

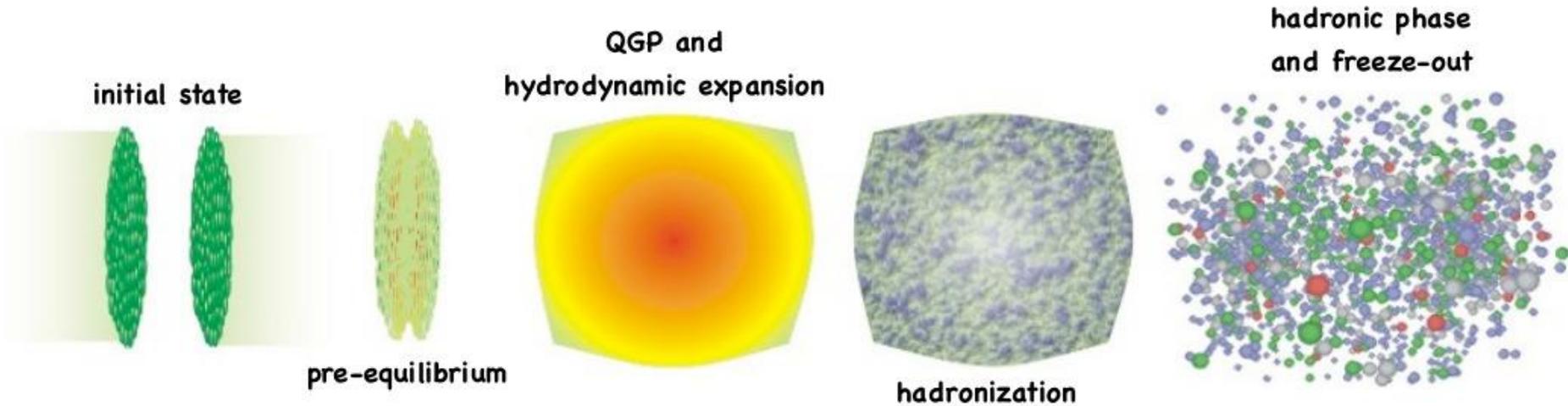
# **Gluon brehmsstrahlung and flow asymmetry in pA Collisions**

**P. Levai, M. Gyulassy, G. Papp, G.G. Barnaföldi  
MTA WIGNER RCP, ELTE Univ.,  
Budapest**

**On the basis of our earlier work:  
M. Gyulassy, P.L. I. Vitev, T.S. Bíró  
Phys. Rev. D90 (2014) 054025. hep-ph/1405.7825**

**Hard Probe Conference, Wuhan, China  
24 September 2016**

# Standard Model of Heavy Ion Collisions:



## Phases:

- **Initial condition:** pre-equilibrium state
- **Hydrodynamical evolution**  
perfect fluid, viscous fluid, EOS
- **Hadronization mechanism**  
phase transition, coalescence/recombin.,  
Cooper-Frye, incl. viscous corrections
- **Hadronic afterburner**  
hadronic interactions, final state effects

## Questions, problems:

- PDF, proton shape, color oscil.
- Glue saturation, shadowing
- Space-time fluctuations
- EOS properties, finite size eff.
- Relativ. viscous hydrodynamics
- Confinement-deconfinement
- Order of phase transition
- Mesoscopic system, size effects
- Freeze-out characteristics
- Dense hadronic matter
- Resonance decays, ...

## **Standard Model of Heavy Ion Collisions:**

**Question: What is the smallest size, where  
this Standard Model (and hydro) remains valid?**

**What about if specific data display a good agreement between  
periferic AA collisions  
average pA collisions  
high multiplicity pp collisions ??  
..... (even smaller system) ???**

**Could we find consistent description and/or a new approach,  
beyond the usual hydrodynamical description ?**

**Let us see the experimental data and explore the opportunities!**

# Proton-antiproton collisions at FERMILAB, $\sqrt{s} = 1.8$ TeV

VOLUME 67, NUMBER 12

PHYSICAL REVIEW LETTERS

16 SEPTEMBER 1991

## Transverse Baryon Flow as Possible Evidence for a Quark-Gluon-Plasma Phase

Péter Lévai<sup>(a)</sup> and Berndt Müller

Department of Physics, Duke University, Durham, North Carolina 27706

(Received 13 March 1991)

In order to investigate the coupling between the collective flow of nucleons and pions in hot pion-dominated hadronic matter, we calculate the pion-nucleon drag coefficient in linearized transport theory. We find that the characteristic time for flow equalization is longer than the time scale of the expansion of a hadronic fireball created in high-energy collisions. The analysis of transverse-momentum data from  $p + \bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV reveals the same flow velocity for mesons and antinucleons. We argue that this may be evidence for the formation of a quark-gluon plasma in these collisions.

PACS numbers: 25.70.Np, 12.38.Mh, 13.85.Hd

Rather general arguments indicate that the state of high energy density temporarily formed in ultrarelativistic central collisions of nuclei, and possibly even of single hadrons, exhibits approximate local thermal equilibrium and thus can be characterized by a temperature. This scenario is generally supported by the observation that transverse-momentum spectra of emitted particles fall exponentially at high  $p_T$ . It has often been speculated that a collective outward flow may develop during the expansion and final breakup of the high-density state [1]. The presence of a collective flow would be manifest in a non-thermal shape of the transverse-momentum spectrum. Because the flow velocity is superimposed with the random thermal motion, this effect grows with the mass of the emitted particles, and should be most clearly visible in baryon spectra. So far, experimental evidence for the existence of transverse flow at center-of-mass energies far above 1 GeV/u has been inconclusive [2,3], in contrast to collisions below this energy [4].

Gerber, Leutwyler, and Goity [5] recently showed that the expansion of a dense pion gas, as is formed in the central rapidity region after a highly relativistic nuclear collision, must lead to a rapid transverse flow. Gavin [6] pointed out that the expansion is even so rapid that the

violation from local thermal equilibrium is not too severe. We will now calculate  $\delta$  and  $\theta$  from first principles.

We assume that the evolution of the phase-space distribution functions  $f_i(x, p)$ ,  $i = \pi, N$ , of pions and nucleons in the dense hadronic phase is described by the relativistic Boltzmann equation:

$$p^\nu \partial_\nu f_i(x, p) = \sum_j \mathcal{C}_{ij}(x, p). \quad (3)$$

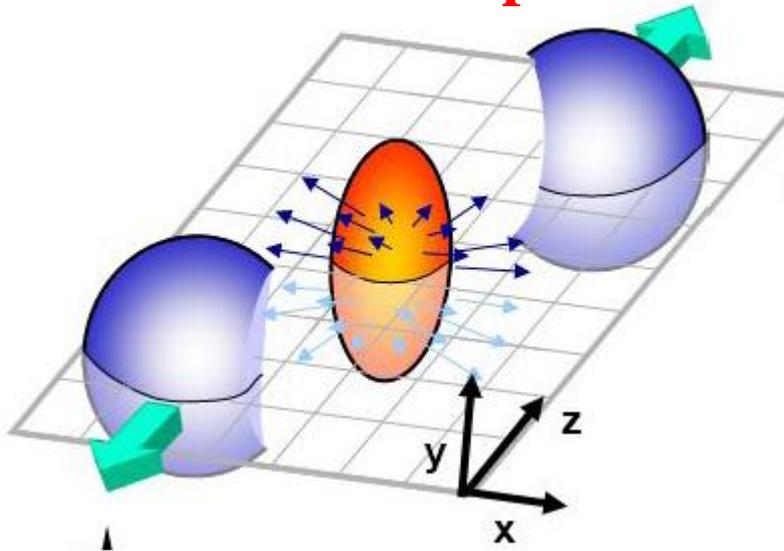
Here  $\mathcal{C}_{ij}$  are the collision terms, which can be calculated from the known cross section for collisions between particles of type  $i$  and type  $j$ . In order to make contact with collective variables, such as the local flow velocity  $u^\mu$ , it is useful to consider the momentum-space-integrated form of Eq. (3), introducing the energy-momentum tensor  $T_i^{\mu\nu}$ . Dissipative terms can then be expressed as the failure of the energy-momentum tensor to be locally conserved for each fluid component separately:

$$\partial_\nu T_i^{\mu\nu} = \mathcal{S}_i^\mu \equiv \sum_j \int d\Gamma_p p^\mu \mathcal{C}_{ij}(x, p), \quad (4)$$

where  $d\Gamma_p = d^3p / (2\pi)^3 p^0$  is the invariant volume element in momentum space and  $\mathcal{S}_i^\mu$  is the covariant dissipation four-vector.

**Hidrodynamical analysis of  $\pi$ , K, p data (P. Lévai, B. Müller PRL, '91)**

# 2016 – Latest experimental results at RHIC and LHC: azimuthal particle distributions and anisotropic flow



**Spatial anisotropy**

→ eccentricities

**2: ellipticity**

**3: triangularity**

**4: quadracity**

**5: pentacity**

$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2}}{\langle r^n \rangle}$$

→ Investigating peripheral AA collisions

→ Overlap region is asymmetric in space, almond shape (or more complicated)

→ Spatial anisotropy generates momentum anisotropy, this is „pressure induced” → EOS

→ Fourier decomposition of the azimuthal particle distributions leads to the harmonic flow components

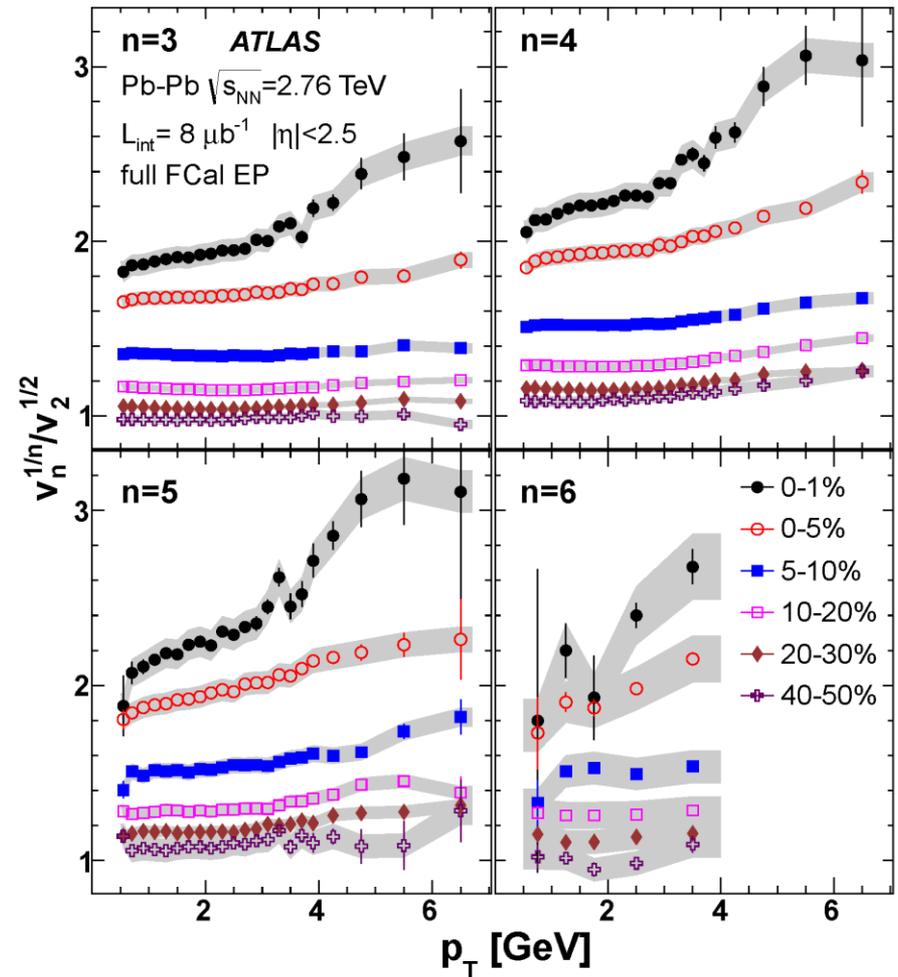
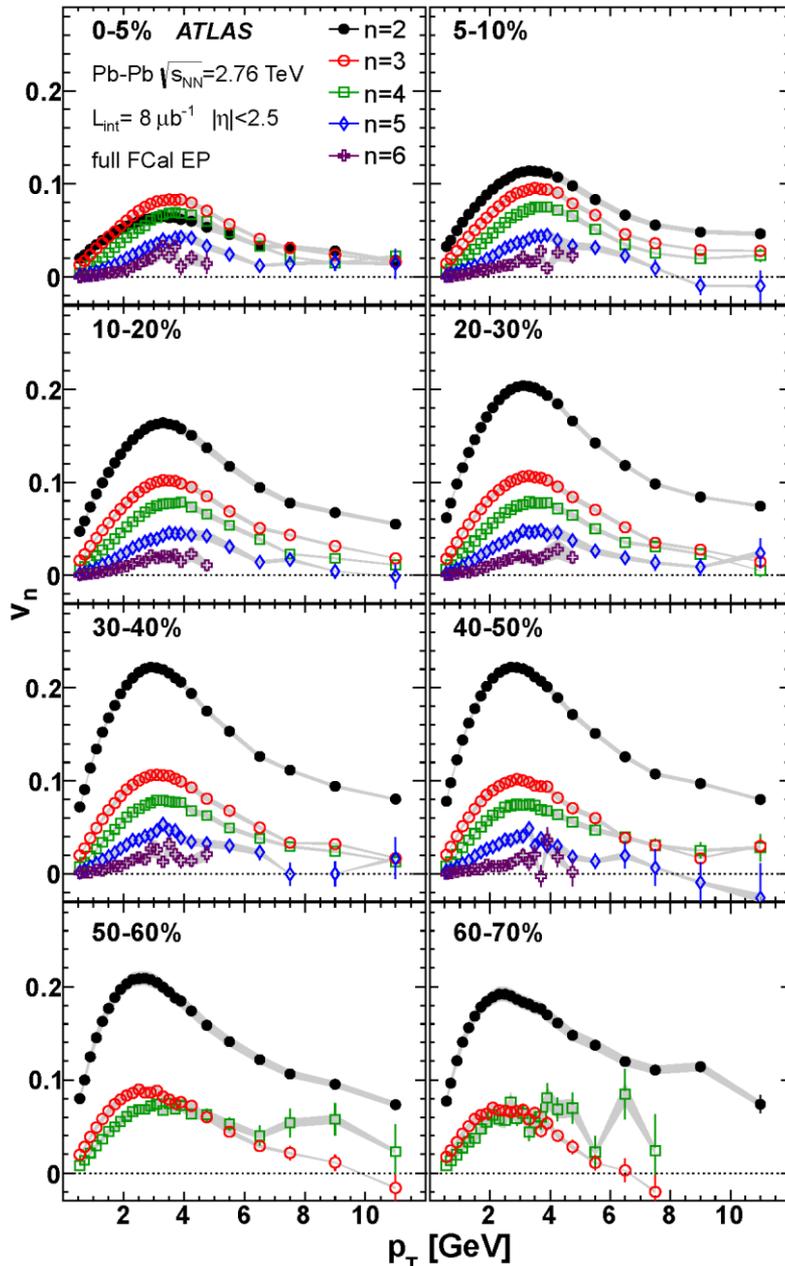
$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left( 1 + \sum_n 2 v_n \cos(n\phi) \right)$$

