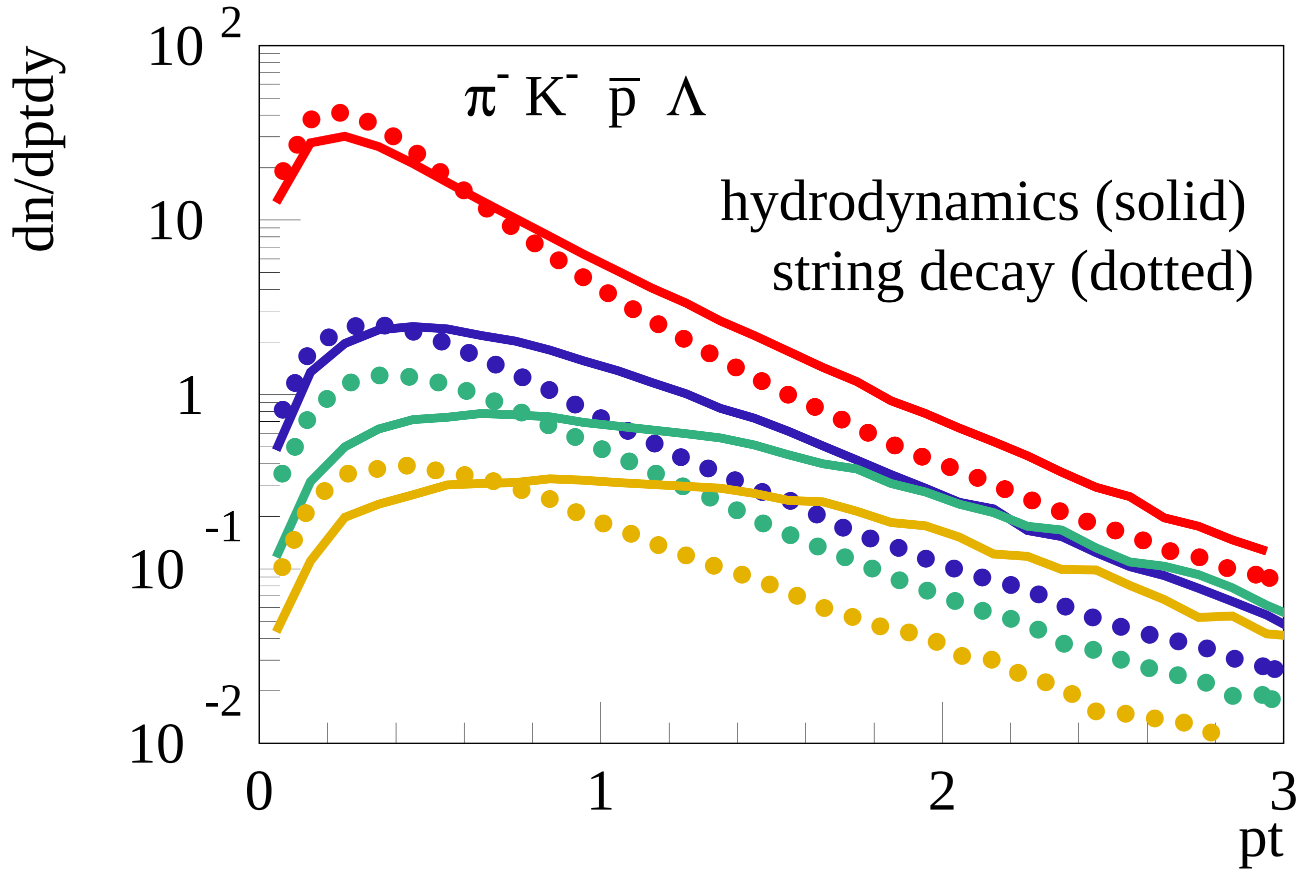
Flow in proton-nucleus collisions at 5 TeV

Manifestation of flow:

Particle spectra affected by radial flow



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

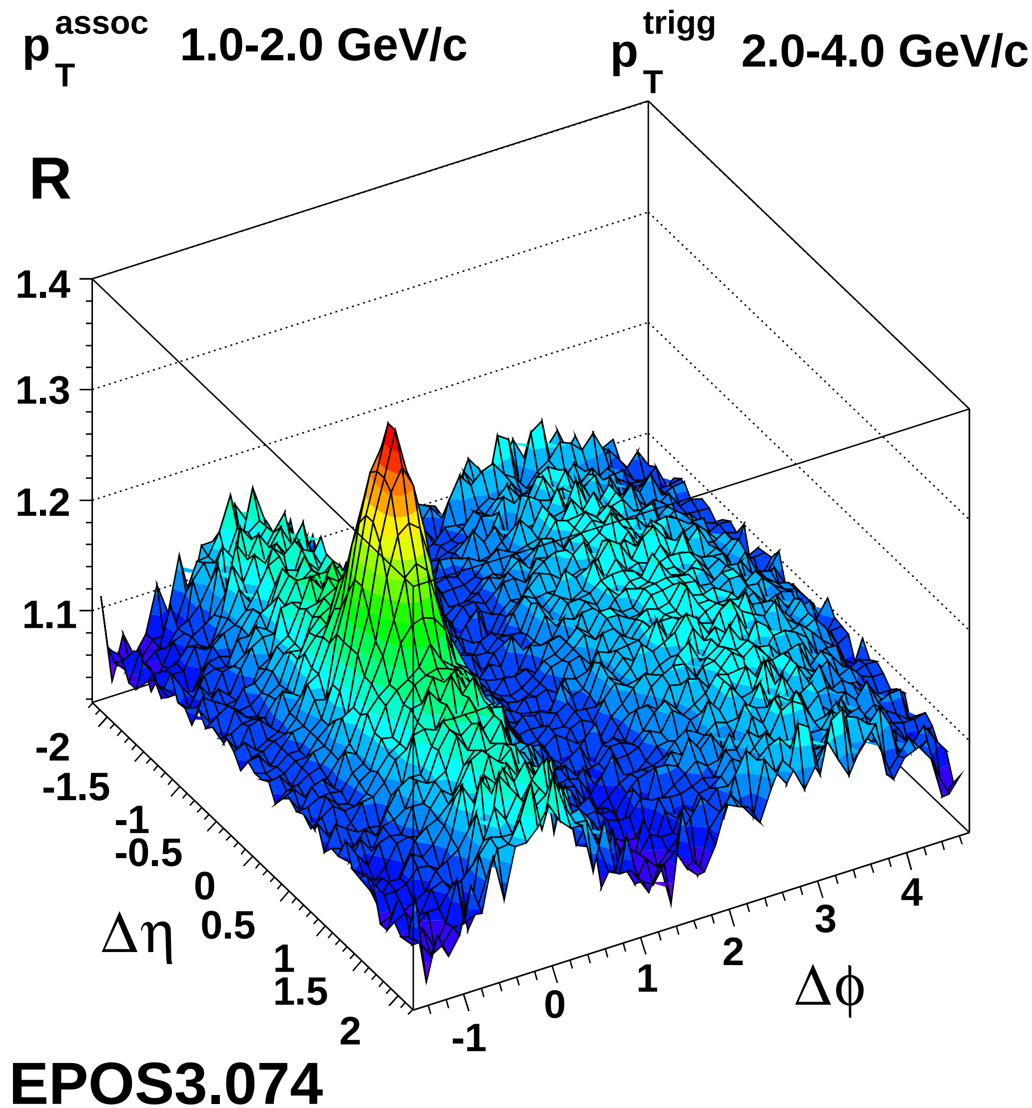
Ridges & flow harmonics

Ridges appear in

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

due to initial azimuthal anisotropies

(longitudinally invariant)



pPb data, interpreted in terms of hydrodynamic flow

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, $\eta/s = 0.08$

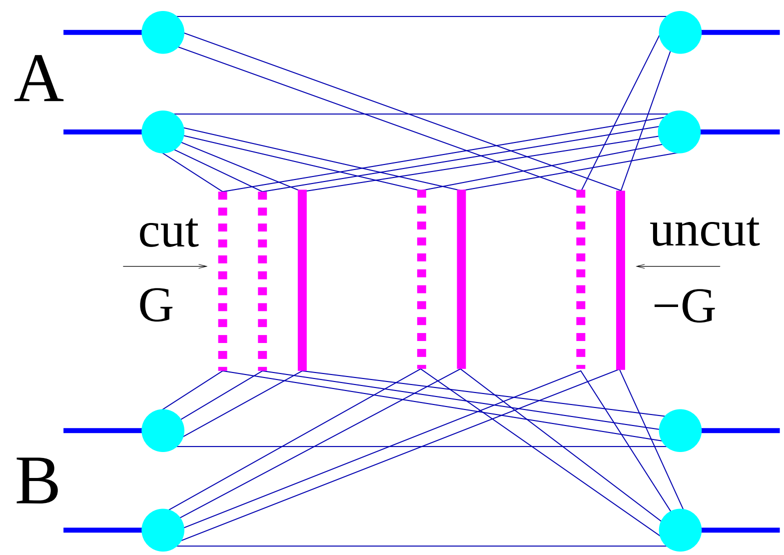
EPOS3, B. Guiot, Y. Karpenko, T. Pierog, K. Werner

- ☐ 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

EPOS IC: Marriage pQCD+GRT+energy sharing
(Drescher, Hladik, Ostapchenko, Pierog, and Werner, Phys. Rept. 350, 2001)

$$\sigma^{\mathrm{tot}} = \sum_{\mathrm{cut\,P}} \int \sum_{\mathrm{uncut\,P}} \int \underbrace{\qquad\qquad}_{d\sigma_{\mathrm{exclusive}}}$$



