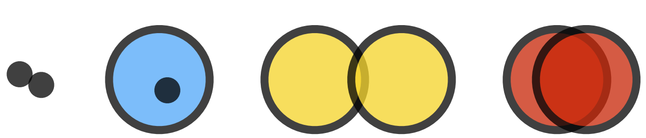
Soft physics at the LHC

Roberto Preghenella
Istituto Nazionale di Fisica Nucleare
CERN

ESD Blois 2015
Borgo, Corsica
29th June – 4th July 2015



Soft physics at the LHC

this is what I will discuss in the following slides

- proton-proton collisions
  → constraints on **soft particle production**
  → test **non-perturbative** regime of **QCD**
  → tune multi-purpose **event generators**

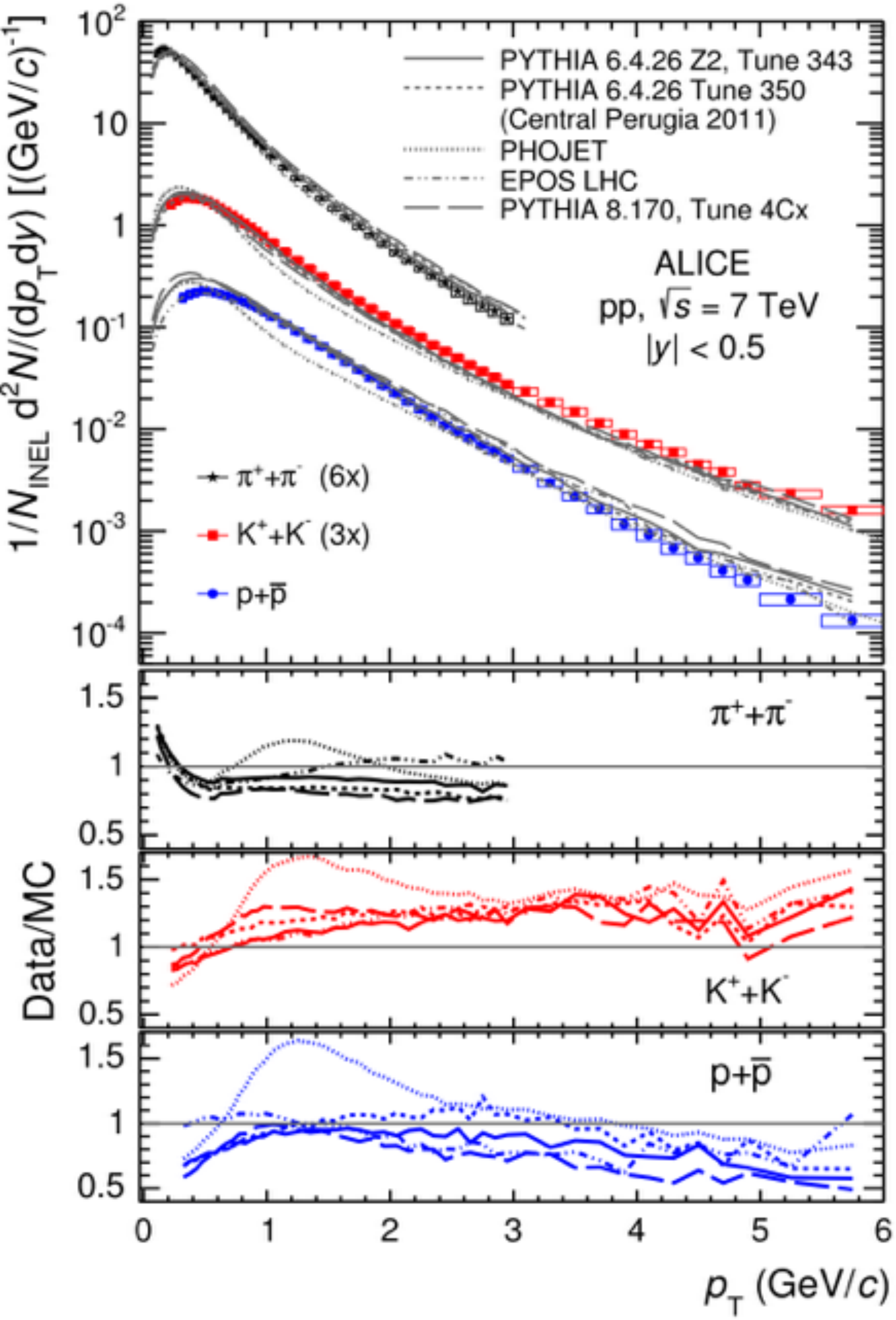
- nucleus-nucleus collisions
  → produce **hot nuclear matter**: QGP
  → investigate **QCD phase transition** / diagram
  → **thermodynamics** and **collectivity**

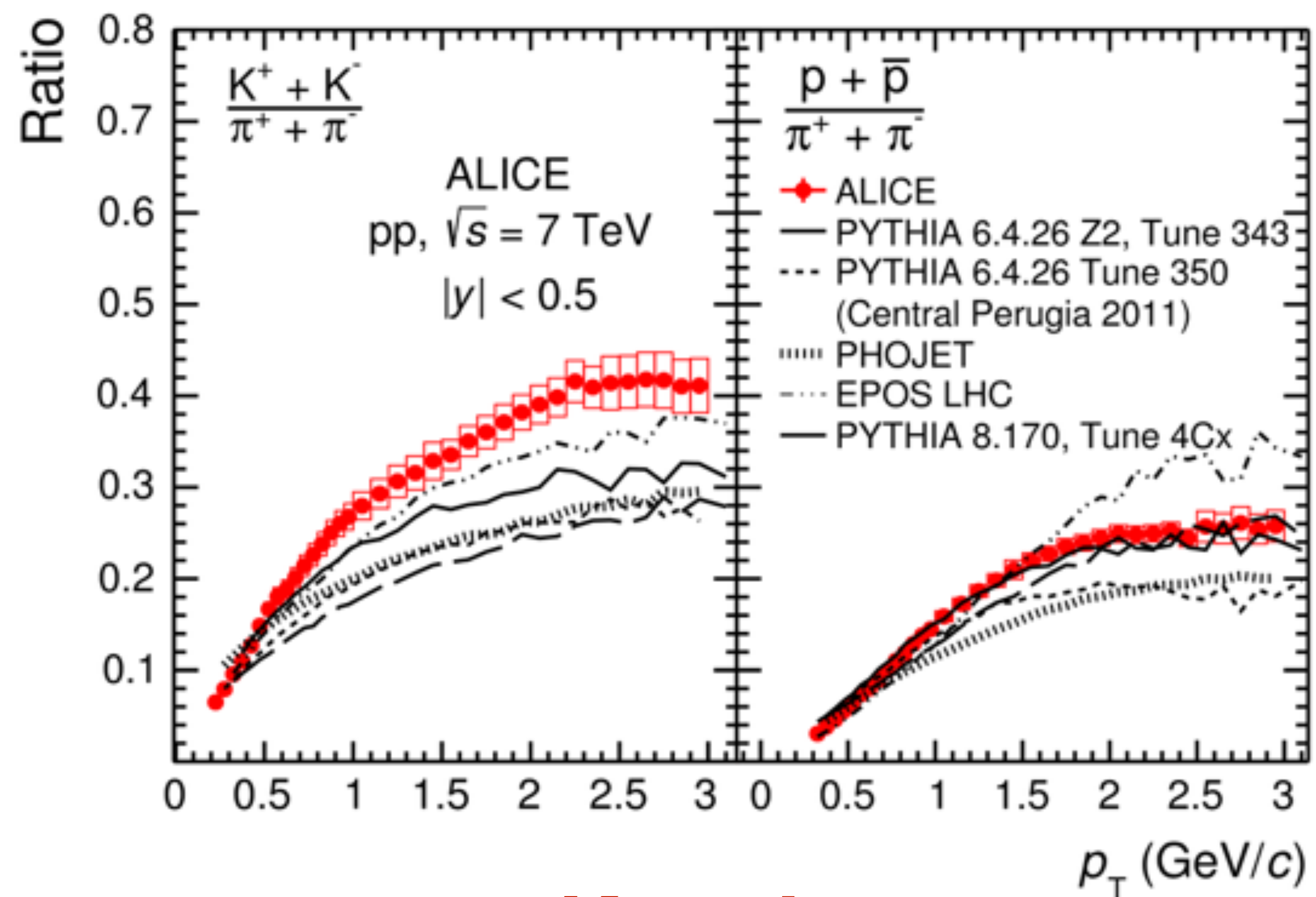
- proton-nucleus collisions
  → control experiment
  → disentangle **cold / hot nuclear matter** effects
  → **surprising features** in high-multiplicity events

but there is much more soft physics than this at the LHC

Particle production in proton-proton collisions

π K p production





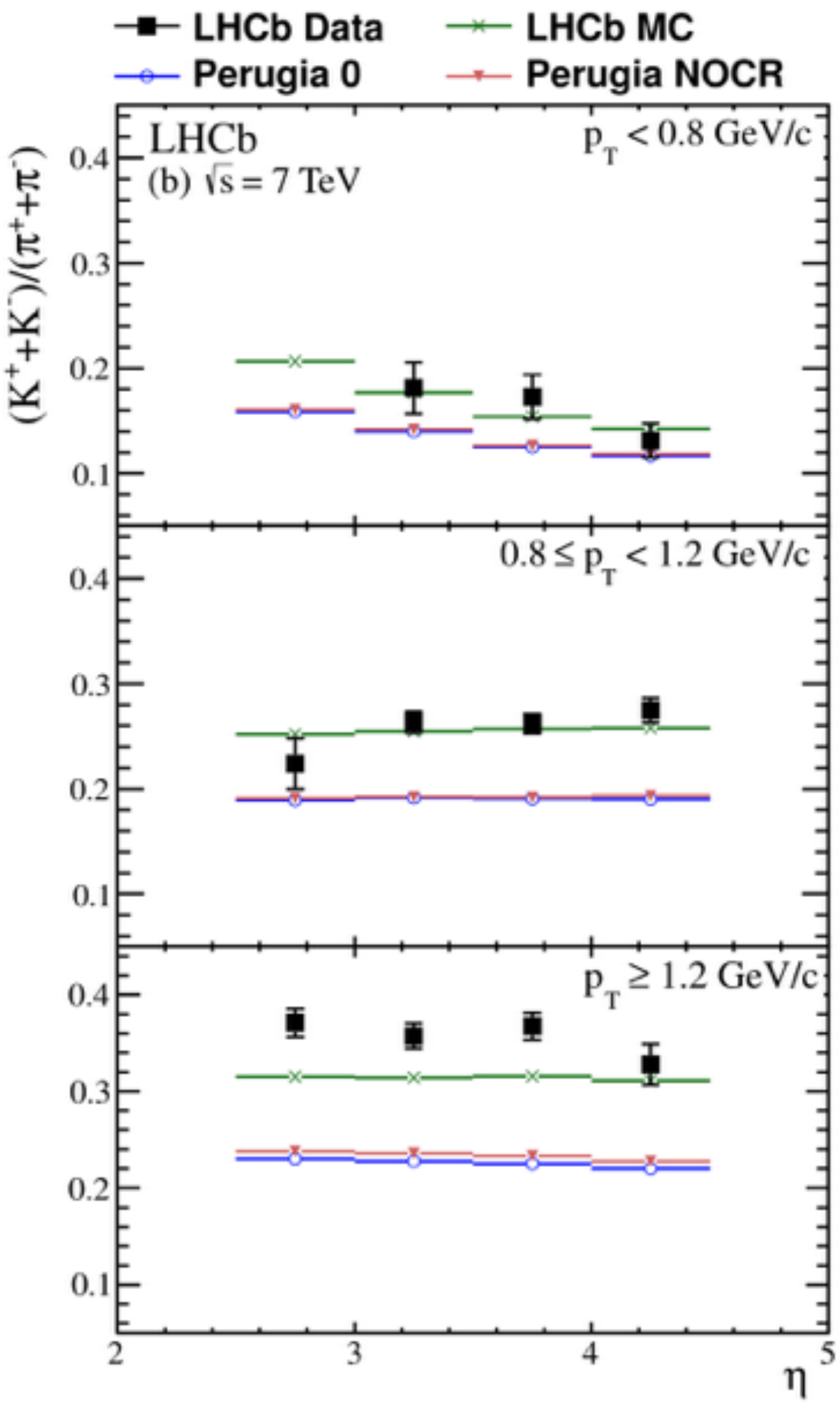
π, K and p

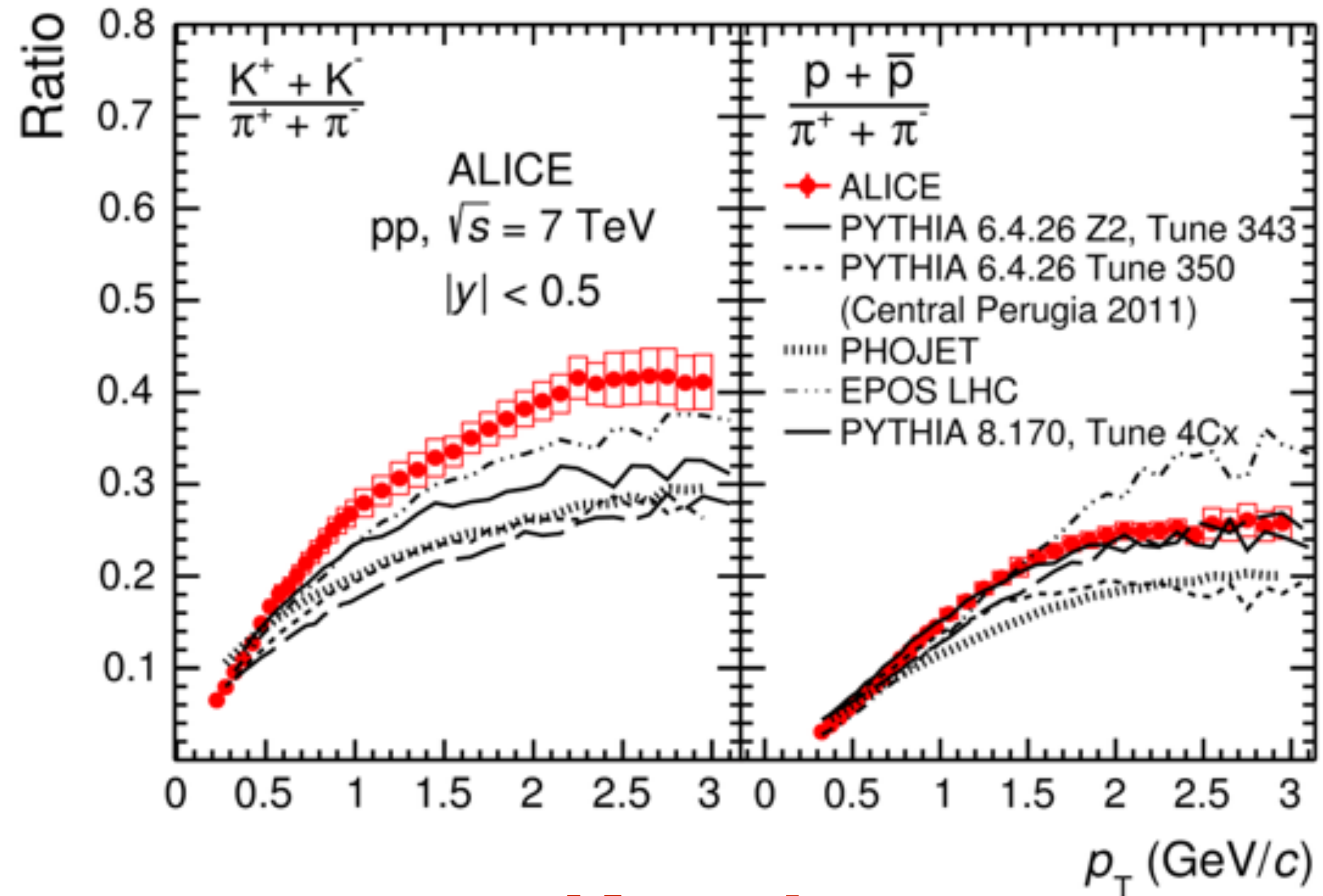
most abundantly produced stable particles measured over a very wide p_T range

reference for Pb-Pb studies

significant **constraints for soft and pQCD models and FF**

Forward rapidity





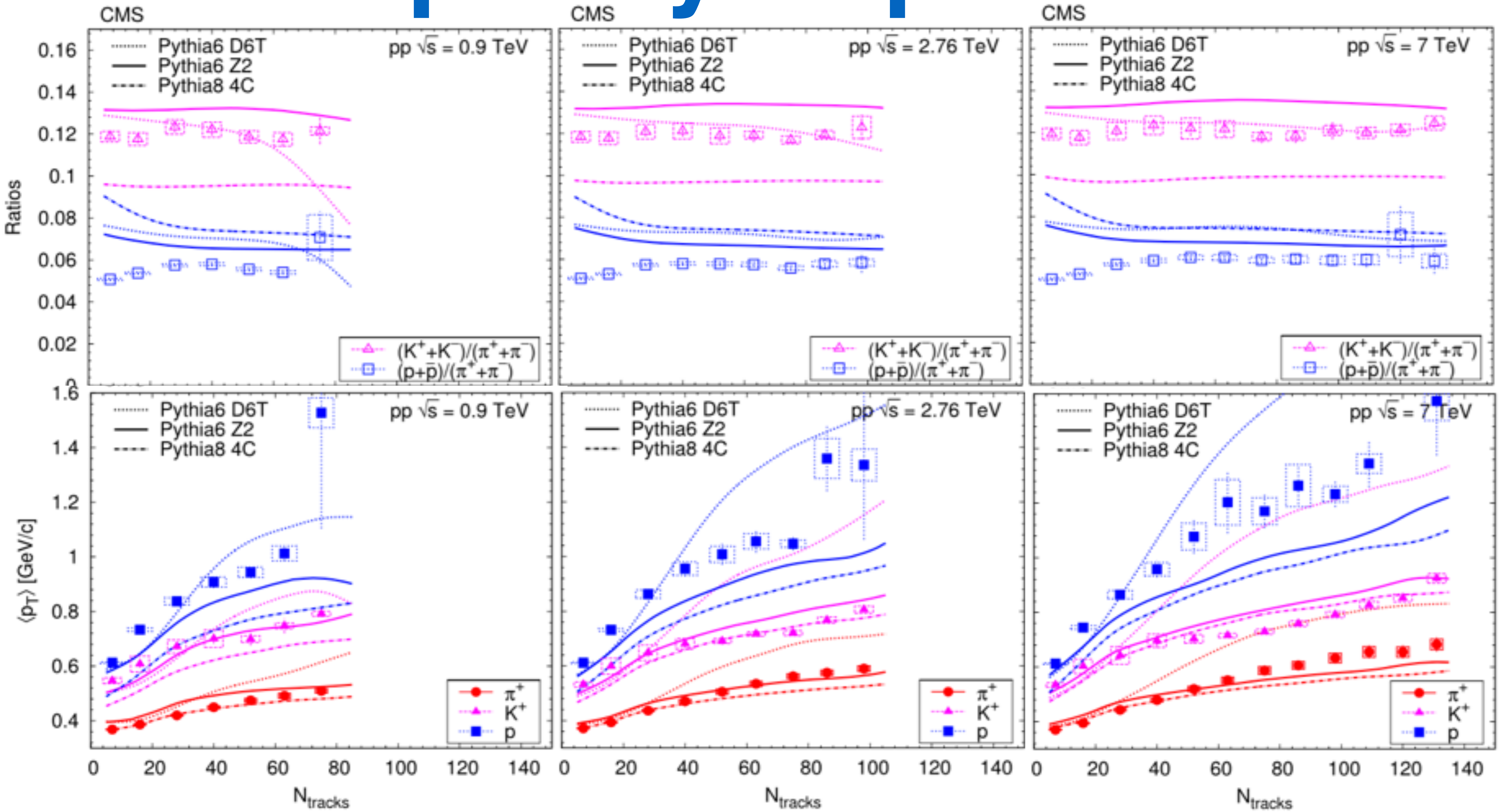
π, K and p

most abundantly produced stable particles measured over a very wide rapidity range

reference for Pb-Pb studies

significant **constraints for soft and pQCD models and FF**

Multiplicity dependence



particle production at LHC energies

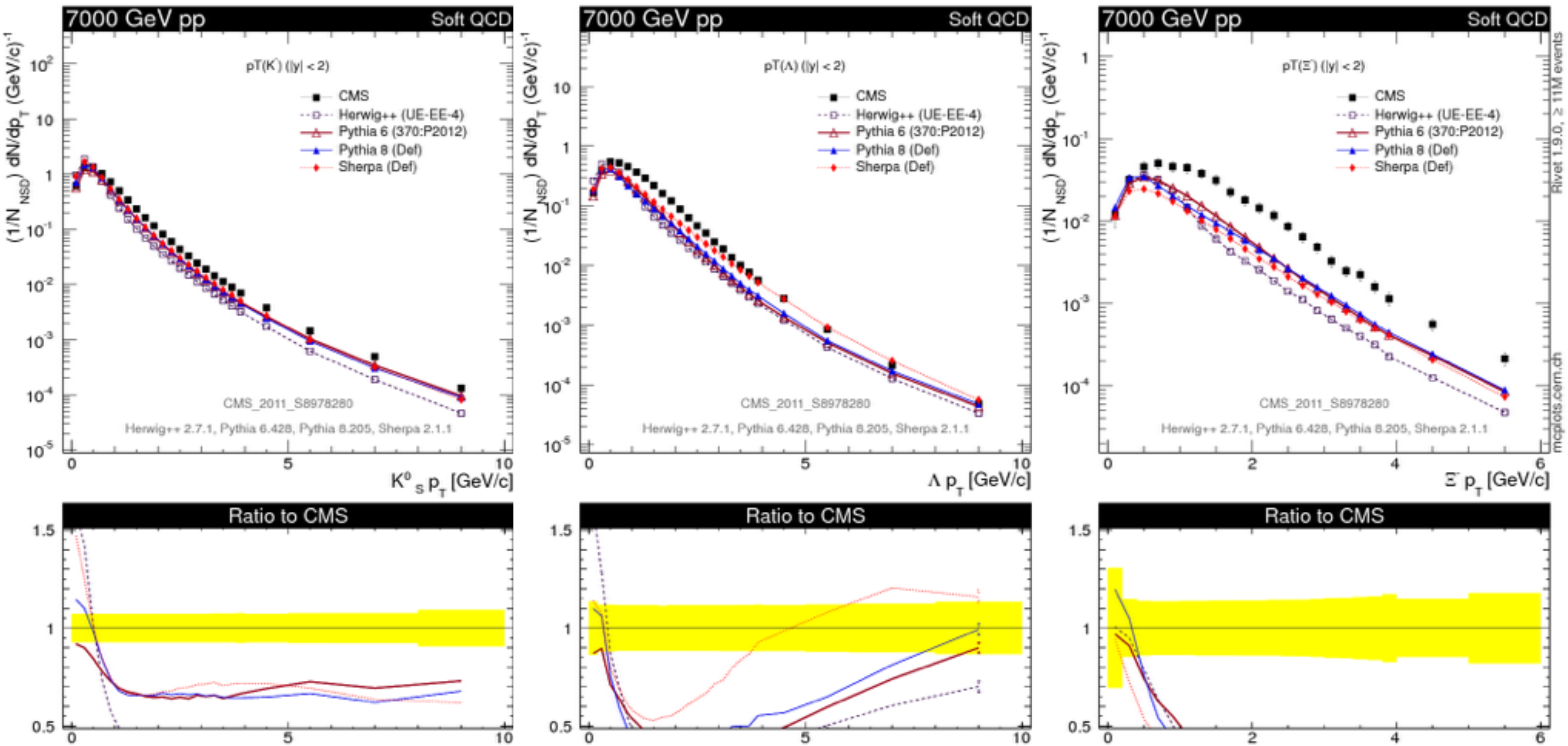
strongly **correlated with event particle multiplicity**

not with centre-of-mass energy

constrained by the amount of initial parton energy available?

CMS, EPJC 72 (2012) 2164

Strangeness production

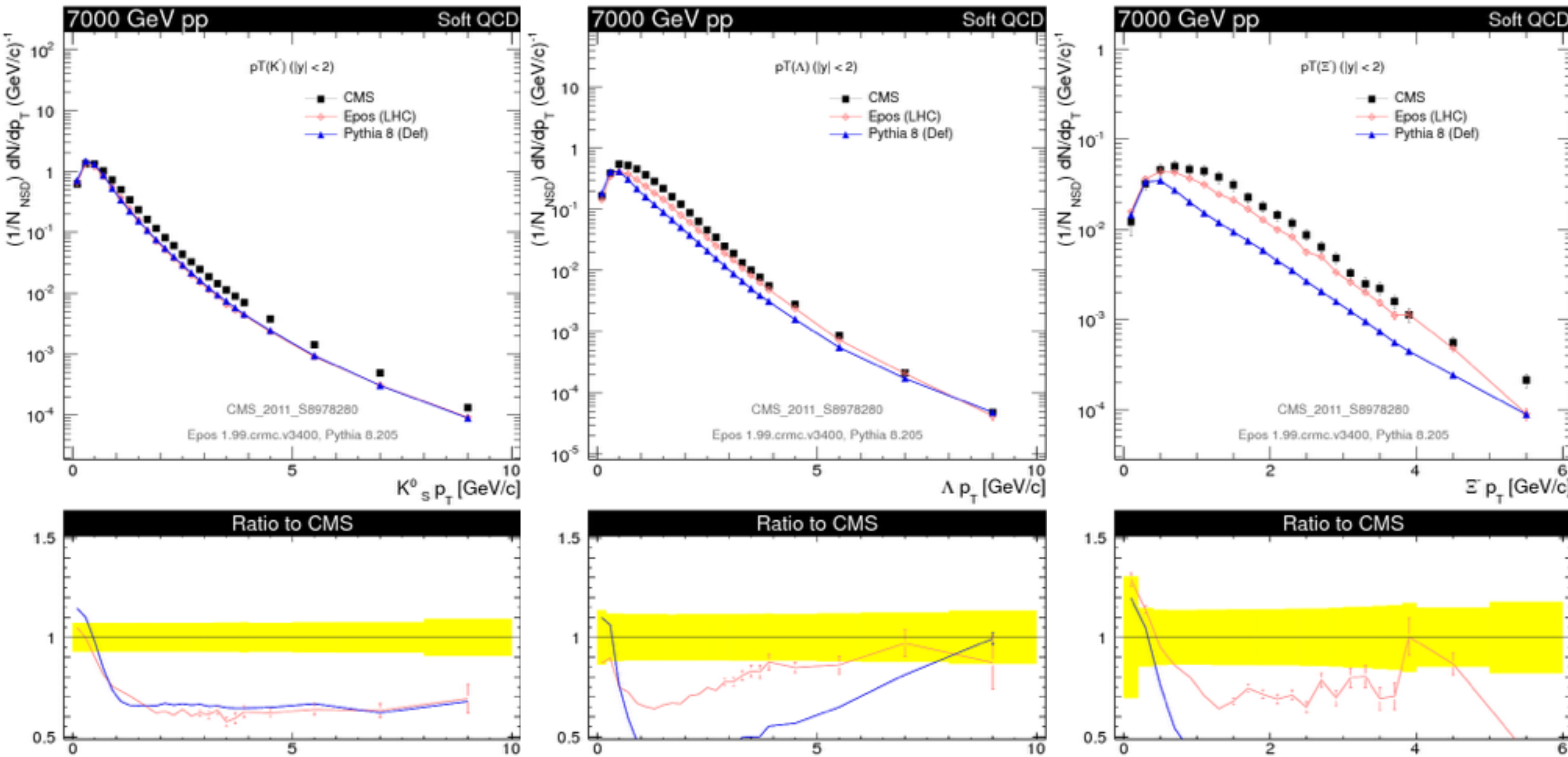


precise measurement of strange and multi-strange production in pp compared with several event generators

deviations in the soft region, increase with strangeness content

hint for possible agreement at higher p_T, hard time for MC generators

Strangeness production

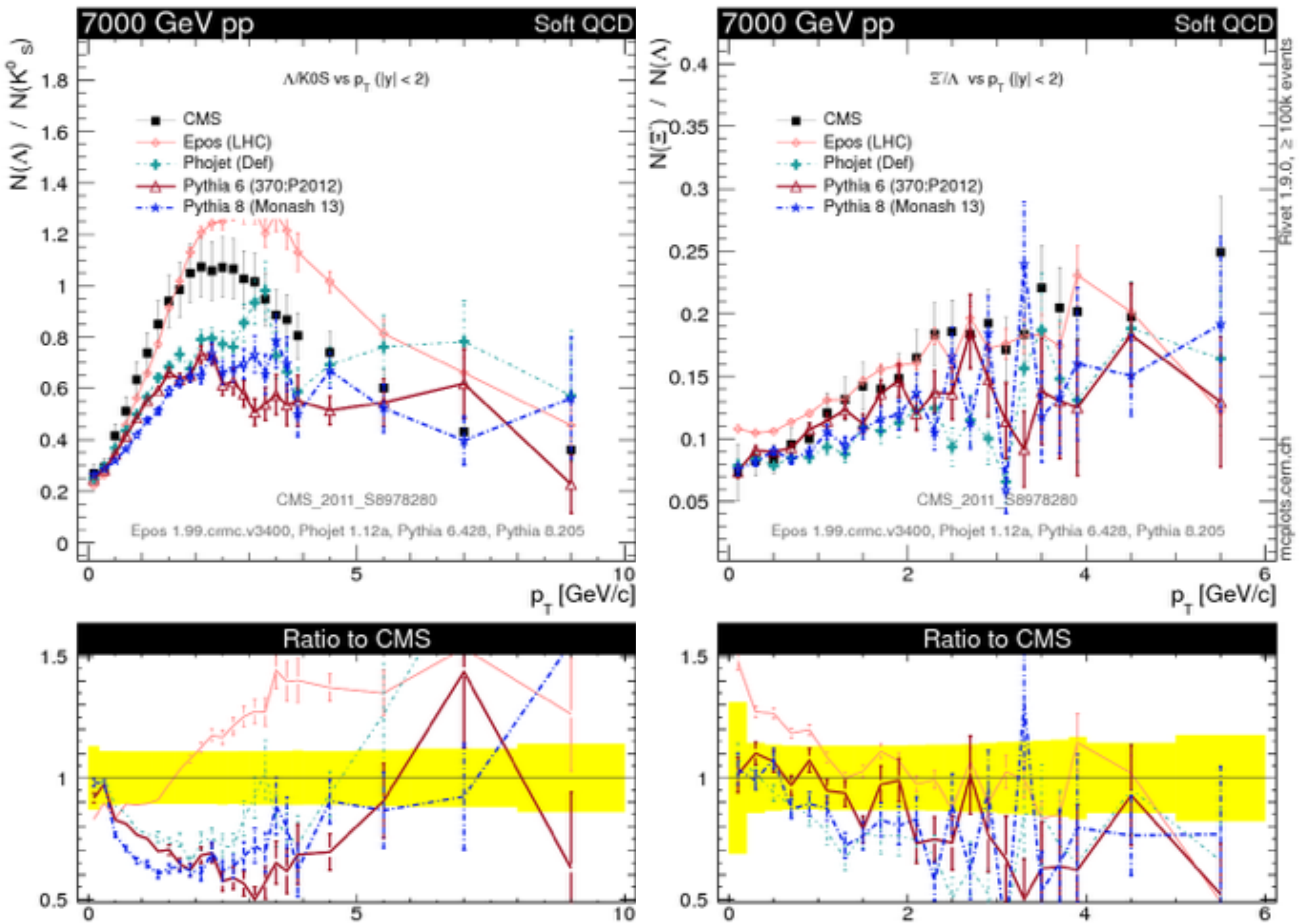


precise measurement of strange and multi-strange production in pp compared with several event generators

deviations in the soft region, increase with strangeness content

EPOS LHC does a slightly better job, but it is still low in strangeness

Strangeness production



precise measurement of strange and multi-strange production in pp compared with several event generators

deviations in the soft region, increase with strangeness content

EPOS LHC does a slightly better job, but it overshoots Λ / K^0_S ratio

Particle production in nucleus-nucleus collisions

Heavy-ion physics

study QCD matter under extreme conditions

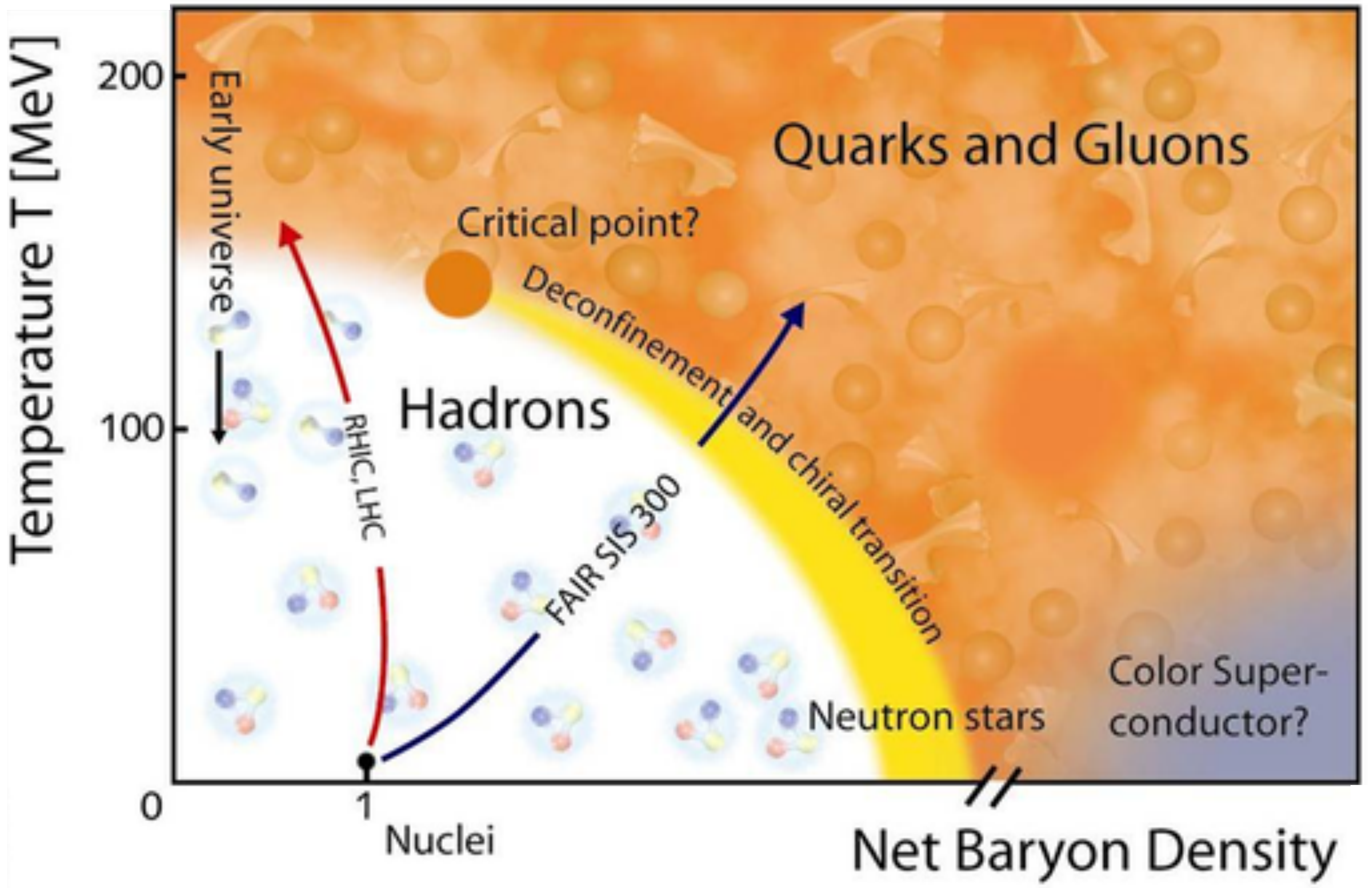
high temperature and energy-density

expected to undergo a **phase-transition**

hadronic matter → deconfined quarks and gluons (QGP)

study the phase diagram and the properties of hot QCD matter

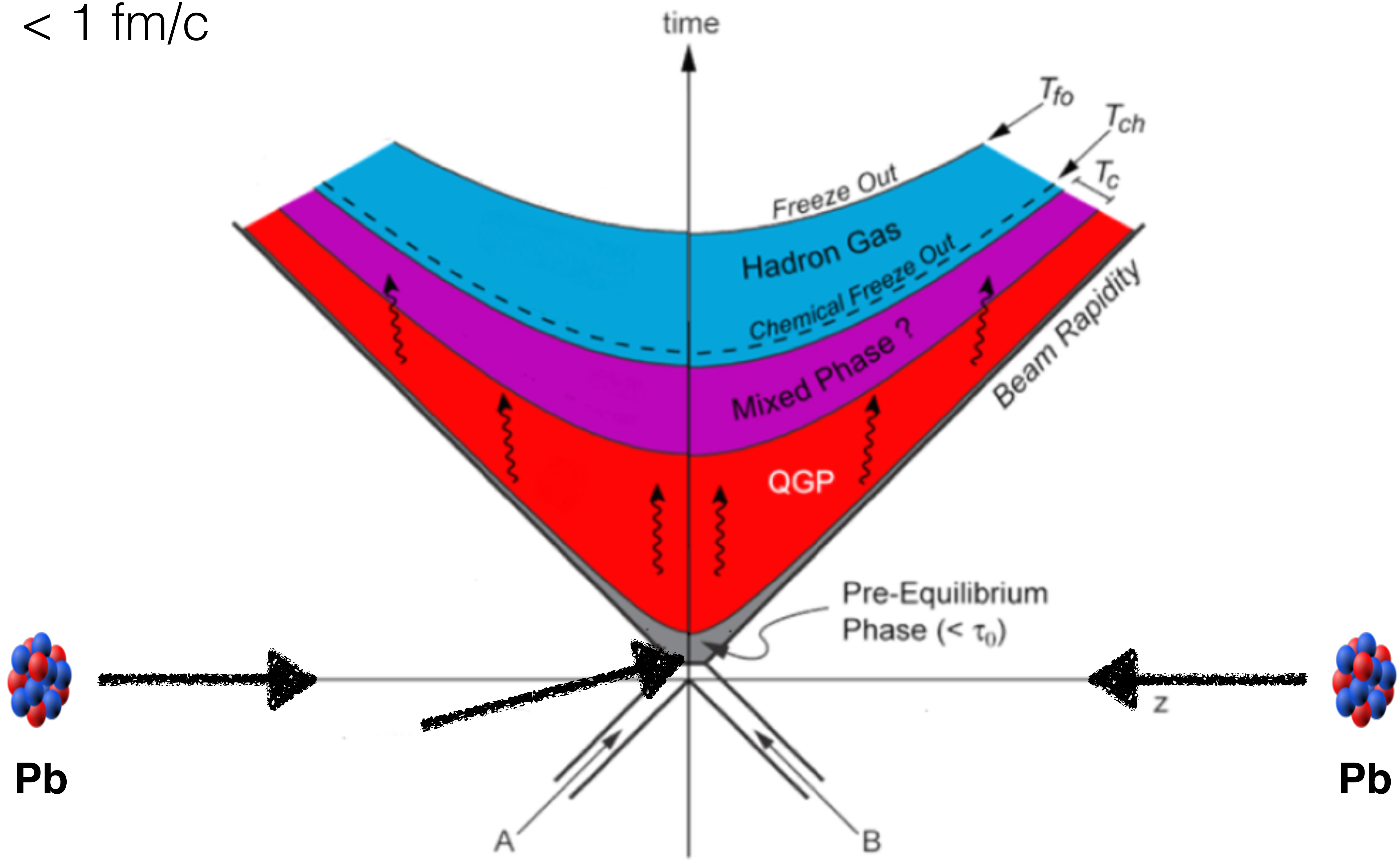
past:	GSI	SIS	~2 GeV
	BNL	AGS	~5 GeV
	CERN	SPS	~20 GeV
present:	BNL	RHIC	~200 GeV
	CERN	LHC	~5 TeV
future:	GSI	FAIR	~45 GeV



