Hadron production in heavy-ion and pp collisions at the LHC with ALICE

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on behalf of the ALICE Collaboration

Workshop "Hard Problems of Hadron Physics: Non-Perturbative QCD & Related Quests"

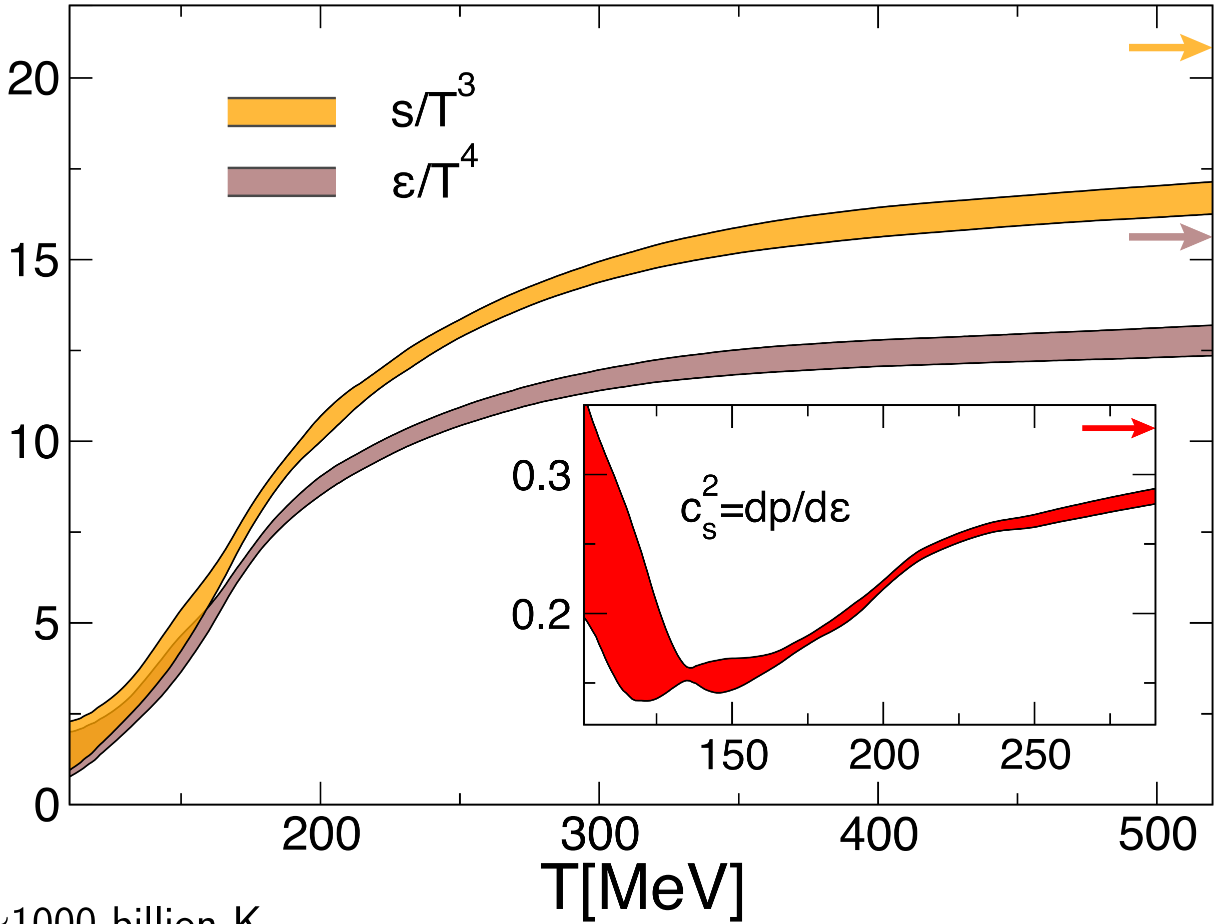
Protvino, 8-12 Nov. 2021

Outline

- Hadron production in Pb–Pb collisions (hot QCD)
- Hadron production in pp and p–Pb collisions (vs. multiplicity)
- Summary and outlook

a biased selection of results

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)

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

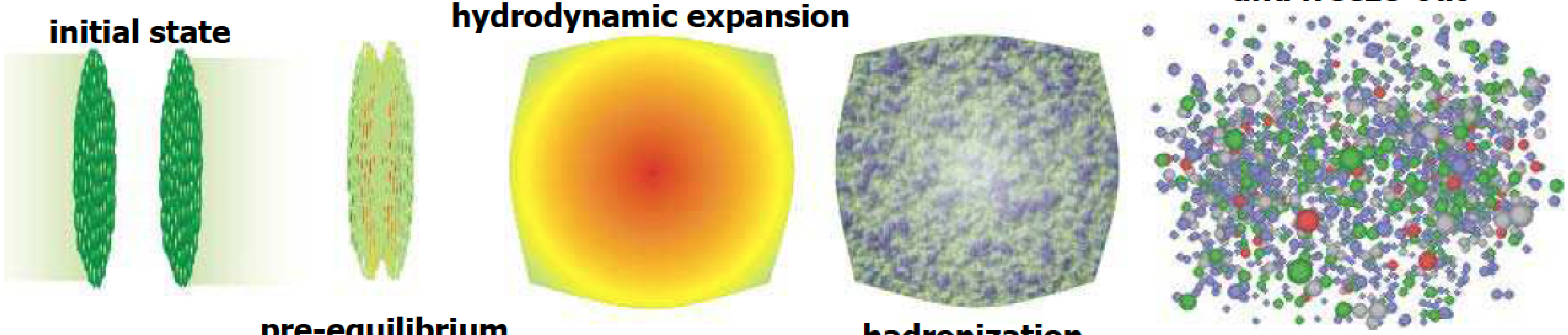
$\simeq$1000 billion K

Borsanyi et al., PLB 370 (2014) 99 Bazavov et al., PLB 795 (2019) 15

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

T_c=156.5±1.5 MeV, $\varepsilon_c \simeq$0.4 GeV/fm^3, or 2.5$\varepsilon_{nuclear}$

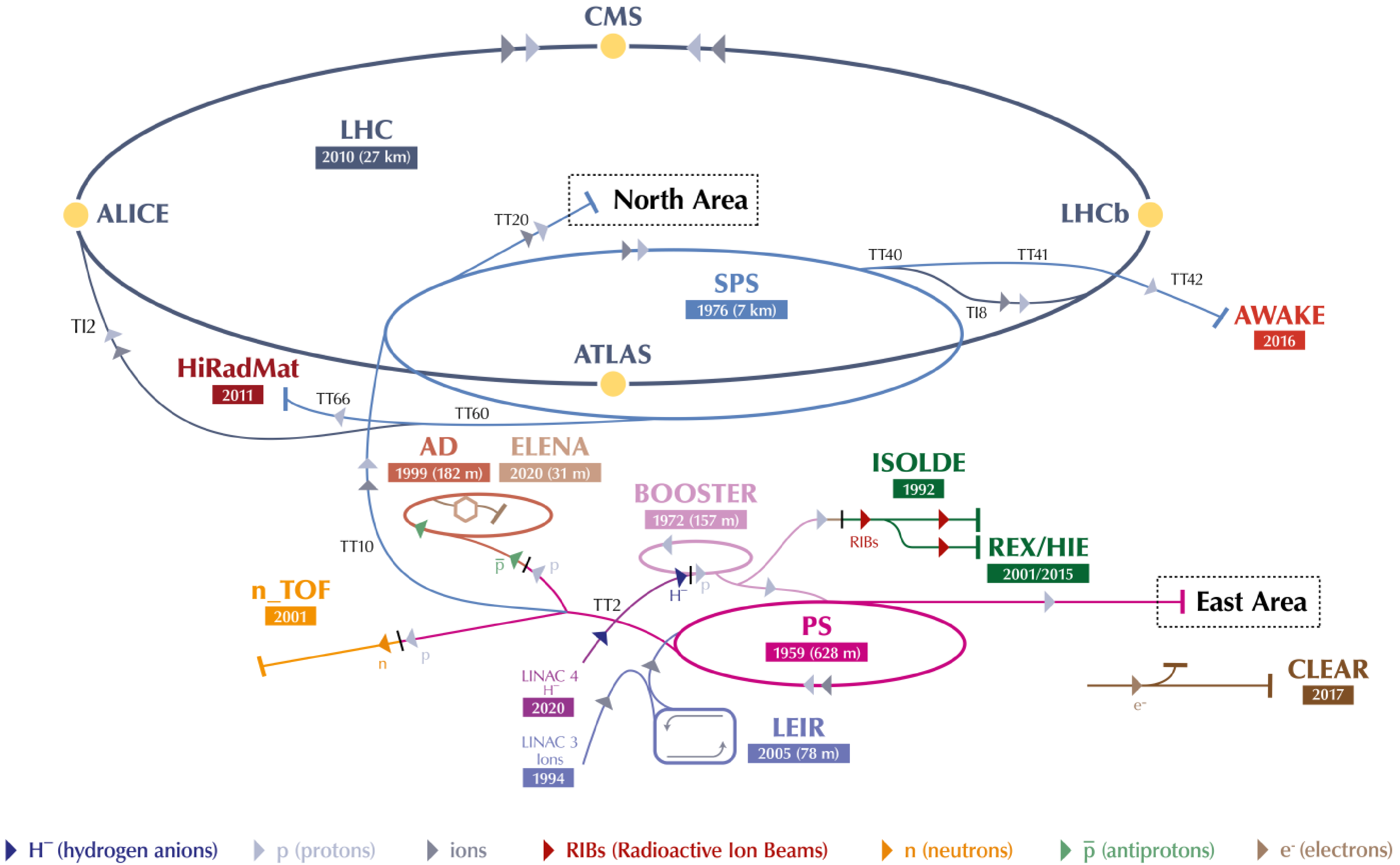
Hot matter creation in the laboratory



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

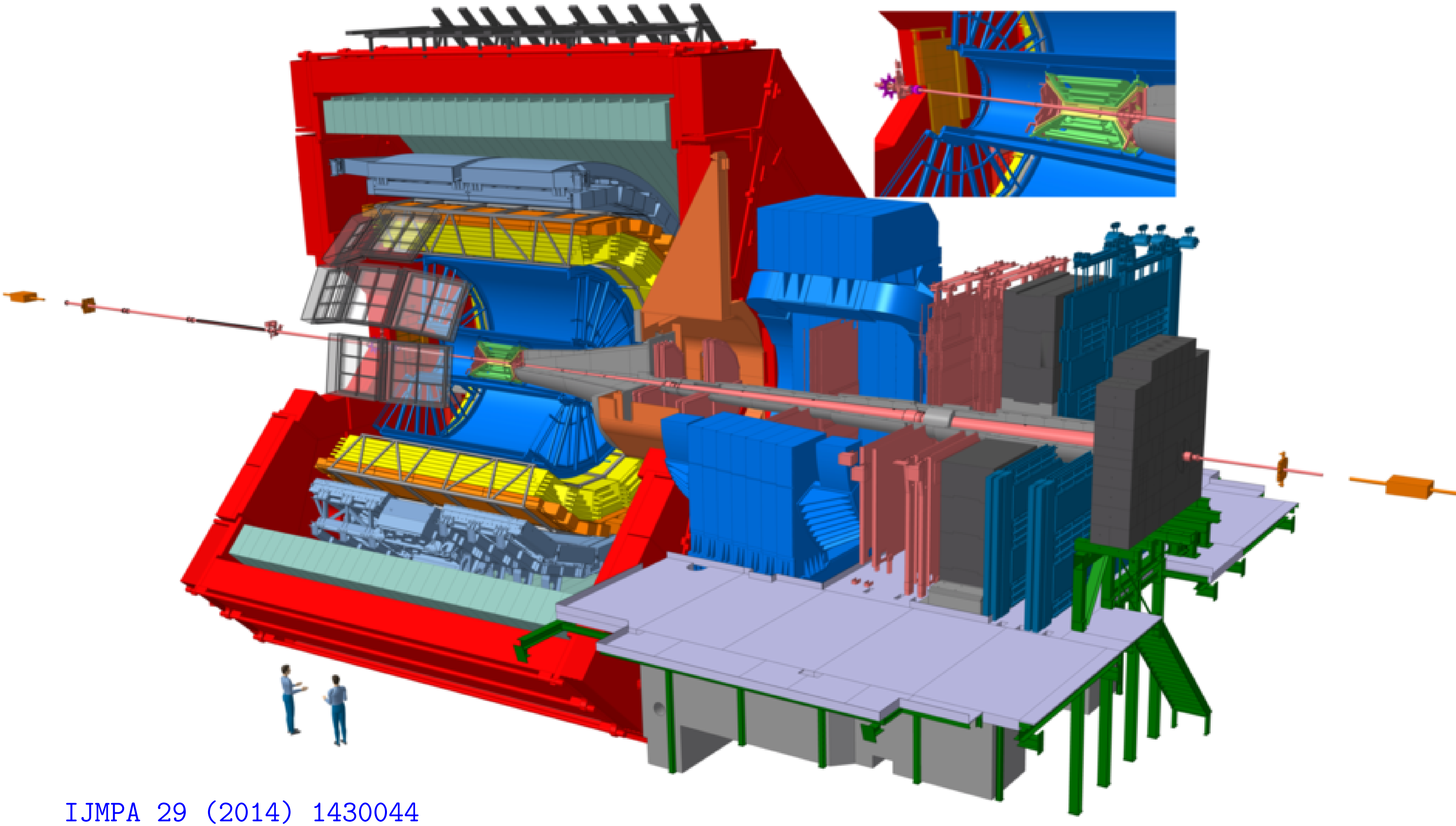
1. initial collisions ($t \leq t_{coll} = 2R/\gamma_{\rm cm}c$; $R_{Pb} \simeq$7 fm)
2. thermalization: equilibrium is established ($t \lesssim$ 1 fm/c $= 3 \times 10^{-24}$ s)
3. expansion ($\langle v \rangle \simeq 0.6c$) and cooling ($t <$ 10-15 fm/c) ...deconfined stage
4. hadronization (quarks and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

The CERN accelerator complex
Complexe des accélérateurs du CERN



The accelerator complex at CERN

A detector at the LHC - ALICE



IJMPA 29 (2014) 1430044

ALICE Collaboration: 40 countries, 170 institutions, 1973 members

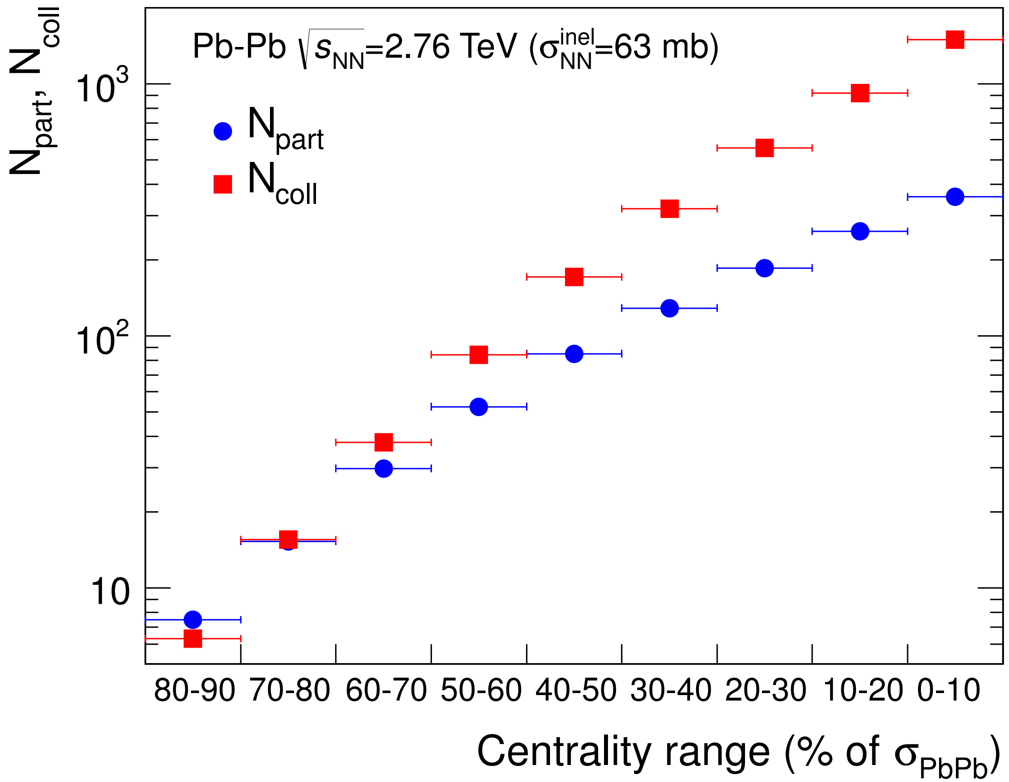
What are the ”control parameters”

