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ALICE Overview

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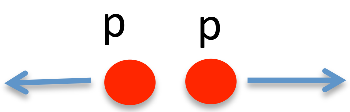
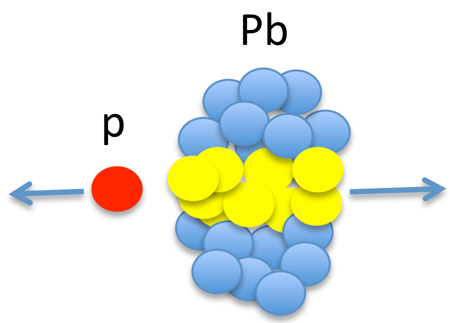
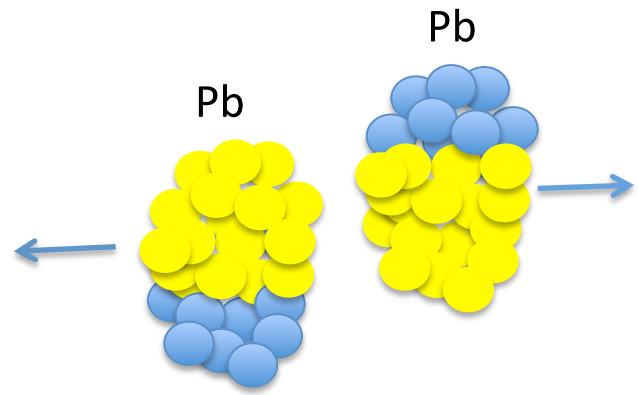
ALICE measurements in pp, p-Pb and Pb-Pb collisions



Soft QCD and pQCD and jet fragmentation in vacuum. Reference for p-Pb and Pb-Pb.



Initial state effects (shadowing/ gluon saturation). Collective effects. Reference for Pb-Pb.

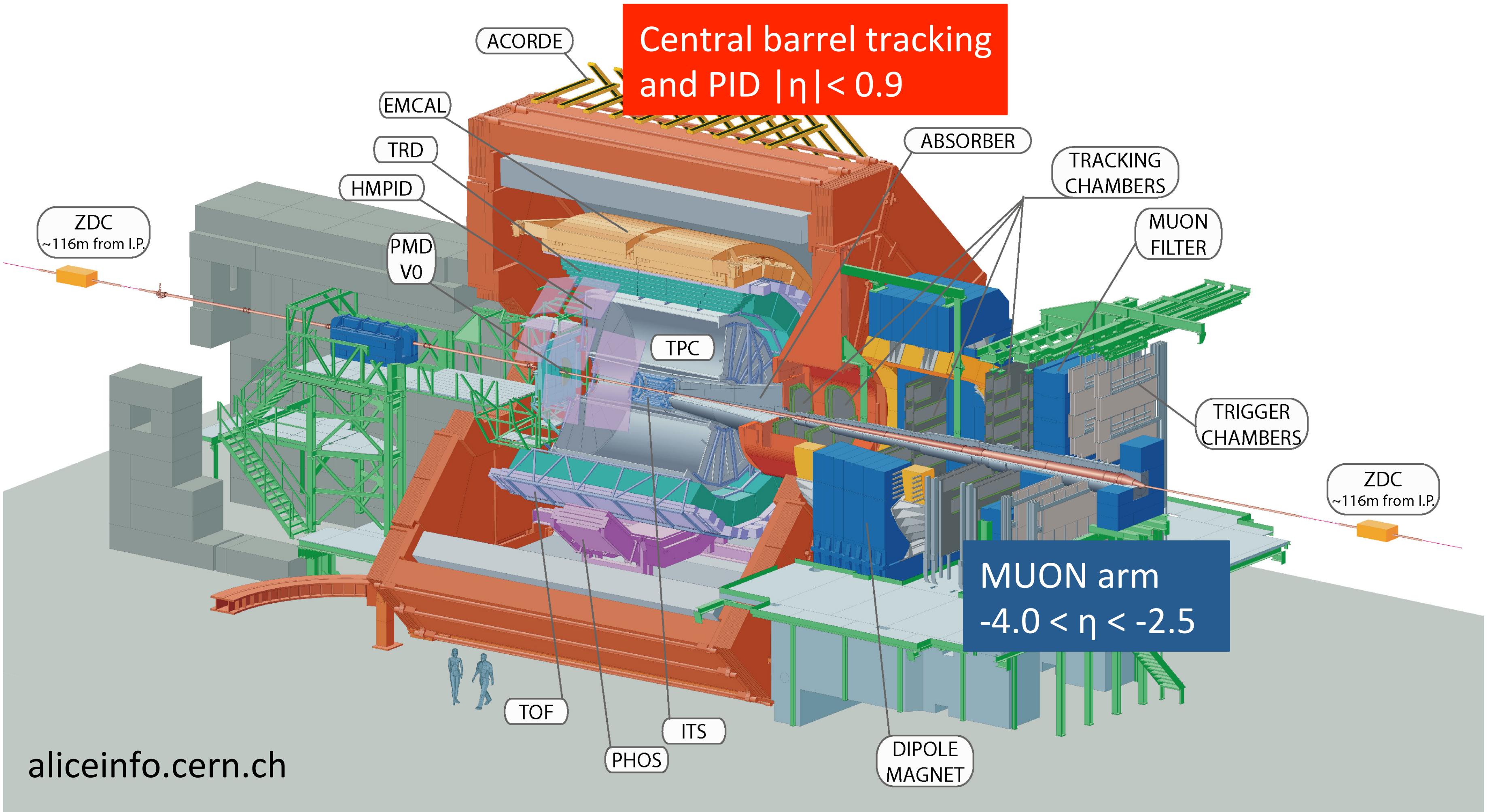


Thermal particle production, collectivity, recombination, jet quenching and fragmentation in the quark-gluon plasma (QGP).

Today correlation measurements with main focus on p-Pb

A Large Ion Collider Experiment

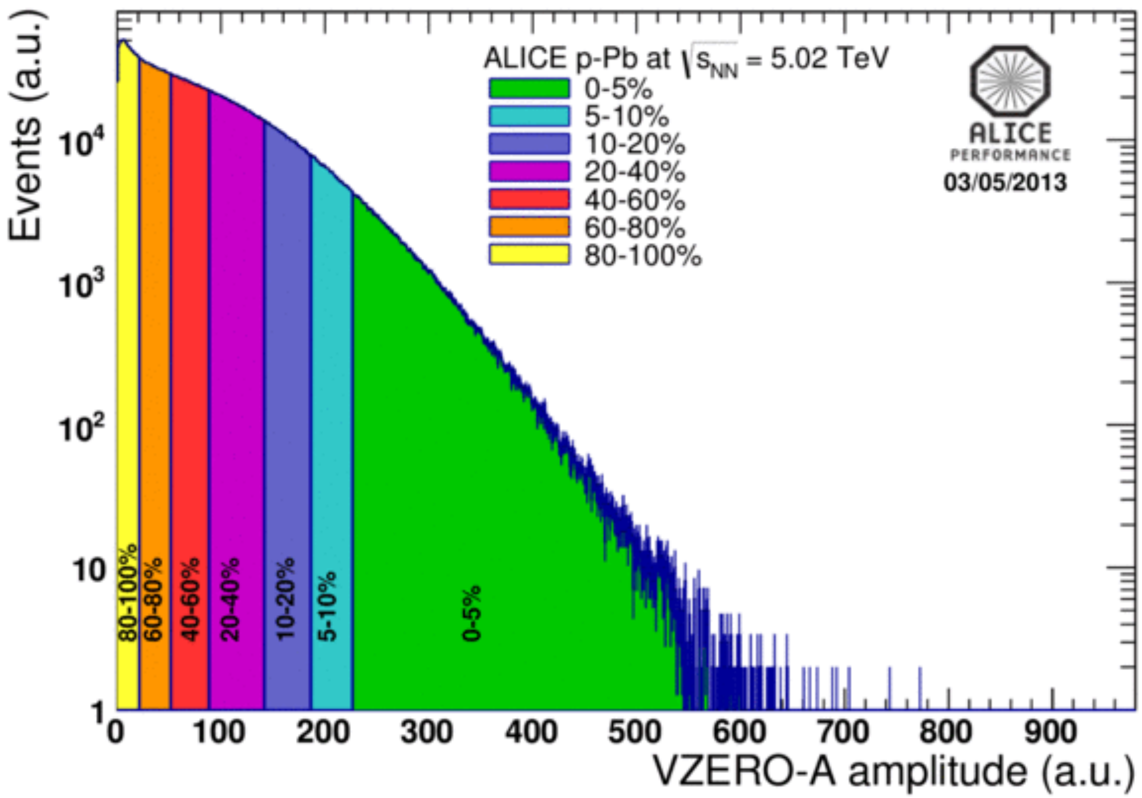
- Excellent particle identification capabilities in a large p_T range 0.1-20 GeV/c
- Good momentum resolution ~1-5% at p_T = 0.1-50 GeV/c



Event centrality/multiplicity selection in p-Pb

At the LHC, the correlation between geometry and track multiplicity (Glauber model) in p-Pb is not as straightforward as in Pb-Pb (ALICE, arXiv:1412.6828)

→ Event centrality selection based on track multiplicity in VZERO-A detector ($2.8<\eta<5.1$) – Pb-side



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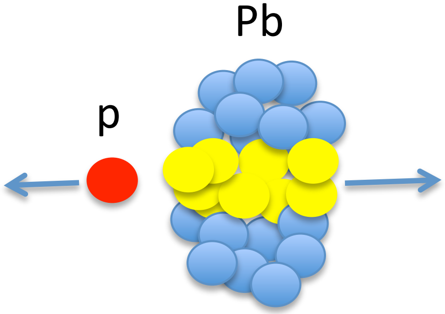


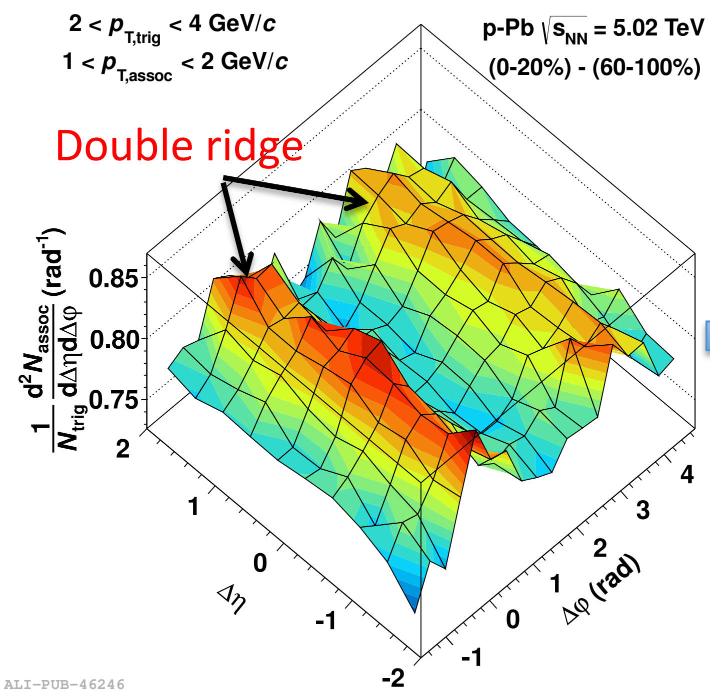
VZERO-A amplitude ~ track multiplicity

Double ridge in high multiplicity p-Pb collisions

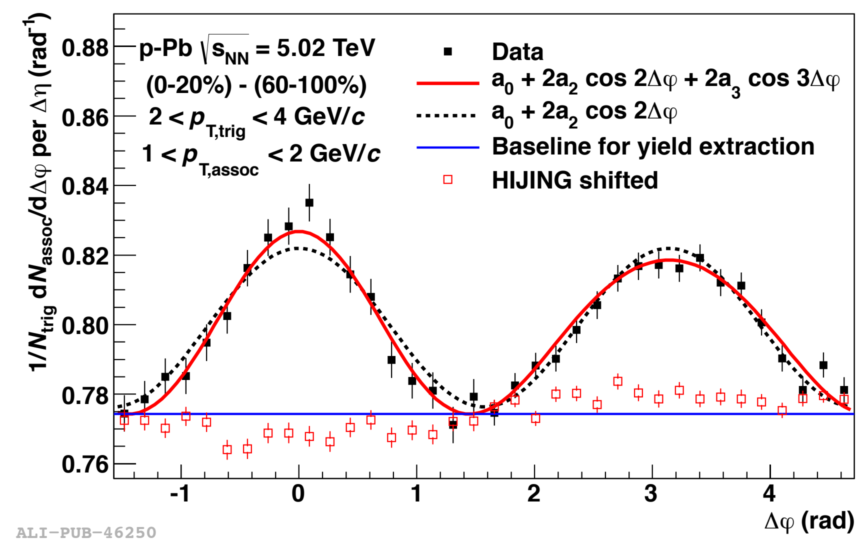
ALICE

ALICE: Phys. Lett. B719 (2013) 29

Double ridge: Long range h-h angular correlations.



Projection on Δϕ.



v_2 and v_3 flow components.

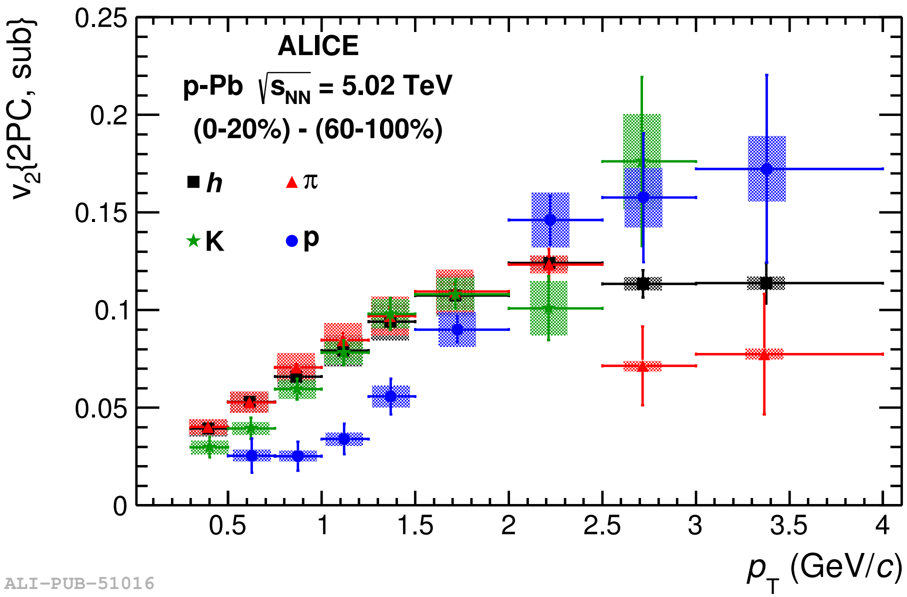
Also seen in Pb-Pb and high multiplicity pp collisions by CMS and ATLAS.

