INSTITUTE FOR HIGH ENERGY PHYSICS
PROTVINO

NATIONAL RESEARCH CENTER «KURCHATOV INSTITUTE»

Optical Scheme of the Neutrino Channel with Magnetic Horns and Dipoles at the U-70 Accelerator Complex

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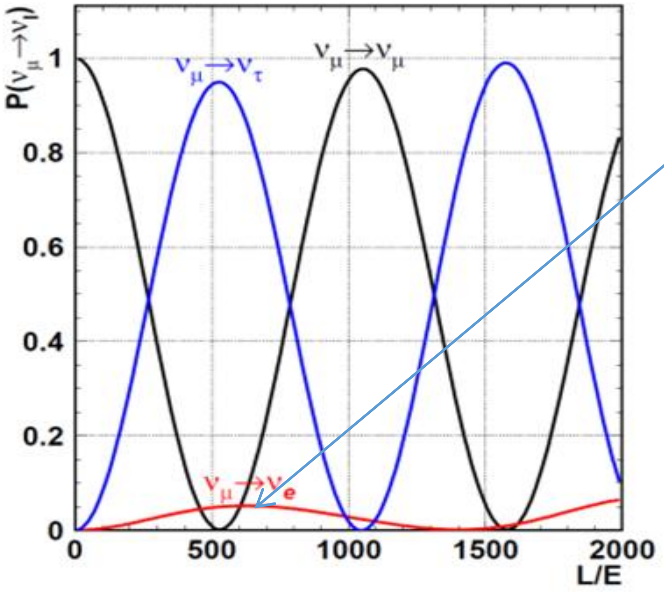
Introduction

The U-70 accelerator complex of the NRC KI-IHEP (Moscow region, Protvino) has a high potential for carrying out an extensive program of scientific experiments.

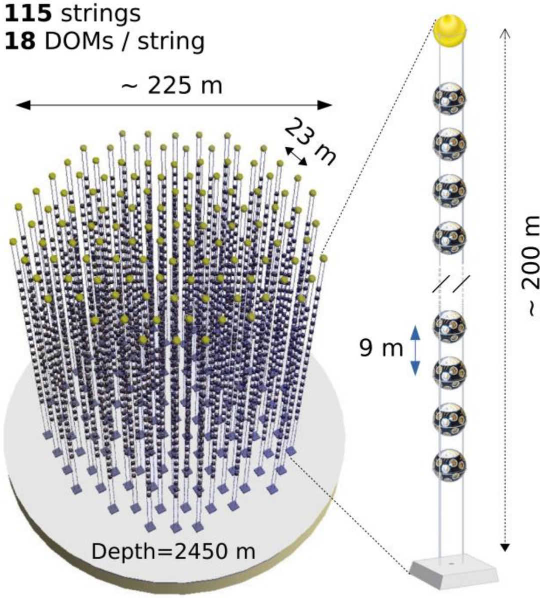
Several years ago, an idea was put forward to use a neutrino beam from the U-70 accelerator directed to the Mediterranean Sea to register neutrinos by the ORCA (Oscillation Research with Cosmics in the Abyss) deep-sea detector being built near the coast of France to conduct experiments to determine the neutrino mass hierarchy and search for CP violation in the lepton sector. The distance from Protvino to the ORCA detector is 2595 km.



The U-70 accelerator can form muon neutrino beams with an energy of ~4.5 GeV, which corresponds to the first oscillation maximum $\nu_\mu \leftrightarrow \nu_e$ for a distance of 2595 km, which is optimal for the experiment.

Thus, the planned experiment, called P2O (Protvino-to-ORCA), will have unique characteristics, even at a relatively low beam intensity of the U-70 accelerator. At present, the intensity is approximately 15 kW, but, in principle, it can be increased to 90 kW.

To implement the project, it is necessary to build a new neutrino channel on the IHEP U-70 accelerator complex in Protvino.



