Initial State Bremsstrahlung or Final State Hydrodynamics in pA Collisions

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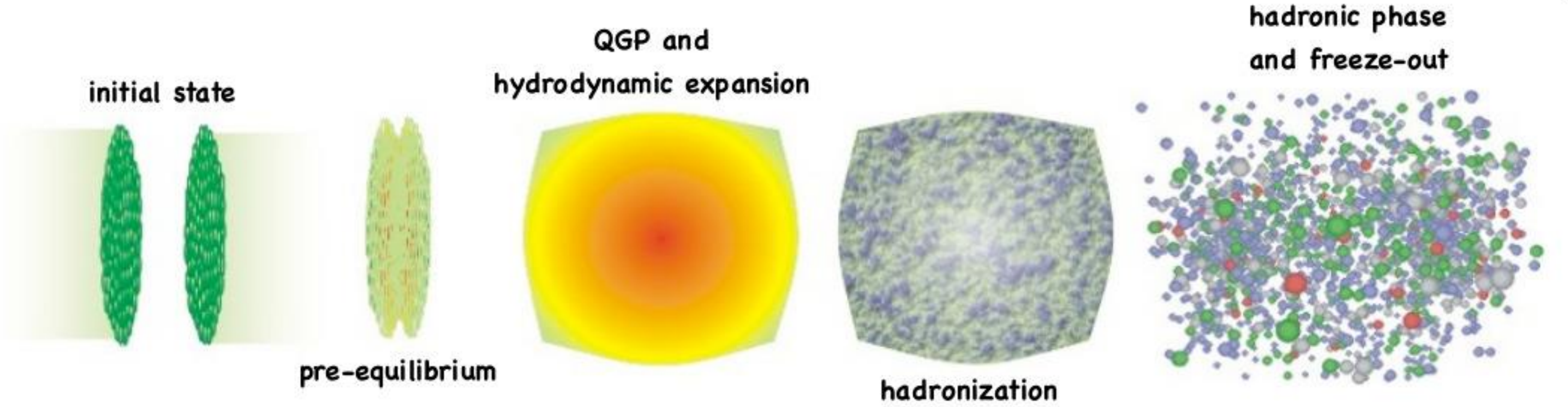
On the basis of our work:
M. Gyulassy, P.L. I. Vitev, T.S. Bíró
Phys. Rev. D90 (2014) 054025.   hep-ph/1805.7825

Zimanyi Winter School, Budapest
11 December 2015

Standard Model of Heavy Ion Collisions:



Phases:

--- Initial condition: pre-equilibrium state

--- Hydrodynamical evolution
perfect fluid, viscous fluid, EOS

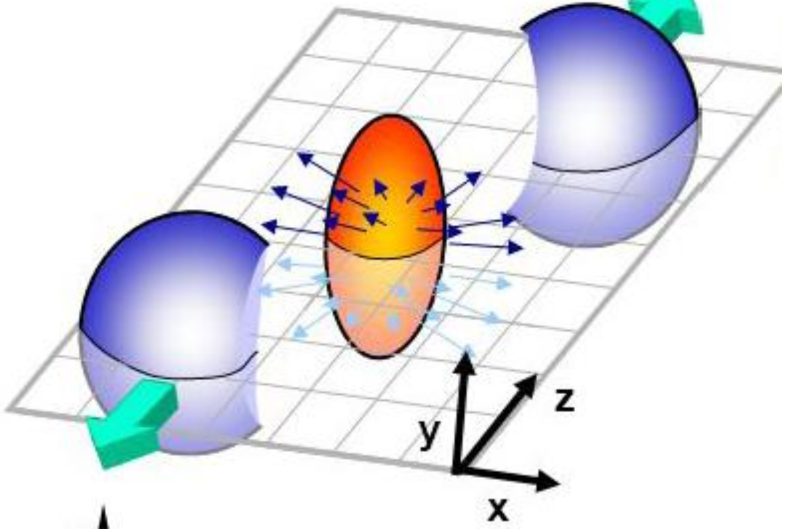
--- Hadronization mechanism
phase transition, coalescence/recombin.,
Cooper-Frye, incl. viscous corrections

--- Hadronic afterburner
hadronic interactions, final state effects

Questions, problems:

PDF, proton shape, color oscil.
Gluon 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, …

RUN1 experimental results at RHIC and LHC: azimuthal particle distributions and anisotropic flow



→ 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 distibutions
leads to the harmonic flow component

Spatial anisotropy
→ eccentriticies
2: ellipticity
3: triangularity
4: quadracity
5: pentacity

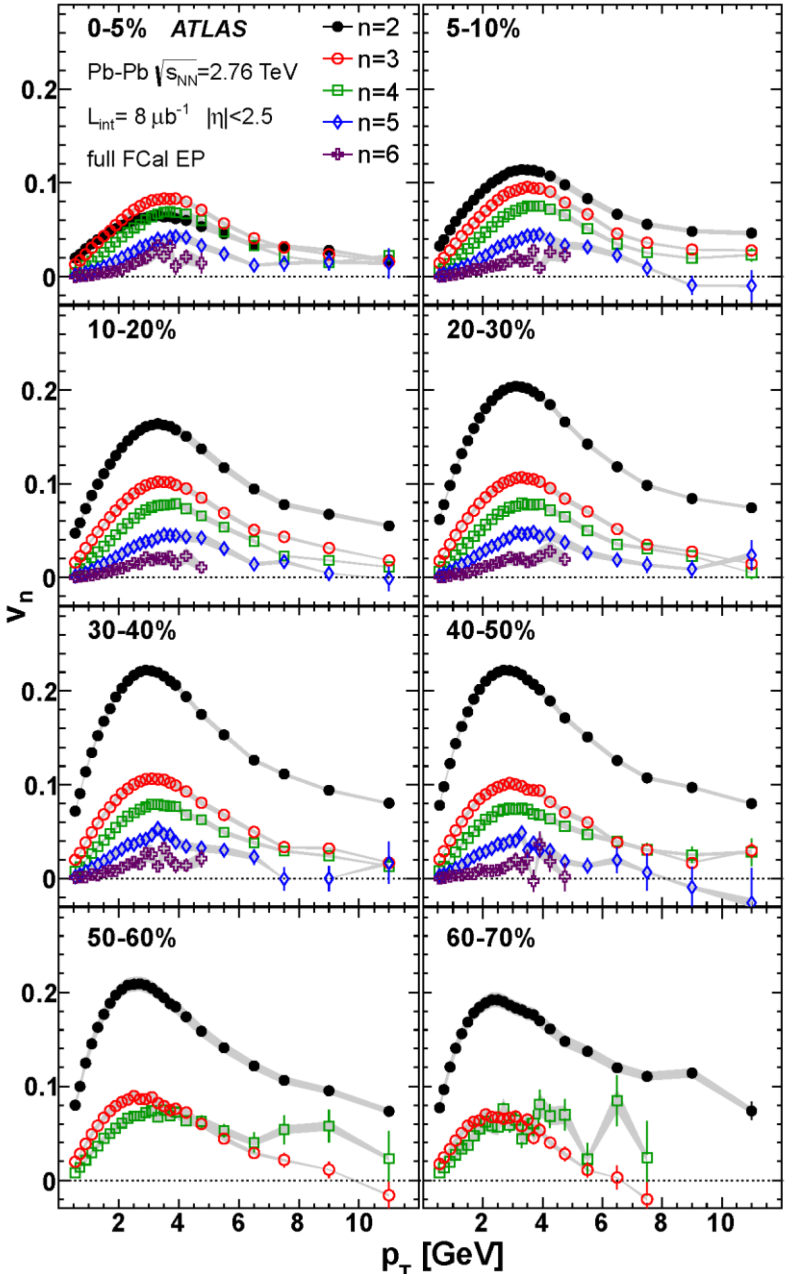
$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n\rangle}$$

⍰

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\ \left(1 + \sum_n 2\,\mathrm{v}_n\,(\cos(n\quad))\ \right)$$

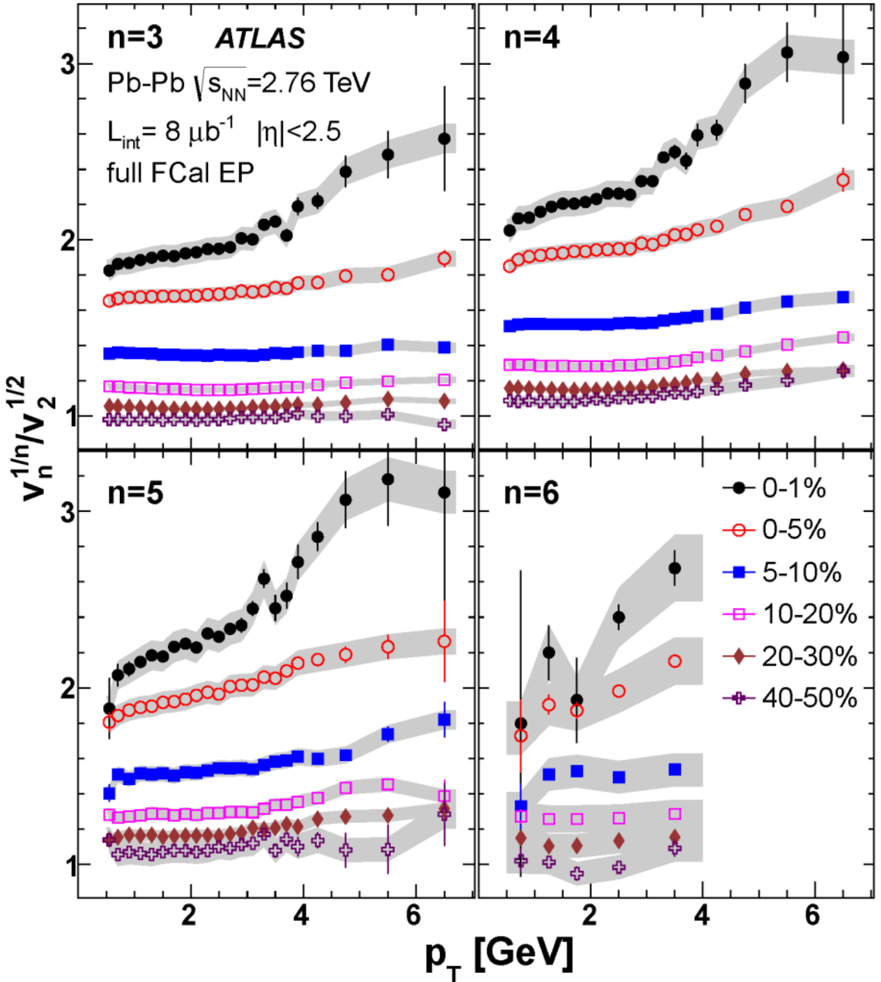
v1: directed flow; v2: elliptic flow; v3: …