Collective flow: Bożek & Broniowski (Phys. Lett. B718 (2012) 4)

Qualitatively similar to Pb-Pb:
→ Indication of collective flow in high multiplicity p-Pb

v_2 of identified particles from the ridge in p-Pb

h-π, h-p, h-K correlations in p-Pb



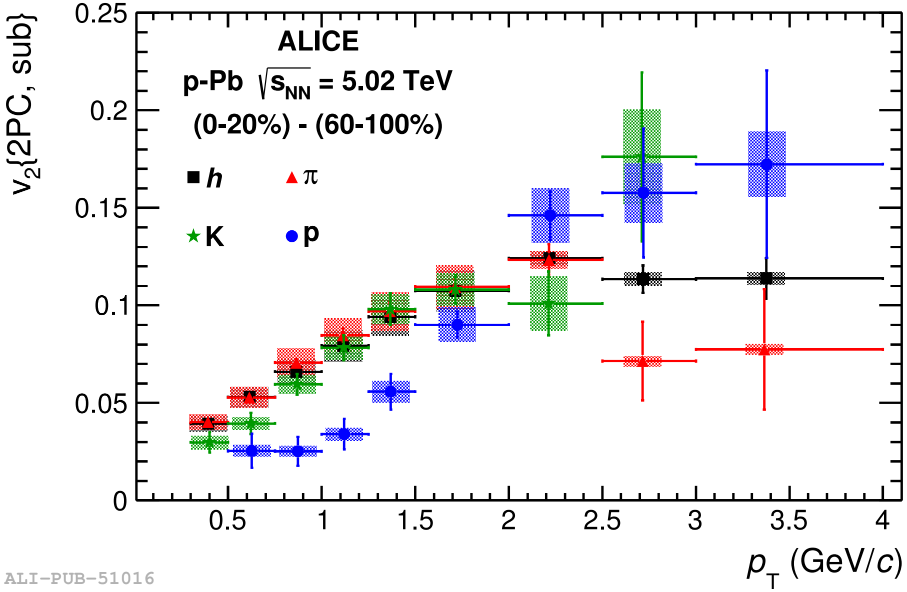
ALI-PUB-51016

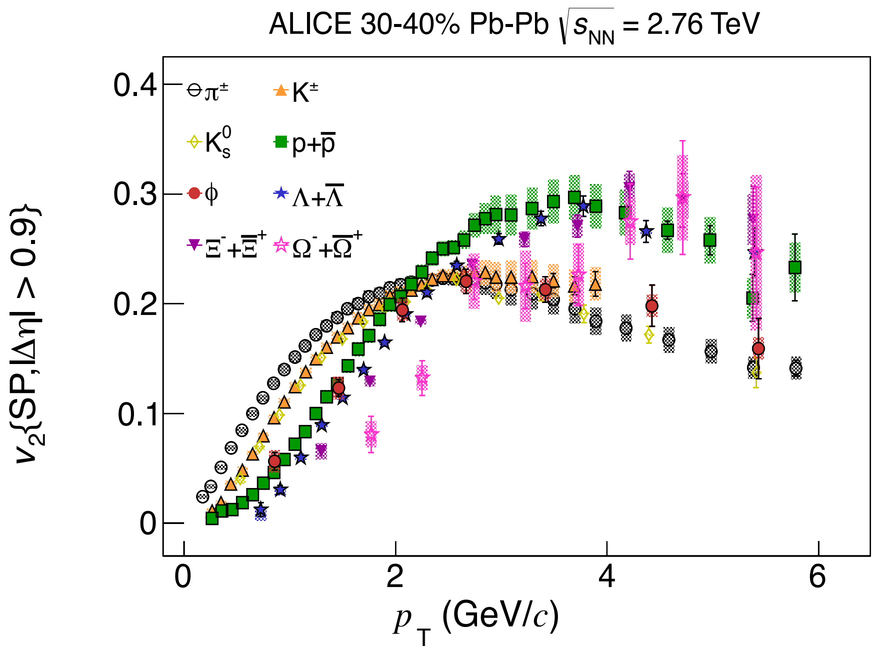
ALICE, Phys. Lett. B726 (2013) 164

Flow coefficient v_2 vs. p_T for identified hadrons from the ridge shows hierarchy in mass at low p_T.

v_2 of identified particles from the ridge in p-Pb

h-π, h-p, h-K correlations in p-Pb





ALICE, Phys. Lett. B726 (2013) 164

ALICE, arXiv:1405.4632

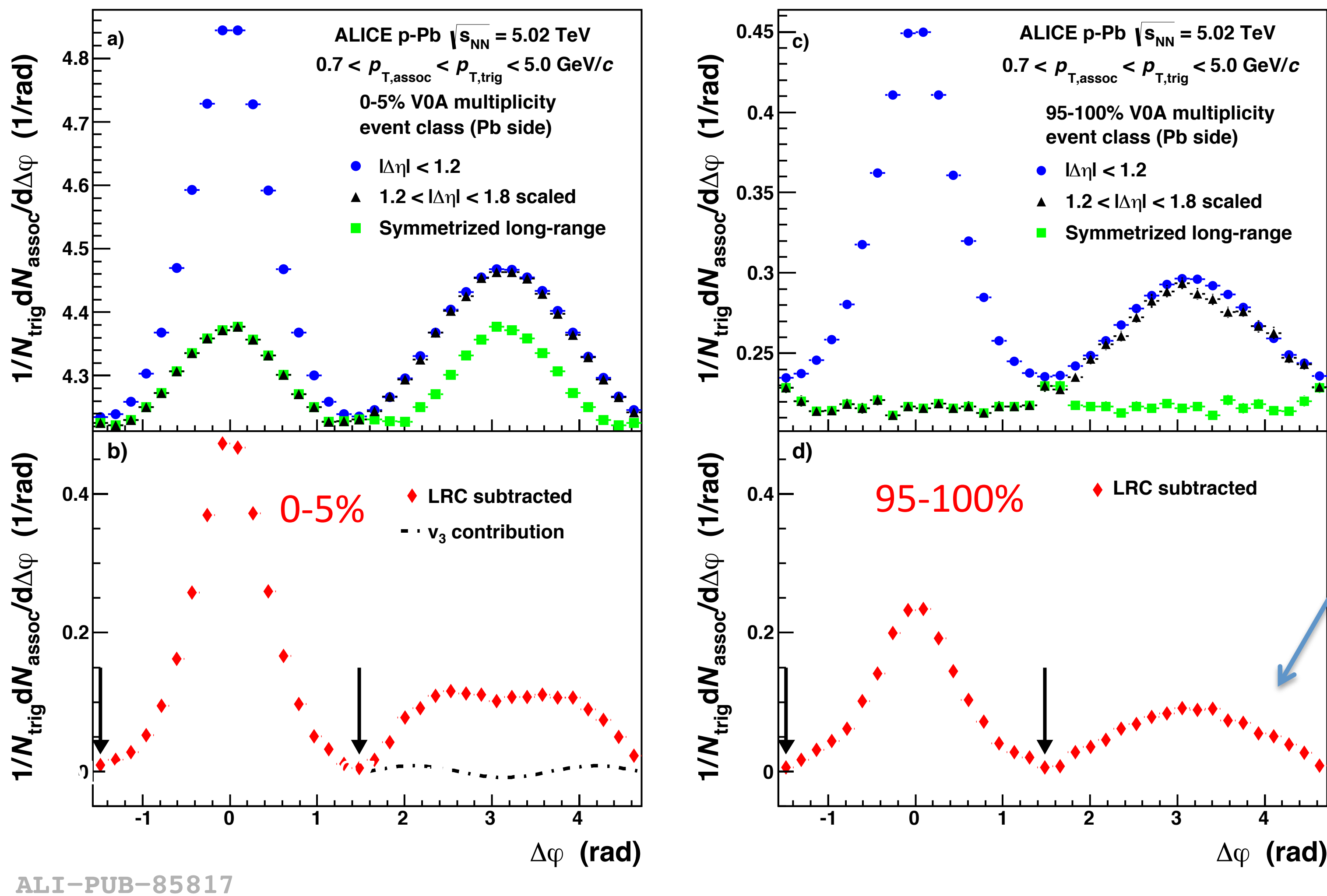
Flow coefficient v_2 vs. p_T for identified hadrons from the ridge shows hierarchy in mass at low p_T.

Qualitatively similar to Pb-Pb:
→ Indication of collective flow in high multiplicity p-Pb

Jet-like two particle correlations in p-Pb

Double ridge projection on the Δϕ.

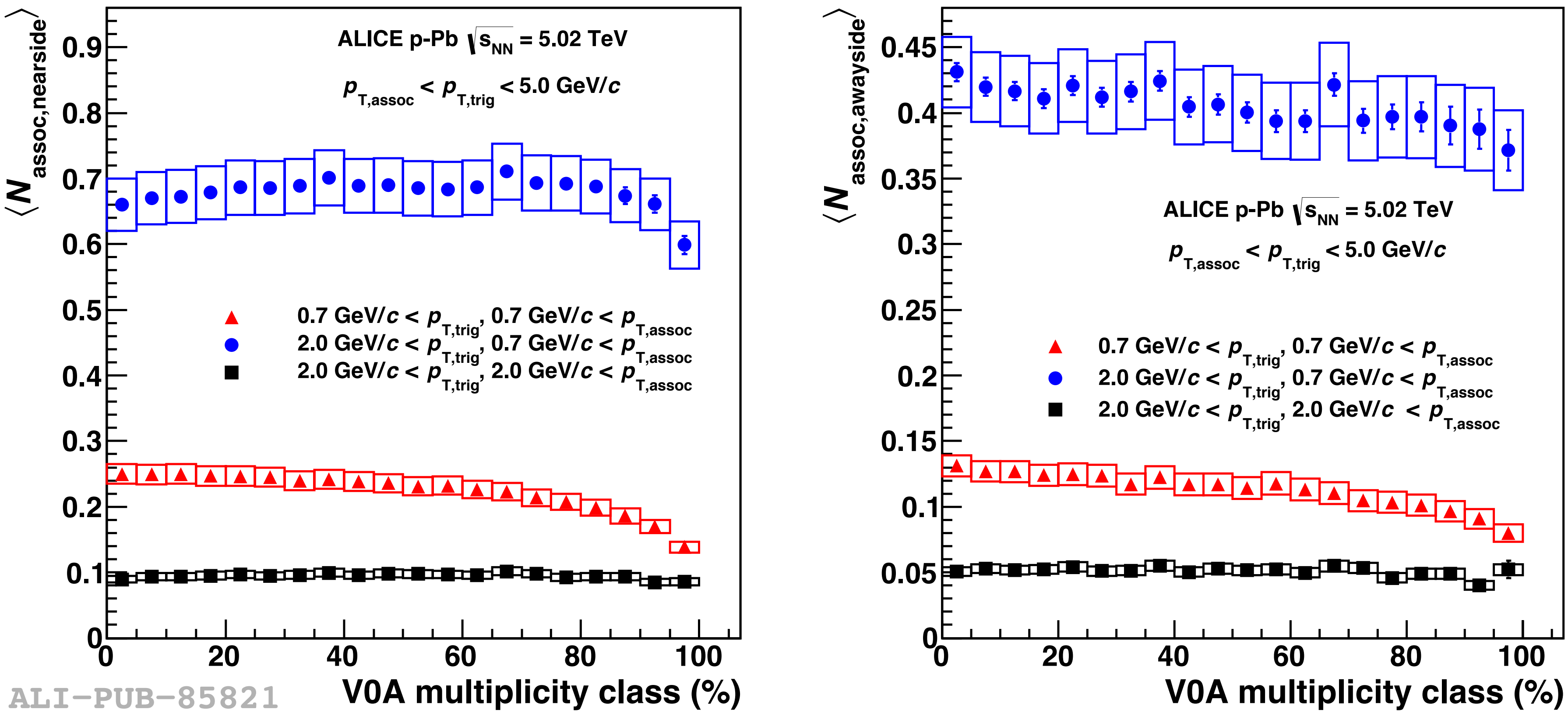
ALICE, Phys. Lett. B 741 (2015) 38



Long range correlations subtracted!

Jet-like two particle correlations in p-Pb

Near side | Away side



Yields in the jet-like peaks are invariant with event multiplicity (except small multiplicity)

→ Jet production via incoherent fragmentation of multiple particle-particle interactions

→ Ridge structure is not jet-related

ALICE, Phys. Lett. B 741 (2015) 38

Multiparticle azimuthal correlations in p-Pb and Pb-Pb

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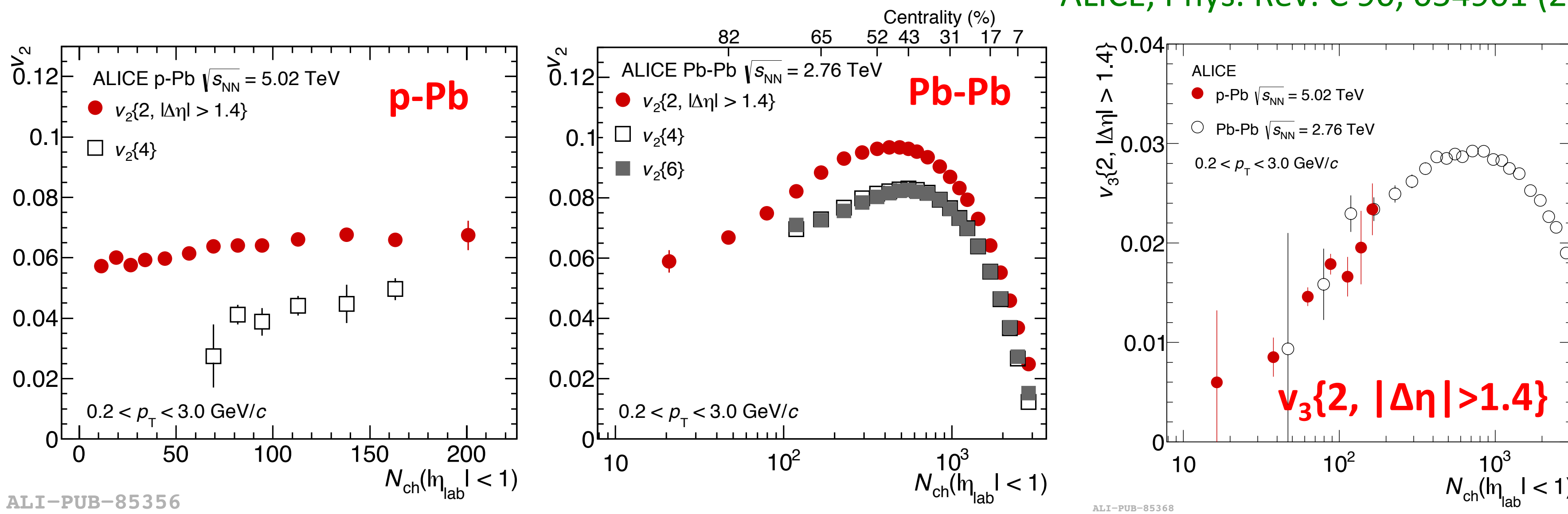
Multiparticle particle correlation (cumulants) c_n
(different sensitivity to fluctuations and nonflow contribution)
$c_n\{2\} = c_n(4) = c_n\{6\}$, if no fluctuations and nonflow contribution

ALICE, Phys. Rev. C 90, 054901 (2014)



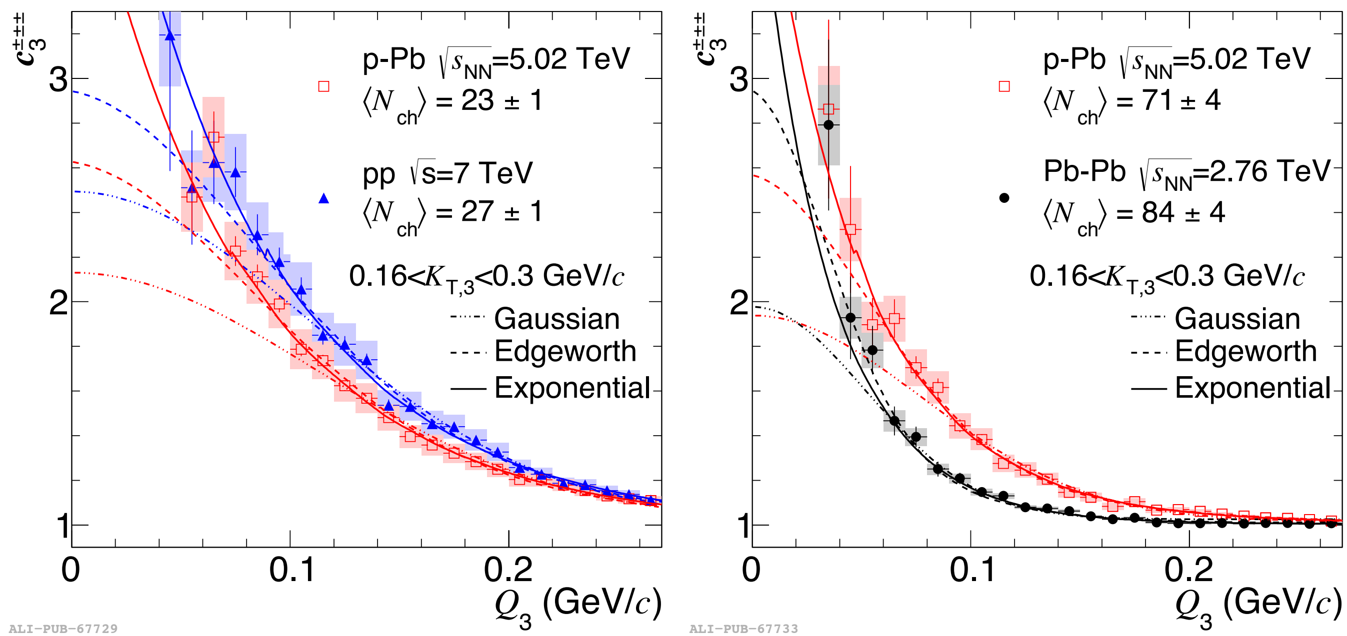
- Second harmonic cumulants are larger in Pb-Pb than in p-Pb at high multiplicities → larger eccentricity of Pb-Pb initial state
- $v_2\{2, \Delta\eta|>1.4\}$ rises with multiplicity → indication of collective flow rather than few-particle correlations
- Third harmonic two-particle cumulants are similar in p-Pb and Pb-Pb for overlapping multiplicities for $|\Delta\eta|>1.4$ → similar third harmonic eccentricities

Freeze-out radii measured in pp, p-Pb and Pb-Pb

Three pion Bose-Einstein correlations (small non-femtoscopic background)
Comparison for similar multiplicity events in pp, p-Pb and Pb-Pb.

