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

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with Wei-Tian Deng (KEK), Carsten Greiner (Frankfurt U.)

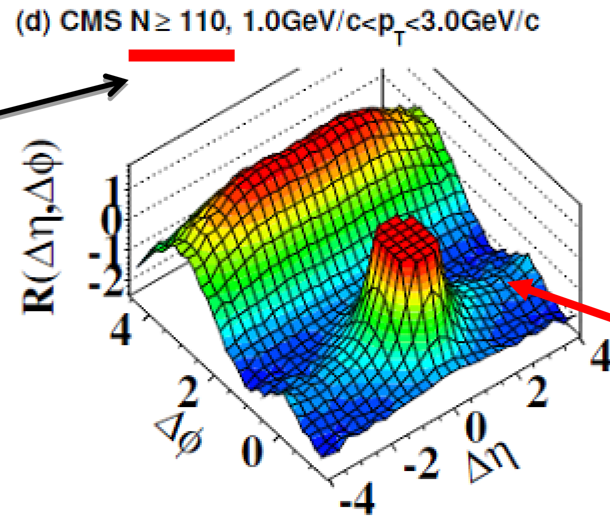
Phys.Lett. B711 (2012) 301-306; arXiv:1112.0470 [hep-ph]

NeD/TURIC 2012, Crete, June 29

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

experiment

high multiplicity events

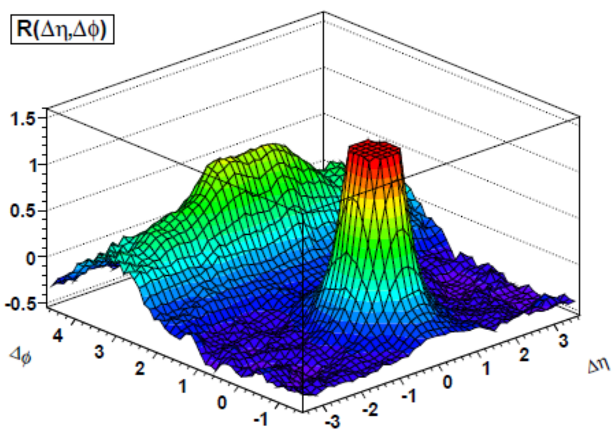


ridge

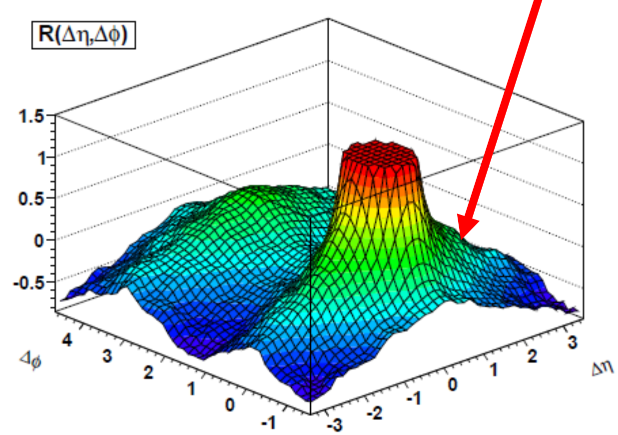
CMS Collaboration, JHEP 1009, 091 (2010)

theory

EPOS without hydro

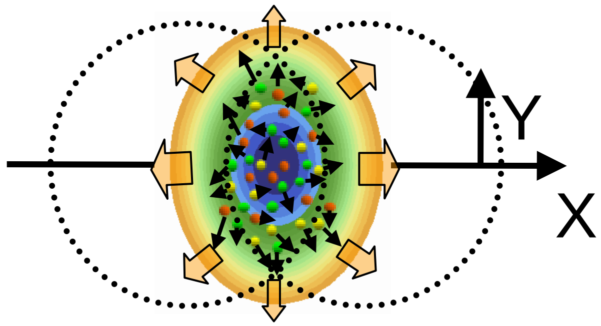


EPOS with hydro

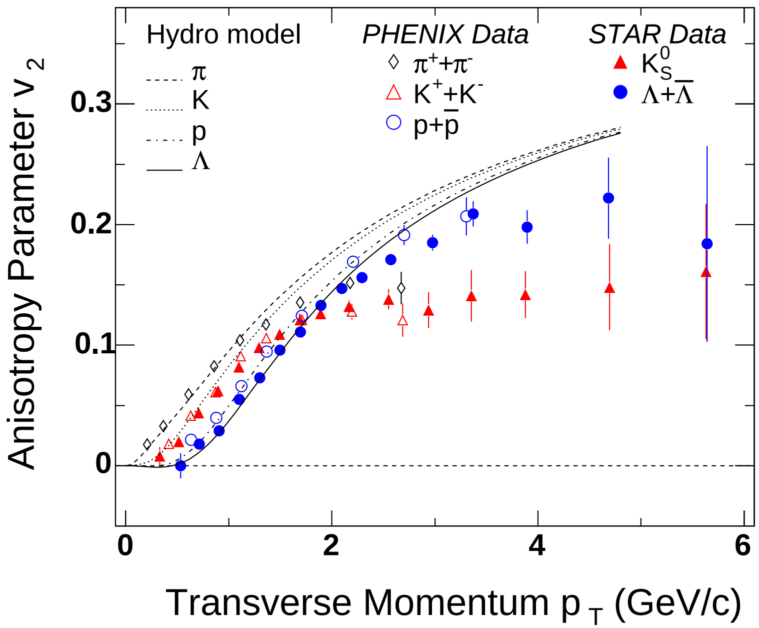


K. Werner, I. Karpenko and T. Pierog, PRL106, 122004 (2011)

Au+Au Collisions at RHIC-200 GeV

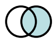


eccentricity –> elliptic flow



QGP at RHIC is a nearly perfect fluid.

p+p Collisions at LHC-14 TeV



collective flow ?

NO: too small volume

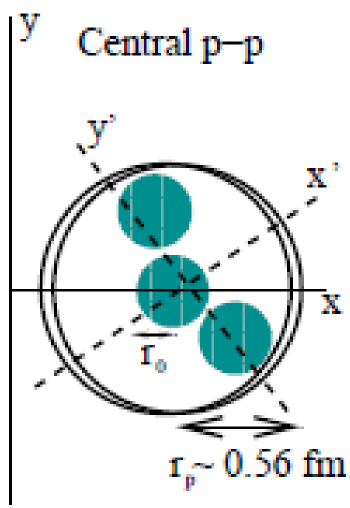
YES: very high energy density
high multiplicity events

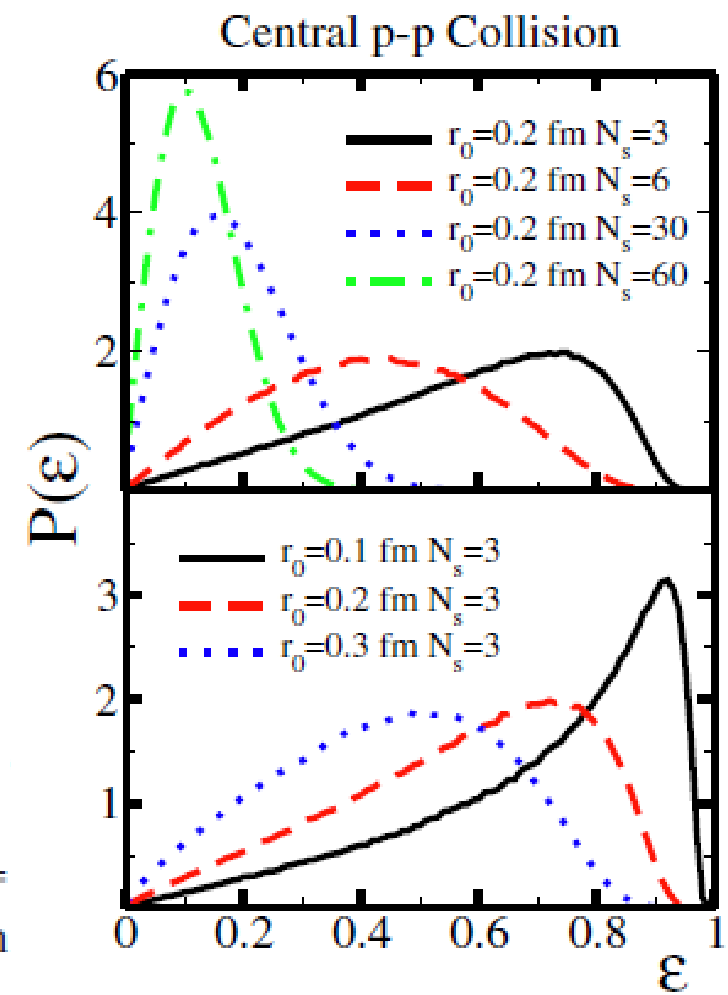
NO: symmetry in central collisions

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

- 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:

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

R. S. Bhalerao, et al., Phys. Lett. B 627 (2005)

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

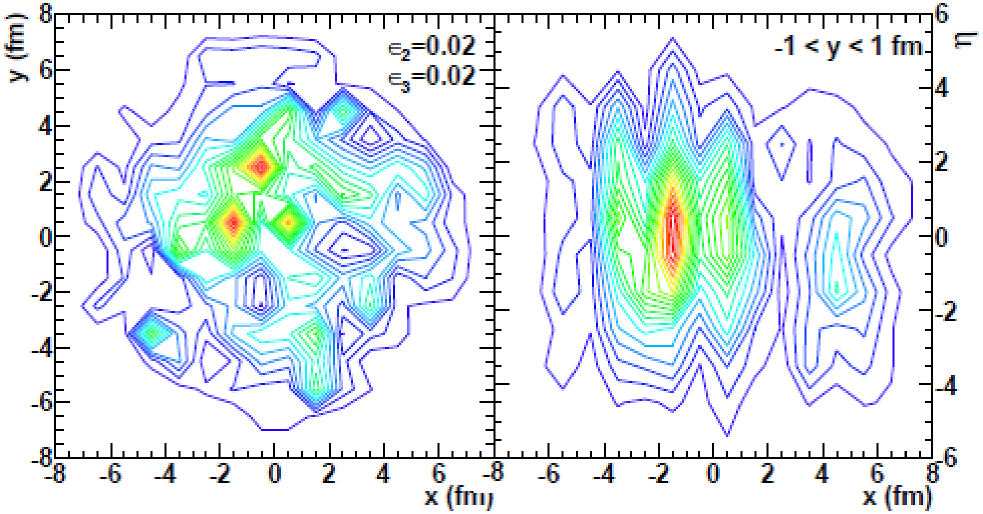
- initial fluctuations (hot spots) (large v_2~5-25%)

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

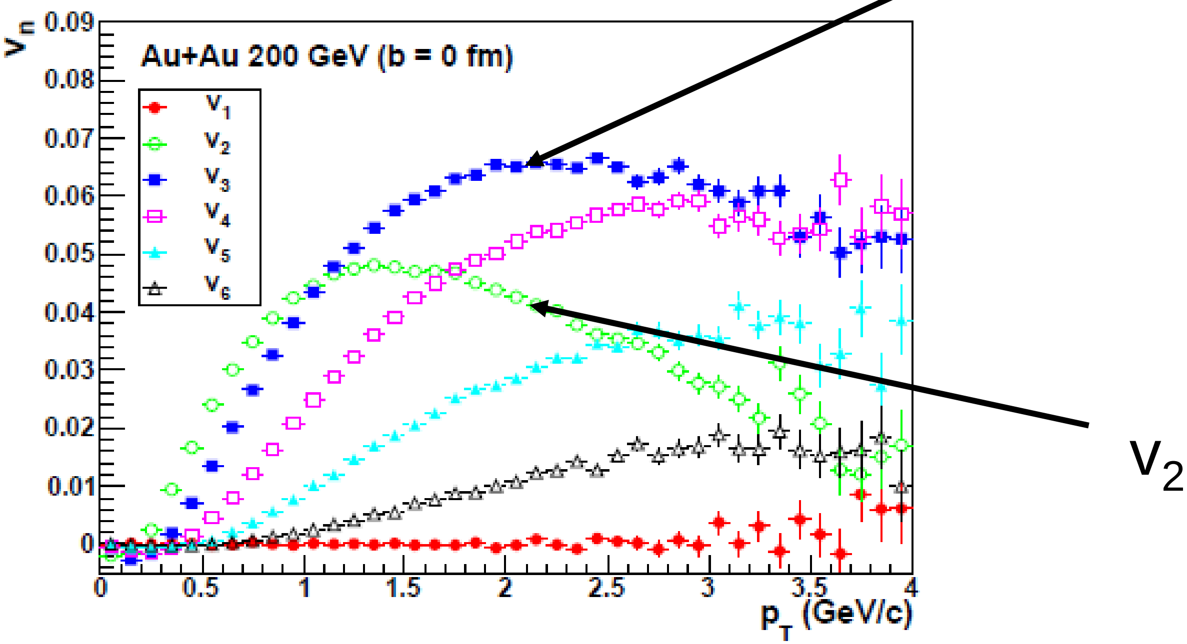
ε_2-v_2 scaling:
J. Casalderrey-Solana, U. A. Wiedemann, PRL104 (2010).
E. Avsar, et al., Phys. Lett. B702 (2011).

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

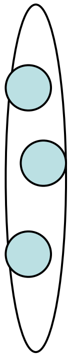
Hot spots and harmonic flow



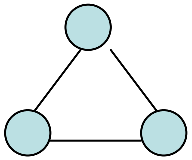
AMPT for central Au+Au
G.-L. Ma and X.-N. Wang,
PRL 106, 162301 (2011)



p+p @ LHC



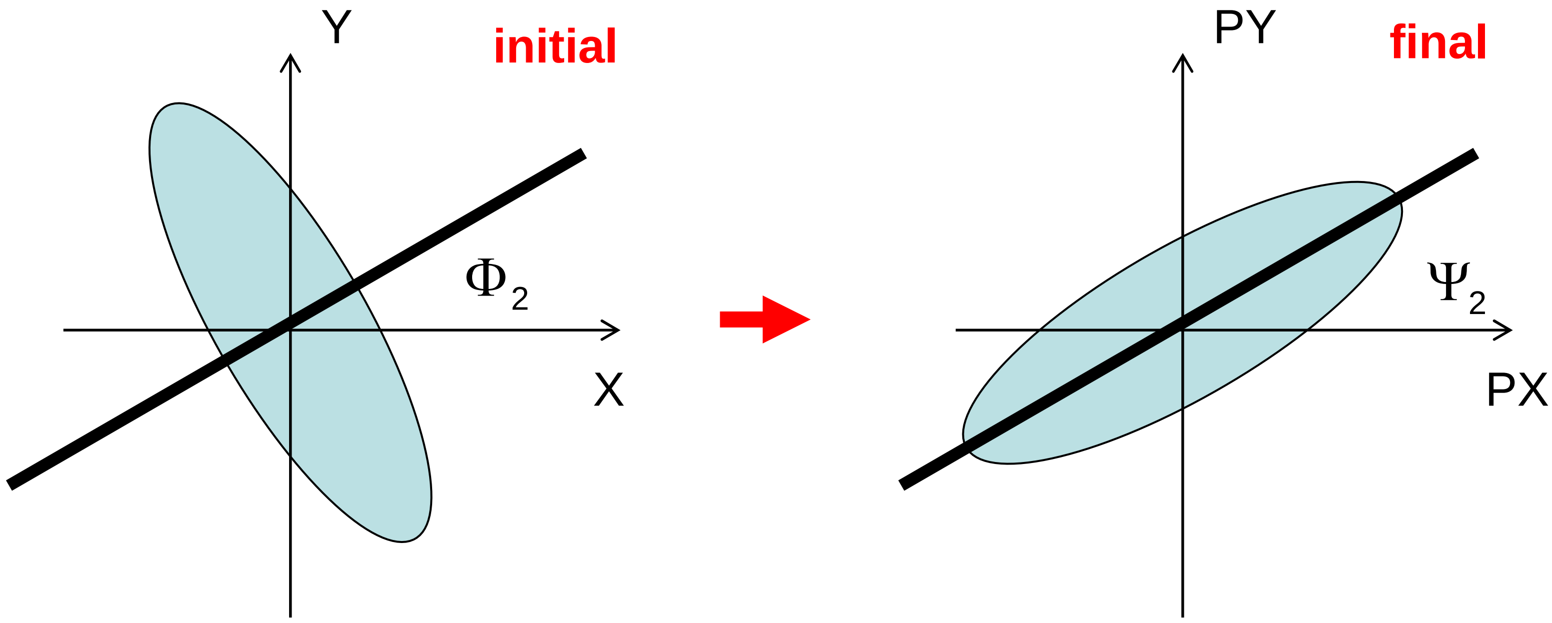
ε_2 dominant $\Rightarrow v_2$



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-plane angles



Initial eccentricity ε_2
Initial event-plane angle Φ_2

Elliptic flow v_2
Final event-plane 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

