Studying nuclear matter under extreme conditions with the ALICE experiment at the LHC

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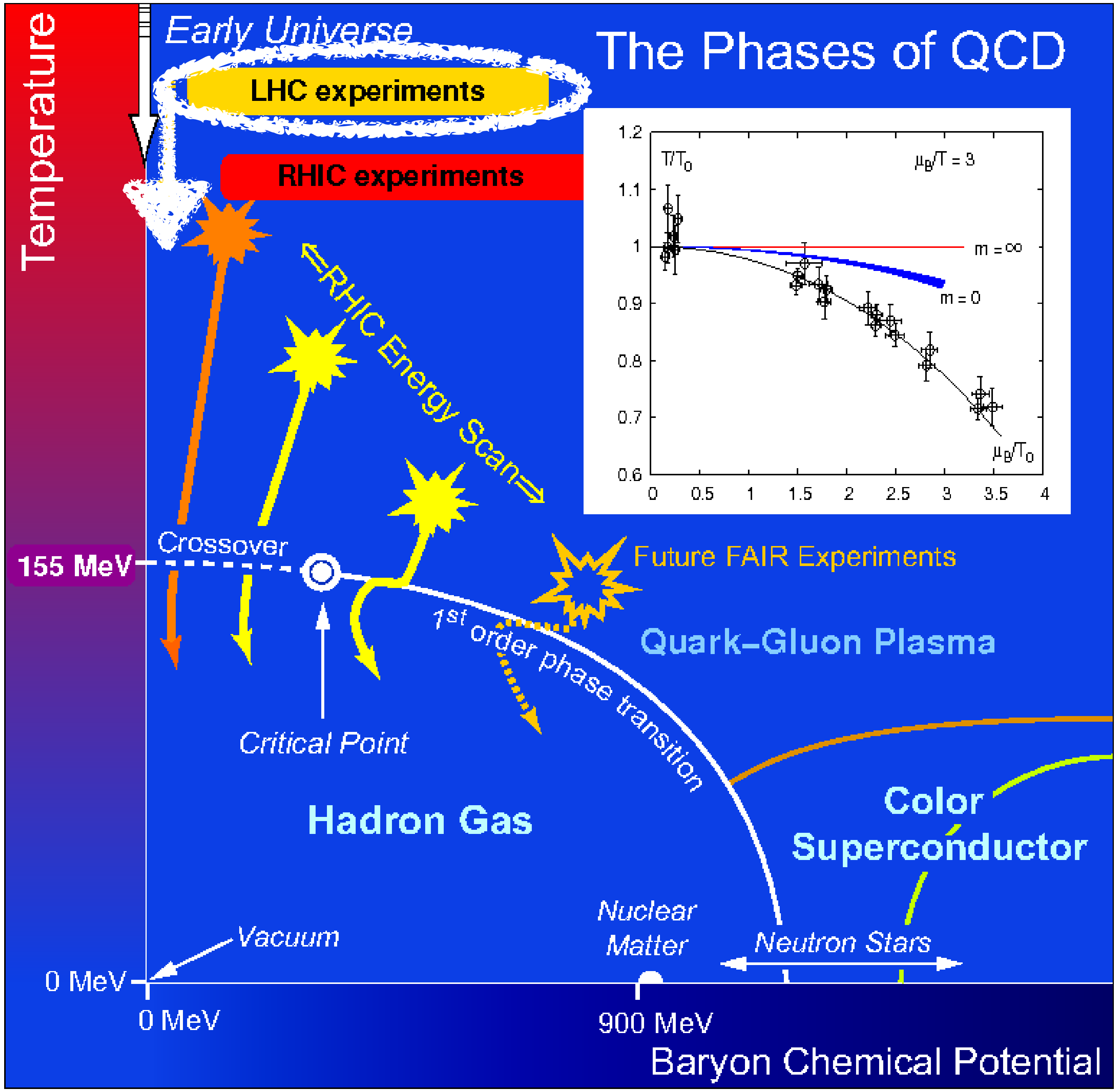
Heavy-ion physics

nuclear matter under extreme conditions
high temperature and energy-density

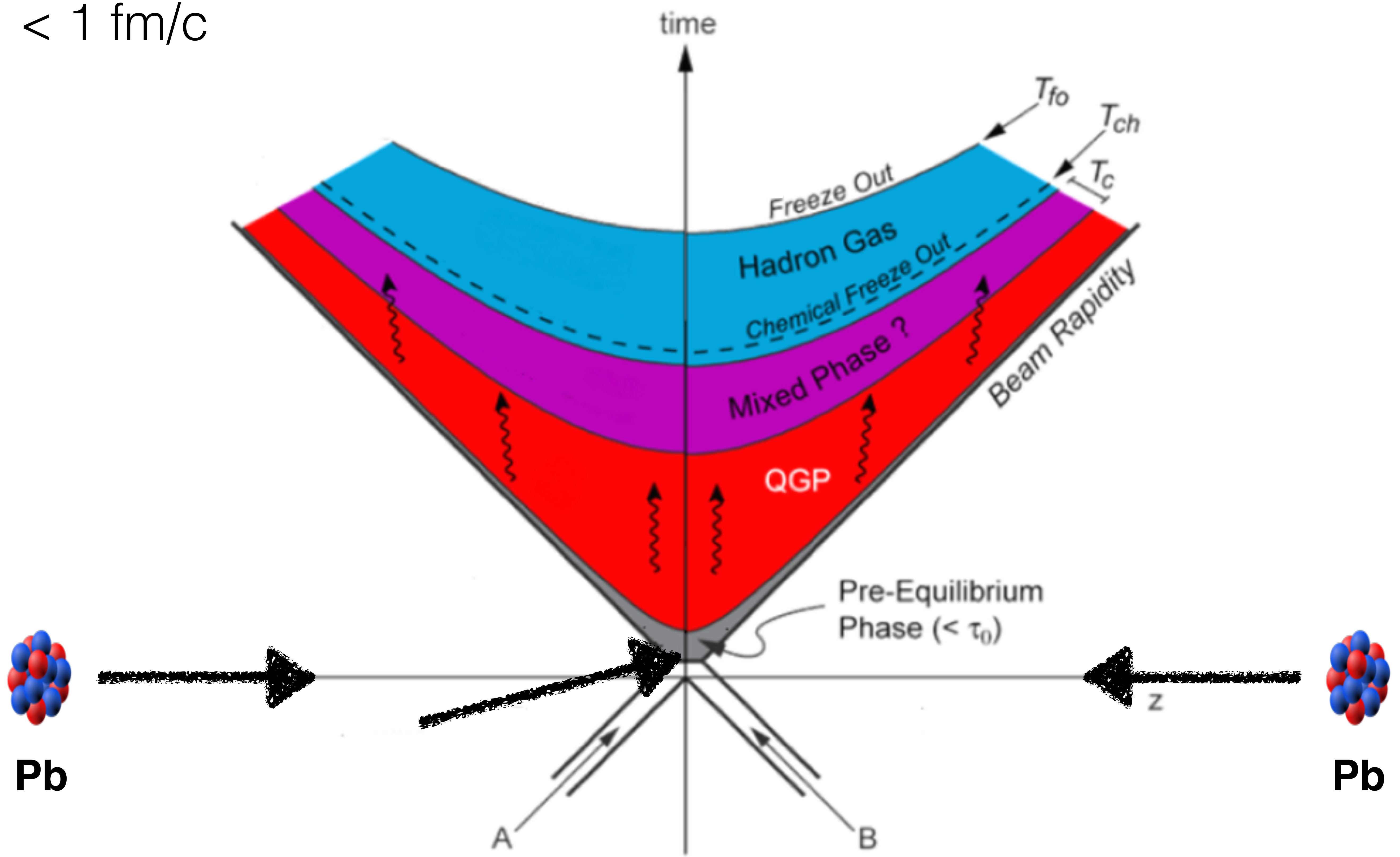
expected to undergo a **phase-transition**
hadronic matter
↓
Quark-Gluon Plasma (QGP)

study the phase diagram and the properties of hot QCD matter



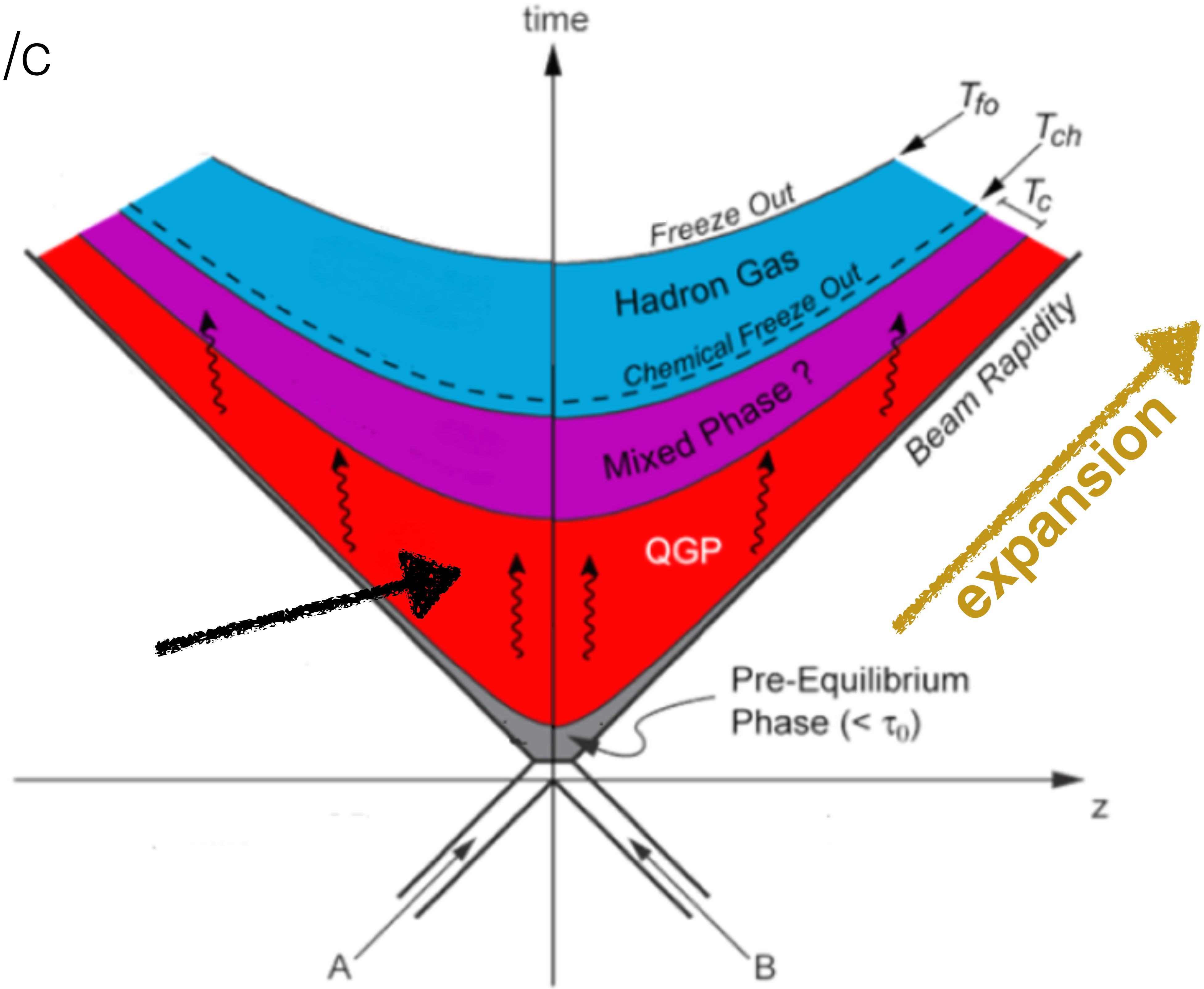
Hard scattering + thermalisation

< 1 fm/c



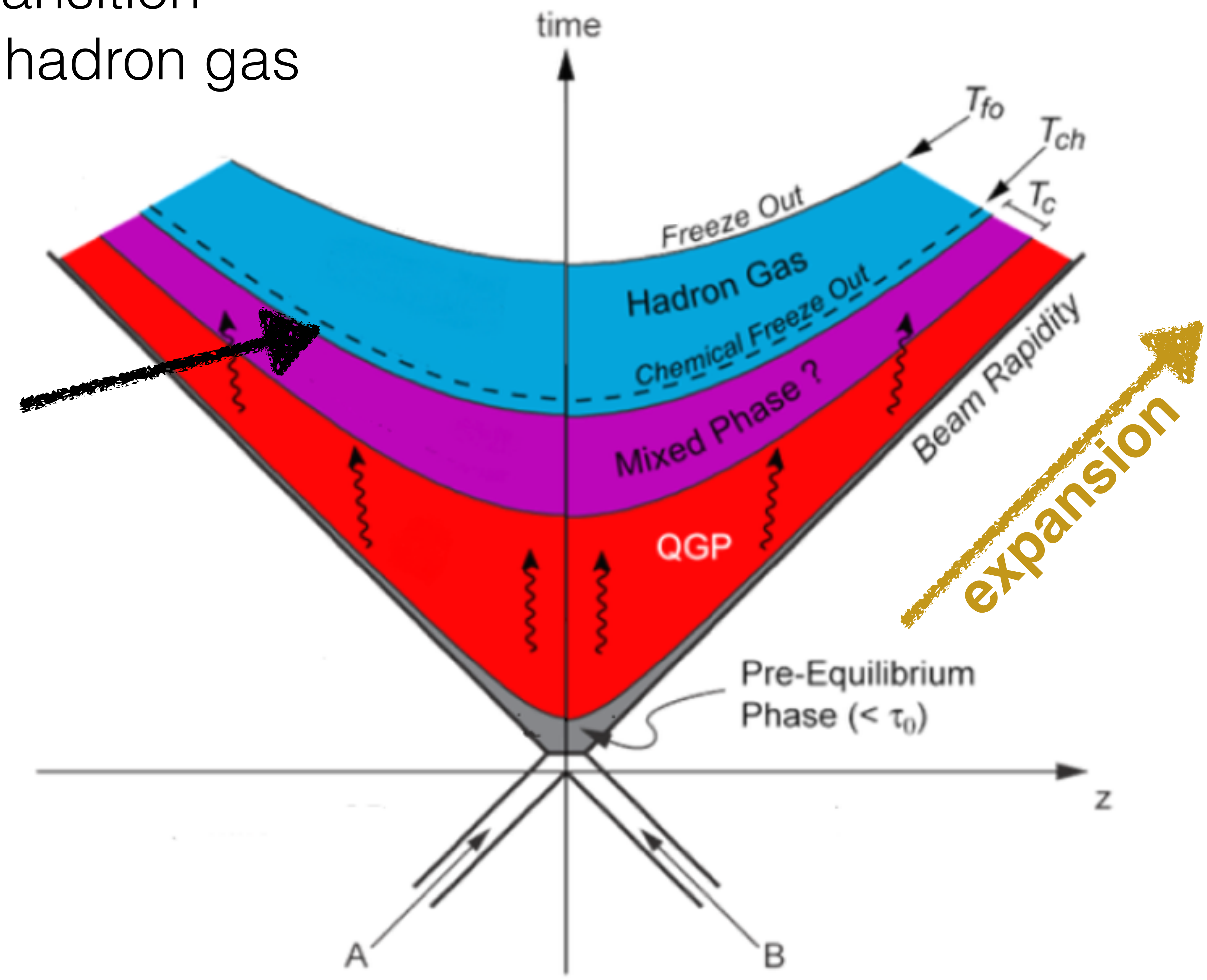
Partonic phase

QGP
~ few fm/c



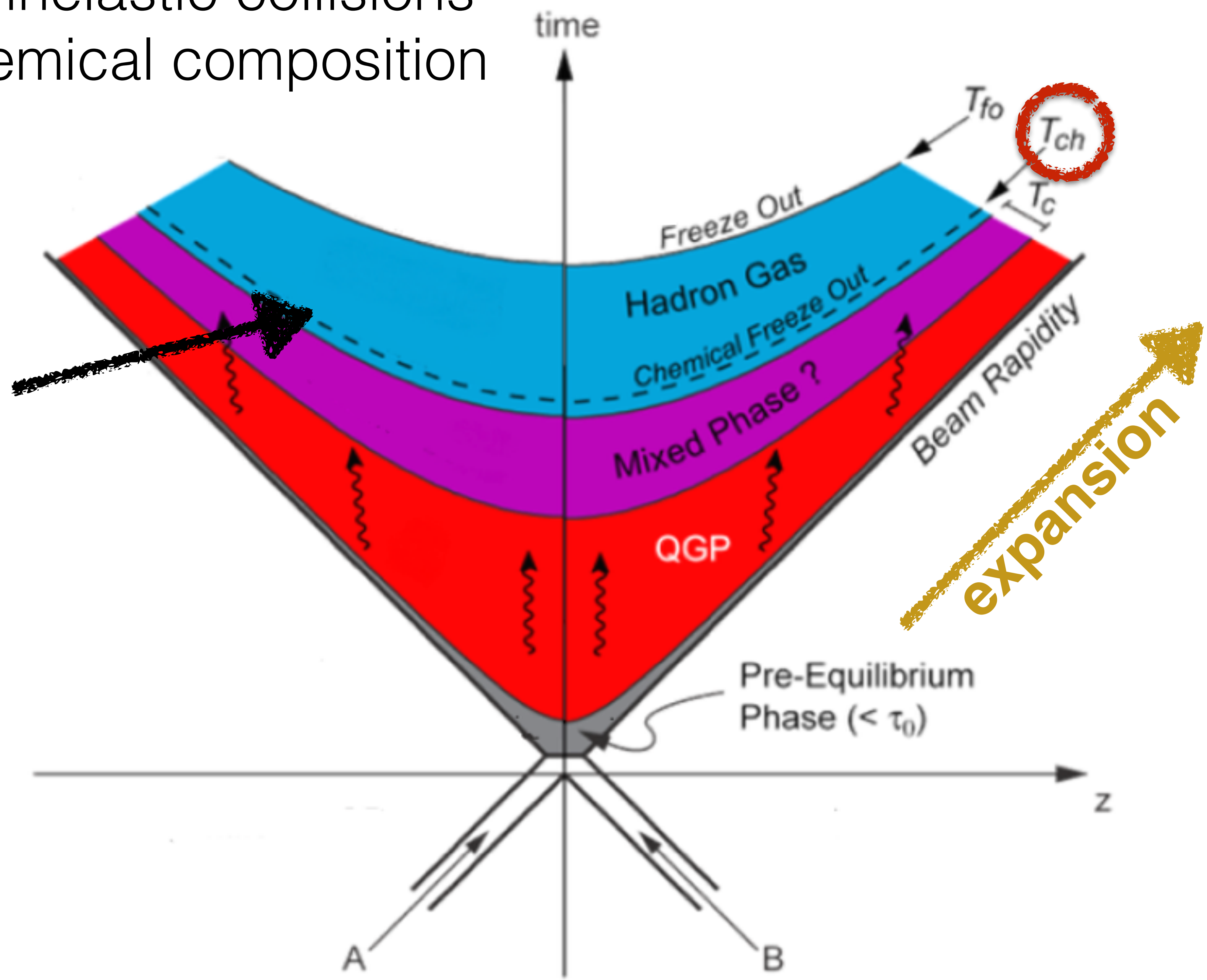
Hadronisation

phase transition
QGP → hadron gas



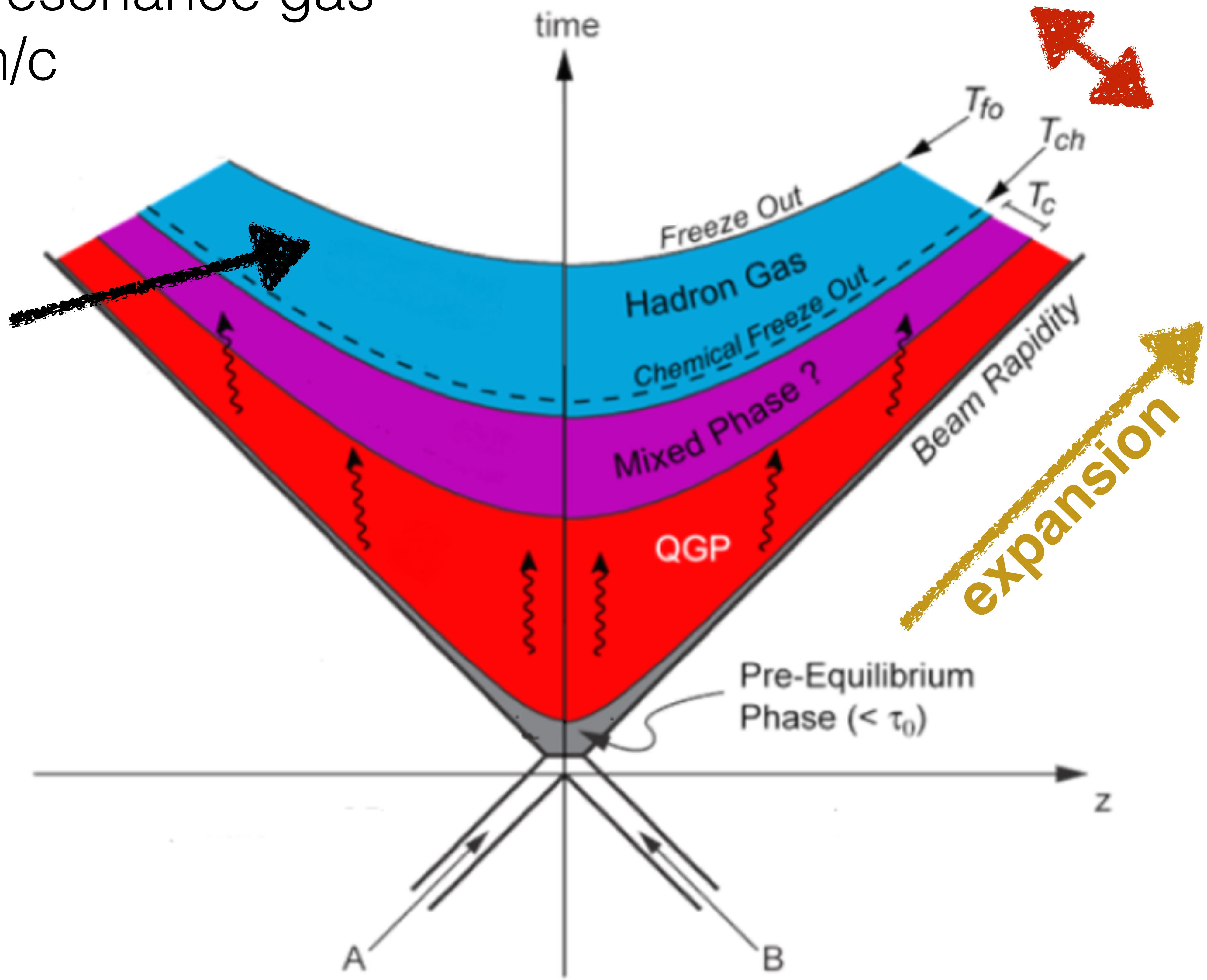
Chemical freeze-out

no more inelastic collisions
fixed chemical composition



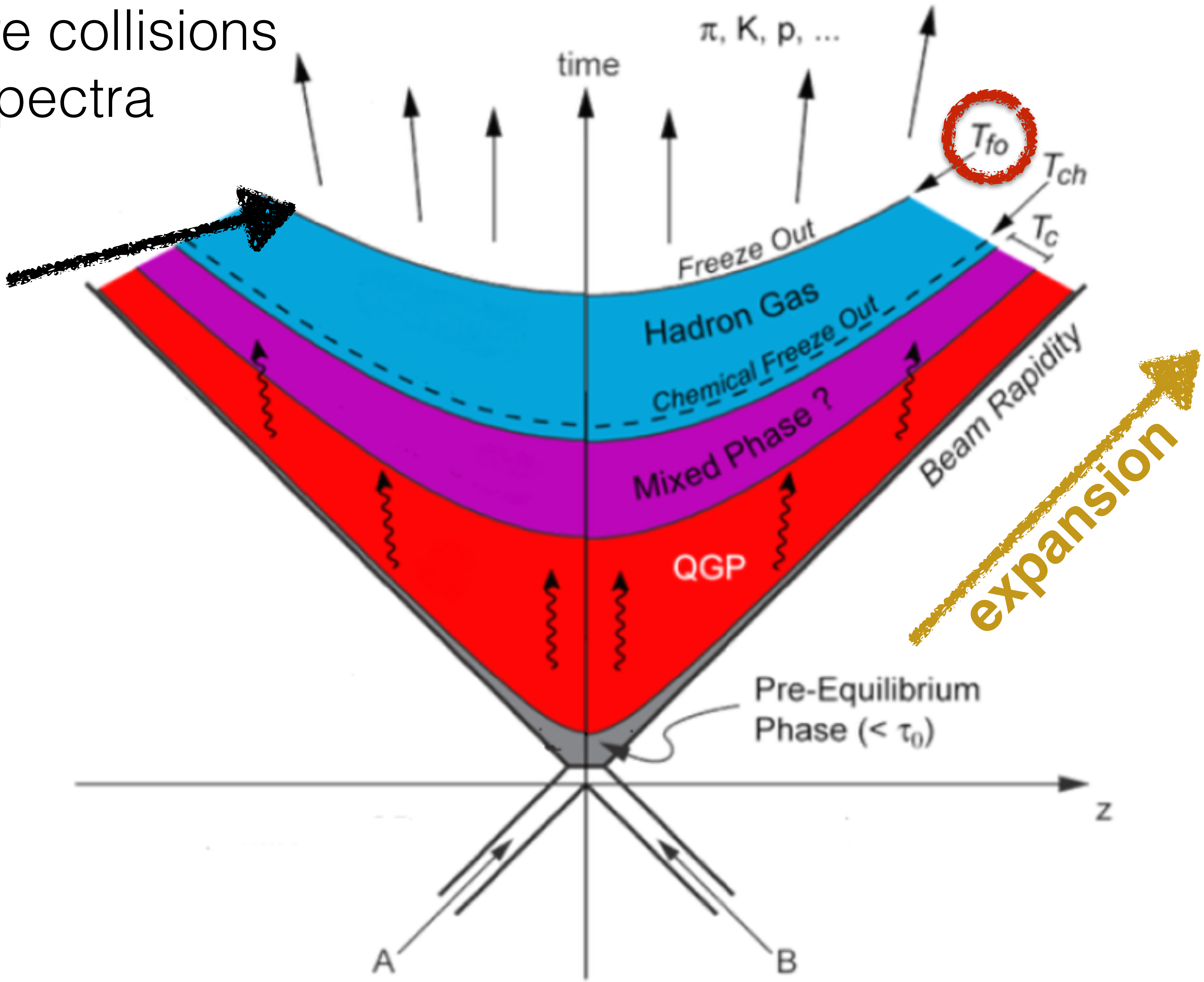
Hadronic phase

hadron-resonance gas
~ few fm/c

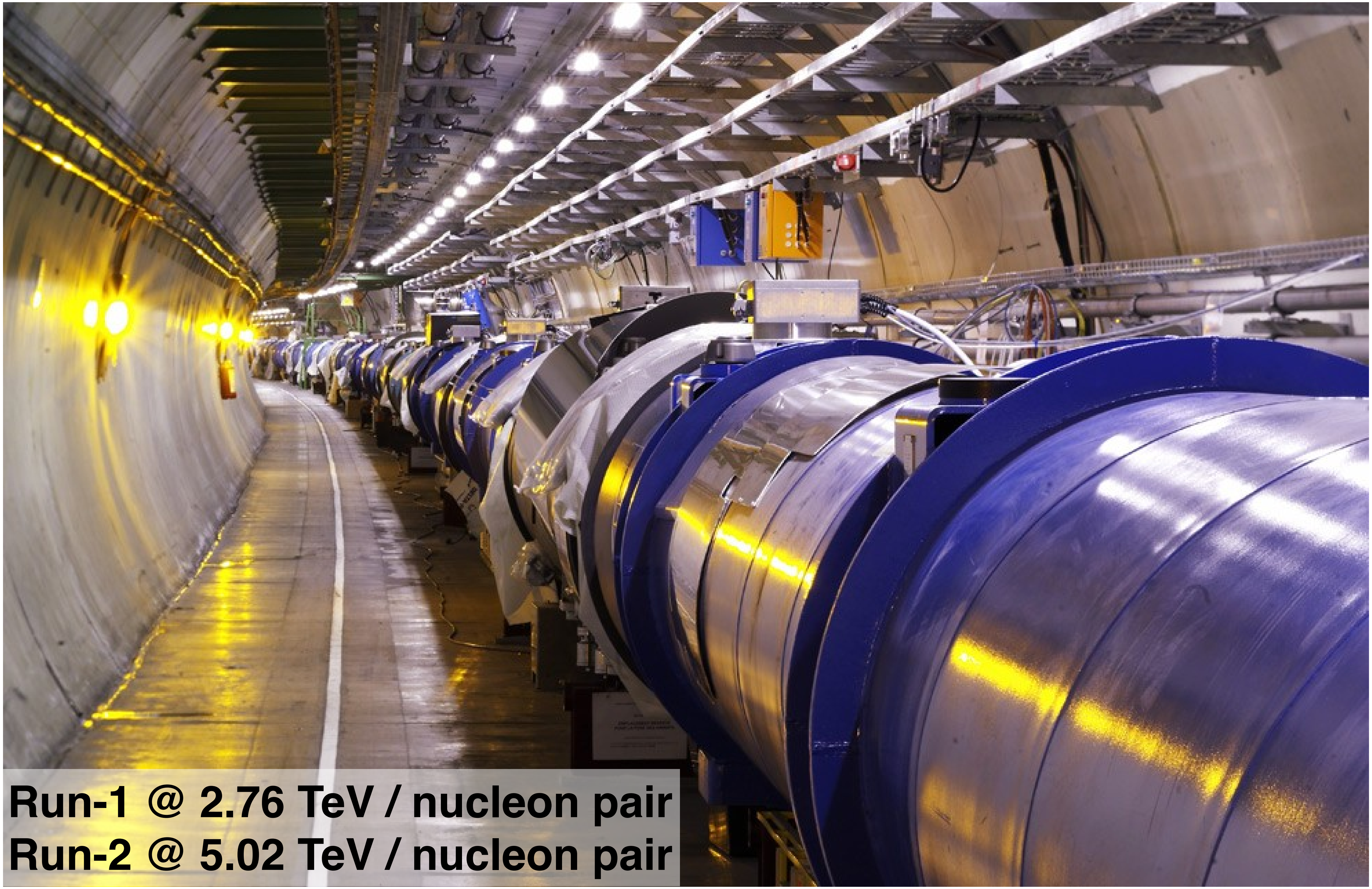


Kinetic freeze-out

no more collisions
fixed spectra



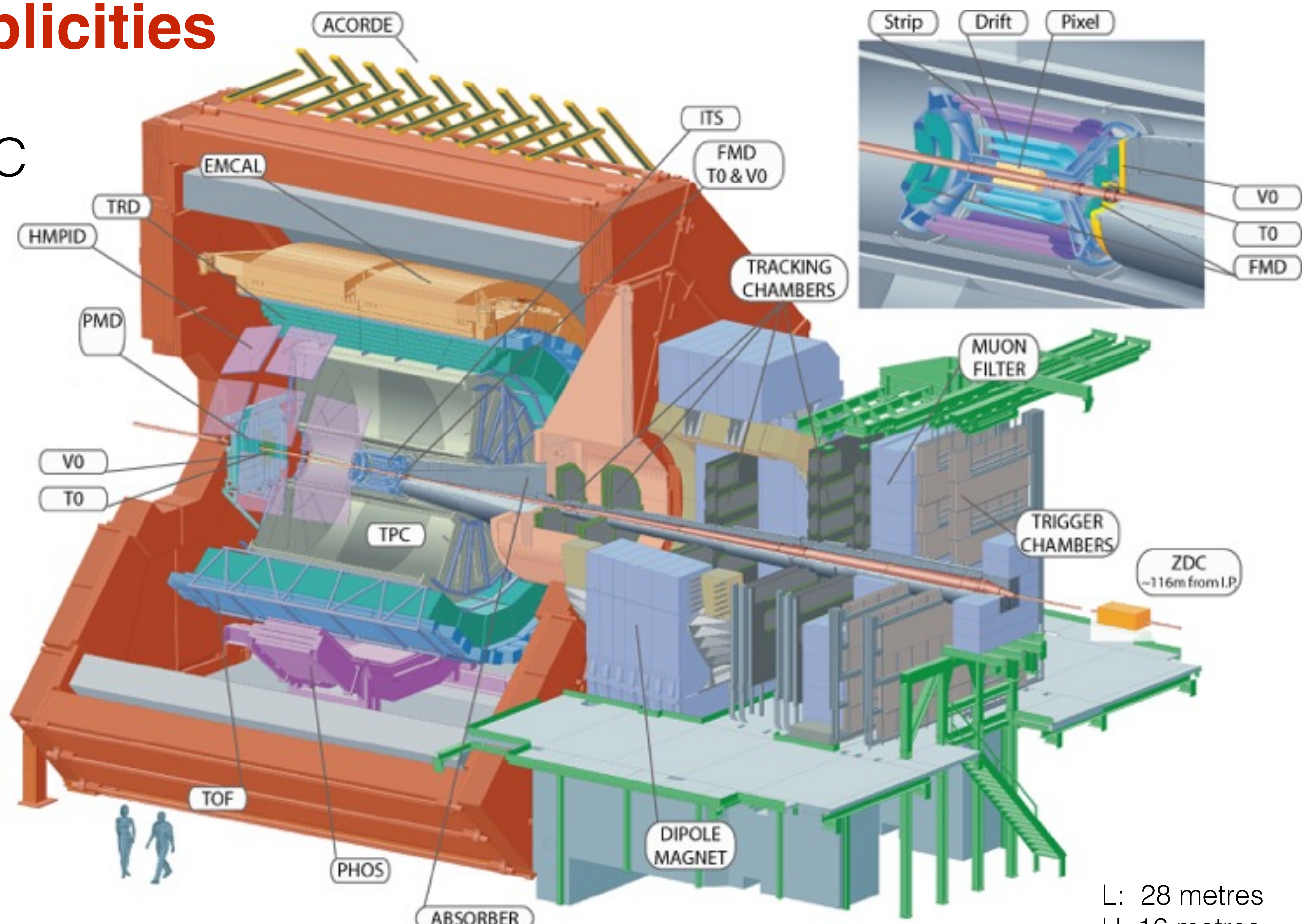
Heavy-ion collisions at the LHC



The ALICE detector

a dedicated heavy-ion experiment at the LHC

designed to cope with
very high multiplicities
$dN_{ch}/d\eta \leq 8000$
3D tracking with TPC

