7TH INTERNATIONAL CONFERENCE ON PARTICLE PHYSICS AND ASTROPHYSICS (ICPPA-2024)

OCTOBER 22–25

MOSCOW RUSSIA

Calculation of the sensitivity of the CP-violation phase measurement in the lepton sector in the P2O experiment

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23.10.2024

Outline

- Protvino to ORCA (P2O) project
- Neutrino beams for the P2O experiment
- Sensitivity of the δ_{CP} measurement comparision
- Neutrino tagging concept
- Conclusion

NEUTRINO OSCILLATION

PMNS matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & \tilde{s}_{13}^{*} \\ -s_{12}c_{23} - c_{12}\tilde{s}_{13}s_{23} & c_{12}c_{23} - s_{12}\tilde{s}_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}\tilde{s}_{13}c_{23} & -c_{12}s_{23} - s_{12}\tilde{s}_{13}c_{23} & c_{13}c_{23} \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$

θ_{ij} [0, π/2] neutrino mixing angles

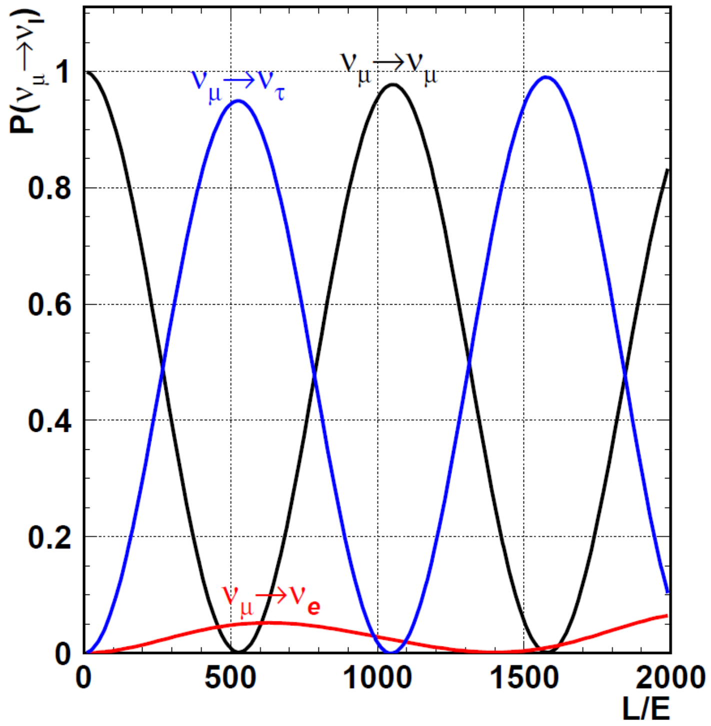
$\tilde{s}_{13} = s_{13}e^{i\delta_{CP}}$ δ_{CP} [0, 2π] CP violation phase

Unknown - CP violation phase δ_{CP},

Δm_{13}^2 sign (neutrino mass hierarchy)

Neutrino oscillation experiments have previously measured **three mixing angles** and their squared mass differences: $\Delta m_{12}^2 = m_1^2 - m_2^2$, $\Delta m_{23}^2 = m_2^2 - m_3^2$.

Appearance and Disappearance experiments



1[st] oscillation maximum $\nu_\mu \to \nu_{e,\tau}$

at ***L/E* ~ 533 km/GeV**

$(\ 1.27\Delta m^2_{23}(эВ^2)L(км)/E(ГэВ) = \pi/2 \ )$

P2O	P2B(aikal)	P2Bak(san)
L ~ 2600 km	4200 km	1600 km
E ~ 4.9 GeV	7.9 GeV	3.0 GeV

$(\ \Delta m^2_{12} L/2E \ll 1 \ )$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \cdot \sin^2(1.27\Delta m^2_{23} \frac{L}{E}) \approx 0.05 \cdot \sin^2(1.27\Delta m^2_{23} \frac{L}{E})$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 \underline{2\theta_{23}} \cdot \cos^4 \theta_{13} \cdot \sin^2(1.27\underline{\Delta m^2_{23}} \frac{L}{E}) - P(\nu_\mu \to \nu_e)$$

Measure $N_{\nu_\mu}, N_{\nu_e}, N_{\nu_\tau}$ as a function of ***L/E*** to measure the PMNS matrix parameters

