Flow in pPb and pp collisions at the LHC

K.W. in collaboration with

B. Guiot, Iu. Karpenko, T. Pierog

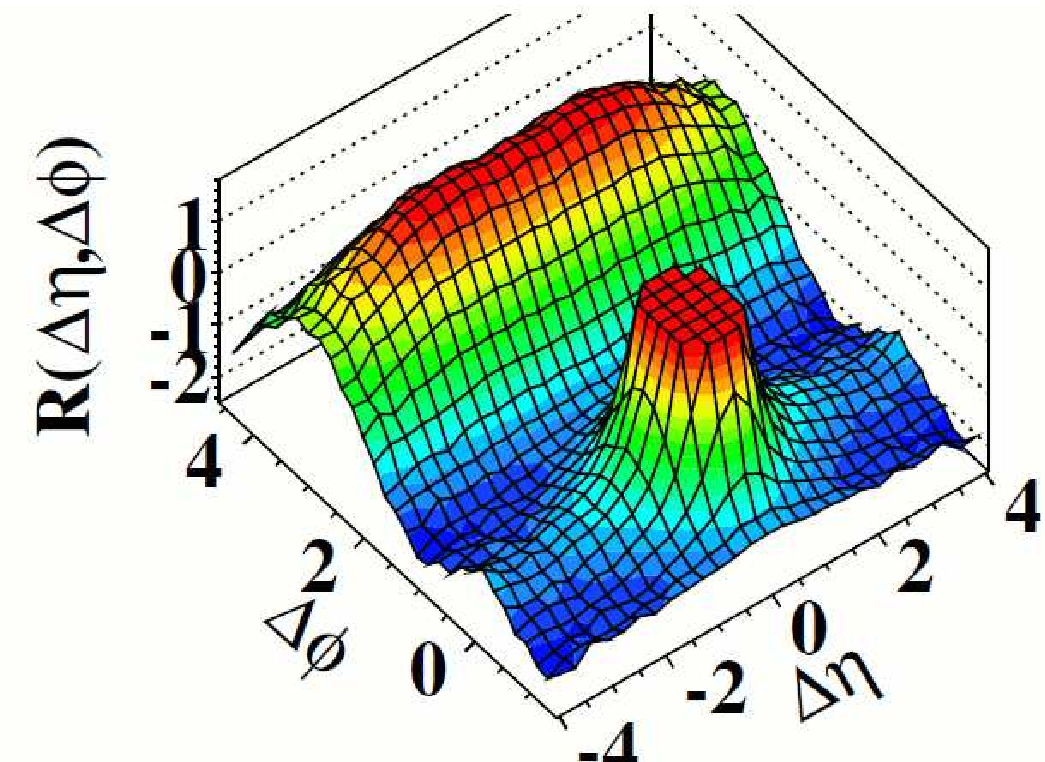
Main lesson from QM2014

- **pp and pA scatterings are no "simple baselines" any more**

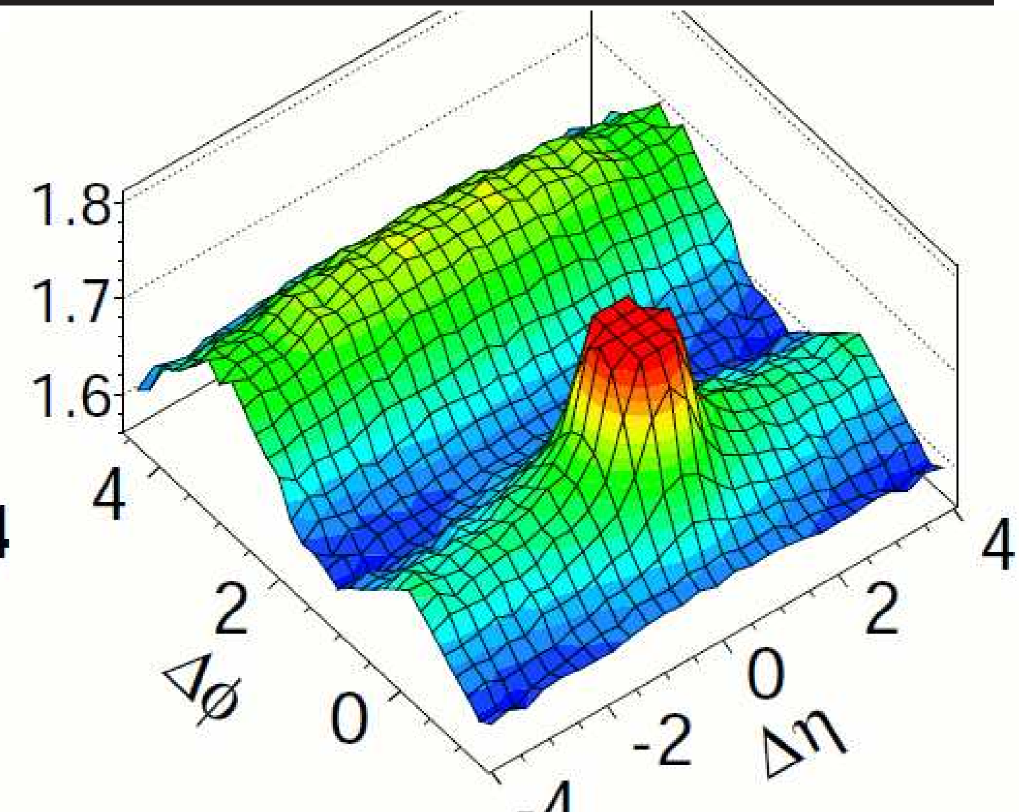
  (which allow to see NEW PHYSICS like QGP, flow, ... in AA)

2010-2014: incredibly interesting and unexpected pp and pPb results at the LHC (confirmed by RHIC)

Ridges (in dihadron correlation functions) also seen in pp (left) and pPb (right)



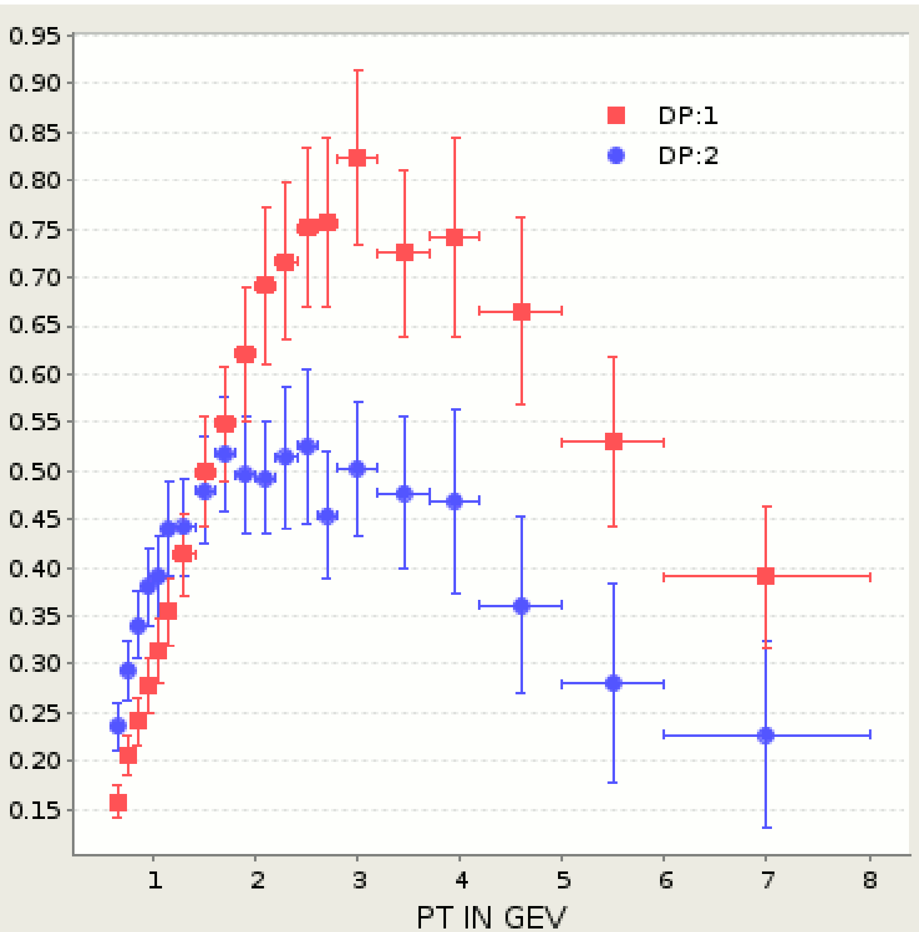
CMS (**2010**) arXiv:1009.4122
JHEP 1009:091,2010



