Azimuthal alignment of high-energy particles in relativistic ion collisions

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Our motivation / Pamir experiment

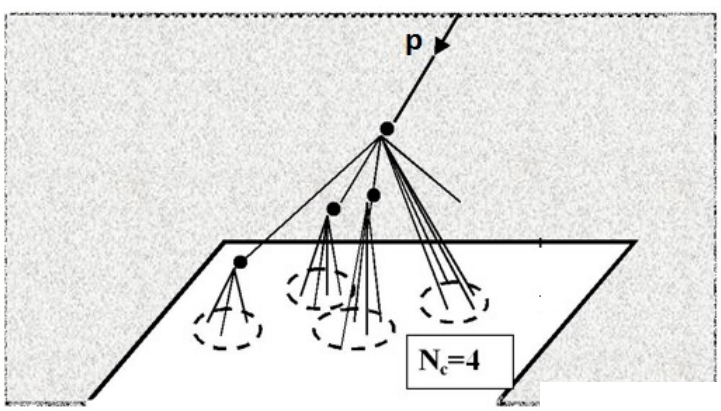
Pamir experiment with cosmic rays

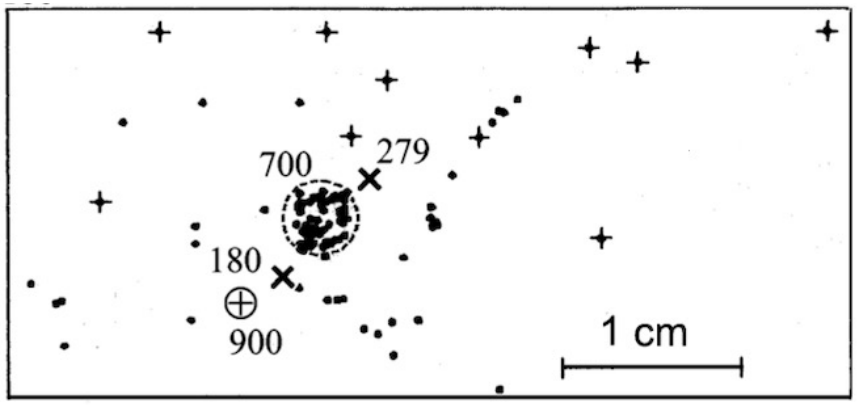
- The Pamir Mountains are a mountain range between Central Asia and Pakistan;
- X-ray emulsion chambers were used at altitude 4400 meters (and above);
- The observed events – families of hadrons and gamma quanta, are initiated by protons with an energy of 10 PeV and higher.

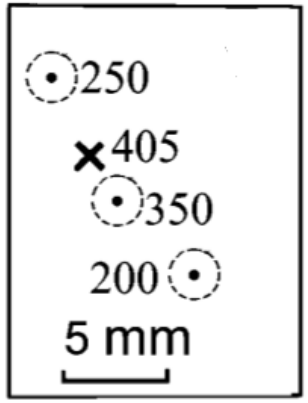
- The collaboration «Pamir» included 8 countries: Russia, Japan, Poland, Brazil, Bolivia, Georgia, Uzbekistan and Tajikistan.

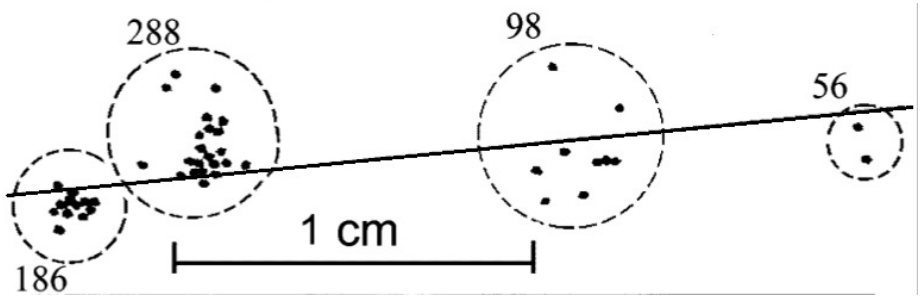
Our motivation / Pamir experiment

- One of the main results of the Pamir experiment is the observation of the «**alignment**» phenomenon.
- Alignment is the **angular feature** and demonstrates the deviation of the points (the most energetic particles) from a straight line on the plane of the emulsion film.





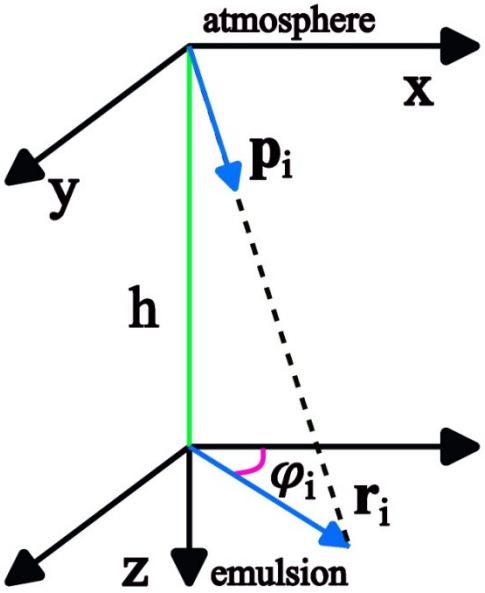




- Pamir Collaboration, A. Borisov et al., in Proceedings of 4th International Symposium on Very High Energy Cosmic Ray Interactions, Beijing, ed. by D. Linkai (1986), p. 4.
- Pamir Collaboration, in Proceedings of the 21st International Cosmic Ray Conference, Adelaide, Australia (1989), ed. By R.J. Protheroe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

Definition of alignment and kinematics

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



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

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

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

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

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*:

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

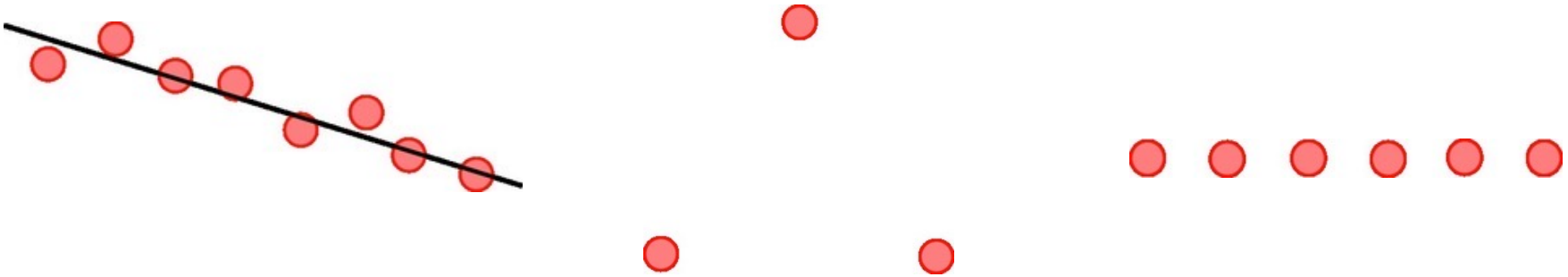
*Pamir Collaboration, L.T. Baradzei et al., Izv. Akad. Nauk, SSSR Ser. Fiz. 50, 2125 (1986)

Definition of alignment

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

here β_{ijk} is the angle between the two vectors $(\mathbf{r}_k - \mathbf{r}_j)$ and $(\mathbf{r}_k - \mathbf{r}_i)$, for the central point $\mathbf{r} = 0$.

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



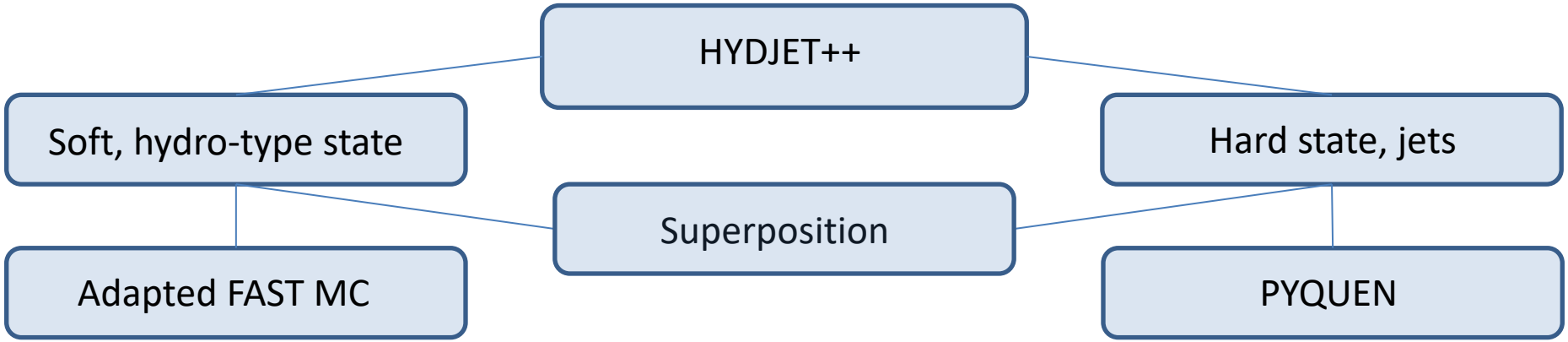
λ_N $\lambda_3 = -0.5$ $\lambda_N = 1$

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

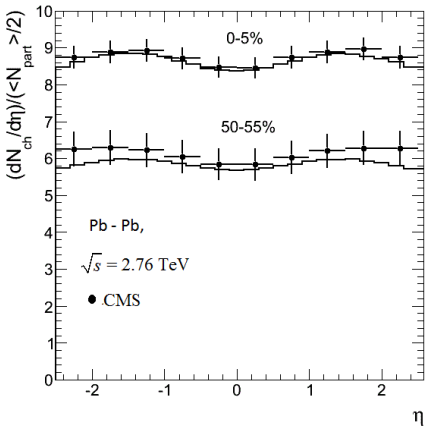
HYDJET++ model

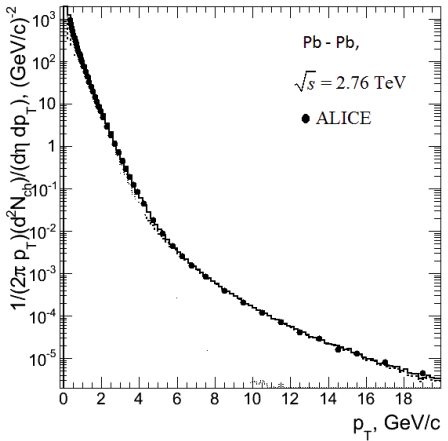
- HYDJET++ (HYDrodynamics plus JETs)* – Monte Carlo generator of events, relativistic heavy ion collisions, based on the superposition of the soft hydrodynamic and hard jet components of the nuclear reaction.

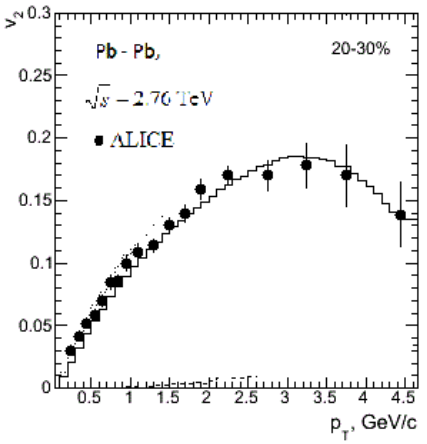
* *I.P. Lokhtin et al.. Comp. Phys. Commun. 180 (2009) 779*



- The HJ model successfully describes the large number of physical observables measured in heavy ion collisions during RHIC and LHC operations.



