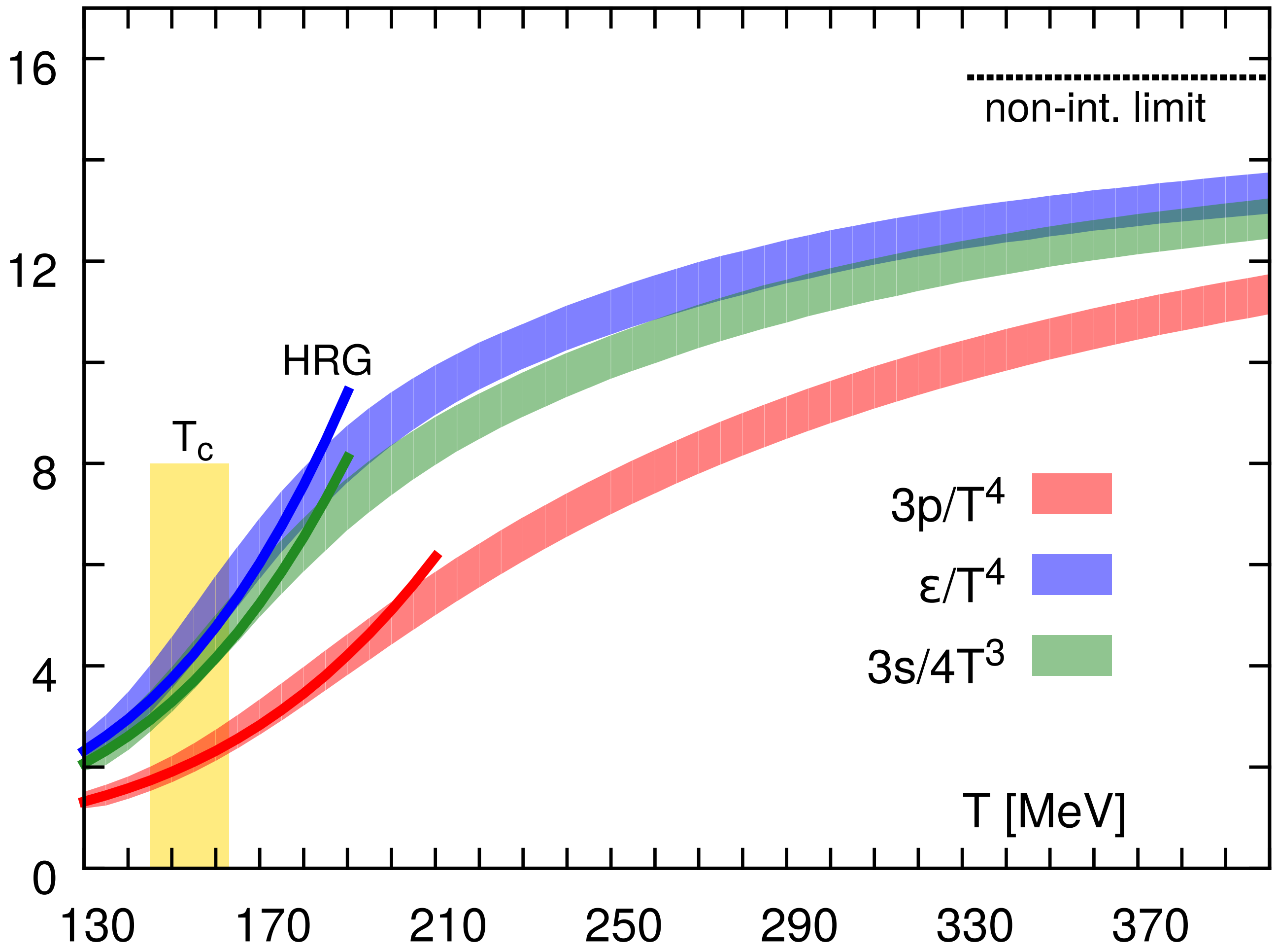
Studies of deconfined matter at the LHC with ALICE

A. Andronic – GSI Darmstadt

on behalf of the ALICE Collaboration

- Introduction: hot QCD (quark-gluon) matter; ALICE apparatus
- Hadrons with light-flavor (u,d,s) and the QCD phase diagram
- Quarkonium and deconfined matter
- Jet quenching (if time allows)
- Summary

Lattice QCD predicts a phase transition



(ideal gas)

quarks and gluons

$\varepsilon_{qg}/T^4 = (16 + \frac{7}{8}12N_f)\frac{\pi^2}{30}$

N_f=3 (u,d,s)

hadrons (pions)

$\varepsilon_{had}/T^4 = 3\frac{\pi^2}{30}$

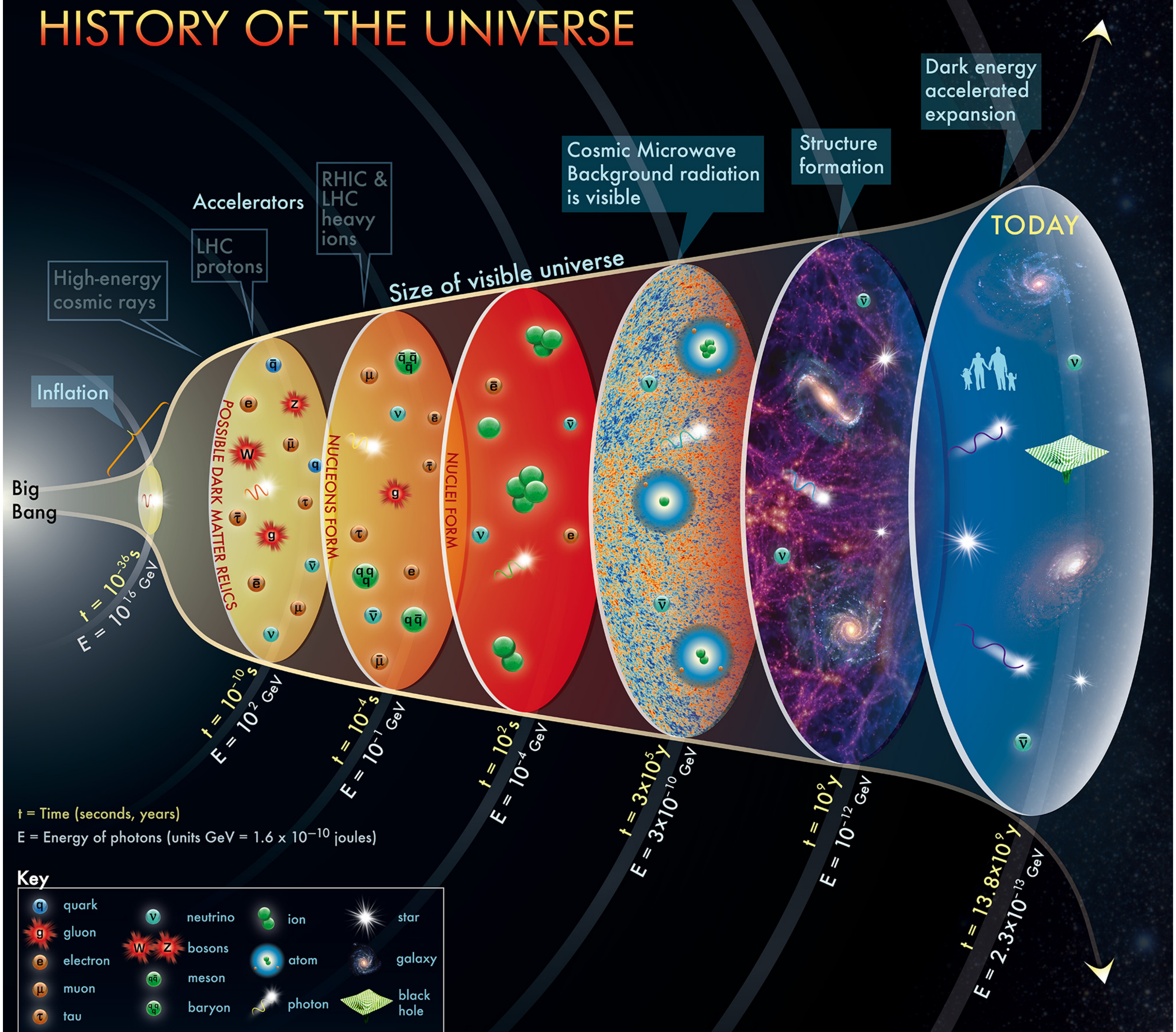
$\simeq$1000 billion K

see e.g: A. Bazavov et al., arXiv:1701.04325

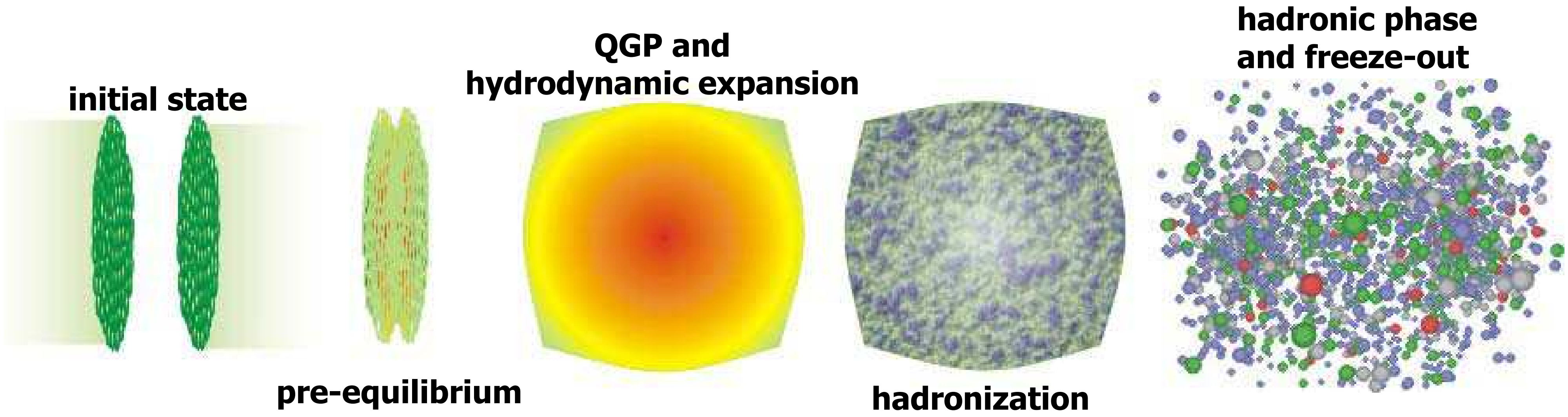
transition is a crossover, Y. Aoki et al., Nature 443 (2006) 675

$T_c \simeq$145-164 MeV, $\varepsilon_c \simeq (0.18 - 0.5)$ GeV/fm^3, or (1.2-3.1)$\varepsilon_{nuclear}$

numerical solutions of QCD on a discrete space-time grid (sophisticated formalism, huge computers)



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
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

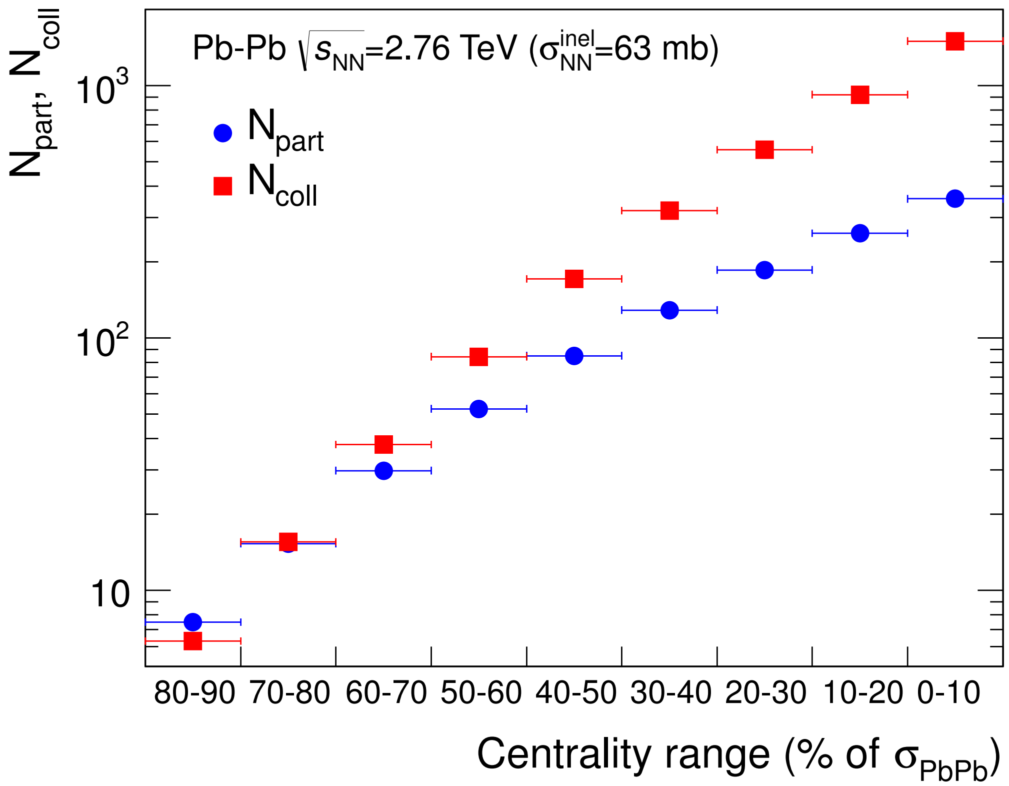


$t \simeq 10^{-23}$ s, $V \simeq 10^{-40}$ m^3

1. initial collisions ($t \leq t_{coll} = 2R/\gamma_{\mathrm{cm}}c$; $R_{Pb} \simeq$7 fm)
2. thermalization: equilibrium is established ($t \lesssim 1$ fm/c $= 3 \times 10^{-24}$ s)
3. expansion ($\sim 0.6c$) and cooling ($t <$ 10-15 fm/c) ...deconfined stage?
4. hadronization (quarks and gluons form hadrons)
5. chemical freeze-out: inelastic collisions cease; particle identities (yields) frozen
6. kinetic freeze-out: elastic collisions cease; spectra are frozen ($t+ =$ 3-5 fm/c)

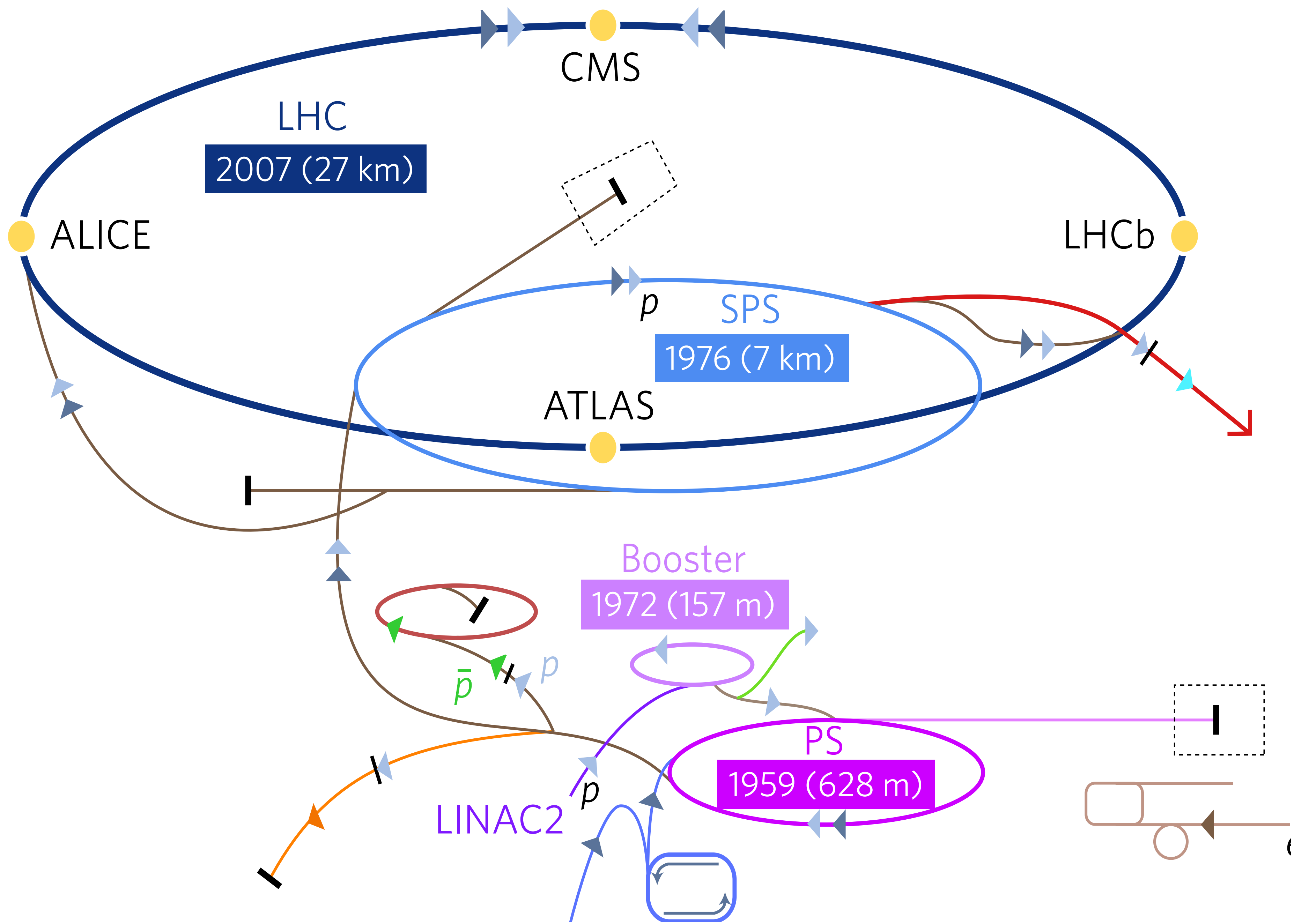
What are the "control parameters"

- Energy of the collision (per nucleon pair, $\sqrt{s_{NN}}$)
- Centrality of the collision (number of "participating" nucleons, N_{part})
  [at high energies geometric concepts valid: "participant-spectator" picture]
  measured in percentage of the geometric cross section ($\sigma_{AB} = \pi(R_A + R_B)^2$)
  NB: we sort the collisions offline, based on detector signals



