Experimental investigations of hot QCD matter

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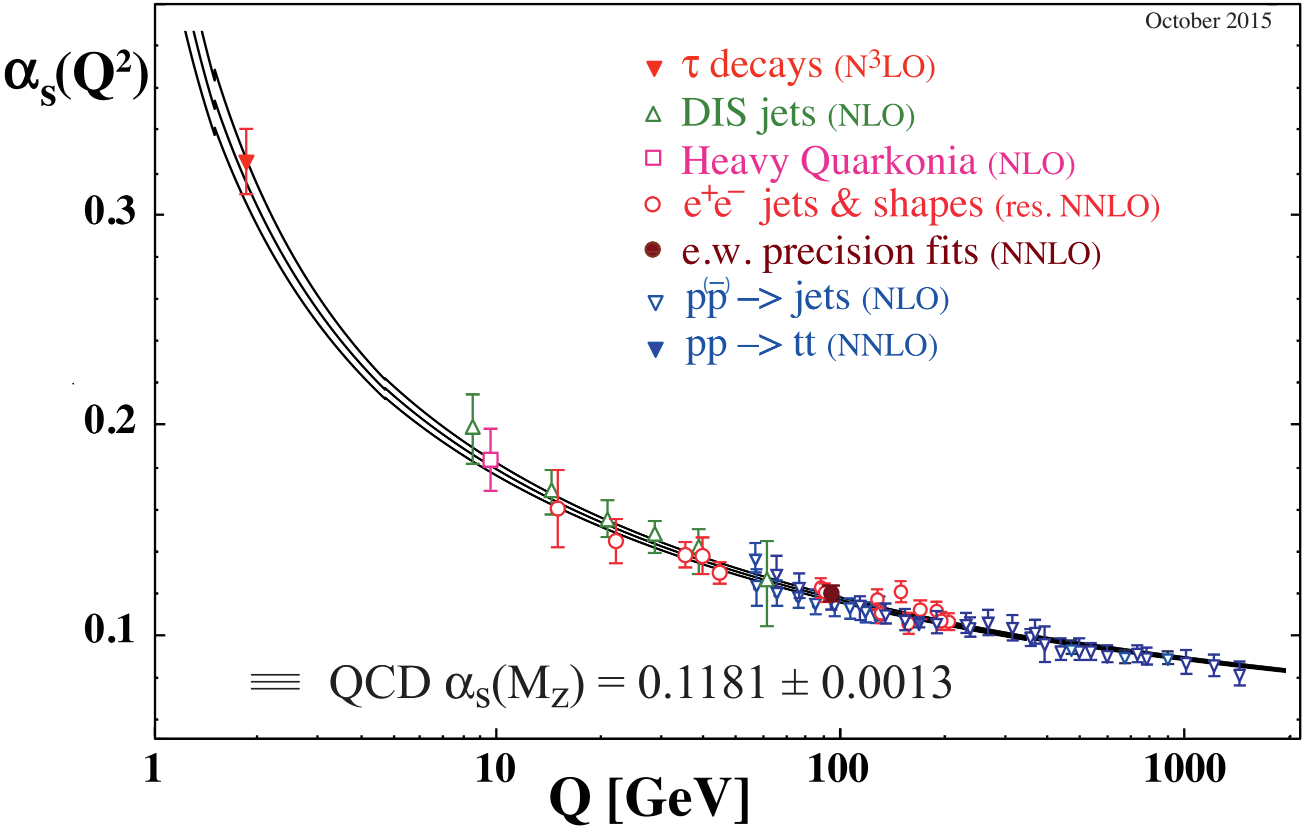
- Setting the stage
- Methods of producing hot QCD (quark-gluon) matter
- The LHC and the ALICE experiment
- Measurements with light-flavor (u,d,s) hadrons
  (heavy-flavors in the additional slides)
- Summary and outlook

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

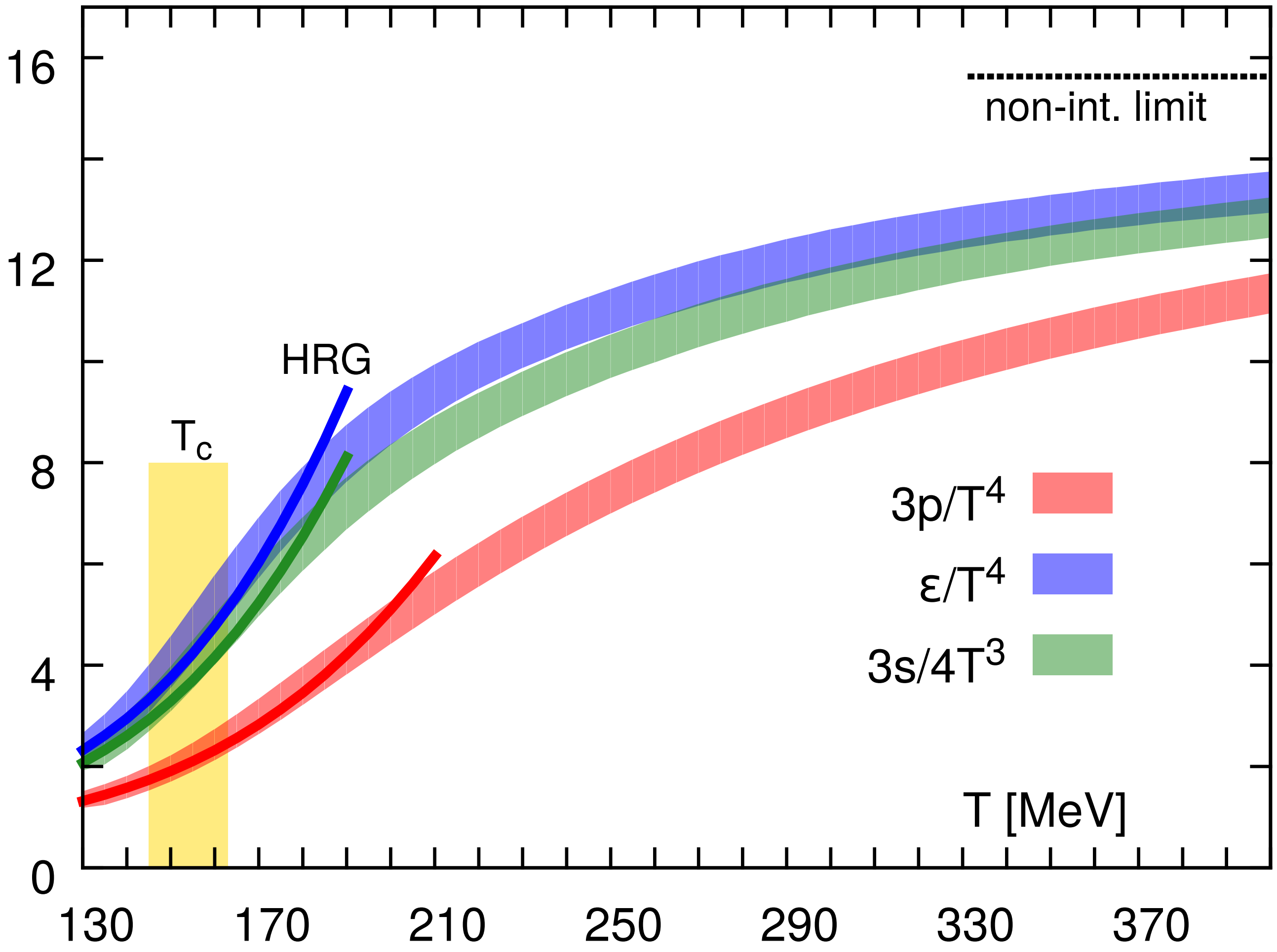
Low Q: confinement; α_s diverges at Λ_{QCD} ≃200 MeV

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)

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)

Setting the units straight

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$\hbar = h/2\pi$=6.582×10^{-22} MeV s

$\hbar c = 6.582 \times 10^{-22} \times 3 \times 10^{23} = 197.3$ 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 / $\hbar c = \frac{1}{137} = \alpha$

Natural units: $\hbar = c = 1$

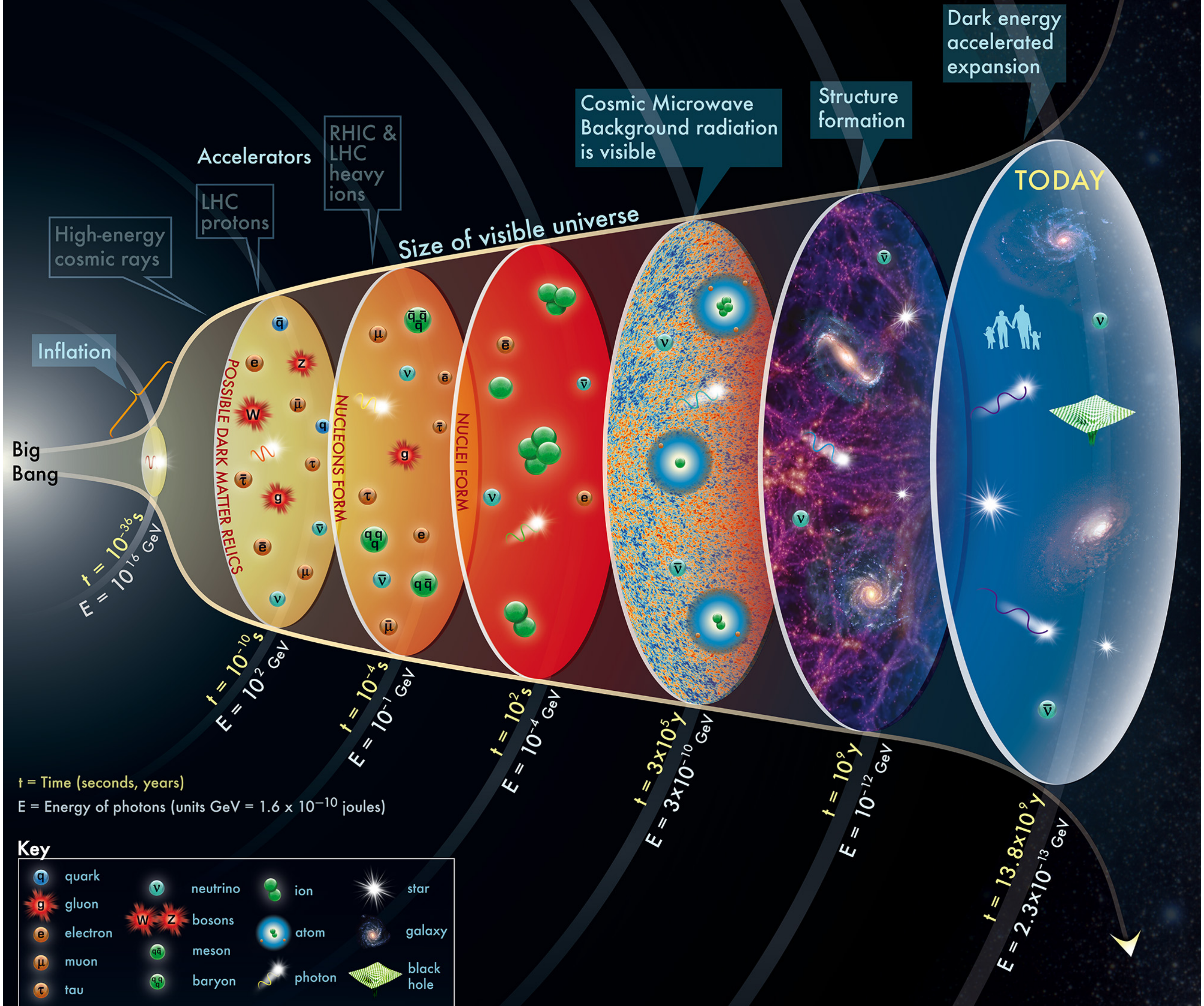
In this system: [m]=[E]=[p]=[L]$^{-1}$=[t]$^{-1}$

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

$$1\,\mathrm{s} = 3 \times 10^{23}\,\mathrm{fm};\ 1\,\mathrm{m} = 5.07 \times 10^{6}\,\mathrm{eV}^{-1}$$

...this is why energy density $\varepsilon = E/V$ has units of T^4 (k_B=1 too:)

HISTORY OF THE UNIVERSE



Big Bang

Inflation

High-energy cosmic rays

Accelerators

LHC protons

RHIC & LHC heavy ions

Size of visible universe

Cosmic Microwave Background radiation is visible

Structure formation

Dark energy accelerated expansion

TODAY

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

$t = 3\text{x}10^{5}$ y
$E = 3\text{x}10^{-10}$ GeV

$t = 10^{9}$ y
$E = 10^{-12}$ GeV

$t = 13.8\text{x}10^{9}$ y
$E = 2.3\text{x}10^{-13}$ GeV

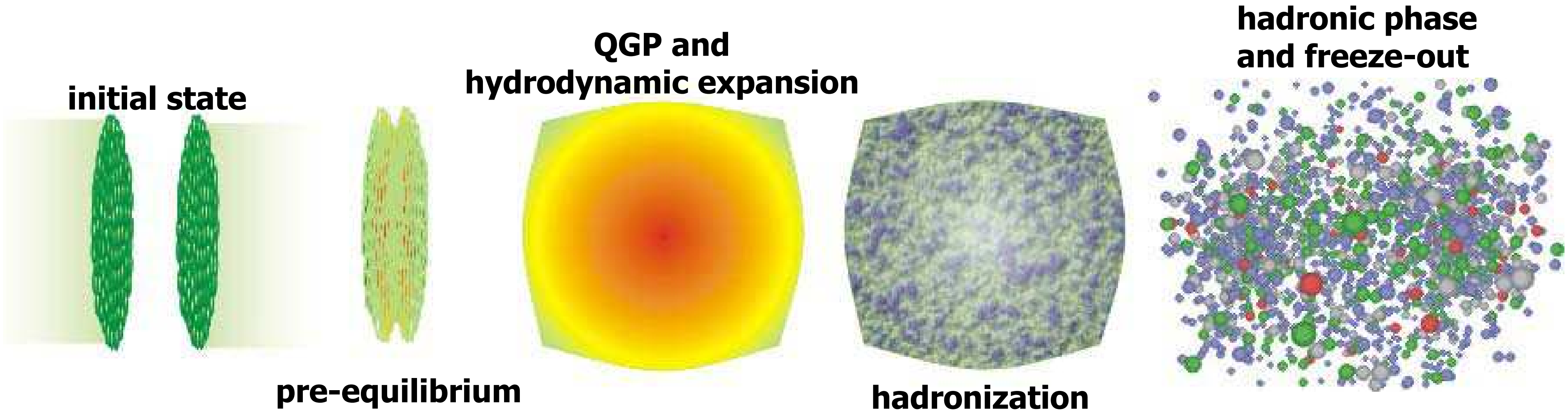
t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)

Key

- q quark
- g gluon
- e electron
- μ muon
- τ tau
- ν neutrino
- W Z bosons
- $q\bar{q}$ meson
- qqq baryon
- ion
- atom
- photon
- star
- galaxy
- black hole