**v1: directed flow; v2: elliptic flow; v3: ...**

# Experimental results on $v_n$ : PbPb, $\sqrt{s}=2.76$ ATeV ATLAS

PRC86 (2012) 014907, ArXiv: 1203.3087

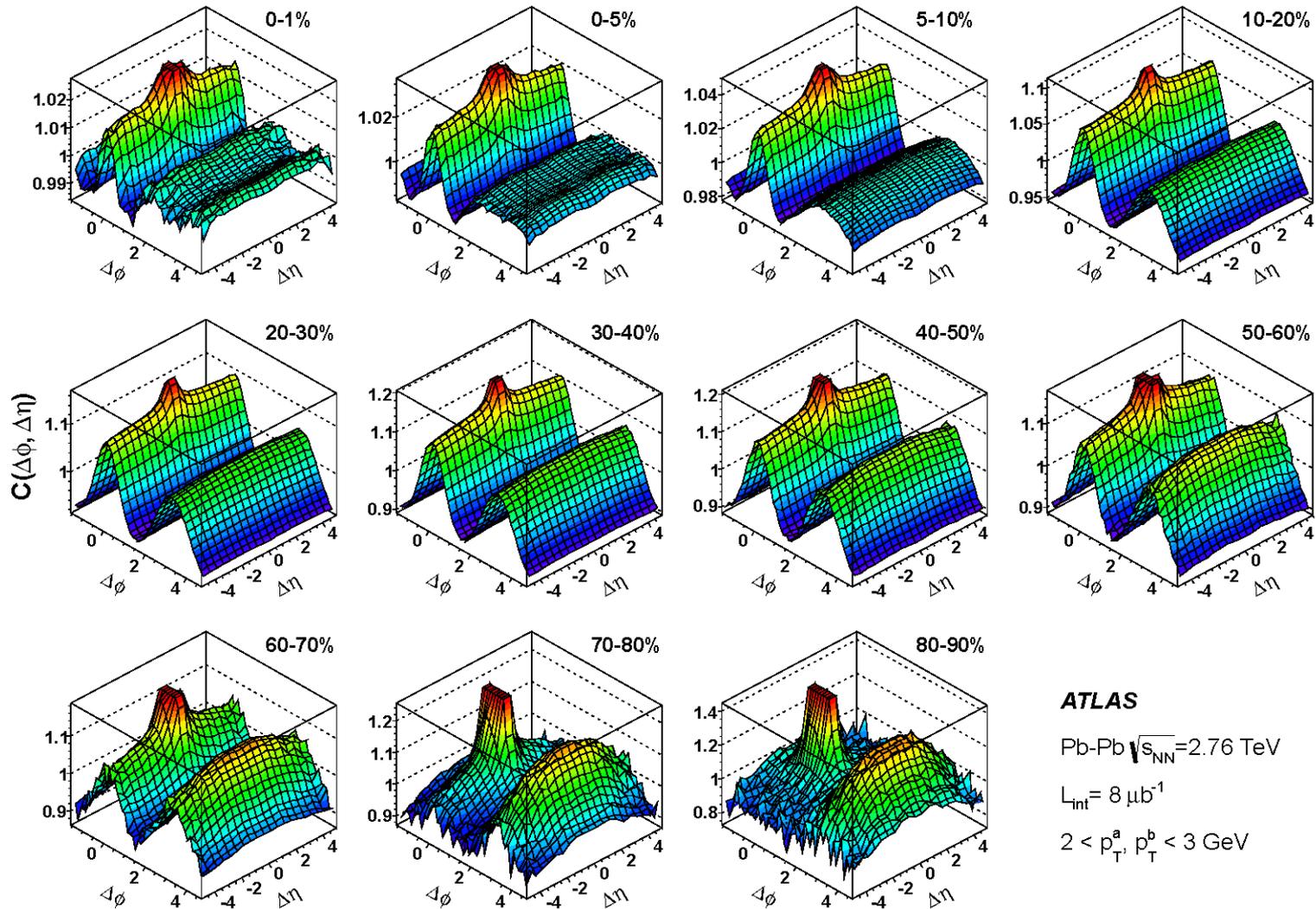
$v_2, v_3, v_4, v_5$  and  $v_6$  at different centralities  
and the scaling  $(v_n)^{1/n}$   
for central and peripheral collisions



# Experimental results on $v_n$ : PbPb, $\sqrt{s}=2.76$ ATeV ATLAS

PRC86 (2012) 014907, ArXiv: 1203.3087

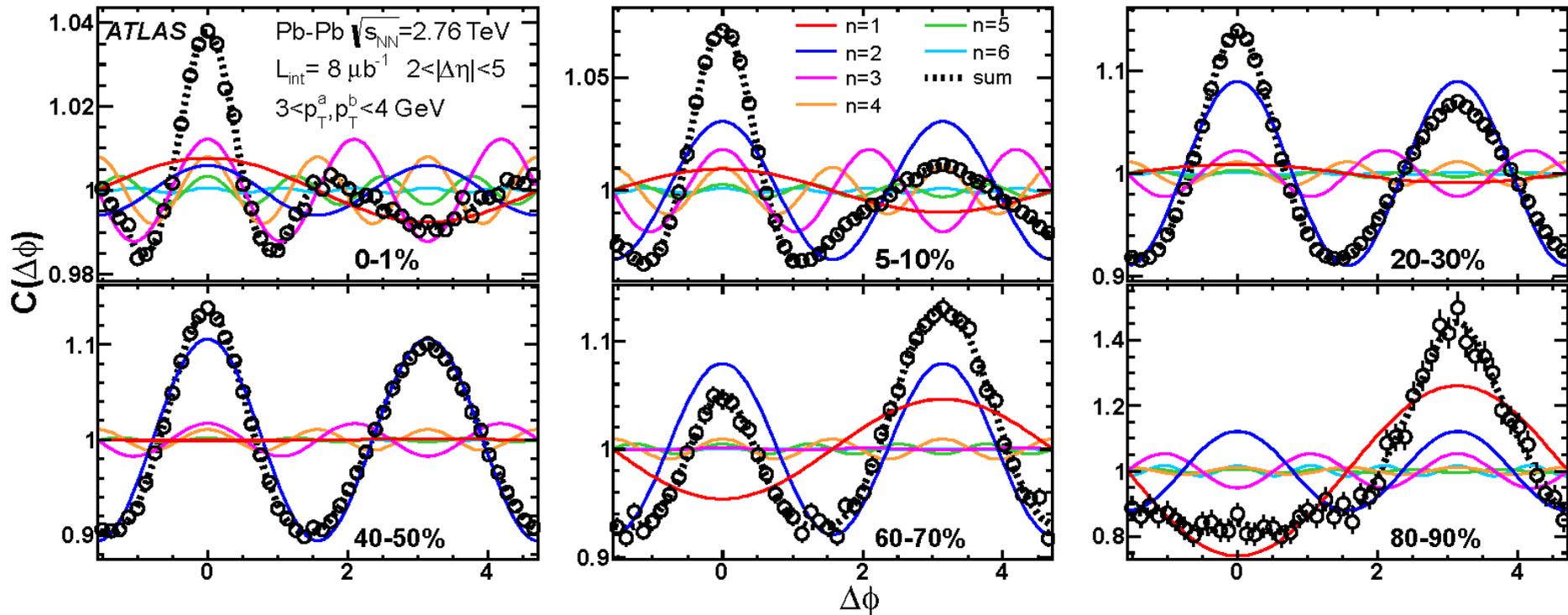
## Long range correlations and ridge in PbPb at different centralities



# Experimental results on $v_n$ : PbPb, $\sqrt{s}=2.76$ ATeV ATLAS

PRC86 (2012) 014907, ArXiv: 1203.3087

## Superposition of flow harmonics $v_1, v_2, v_3, v_4, v_5$ and $v_6$ at different centralities



**Bye-bye shock-wave and  
gluonic Cherenkov radiation !**

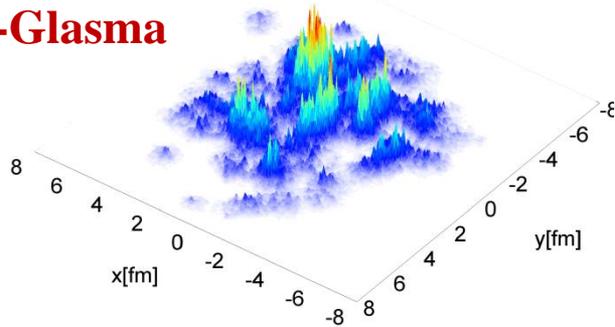
# Theoretical investigations, following the Standard Model of HIC

## Initial Conditions – Energy Density Profiles in AuAu at RHIC energies

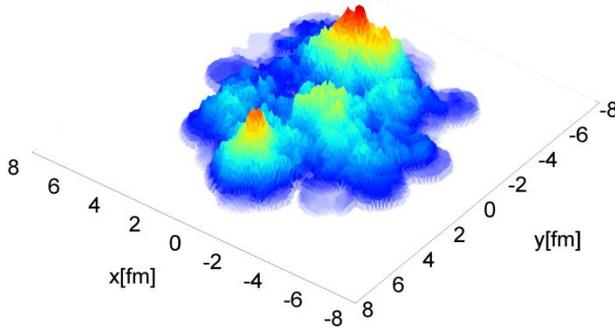
B. Schenke, P. Tribedy, R. Venugopalan, PRL108 (2012) 252301, PRC86 (2012) 034908.

[Glasma  $\rightarrow$  hydro :  $\tau(\text{switch}) \approx 1/Q_s = 0.2 - 0.4 \text{ fm/c}$ ]

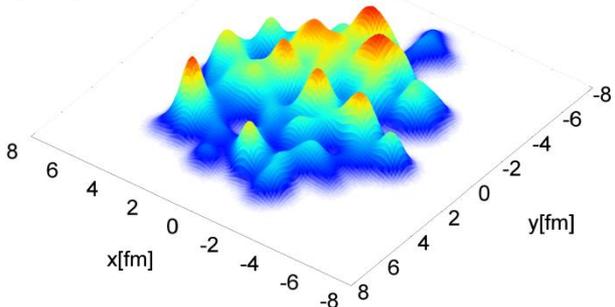
**IP-Glasma**



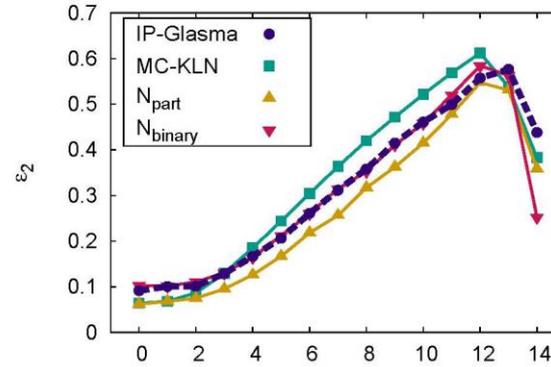
**MC-KLN**



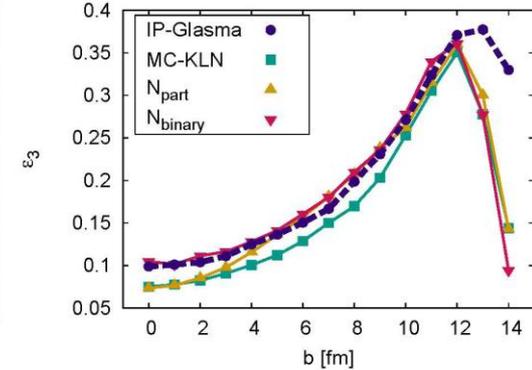
**MC-Glauber**



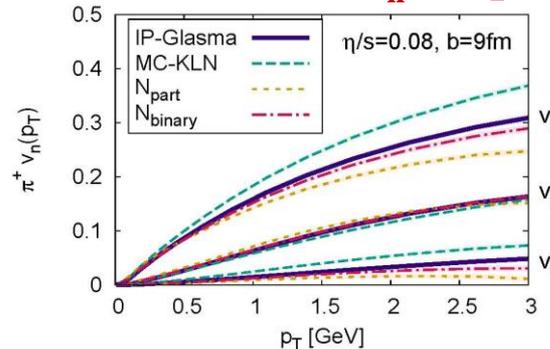
$\epsilon_2$  : ellipticity



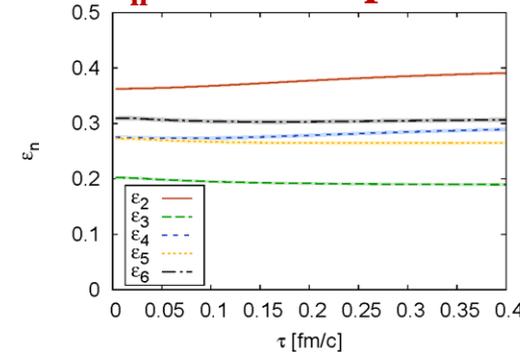
$\epsilon_3$  : triangularity



$v_n$  for pions



$\epsilon_n$  time independ.



„... the change in all  $\epsilon_n$  is very weak over the first 0.4 fm/c. After this time all  $\epsilon_n$  begin dropping as the systems is freely streaming and hence becoming more isotrop.” (Schenke et al, PRC86)

When will the  $v_n$  be developed ?