so far, a rich ultra relativistic heavy-ion programme

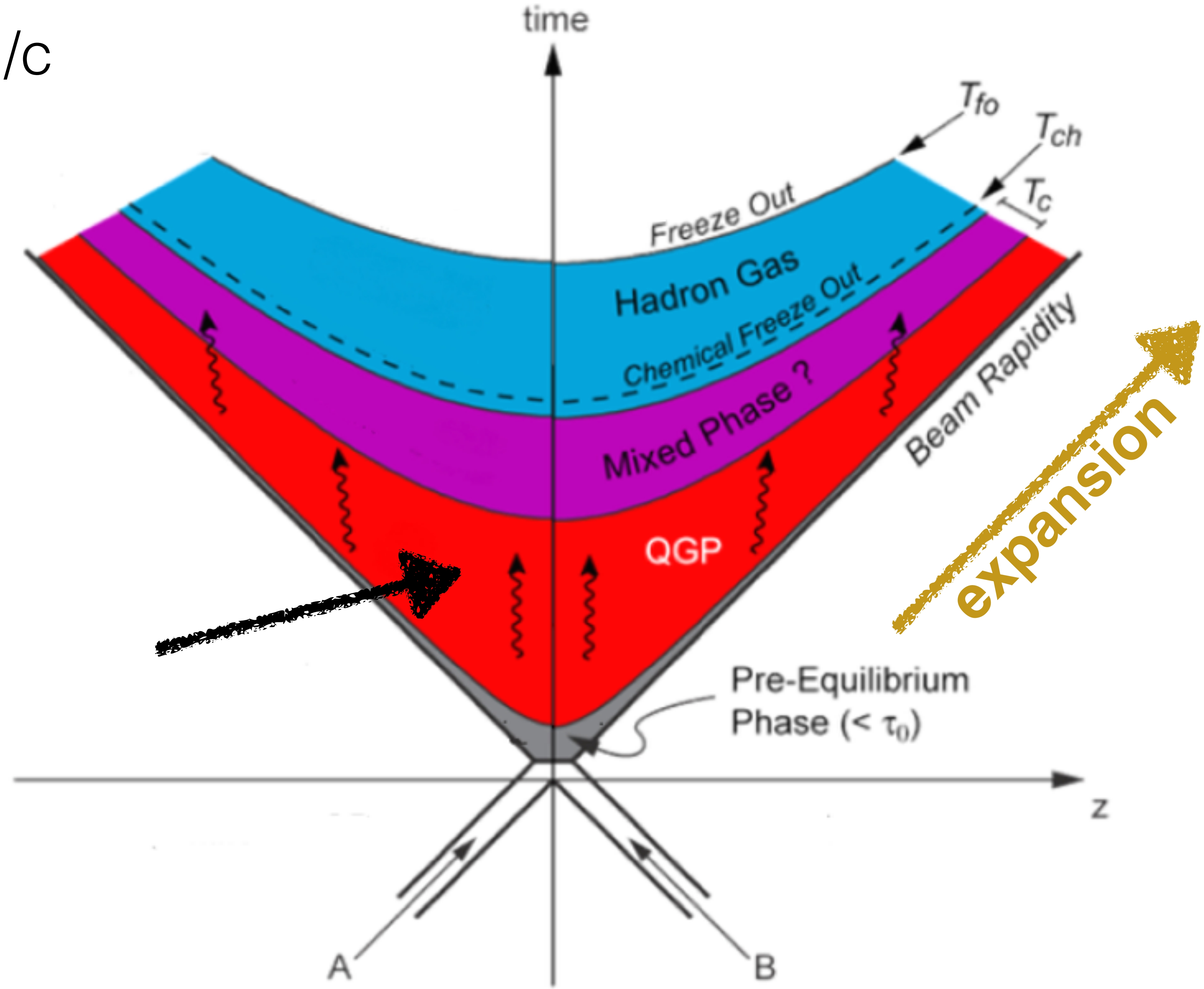
Hard scattering + thermalisation

< 1 fm/c



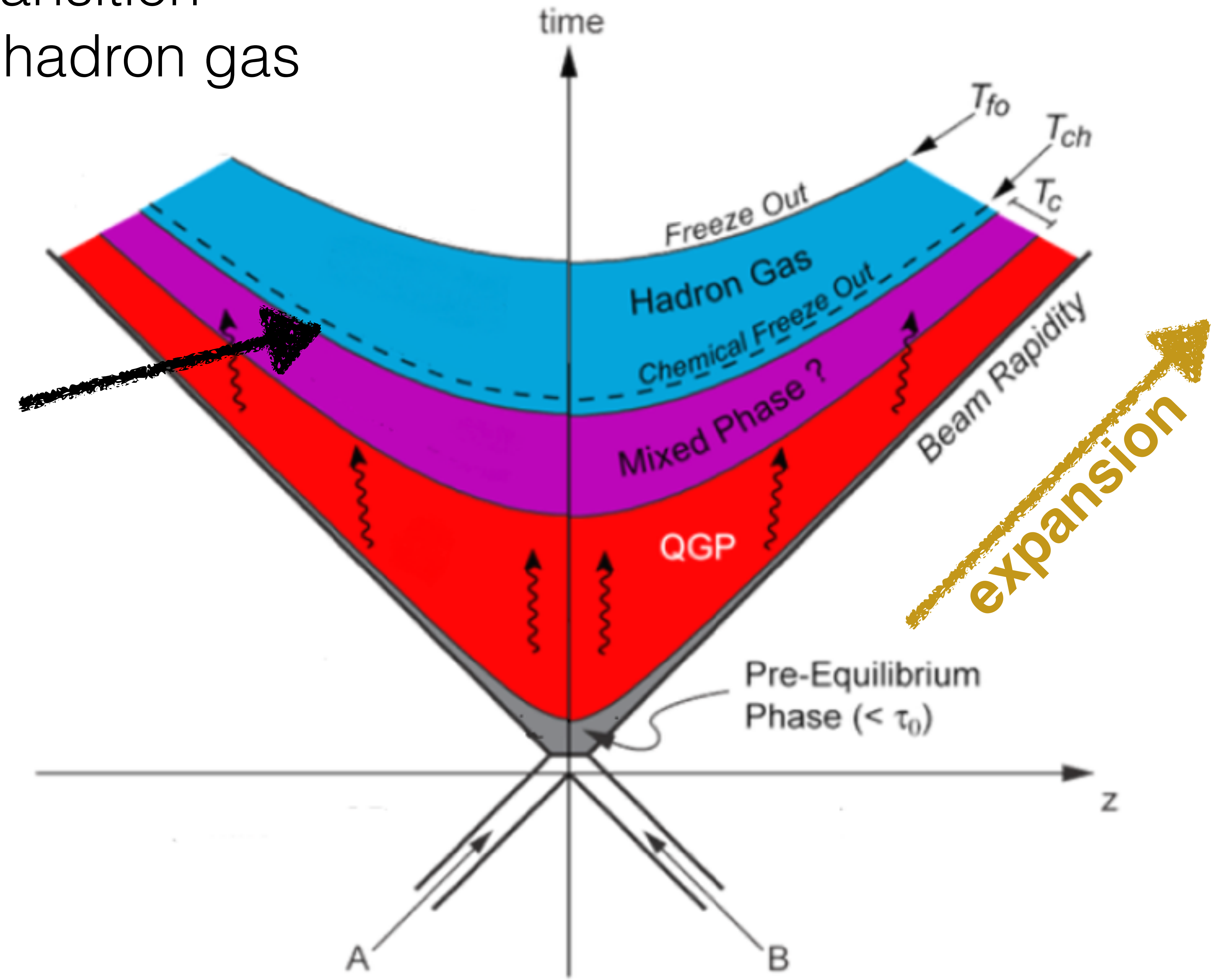
Partonic phase

QGP
~ few fm/c



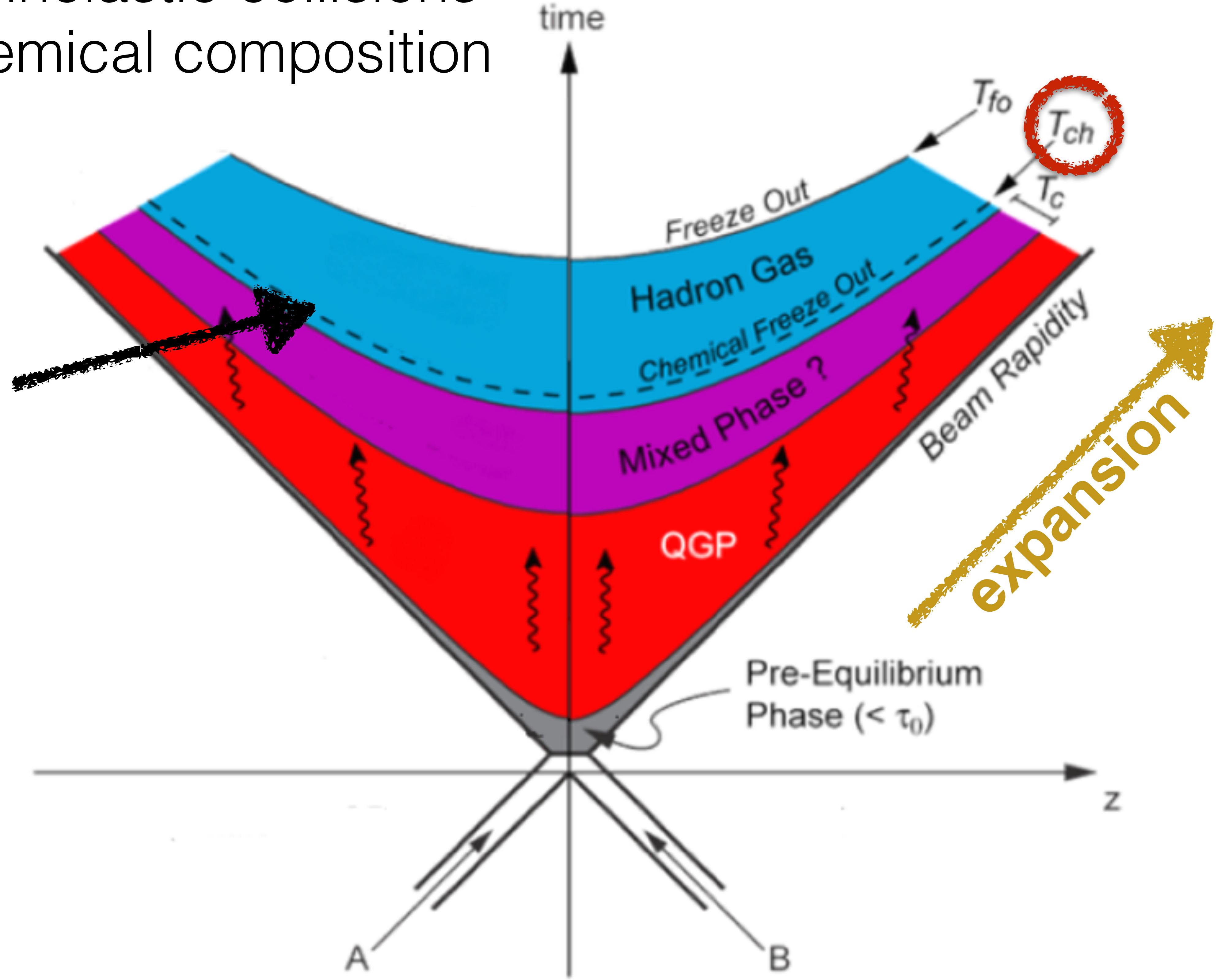
Hadronisation

phase transition
QGP → hadron gas



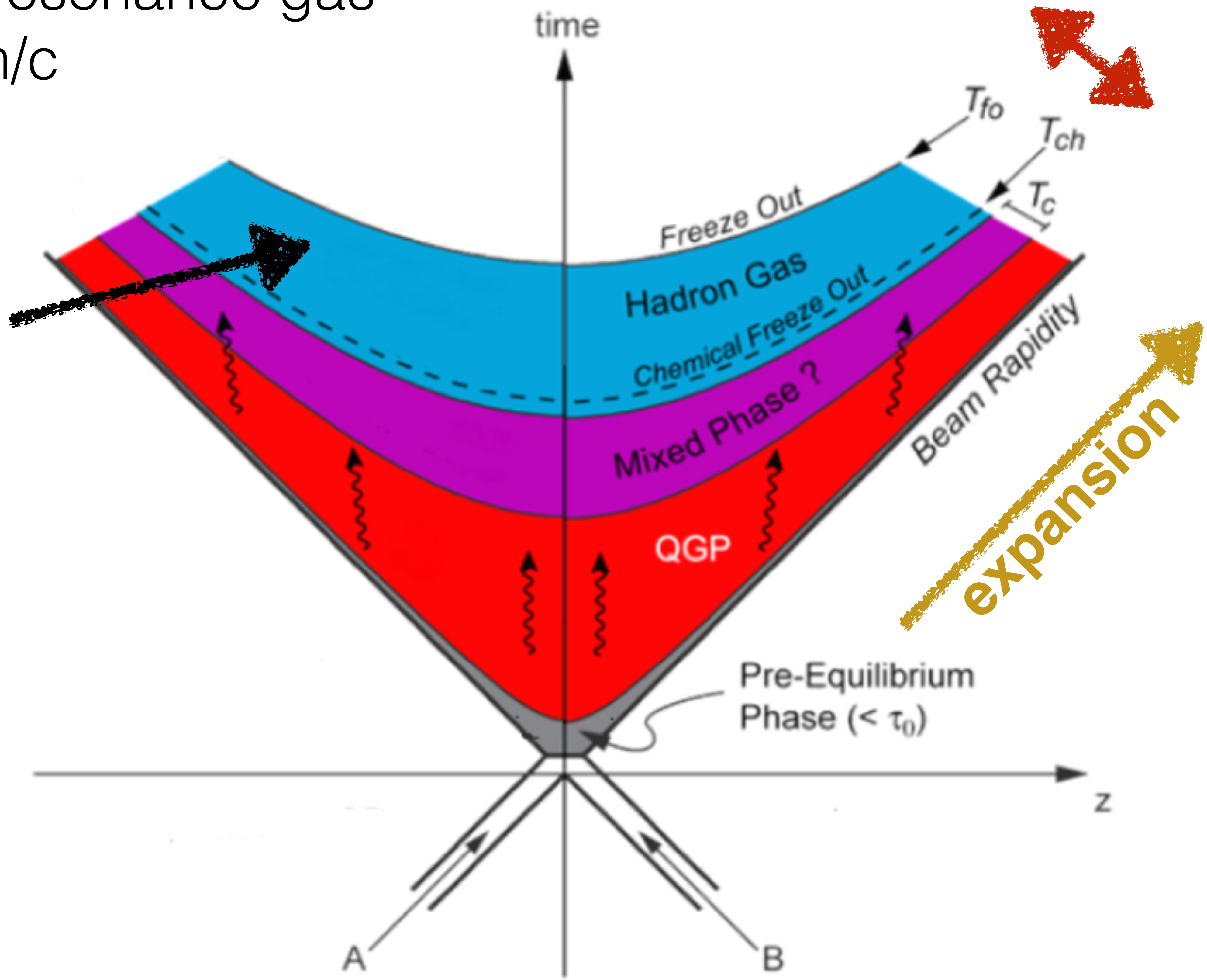
Chemical freeze-out

no more inelastic collisions
fixed chemical composition



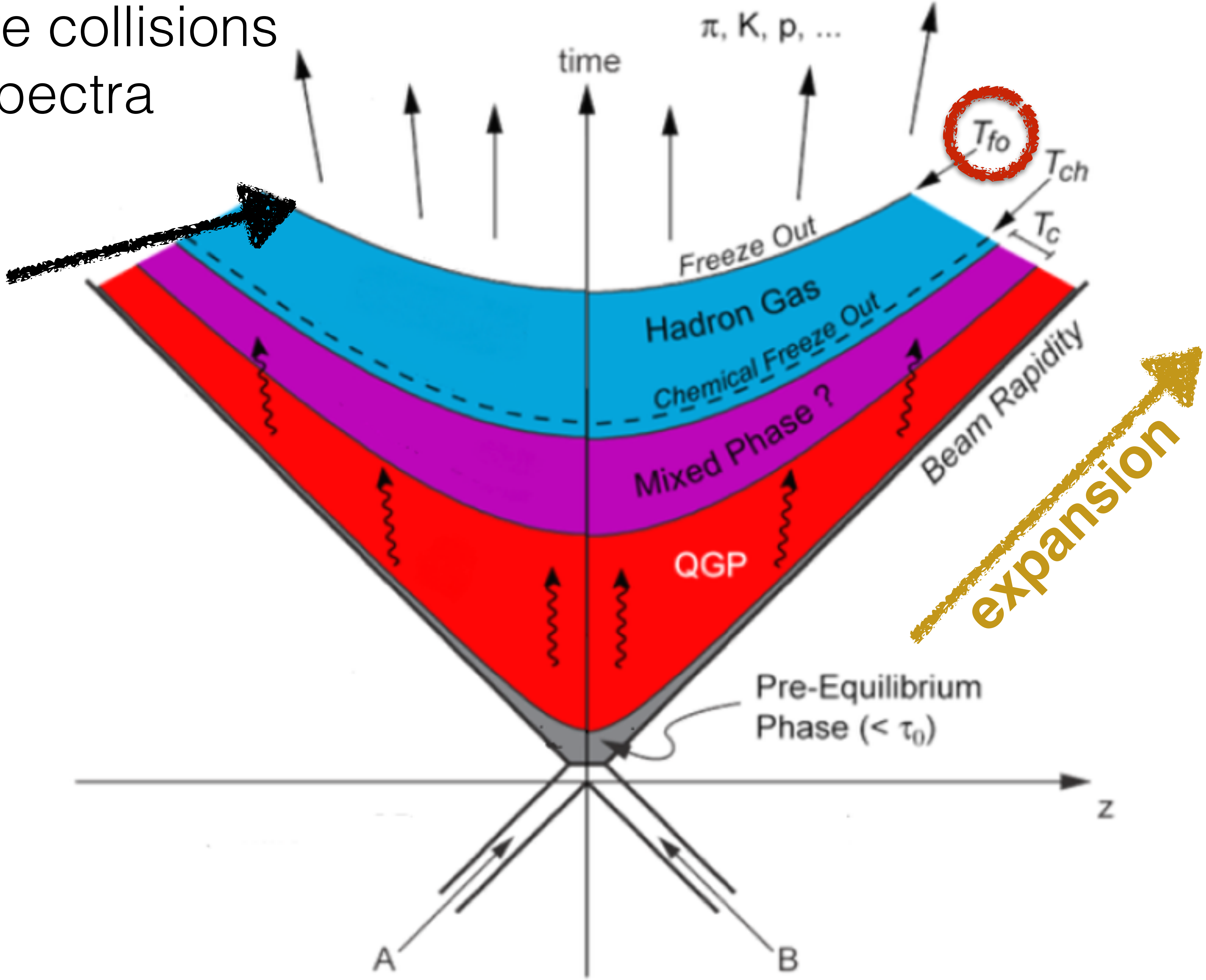
Hadronic phase

hadron-resonance gas
~ few fm/c

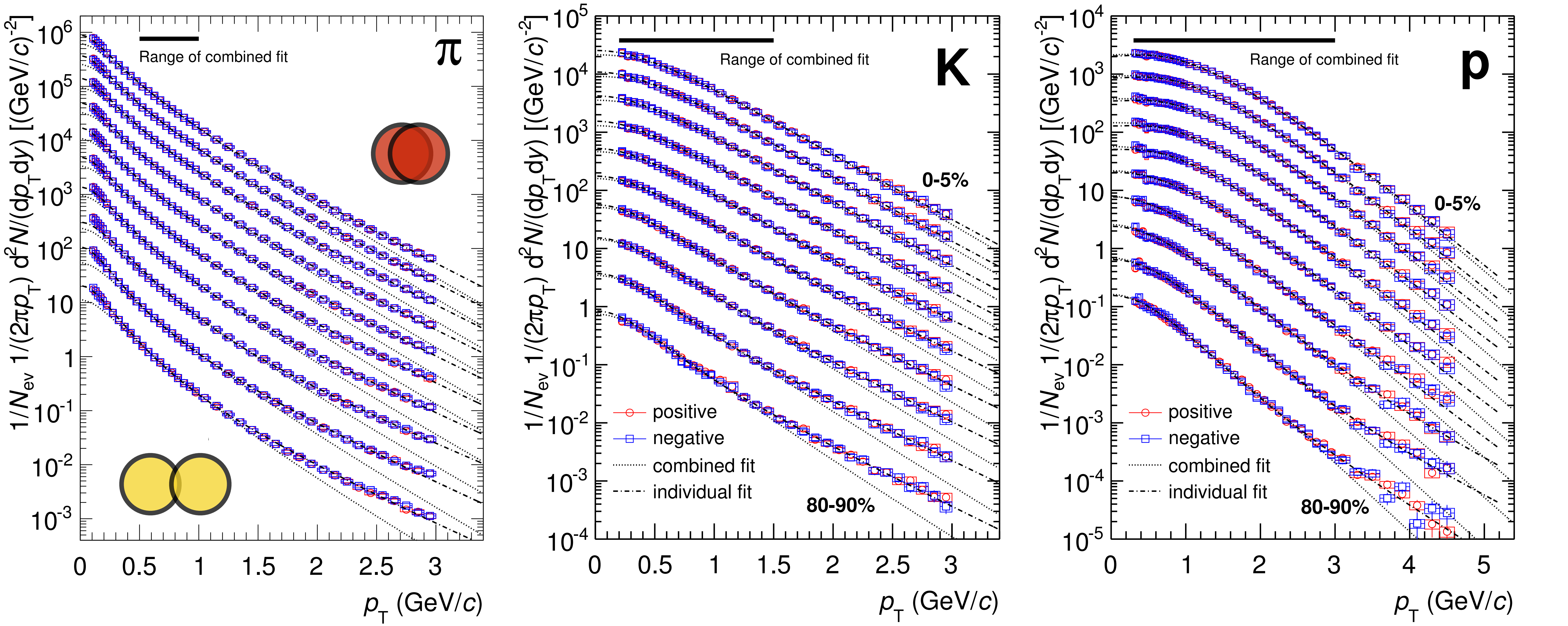


Kinetic freeze-out

no more collisions
fixed spectra



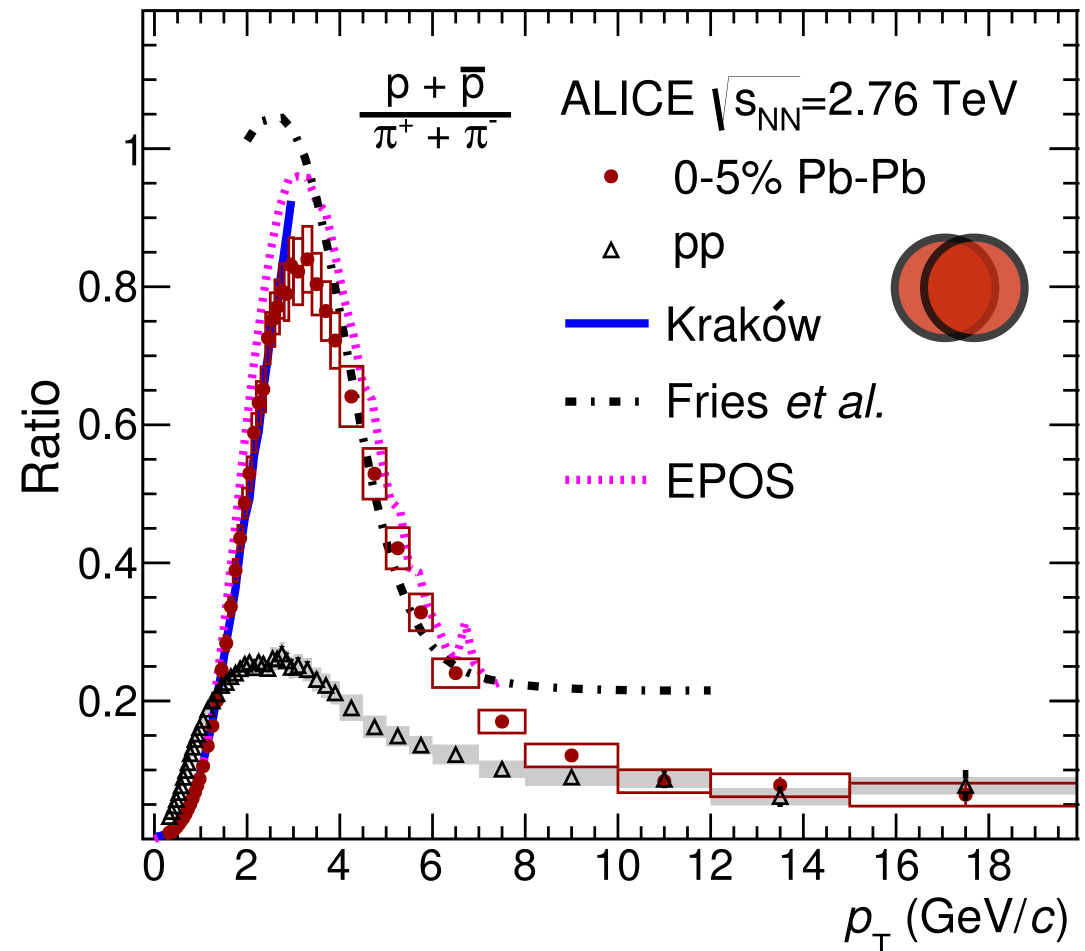
Bulk particle production in Pb-Pb

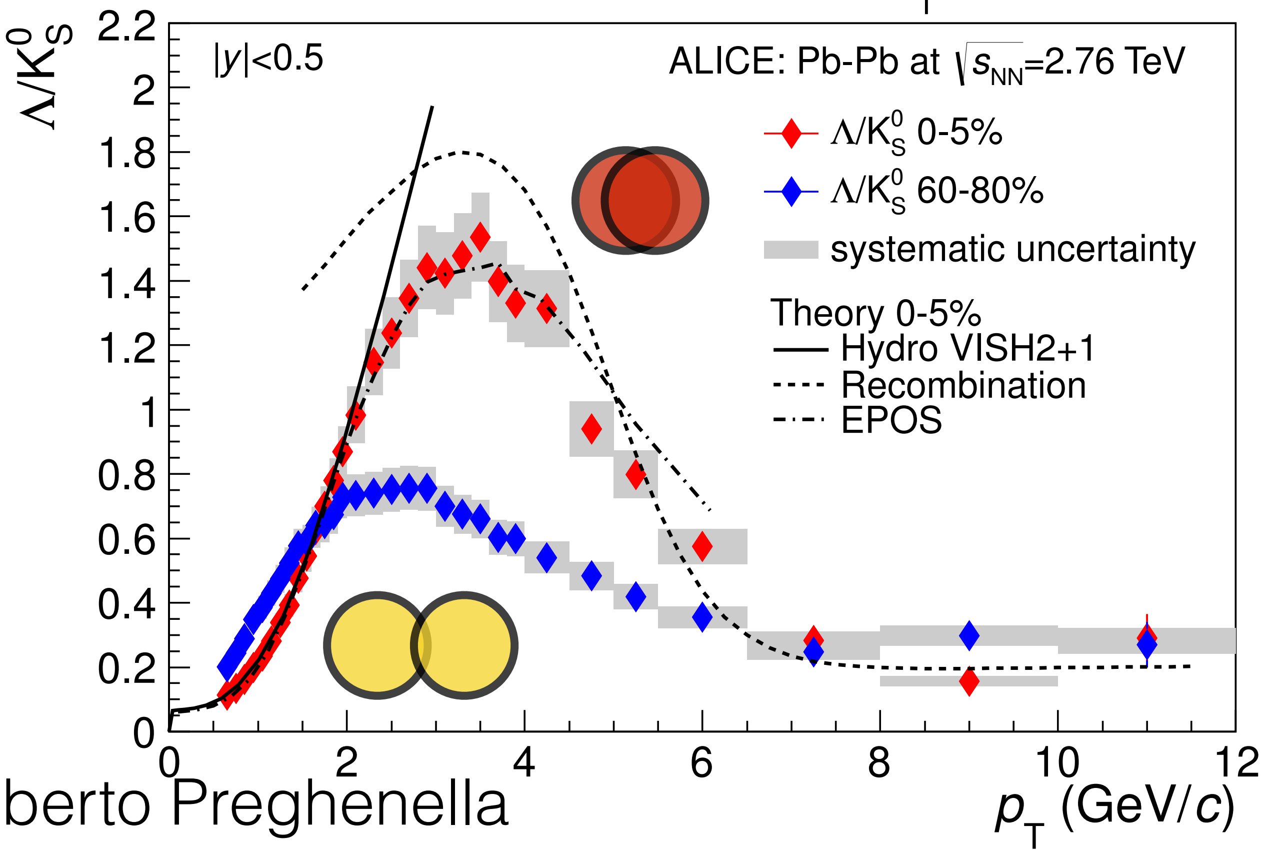


clear evolution of particle spectra → hardening with centrality
more pronounced for protons than for pions
mass ordering as expected from collective hydro expansion

Baryon-meson enhancement in Pb-Pb

ALICE, PLB 728 (2014) 25





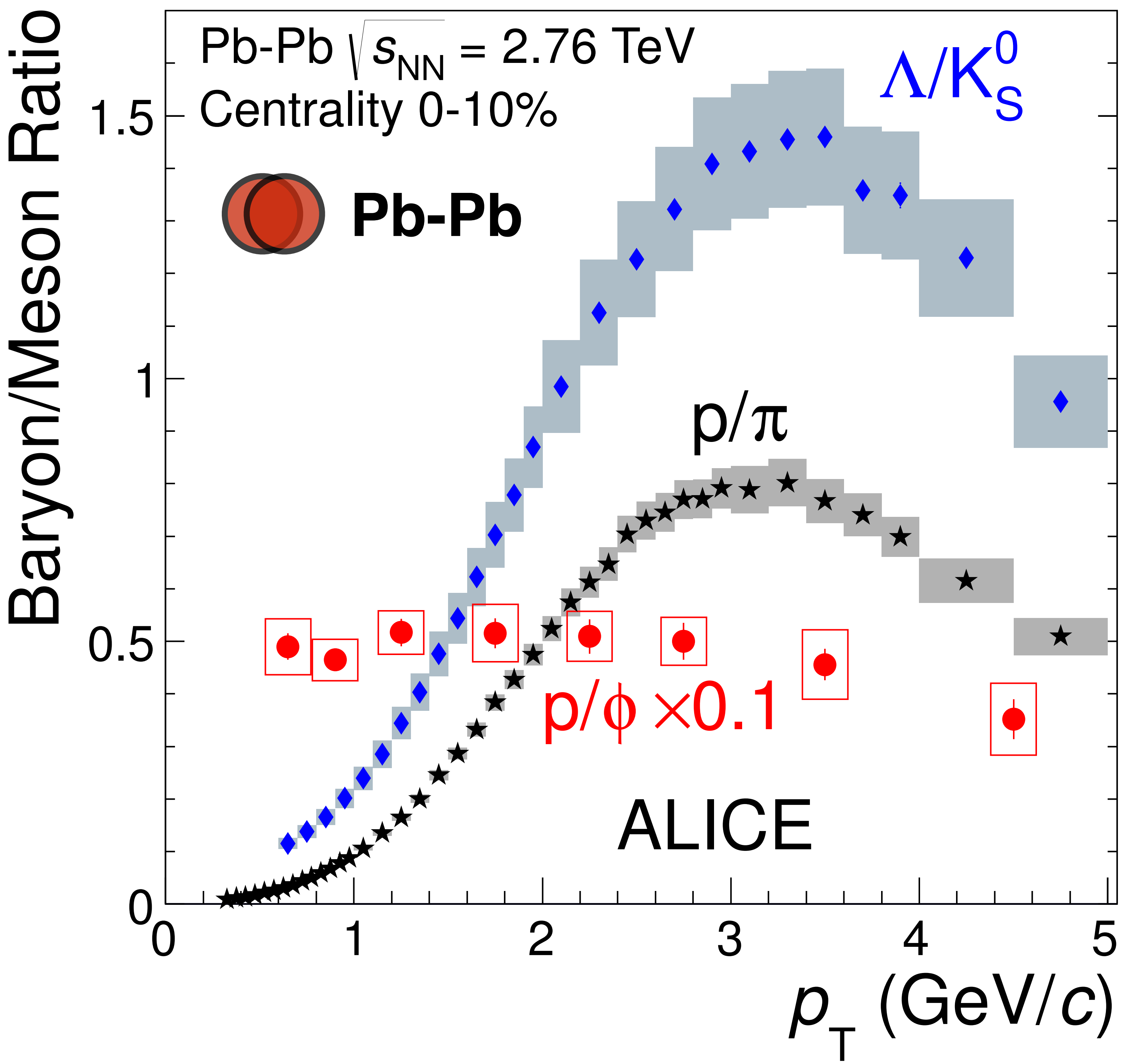
ALICE, PRL 111 (2013) 222301

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

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

p/ϕ 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**

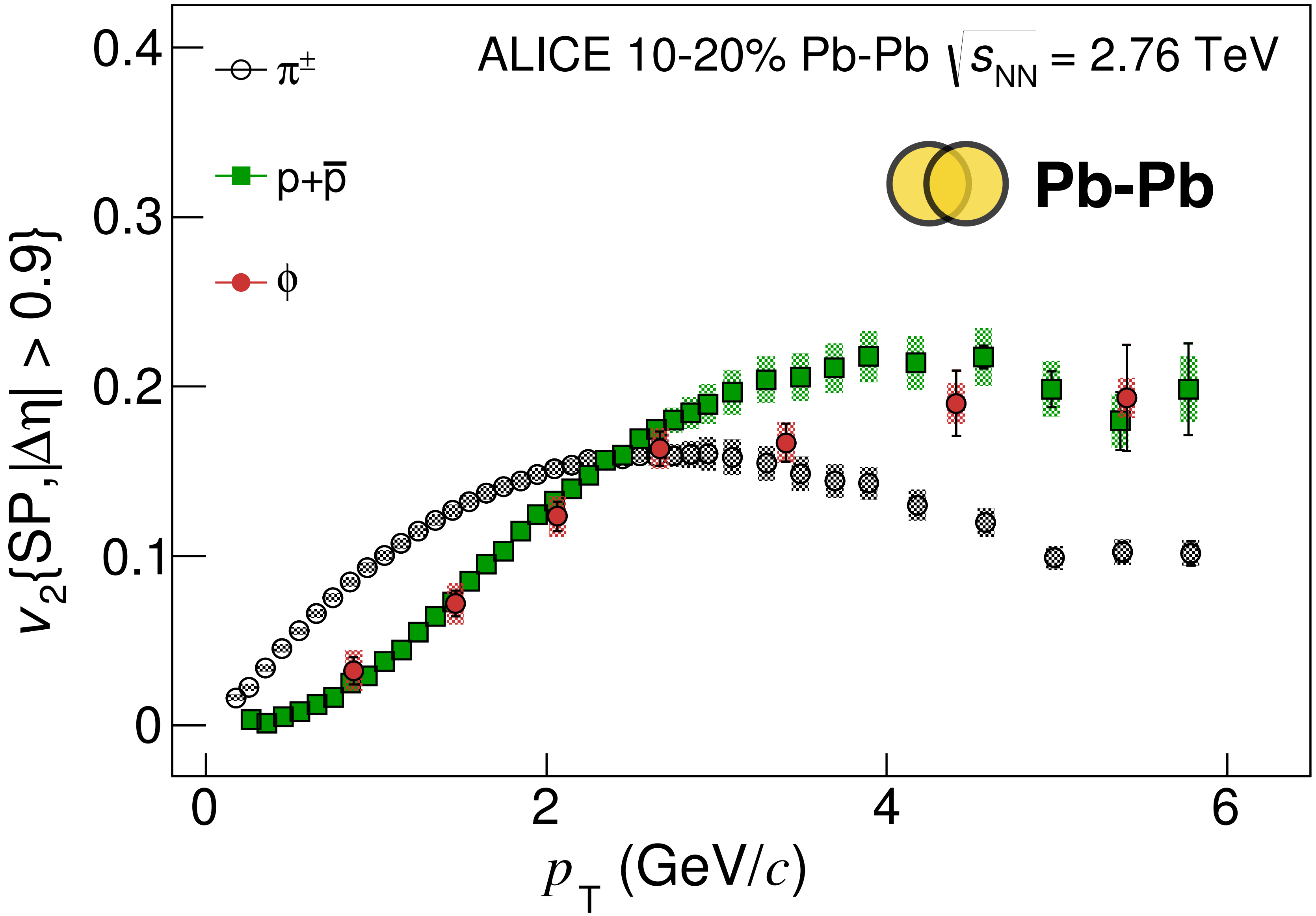
p/ϕ ratio is constant

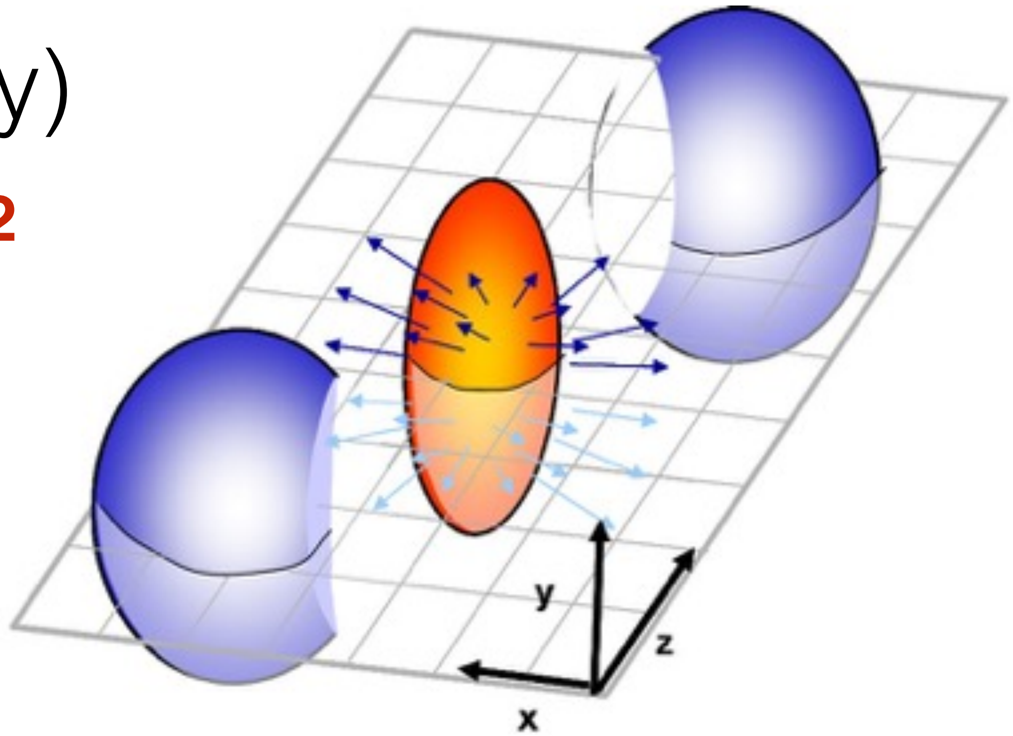
the data seems to indicate that **mass is the main parameter driving particle spectra**

