Kinematic description of alignment in the Pamir experiment

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I.P. Lokhtin [1], A.V. Nikolskii [2], A.M. Snigirev [1]

1) Skobeltsyn Institute of Nuclear Physics (SINP), Lomonosov Moscow State University, Moscow, Russia ;

2) Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research (JINR), Dubna, Russia

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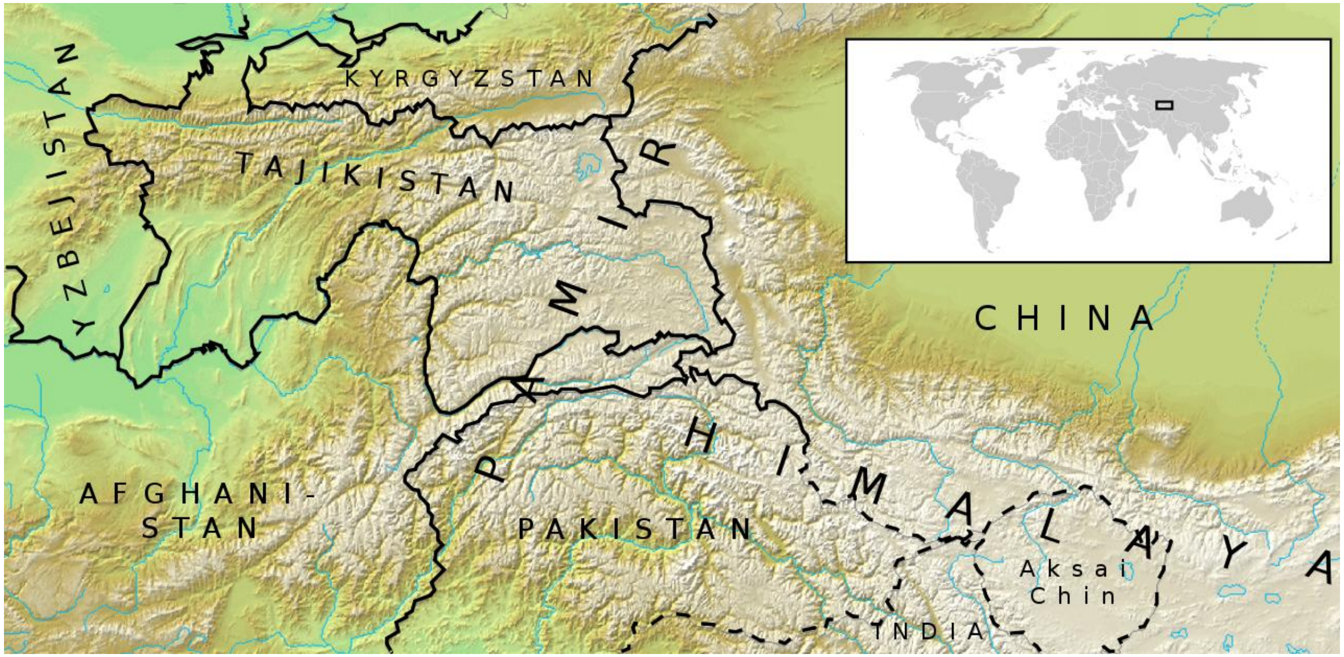
Our motivation / Pamir experiment

Pamir experiment with cosmic rays

- The Pamir Mountains are a mountain range between Central Asia and Pakistan;
- X-ray emulsion chambers at altitude 4400 meters (and above);
- The observed events, families of hadrons and gamma quanta, are initiated by protons with an energy of 10^4 TeV and higher.

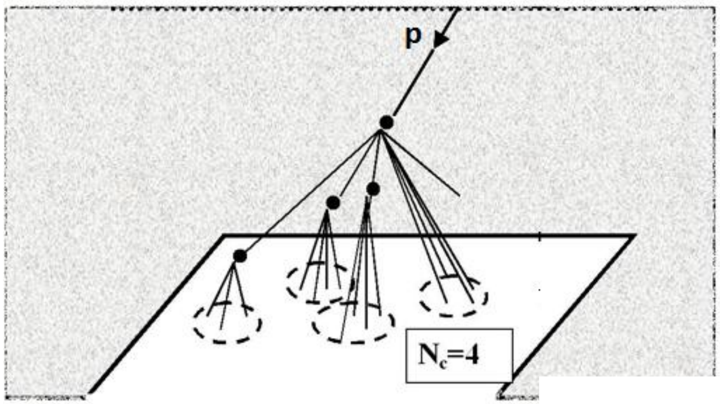


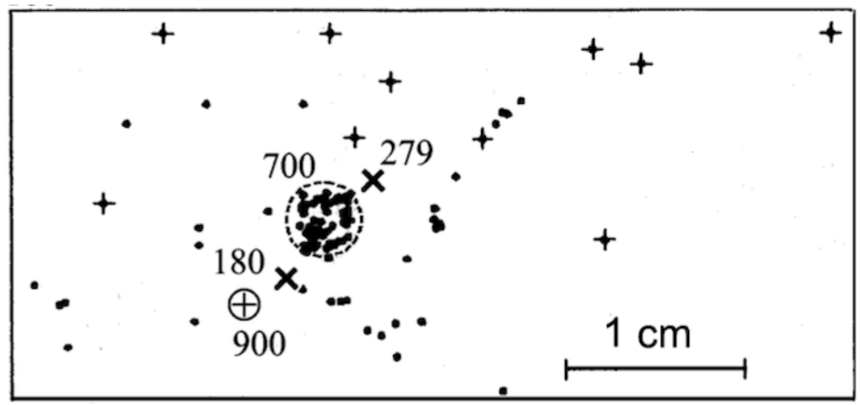
The collaboration «Pamir» included 8 countries: Russia, Japan, Poland, Brazil, Bolivia, Georgia, Uzbekistan and Tajikistan.