RUN1 experimental results on v_n: PbPb, $\sqrt{s}$= 2.76 ATeV ATLAS



PRC86 (2012) 014907, Arxiv: 1203.3087

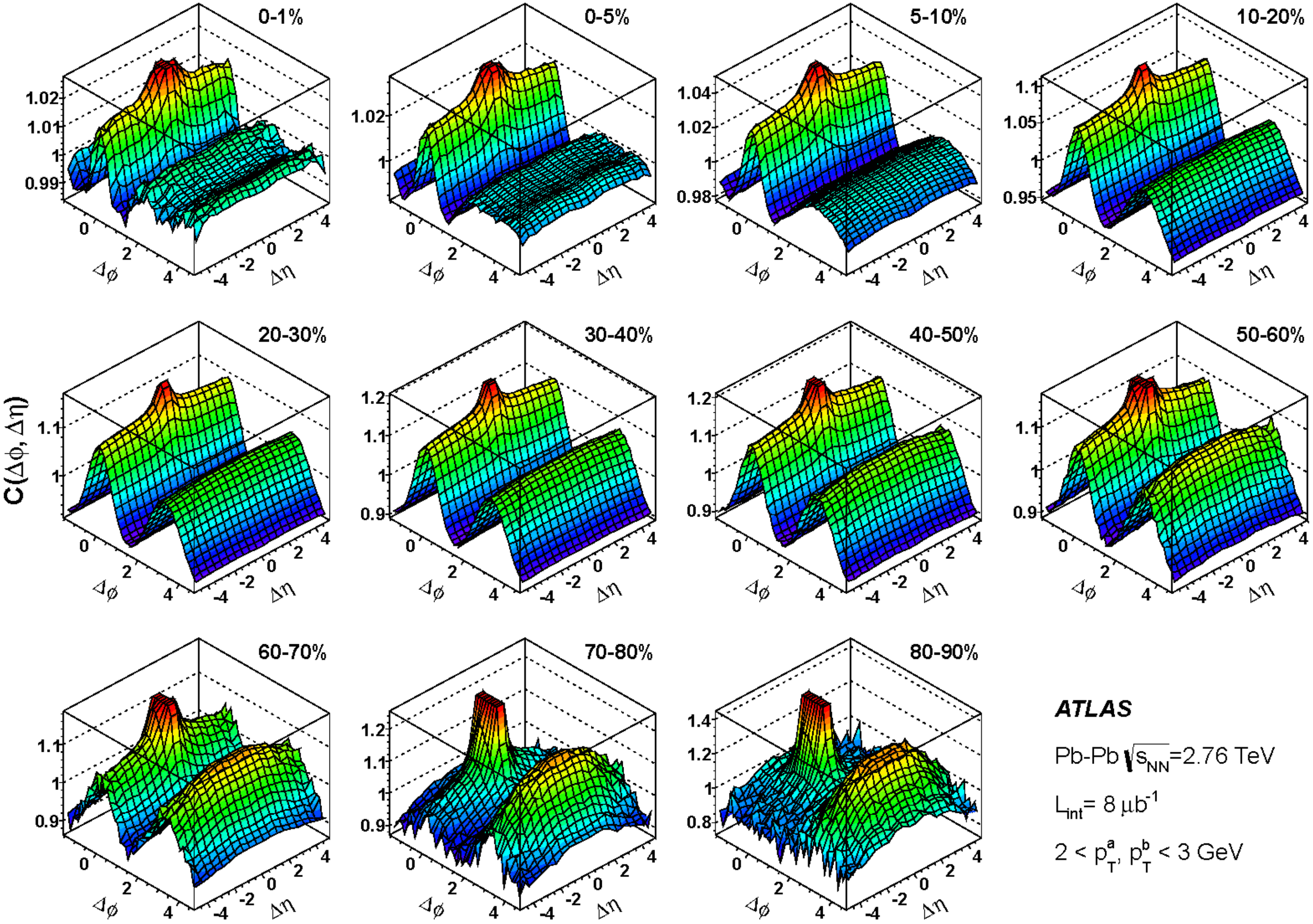
v_2, v_3, v_4, v_5 and v_6 at different centralities and the scaling $(v_n)^{1/n}$ for central and peripheral collisions



RUN1 experimental results on v_n: PbPb, $\sqrt{s}$= 2.76 ATeV ATLAS

PRC86 (2012) 014907, Arxiv: 1203.3087

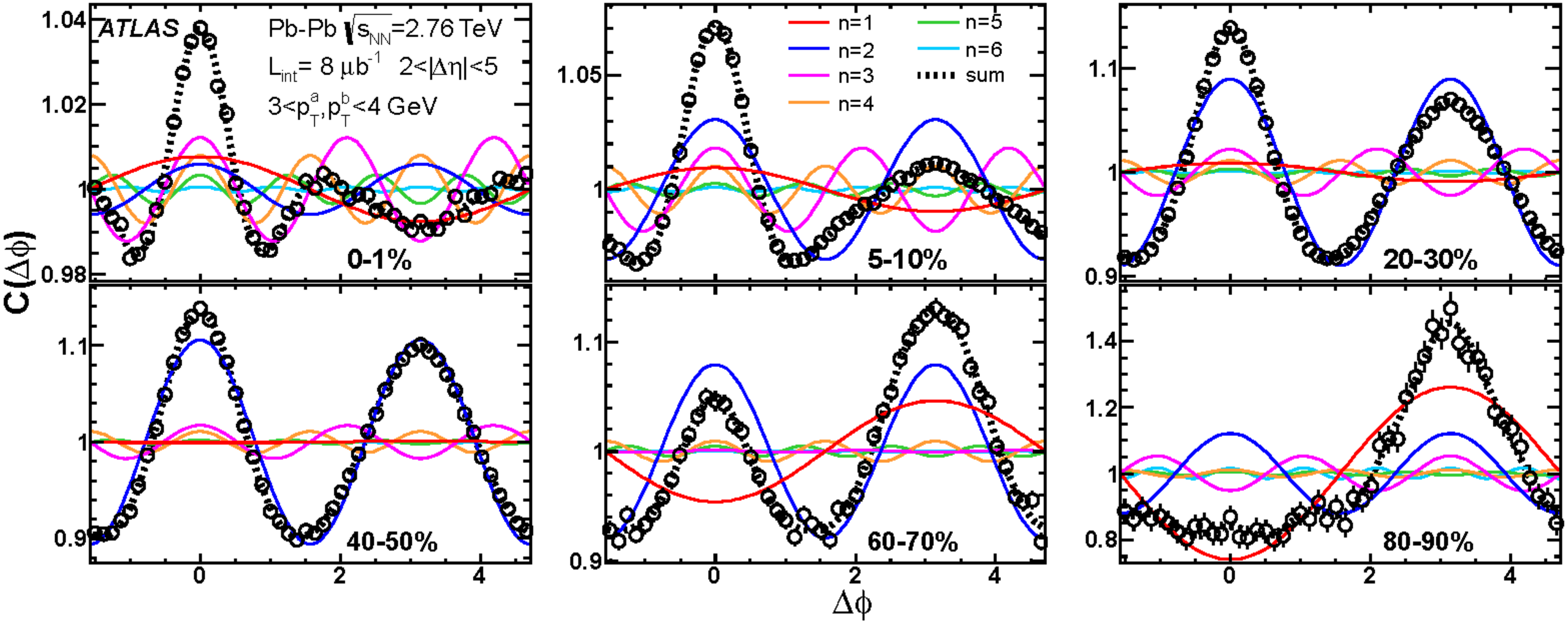
Long range correlations and ridge in PbPb at different centralities



RUN1 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



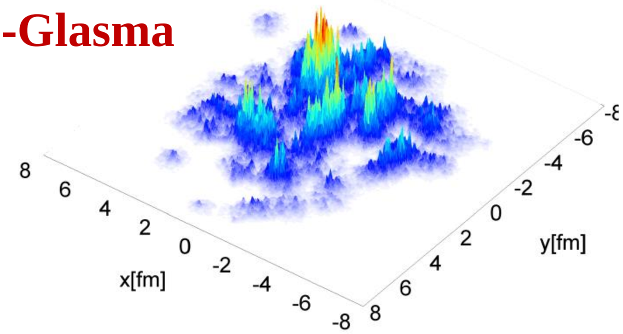
Bye-bye shock-wave and gluonic Cherenkov radiation !

Theoretical investigations, following the Standard Model of HIC
Initial Conditions – Energy Density Profiles in AuAu at RHIC energies

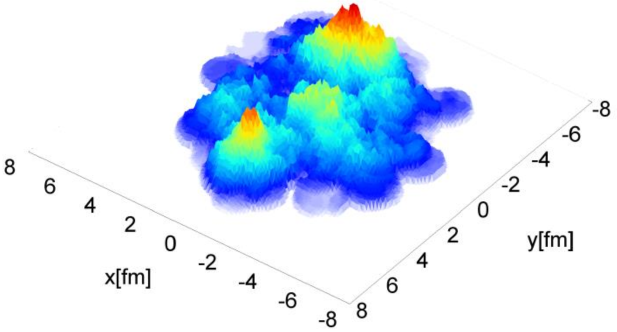
B. Schenke, P. Tribedy, R. Venugopalan, PRL108 (2012) 252301, PRC86 (2012) 034908.

