Studying Big Bang matter created in experiments at the LHC

Anton Andronic – GSI Darmstadt

- Brief reminder about the quarks and gluons
- Methods of producing hot QCD (quark-gluon) matter
- The LHC and the ALICE experiment
- Hadrons with light-flavor (u,d,s) and the QCD phase diagram
- Quarkonium and deconfined matter
- Summary and outlook

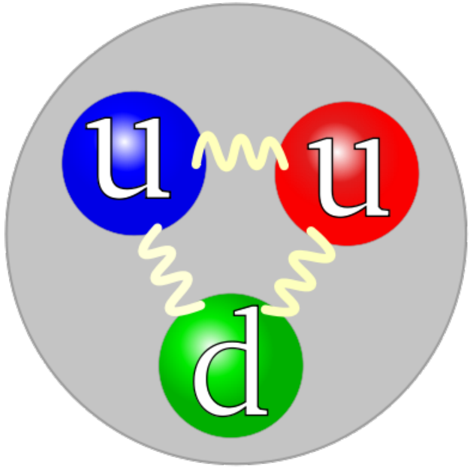
Kolloquium, University of Heidelberg - 17 Nov. 2017

in honor of Prof. Hüfner, on his 80th birthday

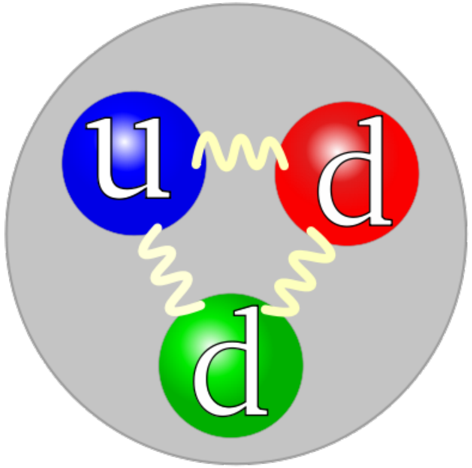
Structure of matter at smallest scales: a sketchy view

A. Andronic

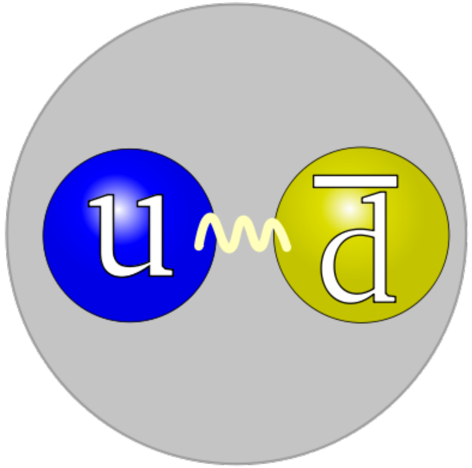
Proton



Neutron



Pion (mc^2=139.6 MeV)



Baryons (p, n, Λ) made of 3 quarks (antibaryons: 3 antiquarks; $\bar{\mathrm{p}}$: $\bar{\mathrm{u}}\bar{\mathrm{u}}\bar{\mathrm{d}}$)
Mesons (π, K, J/ψ) made of quark-antiquark; all bound by gluons (strong force)

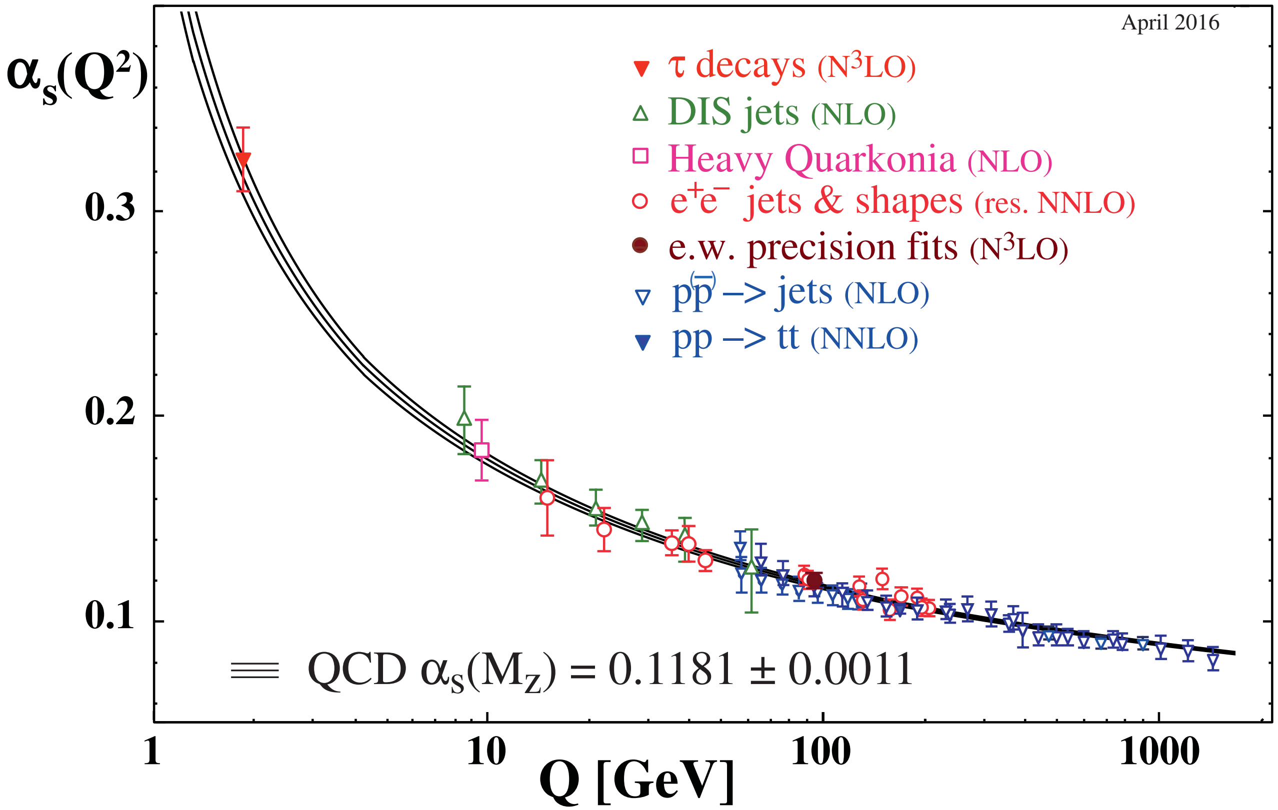
Quarks and gluons (partons) have a special quantum number called "color"
(comes in 3 values, RGB; sum is white = proton has no color)

Quarks: up, down, strange, charm, bottom, top

Quantum ChromoDynamics (QCD)

the quantum field theory of colored quarks and gluons (no analytical solutions, except 1+1)

▷ *strong force*, running coupling (compare to QED: $\alpha \simeq 1/137$)



PDG.lbl.gov

Low Q: confinement; α_s diverges at Λ_{QCD} ≃200 MeV

High Q: asymptotic freedom (perturbative QCD reigns)

...has led to the proposal of the Quark-Gluon Plasma

Collins & Perry, Cabibbo & Parisi, 1975 (Itoh, 1970; Carruthers, 1973; Shuryak)

Setting the units straight

Natural units: $\hbar = c = 1$; k_B=1

In this system: [m]=[E]=[p]=[T]=[L]$^{-1}$=[t]$^{-1}$

For instance, energy density $\varepsilon = E/V$ has units of T^4

$$1\,\mathrm{fm} = \frac{1}{197.3\,\mathrm{MeV}};\ 1\,\mathrm{MeV}^{-1} = 197.3\,\mathrm{fm}$$

$$1\,\mathrm{s} = 3\times10^{23}\,\mathrm{fm};\ 1\,\mathrm{m} = 5.07\times10^{6}\,\mathrm{eV}^{-1}$$

$$300\,\mathrm{K} = 26\,\mathrm{meV};\ 100\,\mathrm{MeV} = 1.16\times10^{12}\,\mathrm{K}$$

$\hbar = h/2\pi$=6.582$\times$10^{-22} MeV·s; $\hbar c = 6.582\times10^{-22}\times3\times10^{23} = 197.3$ MeV·fm (conversion constant)

Compton wavelength of electron:

$$\lambda_C = \frac{\hbar}{m_e c} = \frac{\hbar c}{m_e c^2} = \frac{197.3}{0.511} \simeq 385\,\mathrm{fm}$$

Strength of electromagnetism: $\frac{e^2}{4\pi\varepsilon_0}$=1.44 MeV fm / $\hbar c = \frac{1}{137} = \alpha$

Lattice QCD predicts a phase transition

(ideal gas)

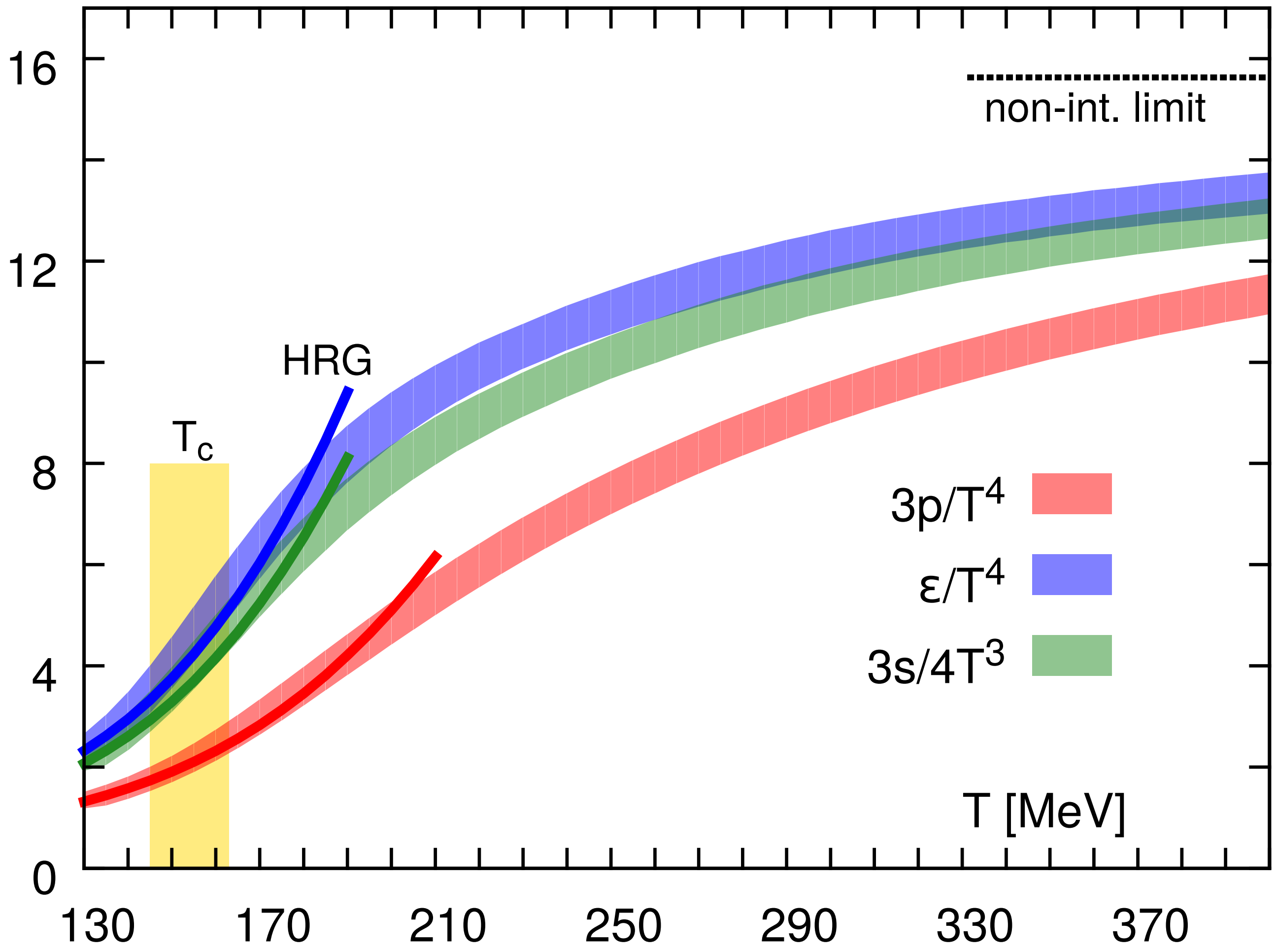
quarks and gluons

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

N_f=3 (u,d,s)

hadrons (pions)

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



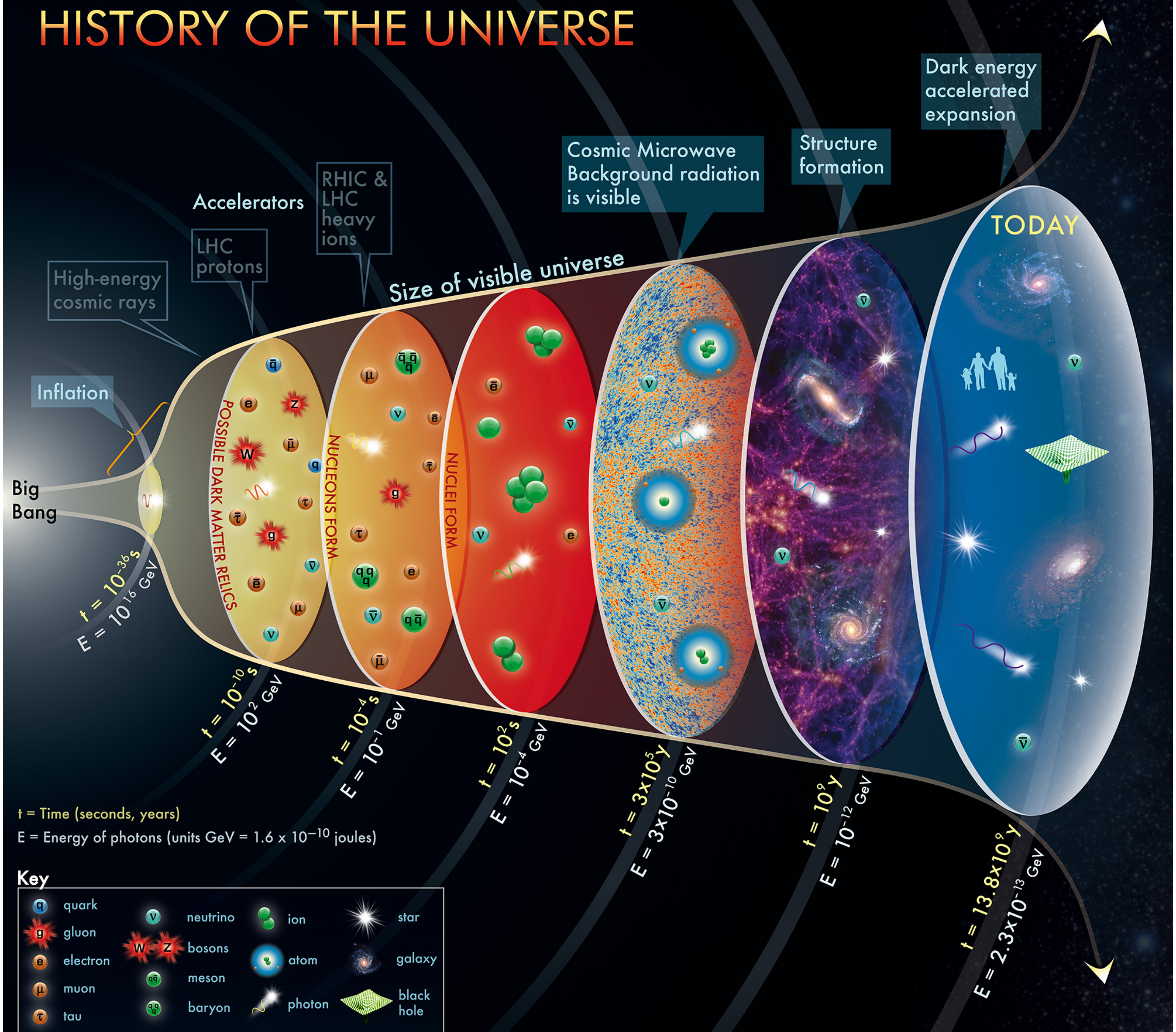
≃1000 billion K

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

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

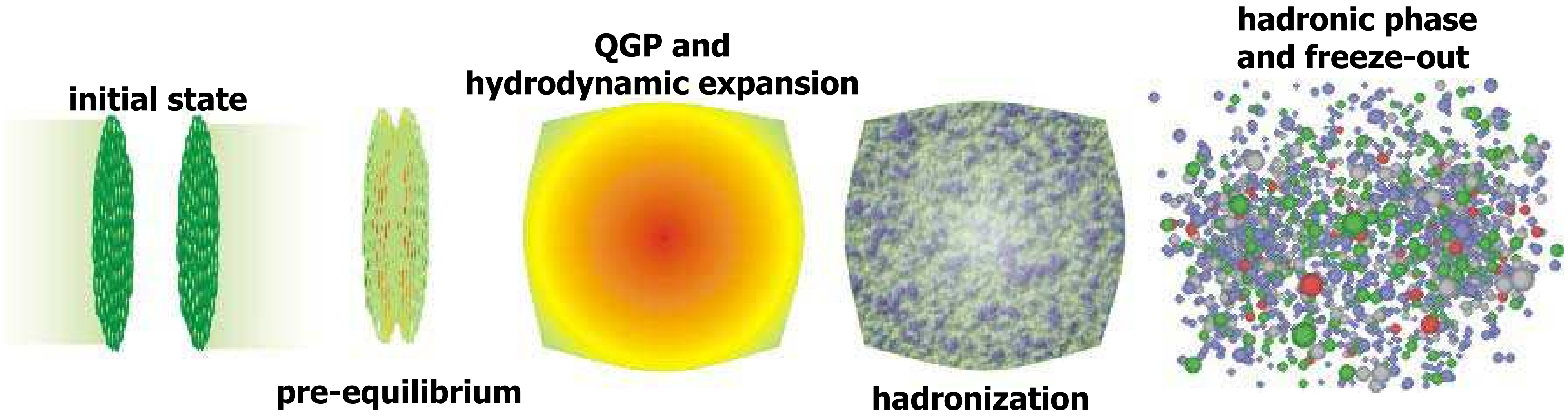
T_c ≃145-164 MeV, $\varepsilon_c \simeq (0.18 - 0.5)$ GeV/fm^3, or (1.2-3.1)$\varepsilon_{nuclear}$

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
Inflation
Size of visible universe
TODAY
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

How to "simulate" in laboratory the early Universe?

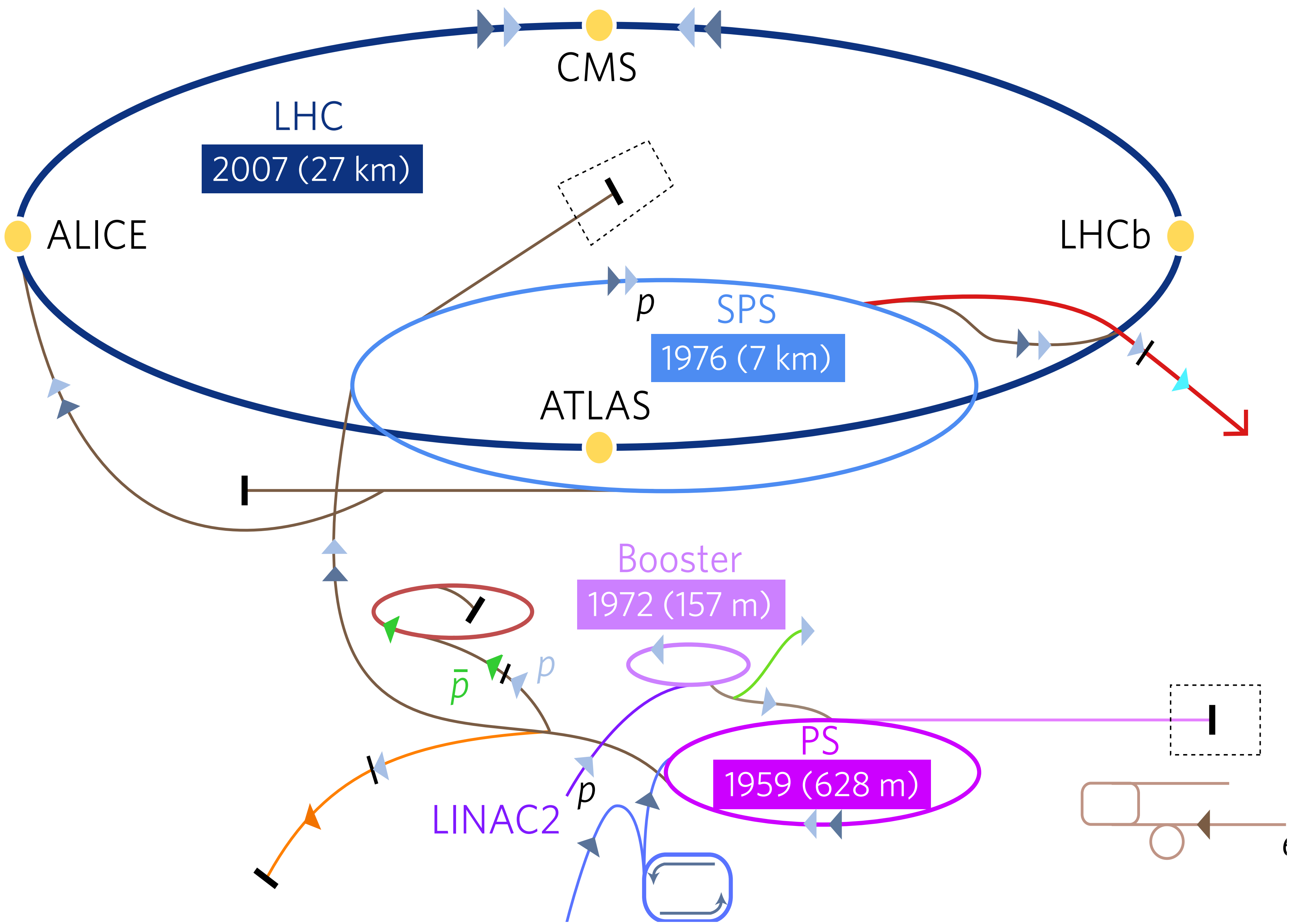
A. Andronic



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

1. initial collisions ($t \leq t_{coll} = 2R/\gamma_{\rm cm}c$; $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)