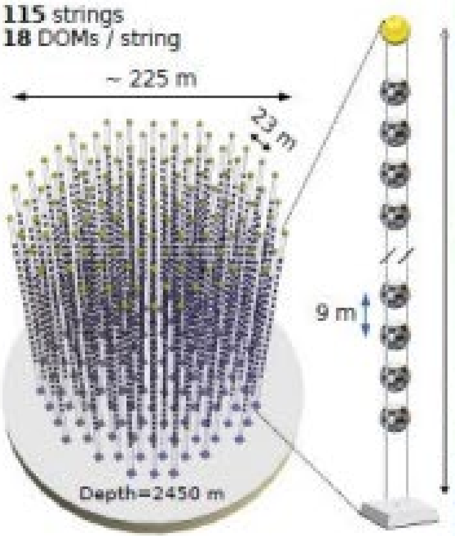
Protvino to ORCA project

P2O

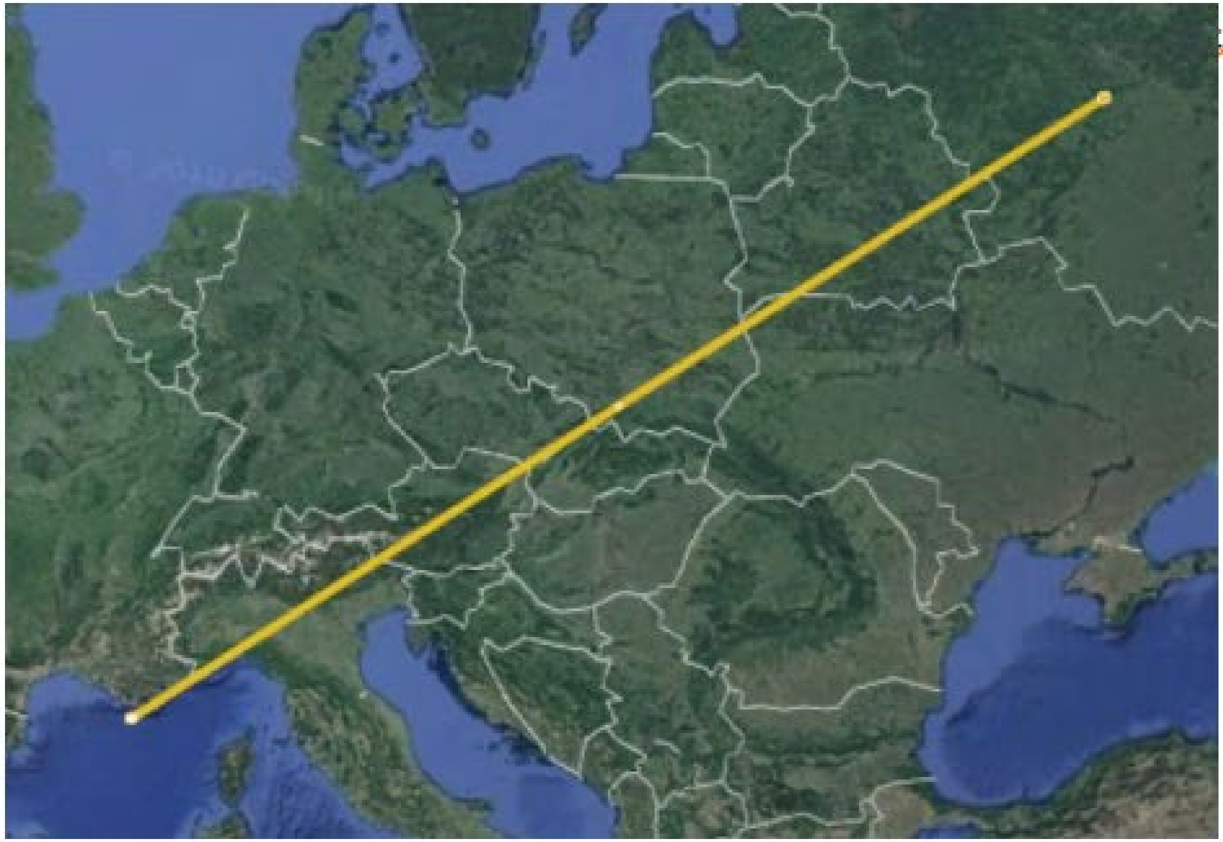
Experimental scheme

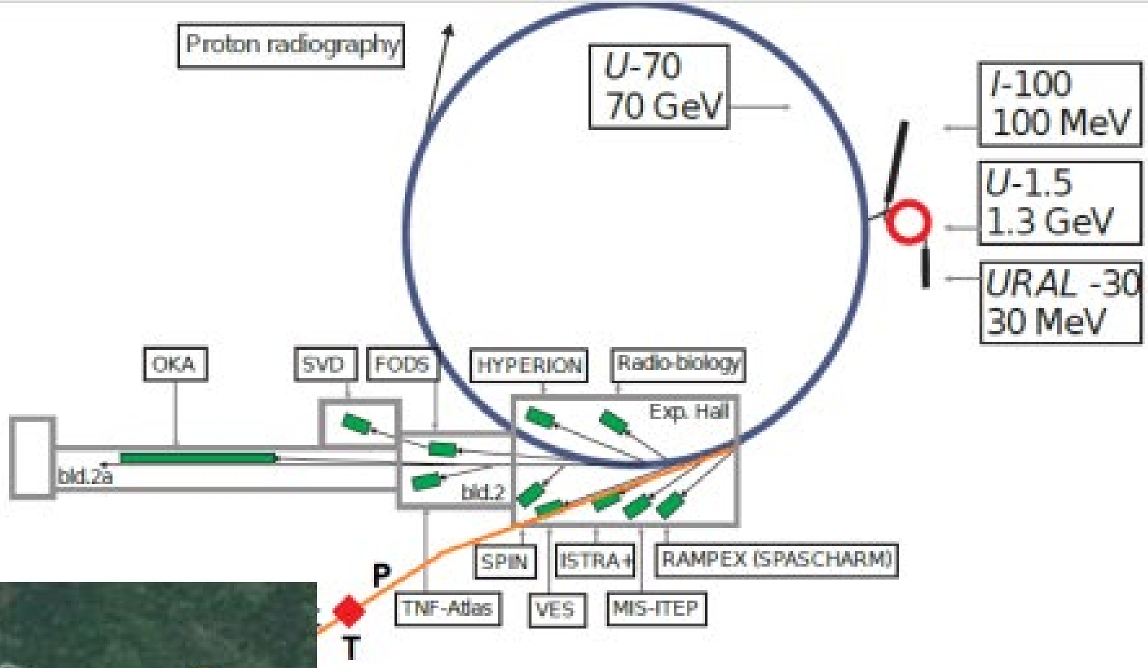
LOI, Eur. Phys. J. C (2019) 79,758

Detector mass
8 Mt



L = 2595 km





E=69 GeV

I = $5\cdot10^{13}$ ppp

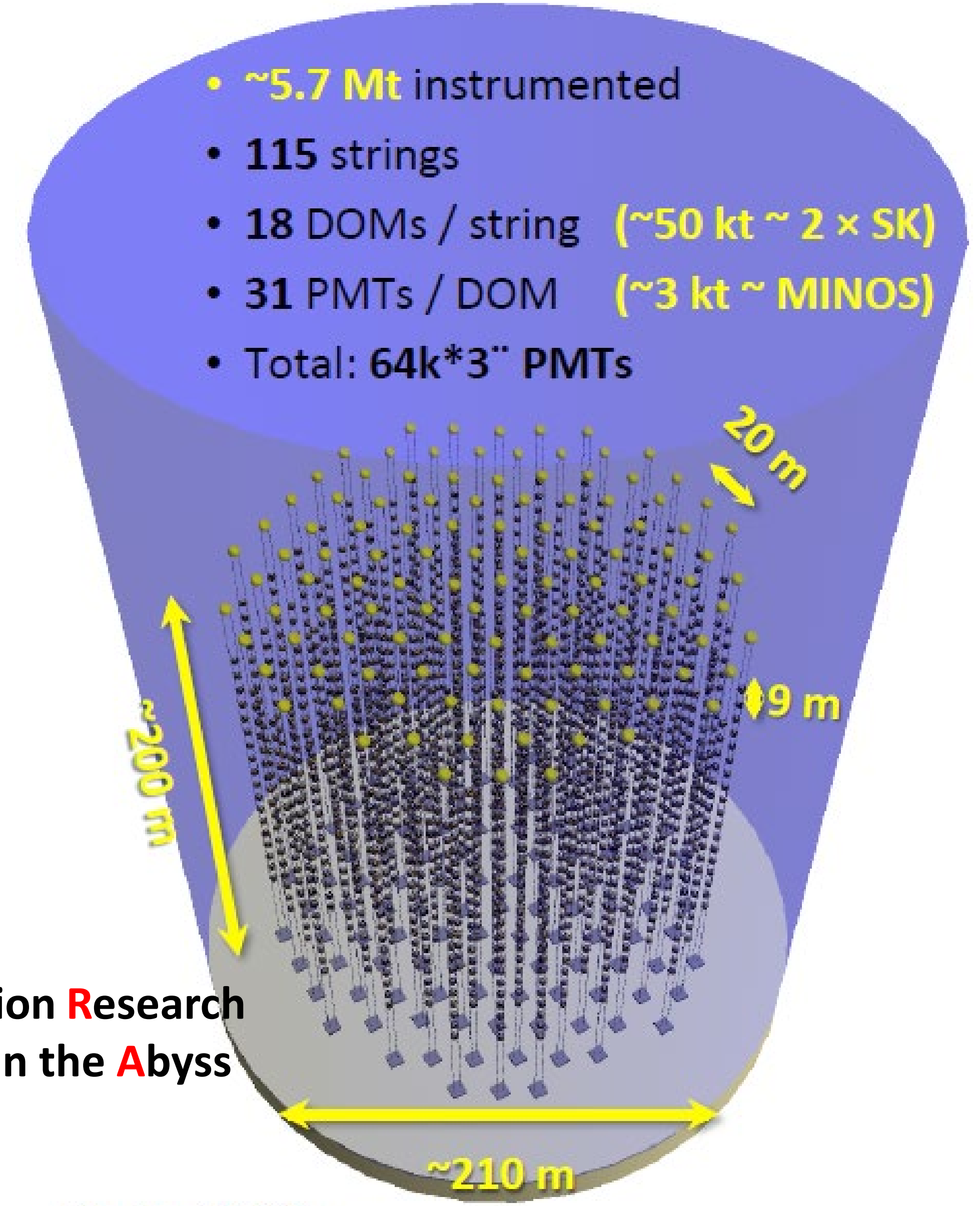
T_c = 7,3 sec

Phase I 90 kW

