

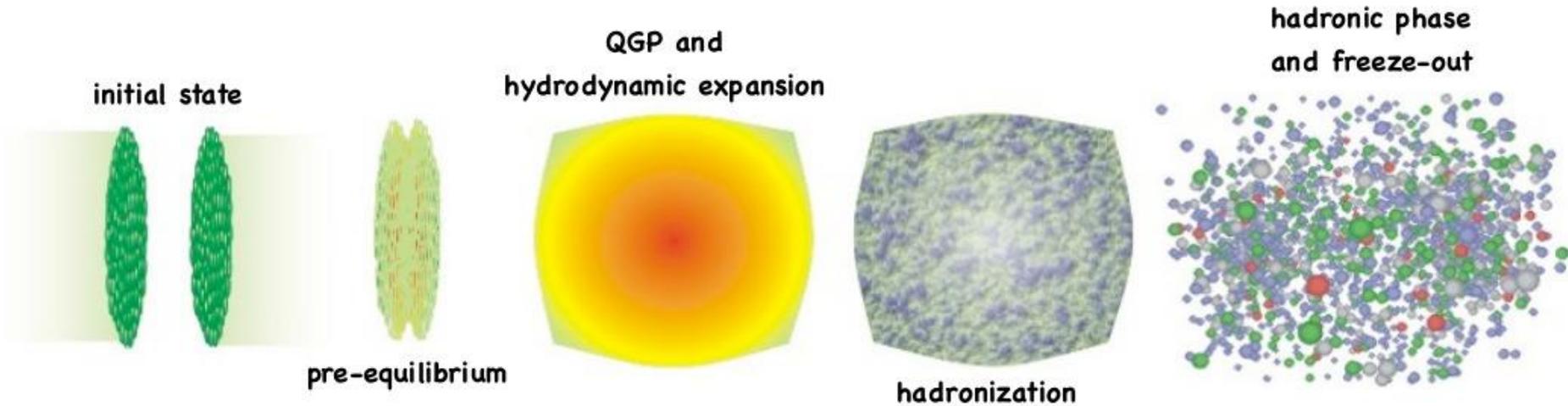
Initial State Bremsstrahlung versus Final State Hydrodynamics in pA Collisions

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On the basis of our work:
M. Gyulassy, P.L. I. Vitev, T.S. Bíró
Phys. Rev. D90 (2014) 054025. hep-ph/1805.7825

IS 2014 Conference, Napa Valley, CA, USA
7 December 2014

Standard Model of Heavy Ion Collisions:



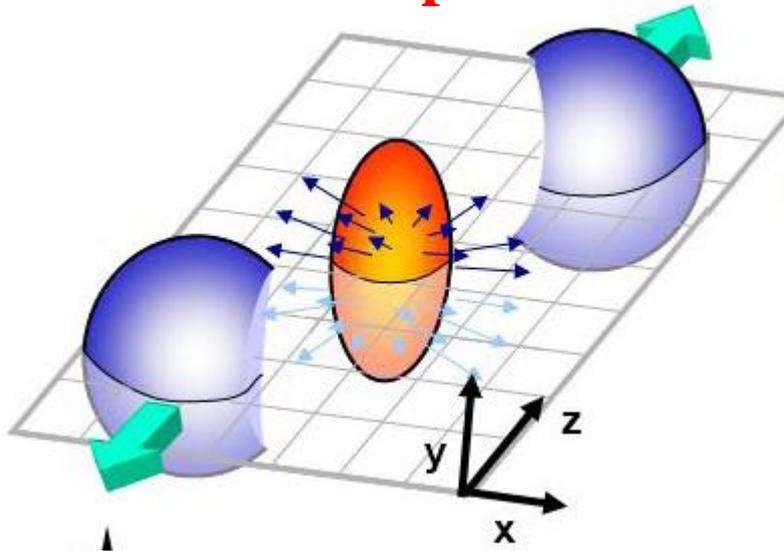
Phases:

- **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.
- Gloun 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, ...

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

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

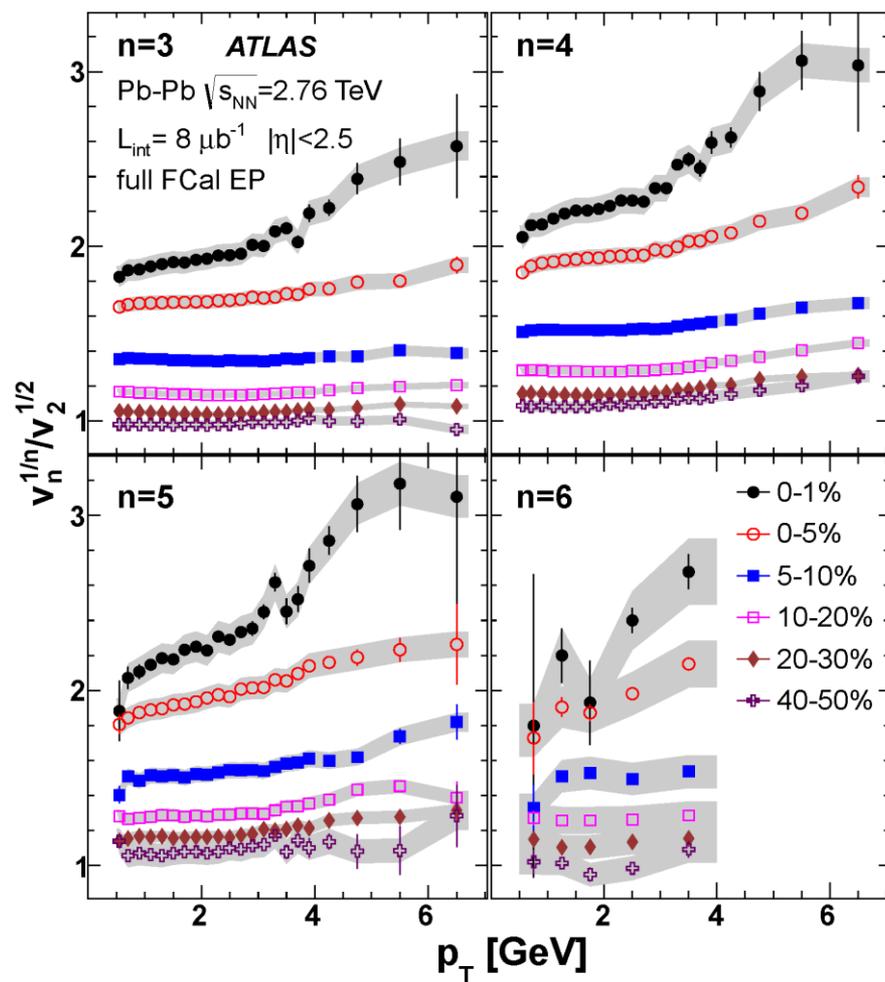
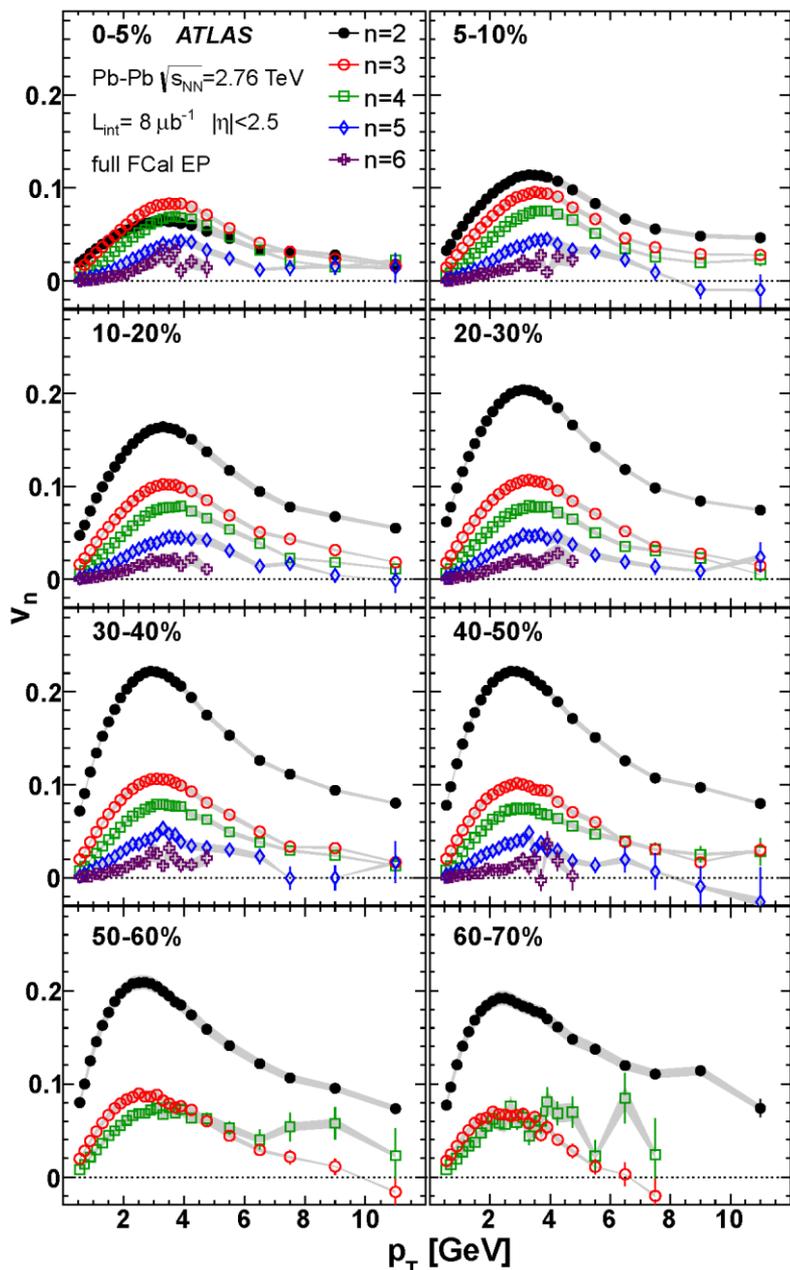
[?]