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

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

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

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

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

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

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

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

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

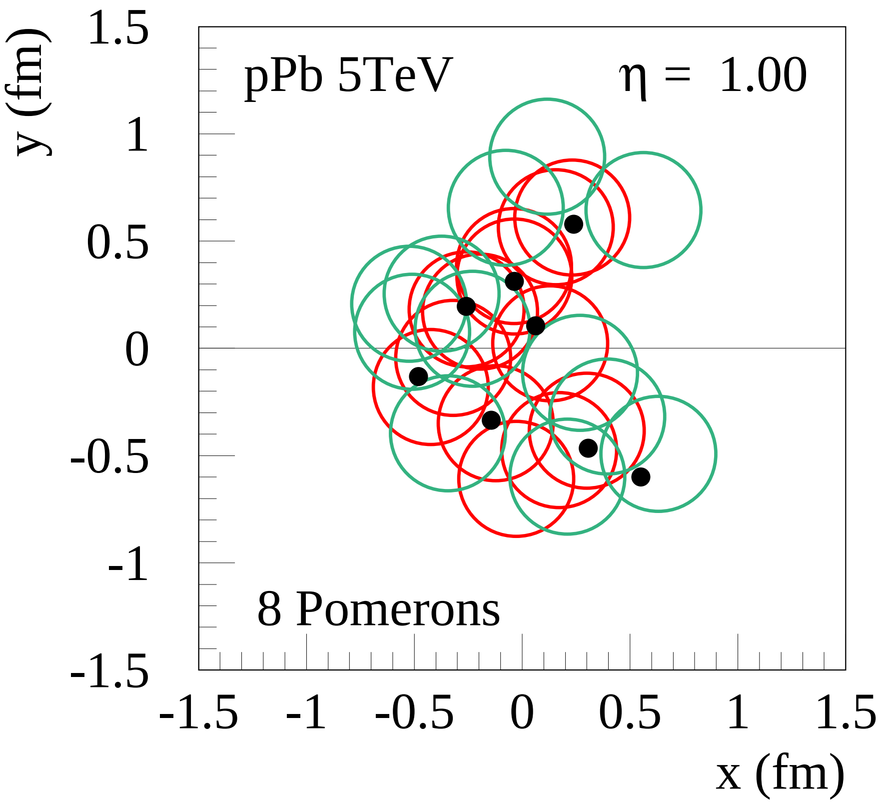
$$\begin{aligned} \partial_{;\nu} T^{\mu\nu} &= \partial_\nu T^{\mu\nu} + \Gamma^\mu_{\nu\lambda} T^{\nu\lambda} + \Gamma^\nu_{\nu\lambda} T^{\mu\lambda} = 0 \\ \gamma\left(\partial_t + v_i \partial_i\right)\pi^{\mu\nu} &= -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\mathrm{NS}}}{\tau_\pi} + I^{\mu\nu}_\pi \\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

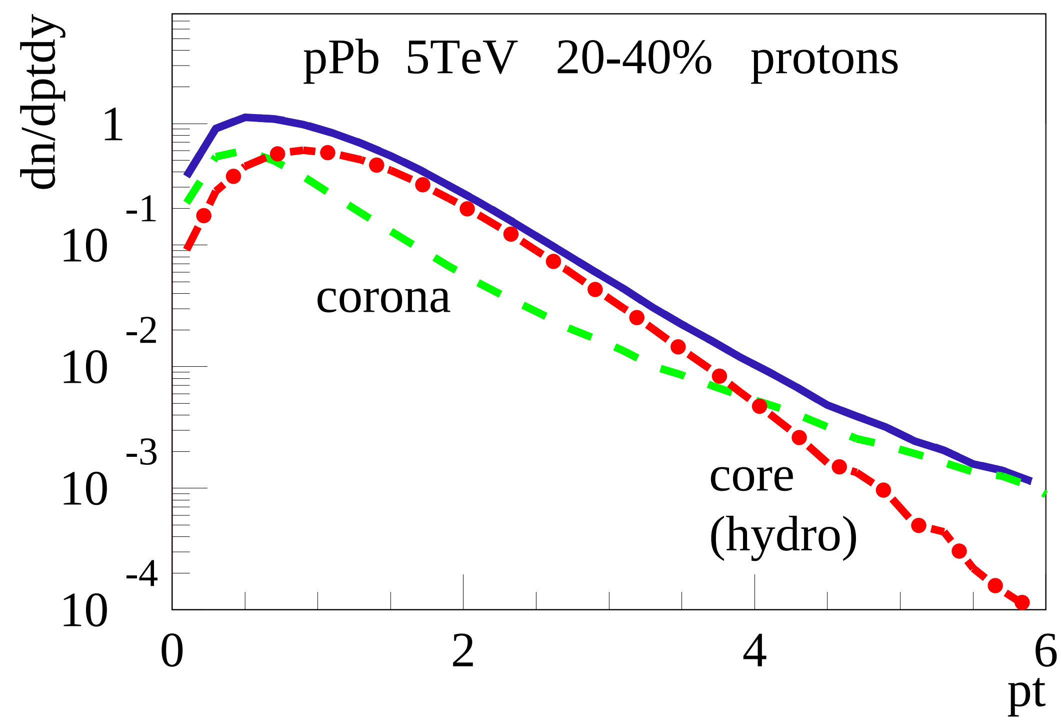
- $T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$,
- $\partial_{;\nu}$ denotes a covariant derivative,
- $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$ is the projector orthogonal to u^μ,
- $\pi^{\mu\nu}$ and Π are the shear stress tensor and bulk pressure, respectively.
-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

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





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 $|\eta| < 2.4$)

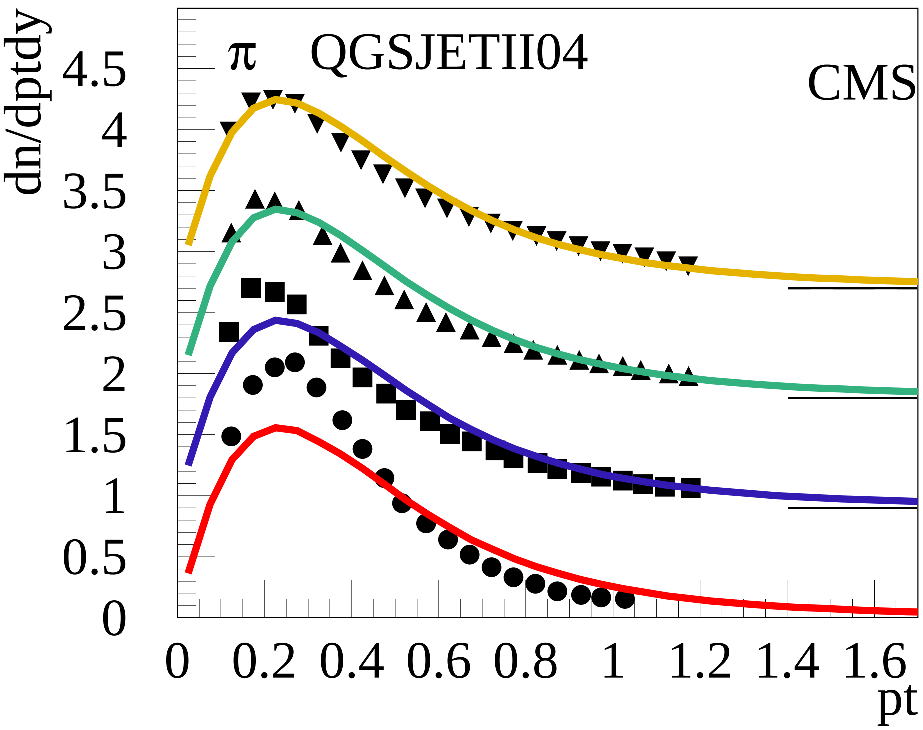
Multiplicity = centrality measure
in EPOS: high multiplicity = many Pomerons

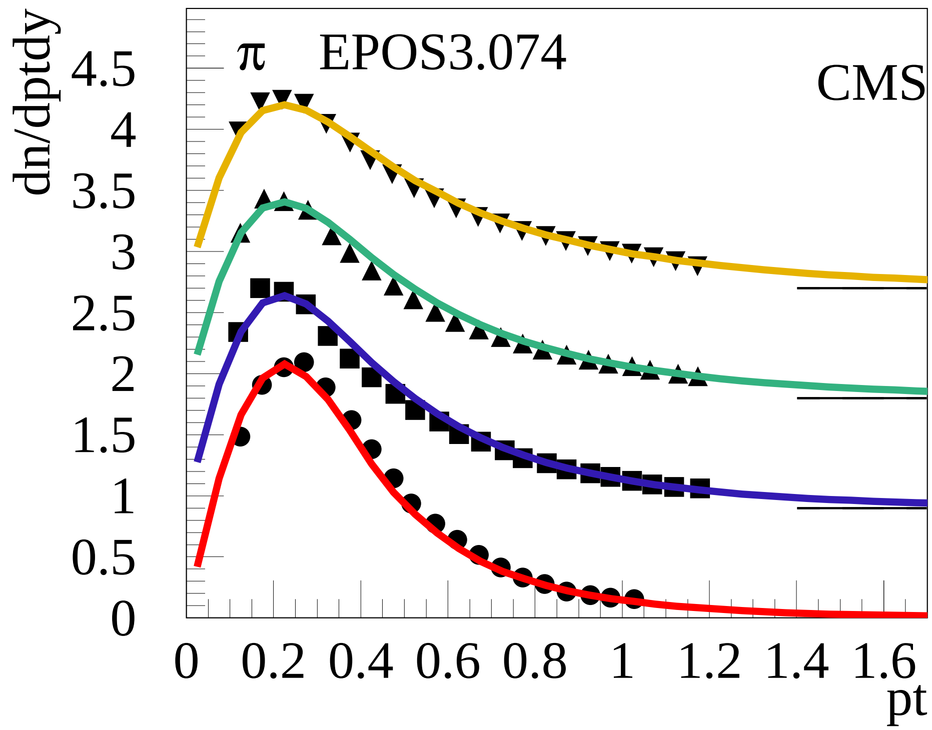
Data compared to

- ☐ **EPOS3 (hydrodynamic expansion, flow)**
- ☐ **QGSJETII (no flow effects, only string decay)**

