Light flavour, (hyper)nuclei and correlations

soft probes for heavy-ion physics

Roberto Preghenella
Istituto Nazionale di Fisica Nucleare
Bologna

2nd Italian Workshop on Hadron Physics and Non-Perturbative QCD
Pollenzo (CN)
23 May 2016

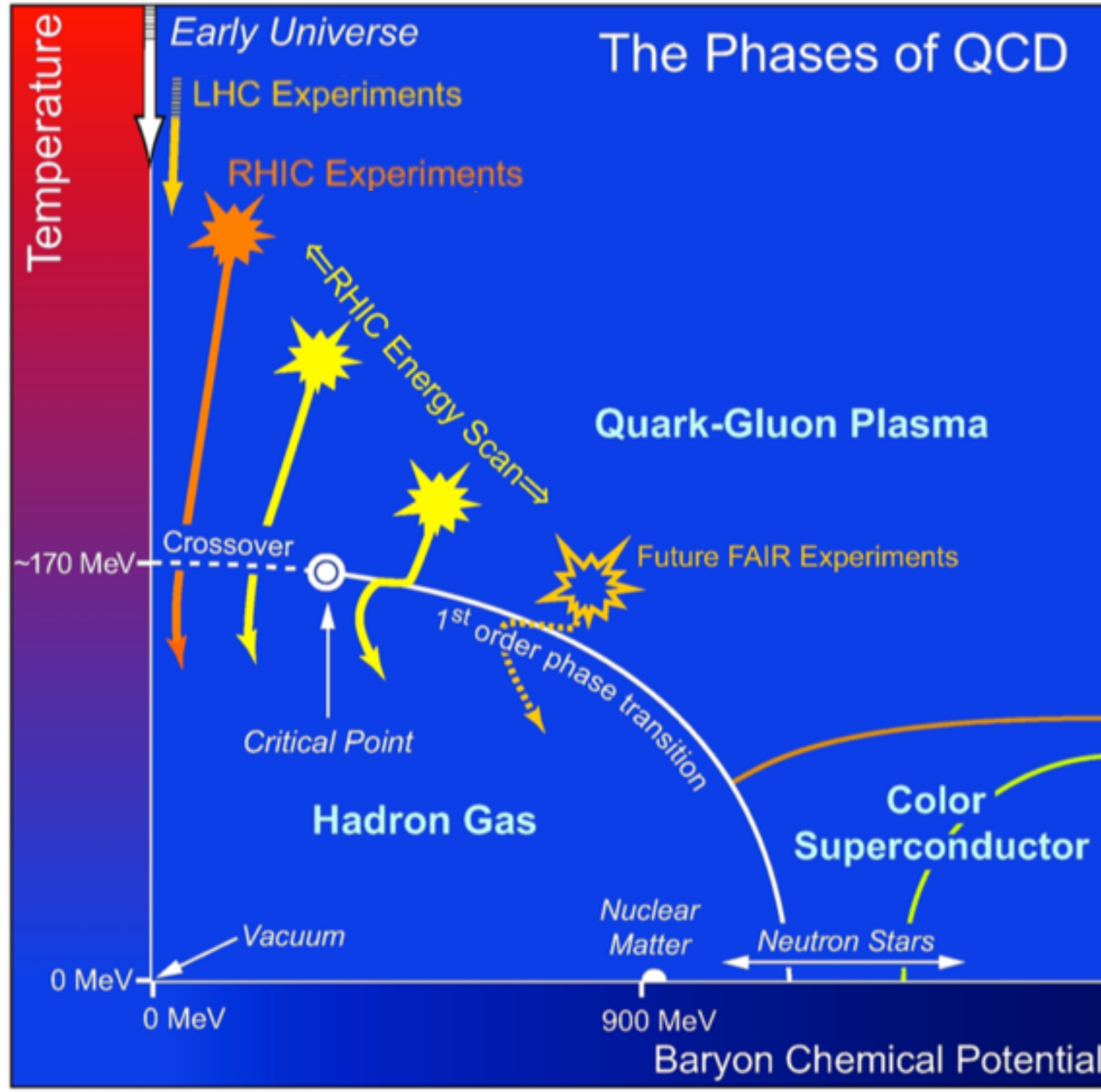
preghenella@bo.infn.it

Heavy-ion physics

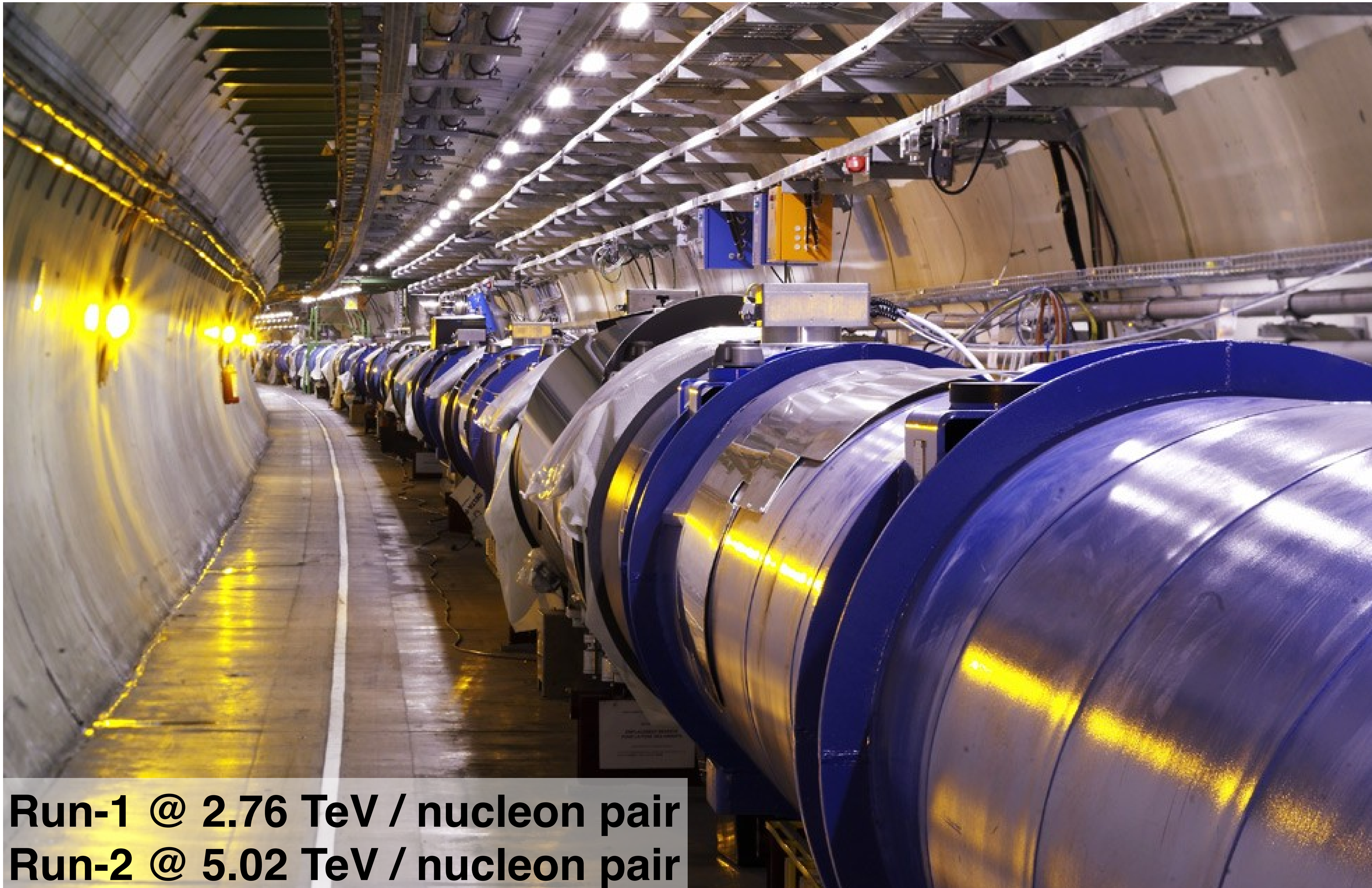
nuclear matter under extreme conditions
high temperature and energy-density

expected to undergo a
phase-transition
hadronic matter
↓
Quark-Gluon Plasma (QGP)

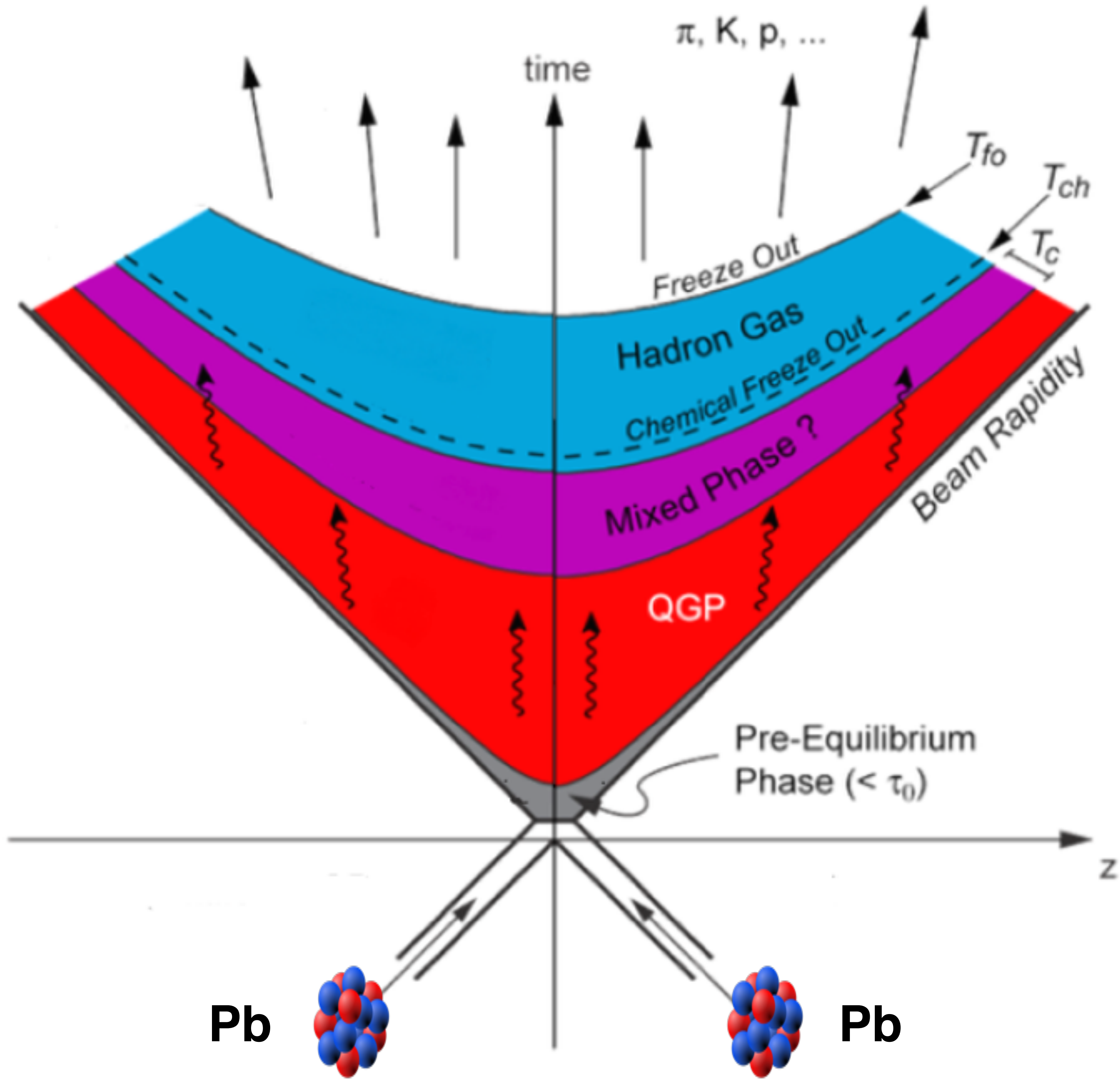
study the phase diagram and the properties of hot QCD matter