$$C_3(p_1, p_2, p_3) = \alpha_3 \frac{N_3(p_1, p_2, p_3)}{N_1(p_1)N_1(p_2)N_1(p_3)} \qquad Q_3 = \sqrt{q_{12}^2 + q_{31}^2 + q_{23}^2}$$

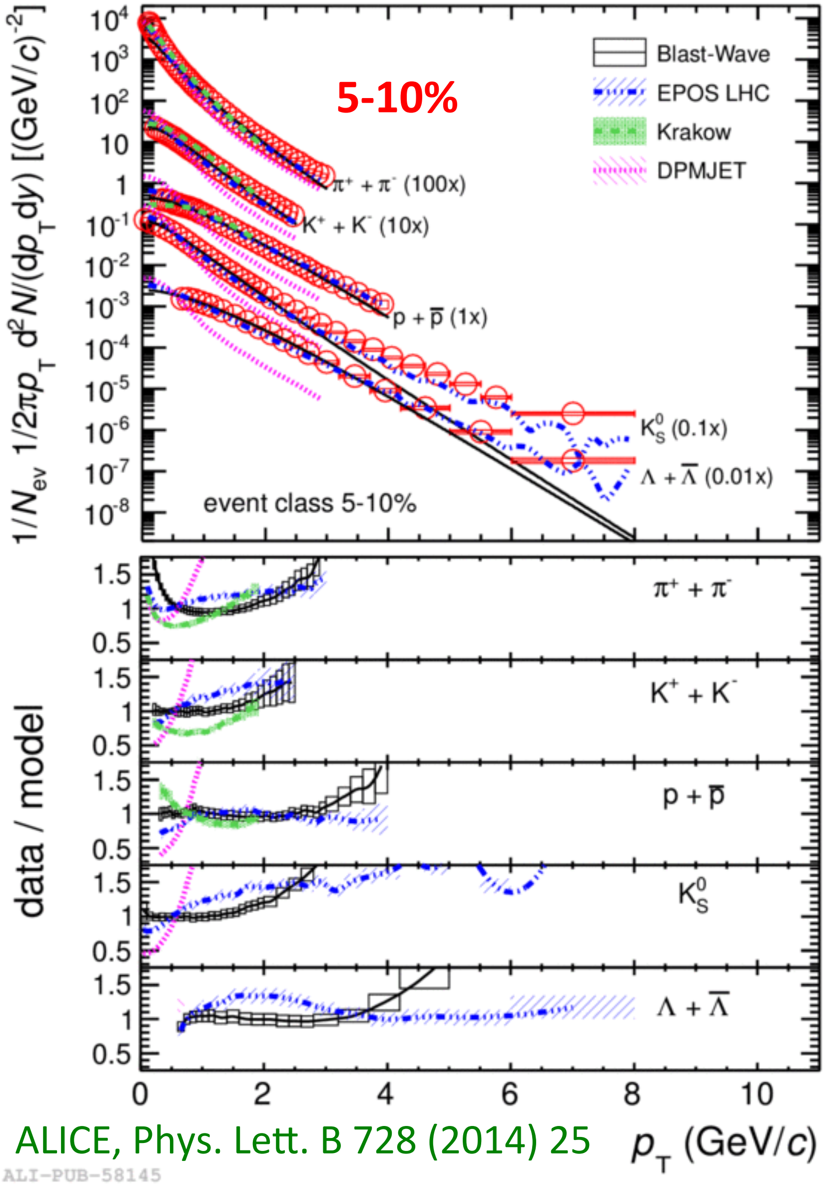
ALICE: Phys. Lett. B 739 (2014) 139



From comparison of radii extracted from Edgeworth fit:

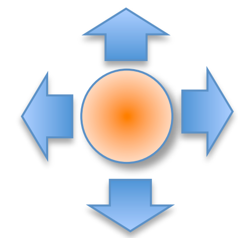
- R_{inv} (pp) < R_{inv} (pPb) ~ 5-15% (disfavor models with stronger collective expansion in p-Pb, consistent with CGC (Bzdak et al. Phys. Rev. C 87 (2013) 064906))
- R_{inv} (pPb) < R_{inv} (PbPb) ~ 35-55% (stronger expansion or different initial conditions in Pb-Pb compared to p-Pb)

Low-p_T hadron production in p-Pb vs. models



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

p-Pb high multiplicity events



Blast-wave
- Hydro inspired model

EPOS LHC
- hard/soft scattering contribute to jet/bulk
- bulk matter described with hydro

Kraków
- initial conditions from Glauber MC
- viscous hydrodynamic expansion
- statistical hadronization at freeze-out

DPMJET
- QCD-inspired model based on Gribov-Glauber approach
- reproduces $dN_{ch}/d\eta$ in NSD p-Pb

Hydro models reasonably well describe data in p-Pb → indication of flow

Identified hadrons at low p_T vs. multiplicity

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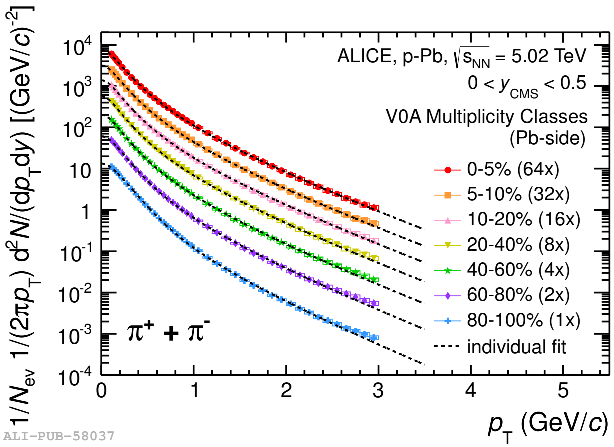
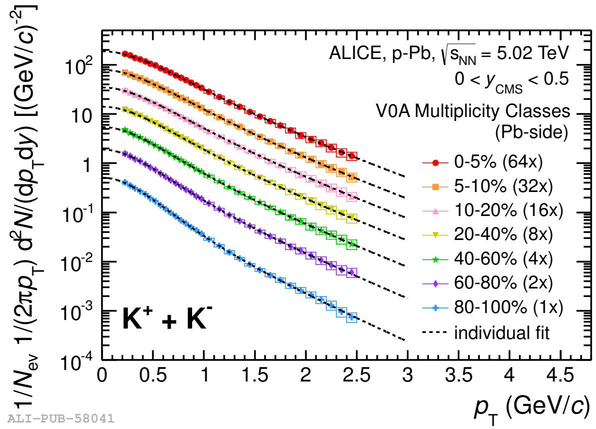
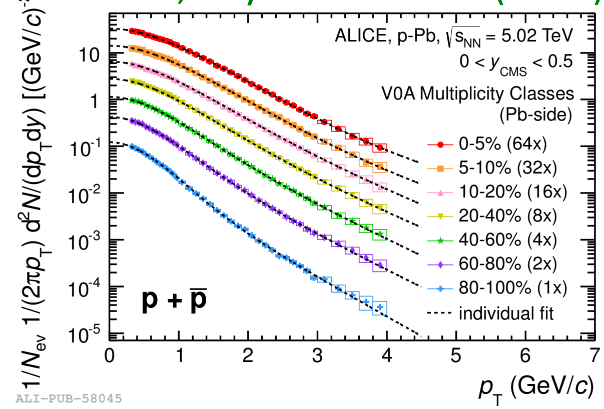
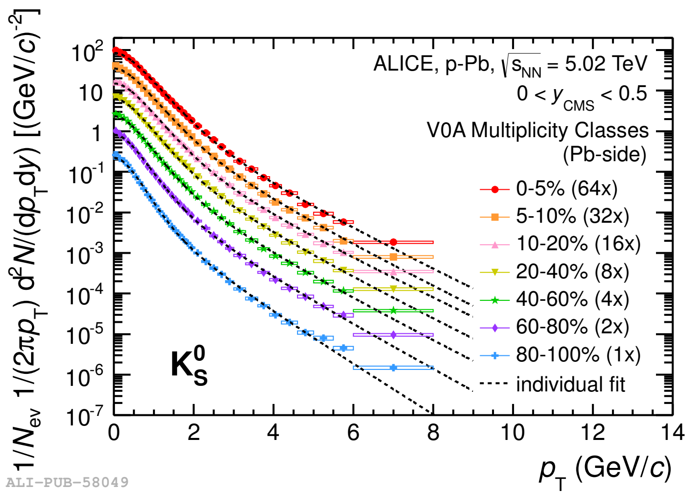
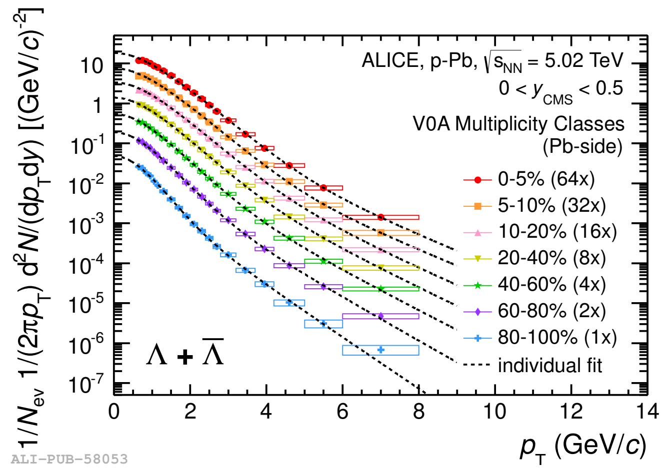
ALICE, Phys. Lett. B 728 (2014) 25

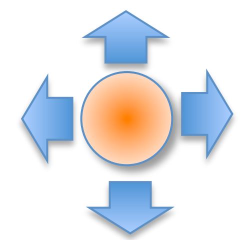












Blast-wave model fit (thermal + collective)

Schnedermann et al.
Phys. Rev. C48 (1993) 2462

$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r\,dr\, m_T\, I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

$$\rho = \tanh^{-1}\beta_T$$

T_{kin} – kinetic freeze-out
β_T – transverse velocity

Blast-wave comparison of pp, p-Pb and Pb-Pb

- pp, p-Pb and Pb-Pb data in multiplicity bins
- pp PYTHIA8 in multiplicity bins

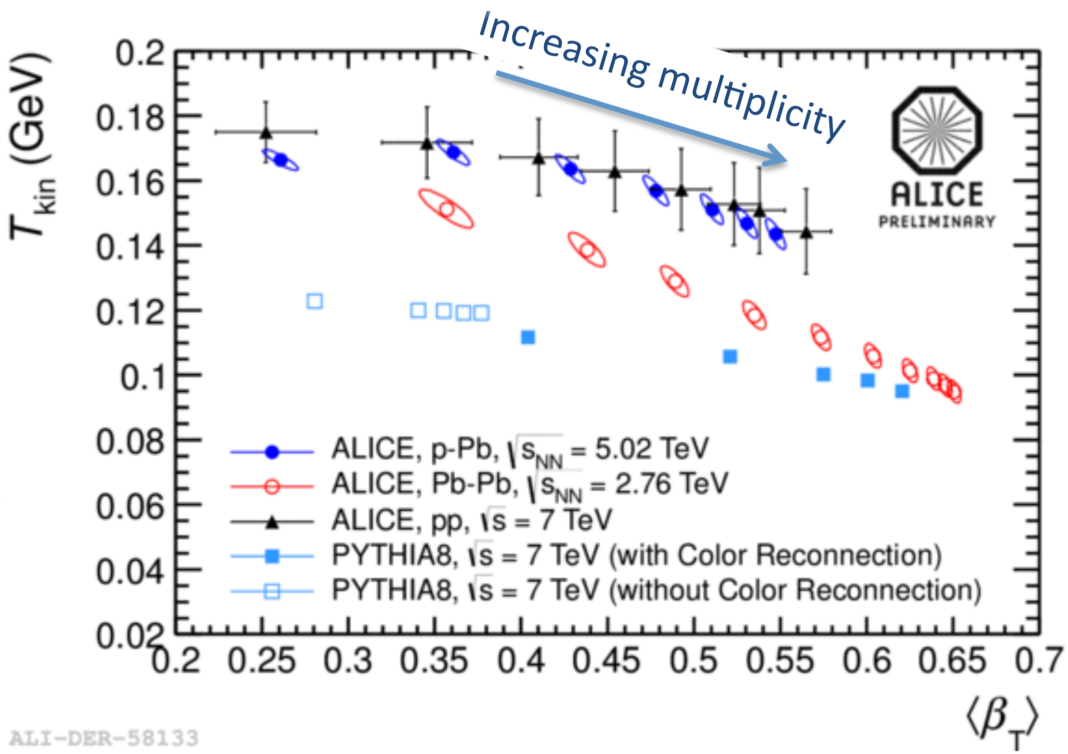
Published p-Pb and Pb-Pb results:
ALICE, Phys. Lett. B 728 (2014) 25

Blast-wave fit parameters:
T_{kin} – kinetic freeze-out temperature
$\langle\beta_T\rangle$ - average transverse velocity

- Similar evolution of the blast-wave parameters with increasing multiplicity

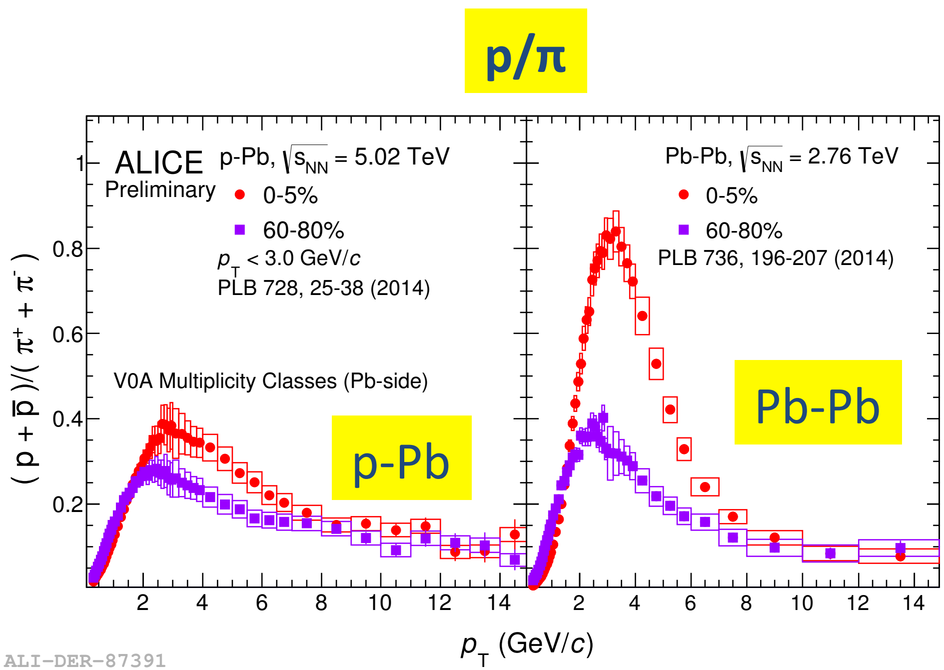
PYTHIA8 pp events (no hydrodynamic evolution) also show the same trend

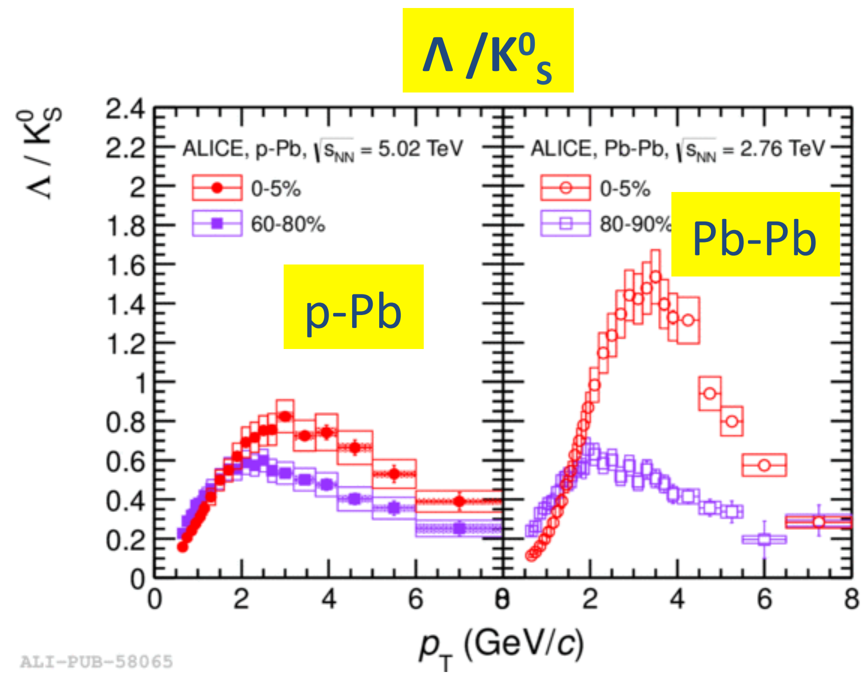
- Color reconnection causes similar effect as flow



NB: Multiplicity selection introduces bias on p_T spectra in pp and p-Pb.