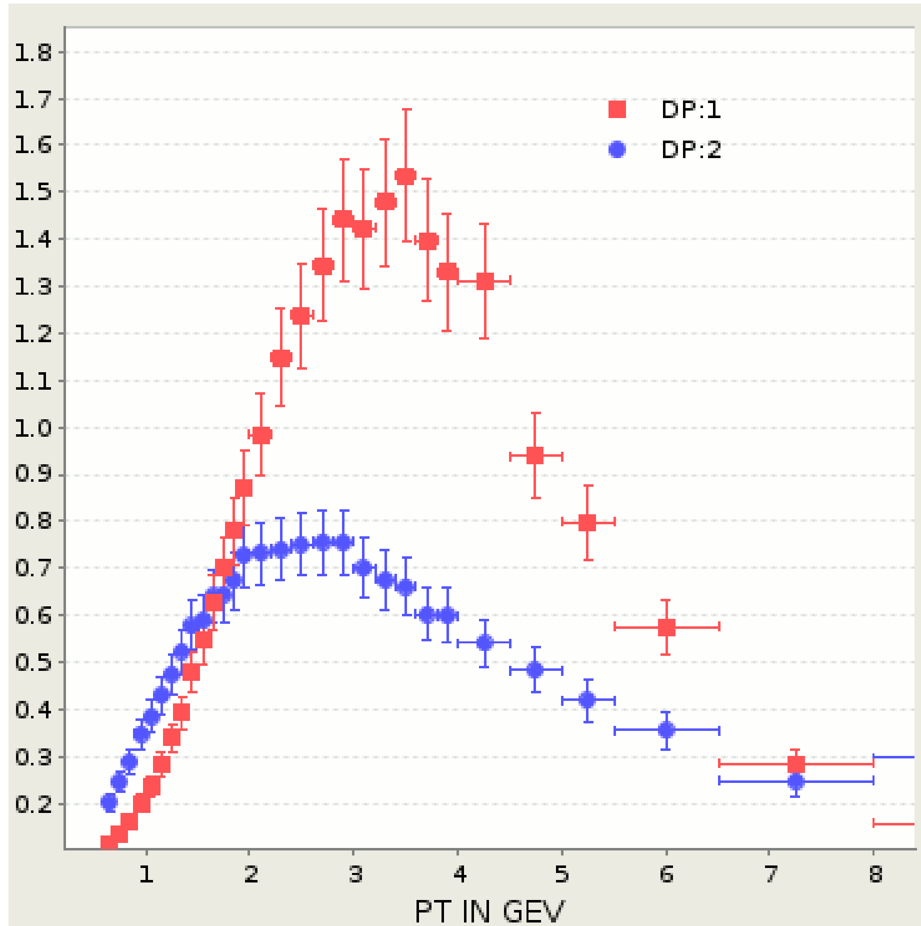
CMS (**2012**) arXiv:1210.5482
Phys. Lett. B 718 (2013) 795

In AA: due to initial anisotropies + flow

Λ/K_s versus pT (high compared to low multiplicity) in pPb (left) similar to PbPb (right)



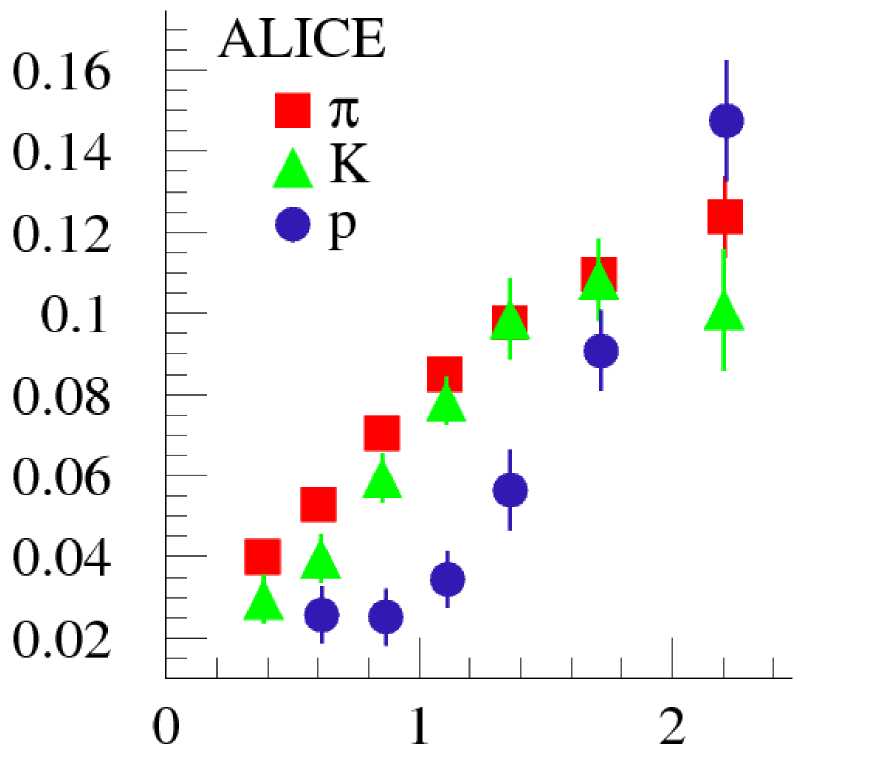
ALICE (**2013**) arXiv:1307.6796



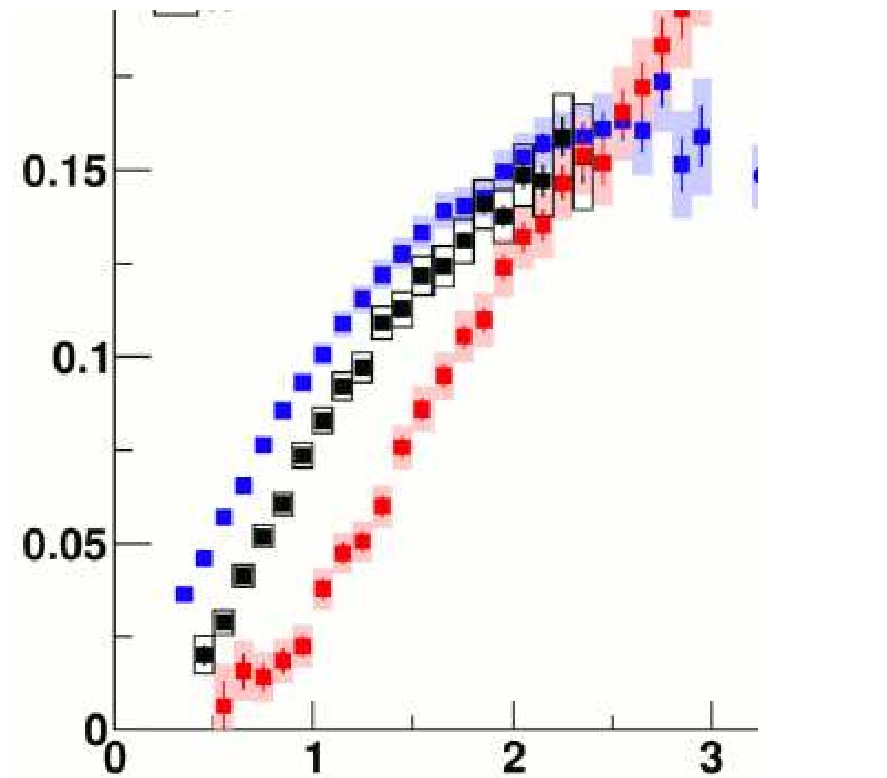
ALICE (**2013**) arXiv:1307.5530
Phys. Rev. Lett. 111, 222301 (2013)

In AA: partially due to flow

v2 versus pT: mass splitting (π, K, p) in pPb (left) similar to PbPb (right)



ALICE (**201**3) arXiv:1307.3237



ALICE (**201**2) F. Noferini QM2012

In AA: Understood in terms of flow

Universal approach: pp, pA, AA

For ALL reactions: Same procedure, several stages

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

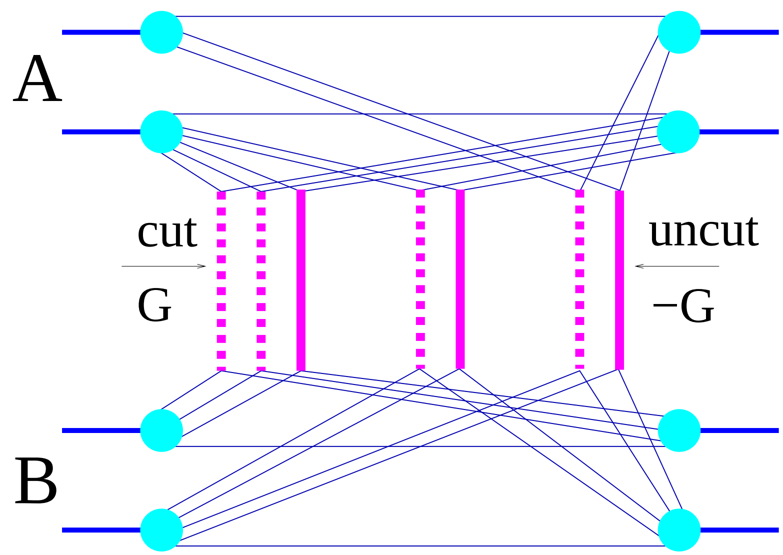
Realization: EPOS3, arXiv:1312.1233 , arXix:1307.4379,
B. Guiot, Y. Karpenko, T. Pierog, M. Bleicher, K. W.