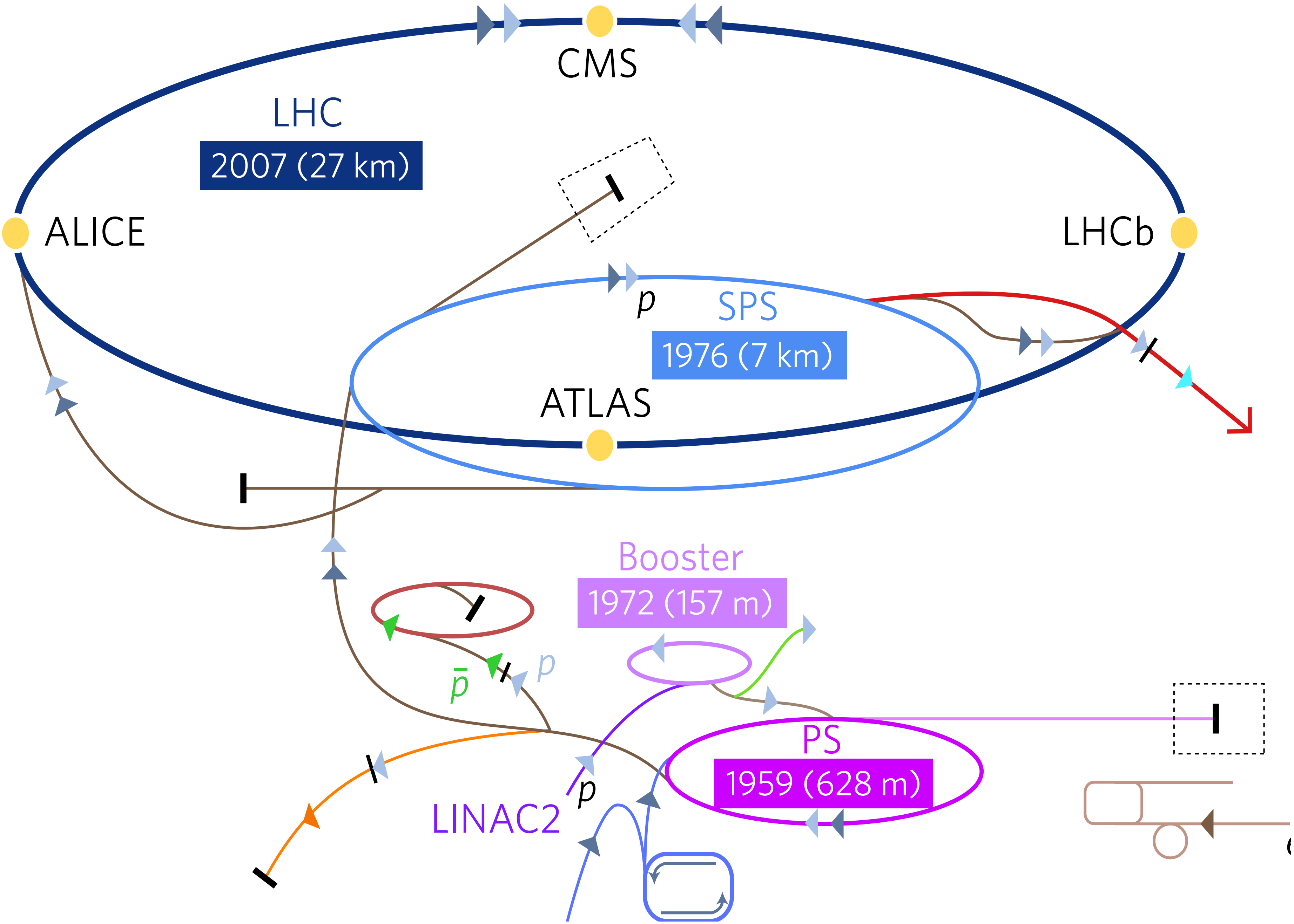
How to "simulate" in laboratory the early Universe?



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

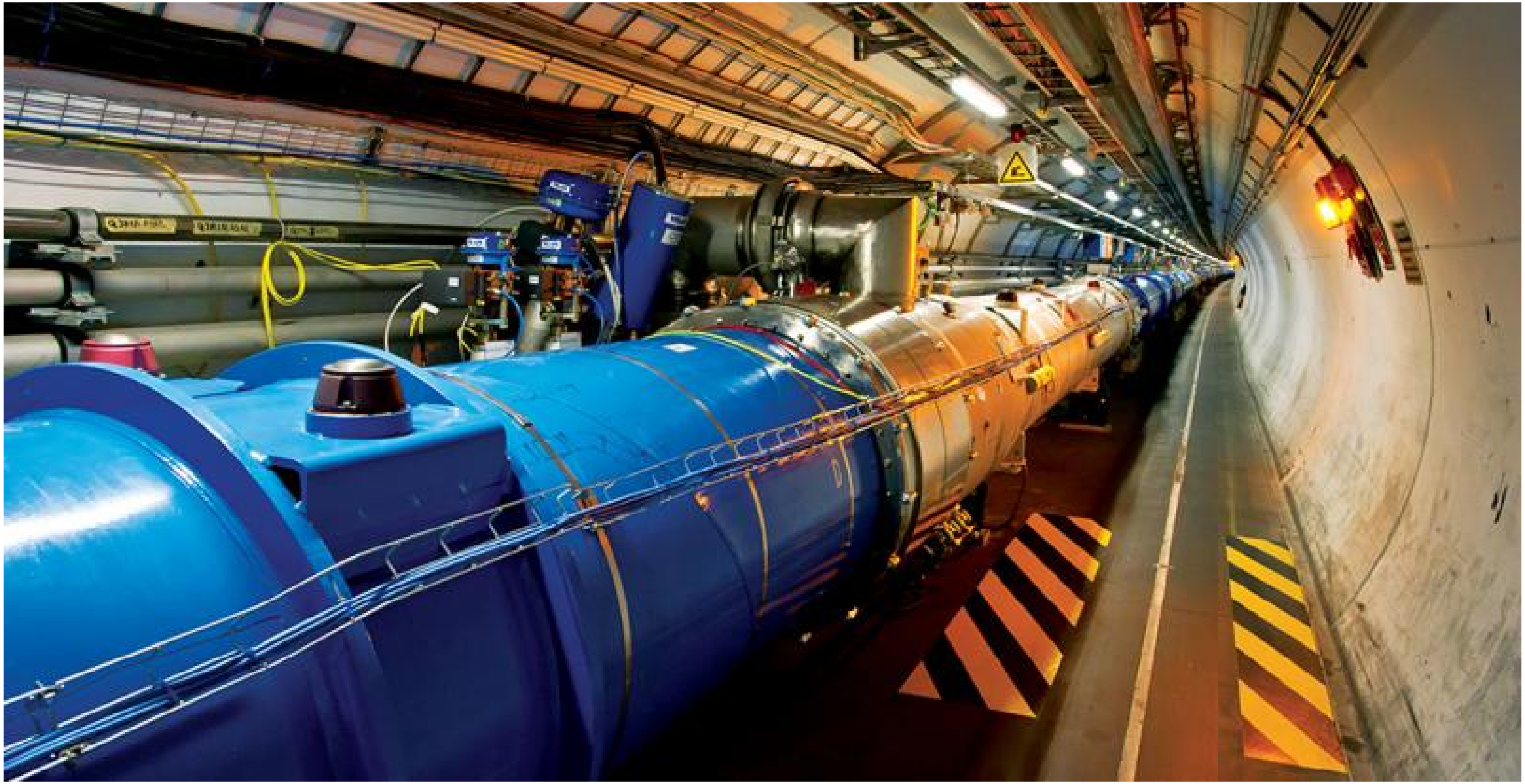
1. initial collisions ($t \leq t_{coll} = 2R/\gamma_{\rm cm}c$; $R_{Pb} \simeq$7 fm)
2. thermalization: equilibrium is established ($t \lesssim$ 1 fm/c $= 3 \times 10^{-24}$ s)
3. expansion ($\sim 0.6c$) and cooling ($t <$ 10-15 fm/c) ...deconfined stage?
4. hadronization (quarks and gluons form hadrons)
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



The accelerator complex at CERN

The Large Hadron Collider at CERN



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 ($H \to \gamma\gamma$; ATLAS, CMS, 2012)

Nobel Prize Higgs, Englert, 2013

A detector at the LHC - ALICE

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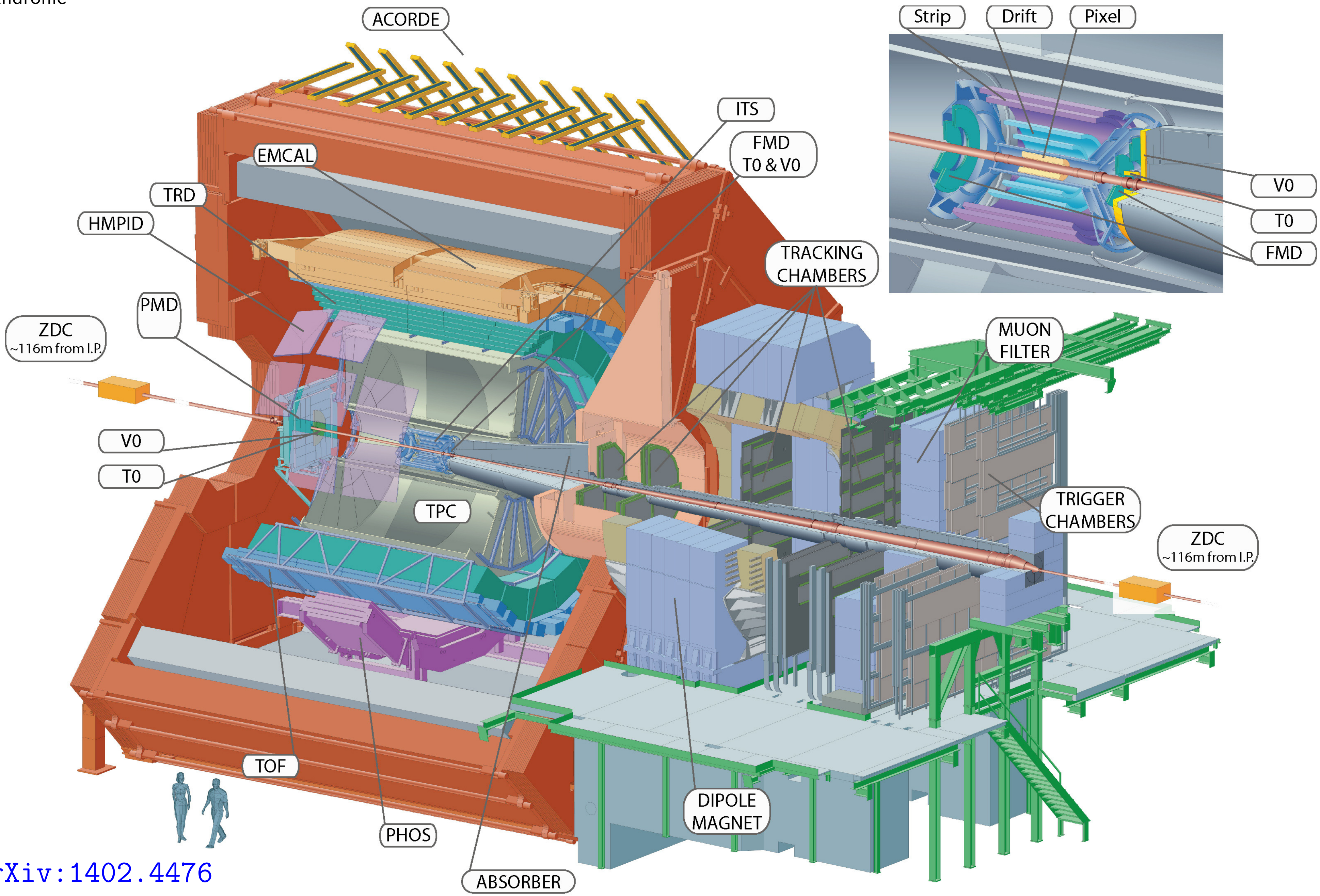


arXiv:1402.4476

ALICE Collaboration: 37 countries, 160 institutions, 1600 members

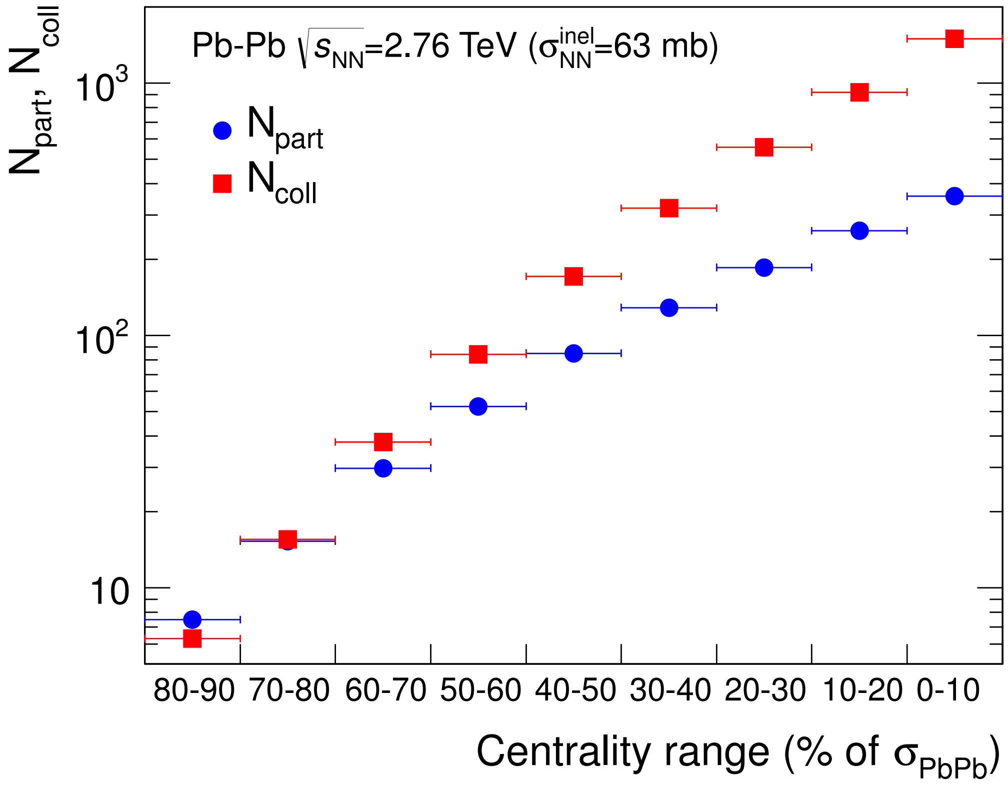
What are the ”control parameters”

- 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



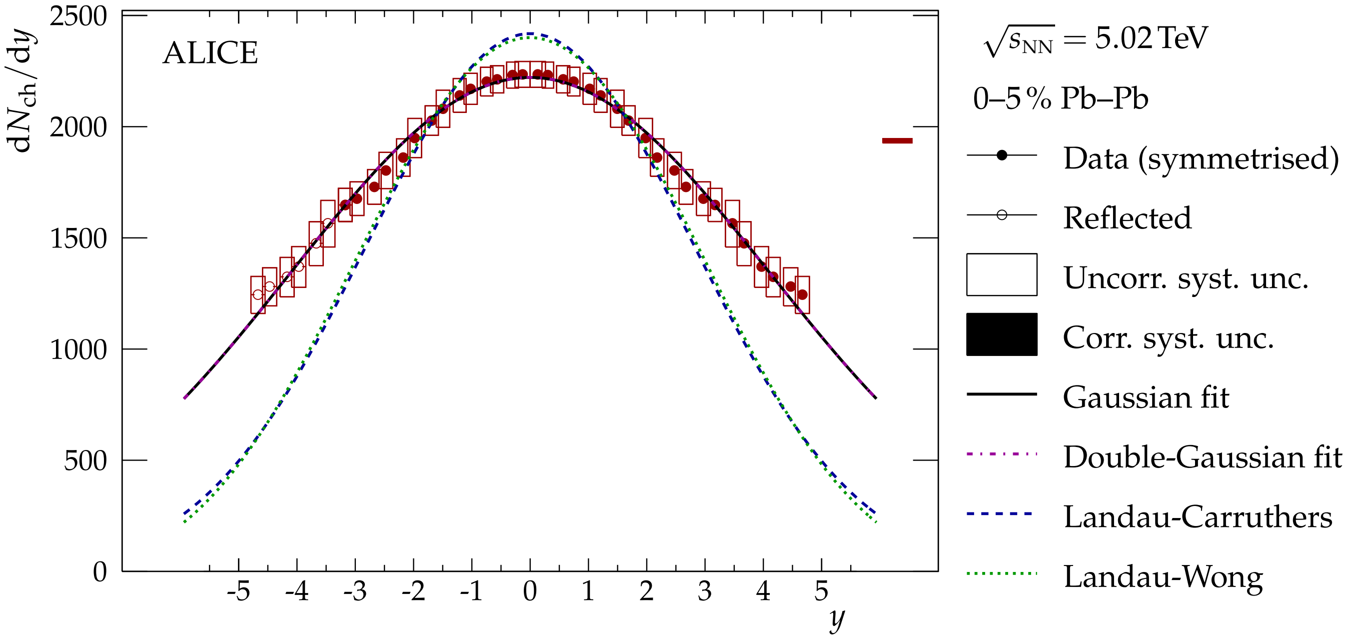
...while often taking as reference the measurement in proton-proton collisions (at the same energy), for “hard probes” (pQCD) scaled by the number of collisions corresponding to the given centrality class

