Collective dynamics of the p-Pb collisions at the LHC

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[based on PLB 718 (2013) 1557, PLB 720 (2013) 250, PRC 88 (2013) 014903, and PB+WB+G. Torrieri, arXiv:1307.5060]

Signatures of sQGP

Main signatures of sQGP in ultra-relativistic A+A collisions:

- Collective flow
- Jet quenching

Flow manifests itself in harmonic components in the momentum spectra (v_n), in correlation data (ridges), in mass hierarchy of p_T spectra and v_n of identified particles, in certain features of interferometry (femtoscopy), ...

- Ridges found experimentally at the LHC in small systems, p+Pb and p+p (high-multiplicity events)
- Large elliptic and triangular flow measured in p+Pb
- Mass hierarchy recently found in p+A

Collectivity in small systems?

Main questions:

Are the central p-Pb collisions collective?

What is the nature of the initial state and correlations therein?
What are the limits/conditions on applicability of hydrodynamics?

Other analyses of collectivity in small systems:

Romatschke, Luzum, arXiv:0901.4588, Prasad et al., arXiv:0910.4844,
Bozek, arXiv:0911.2393, Werner et al., arXiv:1010.0400,
Deng, Xu, Greiner, arXiv:1112.0470, Yan et al., arXiv: 0912.3342,
Bozek, arXiv:1112.0912 Shuryak, Zahed, arXiv:1301.4470,
Bzdak et al.,arXiv:1304.3403, Qin, Müller, arXiv:1306.3439,
Werner et al., arXiv:1307.4379

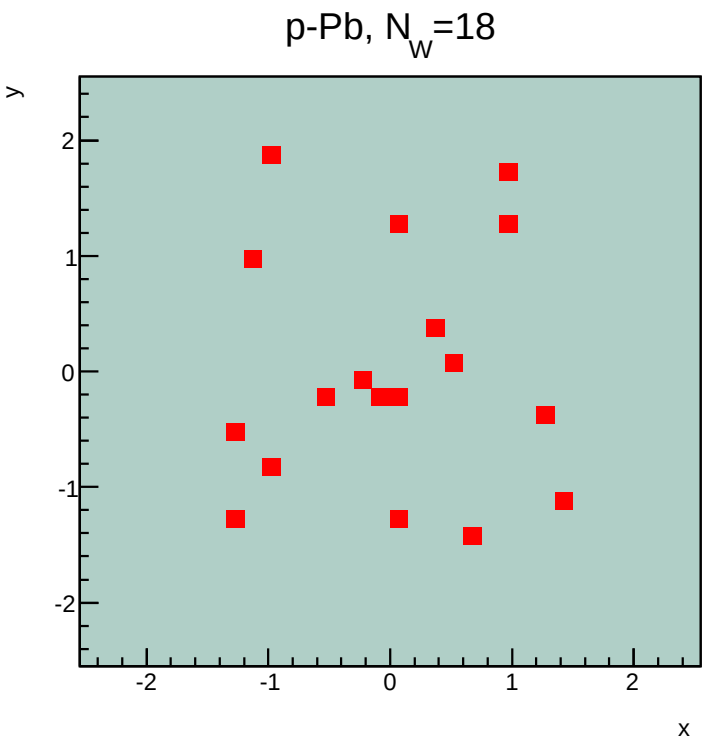
3-stage approach

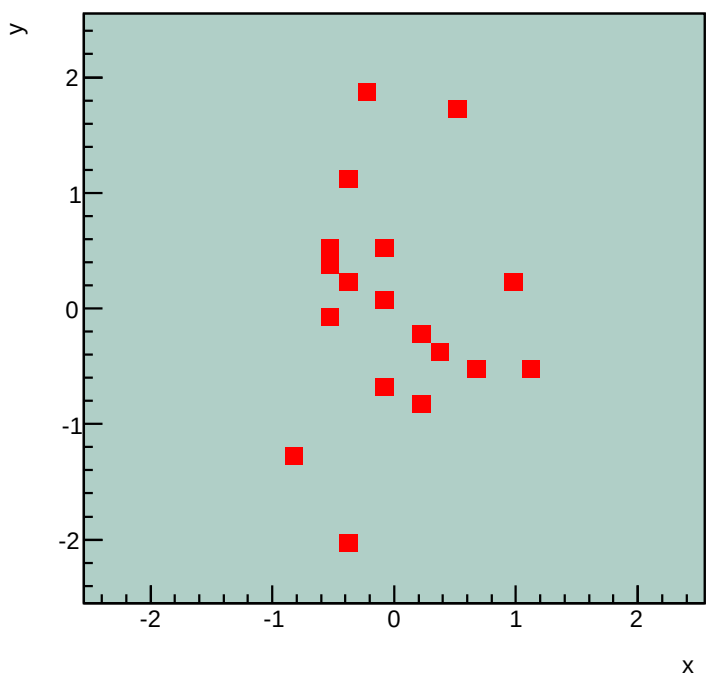
Our three-phase approach: initial $\rightarrow$ hydro $\rightarrow$ statistical hadronization (successful in description of A+A collisions)

- **Initial phase** - Glauber model
- **Hydrodynamics** - 3+1 D viscous event-by-event
- **Statistical hadronization**

The transverse size in central p+Pb

A typical transverse-plane configuration of the participant nucleons in a p+Pb collision generated with GLISSANDO
5% of collisions have more than 18 participants, rms ~ 1.5 fm – quite large!

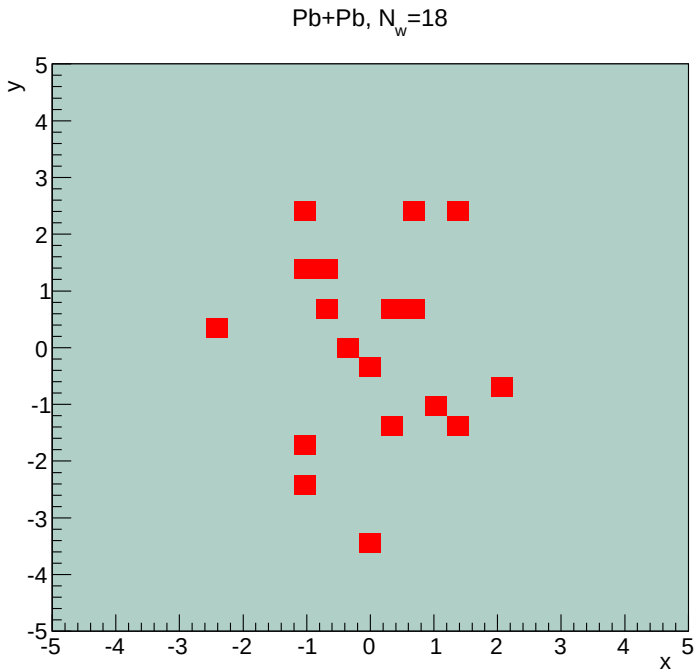




Snapshot of peripheral Pb+Pb

5% most central values of N_w in p-Pb fall between the 60-70% and 70-80% centrality class in Pb+Pb

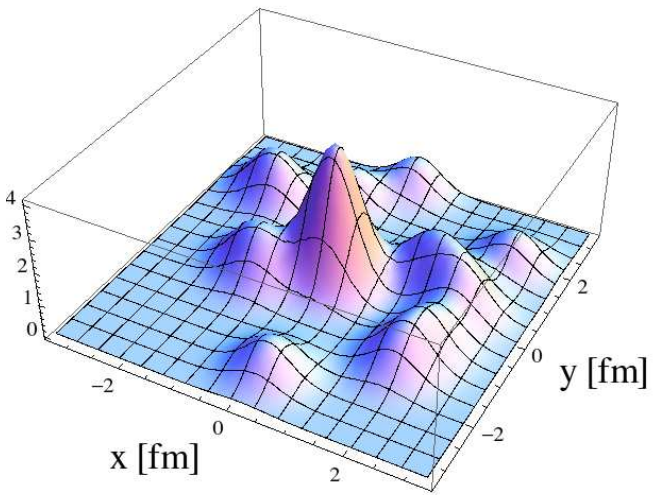
Pb+Pb: c=60-70% $\equiv 22 \leq N_w \leq 40$, c=70-80% $\equiv 11 \leq N_w \leq 21$