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

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

PRC86 (2012) 014907, Arxiv: 1203.3087

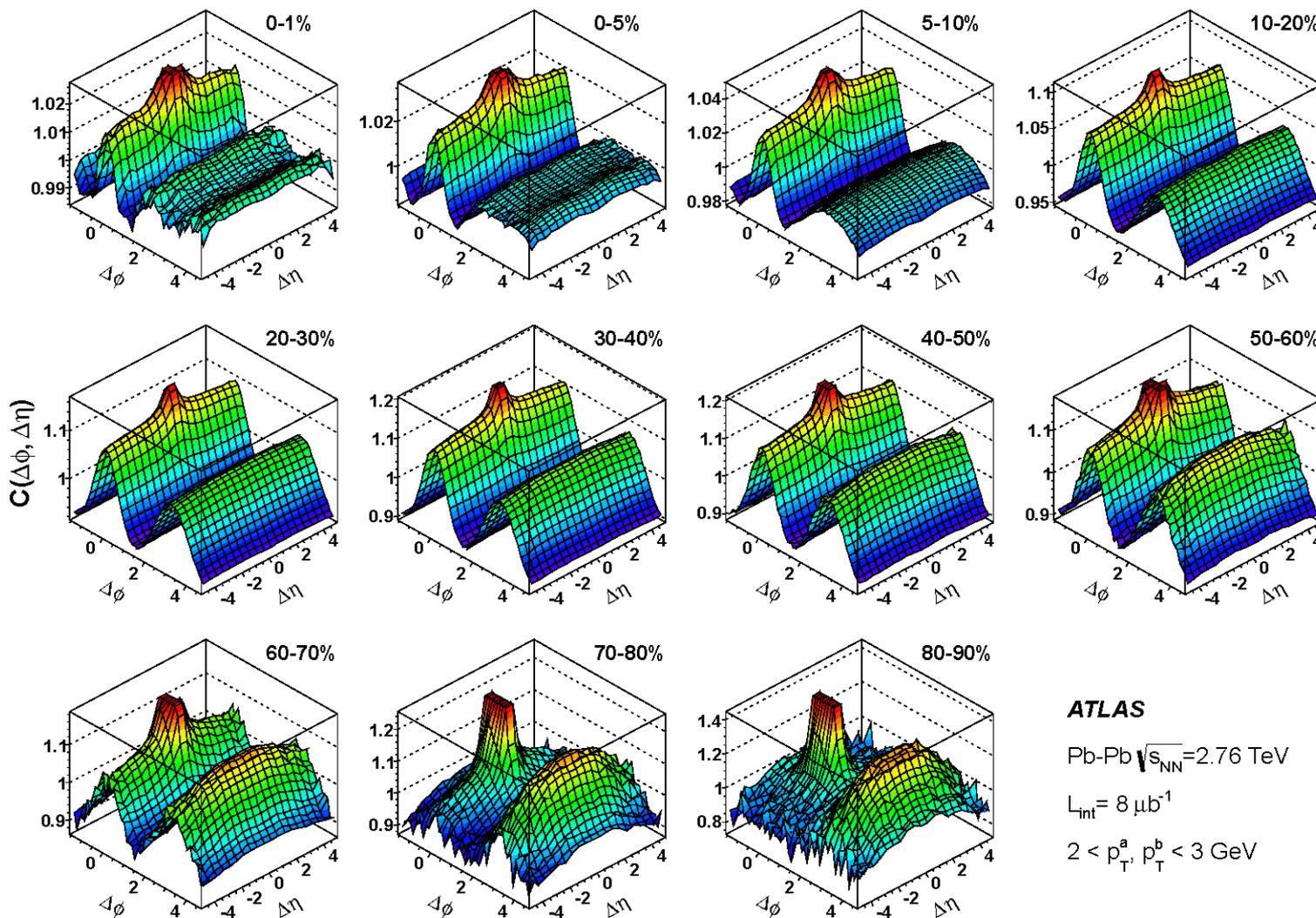
v_2, v_3, v_4, v_5 and v_6 at different centralities
and the scaling $(v_n)^{1/n}$
for central and peripheral collisions



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

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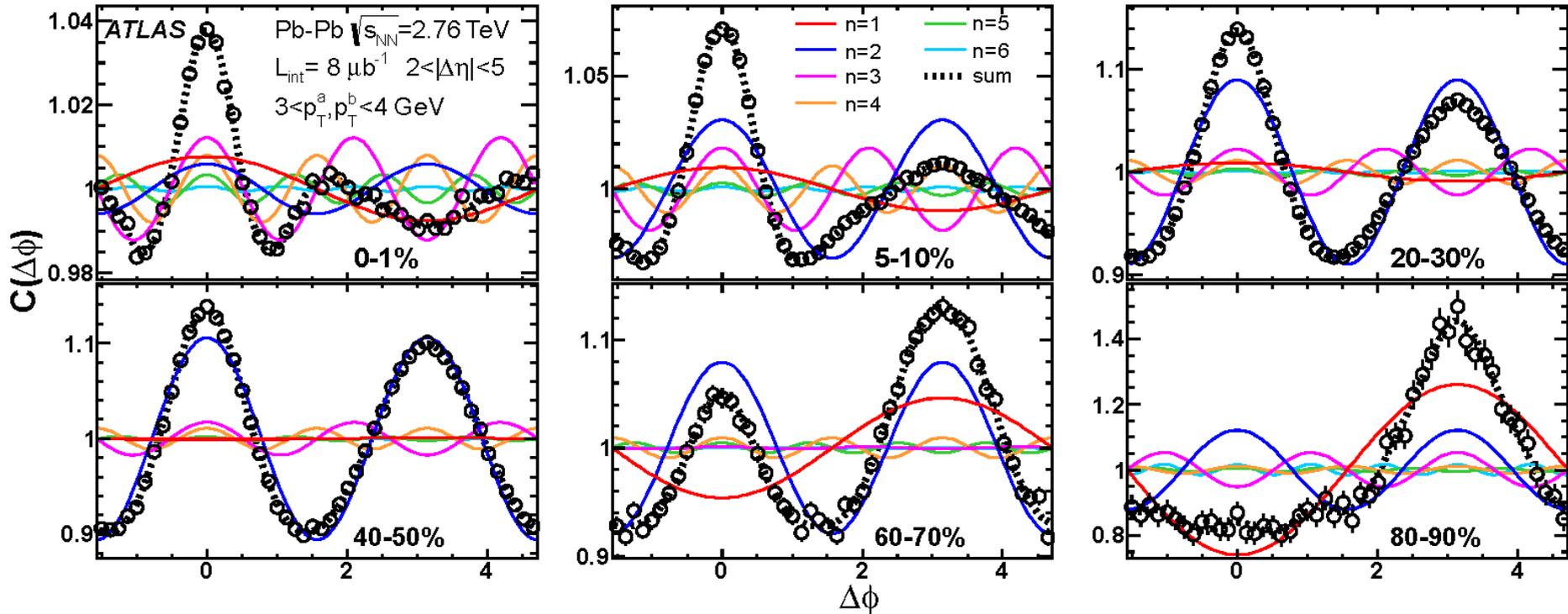
Long range correlations and ridge in PbPb at different centralities



Latest 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 !

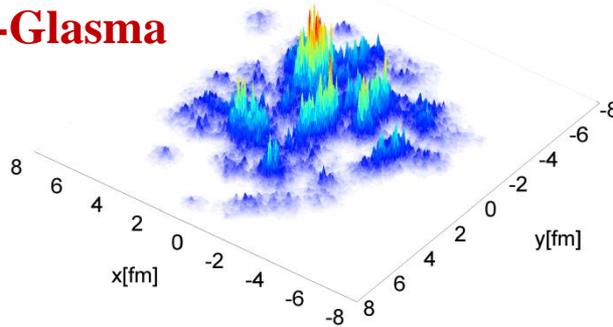
Theoretical investigations, following the Standard Model of HIC

Initial Conditions – Energy Density Profiles in AuAu at RHIC energies

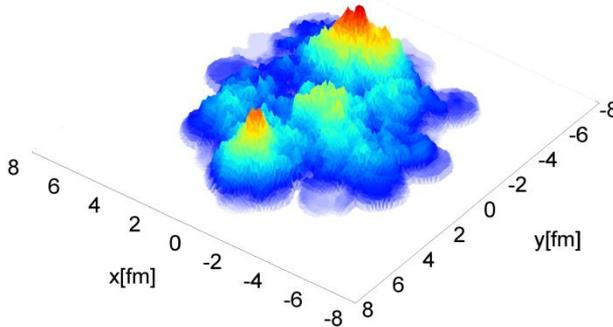
B. Schenke, P. Tribedy, R. Venugopalan, PRL108 (2012) 252301, PRC86 (2012) 034908.

