Hydrodynamic flow in proton-nucleus collisions at the LHC

K.W. in collaboration with

B. Guiot, Iu. Karpenko, T. Pierog

Signatures of flow?

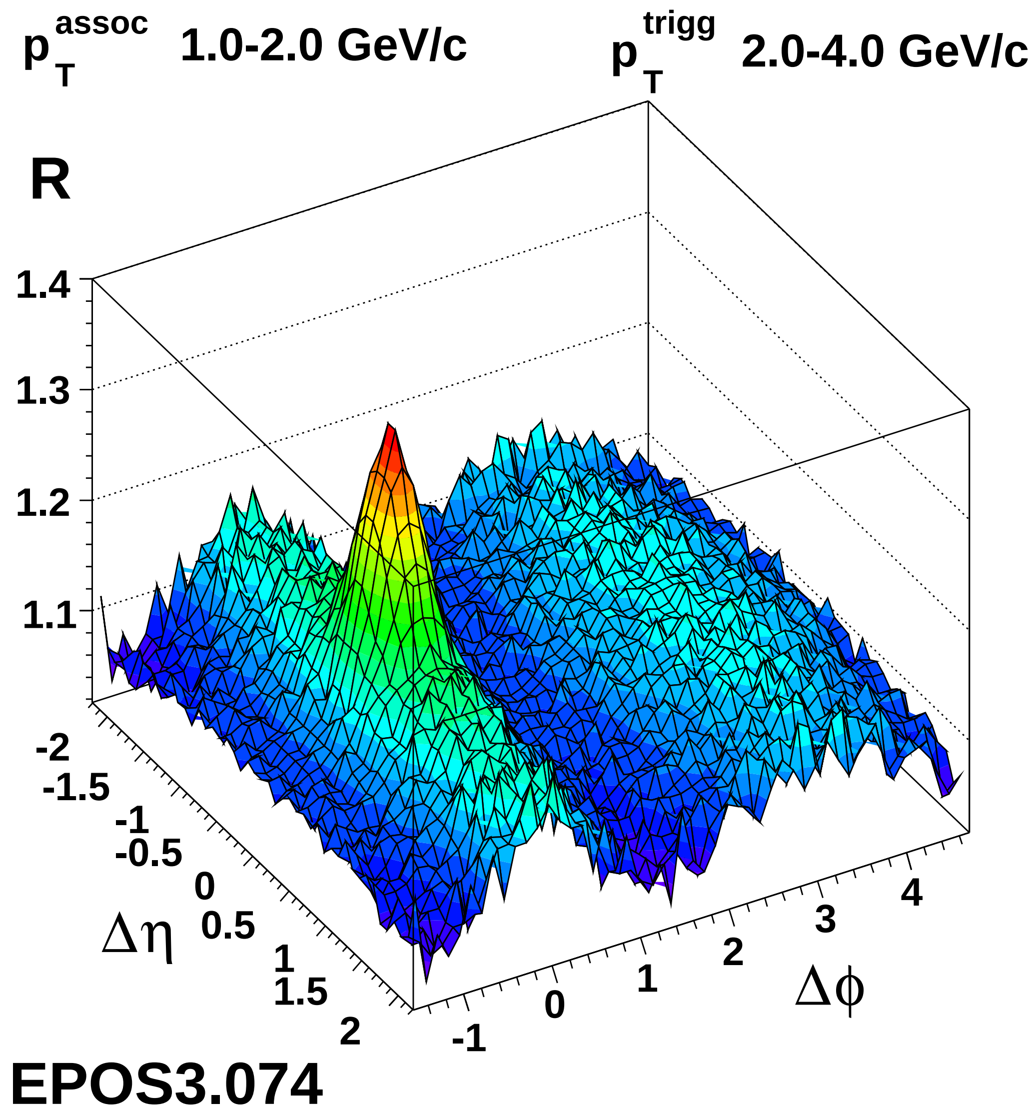
Ridges & flow harmonics

Ridges appear in

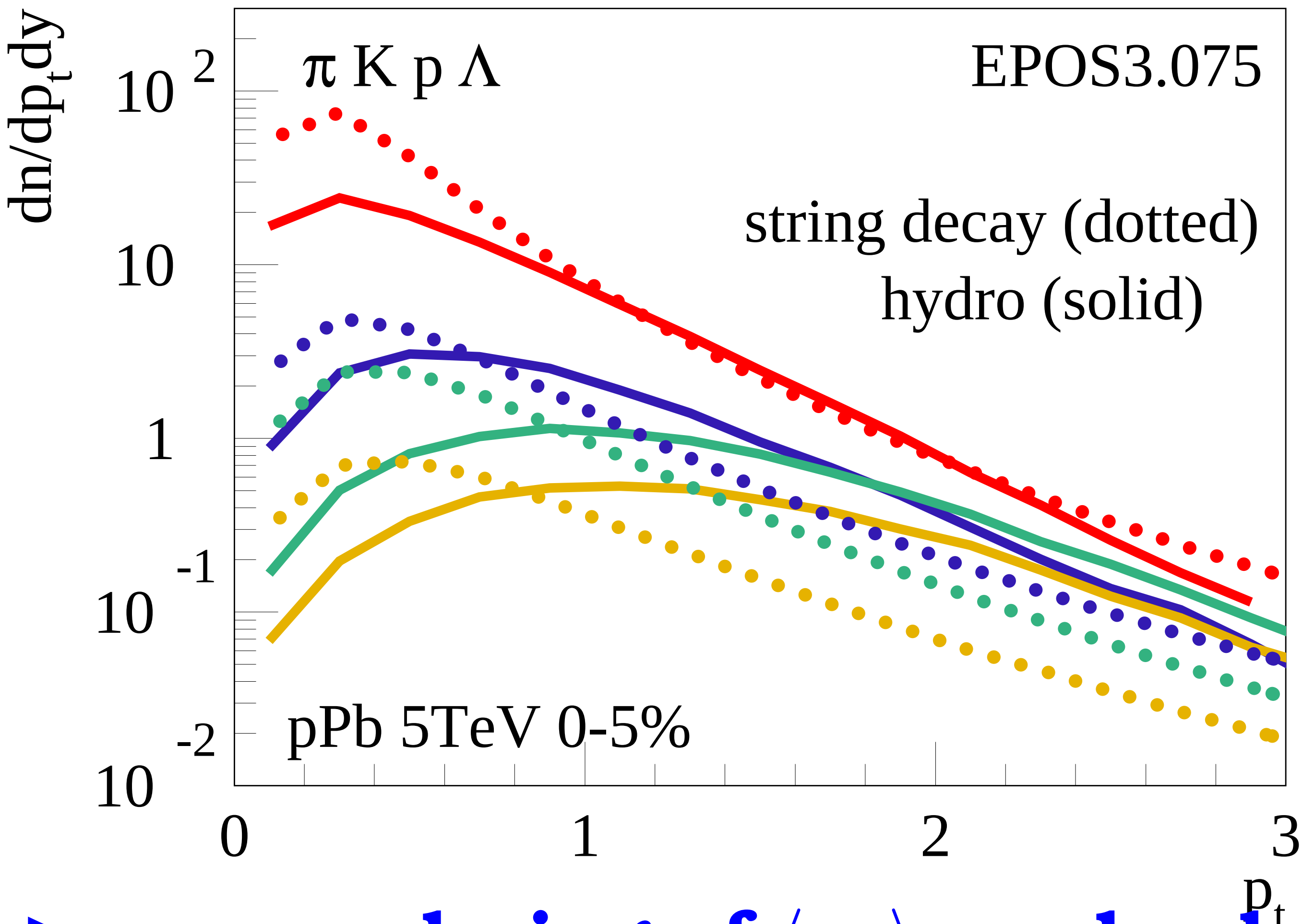
$$R = \frac{1}{N_{\mathrm{trigg}}} \frac{dn}{d\Delta\phi\Delta\eta}$$

due to initial azimuthal anisotropies

(longitudinally invariant)



