CPOD 2011, Wuhan, Nov 10

Elliptic and Triangular Flow and their Correlations in ultrarelativistic High Multiplicity Proton Proton Collisions at 14 TeV

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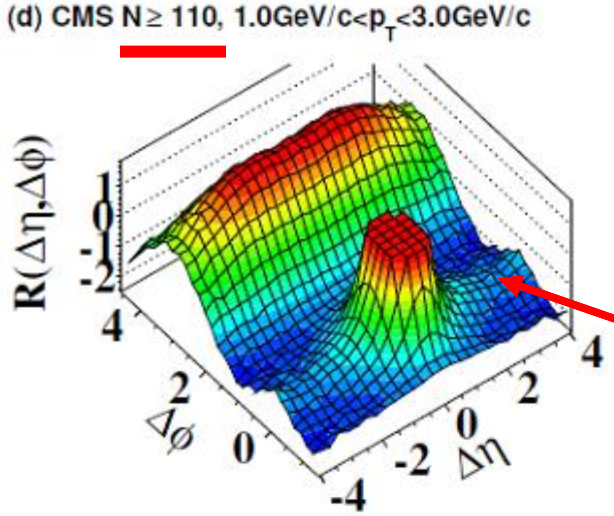
Near side "ridge" in p-p Collisions at 7 TeV

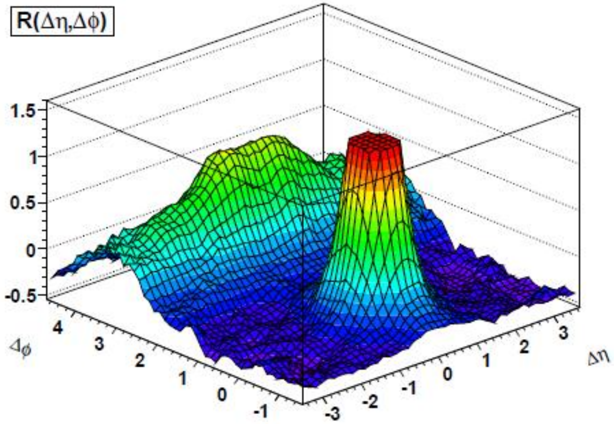
experiment



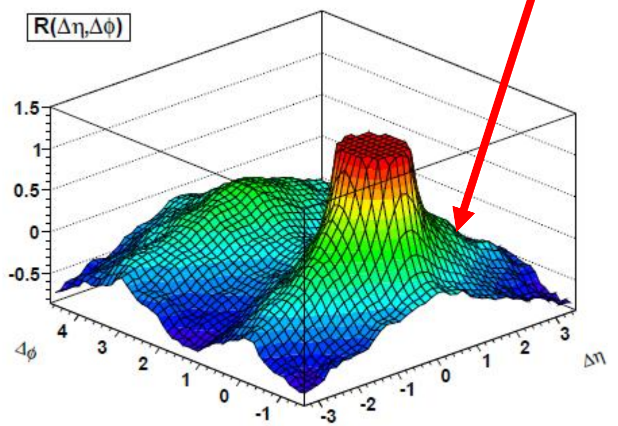
CMS Collaboration, JHEP 1009, 091 (2010)

theory

EPOS without hydro

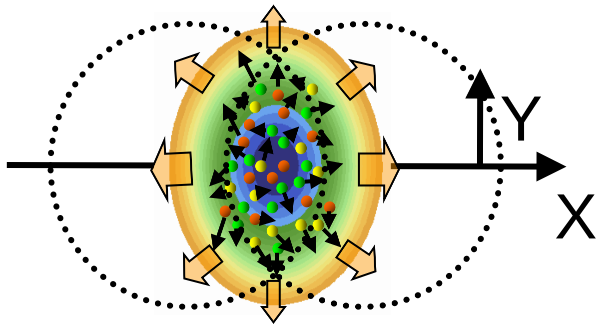


EPOS with hydro

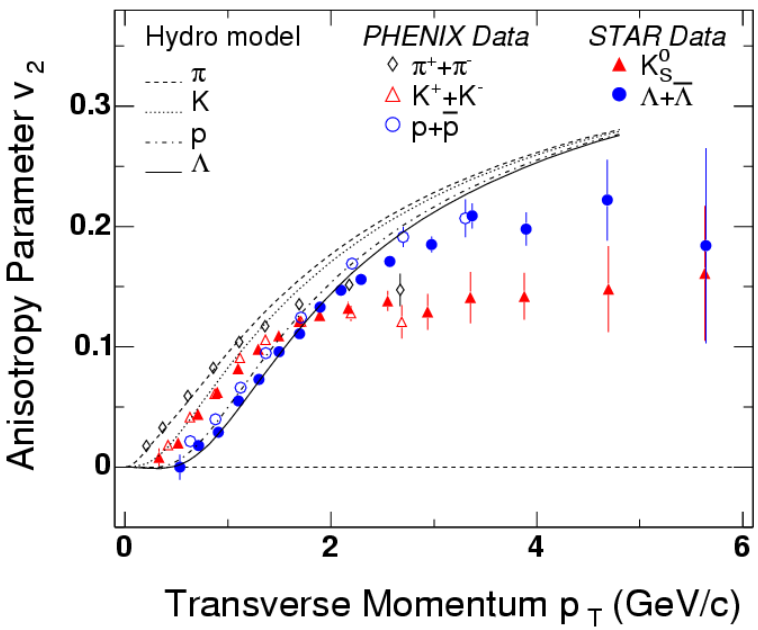


K. Werner, I. Karpenko and T. Pierog, PRL106, 122004 (2011)

Au+Au Collisions at RHIC-200 GeV

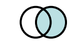


eccentricity –> elliptic flow



QGP at RHIC is a nearly perfect fluid.

p+p Collisions at LHC-14 TeV



collective flow ?

NO: too small volume

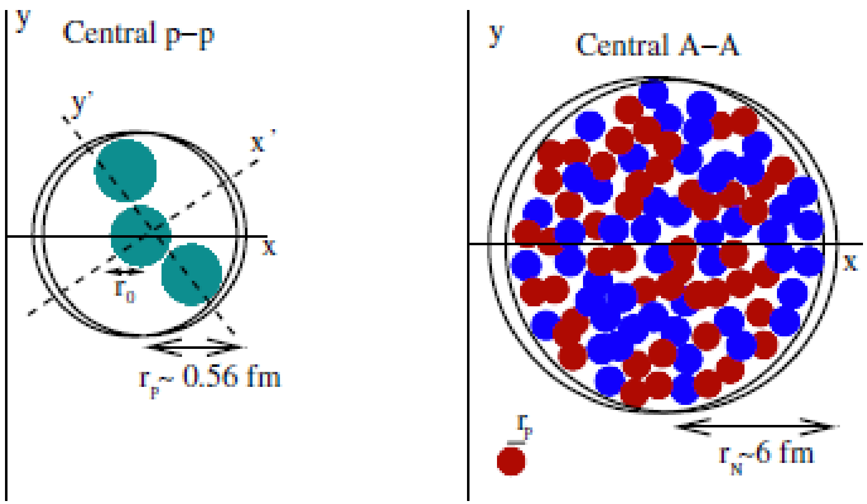
YES: very high energy density
high multiplicity events

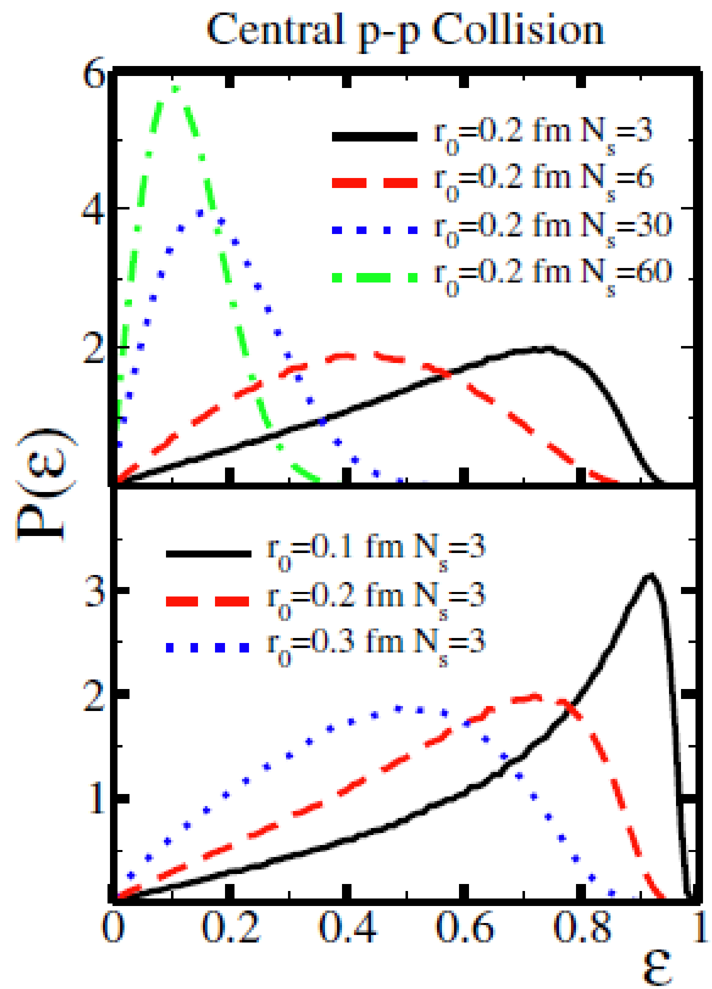
NO: symmetry in central collisions

YES: initial fluctuations

Eccentricity Fluctuations Make Flow Measurable in High Multiplicity *p-p* Collisions

