The Quark-Gluon Plasma

Characterizing the early Universe matter with the first 10 years of heavy-ion collisions at the LHC

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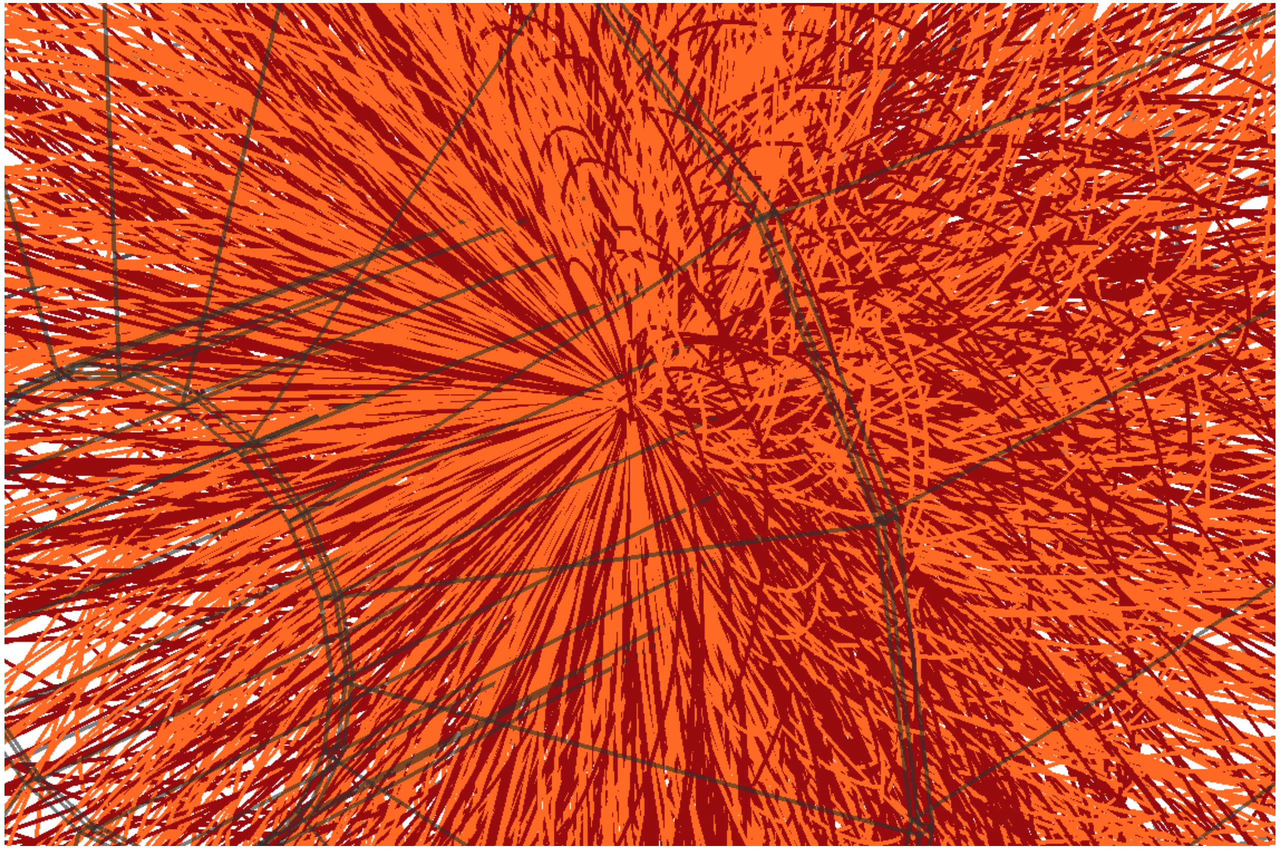


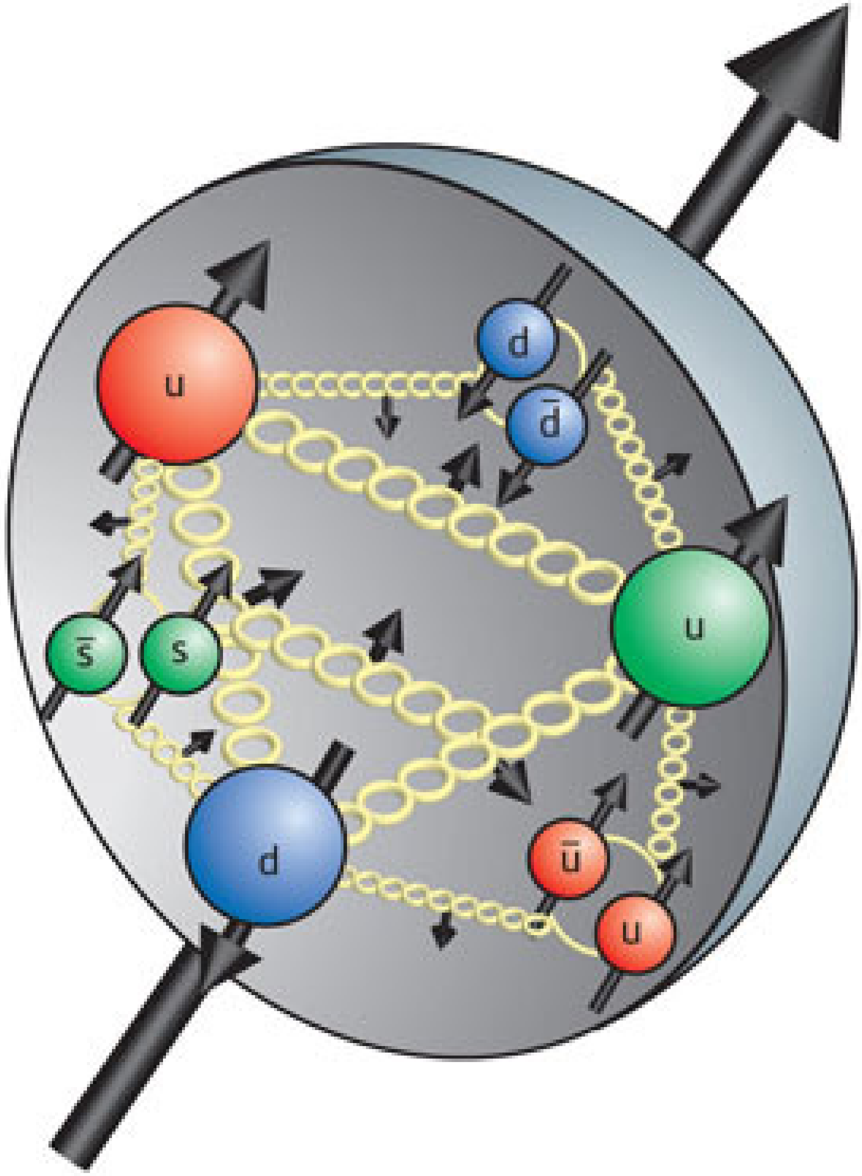
2024 CTEQ Summer School - Bramsche, 30.08.2024

Outline

- Introduction, theoretical basis
- The LHC and the detectors; what is measured
- Hadrons with light-flavor (u,d,s) and the QCD phase diagram
- Collective flow, hydrodynamics
- Jet quenching (parton energy loss)
- Heavy quarks and deconfined matter
- Summary

see reviews: AA, arXiv:1407.5003; Busza, Rajagopal, van der Schee, 1802.04801

The proton at high resolution (energies)



There are more quarks than the “constituent” (valence) u,u,d ...virtual quark-antiquark pairs; also many gluons

This is one of many possible configurations

...obtained in (deep-inelastic) electron scattering experiments with resolution 10^{-18}-10^{-19} m (leading to Parton Distribution Functions)

The quarks are never found free *quark confinement* (principle)

...are free only asymptotically $(Q \to \infty)$

Gross, Wilczek, Politzer, 1974 (Nobel Prize 2004)

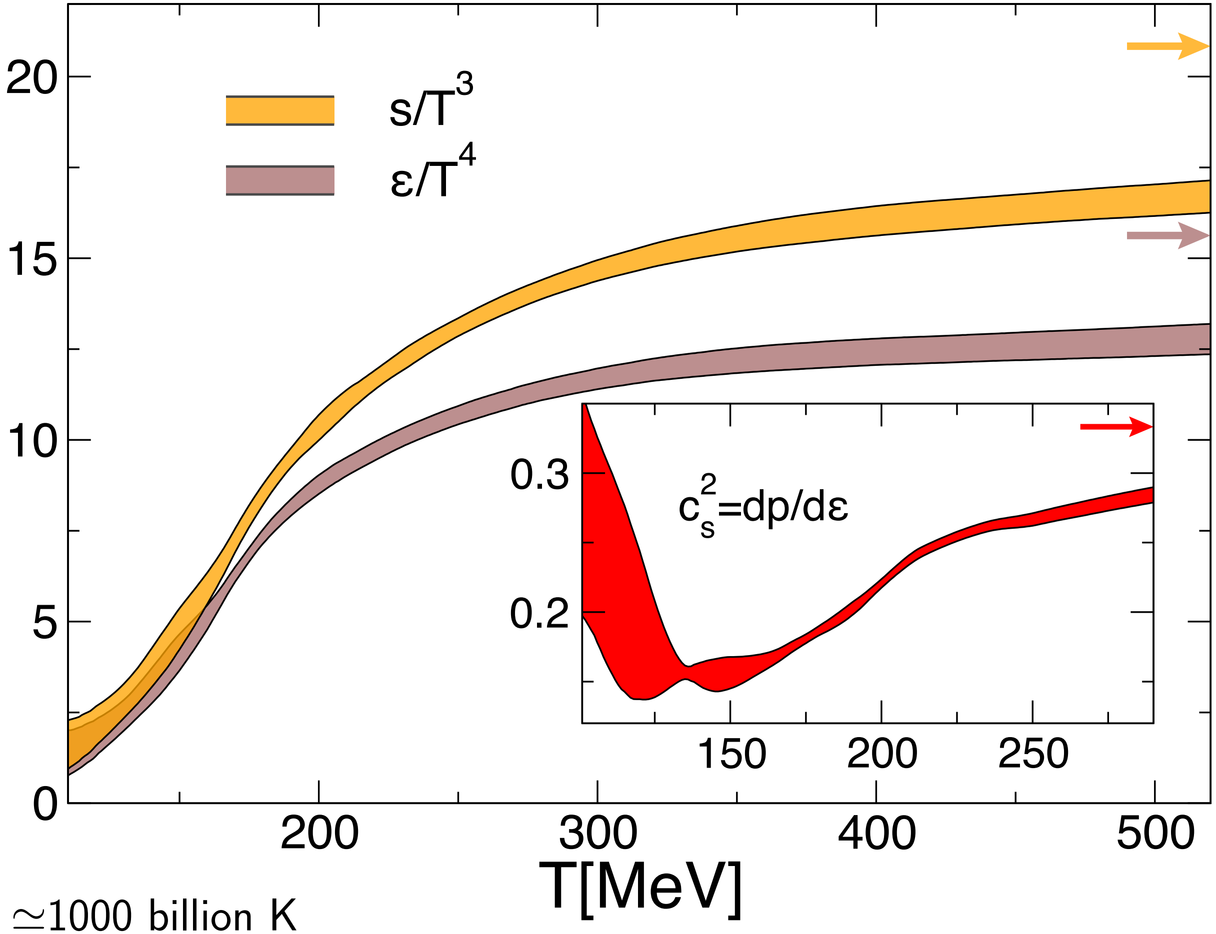
...has led to the proposal of the Quark-Gluon Plasma (high T)

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

Lattice QCD predicts a phase transition (μ_B=0)

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

crossover



(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)

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

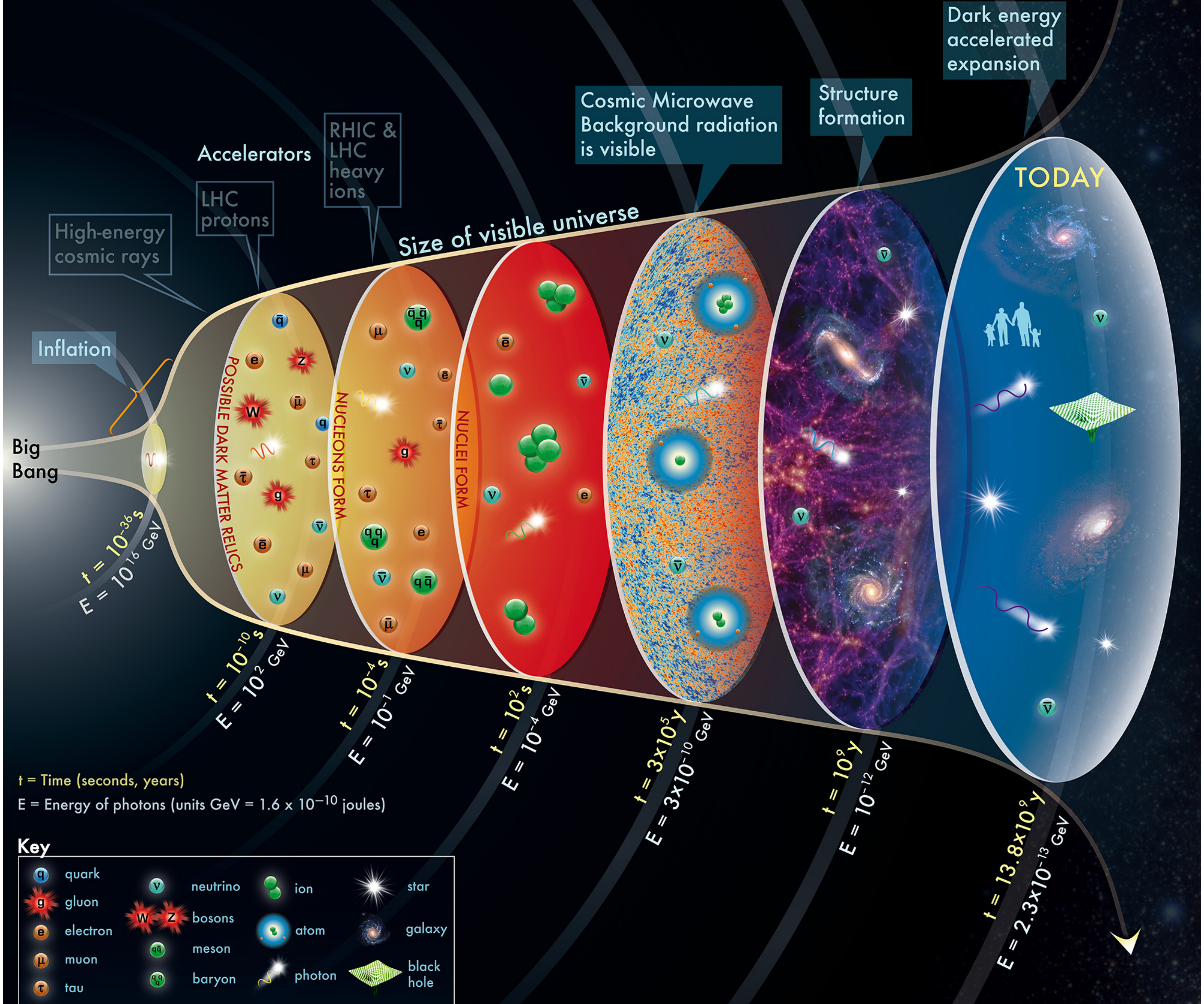
$\simeq$1000 billion K

Borsanyi et al., PLB 370 (2014) 99 , PRL 125 (2020) 052001 ; Bazavov et al., PLB 795 (2019) 15

T_c=156.5±1.5 (158.0±0.6) MeV, ε_c $\simeq$0.4 GeV/fm^3, or 2.5$\varepsilon_{nuclear}$

ideal-gas limit not reached at very large temperatures (GeV range explored)

HISTORY OF THE UNIVERSE



Dark energy accelerated expansion

Structure formation

Cosmic Microwave Background radiation is visible

Accelerators

RHIC & LHC heavy ions

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 = 3×10^{5} y
E = 3×10^{-10} GeV

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

t = 13.8×10^{9} y
E = 2.3×10^{-13} GeV

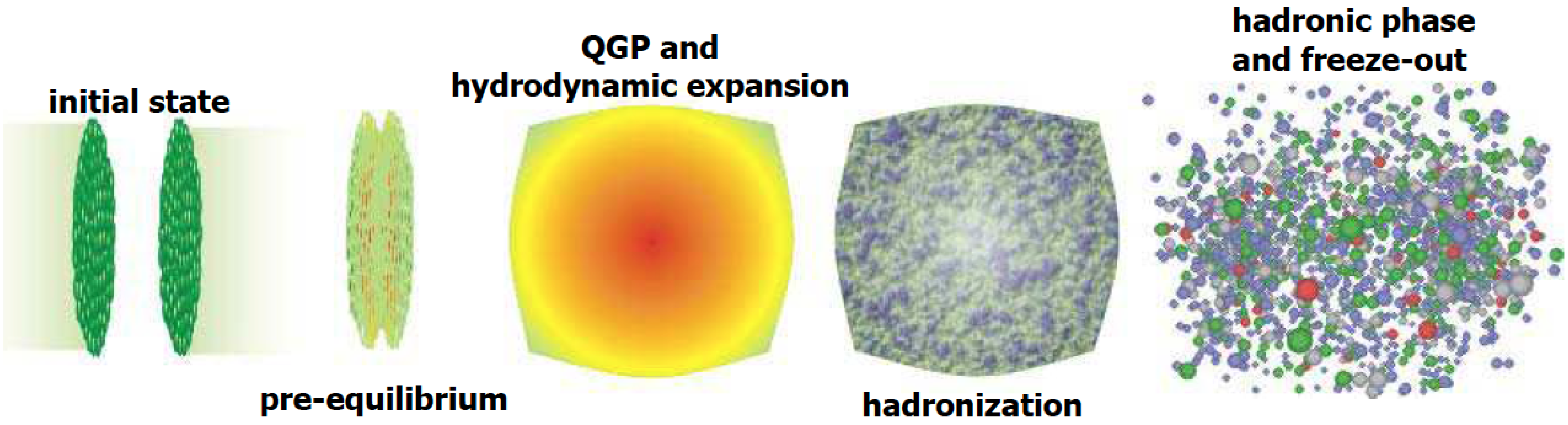
t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6×10^{-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

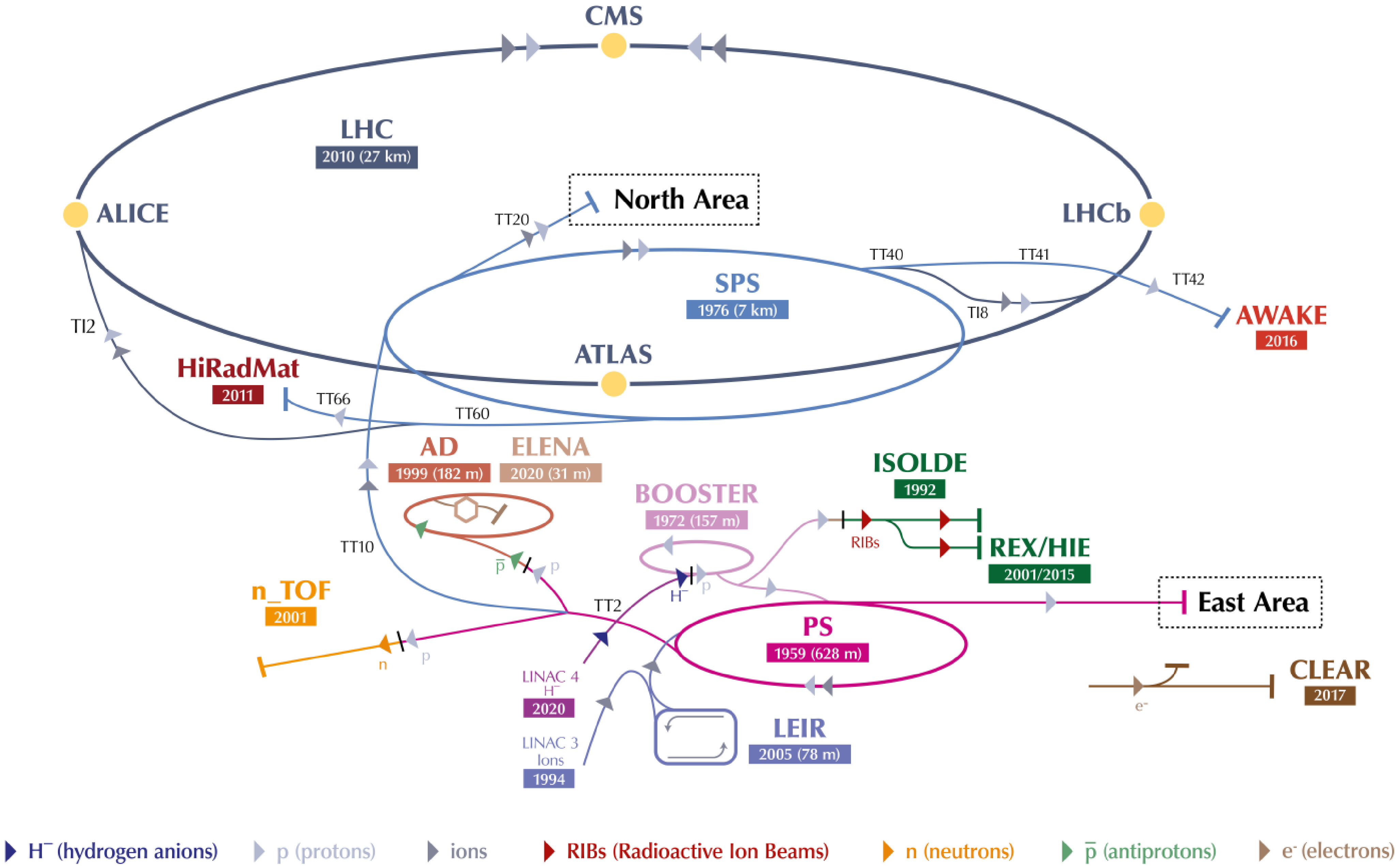
How to "simulate" in laboratory the early Universe?



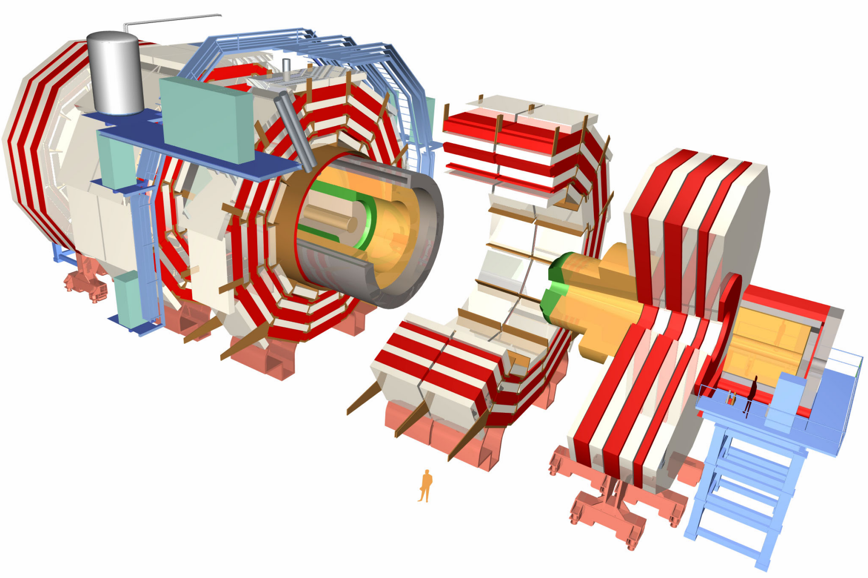
$t \simeq 10^{-23}$ s, $V \simeq 10^{-40}$ m^3

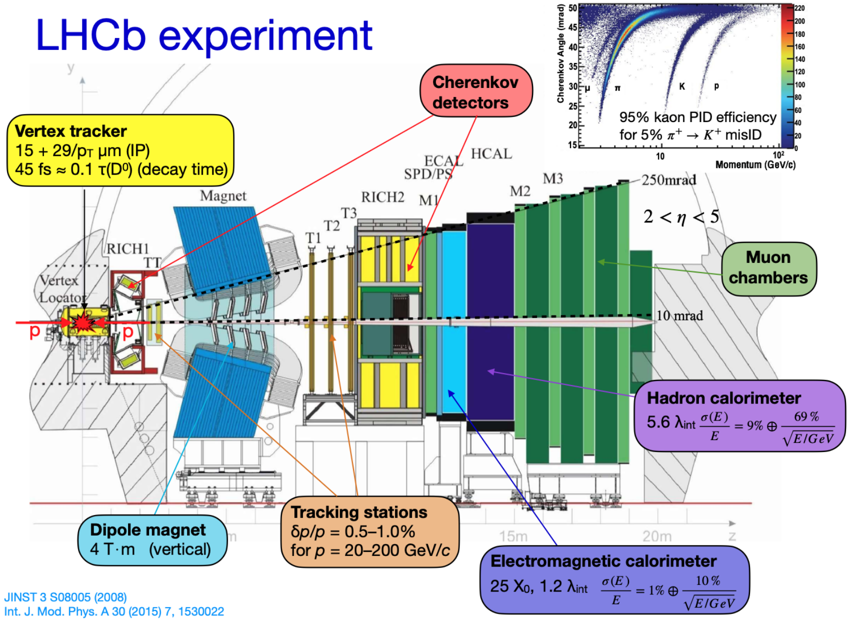
1. initial collisions ($t \leq t_{coll} = 2R/\gamma_{\rm cm}c$; $R_{Pb} \simeq$7 fm)
2. thermalization: equilibrium is established ($t \lesssim$ 1 fm/c $= 3 \times 10^{-24}$ s)
3. expansion ($\sim 0.6c$) and cooling ($t <$ 10-15 fm$/c$) ...deconfined stage?
4. hadronization (quarks and gluons form hadrons)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



The detectors at the LHC all measure heavy-ion collisions





LHCb experiment

Vertex tracker
15 + 29/p_T µm (IP)
45 fs ≈ 0.1 τ(D^0) (decay time)

Cherenkov detectors

95% kaon PID efficiency for 5% $\pi^+ \to K^+$ misID

Muon chambers

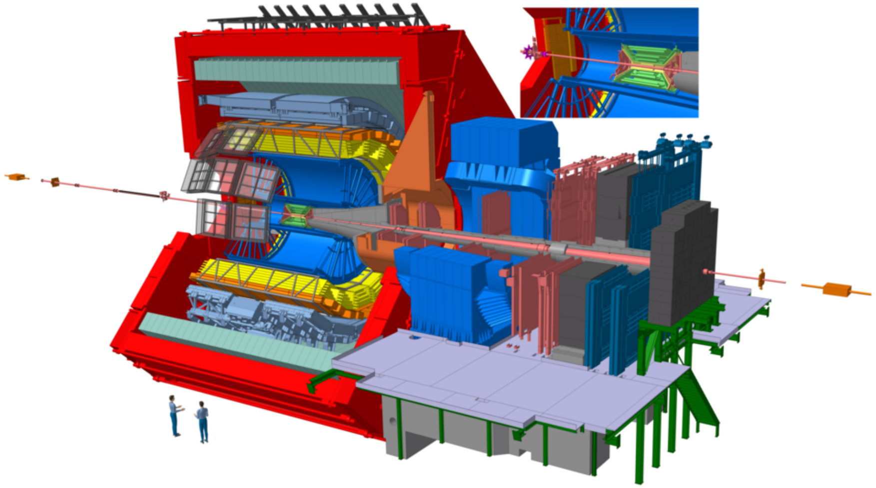
Hadron calorimeter
5.6 λ_{int} $\frac{\sigma(E)}{E} = 9\% \oplus \frac{69\,\%}{\sqrt{E/GeV}}$