Particle spectra affected by radial flow

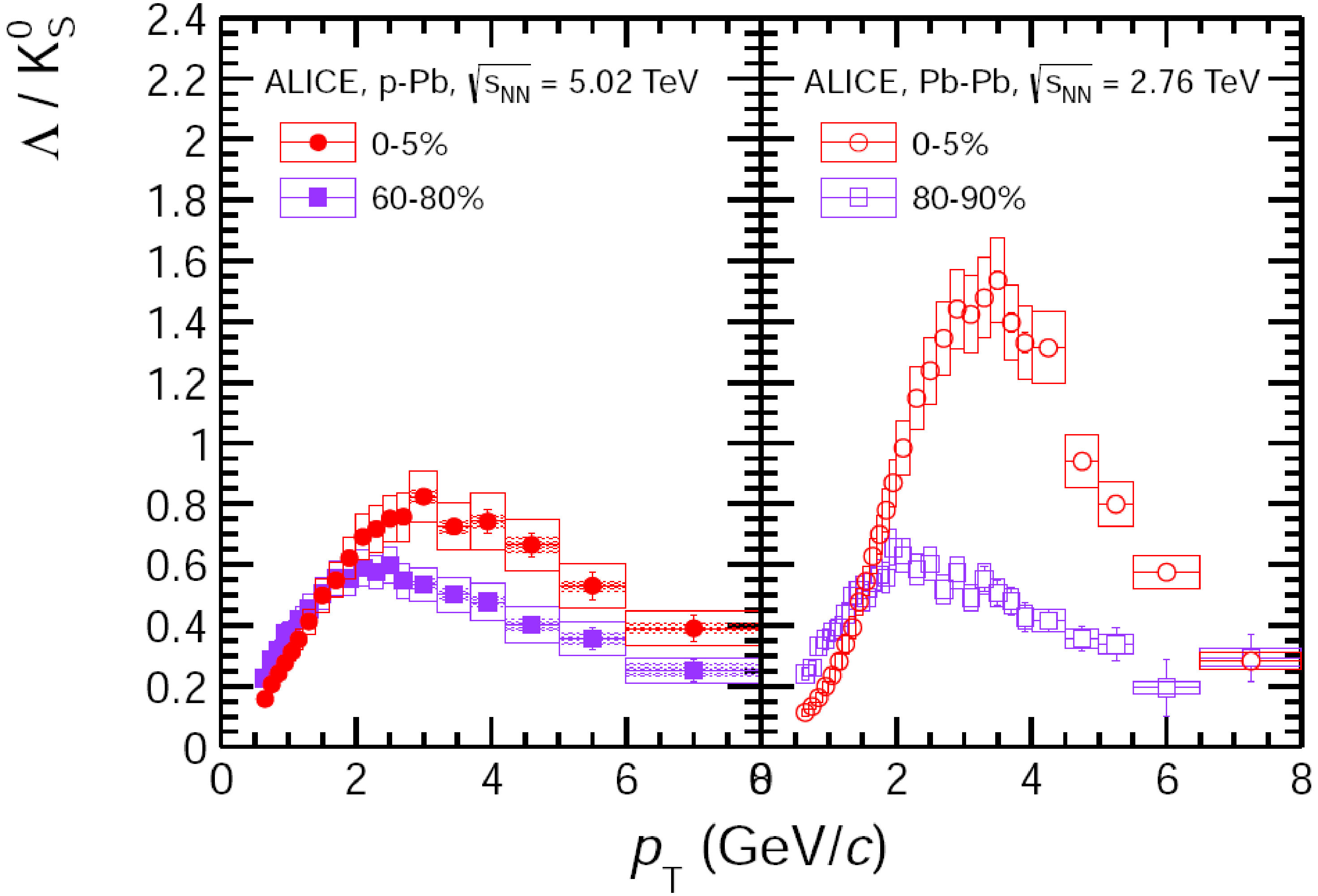


=> mass ordering of $\langle p_t \rangle$, lambda/K increase

Recent LHC data

pPb at 5TeV

ALICE, arXiv:1307.6796

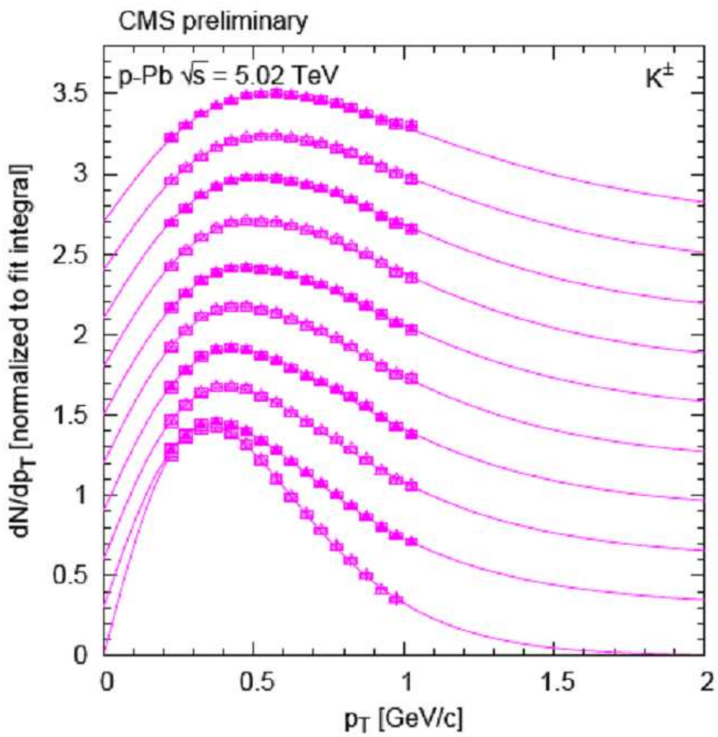


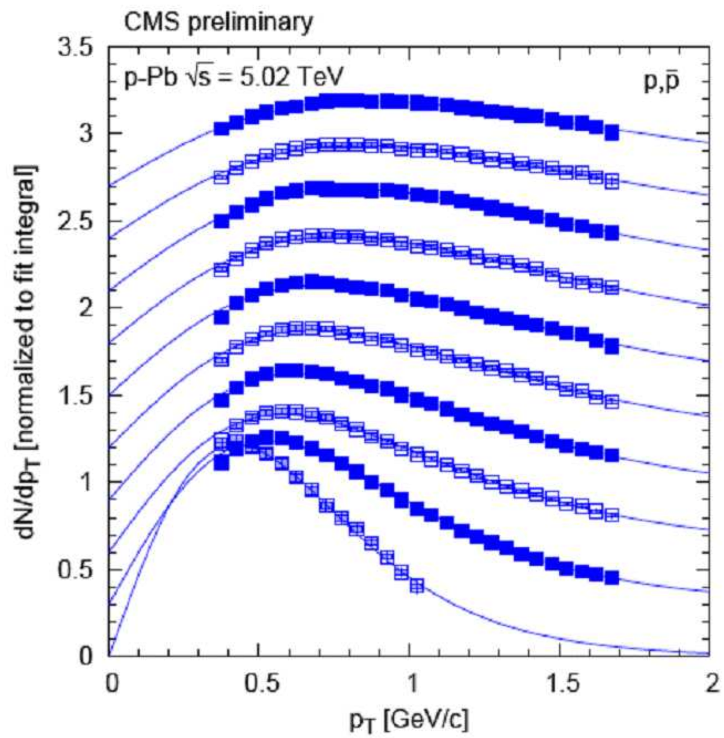
Lambda/Kshort: similar behavior as in PbPb

=> flow?

pPb at 5TeV

CMS, arXiv:1307.3442

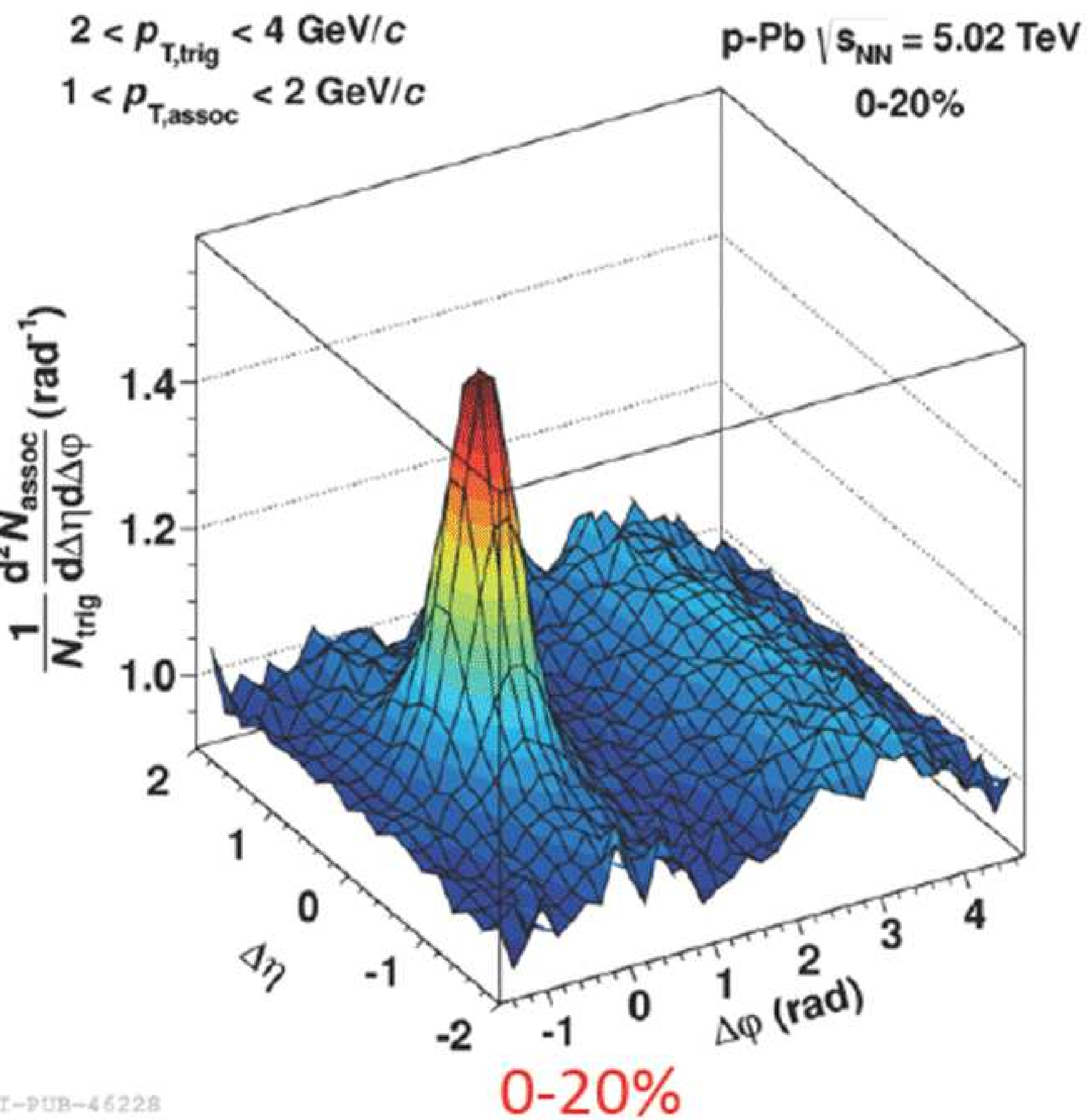




Strong variation of shape with multiplicity

for kaon and even more for proton pt spectra

(flow like)



pPb at 5TeV

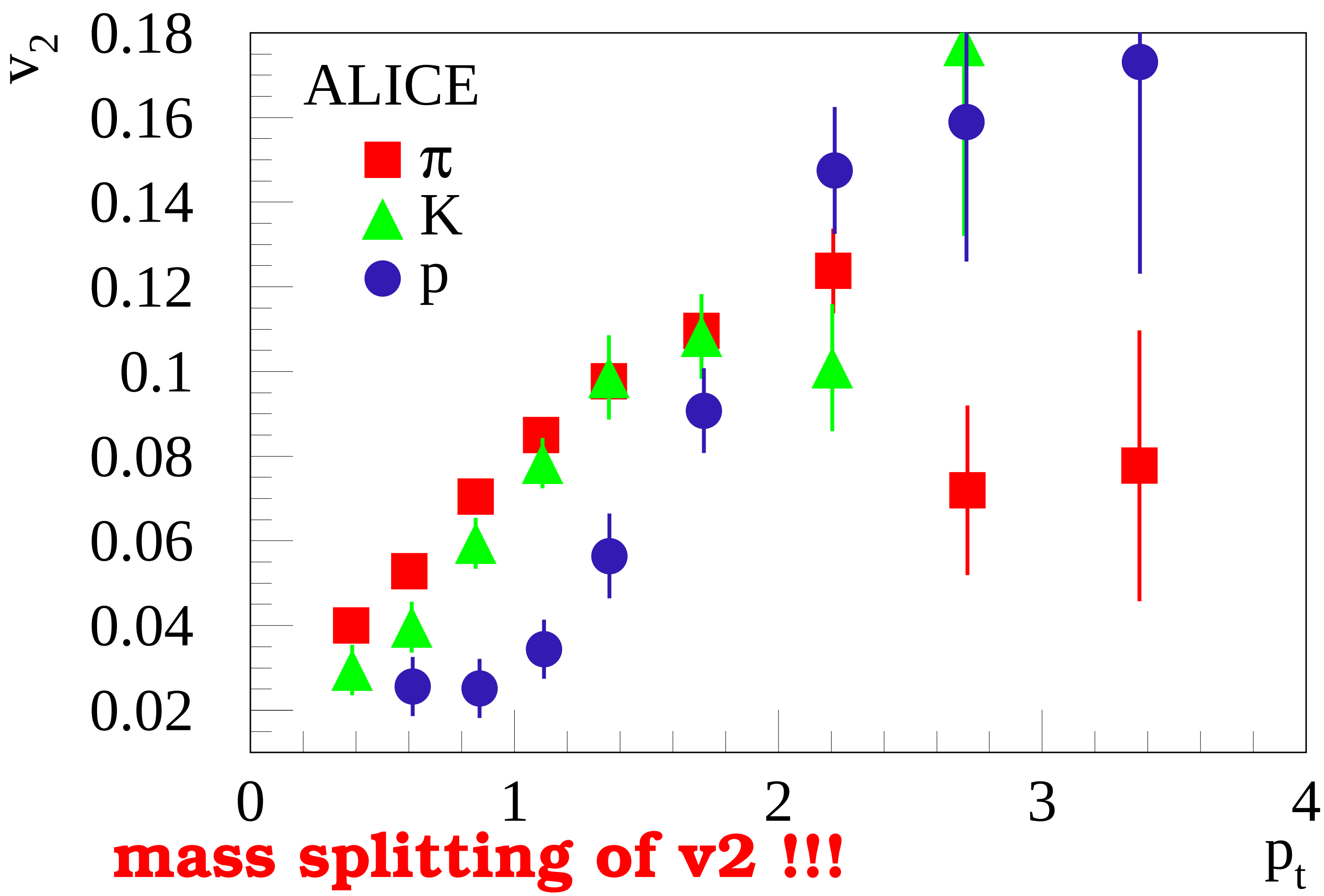
ALICE, Phys.Lett. B719 (2013) 29, arXiv:1212.2001

ridge
& significant v2

as in in PbPb ...

pPb at 5TeV

ALICE, arXiv:1307.3237



mass splitting of v2 !!!

one of the highlights in heavy ion collisions ...

pPb data, interpreted in terms of hydrodynamic flow

Hydrodynamic Models:

P. Bozek, W. Broniowski, arXiv:1304.3044
analysis of pPb@5TeV

- ☐ Glauber model (wounded nucleon model) initial conditions
- ☐ Viscous hydrodynamic expansion, $\eta/s = 0.08$ or 0.16
- ☐ Statistical hadronization using “Terminator”

A. Bzdak, B. Schenke, P. Tribedy, R. Venugopalan, arXiv:1304.3403

- ☐ Theoretical study of flow in pp, pA, dA
- ☐ Glauber model or Color Glass Condensate initial conditions
- ☐ Viscous hydrodynamic expansion, $\eta/s = 0.08$

EPOS3, B. Guiot, Y. Karpenko, T. Pierog, K. Werner
arXiv:1203.5704, arXix:1307.4379

- Initial conditions:
  Gribov-Regge multiple scattering approach,
  elementary object = Pomeron = parton ladder,
  using saturation scale $Q_s \propto N_{part}\,\hat{s}^{\lambda}$
- Core-corona approach
  to separate fluid and jet hadrons
- Viscous hydrodynamic expansion, $\eta/s = 0.08$
- Statistical hadronization, final state hadronic cascade