$0.8\cdot 10^{20} POT/yr$

The ORCA Detector

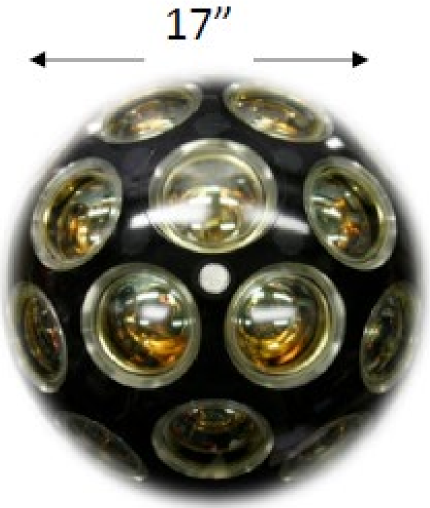
8 Mt



ORCA: Oscillation Research with Cosmics in the Abyss

Depth=2475m

Digital Optical Module

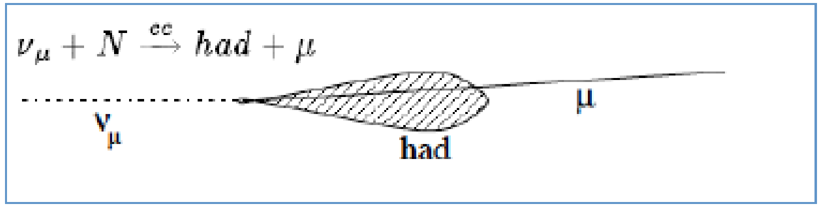


- 31 x 3" PMTs
- Uniform angular coverage
- Directional information
- Digital photon counting
- Background rejection
- All data to shore

