Search for aligned muons recorded by the underground LVD experiment

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Contents

Archived data on atmospheric muon bundles recorded in the Large Volume Detector (LVD, LNGS) during the operation of the facility's tracking system were analyzed to search for aligned events—events with azimuthal asymmetry.

The reconstructed muon bundles contain information about the angles and multiplicity of tracks within an event. A new parameter for muon track alignment is proposed. It is calculated using the root-mean-square deviations of track point coordinates relative to the perpendiculars to the principal axes of the ellipse describing this set of points.

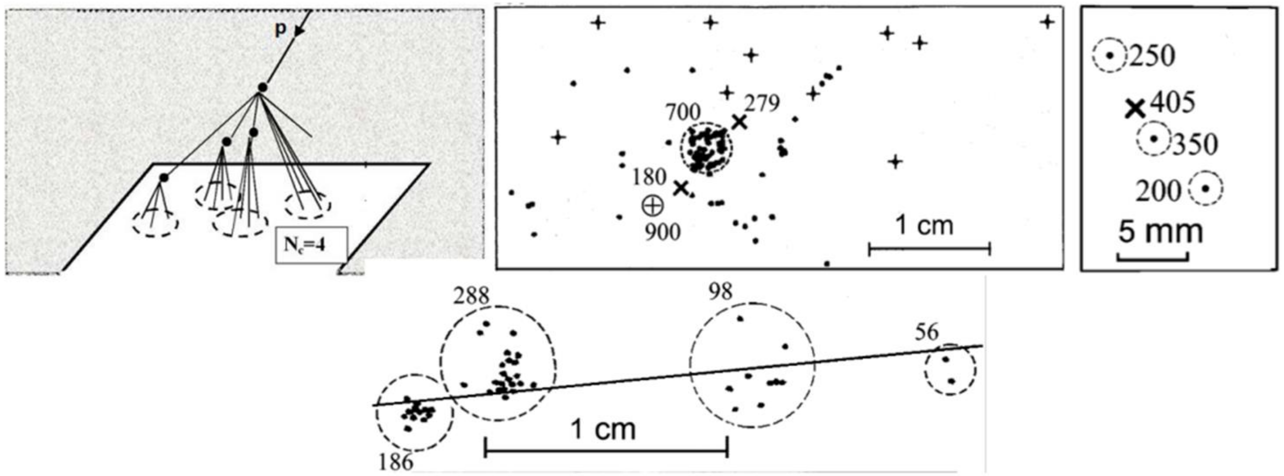
A comparison of the experimental data with statistical Monte Carlo simulations is provided, taking into account the distribution of distances between pairs of muons in a bundle.

Motivation

High-energy muons are produced in extensive air showers (EAS) at high altitudes and carry information about the **transverse momenta of secondary particles**, which influence the spatial **distribution and** multiplicity **spectrum of muons**, which is important for the composition of PCRs.

An interesting phenomenon is observed in the "knee" region: **the alignment of clusters** of adjacent or isolated high-energy particles, which has been detected in gamma-hadron families in emulsion plate chambers at energies >700 TeV.

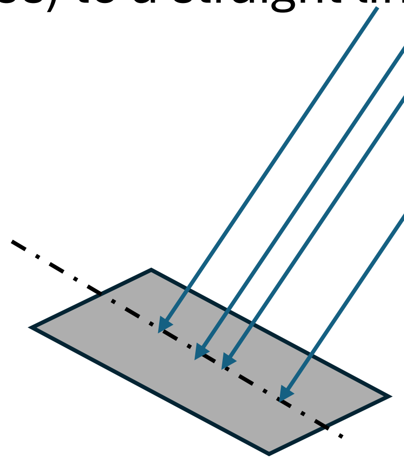
It looks like the particles are arranged along a straight line.



- In 1975, the emulsion stratospheric experiment (**Strana**) detected a gamma-hadron family >10^{16} eV from pure nuclear interactions.
- In the **Pamir** experiment (1984), aligned γ-families with energies >500 TeV were found in lead-emulsion chambers.
- The **Echos** experiments (1978, 1993) on **Concorde** (~17 km) found strange events, including one with E=1586 TeV (~10^4 TeV).
- In **Pierre-Auger**, a violation of the axial symmetry of muons was observed for inclined showers.
- **MACRO** and **BUST** found no significant aligned muon events above background, confirming the standard models.

Aligned parameters

In gamma-hadron cosmic ray families, **the "alignment"** of event points (energetically released centers) **characterizes** the degree of their gravitational attraction (closeness) to a straight line.

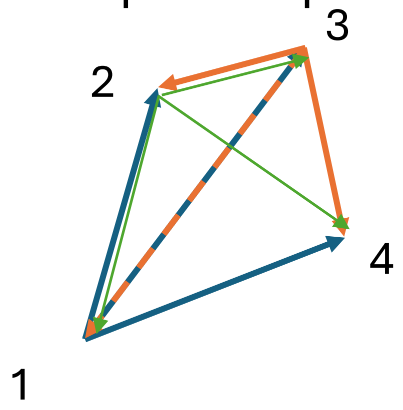


A plane perpendicular to the angle of particles arrival

The parameter λ_N, introduced by A.S. Borisov, is commonly used as a criterion for event alignment.

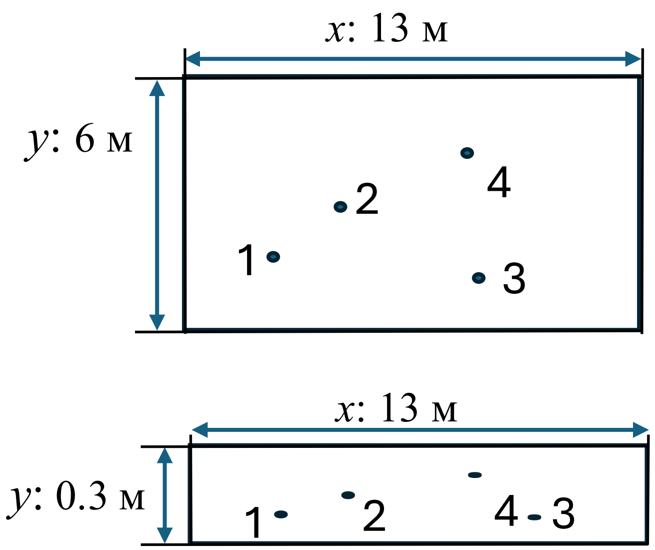
The parameter λ_N, used to determine the alignment of *N* points, includes the cosine of the double angle between the vectors emanating from the k-th point to the i-th and j-th points, as well as the number of such combinations of point triplets in the event:

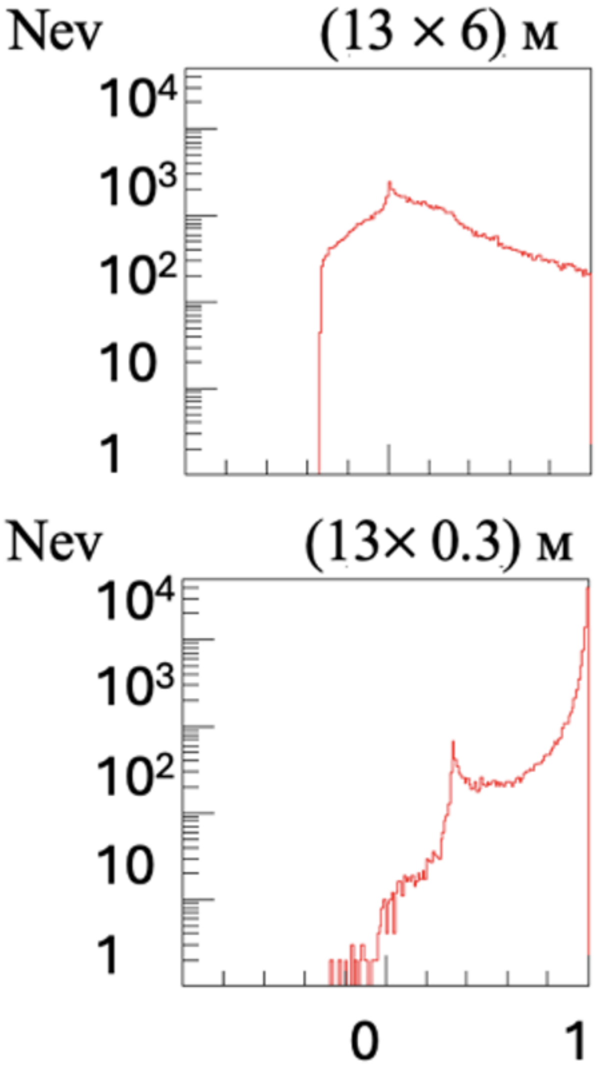
$$\lambda_N = \frac{\sum_{\neq j \neq k}^{N} \cos 2\varphi_{ij}^{k}}{N(N-1)(N-2)}$$