Initial conditions: Marriage pQCD+GRT+energy sharing

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

For pp, pA, AA:

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



$d\sigma_{\text{exclusive}}$

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

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

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

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

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

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

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

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

Historical remark : in 2000

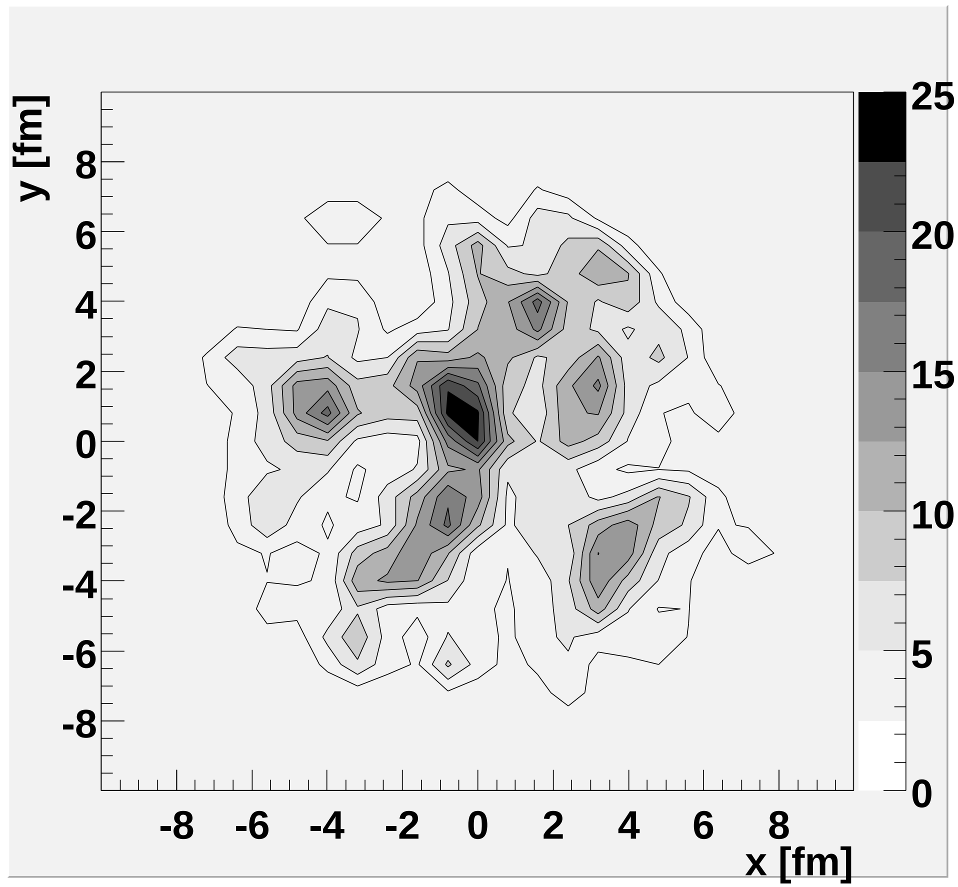
Publication
based on this GR approach:

Initial condition for QGP evolution from NEXUS

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

EPOS
= major NEXUS update

Fig 21: Energy density



Remark 2

- ☐ Introducing a saturation scale (in some way) is crucial !
  (discussion Glauber or CGC (saturation) not useful)
- ☐ Otherwise the total cross section explodes at high energy
  (known since many years)
- ☐ A CGC-like scale $Q_s \propto N_{part}\, \hat{s}^{\lambda}$ works very well,
  actually not trivial to get a consistent picture for
  - e+e-,
  - DIS,
  - pp cross sections (total, elastic),
  - pp jet cross sections,
  - yields and correlations in pp, pA, and AA

Remark 3

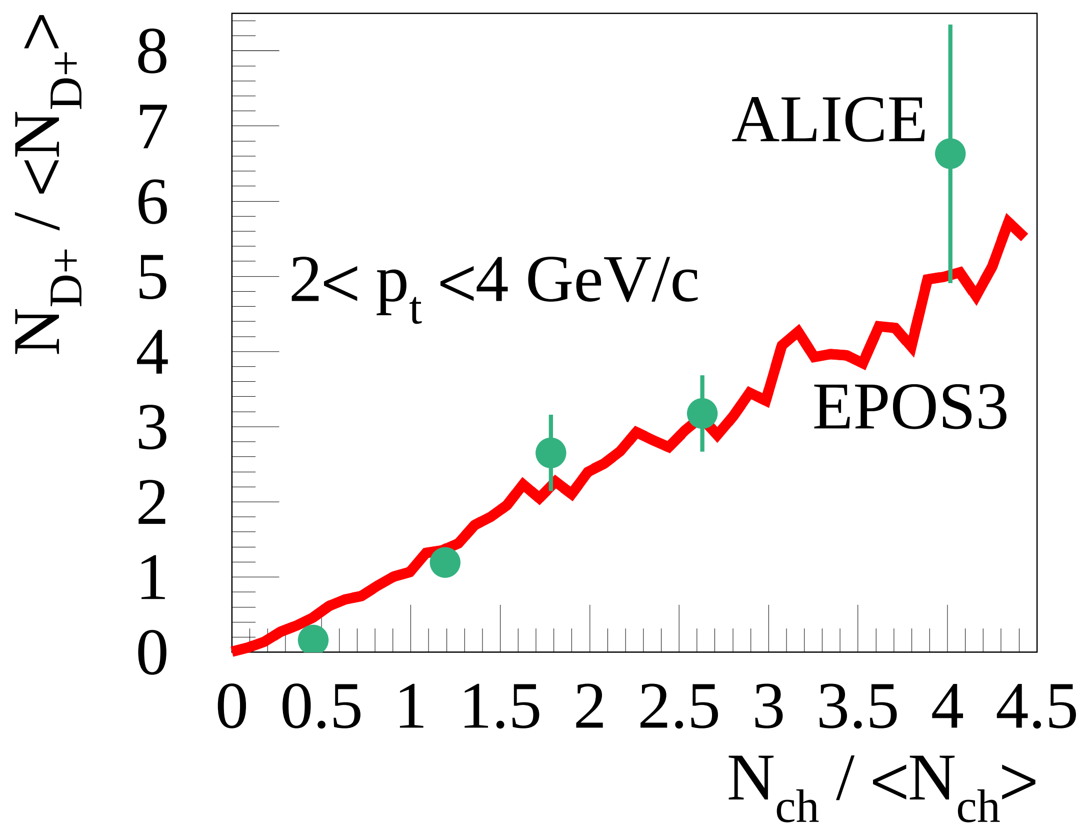
GR multiple scattering gives (automatically)

$$N_{\text{hard}} \propto N_{\text{charged}} \propto N_{\text{Poms}}$$

N_{hard} stands for multiplicity of "hard" particle production.

Example: D$^+$ mesons

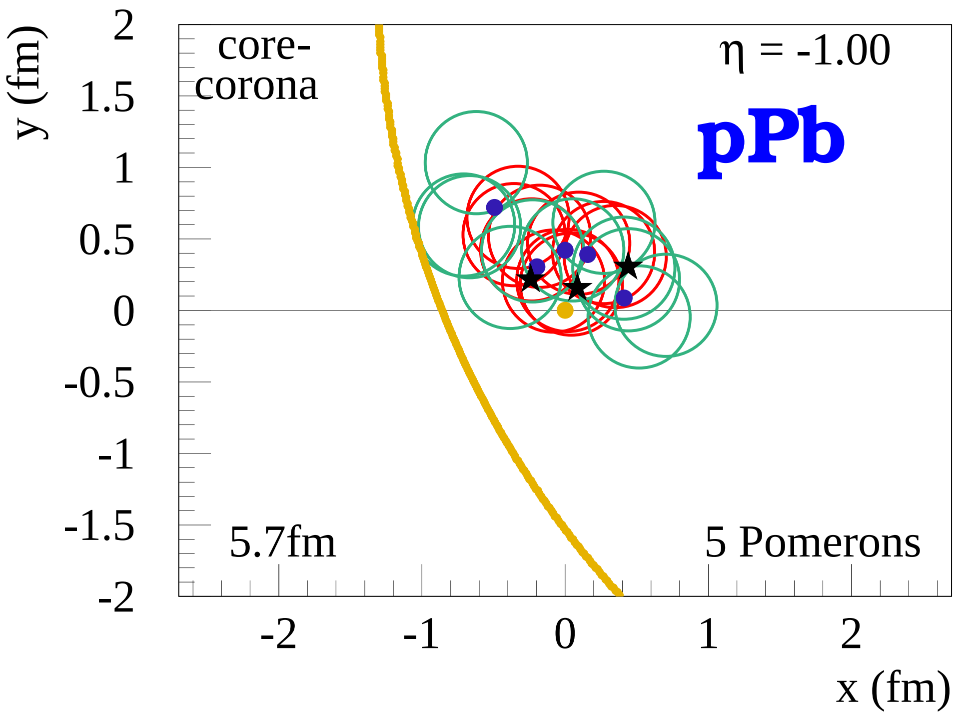
Plot from B. Guiot

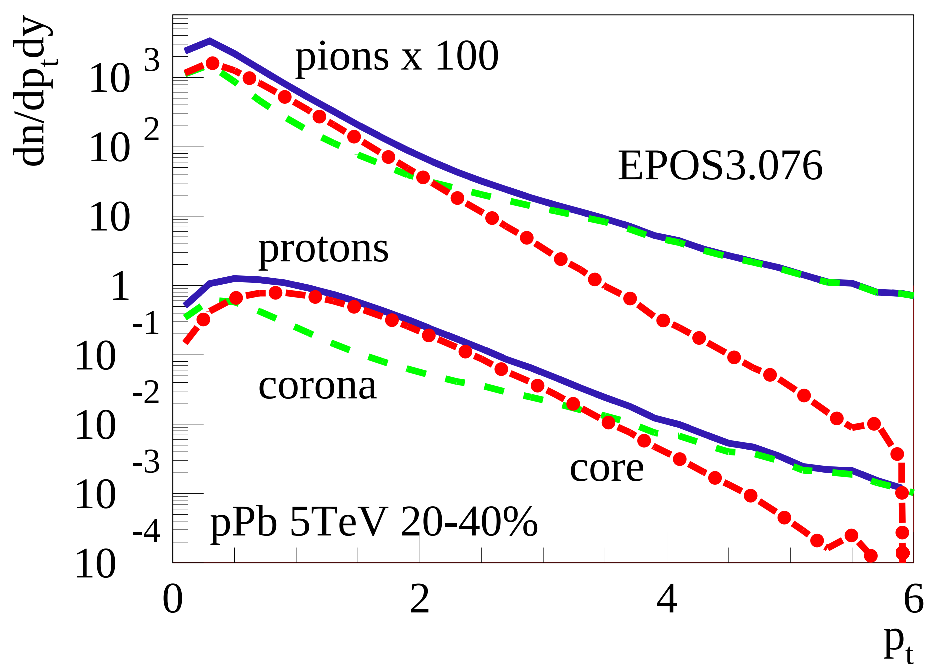


Core-corona procedure (for pp, pA, AA):