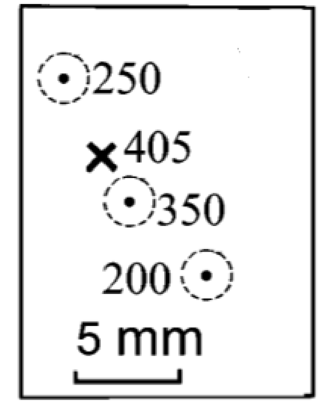
Our motivation / Pamir experiment

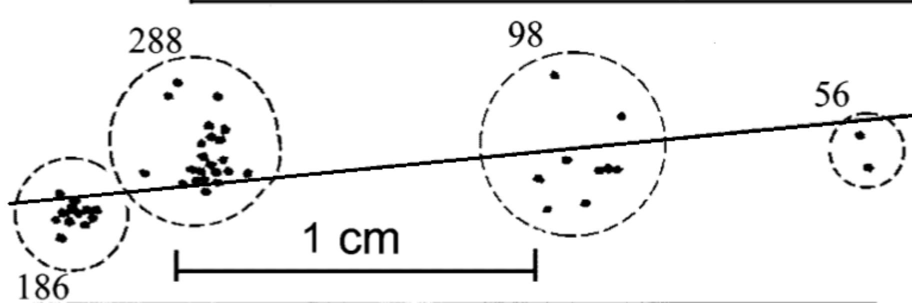
One of the main results of the Pamir experiment is the observation of the «**alignment**» phenomenon.

Alignment demonstrates the deviation of the points (the most energetic cores) from a straight line on the plane of the emulsion film.





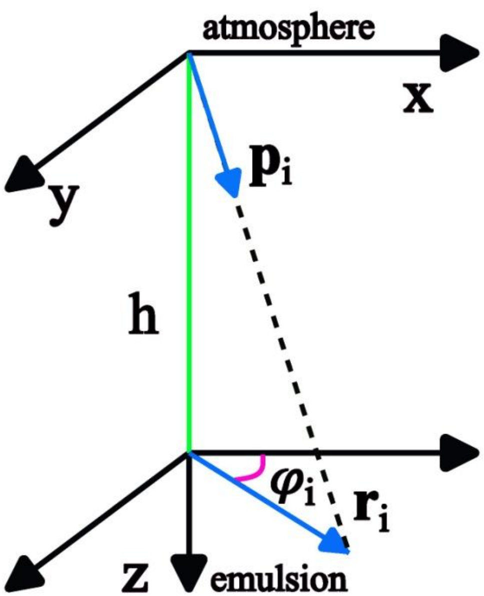




- Pamir Collaboration, A. Borisov et al., in Proceedings of 4th International Symposium on Very High Energy Cosmic Ray Interactions, Beijing, ed. by D. Linkai (1986), p. 4.
- Pamir Collaboration, in Proceedings of the 21st International Cosmic Ray Conference, Adelaide, Australia (1989), ed. By R.J. Protheroe (University of Adelaide, Australia, 1990), p. 227.

Alignment and kinematics

The alignment becomes apparent considerably at $\sum E_\gamma > 0.5$ PeV, that corresponds to interaction energies $\sqrt{s} \geq 4$TeV. **So there is a energetic threshold.**



$$\left(\sqrt{p_{Ti}^2 + m_i^2}\cosh\eta_i,\, p_{Ti}\cos\varphi_i,\, p_{Ti}\sin\varphi_i,\, \sqrt{p_{Ti}^2 + m_i^2}\sinh\eta_i\right) \quad (1)$$

$$\boldsymbol{r}_i = \frac{\boldsymbol{p}_{Ti}}{\sqrt{p_{Ti}^2 + m_i^2}\sinh(\eta_0 + \eta_i)} h, \quad r_{min} < r_i < r_{max} \quad (2)$$

$$d_{ij} = \sqrt{r_i^2 + r_j^2 - 2 r_i r_j \cos(\varphi_i - \varphi_j)}, \quad d_{ij} > r_{min} \quad (3)$$

$$\boldsymbol{r}_{ij} = \left(\boldsymbol{r}_i E_i + \boldsymbol{r}_j E_j\right) / \left(E_i + E_j\right). \quad (4)$$

Among clusters that satisfy the conditions (2), (3) one selects 2,..,7 clusters or particles N which are most energetic. After that one calculates the alignment λ_N using the common definition introduced by A. Borisov*:

$$\boxed{\lambda_N = \sum_{i \neq j \neq k}^{N} \frac{\cos(2\varphi_{ijk})}{N(N-1)(N-2)}.} \quad (5)$$