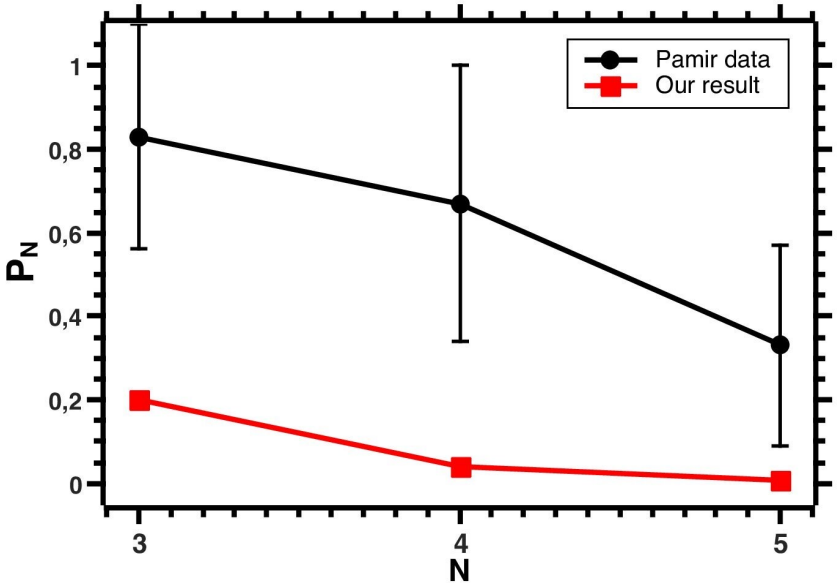




Simulation of alignment in HYDJET++ model

The modeling of alignment in the framework of the HYDJET++ model includes following steps:

- Three to five (N = 3..,5) of the **most energetic particles** (or their clusters) in every event are selected;
- The position of this selected particles in the "film" is calculated according to the expression (2);
- The alignment λ_N is calculated by the definition (5) for the highest-energy particles (one of this particles is fixed in the origin);



- The **alignment degree** of events $\mathbf{P_N}$ is found among the total number of events:

$$\mathbf{P_N} = \mathrm{N}^{\mathrm{ev}}[\lambda_{\mathrm{N}} > 0.8] / \mathrm{N}^{\mathrm{ev}}_{\mathrm{total}}, \quad (\mathrm{N}^{\mathrm{ev}}_{\mathrm{total}} = 10^5).$$

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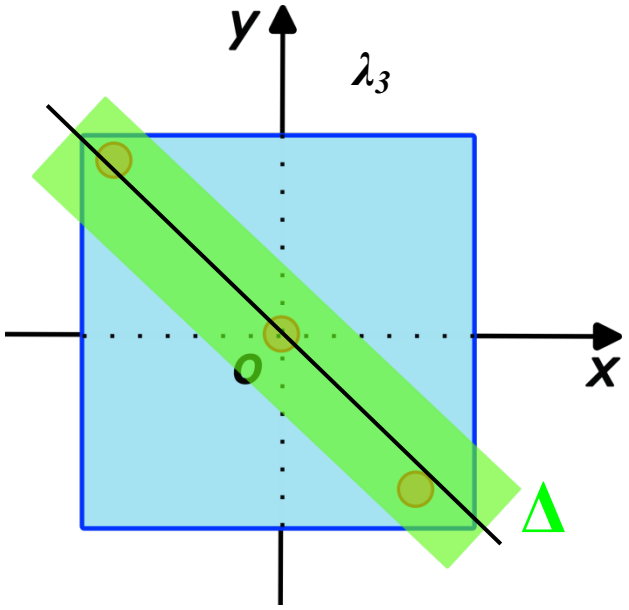
One more thing for our simulation

To add the new kinematic rule – the transverse momentum conservation in every event

$$\left|\mathbf{p}_{T_1} + \mathbf{p}_{T_2} + \cdots + \mathbf{p}_{T_{N-1}}\right| < \Delta ,$$

in the form of "missing" transverse momentum. Δ – the disbalance of conservation. Formally, the effect of the disbalance can be illustrated as



We expect high λ_N → at small Δ and vice versa small λ_N → high Δ.

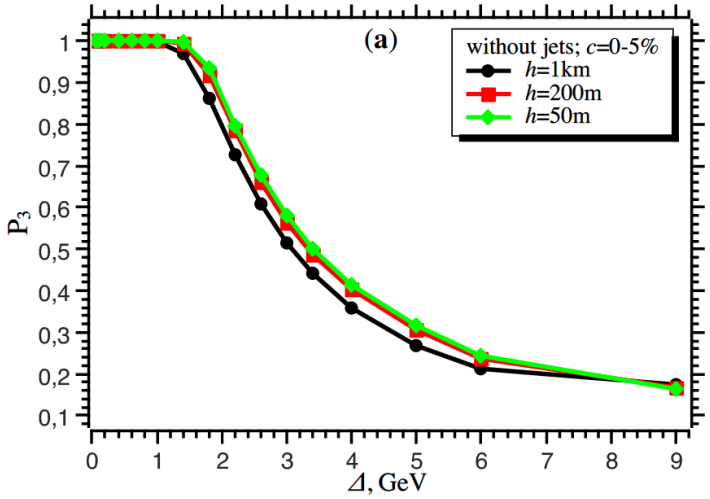
In the HJ model there is a "natural" threshold on collision energy due to QGP hadronization. Energy threshold (0.5 PeV, exp. Pamir) is characteristic of alignment observation.