[Glasma → hydro : τ(switch) $\approx 1/Q_s$ = 0.2 – 0.4 fm/c]

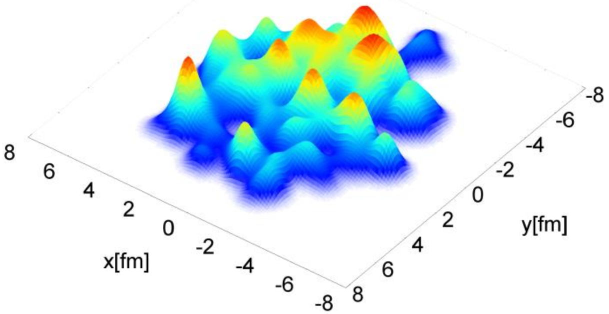
IP-Glasma



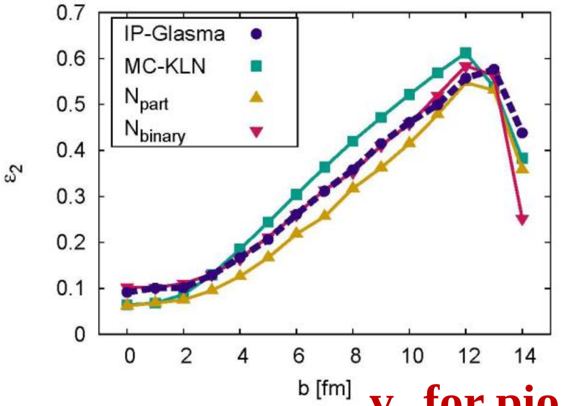
MC-KLN



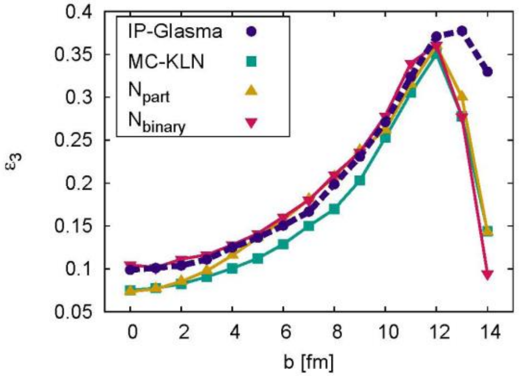
MC-Glauber



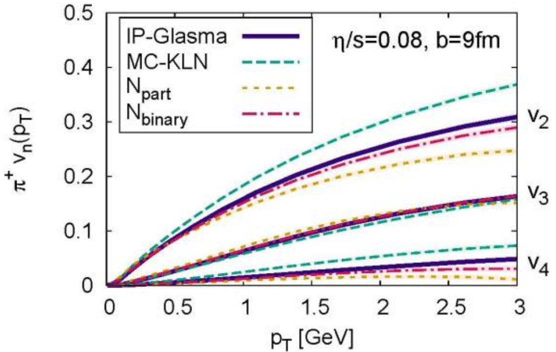
ε_2 : ellipticity



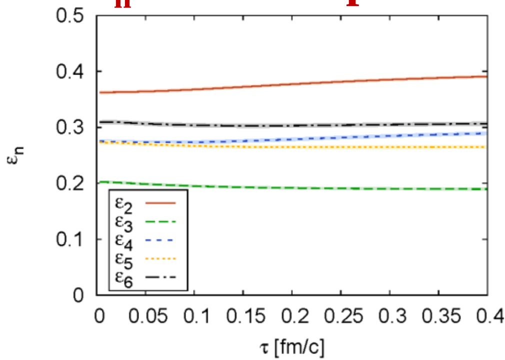
ε_3 : triangularity



v_n for pions



ε_n time independ.



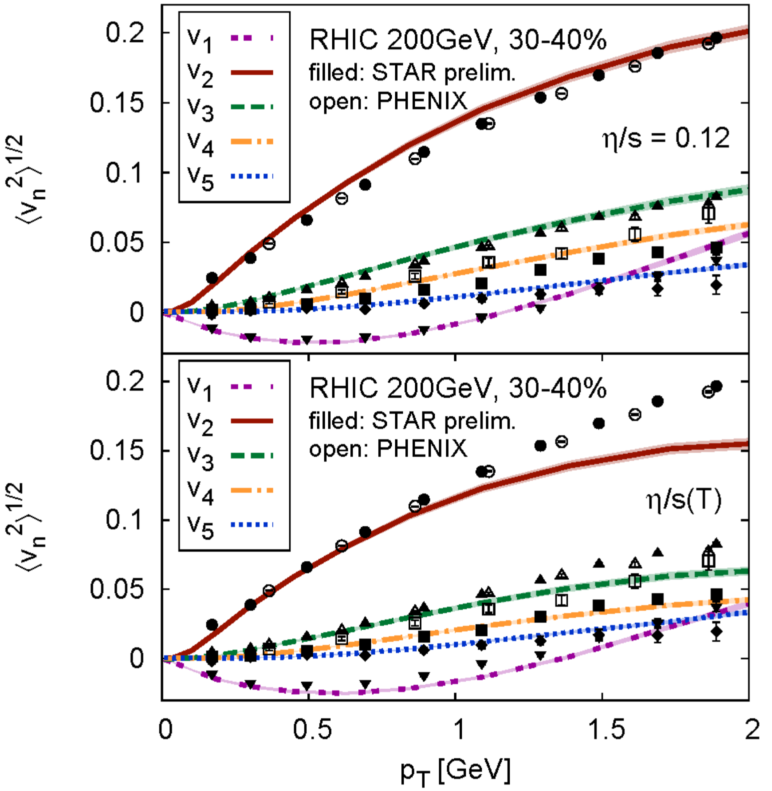
„… the change in all ε_n is very weak over the first 0.4 fm/c. After this time all ε_n begin dropping as the systems is freely streaming and hence becoming more isotrop.” (*Schenke et al, PRC86*)

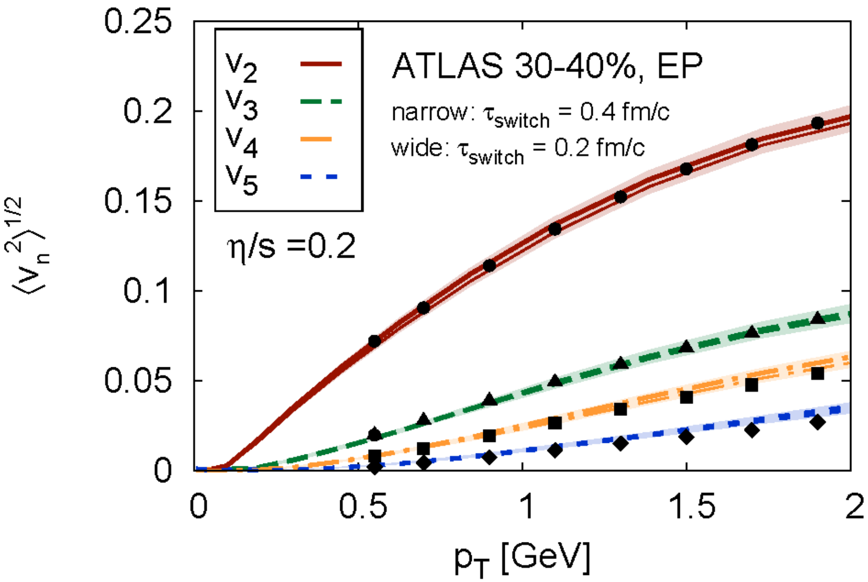
When will the v_n be developed ?

Theoretical investigations, following the Standard Model of HIC
Sensitivity of the harmonic flow components on η/s and the time evolutin

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

IP-Glasma + MUSIC hydro [Glasma → hydro : τ(switch) $\approx 1/Q_s$ = 0.2 – 0.4 fm/c]





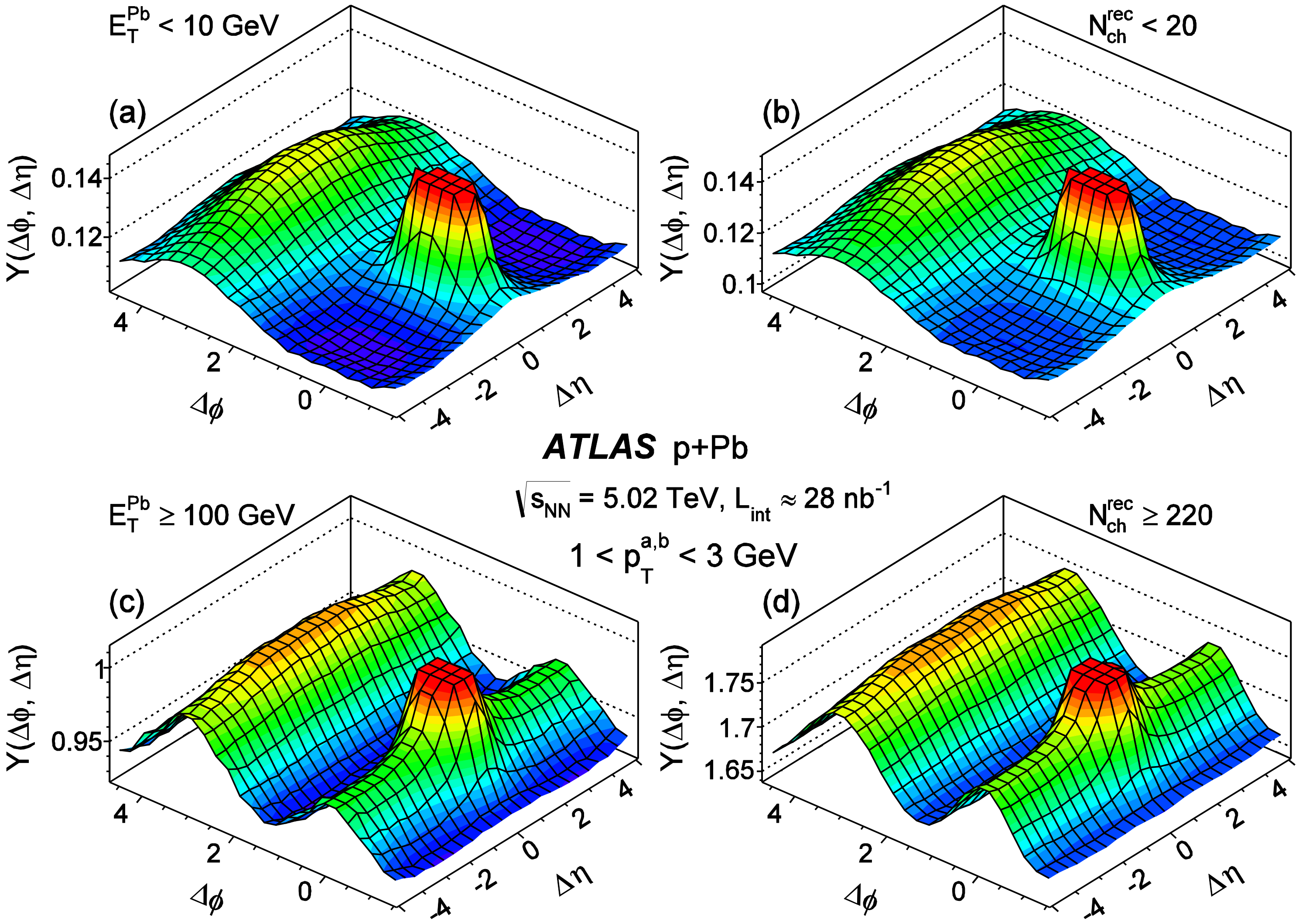
Weak sensitivity of v_n on the switching time τ between IP-Glasma state and hydrodynamics at LHC energy