Heavy-ion collisions at the LHC

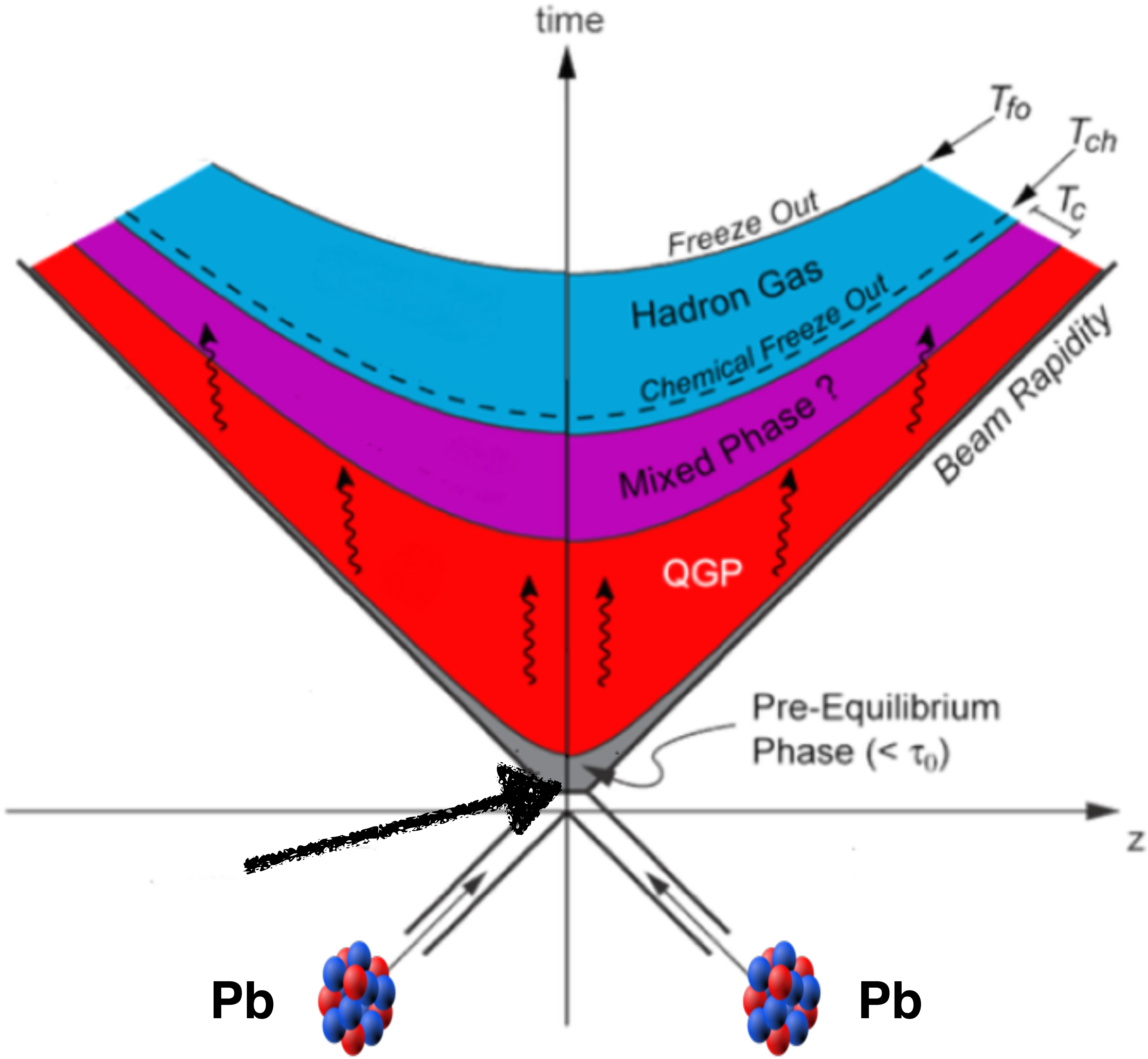


Evolution of the fireball



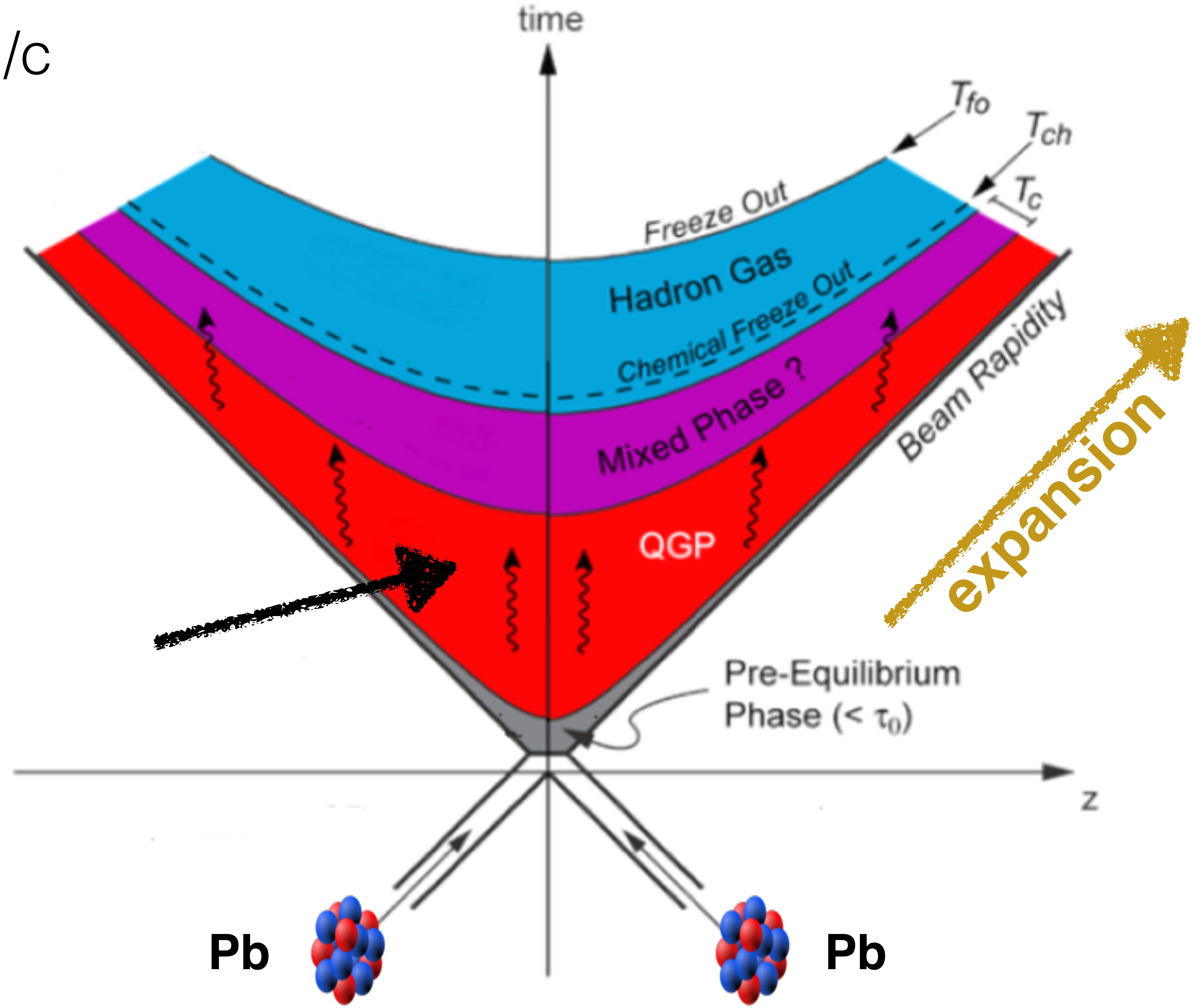
Hard scattering + thermalisation

< 1 fm/c



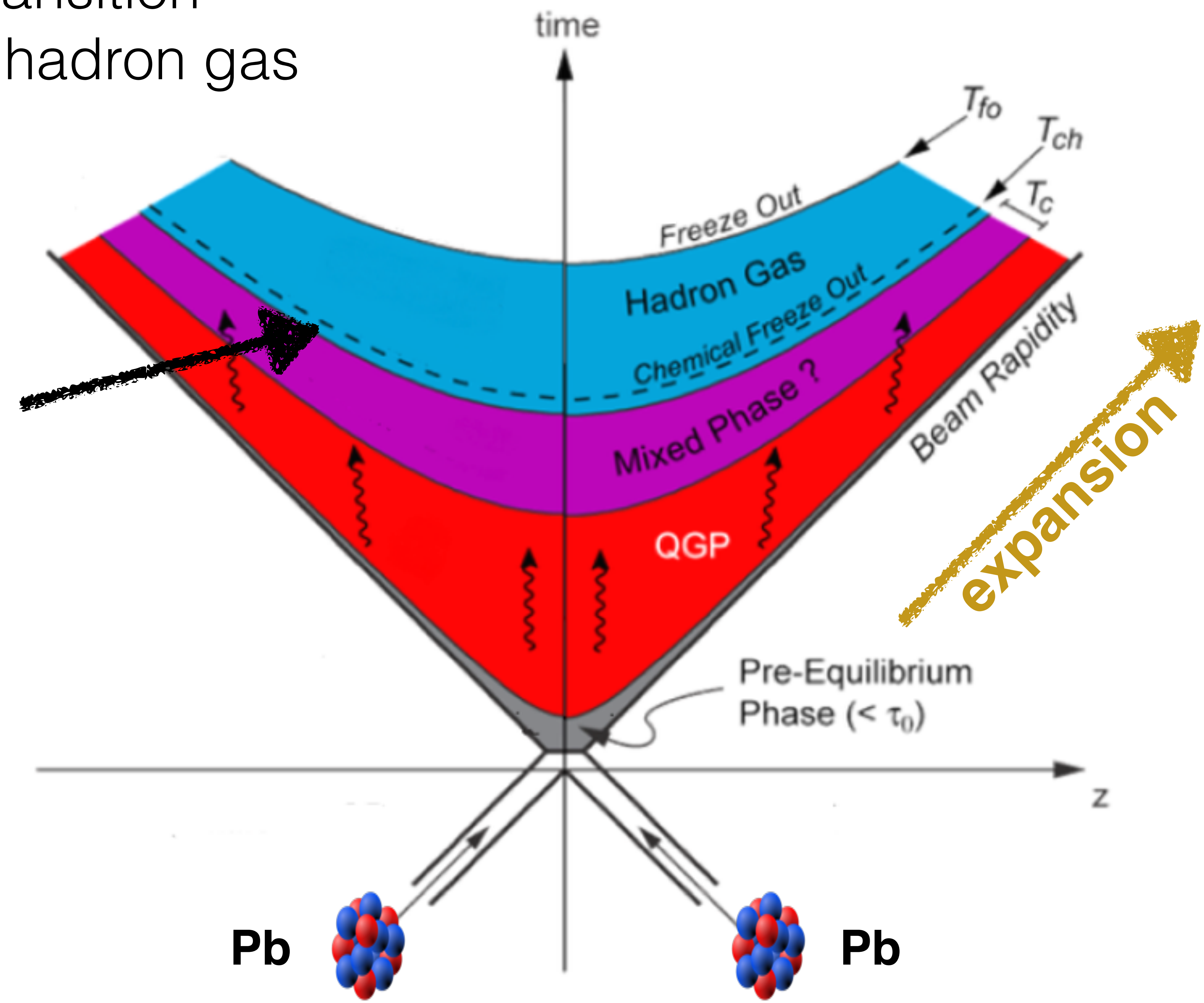
Partonic phase

QGP
~ few fm/c



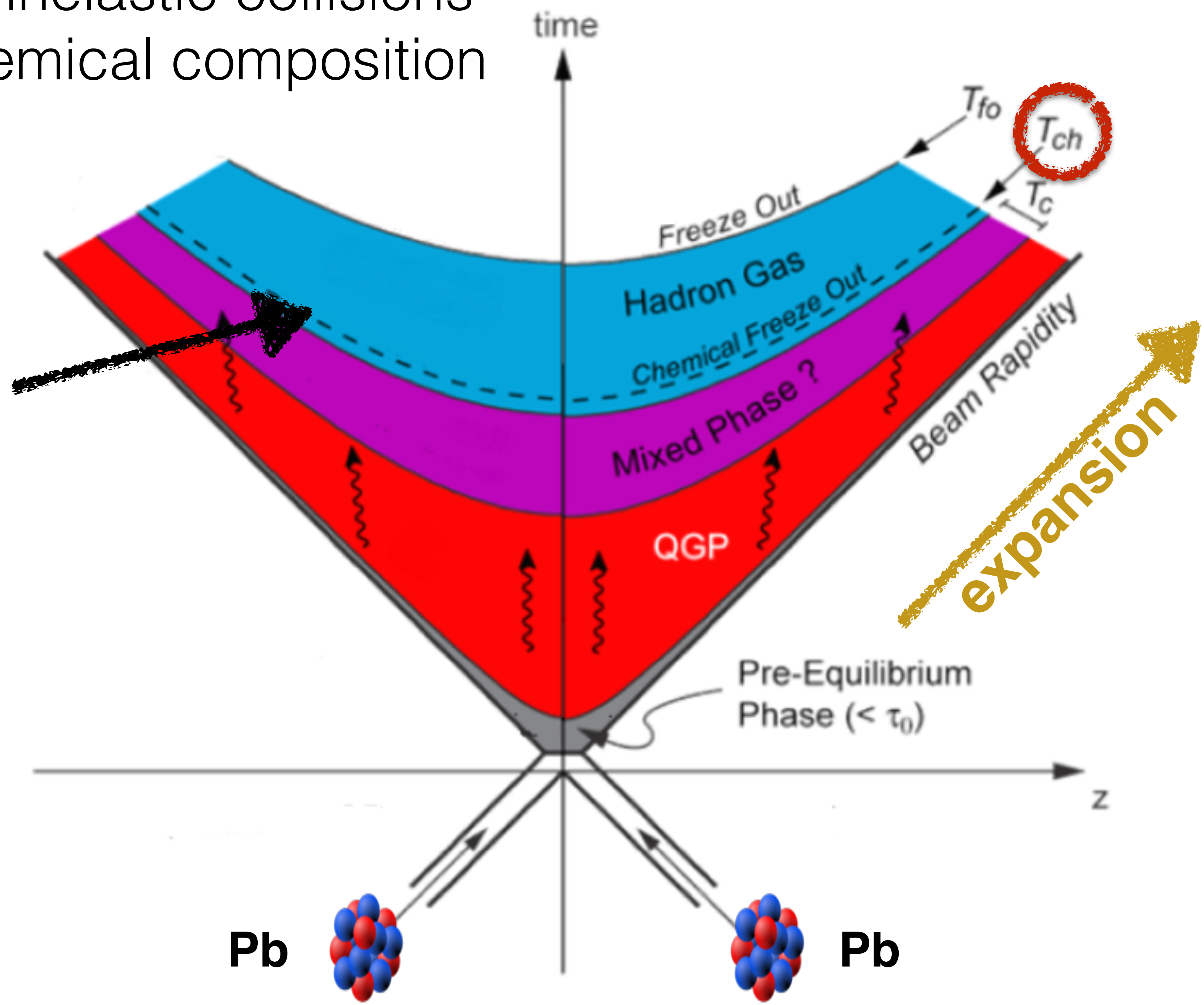
Hadronisation

phase transition
QGP → hadron gas



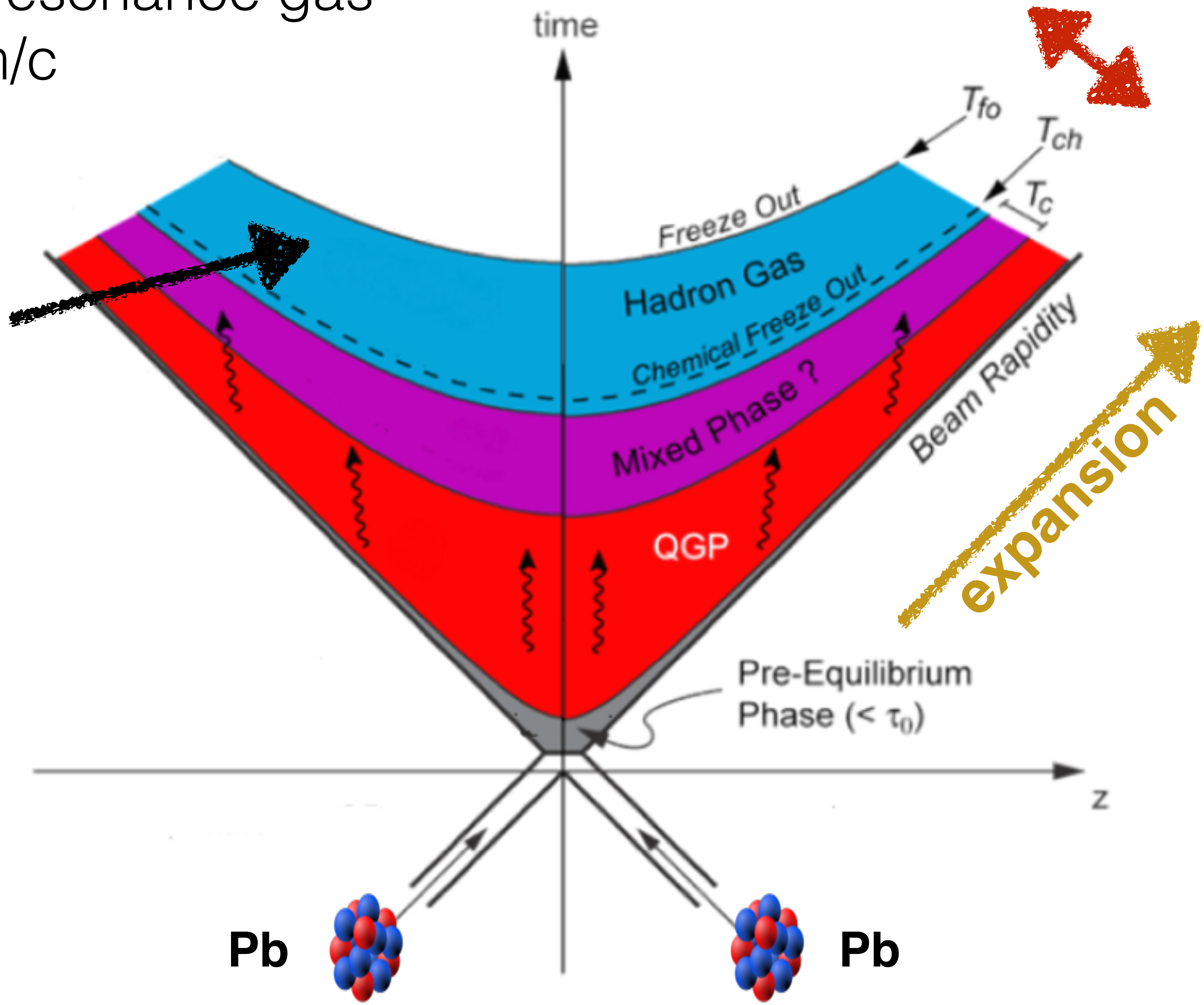
Chemical freeze-out

no more inelastic collisions
fixed chemical composition



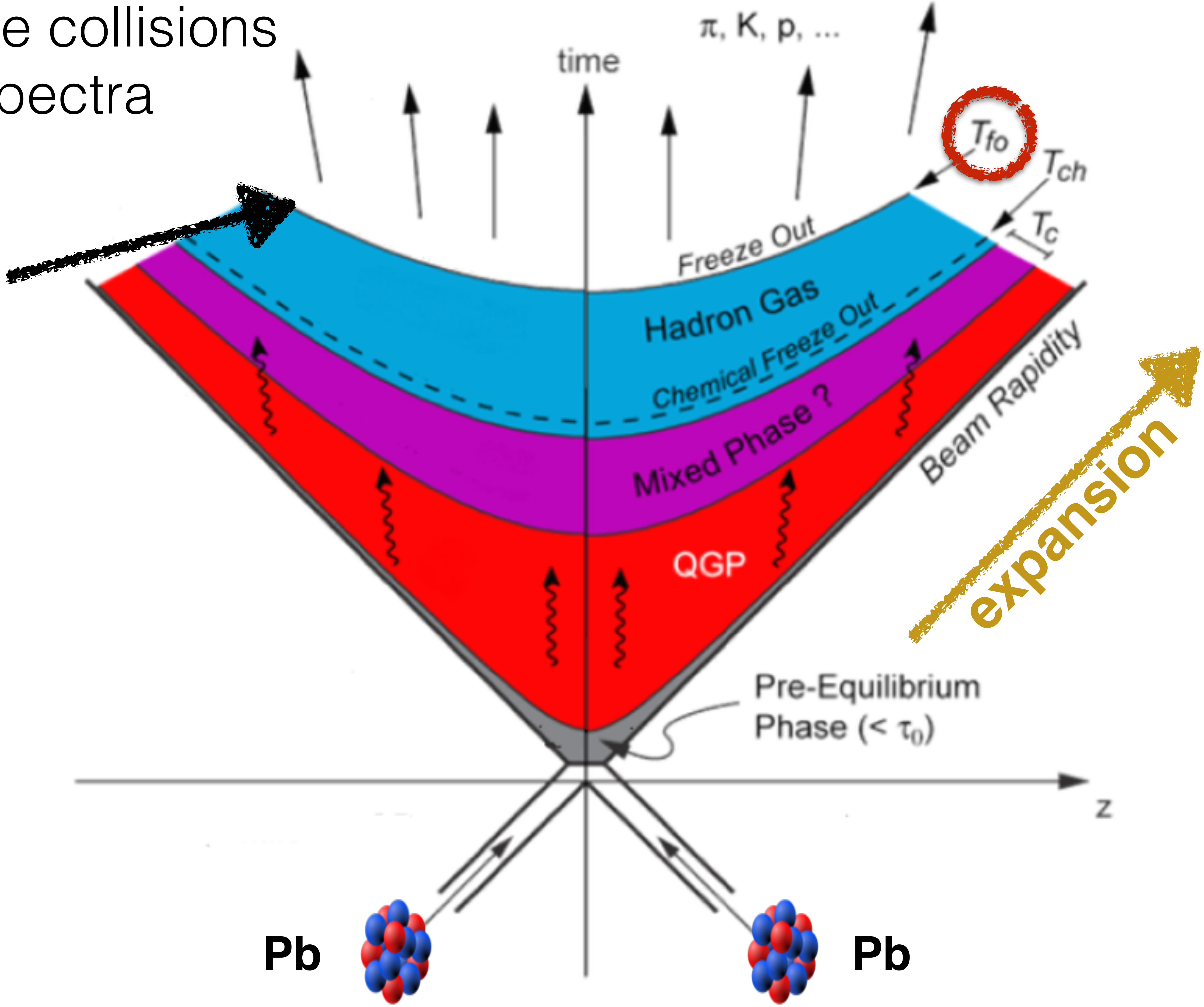
Hadronic phase

hadron-resonance gas
~ few fm/c



Kinetic freeze-out

no more collisions
fixed spectra



Particle production in nucleus-nucleus collisions

The particle zoo

ALICE has measured the production of a large number of **particles, resonances and nuclei** and anti-particles/nuclei

$\pi^{\pm}$	$K^{\pm}$	p	d	^{3}He	^{4}He
π^{0}	K_{S}^{0}	Λ	Ξ	Ω	$^{3}_{\Lambda}H$
η	K^{*}	ϕ	Σ^{*}	Λ^{*}	Ξ^{*}
D^{0}	D^{*+}	D_{S}	J/ψ	ψ'	Υ

The particle zoo

ALICE has measured the production of a large number of **particles, resonances and nuclei** and anti-particles/nuclei

$\pi^{\pm}$	$K^{\pm}$	p	d	^{3}He	^{4}He
π^{0}	K_S^{0}	Λ	Ξ	Ω	$^{3}_{\Lambda}H$
η	K^{*}	φ	Σ^{*}	Λ^{*}	Ξ^{*}
D^{0}	D^{*+}	D_s	J/ψ	ψ'	ϒ

in the next slides, the focus will be on **these particles**

Light-flavour hadrons

what physics one can probe with LF hadrons

- **energy loss** in hot nuclear matter
- study **collective phenomena**
- **thermal production** of particles
- understanding of the **late hadronic stage**
- **nuclei** production and search for **exotic states**

Jet suppression

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma

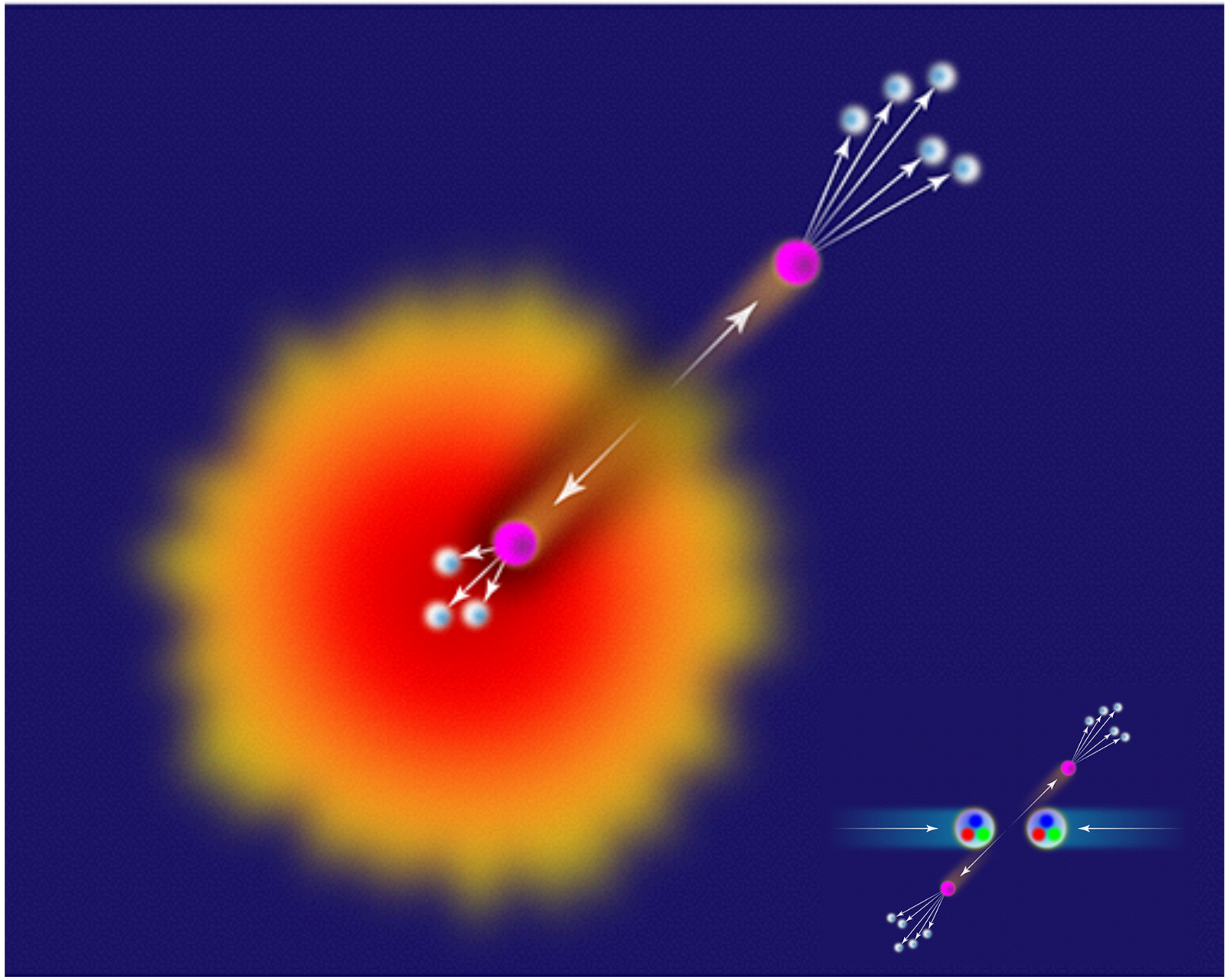
In-medium energy loss

partons produced in high Q^2 processes **lose energy while traversing the medium**

modification (suppression) of high-p_T production

observable: nuclear modification factor

$$R_{AA} = \frac{dN^{AA}/dp_T}{N_{coll}\, dN^{pp}/dp_T}$$

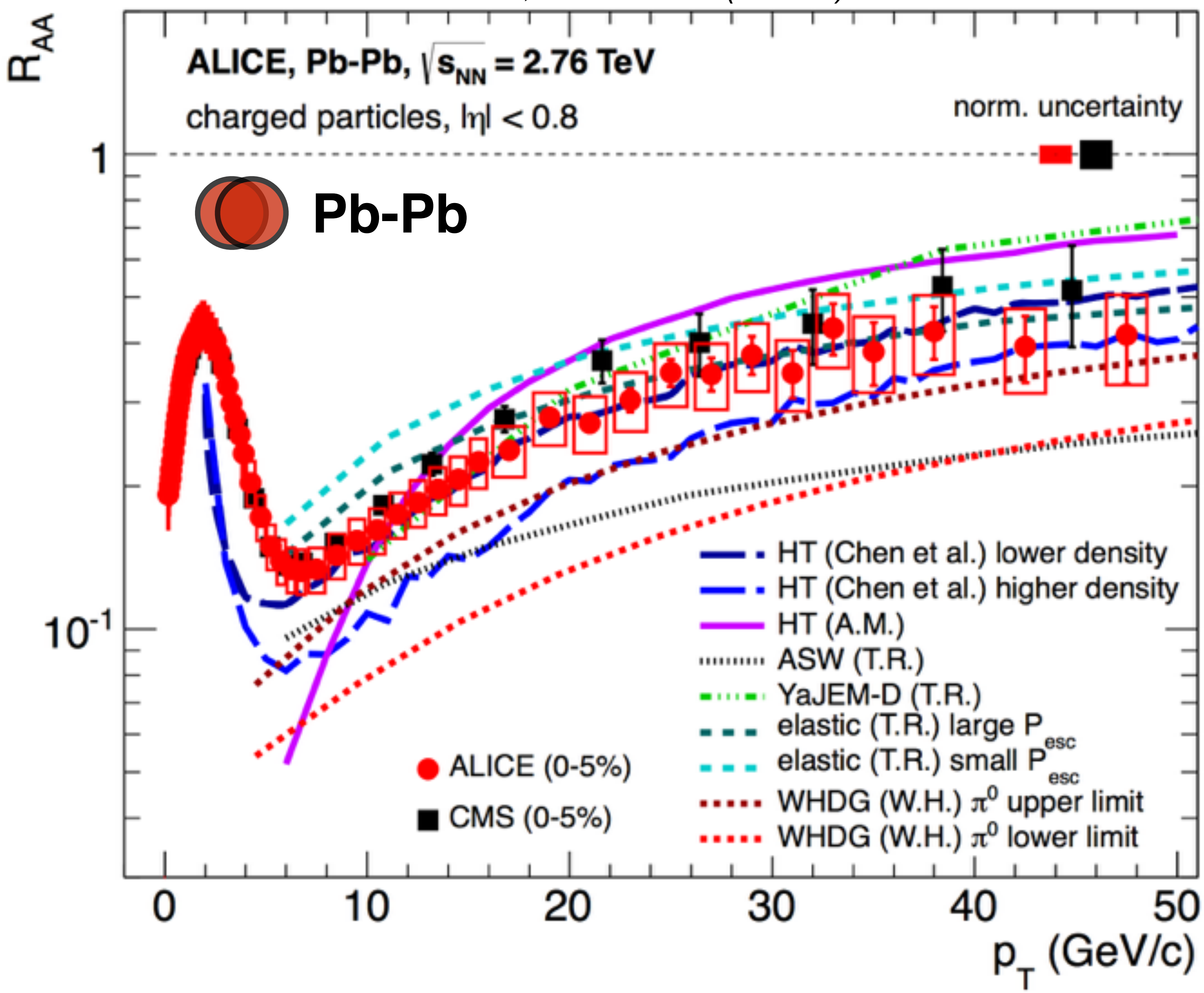


R_{AA} = 1 for hard-processes in the absence of nuclear effects

confirmed in Pb-Pb collisions at LHC (direct-γ, Z^0 and $W^\pm$)