EPOS3 will be used in the following to analyse pPb data

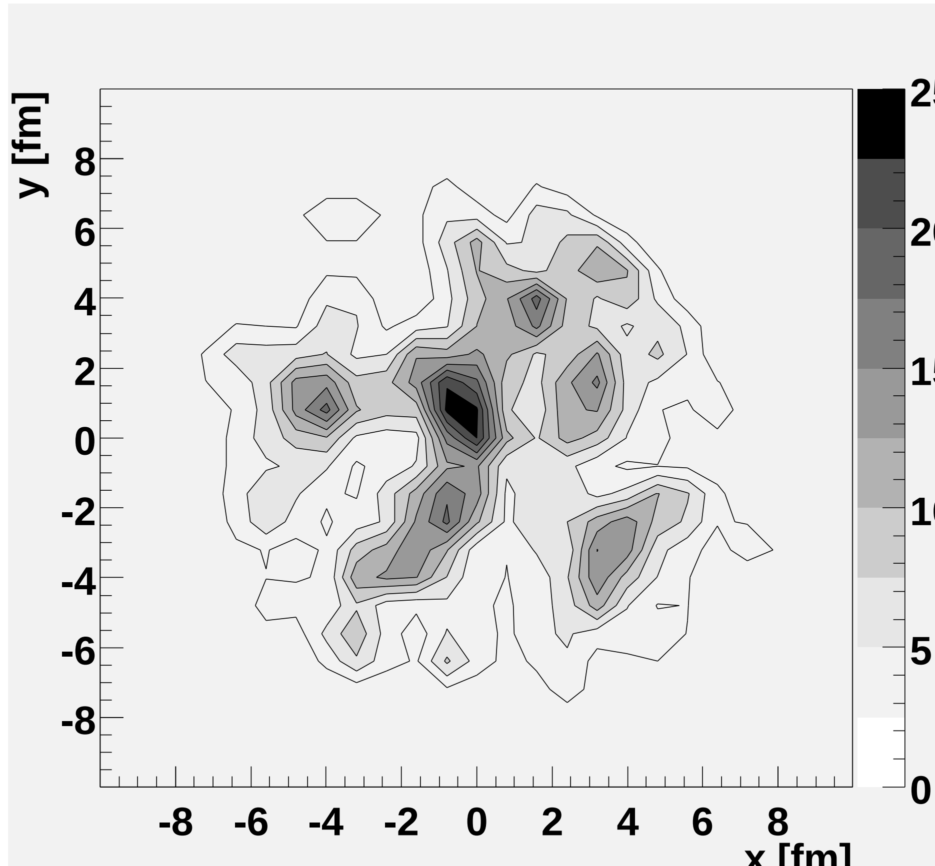
Historical remark : in 2000

Initial condition for QGP evolution from NEXUS

H.J. Drescher, S. Ostapchenko, T. Pierog, K. Werner, hep-ph/0011219, Phys-RevC.65.054902

EPOS
= major NEXUS update

Fig 21: Energy density



NEXUS ICs were coupled to hydro (SPheRIO) in collaboration with ...

.... during an extremely fruitful and pleasant stay in Rio in April 2000

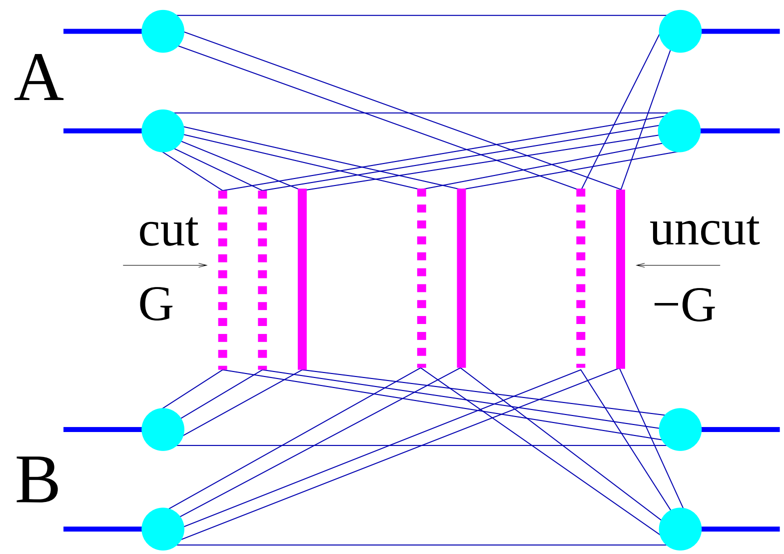
.... during an extremely fruitful and pleasant stay in Rio in April 2000

HAPPY BIRTHDAY, TAKESHI !!

EPOS IC: Marriage pQCD+GRT+energy sharing

(Drescher, Hladik, Ostapchenko, Pierog, and Werner, Phys. Rept. 350, 2001)

$$\sigma^{\mathrm{tot}} = \sum_{\mathrm{cut\,P}} \int \sum_{\mathrm{uncut\,P}} \int$$



$$\underbrace{\qquad\qquad\qquad\qquad}_{d\sigma_{\mathrm{exclusive}}}$$

$$\mathrm{cut\,Pom} : G = \frac{1}{2\hat{s}} 2\mathrm{Im}\,\{\mathcal{FT}\{T\}\}(\hat{s}, b),\; T = i\hat{s}\,\sigma_{hard}(\hat{s})\,\exp(R^2_{\mathrm{hard}}t)$$

Nonlinear effects considered via saturation scale $Q_s \propto N_{part}\,\hat{s}^{\lambda}$

$$\sigma^{\mathrm{tot}} = \int d^2b \int \prod_{i=1}^{A} d^2b_i^A \, dz_i^A \, \rho_A(\sqrt{(b_i^A)^2 + (z_i^A)^2})$$

$$\prod_{j=1}^{B} d^2b_j^B \, dz_j^B \, \rho_B(\sqrt{(b_j^B)^2 + (z_j^B)^2})$$

$$\sum_{m_1 l_1} \ldots \sum_{m_{AB} l_{AB}} (1 - \delta_{0\Sigma m_k}) \int \prod_{k=1}^{AB} \left(\prod_{\mu=1}^{m_k} dx_{k,\mu}^+ dx_{k,\mu}^- \prod_{\lambda=1}^{l_k} d\tilde{x}_{k,\lambda}^+ d\tilde{x}_{k,\lambda}^- \right) \Bigg\{$$

$$\prod_{k=1}^{AB} \left(\frac{1}{m_k!} \frac{1}{l_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, |\vec{b} + \vec{b}_{\pi(k)}^A - \vec{b}_{\tau(k)}^B|) \right.$$

$$\left. \prod_{\lambda=1}^{l_k} -G(\tilde{x}_{k,\lambda}^+, \tilde{x}_{k,\lambda}^-, s, |\vec{b} + \vec{b}_{\pi(k)}^A - \vec{b}_{\tau(k)}^B|) \right)$$

$$\prod_{i=1}^{A} \left(1 - \sum_{\pi(k)=i} x_{k,\mu,}^+ - \sum_{\pi(k)=i} \tilde{x}_{k,\lambda}^+ \right)^{\alpha} \prod_{j=1}^{B} \left(1 - \sum_{\tau(k)=j} x_{k,\mu}^- - \sum_{\tau(k)=j} \tilde{x}_{k,\lambda}^- \right)^{\alpha} \Bigg\}$$

The hydrodynamic equations (Israel-Stewart formulation) in arbitrary coordinate system (implemented/solved by Yuri Karpenko), always $\eta/S = 0.08$, $\zeta/S = 0$

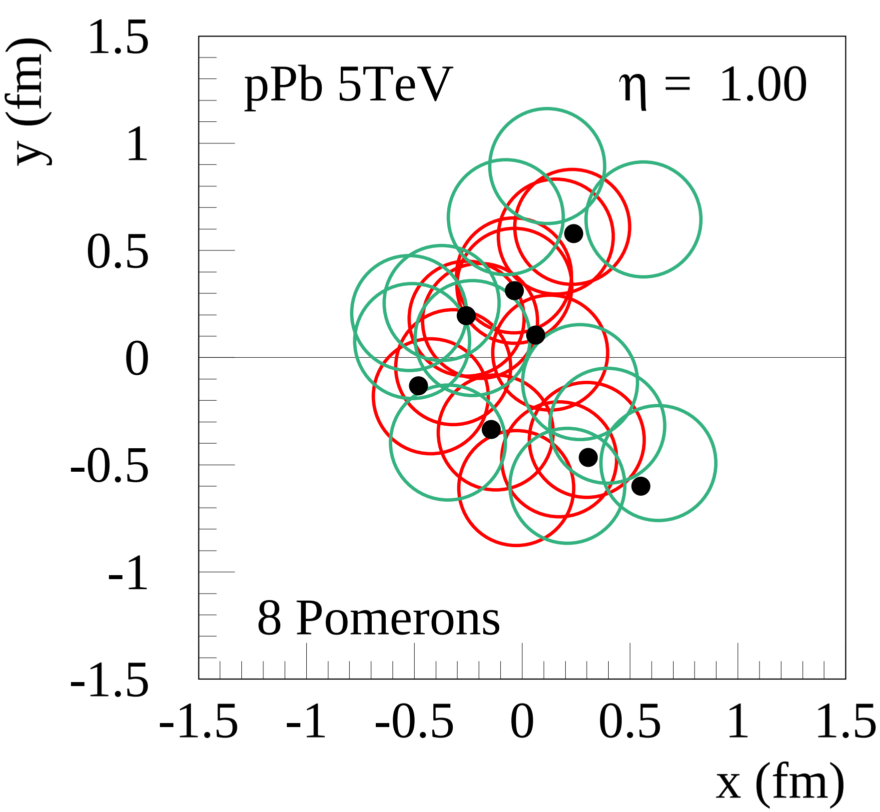
$$\begin{aligned}
\partial_{;\nu} T^{\mu\nu} &= \partial_\nu T^{\mu\nu} + \Gamma^{\mu}_{\nu\lambda} T^{\nu\lambda} + \Gamma^{\nu}_{\nu\lambda} T^{\mu\lambda} = 0 \\
\gamma\left(\partial_t + v_i \partial_i\right) \pi^{\mu\nu} &= -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\mathrm{NS}}}{\tau_\pi} + I^{\mu\nu}_\pi \\
\gamma\left(\partial_t + v_i \partial_i\right) \Pi &= -\frac{\Pi - \Pi_{\mathrm{NS}}}{\tau_\Pi} + I_\Pi
\end{aligned}$$

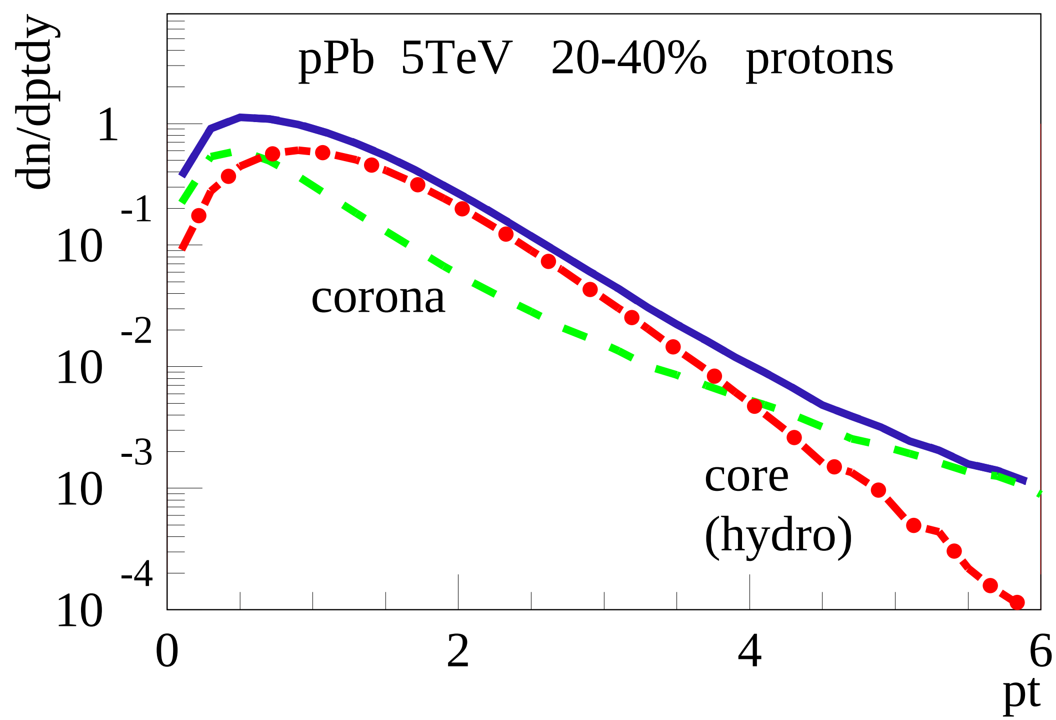
- $T^{\mu\nu} = \epsilon u^\mu u^\nu - (p+\Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$,
- $\partial_{;\nu}$ denotes a covariant derivative,
- $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$ is the projector orthogonal to u^μ,
- $\pi^{\mu\nu}$ and Π are the shear stress tensor and bulk pressure, respectively.
- $\pi^{\mu\nu}_{\mathrm{NS}} = \eta(\Delta^{\mu\lambda}\partial_{;\lambda} u^\nu + \Delta\nu\lambda\partial_{;\lambda} u^\mu) - \frac{2}{3}\eta\Delta^{\mu\nu}\partial_{;\lambda} u^\lambda$
- $\Pi_{\mathrm{NS}} = -\zeta\partial_{;\lambda} u^\lambda$
- $I^{\mu\nu}_\pi = -\frac{4}{3}\pi^{\mu\nu}\partial_{;\gamma} u^\gamma - [u^\nu \pi^{\mu\beta} + u^\mu \pi^{\nu\beta}] u^\lambda \partial_{;\lambda} u_\beta$
- $I_\Pi = -\frac{4}{3}\Pi\partial_{;\gamma} u^\gamma$

EPOS3:

Pomeron => parton ladder => flux tube (kinky string)

String segments with high pt escape => **corona**,
the others form the **core** = initial condition for hydro
depending on the local string density





We will compare EPOS3 with pPb data and also with

EPOS LHC

LHC tune of EPOS1.99, :
same GR, but uses parameterized flow
T. Pierog et al, arXiv:1306.5413

AMPT

Parton + hadron cascade
Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang and S. Pal, Phys. Rev. C 72, 064901 (2005).