Middle size sensitivity of v_n on the viscosity η/s at RHIC energy

RUN1 experimental results on v_n: pPb, $\sqrt{s}$= 5.02 TeV from ATLAS

PRC90 (2014) 044906 (<u>Oct 2014</u>), Arxiv: 1409.1792

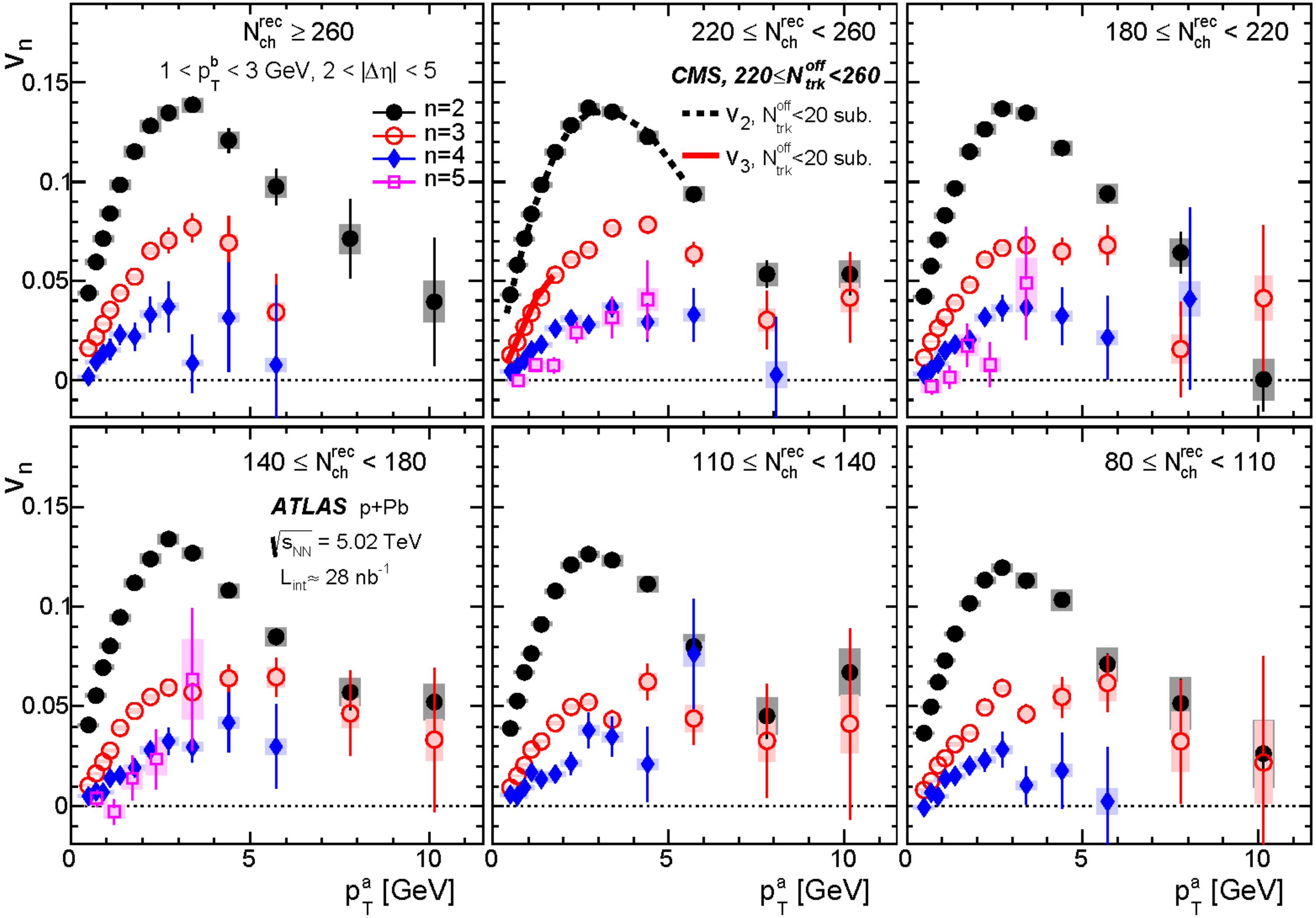
Long range correlations and ridge in pPb at small and large multiplicities



RUN1 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

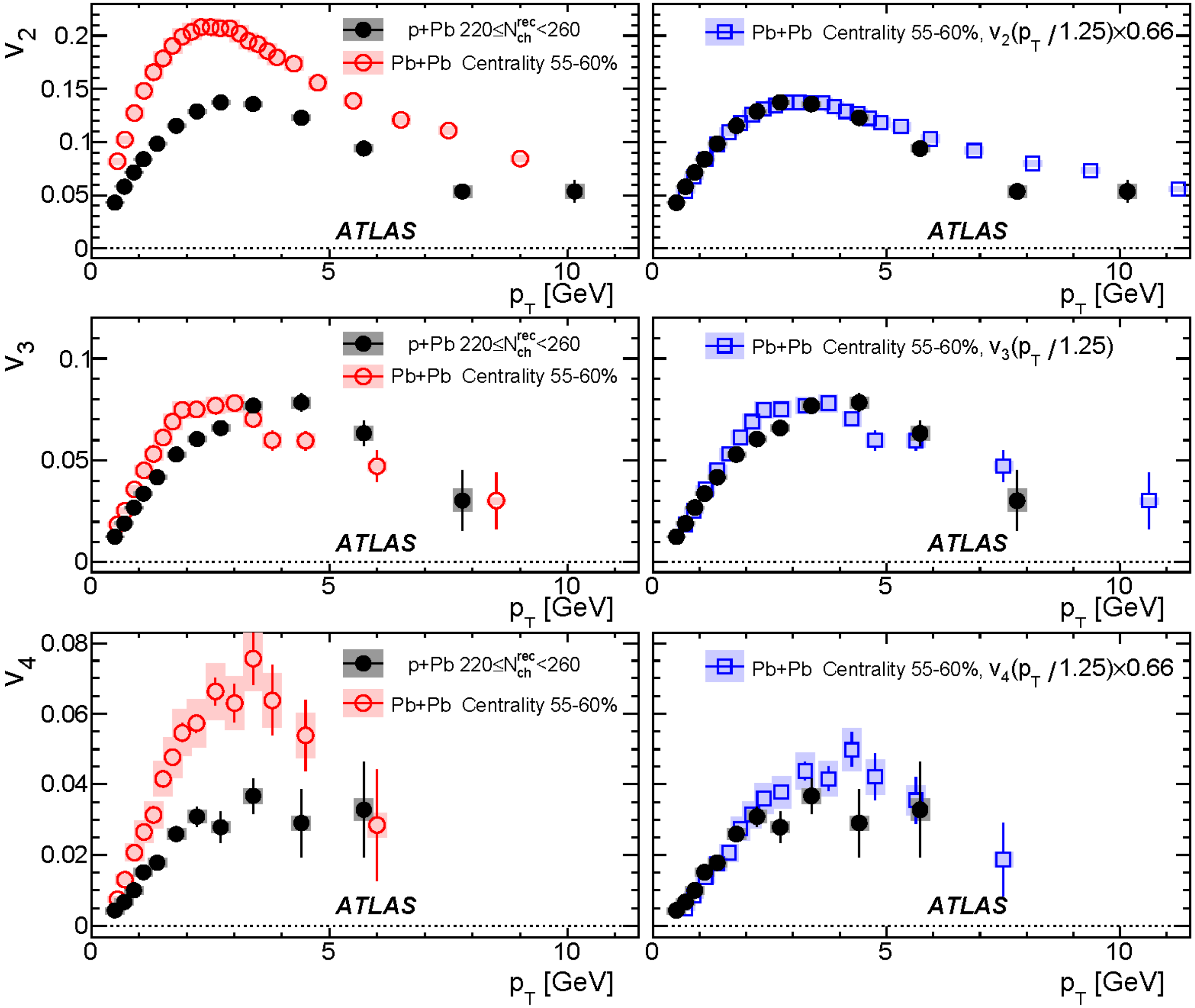


For v_n ATLAS and CMS results overlap

RUN1 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:

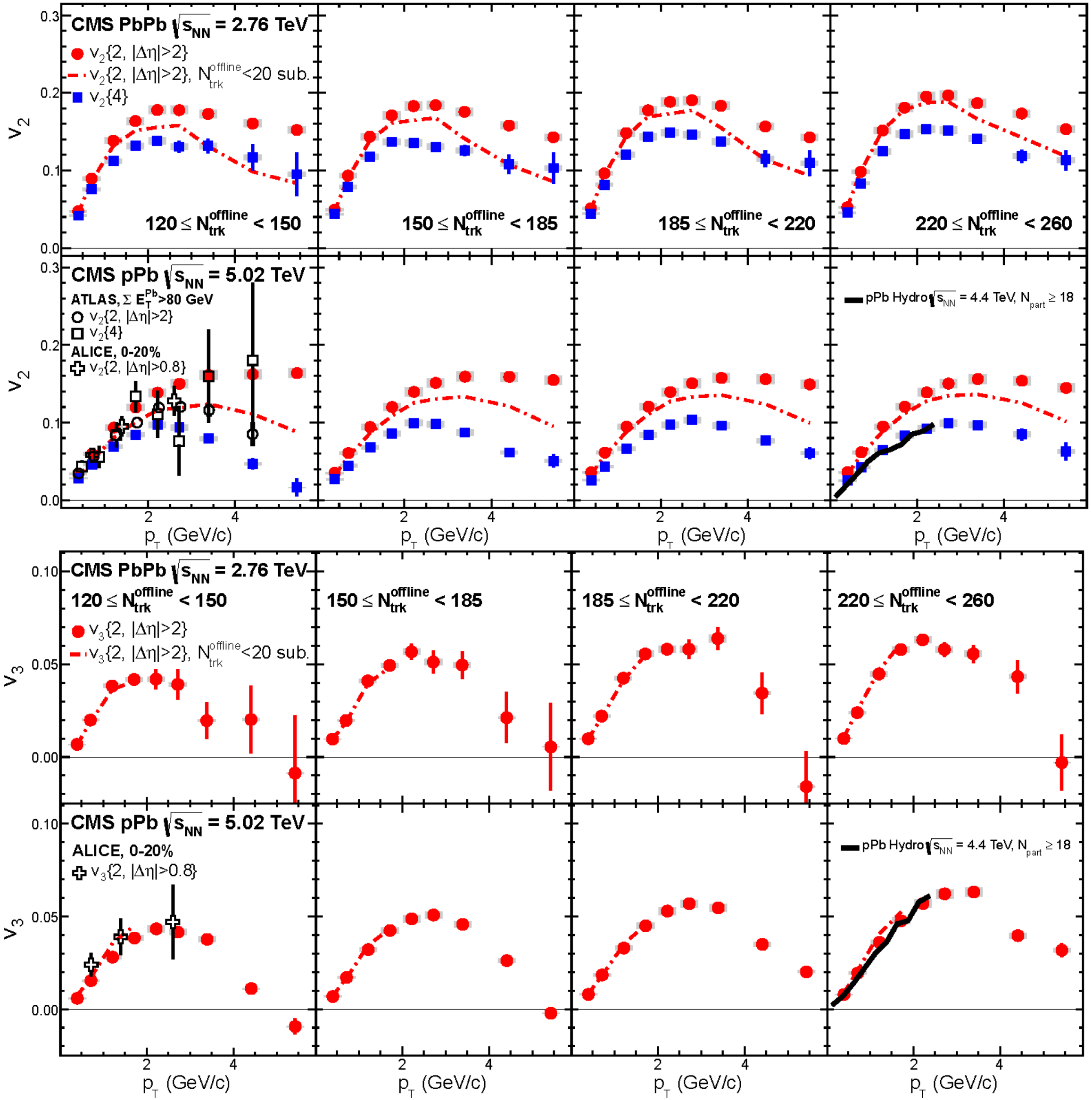
0.66 x $v_n(p_T/1.25)$

Explanation ?!

RUN1 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

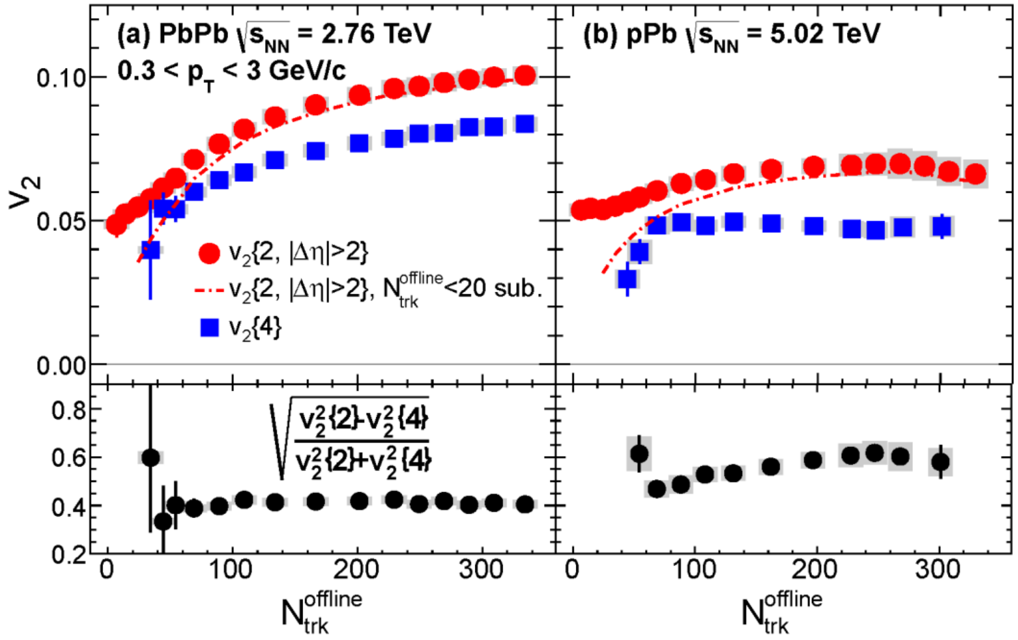


For v_2 {2}, v_3 {2}, v_2 {4} CMS, ALICE and ATLAS results overlap

RUN1 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



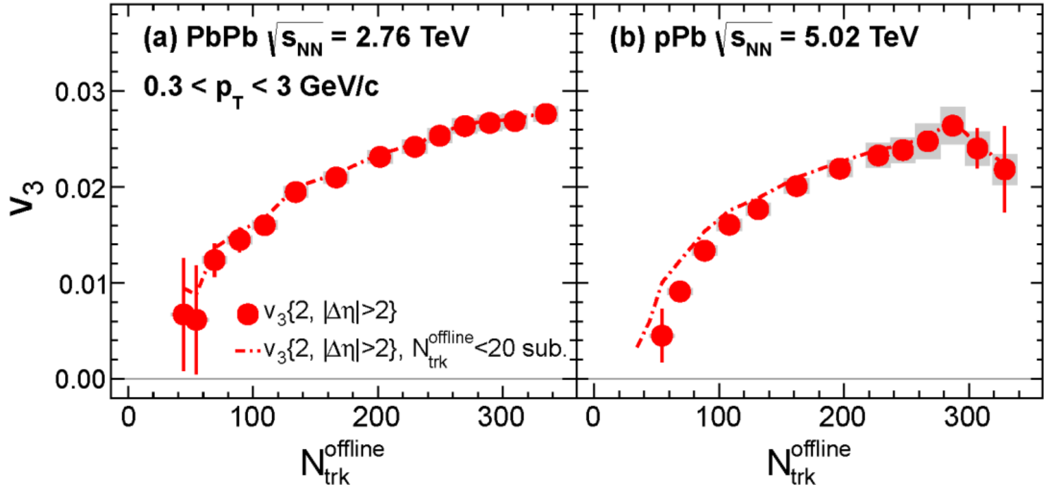
Fluctuations:

40 % in PbPb

50-60 % in pPb

residual nonflow correlations from back-to-back jets

Similar to RHIC results !

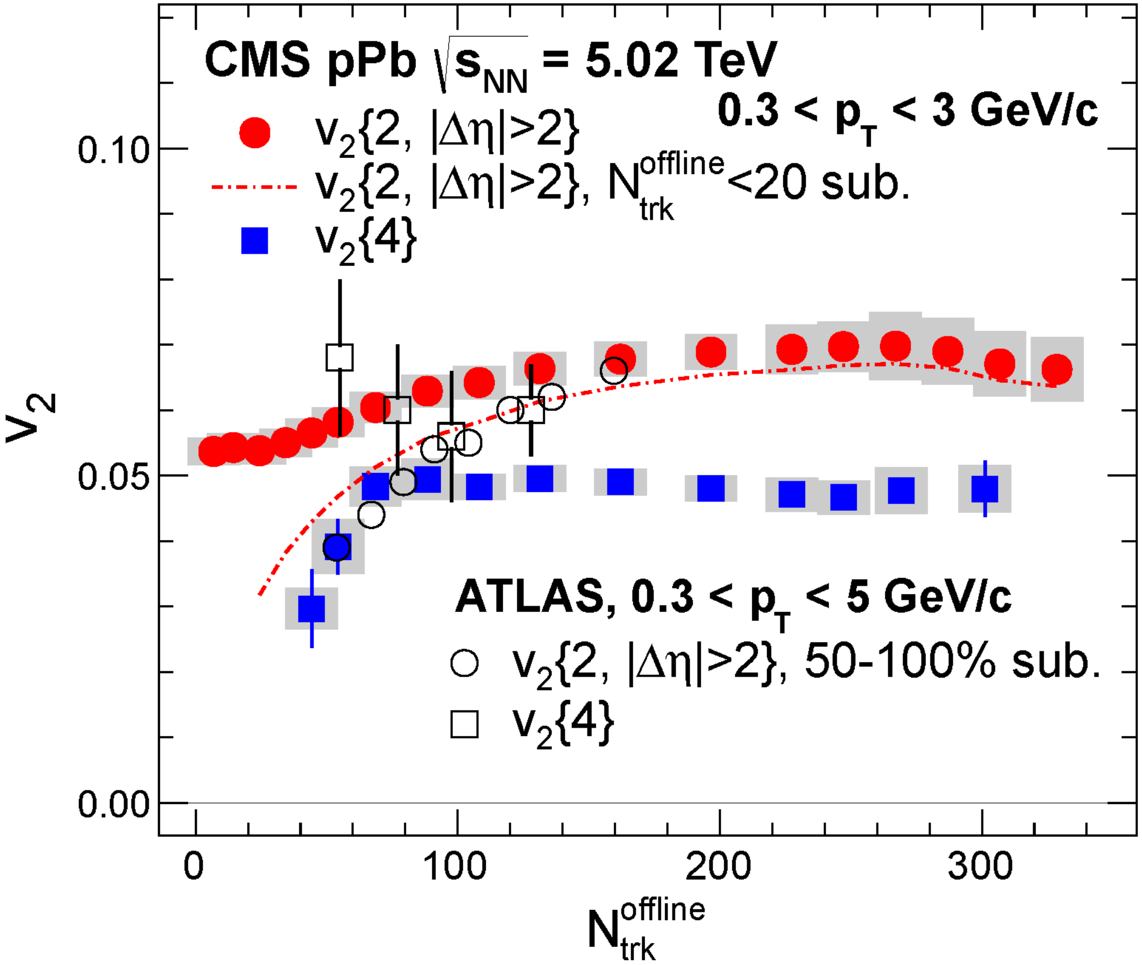


$v_3\{2\}$ are just the same in pPb and PbPb as the function of N_{trk} at longe range , $|\Delta\eta| > 2$!