(as foreseen by hydro)

p/ϕ anisotropic flow

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



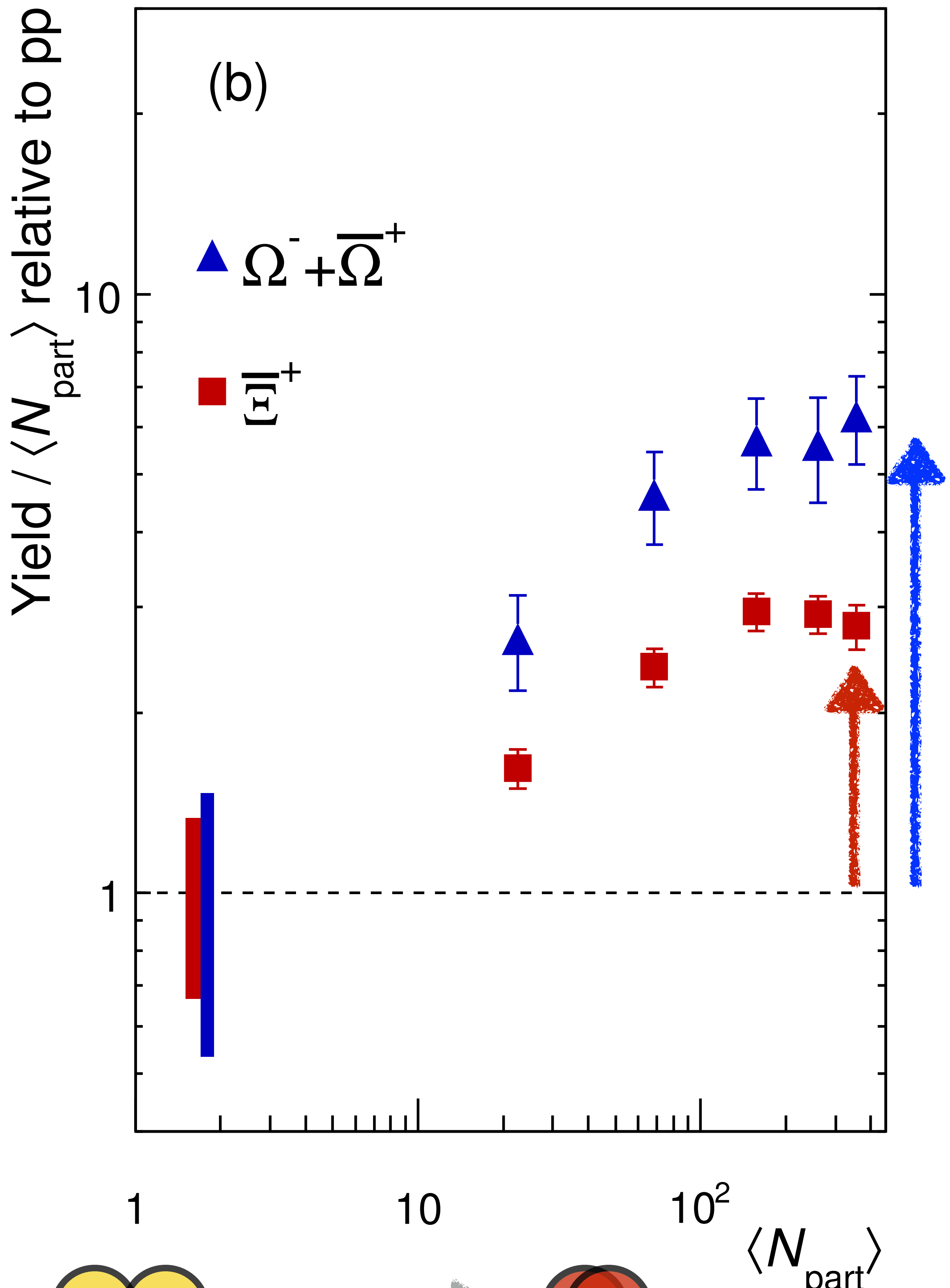


ϕ meson behaves like a proton

mass drives both v_2 and spectra

ALICE, arXiv:1405.4632 [nucl-ex]

Strangeness production in Pb-Pb



strangeness enhancement

one of the first proposed QGP signatures

Rafelski, PRL 48 (1982) 1066

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

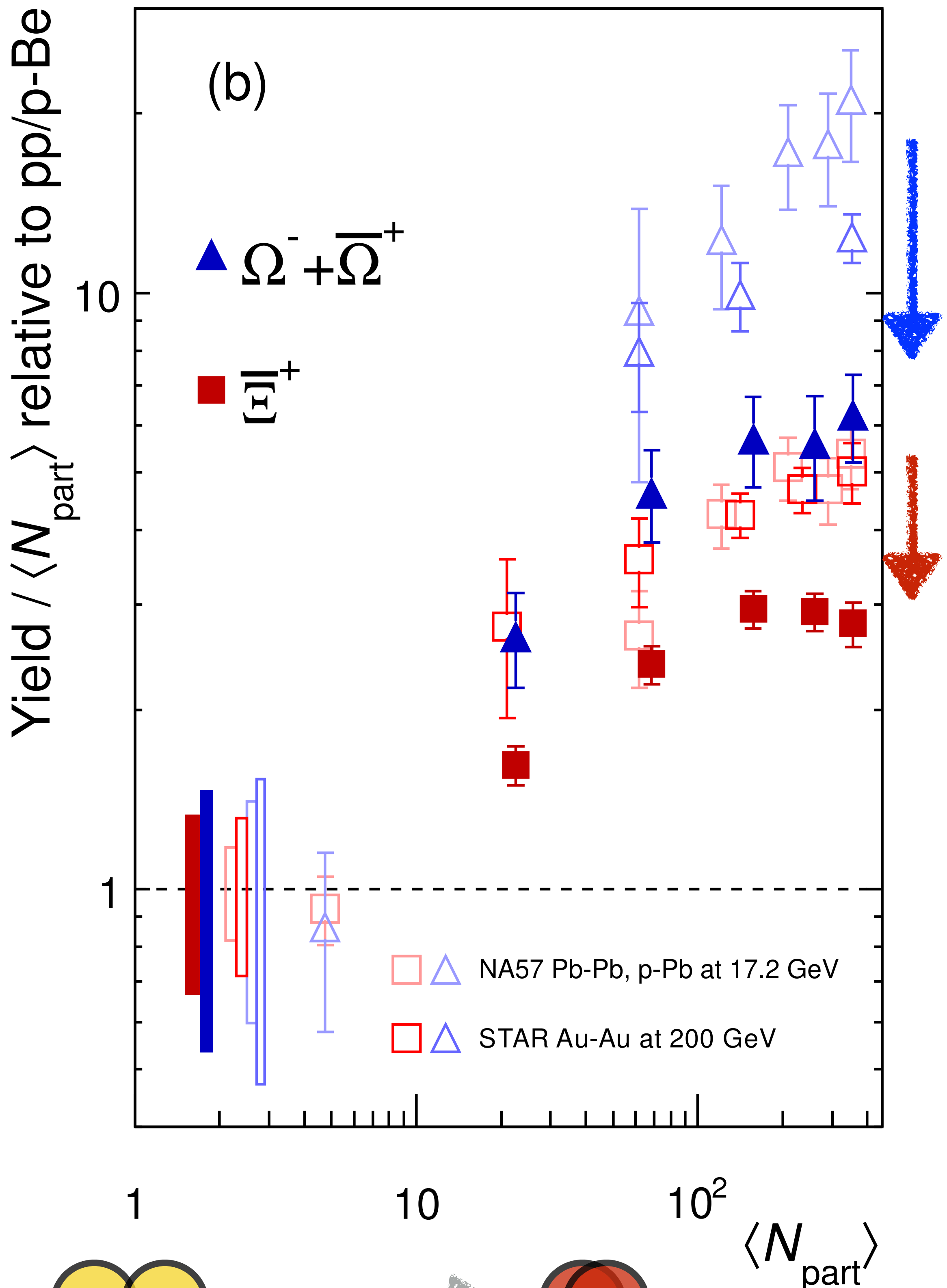
strangeness-content hierarchy

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

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

strangeness-content hierarchy

Ξ (dss) enhanced

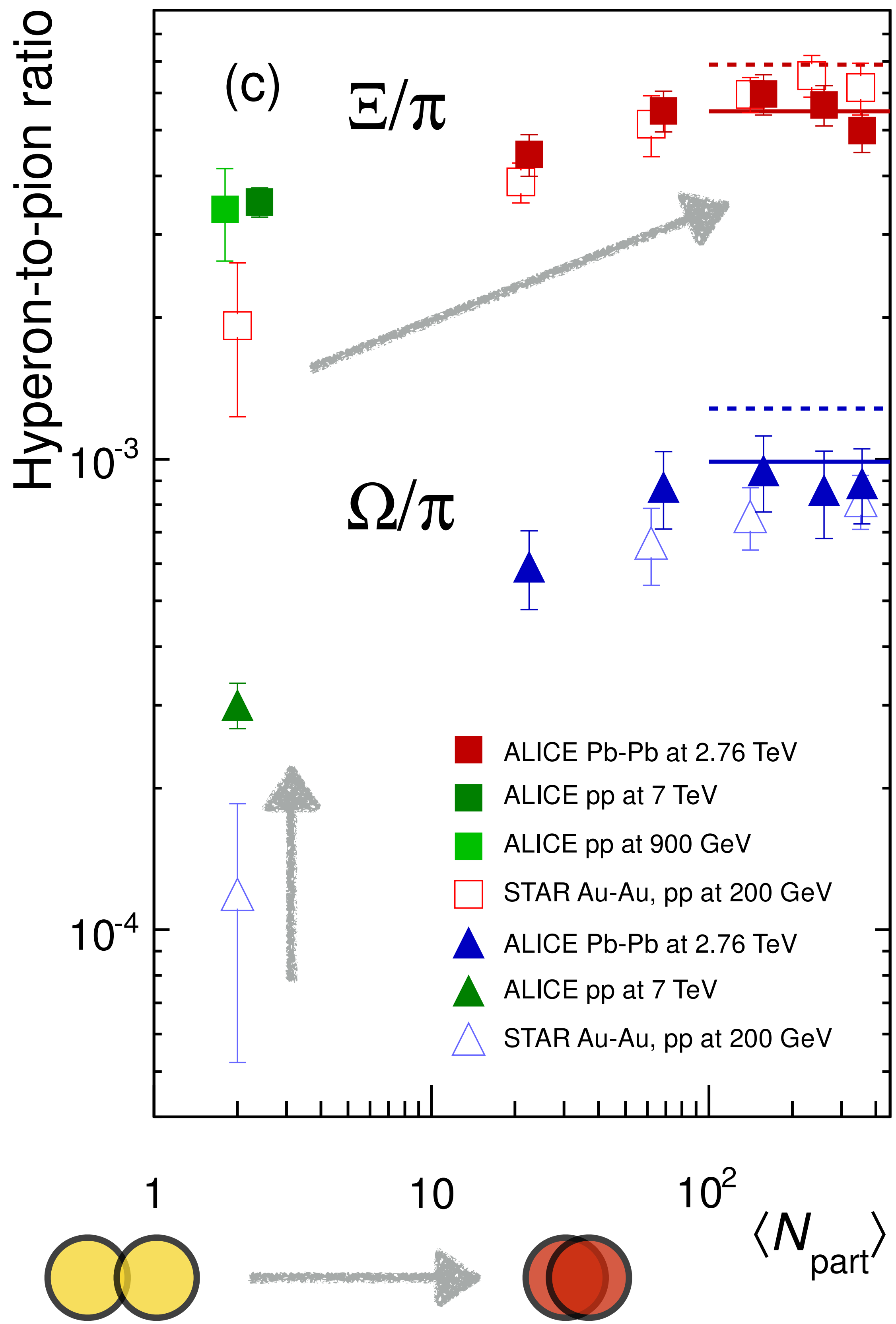
Ω (sss) more enhanced

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

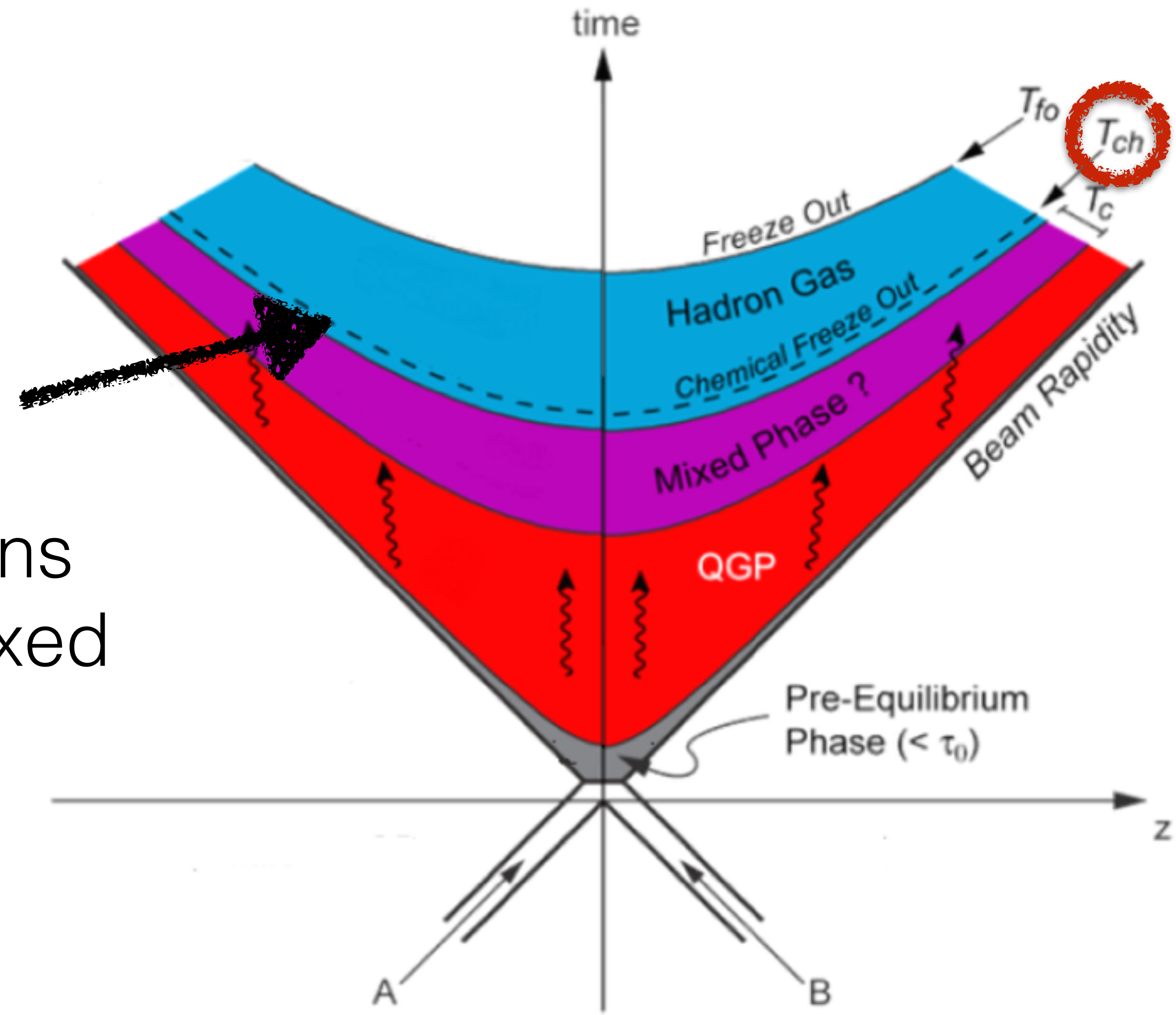
GSI-Heidelberg: T_{ch} = 164 MeV

THERMUS: T_{ch} = 170 MeV

ALICE, PLB 728 (2014) 216

Statistical model of hadron production

Chemical equilibrium achieved during or very shortly after phase transition



chemical freeze-out

end of inelastic interactions

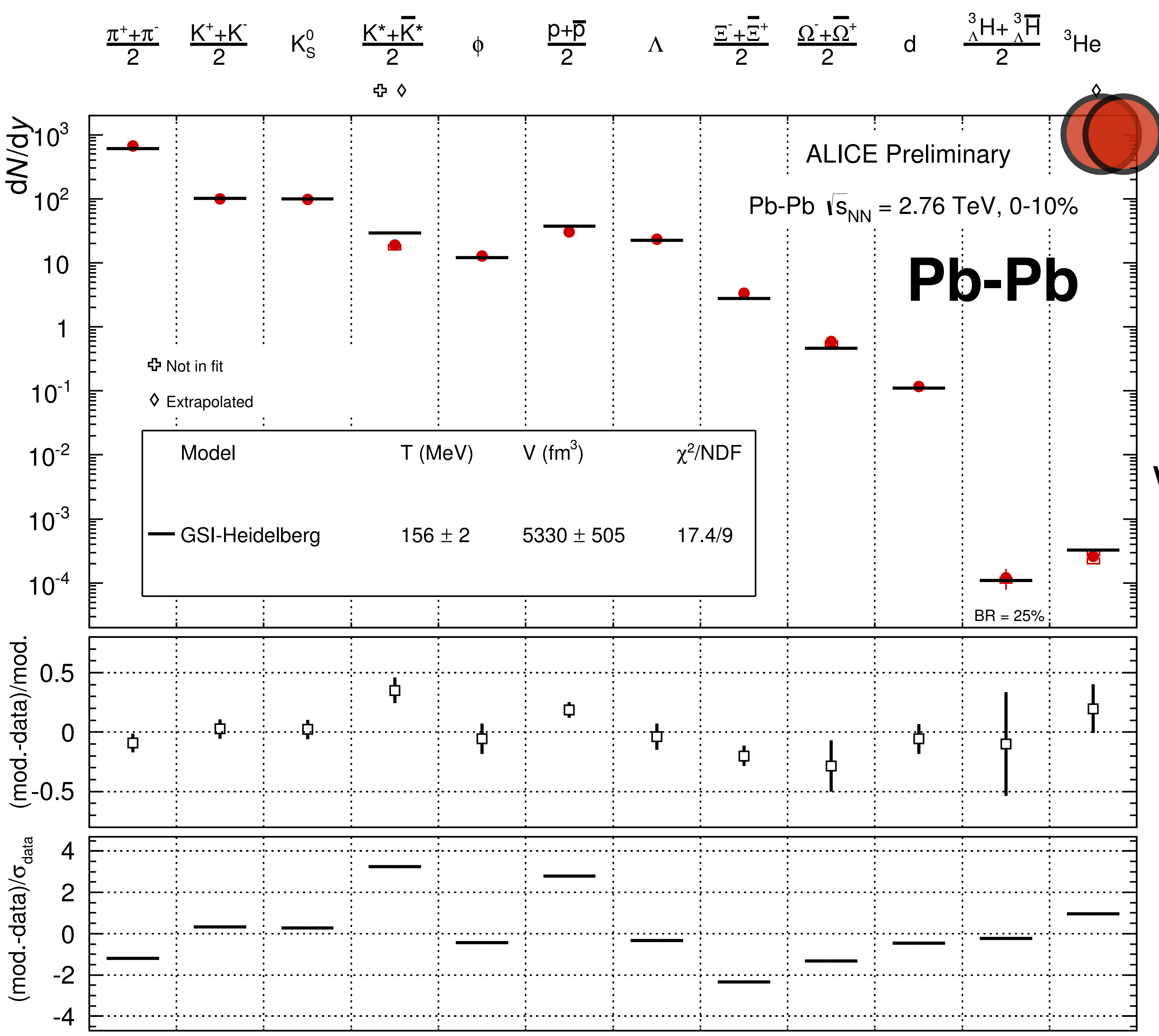
chemical composition is fixed

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

Thermal model of particle 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

$\chi^2/ndf \sim 2$

with a **single temperature**

$T_{ch} \sim 156$ MeV

deviations for K* and p

hint at final-state interactions

other mechanisms under investigation

(flavour hierarchy, non-equilibrium, …)

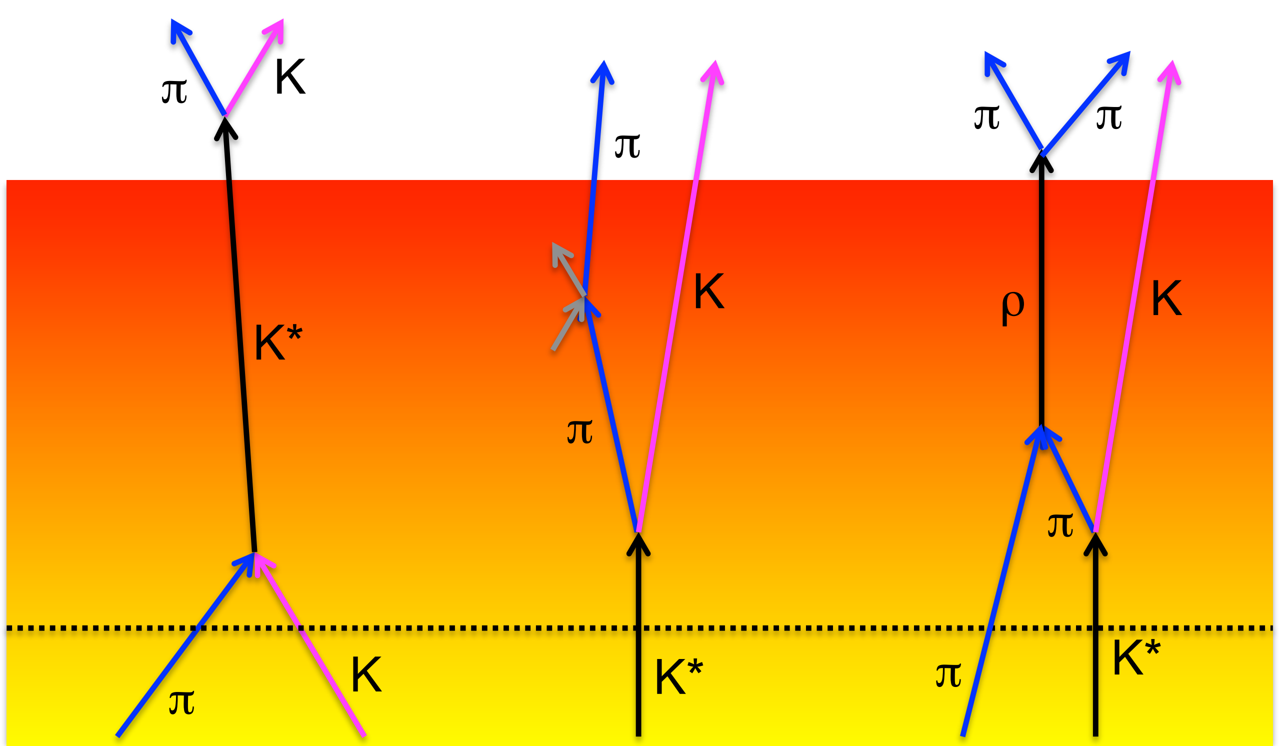
Interactions in the hadronic phase

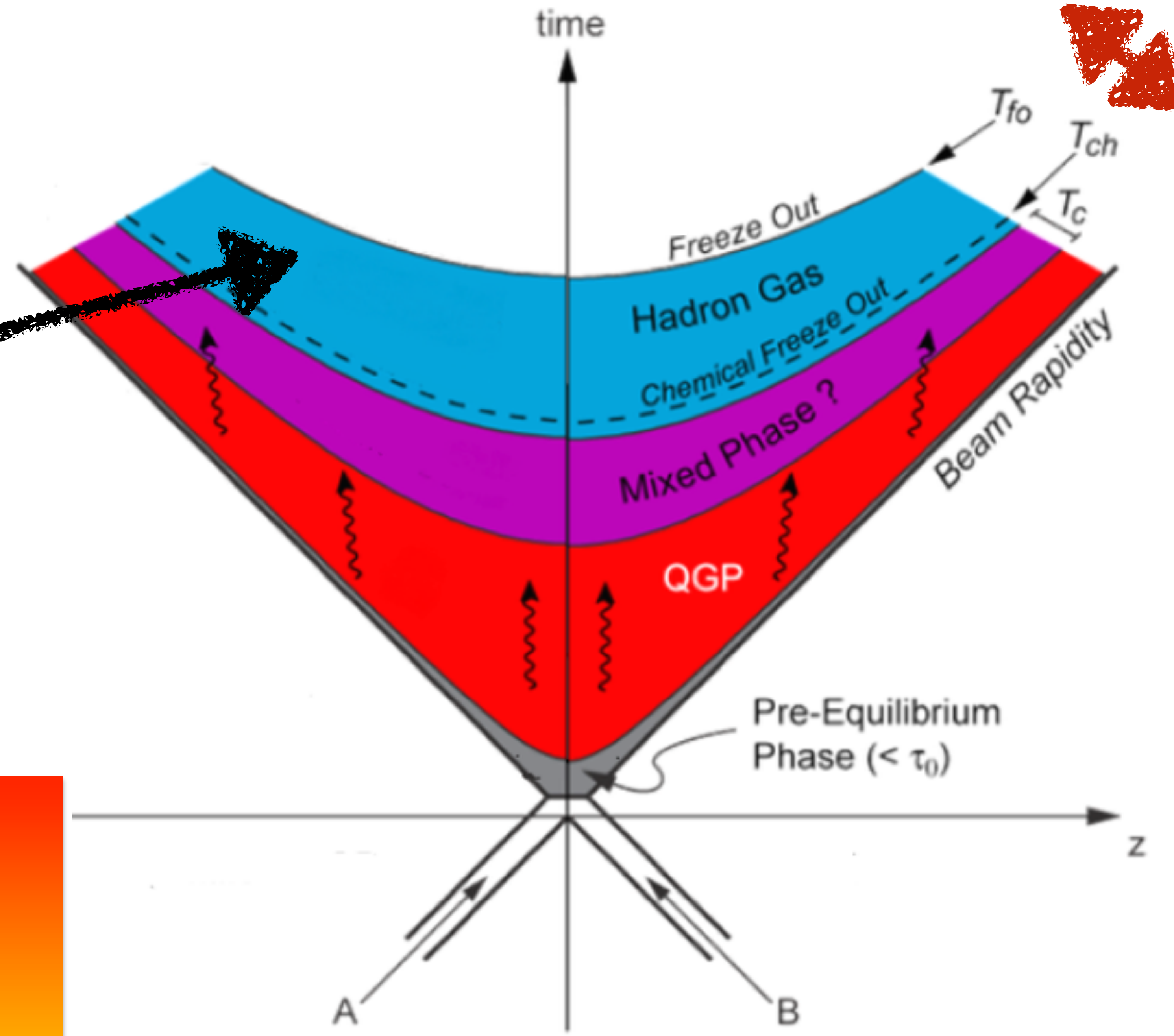
measured yields of resonances might be modified by hadronic processed

hadronic phase

elastic rescattering of decay daughters

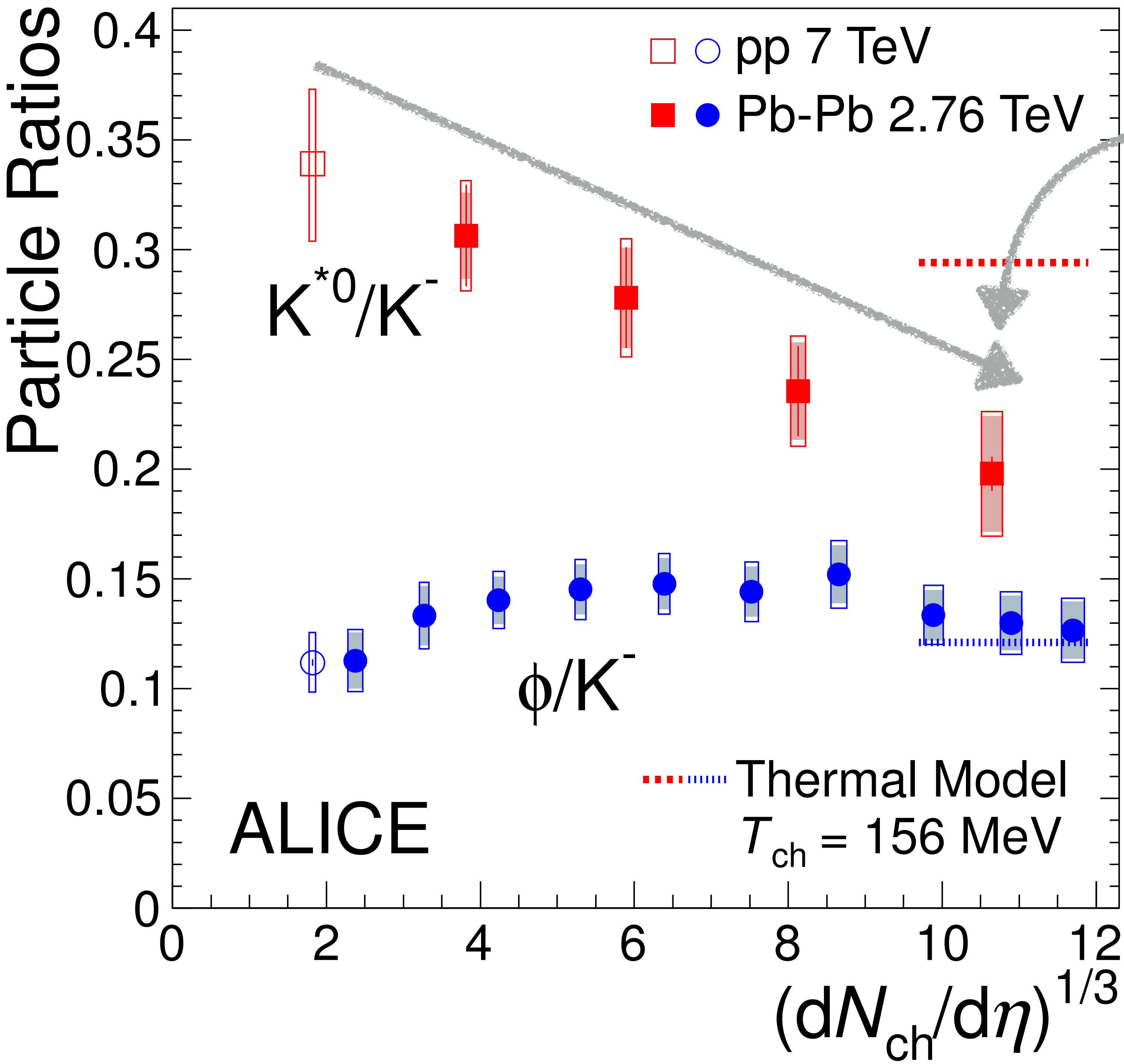
resonances not reconstructed via invariant mass





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

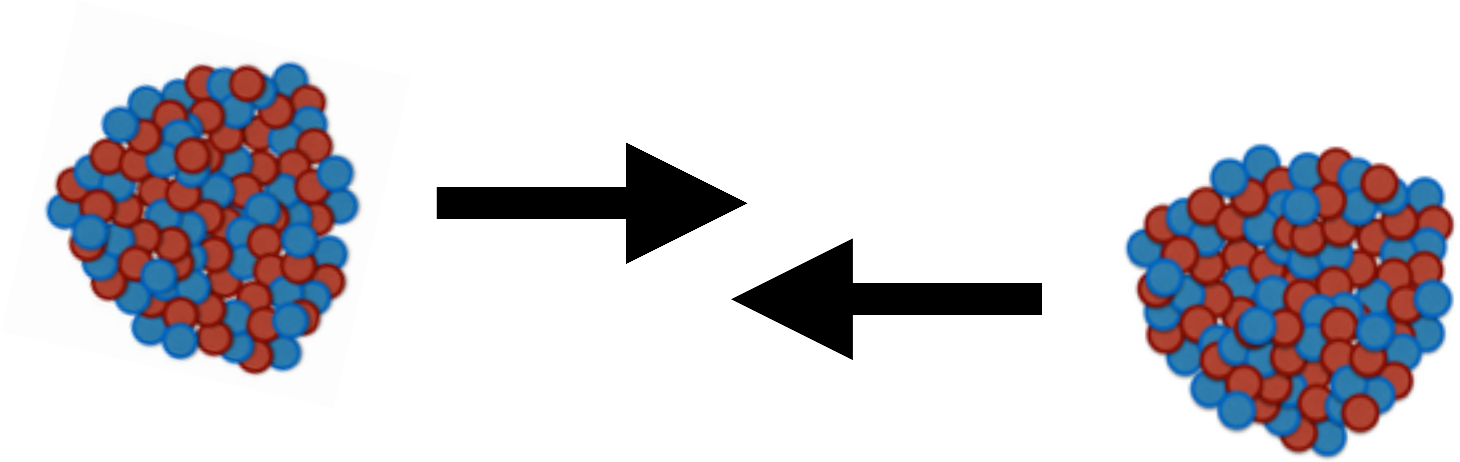
most favoured explanation **re-scattering** of the decay daughters **with final-state** hadronic medium

τ_{K^*} (~4 fm/c) ≪ τ_ϕ

ALICE, arXiv:1404.0495 [nucl-ex]

Particle production in proton-nucleus collisions

Hot / cold nuclear matter



initial: nuclear
final: **hot**

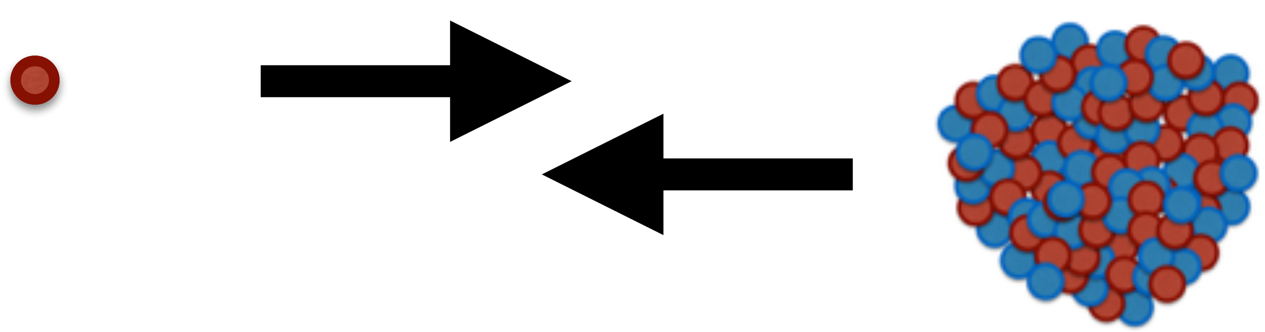
initial-state nuclear effects are present in A-A

Cronin enhancement, nuclear shadowing, parton saturation, …

but difficult to distinguish experimentally from final-state ones

a full understanding of hot QCD matter effects requires

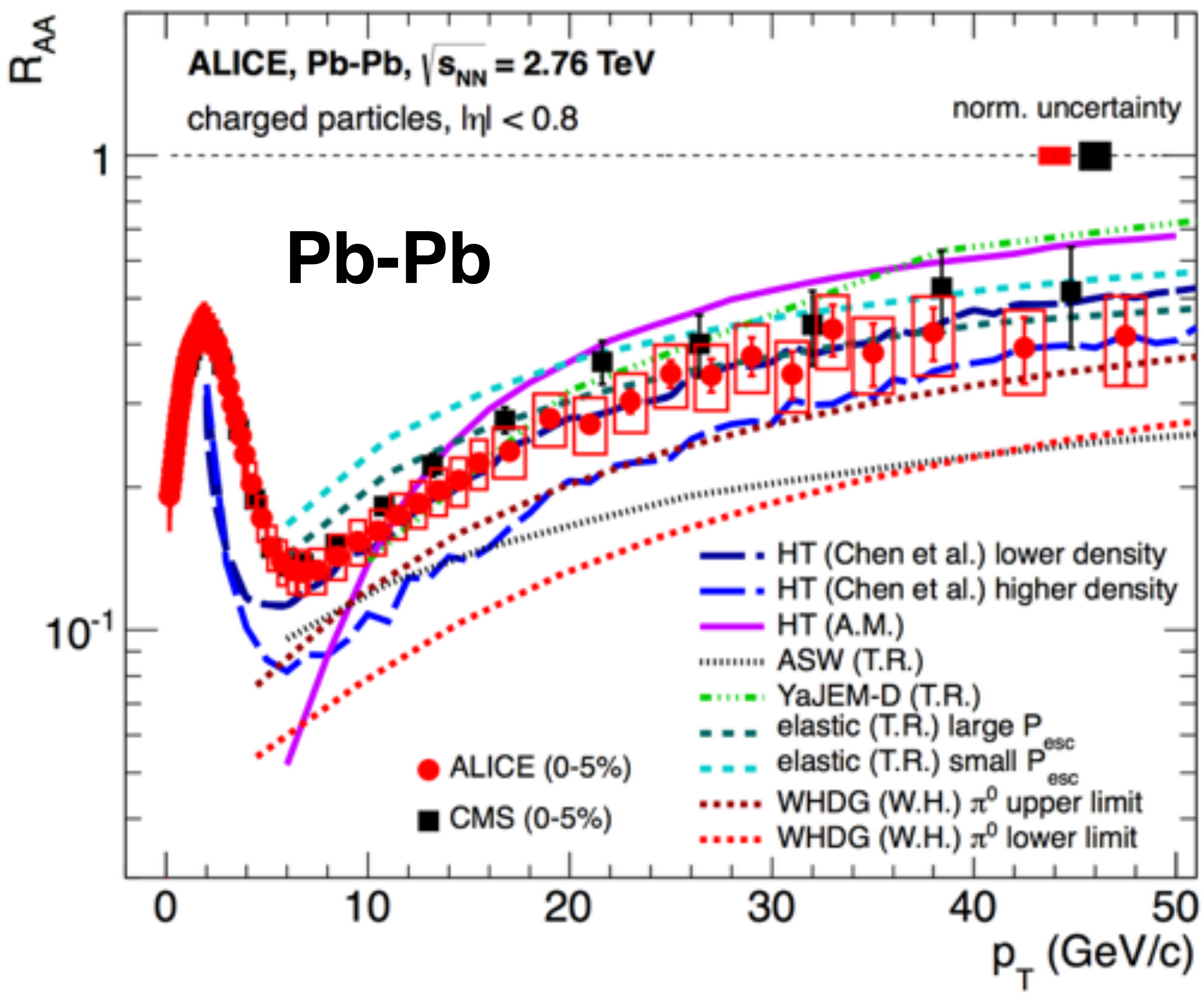
measurements of cold nuclear matter effects with p(d)-A