- 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

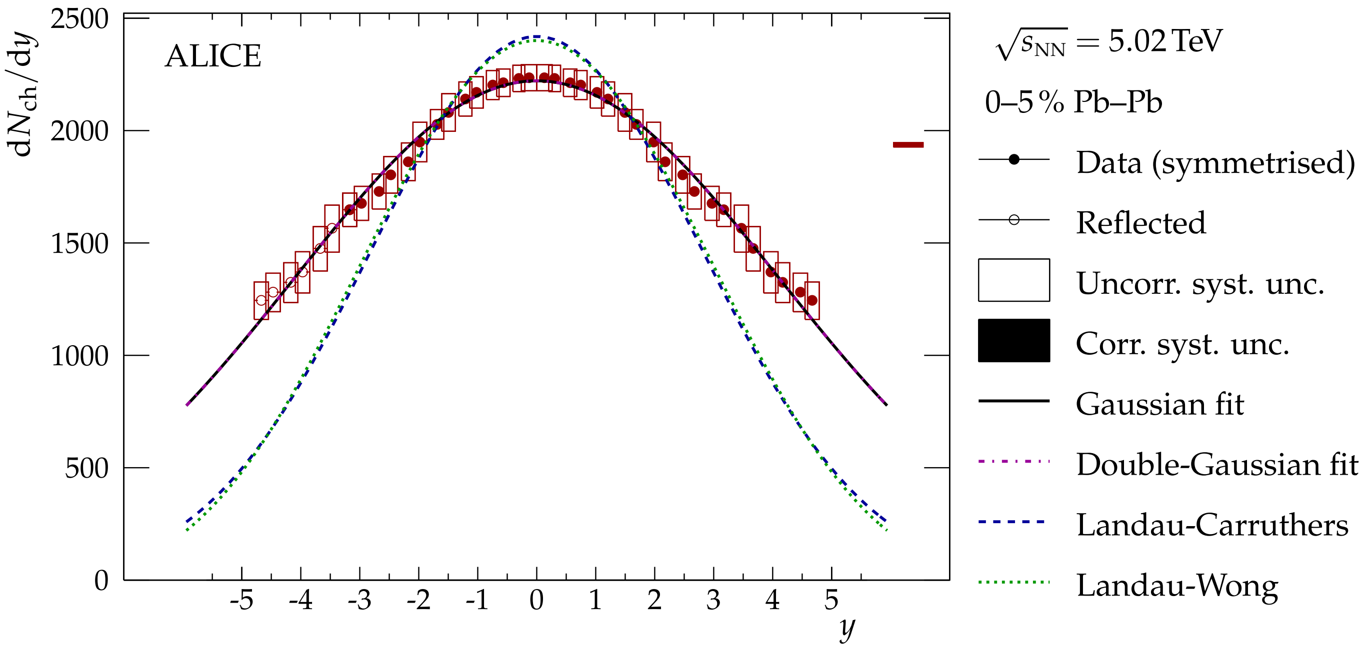


...while often taking as reference the measurement in proton-proton collisions (at the same energy), for “hard probes” (pQCD) scaled by the number of collisions corresponding to the given centrality class

What we measure

Production yields and correlations as a function of kinematic quantities:

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

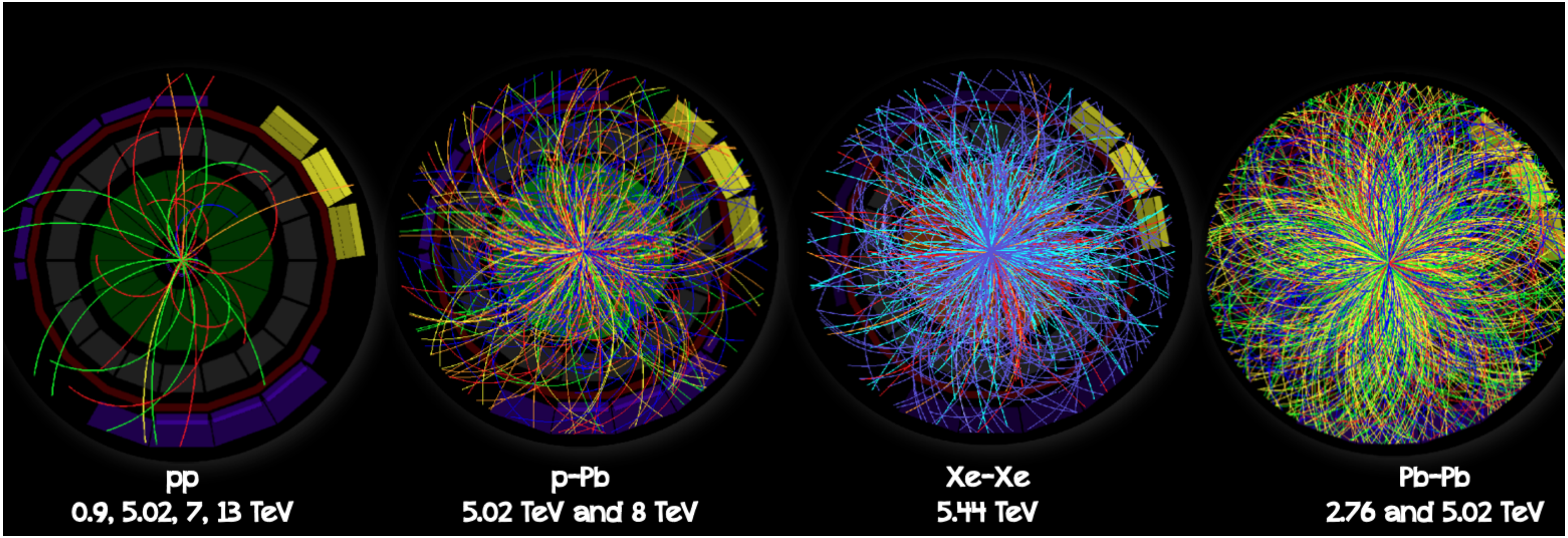


ALICE, PLB 772 (2017) 567

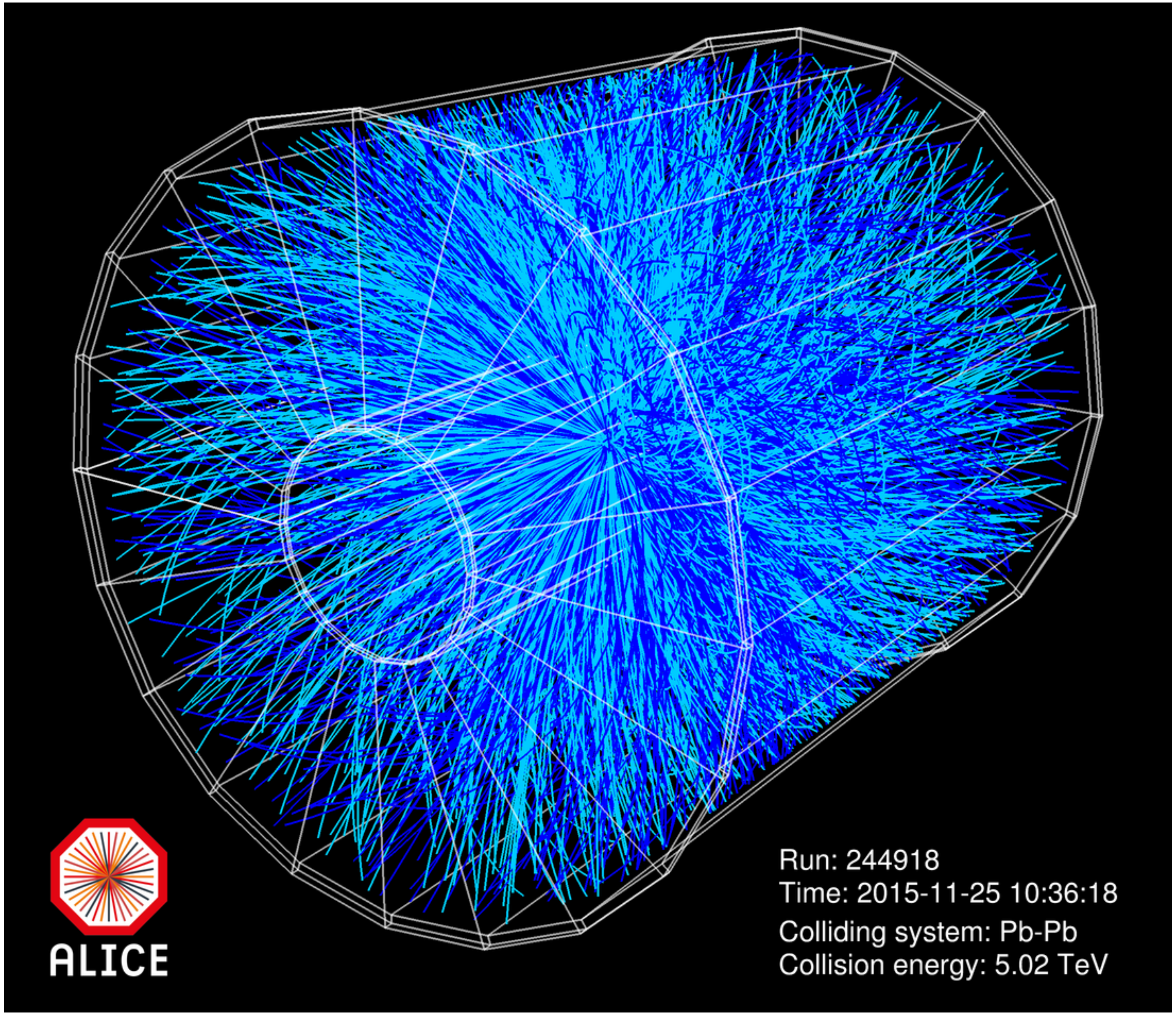
...poor (wo)man's y: "pseudorapidity", $\eta = \tanh^{-1}(p_z/p) = \tanh^{-1}(\cos\theta)$

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

A pictorial summary of collisions at the LHC

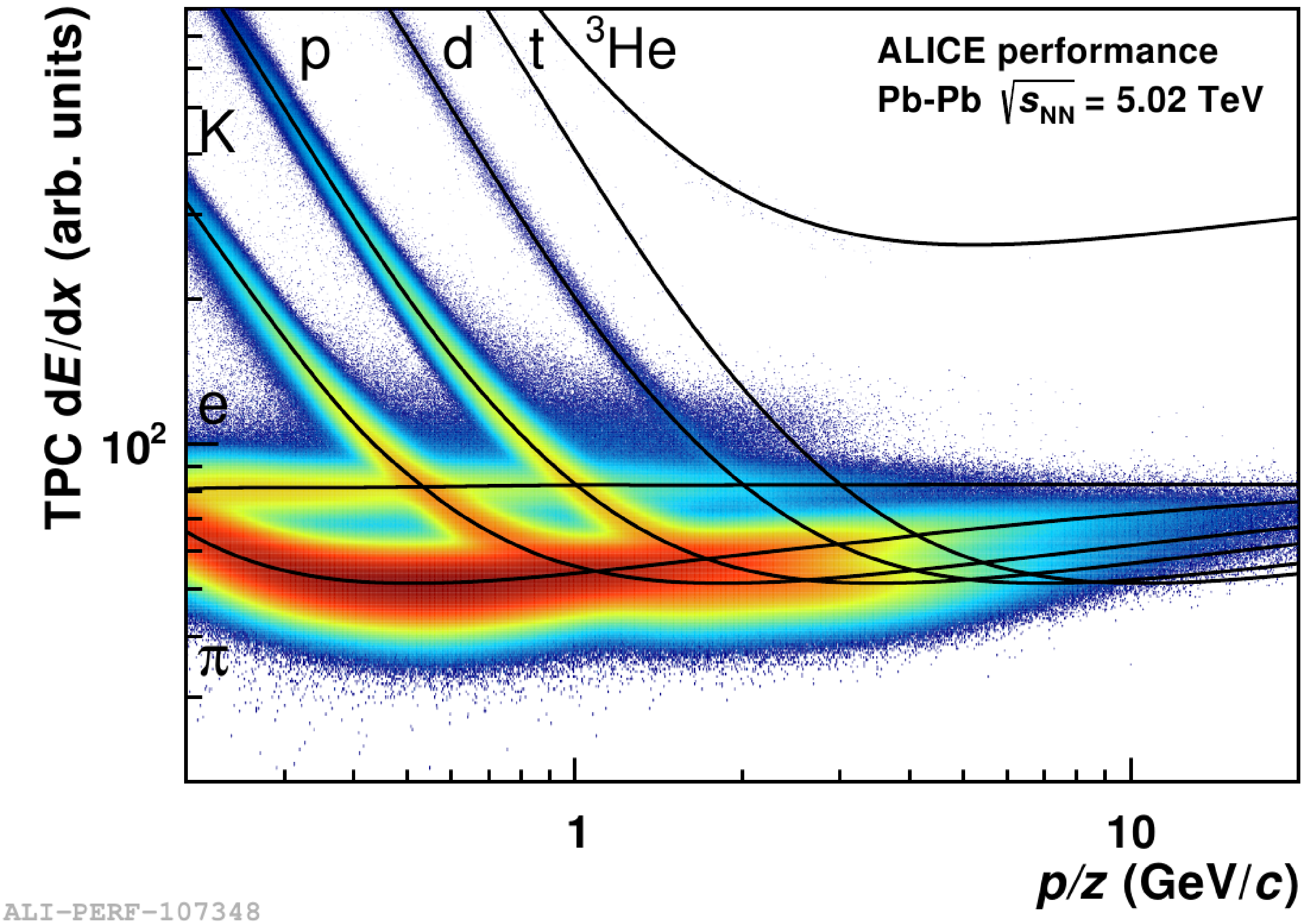


Nucleus-nucleus collisions at the LHC



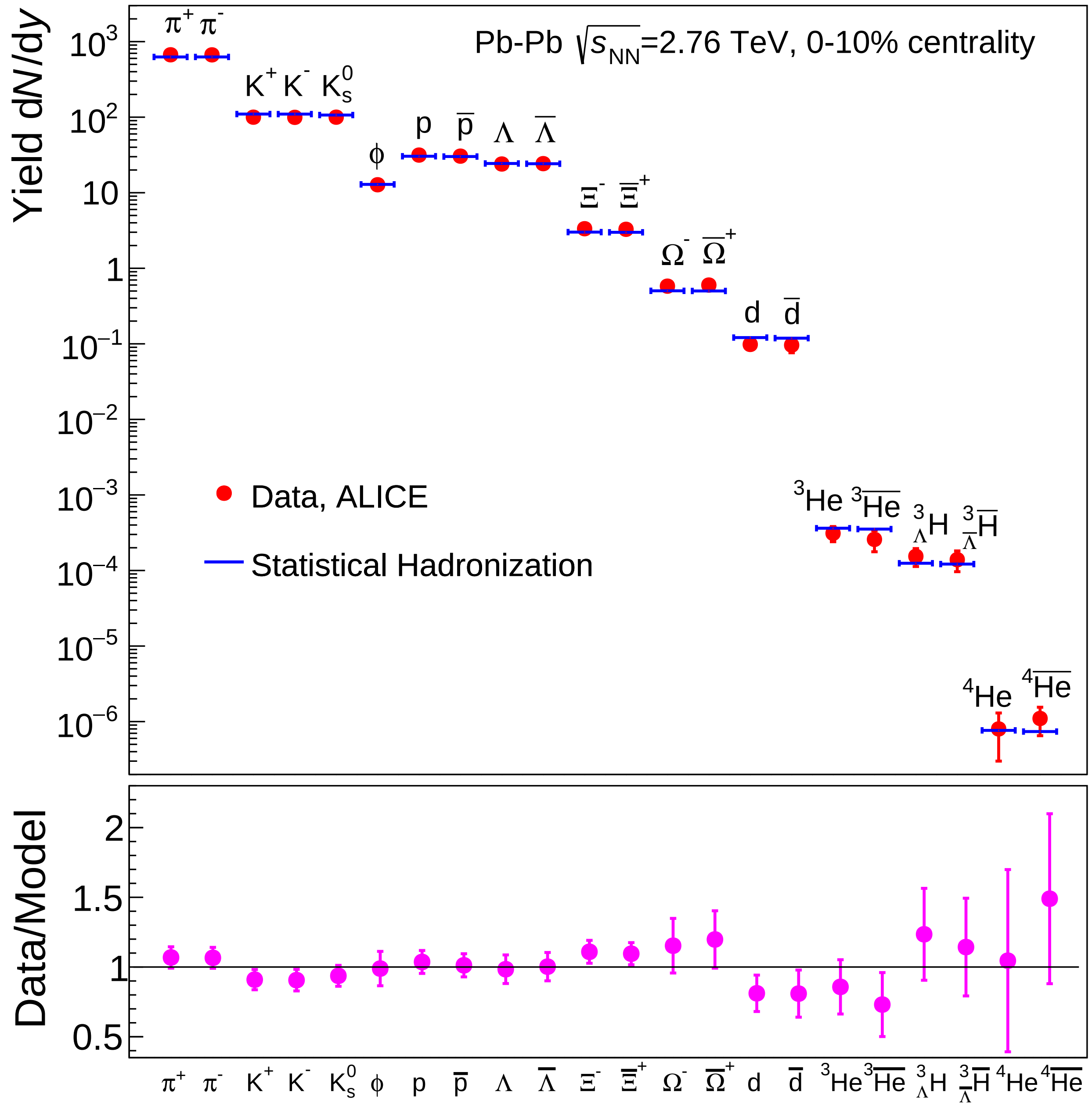
a picture of a central collision (about 3200 primary tracks in $|\eta| < 0.9$); "Camera": Time Projection Chamber, 5 m length, 5 m diam.; 500 mil. pixels; we take a few 100 pictures per second (and are preparing to take 50000)

Particle identification



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

lines: Bethe-Bloch parametrizations particles and antiparticles are shown



matter and antimatter produced in equal amounts at the LHC

best fit:

$T_{CF} = 156.6 \pm 1.7$ MeV
$\mu_B = 0.7 \pm 3.8$ MeV
$V_{\Delta y=1} = 4175 \pm 380$ fm^3
($\chi^2/N_{df} = 16.7/19$)