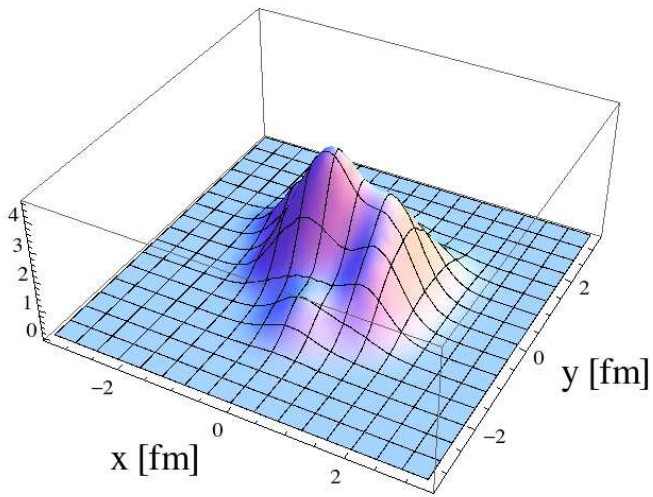


in Pb+Pb somewhat larger size than in p+Pb (all for $N_w = 18$)

Smearing

Gaussian smearing with width 0.4 fm (physical effect)





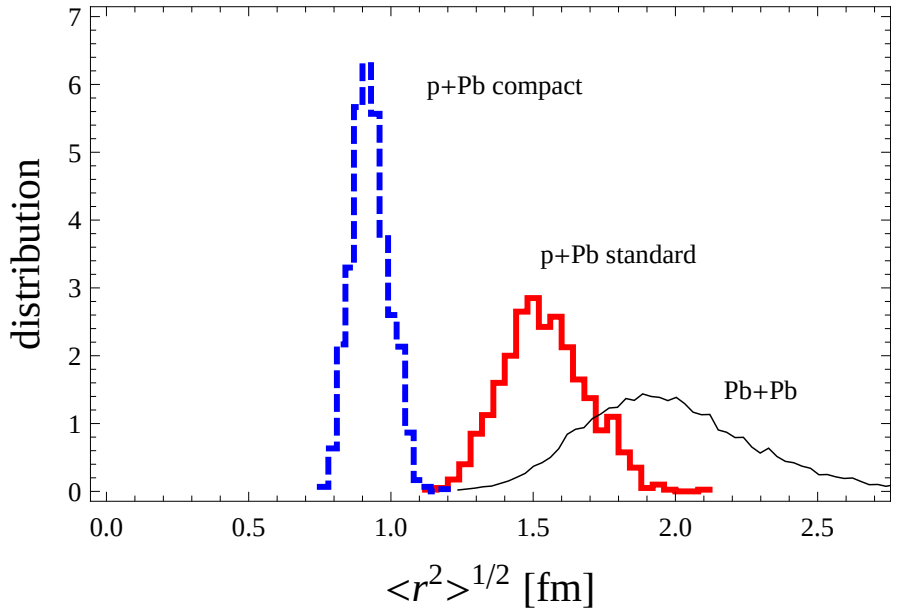
two variants: standard compact

(sources at centers of participants) (sources at centers-of-mass of pairs)

Such transverse entropy profiles are fed into e-by-e hydro as initial conditions

Size in p+Pb vs Pb+Pb

fixed $N_w = 18$



smaller size in p+Pb $\rightarrow$ larger entropy density $\rightarrow$ more rapid expansion

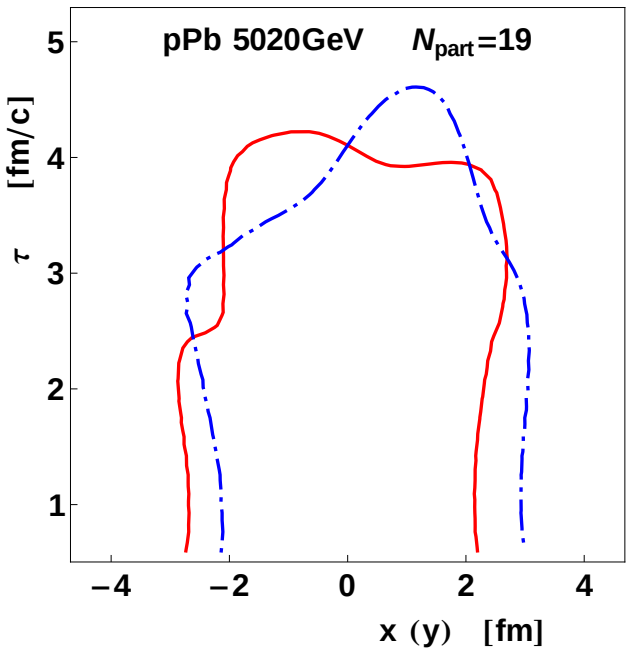
All in all, initial conditions in most central p+Pb not very far from peripheral Pb+Pb

Hydrodynamics [Bożek 2011]

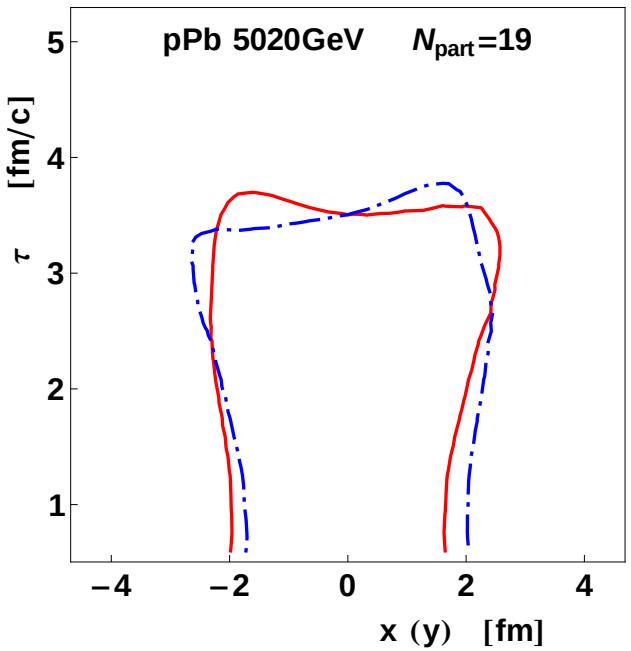
3+1 D viscous event-by-event hydrodynamics (viscous corrections essential due to large gradients)

- $\tau_{\rm init} = 0.6$ fm/c, $\eta/s = 0.08$ (**shear**), $\zeta/s = 0.04$ (**bulk**)
- freezeout at $T_f = 150$ MeV
- average initial temperature in the center of the fireball $T_i = 242$ MeV ($< R^2 >^{1/2} = 1.5$ fm), or 319 MeV ($< R^2 >^{1/2} = 0.9$ fm) – adjusted to fit multiplicity
- realistic equation of state (lattice + hadron gas [Chojnacki & Florkowski 2007]), viscosity necessary for small systems
- lattice spacing of 0.15 fm (**thousands of CPU hours**)