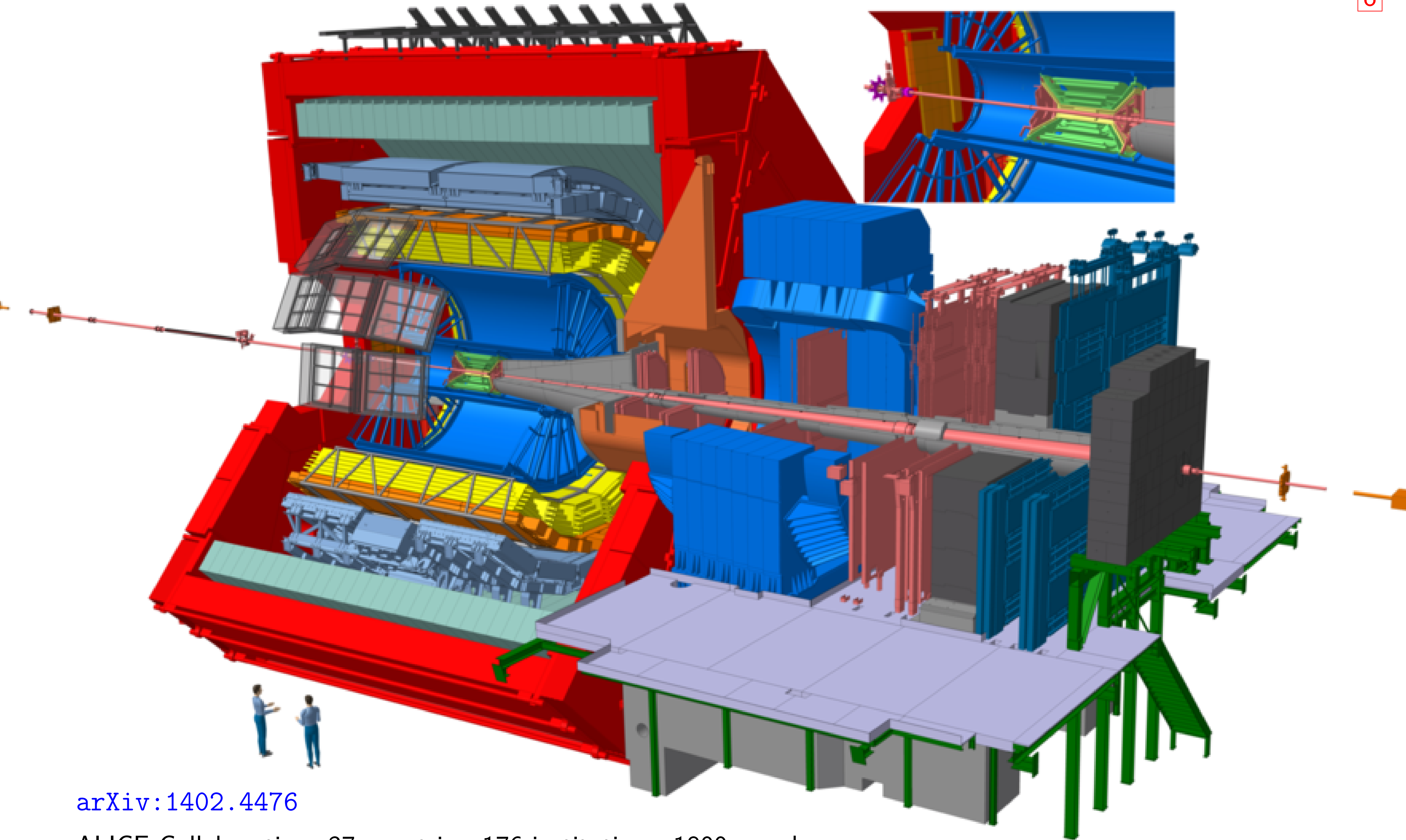
...while often taking as reference the measurement in proton-proton collisions (at the same energy), for "hard probes" (pQCD) scaled by the number of collisions corresponding to the given centrality class

The accelerator complex at CERN



The accelerator complex at CERN

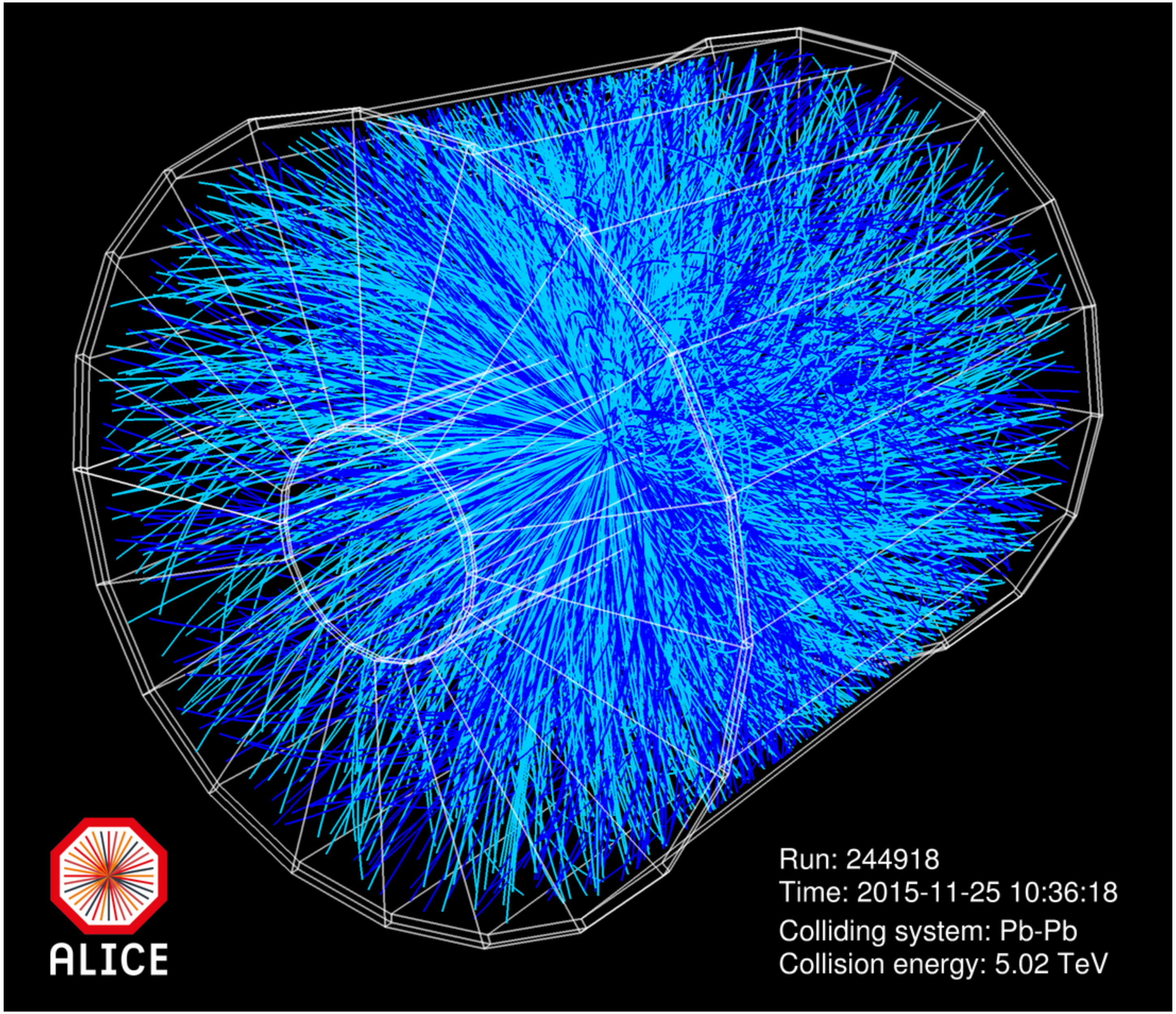
The ALICE apparatus



arXiv:1402.4476

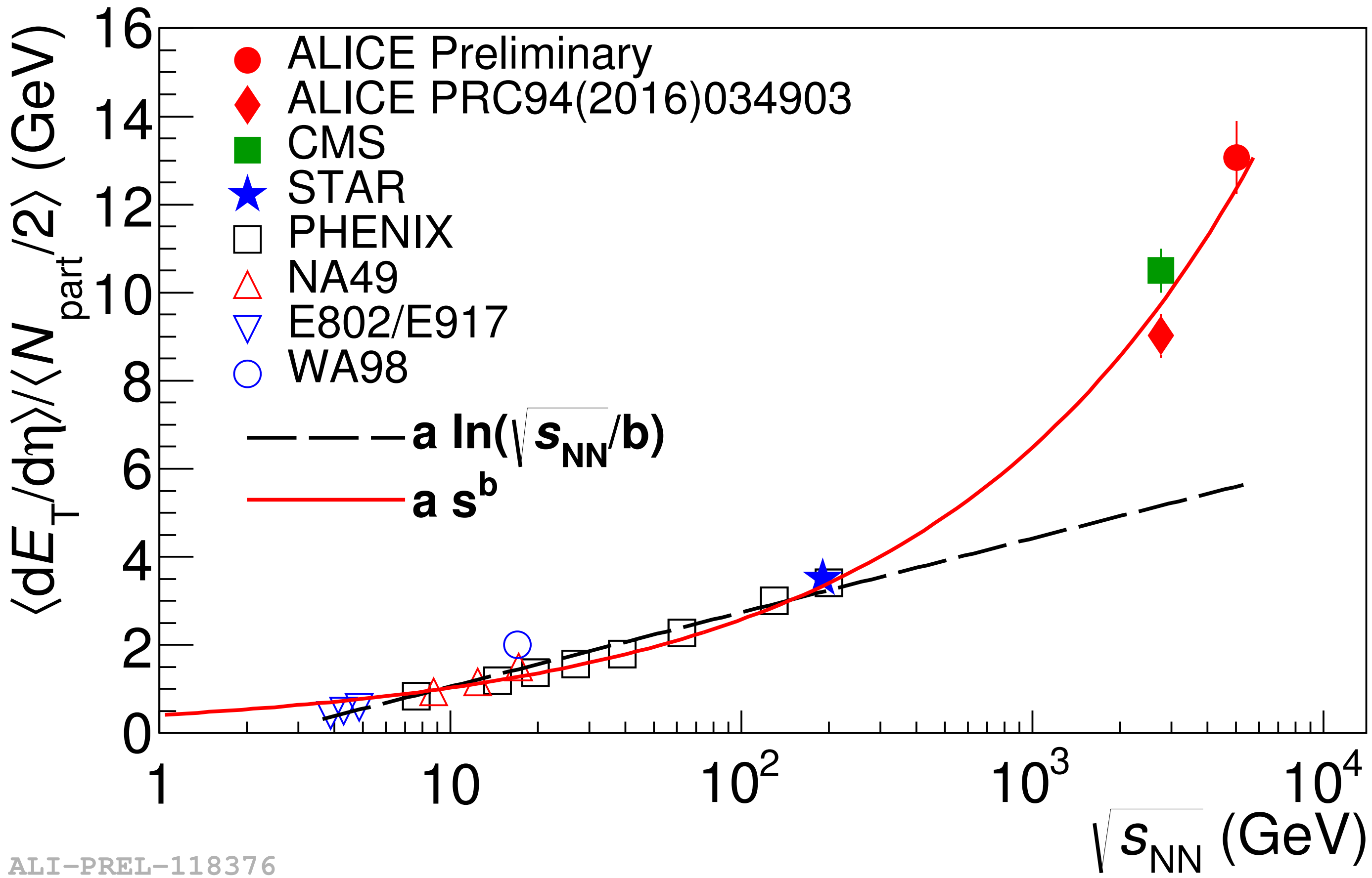
ALICE Collaboration: 37 countries, 176 institutions, 1800 members

Nucleus-nucleus collisions at the LHC



a picture of a central collision (about 3200 primary tracks in $|\eta| < 0.9$); "Camera": Time Projection Chamber

[5 m length, 5 m diam.; 500 mil. pixels; we take a few 100 pictures per second (and are preparing to take 50000)]



E_T: transverse energy (energy built from p_T)

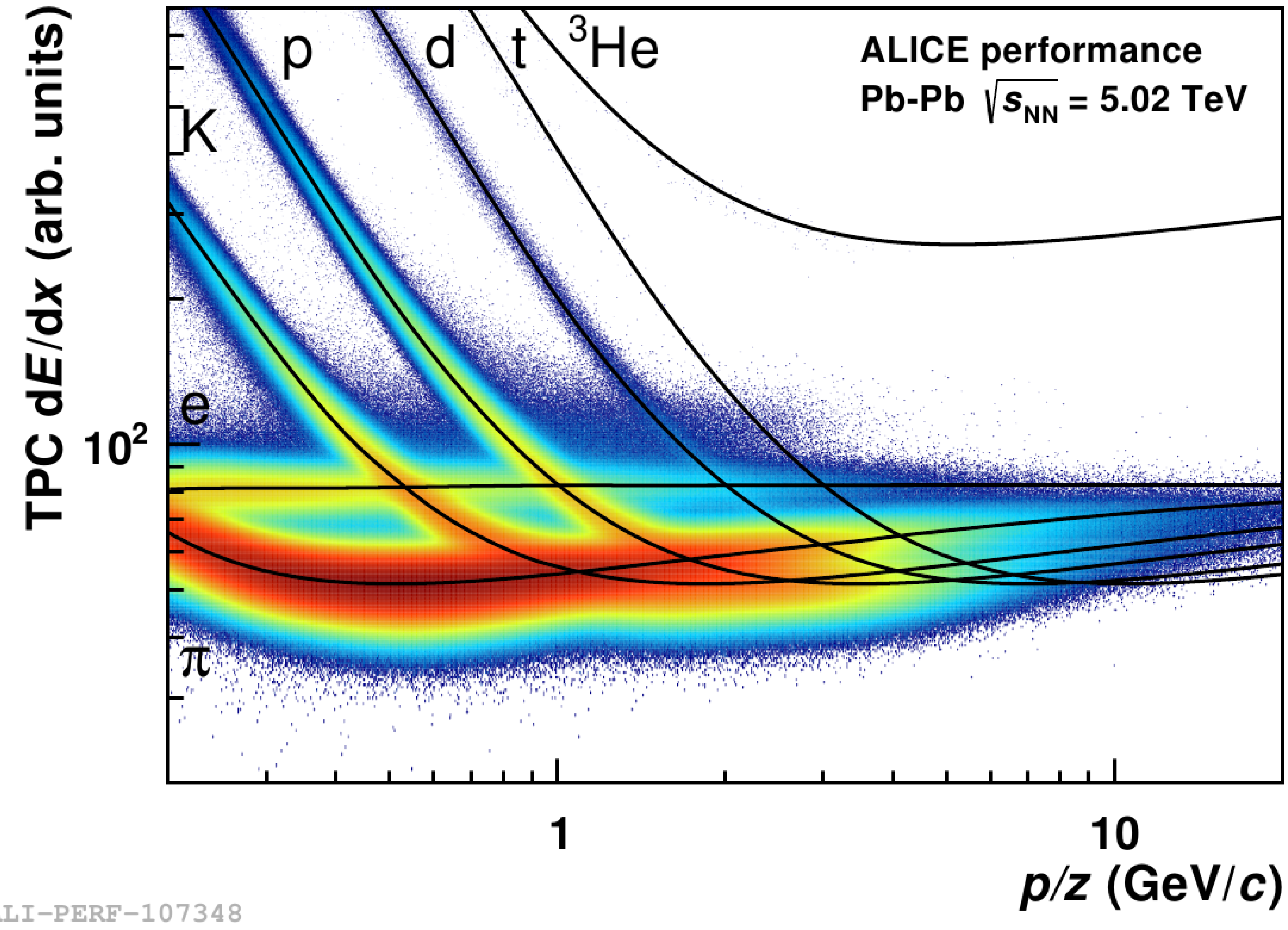
$\varepsilon_{LHC} \simeq 20-40$ GeV/fm^3 (much above ε_c)

$\varepsilon_{FAIR} \lesssim 1$ GeV/fm^3 (around ε_c)

self-similar (Hubble-like) homogeneous (hydrodynamic) expansion of the fireball in the longitudinal (beam) direction ("Bjorken model", J.D. Bjorken, PRD 27 (1983) 140)

Energy density: $\varepsilon = \frac{1}{A_\mathrm{T}}\frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}y}\frac{1}{c\tau}$

- $A_T = \pi R^2$: transverse area (Pb-Pb: A_T =154 fm^2)
- $\tau \simeq$1 fm/c: formation time (establishing the equilibrium) ...*not measurable!*



dE/dx: truncated mean of 159 samples along a track; resolution: 5.8%

lines: Bethe-Bloch parametrization   particles and antiparticles are shown

Hadron yields

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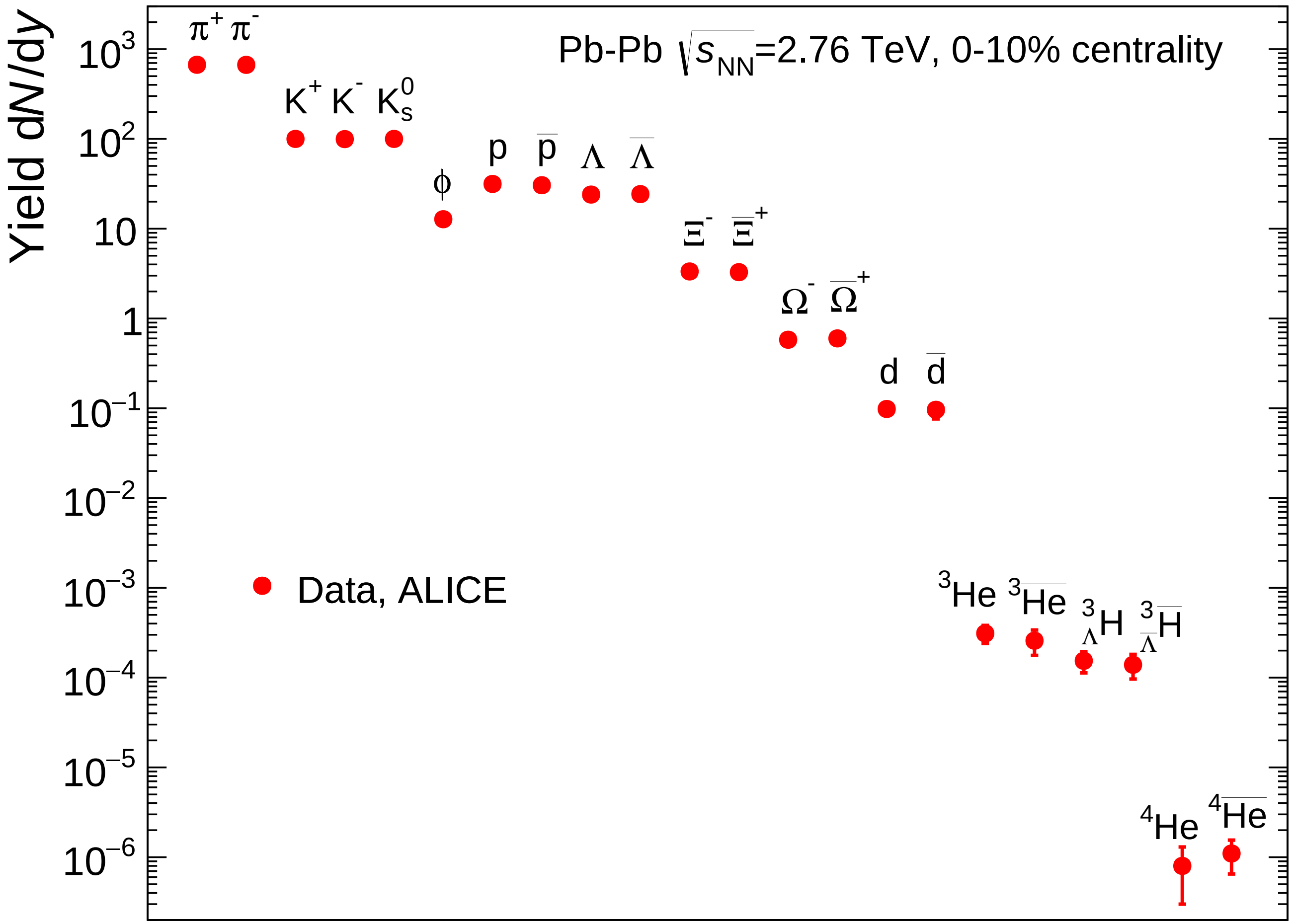
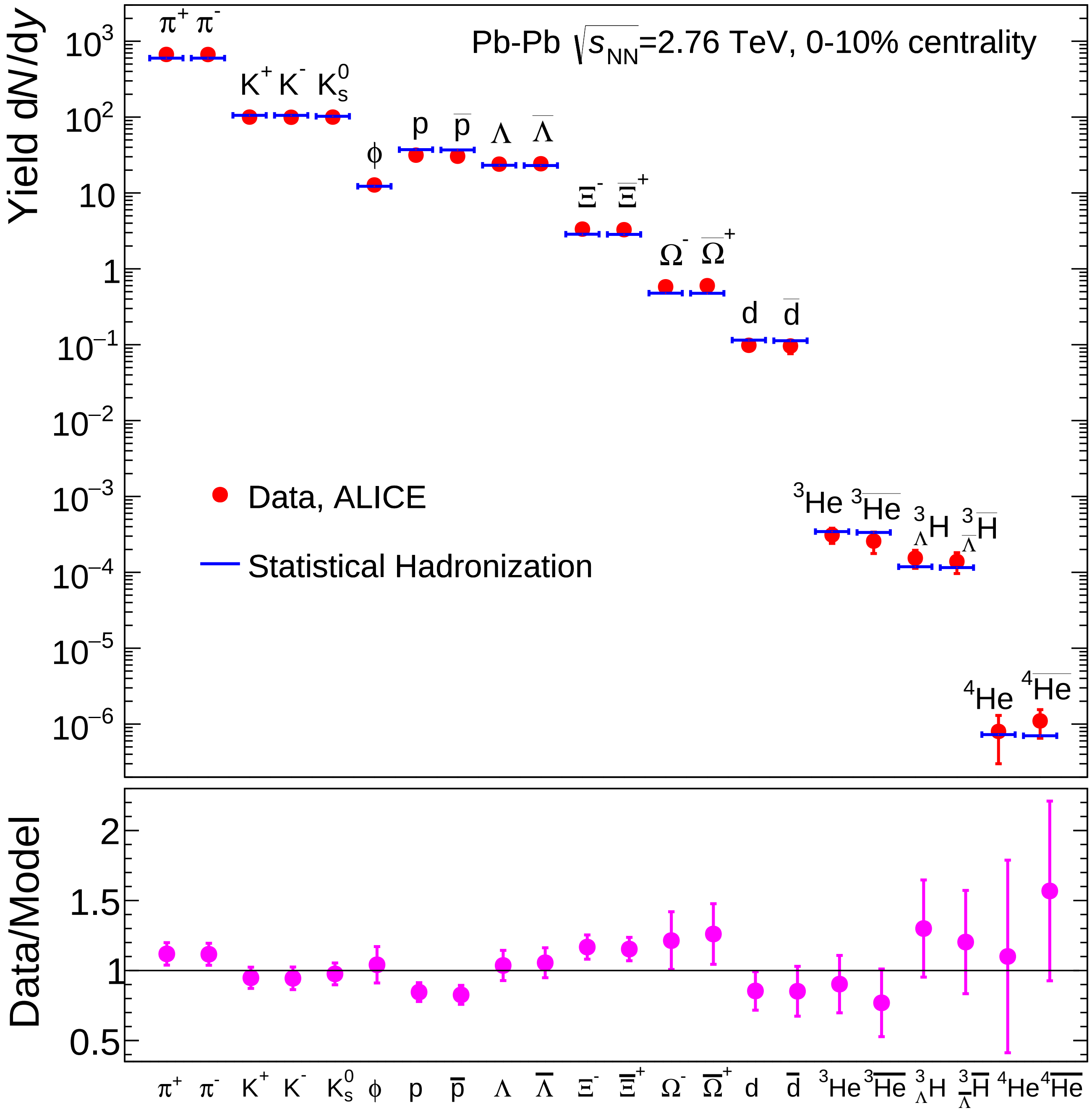