QGSJET

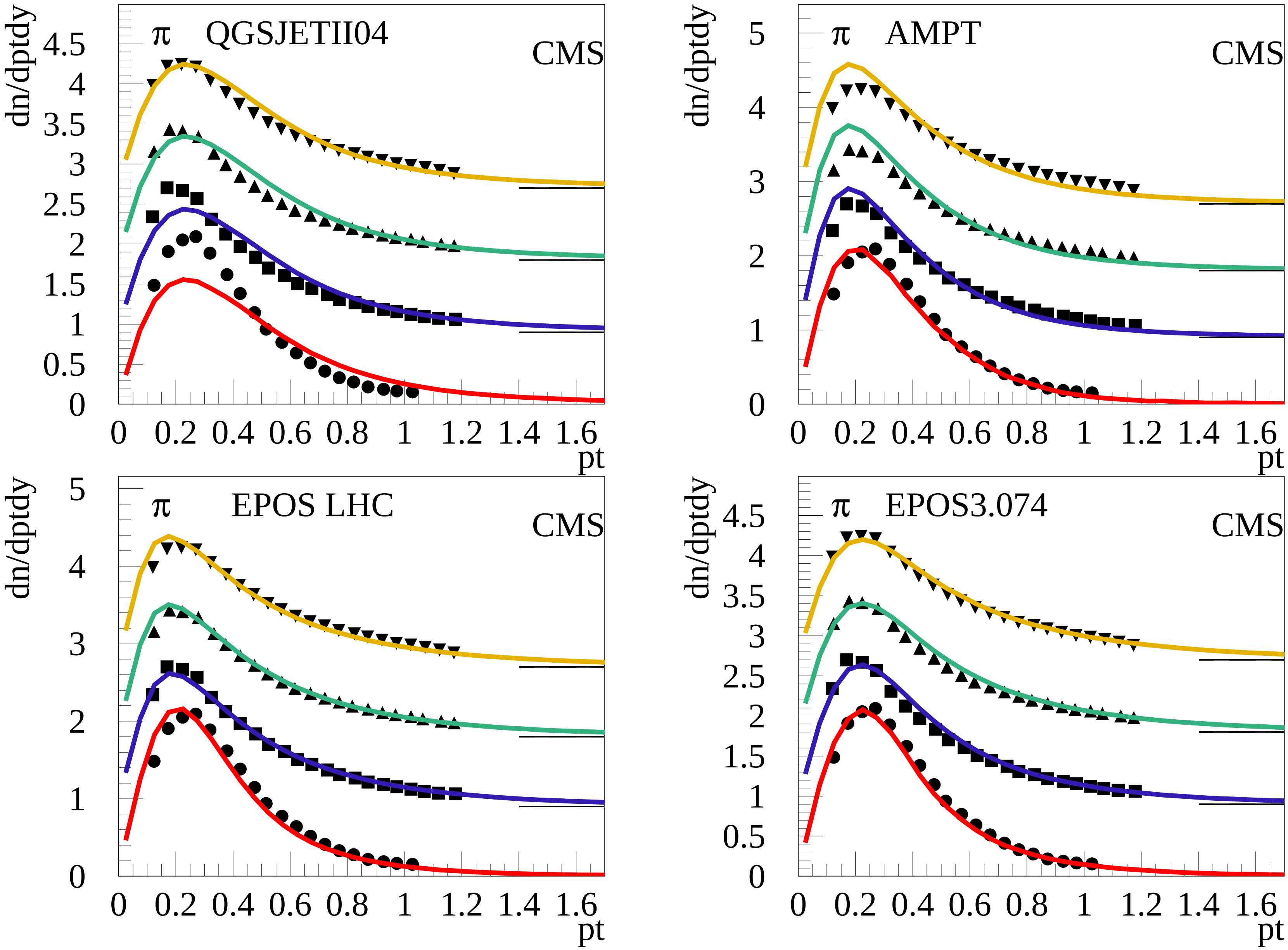
GR approach, No flow
S. Ostapchenko, Phys. Rev. D74 (2006) 014026

CMS: Multiplicity dependence of pion, kaon, proton pt spectra

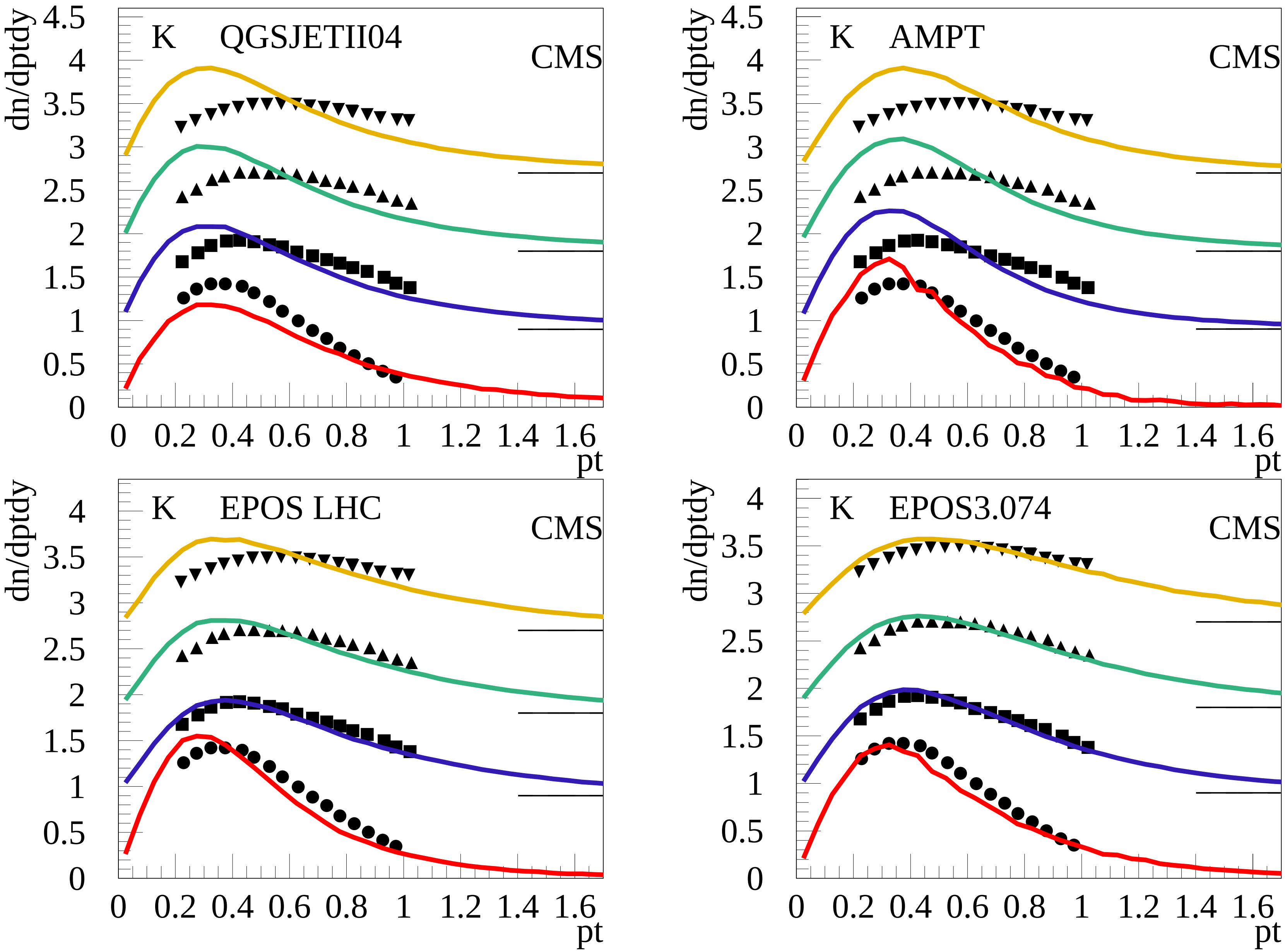
CMS, arXiv:1307.3442

We plot 4 centrality classes:
<N_tracks> = 8, 84, 160, 235 (in $|\eta| < 2.4$)