$< R^2 >^{1/2}= 1.5$ fm



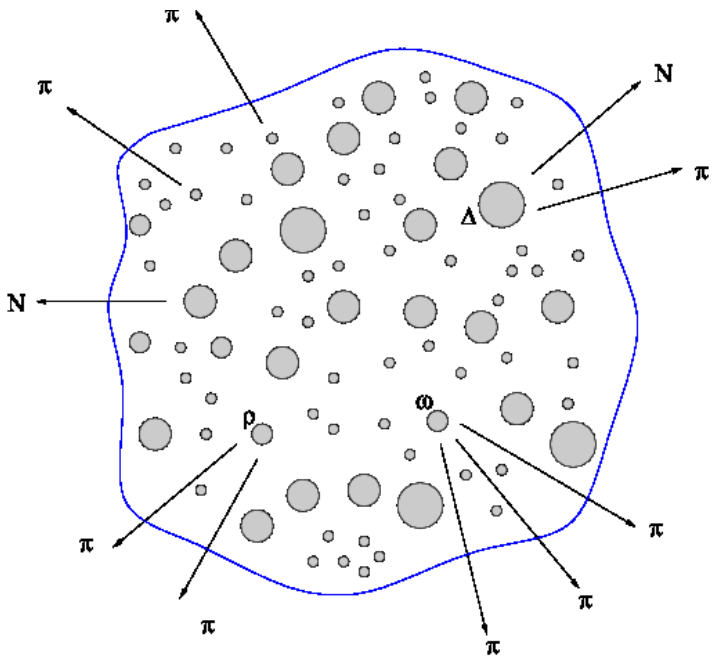
$< R^2 >^{1/2}= 0.9$ fm



isotherms at freeze-out $T_f = 150$ MeV for two sections in the transverse plane

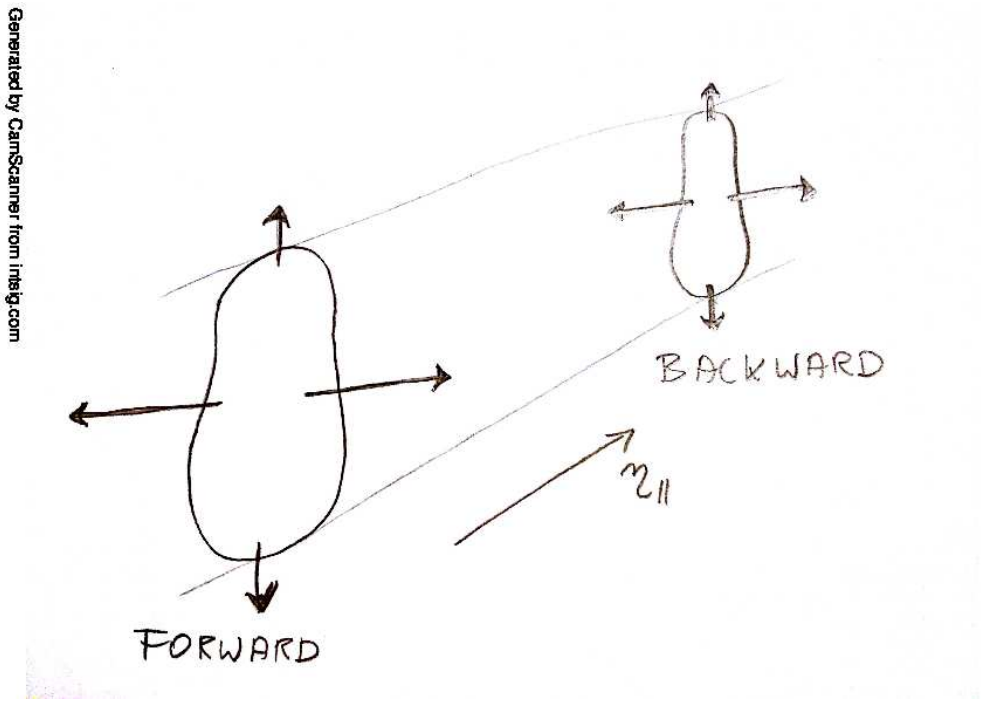
evolution lasts about 4 fm/c - shorter but more rapid than in A+A

Statistical Hadronization



Statistical hadronization via Frye-Cooper formula + resonance decays (THERMINATOR)

Factorization of the transverse and longitudinal distributions



alignment of F and B event planes (can be checked experimentally)

collimation of flow at distant longitudinal separations $\rightarrow$ ridges!

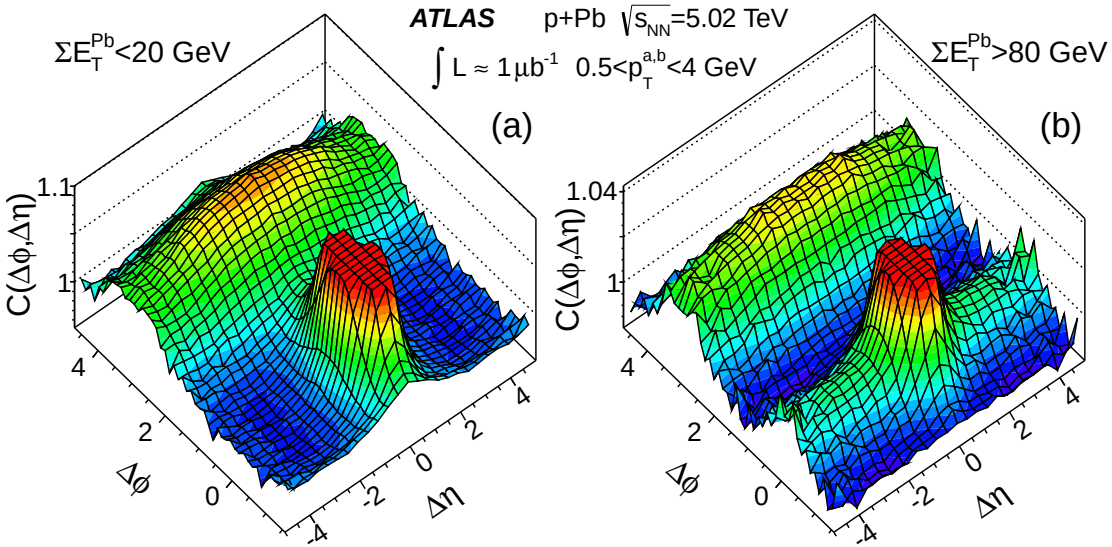
Surfers - the near-side ridge

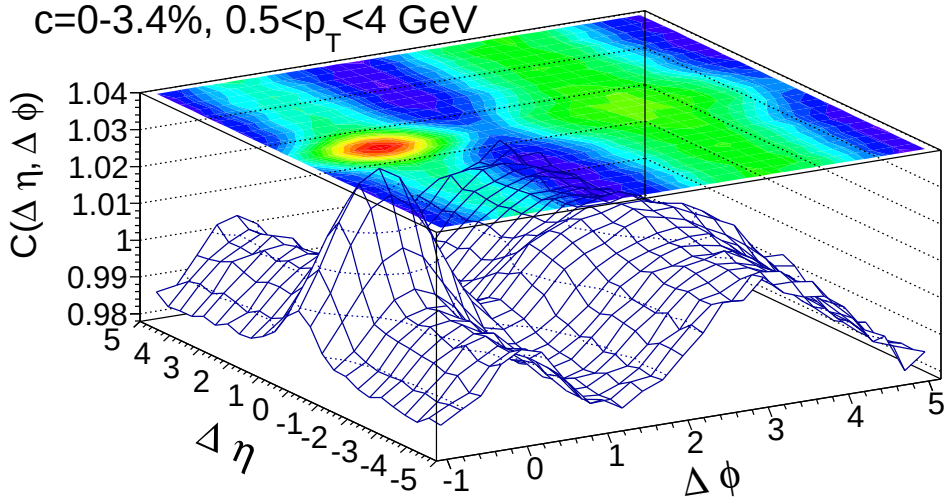
Definition of the 2D correlation function

$$C(\Delta\eta, \Delta\phi) = \frac{N^{\text{pairs}}_{\text{phys}}(\Delta\eta,\Delta\phi)}{N^{\text{pairs}}_{\text{mixed}}(\Delta\eta)} = \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

(more convenient than the "per-trigger" correlations)