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

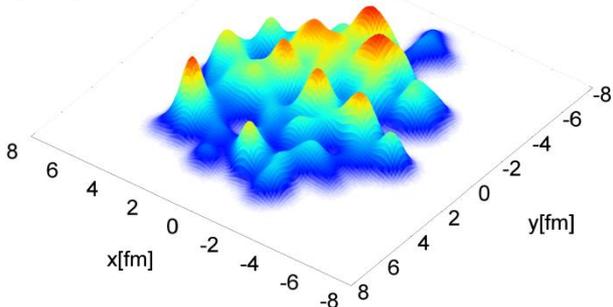
IP-Glasma



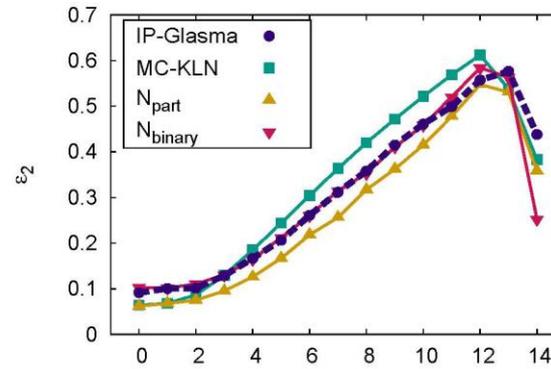
MC-KLN



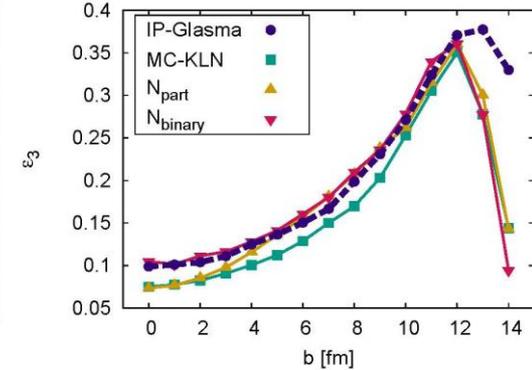
MC-Glauber



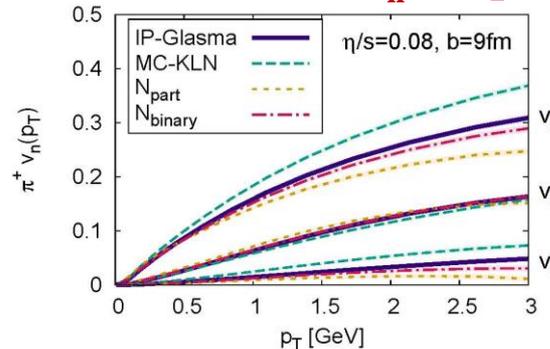
ϵ_2 : ellipticity



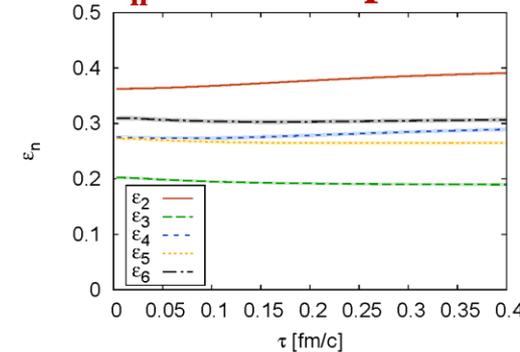
ϵ_3 : triangularity



v_n for pions



ϵ_n time independ.



„... the change in all ϵ_n is very weak over the first 0.4 fm/c. After this time all ϵ_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 ?

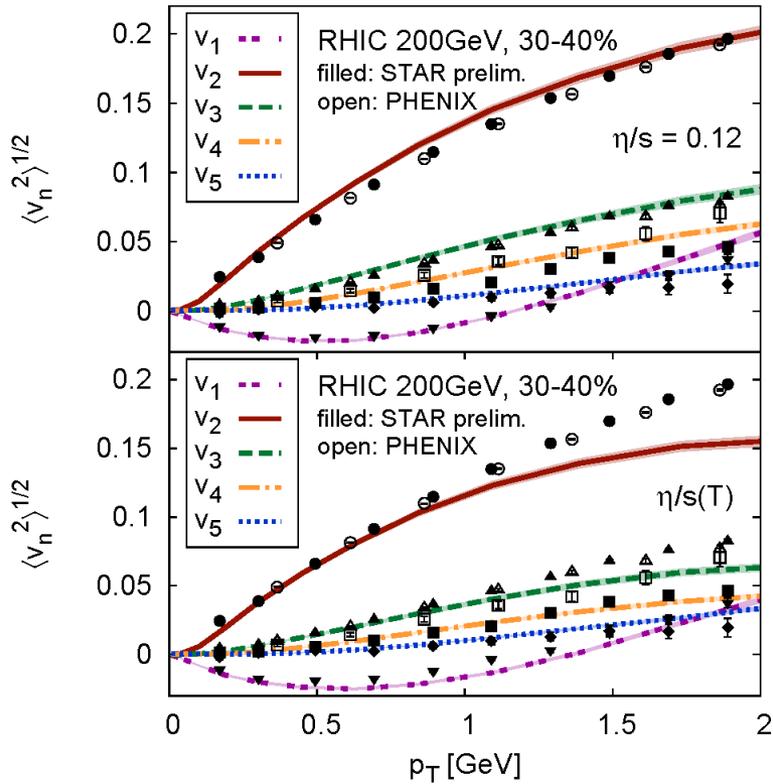
Theoretical investigations, following the Standard Model of HIC

Sensitivity of the harmonic flow components on η/s and the time evolution

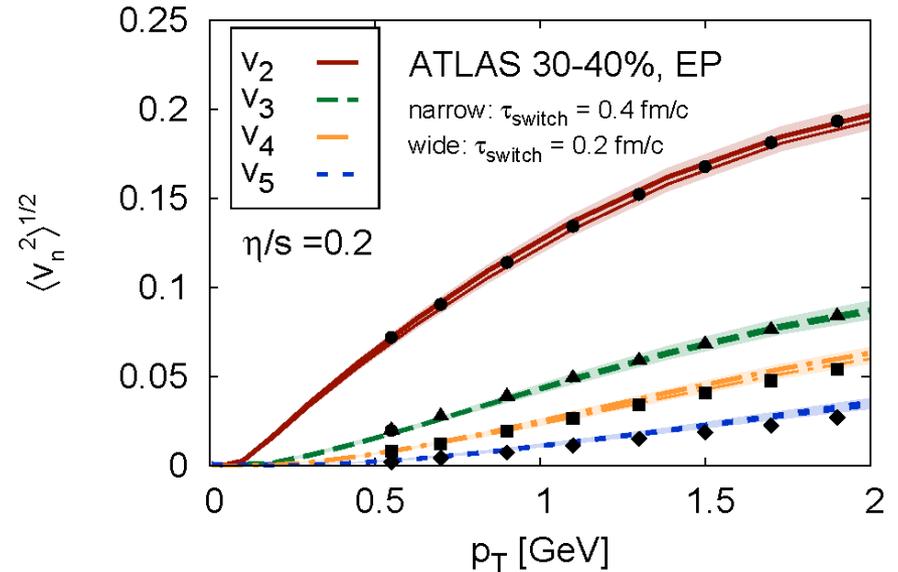
C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, PRL109 (2013) 012302.