Pions

<N_tracks> = 8, 84, 160, 235, from bottom to top, curves shifted by 0.9
spectra normalized to unity, lines = theory

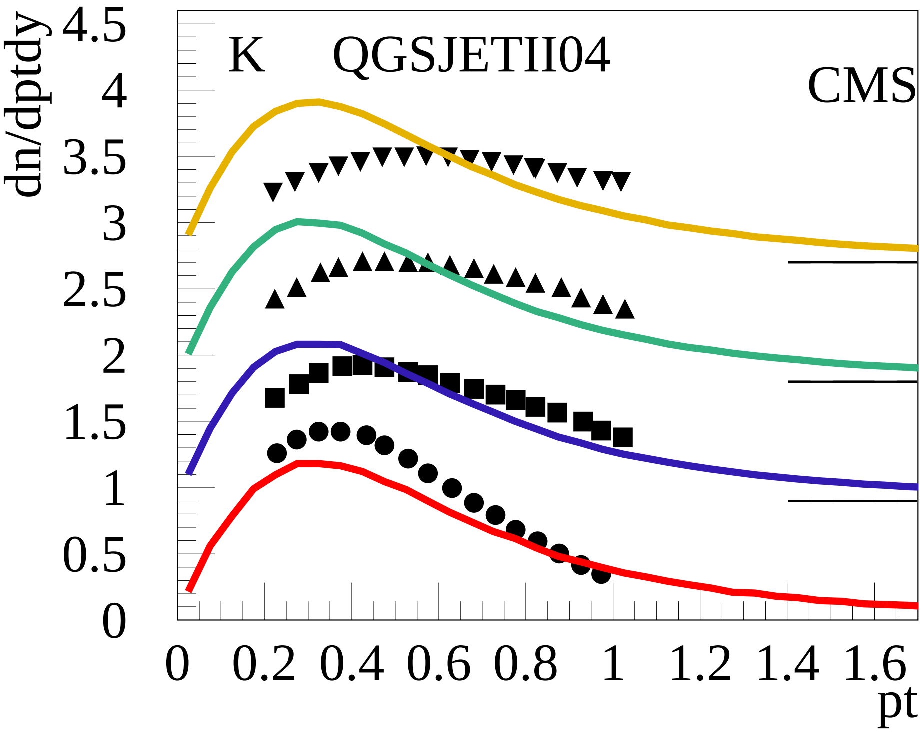


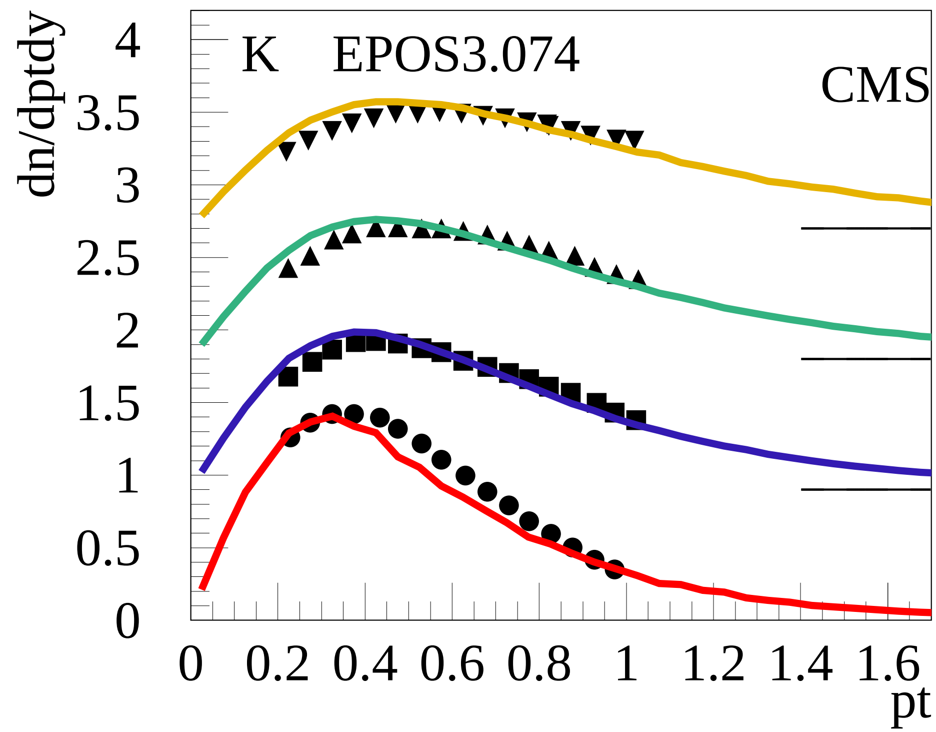


Little change with <N_tracks> for pions

Kaons

<N_tracks> = 8, 84, 160, 235, from bottom to top, curves shifted by 0.9
spectra normalized to unity, lines = theory



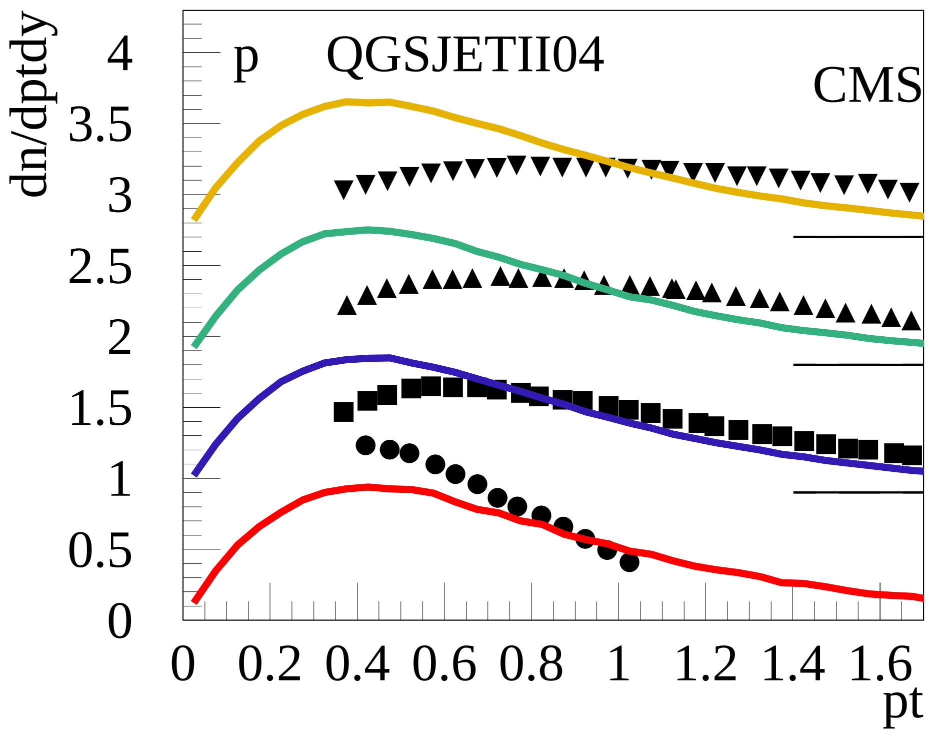


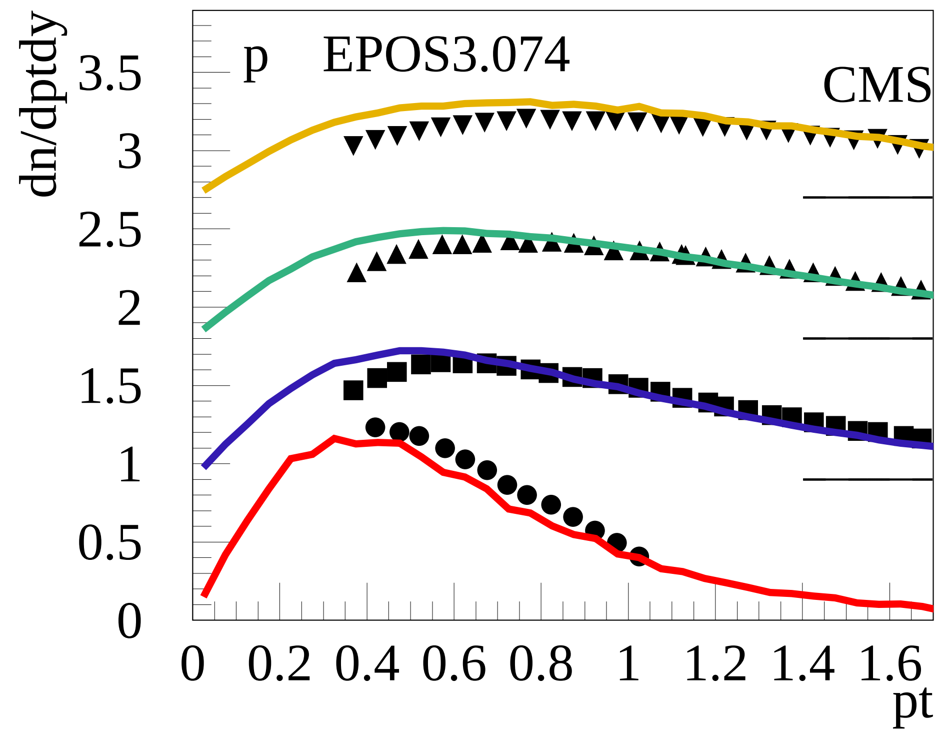
Kaon spectra change significantly with <N_tracks>

in EPOS3: more and more flow contribution

Protons

<N_tracks> = 8, 84, 160, 235, from bottom to top, curves shifted by 0.9
spectra normalized to unity, lines = theory