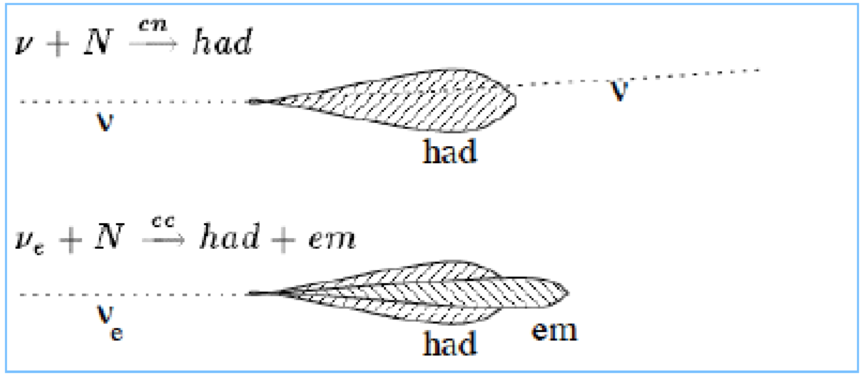
See P1.095: R. Bruijn, The KM3NeT DOM

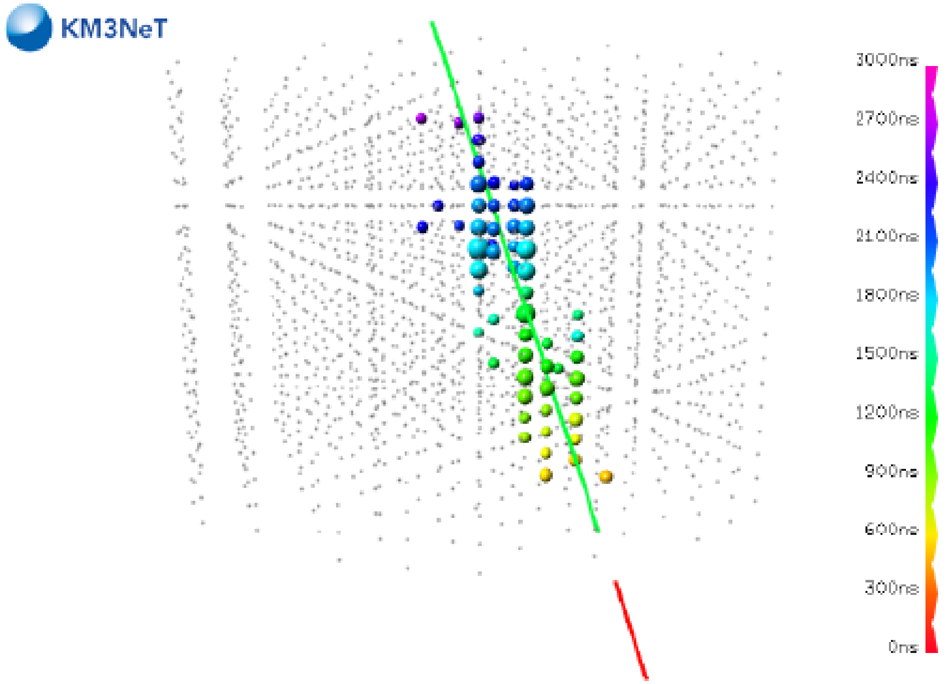
Event Topologies

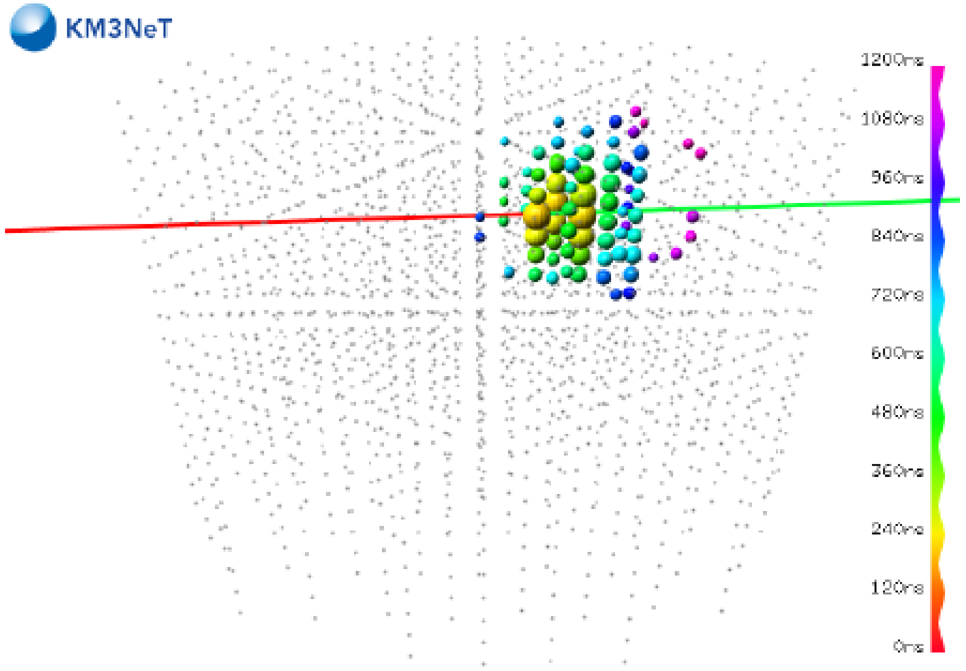
Track-like (ν_μ^{CC})



shower-like (ν^{NC}, ν_e^{CC})

