

# **A unified description of the reaction dynamics from pp to pA to AA collisions**

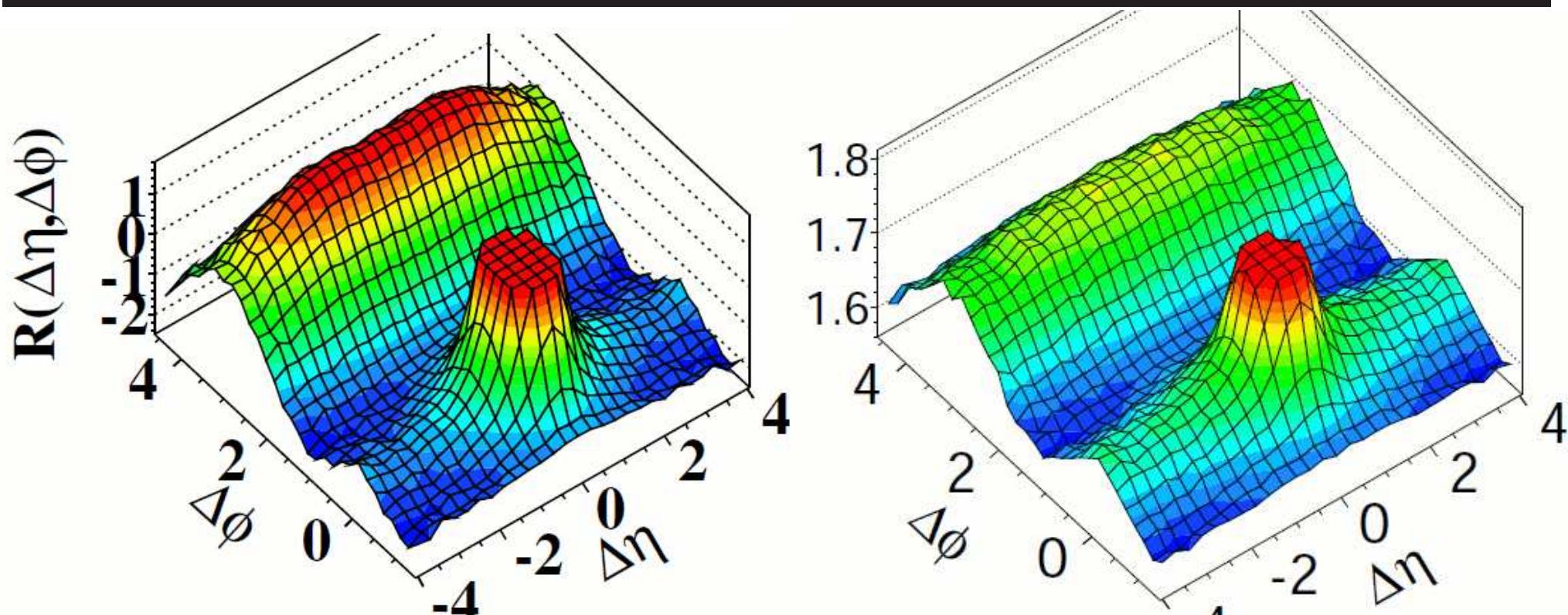
K.W. in collaboration with  
B. Guiot, Iu. Karpenko, T. Pierog

## **Before 2010 (generally accepted prejudices):**

- pp is elementary, conventional physics**  
(but not understood, complicated, not interesting)
- pA still “baseline”, but with “nuclear effects”**
- in AA we see NEW PHYSICS (QGP, flow, ...)**

**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)

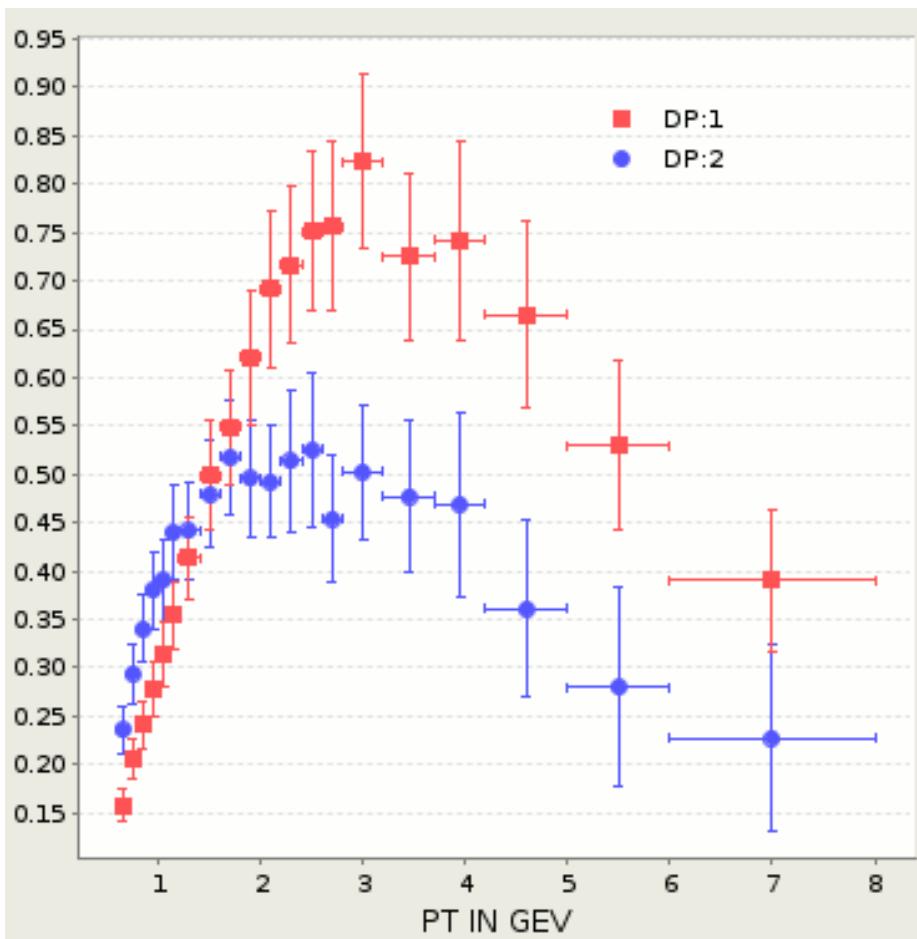


CMS (2010) arXiv:1009.4122  
JHEP 1009:091, 2010

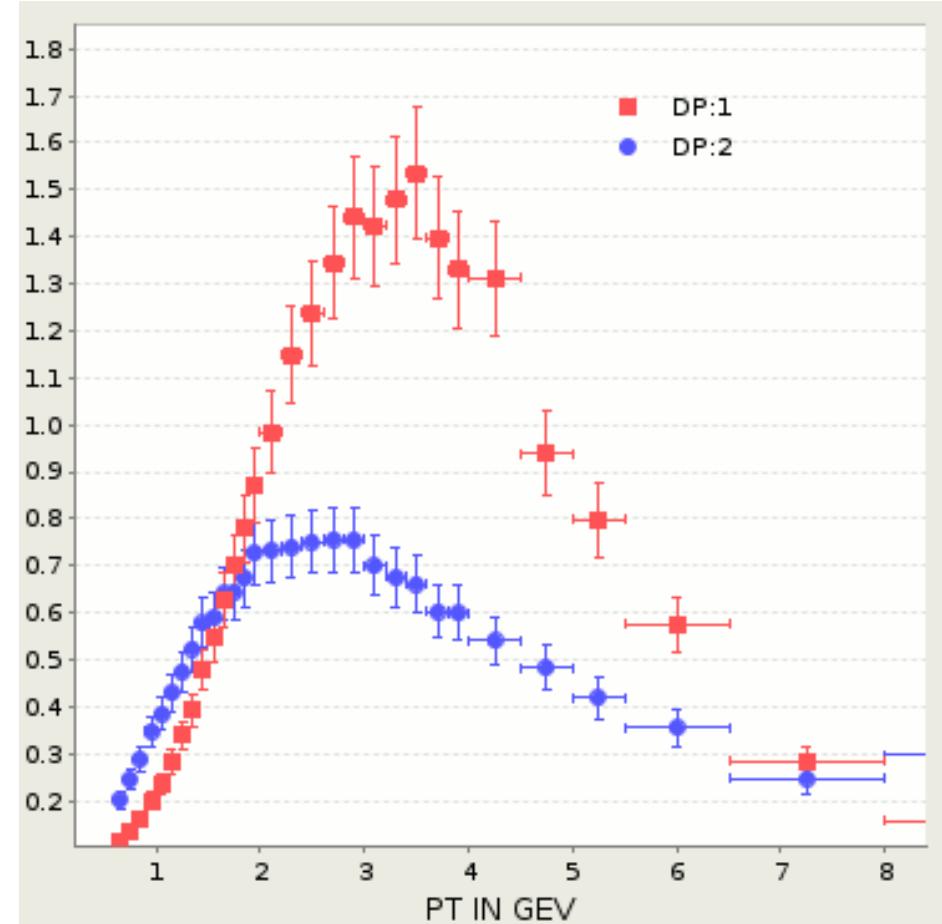
CMS (2012) arXiv:1210.5482  
Phys. Lett. B 718 (2013) 795