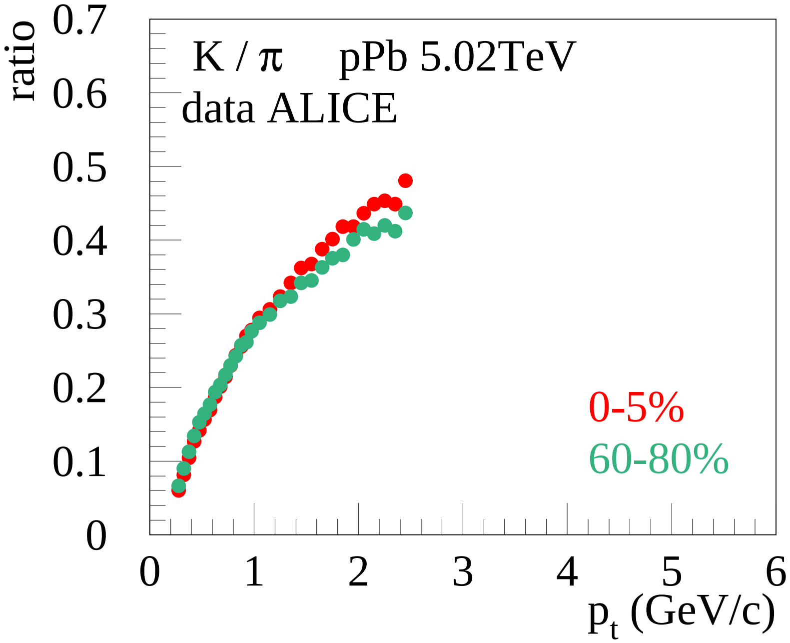


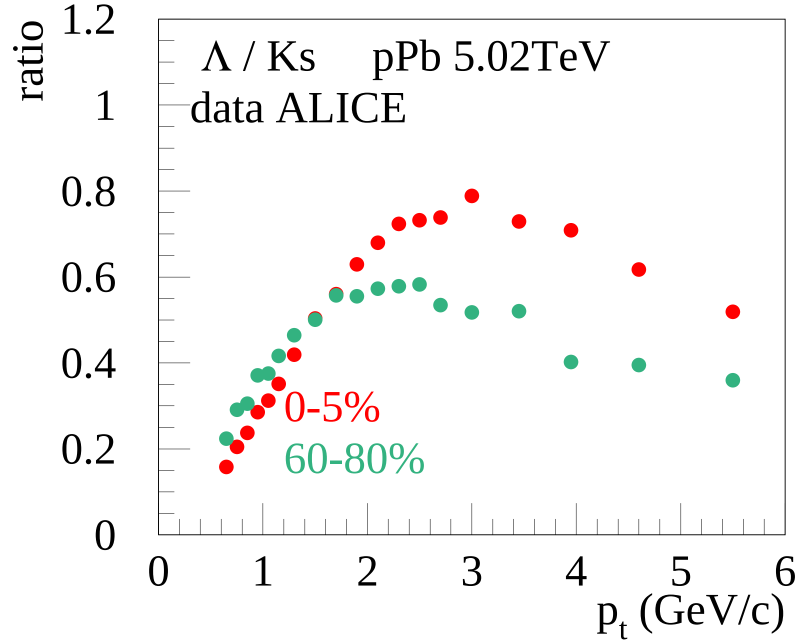
Strong variation of proton spectra

=> flow helps

ALICE: compare pt spectra for identified particles in different multiplicity classes: 0-5%,...,60-80%
(in $2.8 < \eta_{\rm lab} < 5.1$)
R. Preghenella, ALICE, talk Trento workshop 2013

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



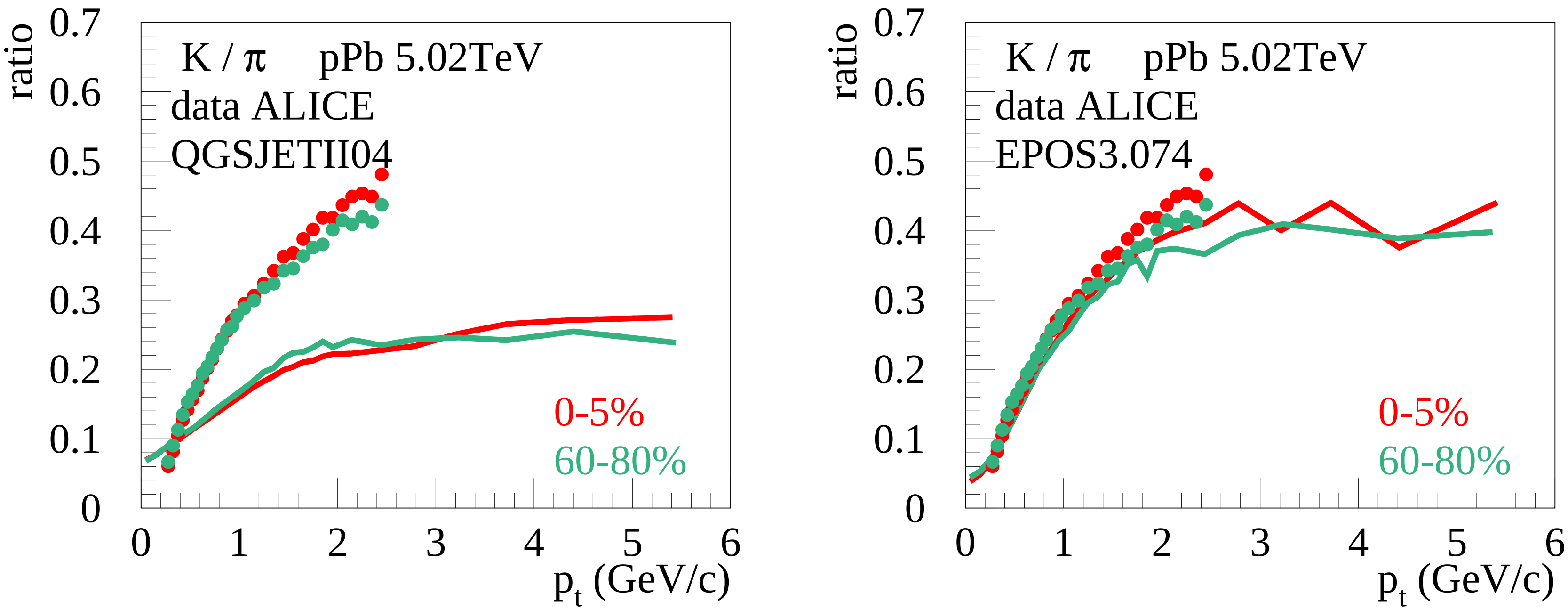


Significant variation of lambda/K – like in PbPb

K/π

High multiplitity (0-5%, red),
low multiplitity (60-80%, green)

lines = theory
points = data



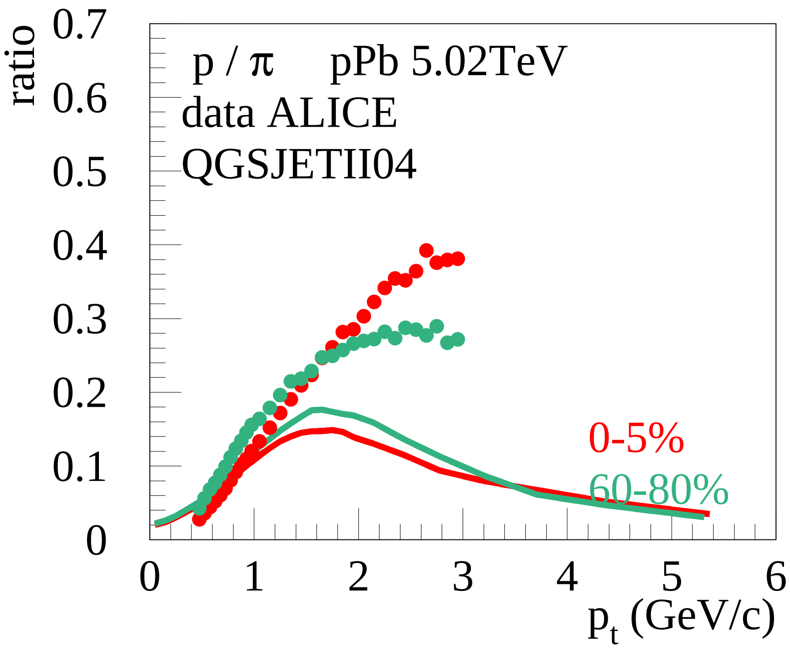
No multiplicity dependence

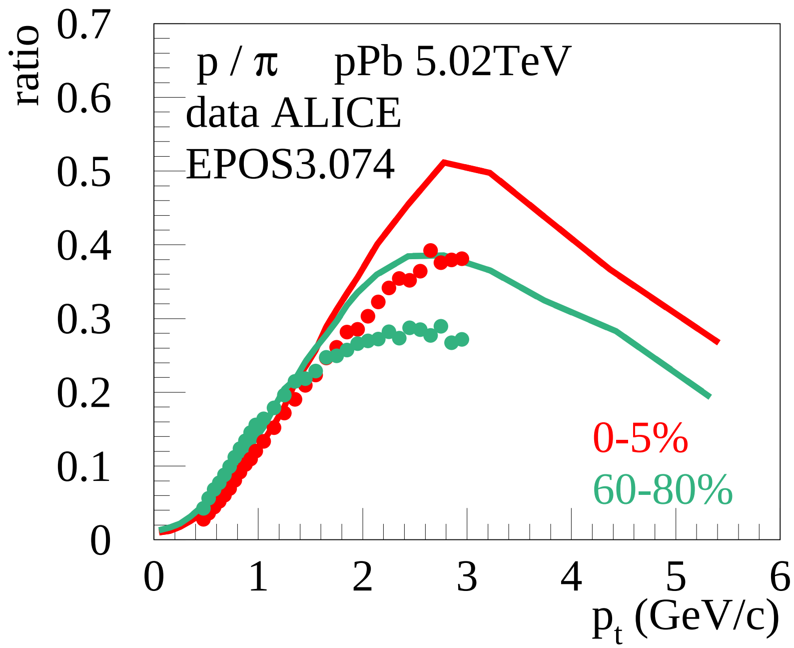
not trivial to get the peripheral right !!