Monte-Carlo simulation for alignment parameter λ_N

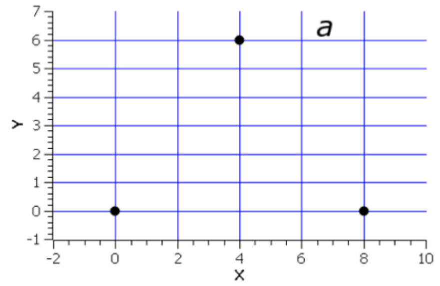
We tested two scenarios:



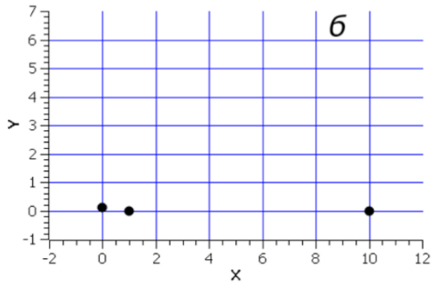


The λ_4 parameter distribution

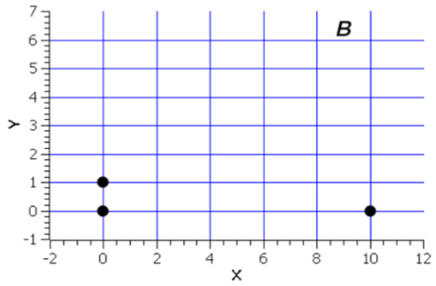
Three cases of calculating lambda for three points:



isotropic case (non-coplanar event – equilateral triangle) $\lambda_N = -0.5$



strongly coplanar event - points almost on a line $\lambda_N = 1.0$

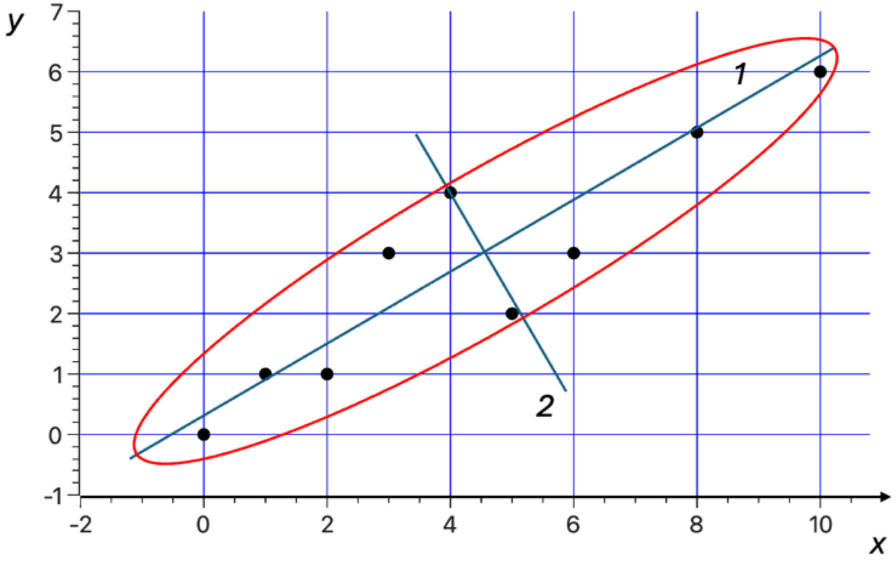


coplanar event (triangle with one right angle) $\lambda_N = -0.3$

Aligned parameters

Our parameter μ_N indicates the degree of coplanarity of particle (muon) tracks and is equal to the ratio of the semi-axes of the scattering ellipse of *N* points in the plane perpendicular to the direction:: $\mu_N = \beta/\alpha$.

- The coefficient α is calculated as the standard deviation of all points (x, y) from fitting line number 1 (the major axis of the point spread ellipse).
- The coefficient β is calculated as the standard deviation of the points from fitting line number 2 (the minor axis of the ellipse), which is perpendicular to fitting line number 1.



Aligned event N = 9.
1 – major axis of the ellipse,
2 – minor axis of the ellipse

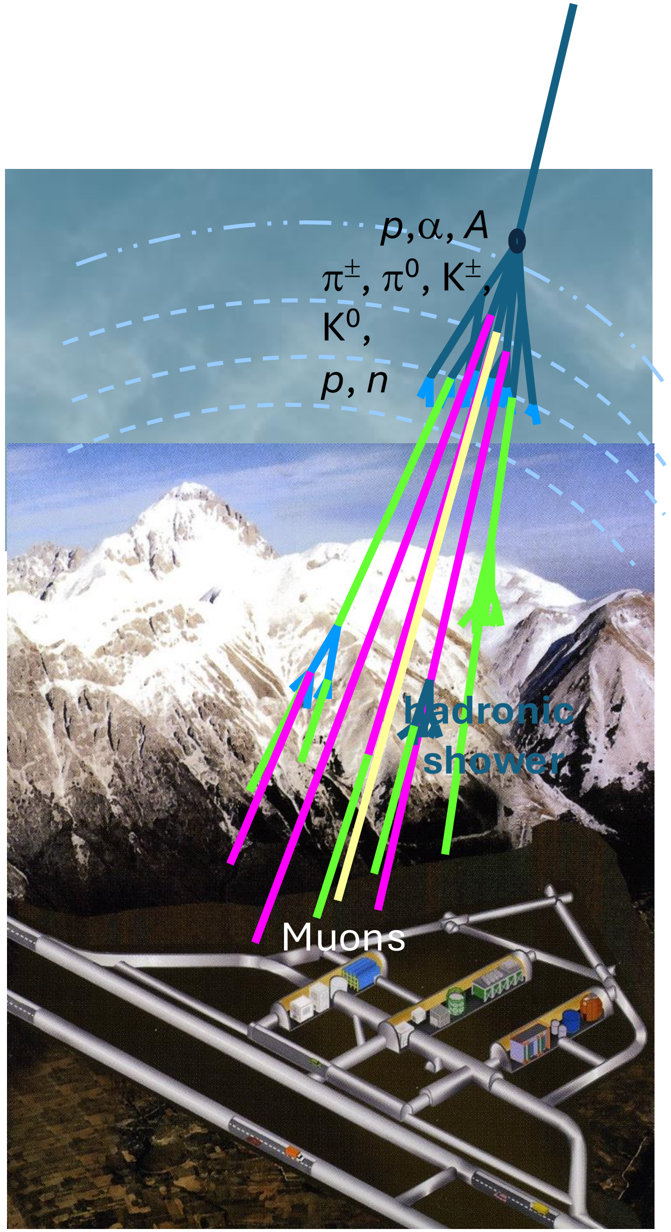
$$\mu_N = \frac{\beta}{\alpha} = \sqrt{\frac{a^2+1}{\frac{1}{a^2}+1}}\sqrt{\frac{\sum_{i=1}^{N}\left(\frac{-1}{a}x_i - y_i + d\right)^2}{\sum_{i=1}^{N}(ax_i - y_i + b)^2}}$$

$$= |a|\sqrt{\frac{\sum_{i=1}^{N}\left(\frac{-1}{a}x_i - y_i + d\right)^2}{\sum_{i=1}^{N}(ax_i - y_i + b)^2}}.$$

For a non-coplanar event (an ellipse is similar to a circle), $\mu_N = 1$; for a highly elongated ellipse, $\mu_N >> 1$ (∞) is a coplanar event.

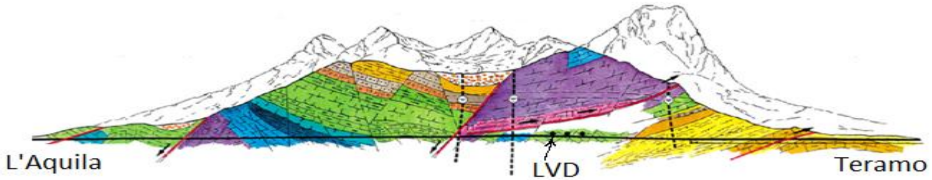
Redefining $\mu_N^* = -(2/\mu_N) + 1$, we obtain the parameter μ_N^* (V.F. Yakushev's parameter) in the range [-1; +1], the same range as λ_N.