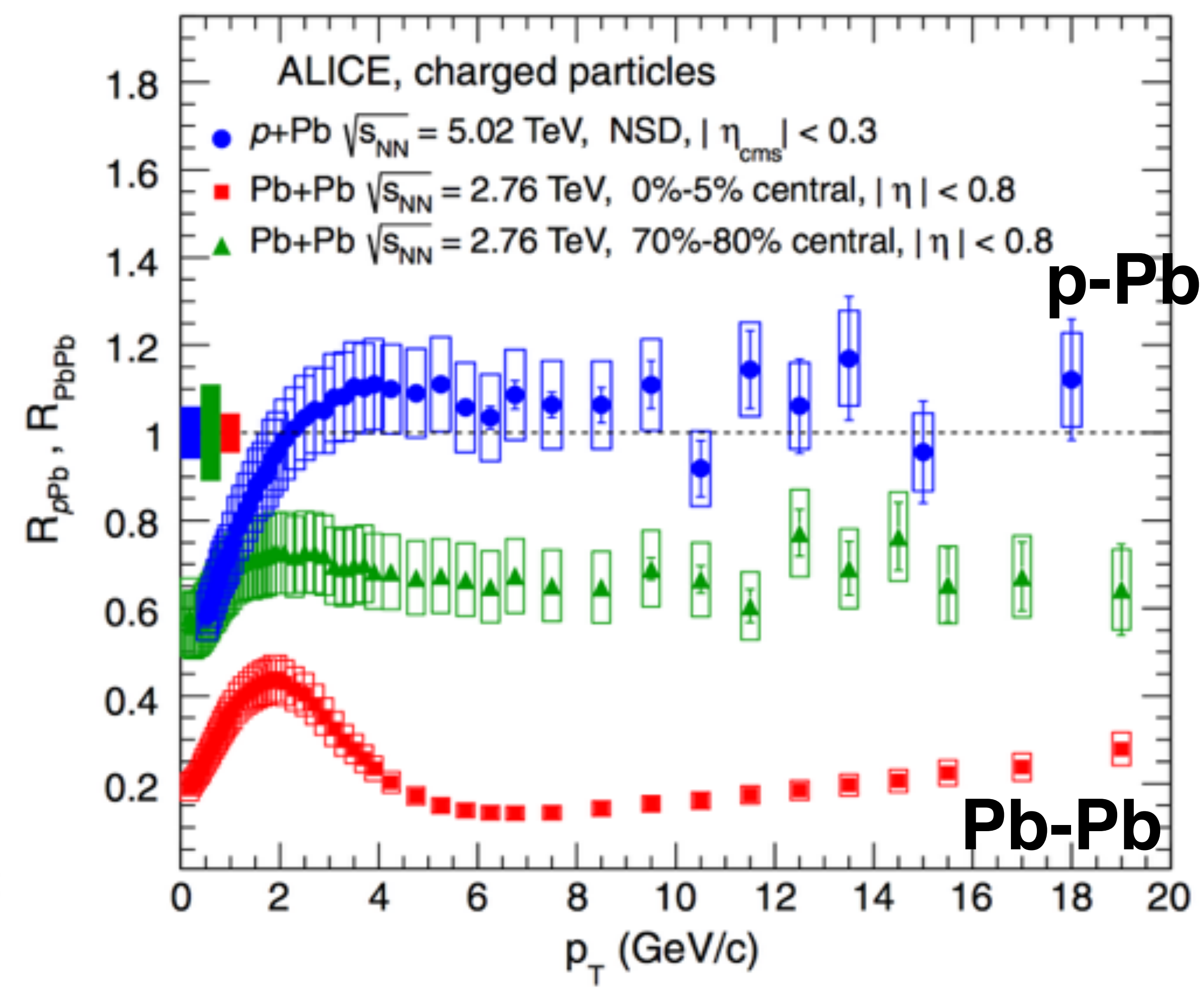
initial: nuclear
final: **cold (?)**

No nuclear modification in p-Pb

ALICE, PLB 720 (2013) 52



ALICE, PRL 110 (2013) 082302



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

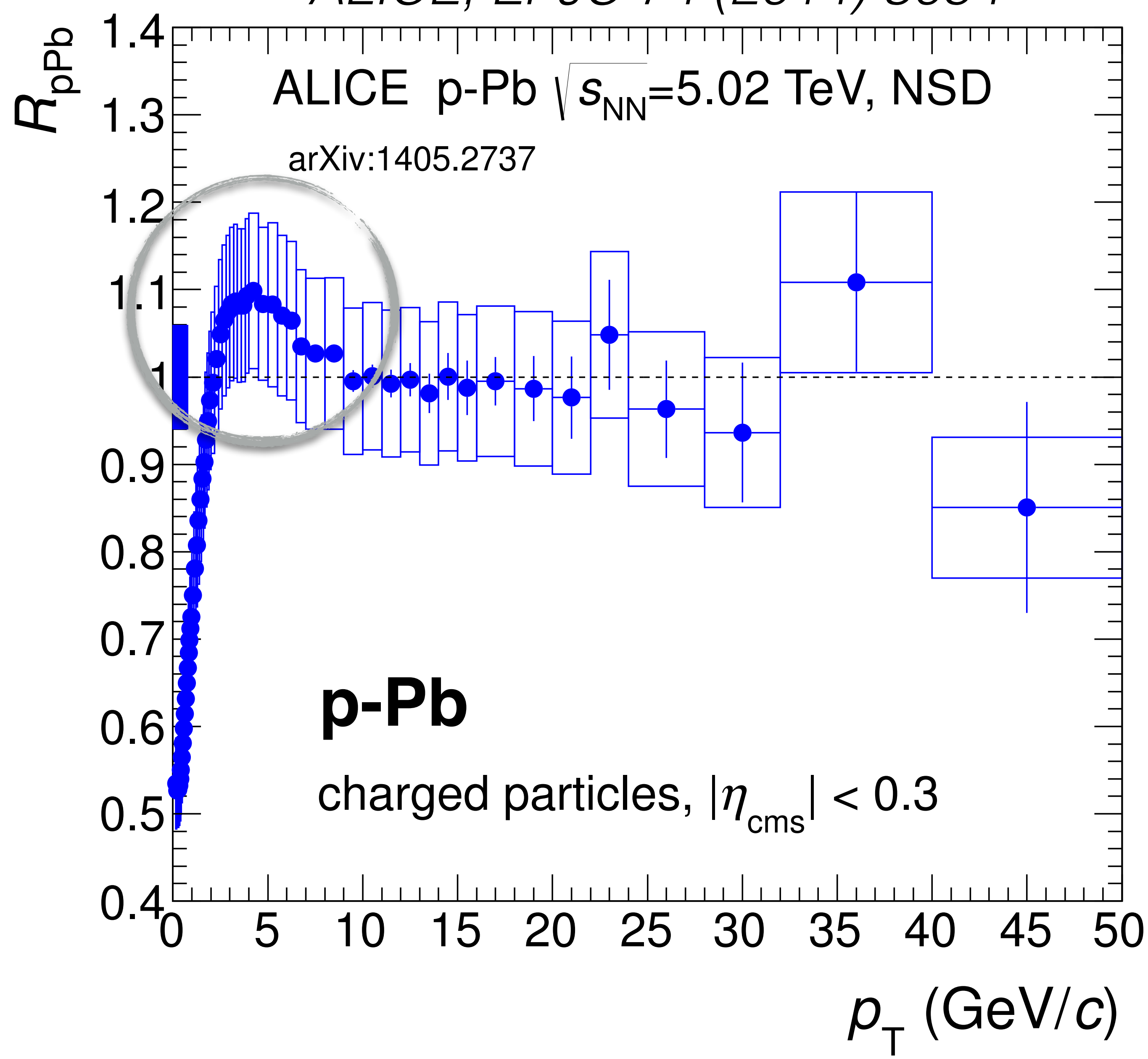
p-Pb confirms that it comes from a **final-state effect** parton in-medium energy loss

R_{pPb} at intermediate p_T

the data indicate a small
enhancement at mid-p_T
where a 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

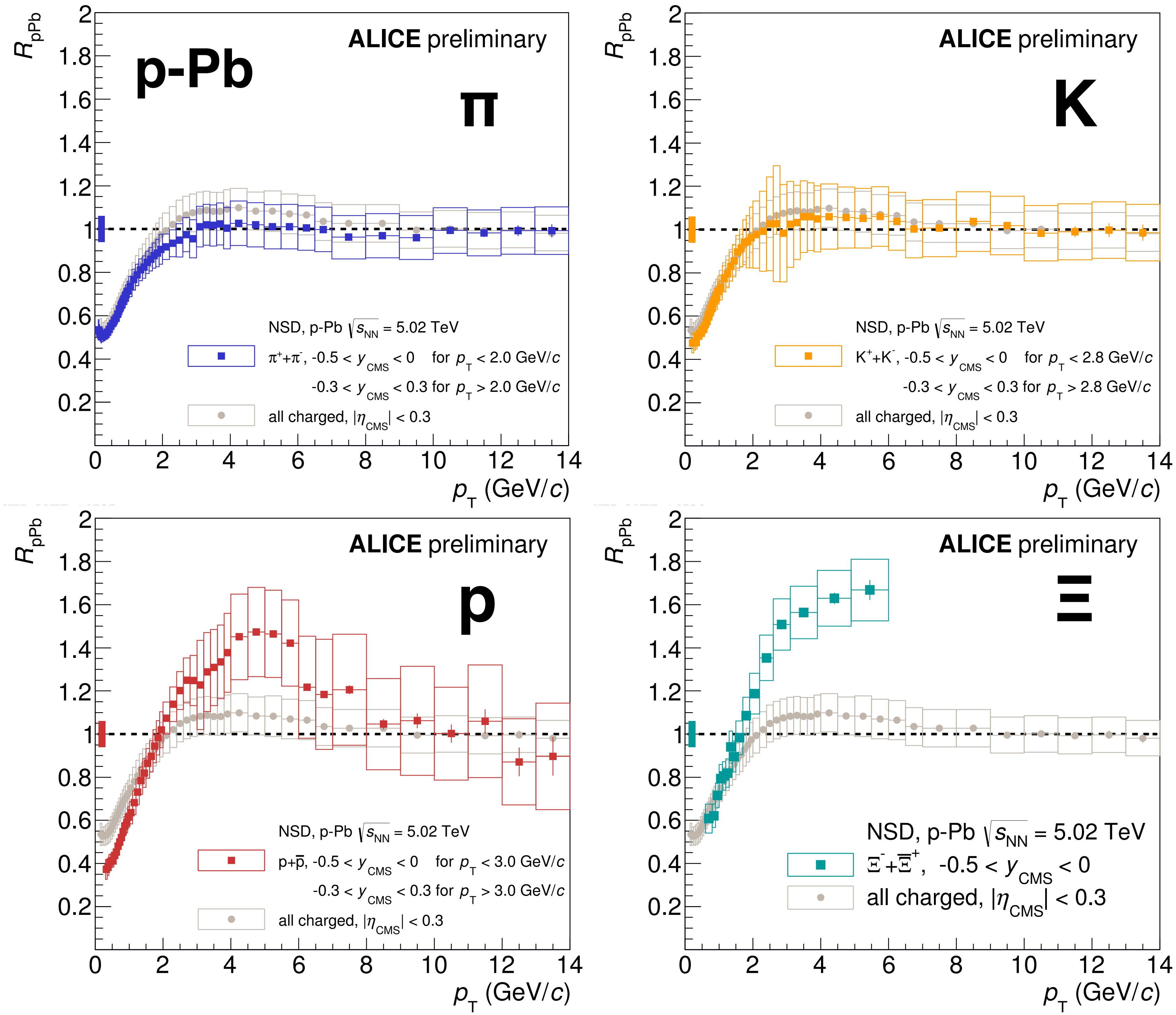


Identified particle R_{pPb}

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

rather pronounced peak for **protons**

even stronger enhancement for **cascades**



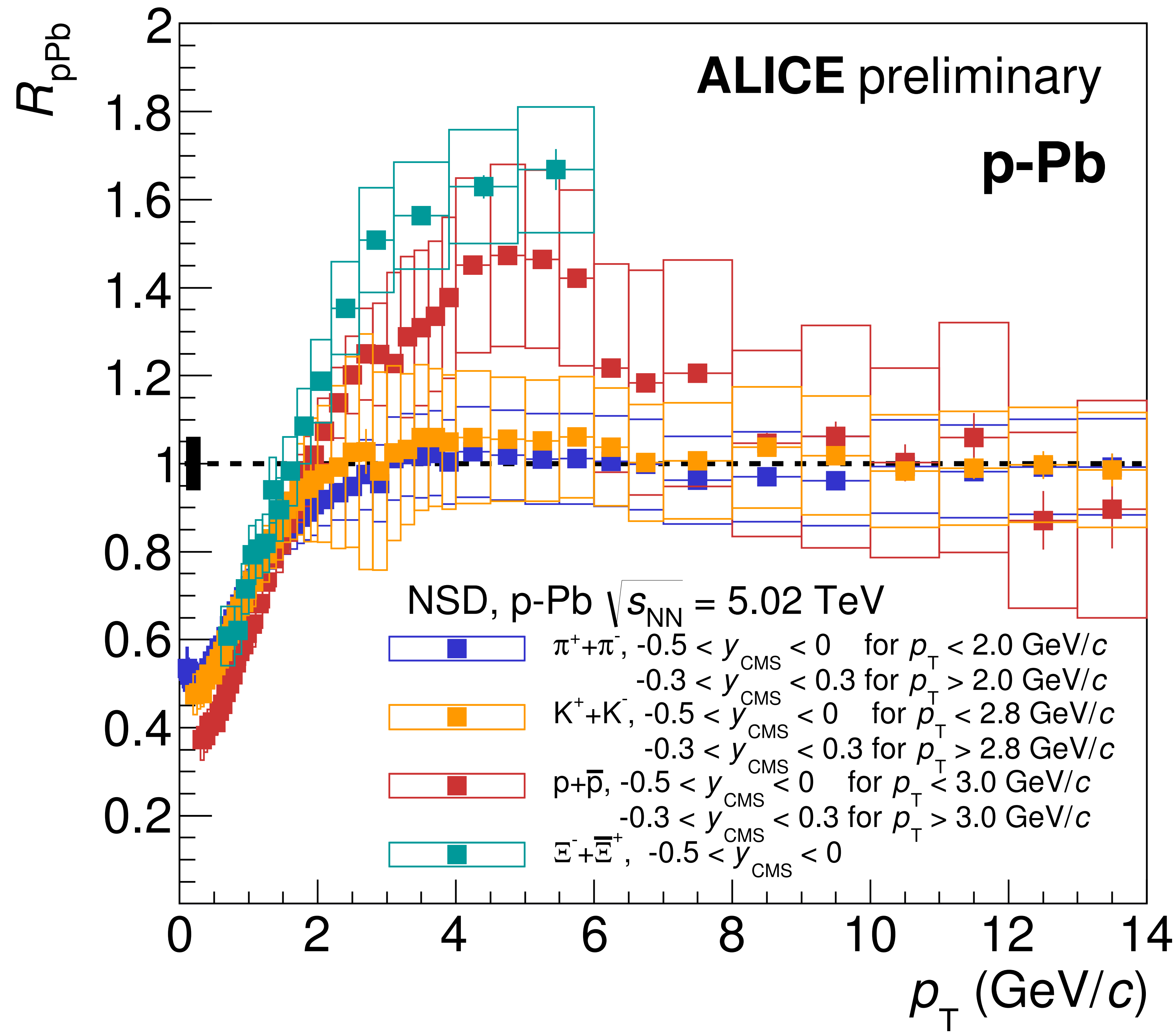
indication of **mass ordering** in the Cronin peak

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**

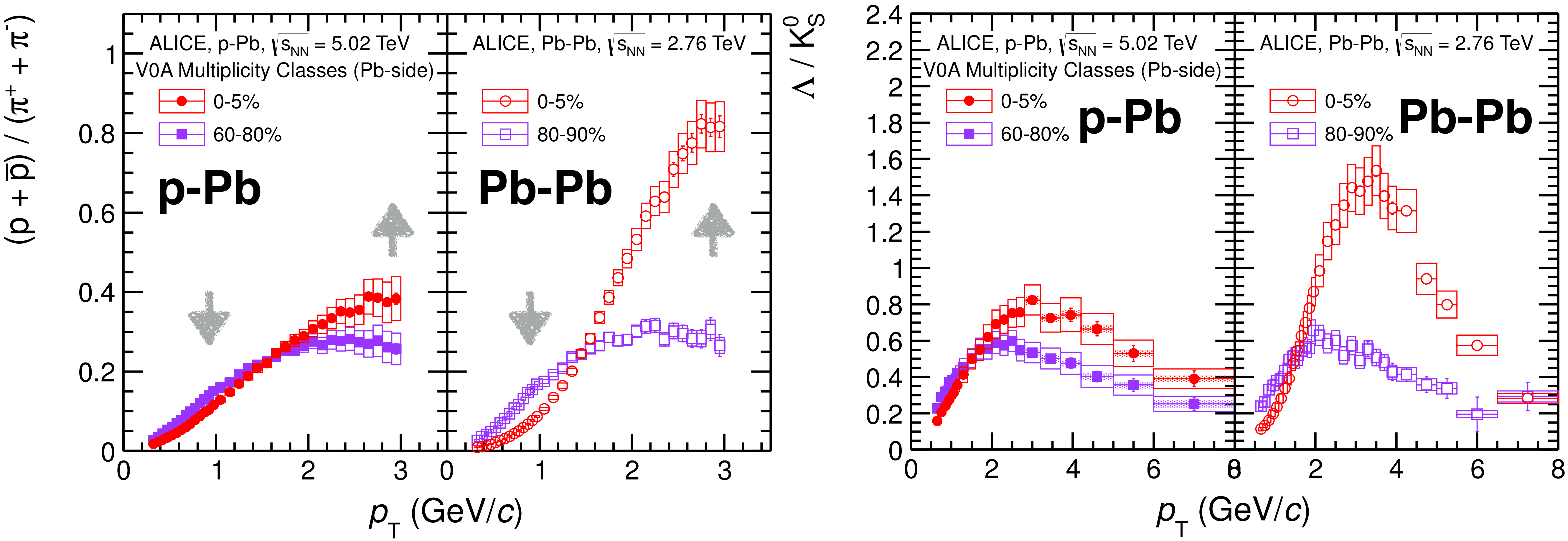


particle species dependence suggests final state effects

recombination, collective flow, …

Baryon enhancement

ALICE, PLB 728 (2014) 25



Significant centrality/multiplicity dependence of the ratios

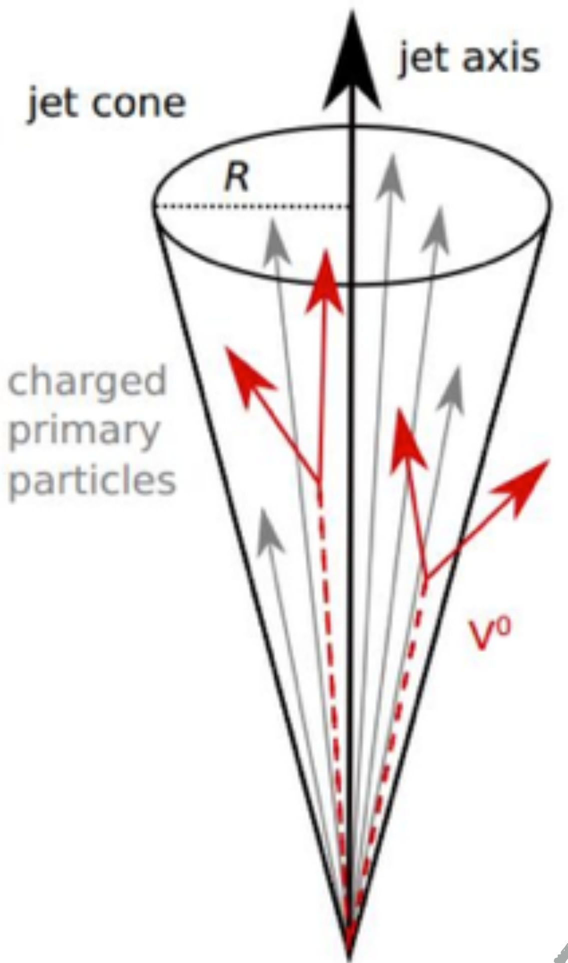
enhancement at mid-p_T with increasing multiplicity

corresponding depletion in the low-p_T region

Reminiscent of A-A observations

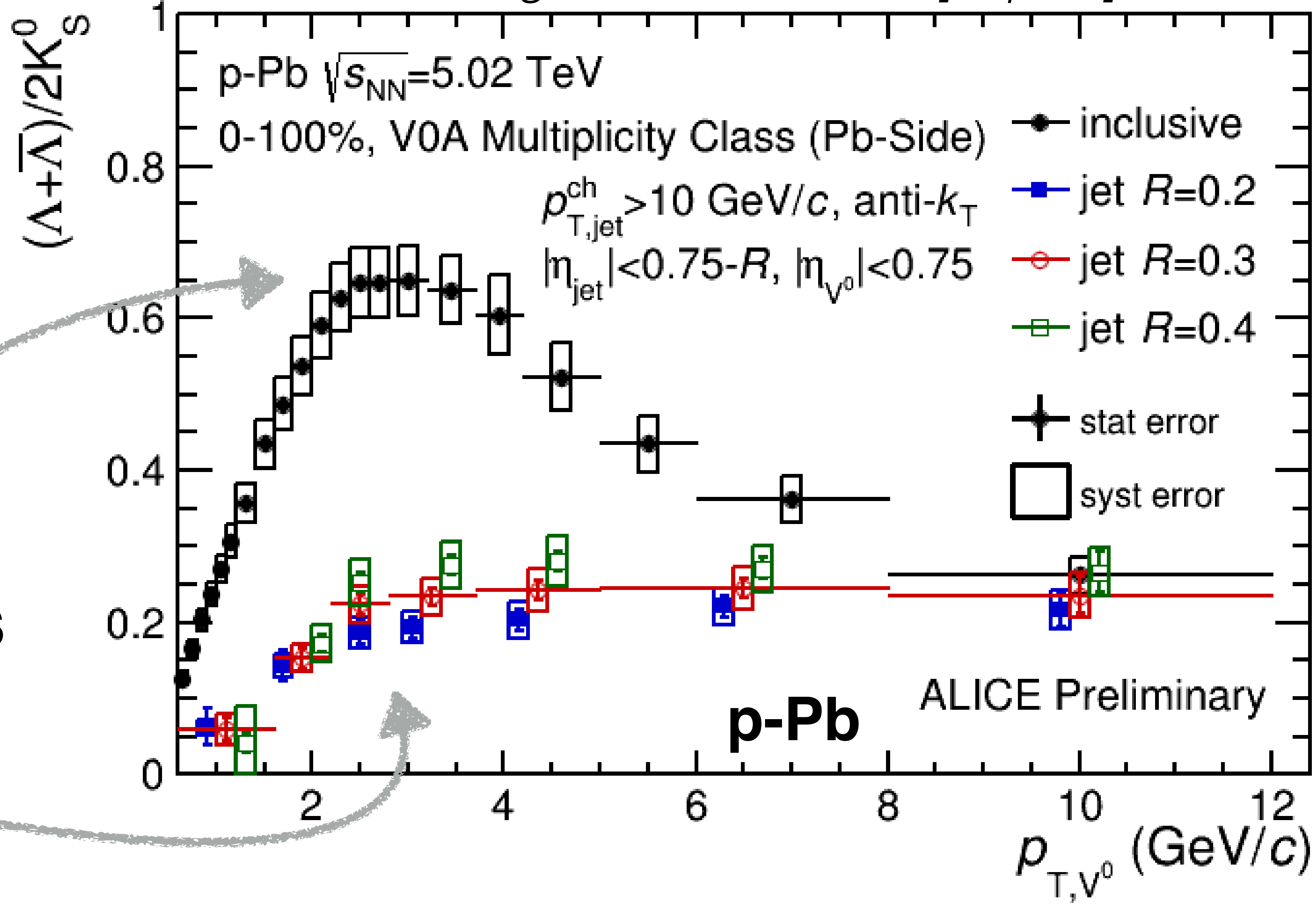
commonly understood in terms of collective flow / quark recombination

Where are the extra baryons from?



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

Zhang, arXiv:1408.2672 [hep-ex]



inclusive particles

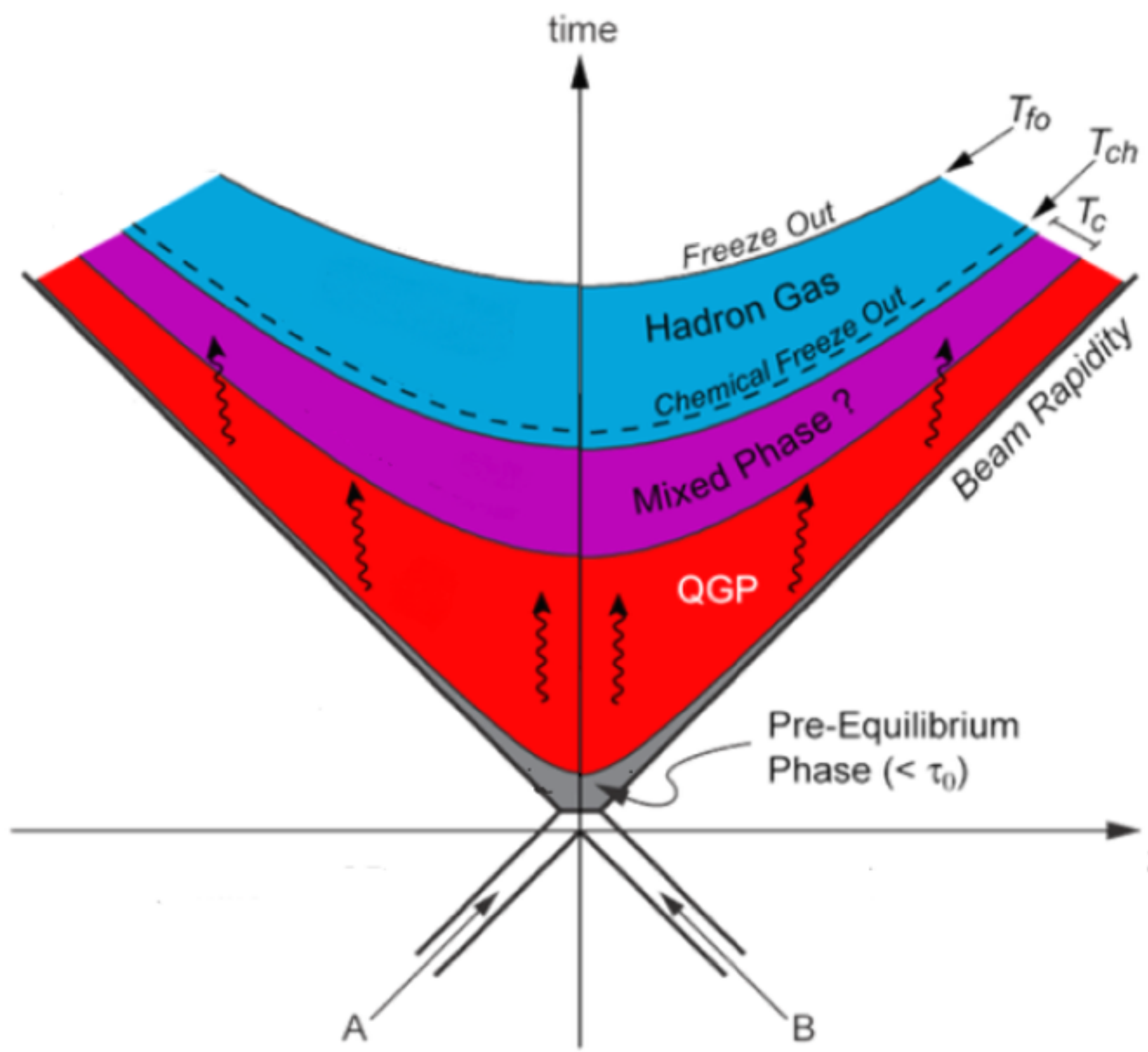
jets do not show enhancement

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



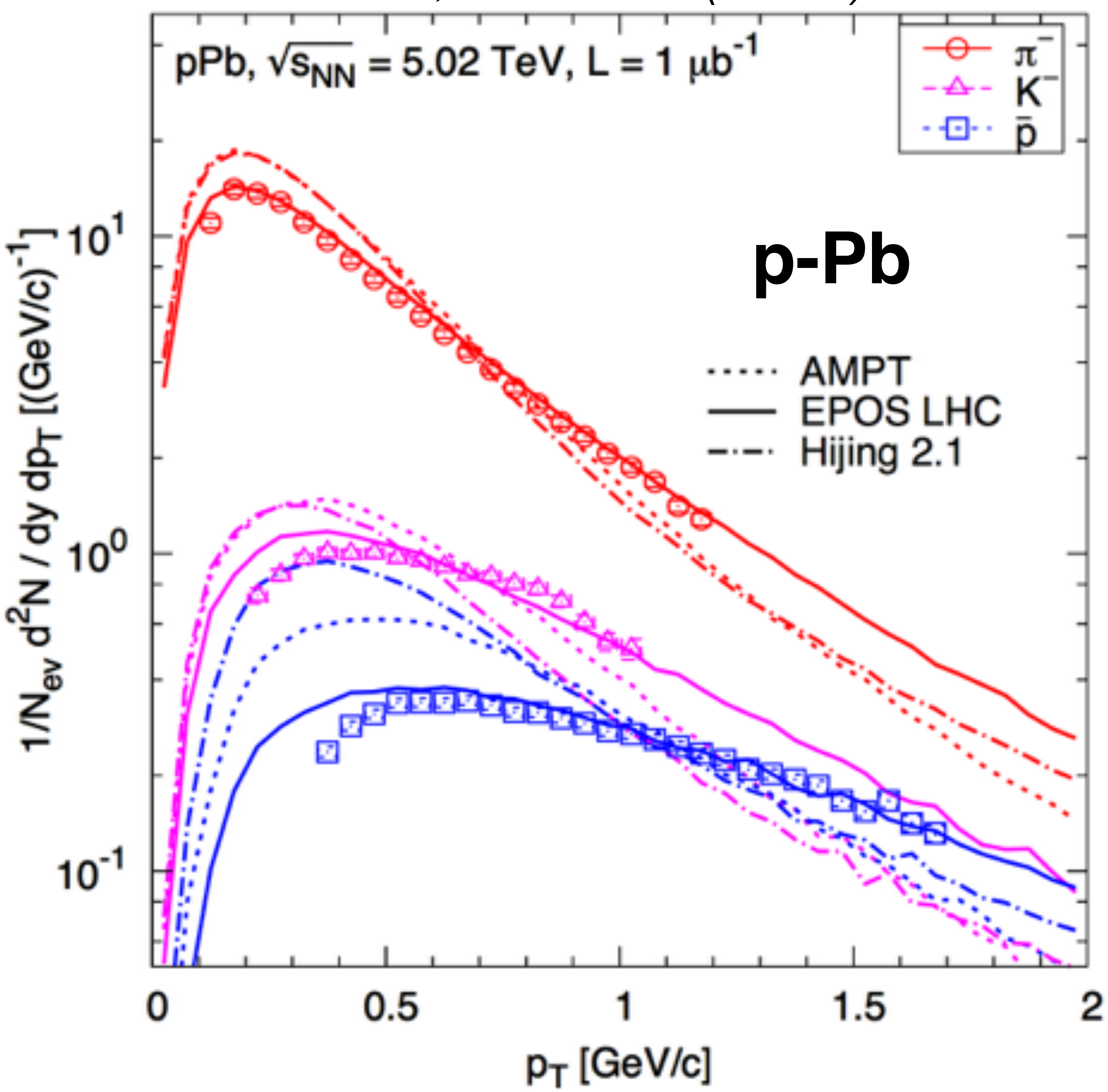
resulting in

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

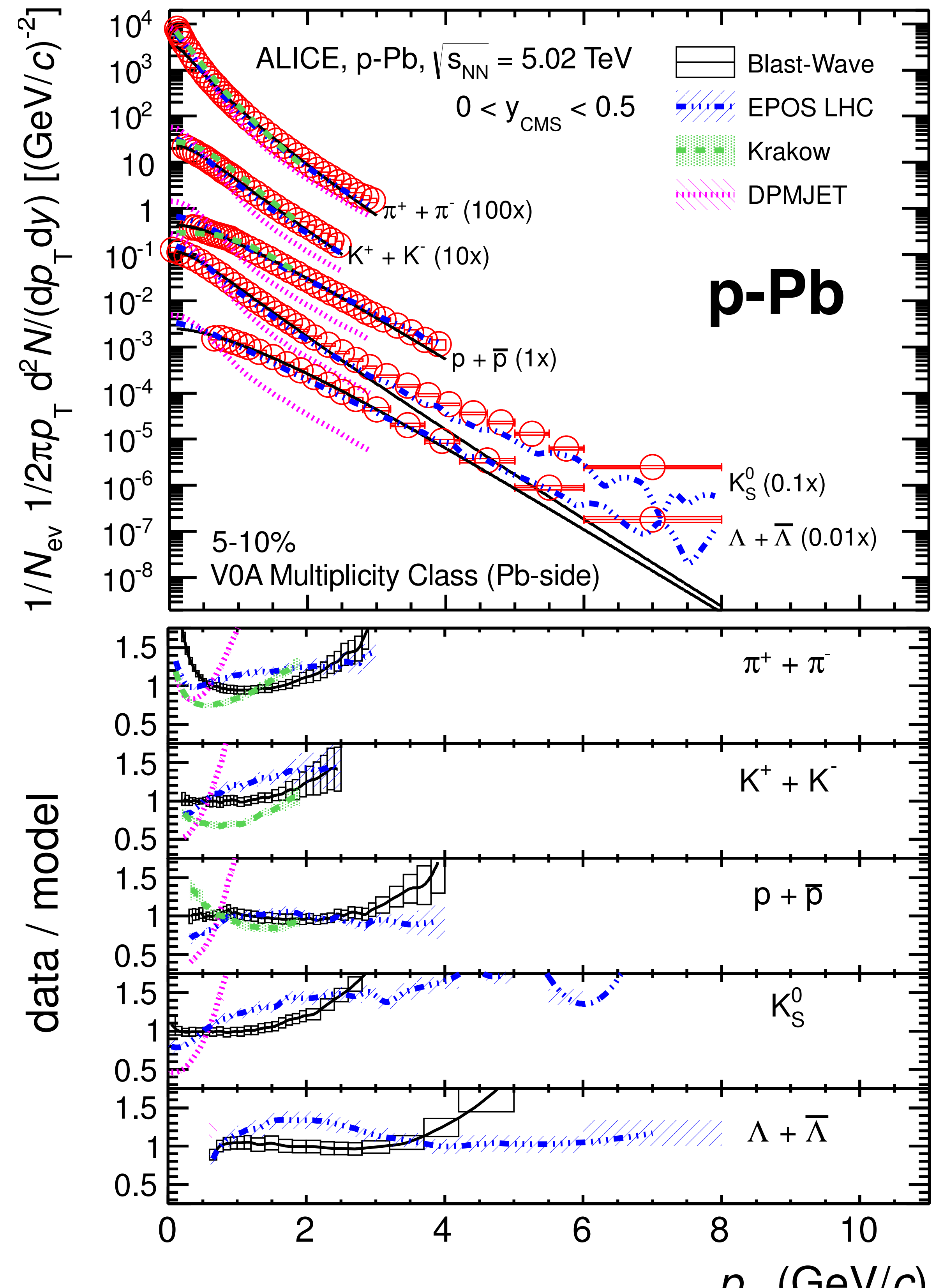
are there final state dense matter effects in p-Pb?

Identified hadron spectra

CMS, EPJC 74 (2014) 2847



ALICE, PLB 728 (2014) 25

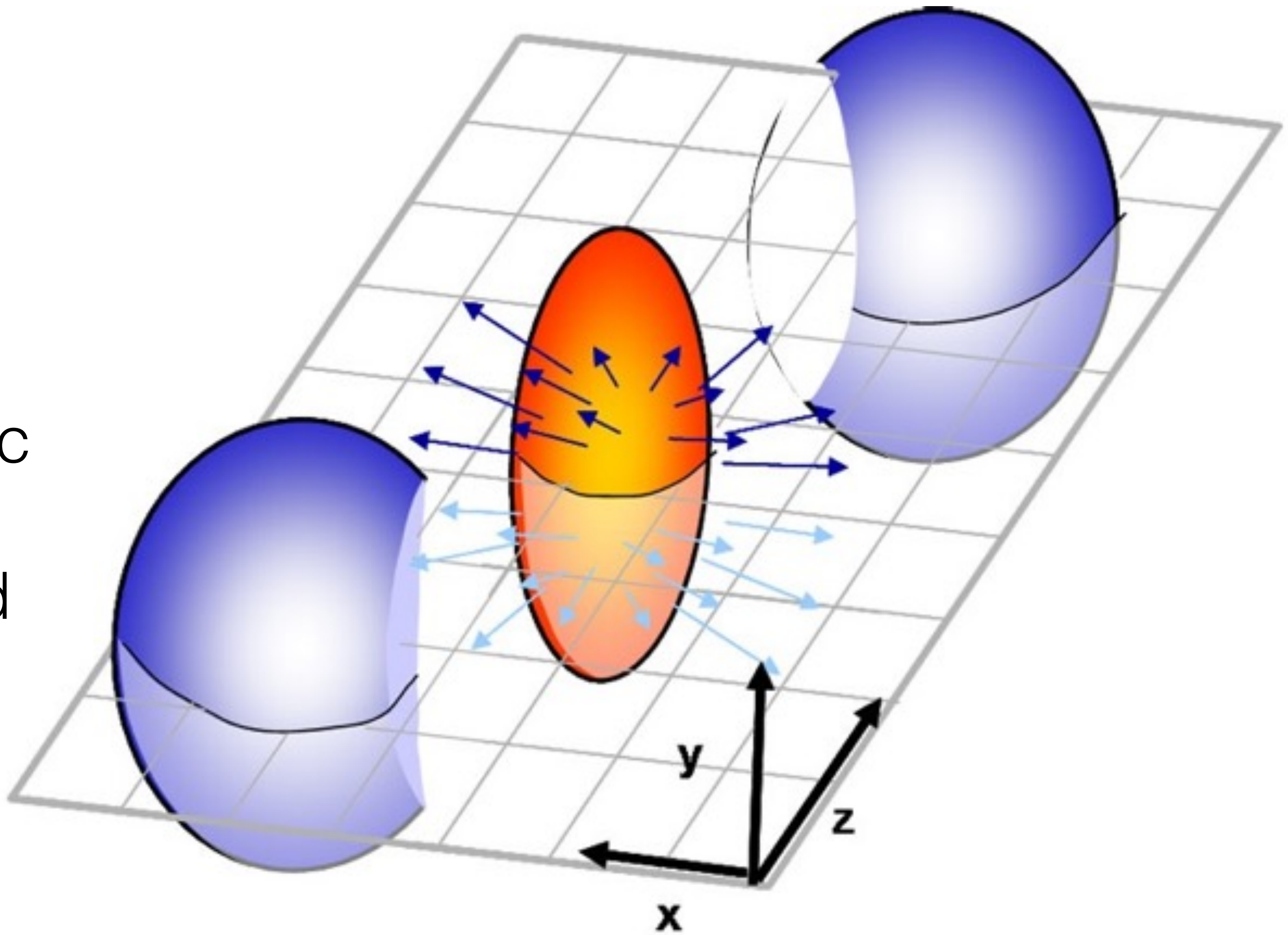


models including hydrodynamics do a better job describing the data

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



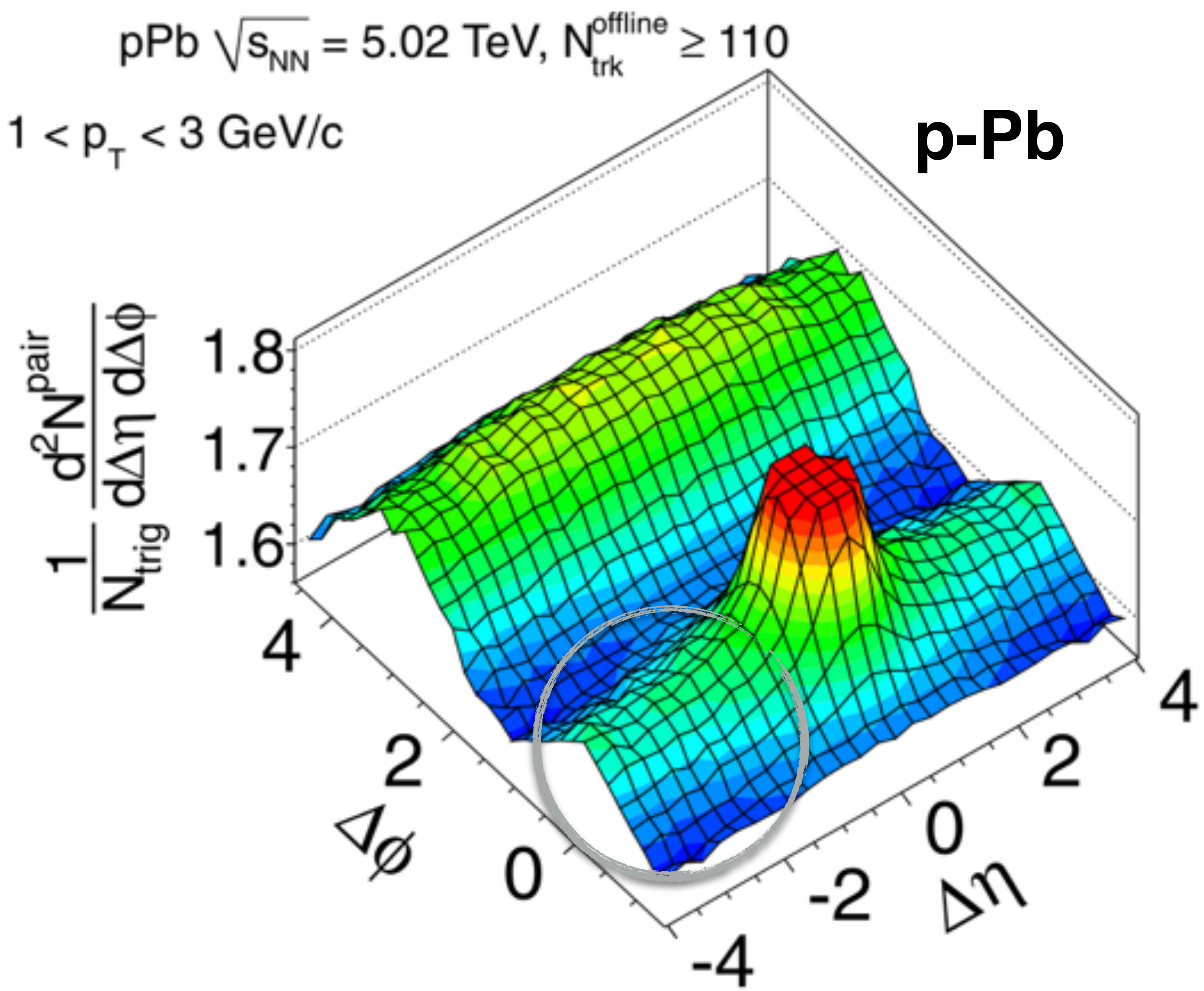
resulting in

- 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?