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

ALICE, NPA 971 (2018) 1

AA et al, Nature 561 (2018) 321

Thermal fits of hadron abundances

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

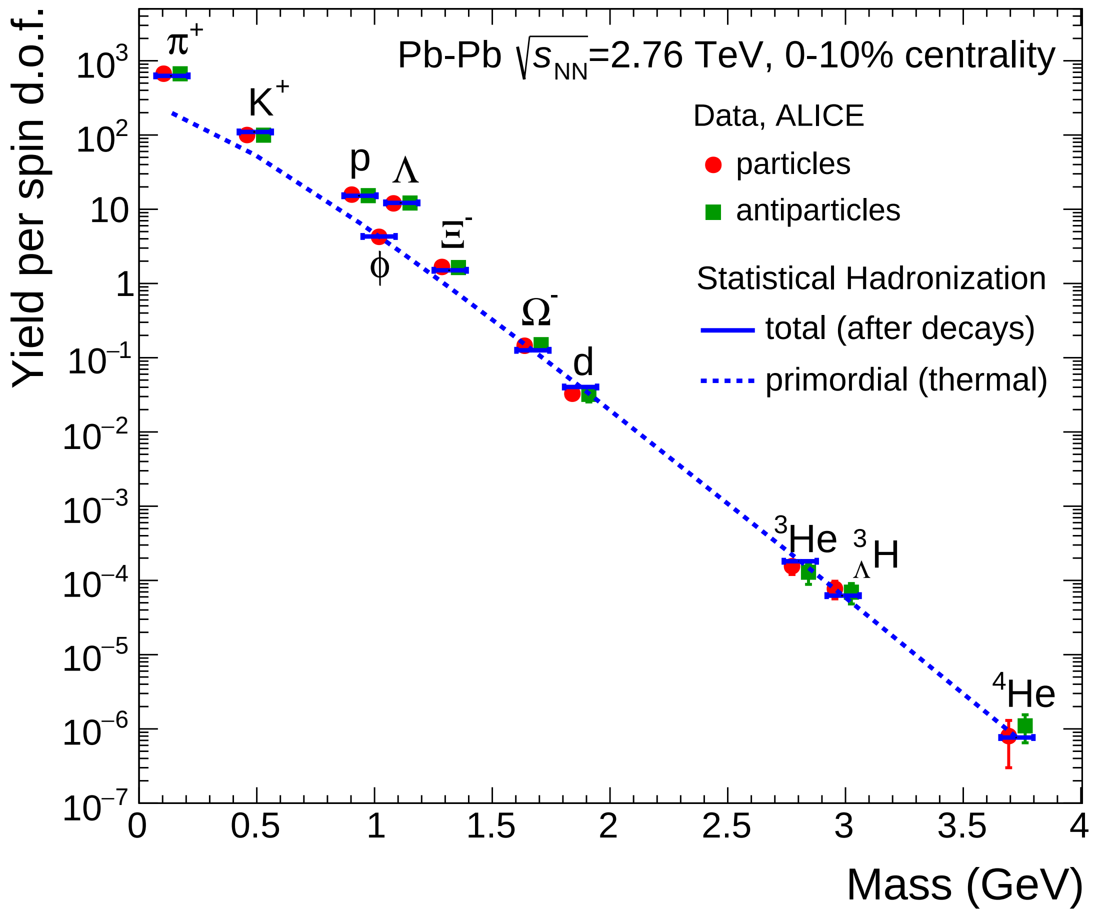
quantum nr. conservation ensured via chemical potentials:

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

Latest PDG hadron mass spectrum (up to 3 GeV, 600 species)

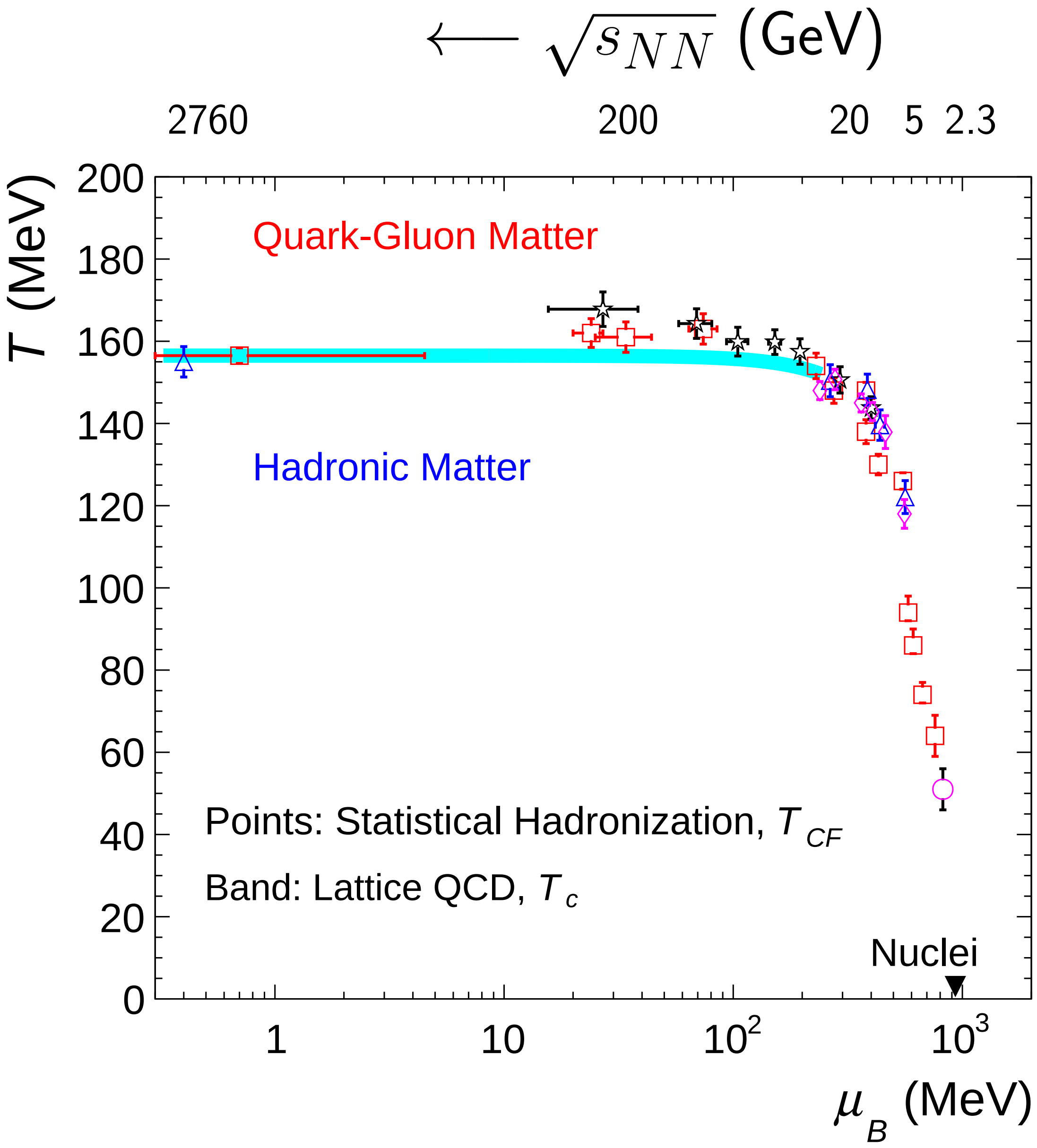
Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

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?



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

Nature 561 (2018) 321

Hot QCD, PLB 795 (2019) 15

Thermodynamic quantities: data-hydrodynamics

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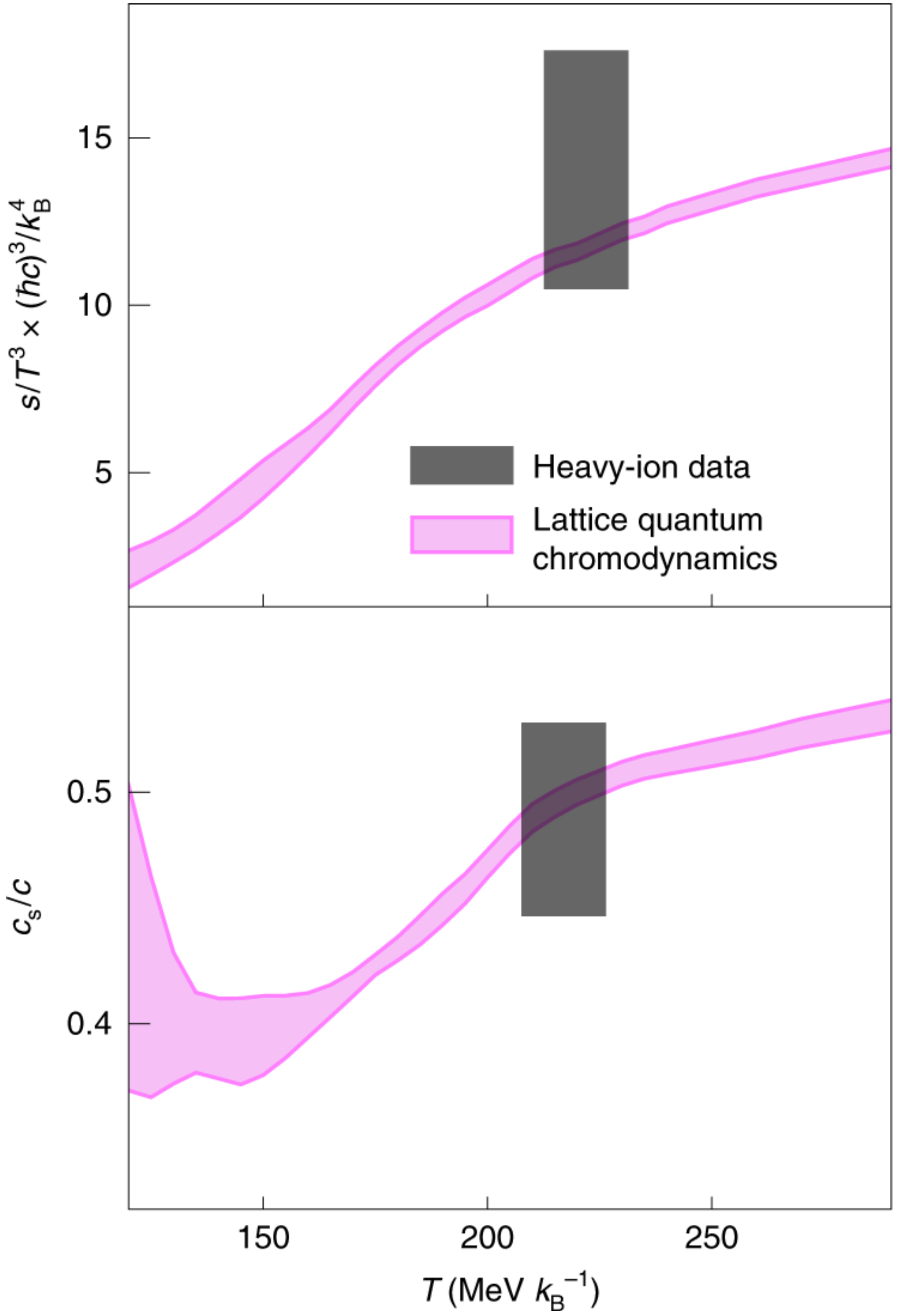
ALICE data: $\langle p_{\mathrm{T}} \rangle$ vs. centrality

processed through
(fitted by) hydrodynamics
$\rightarrow$ effective values (time-averaged)

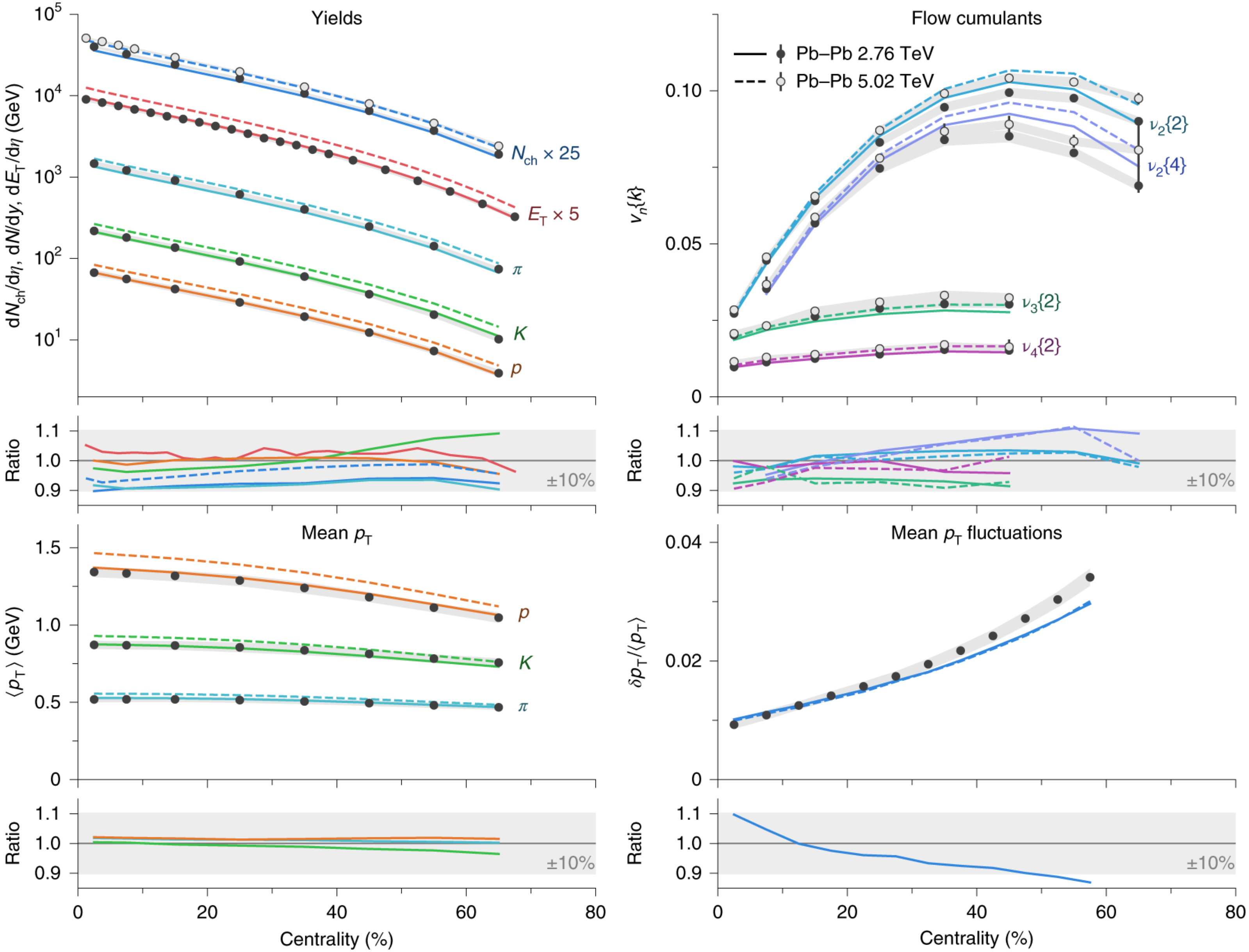
Effective number of
degrees of freedom:
$g \simeq 30$ ($\gg 3$, pions)

ideal gas of quarks
and gluons: $g = 52$



Gardim et al, Nature Physics 16, 615 (2020)

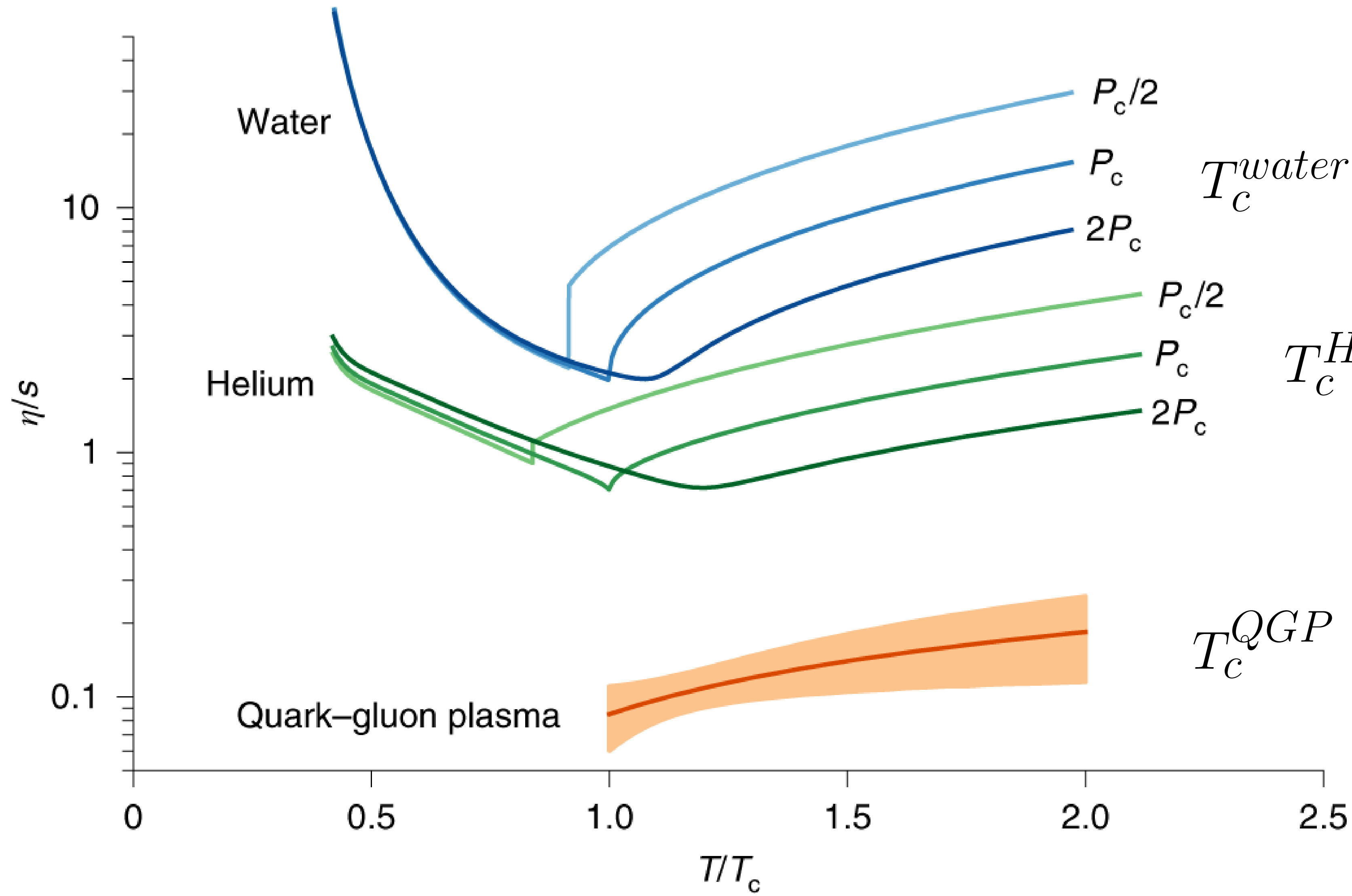
Hydrodynamics: best-fit to data



Bernhard, Moreland, Bass, Nature Physics 15 (2019) 1113

14 fit parameters

Good fluids (ratio viscosity / entropy density)