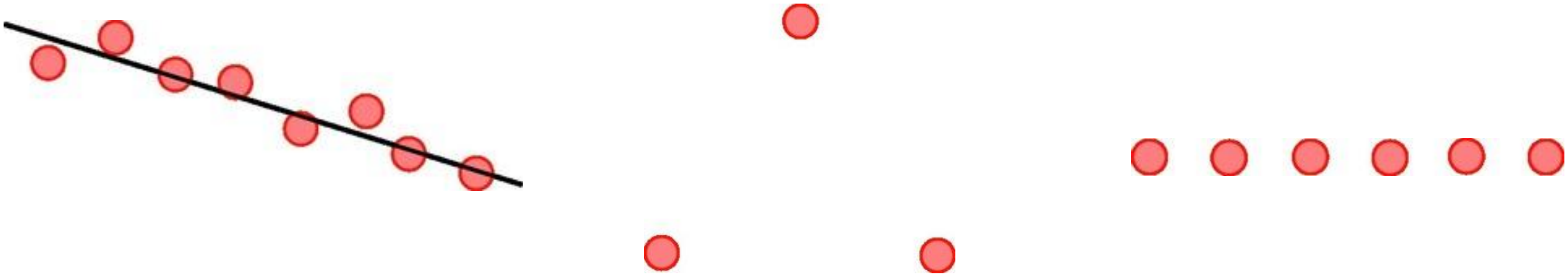
*Pamir Collaboration, L.T. Baradzei et al., Izv. Akad. Nauk, SSSR Ser. Fiz. 50, 2125 (1986)

Alignment

$$\lambda_N = \sum_{i \neq j \neq k}^{N} \frac{\cos(2\varphi_{ijk})}{N(N-1)(N-2)}, \tag{5}$$

here φ_{ijk} is the angle between the two vectors $(\mathbf{r}_\mathrm{k} - \mathbf{r}_\mathrm{j})$ and $(\mathbf{r}_\mathrm{k} - \mathbf{r}_\mathrm{i})$, for the central point $\mathbf{r} = 0$.

This parameter, which changes from $-1/(N-1)$ to 1, characterizes precisely the disposition of N points just along the straight line.



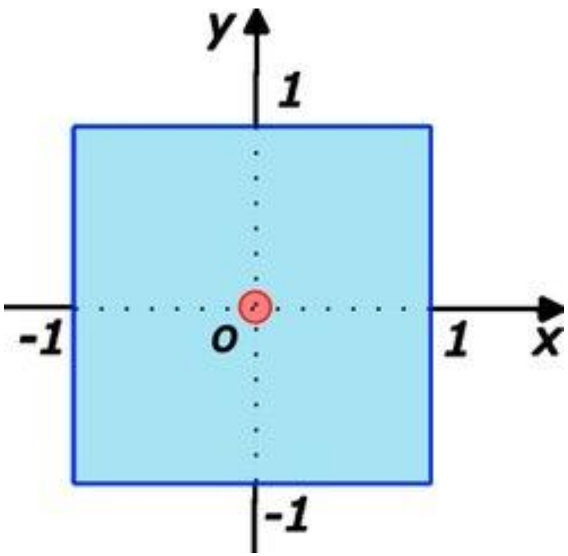
λ_N $\qquad$ $\lambda_3 = -0.5$ $\qquad$ $\lambda_N = 1$

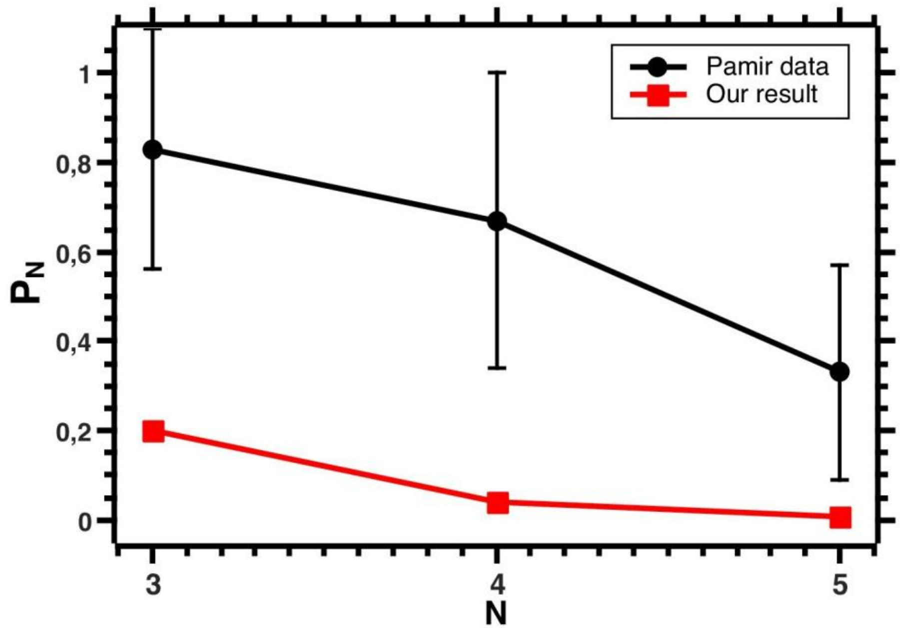
The **degree of alignment P_N** is defined as the fraction of the events for which $\boldsymbol{\lambda_N > 0.8}$ among the total number of events in which the number of cores not less than N.

Our model

Our simulation is based on the Monte Carlo method

- We randomly generate event (2, 3, 4) coordinates on the *(xy)*-plane in a square centered at the origin;
- The coordinates of each event are in the range: x=[-1;1], y=[-1;1]. The central point ***O*** at the origin is fixed;
- We calculate the alignment (the degree of alignment) for the 3, 4, 5 points (2, 3, 4 chaotically located points respectively + central point ***O***).