Large Volume Detector @ LNGS

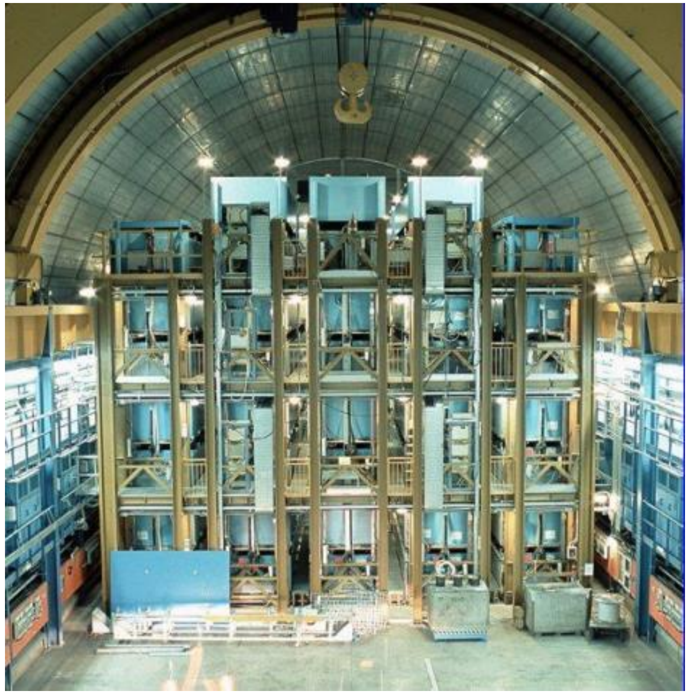


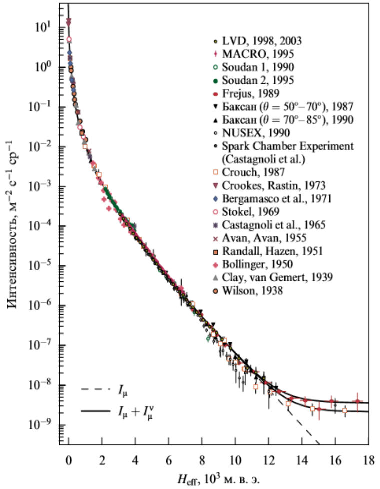
The main goal of LVD is searching for neutrino radiation from stellar core collapse

$$\bar{\nu}_e + p \to n + e^+$$



Dimensions 22m×13m×10m
M_{Fe}=1020 t, M_{sc}=1008 t
Scintil. counters=840
<H> = 3620 m w.e.
$\langle E_{\mu}\rangle$ = 280 GeV
$E_{s.l.}$ = 1.3 TeV
CR_{μ} ~ 120 h^{-1}
ε_{th} = 4 MeV



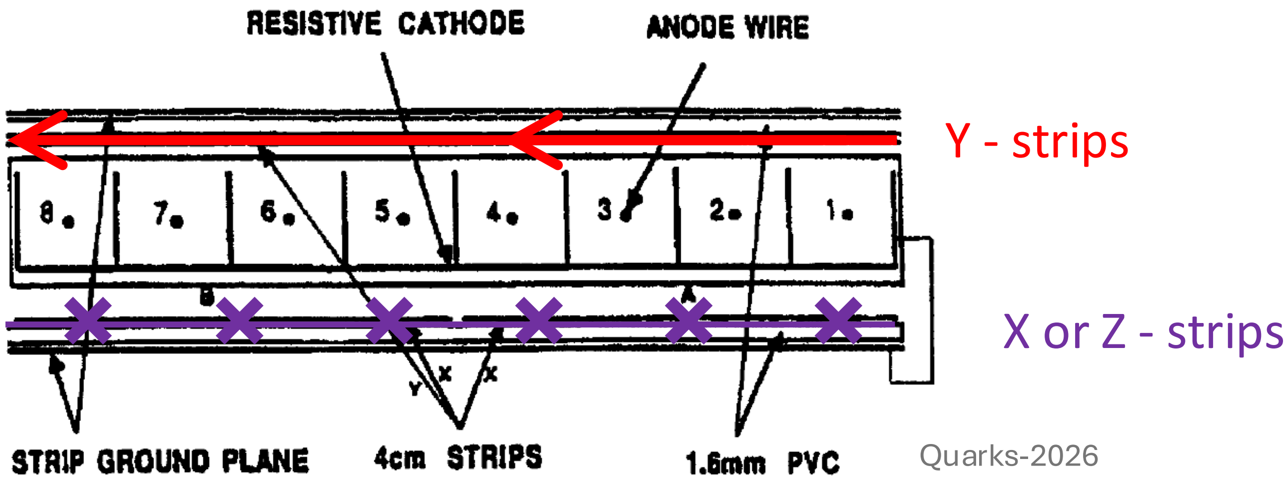


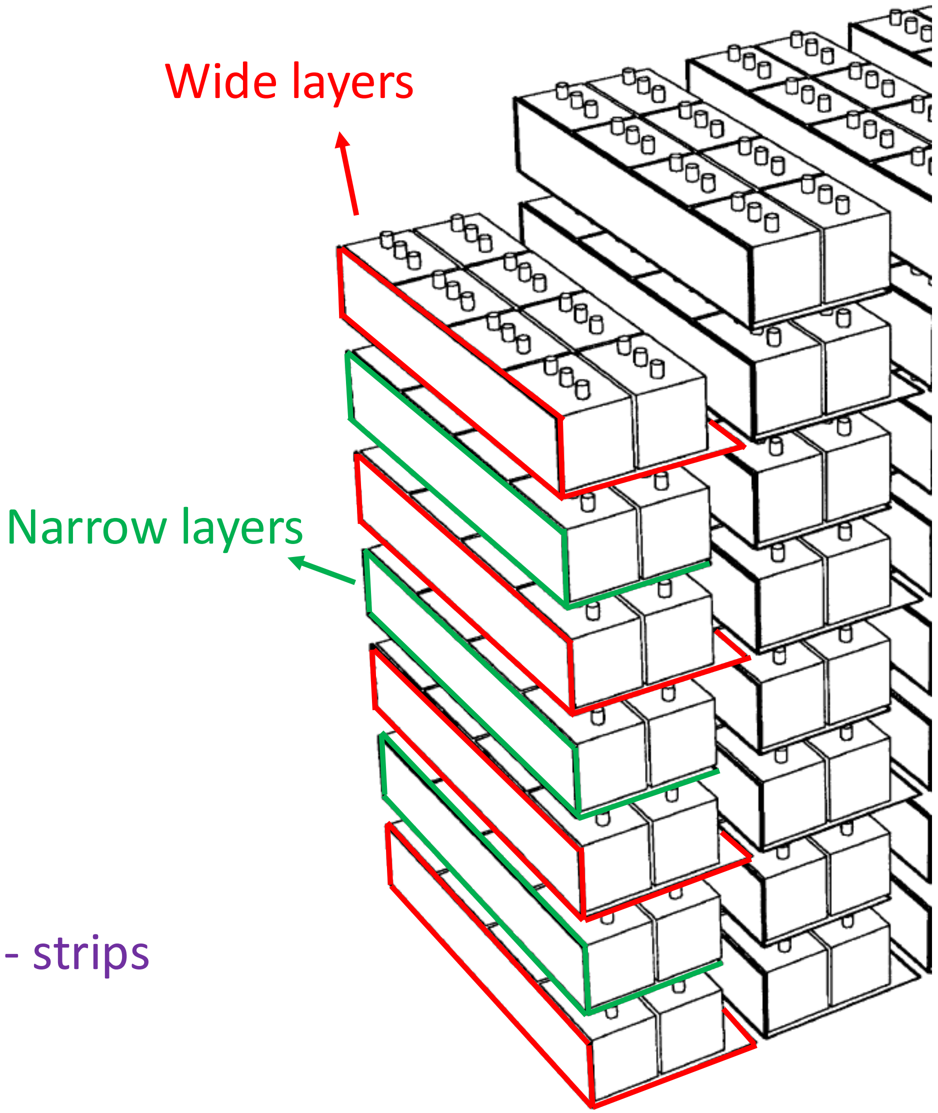
LVD is located in the Gran Sasso underground laboratory at a depth of 3650 m w.e. Detector is designed to search for neutrinos from the collapse of stellar cores and to detect muons.

LVD Track system

<u>Streamer cameras :</u>

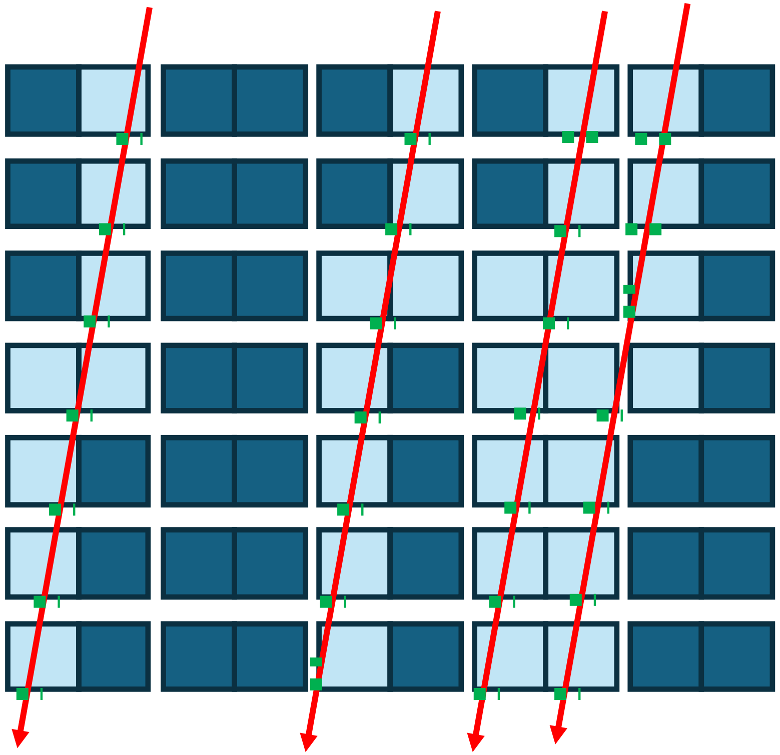
- 8 cells, 1 cm^2 cross-section, 1 mm wall thickness
- Length - 6.3 m
- Anode - 100 µm diameter silver-coated wire
- Cathode - cell walls coated with graphite paint
- Gas: 88% CO^2, 10% isobutane, 2% Ar
- Two layers, offset by 0.5 cm