Matter and antimatter are produced in equal amounts in high-energy Pb-Pb collisions at the LHC

Mass hierarchy in production

arXiv:1710.07531



Matter and antimatter are produced in equal amounts in high-energy Pb-Pb collisions at the LHC

Best fit:

$T_{CF} = 156.5 \pm 1.5$ MeV

$\mu_B = 0.7 \pm 3.8$ MeV

$V = 5280 \pm 410$ fm^3

chemical freeze-out

Laboratory creation of a piece of hot Universe when 10 μs old, $T \simeq 10^{12}$ K

arXiv:1710.07531

arXiv:1710.09425

Thermal fit of hadron abundances

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

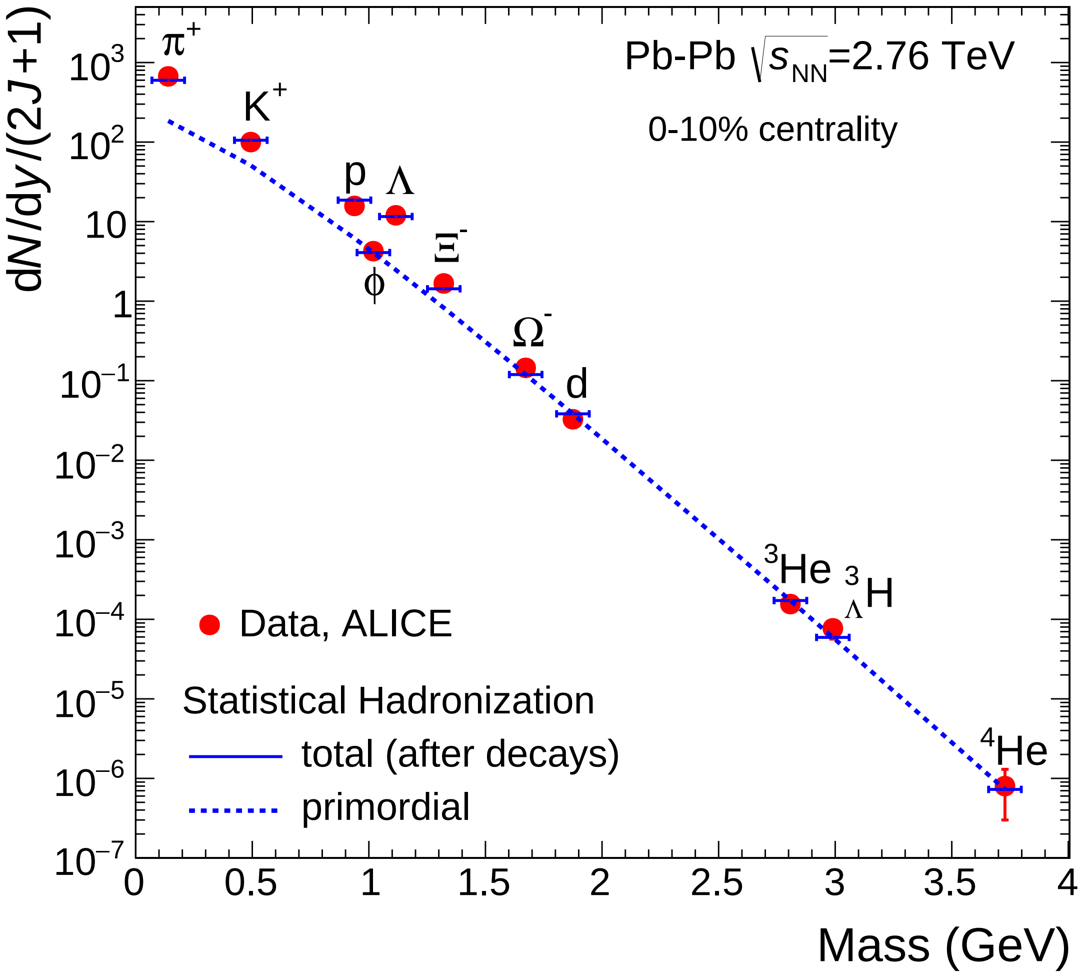
quantum nr. conservation ensured via chemical potentials:

$\mu_i = \mu_B B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$

Latest PDG hadron mass spectrum (up to 3 GeV, 500 species)

Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

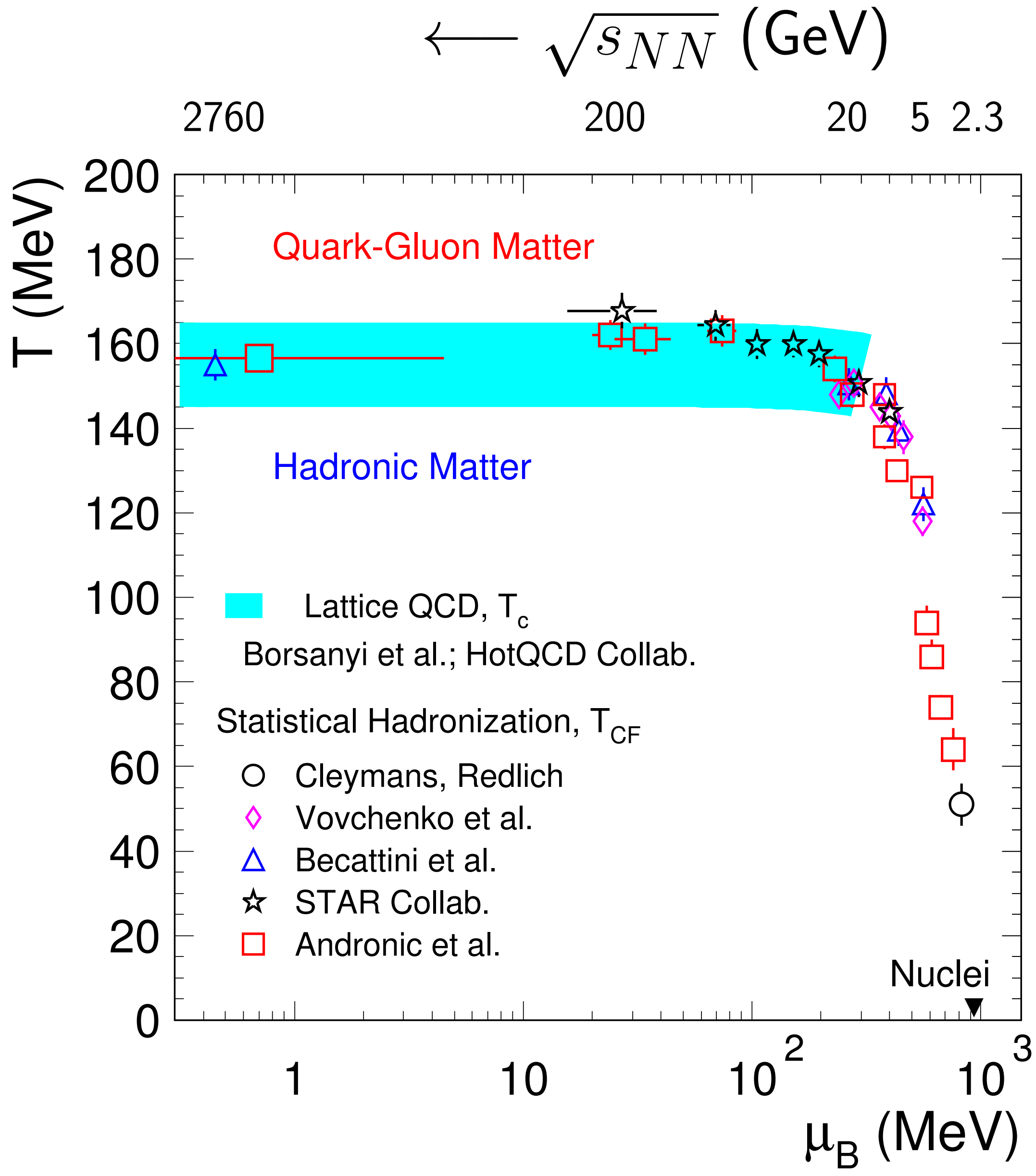
N_i: hadron yield $\Rightarrow (T,\, \mu_B,\, V)$



The hadron abundances are in agreement with a chemically-equilibrated system

...but how can a loosely-bound deuteron "survive" at T=156 MeV?

Chemical freeze-out and the phase diagram of QCD



arXiv:1710.09425

at LHC, remarkable "coincidence" with Lattice QCD results

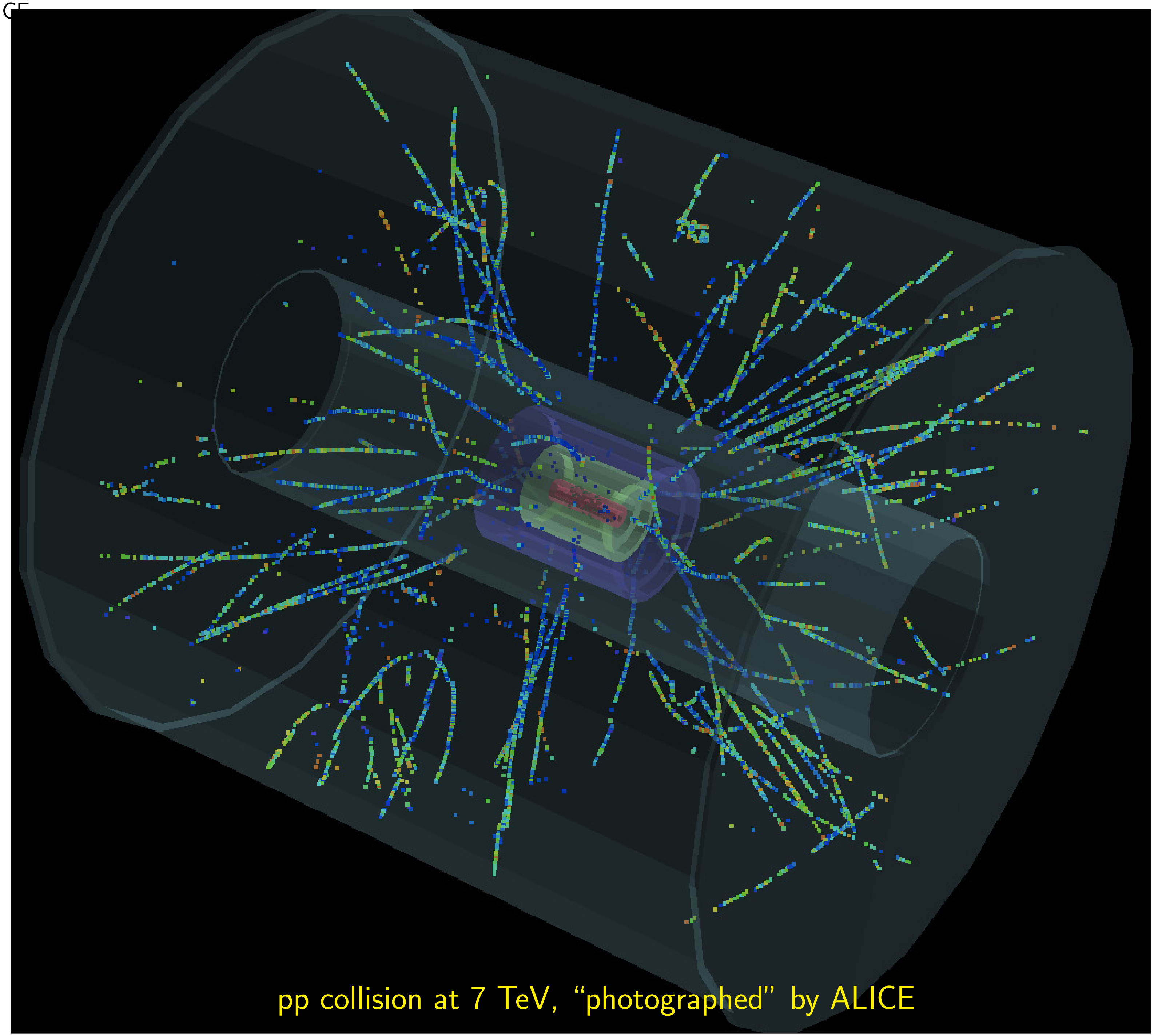
at LHC ($\mu_B \simeq 0$): purely-produced (anti)matter ($m = E/c^2$), as in the Early Universe

$\mu_B > 0$: more matter, from "remnants" of the colliding nuclei

$\mu_B \gtrsim 400$ MeV: *the critical point awaiting discovery*

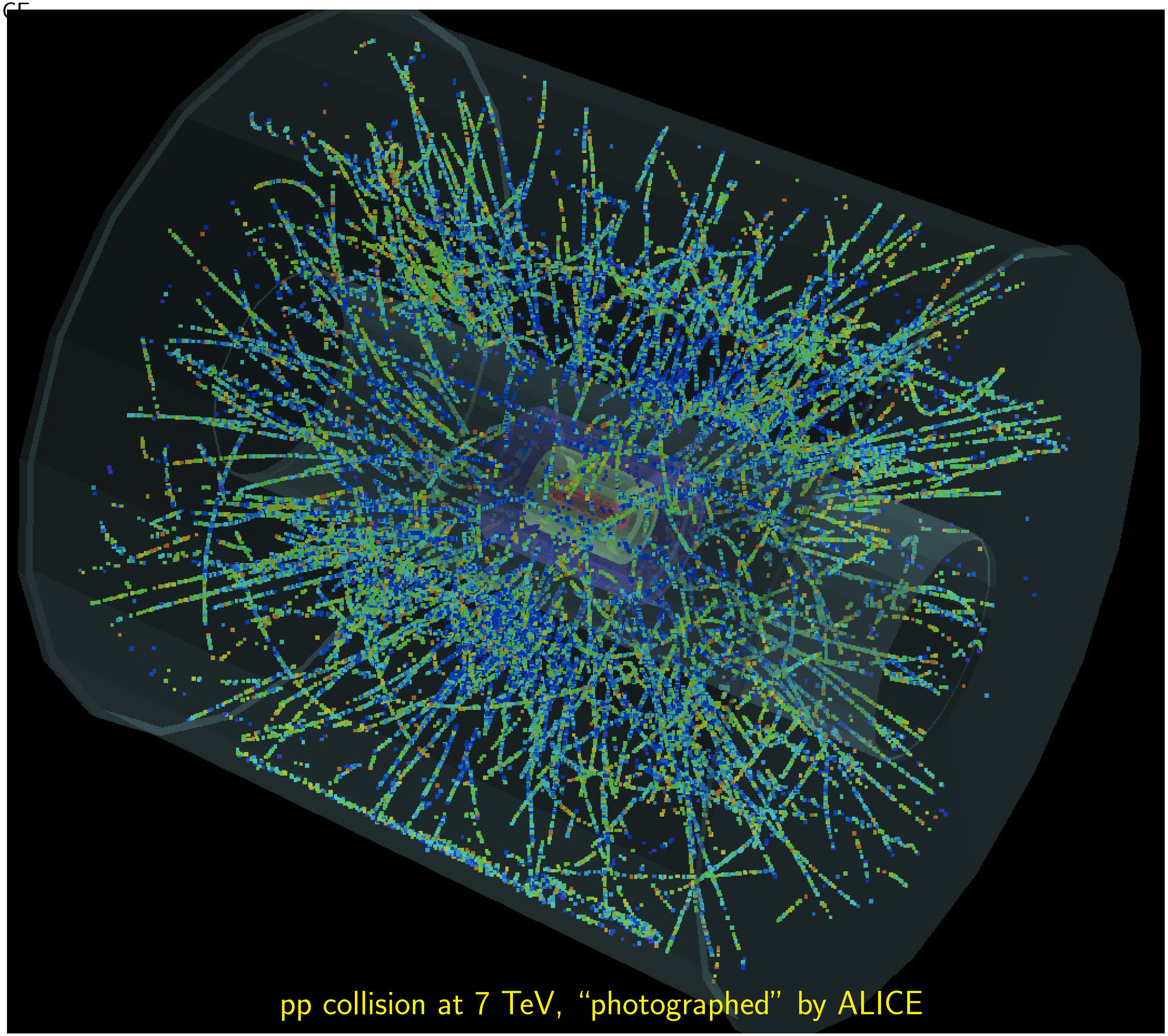
μ_B is a measure of the net-baryon density, or matter-antimatter asymmetry