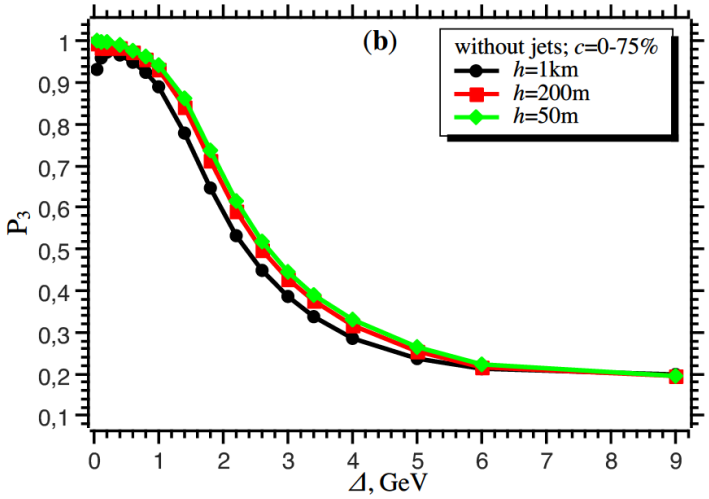
In the HJ model the transverse momentum conservation is performed only in average, for the rapidity interval. **With Δ we take into account event-by-event $\mathbf{p}_T$ conservation**.

Simulation results for the three particles. $P_3(\Delta)$

Pb - Pb,

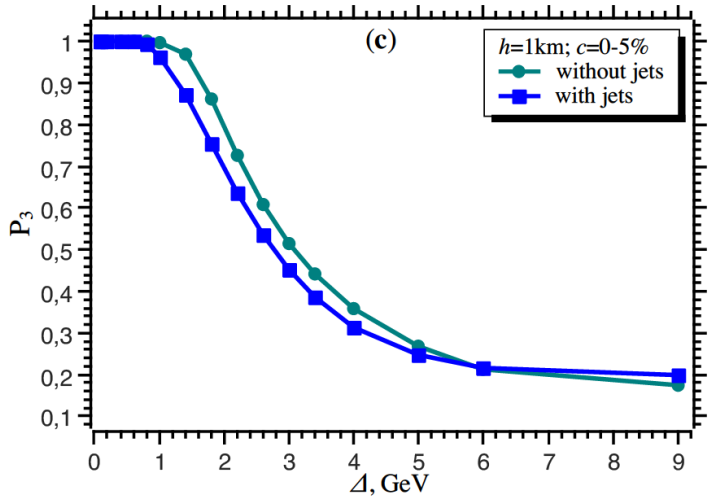
$\sqrt{s} = 5.02\,\mathrm{TeV}.$





N = 3,
one particle at the origin and two selected highest-energy particles.

Our hypothesis is fully confirmed:
high λ_N → at small Δ.

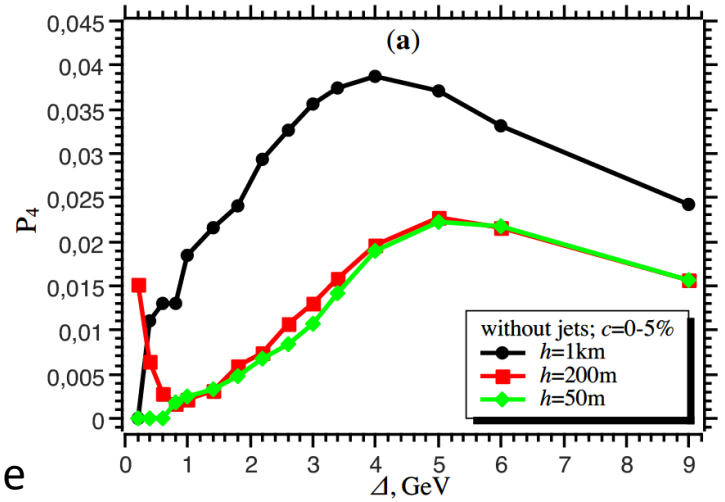


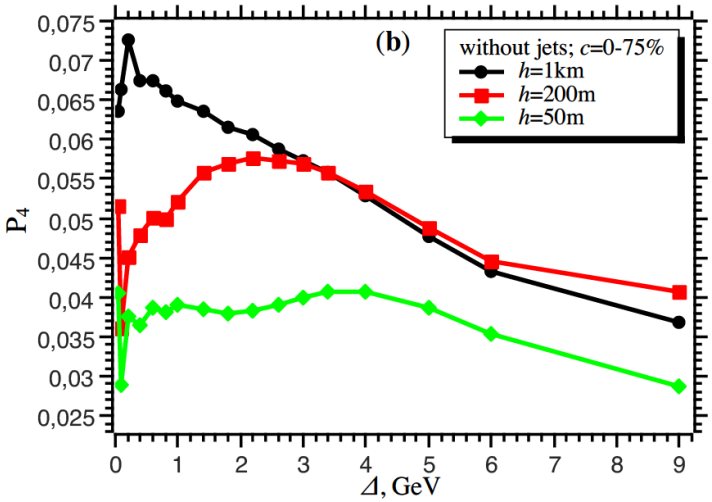
(a) – the results in the centrality class c=0-5%, (b) – c=0-75% for only soft particles at different *h*, (c) – comparing results for the only soft particles with soft + jet mechanism.

