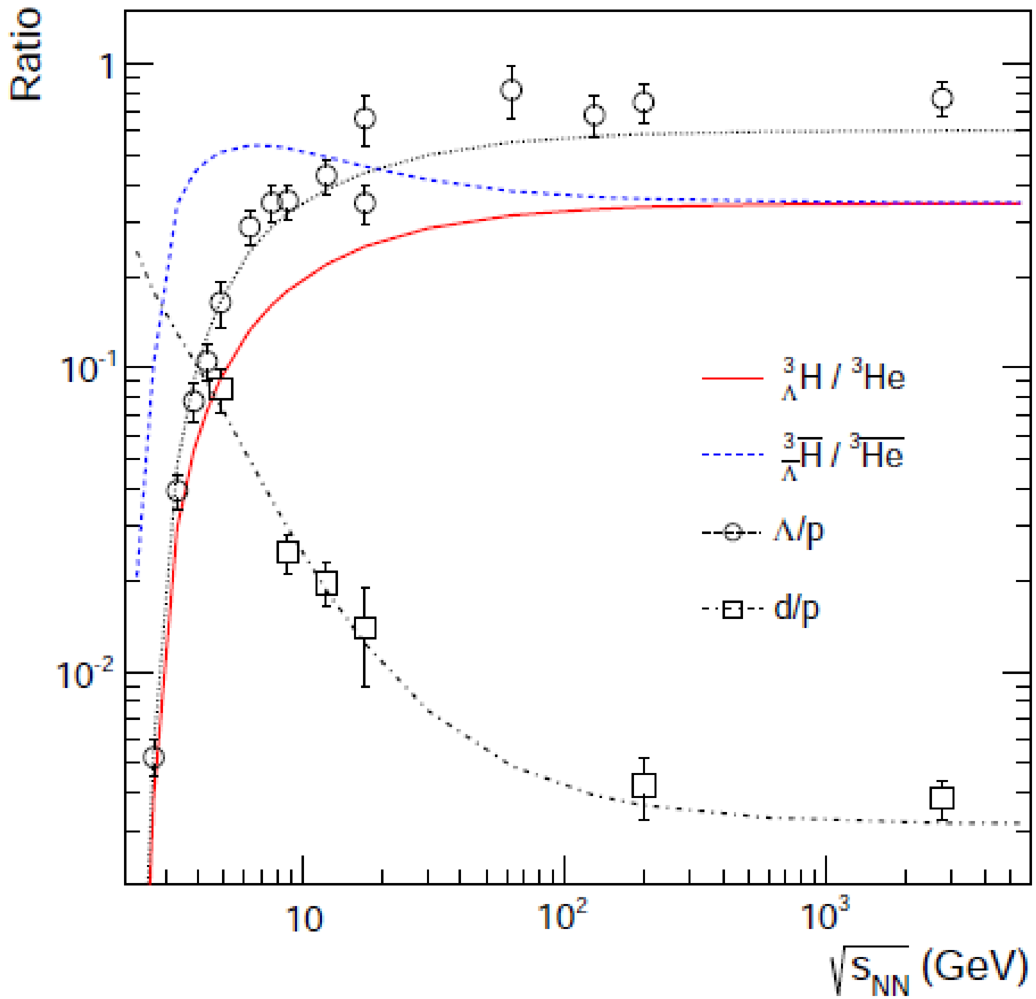
arXiv:1112.2756 WHOT-QCD Coll.

from J/psi data and statistical hadronization analysis:

$m_{Debye}/T > 3.3$

at T = 0.15 GeV

# energy dependence of d/p ratio and thermal model prediction




agreement between thermal model calculations and data from Bevalac/SIS18 to LHC energy

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoecker, Phys. Lett. B697 (2011) 203, arXiv:1010.2995 [nucl-th].