The accelerator complex at CERN



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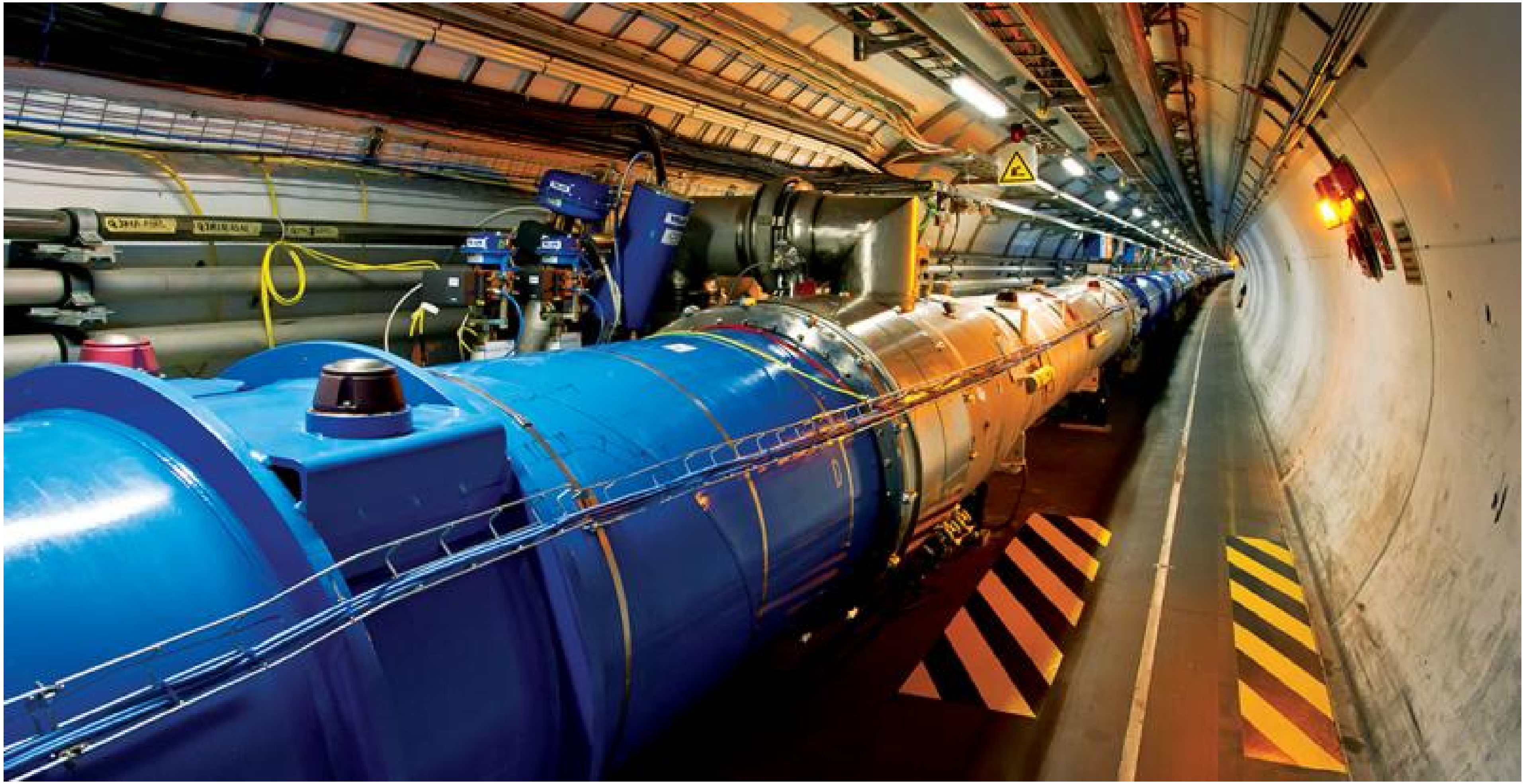
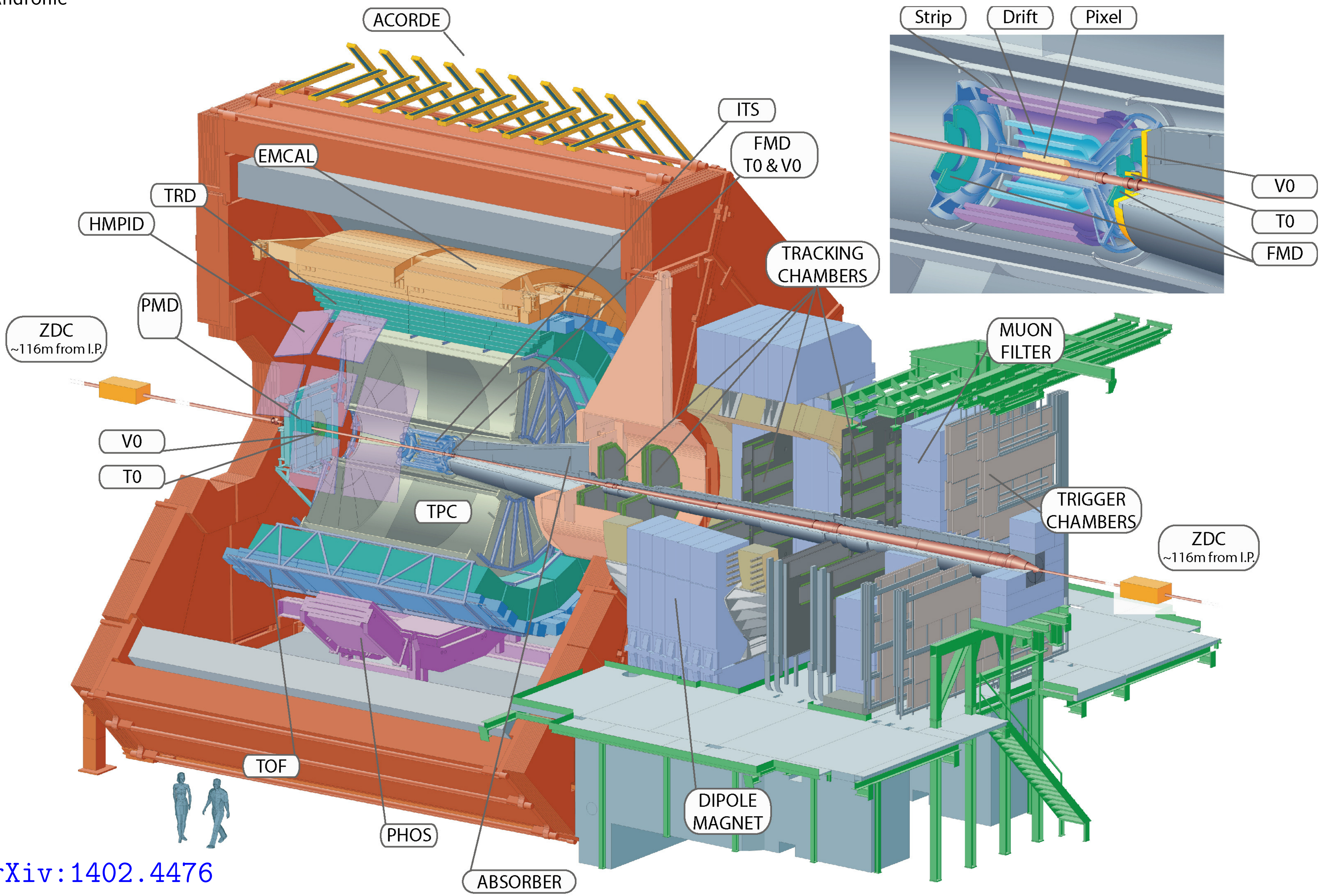


the proton beams circle the 26.6 km ring about 11000 times per second
deflected by superconducting magnets (blue) at T=1.9 K (superfluid He)

produced the Higgs particle ...discovered by ATLAS, CMS collaborations, 2012
Nobel Prize Higgs, Englert, 2013

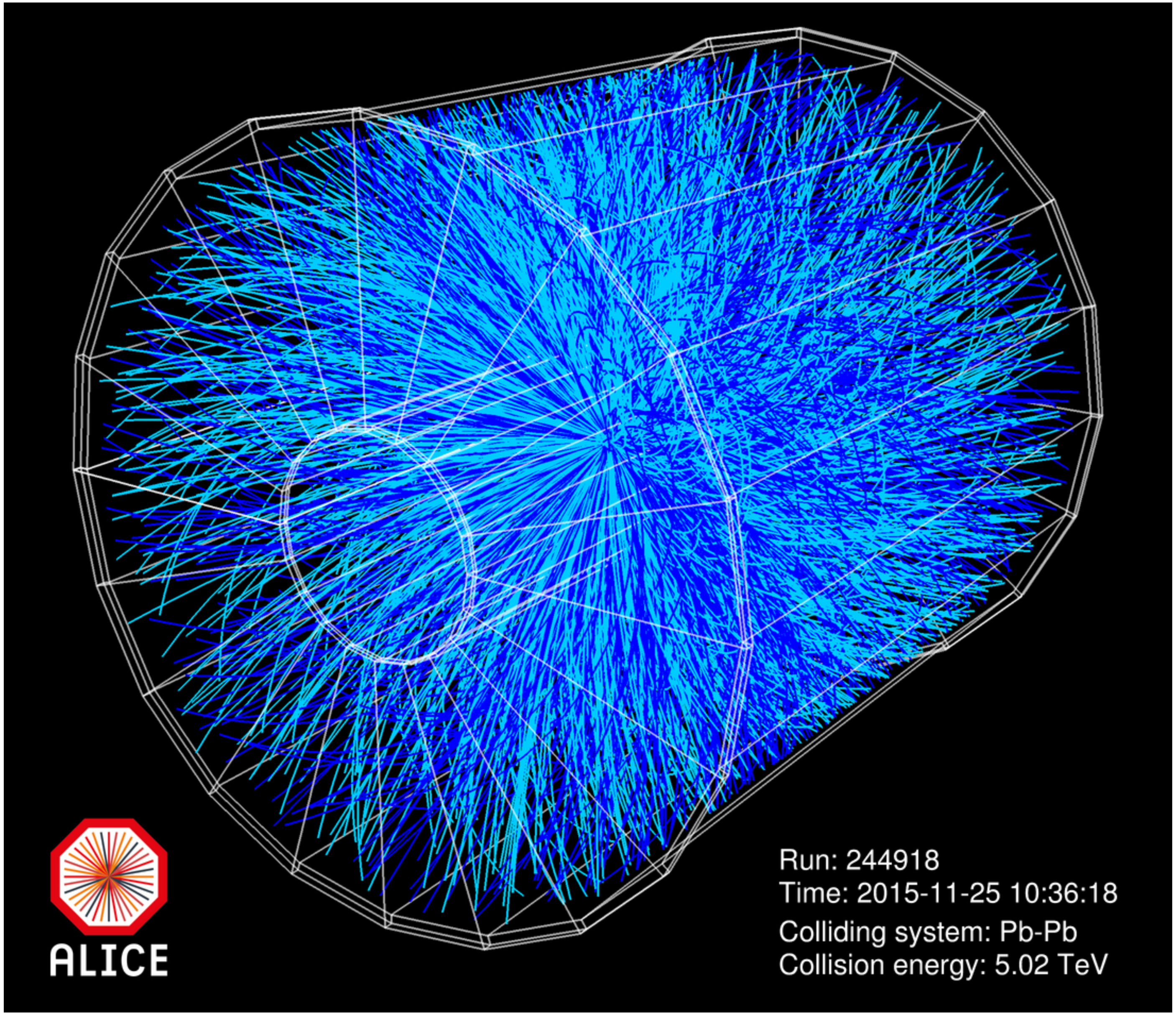
A detector at the LHC - ALICE



arXiv:1402.4476

ALICE Collaboration: 37 countries, 160 institutions, 1600 members

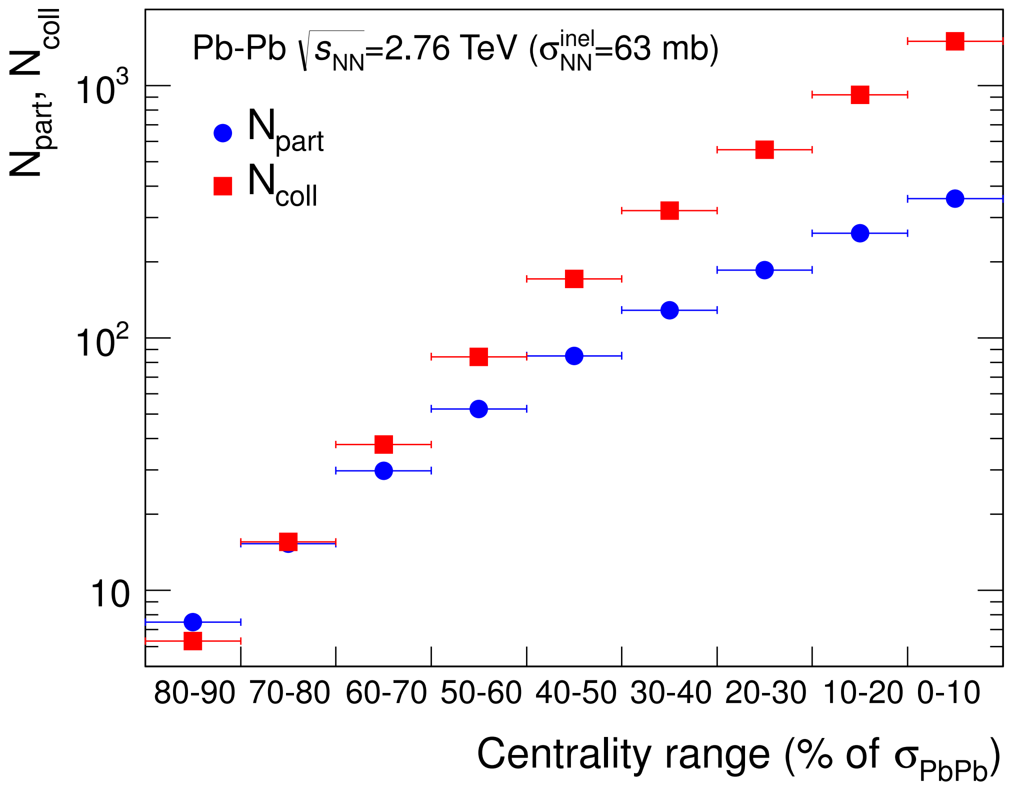
Nucleus-nucleus collisions at the LHC



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)

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

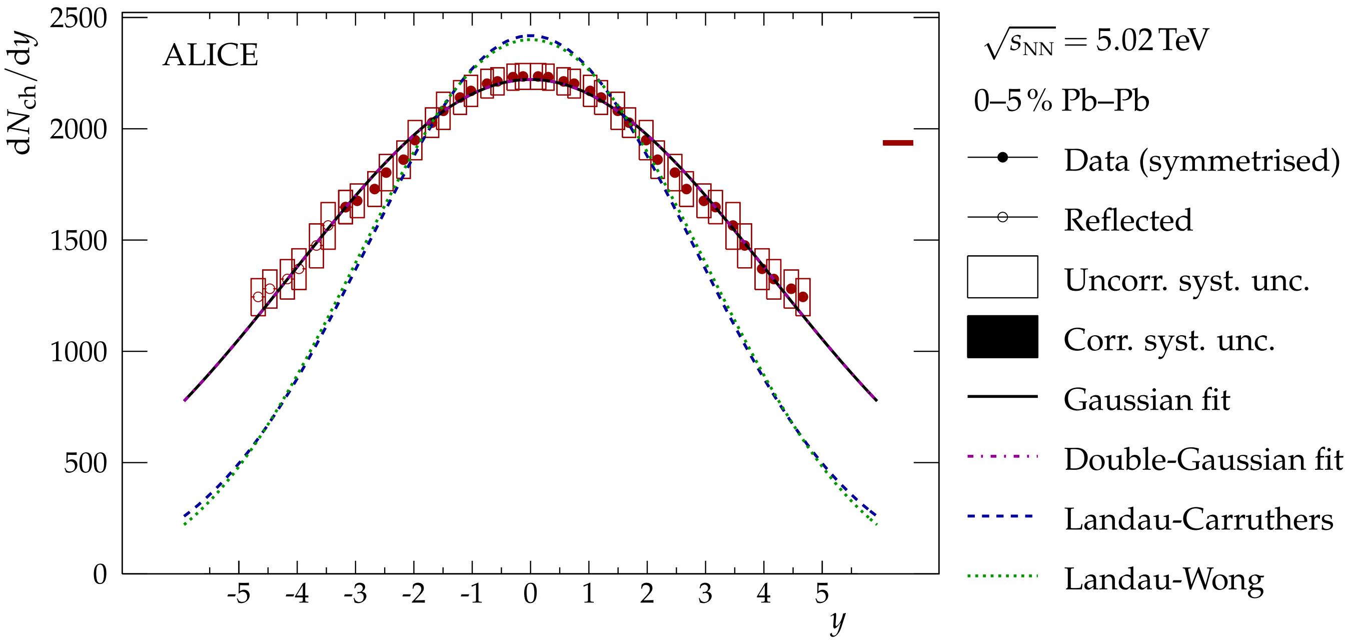


...while often taking as reference the measurement in proton-proton collisions (at the same energy), for "hard probes" (pQCD) scaled by the number of collisions corresponding to the given centrality class

Production yields and correlations as a function of kinematic quantities:

- transverse momentum, $p_{\rm T} = p\sin\theta$ (in GeV/c; recall: $\beta = \frac{v}{c} = \frac{pc}{E}$)
- rapidity, $y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \tanh^{-1}(p_z/E)$; $p_z = p_{\rm L} = p\cos\theta$

  additive for Lorentz transformations (equivalent of velocity for Galilei)



beam rapidity:

$\sqrt{s_{NN}} = 5.02$ TeV:

$y_b = 0.5\ln\frac{2.51+2.5099998}{2.51-2.5099998} = 8.52$

$\sqrt{s_{NN}} = 200$ GeV:

$y_b = 0.5\ln\frac{100.+99.9956}{100.-99.9956} = 5.36$

ALICE, arXiv:1612.08966

...poor (wo)man's y: "pseudorapidity", $\eta = \tanh^{-1}(p_z/p) = \tanh^{-1}(\cos\theta)$

(without particle identification) ... $\eta = y$ for $m = 0$, $\eta \simeq y$ for $p \gg m$

What we measure

we usually measure symmetric collisions of heavy nuclei (Au–Au, Pb–Pb)

we need many collisions (millions), to sample properly the distributions

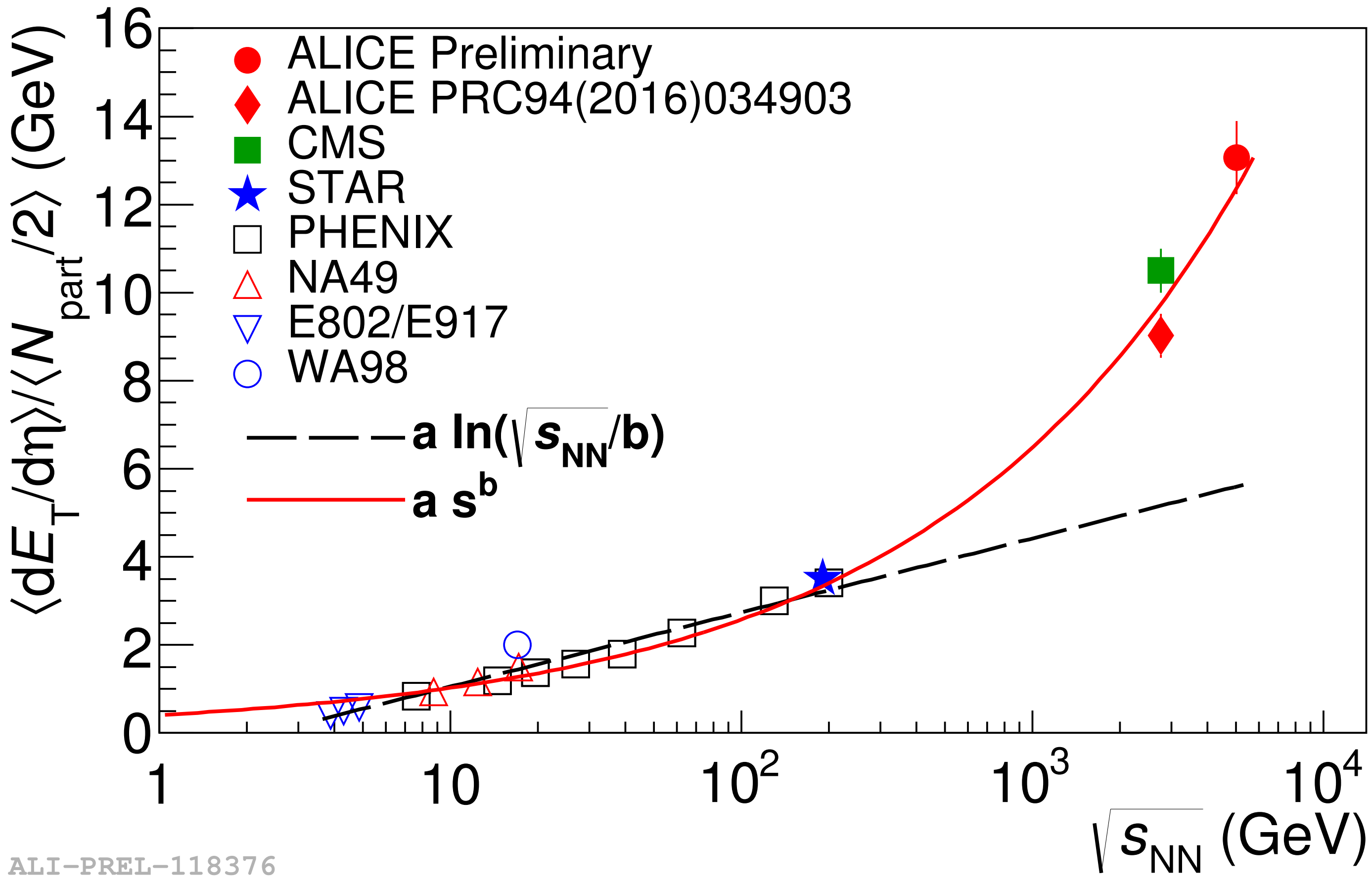
- commonly charged particles, but neutral ones too (via their decays); γ
- the amount of particles (count tracks, assembled from detector points)
- momentum (via curvature in magnetic field) or energy (in a calorimeter)