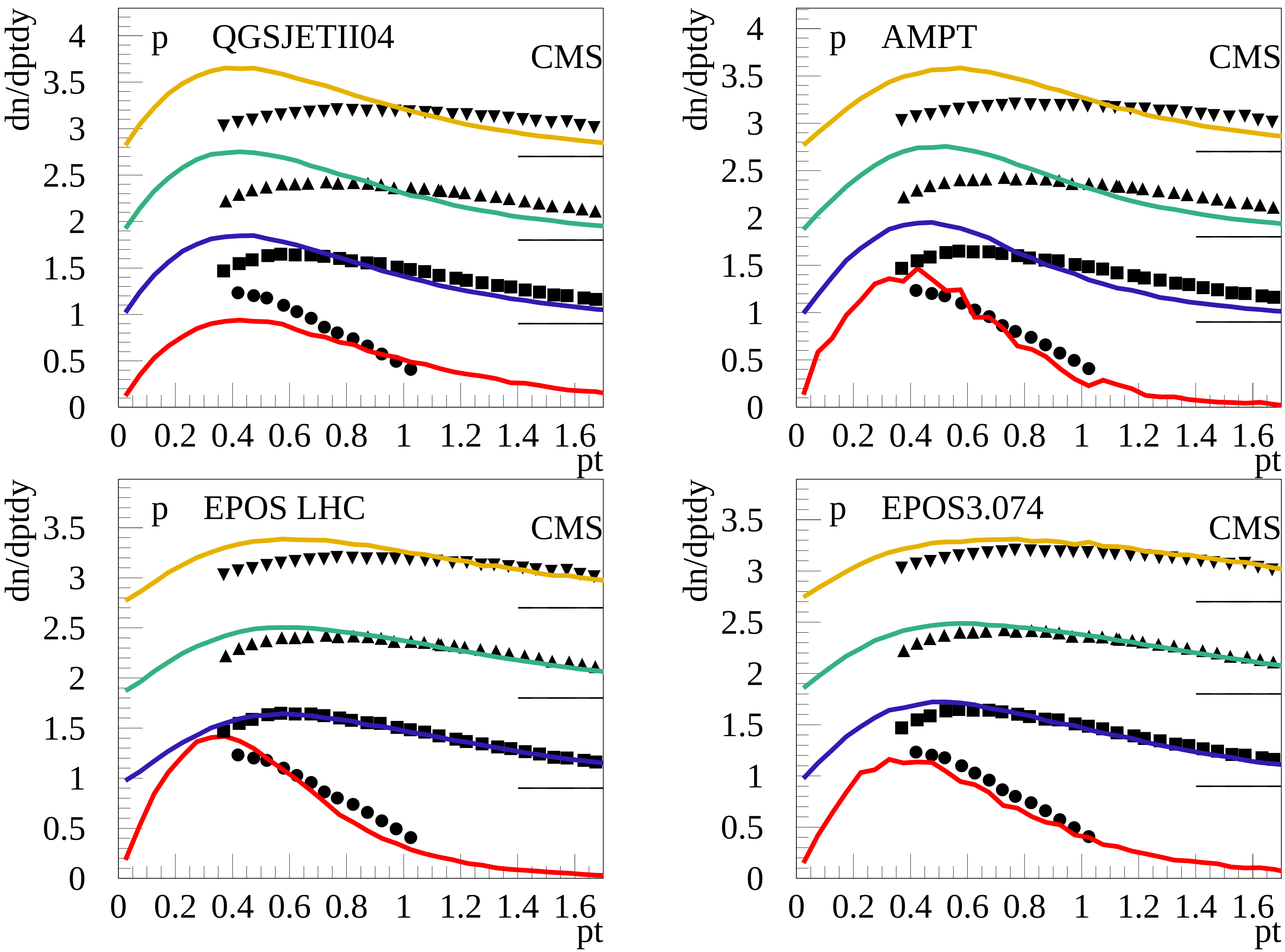
Multiplicity = centrality measure



Little change with <N_tracks> for pions



Kaon spectra change with <N_tracks>
in EPOS3: more and more flow contribution

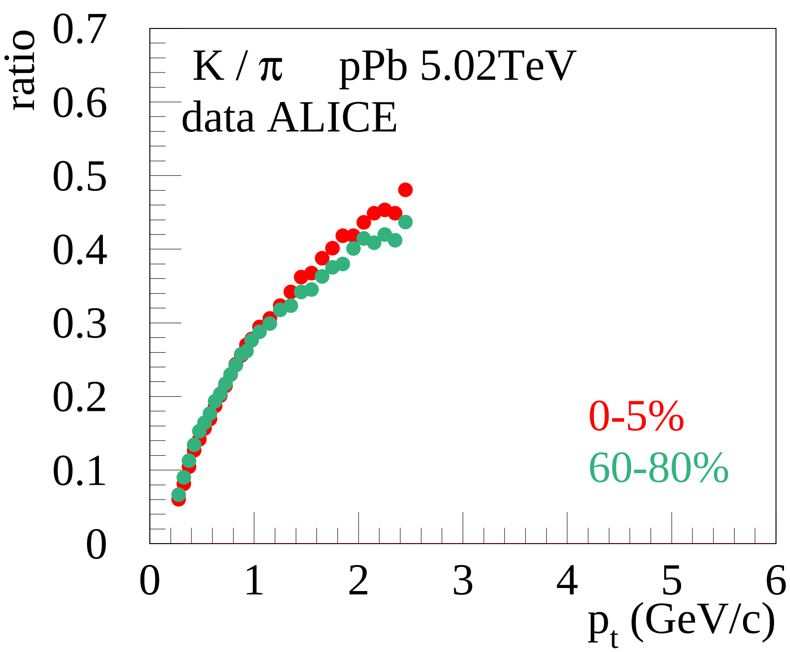


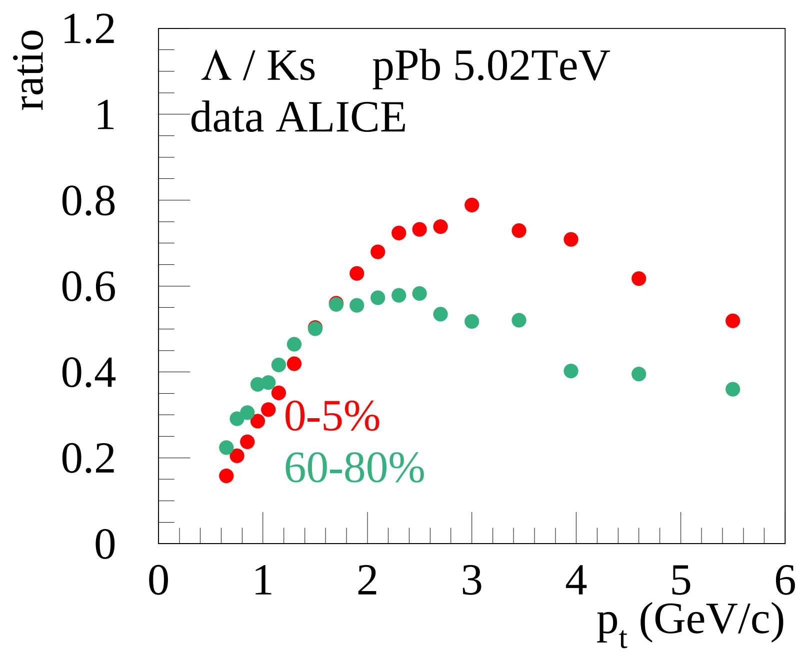
Strong variation of proton spectra => flow helps

ALICE: compare pt spectra for identified particles in different multiplicity classes: 0-5%,...,60-80%

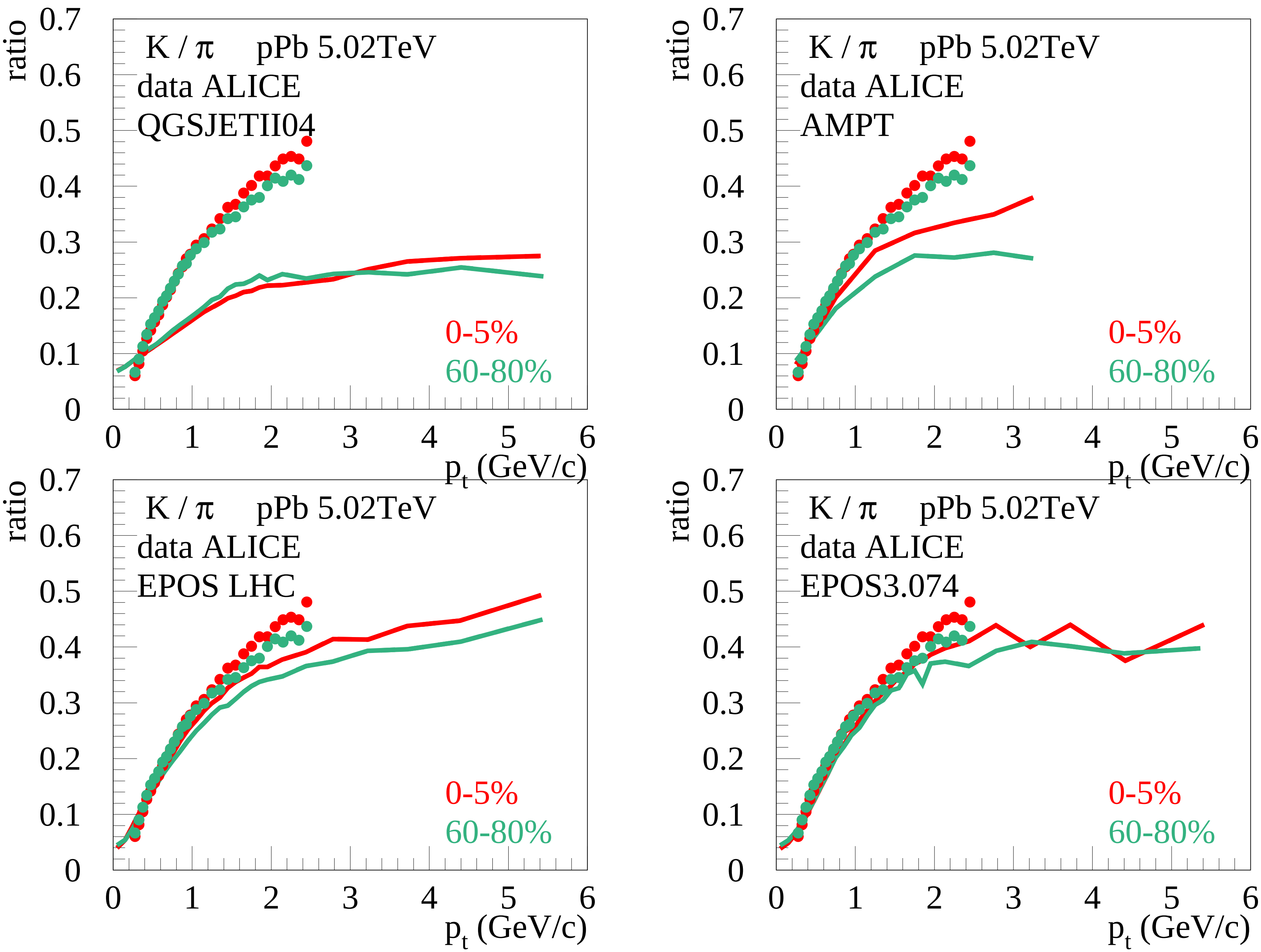
(in $2.8 < \eta_{\mathrm{lab}} < 5.1$) ALICE, arXiv:1307.6796

Useful : ratios (K/pi, p/pi...)

