



# Коллективный поток в столкновениях малых нуклонных систем

**В.Л. Коротких**

(Обзор и обсуждение некоторых данных до 2018 г.)

Ссылки:

1. Wei Li, Report “**Initial states** and collectivity in small systems” on XII Workshop on Particle Correlations and Femtoscopy Amsterdam, 2017
2. I. Tserrruya, “QGP in small systems? “ICCNF, Kolymbaru, 2015.
3. J.L. Nagle, W.A.Zajc, arXiv:1801.03477,  
Small System Collectivity in Relativistic Hadron and Nuclear Collisions.
4. W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song<sup>1</sup>, arXiv:1801.00271  
Hydrodynamic Collectivity in Proton-Proton Collisions at 13 TeV.
5. Опубликованные результаты CMS коллаборации.



# Коллективный поток в столкновениях малых нуклонных систем

## Содержание

1. Предсказания и измерения  $v_2$  в  $pp$
2.  $v_2$  и  $v_3$  в  $p+p$ ,  $p+Pb$ ,  $d+Au$ ,  $^3He+Au$
3. Симметризованная корреляция  $SC(2,3)$
4. “Корреляция  $v_2$  (High- $p_T$ ) и  $v_2$  (Low- $p_T$ )”
5. Некоторые заключения



# Предсказание анизотропии в pp



CERN, CMS WEEK Dec 12, 2008

- Estimates of hadron azimuthal anisotropy from multiparton interactions in proton-proton collisions at  $\sqrt{s} = 14$  TeV
- d'Enterria D., Eyyubova G.Kh., Korotkikh V.L., Lokhtin I.P., Petrushanko S.V., Sarcheva L.I., Snigirev A.M.
- The European Physical Journal C March 2010, Volume 66, Issue 1, pp 173-185

arXiv:0910.3029

Cited by 58 records

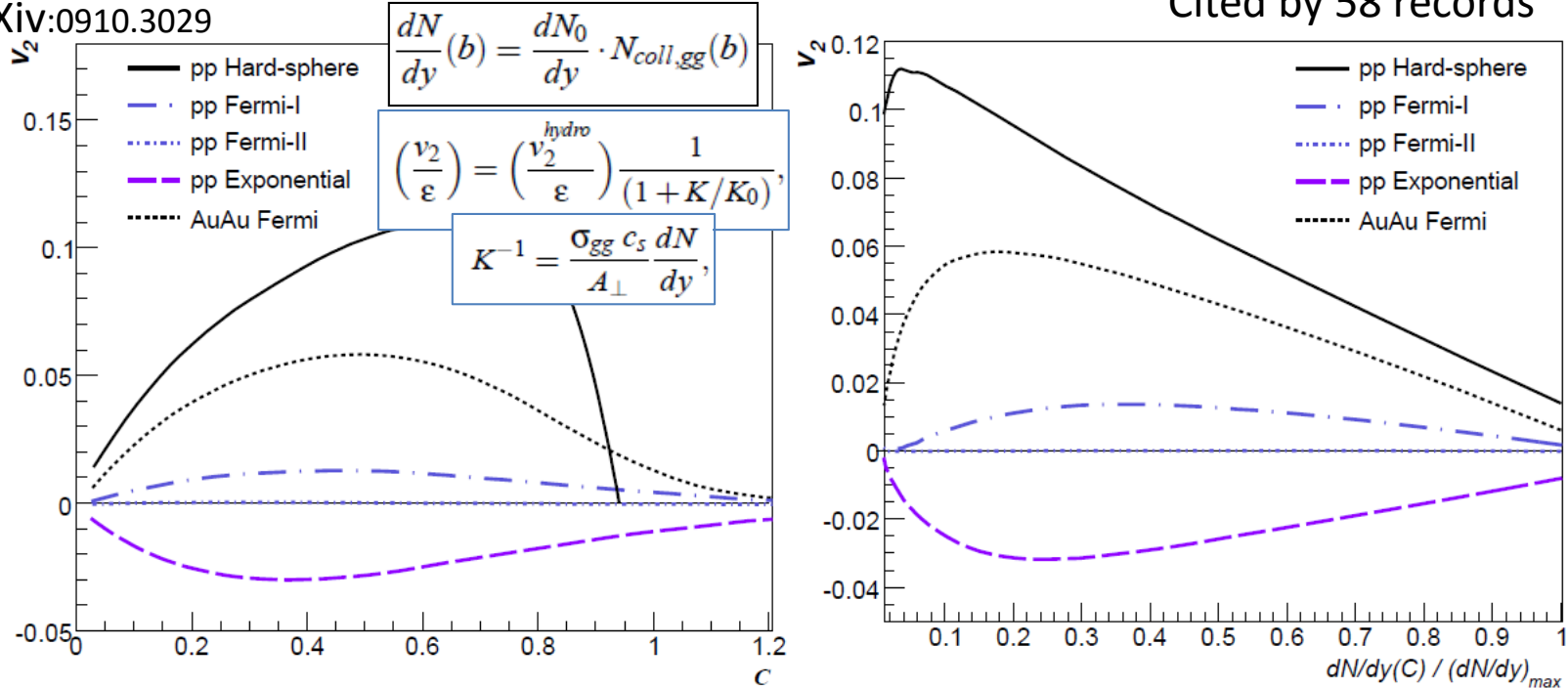


Fig. 8. Integrated elliptic flow  $v_2$  parameter as function of centrality (left panel) and of normalised particle multiplicity (right panel) at midrapidity in  $p$ - $p$  collisions at  $\sqrt{s} = 14$  TeV for the different proton density distributions considered in this work (Table 1). For comparison, the  $v_2$  for  $Au$ - $Au$  at RHIC energies is shown as a dotted line.

For realistic proton transverse profiles, we find integrated elliptic flow  $v_2$  parameters about **3-5% in p-p** collisions at  $\sqrt{s} = 14$  TeV. We were the first to investigate **pp eccentricity!**

12.02.2018



# Предсказание анизотропии в $pp$

Первые работы по предсказанию  $v_2$  в  $pp$  столкновениях (из arXiv:1509.07939)

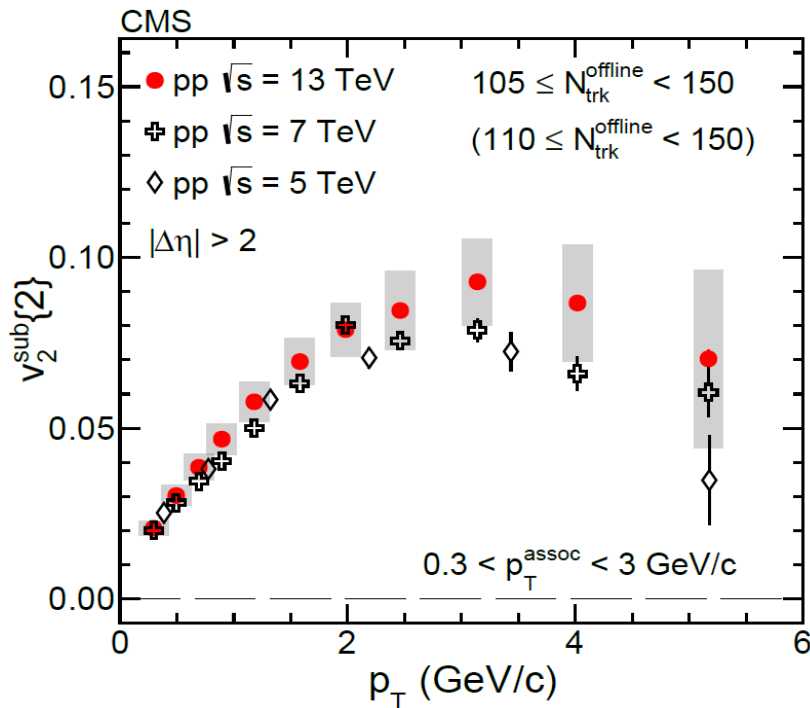
1. M. Luzum and P. Romatschke,  
Phys. Rev. Lett. 103 (2009) 262302, arXiv:0901.4588 [nucl-th].
2. I. Bautista, L. Cunqueiro, J. D. de Deus and C. Pajares,  
J. Phys. G 37 (2010) 015103, arXiv:0905.3058 [hep-ph].
3. **D. d'Enterria, G. K. Eyyubova, V. L. Korotkikh, I. P. Lokhtin, S. V. Petrushanko,  
L.I. Sarycheva and A. M. Snigirev,**  
**Eur. Phys. J. C 66 (2010) 173, arXiv:0910.3029 [hep-ph].**
4. S. K. Prasad, V. Roy, S. Chattopadhyay and A. K. Chaudhuri,  
Phys. Rev. C 82 (2010) 024909, arXiv:0910.4844 [nucl-th].
5. P. Bozek, Acta Phys. Polon. B 41 (2010) 837, arXiv:0911.2392 [nucl-th].
6. J. Casalderrey-Solana and U. A. Wiedemann,  
Phys. Rev. Lett. 104 (2010) 102301, arXiv:0911.4400 [hep-ph].
7. G. Ortona, G. S. Denicol, P. Mota and T. Kodama (2009)  
arXiv:0911.5158 [hep-ph].
8. E. Avsar, C. Flensburg, Y. Hatta, J.-Y. Ollitrault and T. Ueda,  
Phys. Lett. B 702 (2011) 394, arXiv:1009.5643 [hep-ph].
- 9.....



Z.Chen, THESIS CMS 1709.03567

pp collision

$$v_n(2PC, p_T^{ac}) = \frac{V_{n\Delta}(p_T^{tr}, p_T^{ac})}{\sqrt{V_{n\Delta}(p_T^{tr} = p_T^{ac})}} \approx v_n^{EP}\{2\}(p_T^{ac}).$$



Вторая гармоника в  $pp$ -столкновениях для заряженных частиц  
в эксперименте CMS на LHC