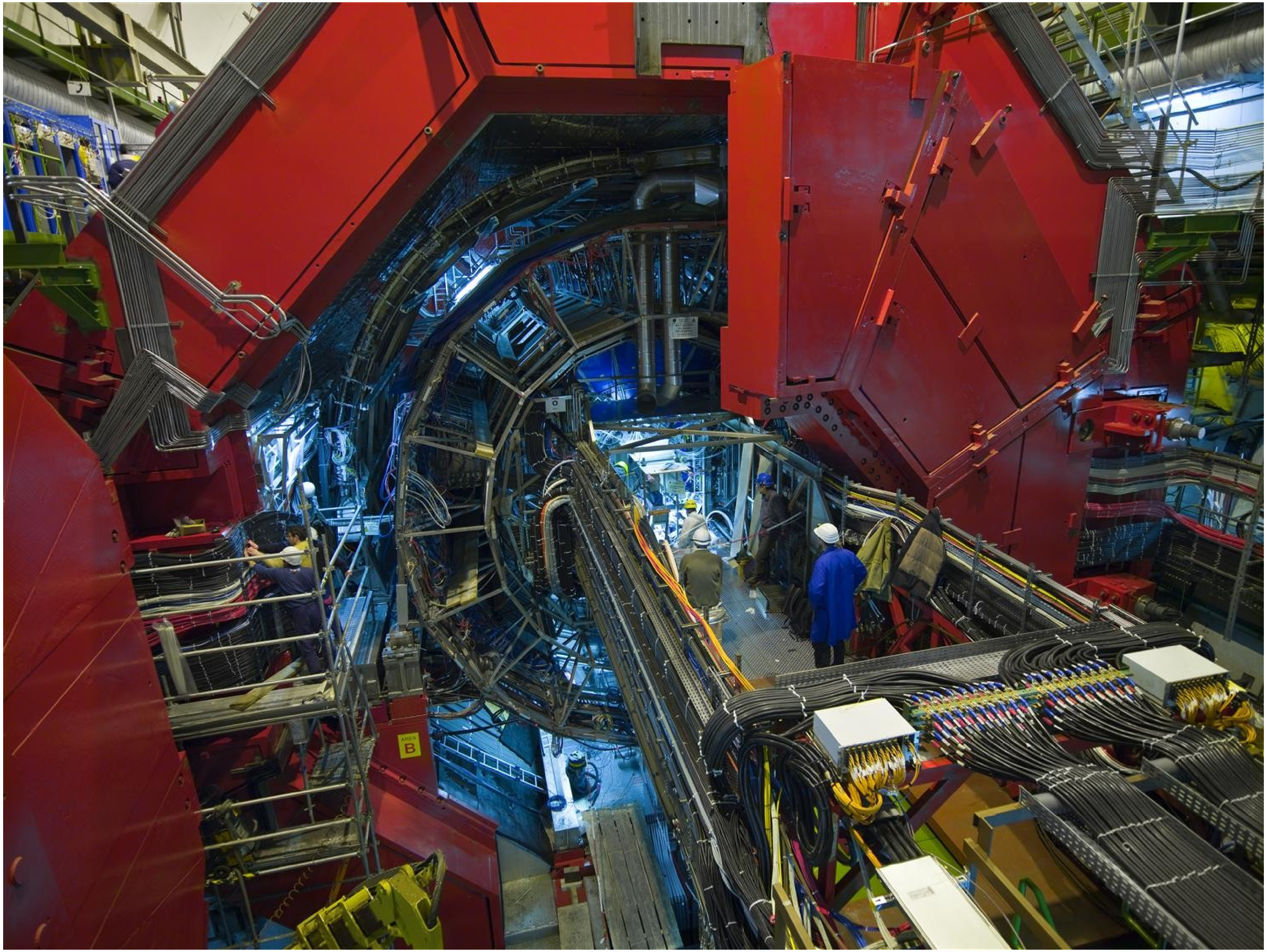


low-p_T tracking
moderate B = 0.5 T
thin materials

uses all known **PID** techniques

L: 28 metres
H: 16 metres
W: 10k t

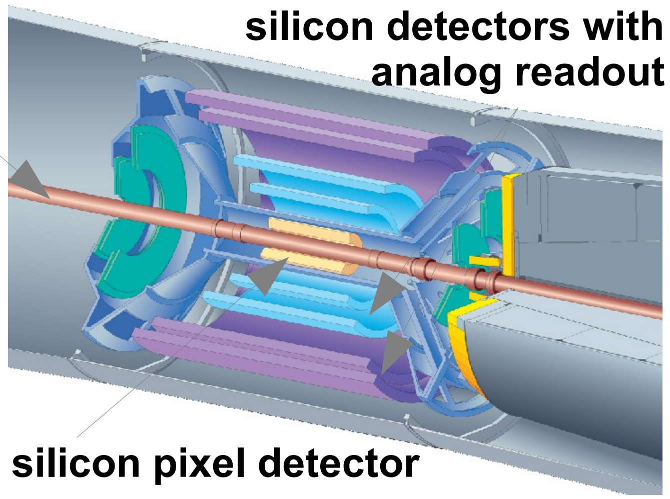
The ALICE detector

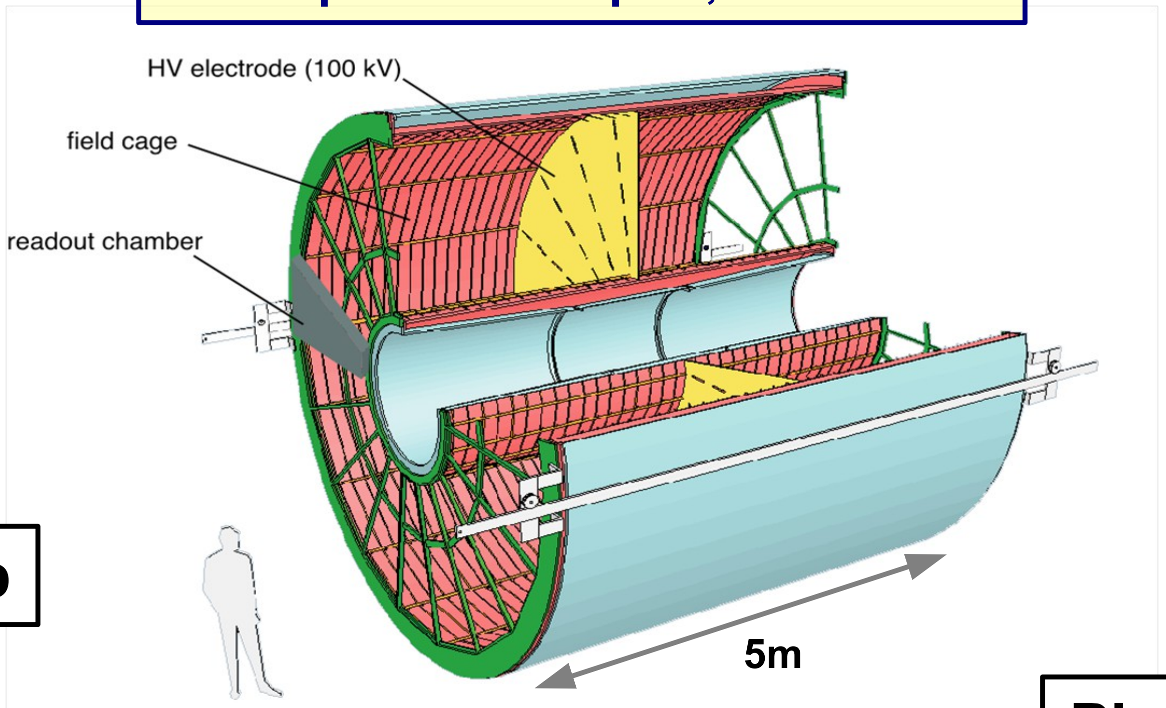


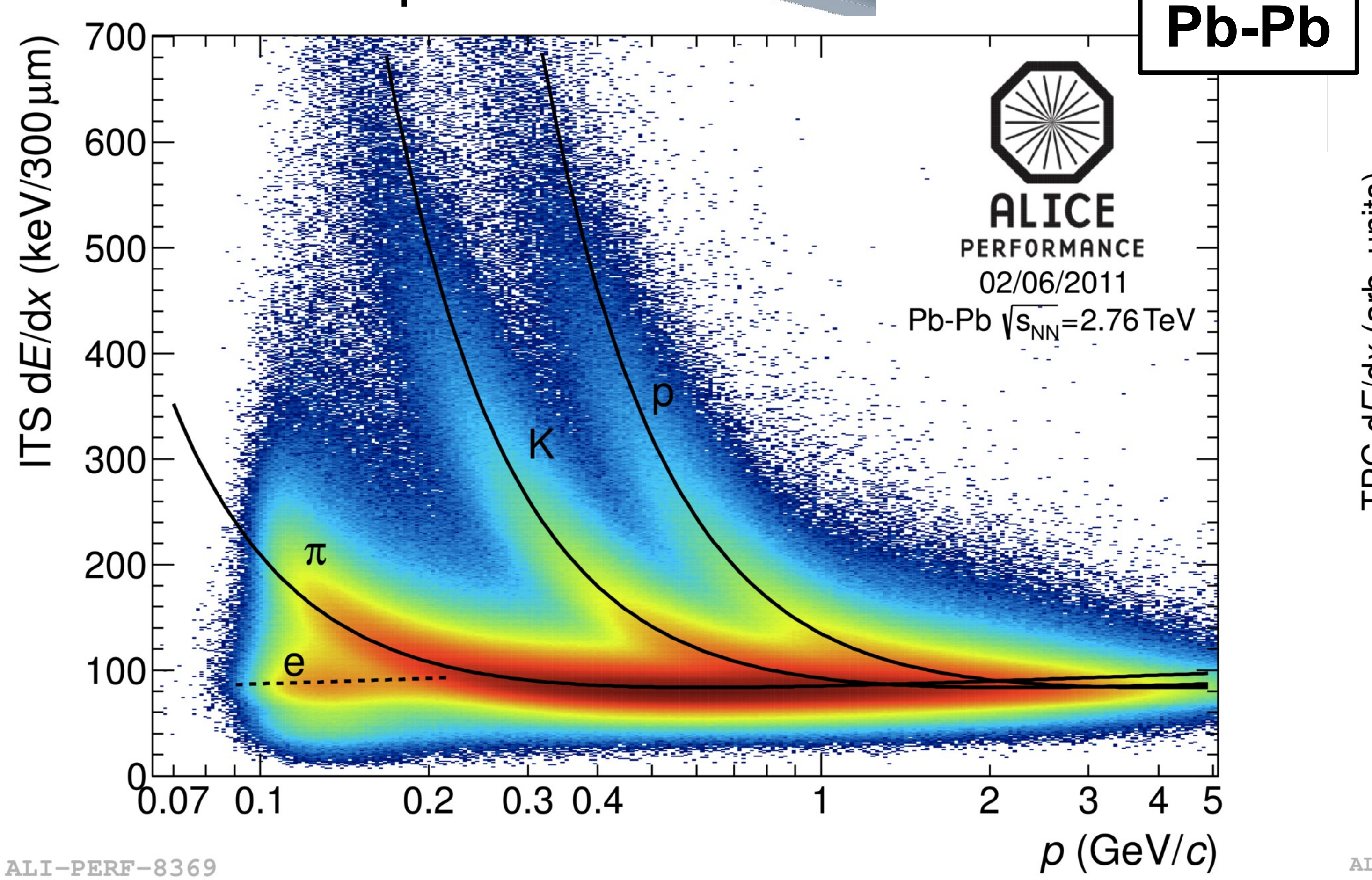
Particle-ID: dE/dx technique

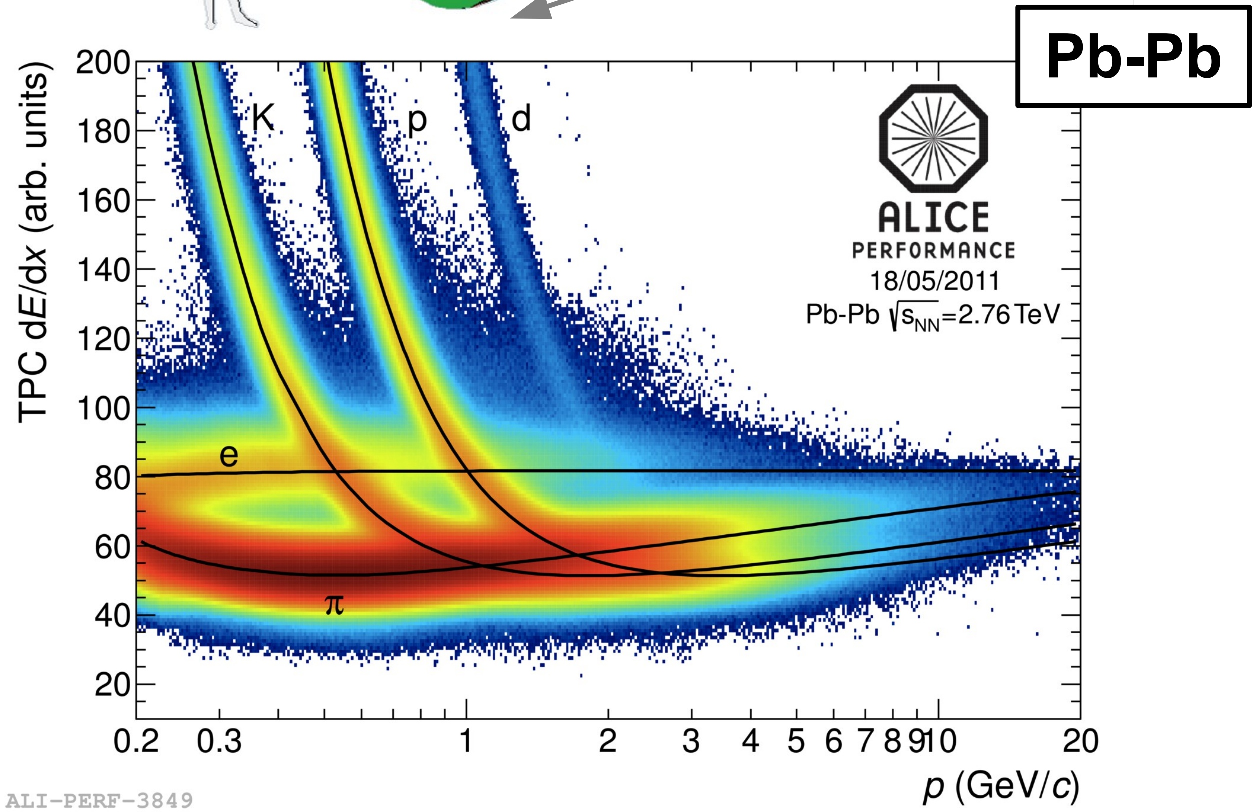
ITS: PID at low momenta
PID via *dE*/*dx* in silicon
up to 4 samples, σ ~10-15%

TPC: main tracking detector
PID via *dE*/*dx* in gas
up to 159 samples, σ ~5%

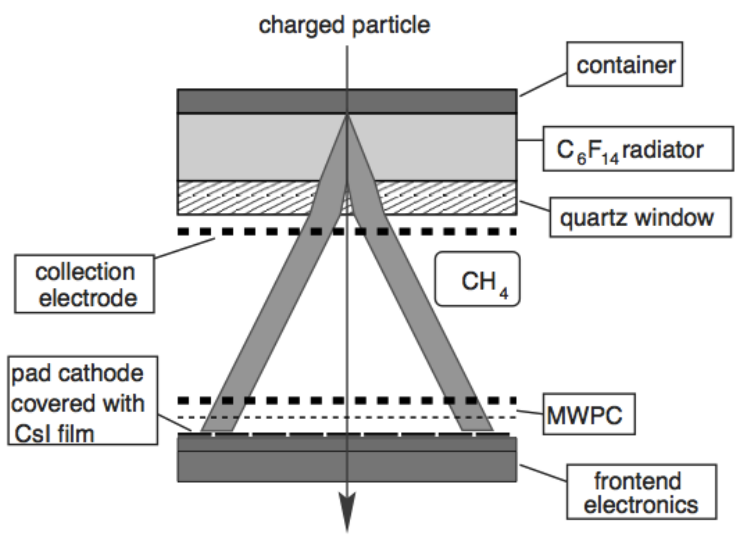






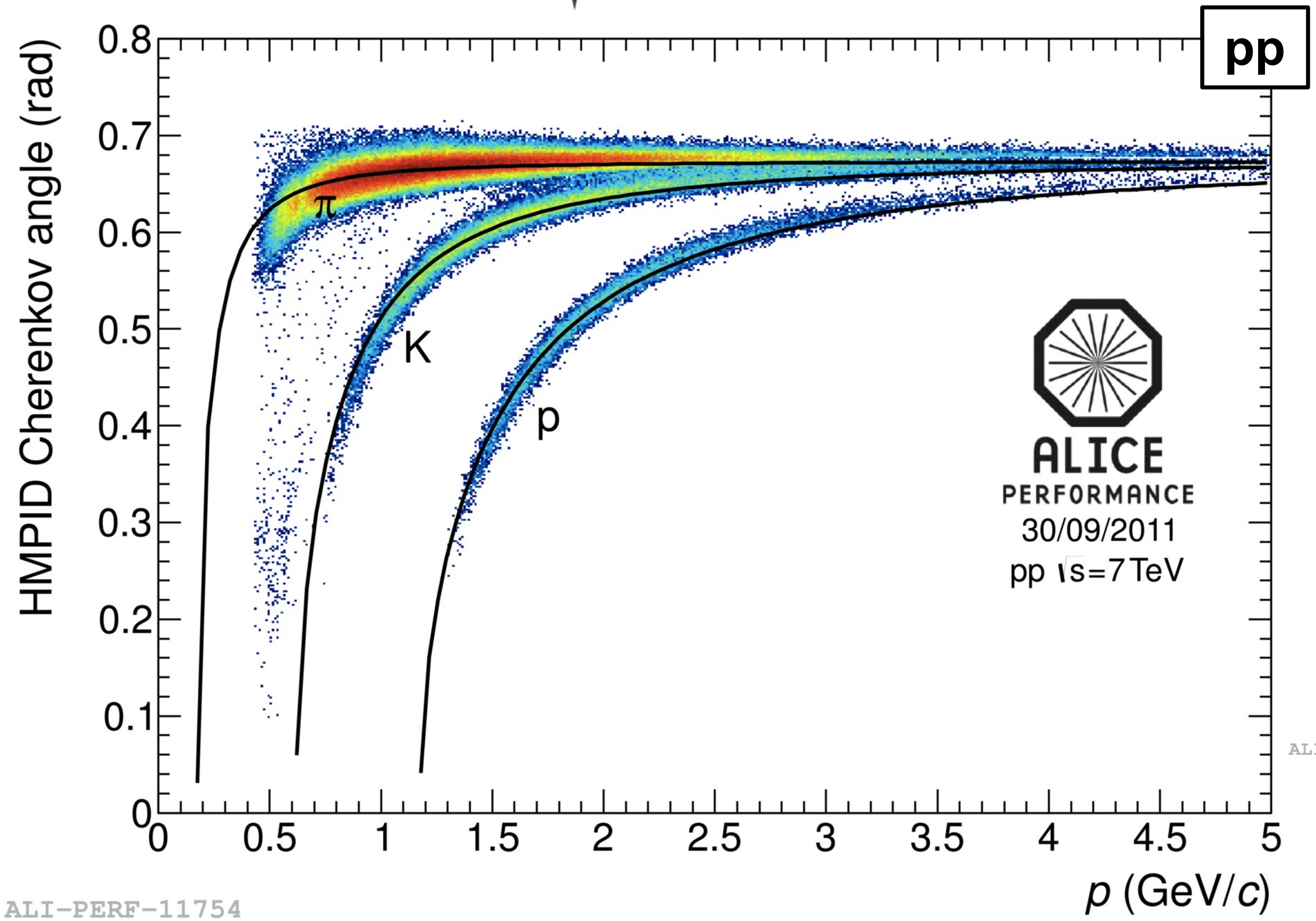


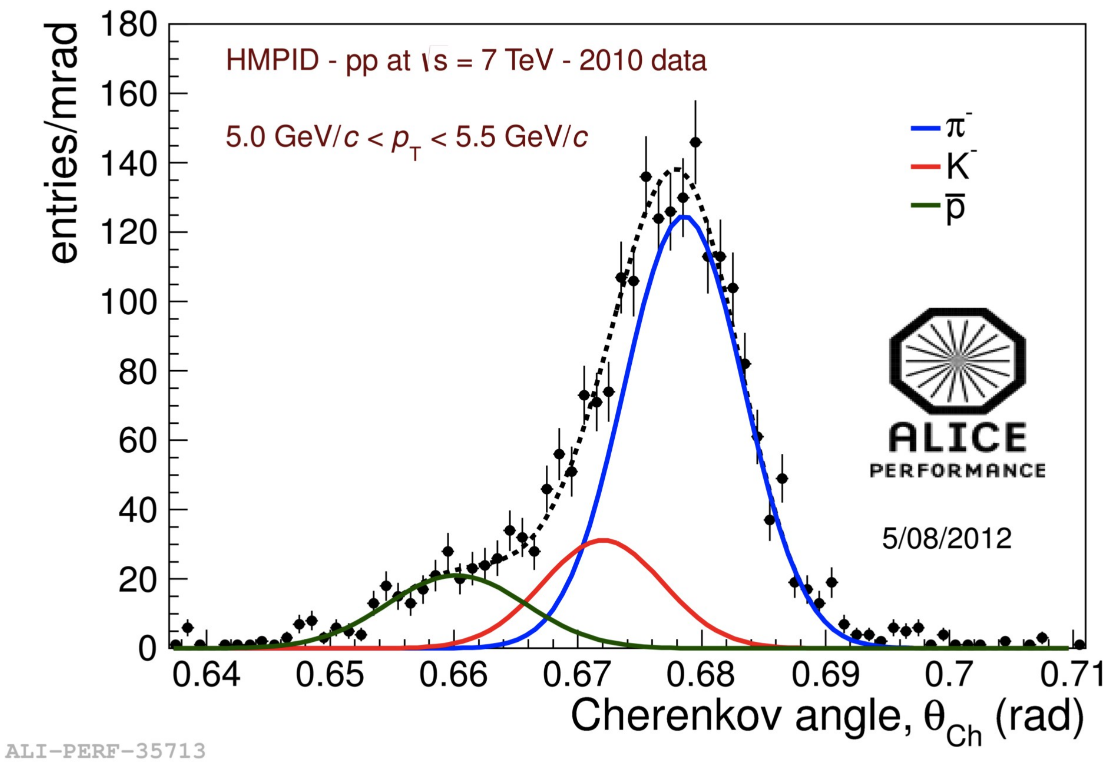
Particle-ID: Cherenkov radiation



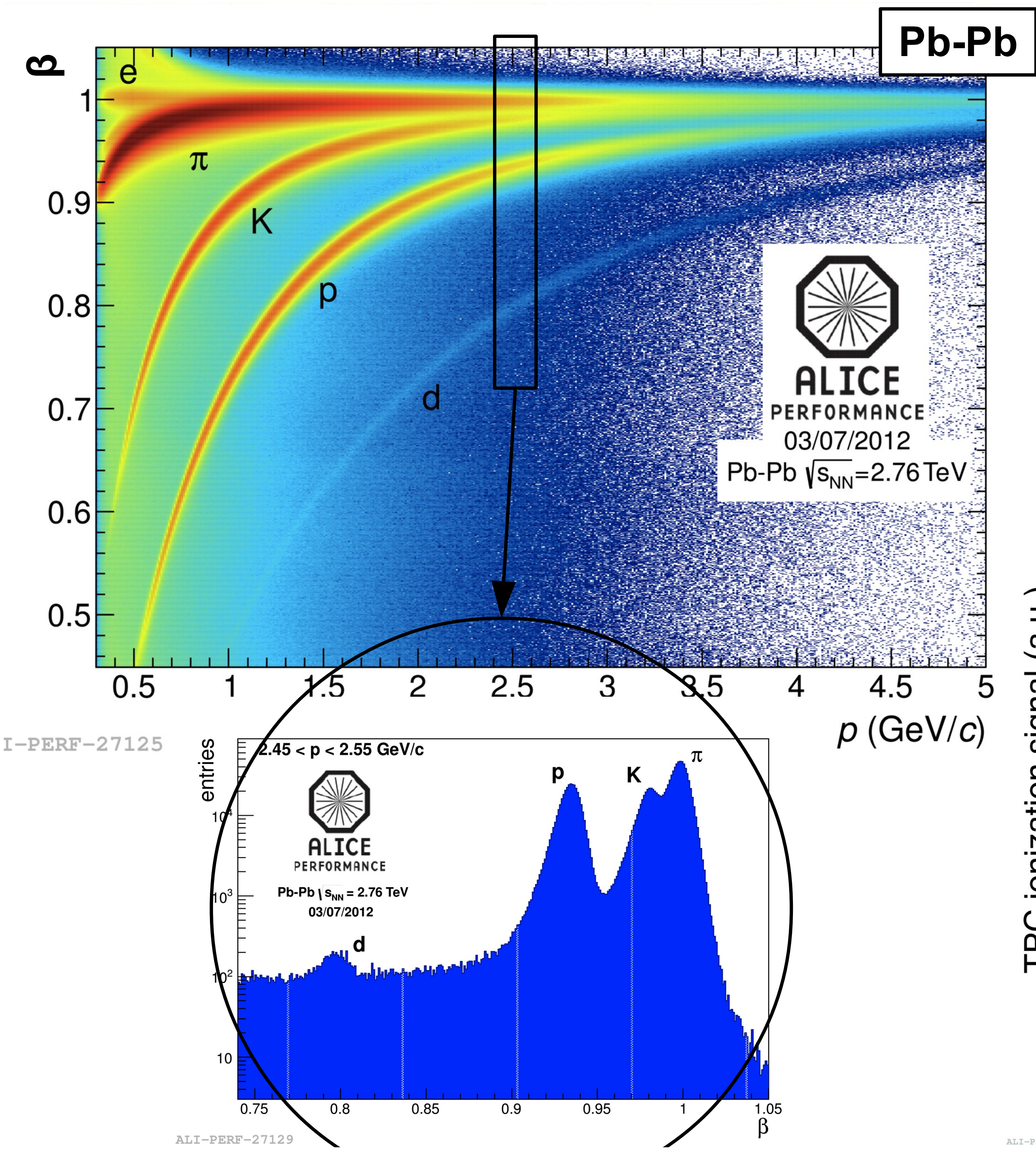
HMPID: extends PID at higher p_T
PID via Cherenkov angle θ_{Ch}
proximity-focus RICH technique

3σ proton separation up to 5.0 GeV/c
2σ proton separation up to 6.0 GeV/c



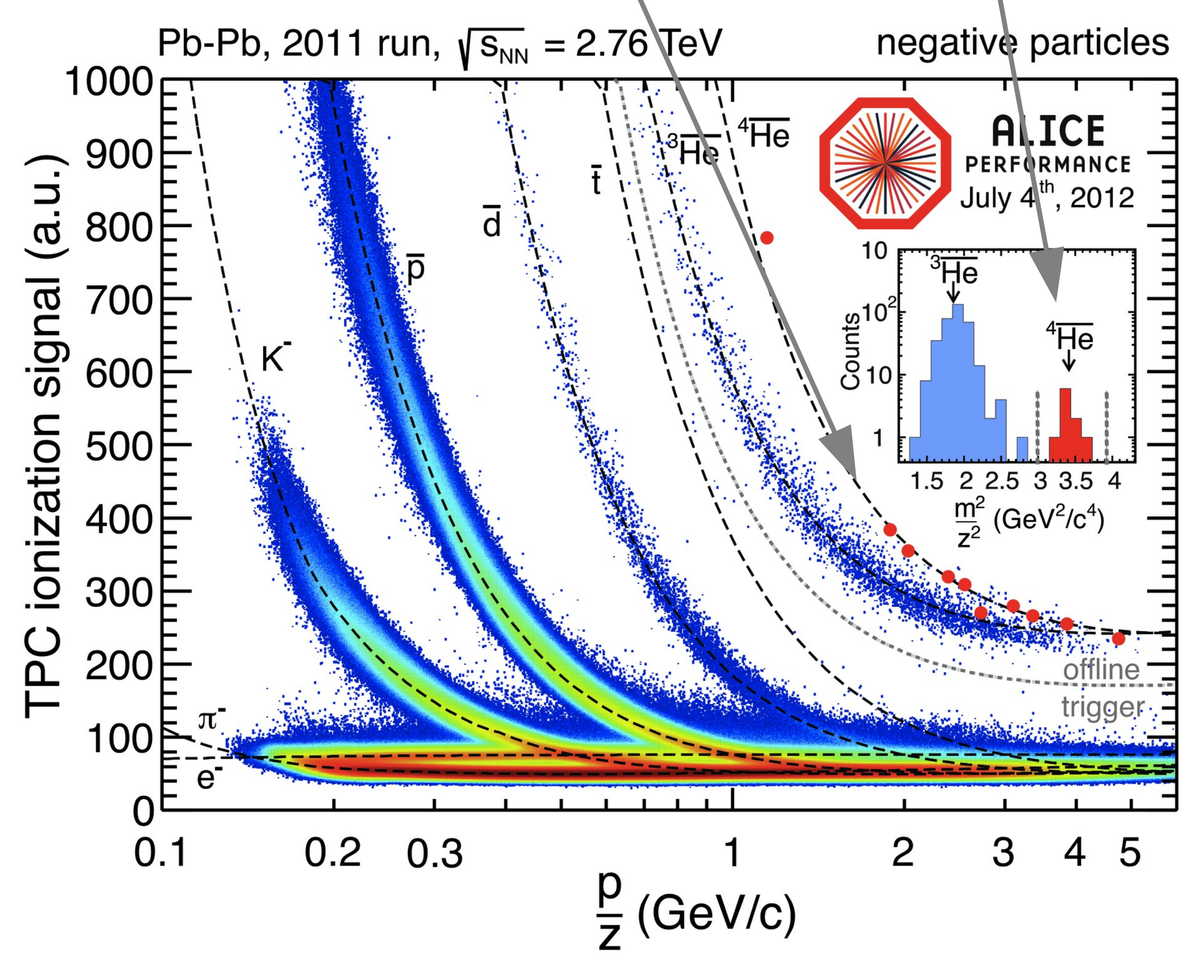


Particle-ID: time-of-flight technique



TOF: PID at intermediate momenta
PID via time-of-flight technique
σ < 100 ps
3σ *K/π* separation up to 2.5 GeV/c
3σ *p/π* separation up to 4.0 GeV/c

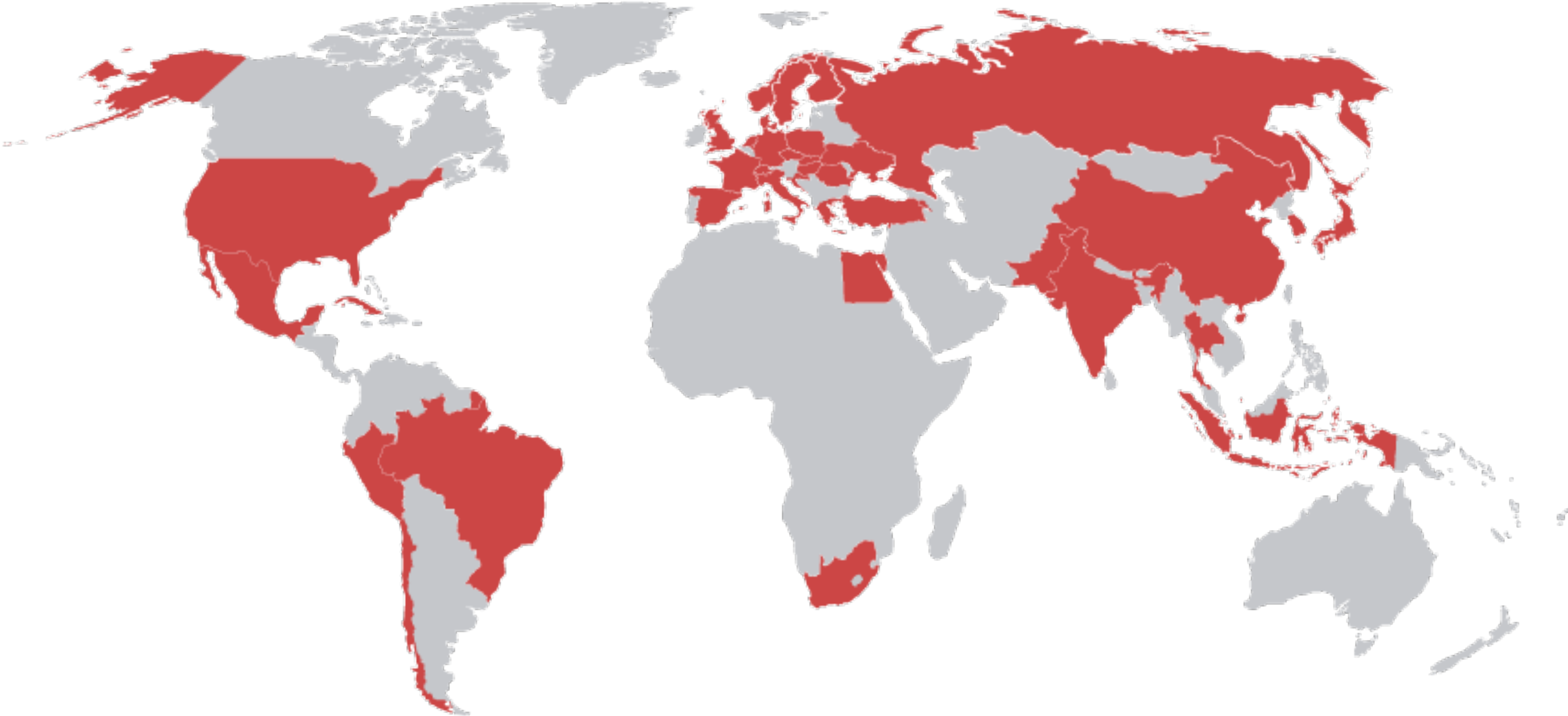
light (anti)nuclei ($\bar{d}$, $\bar{t}$, $^3\overline{He}$, $^4\overline{He}$)
combining TPC *d*E/*dx* + TOF mass



Me building the time-of-flight detector

ALICE Collaboration

37 countries, 154 institutes, over 1500 members



goal is to study QCD phase transition and QGP properties

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

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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**

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

Soft heavy-ion physics at the LHC

p-Pb discussion has a similar flow, but not for today

material is in backup for whoever is interested

- 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
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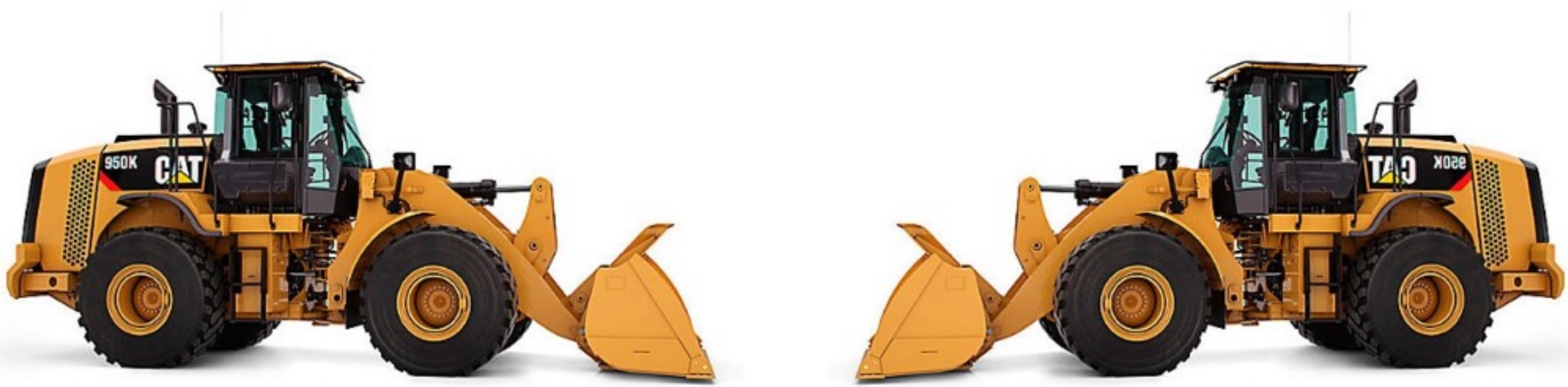
Particle production in nucleus-nucleus collisions