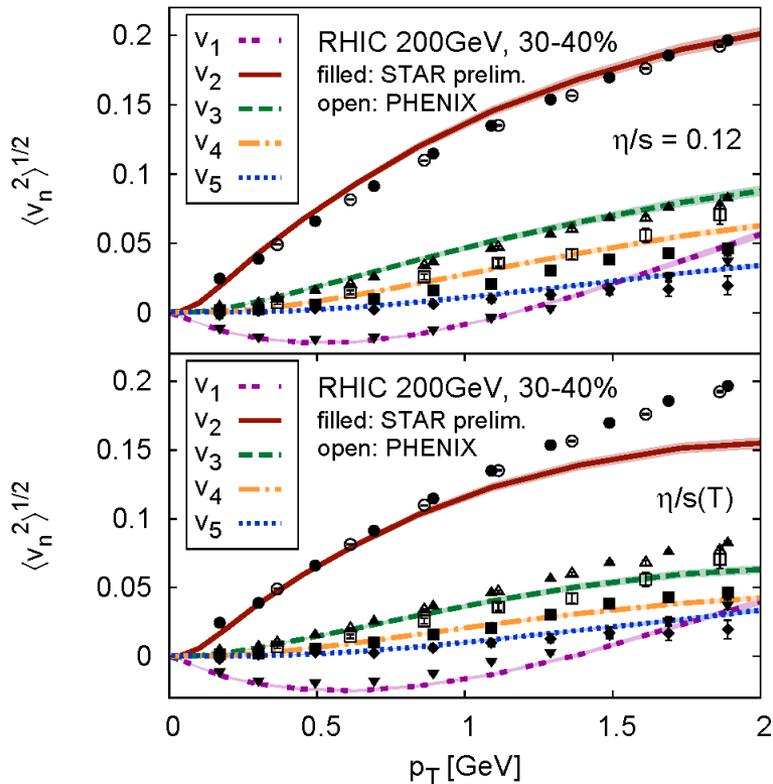
# Theoretical investigations, following the Standard Model of HIC

## Sensitivity of the harmonic flow components on $\eta/s$ and the time evolution

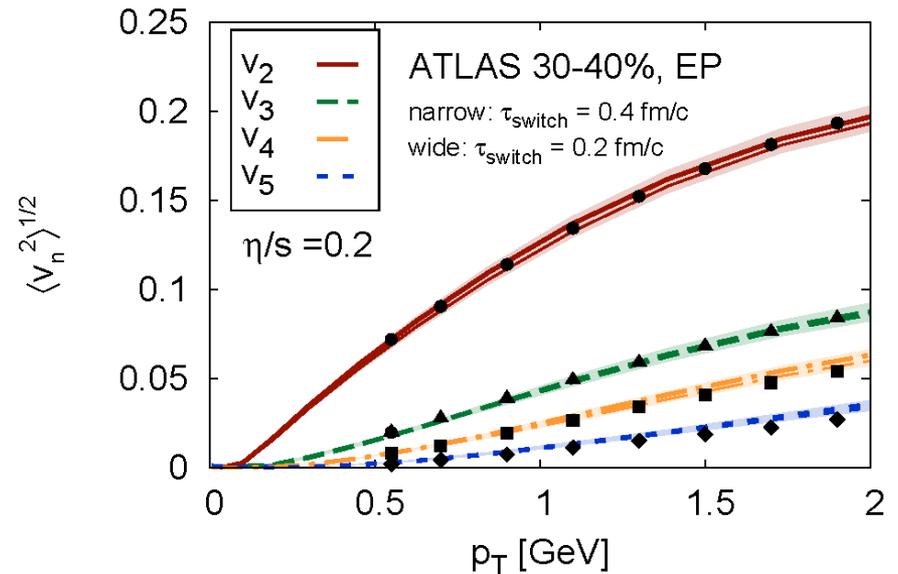
C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, PRL109 (2013) 012302.

IP-Glasma + MUSIC hydro

[Glasma  $\rightarrow$  hydro :  $\tau(\text{switch}) \approx 1/Q_s = 0.2 - 0.4$  fm/c ]



**Middle size sensitivity of  $v_n$  on the viscosity  $\eta/s$  at RHIC energy**

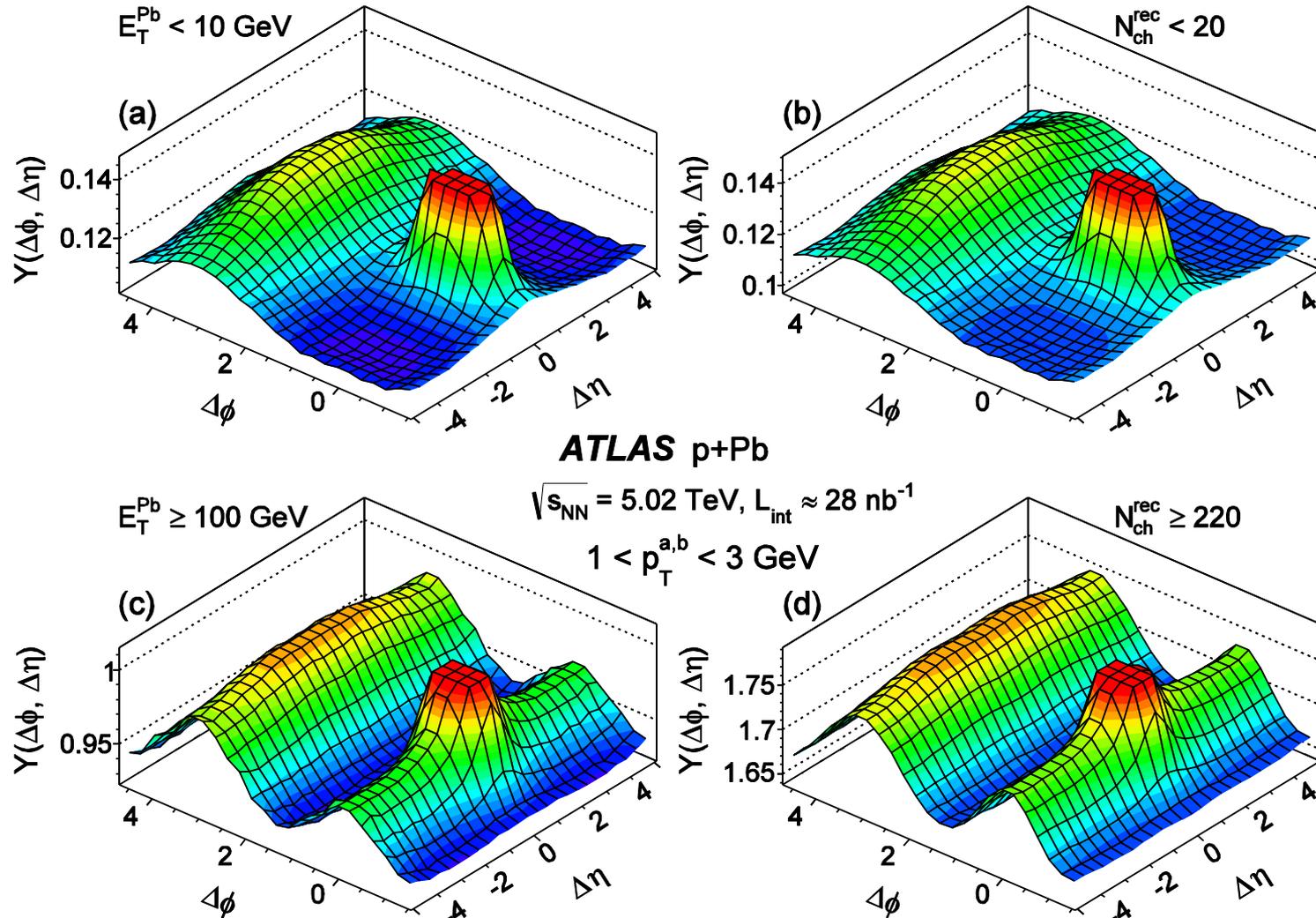


**Weak sensitivity of  $v_n$  on the switching time  $\tau$  between IP-Glasma state and hydrodynamics at LHC energy**

# Experimental results on $v_n$ : pPb, $\sqrt{s}=5.02$ TeV from ATLAS

PRC90 (2014) 044906 (Oct 2014), Arxiv: 1409.1792

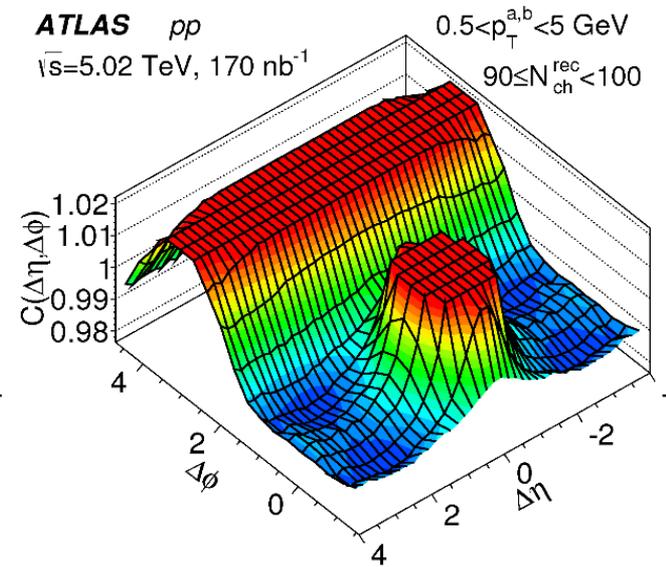
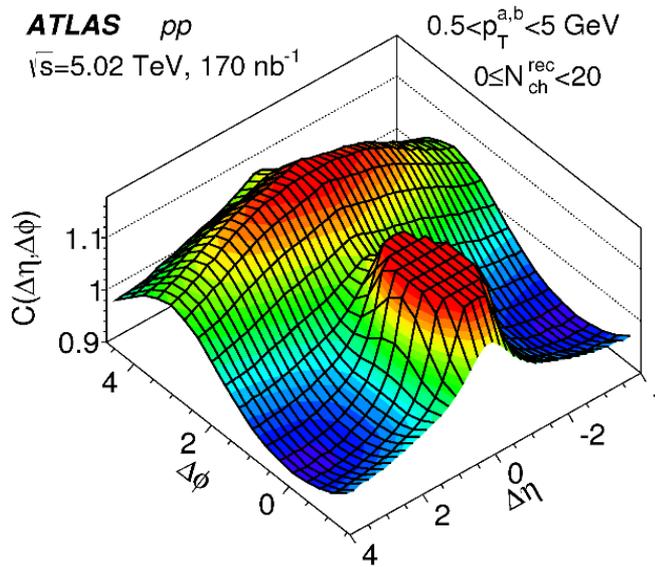
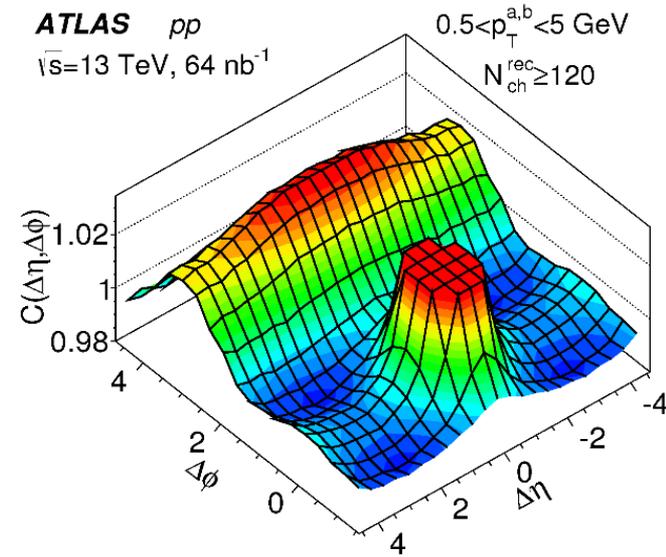
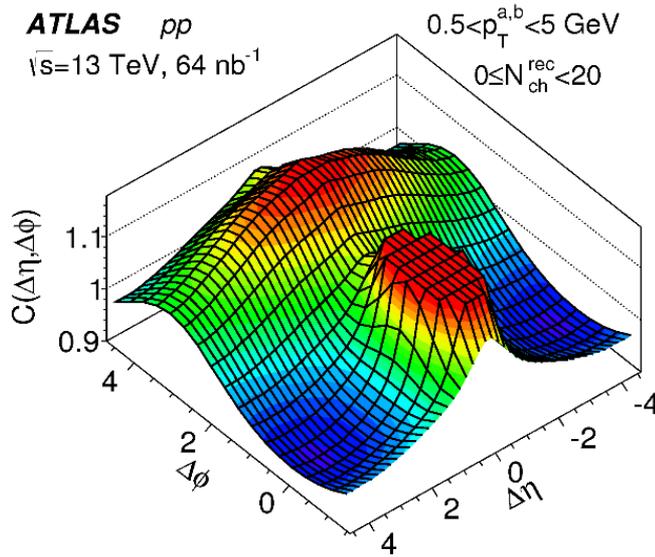
## Long range correlations and ridge in pPb at small and large multiplicities