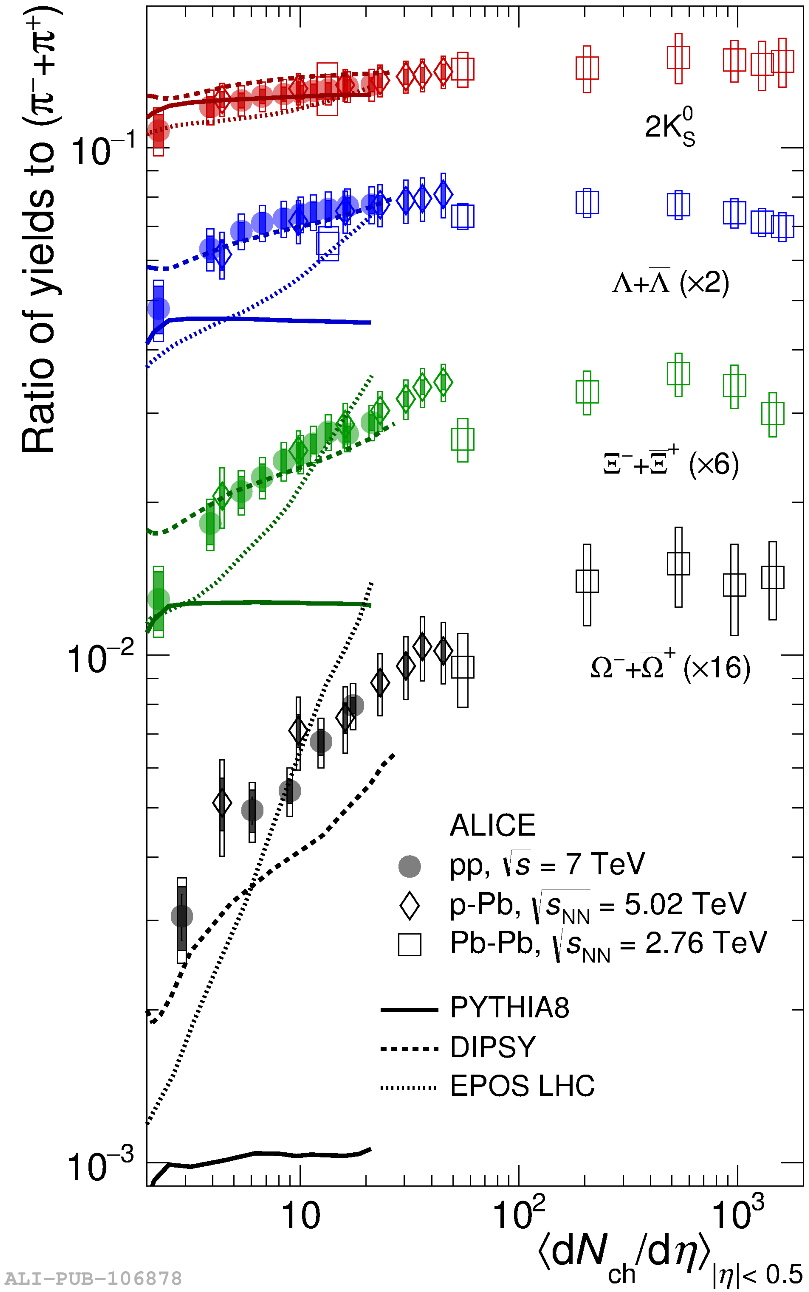
Proton collisions at the LHC



pp collision at 7 TeV, “photographed” by ALICE

Proton collisions at the LHC





Nature Physics 13 (2017) 535

(big geometric) fireball in Pb–Pb reached with violent pp and p–Pb collisions

(grand canonical) statistical description works well in Pb–Pb (with T of QCD phase boundary)

is the same mechanism at work in small systems (at large multiplicities)?

string hadronization models do not describe data well

...new ideas are being put forward

Fischer, Sjöstrand, JHEP 01 (2017) 140

"thermodynamical string fragmentation"

quantified by

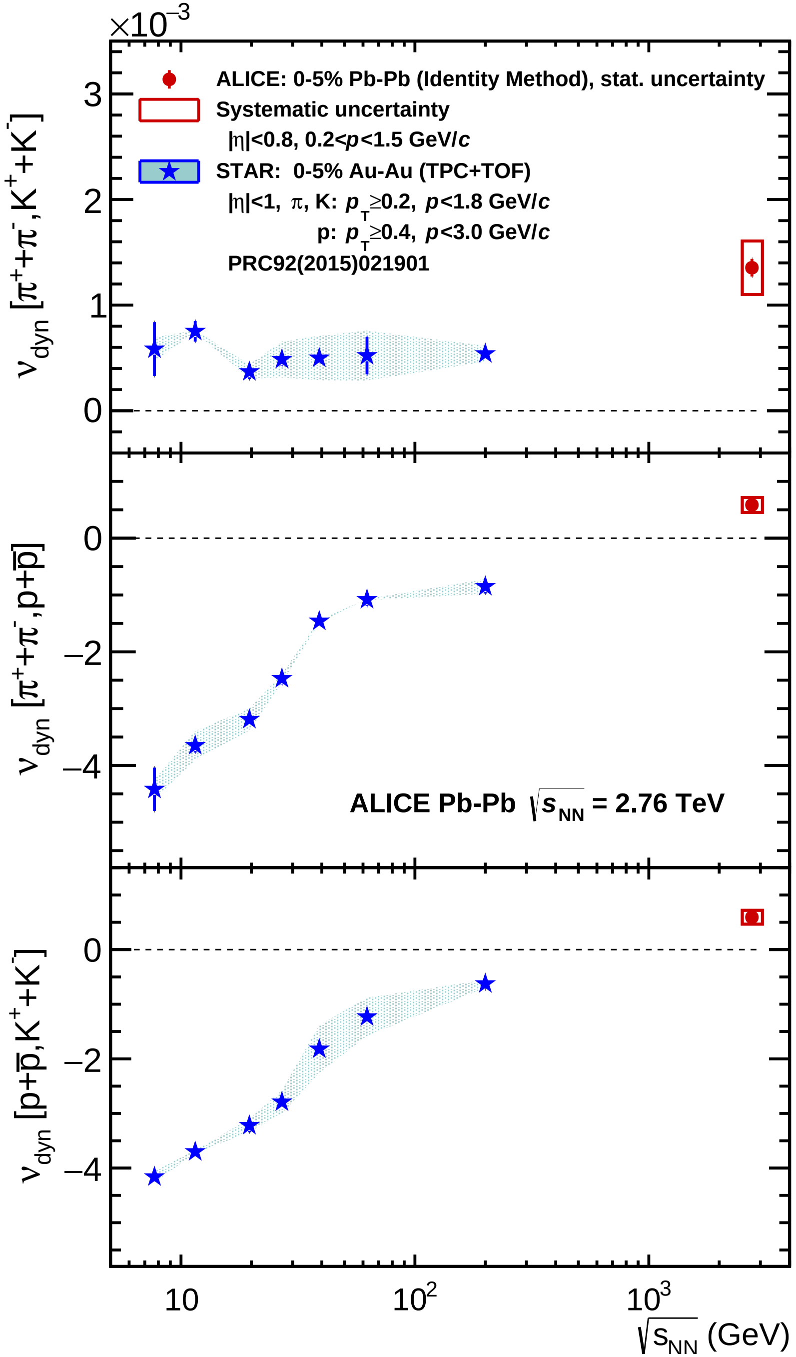
$$\nu_{\rm dyn}[A,B] = \frac{\langle N_A(N_A-1)\rangle}{\langle N_A\rangle^2} + \frac{\langle N_B(N_B-1)\rangle}{\langle N_B\rangle^2} - 2\frac{\langle N_A N_B\rangle}{\langle N_A\rangle\langle N_B\rangle}$$

the relative strength of fluctuations of species A and B - relative strength of correlations between species A and B

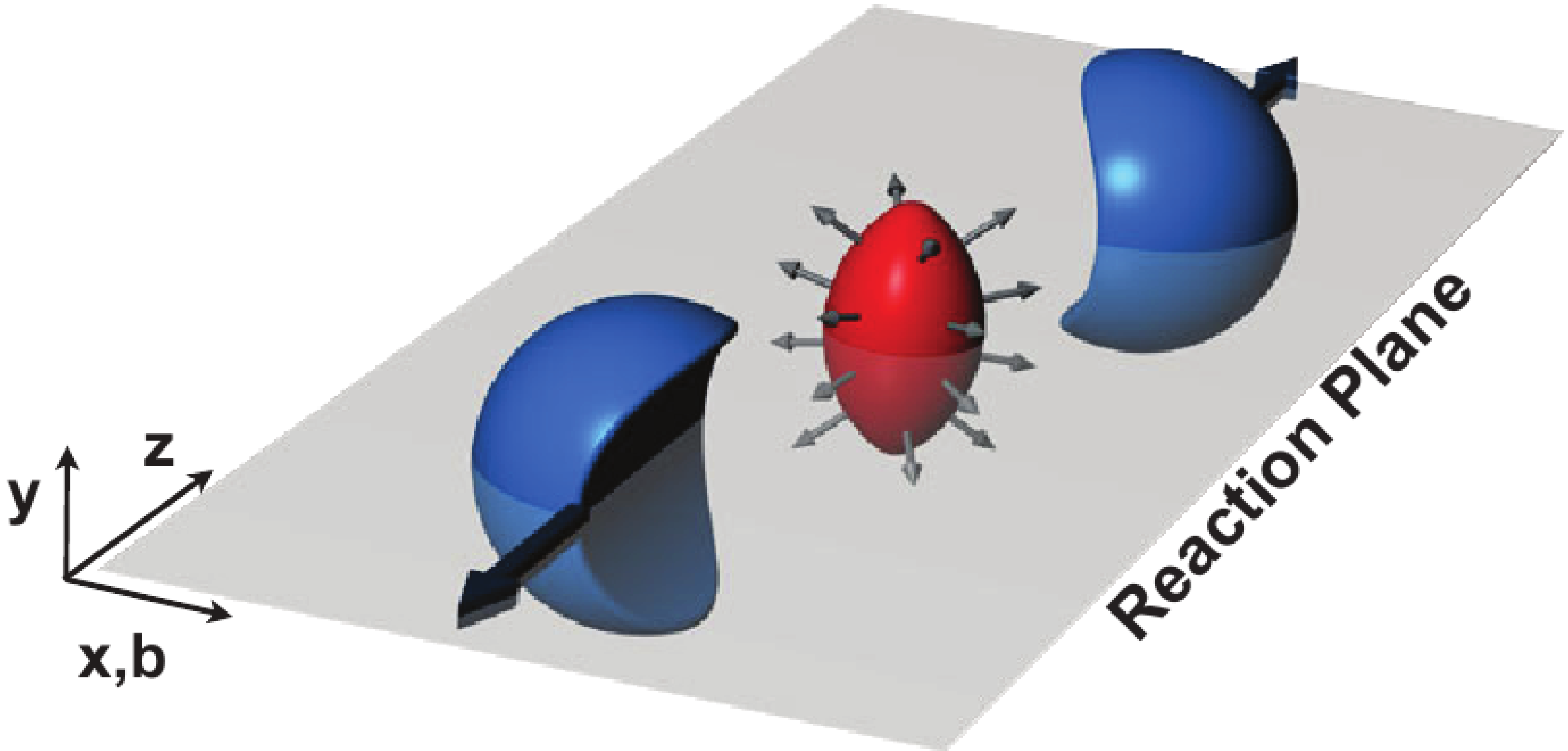
(event-by-event)

$\nu_{\rm dyn}[A,B] = 0$ if A and B are produced in a statistically independent way

arXiv:1712.07929



Collective flow



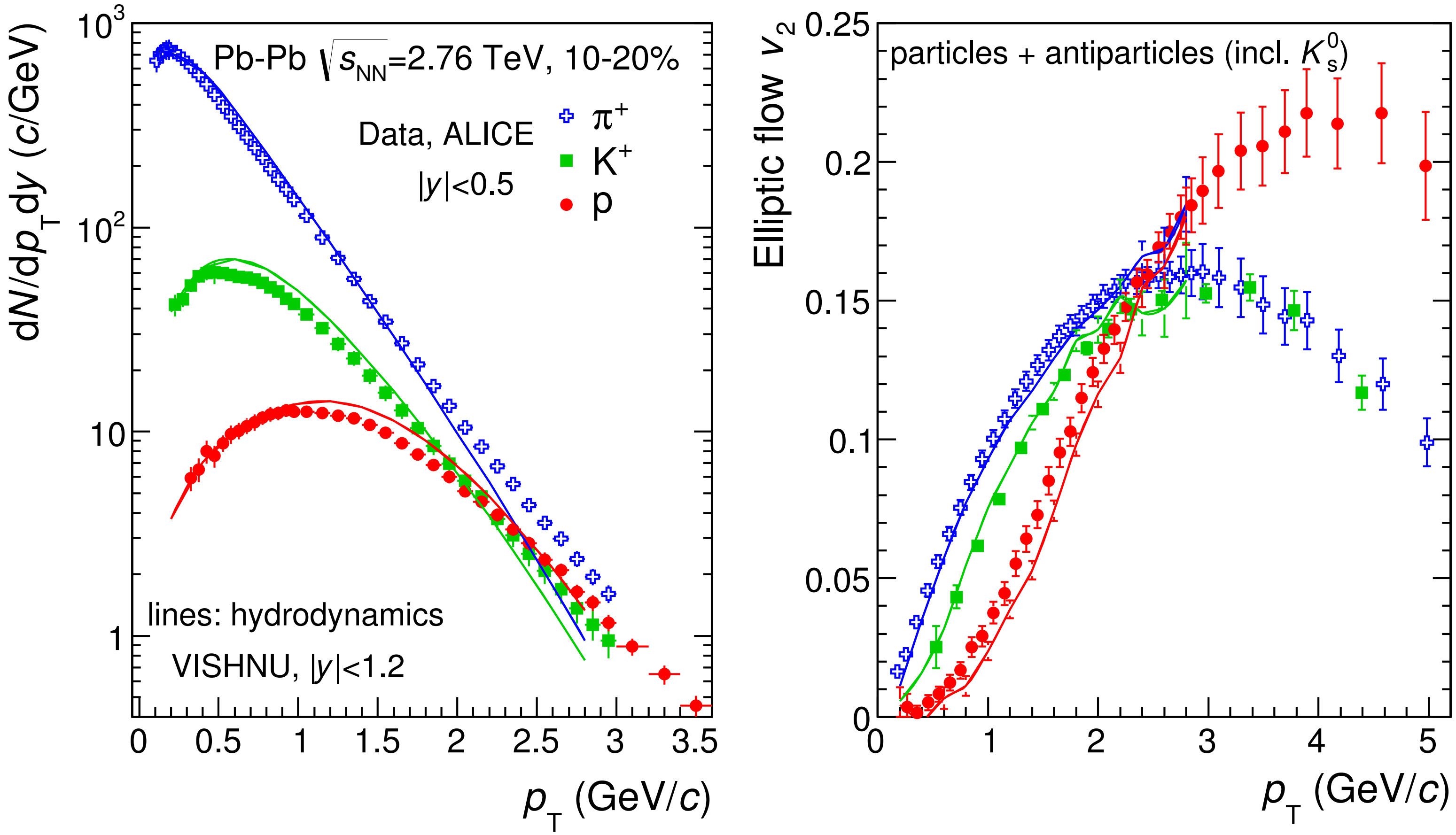
R. Snellings, arXiv:1102.3010

$$\frac{dN}{d\varphi} \sim [1 + 2v_1 \cdot \cos(\varphi) + 2v_2 \cdot \cos(2\varphi) + ...]$$

φ is azimuthal angle with respect to reaction plane

$v_2 = \langle\cos(2\varphi)\rangle$ we call *elliptic flow*, $v_3 = \langle\cos(3\varphi)\rangle$ *triangular flow* (coefficients)

Data and hydrodynamics



mass dependence due to collective flow

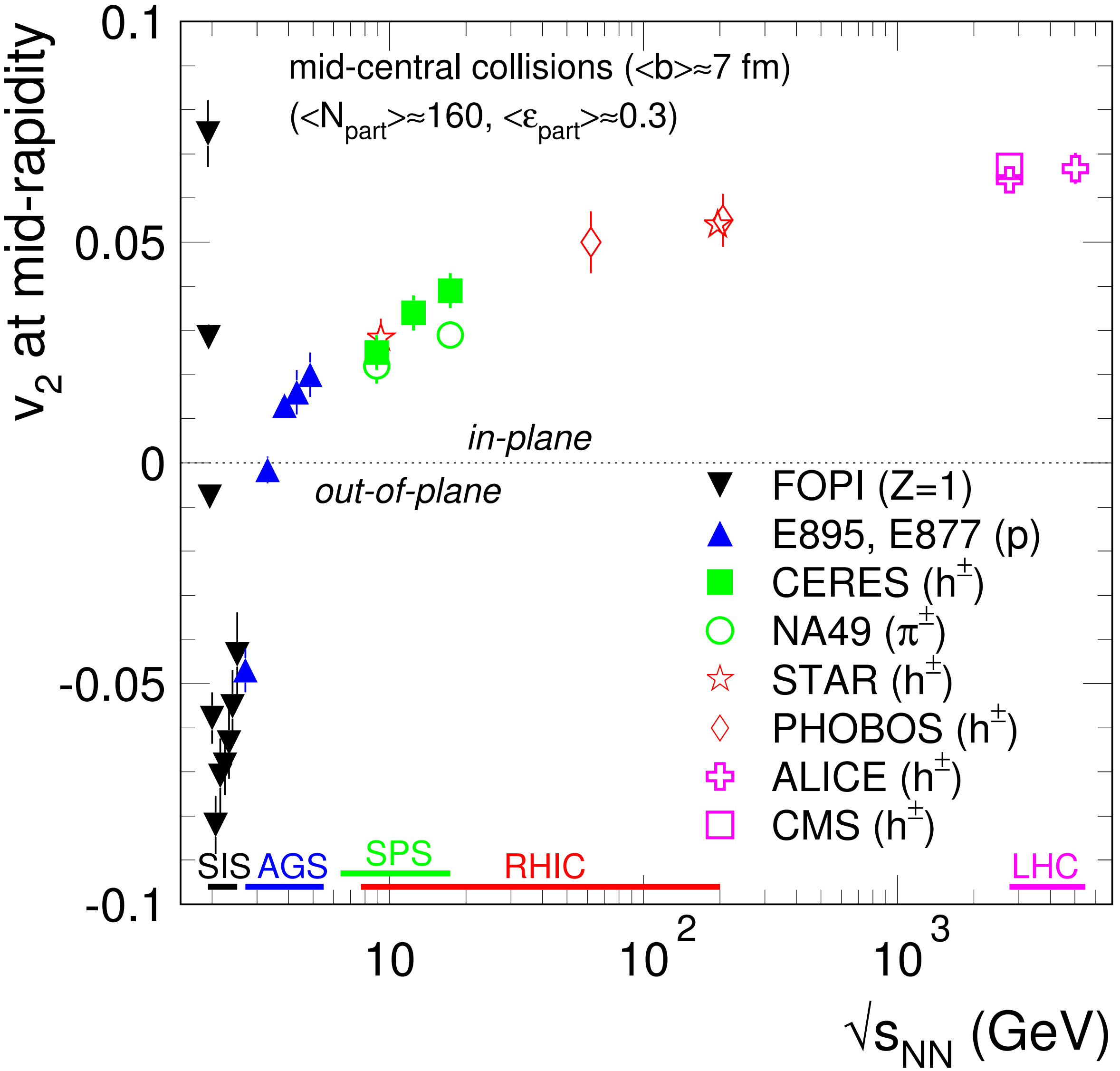
hydrodynamic models reproduce the data with a very small viscosity/entropy density, η/s ($\sim T\lambda c_s$)

lower bound conjectured (AdS/CFT): $\eta/s \geq 1/4\pi$

Kovtun, Son, Starinets, PRL 94 (2005) 111601

Data:
PRC 88 (2013) 044910
JHEP 06 (2015) 190

VISHNU:
PRC 89 (2014) 034919



$v_2 > 0$ at high energies: "free" fireball (almond-shape) expansion ("genuine" elliptic flow)

hydrodynamic description determined by η/s *and initial conditions* (matter/energy fluctuations of colliding nuclei)

...constrained by correlations between v_n coeff., arXiv:1709.01127

we do also "event-shape engineering", arXiv:1709.04723

PRL 116 (2016) 132302

up to now we only considered hadrons built with u, d, s quarks
...these are light, masses from a few MeV (u, d) to ∼90 MeV (s)

what about heavier ones?
...for instance c, which weights about 1.2 GeV

produced in pairs ($c\bar{c}$) in initial hard collisions ($t \sim \hbar c/(2m_c) \leq 0.1$ fm/c)

observable: $R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_\mathrm{T}\mathrm{d}y}{N_{coll}\cdot \mathrm{d}N_{pp}/\mathrm{d}p_\mathrm{T}\mathrm{d}y}$, the nuclear modification factor

one meson, the J/ψ (a bound state of c and $\bar{c}$, charmonium) is of particular interest

the original idea: Matsui & Satz, PLB 178 (1986) 178

"If high energy heavy-ion collisions lead to the formation of a hot quark-gluon-plasma, then color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region."