The ridge

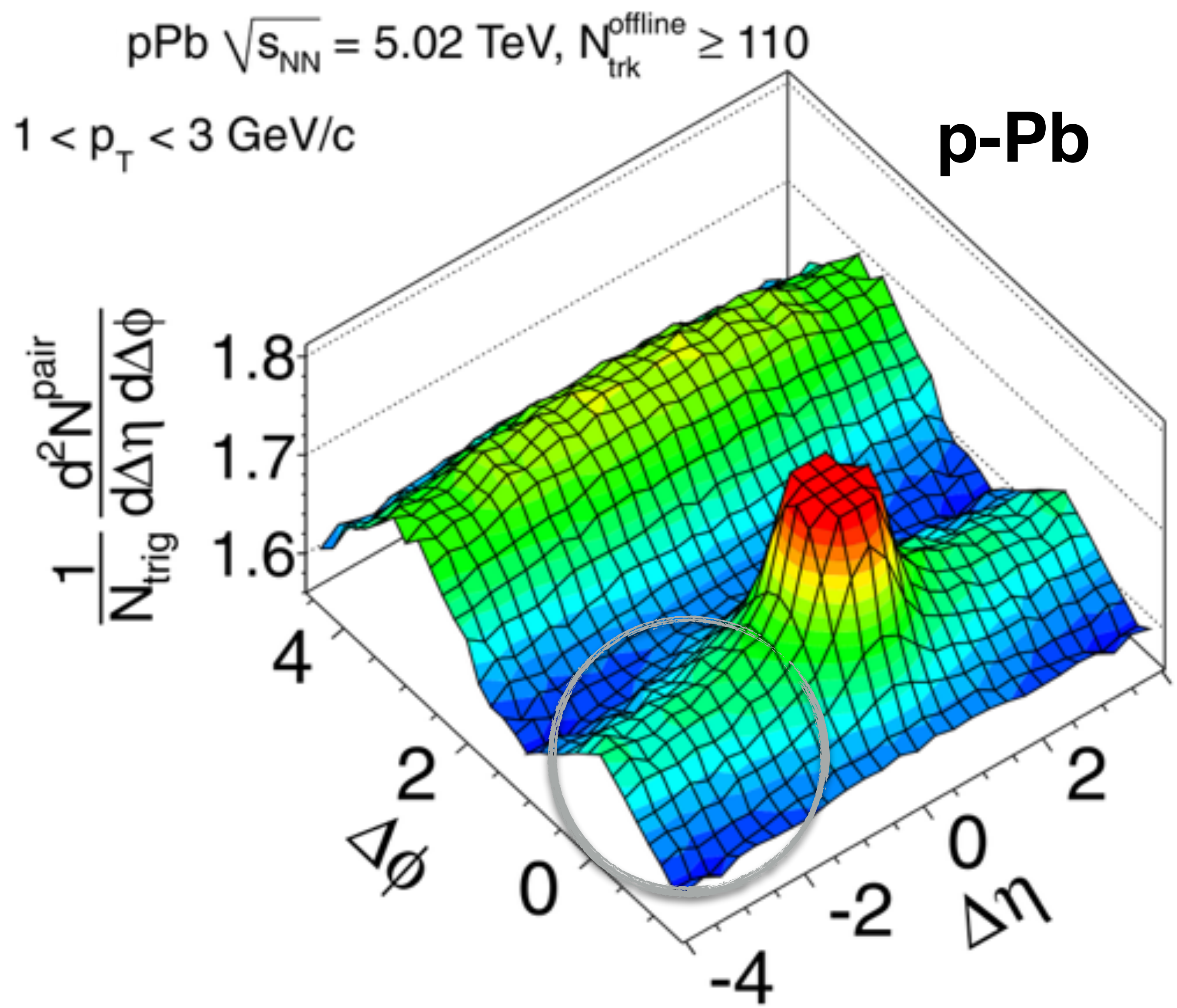
study of two-particle correlations led to the observation of **long-range** ($2 < |\Delta\eta| < 4$), **near-side** ($\Delta\phi \approx 0$) angular correlations in high-multiplicity p-Pb events



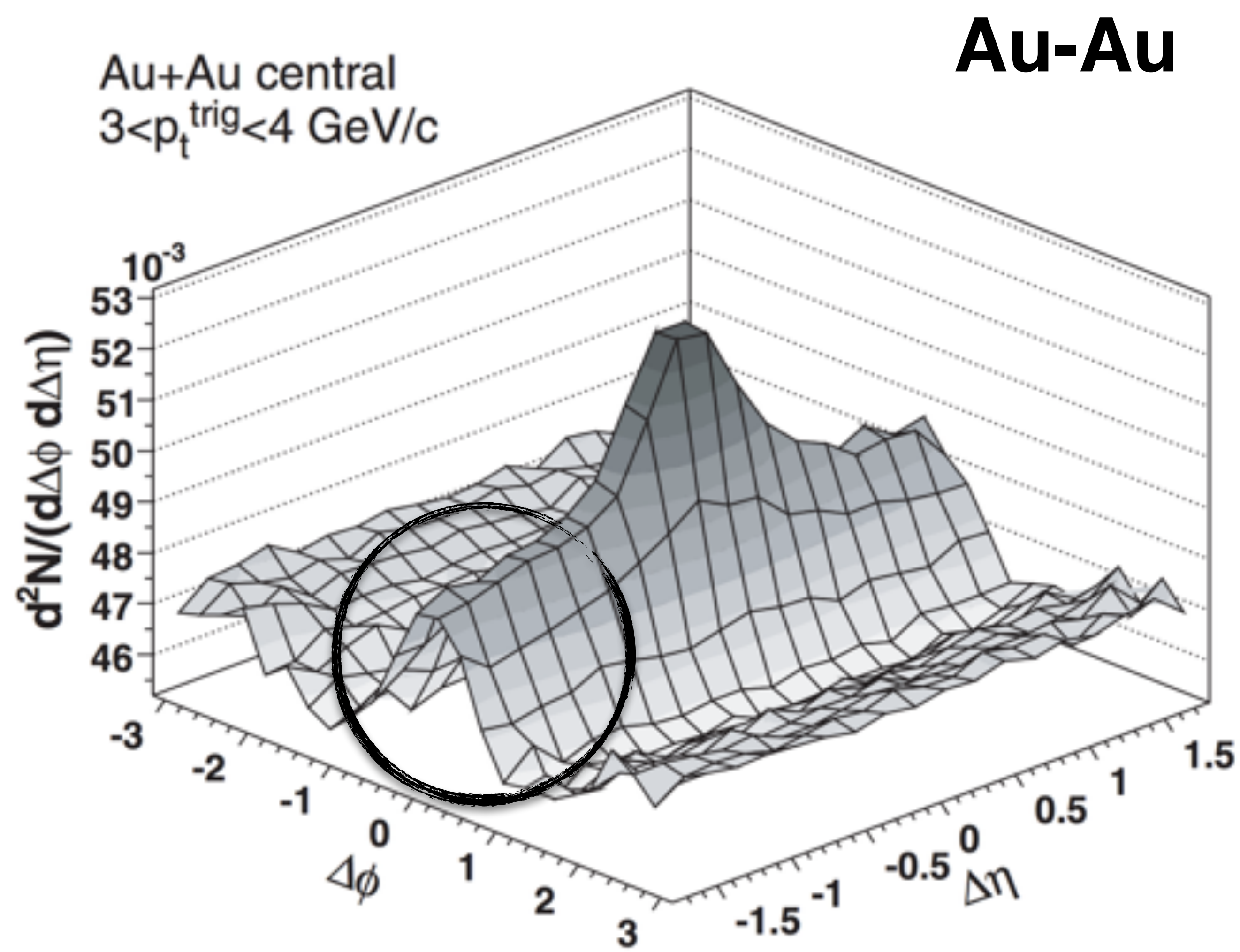
CMS, PLB 718 (2013) 795

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



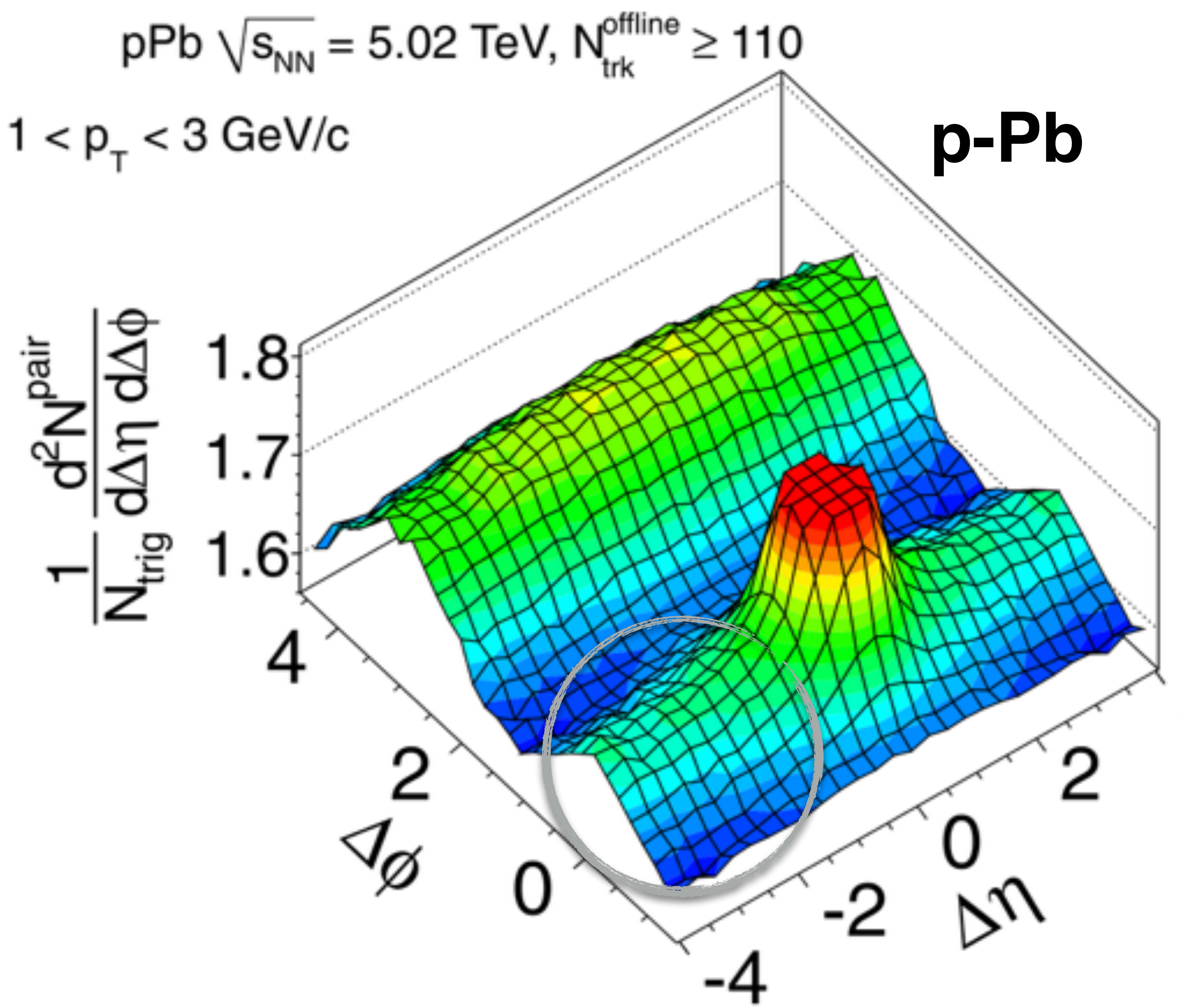
STAR, PRC 80 (2010) 064912

The ridge

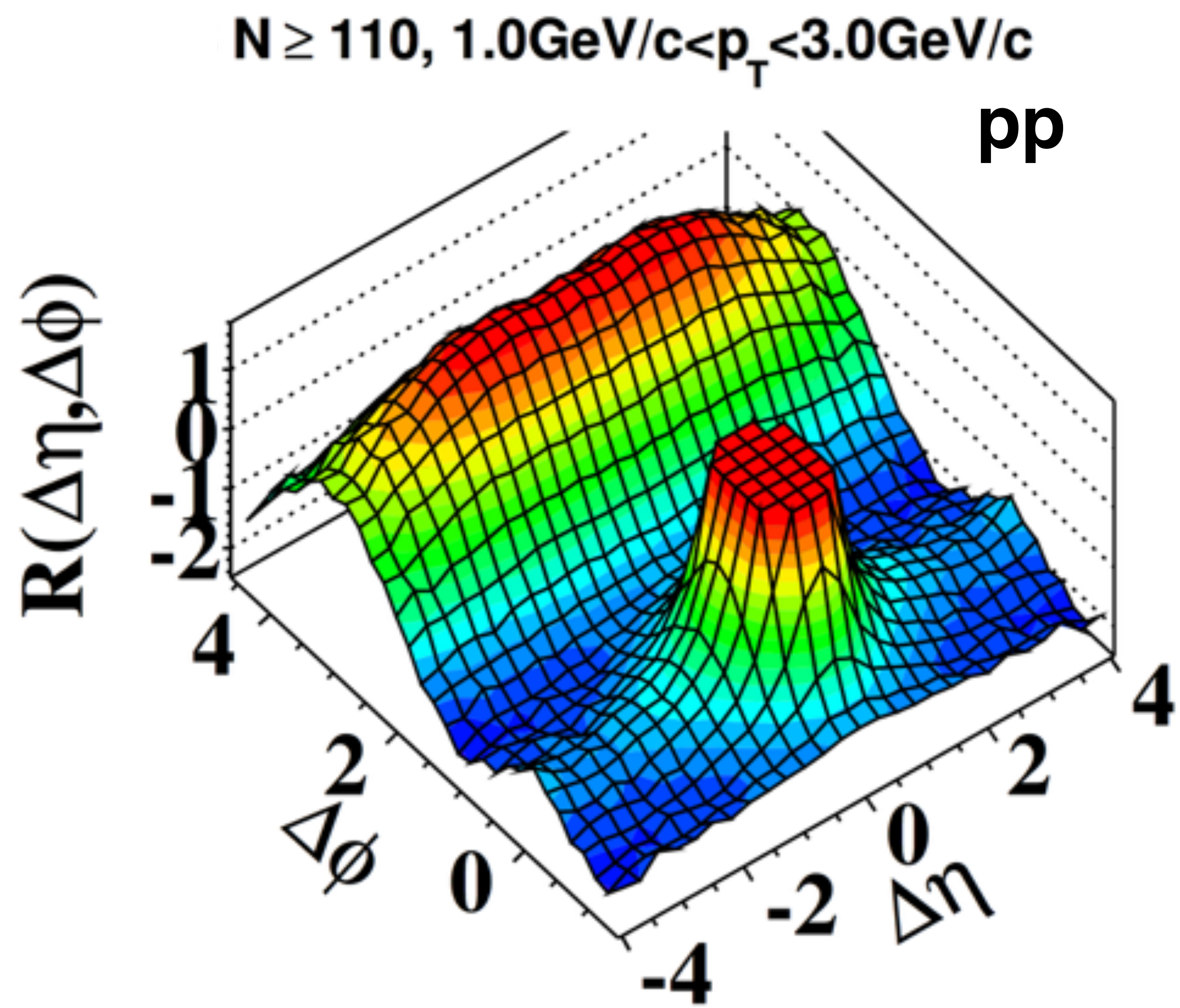
long-range (2 < |Δη| < 4), **near-side** (Δϕ ≈ 0)

was also observed in high-multiplicity proton-proton events

it was actually observed before in pp than in p-Pb



CMS, PLB 718 (2013) 795



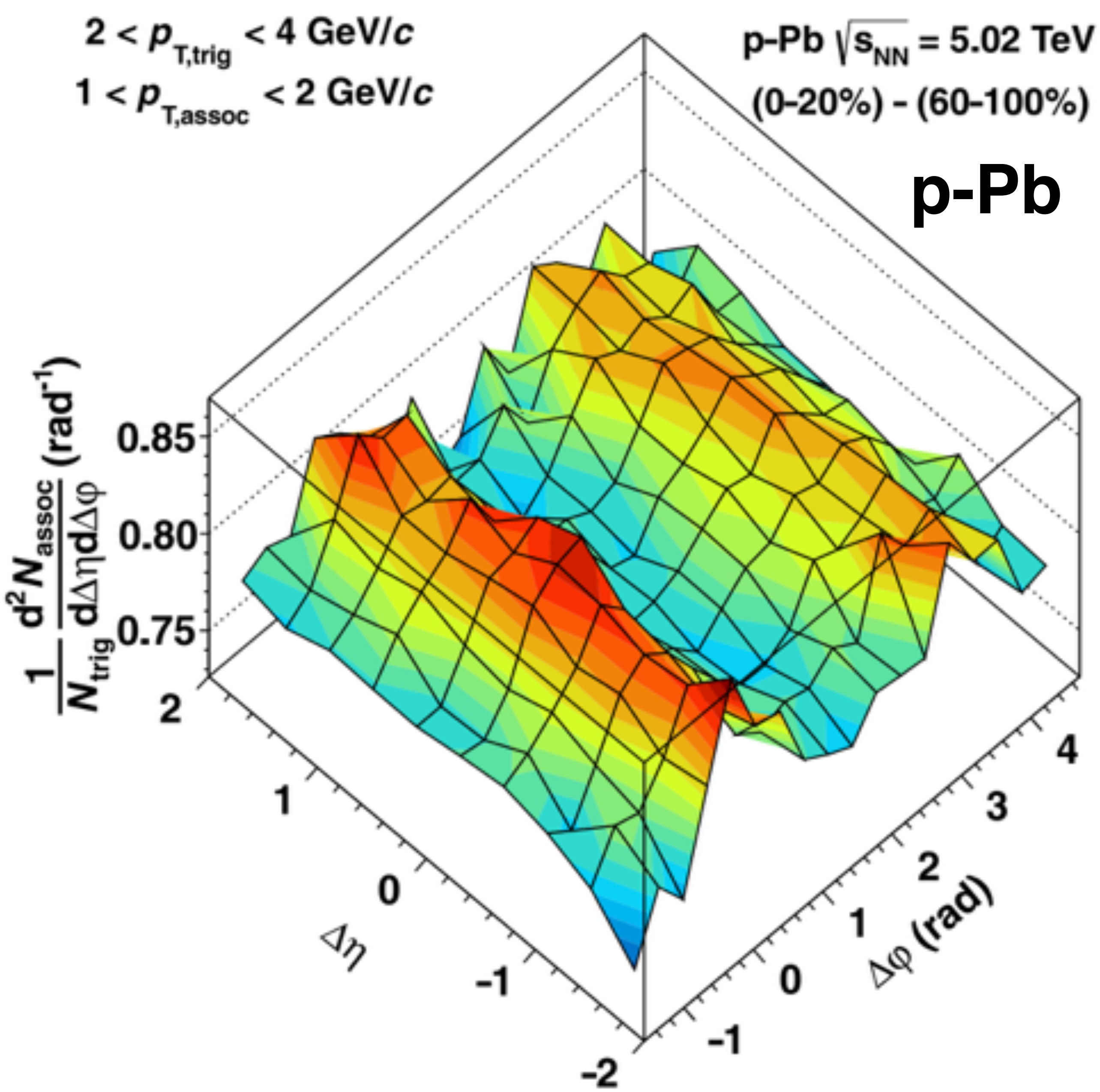
CMS, JHEP 09 (2010) 091

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**



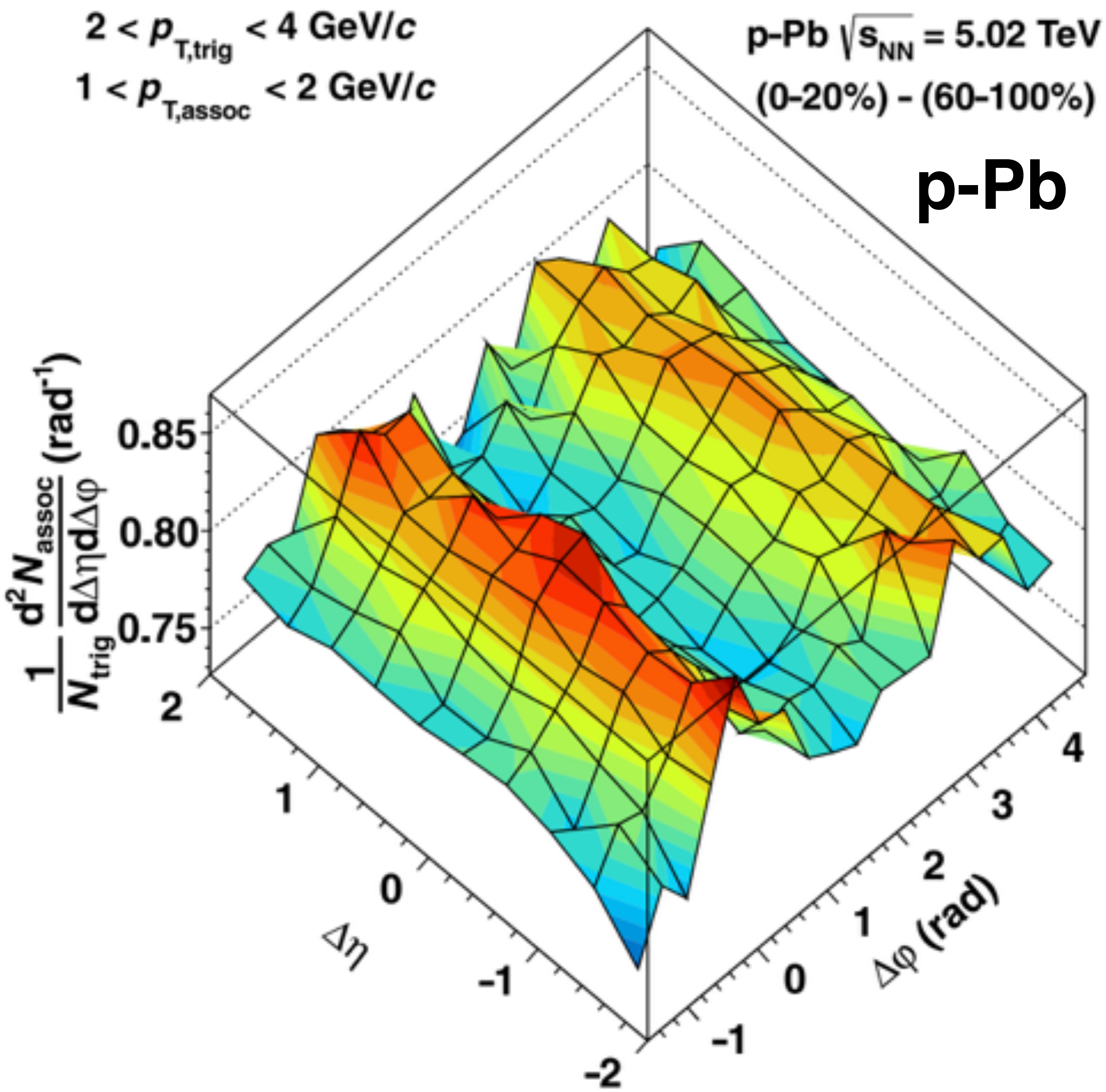
ALICE, PLB 719 (2013) 29

The double ridge

the ridge in p-Pb events triggered further investigations

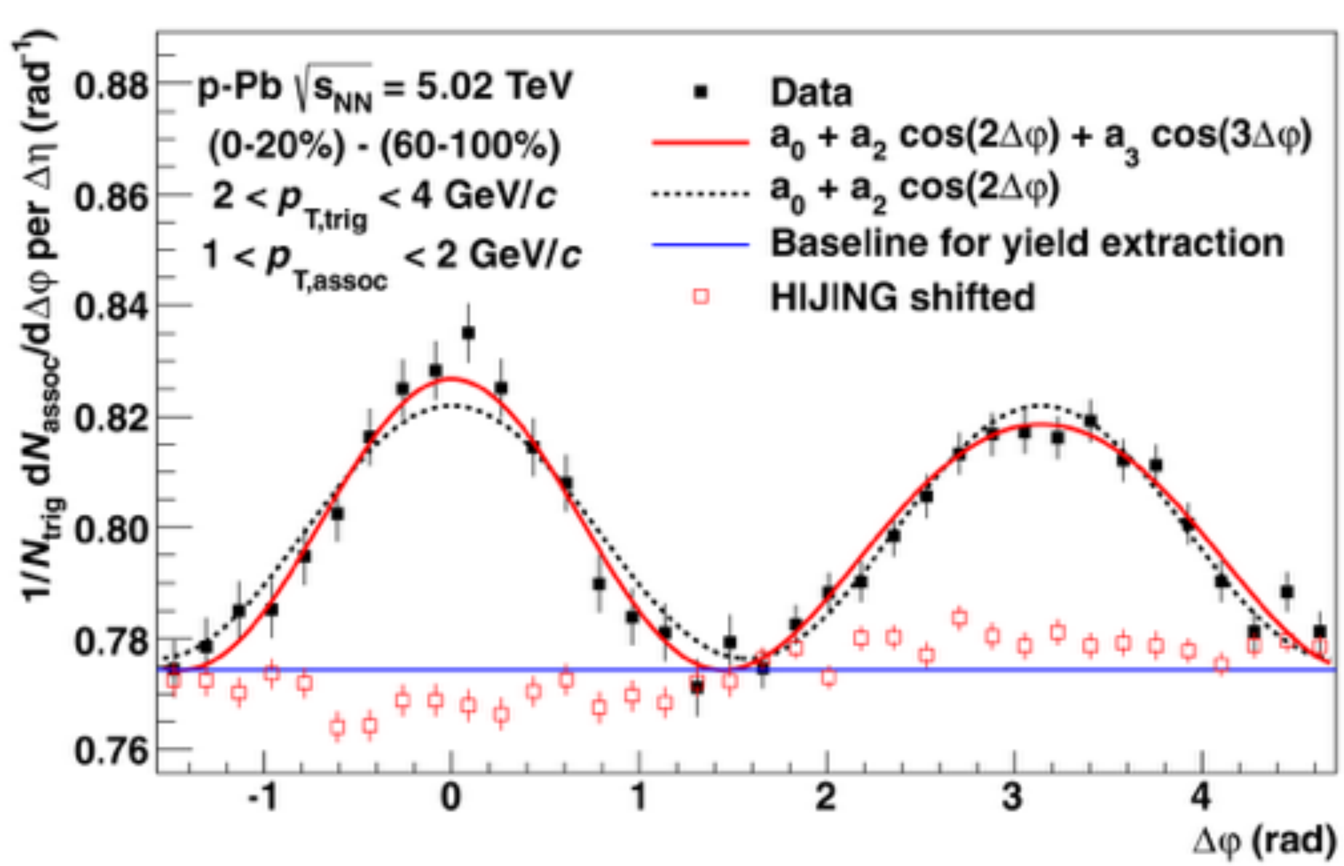
jet contribution removed by subtracting low-multiplicity events

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



this looks so much like flow

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



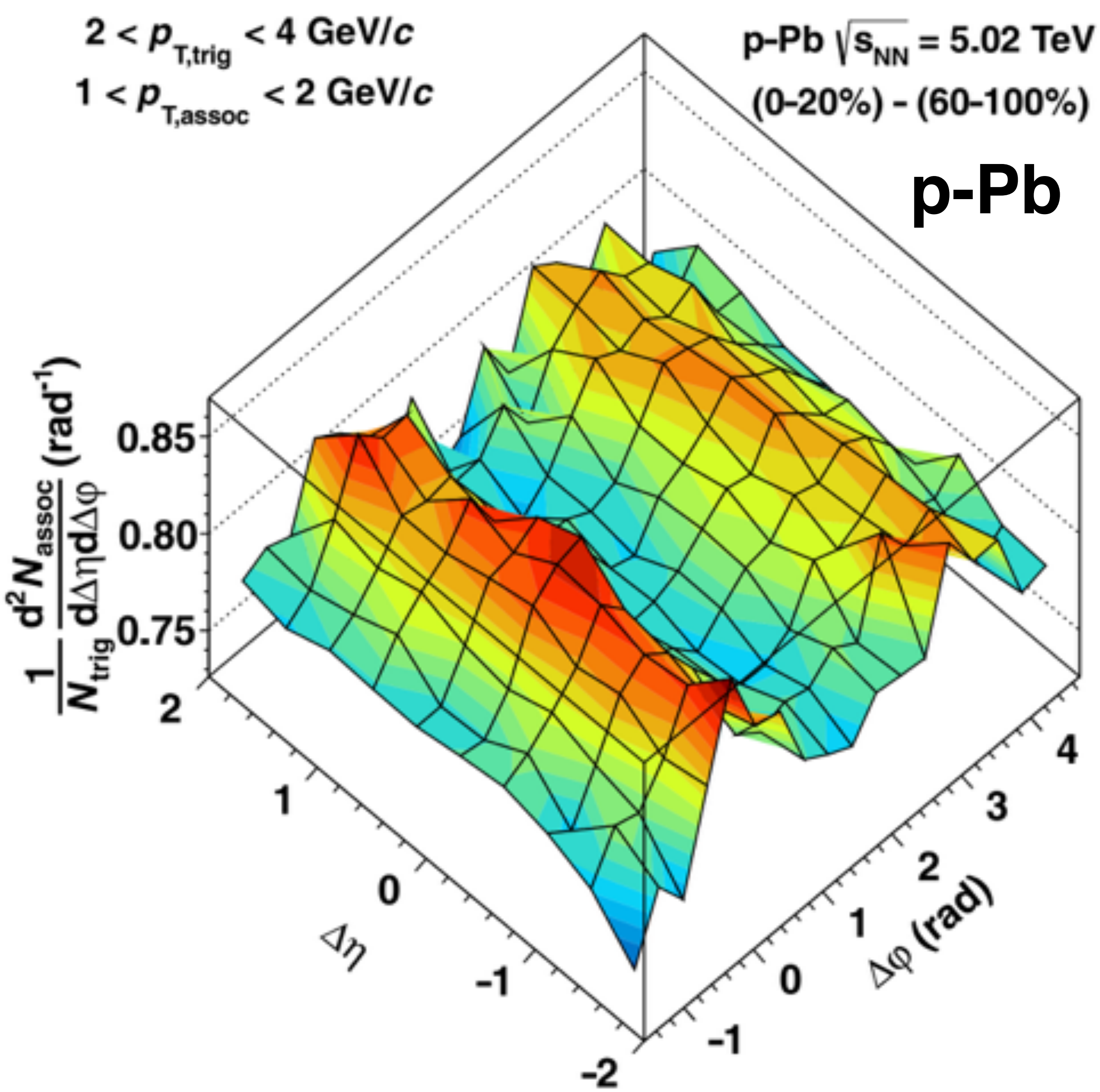
ALICE, PLB 719 (2013) 29

The double ridge

the ridge in p-Pb events triggered further investigations

jet contribution removed by subtracting low-multiplicity events

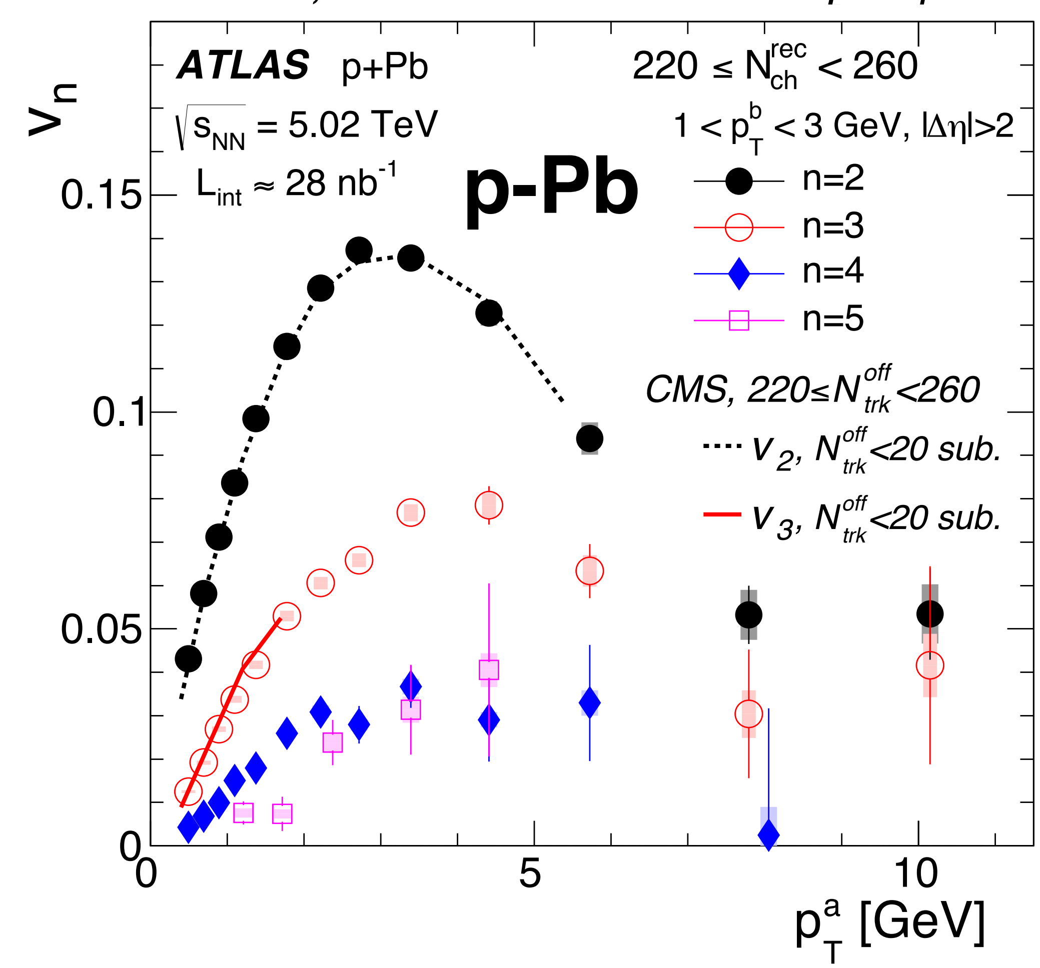
a **double ridge** structure **was revealed**



this looks so much like flow

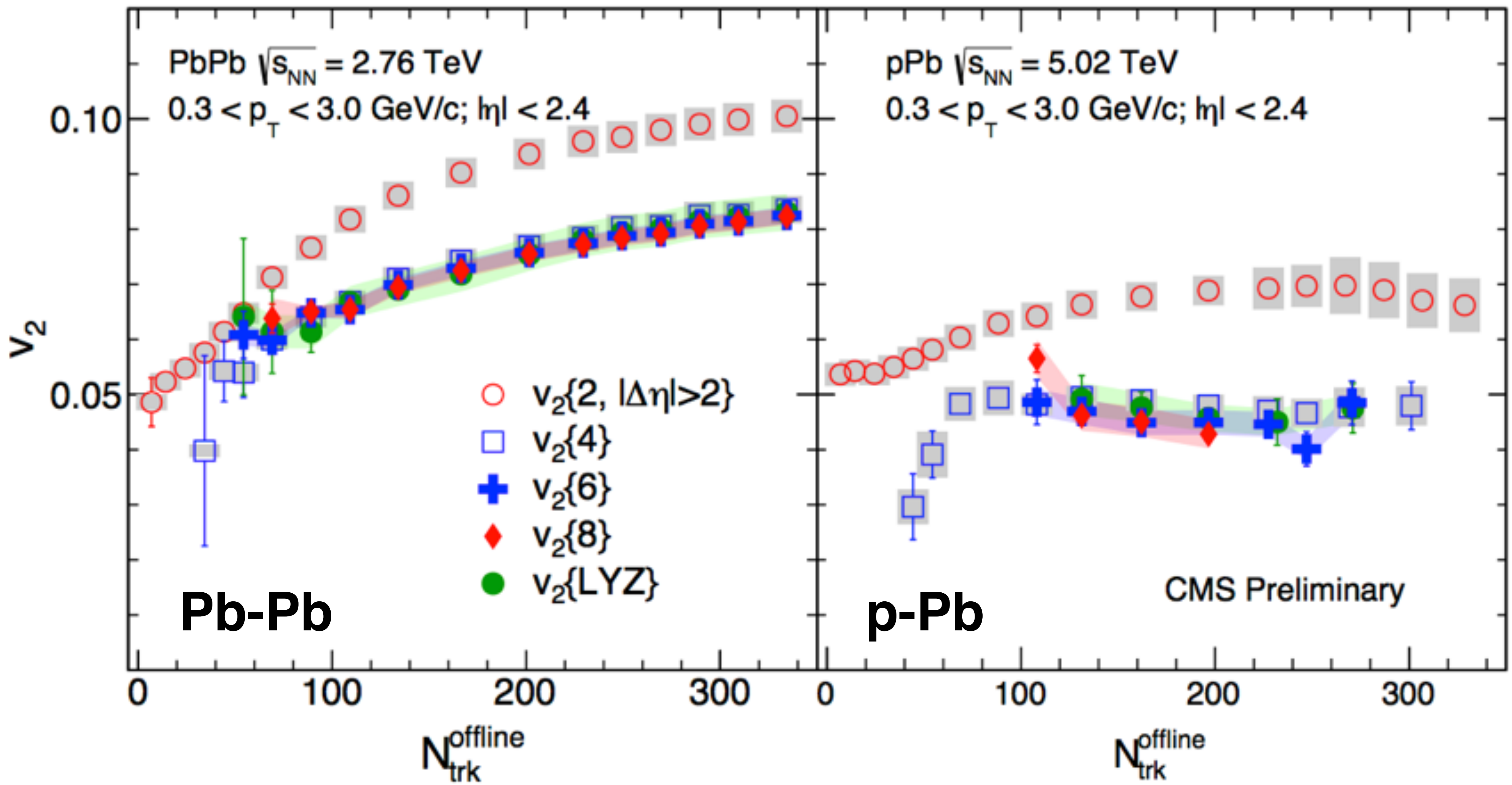
Fourier decomposition of Δϕ: v_2, v_3, …

ATLAS, arXiv:1409.1792 [hep-ex]