Very dense matter

ALICE, PLB 720 (2013) 52



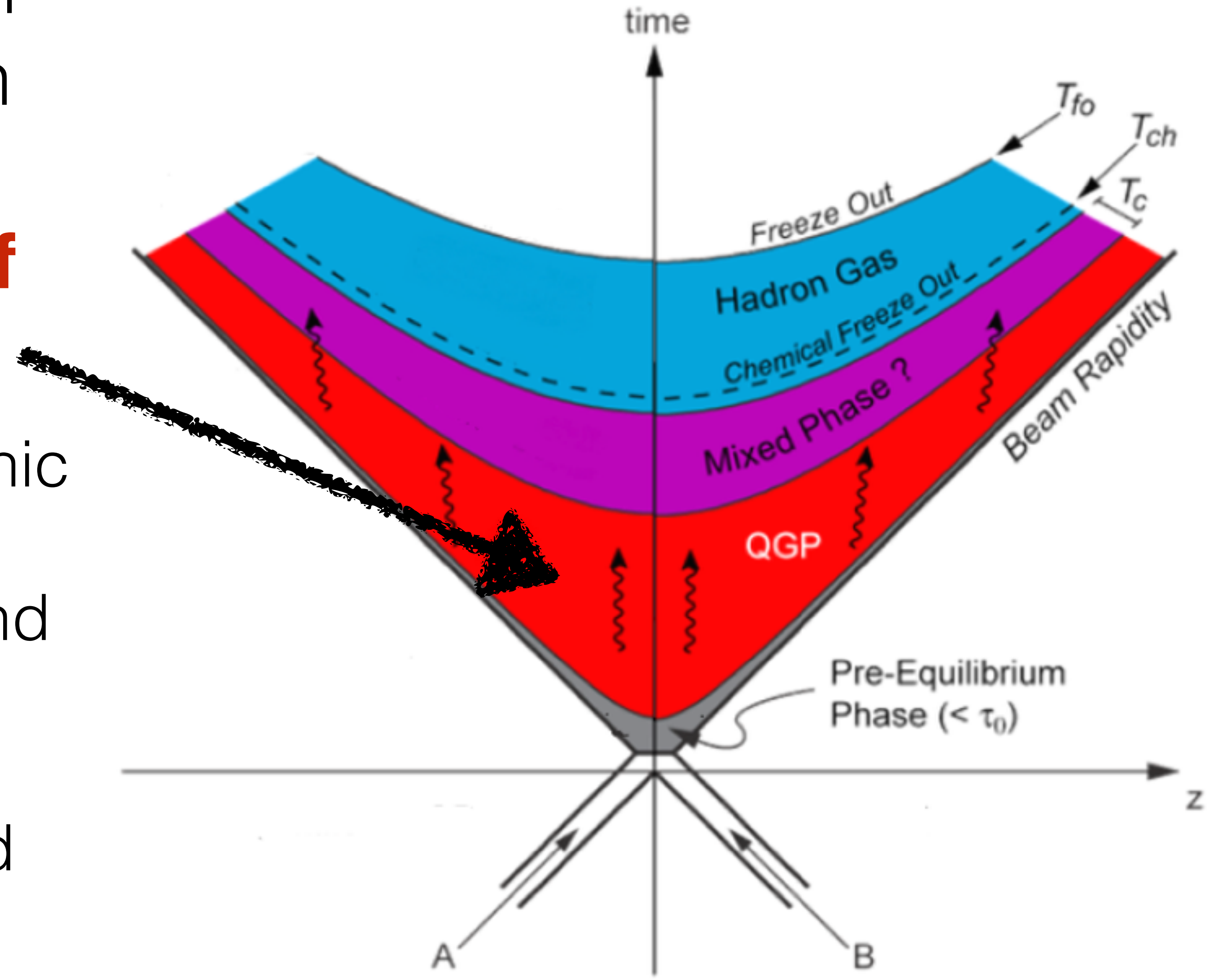
hadron production **strongly modified in Pb-Pb** collisions

large suppression in a wide p_T range

Collective phenomena

bulk matter created in high-energy heavy-ion collisions **can be described in terms of hydrodynamics**

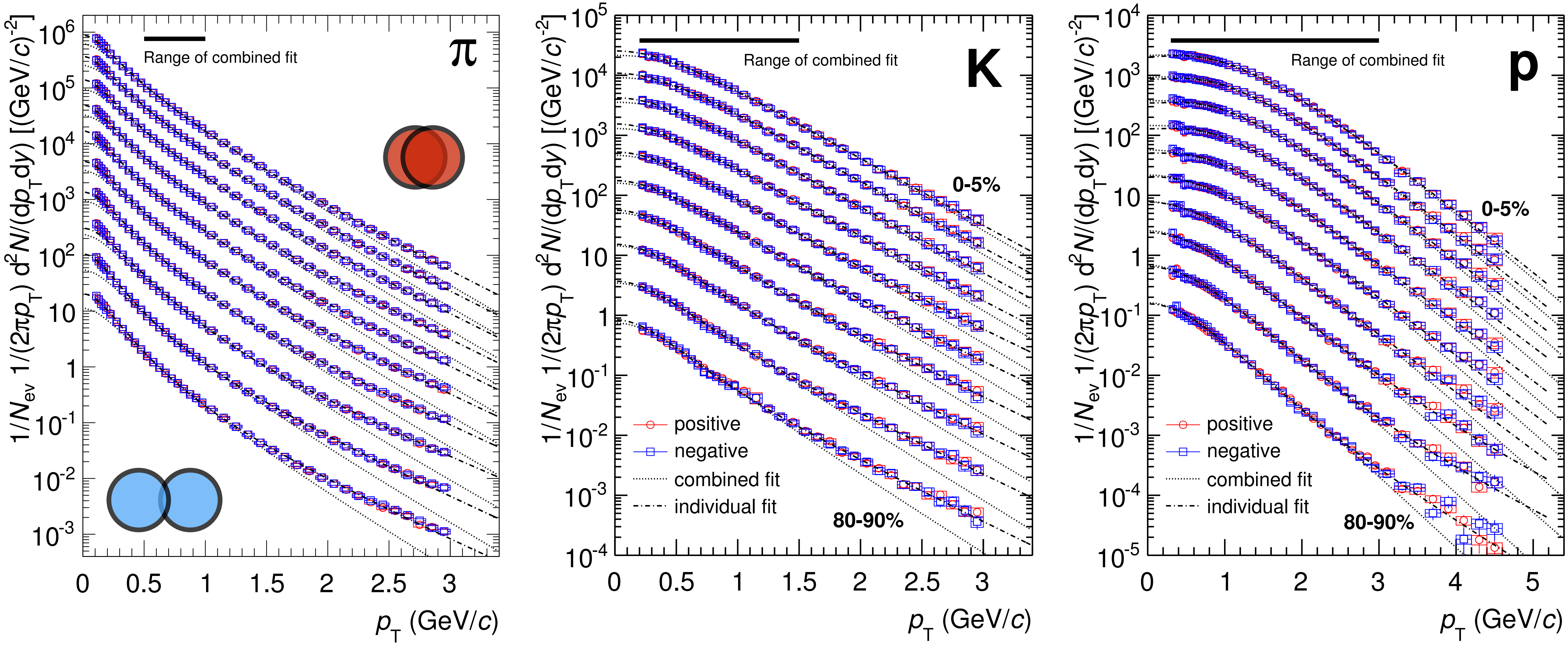
- initial hot and dense partonic matter rapidly expands
- collective flow develops and the system cools down
- phase transition to hadron gas when $T_{critical}$ is reached



resulting in

- **dependence of the shape of the p_T distribution on the particle mass**
- azimuthal anisotropic flow patterns (initial spatial anisotropy)

Bulk particle production in Pb-Pb

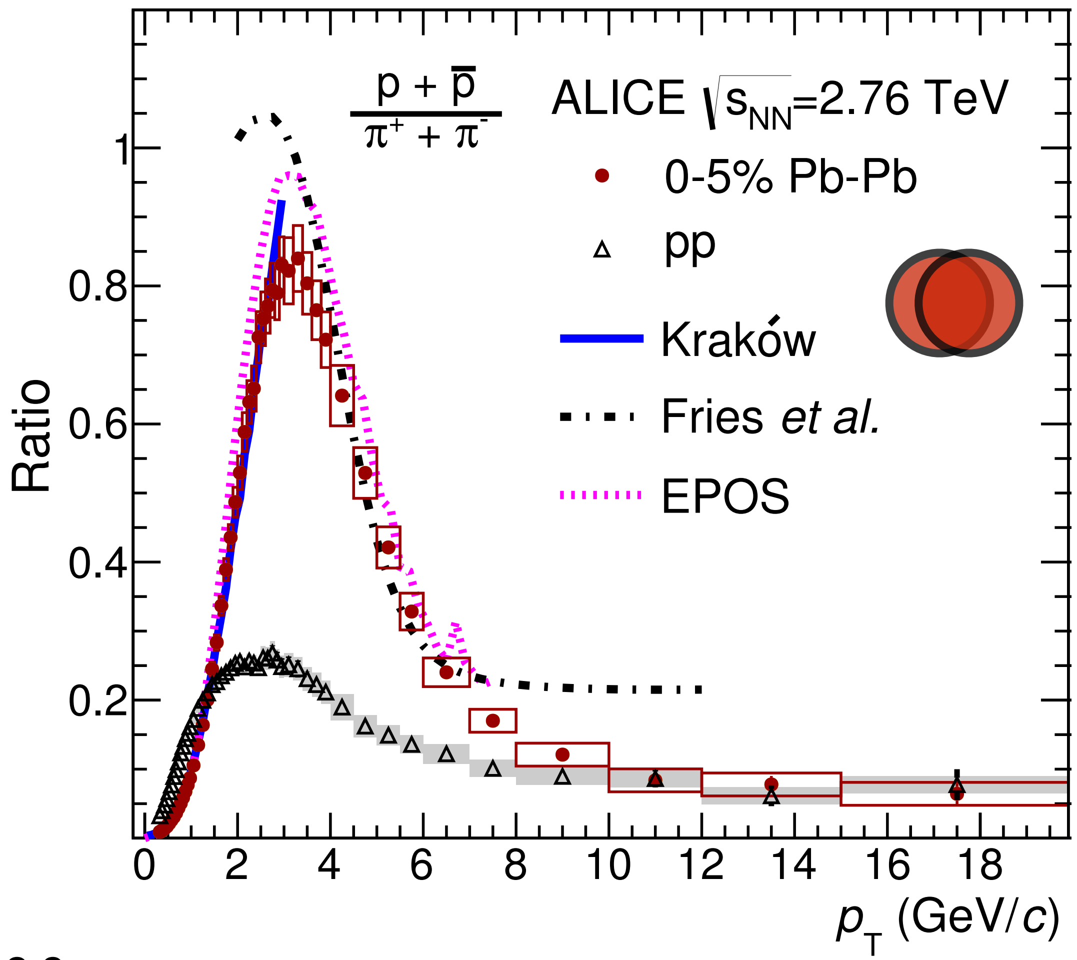


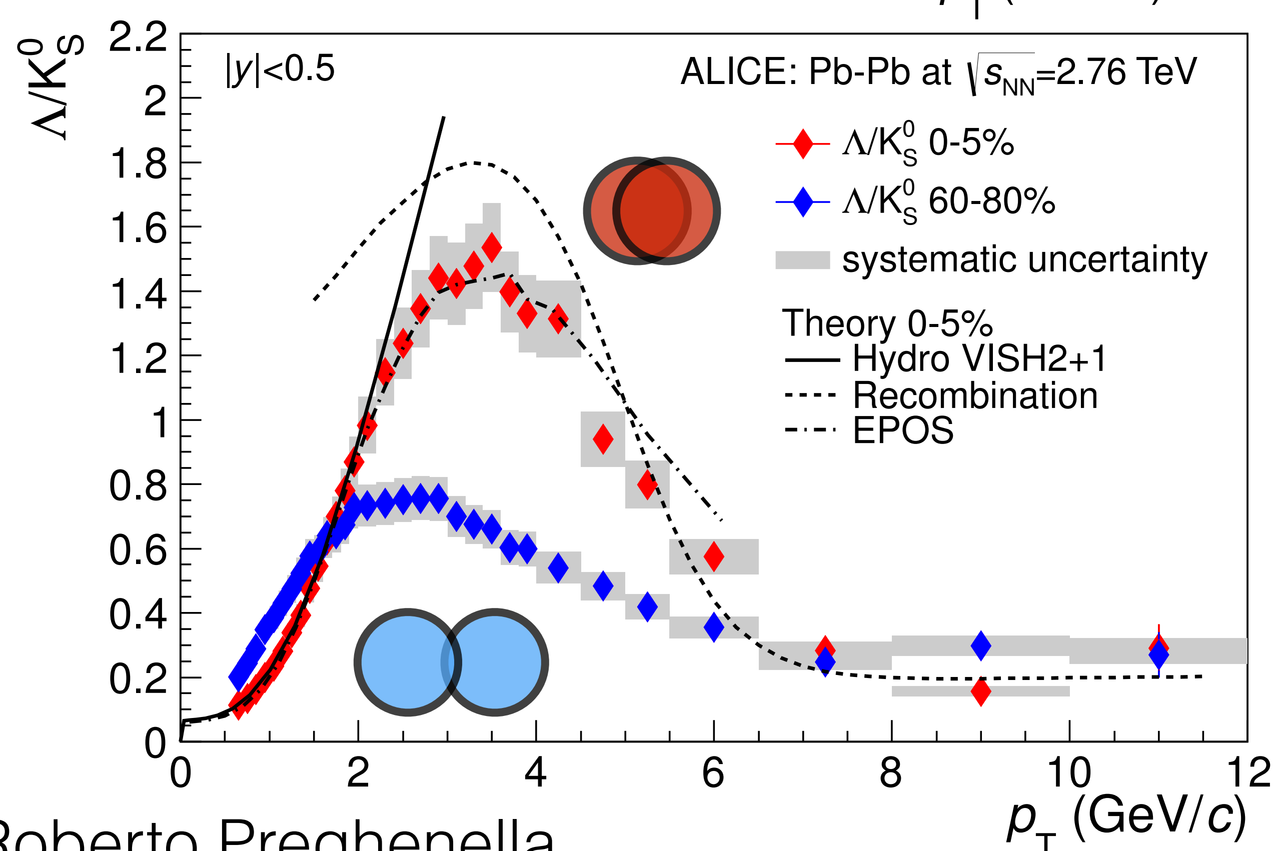
clear evolution of particle spectra → hardening with centrality

more pronounced for protons than for pions

mass ordering as expected from collective hydro expansion

Baryon-meson enhancement in Pb-Pb





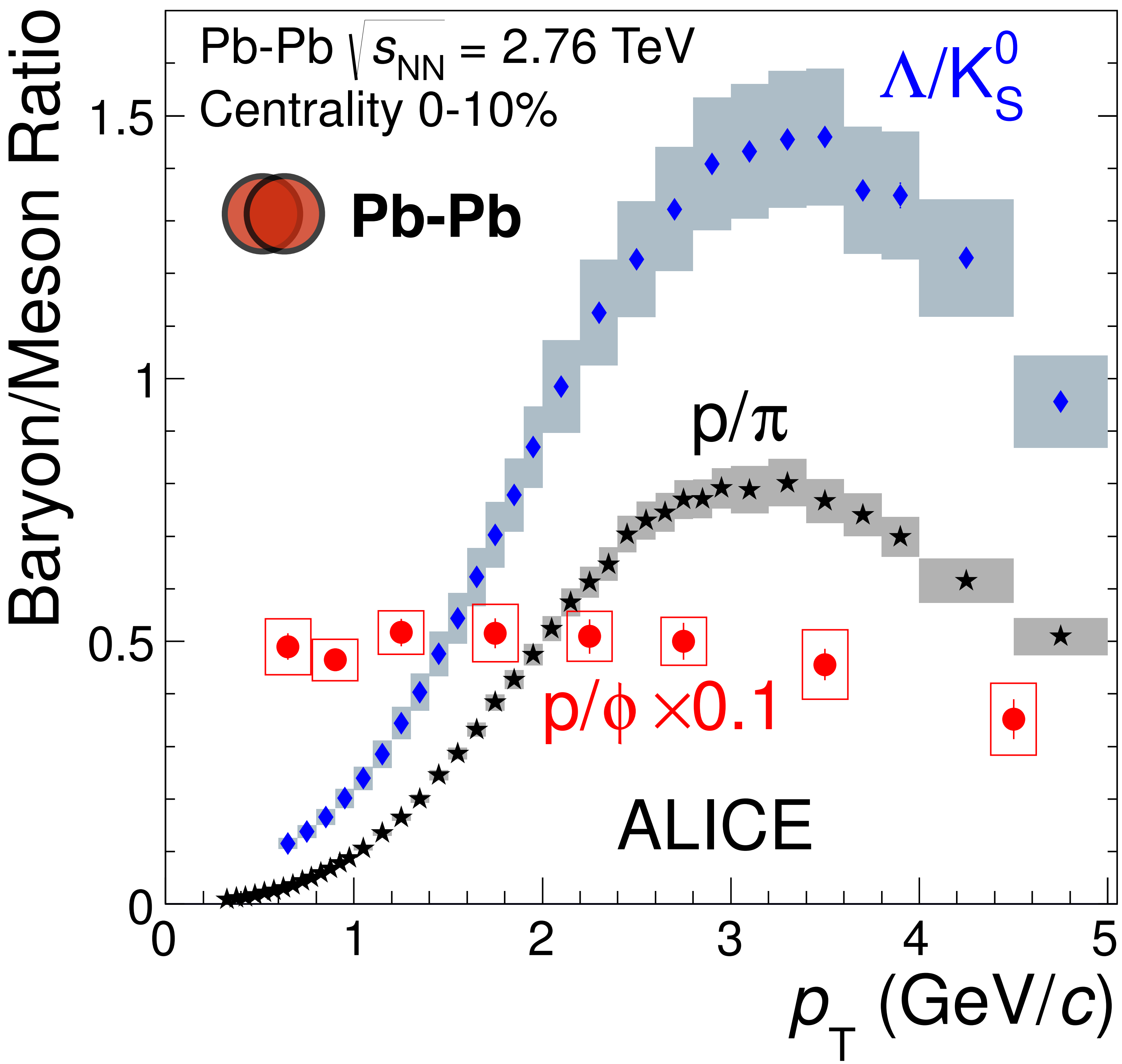
hydro model works fine for $p_T < 2$ GeV
but **deviates for higher p_T**
Song, PLB 658 (2008) 279

recombination approximately reproduces shape
but **overestimates effect**
Fries, Ann.Rev.Nucl.Part.Sci. 58 (2008) 177

EPOS provides **good description** of data
Werner, PRL 109 (2012) 102301

ALICE, PRL 111 (2013) 222301
ALICE, PLB 728 (2014) 25

p/ϕ spectra ratio in Pb-Pb



test baryon enhancement:

p: 938 MeV/c^2 qqq

ϕ: 1018 MeV/c^2 $q\bar{q}$

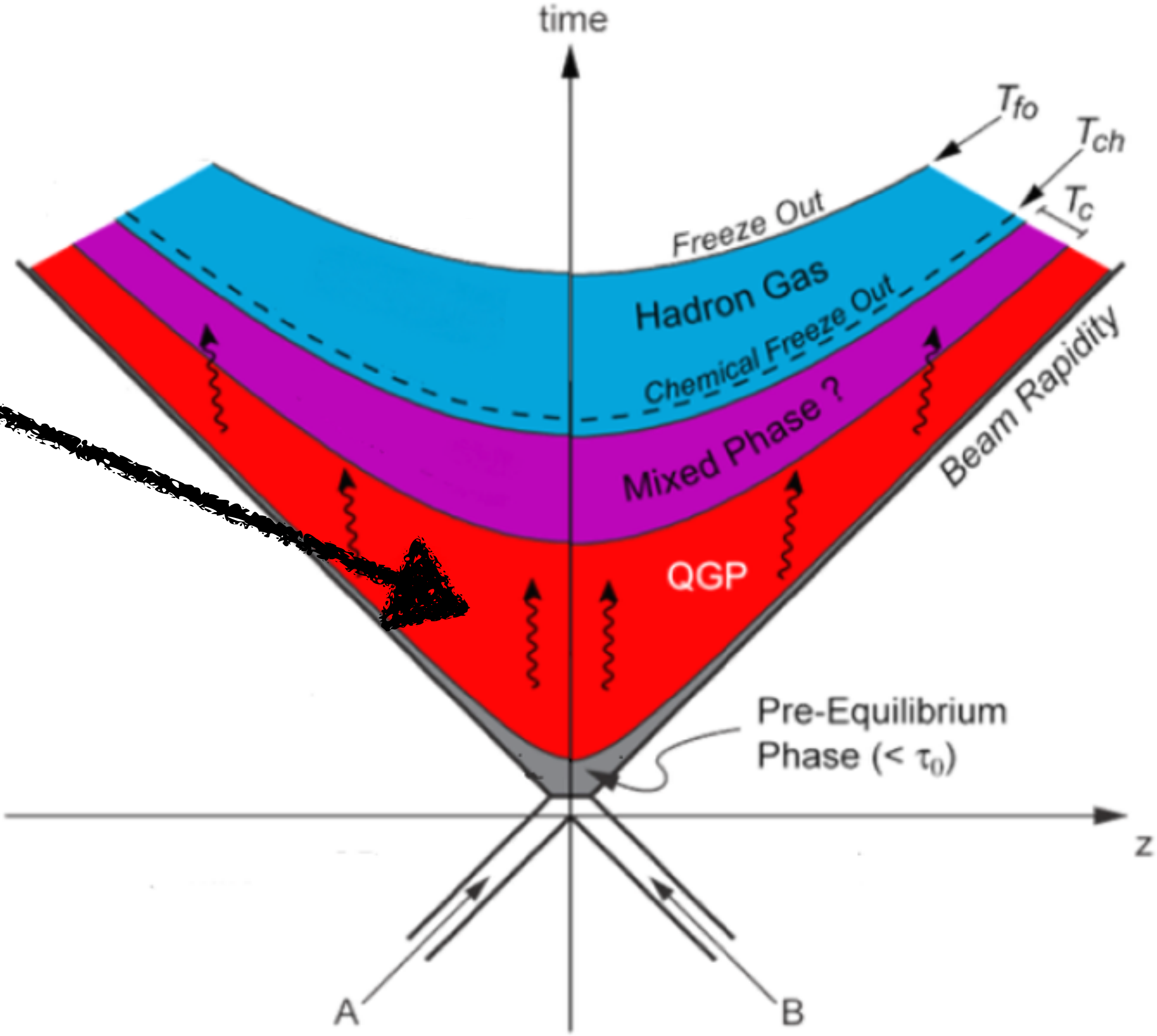
spectral shapes are **very similar if particles have similar mass**
p/ϕ ratio is constant

the data seems to indicate that **mass is the main parameter driving particle spectra**
(as foreseen by hydro)

Collective phenomena

bulk matter created in high-energy heavy-ion collisions **can be described in terms of hydrodynamics**