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

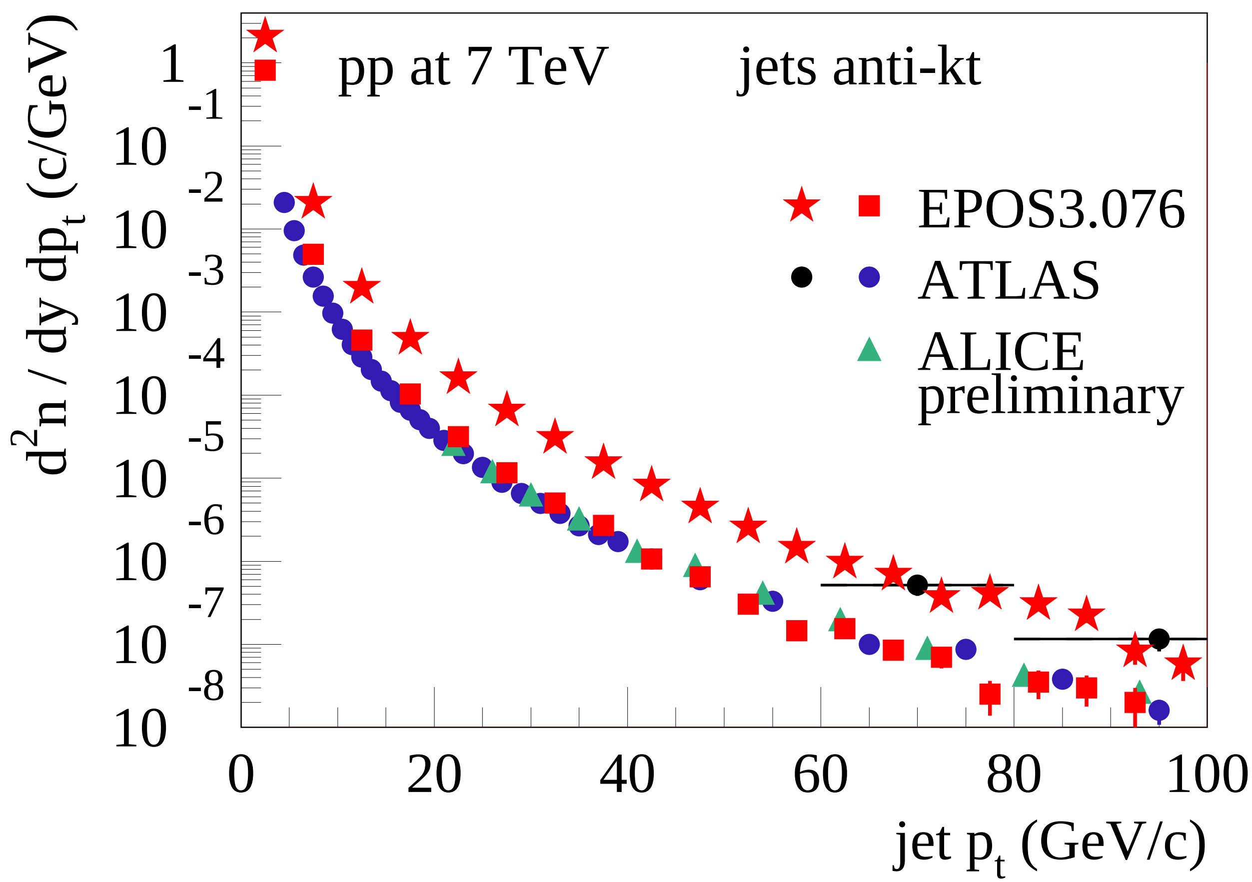
String segments with high pt escape => **corona**,
the others form the **core** = initial condition for hydro
depending on the local string density





Checking high pt "corona" :

jets in pp at 7TeV



Hydro (Yuri Karpenko)

Israel-Stewart formulation, $\eta - \tau$ coordinates, $\eta/S = 0.08$, $\zeta/S = 0$

$$\partial_{;\nu} T^{\mu\nu} = \partial_\nu T^{\mu\nu} + \Gamma^\mu_{\nu\lambda} T^{\nu\lambda} + \Gamma^\nu_{\nu\lambda} T^{\mu\lambda} = 0$$

$$\gamma\left(\partial_t + v_i \partial_i\right) \pi^{\mu\nu} = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\mathrm{NS}}}{\tau_\pi} + I^{\mu\nu}_\pi \qquad \gamma\left(\partial_t + v_i \partial_i\right) \Pi = -\frac{\Pi - \Pi_{\mathrm{NS}}}{\tau_\Pi} + I_\Pi$$

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

Freeze out: at 168 MeV, Cooper-Frye, equilibrium distr

Hadronic afterburner: UrQMD

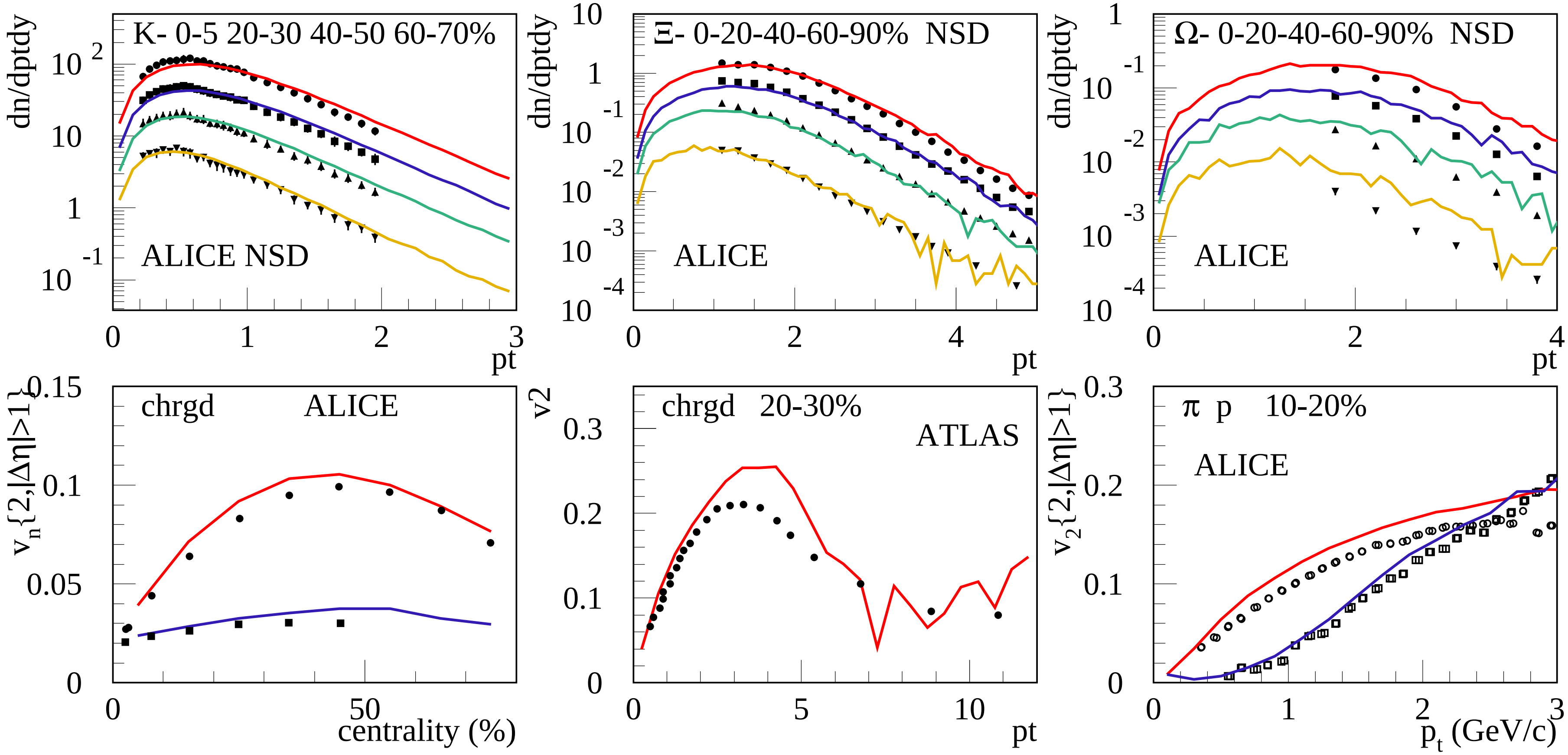
Marcus Bleicher

Jan Steinheimer : implementing new update (Ω)

Results

PbPb : VERY preliminary

(first shot, parameters good guesses, essentially optimized for pp, pPb)



Systematic study is under way...

pPb results (more results: arXiv:1312.1233)