Jet suppression

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

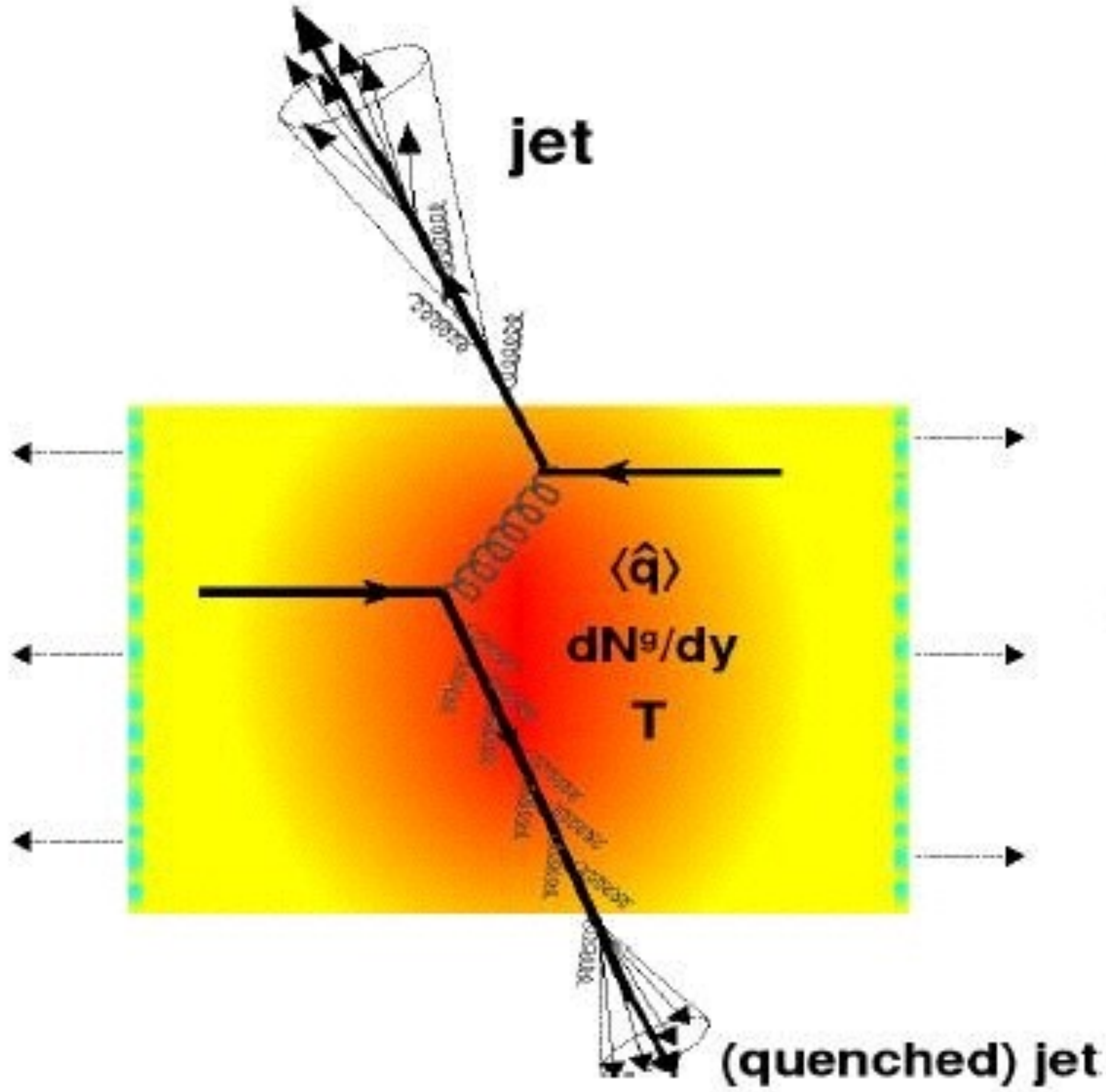
FERMILAB-Pub-82/59-THY
August, 1982

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

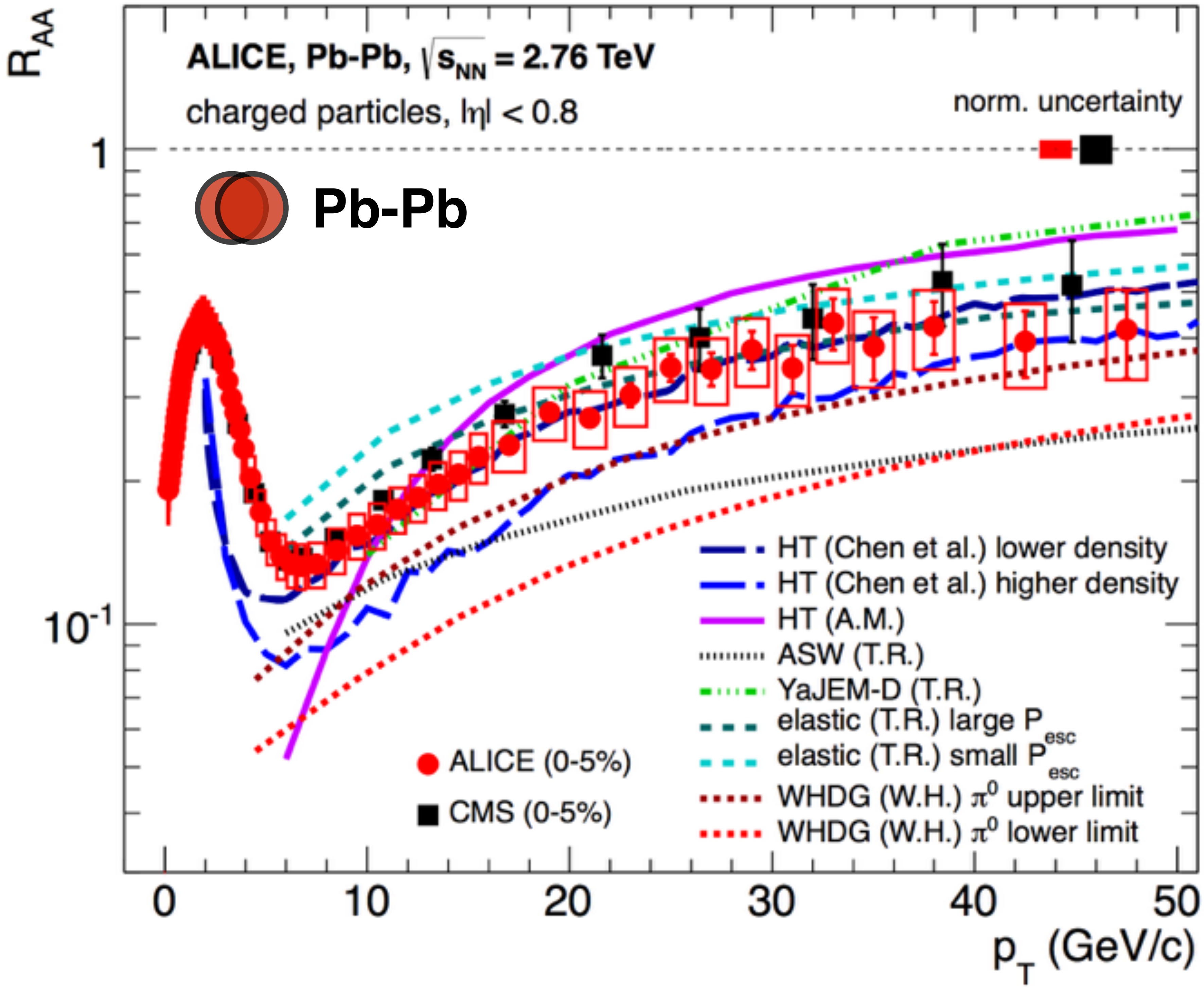
$$R_{AA} = \frac{dN^{AA}/dp_T}{N_{coll}\, dN^{pp}/dp_T}$$

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

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

High-p_T suppression

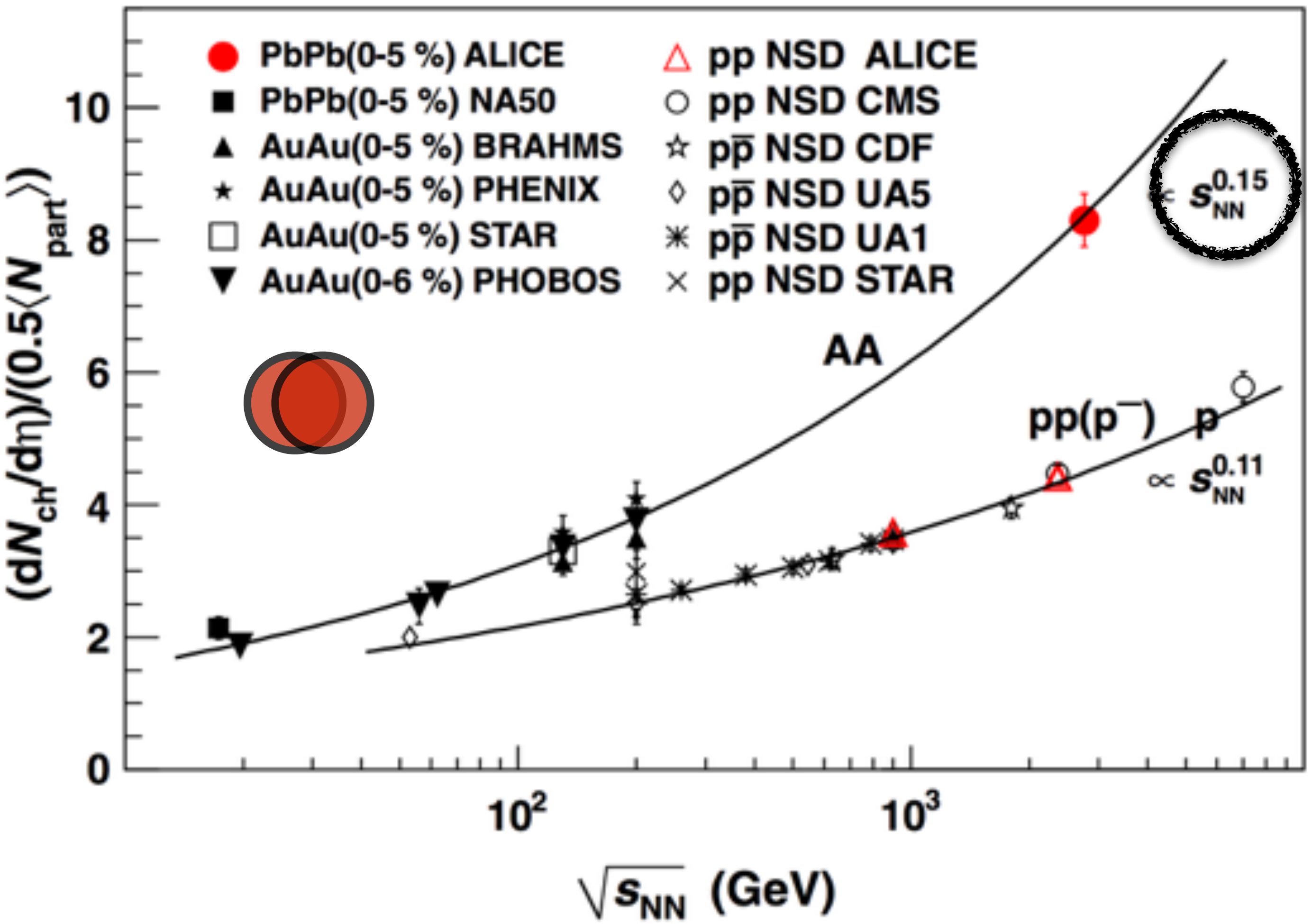
ALICE, PLB 720 (2013) 52

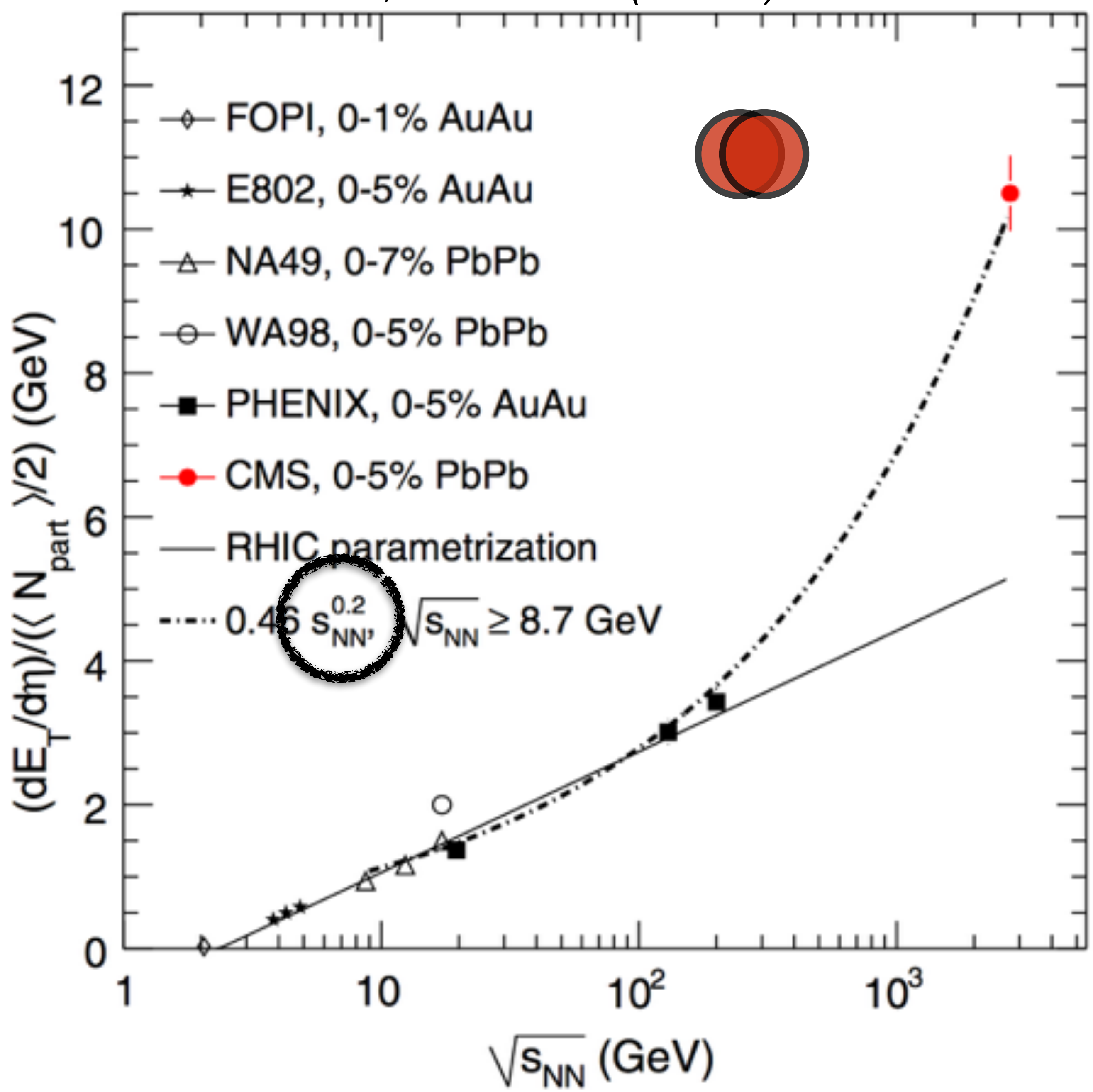


hadron production **strongly modified in Pb-Pb** collisions

large suppression in a wide p_T range

Multiplicity and transverse energy

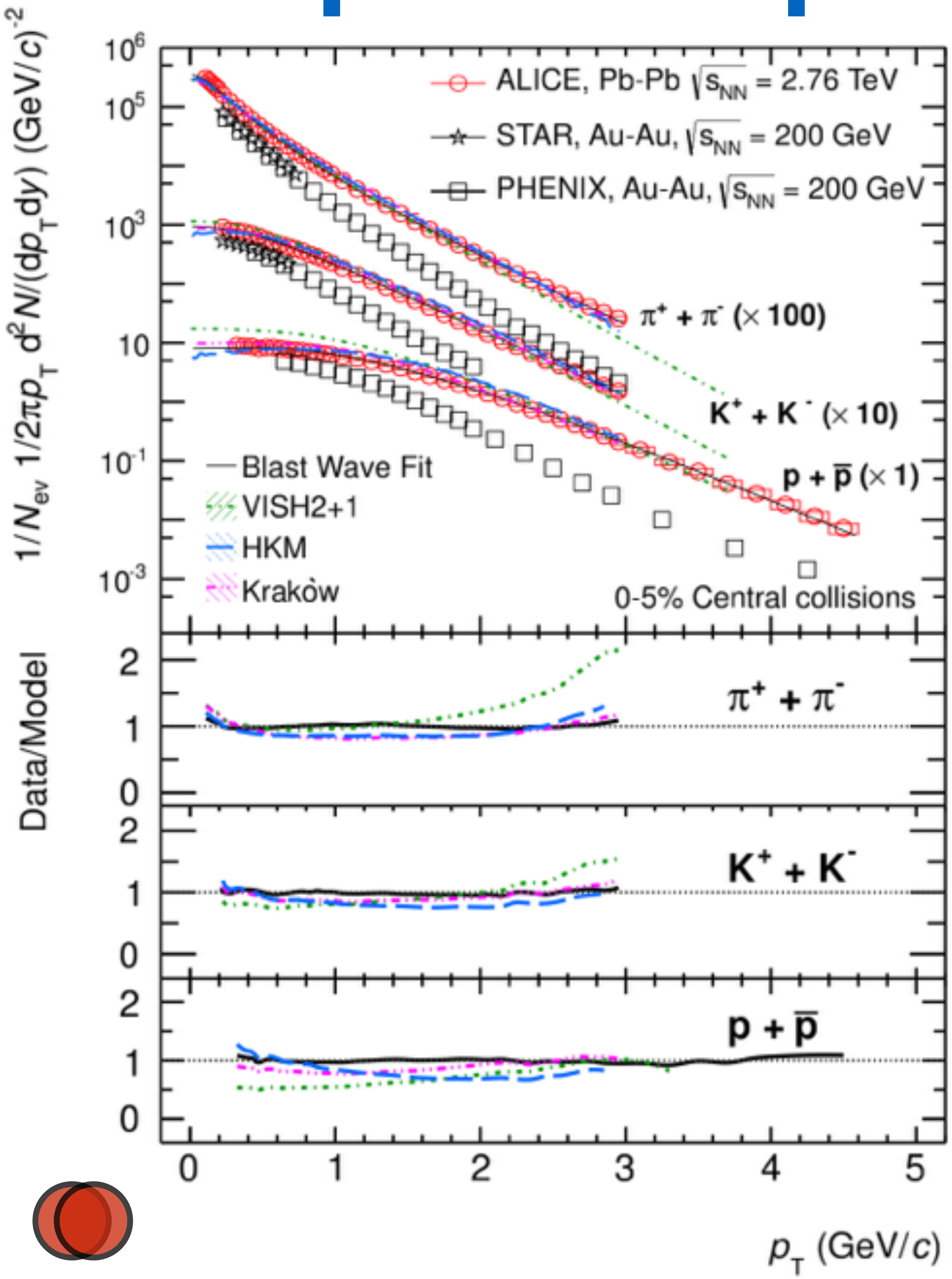




$\langle E_T \rangle$ grows faster with energy than the multiplicity

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

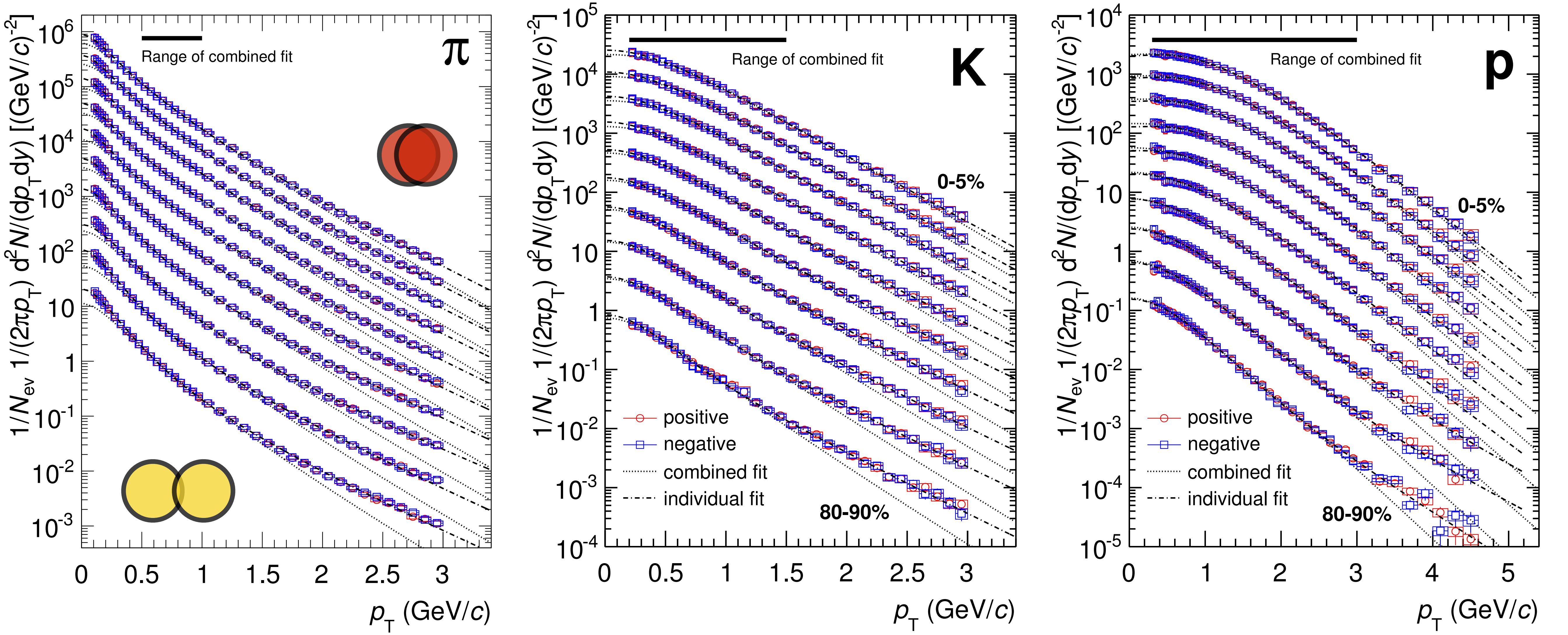
Bulk particle production in Pb-Pb



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

ALICE, PRL 109 (2012) 252301

Bulk particle production in Pb-Pb

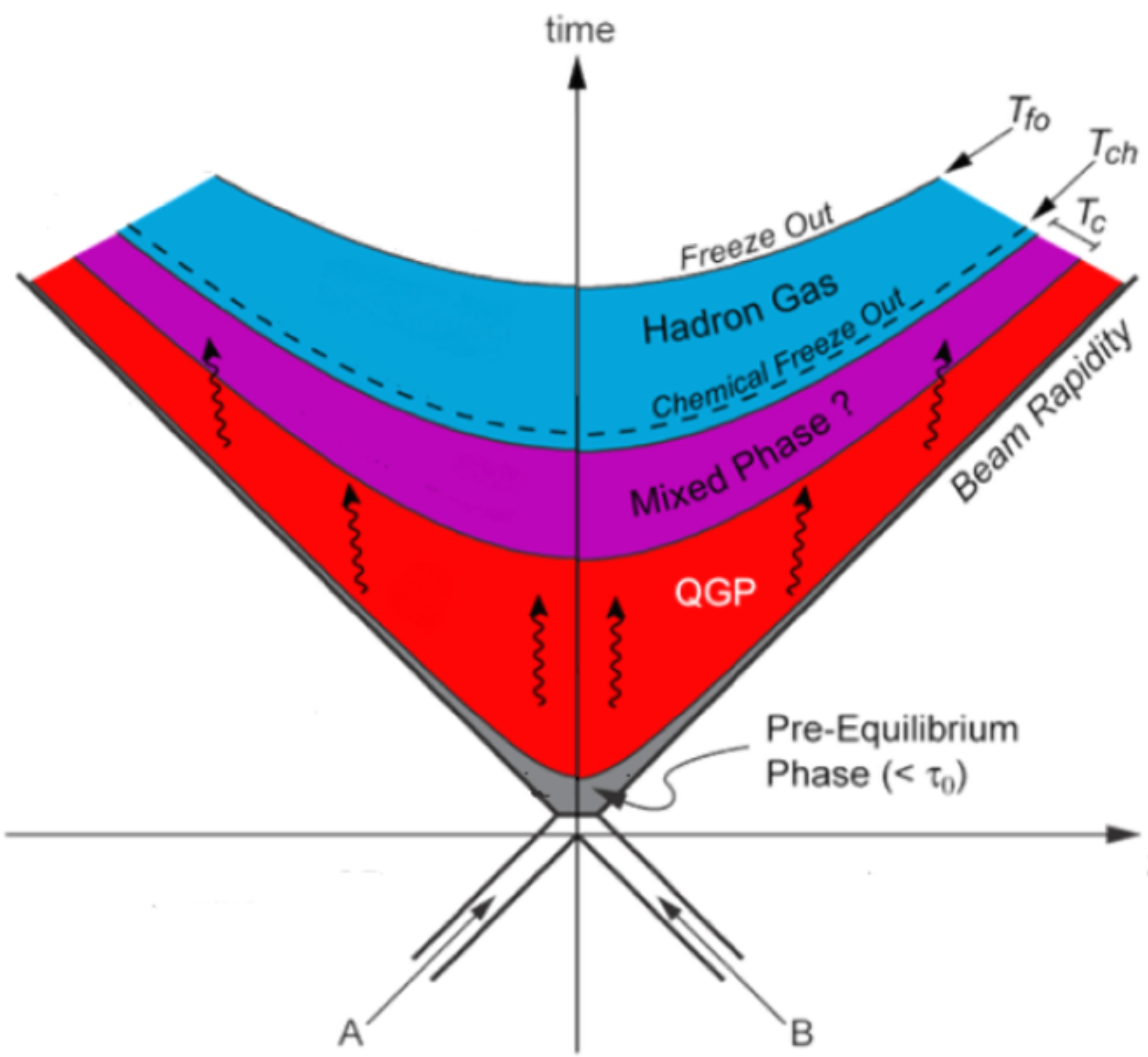


clear evolution of particle spectra → hardening with centrality
more pronounced for protons than for pions
mass ordering as expected from collective hydro expansion

Collective phenomena

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

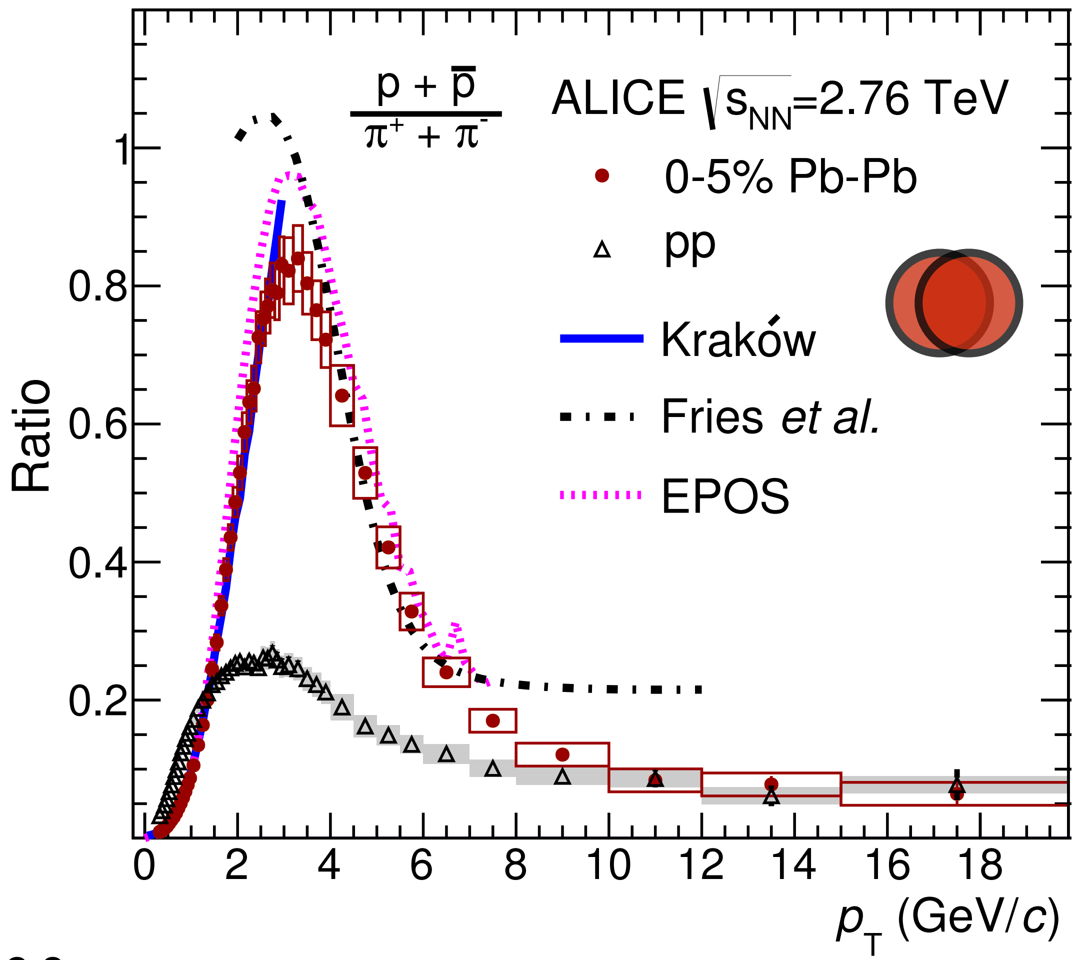
- initial hot and dense partonic matter rapidly expands
- collective flow develops and the system cools down
- phase transition to hadron gas when $T_{critical}$ is reached

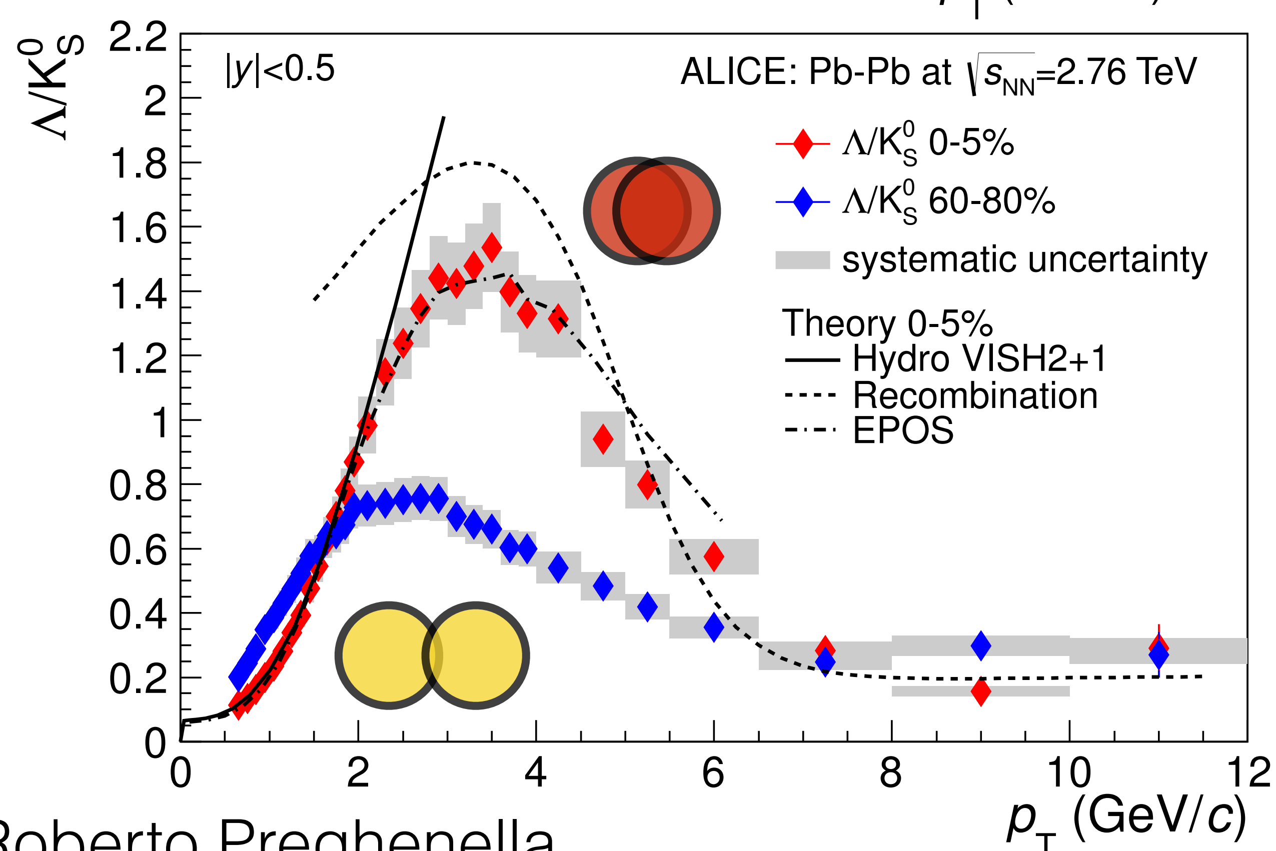


resulting in

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

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**

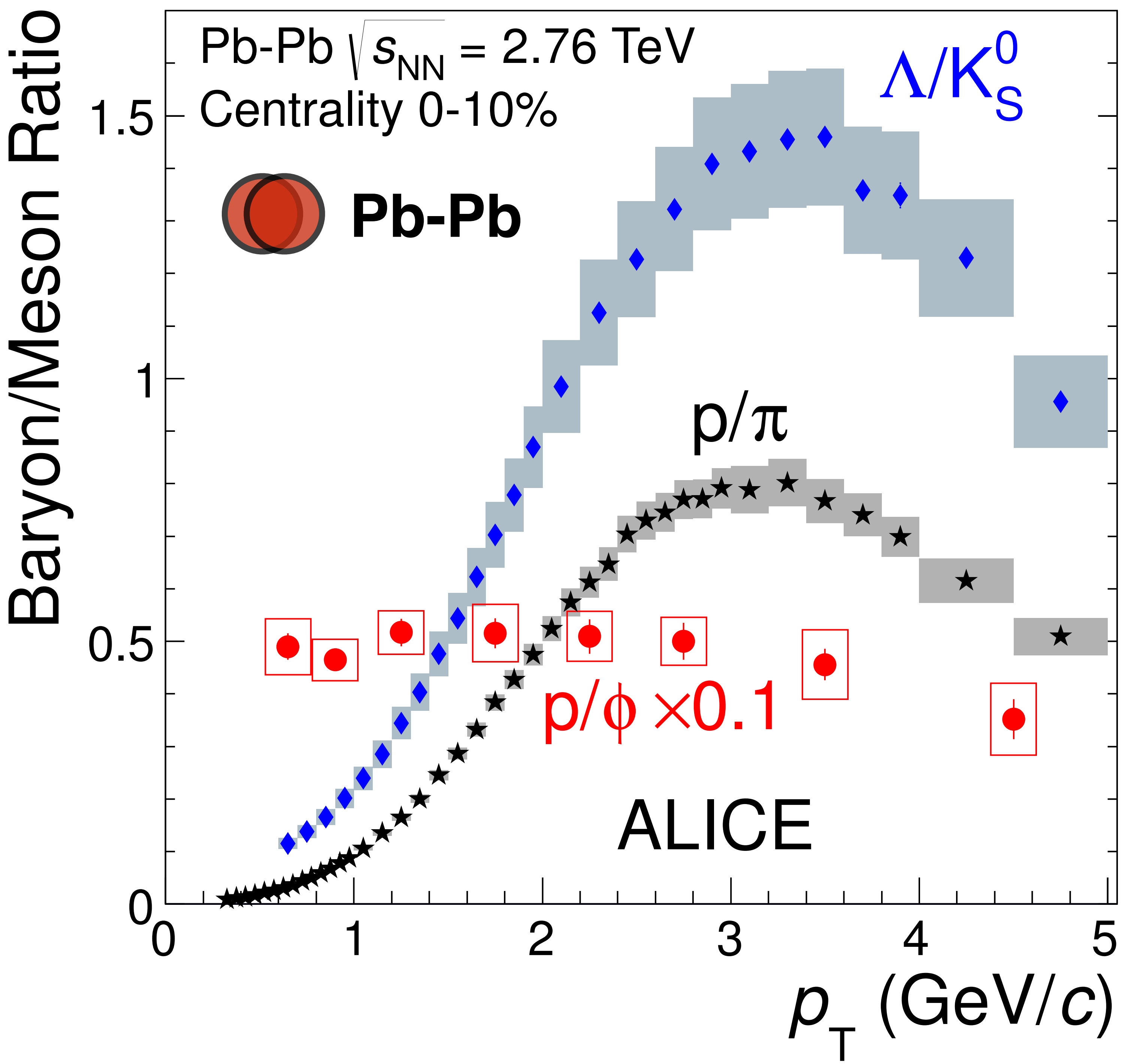
Fries, Ann.Rev.Nucl.Part.Sci. 58 (2008) 177

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/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