$T_c^{water} \simeq$650 K

$T_c^{He} \simeq$4 K

$T_c^{QGP} \simeq 10^{12}$ K

Bernhard, Moreland, Bass, Nature Physics 15 (2019) 1113

Lowest value of $1/4\pi$ predicted by gravity-gauge duality (AdS-CFT) conjecture

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

Probing early stages

...with "hard probes" ($m \gg T$): jets or high-p_{T} hadrons (or heavy quarks) produced very early in the collision, $t \simeq 1/m$

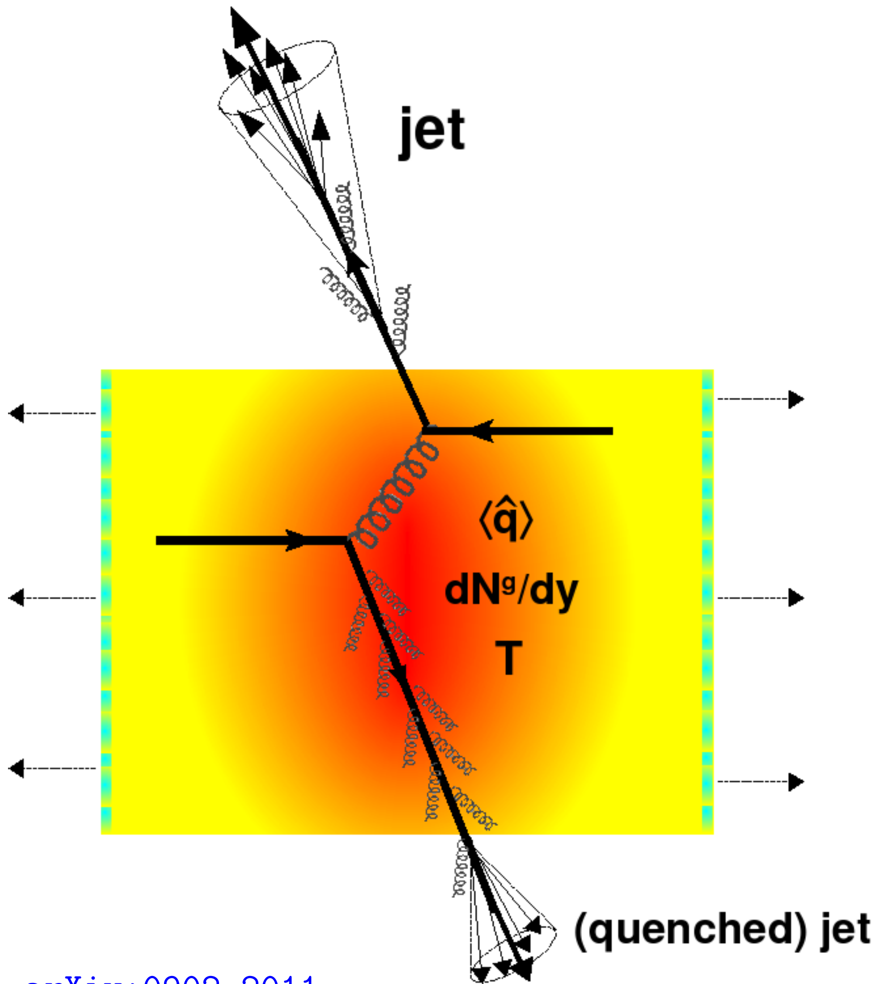
(jets - sprays of hadrons from high-speed quarks)

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

Jets

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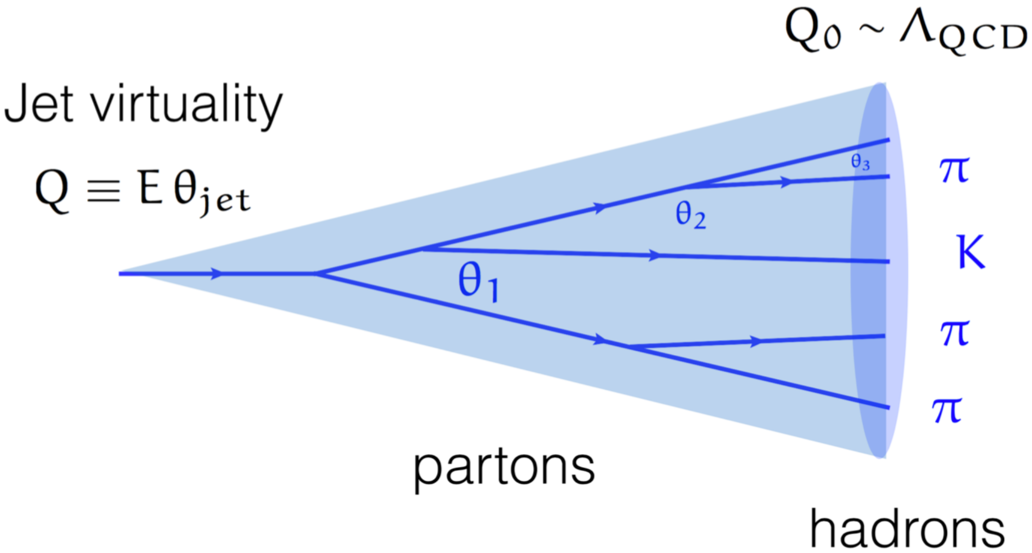
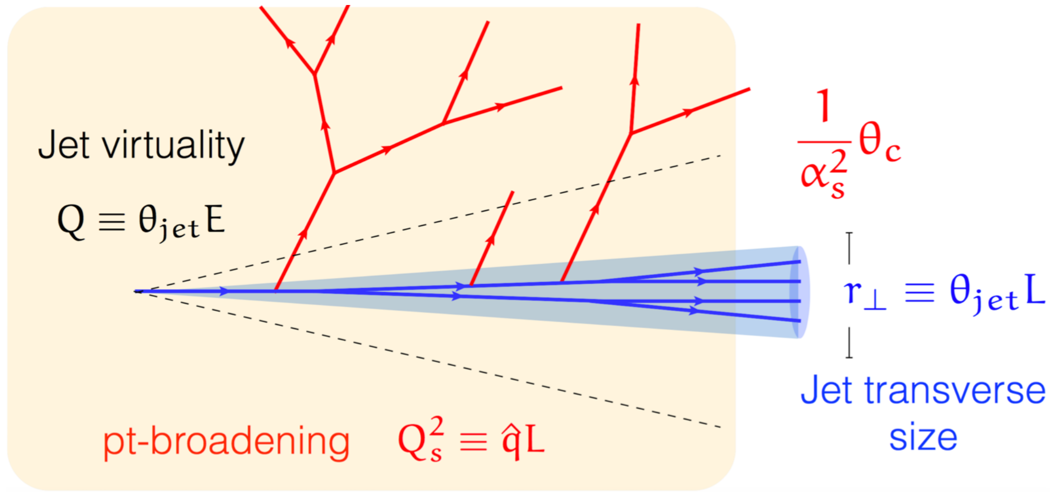
...in vacuum



...in medium

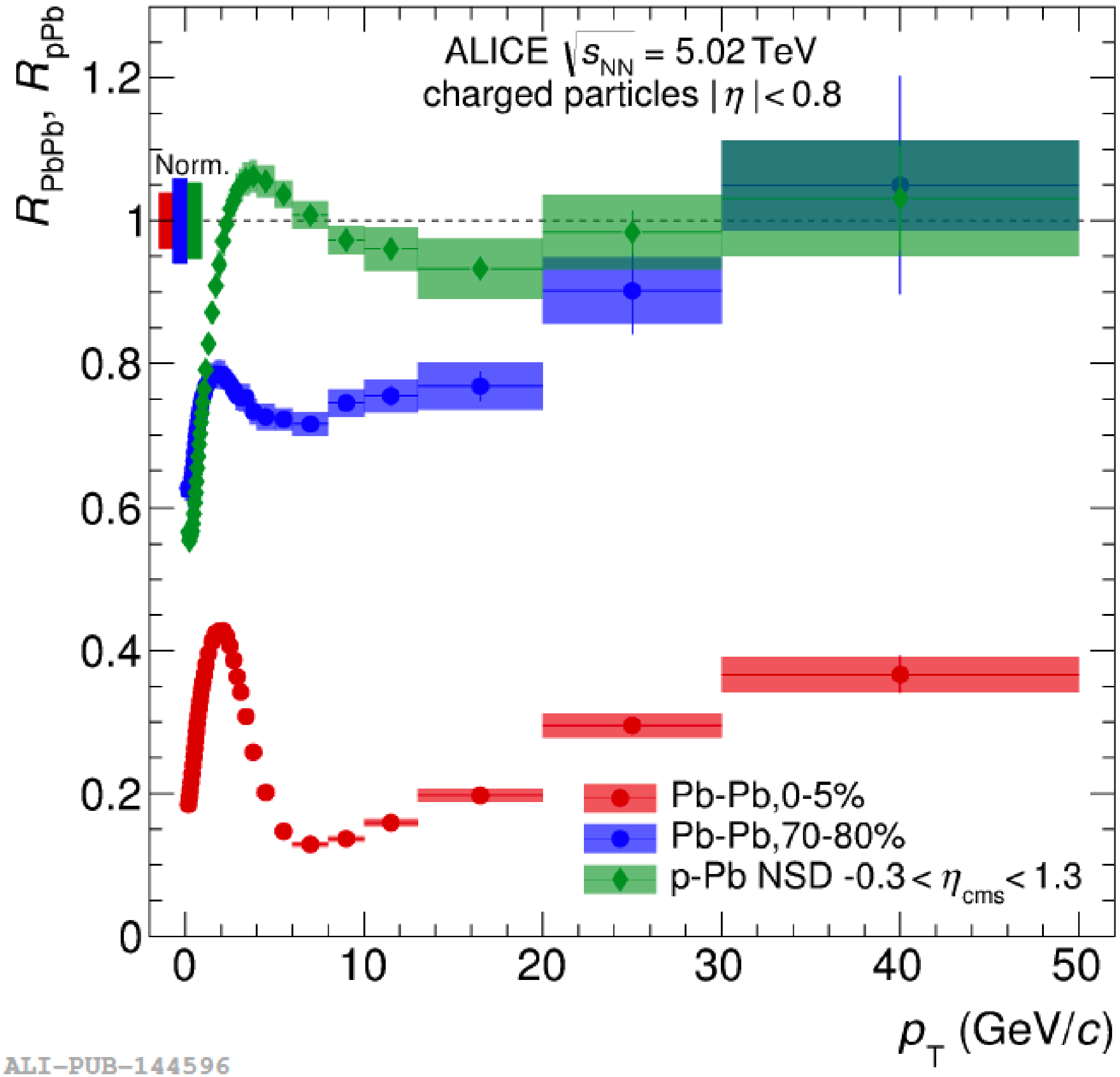


E: E_T or p_T; θ_{jet}: opening angle (R or ΔR)

This is the quantitative effect of the medium not just a sketch

For energetic partons radiative energy loss dominate, $\Delta E_{rad} \sim \alpha_s\, \hat{q}$

Y. Mehtar-Tani, arXiv:1602.01047



measured with "leading hadrons"

strong suppression, reaching a factor of about 7, $p_T \simeq 7$ GeV/c

remains substantial even at 50 GeV/c

seen also with reconstructed jets

not seen in p-Pb collisions ($p_T \lesssim 3$ GeV/c, gluon saturation)

ALICE, JHEP 1811 (2018) 013

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

Quark interlude

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

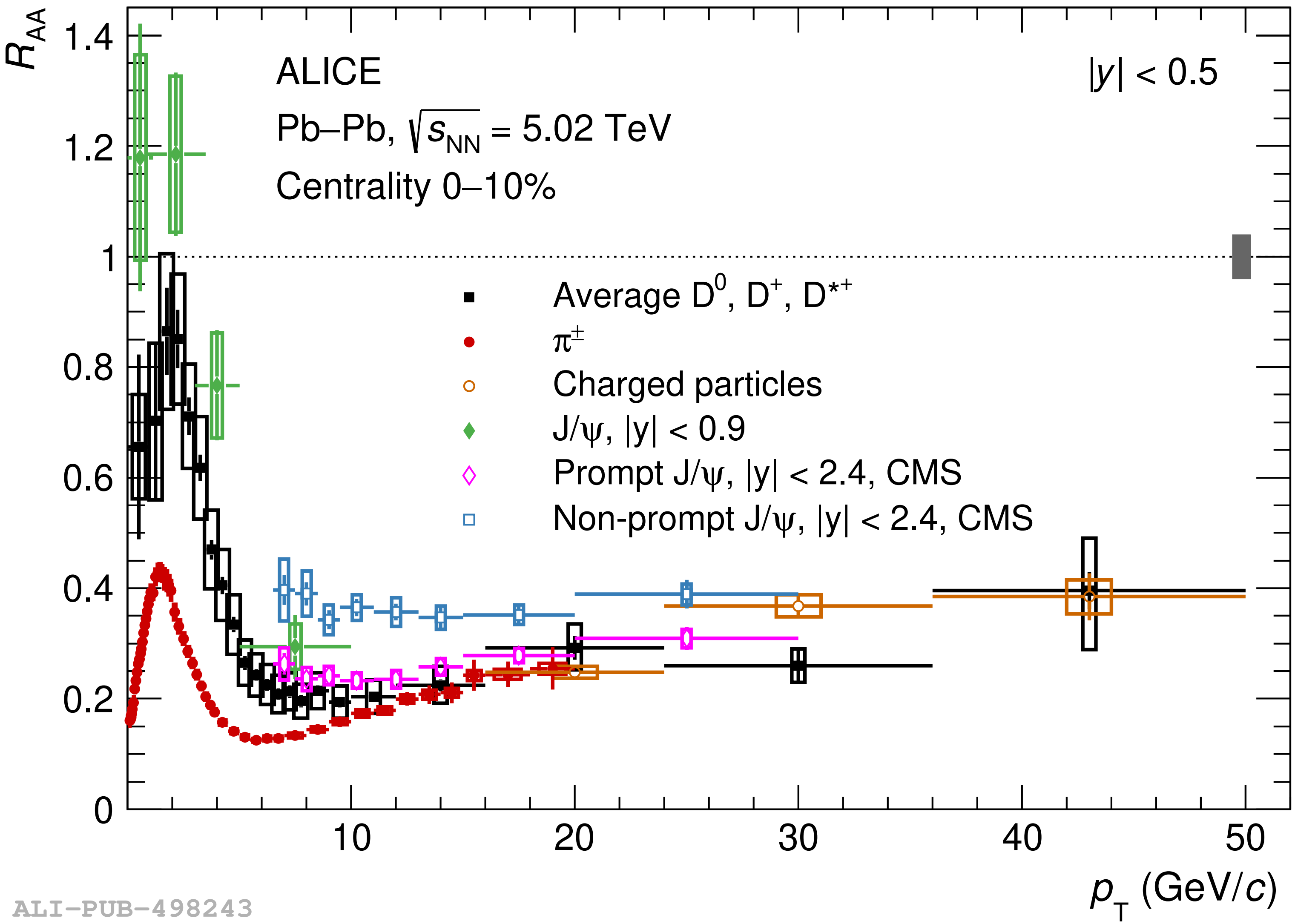
what about heavier ones?
...for instance *charm*, which weights about 1.2 GeV

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

preserve their identity throughout the evolution of the fireball

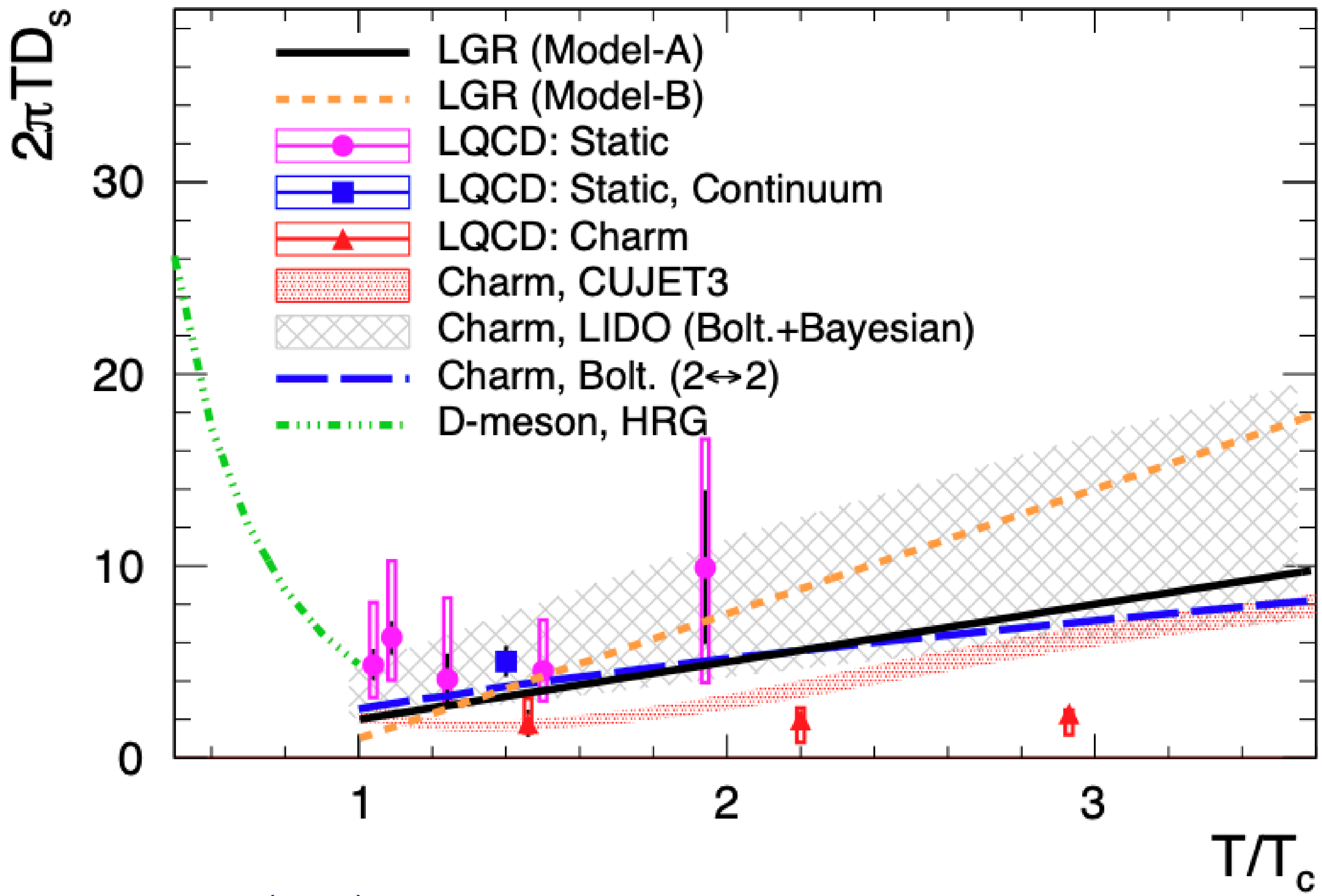
...ideal messengers of the early stage

Charm quark energy loss



ALICE, arXiv:2110.09420

Strong energy loss also for heavy quarks; non-thermal production can be guessed key transport parameter (quantifies drag, thermal, recoil forces)