What we measure

Production yields and correlations as a function of kinematic quantities:

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

  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)

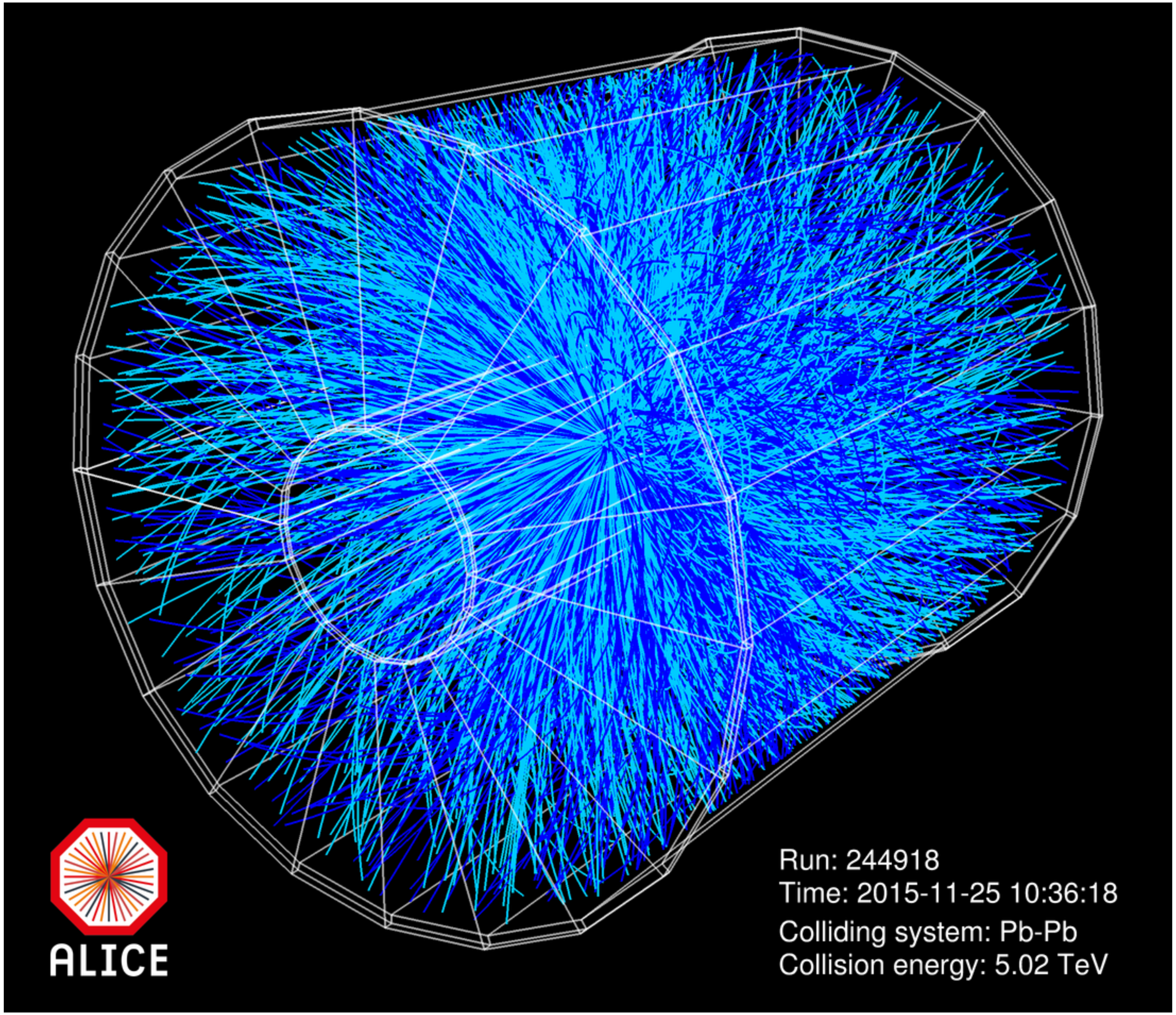
we need many collisions (millions), to sample properly the distributions

- 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 transversal direction ($y, \eta \simeq 0$), to separate from the beam movement

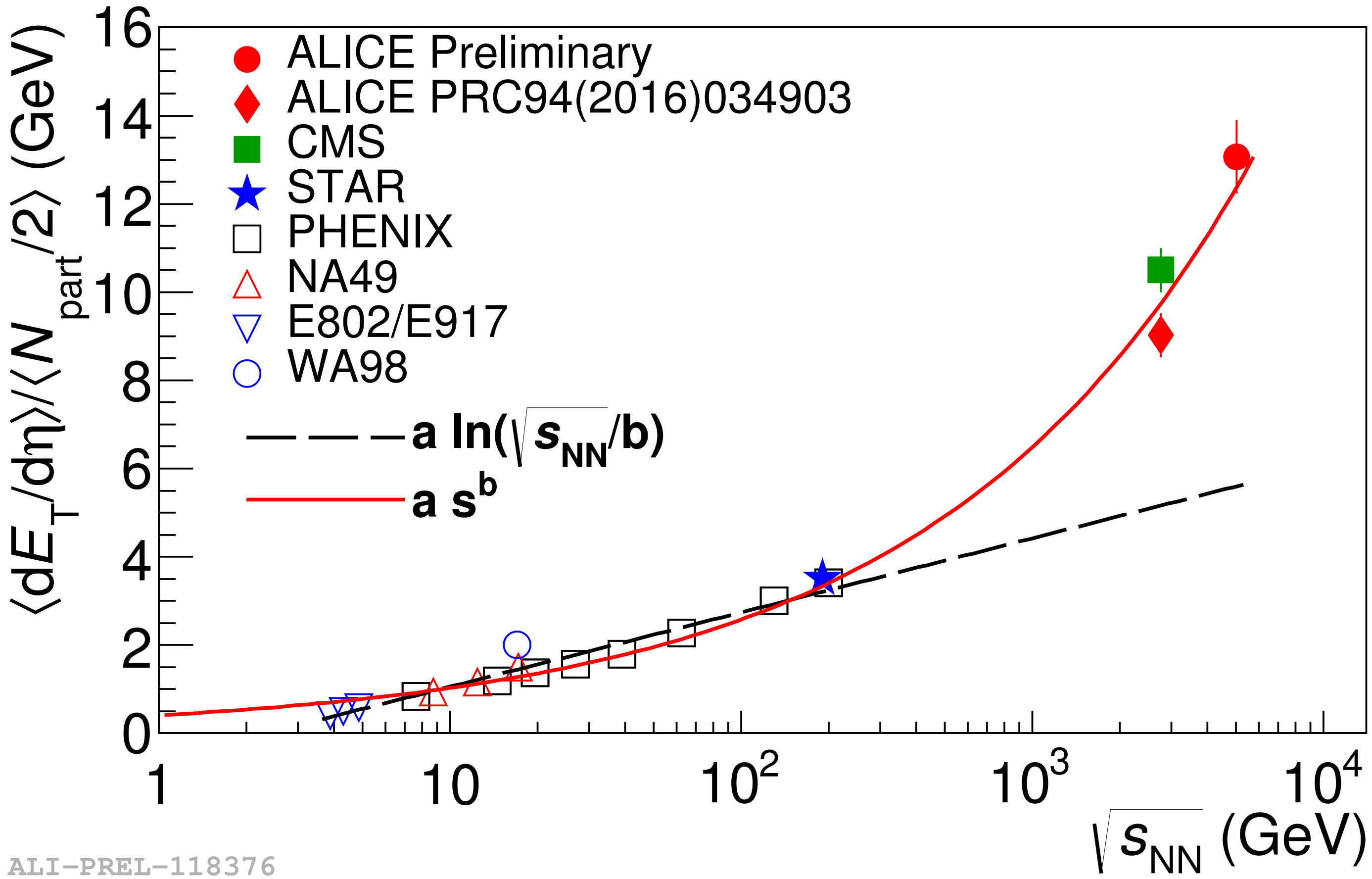
single-particle detection efficiency: about 70-80%

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)

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)

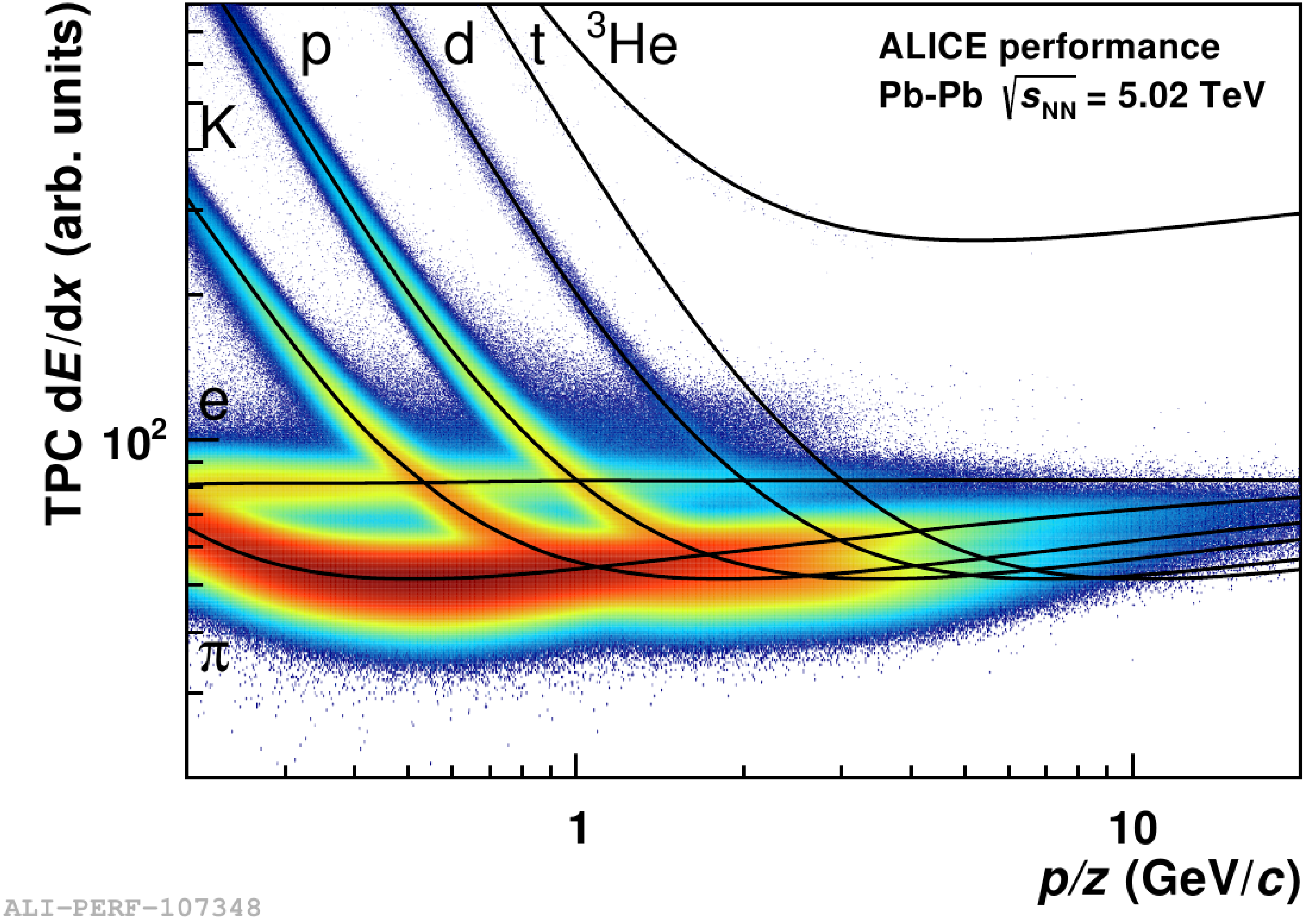
$\varepsilon_{FAIR} \lesssim 1$ GeV/fm^3 (around ε_c)

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

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

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

Particle identification

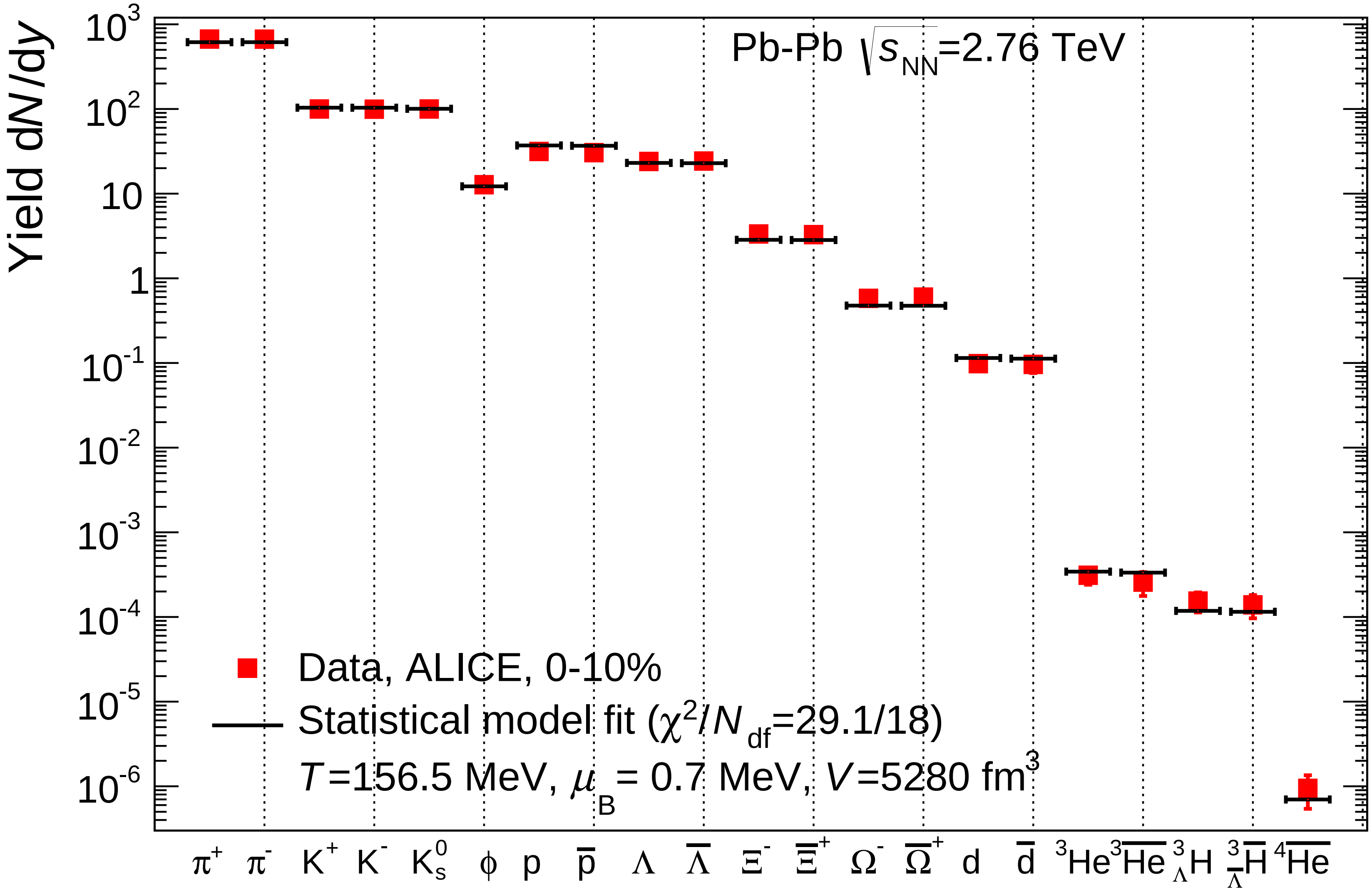


dE/dx: truncated mean of 159 samples along a track; resolution: 5.8%

lines: Bethe-Bloch parametrizations particles and antiparticles are shown

From quarks and gluons to hadrons

Matter and antimatter are produced in equal amounts in high-energy Pb-Pb collisions (LHC)