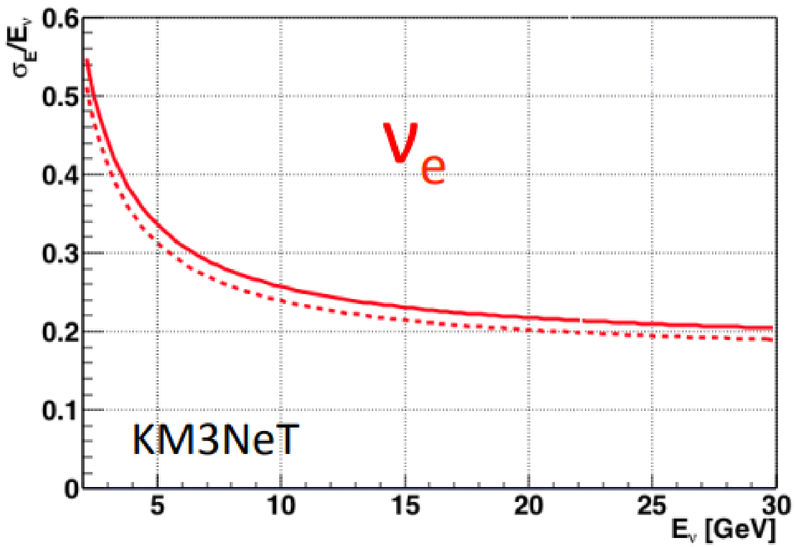




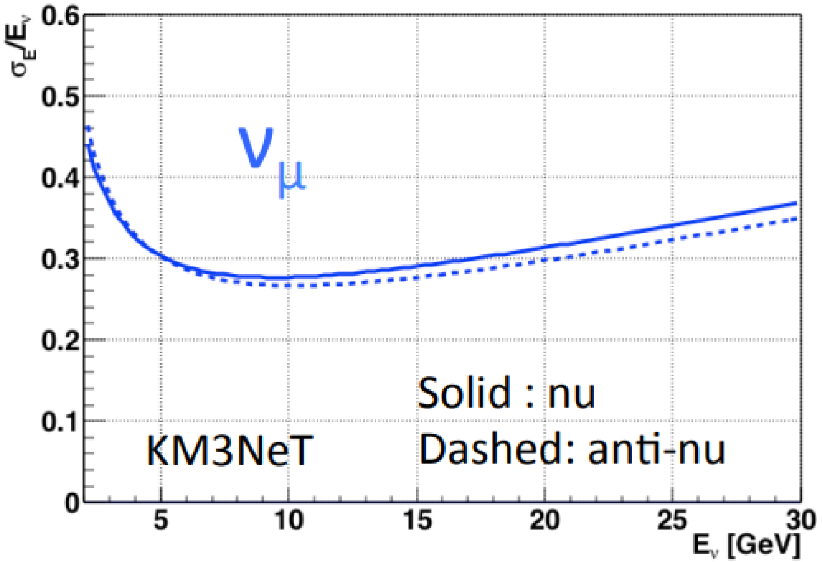


Energy Resolutions

Shower

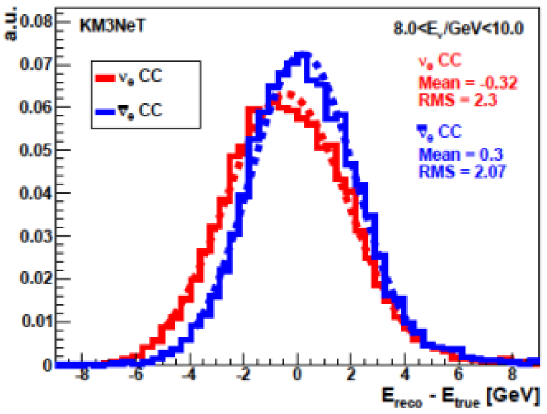


Track



$$\nu_\mu N \to \mu^- X$$

- Energy resolution better than 30% in relevant range
- Close to Gaussian



δ_{CP} measurement. Important variables

1. ν_μ , ν_e , ν_τ **events separation**

Background (E_ν ~ 5 GeV)

	eff. (track-like, 9 m spacing)	eff. (shower-like)
$\nu_\mu N$ (CC ev)	0.52	0.48
$\nu_e N$ (CC ev)	0.12	0.88
νN (NC ev)	0.17	0.83
$\nu_\tau N$ (CC ev)	0.25	0.75

detector

2. **Event energy measurement - $\Delta E_\nu/E_\nu$?**

- detector $\Delta E_\nu/E_\nu$ ~ **30%** (at E_ν ~ 5 GeV)
- monochromatic neutrino beam $\Delta E_\nu/E_\nu$ ~ **6 - 10%**
- tagging neutrino $\Delta E_\nu/E_\nu$ ~ **1 - 5%**

detector/beam

3. **Event statistics** (M_{Det}, P_{pr})