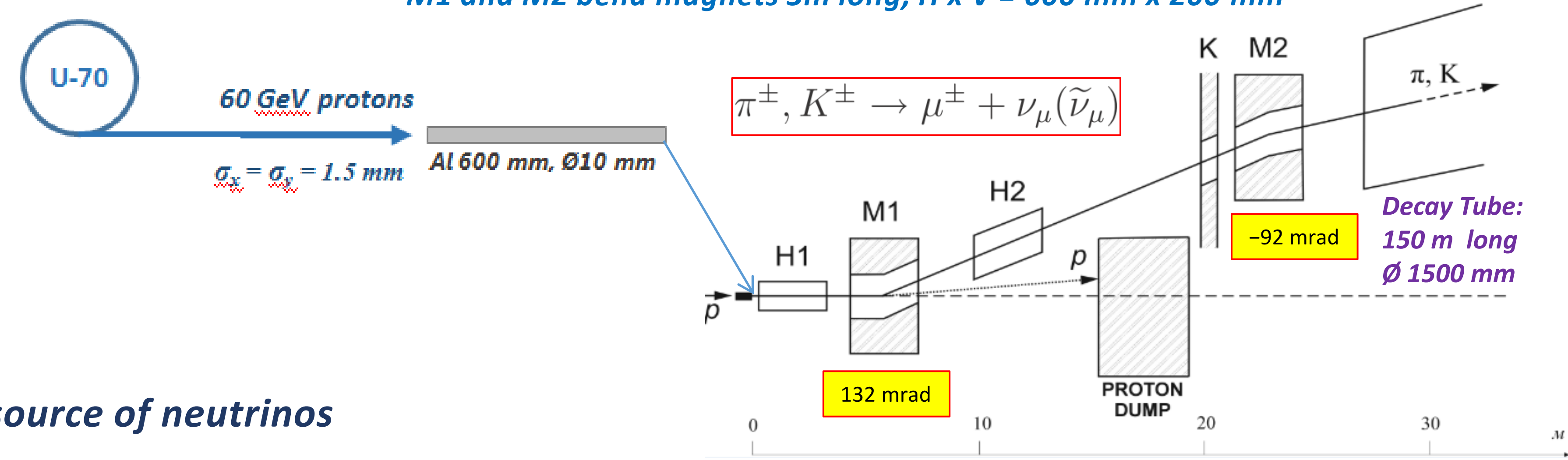
Schematic view of the ORCA detector

Conceptual design of beamline

U-70 current operation:

- Protons up to 70 GeV (60 GeV)
- 10^{13} protons/cycle
- 5 μs spill every 10 s

M1 and M2 bend magnets 3m long, H x V = 600 mm x 200 mm

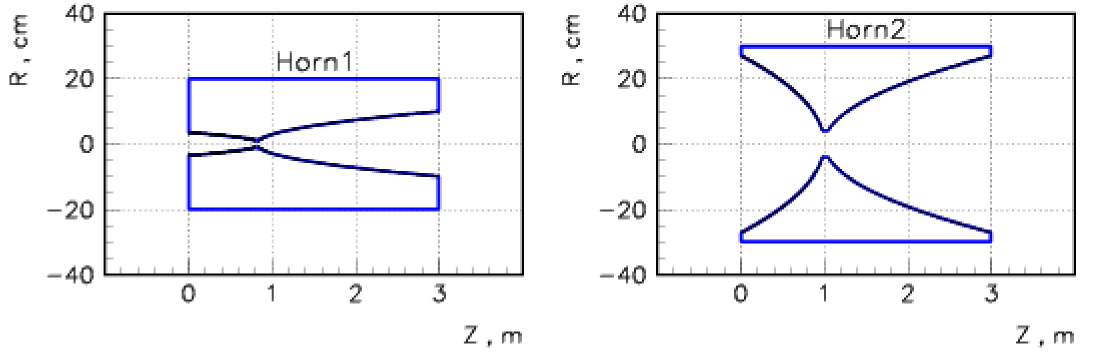


Assumptions:

- *only $\pi^{\pm}$ are considered as a source of neutrinos*
- *pions that get into the matter during transport are excluded from consideration*

Configuration of the optical system and collimator parameters were chosen based on the requirements of the neutrino spectrum at the far detector