<http://www.arxiv.org/abs/1009.4122>

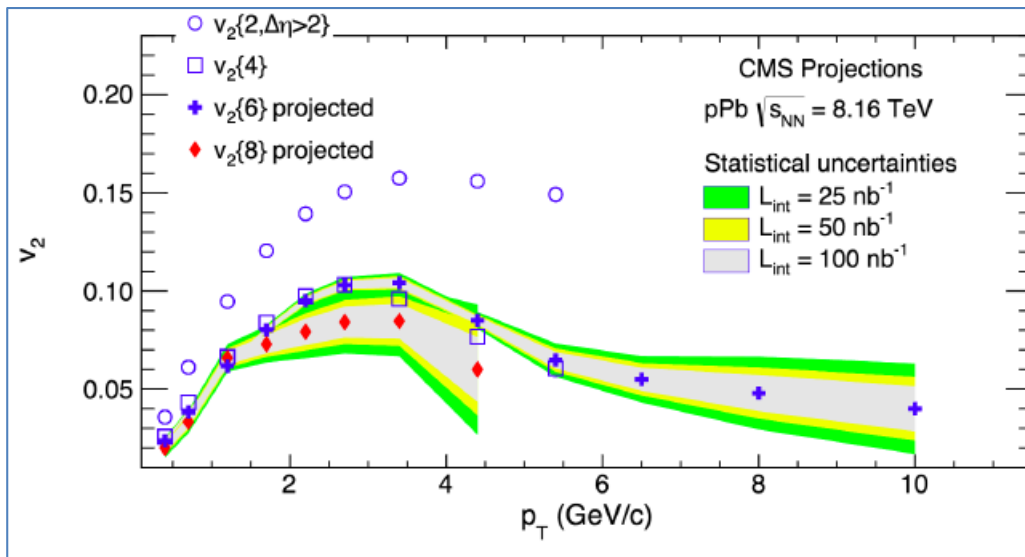
<http://www.arxiv.org/abs/1509.04776>

<http://www.arxiv.org/abs/1510.03068>



Wey Li, WPCF2017-weili-06122017

**pPb collision**



multiparticle  $v_2$   
at high  $p_T$

**$L_{int} \sim 186 \text{ nb}^{-1}$**   
collected in 2016

<http://www.arxiv.org/abs/1210.5482>

<http://www.arxiv.org/abs/1212.2001>

<http://www.arxiv.org/abs/1212.5198>

<http://www.arxiv.org/abs/1512.00439>

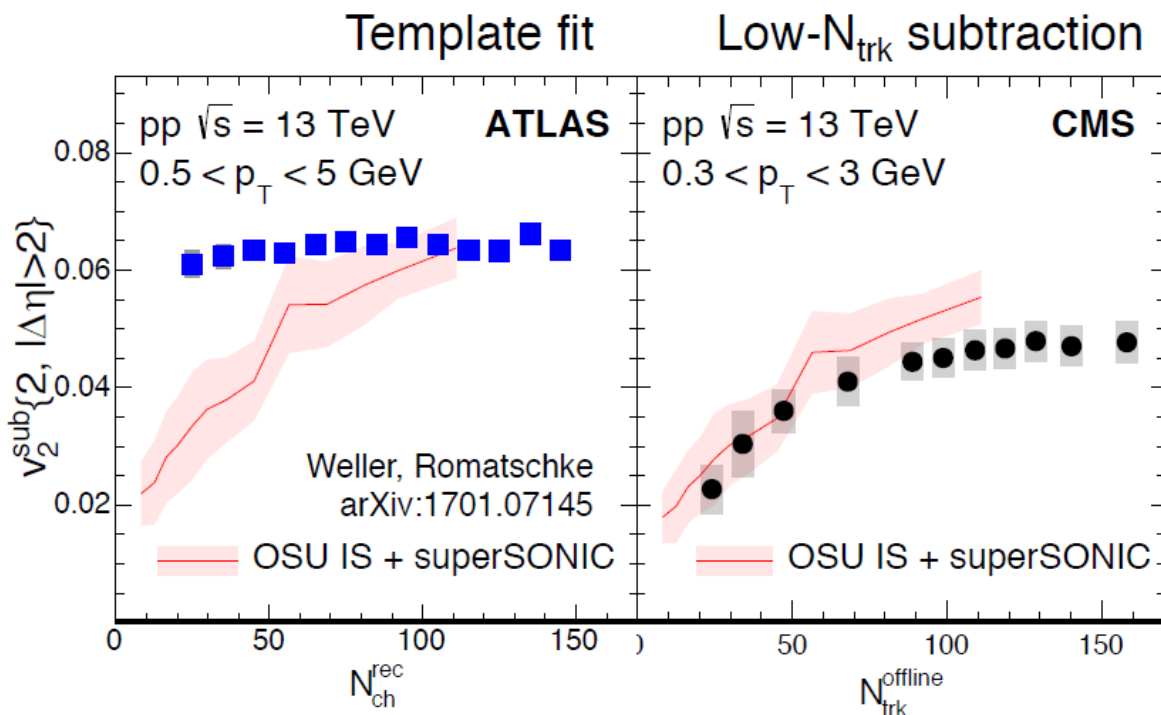


Wey Li, WPCF2017-weili-06122017

## Collectivity toward low multiplicity

Hydro. down to  $dN/dy \sim 2$

**pp**

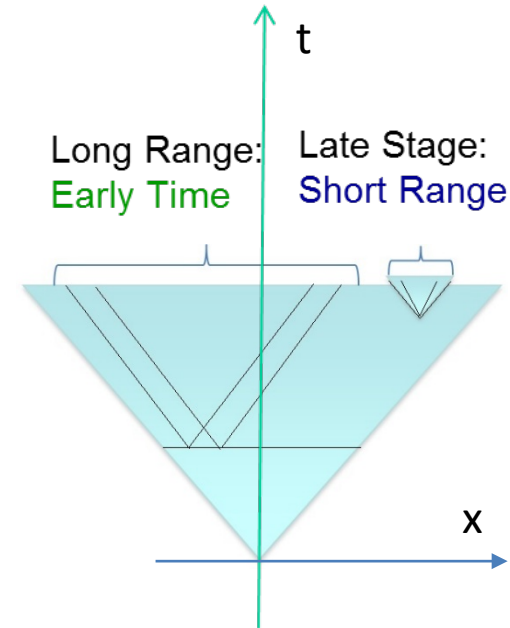
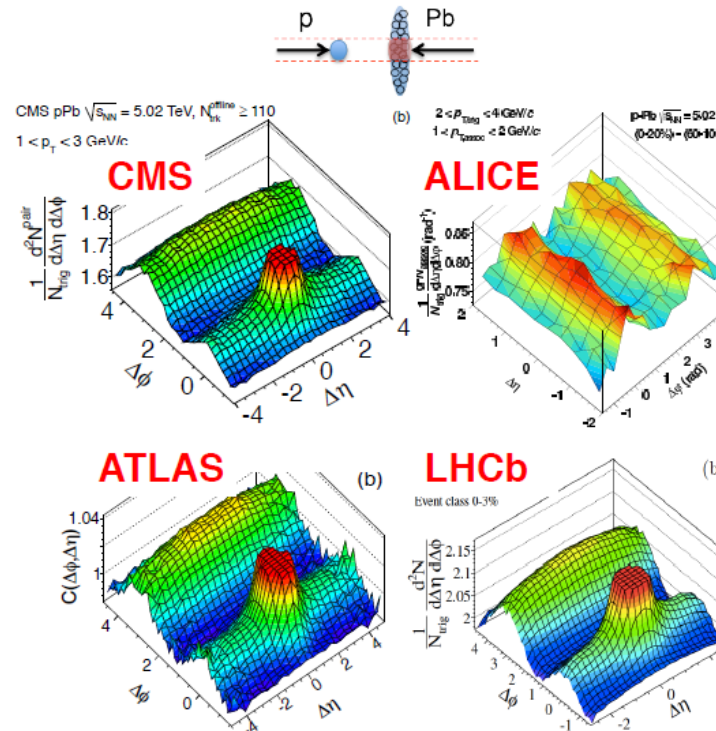
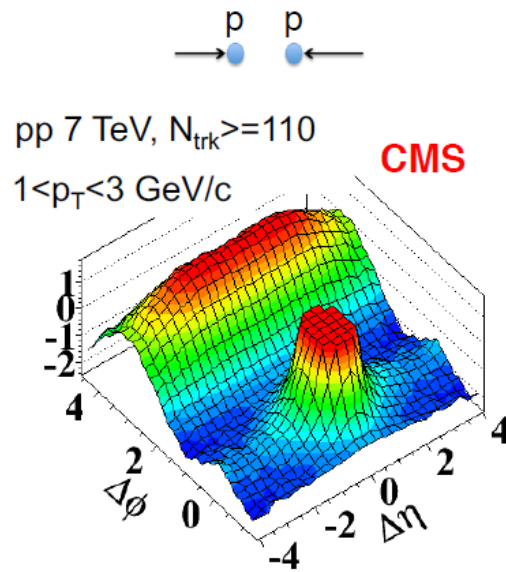


**If hydro.,  $v_2$  should go down toward low  $N_{\text{trk}}$**



Wey Li, WPCF2017-weili-06122017

## Phase I (2010 – 2012): “Ridge”



### Long-range correlations up to $\Delta\eta \sim 10$

- Not in MB pp (?) but resemble features in large AA
- very early stage  $\tau_0 \leq \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right) \sim 0.1$  fm/c

$$\Delta\eta=10 \rightarrow \exp(-5)=0.013$$

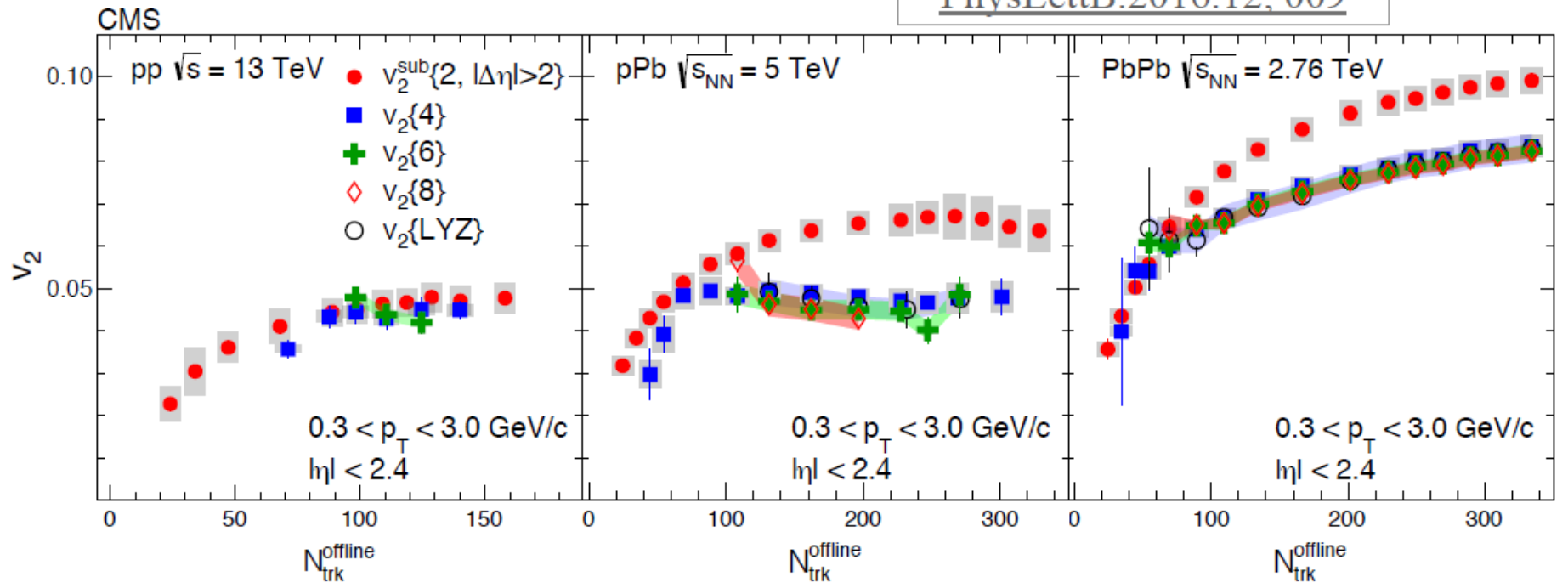




QM2017, M. Guilbaud, CMS

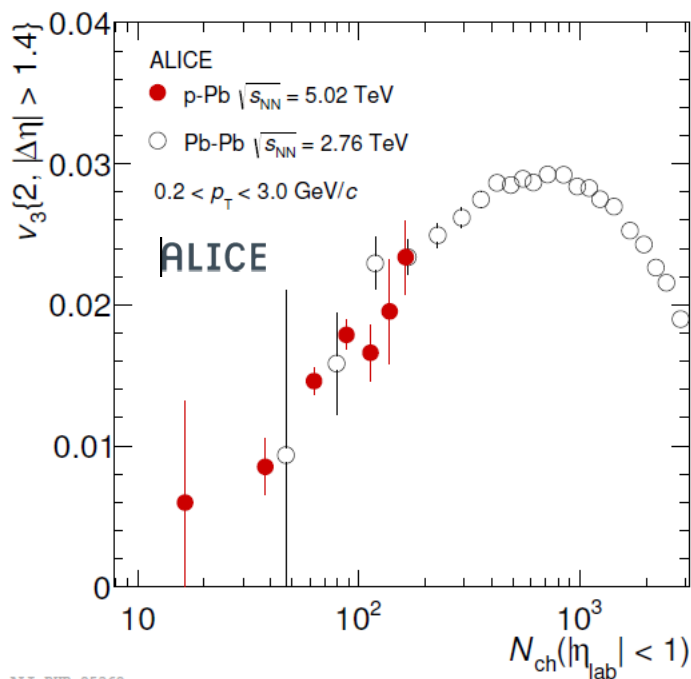
- Measurement of Fourier harmonics with multi-particle cumulants
  - See Z.Chen's talk tomorrow 11.40 am