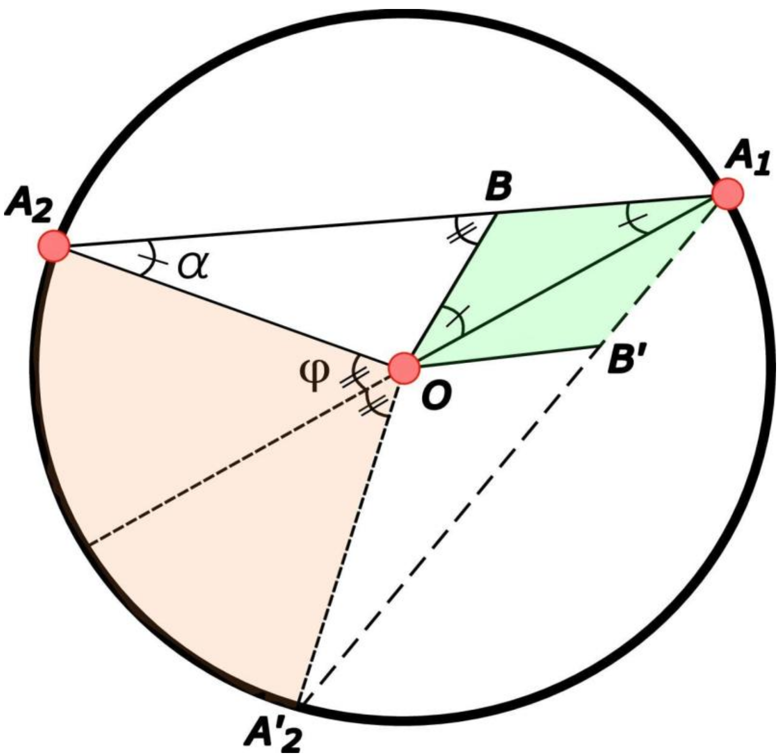




Number of generated events $N_{total}=10^7$. The degree of alignment: P_N= N with $\lambda_N > 0.8$ / N_{total}.

Our model

The degree of alignment of the three points P_3 (the two randomly located points A_1, A_2 and the fixed central point O in an origin) can be estimated from geometric relations.



At small enough angle α the alignment for the three points OA_1A_2 and OA_1B is easily calculated:

$$\lambda(OA_1A_2) = \lambda(OA_1B) \simeq 1 - 4\alpha^2. \tag{6}$$

The minimum value of alignment:

$$\lambda_0 = 1 - \frac{16\alpha^2}{3}. \tag{7}$$

The minimum value of the alignment degree:

$$P_3^{\min}(\lambda_0) \simeq \frac{5\alpha}{2\pi} = \frac{5\sqrt{3}}{2}\frac{\sqrt{1-\lambda_0}}{4\pi}. \tag{8}$$

At $\lambda_0 = 0.8$ one obtains $P_3^{\min}(\lambda_0) \simeq 0.16$ that is **close** to the value of our numerical simulation $P_3 = 0.2$. Also $P_N = P_3^{N-2}$ that is a good agreement with our result.

One more thing for our model

Now we examine how the additional kinematic restrictions, imitating the experimental one in some sense, influence on the degree of alignment.

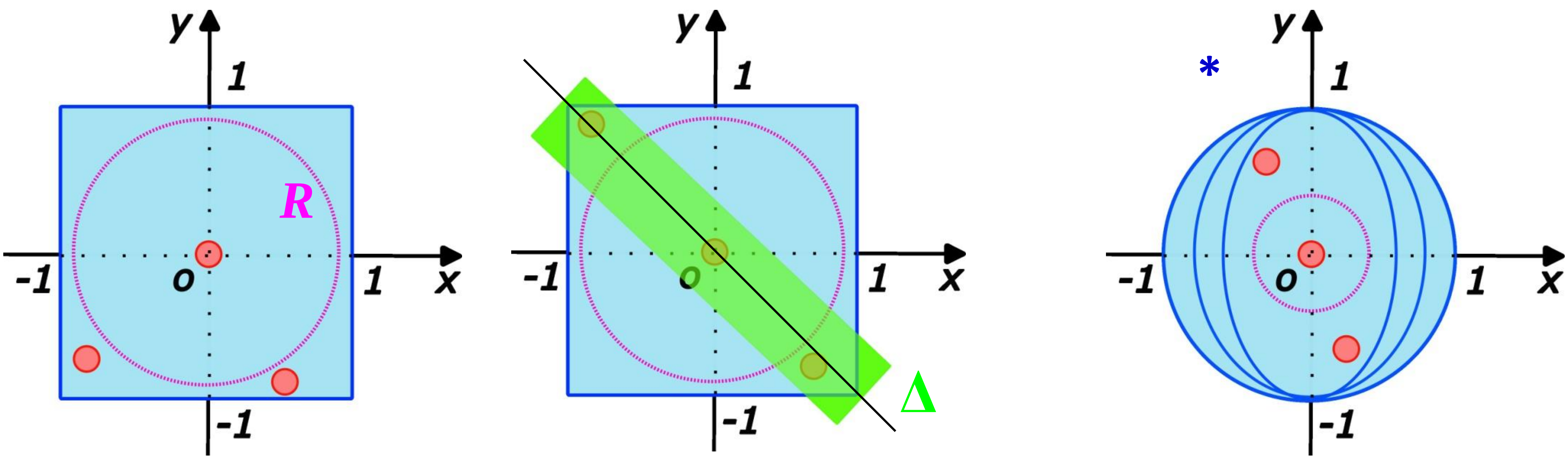
1) **Energetic threshold** $\boldsymbol{R}$ for the detected particles

$$|\boldsymbol{r}_1| + |\boldsymbol{r}_2| + \cdots + |\boldsymbol{r}_{N-1}| > (N-1)\,\boldsymbol{R}.$$