detector/beam

4. **Beam background** $\bar{\nu}_\mu, \nu_e, \bar{\nu}_e$

beam

Федеральное государственное бюджетное учреждение

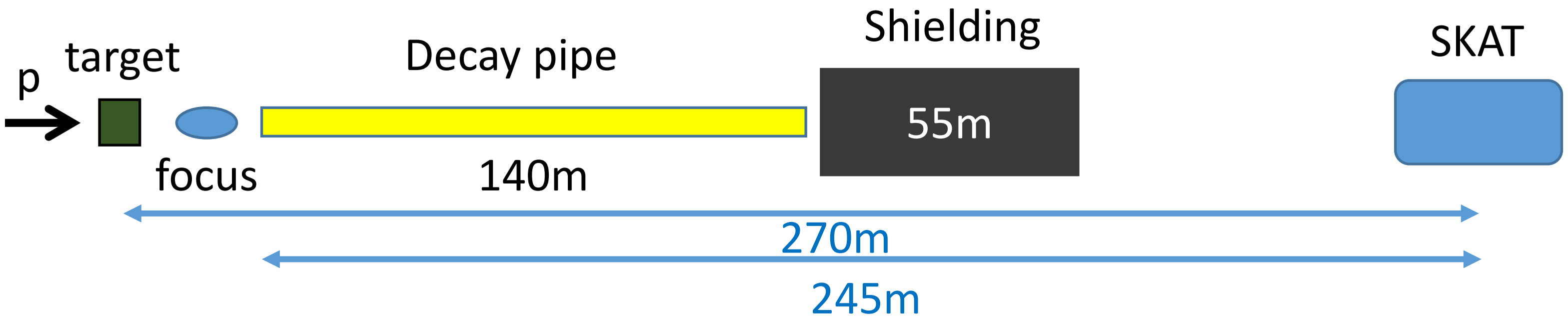
«ИНСТИТУТ ФИЗИКИ ВЫСОКИХ ЭНЕРГИЙ

имени А.А.Логунова

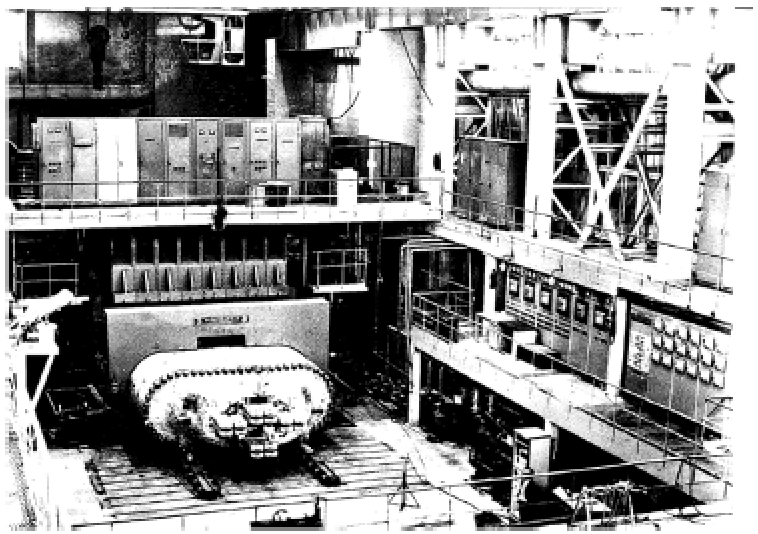
Национального исследовательского центра «Курчатовский институт»

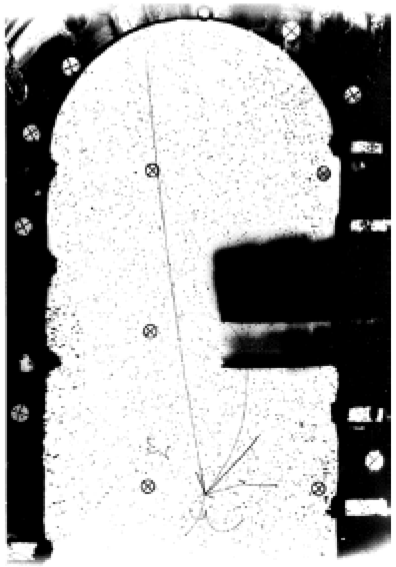
IHEP neutrino experiment (1975 - 2000)

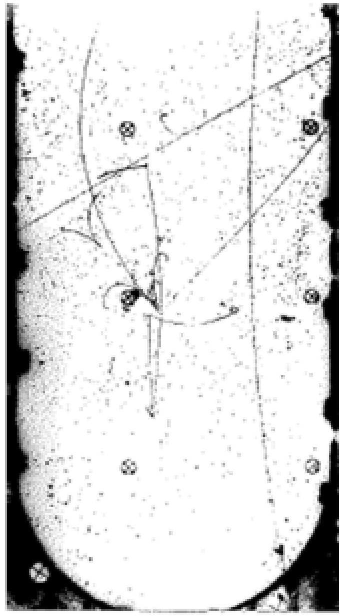
$$p + A \rightarrow \pi(K) + X \qquad \pi(K) \rightarrow \nu_\mu(\nu_e, \bar{\nu}_\mu, \bar{\nu}_e)...$$