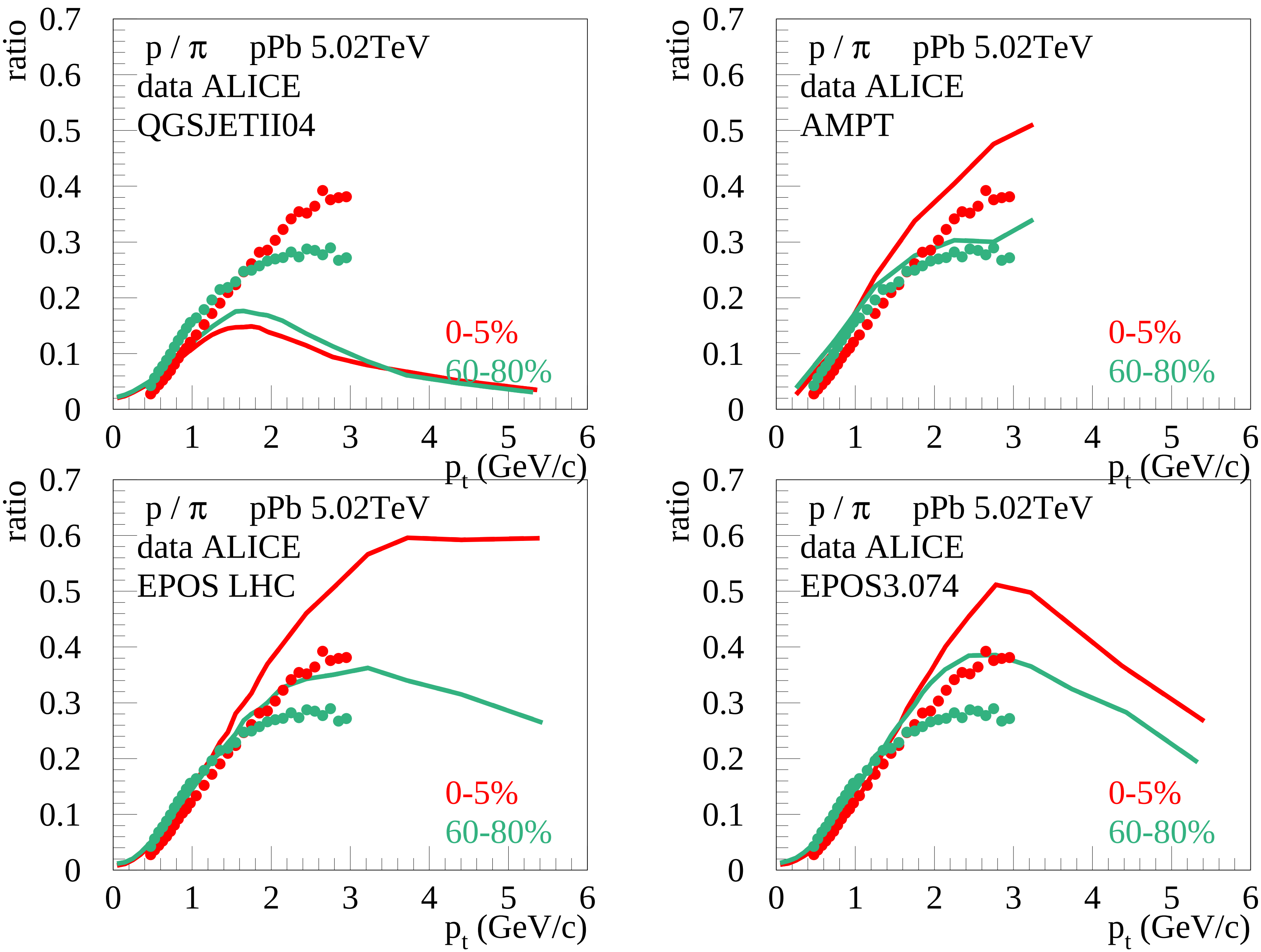




Significant variation of lambda/K – like in PbPb

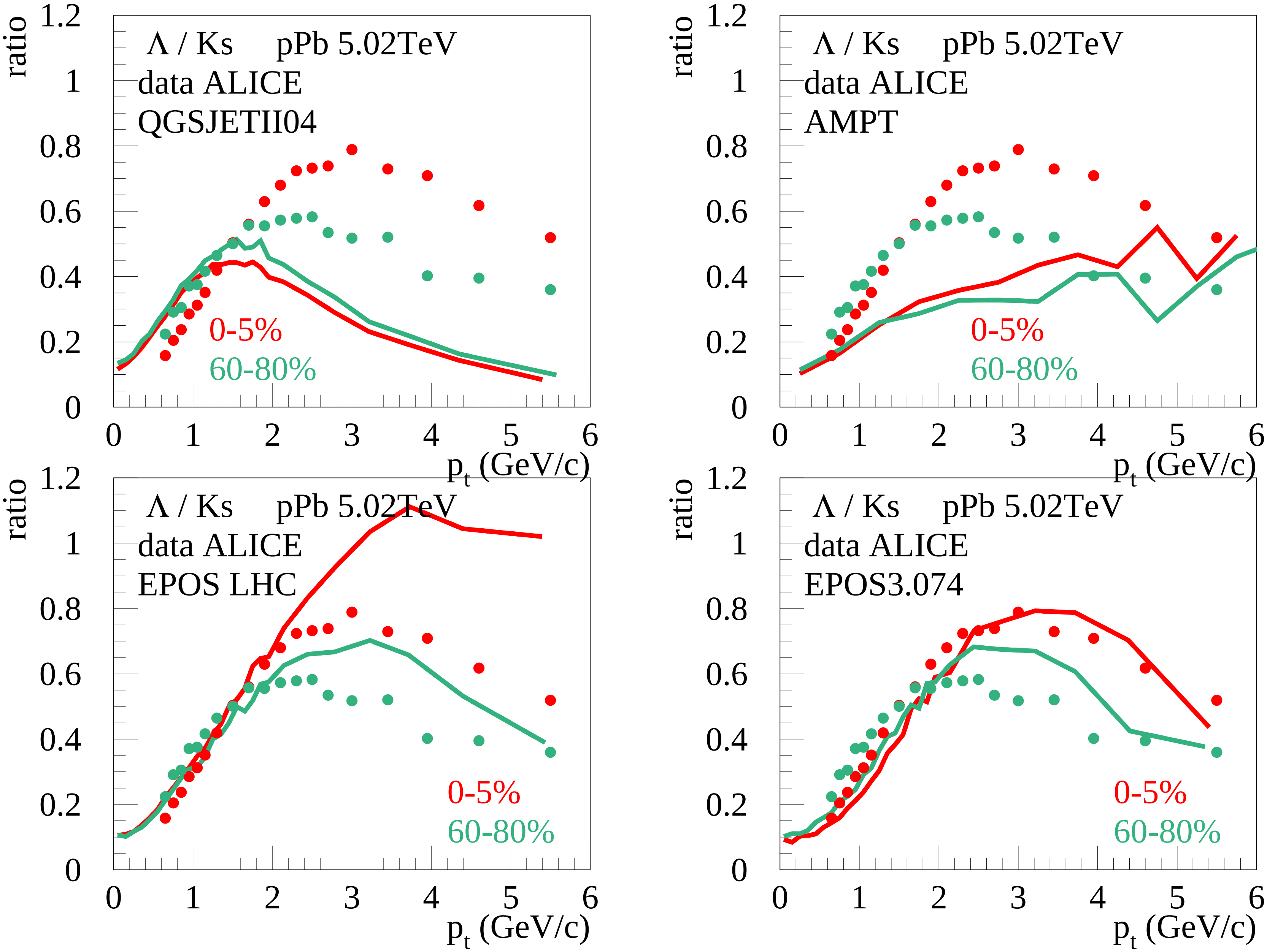


No multiplicity dependence (not trivial to get the peripheral right)



Significant multiplicity dependence

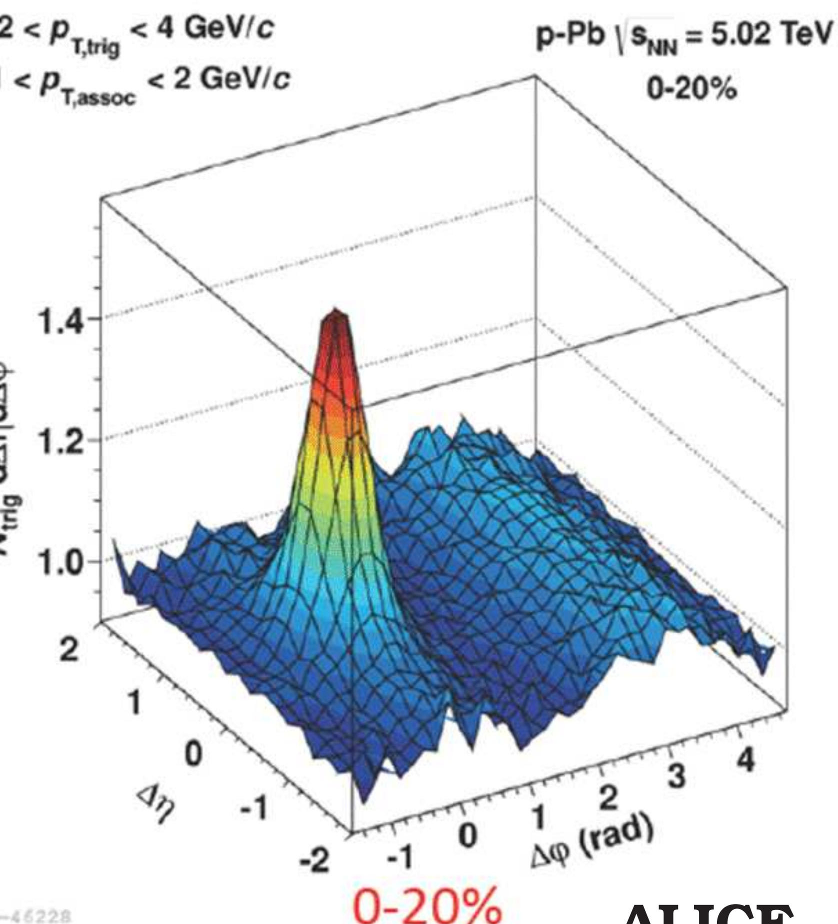
in EPOS, flow already affects the low multiplicity case



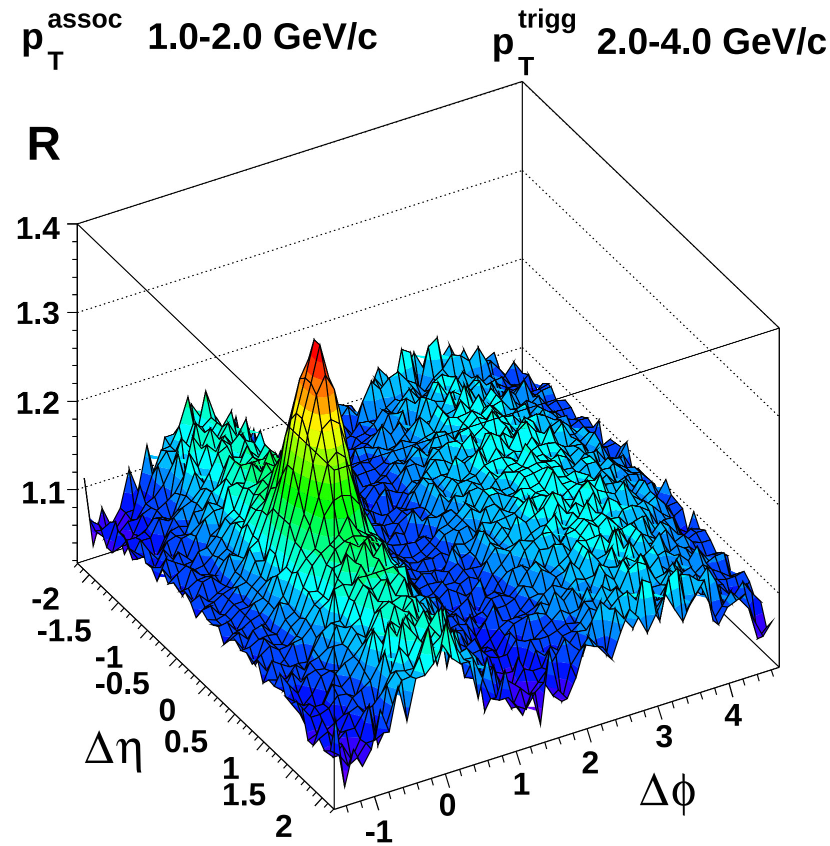
again, flow already needed for low multiplicity (even in pp!)
=> flow peak

"Ridges" in pA

ALICE, arXiv:1212.2001, arXiv:1307.3237

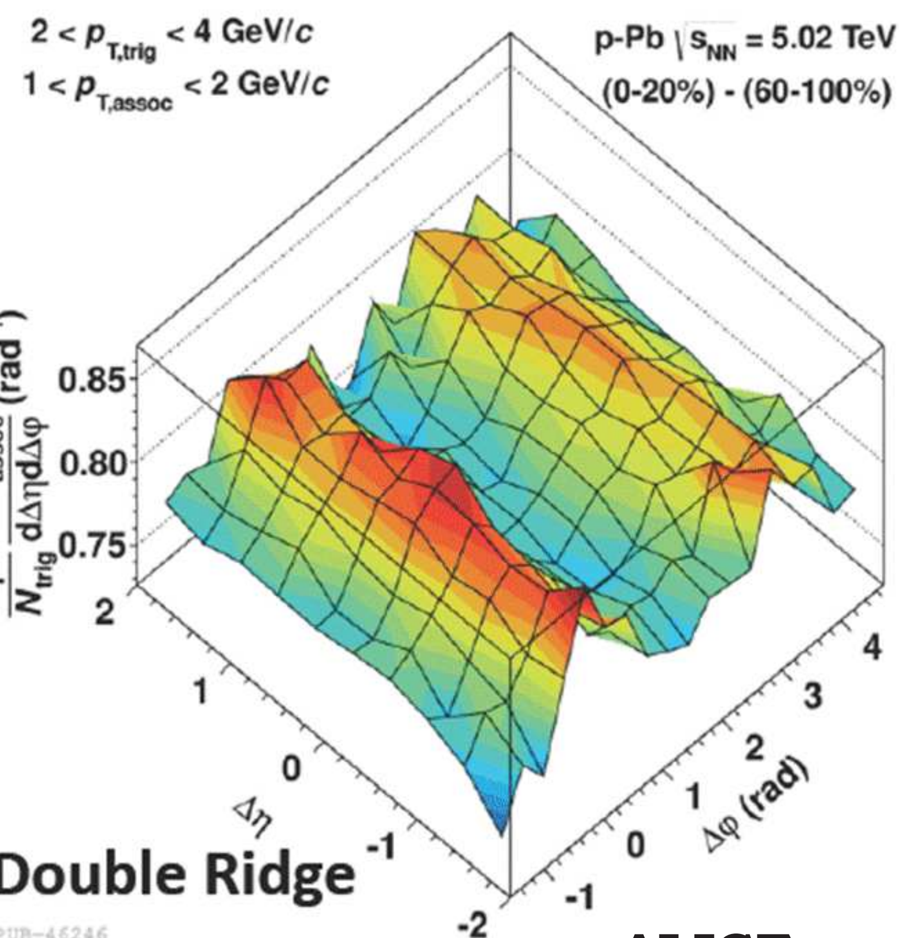


ALICE

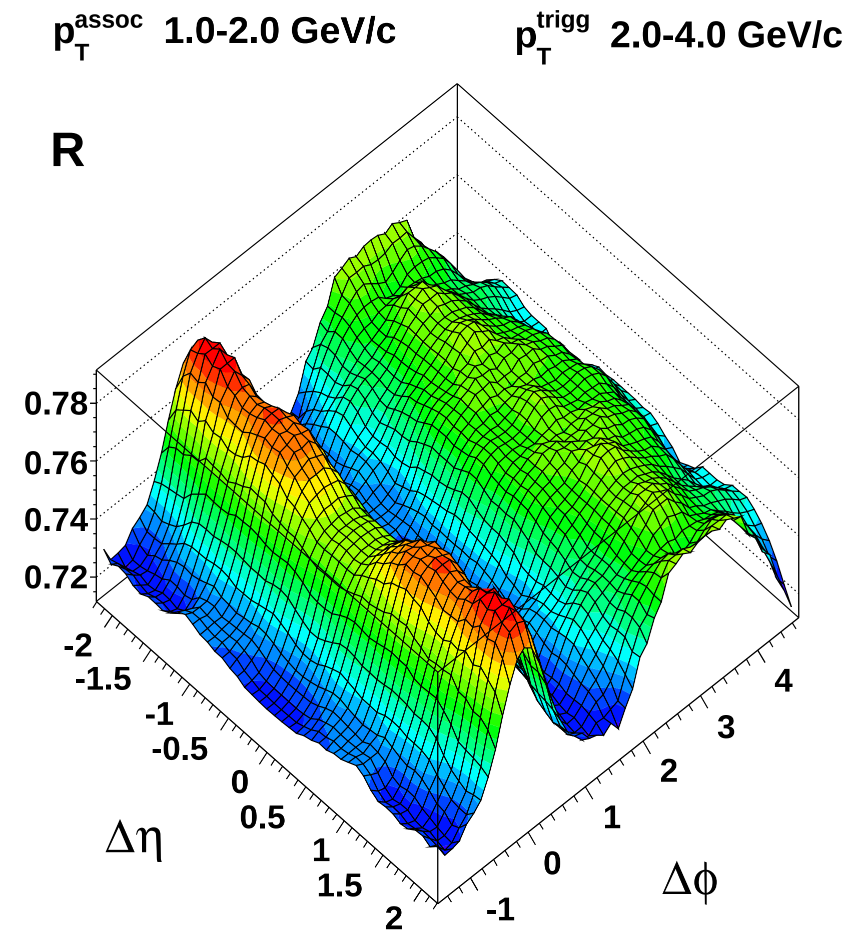


EPOS3.074

Central - peripheral (to get rid of jets)