Simulation results for the four particles. $P_4(\Delta)$

Pb - Pb,

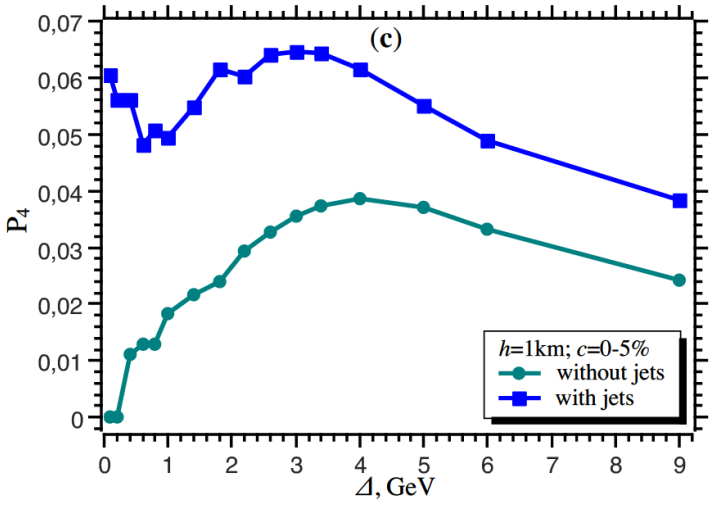
$\sqrt{s} = 5.02\,\mathrm{TeV}.$





N = 4,

(a), (c) - the effect of the odd quantity particles in P_4 are clearly seen:
small Δ is not achievable for 3 selected highest-energy particles and 1 particle at the origin.



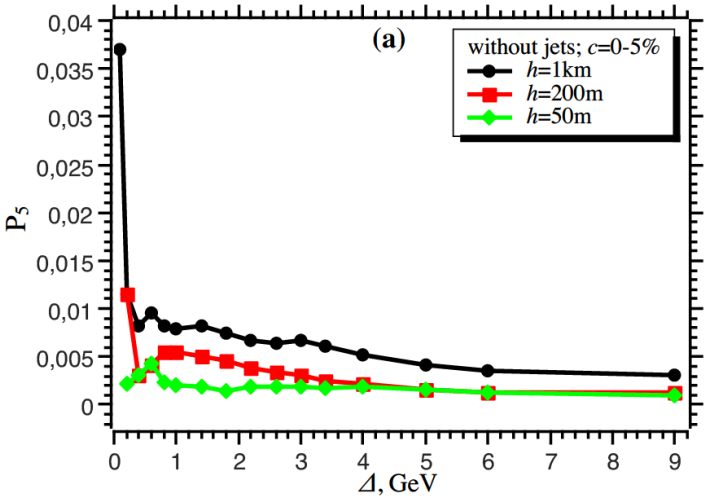
(b) - the p_T of one selected particle enhanced of anisotropic flow are equal the p_T of two other selected highest-energy particles.

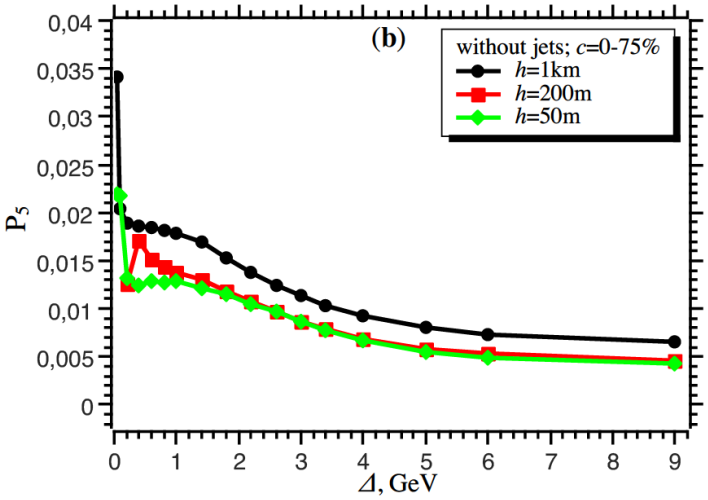
(a) – the results in the centrality class c=0-5%, (b) – c=0-75% for only soft particles at different *h*,
(c) – comparing results for the only soft particles with soft + jet mechanism.

Simulation results for the five particles. $P_5(\Delta)$

Pb - Pb,

$\sqrt{s} = 5.02\,\mathrm{TeV}.$

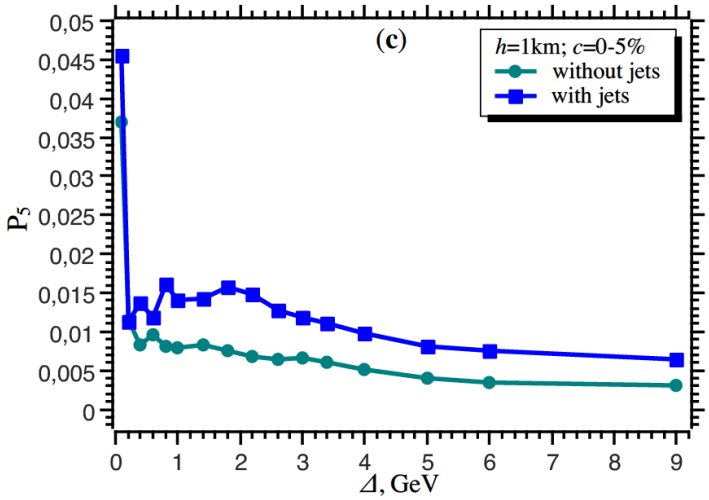




N = 5,
one particle at the origin and
four selected highest-energy particles.