# Latest experimental results on $v_n$ : pp, $\sqrt{s}=5, 13$ TeV from ATLAS

ArXiv: 1609.06213

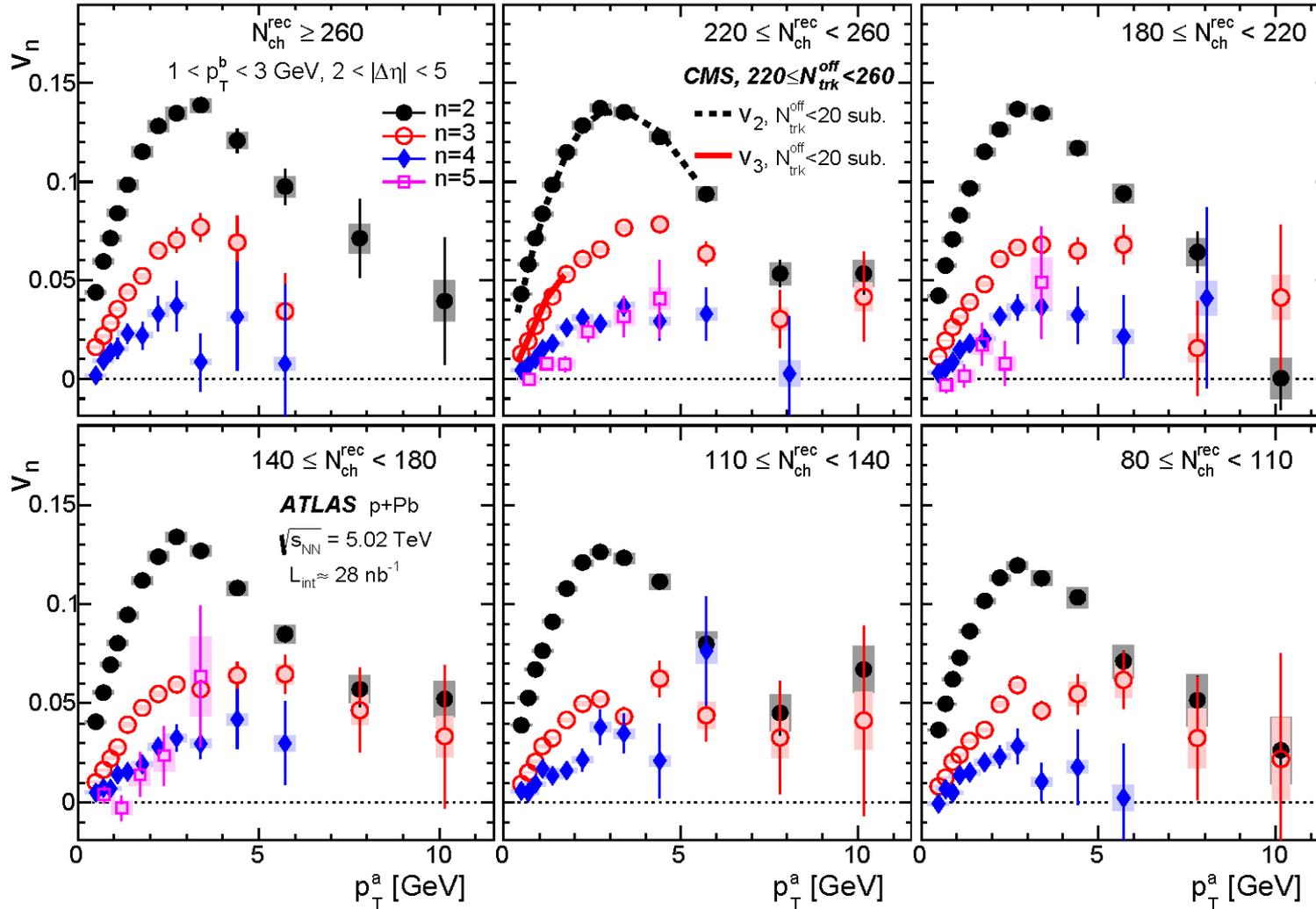
## Long range correlations and ridge in pp at large multiplicities !!



# Experimental results on $v_n$ : pPb, $\sqrt{s}=5.02$ TeV from ATLAS

PRC90 (2014) 044906, Arxiv: 1409.1792

## $v_2, v_3, v_4$ and $v_5$ in pPb at different (high) multiplicities

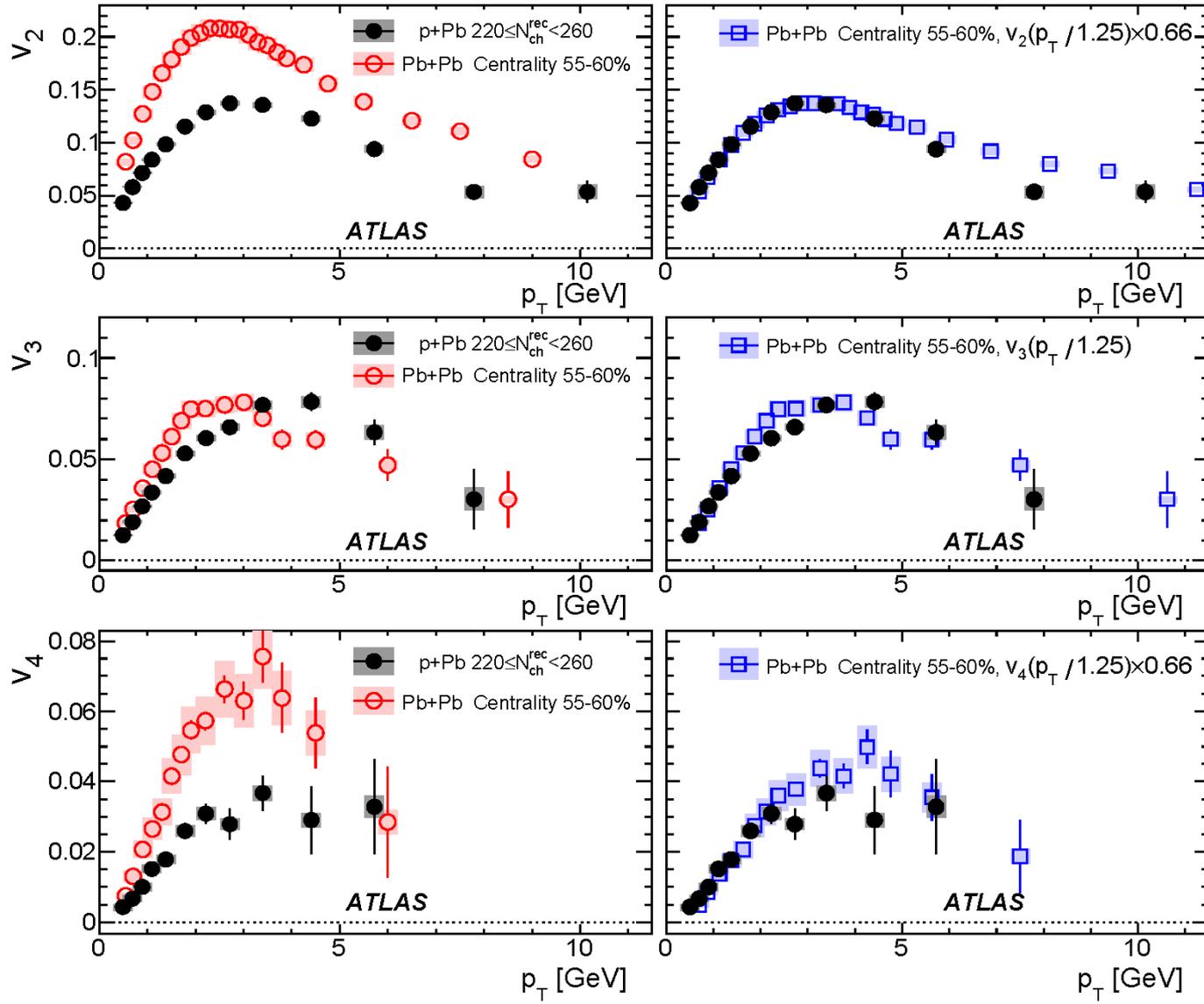


For  $v_n$   
ATLAS and  
CMS results  
overlap

# Experimental results on $v_n$ : pPb, $\sqrt{s}=5.02$ TeV from ATLAS

PRC90 (2014) 044906, Arxiv: 1409.1792

## $v_2, v_3$ and $v_4$ in pPb and in peripheral PbPb at fix multiplicity window



**Magic factors:**  
 $0.66 \times v_n(p_T/1.25)$

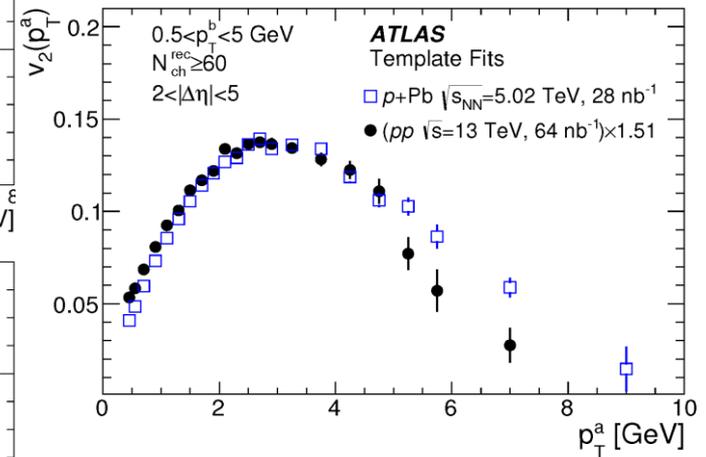
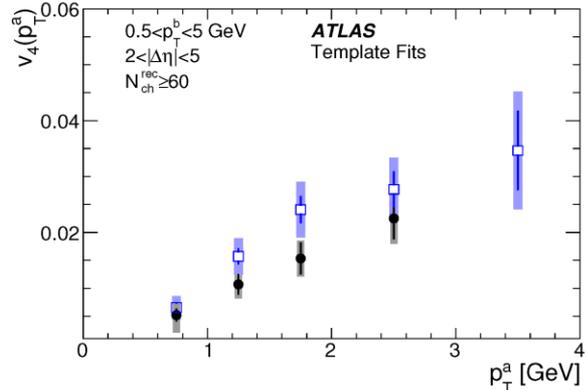
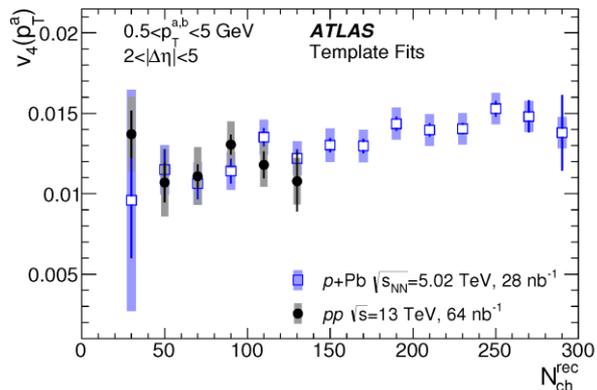
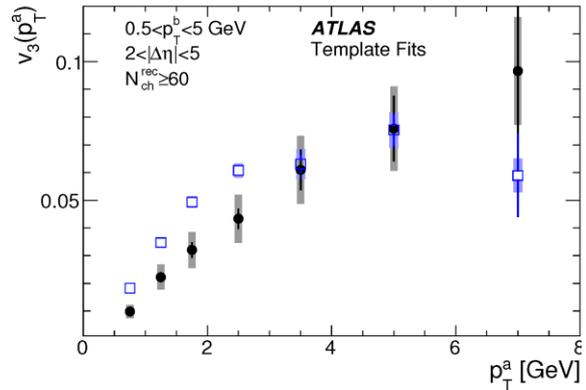
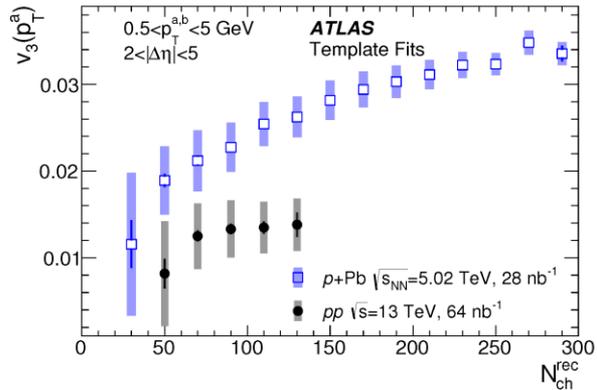
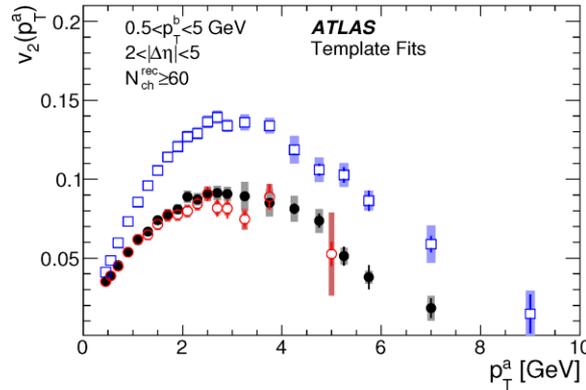
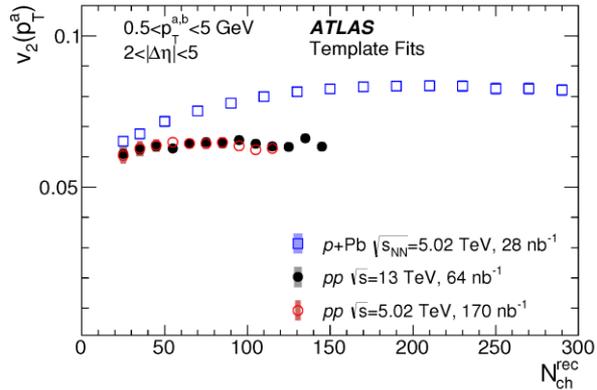
**Explanation ?!**