Jorge Casalderrey-Solana and Urs Achim Wiedemann



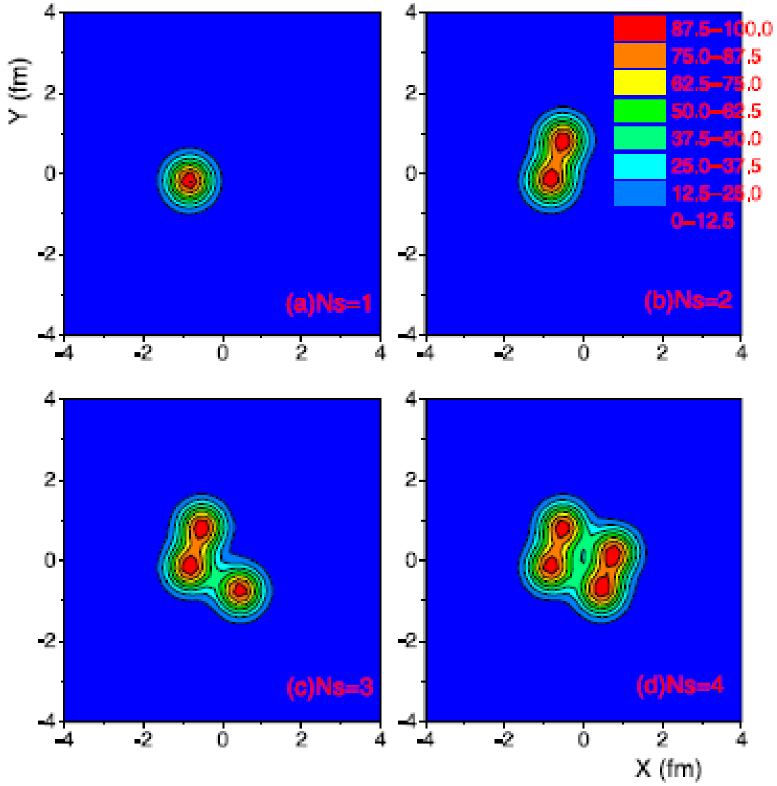


$$\epsilon = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}.$$

Here $\sigma_x^2 = \{x^2\} - \{x\}^2$, $\sigma_y^2 = \{y^2\} - \{y\}^2$, $\sigma_{xy} = \{xy\} - \{x\}\{y\}$ and the event-by-event average $\{\ldots\}$ is taken

ideal hydrodynamic calculations: Chaudhuri, PLB 692 (2010) 15

p+p @ 14 TeV



N_s	ϵ	$\langle n_{mult} \rangle$	$\langle p_T \rangle$ (GeV)	$\langle v_2 \rangle$
1	0	4.97 ± 0.02 (4.97 ± 0.02)	0.722 ± 0.001 (0.722 ± 0.001)	0.003 ± 0.001 (0.003 ± 0.001)
2	0.532 ± 0.052	7.75 ± 1.17 (7.88 ± 1.11)	0.634 ± 0.054 (0.632 ± 0.054)	0.147 ± 0.071 (0.152 ± 0.068)
3	0.536 ± 0.051	9.68 ± 2.24 (9.87 ± 2.12)	0.599 ± 0.037 (0.601 ± 0.040)	0.160 ± 0.053 (0.158 ± 0.056)
4	0.457 ± 0.048	11.05 ± 2.58 (11.39 ± 2.67)	0.582 ± 0.029 (0.581 ± 0.026)	0.161 ± 0.050 (0.160 ± 0.049)
EI		8.36 ± 2.91	0.634 ± 0.065	0.118 ± 0.019
EII		8.45 ± 2.36	0.627 ± 0.057	0.138 ± 0.022

$v_2 \approx 0.16$ for 3 hot spots, even in low multiplicity ($n_{mult} \sim 10$) events

- geometrical overlap in p+p like in A+A (small v_2~3%)

hydro: M. Luzum, P. Romatschke, PRL103 (2009).
S. K. Prasad, V. Roy, S. Chattopadhyay, A. K. Chaudhuri, PRC82 (2010).
G. Ortona, G. S. Denicol, P. .Mota, T. Kodama, arXiv:0911.5158.

ε_2-v_2 scaling:

$$v_2\{4\} = \epsilon\{4\}\left(\frac{v_2}{\epsilon}\right)^{\text{hydro}} \frac{1}{1 + \frac{\bar{\lambda}}{K_0} \frac{\langle S \rangle}{\frac{dN}{dy}}}$$

L. Cunqueiro, J. Dias de Deus, C. Pajares, Eur. Phys. J. C65 (2010).
D. d'Enterria, et al., Eur. Phys. J. C66 (2010).

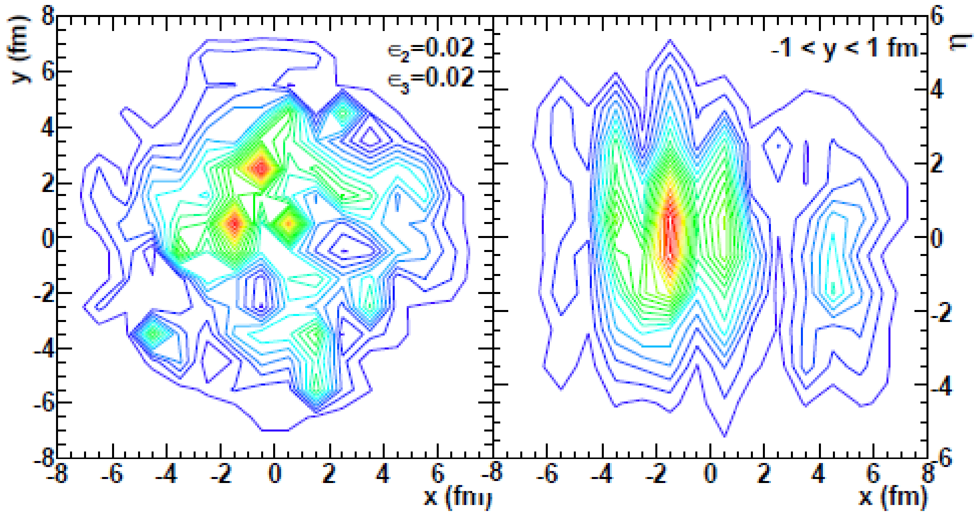
- initial fluctuations (hot spots)

hydro: P. Bozek, Acta Phys. Polon. B41 (2010).
A. K. Chaudhuri, Phys. Lett. B692 (2010).

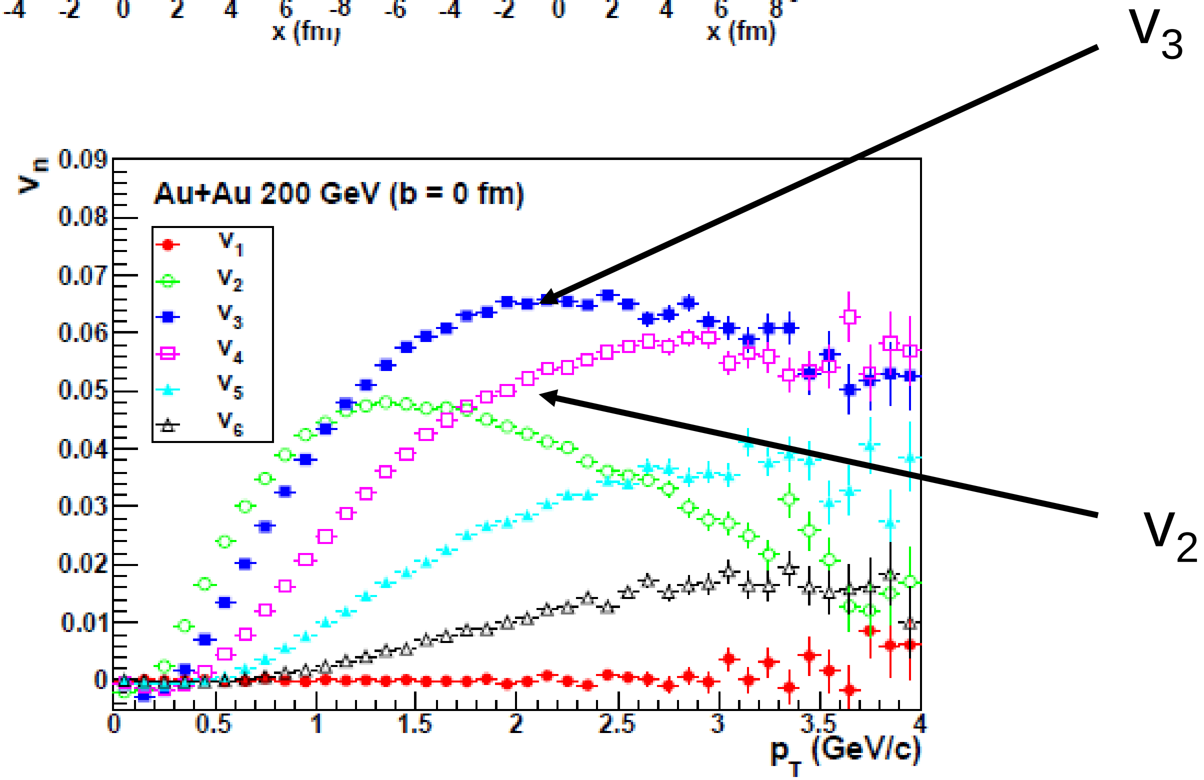
ε_2-v_2 scaling:
J. Casalderrey-Solana, U. A. Wiedemann, PRL104 (2010).
E. Avsar, et al., Phys. Lett. B702 (2011).

transport:
D. -M. Zhou, et al., Nucl. Phys. A860 (2011).