Refinements: "sequential suppression":

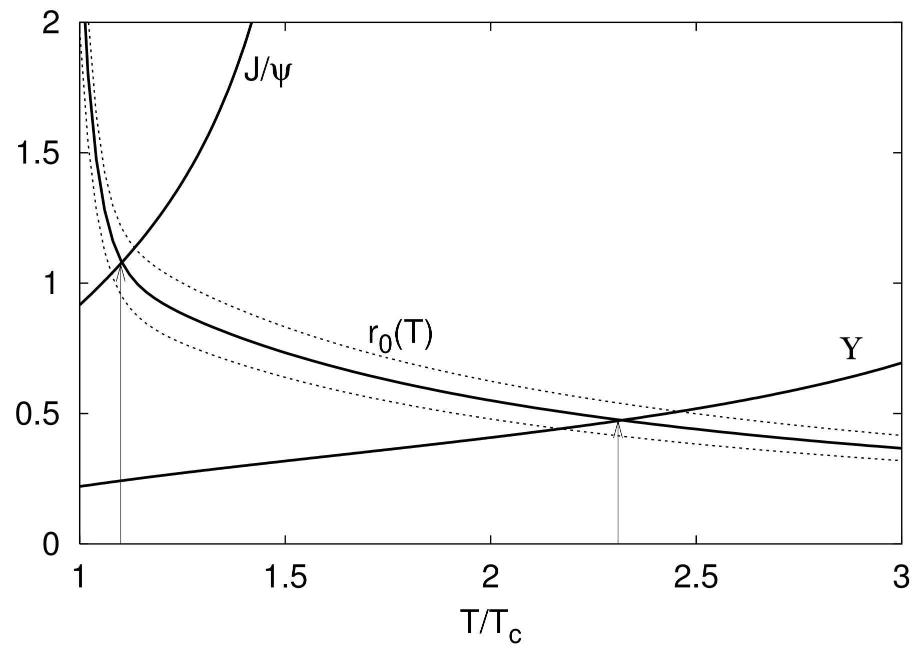
Digal et al., PRD 64 (2001) 75

no $\mathrm{q\bar{q}}$ bound state if

$r_{\mathrm{q\bar{q}}}(T) > r_0(T) \simeq 1/(g(T)T)$

r_0 Debye length in QGP

$\Rightarrow$ $\mathrm{q\bar{q}}$ "thermometer" of QGP



Thermal picture ($n_{partons} = 5.2T^3$ for 3 flavors)

for T=500 MeV: $n_p \simeq$84/fm^3, mean separation $\bar{r}$=0.2 fm $< r_{J/\psi}$

Models ...implementing Debye screening and more

Statistical hadronization model

all charm quarks are produced in primary hard collisions ($t_{c\bar{c}} \sim 1/2m_c \simeq$ 0.1 fm/c)

...survive and thermalize **in QGP** (thermal, but not chemical equilibrium)

charmed hadrons are formed at chemical freeze-out together with all hadrons

"generation" ...no J/ψ survival in QGP (full screening)

if supported by data, J/ψ looses status as "thermometer" of QGP

...and gains status as a powerful observable for the phase boundary

Braun-Munzinger, Stachel, PLB 490 (2000) 196; NPA 789 (2006) 334, PLB 652 (2007) 259

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Transport models

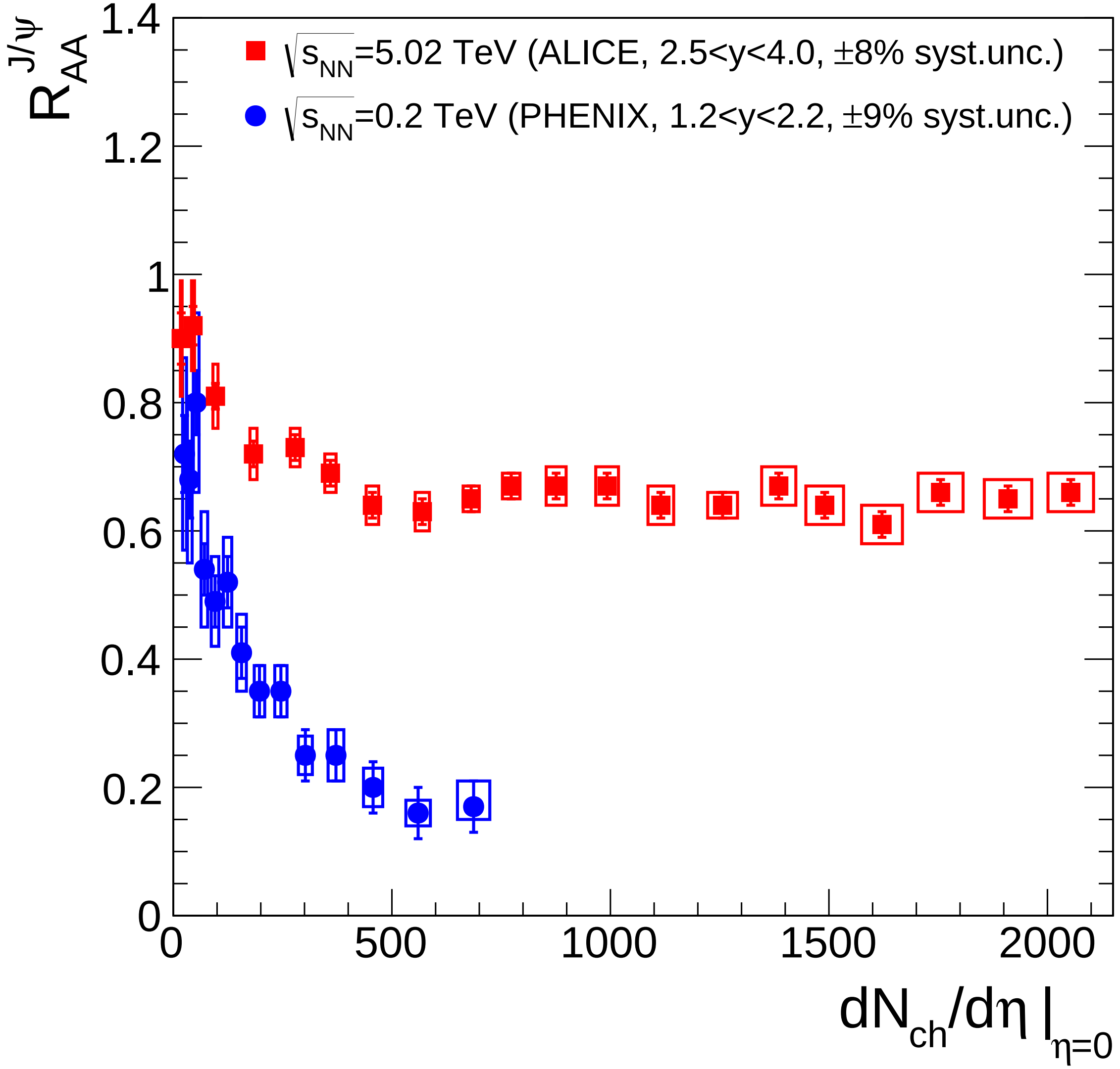
implement screening picture with space-time evolution of QGP (hydrodynamics)
continuous destruction and "(re)generation" ("recombination")

Thews et al., PRC 63 (2001) 054905 ...

"TAMU", PLB 664 (2008) 253, NPA 859 (2011) 114, EPJA 48 (2012) 72

"Tsinghua", PLB 607 (2005) 107, PLB 678 (2009) 72, PRC 89 (2014) 054911

Strickland, Bazow, NPA 879 (2012) 25



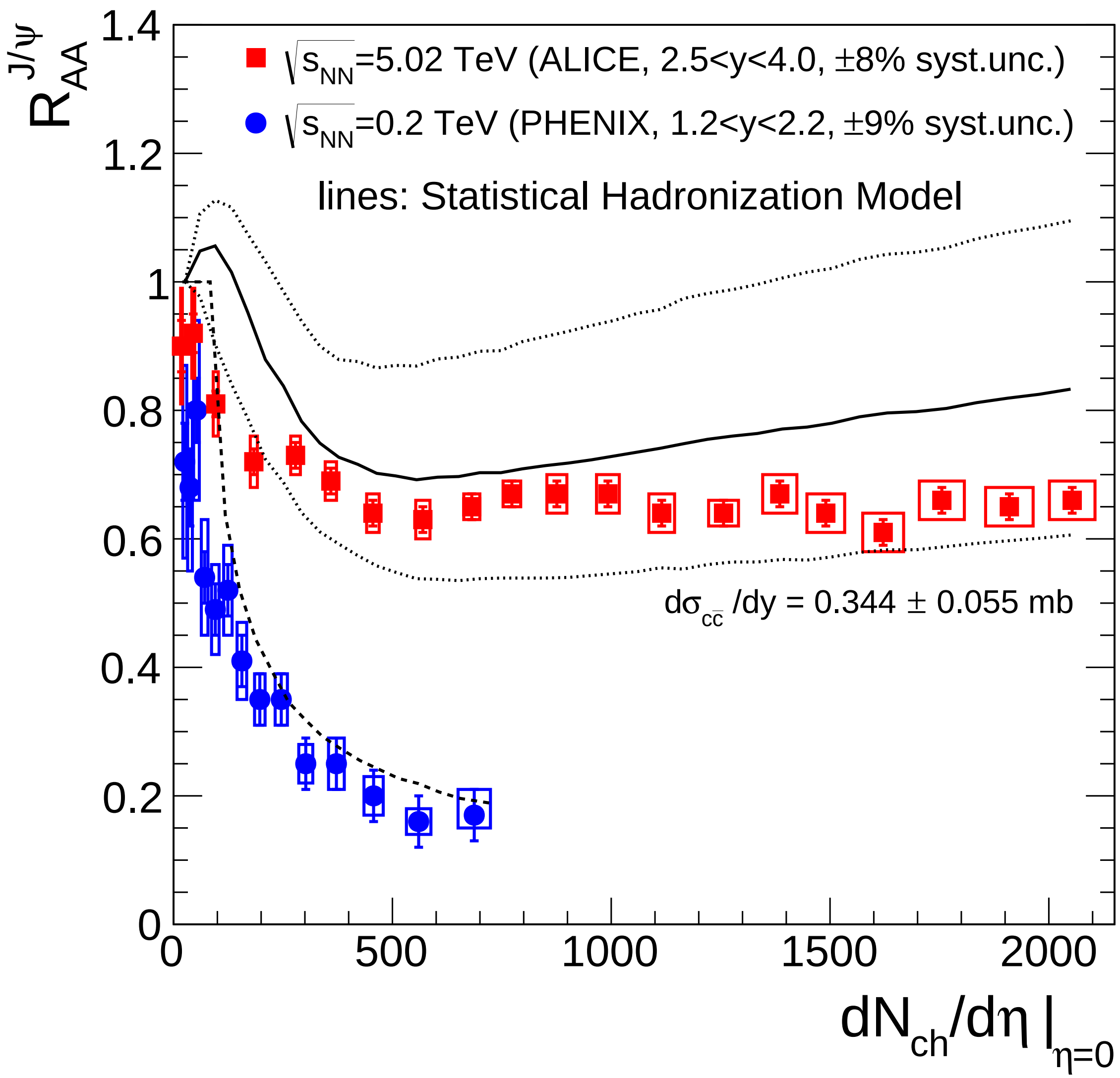
$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_\mathrm{T}\mathrm{d}y}{N_{coll}\cdot\mathrm{d}N_{pp}/\mathrm{d}p_\mathrm{T}\mathrm{d}y}$$

nuclear modification factor

- "suppression" at RHIC (PHENIX)
- dramatically different at the LHC

$\mathrm{d}N_{ch}/\mathrm{d}\eta \sim \varepsilon$ (>20 GeV/fm^3, for $\mathrm{d}N_{ch}/\mathrm{d}\eta \simeq$ 2000)

ALICE, PLB 766 (2017) 212; PHENIX, PRC 84 (2011) 054912



$dN_{ch}/d\eta \sim \varepsilon$ (>20 GeV/fm^3, for $dN_{ch}/d\eta \simeq$ 2000)

arXiv:1710.09425

$$R_{AA} = \frac{dN_{AA}/dp_T dy}{N_{coll} \cdot dN_{pp}/dp_T dy}$$

nuclear modification factor

- "suppression" at RHIC (PHENIX)
- dramatically different at the LHC

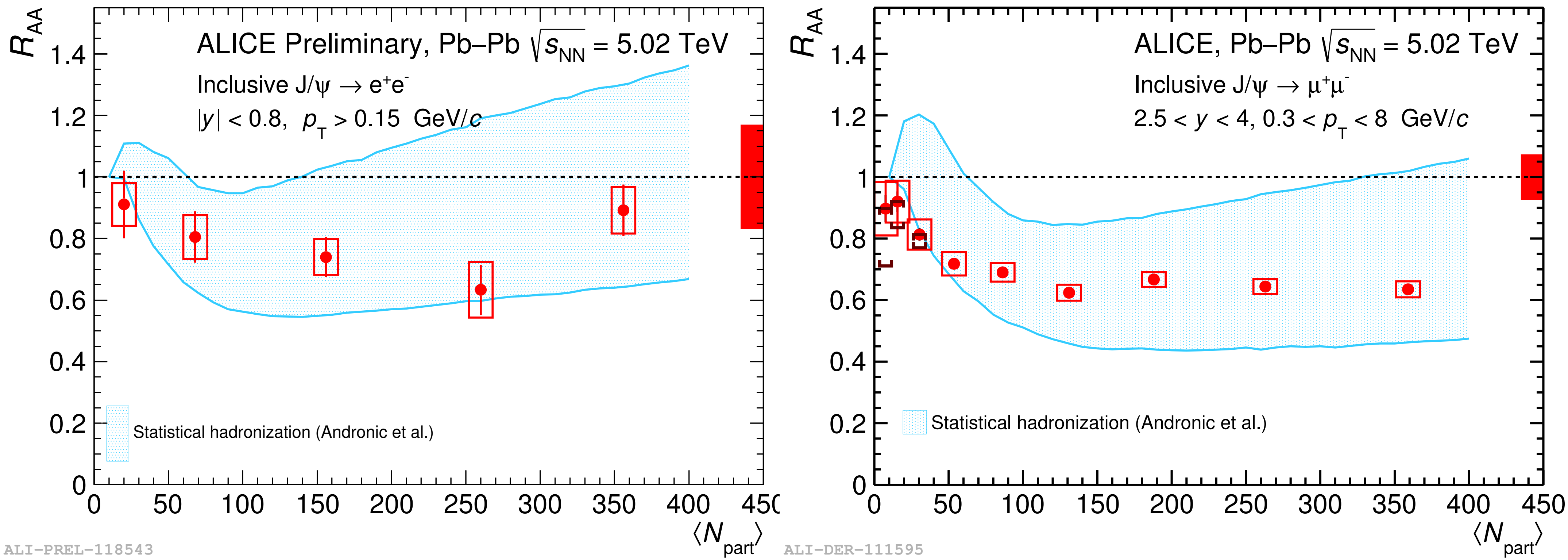
Statistical Hadronization Model

$N_{J/\psi} \sim (N_{c\bar{c}}^{dir})^2$

J/ψ is another observable (charm) for the phase boundary

calculations are for T=156 MeV

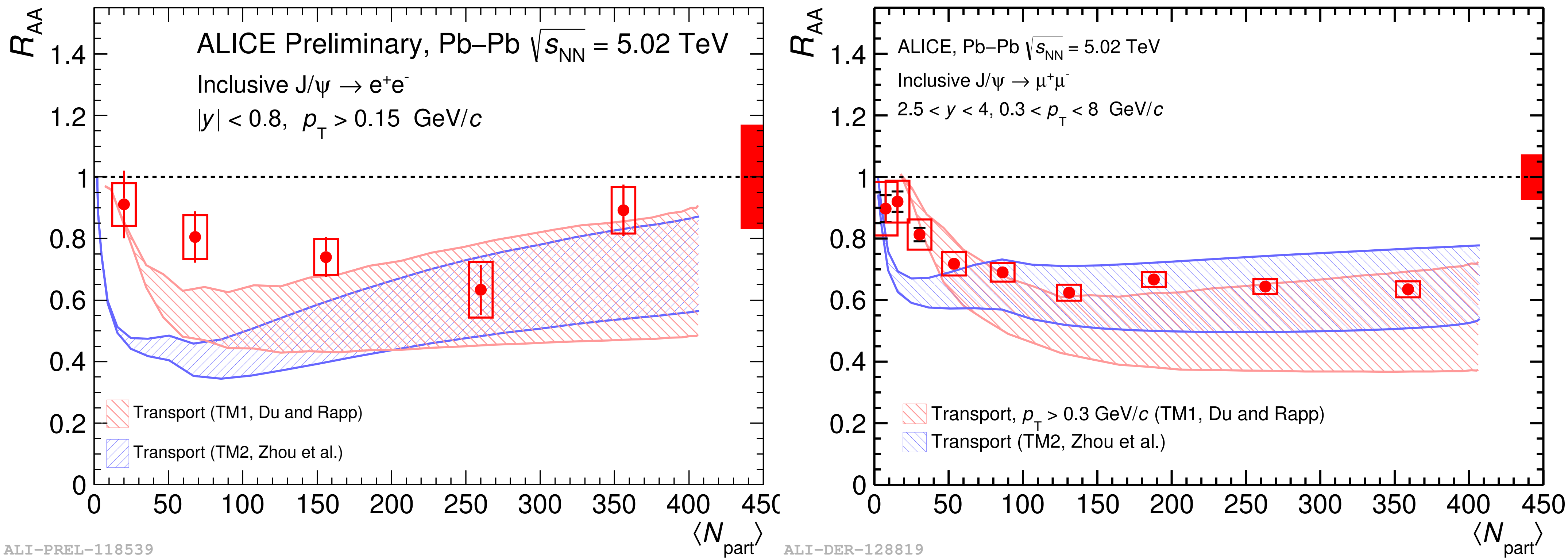
J/ψ data and the statistical model



ALICE, PLB 766 (2017) 212

The statistical hadronization model assumes full thermalization of charm quarks, full dissociation of J/ψ mesons in QGP and formation at the hadronization

within this model, the "thermometer" status is lost, but J/ψ (charm) becomes a remarkable observable for the QCD phase boundary (hadronization)

