Fourth Annual Conference On
Large Hadron Collider Physics

Soft probes in heavy-ion collisions at the LHC

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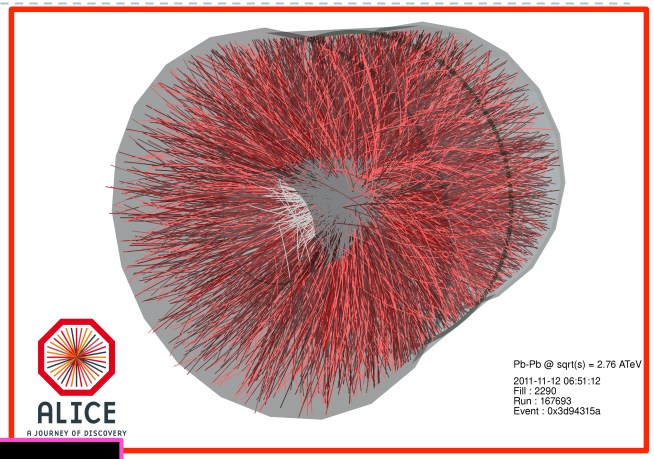
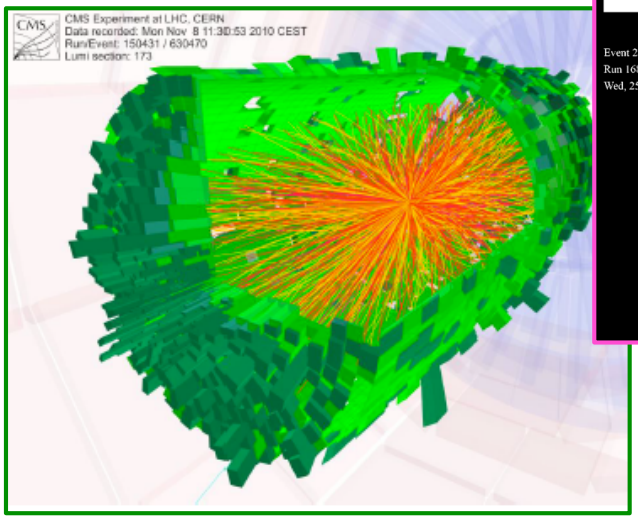
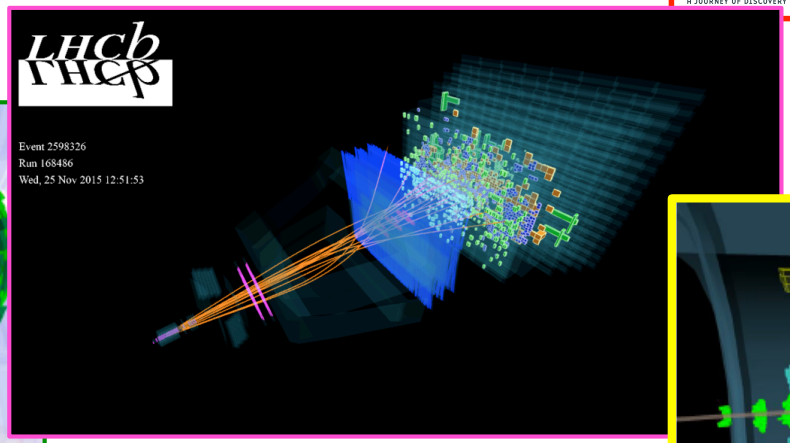
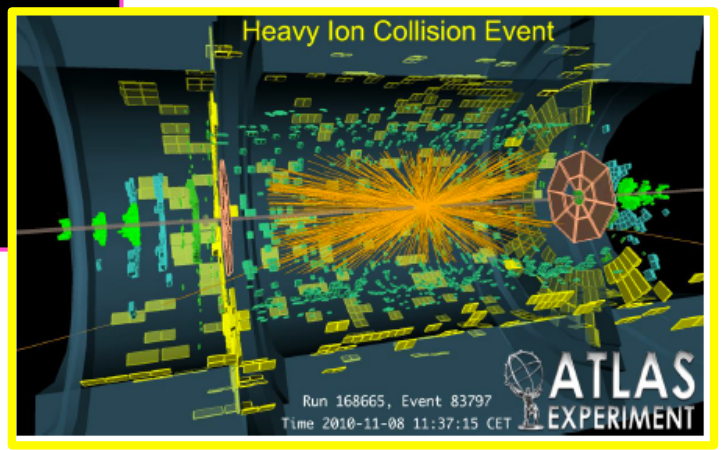
Outline

- Introduction on heavy-ion physics
- Selection of results
  - Global properties
  - Soft probes in nucleus-nucleus collisions
  - Collectivity in p-Pb collisions









This is far from being an exhaustive summary of the soft heavy-ion physics

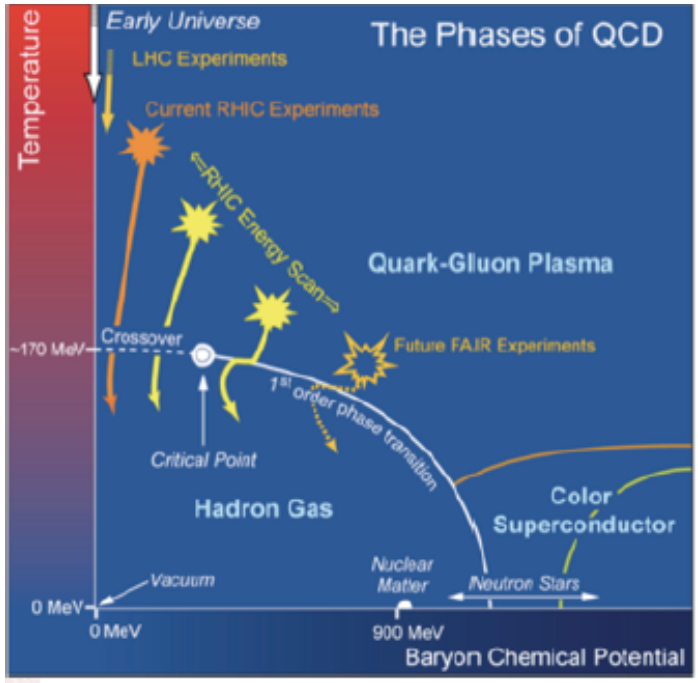
Heavy-ion physics

study QCD matter under extreme conditions

high temperature and/or energy-density

that undergoes a phase transition

hadronic matter → deconfined quarks and gluons (QGP)



past: GSI SIS ~2 GeV
BNL AGS ~5 GeV
CERN SPS ~20 GeV

present: BNL RHIC ~200 GeV
CERN LHC ~5 TeV

future: CERN HI-LHC
GSI FAIR ~45 GeV

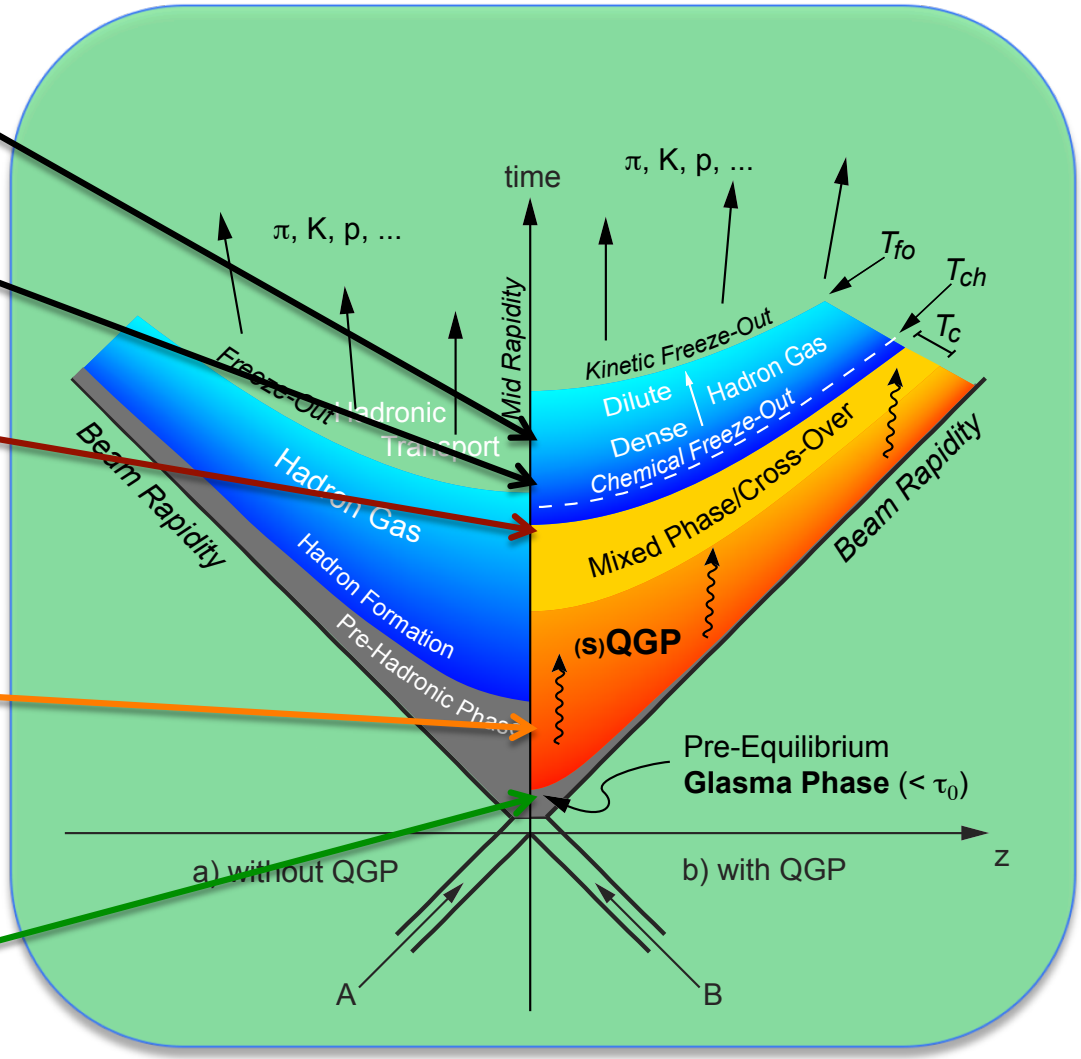
Nucleus-Nucleus collision: a process

Freeze-out:
- chemical: particle compositions is fixed (no more inel. Collisions)
→ $T_{ch} \cong$ 160 MeV
- thermal: momentum spectra are fixed (no more elastic collisions)
→ $T_{f0} \cong$ 110÷ 130 MeV

Soft processes:
- high cross section
- decouple late – indirect signals for QGP

Photons (real and virtual):
- insensitive to the hadronization phase

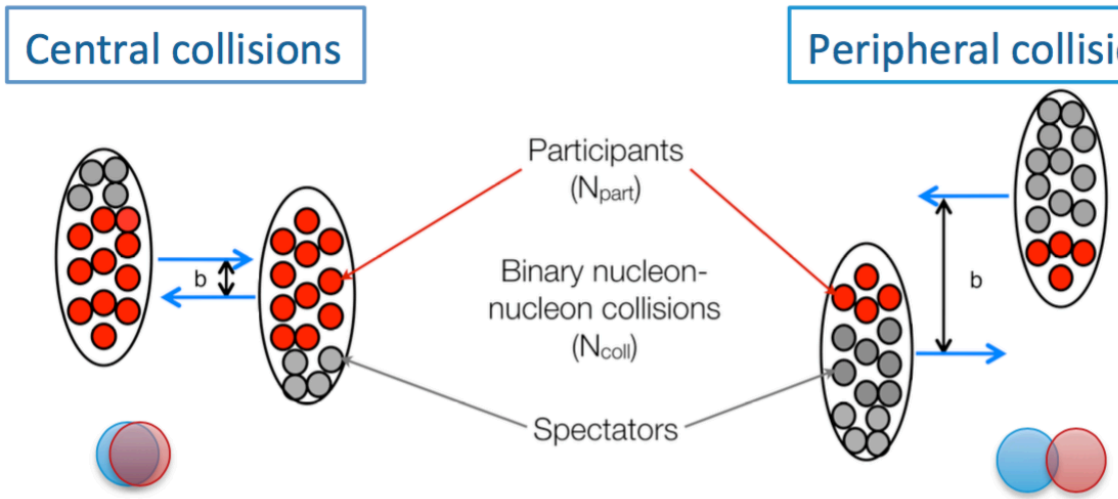
Hard processes:
- Charm, Beauty, Jets
- Probe the whole evolution of the collision
- Thermalization time (RHIC)
$\tau_{th} \cong$ 0.6 fm/c

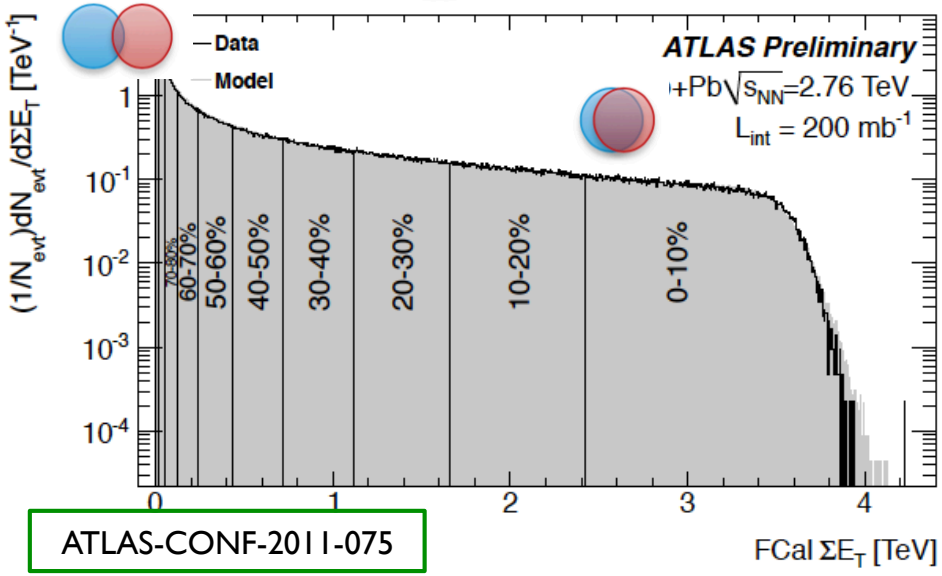


Global event features

Centrality estimation

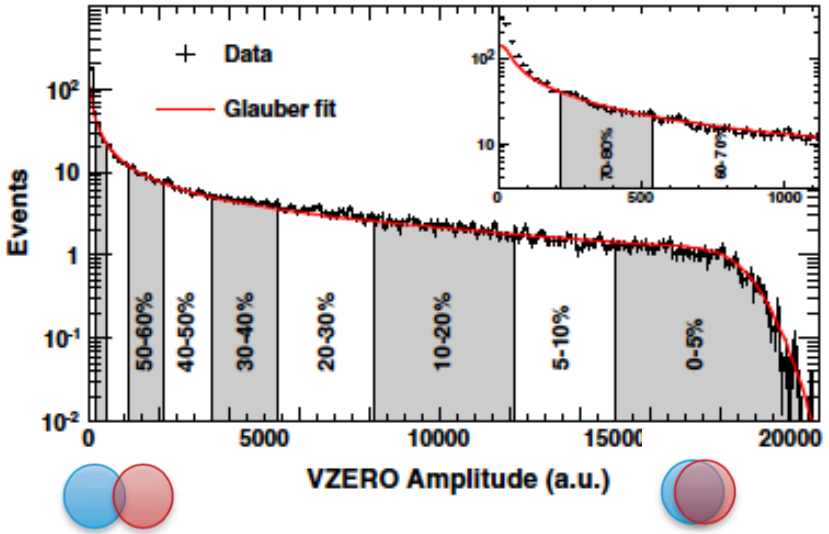
A-A collisions can be characterized by the centrality, defined through b, N_{part} (N_{spec})



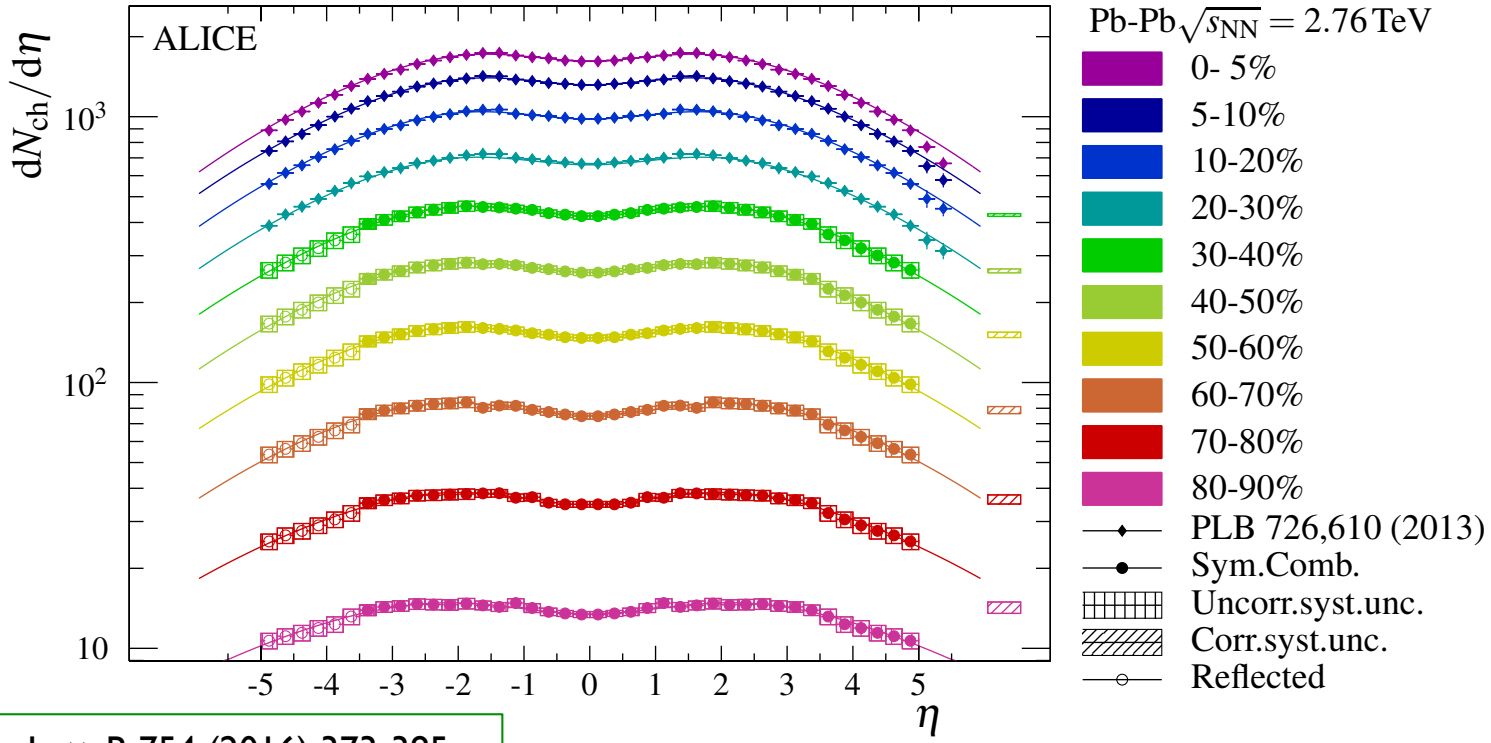


ATLAS-CONF-2011-075

ALICE PRL 113 (2011) 032301



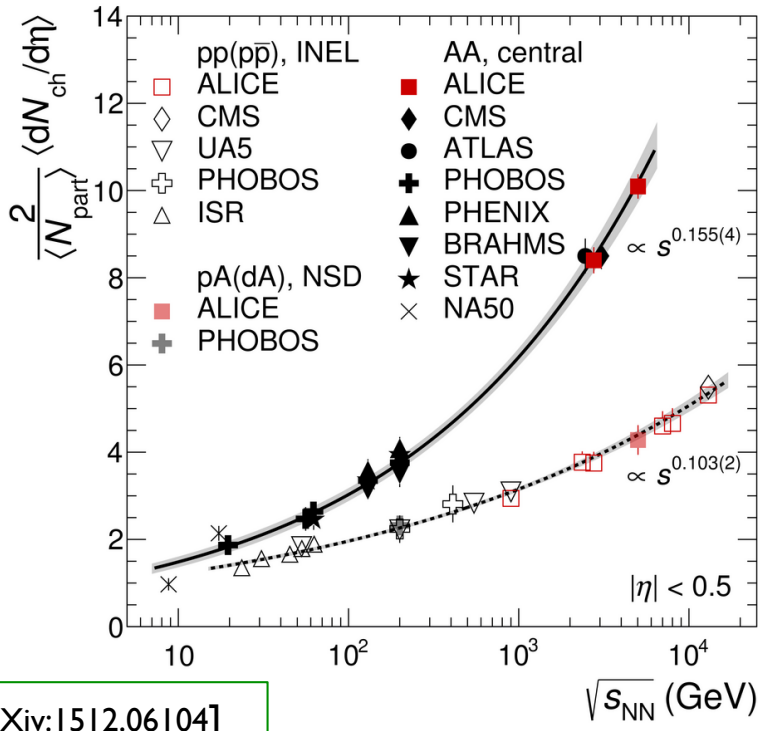
Pb-Pb @ 2.76 TeV: charged particle multiplicity