Pulsed magnetic horns 3m long, aperture: Ø400 and Ø600 mm

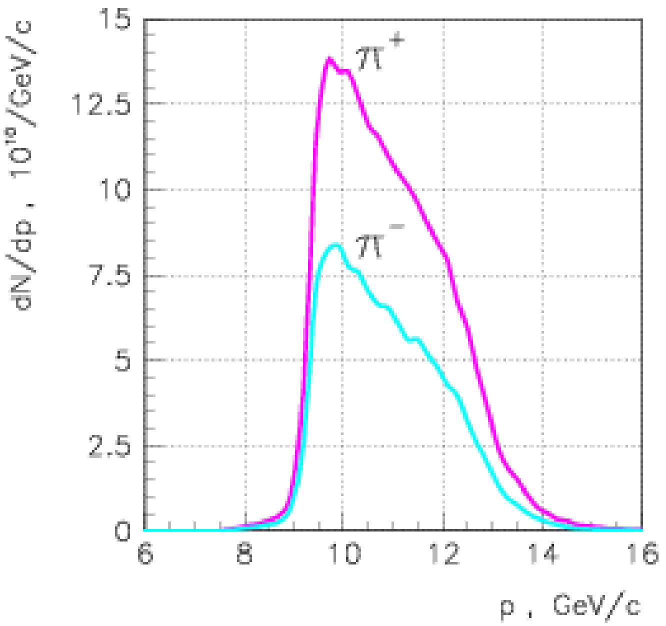


I = 220 kA

The pion and kaon yields from the aluminum target were calculated based on the parameterization of the inclusive invariant cross sections of secondary particle yields measured in p-Be interactions and extrapolation of these data for other target materials: M.Bonesini et al. On particle production for high energy neutrino beams. Eur. Phys. J. C 20, 13-27 (2001). (DOI) 10.1007/s100520100656.

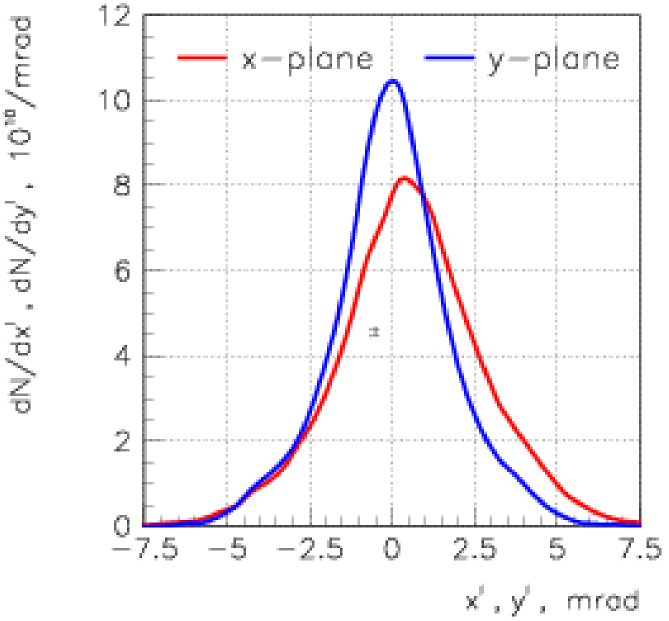
Parameters of the π-mesons at the decay tube beginning

With the momentum collimator fully open ±300 mm a narrowly divergent beam of positively (or negatively) particles in the momentum range of 8-15 GeV/c is formed at the decay tube beginning.



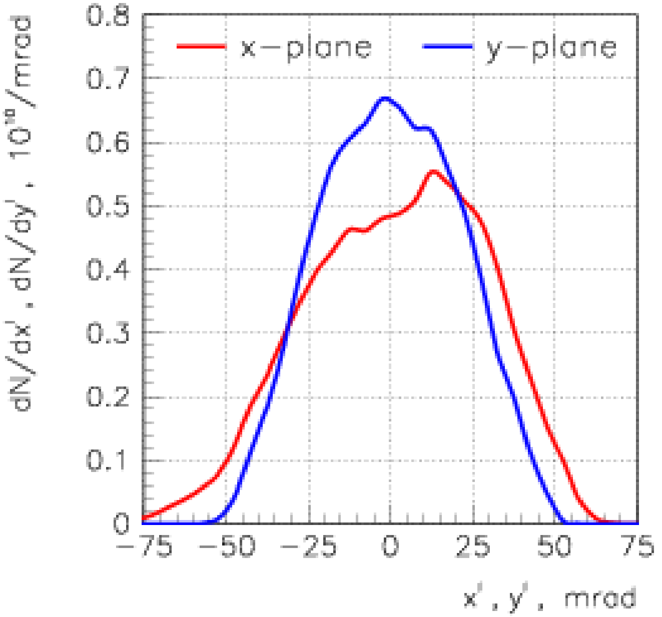
Decay tube beginning:

$N(\pi^+) = 3.97 \cdot 10^{11}$ $N(\pi^-) = 2.31 \cdot 10^{11}$



Decay tube beginning:

rms[x'] = 2.33 мрад**, **rms[y'] = 1.82 мрад



After target:

rms[x'] = 26.7 мрад**, **rms[y'] = 20.8 мрад

Red lines – horizontal plane. Blue lines – vertical plane.

$x' = p_x/p_z$, $y' = p_y/p_z$

Neutrino spectrum of $\nu_\mu N$ events at the far detector

$\nu_\mu N$ events ~ $\Phi_\nu \cdot m_{det} \cdot f(E_\nu)$

Detector: L_{det} = 2595 km, R_{det} = 100 m, Θ_{det} = 0.04 mrad
π-beam: σ[x'] = 2.3 mrad, σ[y'] = 1.8 mrad, σ[Θ_π] = 3 mrad

The inequality $\Theta_{det} << \sigma[\Theta_\pi]$ is the condition of using a simplified scheme of calculating the neurino spectra.