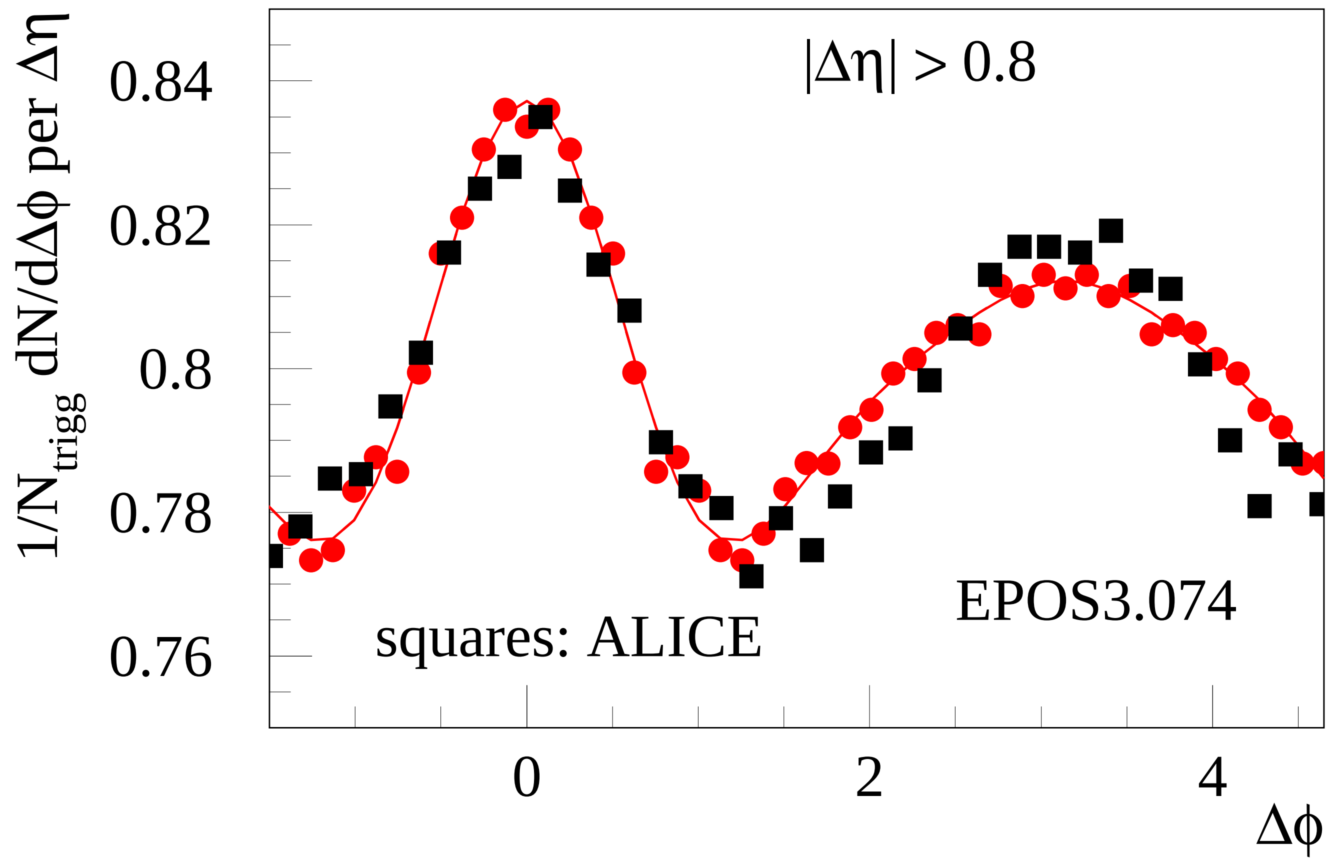


ALICE



EPOS3.074

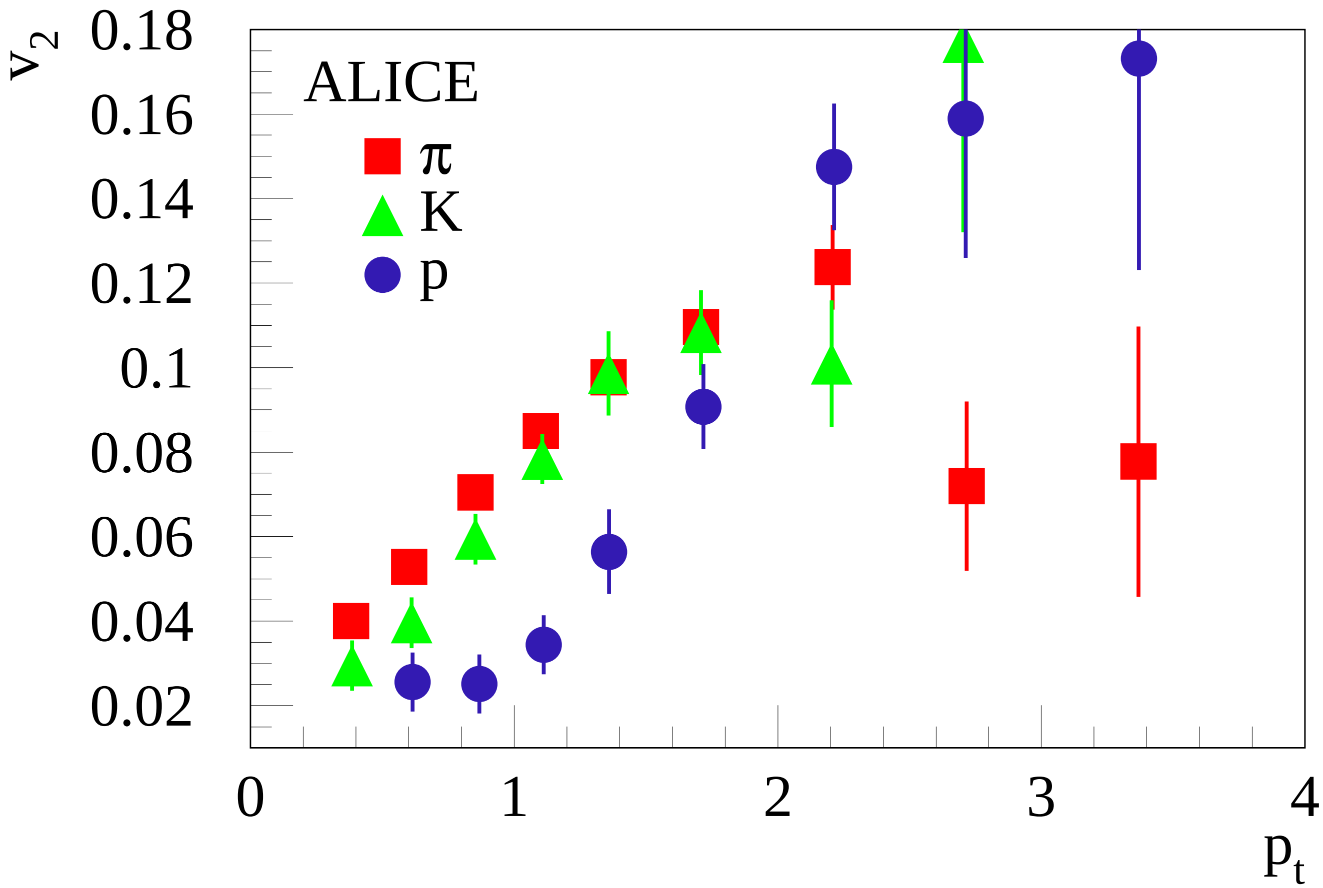
Projection



$$\text{red line}: \sum 2a_n \cos(n\Delta\phi);$$

$$\Longrightarrow \qquad v_n = \sqrt{\frac{a_n}{b}}$$

Identified particle v2



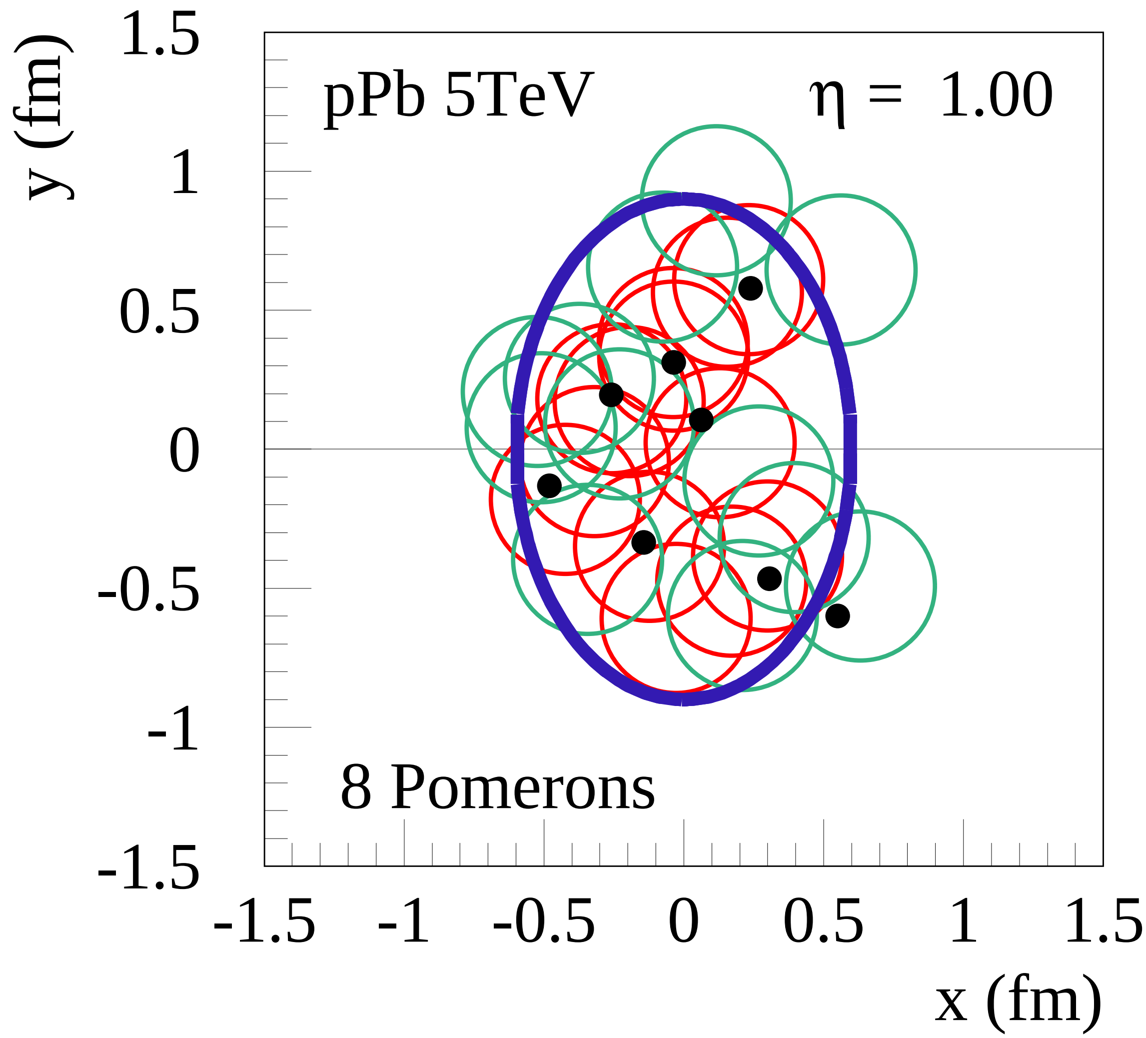
mass splitting, as in PbPb !!!

