Soft probes in heavy-ion collisions

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Soft heavy-ion physics at the LHC

what I will discuss in the following slides

- nucleus-nucleus collisions
  → produce **hot nuclear matter**: QGP
  → investigate **QCD phase transition** / diagram
  → **thermodynamics** and **collectivity**
  → space-time **evolution** of the fireball

- proton-nucleus collisions
  → control experiment
  → disentangle **cold / hot nuclear matter** effects
  → **surprising features** in high-multiplicity events

is far to be a comprehensive summary of soft heavy-ion physics

Heavy-ion physics

study QCD matter under extreme conditions

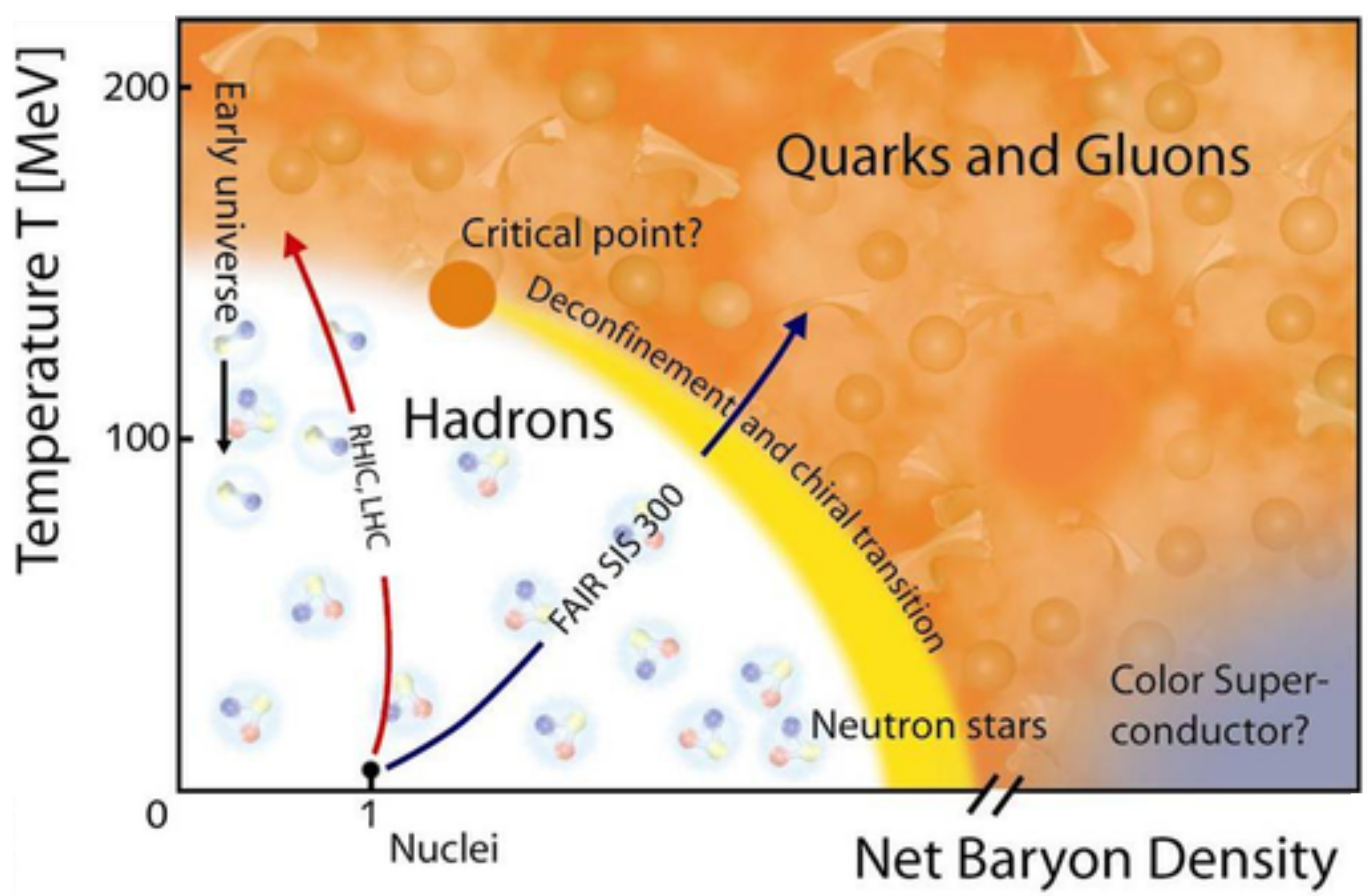
high temperature and energy-density

expected to undergo a **phase-transition**

hadronic matter → deconfined quarks and gluons (QGP)

study the phase diagram and the properties of hot QCD matter

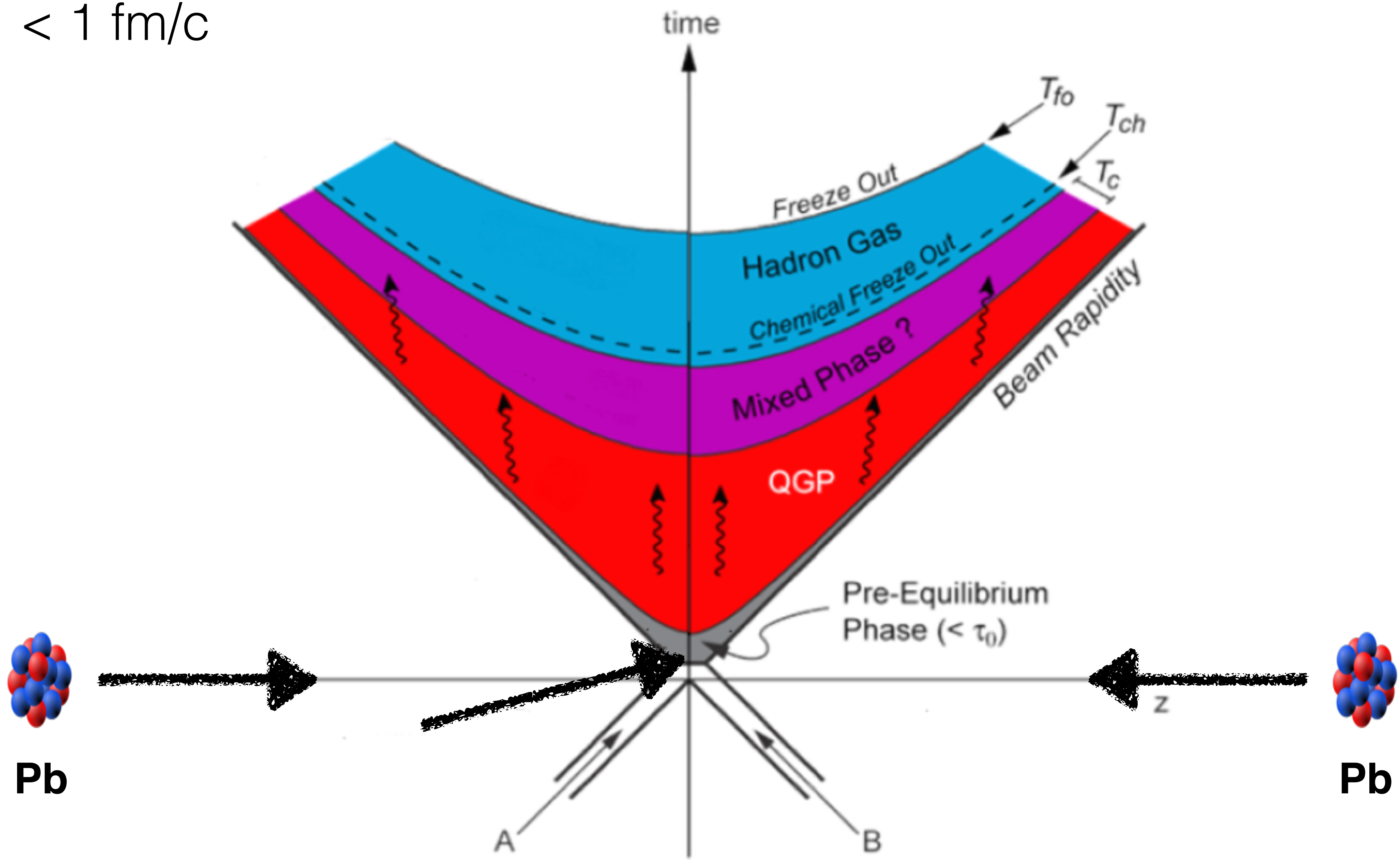
past:	GSI	SIS	~2 GeV
	BNL	AGS	~5 GeV
	CERN	SPS	~20 GeV
present:	BNL	RHIC	~200 GeV
	CERN	LHC	~5 TeV
future:	GSI	FAIR	~45 GeV