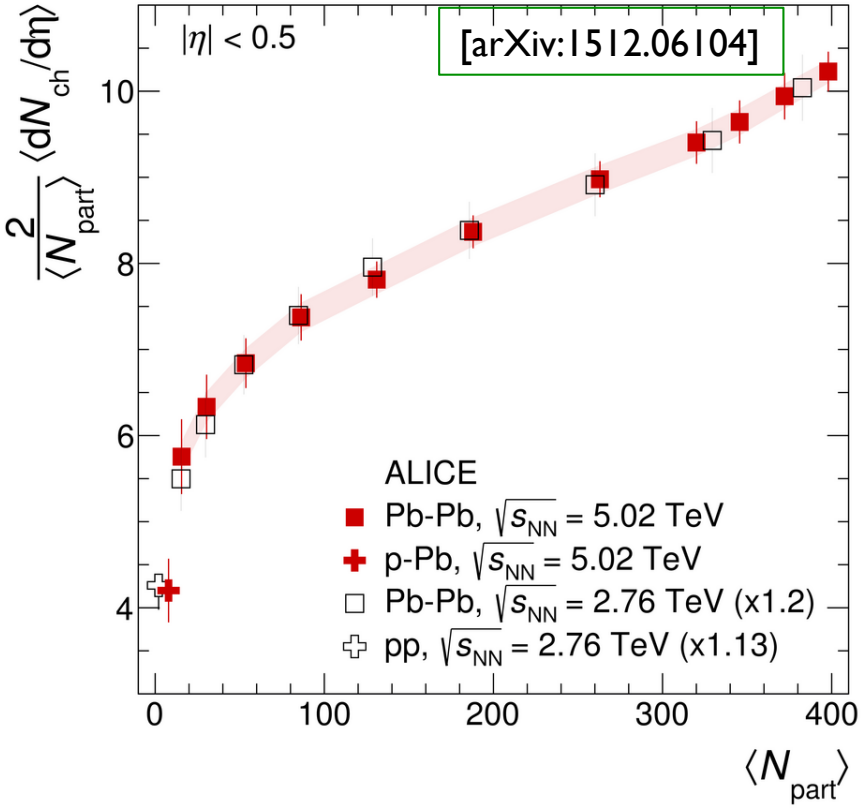
Phys. Lett. B 754 (2016) 373-385

- Charged particle multiplicity has been measured in a wide pseudo rapidity range (-3.5< η <5)
- the total number of charged particles ranges from
162 ± 22 for centrality class 80-90% to 17170 ± 770 for centrality class 0-5%
- in the central barrel they can be also identified over a broad momentum range

Pb-Pb @ 5.02 TeV: charged particle multiplicity



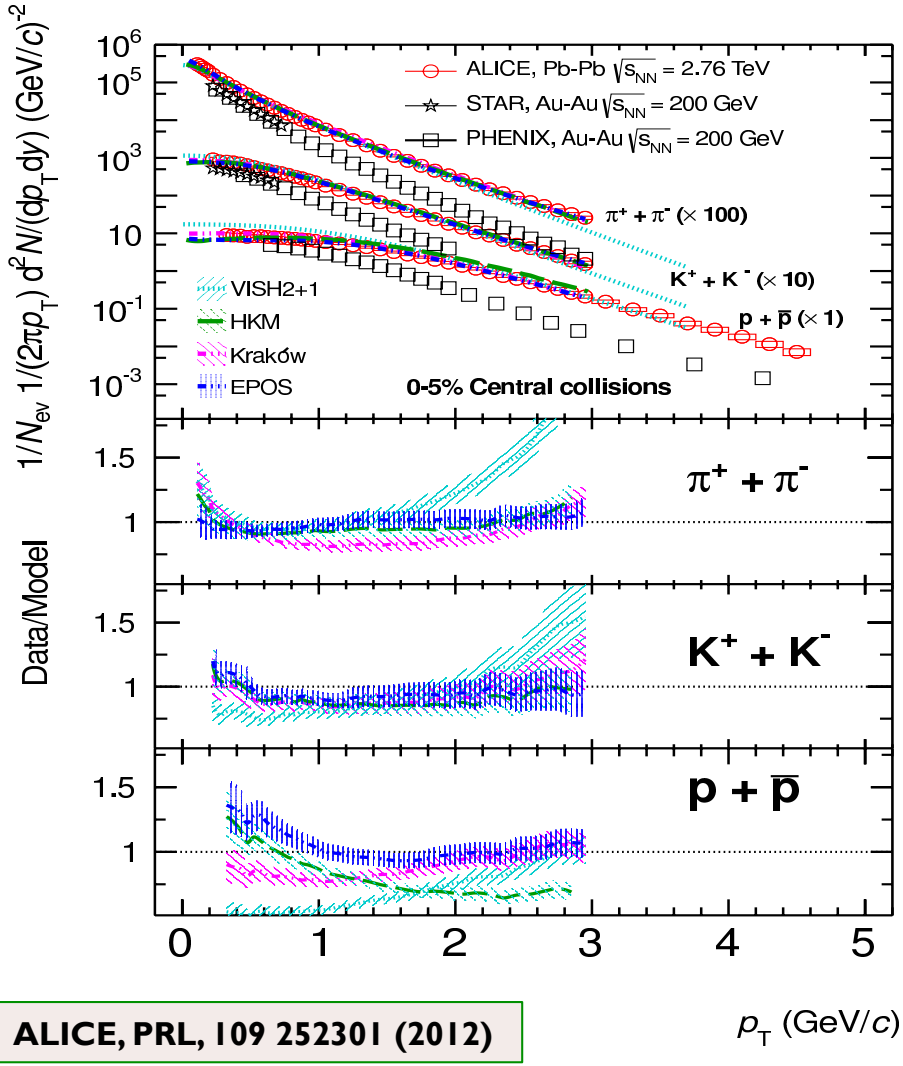
[arXiv:1512.06104]

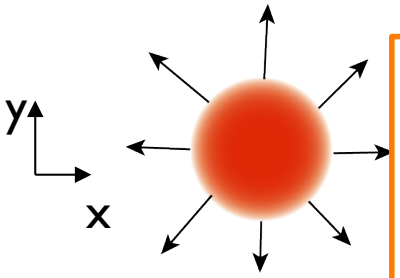


- for the 5% most central collisions: $\langle dN_{ch}/d\eta \rangle = 1943 \pm 54$ in $|\eta| < 0.5$
- steeper rise with the centre-of-mass energy
- centrality dependence: a factor of ~1.2 describes the increase from 2.76 to 5.02 TeV
- essential constraints for models

Bulk properties and collective expansion

Bulk particle production in Pb-Pb





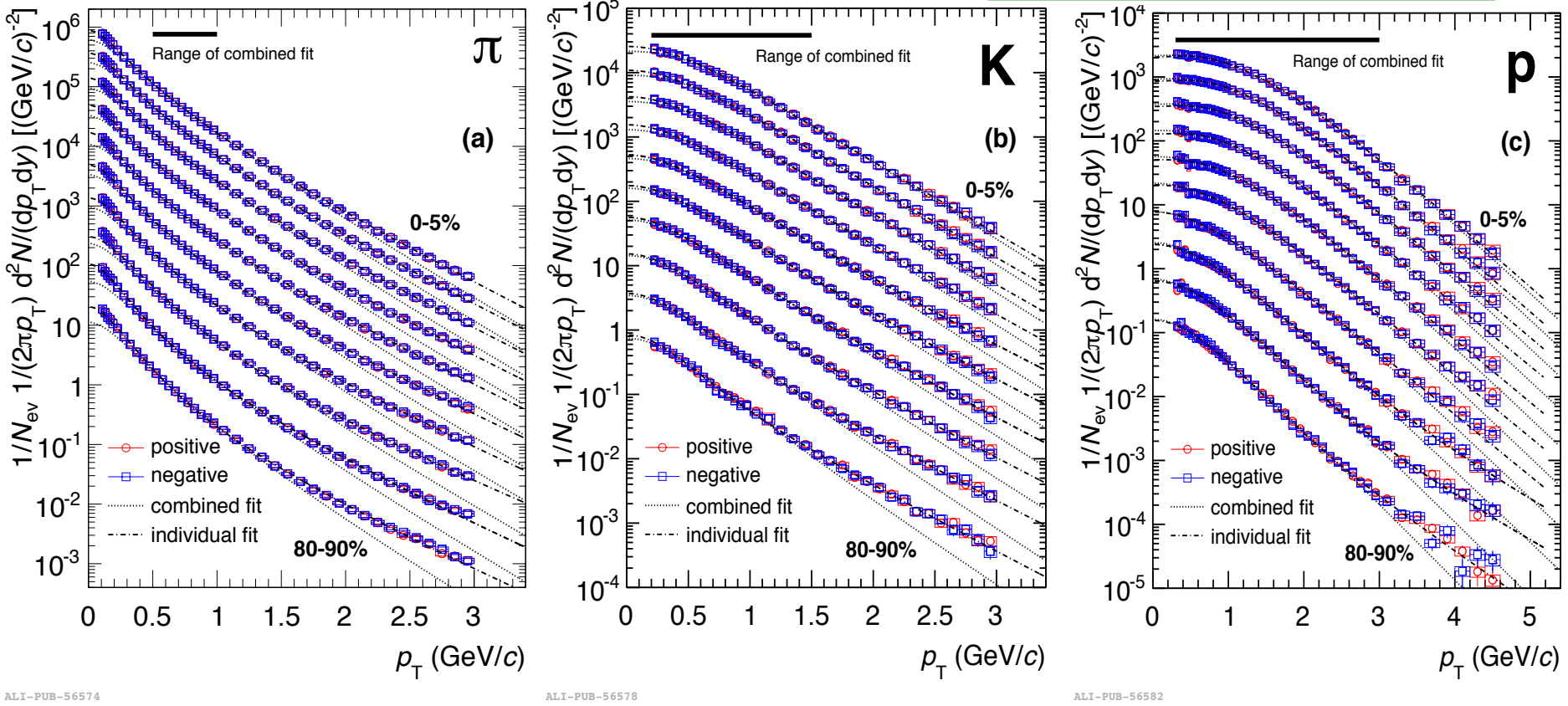
In a thermalized system the radial expansion is driven by the pressure gradient from inside to outside, resulting in boosted p_T spectra

Simultaneous **Blast-Wave model fit to** the π, K, p spectra in central Pb-Pb collisions:
- radial flow **$<\beta_T> \approx 0.65$ ~10% larger** than at RHIC
- kinetic freeze-out temperature ***$T_{kin} \approx 95$ MeV***

ALICE, PRL, 109 252301 (2012)

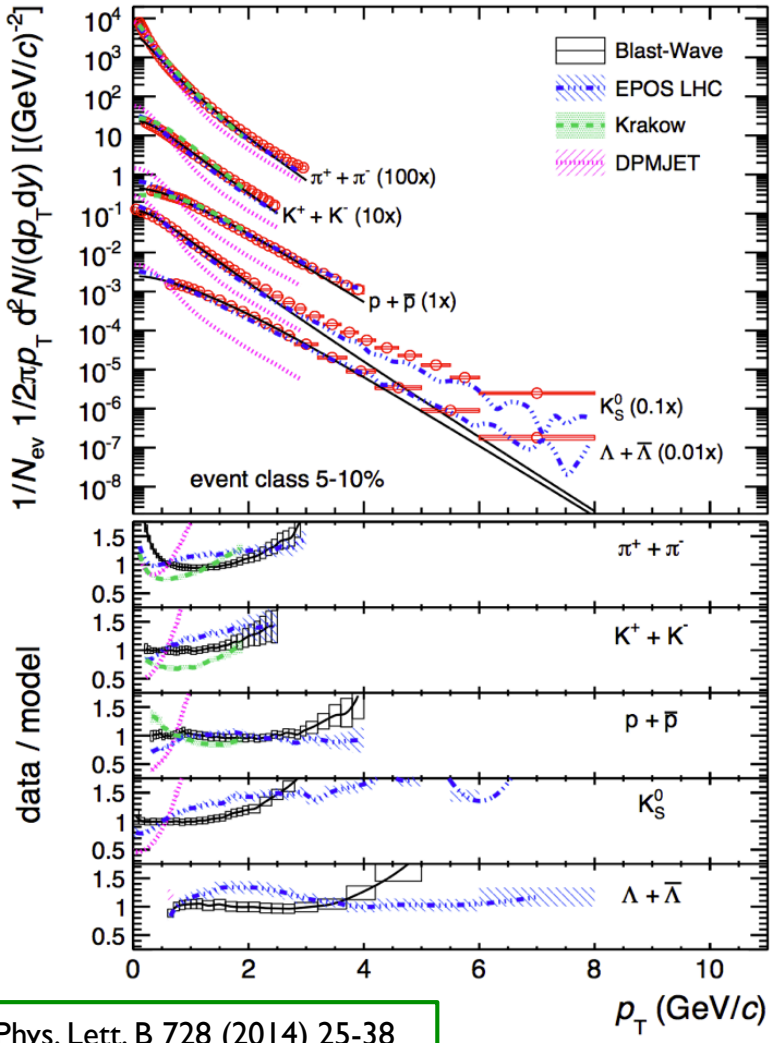
Bulk particle production in Pb-Pb

ALICE, Phys. Rev. C 88, 044910 (2013)



Clear evolution: hardening of the spectrum with increasing centrality
It is more pronounced for the heavier particles
→ ***Mass ordering*** *as* expected from collective hydro expansion

Bulk production in p-Pb

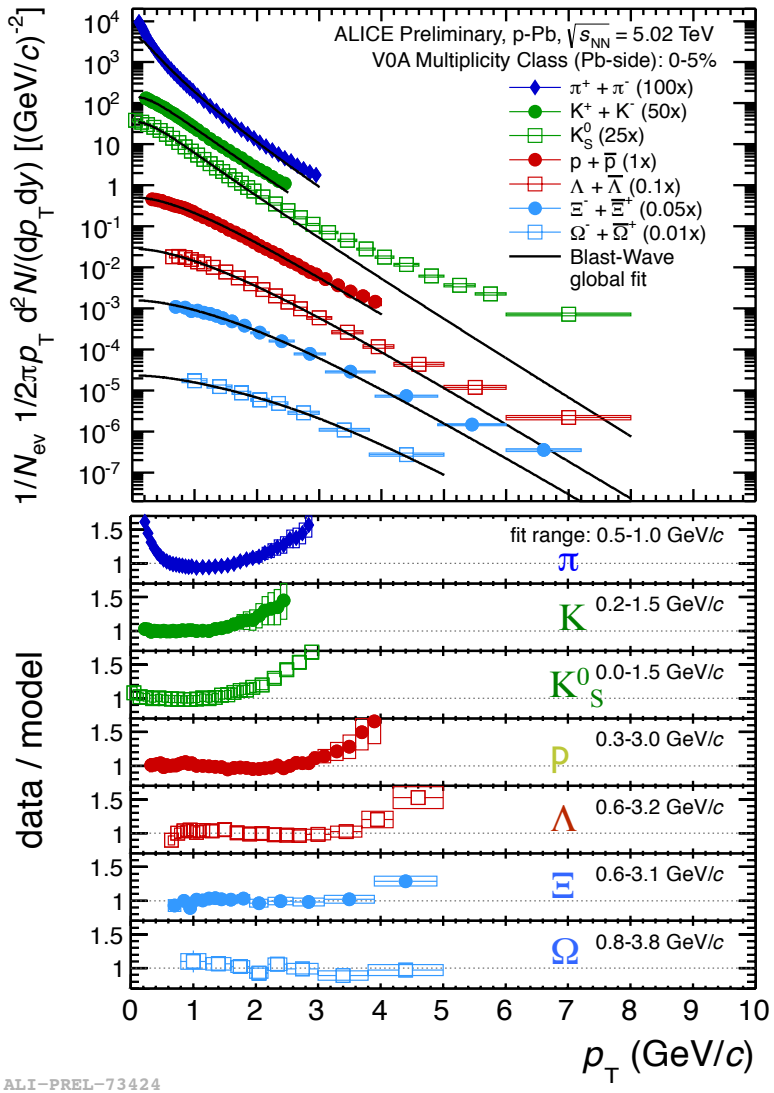


Phys. Lett. B 728 (2014) 25-38

Hydro models (krakow EPOS-LHC) reproduce data better than QCD inspired models (DPMJET)

A combined BW fit describes the spectra fairly well also in p-Pb

Bulk production in p-Pb



ALI-PREL-73424

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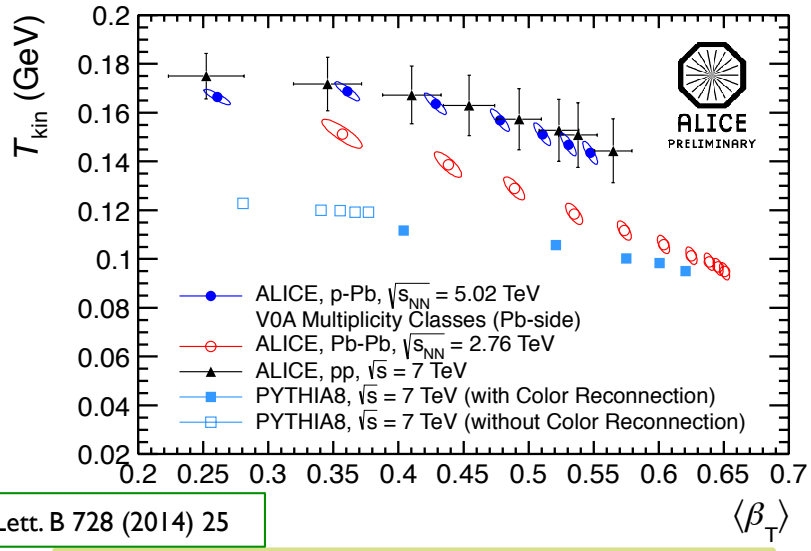
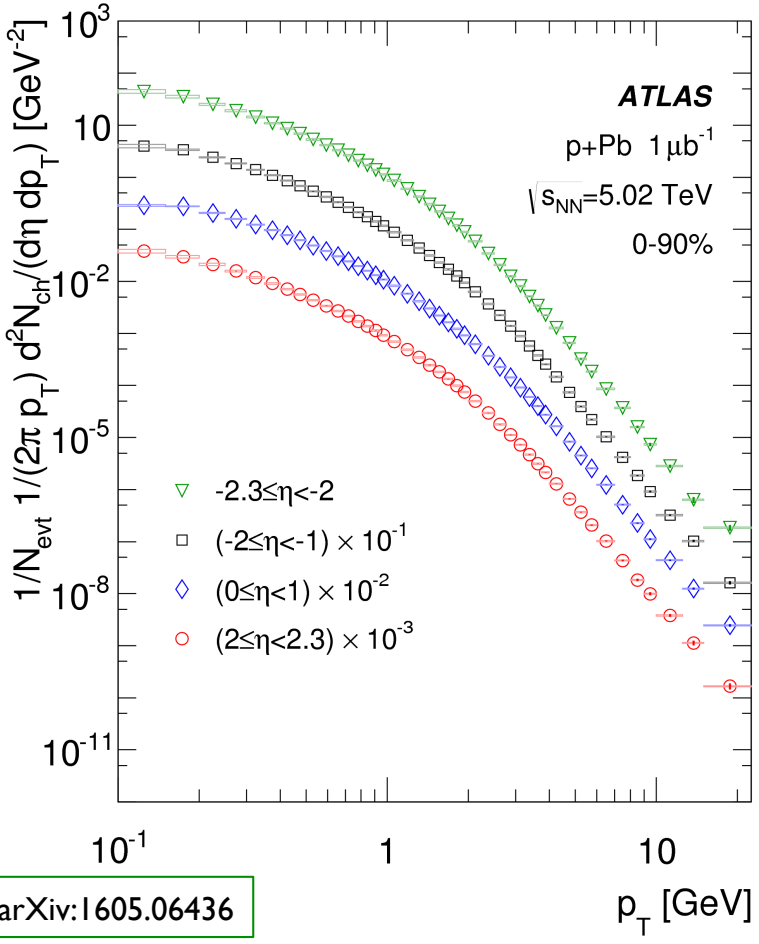


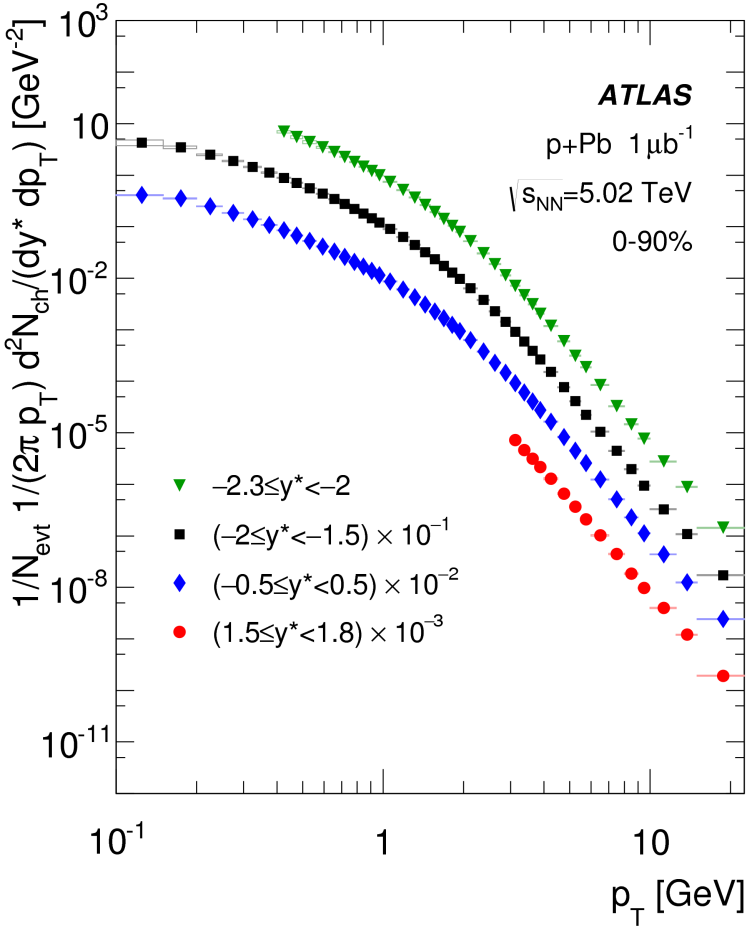
ALICE, Phys. Lett. B 728 (2014) 25

similar trends in the T_{kin}-$<\beta_T>$ correlation for **pp and p-Pb**

Qualitatively PYTHIA (with Color Reconnection) shows a similar trend as the data
→ other final state mechanisms can mimic the effects of radial flow!