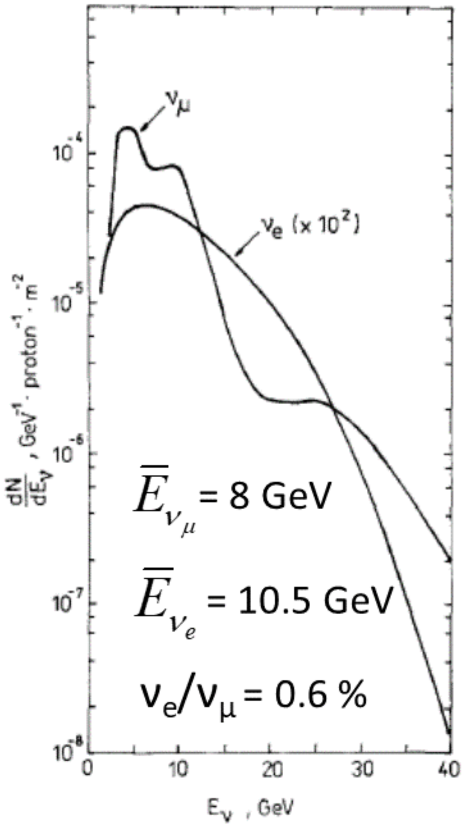


Horn
L=143 cm
Ø=50 cm







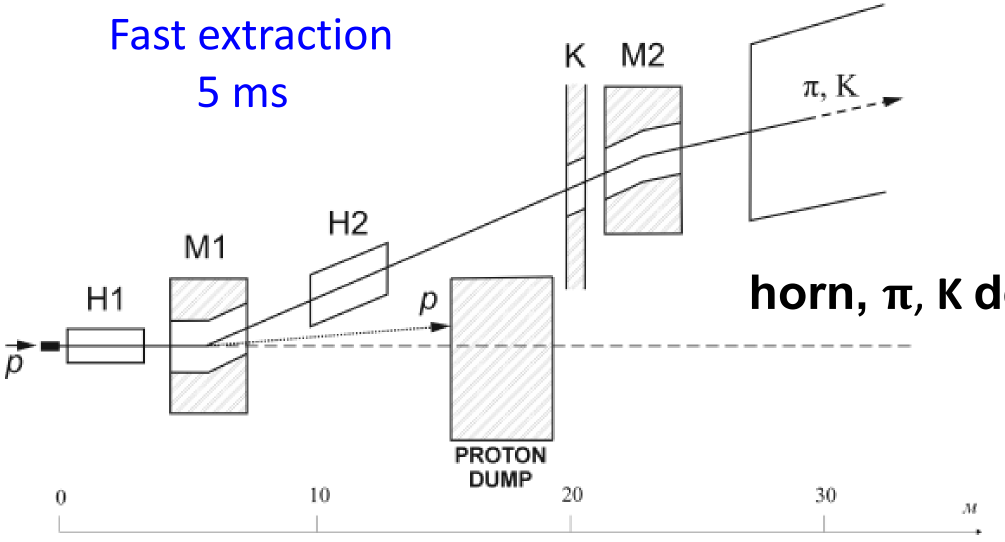


NEUTRINO CHANNELS

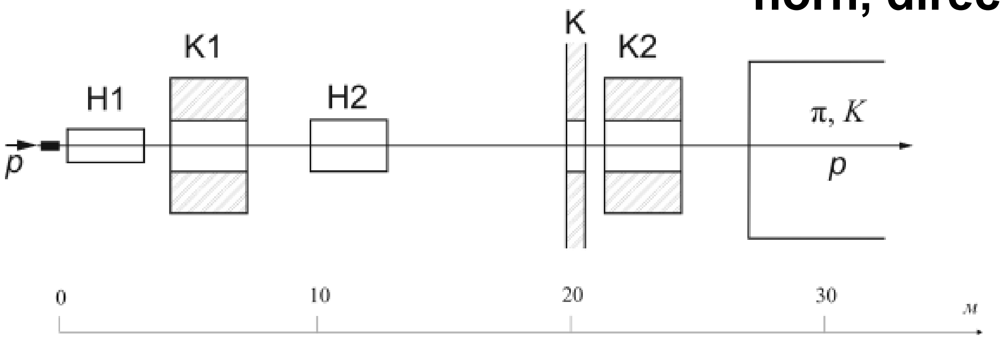
NEUTRINO CHANNELS

Fast extraction
5 ms

horn, π, K deflection

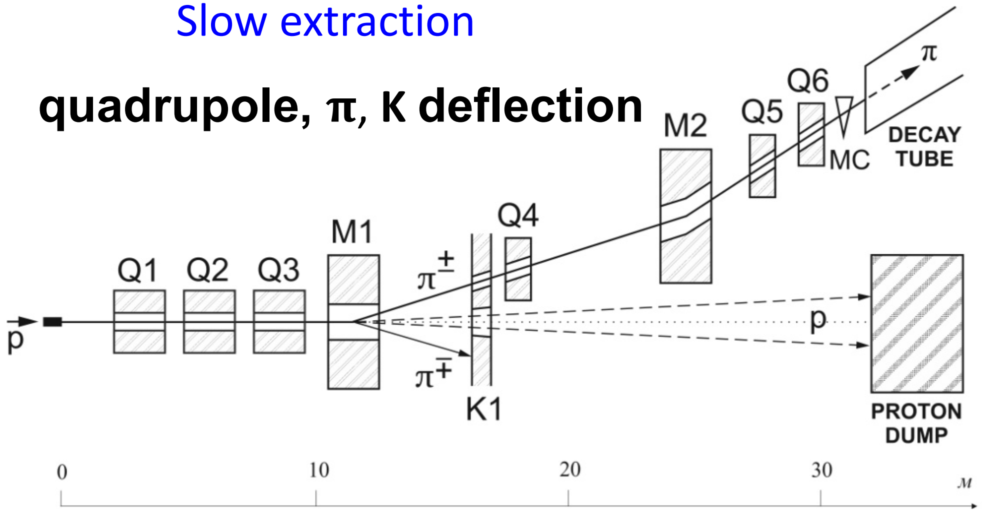


horn, direct



Slow extraction

quadrupole, π, K deflection



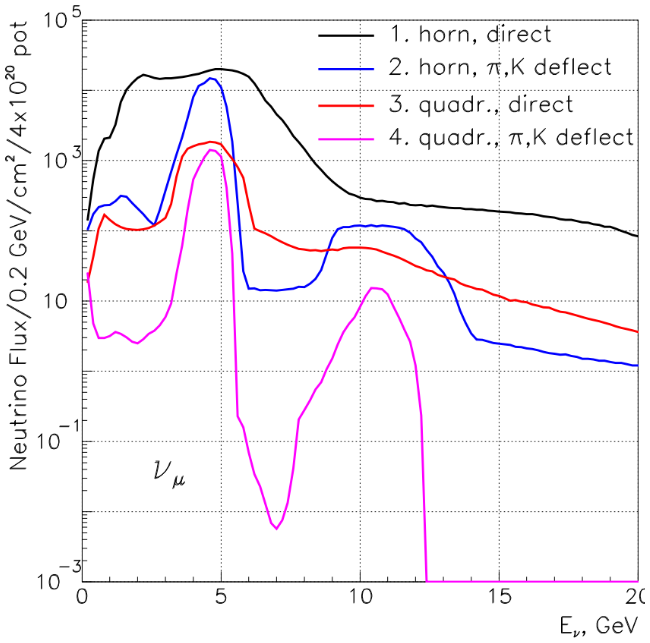
U-70 Accelerator Complex
E = 69 GeV, I = $5 \cdot 10^{13}$ ppp,
T_{cycle} = 7.3 sec