2) **Missing transverse momentum** Δ for the detected particles

$$|\boldsymbol{r}_1 + \boldsymbol{r}_2 + \cdots + \boldsymbol{r}_{N-1}| < \Delta\,.$$

* Also generation of the events in a square → in an ellipse with different $\boldsymbol{e}$

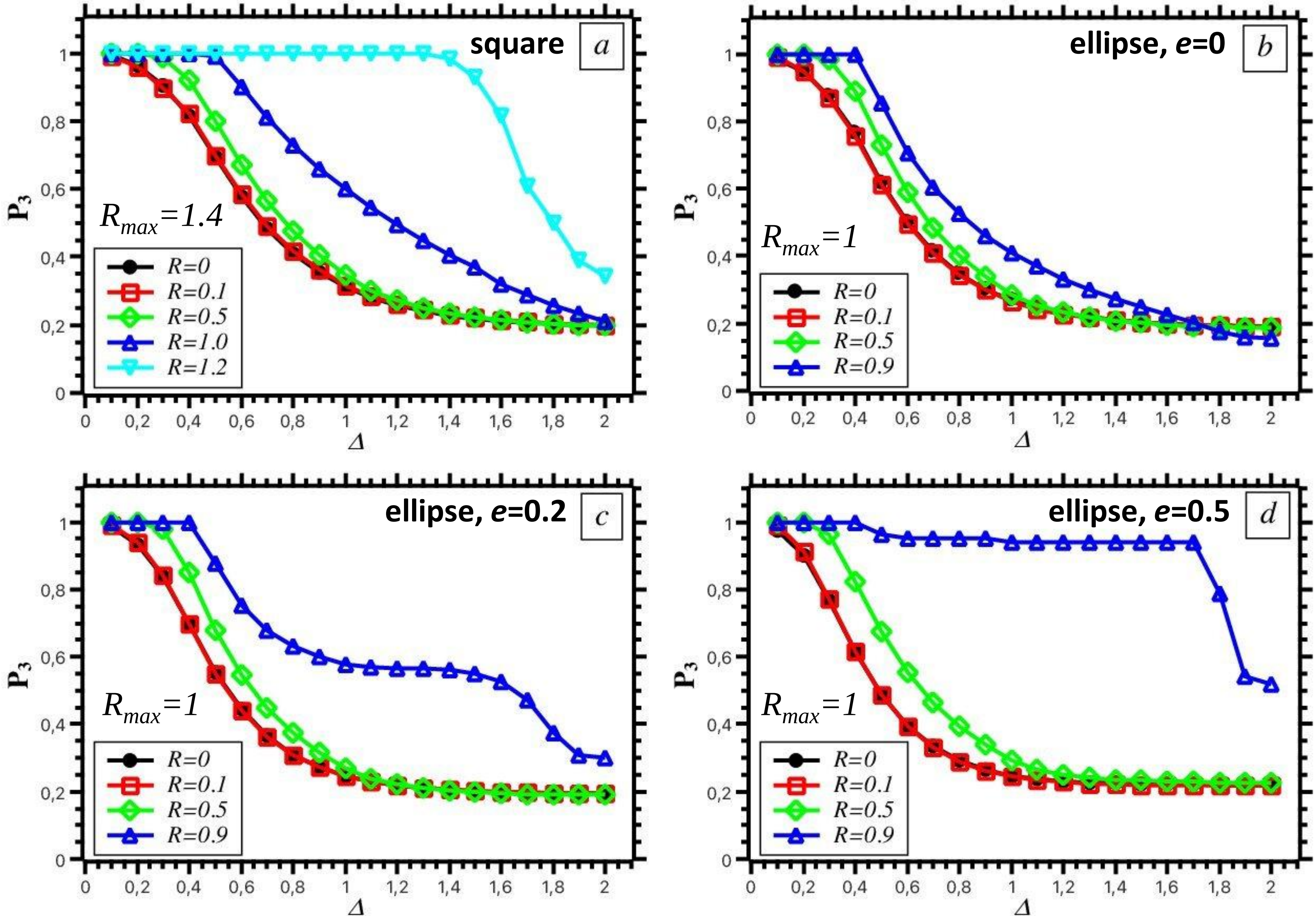


1)