Li, Liao, EPJC 80 (2020) 671

latest ALICE data (including elliptic flow), arXiv:2110.09420: $1.5 < 2\pi T_c D_s < 4.5$

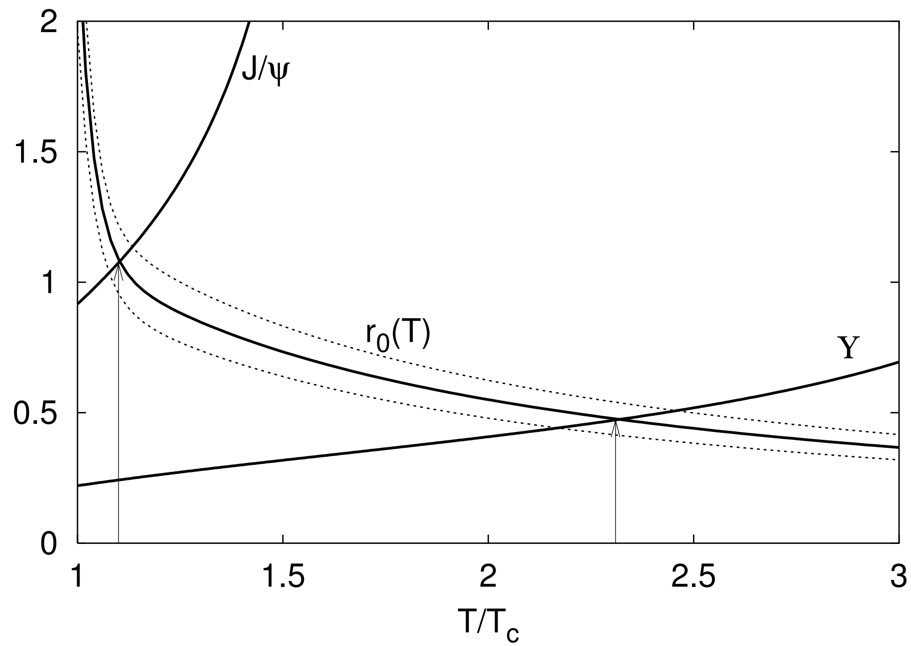
the original idea: Matsui & Satz, Phys.Lett. B 178 (1986) 178

"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, Satz, Petrecky, PRD 64 (2001) 75

Karsch, Kharzeev, Satz, PLB 637 (2006) 75



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

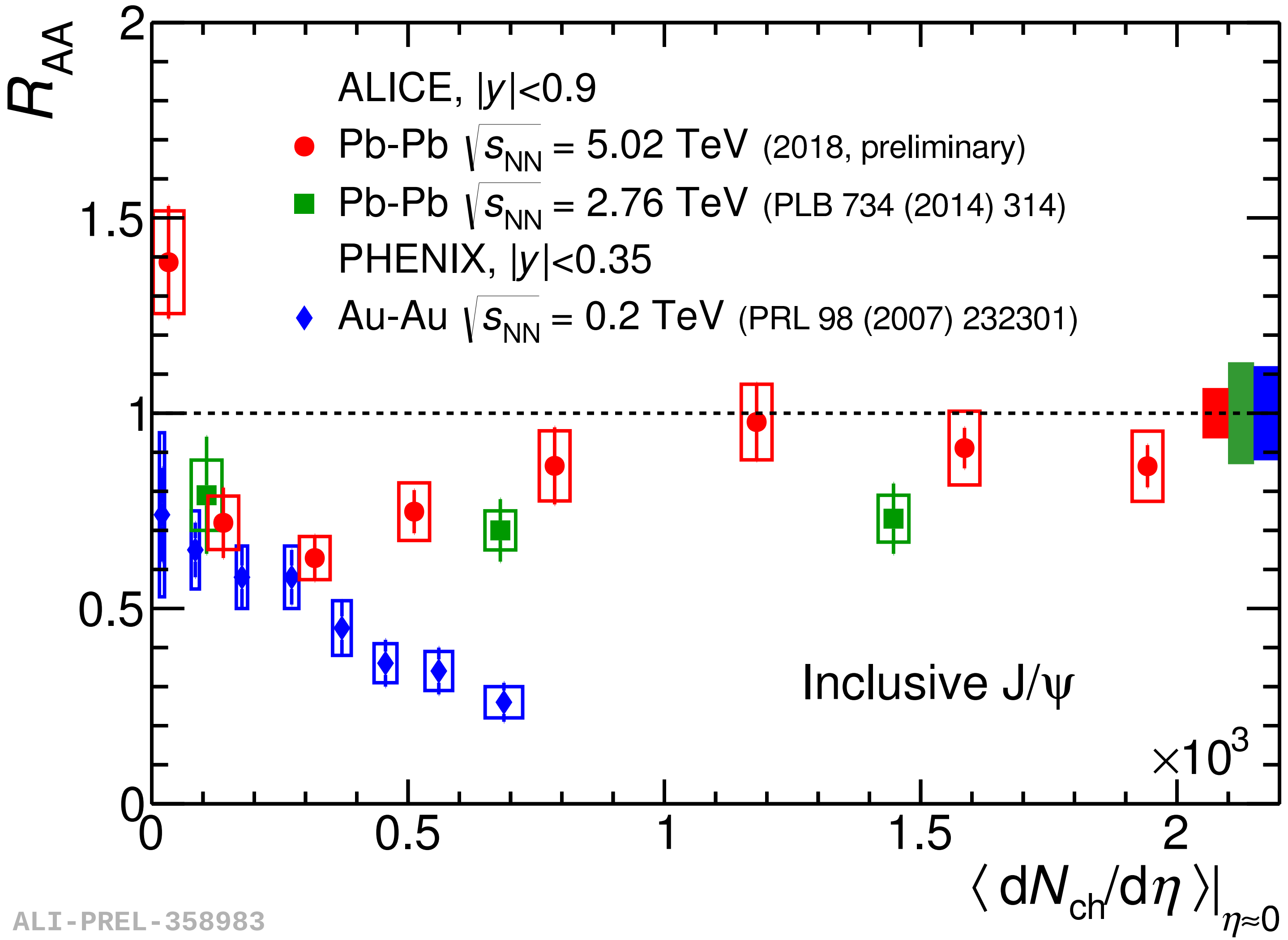
$r_{\mathrm{q\bar{q}}}(T) > r_0(T) \simeq 1/(g(T)T)$

r_0 Debye length in QGP

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

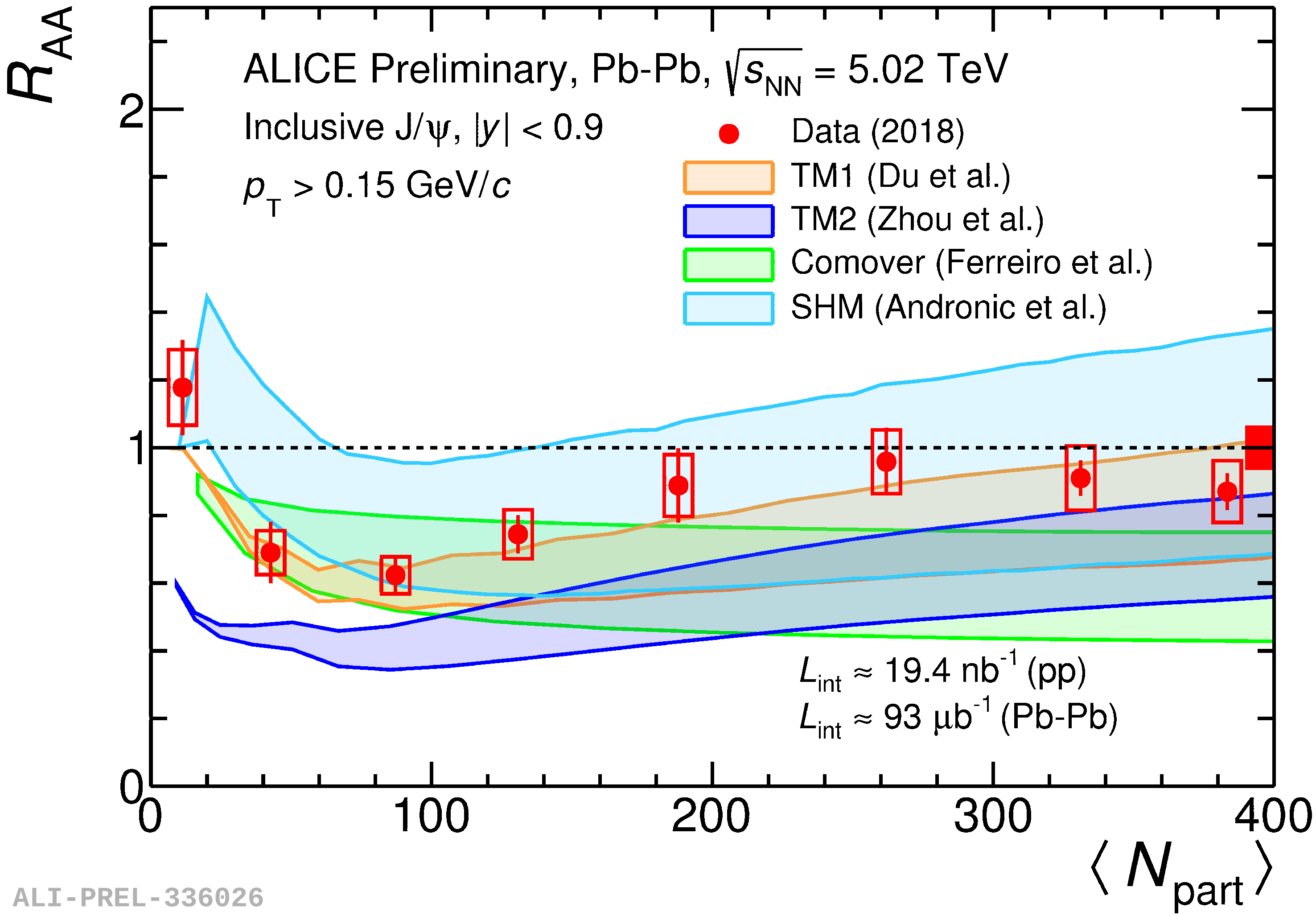
Thermal picture ($n_{partons} = 5.2T^3$ for 3 flavors)

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



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

production dramatically different at the LHC compared to RHIC (PHENIX data) (re)generation was actually predicted by models (SHM, AA et al., PLB 652 (2007) 259)

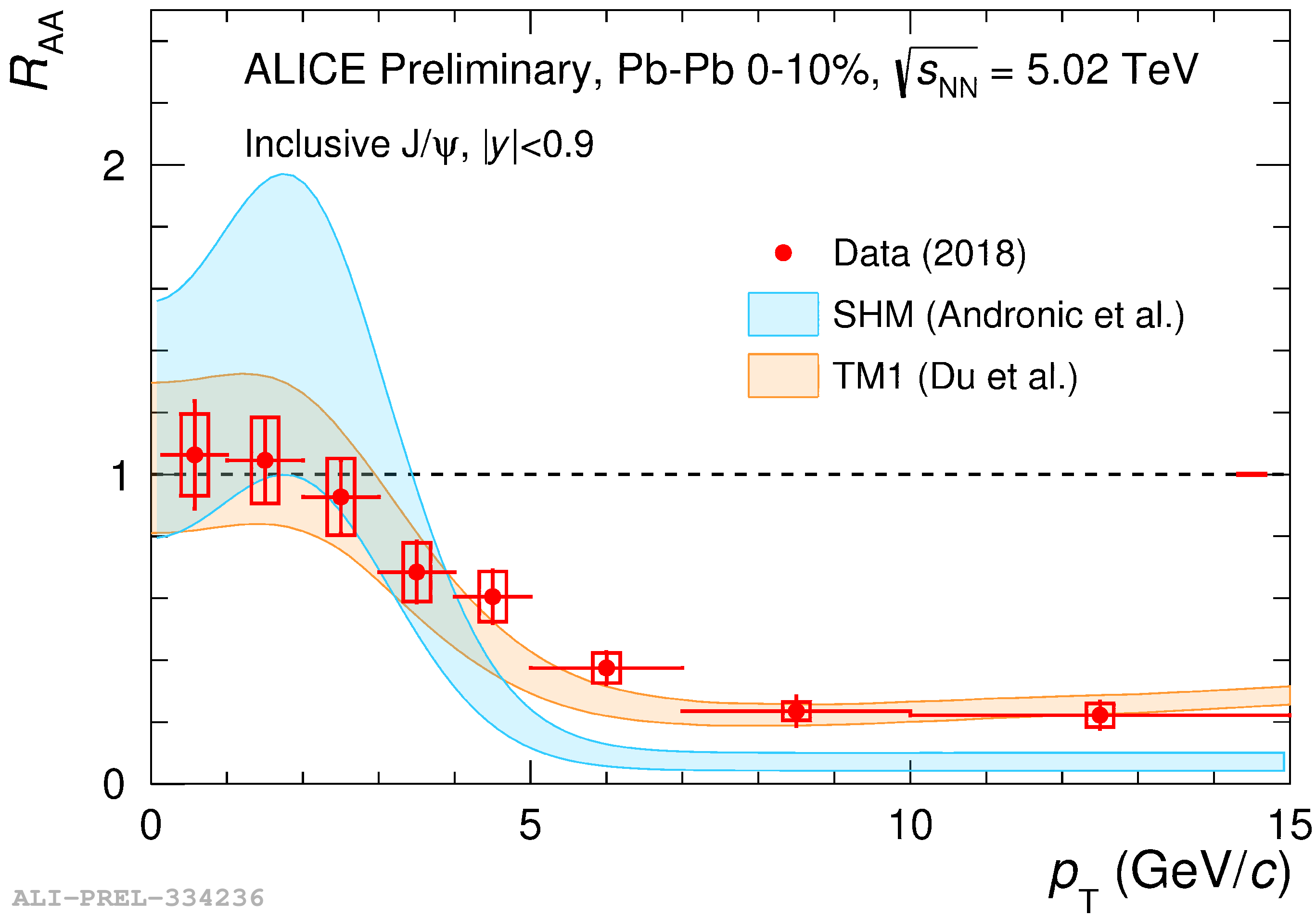


SHM: production at phase boundary (T_c)

Transport models: destruction and regeneration in QGP

different mechanisms

Charmonium production at the LHC

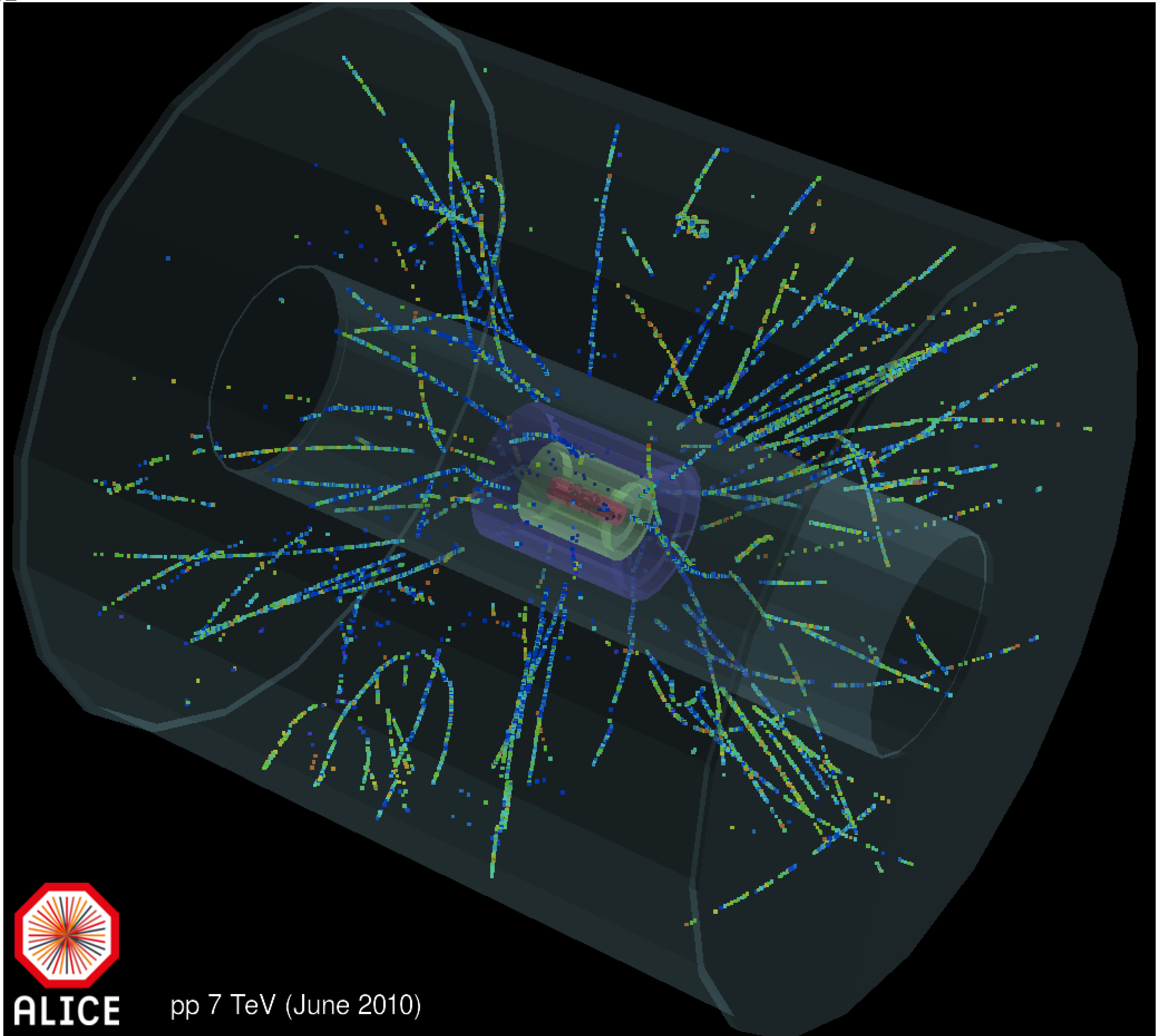


(even better measured at forward rapidity, ALICE, JHEP 02 (2020) 041)