True collective effect

CMS, PAS HIN-14-006



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

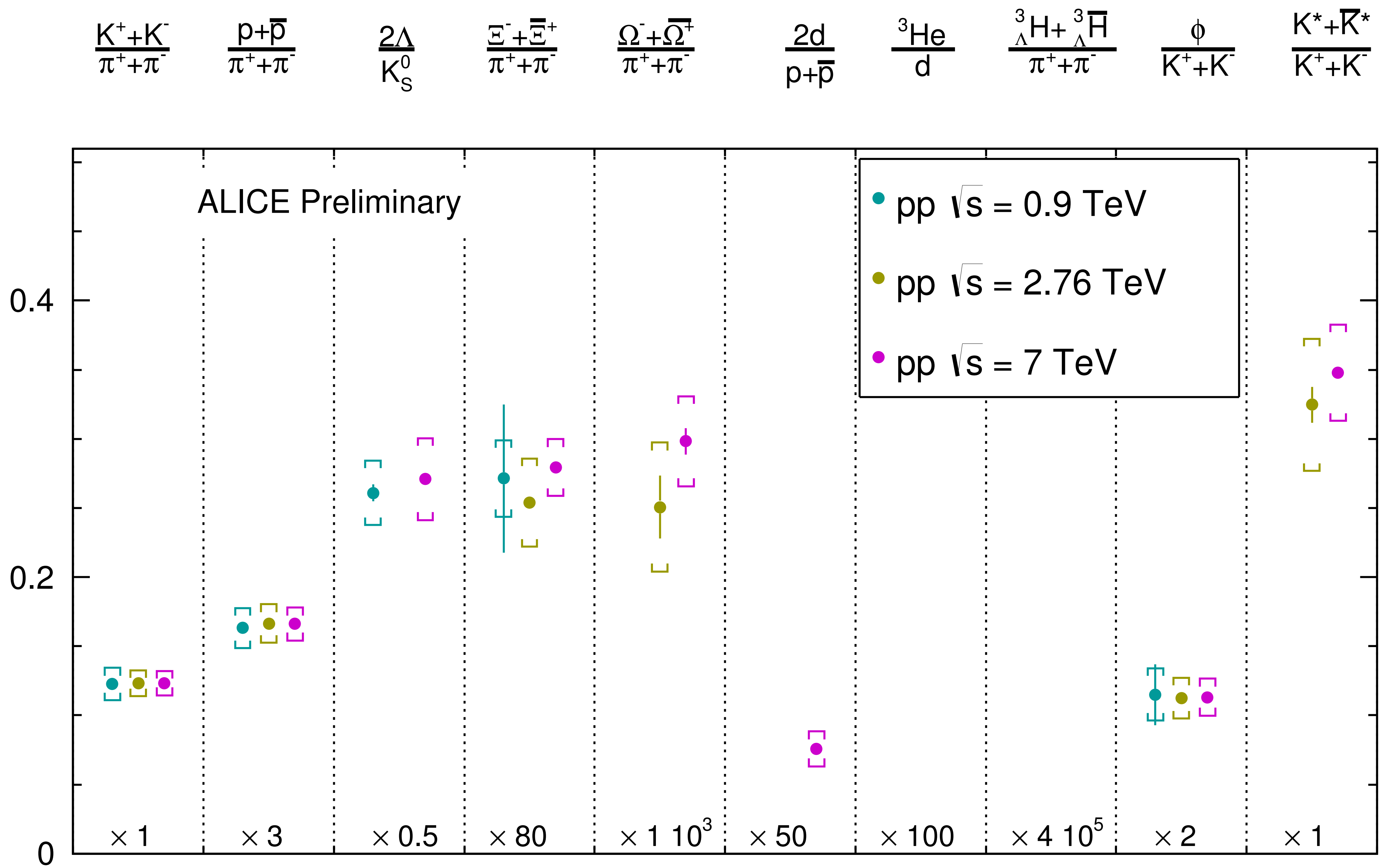
there is **true collectivity in p-Pb**

Overview of particle production at the LHC

Overview of particle production

Particle ratios measured in pp collisions

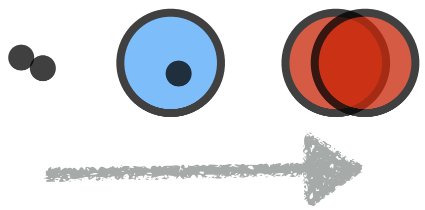
do not show significant energy dependence

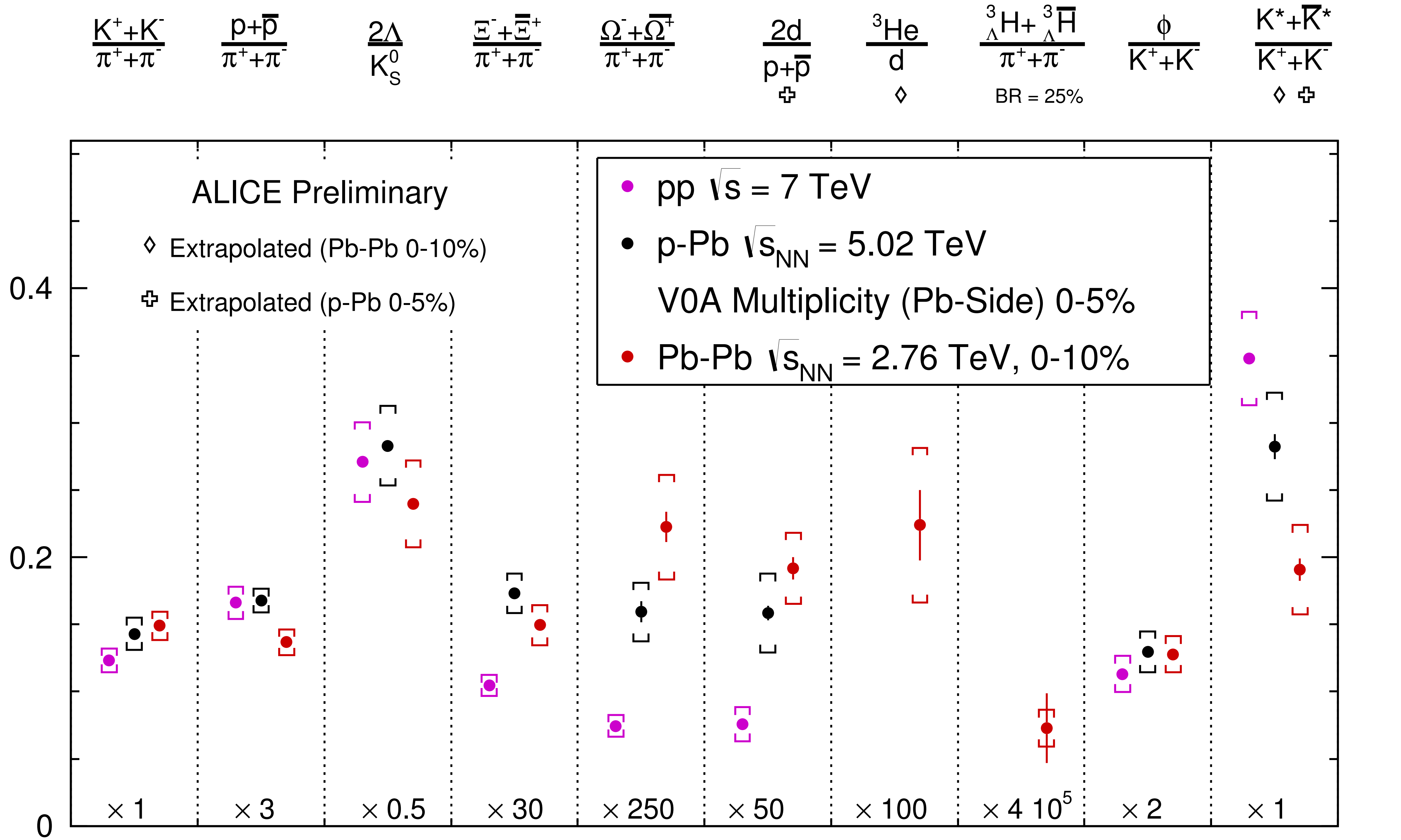


Overview of particle production

Particle ratios evolve as a function of the system size

from small (pp), intermediate (p-Pb) to large (Pb-Pb) collision systems

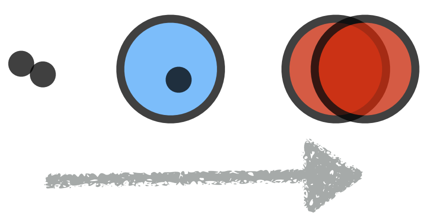




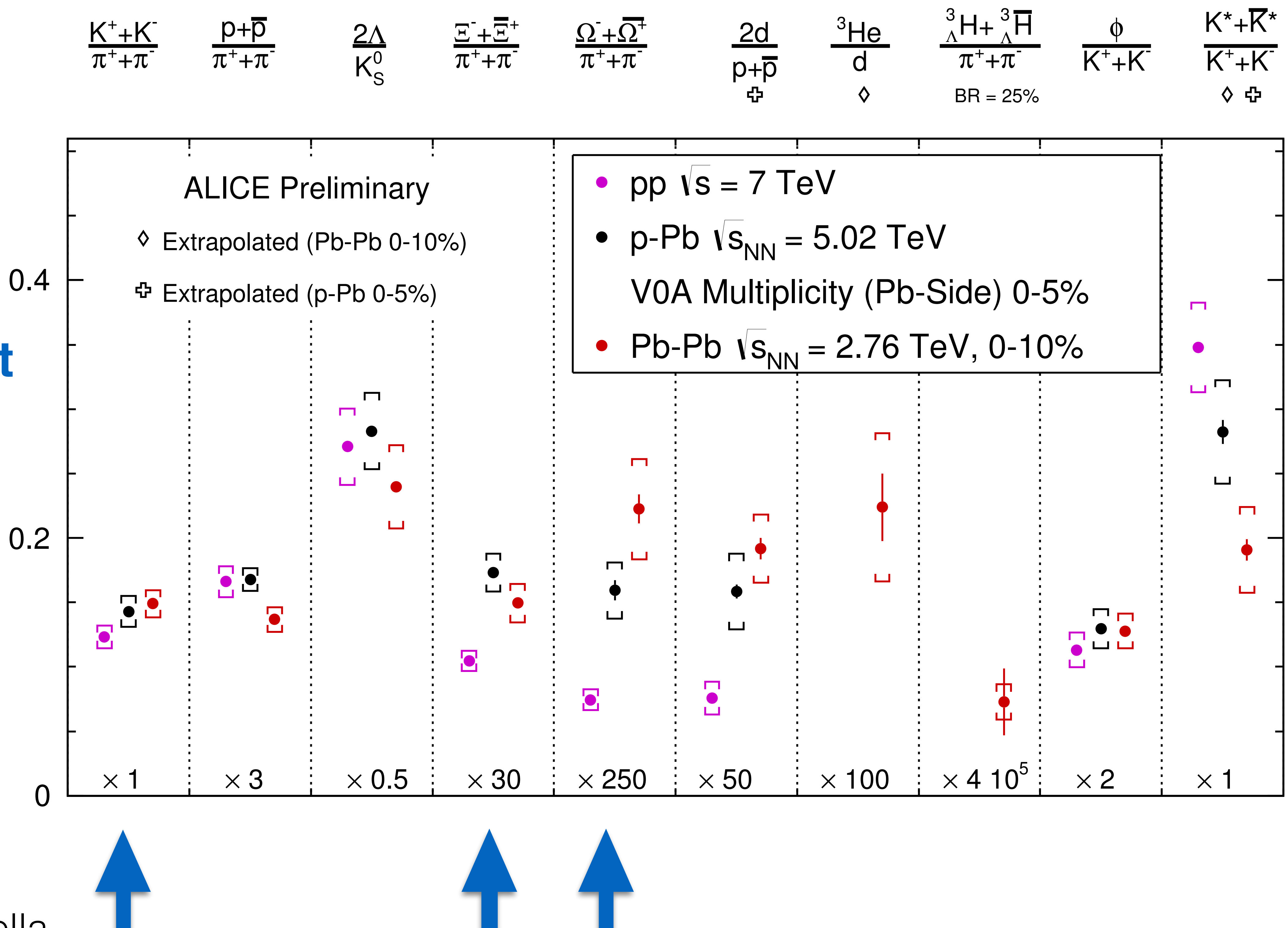
Overview of particle production

Particle ratios evolve as a function of the system size

from small (pp), intermediate (p-Pb) to large (Pb-Pb) collision systems



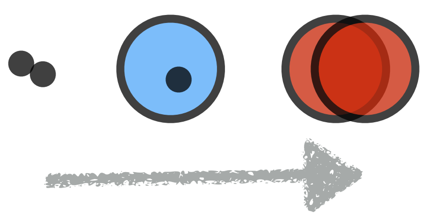
strangeness enhancement



Overview of particle production

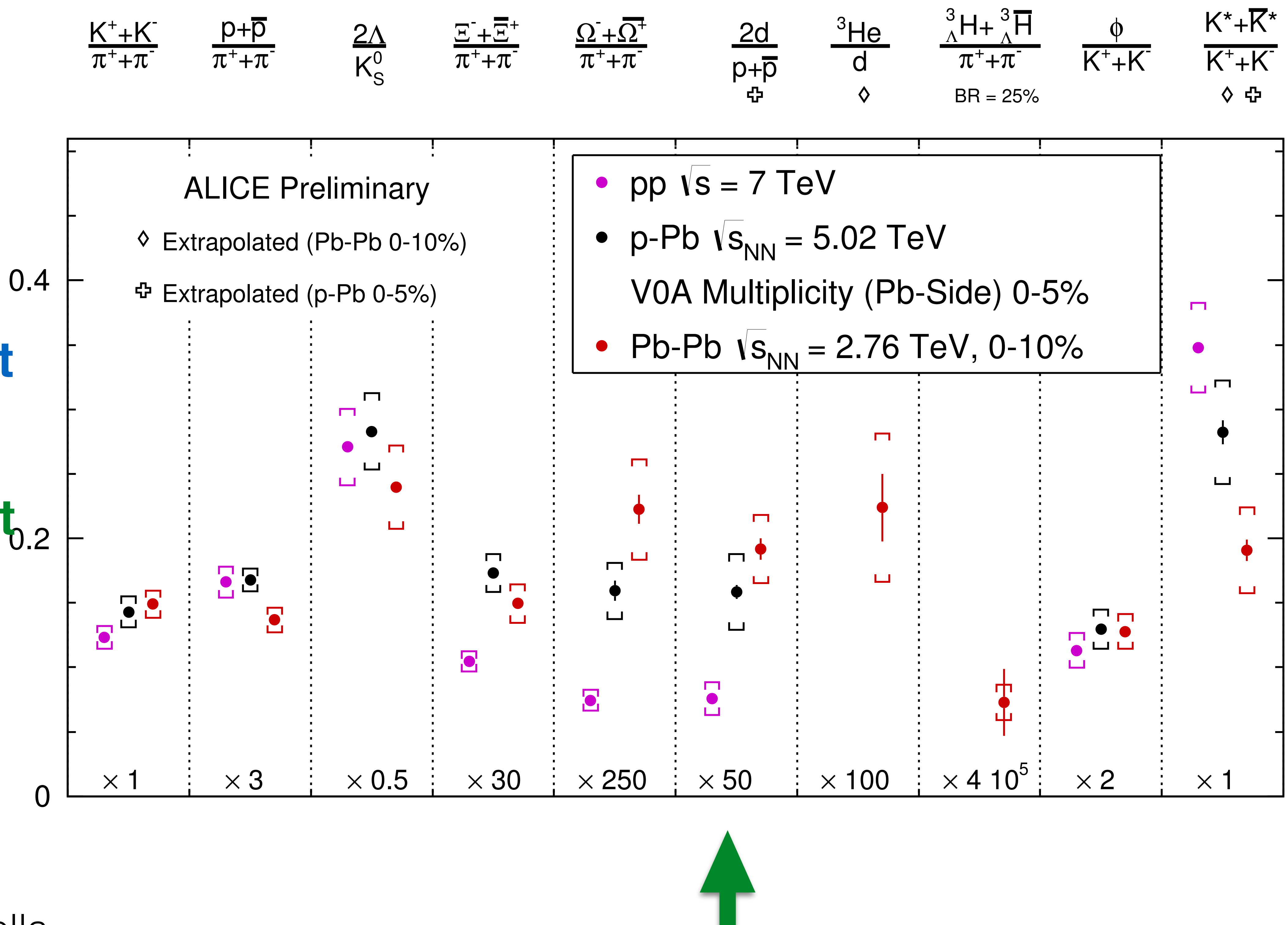
Particle ratios evolve as a function of the system size

from small (pp), intermediate (p-Pb) to large (Pb-Pb) collision systems



strangeness enhancement

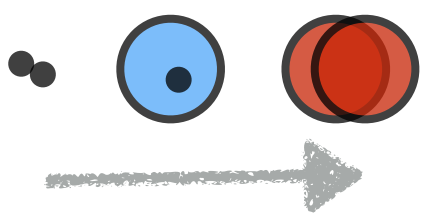
deuteron enhancement



Overview of particle production

Particle ratios evolve as a function of the system size

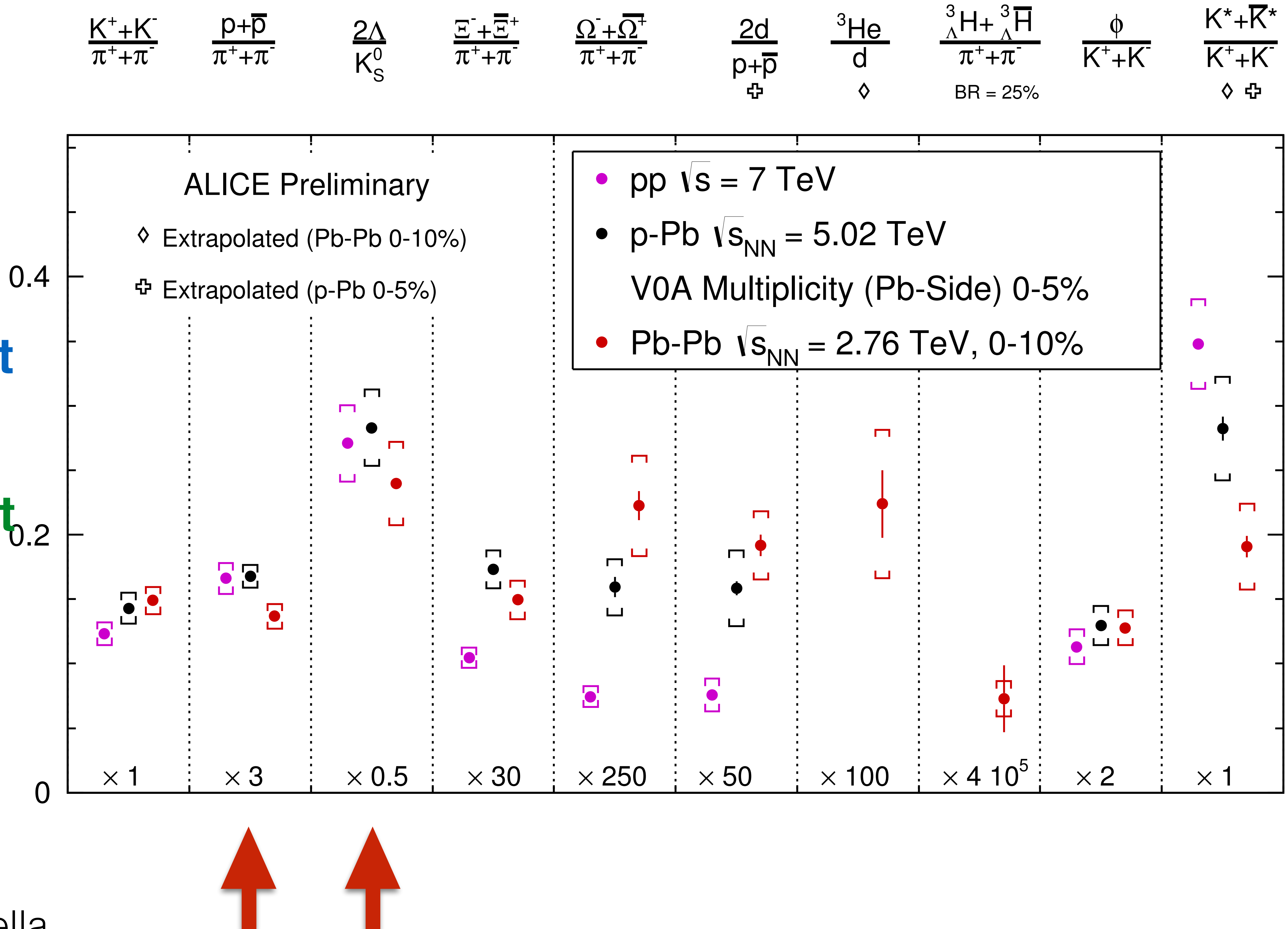
from small (pp), intermediate (p-Pb) to large (Pb-Pb) collision systems



strangeness enhancement

deuteron enhancement

baryon suppression



Overview of particle production

Particle ratios evolve as a function of the system size

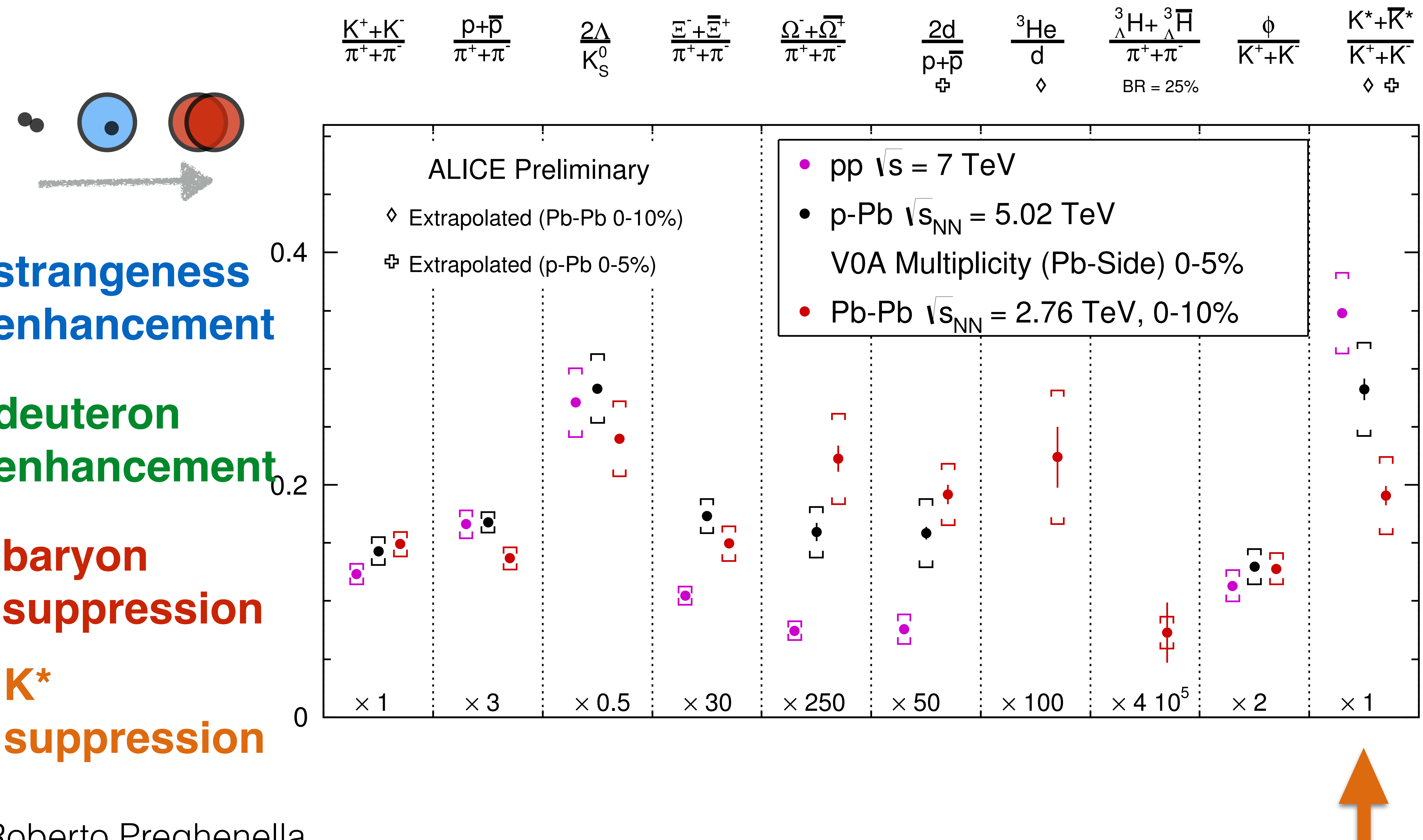
from small (pp), intermediate (p-Pb) to large (Pb-Pb) collision systems

strangeness enhancement

deuteron enhancement

baryon suppression

K* suppression



Summary

proton-proton data provide valuable information to constrain models for particle production in non-pQCD

difficult to get strange-particle production

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

signatures of thermalisation, final-state effects and collectivity

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
interesting phenomena, need more investigation on small systems

particle production evolves with increasing system size

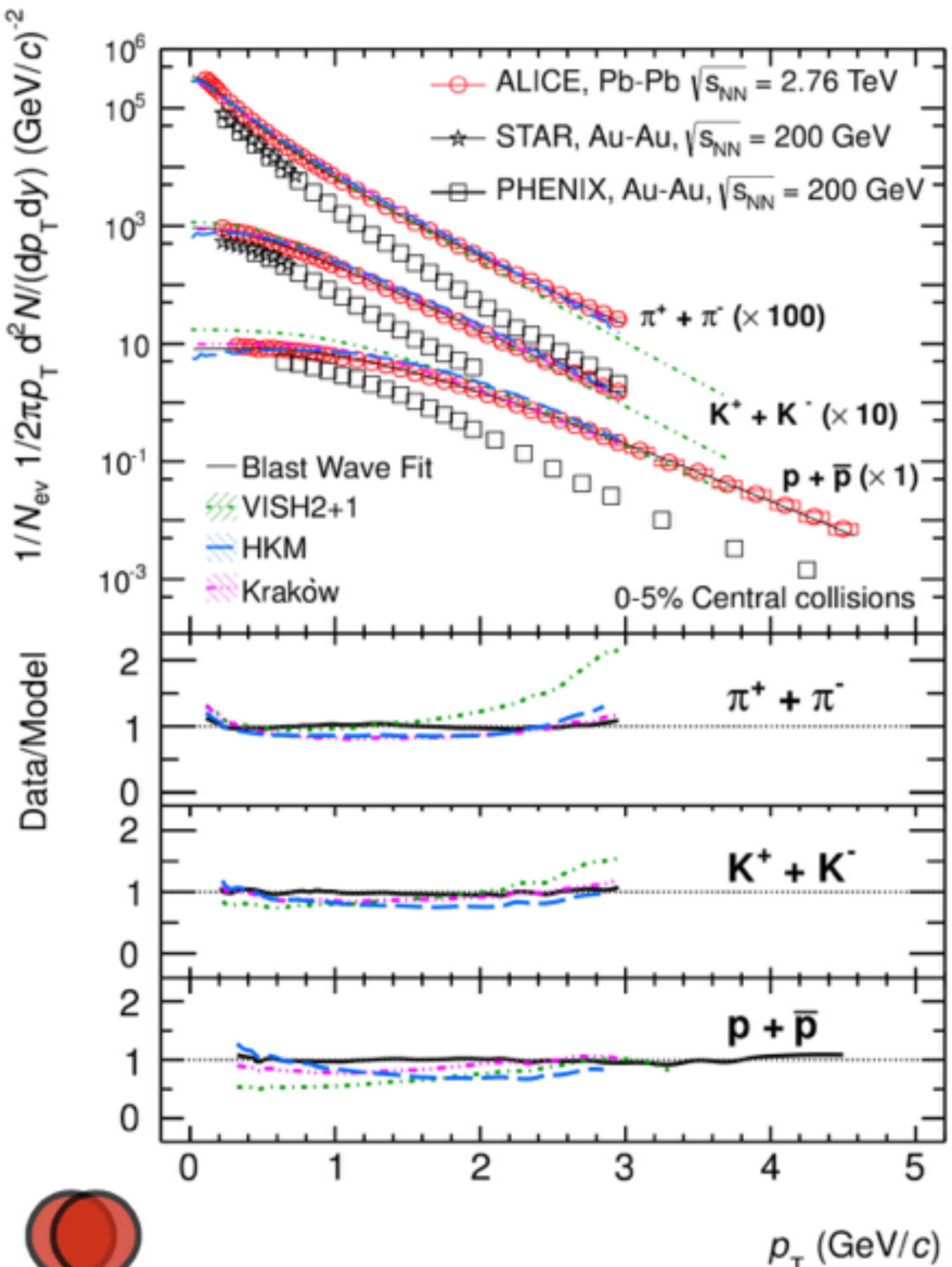
baryon and K* suppression, strangeness and deuteron enhancement
central Pb-Pb well described by GC thermal models, T_{ch} = 156 MeV

many more results and a bright future

new data and more ideas for LHC Run-2

END

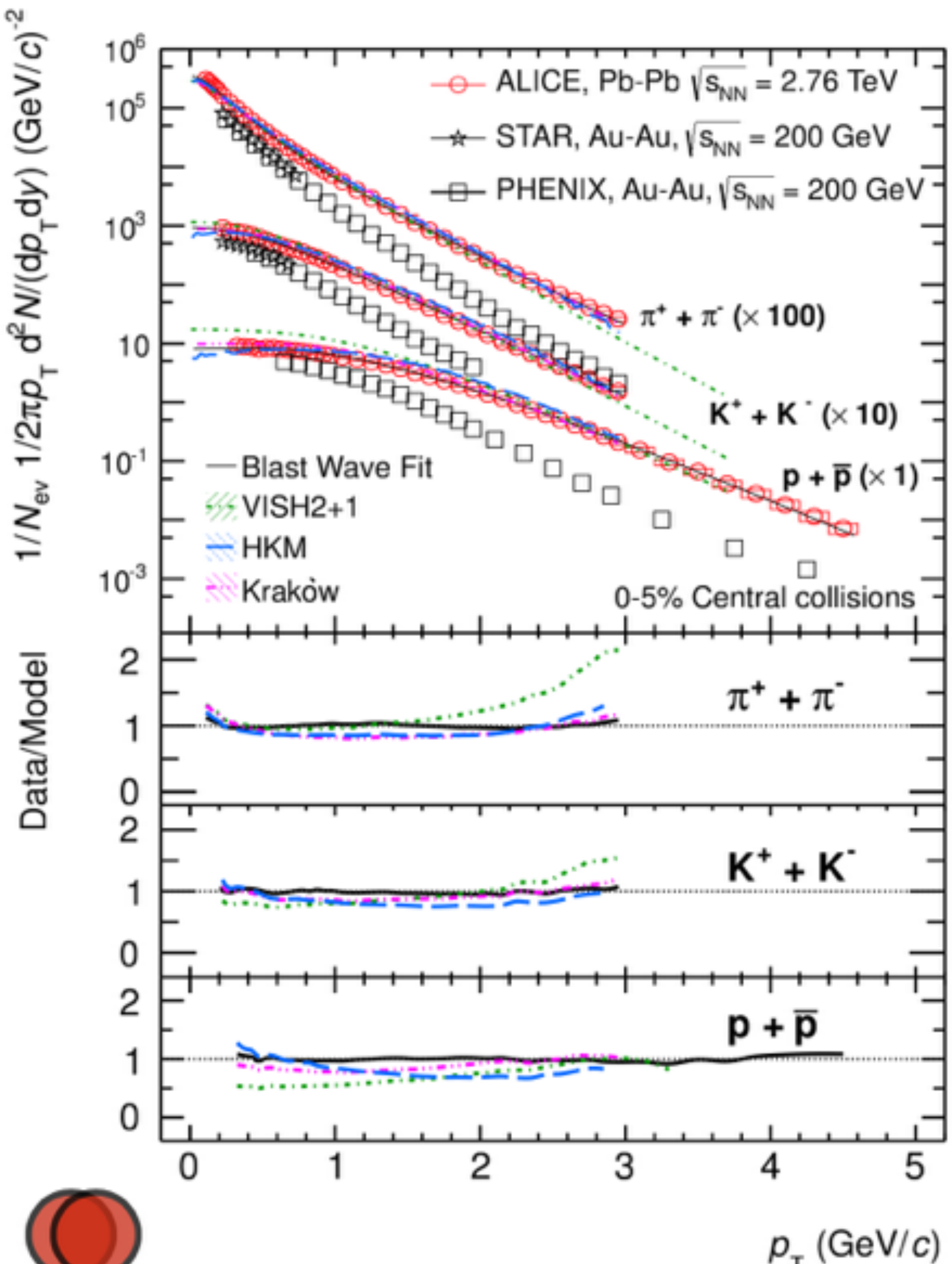
Bulk particle production in Pb-Pb

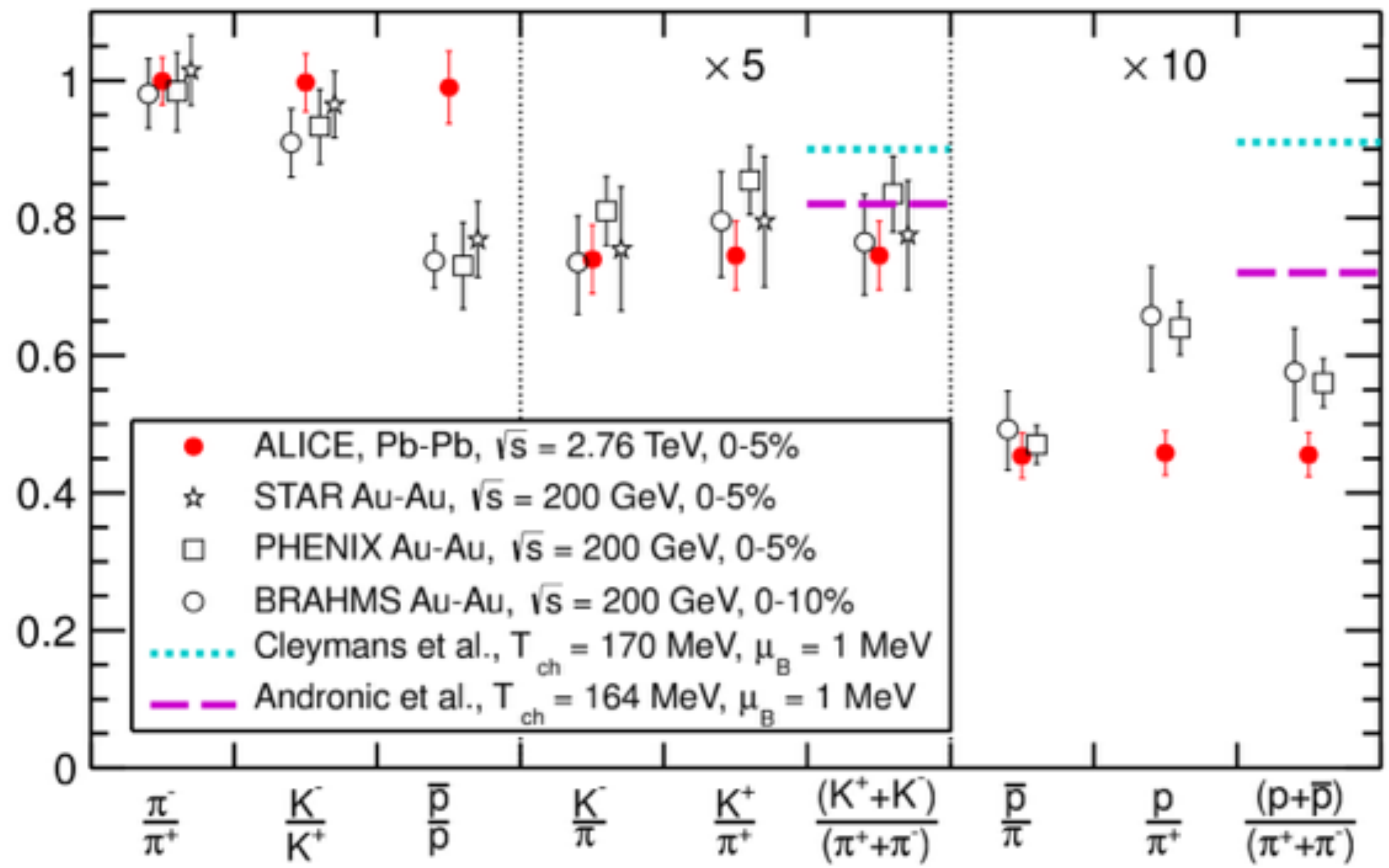


LHC significantly harder than RHIC spectra **nicely described by hydro models**

ALICE, PRL 109 (2012) 252301

Bulk particle production in Pb-Pb



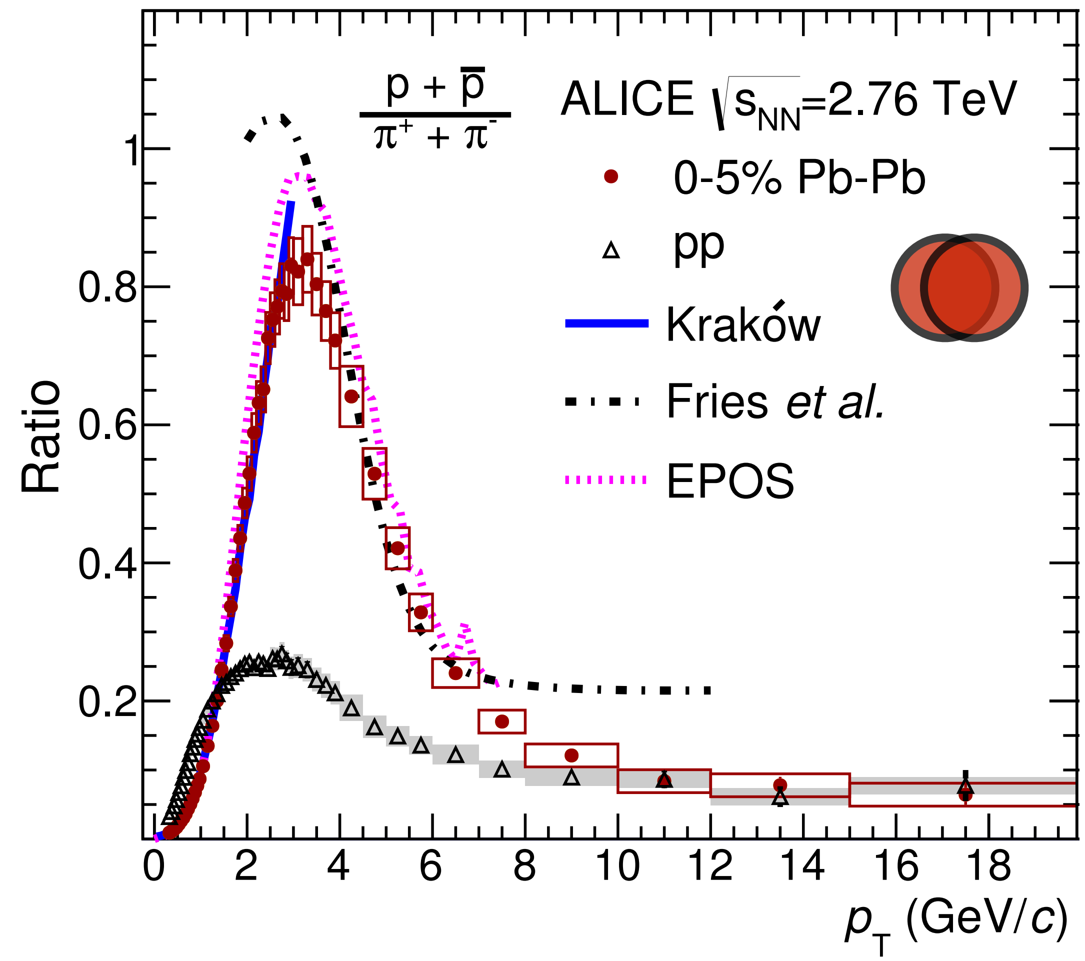


antiparticle/particle ratios = 1 consistent with vanishing μ_B

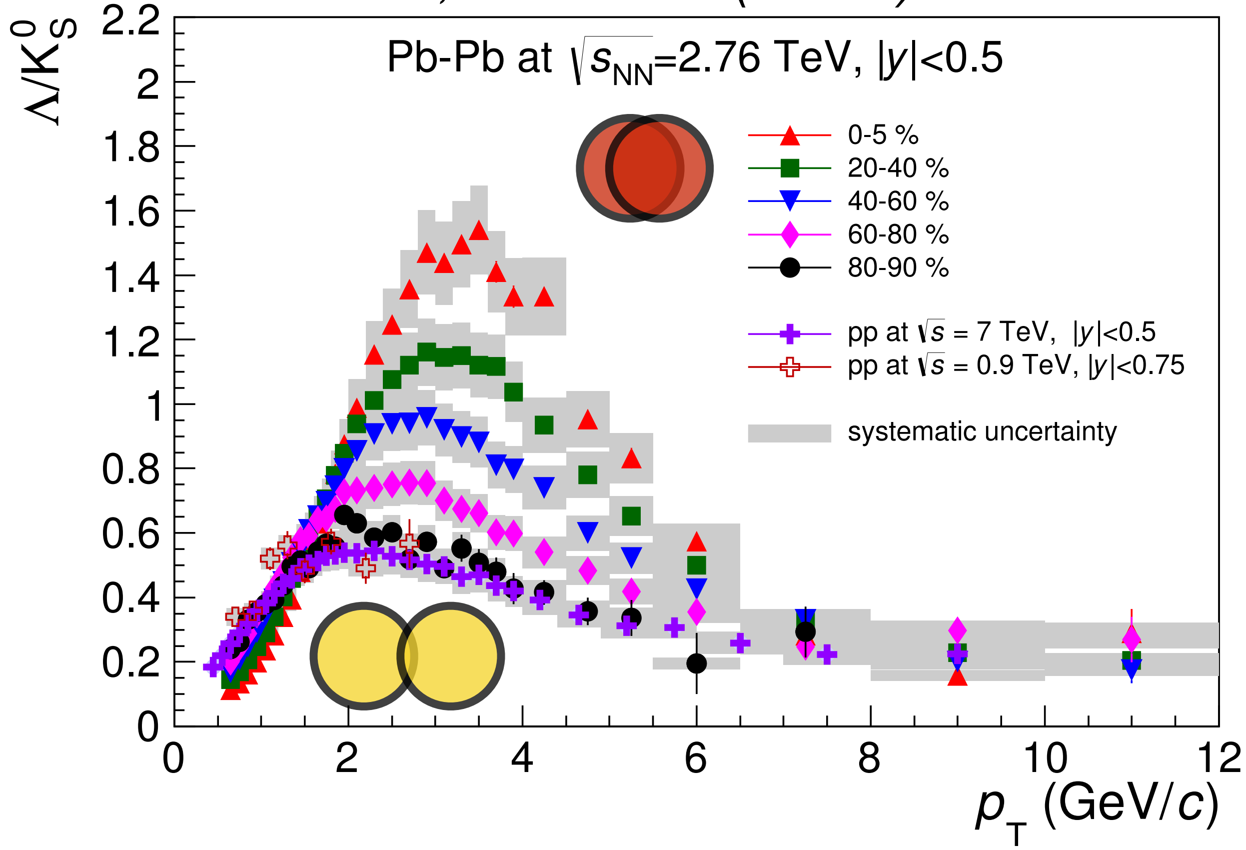
p/π ratio significantly (~1.5x) **lower than expectations** from RHIC extrapolations (T_{ch} = 164)