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 η/s at RHIC energy

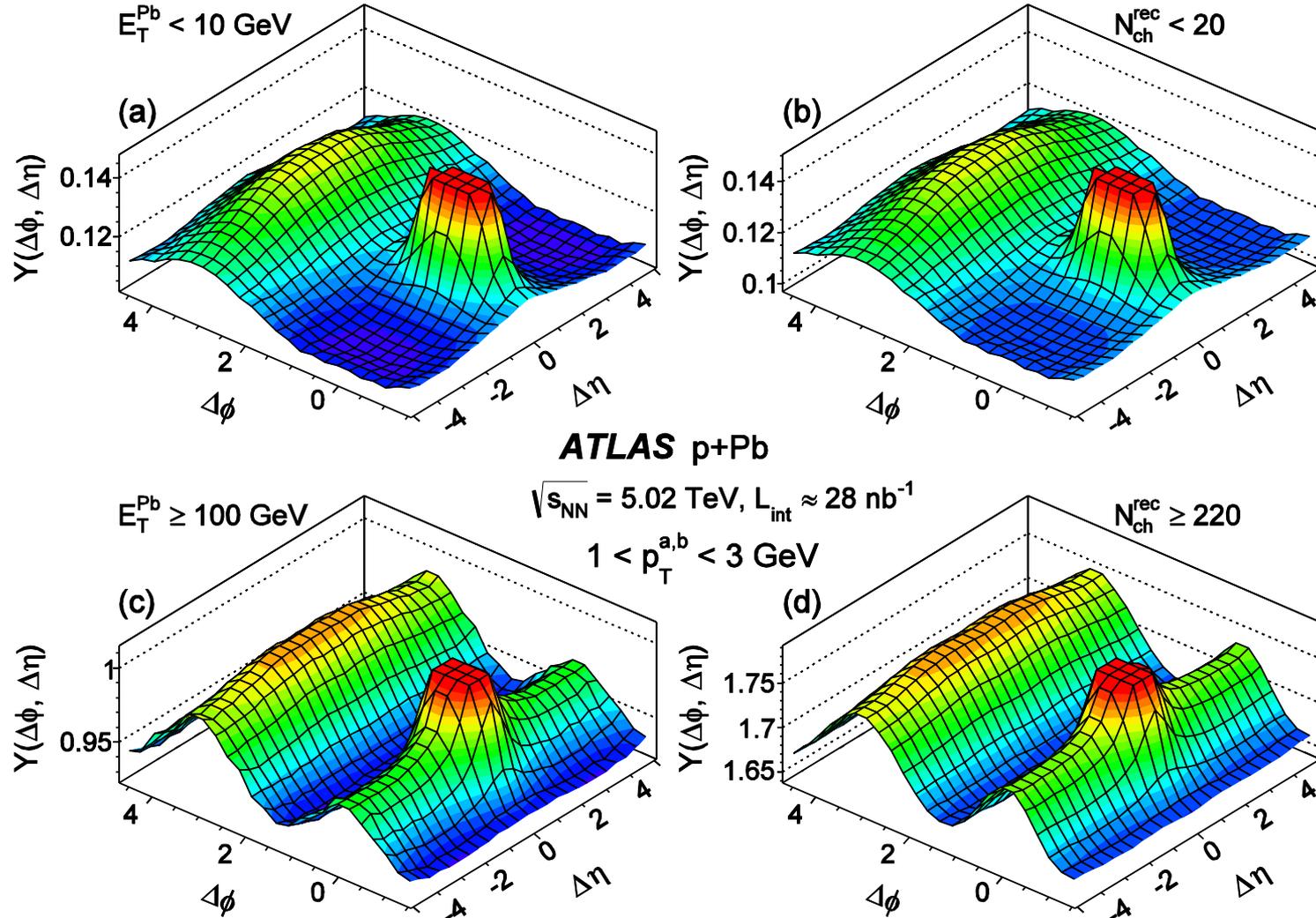


Weak sensitivity of v_n on the switching time τ between IP-Glasma state and hydrodynamics at LHC energy

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

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

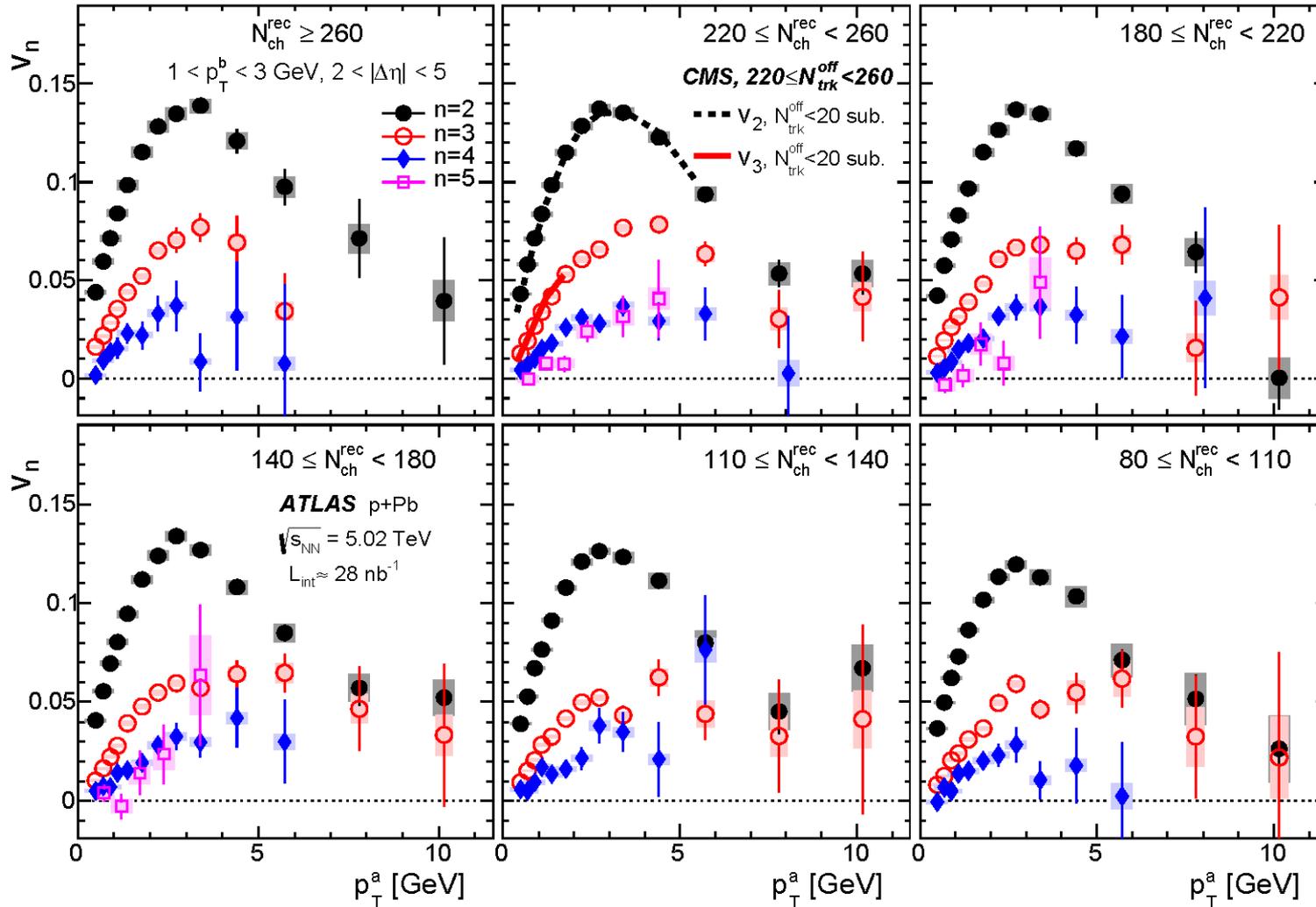
Long range correlations and ridge in pPb at small and large multiplicities



Latest experimental results on v_n : 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