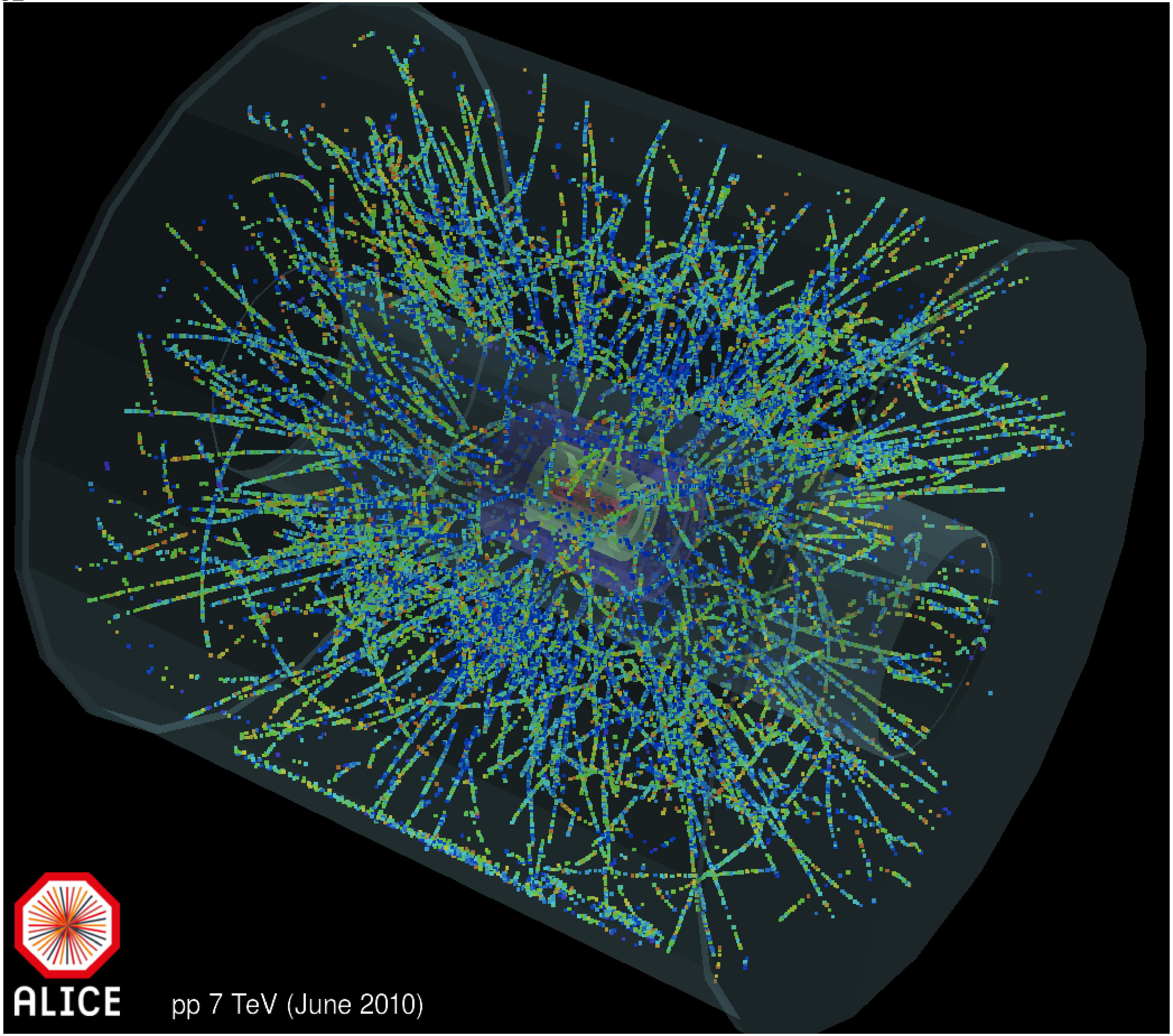
disentangling the two different mechanisms a central goal for Runs 3, 4

→ *fundamental question: fate of hadrons in hot QGP medium*

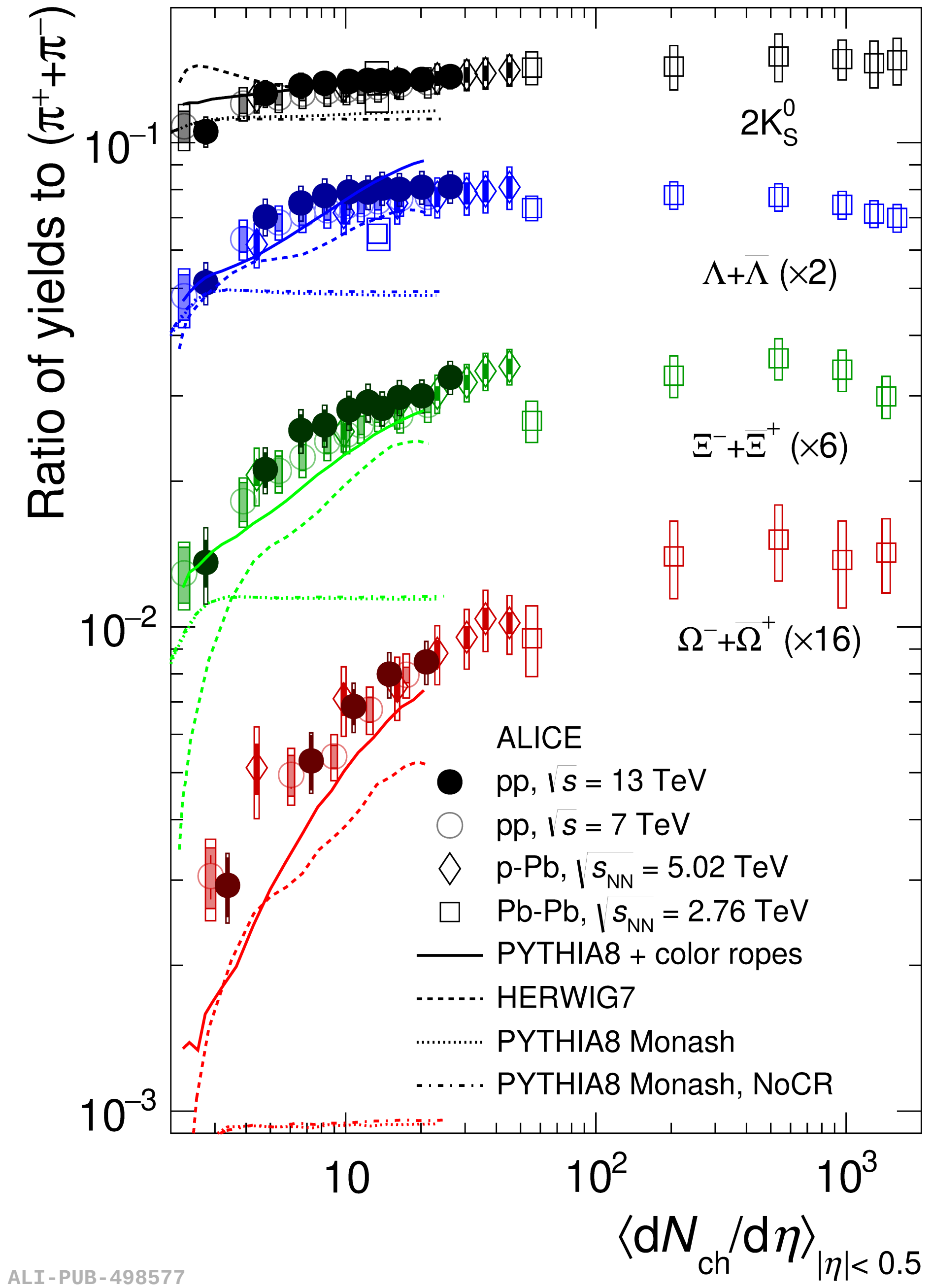
The proton at low resolution ...in collisions at the LHC



The proton at high resolution ...in collisions at the LHC



Strangeness production - from small to large systems



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

ALICE, EPJC 80 (2020) 693

canonical to grand-canonical strangeness production regime

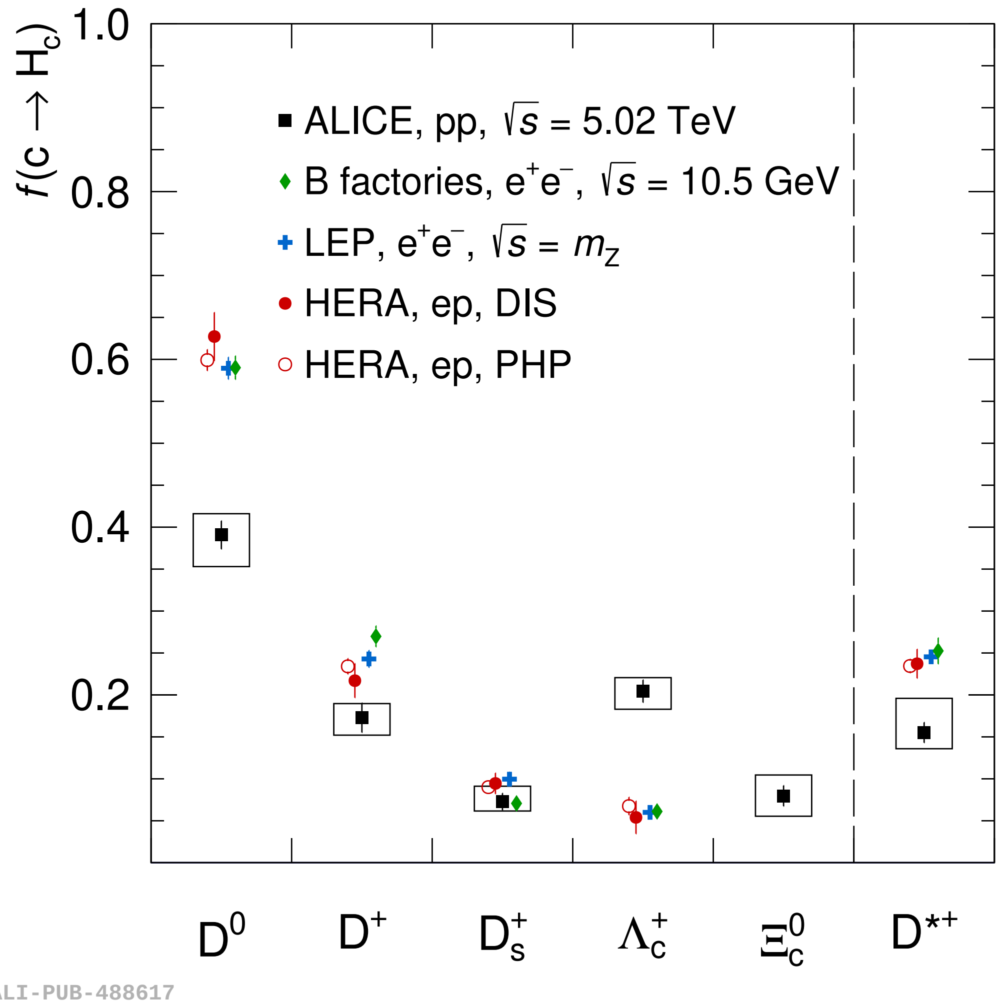
Cleymans et al., PRC 103 (2021) 014904

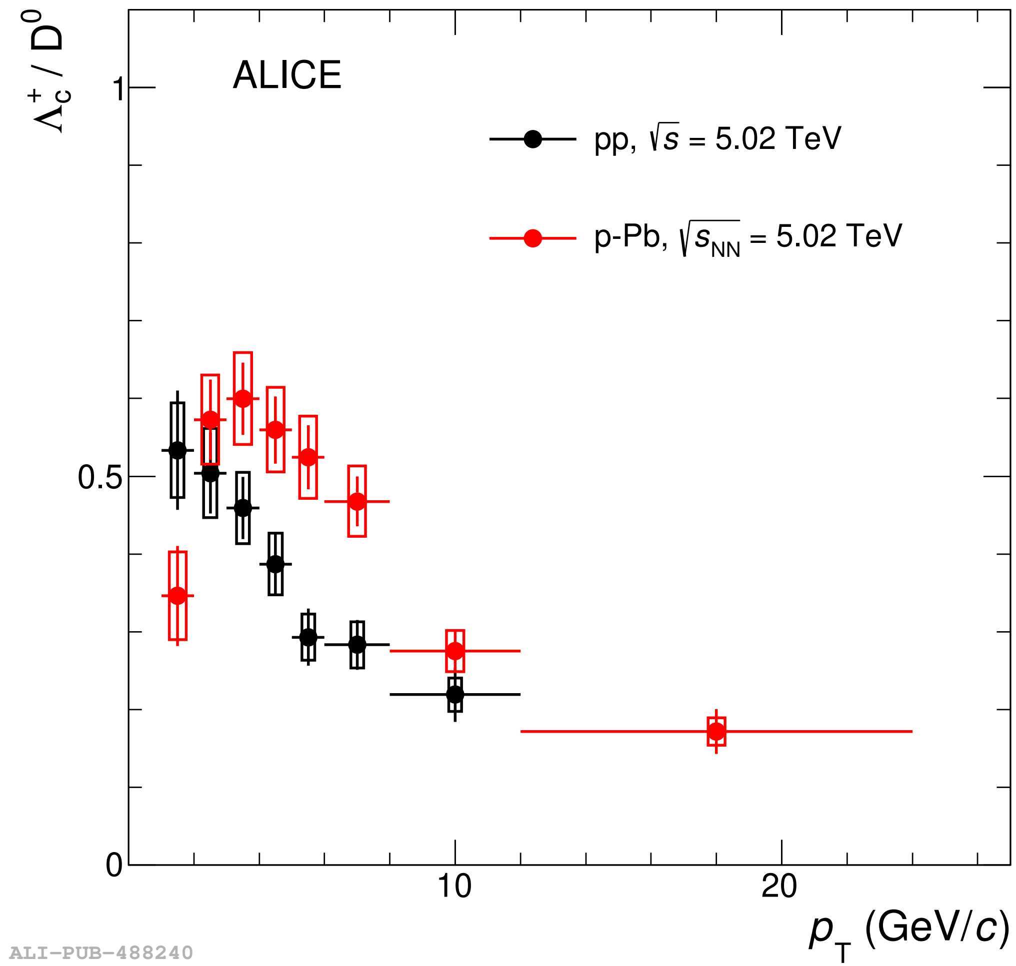
is the same mechanism at work in small systems (at large multiplicities)?

recent ideas on hadronization:
string ropes, shoving

Bierlich et al., JHEP 03 (2015) 148, PLB 779 (2018) 58

Charm baryon production in pp and p–Pb





ALICE, arXiv:2105.06335

ALICE, arXiv:2011.06079

Fragmentation Fractions clearly different in pp (p–Pb)compared to e^+e^-, ep

Summary

- nucleus-nucleus collisions are highly-dynamic
  ...we establish observables for various stages
- abundance of hadrons with light quarks consistent with chemical equilibrium
  the thermal model provides a simple way to access the QCD phase boundary
- charmonium also (mostly) produced at the phase boundary
  ... from $c\bar{c}$ pairs (to a large extent) thermalized in QGP
- we see strong jet quenching (parton energy loss) in quark-gluon matter
  data $+$ theoretical models $\rightarrow$ extraction of transport coefficients
- strong collective flow, well described by hydrodynamics (not shown, available in spare slides)
- strong multiplicity dependence of hadron production in pp (p–Pb) collisions
- charm fragmentation different in pp compared to e^+e^-, ep