so far, a rich ultra relativistic heavy-ion programme

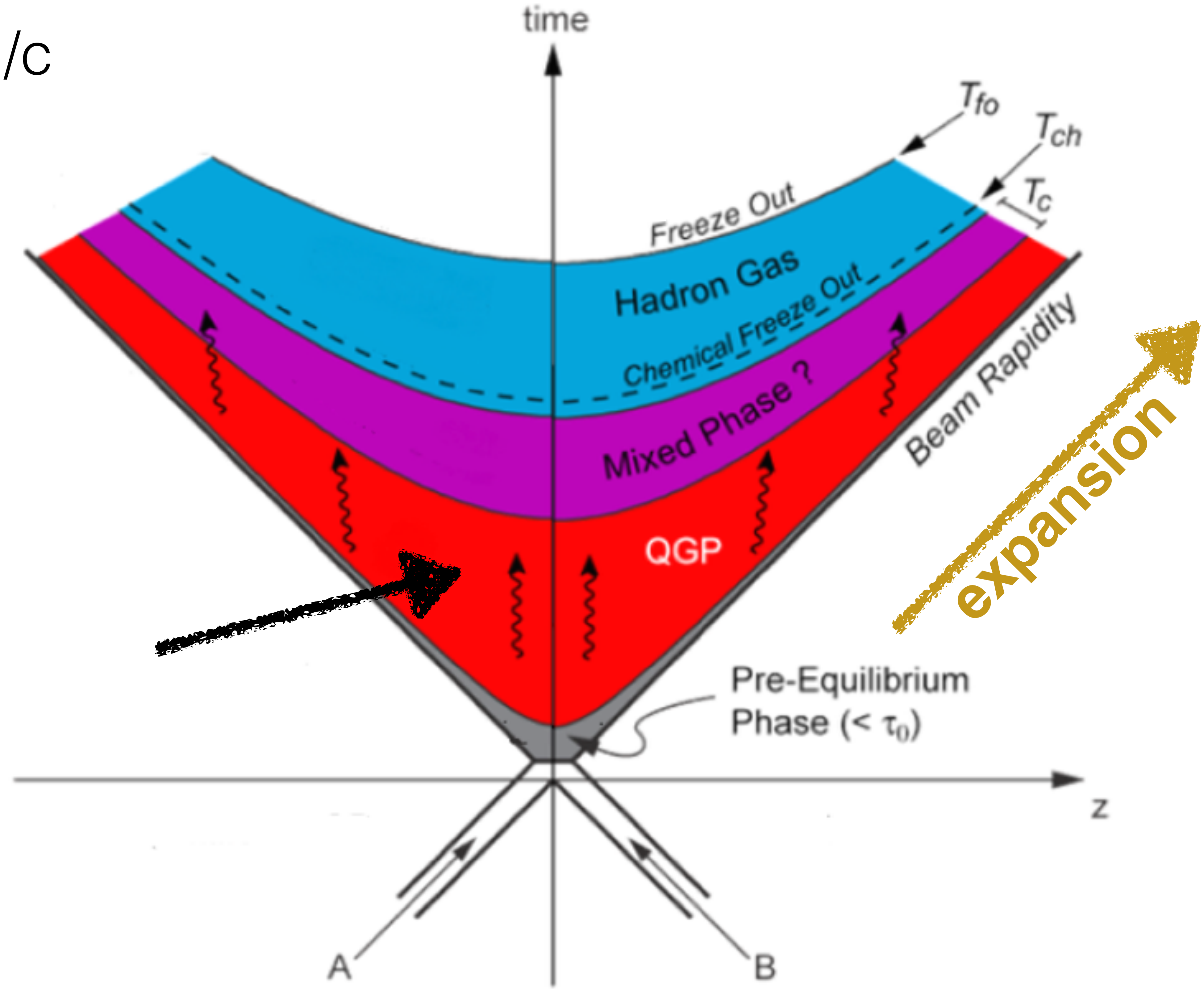
Hard scattering + thermalisation

< 1 fm/c



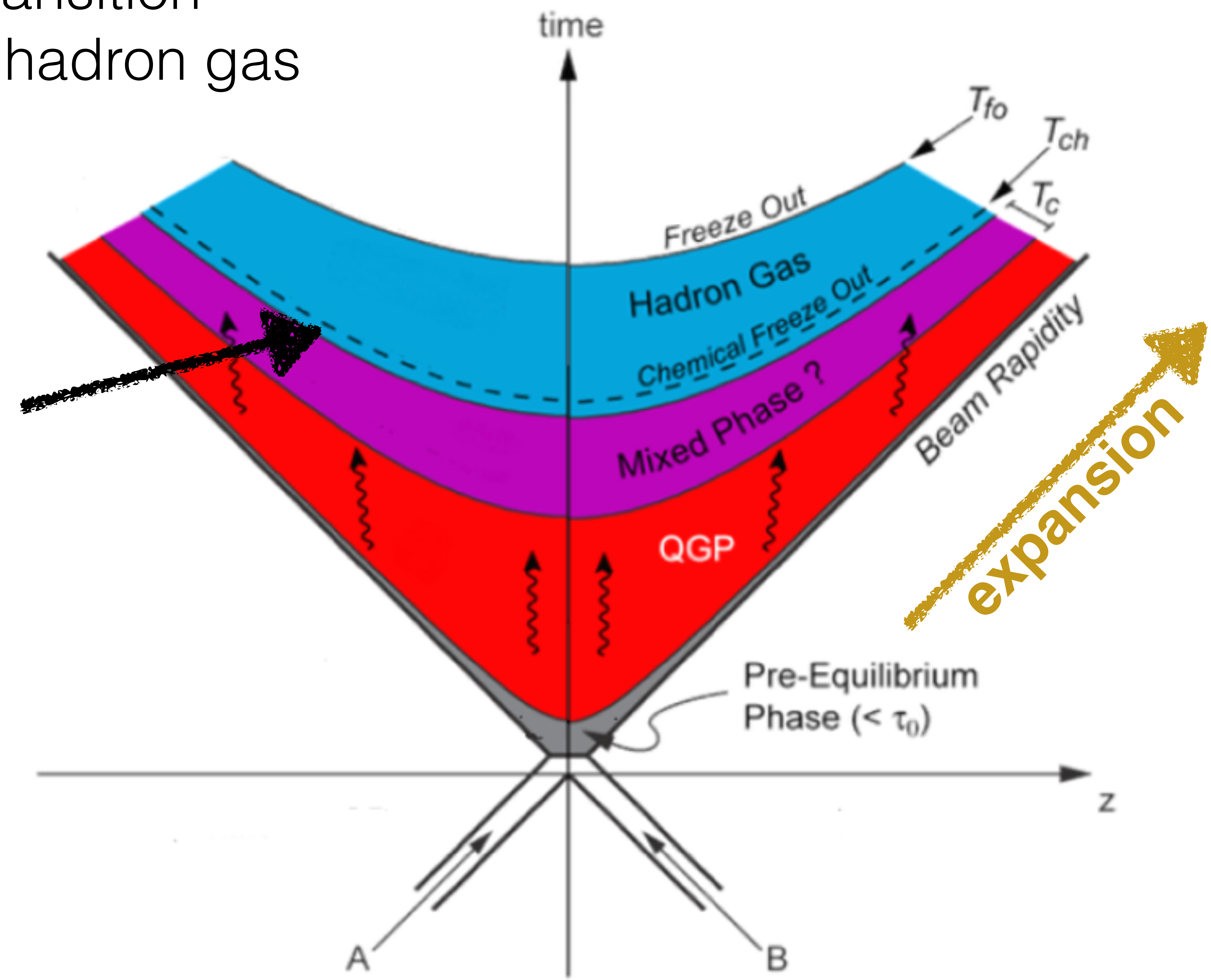
Partonic phase

QGP
~ few fm/c



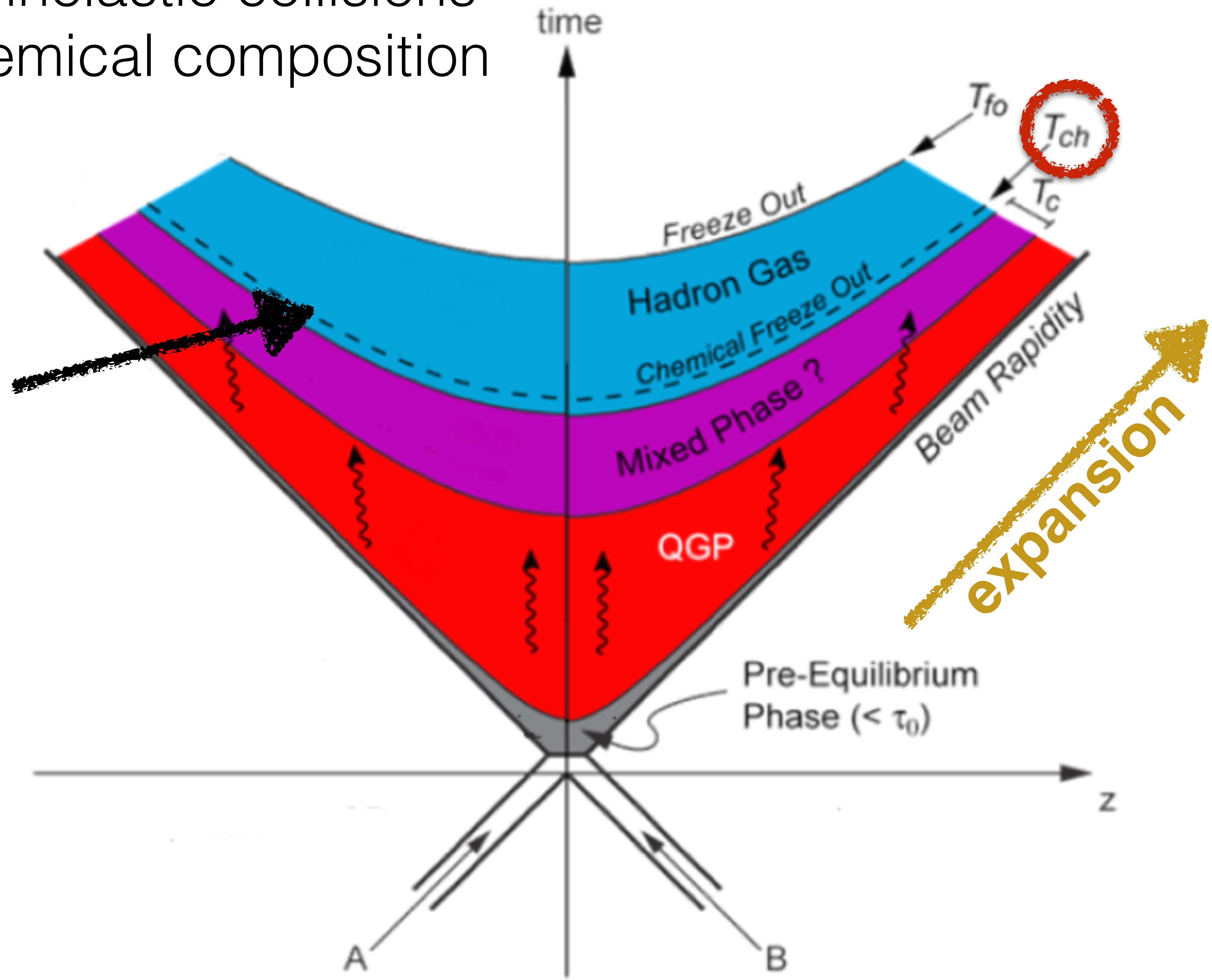
Hadronisation

phase transition
QGP → hadron gas



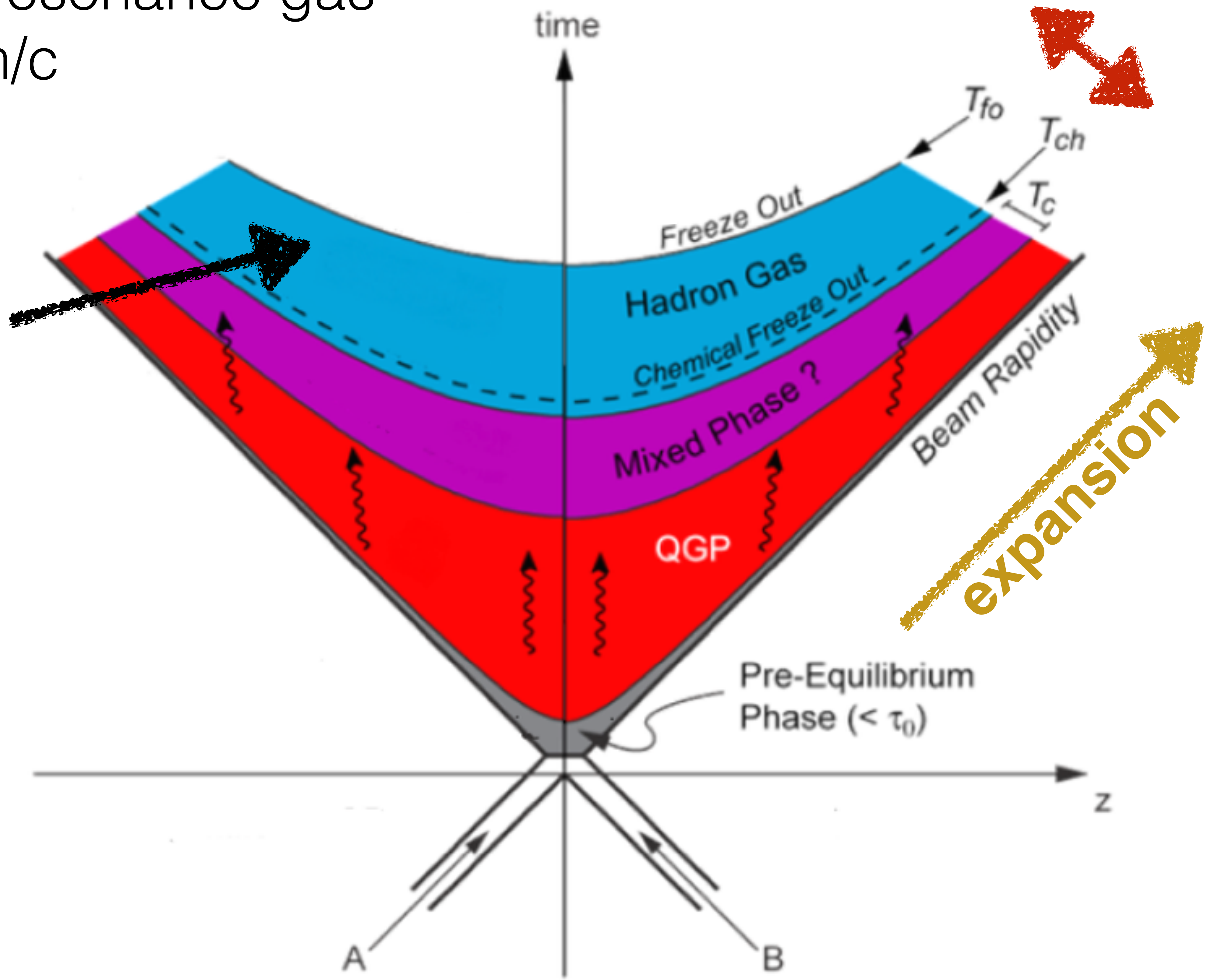
Chemical freeze-out

no more inelastic collisions
fixed chemical composition



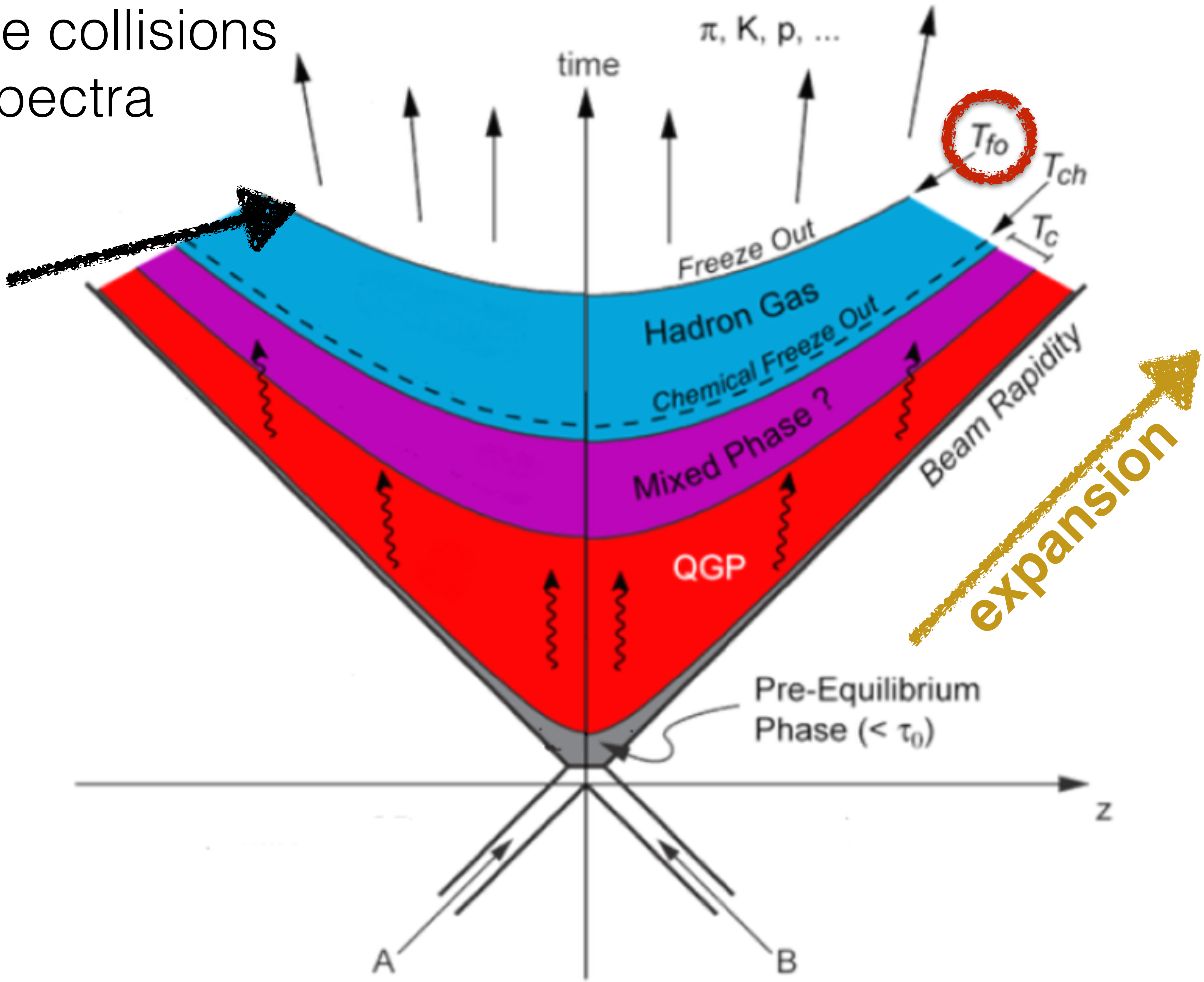
Hadronic phase

hadron-resonance gas
~ few fm/c



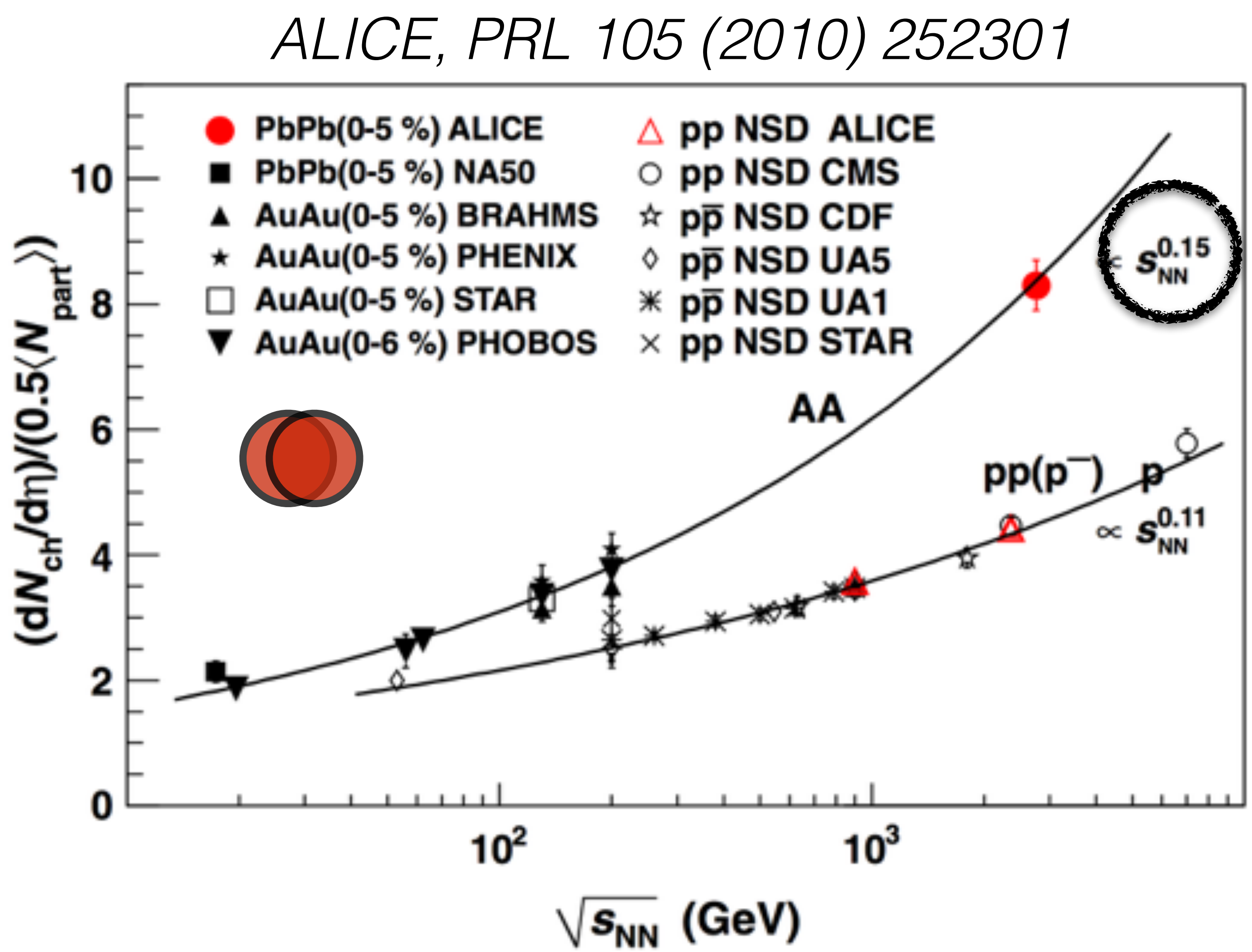
Kinetic freeze-out

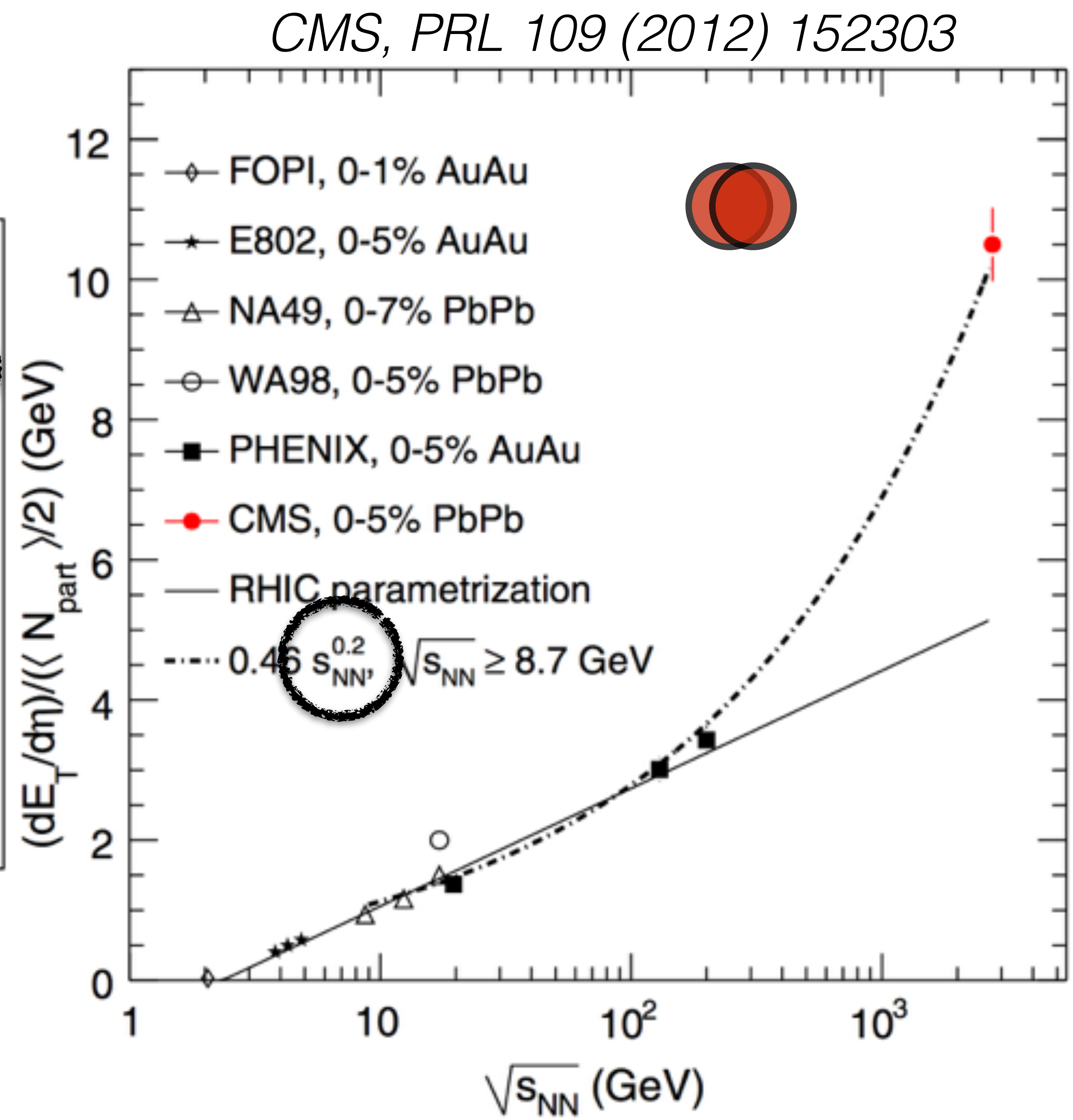
no more collisions
fixed spectra



Particle production in nucleus-nucleus collisions

Multiplicity and transverse energy

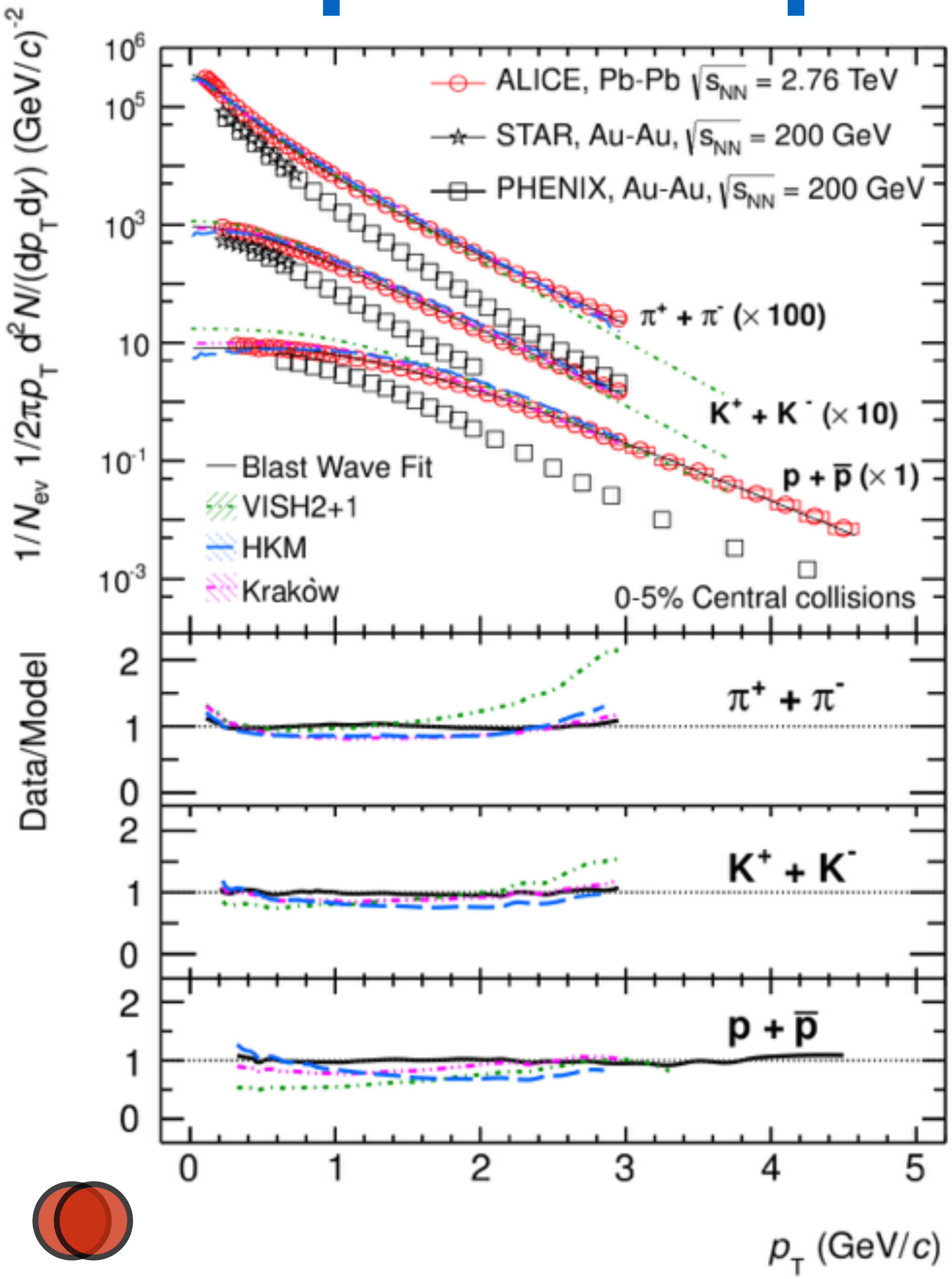




$\langle E_T \rangle$ grows faster with energy than the multiplicity

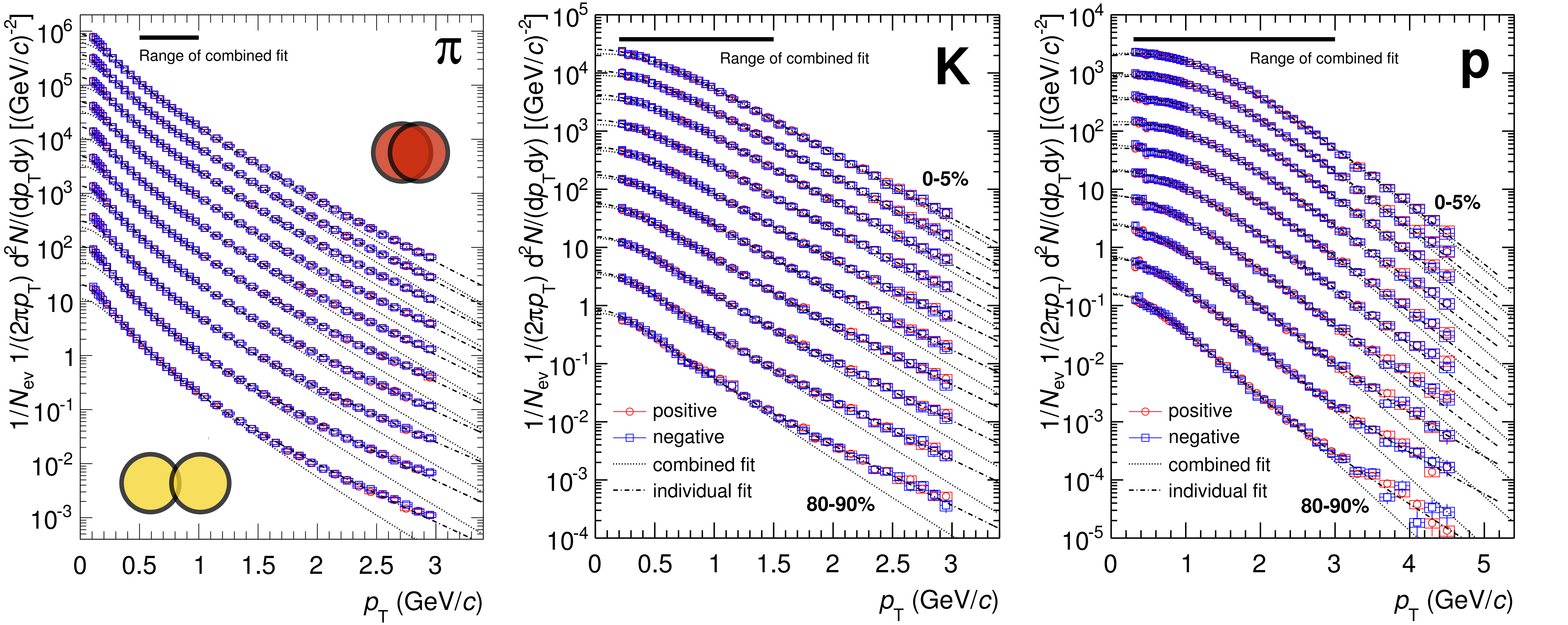
significant increase of $\langle E_T \rangle$ per particle compared to lower-energy data

Bulk particle production in Pb-Pb



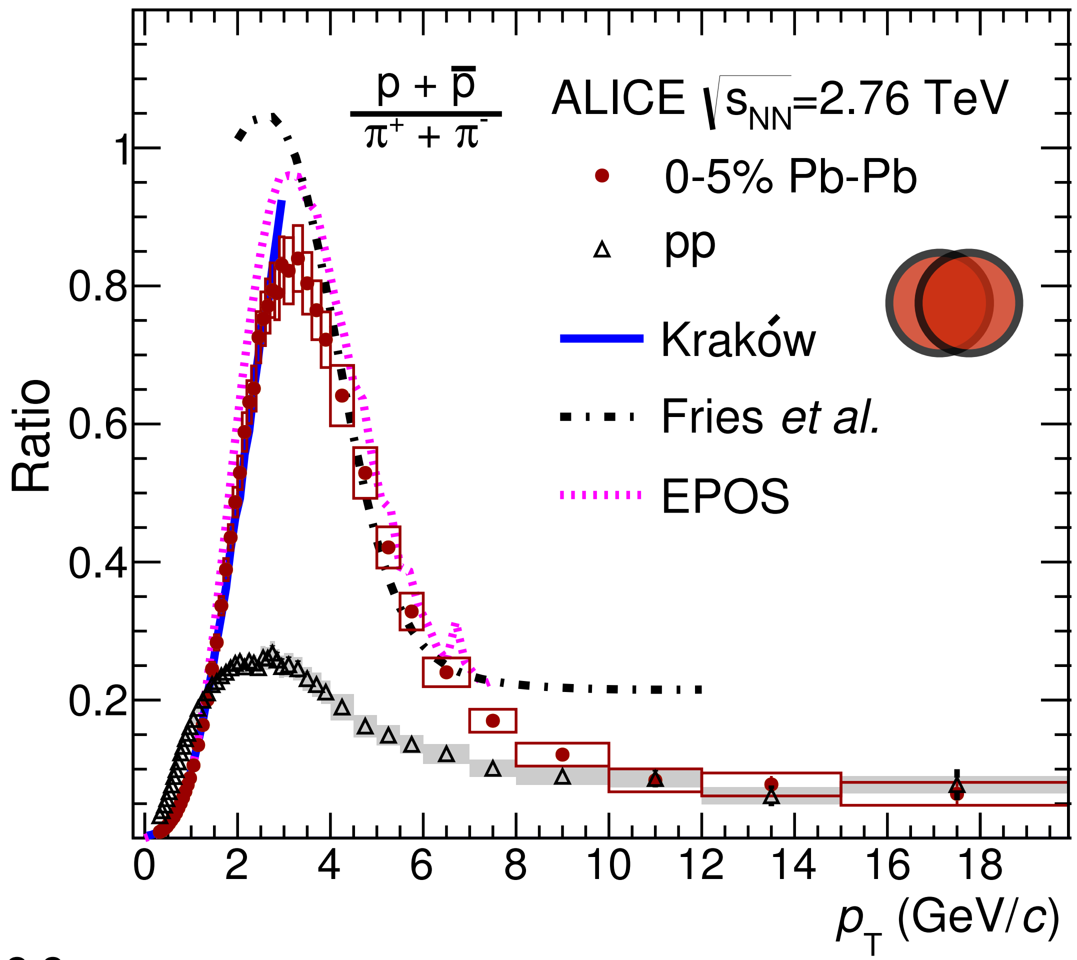
transverse momentum spectra in central Pb-Pb collisions at the LHC **are significantly harder** than in central Au-Au collisions at RHIC

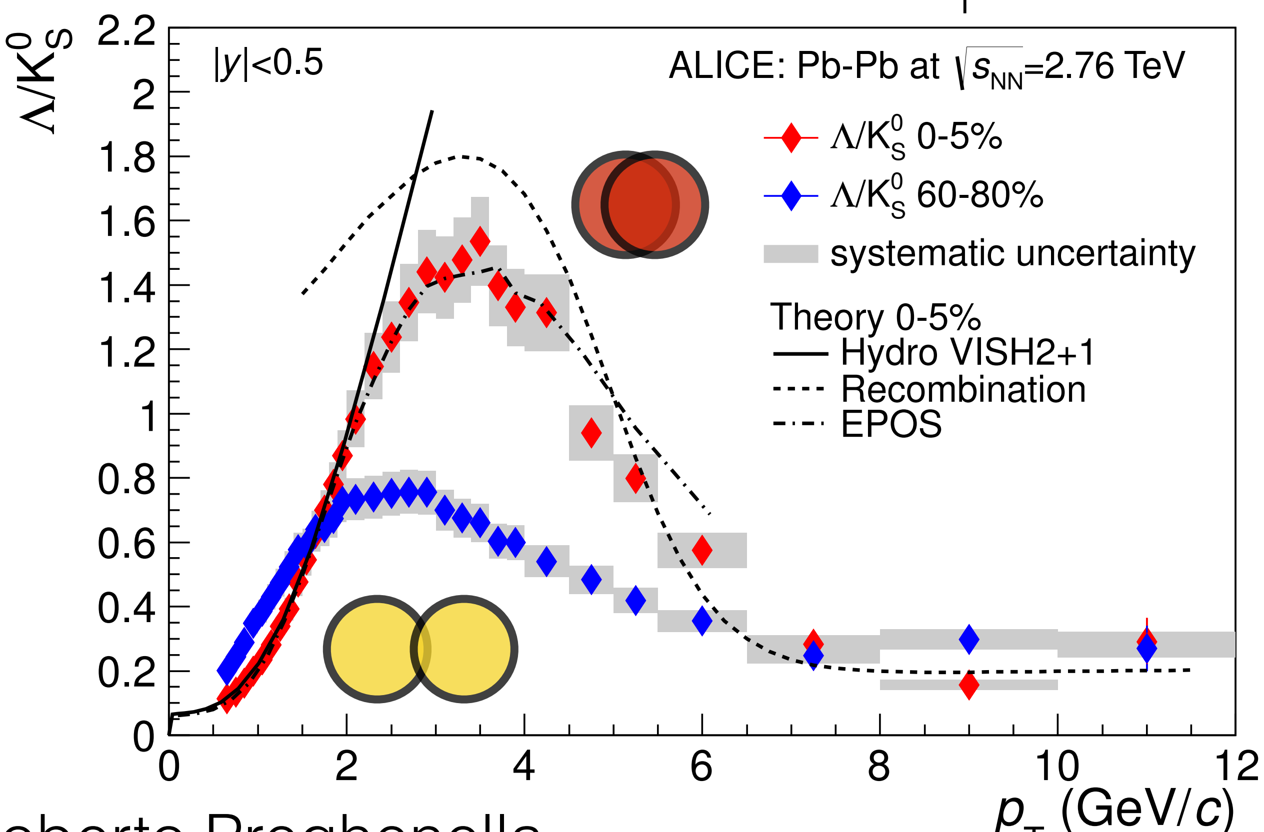
Bulk particle production in Pb-Pb



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

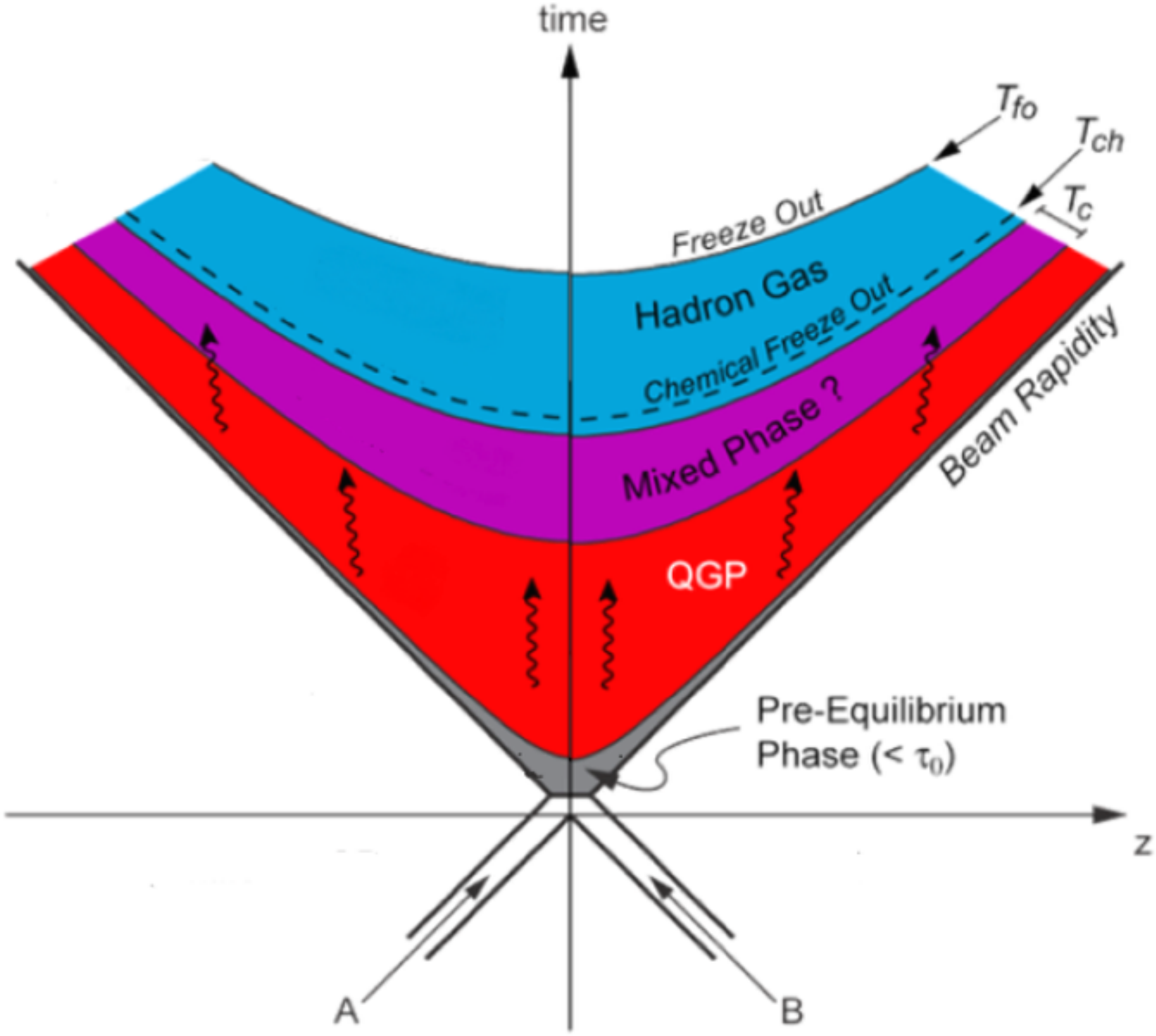
EPOS provides **good description** of data
Werner, PRL 109 (2012) 102301