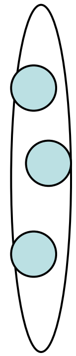
Hot spots and harmonic flow



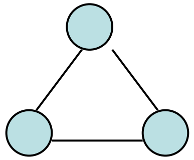
AMPT for central Au+Au
G.-L. Ma and X.-N. Wang,
PRL 106, 162301 (2011)



p+p @ LHC



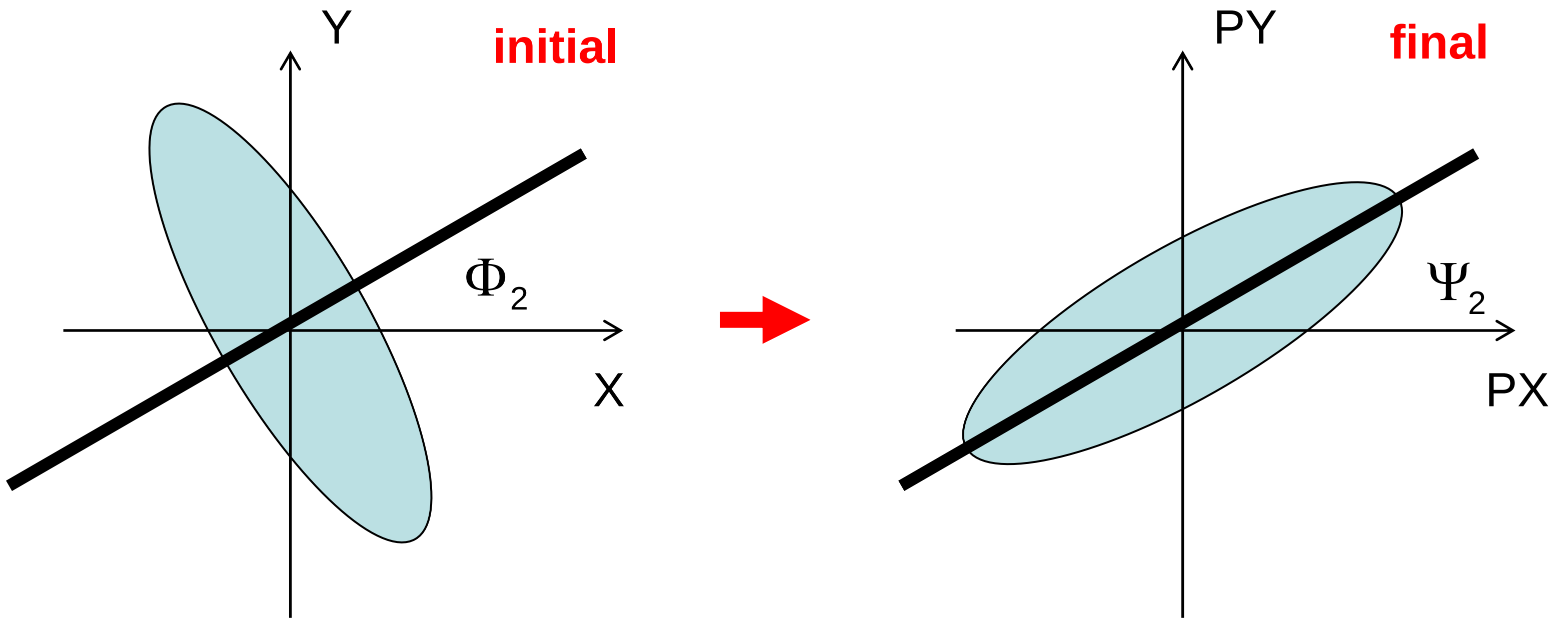
ε_2 dominant $\Rightarrow v_2$



ε_3 dominant $\Rightarrow v_3$

In contrast to Au+Au b=0 at RHIC there may be ε_2-ε_3 event-by-event correlation in p+p at LHC.

Definitions of event-plan angles



Initial eccentricity ε_2
Initial event-plan angle Φ_2

Elliptic flow v_2
Final event-plan angle Ψ_2

$$\Phi_2 = \Psi_2$$

eccentricities

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

collective flow

$$v_n(p_T) = \langle \cos n(\psi - \Psi_n)\rangle$$

initial event-plane angle

$$\Phi_n = \frac{1}{n}\arctan\frac{\langle r^n \sin(n\phi)\rangle}{\langle r^n \cos(n\phi)\rangle}$$

final event-plane angle

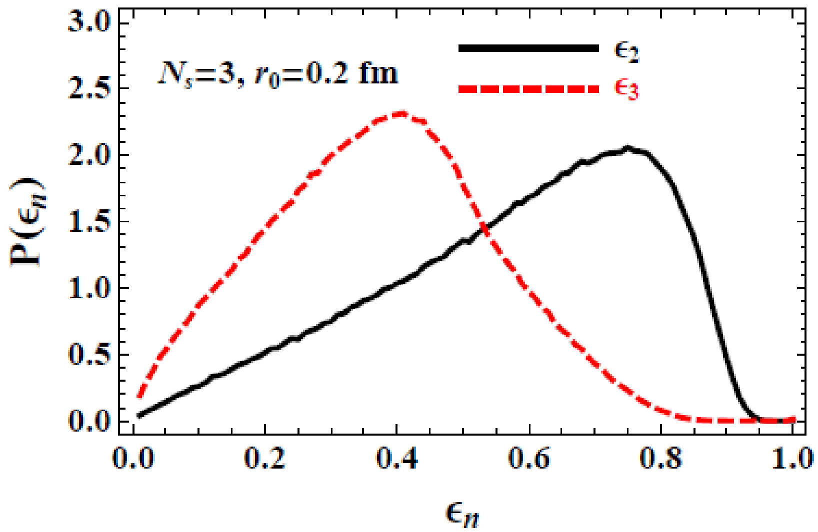
$$\Psi_n = \frac{1}{n}\arctan\frac{\langle \sin(n\psi)\rangle}{\langle \cos(n\psi)\rangle}$$

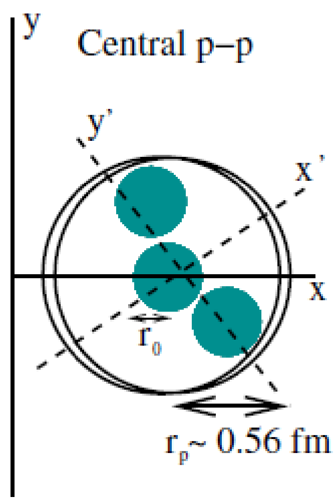
If the translations from ε_n to v_n (n=2,3,...) are completely independent

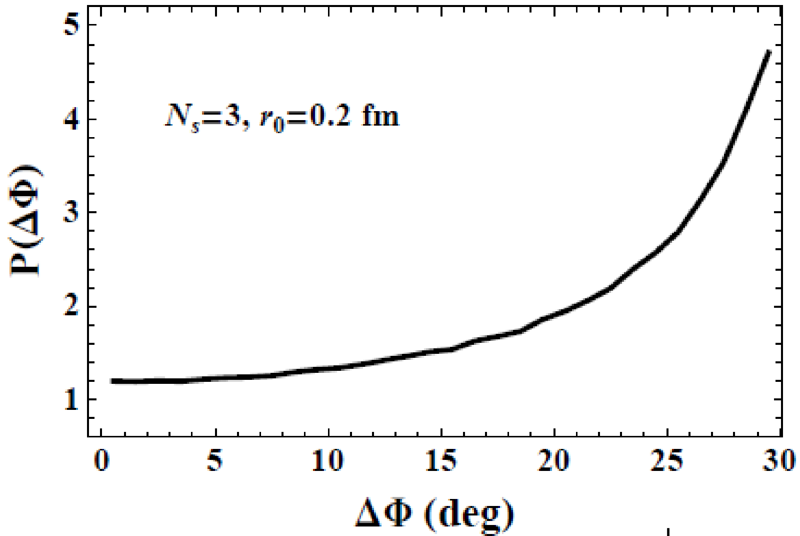
$$\Rightarrow \quad \Phi_n = \Psi_n$$

$$\Phi_2 - \Phi_3 = \Psi_2 - \Psi_3$$

ε_2, ε_3 and their correlation in the hot spots scenario







If ε_n to v_n translations are independent ?