# ALICE TRD Detector complete Nov. 26, 2014

first fully operational barrel TRD
project coordination: Heidelberg

Quarkonia:
heavy quark bound states stable under strong decay

heavy: charm ($m_c \simeq 1.3$ GeV) or beauty ($m_b \simeq 4.7$ GeV)
stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

heavy quarks ⇒ quarkonium spectroscopy via
non-relativistic potential theory

Schrödinger equation $\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$

confining ("Cornell") potential $V(r) = \sigma\ r - \frac{\alpha}{r}$

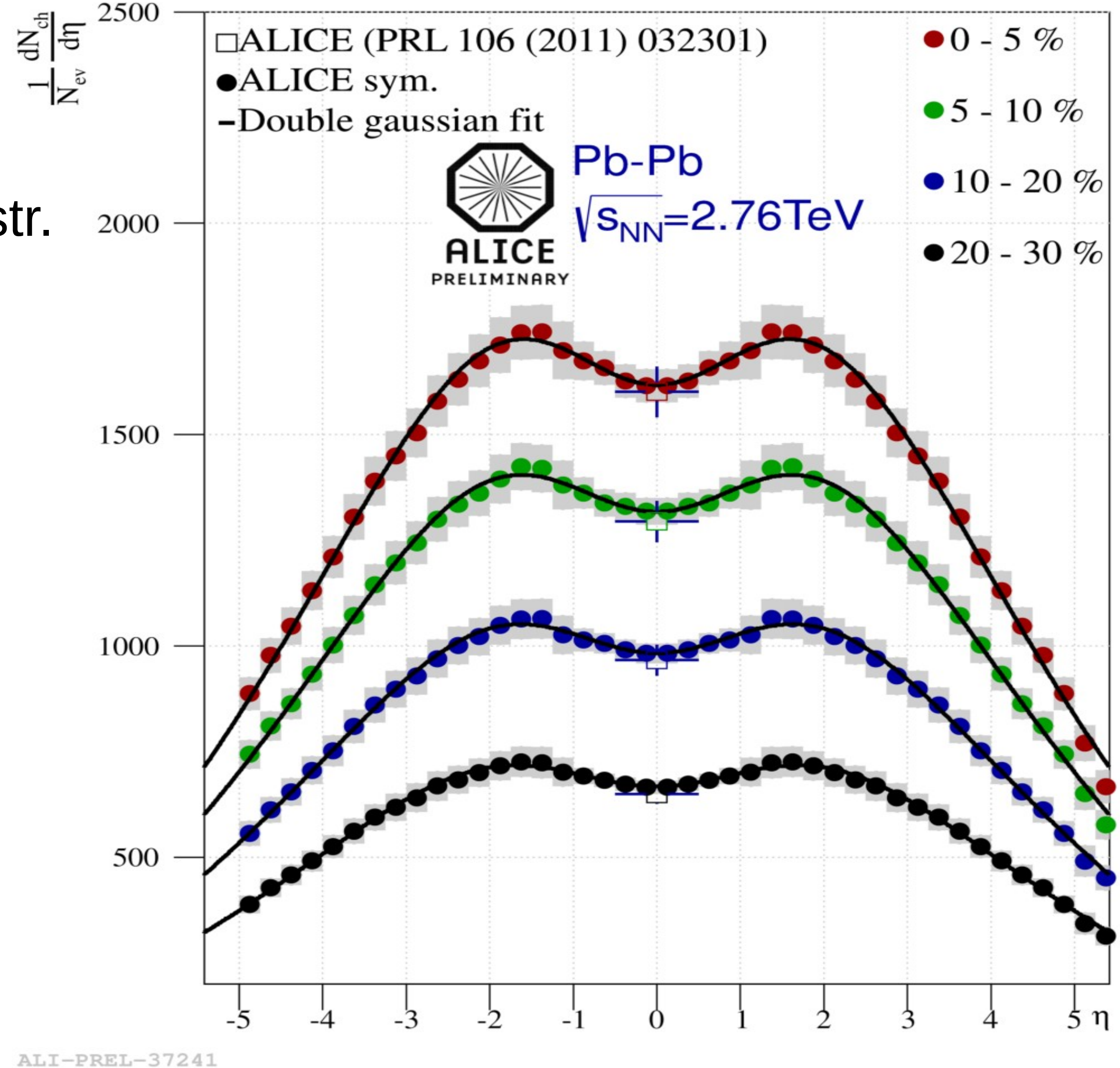
string tension $\sigma \simeq 0.2$ GeV$^2$, gauge coupling $\alpha \simeq \pi/12$