Baryon-meson enhancement in Pb-Pb

ALICE, PLB 728 (2014) 25



ALICE, PRL 111 (2013) 222301



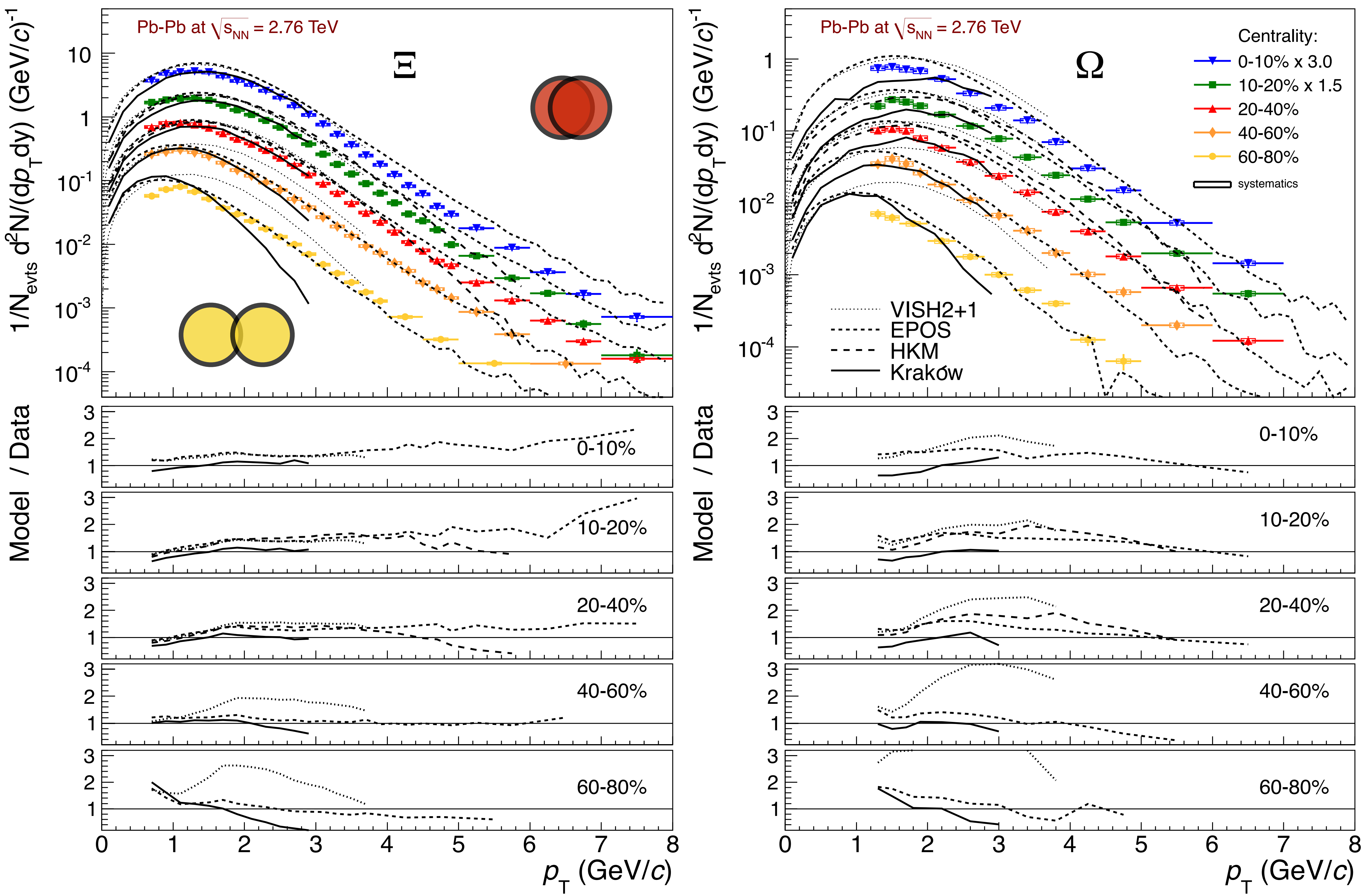
Λ/K^0_S and p/π ratios are **enhanced in central A-A wrt. pp**

already observed at lower energies

pp / peripheral Pb-Pb → central Pb-Pb:

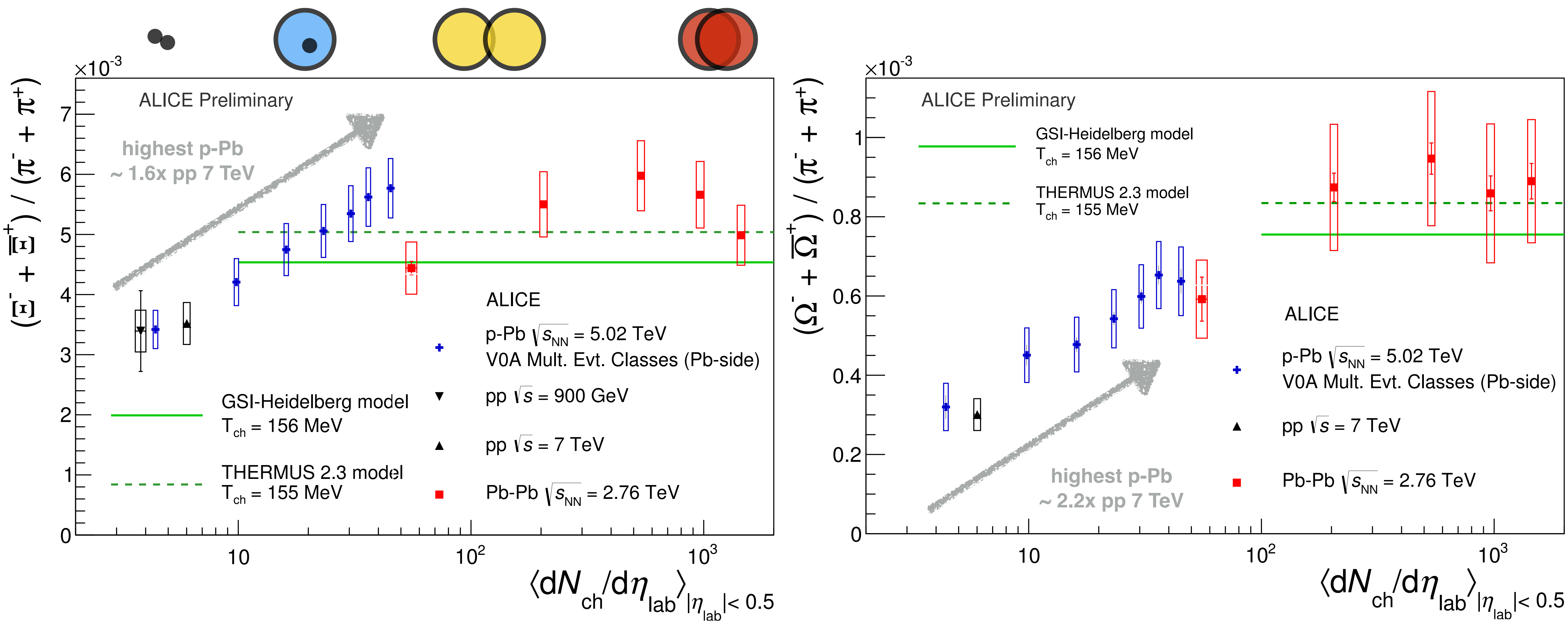
the maximum increases and shifts to higher p_T

Strangeness production in Pb-Pb



hydro models → reasonable description of spectral shapes

Strangeness production in p-Pb



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

Statistical 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

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

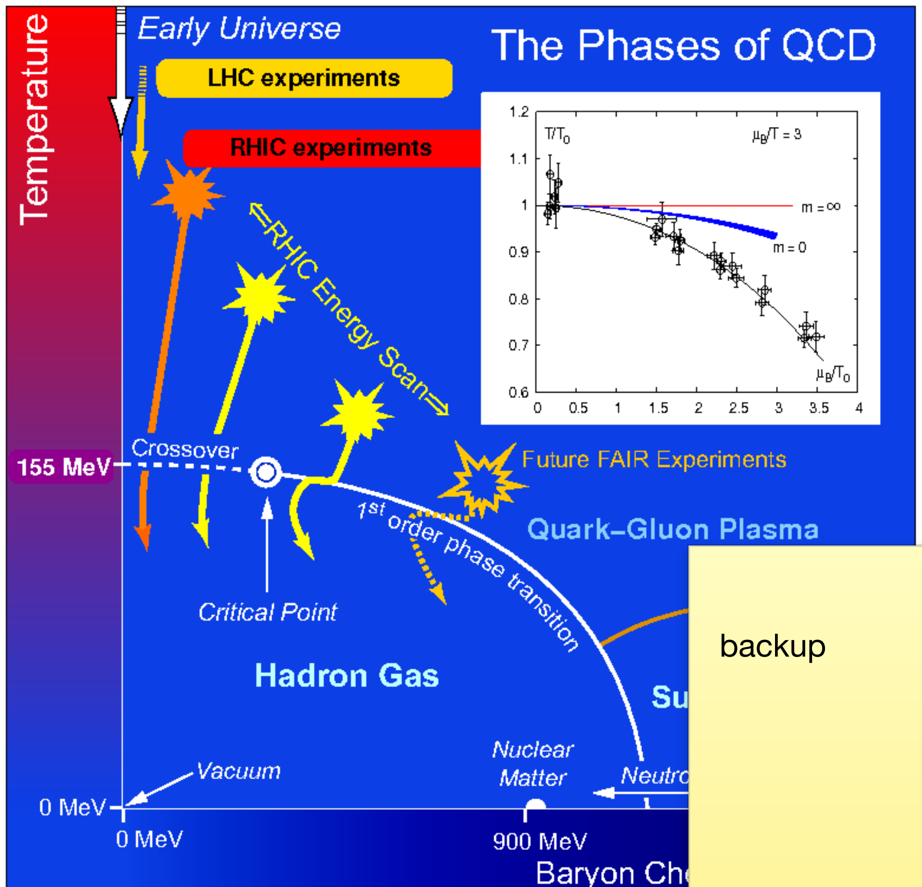
backup

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

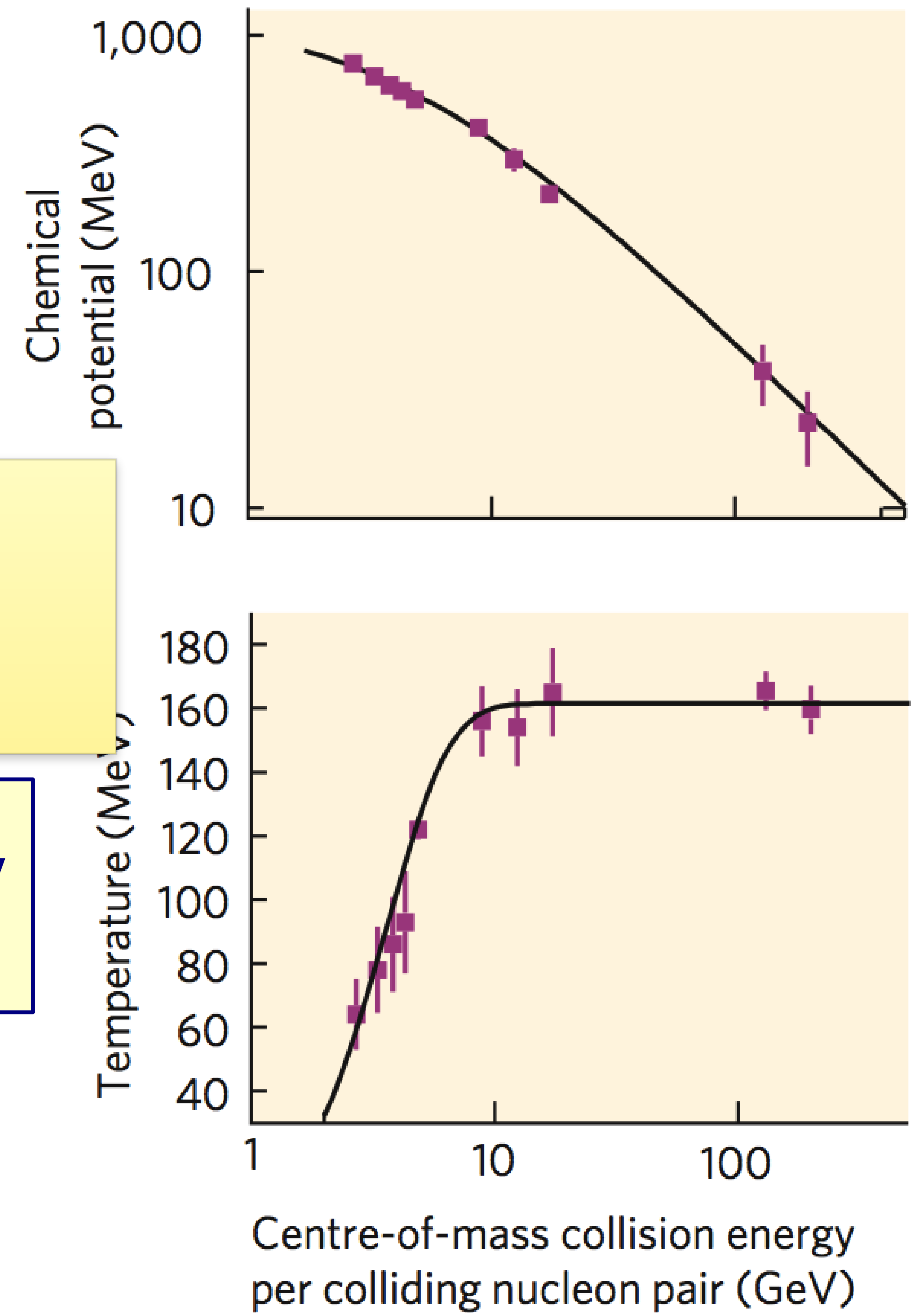
n = particle density (N / V)
M = hadron mass
T = temperature
μ = chemical potential dE/dN

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

Hadron chemistry in A-A collisions



backup



successfully described by statistical (thermal) **model** in a wide range of energies, $\sqrt{s_{NN}}$ = 2-200 GeV

consistent with equilibrium population → (T_{ch}, μ_B)

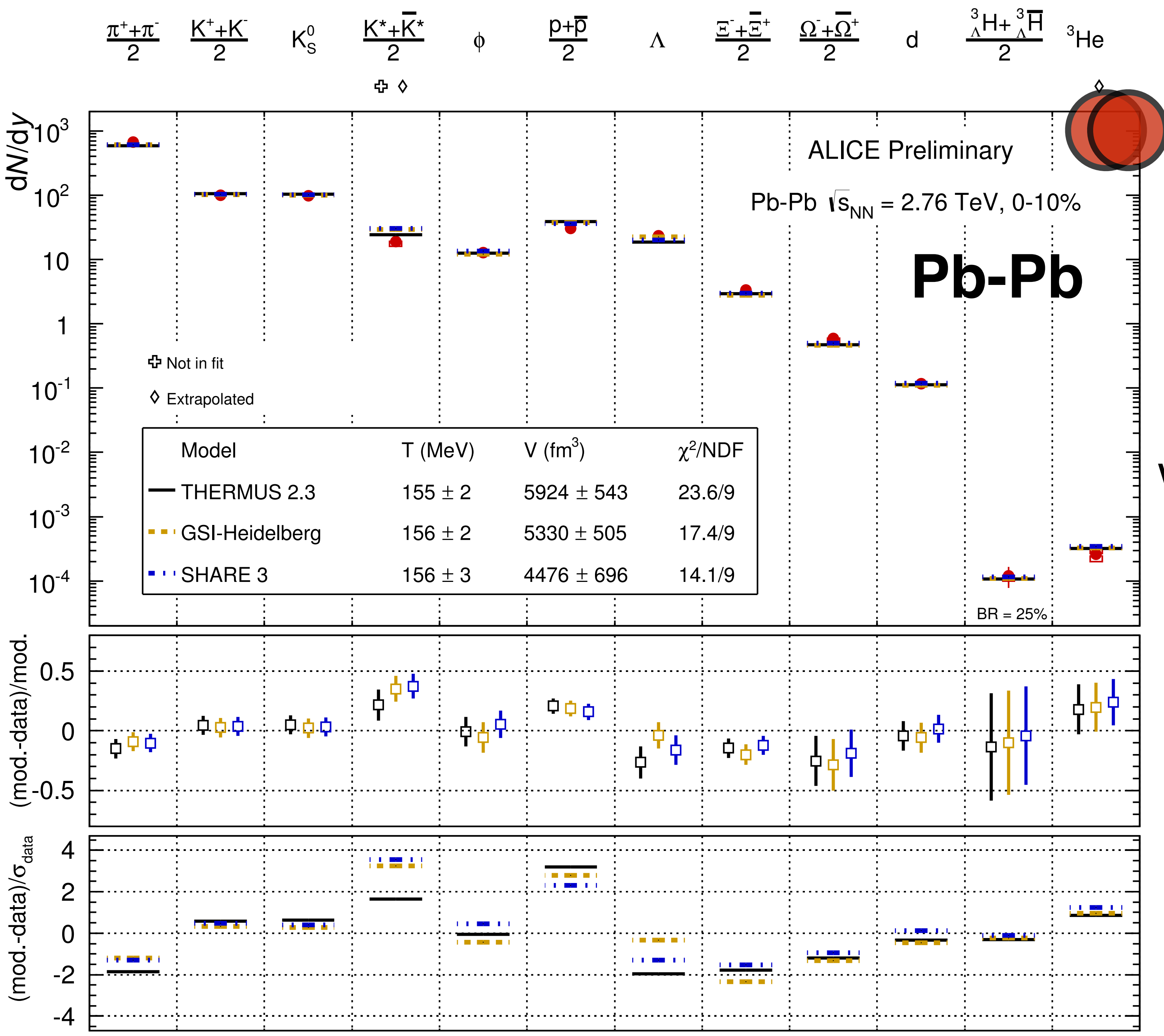
Predicted temperature at the LHC:
Andronic et al., NPA 772, 167 (2006)

T_{ch} = 164 MeV

Thermal model of particle production

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

same conclusions and parameters from different model implementations



d*N*/d*y* of particle species well described in Pb-Pb

χ^2/ndf ~ 2

with a **single temperature**

T_{ch} ~156 MeV

deviations for K* and p

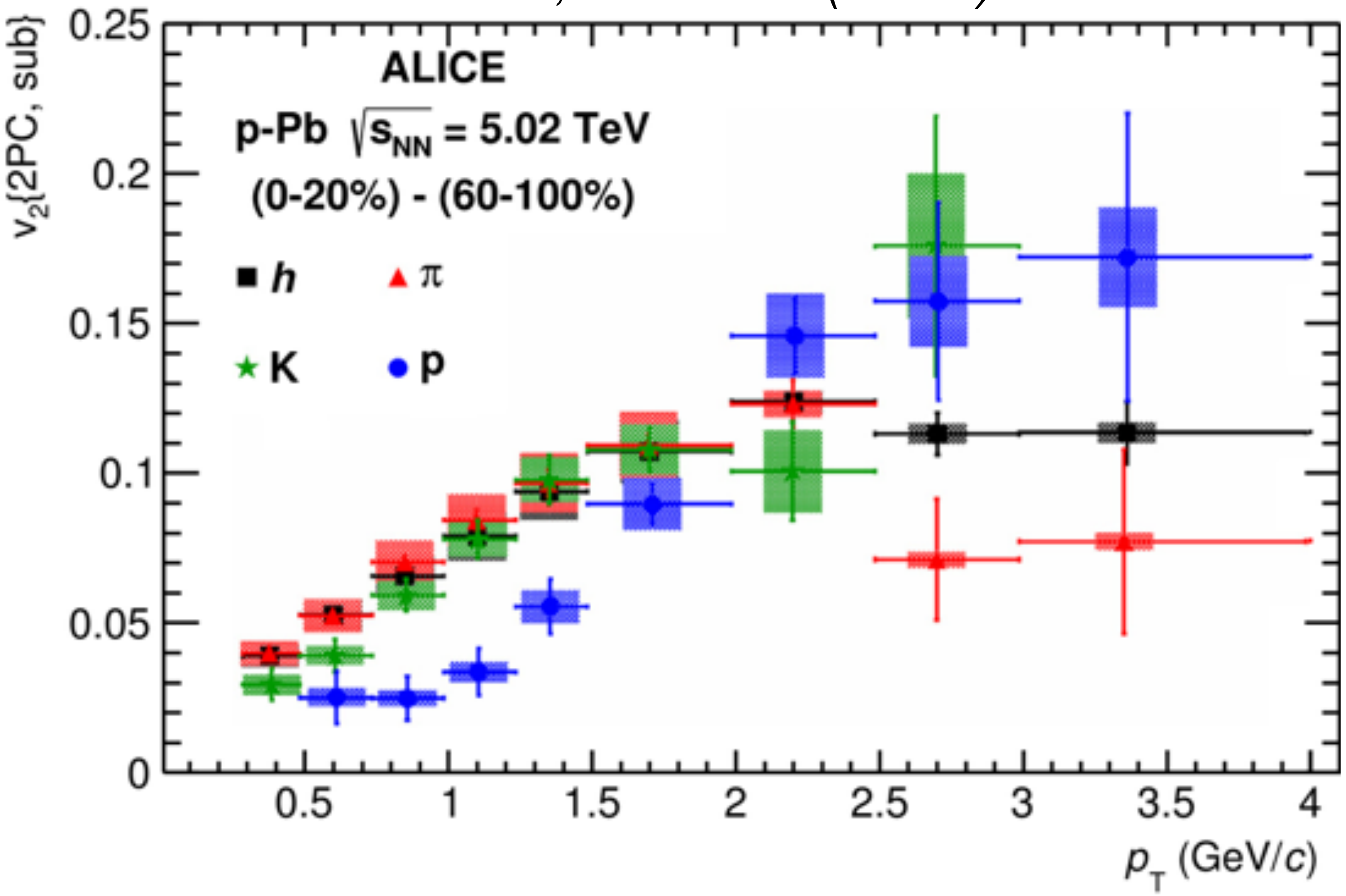
hint at final-state interactions

other mechanisms under investigation

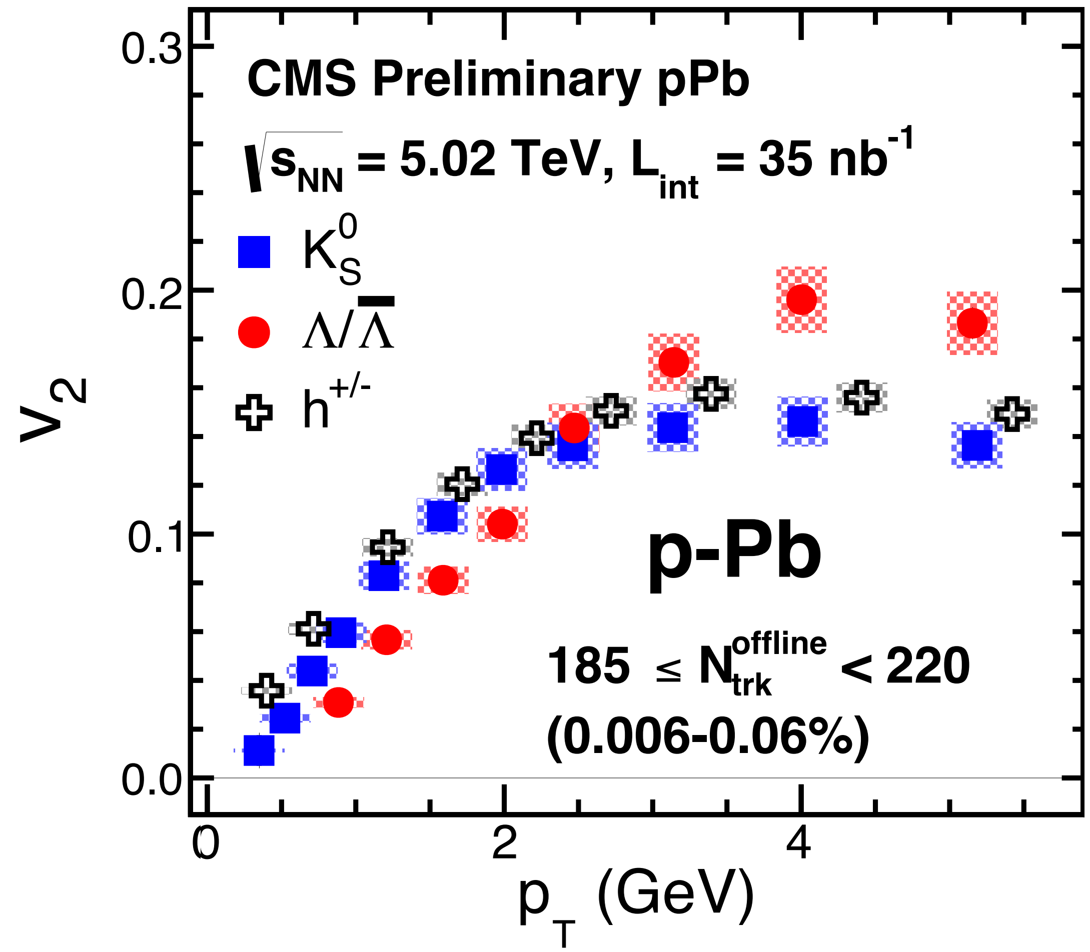
(flavour hierarchy, non-equilibrium, …)

v_2 of identified particles

ALICE, PLB 726 (2013) 164



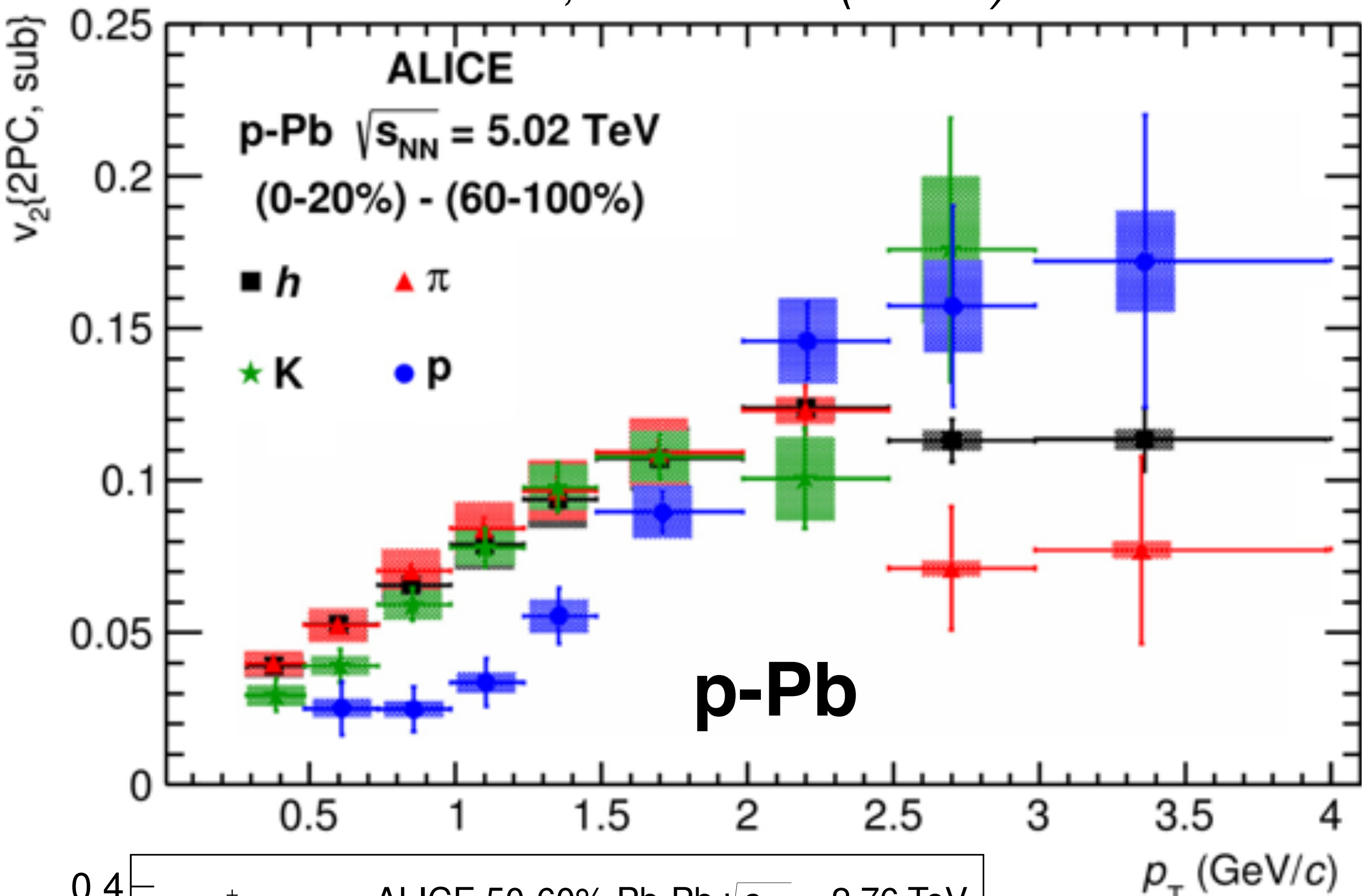
CMS, PAS HIN-14-002



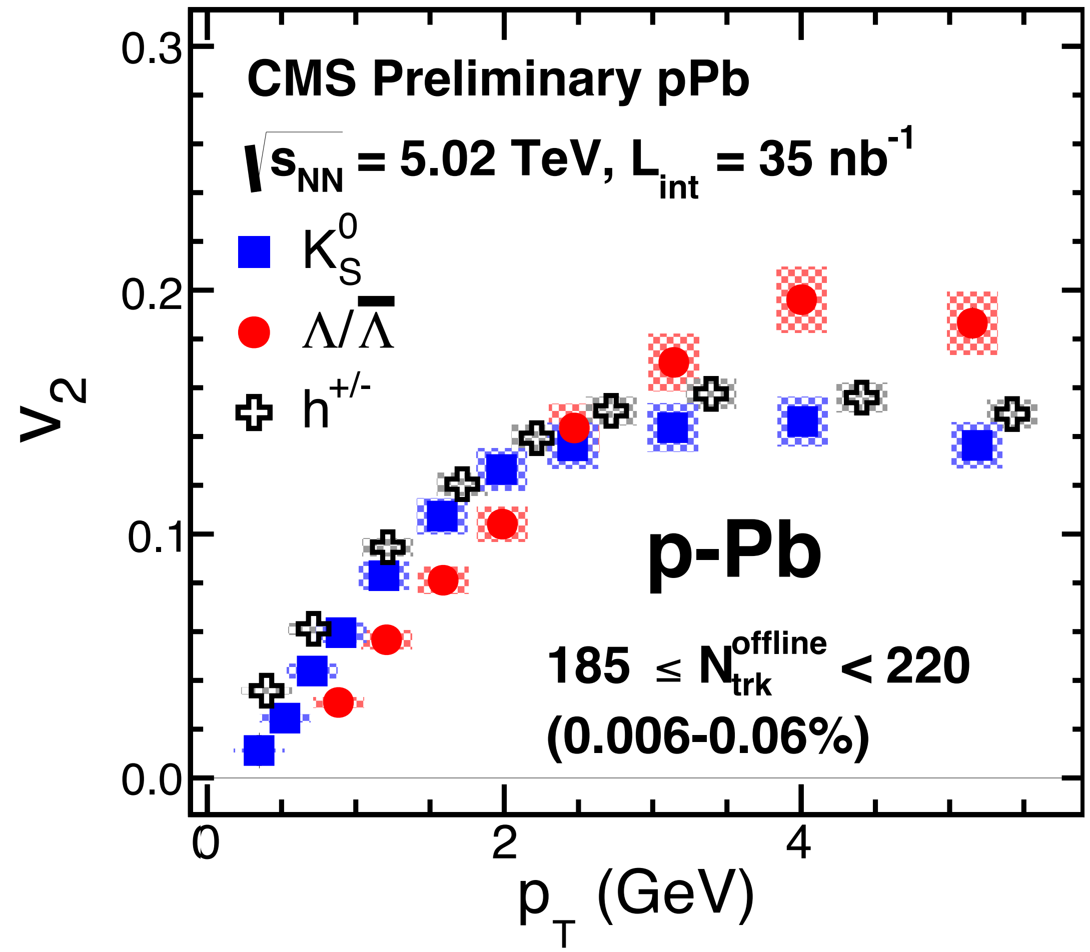
mass ordering observed at low p_T
lower v_2 for heavier particles
crossing at higher p_T