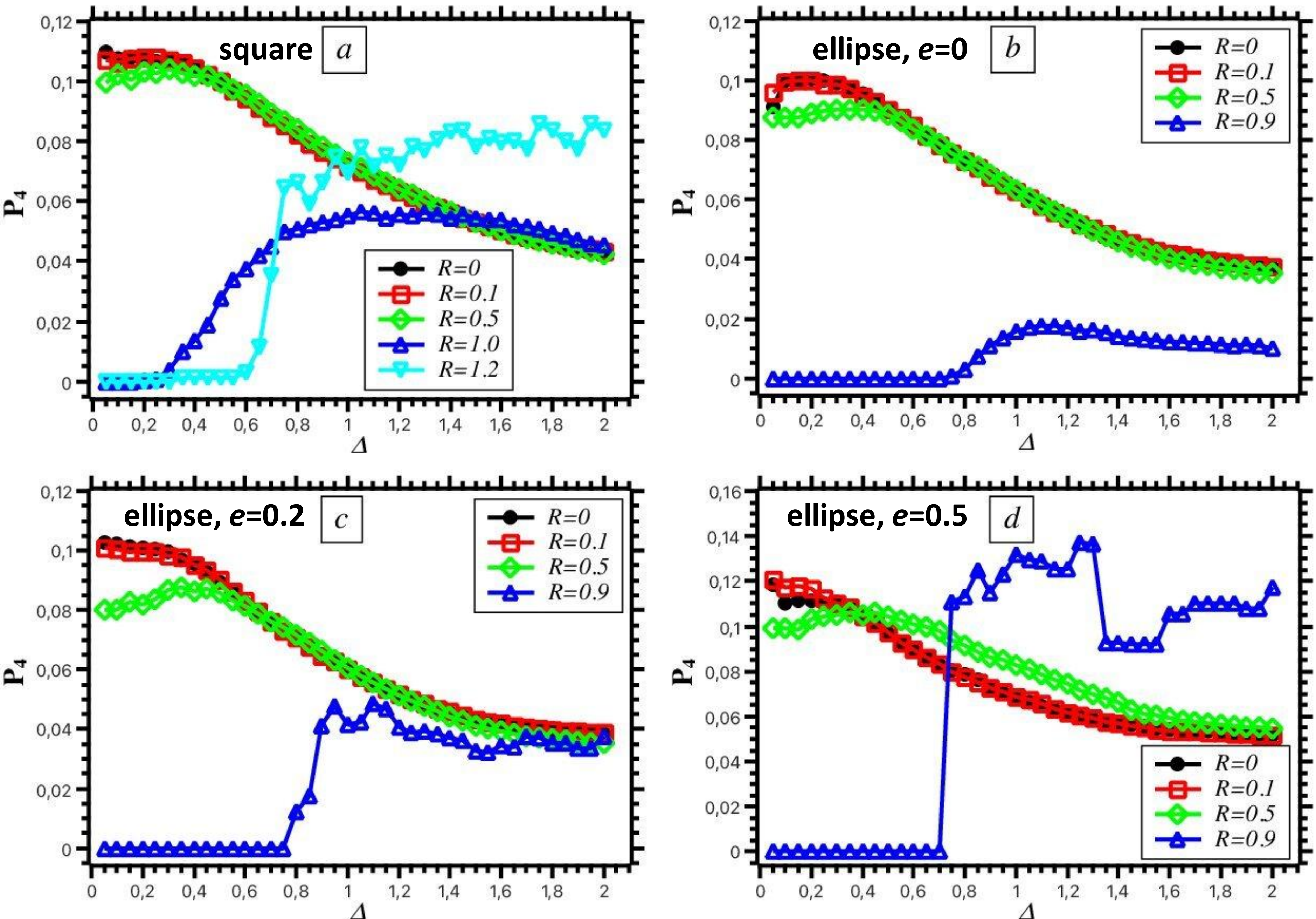
1) + 2)

We expect:
High P_N → large R small Δ

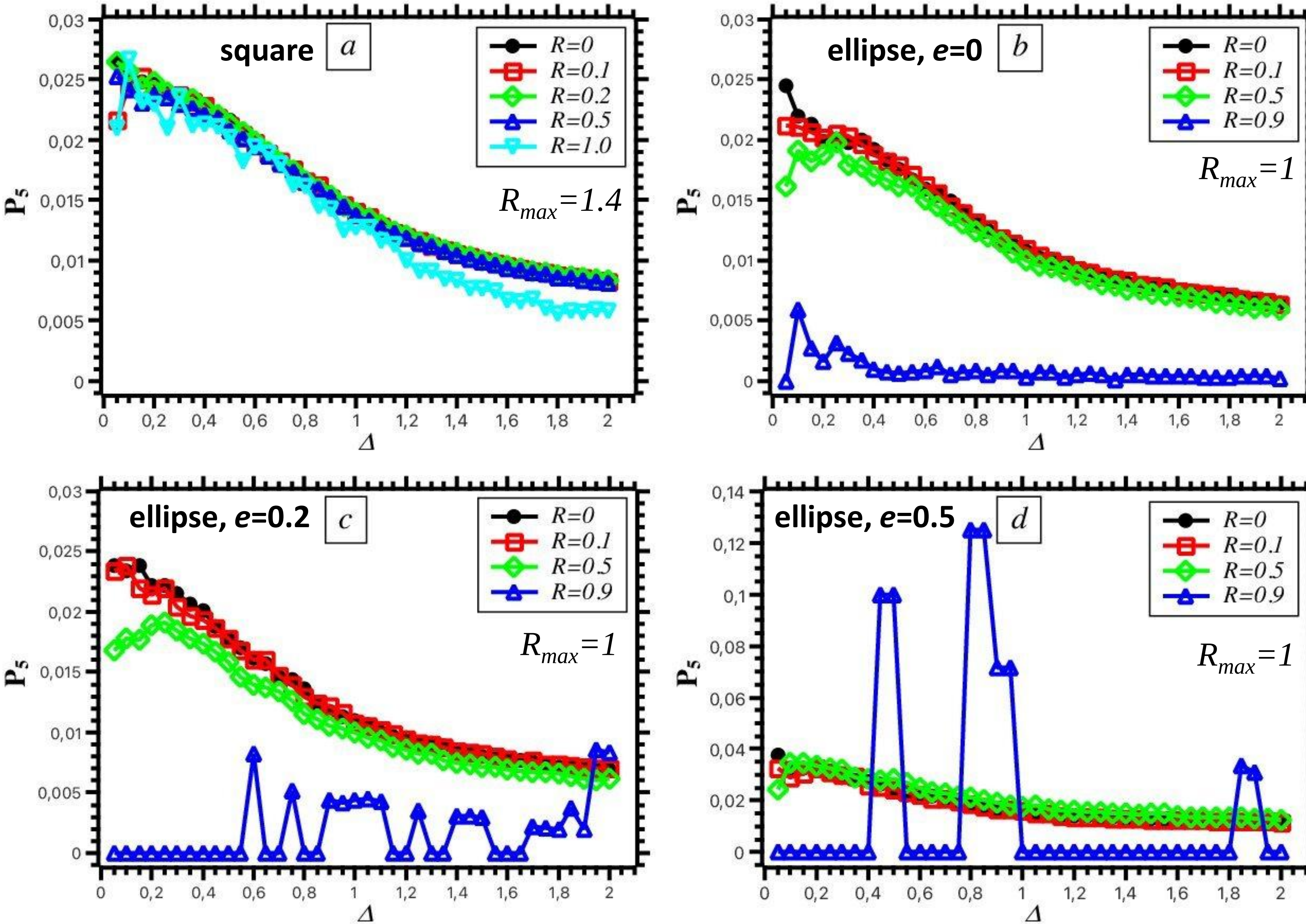
Results for the three points. $P_3(\Delta)$