In AA: due to initial anisotropies + flow

## $\Lambda/K_s$ versus pT (high compared to low multiplicity) in pPb (left) similar to PbPb (right)



ALICE (2013) arXiv:1307.6796

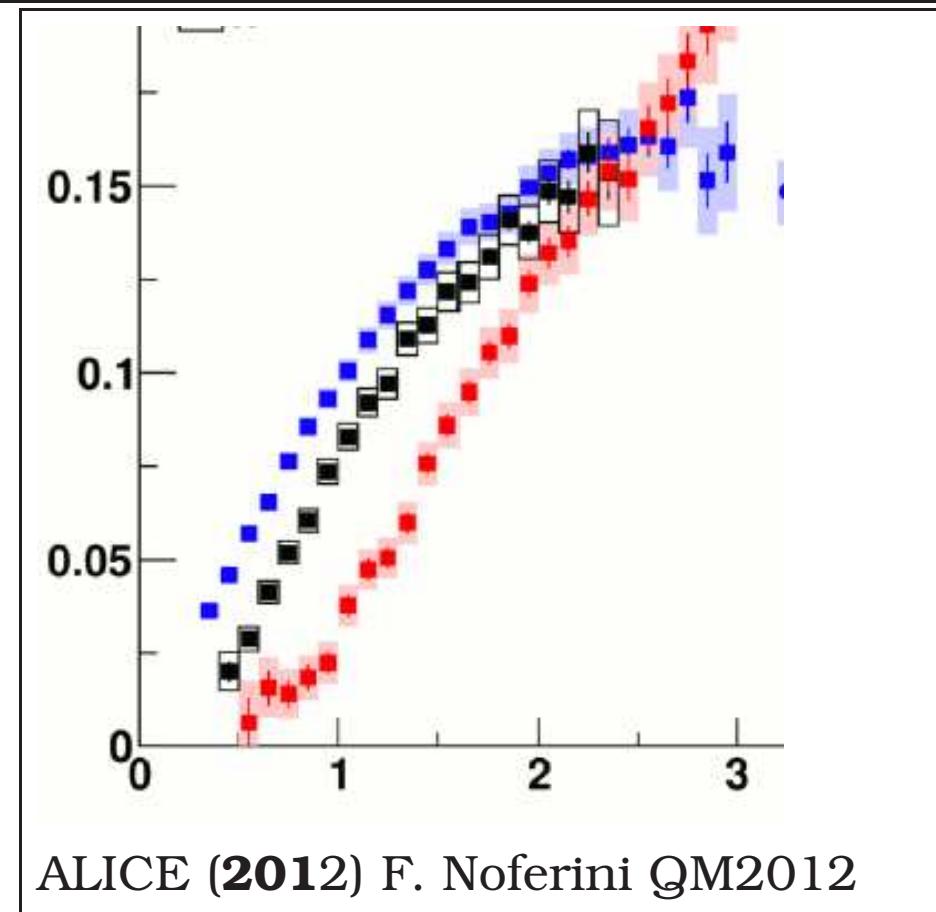
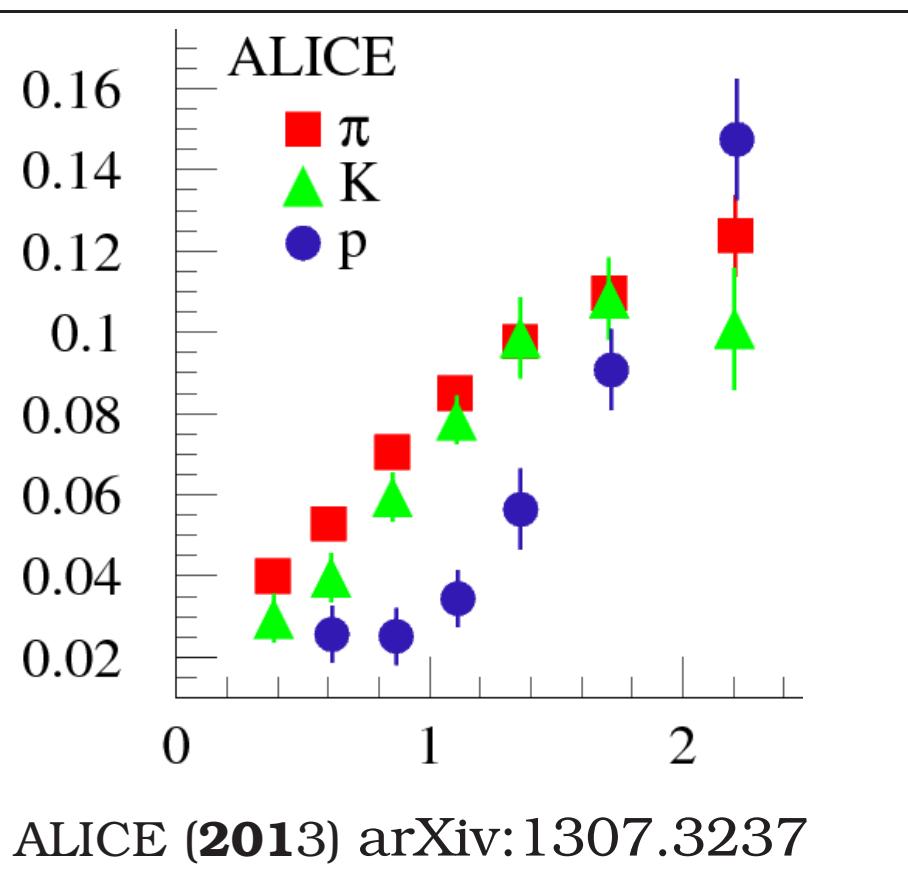


ALICE (2013) arXiv:1307.5530

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

In AA: partially due to flow

## v2 versus pT: mass splitting ( $\pi$ , $K$ , $p$ ) in pPb (left) similar to PbPb (right)



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

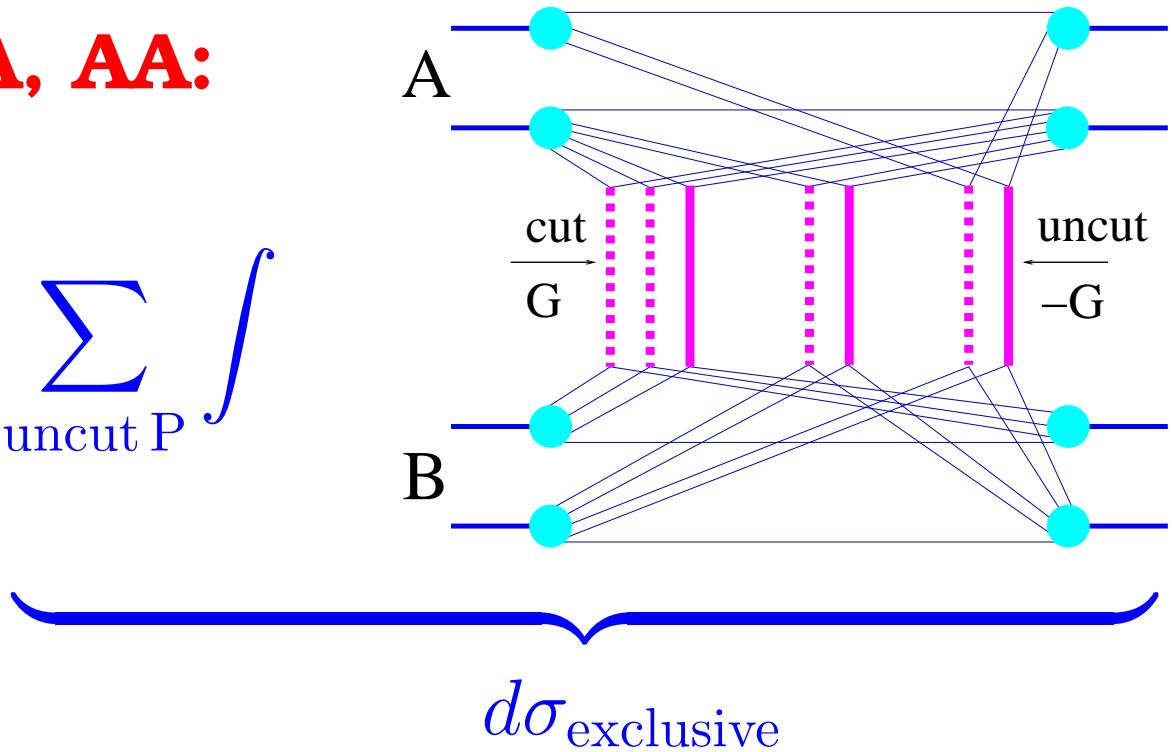
Realization: EPOS3, [arXiv:1312.1233](https://arxiv.org/abs/1312.1233) , arXiv:1307.4379,  
B. Guiot, Y. Karpenko, T. Pierog, M. Bleicher, K. W.

## Initial conditions: Marriage pQCD+GRT+energy sharing

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

**For pp, pA, AA:**

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



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

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

$$\begin{aligned}
\sigma^{\text{tot}} = & \int d^2 b \int \prod_{i=1}^A d^2 b_i^A dz_i^A \rho_A(\sqrt{(b_i^A)^2 + (z_i^A)^2}) \\
& \prod_{j=1}^B d^2 b_j^B dz_j^B \rho_B(\sqrt{(b_j^B)^2 + (z_j^B)^2}) \\
& \sum_{m_1 l_1} \dots \sum_{m_{AB} l_{AB}} (1 - \delta_{0\Sigma m_k}) \int \prod_{k=1}^{AB} \left( \prod_{\mu=1}^{m_k} dx_{k,\mu}^+ dx_{k,\mu}^- \prod_{\lambda=1}^{l_k} d\tilde{x}_{k,\lambda}^+ d\tilde{x}_{k,\lambda}^- \right) \Bigg\{ \\
& \prod_{k=1}^{AB} \left( \frac{1}{m_k!} \frac{1}{l_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, |\vec{b} + \vec{b}_{\pi(k)}^A - \vec{b}_{\tau(k)}^B|) \right. \\
& \quad \left. \prod_{\lambda=1}^{l_k} -G(\tilde{x}_{k,\lambda}^+, \tilde{x}_{k,\lambda}^-, s, |\vec{b} + \vec{b}_{\pi(k)}^A - \vec{b}_{\tau(k)}^B|) \right) \\
& \prod_{i=1}^A \left( 1 - \sum_{\pi(k)=i} x_{k,\mu}^+ - \sum_{\pi(k)=i} \tilde{x}_{k,\lambda}^+ \right)^\alpha \prod_{j=1}^B \left( 1 - \sum_{\tau(k)=j} x_{k,\mu}^- - \sum_{\tau(k)=j} \tilde{x}_{k,\lambda}^- \right)^\alpha \Bigg\}
\end{aligned}$$

## Historical remark : in 2000

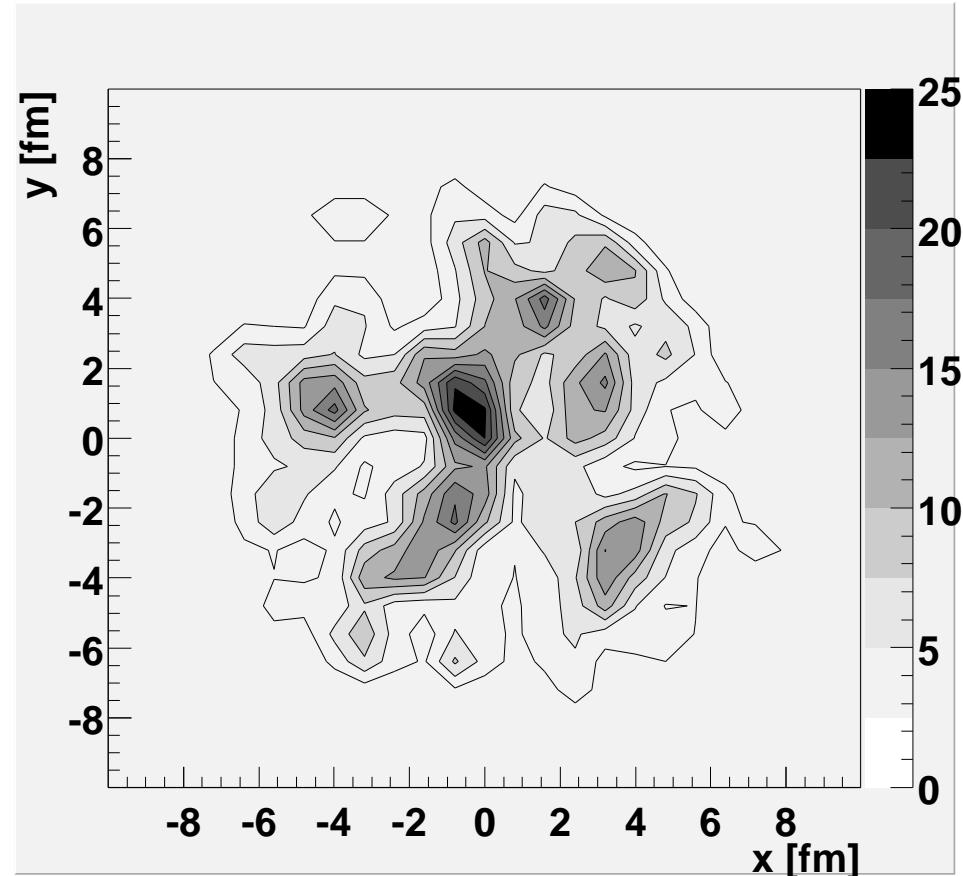
Publication  
based on this GR approach:

### **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

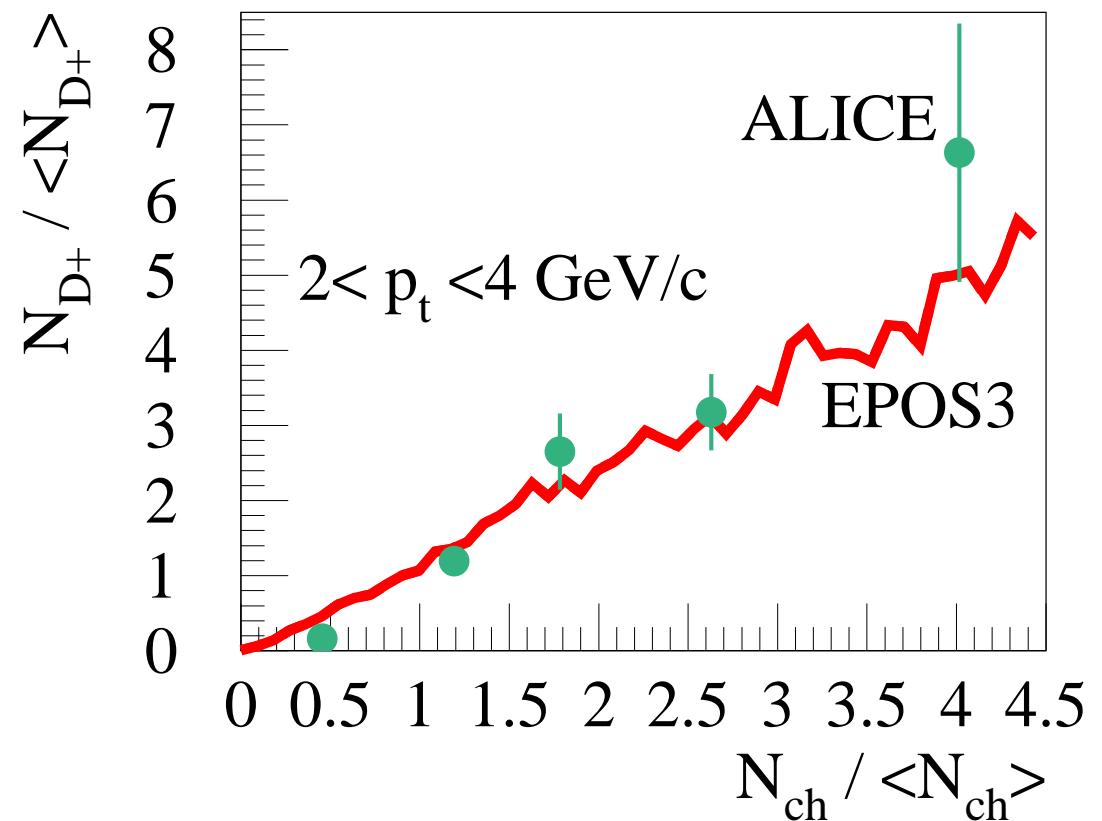
**GR multiple scattering gives (automatically)**

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

$N_{\text{hard}}$  stands for multiplicity of “hard” particle production.

**Example:  $D^+$  mesons**

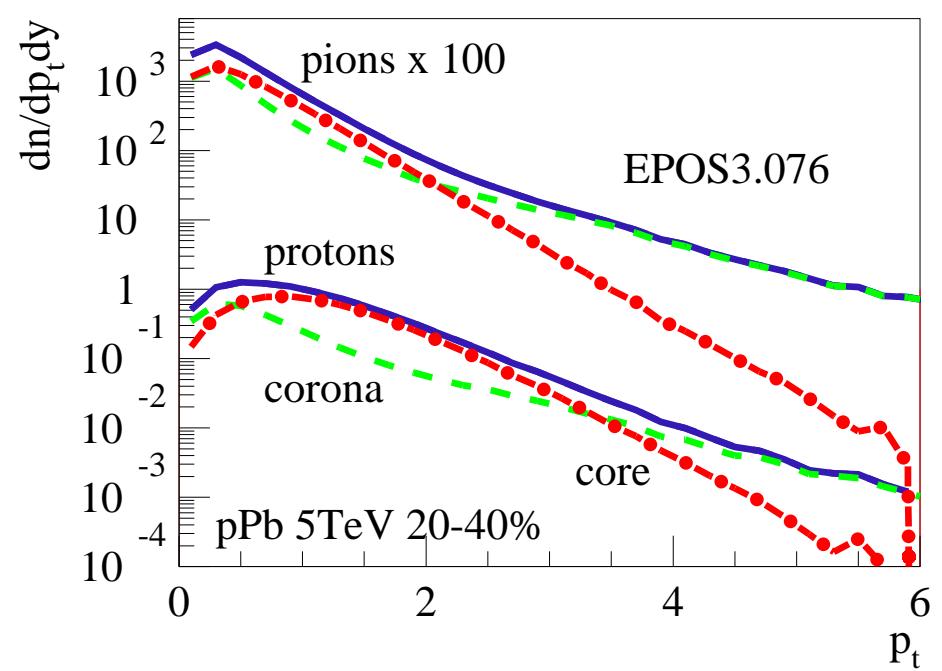
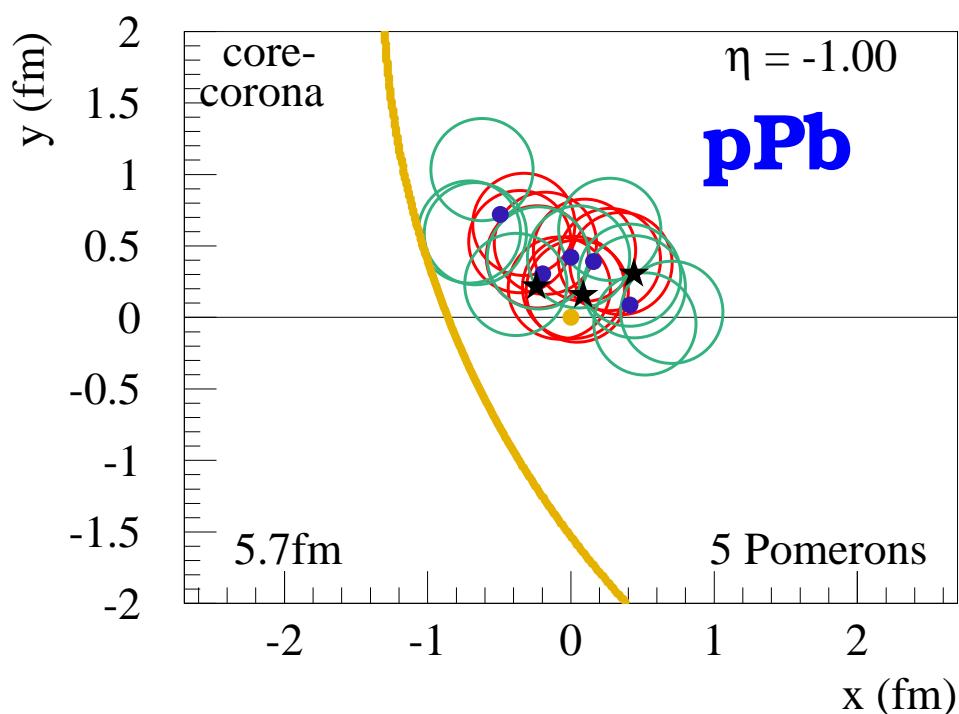
Plot from B. Guiot



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

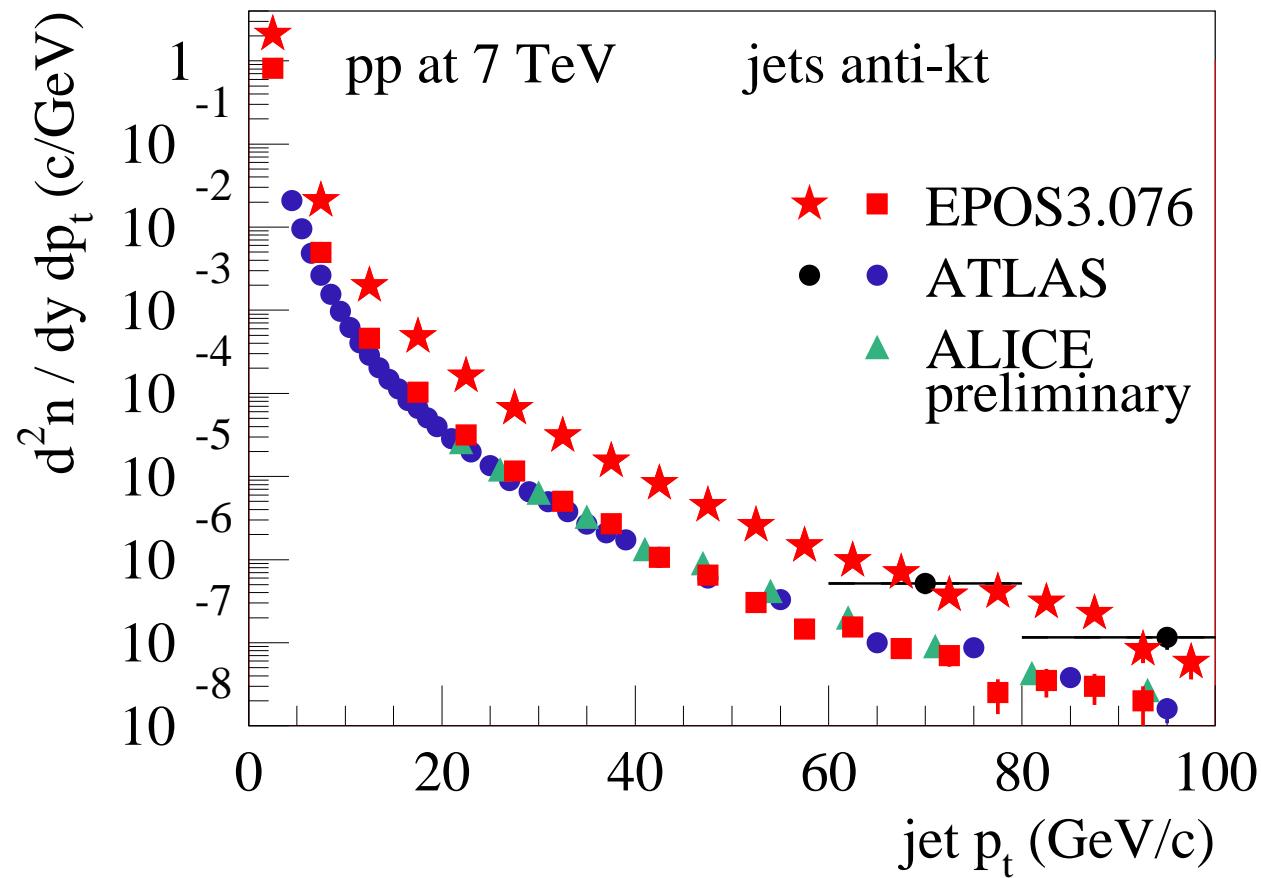
Pomeron => parton ladder => flux tube (kinky string)