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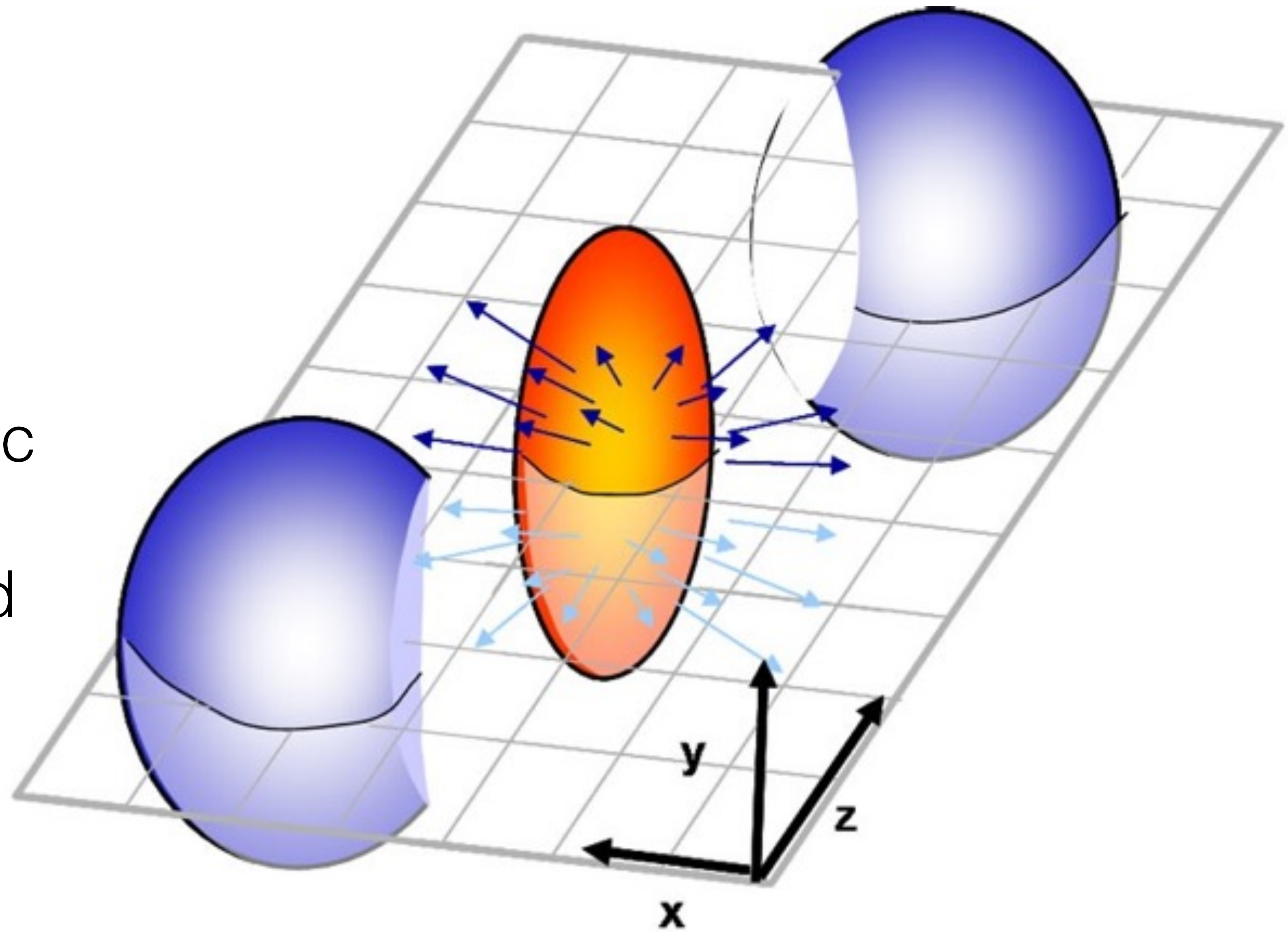

resulting in

- dependence of the shape of the p_T distribution on the particle mass
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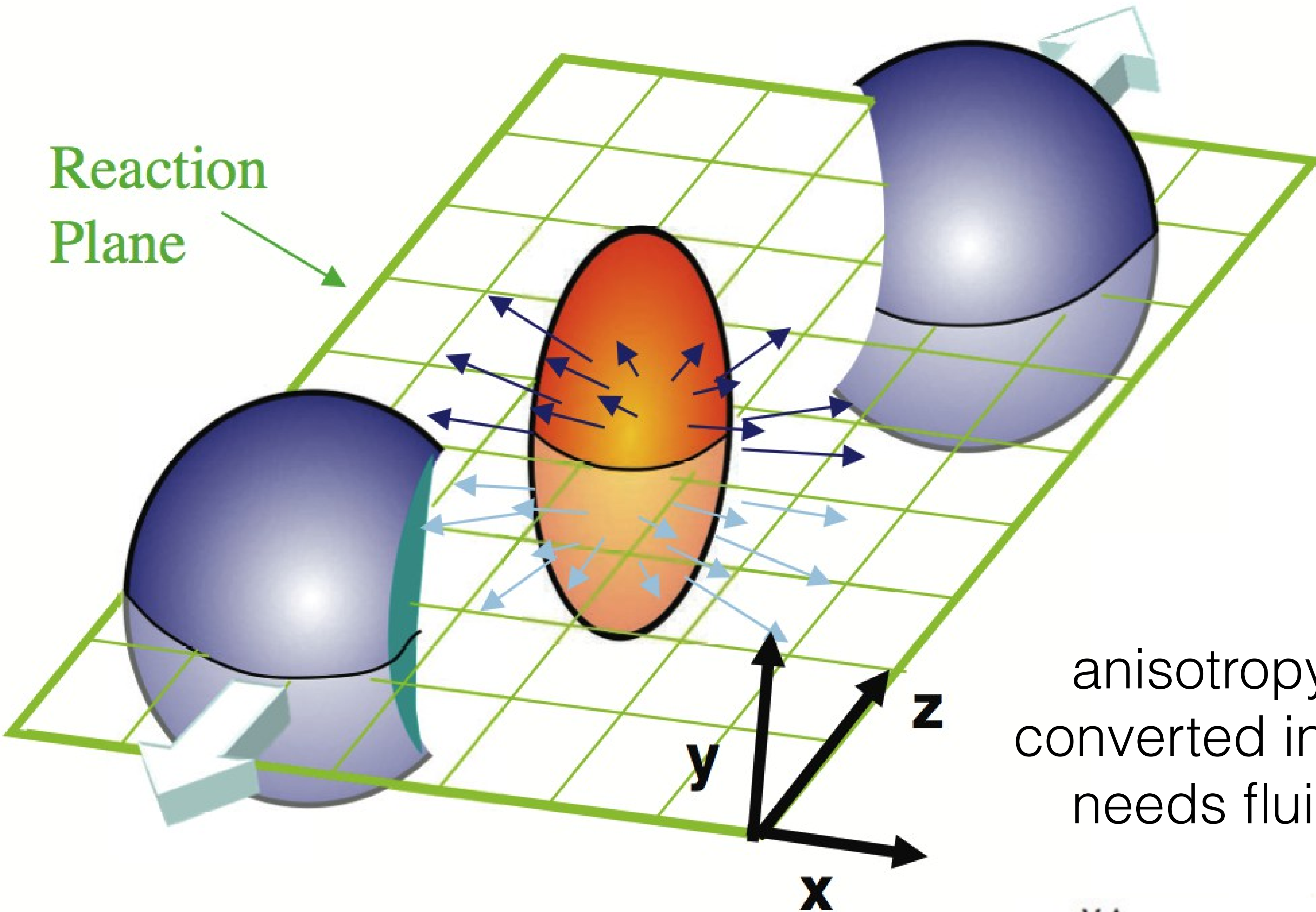
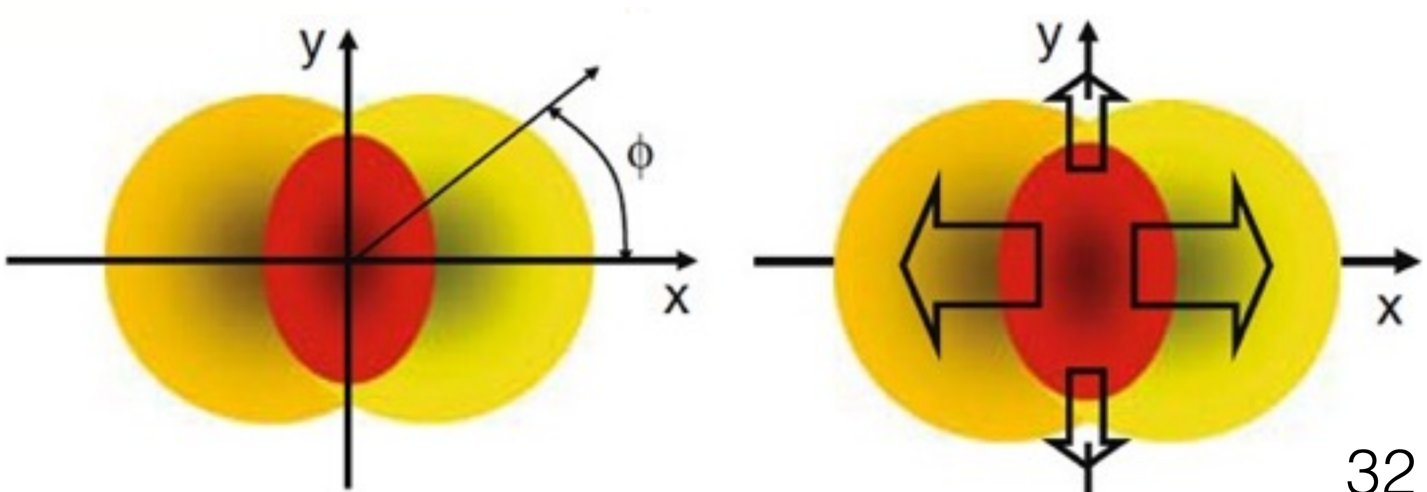
Anisotropic flow

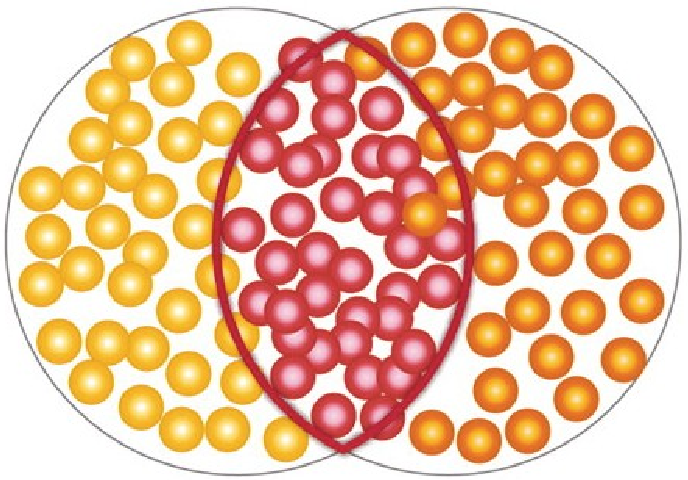


anisotropy in **spatial** space
converted in **momentum** space
needs fluid-like **collectivity**

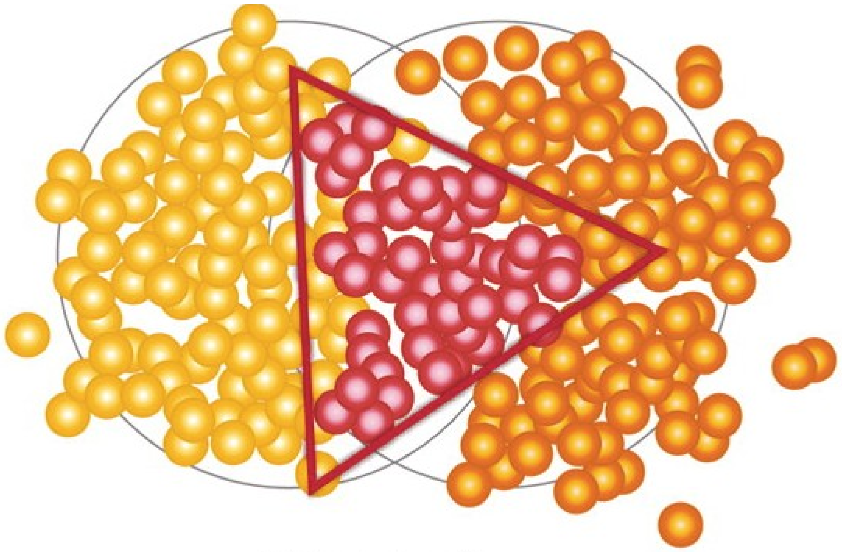
elliptical collision **geometry**
anisotropic pressure gradients



Anisotropic flow



Elliptic flow

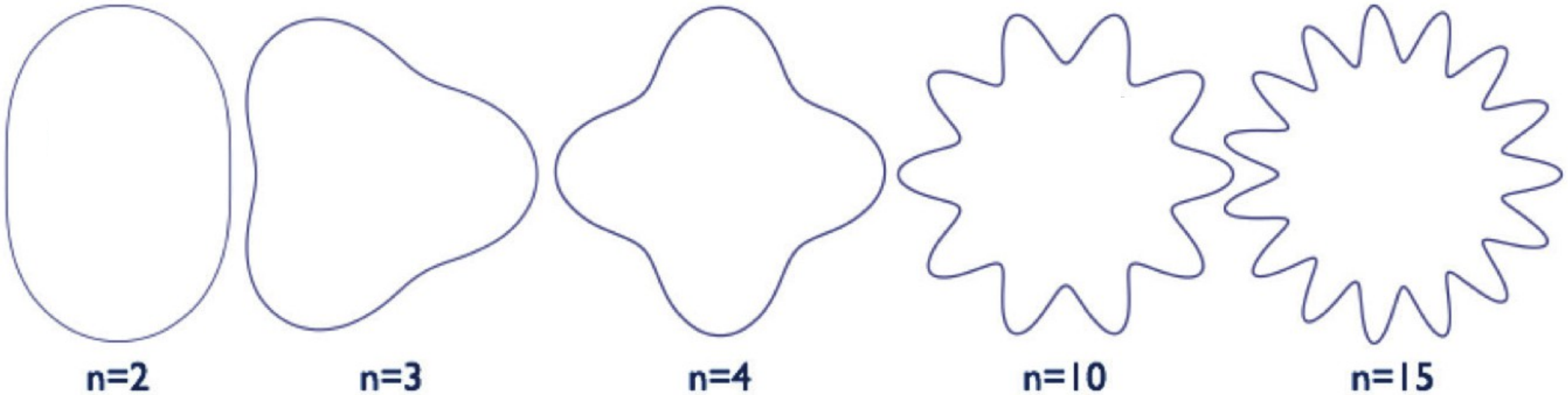


Triangular flow

anisotropic momentum distributions
dependence can be decomposed in
Fourier series

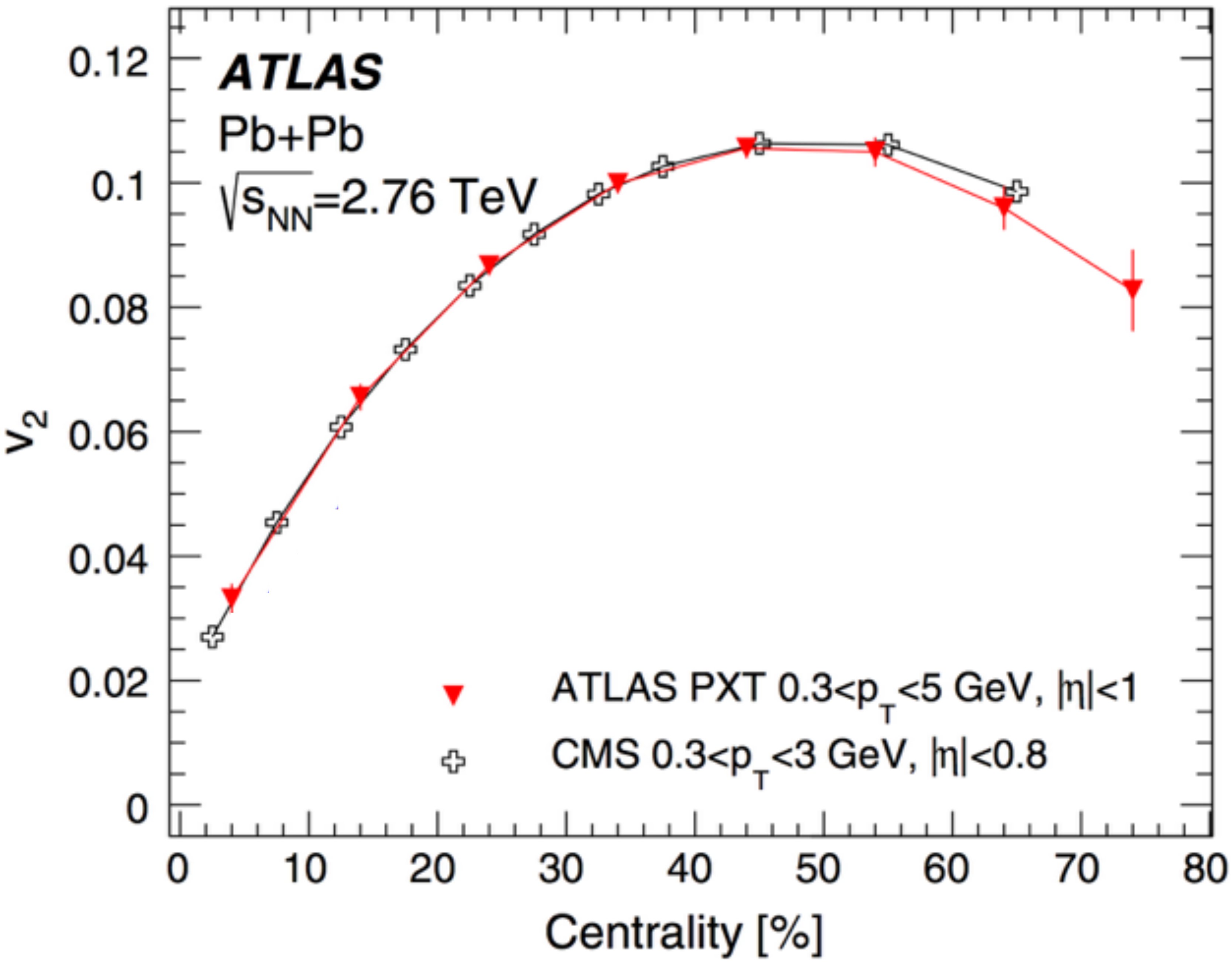
$$\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_R)]\right)$$

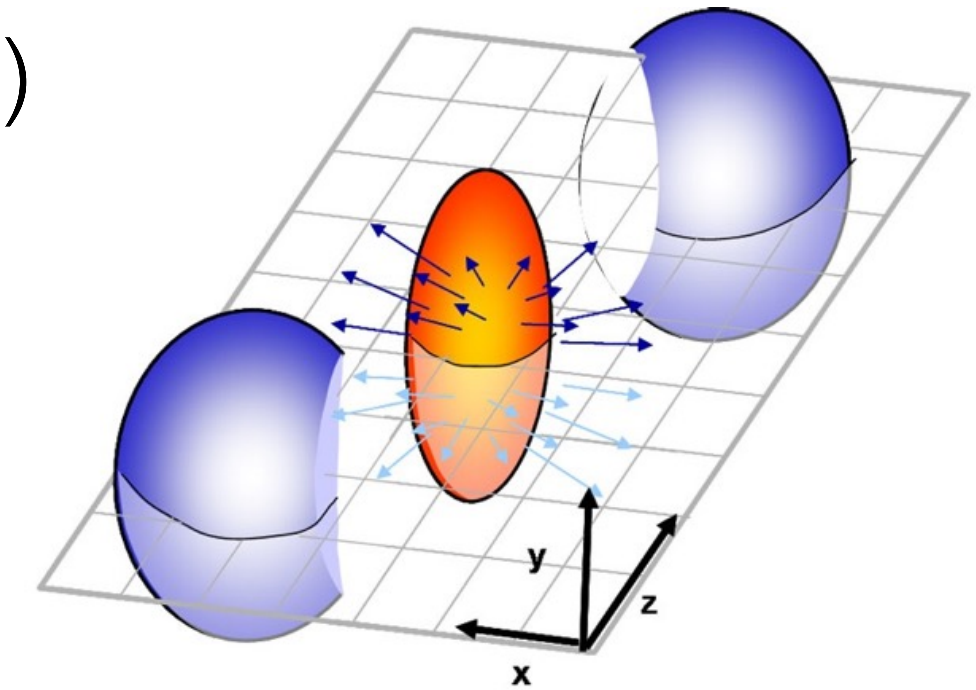
magnitude characterised by
v_n coefficients



Collective anisotropic flow

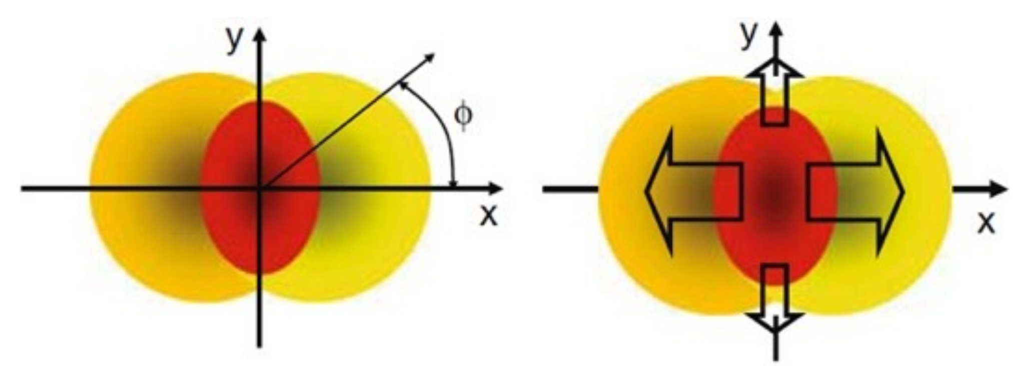
spatial anisotropy (collisions geometry)
⟶ anisotropy in momentum space: v_2





strong collective flow persists at the LHC

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



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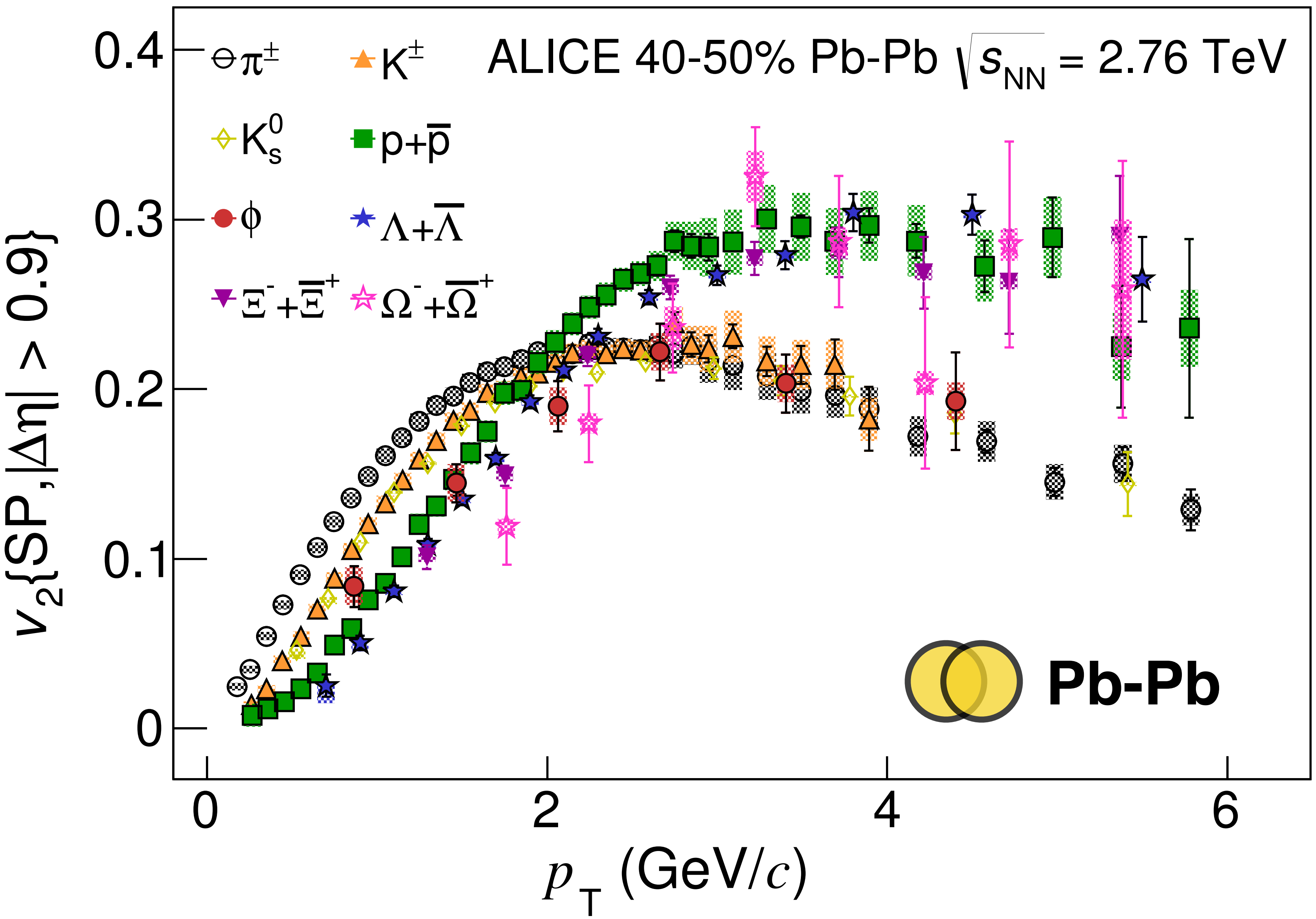
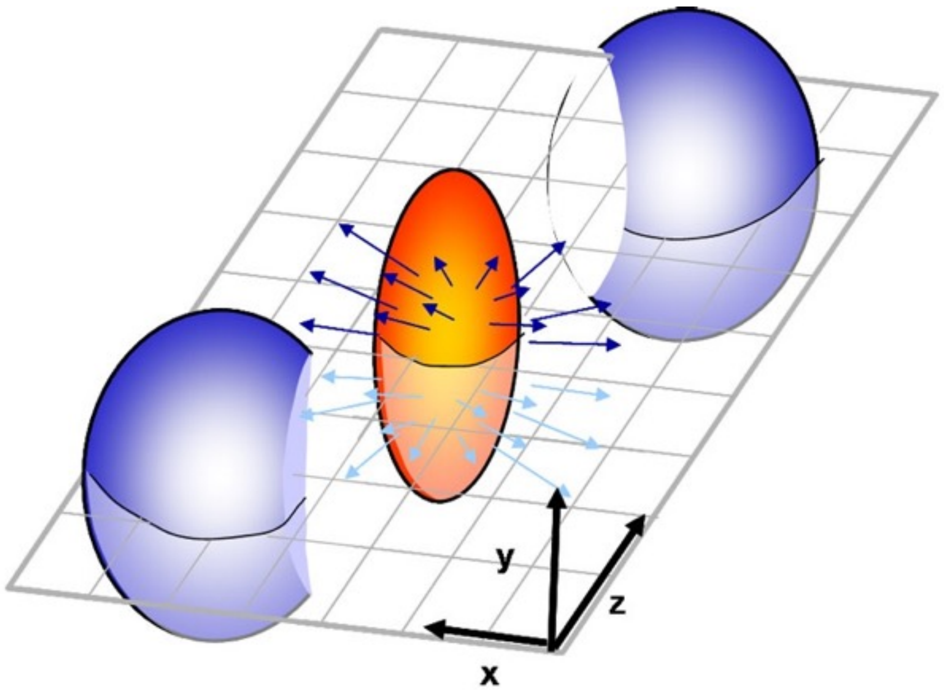




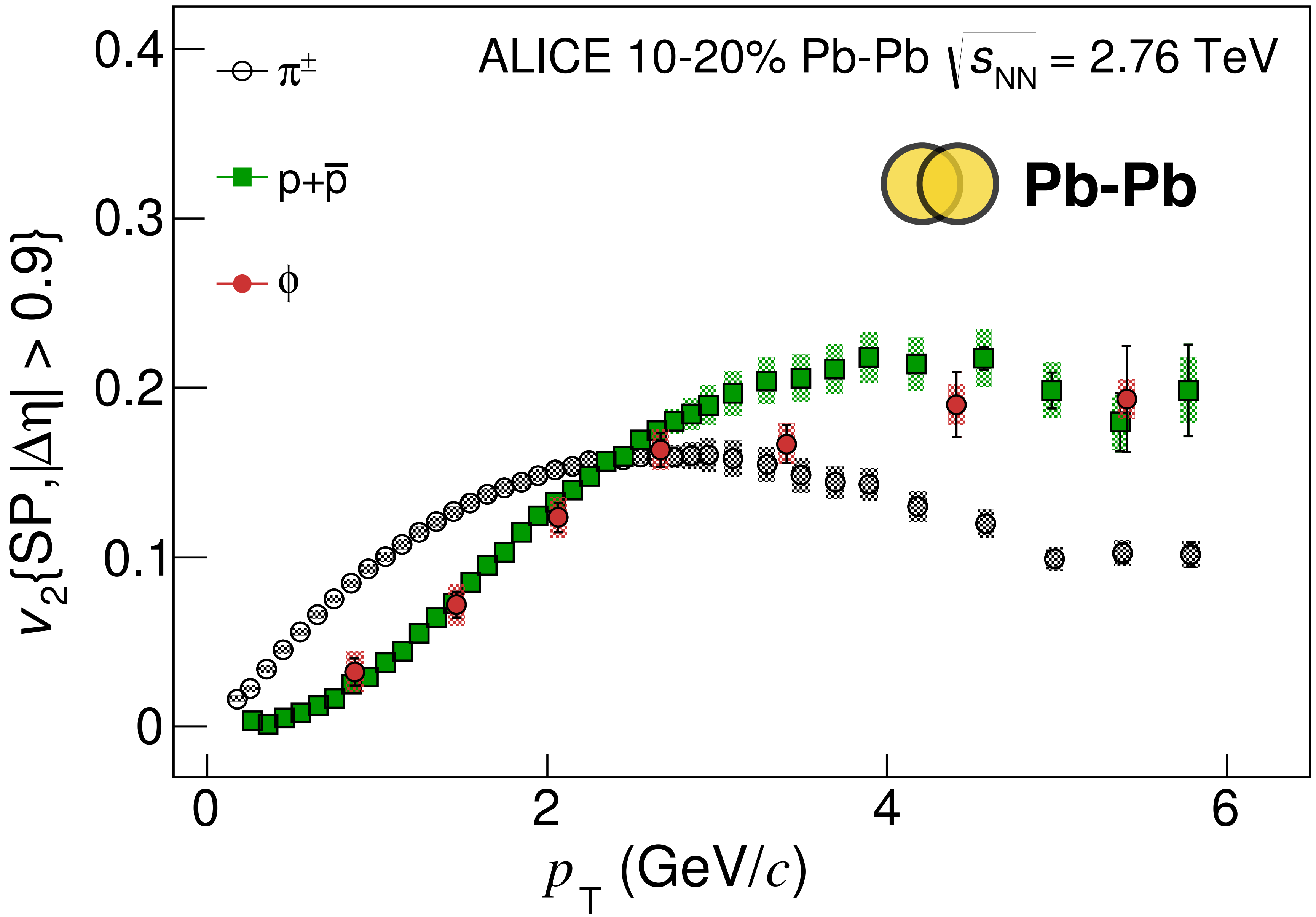
v_2 measured for
$\pi^{\pm}$, $K^{\pm}$, K^0_S, p, ϕ, Λ, Ξ, Ω

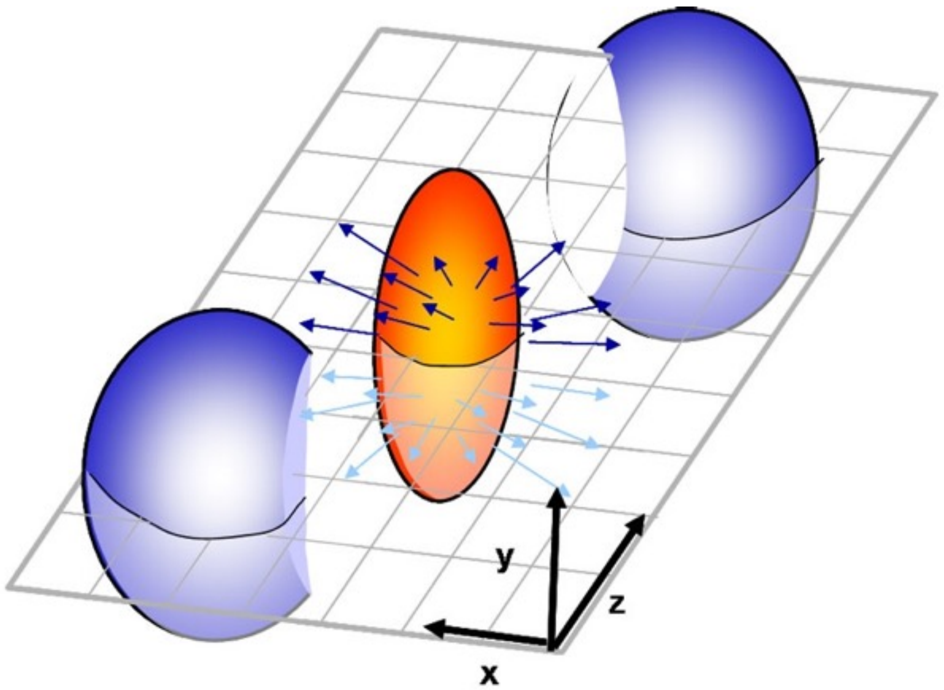
mass ordering
attributed to common
radial expansion velocity

ALICE, JHEP 06 (2015) 190

Collective anisotropic flow

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





ϕ meson behaves like a proton

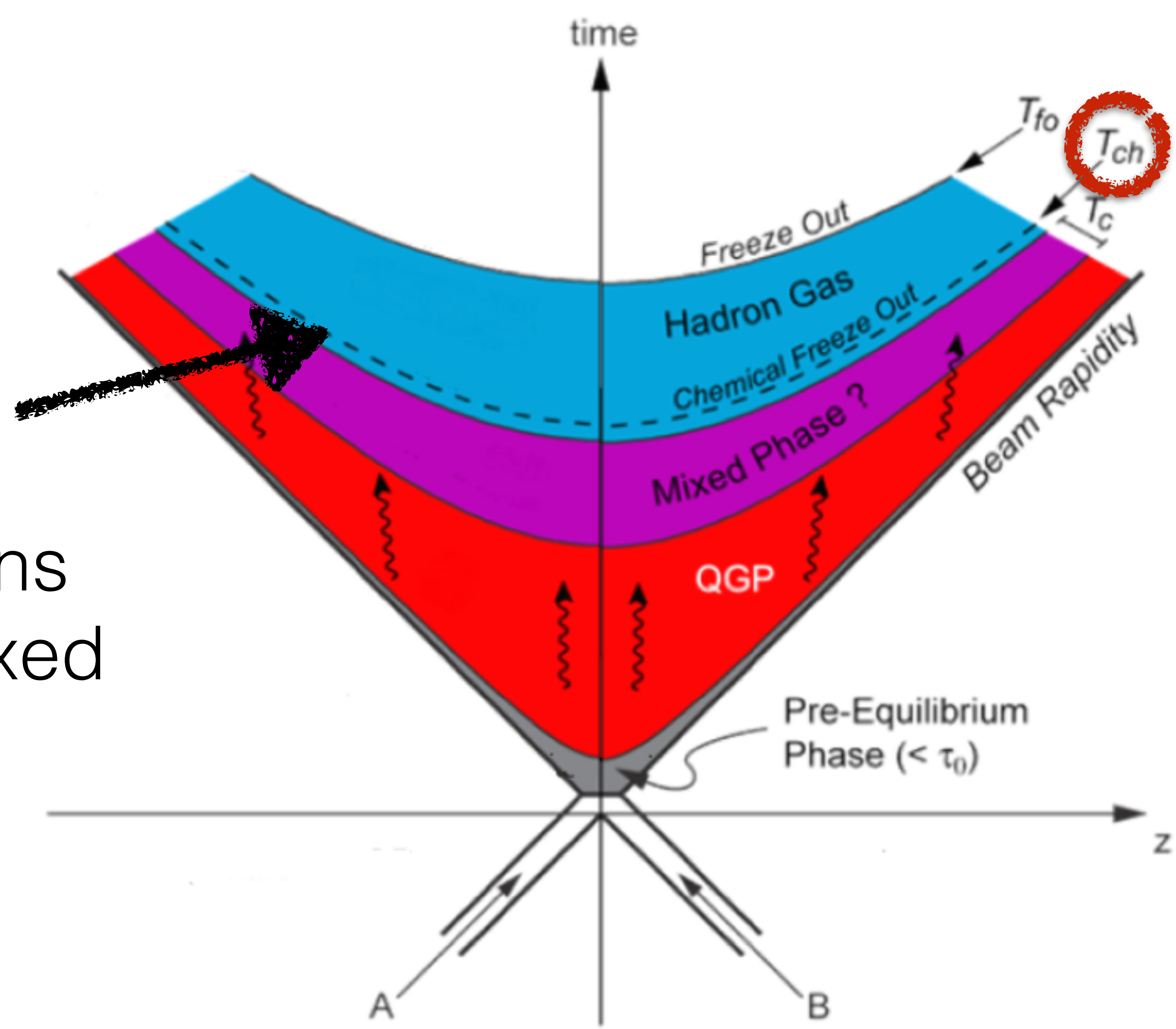
mass drives v_2 and spectra, not number of constituent quarks