# Latest experimental results on $v_n$ : pp, $\sqrt{s}=5, 13$ TeV from ATLAS

ArXiv: 1609.06213

$v_2, v_3$  and  $v_4$  in pp, pPb  
at low & high multiplicities

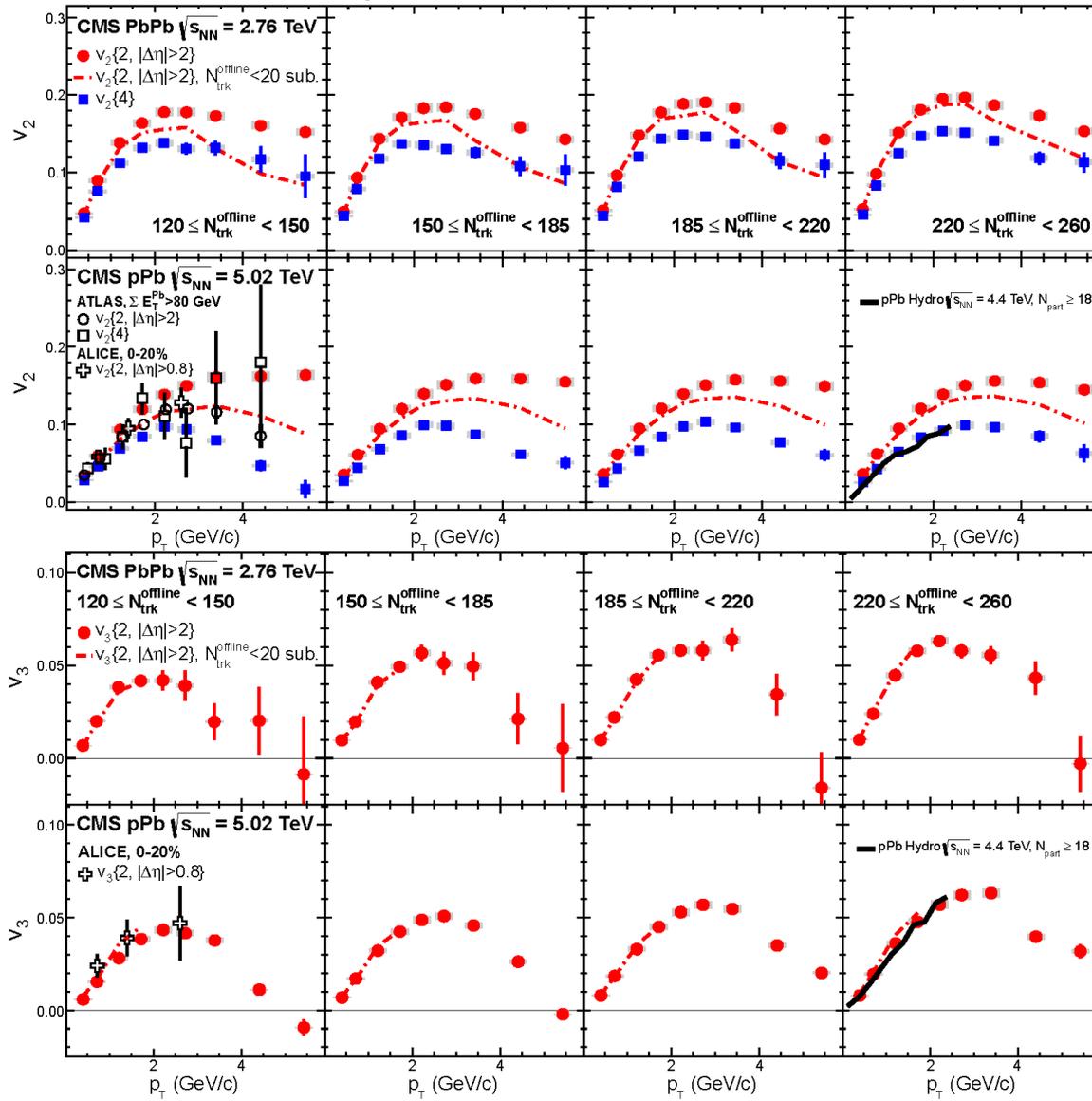
For  $v_2$   
pPb and pp results  
Overlap with  
Magic factor x 1.51



# Experimental results on $v_n$ : pPb, $\sqrt{s}=5.02$ TeV from CMS

PLB724 (2013) 213., Arxiv: 1305.0609

## $v_2\{2\}$ and $v_3\{2\}$ in pPb and peripheral PbPb in fix-multiplicity windows

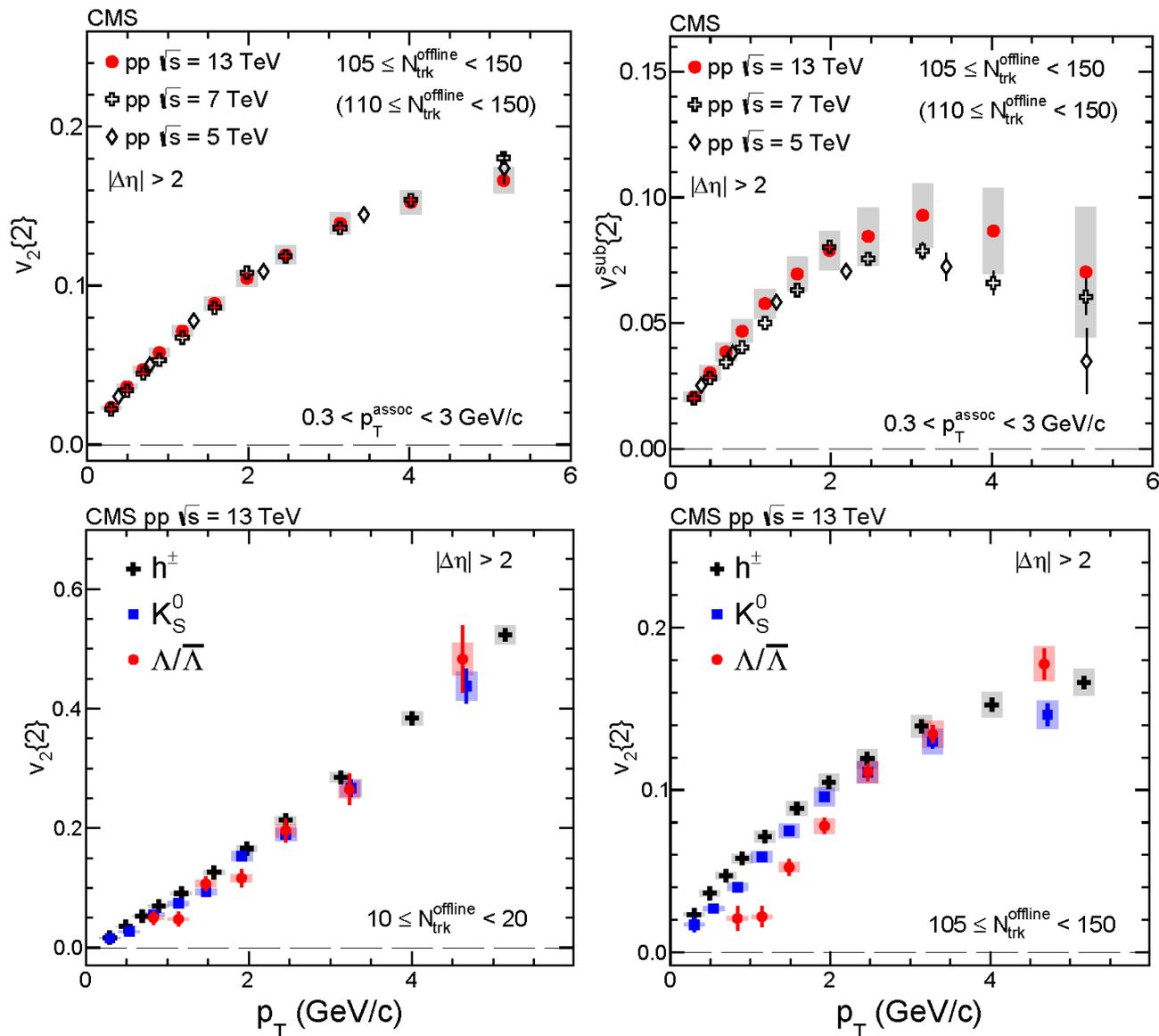


For  $v_2\{2\}$ ,  $v_3\{2\}$ ,  $v_2\{4\}$   
CMS, ALICE and  
ATLAS results overlap

# Latest experimental results on $v_n$ : pp, $\sqrt{s}=5,7,13$ TeV from CMS

Arxiv: 1606.06198

## $v_2\{2\}$ in pp in high-multiplicity windows

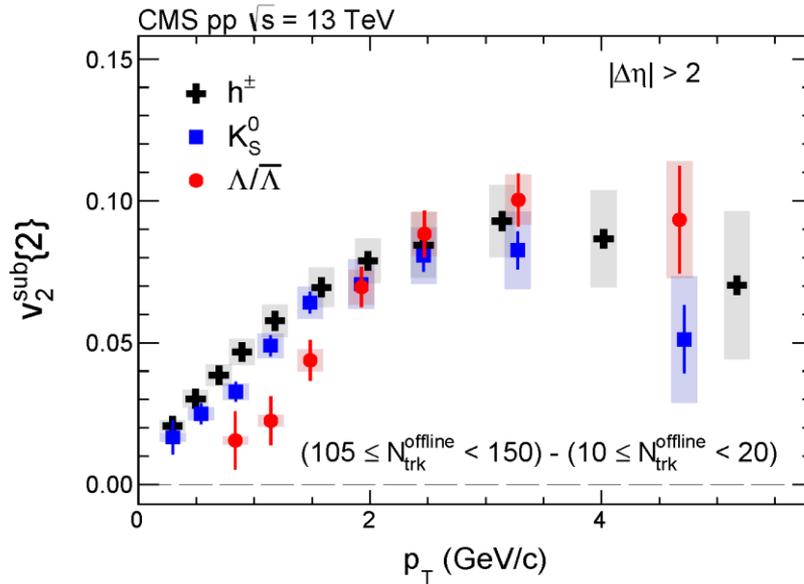


**Flavour and  
Mass dependence  
in the CMS results**

# Latest experimental results on $v_n$ : pp, $\sqrt{s} = 13$ TeV from CMS

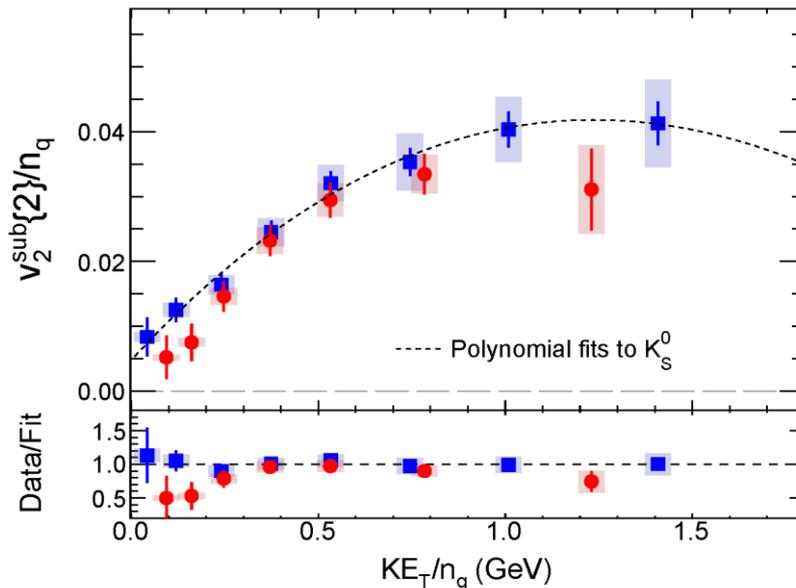
Arxiv: 1606.06198

$v_2\{2\}$  in pp in high-multiplicity windows



Flavour and mass dependence  
in the CMS results for pp collision

Nq-scaling ????



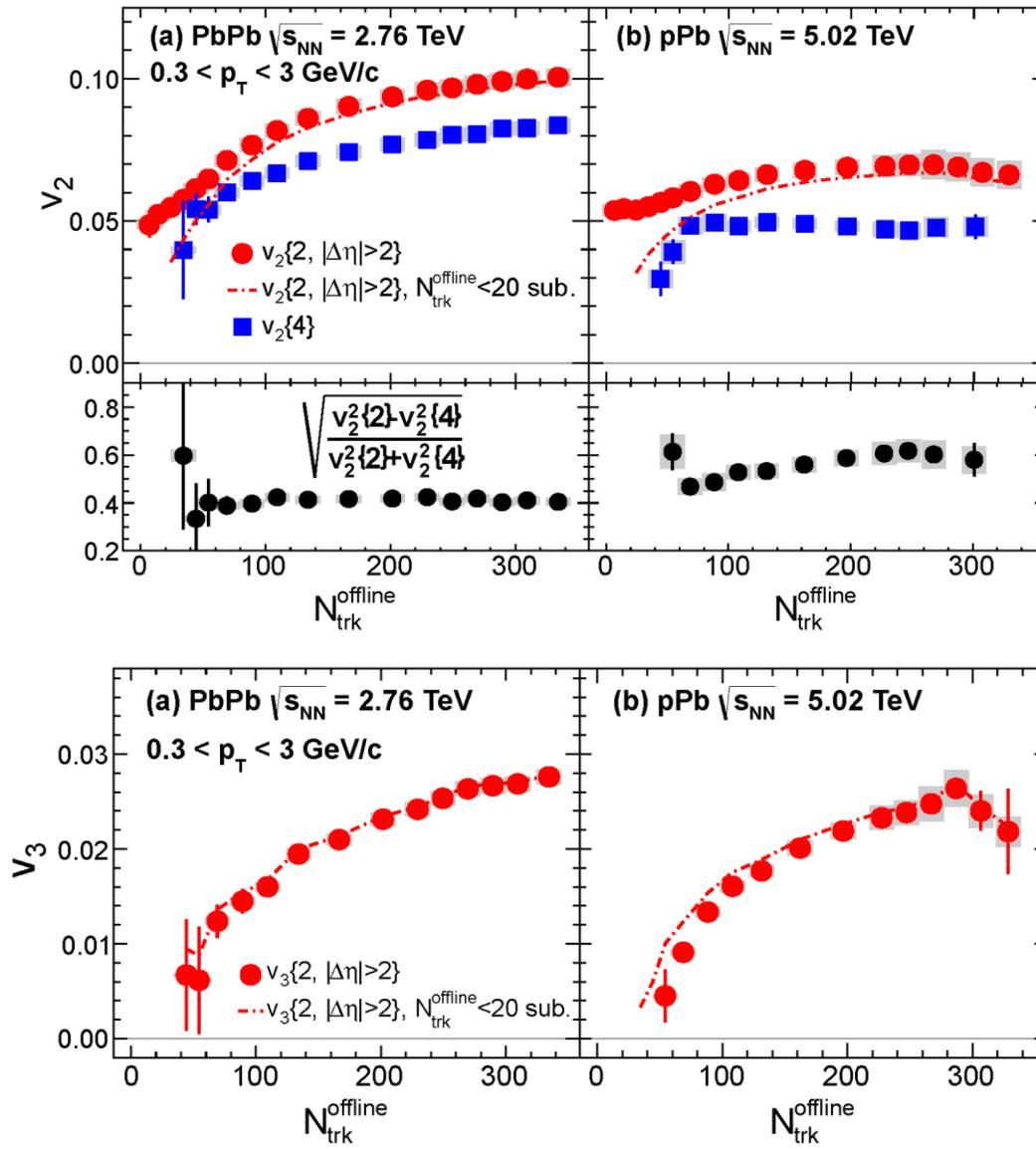
R.C. Hwa, C.B. Yang, PRC 2011:  
Ridge in pp collision at 7 TeV

Investigate proton/pion ratio!!!