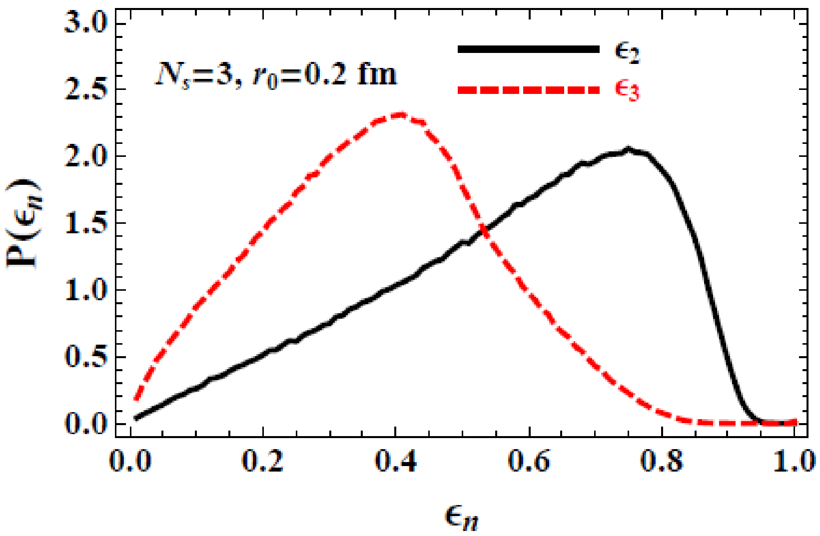
$$\Psi_n = \frac{1}{n}\arctan\frac{\langle \sin(n\psi)\rangle}{\langle \cos(n\psi)\rangle}$$

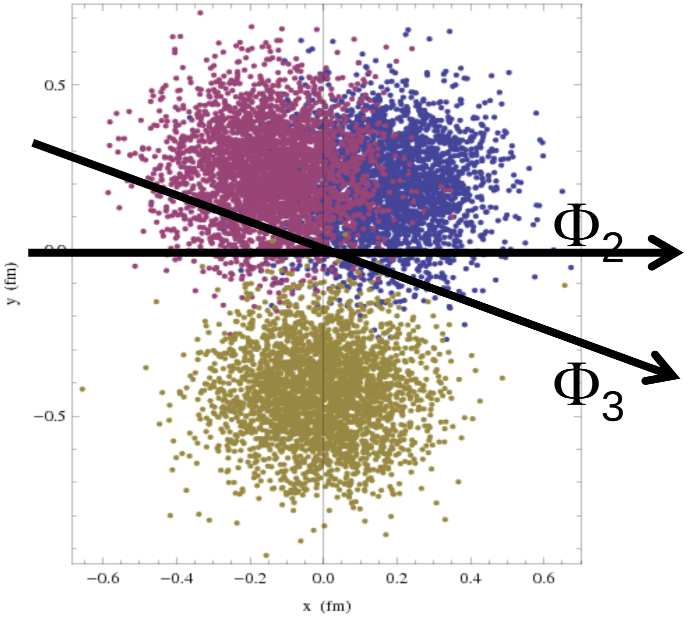
If the translations from ε_n to v_n (n=2,3,...) are completely independent

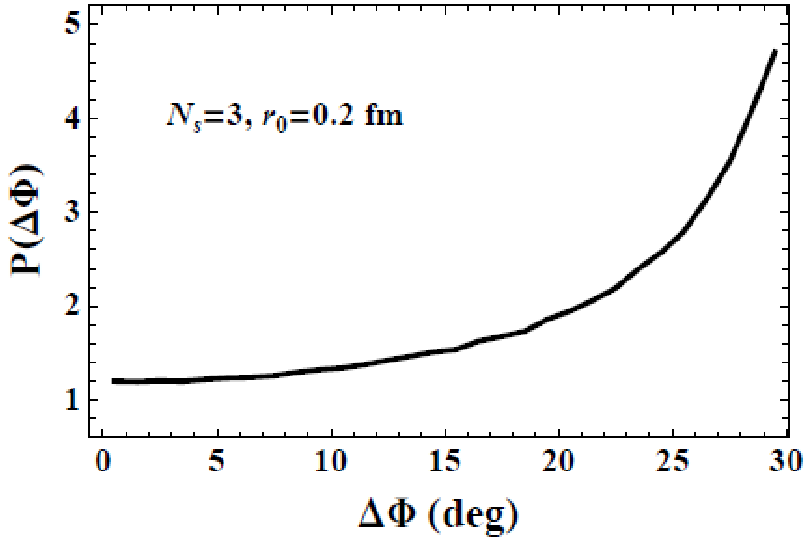
$$\Rightarrow \quad \Phi_n = \Psi_n$$

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

ε_2, ε_3 and their correlation in the hot spots scenario







If ε_n to v_n translations are independent ?

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

$$\Delta\Phi = |\Phi_2 - \Phi_3|; \quad \Delta\Psi = |\Psi_2 - \Psi_3|$$

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

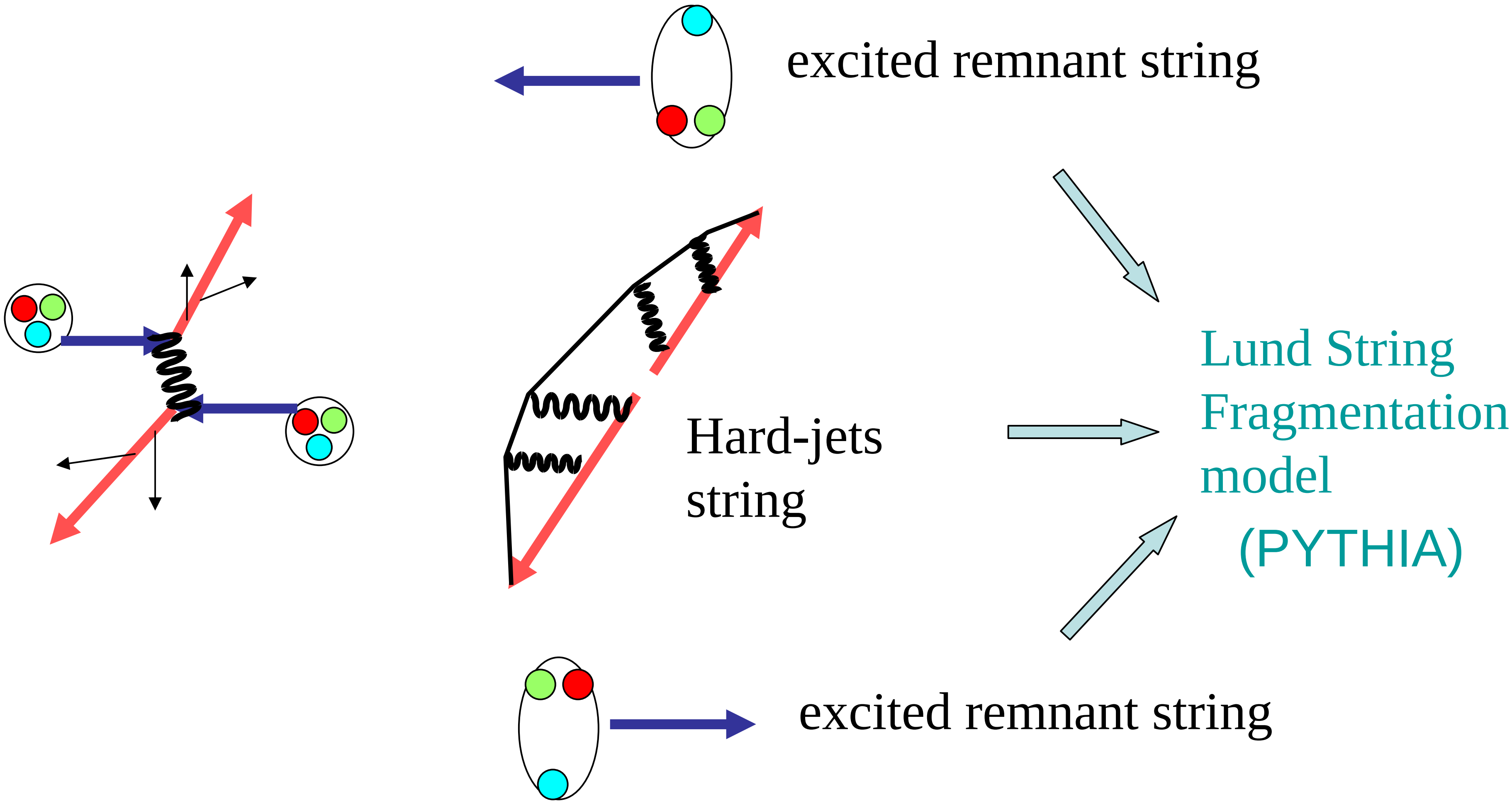
Our Model:

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).