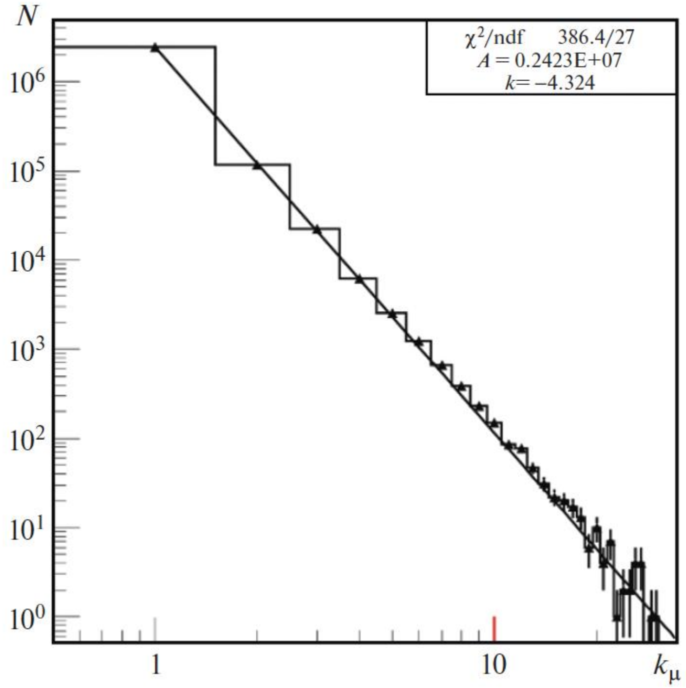


Muon bundles reconstruction

The reconstructed muon archive data includes 2,424,826 single muons and 151,090 muon bundles [1998-2002].



Four-muon event in a bundle

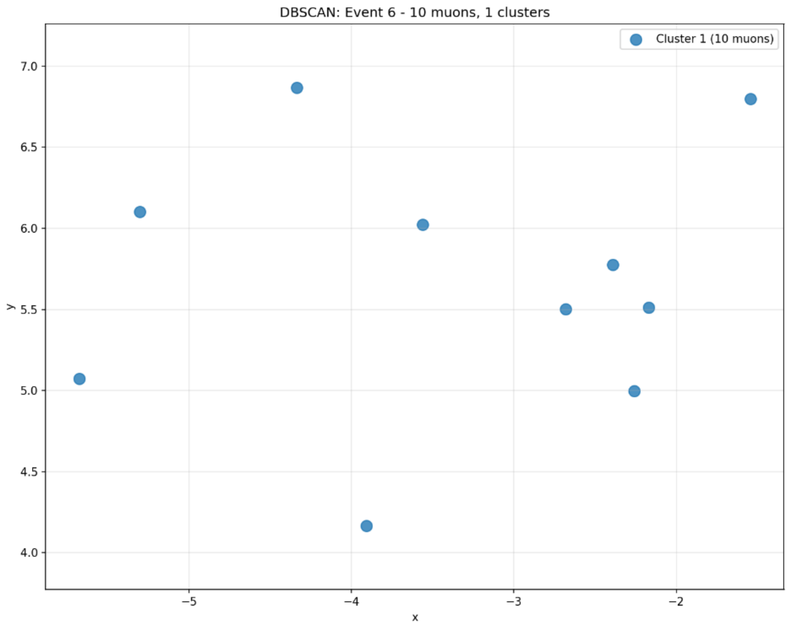


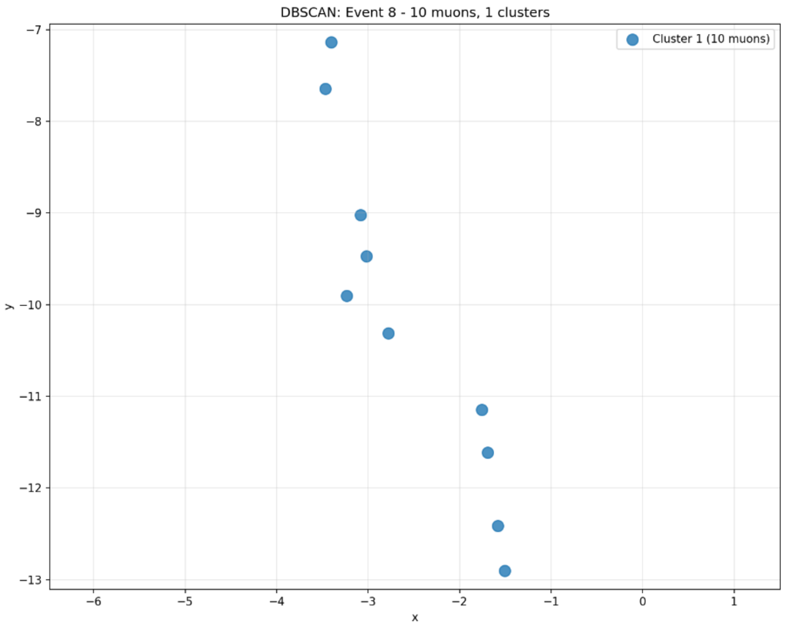
Distribution of the number of events with respect to the multiplicity of reconstructed muons. The curve stands for the approximation by the form f(x) = Ax^{-k}, where k = 4.32.

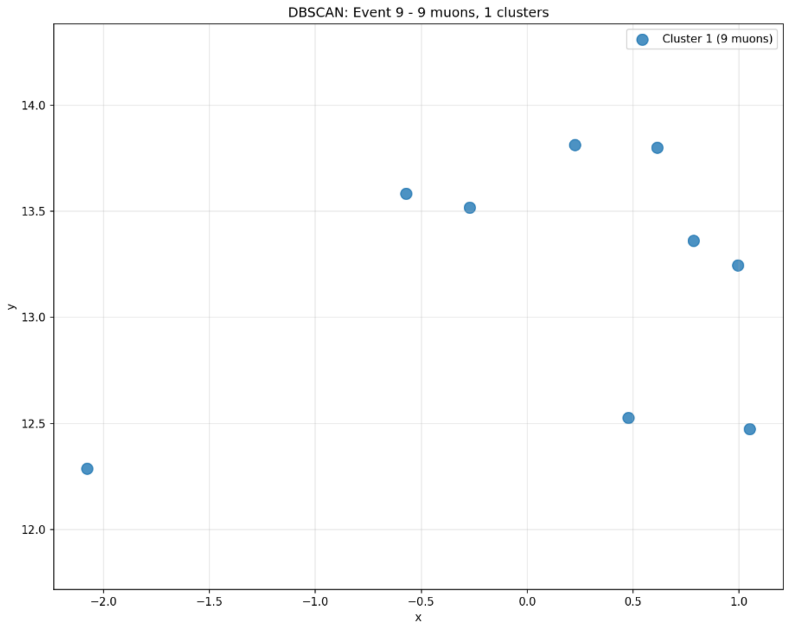
The number of detected in the LVD muon bundles with a multiplicity greater than 4.

multiplicity k_μ	Number of events
4	6092
5	2491
6	1219
7	657
8	382
9	228
10	149
>11	356