Ridge in p-Pb, ATLAS

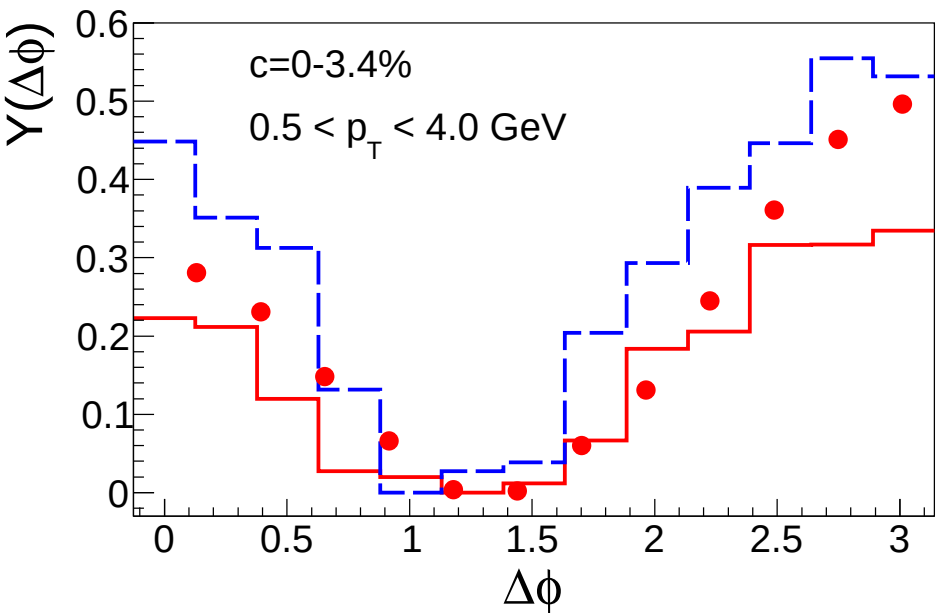




Projection on $2 \leq |\Delta\eta| \leq 5$, ATLAS

$$Y(\Delta\phi) = \frac{\int B(\Delta\phi)d(\Delta\phi)}{N} C(\Delta\phi) - b_{\mathrm{ZYAM}}$$

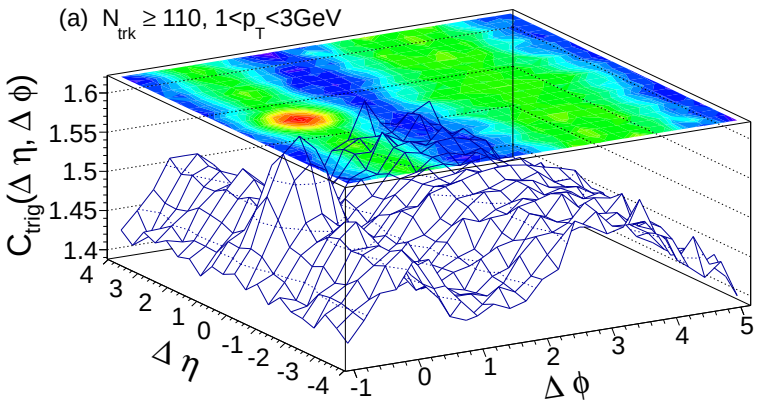
The near-side ridge from our model:

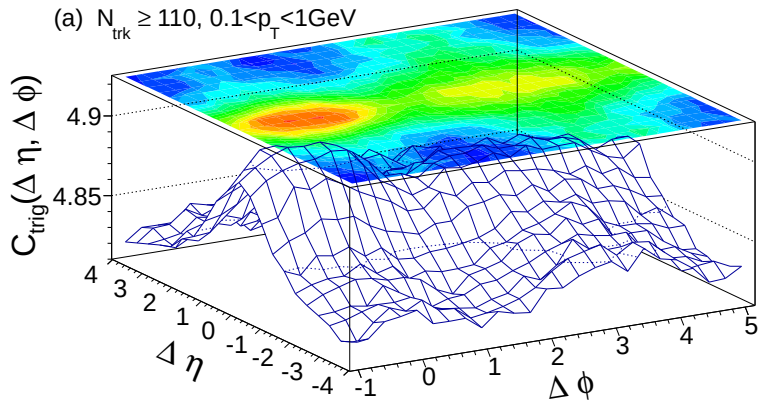


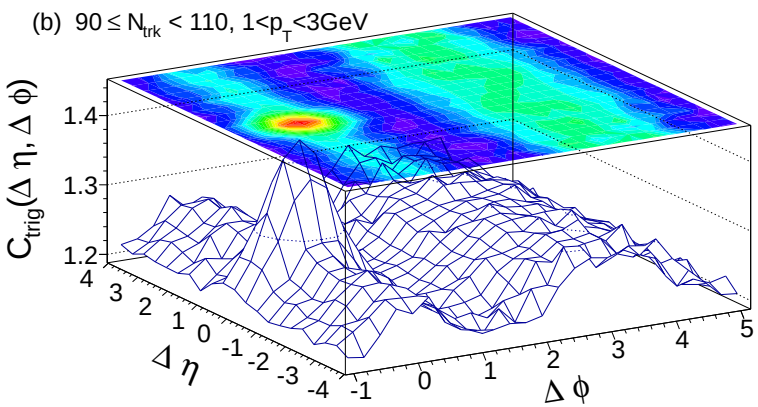
red - $< R^2 >^{1/2} = 1.5$ fm, blue - $< R^2 >^{1/2} = 0.9$ fm

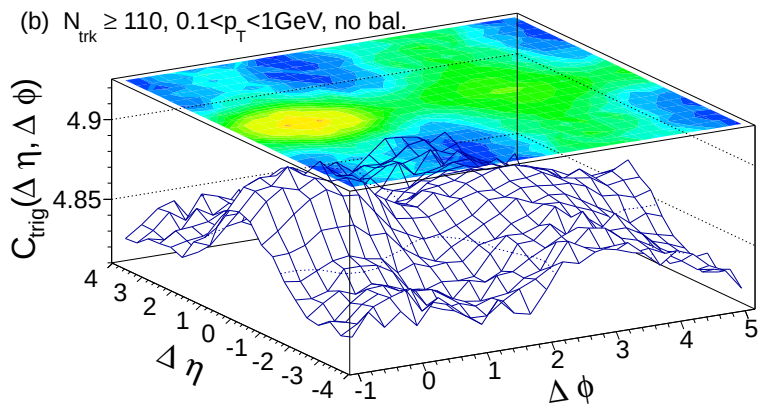
[CGC: Dusling, Venugopalan, arXiv:1210.3890, 1211.3701, 1302.7018]

Ridge in p-Pb


(a) $N_{trk} \geq 110$, $1<p_T<3$GeV
$C_{trig}(\Delta\eta, \Delta\phi)$
1.6
1.55
1.5
1.45
1.4
$\Delta\eta$
$\Delta\phi$