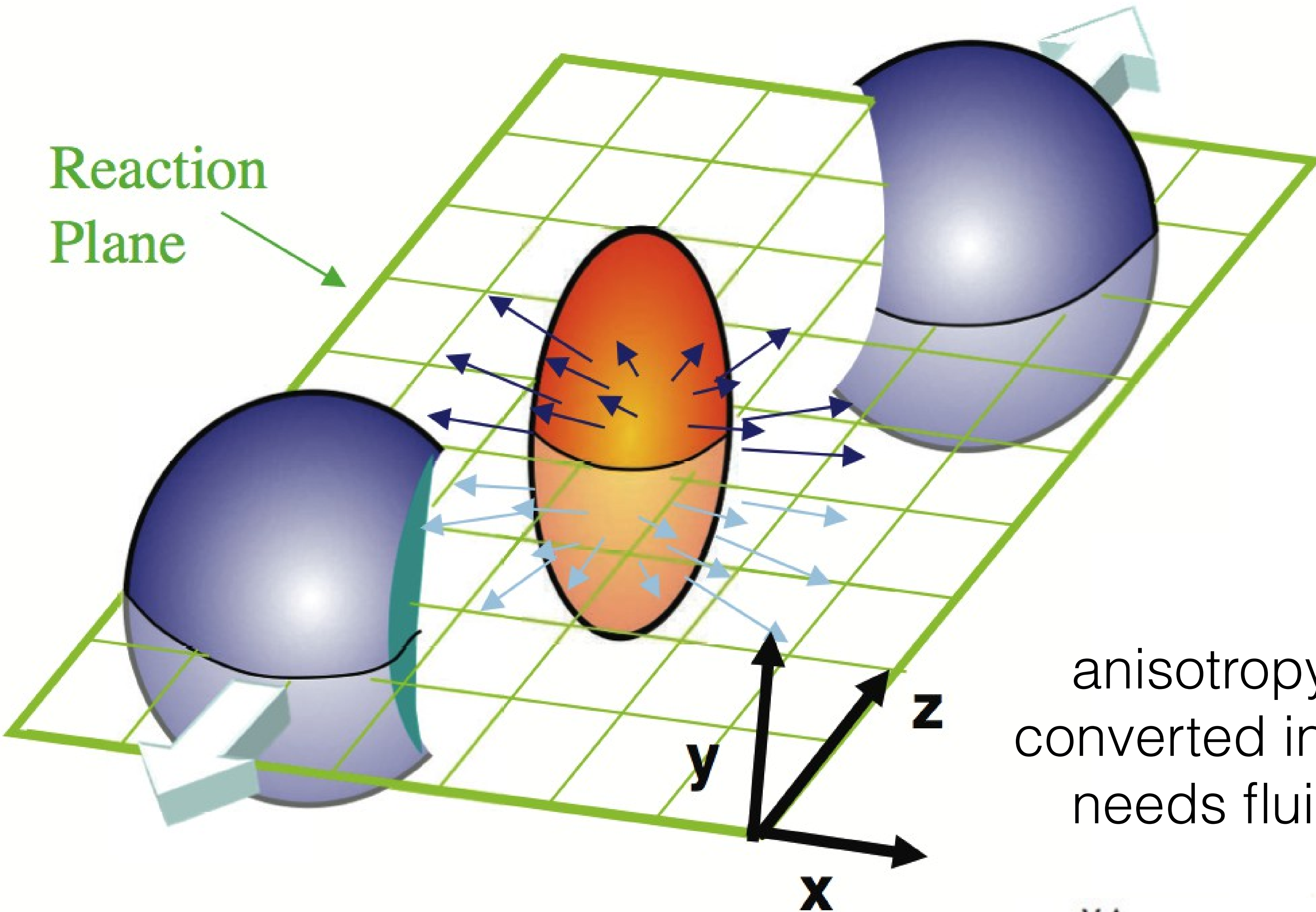
- initial hot and dense partonic matter rapidly expands
- collective flow develops and the system cools down
- phase transition to hadron gas when $T_{critical}$ is reached



resulting in

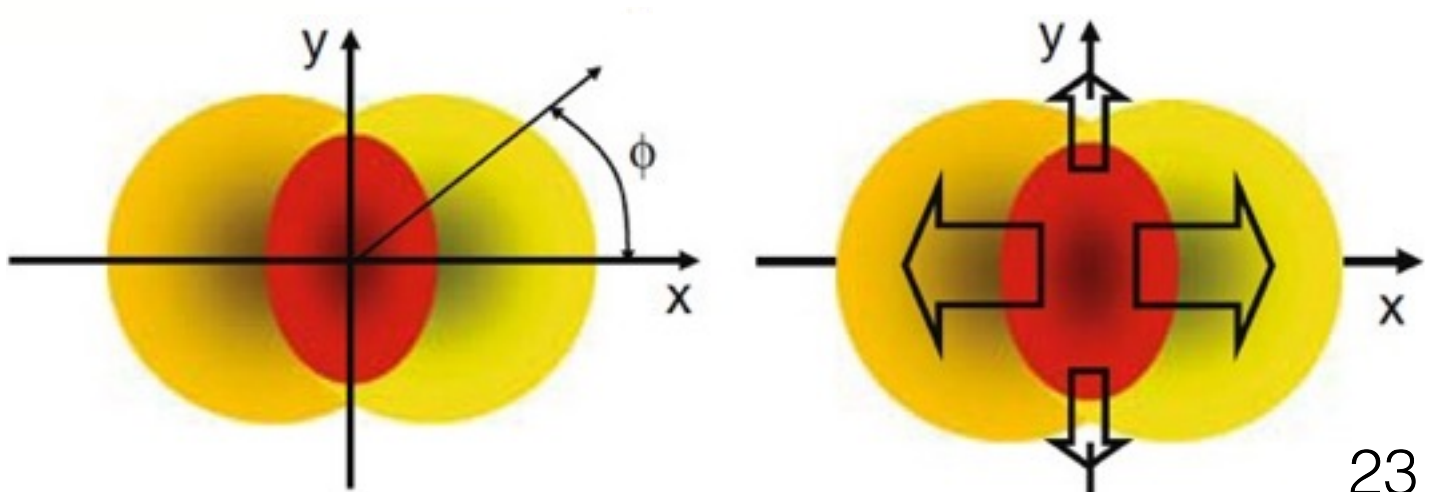
- dependence of the shape of the p_T distribution on the particle mass
- **azimuthal anisotropic flow patterns (initial spatial anisotropy)**

Anisotropic flow

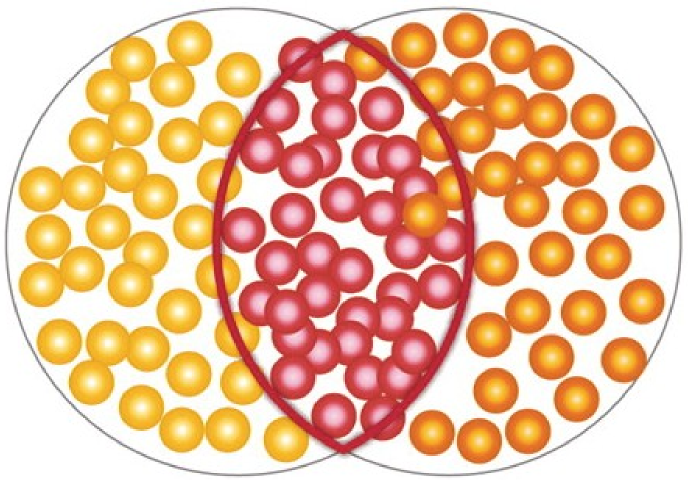


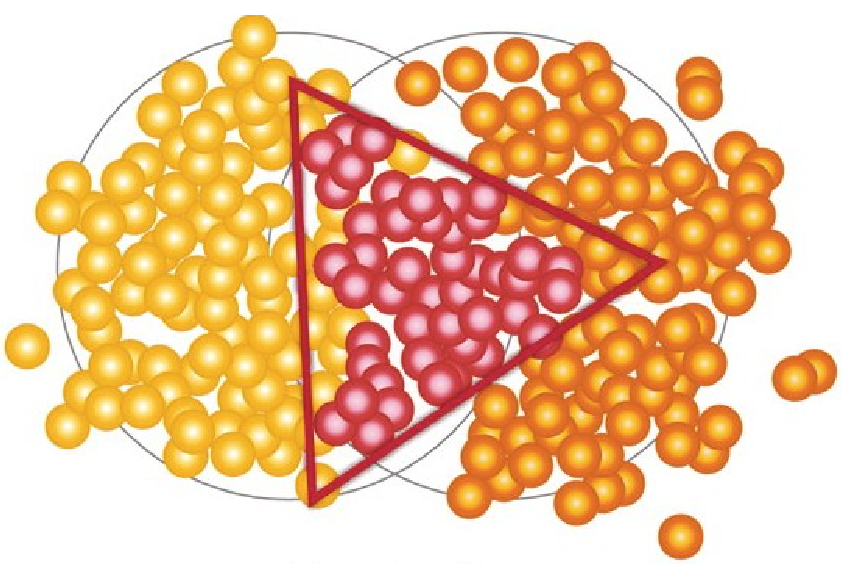
anisotropy in **spatial** space
converted in **momentum** space
needs fluid-like **collectivity**

elliptical collision **geometry**
anisotropic pressure gradients



Anisotropic flow





anisotropic momentum distributions

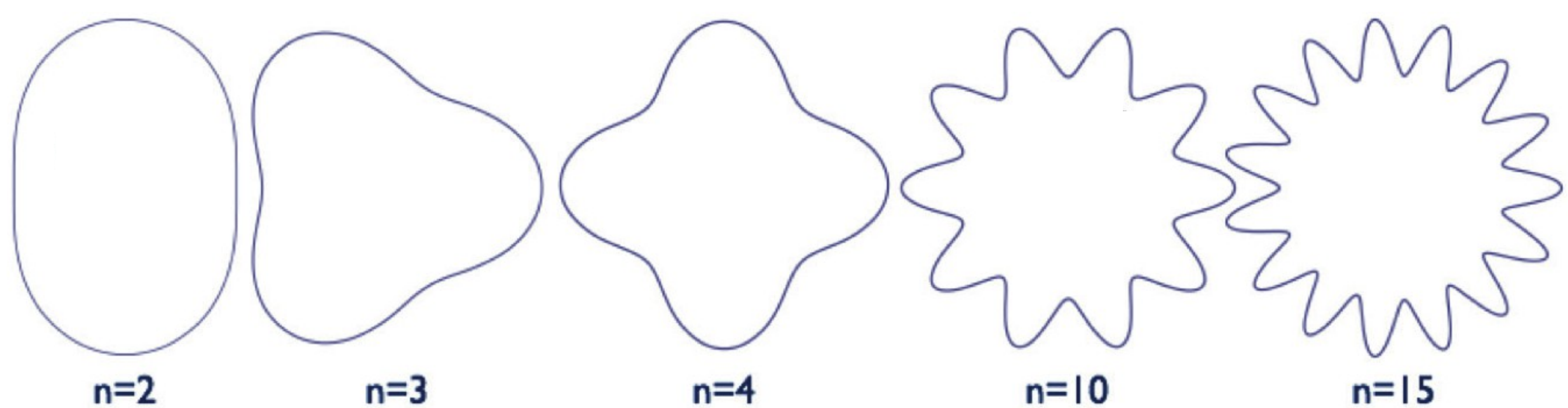
dependence can be decomposed in

Fourier series

$$\frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_t dp_t dy} \left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_R)]\right)$$

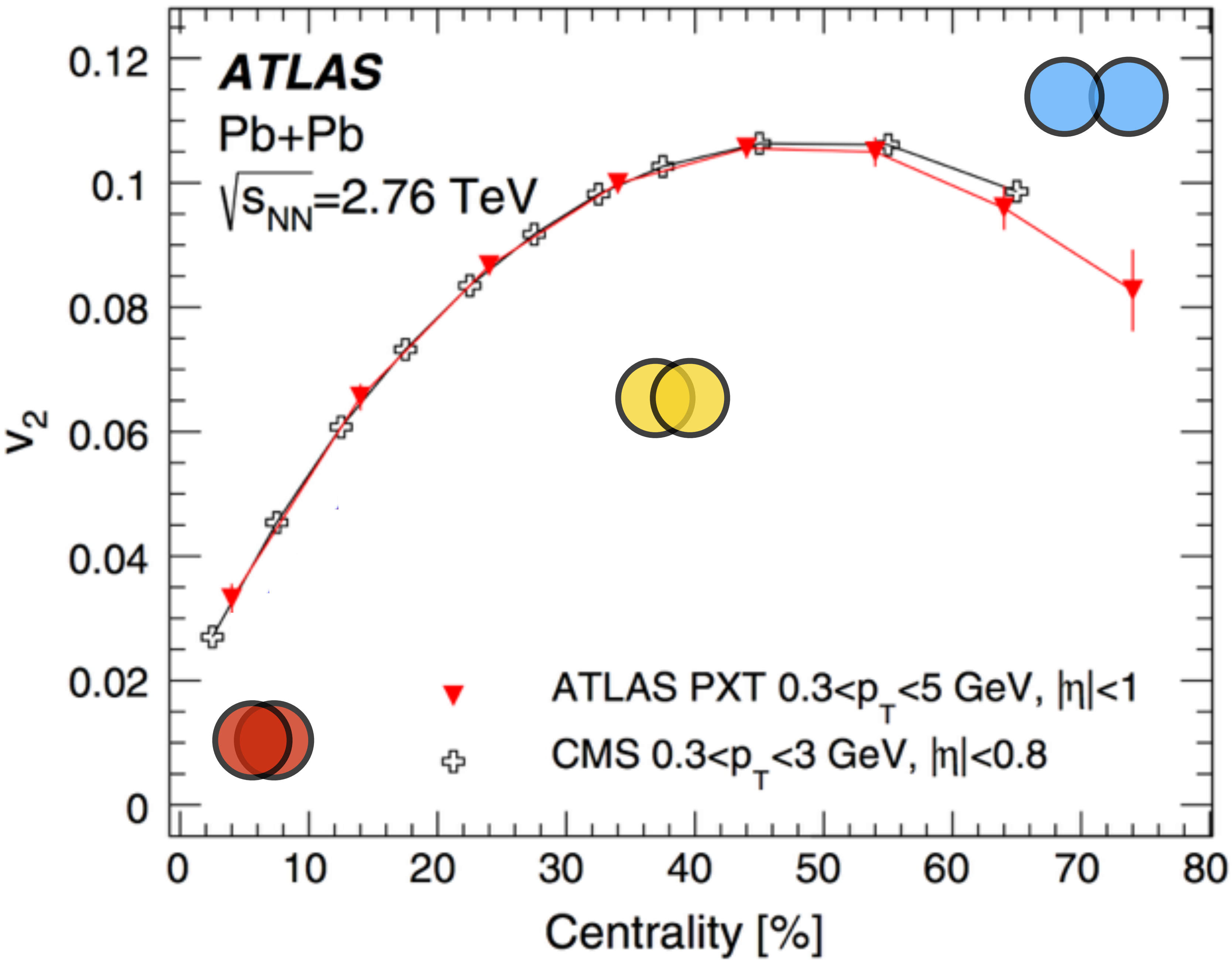
magnitude characterised by

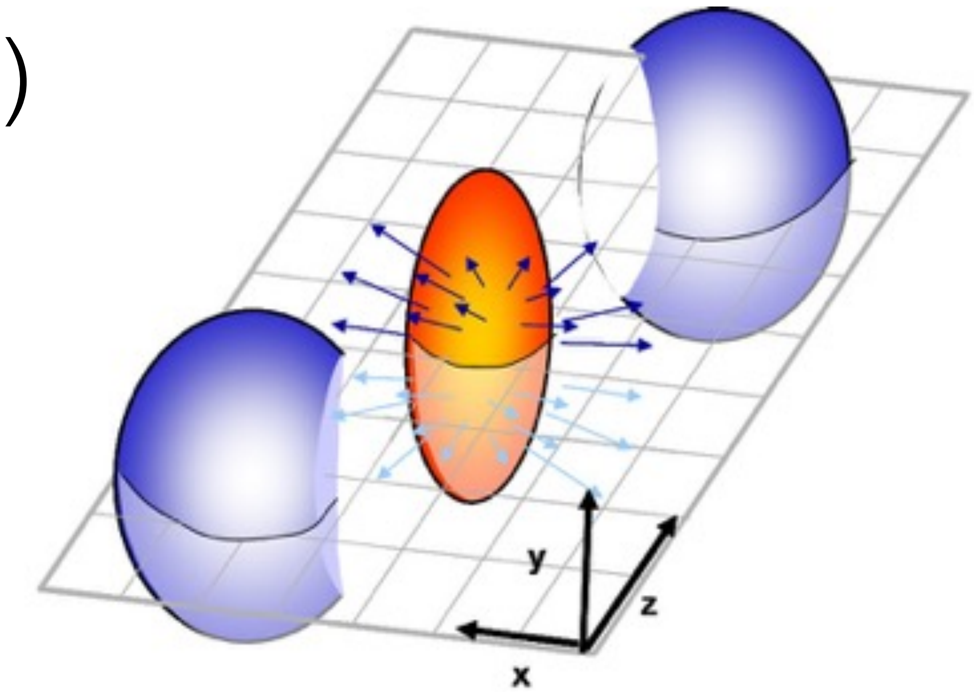
v_n coefficients



Collective anisotropic flow

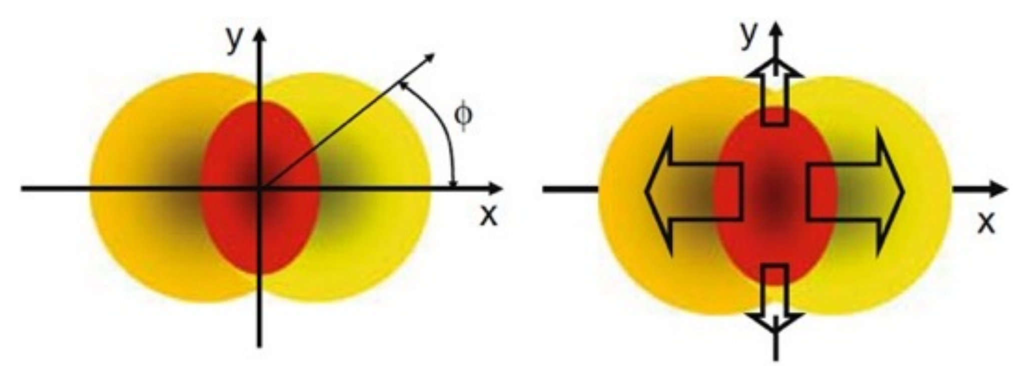
spatial anisotropy (collisions geometry)
⟶ anisotropy in momentum space: v_2





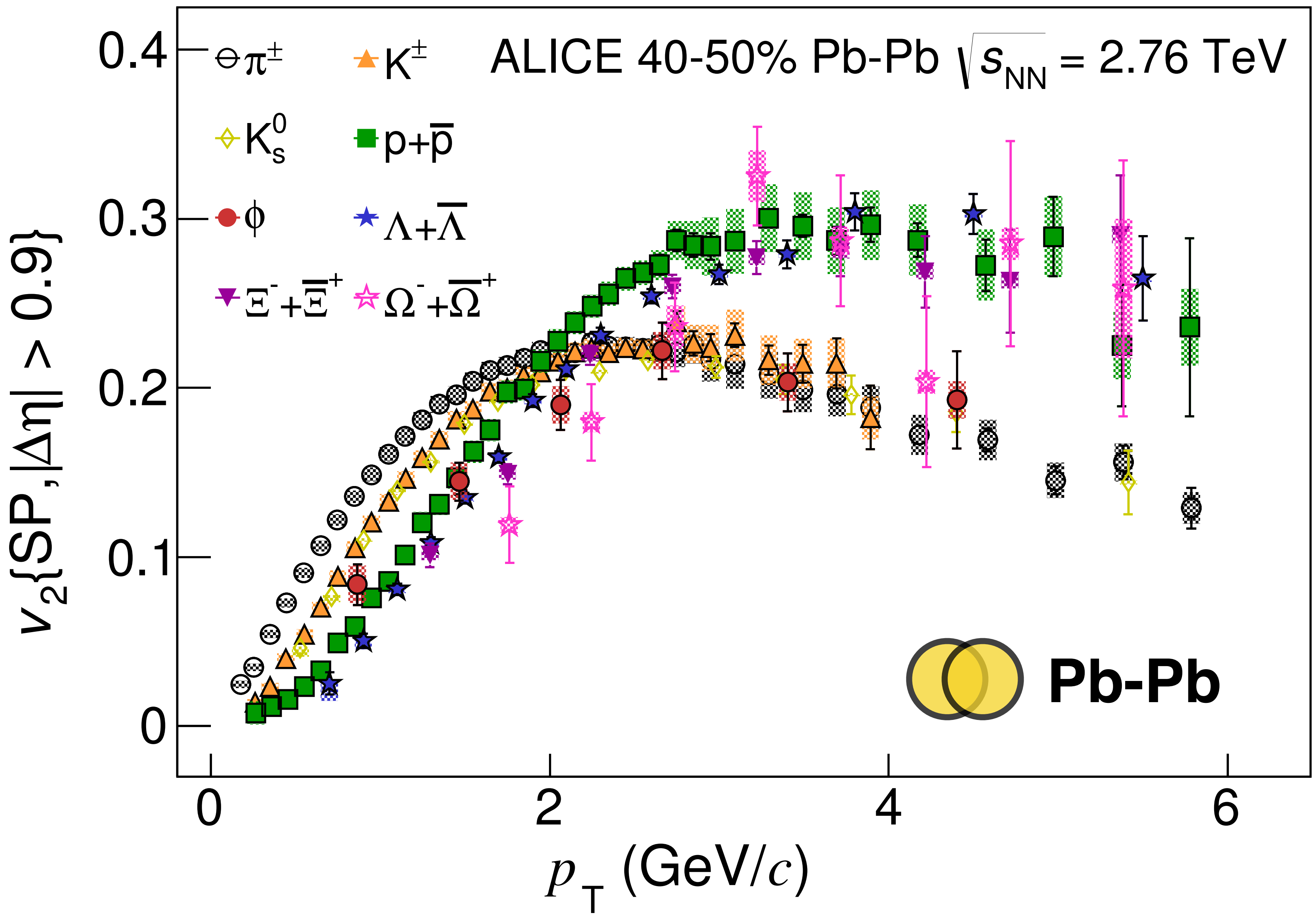
strong collective flow persists at the LHC