  ...or velocity (via a time-of-flight measurement, resolution 70 ps)
- identify particles (via energy deposit in detector; ToF; invariant mass)
- correlations between particles (in each event/collision)

we focus on measurements in the transverse direction to separate from the beam movement

single-particle detection efficiency: about 70-80%

Nucleus-nucleus collisions: energy density



E_T: transverse energy (energy built from p_T)

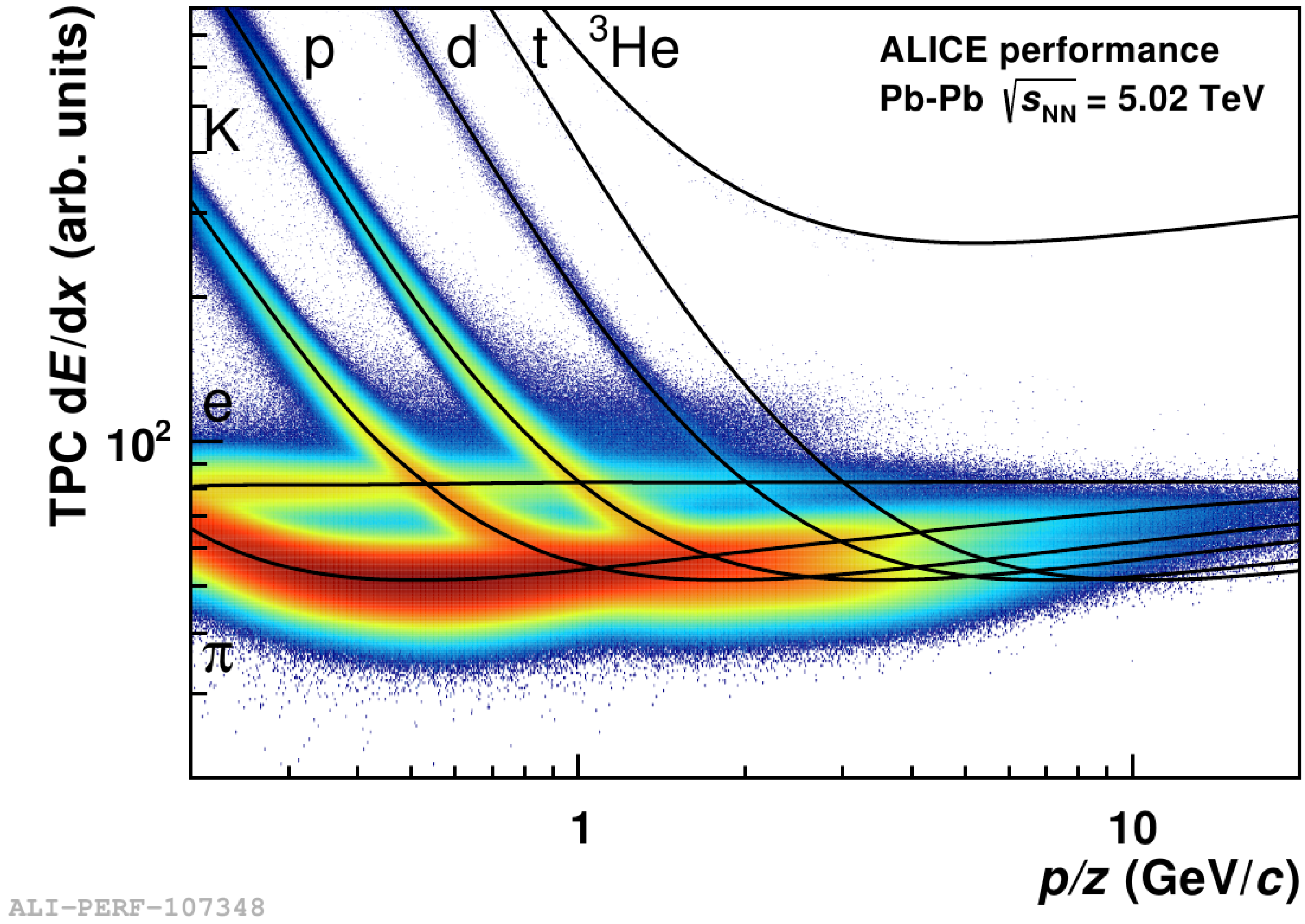
$\varepsilon_{LHC} \simeq 20 - 40$ GeV/fm^3 (much above ε_c)

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

self-similar (Hubble-like) homogeneous (hydrodynamic) expansion of the fireball in the longitudinal (beam) direction ("Bjorken model", 1983)

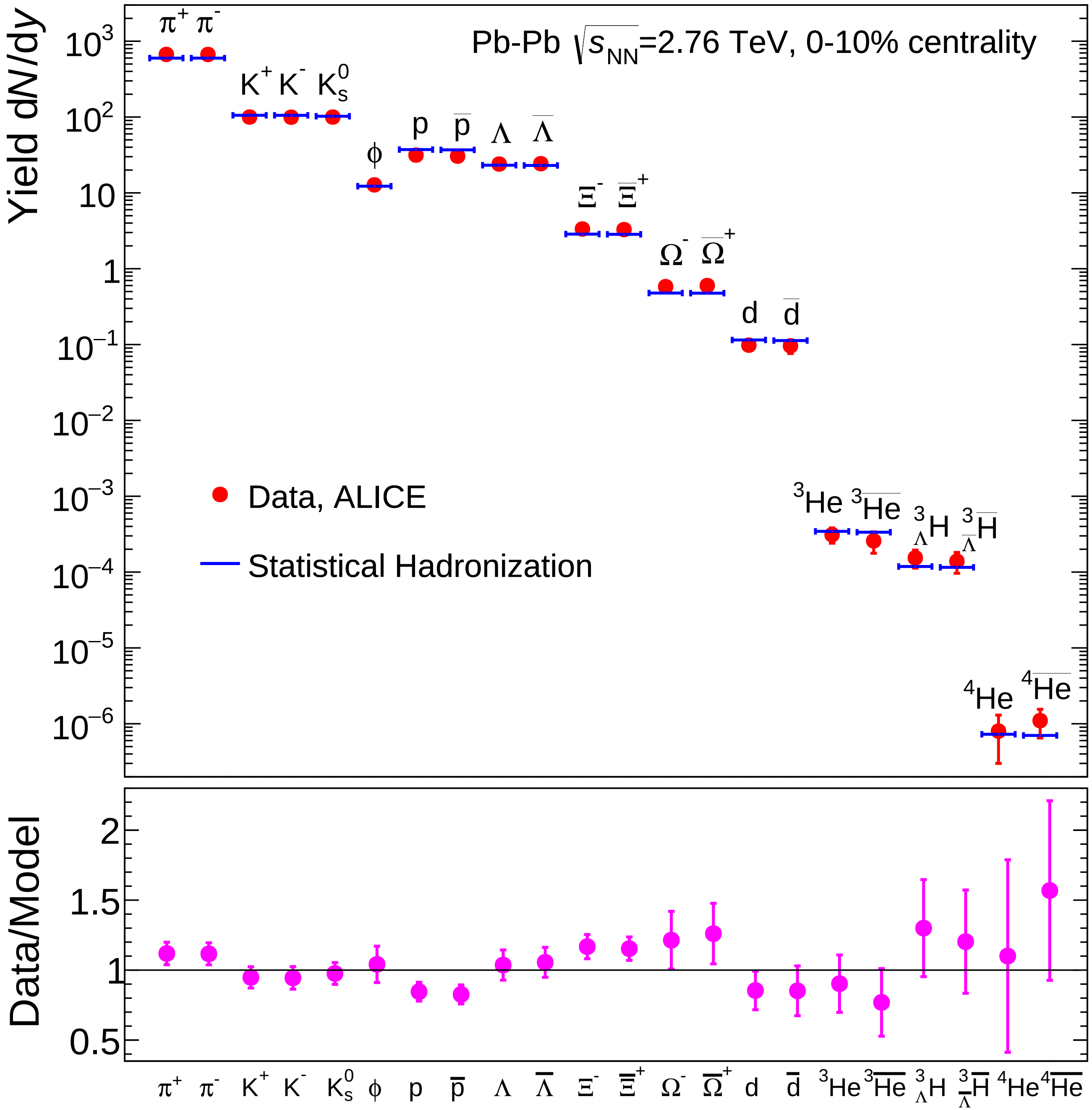
Energy density: $\varepsilon = \frac{1}{A_T}\frac{dE_T}{dy}\frac{1}{c\tau}$

- $A_T = \pi R^2$: 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



Matter and antimatter are produced in equal amounts in high-energy Pb-Pb collisions (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:1710.09425

Thermal fits of hadron abundances

A. Andronic

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

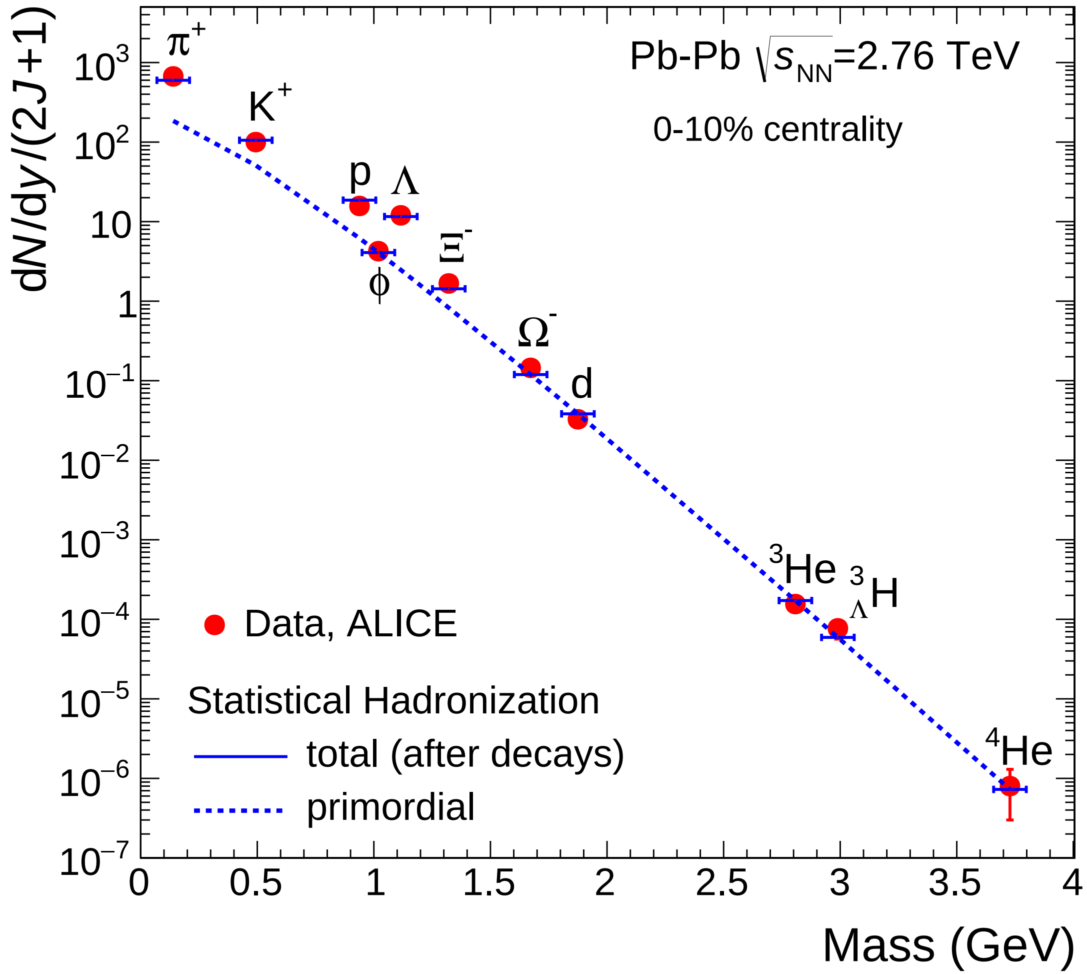
quantum nr. conservation ensured via chemical potentials:

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

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

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

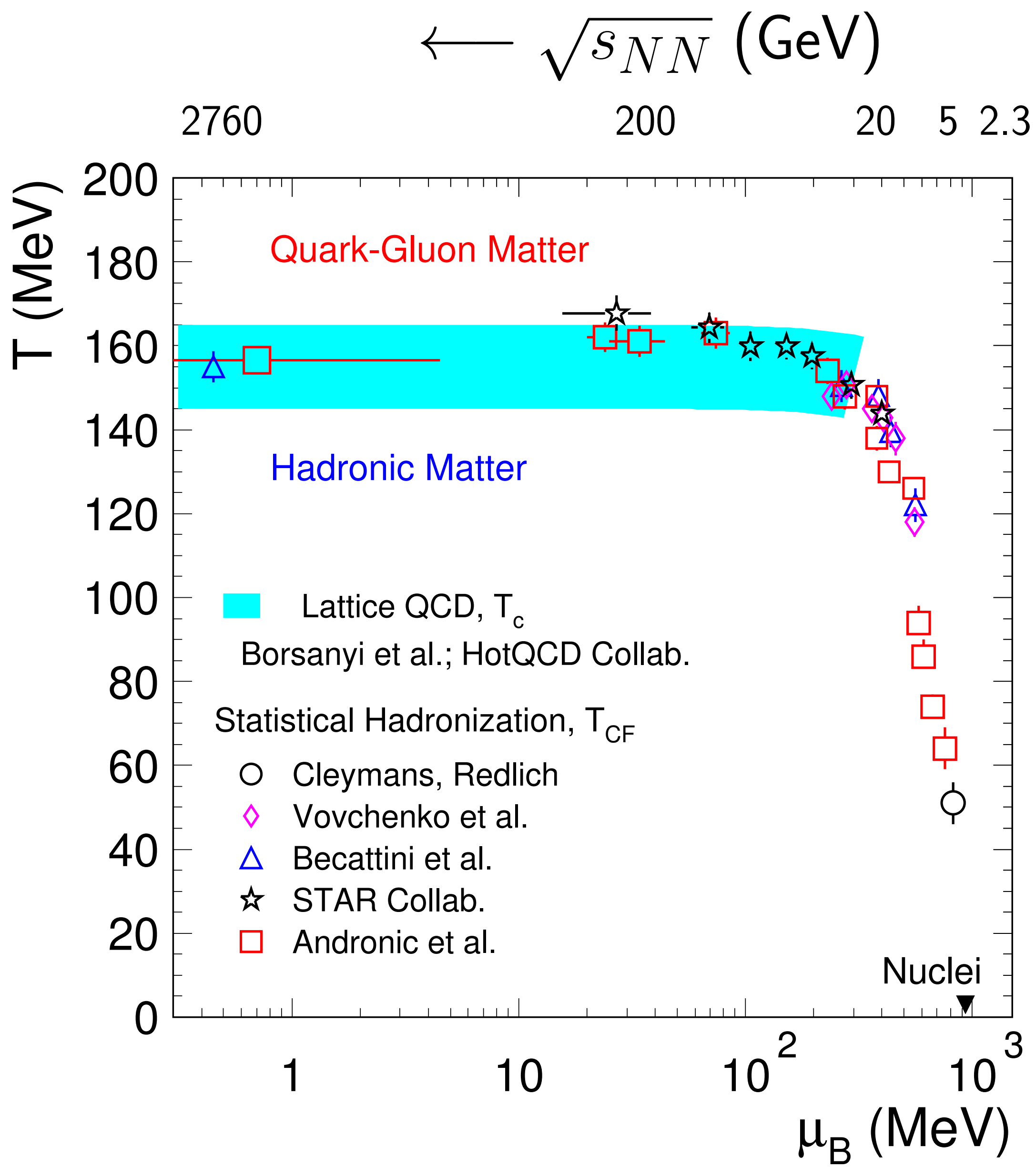
N_i: hadron yield $\Rightarrow (T,\ \mu_B,\ V)$



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

...but how can a loosely-bound deuteron be produced at T=156 MeV?

The phase diagram of QCD



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* (at FAIR?)

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

arXiv:1710.09425

Quark interlude

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 ($t \sim 1/(2m_c) \leq 0.1$ fm/c)

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

Charmonium and deconfined matter

the original idea: Matsui & Satz, Phys. Lett. B 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":

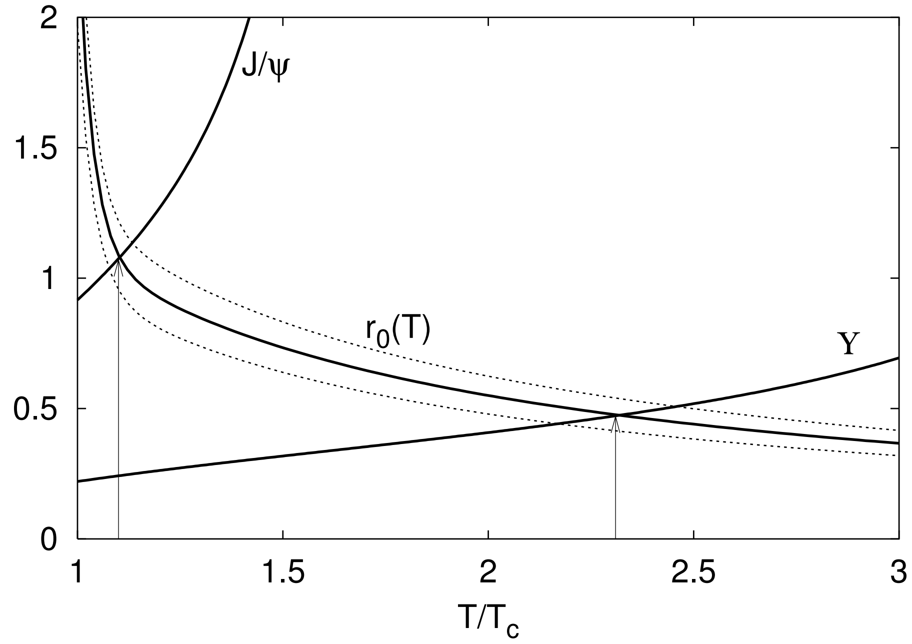
Digal et al., PRD 64 (2001) 75

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

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

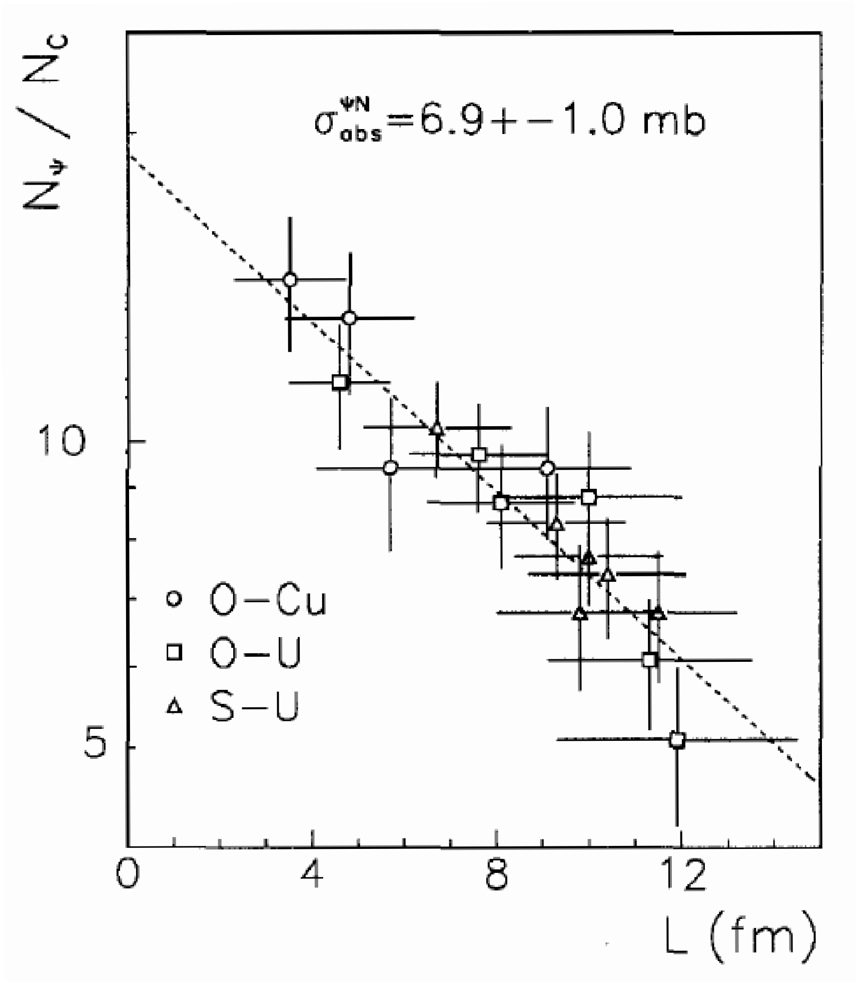
r_0 Debye length in QGP

$\Rightarrow$ $\mathrm{q}\bar{\mathrm{q}}$ "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 $< r_{J/\psi}$



J.Hüfner, C.Gerschel, Z. Phys C 56 (1992) 171

Comparison of J/ψ suppression in photon, hadron and nucleus-nucleus collisions: Where is the quark-gluon plasma?