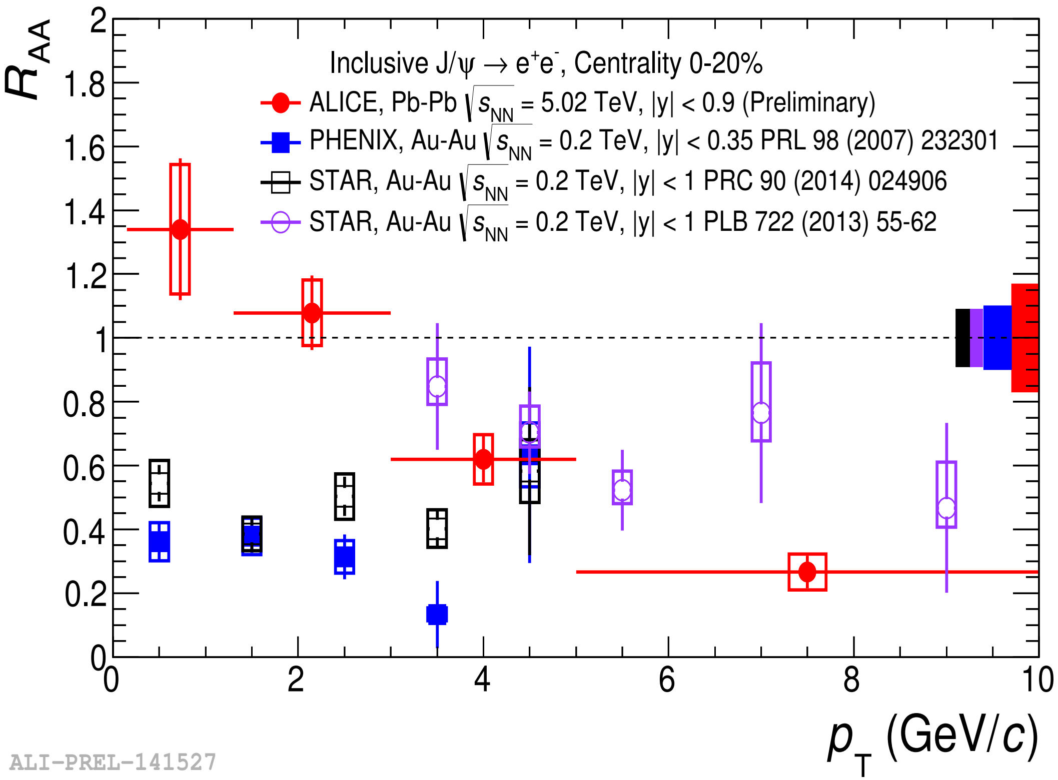


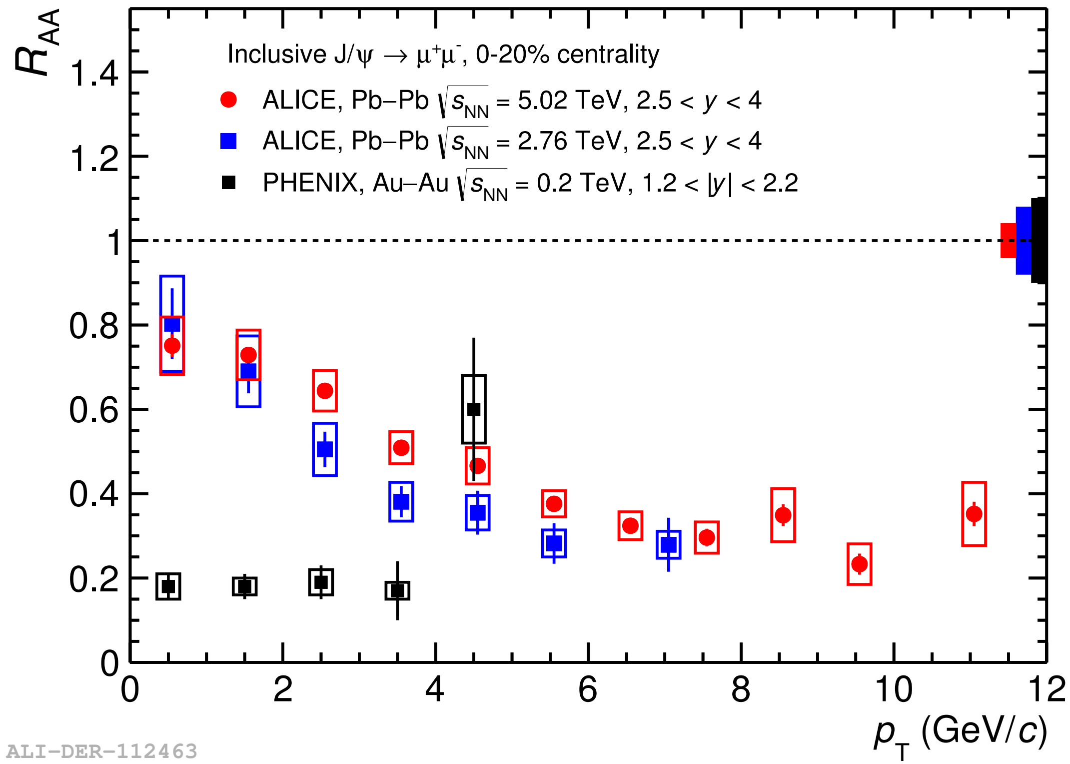
ALICE, PLB 766 (2017) 212

Transport models assume continuous dissociation and formation during the whole lifetime of QGP (time evolution of T constrained by other measurements)

(employ smaller uncert. of $d\sigma_{c\bar{c}}/dy$)

J/ψ production vs. p_T





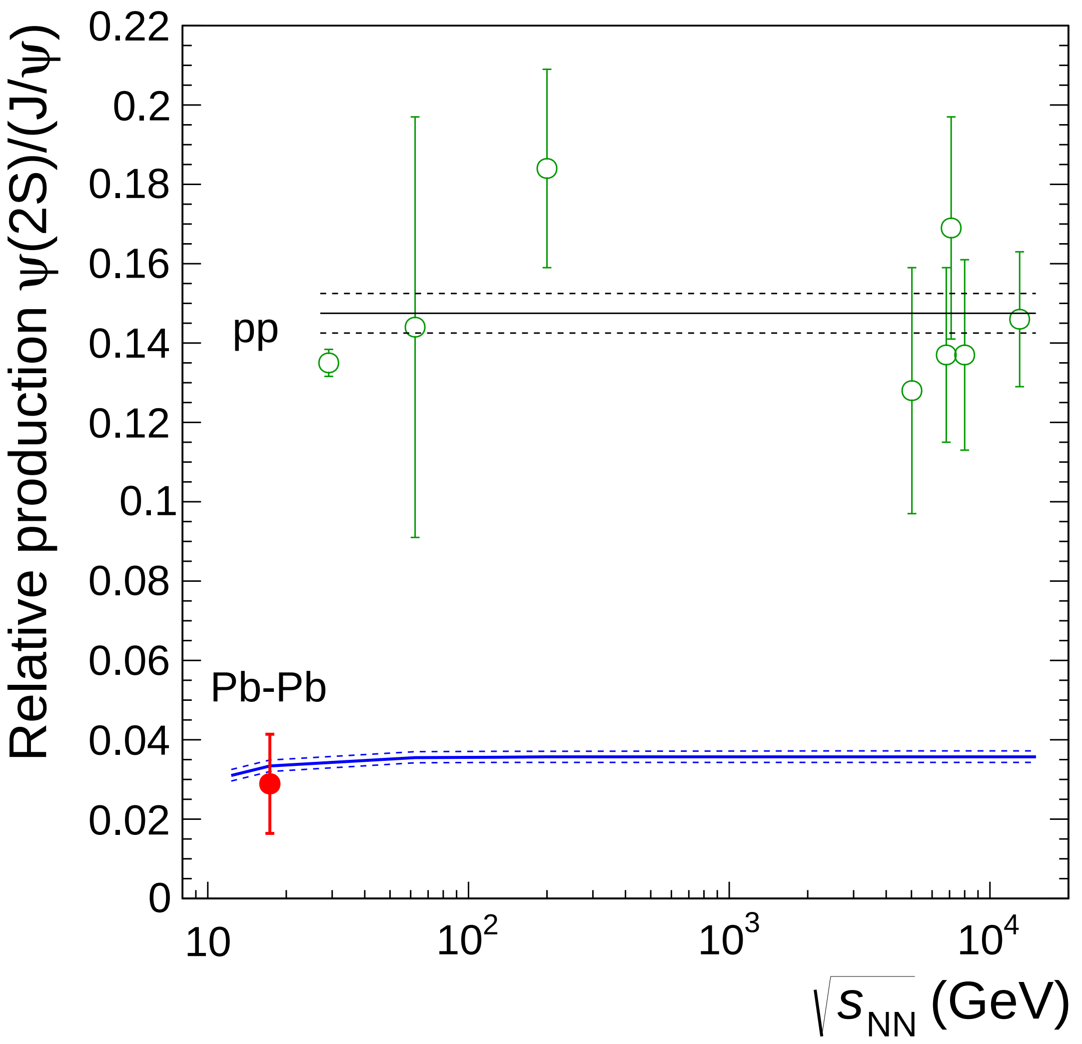
ALICE, JHEP 06 (2015) 055

as expected, (re)generation is a low-p_T phenomenon

significantly different trend at the LHC compared to RHIC

J/ψ at high-p_T suppressed as consequence of charm energy loss in QGP

Production of excited states crucial to investigate ...possible with HL-LHC



statistical description, arXiv:1710.09425 ...transport models predict larger relative production

Summary

- in nucleus-nucleus collisions we create a (small:) chunk of the hot early Universe

  ...a highly-dynamic and collective system; we measure observables for various stages

- measured energy densities are well above the values expected for deconfinement

- collective flow (developed early in the deconfined stage) described by hydrodynamics; allows extraction of η/s

- abundance of hadrons with light quarks consistent with chemical equilibration

  the thermal model provides a simple way to access the QCD phase boundary

  ...but is it more than a 1st order description (of loosely-bound objects)?

  ...and what fundamental point does it make about hadronization?

- we see (re)combination of charm quarks at the LHC ...either over the full history of QGP or at the phase boundary

  ...conclusion expected with the ALICE upgrade (HL-LHC, 2021-2029)

- some of the features in heavy-ion collisions are observed in high-multiplicity pp and p–Pb collisions

- *not shown but available in spare slides*

  we measure strong jet quenching (parton energy loss) in quark-gluon matter

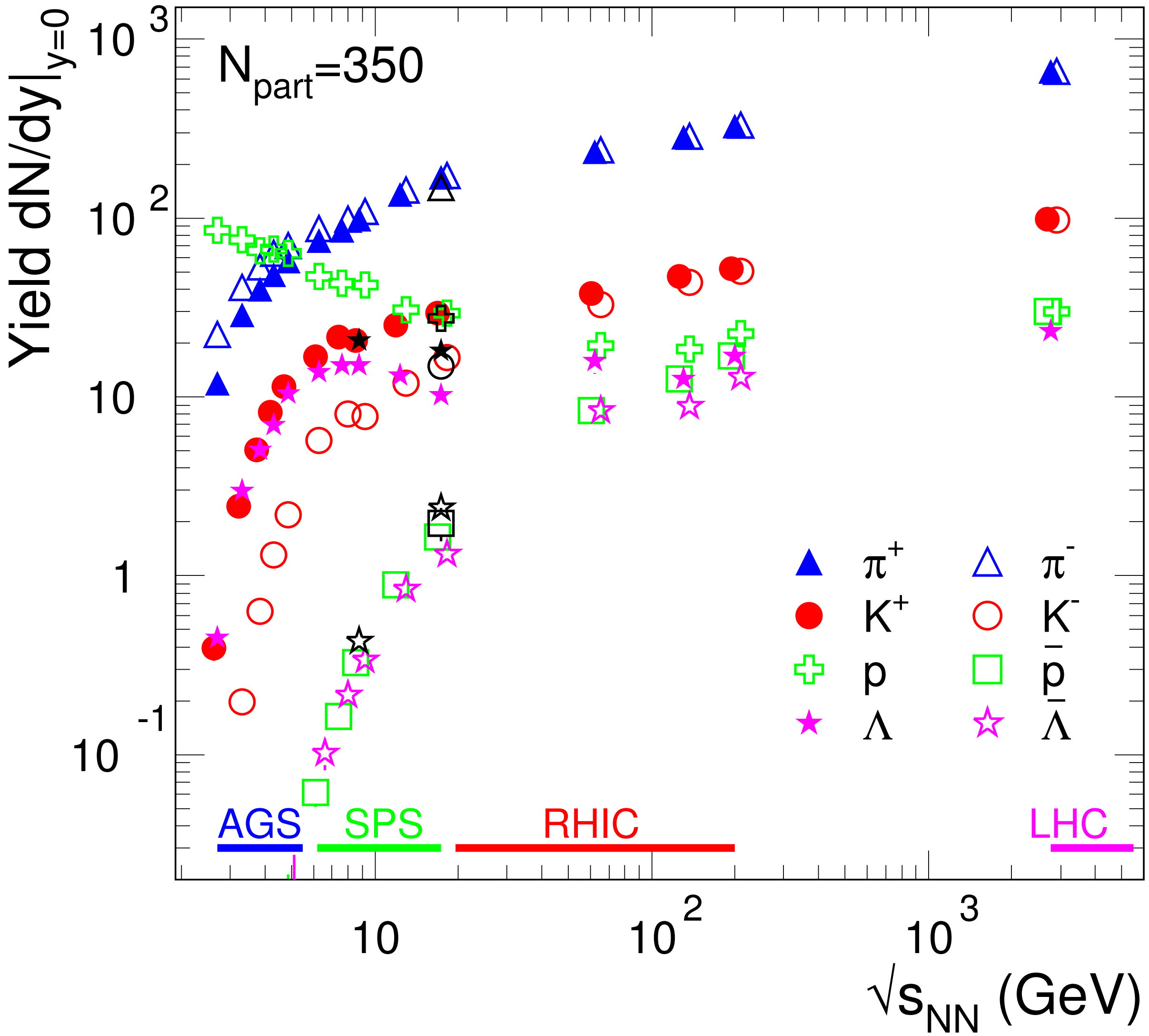
  jet quenching data (for light and heavy-flavor hadrons) described by theoretical models; allows extraction of transport coefficients (in range $T = (1-3)T_c$)

More in talks by Ivan Vorobyev (Wed) and Jeremy Wilkinson (Fri)

Additional slides

A.Andronic

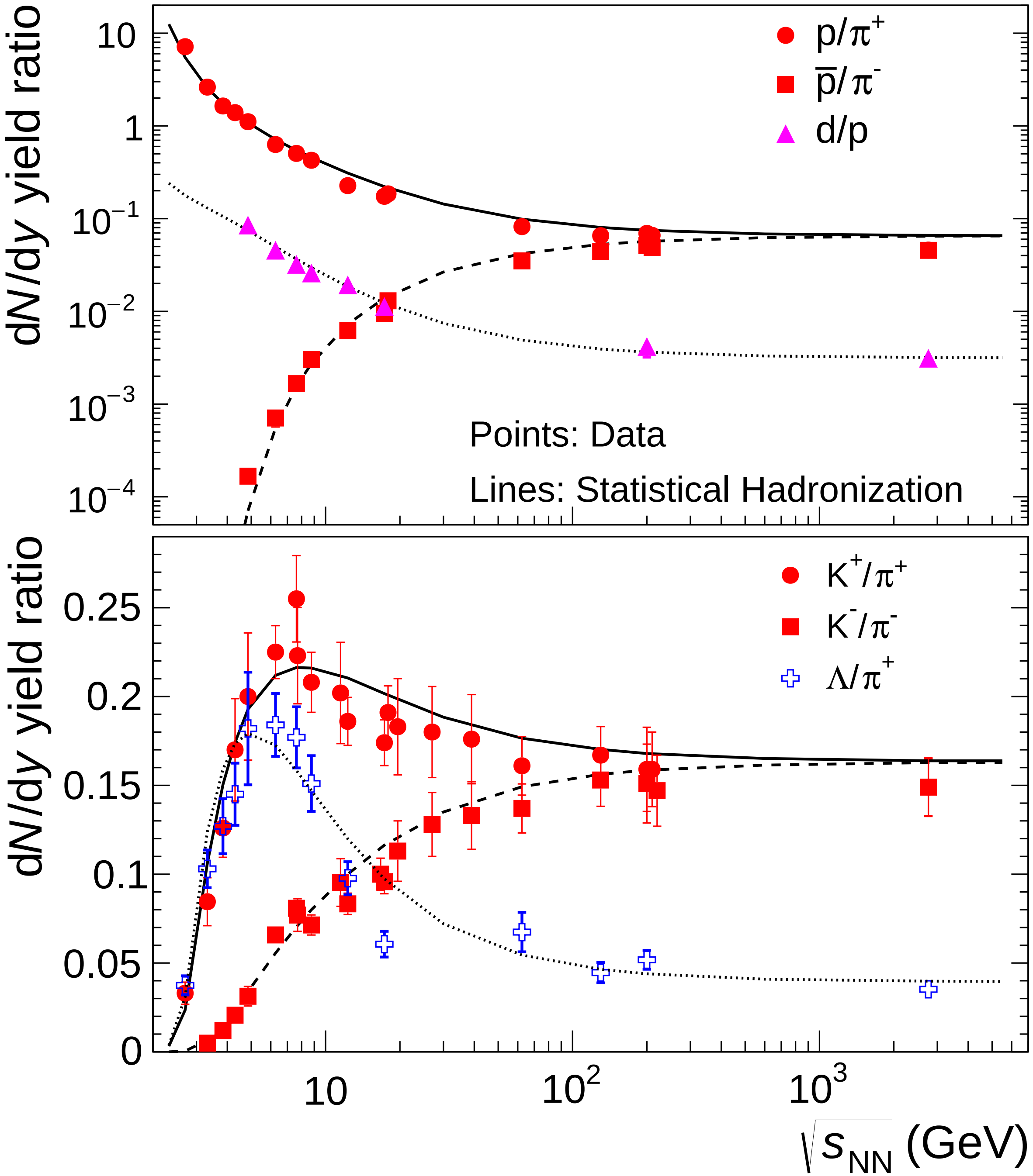
Overview of hadron production



- lots of particles, mostly newly created ($m = E/c^2$)
- a great variety of species:

  $\pi^{\pm}$ $(u\bar{d},\ d\bar{u})$, m=140 MeV
  $K^{\pm}$ $(u\bar{s},\ \bar{u}s)$, m=494 MeV
  p (uud), m=938 MeV
  Λ (uds), m=1116 MeV
  also: $\Xi(dss)$, $\Omega(sss)$...

- mass hierarchy in production (u, d quarks: remnants from the incoming nuclei)