String segments with high  $p_T$  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,  $\eta/S = 0.08$ ,  $\zeta/S = 0$

$$\partial_{;\nu} T^{\mu\nu} = \partial_\nu T^{\mu\nu} + \Gamma_{\nu\lambda}^\mu T^{\nu\lambda} + \Gamma_{\nu\lambda}^\nu T^{\mu\lambda} = 0$$

$$\gamma (\partial_t + v_i \partial_i) \pi^{\mu\nu} = -\frac{\pi^{\mu\nu} - \pi_{\text{NS}}^{\mu\nu}}{\tau_\pi} + I_\pi^{\mu\nu} \quad \gamma (\partial_t + v_i \partial_i) \Pi = -\frac{\Pi - \Pi_{\text{NS}}}{\tau_\Pi} + I_\Pi$$

- |  |   |
|--|---|
| <input type="checkbox"/> $T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi) \Delta^{\mu\nu} + \pi^{\mu\nu}$ ,      | <input type="checkbox"/> $\pi_{\text{NS}}^{\mu\nu} = \eta (\Delta^{\mu\lambda} \partial_{;\lambda} u^\nu + \Delta^{\nu\lambda} \partial_{;\lambda} u^\mu) - \frac{2}{3} \eta \Delta^{\mu\nu} \partial_{;\lambda} u^\lambda$ |
| <input type="checkbox"/> $\partial_{;\nu}$ denotes a covariant derivative,                                     | <input type="checkbox"/> $\Pi_{\text{NS}} = -\zeta \partial_{;\lambda} u^\lambda$   |
| <input type="checkbox"/> $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$ is the projector orthogonal to $u^\mu$ , | <input type="checkbox"/> $I_\pi^{\mu\nu} = -\frac{4}{3} \pi^{\mu\nu} \partial_{;\gamma} u^\gamma - [u^\nu \pi^{\mu\beta} + u^\mu \pi^{\nu\beta}] u^\lambda \partial_{;\lambda} u_\beta$                                     |
| <input type="checkbox"/> $\pi^{\mu\nu}$ , $\Pi$ shear stress tensor, bulk pressure                             | <input type="checkbox"/> $I_\Pi = -\frac{4}{3} \Pi \partial_{;\gamma} u^\gamma$   |

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

**Hadronic afterburner: UrQMD**

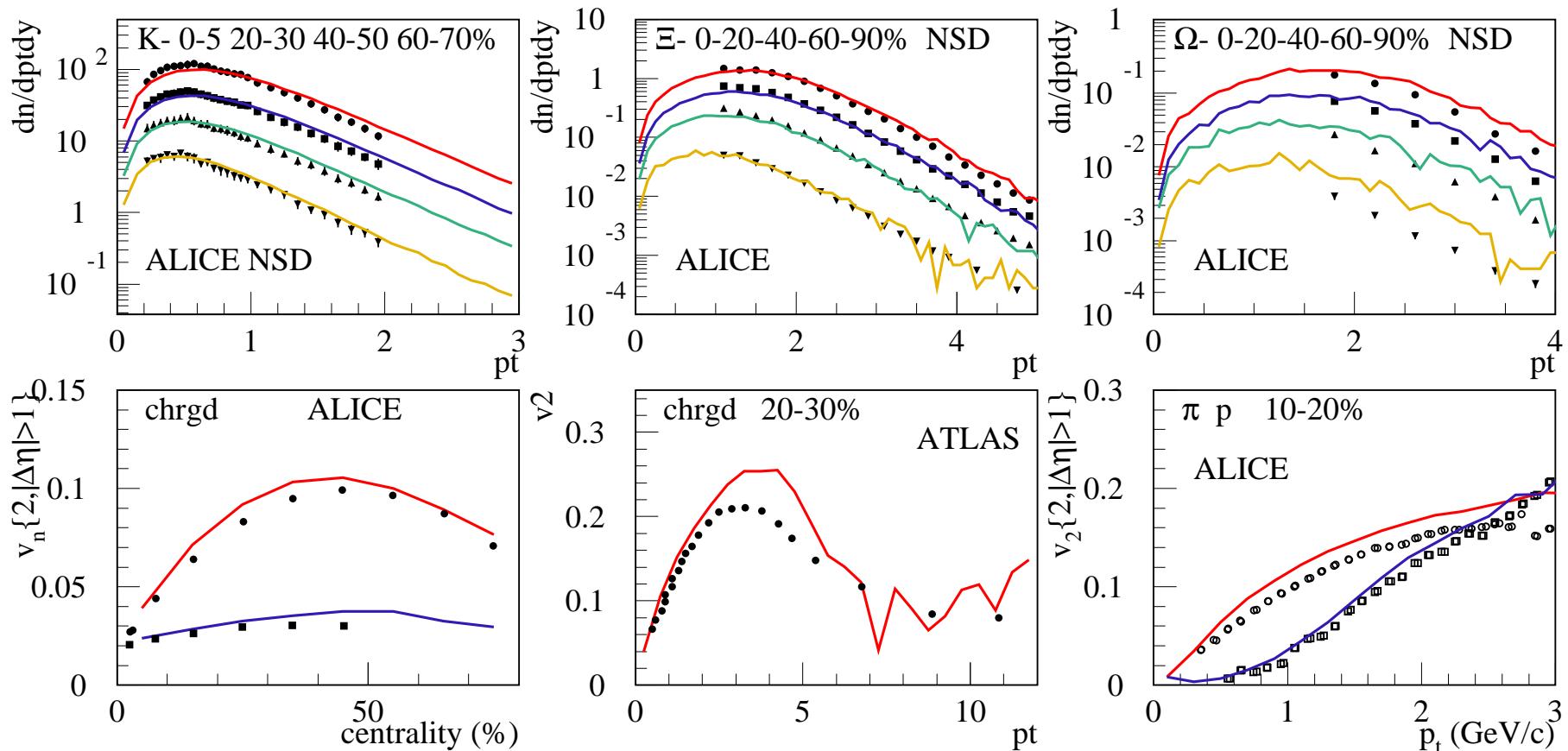
Marcus Bleicher

Jan Steinheimer : implementing new update ( $\Omega$ )