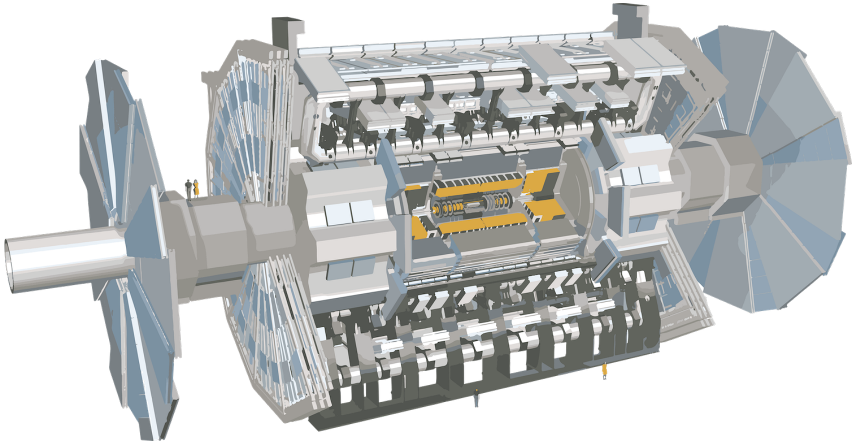
Dipole magnet
4 T·m (vertical)

Tracking stations
δp/p = 0.5–1.0%
for p = 20–200 GeV/c

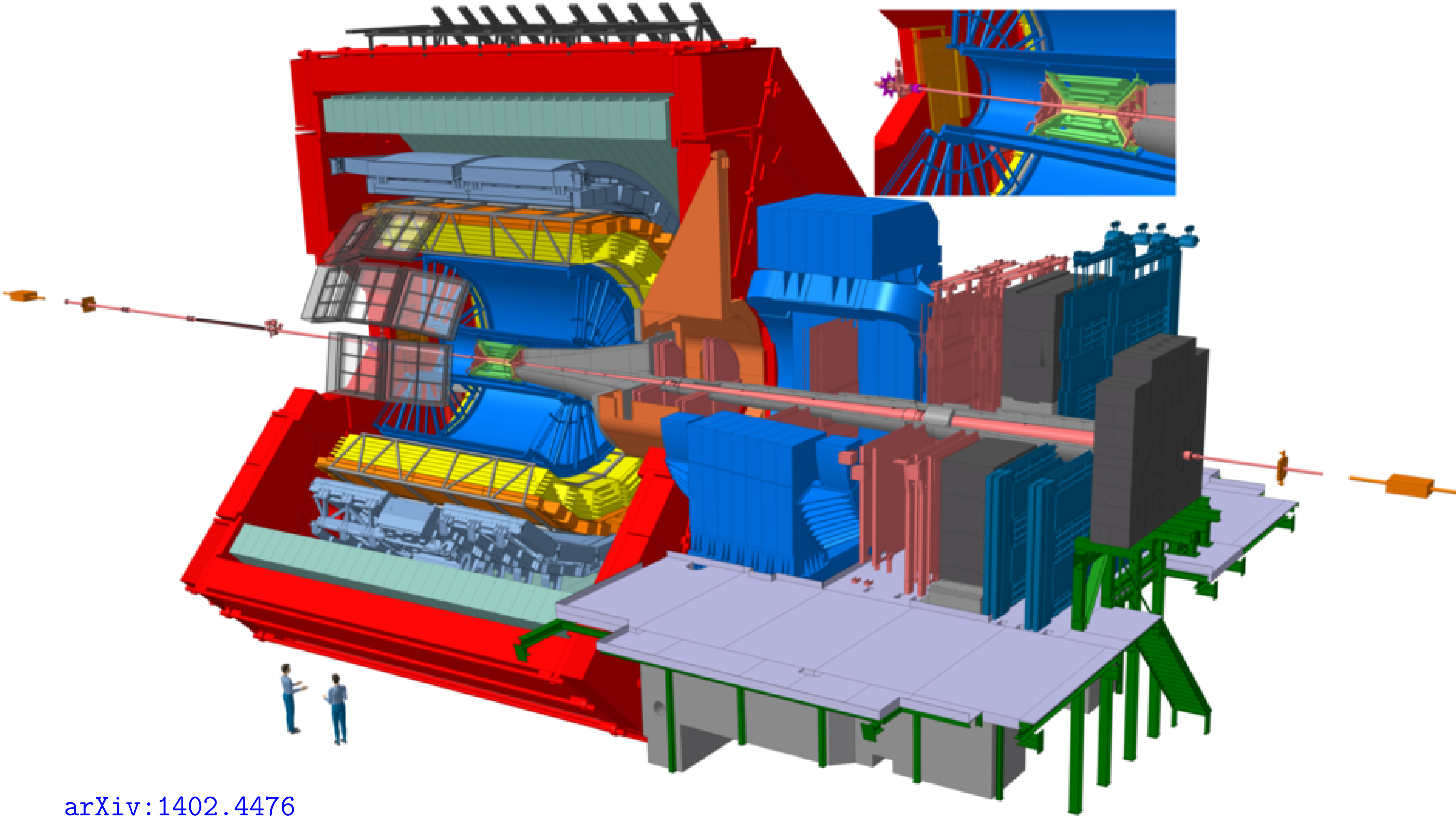
Electromagnetic calorimeter
25 X_0, 1.2 λ_{int} $\frac{\sigma(E)}{E} = 1\% \oplus \frac{10\,\%}{\sqrt{E/GeV}}$

JINST 3 S08005 (2008)
Int. J. Mod. Phys. A 30 (2015) 7, 1530022





A detector at the LHC - ALICE

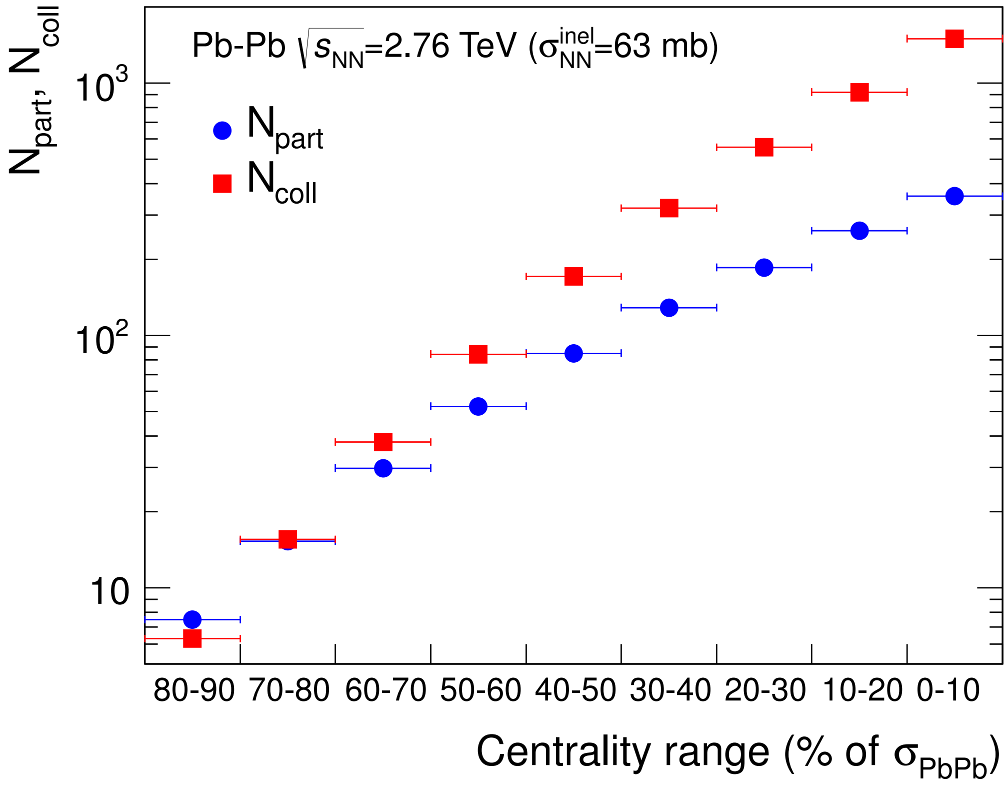


arXiv:1402.4476

ALICE Collaboration: 40 countries, 170 institutions, 2009 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



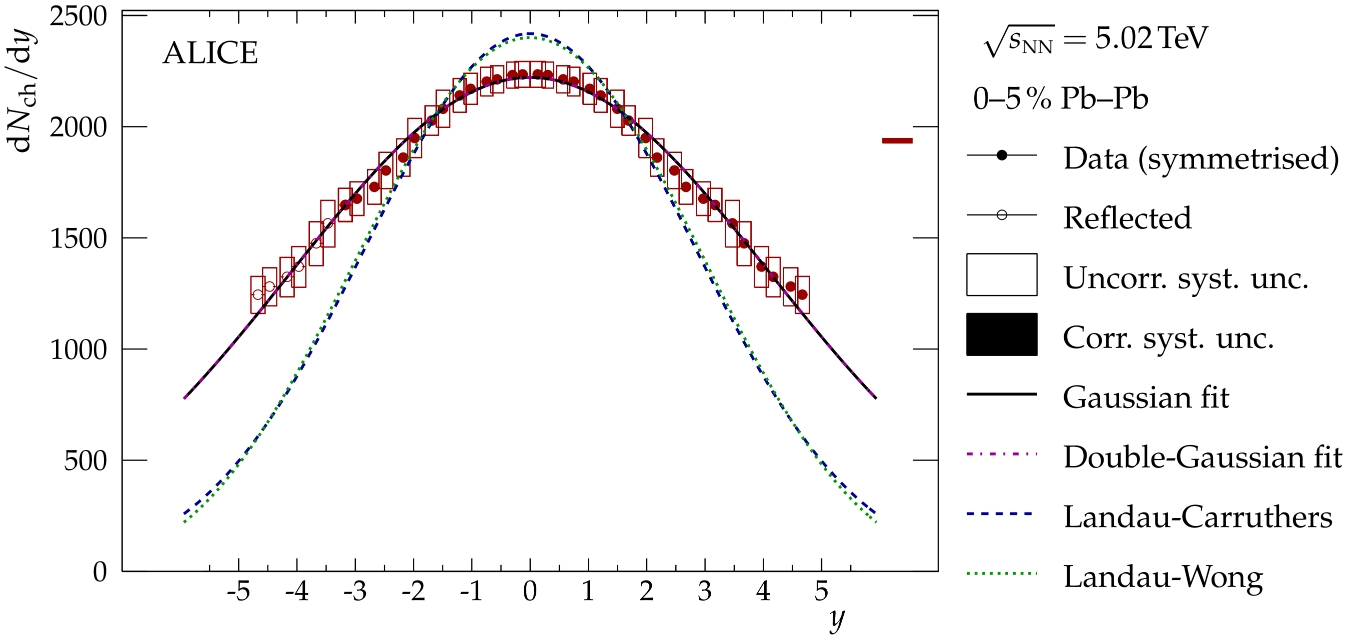
...while often taking as reference the measurement in proton-proton collisions (at the same energy), for "hard probes" (pQCD) scaled by the number of collisions corresponding to the given centrality class

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

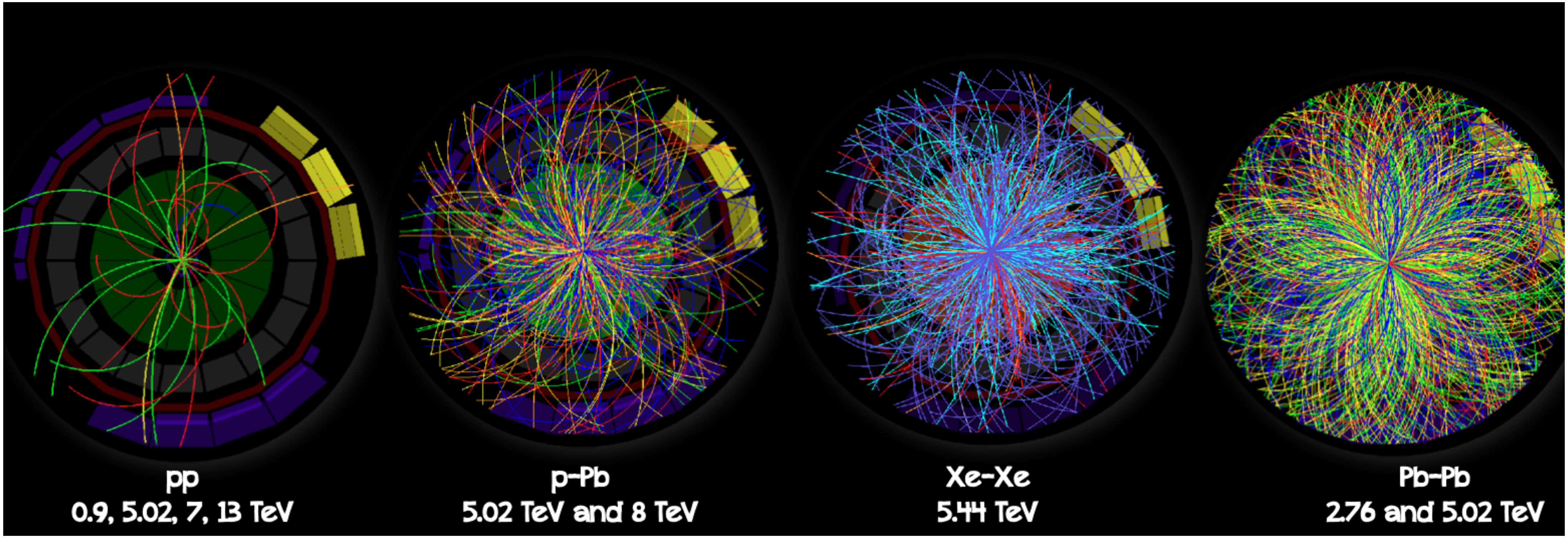
We usually measure symmetric collisions of heavy nuclei (Au–Au, Pb–Pb)
pp and p-Pb collisions as reference, but interesting on their own (limits of QGP)
Need many collisions (millions), to sample properly the distributions

- 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)

Detector acceptance restricted around midrapidity ($y, \eta = 0$)

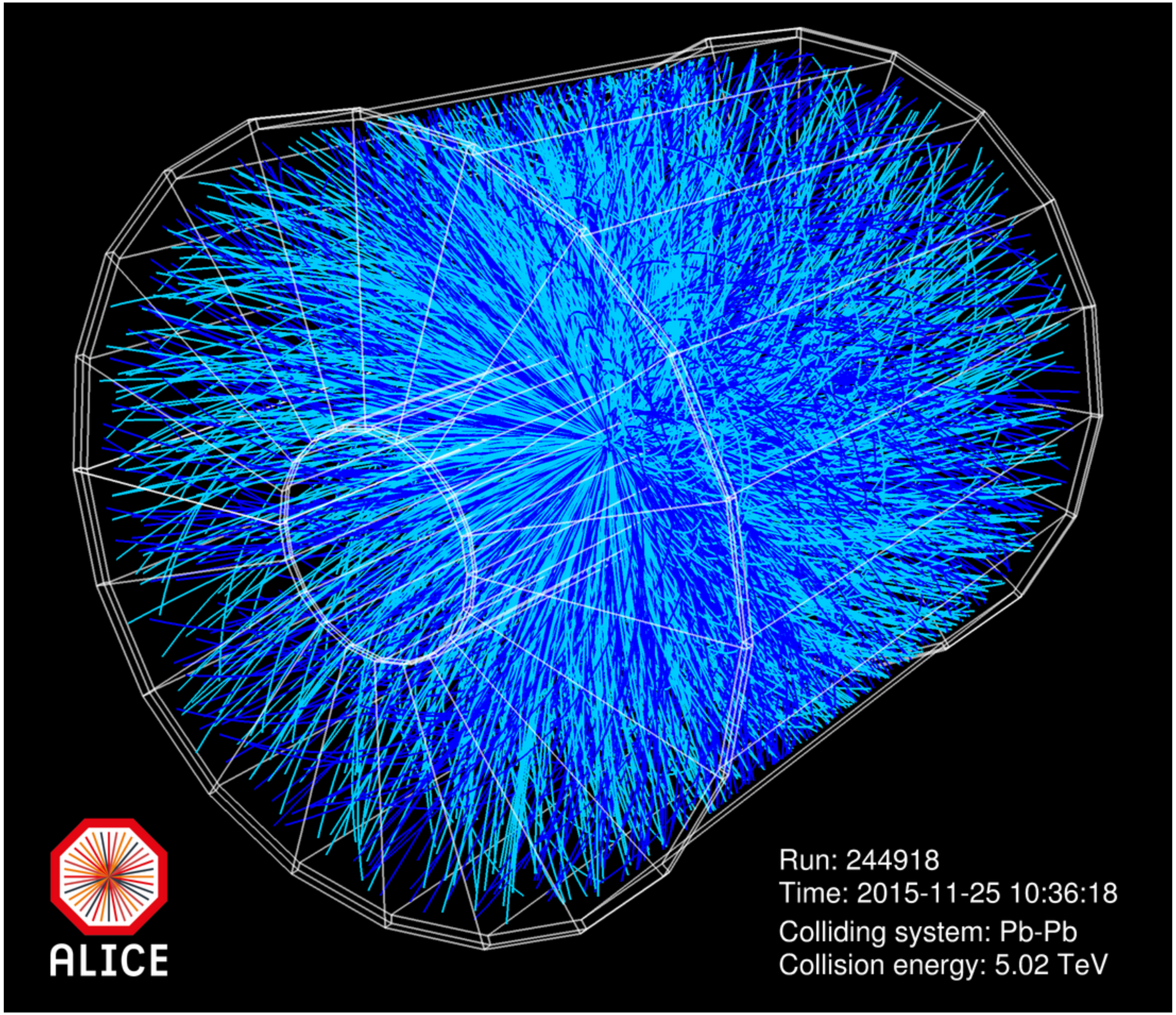
Single-particle detection efficiency: about 70-80%
(from detailed Monte Carlo modelling of the detector)

A pictorial summary of collisions at the LHC



©C.Oppedisano/ALICE

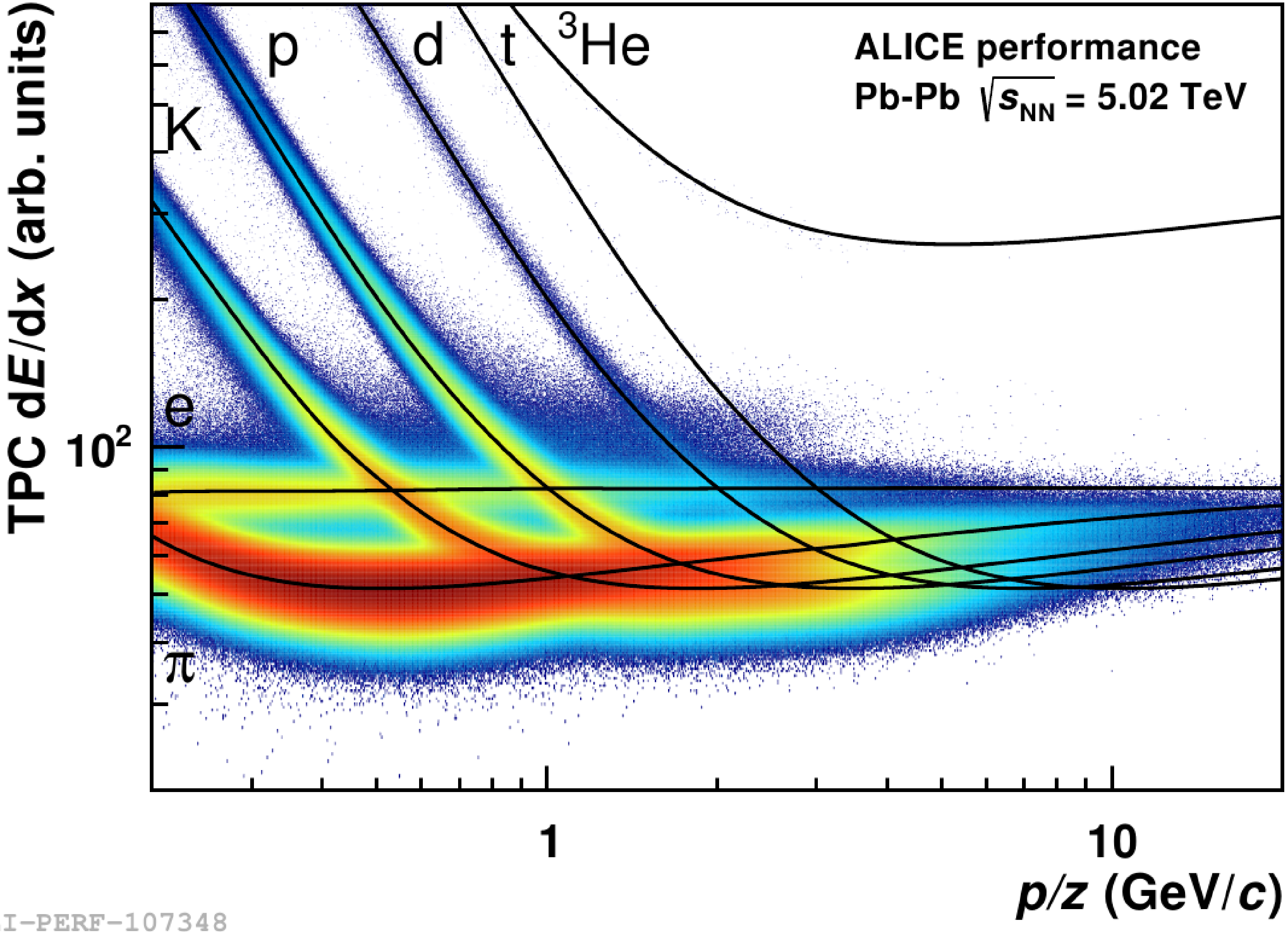
Nucleus-nucleus collisions at the LHC



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 50000 Pb-Pb “pictures” per second (fewer until 2021)

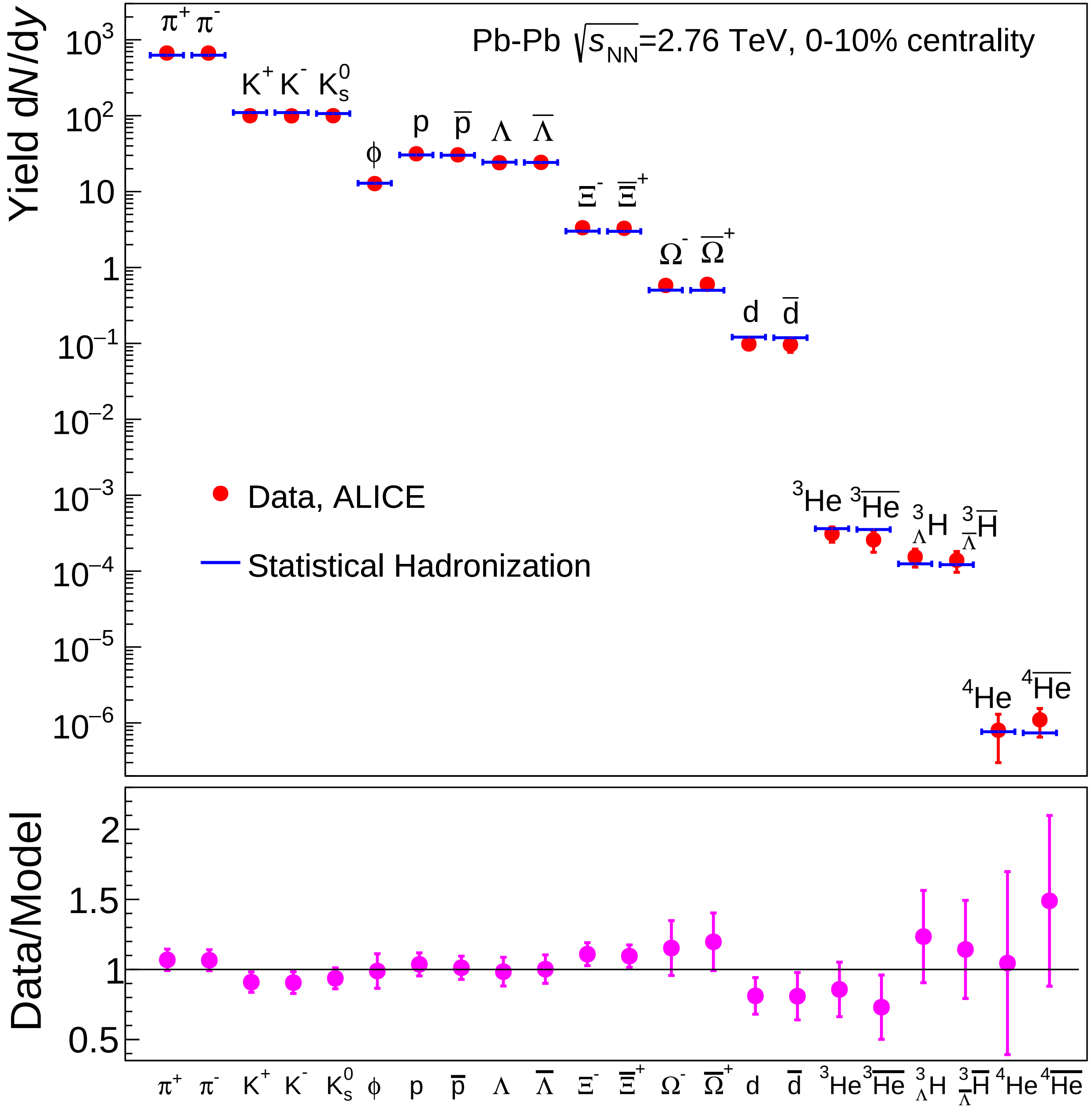
Particle identification



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

lines: Bethe-Bloch parametrizations   particles and antiparticles are shown

Hadron yields (central collisions)



matter and antimatter produced in equal amounts at the LHC

hadron abundances governed by chemical equilibrium

best fit:

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

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

Nature 561 (2018) 321

Statistical hadronization ("thermal") fits

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

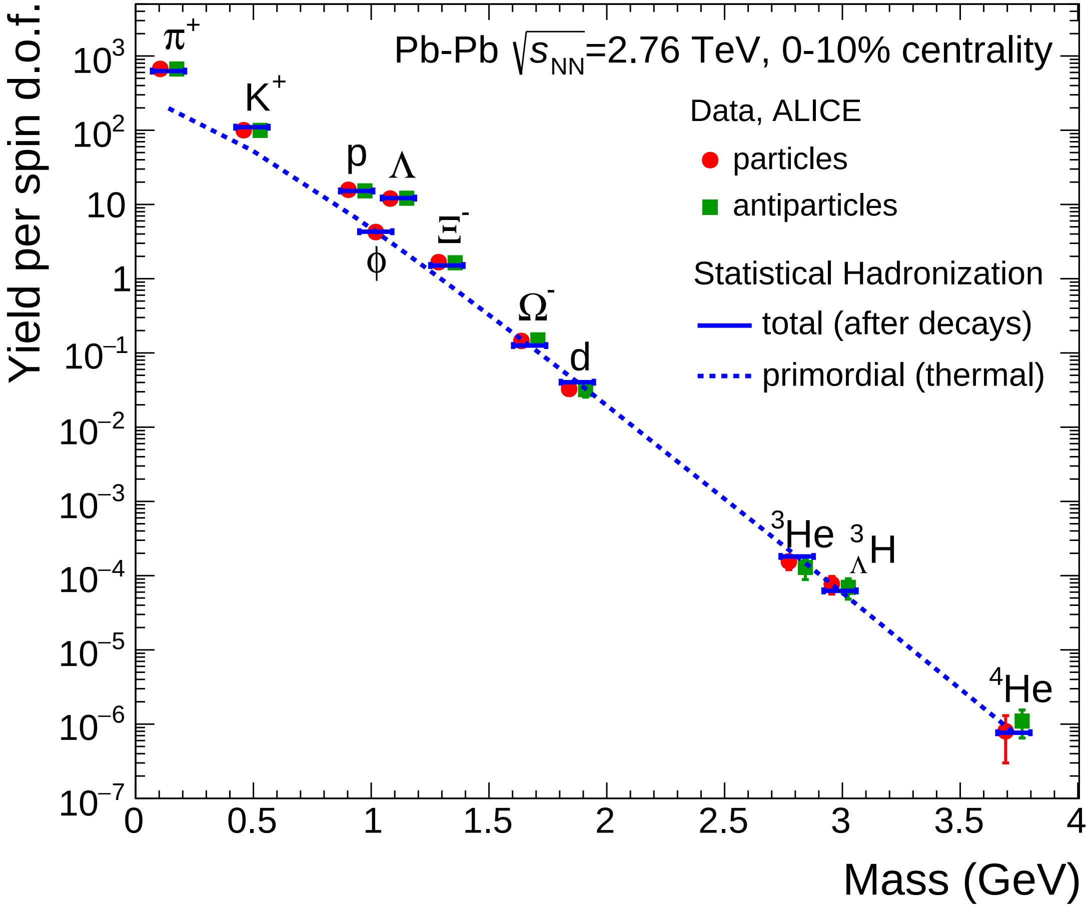
quantum nr. conservation ensured via chemical potentials:

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

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

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

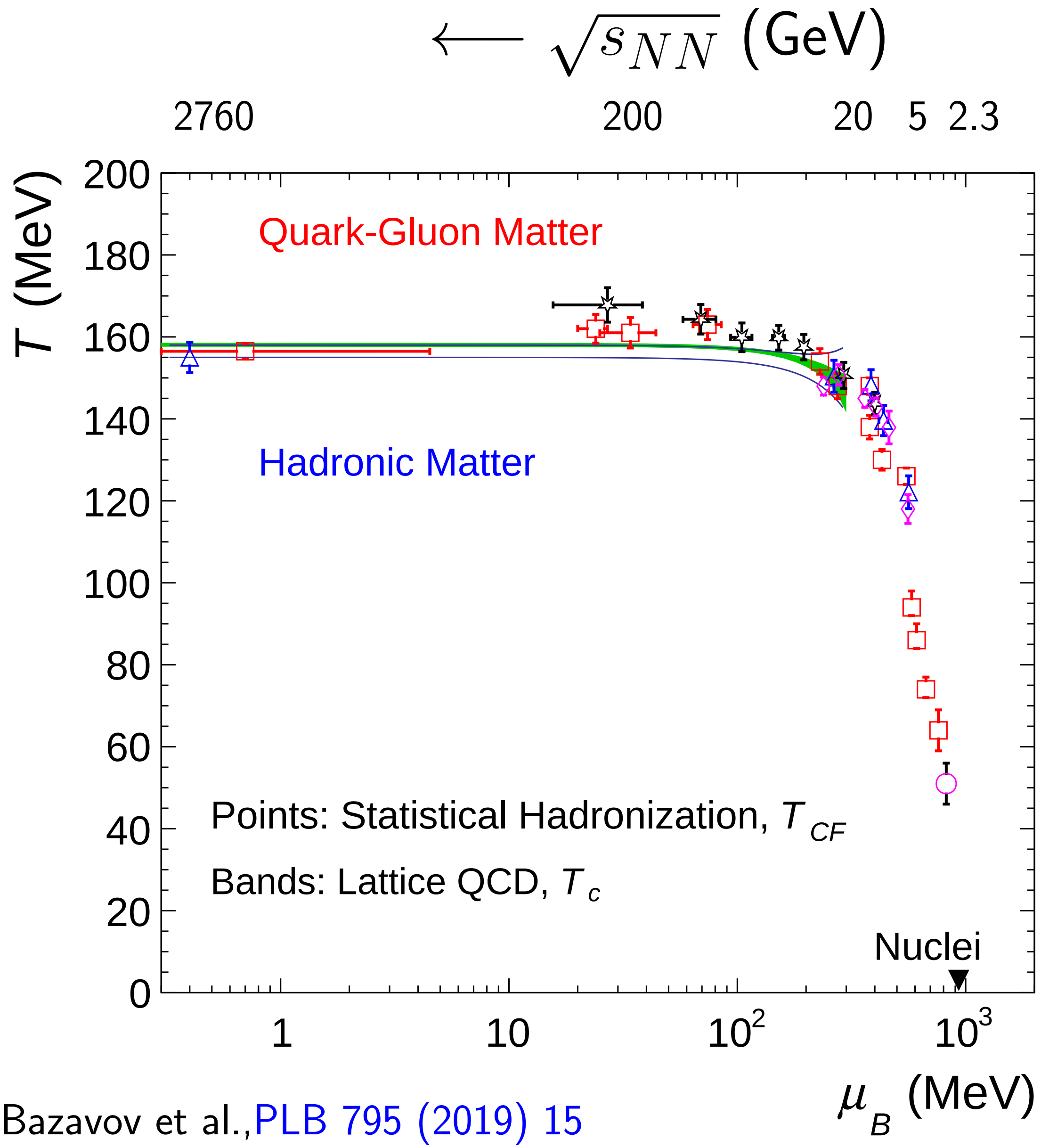
N_i: hadron yield ⇒ $(T,\ \mu_B,\ V)$



Strong (and EM, for Λ) decays play a major role; approx.: $\ln N \sim \ln(mT) - \frac{m}{T}$

Even loosely-bound objects (d, $^3_\Lambda$H) seem produced at T=156 MeV (?)

The phase diagram of QCD



at LHC, remarkable "coincidence" with Lattice QCD phase crossover

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

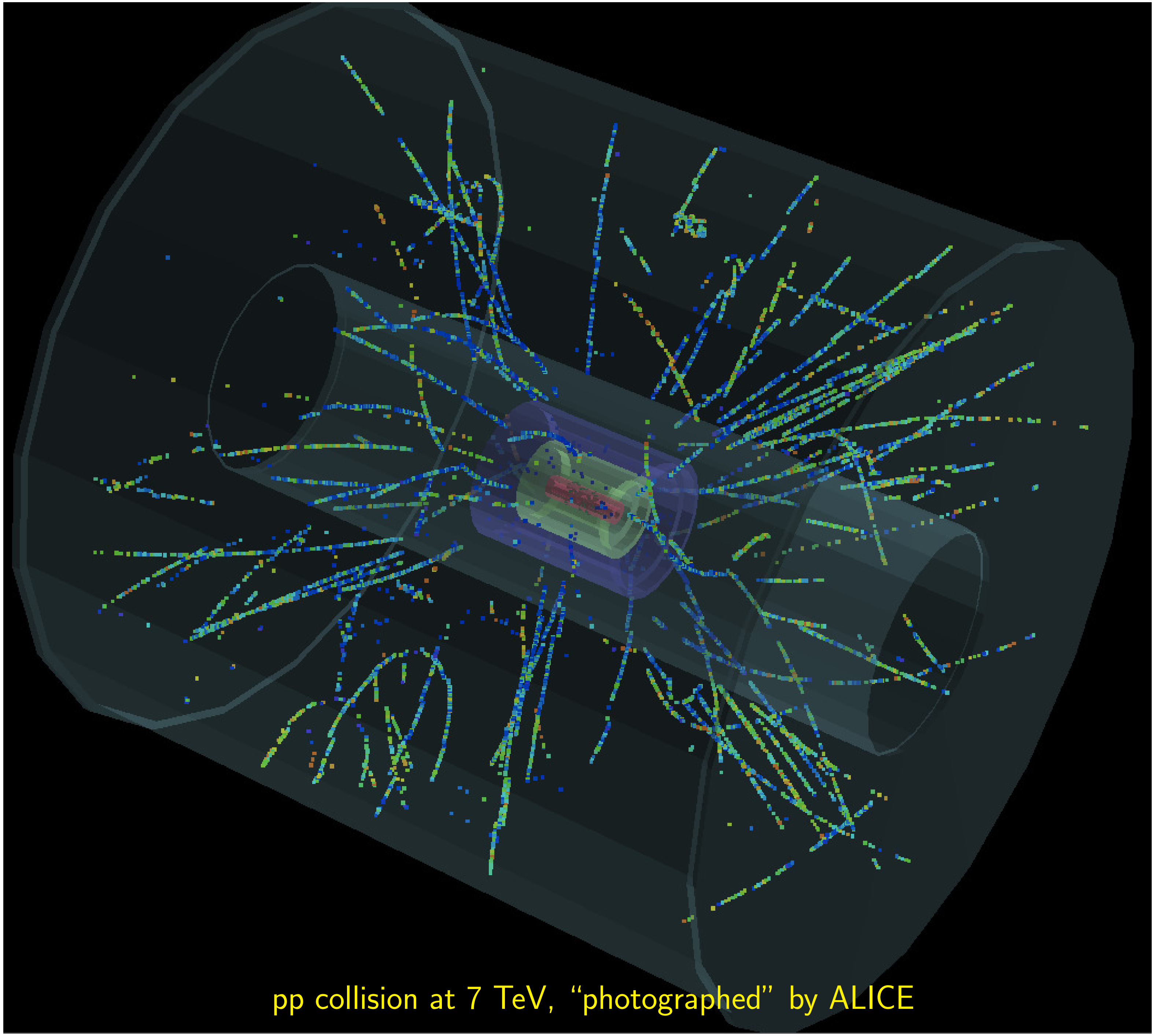
$\mu_B > 0$: more matter, from "remnants" of the colliding nuclei

$\mu_B \gtrsim 400$ MeV: *the critical point awaiting discovery* (at FAIR?)

Bazavov et al.,PLB 795 (2019) 15
Borsanyi et al., PRL 125 (2020) 052001
Andronic et al., Nature 561 (2018) 321

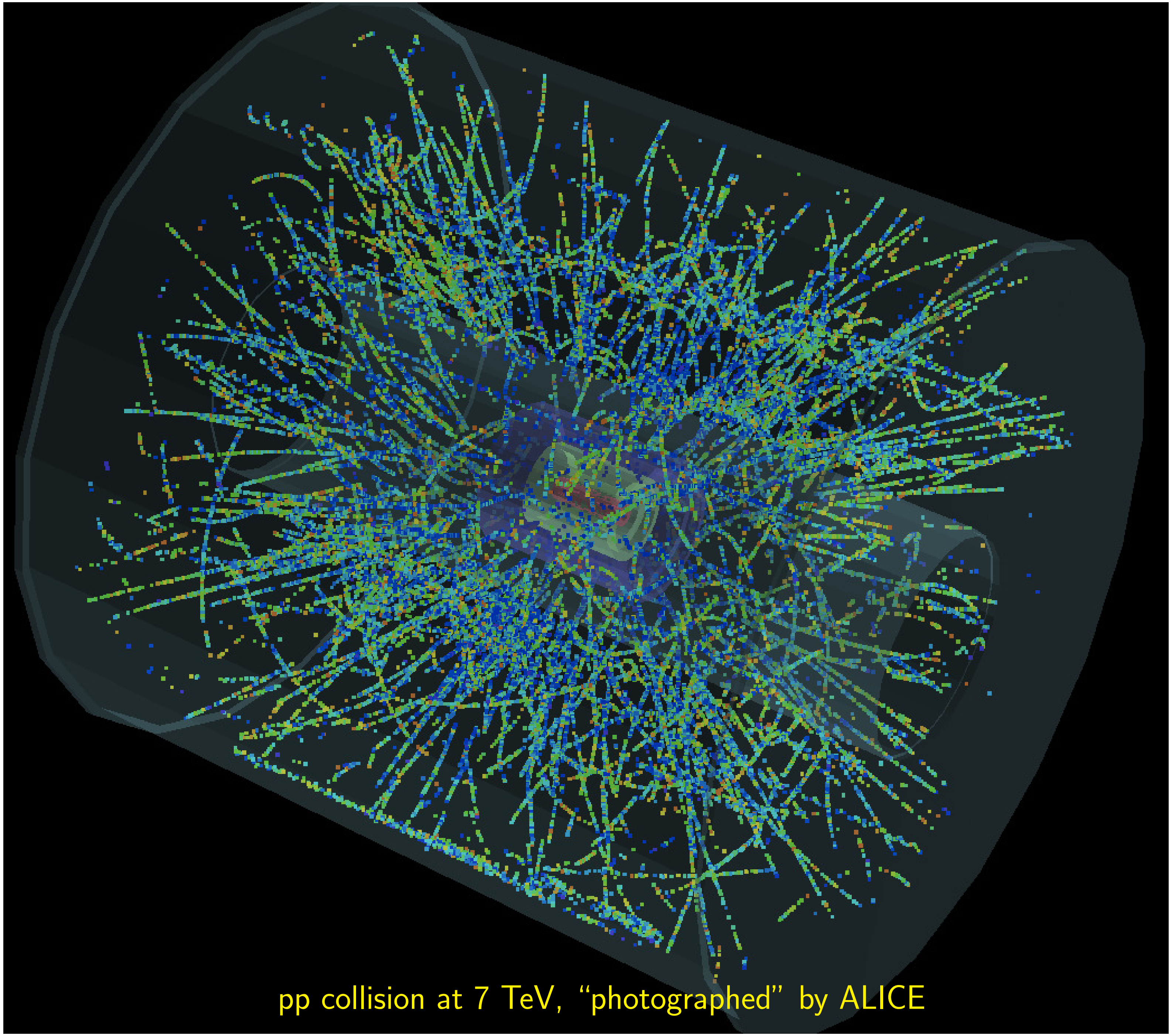
μ_B: a measure of the net-baryon density, or matter-antimatter asymmetry

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



pp collision at 7 TeV, “photographed” by ALICE

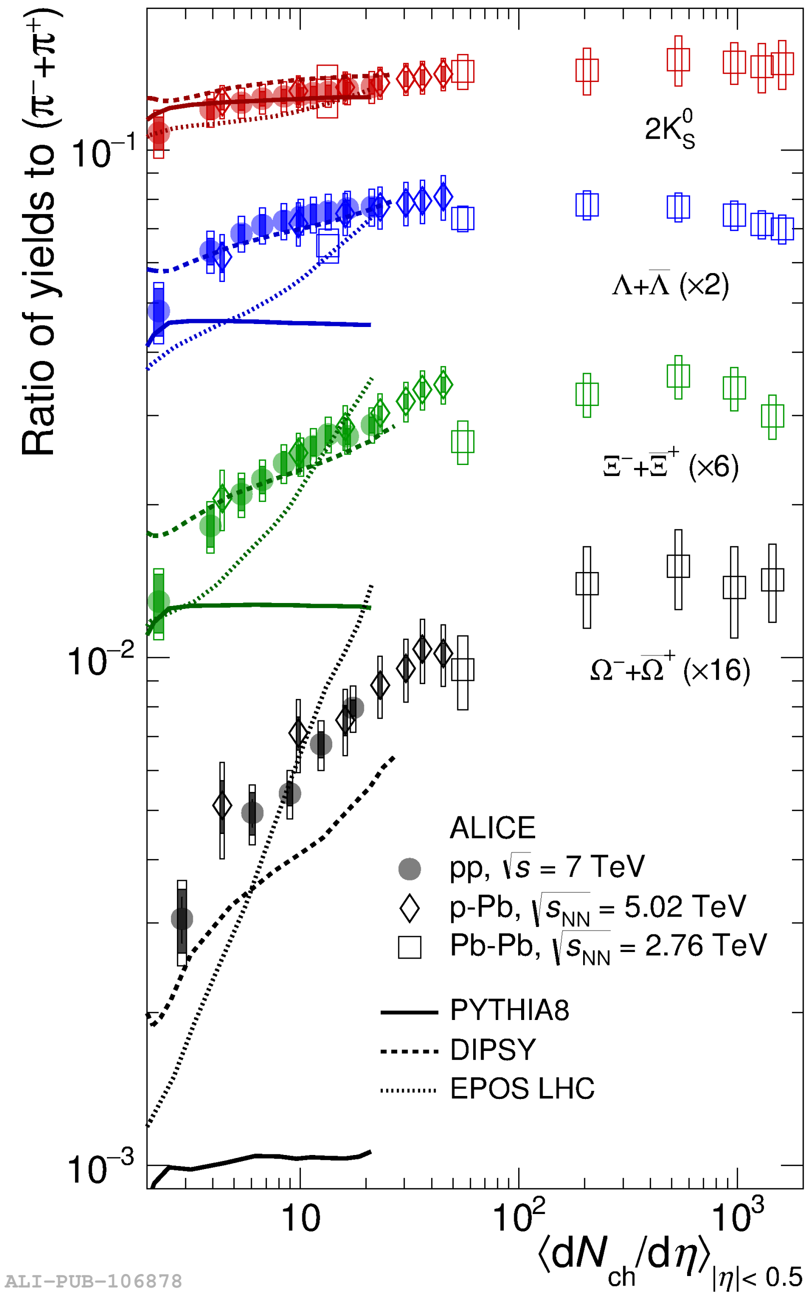
The proton at high resolution ...in collisions at the LHC



pp collision at 7 TeV, “photographed” by ALICE

Strangeness production - from small to large systems

A. Andronic



ALICE, Nature Physics 13 (2017) 535

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

canonical to grand-canonical strangeness production regime Vislavicius, Kalweit, arXiv:1610.03001

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

string hadronization (PYTHIA8) does not describe data

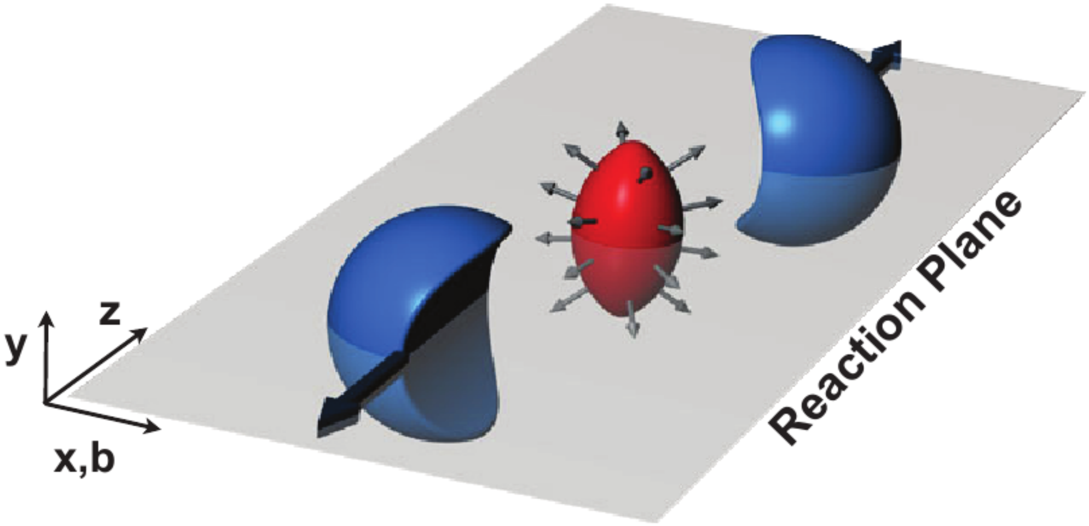
DIPSY (Mueller's dipole, BFKL evolution) fares better Dipole evolution in Impact Parameter Space and rapiditY Flensburg, Gustafson, Lonnblad, arXiv:1103.4321

EPOS LHC: core(QGP)-corona model

new ideas: ropes; thermodynamical string fragmentation

Elliptic flow

A. Andronic

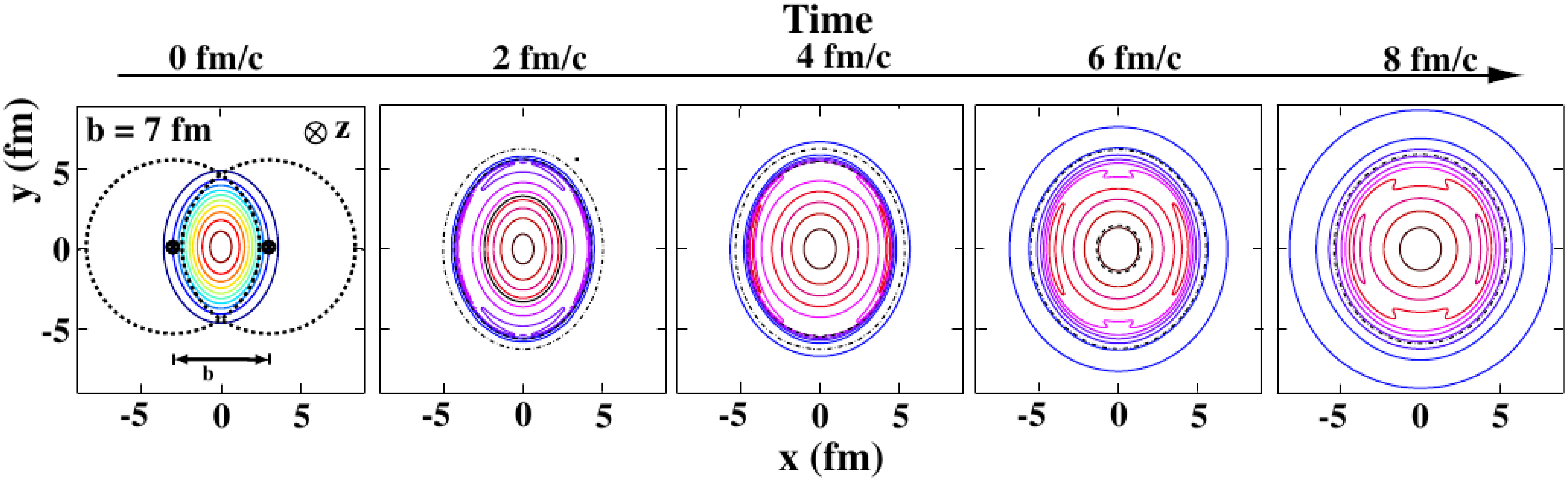


$$\frac{dN}{d\varphi} \sim [1+2v_1\cdot\cos(\varphi)+2v_2\cdot\cos(2\varphi)+...]$$

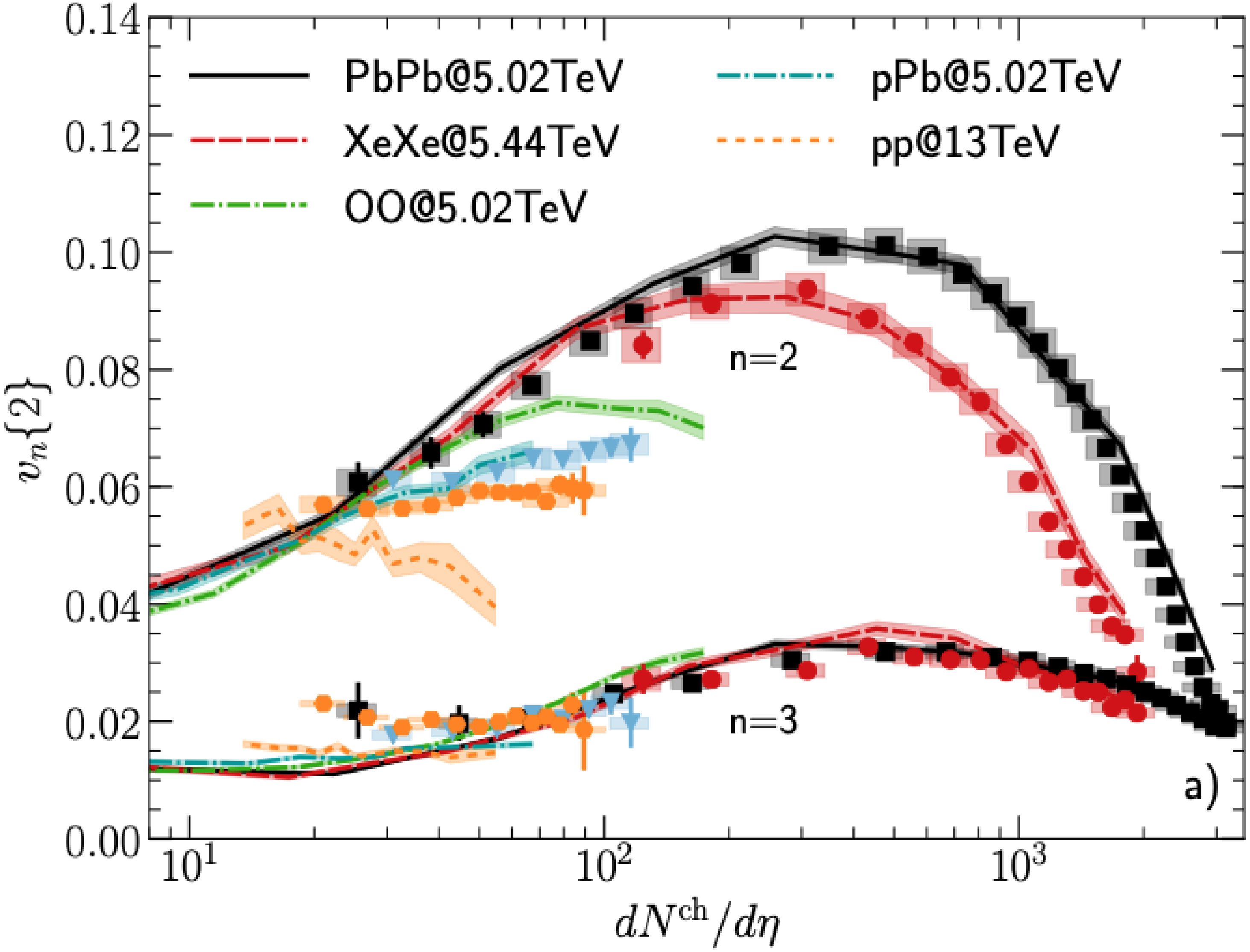
φ = azimuthal angle with respect to reaction plane