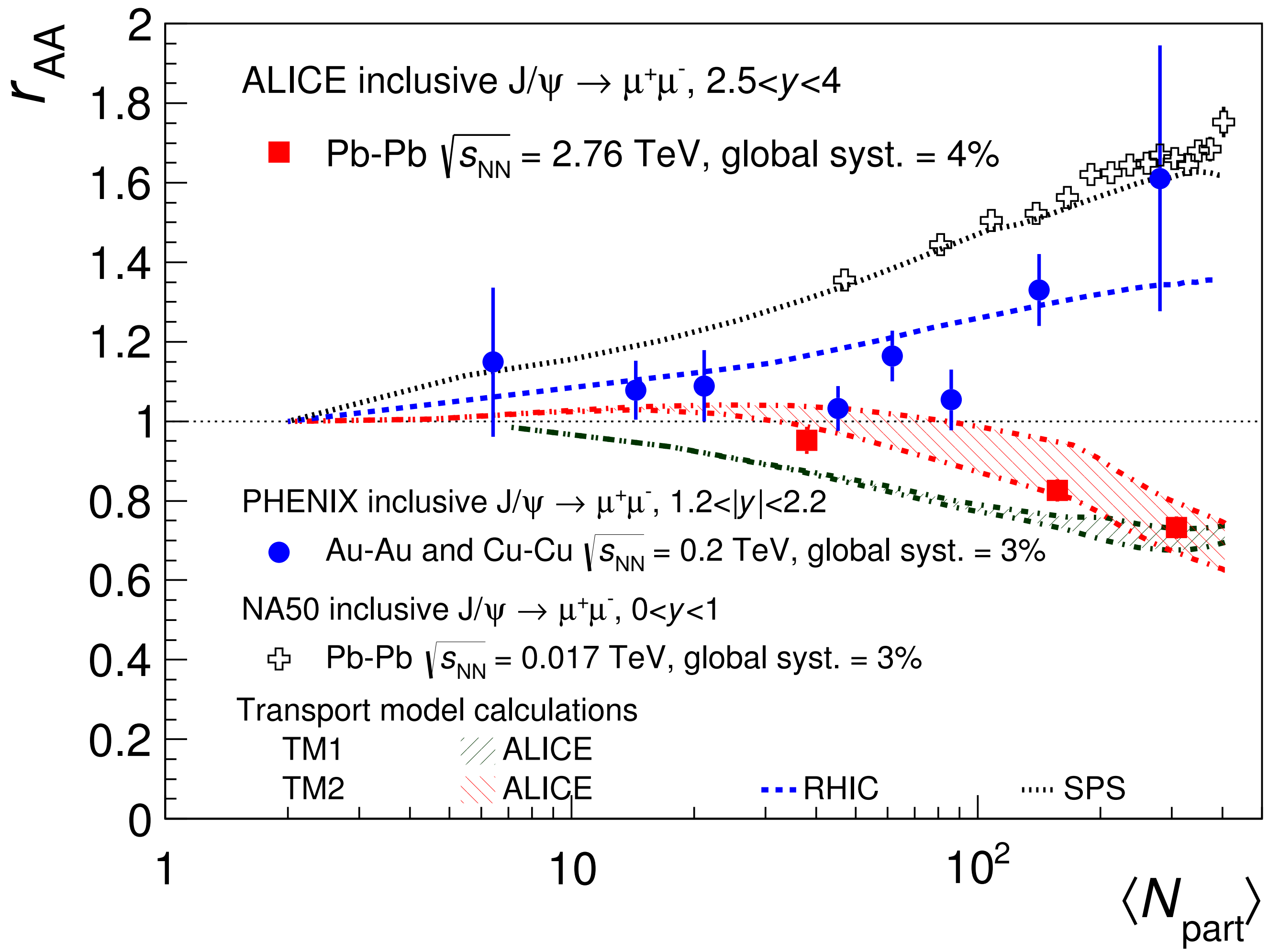


Data:
AGS: E895, E864, E866,
E917, E877
SPS: NA49, NA44
RHIC: STAR, BRAHMS
LHC: ALICE

NB: no contribution from weak decays

data consistent with smooth behaviour vs. energy

Mean transverse momentum of J/ψ mesons



$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

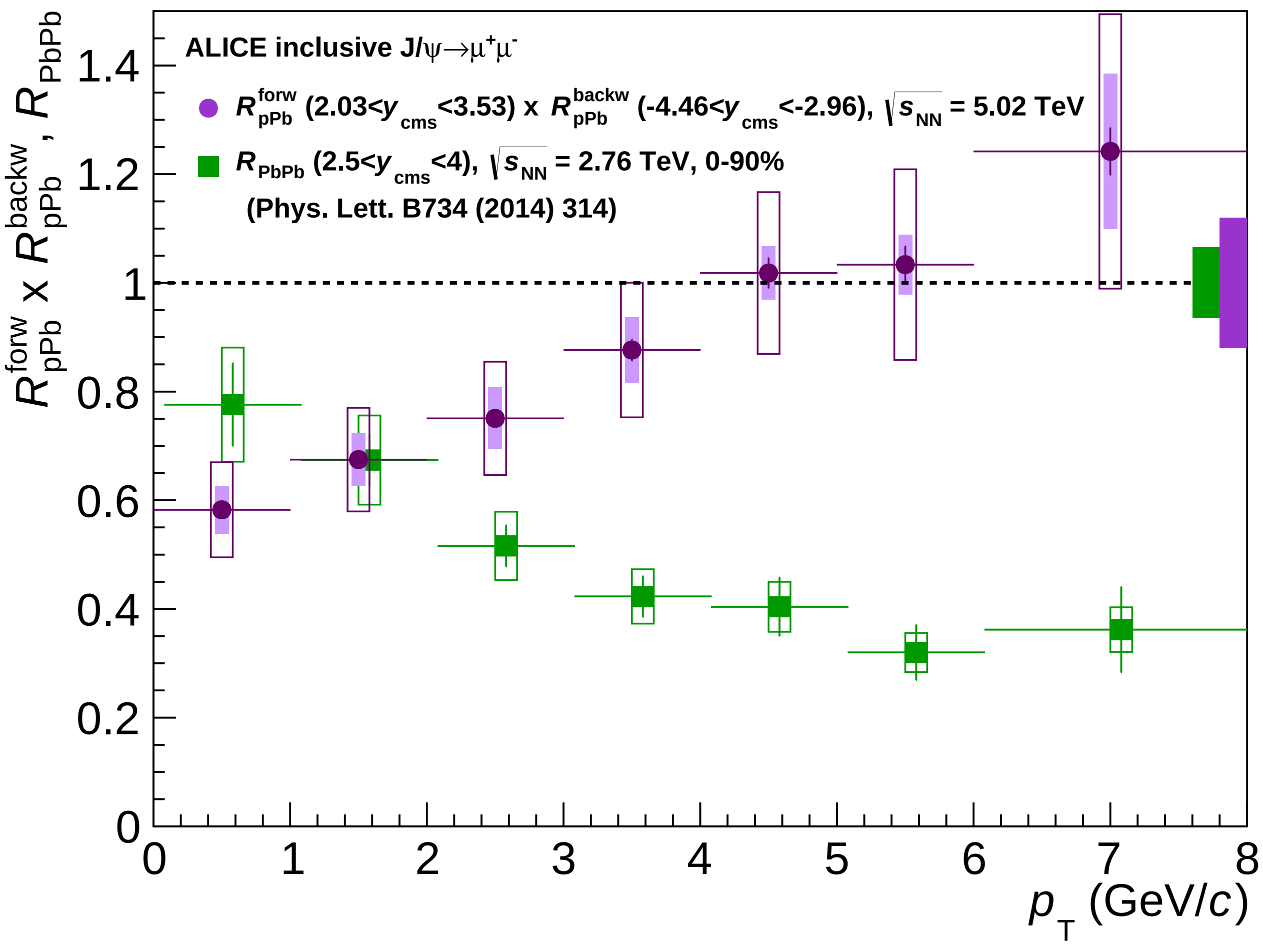
ALICE, JHEP 05 (2016) 179

softening of p_T is significant at the LHC, clear indication of (re)generation

thermalization of charm quarks demonstrated by collective flow of D and J/ψ

J/ψ production vs. p_T

A. Andronic - ALICE

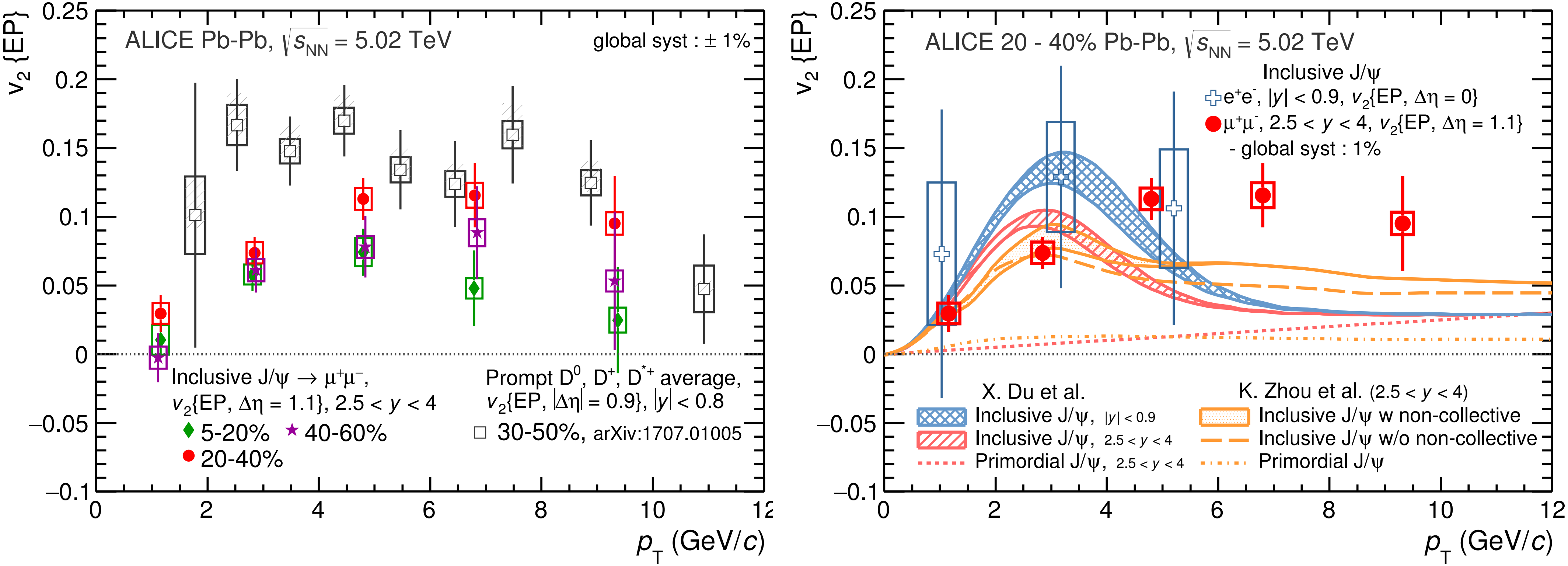


ALICE, JHEP 06 (2015) 055

Distinct differences between Pb–Pb and p–Pb; crucial support that low-p_T J/ψ are from (re)generation (while at high-p_T outcome of charm energy loss in QGP)

for mid-rapidity: Run 1 data stat.-limited; Run 2 data will bring significance

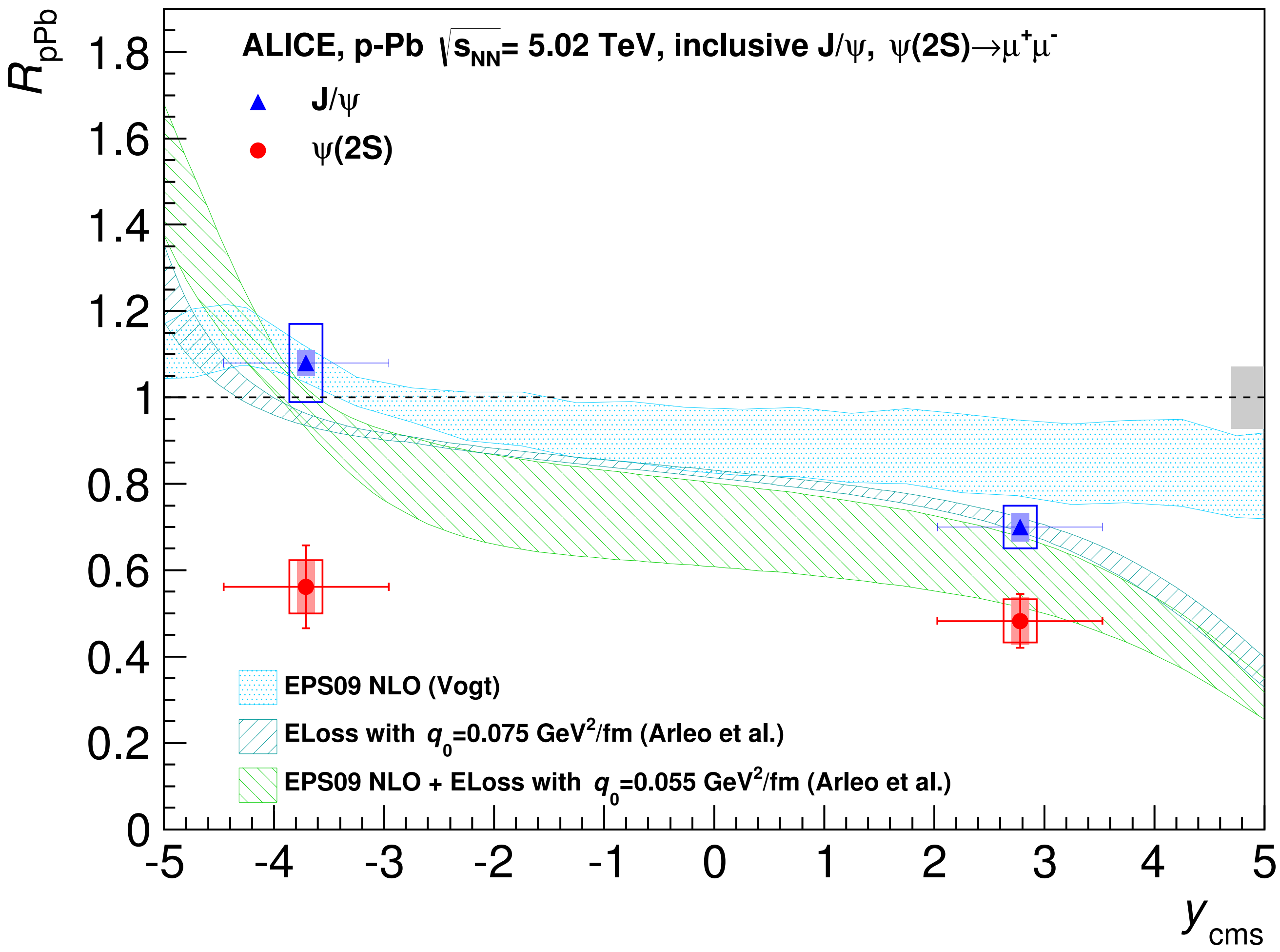
J/ψ and D mesons exhibit collective flow



ALICE, PRL 119 (2017) 242301

Implies thermalization of charm quarks ...full thermalization? (high-p_T?)

...and how to make distinction between statistical and dynamical production?



ALICE, JHEP 12 (2014) 073

(at least in first order) models give same result for $\psi(2S)$ as for J$/\psi$ in data, difference predominantly at low p_T

...with "hard probes" ($m \gg T$): jets or high-p_{T} hadrons (or heavy quarks)

produced very early in the collision, $t \simeq 1/m$

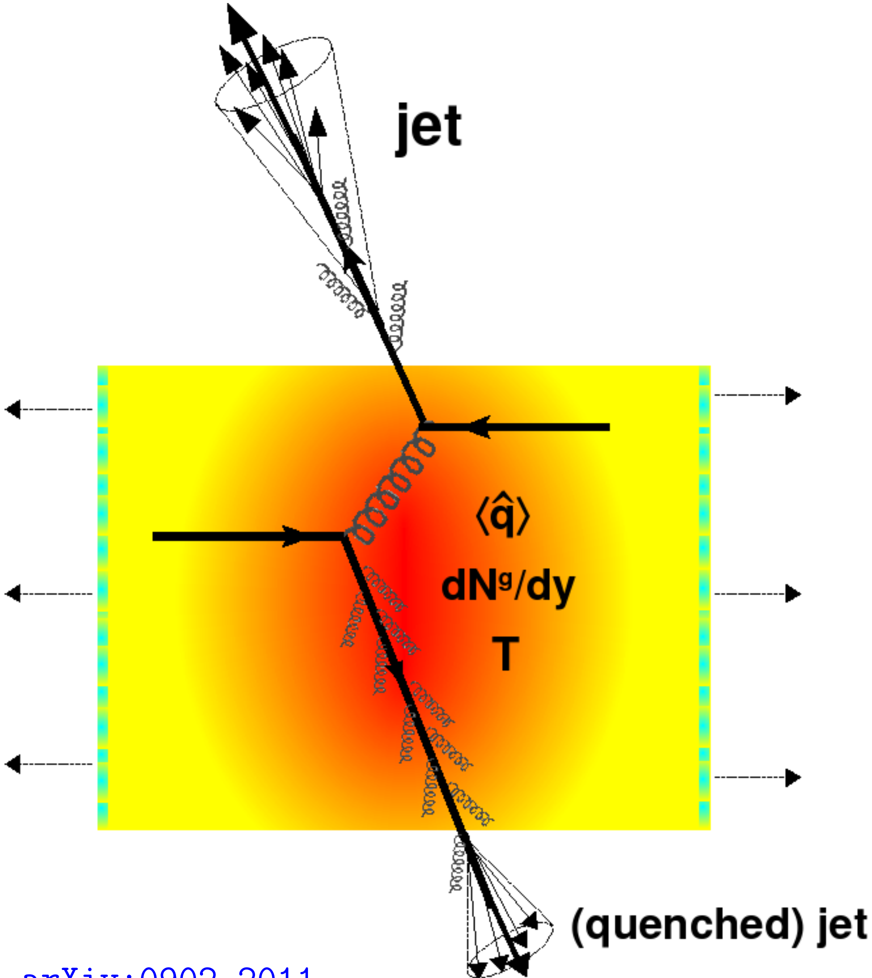
(jets - sprays of hadrons from high-speed quarks)

- $q, \bar{q}, g$ travel through QGP, lose energy
- hadronize (neutralize color picking up partners from the vacuum)
- hadrons fly towards detectors

...where we observe a deficit at high momenta (p_{T}): "jet quenching"
(Bjorken, FERMILAB-PUB-82-059-T)

quantified by the nuclear modification factor:

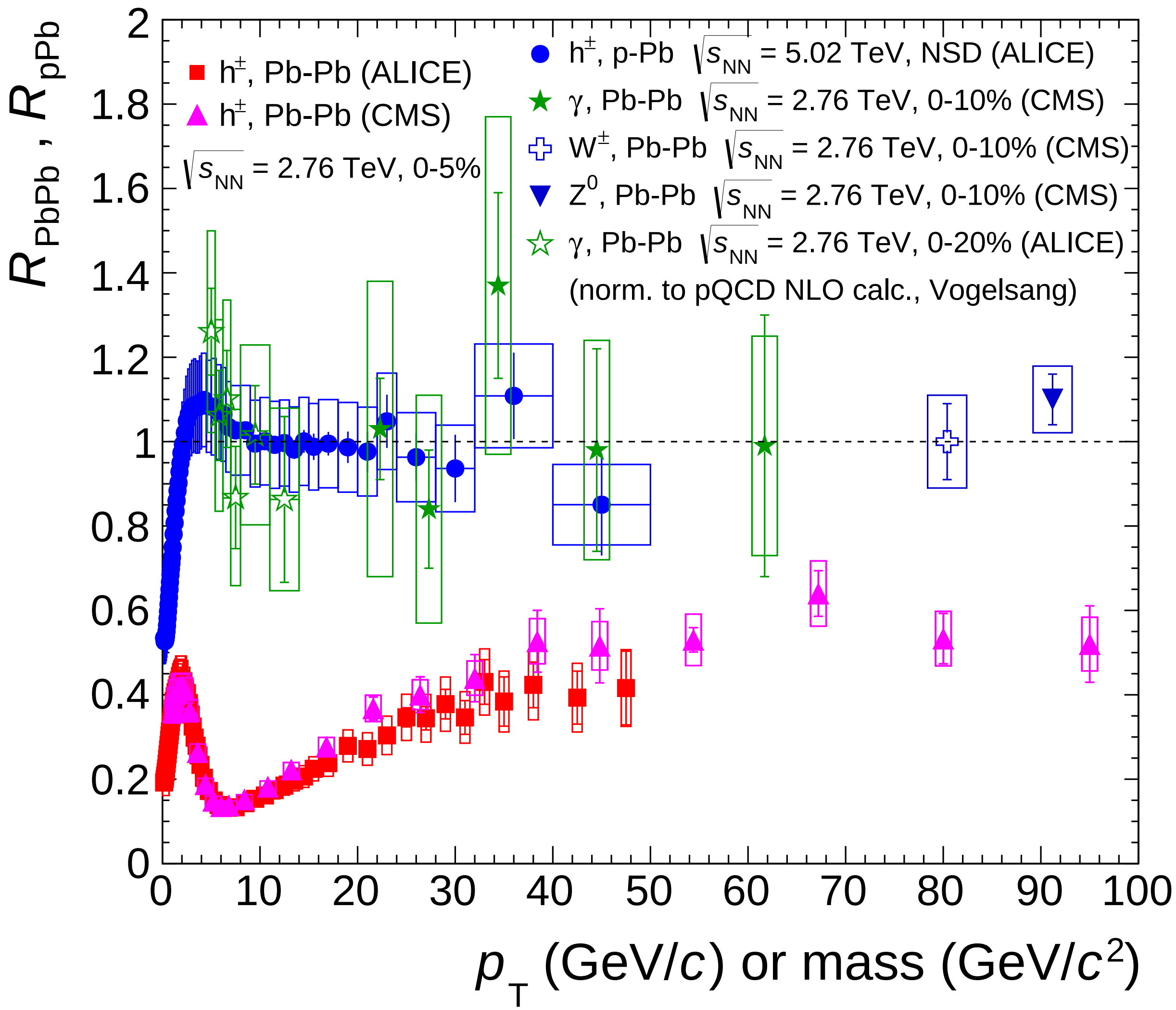
$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{N_{coll}\cdot\mathrm{d}N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$



D. d'Enterria, arXiv:0902.2011

Jet quenching at the LHC

...measured with "leading hadrons" ($h^{\pm}$)
(carry largest fraction of parton p_T)