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

Collective phenomena

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

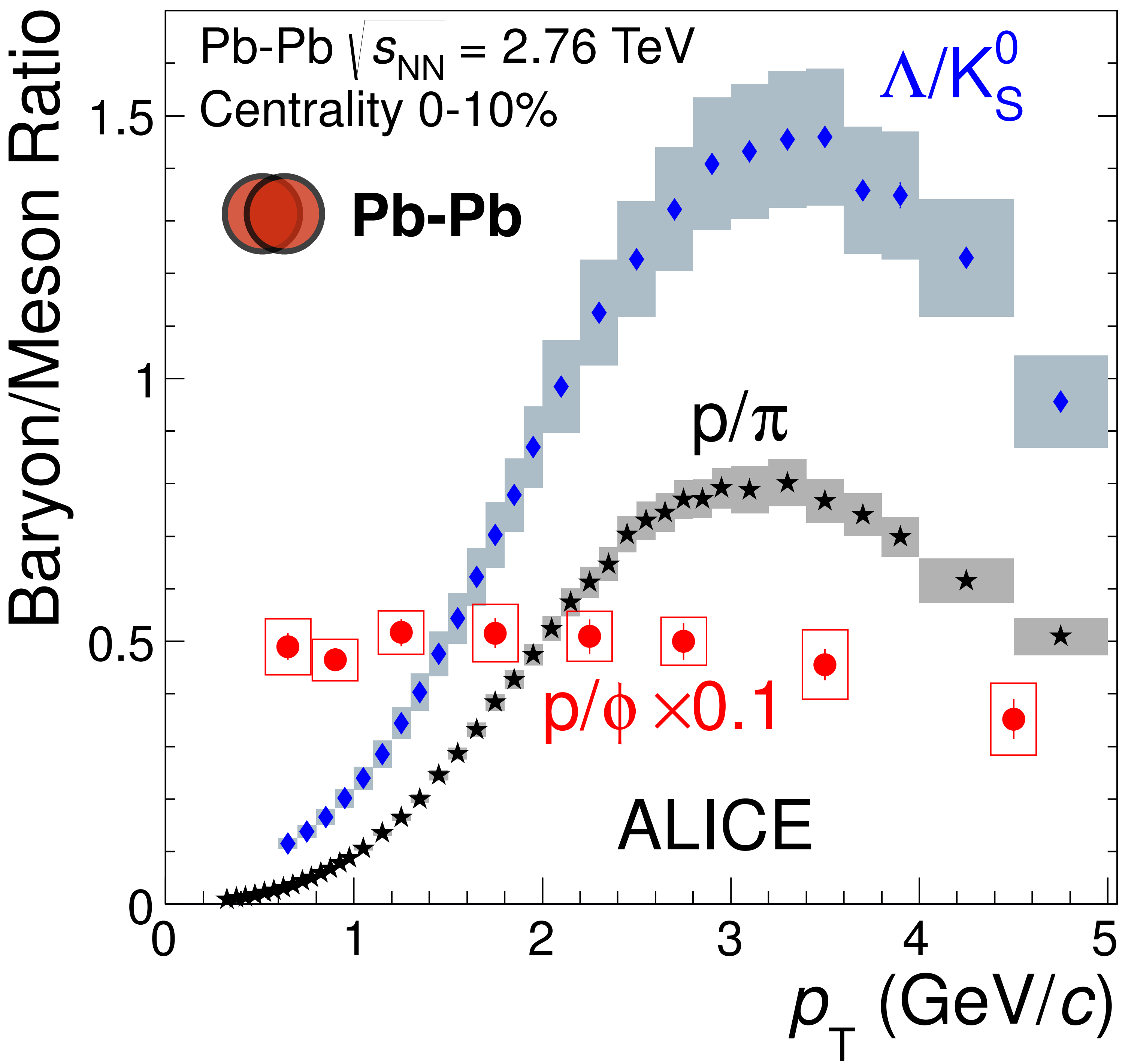
- initial hot and dense partonic matter rapidly expands
- collective flow develops and the system cools down
- phase transition to hadron gas when $T_{critical}$ is reached



resulting in

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

p/ϕ spectra ratio in Pb-Pb



test baryon enhancement:

p: 938 MeV/c² *qqq*

ϕ: 1018 MeV/c² $q\bar{q}$

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**

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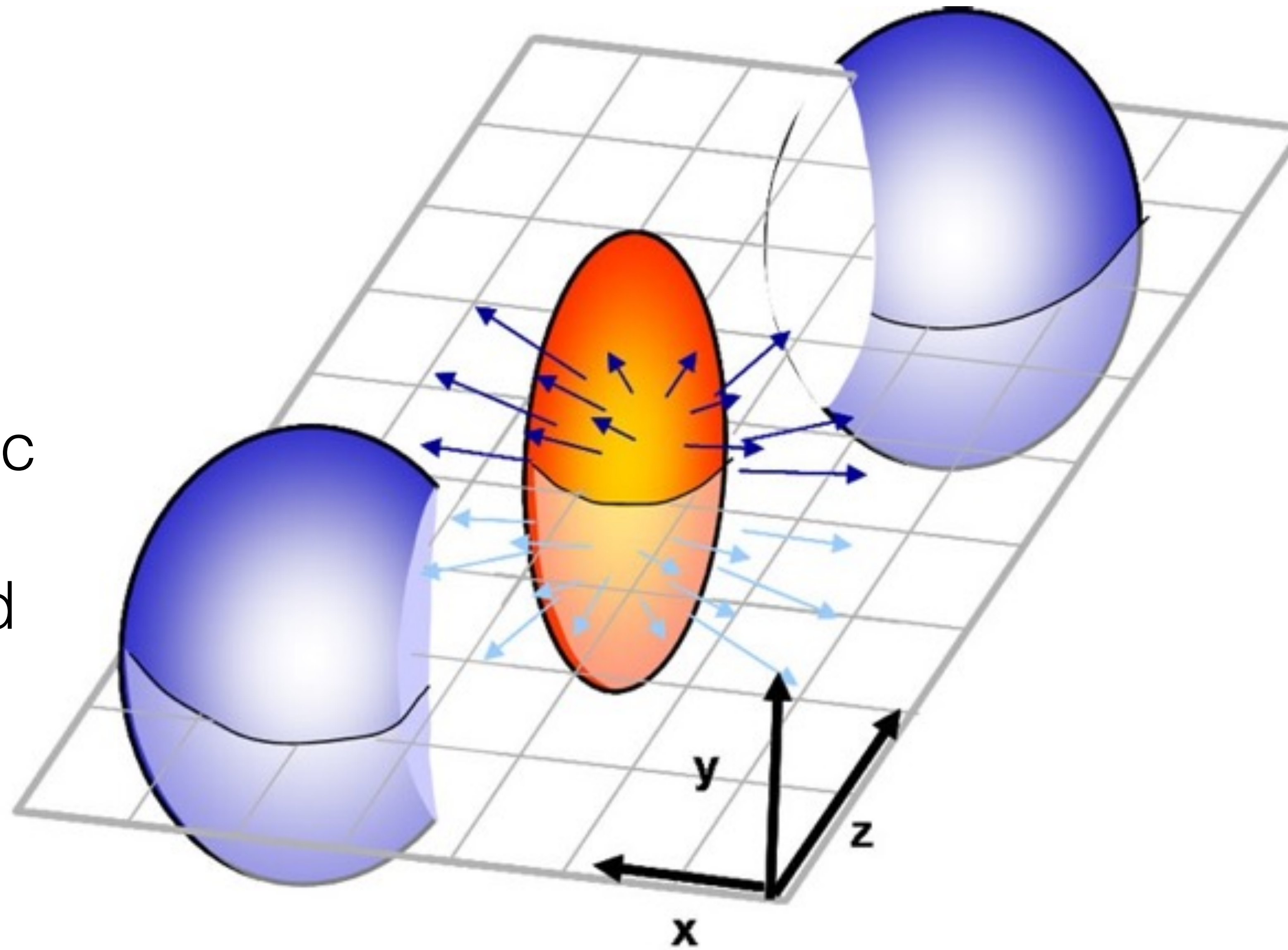

resulting in

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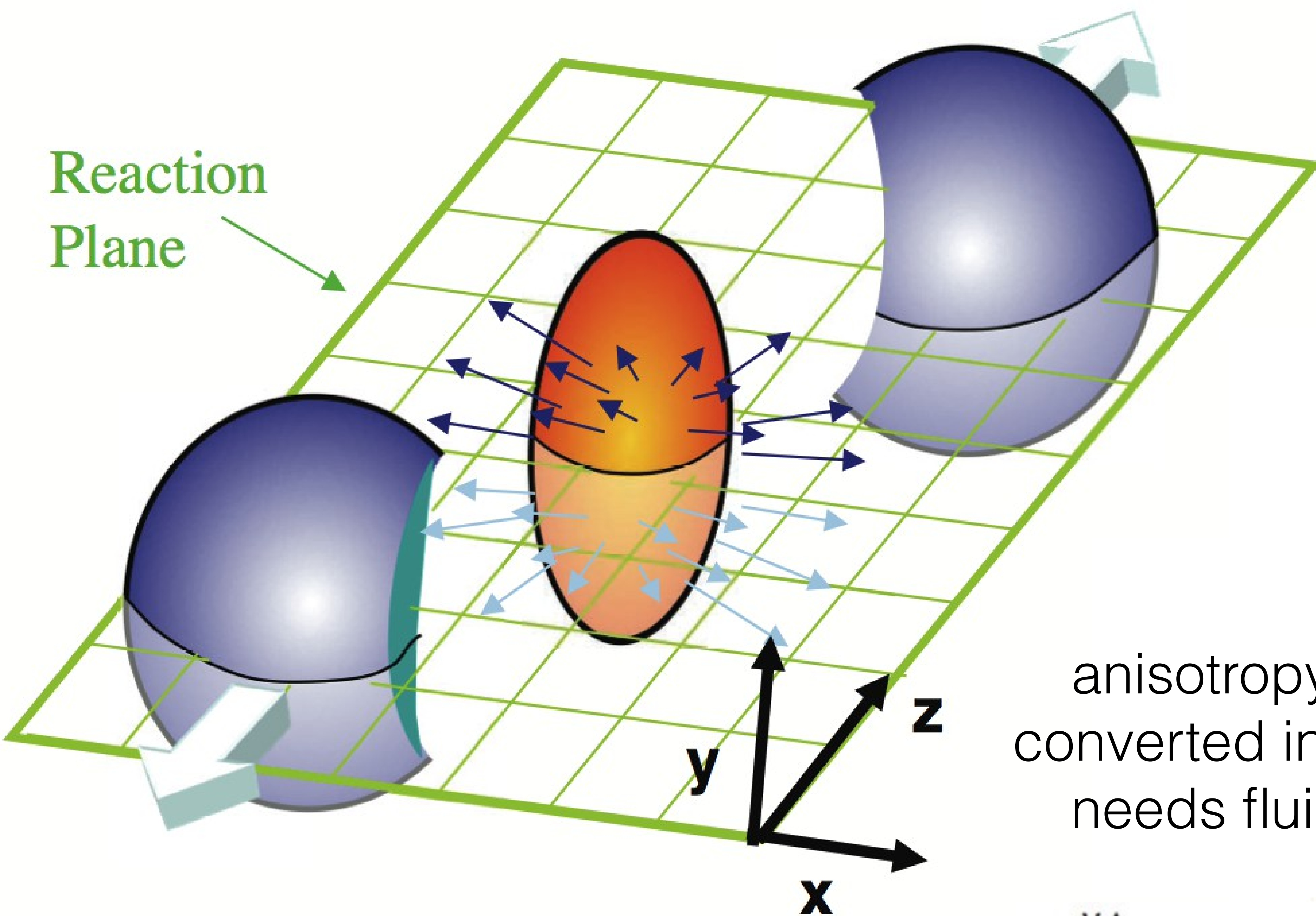
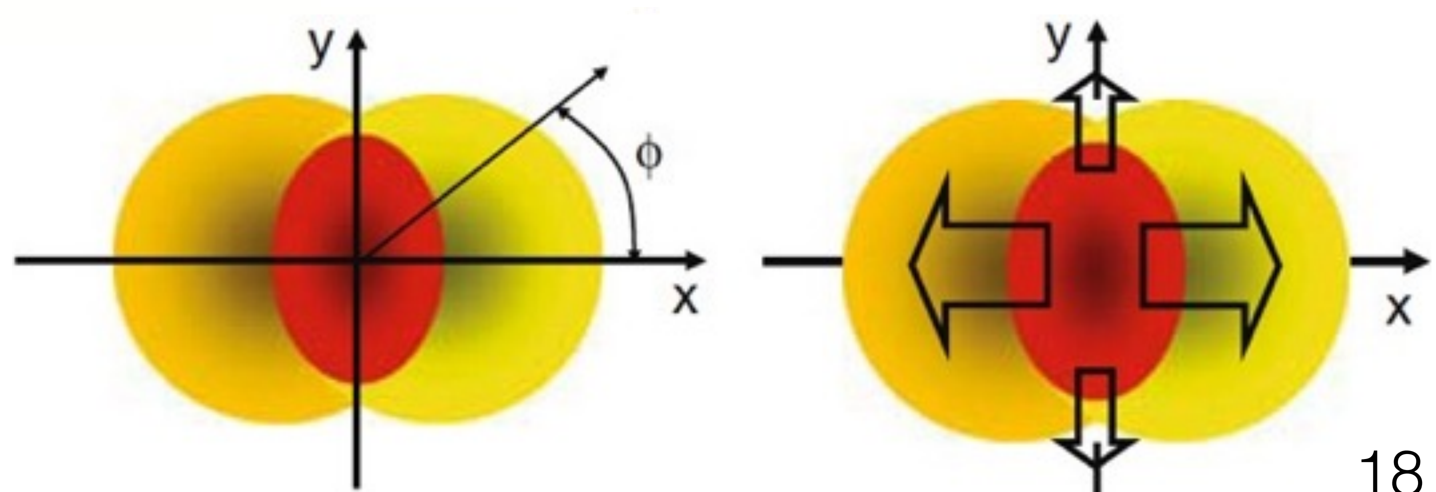
Anisotropic flow



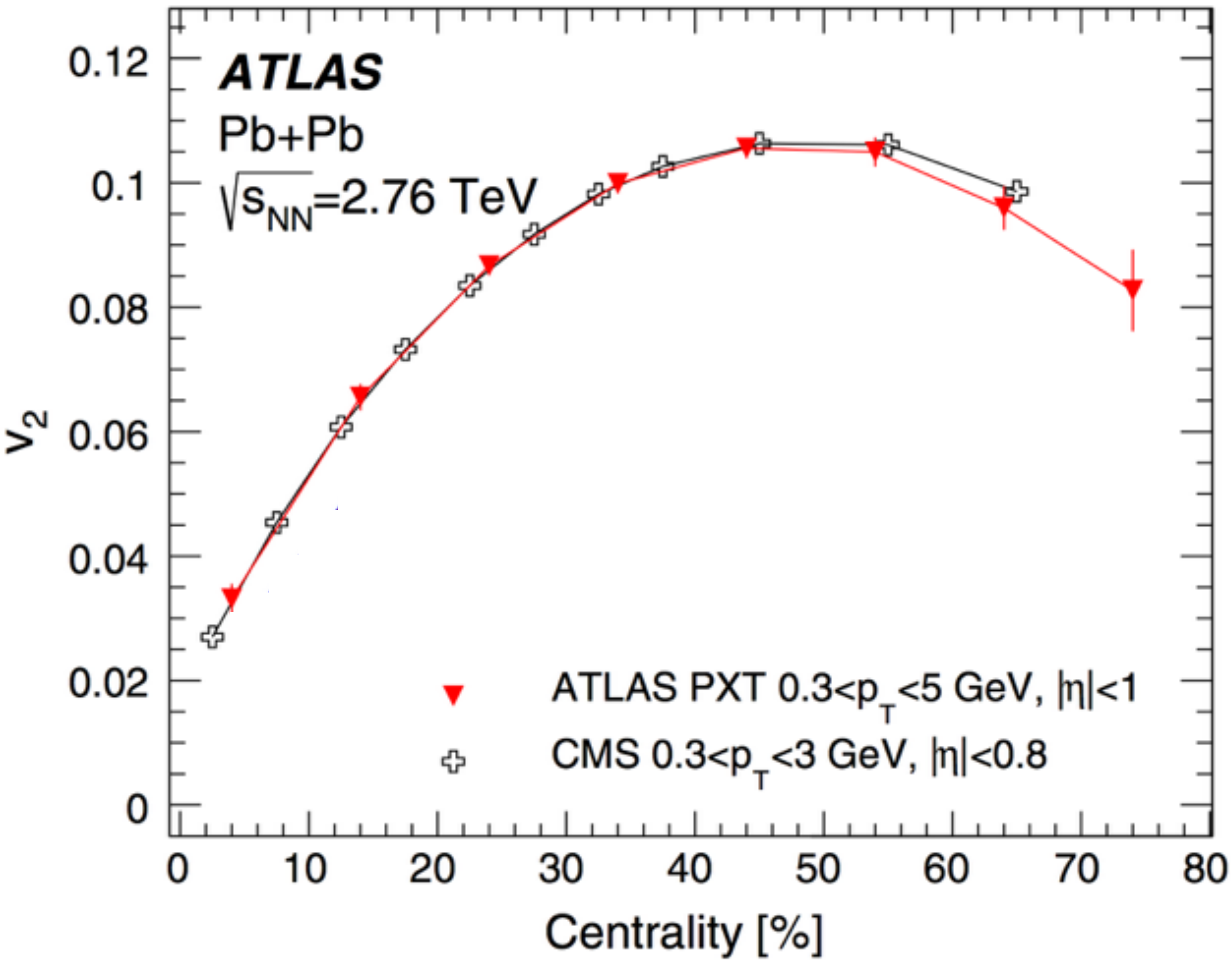
anisotropy in **spatial** space
converted in **momentum** space
needs fluid-like **collectivity**

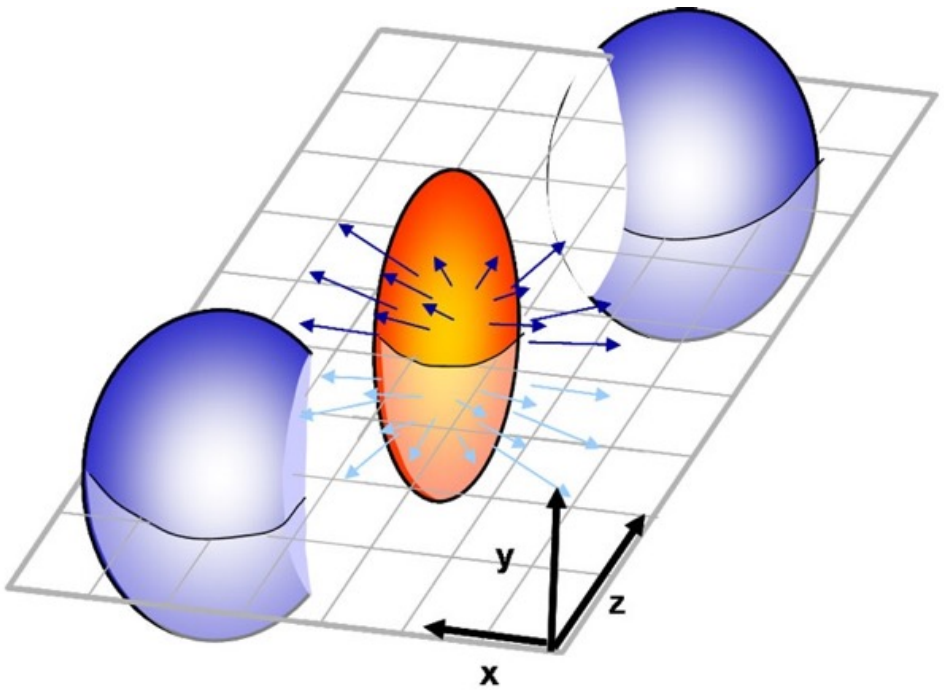
asymmetric pressure gradients
develop after collisions



Collective anisotropic flow

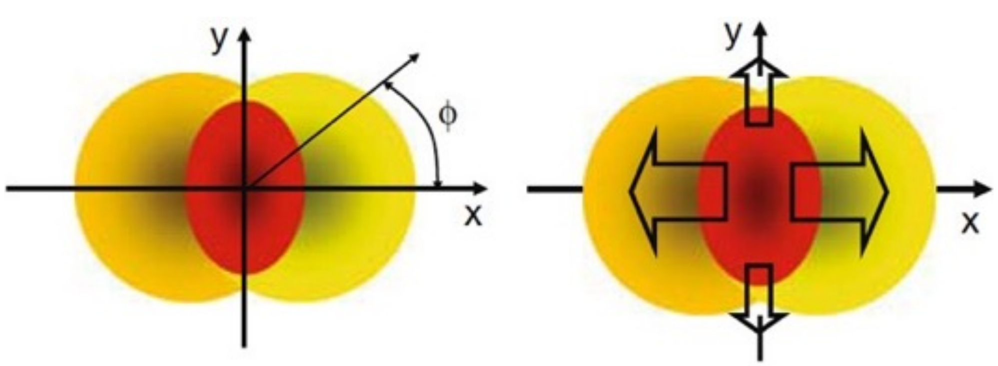
spatial anisotropy (collisions geometry)
⟶ anisotropy in momentum space: v_2





strong collective flow persists at the LHC

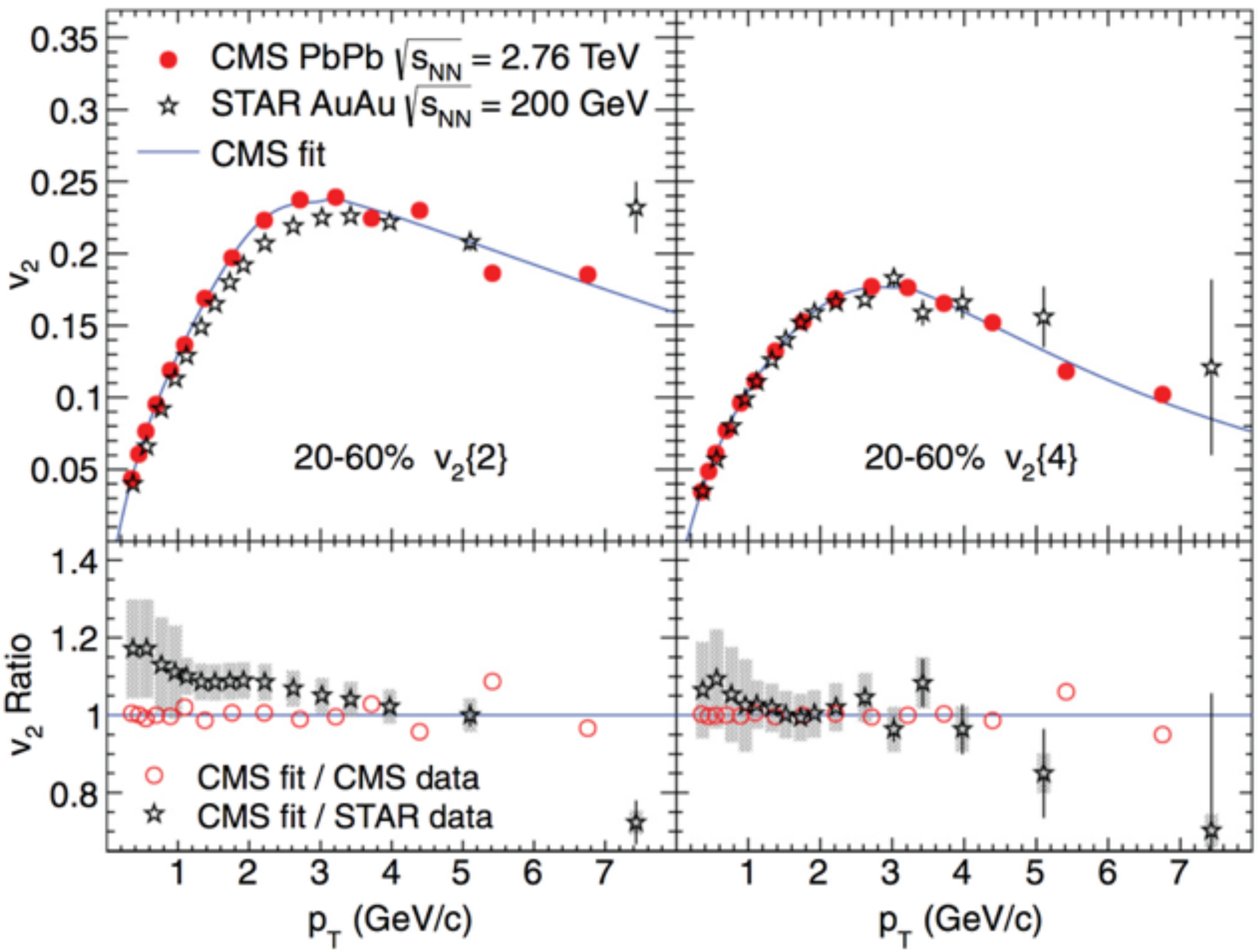
flow is driven by **initial-state geometry**

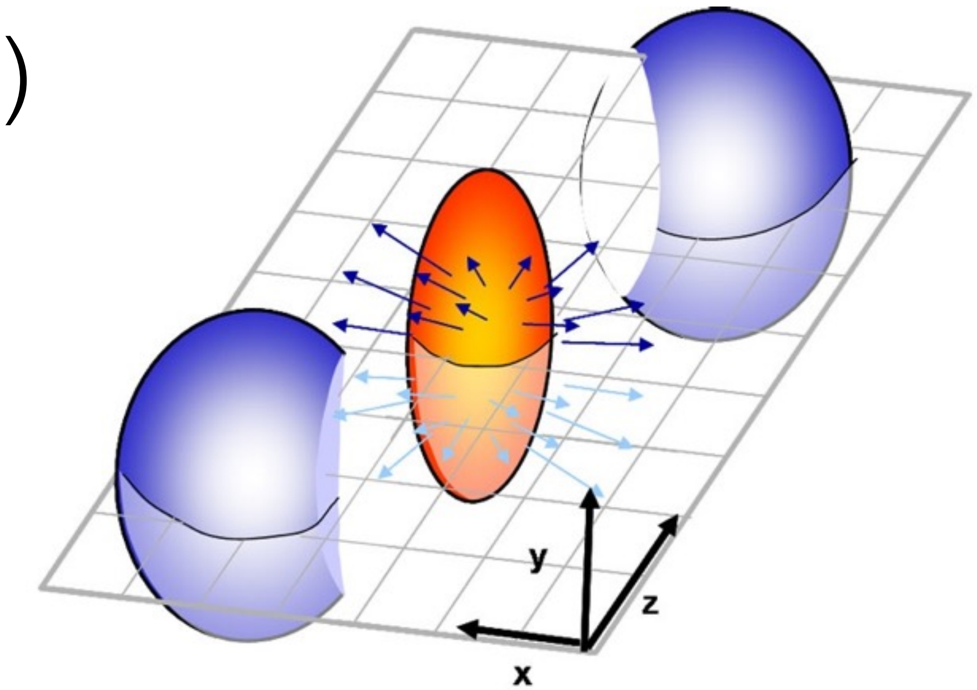


ATLAS, EPJC 74 (2014) 2982

Collective anisotropic flow

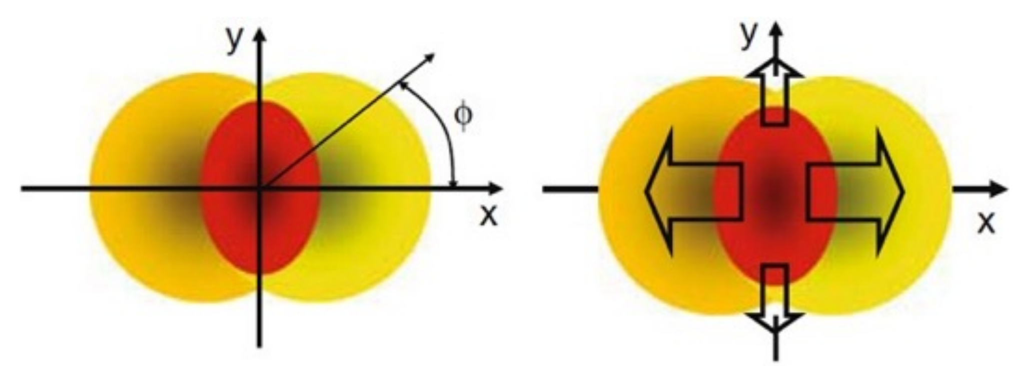
spatial anisotropy (collisions geometry)
⟶ anisotropy in momentum space: ***v_2***