ALICE, JHEP 06 (2015) 190

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

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

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

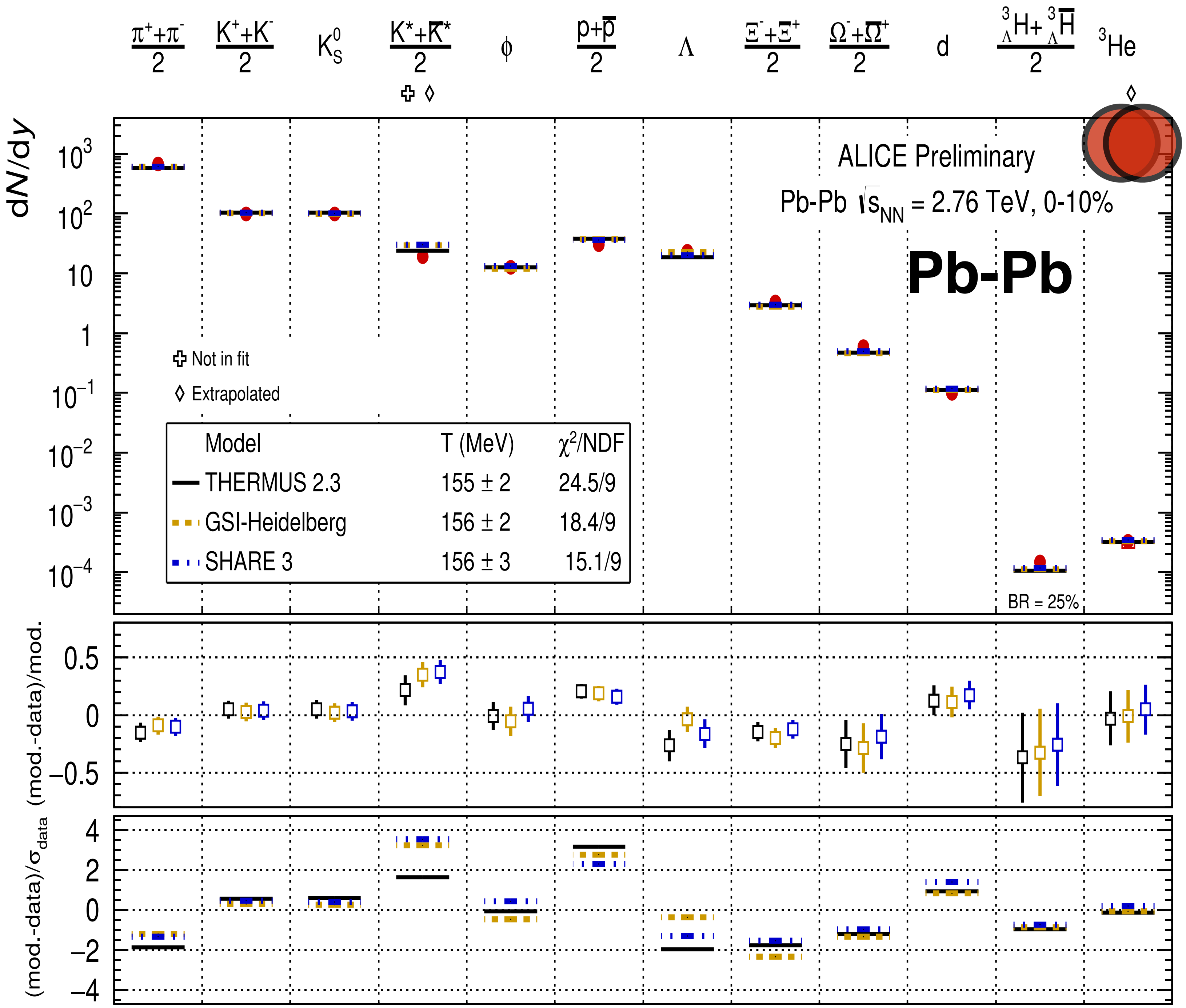
n = particle density (N / V)
M = hadron mass
T = temperature
μ = chemical potential dE/dN

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, …)

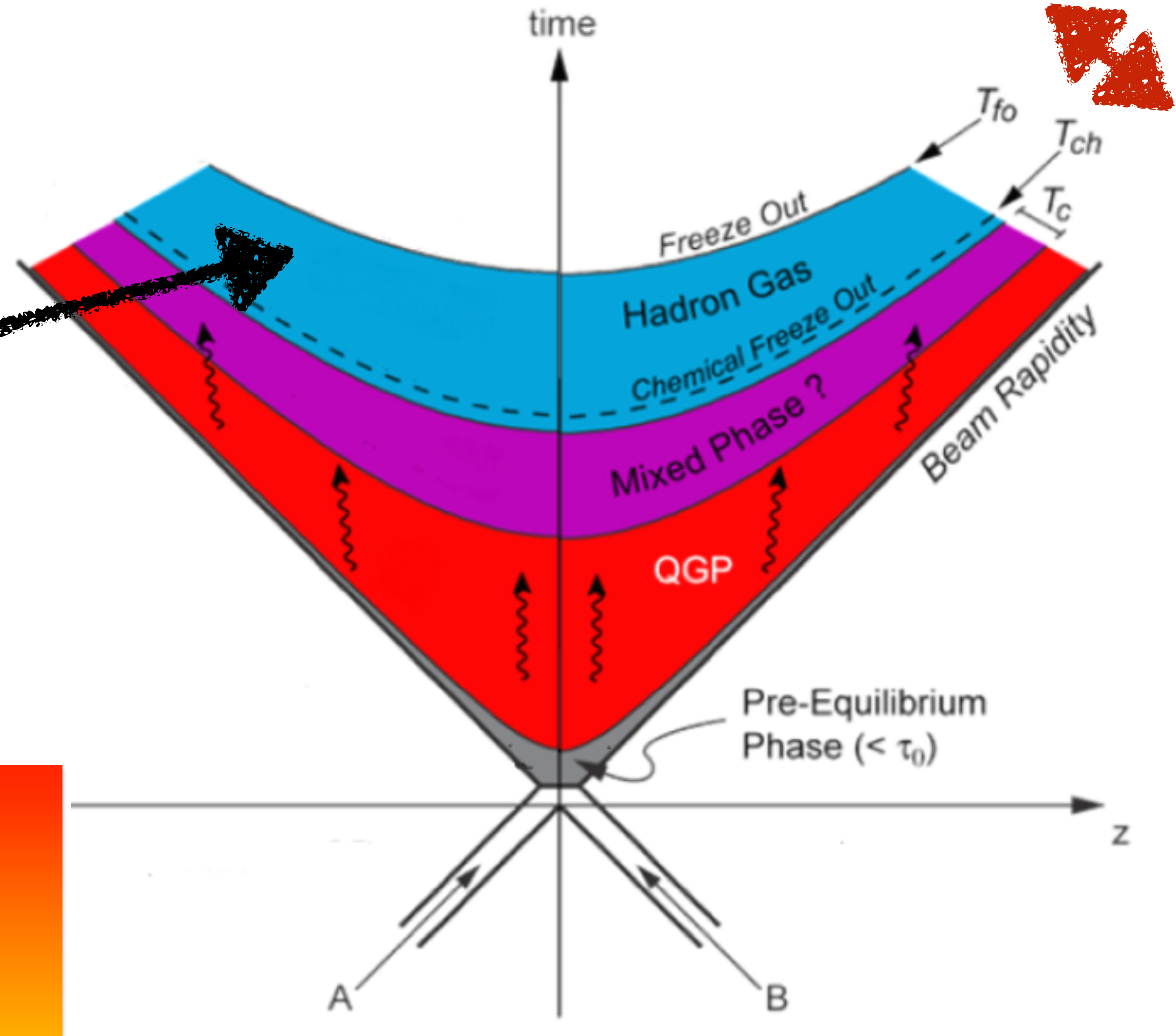
Interactions in the hadronic phase

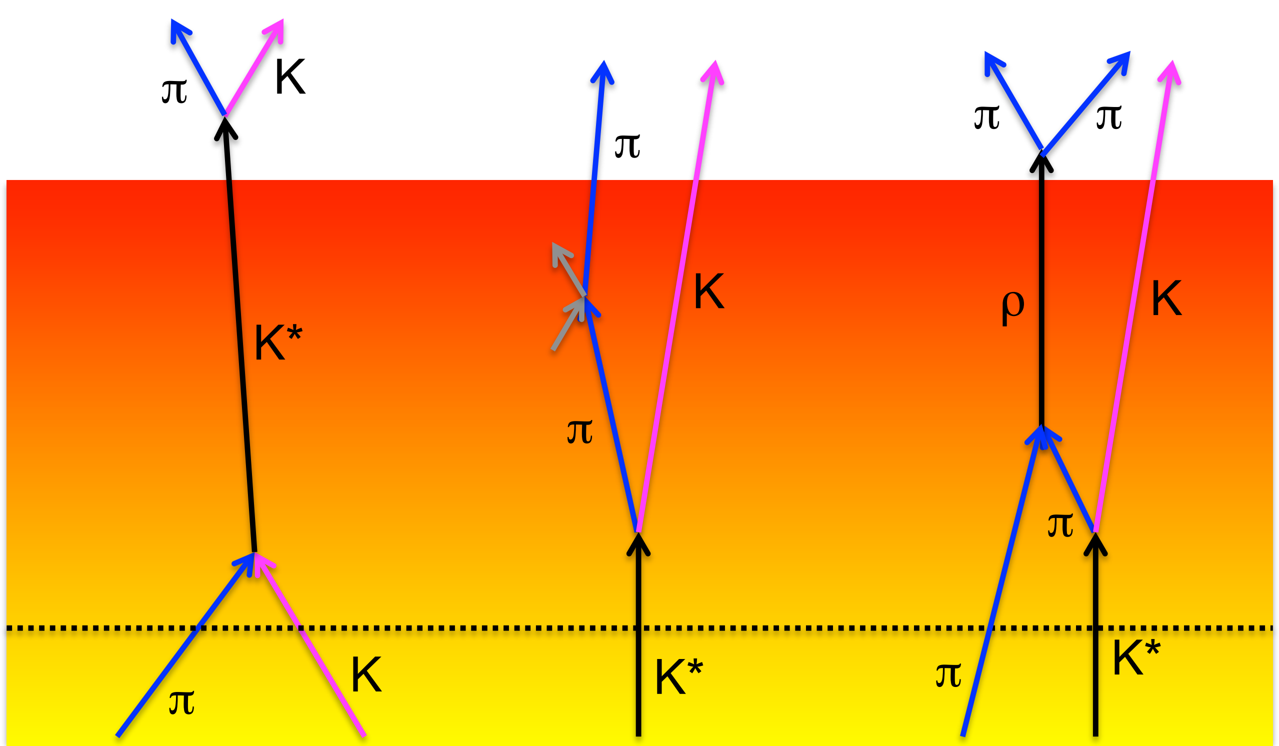
measured yields of resonances might be modified by hadronic processed

hadronic phase

elastic rescattering of decay daughters

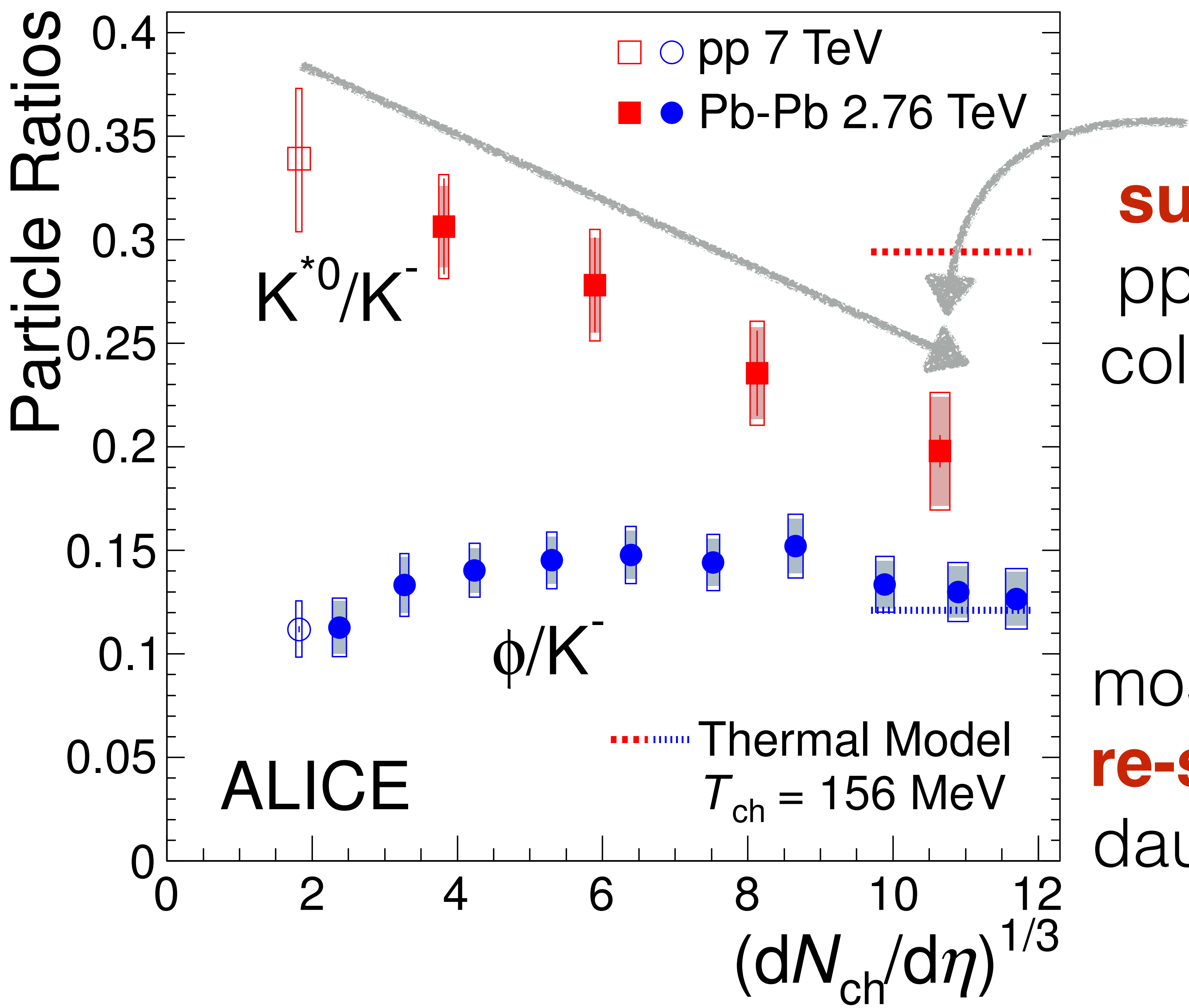
resonances not reconstructed via invariant mass





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

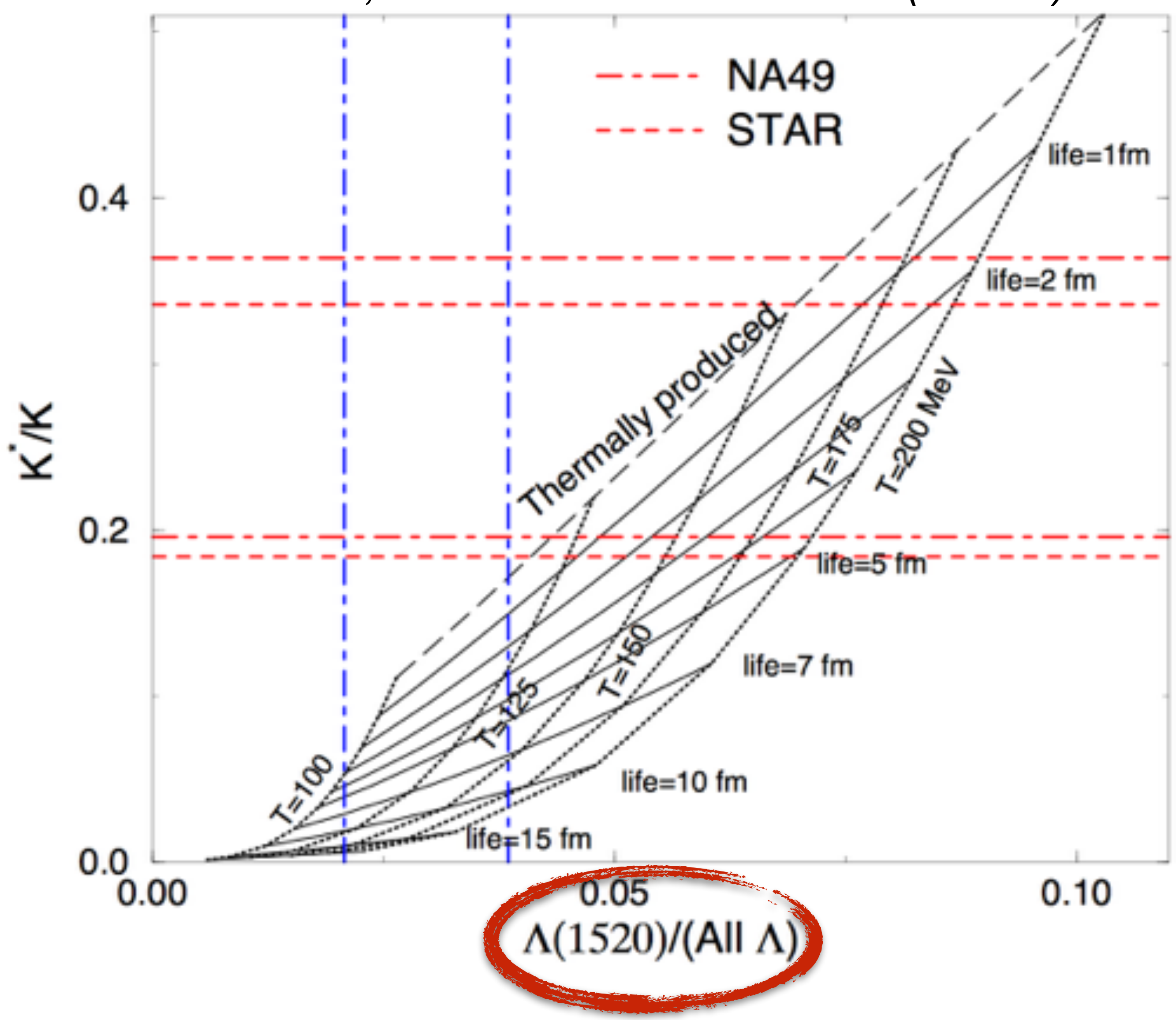
τ_{K^*} (~4 fm/c) ≪ τ_ϕ

ALICE, PRC 91 (2015) 024609

Properties of hadronic phase

Markert, AIP Conf. Proc. 631 (2002) 533

- 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 $\geq$ 2 fm/c

important to measure other resonances to determine the upper limit for the lifetime

Particle production in proton-nucleus collisions

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
<u>interesting!</u> need more investigation on small systems

many more results and a bright future

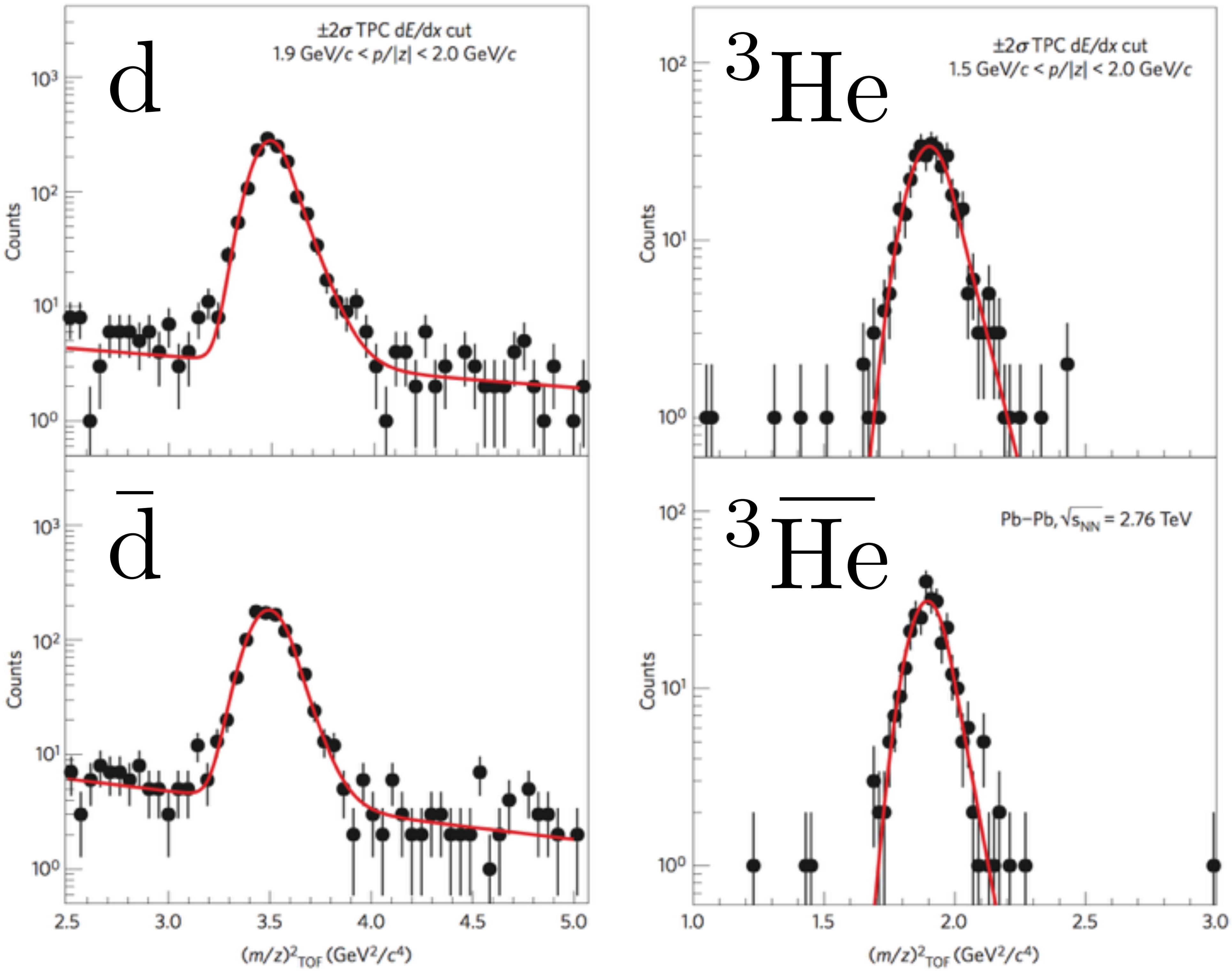
new data and more ideas for LHC Run-2

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

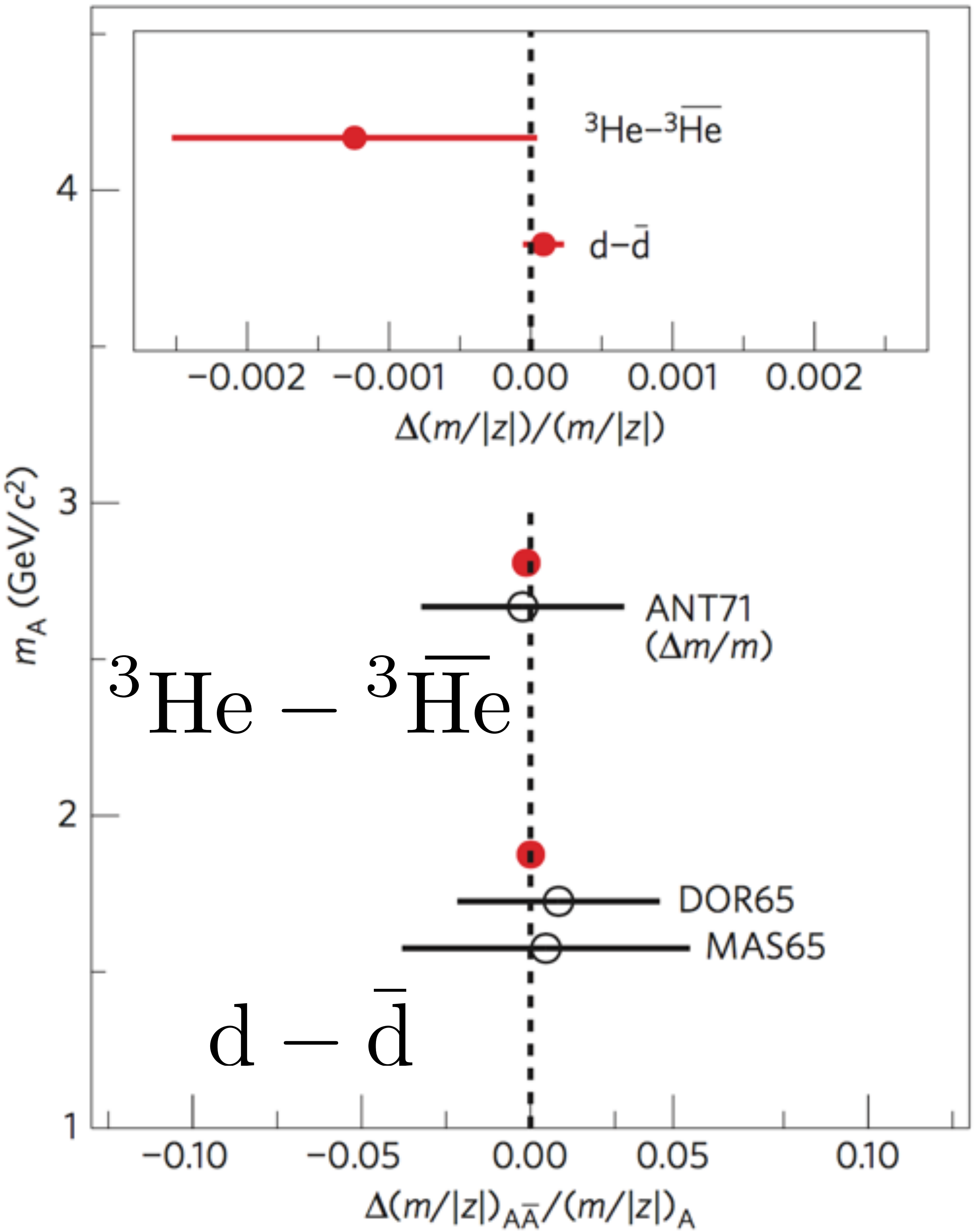
heavy-ion collisions as an **efficient source of nuclei and anti-nuclei**

combined with

high-precision **tracking and identification** capabilities of ALICE

Nature Physics 11 (2015) 811

CPT invariance in nuclear systems



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

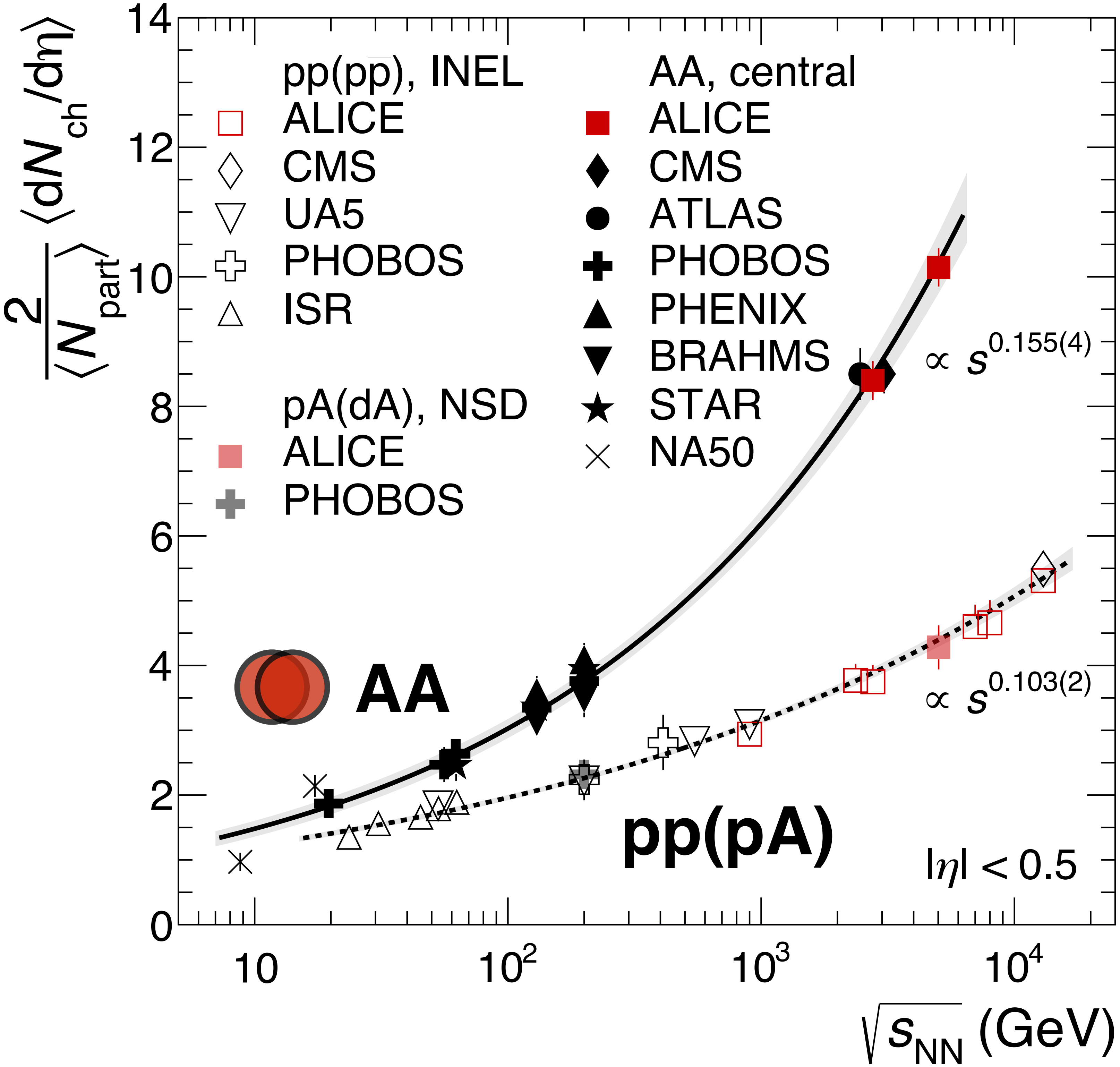
measuring mass differences
rather than absolute values
→ <u>reduced uncertainties</u>
momentum, time-of-flight, track length

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

First results from LHC Run-2

Charged particles in Pb-Pb@5.02 TeV

centre-of-mass energy dependence



charged-particle multiplicity density

at mid-rapidity, $|\eta| < 0.5$

reaches a value of

1943 ± 56

in most central collisions

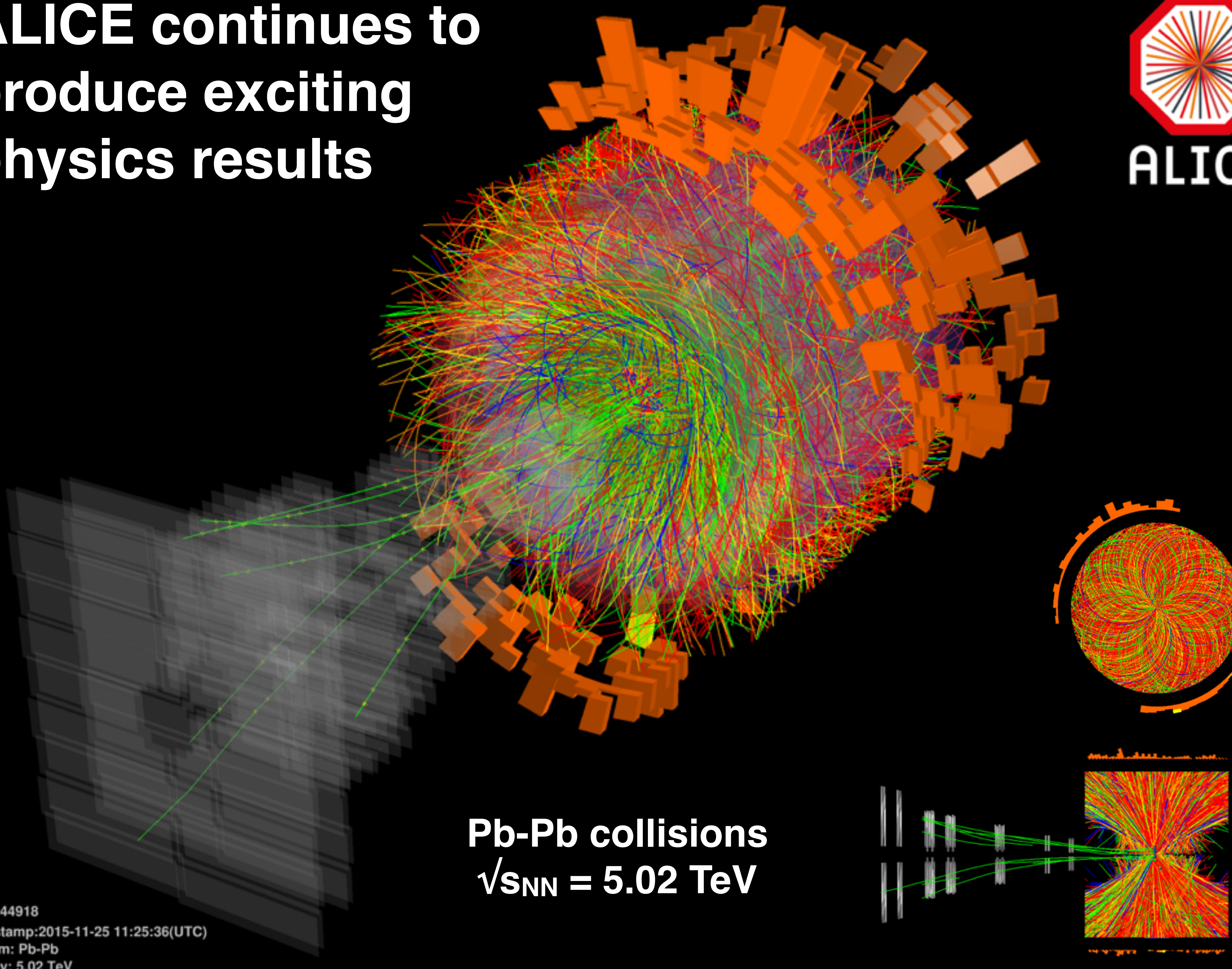
much stronger √s dependence than pp

<u>2.4x larger charged-particle multiplicity than p-Pb</u>

at same energy

scaled by the average number of participating nucleon pairs $\langle N_{part} \rangle/2$