$$\Rightarrow \quad P(\Delta\Psi) = P(\Delta\Phi)$$

From final event-plane correlations one can extract informations about initial conditions.

$$\Delta\Phi = \left|\Phi_2 - \Phi_3\right|$$

$$\Delta\Psi = \left|\Psi_2 - \Psi_3\right|$$

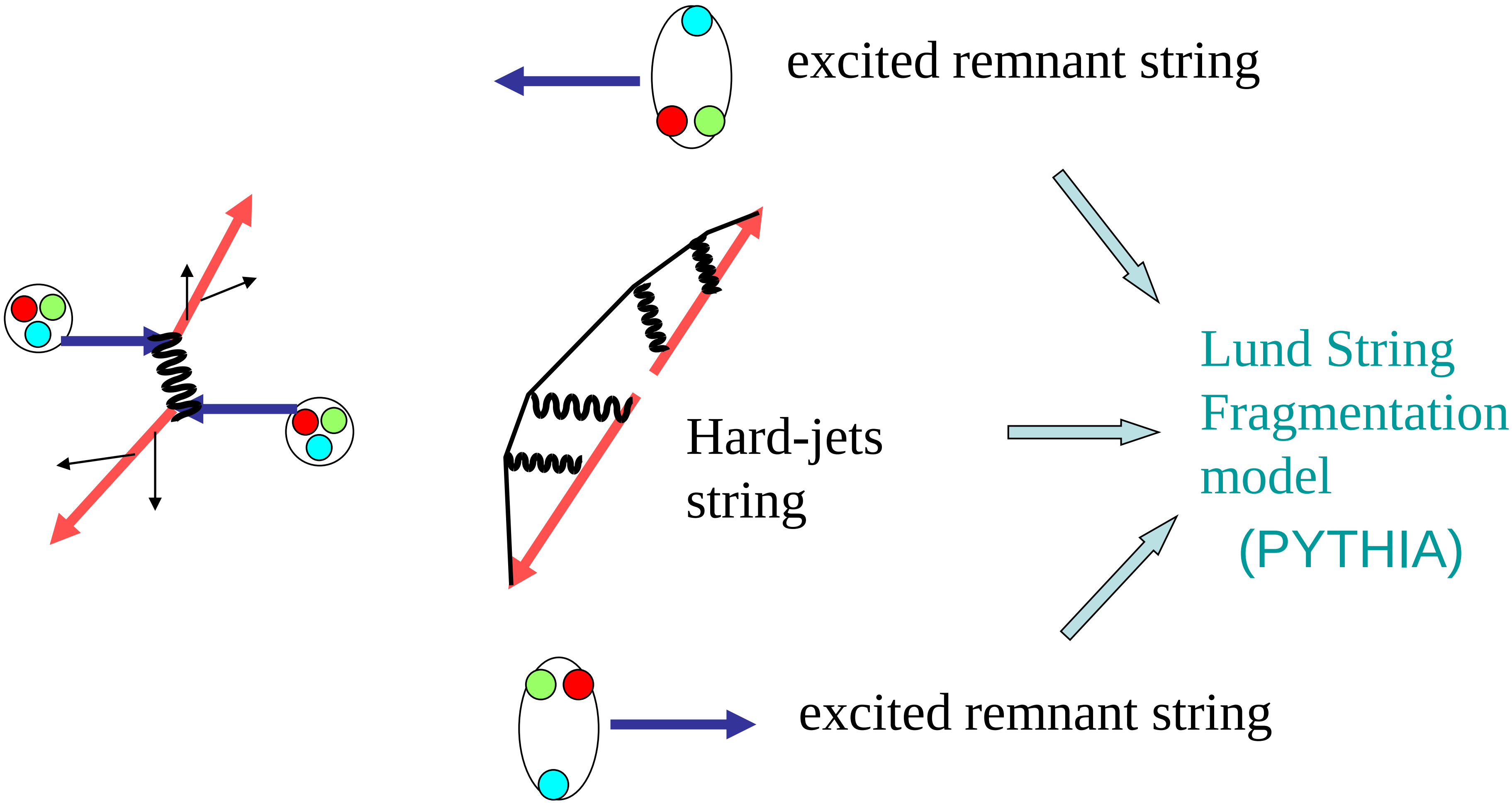
Our Model:

Hot Spots + HIJING + Parton Transport(BAMPS)

HIJING

X.N. Wang and M. Gyulassy, Phys, Rev. D44, 3501 (1991).

W.T. Deng, X.N. Wang and R. Xu, Phys. Rev. C83, 014915 (2011).