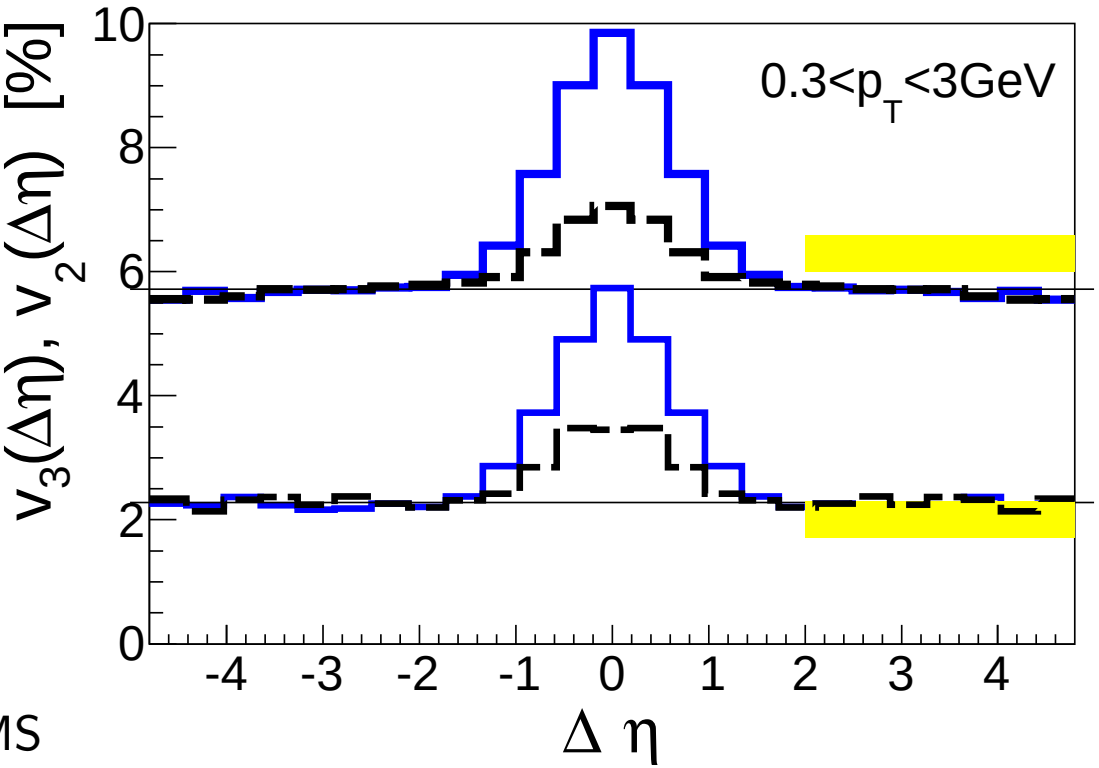

(a) $N_{trk} \geq 110$, $0.1<p_T<1$GeV
$C_{trig}(\Delta\eta, \Delta\phi)$
4.9
4.85
$\Delta\eta$
$\Delta\phi$


(b) $90 \leq N_{trk} < 110$, $1<p_T<3$GeV
$C_{trig}(\Delta\eta, \Delta\phi)$
1.4
1.3
1.2
$\Delta\eta$
$\Delta\phi$


(b) $N_{trk} \geq 110$, $0.1<p_T<1$GeV, no bal.
$C_{trig}(\Delta\eta, \Delta\phi)$
4.9
4.85
$\Delta\eta$
$\Delta\phi$

Flow from correlations (two-particle cumulants, η gap)

$v_n\{2, |\Delta\eta| > 2\mathrm{GeV}\}$

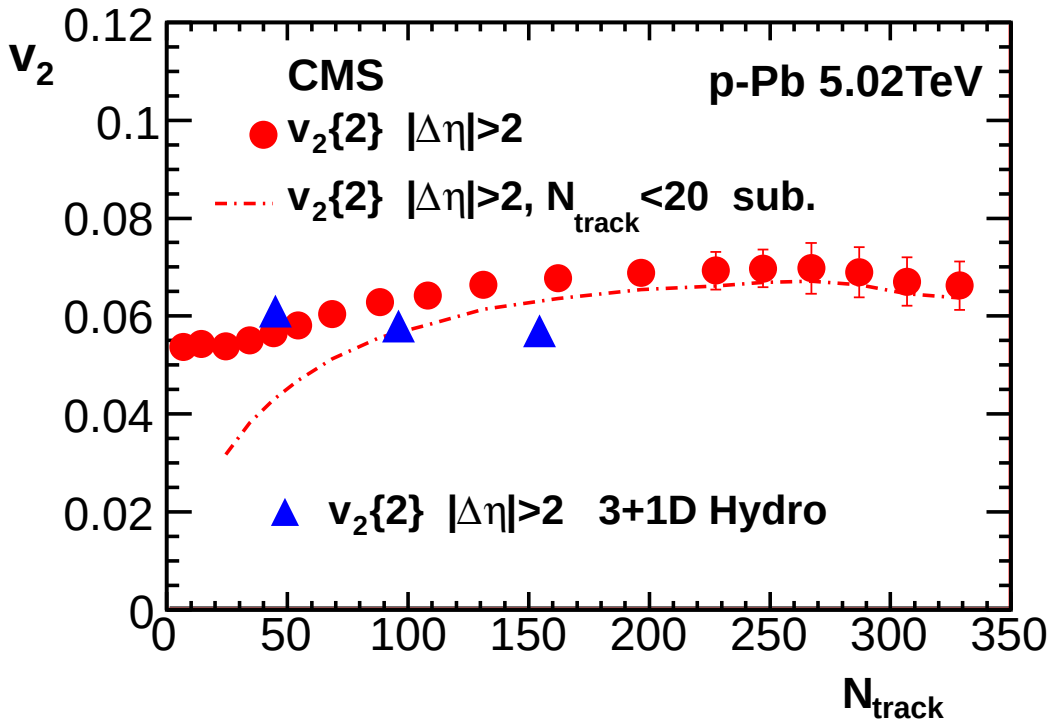


bands - CMS

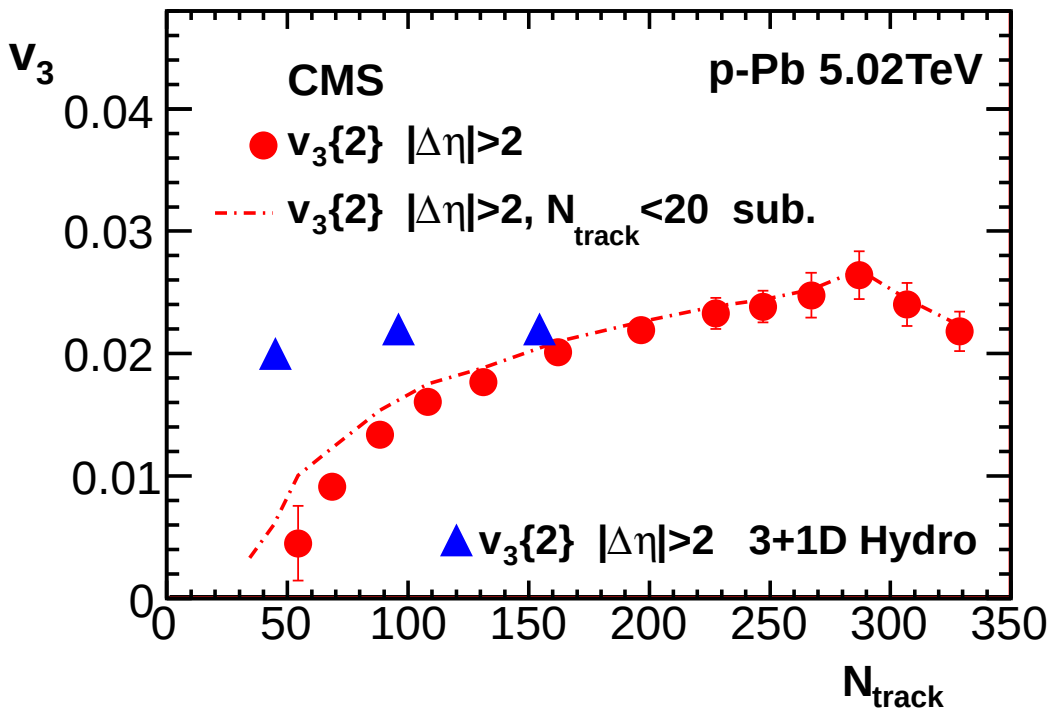
same-sign pairs, opposite-sign pairs

(compact source: $< R^2 >^{1/2} = 0.9$ fm, $\langle N_{\mathrm{trk}} \rangle = 154.5$)