# 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).

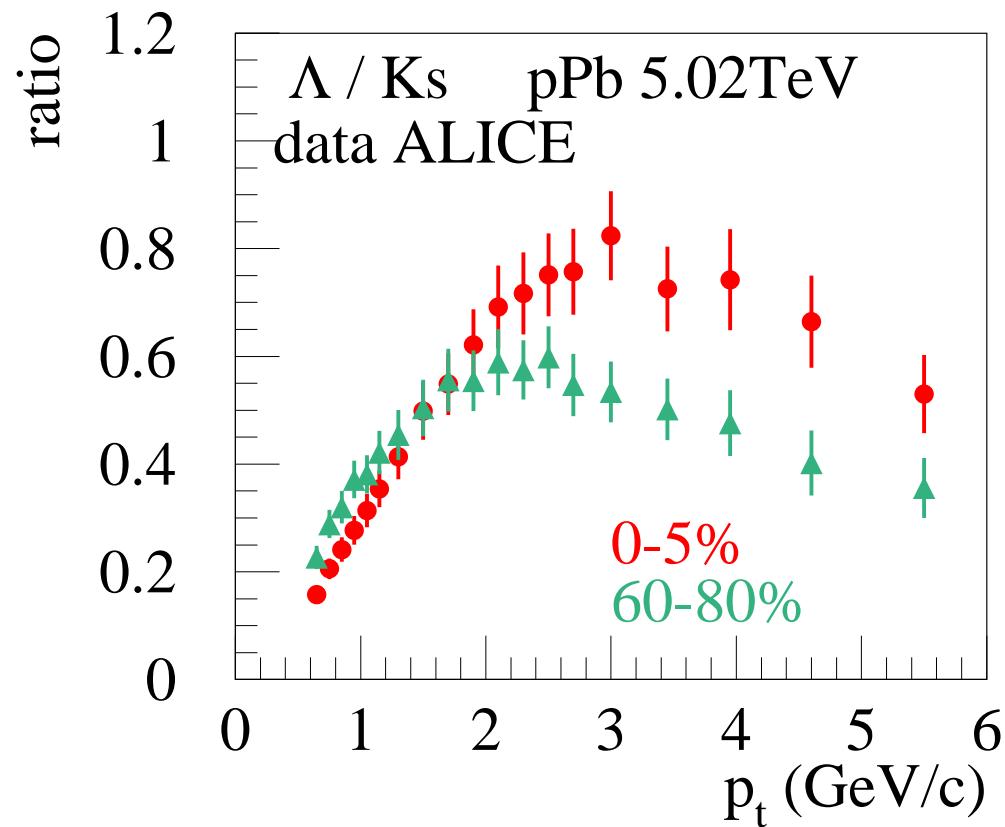
### **QGSJET**

GR approach, **no flow**

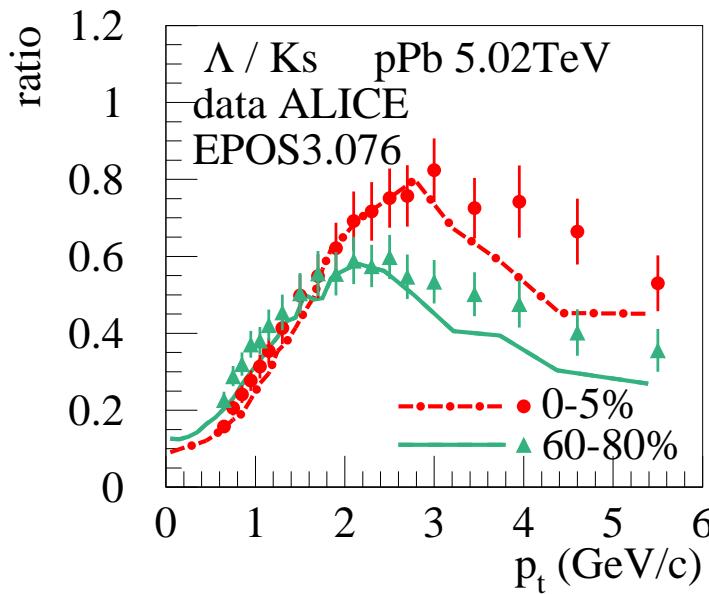
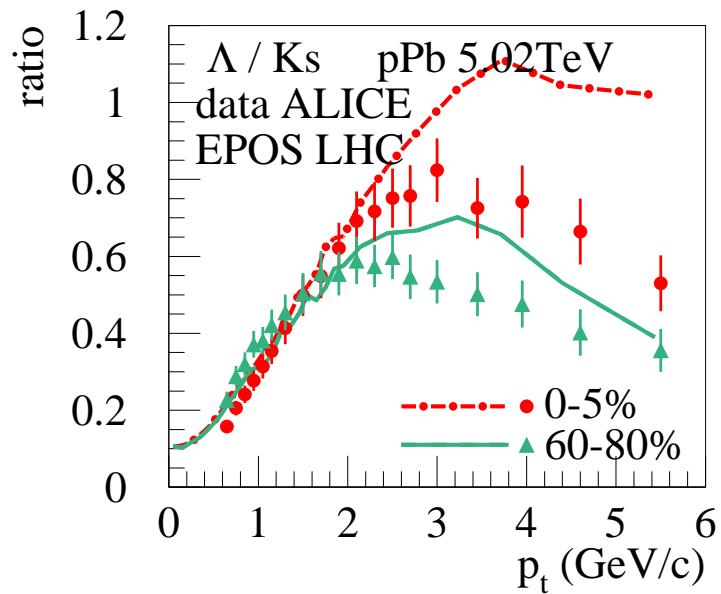
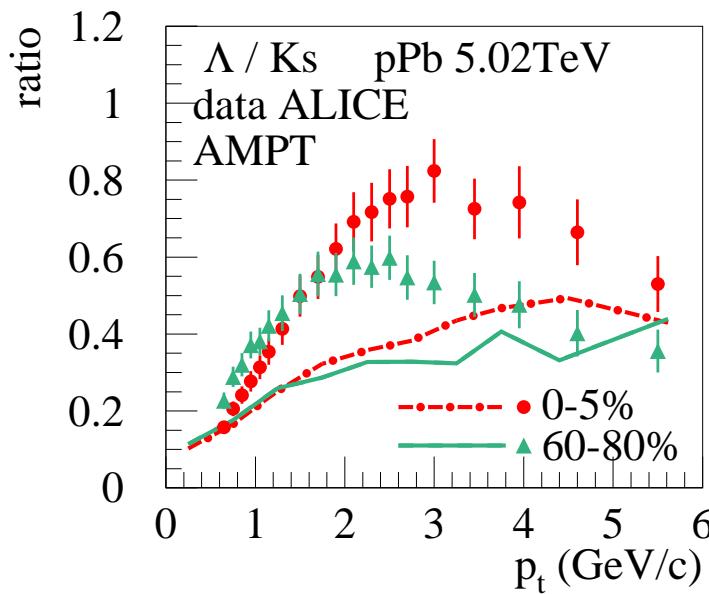
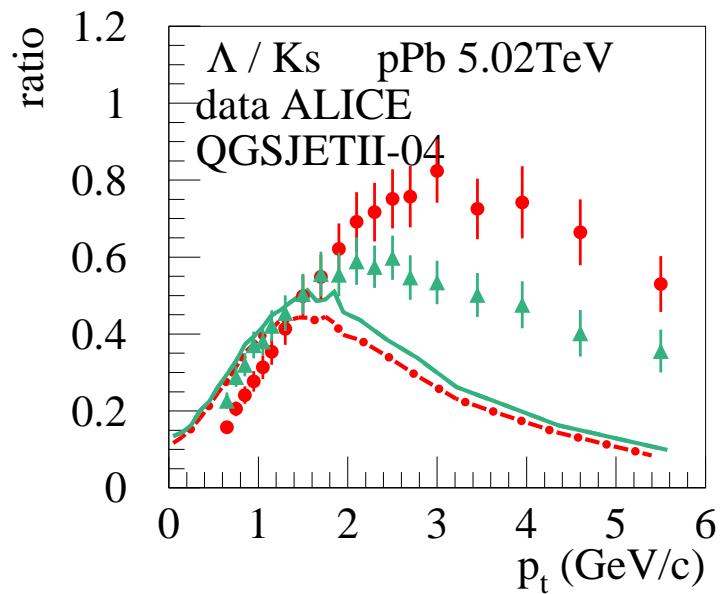
S. Ostapchenko, Phys. Rev. D74 (2006) 014026

**$\Lambda/K$  ratios : ALICE** arXiv:1307.6796

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

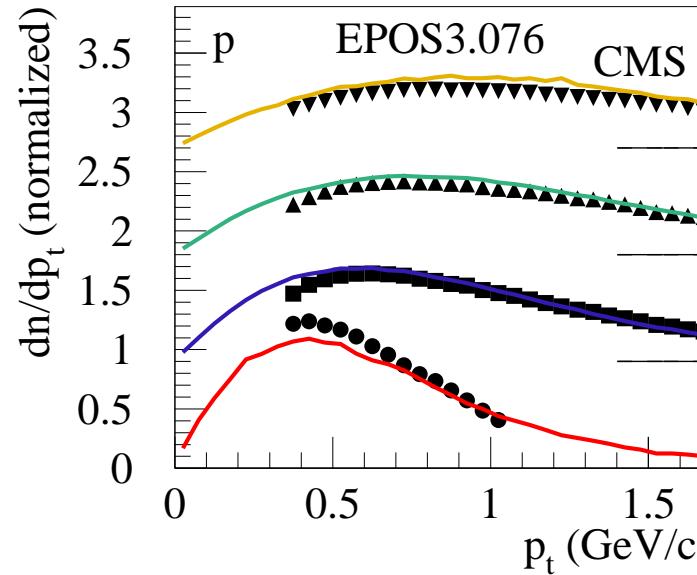
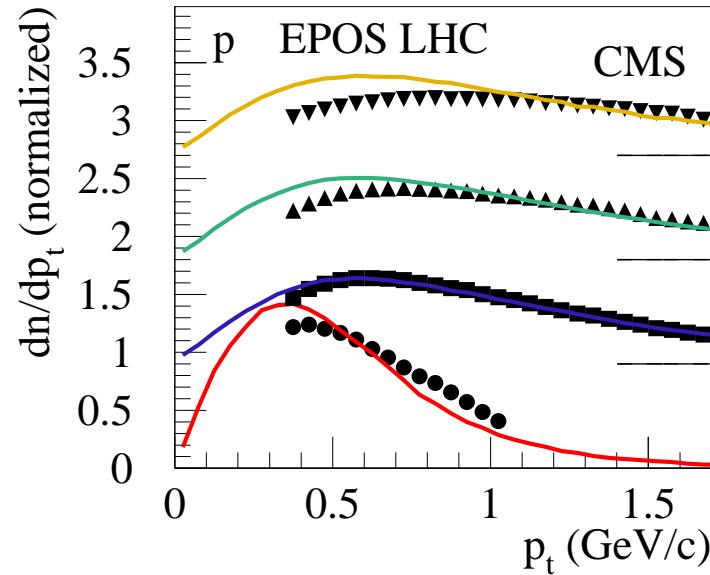
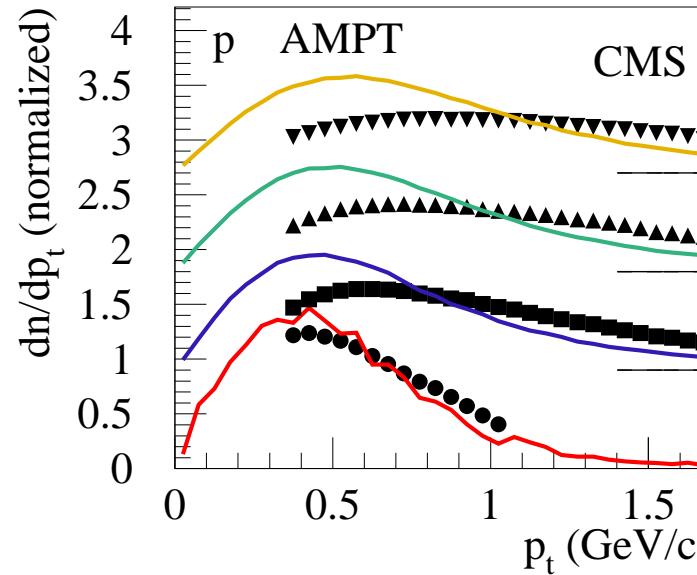
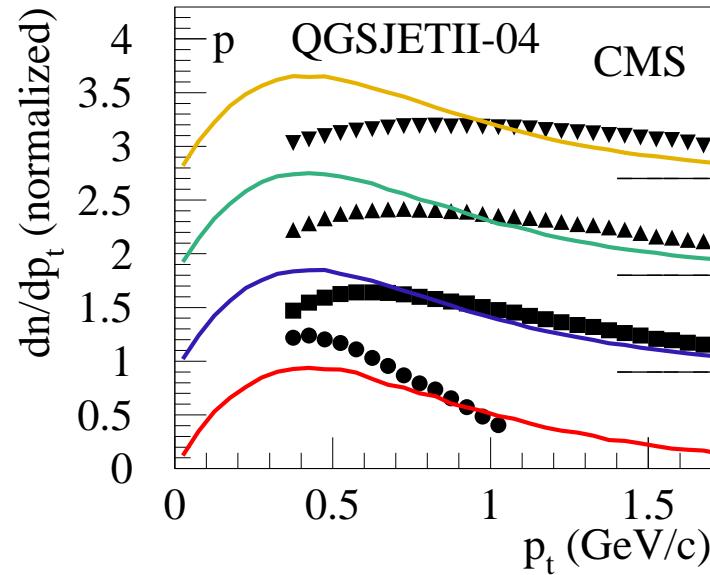