PhysLettB.2016.12, 009

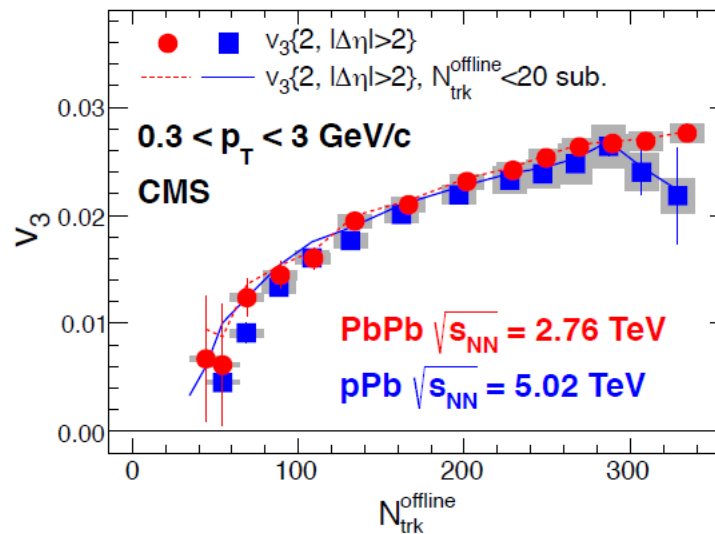


- IS fluctuations play an important role for  $v_n$  in small systems

# Поток $V_3$ в PbPb и pPb



ALI-PUB-85368



Совпадение зависимостей  $V_3(N_{track})$  для **PbPb** и **pPb**

- $v_3$  is similar for both systems at same multiplicity
- Driven by fluctuations?

*Phys. Lett. B* 724, (2013) 213  
 arXiv:1406.2474 [nucl-ex]

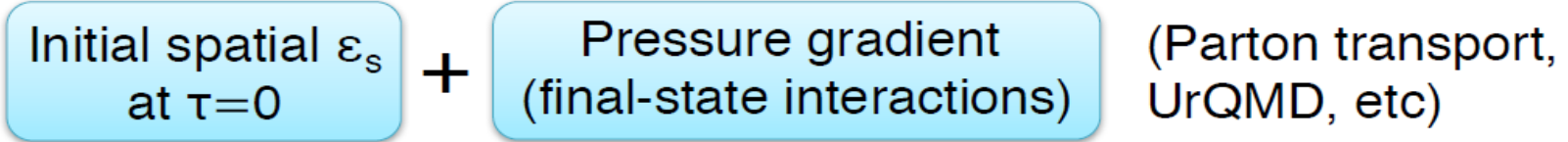
Michael Weber (CERN) - WPCF 2014 - 25.08.2014

21



# Phase III (2017 – ...): Why collective?

“Hydrodynamic” scenario: accepted paradigm in AA



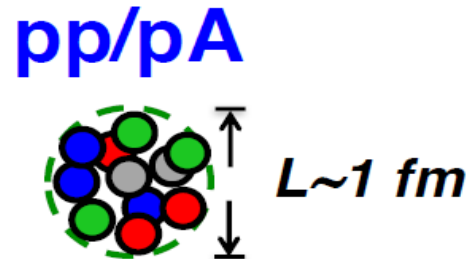
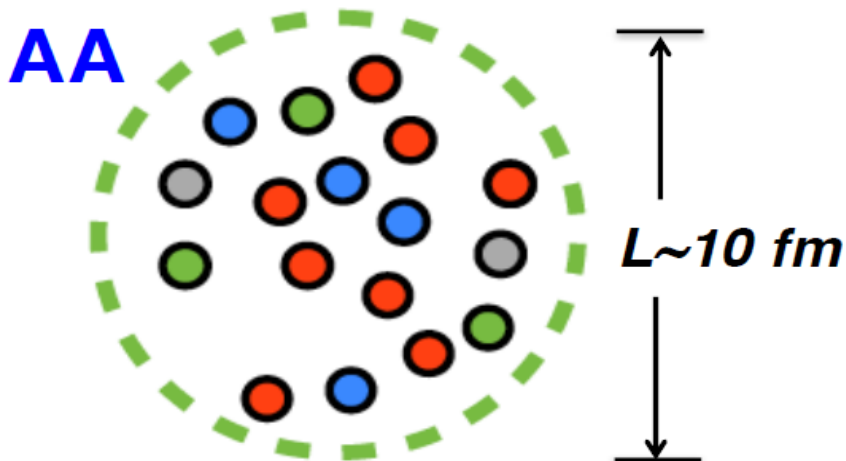
requires:

$$L \gg \lambda_{m.f.p.}$$

*Fast equilibrium/thermalization?*

➤ **No need!** Systems may well be out-of-equilibrium

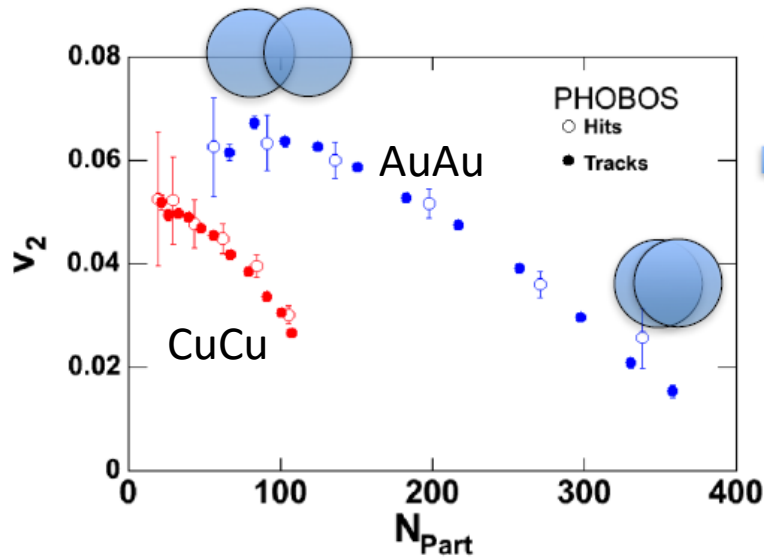
P. Romatschke  
[arXiv:1609.02820](https://arxiv.org/abs/1609.02820)



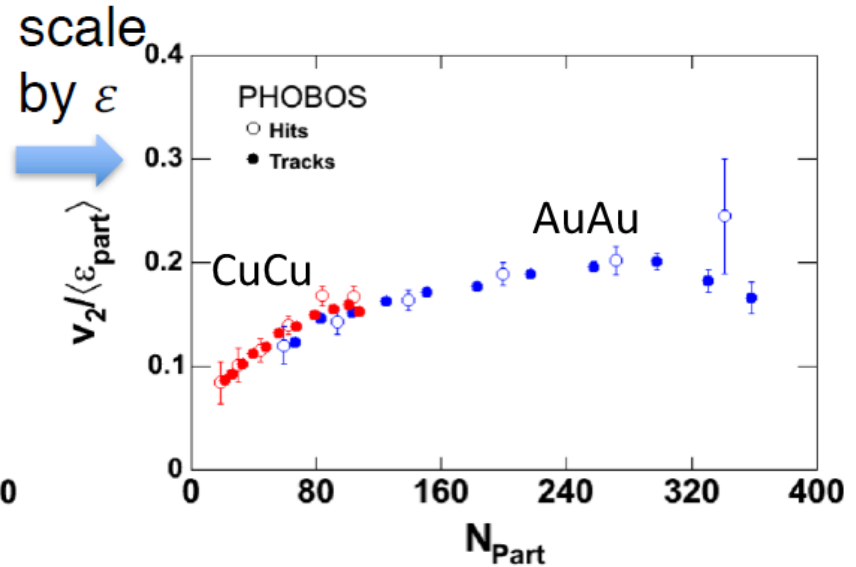
K. Srivastava, **transport dynamics of partons**  
<http://arxiv.org/abs/1801.07482v1>

# “Perfect” fluid paradigm in AA

➤ Geometry ( $\epsilon_s$ ) at work! — even for  $A_1(A_2)$  down to 2



Centrality dependence



CuCu vs AuAu scaling

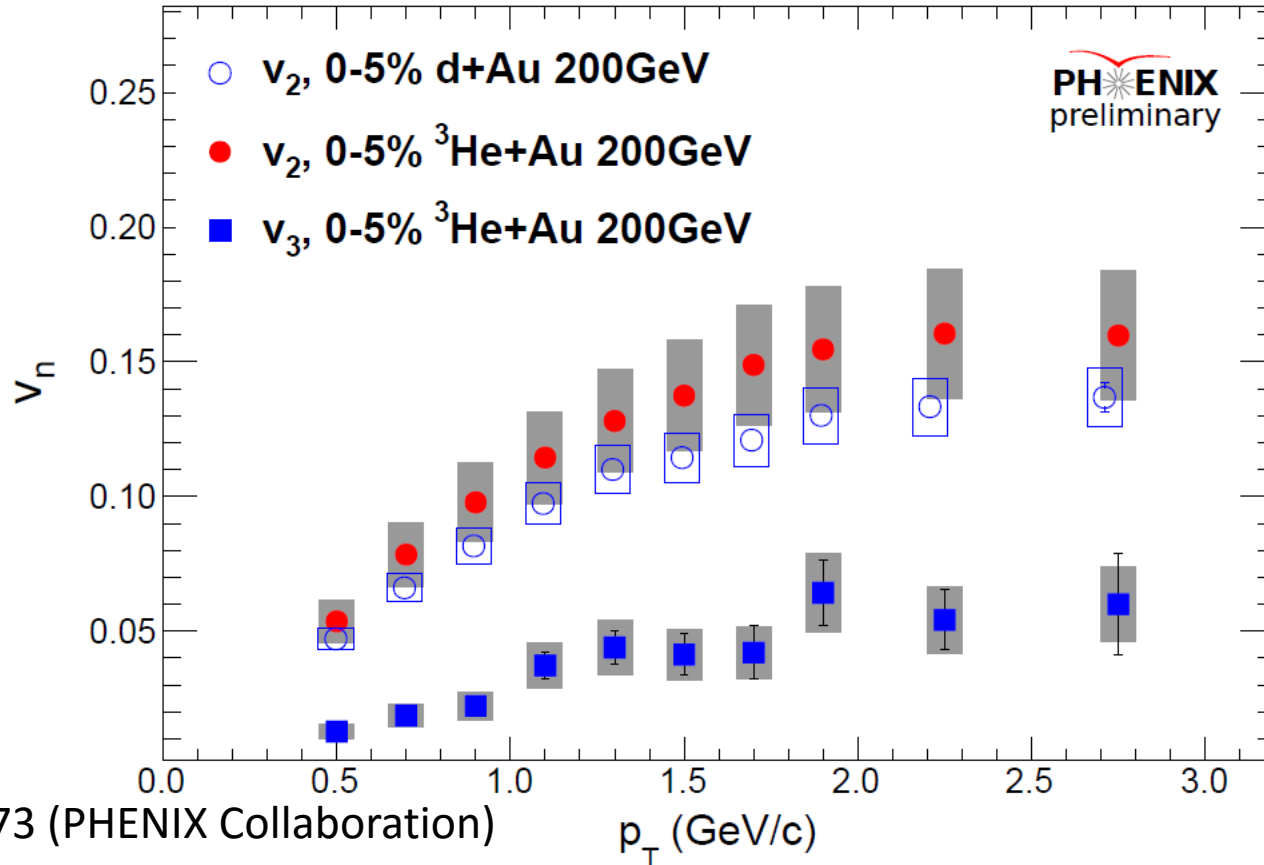
**Свидетельство “управления” коллективного потока геометрией начального состояния**