# Experimental results on $v_n$ : pPb, $\sqrt{s}=5.02$ TeV from CMS

PLB724 (2013) 213., Arxiv: 1305.0609

## $v_2\{2\}$ and $v_3\{2\}$ in pPb and peripheral PbPb at fix multiplicity window



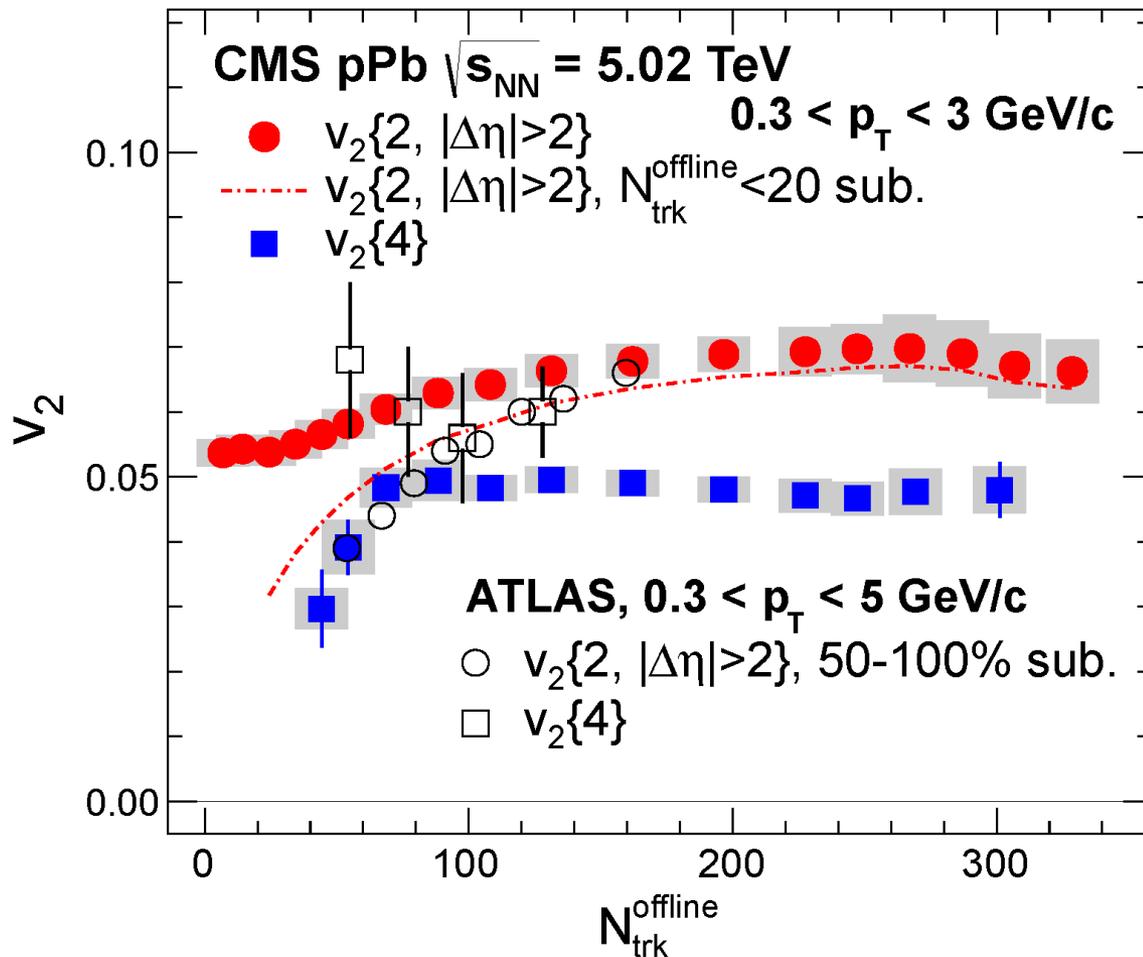
**Fluctuations:**  
**40 % in PbPb**  
**50-60 % in pPb**  
residual nonflow correlations  
from back-to-back jets  
Similar to RHIC results !

$v_3\{2\}$  are just the same  
in pPb and PbPb  
as the function of  $N_{trk}$   
at long range,  $|\Delta\eta| > 2$ !

# Experimental results on $v_n$ : pPb, $\sqrt{s}=5.02$ TeV from CMS

PLB724 (2013) 213., Arxiv: 1305.0609

$v_2\{2\}$  and  $v_2\{4\}$  in pPb and peripheral PbPb at fix multiplicity window



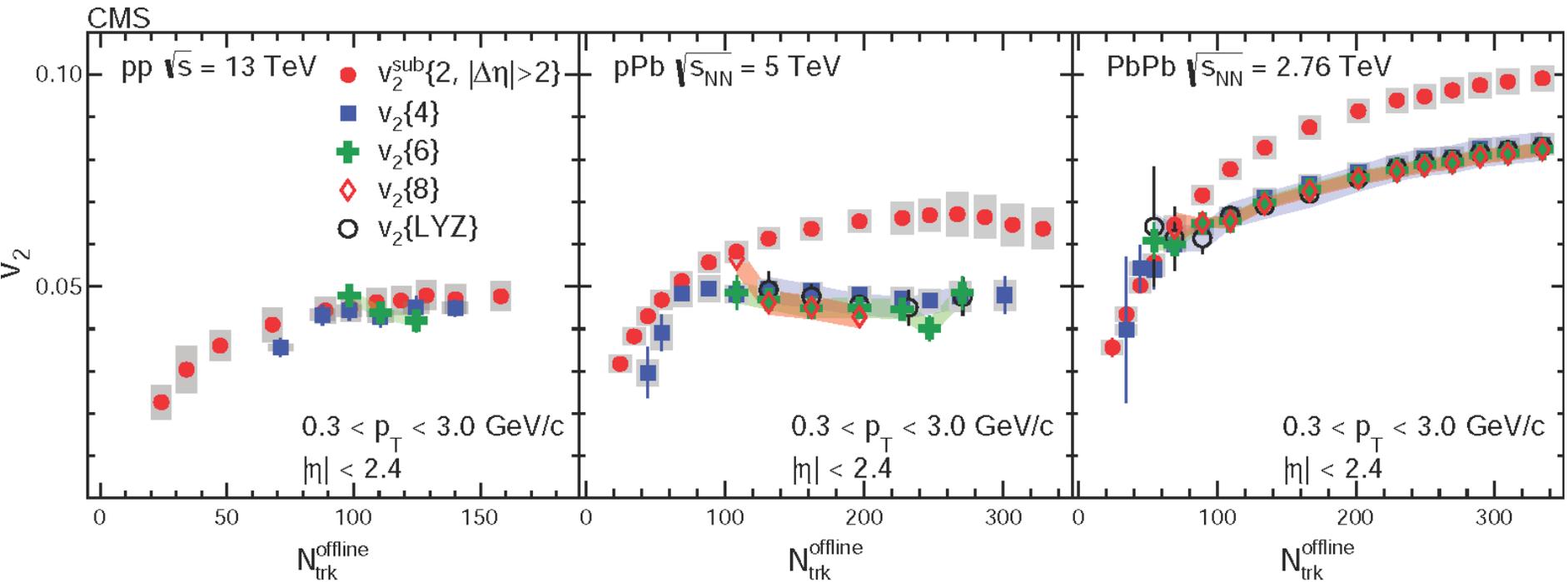
**CMS and ATLAS data on  $v_2\{2\}$  slightly differ, but not very much. (slightly diff. windows)**

**ATLAS also claims the presence of large fluctuations in pPb collisions**

# Latest experimental results on $v_n$ : pp, pPb, PbPb at $\sqrt{s}=13, 5, 2.76$ ATeV from CMS

Arxiv: 1606.06198

## Analyzing $v_2\{N\}$ in pp, pPb and PbPb



**CMS: Fluctuations are larger in pp than in pPb and PbPb !!!!**  
**Interesting measure for defining collectivity !**

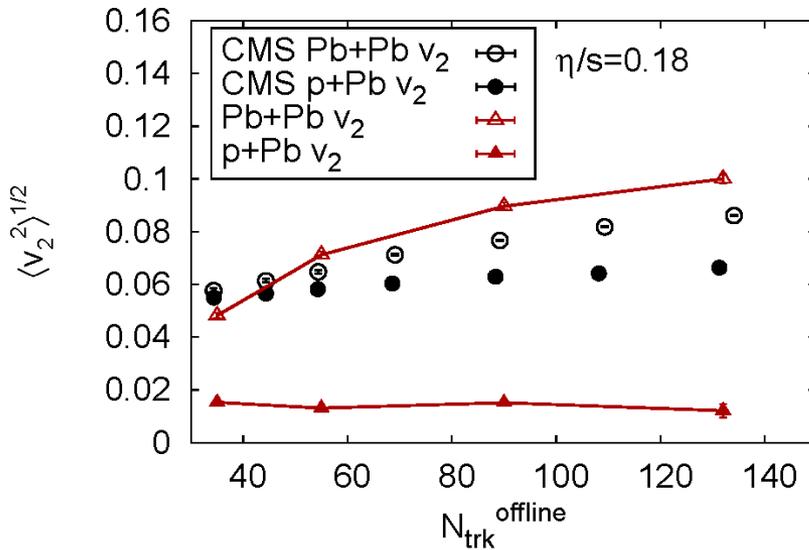
# Theoretical investigations, following the Standard Model of HIC for pPb

## Sensitivity of the harmonic flow components on $\eta/s$ and the time evolution

B. Schenke, R. Venugopalan, PRL113 (2014) 102301, Arxiv: 1405.3605

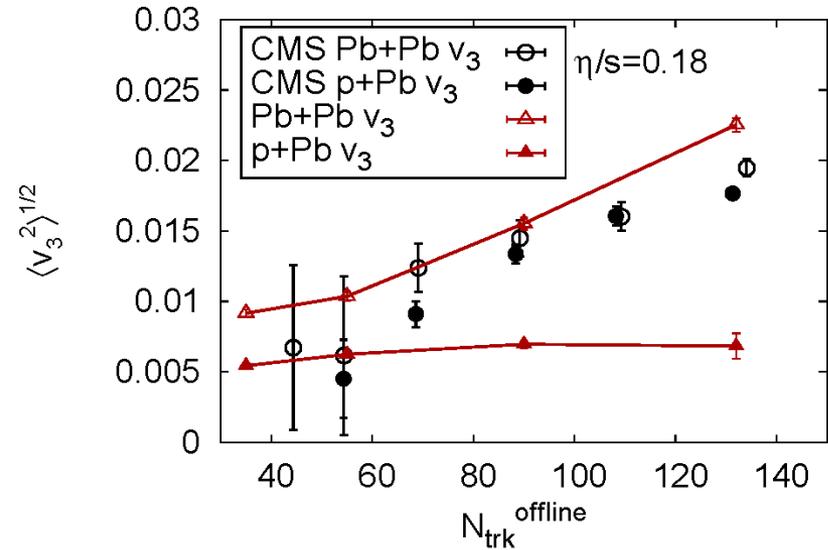
IP-Glasma + MUSIC hydro

[Glasma  $\rightarrow$  hydro :  $\tau(\text{switch}) \approx 1/Q_s = 0.2 - 0.4 \text{ fm/c}$  ]



CMS data and theory for  $v_2$

PbPb results can be reproduced  
pPb data are underestimated by  
IP-Glasma+ MUSIC model  
at LHC energy



CMS data and theory for  $v_3$

PbPb results can be reproduced  
pPb data are underestimated by  
IP-Glasma+ MUSIC model  
at LHC energy

„... possible breakdown of the hydrodynamical paradigm ,  
when (it is) extended to very small systems.”

**Recent data indicates strong similarities for anisotrop flow components in pPb collisions and peripheral PbPb collisions at the same multiplicity windows.**

**First conclusion: hydrodynamical behaviour in pPb at LHC energies**

**But:**

**Fluctuation contributions seems to be large**

**Hybrid model (IP Glasma + MUSIC) does not work for pPb, although it was working for PbPb collisions.**

**Our suggestion:**

**Non-abelian beam jet bremsstrahlung**

**Projectile beam jet form Color Scintillation Antenna (CSA)**

**Bremsstrahlung from CSA clusters and arrays**

**Analitic calculations on the basis of GLV approximation**

**Including GLVB into HIJING for numerical calculations**

**Phys. Rev. D90 (2014) 054025. hep-ph/1805.7825**

**Non-Abelian Bremsstrahlung and Azimuthal Asymmetries in High Energy p+A**

M. Gyulassy,<sup>1,2,\*</sup> P. Levai,<sup>1</sup> I. Vitev,<sup>3</sup> and T. Biro<sup>1</sup>

<sup>1</sup>*MTA WIGNER Research Centre for Physics, RMI, Budapest, Hungary*

<sup>2</sup>*Department of Physics, Columbia University, New York, NY 10027, USA*

<sup>3</sup>*Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

(Dated: May 13, 2014 v11)

**II. FIRST ORDER IN OPACITY (GB) BREMSSTRAHLUNG AND AZIMUTHAL ASYMMETRIES  $v_n$**

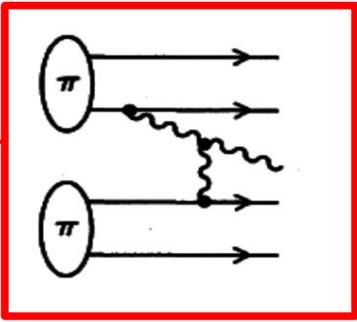
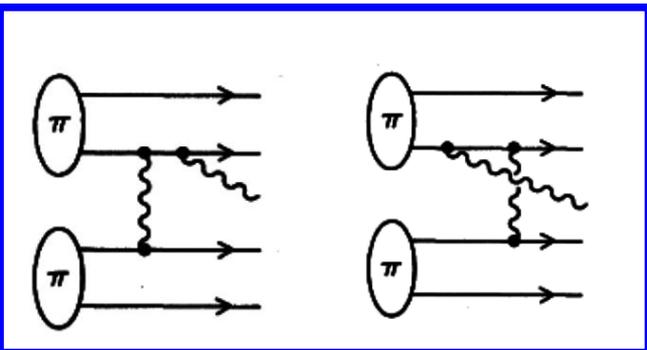
The above puzzles with BES and  $D + Au$  at RHIC and with  $p + Pb$  at LHC and models proposed so far motivate us to consider simpler more basic perturbative QCD sources of azimuthal asymmetries. The well known non-abelian bremsstrahlung Gunion-Bertsch (GB) formula[29] for the soft gluon radiation single inclusive distribution is

$$\frac{dN_g^{(1)}}{d\eta d^2\mathbf{k} d^2\mathbf{q}} \equiv f(\eta, \mathbf{k}, \mathbf{q})$$

$$= \frac{C_R \alpha_s}{\pi^2 k^2} \frac{\mu^2}{(\mathbf{q}^2 + \mu^2)} \frac{P_\eta}{(\mathbf{k} - \mathbf{q})^2 + \mu^2}$$

$$\equiv \frac{F \cdot P}{A_{kq} - \cos(\phi - \psi)}$$

**Color Dipole Form factor**



**Gluon Bremsstrahlung peaks in transverse direction near net momentum transfer  $\mathbf{Q} = (Q, \psi)$  that also defined reaction Event Plane (EP)**