We will compare EPOS3 with 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

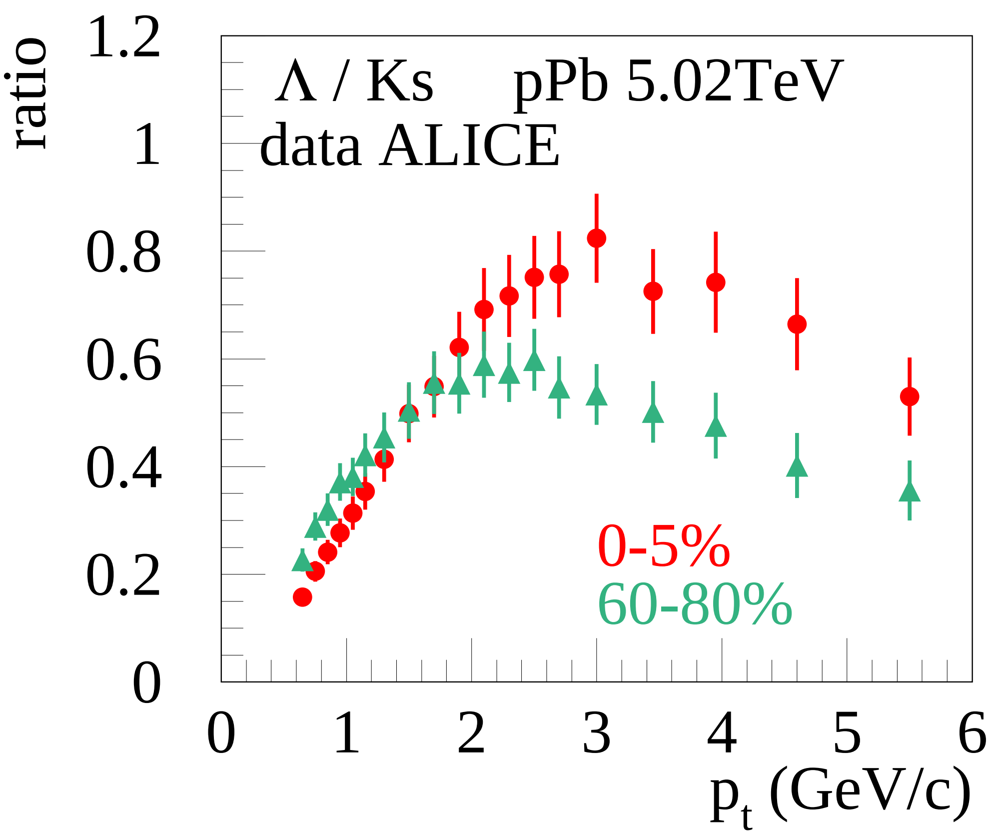
Parton + hadron cascade **-> some collectivity**
Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang and S. Pal, Phys. Rev. C 72, 064901 (2005).

QGSJET

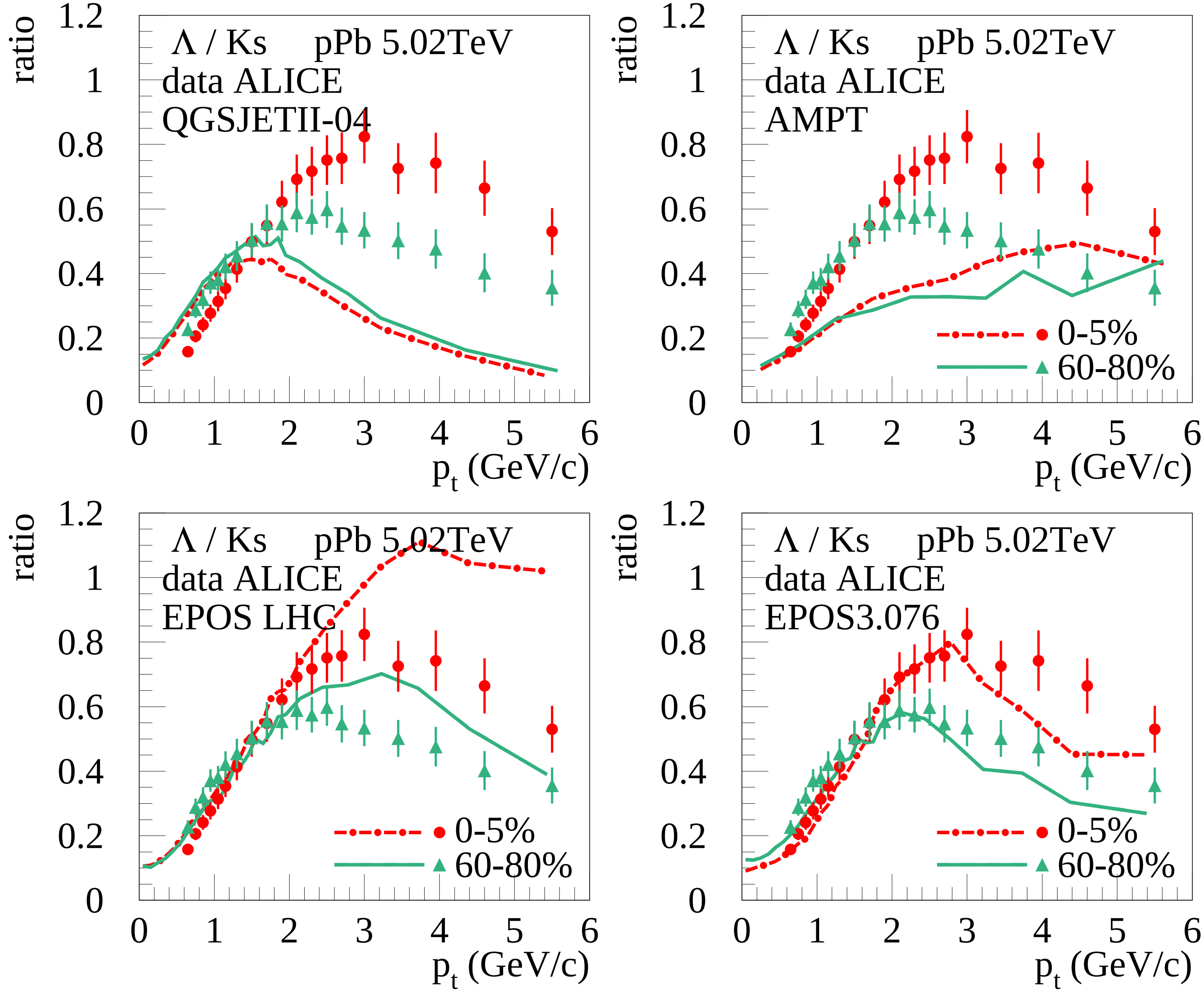
GR approach, **no flow**
S. Ostapchenko, Phys. Rev. D74 (2006) 014026

Λ/K ratios : ALICE arXiv:1307.6796

Two multiplicity classes: 0-5%, 60-80% (in $2.8 < \eta_{\rm lab} < 5.1$)

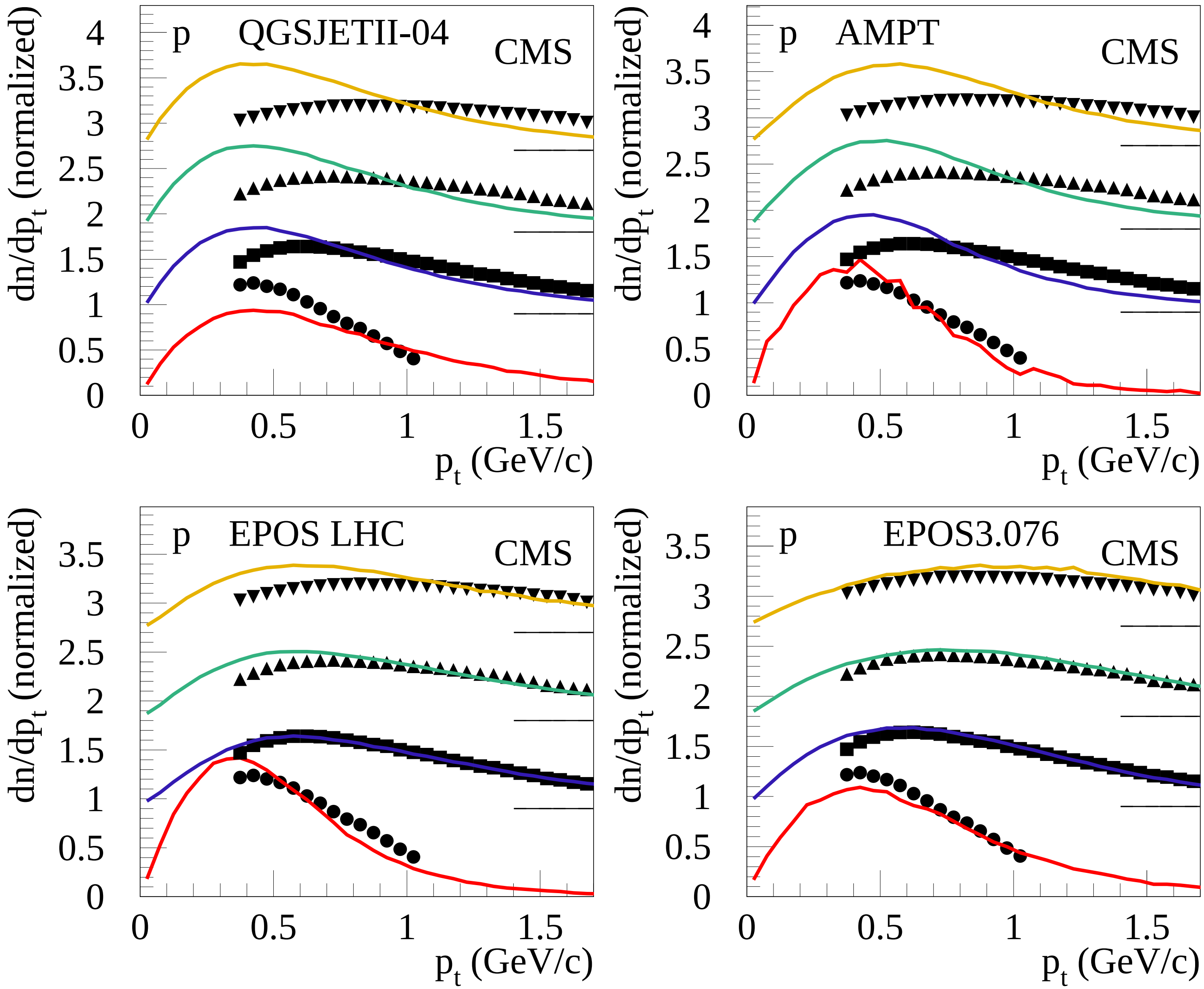


Significant variation of lambda/K – like in PbPb



Flow helps, already needed for low multiplicity (even in pp!)