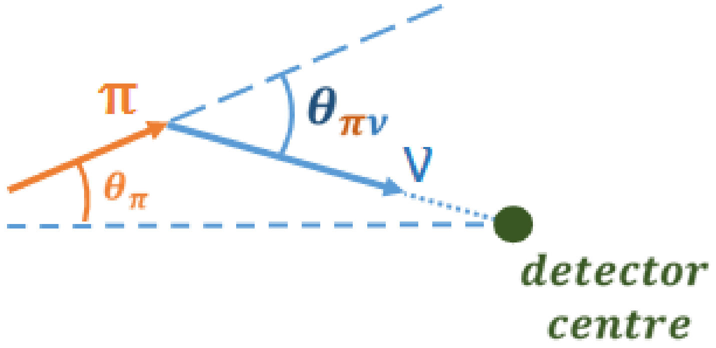
The density of the angular distribution of neutrinos at decay of π-meson

$$\frac{dN}{d\Omega} = \frac{1}{4\pi\gamma^2(1-\beta\cos\theta_{\pi\nu})^2}$$

is almost constant within the angular size of the detector $\Theta_{det} << \sigma[\Theta_\pi]$.

β and γ are the velocity and gamma-factor of the decaying π-meson.

$\Theta_{\pi\nu}$ is the angle of departure of neutrinos relative to the direction of motion of the π-meson in the laboratory coordinate system.

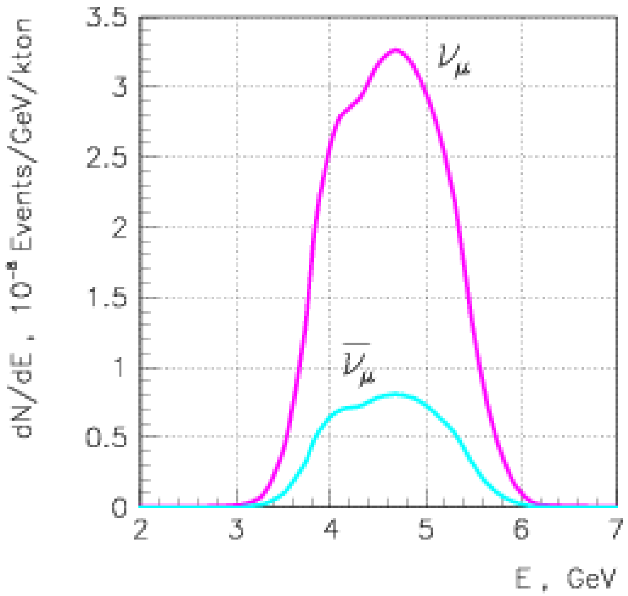


The neutrino flux Φ through the detector with a transverse area of S is

$$\Phi = \frac{N}{S} = \frac{1}{S}\int \frac{dN}{d\Omega} d\Omega \simeq \frac{1}{S}\frac{dN}{d\Omega}\Delta\Omega \simeq \frac{1}{S}\frac{dN}{d\Omega}\frac{S}{z^2} = \frac{1}{z^2}\frac{dN}{d\Omega}$$

and is independent of the detector area. To calculate the value of cosϑ, it suffices to assume that all neutrinos always hit the center of the detector, which allows us to clearly determine their energy E (E is the neutrino energy in c.m.s.):*

$$E = \frac{E^*}{\gamma(1-\beta\cos\theta_{\pi\nu})}$$



The total number of $\nu_\mu N$ and $\bar{\nu}_\mu N$ events are 2.30×10^{-7} and 5.25×10^{-8} events per cycle per 1 kt of detector mass respectively.

ν_μN events radial distribution at the far detector

z – distance to detector
r – current radius of detector

$$N_{Ev} \sim \mathrm{m} \cdot \Phi \cdot f(E)$$

$$\frac{dN_{Ev}}{dS} \sim \Phi \cdot f(E)$$

We neglect:

- the length of the neutrino channel compared with the distance to the detector
- the transverse dimensions of the π-meson beam in the decay section of the channel compared to the size of the detector
- the angular divergence of the π-meson beam in the decay section

We assume:

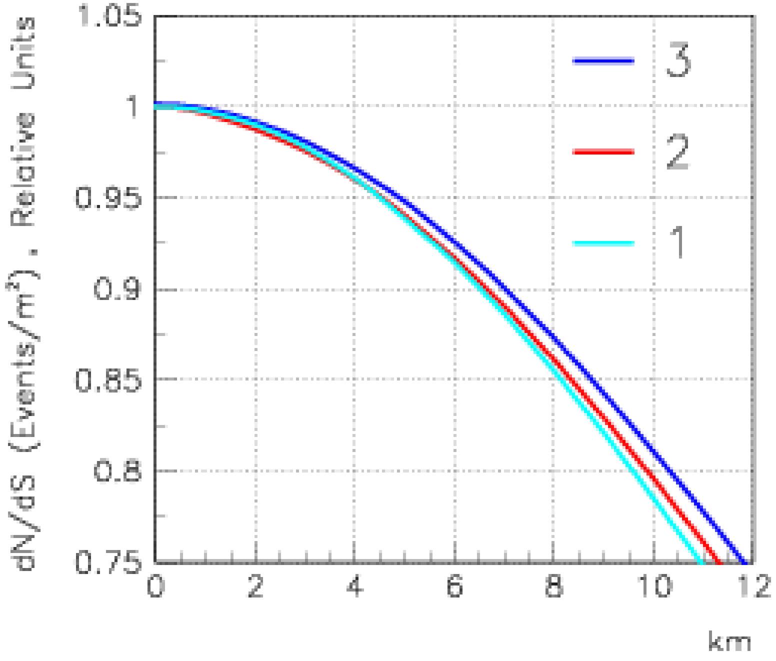
- that the dependence *f(E) ~ E*

$$\frac{dN_{Ev}}{dS} \sim \frac{1}{(1-\beta cos\theta)^3}$$

$$\cos\theta = z/\sqrt{z^2+r^2}$$

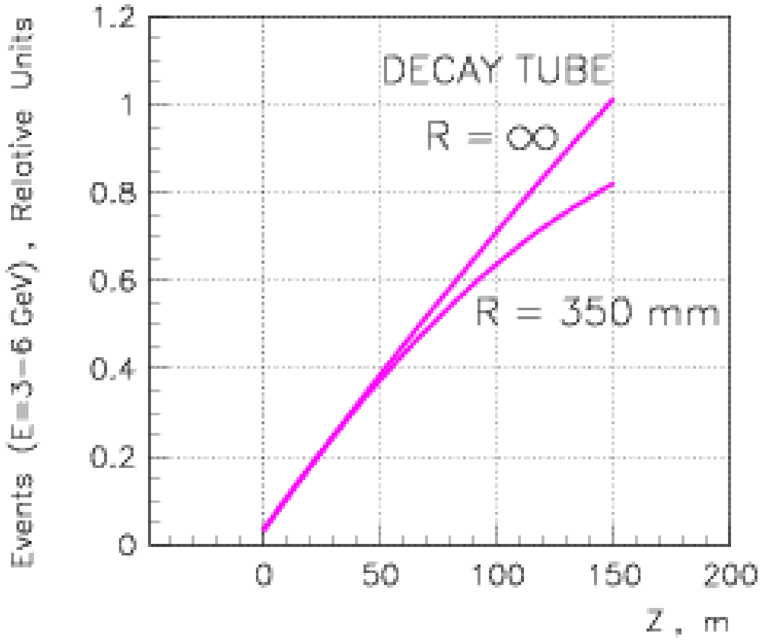
The density function of ν_μN interactions in the far detector:

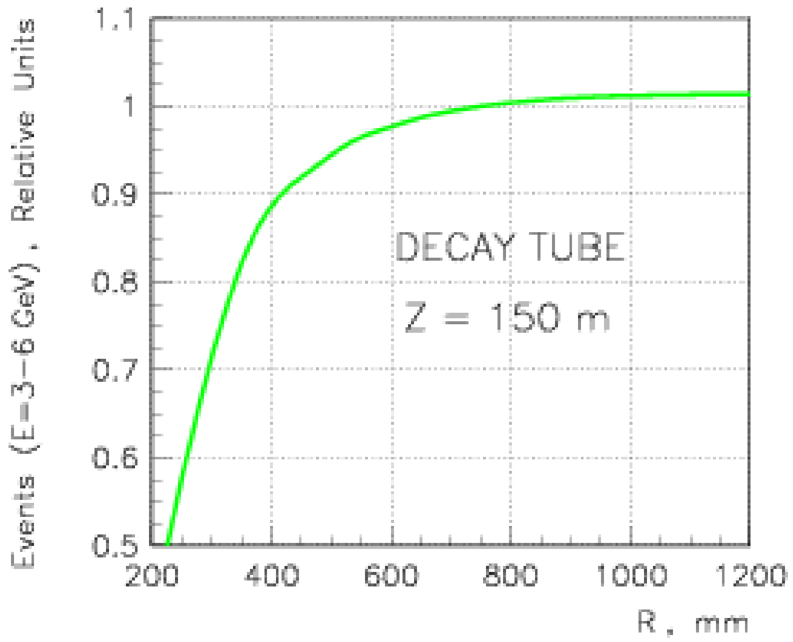
line **1** – estimate for the π-mesons beam momentum p_π = 10.9 GeV/c;
line **2** – calculated values along the vertical at x = 0;
line **3** – calculated values along the horizontal at y = 0.