Examples of aligned muon events





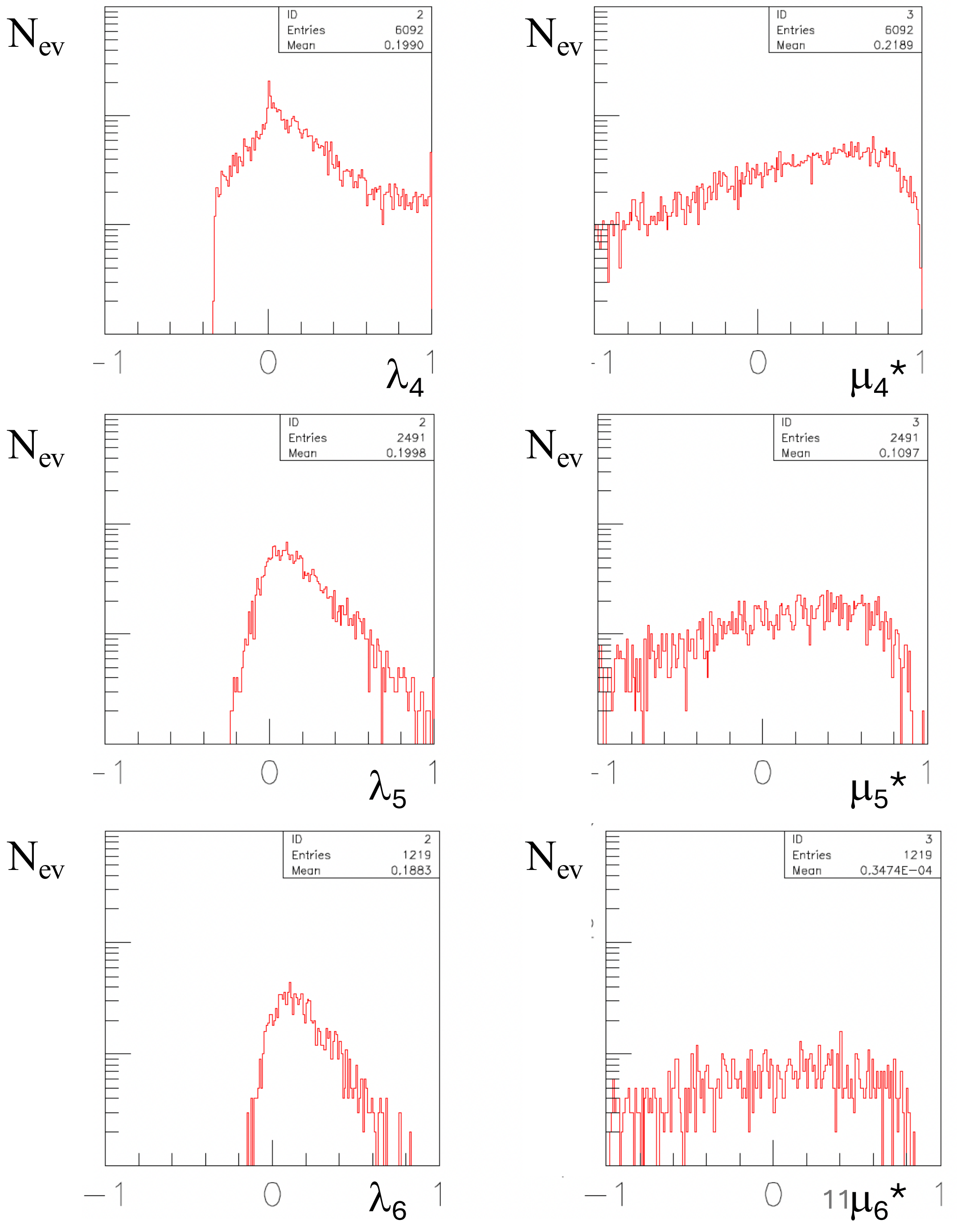


examples of events with aligned muons in a plane perpendicular to the muon arrival angle.

Search for alignment events in LVD

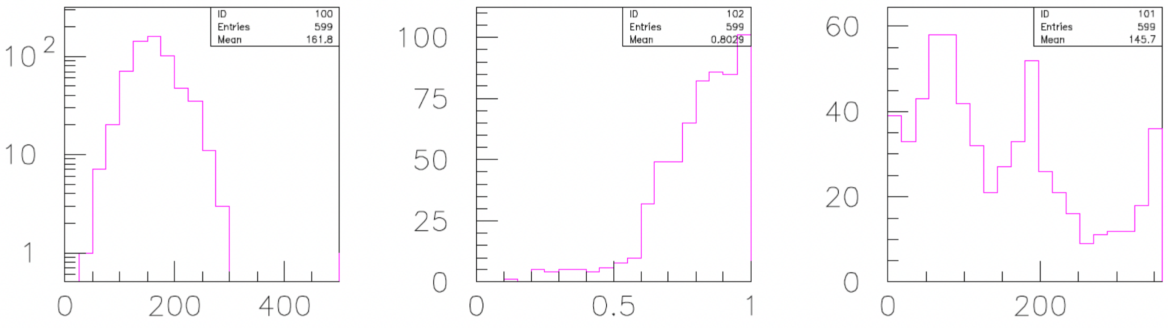
The number of events depending on the alignment threshold for different numbers of muons in bundles

k_μ	Events	Alignment parameter	$\lambda_N > 0.5$ $\mu_N^* > 0.5$	$\lambda_N > 0.6$ $\mu_N^* > 0.6$	$\lambda_N > 0.7$ $\mu_N^* > 0.7$	$\lambda_N > 0.8$ $\mu_N^* > 0.8$	$\lambda_N > 0.9$ $\mu_N^* > 0.9$
4	6092	λ_N	1021	748	556	367	201
		μ^*	1899	1418	961	507	174
5	2491	λ_N	277	156	94	52	20
		μ^*	520	351	189	76	9
6	1219	λ_N	80	36	11	6	2
		μ^*	172	107	53	16	1
7	657	λ_N	23	10	7	2	0
		μ^*	54	23	7	1	0
8	382	λ_N	7	2	1	0	0
		μ^*	22	8	3	0	0
9	228	λ_N	5	1	1	1	0
		μ^*	13	4	1	0	0
10	149	λ_N	3	1	0	0	0
		μ^*	1	0	0	0	0
>11	356	λ_N	0	0	0	0	0
		μ^*	3	1	0	0	0