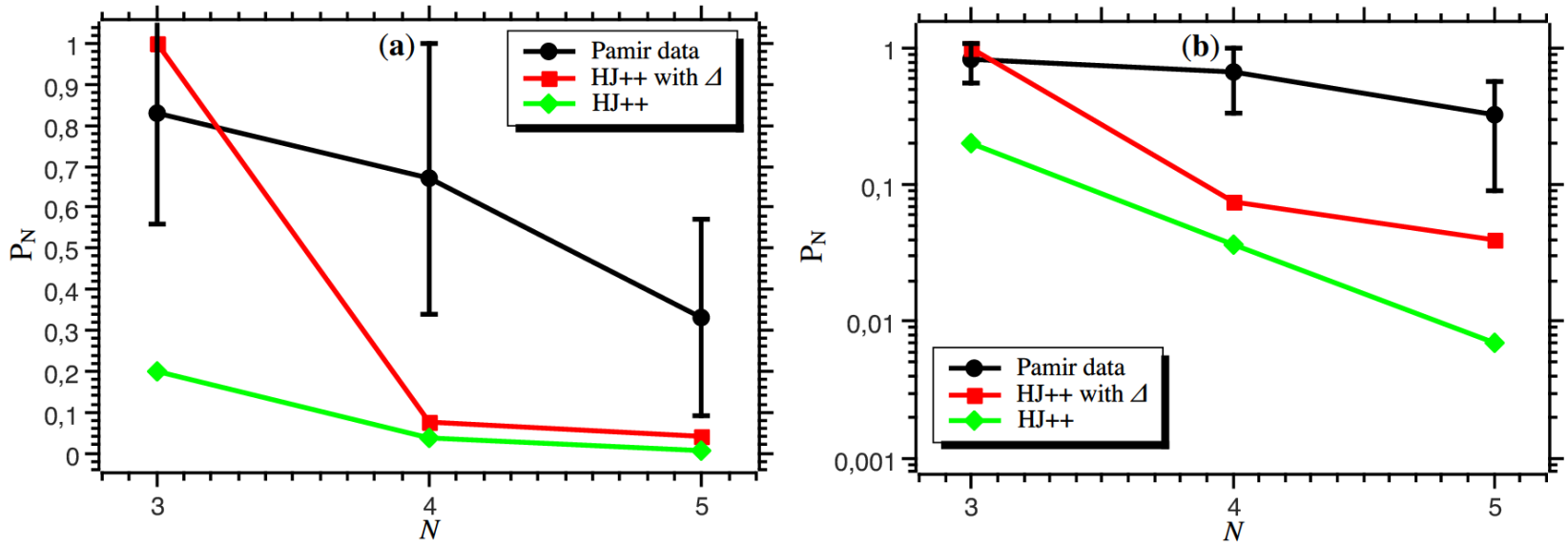
A moderately high $\lambda_N \rightarrow$ at small Δ.

P_N are **increased at factor 5** in comparison with result of without event-by-event p_T conservation.



(a) – the results in the centrality class c=0-5%, (b) – c=0-75% for only soft particles at different *h*,
(c) – comparing results for the only soft particles with soft + jet mechanism.

Comparison our result with Pamir data



A comparison of the simulation results of the alignment degree P_N for three, four, five particles with the data of the Pamir collaboration.

(a) – linear scale, (b) – logarithmic scale. “HJ++ with Δ” – the modeling with the local transverse momentum conservation via disbalance Δ; “HJ++” – the modeling without p_T conservation in every event.

The values of the disbalance Δ, which correspond to the our “best” alignment degree, are in the range of $\Delta = 0 \div 1$ GeV.

arXiv: 2406.06114[hep-ph], EPJ A 61 3, 50 (2025)

Hot Off the Press: NEWEST RESULTS – Clusterization effect

- Previously, we considered detected particles as clusters, **by default**.

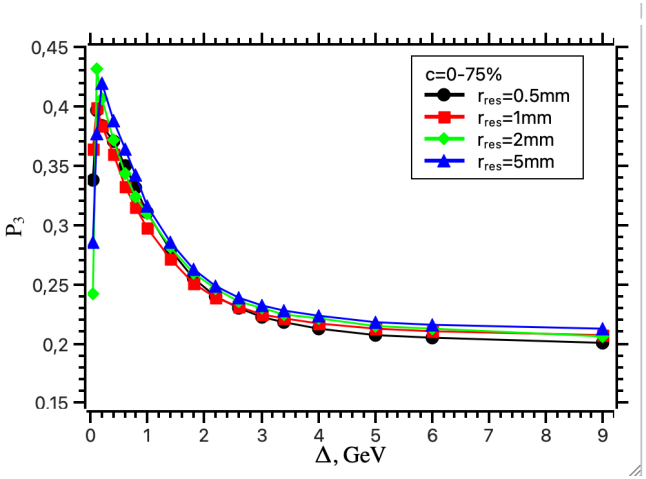
- We did not fix their "size" or the distance between them – only condition was that particles did not merge with the center ***O*** within a 1mm radius.

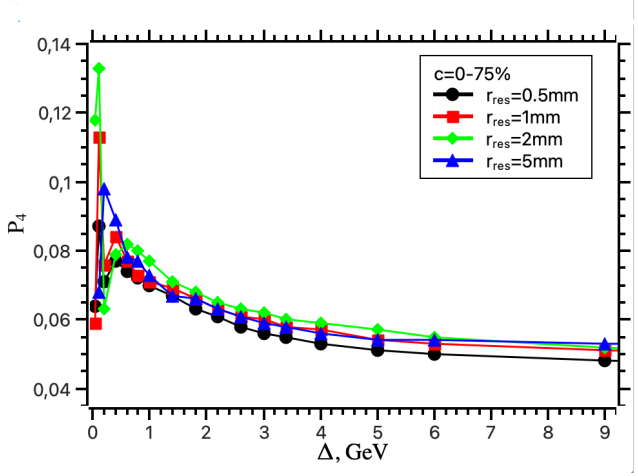
- Now, we calculate the distance $\mathbf{d_{ij}}$ between particles, and if it is below a given threshold $\mathbf{r_{res}}$ – the particles are **merged into a cluster** with updated coordinates, Eqs. (2) – (4) in Slide 4.