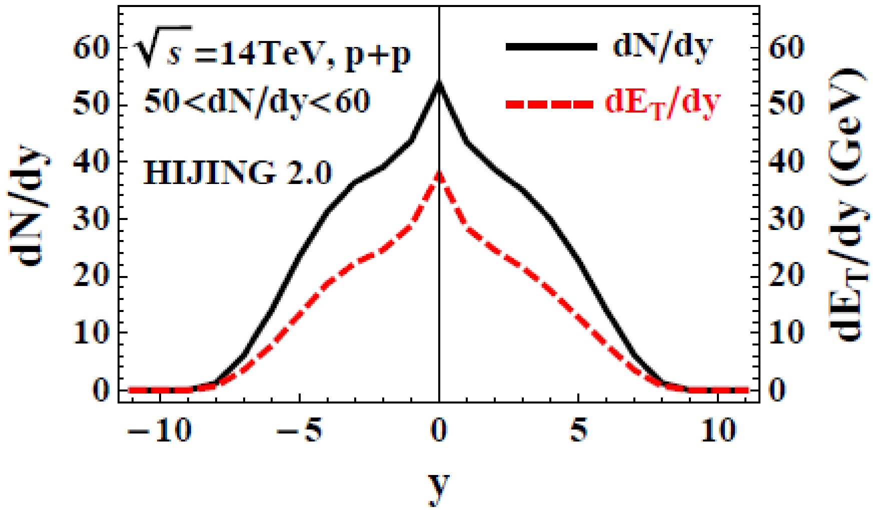


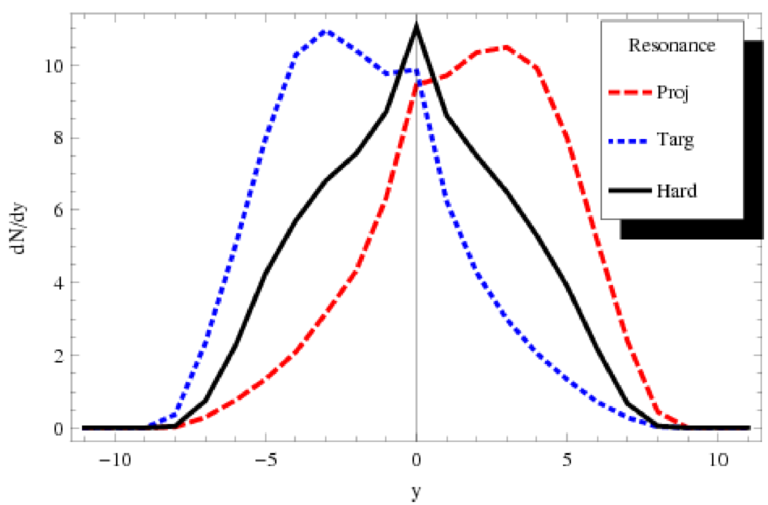
3 strings --> 3 hot spots

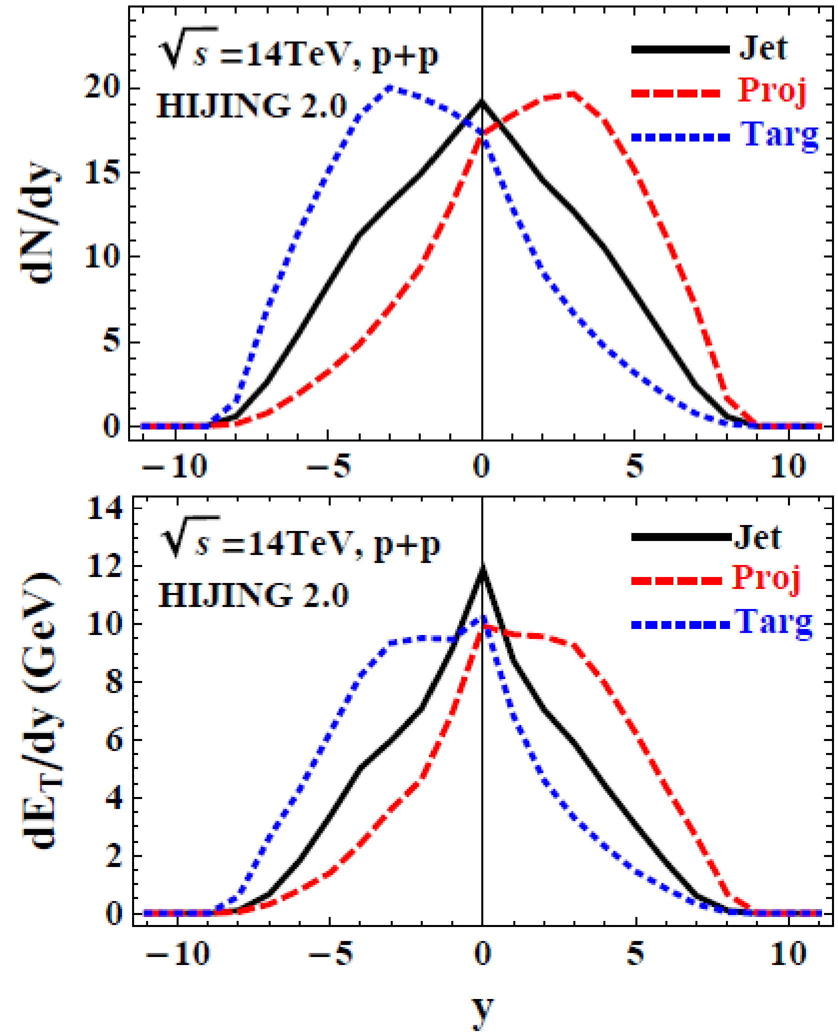
HIJING

at $\sqrt{s} = 14\,\mathrm{TeV}$

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

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

new development ggg → gg

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

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

ZX, Greiner, Stöcker, PRL 101, 2008

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:

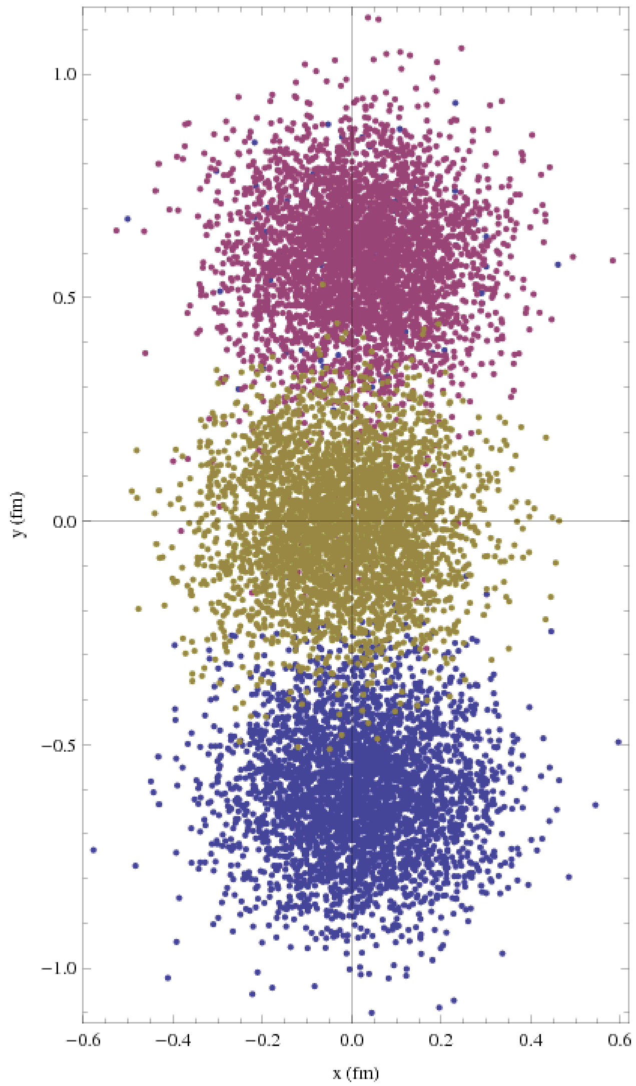
  Partons stop interacting when e < 1.0 GeV/fm^3.