A significantly-upgraded ALICE detector ready to take data (Runs 3,4)

after a 3 years break, first pp collisions (pilot beam at 900 GeV) just recorded

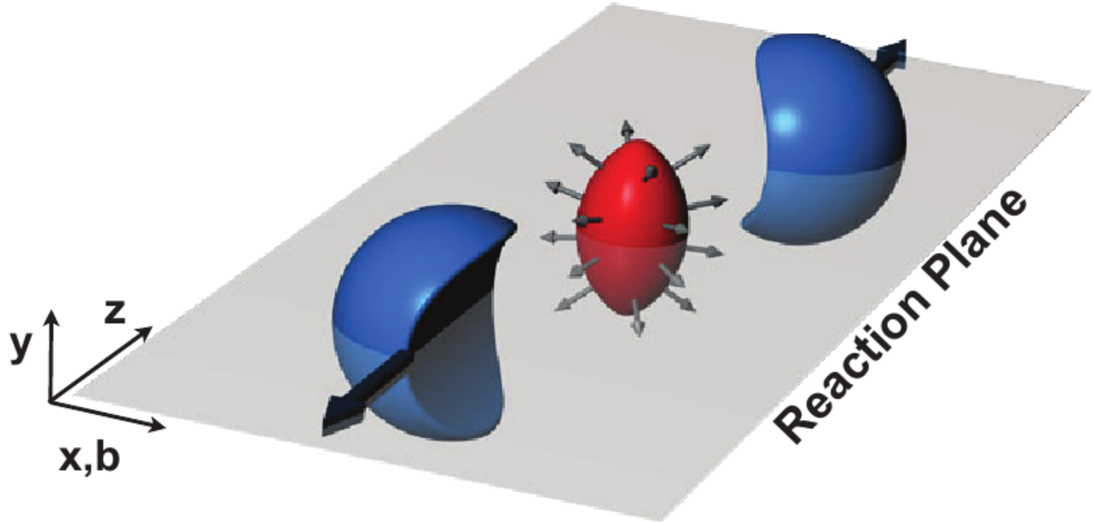
Goal: precision studies in pp, p-Pb and Pb–Pb, with rarer observables, among them:

- charm and beauty
- dileptons and photons
- correlations and fluctuations

CERN Courier 2021

Additional slides

Elliptic flow

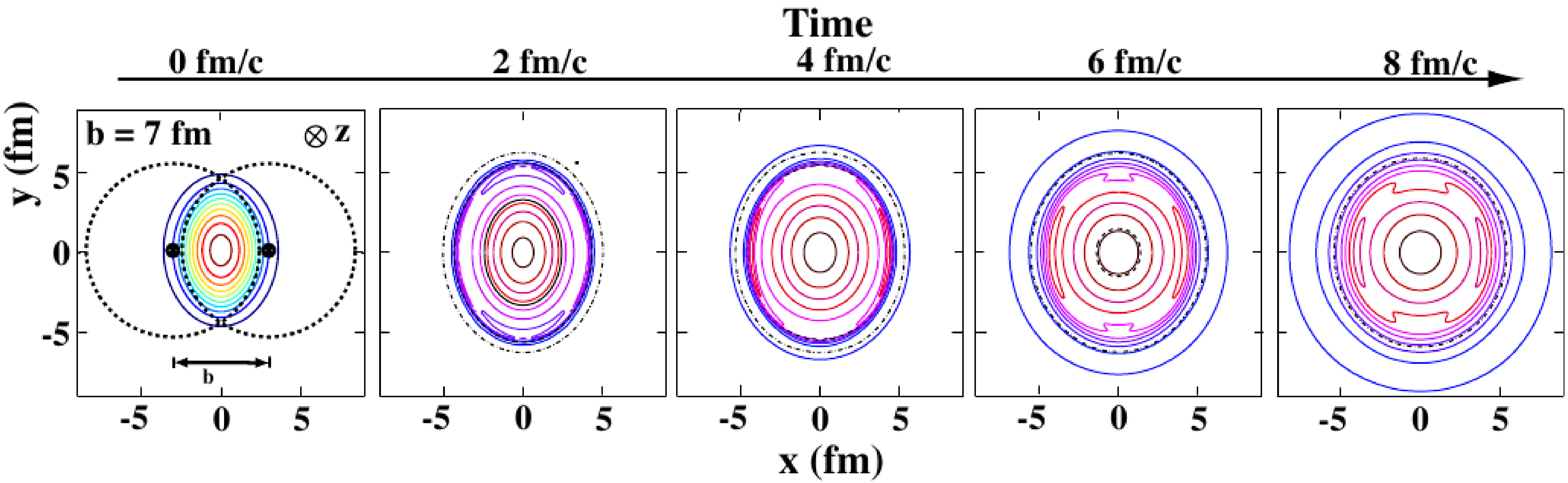


R. Snellings, arXiv:1102.3010

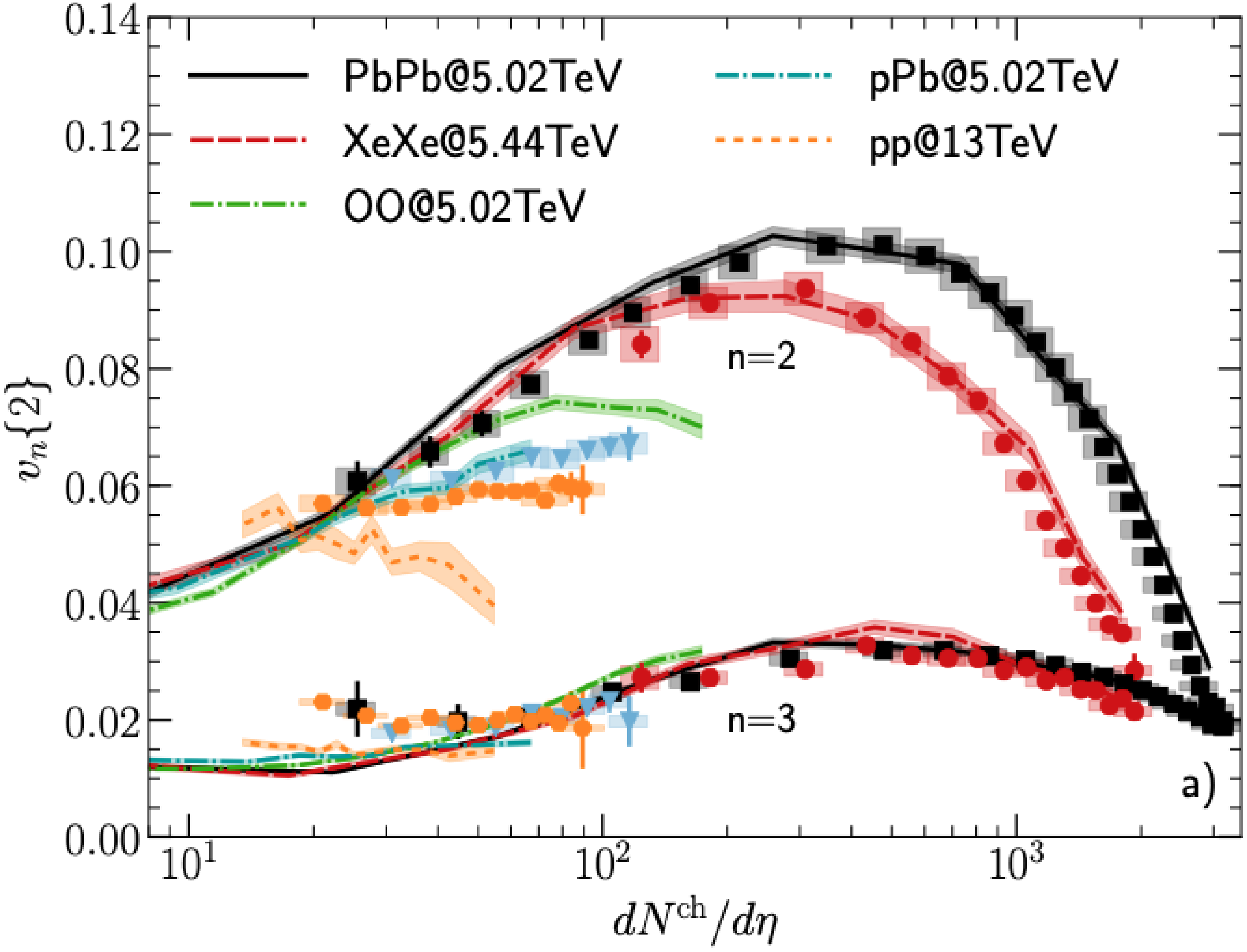
$$\frac{dN}{d\varphi} \sim [1+2v_1 \cdot \cos(\varphi)+2v_2 \cdot \cos(2\varphi)+\ldots]$$

φ = azimuthal angle with respect to reaction plane

$v_2 = \langle \cos(2\varphi) \rangle$ we call *elliptic flow*



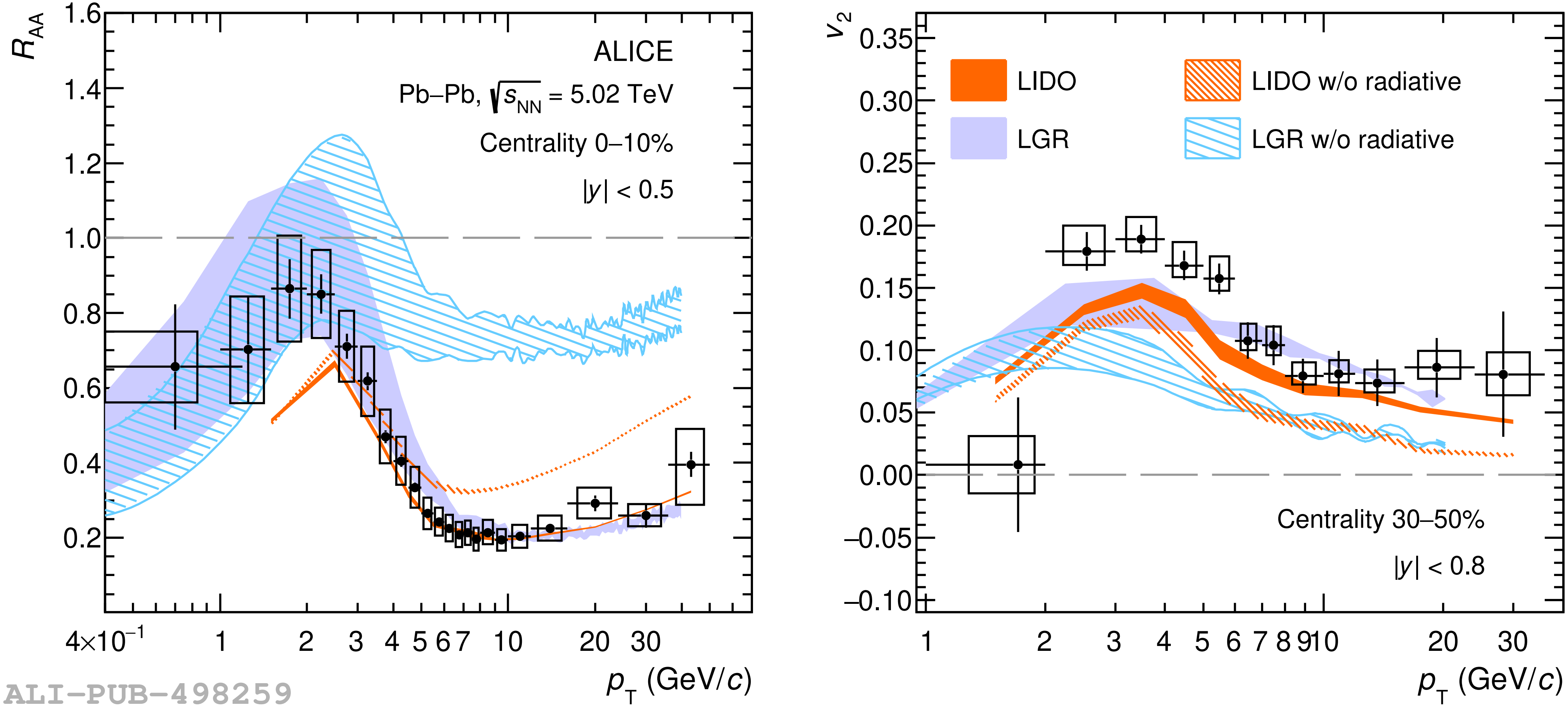
Flow harmonics: all collision systems



Symbols: data, ALICE, PRL 123 (2019) 142301

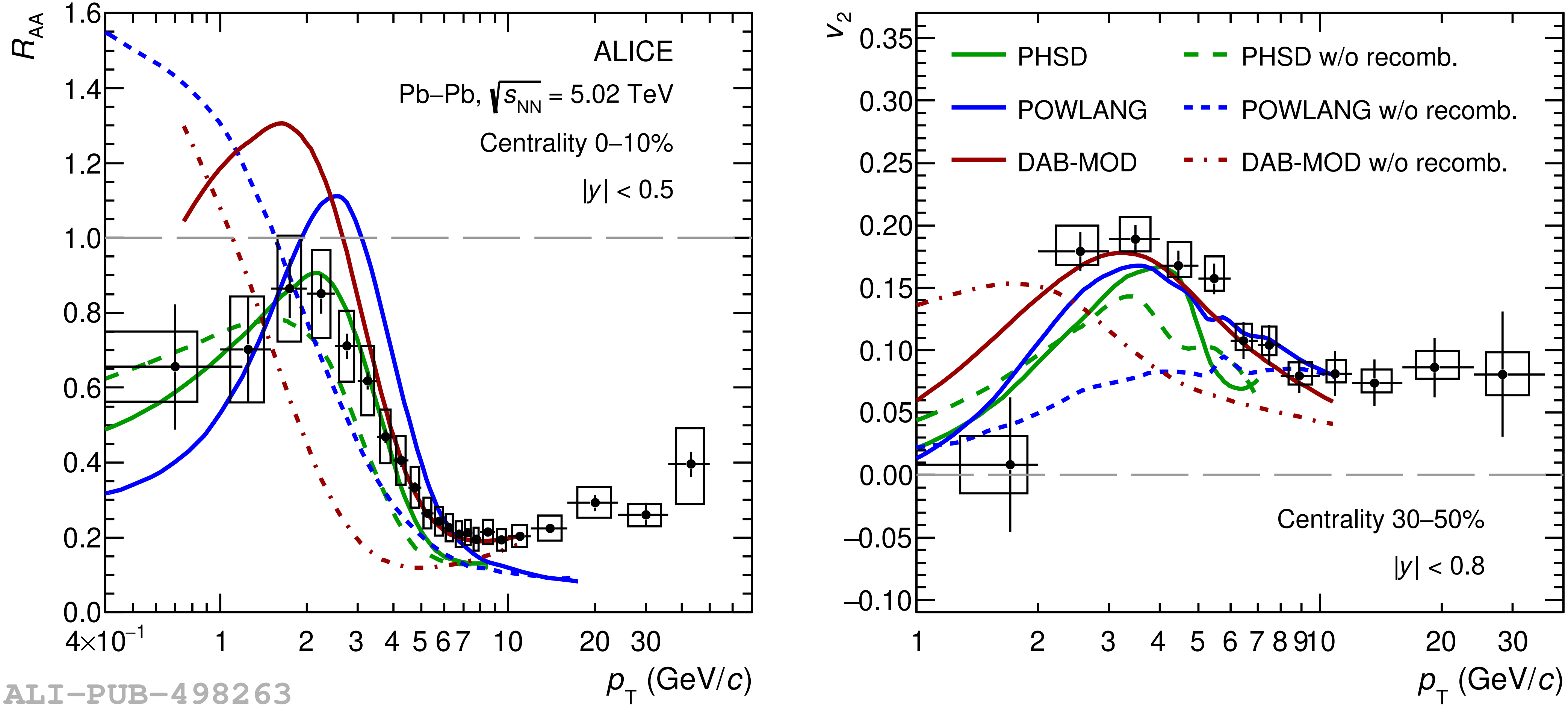
Lines: hydrodynamics, Schenke, Shen, Tribedy PRC 102 (2020) 044905