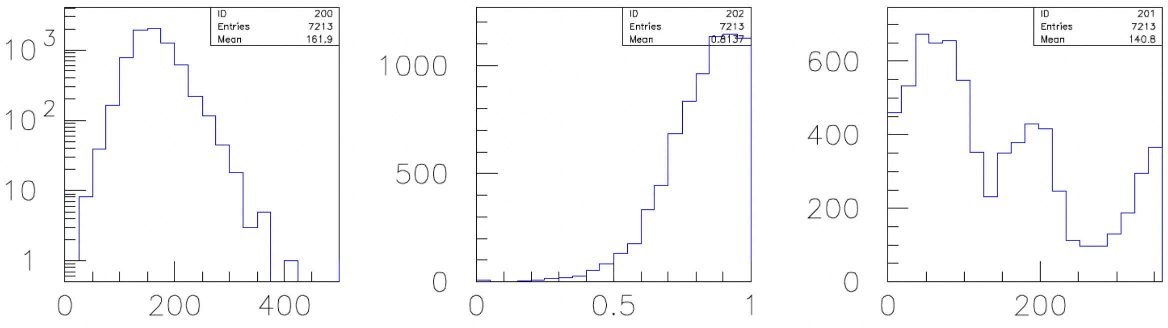


Characteristics of alignment events in LVD

$\mu_N^* > 0.8$



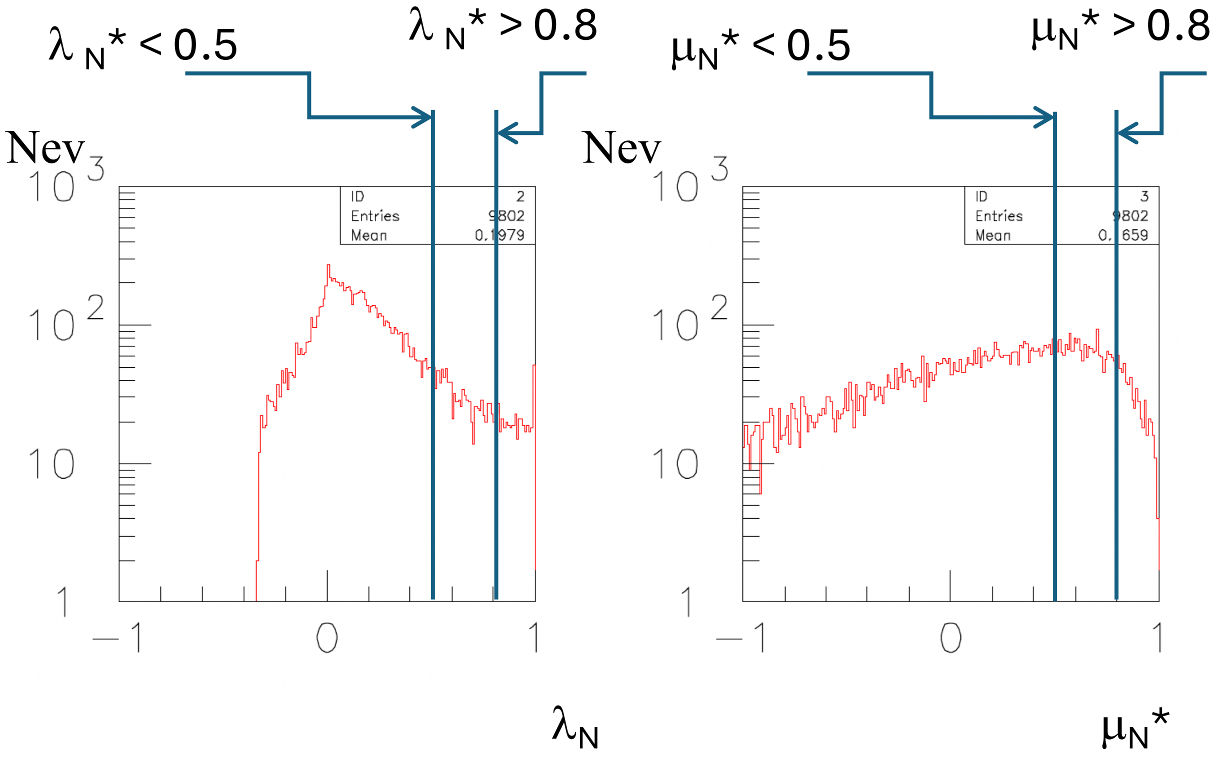
$\mu_N^* < 0.5$



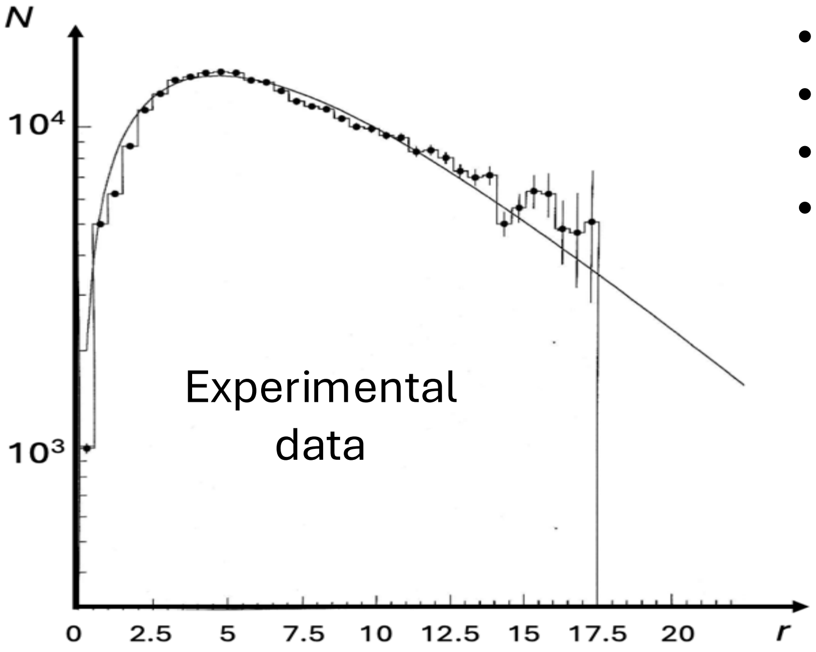
$\Sigma E_i / \Sigma$counters

Cos θ

φ

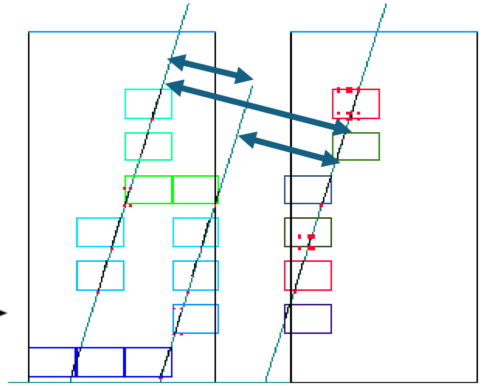


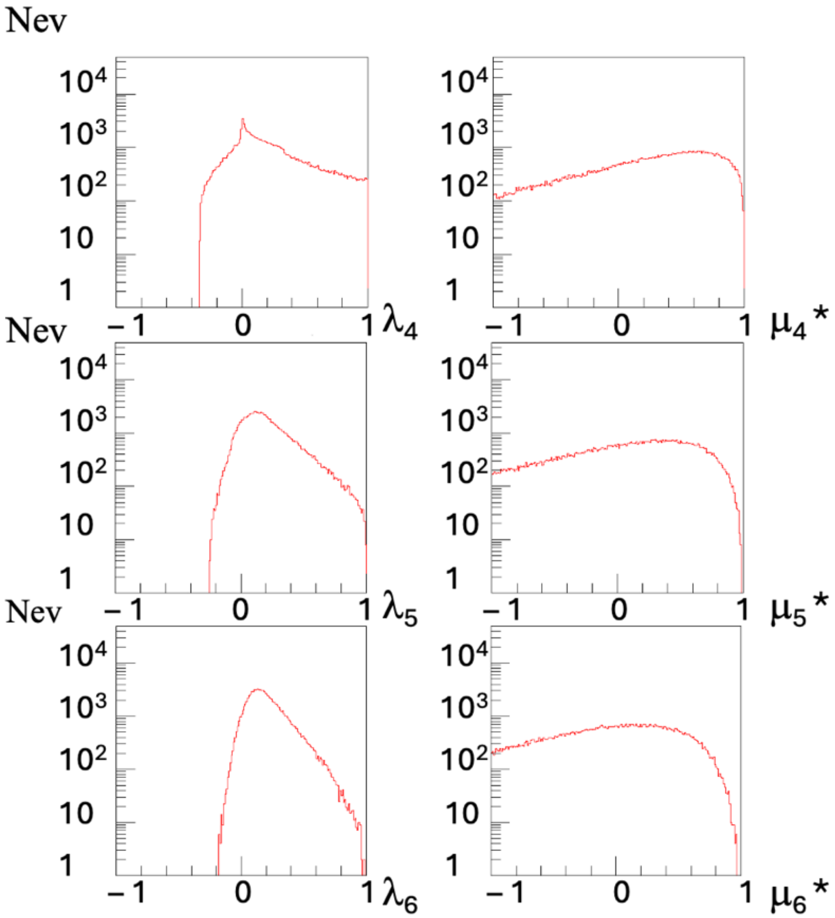
Monte-Carlo simulation



Event simulation:

- events with different N (multiple muons in a group),
- coordinates were randomly generated according to the law (function *f(r)*),
- the parameters λ_N and μ_N^* were calculated.
- 10^6 events

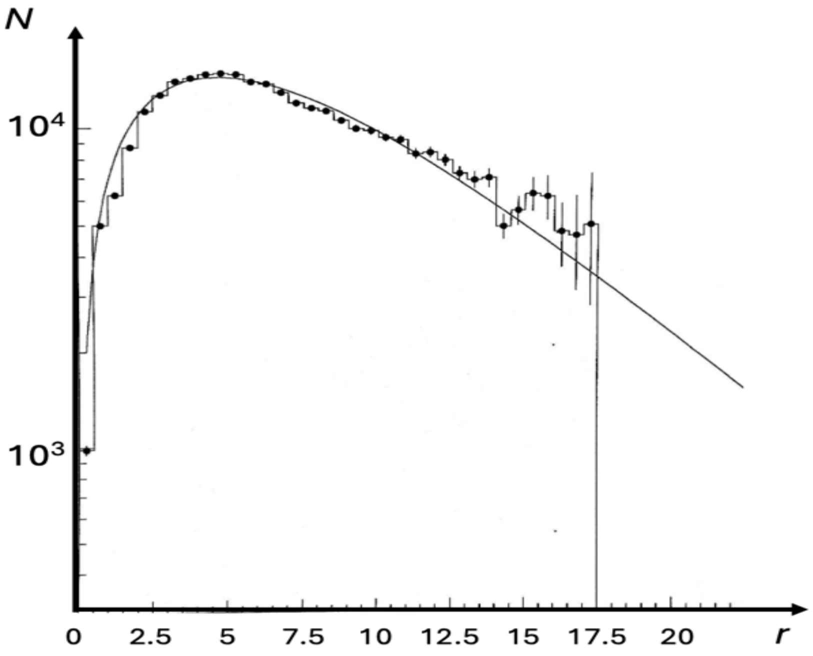




Using the track coordinates of real muons recorded in the LVD, a decoherence curve (or separation curve) was obtained. The decoherence curve is the distribution of muon pairs by the distance between muons.

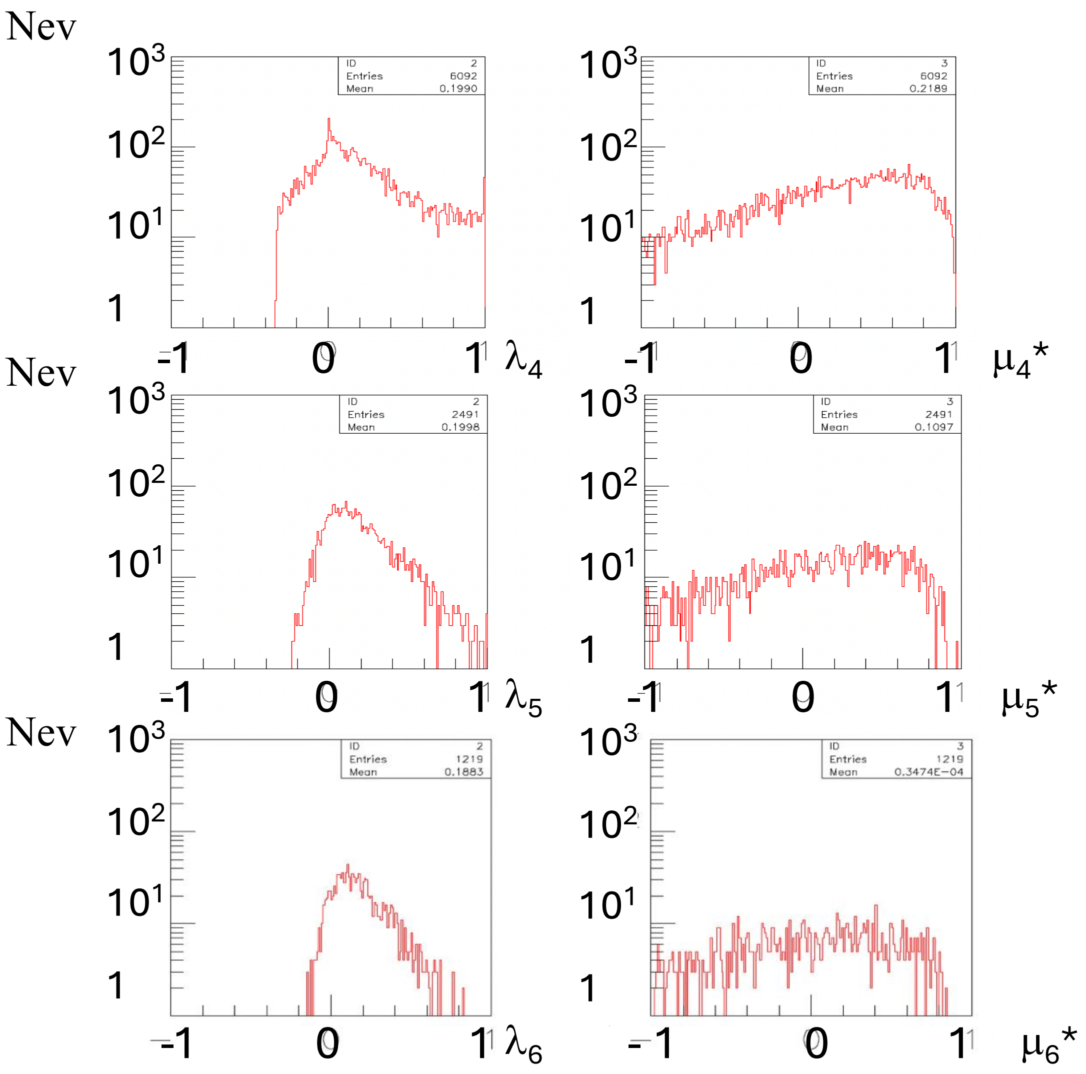
This distribution was approximated using the function $f(r) = A \times r/R^2 \times \exp(-r/R)$, where $A = 0.181 \times 10^6$, $R = 4.63$.