$$N_\psi/N_c \sim \exp(-L\rho_0\sigma_{abs}^{\psi N})$$

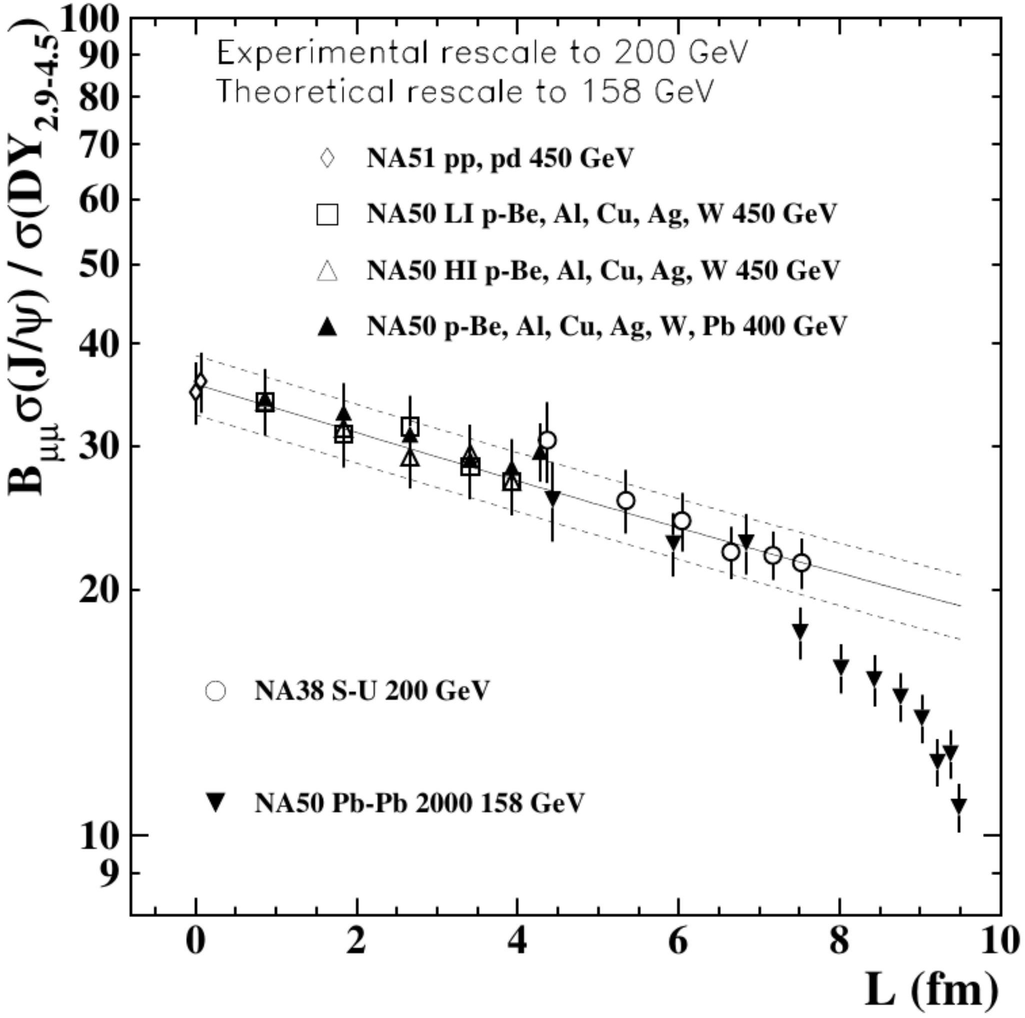
L average length traversed by J/ψ (in statu nascendi)

quantifying "normal" absorption in nuclear matter

"whatever the microscopic physical origin is"

...and expecting departures if color screening sets in

Charmonium production at the SPS



NA50, EPJ C 39 (2005) 335

$$N_\psi/N_c \sim \exp(-L\rho_0\sigma_{abs}^{\psi N})$$

updated $\sigma_{abs}^{\psi N} = 4.2 \pm 0.35$ mb

significant "anomalous" suppression

J.Hüfner, P.Zhuang, Phys.Lett.B 559 (2003) 193

Time structure of anomalous J/ψ and ψ' suppression in nuclear collisions

a dynamical treatment (transport equation)

...planted the seed for studies at RHIC and LHC

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")

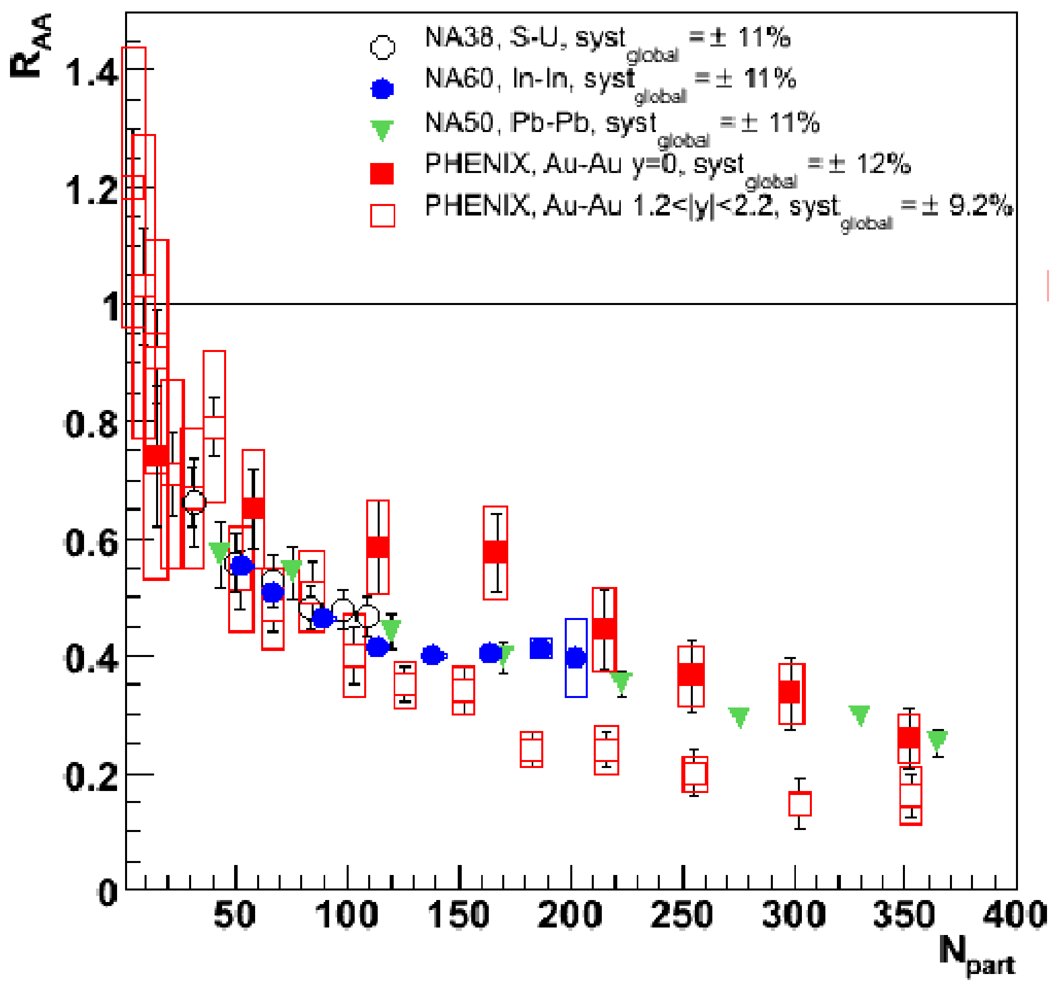
Thews et al., PRC 63 (2001) 054905 ...

"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

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



plot: courtesy Roberta Arnaldi

The surprise was that the suppression is at RHIC similar to that at SPS despite:

- $\sigma_{abs}^{\psi N}$ was expected (and measured) to decrease at RHIC

- ε was expected (and measured) to increase

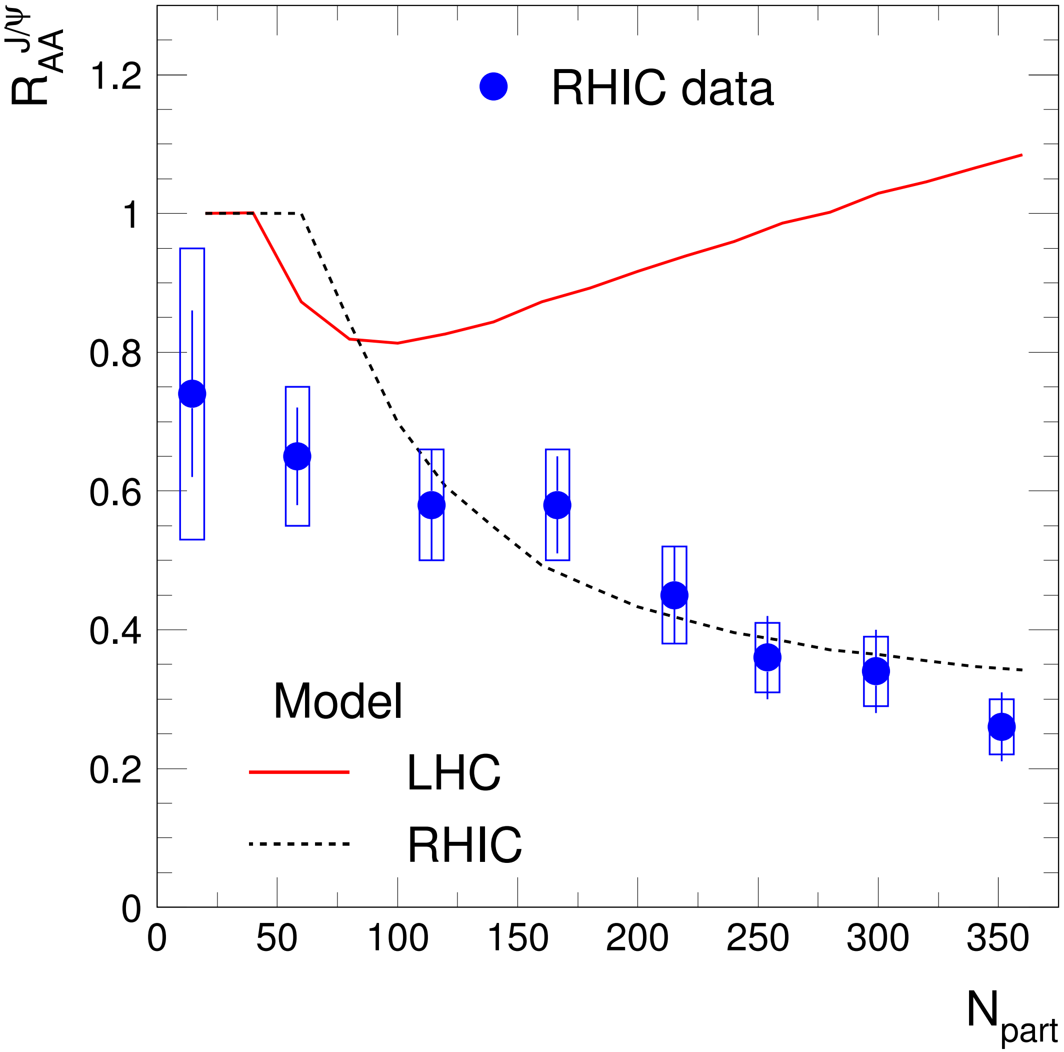
Another surprise: suppression smaller at mid-rapidity (y=0)

an early forecast:

Scanning of the quark - gluon plasma with charmonium

B.Kopeliovich, A.Polleri, J.Hüfner PRL 87 (2001) 112302 (also foresaw R_{AA} as observable)

Charmonium and the statistical model



$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

- "suppression" at RHIC
- "enhancement" at LHC

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

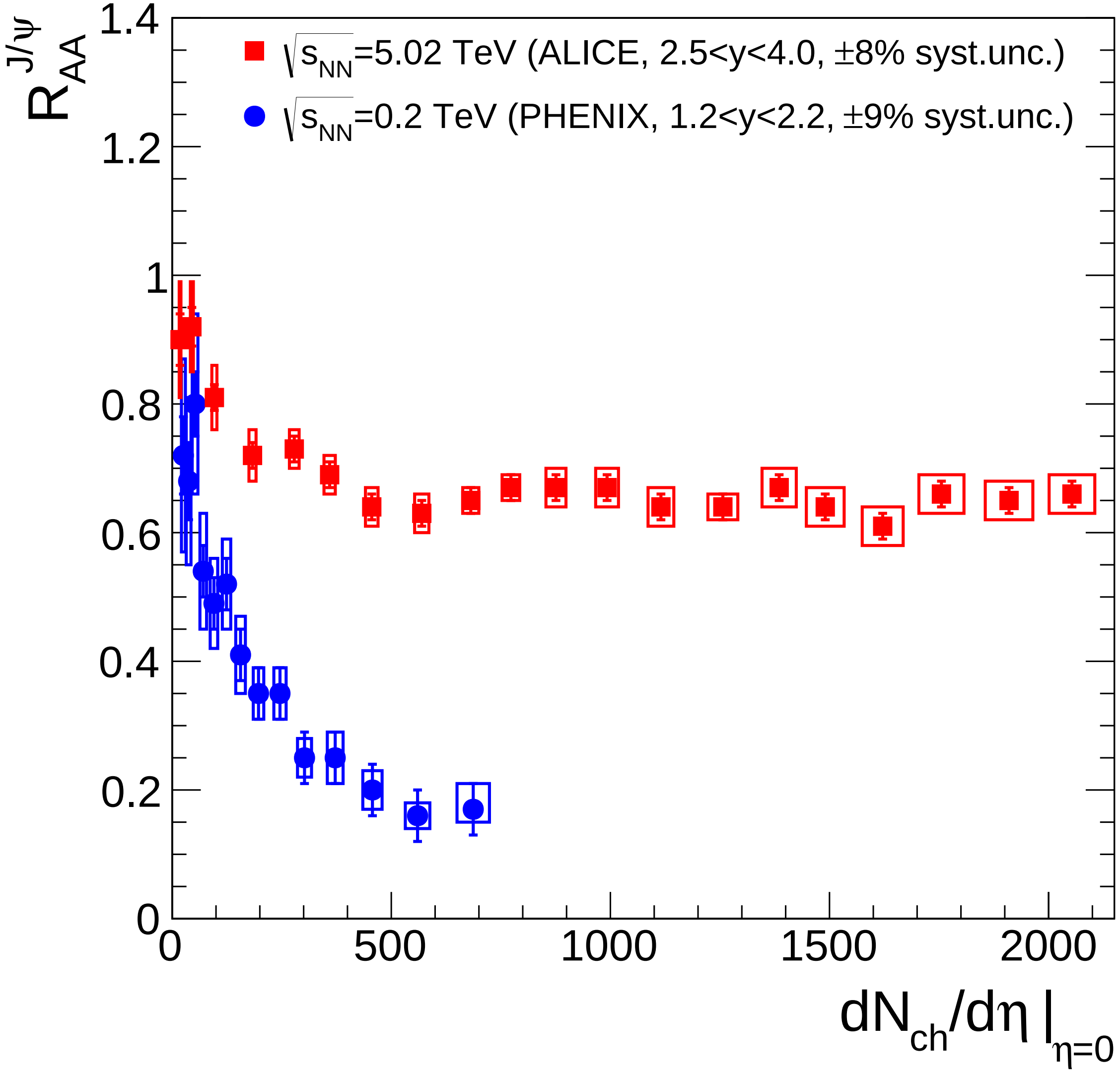
  What is so different at LHC? (compared to RHIC)

  $\sigma_{c\bar{c}}$: $\sim$10x, Volume: 2.2-3x

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

this was for full LHC energy... is a generic prediction of (re)generation models

(Liu et al., PLB 678 (2009) 72; Zhao, Rapp, NPA 859 (2011) 114)

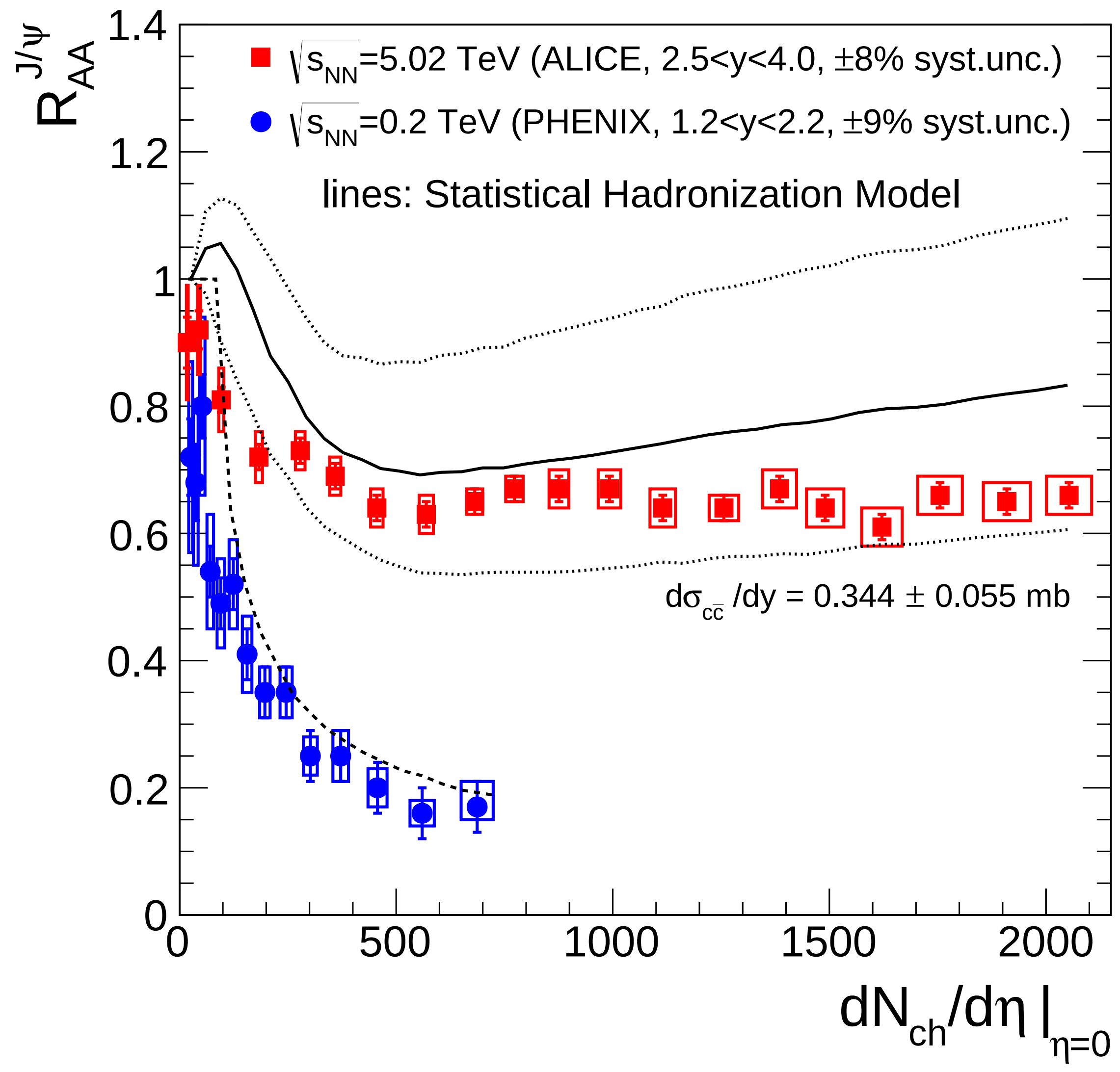


- "suppression" at RHIC (PHENIX)
- dramatically different at the LHC

...

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

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



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Statistical Hadronization Model

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

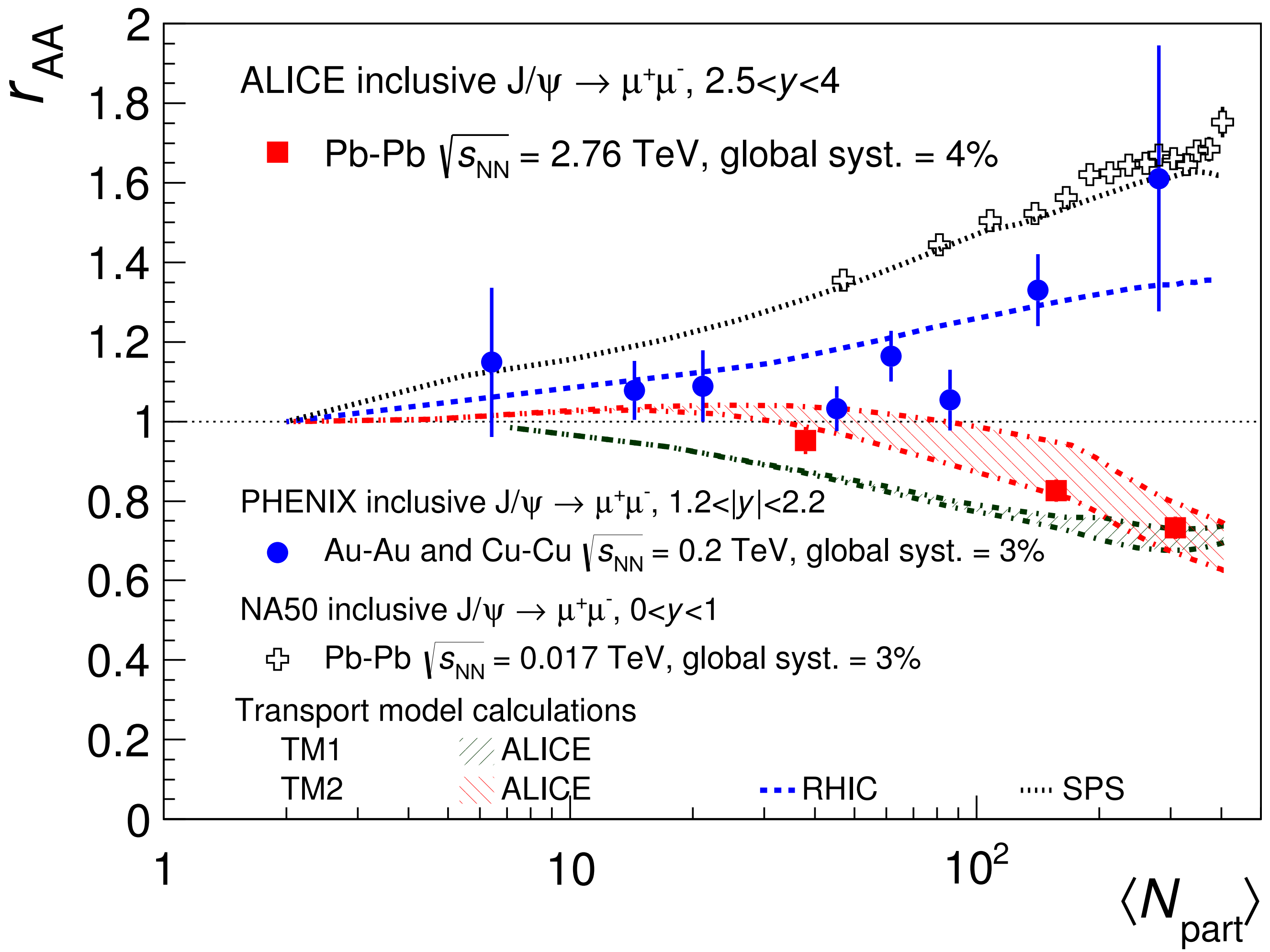
J/ψ is another observable (charm) for the phase boundary

calculations are for T=156 MeV

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

arXiv:1710.09425

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

Summary

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

  ...a highly-dynamic system; we establish observables for various stages
- measured energy densities are well above the values expected for deconfinement
- 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)

  quarkonium as a (intricate) "golden probe" for QGP comes of age

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  ...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)
  quarkonium as a (intricate) "golden probe" for QGP comes of age

Happy Birthday, Prof. Hüfner!