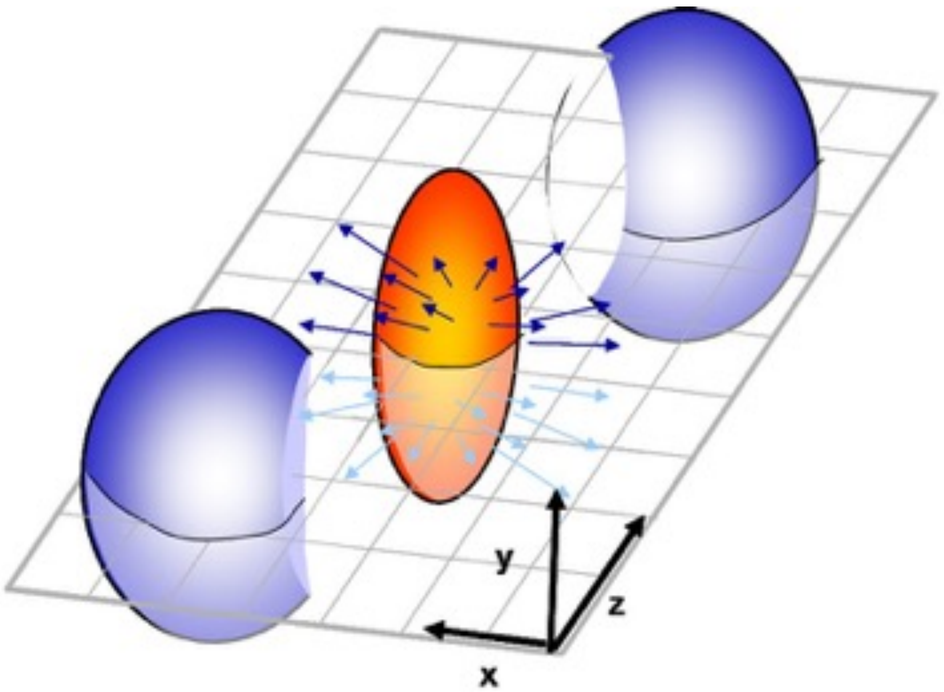
flow is driven by **initial-state geometry**



Collective anisotropic flow

spatial anisotropy (collisions geometry)
⟶ anisotropy in momentum space: ***v_2***





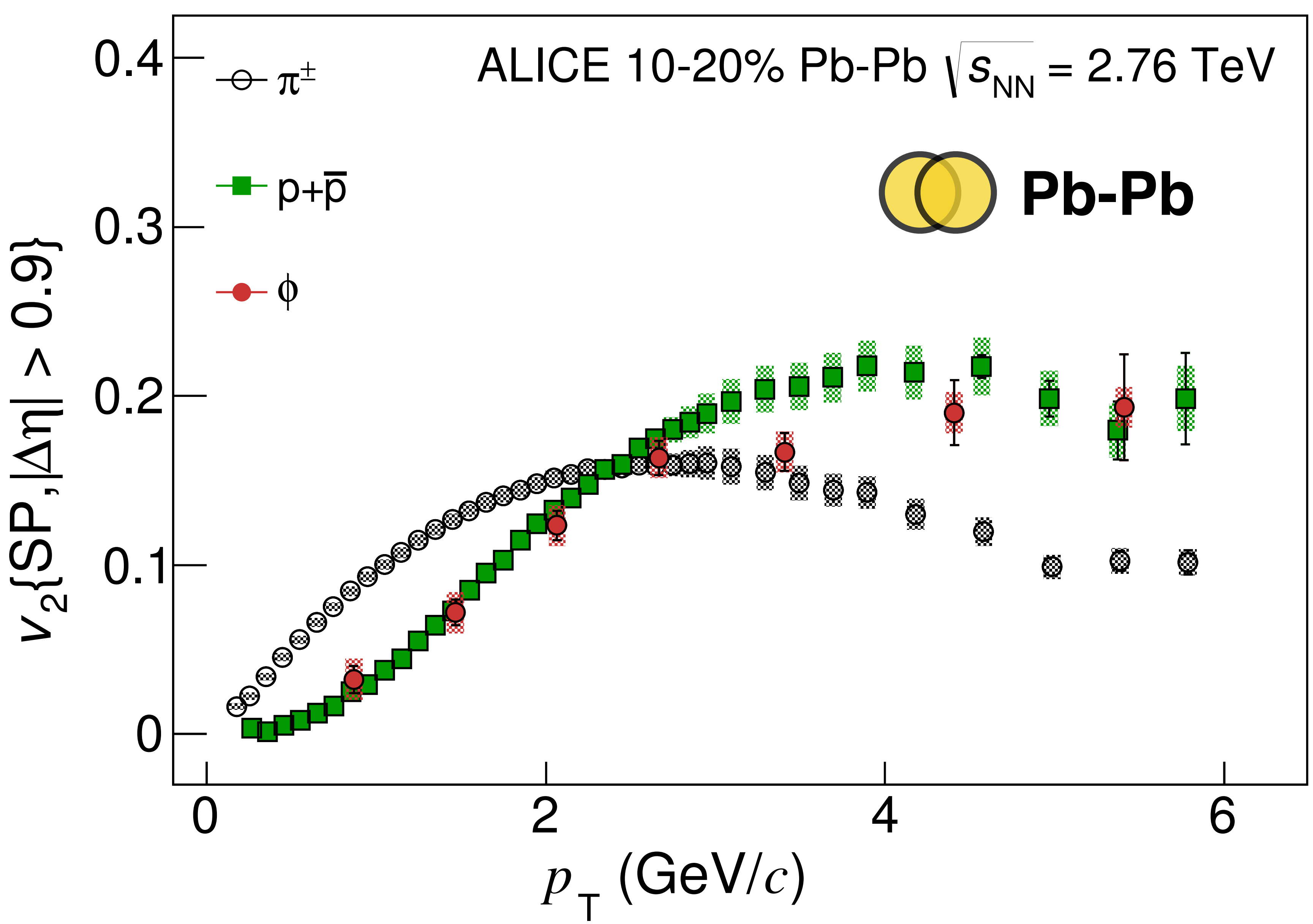
v_2 measured for
$\pi^{\pm}$, $K^{\pm}$, K^0_S, p, ϕ, Λ, Ξ, Ω

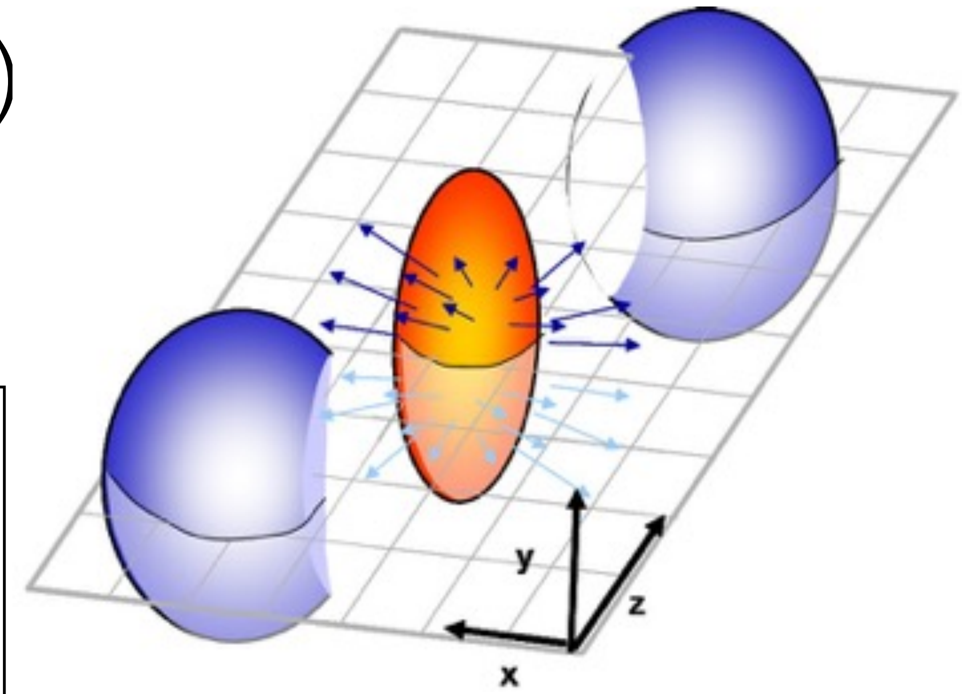
mass ordering
attributed to common radial expansion velocity

ALICE, JHEP 06 (2015) 190

Collective anisotropic flow

spatial anisotropy (collisions geometry)
⟶ anisotropy in momentum space: v_2





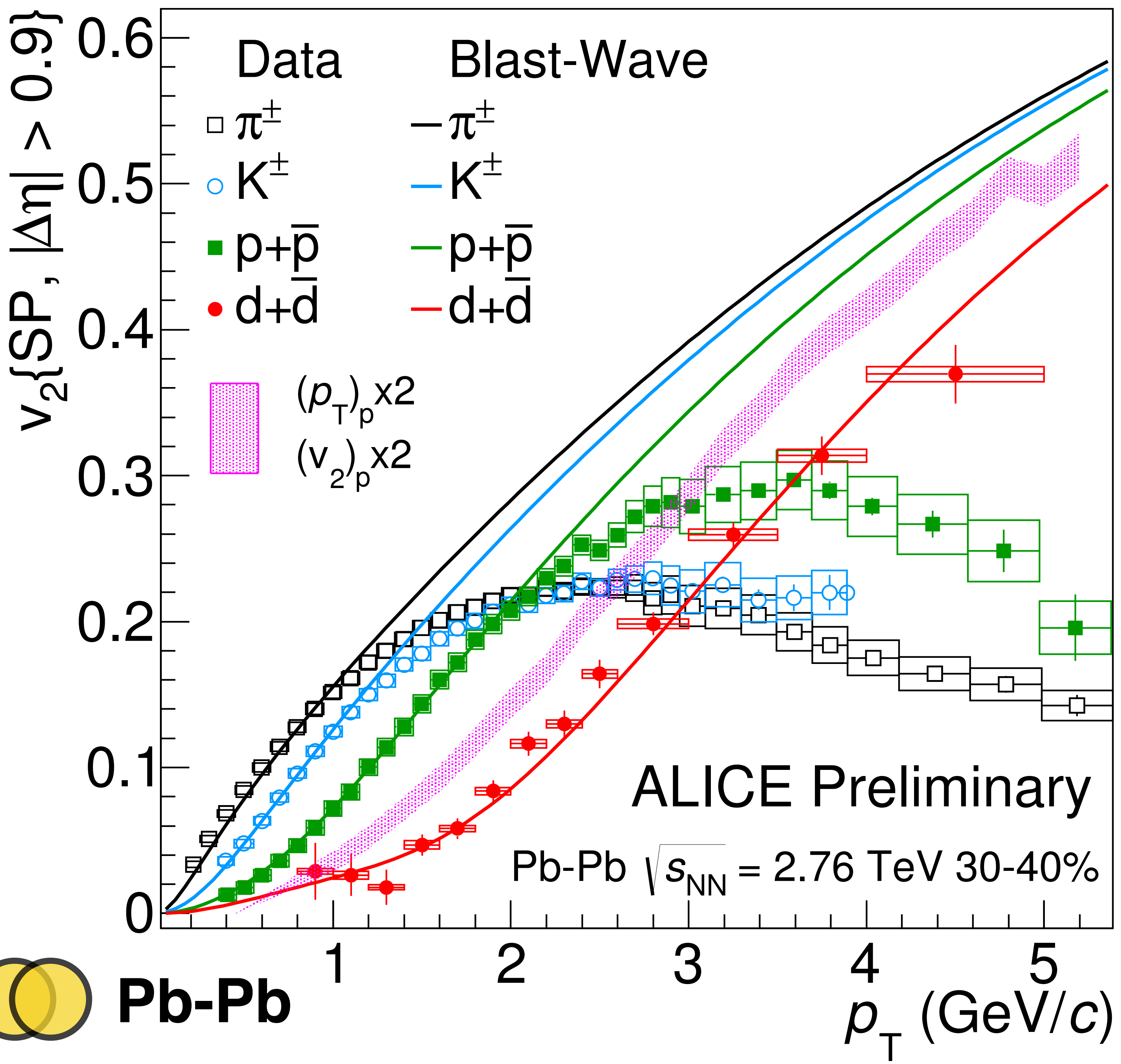
ϕ meson behaves like a proton

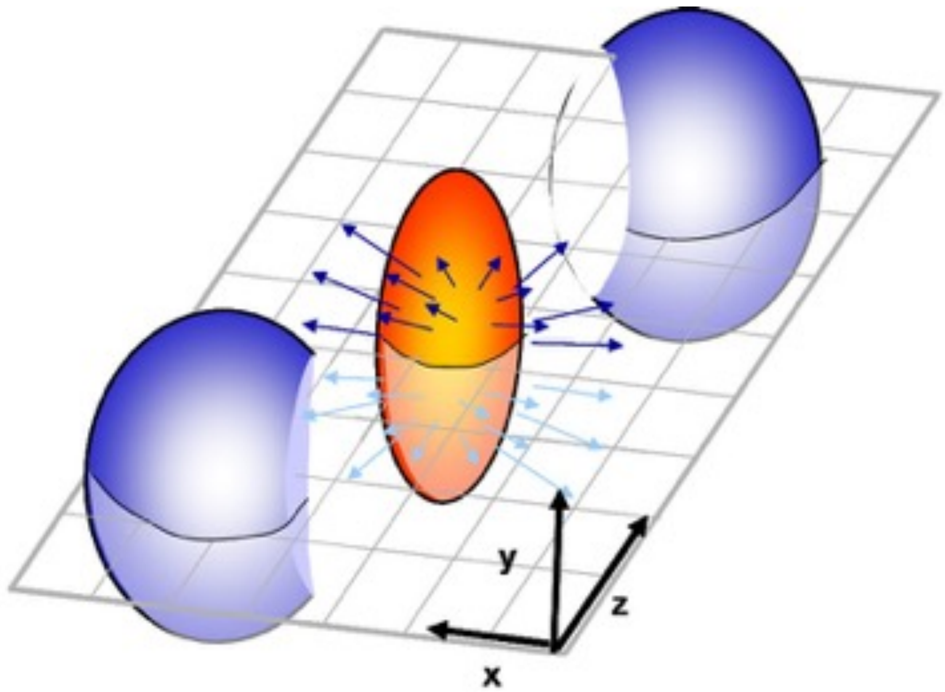
mass drives v_2 and spectra, not number of constituent quarks

ALICE, JHEP 06 (2015) 190

Collective anisotropic flow

spatial anisotropy (collisions geometry)
⟶ anisotropy in momentum space: v_2





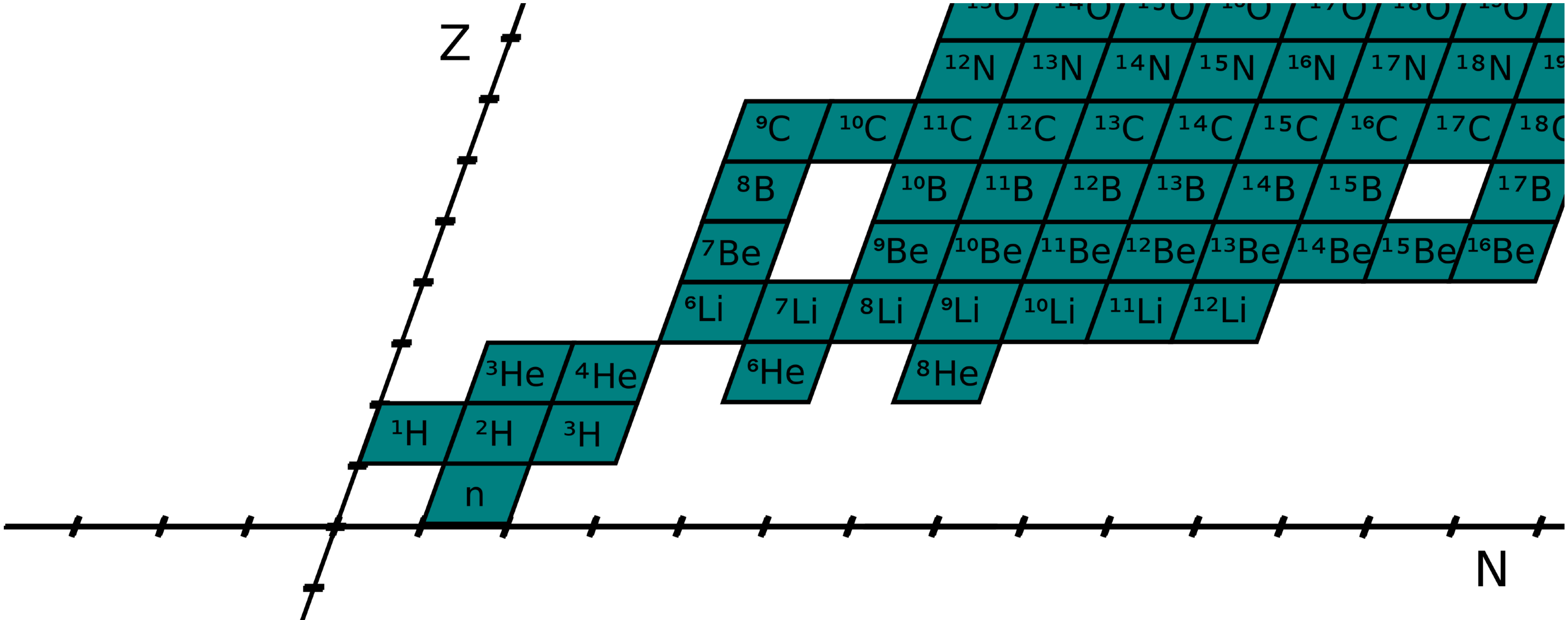
deuterons follow Blast-Wave prediction

hydrodynamics at work
simple coalescence scaling does not work for nuclei

Pb-Pb

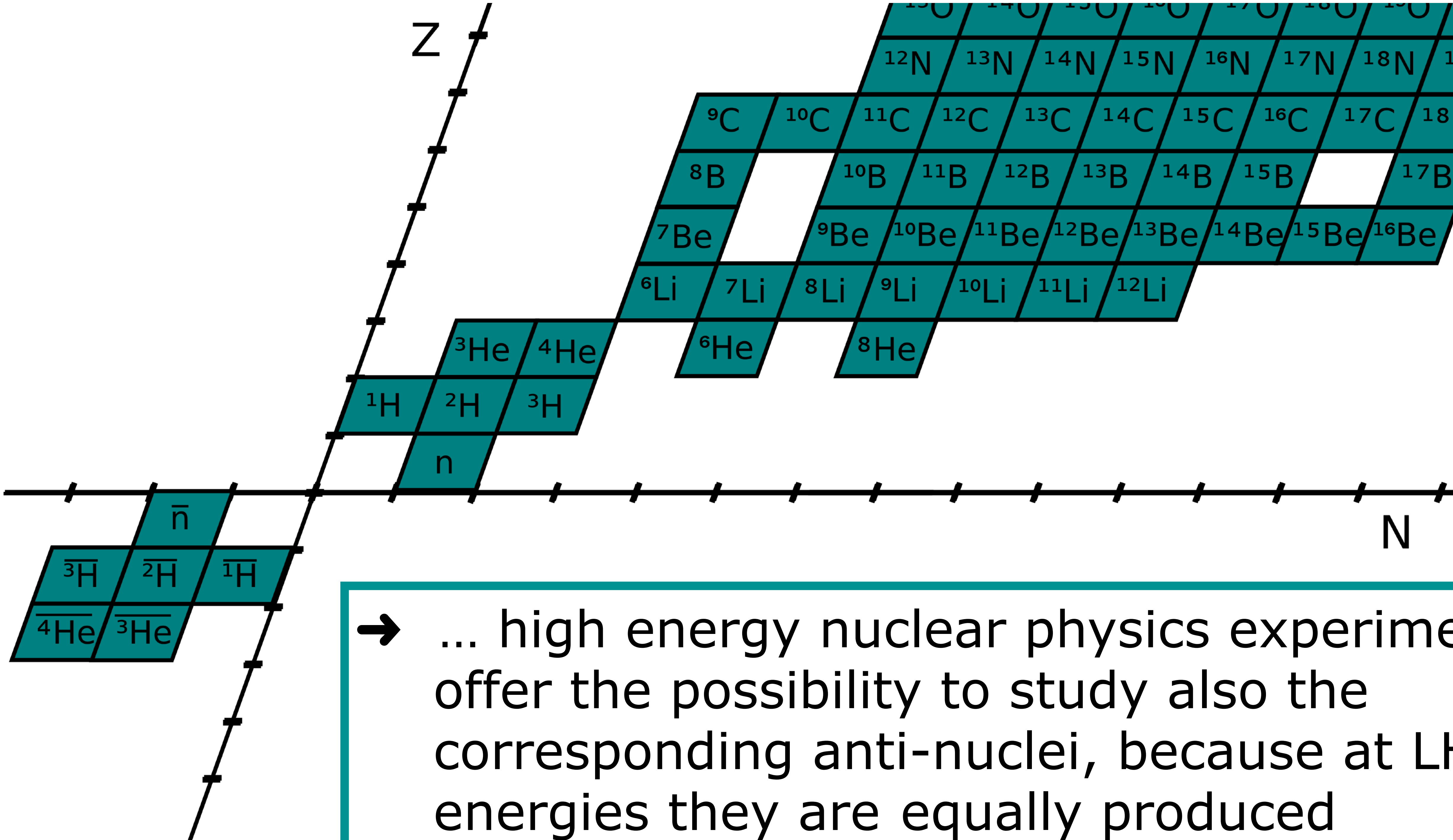
ALICE, JHEP 06 (2015) 190

Table of nuclides



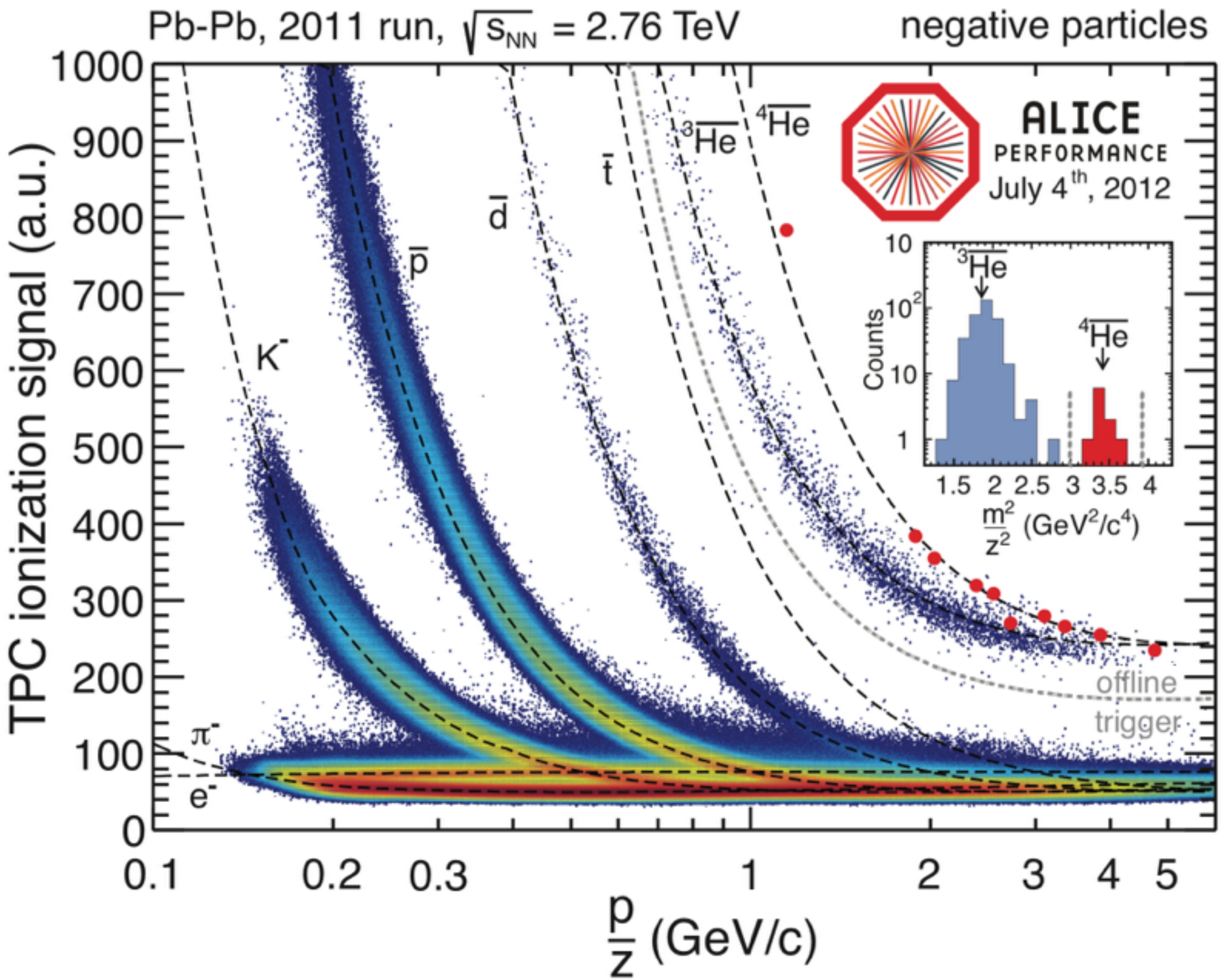
➜ Compared to light particles like π, K and p light nuclei like d, ^{3}He and ^{4}He are rarely produced in heavy-ion collisions, but …