RUN1 experimental results on v_n: pPb, √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



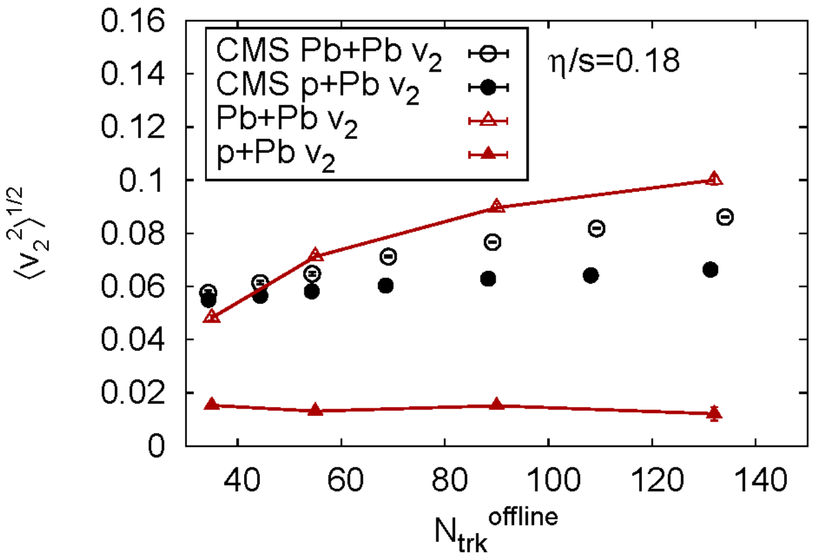
CMS and ATLAS data on $v_2\{2\}$ slightly differ, but not very much. (sligthly diff. windows)

ATLAS also claims the presence of large fluctuations in pPb collisions

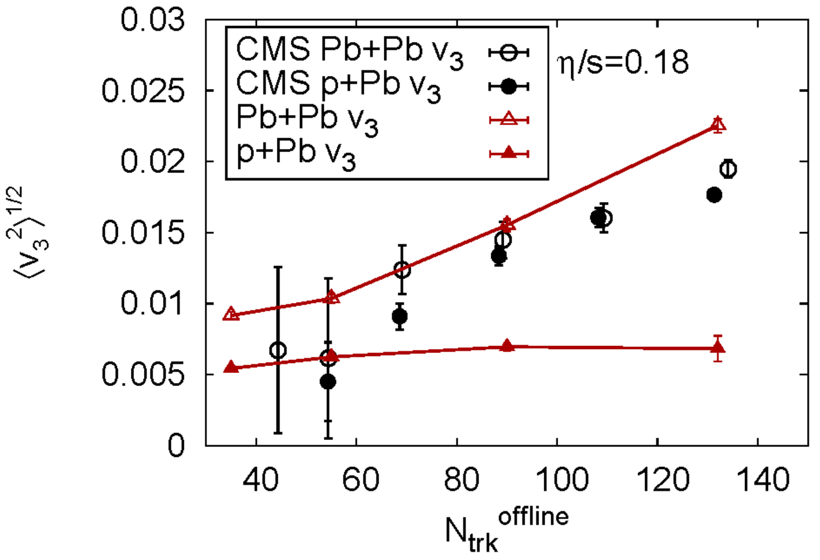
Theoretical investigations, following the Standard Model of HIC for pPb
Sensitivity of the harmonic flow components on η/s and the time evolutin

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

IP-Glasma + MUSIC hydro [Glasma → hydro : τ(switch) $\approx 1/Q_s$ = 0.2 – 0.4 fm/c]



CMS data and theory for v_2



CMS data and theory for v_3

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

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.

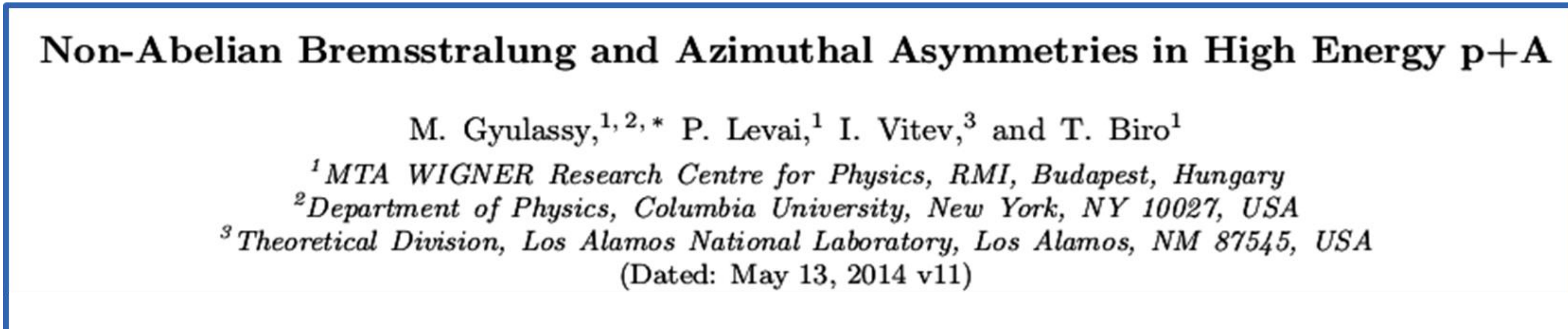
First conclusion: hydrodynamical behaviour in pPb at LHC energies
But:

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 Bremsstralung and Azimuthal Asymmetries in High Energy p+A

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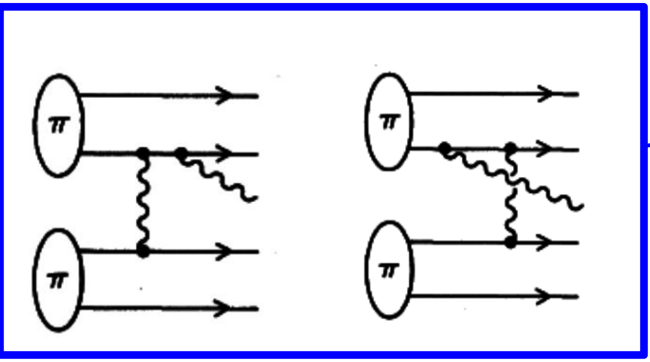
(Dated: May 13, 2014 v11)

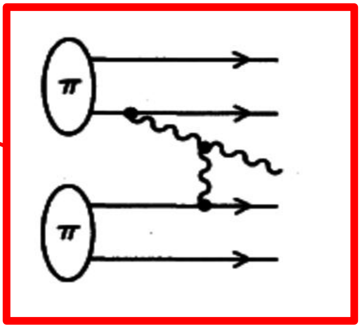
II. FIRST ORDER IN OPACITY (GB) BREMSSTRAHLUNG AND AZIMUTHAL ASYMMETRIES v_n

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 bremstralung Gunion-Bertsch (GB) formula[29] for the soft gluon radiation single inclusive distribution is

Color Dipole Form factor

$$\begin{aligned}\frac{dN_g^{(1)}}{d\eta\, d^2\mathbf{k}\, d^2\mathbf{q}} &\equiv f(\eta,\mathbf{k},\mathbf{q}) \\ &= \frac{C_R\alpha_s}{\pi^2 k^2}\,\frac{\mu^2}{(\mathbf{q}^2+\mu^2)}\,\frac{P_\eta}{(\mathbf{k}-\mathbf{q})^2+\mu^2} \\ &\equiv \frac{F\cdot P}{A_{kq}-\cos(\phi-\psi)}\end{aligned}$$





Gluon Bremsstrahlung peaks in transverse direction near net momentum transfer $\vec{Q} = (Q, \psi)$ 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 abreviations

$$\begin{aligned} A \equiv A_{kq} &\equiv (k^2+q^2+\mu^2)/(2k\,q) \geq 1 \\ F \equiv F_{kq} &\equiv \frac{C_R\alpha_s}{\pi^2 k^2}\frac{\mu^2}{(\mathbf{q}^2+\mu^2)}\frac{1}{2kq}P_\eta \end{aligned}$$

Kinematic rapidity envelope

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

$$\begin{aligned} v_n(k,q,\psi)f_0(k,q) &\equiv \int\frac{d\phi}{2\pi}\cos(n\phi)f(\eta,k,\phi,q,\psi) \\ &= F\int\frac{d\phi}{2\pi}\frac{\cos(n\phi)}{A-\cos(\phi-\psi)} \\ &= \cos(n\psi)\;F\int\frac{d\phi}{2\pi}\frac{\cos(n\phi)}{A-\cos(\phi)} \quad . \end{aligned}$$

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

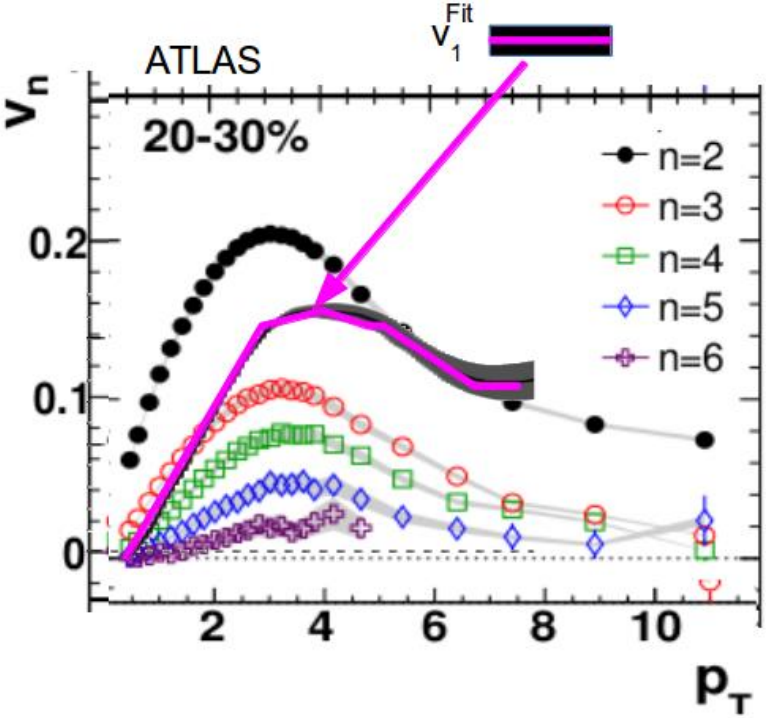
$$dN/d\eta dk^2 = F_{kq}P_\eta/(A_{kq}^2-1)^{1/2}$$