# “Малые нуклонные” системы d+Au, $^3\text{He}+\text{Au}$



ICNFP, Kolymbari, Aug. 23-30, 2015

Itzhak Tserruya



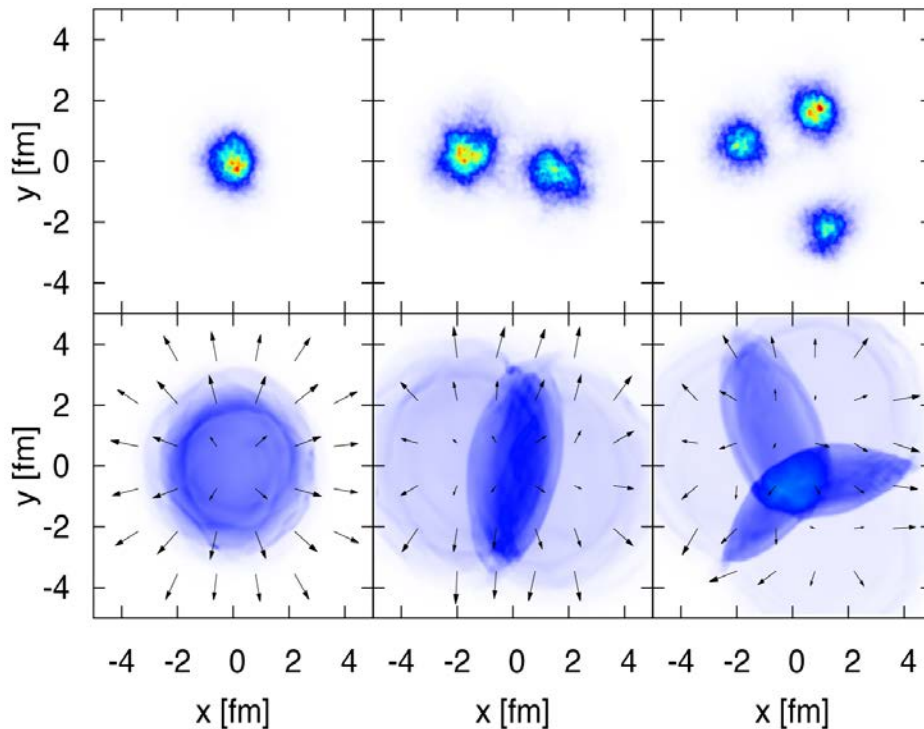
arXiv:1507.06273 (PHENIX Collaboration)

Comparison with **various** theoretical predictions are made, including to models where the hot spots created by the impact of the three  $^3\text{He}$  nucleons on the Au nucleus expand hydrodynamically to generate the triangular flow. **The agreement of these models with data may indicate the formation of low-viscosity quark-gluon plasma even in these small collision systems.**

“Tiny Drops of Early Universe 'Perfect' Fluid”

$\text{He}^3 + \text{Au}$ , RHIC

<https://www.bnl.gov/newsroom/news.php?a=11749>



**Jamie Nagle**

**Идея горячих капель КГП состоит в том, что 3 нуклона в столкновении с тяжёлым ядром Au образуют одно, два или три мгновенных капельки первичной КГП, которые затем дают анизотропное распределение частиц**

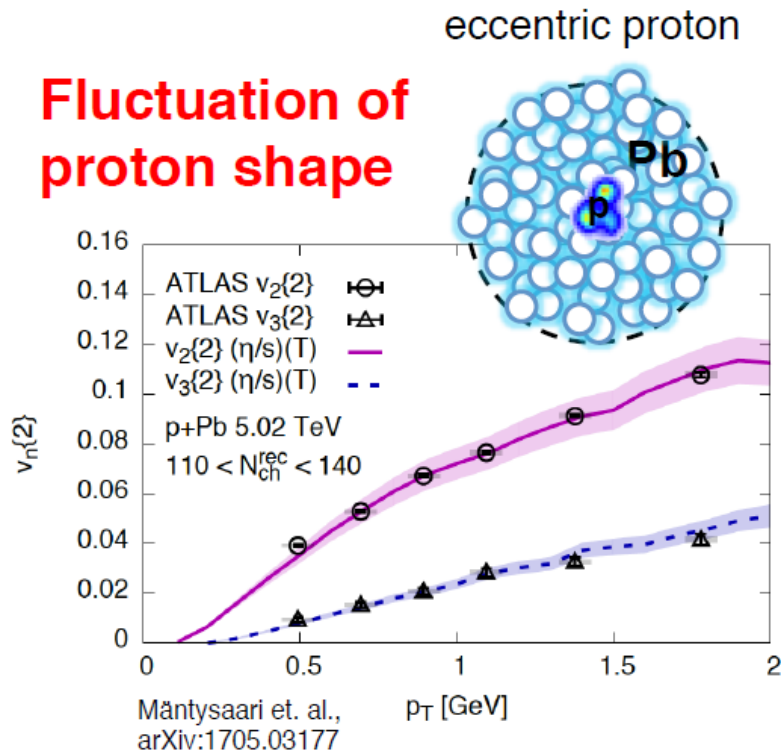
The upper panel of this image represents initial hot spots created by collisions of one, two, and three-particle ions with heavy nuclei. The lower panel shows the geometrical patterns of particle flow that would be expected if the small-particle collisions are creating tiny hot spots of quark-gluon plasma.



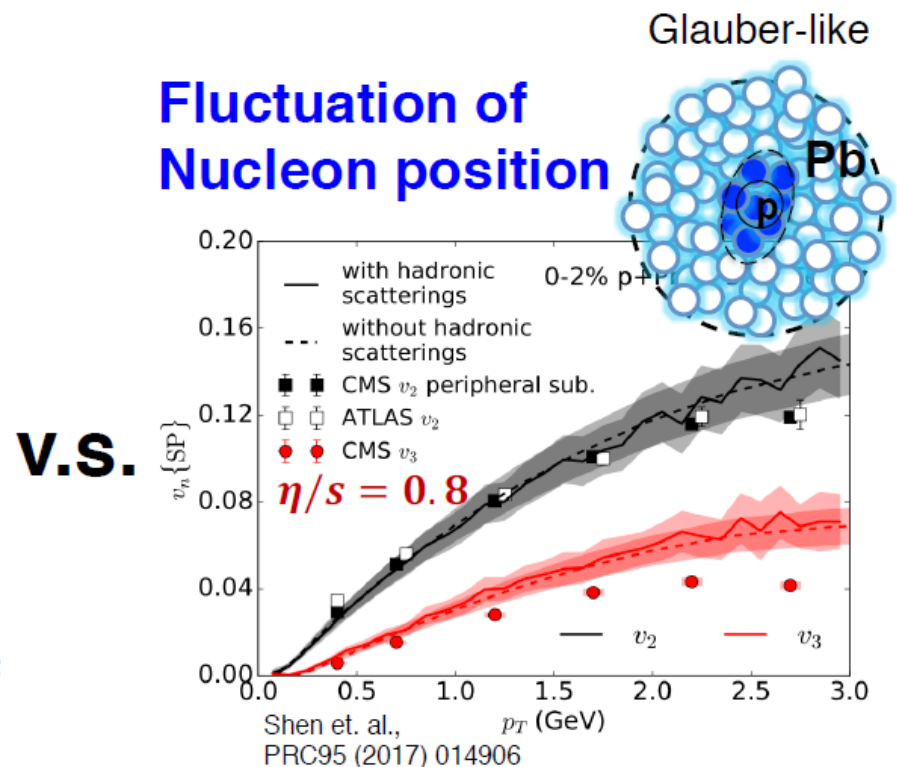
Wey Li, WPCF2017-weili-06122017

## Hydro. can fit the data ... pPb collision

### Fluctuation of proton shape



### Fluctuation of Nucleon position



**V.S.**

While these measurements are consistent with a hydrodynamic expansion of a tiny QGP droplet, alternative scenarios based on **gluon saturation in the initial state** also claim to capture the main features of the correlation data (K. Dusling et al., [1509.07939](#))



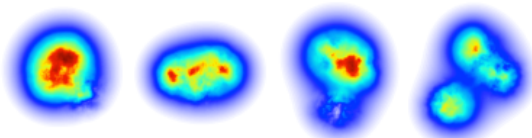
Wey Li, WPCF2017-weili-06122017

## How to probe connections to IS in pp/pA?

Flow observables mainly sensitive to initial states

- I. Universality in higher-order cumulants
- II. Symmetric cumulants ( $v_n$ - $v_m$  correlation)
- III. Factorization breaking (in  $\eta$  and  $p_T$ )

Subnucleonic-scale fluctuations relevant for  $v_n$  in pp



Mantysaari, Schenke, PRL 117, 052301 (2016)

P. Bożek, W. Broniowski, M. Rybczyński, PRC94 (2016) 014902  
 K. Welsh, J. Singer, U.W. Heinz, PRC94 (2016) 024919  
 R. D. Weller and P. Romatschke arXiv:1701.07145  
 P. Bożek, W. Broniowski, arXiv:1701.09105

**Can any IS model (w/ subnucleon fluc.) for pp/pA quantitatively describe a wide range of data?**





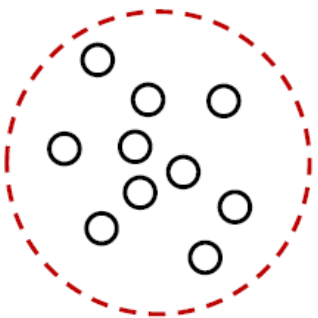
# Initial states in pp/pA: (I) universality

Universal features of fluctuation-driven  $\varepsilon_n$  **pPb, PbPb**

Yan, Ollitrault, PRL 112, 082301 (2014)