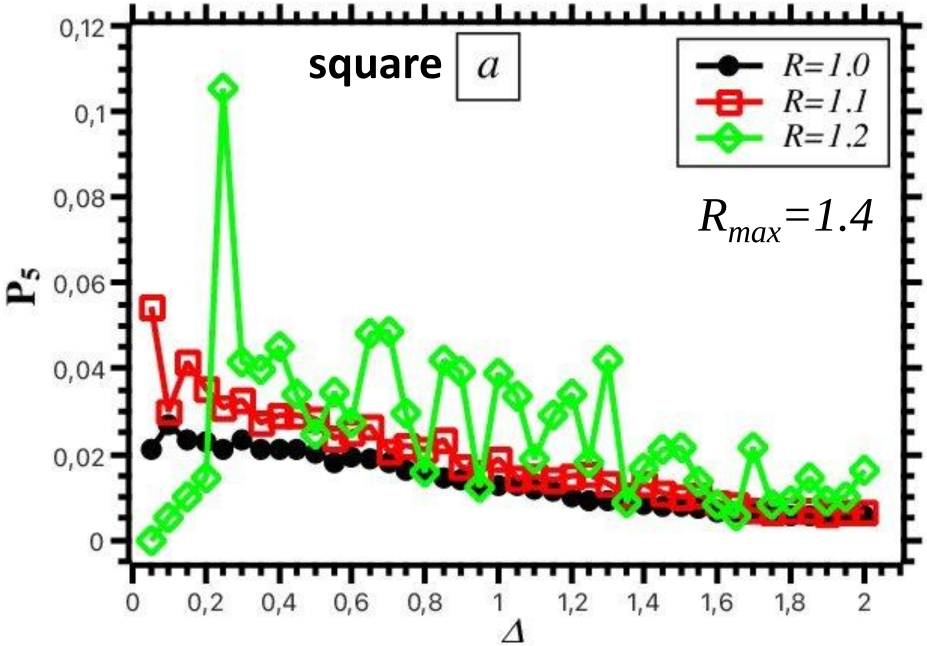
Results for the four points. $P_4(\Delta)$