ALICE continues to produce exciting physics results

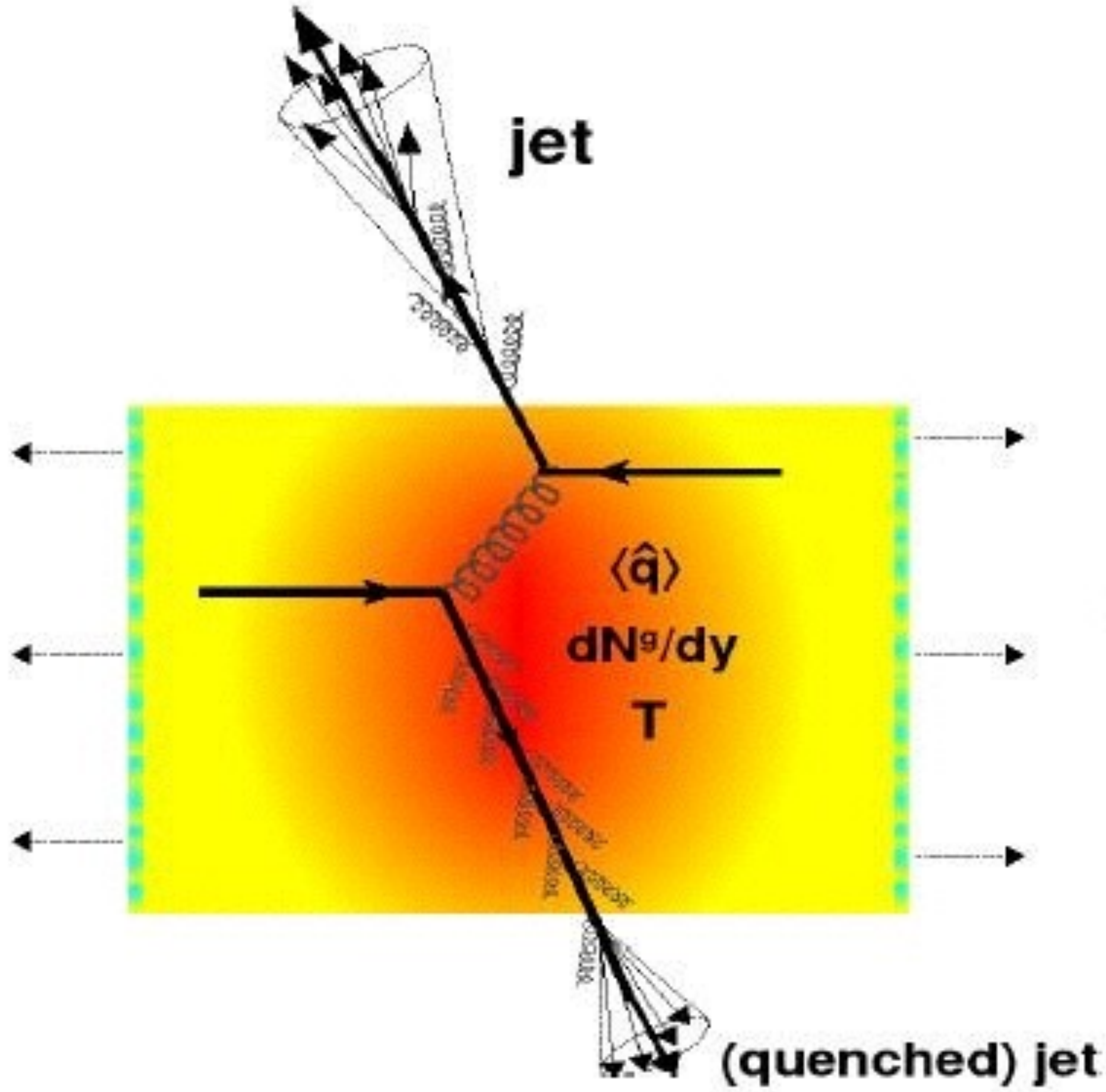


ALICE

Particle production in proton-nucleus collisions

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

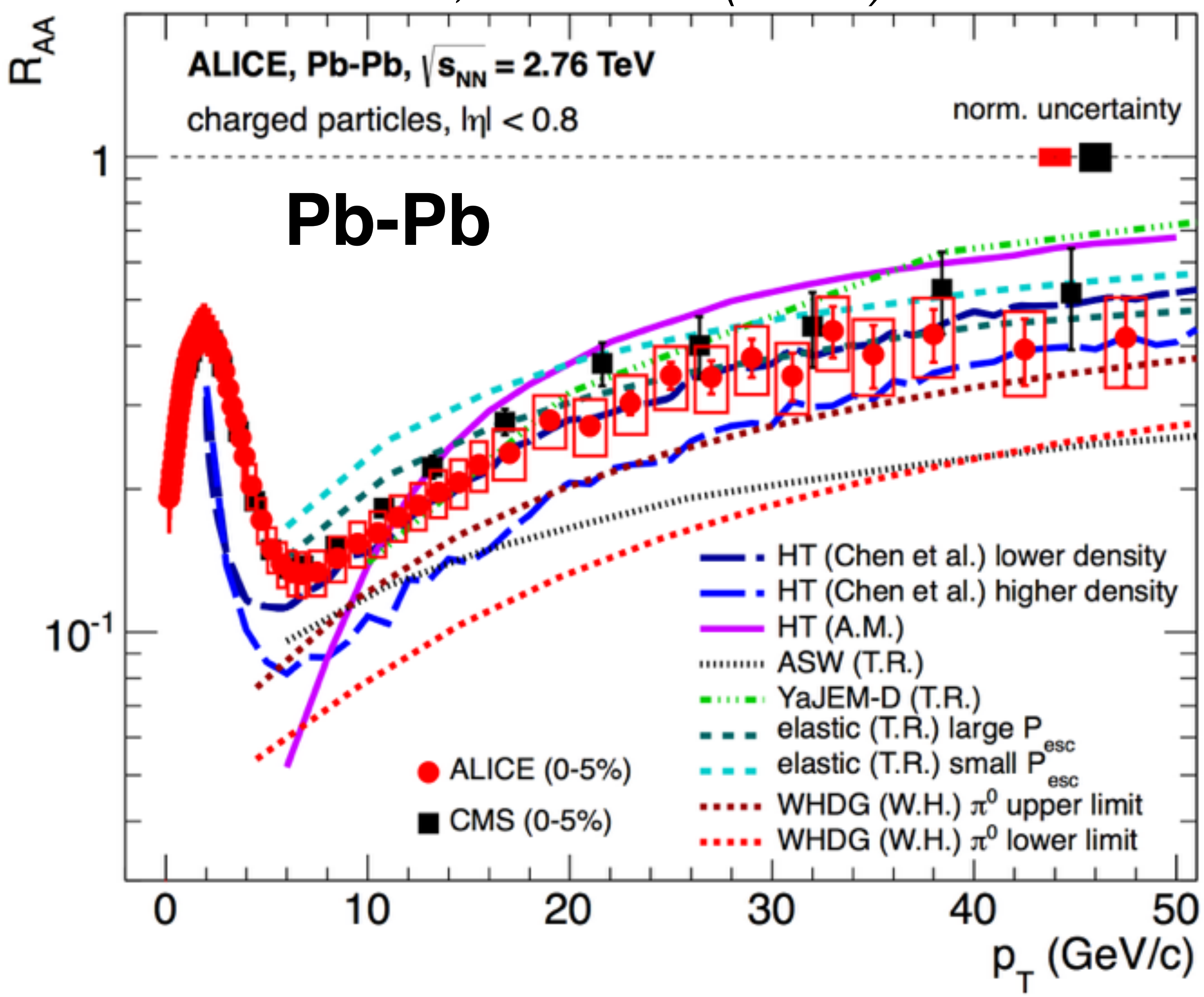
$$R_{AA} = \frac{dN^{AA}/dp_T}{N_{coll}\, dN^{pp}/dp_T}$$

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

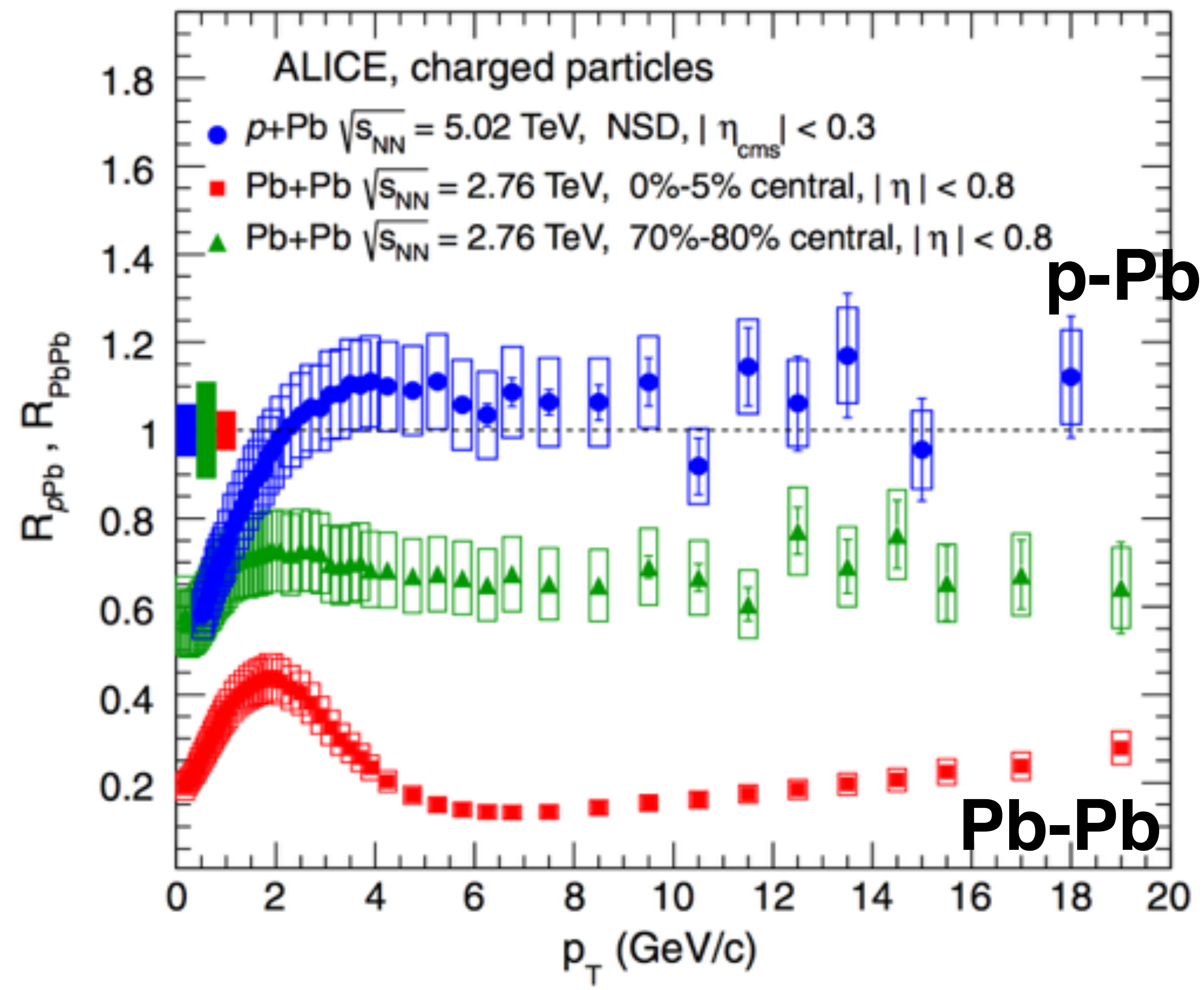
confirmed in Pb-Pb collisions at LHC (direct-γ, Z^0 and $W^{\pm}$)

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

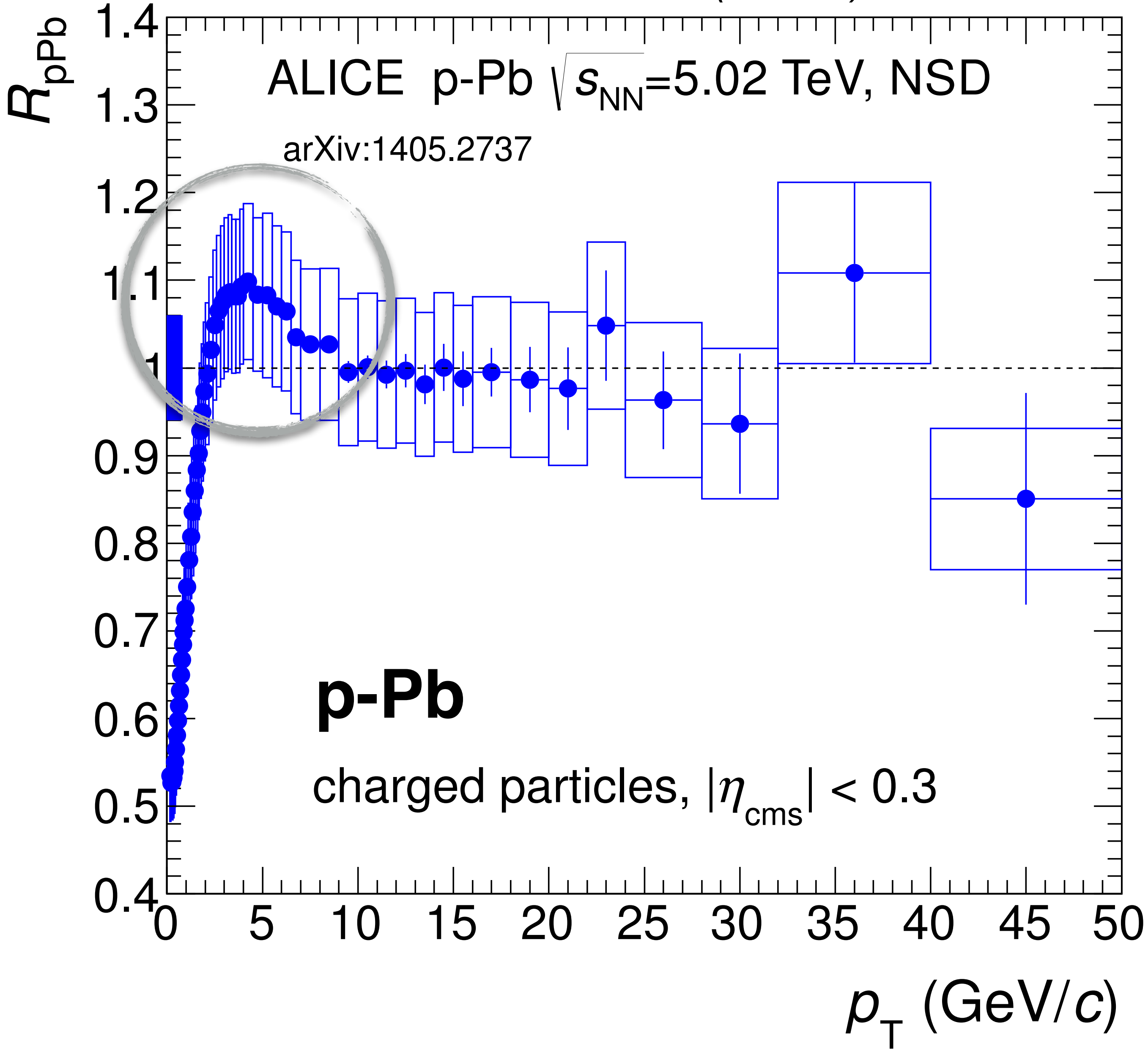
p-Pb confirms that it comes from a **final-state effect**
parton in-medium energy loss

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

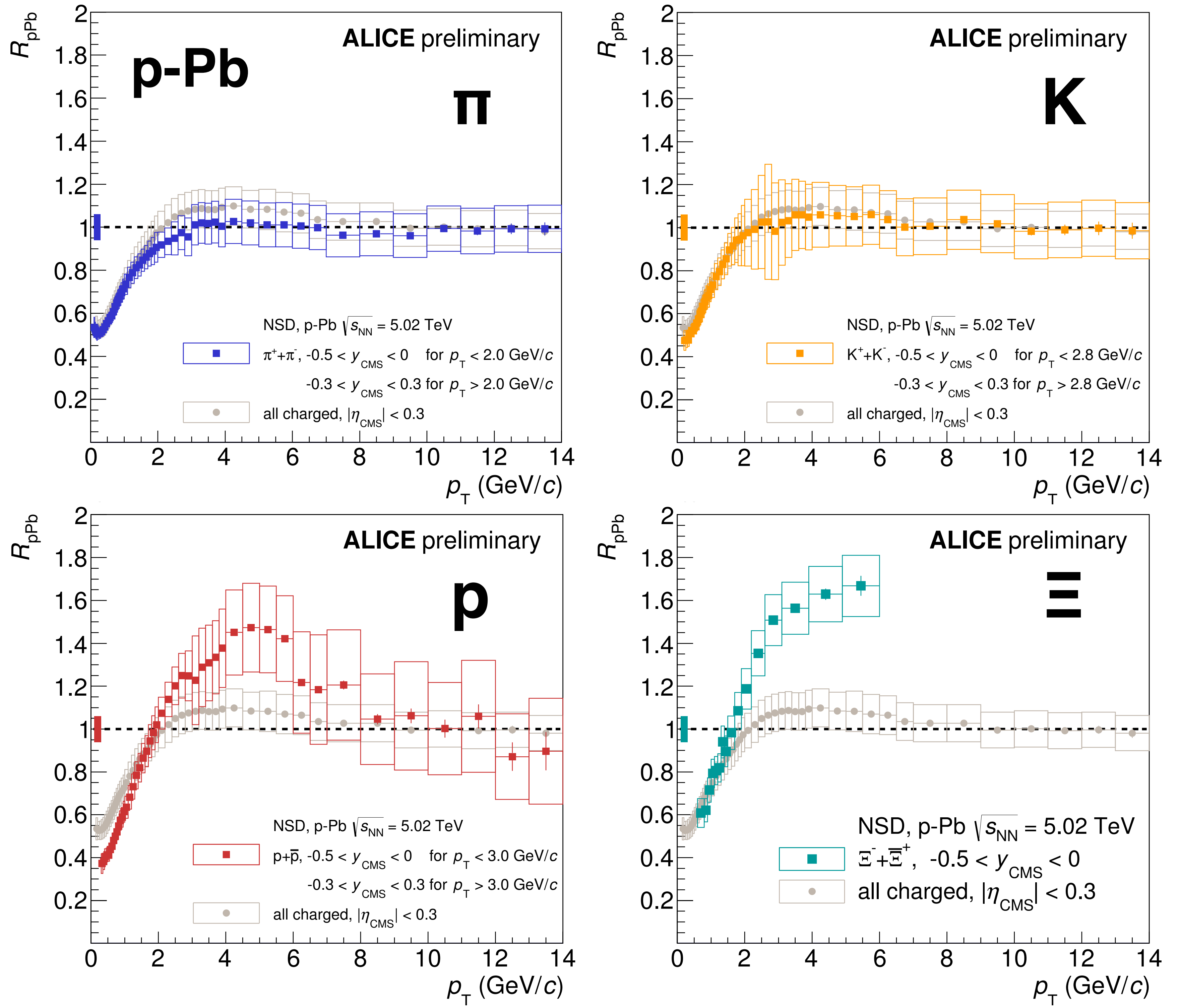


Identified particle R_{pPb}

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

rather pronounced peak for **protons**

even stronger enhancement for **cascades**

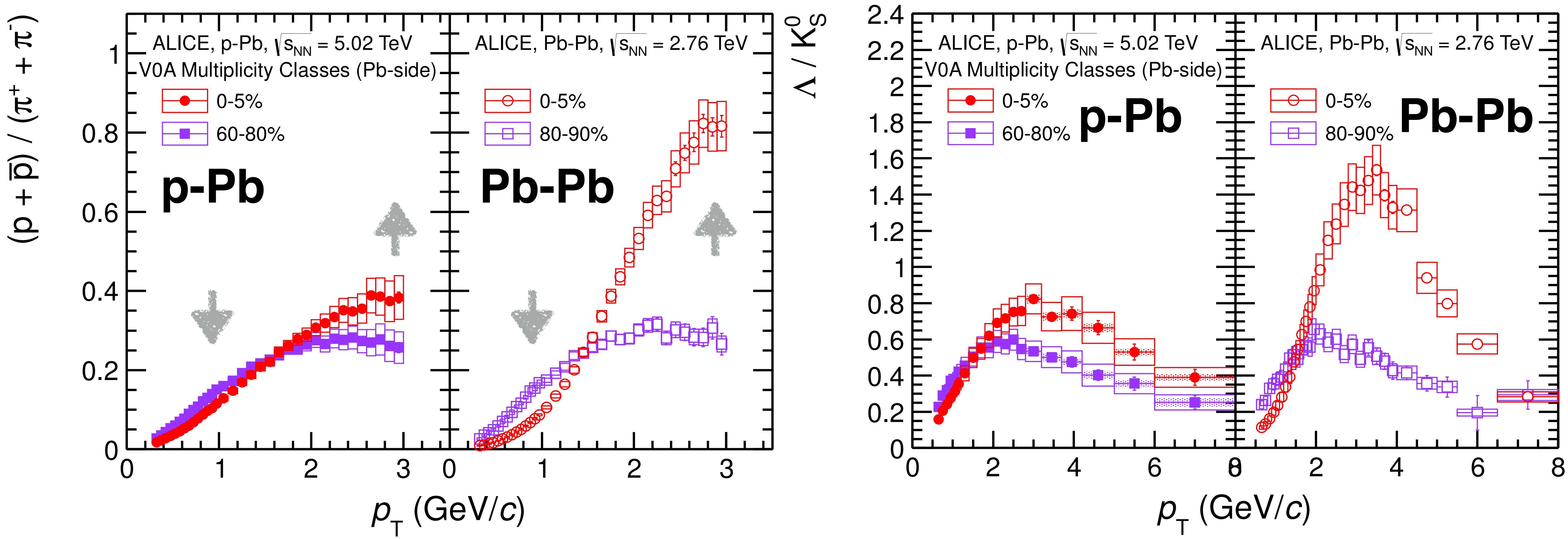


particle species dependence suggests final state effects

recombination, collective flow, …

Baryon enhancement

ALICE, PLB 728 (2014) 25



Significant centrality/multiplicity dependence of the ratios

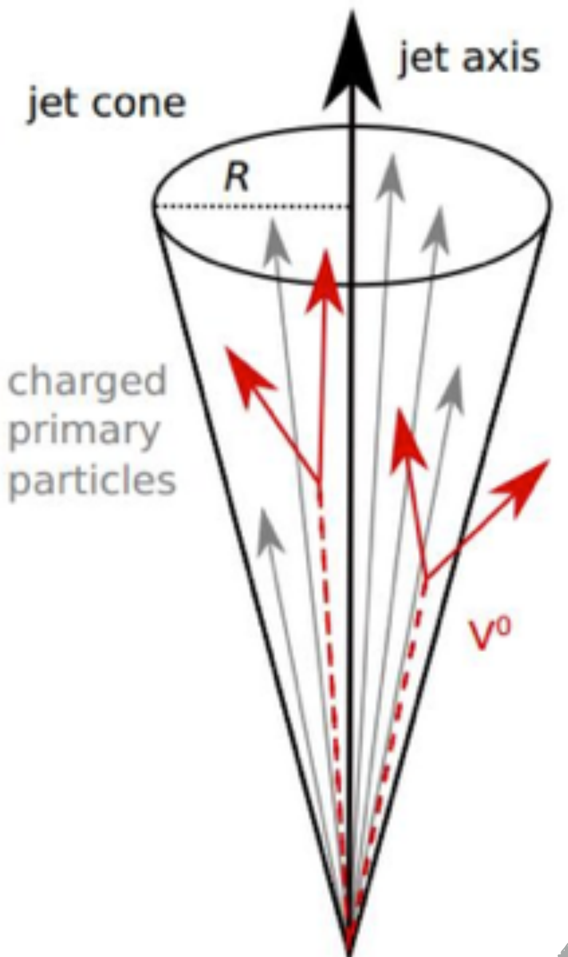
enhancement at mid-p_T with increasing multiplicity

corresponding depletion in the low-p_T region

Reminiscent of A-A observations

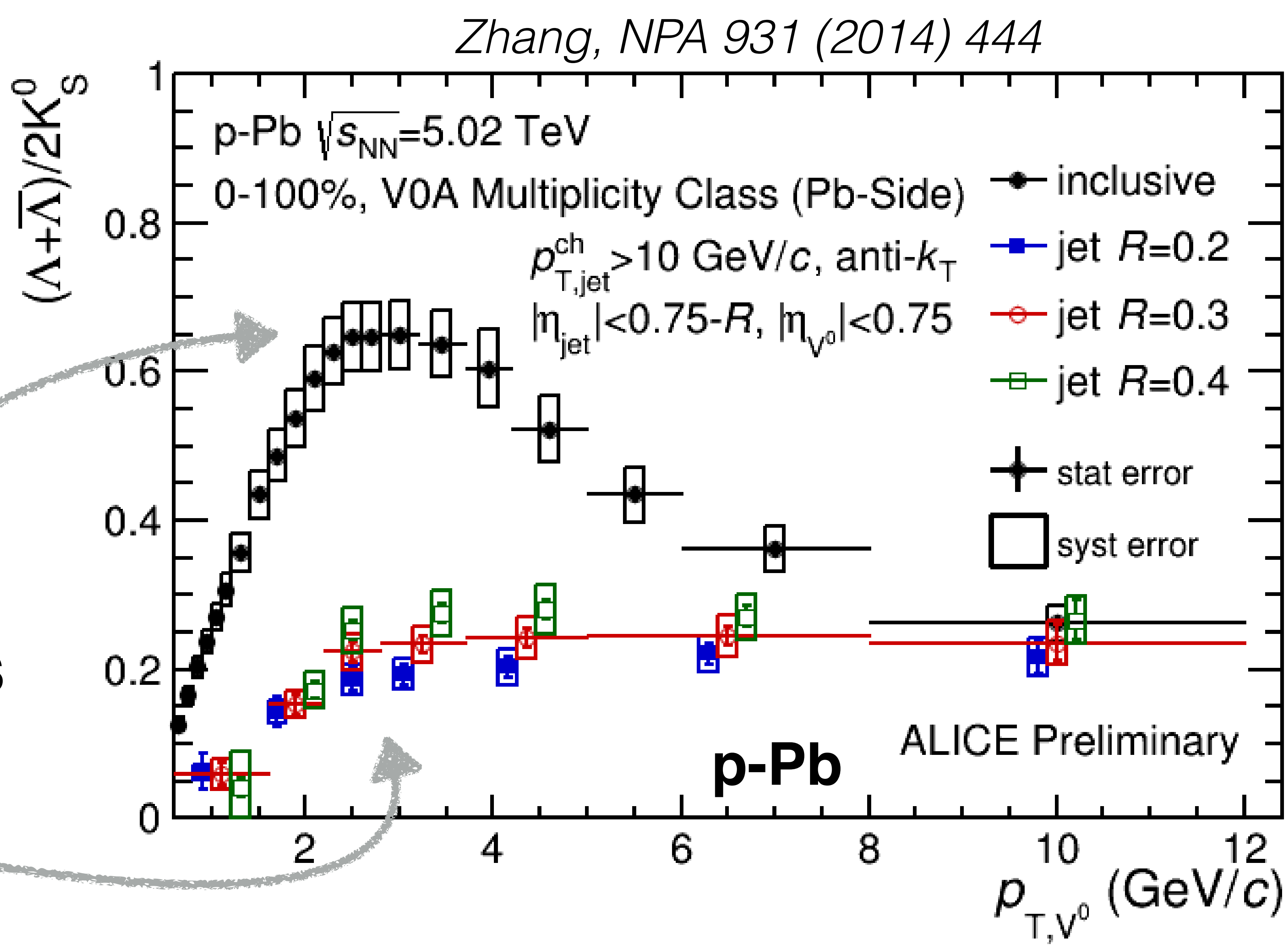
commonly understood in terms of collective flow / quark recombination

Where are the extra baryons from?



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

Zhang, NPA 931 (2014) 444



inclusive particles

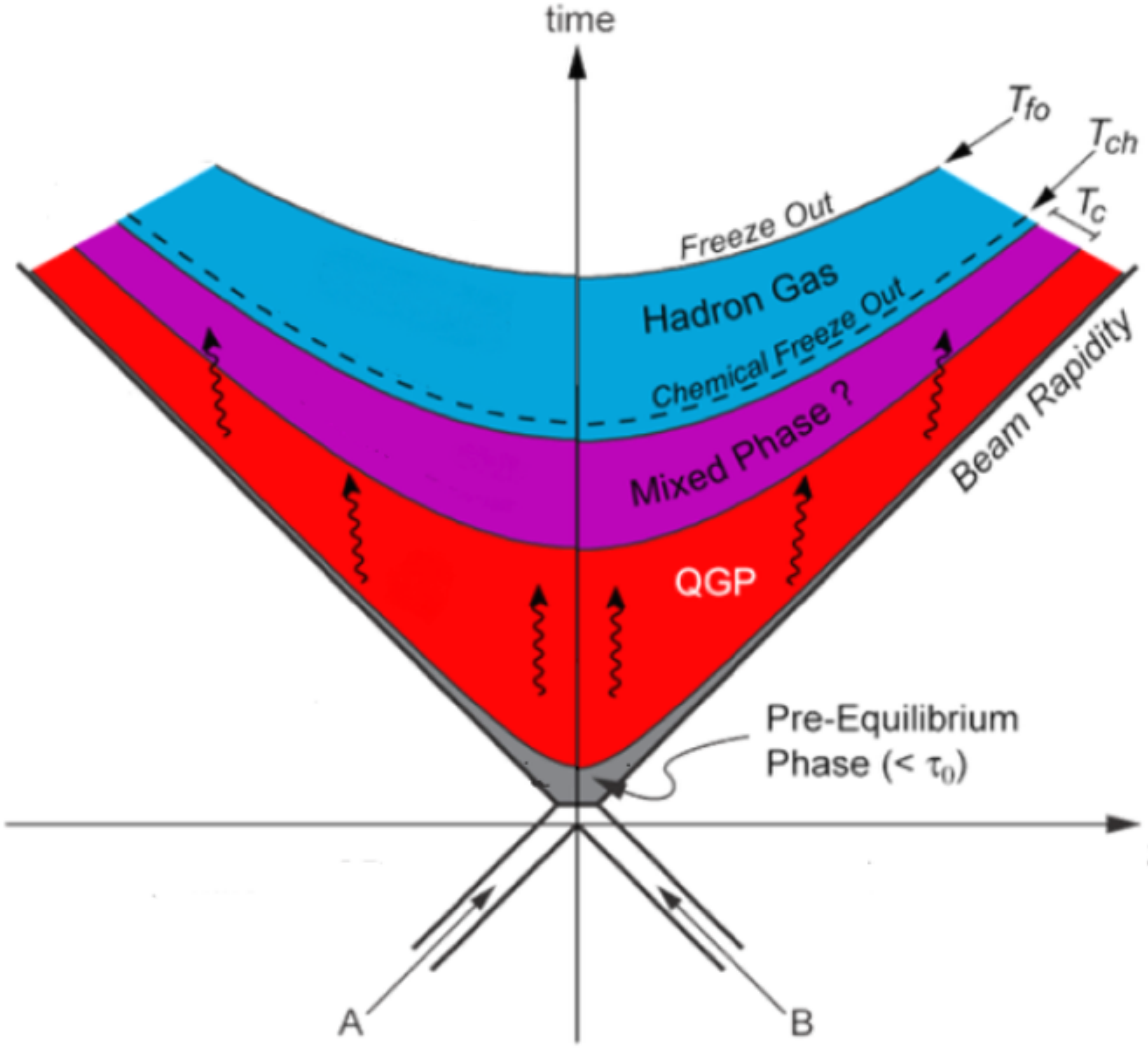
jets do not show enhancement

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

- <u>dependence of the shape of the p_T distribution on the particle mass</u>
- 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

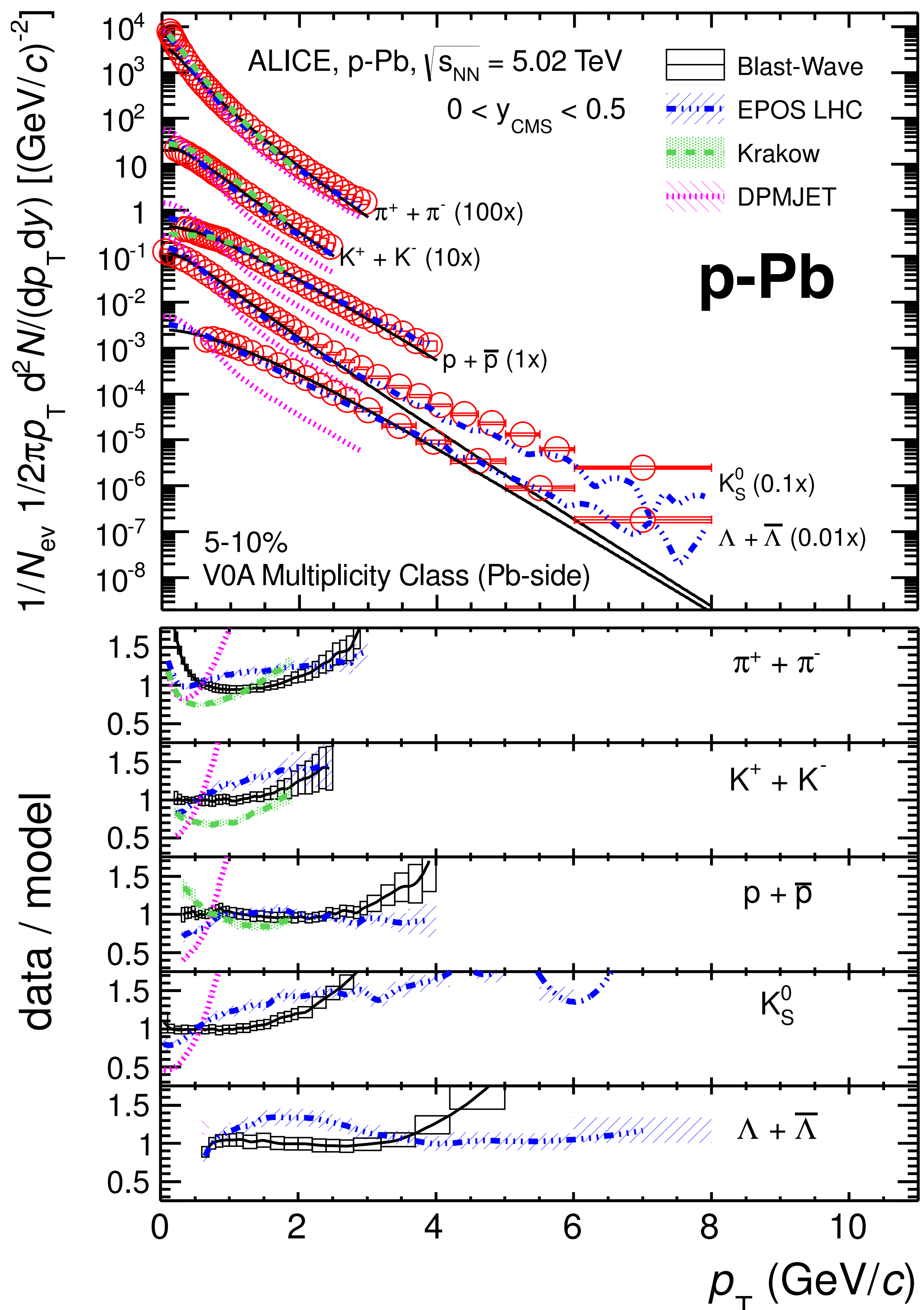
Krakow

3+1 viscous hydro

DPMJET

pQCD based

Models including hydrodynamics do a better job describing the data



ALICE, PLB 728 (2014) 25

Collective phenomena

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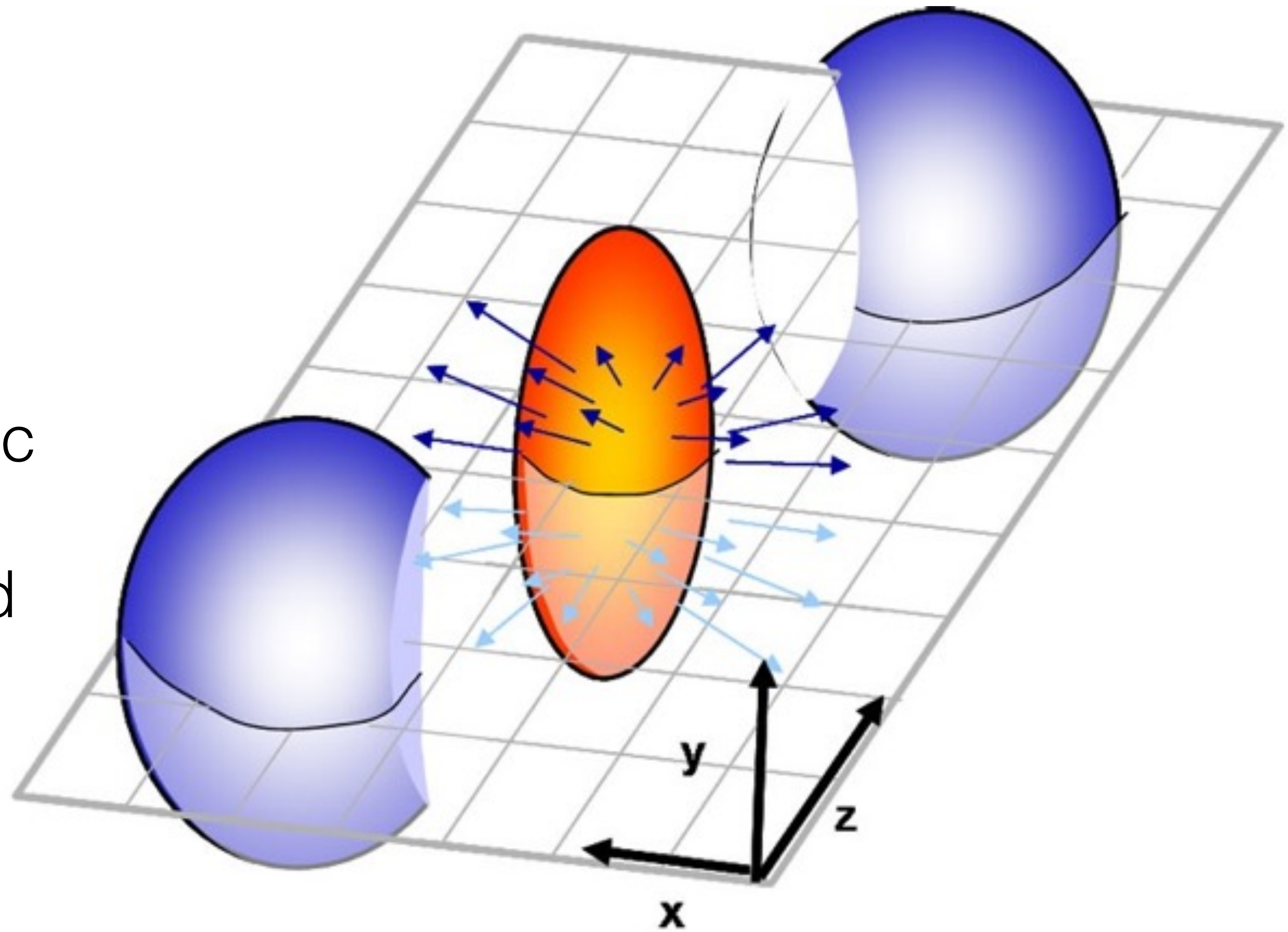