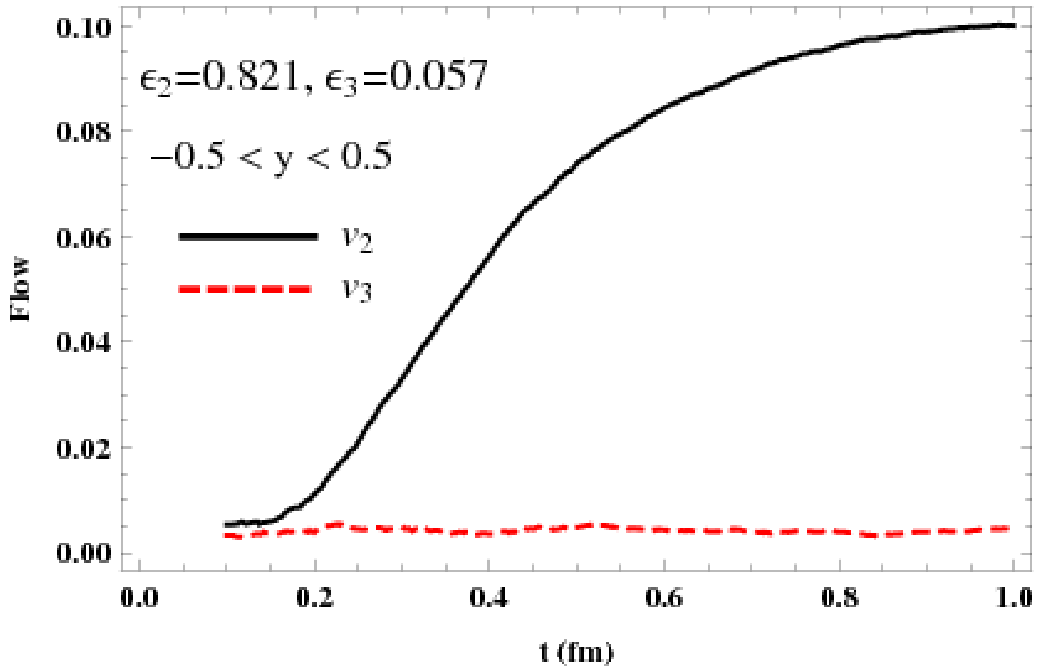
- technique details:

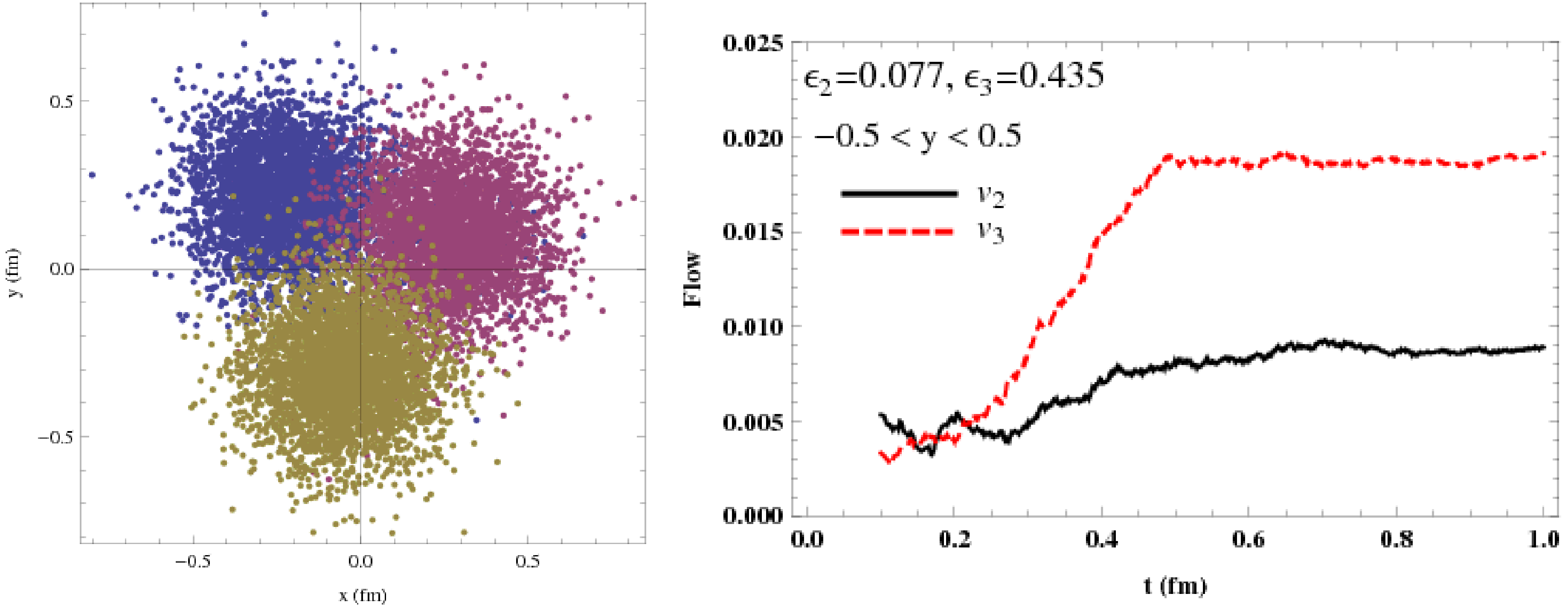
  cell length Δx=Δy=0.02 fm, $\Delta\eta$=0.1