p/π

High multiplitity (0-5%, red),
low multiplitity (60-80%, green)

lines = theory
points = data





Significant multiplicity dependence

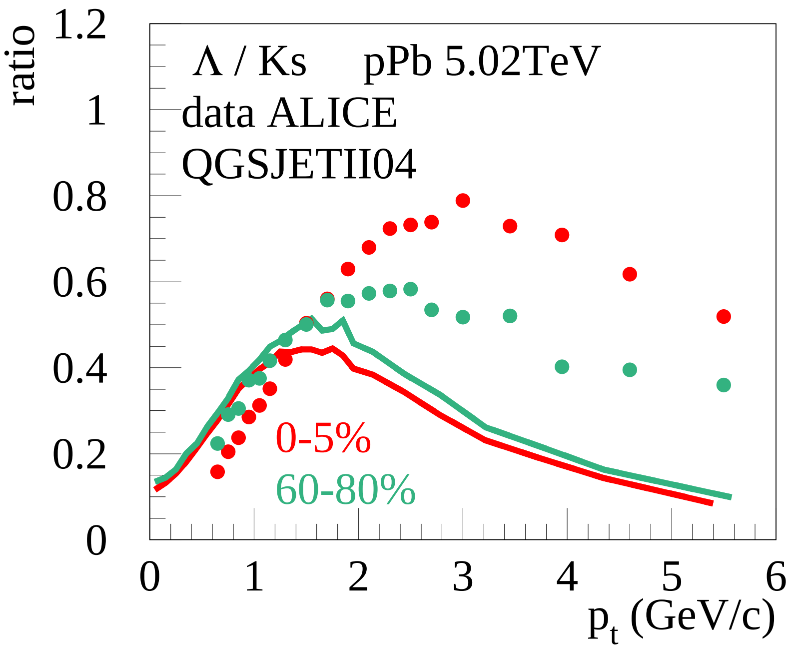
in EPOS, flow already affects the low multiplicity case

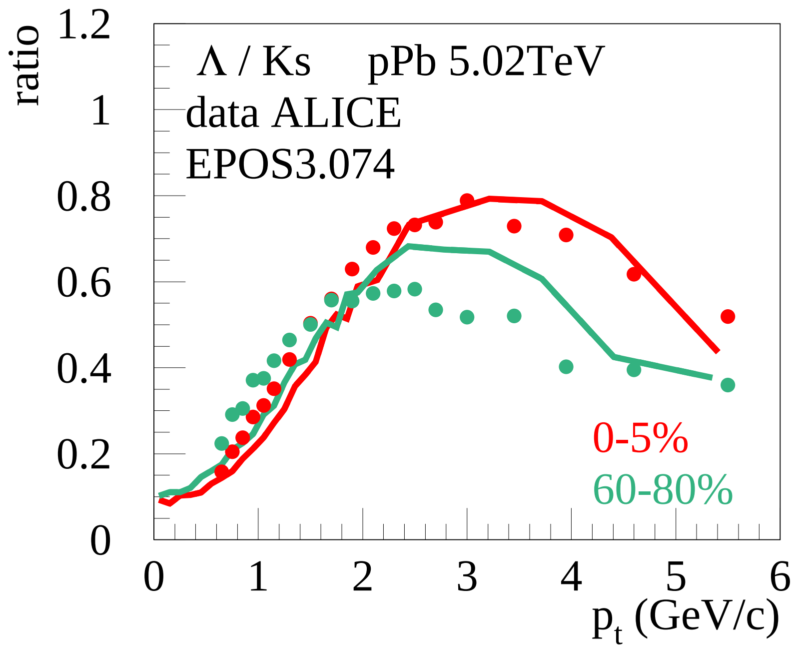
"flow peak" around 2-3 GeV/c,
beyond 5GeV/c corona (minjets) dominate

Λ/K_s

High multiplitity (0-5%, red),
low multiplitity (60-80%, green)