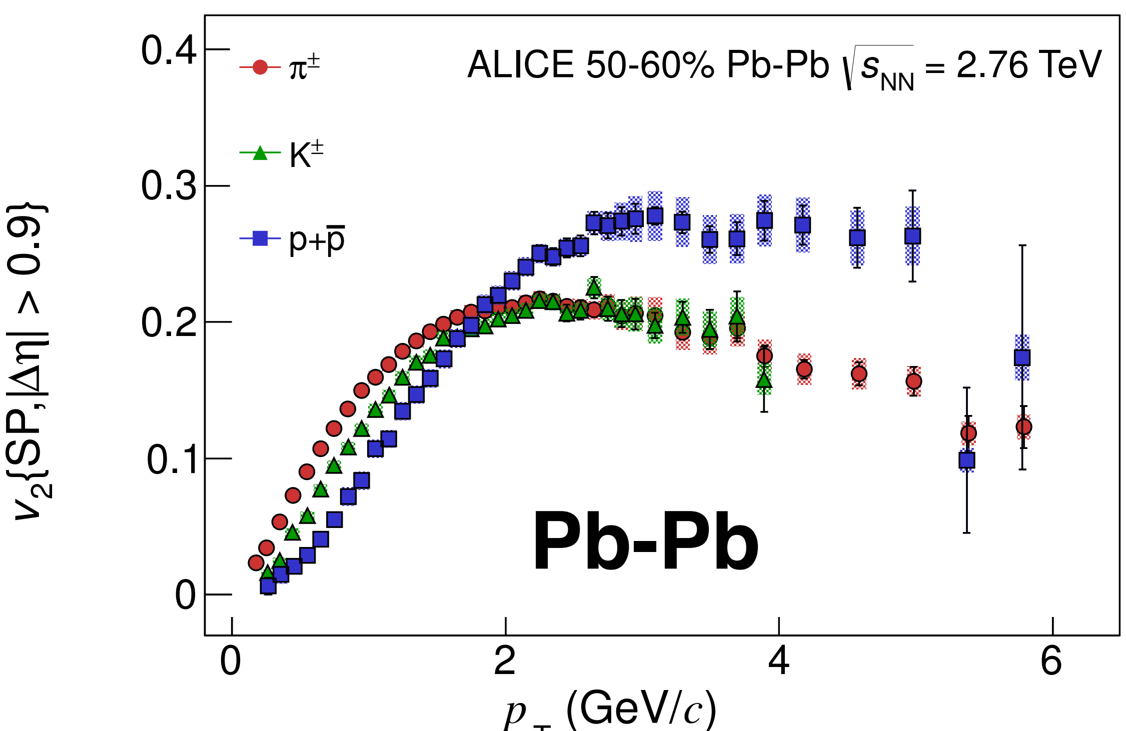
v_2 of identified particles

ALICE, PLB 726 (2013) 164



CMS, PAS HIN-14-002





mass ordering observed at low p_T

lower v_2 for heavier particles

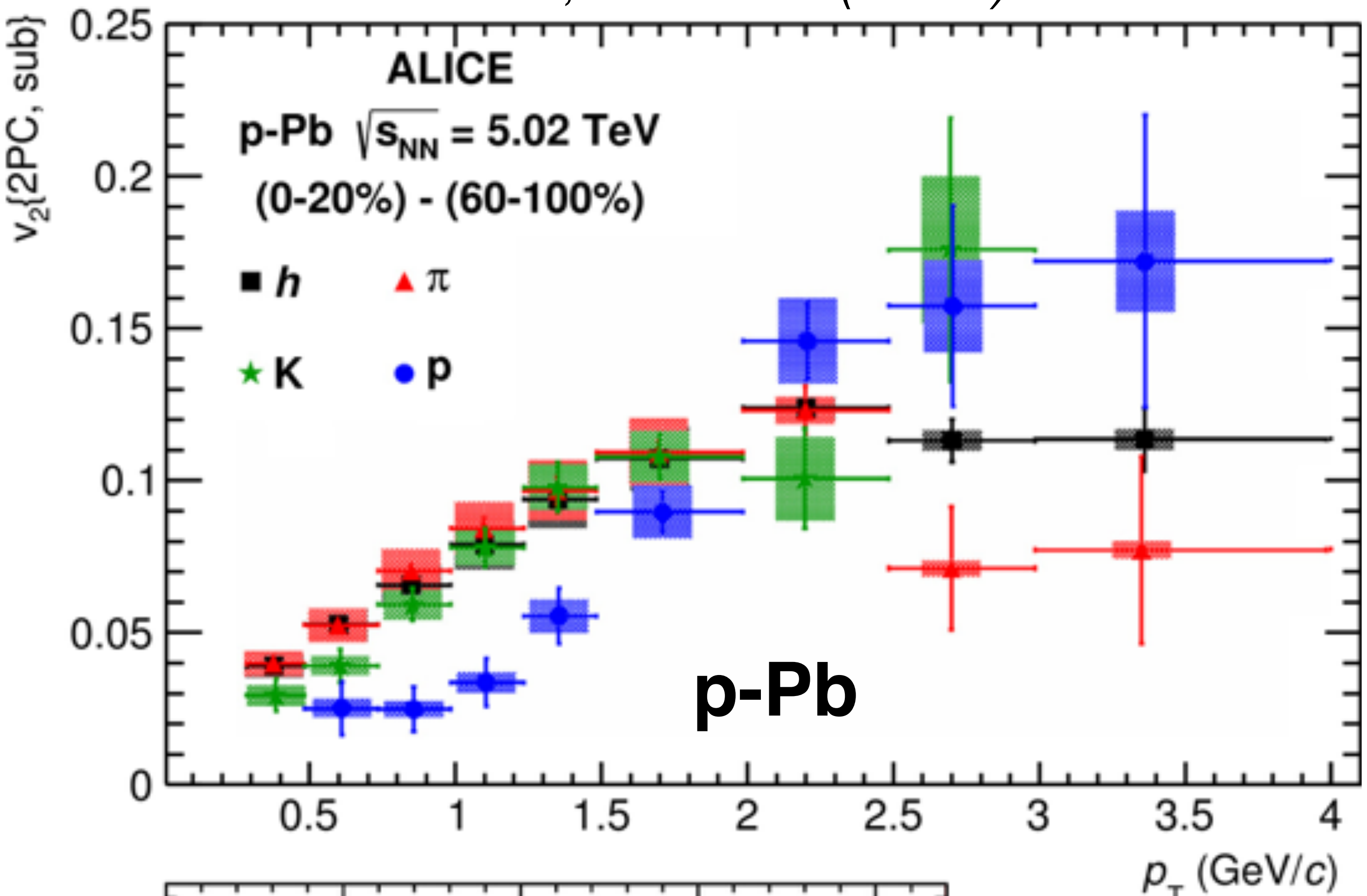
crossing at higher p_T

reminiscent of A-A observations

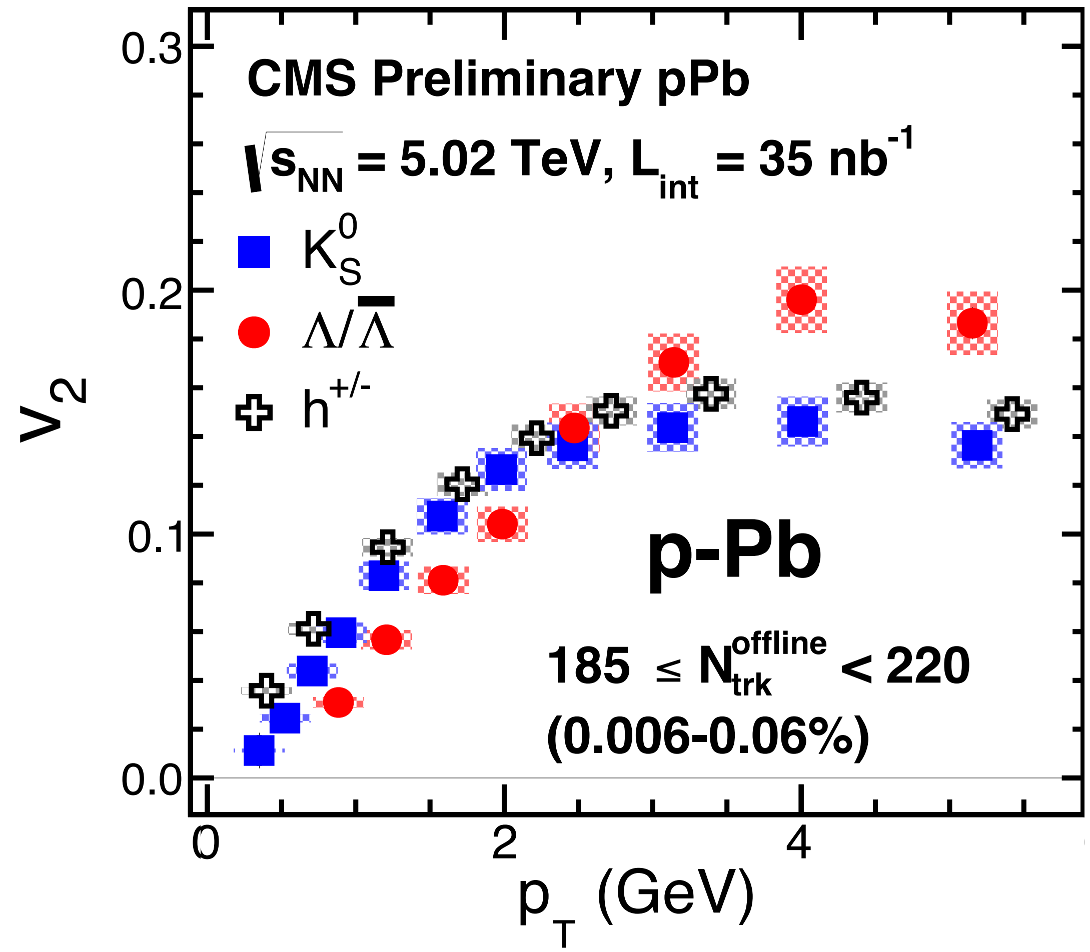
ALICE, arXiv:1405.4632 [nucl-ex]

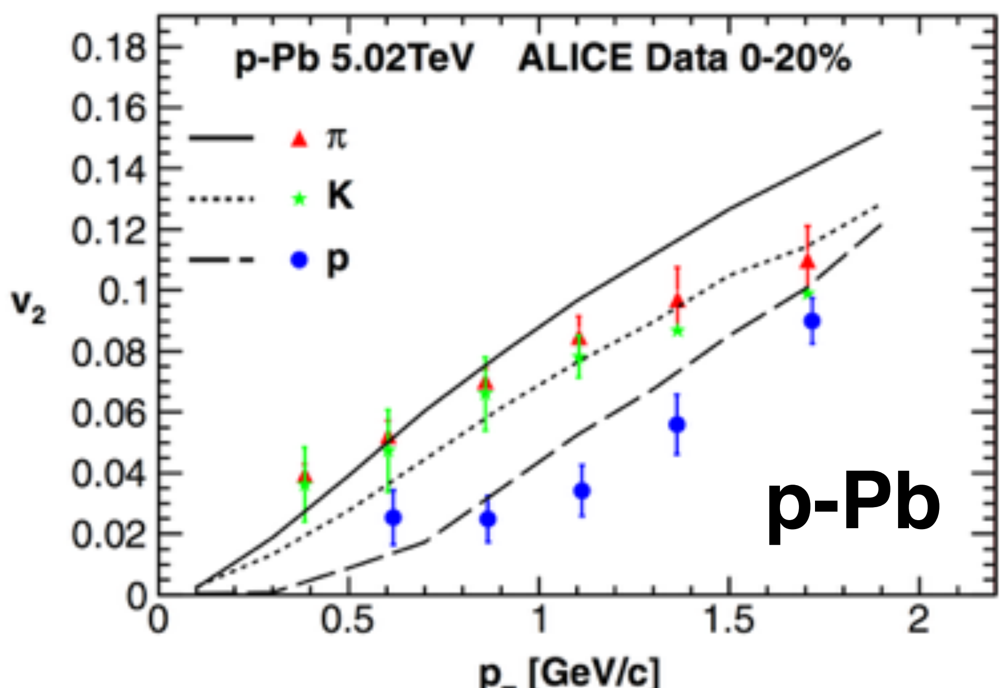
v_2 of identified particles

ALICE, PLB 726 (2013) 164



CMS, CMS-HIN-14-002





mass ordering observed at low p_T

lower v_2 for heavier particles

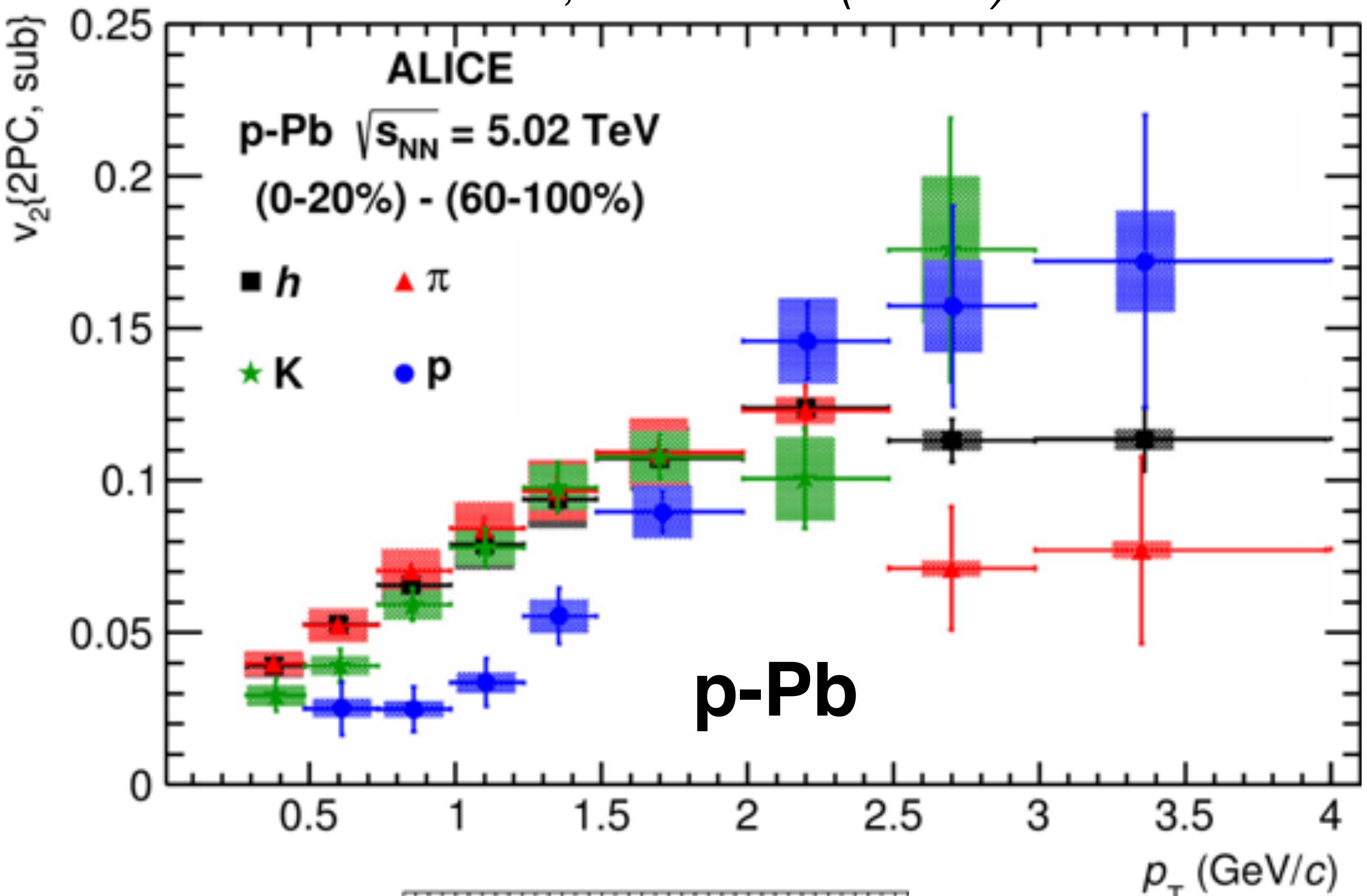
crossing at higher p_T

consistent with expectations from collective hydrodynamic expansion

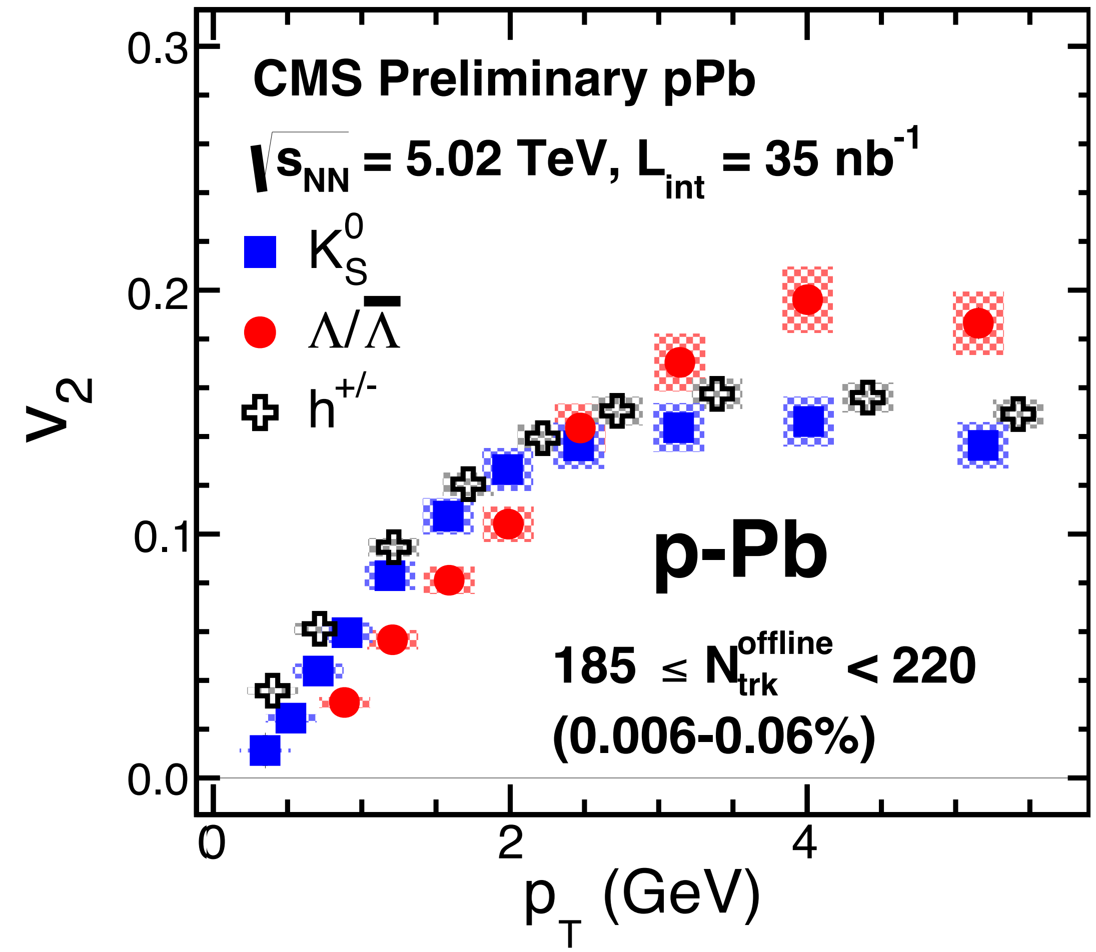
Bozek et al., PRL 111 (2013) 172303

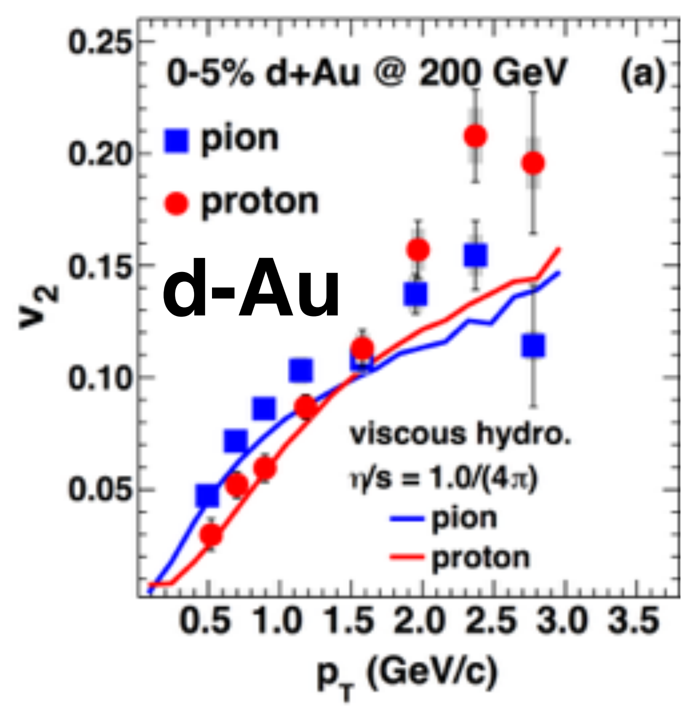
v_2 of identified particles

ALICE, PLB 726 (2013) 164



CMS, PAS HIN-14-002





mass ordering observed at low p_T

lower v_2 for heavier particles

crossing at higher p_T

also at RHIC in d-Au collisions

PHENIX, arXiv:1404.7461 [nucl-ex]

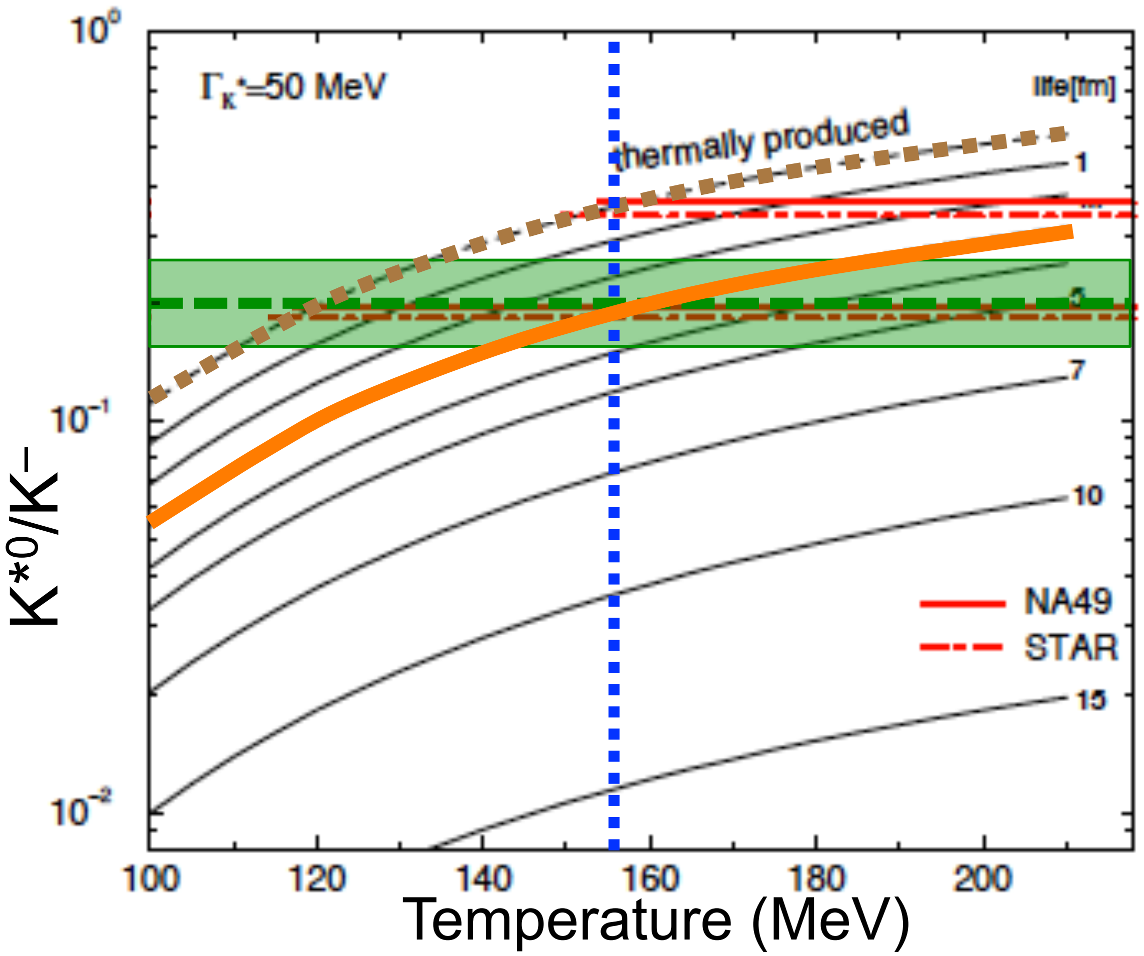
Properties of hadronic phase

- 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

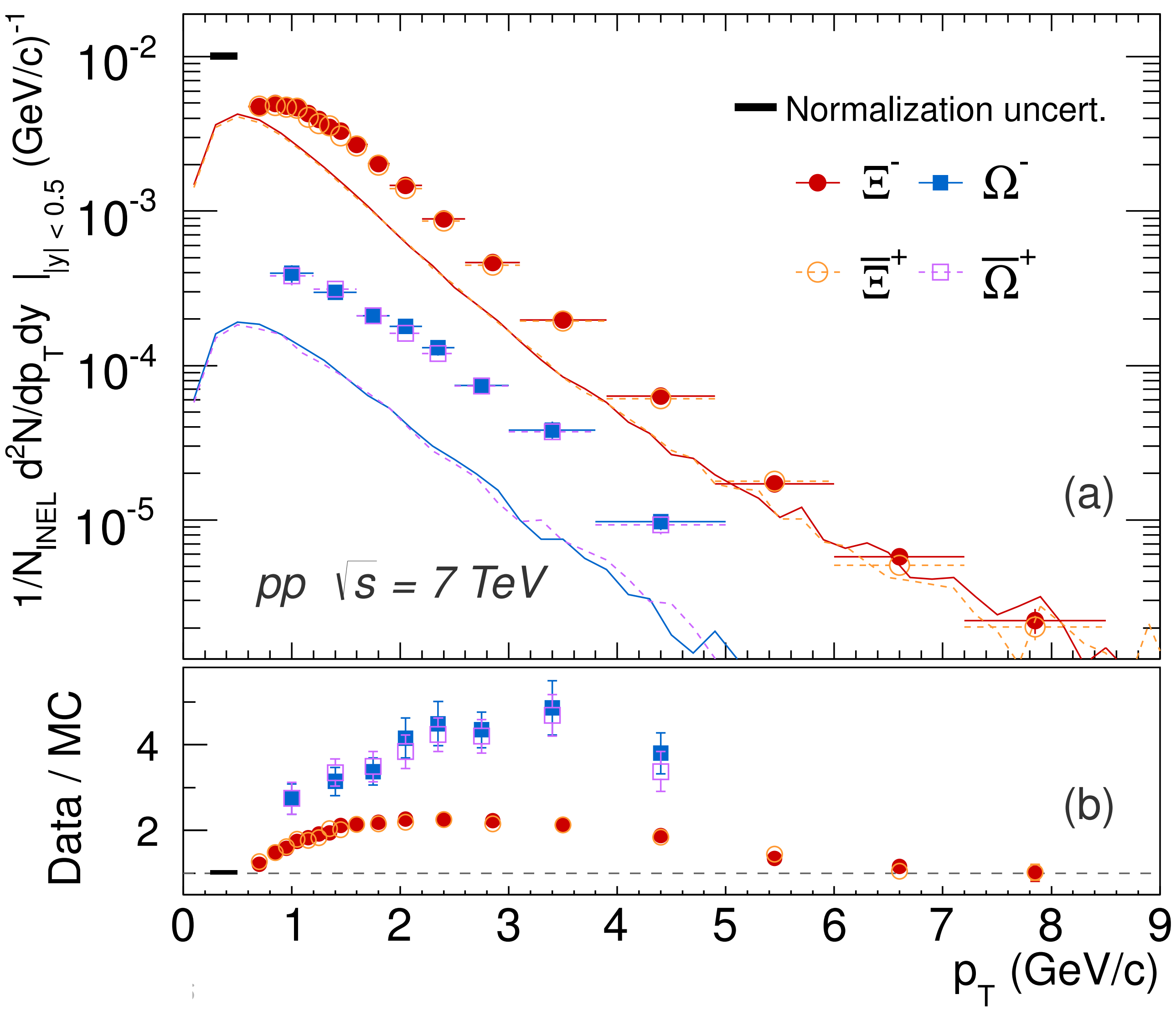
Torrieri/Rafelski*
no re-scattering
measured K^{*0}/K^{-}
→ Prediction: T_{ch} = 120±7 MeV

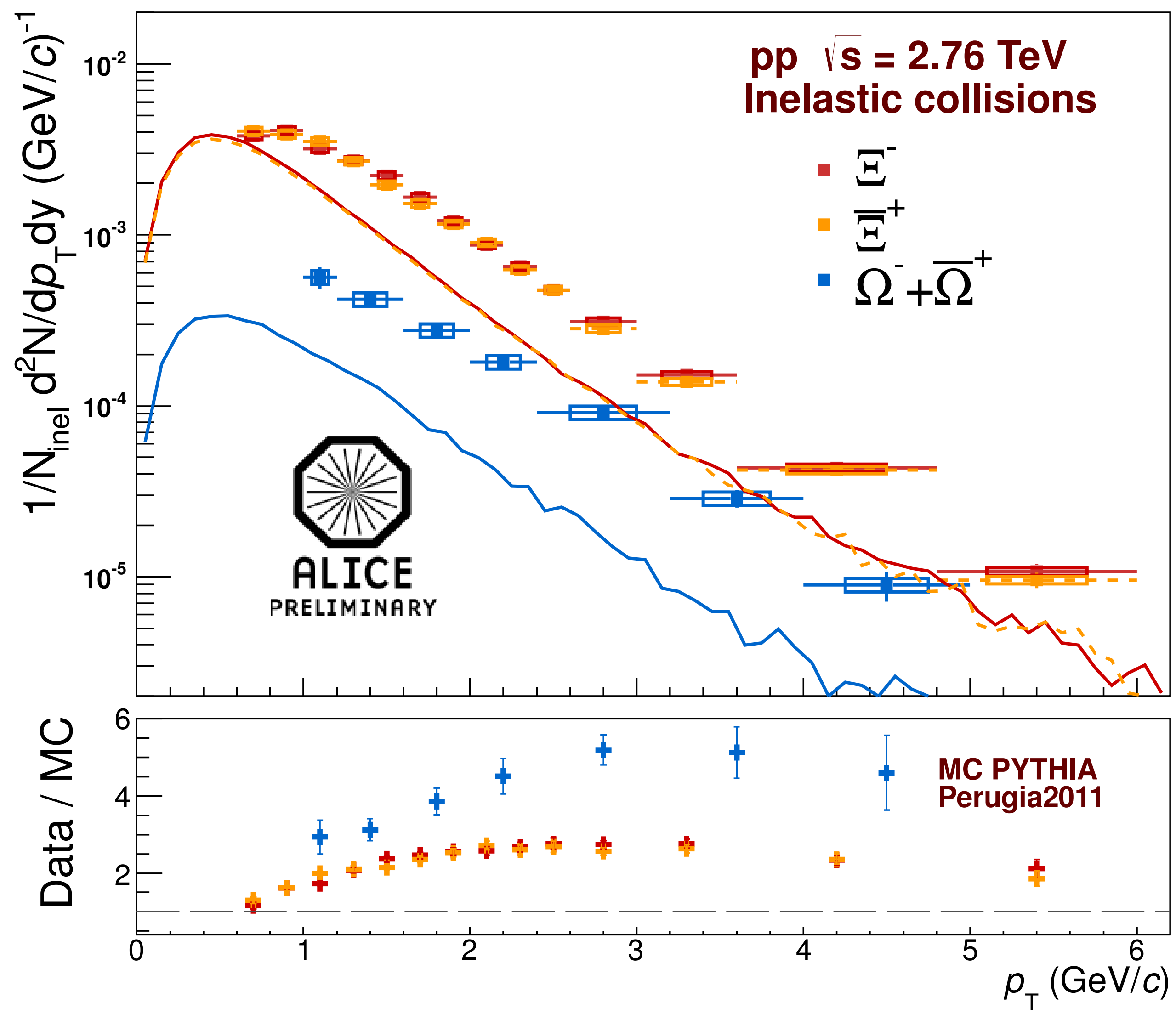
Torrieri/Rafelski*
measured K^{*0}/K^{-}
T_{ch} = 156 MeV
→ Prediction: Lifetime ≥ 2 fm/c



*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)

Strangeness production in pp





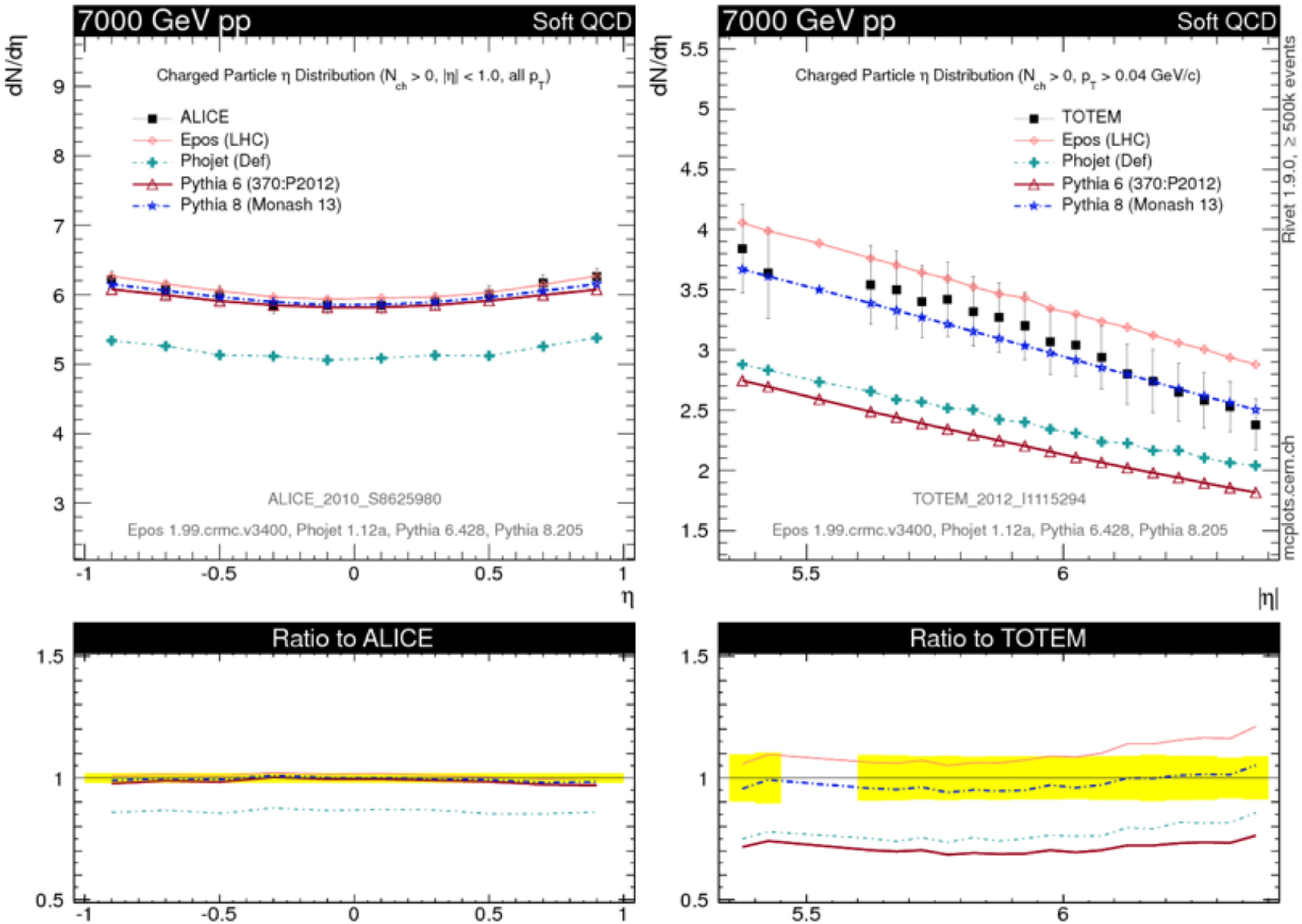
precise measurement of strange and multi-strange production in pp compared with several event generators

deviations in the soft region, increase with strangeness content

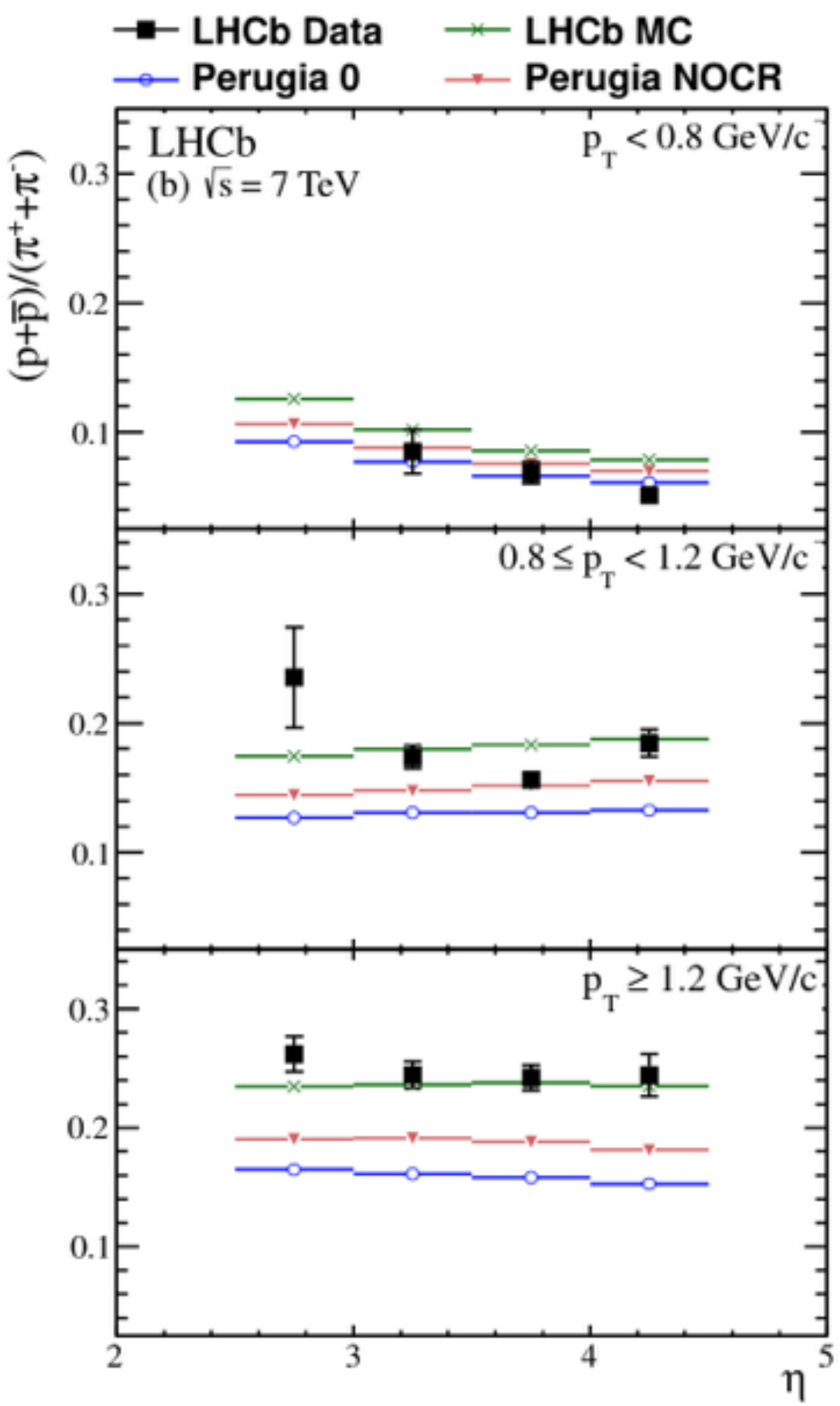
hint for possible agreement at higher p_T

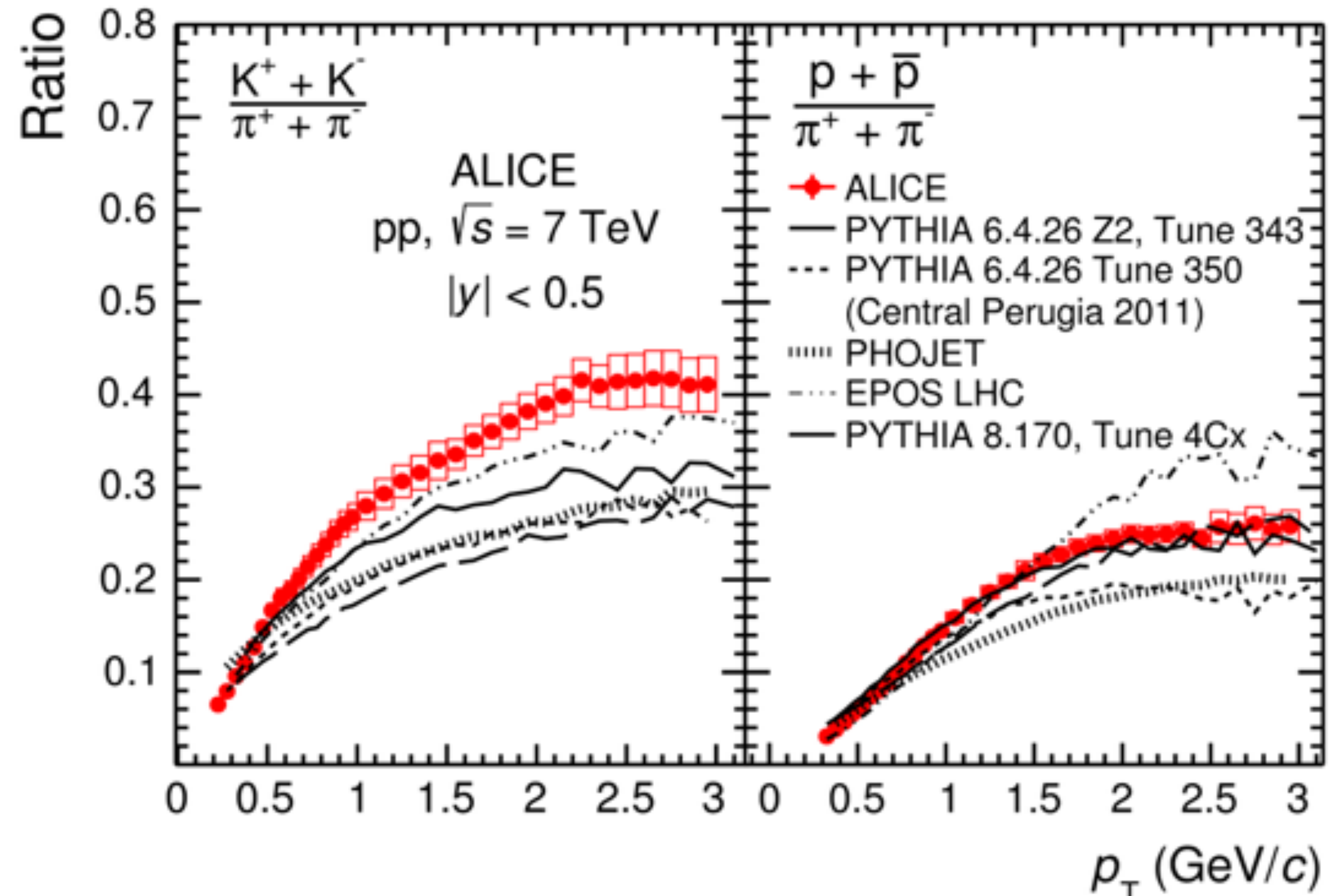
ALICE, PLB 712 (2012) 309

Multiplicity in pp



π K p production





π, K and p

most abundantly produced stable particles measured over a very wide rapidity range

reference for Pb-Pb studies

significant **constraints for soft and pQCD models and FF**