pPb in EPOS3

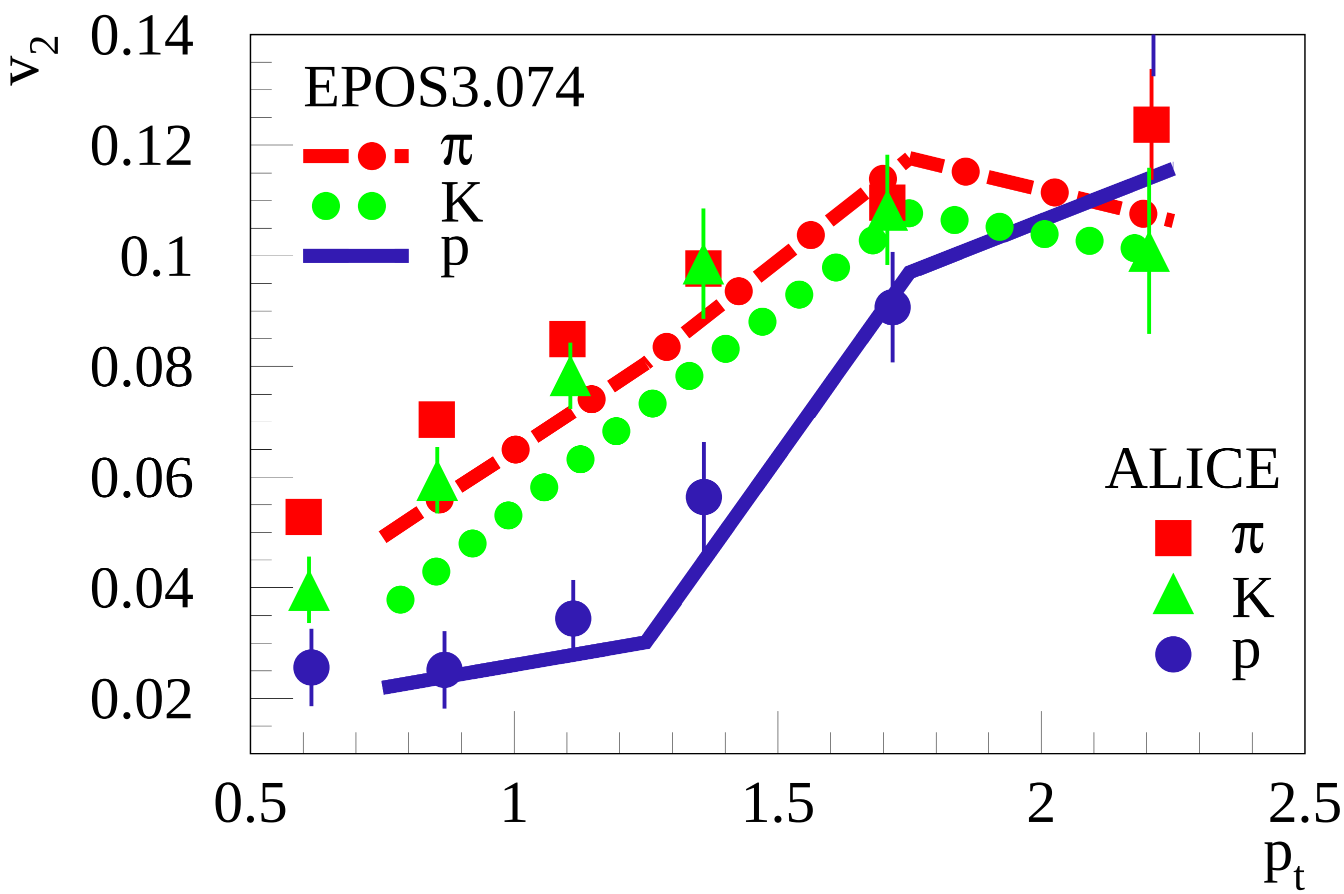
Pomerons (number and positions)
characterize geometry (P. number ∝ multiplicity)

random
azimuthal
asymmetry
=>
asymmetric flow
seen at higher pt
for heavier ptls

Robust results

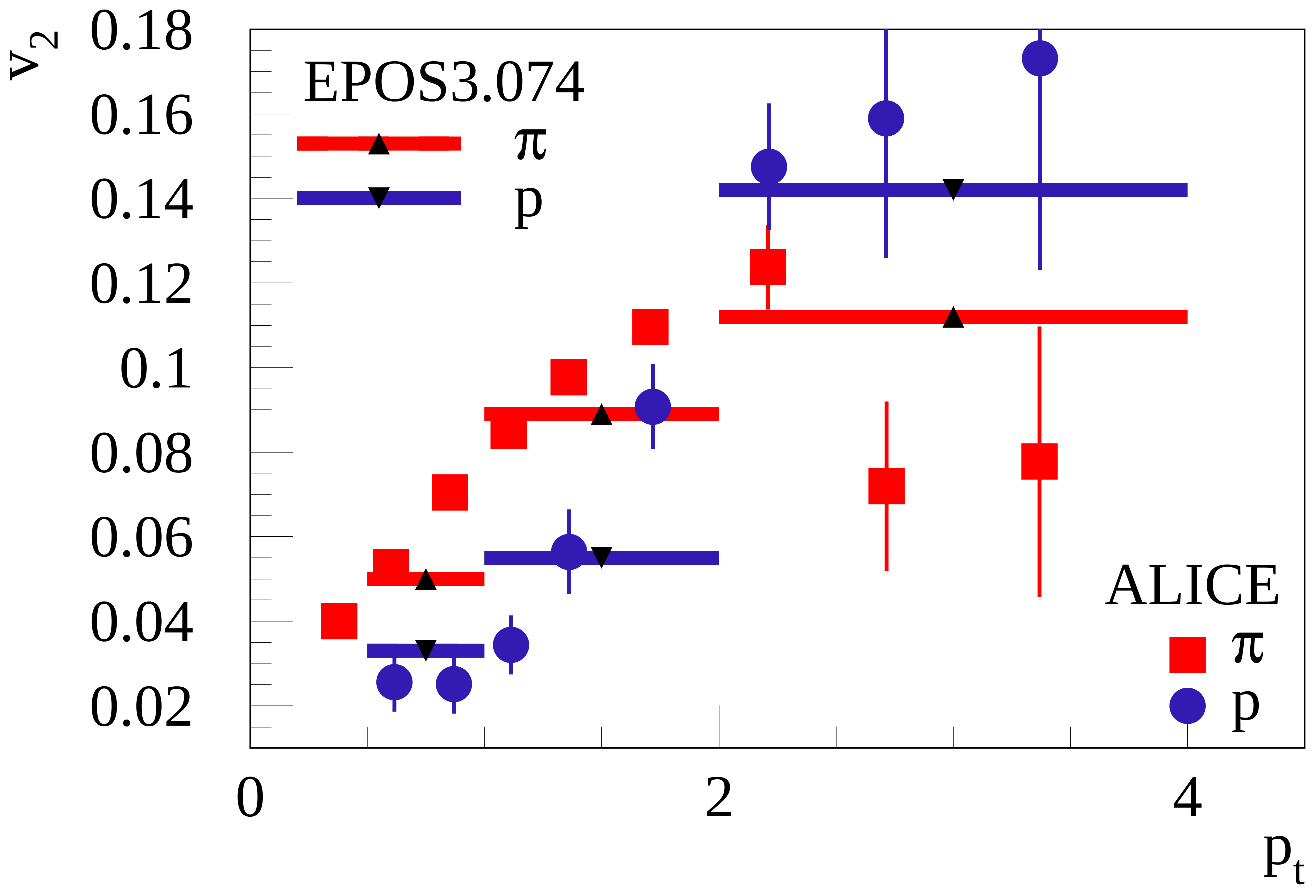


v2 for π, K, p clearly differ



mass splitting, due to flow

different binning:

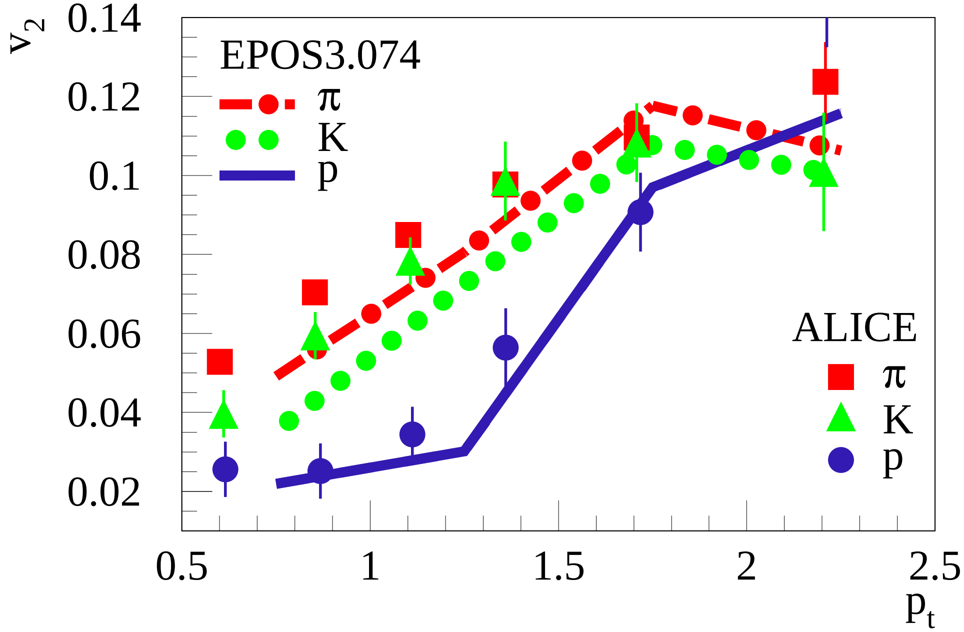


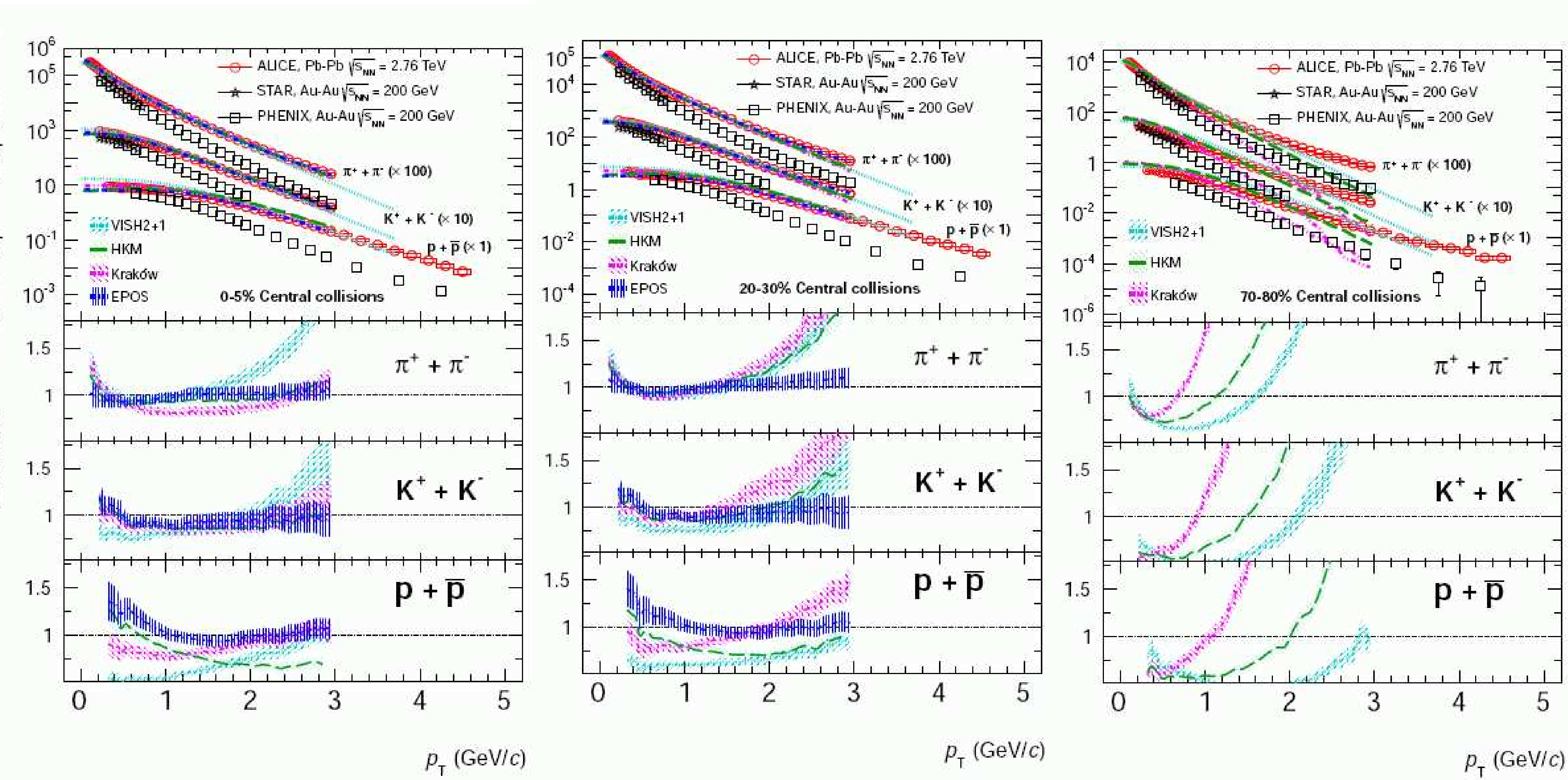
v2(protons) > v2(pions) beyond 2GeV

Summary

Analyzing pt-spectra, ratios, and dihadrons correlations for identified hadrons:

- **pPb looks very much like**
  a hydrodynamically expanding system
  (more clean than PbPb, where hydro and minijets heavily interact, as well as the final hadrons among themselves)





ALICE arXiv:1303.0737