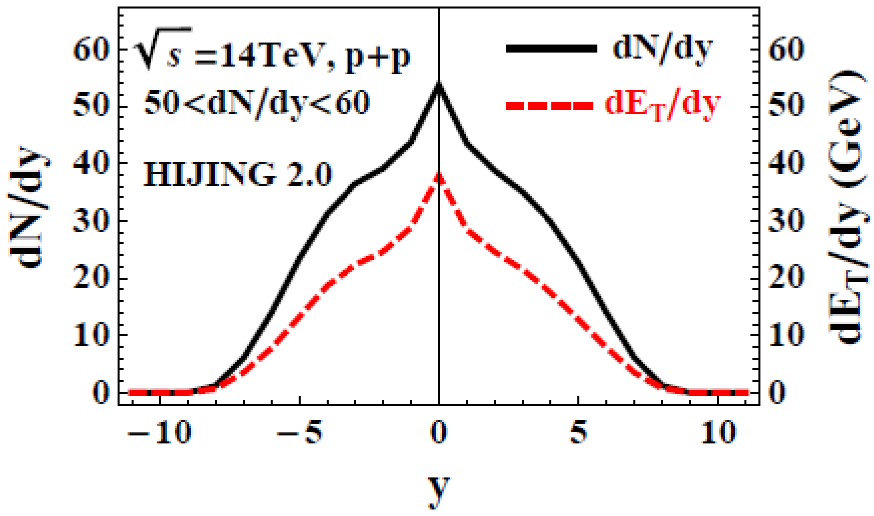


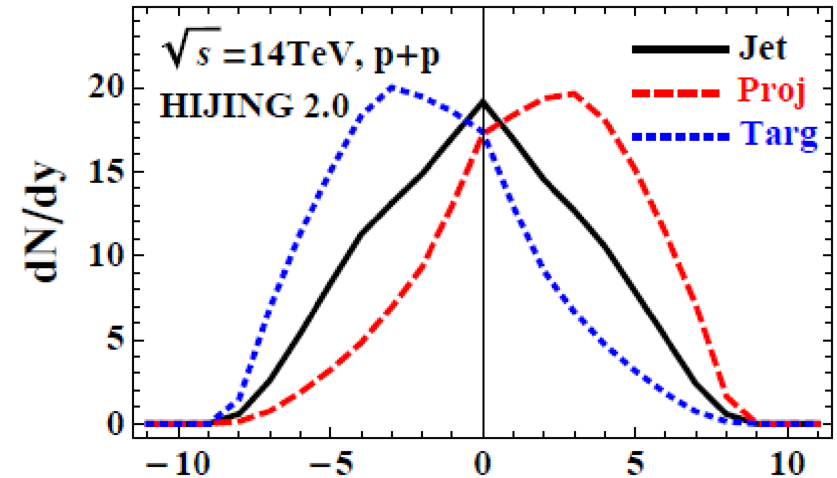
3 strings

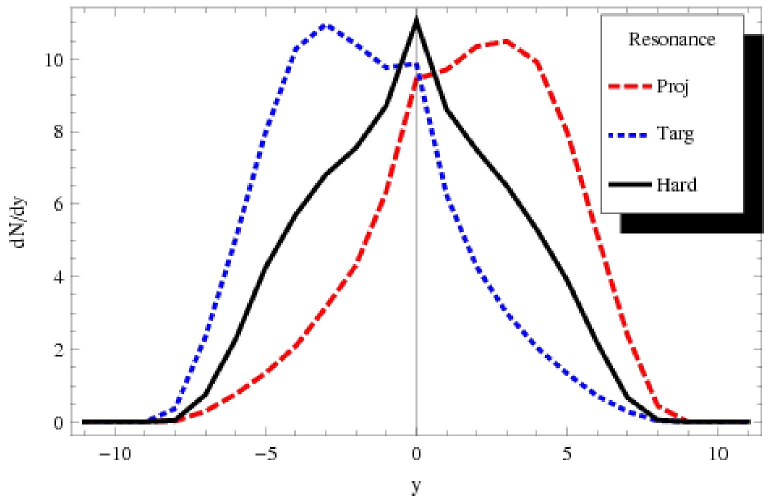
HIJING

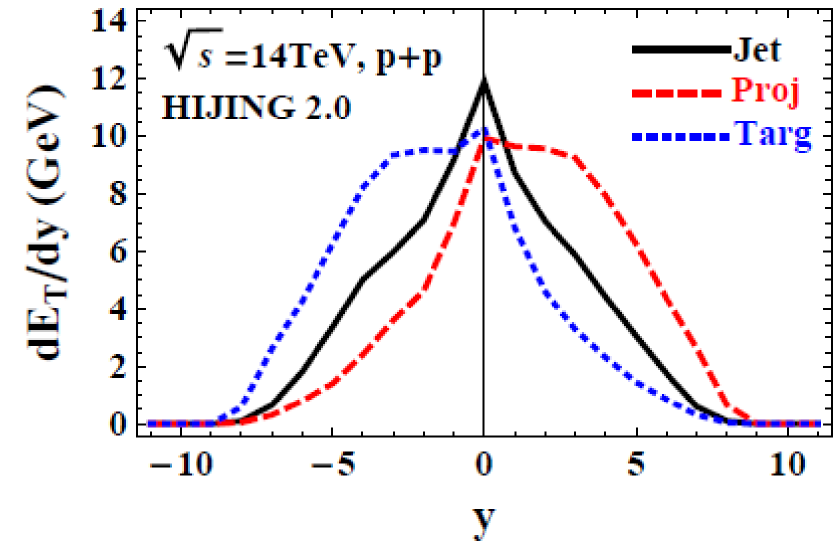
at $\sqrt{s} = 14$ TeV

Resonances break to quark-antiquark pairs.









Parton Transport Model

BAMPS: Boltzmann Approach of MultiParton Scatterings

ZX and C. Greiner, PRC 71, 064901 (2005)

A transport algorithm solving the Boltzmann-Equations for on-shell partons with pQCD interactions

$$(\partial_t + \frac{\vec{p}}{E}\vec{\nabla}) f(x,p) = C_{gg\to gg} + C_{gg\leftrightarrow ggg}$$

(Z)MPC, VNI/BMS, AMPT, PACIAE

new development ggg → gg

2<–>3 are essential for fast thermalization and the buidup of elliptic flow due to large open angle.

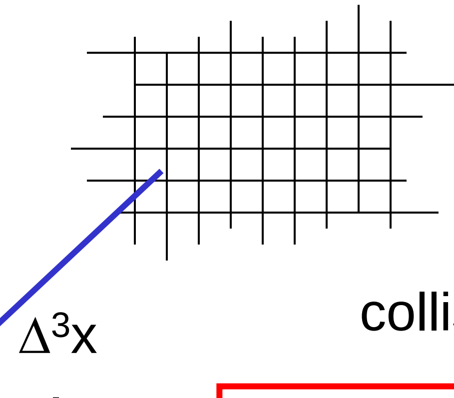
ZX, Greiner, Stöcker, PRL 101, 2008

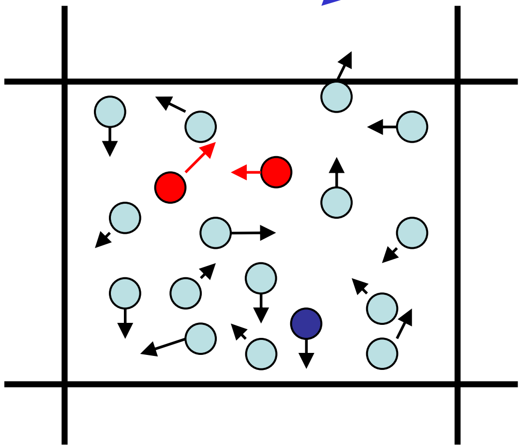
Stochastic algorithm

A.Lang et al., J. Comp. Phys. 106, 391(1993)

$$f(\vec{p},\vec{x},t)=\sum_{i}^{N}\delta^{(3)}(\vec{p}_i-\vec{p})\,\delta^{(3)}(\vec{x}_i(t)-\vec{x})$$

Space is divided into small cells !





collision probability -- stochastic

for $2\rightarrow 2$ $\quad P_{22}=v_{rel}\dfrac{\sigma_{22}}{N_{test}}\dfrac{\Delta t}{\Delta^3 x}$

for $2\rightarrow 3$ $\quad P_{23}=v_{rel}\dfrac{\sigma_{23}}{N_{test}}\dfrac{\Delta t}{\Delta^3 x}$

for $3\rightarrow 2$ $\quad P_{32}=\dfrac{1}{8E_1E_2E_3}\dfrac{I_{32}}{N_{test}^2}\dfrac{\Delta t}{(\Delta^3 x)^2}$

$$I_{32}=\frac{1}{2}\int\frac{d^3p'_1}{(2\pi)^3 2E'_1}\frac{d^3p'_2}{(2\pi)^3 2E'_2}\left|M_{123\rightarrow 1'2'}\right|^2(2\pi)^4\delta^{(4)}(p_1+p_2+p_3-p'_1-p'_2)$$

Setups of BAMPS

- initial time: τ_0=0.1 fm/c

- interactions:

  2–>2, isotropic distribution of the collision angle

  mean free path $\lambda_{mfp} = (n\sigma)^{-1}$

  mean particle distance $d = n^{-1/3}$

  $\lambda_{mfp} / d = 2 \quad \Rightarrow \quad \eta/s \approx 0.4$

- freeze-out:

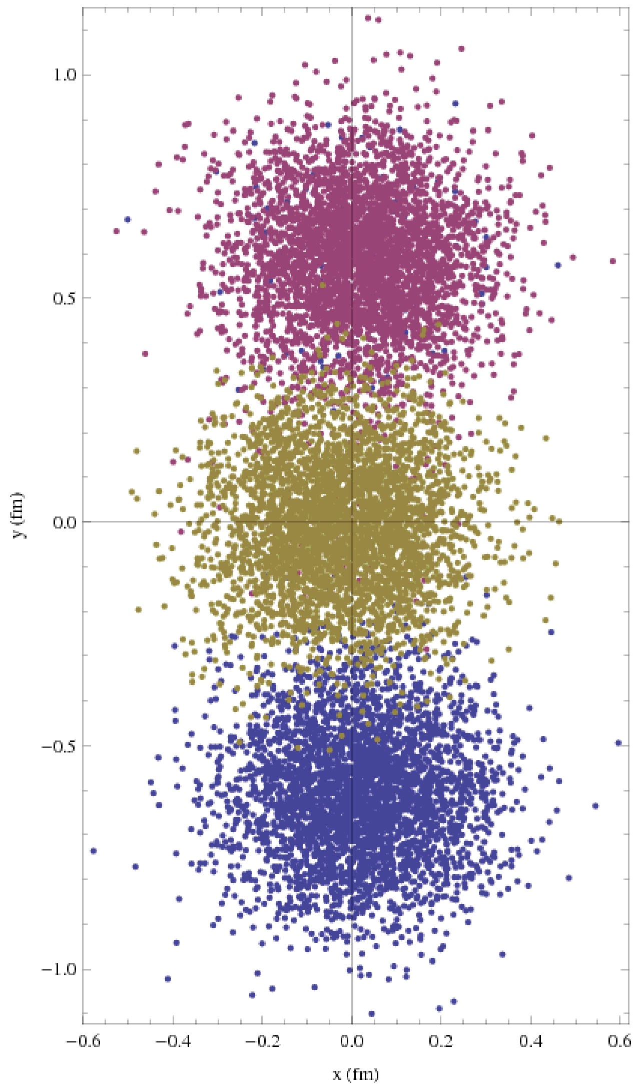
  Partons stop interacting when e < 1.0 GeV/fm^3.