**Significant variation of lambda/K – like in PbPb**



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

## CMS: Multiplicity dependence of pt spectra, protons

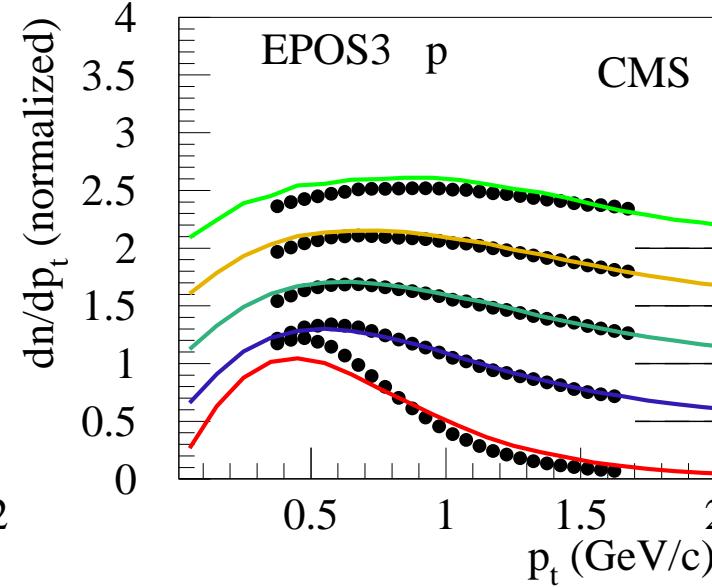
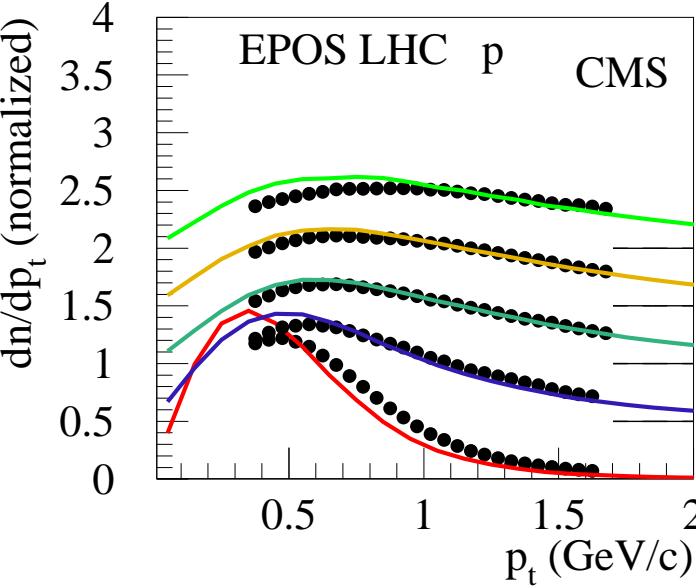
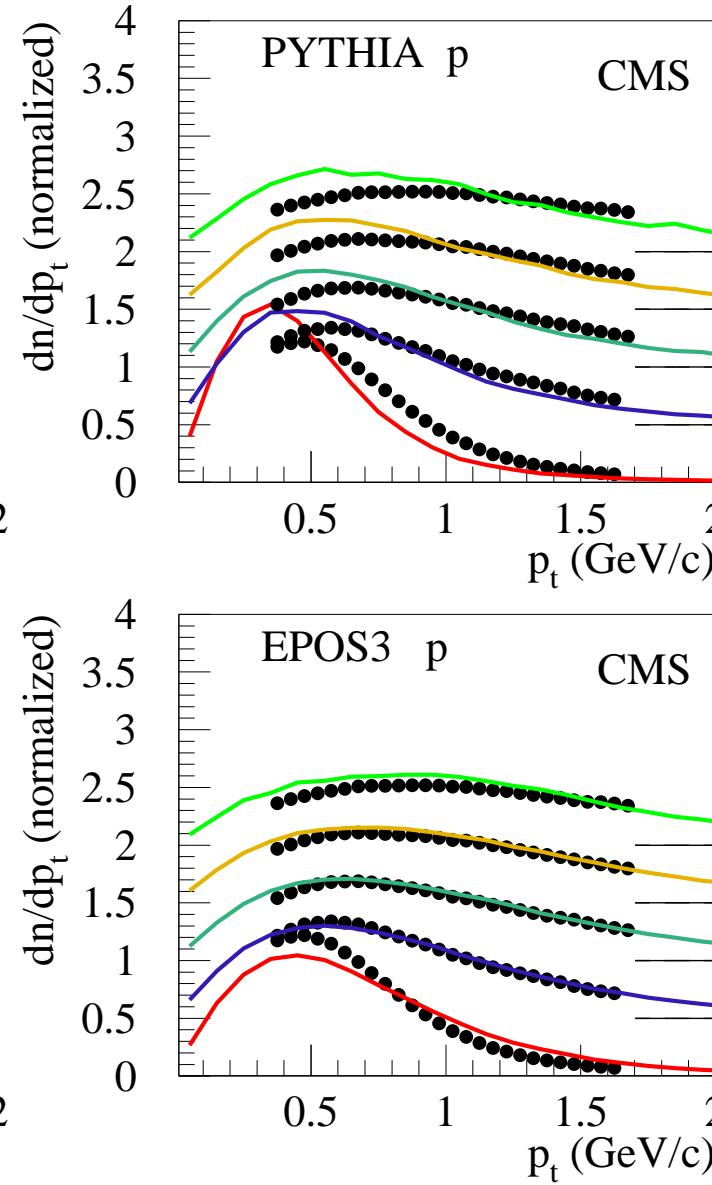
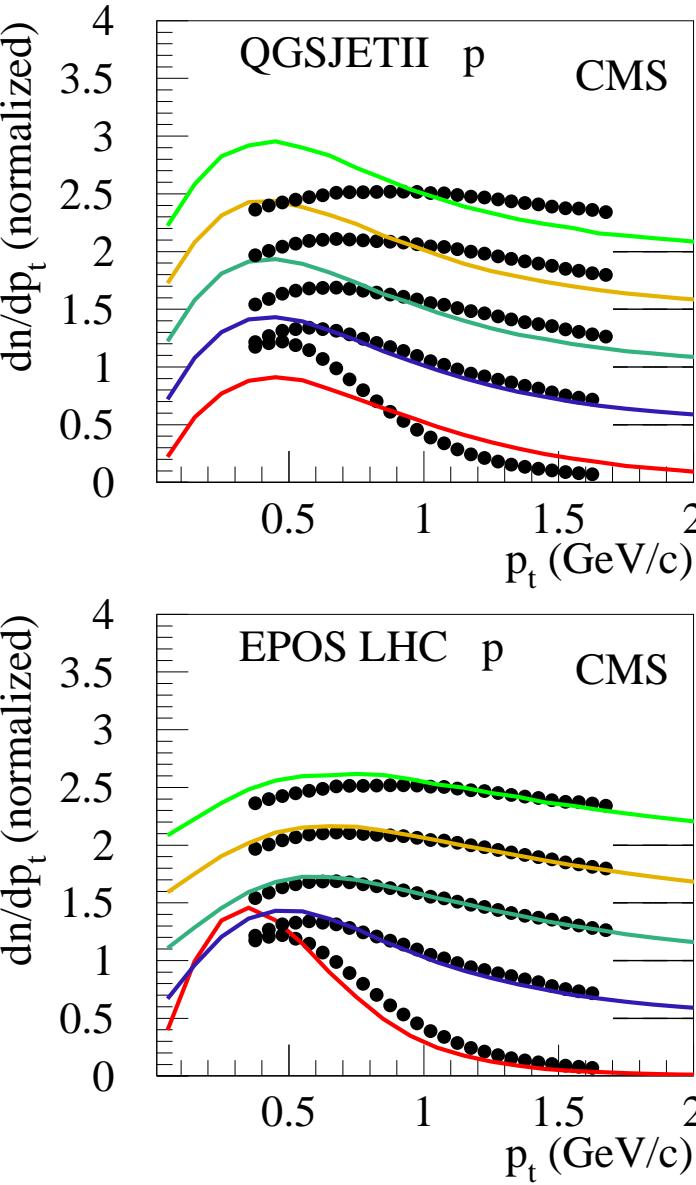


4  
multiplicity  
classes:

$\langle N_{\text{tracks}} \rangle :$   
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)



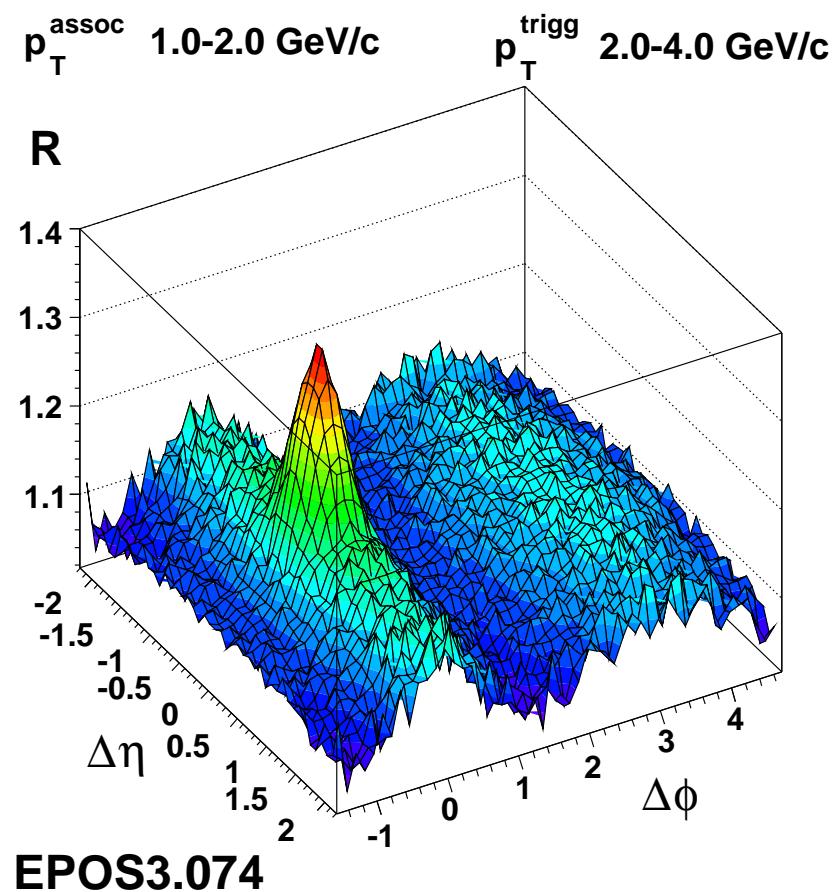
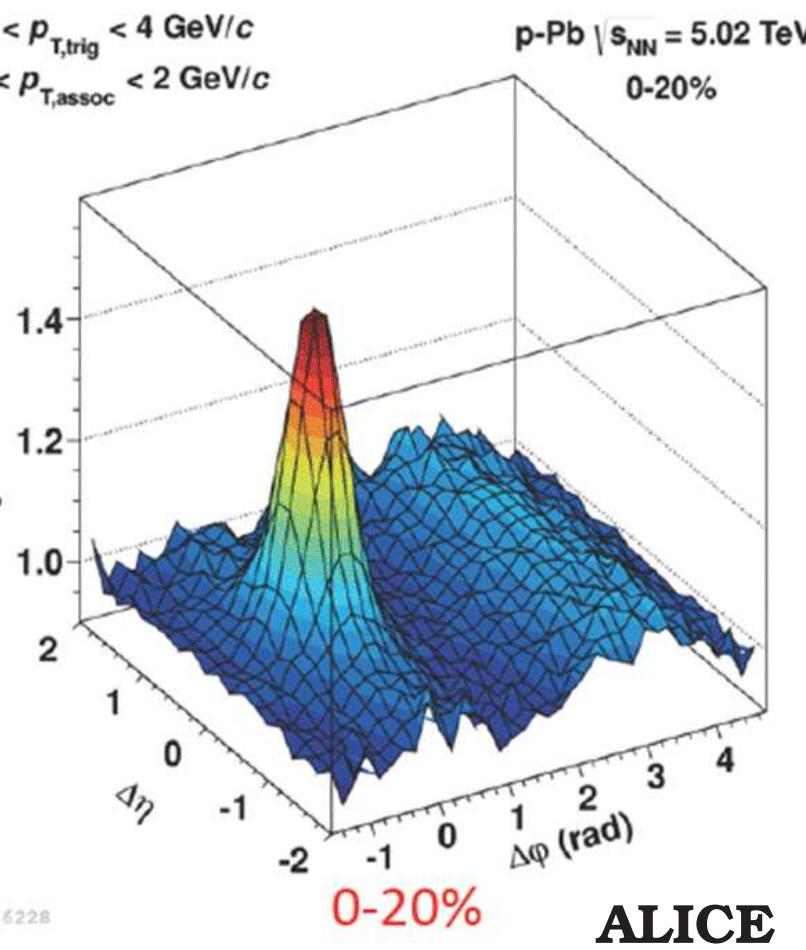
5  
multiplicity  
classes:

$\langle N_{\text{tracks}} \rangle :$   
7, 40, 75,  
98, and 131  
(in  $|\eta| < 2.4$ )

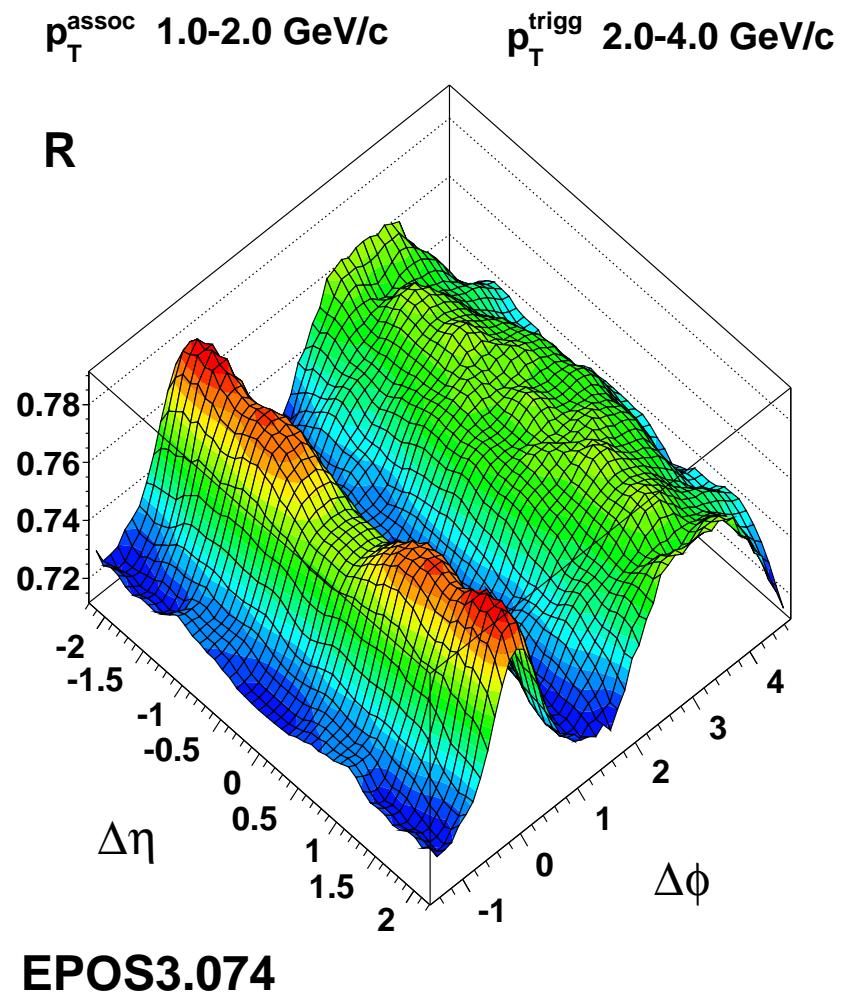
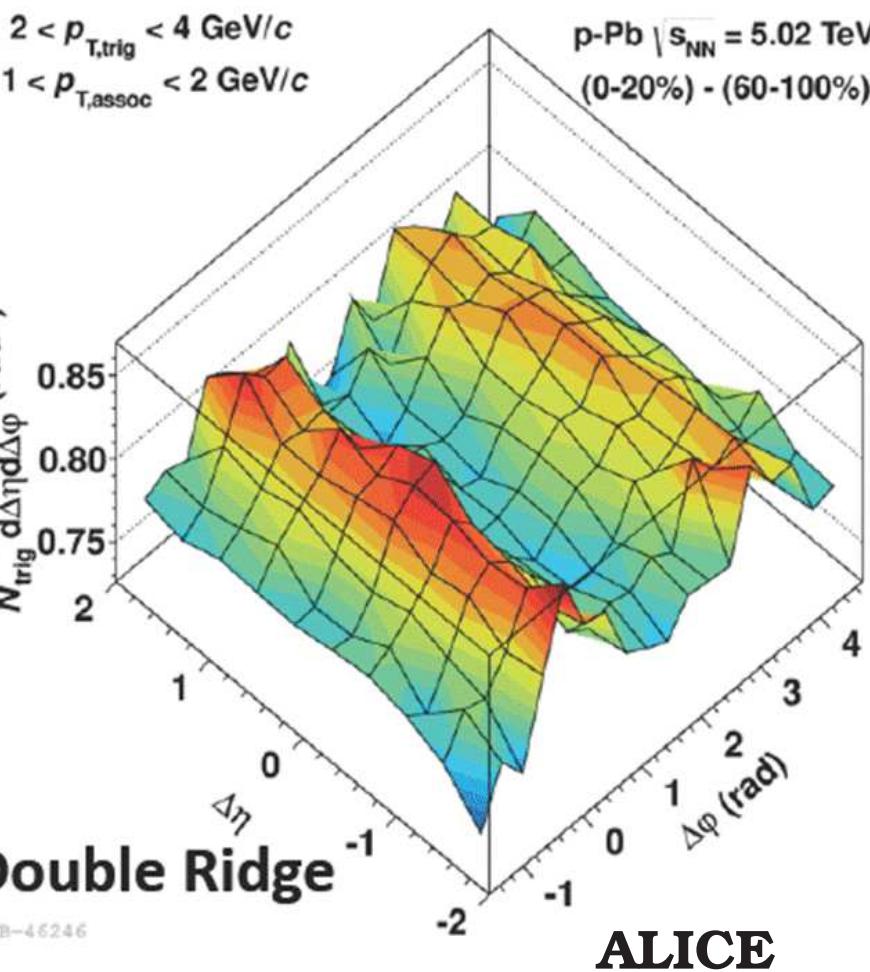
**Also in pp: flow helps !!**