lines = theory
points = data





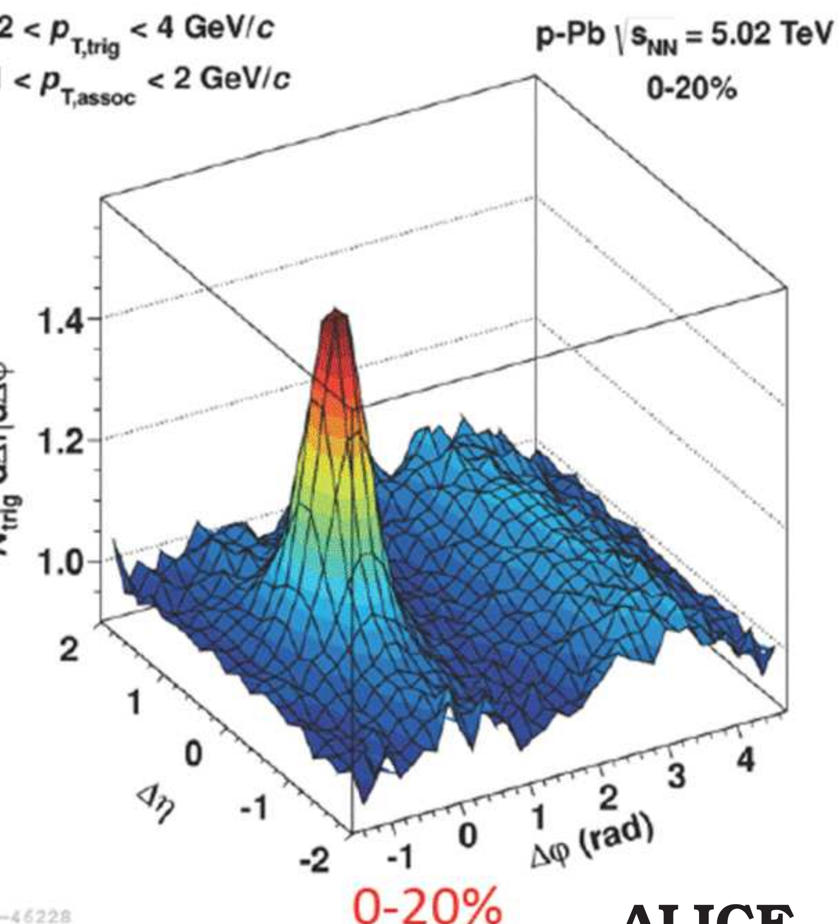
Significant multiplicity dependence

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

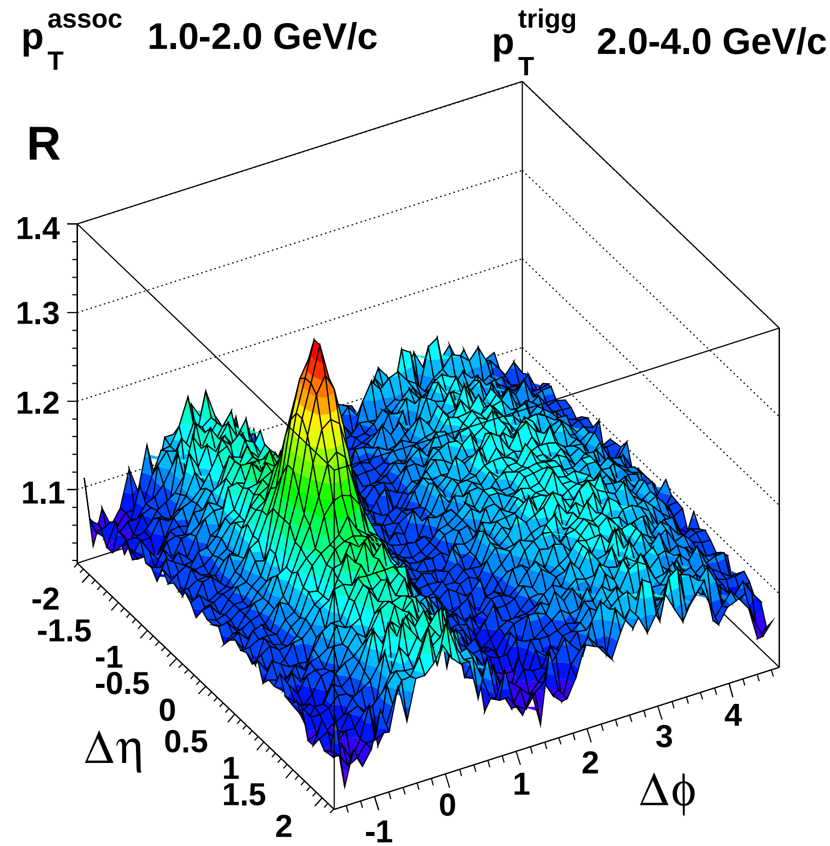
flow dominates 2-5 GeV/c

“Ridges” in pA

ALICE, arXiv:1212.2001, arXiv:1307.3237

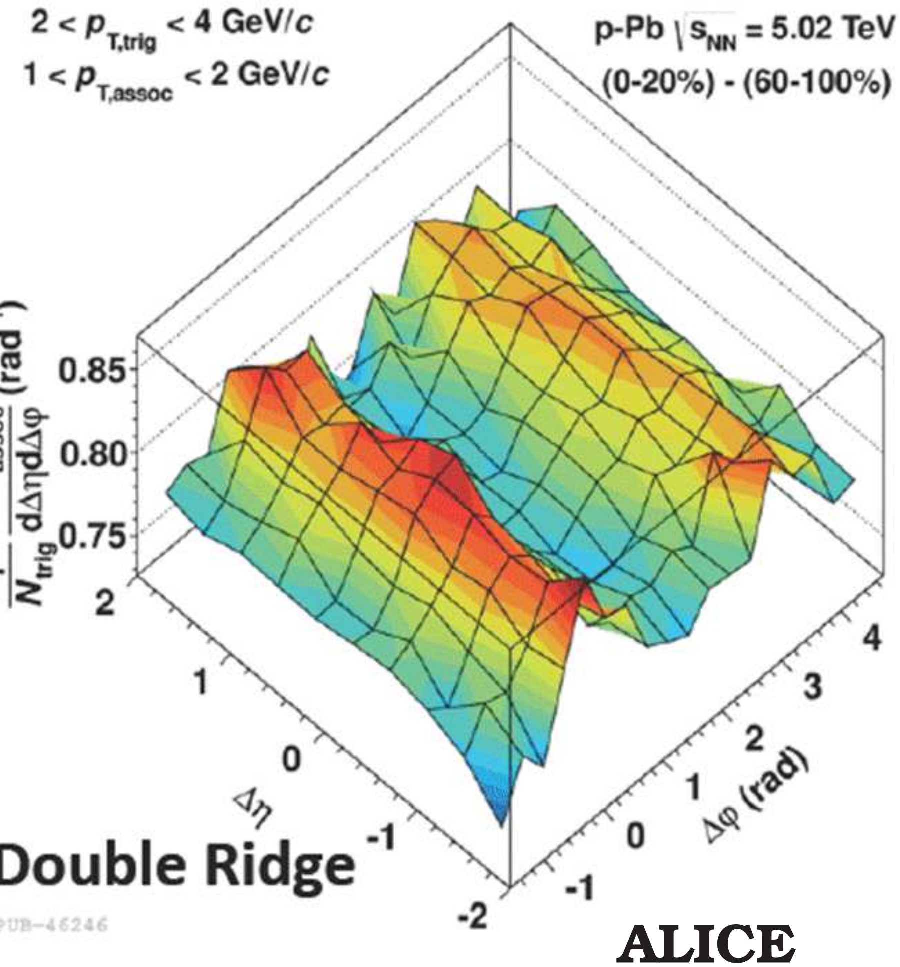


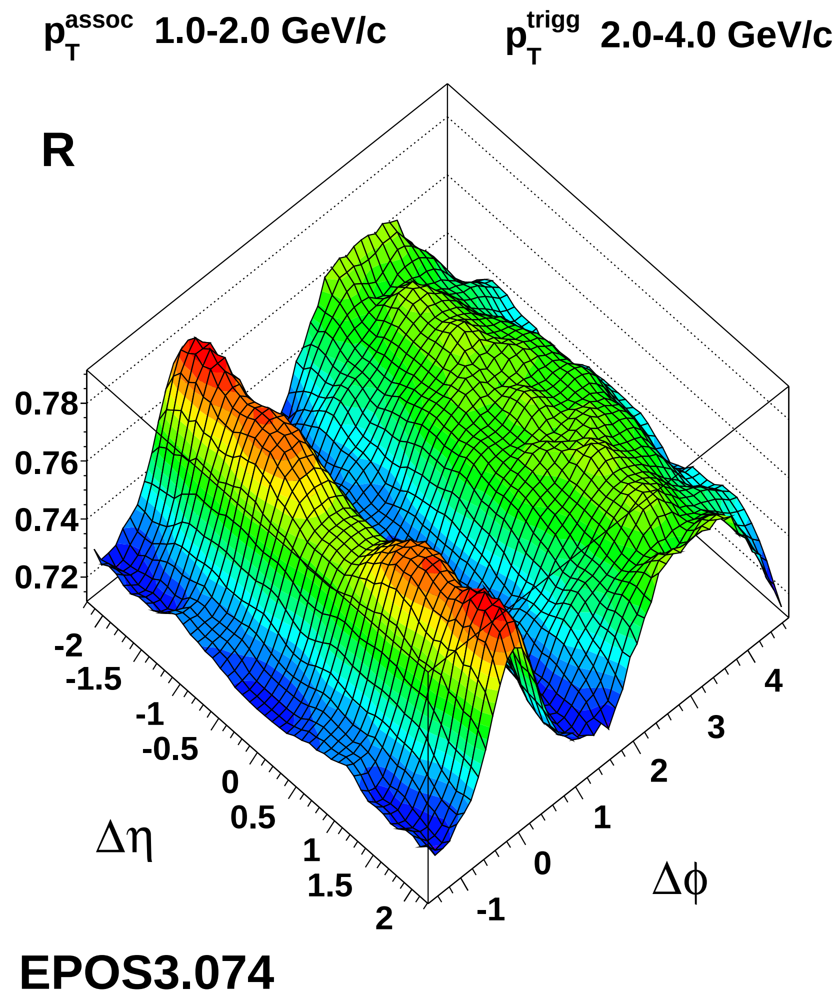
ALICE



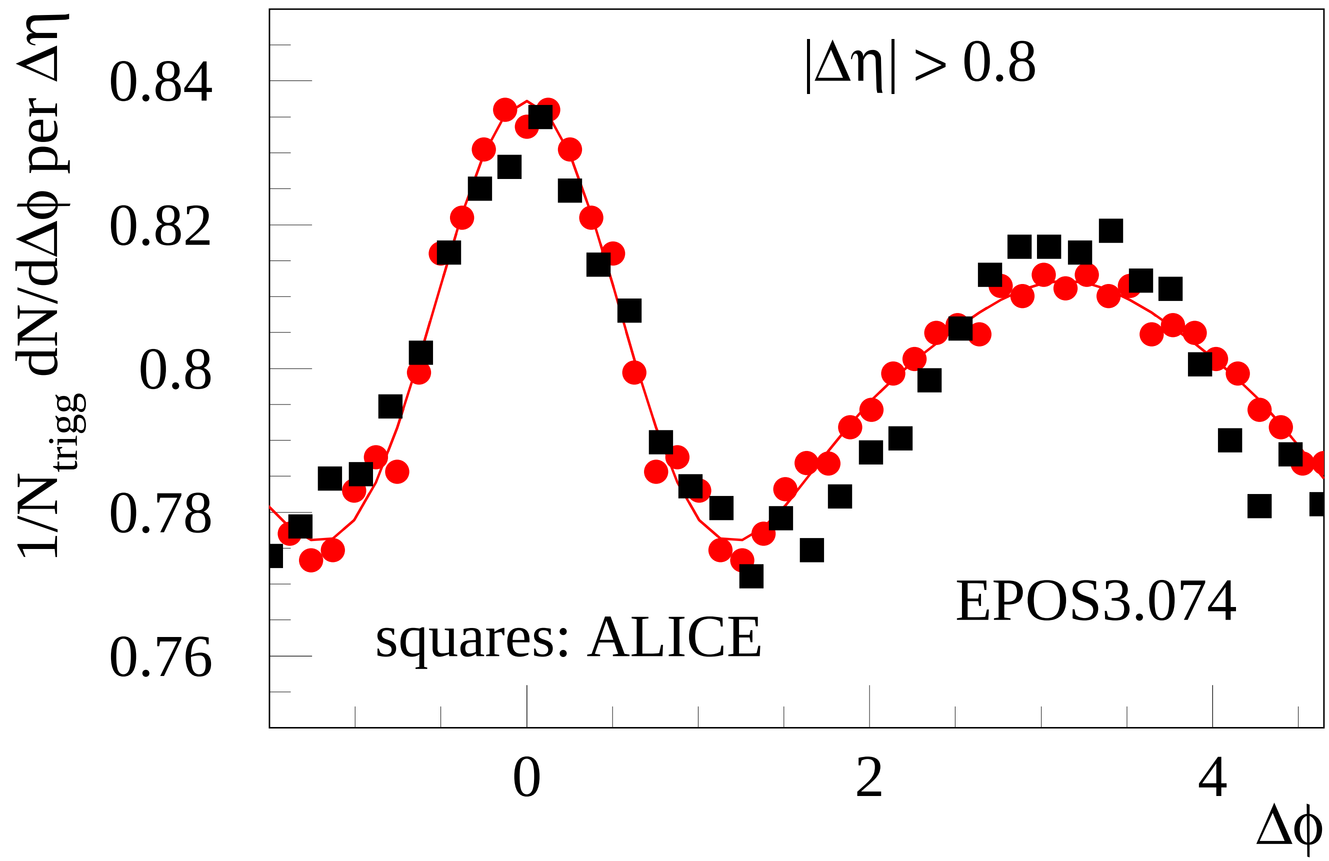
EPOS3.074

Central - peripheral (to get rid of jets)