strong collective flow persists at the LHC

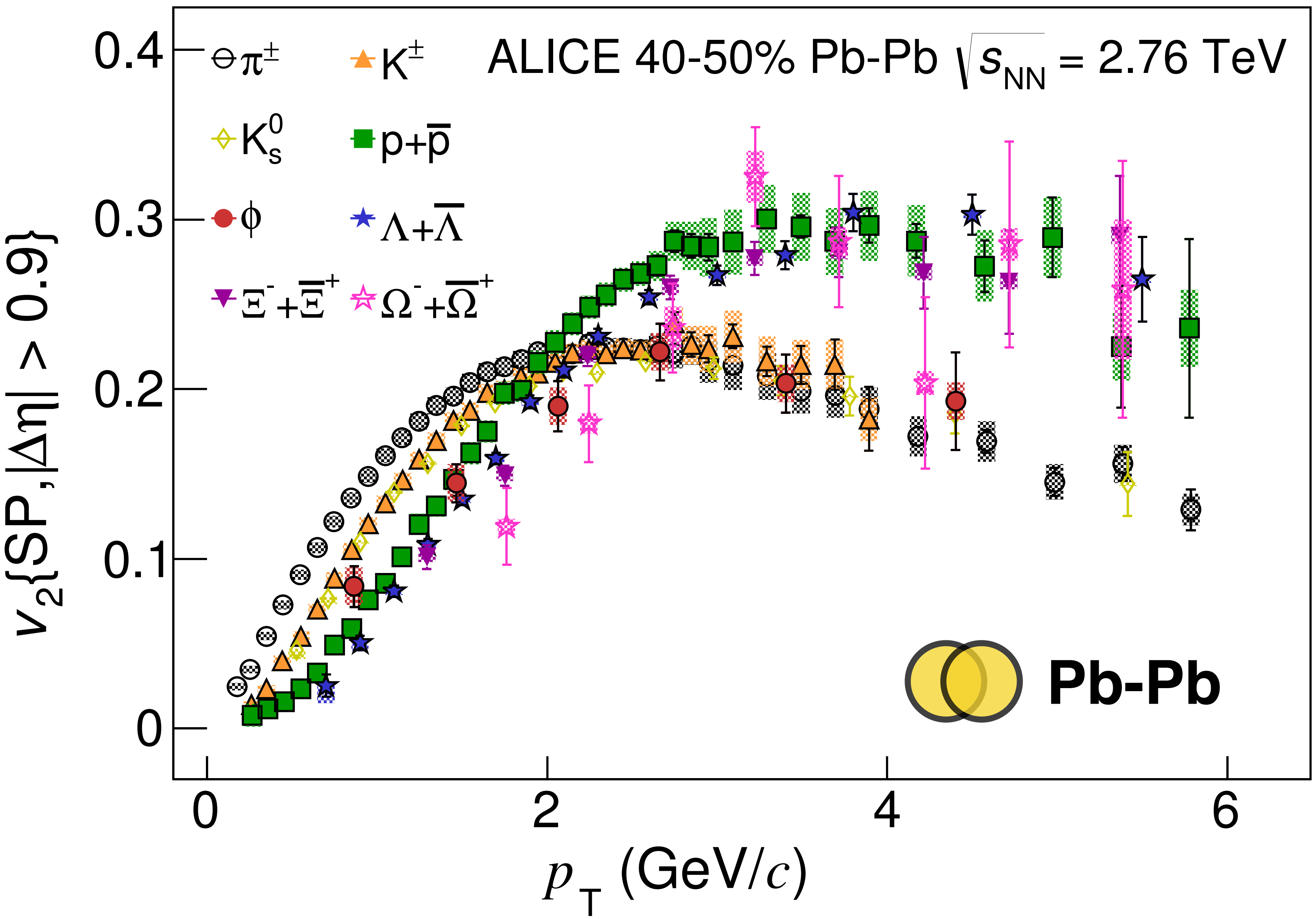
flow is similar at the LHC and at RHIC

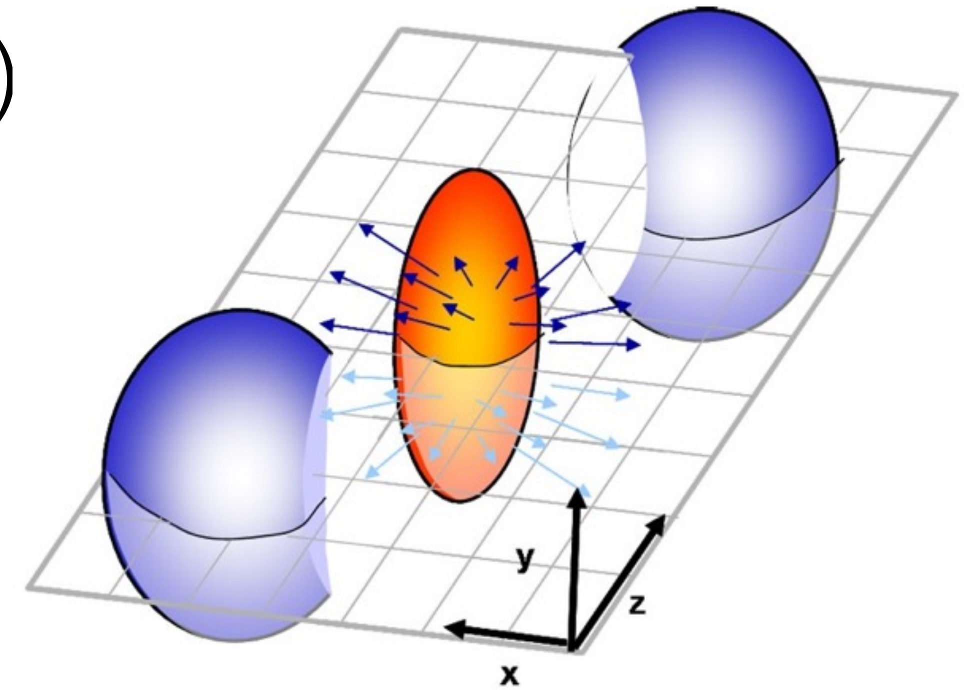


CMS, PRC 87 (2013) 014902

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

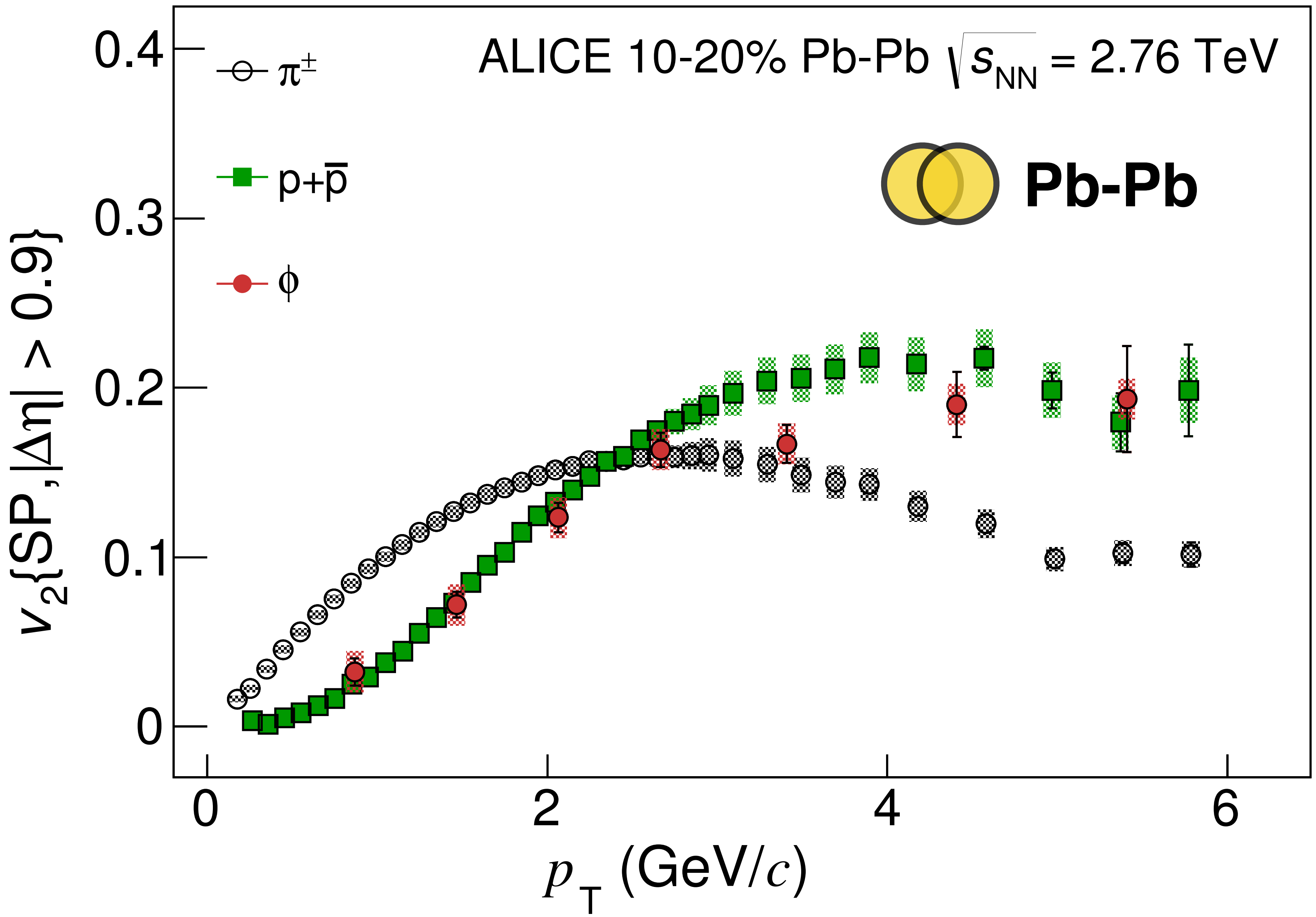
Igor Altsybeev

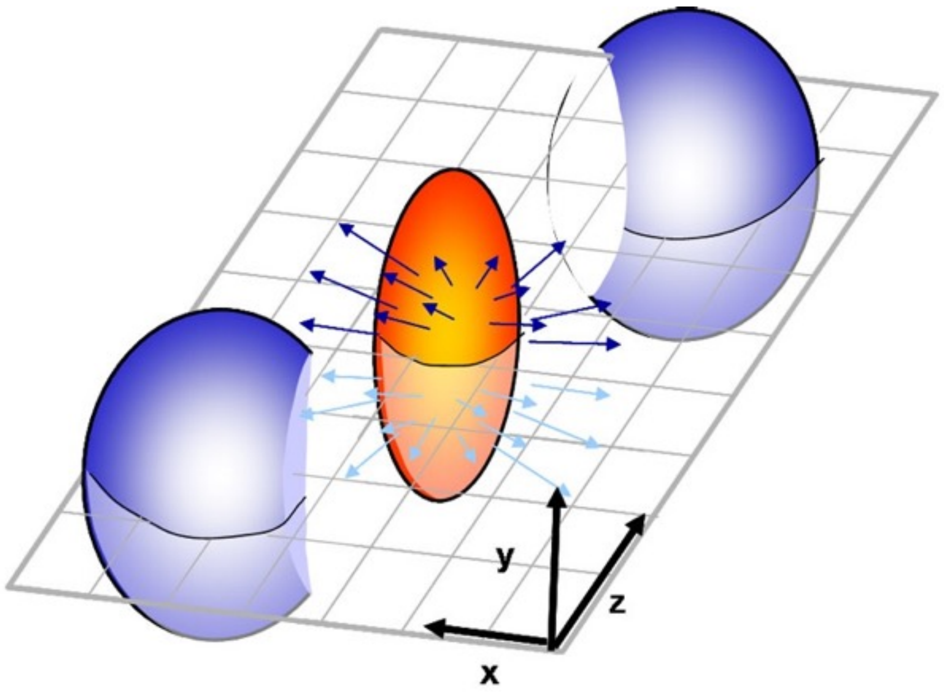
ALICE, JHEP 06 (2015) 190

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

Igor Altsybeev

ALICE, JHEP 06 (2015) 190

Strangeness enhancement

one of the first proposed QGP signatures

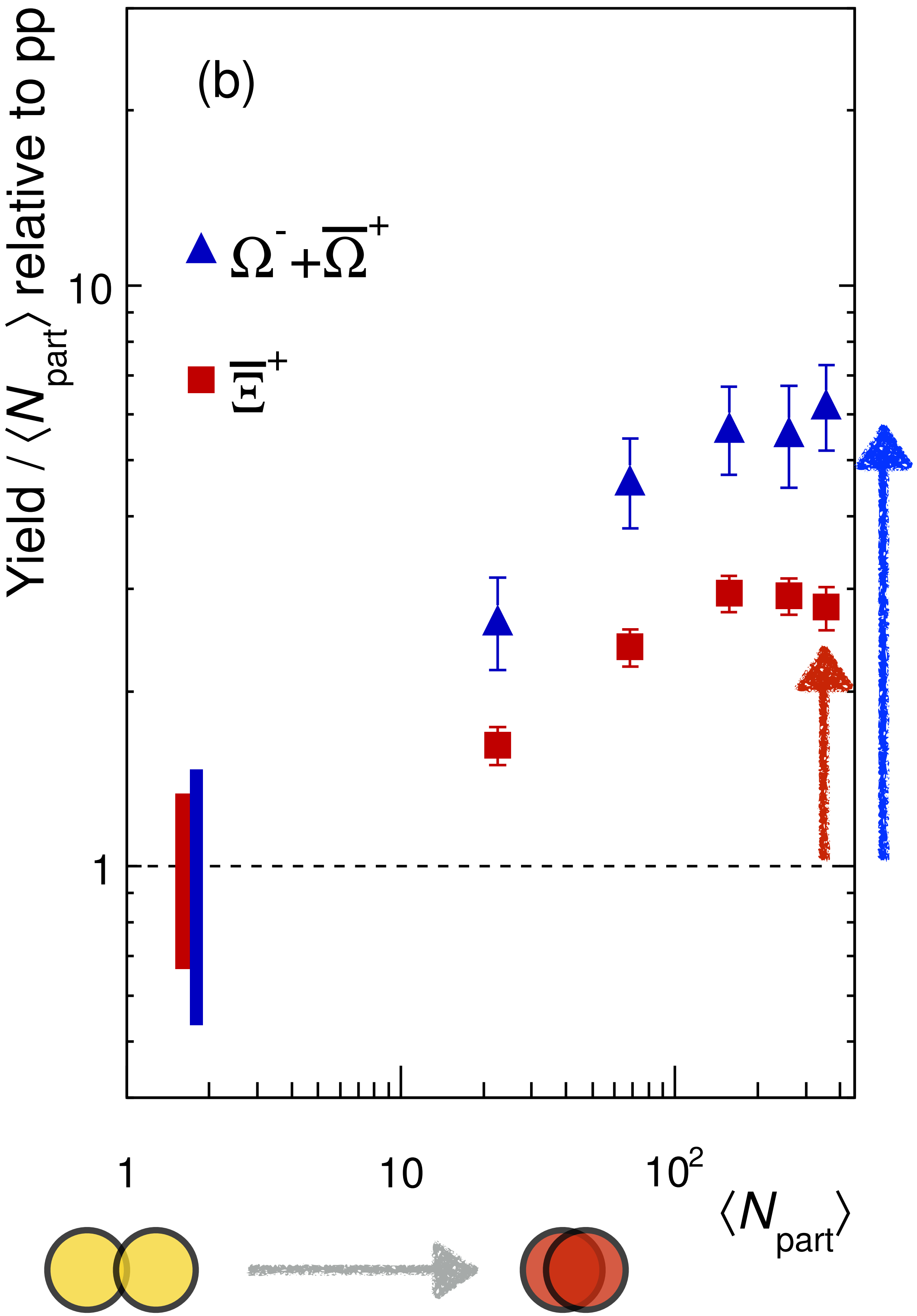
VOLUME 48, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1982

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 ($\overline{\Lambda}$, $\overline{\Omega}$, 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

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

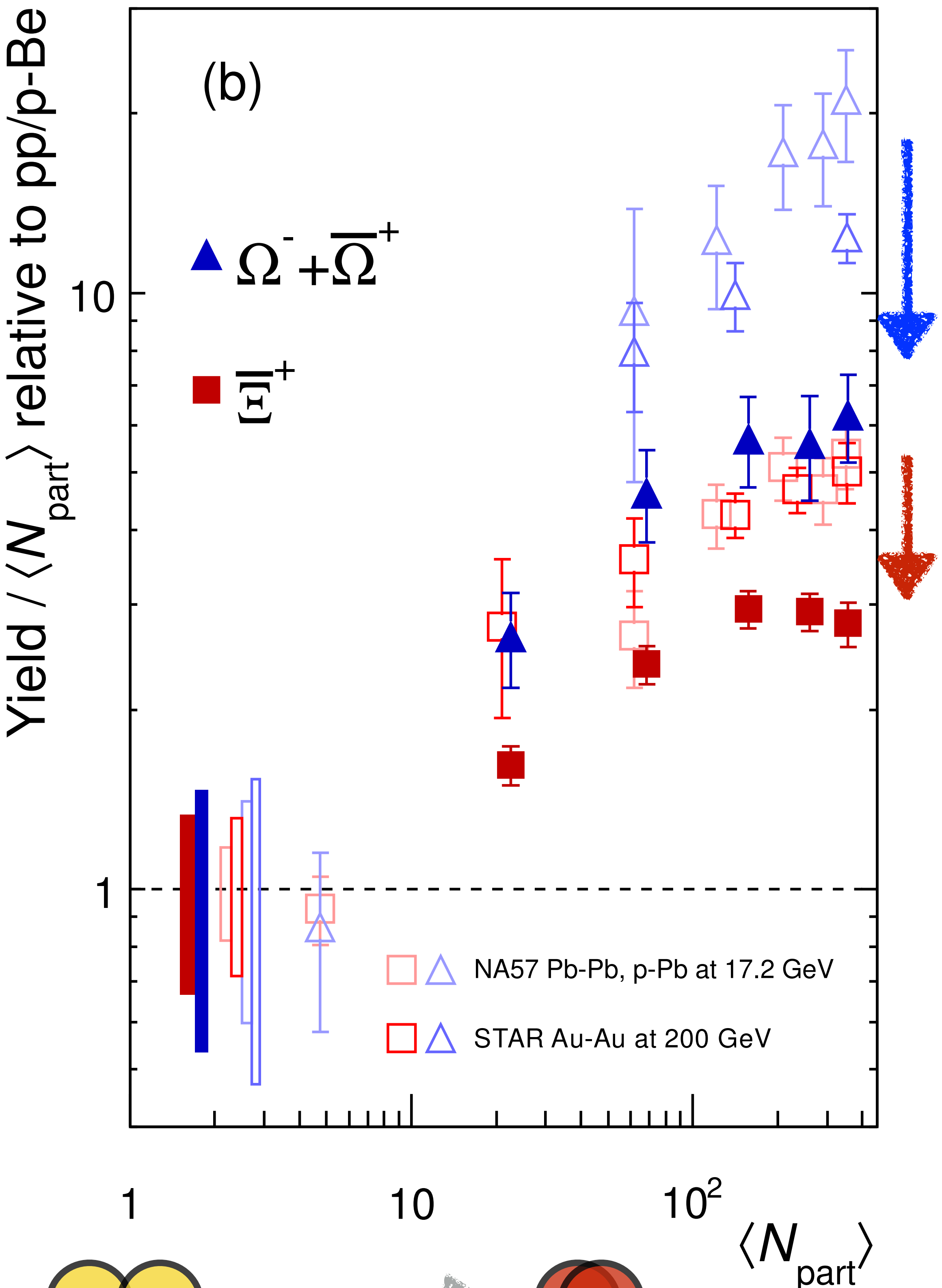
strangeness-content hierarchy

Ξ (dss) enhanced

Ω (sss) more enhanced

ALICE, PLB 728 (2014) 216

Strangeness production in Pb-Pb



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strangeness-content hierarchy

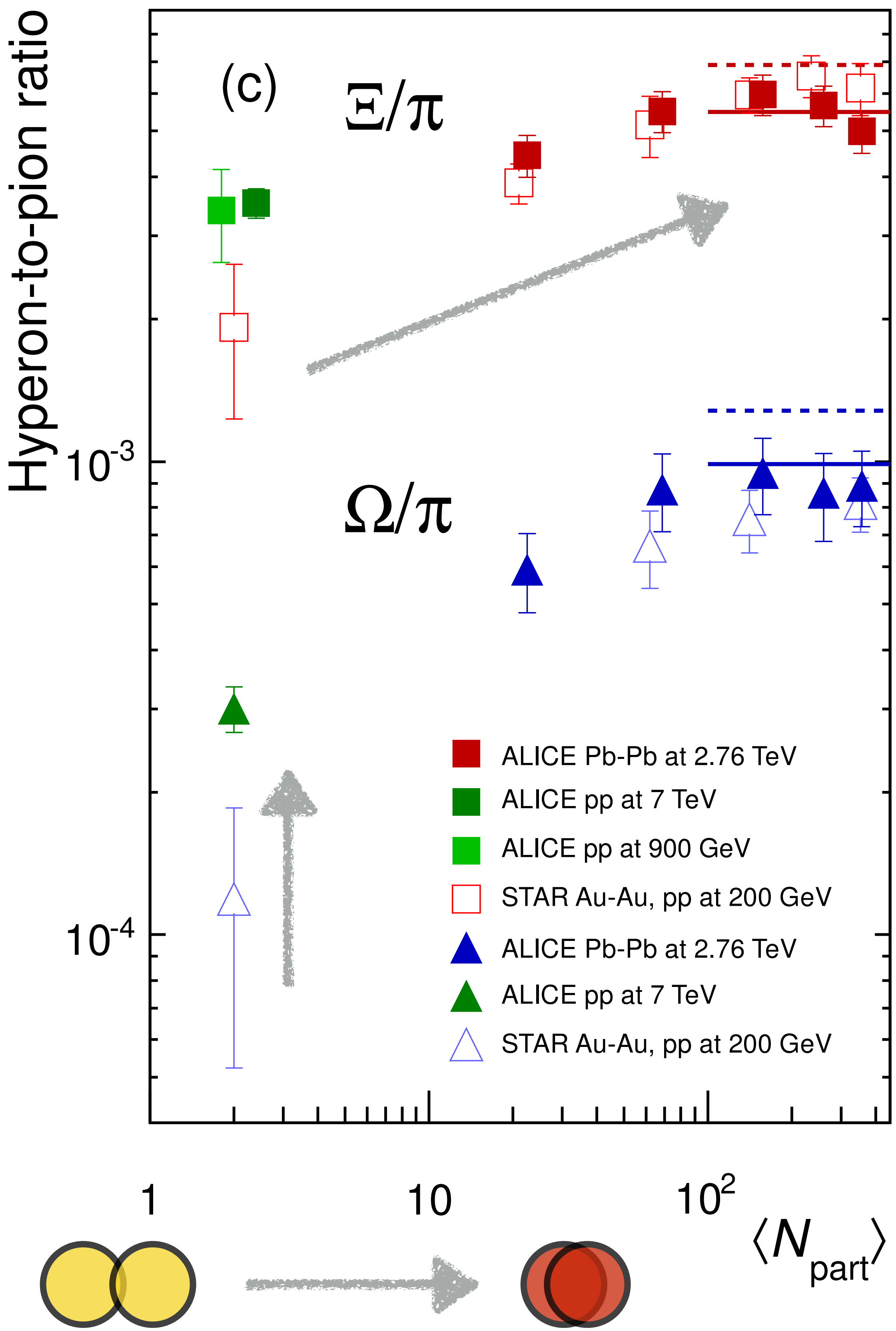
Ξ (dss) enhanced

Ω (sss) more enhanced

decreasing trend with increasing √s (from SPS to LHC)

progressive removal of canonical suppression in pp

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

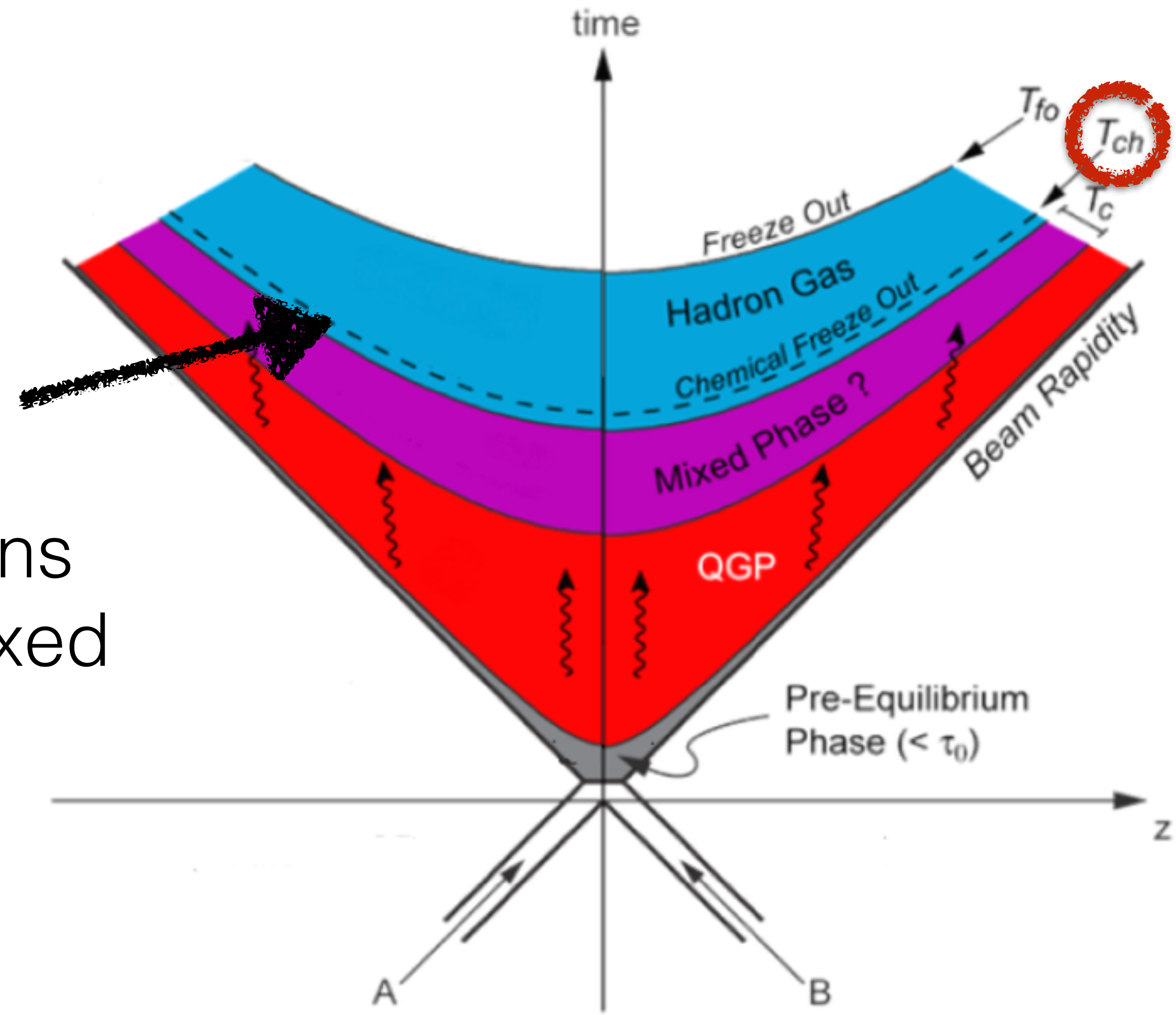
GSI-Heidelberg: T_{ch} = 164 MeV

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

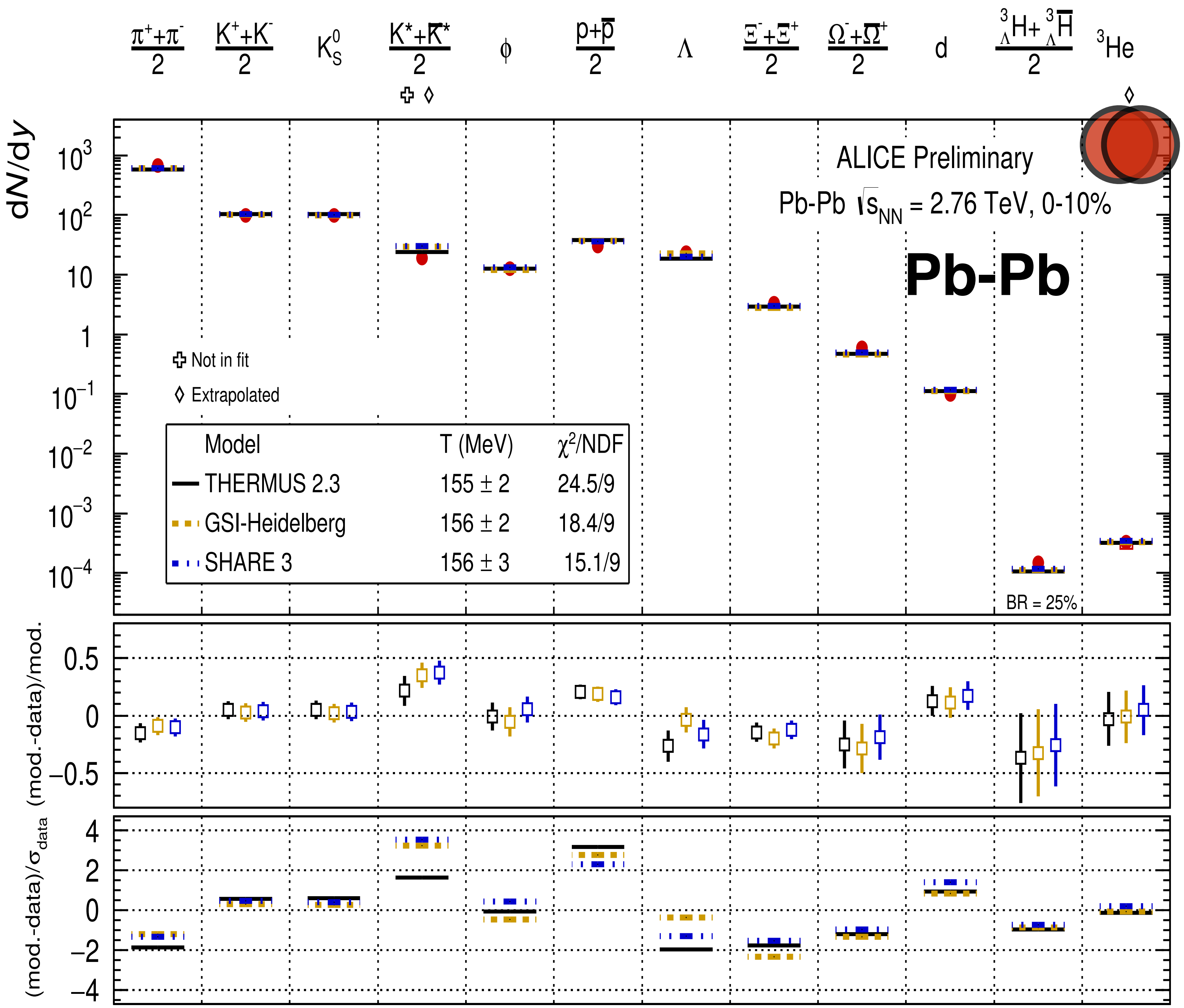
chemical composition is fixed

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

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

Andronic et al., NPA 772 (2006) 167



dN/dy 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, …)