Bulk production in p-Pb

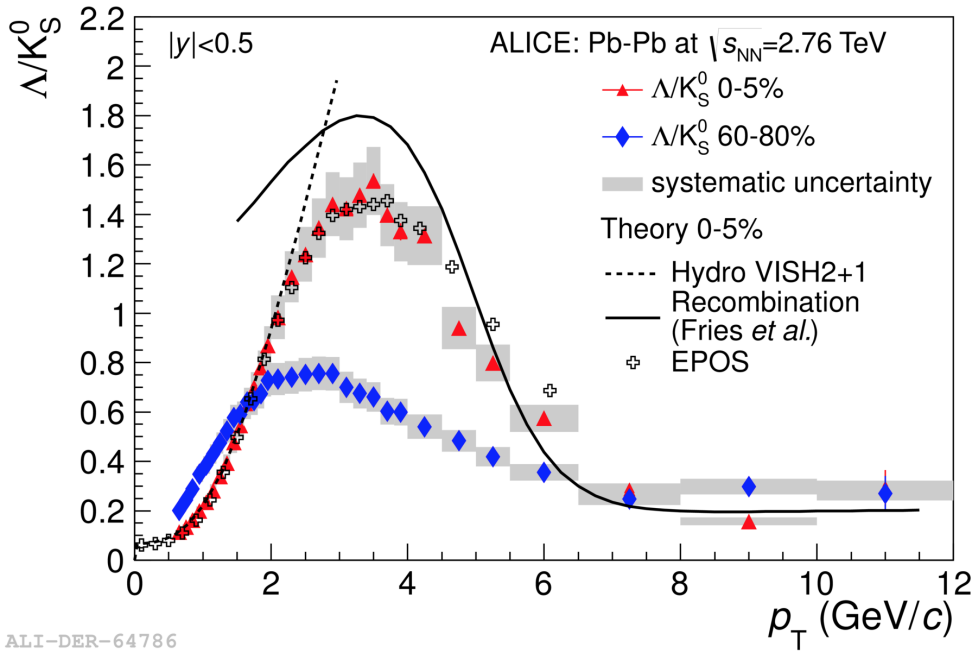




ATLAS, arXiv:1605.06436

differential invariant yields as a function of charged-particle transverse momentum for several intervals of η and y*

Baryon-to-meson ratio in Pb-Pb

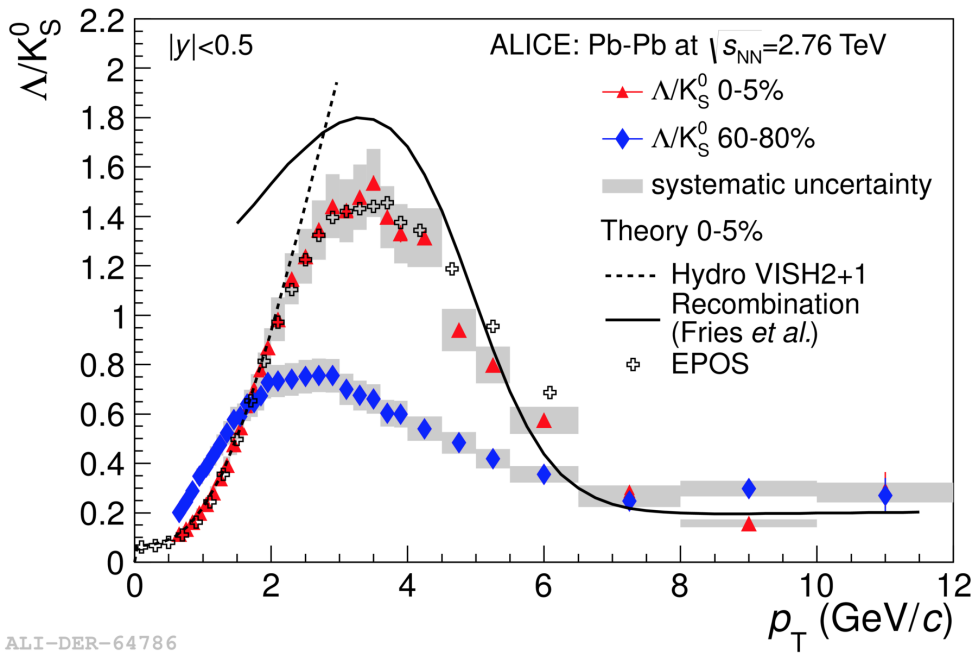


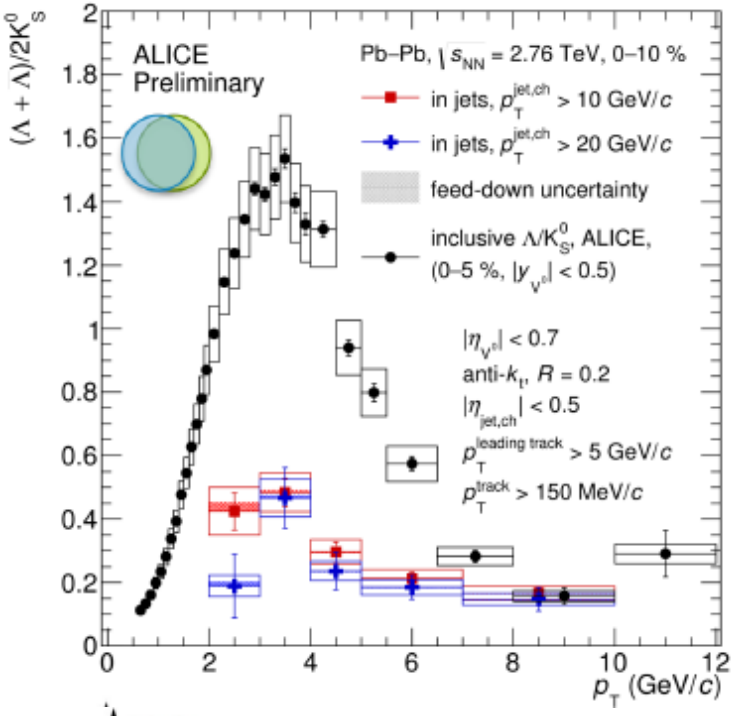
ALICE, Phys. Rev. Lett. 111 (2013) 22301
Song, Phys. Lett. B 658 (2008) 279
Fries et al. , Ann. Rev. Nucl. Part. Sci. 58 (2008) 177
Werner, Phys. Rev. Lett. 109 (2012) 102301

Ratio enhancement at intermediate p_T

- **Hydro** describes only the rise < 2 GeV/c
- **Recombination** overestimates the effect
- **EPOS** gives good description of the data (with **flow**)

Baryon-to-meson ratio in Pb-Pb





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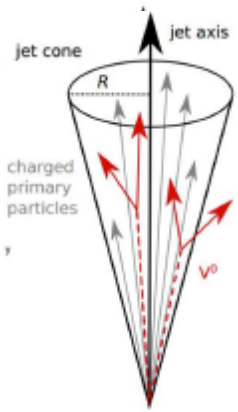
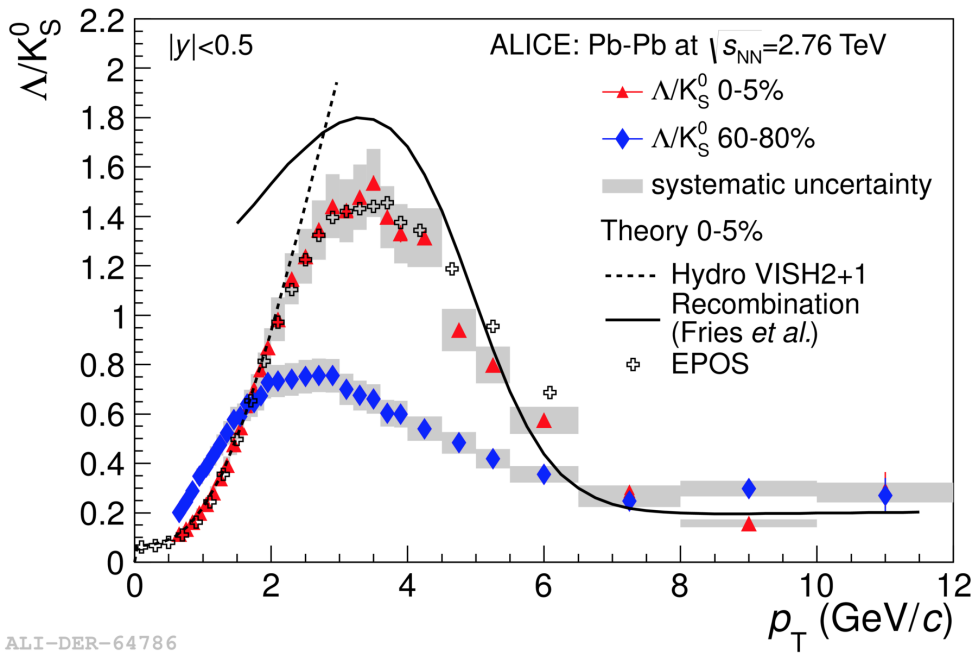
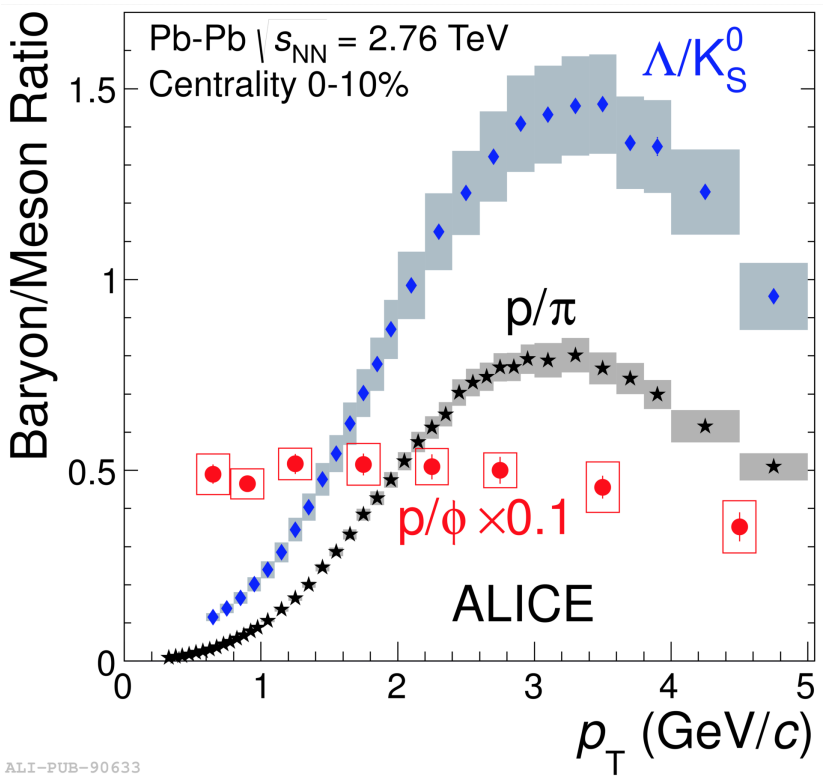


B/M ratio in jets significantly lower than in inclusive
→baryon excess w.r.t basic fragmentation picture is not seen in jets, but arises from the bulk

Baryon-to-meson ratio in Pb-Pb



ALICE, Phys. Lett. B 728 (2014) 25-38
ALICE, Phys. Rev. C 91 (2015) 024609



Ratio enhancement at intermediate p_T

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Flat p/φ ratio
Mass dependence of the spectral shapes (**hydro**)

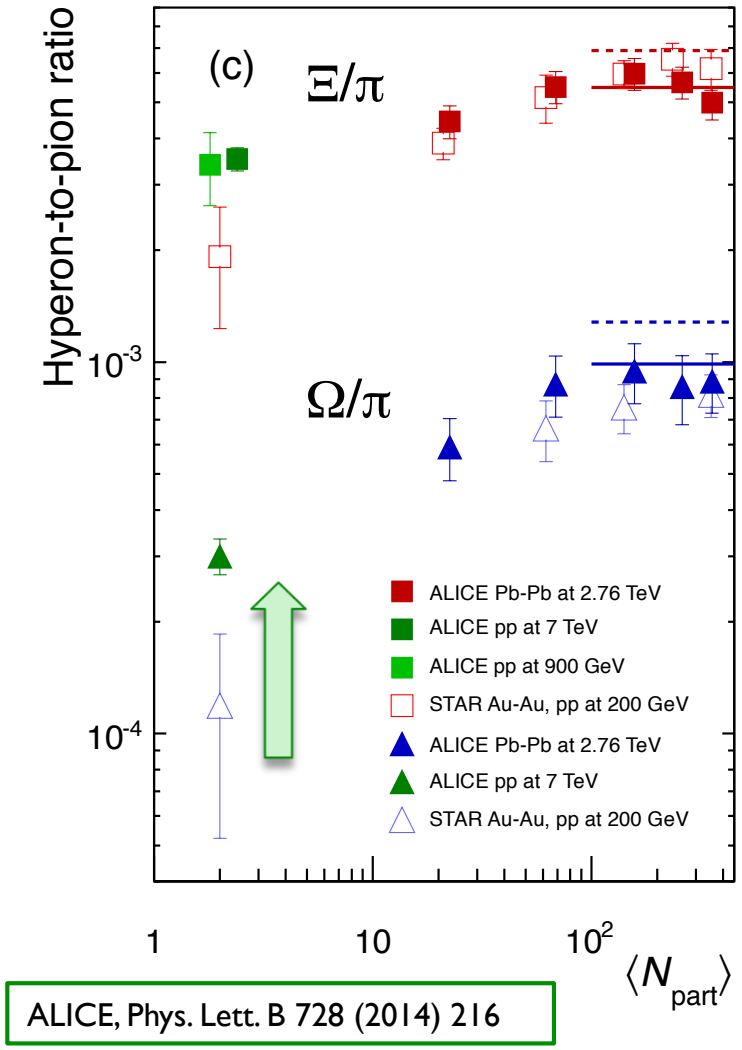
Strangeness enhancement

Long-standing ideas

– J. Rafelski and B. Müller PRL, 48, 106-1069 (1982)

– J. Rafelski and R. Hagedorn, in *Statistical Mechanics of Quark and Hadrons*

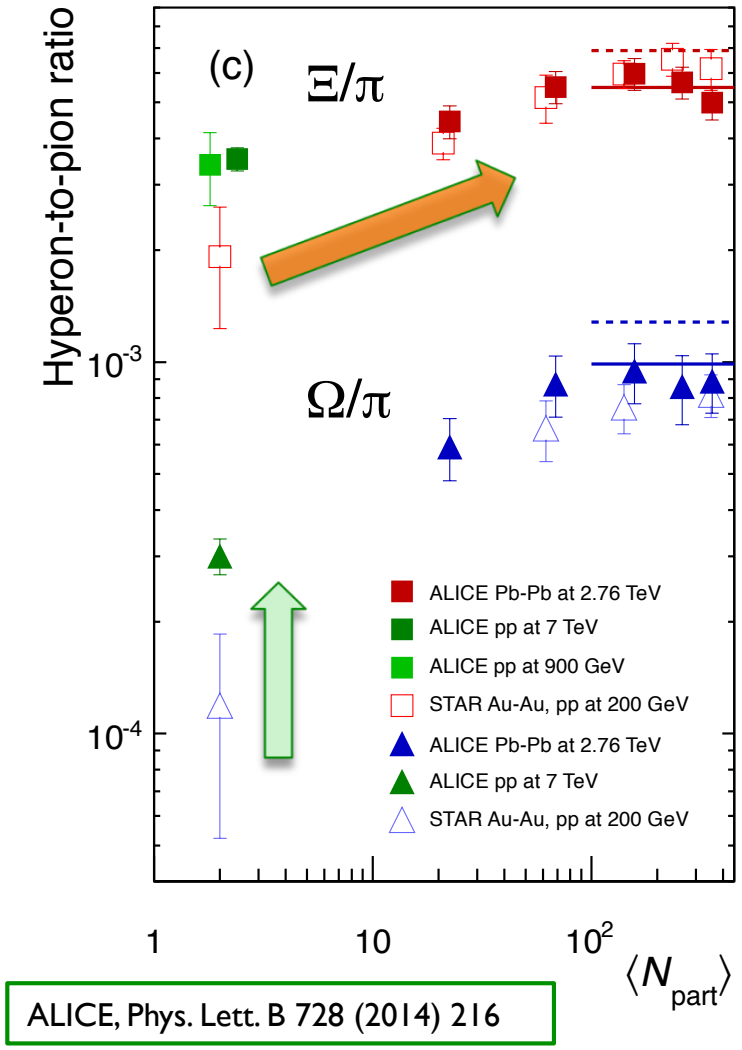
Strangeness ehancement in PbPb



ALICE, Phys. Lett. B 728 (2014) 216

In **pp collisions** the production of strangeness relative to π at LHC is larger than at RHIC