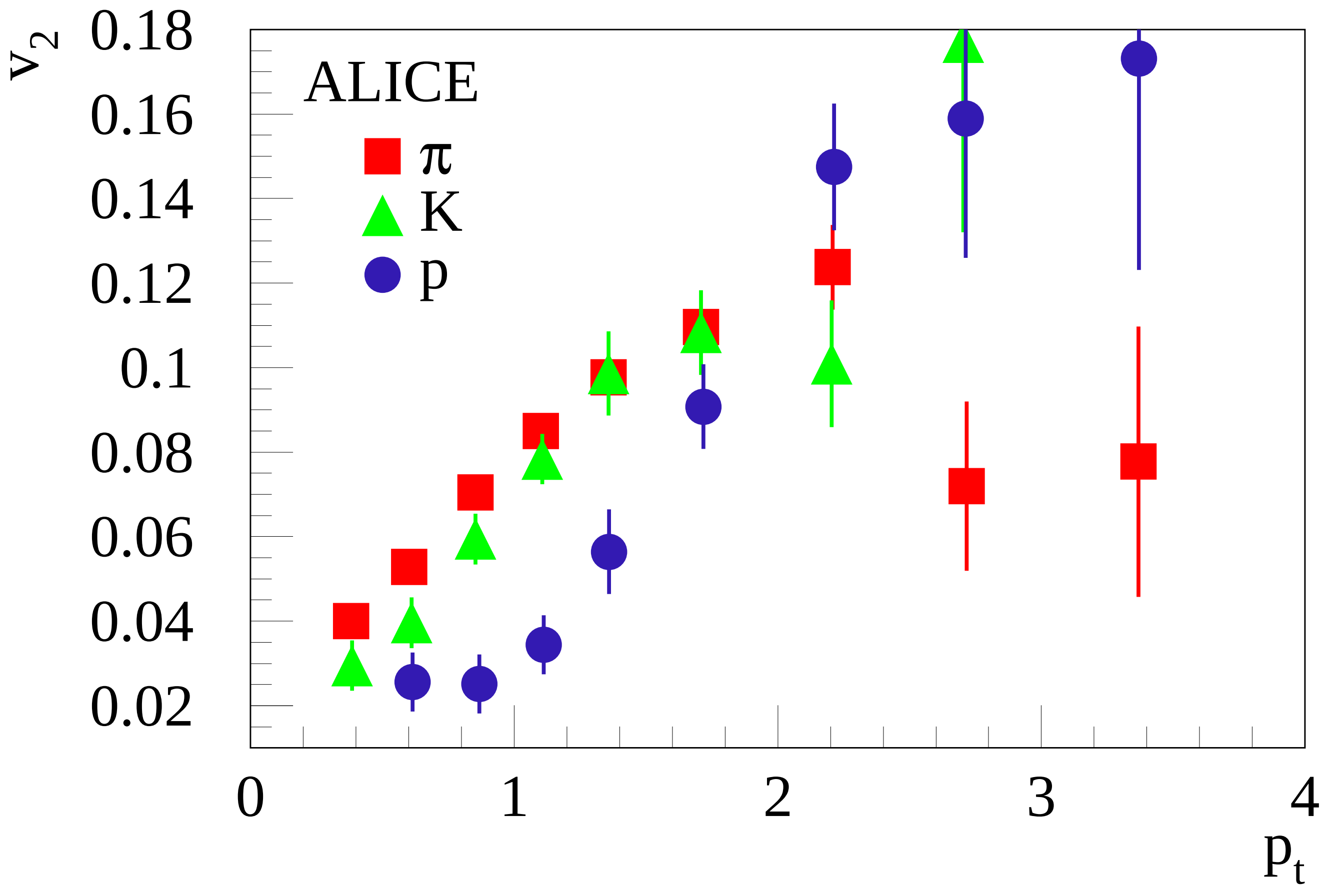
Projection



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

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

Identified particle v2



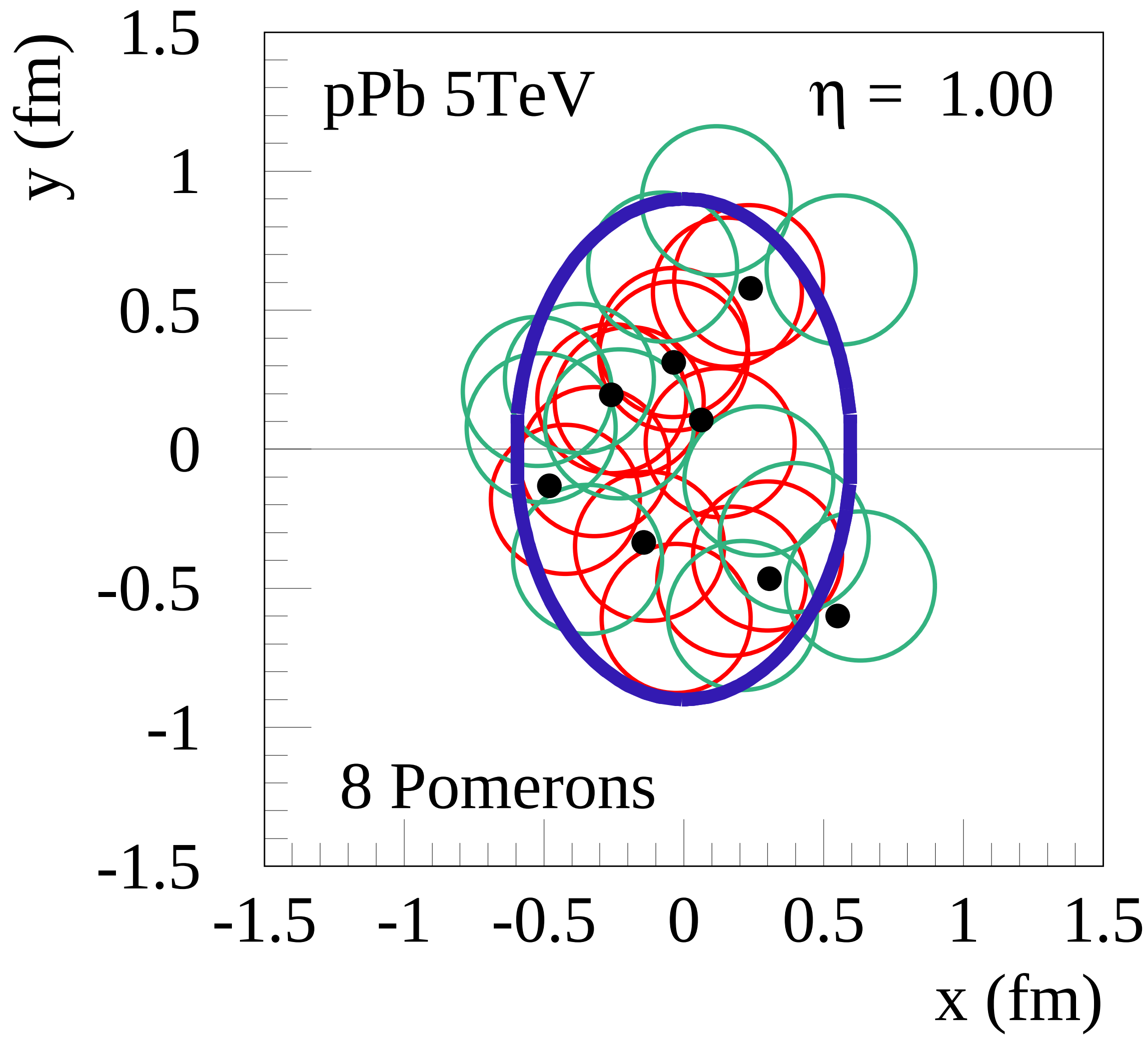
mass splitting, as in PbPb !!!

pPb in EPOS3

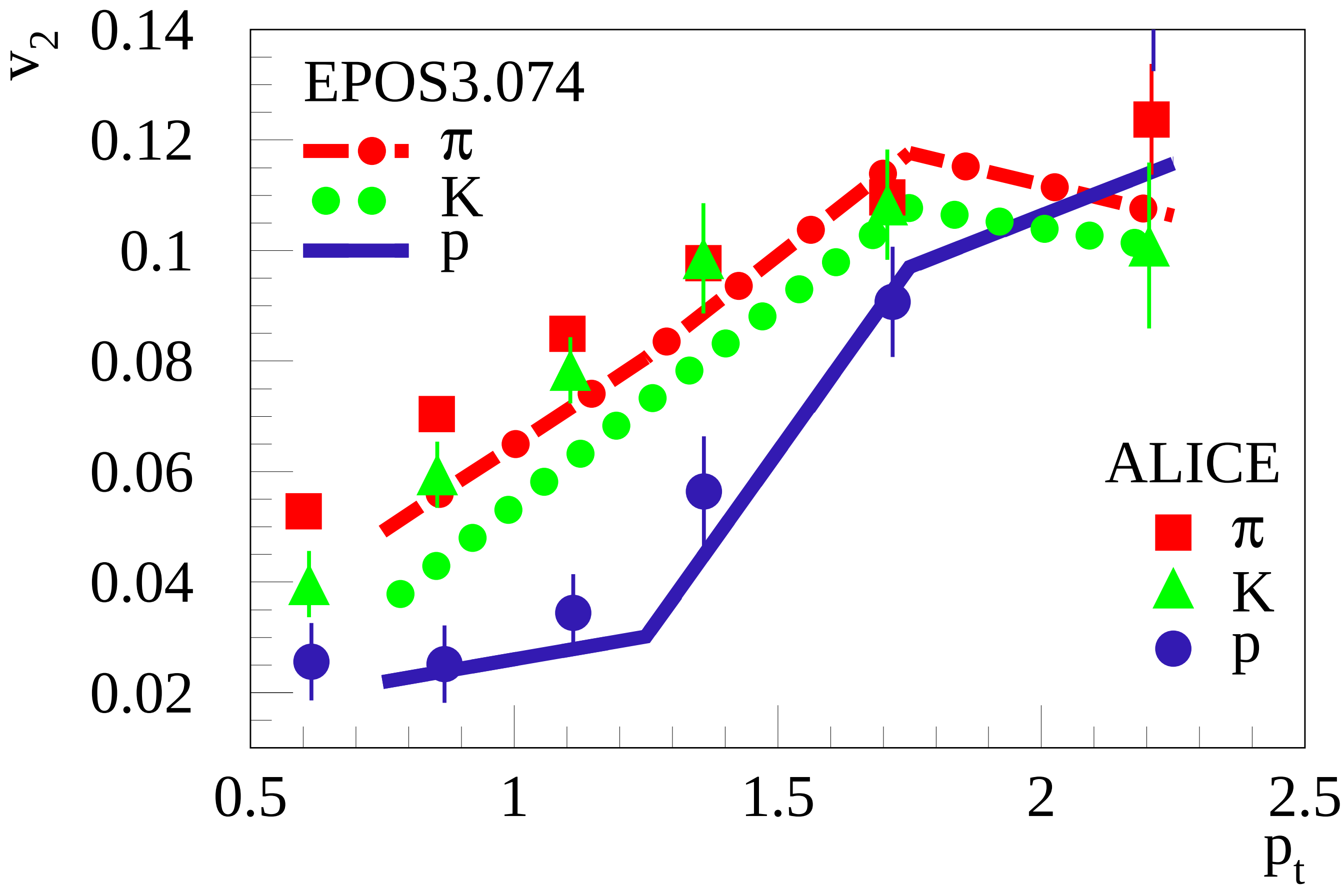
Pomerons (number and positions) characterize geometry (P. number $\propto$ multiplicity)