CMS: Multiplicity dependence of pt spectra, protons



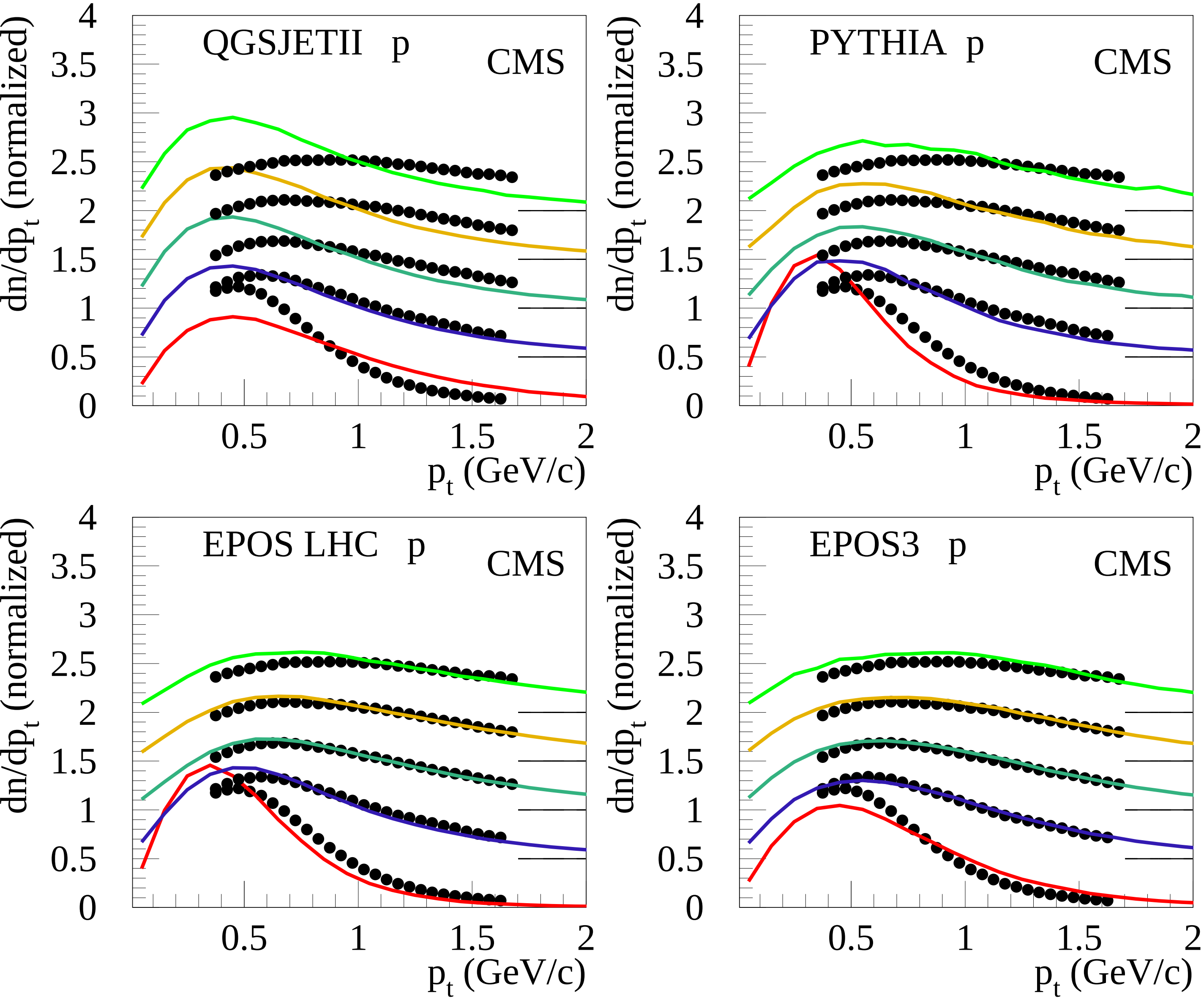
4 multiplicity classes:

<N_tracks> :

8, 84, 160, 235 (in $|\eta| < 2.4$)

Strong variation of proton spectra => flow helps

Very similar in pp at 7TeV !! (here we use PYTHIA6.4.27)



5 multiplicity classes:

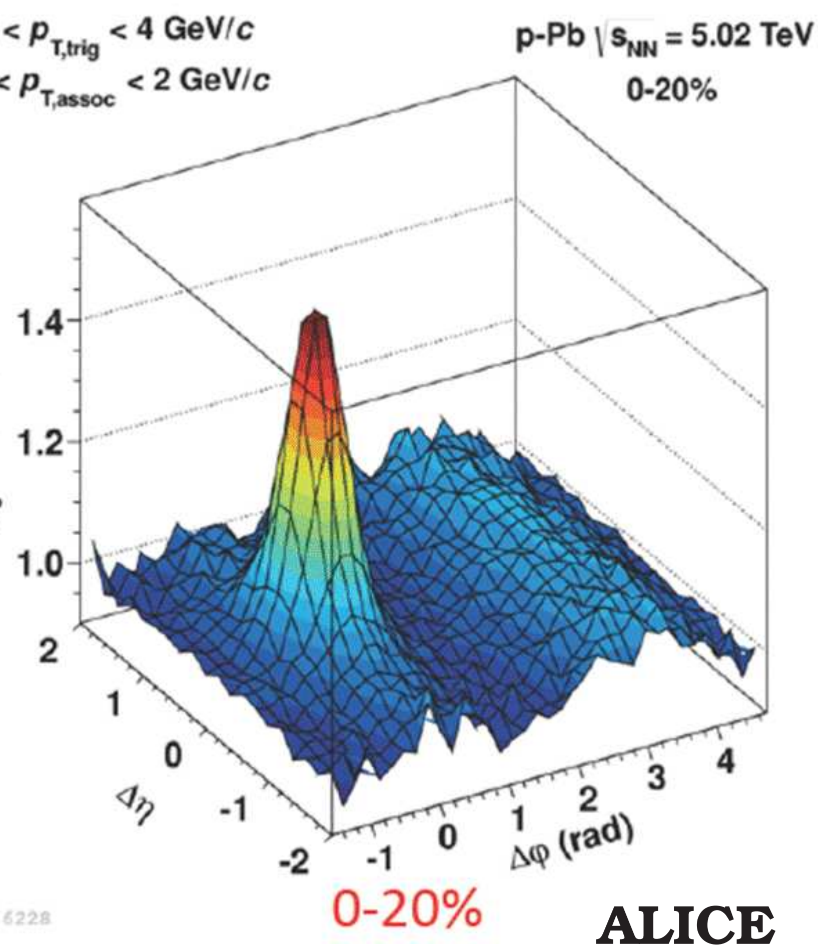
<N_tracks> :

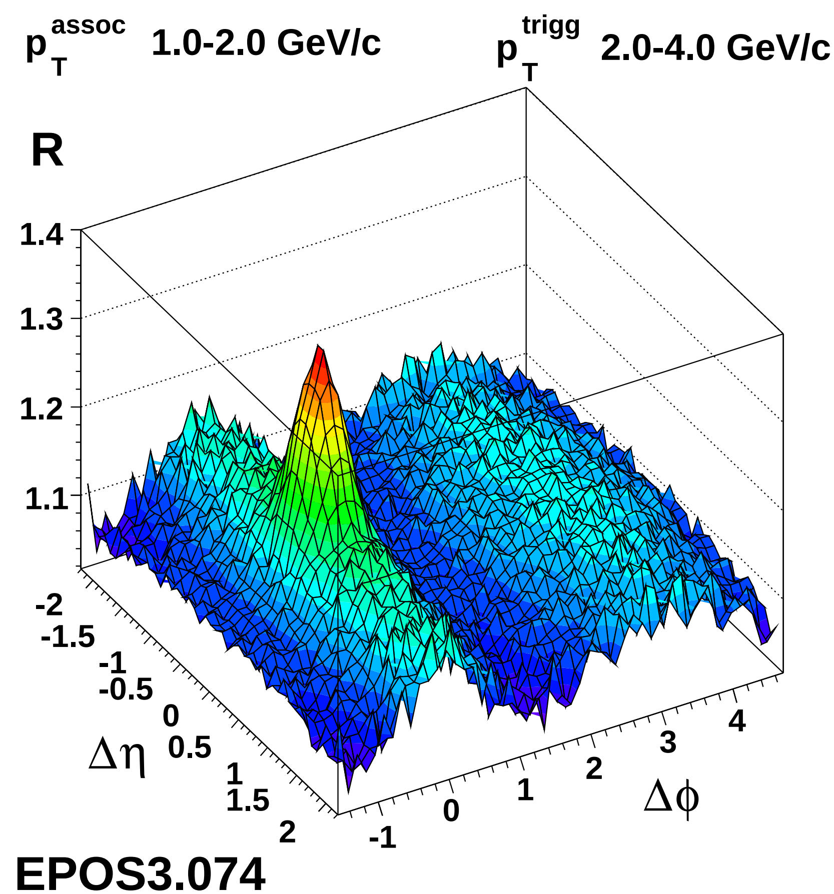
7, 40, 75, 98, and 131 (in $|\eta| < 2.4$)

Also in pp: flow helps !!