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

Thermal fits of hadron abundances

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

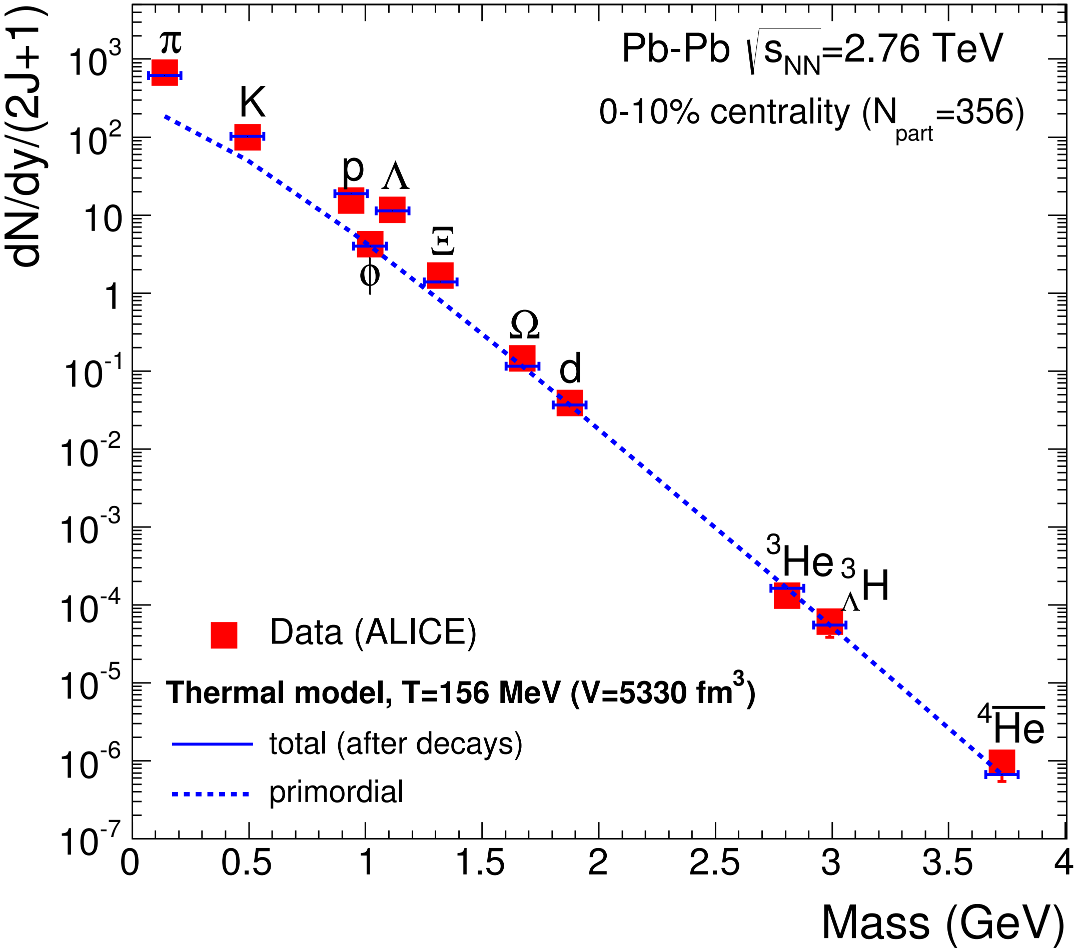
quantum nr. conservation ensured via chemical potentials:

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

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 ⇒ $(T,\ \mu_B,\ V)$



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

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

Overview of hadron production

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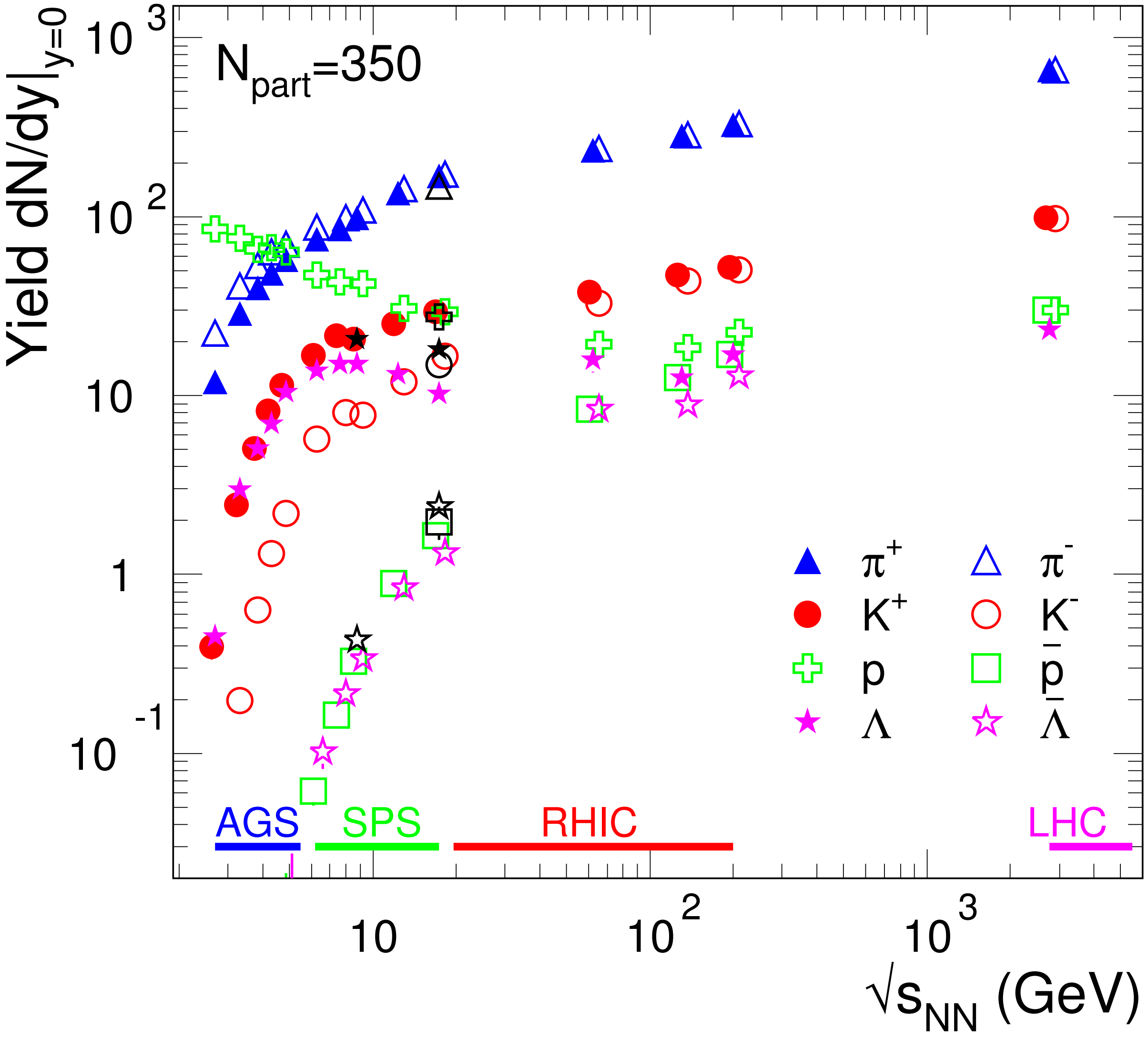
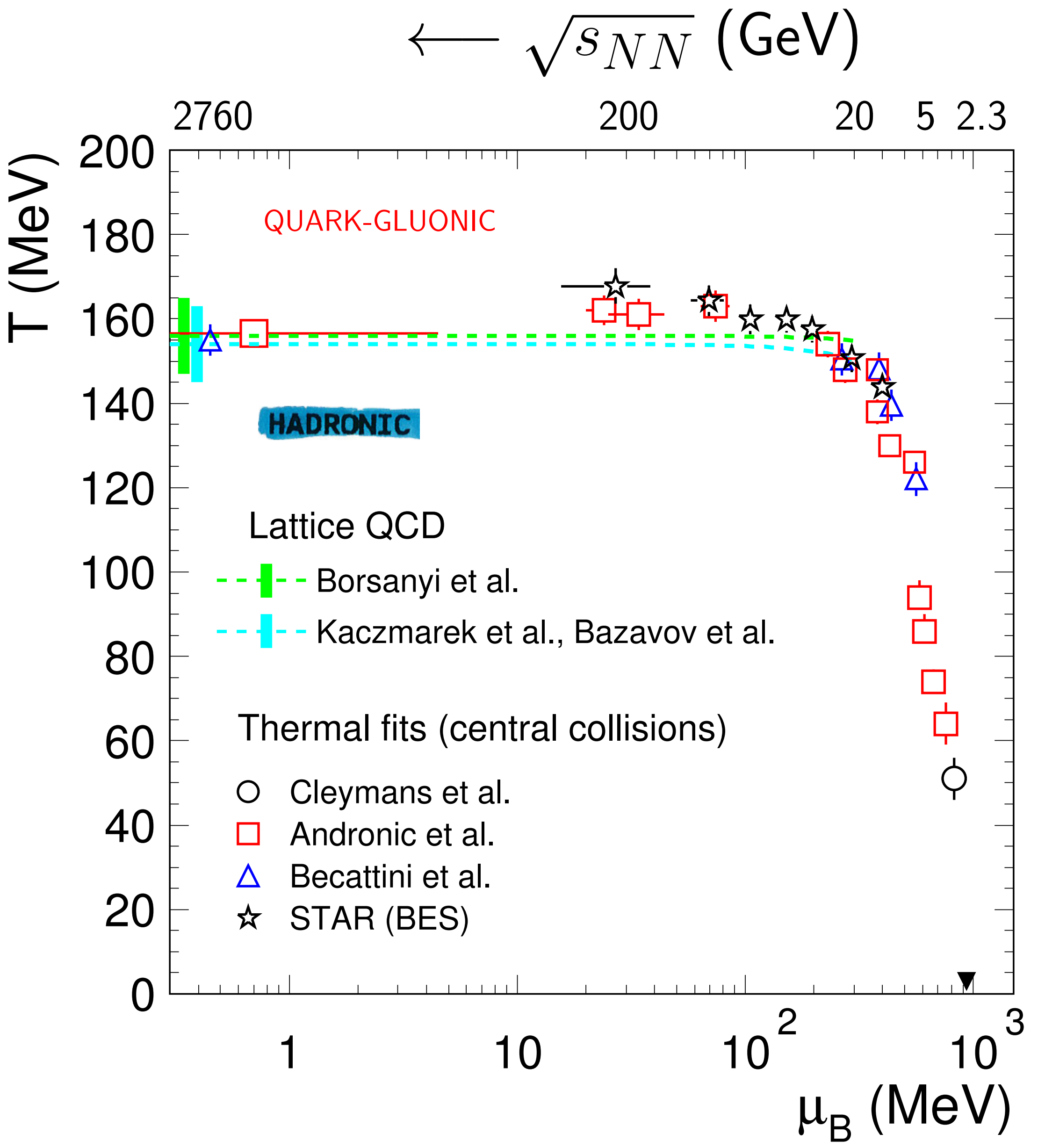


- lots of particles, mostly newly created ($m = E/c^2$)
- a great variety of species:

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

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

Probing early stages

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

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

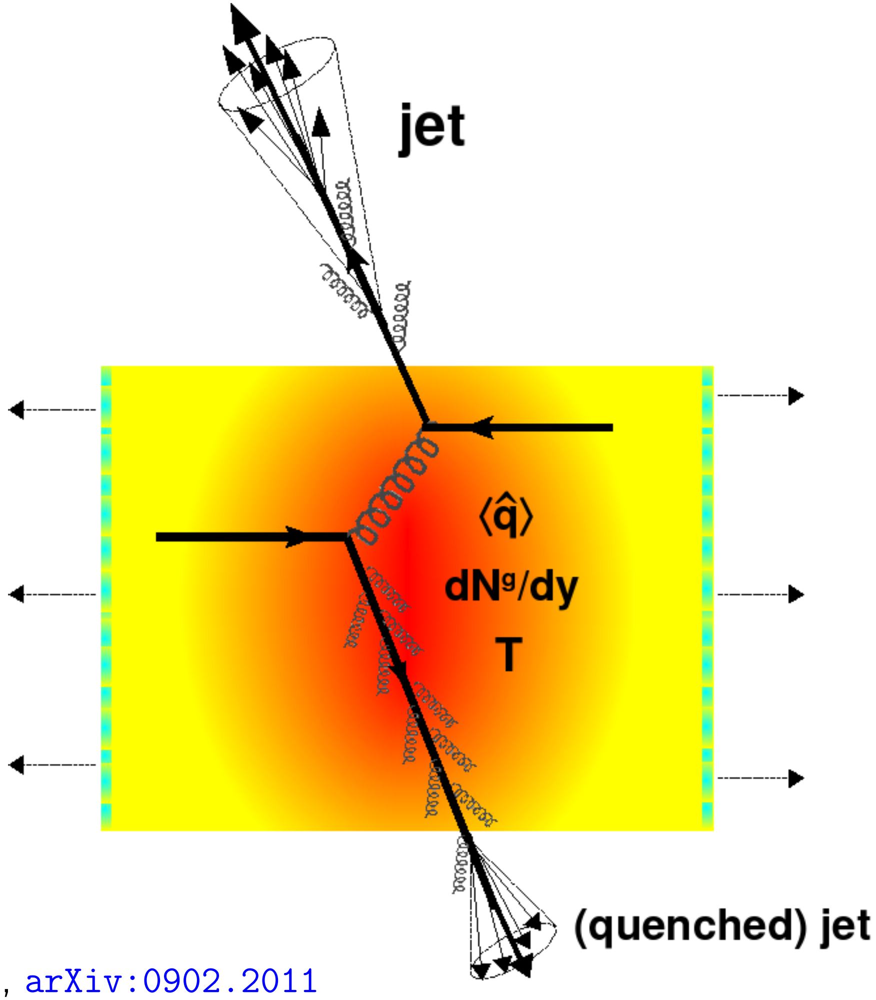
(jets - sprays of hadrons from high-speed quarks)

- $q, \bar{q}, g$ 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:

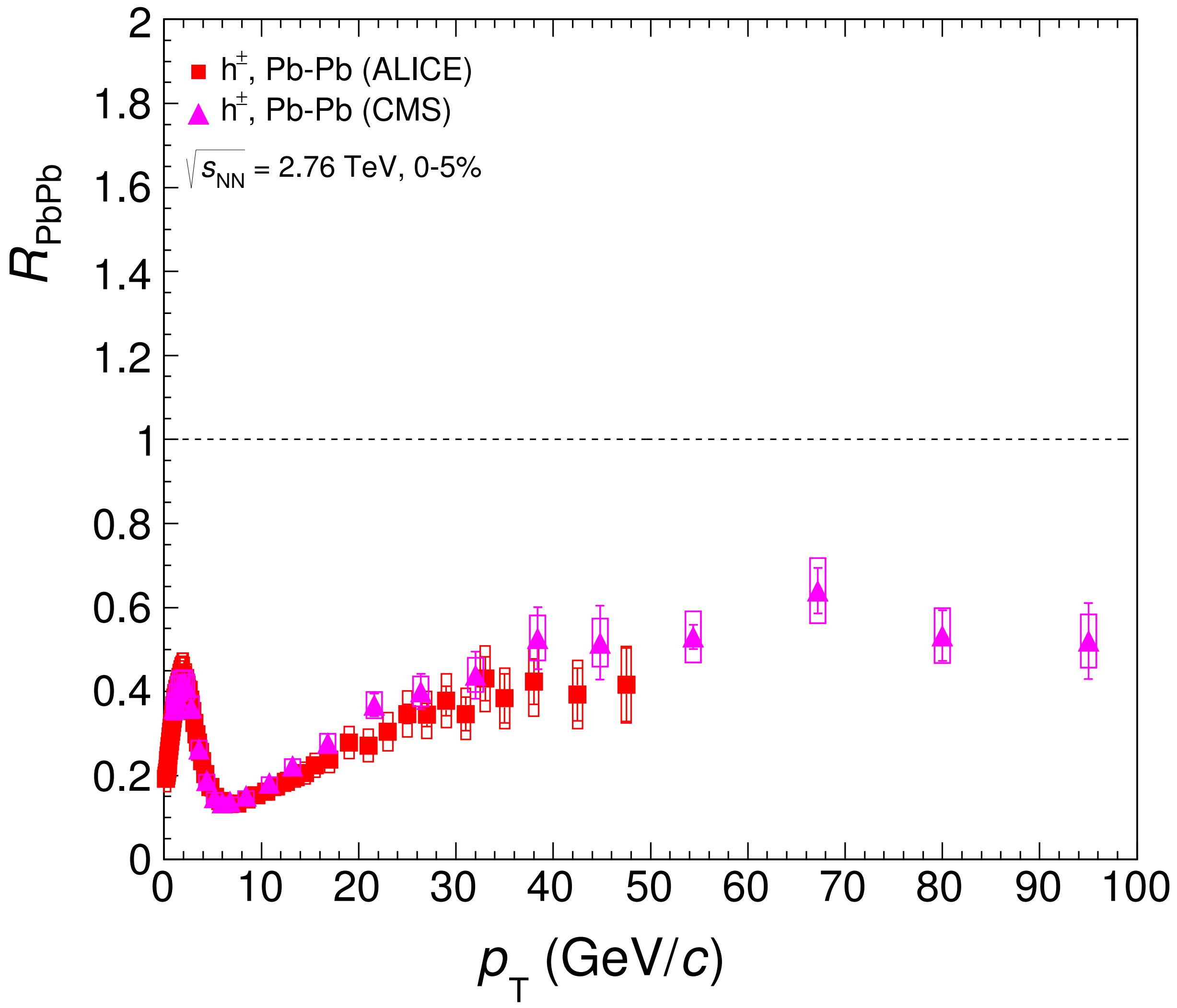
$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{N_{coll}\cdot\mathrm{d}N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$



D. d'Enterria, arXiv:0902.2011

Jet quenching at the LHC

...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

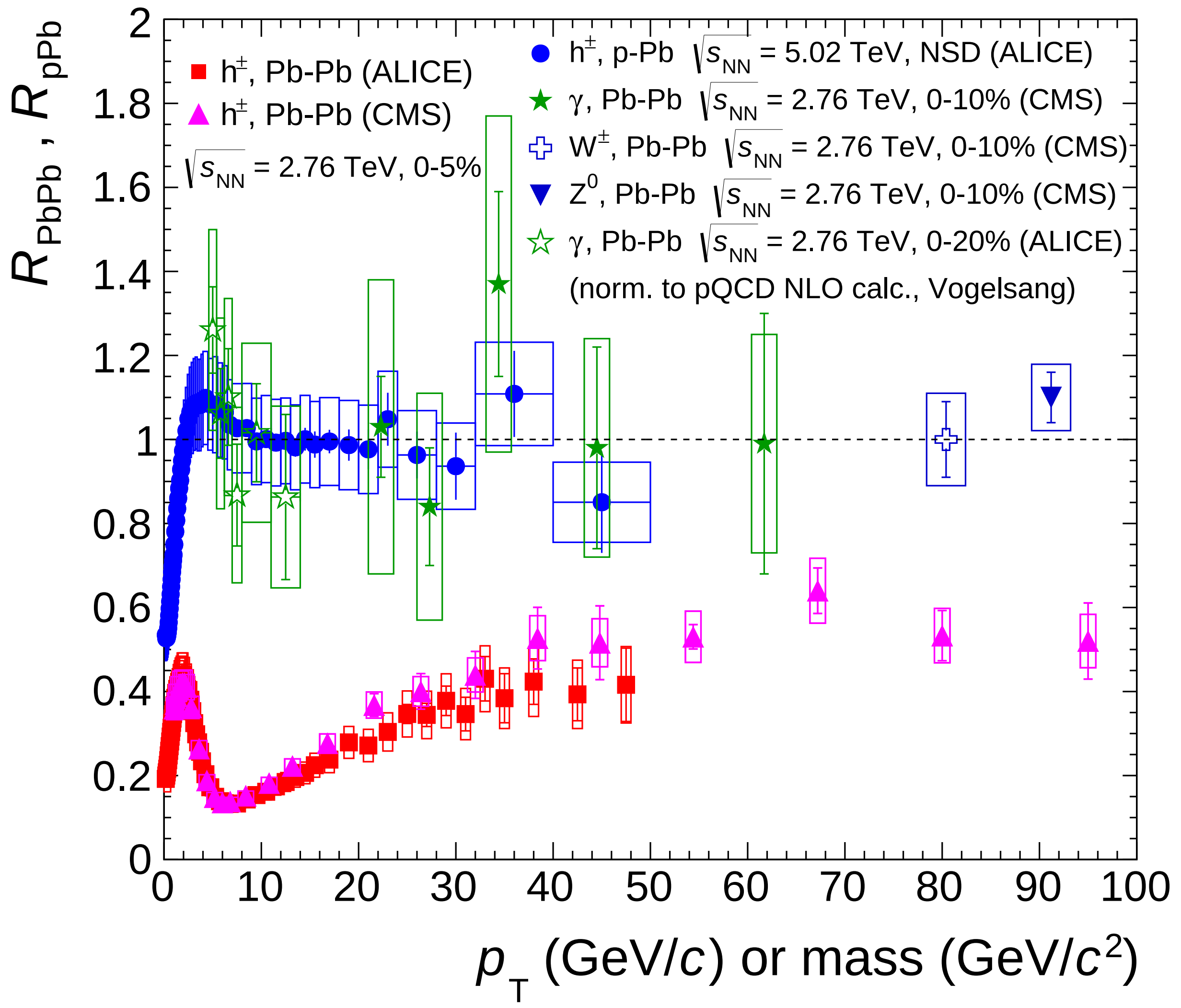
strong suppression, reaching a factor of ∼7, $p_{\mathrm{T}} \simeq 7$ GeV/c

remains substantial even at 50-100 GeV/c

seen also with reconstructed jets (...done in Münster:)

Jet quenching at the LHC

...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

...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

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

Summary of things not discussed

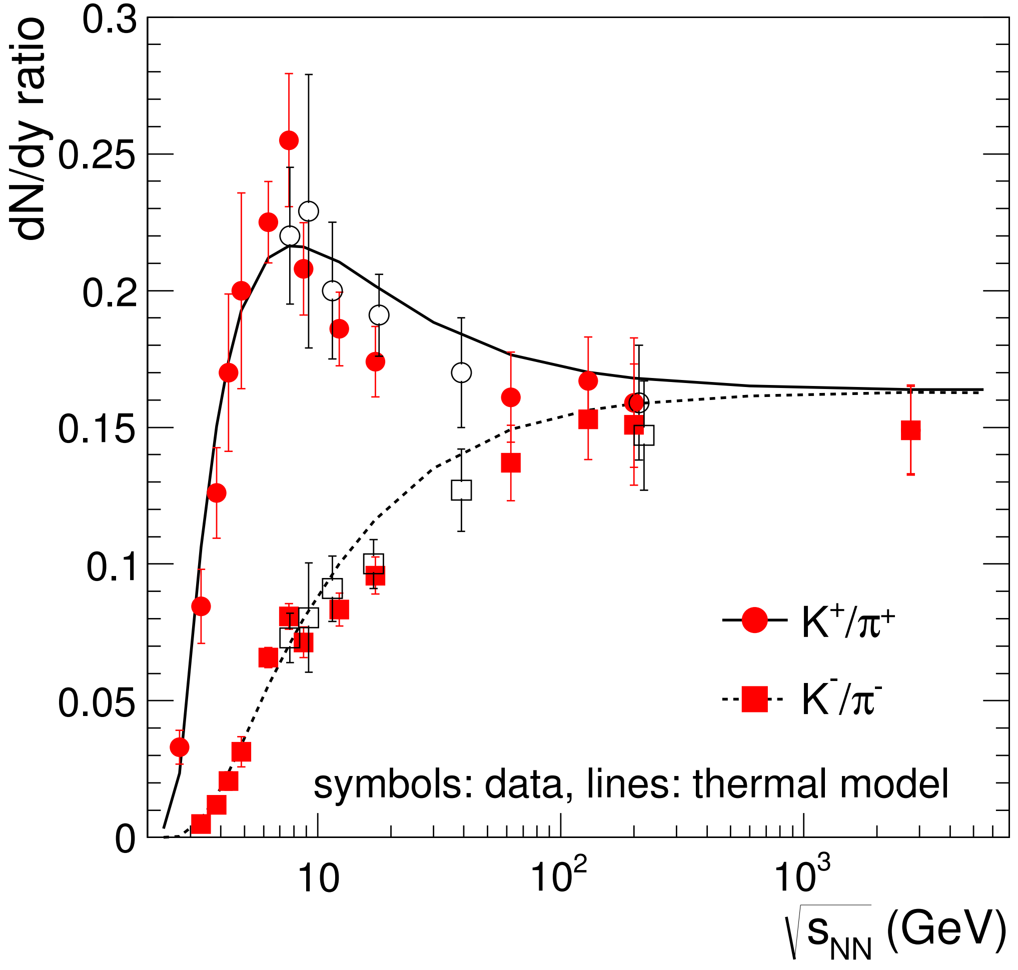
...but available in the following additional slides

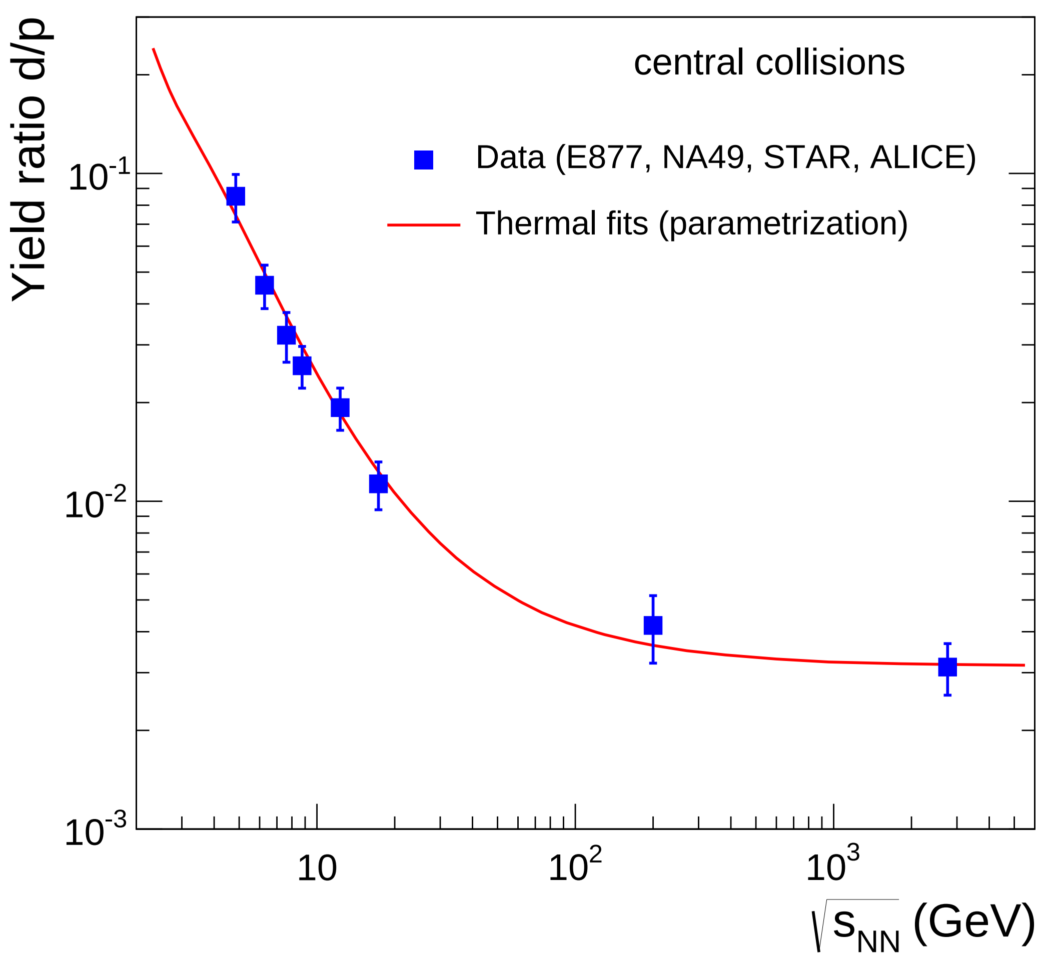
- jet quenching data (for light and heavy-flavor) hadrons described by theoretical models; allows extraction of transport coefficients (in range $T = (1-3)T_c$)
- we see (re)combination of charm quarks at the LHC ...either over the full history of QGP or at the phase boundary ...conclusion expected with the ALICE upgrade (Run 3, Run 4)
- 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

A "global" look (ratios)