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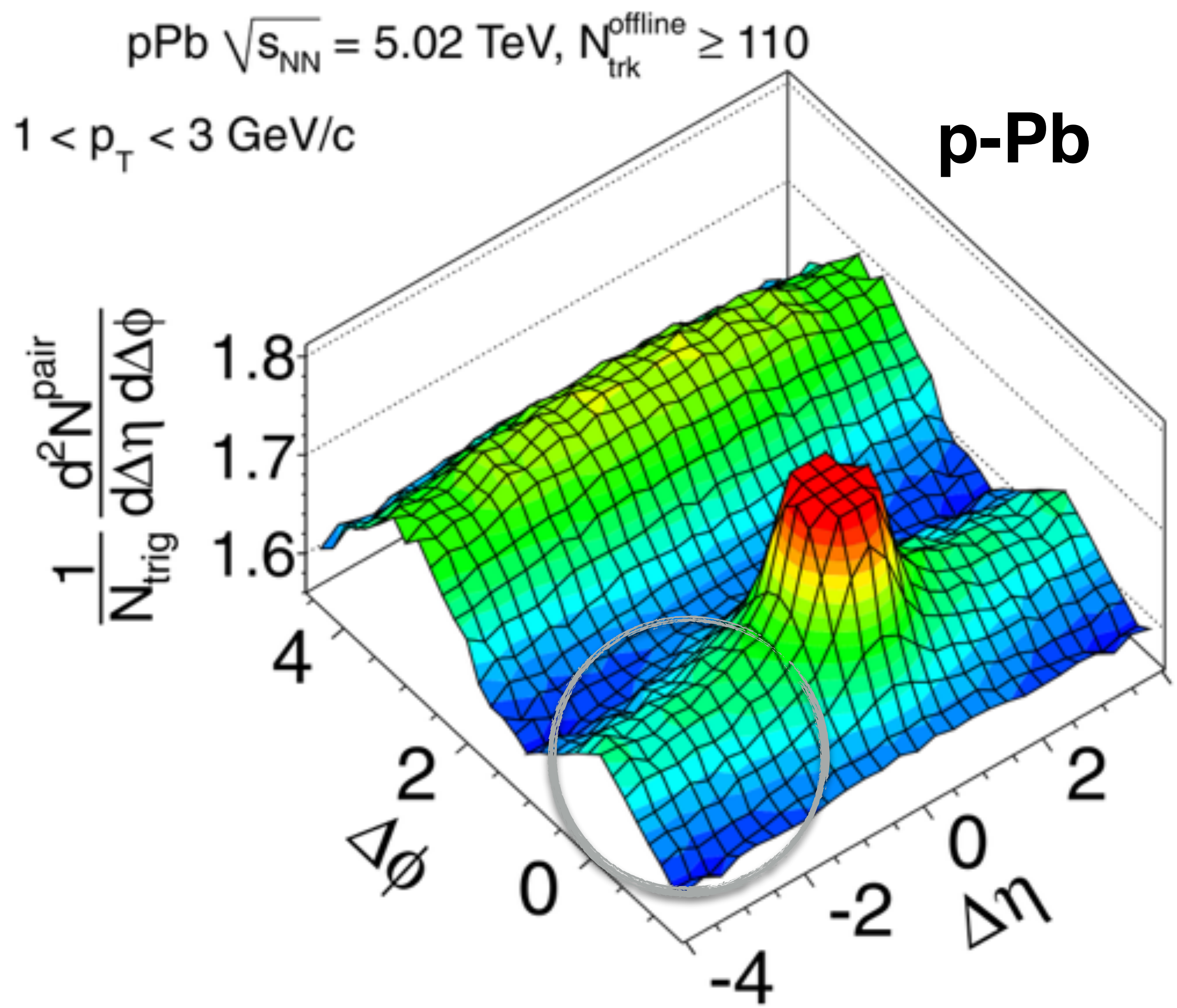
- <u>azimuthal anisotropic flow patterns (initial spatial anisotropy)</u>

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

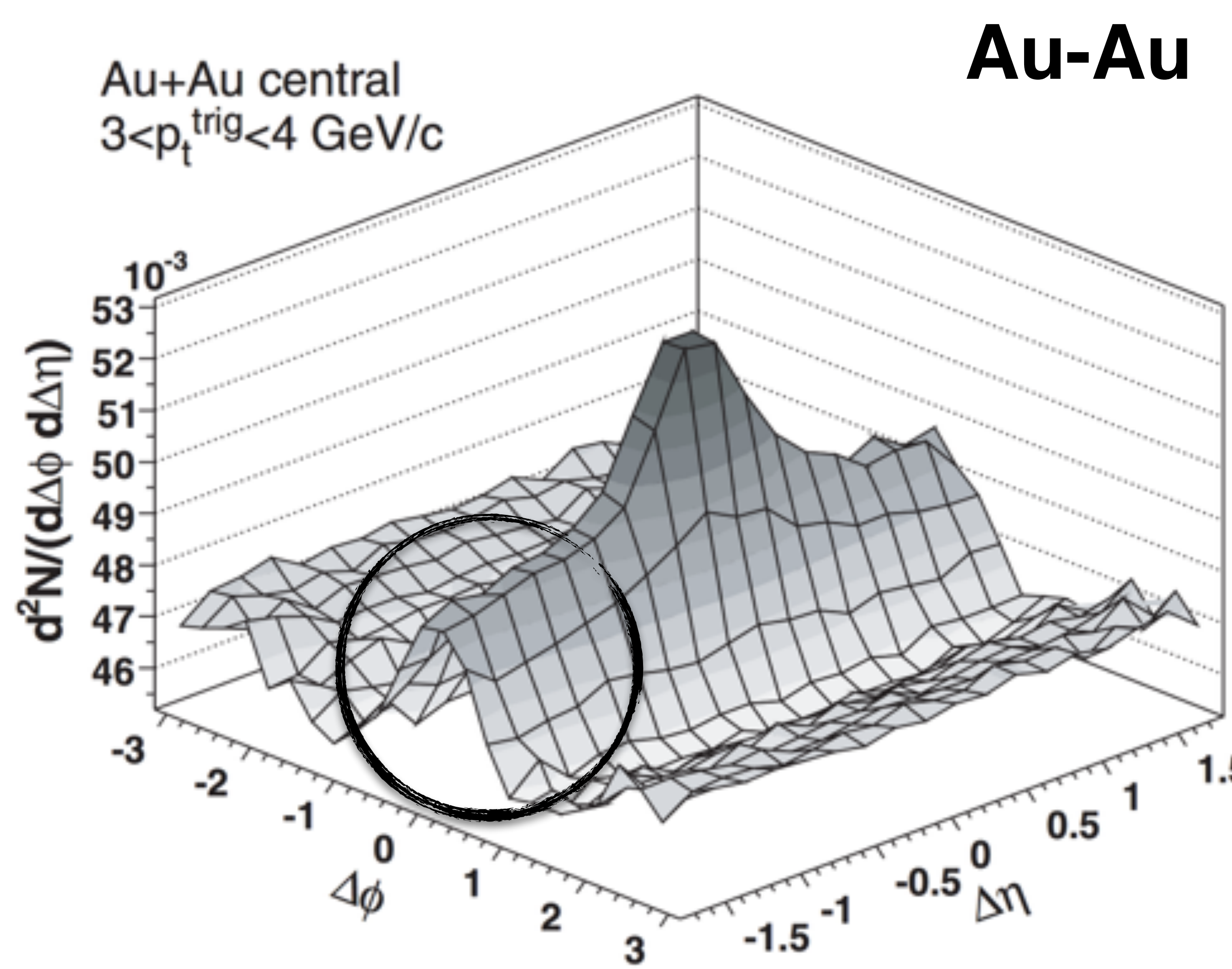
The ridge

long-range ($2 < |\Delta\eta| < 4$), **near-side** ($\Delta\phi \approx 0$)

resembles the ridge-like correlation seen in A-A collisions interpreted as consequence of hydrodynamic flow



CMS, PLB 718 (2013) 795



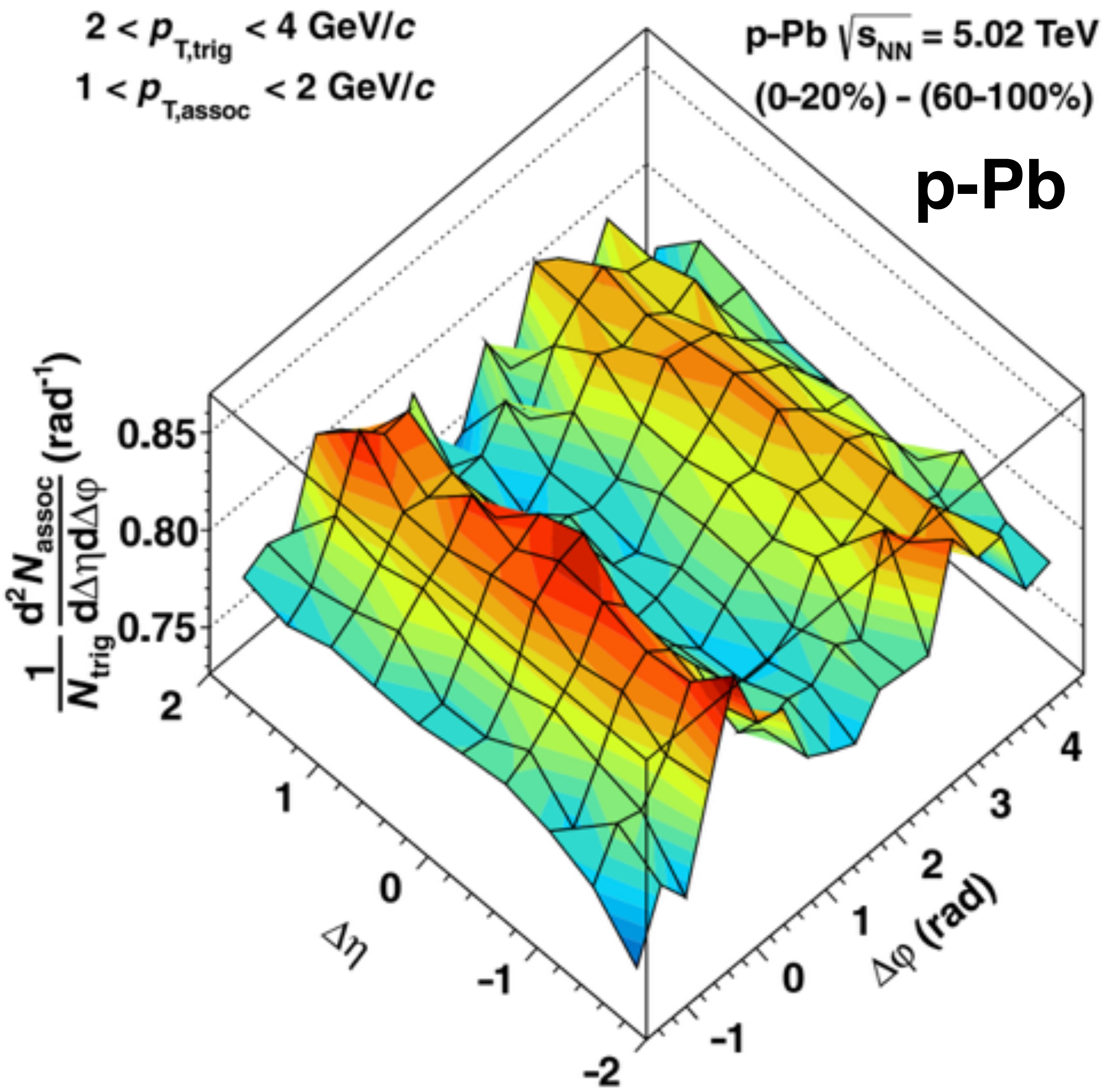
STAR, PRC 80 (2010) 064912

The double ridge

the ridge in p-Pb events triggered further investigations

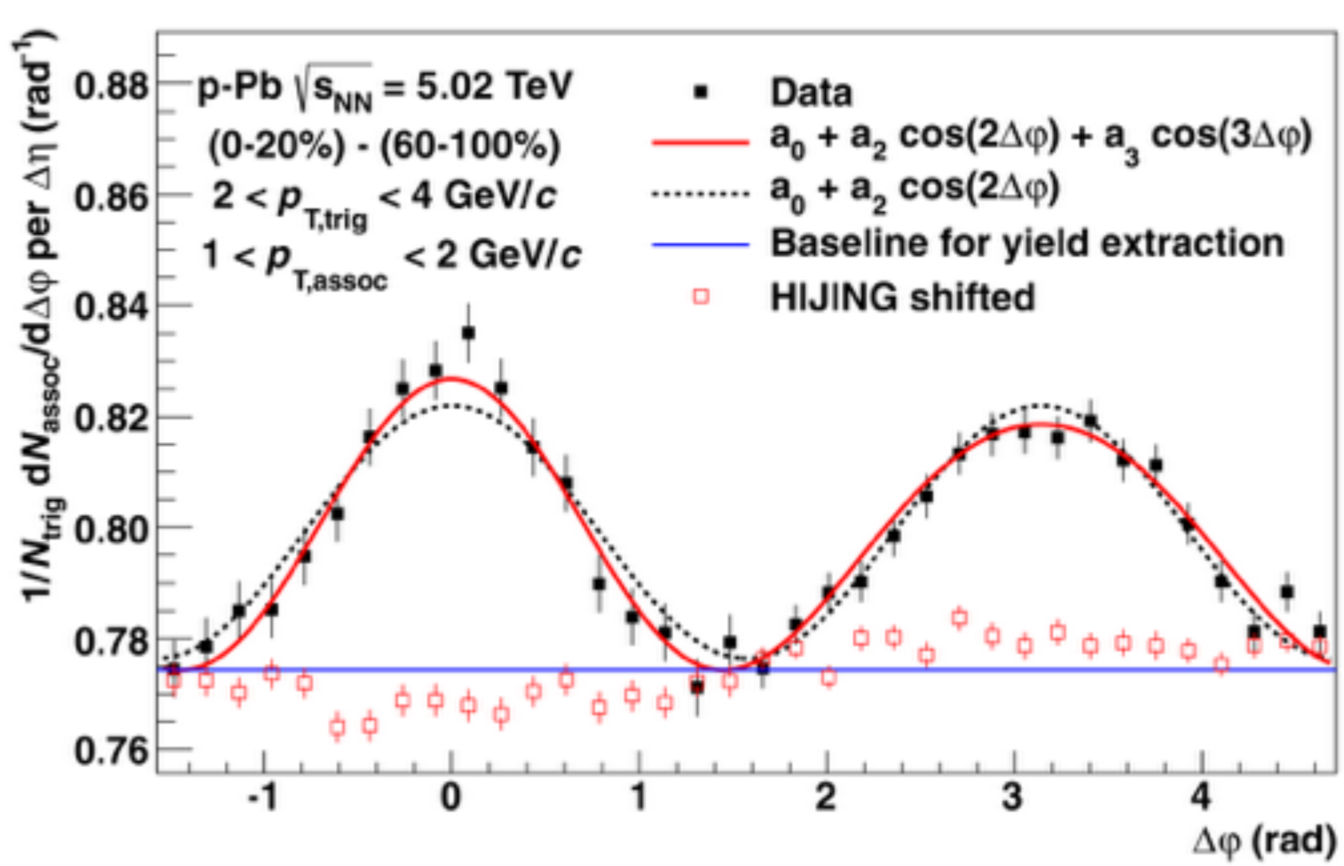
jet contribution removed by subtracting low-multiplicity events

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



this looks so much like flow

Fourier decomposition of Δϕ: v_2, v_3, ...



ALICE, PLB 719 (2013) 29

The double ridge

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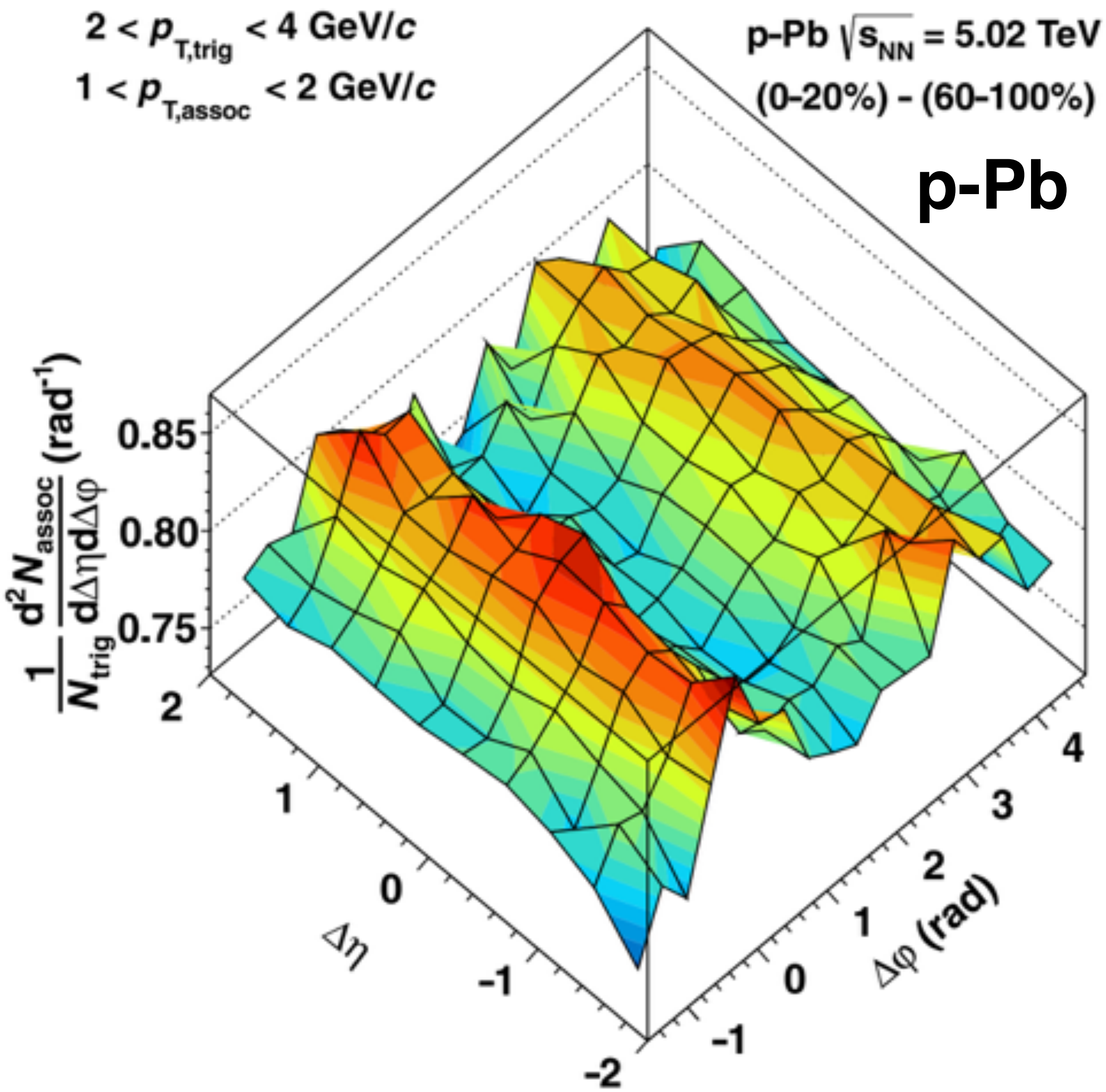
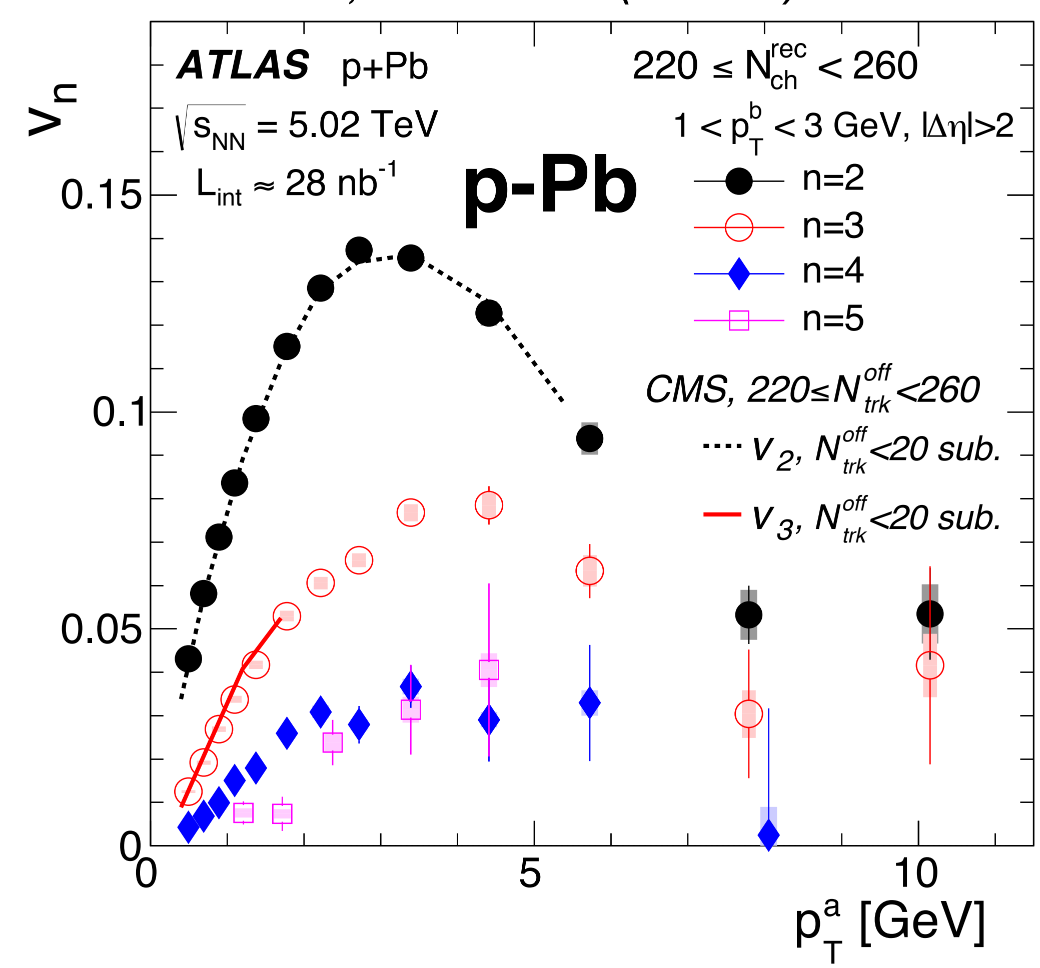


this looks so much like flow

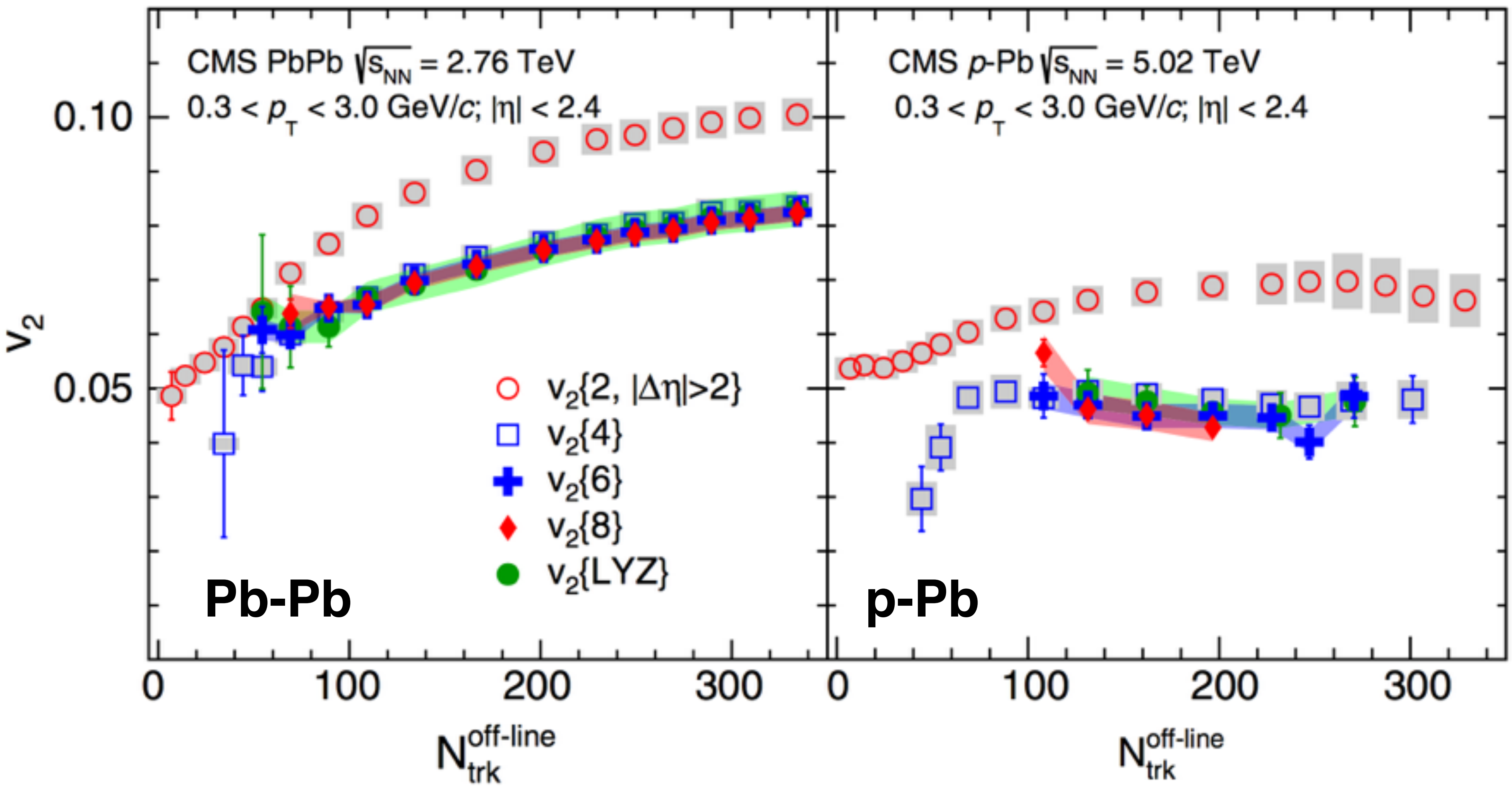
Fourier decomposition of Δφ: v_2, v_3, ...

ATLAS, PRC 90 (2014) 044906



True collective effect

CMS, PRL 115 (2015) 012301



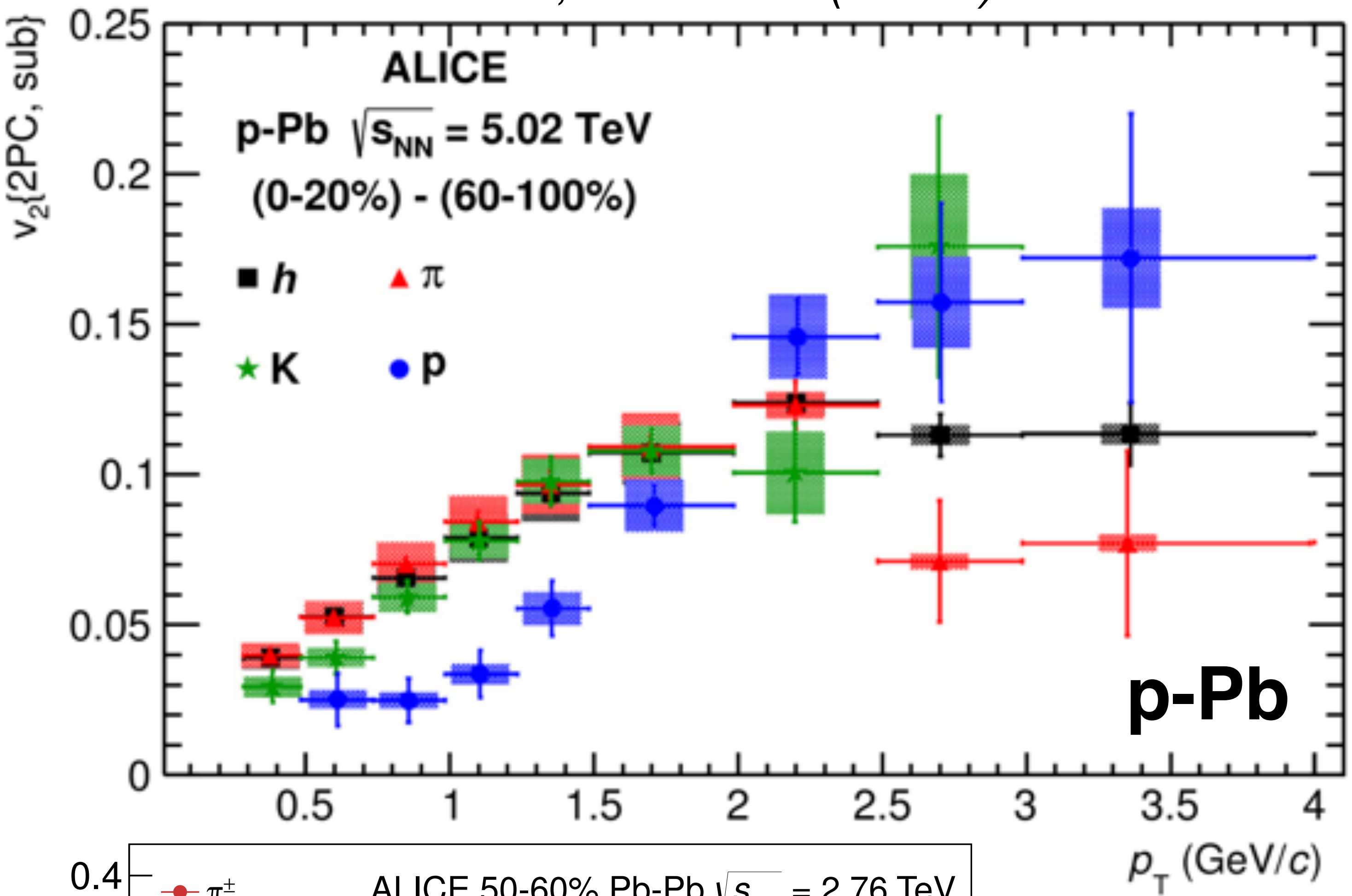
v_2 stays large when computed with multi-particles