  3000 test particles per real particle

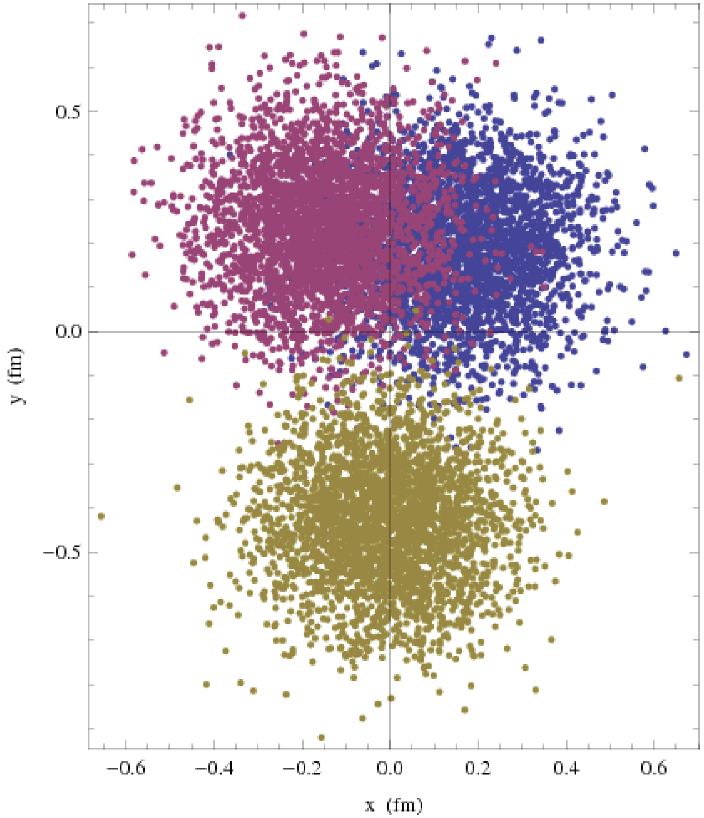
Results of v_2 and v_3 at midrapidity



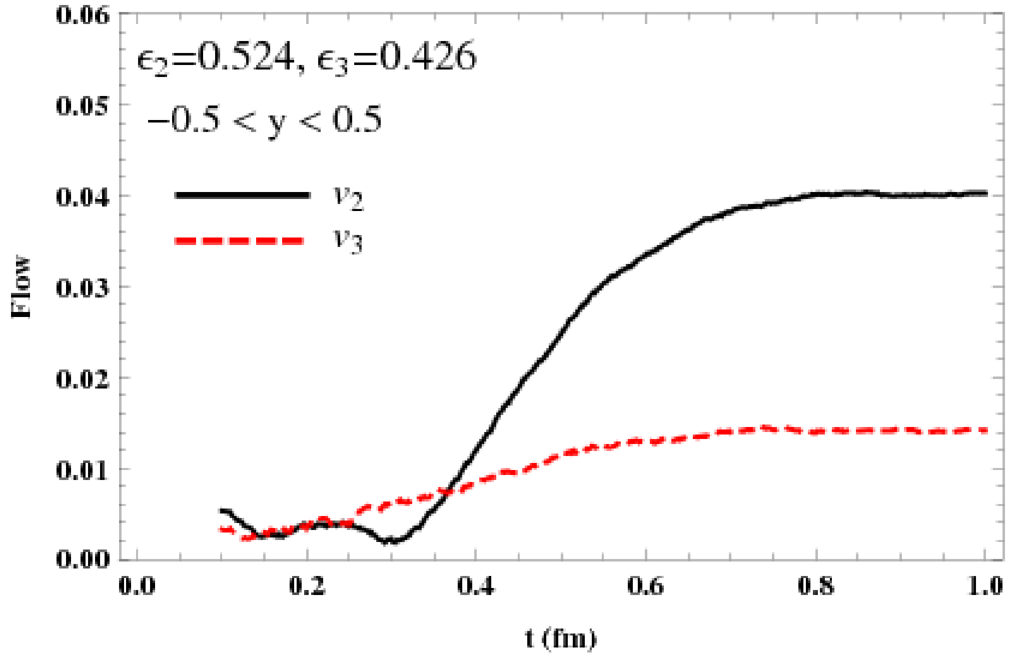




0.5
0.0
−0.5
y (fm)
−0.5
0.0
0.5
x (fm)
0.025
0.020
0.015
0.010
0.005
0.000
Flow
ϵ_2=0.077, ϵ_3=0.435
−0.5 < y < 0.5
v_2
v_3
0.0
0.2
0.4
0.6
0.8
1.0
t (fm)

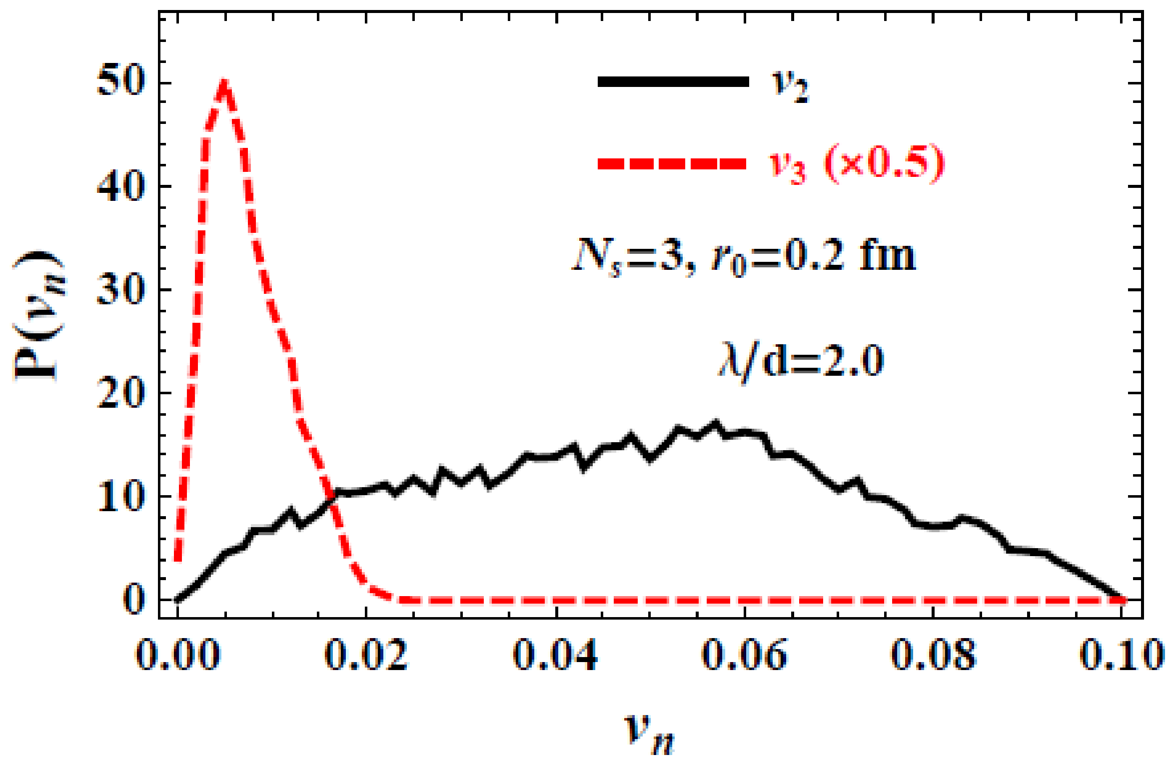


0.5
0.0
−0.5
y (fm)
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
x (fm)

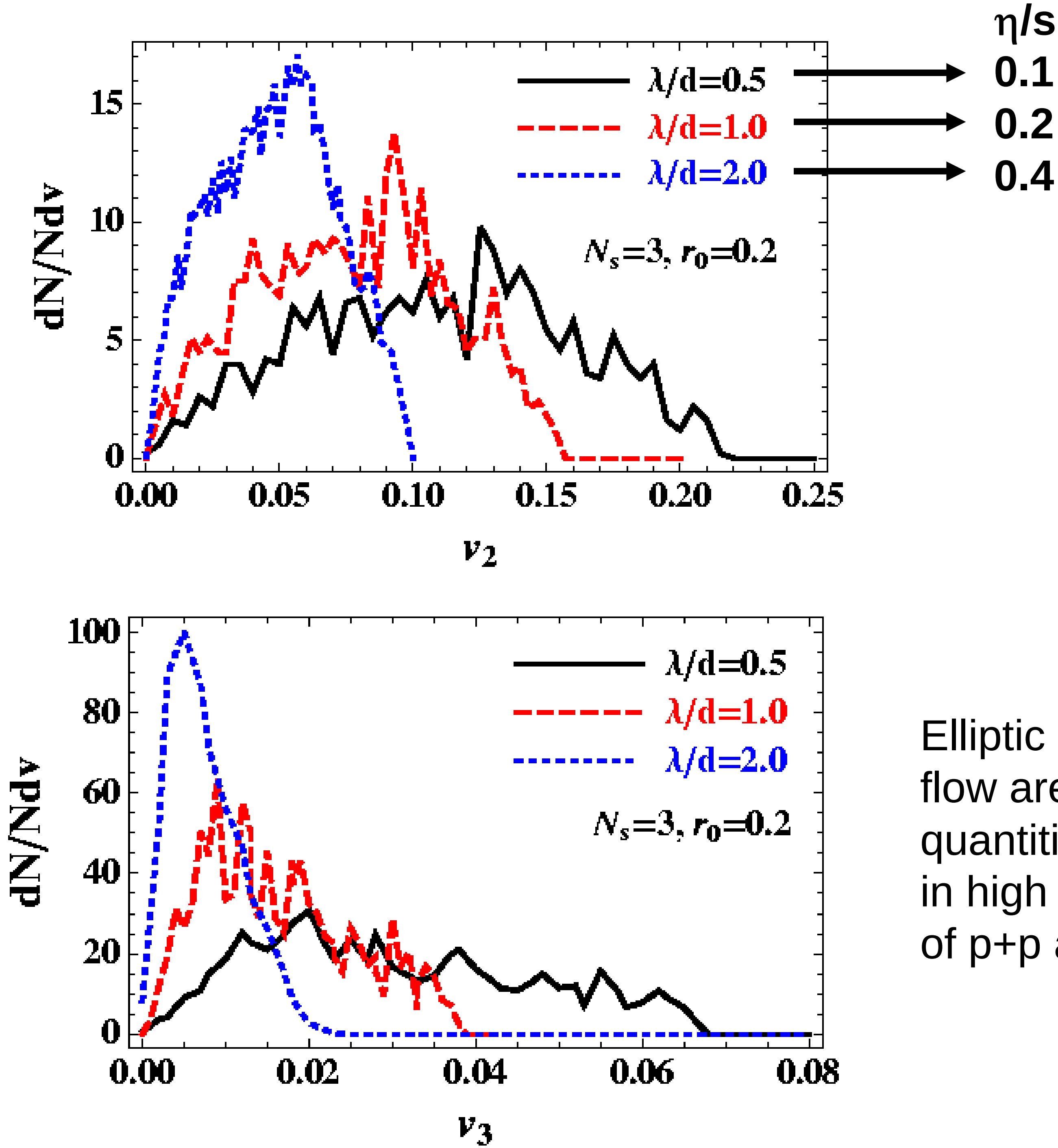


ϵ_2=0.524, ϵ_3=0.426
−0.5 < y < 0.5
v_2
v_3
Flow
t (fm)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.0
0.2
0.4
0.6
0.8
1.0