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

R. Snellings, arXiv:1102.3010



Flow harmonics: all collision systems



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

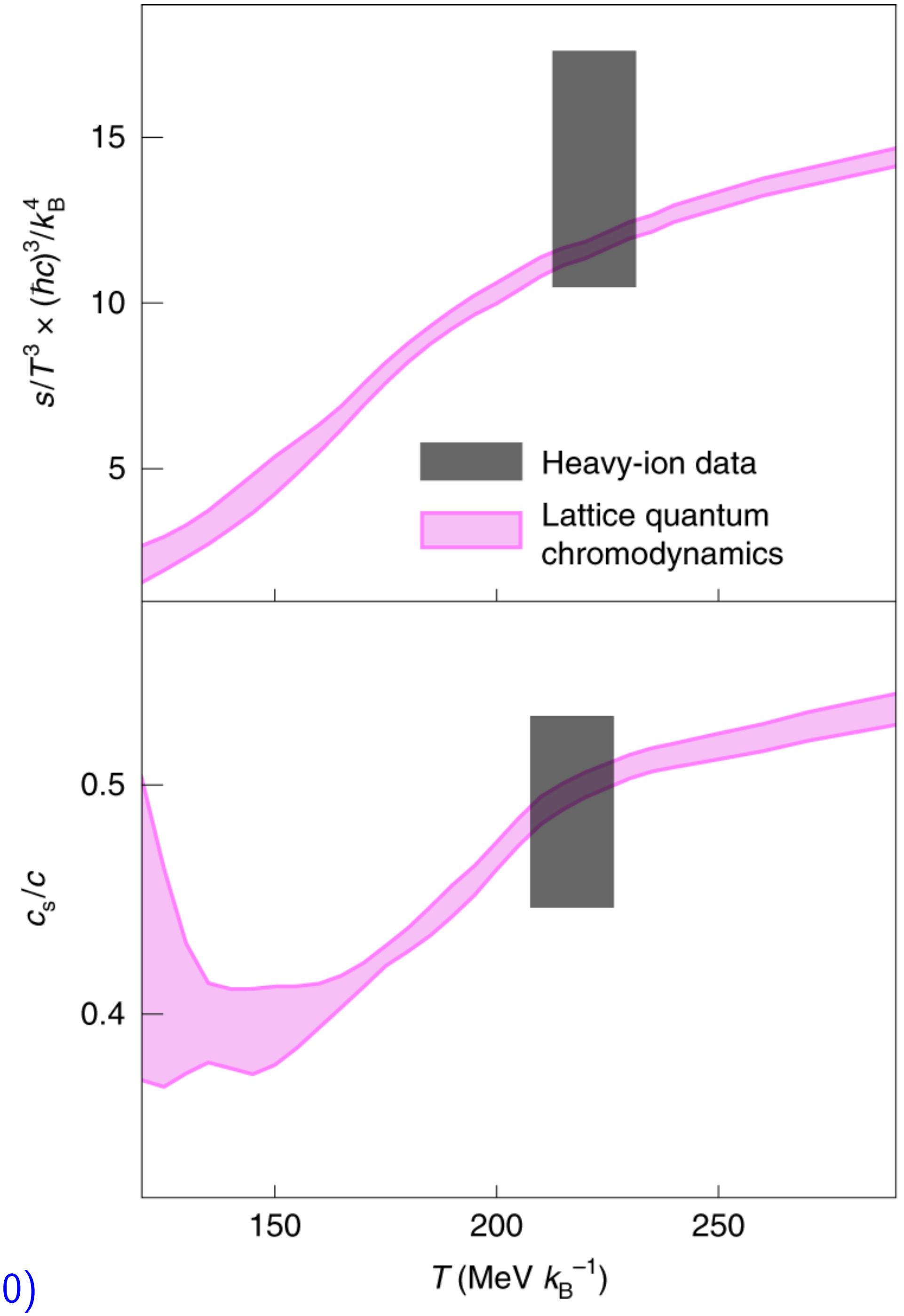
Lines: hydrodynamics, Schenke, Shen, Tribedy PRC 102 (2020) 044905

Thermodynamic quantities: data-hydrodynamics

Data: effective values (average over time) processed through hydrodynamics

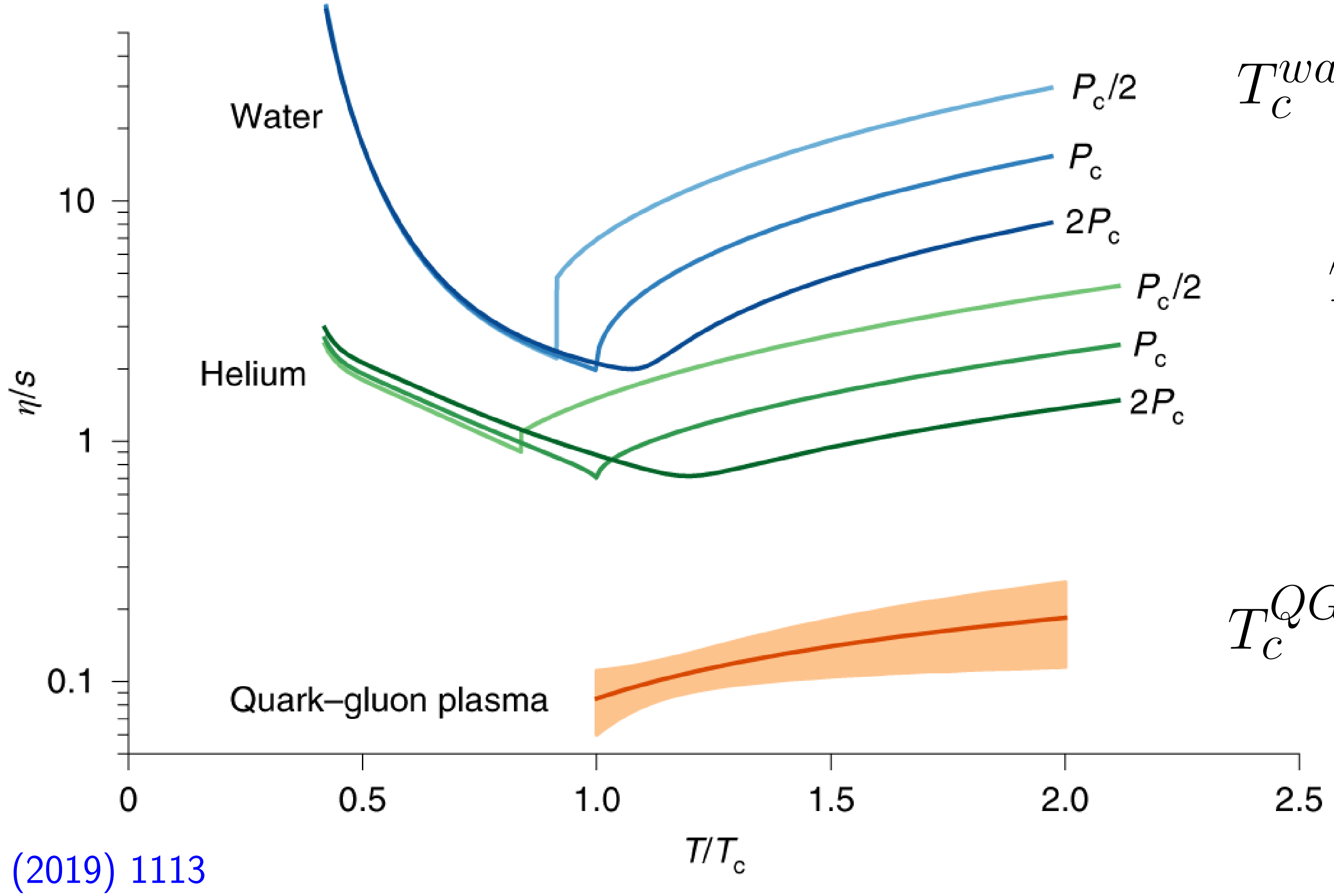
Effective number of degrees of freedom: $g \simeq 30$ ($\gg 3$, pions)

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



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

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, et al., Nature Physics 15 (2019) 1113

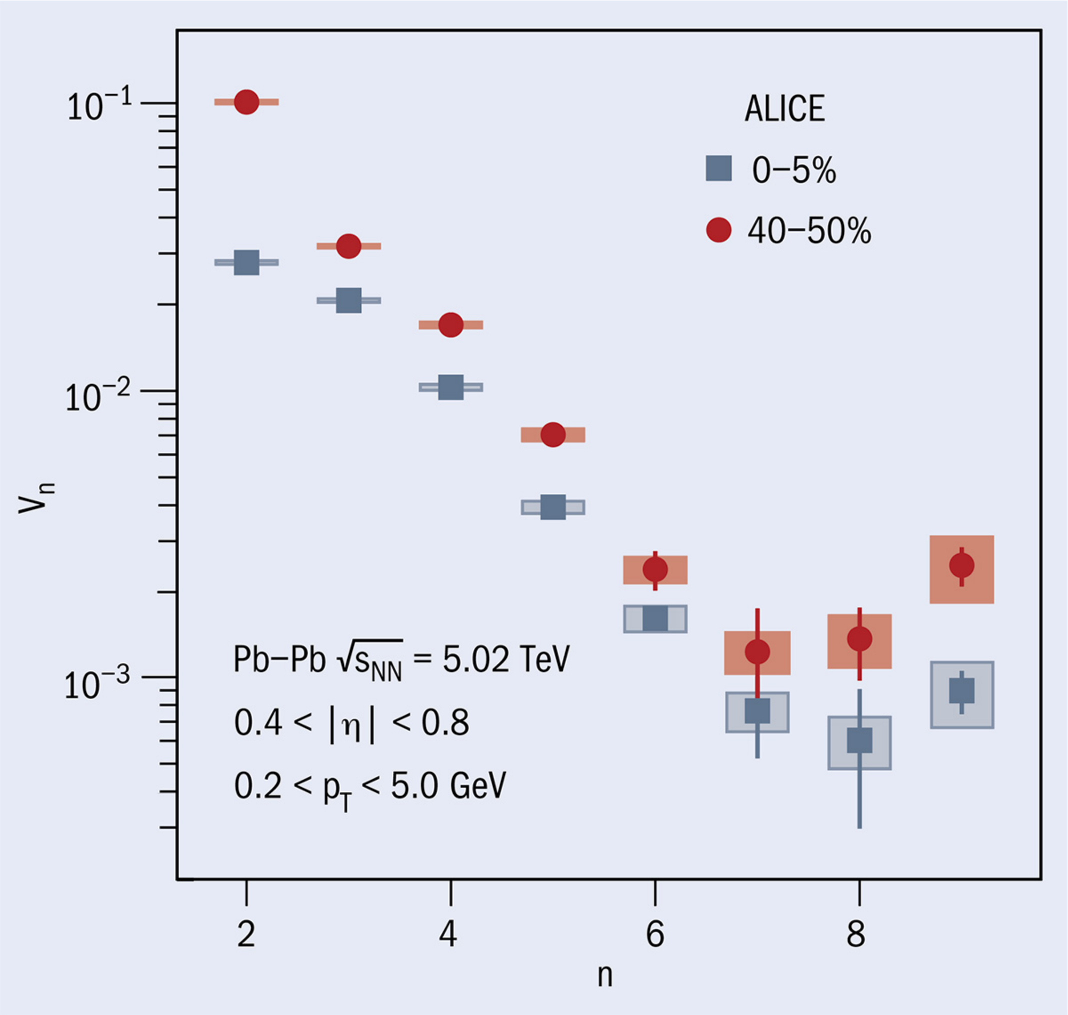
Dilute gas: $\eta = \frac{1}{3} n \langle p \rangle \lambda$; $\lambda \sim \frac{1}{n} \rightarrow \eta$ indep. on n

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

"Simple-minded": $\eta/s \simeq \eta/(k_B n) = p\lambda/3k_B \gtrsim \hbar/3k_B$ $(\Delta p \cdot \Delta x \geq \hbar)$

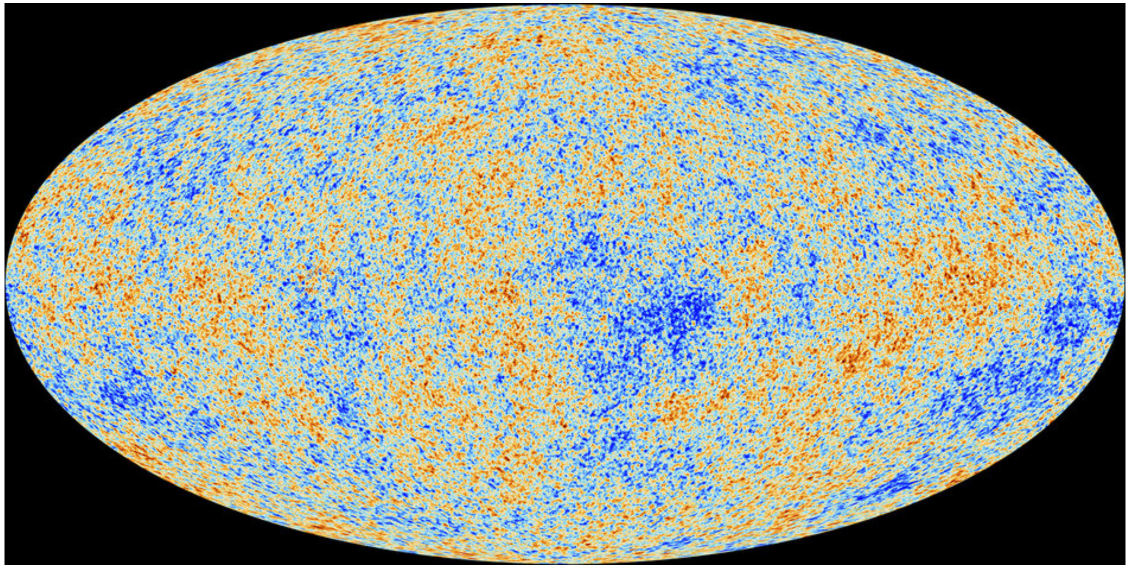
Flow harmonics

v_2 (elliptic flow) is the dominant flow harmonics, except for most central collisions



ALICE, JHEP 05 (2020) 085

Analogy?



http://www.esa.int/Our_Activities/Space_Science/Planck

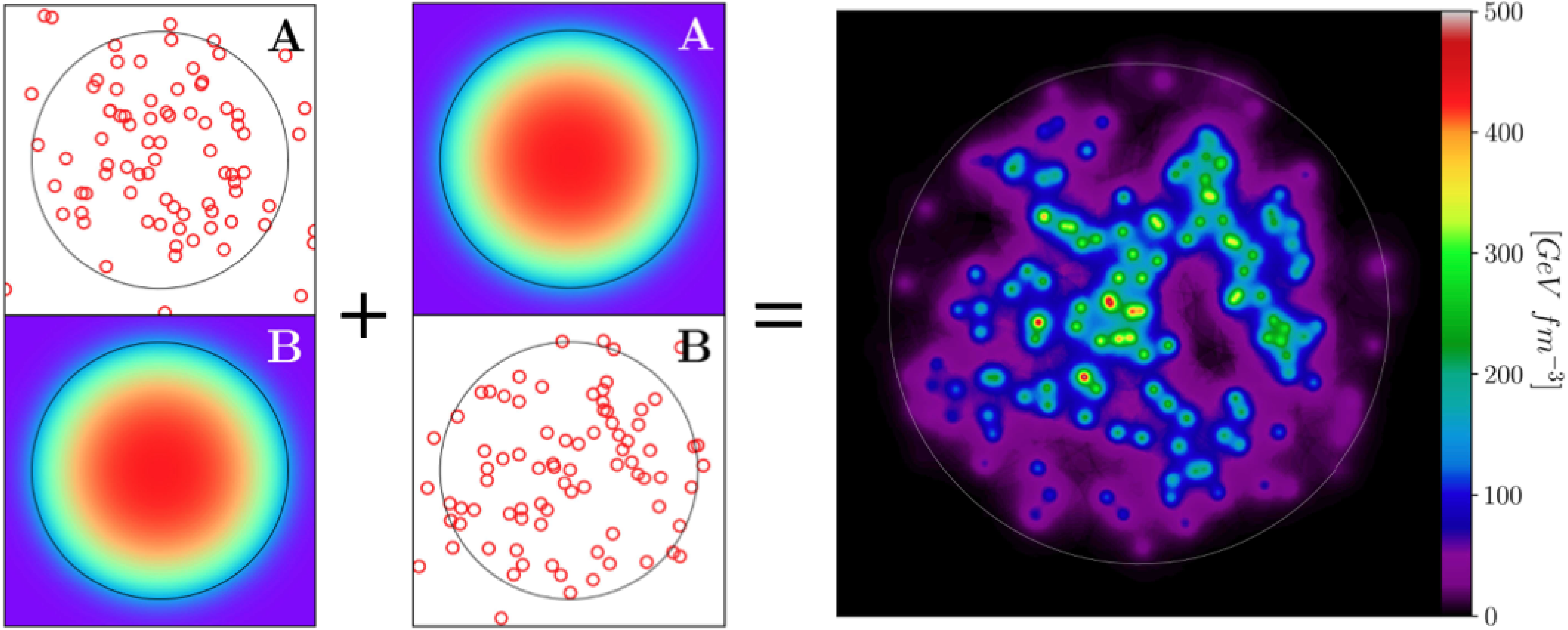
the non-uniformities (10^{-5}) are the seeds of the ∼100 billion of seen galaxies

Dominant multipole $l \simeq 100$ (angular scale: 1°)

The initial femtoscopic (gluonic) state

central Pb–Pb collision, $\sqrt{s_{NN}}$=5.02 TeV (R_{Pb}=6.62 fm)

theoretical calculation (Color Glass Condensate)



Gelis et al, arXiv:1907.10948

Mean energy density at the center: 131 GeV/fm^3 (α_s=0.25)

Probing early stages

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

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

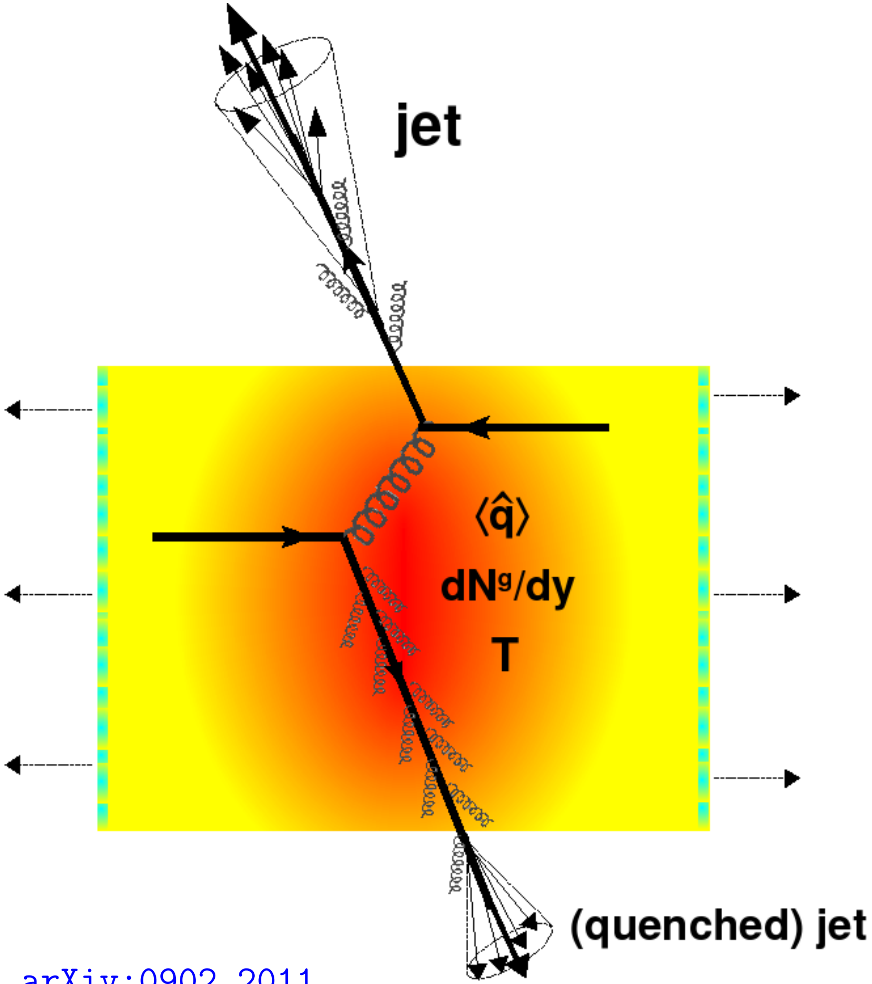
(jets - sprays of hadrons from high-speed quarks)

- $q, \bar{q}, g$ 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 ($p_{\rm T}$): "jet quenching" (Bjorken, 1982)

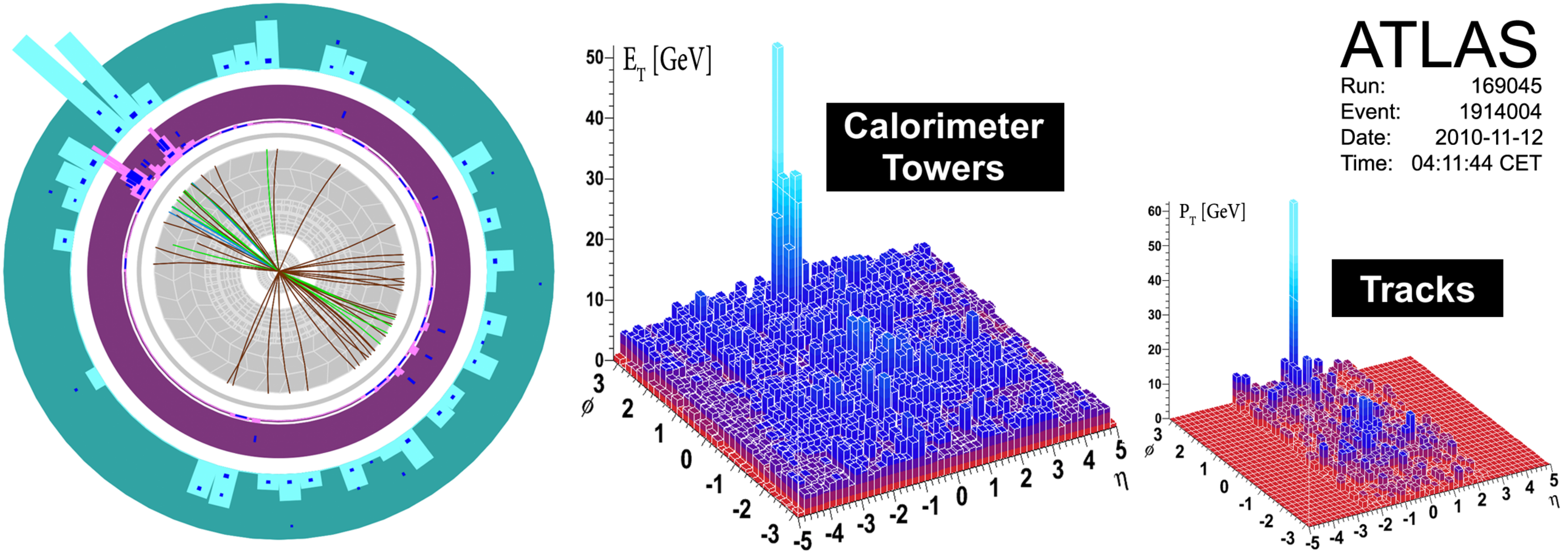
quantified by the nuclear modification factor:

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



D. d'Enterria, arXiv:0902.2011

Jets in Pb–Pb collisions



first “direct” observation of “disappearance” of a jet ($E_T >$100 GeV) in AA

tracks with $p_T > 2.6$ GeV; calorimeter cell thresholds: $E_T > 0.7$ GeV ECAL, $E > 1$ GeV HCAL

quantitatively:

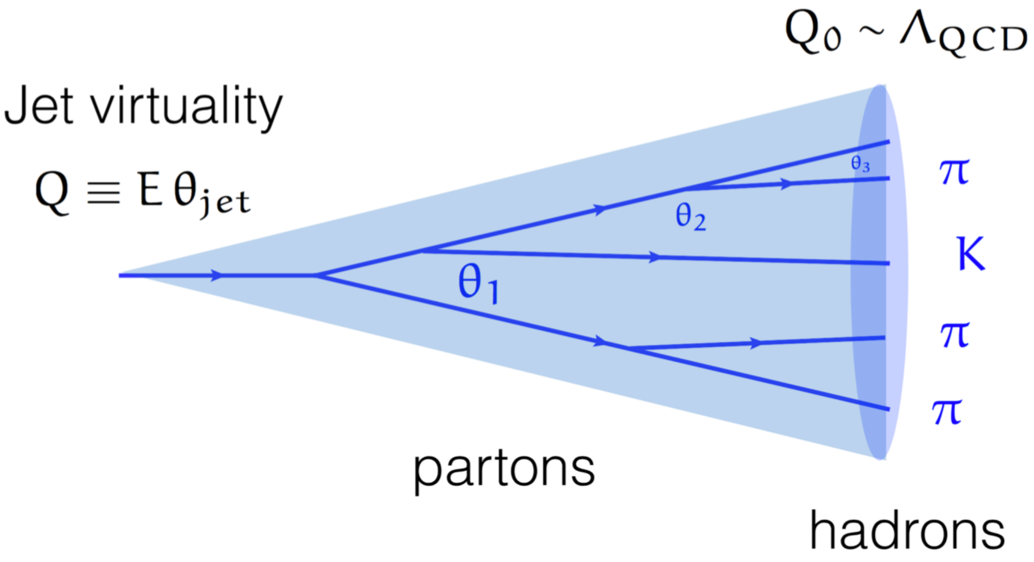
("leading jet") $E_{T1} > 100$ GeV vs. the highest E_T jet in the opposite hemisphere, $E_{T2} > 25$ GeV

E_T after subtracting the average contribution of the **underlying event** (≃75 GeV for central coll.)