Baryon to meson ratios



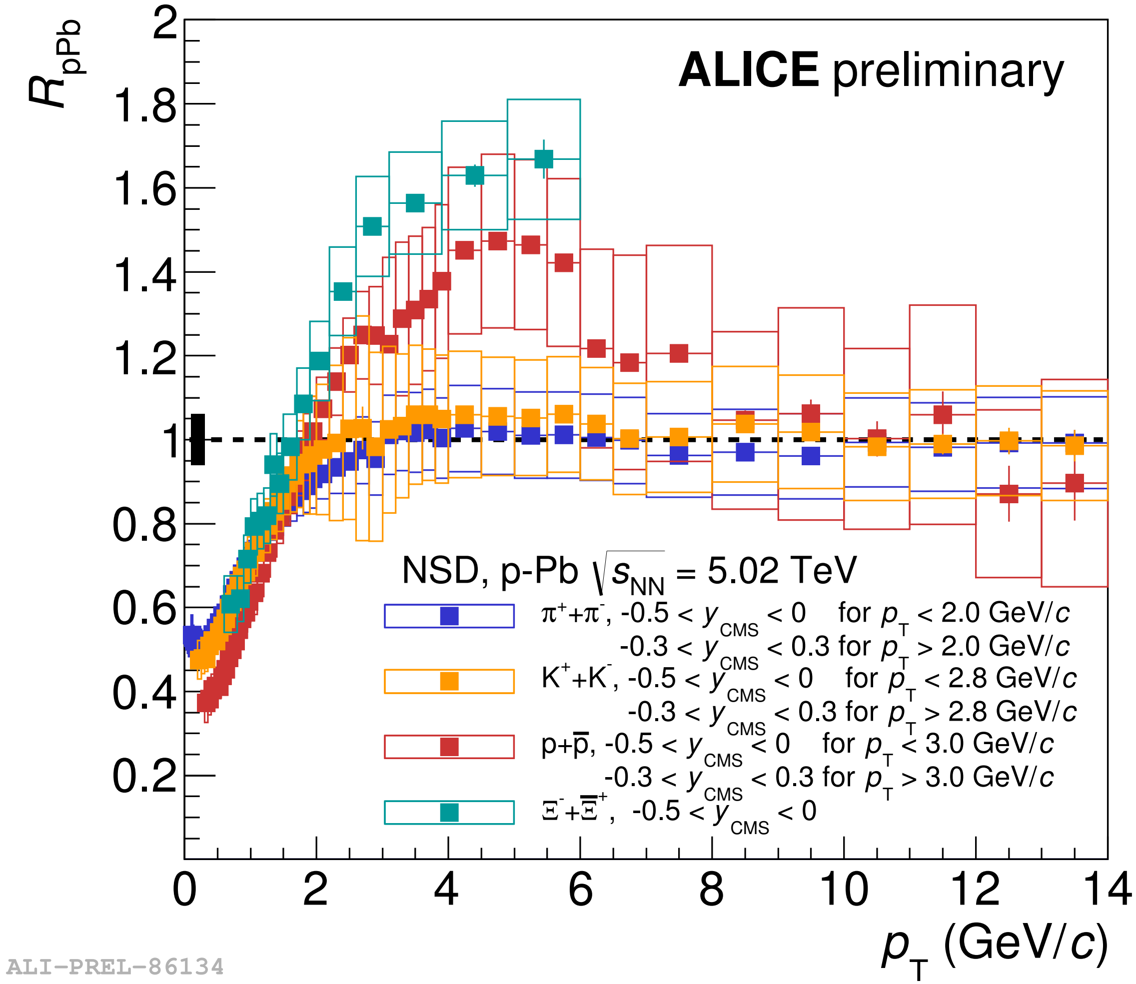


ALICE, Phys. Lett. B728 (2014) 25
ALICE, Phys. Lett. B736 (2014) 196

Baryon to meson ratio increases with multiplicity

- p-Pb: flow like effect?
- Pb-Pb: flow and coalescence

R_{pPb} for identified hadrons



$$R_{pPb} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pPb} / dp_T}{dN_{pp} / dp_T}$$

p-Pb (minimum bias, NSD)

- **Low p_T < 2 GeV/c**: depletion similar for all particle species
- **Intermediate 2 < p_T < 7 GeV/c:** enhancement for protons and Xi (mass hierarchy)
  → flow like effect
- **High p_T > 7 GeV/c:** R_{pPb} ~ 1 (no modification)

Summary and Outlook

- Flow like effects observed in high multiplicity p-Pb collisions
  - Double ridge from bulk of the matter
  - Mass hierarchy in v_2
  - Second and third harmonic cumulants
  - p_T spectra reasonable described within hydro models
  - Baryon to meson ratios

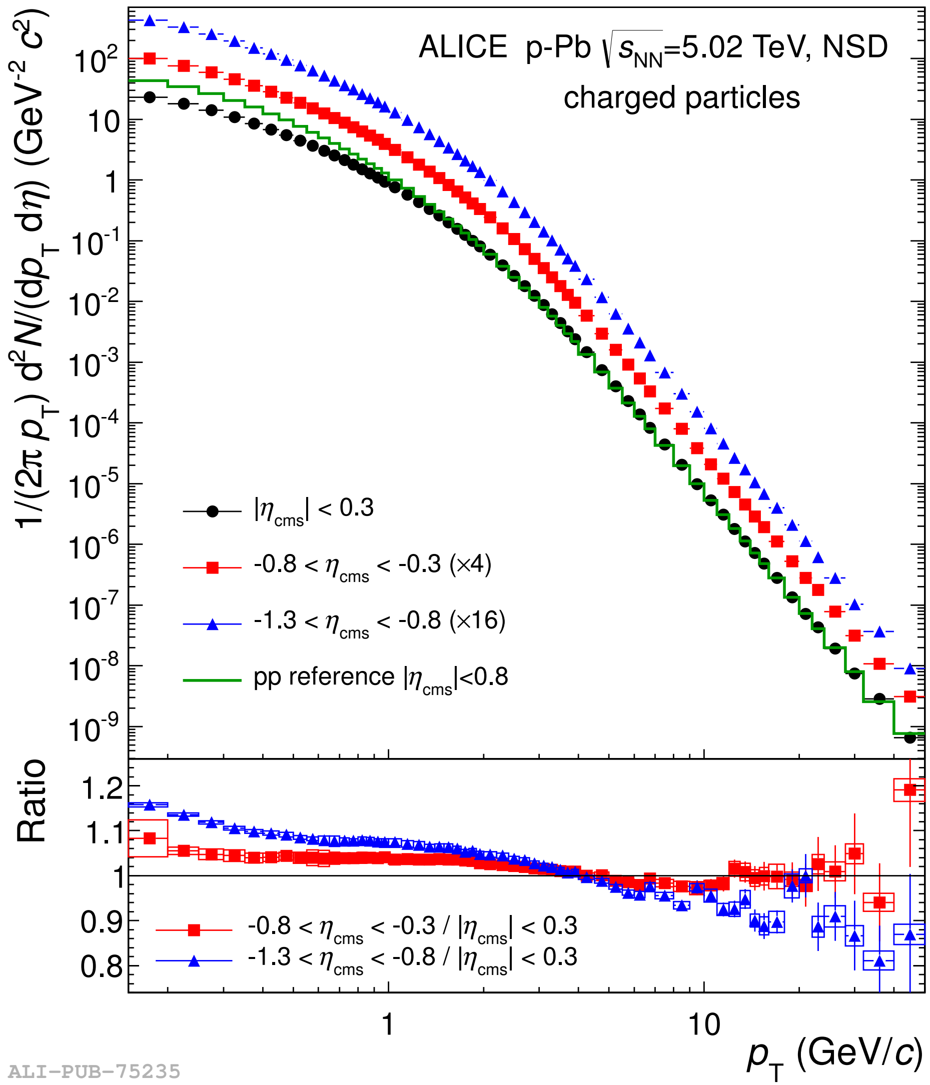
However

- Color reconnection also introduces flow like effects in pp collisions
- Freeze-out radii of p-Pb system only 15% larger than of pp system
- No suppression of high-p_T hadron production in p-Pb

What is the nature of collectivity in pp and p-Pb collision compared to Pb-Pb?

BACKUP

Charged particle p_T spectra in p-Pb



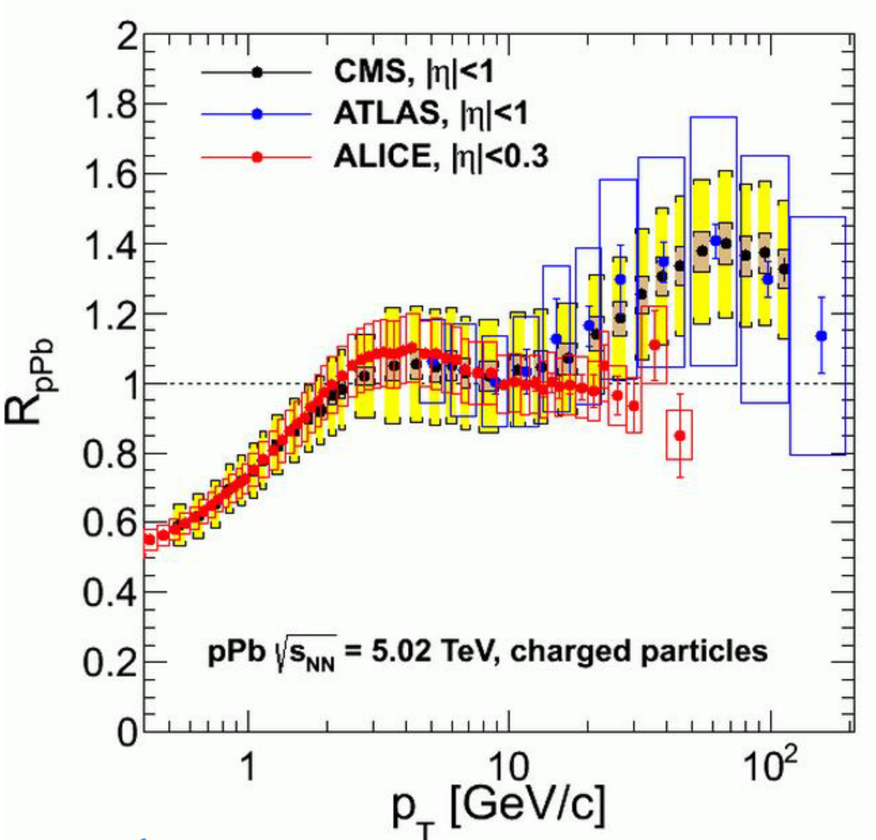
p-Pb min. bias, non-single diffractive (NSD)

- p_T range: 0.15 – 50 GeV/c
- 3 pseudorapidity ranges
- η_{cms} = η - 0.465 using Jacobian (dy/dη) with measured identified hadrons (π, K, p) by ALICE
- pp reference at $\sqrt{s_{NN}}$ = 5.02 TeV constructed from pp at 2.76 and 7 TeV (no pp measurement available at this energy)

ALICE, Eur. Phys. J. C74 (2014) 3054

R_{pPb} at very high p_T

- Surprising enhancement at very high-p_T measured by CMS and ATLAS
- ALICE data shows different trend – difference mostly in pp reference



Smaller Q^2 and x

Larger Q^2 and x

Yen-Jie Lee (Quark Matter 2014)

→ Necessity to measure pp reference at $\sqrt{s_{NN}}$ = 5.02 TeV!

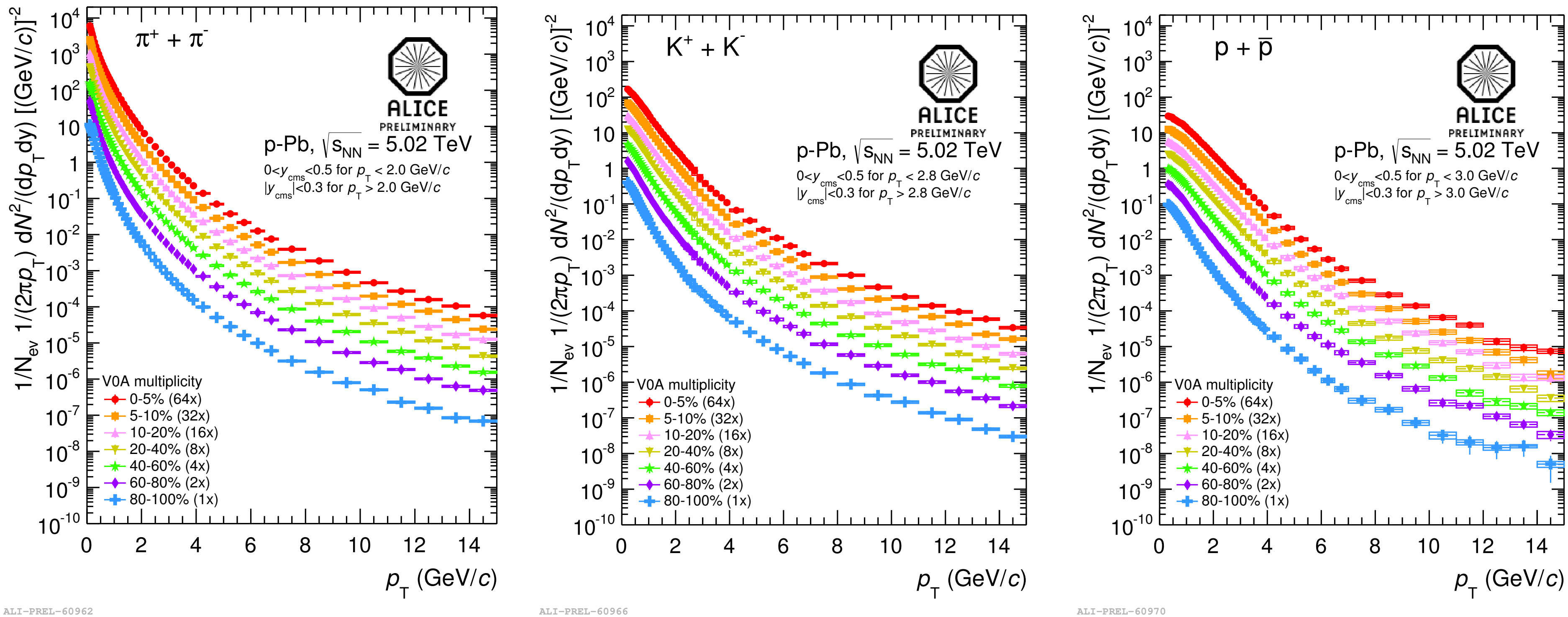
Enhancement at very high p_T not seen for jets

→ Modification of fragmentation function?