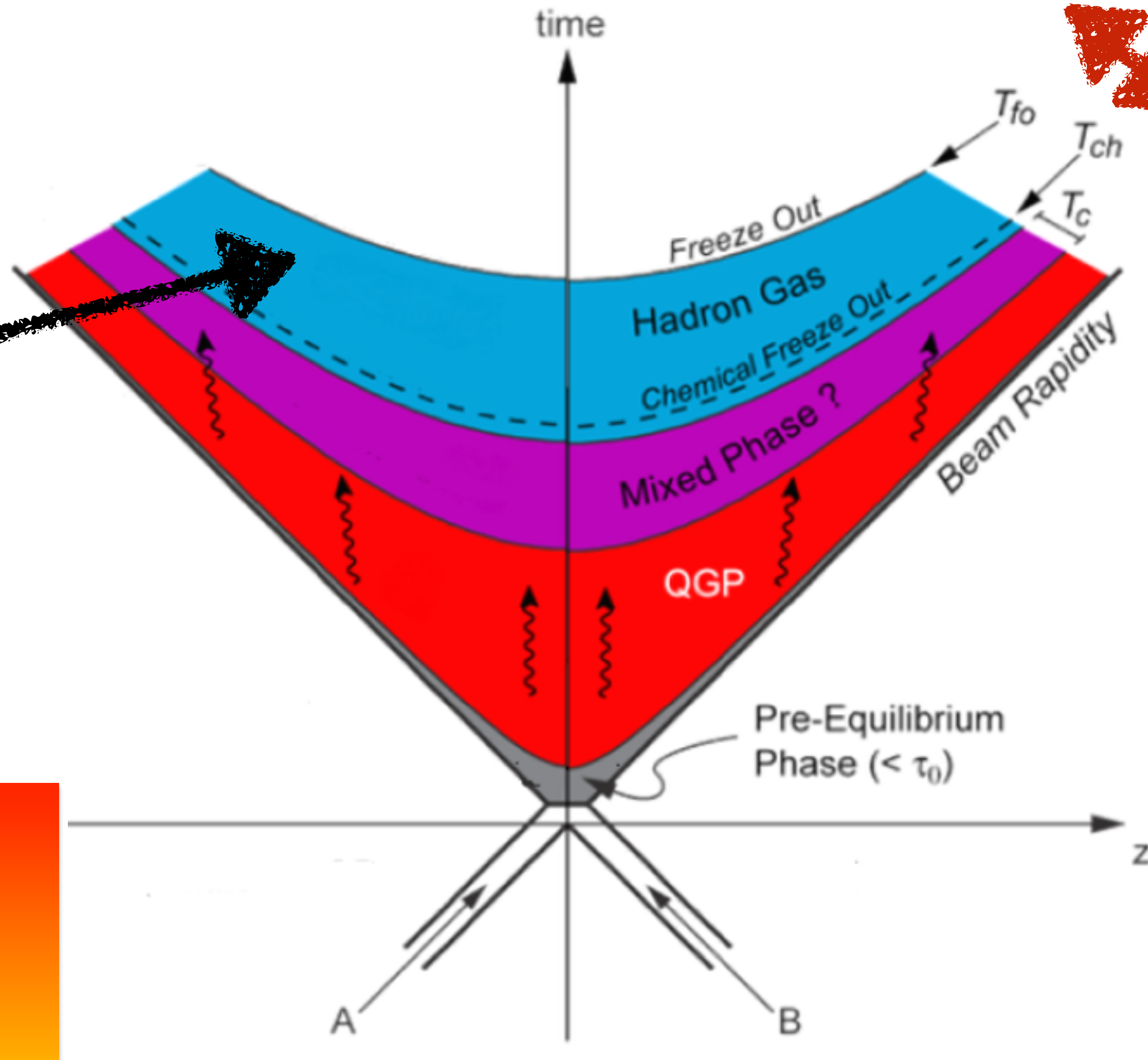
Interactions in the hadronic phase

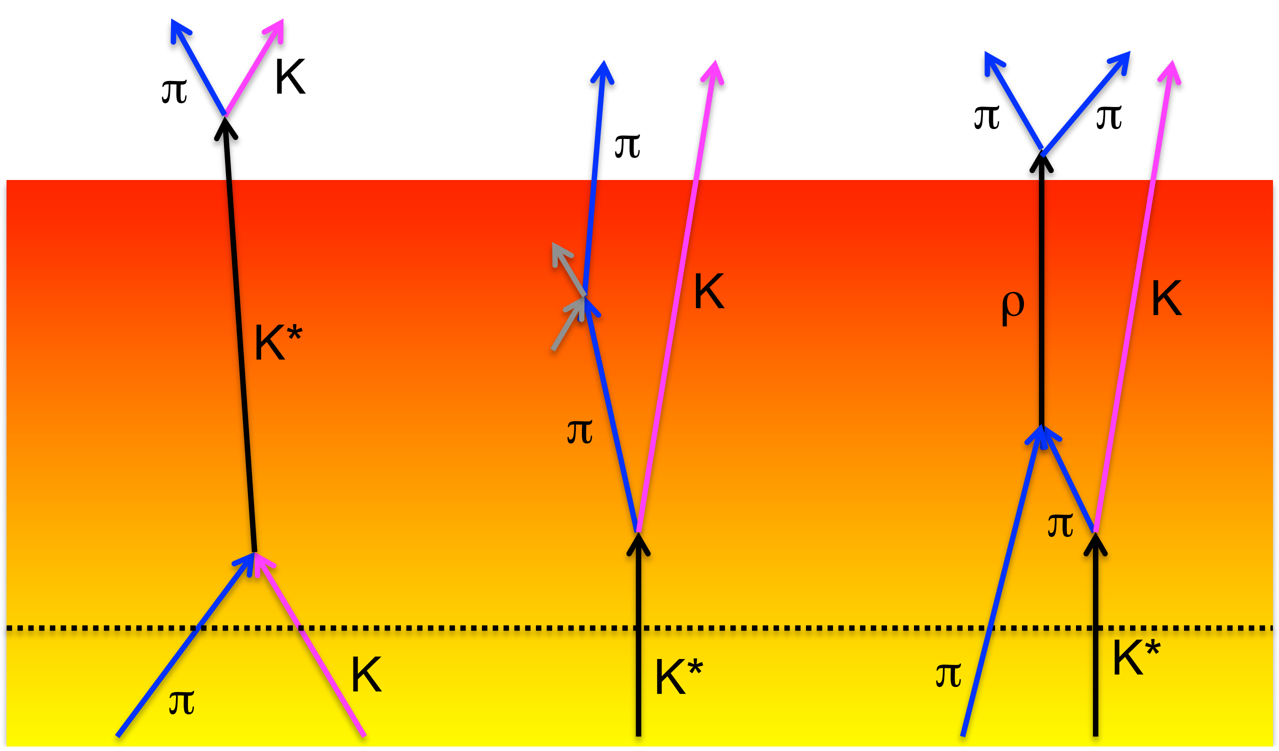
measured yields of resonances might be modified by hadronic processed

hadronic phase

elastic rescattering of decay daughters

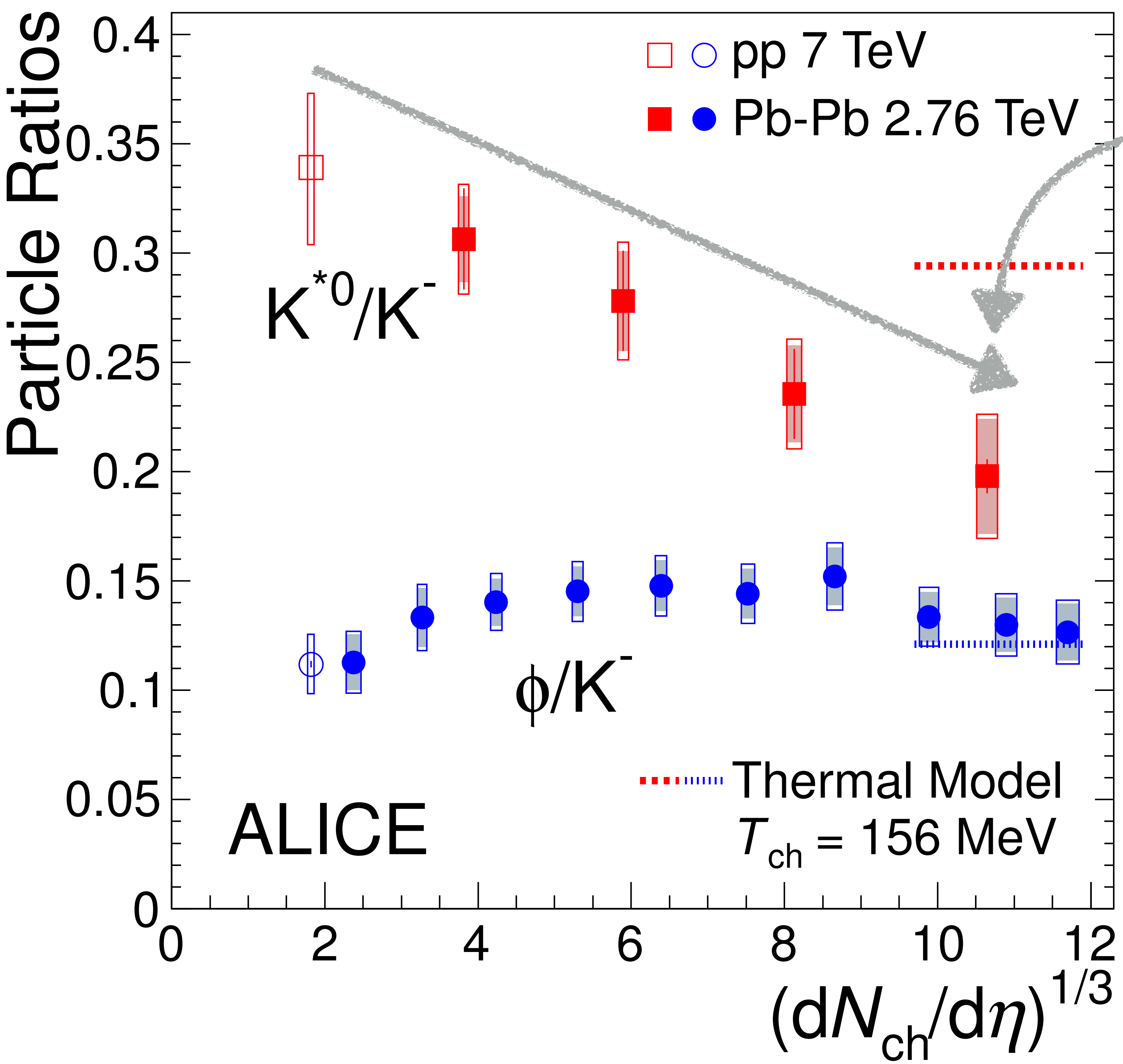
resonances not reconstructed via invariant mass





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

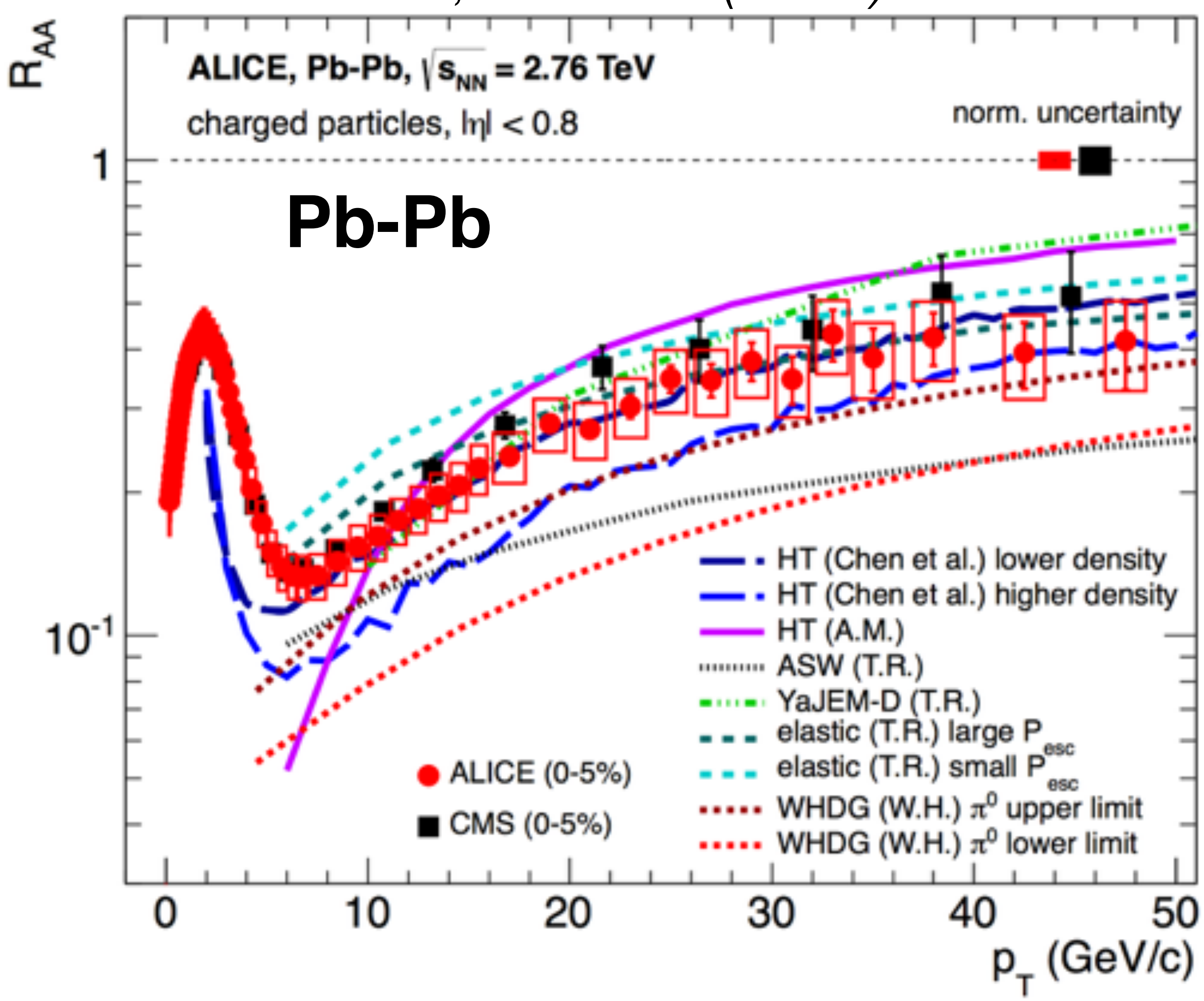
τ_{K^*} (~4 fm/c) ≪ τ_ϕ

Igor Lokhotin

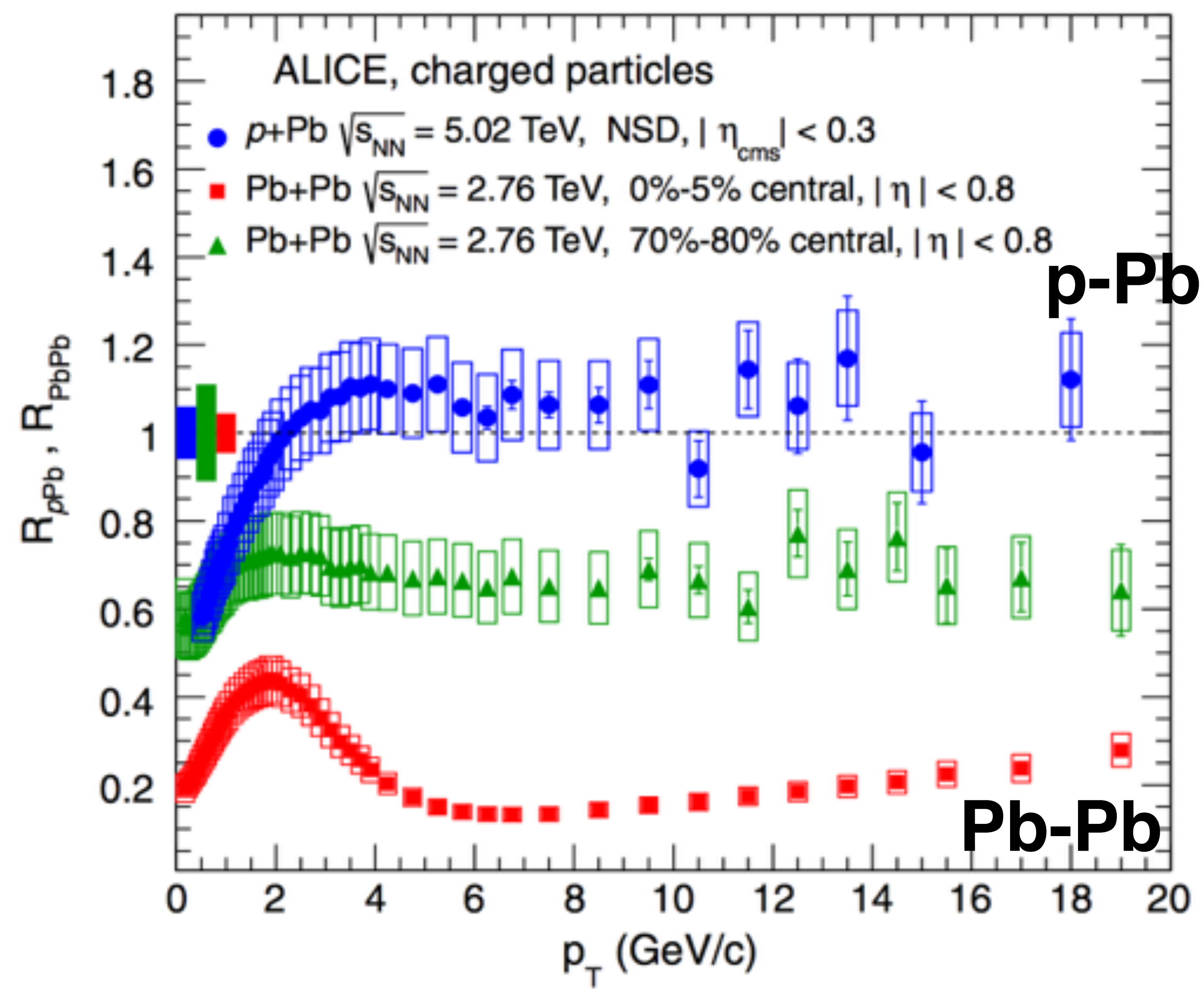
Particle production in proton-nucleus collisions

No nuclear modification in p-Pb

ALICE, PLB 720 (2013) 52
ALICE, EPJC 72 (2012) 1945



ALICE, PRL 110 (2013) 082302



charged particle spectra
strongly modified in Pb-Pb
collisions in a wide p_T range

p-Pb confirms that it comes
from a **final-state effect**
parton in-medium energy loss

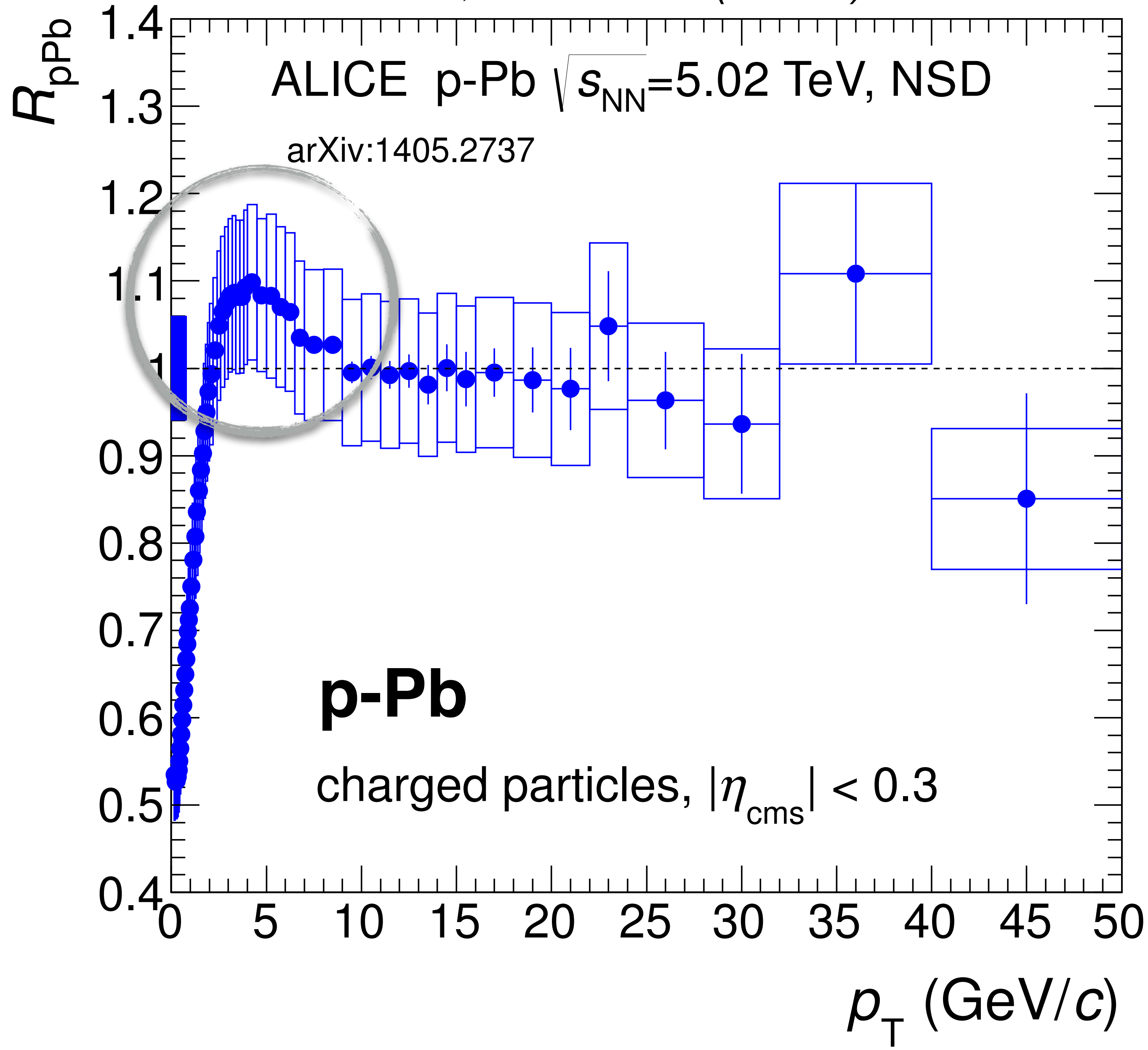
Giuseppe Bruno

R_{pPb} at intermediate p_T

the data indicate a small
enhancement at mid-p_T
stronger enhancement is seen
at lower energies
Cronin, PRD 11 (1975) 3105

traditional explanations of
Cronin enhancement
multiple soft scatterings in the initial
state prior to the hard scattering
Accardi, arXiv:hep-ph/0212148

ALICE, EPJC 74 (2014) 3054

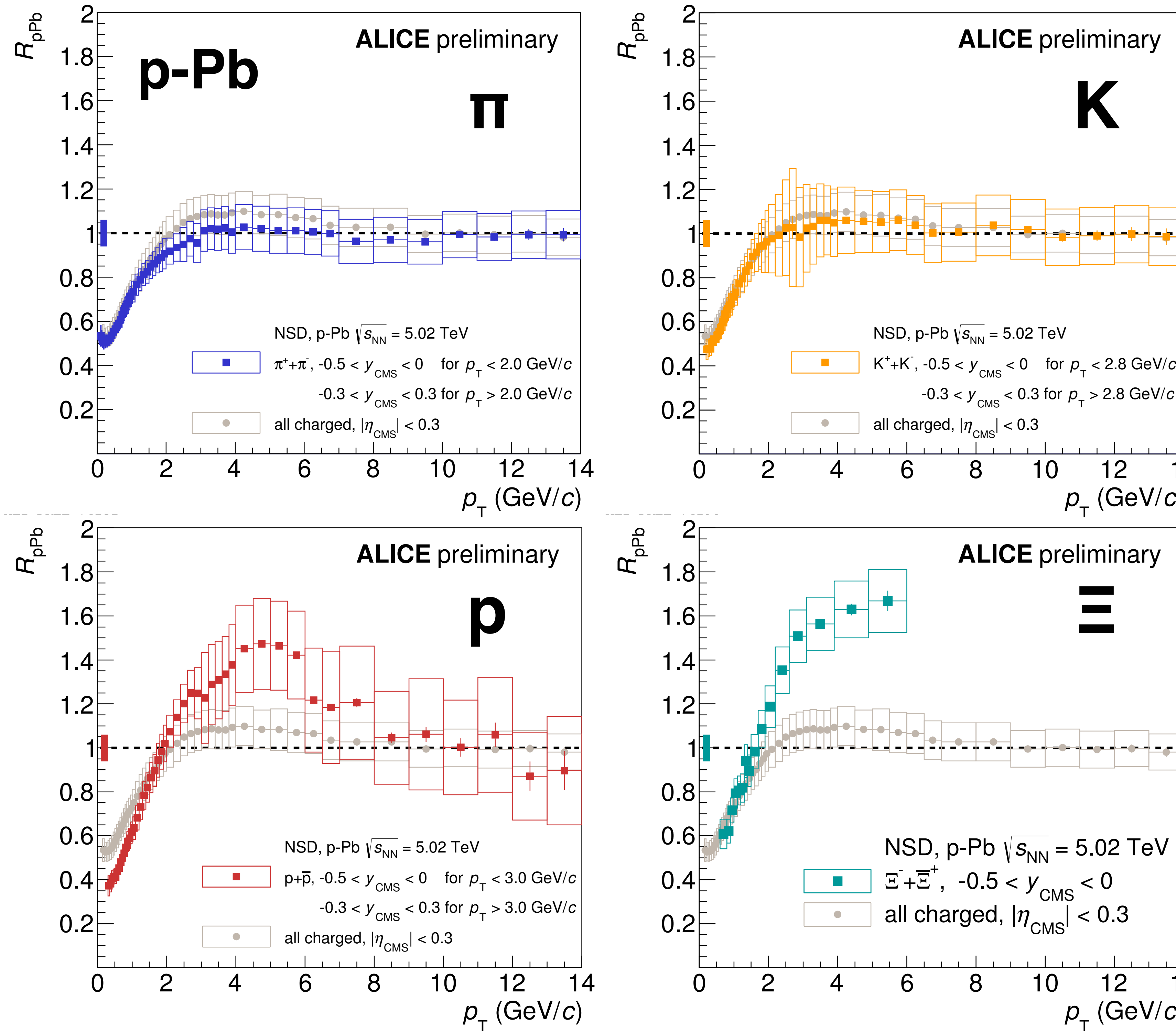


Identified particle R_{pPb}

pions and **kaons** consistent with no modification at mid-p_T

rather pronounced peak for **protons**

even stronger enhancement for **cascades**

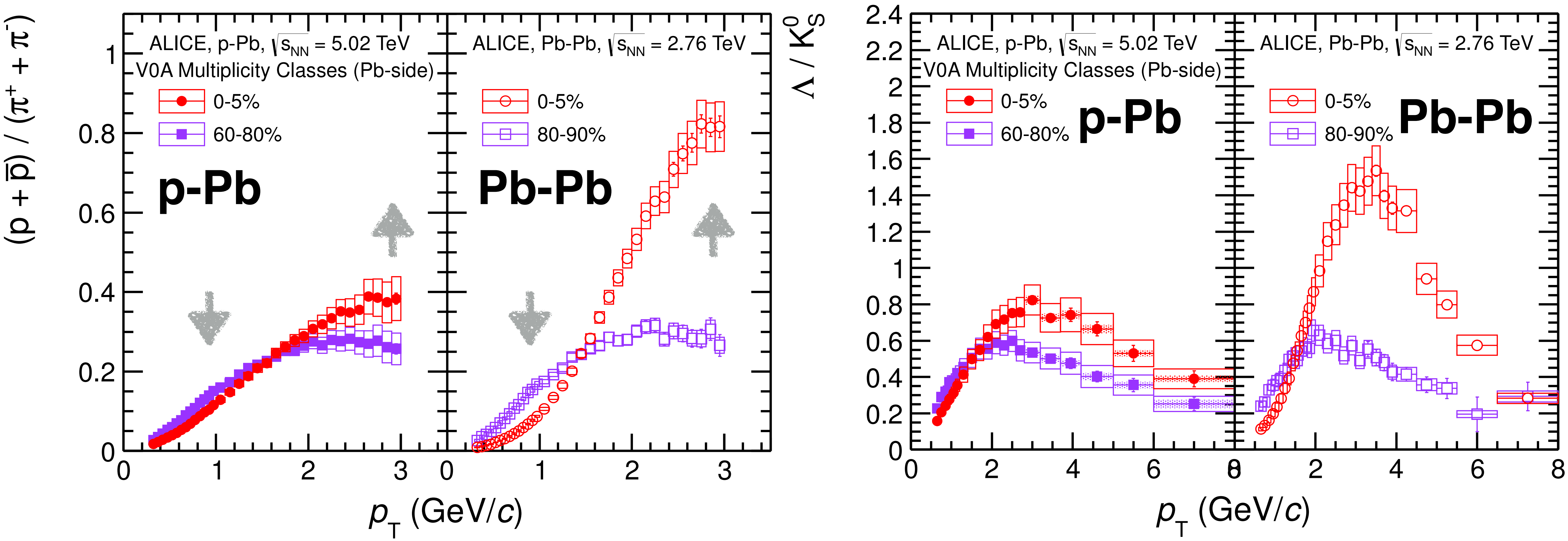


particle species dependence suggests final state effects

recombination, collective flow, …

Baryon enhancement

ALICE, PLB 728 (2014) 25



Significant centrality/multiplicity dependence of the ratios

enhancement at mid-p_T with increasing multiplicity

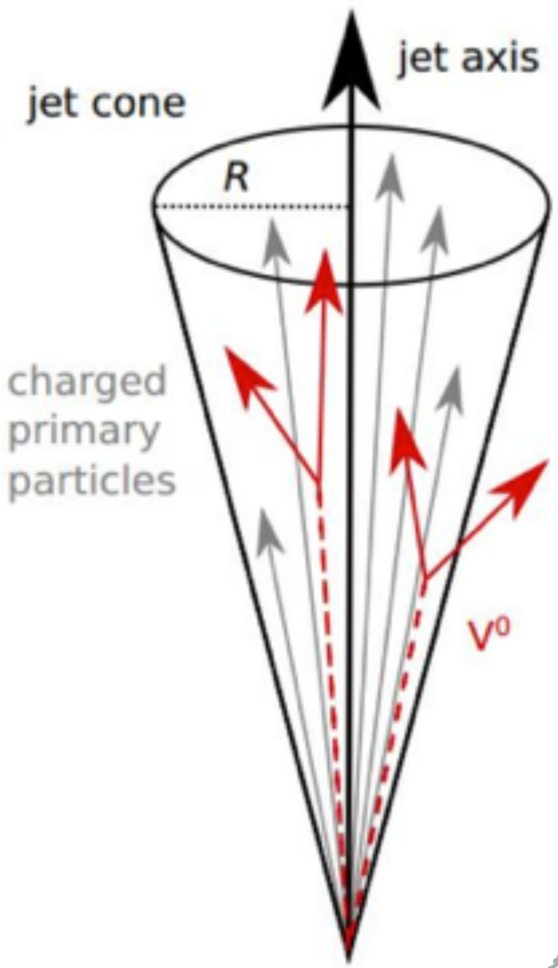
corresponding depletion in the low-p_T region