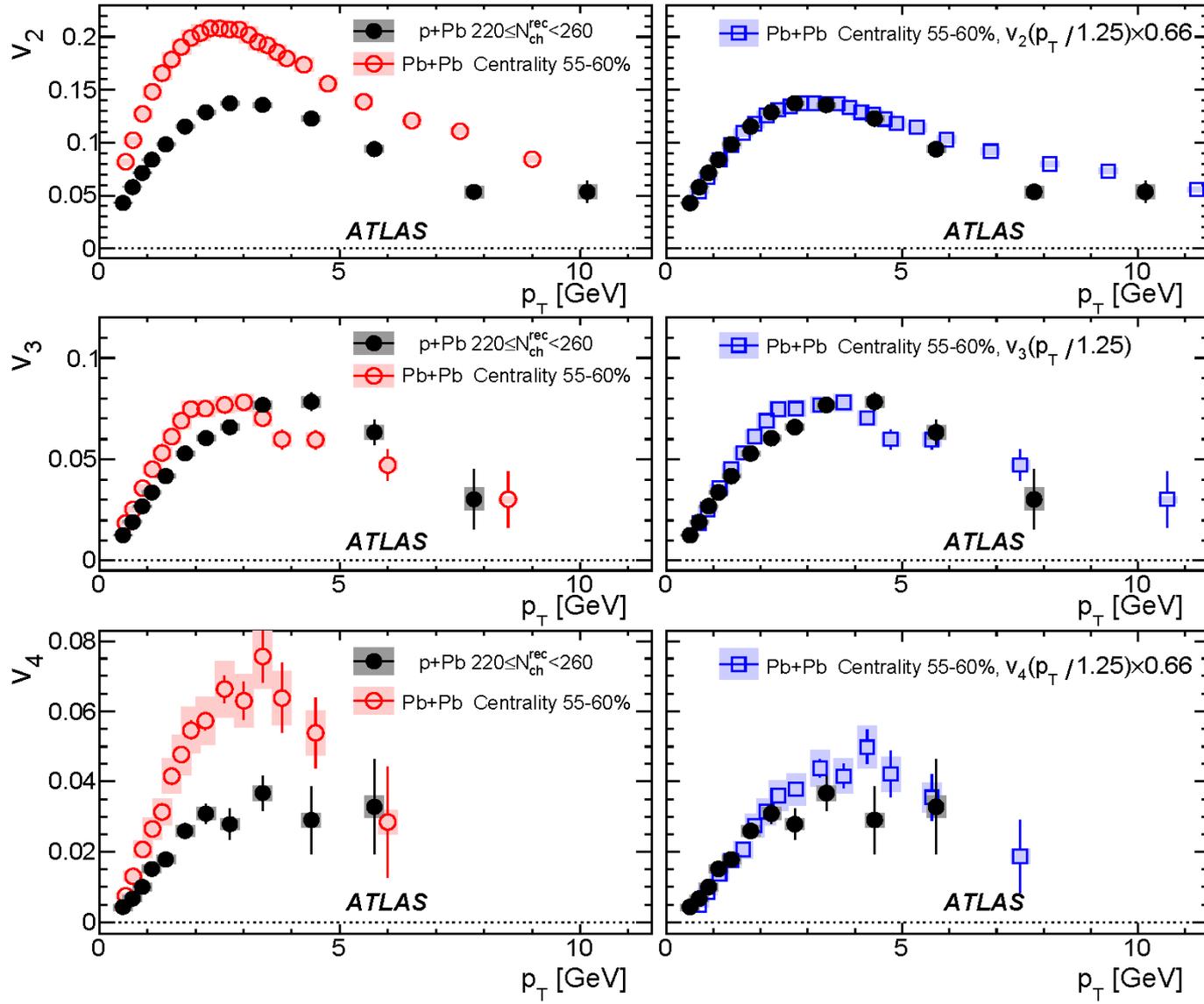


For v_n
ATLAS and
CMS results
overlap

Latest 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



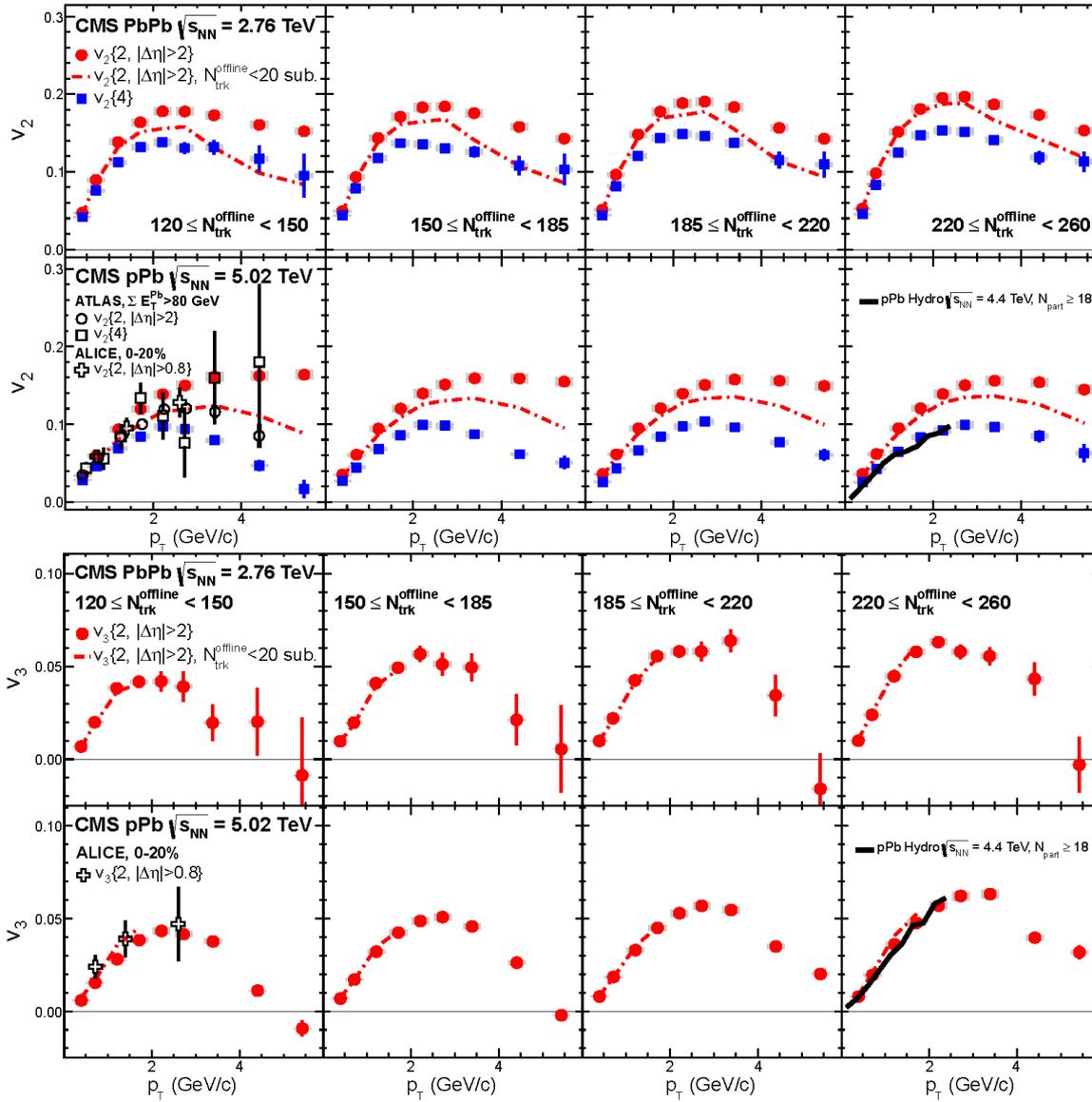
Magic factors:
 $0.66 \times v_n(p_T/1.25)$

Explanation ?!

Latest experimental results on v_n : 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

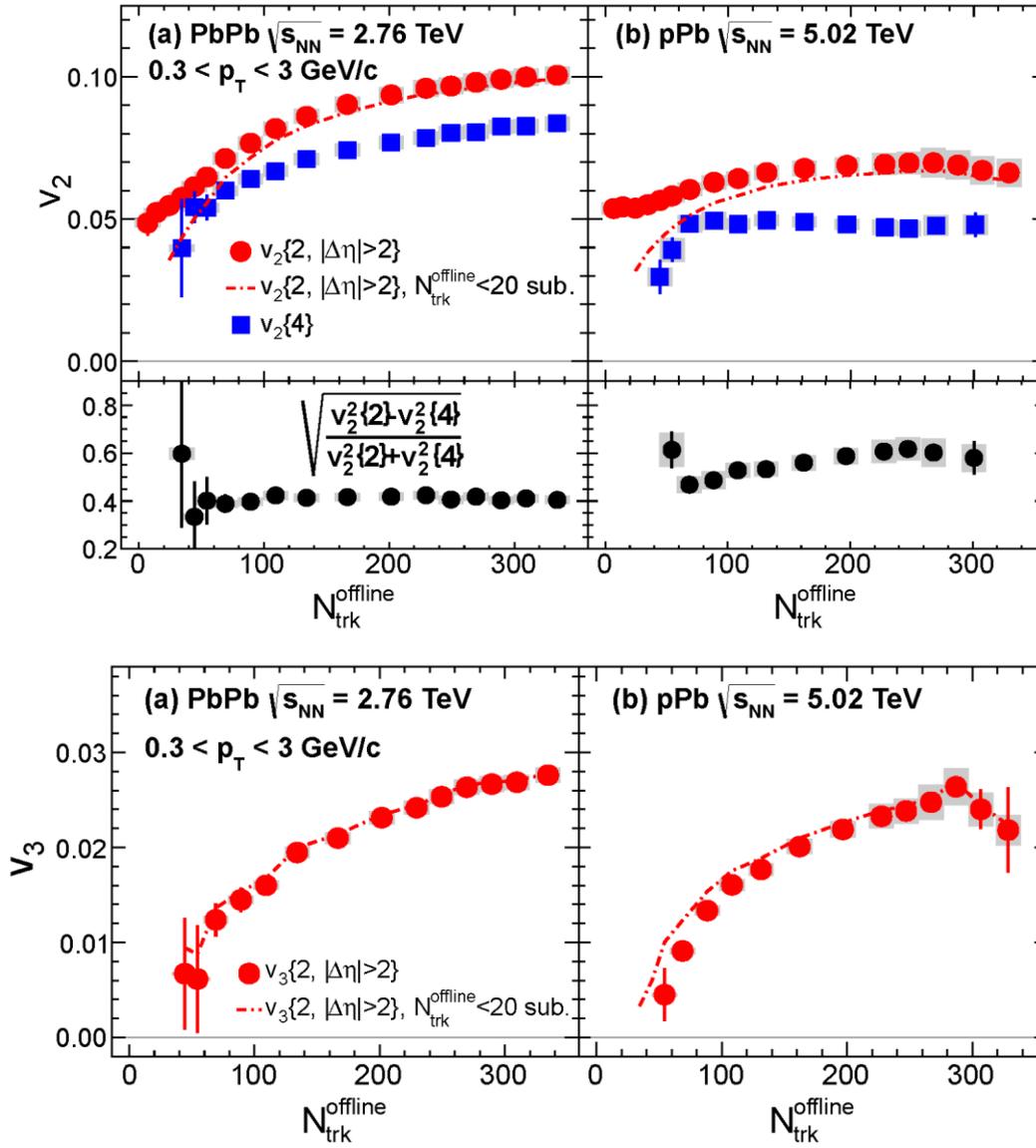


For $v_2\{2\}$, $v_3\{2\}$, $v_2\{4\}$
CMS, ALICE and
ATLAS results overlap

Latest experimental results on v_n : 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