Distributions of v_2 and v_3

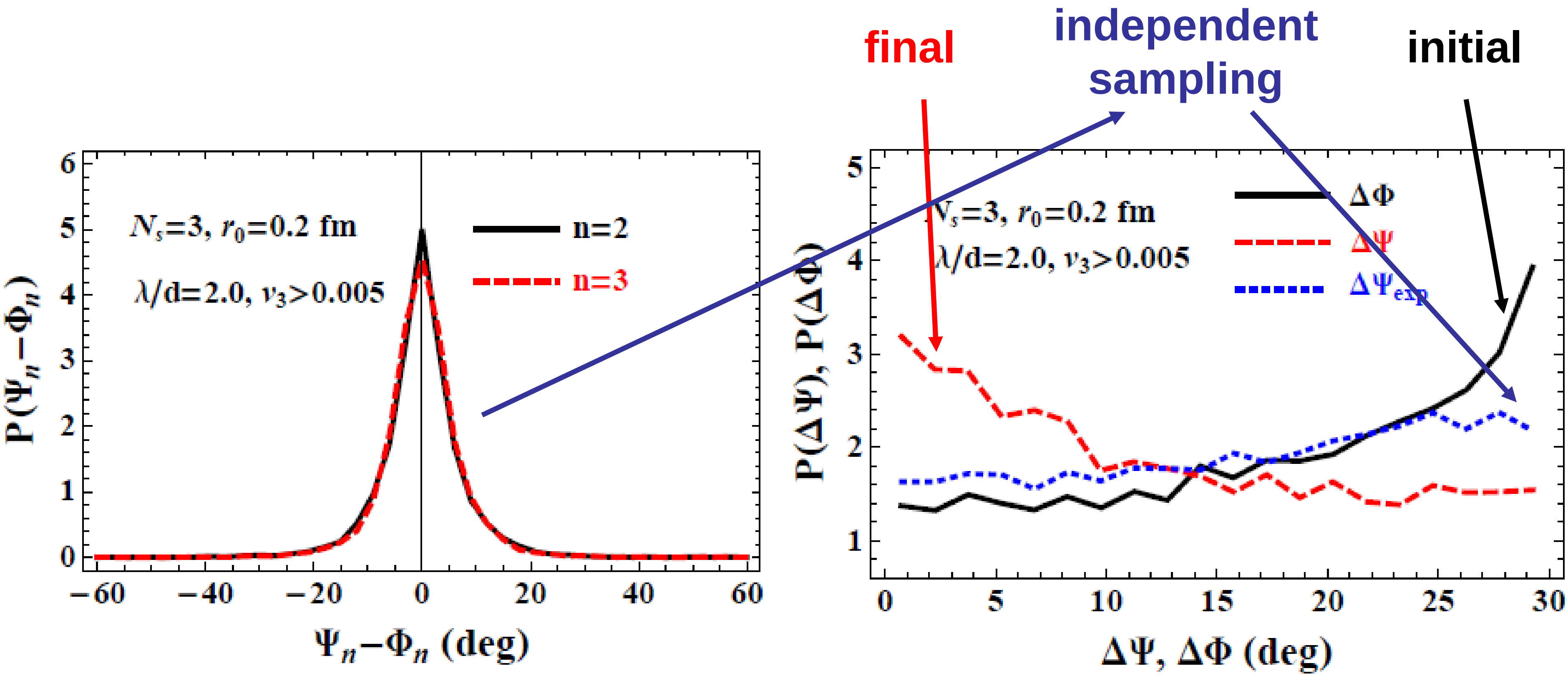


10^4 runs



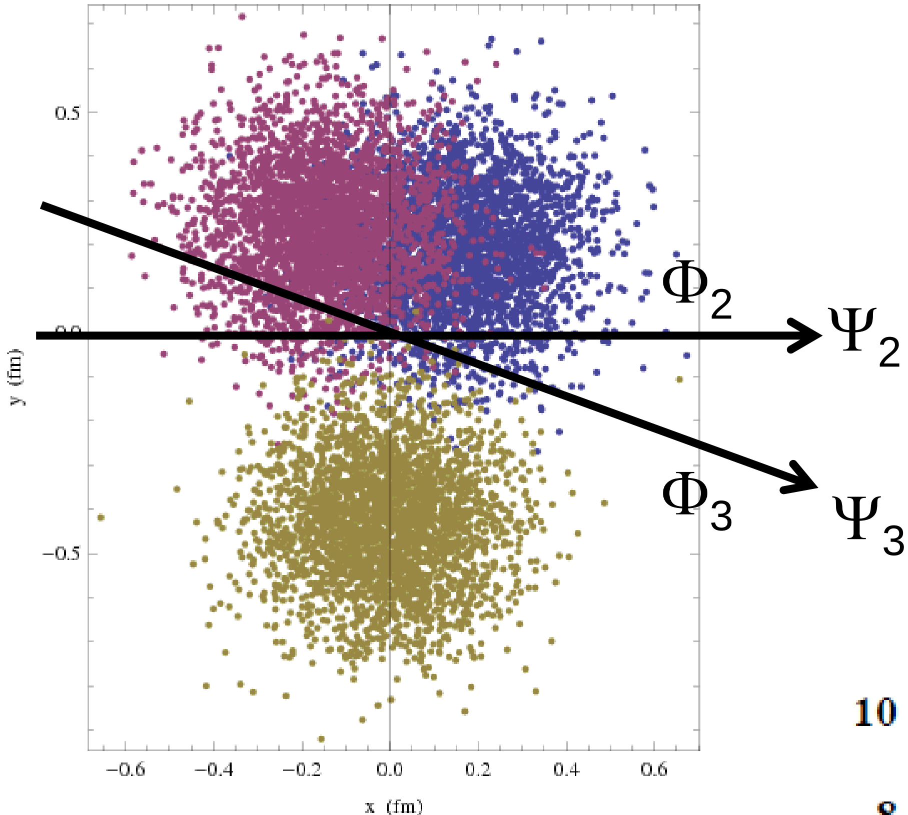
Elliptic and triangular flow are measurable quantities for η/s=0.1-0.4 in high multiplicity events of p+p at 14 TeV.

event-plane angular correlations



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

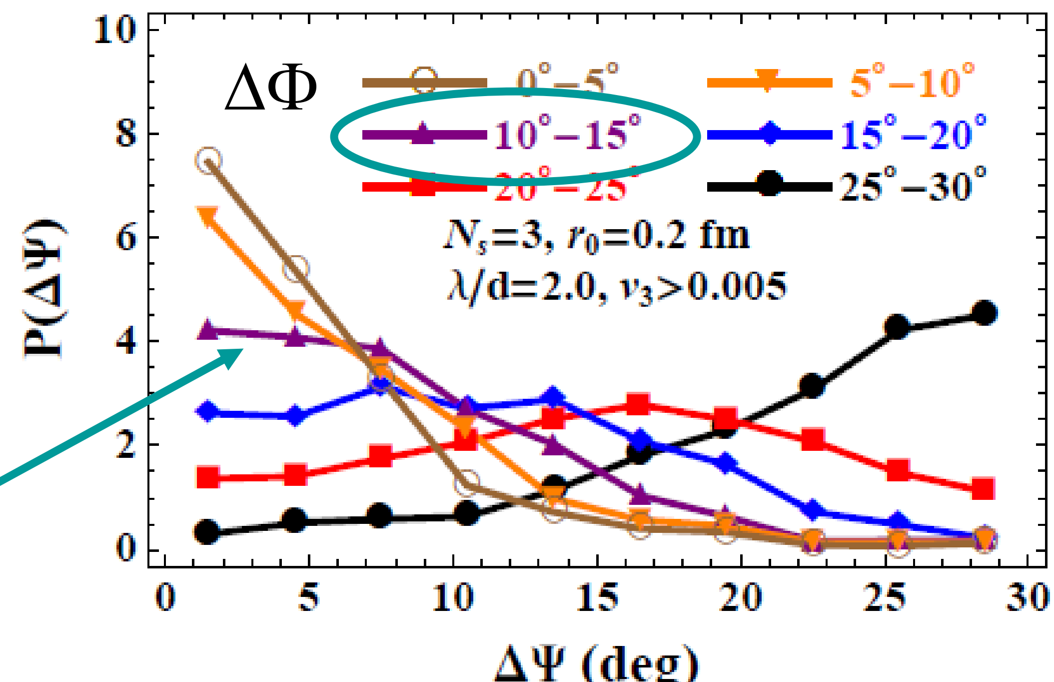
Elliptic and triangular flow are **correlated** during the dynamical expansion.