ALICE, Eur. Phys. J. C74 (2014) 3054
CMS-PAS-HIN-12017
ATLAS-CONF-2014-029

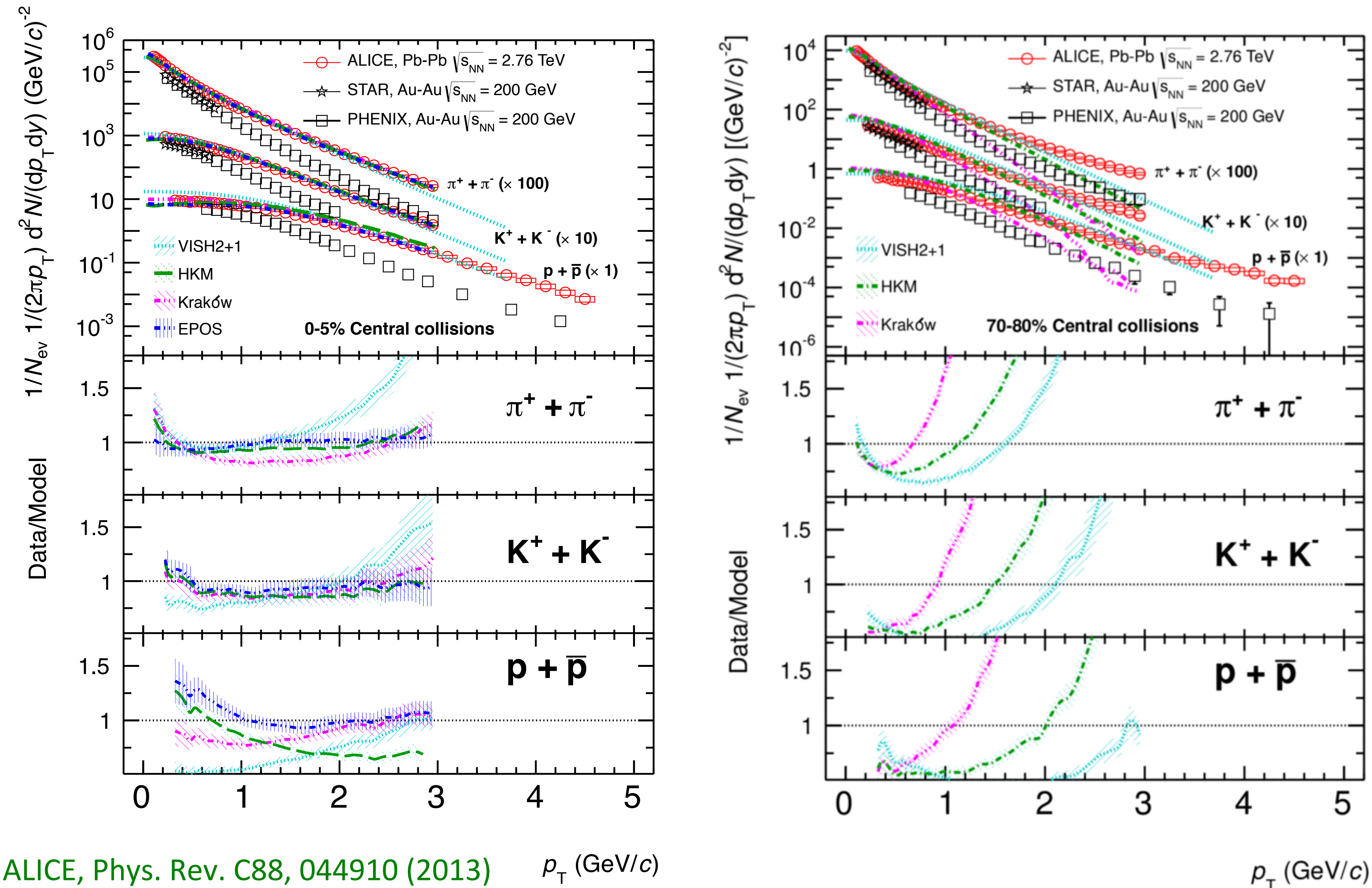
Pions, kaons and protons in p-Pb

- Harder spectra with increasing multiplicity and with increasing particle mass
- Flattening of proton spectra at low p_T with increasing multiplicity → indication of flow



Results for low p_T: ALICE, Phys. Lett. B728 (2014) 25

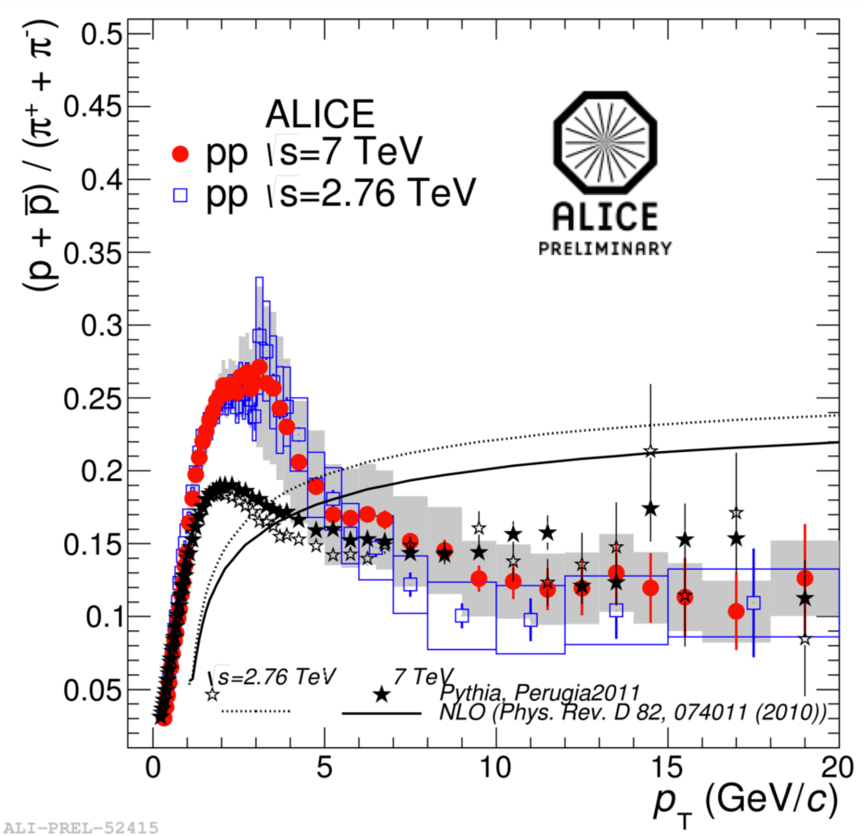
Comparison to hydro models

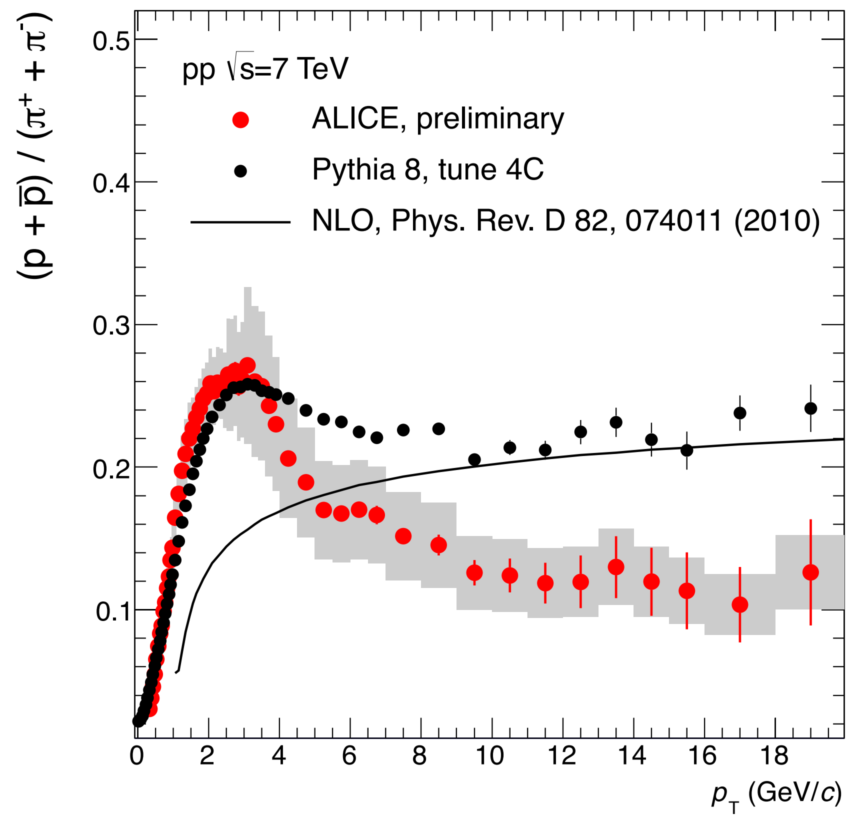


ALICE, Phys. Rev. C88, 044910 (2013)

p/π ratio in pp collisions

Ortiz et al. Phys. Rev. Lett. 111 (2013) 042001





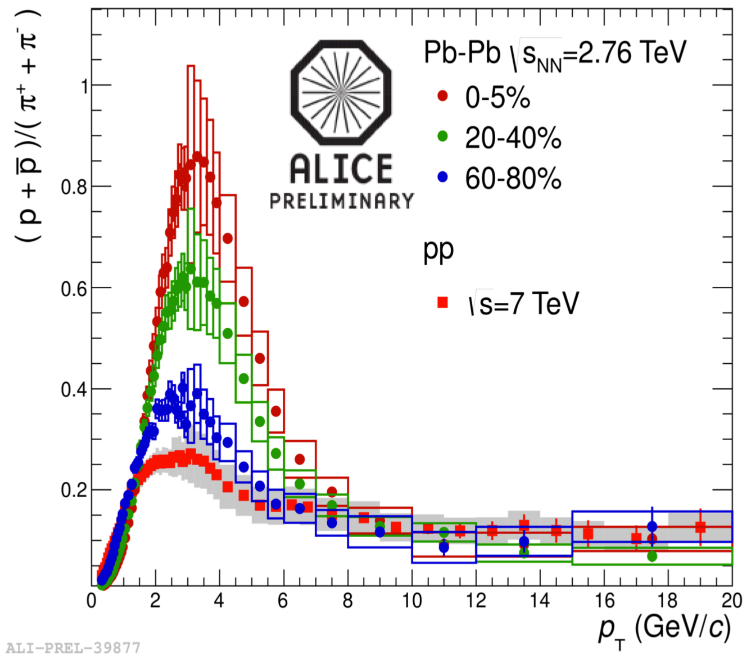
Maximum in proton to pion ratio ~3 GeV/c in PYTHIA related to color reconnection

Baryon-meson "anomaly"

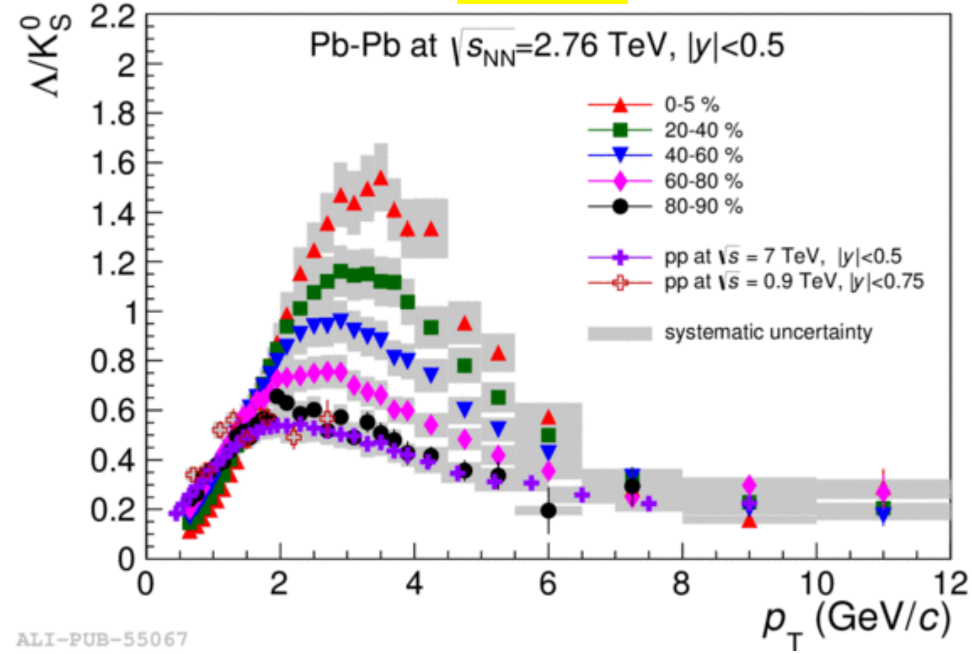
ALICE

Ratios of hadrons with different mass

p/π



Λ / K^0_S



ALICE, Phys. Rev. Lett. 111, 222301 (2013)

- Baryon to meson ratio increasing with centrality for p_T < 8 GeV/c
- Similar baryon to meson ratio in peripheral Pb-Pb and pp collisions
- For p_T > 8 GeV/c no dependence on centrality and collision system

Baryon-meson "anomaly" vs. models

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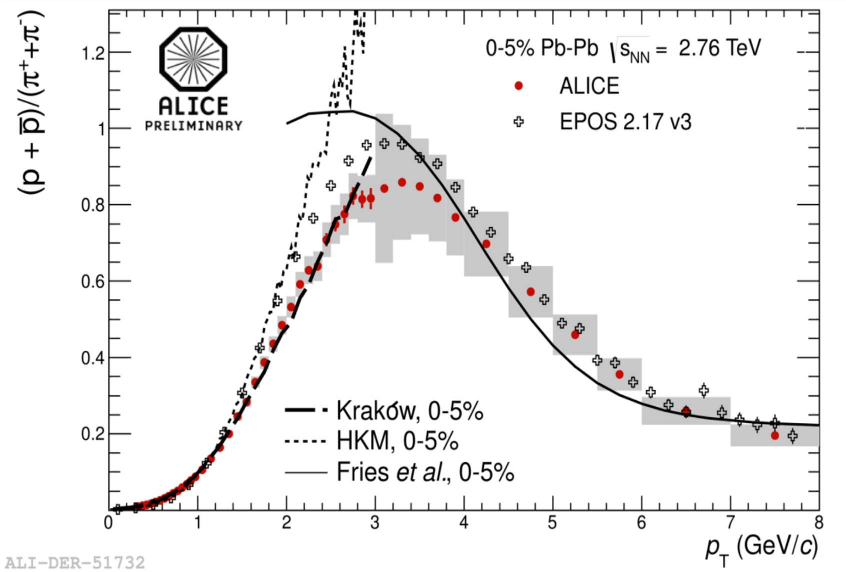
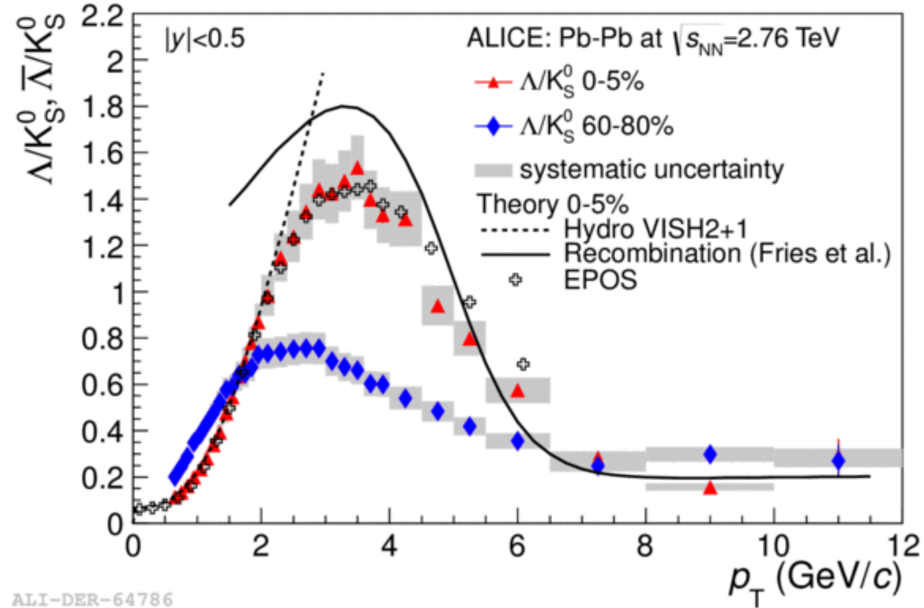
p/π



Λ/K^0_S



ALICE, Phys. Rev. Lett. 111, 222301 (2013)

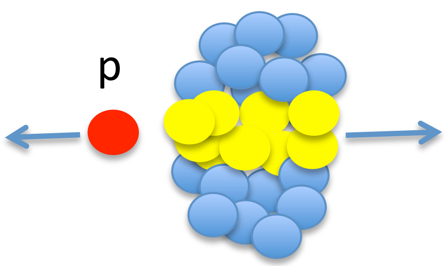
- Hydro models (**Kraków, HKM, VISH2+1**): good agreement at low p_T < 2 GeV/c
- Recombination models (**Fries et al.**): work for p_T > 3-5 GeV/c

EPOS best agreement with data at whole p_T range:

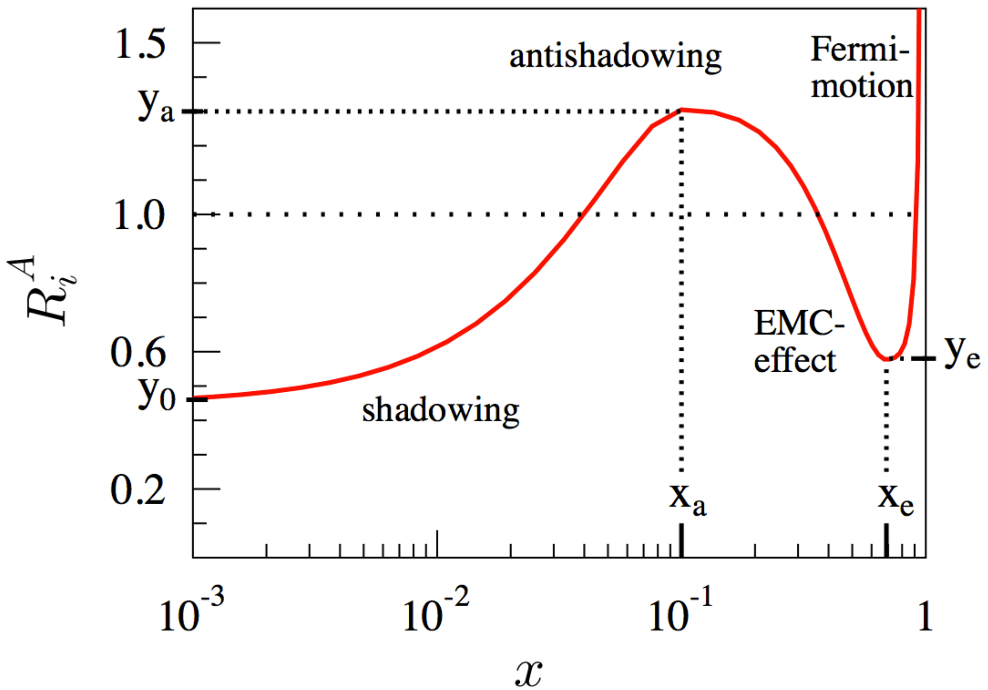
- Hydro at low p_T
- Medium modified jet fragmentation at intermediate p_T
- Vacuum jet fragmentation at high p_T