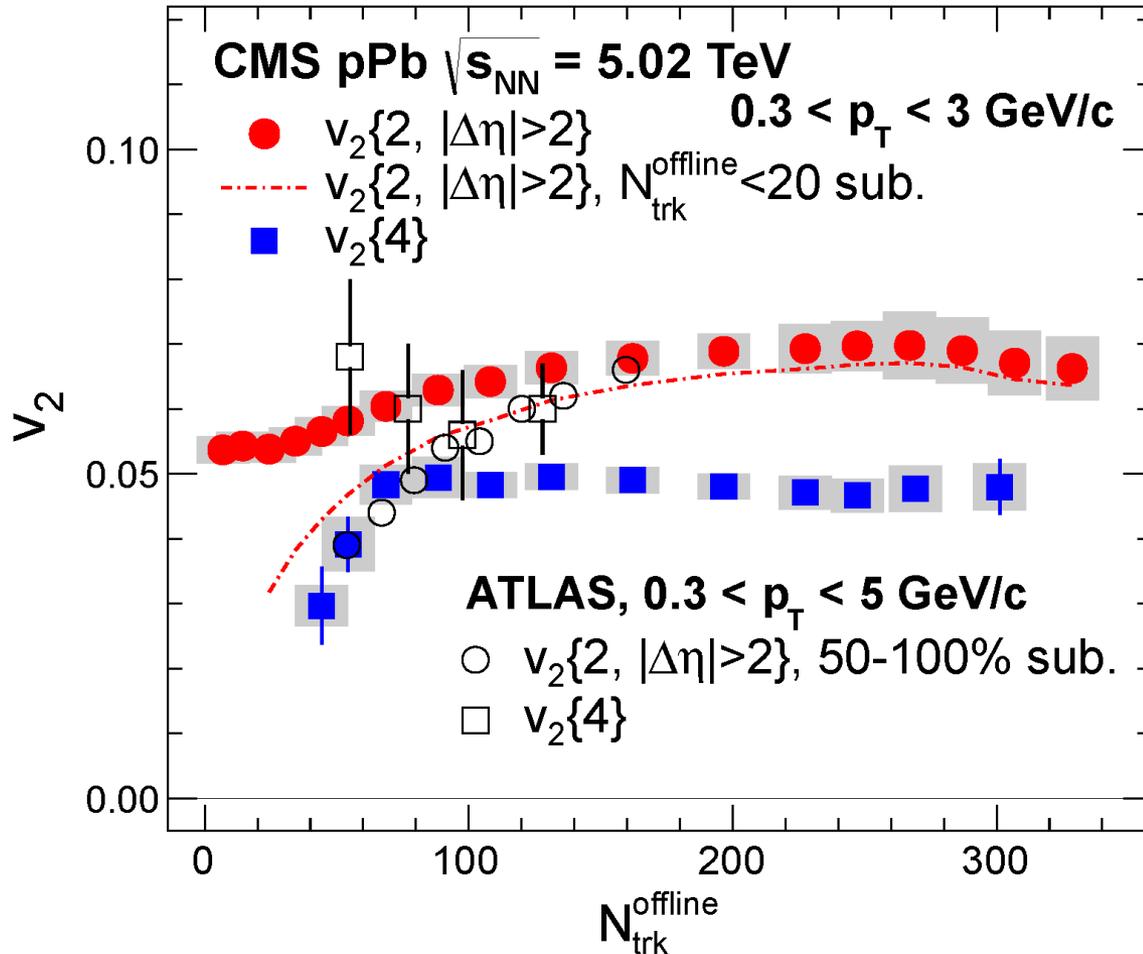
Fluctuations:
40 % in PbPb
50-60 % in pPb
residual nonflow correlations
from back-to-back jets
Similar to RHIC results !

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

Latest 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

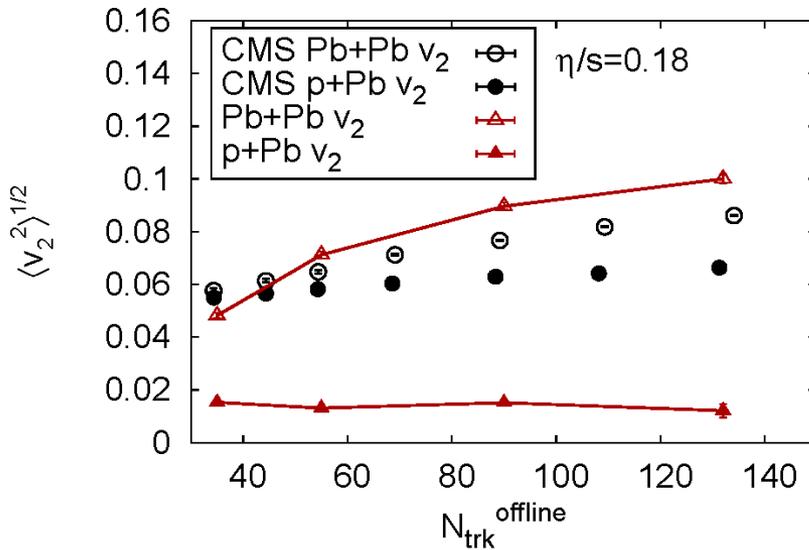
Theoretical investigations, following the Standard Model of HIC for pPb

Sensitivity of the harmonic flow components on η/s and the time evolution

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

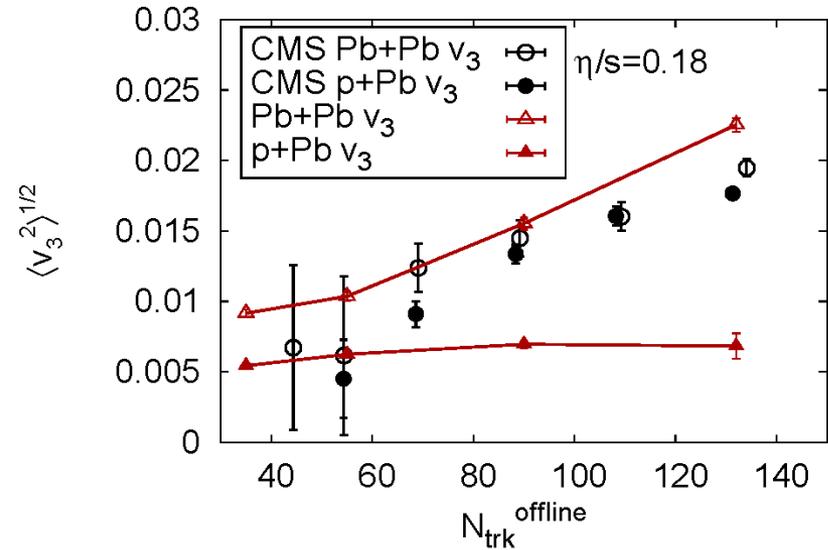
IP-Glasma + MUSIC hydro

[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

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²*Department of Physics, Columbia University, New York, NY 10027, USA*

³*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

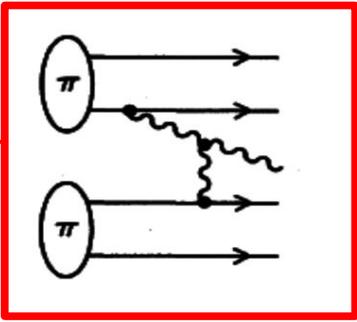
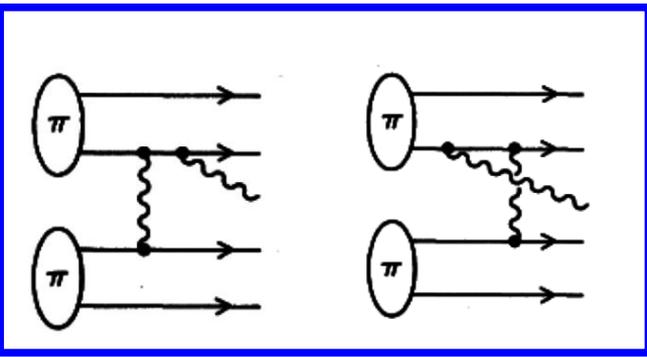
The above puzzles with BES and $D + Au$ at RHIC and with $p + Pb$ at LHC and models proposed so far motivate us to consider simpler more basic perturbative QCD sources of azimuthal asymmetries. The well known non-abelian bremsstrahlung Gunion-Bertsch (GB) formula[29] for the soft gluon radiation single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

ϕ is the azimuthal angle of \mathbf{k} and ψ 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 ϕ 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 : $A_{kq} \equiv (k^2 + q^2 + \mu^2)/(2kq) \geq 1$