Longitudinal and transverse dimensions of the decay tube

Number of $\nu_\mu N$ events in the far detector in the energy range 3–6 GeV over the length of the decay tube (on the left) and its transverse dimension (on the right). All results are normalized to the number of neutrino events at Z = 150 m and R = 750 mm.





Thus, a weak dependence of the number of $\nu_\mu N$ events on the transverse dimension of the decay tube. For instance, for a length of decay tube of 150 m and its radius of 350 mm, the number of events in the far detector is only by 19% less than the maximally possible. Obviously, a decay segment with a gradually increasing cross section can be used.

Spectra of background neutrinos

When calculating the interaction spectra of both main and background neutrinos, in addition to two-particle decays of $\pi^{\pm}$-mesons, we also modeled the following decays:

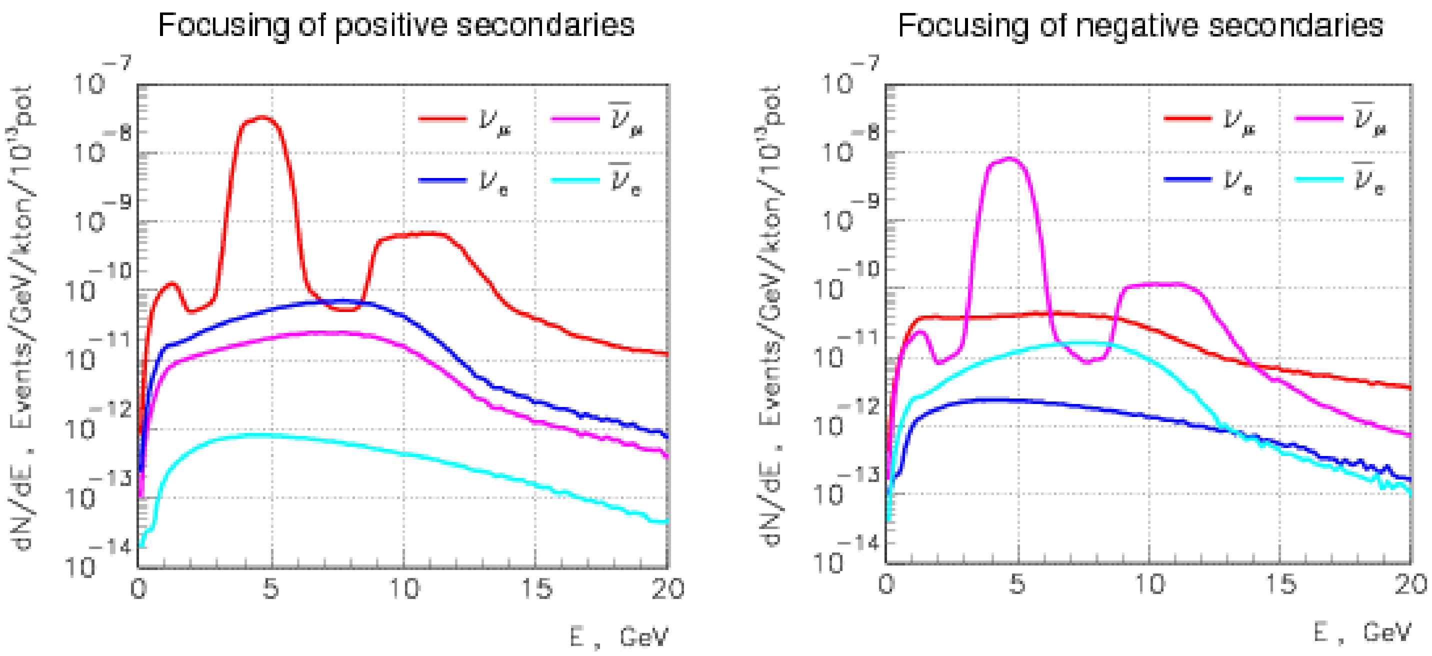
$$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\widetilde{\nu}_{\mu})$$

$$K^{\pm} \rightarrow \pi^{0} + e^{\pm} + \nu_{e}(\widetilde{\nu}_{e})$$

$$K^{0}_{L} \rightarrow \pi^{\mp} + e^{\pm} + \nu_{e}(\widetilde{\nu}_{e})$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\widetilde{\nu}_{e}) + \widetilde{\nu}_{\mu}(\nu_{\mu})$$