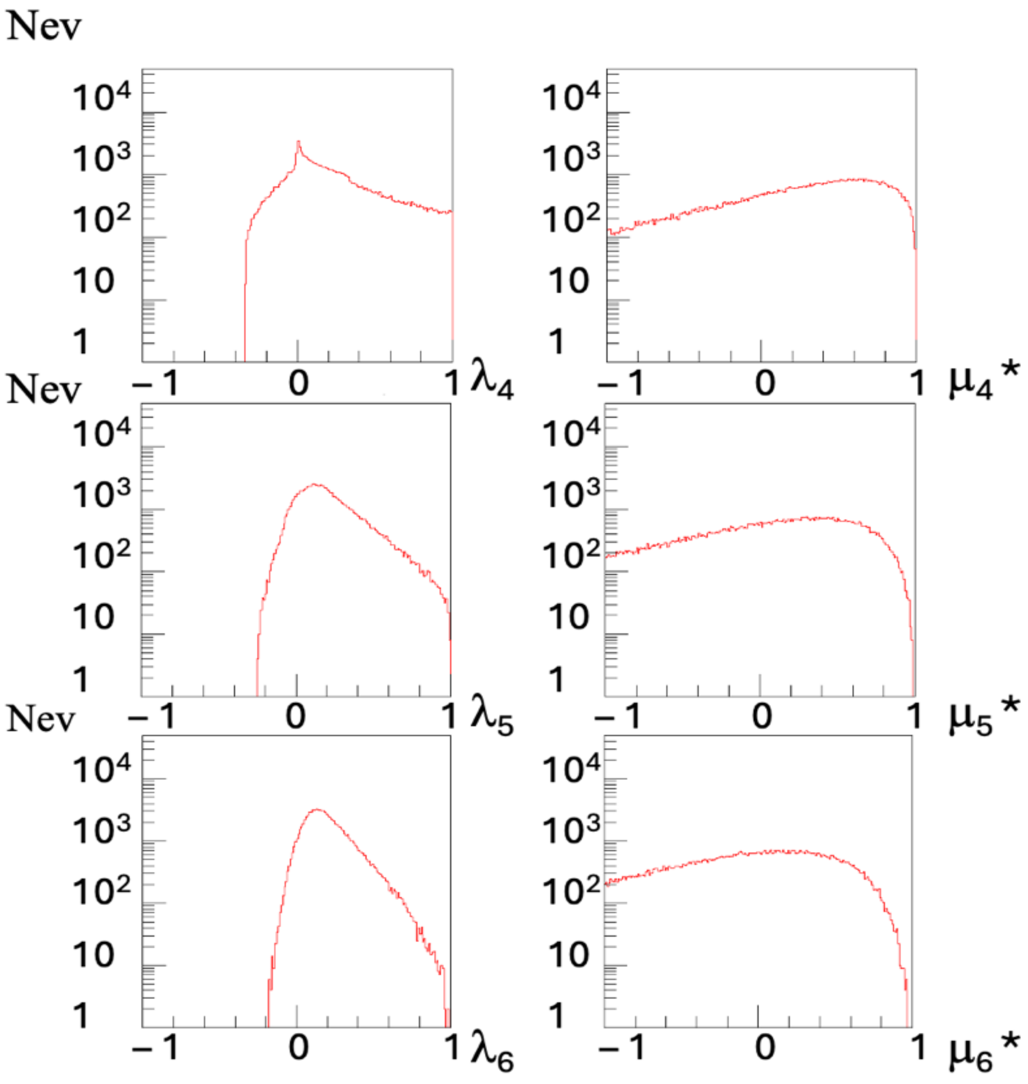
The Monte-Carlo simulation results



k_μ	Total events	Aligned parameters	$\lambda_N > 0.5$ $\mu_N^* > 0.5$	$\lambda_N > 0.6$ $\mu_N^* > 0.6$	$\lambda_N > 0.7$ $\mu_N^* > 0.7$	$\lambda_N > 0.8$ $\mu_N^* > 0.8$	$\lambda_N > 0.9$ $\mu_N^* > 0.9$
4	10^5	λ_N	0.1735	0.1269	0.0884	0.0554	0.0259
		μ^*	0.3356	0.2543	0.1725	0.0949	0.0323
5	10^5	λ_N	0.0945	0.0531	0.0287	0.0134	0.0042
		μ^*	0.1921	0.1262	0.0697	0.0281	0.0054
6	10^5	λ_N	0.0523	0.0233	0.0092	0.0031	0.0007
		μ^*	0.1096	0.0625	0.0282	0.0085	0.0009
7	10^5	λ_N	0.0282	0.0098	0.0030	0.0007	0.00008
		μ^*	0.0619	0.0305	0.0112	0.0026	0.0002
8	10^5	λ_N	0.0151	0.0042	0.0009	0.00016	0.000014
		μ^*	0.0352	0.0147	0.0044	0.0007	0.00003
9	10^5	λ_N	0.00791	0.00164	0.00025	0.00002	0.000001
		μ^*	0.01986	0.00703	0.00172	0.00019	0.00001
10	10^5	λ_N	0.00420	0.000687	0.00008	0.000008	0
		μ^*	0.01138	0.003449	0.000698	0.000066	0