## “Ridges” in pA

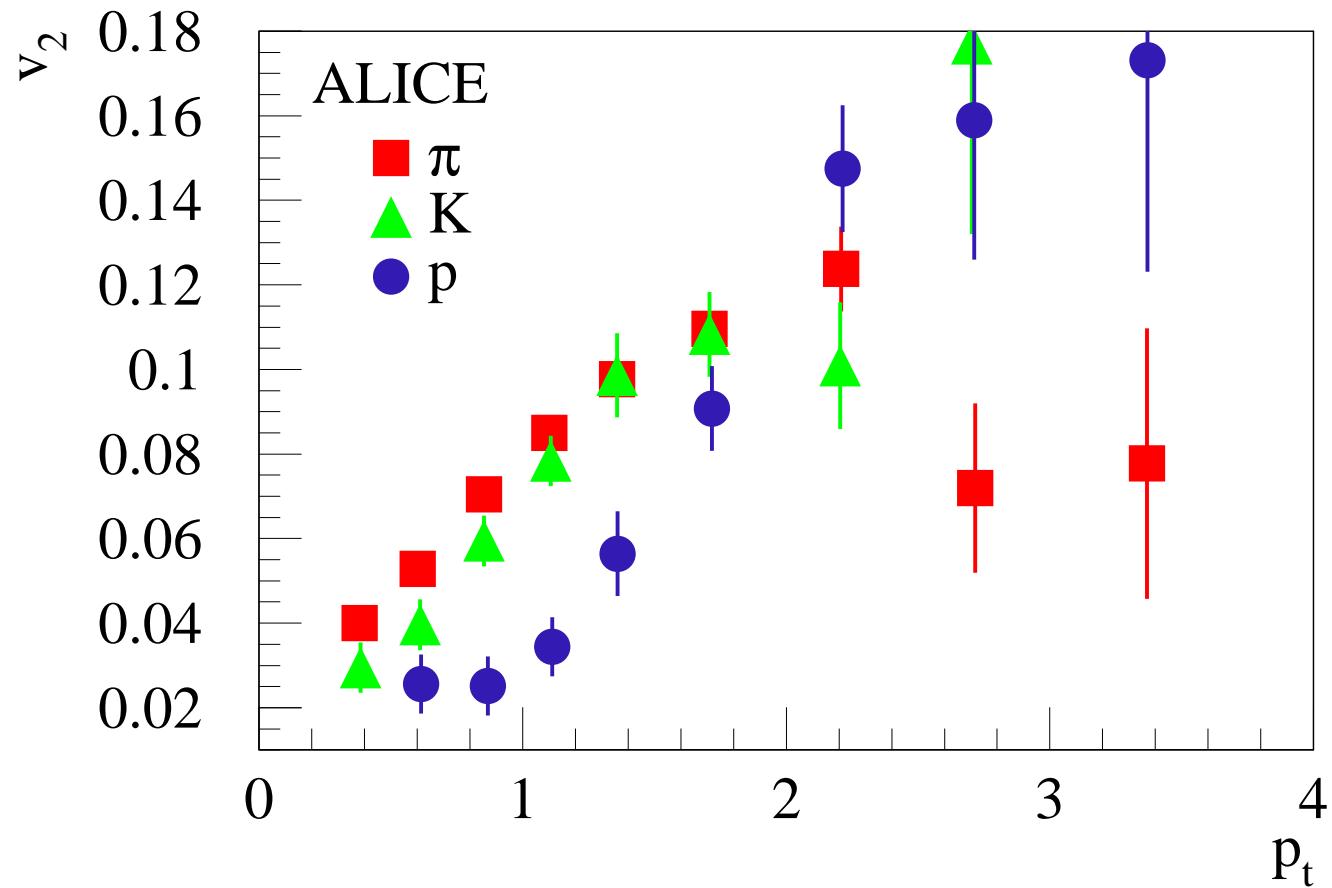
ALICE, arXiv:1212.2001, arXiv:1307.3237



## Central - peripheral (to get rid of jets)



## Identified particle v2

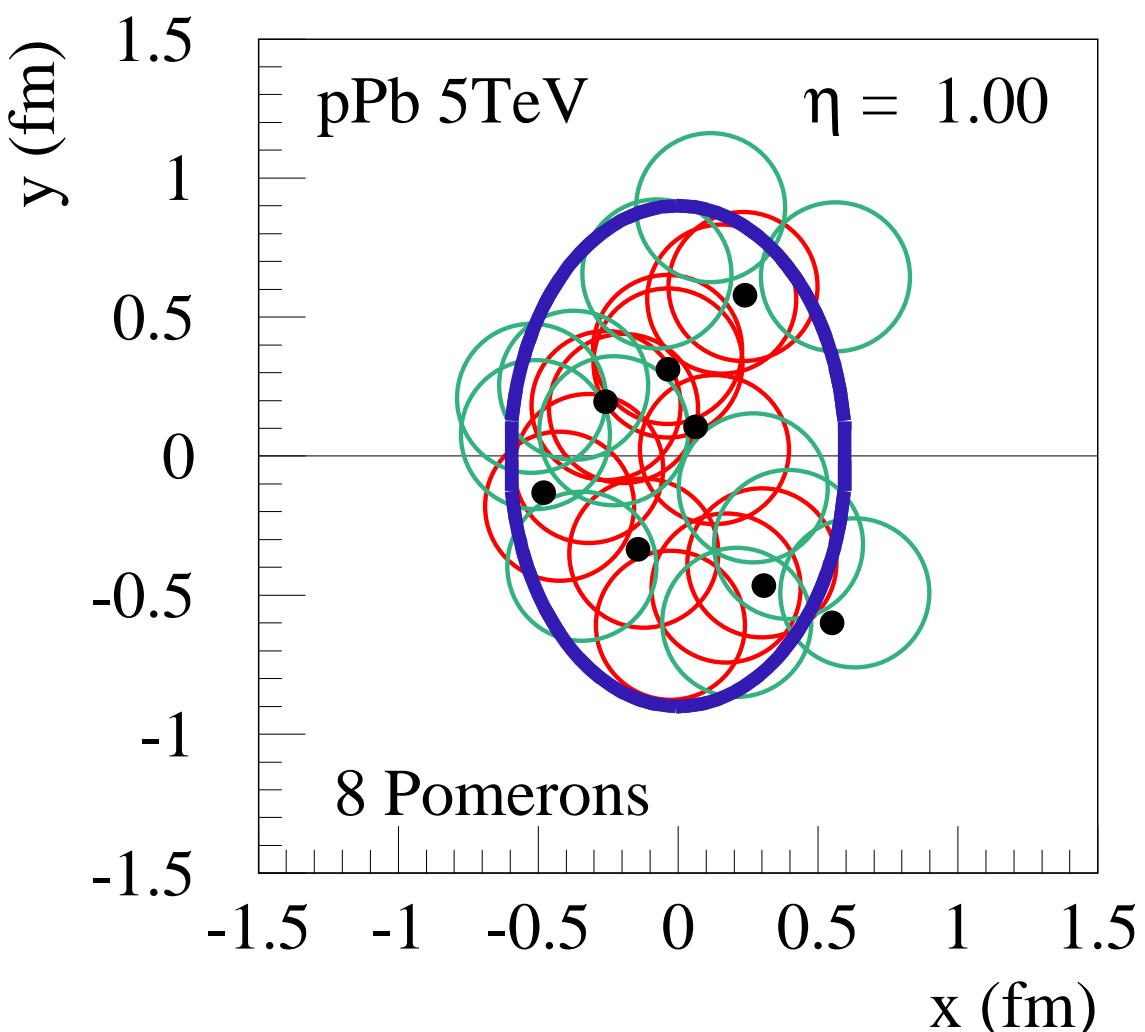


**mass splitting, as in PbPb !!!**

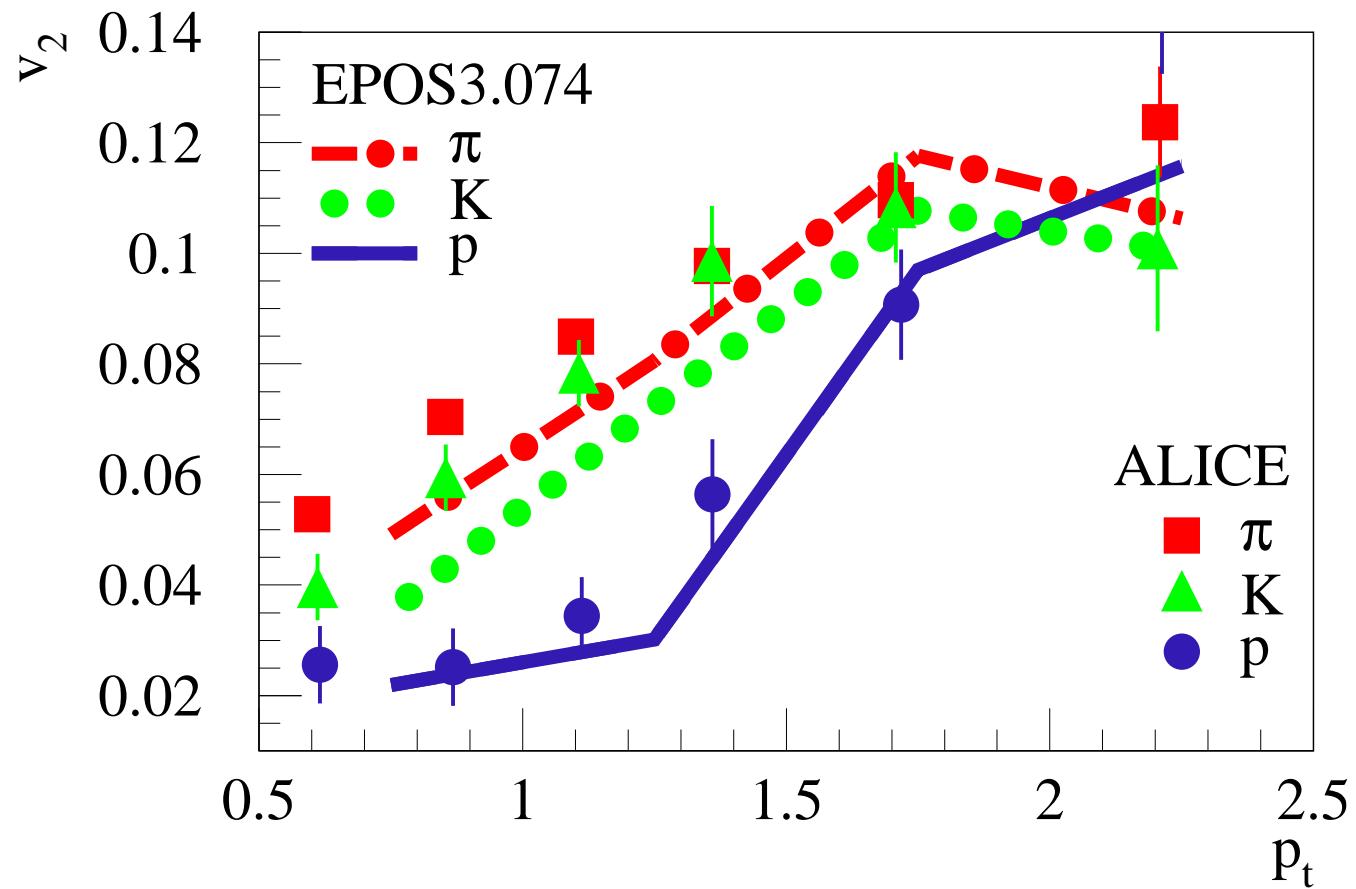
## pPb in EPOS3:

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

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



## v2 for $\pi$ , K, p clearly differ

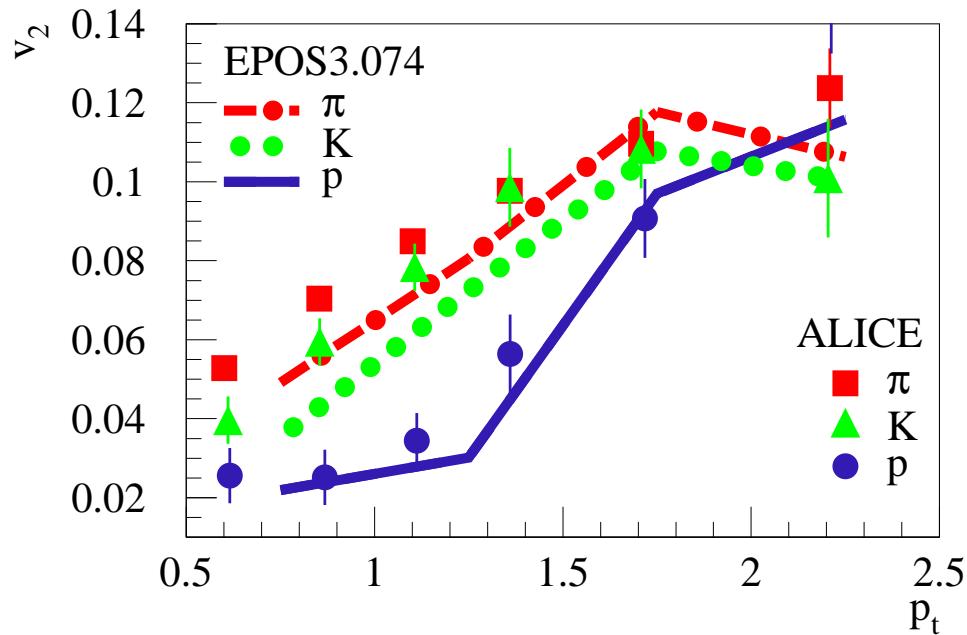


**mass splitting, due to flow**

# Summary

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

**A realization (EPOS3) shows promising results**



arXiv:1307.4379

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

arXiv:1312.1233

Future: Wider coverage (HQ collaboration, Pol Bernard Gossiaux, Marlene Nahrgang, Jörg Aichelin); Jets ; ...  
Making code public...