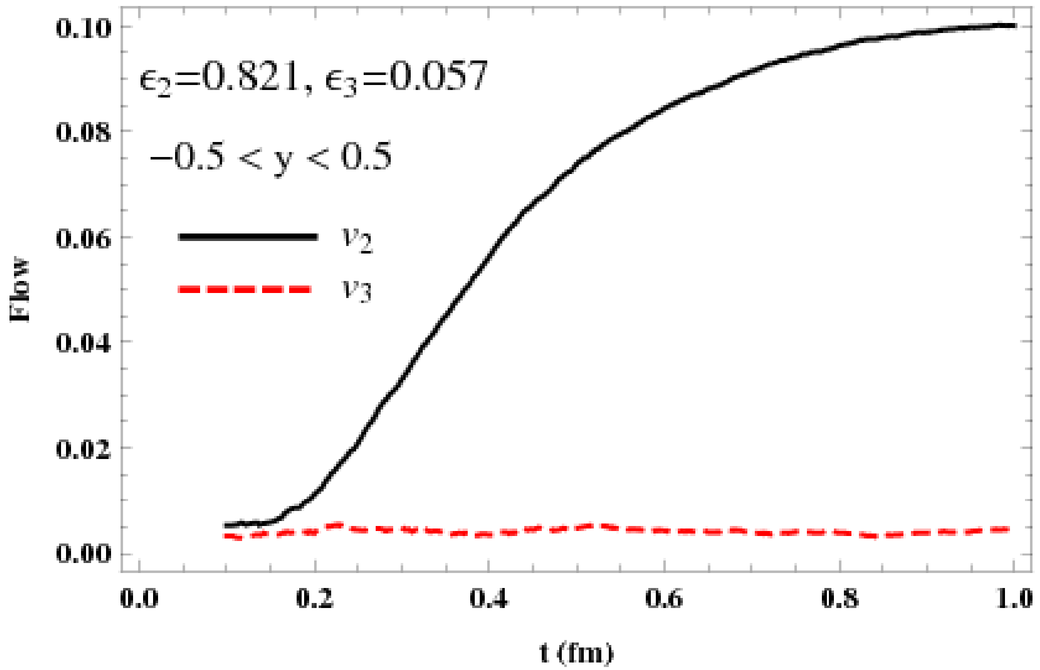
- technique details:

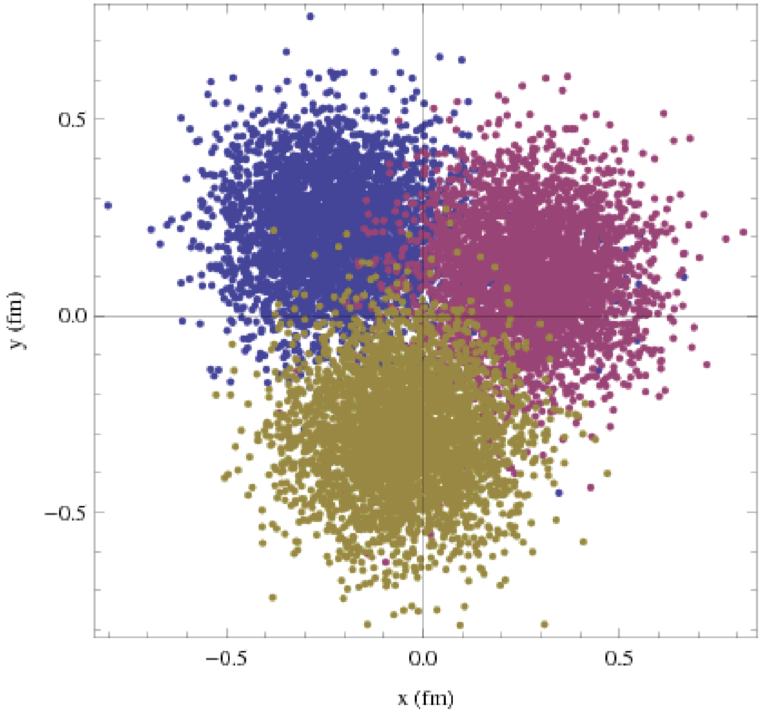
  cell length Δx=Δy=0.02 fm, $\Delta\eta$=0.1