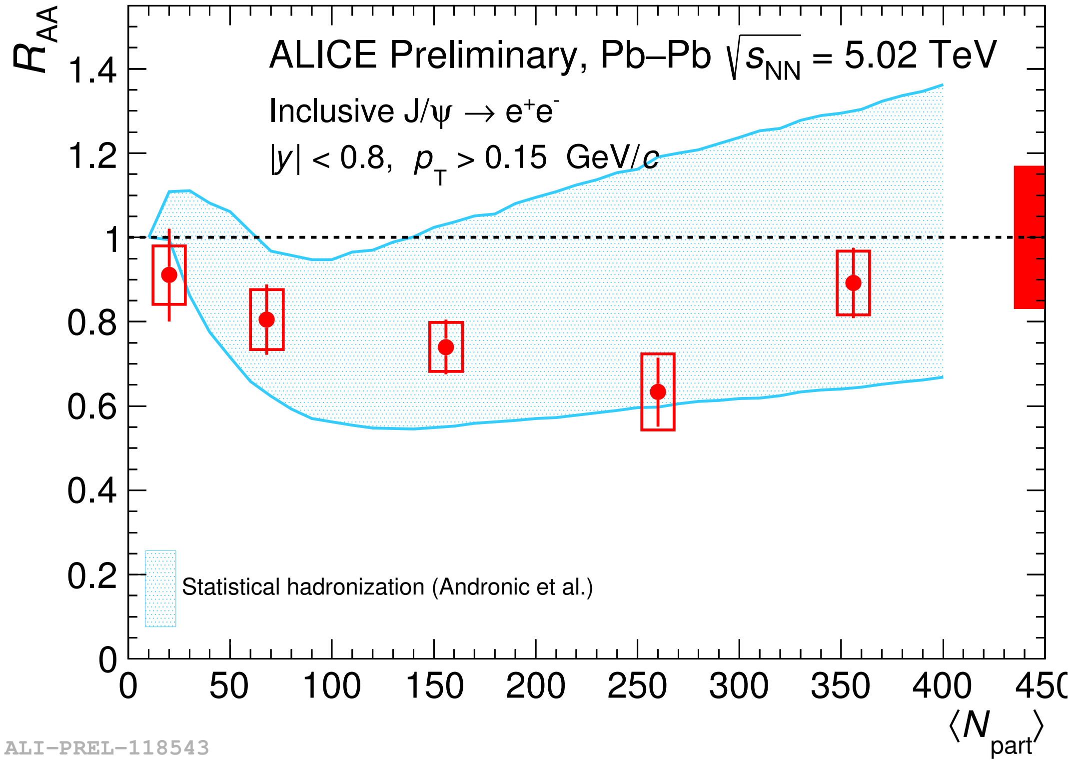
Things not discussed

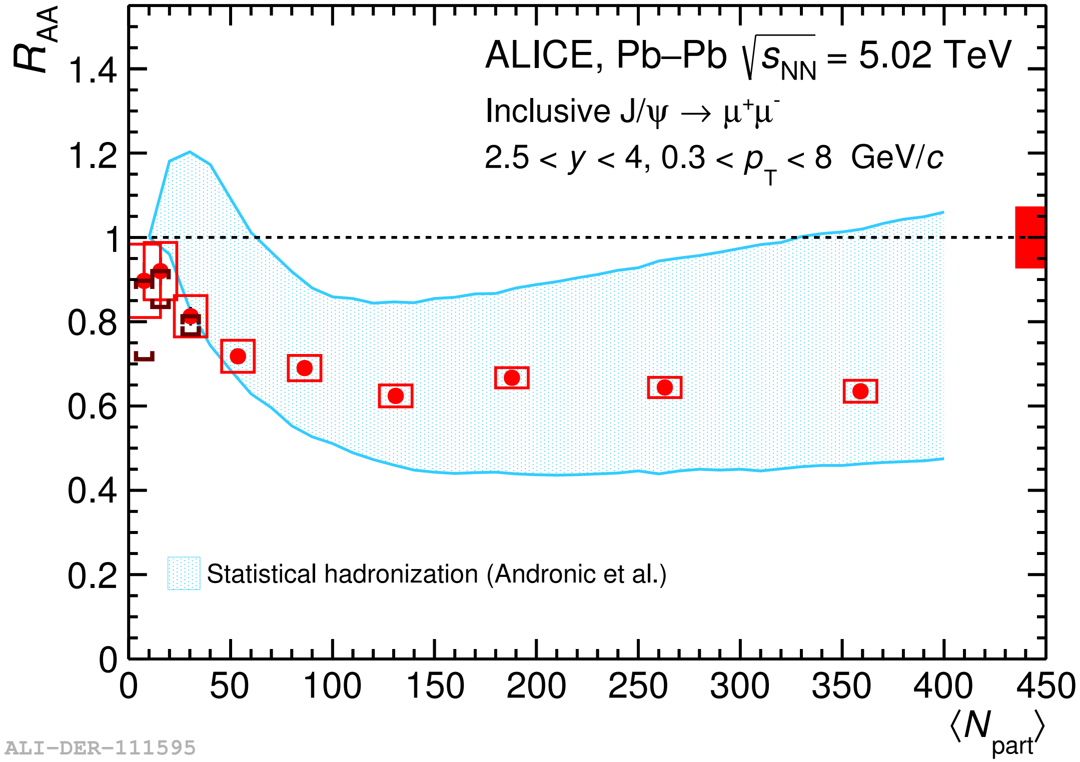
...but available in the following additional slides

- we see 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 $T = (1 - 3)T_c$)
- collective flow (developed early in the deconfined stage) described by hydrodynamics; allows extraction of η/s
- some of the features in heavy-ion collisions are observed in high-multiplicity pp and p–Pb collisions

Other studies: chiral symmetry restoration; thermal photons; critical point

Additional slides





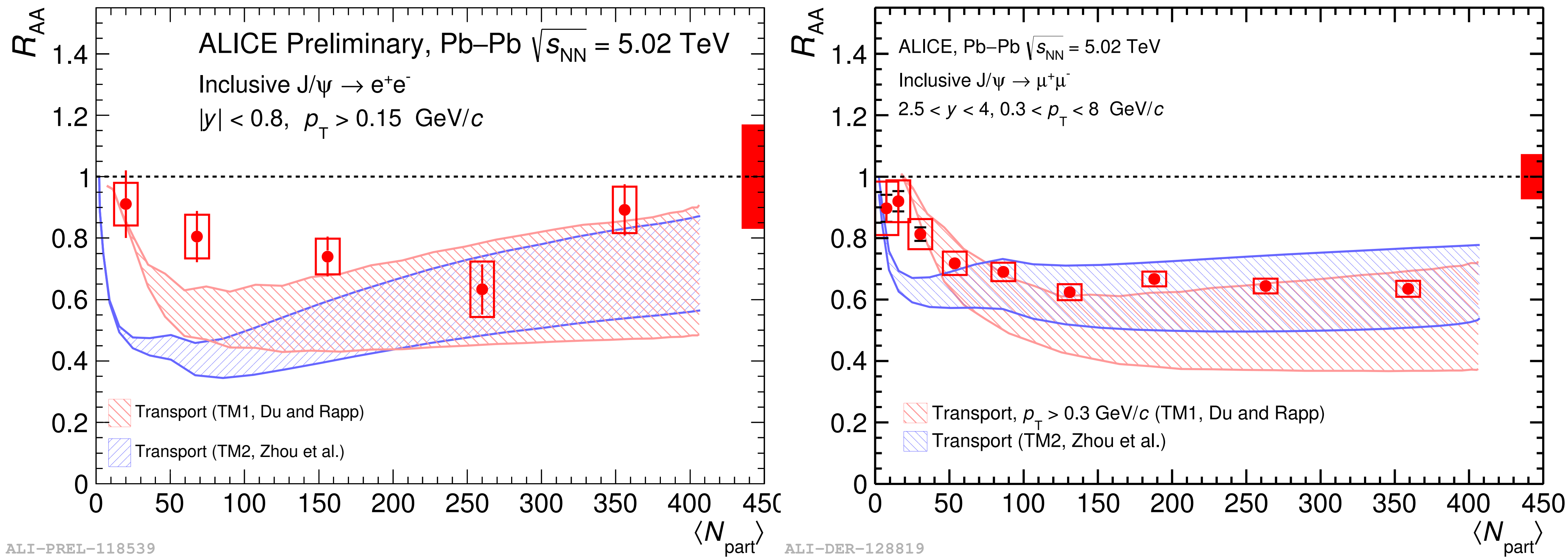
ALICE, PLB 766 (2017) 212

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)

J/ψ data and transport models

A. Andronic



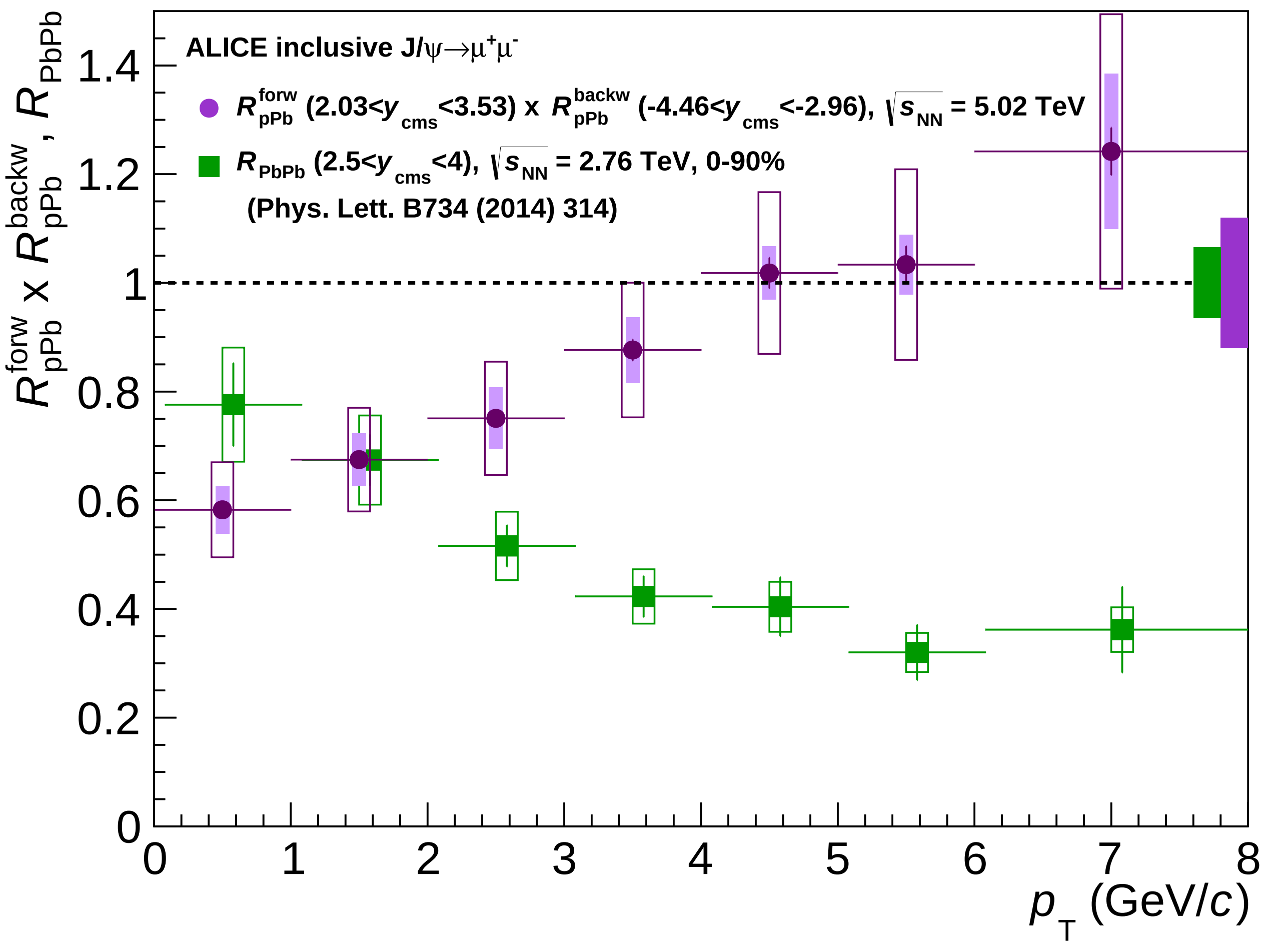
ALICE, PLB 766 (2017) 212

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 $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$)

TM2: Pengfei Zhuang, a former collaborator of J. Hüfner

J/ψ production vs. p_T

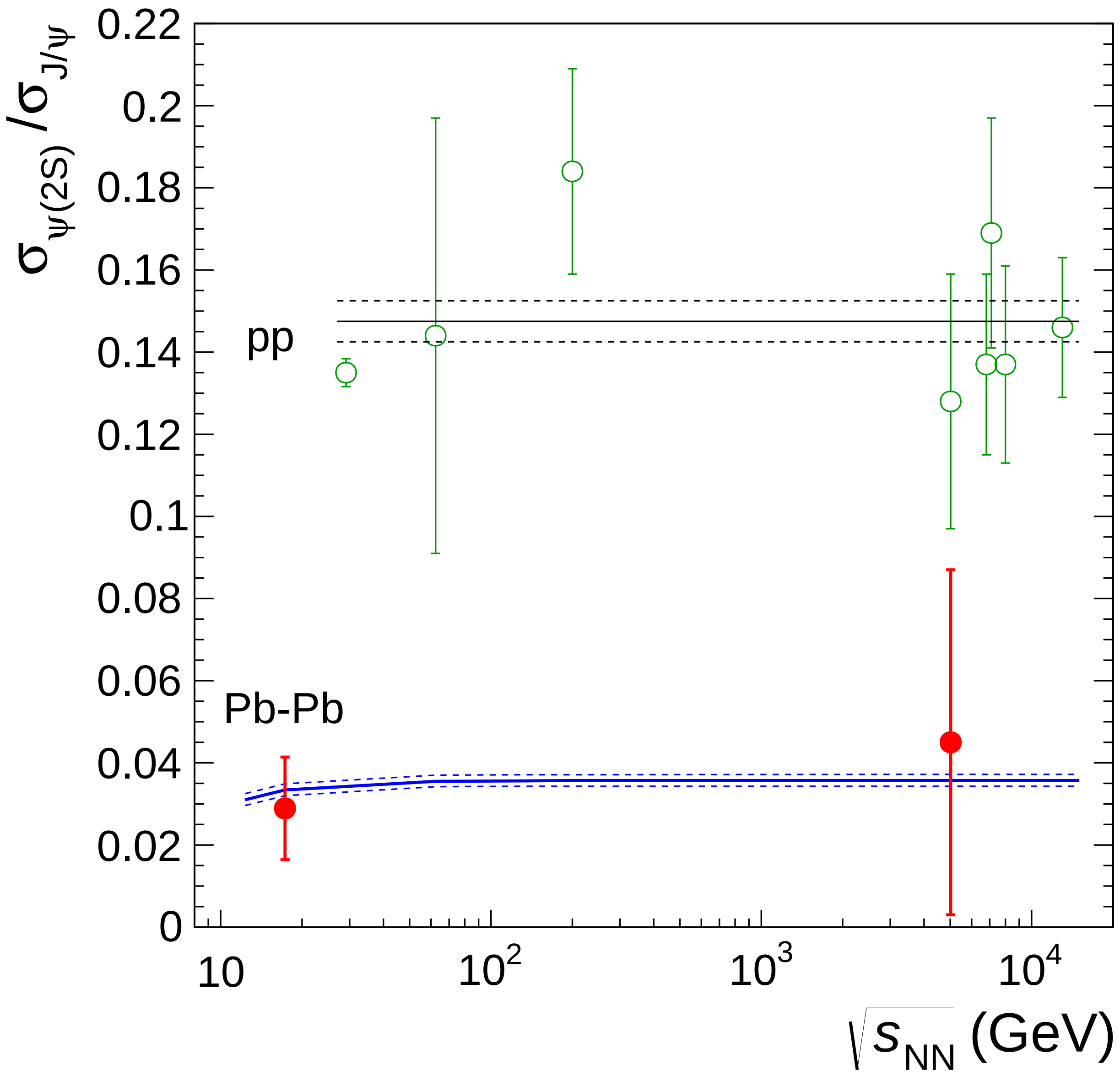


ALICE, JHEP 06 (2015) 055

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)

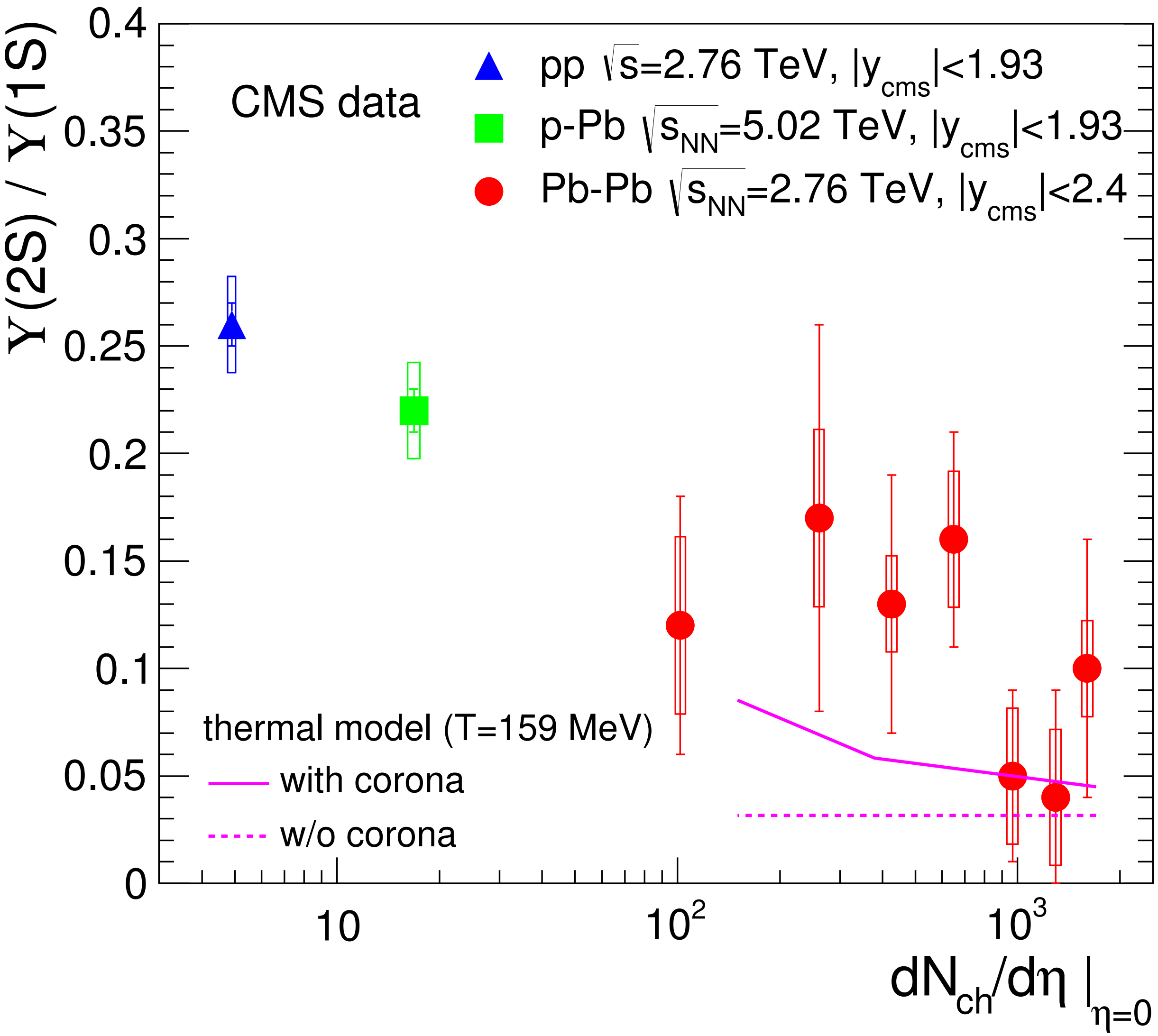
for mid-rapidity: Run 1 data stat.-limited; Run 2 data will bring significance (Heidelberg-Darmstadt-Frankfurt)