⇒ quarkonium masses $M_i$ and radii $r_i$

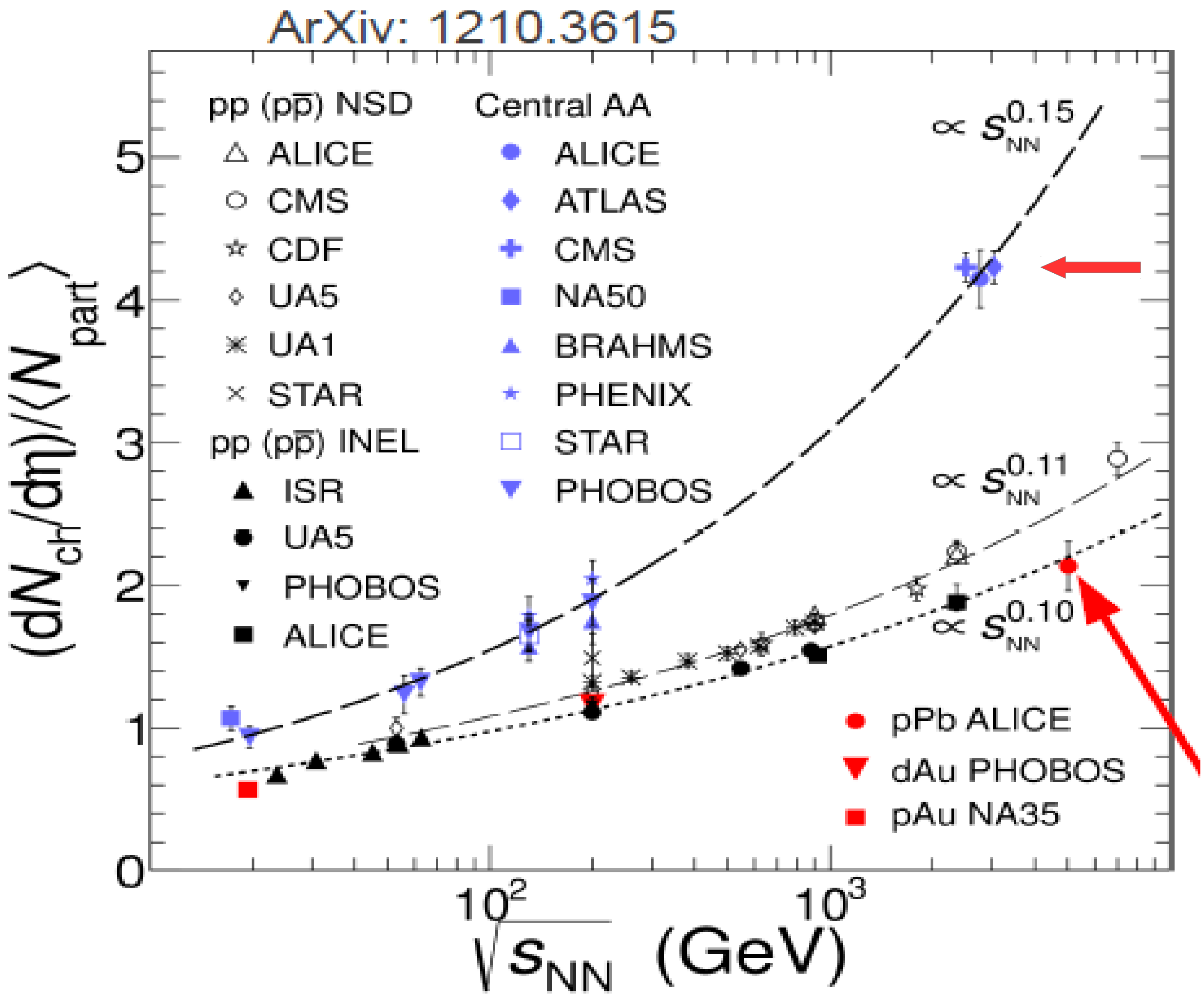
# Complete angular (pseudo-rapidity) distributions