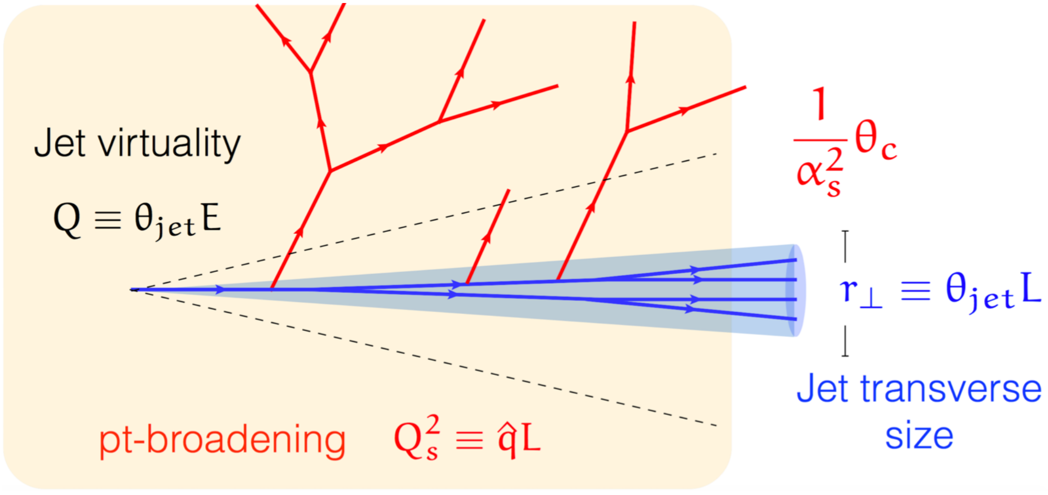
ATLAS, PRL 105 (2010) 252303

Jets

...in vacuum



...in medium



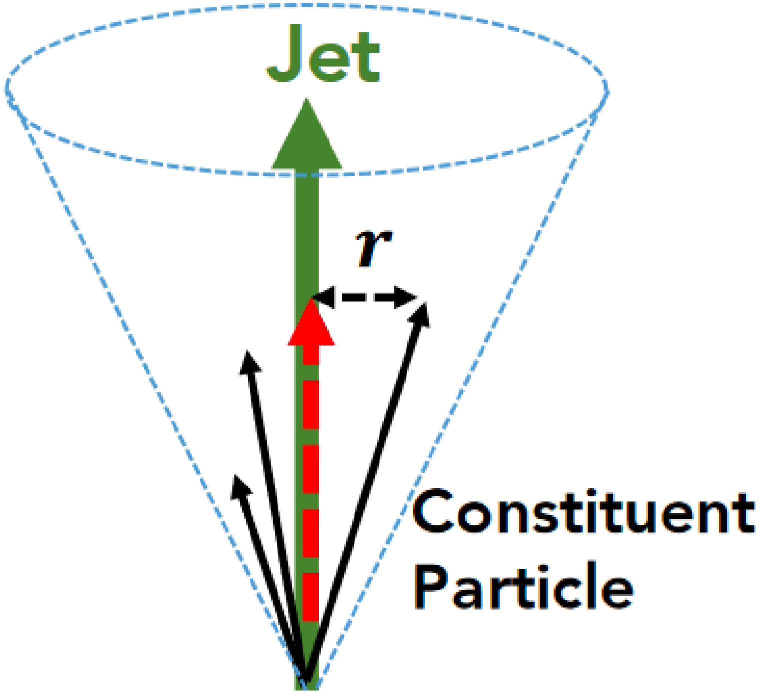
E: E_T or p_T; θ_{jet}: opening angle (R or ΔR)

Is this (theoretical expectation) a quantitative effect of the medium?

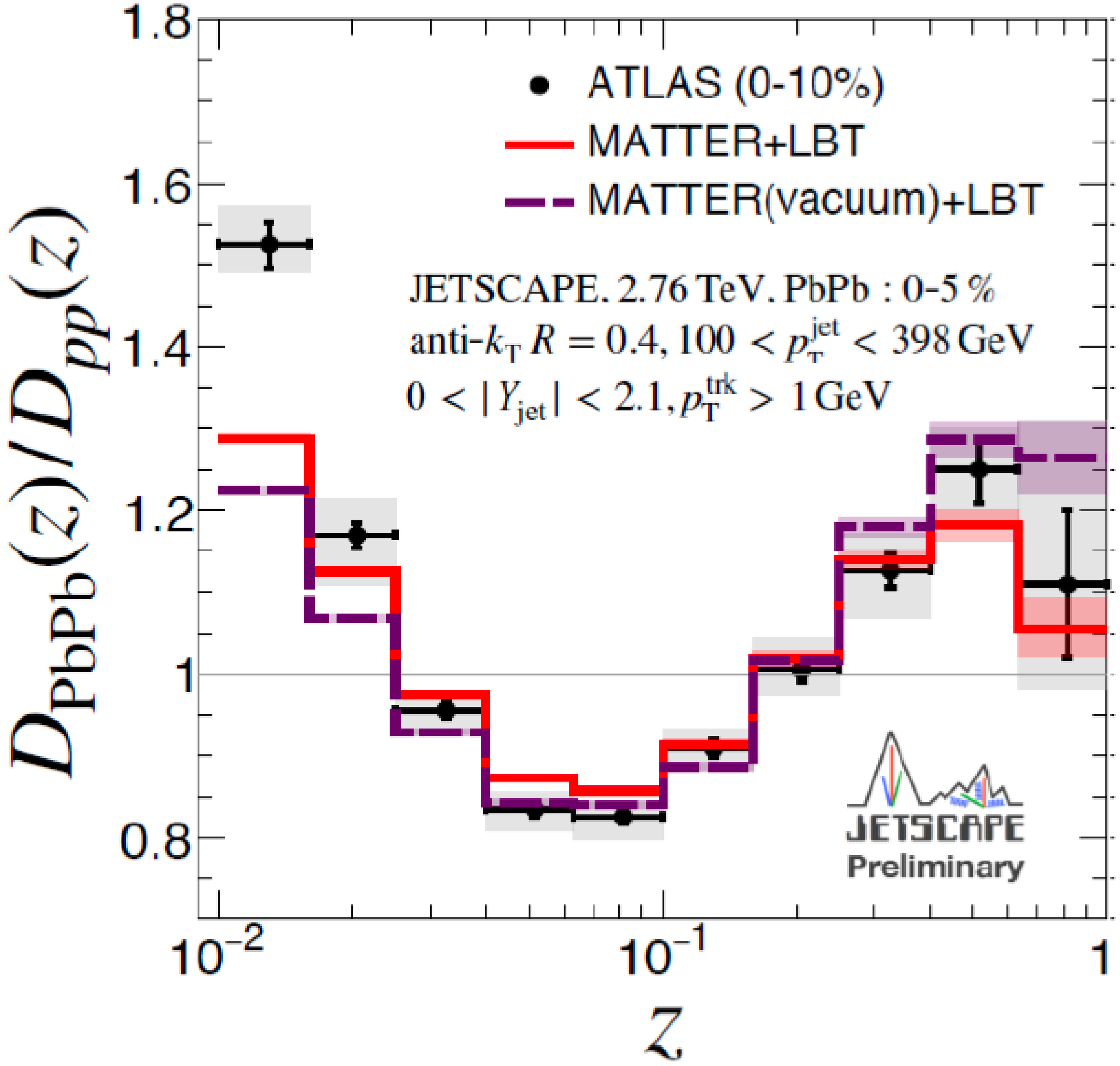
Y. Mehtar-Tani, arXiv:1602.01047

Jet fragmentation function

Fraction of jet (parton) p_T carried by constituent hadrons



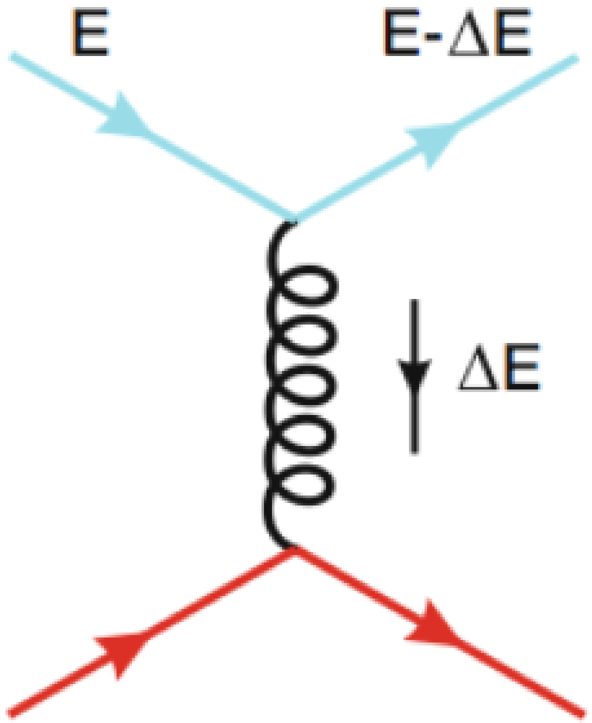
$$z = \frac{p_{\mathrm{T,track}}\cos(r)}{p_{\mathrm{T,jet}}}$$



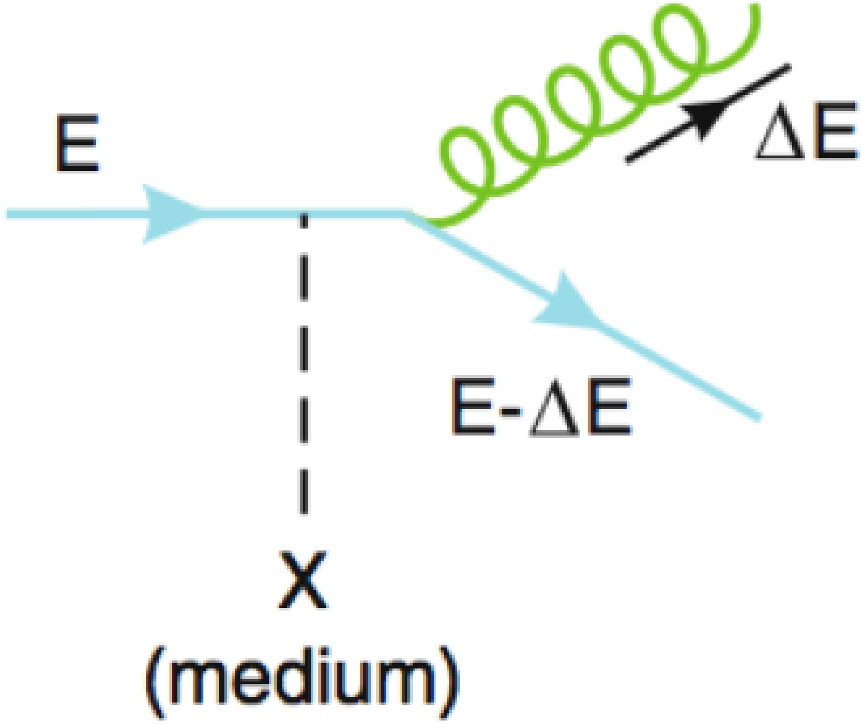
Significantly modified in Pb-Pb (more high- and low-p_T constituents)

Parton energy loss in the medium (T)

Collisional



Radiative



Important at low momenta

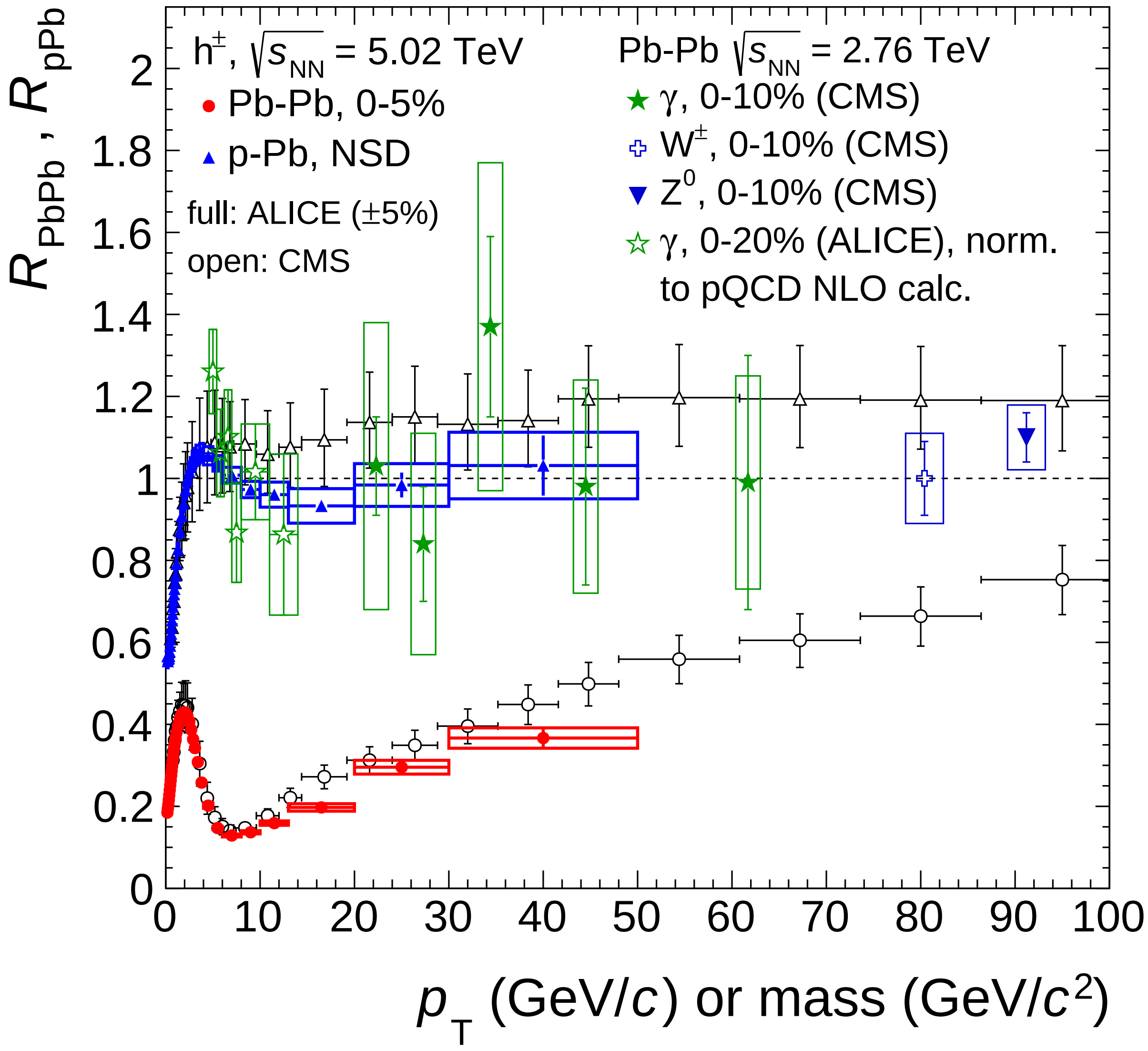
$$\Delta E \sim L, T^3$$

Important at high momenta

$$\Delta E \sim L^2, T^3$$

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

Jet quenching at the LHC - leading hadrons



measured with "leading hadrons"

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

remains substantial even at 50-100 GeV/c

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

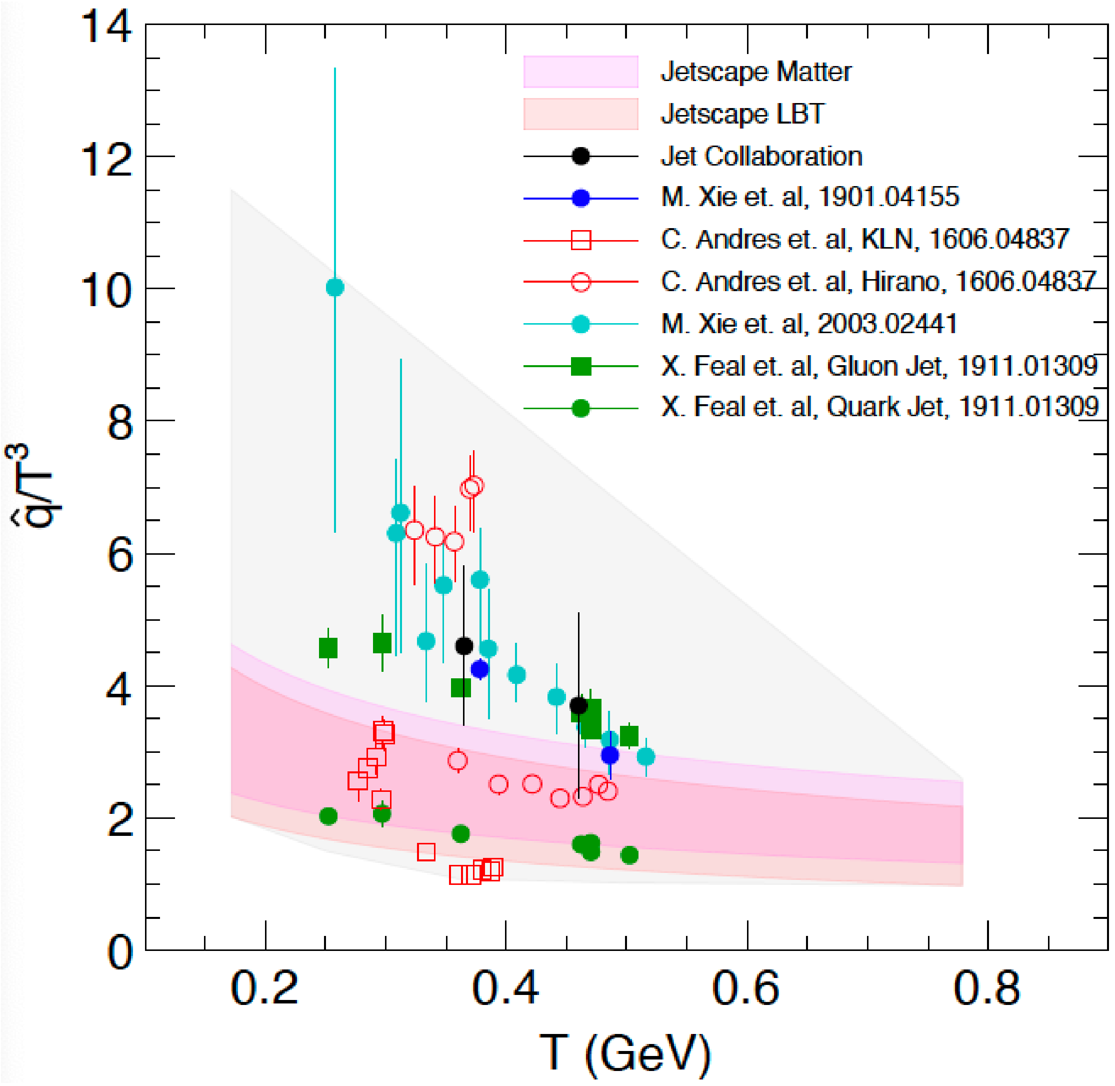
not seen in p-Pb collisions ($p_{\rm T} \lesssim 3$ GeV/c, gluon saturation)

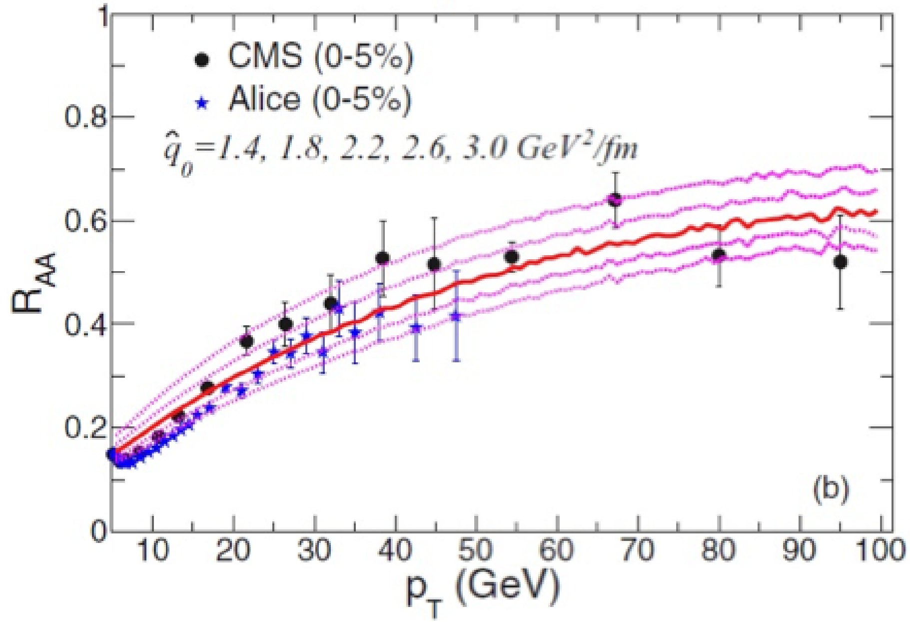
ALICE, JHEP 1811 (2018) 013

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

Jet quenching: transport coefficient

...extracted from a global fit of data





Cao, Wang, arXiv:2002.04028

Apollinario, Lee, Winn,arXiv:2203.16352

Knowledge of the initial state plays a major role

Quark interlude

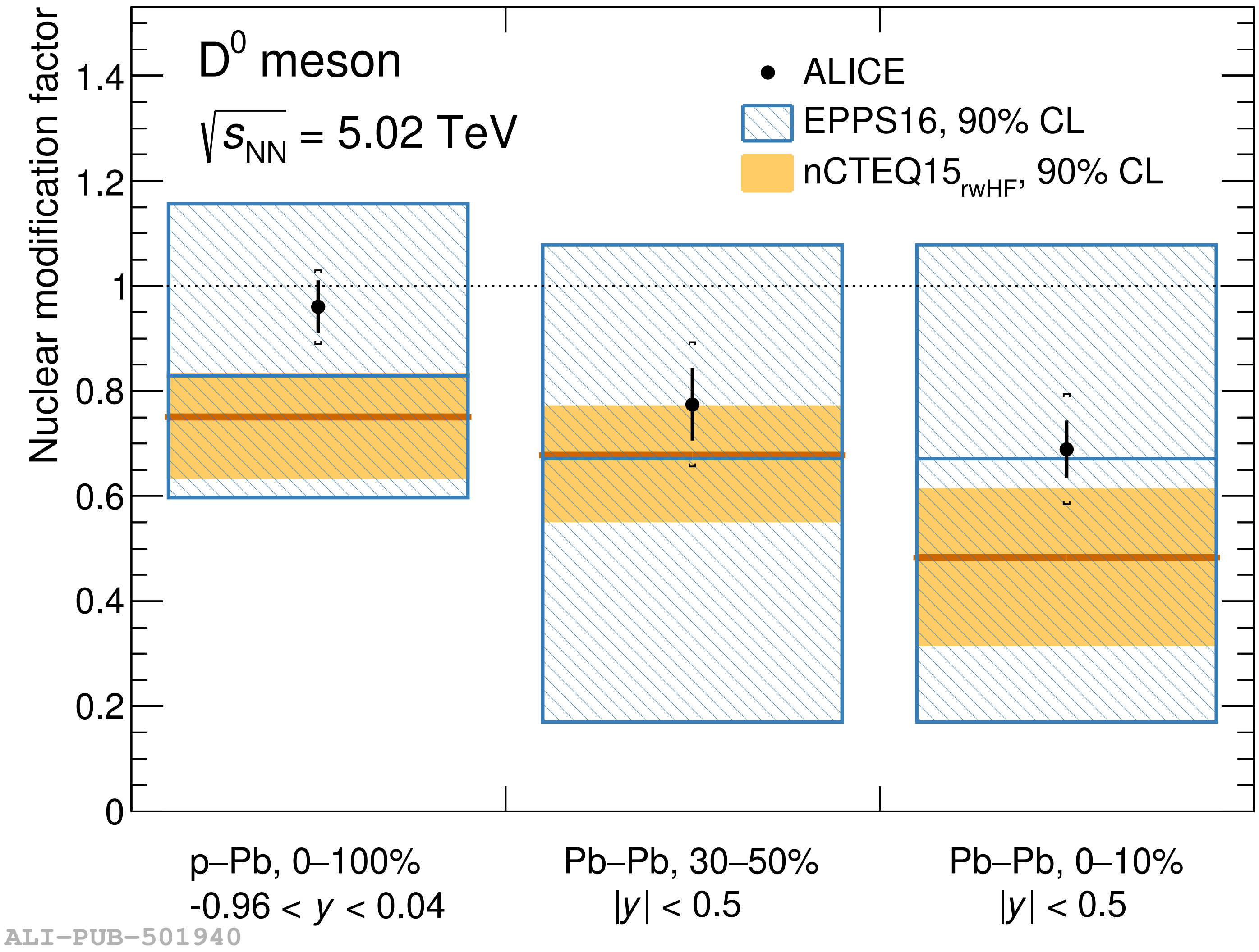
up to now we only considered hadrons built with *up, down, strange* quarks
...these are light, masses from a few MeV (u, d) to ∼90 MeV (s)

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 production in p-Pb, Pb-Pb vs. pp