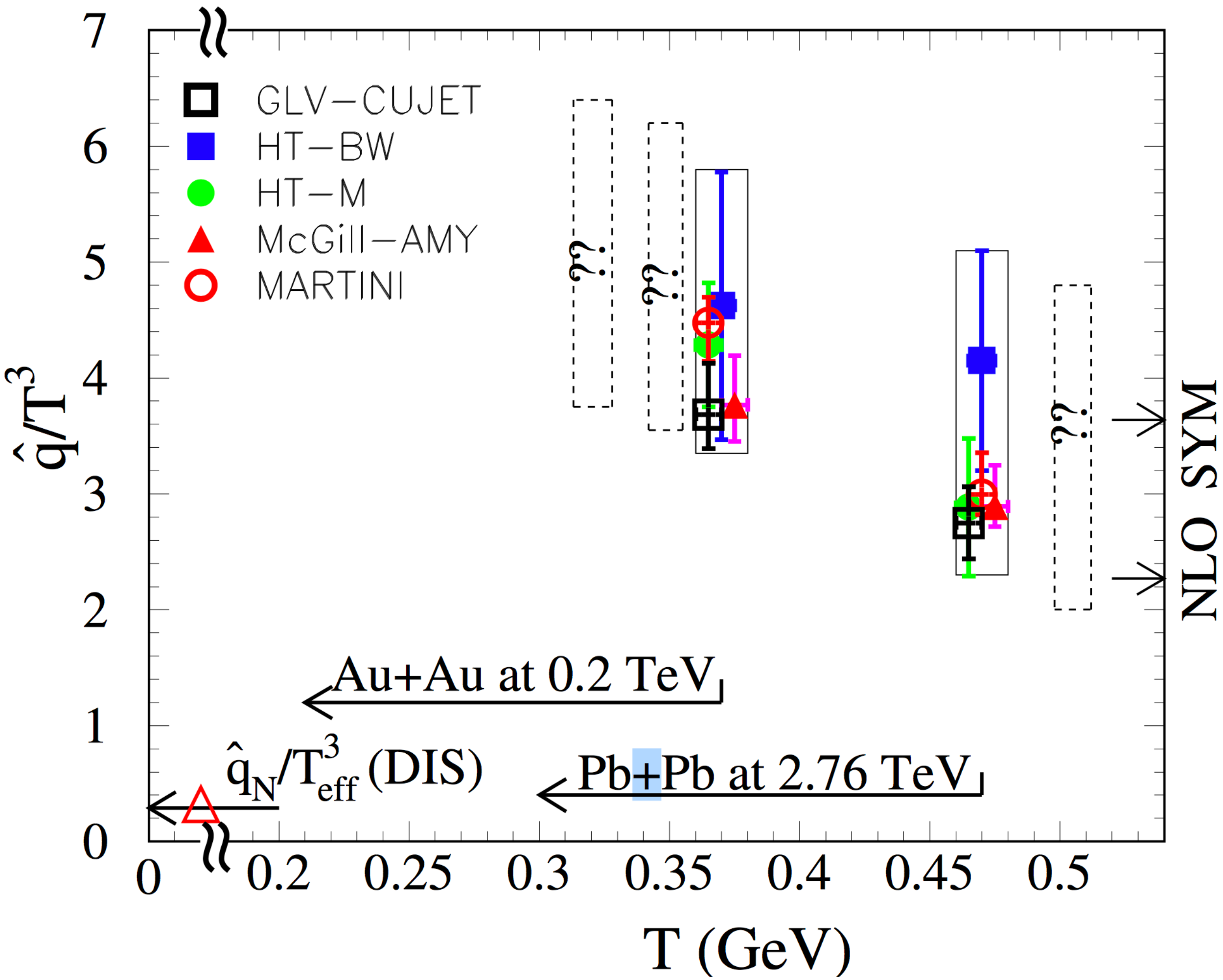
a thermal component, $p_{\mathrm{T}} \lesssim 6$ GeV/c (scaling with N_{part}) determined by gluon saturation and collective flow

strong suppression, reaching a factor of ∼7, $p_{\mathrm{T}} \simeq 7$ GeV/c

...not seen with EW observables (γ, $W^{\pm}$, Z^0) *...ALICE γ / pQCD NLO calc.*

not seen in p-Pb collisions ($p_{\mathrm{T}} \lesssim 3$ GeV/c, gluon saturation)

ALICE, EPJ C 74 (2014) 3054 and refs. therein



An initial quark with energy of 10 GeV at the center of a most-central A–A collision

JET Collab., PRC 90 (2014) 014909

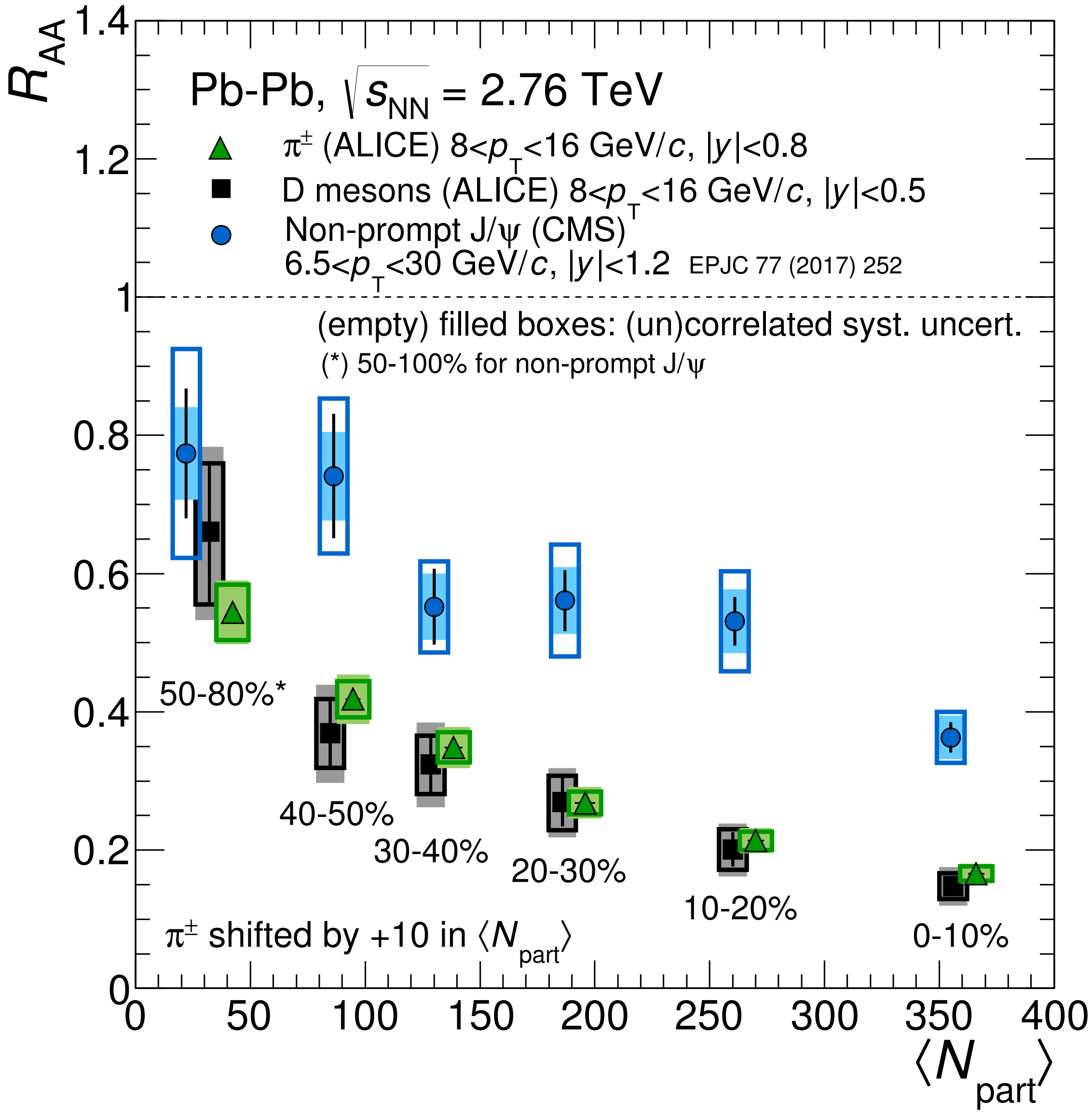
transport coefficient:

$\hat{q} = \mathrm{d}\langle p_T^2 \rangle / \mathrm{d}x$

(proportional to gluon density)

The data of Run 2 (about to be published) are significantly more precise

In-medium energy loss as a function of quark mass



D mesons are as much suppressed as pions at high p_T

...is expected ordering vs. quark mass

$\Delta E_b < \Delta E_c < \Delta E_{u,d,s} < \Delta E_g$

established in data?

(naively: $\Delta E \sim 1 - R_{AA}$)

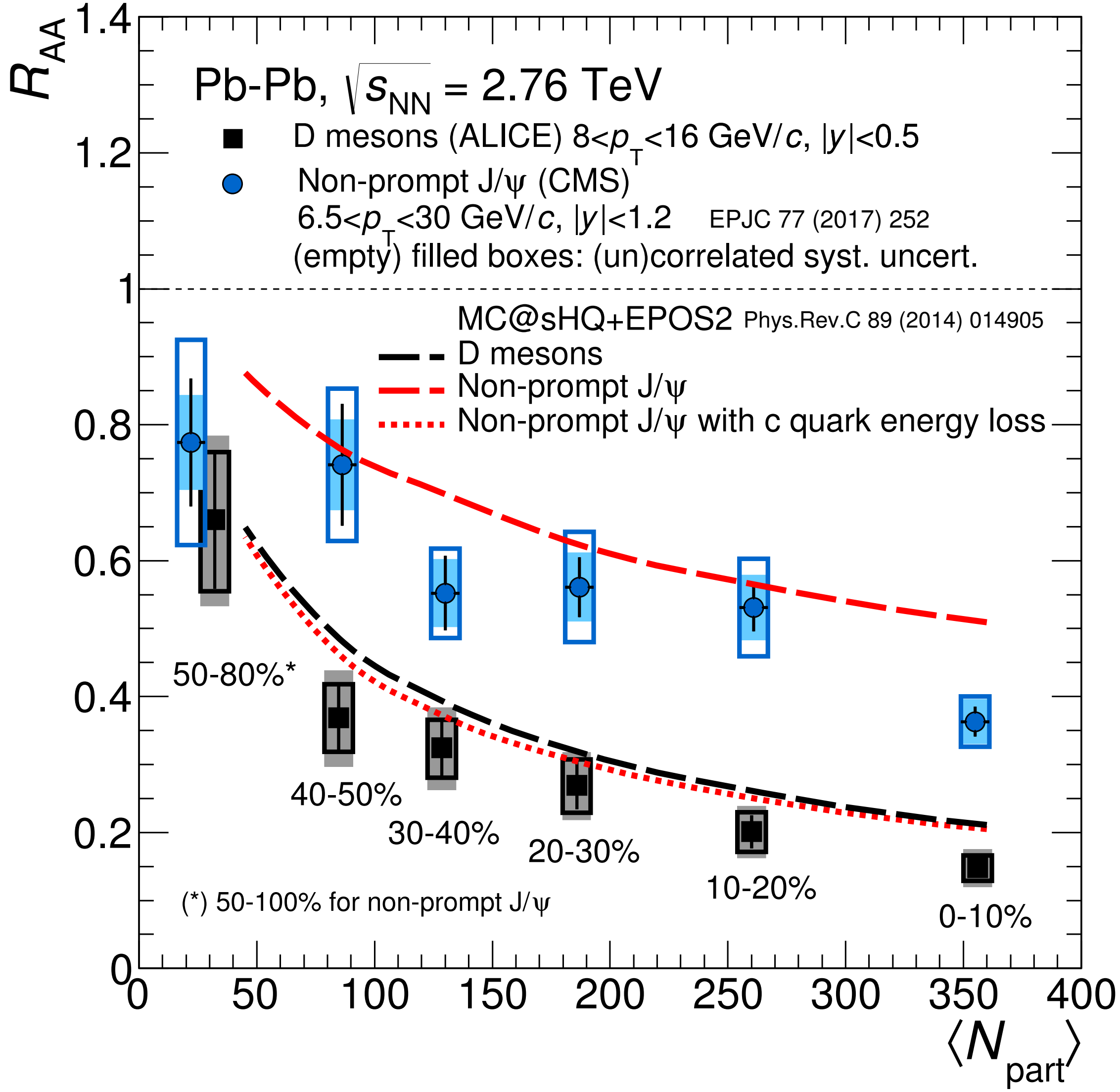
to some extent, yes

JHEP 11 (2015) 205

ALICE-PUBLIC-2017-004

on-going effort: determine heavy quark (momentum) diffusion coefficient

...calculable in lattice QCD Banerjee et al., Phys. Rev. D 85 (2012) 014510



Theoretical model(s) reproduce the data (reasonably) well

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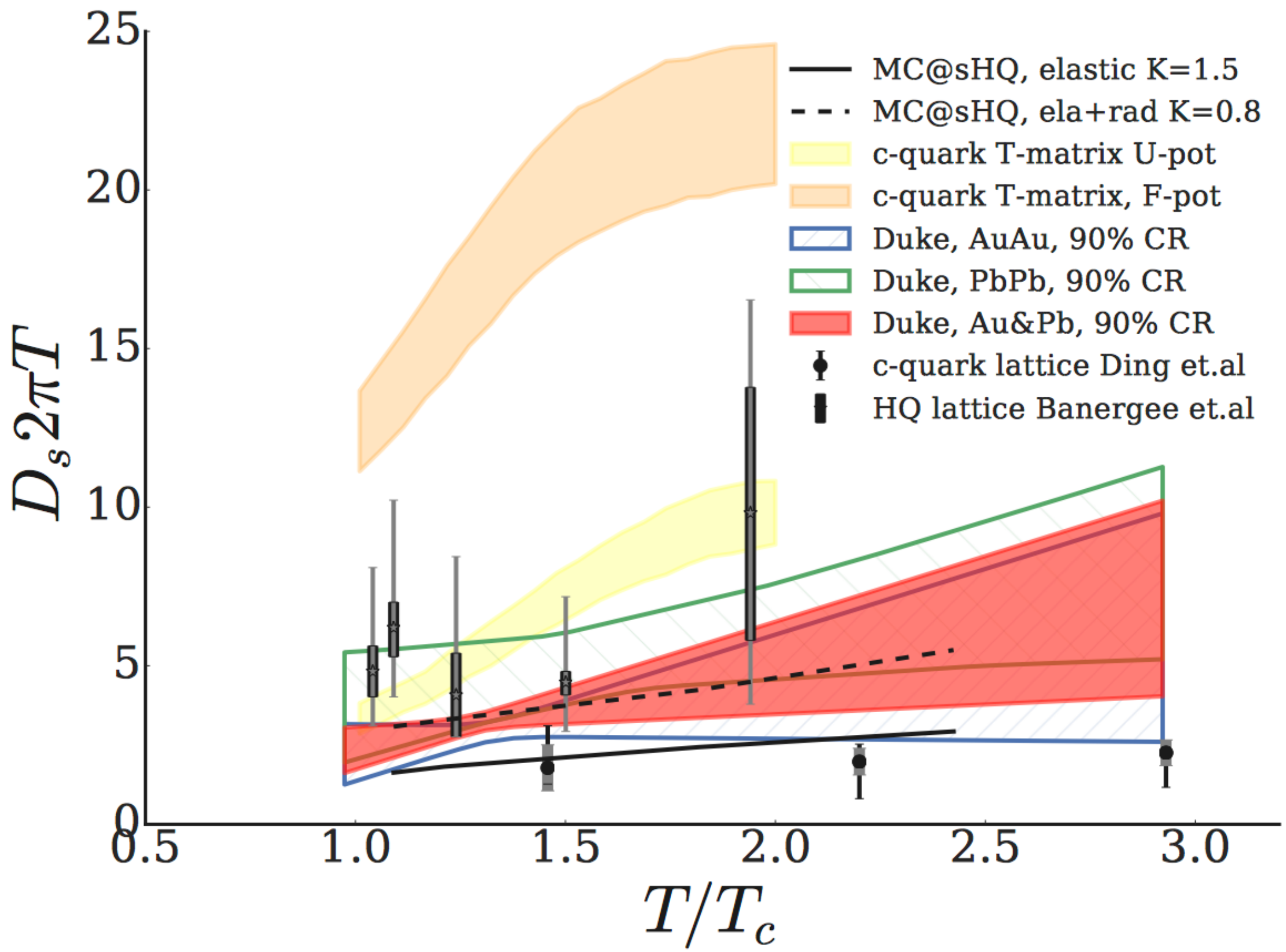
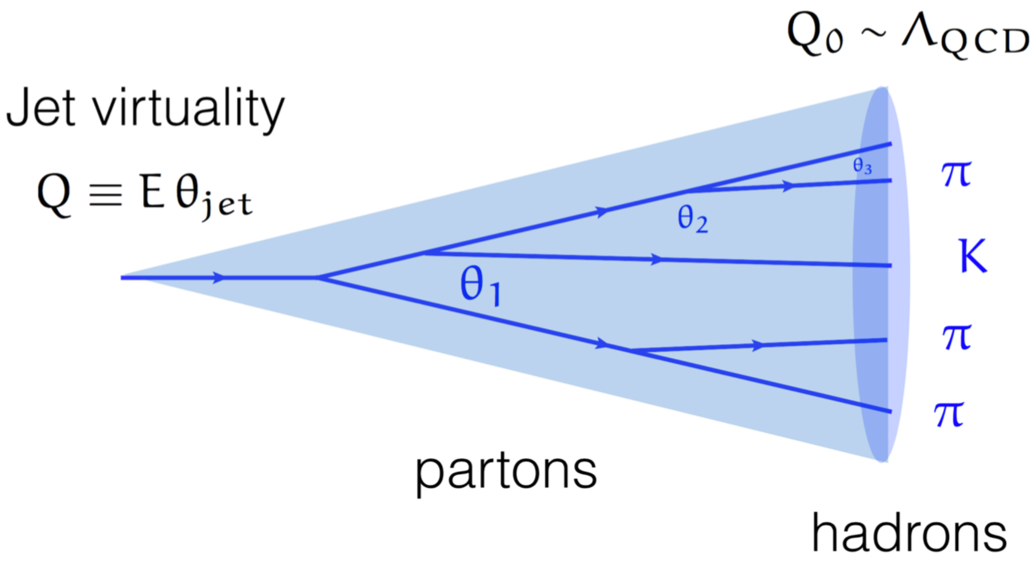
Charm diffusion coefficient

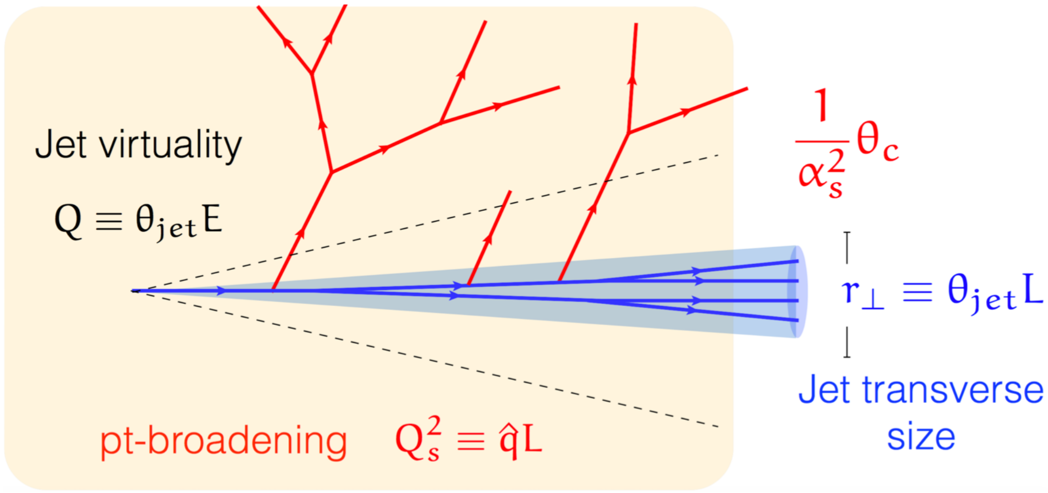


heavy quark spatial diffusion coefficient $D_s = 4T^2/\hat{q}$

arXiv:1704.07800

...in vacuum **...in medium**





E: E_T or p_T; θ_{jet}: opening angle (R or ΔR)

Y. Mehtar-Tani, arXiv:1602.01047

Advantage of heavy quarks

Their mass, $m_c \simeq$1.2 GeV, $m_b \simeq$4.6 GeV, is much larger than T
(so we are sure they do not originate in thermal processes ...but pQCD processes)

Are produced in pairs ($c\bar{c}$) in initial hard collisions ($t \sim 1/(2m_c) \leq 0.1$ fm/c)

Their identity (flavor) is assured to be preserved from early times of production throughout the QGP phase (until hadronization: $c \to D$; $b \to B$)

Expectation:
Due to high mass the gluon radiation by HQ is suppressed at small angles
this is called "the dead-cone effect"

Consequence: hierarchy in energy loss:

$\Delta E_b < \Delta E_c < \Delta E_{u,d,s} < \Delta E_g$

At the LHC, there are about 100 $c\bar{c}$ pairs produced in a central Pb–Pb collisions (not all are measurable, though)