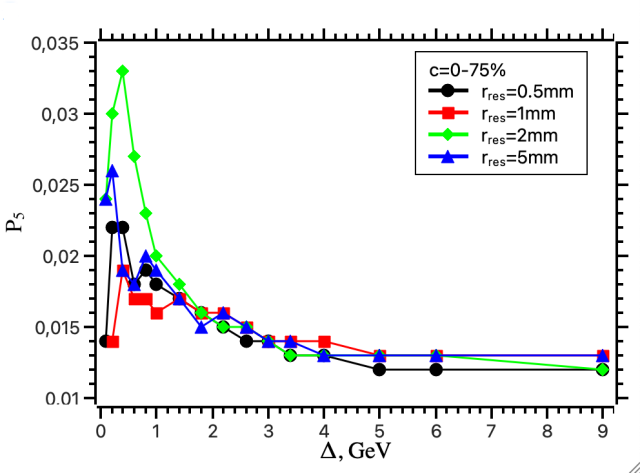
- This clustering procedure is **repeated** until all particles either form clusters or remain as separate ones – that is, only particles and clusters satisfying the condition $\mathbf{d_{ij} > r_{res}}$ remain.

- Let's now see how this affects the alignment.

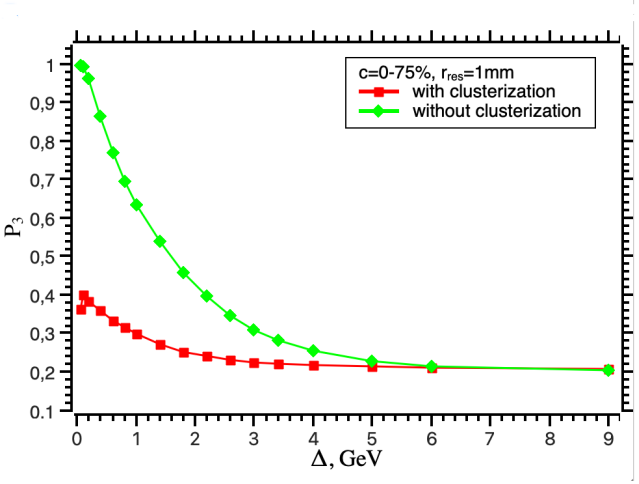
Hot Off the Press: NEWEST RESULTS – Clusterization effect

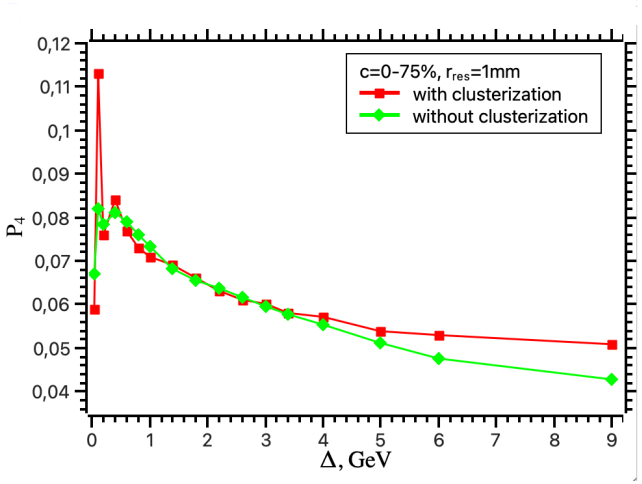


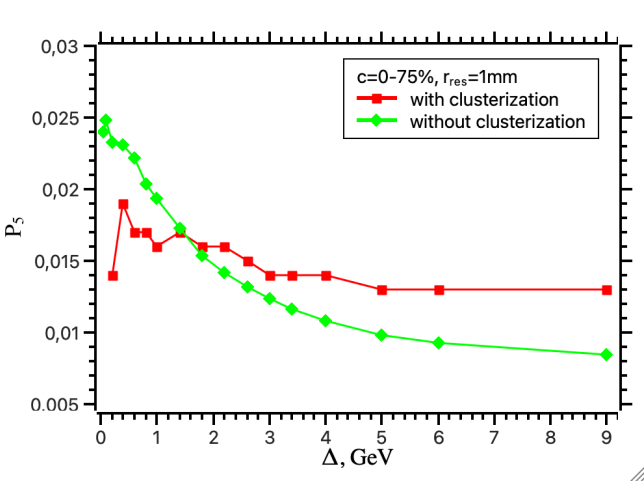




$P_3(\Delta)$, $P_4(\Delta)$, $P_5(\Delta)$ at different rres. c=0-75%, h=1km. Soft + jets generation.







Comparison $P_3(\Delta)$, $P_4(\Delta)$, $P_5(\Delta)$ with and without clusterization for c=0-75%.

Conclusions

- A simulation of the alignment phenomenon within the framework of the HYDJET++ model is made;
- It is shown that high alignment can be a consequence of the most energetic particles selection and the event-by-event transverse momentum conservation;
- The local p_T conservation has been taken into account in the form of minimization of missing transverse momentum Δ;

- For the three points, we obtain 100% alignment in a range of the $\Delta = 0 \div 1$ GeV;
- For the four and five points, we do not reproduce the experimental values of the Pamir experiment, but the values P_4 and P_5 increases by a factor 2 and 5 respectively due to p_T conservation in every event;