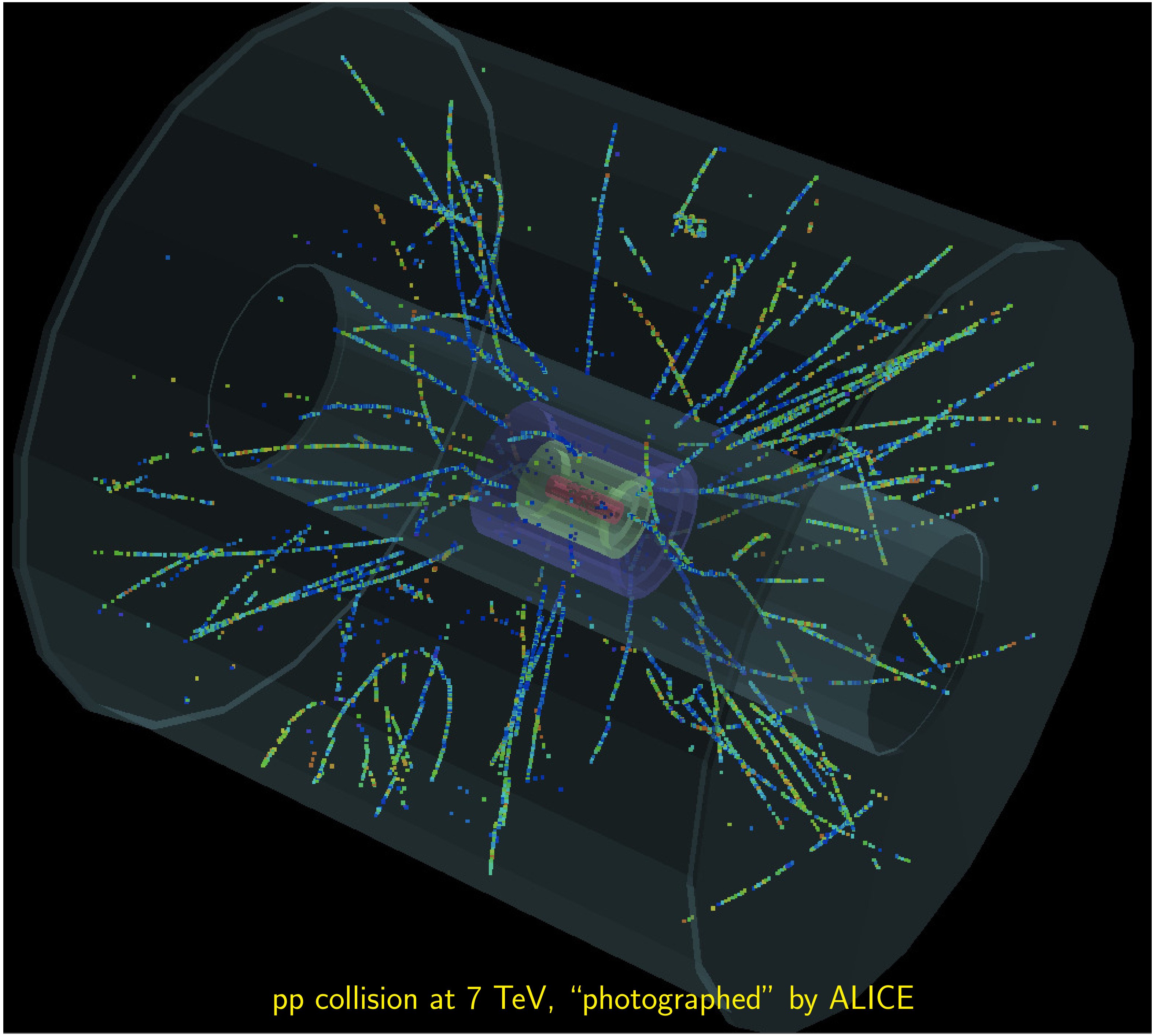




the statistical description works well over a broad range of collision energies (for all hadrons measured)

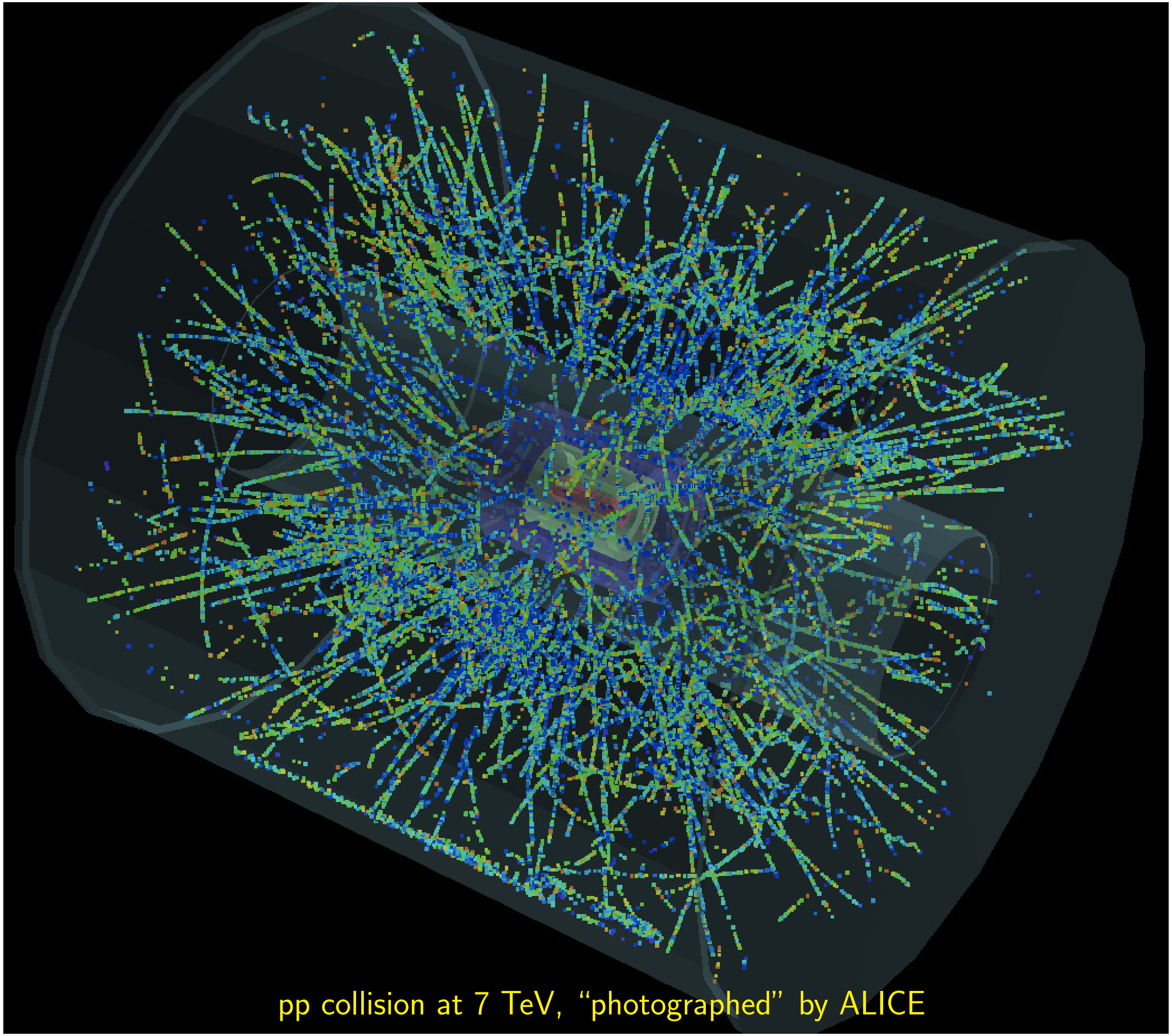
is this a (or the?) universal production mechanism?

Proton collisions at the LHC



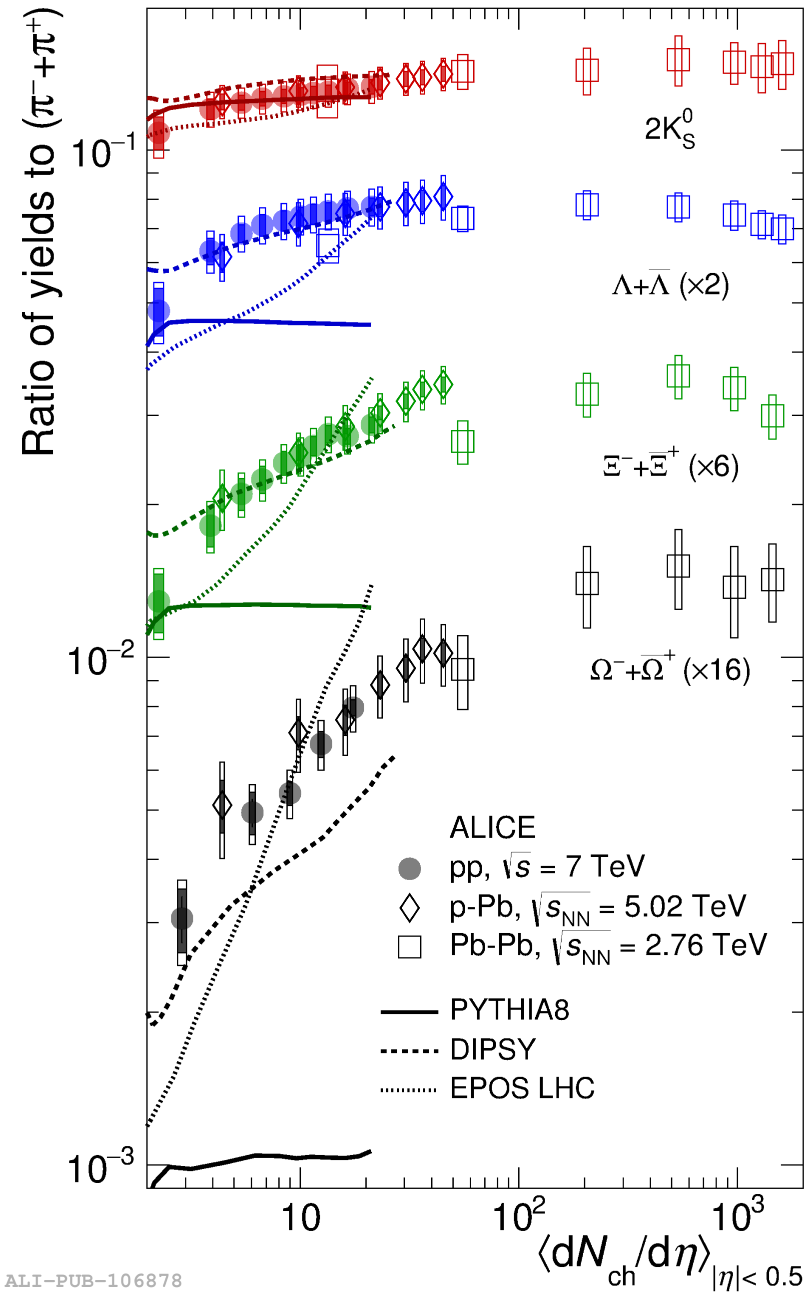
pp collision at 7 TeV, “photographed” by ALICE

Proton collisions at the LHC



pp collision at 7 TeV, “photographed” by ALICE

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

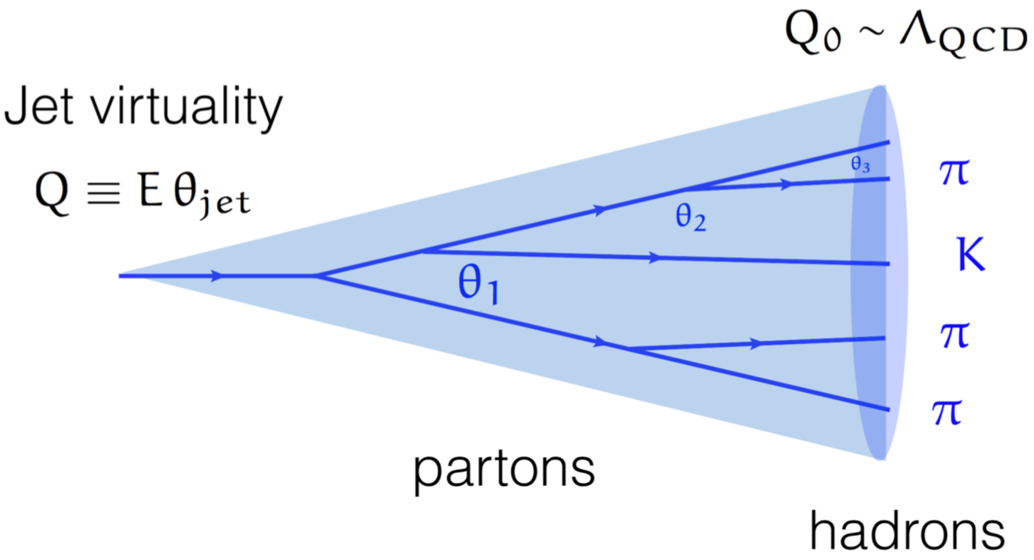
...new ideas are being put forward

Fischer, Sjöstrand, arXiv:1610.09818

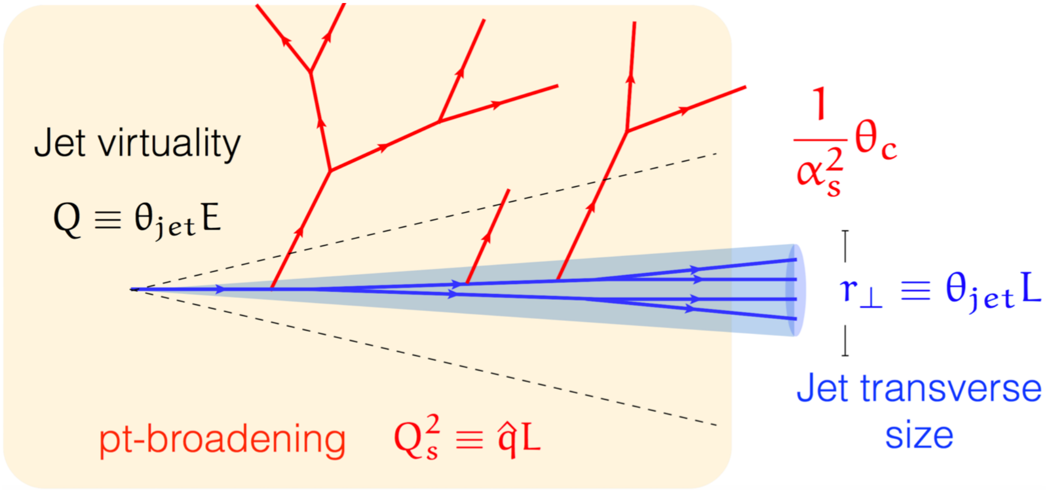
“thermodynamical string fragmentation”

Jets

...in vacuum



...in medium



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

Y. Mehtar-Tani, arXiv:1602.01047

Jet quenching: transport coefficient

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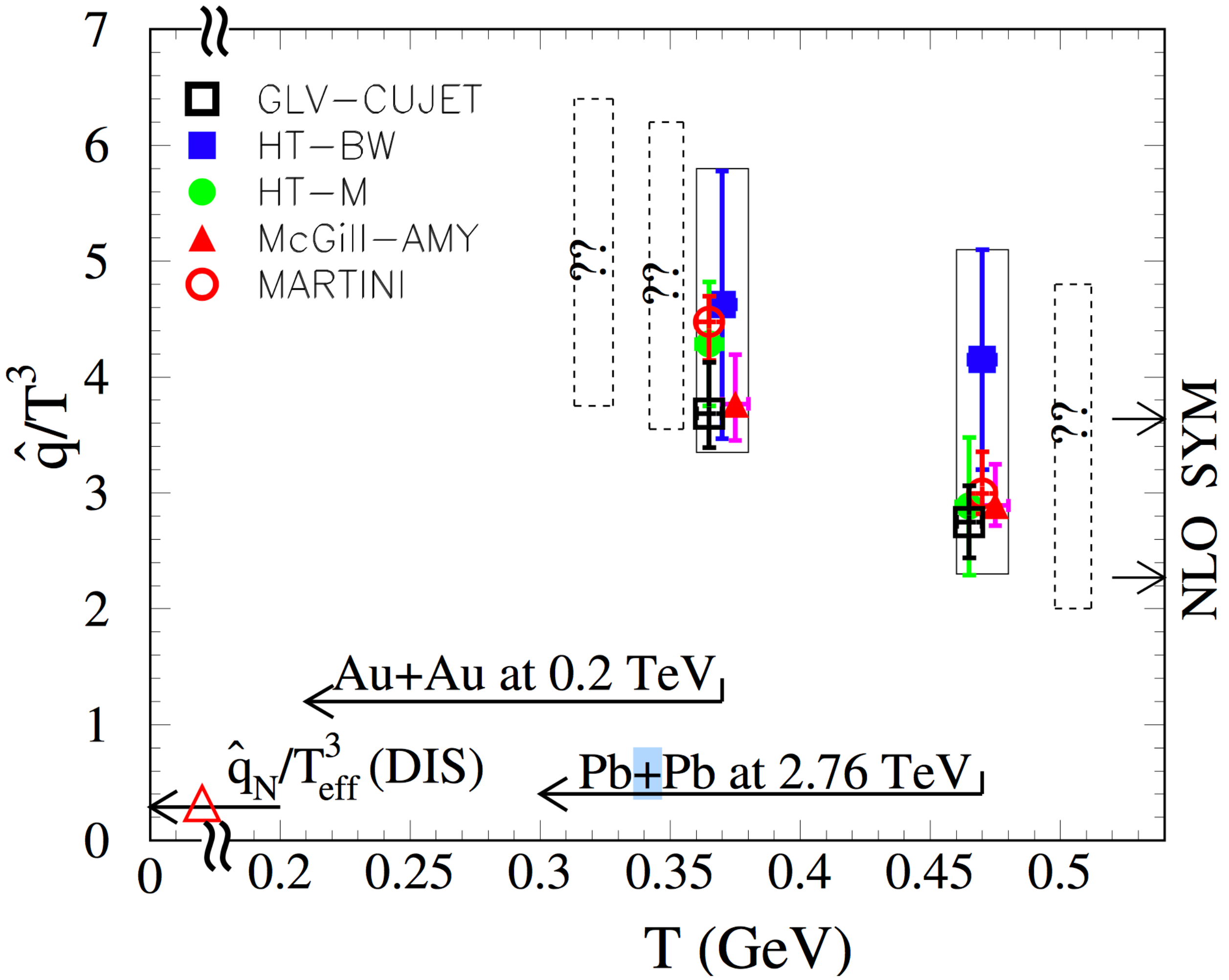