A. Andronic



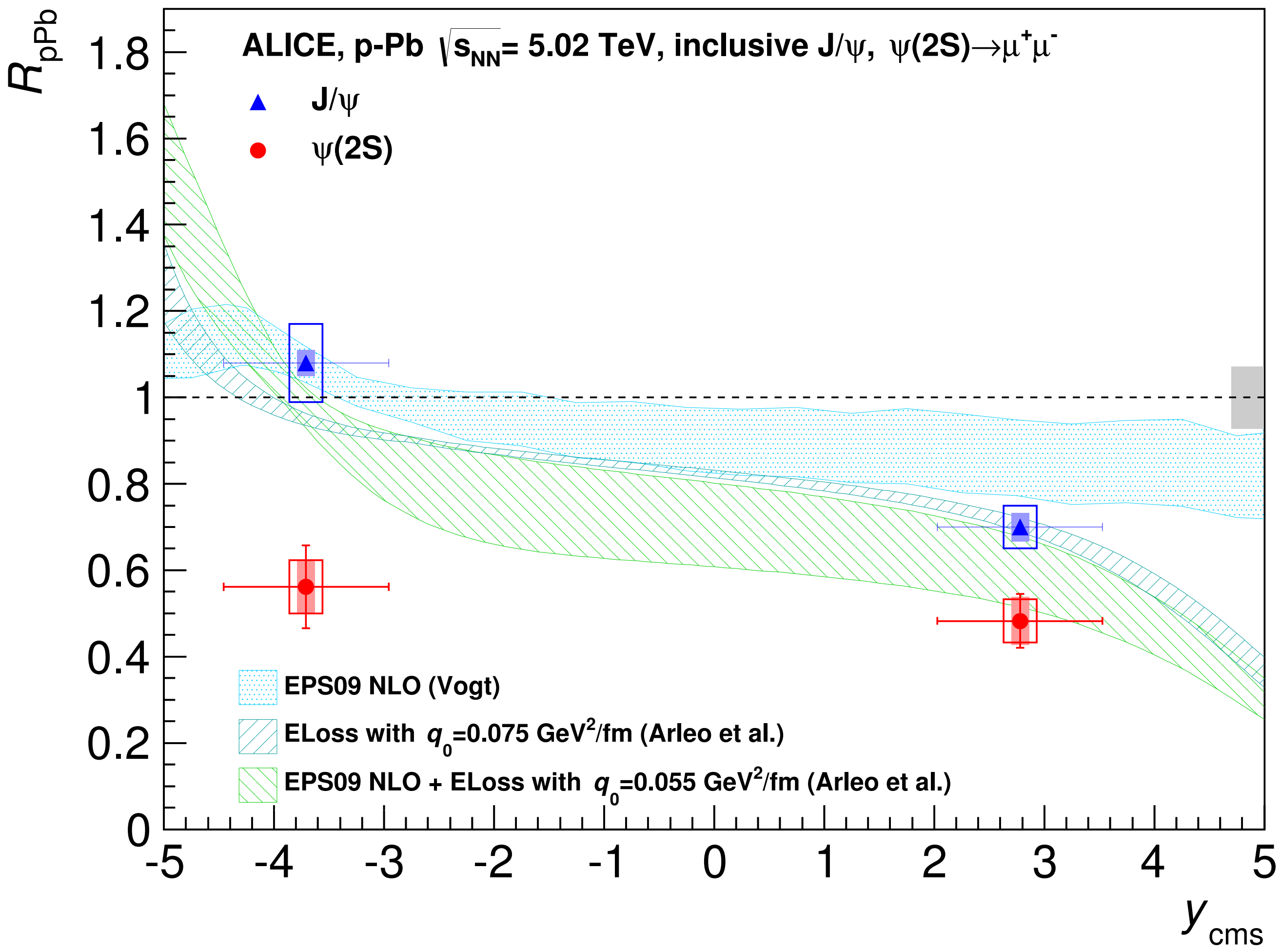
arXiv:1710.09425

Bottomonium production



arXiv:1710.09425

Charmonium production in p–Pb collisions

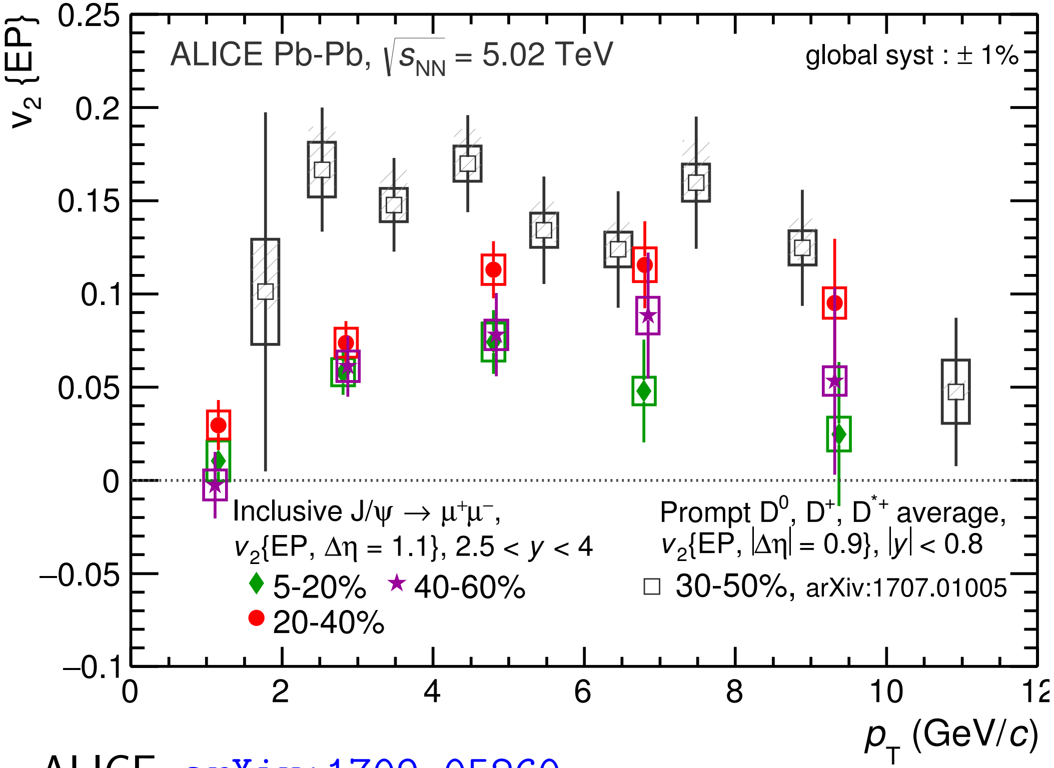


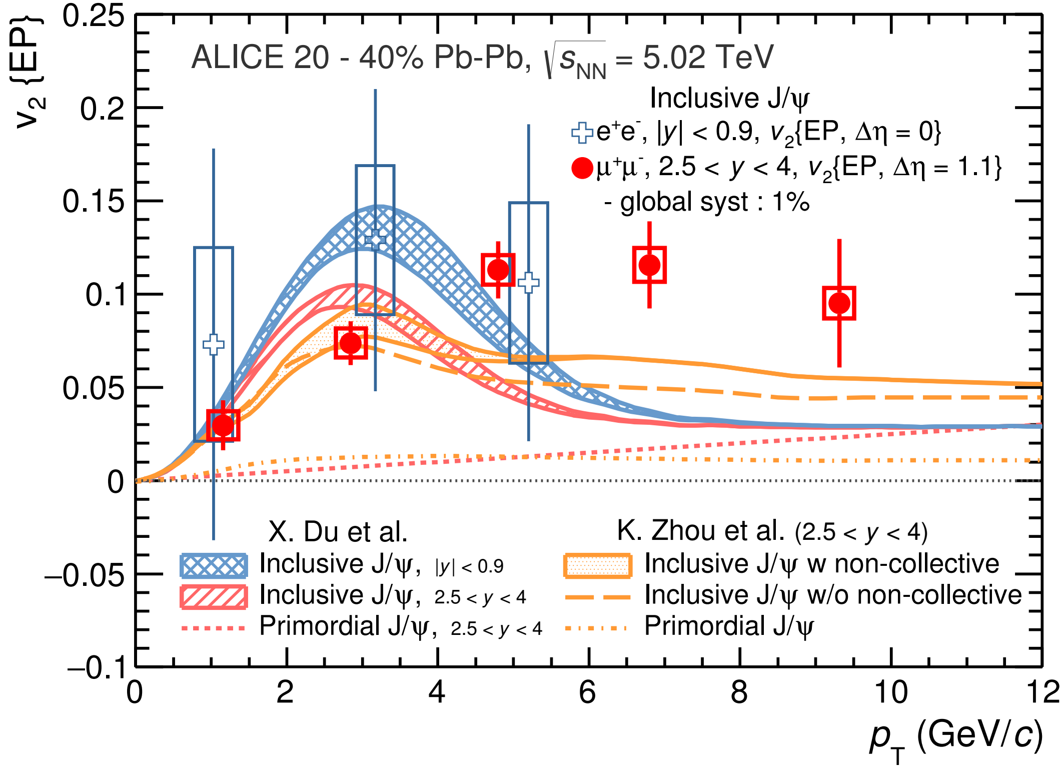
ALICE, JHEP 12 (2014) 073

(at least in first order) models give same result for $\psi(2S)$ as for J/ψ

in data, difference predominantly at low p_T

J/ψ mesons exhibit collective flow





ALICE, arXiv:1709.05260

...as quantified by the 2nd Fourier coefficient $v_2 = \langle \cos 2(\phi - \Phi_{EP}) \rangle$

measure of asymmetry of azimuthal angle of J/ψ w.r.t. the event plane (EP), defined by colliding nuclei

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

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

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

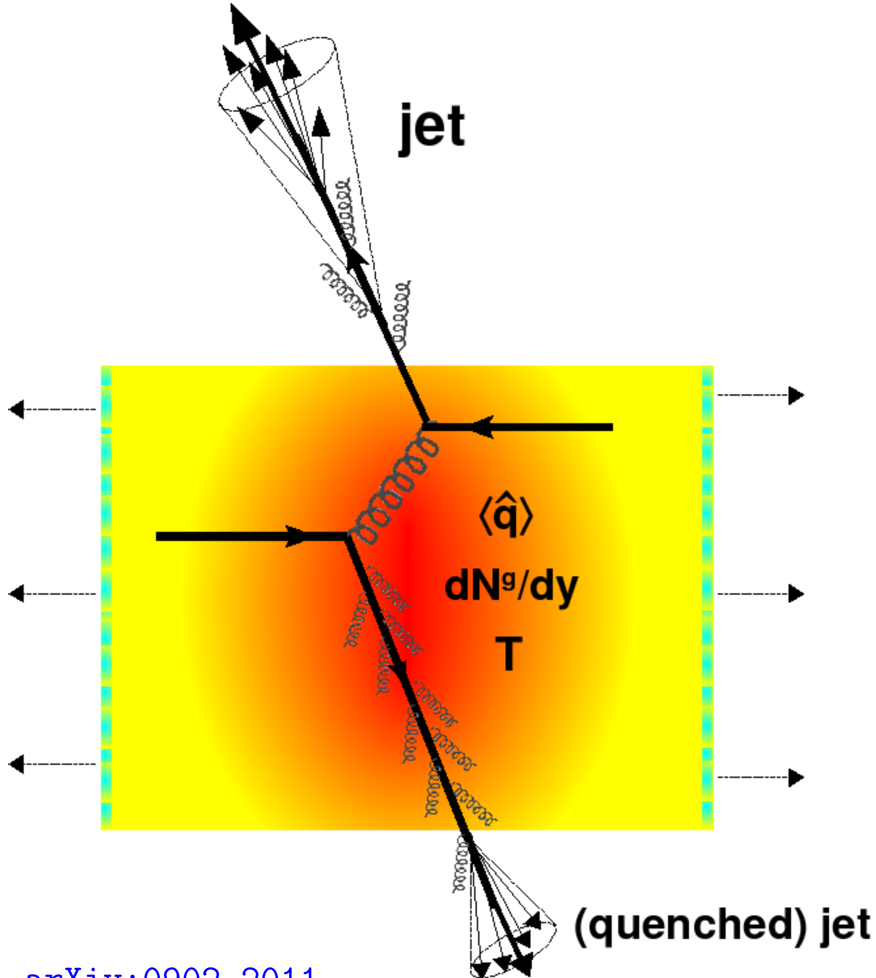
(jets - sprays of hadrons from high-speed quarks)

- $q, \bar{q}, g$ 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, 1982)

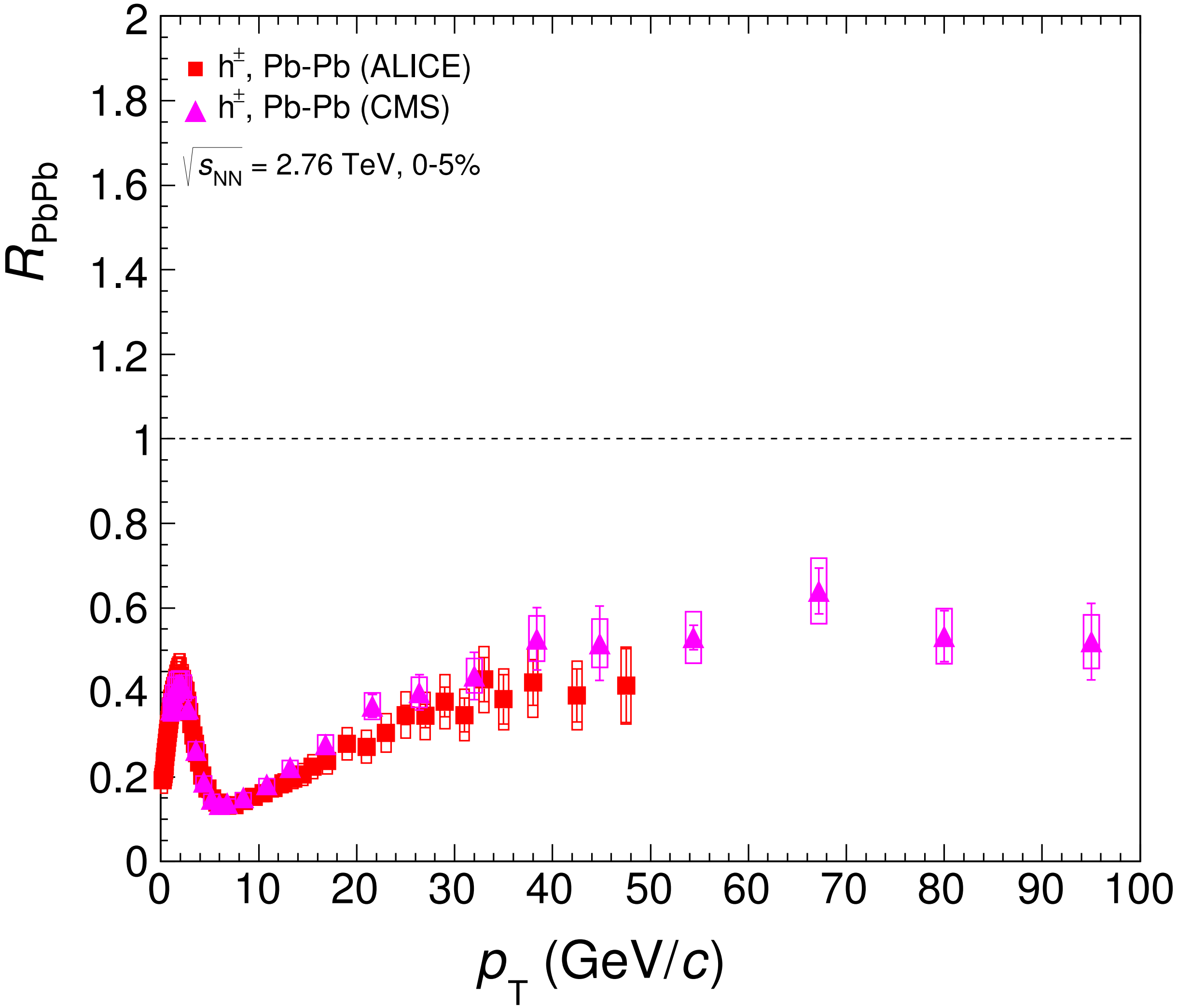
quantified by the nuclear modification factor:

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



D. d'Enterria, arXiv:0902.2011

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



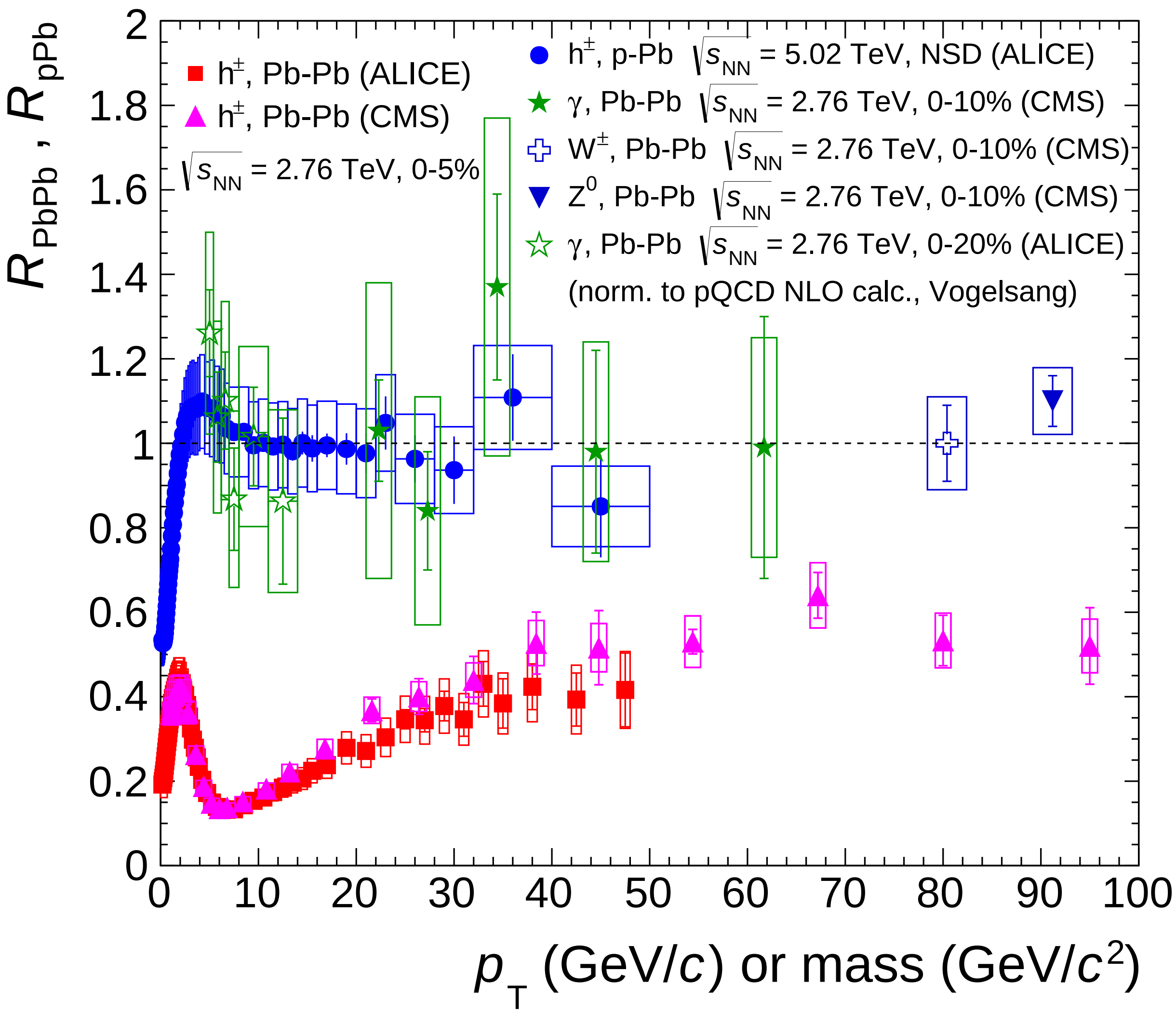
a thermal component, $p_{\mathrm{T}} \lesssim 6$ GeV/c (scaling with N_{part}) determined by gluon saturation and collective flow

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

remains substantial even at 50-100 GeV/c

seen also with reconstructed jets up to 1 TeV (ATLAS)

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



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

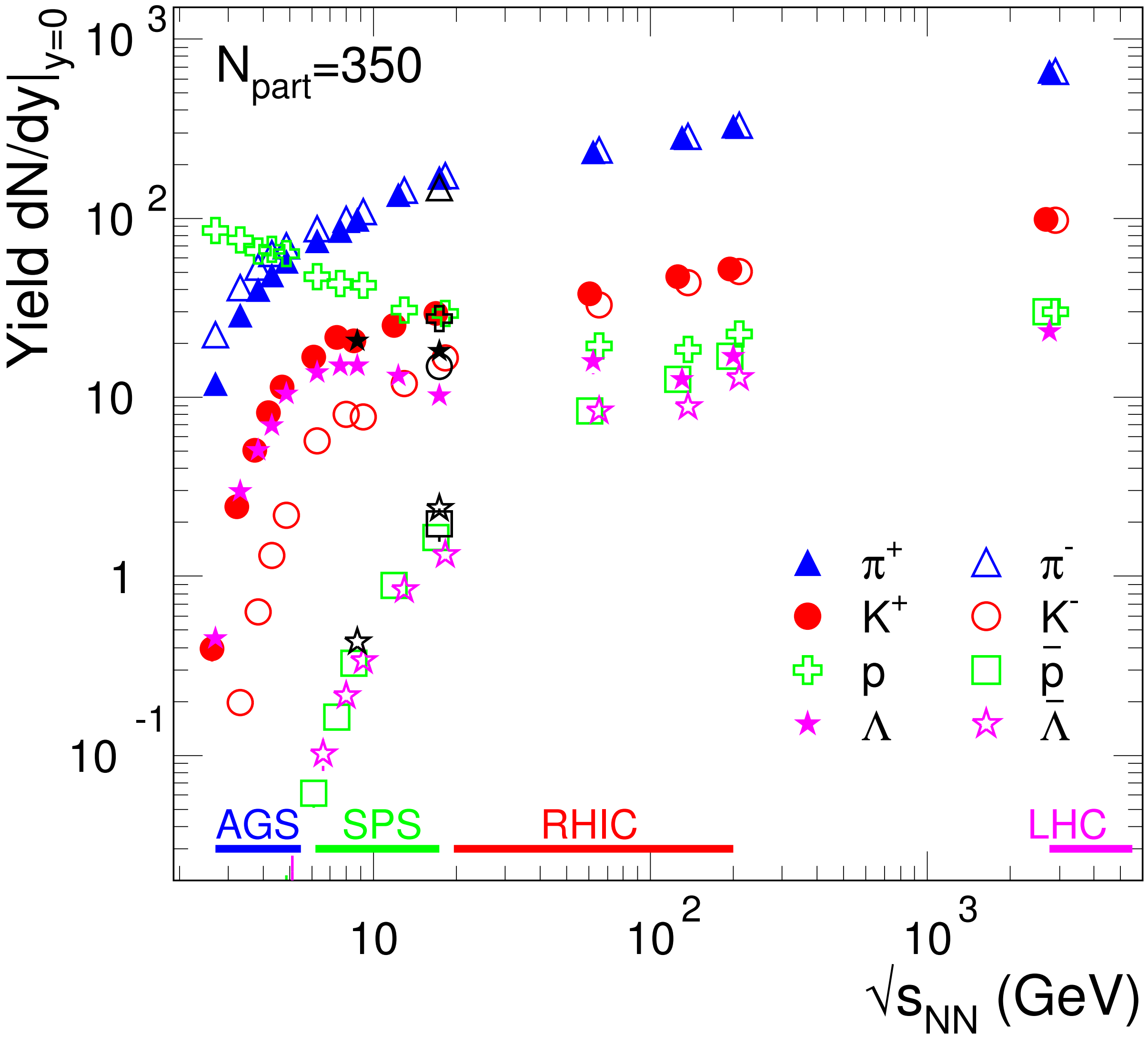
strong suppression, reaching a factor of ∼7, $p_{\rm T} \simeq 7$ GeV/c