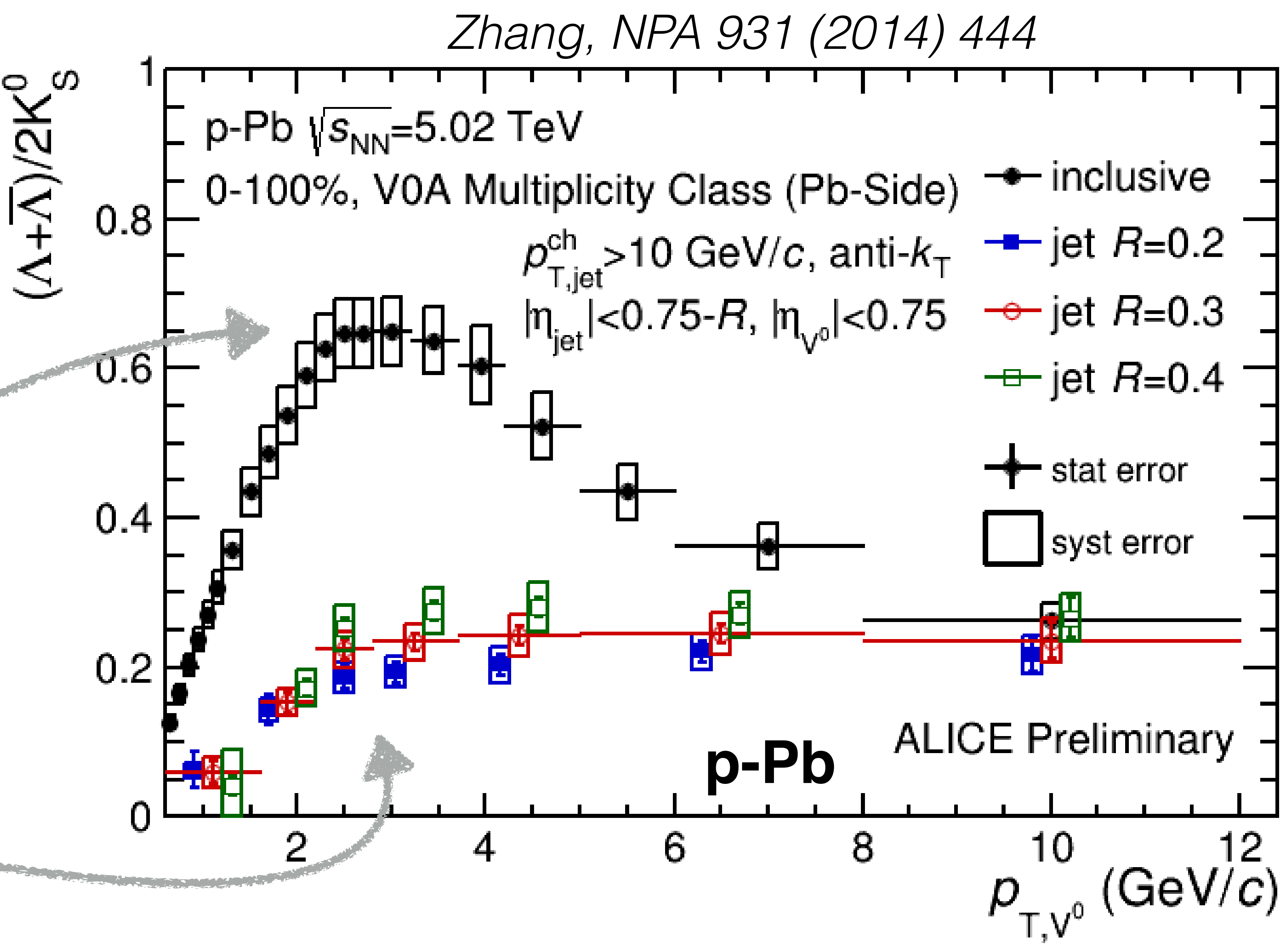
Reminiscent of A-A observations

commonly understood in terms of collective flow / quark recombination

Where are the extra baryons from?

Λ/K^0_S production ratio measured in charged jets





inclusive particles

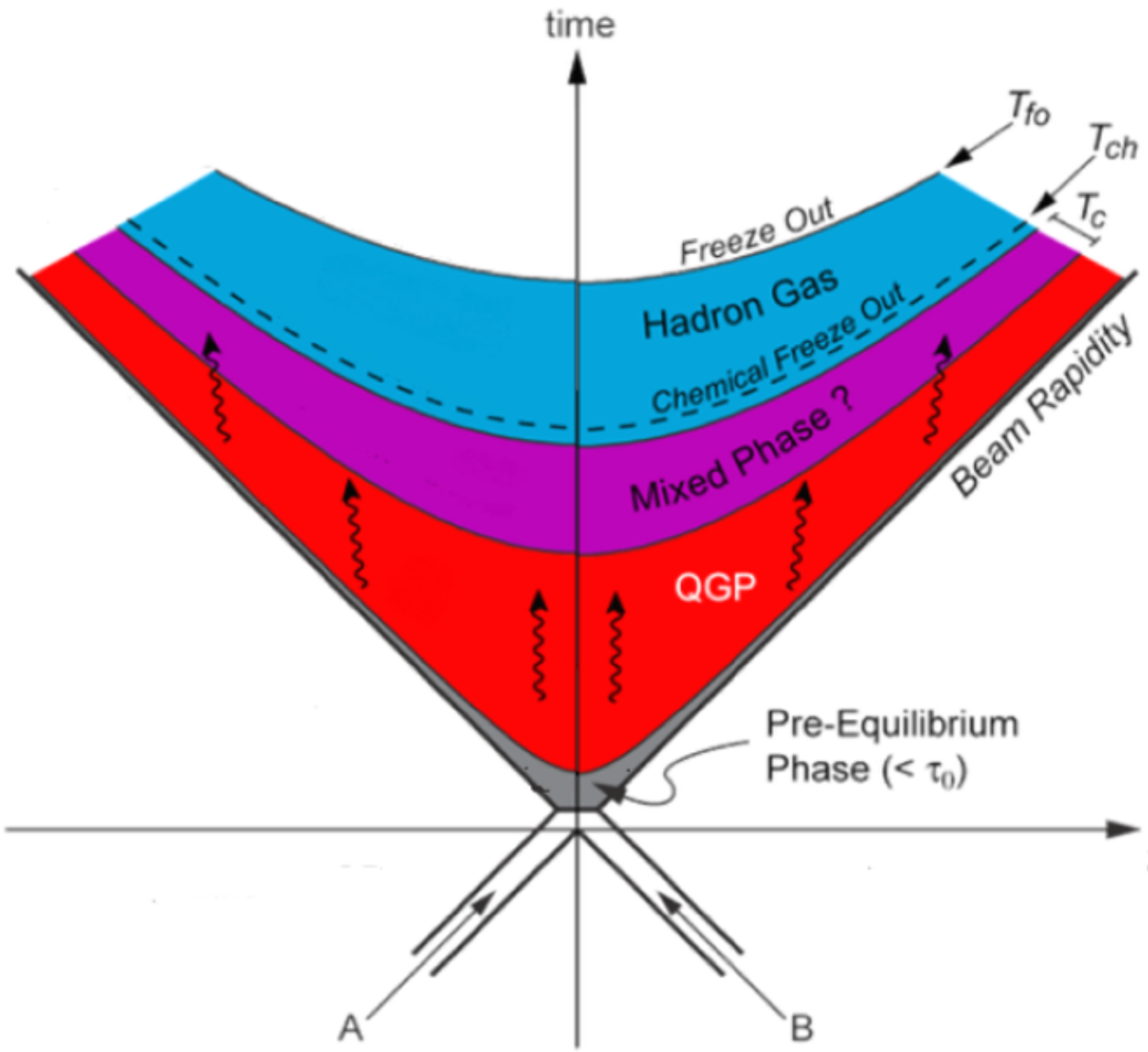
jets do not show enhancement

the extra baryons are **not coming from jets**

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)

are there final state dense matter effects in p-Pb?

Bulk π, K, p production in p-Pb

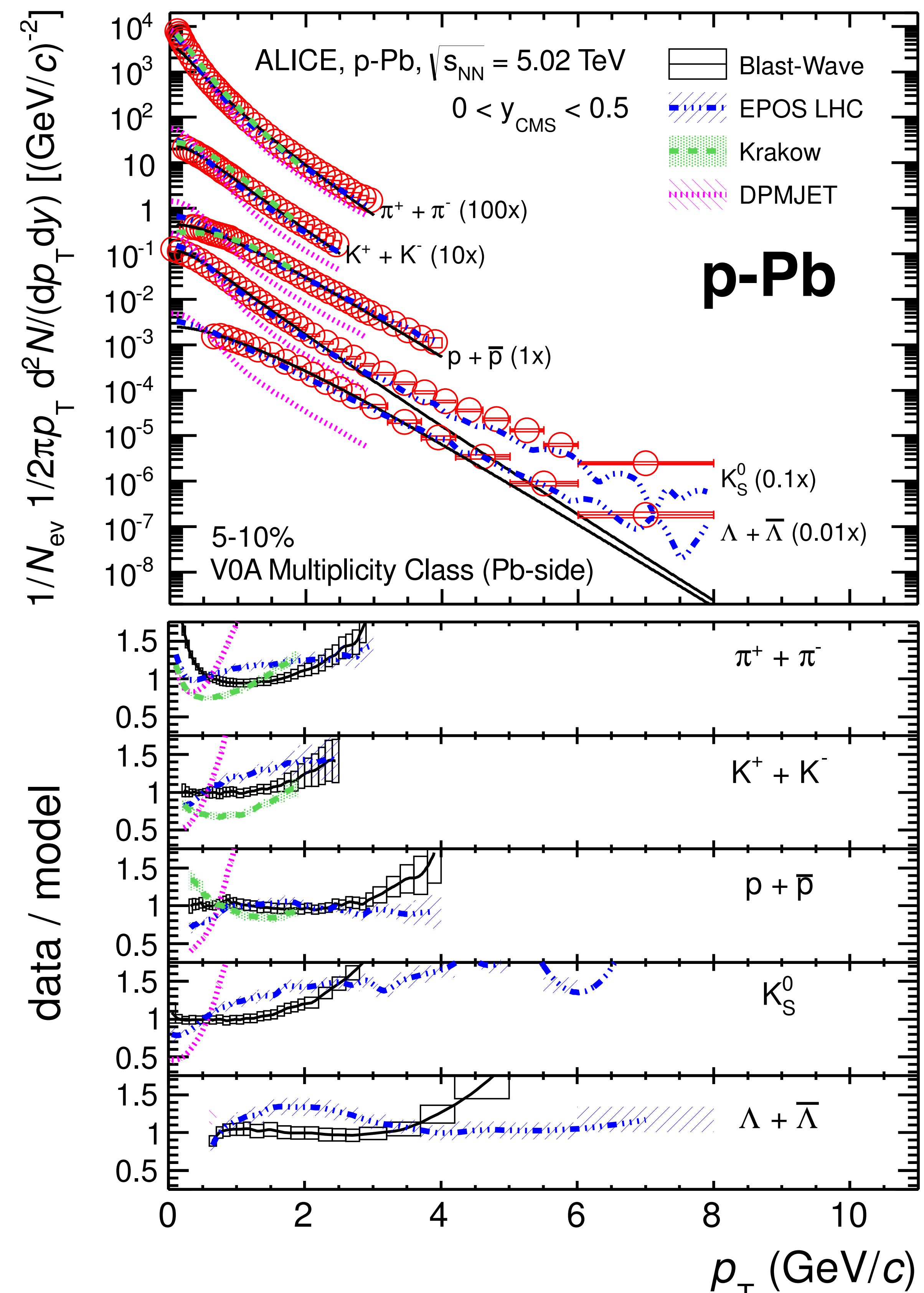
Blast-Wave
hydro-motivated fit
thermal sources expanding
with common velocity

EPOS LHC
full event generator with
hydro evolution

Krakow
3+1 viscous hydro

DPMJET
pQCD based

Models including hydrodynamics do a better job describing the data



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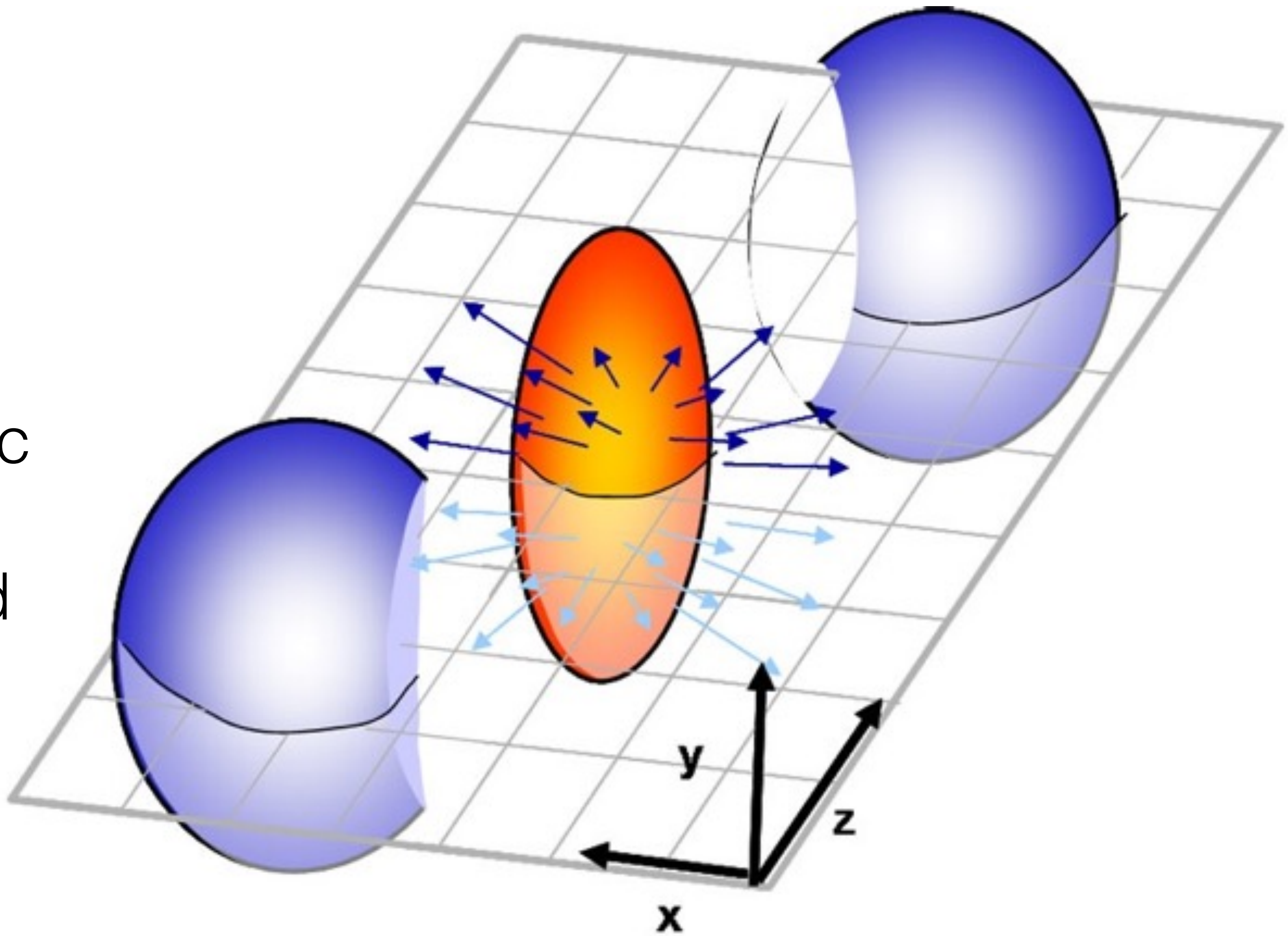

resulting in

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- <u>azimuthal anisotropic flow patterns (initial spatial anisotropy)</u>

are there final state dense matter effects in p-Pb?

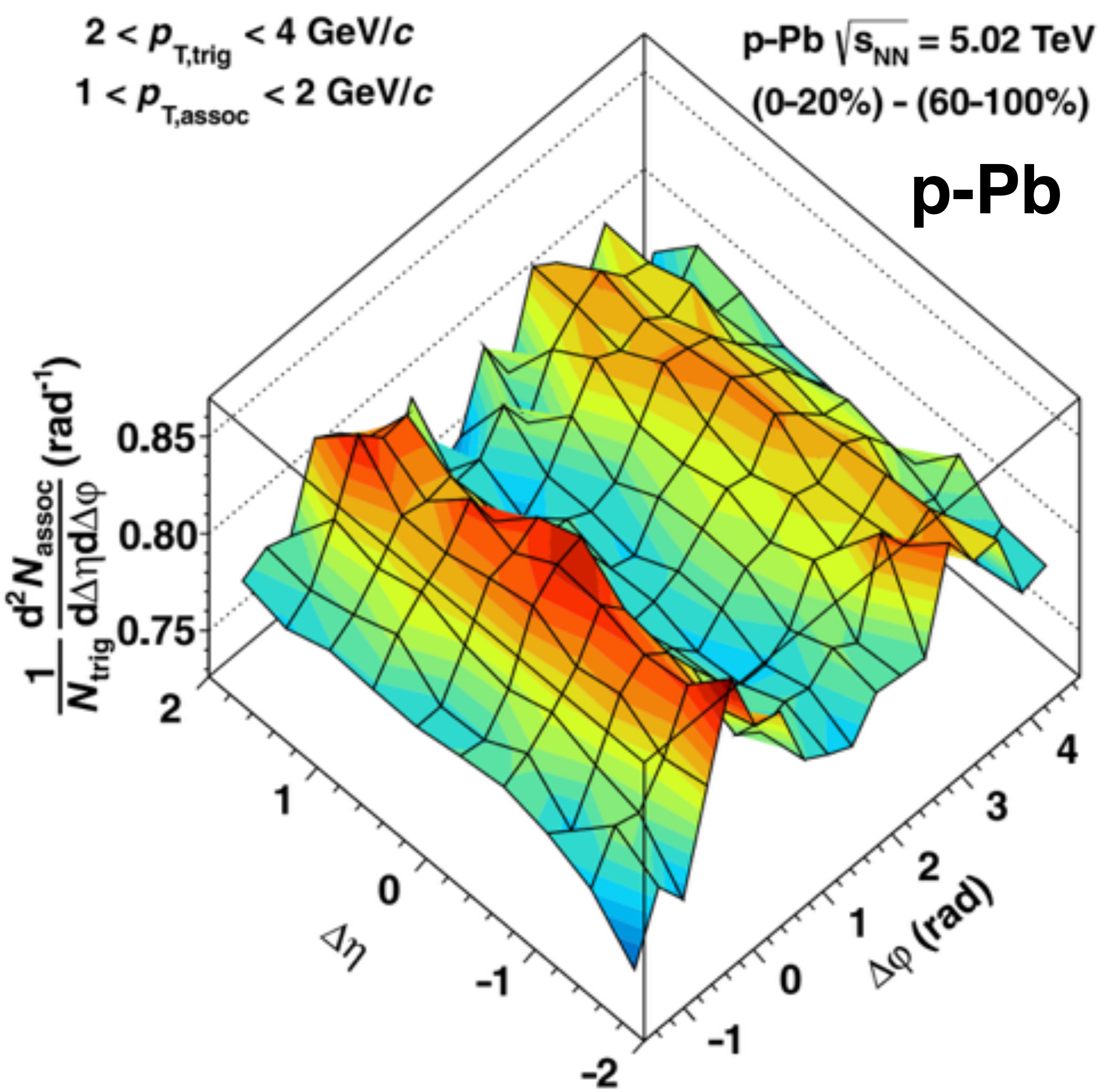
The double ridge

Alice Ohlson

the ridge in p-Pb events triggered further investigations

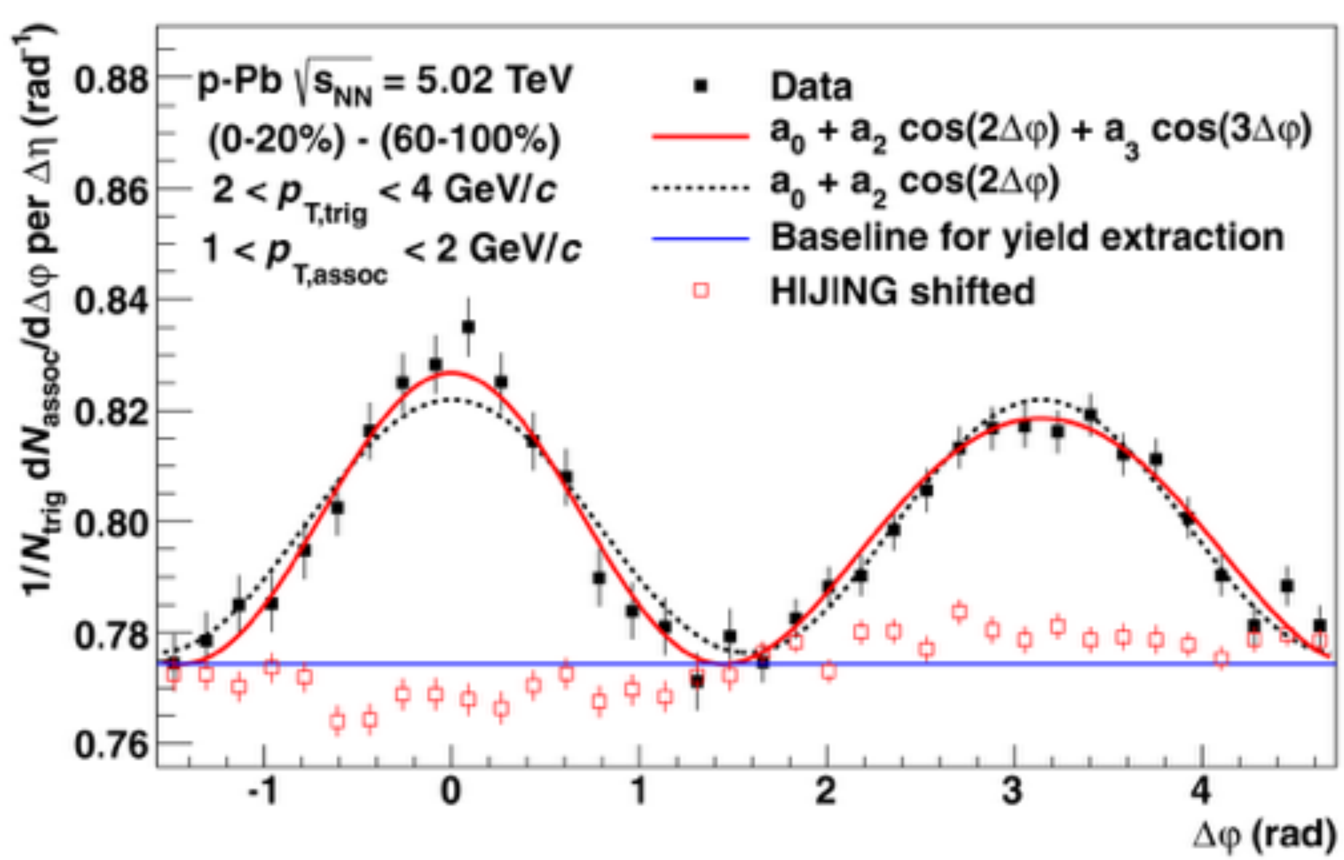
jet contribution removed by subtracting low-multiplicity events

a **double ridge** structure **was revealed**



this looks so much like flow

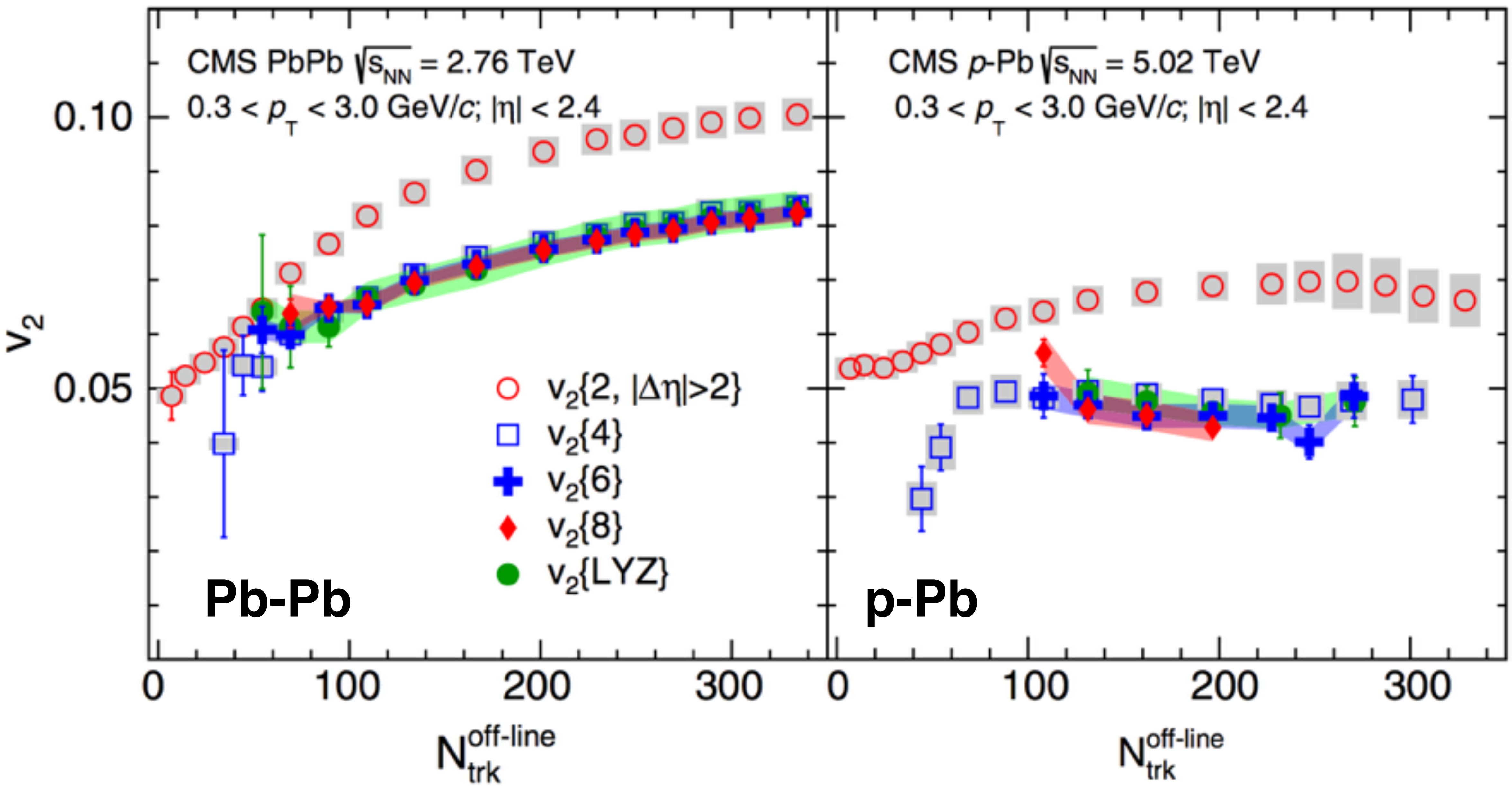
Fourier decomposition of $\Delta\phi$: v_2, v_3, ...