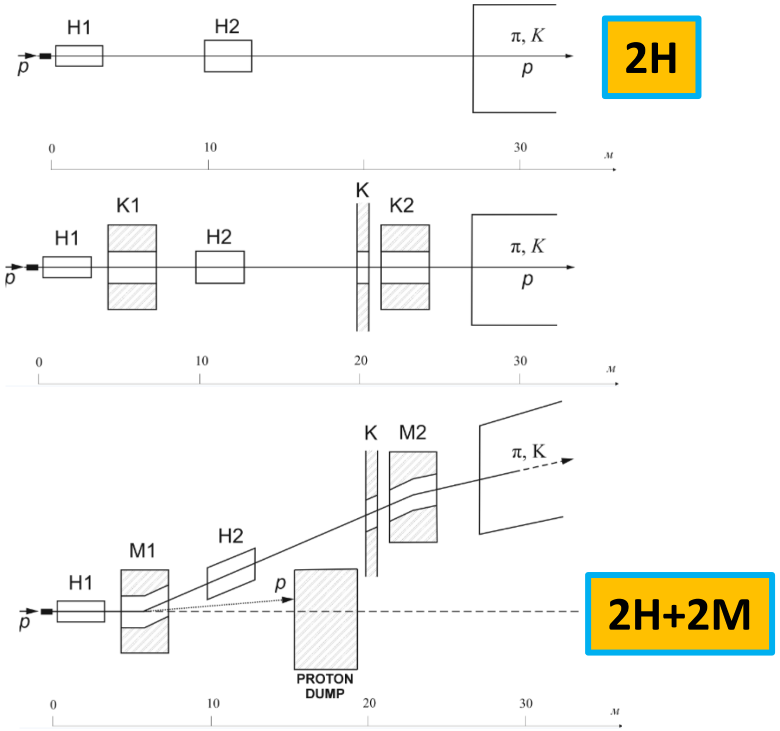
The νN interaction spectra of both main and background neutrinos in the far detector.

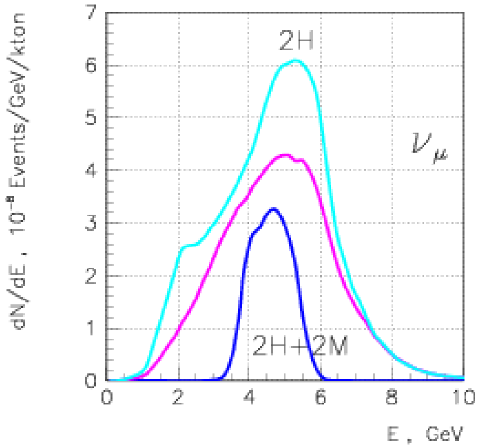


E, GeV	Focusing of positive secodaries			Focusing of negative secodaries		
	ν_μ	$\widetilde{\nu}_\mu+\nu_e+\widetilde{\nu}_e$		$\widetilde{\nu}_\mu$	$\nu_\mu+\nu_e+\widetilde{\nu}_e$	
0–60	$5.56\cdot10^{-8}$	$7.37\cdot10^{-10}$	1.33%	$1.34\cdot10^{-8}$	$6.19\cdot10^{-10}$	4.62%
3–6	$5.25\cdot10^{-8}$	$2.03\cdot10^{-10}$	0.39%	$1.29\cdot10^{-8}$	$1.61\cdot10^{-10}$	1.25%

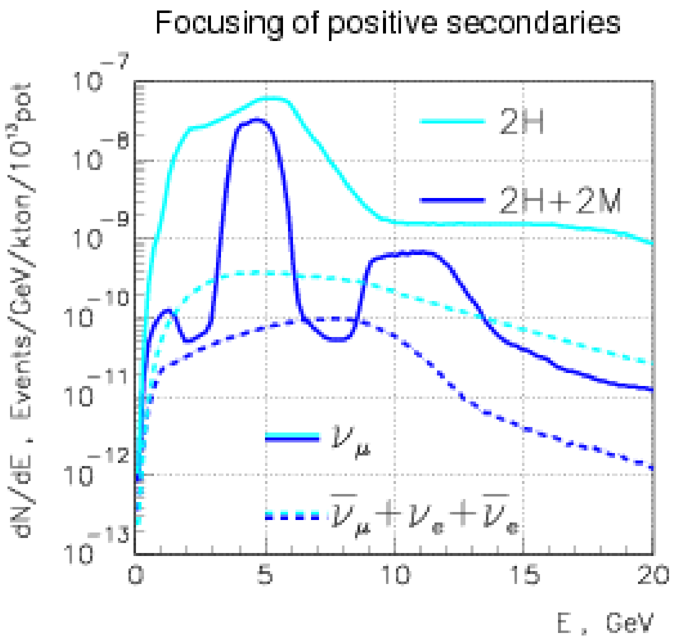
The total number of the νN events of both main and background neutrinos in the far detector.