CMS, arXiv:1502.05382

	Gauss	BG	Power
$\varepsilon\{2\}$	$\sigma$	$\sqrt{\sigma^2 + \bar{\varepsilon}^2}$	$\frac{1}{\sqrt{1+\alpha}}$
$\varepsilon\{4\}$	0	$\bar{\varepsilon}$	$\left[\frac{2}{(1+\alpha)^2(2+\alpha)}\right]^{1/4}$
$\varepsilon\{6\}$	0	$\bar{\varepsilon}$	$\left[\frac{6}{(1+\alpha)^3(2+\alpha)(3+\alpha)}\right]^{1/6}$
$\varepsilon\{8\}$	0	$\bar{\varepsilon}$	$\left[\frac{48\left(1+\frac{5\alpha}{11}\right)}{(1+\alpha)^4(2+\alpha)^2(3+\alpha)(4+\alpha)}\right]^{1/8}$



$$\alpha = \frac{N_S}{2} - 1$$

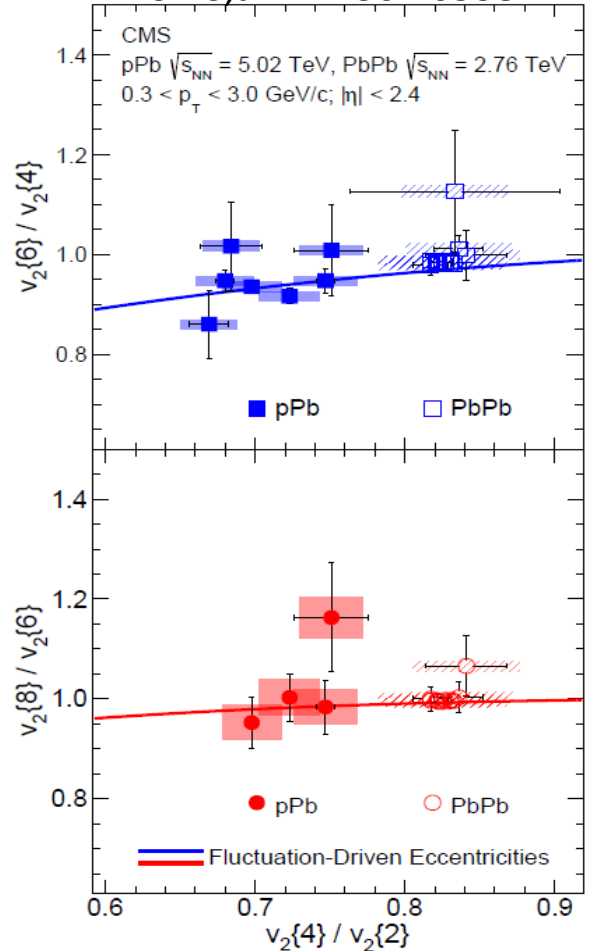
$$P(\varepsilon) = 2\alpha\varepsilon(1 - \varepsilon^2)^{\alpha-1}$$

Predictions:

- Fine splitting among  $v_2\{4\}$ ,  $v_2\{6\}$  and  $v_2\{8\}$



**Многочастичная коллективность  $V_2\{m\}$  в pPb и PbPb “управляется” флуктуациями эксцентриситета  $\rho(\varepsilon_2)$**



# Коллективный поток в **PbPb** и скошенность $p(\varepsilon_n|\varepsilon_0, \alpha)$

Nazarova Elizaveta, XII Workshop on Particle Correlations and Femtoscopy  
Amsterdam, 16.06.2017

CMS collaboration arXiv:1711.05594, HIN-16-019

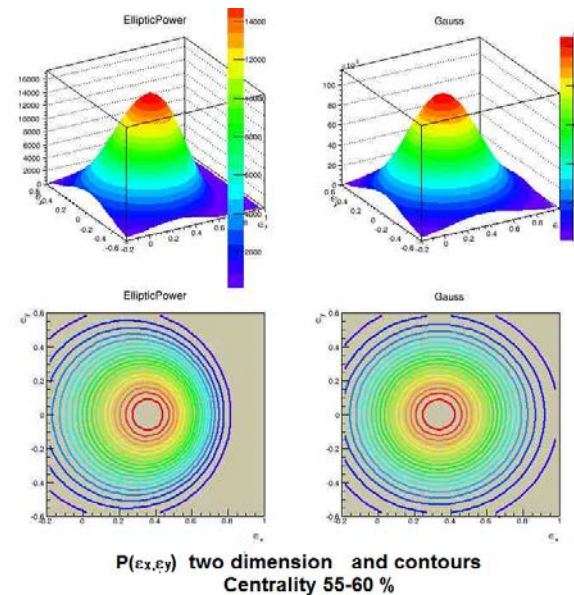
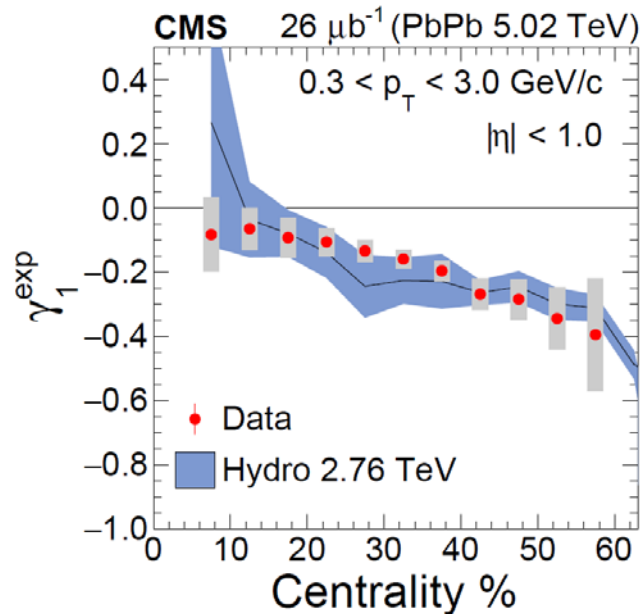
<sup>12</sup>L. Yan, J.-Y. Ollitrault, A. M. Poskanzer, Phys.Rev. C90 (2014), 024903 <https://arxiv.org/abs/1405.6595v2>

Elliptic Power distribution

$$p(v_n) = \frac{d\varepsilon_n}{dv_n} p(\varepsilon_n) = \frac{1}{k_n} p\left(\frac{v_n}{k_n}\right)$$

$$p(\varepsilon_n) = \frac{2\alpha\varepsilon_n}{\pi} (1 - \varepsilon_0^2)^{\alpha + \frac{1}{2}} \int_0^\pi \frac{(1 - \varepsilon_n^2)^{\alpha - 1} d\phi}{(1 - \varepsilon_0\varepsilon_n \cos \phi)^{2\alpha + 1}}$$

$$\gamma_1^{\text{exp}} \equiv -6\sqrt{2} v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}} \cdot p(\varepsilon_x, \varepsilon_y) = \frac{\alpha}{\pi} (1 - \varepsilon_0^2)^{\alpha + \frac{1}{2}} \frac{(1 - \varepsilon_x^2 - \varepsilon_y^2)^{\alpha - 1}}{(1 - \varepsilon_0\varepsilon_x)^{2\alpha + 1}}$$



**Очень тонкое свидетельство “управления” коллективного потока  
геометрией начального состояния**

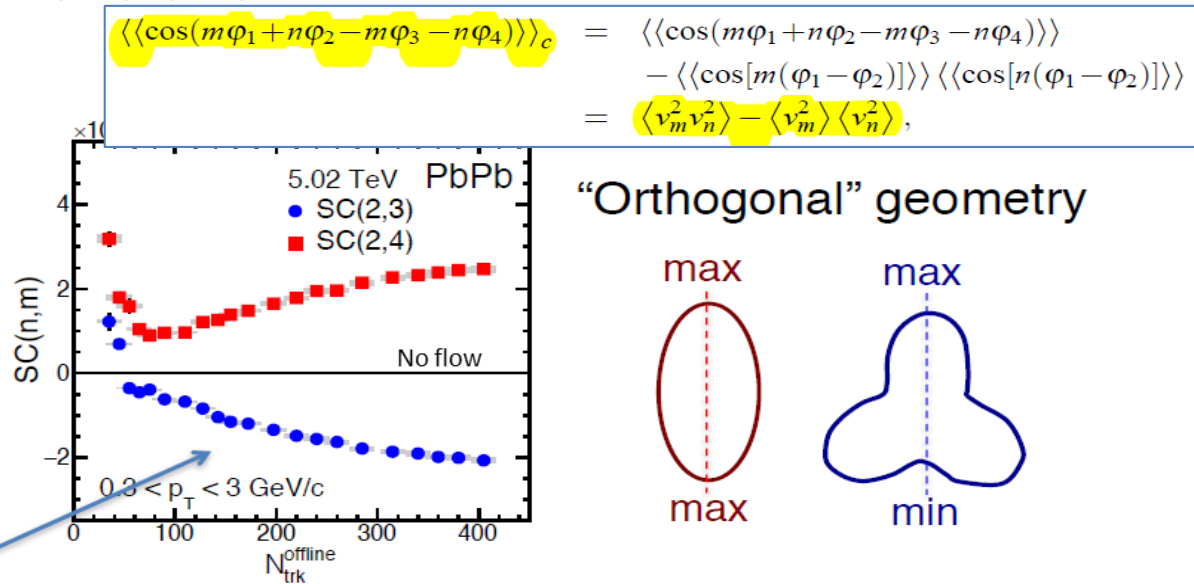
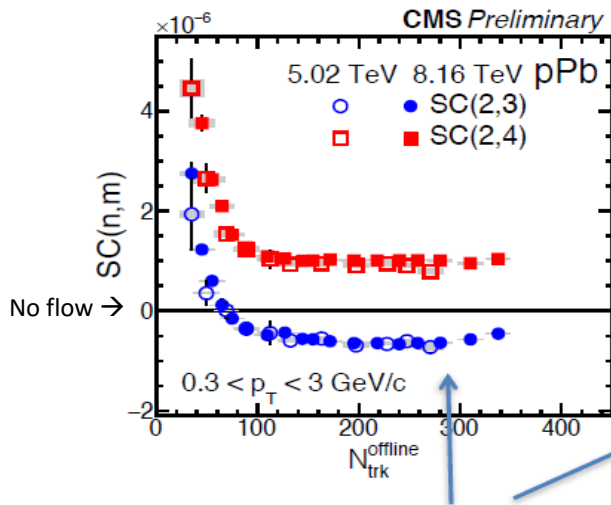


## Initial states in pp/pA: (II) $v_n$ - $v_m$ correlation

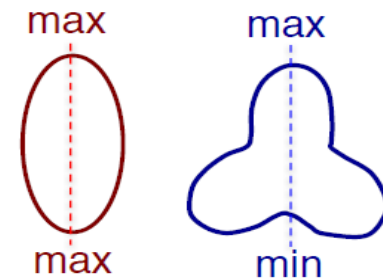
$$SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle \text{ in small systems}$$

1604.07663, ALICE

**2016 pPb data!**



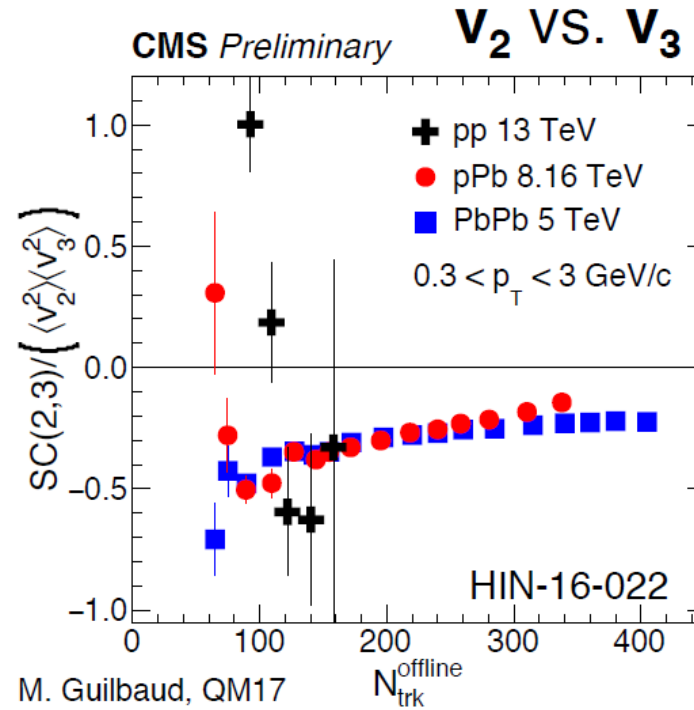
“Orthogonal” geometry



**Anti-correlation of  $v_2$  and  $v_3$  in pPb, same as in PbPb**  
 Natural feature from geometric fluctuations

**Свидетельство «управления» коллективного потока  
 геометрией начального состояния**

## Initial states in pp/pA: (II) $v_n-v_m$ correlation



Scaling consistent with initial geometry fluctuations (?)