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

- study v_2-v_3 correlation with smooth initial conditions

event-plane angular correlations

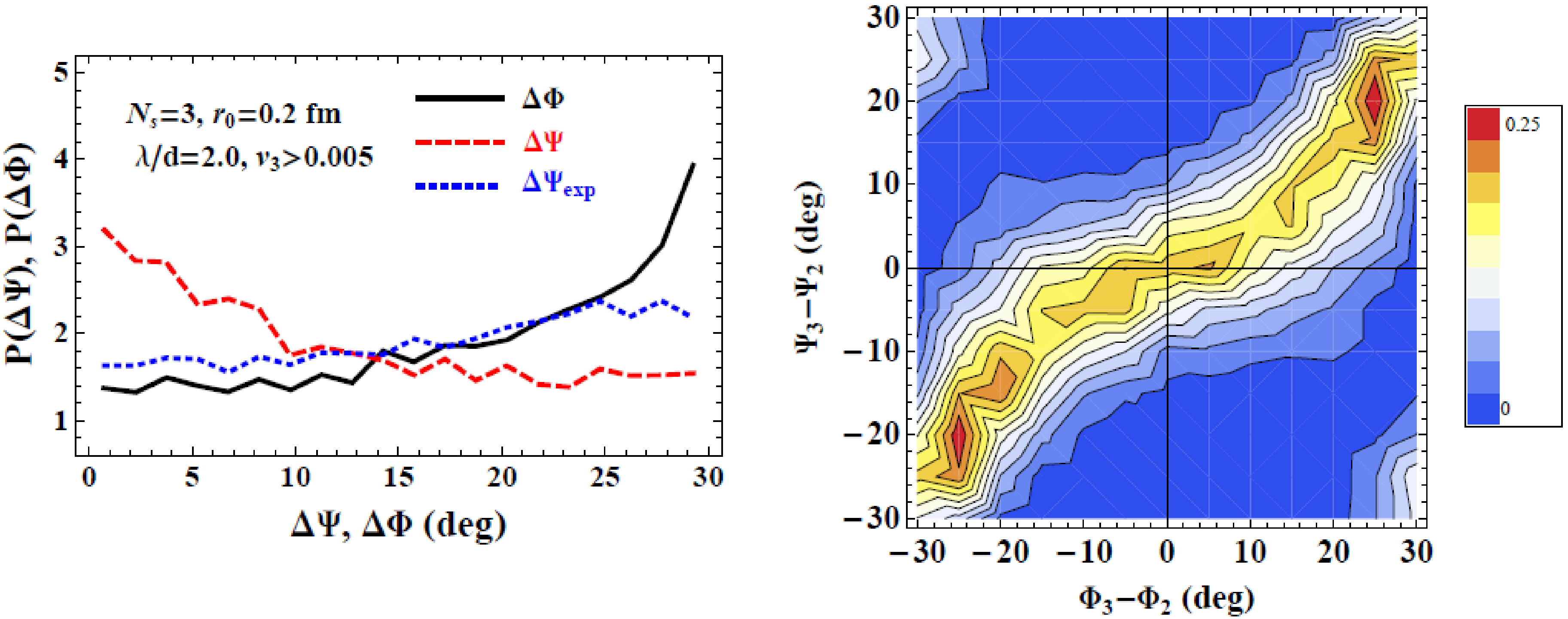
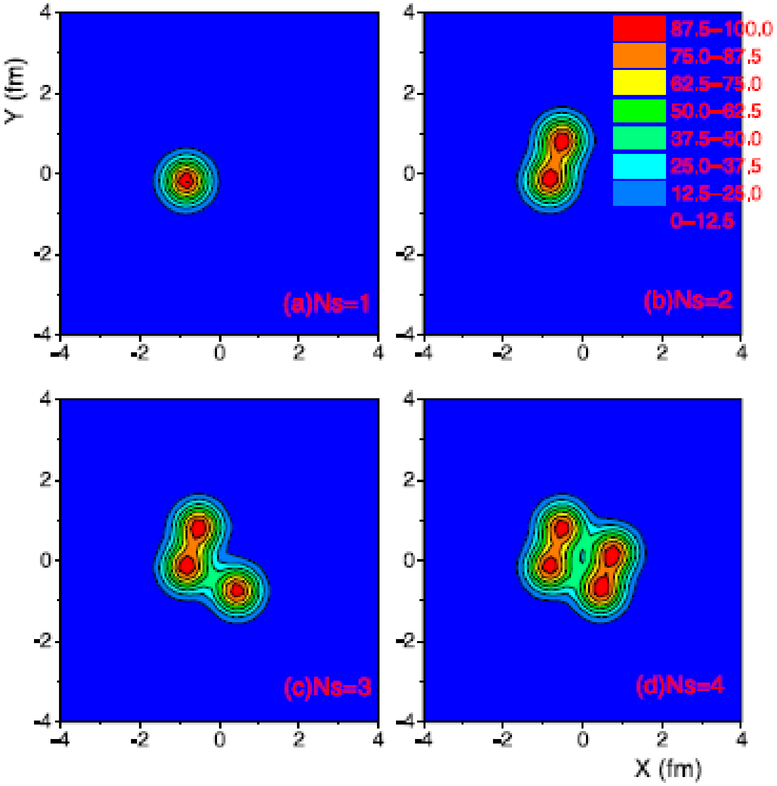


FIG. 7: (Color online) Contour plot $d^2N/d(\Phi_3-\Phi_2)/d(\Psi_3-\Psi_2)$ (arbitrary unit).

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

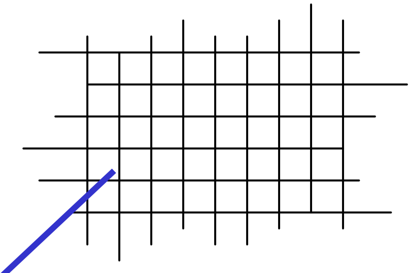
$v_2 \approx 0.16$ for 3 hot spots, even in low multiplicity ($n_{mult} \sim 10$) events

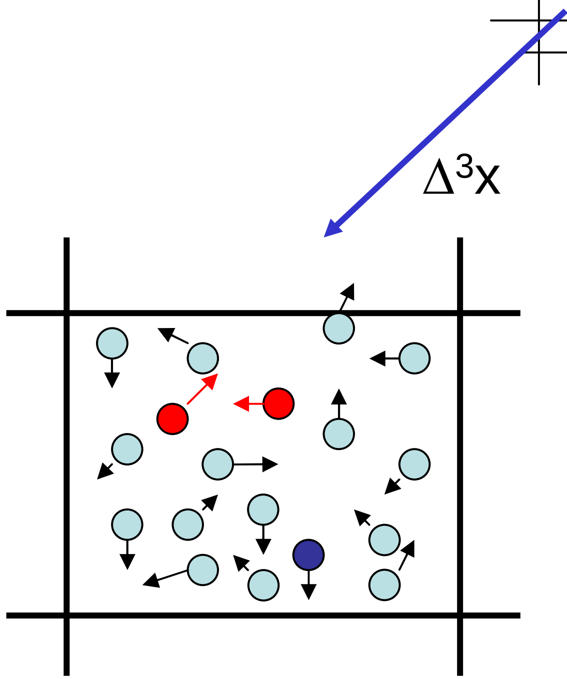
Stochastic algorithm

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

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