**Basic Non-Abelian feature: uniform rapidity “ridge” (unlike in QED)**

**Also peaks in beam direction  $1/k^2$  (as in QED)**

$\phi$  is the azimuthal angle of  $\mathbf{k}$  and  $\psi$  is the azimuthal angle of  $\mathbf{q}$  and abbreviations

$$A \equiv A_{kq} \equiv (k^2 + q^2 + \mu^2)/(2kq) \geq 1$$

$$F \equiv F_{kq} \equiv \frac{C_R \alpha_s}{\pi^2 k^2} \frac{\mu^2}{(\mathbf{q}^2 + \mu^2)} \frac{1}{2kq} P_\eta$$

**Kinematic rapidity envelope**

$$P_\eta \equiv (1 - e^{Y_T - \eta})^{n_f} (1 - e^{\eta - Y_P})^{n_f} ,$$

$$v_n(k, q, \psi) f_0(k, q) \equiv \int \frac{d\phi}{2\pi} \cos(n\phi) f(\eta, k, \phi, q, \psi)$$

$$= F \int \frac{d\phi}{2\pi} \frac{\cos(n\phi)}{A - \cos(\phi - \psi)}$$

$$= \cos(n\psi) F \int \frac{d\phi}{2\pi} \frac{\cos(n\phi)}{A - \cos(\phi)} .$$

$f_0 \equiv \int d\phi f = \int d\phi d^7 N / d\eta dk^2 d\phi dq^2 d\psi$  is the  $\phi$  integrated single gluon inclusive

$$dN / d\eta dk^2 = F_{kq} P_\eta / (A_{kq}^2 - 1)^{1/2}$$

A single GB color antenna has analytic  $v_n$ :  $A_{kq} \equiv (k^2 + q^2 + \mu^2)/(2kq) \geq 1$

$$v_1^{GB}(k, q, \psi) = \cos[\psi](A_{kq} - \sqrt{A_{kq}^2 - 1})$$

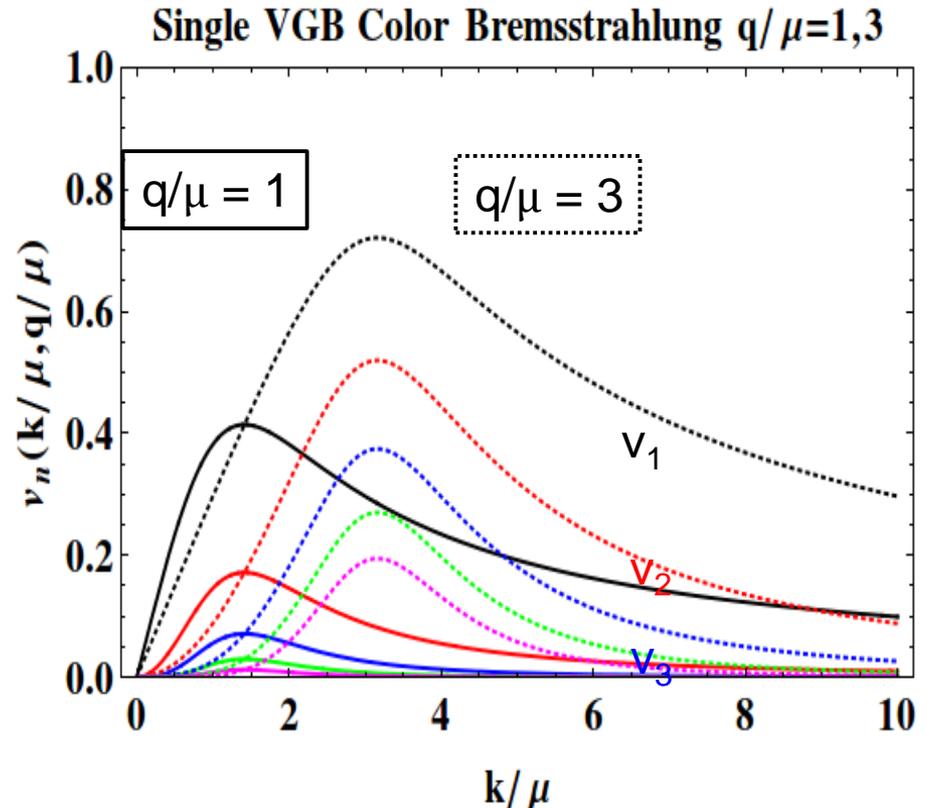
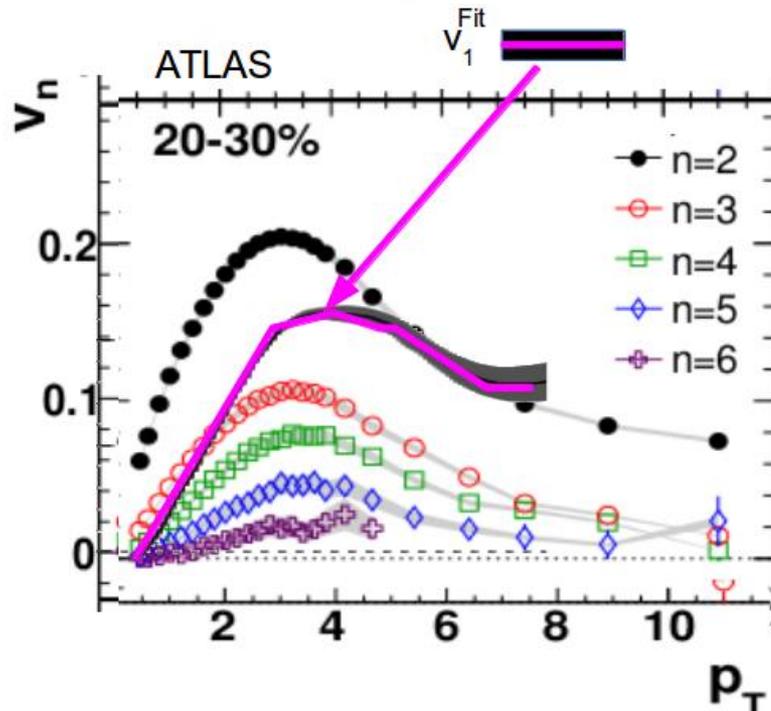
$$\lim_{\mu \rightarrow 0} v_1^{GB}(k, q, 0) = (k/q) \theta(q - k)$$

$$v_n^{GB}(k, q, \psi) = \cos[n\psi] (v_1^{GB}(k, q, 0))^n$$

$$\lim_{\mu \rightarrow 0} v_n^{GB}(k, q, 0) = (k/q)^n \theta(q - k)$$

Perfect  $v_n^{1/n} = v_1$  Scaling

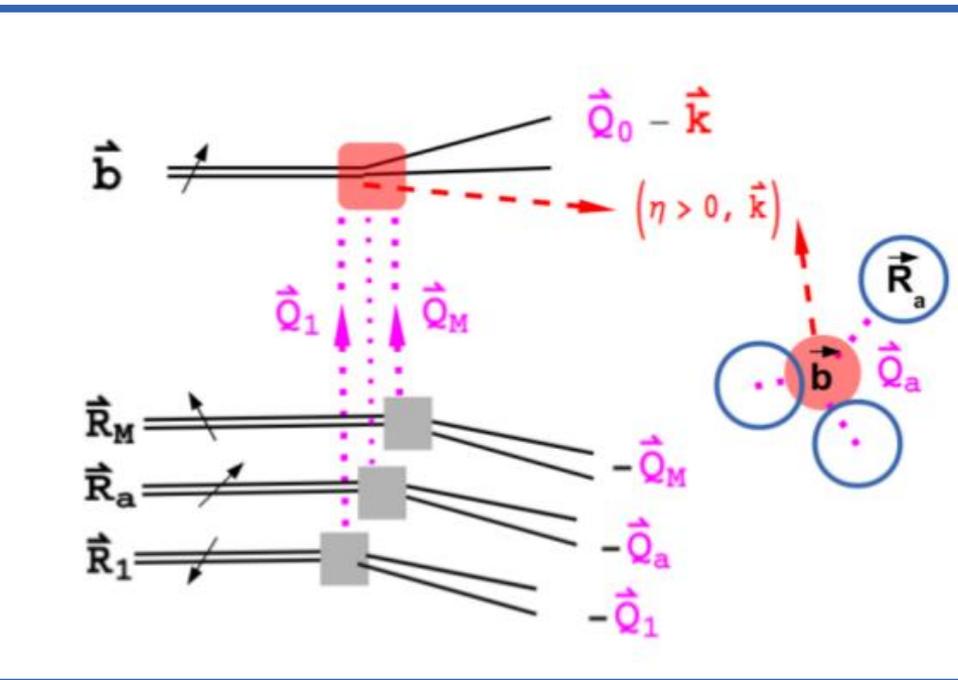
### Two particle $v_n$ from ATLAS



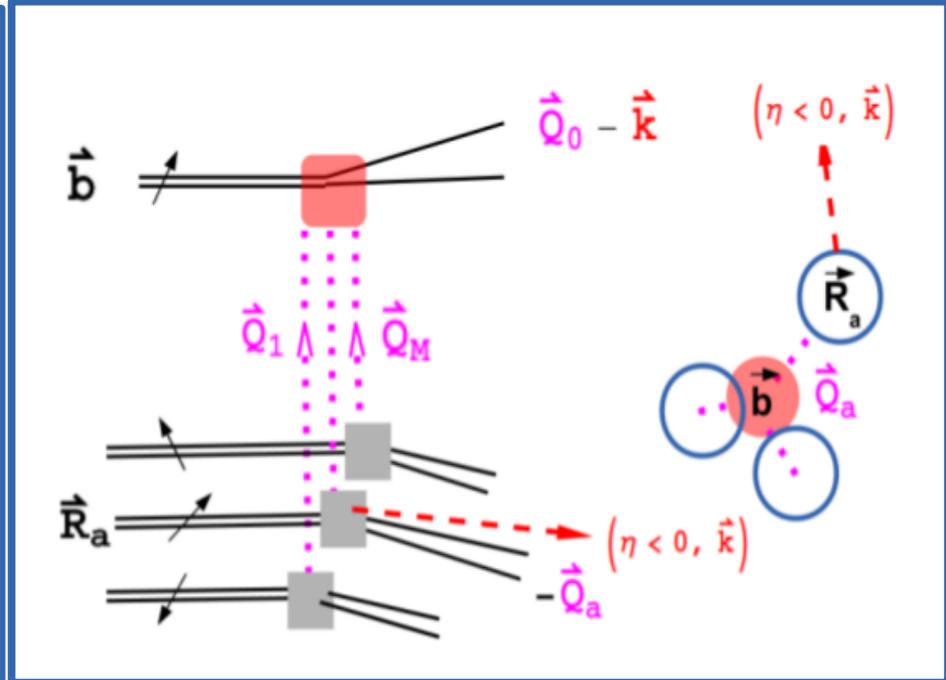
Note intrinsic huge even and odd  $v_n$  peaking near  $\mu \sim Q_{sat}$

# Combined projectile and target participants soft recoil Bremsstrahlung

Projectile Beam Jet Brems.



Participant Recoil Target Beam Jets Brems.



Target dipoles act coherently if transverse separation cannot be resolved

$$R_{ij} \lesssim d(k) = \frac{c}{k}$$

$1 < M < N$  coherent target clusters varies with gluon resolution scale  $k$

If  $i \in I_a$  and  $j \in I_a$  as well as  $j \in I_b$ , then  $j$  is added to  $I_a$  if its  $\langle d_{ij} \rangle_{i \in I_a} < \langle d_{ij} \rangle_{i \in I_b}$

Vitev → all order in opacity multiple scattering VGB generalization of GB Brems.

$$dN_{coh}^{VGB}(\mathbf{k}) = \sum_{n=1}^{\infty} \int d^2\mathbf{Q} P_n^{el}(\mathbf{Q}) dN^{GB}(\mathbf{k}, \mathbf{Q})$$

$$P_n^{el}(\mathbf{Q}) = \exp[-\chi] \frac{\chi^n}{n!} \int \left\{ \prod_{j=1}^n \frac{d^2\mathbf{q}_j}{\sigma_{el}} \frac{d\sigma_{el}}{d^2\mathbf{q}_j} \right\} \times \delta^2(\mathbf{Q} - (\mathbf{q}_1 + \dots + \mathbf{q}_n))$$

Cumulative momentum transfer from n coherent scatterings

At n=N<sup>th</sup> order in opacity with M coherent target clusters that can resolved by k  
Projectile plus Target bremsstrahlung sums to

$$\begin{aligned} dN^{M,N} &= dN_P^N(\eta, \mathbf{k}_1; \mathbf{Q}_P) + dN_T^{M,N}(\eta, \mathbf{k}_1; \{\mathbf{Q}_a\}) \\ &= \sum_{a=0}^M \frac{B_{1a}}{(\mathbf{k}_1 + \mathbf{Q}_a)^2 + \mu_a^2}, \end{aligned}$$

$$\begin{aligned} B_{ia} &\equiv F_{k_i, Q_a} P_a(\eta_i) \\ \mathbf{Q}_0 &\equiv -\mathbf{Q}_P = -\sum_a \mathbf{Q}_a \end{aligned}$$

2 glue Brems in independent emission approx.

$$dN_2^{N,M}(\mathbf{k}_1, \mathbf{k}_2) = \sum_{a=0}^M \sum_{b=0}^M \frac{B_{1a}}{A_{1a} - \cos(\phi_1 + \psi_a)} \frac{B_{2b}}{A_{2b} - \cos(\phi_2 + \psi_b)}$$

## Two gluon relative $\text{Cos}(n(\phi_1 - \phi_2))$ analytic azimuthal harmonics CSA color antennas

$$\begin{aligned}
 f_n^{N,M}(k_1, k_2) &\equiv \int_{-\pi}^{\pi} d\Phi \int_{-\pi}^{\pi} d\Delta\phi \cos(n\Delta\phi) dN_2^{N,M}(k_1, \Phi + \Delta\phi/2, k_2, \Phi - \Delta\phi/2) \\
 &= \sum_{a,b=0}^M B_{1a} B_{2b} \int_{-\pi}^{\pi} d\Phi' \frac{1}{A_{1a} - \cos(\Phi')} \int_{-\pi}^{\pi} d\Delta\phi \frac{\cos(n\Delta\phi)}{A_{2b} - \cos((\Phi' + \psi_b - \psi_a) - \Delta\phi)} \\
 &= \sum_{a,b=0}^M B_{1a} B_{2b} f_{0,1,a} f_{0,2,b} \boxed{(v_1^{GB}(k_1, Q_a) v_1^{GB}(k_2, Q_b))^n \cos(n(\psi_b - \psi_a))}
 \end{aligned}$$