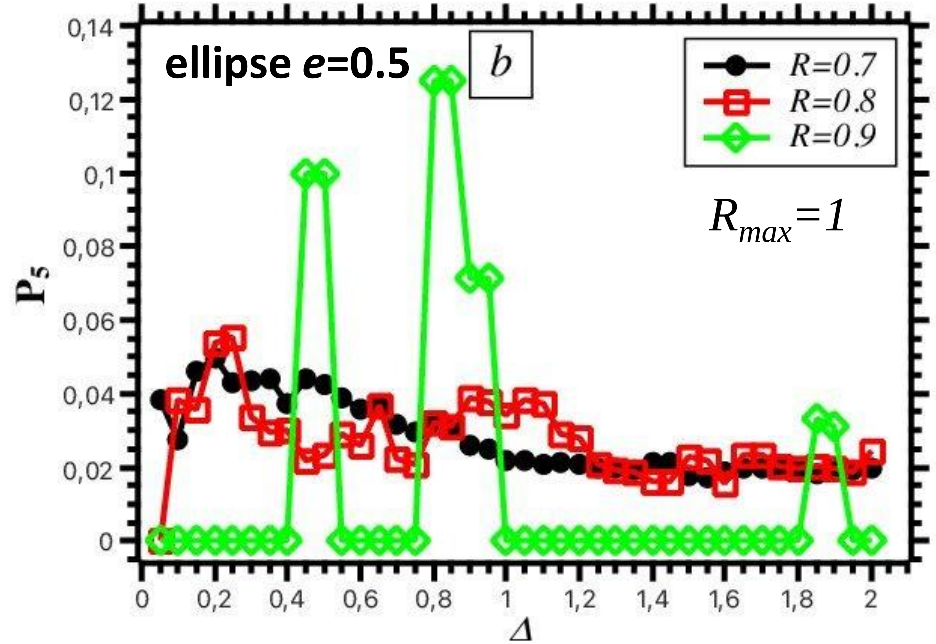


Results for the five points. $P_5(\Delta)$



Results for the five points. $P_5(\Delta)$



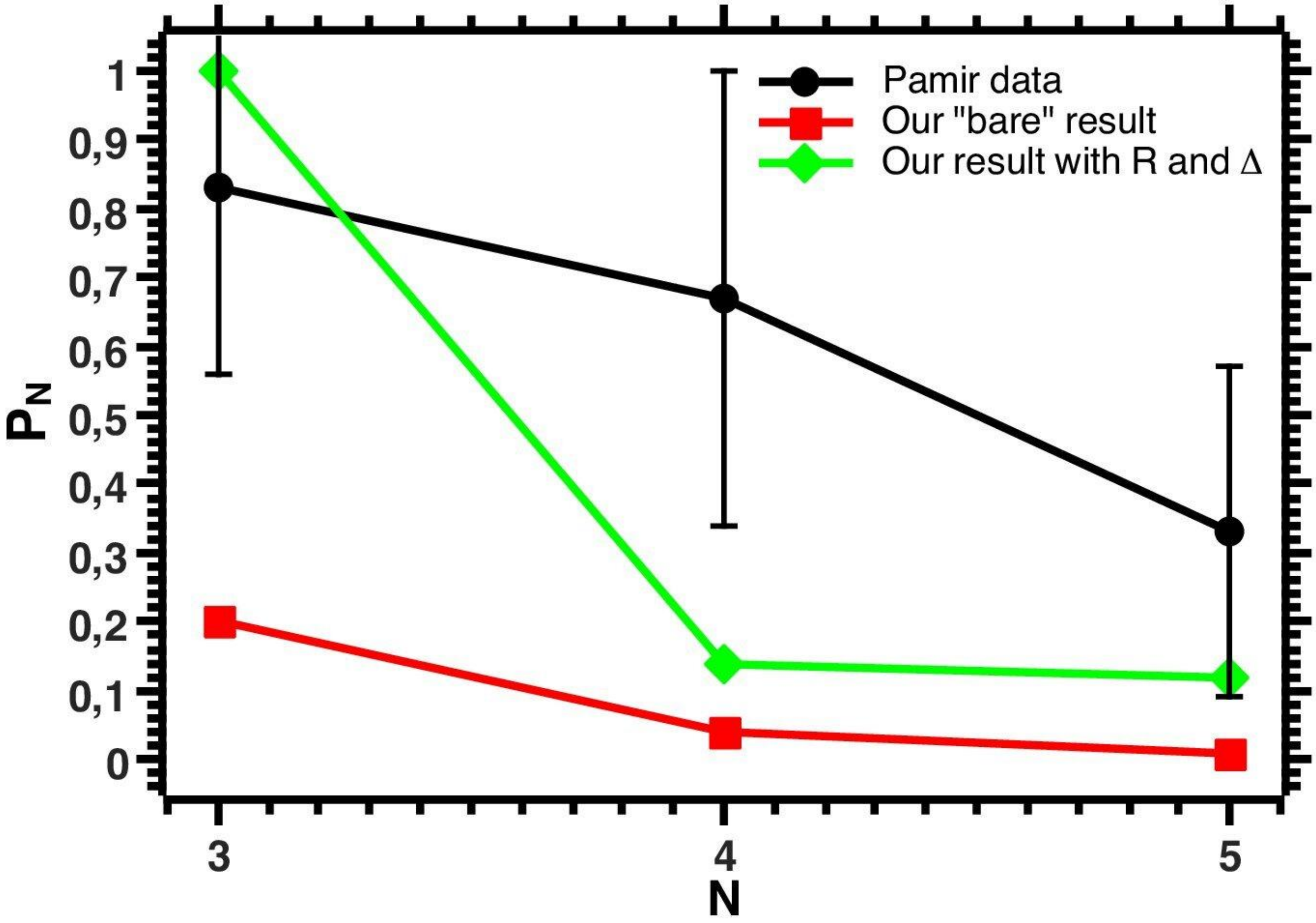


The energetic threshold ***R*** has the **azimuthal symmetry** (circle), but the region in which the events are generated have **other types of the symmetry** (ellipse and square).

The degree of alignment P_N is sensitive to the region form at R close to the maximum possible value R_{max}.

The boundary effect leads to the fluctuations in P_N, which are especially pronounced for five points.

Comparison our result with Pamir data



The degree of alignment for the three, four, five points.

Conclusions

- We have developed a geometric–kinematic model of alignment phenomenon, which was observed in the Pamir experiment;
- Model demonstrates that the high degree of alignment can appear due to the selection procedure of most energetic particles itself and the threshold on the energy deposition (***R***) together with the transverse momentum conservation;
- The effect of the conservation law of transverse momentum imitates over the disbalance of the total radius-vector (Δ) or missing transverse momentum;

- For the three points, we obtain 100% alignment in a wide range of the disbalance of the transverse momentum for the detected particles;
- For the four and five points, model is not enough to describe the central values of the alignment degree in the Pamir experiment;
- Our modeling is independent of the absolute size scale of the region, but is sensitive to its form and boundary, which leads to fluctuations, especially for five points.

Possible ways to improve our model

- To add the anisotropy of particle flow for non-central collisions, for example, the using HYDJET++ event generator.

Thanks for your attention !