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

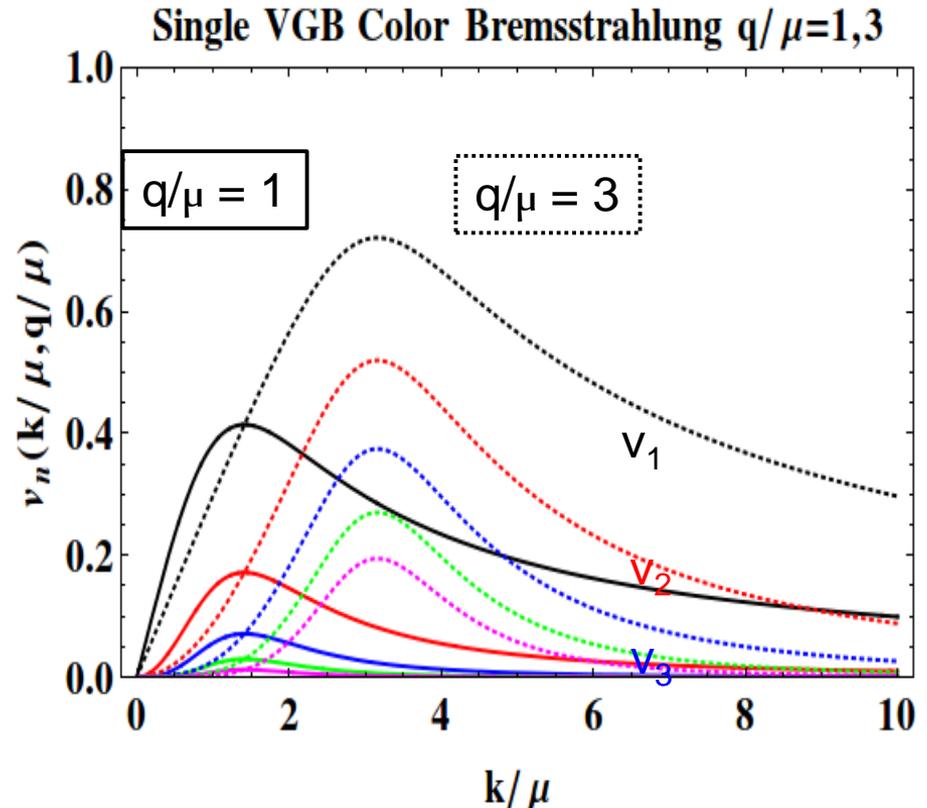
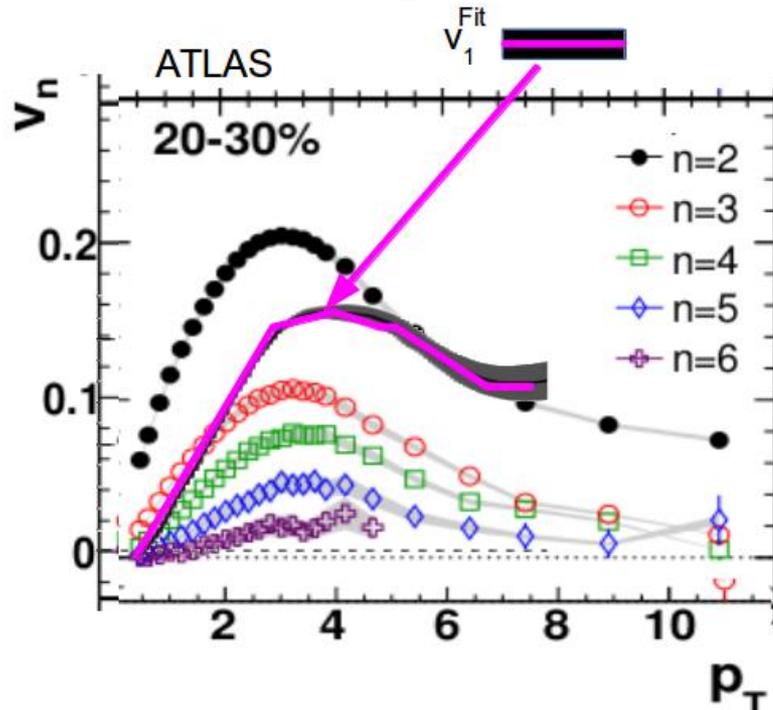
$$\lim_{\mu \rightarrow 0} v_1^{GB}(k, q, 0) = (k/q) \theta(q - k)$$

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

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

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

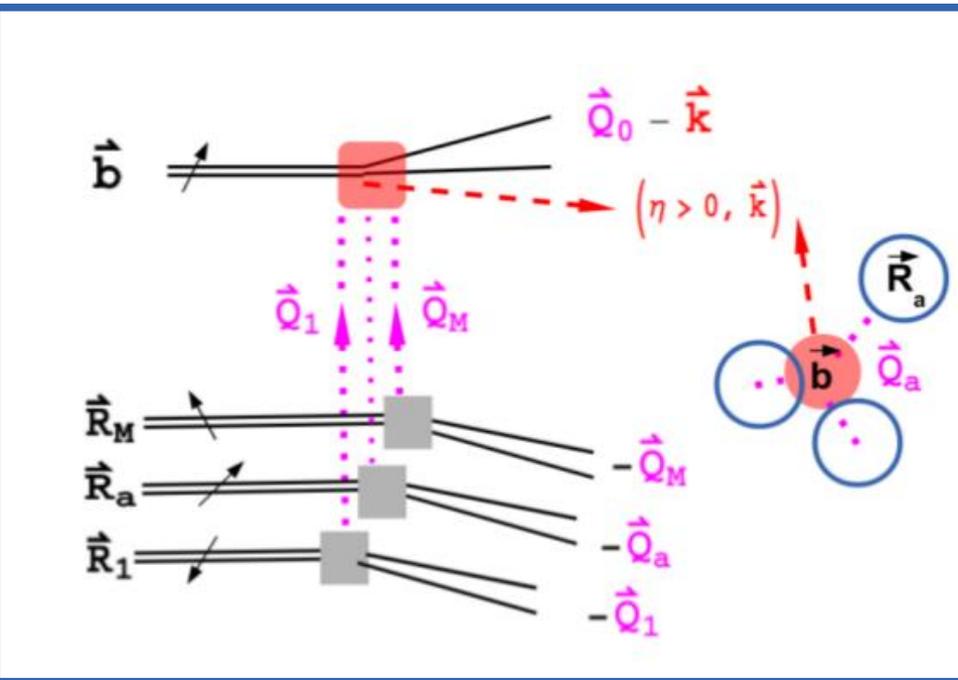
Two particle v_n from ATLAS



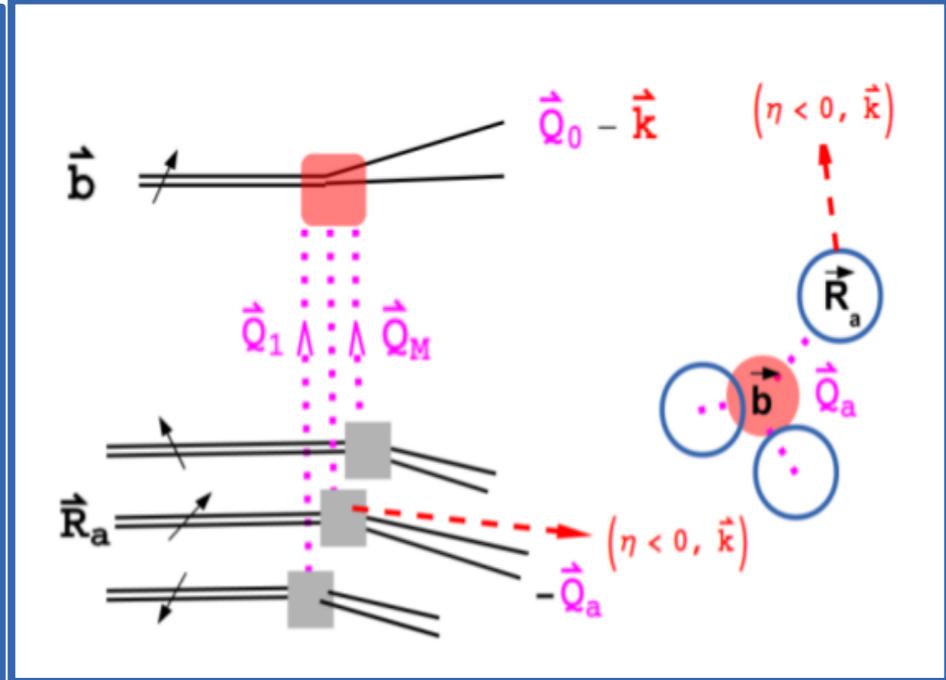
Note intrinsic huge even and odd v_n peaking near $\mu \sim Q_{sat}$

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=Nth order in opacity with M coherent target clusters that can resolved by k
Projectile plus Target bremsstrahlung sums to

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

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

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

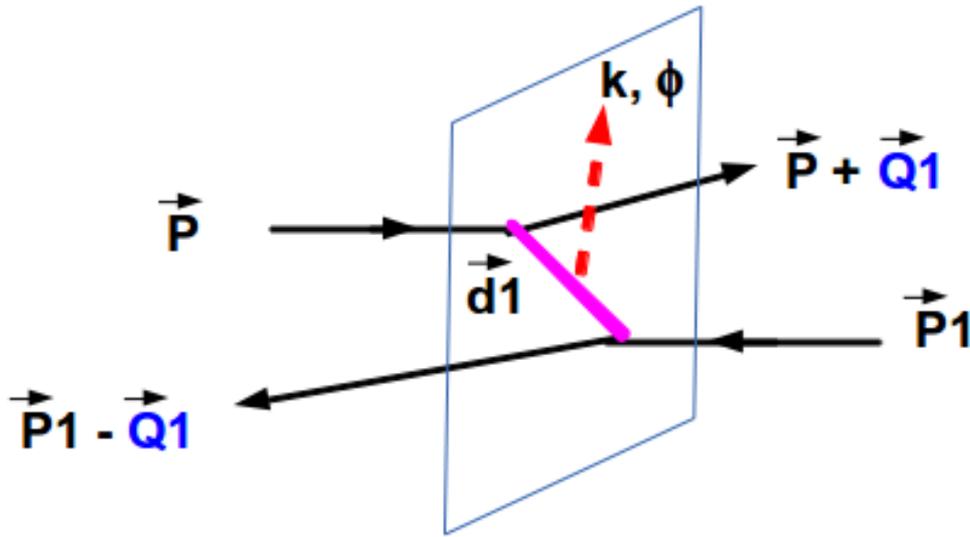
$$\begin{aligned}
 f_n^{N,M}(k_1, k_2) &\equiv \int_{-\pi}^{\pi} d\Phi \int_{-\pi}^{\pi} d\Delta\phi \cos(n\Delta\phi) dN_2^{N,M}(k_1, \Phi + \Delta\phi/2, k_2, \Phi - \Delta\phi/2) \\
 &= \sum_{a,b=0}^M B_{1a} B_{2b} \int_{-\pi}^{\pi} d\Phi' \frac{1}{A_{1a} - \cos(\Phi')} \int_{-\pi}^{\pi} d\Delta\phi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