Можно ли считать «масштабирование» (совпадение) нормированной симметризованной корреляции **свидетельством того, что флуктуации начальной пространственной геометрии переходят во флуктуации потока?**

# Hydro – Non-Hydro in Pb+Pb

Do nuclear collisions create a locally equilibrated quark-gluon plasma?

P. Romatschke, <http://arxiv.org/abs/1609.02820v2>

B.Abelev et al., (ALICE) <http://arxiv.org/abs/1205.5761>,  $V_n(EP, |\Delta\eta|>2.0)$

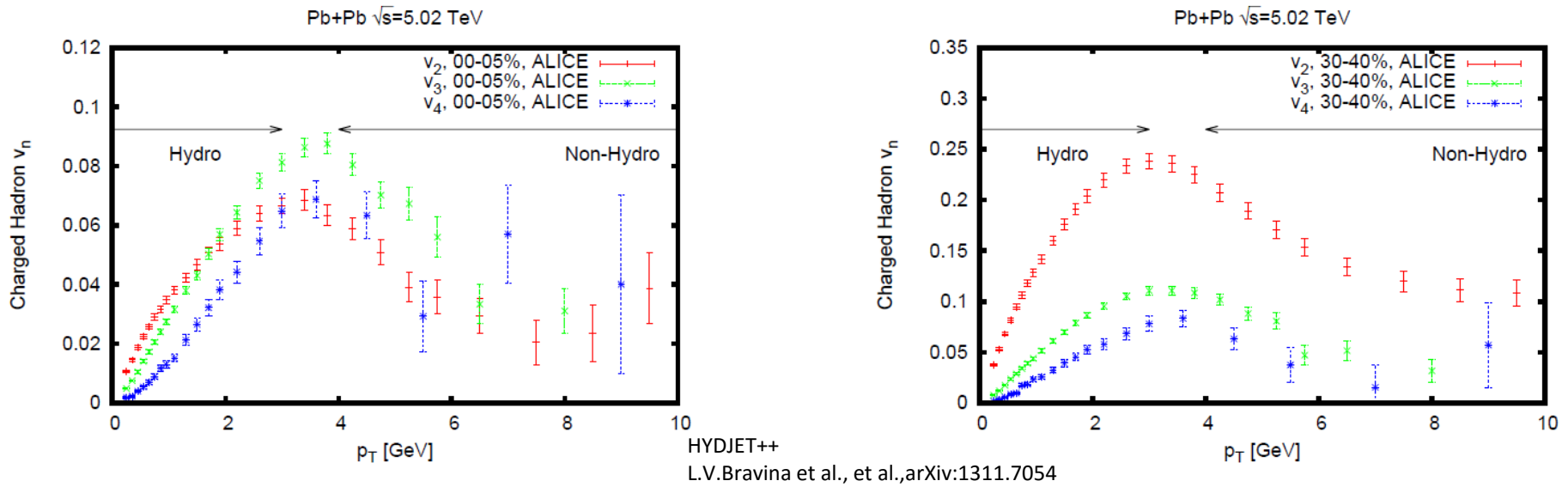
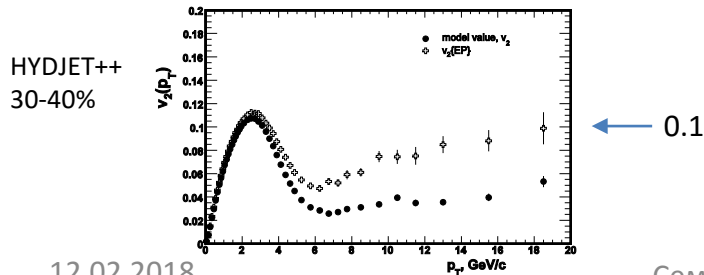


FIG. 5. Experimental data for flow coefficients  $v_n$  as a function of particle  $p_T$  for Pb+Pb collisions at  $\sqrt{s} = 5.02$  TeV (ALICE, [59]). No hydrodynamic curves are shown, but it is known that hydrodynamics well describes the experimental data in the regime indicated as 'hydro' in the plot [60], possibly extending up to  $p_T \simeq 3$  GeV. By contrast, for  $p_T \gtrsim 4$  GeV, the experimental data seems to deviate systematically from the low-momentum behavior, and I have labeled this region 'non-hydro'.



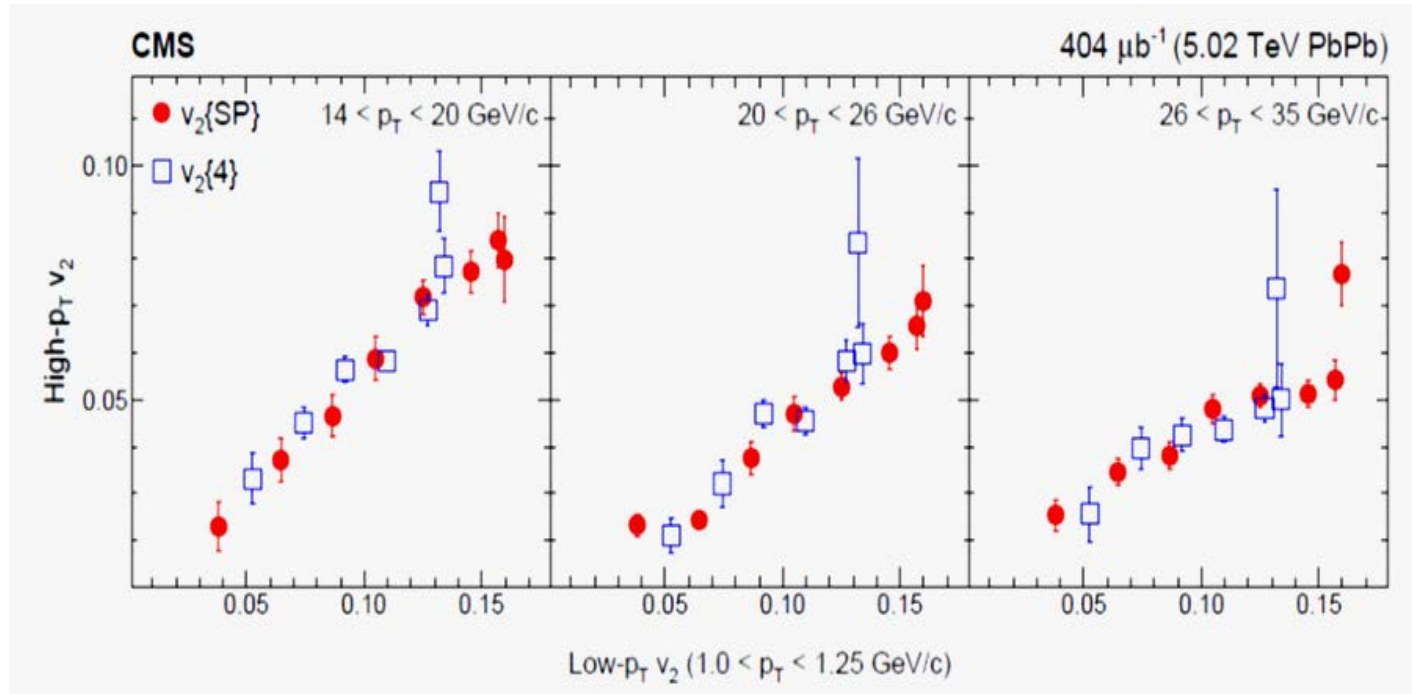
1. Hydro  $p_T = 0 - 4$  GeV/c, non-Hydro  $p_T = 4 - 10$  GeV/c
2.  $V_n$  (high  $p_T$ ) is increased in peripheral region

Есть что улучшить в HYDJET++ !

# Корреляция параметра $v_2$ при малых и больших $p_T$

Считается, что механизм формирования азимутальной эллиптической анизотропии при малых и больших  $p_T$  разный, т.к. при больших  $p_T$  доминирует механизм образования струй, а при малых  $p_T$  гидродинамический разлёт частиц. Так ли это?

CMS Phys.Lett. B776 (2018) 195,  
arXiv:1702.00630



*Зависимость параметра  $v_2$  (High- $p_T$ ) от  $v_2$  (Low- $p_T$ ) для разных центральностей. Рост значений  $v_2(p_T)$  соответствует переходу от центральных к периферическим соударениям.*

**Почему при больших  $p_T$  (область рождения струй) поток увеличивается с ростом периферичности столкновения?**

**Не появляется ли поток из-за модификации среды при погашении струй, излучающей быстрые частицы ?**



Некоторые заключения:

- 1. Исследование наблюдаемых в зависимости от множественности – новый тренд в физике столкновения ионов.**
- 2. Имеется много свидетельств того, что коллективный поток «управляется» геометрией начального состояния.**
- 3. НИ сообщество всё больше склоняется к идее образования кластеров (горячих капель) КГП, которые, перекрываясь, испускают анизотропный коллективный поток частиц.**
- 4. Коллективность потока может возникнуть независимо от локального равновесия и термализации как свойство сильных взаимодействий (the transport dynamics of partons).**
- 5. Погашение струй может привести к изменению излучающей материи с появлением потока быстрых частиц.**