Charm quark energy loss



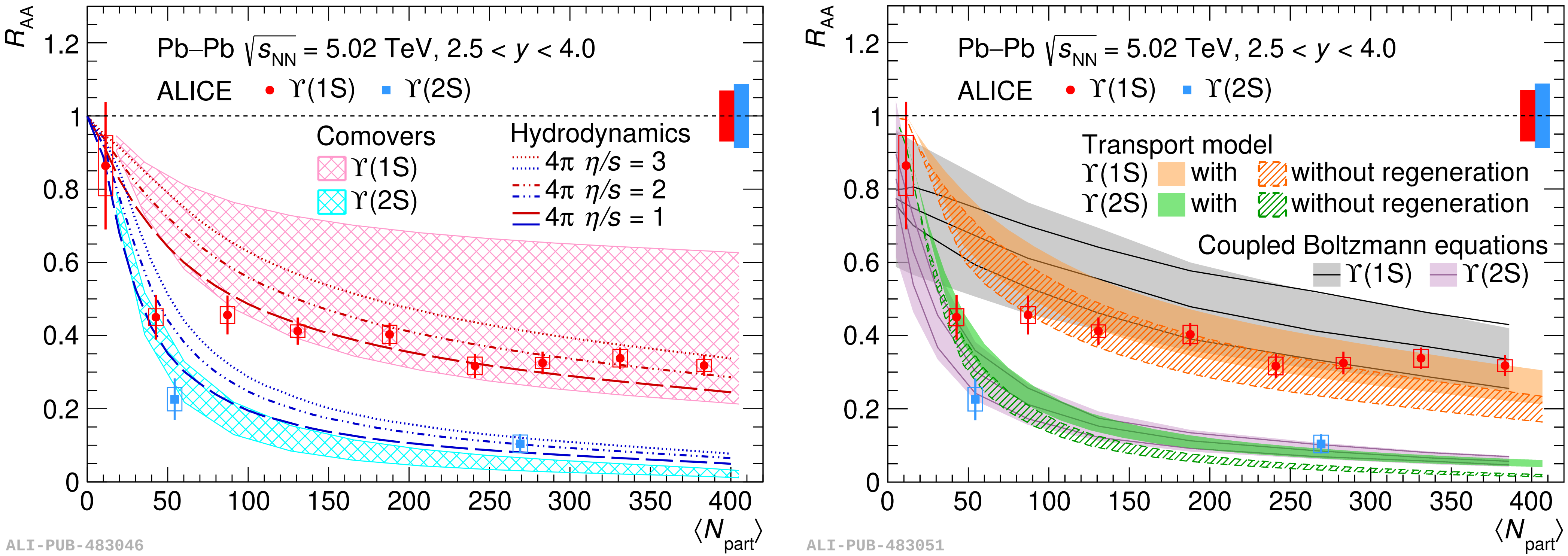
ALICE, arXiv:2110.09420

Charm quark energy loss



ALICE, arXiv:2110.09420

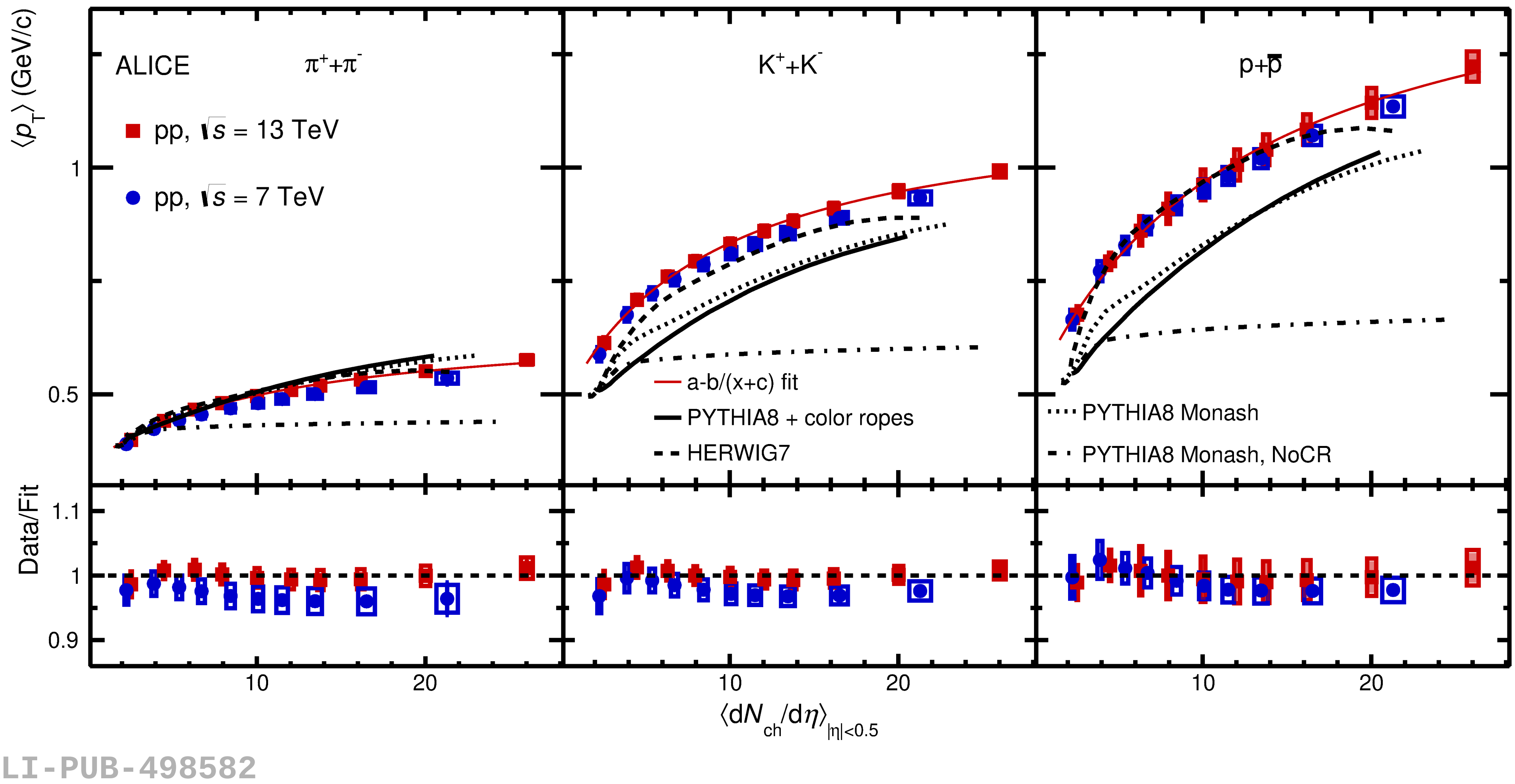
Υ production



ALICE, PLB 822 (2021) 136579

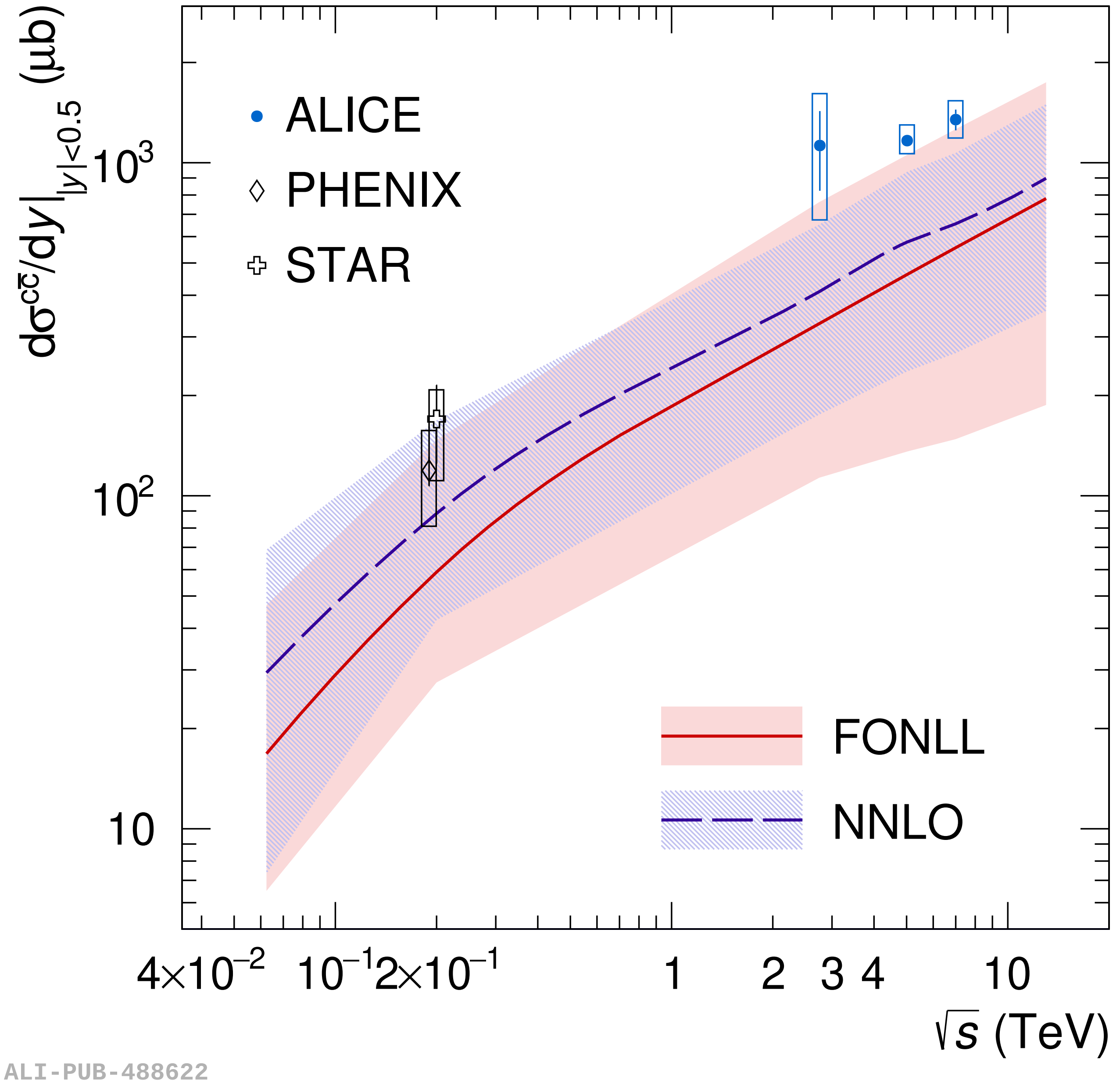
suppression pattern well described ...by various models

Hadron production in pp



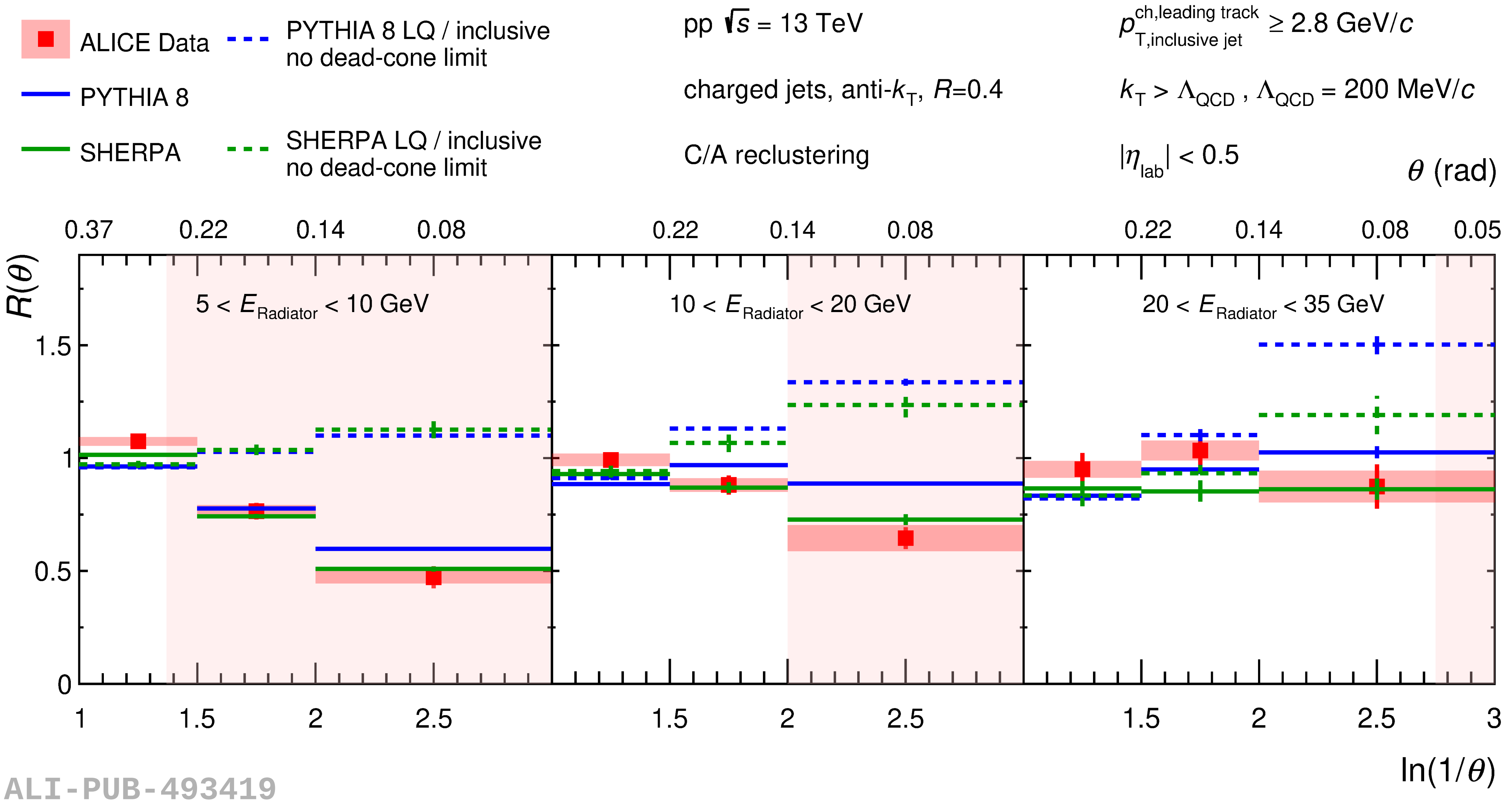
ALICE, EPJC 80 (2020) 693

Charm baryon production in pp and p–Pb



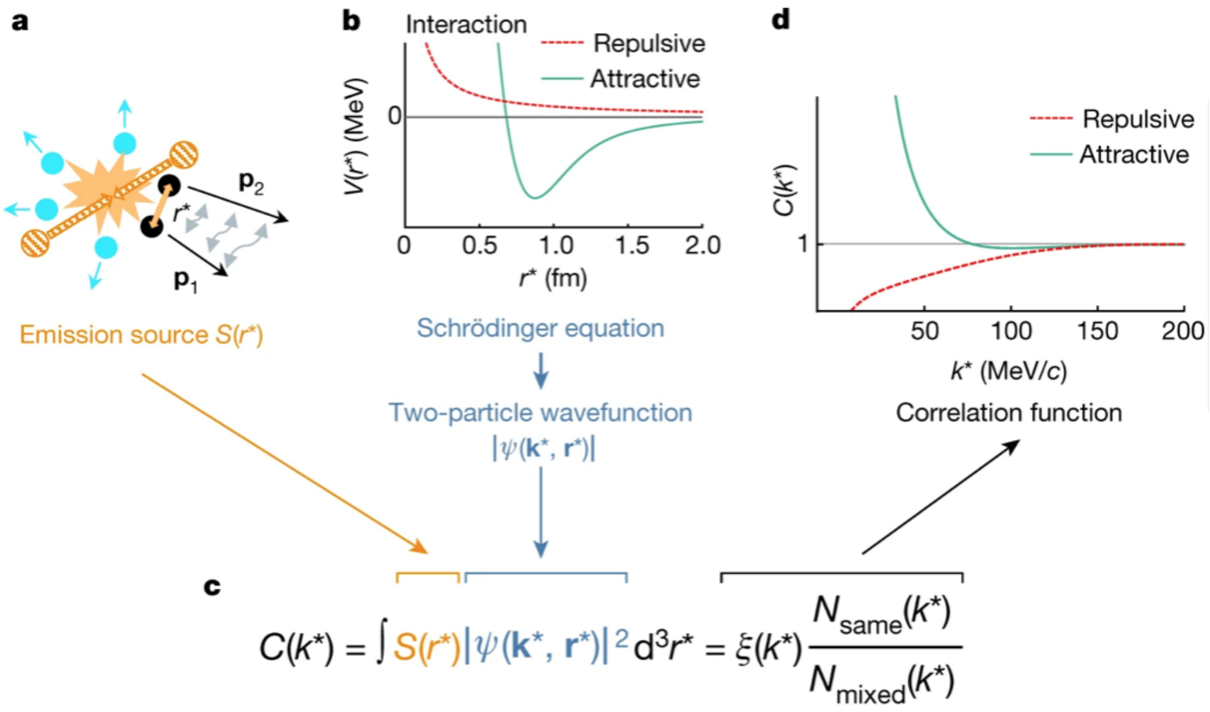
ALICE, arXiv:2105.06335

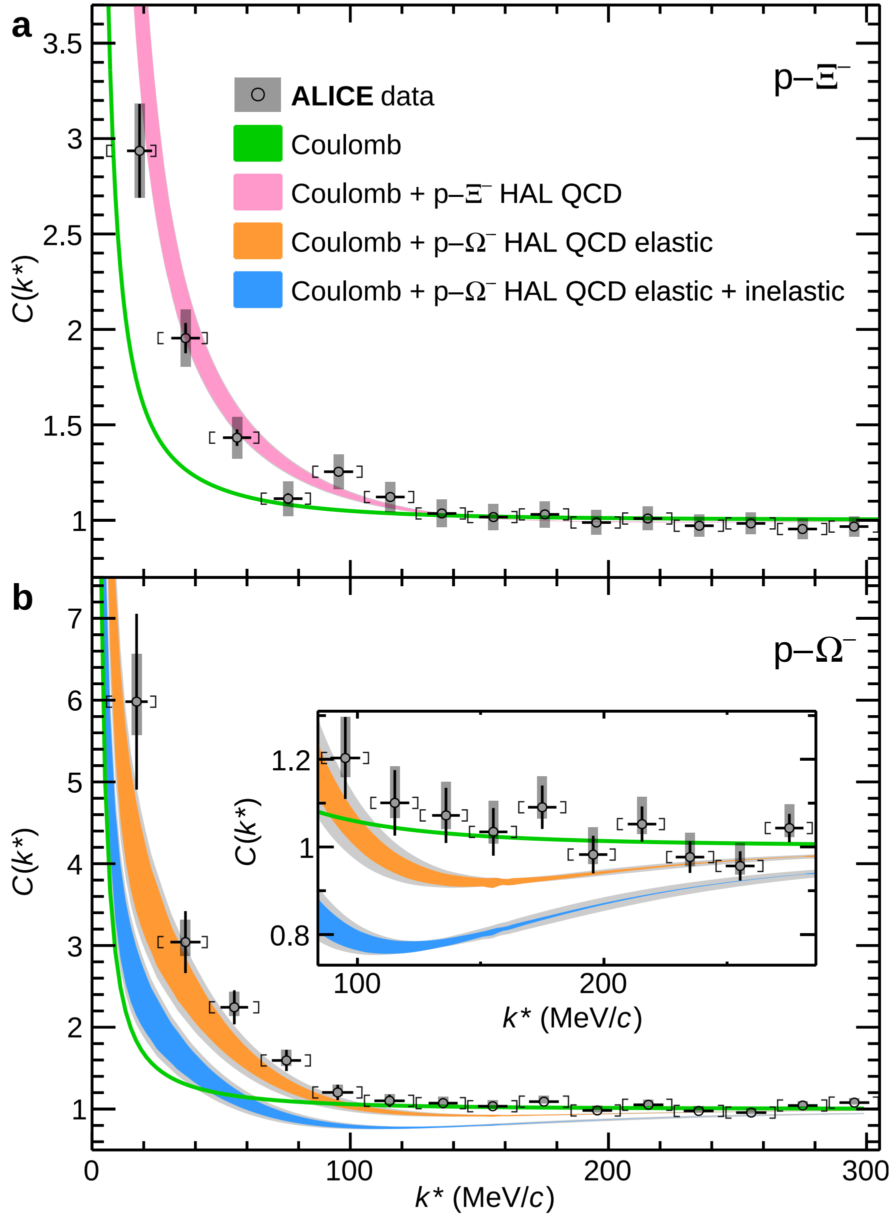
The dead cone effect observed (charm quarks)



ALICE, arXiv:2106.05713

Unveiling the proton-hyperon interaction





ALICE, Nature 588 (2020) 232

p-ϕ interaction: PRL 127 (2021) 172301