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

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

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

Overview of hadron production

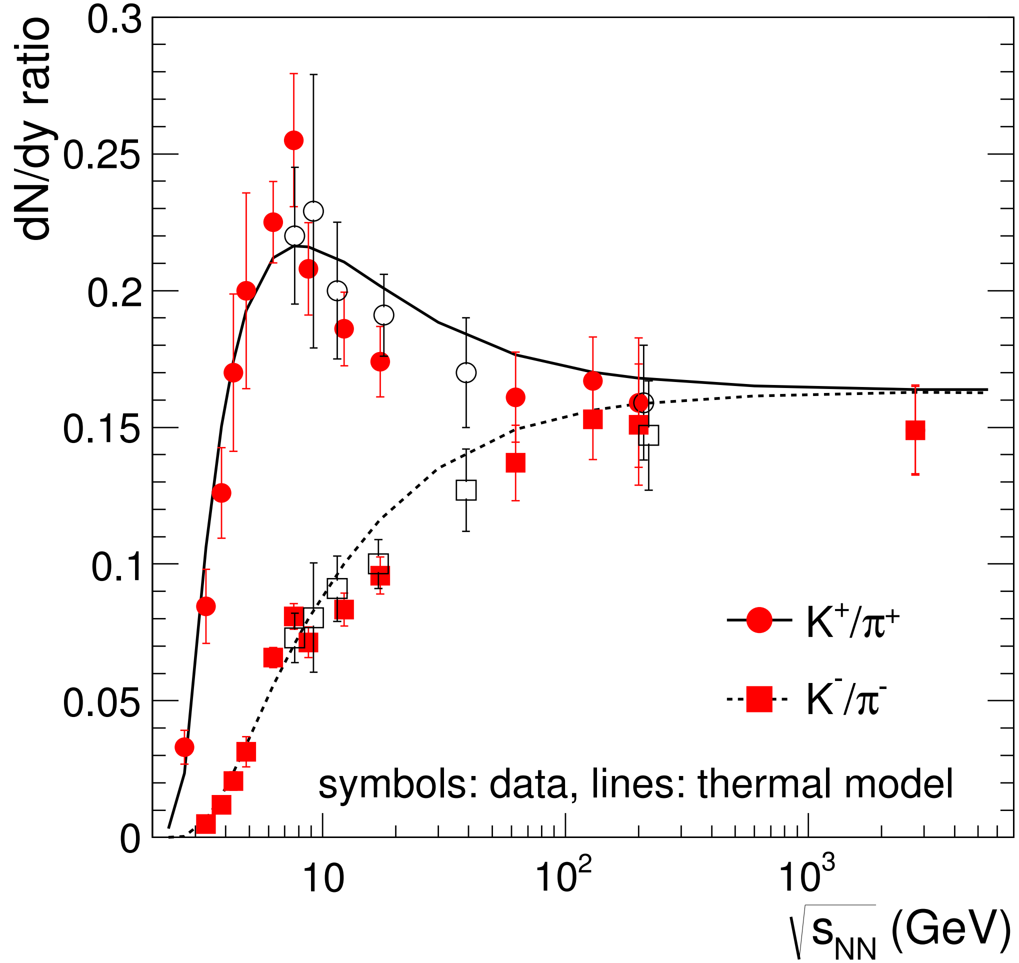


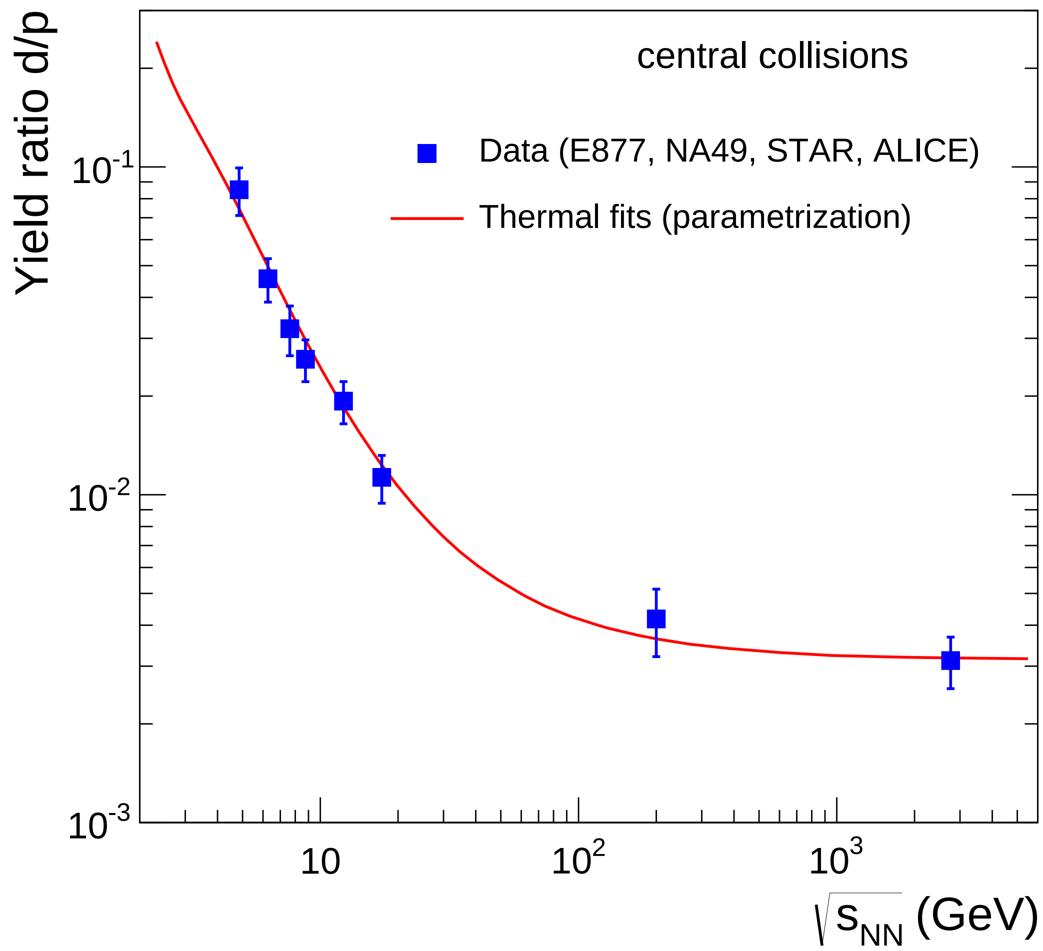
- lots of particles, mostly newly created ($m = E/c^2$)
- a great variety of species:

  $\pi^{\pm}$ $(u\bar{d},\, d\bar{u})$, 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)

A "global" look (ratios)

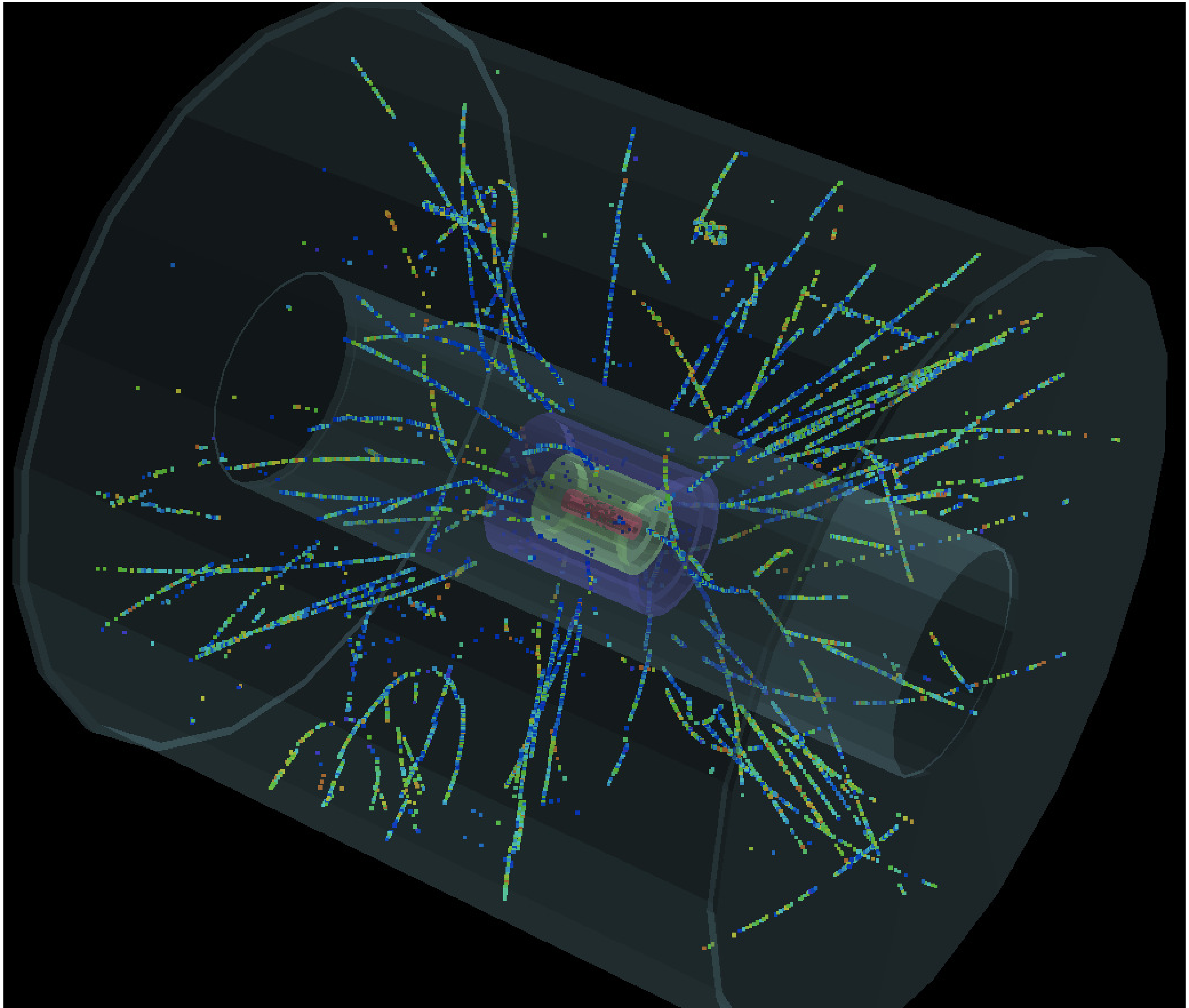




the statistical description works well over a broad range of collision energies (for all hadrons measured)

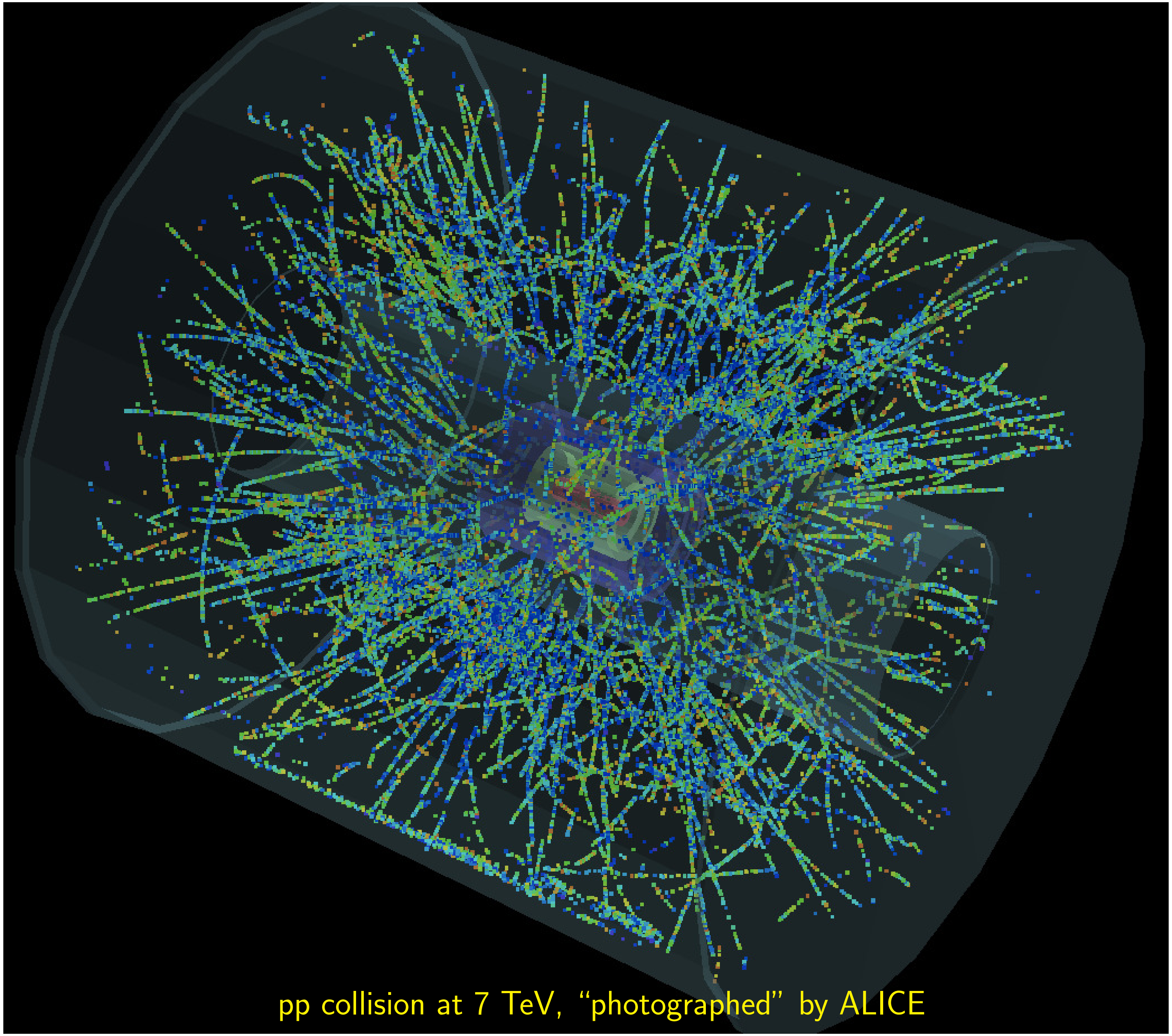
is this a (or the?) universal production mechanism?

Proton collisions at the LHC

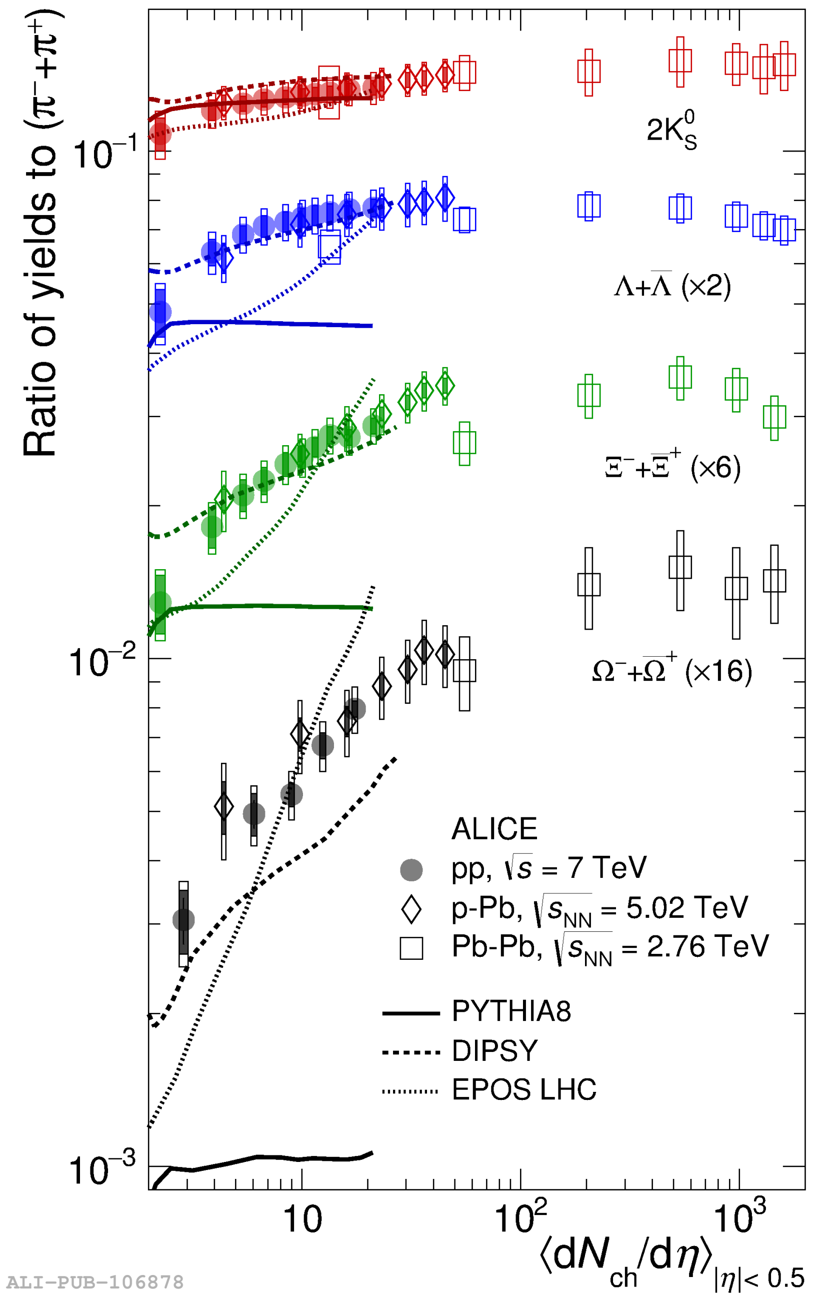


pp collision at 7 TeV, "photographed" by ALICE

Proton collisions at the LHC



Hyperon production - from small to large systems



arXiv:1606.07424

(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)?

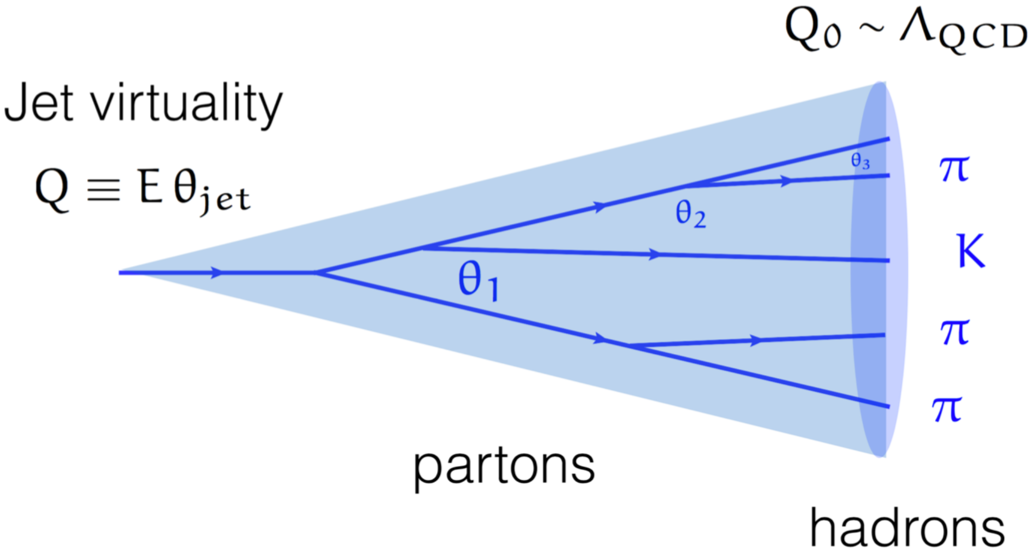
string hadronization models do not describe data well

...new ideas are being put forward

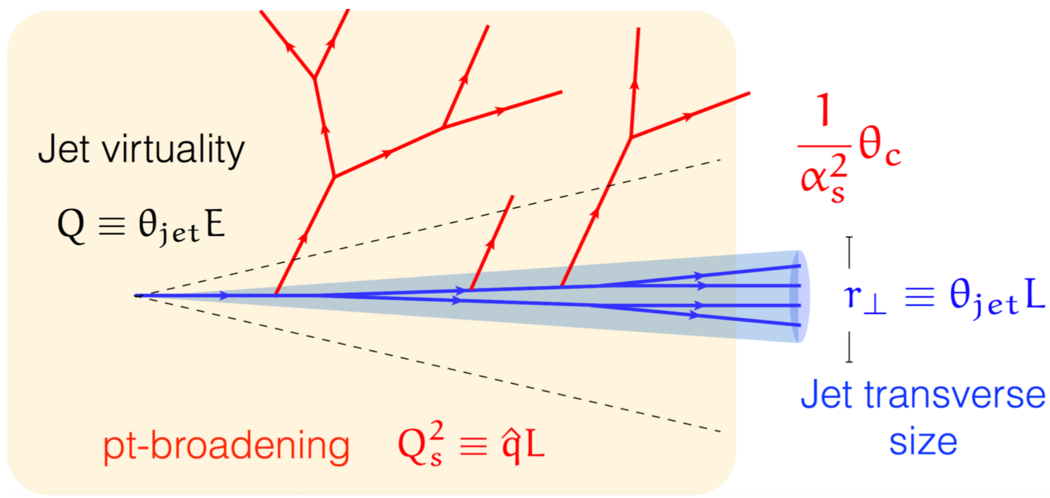
Fischer, Sjöstrand, arXiv:1610.09818

"thermodynamical string fragmentation"