complete angular distr. between 1 and 179 deg

excellent pseudo-rapidity coverage



# Charged particle multiplicity in pp, pPb and central PbPb collisions



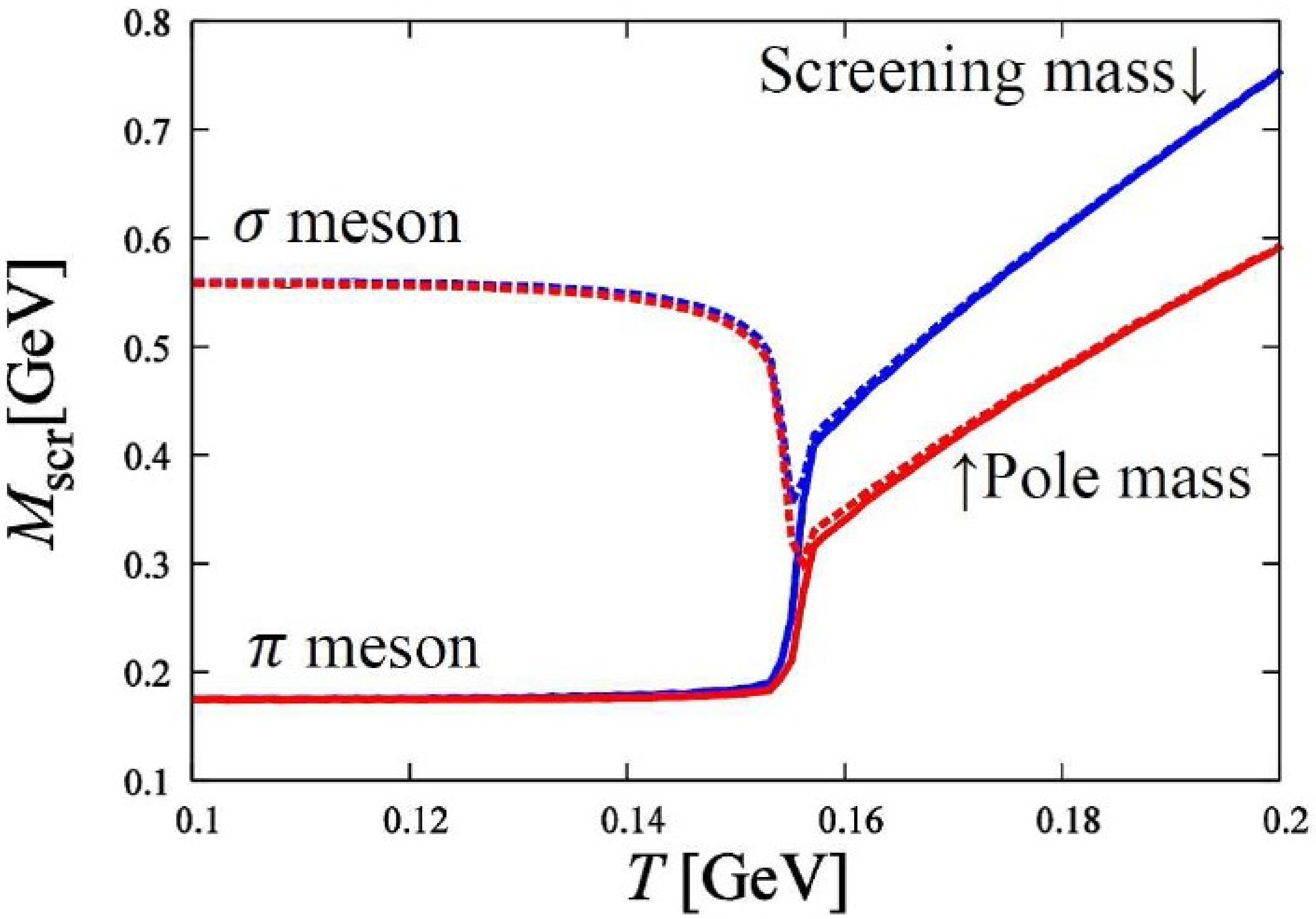

increase with beam energy significantly steeper than in pp

pPb similar to pp inelastic

can the fireball formed in central nuclear collisions be considered matter in equilibrium?

Phys. Rev. Lett. 105(2010)252301

# Temperature dependence of meson masses in a NJL model




Mesonic correlation functions at finite temperature and density in the Nambu-Jona-Lasinio model with a Polyakov loop

H. Hansen, W.M. Alberico (INFN, Turin & Turin U.), A. Beraudo (Saclay, SPhT), A. Molinari, M. Nardi (INFN, Turin & Turin U.), C. Ratti (ECT, Trento & INFN, Trento). Sep 2006. 26 pp.

Published in Phys.Rev. D75 (2007) 065004