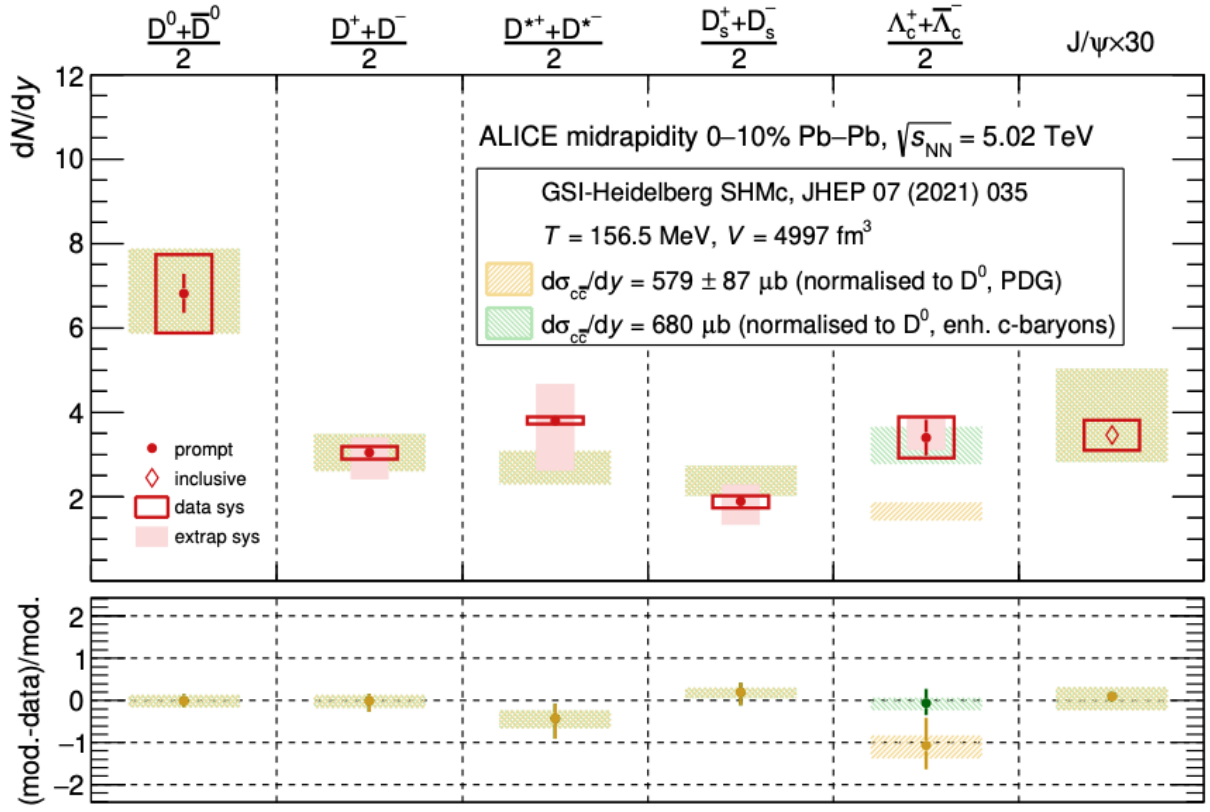


ALICE, arXiv:2110.09420

From charm quarks to hadrons

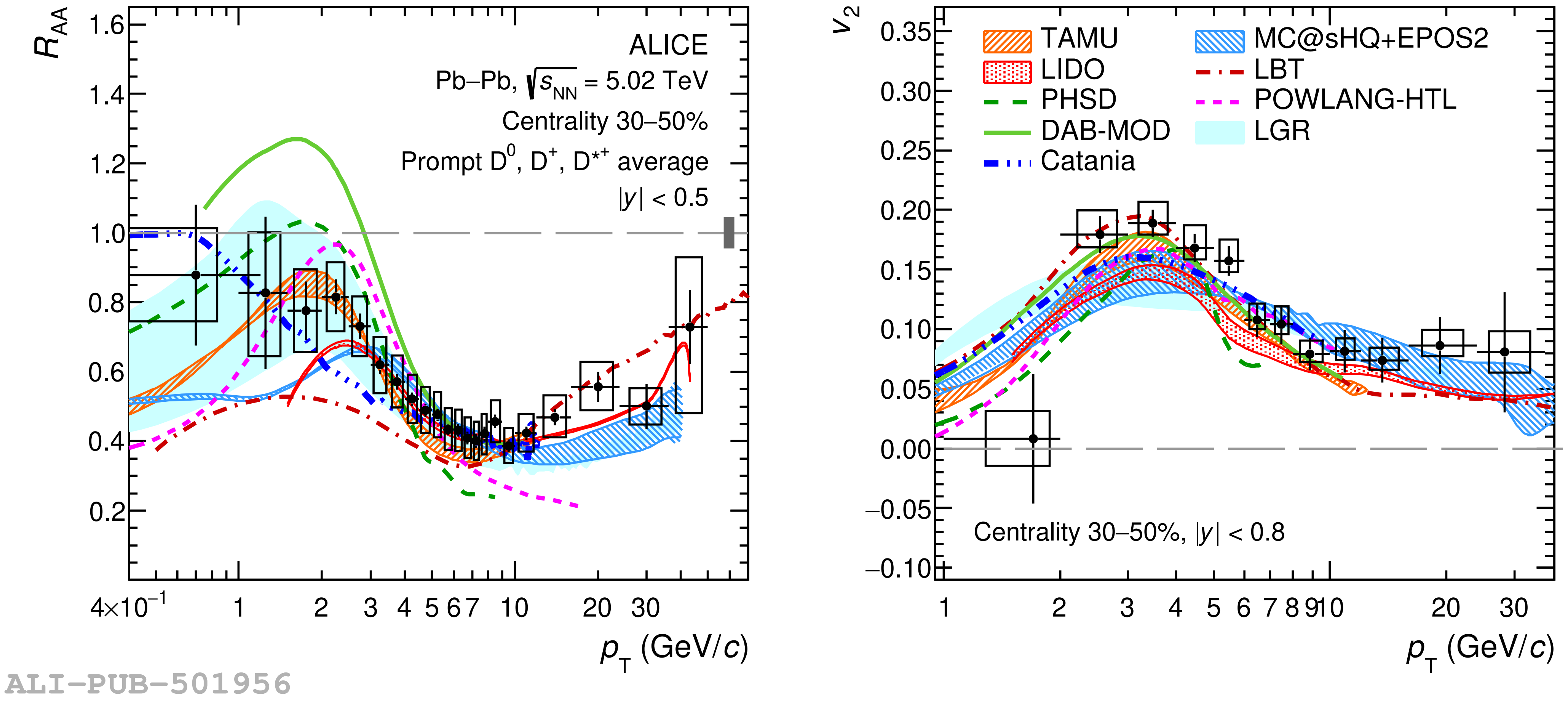
...an unsolved mystery

- Fragmentation, $c \to D, D^*, D_s, \Lambda_c$ (empirical functions $D_{c\to H_c}(z)$)
- Coalescence / (re)combination, $c+q \to D$, $c+q+q \to \Lambda_c$
  in phase space (in momentum space, resonance recombination)
- Statistical hadronization (as for u,d,s quarks, at T_{CF})



arXiv:2211.04384

Charm energy loss and flow: data and models



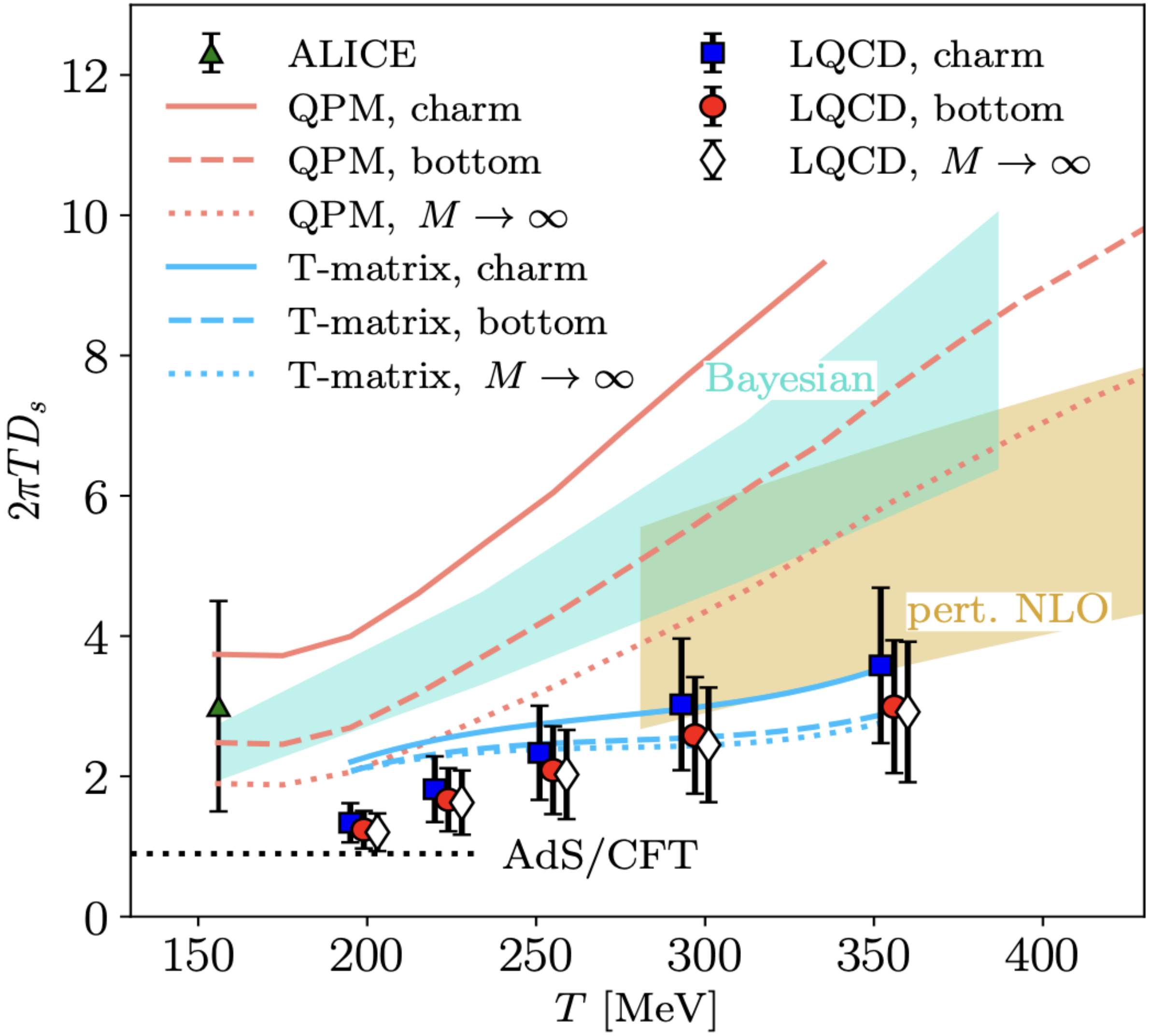
ALICE, arXiv:2110.09420

In general a good description; a large variation of model results at low p_T
...theoretical uncertainties: nPDFs, hadronization

...some "unification" is being attempted (arXiv:1803.03824)

Charm spatial diffusion coefficient

key transport parameter (quantifies drag, thermal, recoil forces)



Altenkort et al., PRL 132 (2024) 051902

spatial diffusion coefficient $D_s \simeq T^2/\hat{q}$; $\hat{q} \sim T^3$

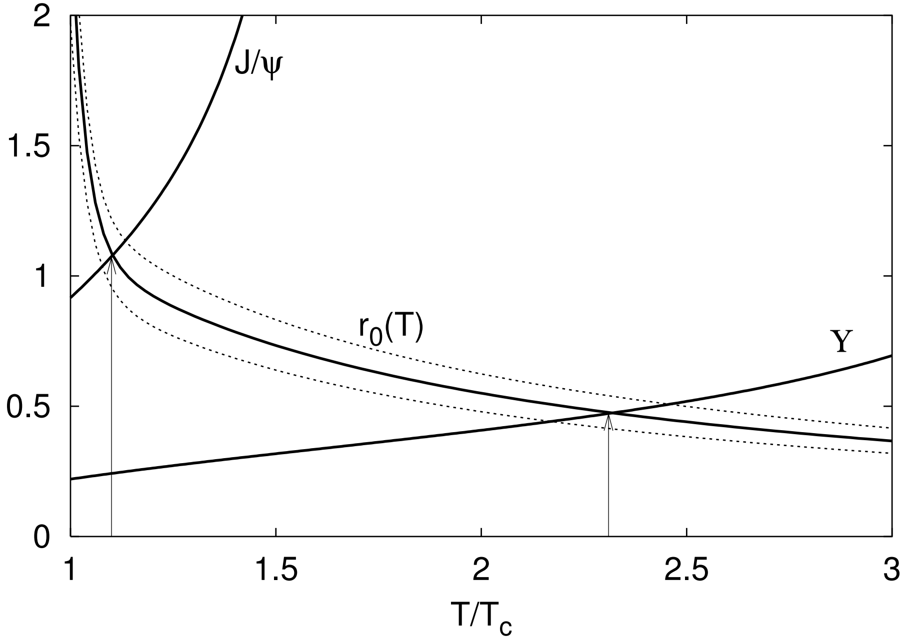
Charmonium and deconfined matter

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, Satz, Petrecky, `PRD 64 (2001) 75`
Karsch, Kharzeev, Satz, PLB 637 (2006) 75



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

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

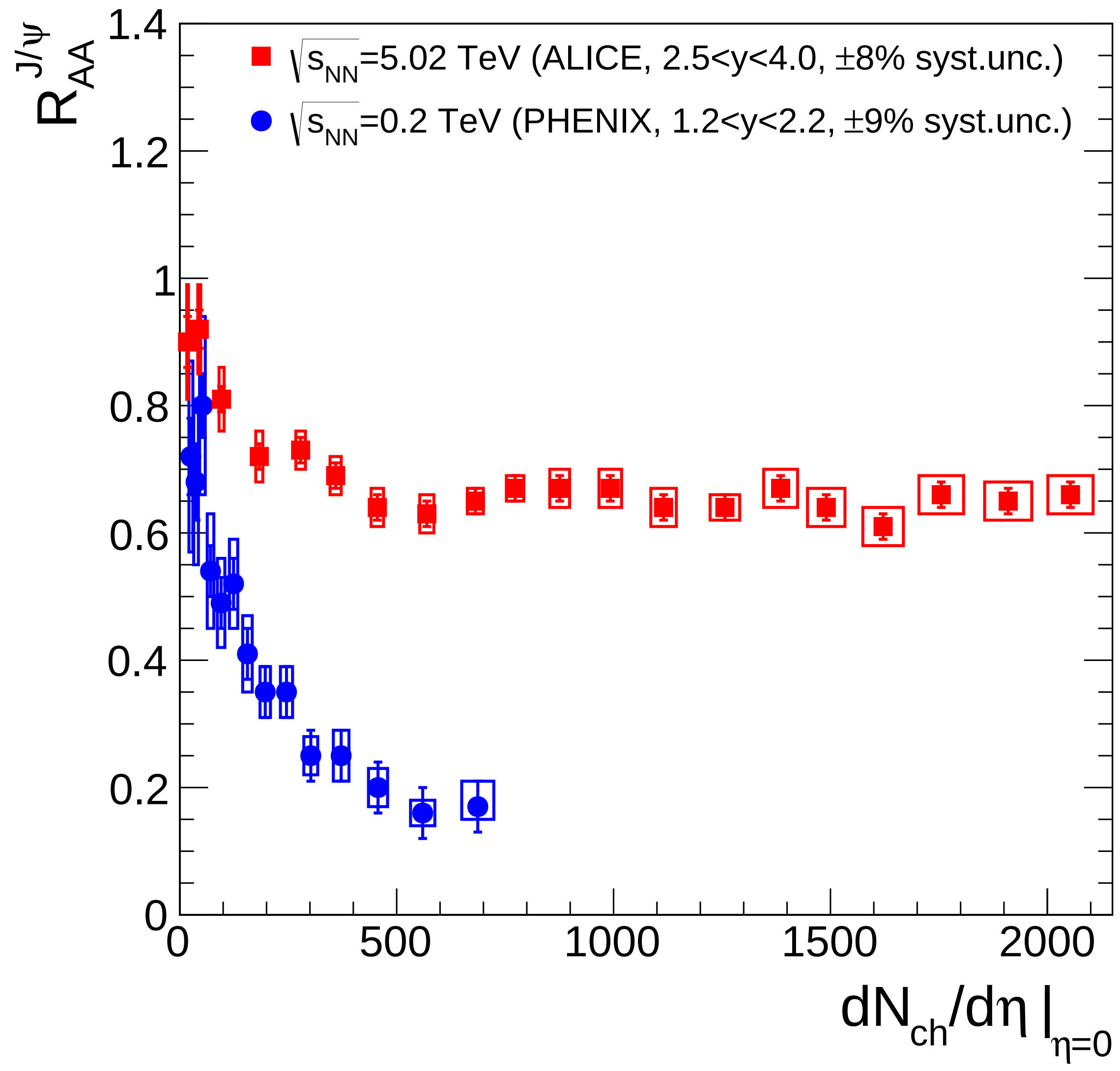
r_0 Debye length in QGP

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

Charmonium data at RHIC and the LHC



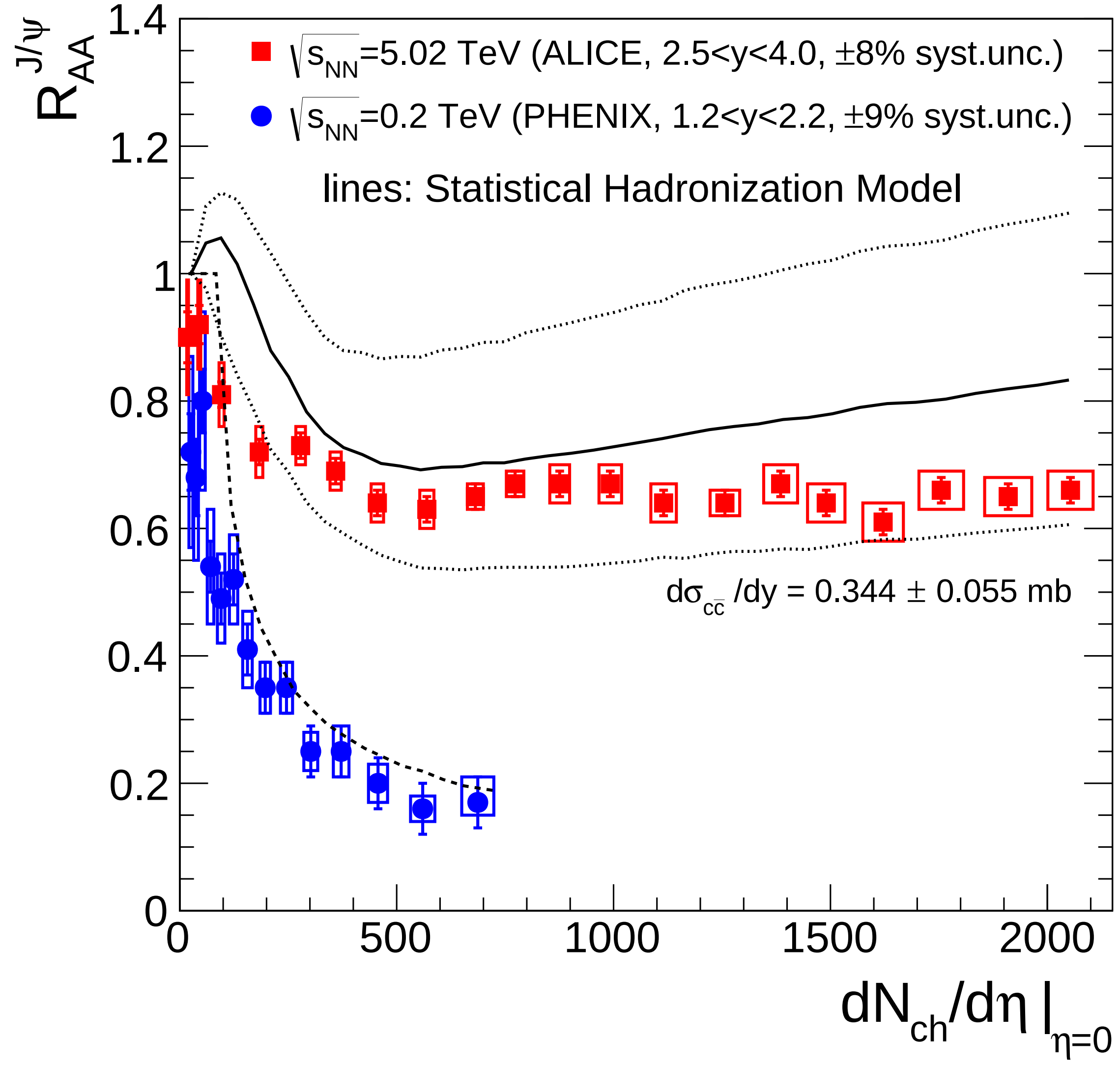
- "suppression" at RHIC (PHENIX)
- dramatically different at the LHC

...

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

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

Charmonium data at RHIC and 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)

Nature 561 (2018) 321

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

Statistical Hadronization Model

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

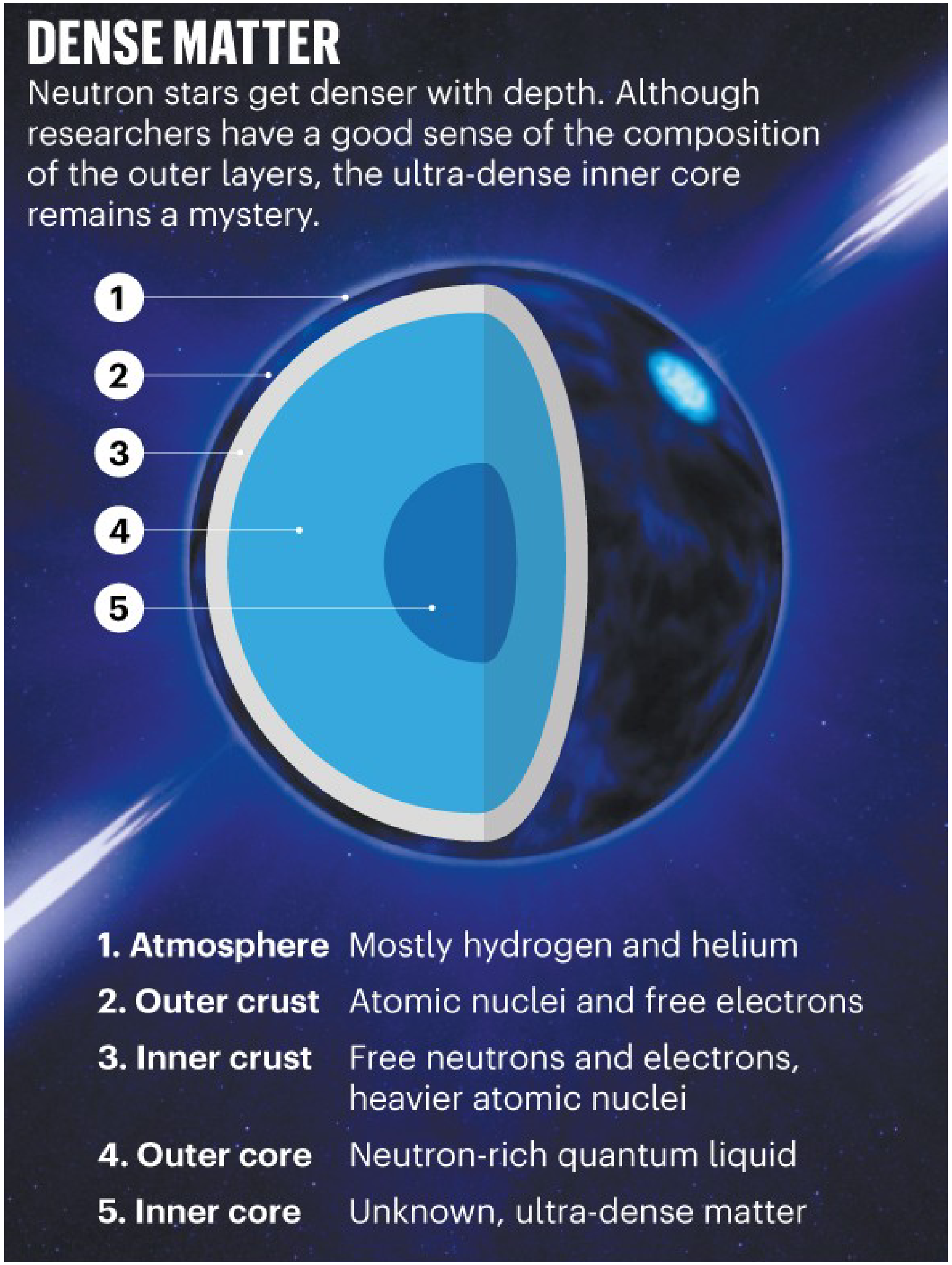
J/ψ is another observable (charm)

for the phase boundary

calculations are for T=156 MeV

Quark matter in neutron stars?

A. Andronic



DENSE MATTER

Neutron stars get denser with depth. Although researchers have a good sense of the composition of the outer layers, the ultra-dense inner core remains a mystery.

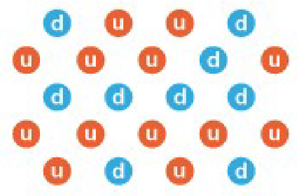
1. Atmosphere	Mostly hydrogen and helium
2. Outer crust	Atomic nuclei and free electrons
3. Inner crust	Free neutrons and electrons, heavier atomic nuclei
4. Outer core	Neutron-rich quantum liquid
5. Inner core	Unknown, ultra-dense matter

Core scenarios

A number of possibilities have been suggested for the inner core, including these three options.

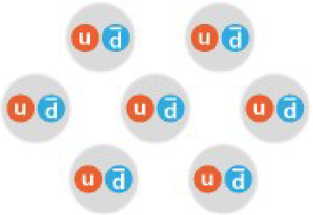
u Up quark s Strange quark

d Down quark $\bar{d}$ Anti-down quark



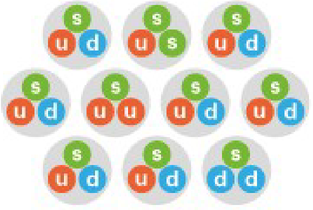
Quarks

The constituents of protons and neutrons — up and down quarks — roam freely.



Bose–Einstein condensate

Particles such as pions containing an up quark and an anti-down quark combine to form a single quantum-mechanical entity.



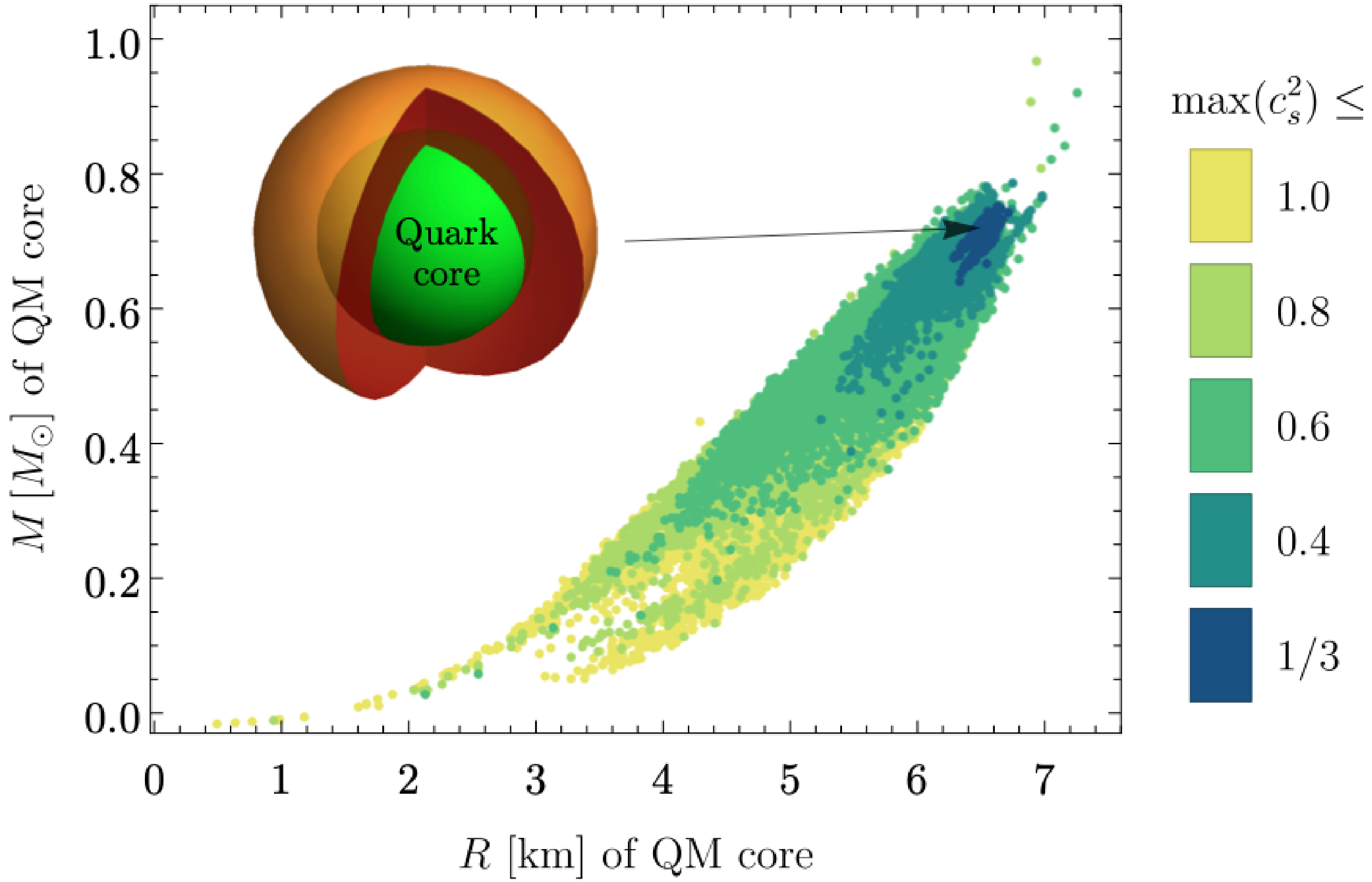
Hyperons

Particles called hyperons form. Like protons and neutrons, they contain three quarks but include 'strange' quarks.