Strangeness ehancement in PbPb

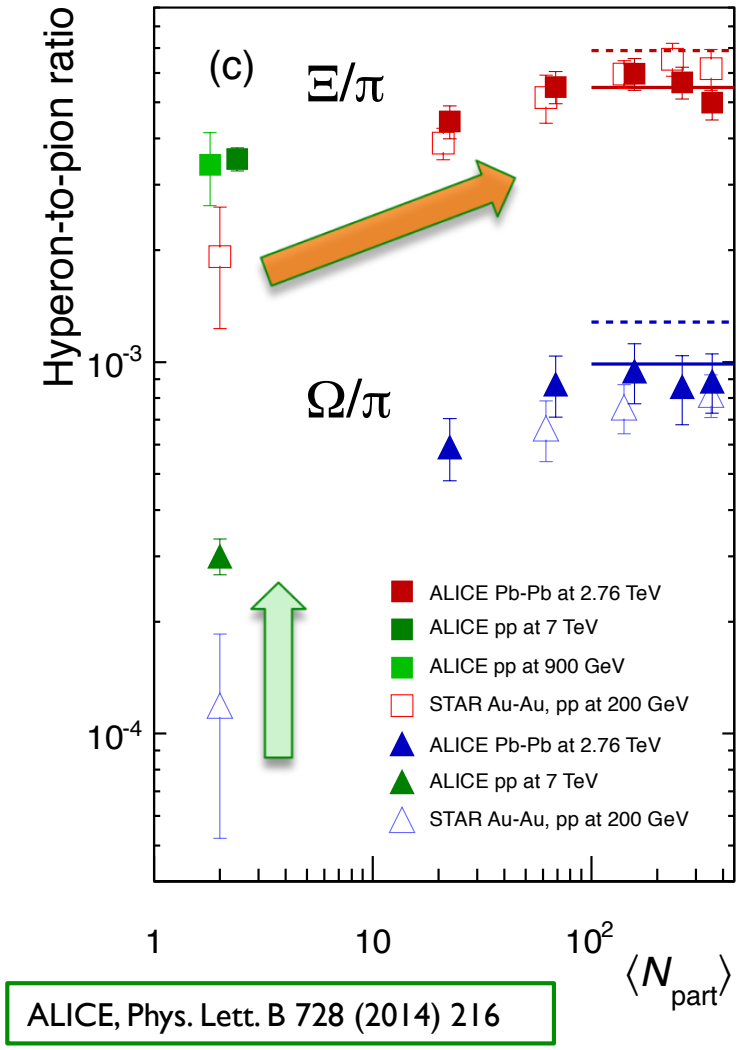


ALICE, Phys. Lett. B 728 (2014) 216

In **pp collisions** the production of strangeness relative to π at LHC is larger than at RHIC

From pp to Pb-Pb strangeness production increases

Strangeness ehancement in PbPb



ALICE, Phys. Lett. B 728 (2014) 216

In **pp collisions** the production of strangeness relative to π at LHC is larger than at RHIC

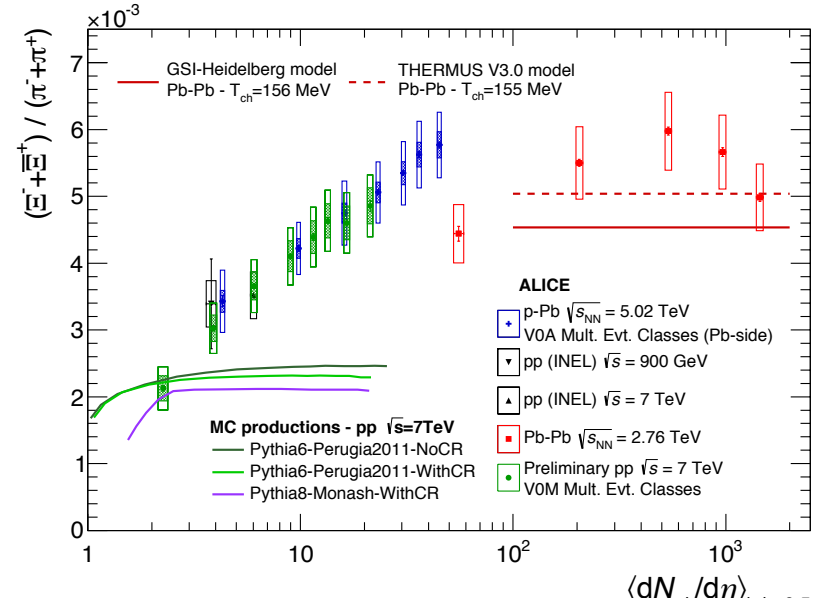
From pp to Pb-Pb strangeness production increases

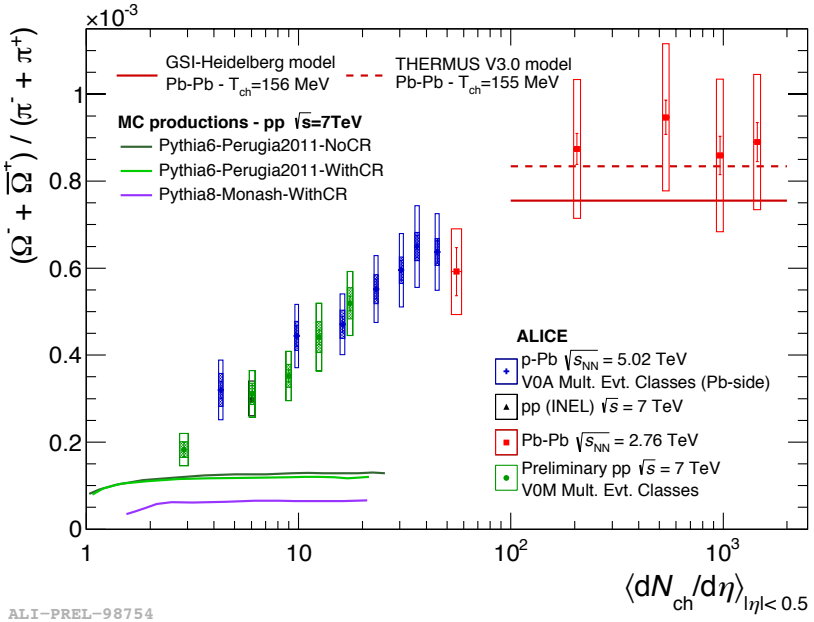
For N_{part} >150 the ratios saturate and match predictions from the grand-canonical thermal models

—— GSI-Heidelberg: T_{ch} = 164 MeV

----- THERMUS: T_{ch} = 170 MeV

Strangeness ehancement in PbPb





ALI-PREL-98754

In **pp collisions** the production of strangeness relative to π at LHC is larger than at RHIC

From pp to Pb-Pb strangeness production increases

Talk by A. Mischke in this session

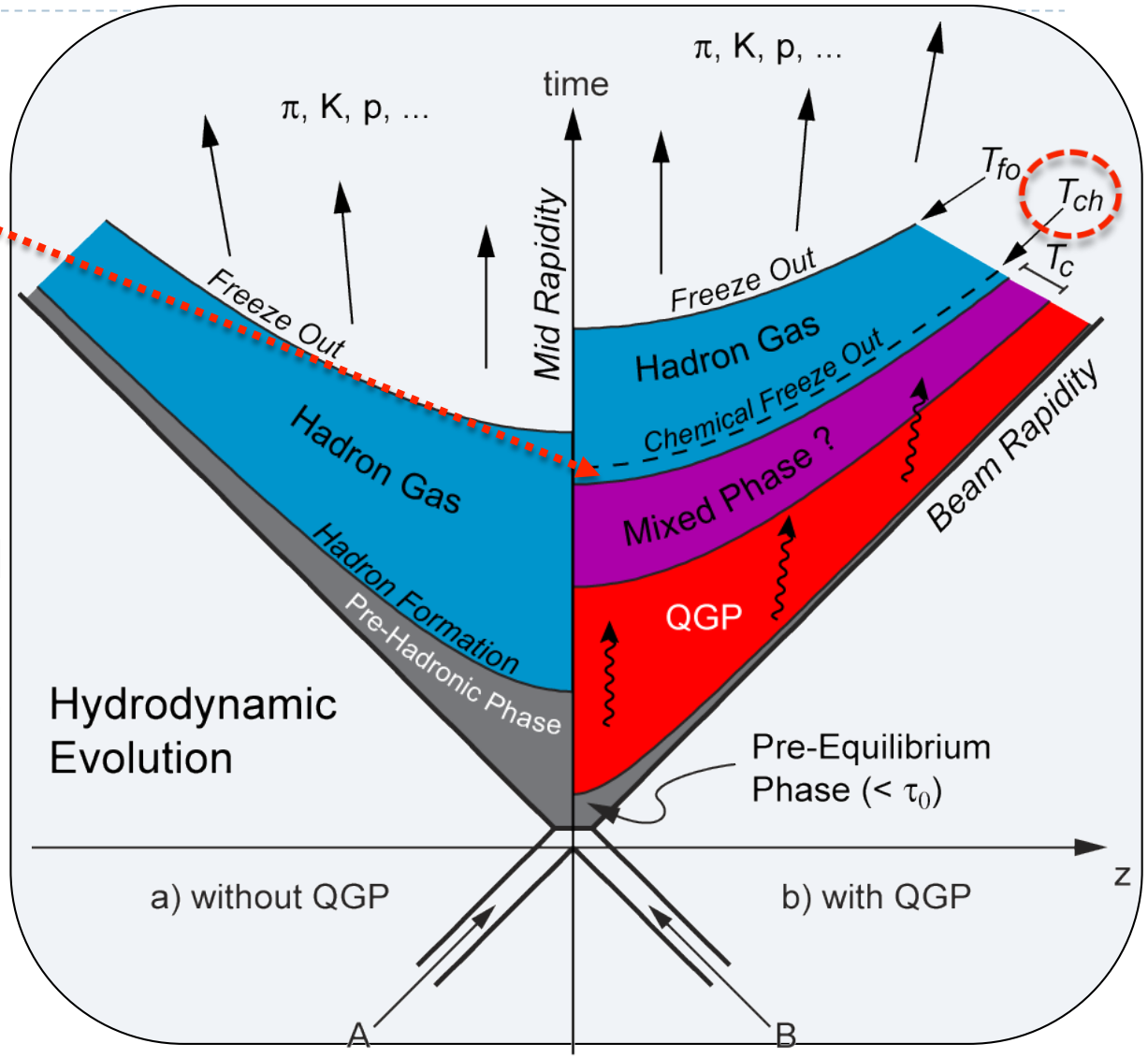
In high-multiplicity p-Pb
- Ξ /π compatible with central Pb-Pb
- Ω /π compatible with 60-80% Pb-Pb

Neither Pythia 6 nor 8 reproduces the values and the data evolution in any of the tunes tested.

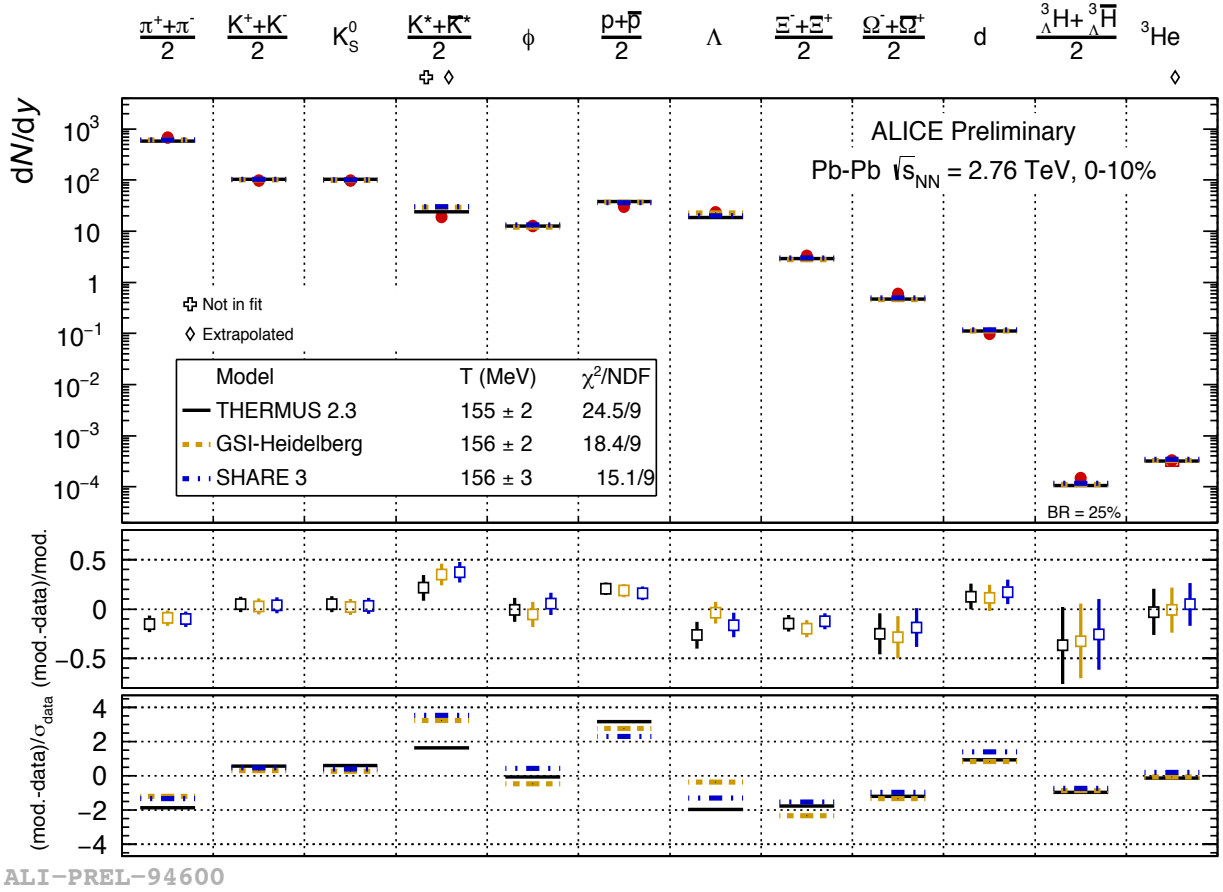
Thermal model of hadron production

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

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

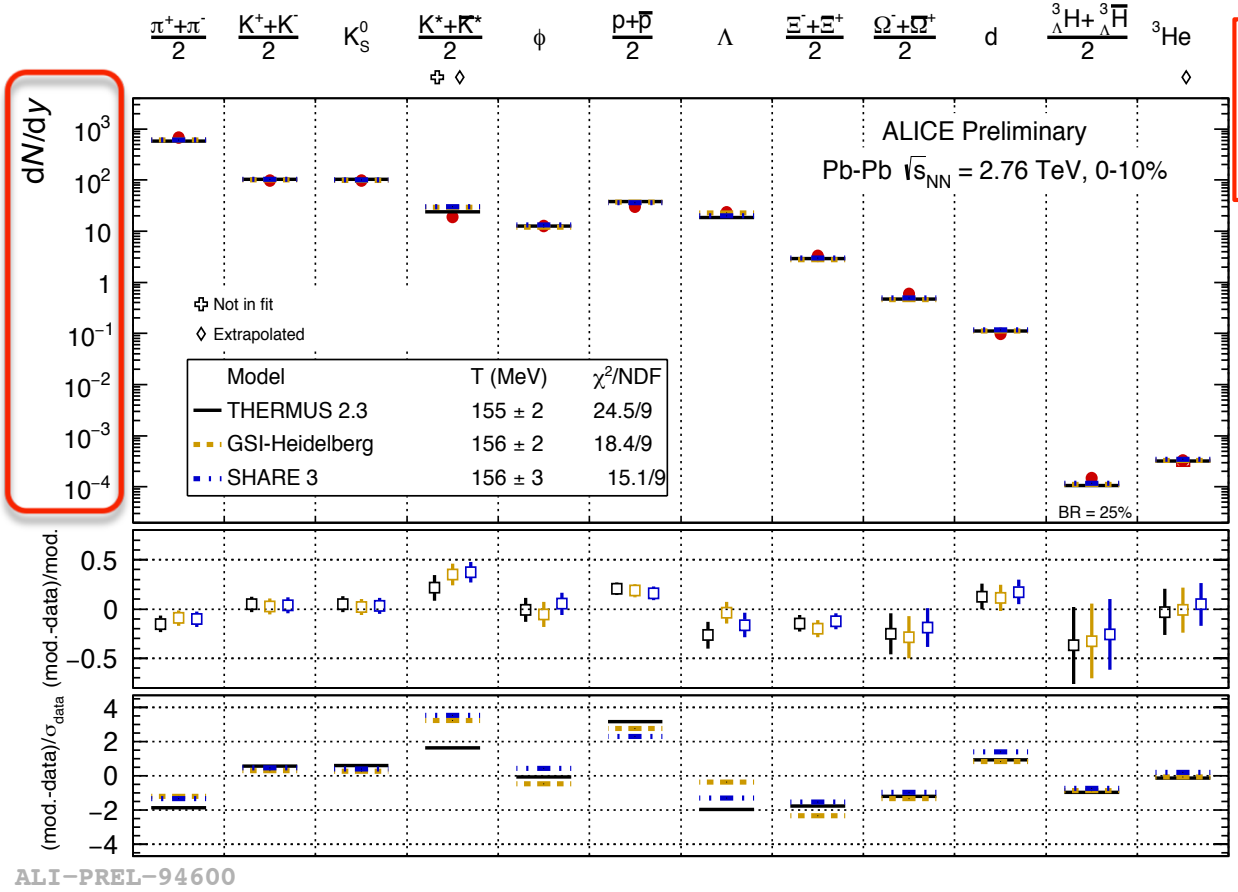


Thermal model fit



THERMUS: Wheaton et al, Comput. Phys. Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673, 142
SHARE: Petran et al, Comput. Phys. Commun, 185 Issue 7, 2056

Thermal model fit



- Describes hadron production assuming **chemical equilibrium over seven order of magnitude**

THERMUS: Wheaton et al, Comput. Phys. Commun, 180 84
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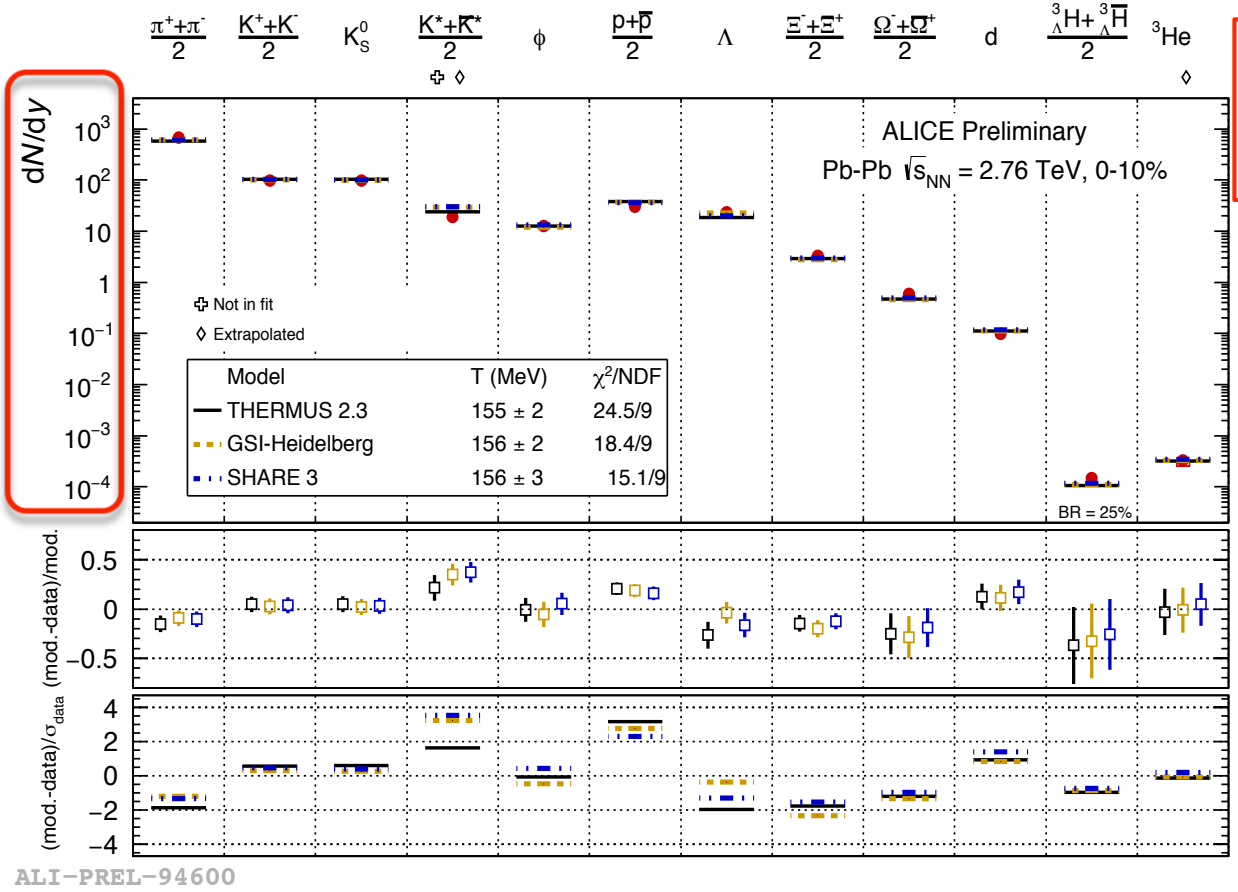