v_2 vs CMS

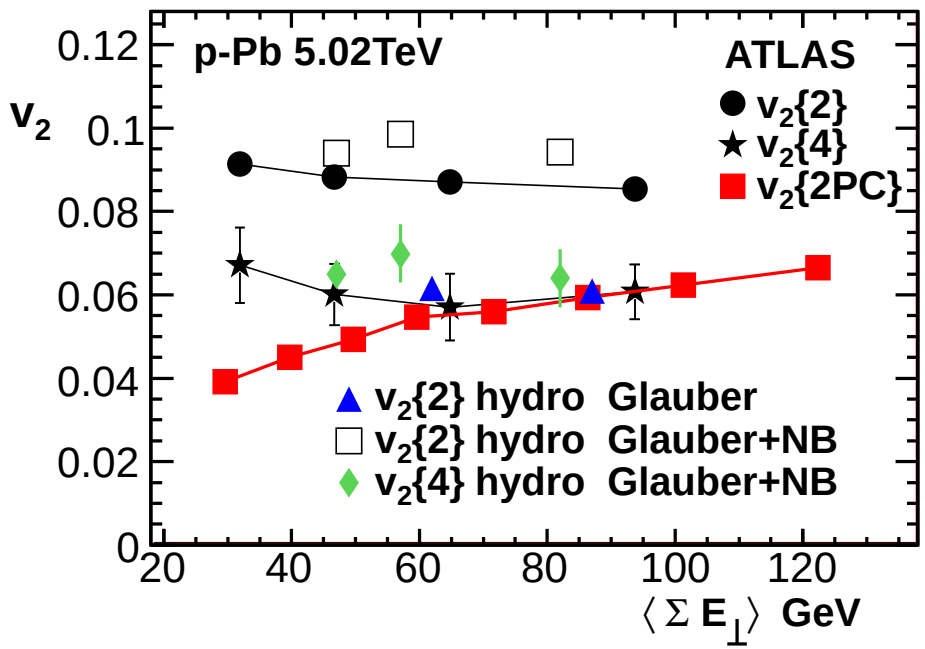

v2
0.12
0.1
0.08
0.06
0.04
0.02
0
0
50
100
150
200
250
300
350
Ntrack
CMS
p-Pb 5.02TeV
v2{2} |Δη|>2
v2{2} |Δη|>2, Ntrack<20 sub.
v2{2} |Δη|>2 3+1D Hydro

v_3 vs CMS

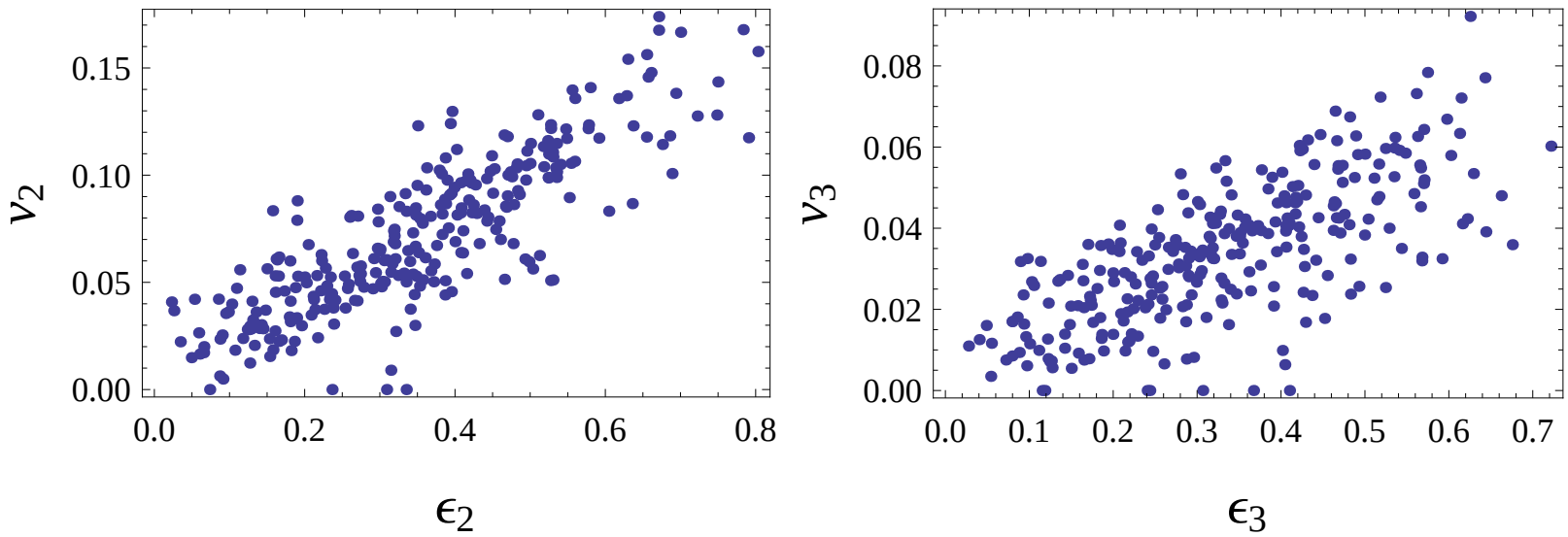


v_3 too large for peripheral collisions $\rightarrow$ limit of validity of the model