Shadowing / Gluon Saturation

- Nuclear modification of the parton distribution functions
  - Parton distribution in nucleus differs from that in hadron



$$R_i^A\left(x,Q^2\right) \equiv f_i^A\left(x_1,Q^2\right) / f_i^p\left(x,Q^2\right)$$



Salgado et al. JHEP 0904:065,2009

LHC: x ~10^{-1}-10^{-5}
- shadowing
- antishdowing

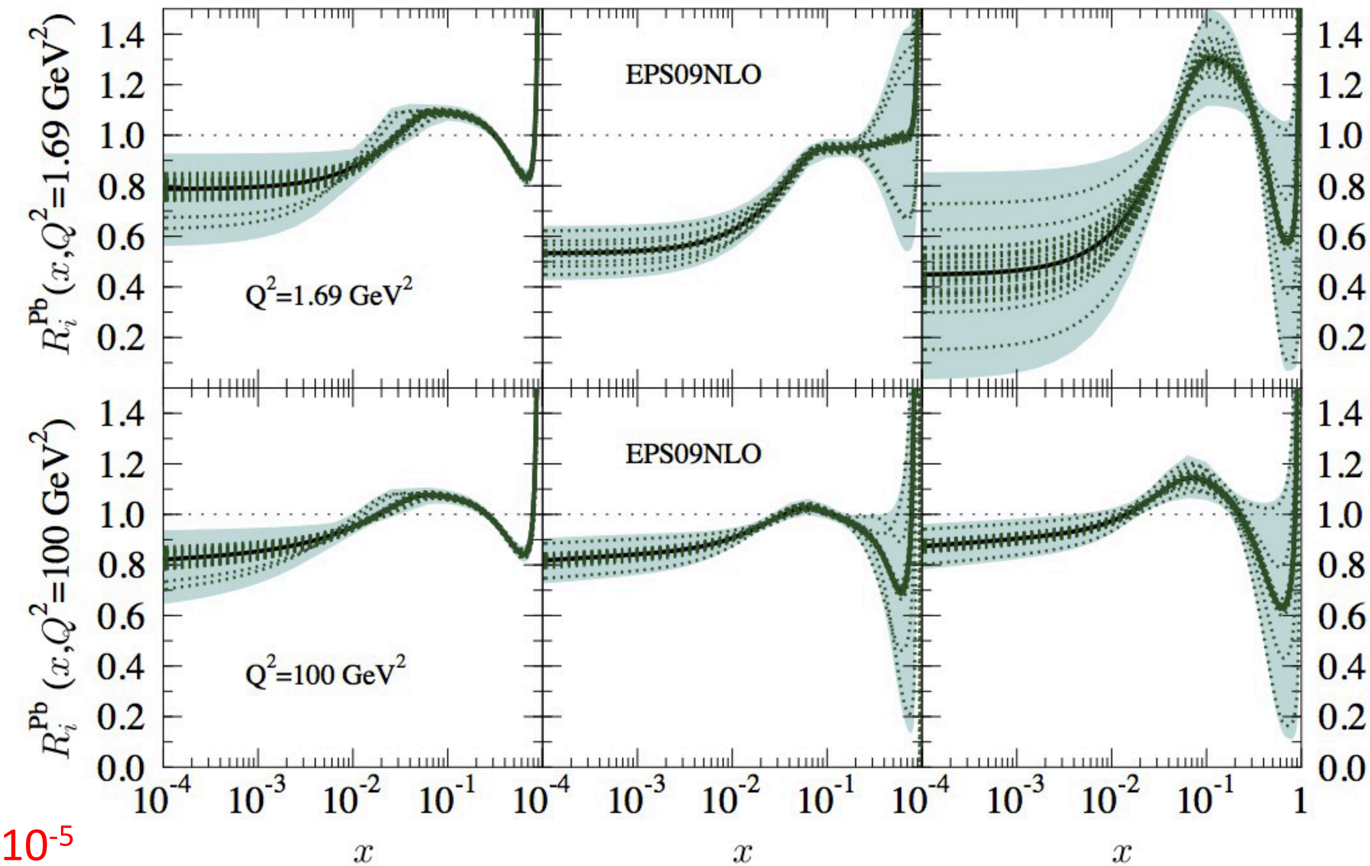
Nuclear Parton Distribution Functions – EPS09

$$R_i^{Pb}\left(x,Q^2\right) \equiv f_i^{Pb}\left(x_1,Q^2\right) / f_i^{p}\left(x,Q^2\right)$$

NLO fits to measured data

Salgado et al. JHEP 0904:065,2009

Valence quarks R_V^{Pb} See quarks R_S^{Pb} Gluons R_G^{Pb}



LHC: x ~10^{-1}-10^{-5}

Possibility to reach gluon saturation at small x (Color Glass Condensate)

Nuclear modification factors

$$R_{PbPb} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{PbPb} / dp_T}{dN_{pp} / dp_T}$$

N_{coll} from Glauber MC

R_{PbPb} = 1 (no modification)

Pb-Pb (central collisions)

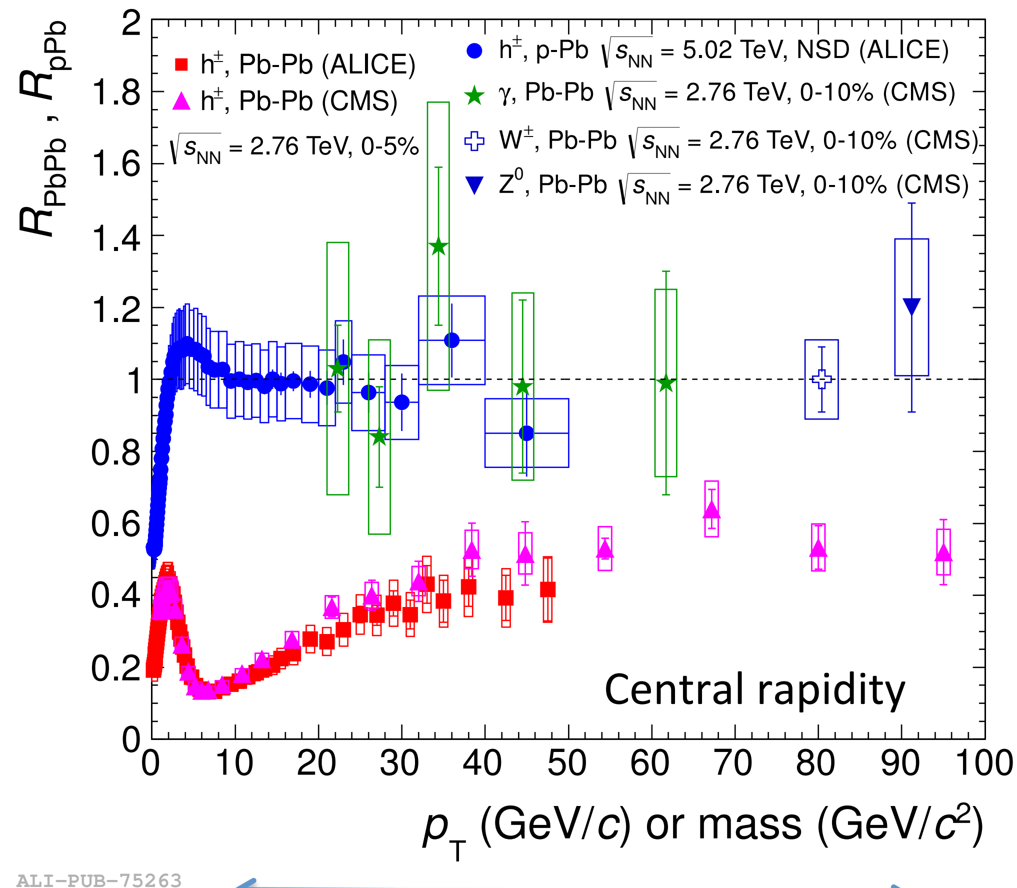
- No modification of W, Z and γ boson production
- Strong hadron suppression at high p_T (R_{PbPb}~ 0.2-0.5)

p-Pb (minimum bias, NSD):

- Depletion at low p_T
- No modification at high p_T (R_{pPb} ~ 1)

→ Particle suppression in Pb-Pb related to final state effects

ALICE, Eur. Phys. J. C74 (2014) 3054



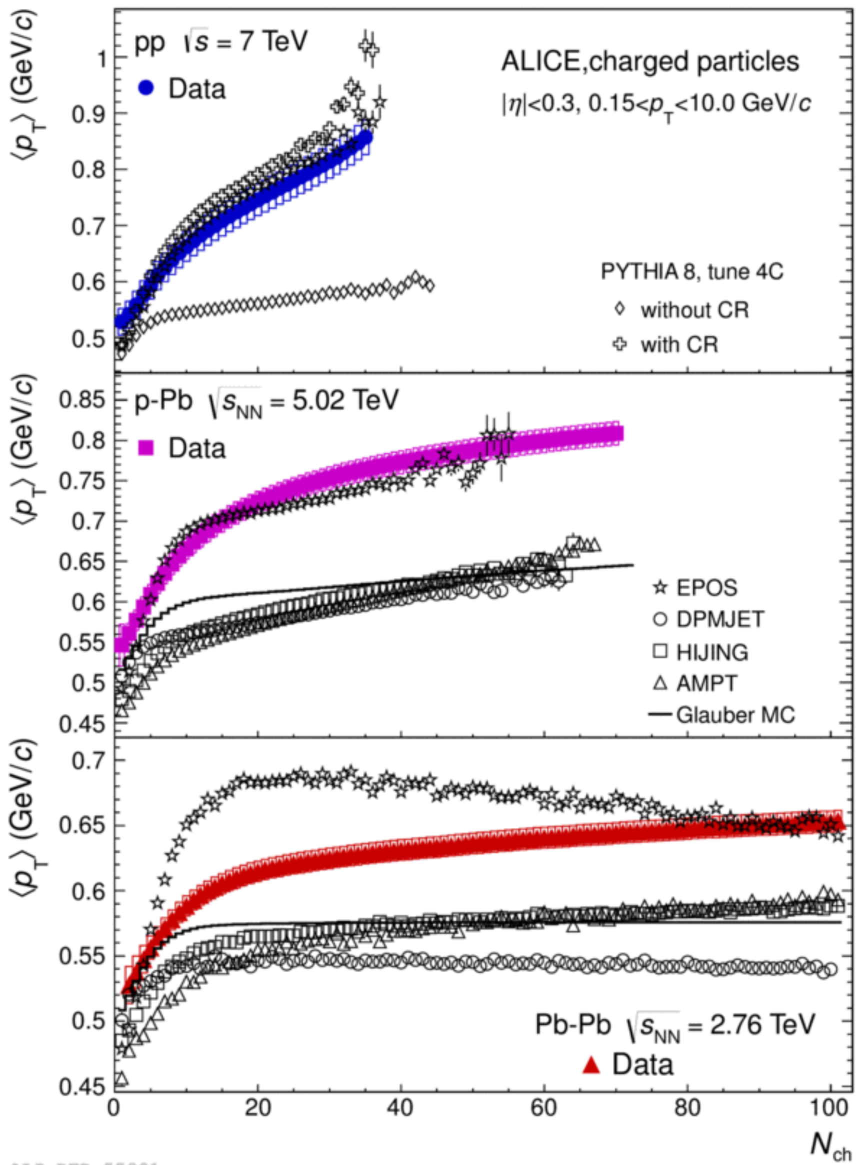
Smaller Q^2 and x

Larger Q^2 and x

Central rapidity: x ~ 10^{-2}–10^{-3}

Confirmed with jet measurements

$\langle p_T \rangle$ vs. N_{ch}: data vs. MC models



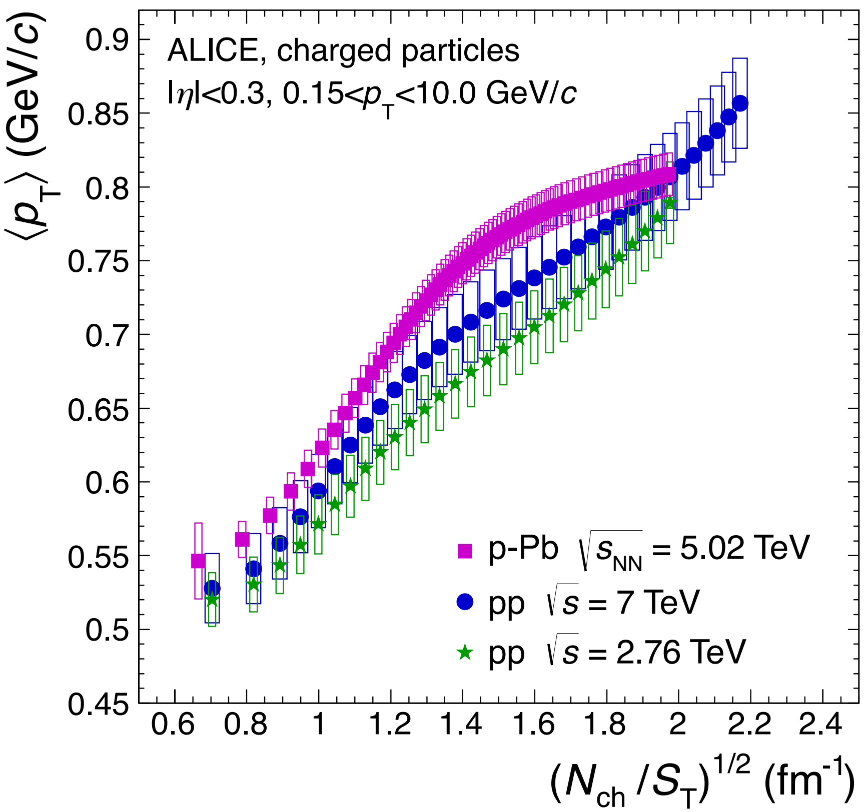
Comparison with model predictions

- **PYTHIA8** with color reconnection (CR) consistent with pp data → coherent MPIs
- **EPOS** (collective effects) describes pp and is consistent with p-Pb
  - Is it related to color reconnection?
- **Glauber MC** (incoherent superposition of nucleon-nucleon collisions) does not describe p-Pb and Pb-Pb data