---

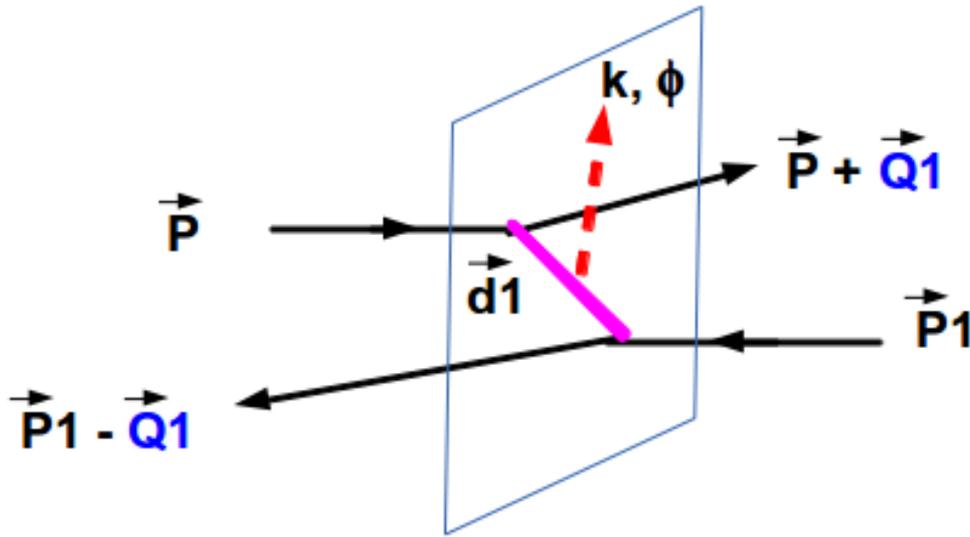

$$f_{n,1,a} = \int_{-\pi}^{\pi} d\Phi \frac{\cos(n\Phi)}{A_{1a} - \cos(\Phi)} = (v_1^{GB}(k_1, Q_a))^n f_{0,1,a} = \frac{(A_{k_1, Q_a} - \sqrt{A_{k_1, Q_a}^2 - 1})^n}{\sqrt{A_{k_1, Q_a}^2 - 1}}$$


---

$$v_n^{M,N}\{2\}[k_1, k_2] \equiv \langle \cos(n(\phi_1 - \phi_2)) \rangle_{k_1, k_2} = \frac{\langle f_n^{M,N}(k_1, k_2) \rangle}{\langle f_0^{M,N}(k_1, k_2) \rangle}$$

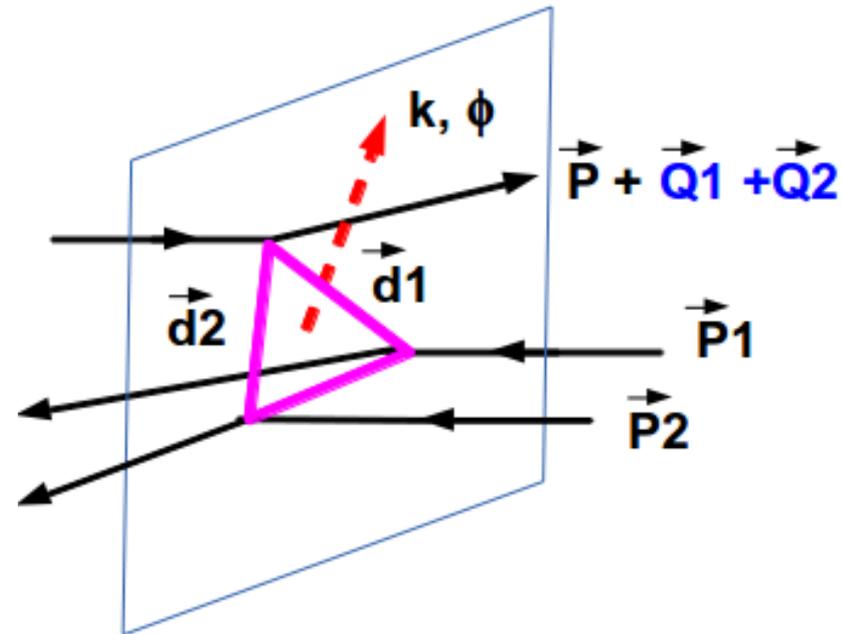
$$\langle \dots \rangle = \int \left\{ \prod_{a=0}^M d\mathbf{Q}_a \right\} \delta\left(\sum_{a=0}^M \mathbf{Q}_a\right) \sum_{m_1, \dots, m_M} \delta\left(N - \sum_{a=1}^M m_a\right) p_{\{m_j\}}^{M,N} P_{m_1}^{el}(\mathbf{Q}_1) \dots P_{m_M}^{el}(\mathbf{Q}_M)$$

# Classical Color Field Produced by 2 or 3 Interfering dipole currents



Two BG dipole antenna array

Produce only  $n=2,4,6, \dots$



Three BG dipole antenna array

Produce all  $n=1, 2, 3, 4, \dots$

**Numerical calculations for pp, pA and AA collisions:  
HIJING model with radiating dipole antennas**

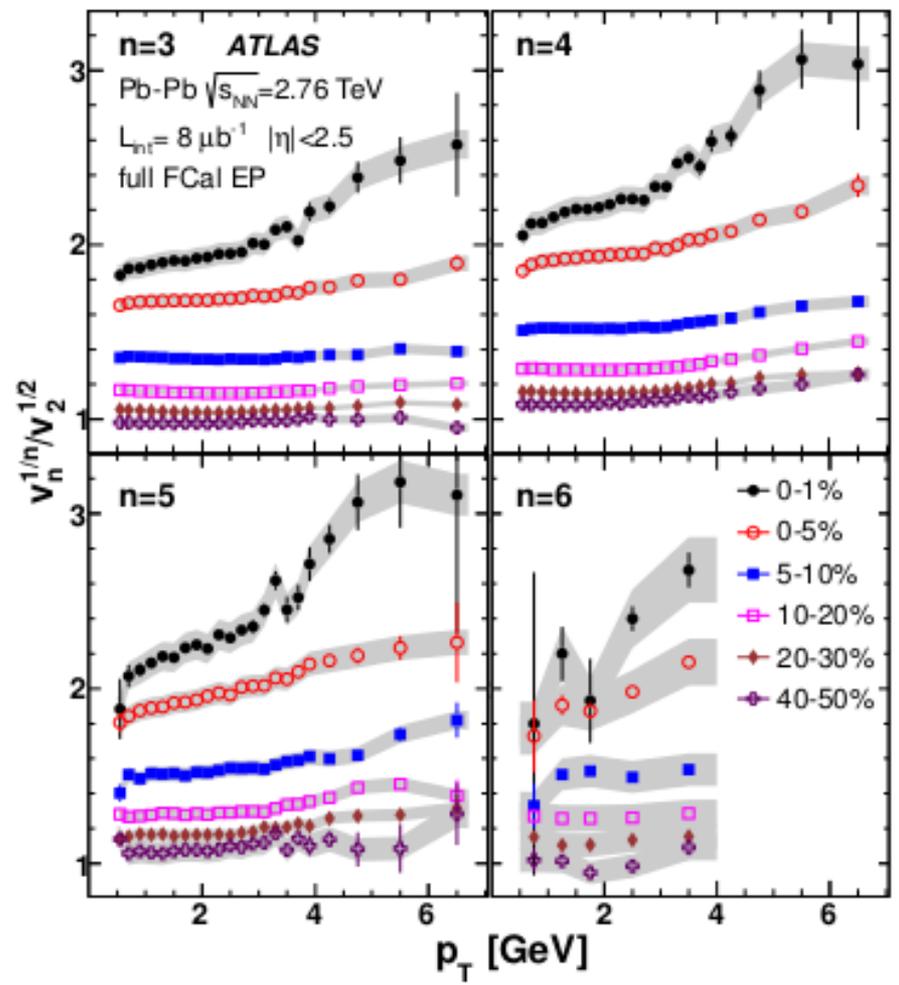
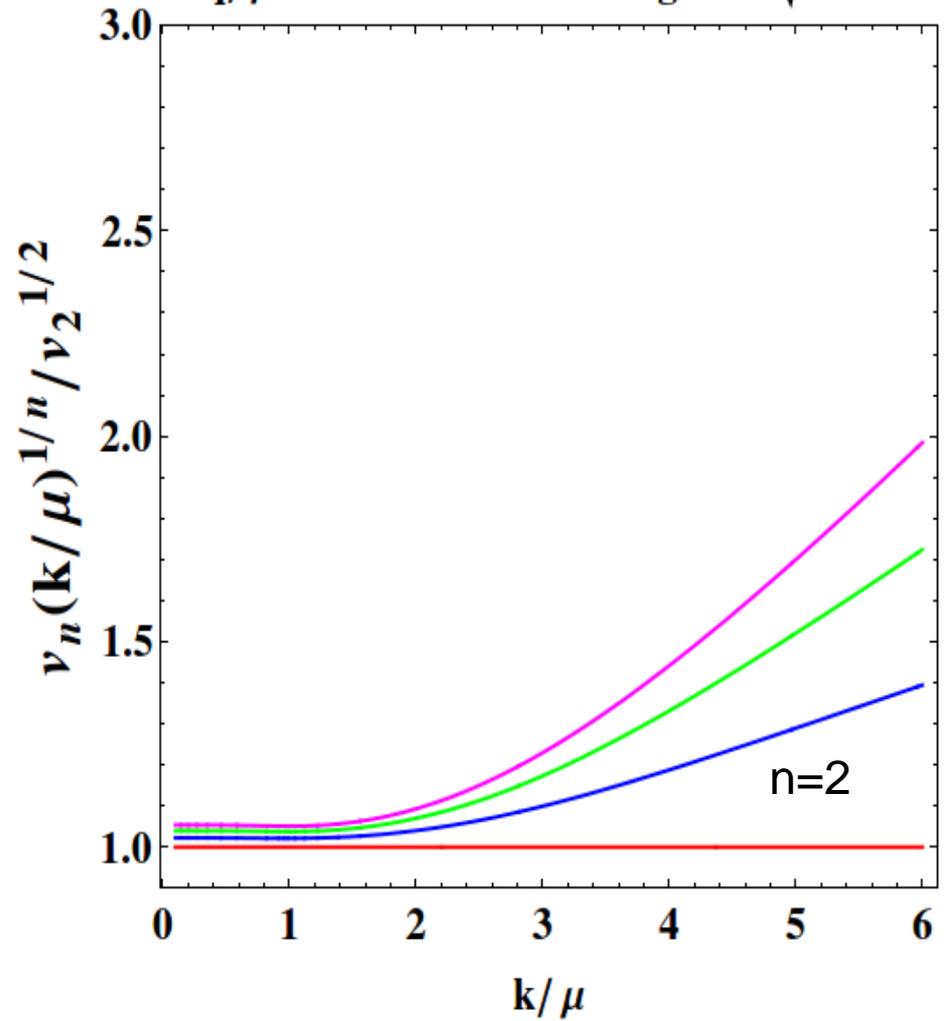
# Fixed q GB pQCD Bremsstrahlung harmonics scale perfectly via 1/n power law

$$[v_n^{GB}(k, q, 0)]^{1/n} = [v_m^{GB}(k, q, 0)]^{1/m}$$

For Yukawa averaged  $\langle q/\mu \rangle = \sqrt{M}$ ,

GB 1/n scaling hold for  $k < \sqrt{M}$  and breaks down for  $k > \sqrt{M}$

Yukawa  $\langle q/\mu \rangle = 3$  ave  $v_n^{1/n}$  scaling wrt  $\sqrt{v_2}$  GB Brems



**Recent data indicates strong similarities for anisotrop flow components in pPb collisions and peripheral PbPb collisions at the same multiplicity windows.**

**Realistic IC + hydrodynamical evolution does not work for pPb at LHC energies  
Fluctuation contributions seems to be large**

**Suggestion-1: GLVB model with fluctuating non-abelian beam jet bremsstrahlung  
Projectile beam jet form Color Scintillation Antenna (CSA)  
Gluon bremsstrahlung from CSA clusters and arrays → HIJING  
GLVB, Phys. Rev. D90 (2014) 054025; 1405.7825; 1407.7306**

**Suggestion-2: CGC with color charge fluctuations  
„collectivity” from multi-particle correlation  
non-trivial coherence patterns associated as initial state effects  
L. McLerran, V.V. Skokov, A. Dumitru,  
arXiv: 1407. 2651; PLB743 (2015) 134; PRD91 (2015) 074006;**

**Suggestion-3: BFKL Pomeron with gluon interference, two-gluon correlations  
E. Levin, A. H. Rezaeian, PRD84 (2011) 034031  
R.L. Ray, PRD90 (2014) 054013**

**Need more data and better understanding of experimental data on fluctuation !!!  
J. Y. Ollitrault, A. Poskanzer, (on cumulants) PLB742 (2015) 290**

## Summary:

### 1. Latest experimental data display

- a) Strong similarity of flow harmonics in pA and peripheral AA collisions  
Beam-size independence ! (Depends on multiplicity!)
- b) dAu/AuAu and pPb/PbPb comparisons are very similar  
Beam energy independence

**These are bad news !**

2. „Perfect Fluidity” is „Sufficient” (with suitable initial conditions) to fit data and hydro is working well for AA collisions but seems to fail for pA at the same multiplicities to reproduce  $v_n$

*Perfect Fluidity may not be „Necessary”*

### 3. New theoretical suggestions appeared for pA collisions (influence on AA ??):

- GLVB with fluctuating non-abelian jet bremsstrahlung and CSA**
- CGC with color charge fluctuations and multi-particle correlations**
- BFKL Pomeron with gluon interference, two-gluon correlations**

4. **GLVB: Work in progress is to implement anisotropic bremsstrahlung into HIJING in order to compute pA/AA results comparable to data**

5. **Need more data and better understanding of exp. data on/with fluctuation !!!**  
(e.g. proton/pion ratio in high multiplicity pp collisions)