ALICE, PLB 719 (2013) 29

True collective effect

CMS, PRL 115 (2015) 012301



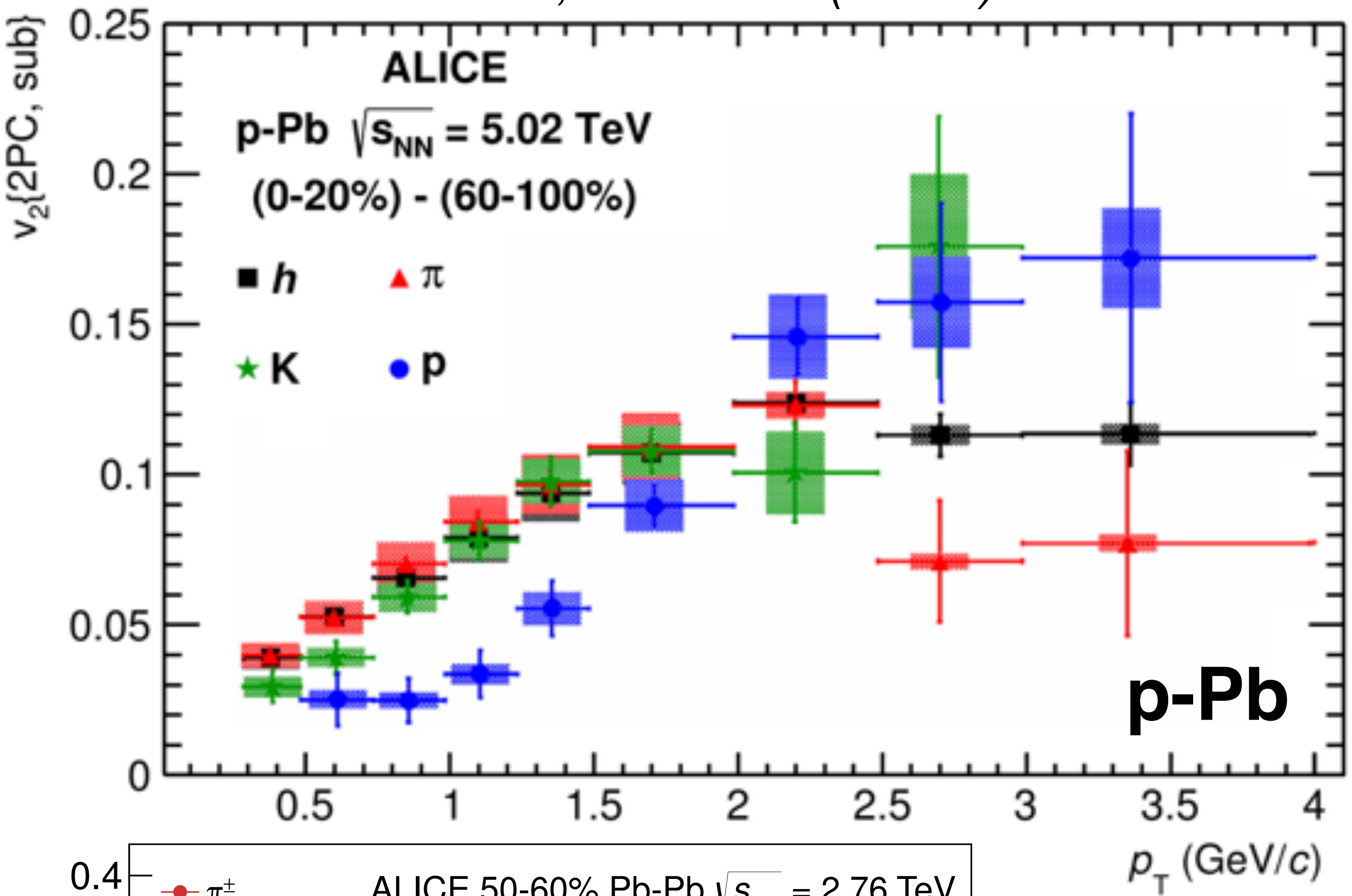
v_2 stays large when computed with multi-particles

$v_2\{4\} = v_2\{6\} = v_2\{8\} = v_2\{LYZ\}$ have different sensitivity to non-flow effects

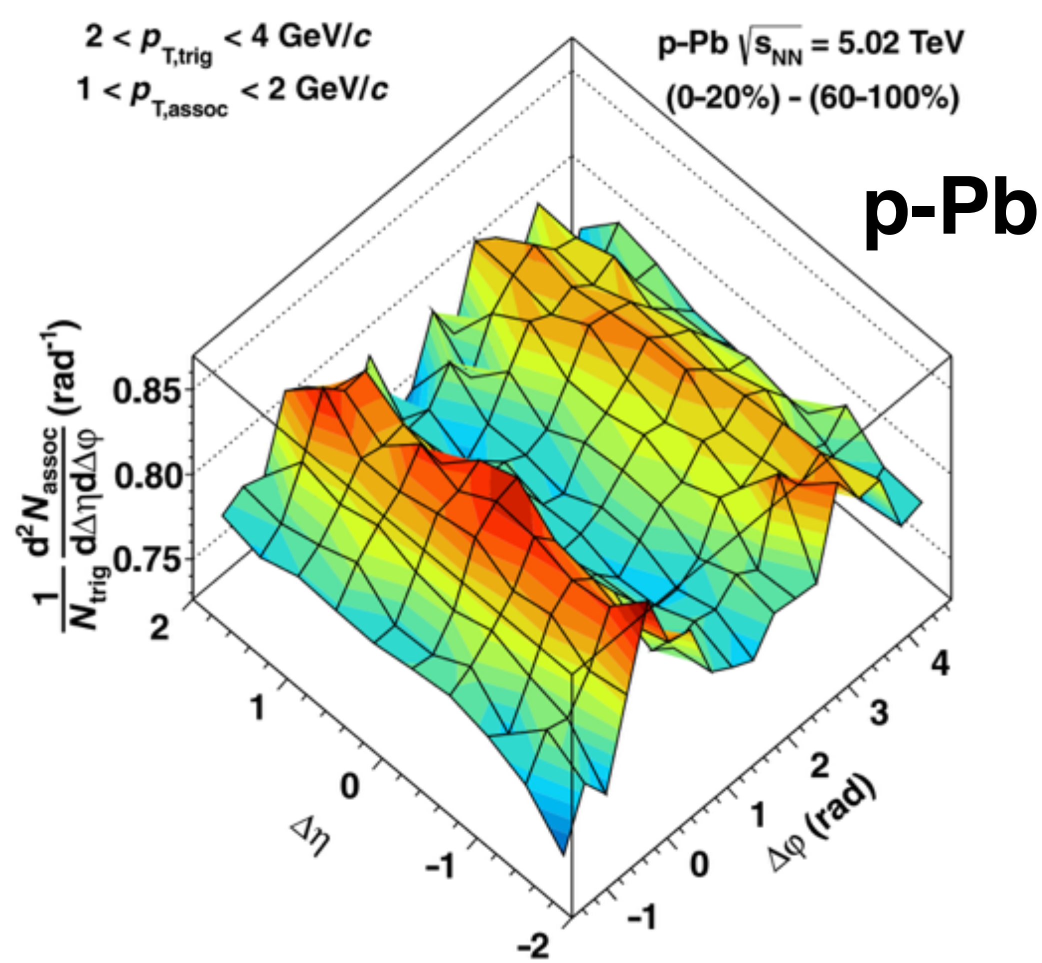
there is **true collectivity in p-Pb**

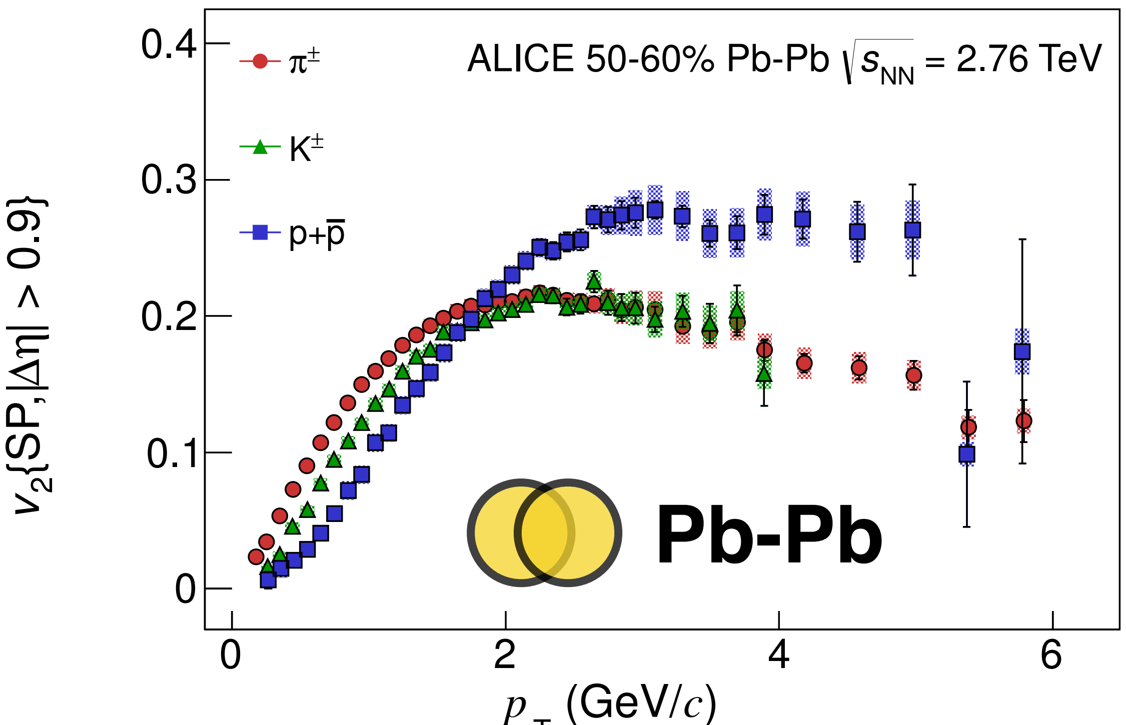
v_2 of identified particles in p-Pb

ALICE, PLB 726 (2013) 164



ALICE, PLB 719 (2013) 29





mass ordering observed at low p_T

lower v_2 for heavier particles

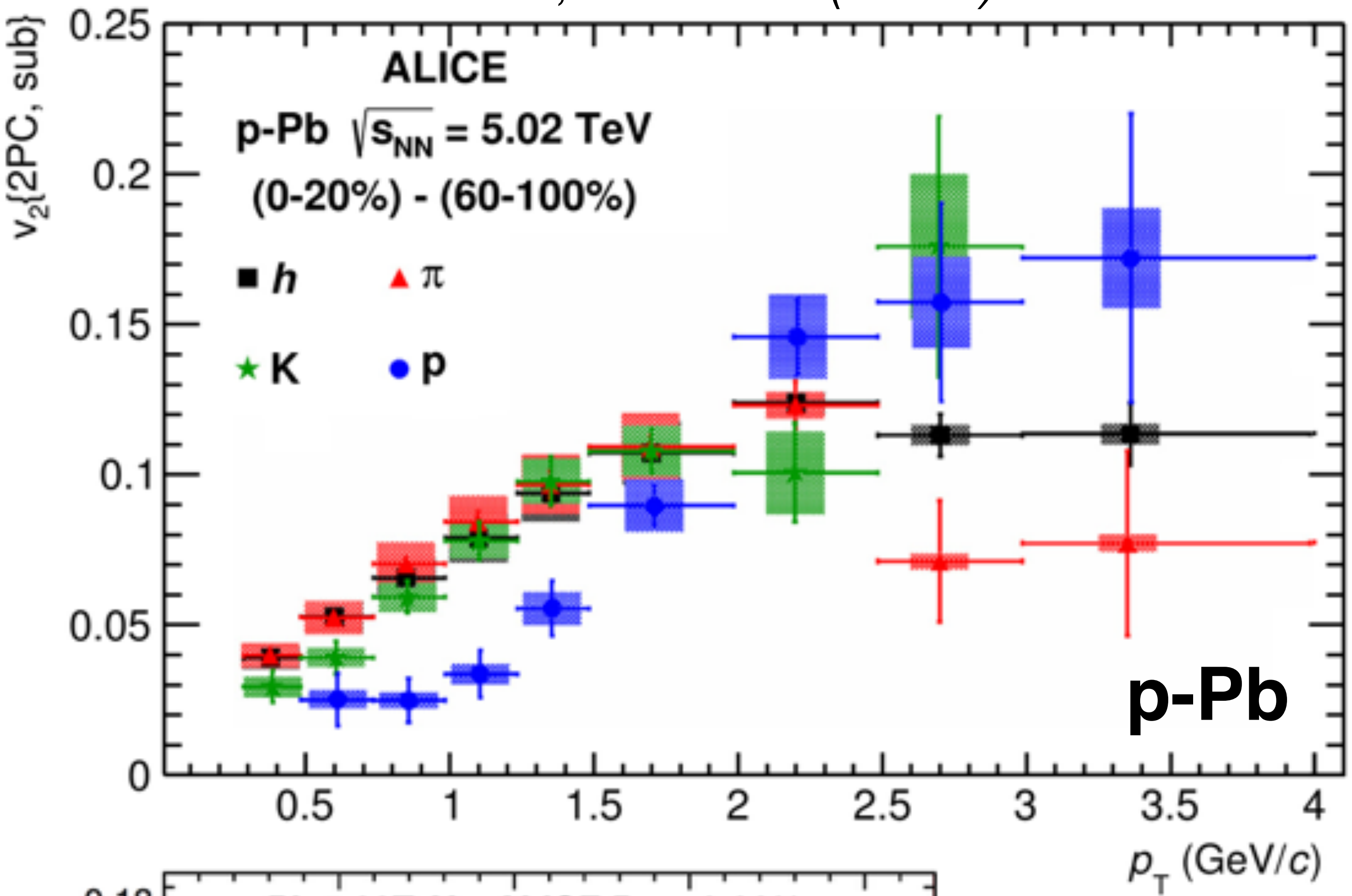
crossing at higher p_T

reminiscent of A-A observations

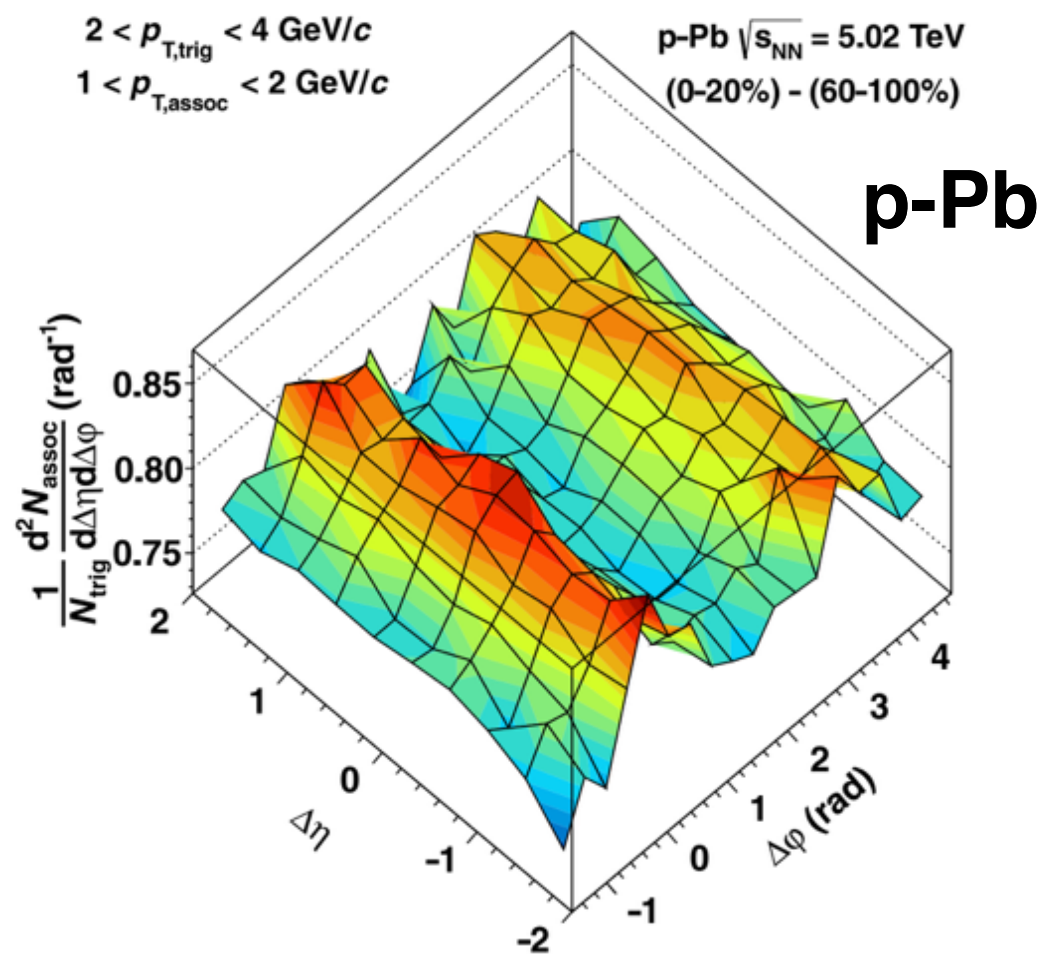
ALICE, JHEP 1506 (2015) 190

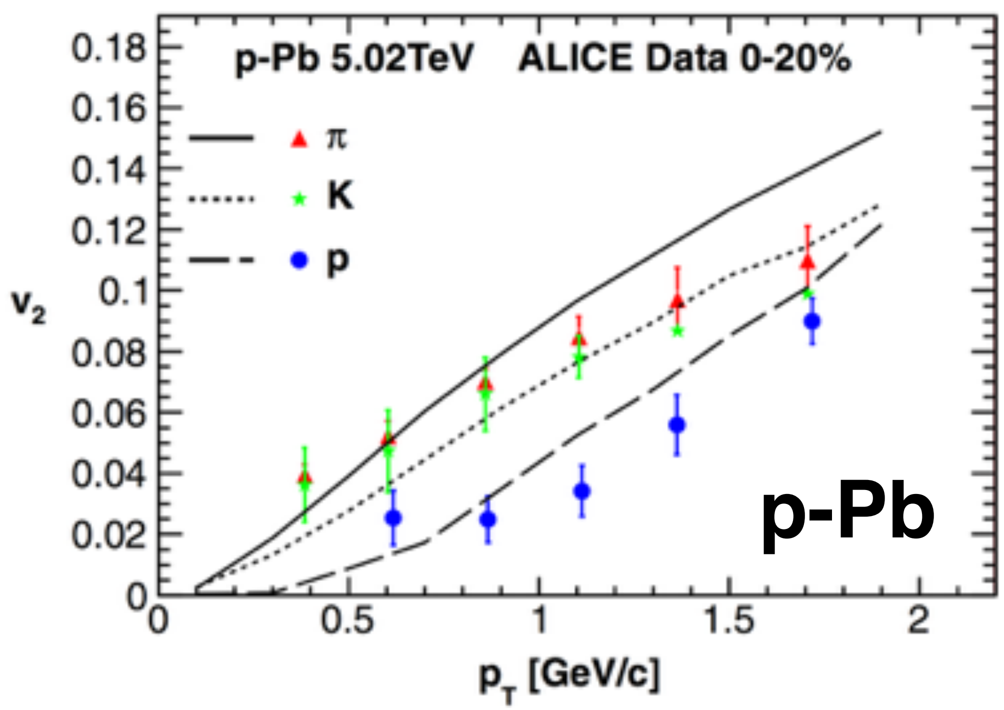
v_2 of identified particles in p-Pb

ALICE, PLB 726 (2013) 164



ALICE, PLB 719 (2013) 29





mass ordering observed at low p_T

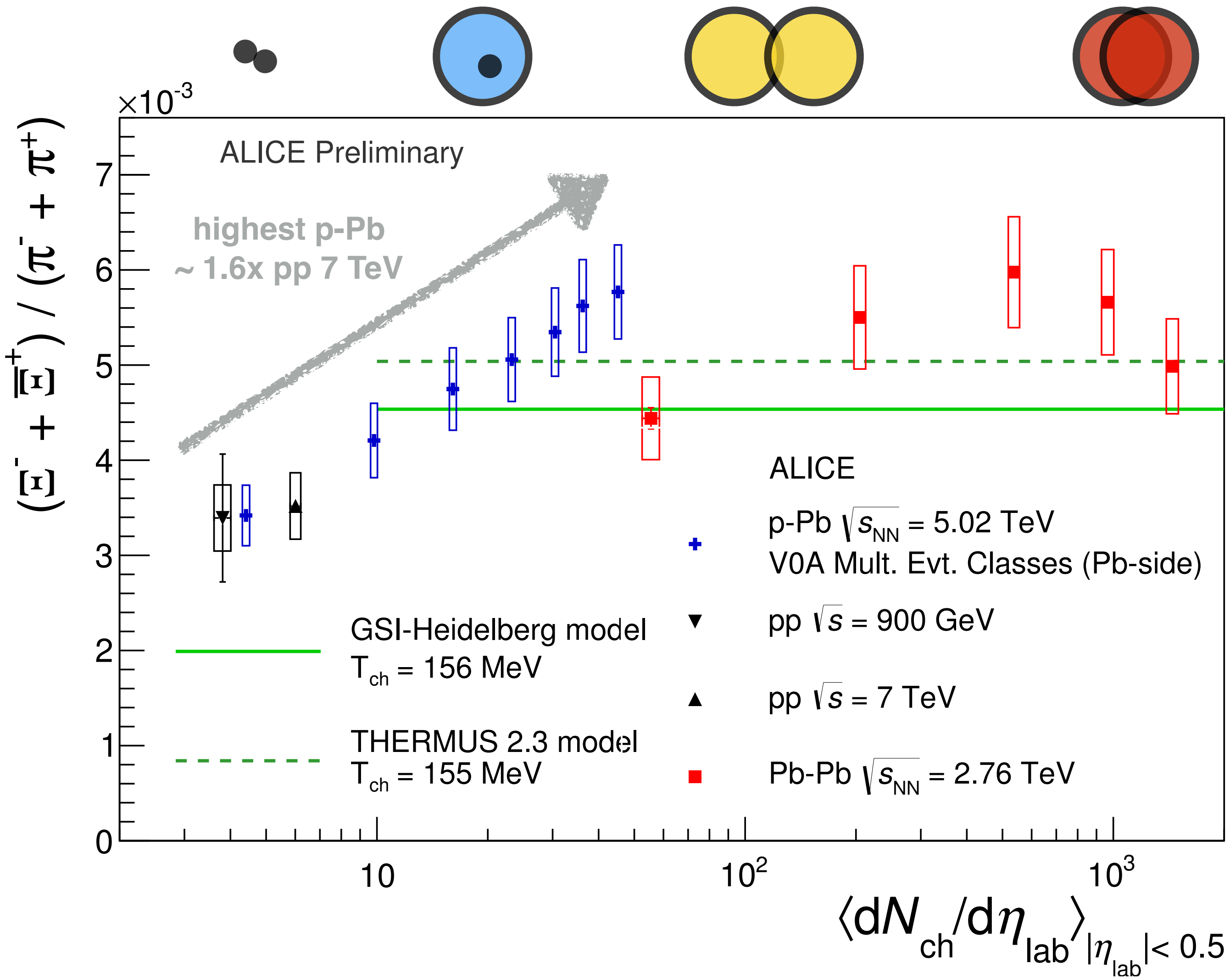
lower v_2 for heavier particles

crossing at higher p_T

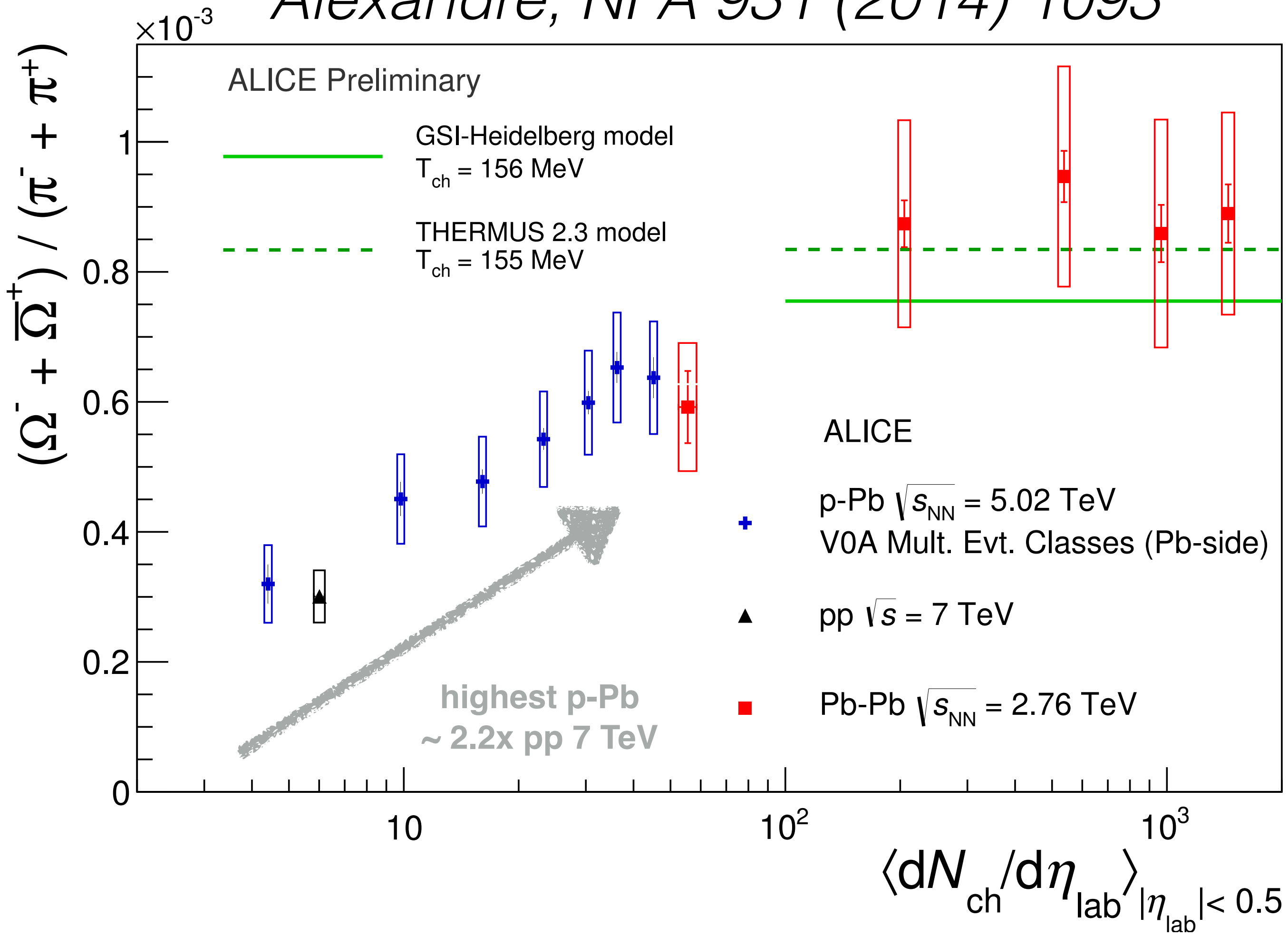
consistent with expectations from collective hydrodynamic expansion