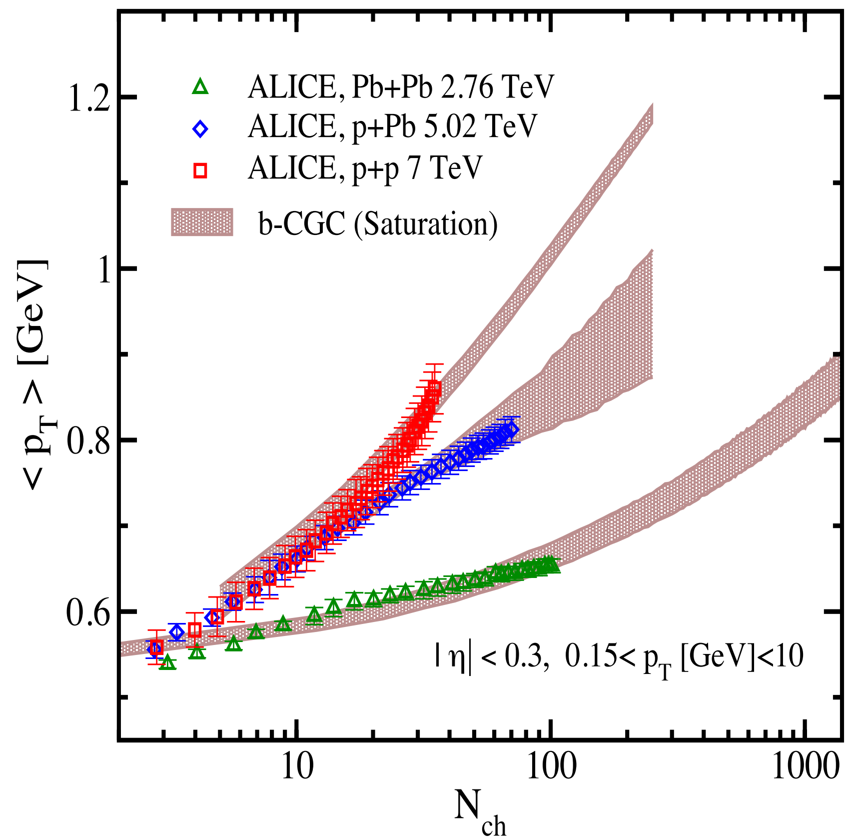
ALICE, Phys. Lett. B727 (2013) 371

$<p_T>$ vs. N_{ch}: data vs. saturation models

ALICE, Phys. Lett. B727 (2013) 371



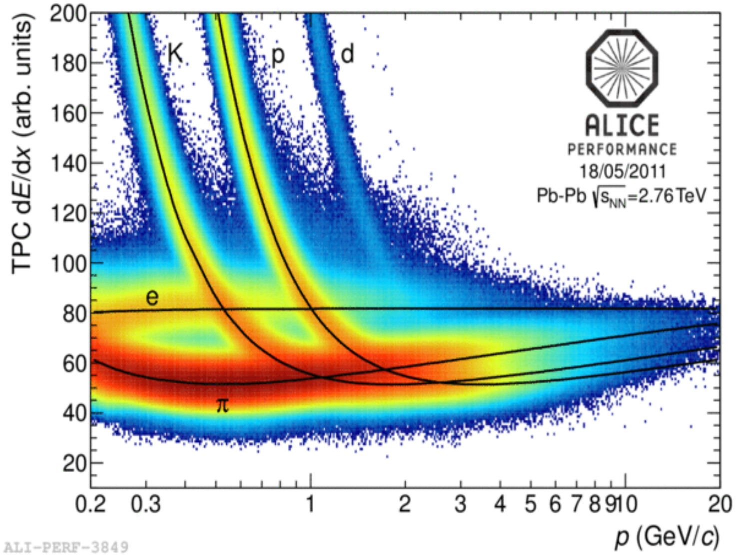
Razeian, Phys. Lett. B727 (2013) 218

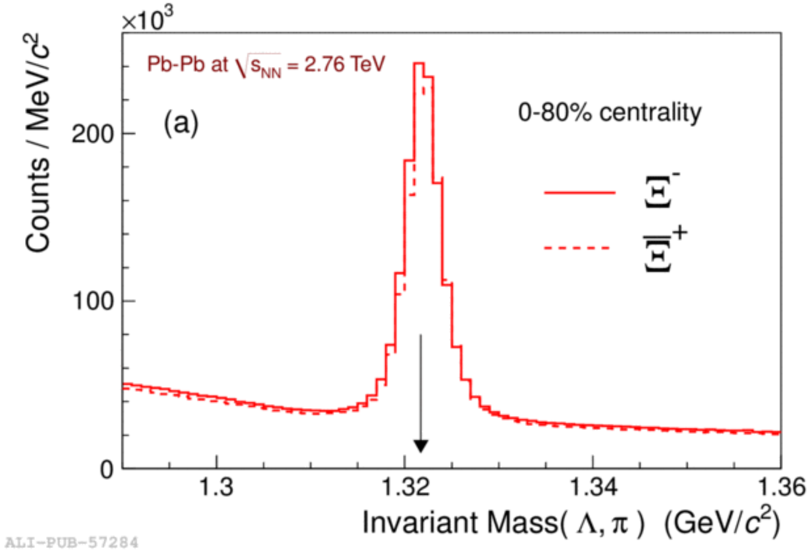


Scaling with transverse area S_T based on Color Glass Condensate (CGC) model [McLerran et al., Nucl. Phys. A916 210 (2013)]

Works but with tension for pp and p-Pb

Good data description



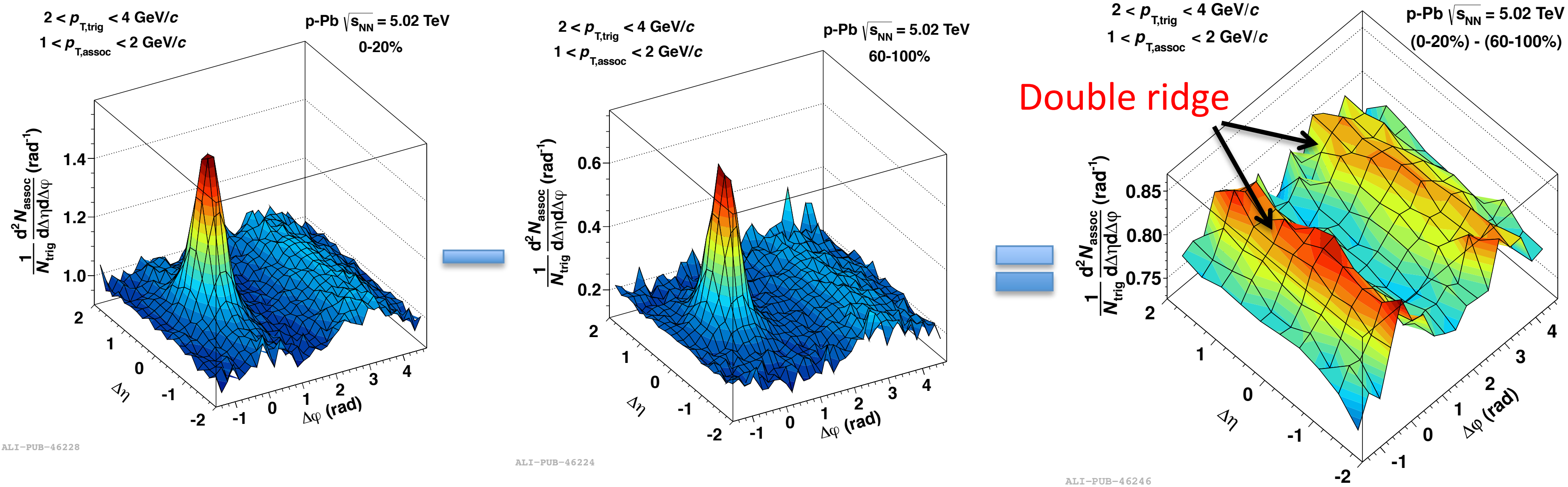


IDENTIFIED HADRONS

Double ridge in high multiplicity p-Pb collisions

Double ridge: Long range h-h angular correlations.

ALICE: Phys. Lett. B719 (2013) 29



Also seen in Pb-Pb and high multiplicity pp collisions by CMS and ATLAS.

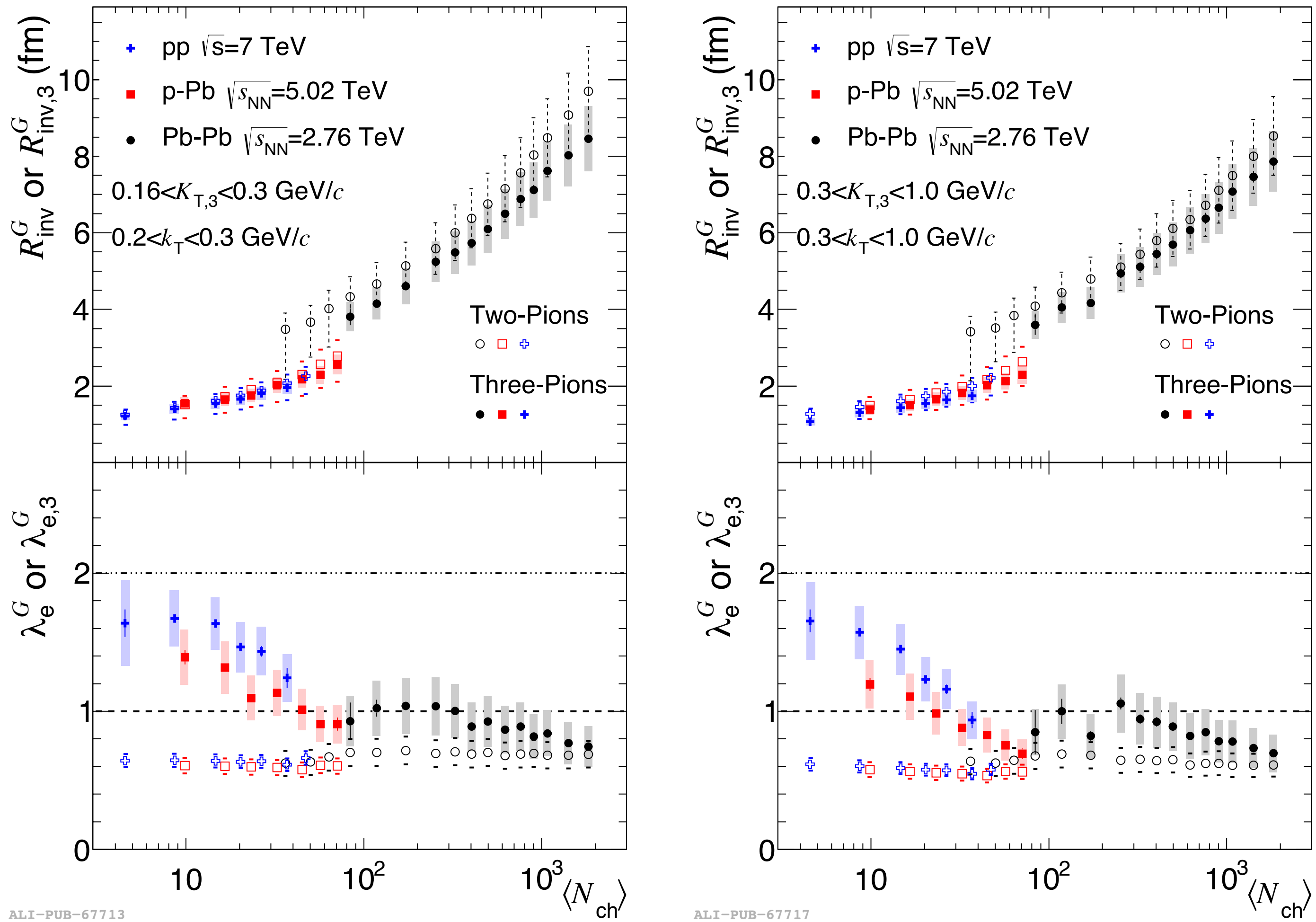
Collective flow: Bożek & Broniowski (e.g. Phys. Lett. B718 (2012) 4)

Qualitatively similar to Pb-Pb:
→ Indication of collective flow in high multiplicity p-Pb