Table of nuclides



➜ … high energy nuclear physics experiments offer the possibility to study also the corresponding anti-nuclei, because at LHC energies they are equally produced

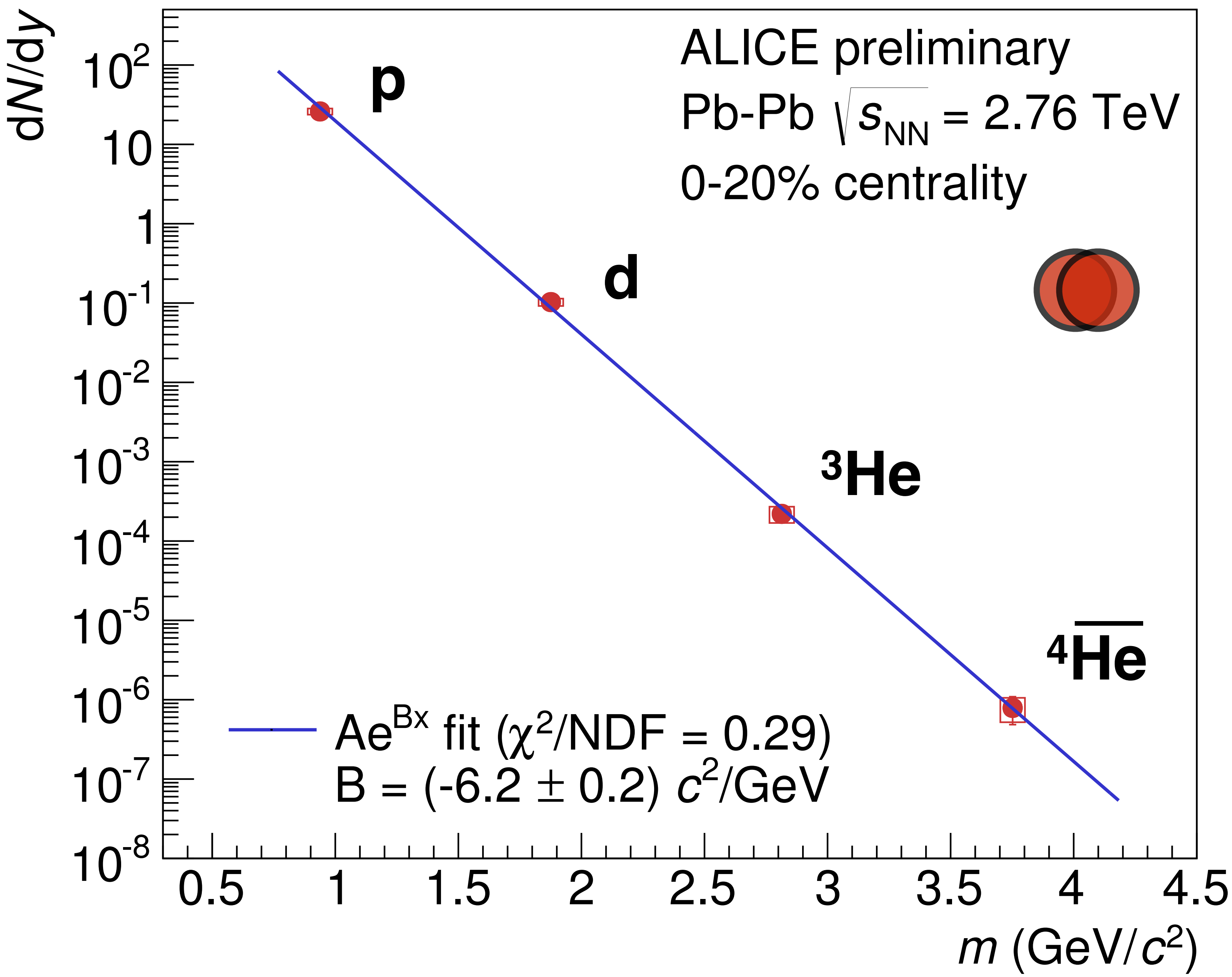
Light (anti)nuclei production



Anti-alpha production

First observed at RHIC in heavy-ion collisions

STAR, Nature 473 (2011) 353



ALICE measures dN/dy in defined centrality interval to compare to other light nuclei

follows the predicted exponential fall

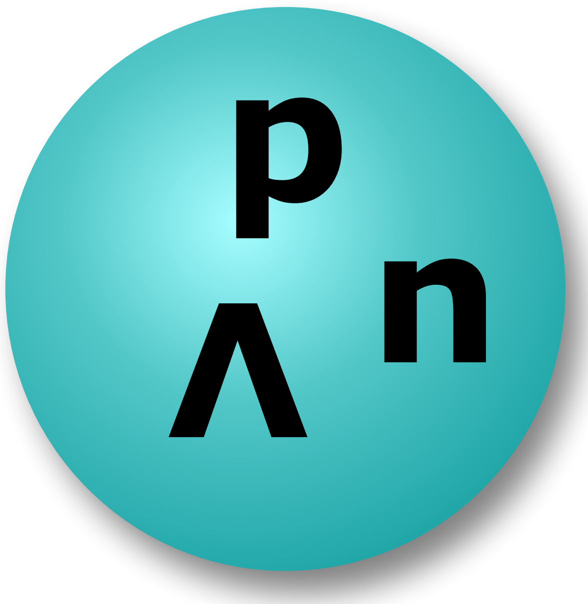
~ 300 penalty factor for each added baryon

Hyper-nuclei

Hyperons: Baryons, which have at least one s-quark as one of their 3 valence-quarks for example Λ, Σ, Ξ, or Ω

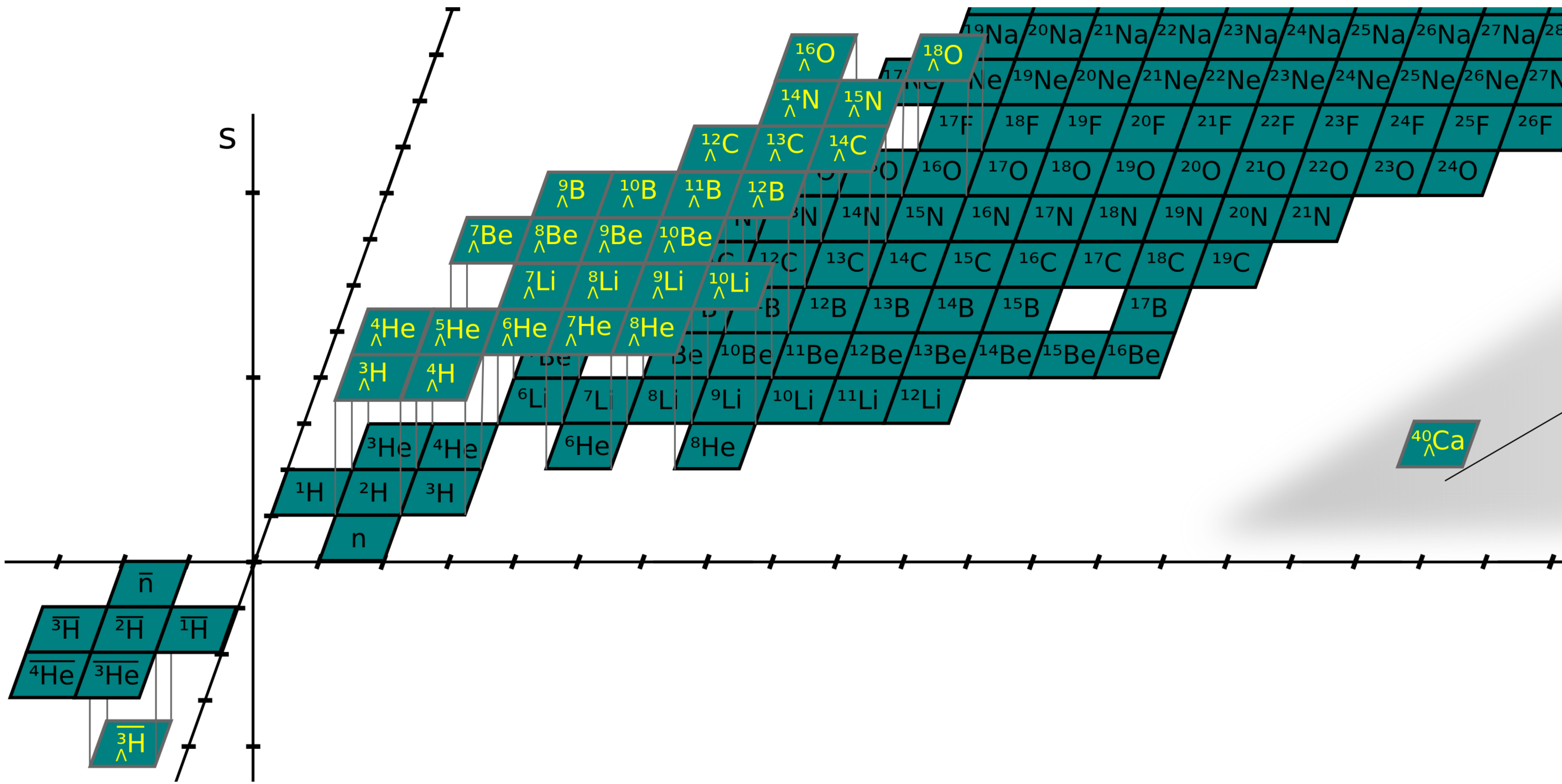
Hypernuclei: nuclei, in which at least one neutron is replaced by a hyperon

Hypertriton



➜ All hypernuclei are unstable

Table of nuclides

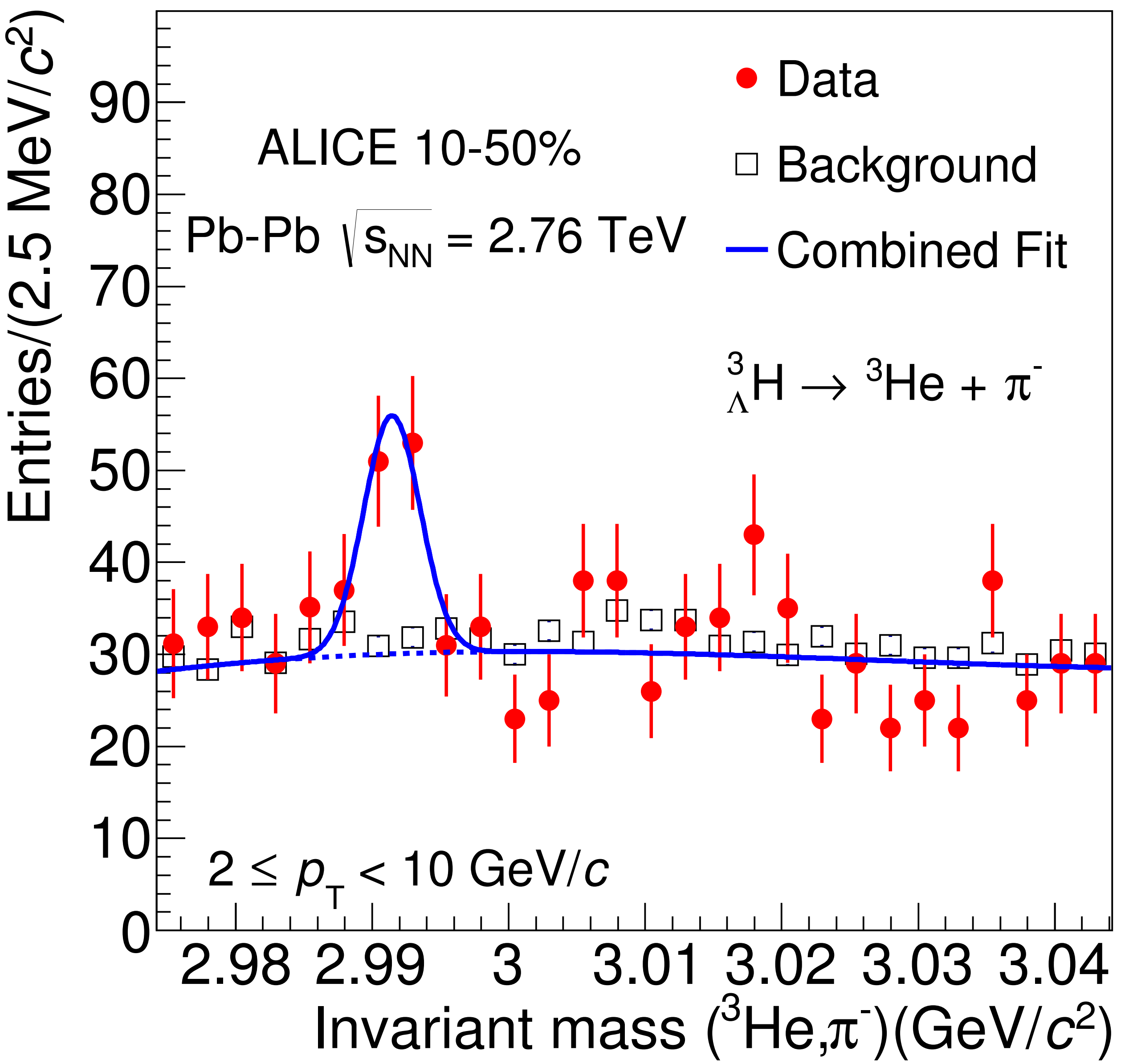


➜ table of nuclei can be extend to include also hypernuclei

Hypertriton production and lifetime

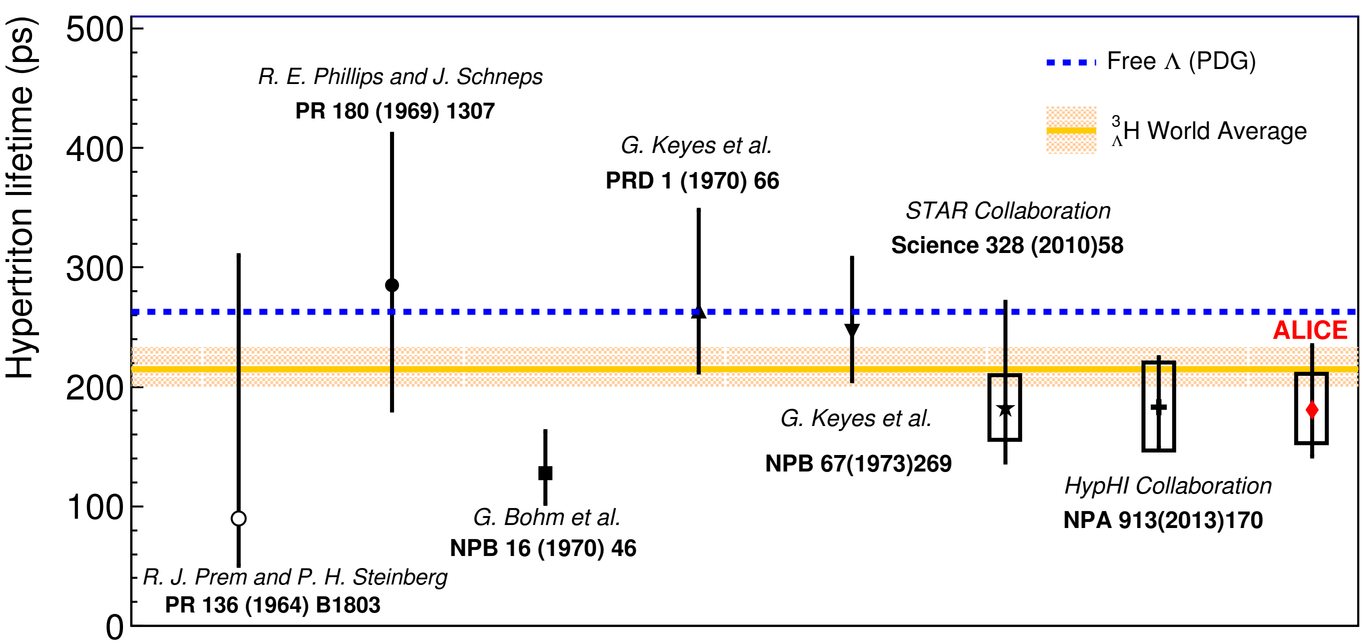
the lightest known hypernucleus

measured in weak-decay: **$^3{}_\Lambda He \rightarrow {}^3He\ \pi$**



topological identification of secondary vertex + ^{3}He and π PID

production **in agreement with thermal model** T_{ch} = 156 MeV



good determination of decay vertex

measurement of lifetime

Strangeness enhancement

one of the first proposed QGP signatures

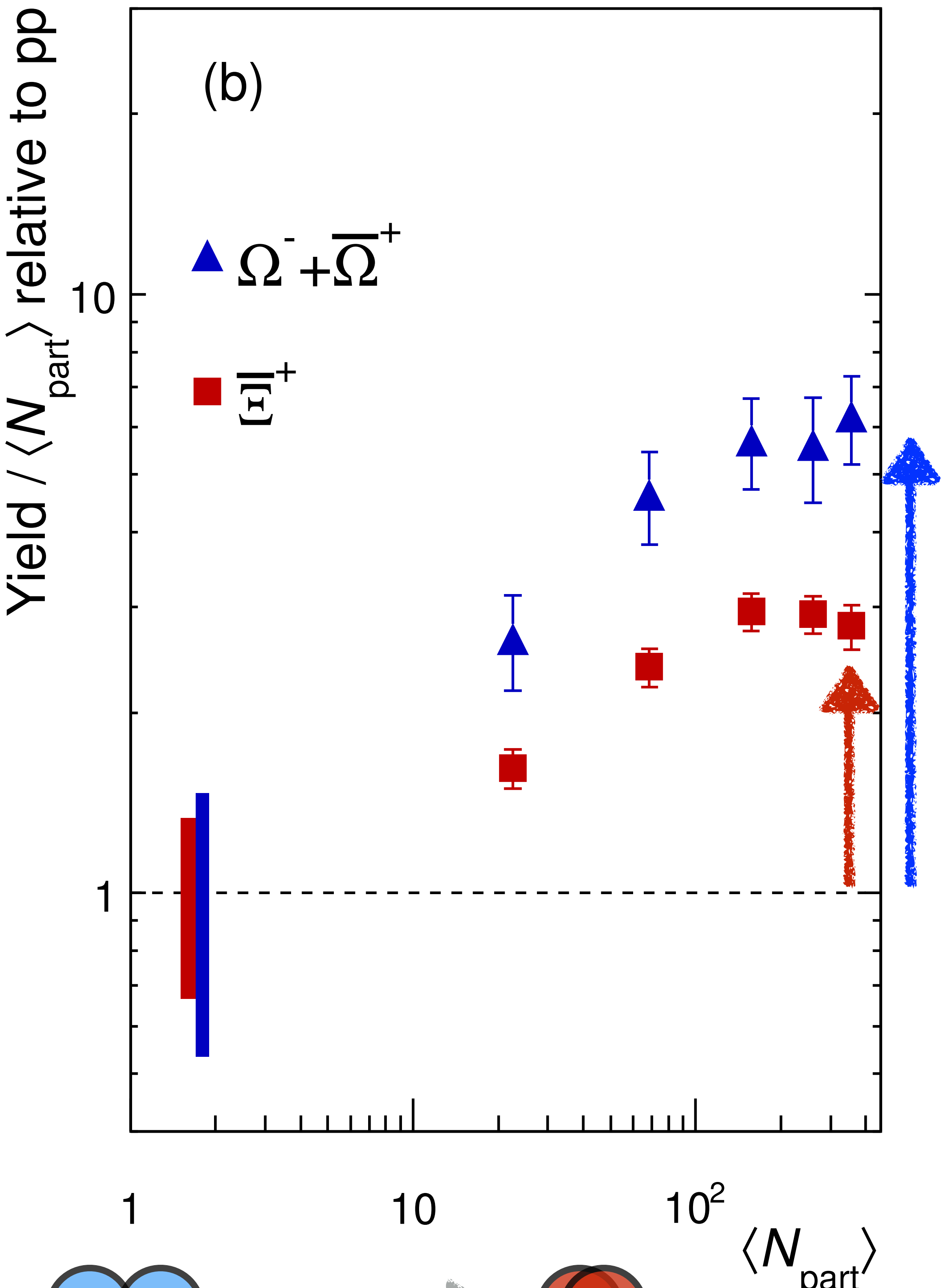
VOLUME 48, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1982

Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller
Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt am Main, Germany
(Received 11 January 1982)

We thus conclude that strangeness abundance saturates in sufficiently excited quark-gluon plasma ($T > 160$ MeV, $E > 1$ GeV/fm^3), allowing us to utilize enhanced abundances of rare, strange hadrons ($\bar{\Lambda}$, $\bar{\Omega}$, etc.) as indicators for the formation of the plasma state in nuclear collisions.