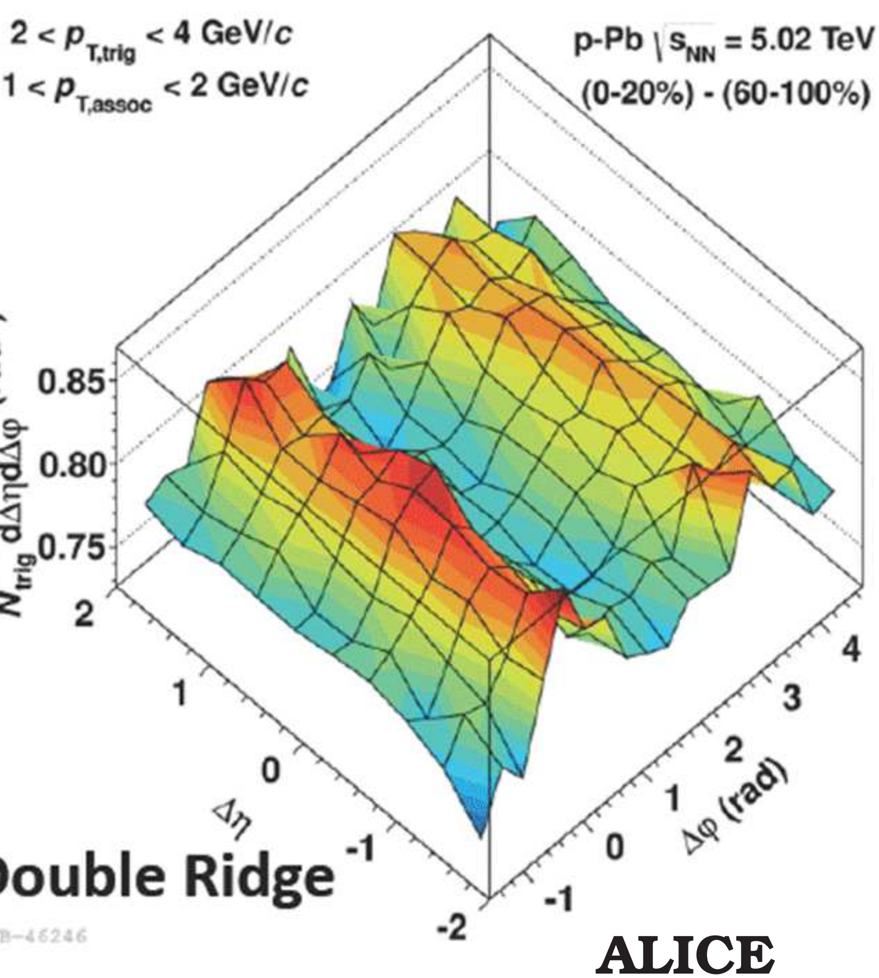
"Ridges" in pA

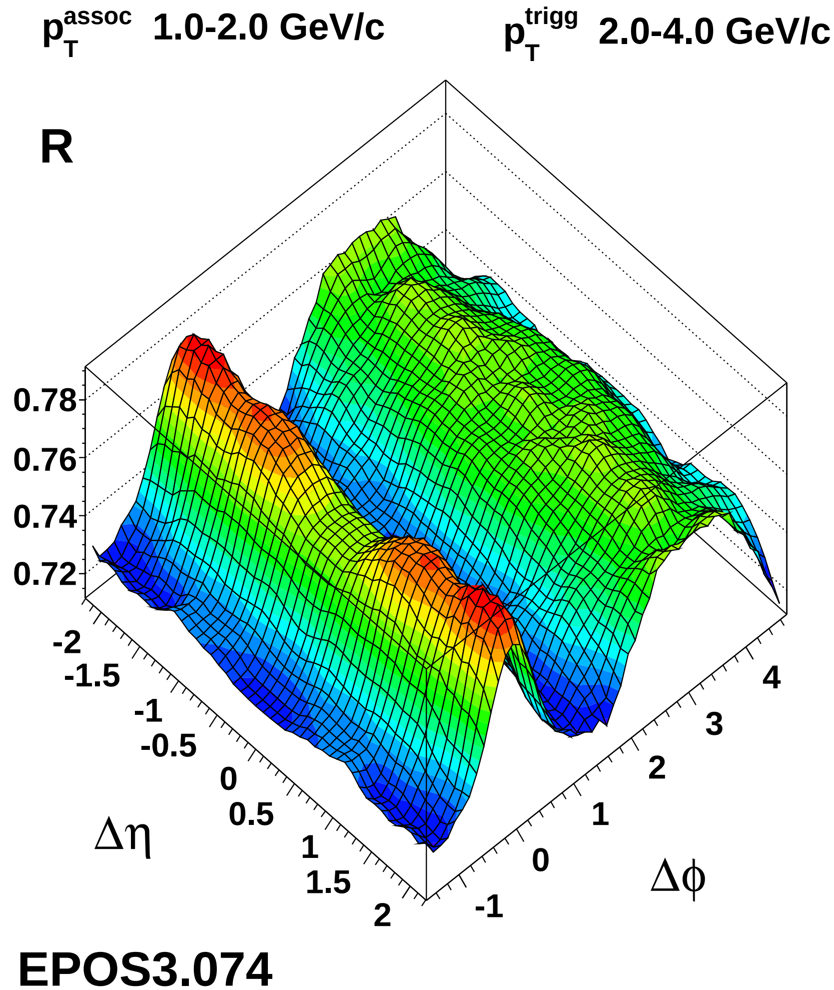
ALICE, arXiv:1212.2001, arXiv:1307.3237



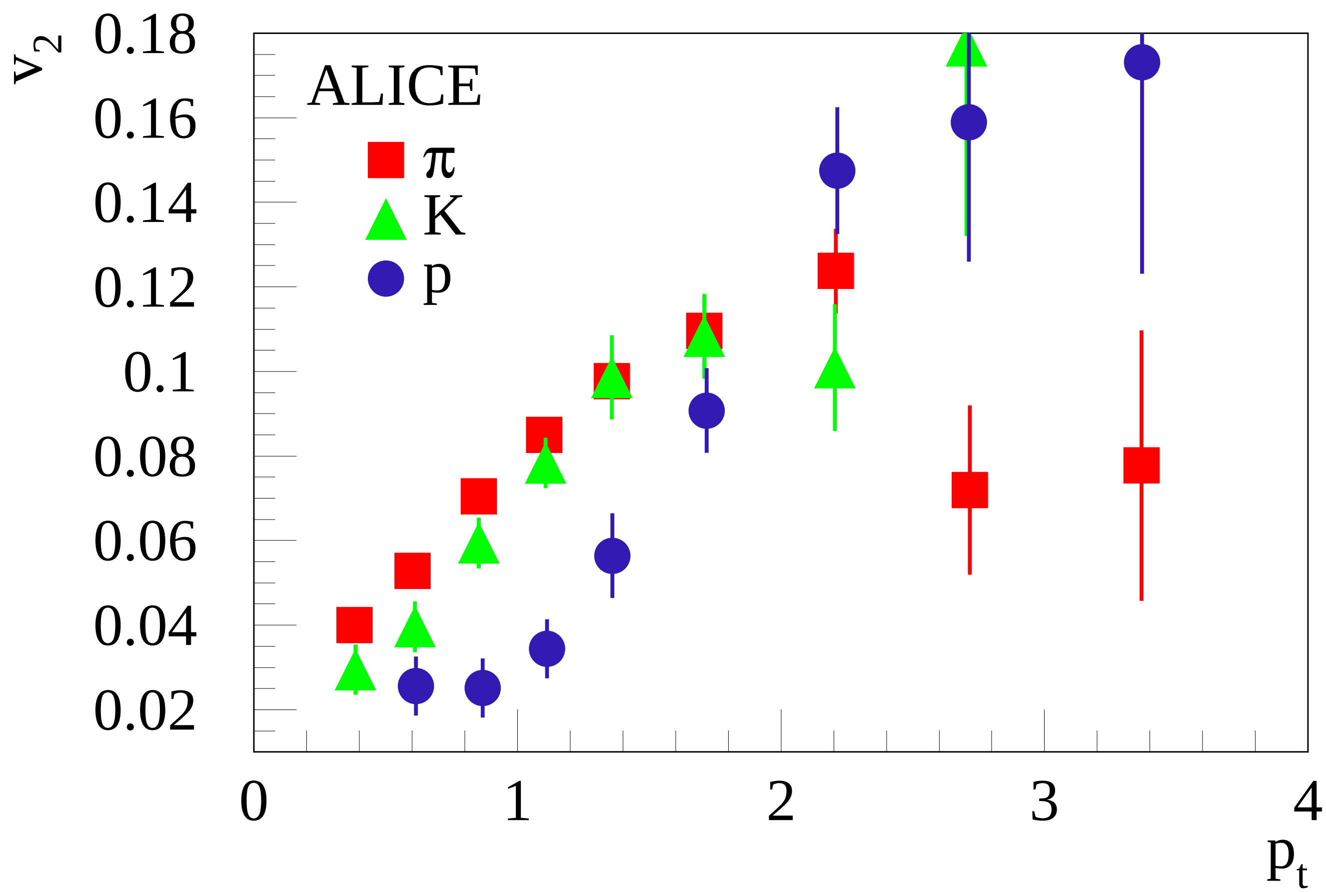


Central - peripheral (to get rid of jets)