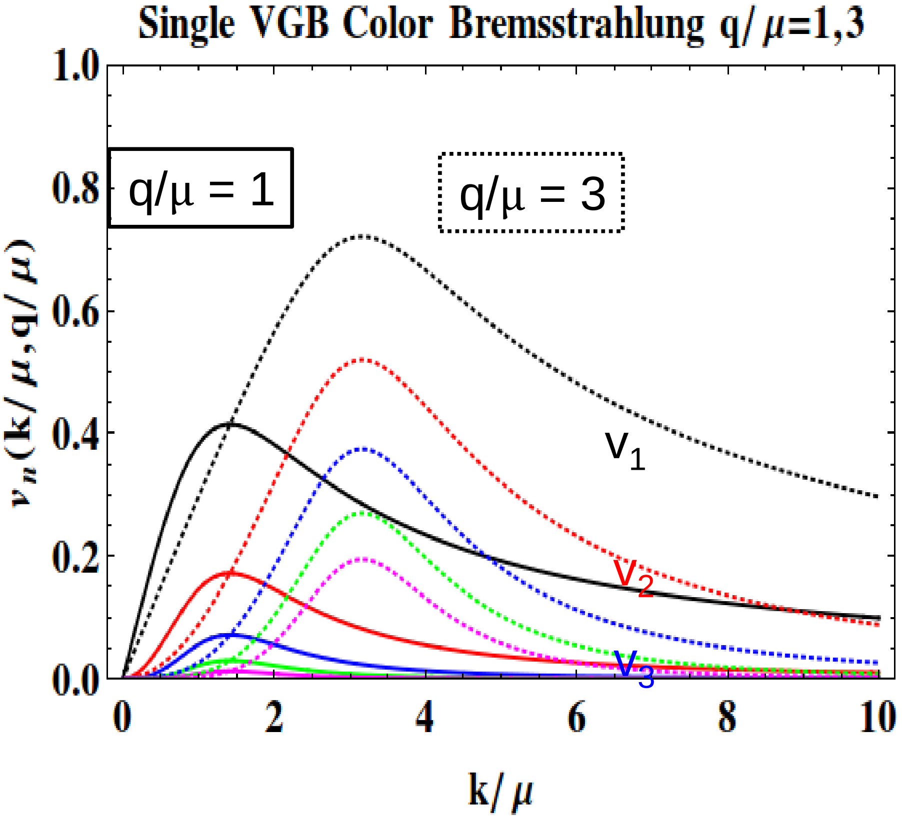
A single GB color antenna has analytic v_n: $A_{kq} \equiv (k^2+q^2+\mu^2)/(2k\,q) \geq 1$

$$
\begin{aligned}
v_1^{GB}(k,q,\psi) &= \cos[\psi](A_{kq} - \sqrt{A_{kq}^2 - 1}) \\
\lim_{\mu\to 0} v_1^{GB}(k,q,0) &= (k/q)\,\theta(q-k) \\
v_n^{GB}(k,q,\psi) &= \cos[n\psi]\,(v_1^{GB}(k,q,0))^n \\
\lim_{\mu\to 0} v_n^{GB}(k,q,0) &= (k/q)^n\,\theta(q-k)\;.
\end{aligned}
$$

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

Two particle v_n from ATLAS

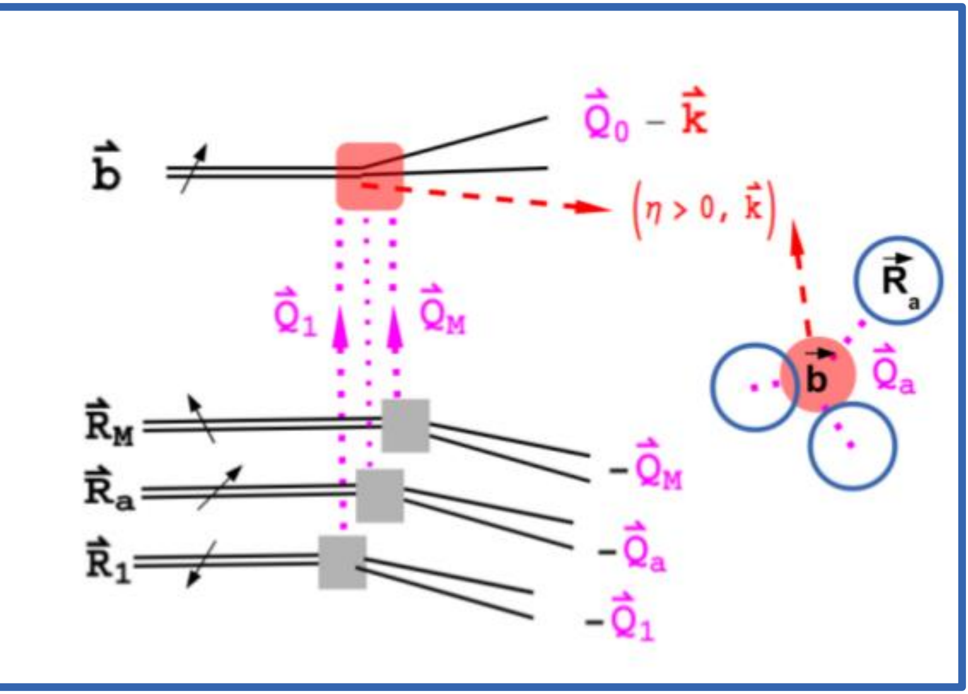




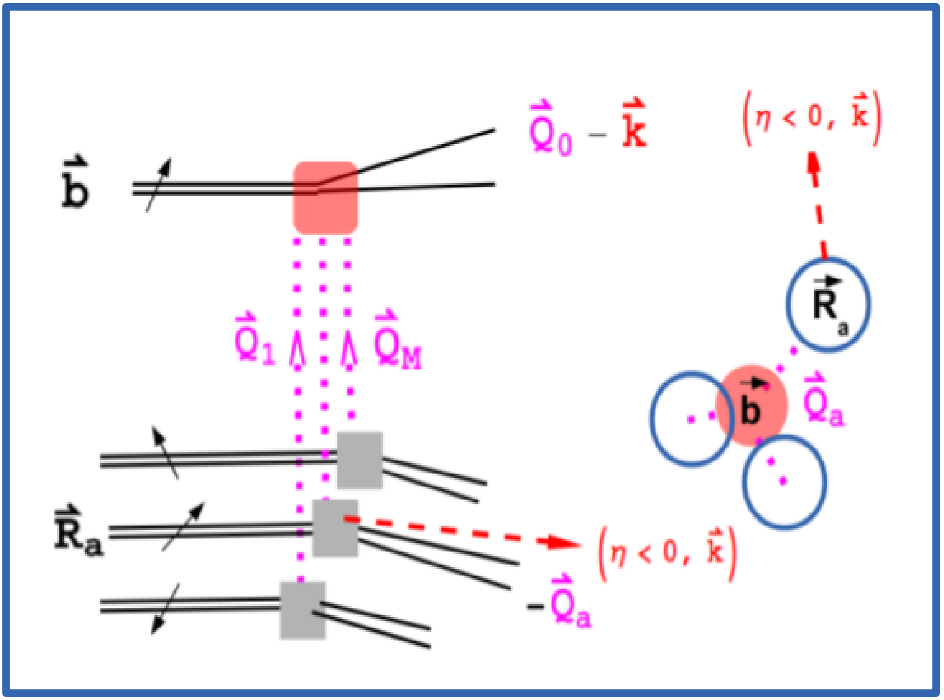
Note intrinsic huge even and odd v_n peaking near $\mu \sim Q_{sat}$

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

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

$1 \leq M \leq N$ 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.

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

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

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

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

$$B_{ia} \equiv F_{k_i,Q_a}\, P_a(\eta_i)$$

$$\mathbf{Q}_0 \equiv -\mathbf{Q}_P = -\textstyle\sum_a \mathbf{Q}_a$$

2 glue Brems in independent emission approx.

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

Two gluon relative Cos(n (φ1 – φ2)) analytic azimuthal harmonics CSA color antennas

$$f_n^{N,M}(k_1,k_2) \equiv \int_{-\pi}^{\pi} d\Phi \int_{-\pi}^{\pi} d\Delta\phi \cos(n\Delta\phi) dN_2^{N,M}(k_1,\Phi+\Delta\phi/2,k_2,\Phi-\Delta\phi/2)$$

$$=\sum_{a,b=0}^{M} B_{1a}B_{2b}\int_{-\pi}^{\pi} d\Phi' \frac{1}{A_{1a}-\cos(\Phi')}\int_{-\pi}^{\pi} d\Delta\phi \frac{\cos(n\Delta\phi)}{A_{2b}-\cos((\Phi'+\psi_b-\psi_a)-\Delta\phi)}$$