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

Robust results

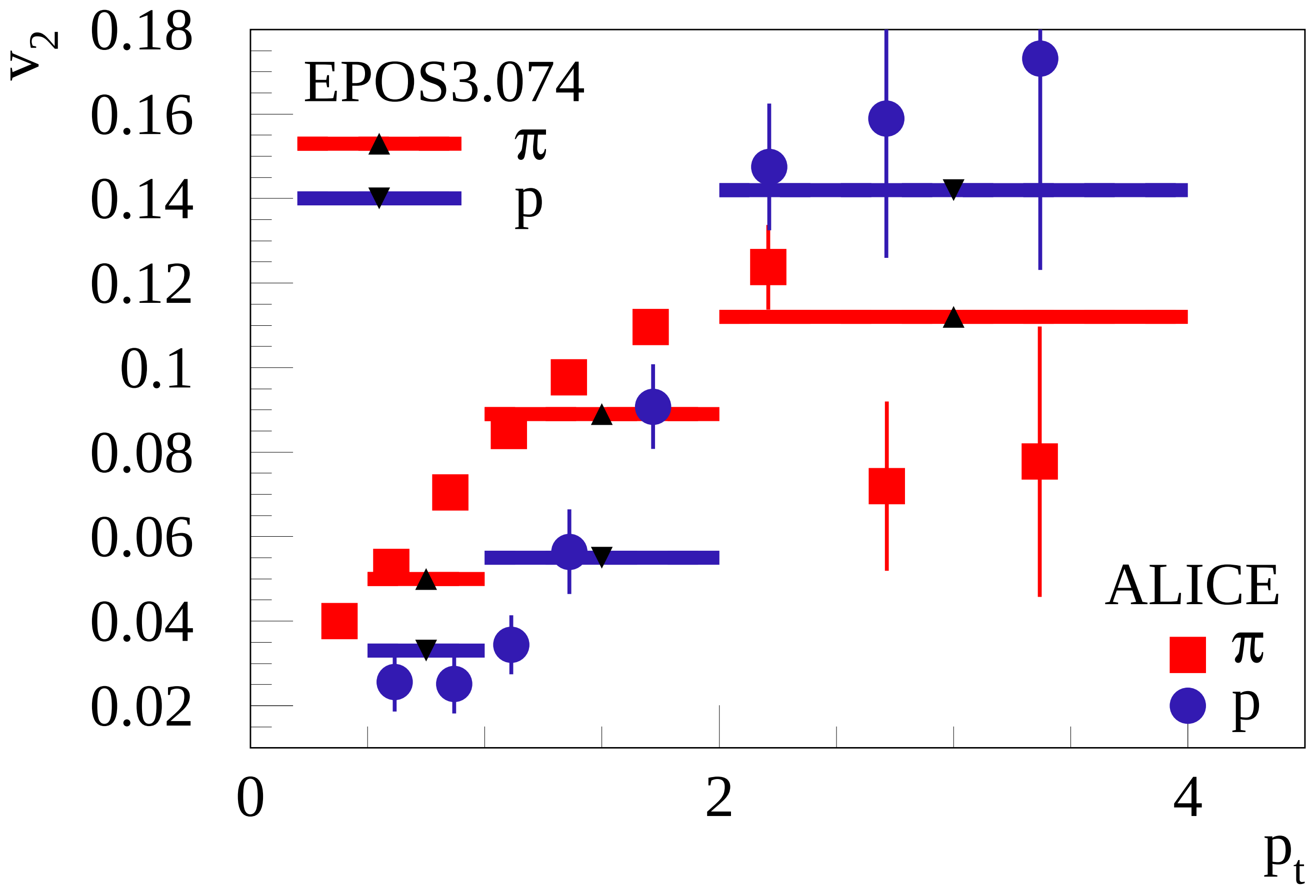


v2 for π, K, p clearly differ



mass splitting, due to flow

different binning:

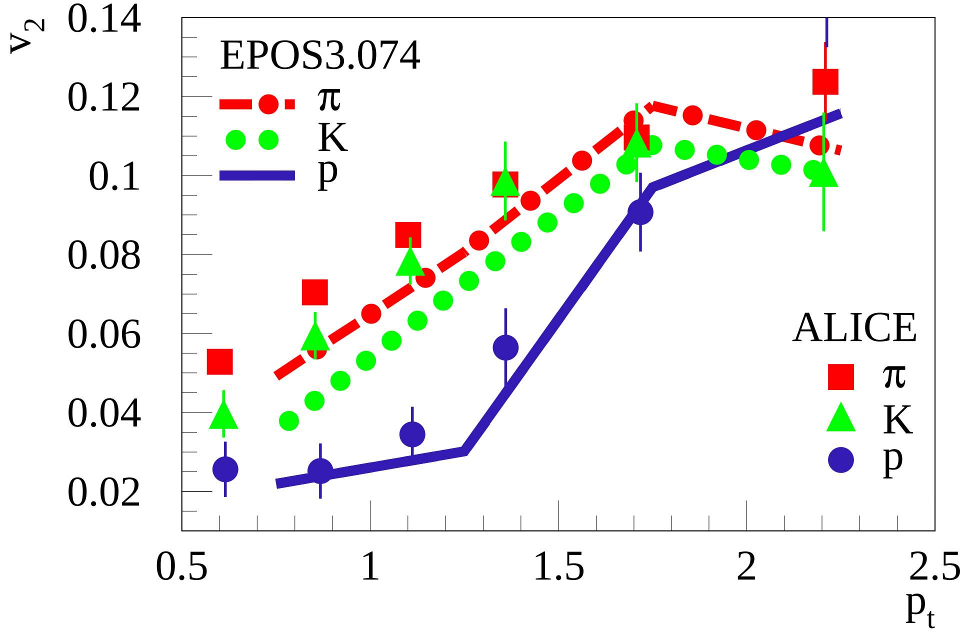


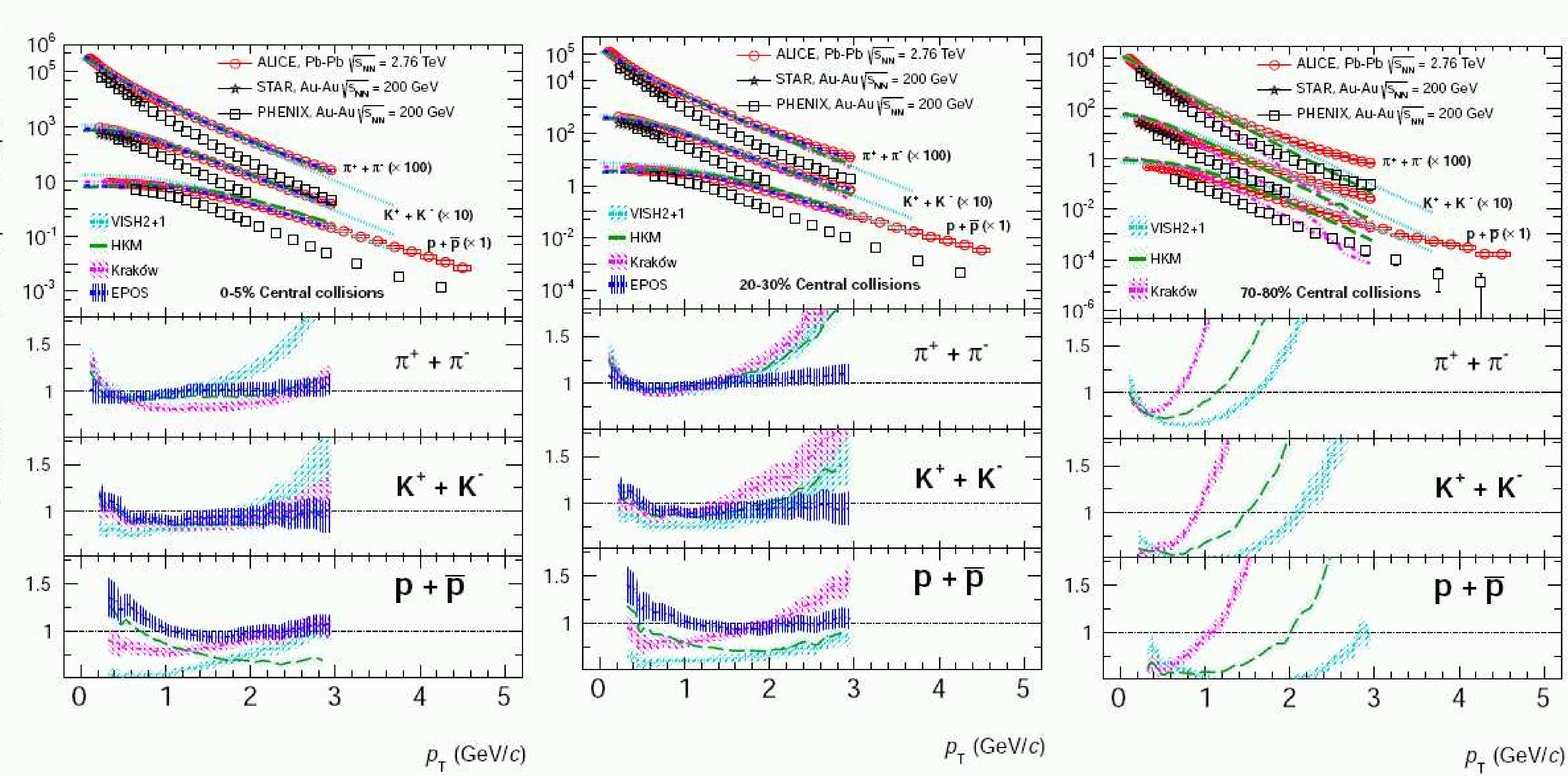
v2(protons) > v2(pions) beyond 2GeV

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