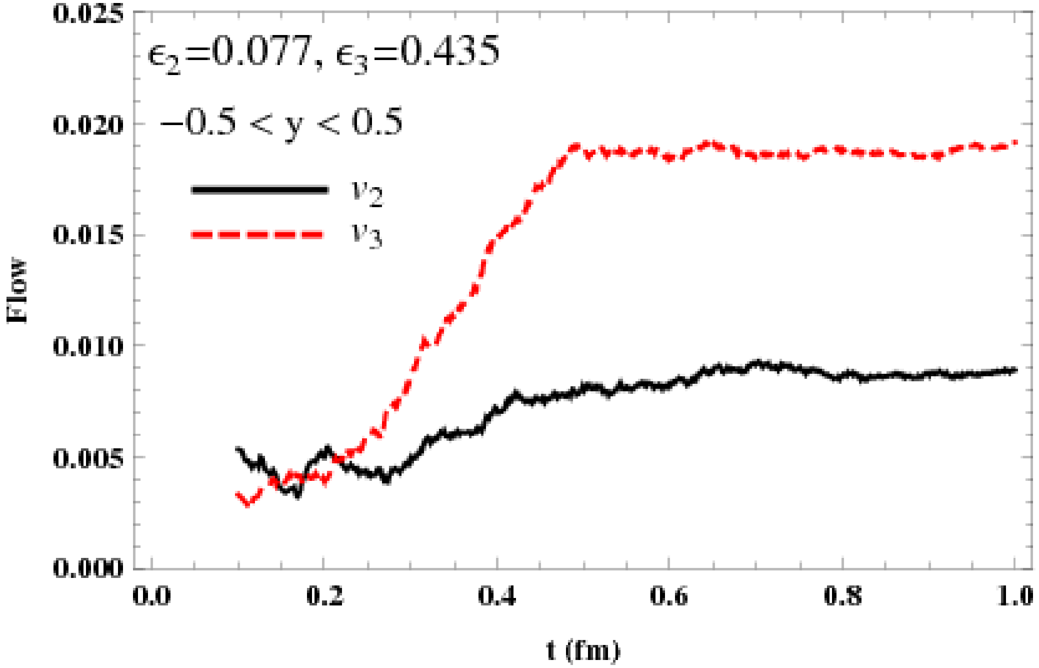
  3000 test particles per real particle

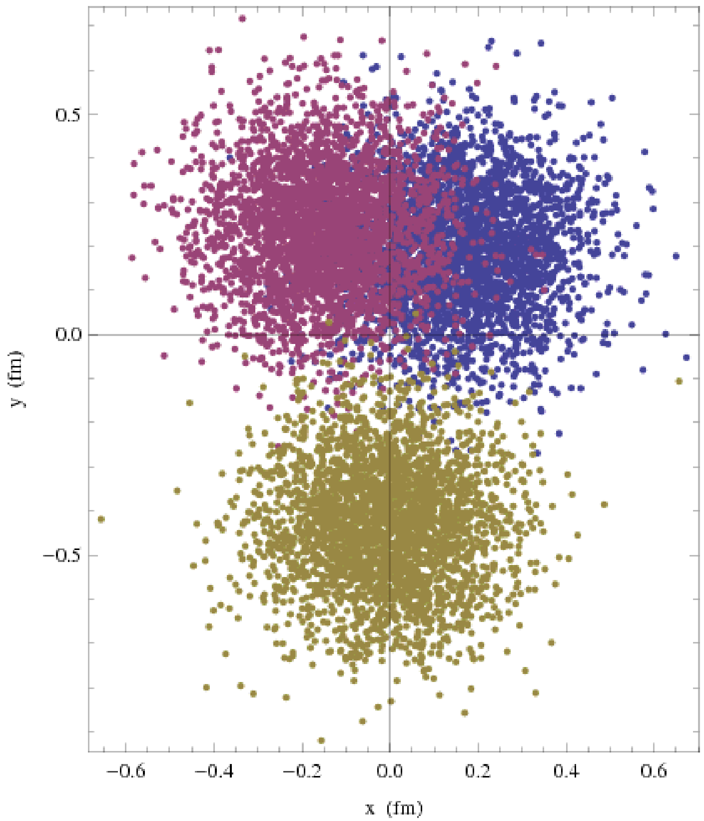
Results of v_2 and v_3 at midrapidity

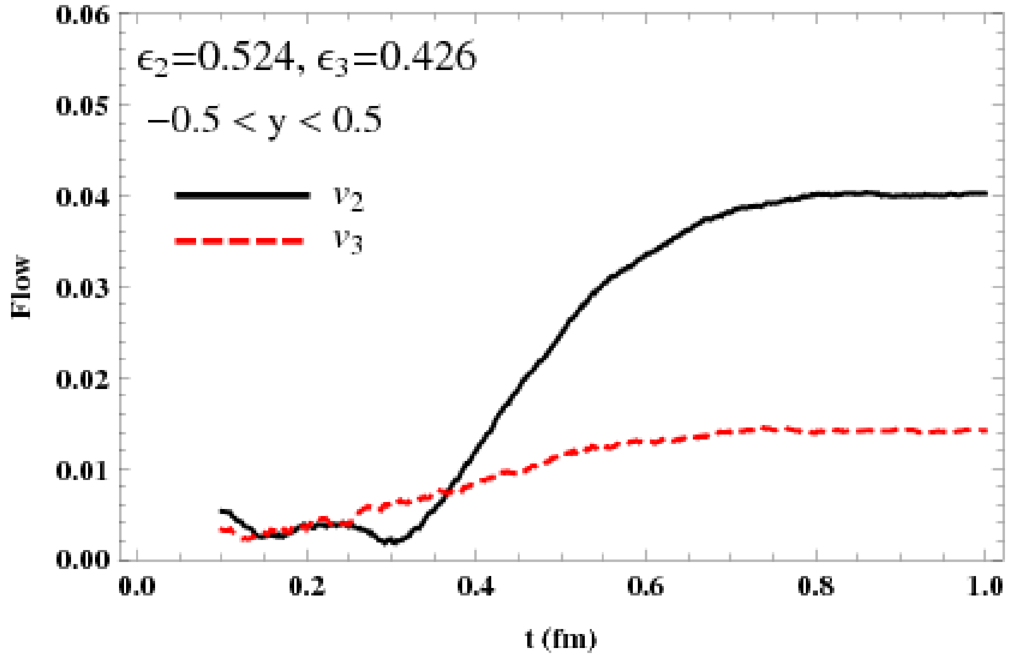




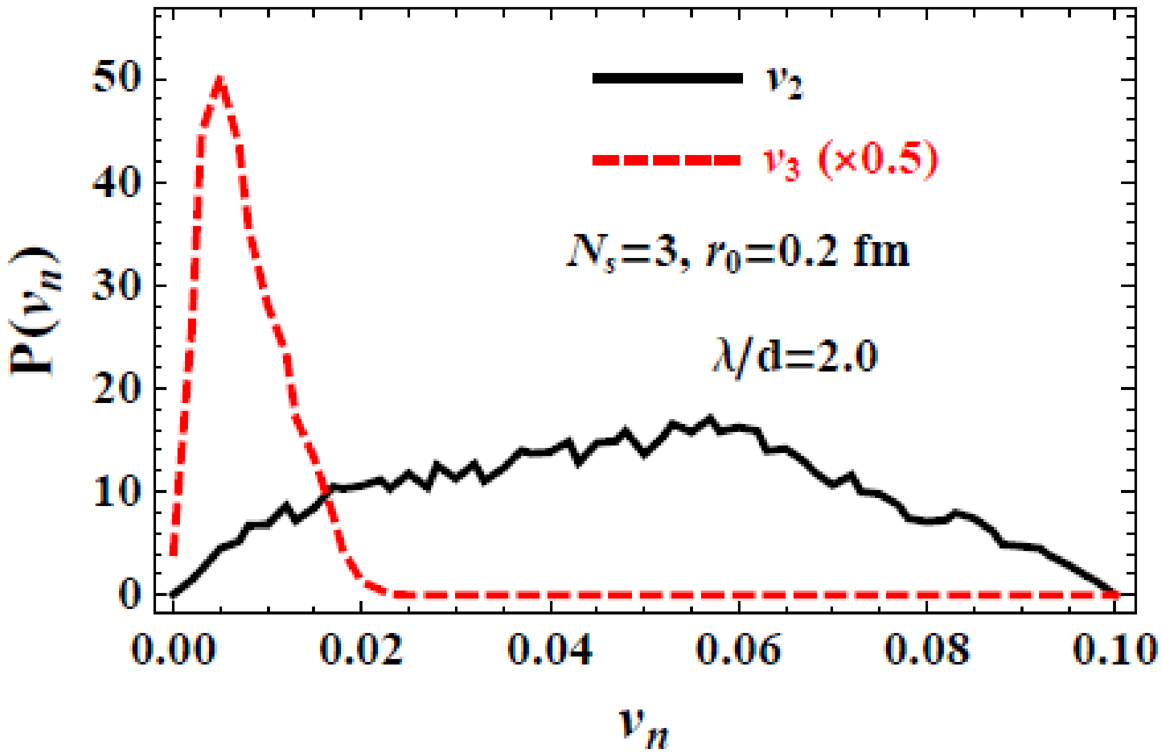

0.5
0.0
−0.5
y (fm)
−0.5
0.0
0.5
x (fm)


ϵ_2=0.077, ϵ_3=0.435
−0.5 < y < 0.5
v_2
v_3
Flow
0.025
0.020
0.015
0.010
0.005
0.000
0.0
0.2
0.4
0.6
0.8
1.0
t (fm)

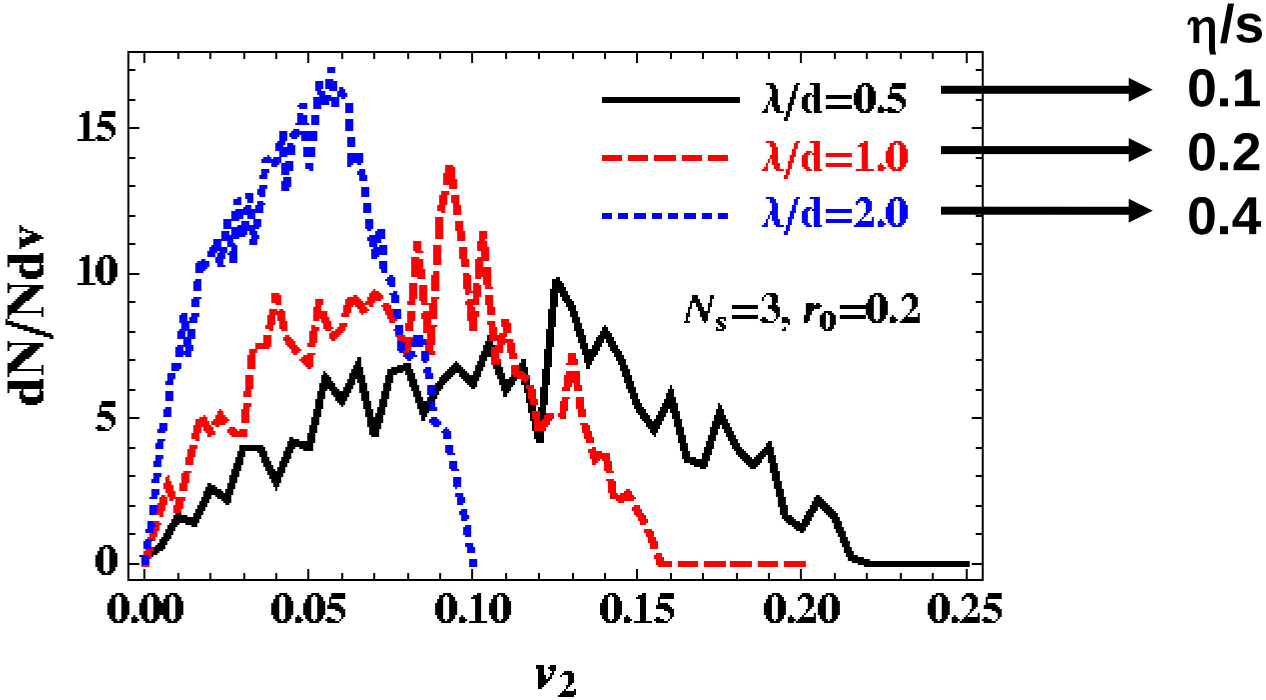

0.5
0.0
−0.5
y (fm)
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
x (fm)

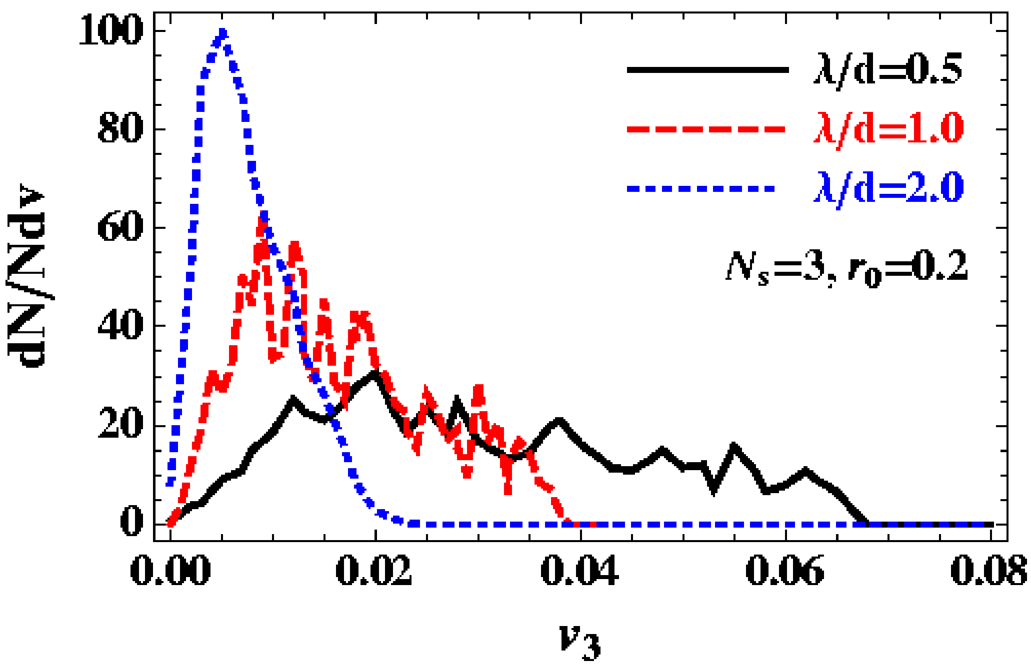

ϵ_2=0.524, ϵ_3=0.426
−0.5 < y < 0.5
v_2
v_3
Flow
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.0
0.2
0.4
0.6
0.8
1.0
t (fm)