- Describes hadron production assuming **chemical equilibrium over seven order of magnitude**

- Measured absolute yields (d*N*/d*y*) in Pb-Pb collisions are well described by a thermal model with a temperature T=156 ± 2 MeV

THERMUS: Wheaton et al, Comput. Phys. Commun, 180 84
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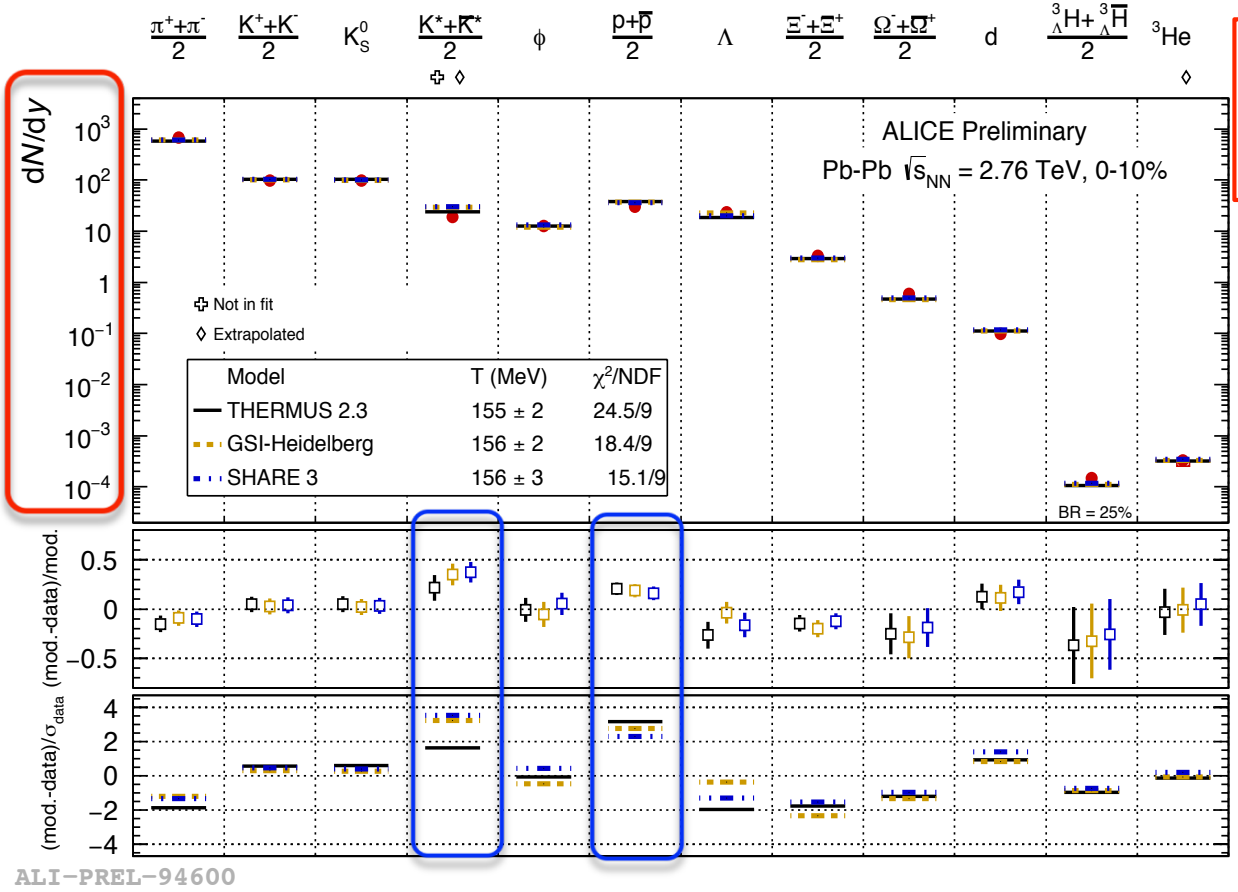
Thermal model fit



- Describes hadron production assuming **chemical equilibrium over seven order of magnitude**

- Measured absolute yields (d*N*/d*y*) in Pb-Pb collisions are well described by a thermal model with a temperature T=156 ± 2 MeV

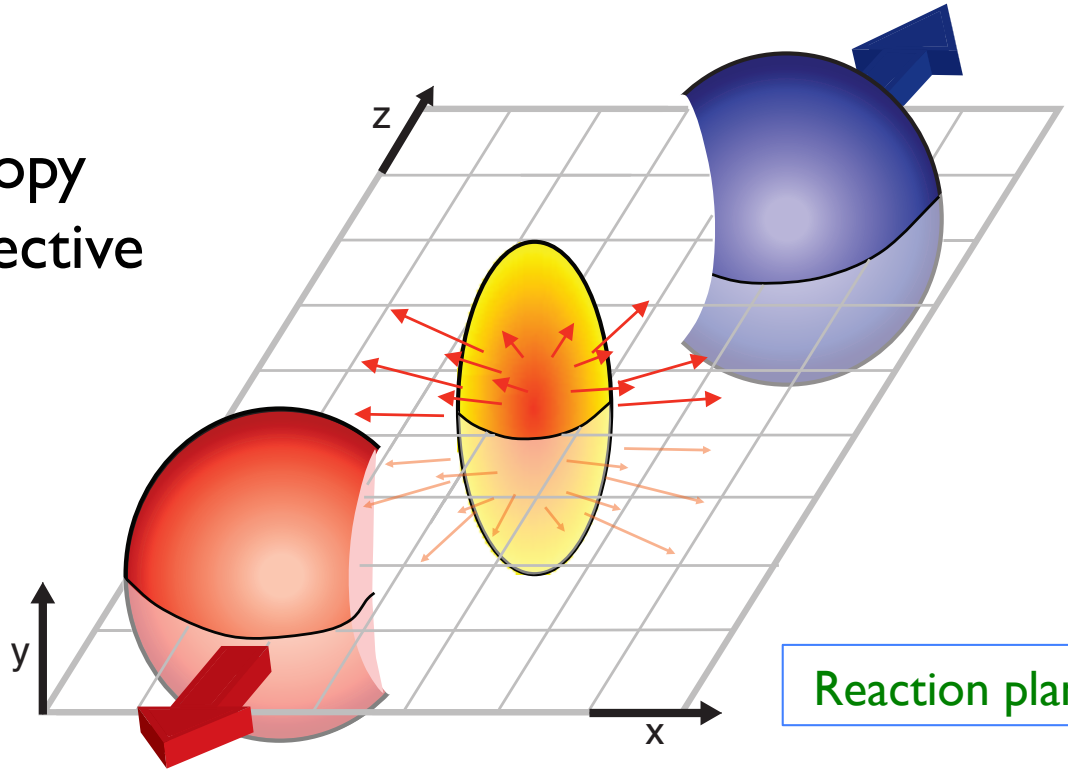
- Deviations for
  - Protons: incomplete hadron spectrum, baryon annihilation in hadronic phase, ...?
  - K^{*0} resonance: re-scattering in the late hadronic phase?

THERMUS: Wheaton et al, Comput. Phys. Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673, 142
SHARE: Petran et al, Comput. Phys. Commun, 185 Issue 7, 2056

Anisotropic flow

- Sensitivity to initial anisotropy

→indicates existence of collective phenomena (flow)

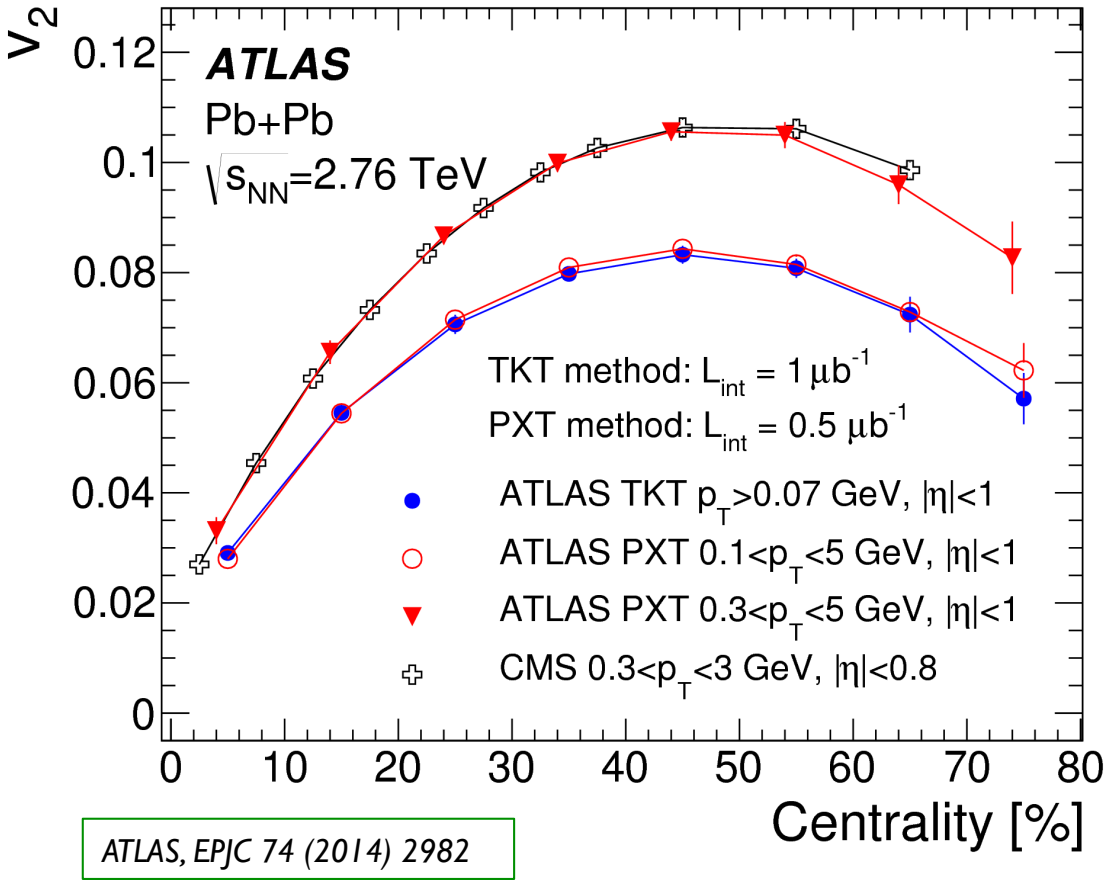


- In non-central collisions, pressure gradients convert the spatial anisotropy in momentum anisotropy

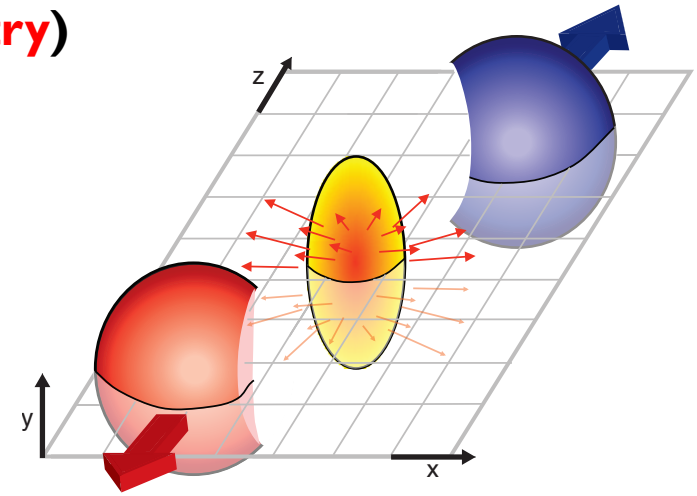
Collective anisotropic flow

spatial anisotropy (collision geometry)

⟶ anisotropy in momentum space: ***v2***



ATLAS, EPJC 74 (2014) 2982

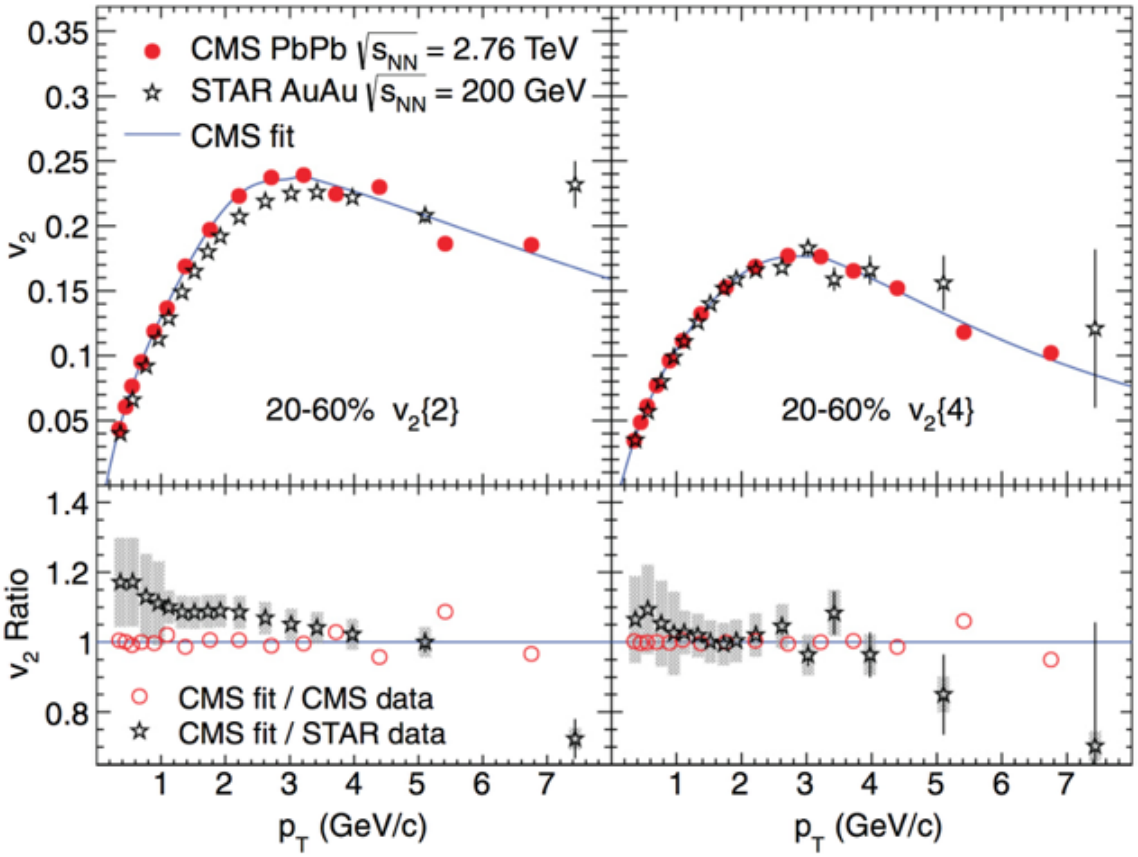


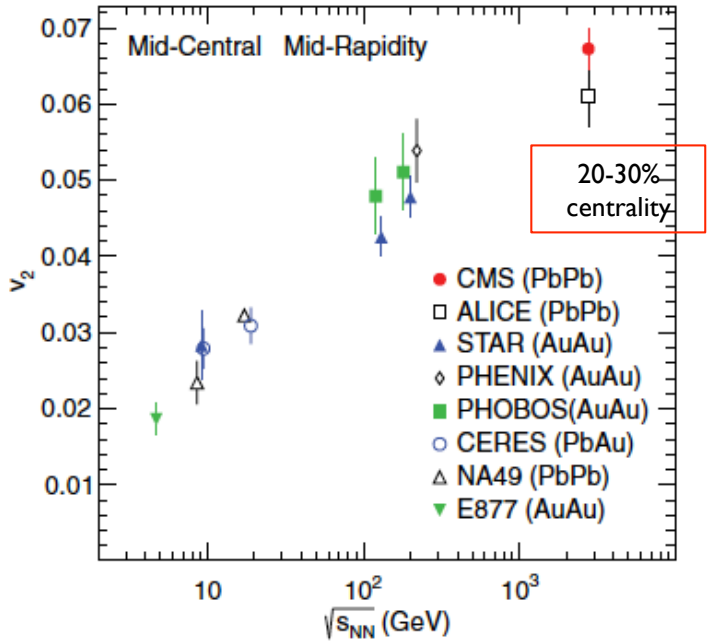
- **strong collective flow** persists at the LHC

- Integrated values of v2 are **sensitive to the range of p_T** included. A systematically larger v_2 is observed for the higher value of p_T

Collective anisotropic flow

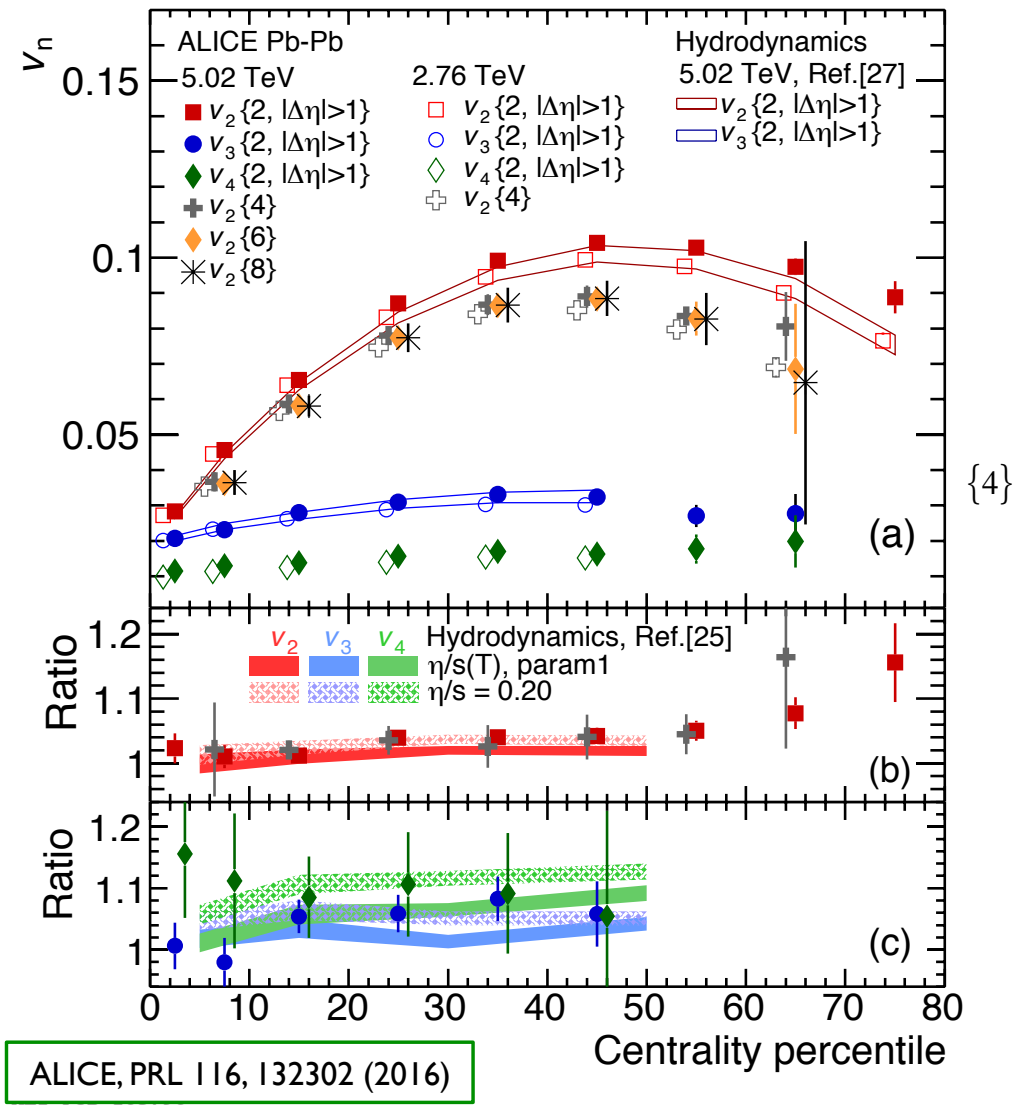
CMS, PRC 87 (2013) 014902





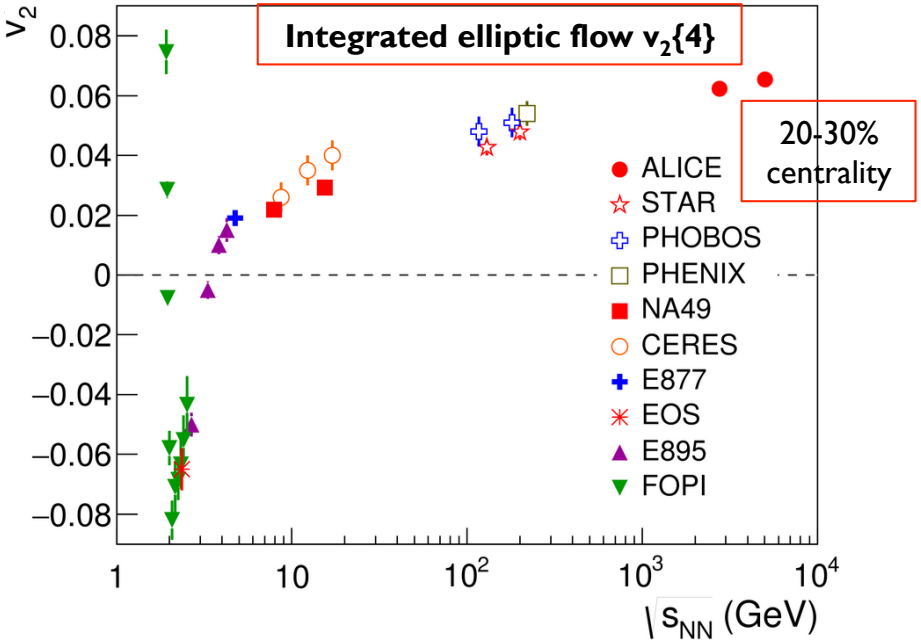
- moderate increase in $v_2(p_T)$ at low p_T from the highest RHIC energy to the LHC, despite the large increase in the centre-of-mass energy.
- integrated v_2 increase approximately logarithmically with $\sqrt{s_{NN}}$ with a 20–30% increase from RHIC to LHC.