An initial quark with energy of 10 GeV at the center of a most-central A–A collision

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

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

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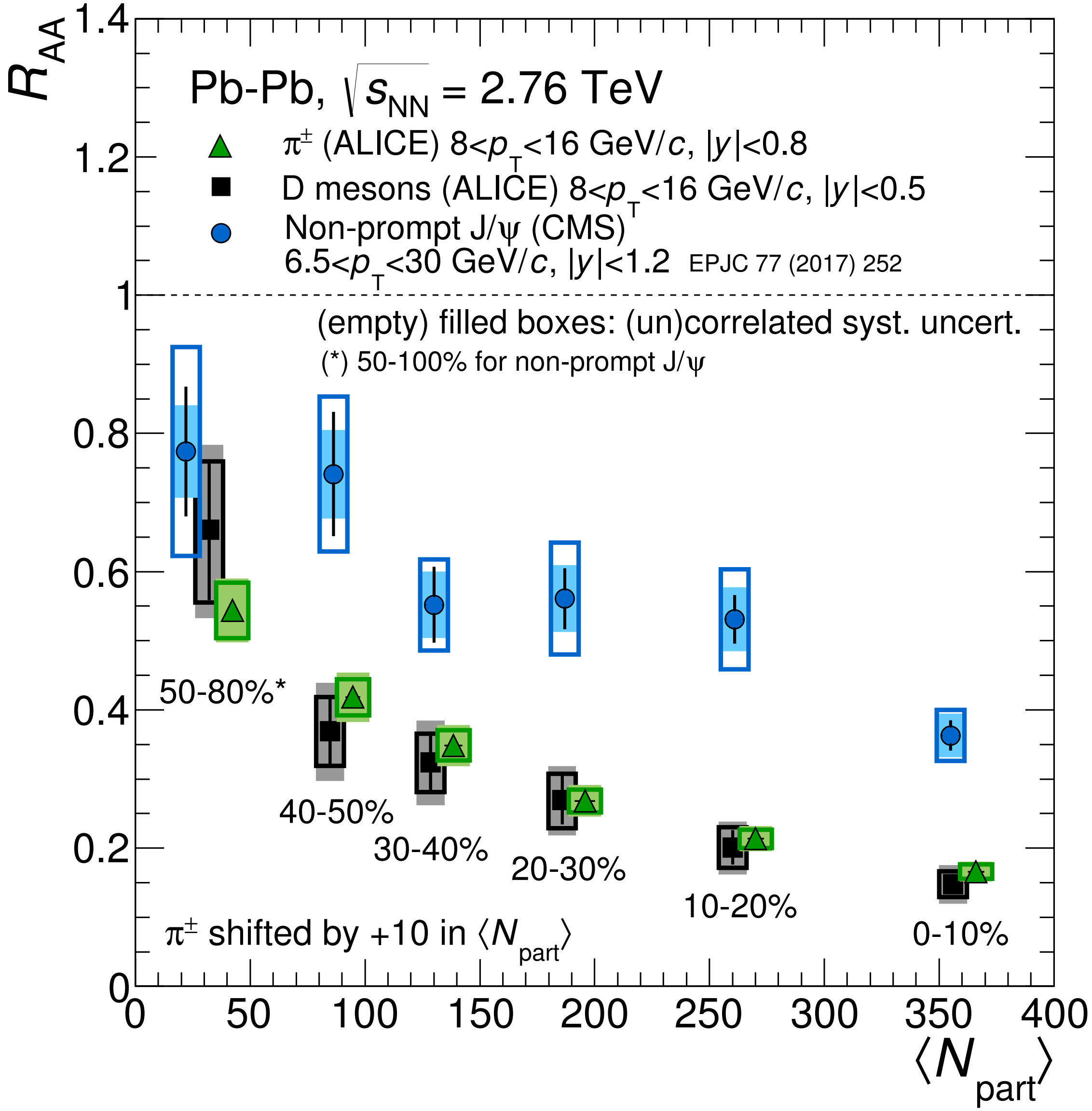


D mesons are as much suppressed as pions at high p_T

...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

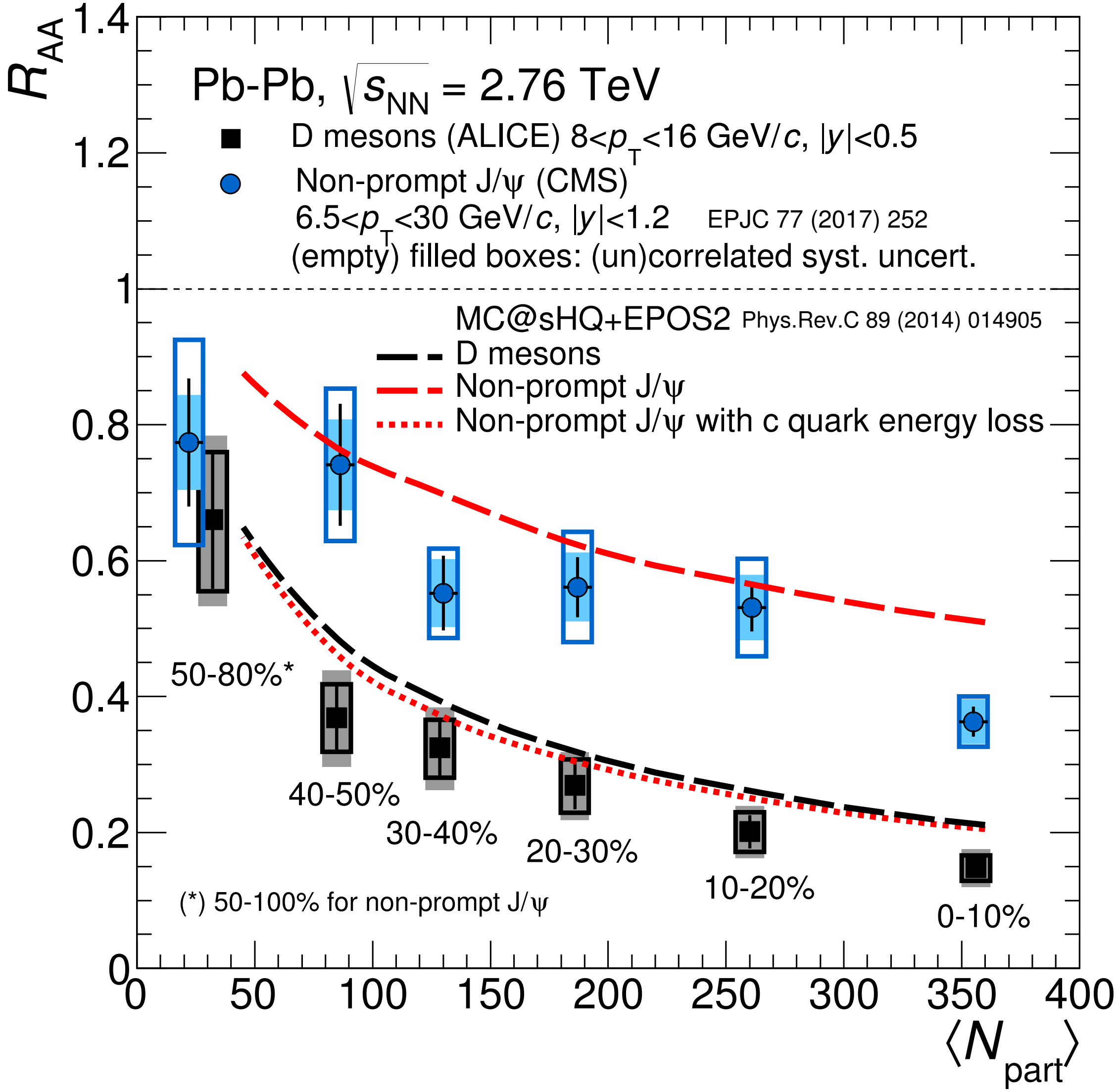
arXiv:1506.06604

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

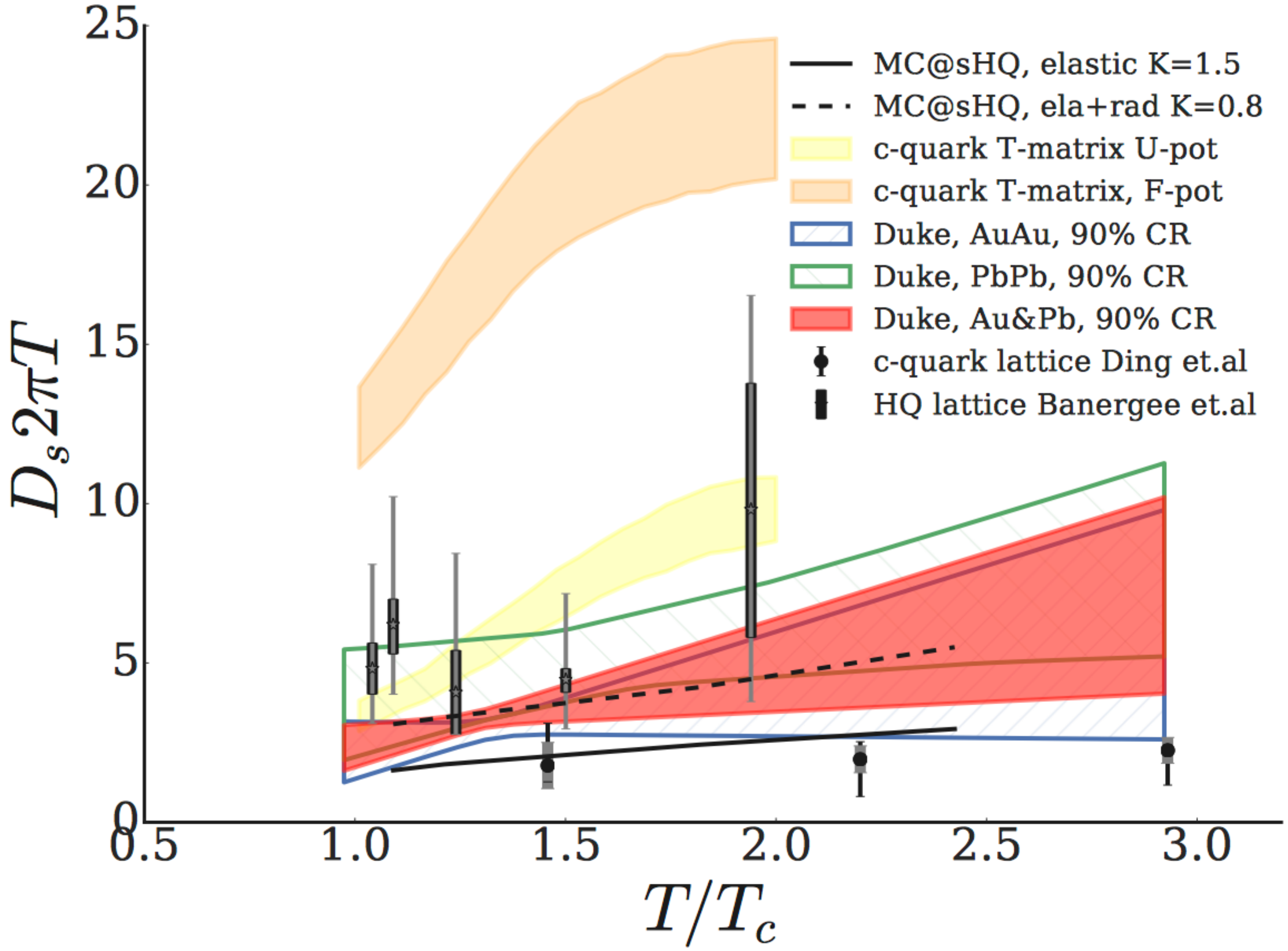


Theoretical model(s) reproduce the data (reasonably) well

arXiv:1506.06604

ALICE-PUBLIC-2017-004

Charm diffusion coefficient



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

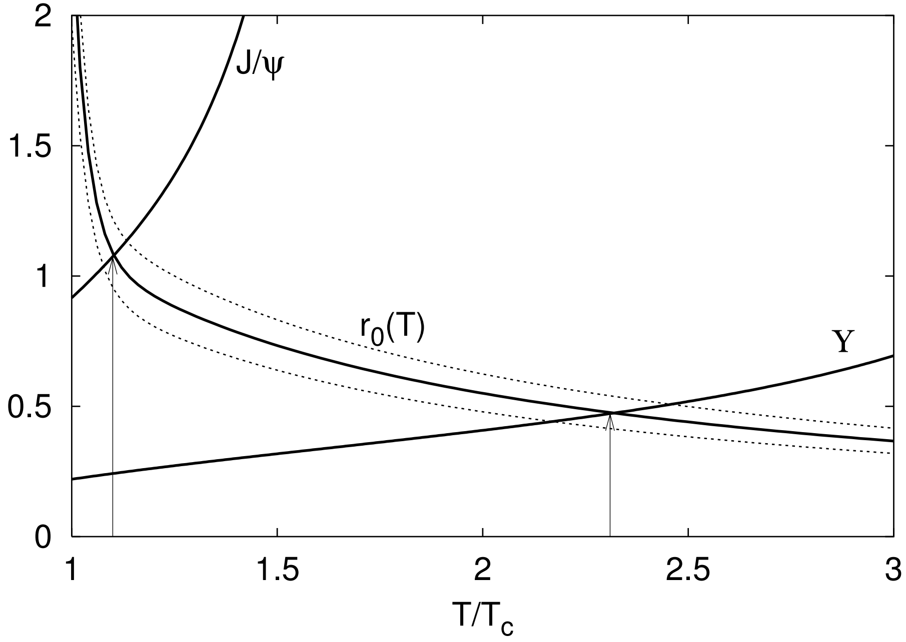
arXiv:1704.07800

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."