Distributions of v_2 and v_3



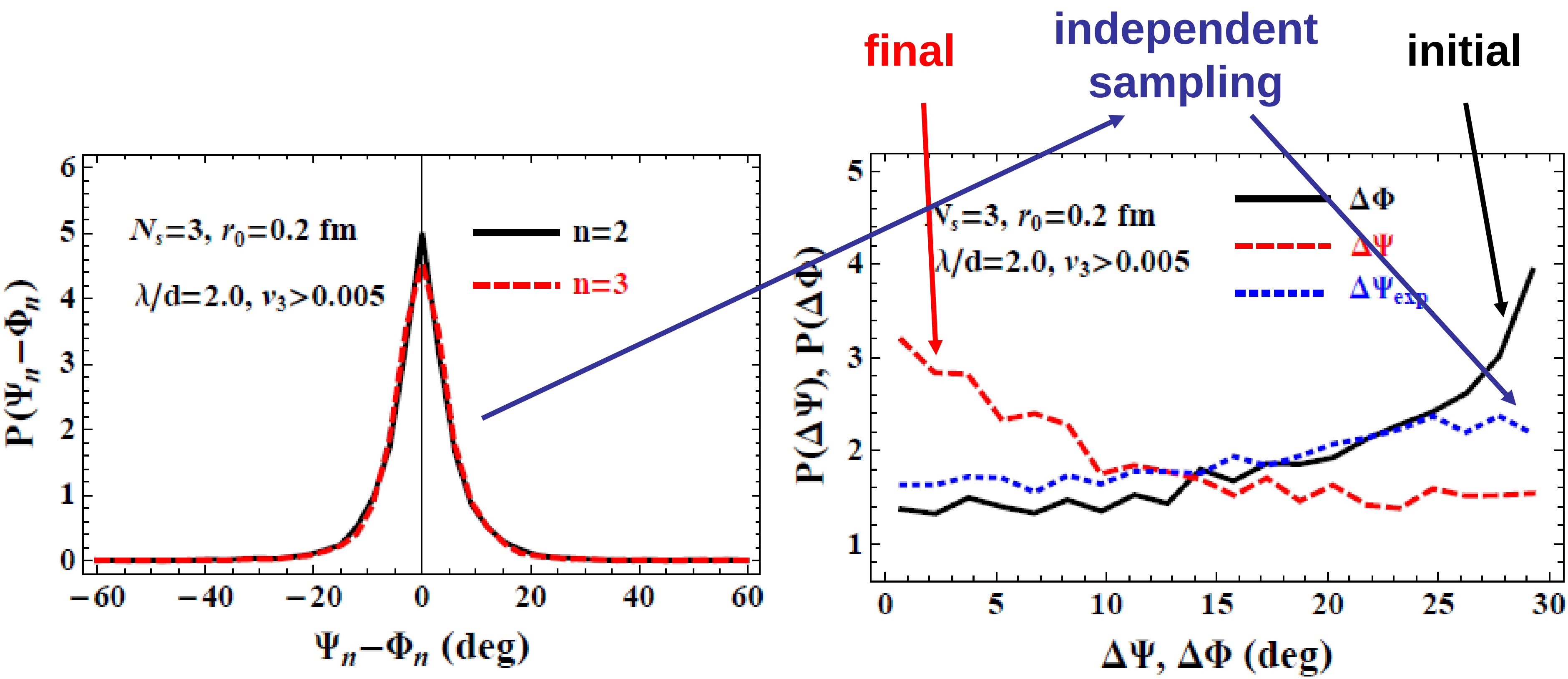
10^4 runs





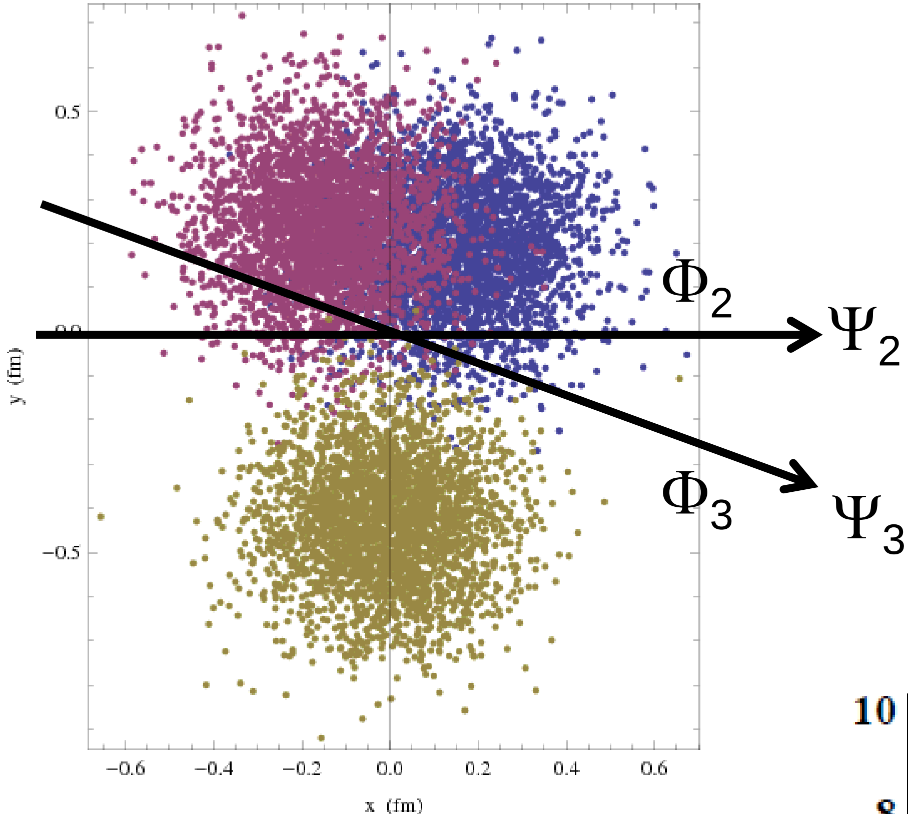
Elliptic and triangular flow are measurable quantities for η/s=0.1-0.4 in high multiplicity events of p+p at 14 TeV.

event-plane angular correlations



It seems **independent** translations from Φ_2, Φ_3 to Ψ_2, Ψ_3.

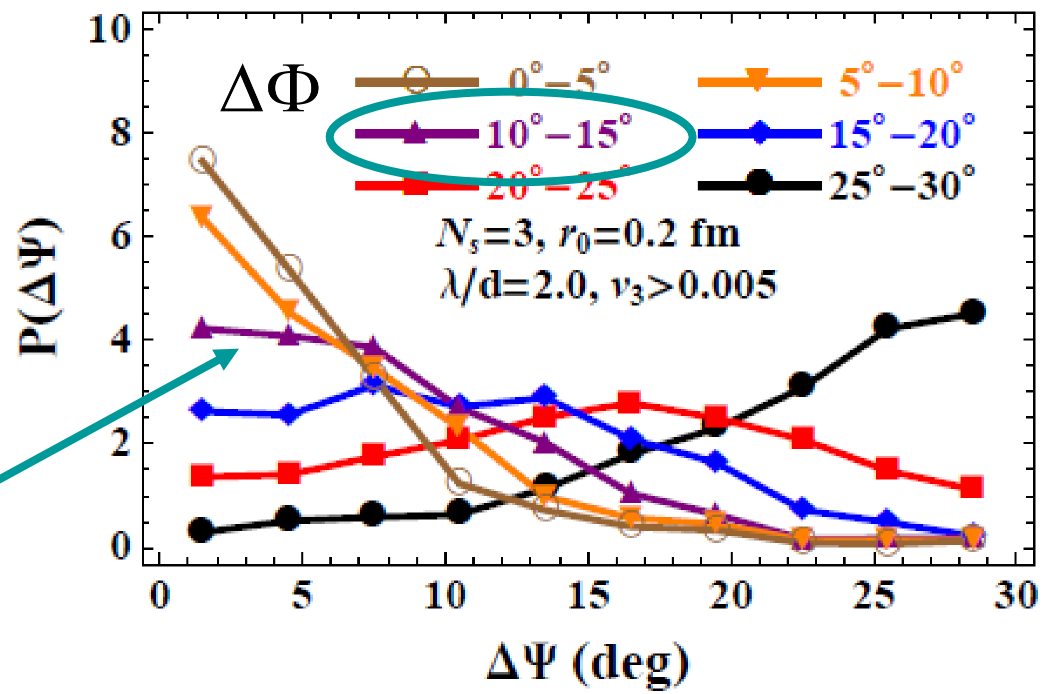
Elliptic and triangular flow are **correlated** during the dynamical expansion.



rotation of different event-planes to a unified event-plane

$\Delta\Phi = \left|\Phi_2 - \Phi_3\right| = 10^0 - 15^0$

$P(\Delta\Psi)$ is broad and peaks at $\Delta\Psi = \left|\Psi_2 - \Psi_3\right| = 0^0$



Summary and Outlook

- Hot spots initial condition in high multiplicity pp events at LHC may generate measurable v_2 and v_3 for $\eta/s=0.1-0.4$.

- Dynamical correlation of v_2 and v_3 during the expansion

- v_2-v_3 correlation in A+A at RHIC and LHC ?

- study v_2-v_3 correlation with smooth initial conditions