Strangeness production in Pb-Pb



strangeness enhancement

one of the first proposed QGP signatures

Rafelski, PRL 48 (1982) 1066

$$E = \frac{2}{\langle N_{part}^{PbPb} \rangle} \frac{(dN/dy)^{PbPb}}{(dN/dy)^{pp}}$$

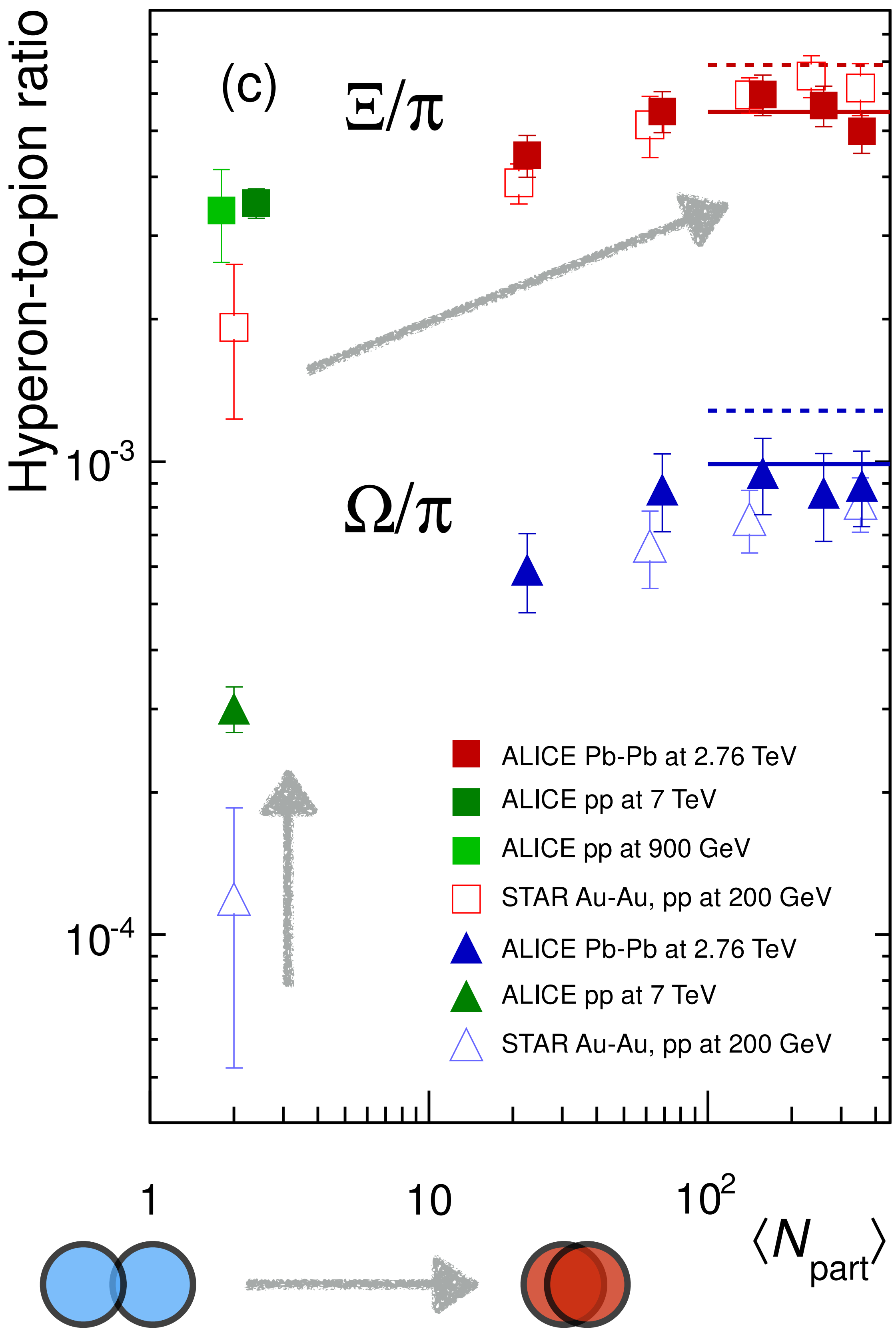
strangeness-content hierarchy

Ξ (dss) enhanced

Ω (sss) more enhanced

ALICE, PLB 728 (2014) 216

Strangeness production in Pb-Pb



strangeness enhancement

one of the first proposed QGP signatures

Rafelski, PRL 48 (1982) 1066

relative production of strangeness in pp collisions is larger at LHC

clear increase of strangeness production from pp to Pb-Pb

saturation of ratios for $N_{part} > 150$

match predictions from Grand Canonical thermal models

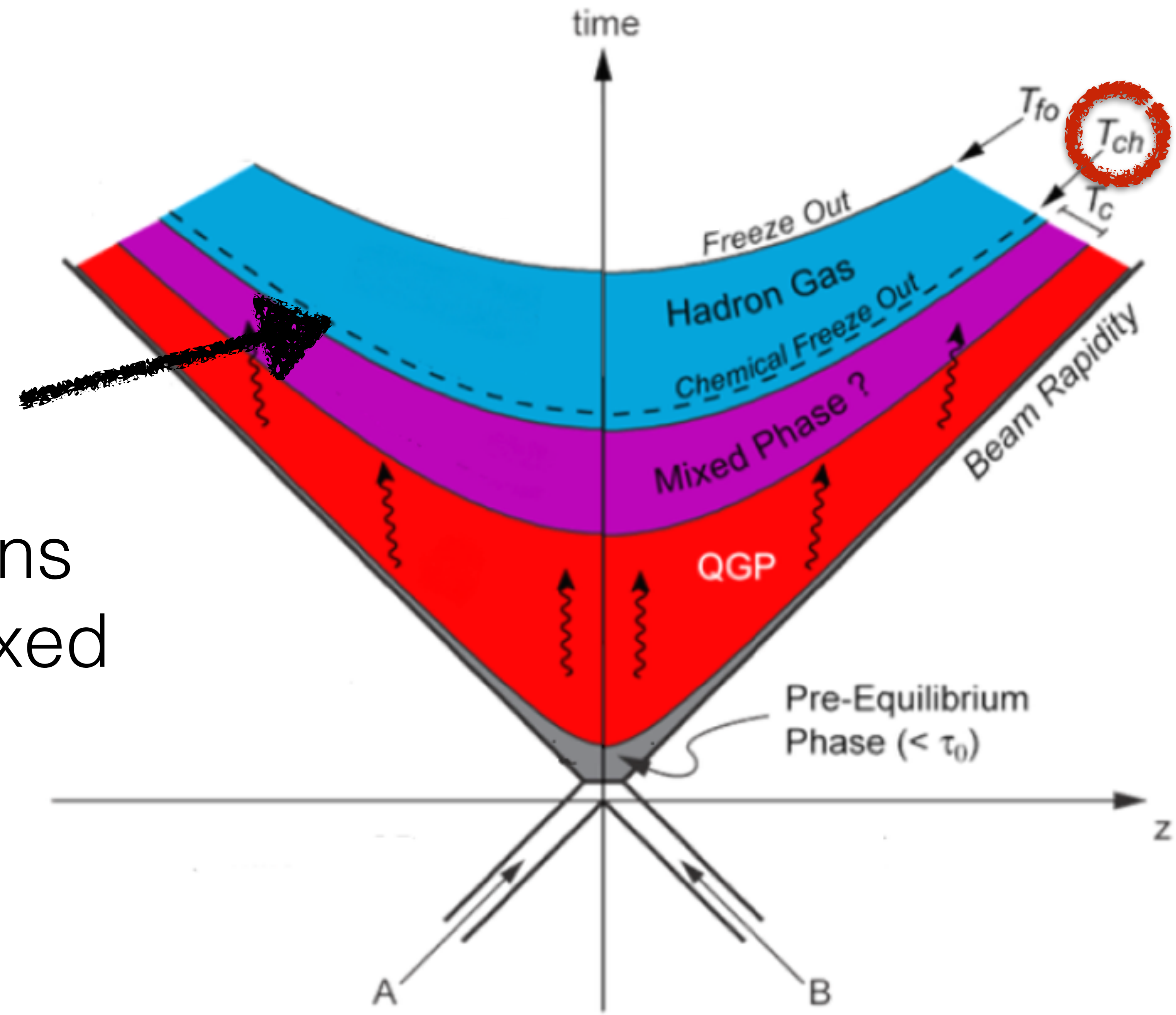
GSI-Heidelberg: T_{ch} = 164 MeV

THERMUS: T_{ch} = 170 MeV

ALICE, PLB 728 (2014) 216

Thermal model of hadron production

Chemical equilibrium achieved during or very shortly after phase transition



chemical freeze-out
end of inelastic interactions
chemical composition is fixed

results of an analysis of the measured abundances allow one to get the **thermodynamic variables (T, μ)** at freeze-out

Thermal model of hadron production

Chemical equilibrium achieved during or very shortly after phase transition abundance described by Bose-Einstein or Fermi-Dirac distributions of an ideal relativistic quantum gas

$$n_j = \frac{g_j}{2\pi^2}\int_0^\infty p^2 dp (\exp\{[E_j(p) - \mu_j]/T\} \pm 1)^{-1}$$

$$E_j^2 = M_j^2 + \vec{p}_j^{\,2}$$

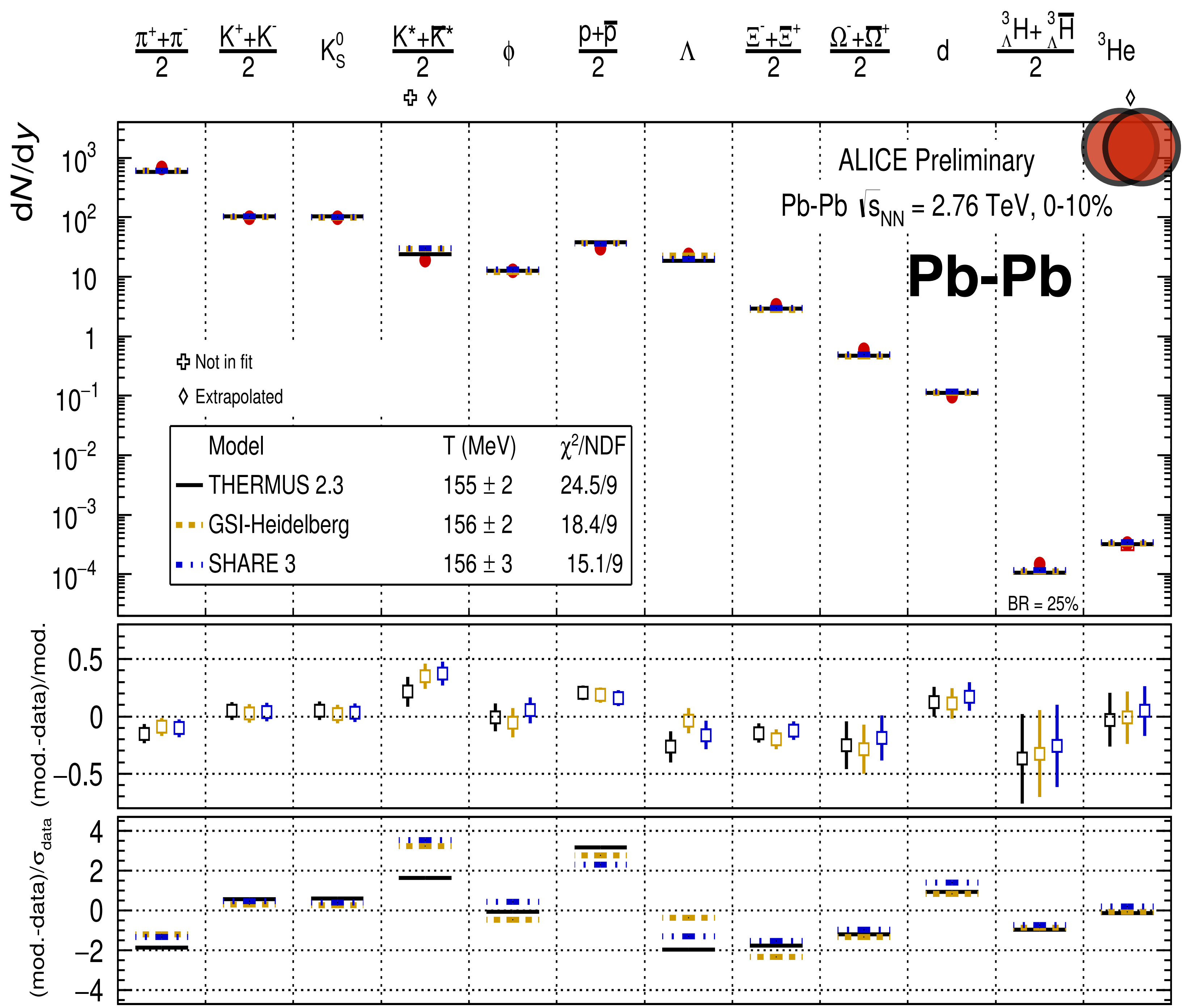
n = particle density (N / V)
M = hadron mass
T = temperature
μ = chemical potential dE/dN

results of an analysis of the measured abundances allow on to set the thermodynamic variables (T, μ) at chemical freeze-out

Thermal model of hadron production

describe hadron yields as produced in **chemical equilibrium**

Andronic et al., NPA 772 (2006) 167



d*N*/d*y* of particle species well described in Pb-Pb
χ^2/ndf ~ 2

same conclusion from different implementations
single temperature
T_{ch} ~156 MeV

deviations for K* and p
hint at final-state interactions
other mechanisms under investigation
(flavour hierarchy, non-equilibrium, …)

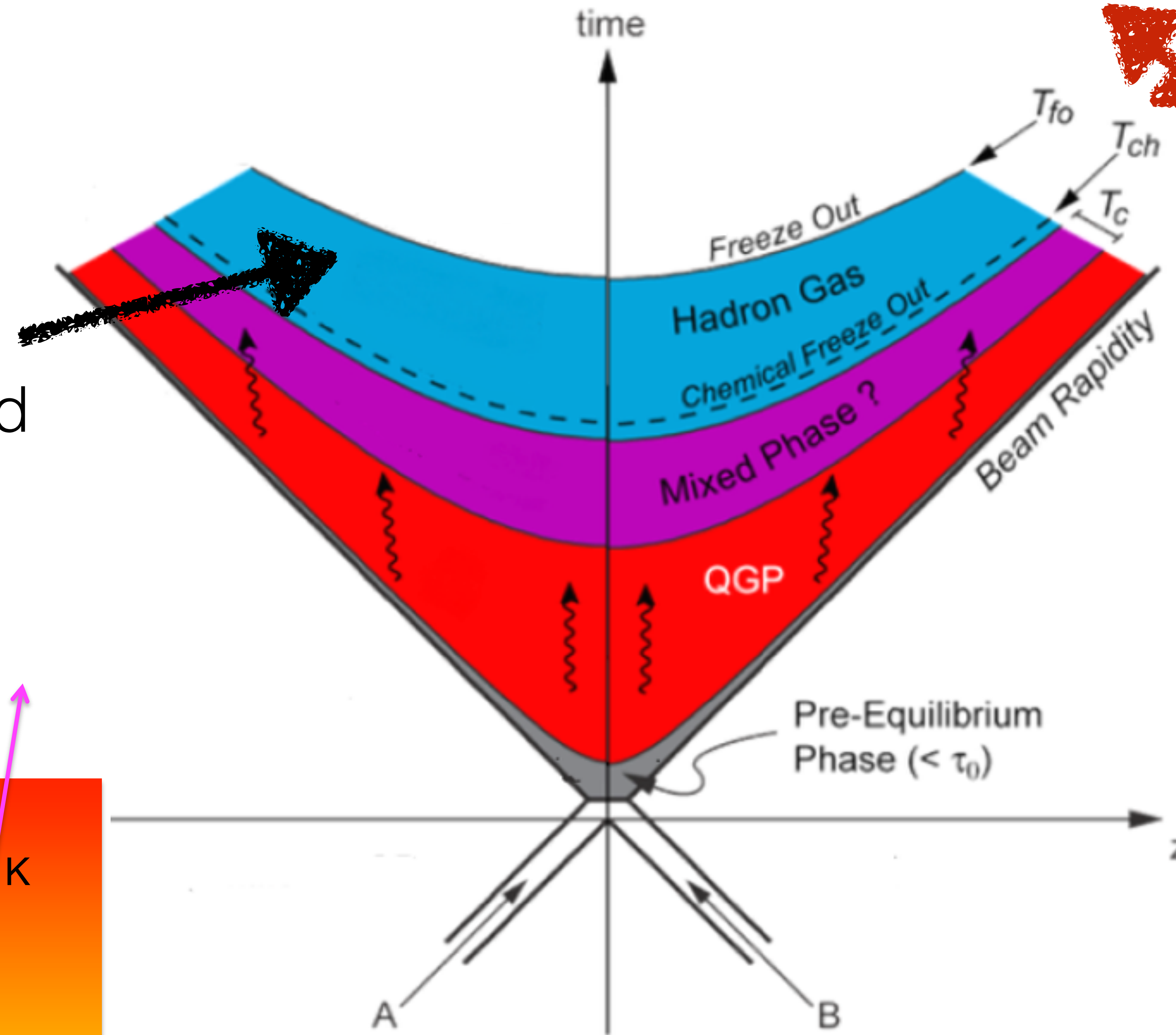
Interactions in the hadronic phase

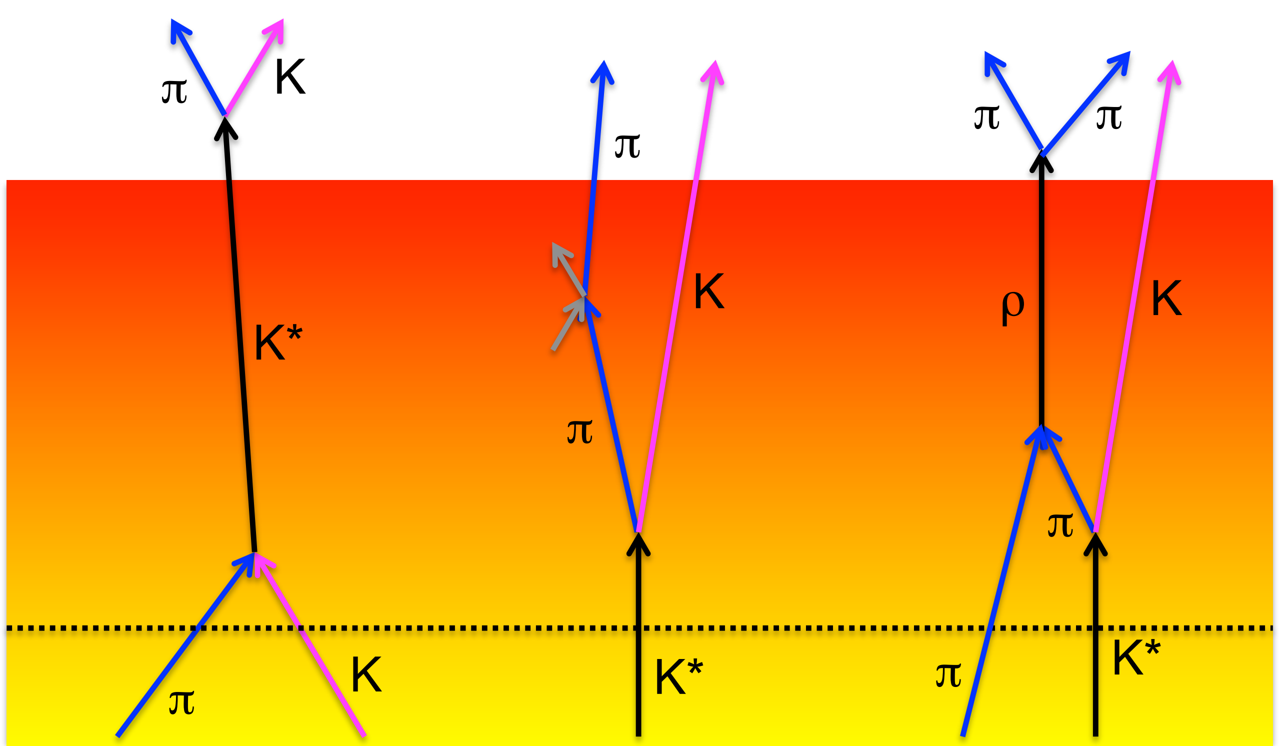
measured yields of resonances might be modified by hadronic processed

hadronic phase

elastic rescattering of decay daughters

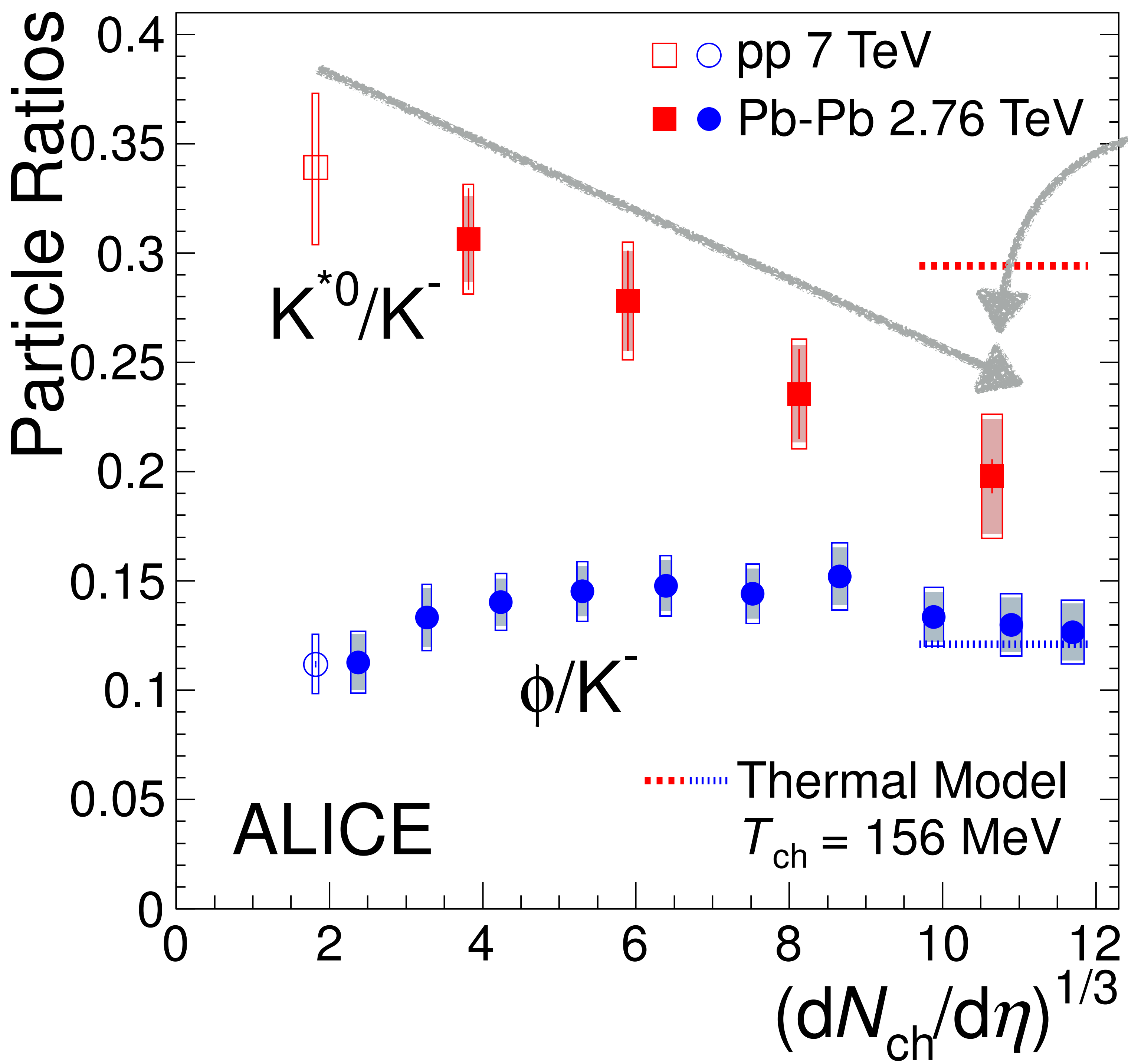
resonances not reconstructed via invariant mass





chemical freeze-out

K* suppression



K*/K shows clear suppression going from pp and peripheral Pb-Pb collisions to central Pb-Pb