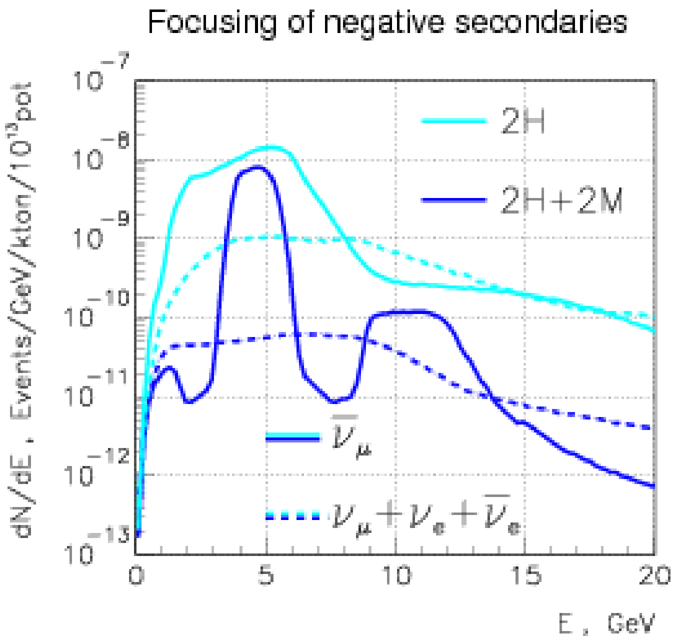
Comparison of 2H+2M and 2H focusing system





The νN interaction spectra of both main and background neutrinos in the far detector.





	E, GeV	Focusing of positive secodaries			Focusing of negative secodaries		
		ν_μ	$\tilde{\nu}_\mu+\nu_e+\tilde{\nu}_e$		$\tilde{\nu}_\mu$	$\nu_\mu+\nu_e+\tilde{\nu}_e$	
2H+2M	0–60	$5.56\cdot10^{-8}$	$7.37\cdot10^{-10}$	1.33%	$1.34\cdot10^{-8}$	$6.19\cdot10^{-10}$	4.62%
	3–6	$5.25\cdot10^{-8}$	$2.03\cdot10^{-10}$	0.39%	$1.29\cdot10^{-8}$	$1.61\cdot10^{-10}$	1.25%
2H	0–60	$2.52\cdot10^{-7}$	$3.63\cdot10^{-9}$	1.44%	$5.51\cdot10^{-8}$	$1.12\cdot10^{-8}$	20.3%
	3–6	$1.48\cdot10^{-7}$	$1.07\cdot10^{-9}$	0.72%	$3.49\cdot10^{-8}$	$2.92\cdot10^{-9}$	8.37%

The total number of the νN events of both main and background neutrinos in the far detector.

Conclusions

In this paper we considered the neutrino channel based on two 220 kA pulsed magnetic horns and two bend dipoles for the formation of neutrino beams with a narrow energy spectrum at the U–70 accelerator complex for the P2O experiment. To organize the channel, it is assumed to use a fast extracted proton beam with an energy of 60 GeV.

To select the required momentum interval of the π-mesons two dipole magnets with opposite polarity is proposed to use. By rotating the decay part of the channel with respect to the primary proton beam directed to the target, we minimize the content of background neutrinos in the main beam of muon neutrinos (antineutrinos) compared to a direct channel with two magnetic horns.

The far detector of the P2O experiment is located at a distance of 2595 km from the end of the decaying part of the neutrino channel. The magnetooptic scheme of the channel is optimized for the formation of muon neutrinos and antineutrinos beam in the energy range 3–6 GeV at the detector, which corresponds to the energy of the first oscillation maximum $\nu_\mu \leftrightarrow \nu_e$ ~4.5 GeV for the distance of 2595 km to the detector.

The main calculated parameters of the π-mesons at the decay tube beginning, characteristics of the neutrino beam at the far detector of P2O experiment and fast calculation algorithm of $\nu_\mu N$ interactions in the far detector were discussed.

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