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

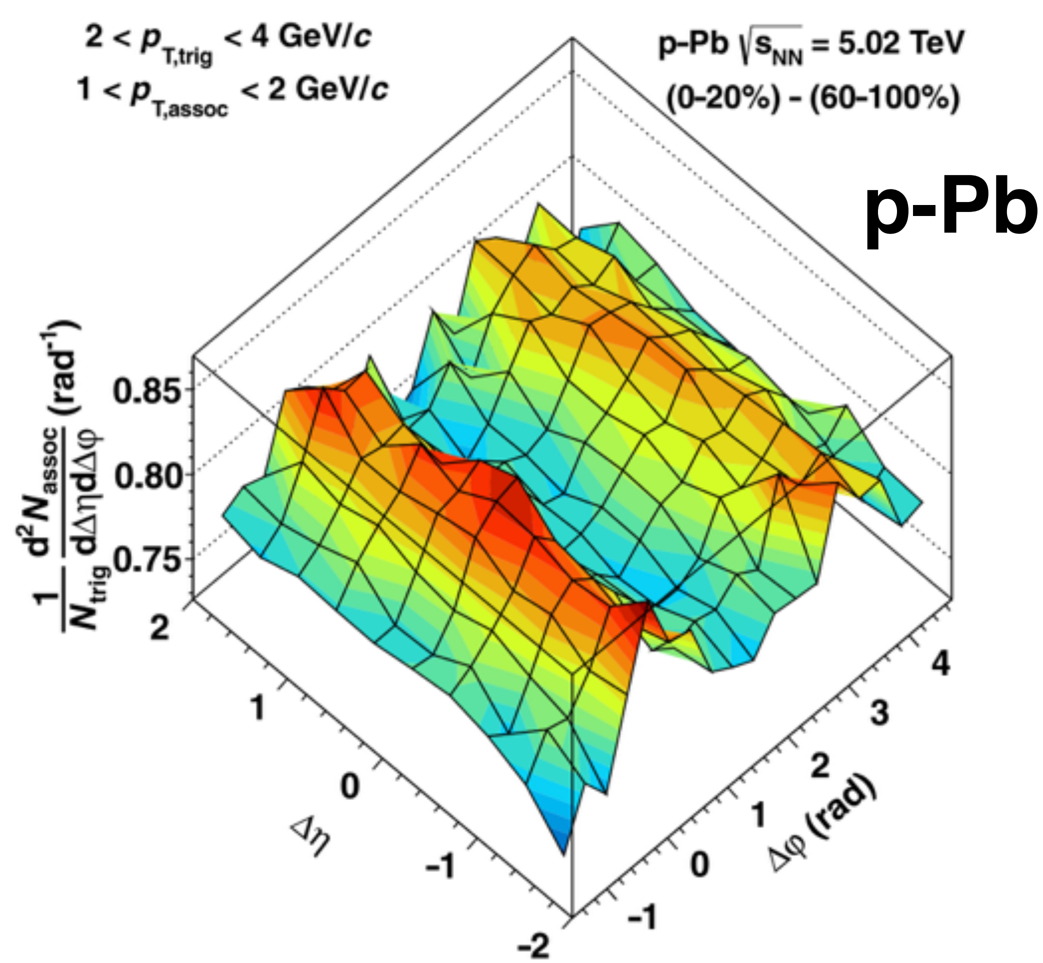
there is **true collectivity in p-Pb**

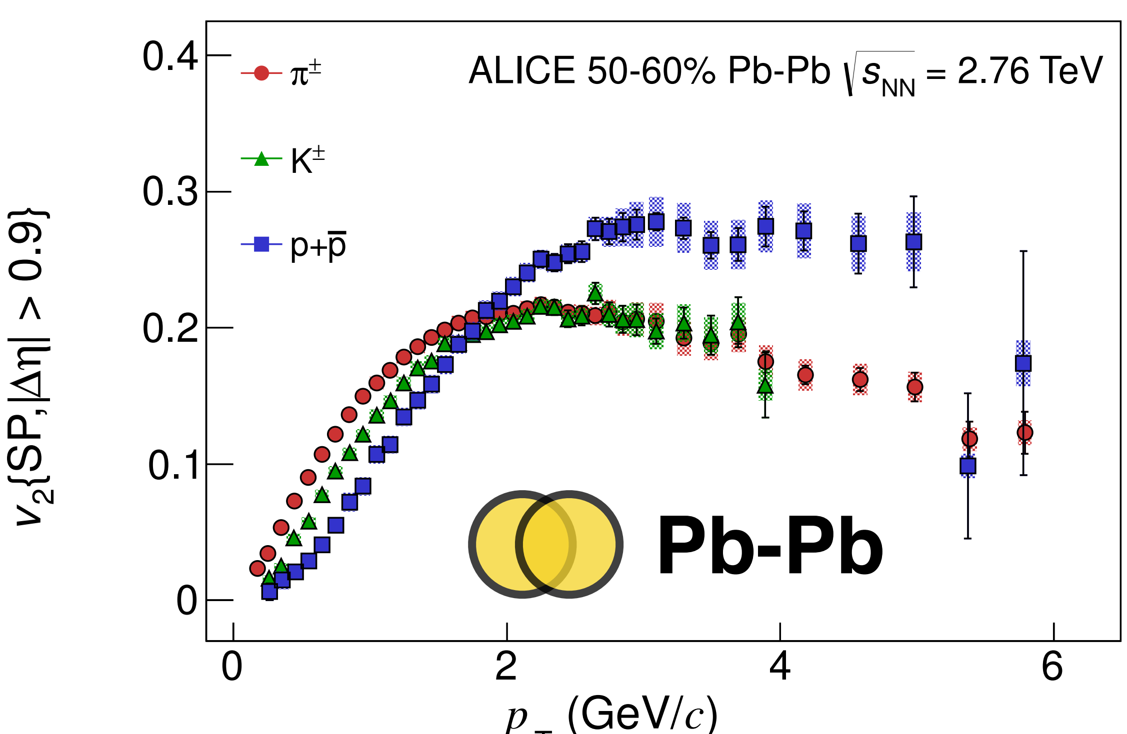
v_2 of identified particles in p-Pb

ALICE, PLB 726 (2013) 164



ALICE, PLB 719 (2013) 29





mass ordering observed at low p_T

lower v_2 for heavier particles

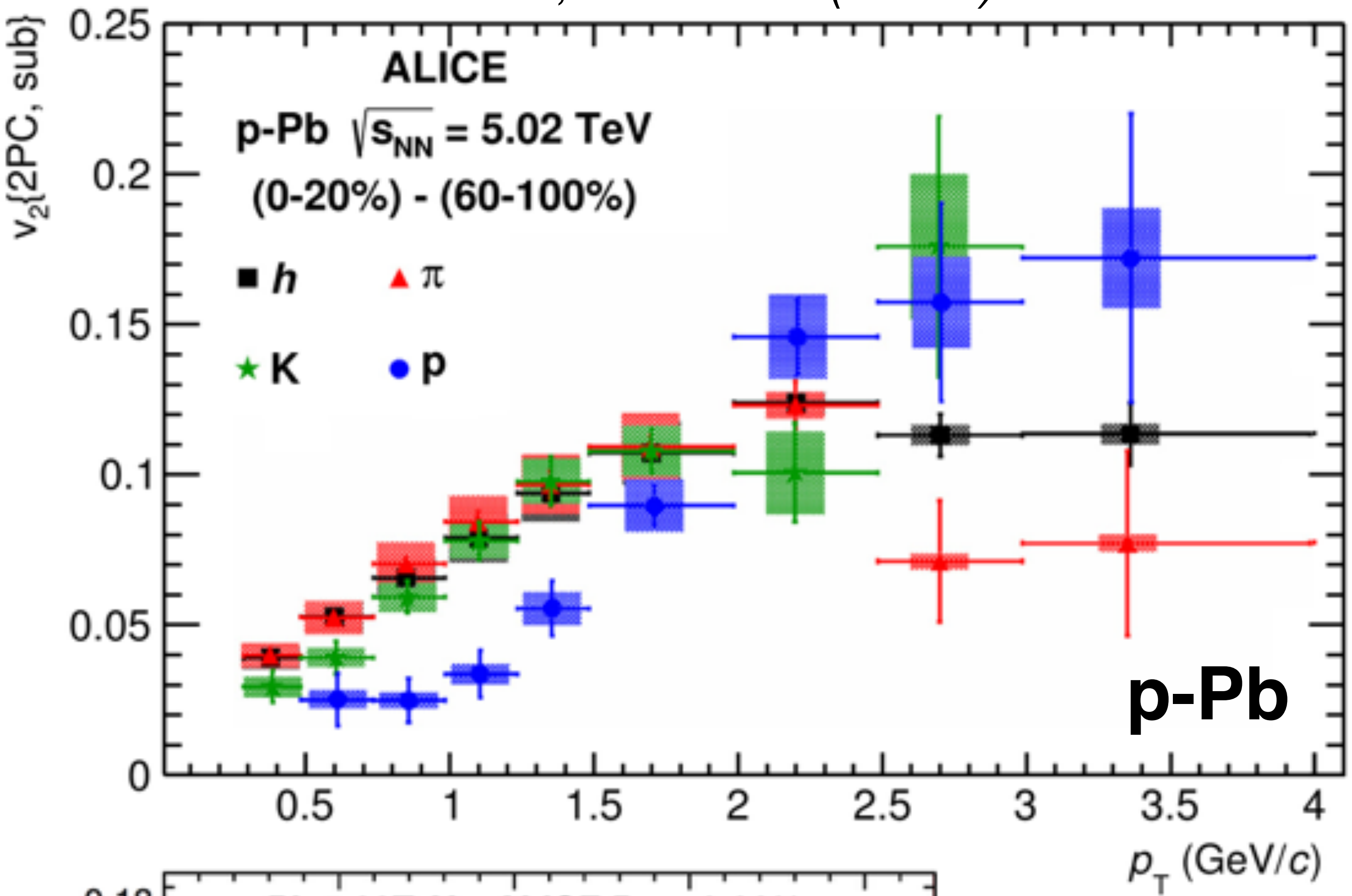
crossing at higher p_T

reminiscent of A-A observations

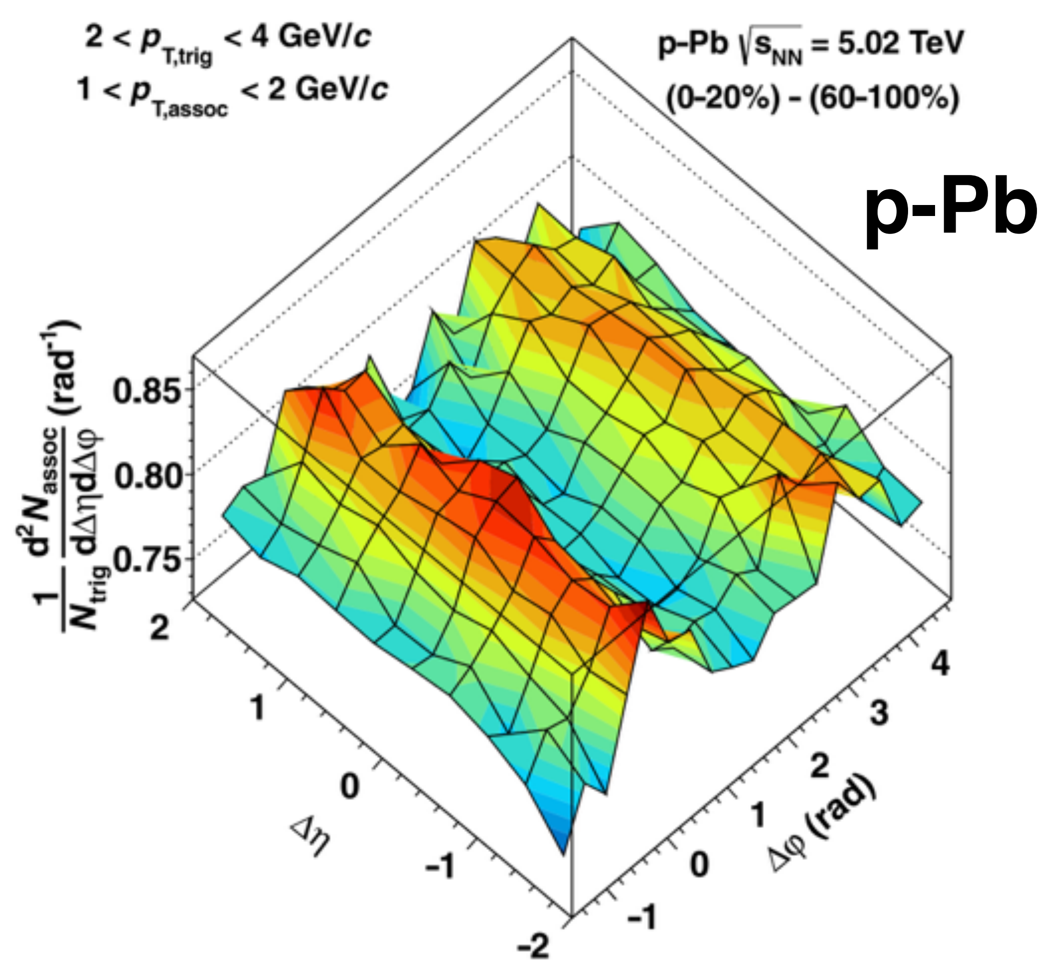
ALICE, JHEP 1506 (2015) 190

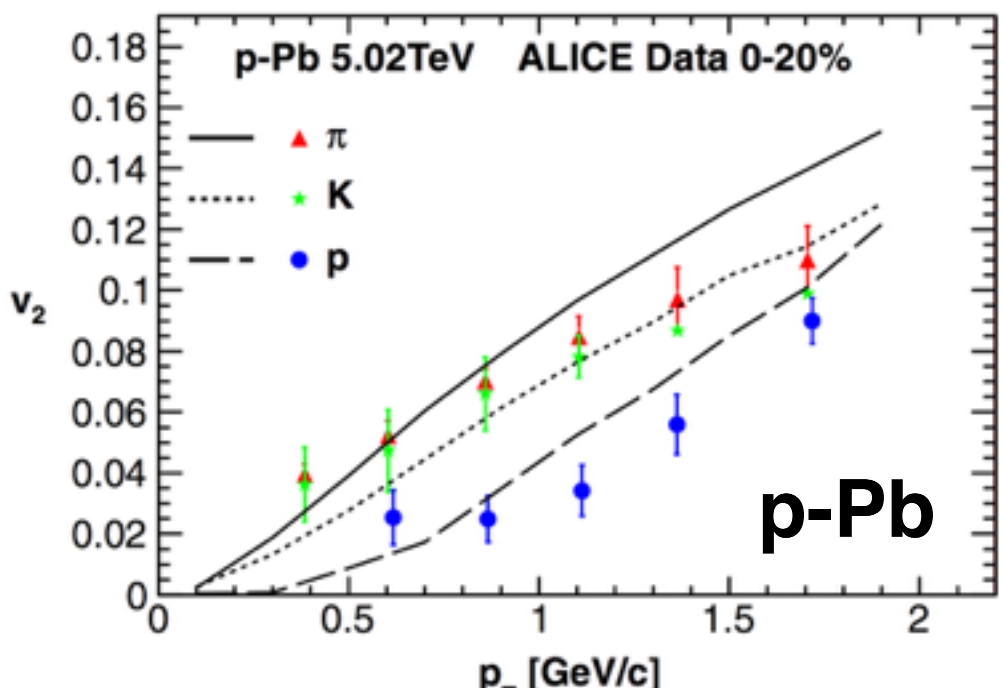
v_2 of identified particles in p-Pb

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 enhancement

one of the first proposed QGP signatures

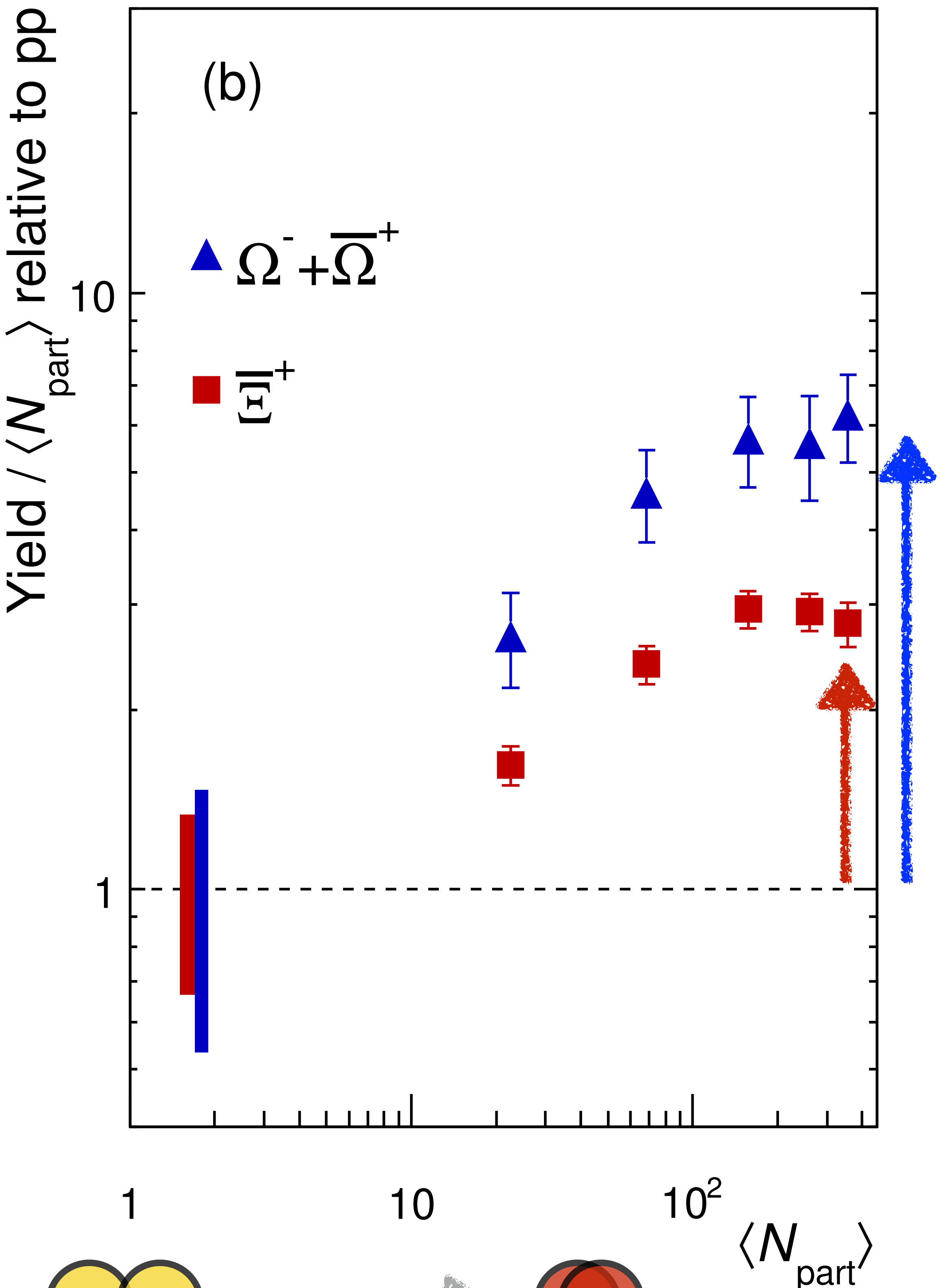
VOLUME 48, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1982

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

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

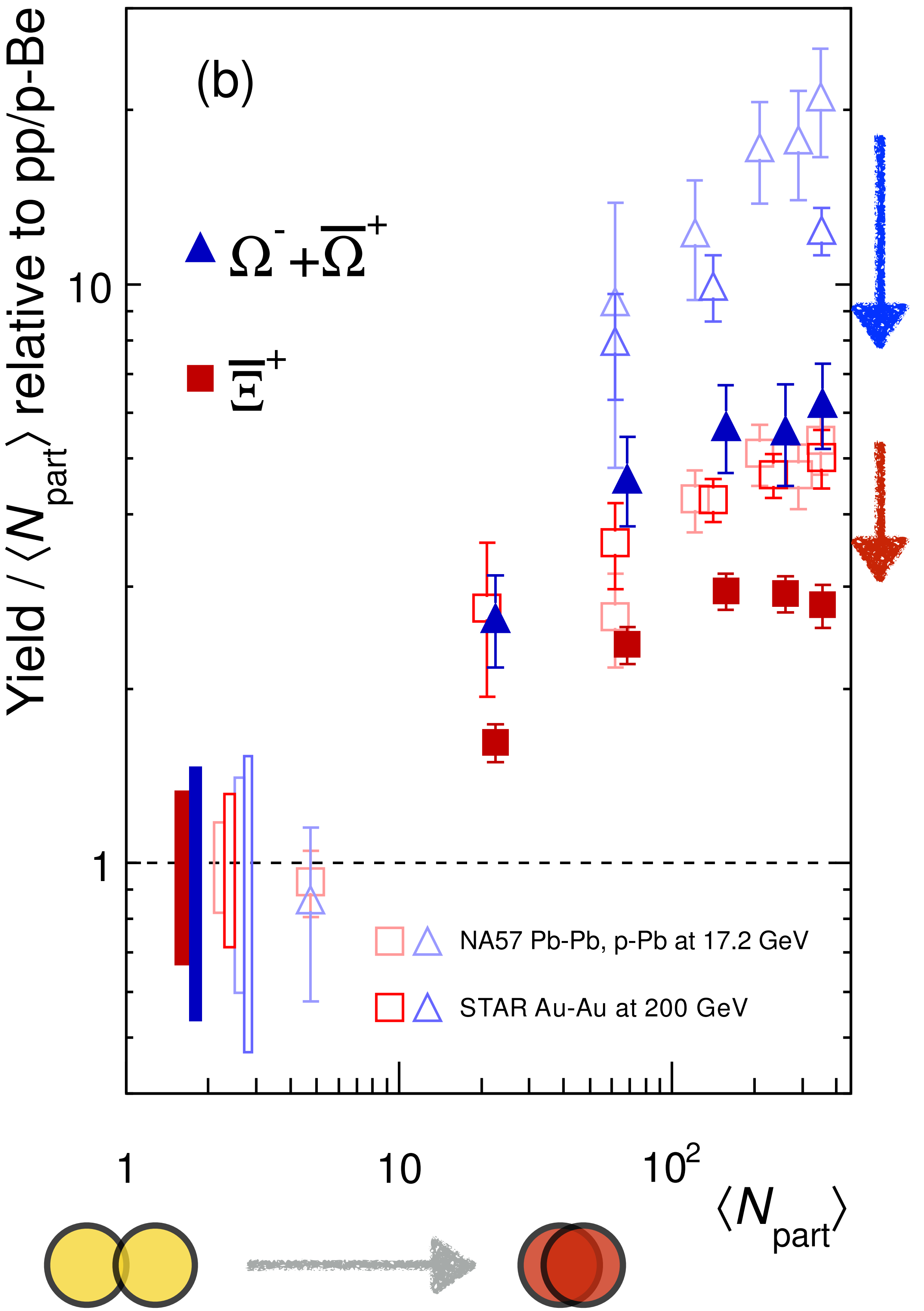
strangeness-content hierarchy

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

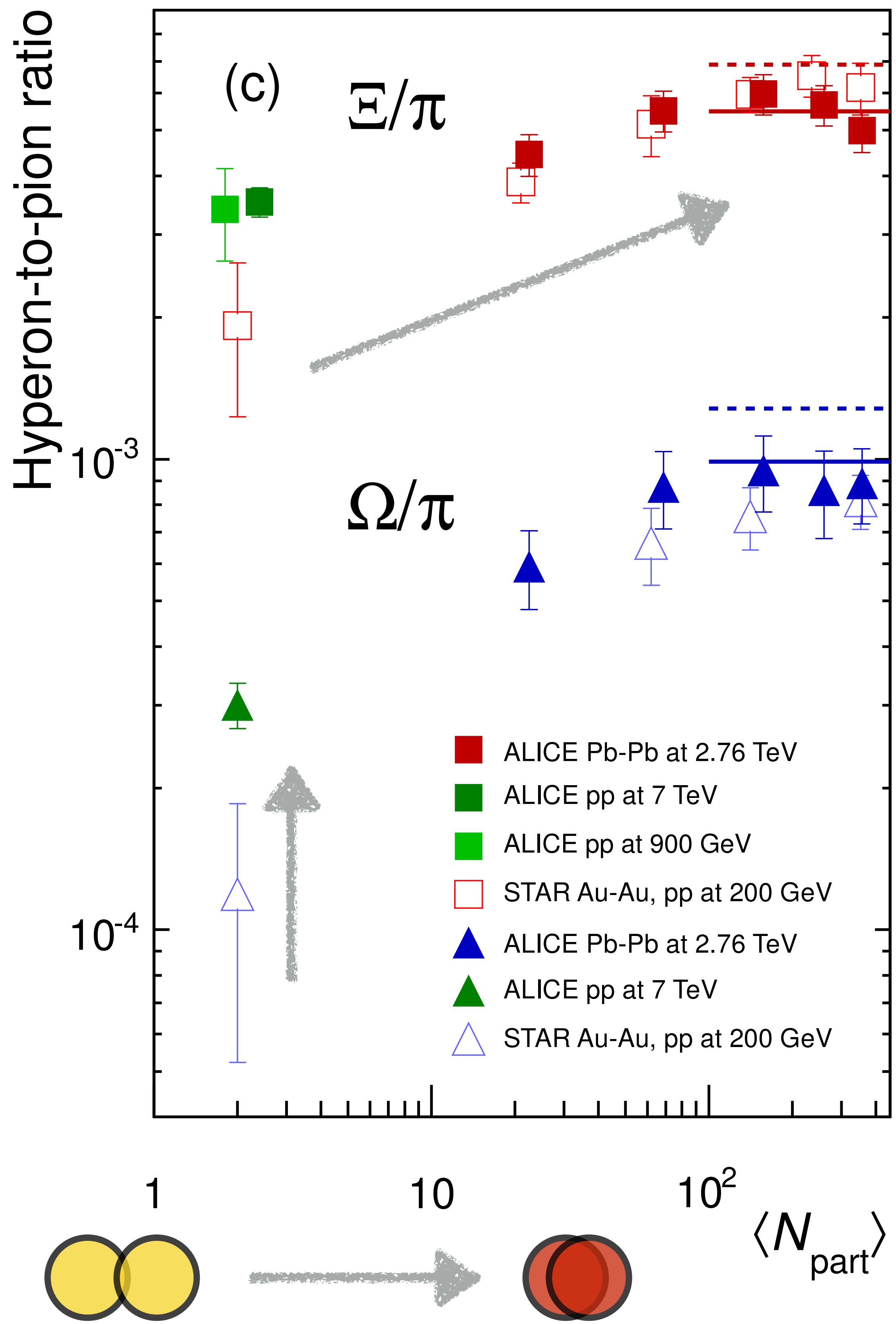
Ω (sss) more enhanced

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

progressive removal of canonical suppression in pp

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 $N_{part} > 150$

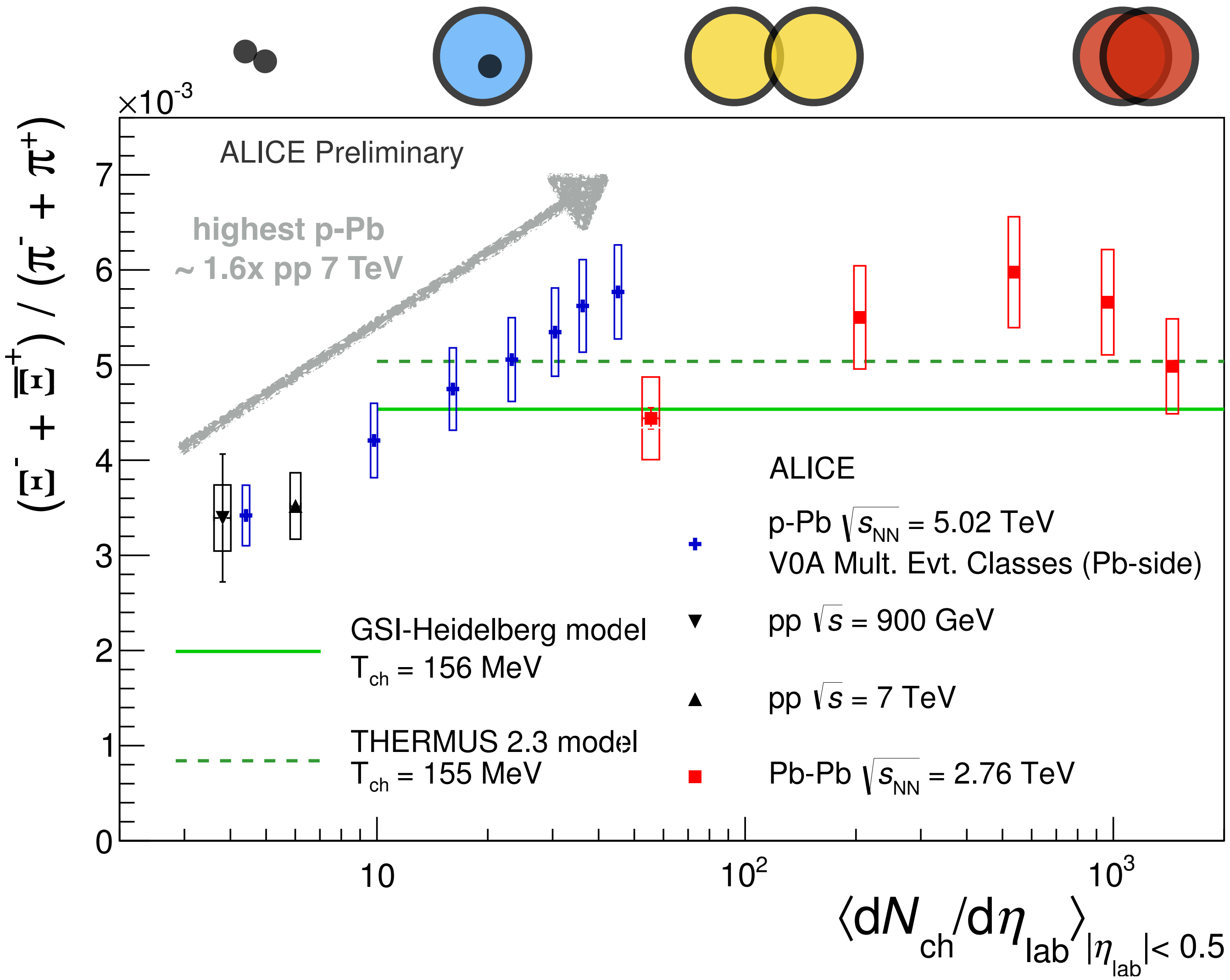
match predictions from Grand Canonical thermal models

GSI-Heidelberg: T_{ch} = 164 MeV

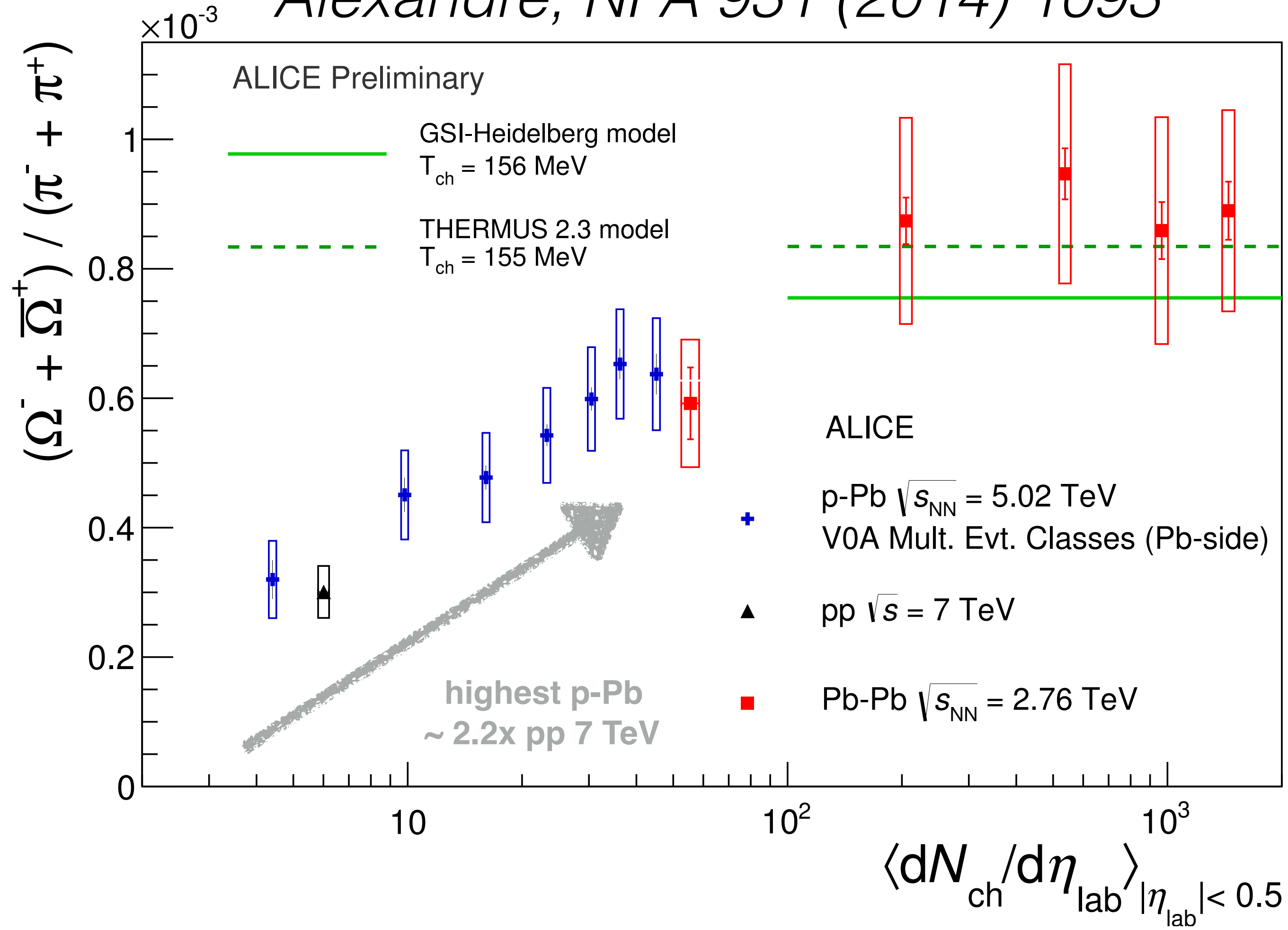
THERMUS: T_{ch} = 170 MeV

ALICE, PLB 728 (2014) 216

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

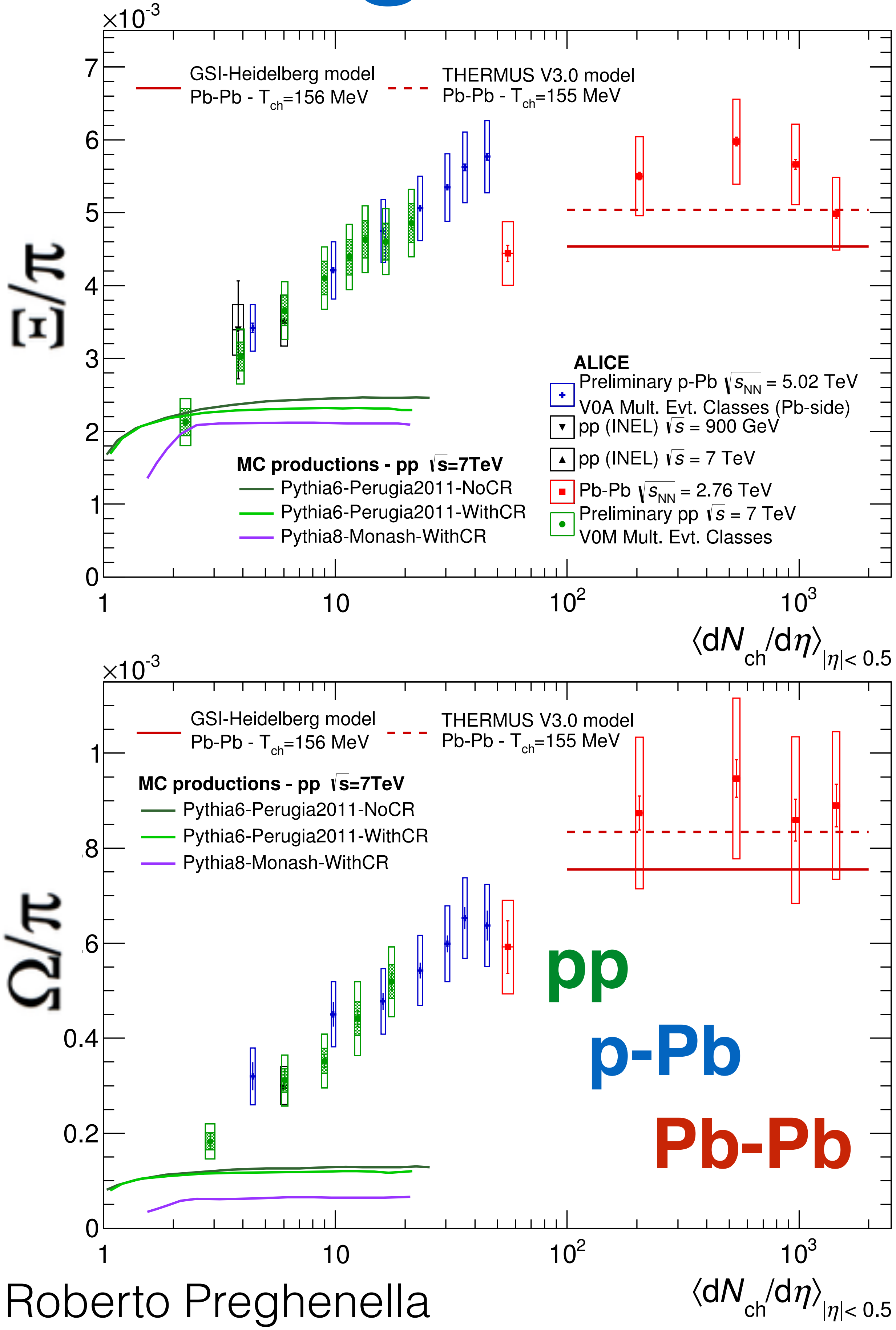
Ξ and Ω → consistent with pp

high-multiplicity

Ξ → compatible with central Pb-Pb

Ω → compatible with peripheral Pb-Pb

Strangeness enhancement in pp



also measured in pp and p-Pb collisions as a function of charged-particle multiplicity

first **observation of enhanced production of strange particles in pp and p-Pb collisions**

ratios to pions reach values measured in Pb-Pb collisions

PYTHIA cannot reproduce the data