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

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

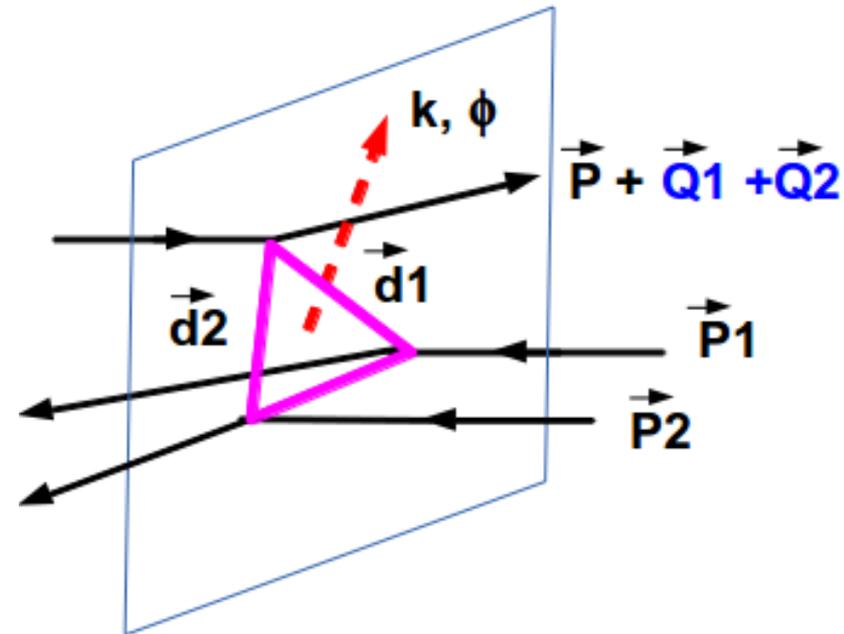
$$\langle \dots \rangle = \int \left\{ \prod_{a=0}^M d\mathbf{Q}_a \right\} \delta\left(\sum_{a=0}^M \mathbf{Q}_a\right) \sum_{m_1, \dots, m_M} \delta\left(N - \sum_{a=1}^M m_a\right) p_{\{m_j\}}^{M,N} P_{m_1}^{el}(\mathbf{Q}_1) \dots P_{m_1}^{el}(\mathbf{Q}_M)$$

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**

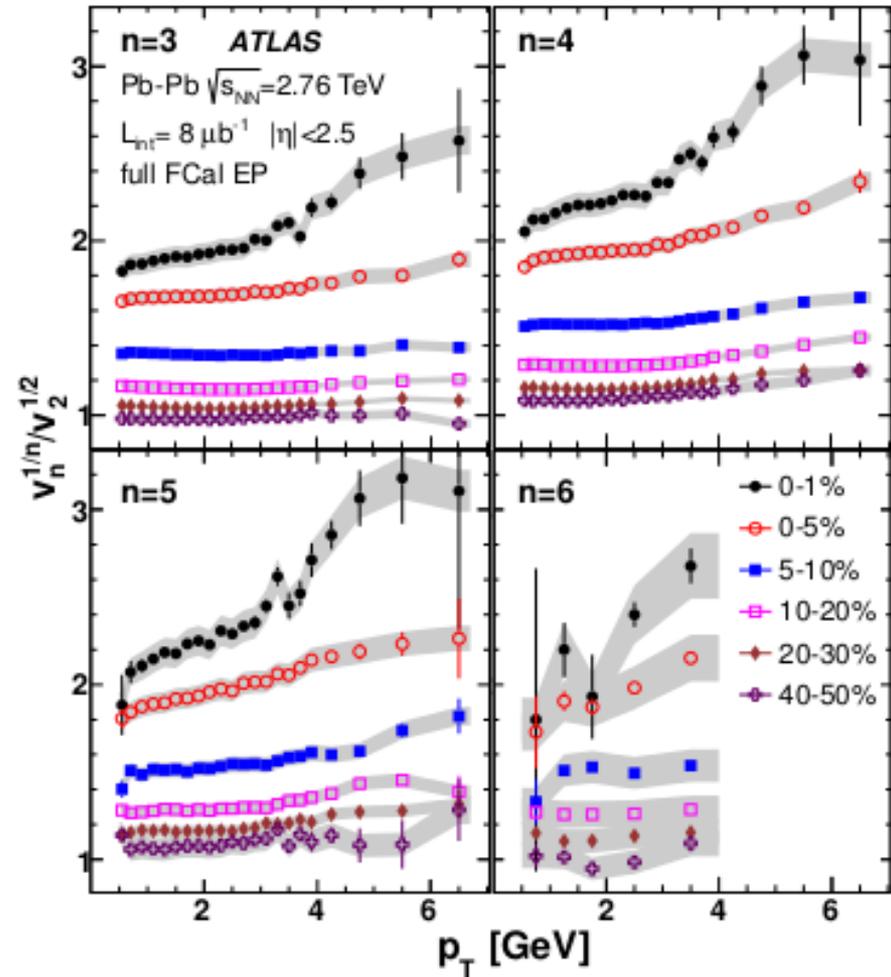
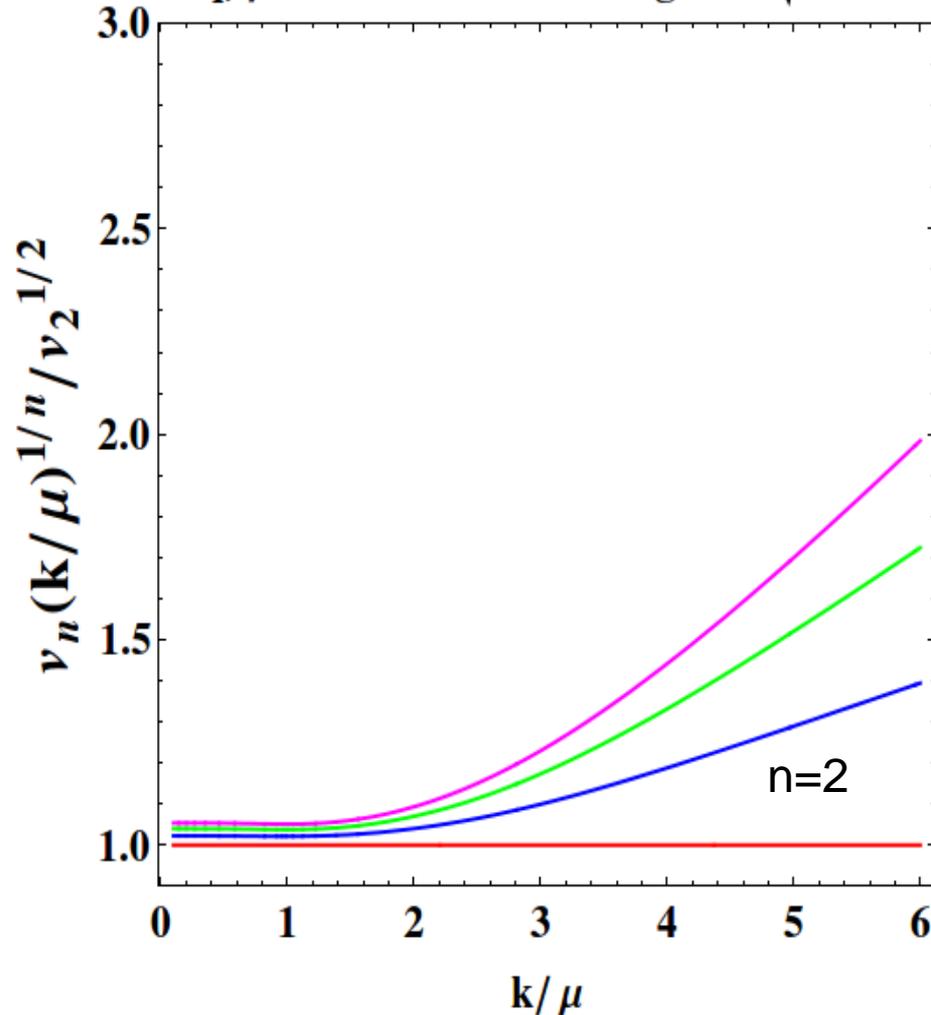
Fixed q GB pQCD Bremsstrahlung harmonics scale perfectly via 1/n power law

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

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; 1805.7825; 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; 1410.4844; 1411.6630 and Talk on IS2014**

**Suggestion-3: BFKL Pomeron with gluon interference, two-gluon correlations
E. Levin, A. H. Rezaeian, PRD84 (2011) 034031
L. Ray, PRD90 (2014) 054013 and Talk on IS2014**

**Need more data and better understanding of experimental data on fluctuation !!!
J. Y. Ollitrault, A. Poskanzer, ... on cumulants (Talks on IS2014)**

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 (see HBT)

- ### 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 !!!