LHC: v_2 vs ATLAS

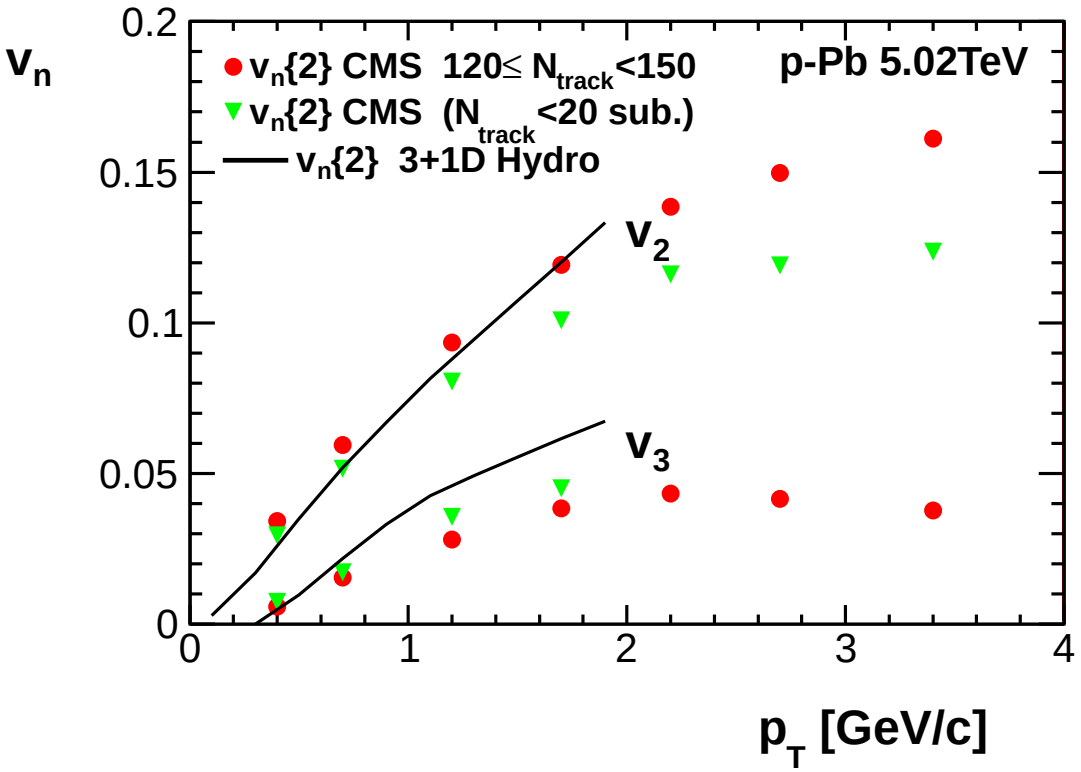


Digression: eccentricity → flow



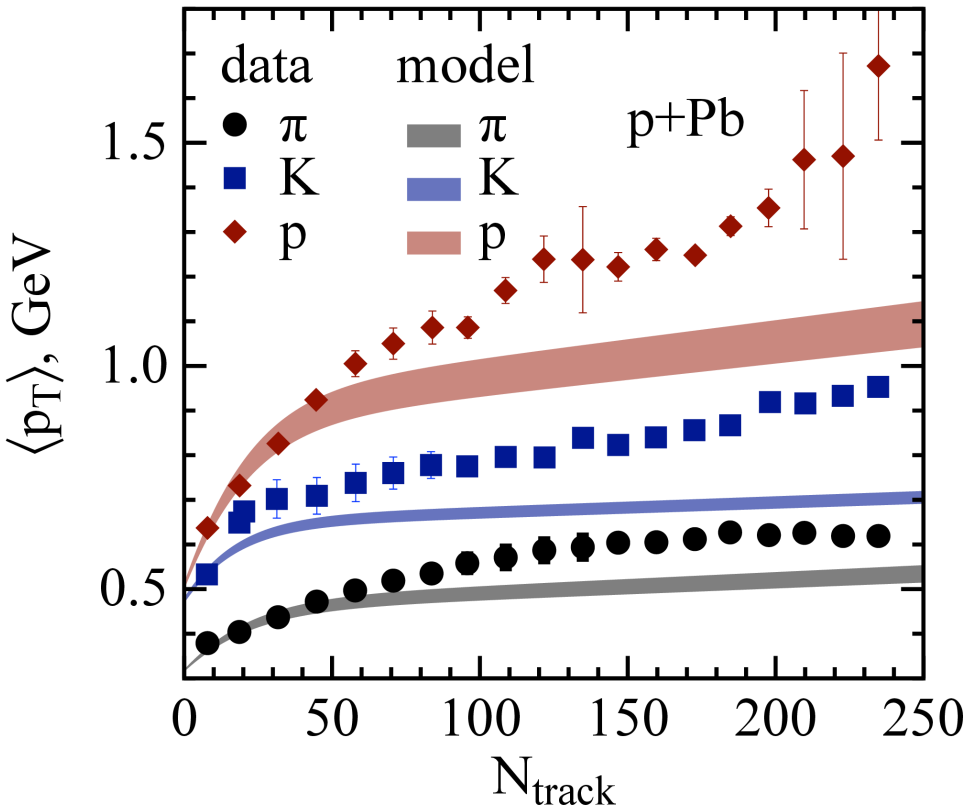
larger fluctuations in the initial distribution → larger flow

v_2, v_3 vs p_T


v_n
v_n{2} CMS 120≤ N_track<150
v_n{2} CMS (N_track<20 sub.)
v_n{2} 3+1D Hydro
p-Pb 5.02TeV
v_2
v_3
0.2
0.15
0.1
0.05
0
0
1
2
3
4
p_T [GeV/c]

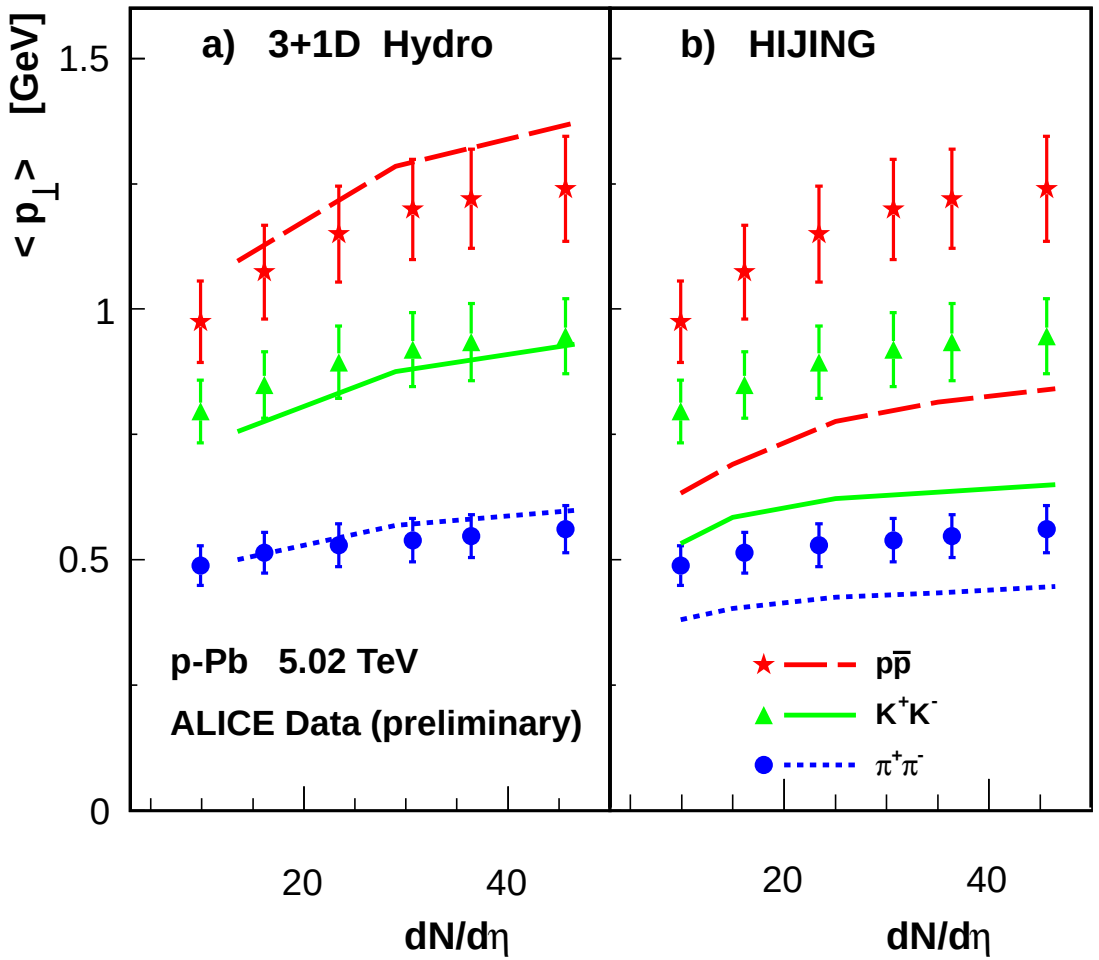
Identified spectra

Linear superposition not enough!

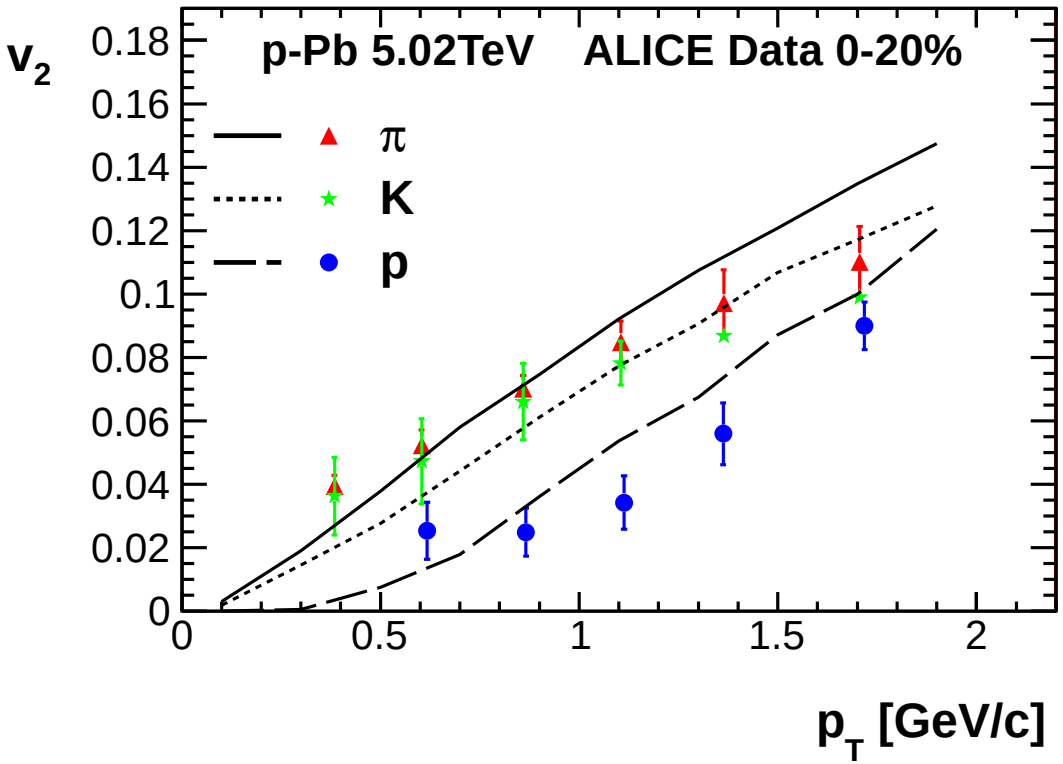


[Bzdak, Skokov, arXiv:1306.5442: Wounded Nucleon Model with experimental pp data at 7 TeV]