Freeze-out radii measured in pp, p-Pb and Pb-Pb

Gaussian fit

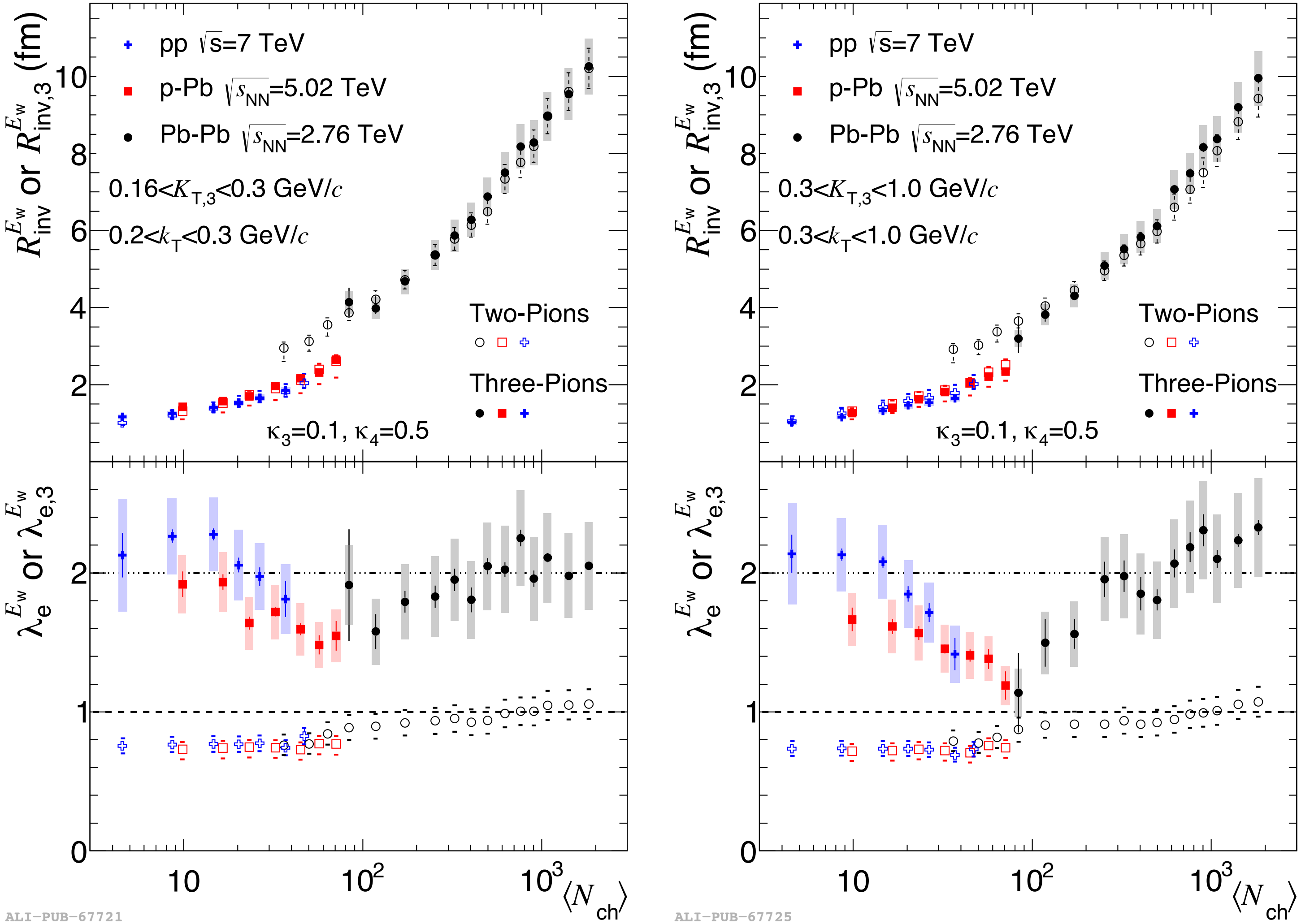
ALICE: Phys. Lett. B 739 (2014) 139



Freeze-out radii measured in pp, p-Pb and Pb-Pb

Edgeworth fit

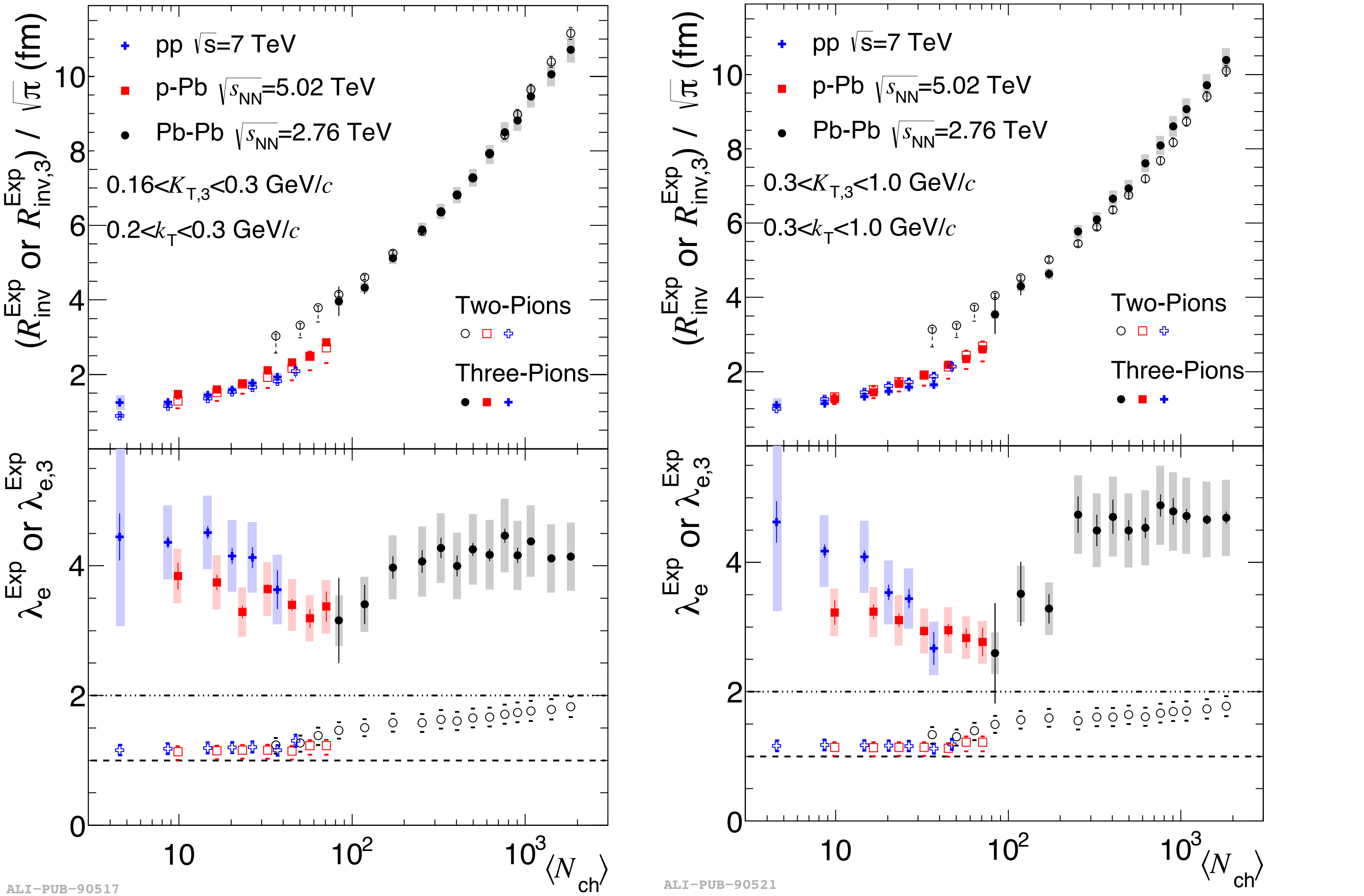
ALICE: Phys. Lett. B 739 (2014) 139



Freeze-out radii measured in pp, p-Pb and Pb-Pb

Exponential fit

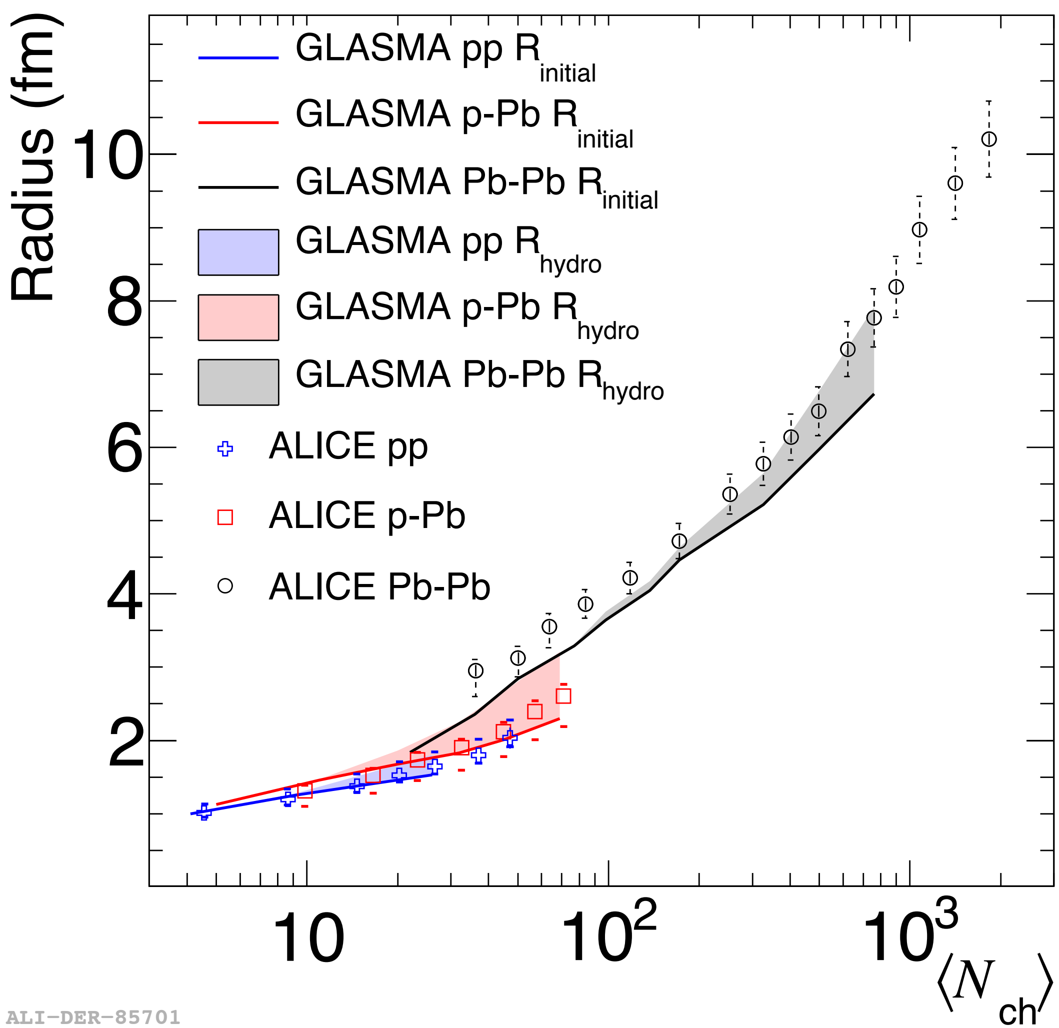
ALICE: Phys. Lett. B 739 (2014) 139



Freeze-out radii measured in pp, p-Pb and Pb-Pb

Comparison to CGC (IP Glasma)

ALICE: Phys. Lett. B 739 (2014) 139

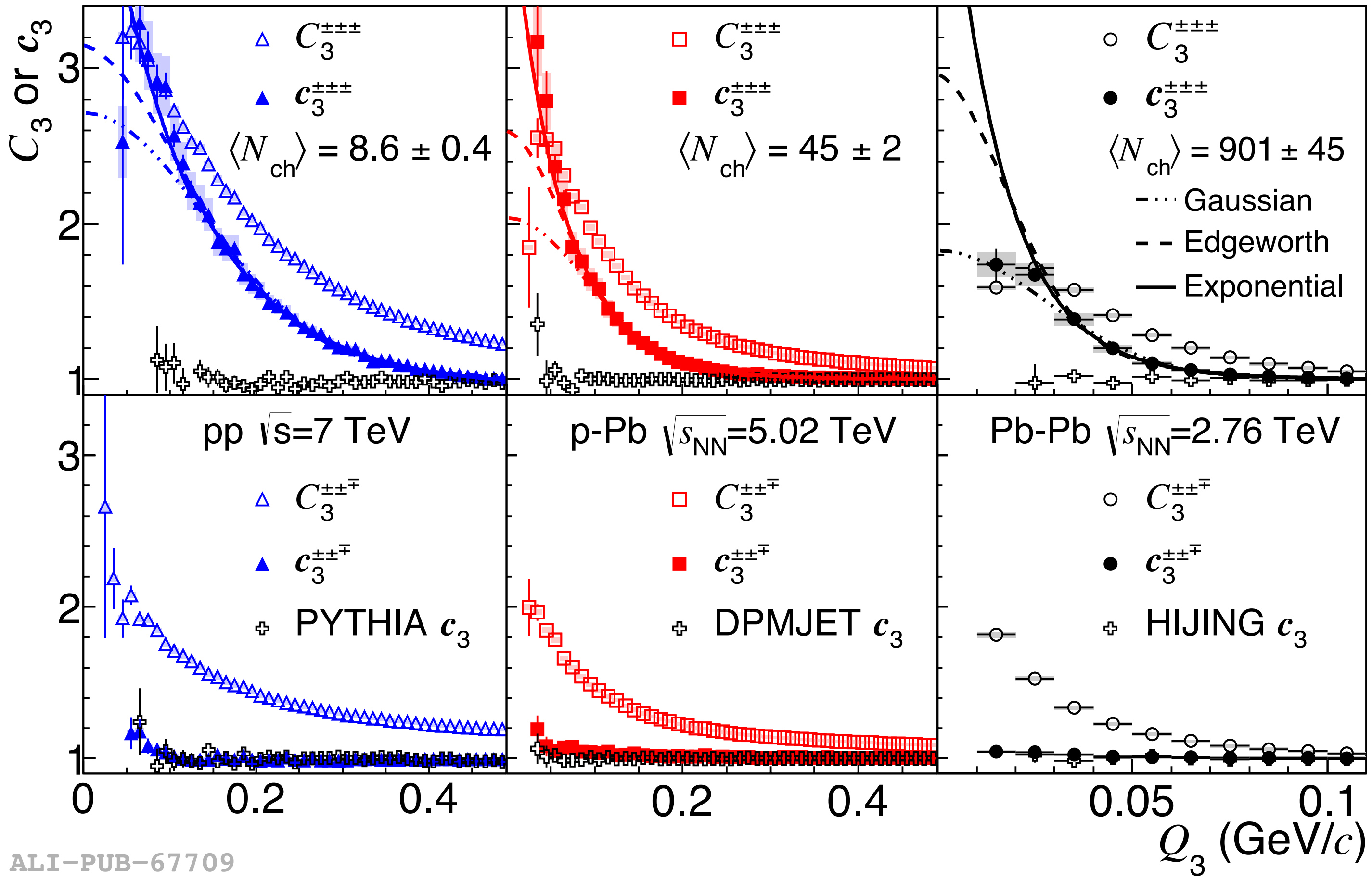


Freeze-out radii measured in pp, p-Pb and Pb-Pb

Three pion Bose-Einstein correlations (signal less susceptible to non-femtoscopic background)

$$C_3(p_1,p_2,p_3)=\alpha_3\frac{N_3(p_1,p_2,p_3)}{N_1(p_1)N_1(p_2)N_1(p_3)}$$

ALICE, Phys. Lett. B 739 (2014) 139



Multiparticle azimuthal correlations in p-Pb and Pb-Pb

Multiparticle particle correlation (cumulants) c_n have different sensitivity to fluctuations and nonflow contribution.

$c_n\{2\} = c_n(4) = c_n\{6\}$ (if no fluctuations and nonflow contribution)

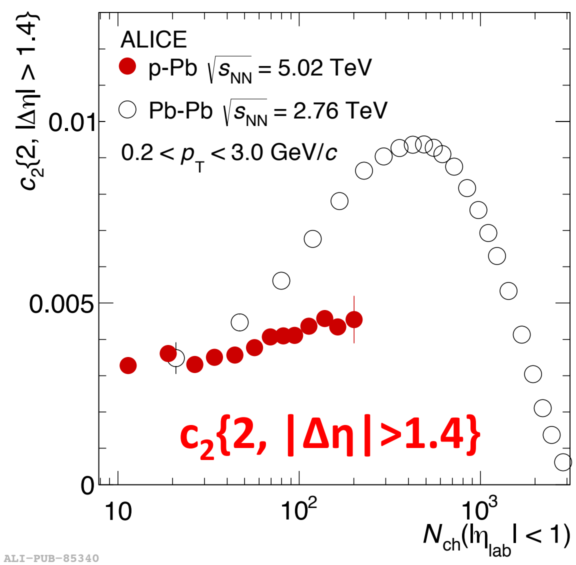
$$v_n\{2\} = \sqrt{c_n\{2\}},$$

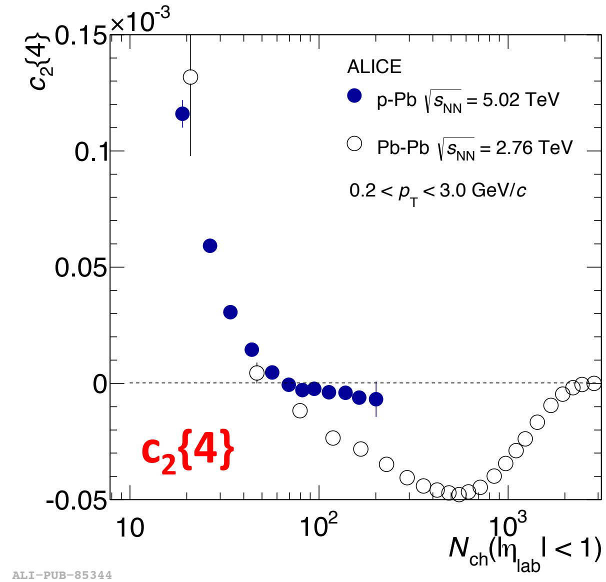
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}},$$

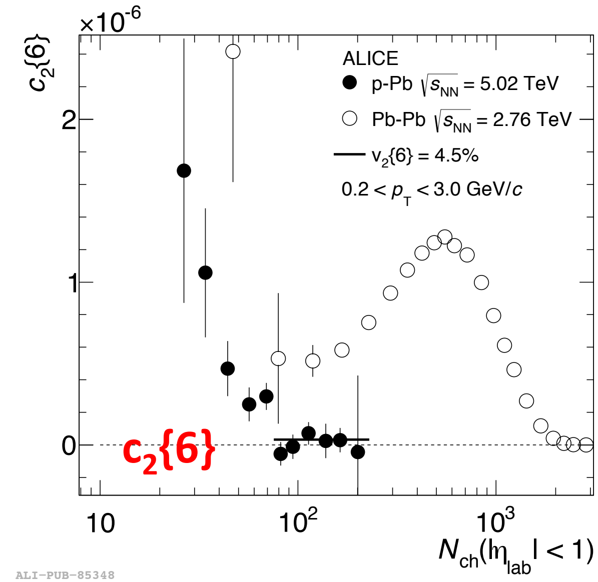
$$v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}.$$

Second harmonic cumulants

ALICE, Phys. Rev. C 90, 054901 (2014)







- Second harmonic cumulants are larger in Pb-Pb than in p-Pb at high multiplicities.
- For very high multiplicity Pb-Pb collisions $c_2(4)$ and $c_2(6)$ consistent with zero.

Multiparticle azimuthal correlations in p-Pb and Pb-Pb

ALICE

Multiparticle particle correlation (cumulants) c_n have different sensitivity to fluctuations and nonflow contribution.

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$$v_n\{2\} = \sqrt{c_n\{2\}},$$

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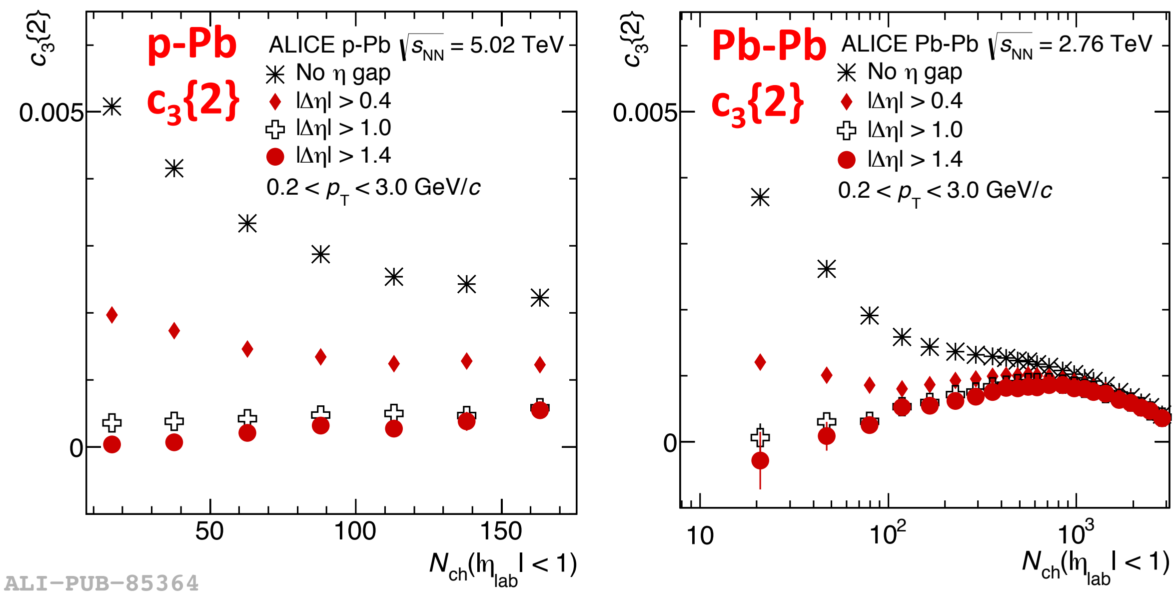
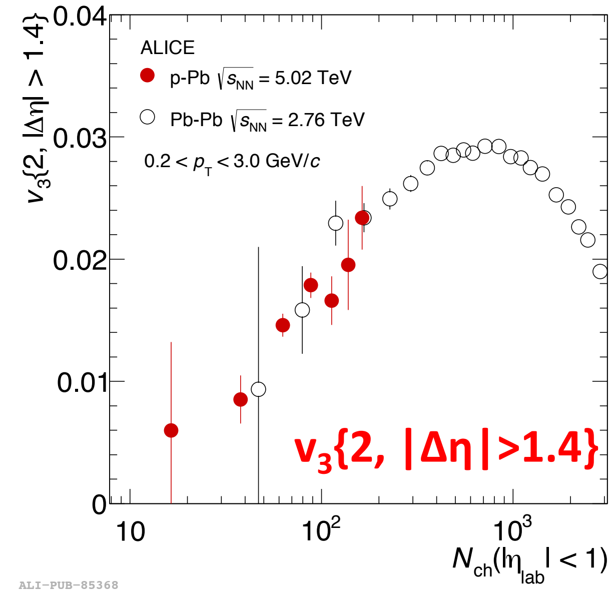
Third harmonic two-particle cumulants

ALICE, Phys. Rev. C 90, 054901 (2014)





Third harmonic two-particle cumulants are similar in p-Pb and Pb-Pb for overlapping multiplicities for |Δη|>1.4.