Collective anisotropic flow



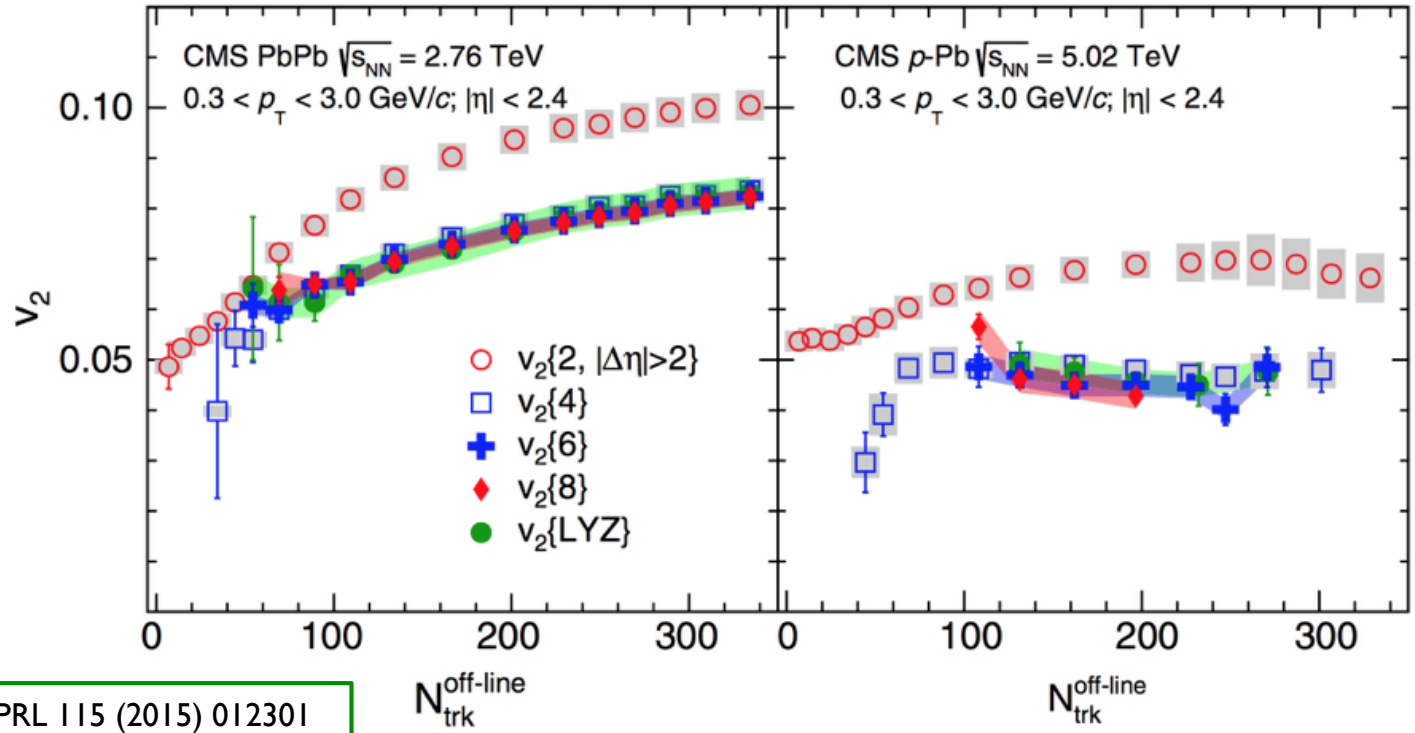
ALICE, PRL 116, 132302 (2016)

$\{4\}$



- Anisotropic flow v_n integrated in the p_T range $0.2 < p_T < 5.0$ GeV/c as function of centrality
- average increse of (3.0 ± 0.6)% for v_2, (4.3 ± 1.4)% for v_3 and (10.2 ± 3.8)% for v_4 from 2.76 to 5.02 TeV
- results compatible with predictions from hydrodynamic models

Collective effect



CMS, PRL 115 (2015) 012301

The v_2 data from two-particle correlations systematically above the multiparticle correlation data

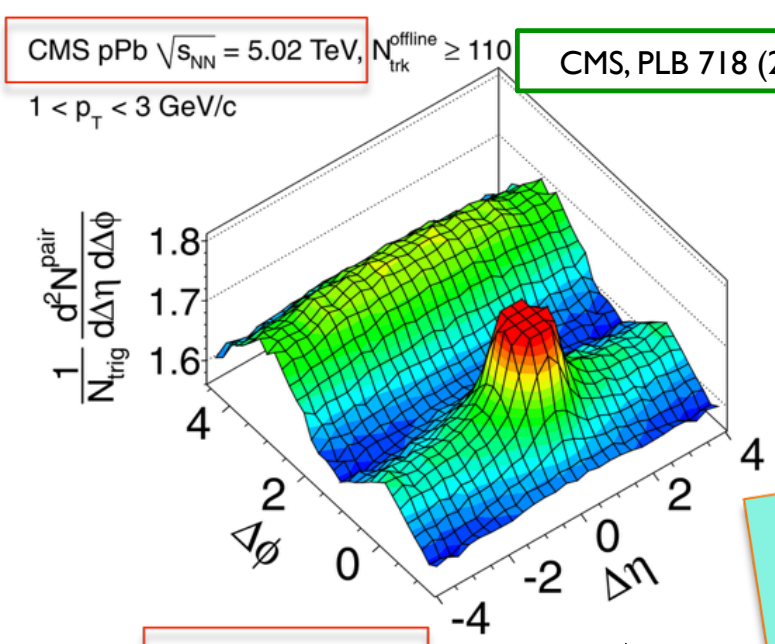
→consistent with hydrodynamic models

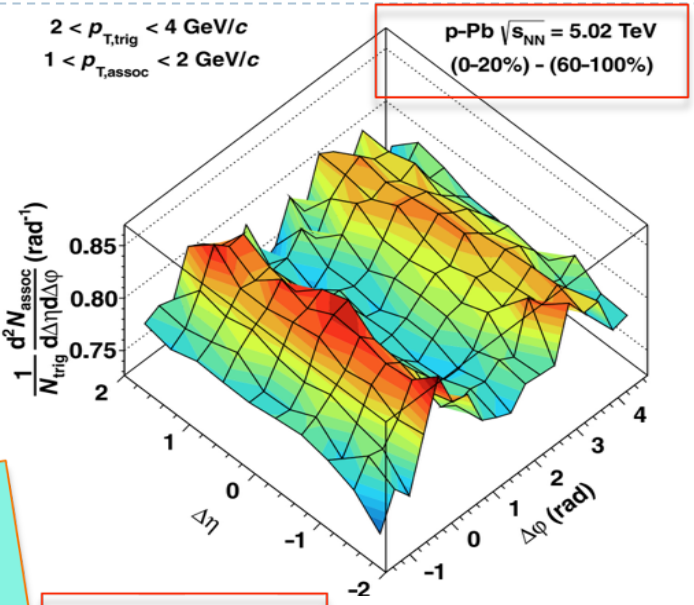
Same behaviour in Pb-Pb and p-Pb → true collective effect

The ridge

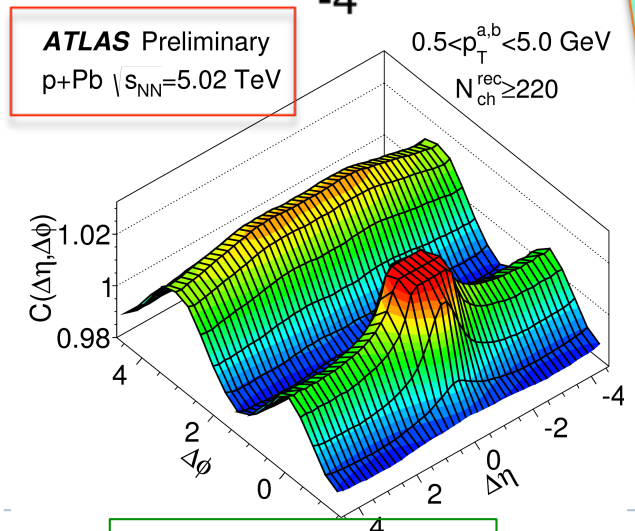
ALICE, PLB 719 (2013) 29

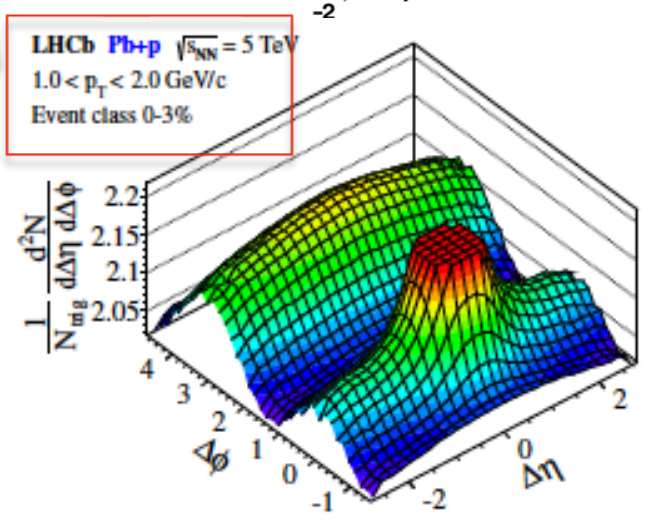
CMS, PLB 718 (2013) 795





Talk by A. Mischke in this session





ATLAS-CONF-2016-026

LHCB, arXiv:1512.00439

Summary

Clear support for the creation of a fireball in local thermodynamics equilibrium in Pb-Pb collisions

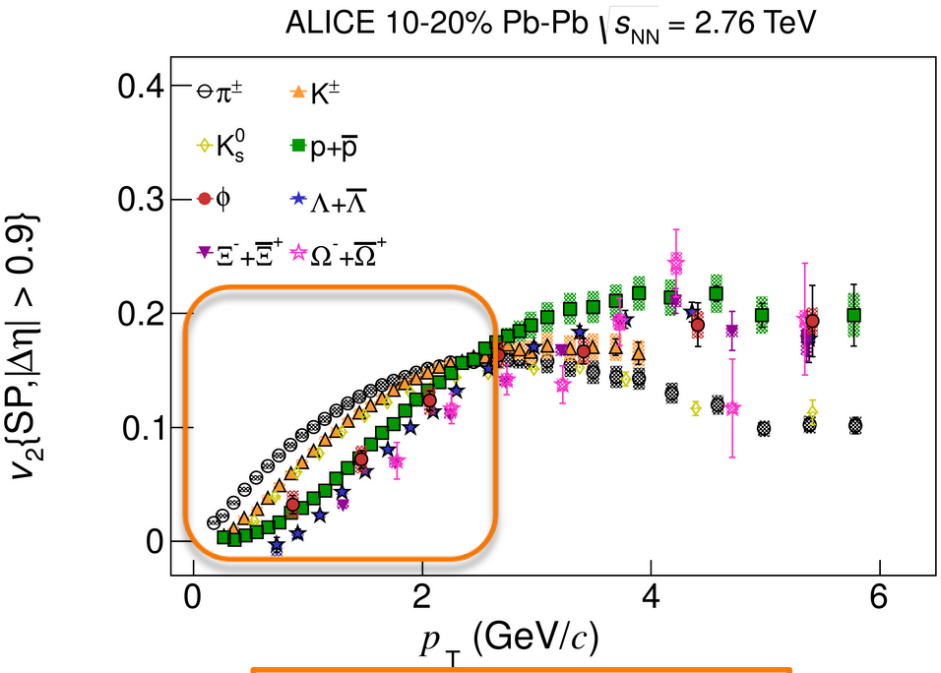
Medium created at the LHC appears to be hotter in the initial phase than the medium at RHIC

- **Bulk particle production**
  - Central Pb-Pb hadron production described successfully by thermal fit with T_{ch} = 156 MeV
  - Deviations can be attributed to flow
- **Strangeness Enhancement**
  - seen clearly in Pb-Pb, evolution of ratios observed in p-Pb
- **Anisotropic flow**
  - **suggestions for collective behaviour in small systems**

Many more results and a bright future for soft physics with the complete sample of Run 2