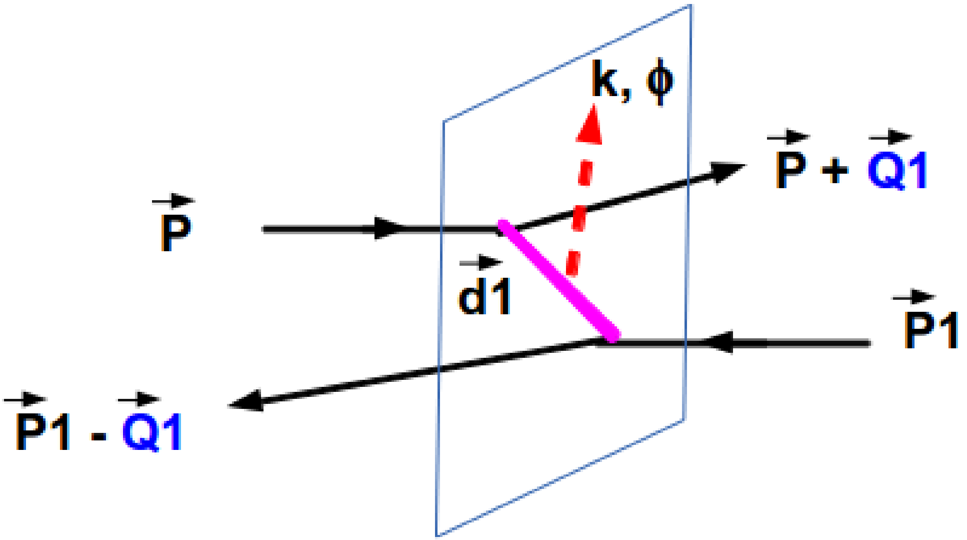
$$=\sum_{a,b=0}^{M} B_{1a}B_{2b}\, f_{0,1,a}\, f_{0,2,b} \boxed{(v_1^{GB}(k_1,Q_a)v_1^{GB}(k_2,Q_b))^n \cos(n(\psi_b-\psi_a))}$$

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

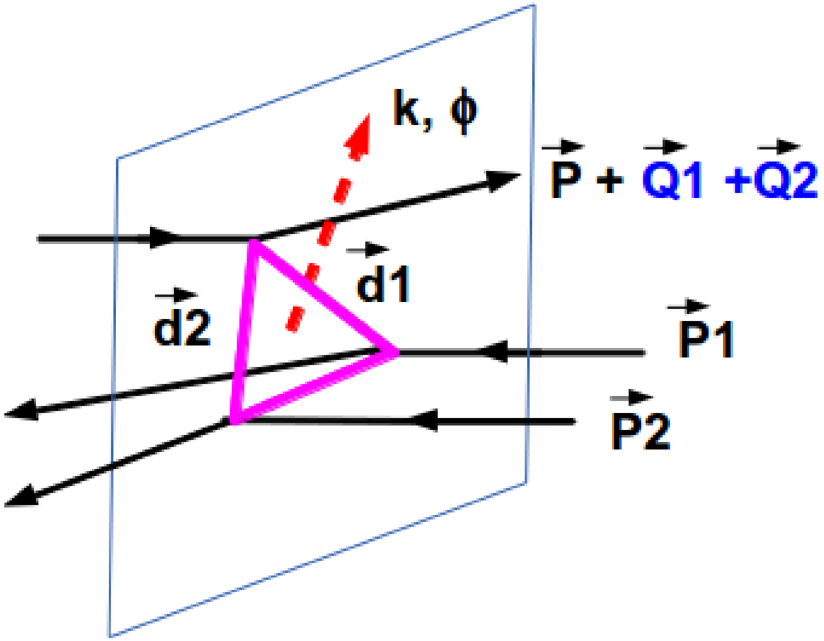
$$\boxed{v_n^{M,N}\{2\}[k_1,k_2] \equiv= \langle\cos(n(\phi_1-\phi_2))\rangle_{k_1,k_2} = \frac{\langle f_n^{M,N}(k_1,k_2)\rangle}{\langle f_0^{M,N}(k_1,k_2)\rangle}}$$

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

Classical Color Field Produced by 2 or 3 Interfering dipole currents



Two BG dipole antenna array



Three BG dipole antenna array

Produce only n=2,4,6, ...

Produce all n=1, 2, 3, 4, ...

Numerical calculations for pp, pA and AA collisions:
HIJING++ model with radiating dipole antennas
(Harangozó SZ., Papp G., Barnaföldi GG,   Wang X-N-, Zhang BW, …

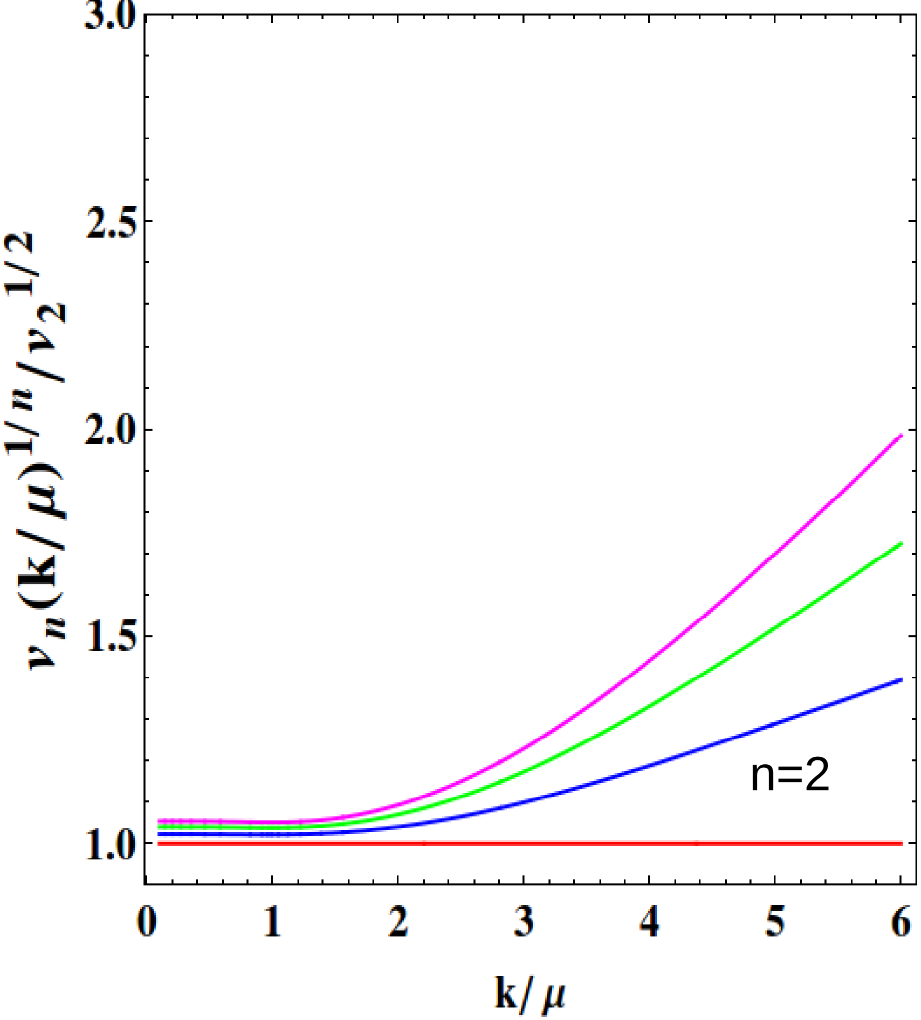
Fixed q GB pQCD Bremsstrahlung harmonics scale perfectly via 1/n power law

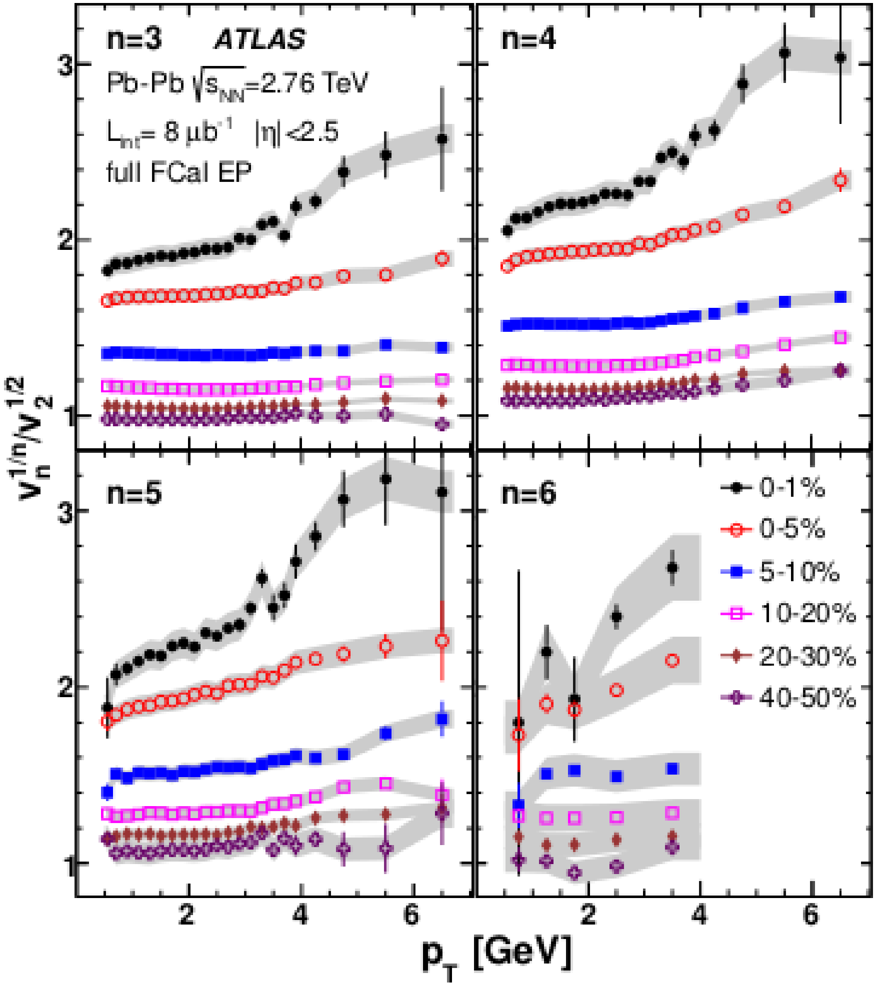
$$[v_n^{GB}(k,q,0)]^{1/n} \;=\; [v_m^{GB}(k,q,0)]^{1/m}$$

For Yukawa averaged ⟨q/μ⟩ =√M,

GB 1/n scaling hold for k < √M and breaks down for k > √M

Yukawa <q/ μ>=3 ave vn$^{1/n}$ scaling wrt √ v2   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

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

Need more data and better undestanding of experimental data on fluctuation !!!
J. Y. Ollitrault, A. Poskanzer, … on cumulants
Escaping partons from hot intearcting zone → D. Molnár [ZimSchool]

Summary:

1. **Latest experimental data display**
    - a) **Strong similarity of flow harmonics in pA and periferal 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 multiplicitiesto 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 undestanding of exp. data on/with fluctuation !!!**