Identified particle v2

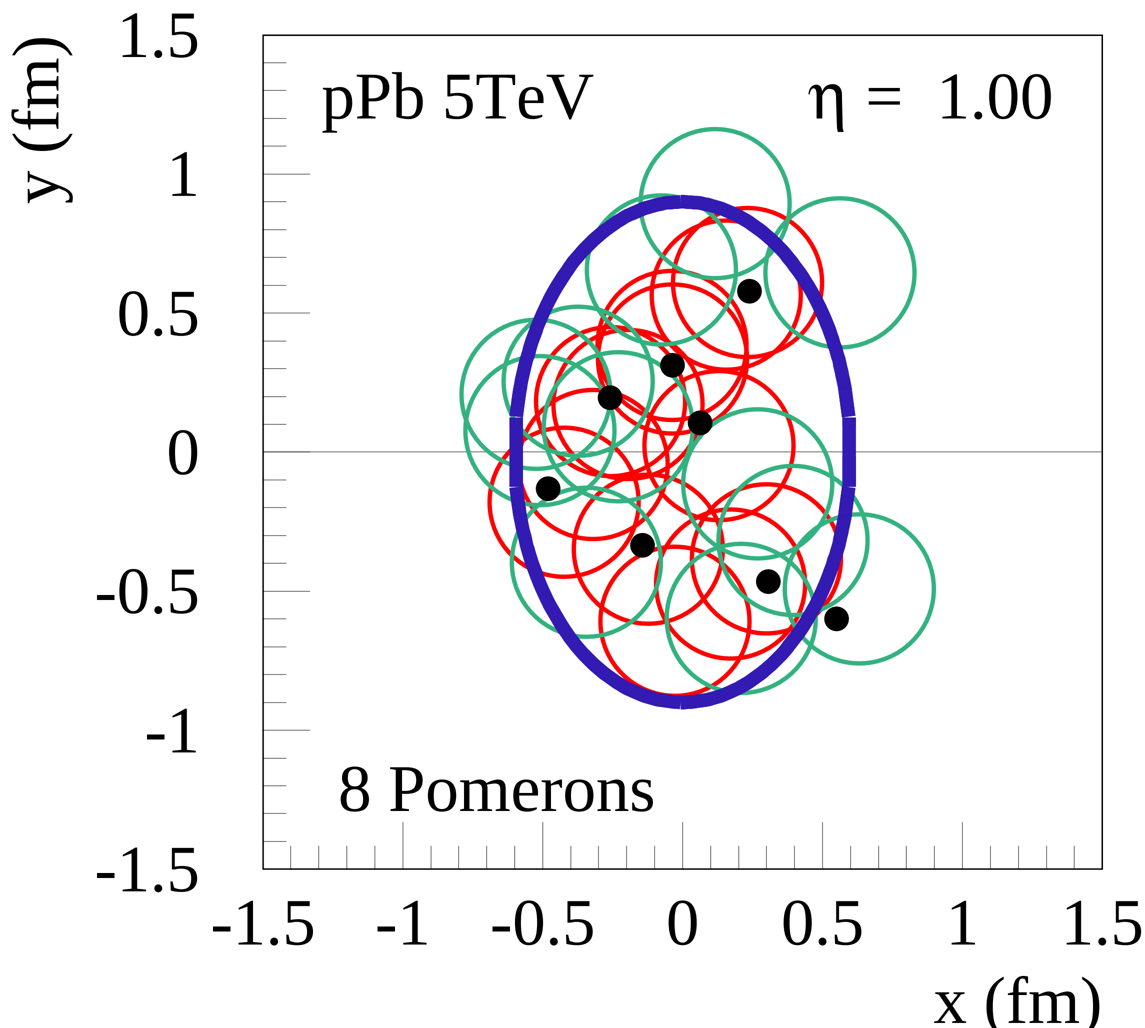


mass splitting, as in PbPb !!!

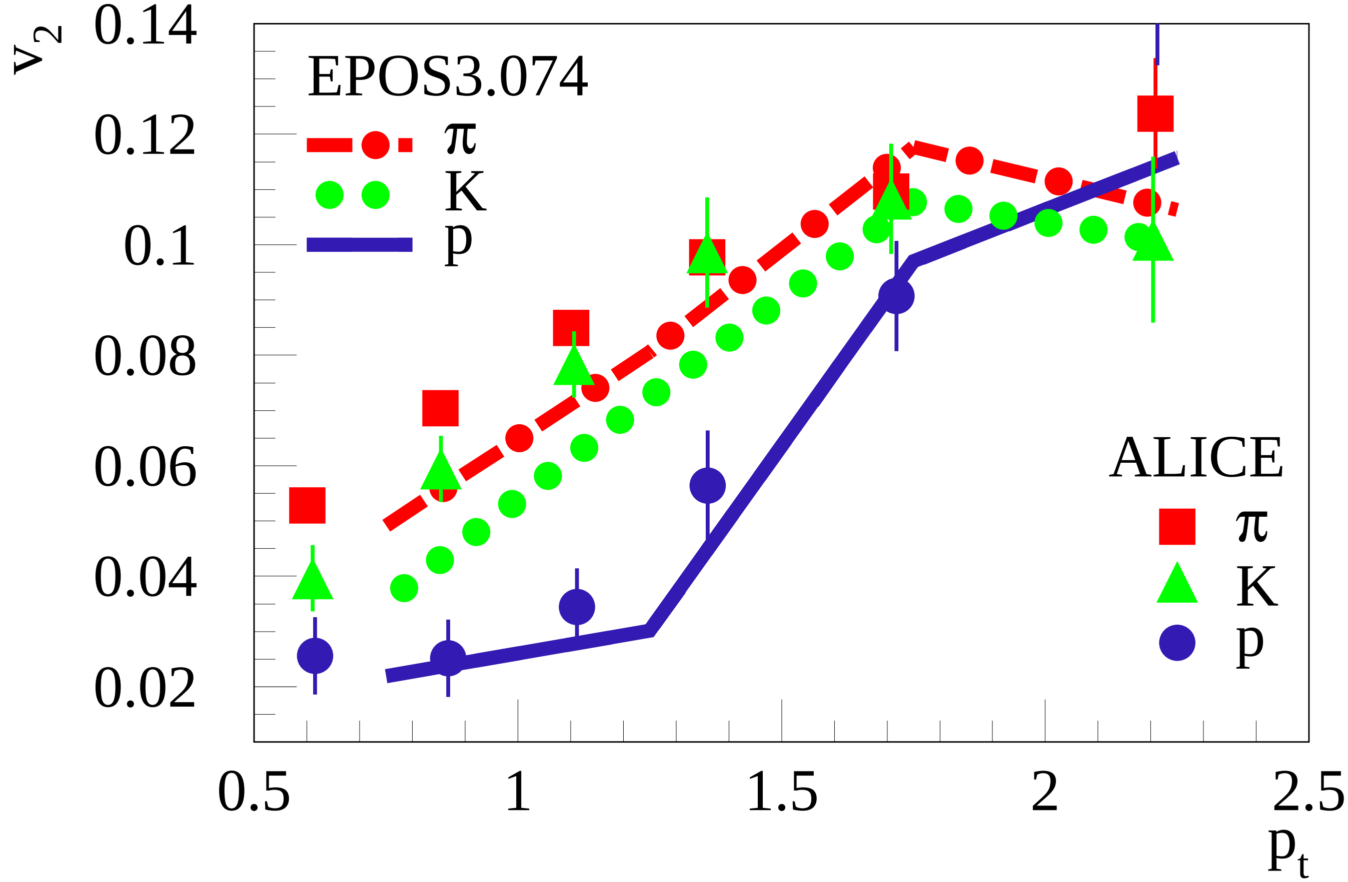
pPb in EPOS3:

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

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



v2 for π, K, p clearly differ

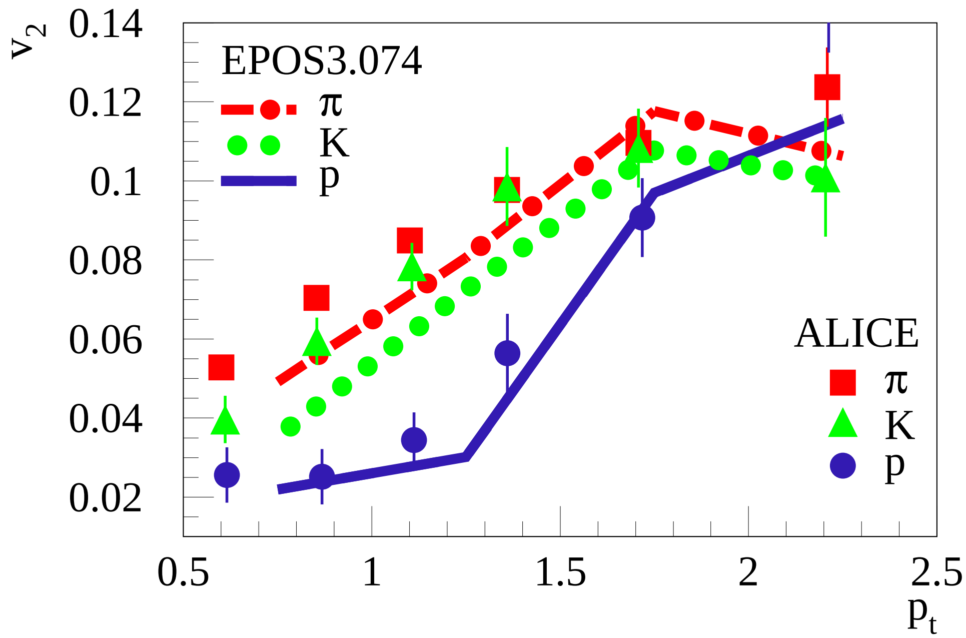


mass splitting, due to flow

Summary

AA, pA and even pp data show striking similarities which litterally ask for a "unified approach".

A realization (EPOS3) shows promising results



arXix:1307.4379

Much more about EPOS3 and model-data comparisons in pp, pPb:

arXiv:1312.1233