Backup

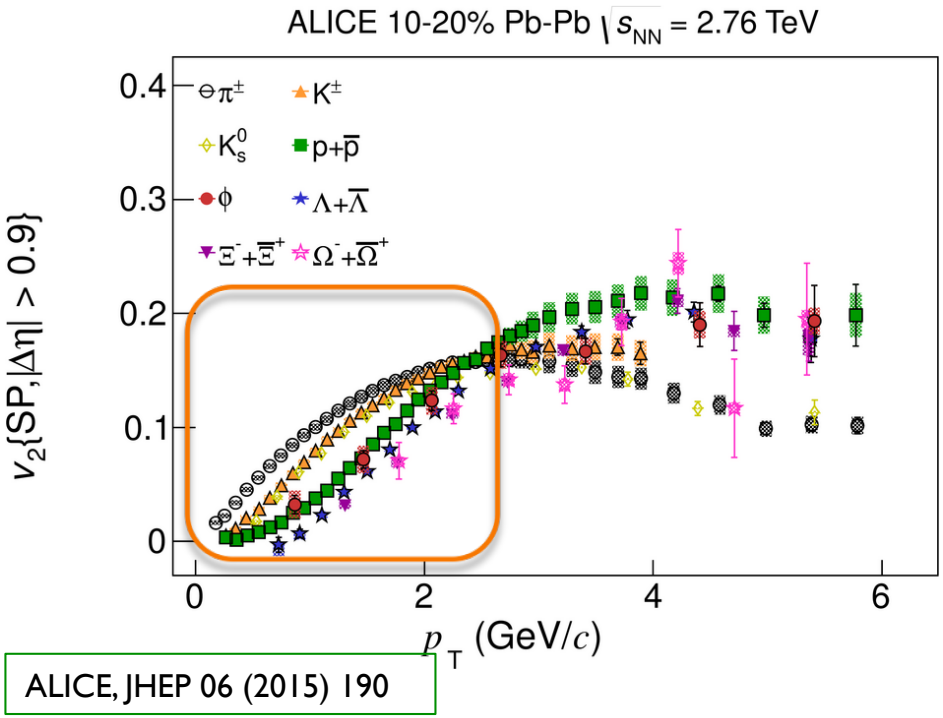
Identified particles v_2



mass ordering attributed to common radial expansion velocity

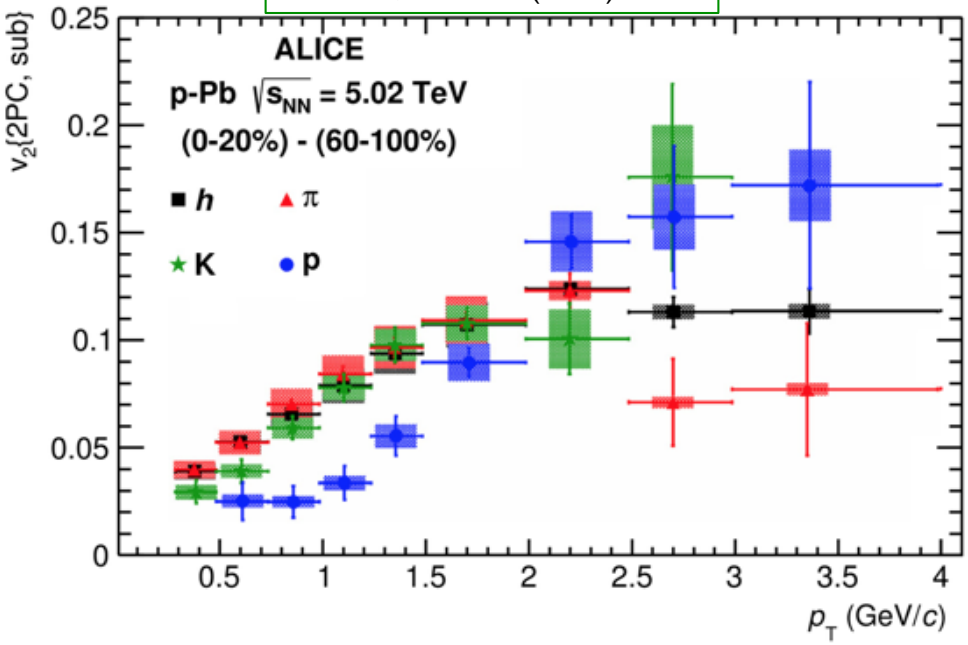
ALICE, JHEP 06 (2015) 190

Identified particles v_2



ALICE, JHEP 06 (2015) 190

ALICE, PLB 726 (2013) 164



also in p-Pb mass ordering observed at low p_T

lower v_2 for heavier particles

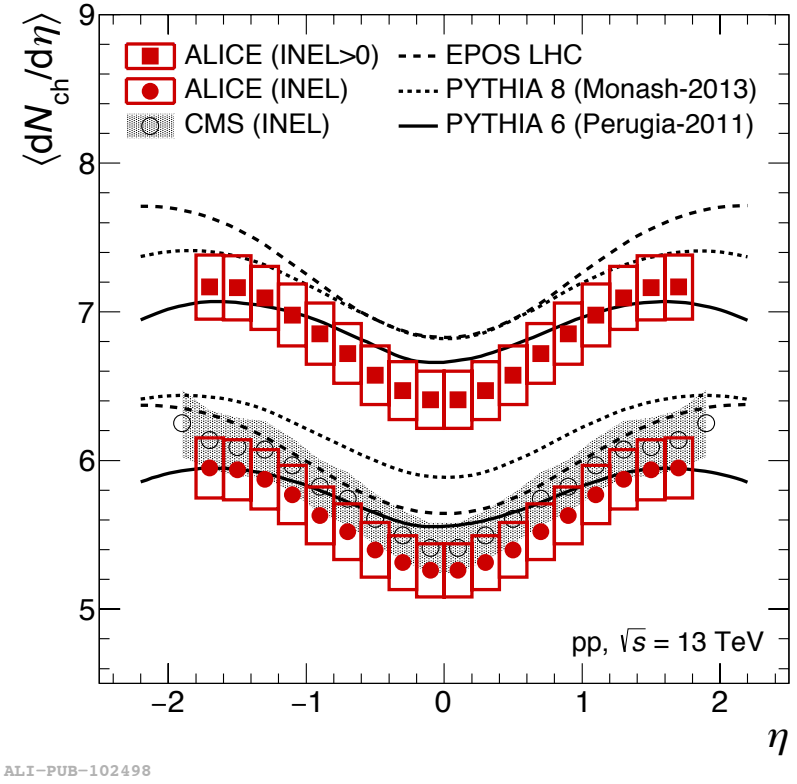
crossing at higher p_T

reminiscent of A-A observations

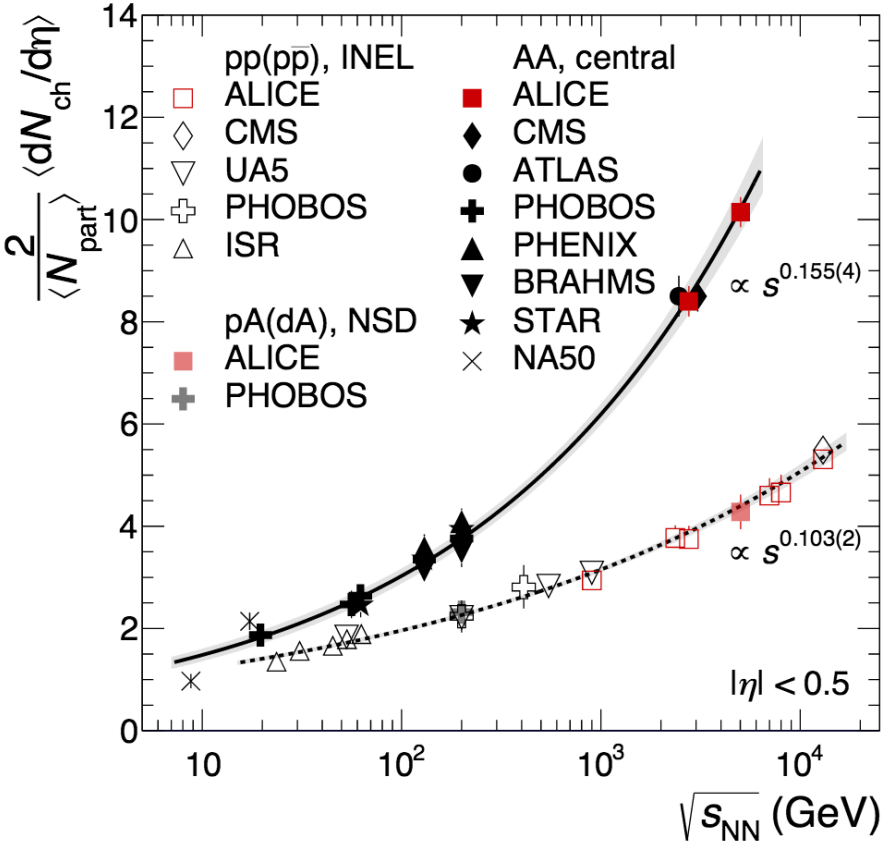
Multiplicity: pp vs Pb-Pb

Phys. Lett. B 753 (2016) 319-329

pp @ 13 TeV



Pb-Pb @ 5 TeV

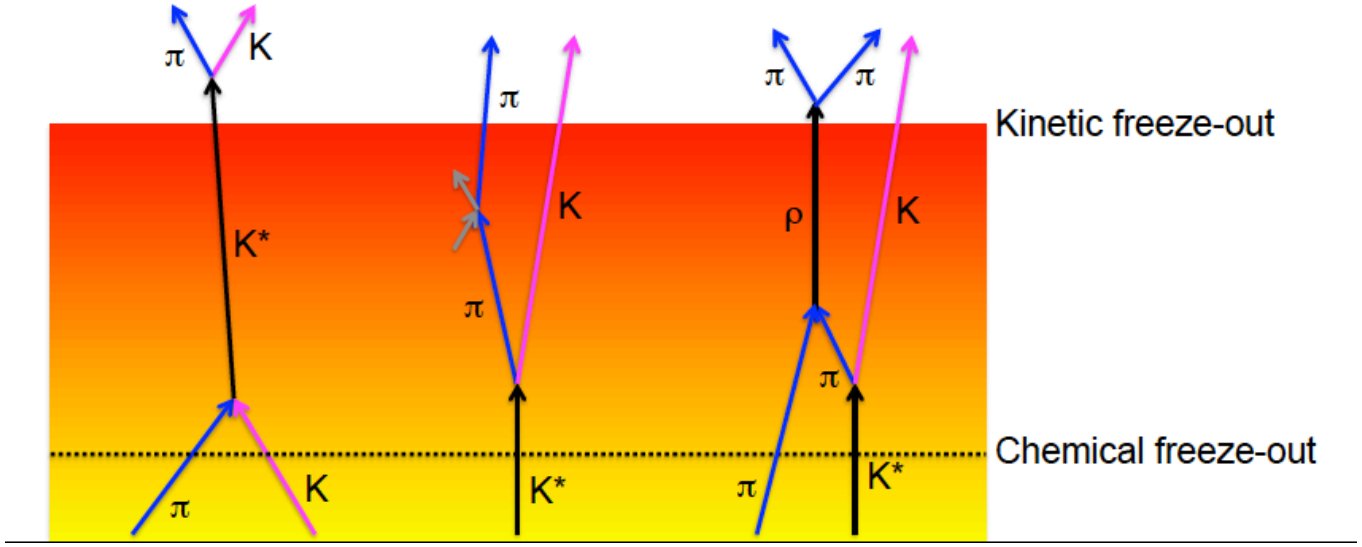


[arXiv:1512.06104]

Hadronic phase

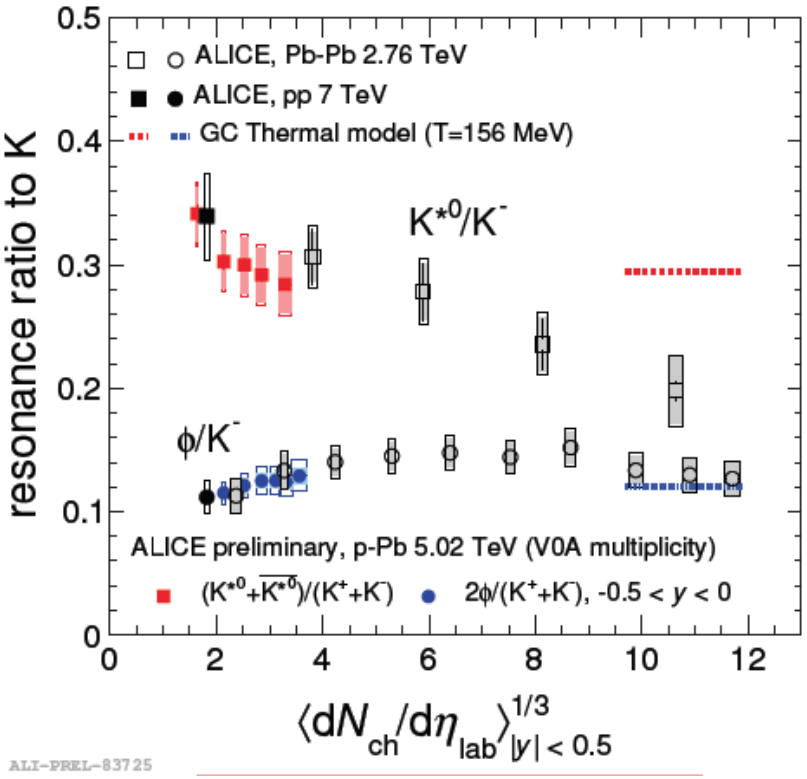
- Reconstructible resonance yields may be changed by hadronic processes after chemical freeze-out:

- Regeneration: pseudo-elastic scattering of decay products (e.g. $\pi k \rightarrow K^* \rightarrow \pi k$)
- Re-scattering:
  - Resonance decay products undergo elastic scattering
  - Or pseudo-elastic scattering through a difference resonance
  - Resonance not reconstructed through invariant mass



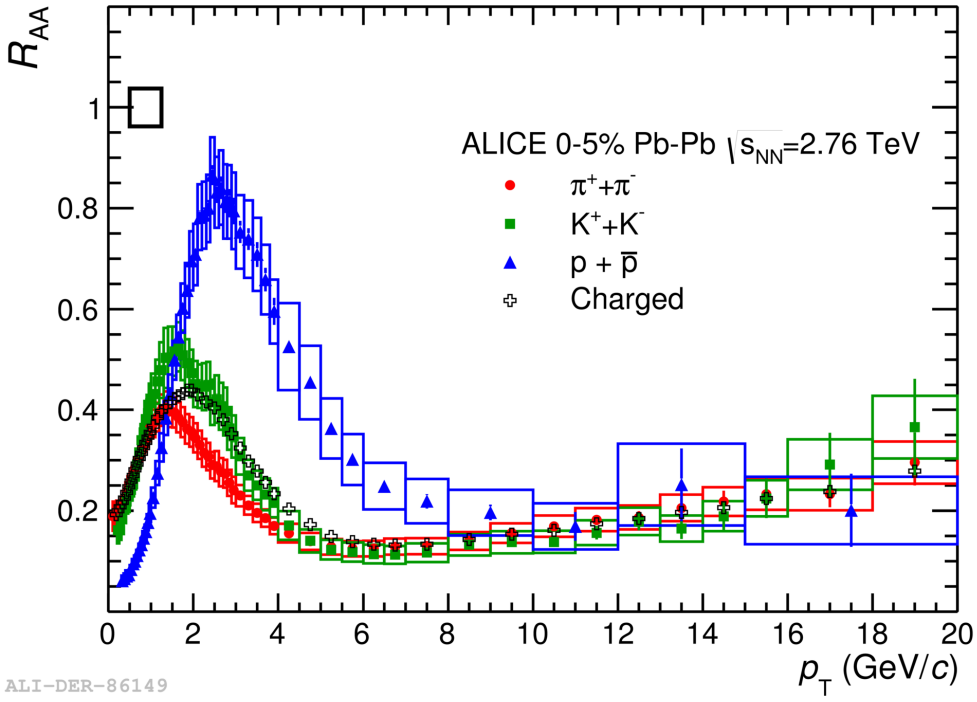
Ratios of Yields

- **K^{*0}/K**
  - Central Pb–Pb: significantly suppressed w.r.t. peripheral, pp, p–Pb, or thermal model
  - Consistent with the hypothesis that re-scattering is dominant over regeneration
- **ϕ/K**
  - No strong dependence on centrality or collision system
  - ϕ lifetime ~10x longer than K^{*0} re-scattering effects not significant
  - Ratio for central Pb–Pb consistent with thermal model
- Ratios in p–Pb consistent with trend from pp to peripheral Pb–Pb



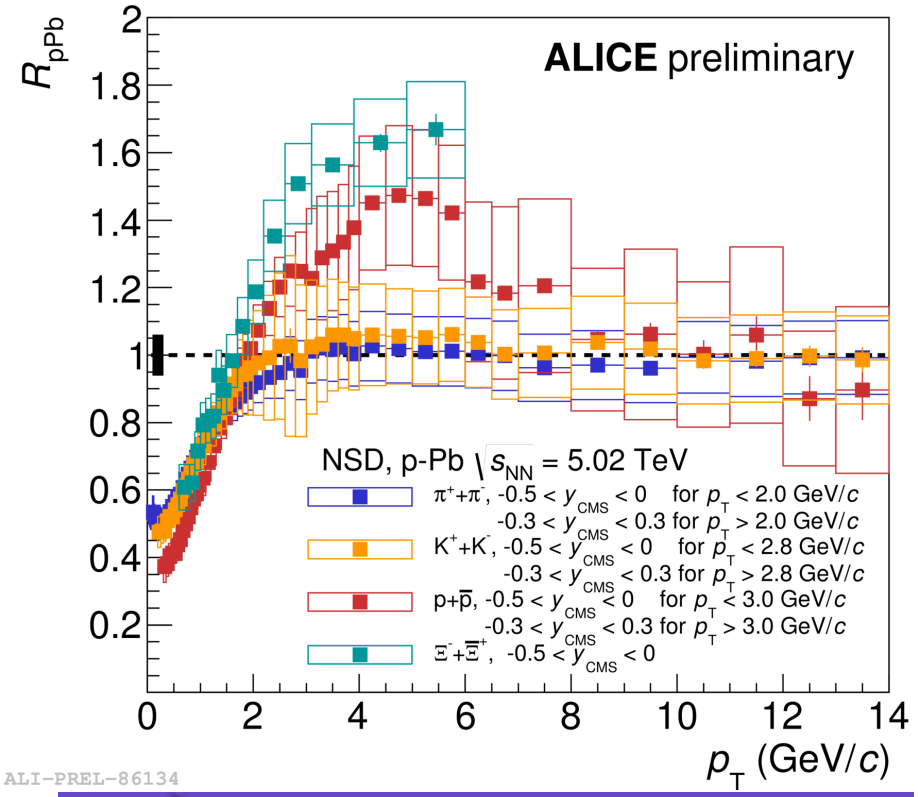
pp: ALICE, *Eur. Phys. J. C 72 2183 (2012)*
Pb–Pb: ALICE, *Phys. Rev. C 91 024609 (2015)*
Thermal Model: J. Stachel *et al., SQM 2013*

$R_{AA,pPb}$ of identified particles



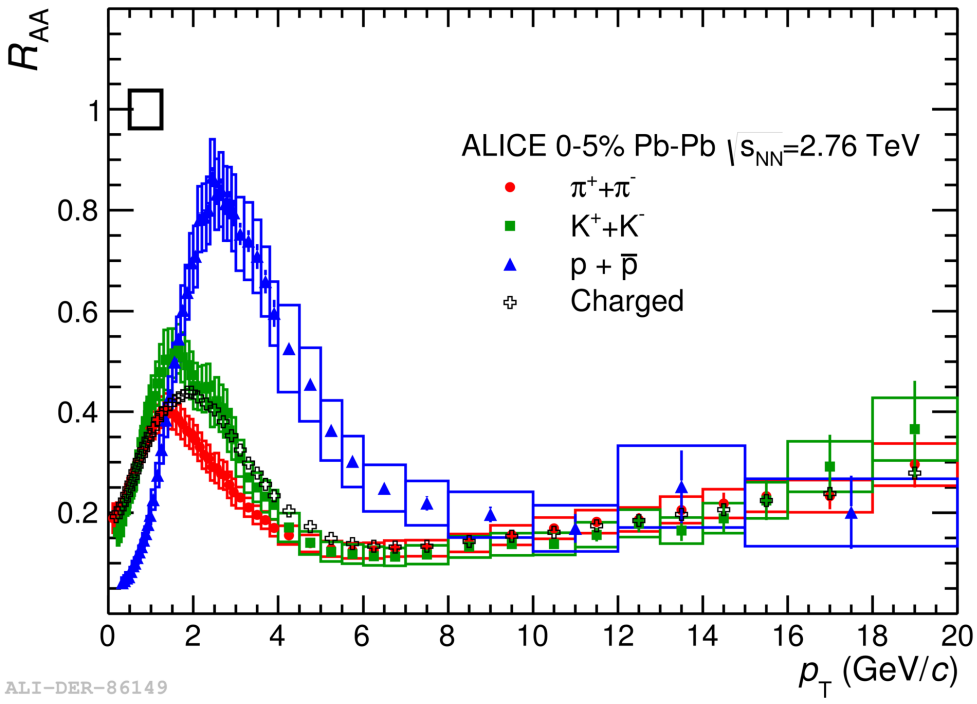
In Pb-Pb collisions, for $p_T > 10$ GeV/c the suppression is the same for different particle species

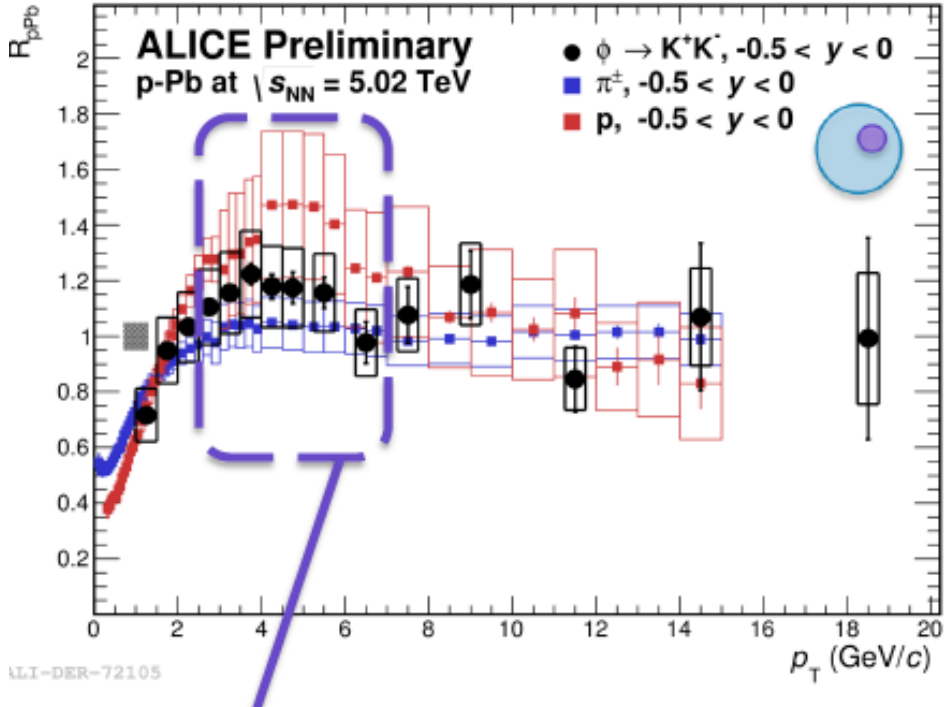
ALICE, PLB 720 (2013) 52
ALICE, PLB 736 (2014) 196



Indications for mass ordering of the Cronin peak
→ presence of other final state effects (flow, recombination, …)?

$R_{AA,pPb}$ of identified particles





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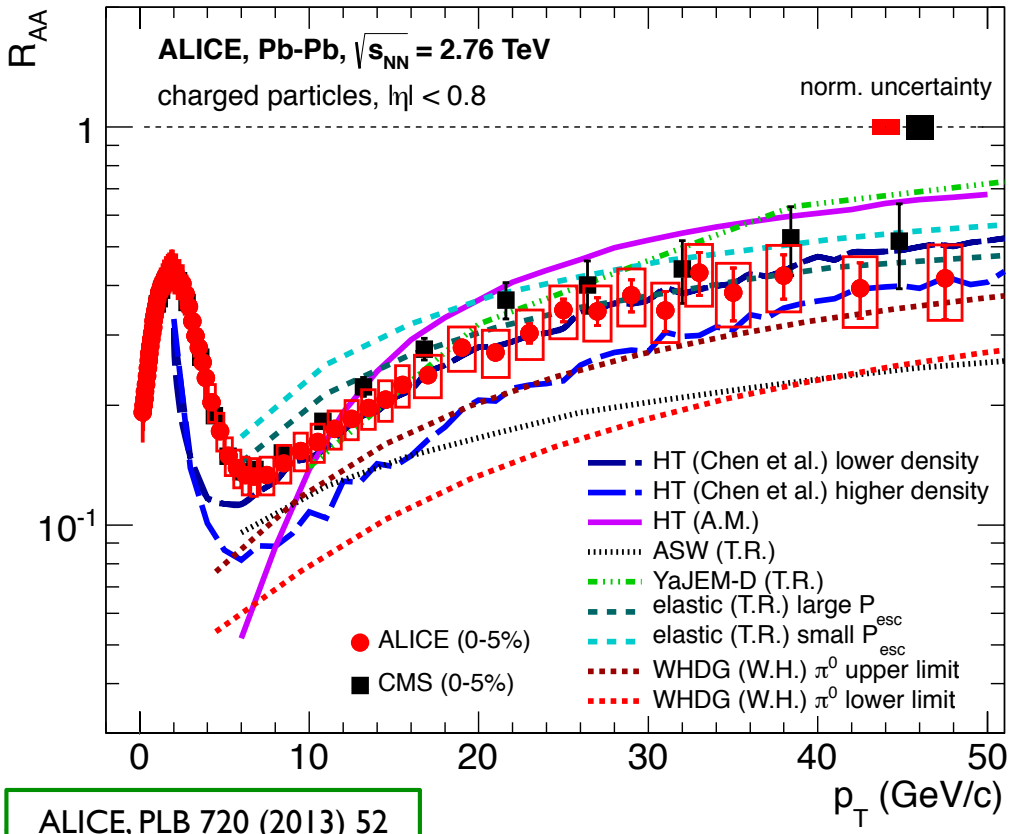
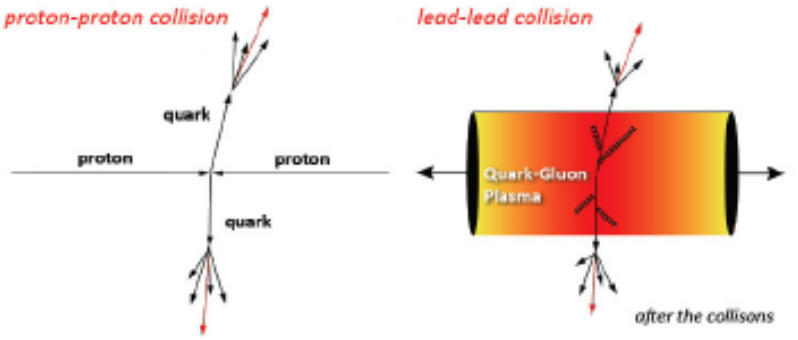
→ presence of other final state effects (flow, recombination, …)?