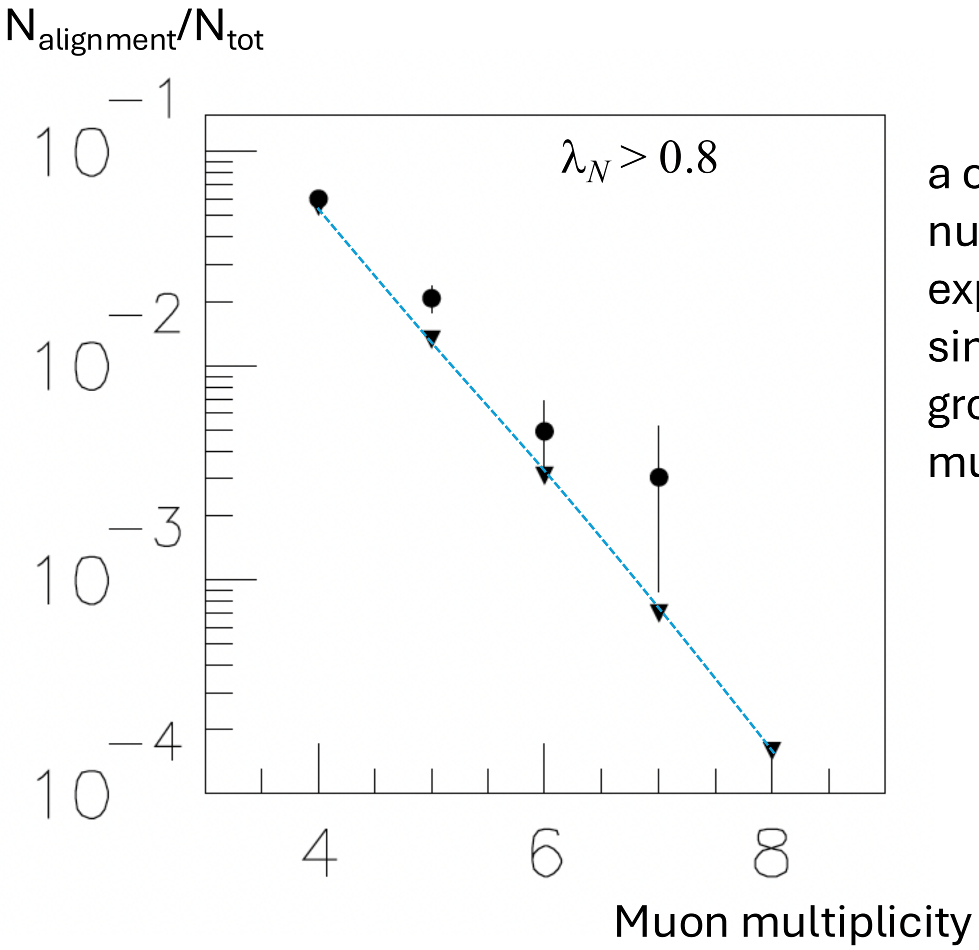
LVD data vs M-C simulation



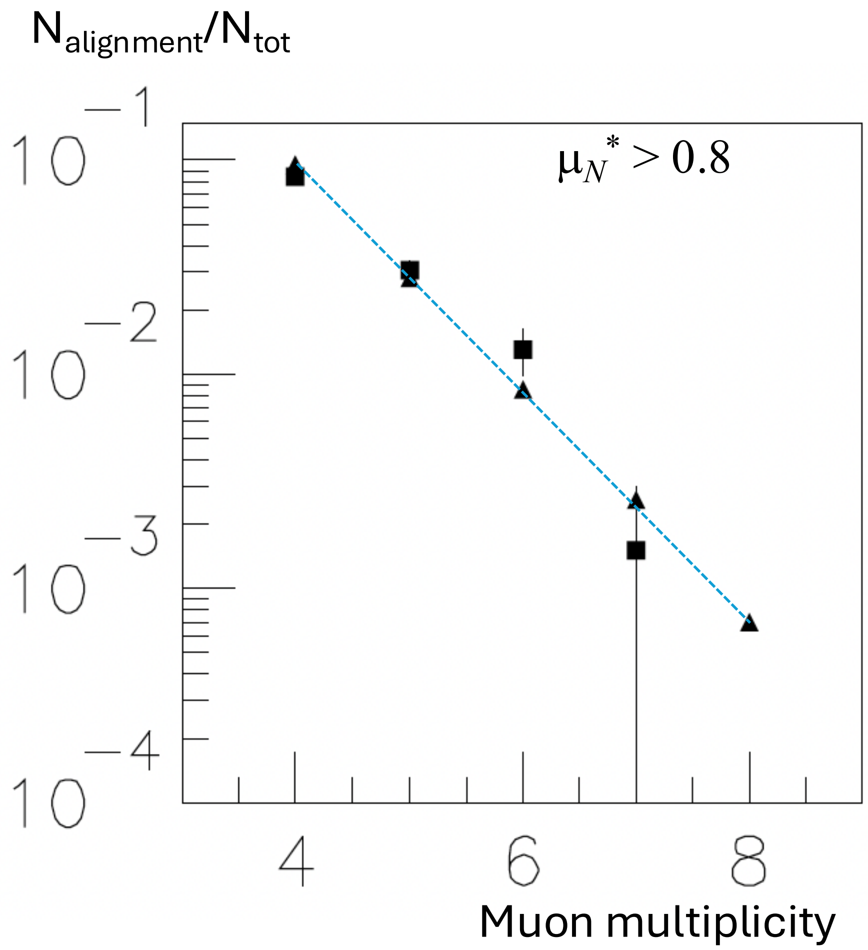


the distributions of alignment parameters

LVD data vs M-C simulation



a comparison of the number of experimental and simulated events for groups of different multiplicities

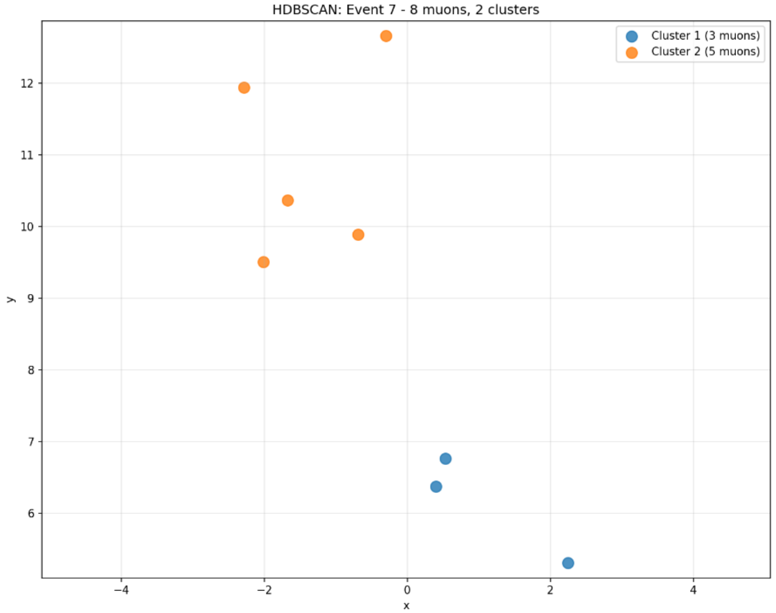


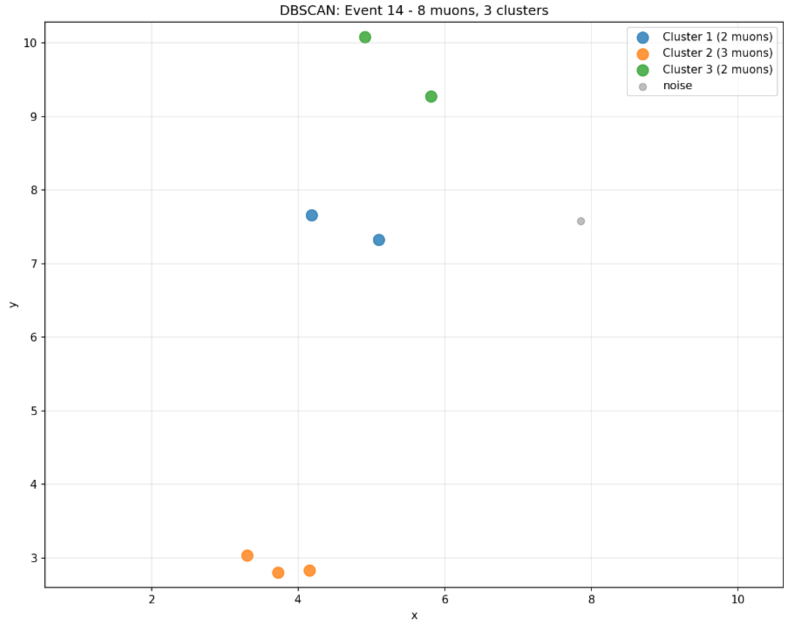
Points with errors – LVD experiment data

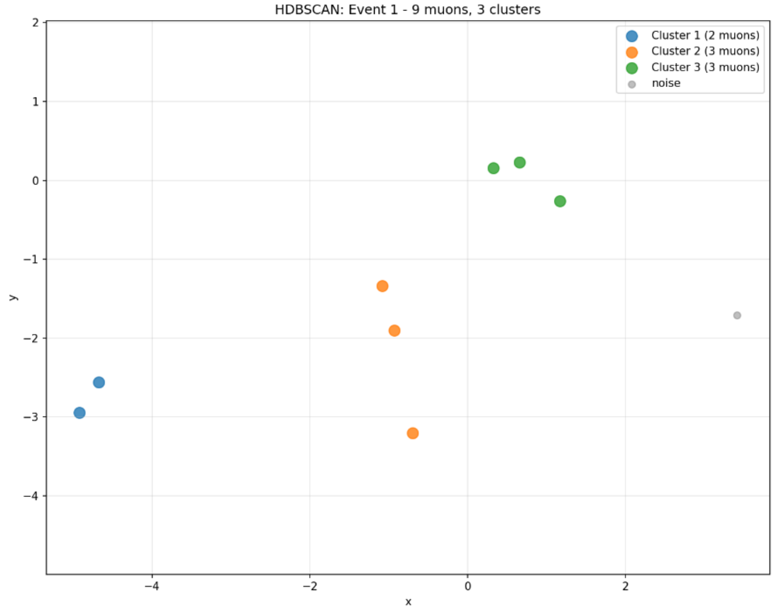
Triangles – Monte-Carlo simulation

Investigation of muon events topology

by A. Grigoryeva (student, MEPhI)







Combining tracks into clusters (thickening)

Conclusion

Our next steps:

1. Check large zenith angles (greater than 70 degrees) in LVD muon bundles. The energy of such muon bundles is higher.
2. Look for alignment at distances greater than 5 meters. Alignment at short distances can be lost (washed out) by scattering in the ground.
3. Combine the tracks into clusters. Study the muon topology. For example, as was done in the MACRO experiment. Find clusters within a group and look for alignment within the clusters.
4. Use CORSICA or FANSY to separate events by interaction type. In the LVD experiment, separate the events into wide and narrow muon bundles.

Thank you!