Bozek et al., PRL 111 (2013) 172303

Strangeness production in p-Pb



Alexandre, NPA 931 (2014) 1093



Ξ/π and Ω/π ratios in p-Pb increase with increasing $\langle N_{ch} \rangle$

low-multiplicity

Ξ and Ω → consistent with pp

high-multiplicity

Ξ → compatible with central Pb-Pb

Ω → compatible with peripheral Pb-Pb

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

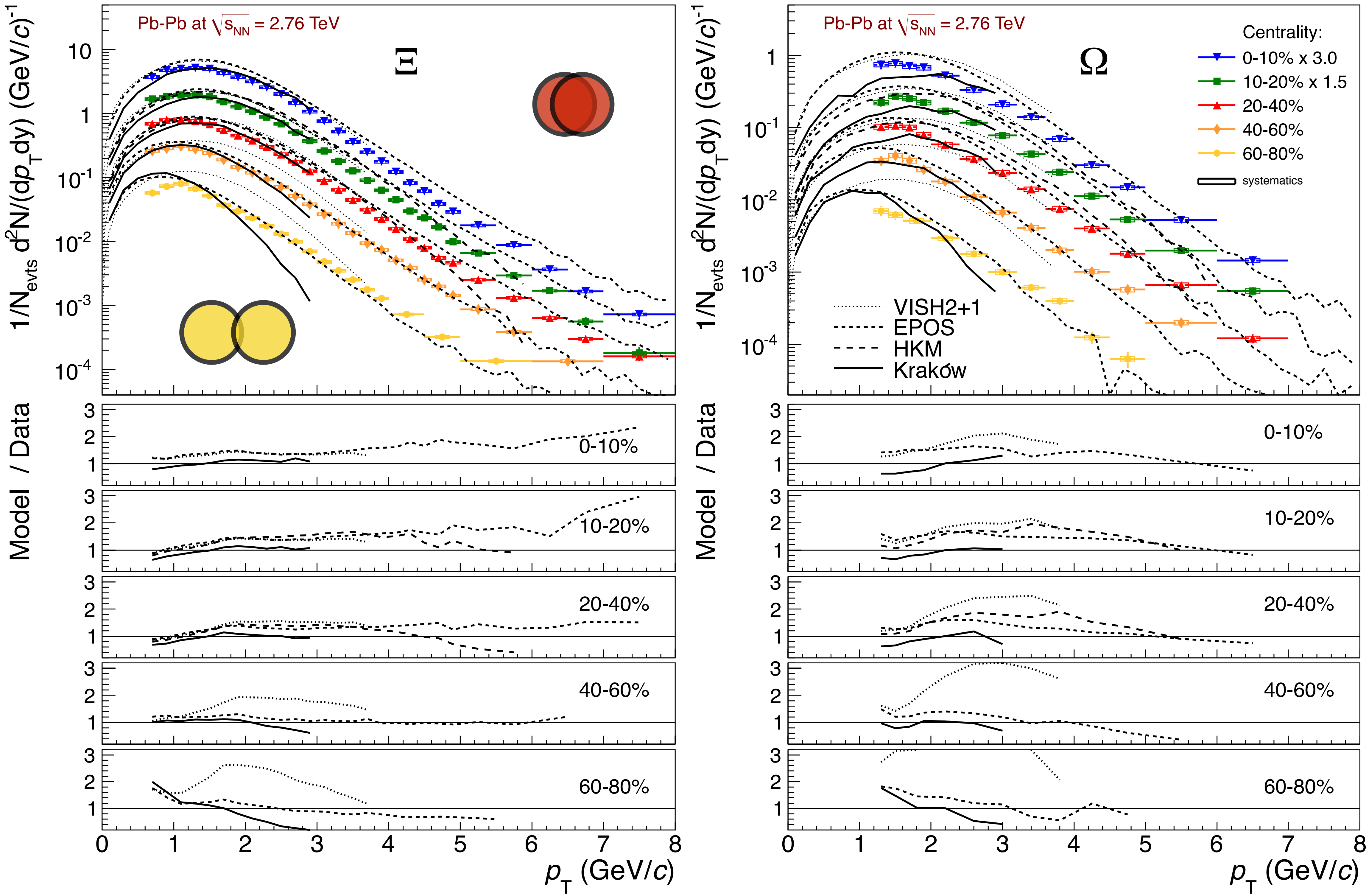
non-zero elliptic flow, mass-dependence of p_T spectra and v_2
enhanced production of strange and multi-strange hadrons
interesting! need more investigation on small systems

many more results and a bright future

new data and more ideas for LHC Run-2

END

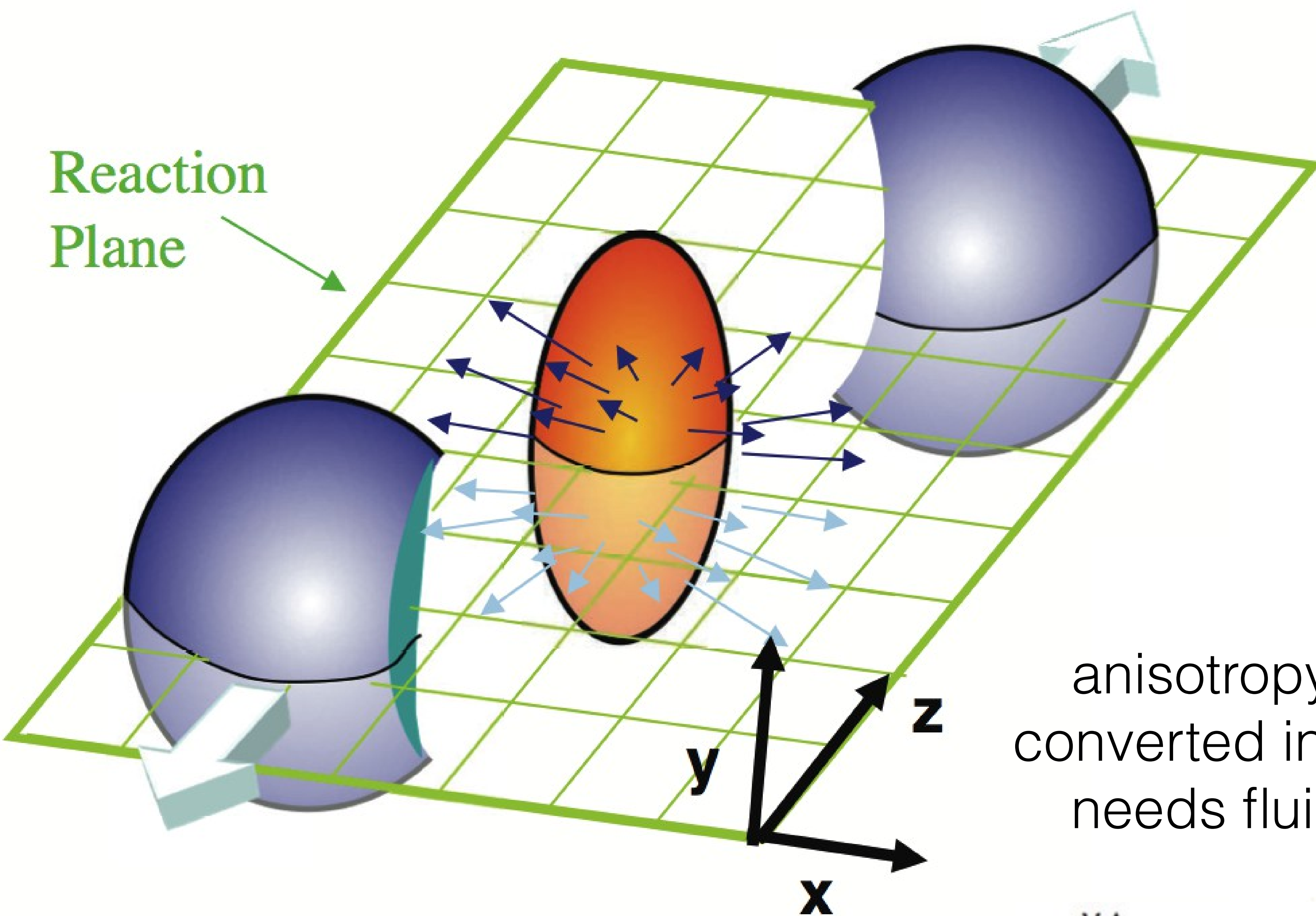
Strangeness production in Pb-Pb



hydro models → reasonable description of spectral shapes

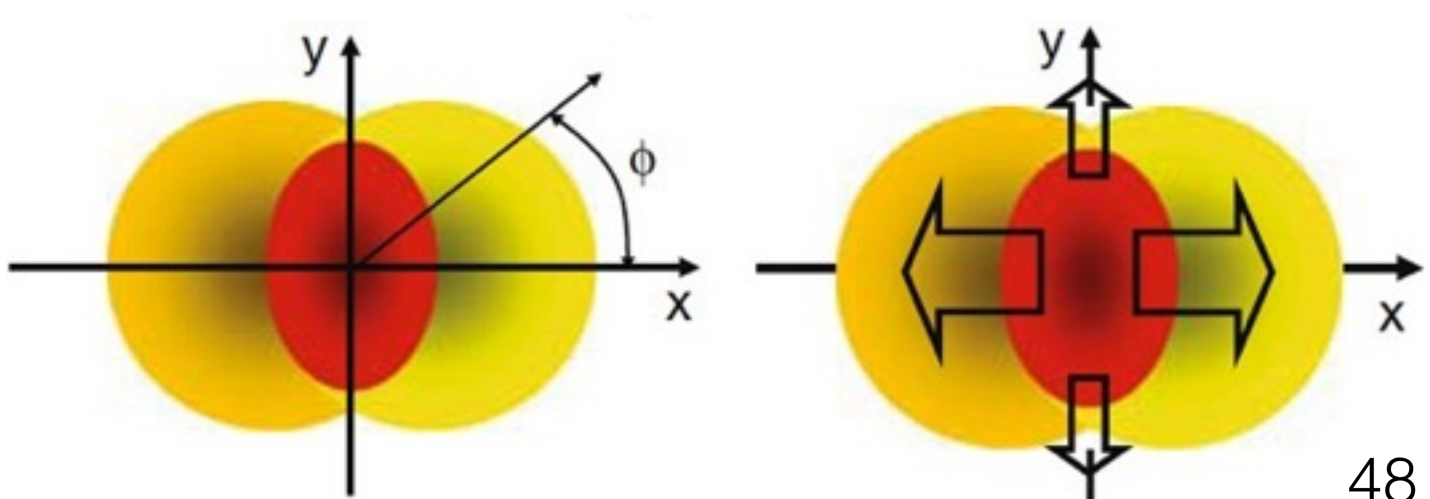
ALICE, PLB 728 (2014) 216

Anisotropic flow

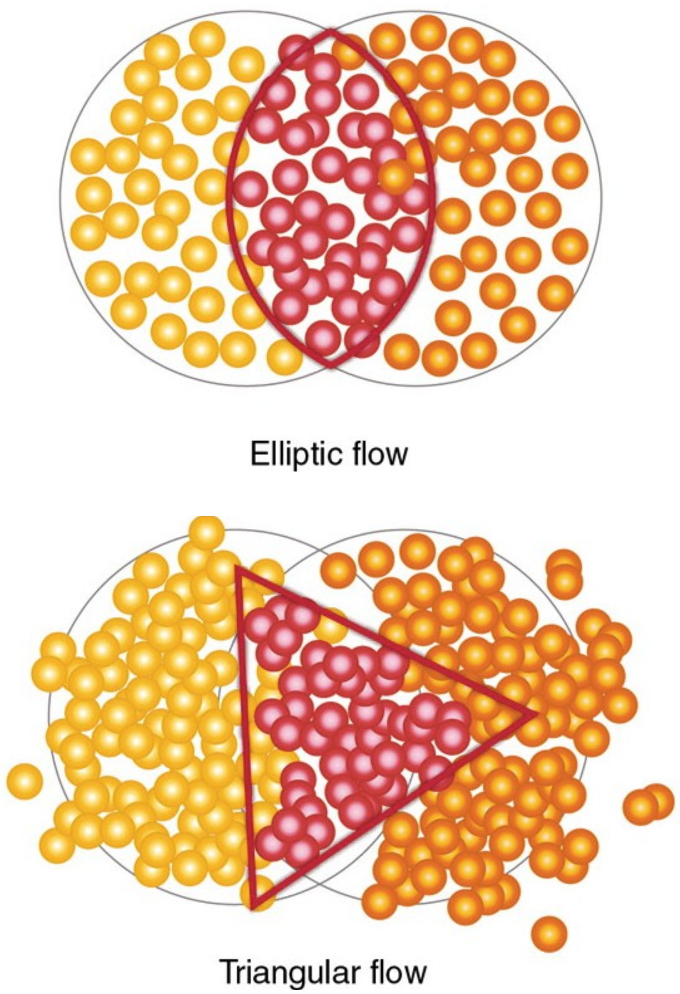


anisotropy in **spatial** space
converted in **momentum** space
needs fluid-like **collectivity**

elliptical collision **geometric**
anisotropic pressure gradients



Anisotropic flow



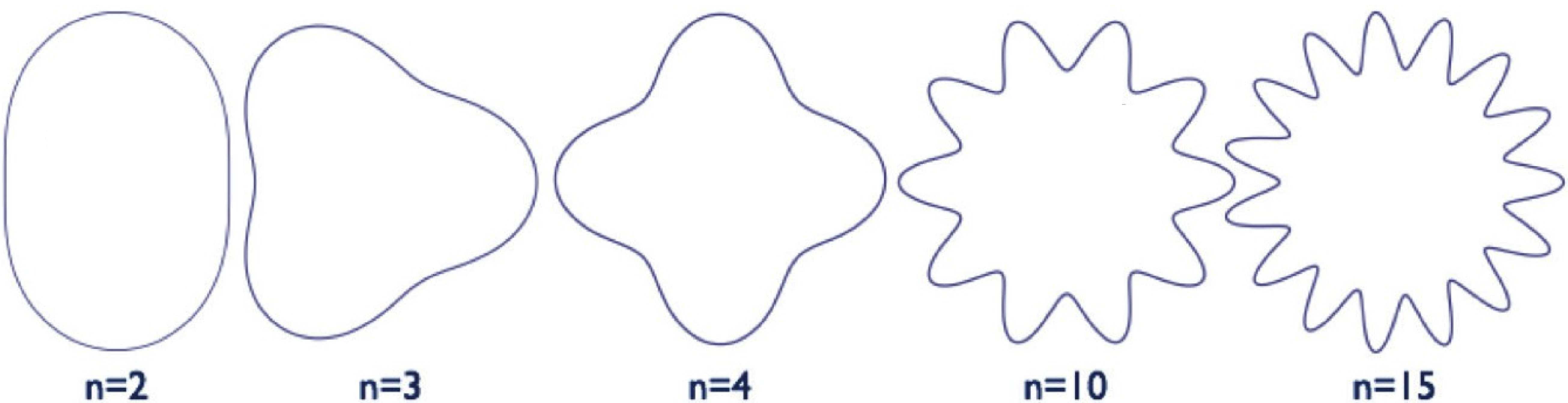
azimuthal distribution of particles wrt. plane perpendicular to the beam

anisotropic momentum distributions

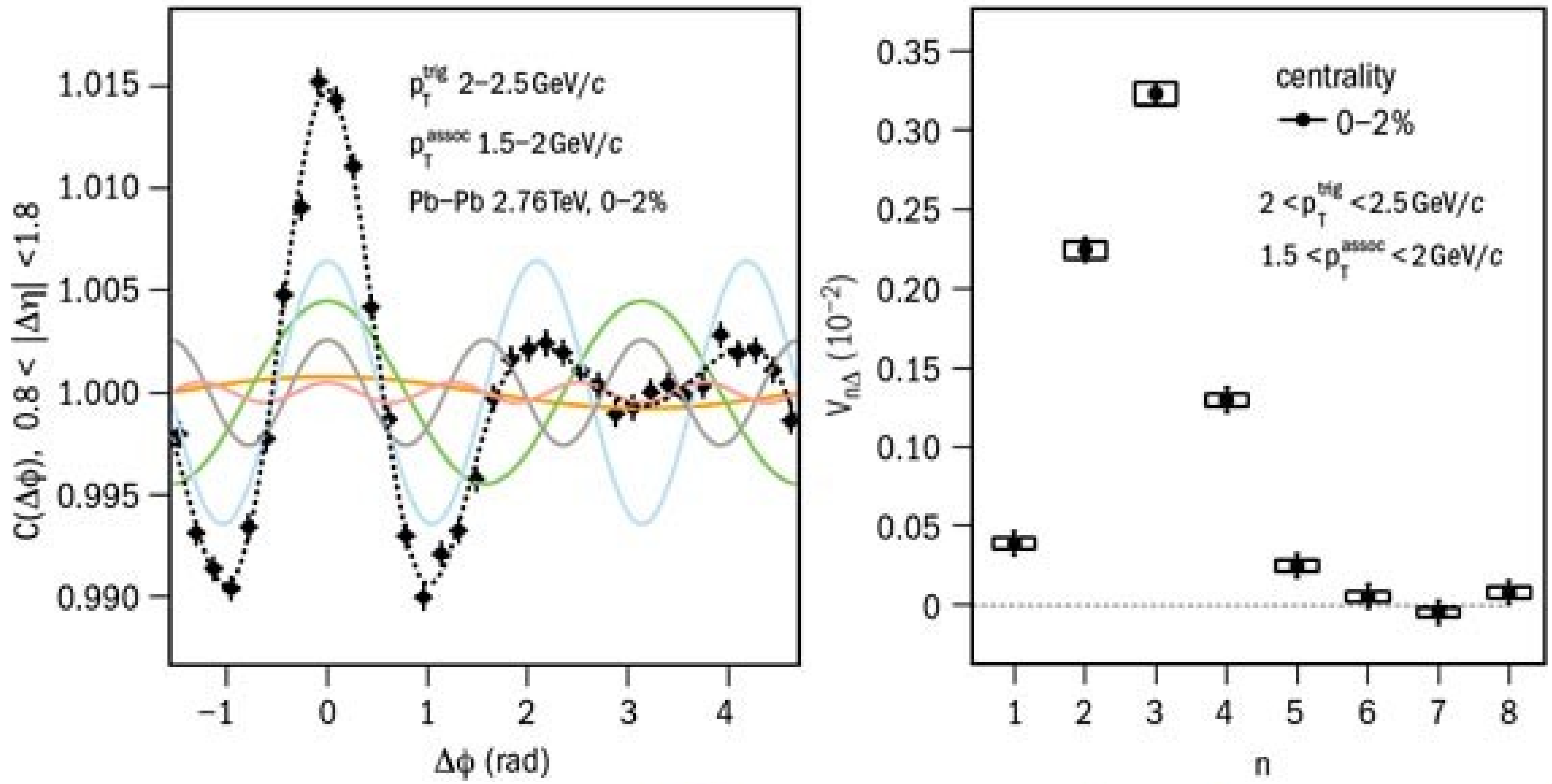
azimuthal dependence can be written in the form of a Fourier series

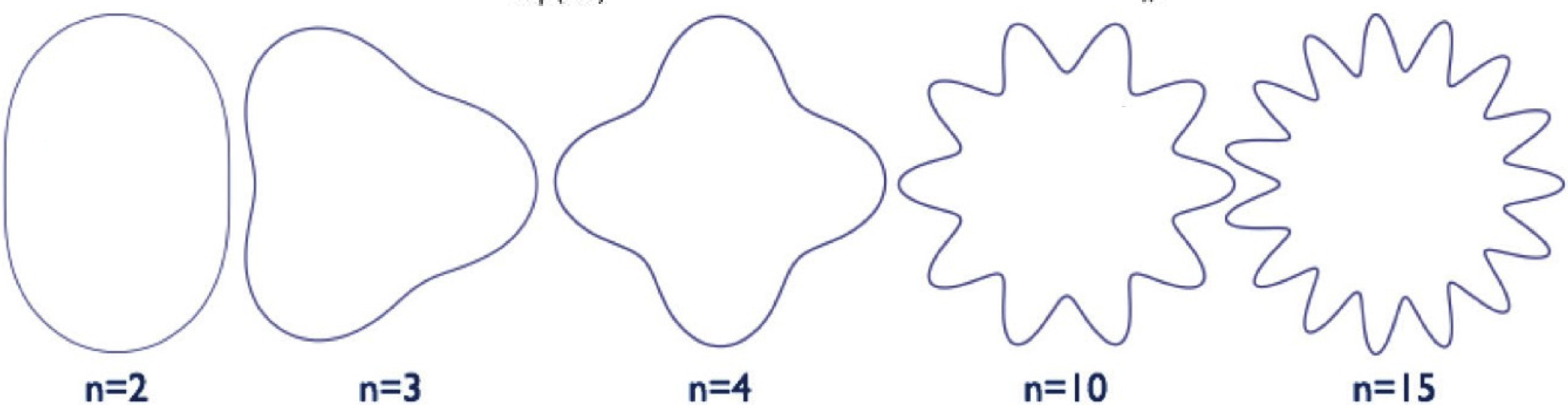
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_R)]\right)$$

the magnitude of the anisotropic flow is characterized by the coefficients v_n of the Fourier expansion



Anisotropic flow





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

Properties of hadronic phase

- Model of Torrieri, Rafelski, *et al.* predicts particle ratios as functions of chemical freeze-out temperature and lifetime of hadronic phase
- Model Predictions:

Torrieri/Rafelski*
no re-scattering
T_{ch} = 156 MeV

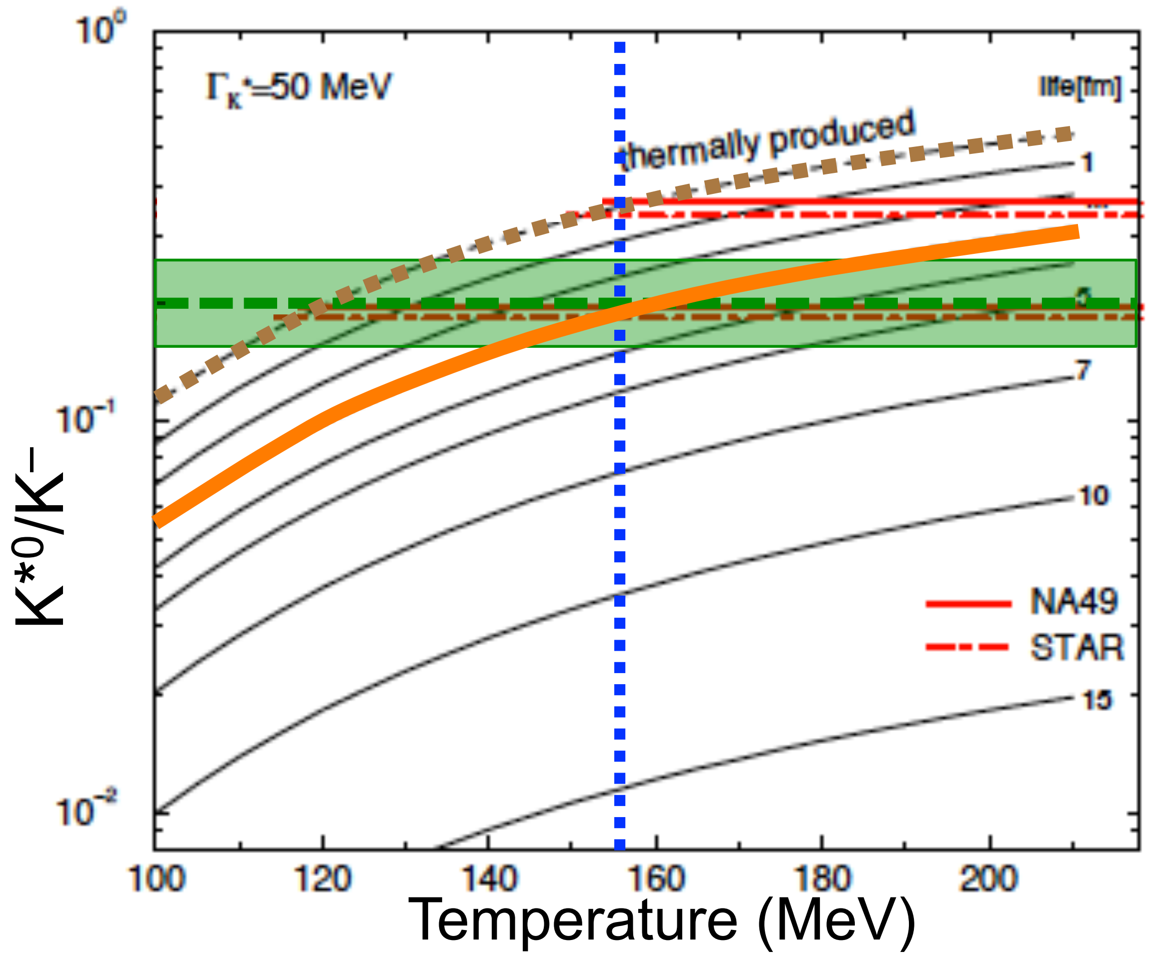
→ Prediction:
K^{*0}/K^{-} = 0.35

Torrieri/Rafelski*
no re-scattering
measured K^{*0}/K^{-}

→ Prediction:
T_{ch} = 120±7 MeV

Torrieri/Rafelski*
measured K^{*0}/K^{-}
T_{ch} = 156 MeV

→ Prediction:
Lifetime ≥ 2 fm/c



*References:
G. Torrieri and J. Rafelski, *J. Phys. G* **28**, 1911 (2002)
J. Rafelski *et al.*, *Phys. Rev. C* **64**, 054907 (2001)
J. Rafelski *et al.*, *Phys. Rev. C* **65**, 069902(E) (2002)
C. Markert *et al.*, arXiv:hep-ph/0206260v2 (2002)