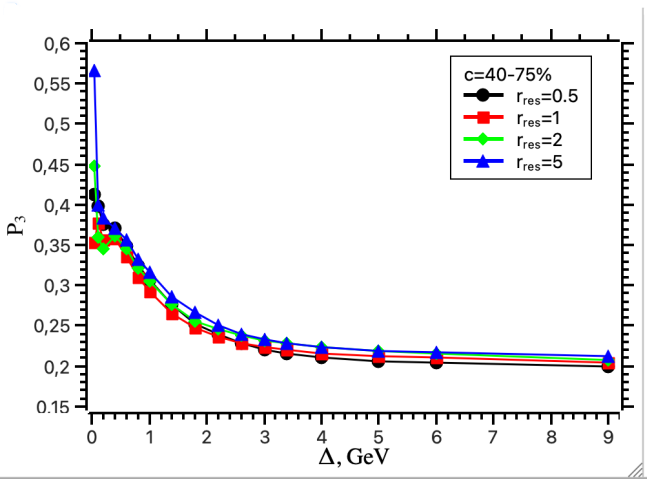
Outlook

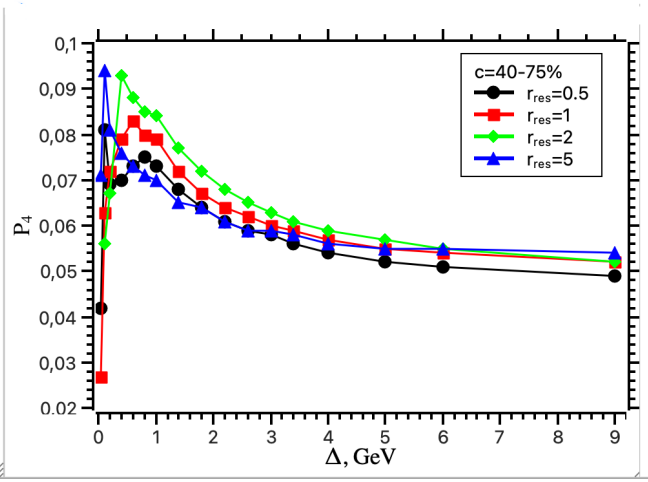
- Consider the clusterization of particles to enhance (?) an alignment.

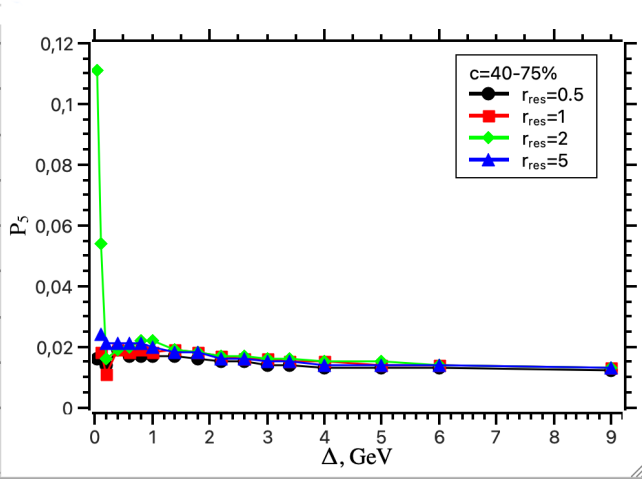
This work is supported by the Russian Science Foundation, grant 24-22-00011.

Thanks for your attention !

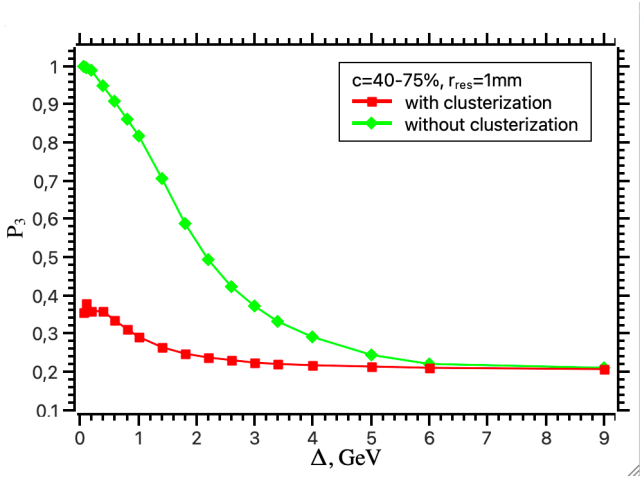
Backup: NEWEST RESULTS – Clusterization effect

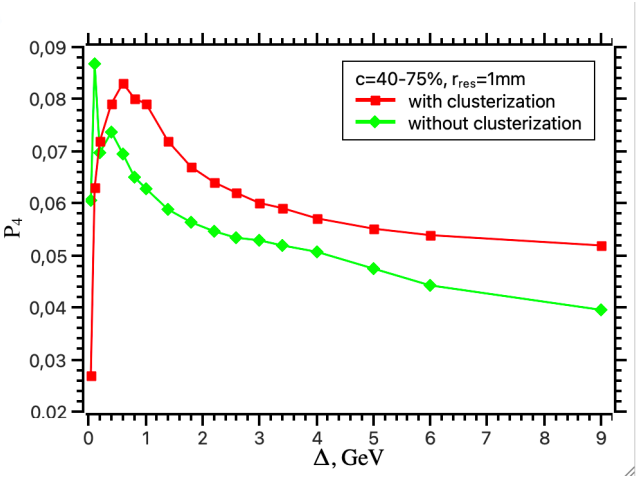


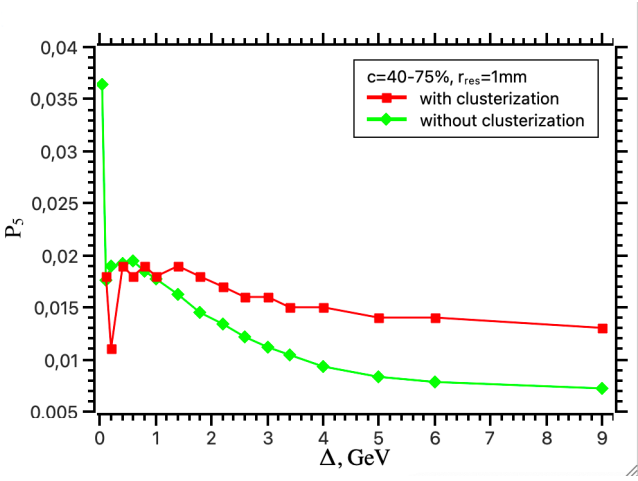




$P_3(\Delta)$, $P_4(\Delta)$, $P_5(\Delta)$ at different rres. c=40-75%, h=1km. Soft + jets generation.







Comparison $P_3(\Delta)$, $P_4(\Delta)$, $P_5(\Delta)$ with and without clusterization for c=40-75%.