"Debye screening": no J/ψ if $r_{J/\psi} > \lambda_D$



Refinements: "sequential suppression":

Digal et al., PRD 64 (2001) 75

Debye length in QGP: $\lambda_D \simeq 1/(g(T) \cdot T)$

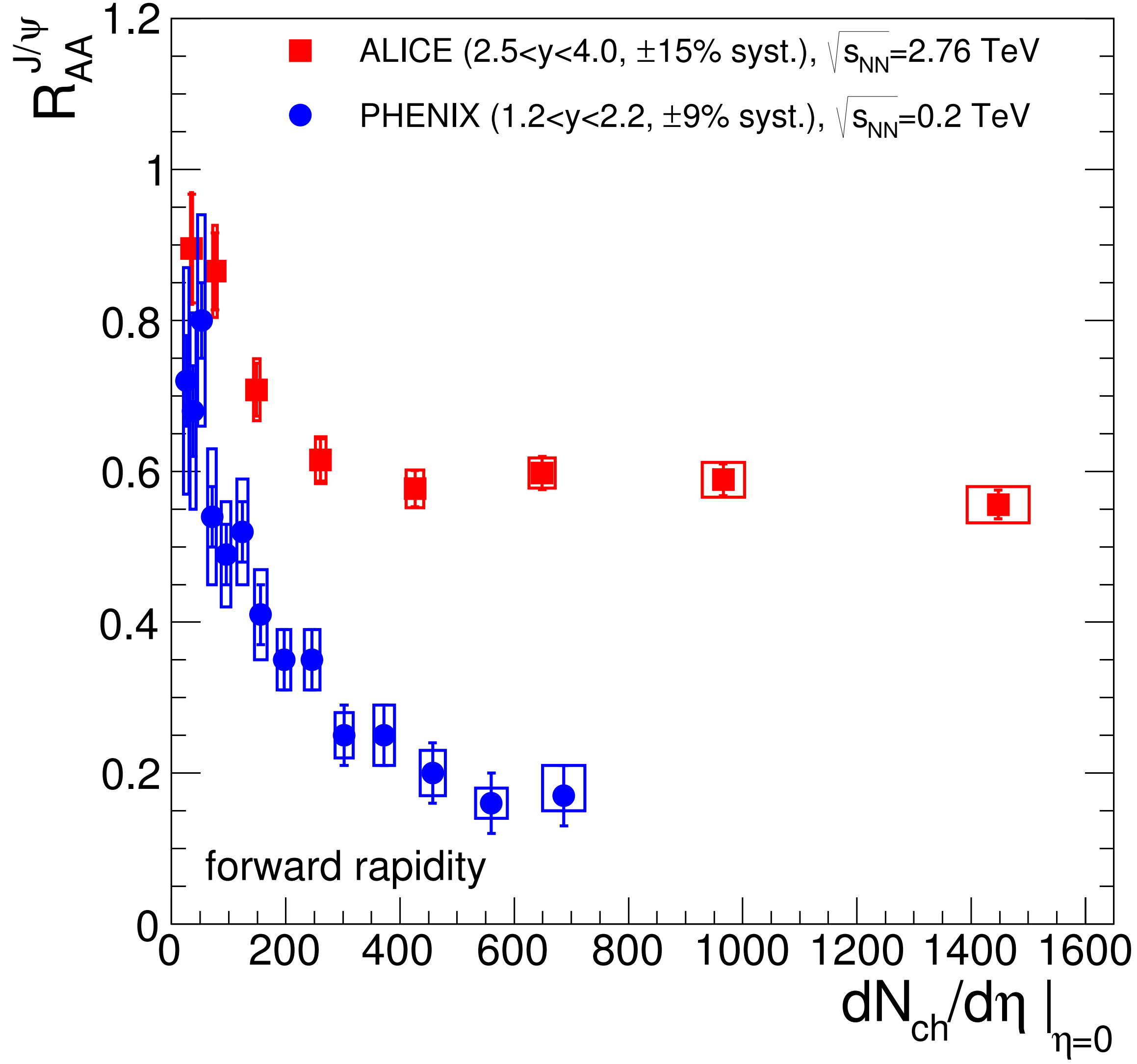
$r_{q\bar{q}} = f(T)$ (Lattice QCD results)

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

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

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

Charmonium data at RHIC and the LHC



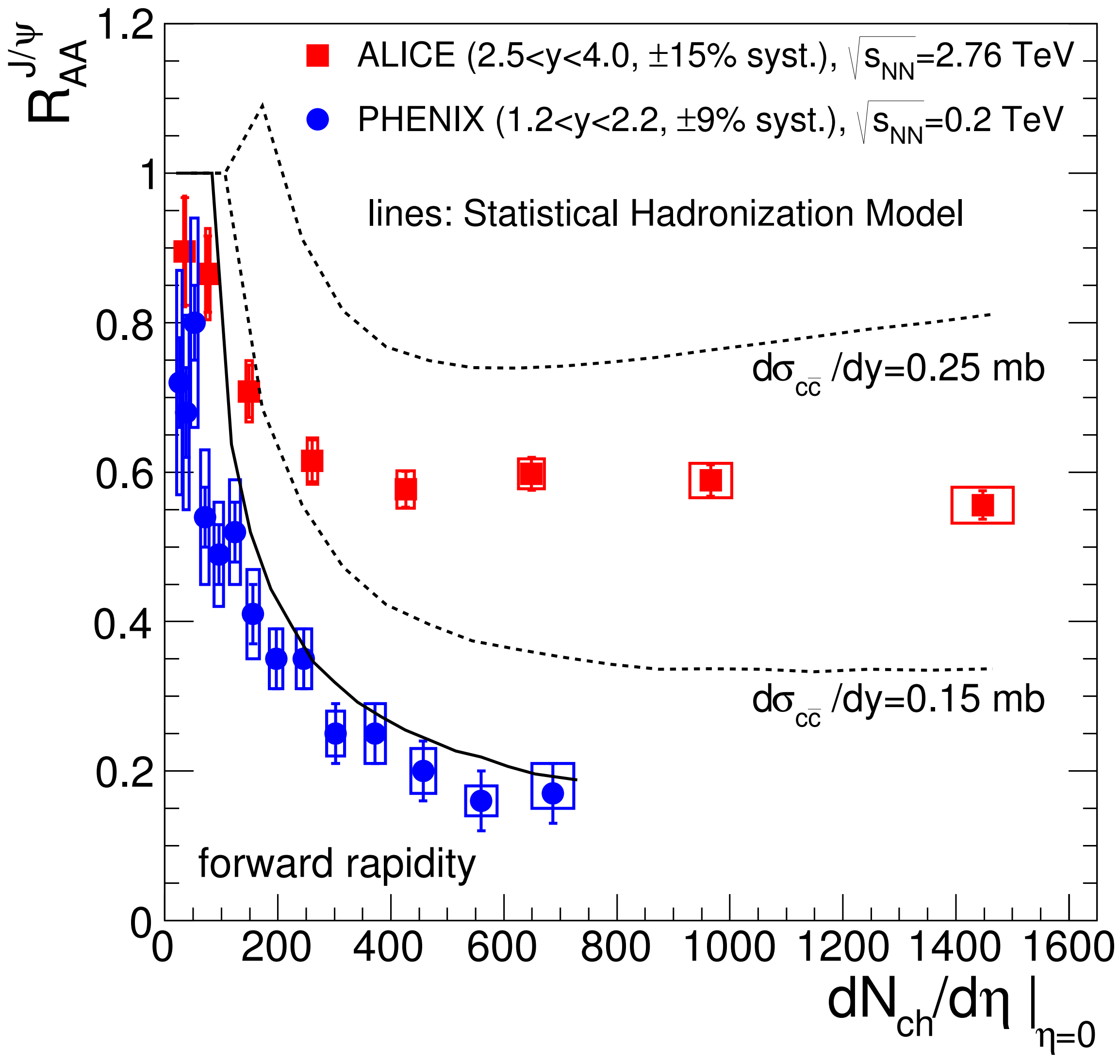
- "suppression" at RHIC (PHENIX)
- dramatically different at the LHC

$\mathrm{d}N_{ch}/\mathrm{d}\eta \sim \varepsilon$ (>16 GeV/fm^3, for $\mathrm{d}N_{ch}/\mathrm{d}\eta \simeq$ 1500)

ALICE, `Phys.Lett.B 734 (2014) 314`

...

Charmonium data at RHIC and the LHC



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ALICE, Phys.Lett.B 734 (2014) 314

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- dramatically different at the LHC

Statistical Hadronization Model

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

What is so different at the LHC?

(compared to RHIC)

$\sigma_{c\bar{c}}$: ∼10x, Volume: ∼2.2x

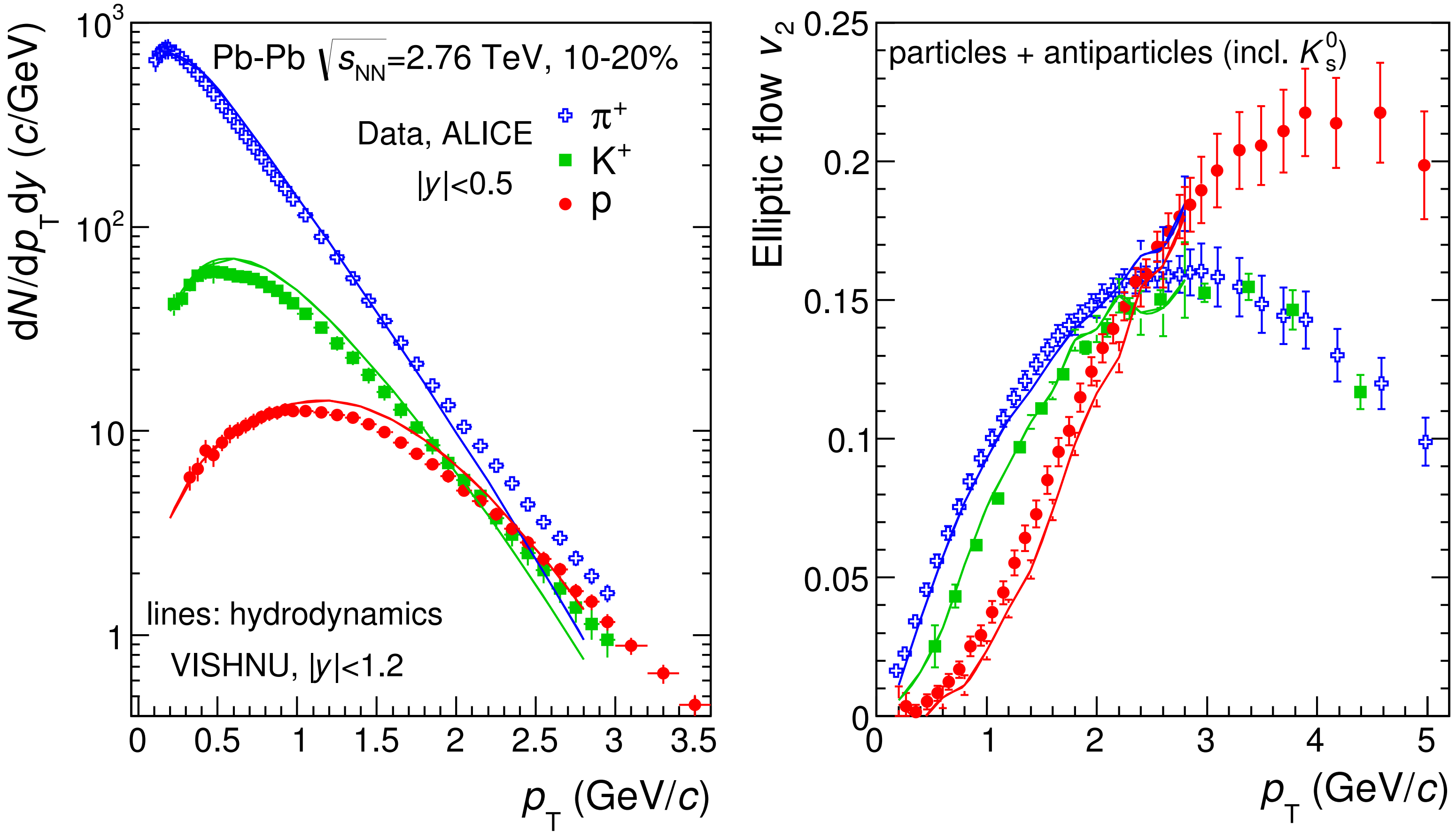
J/ψ is another observable (charm)

for the phase boundary

calculations are for T=156 MeV

AA et al., PLB 652 (2007) 259

Data and hydrodynamics

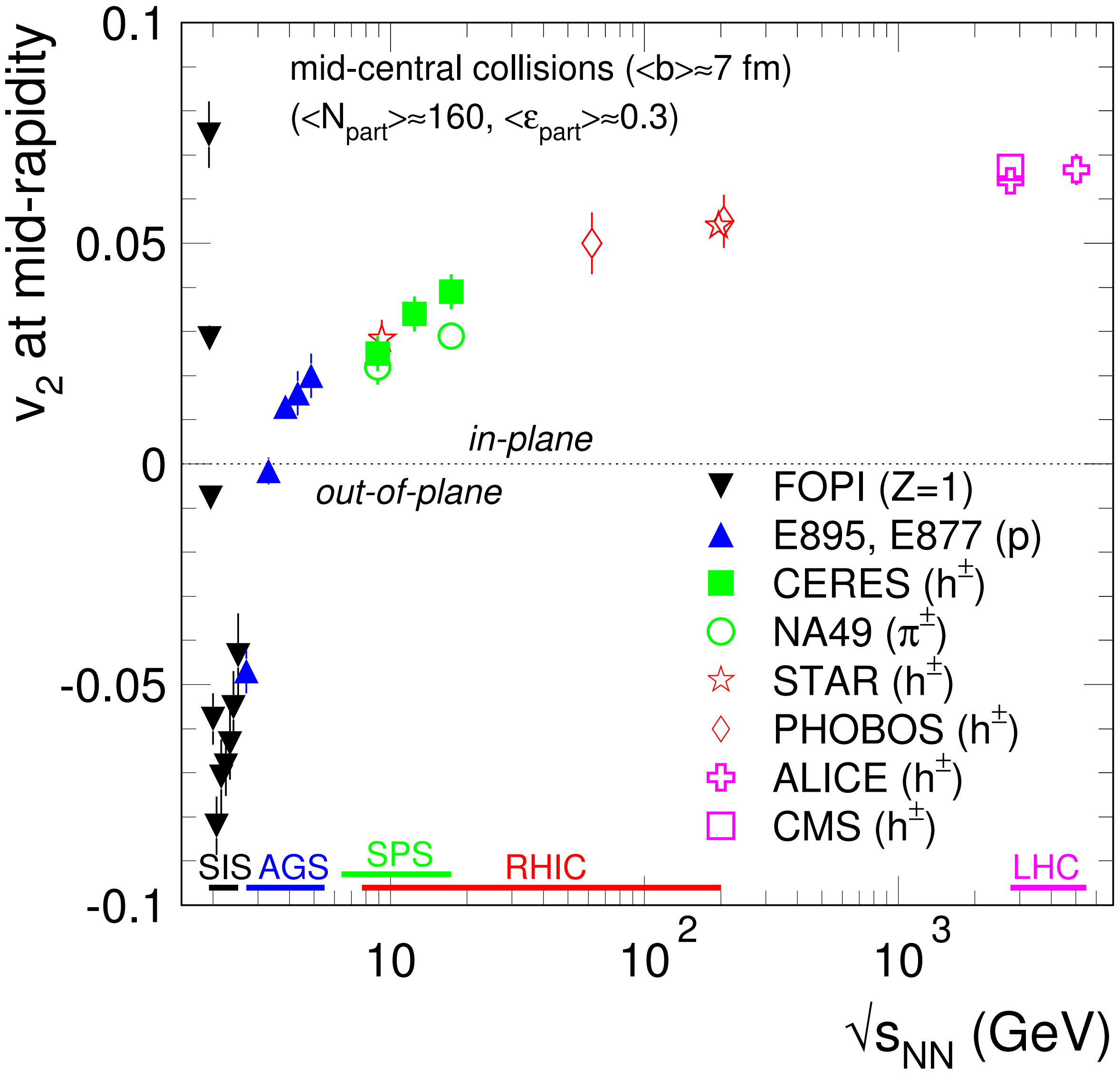


mass dependence due to collective flow

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



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

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