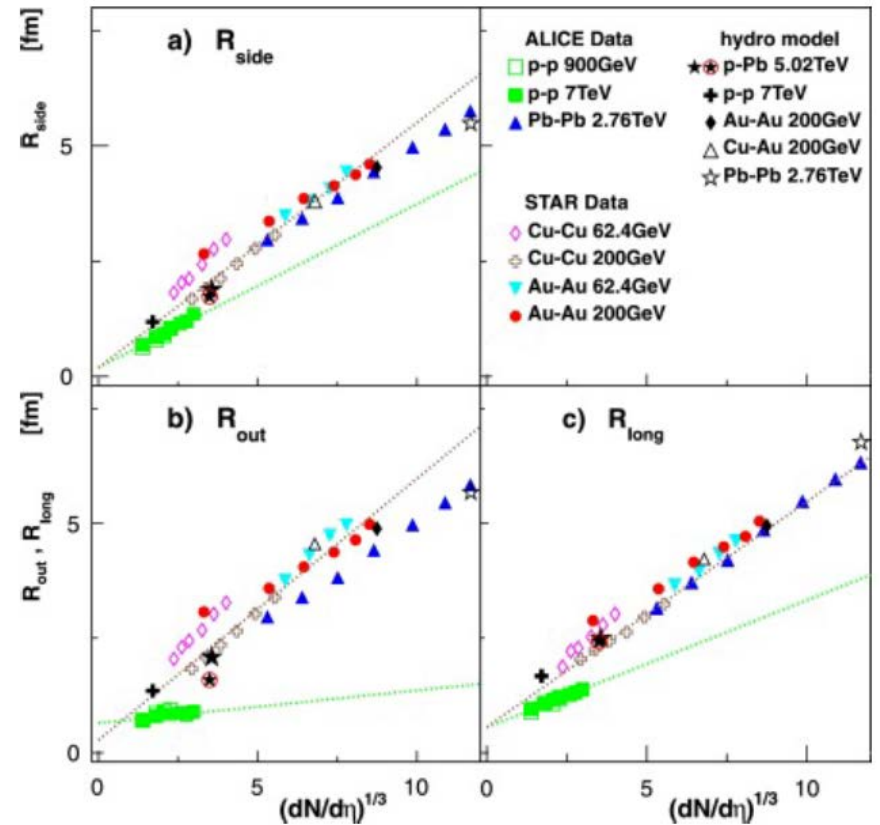
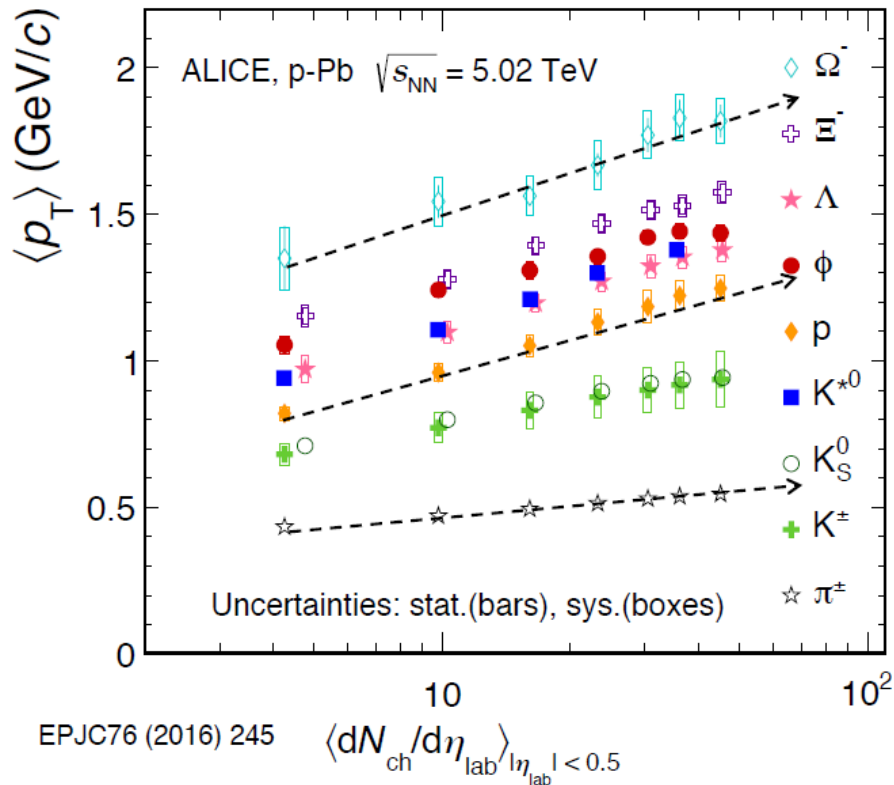
Спасибо за внимание





Wey Li, WPCF2017-weili-06122017

## Phase II (2012 – 2017): Collectivity





# Описание V2 в pp при 13 ТэВ, CMS и ATLAS (публикация 2018 г.)

W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song<sup>1</sup>, [arXiv:1801.00271](https://arxiv.org/abs/1801.00271)  
Hydrodynamic Collectivity in Proton-Proton Collisions at 13 TeV

iEBE-VISHNU [67] is an event-by-event simulation version of the early developed hybrid model VISHNU [68] that combines (2+1)-d viscous hydrodynamics VISH2+1 [69, 70] to describe the QGP expansion with a hadron cascades model UrQMD [71, 72] to simulate the evolution of hadronic matter.

TABLE I: Four sets parameters used in iEBE-VISHNU simulations with HIJING initial conditions for pp collisions at 13 TeV.

	$\sigma_R$	$\sigma_0$	$\tau_0$	$\eta/s$	$T_{sw}(\text{MeV})$
Para-I	0.2	0.7	0.6	0.01	147
Para-II	0.8	0.4	0.4	0.08	148
Para-III	0.4	0.2	0.2	0.24	148
Para-IV	0.6	0.4	0.4	0.05	148

Following [79], the initial energy density profiles in the transverse plane are constructed from the energy decompositions of emitted partons of HIJING together with an additional Gaussian smearing[79]

$$\epsilon(x, y) = K \sum_i \frac{p_i U_0}{2\pi\sigma_0^2\tau_0\Delta\eta_s} \exp\left(-\frac{(x-x_i)^2 + (y-y_i)^2}{2\sigma_0^2}\right), \quad (1)$$

# Описание $V_2$ в pp при 13 ТэВ, CMS и ATLAS (публикация 2018 г.)

W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song<sup>1</sup>, [arXiv:1801.00271](https://arxiv.org/abs/1801.00271)  
Hydrodynamic Collectivity in Proton-Proton Collisions at 13 TeV

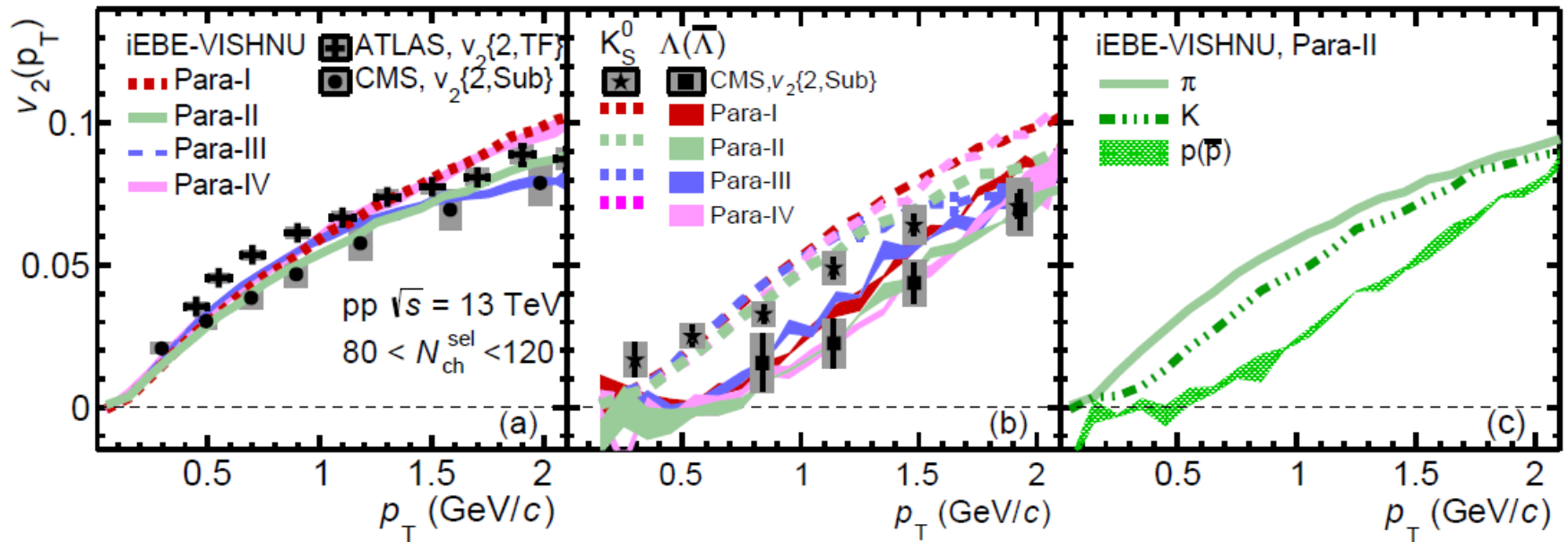
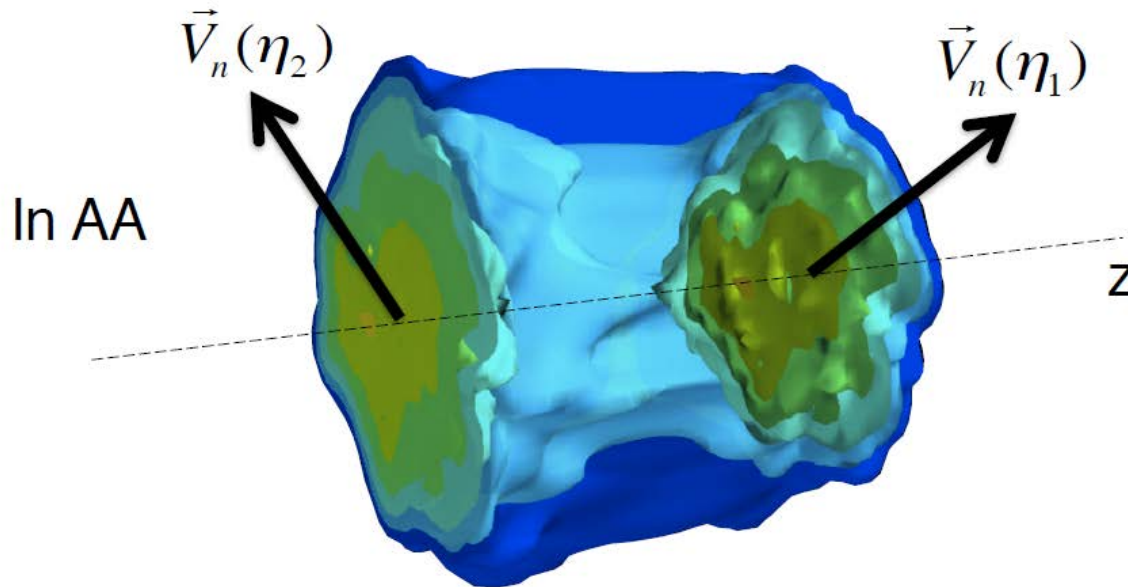


FIG. 3: (Color online)  $v_2(p_T)$  for all charged hadrons (a), for  $K_S^0$  and  $\Lambda$  (b), and for pions, kaons and protons (c) in high multiplicity pp collisions at 13 TeV, calculated by iEBE-VISHNU with HIJING initial condition. The CMS and ATLAS data are taken from [37] and [60], respectively.