©nature

A.Mann, Nature 579 (2020) 20

The quark core in a neutron star ($2M_{Sun}$, R=12 km)



Theoretical calculations, Annala et al, Nature Phys. 16 (2020) 907

the closer to ideal gas ($c_s^2 = 1/3$) quark matter is, the larger/heavier the core

NB: not the quark-gluon matter of LHC (antiquarks and gluons largely absent here; neutron star quark matter may be produced at FAIR/GSI)

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
- charmed hadrons and charmonium also (mostly) produced at phase boundary

  ... from $c\bar{c}$ pairs (largely) thermalized in QGP

  bottomonium suppression observed; bottom thermalization still open
- strong collective flow, well described by hydrodynamics

  the derived energy, entropy densities (initial and averaged) are well above the values expected for deconfinement

  early (rapid) thermalization remains not fully understood
- we see strong jet quenching (parton energy loss) in quark-gluon matter

  data + theoretical models → extraction of transport coefficients

What lies ahead (the next 10 years)

Precision characterization of quark-gluon matter at LHC in Run 3, 4

LHC detectors with major upgrades (ATLAS, CMS major upgrades in LS3)

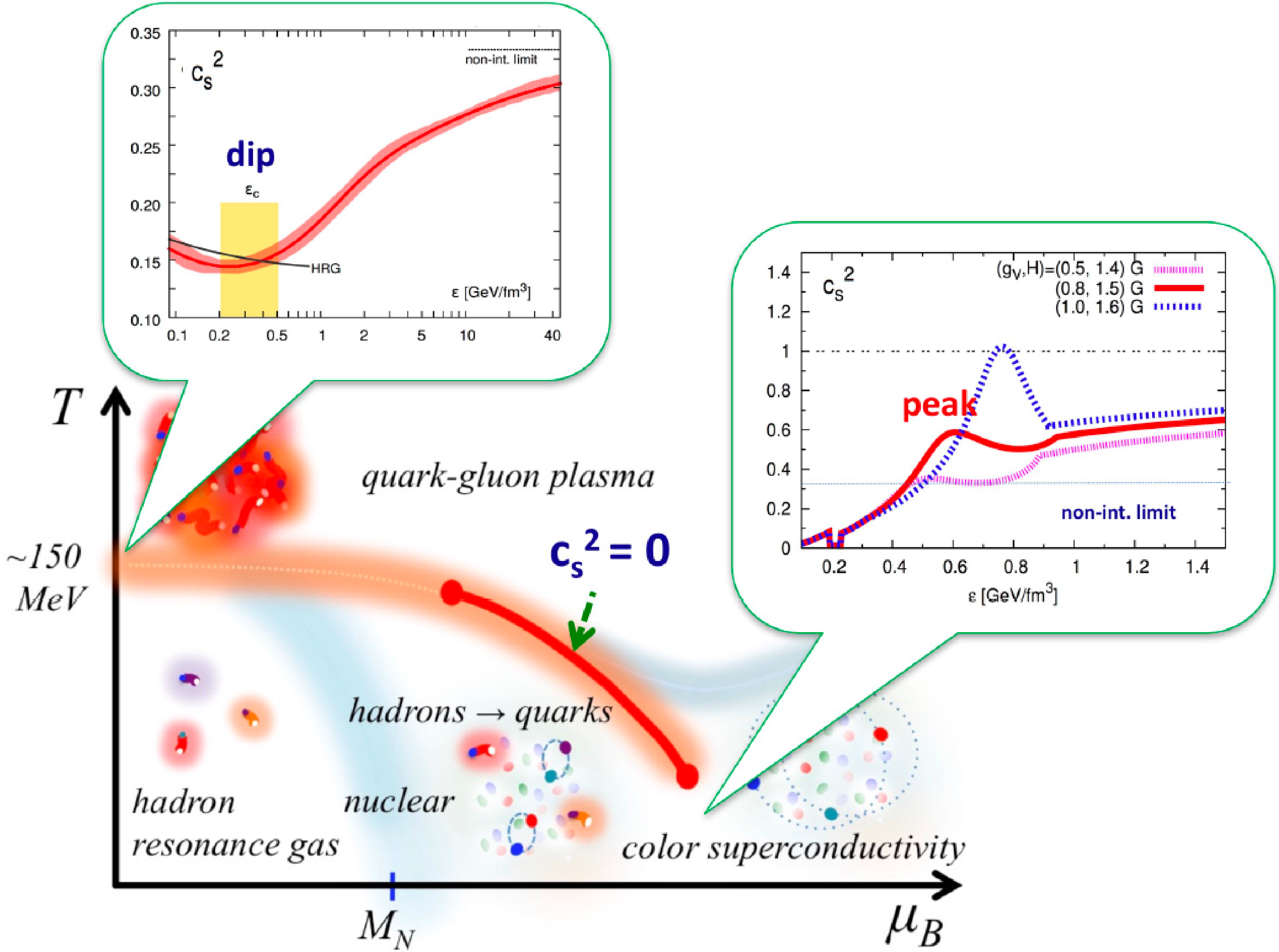
Interestingly: O-O (and p-O) collisions in 2025 (limits of jet quenching)

Measurements at BNL RHIC (STAR, sPHENIX) and FAIR (CBM)

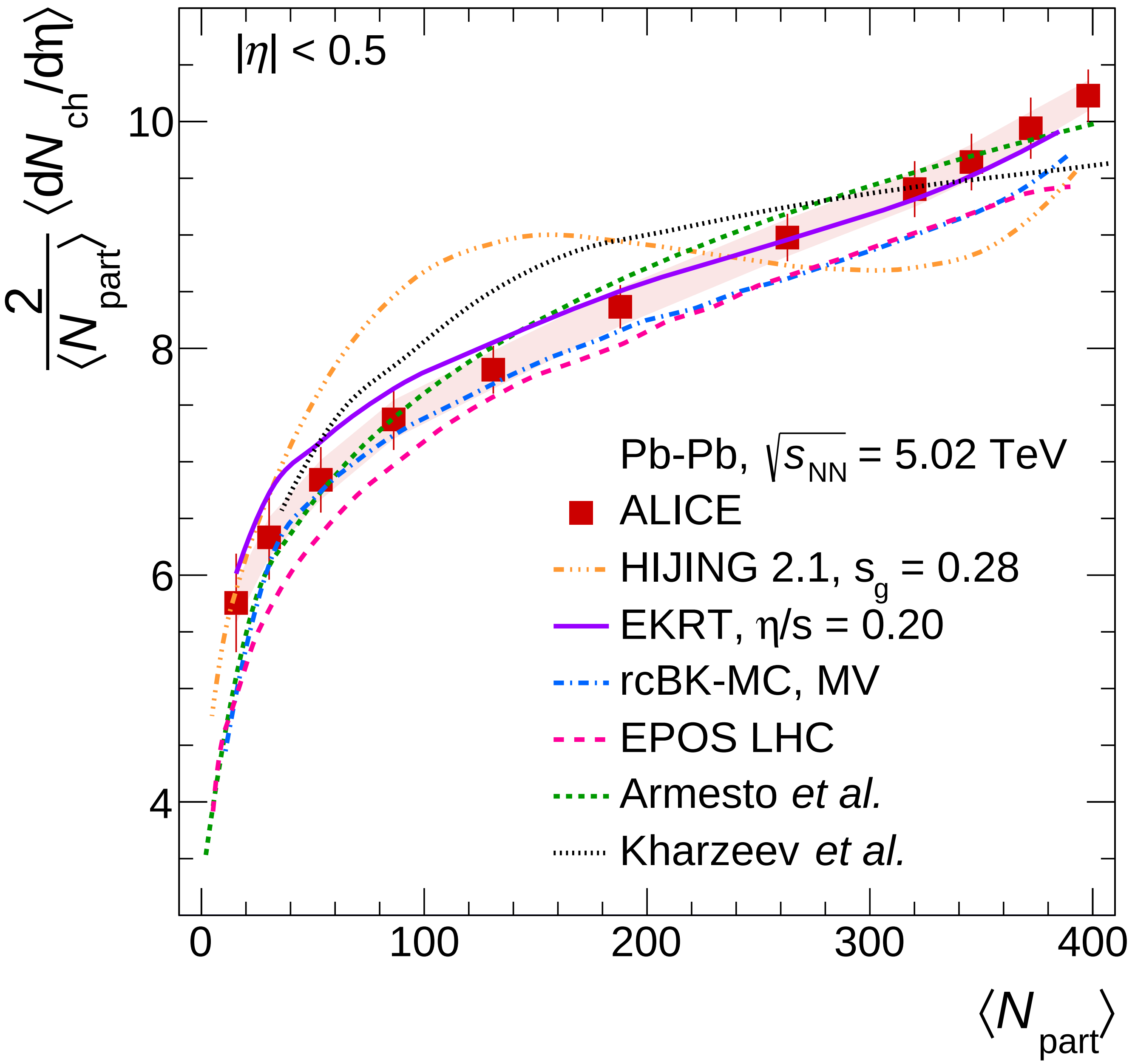
Extra slides

QCD EoS

Kojo, Universe 4 (2018) 42, Baym et al., RPP 81 (2018) 056902

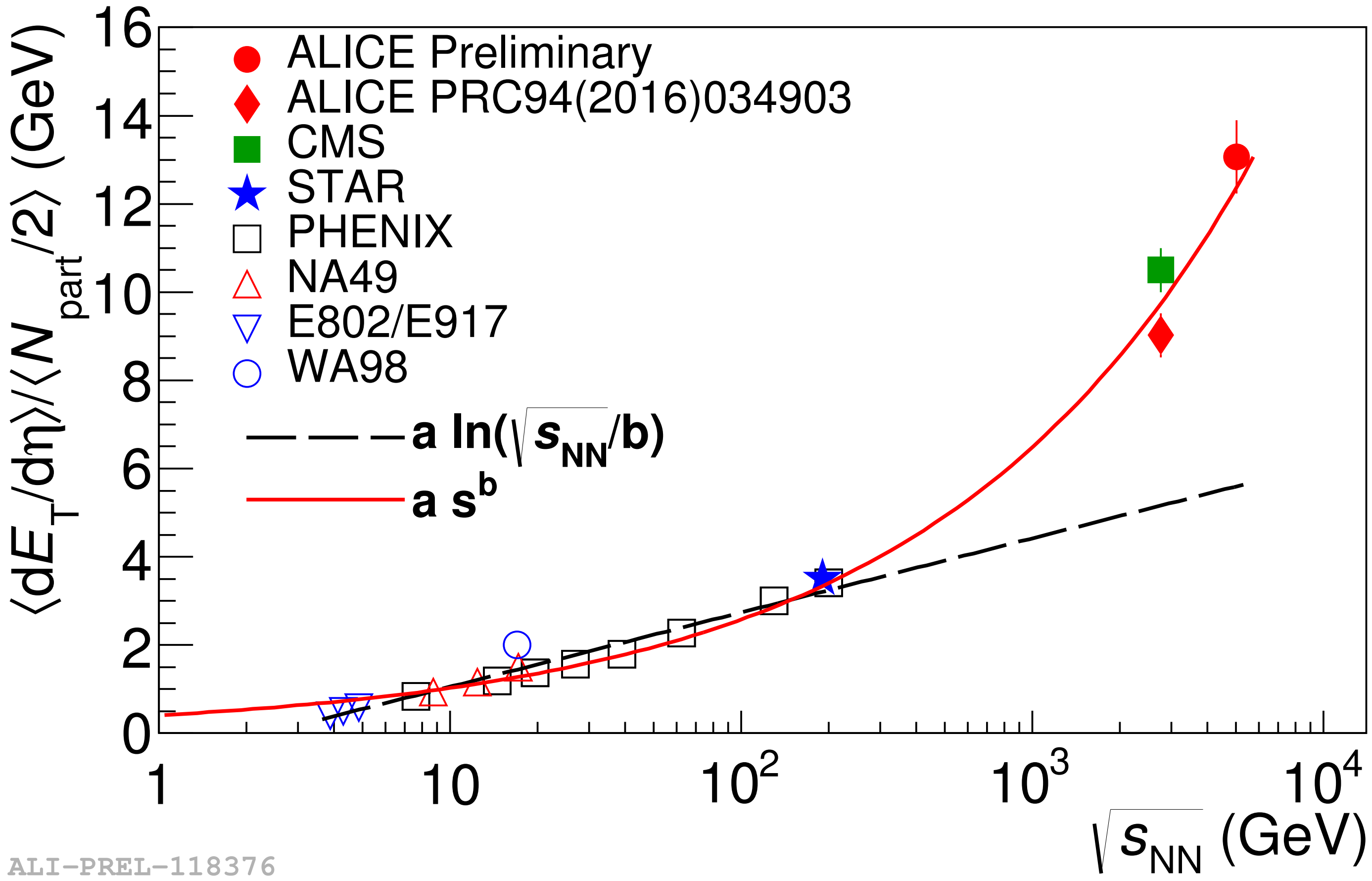


Counting charged particles



ALICE, arXiv:1512.06104

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)

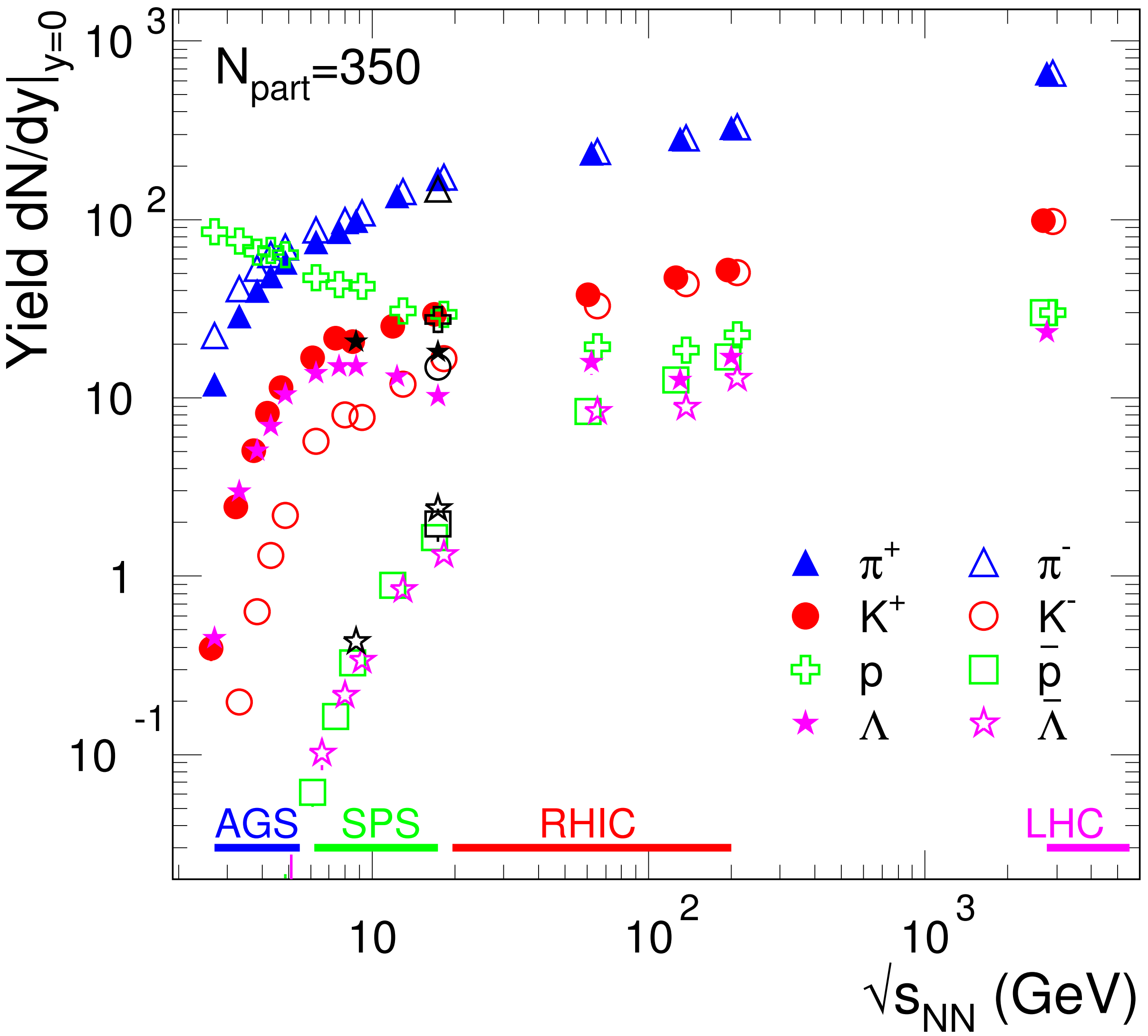
self-similar (Hubble-like) homogeneous (hydrodynamic) expansion of the fireball in the longitudinal (beam) direction ("Bjorken model", 1983)

Energy density: $\varepsilon = \frac{1}{A_\mathrm{T}}\frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}y}\frac{1}{c\tau_0}$

- $A_T = \pi R^2$: transverse area (Pb-Pb: A_T =154 fm^2)
- $\tau_0 \simeq$1 fm/c: formation time (establishing the equilibrium) ...*not measurable!*

Hadron yields at midrapidity (central collisions)

A. Andronic



AA, arXiv:1407.5003

- 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 at high energies ($\mathrm{e}^{-m/T}$)

at lower energies: u, d quarks as "remnants" (stopped) from the incoming nuclei

Viscosity and fluidity

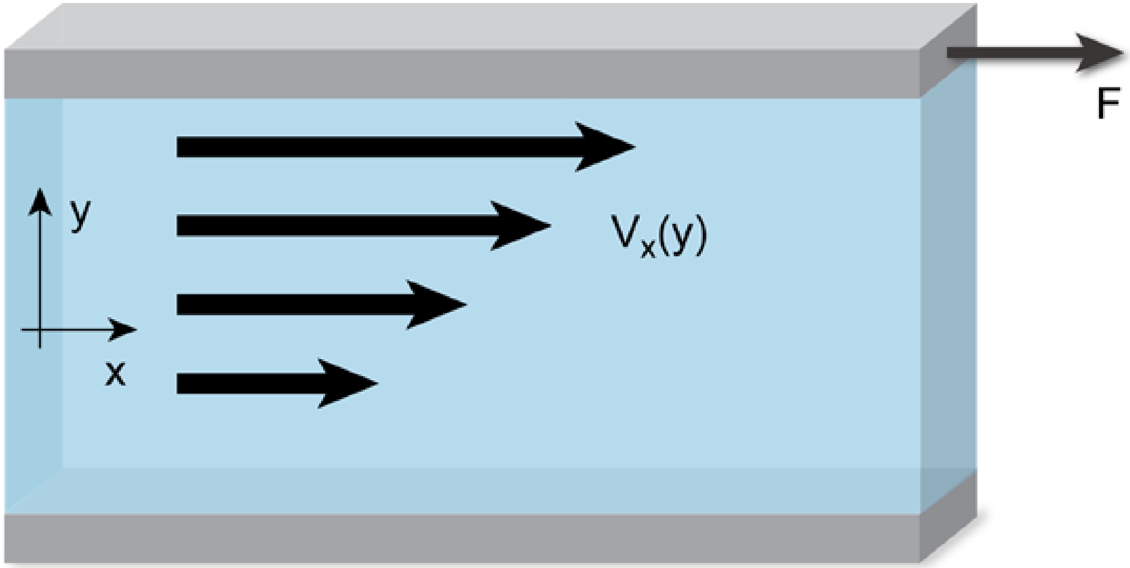


Illustration: Carin Cain

Figure 1: Viscosity—the ratio between a shear force F and the transverse gradient in a velocity profile $\nabla_y v_x$—causes dissipation in a fluid, which converts part of the kinetic energy in the flow to heat. A "good" fluid is therefore characterized by a small shear viscosity.

$\frac{F}{A} = \eta \nabla_y v_x$, η shear viscosity (in Pa·s)

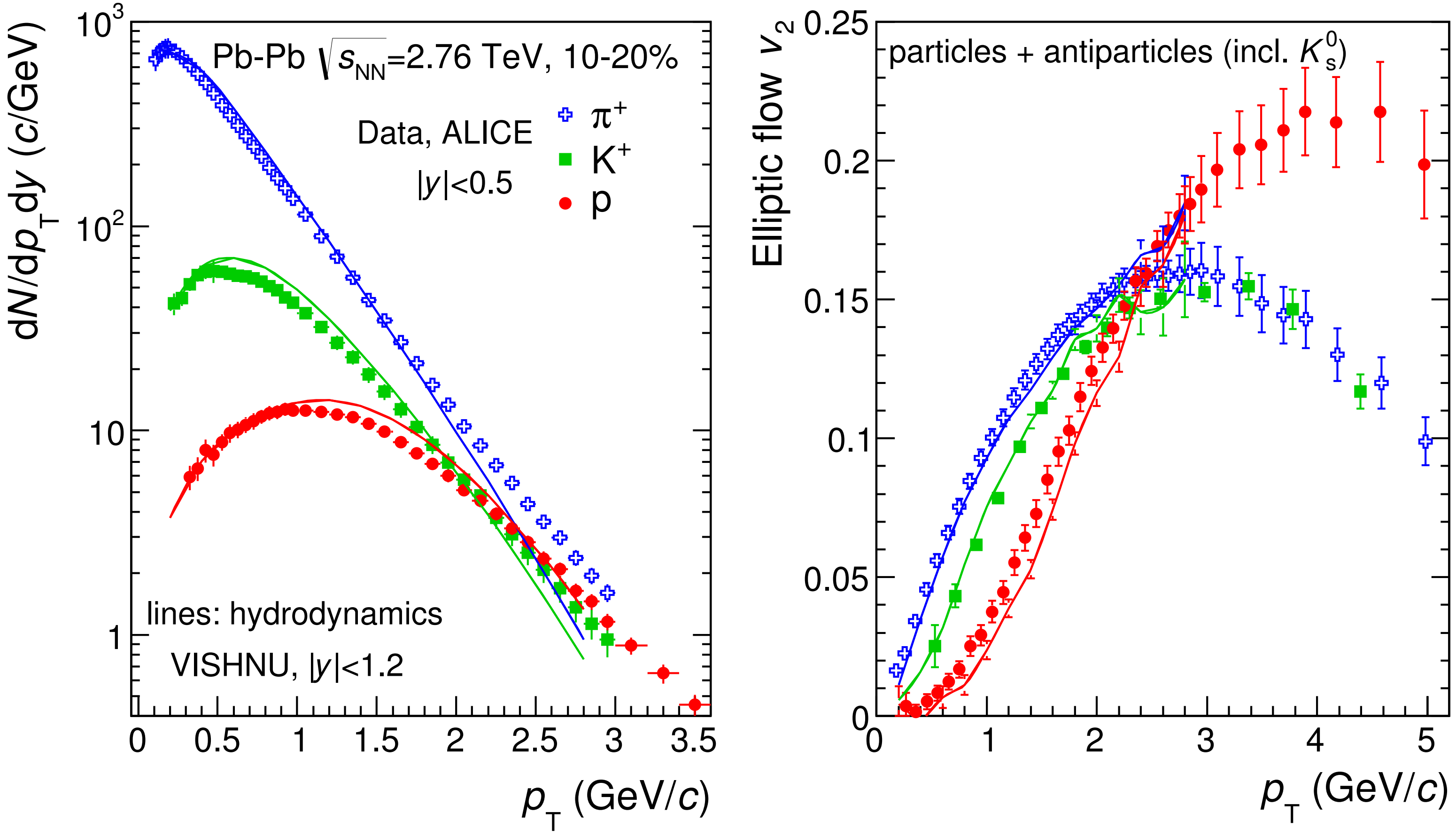
Good fluidity: large Reynolds numbers *Re* $= \frac{mn}{\eta} vL$ (η/n in $\hbar$)