ALICE, PLB 720 (2013) 52
ALICE, PLB 736 (2014) 196

Nuclear modification factor in Pb-Pb



ALICE, PLB 720 (2013) 52



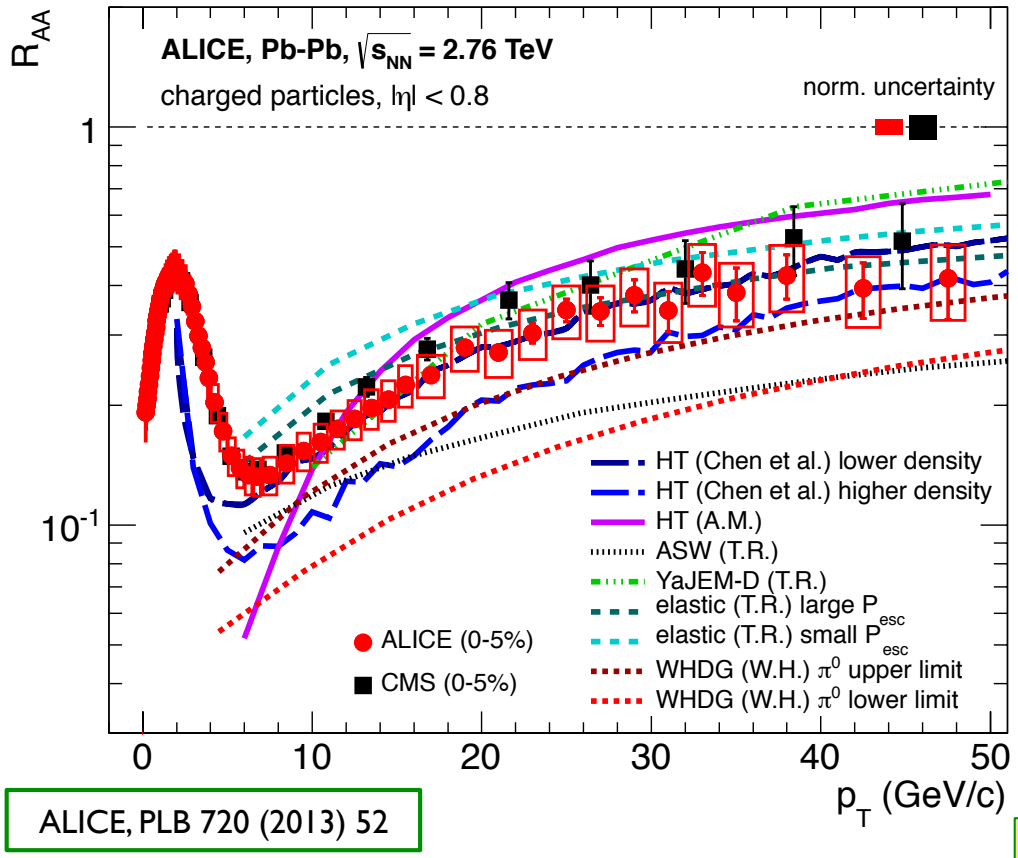
Partons produced in high Q^2 processes lose energy while traversing the QGP, resulting in modifications of high-p_T particle production

→ **Nuclear Modification Factors**

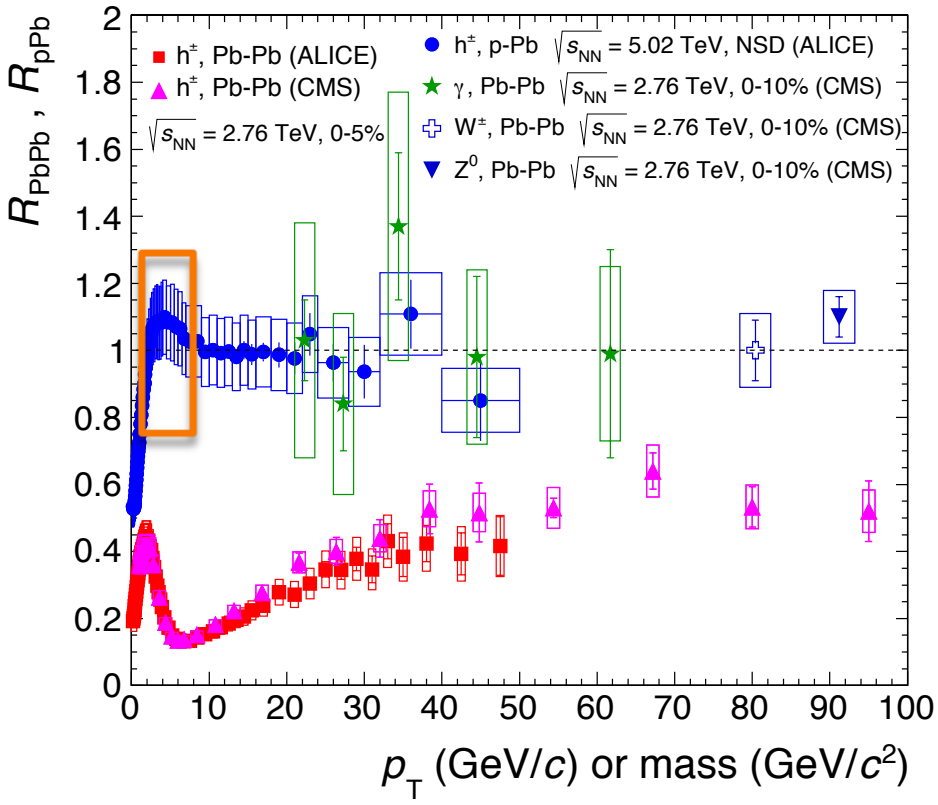
$$R_{xA}(p_T) = \frac{d^2N_{ch}^{xA}/d\eta dp_T}{\langle T_{xA}\rangle d^2\sigma_{ch}^{pp}/d\eta dp_T}$$

Spectra of charged particles are strongly suppressed over a wide transverse momentum range in Pb-Pb collisions

No nuclear modification factor in p-Pb



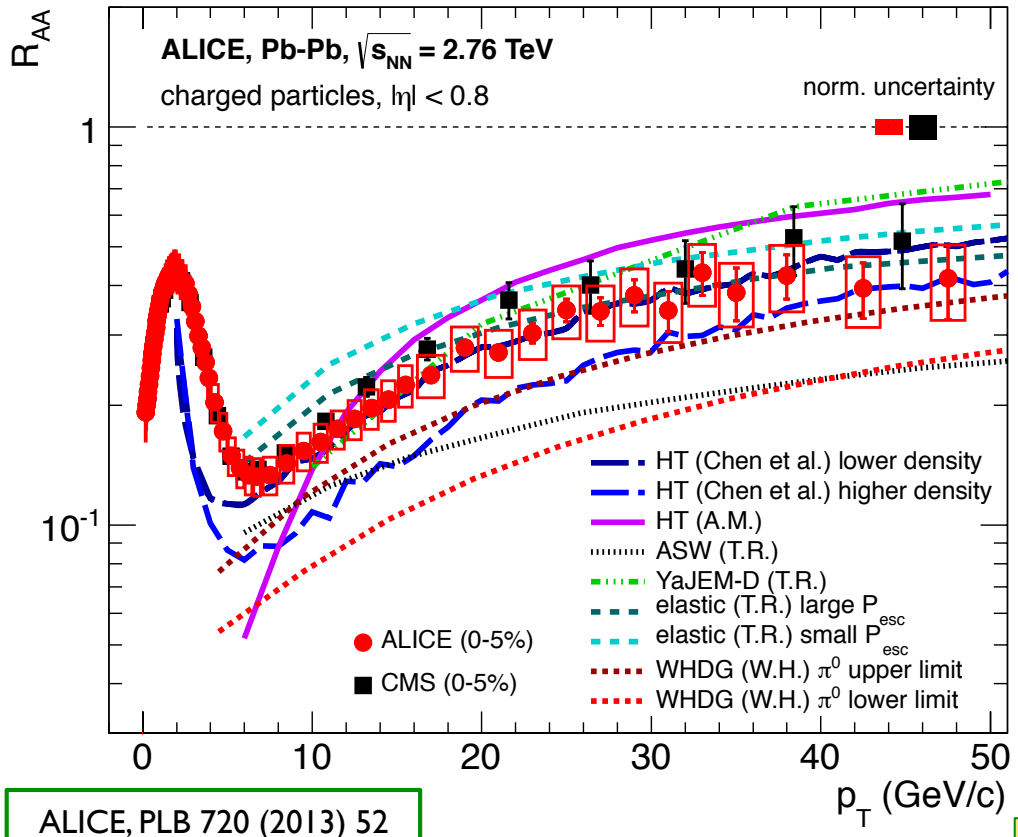
ALICE, PLB 720 (2013) 52



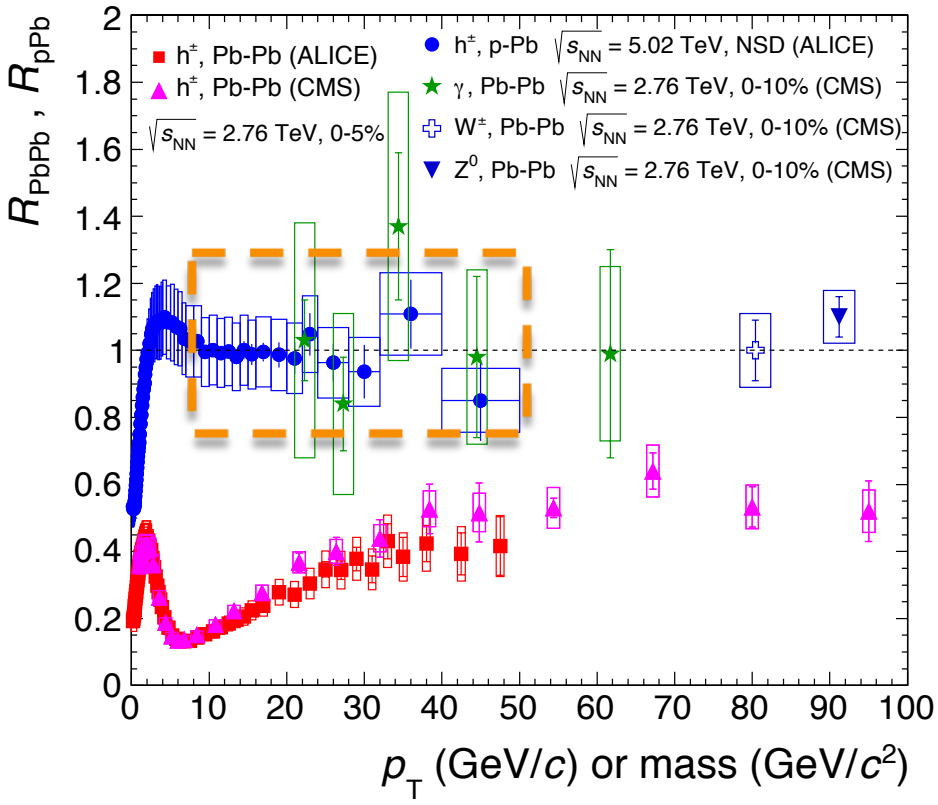
ALICE, Eur. Phys. J. C 74 (2014)3054
Cronin et al, Phys. Rev. D 11(1975) 3105

In p-Pb collisions a small Cronin peak is seen at $3<p_T<6$ GeV/c

No nuclear modification factor in p-Pb



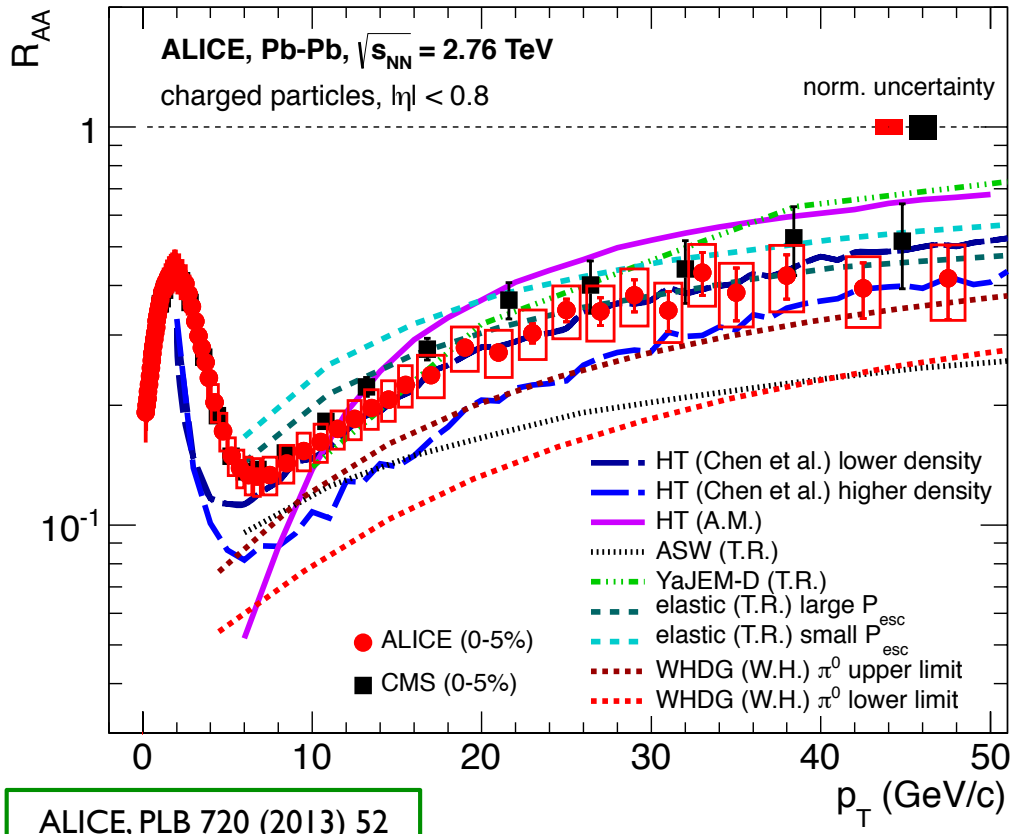
ALICE, PLB 720 (2013) 52



ALICE, Eur. Phys. J. C 74 (2014)3054
Cronin et al, Phys. Rev. D 11(1975) 3105

In p-Pb collisions a small Cronin peak is seen at $3<p_T<6$ GeV/c
No modification is observed up to 50 GeV/c

No nuclear modification factor in p-Pb



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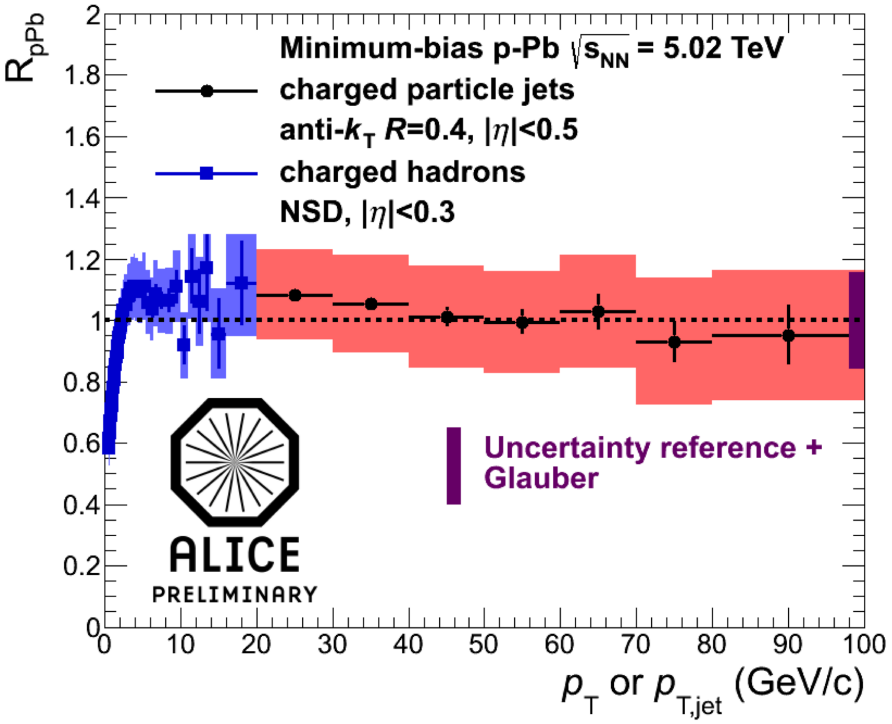


In p-Pb collisions a small Cronin peak is seen at $3<p_T<6$ GeV/c

No modification is observed up to 50 GeV/c

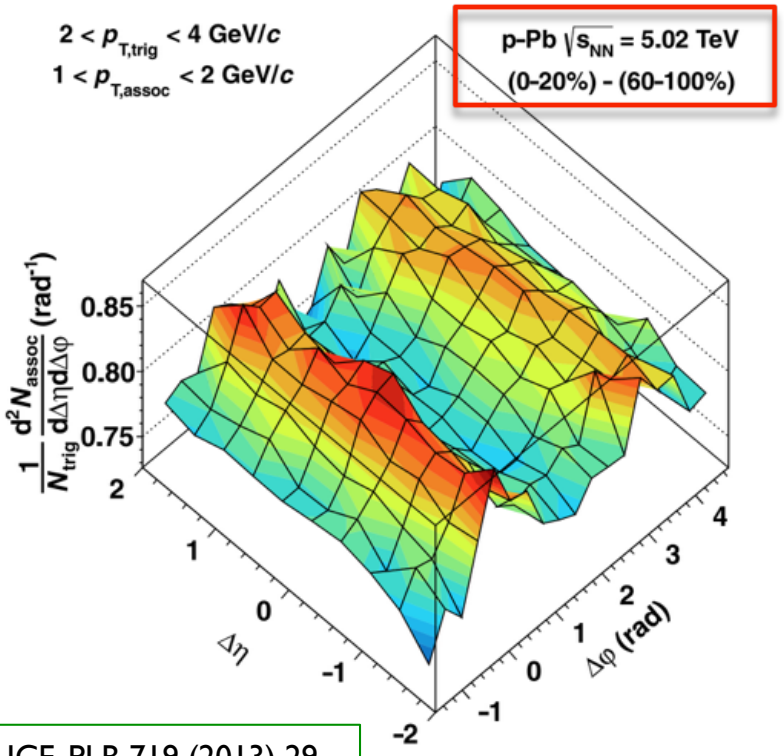
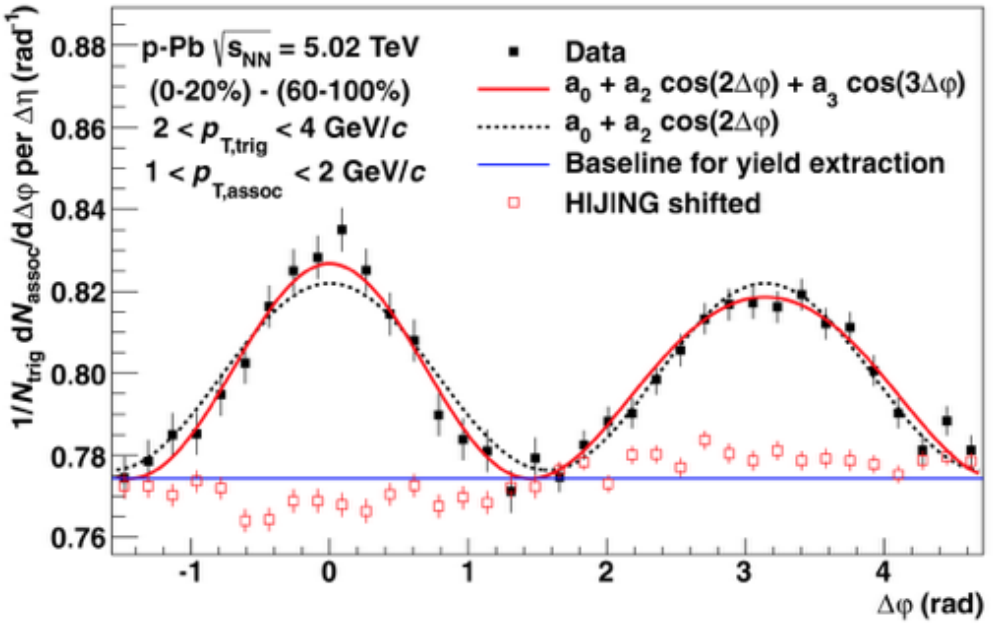
Jet measurements: no modification up to 100GeV/c

The double ridge

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

h-h correlation observed after removal of jet contribution

→ a double ridge was revealed and this looks like flow



ALICE, PLB 719 (2013) 29