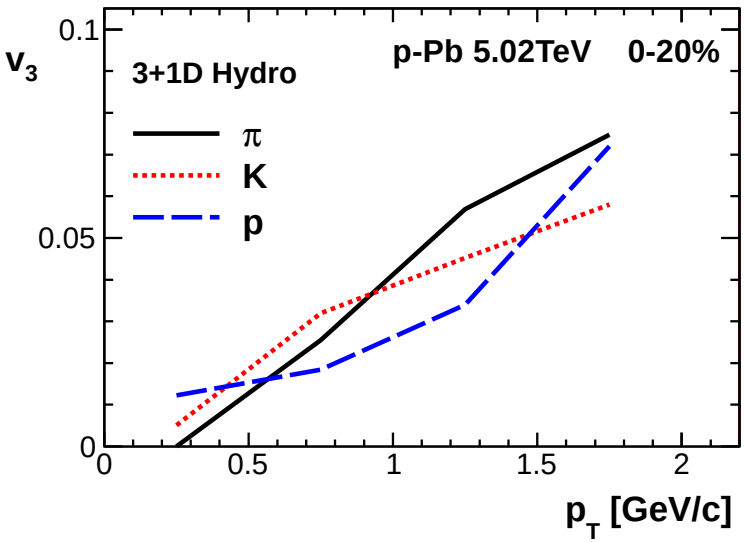
Identified $\langle p_T \rangle$

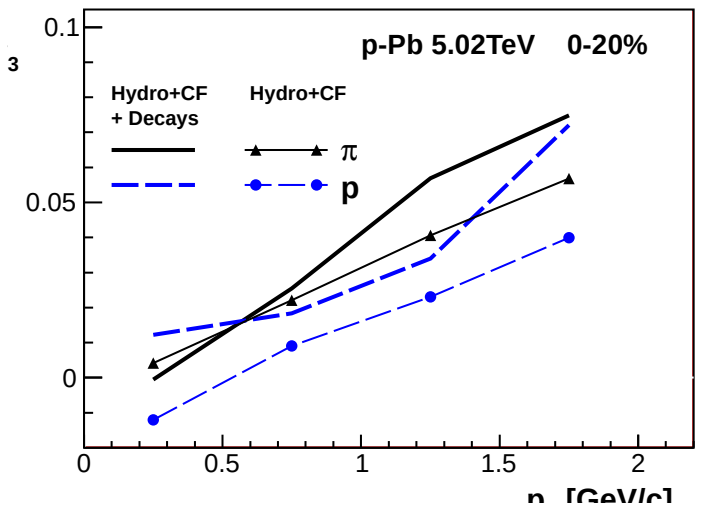


Identified v_2



Identified v_3

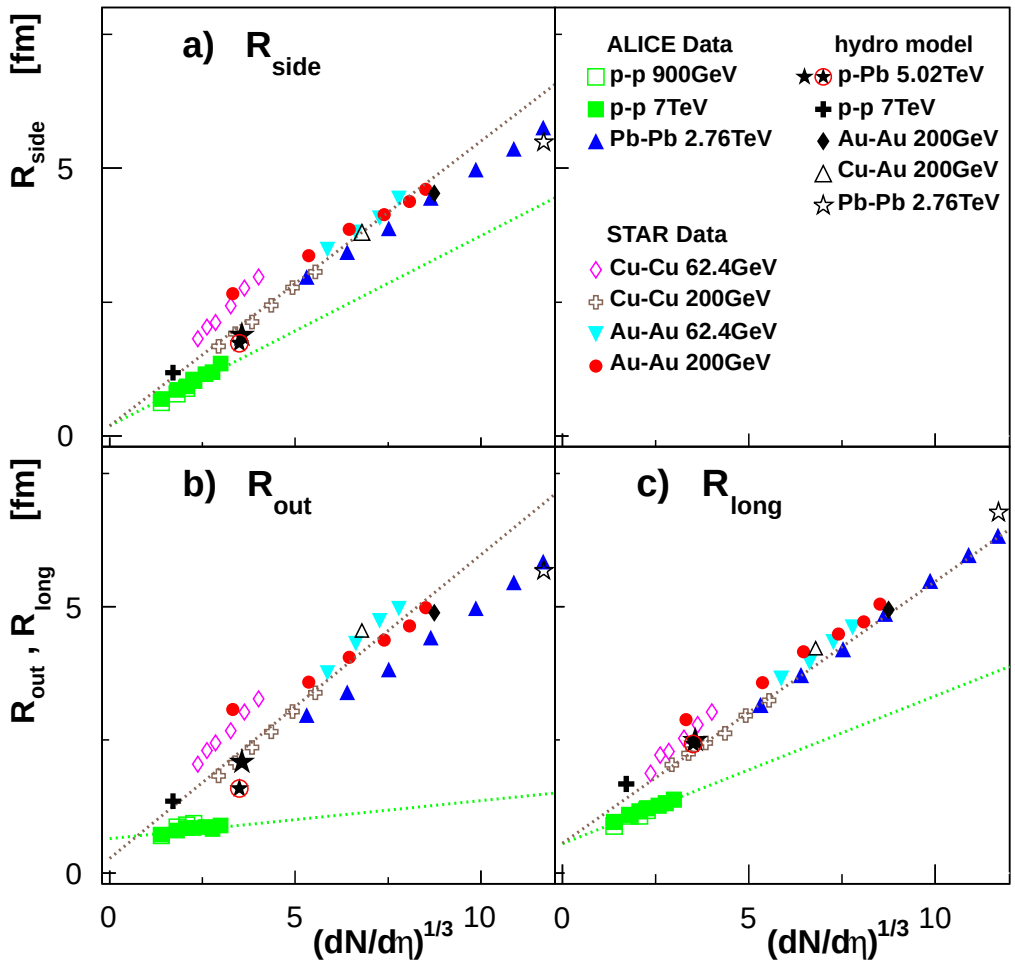




Resonance decays affect the mass ordering!

HBT radii

Interferometric radii due to Bose-Einstein correlations - measure of the size of the system at freeze-out



Conclusions

Is there collectivity in small systems?

$\rightarrow$ collective dynamics is compatible with high-multiplicity LHC soft data for p-Pb

- Large v_2 and v_3 coefficients measured in p-Pb reproduced, including the p_T dependence
- Model 2D correlations exhibit the two ridges, in particular the near-side ridge (hydro $\rightarrow$ "surfers") [flow $\equiv$ near-side ridge!]
- Mass ordering in $\langle p_T \rangle$ and flow coefficients reproduced
- Model predictions for the interferometric radii for p+Pb are closer to the A+A line, farther from the p+p line - way to distinguish

- Numerous effects should still be incorporated (jets, core-corona, ...), more important for the lower-multiplicity events