For relativistic fluids (n not constant): $\eta/(\hbar n) \rightarrow \eta/s$ (in $\hbar/k_B$)

s entropy density

T. Schäfer, Physics 2 (2009) 88; Ann.Rev.Nucl.Part.Sci. 64 (2014) 125

Data and hydrodynamics



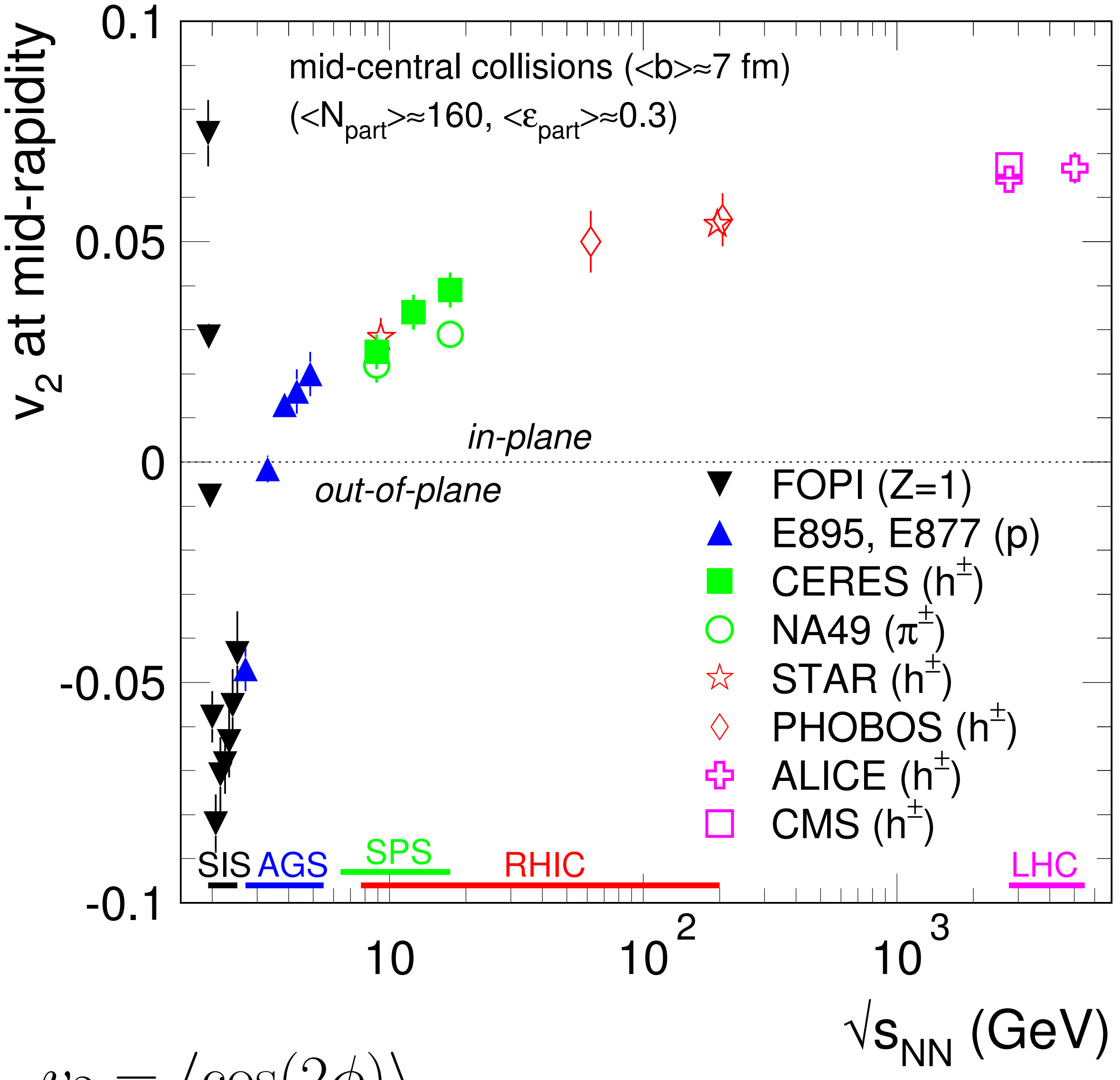
mass dependence due to collective flow

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

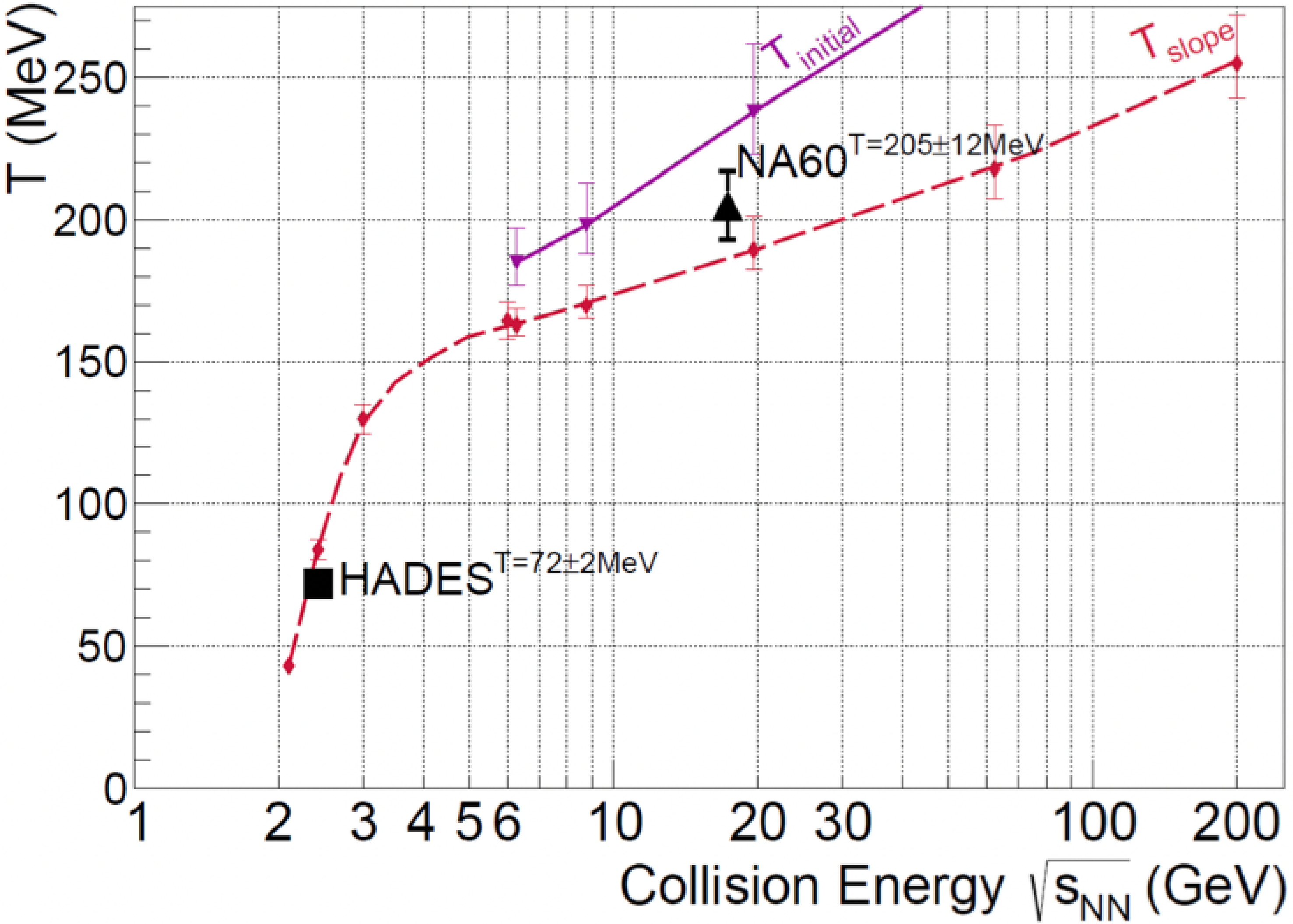
$v_2 < 0$ onset of expansion, in competition with shadowing by spectators (which act as a clock for the collective expansion, t_{pass}=40-10 fm/c)

$v_2 < 0$ at high energies: “free” fireball (almond-shape) expansion (“genuine” elliptic flow)

hydrodynamic description, low η/s

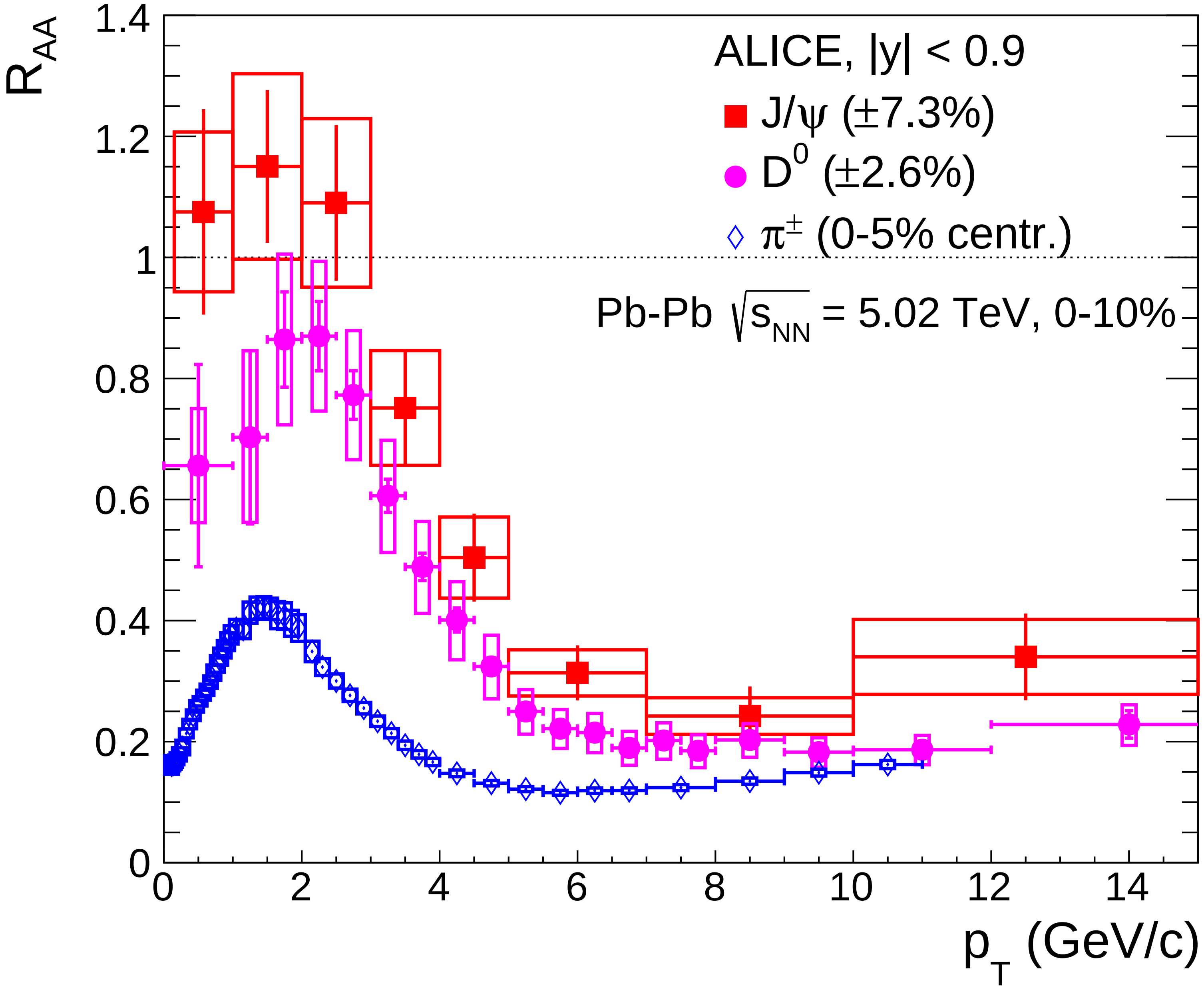
Dileptons: the temperature

...averaged over the space-time history (evolution) of the fireball



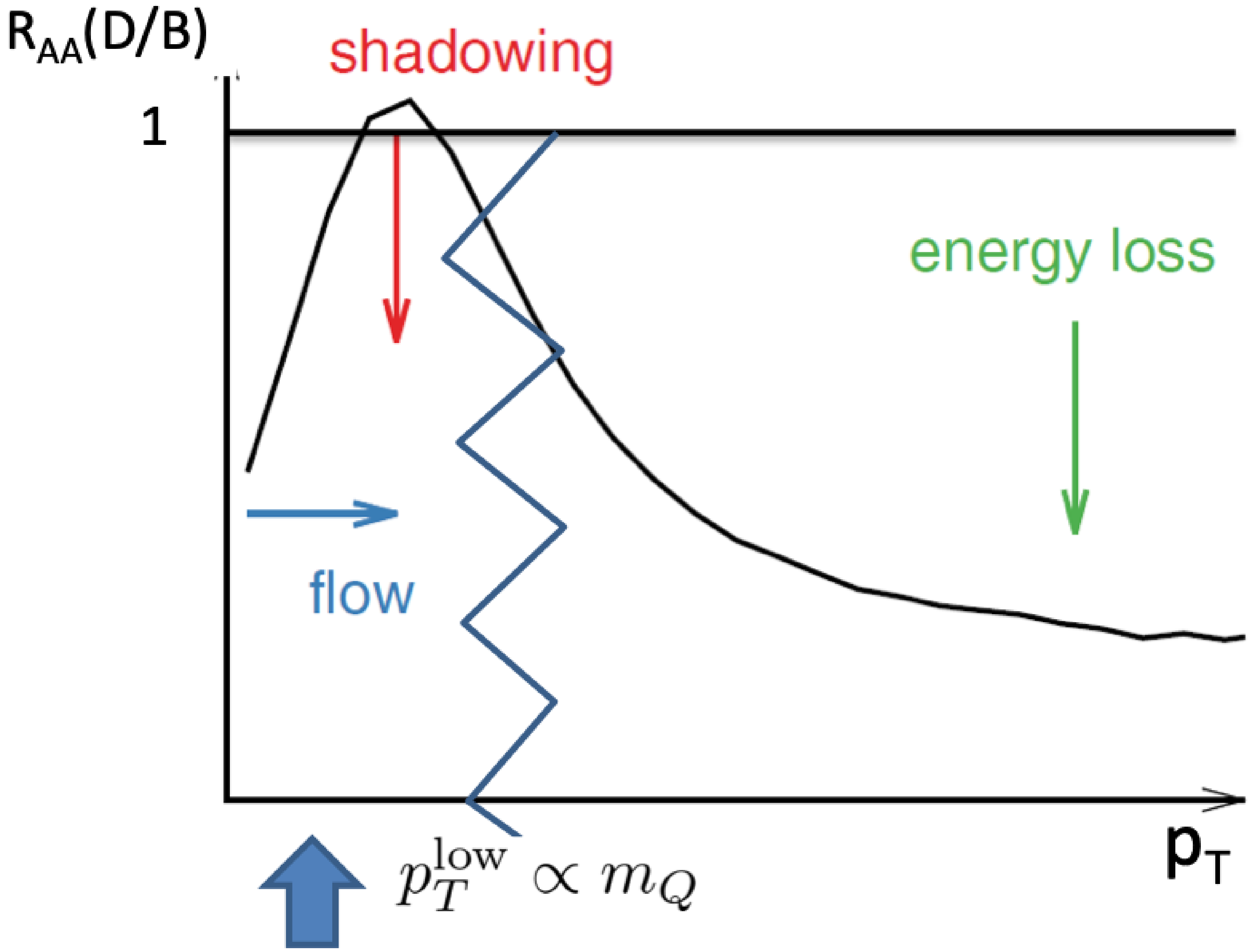
R.-A. Tripolt, arXiv:2001.11232

The light and the heavy quarks



ALICE, arXiv:2303.13361, arXiv:2110.09420, arXiv:1802.09145

Nuclear modification: a sketch



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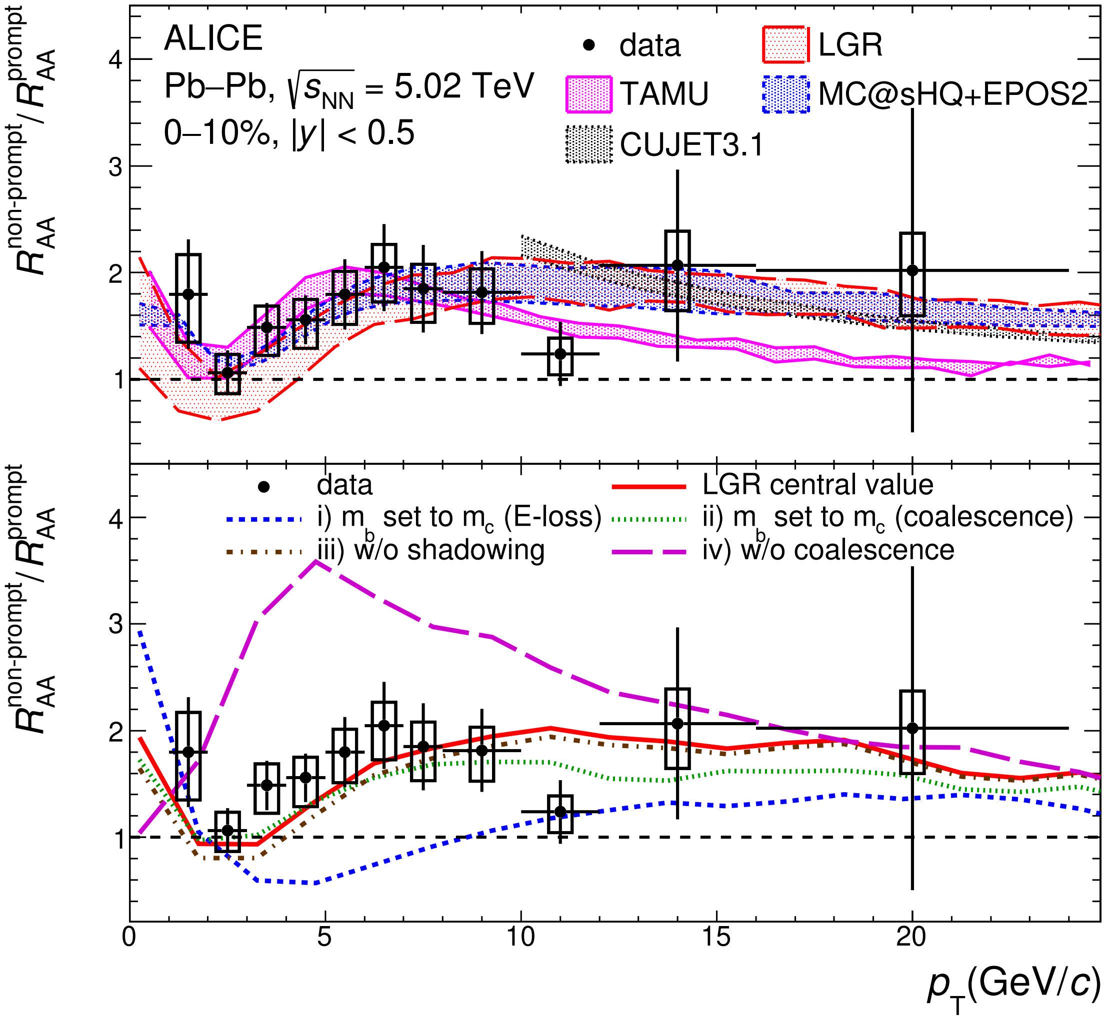
Heavy quark energy loss: data and models

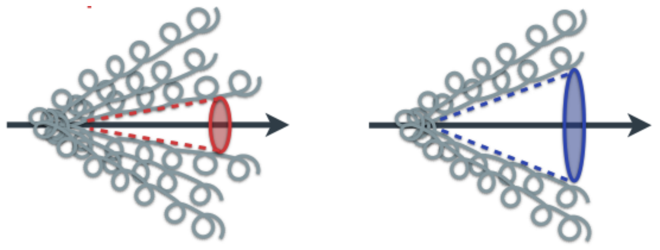


ALI-PUB-501659

ALICE, arXiv:2202.00815

b quarks (*non-prompt* D^0) are less suppressed than c quarks (*prompt* D^0)

dead cone effect:

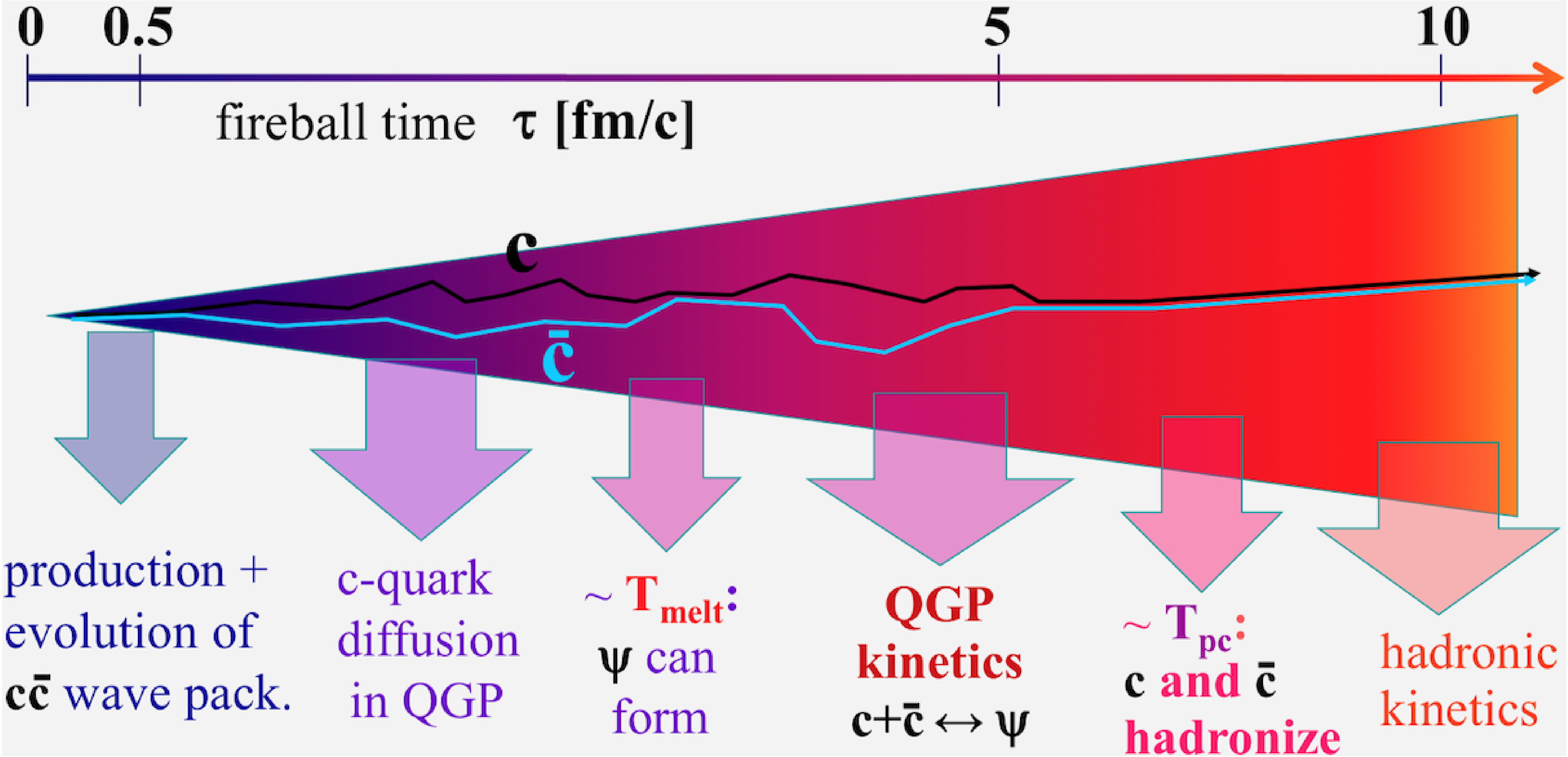


©F.Grosa

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

Models describe data ...but not in a perfect agreement

Transport models - schematics



Rapp, Du, arXiv:1704.07923

Low p_T: Brownian motion (diffusion) of charm (and b) quarks in QGP

example is for J/ψ, same picture for D, Λ_c (except light quarks 'join' late)

Transport models - in (some) depth

$$\frac{\partial f_Q}{\partial t} = \frac{\partial}{\partial p}\left(A(p)pf_Q + B(p)\frac{\partial f_Q}{\partial p}\right) \simeq \frac{\partial(A(p)pf_Q)}{\partial p} + B\Delta_{\vec{p}} f_Q$$

Fokker-Planck equation for HQ phase-space distribution $f_Q(t,\vec{p})$

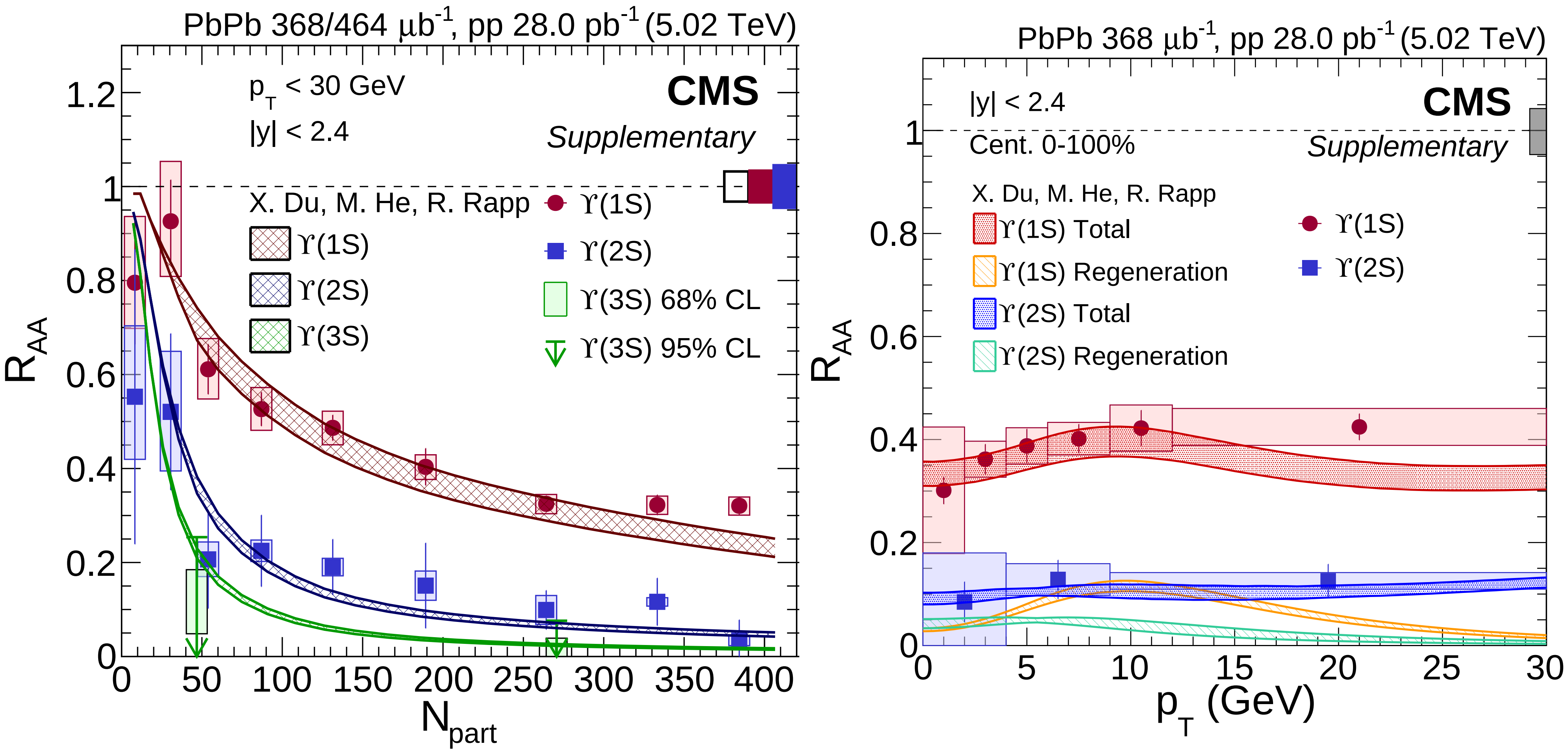
special case of Boltzmann eq., for $p^2 \sim m_Q T \gg T^2$ ($m_Q/T \geq 5$)

- A: drag coeff. / thermalization rate; thermal relaxation time $\tau_Q = 1/A(p=0)$
- B momentum diffusion coefficient; *Einstein relation:* $B(p) = A(p)m_Q T$
- Spatial diffusion constant: $D_s = \frac{T}{A(p=0)m_Q}$; $\langle x^2\rangle - \langle x\rangle^2 = 6D_s t$
- Relation to QCD medium: $D_s(2\pi T) \sim \eta/s(4\pi)$

"Effective" pQCD treatment; no single recipe/formalism, variety of models

$\tau_c \simeq 2$ fm/c (NB: $\simeq 20$ fm/c in leading-order pQCD)

Υ production



CMS, arXiv:1805.09215

$\Upsilon(1S)$ supression to a large extent effect of feed-down from $\Upsilon(2S, 3S)$, which were fully dissociated ("sequential suppression")