Wey Li, WPCF2017-weili-06122017

## Initial states in pp/pA: (III) 3D IS



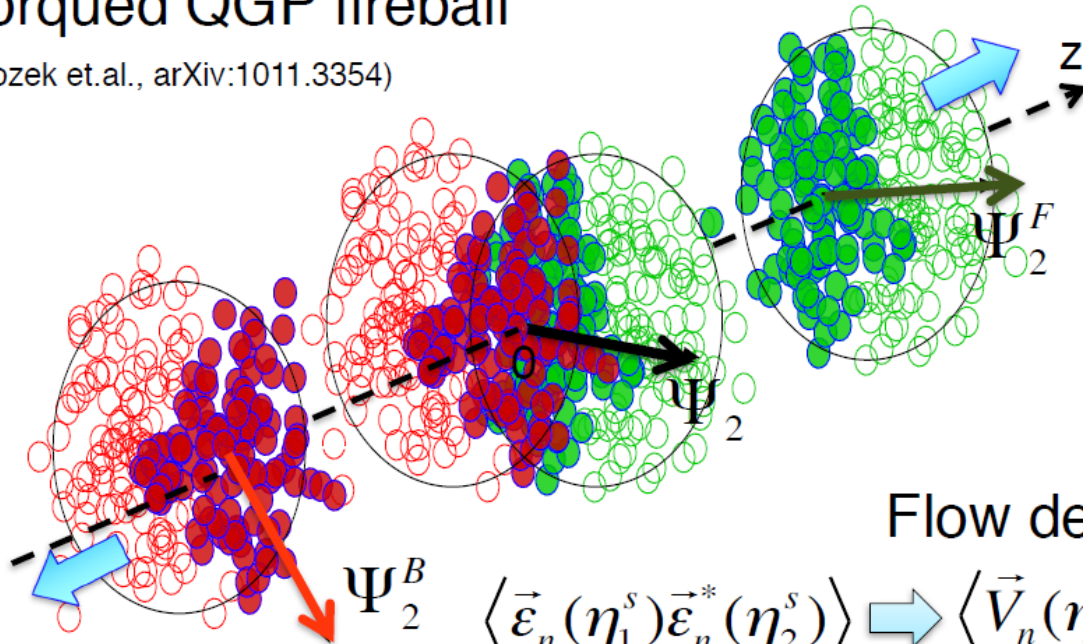
Longitudinal dynamics not fully explored yet



## Initial states in pp/pA: (III) 3D IS

Torqued QGP fireball

(Bozek et.al., arXiv:1011.3354)



Flow decorrelation

$$\langle \vec{\epsilon}_n(\eta_1^s) \vec{\epsilon}_n^*(\eta_2^s) \rangle \Rightarrow \langle \vec{V}_n(\eta_1) \vec{V}_n^*(\eta_2) \rangle$$

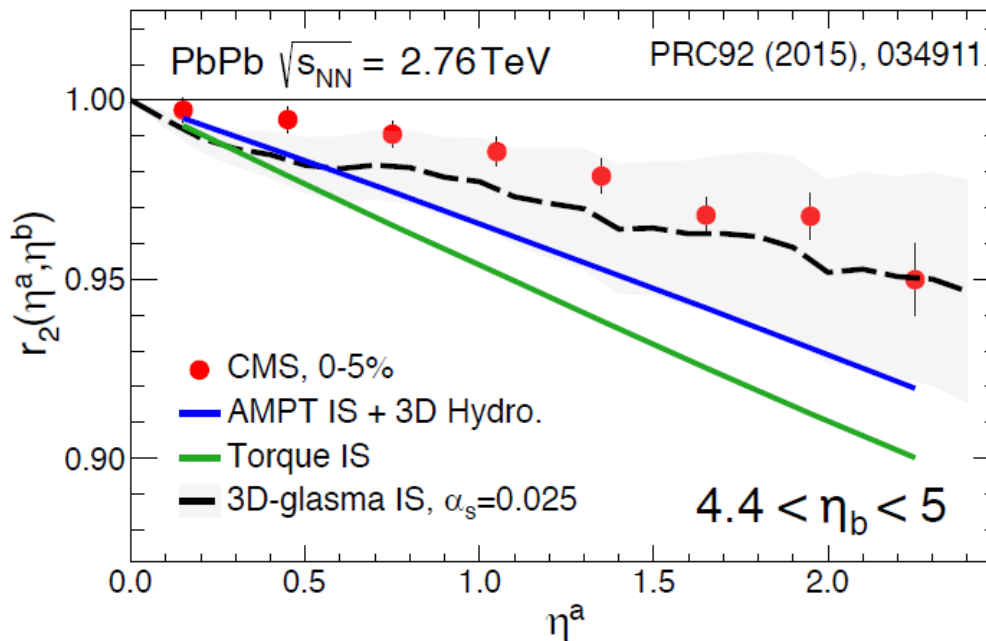
$$= \langle v_2(\eta_1) v_2(\eta_2) \cos(\Psi_n(\eta_1) - \Psi_n(\eta_2)) \rangle$$

$$\neq \langle v_2(\eta_1) \rangle \langle v_2(\eta_2) \rangle \text{ factorization breaking}$$



## Initial states in pp/pA: (III) 3D IS

$$r_n \equiv \frac{\langle \vec{V}_n(-\eta^a) \vec{V}_n^*(\eta^b) \rangle}{\langle \vec{V}_n(\eta^a) \vec{V}_n^*(\eta^b) \rangle} \quad \text{--- “Event-plane decorrelations”}$$



Recent development  
from ATLAS:  
*ATLAS-CONF-2017-003*

Significant effect that can be explained by

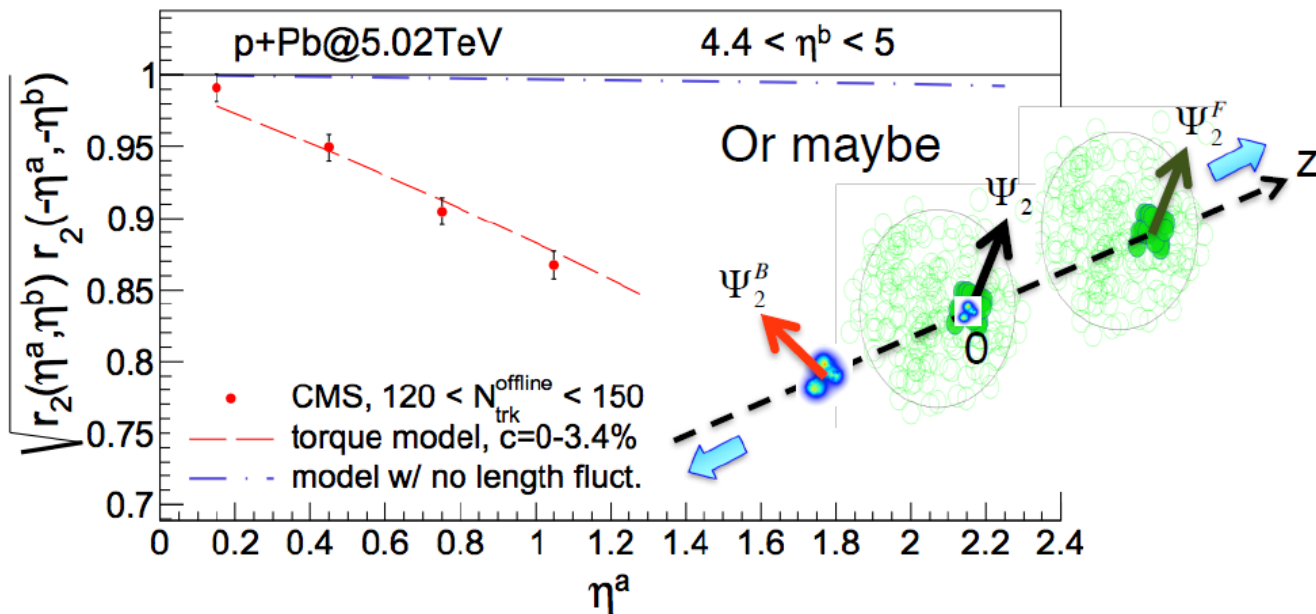
**Non-boost invariant initial-state participant fluct.**



## Initial states in pp/pA: (III) 3D IS

Sizable effect observed in pPb!

arXiv:1506.02817

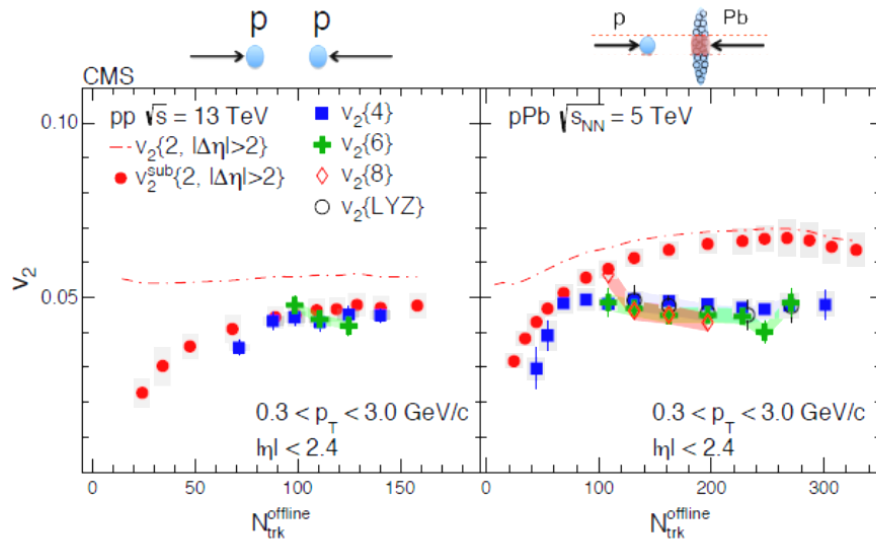


**Evidence for subnucleonic-scale fluctuations!?**

Prediction for  $r_3$ ,  $r_4$  ... and also for pp?  
(reachable with LHC run 2 data)

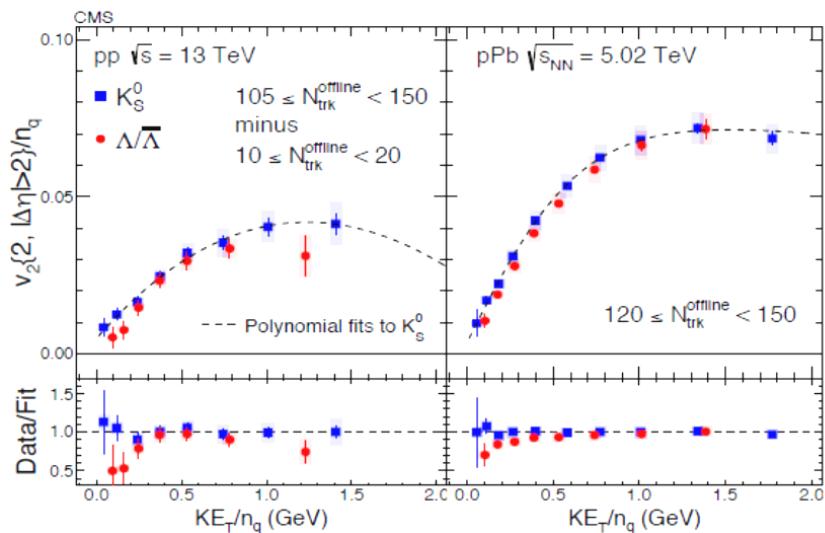


## Phase II (2012 – 2017): Collectivity



Multi-particle  $v_2$

$$v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \dots$$



“Quark Number Scaling”

**Collectivity** at HM  
proven experimentally!





# Коллективный поток в столкновениях малых нуклонных систем