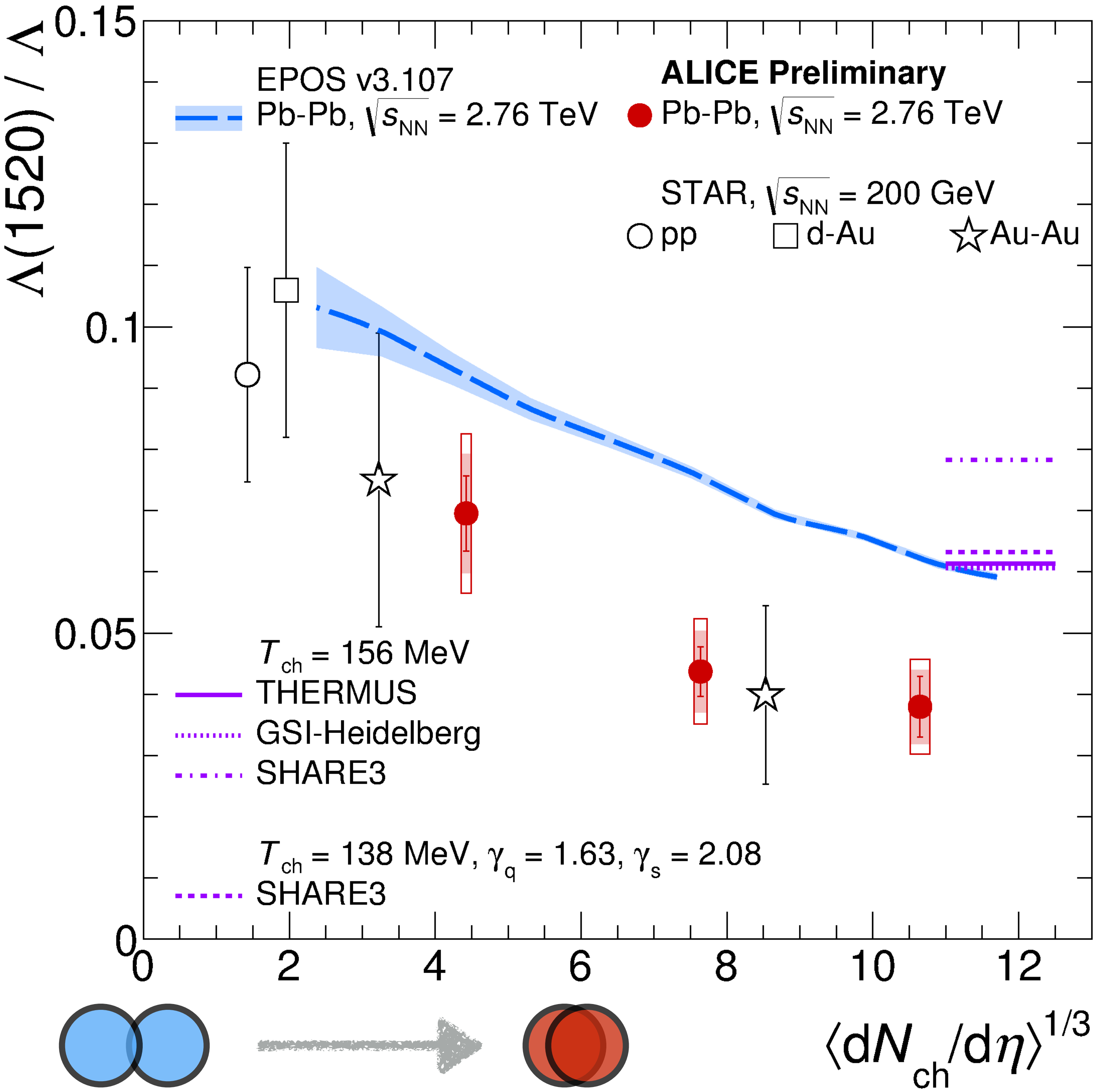
not observed in ϕ/K

most favoured explanation **re-scattering** of the decay daughters **with final-state** hadronic medium

τ_{K^*} (~4 fm/c) « τ_{ϕ}

Λ(1520) suppression

suppression of Λ(1520) in most central Pb-Pb (0-20%)
wrt. pp, peripheral Au-Au and Pb-Pb and thermal models



ALICE results

- follow STAR trend
- higher multiplicity
- better accuracy

EPOS3 with UrQMD

- overestimates the data
- reproduces the trend of the suppression

Thermal models

- all overestimate the data

further supports the existence of a long hadronic phase

Neelima Agrawal, IIT Bombay

Exotic bound states

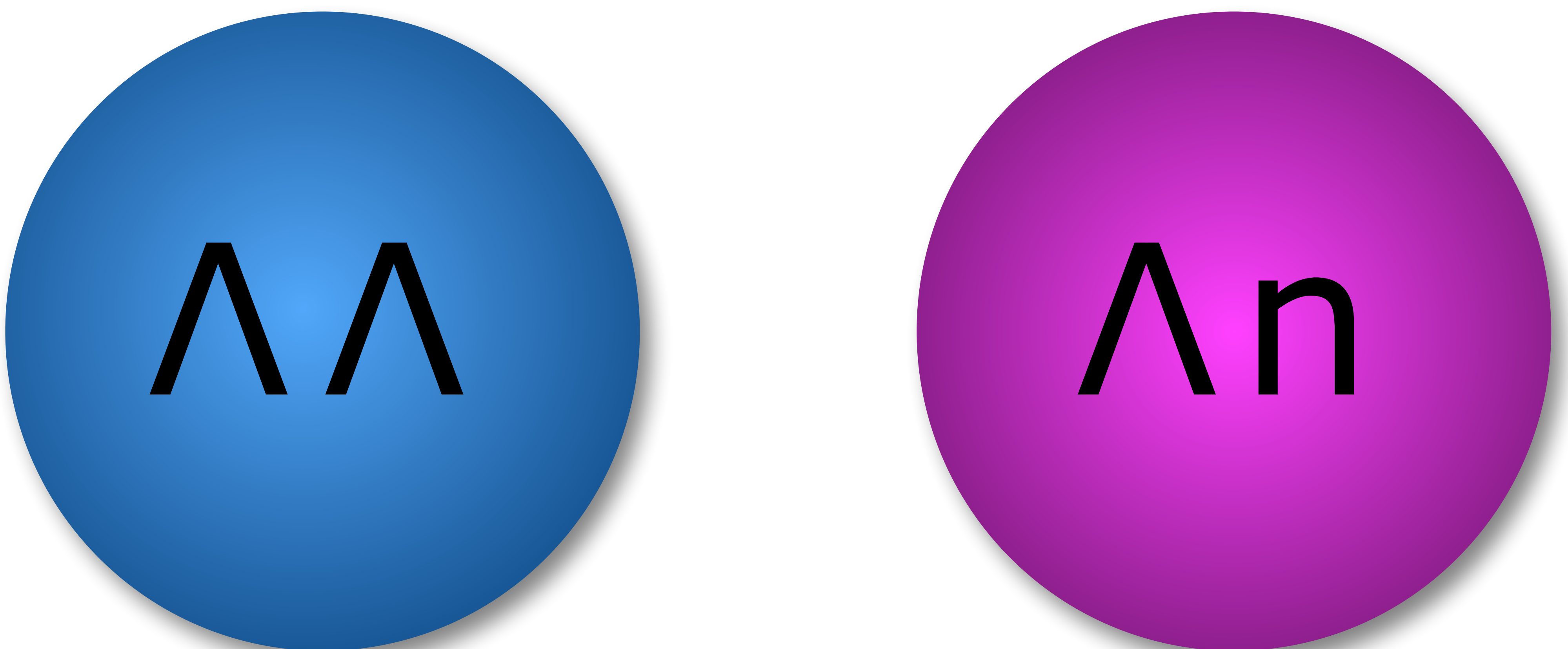
VOLUME 38, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 1977

Perhaps a Stable Dihyperon*

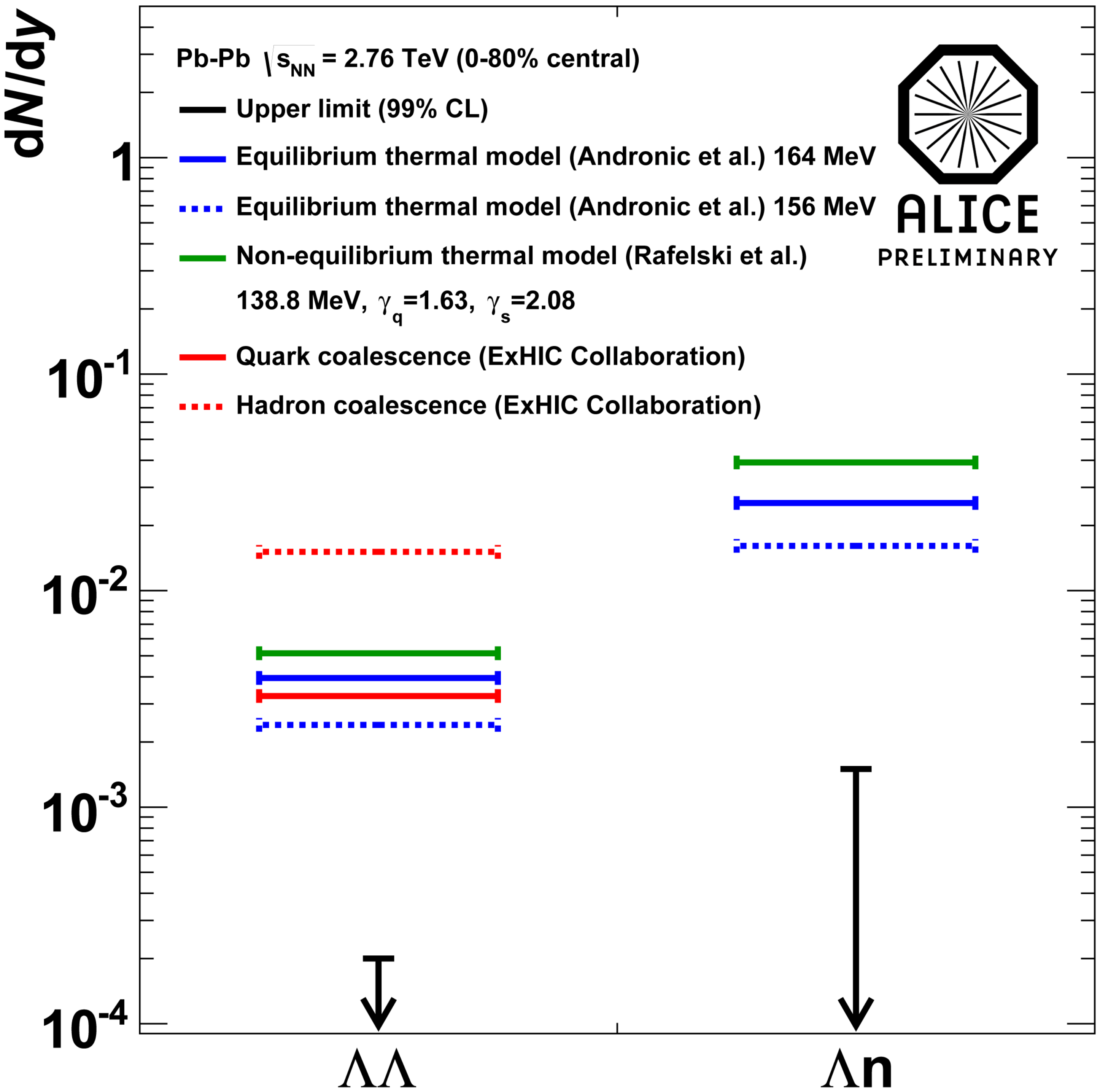
R. L. Jaffe†

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Department of Physics and Laboratory of Nuclear Science,‡ Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 1 November 1976)



Searches for exotic bound-states



Success of thermal model encouraged searches for other bound states

Λn → d π
ΛΛ → Λ p π

no signal observed in weak-decay modes

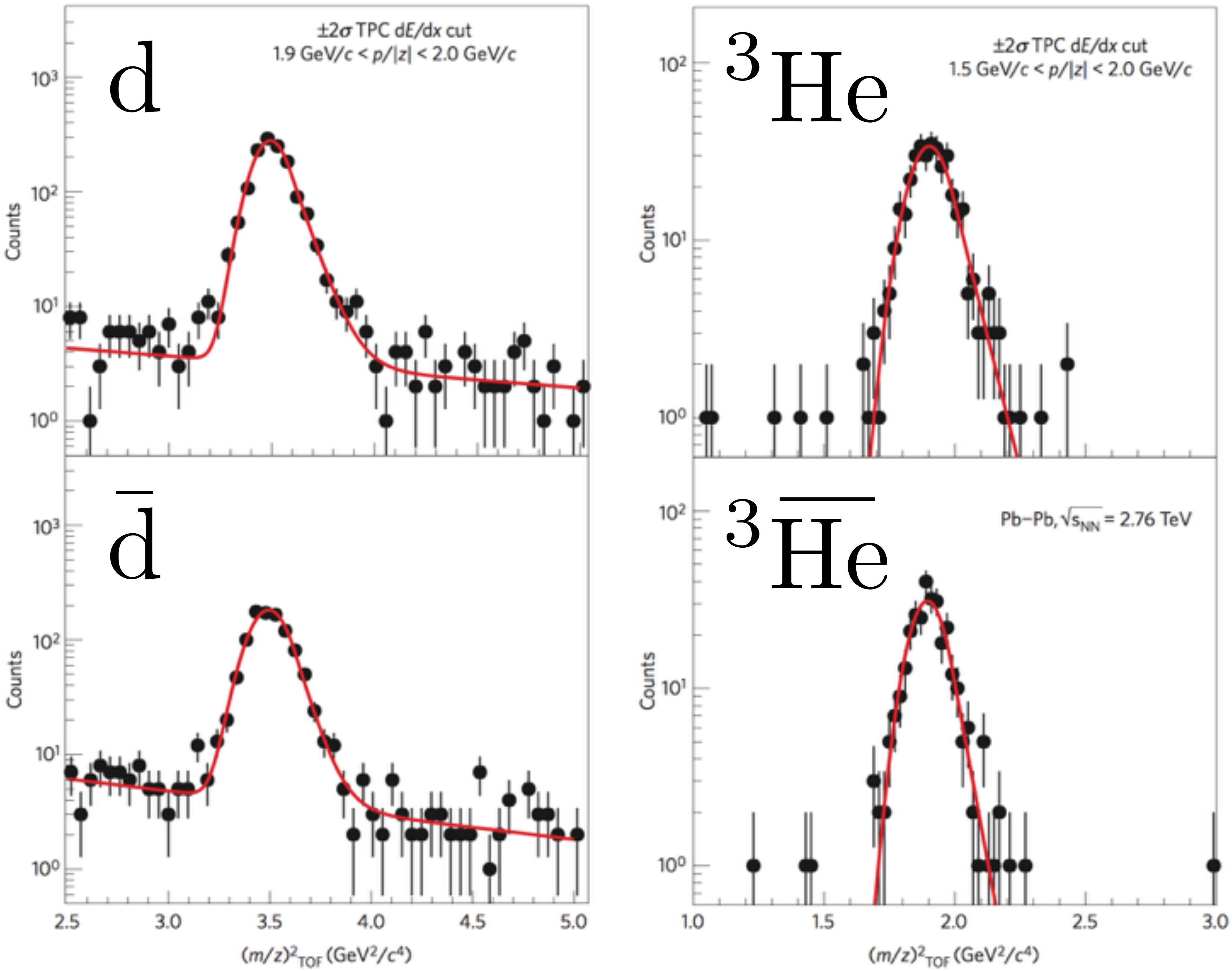
99% CL **limits** on production are significantly **lower than predictions**

More than just Heavy-ion physics

CPT invariance in nuclear systems

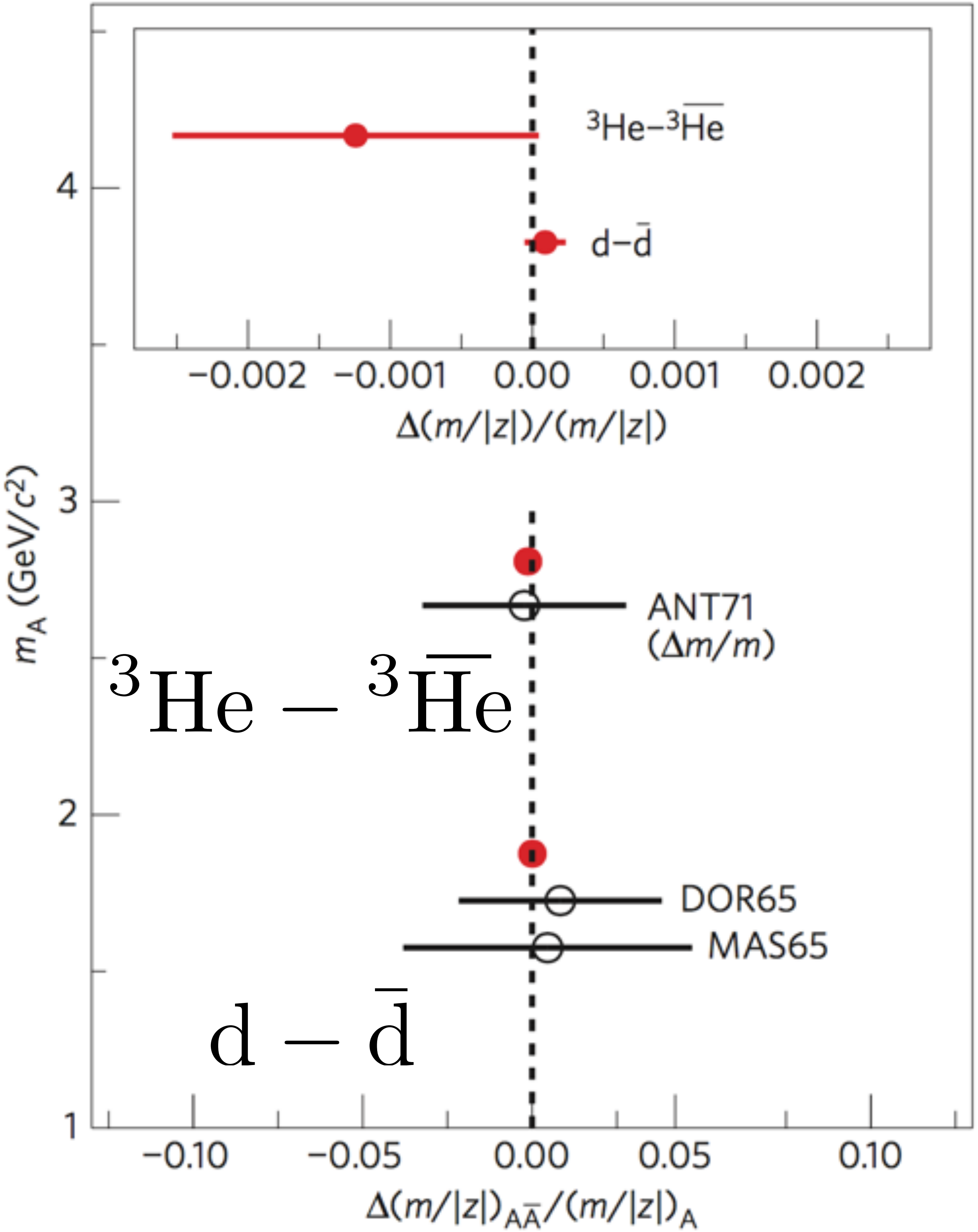
precision measurement of nuclei mass with time-of-flight

$$(m/z)^2_{\mathrm{TOF}} = (p/z)^2\left[(t_{\mathrm{TOF}}/L)^2 - 1/c^2\right]$$



makes use of heavy-ion collisions as an **efficient source of nuclei and anti-nuclei** combined with high-precision **tracking and identification** capabilities of ALICE

CPT invariance in nuclear systems



$$(m/z)^2_{\mathrm{TOF}} = (p/z)^2\left[(t_{\mathrm{TOF}}/L)^2 - 1/c^2\right]$$

measuring mass differences
rather than absolute values
→ reduced uncertainties
momentum, time-of-flight, track length

these results are
the highest precision direct measurement of the mass difference of nuclei/anti-nuclei
improved by one to two orders of magnitude wrt. previous measurements
(dating back to 1965 and 1971)

ALICE, Nature Physics 11 (2015) 811

Summary

detailed study of the properties of hot QCD matter with nucleus-nucleus collisions at the LHC

signatures of thermalisation, final-state effects and collectivity

particle production evolves with increasing system size

baryon and K* suppression, strangeness and deuteron enhancement

central Pb-Pb well described by GC thermal models, T_{ch} = 156 MeV

bulk particle production in proton-nucleus shows nucleus-nucleus features and signatures of collectivity

non-zero elliptic flow, mass-dependence of p_T spectra and v_2

enhanced production of strange and multi-strange hadrons

interesting! **also in high-multiplicity proton-proton collisions**

many more results and a bright future

new data and more ideas for LHC Run-2