...in vacuum

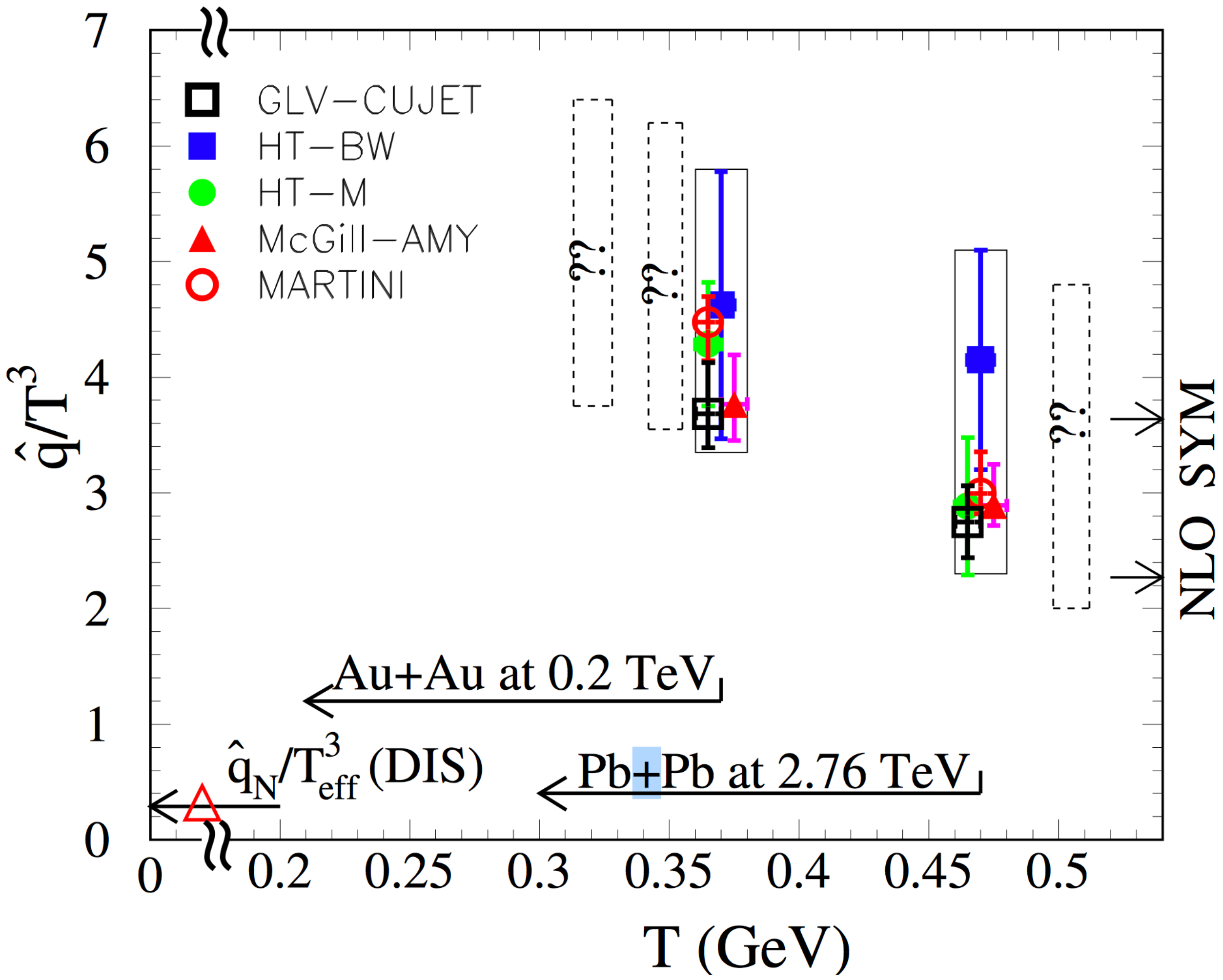


...in medium



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

Y. Mehtar-Tani, arXiv:1602.01047



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)

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: $c \to D$; $b \to B$)

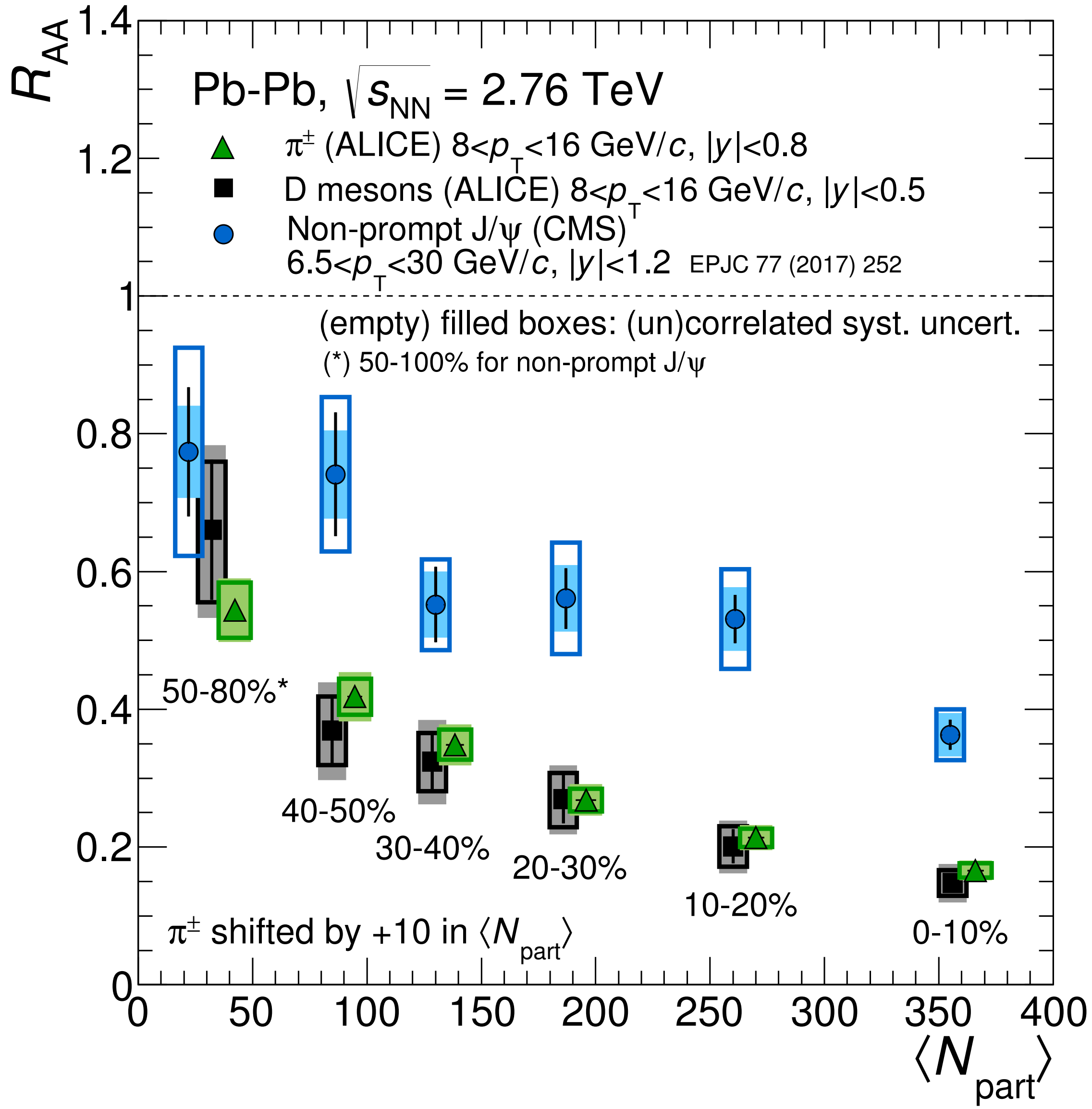
Expectation:
Due to high mass the gluon radiation by HQ is suppressed at small angles
this is called "the dead-cone effect"

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)

In-medium energy loss as a function of quark flavor



D mesons are as much suppressed as pions at high p_T

...is expected ordering vs. quark mass ($\Delta E \sim 1 - R_{AA}$)

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

established in data?

to some extent, yes

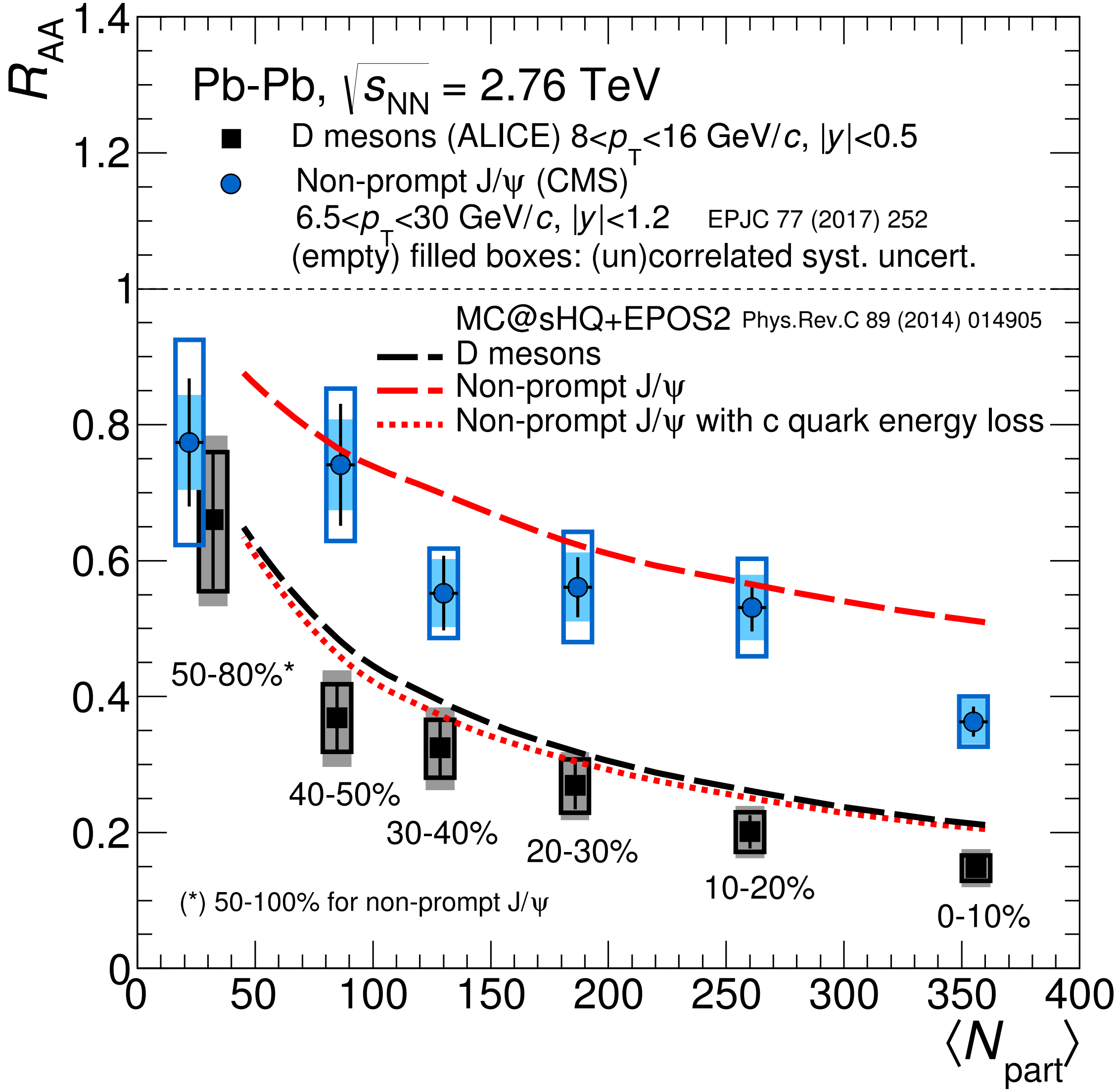
arXiv:1506.06604

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

In-medium energy loss as a function of quark flavor

A. Andronic

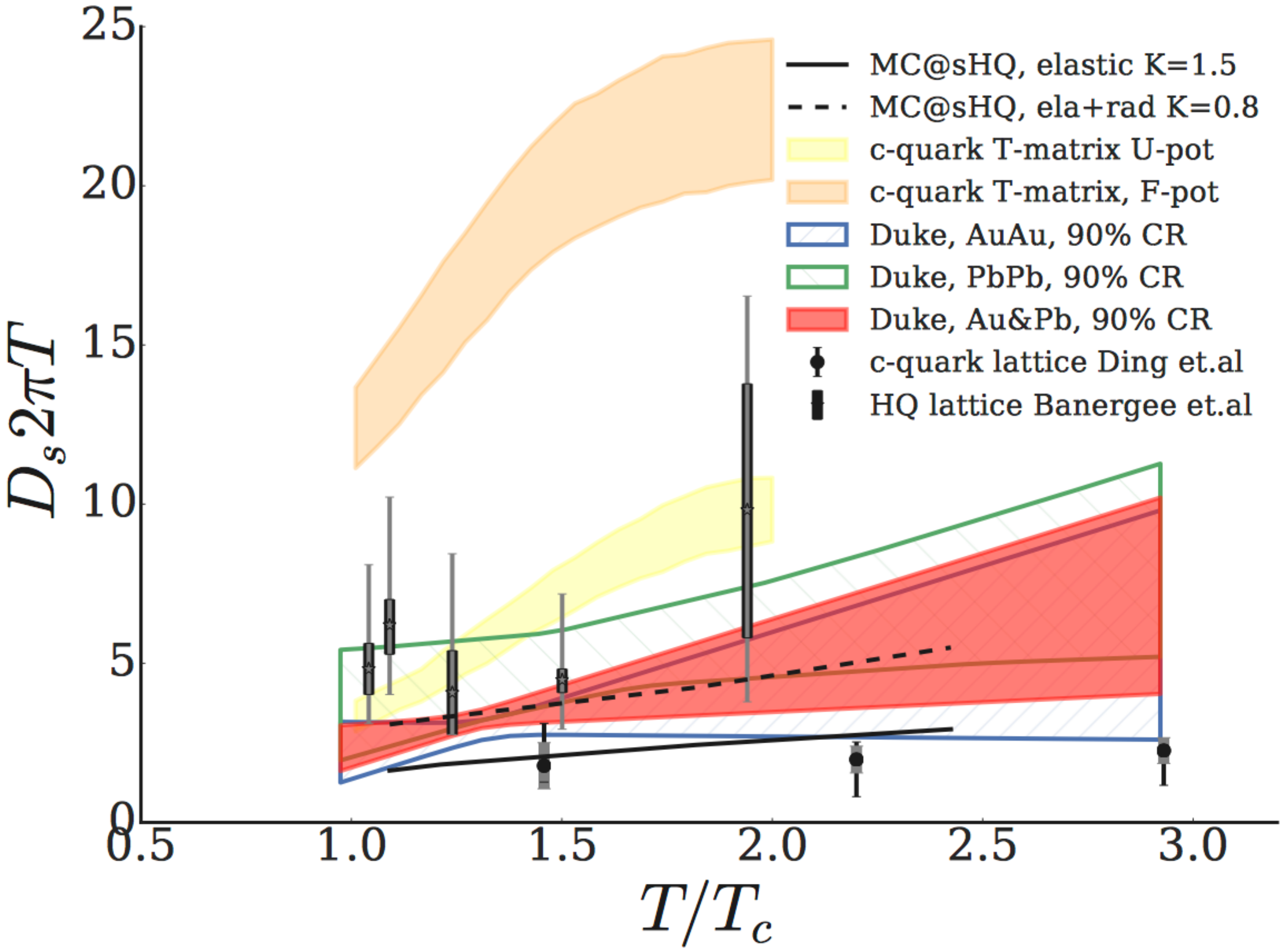


Theoretical model(s) reproduce the data (reasonably) well

arXiv:1506.06604

ALICE-PUBLIC-2017-004

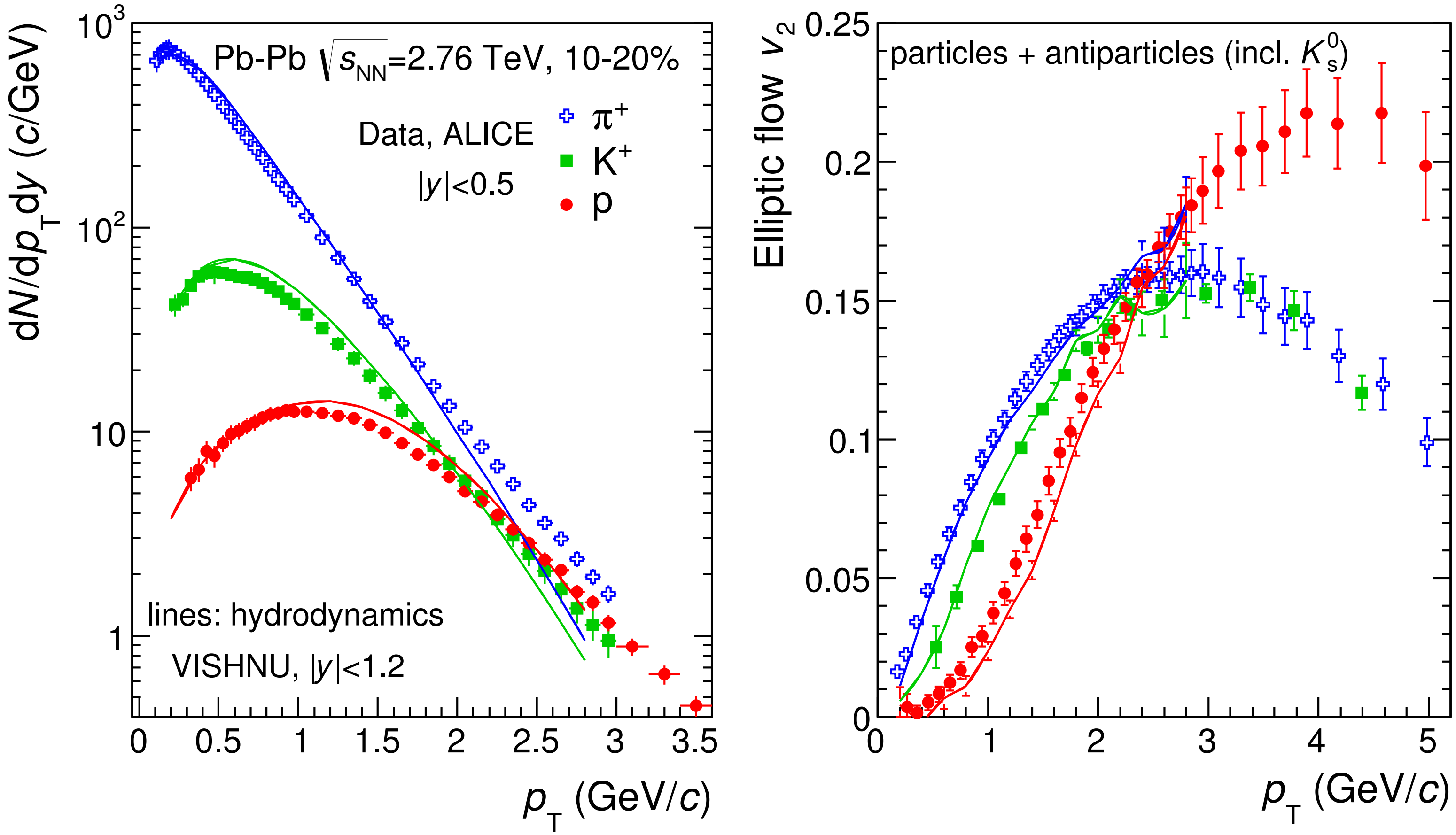
Charm diffusion coefficient



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

arXiv:1704.07800

Data and hydrodynamics



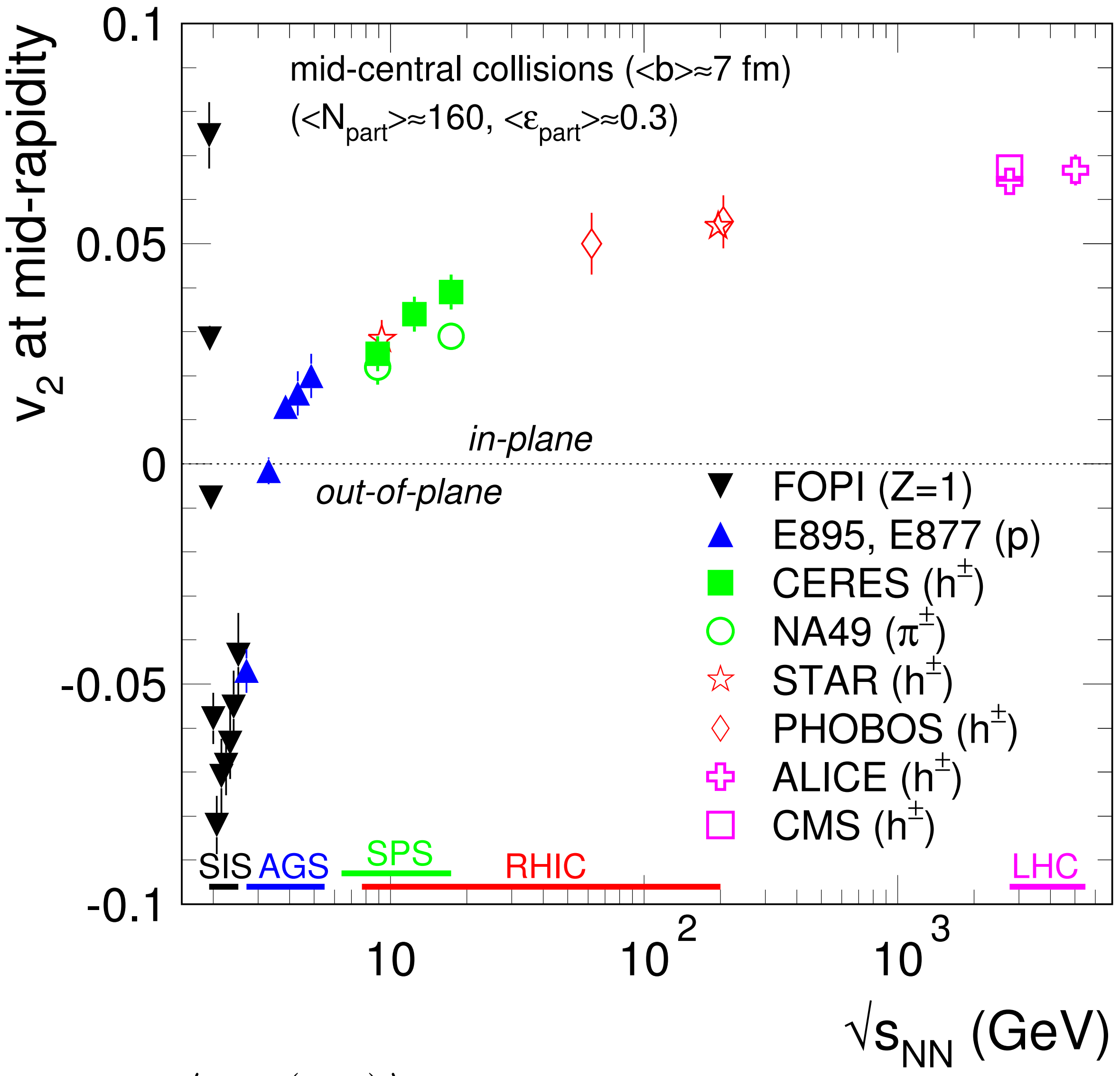
mass dependence due to collective flow

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

lower bound conjectured (AdS/CFT): $\eta/s \geq 1/4\pi$ Kovtun, Son, Starinets, hep-th/0405231

Elliptic flow: energy dependence

A. Andronic



$v_2 = \langle \cos(2\phi) \rangle$

3 regimes:

$v_2 > 0$ at low energies: in-plane, rotation-like emission

$v_2 < 0$ onset of expansion, in competition with shadowing by spectators (which act as a clock for the collective expansion, t_{pass}=40-10 fm/c)

$v_2 > 0$ at high energies: "free" fireball (almond-shape) expansion ("genuine" elliptic flow) Ollitrault, 1992

hydrodynamic description, low η/s