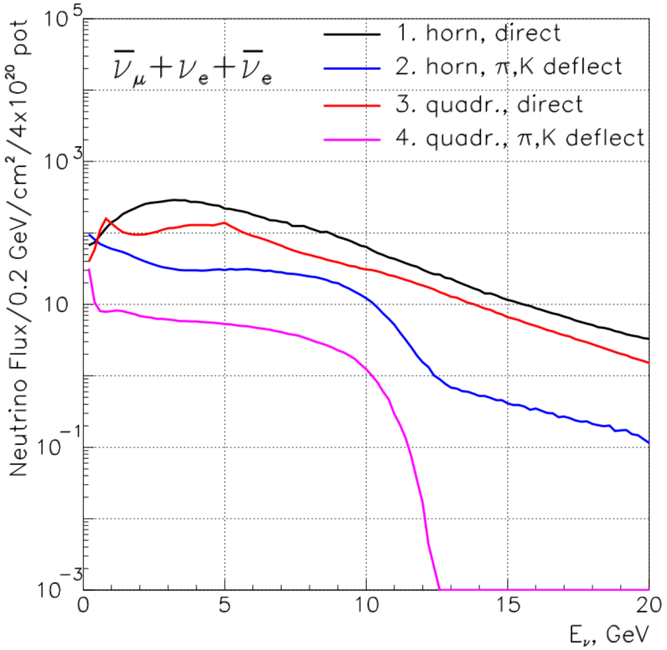
Phase I 90 kW
$0.8 \cdot 10^{20}$ POT/yr

Schematic plans of the initial part of neutrino channels

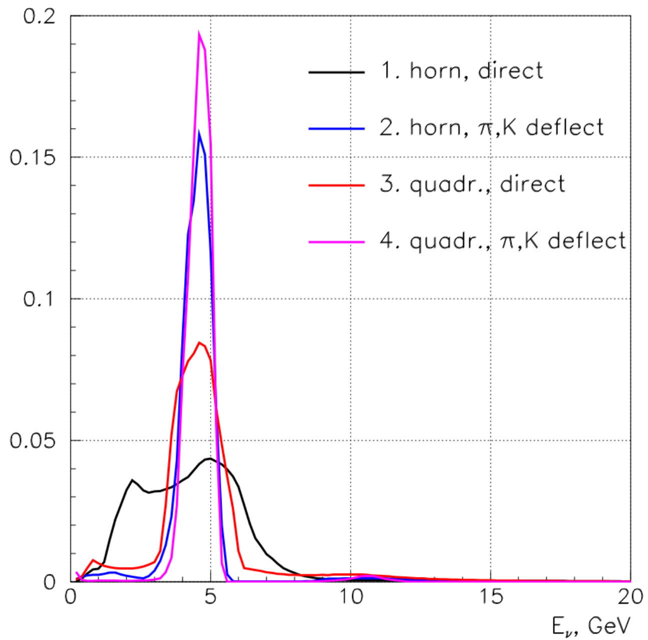
NEUTRINO FLUXES

Focusing of positive secondaries





Phase II 450 kW
$4 \cdot 10^{20}\ POT/yr$



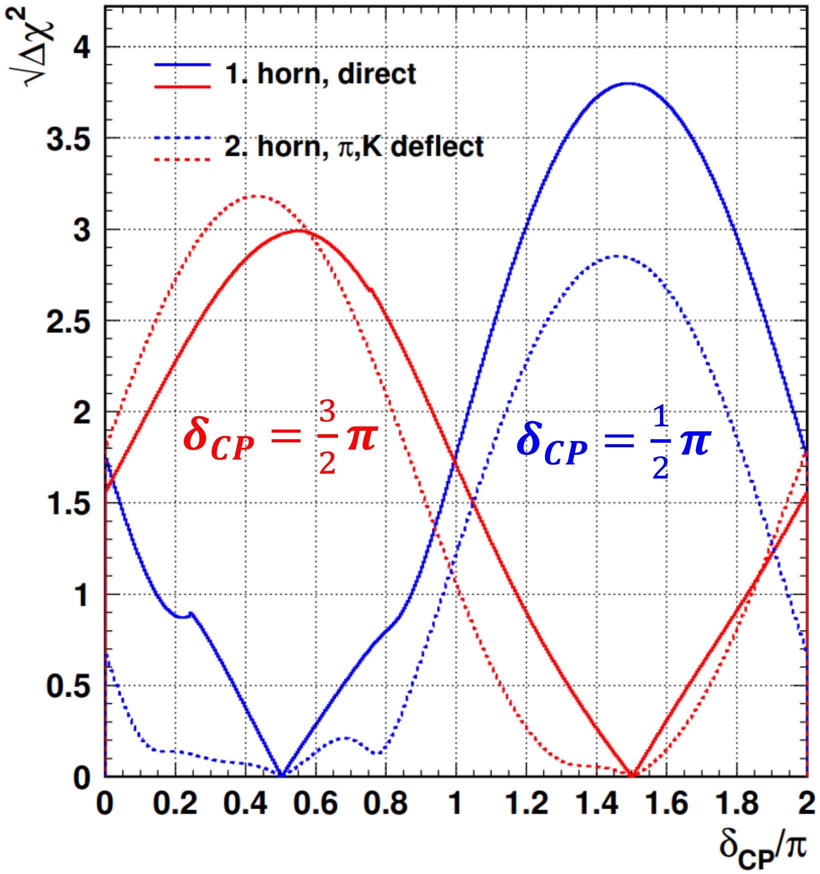
Chan.	$E(\nu_\mu)$, GeV	$\Delta E(\nu_\mu)/E(\nu_\mu)$, %	$N(\nu_\mu)$, ev	$N(\nu,bkg)/N(\nu_\mu)$ %
1	0-60	**40.6**	**66950**	**1.44**
	3-6		**40090**	**0.72**
2	0-60	**9.6**	**14100**	**1.32**
	3-6		**13120**	**0.39**
3	0-60	**16.7**	**3680**	**13.9**
	3-6		**2880**	**5.65**
4	0-60	**7.0**	**1120**	**2.22**
	3-6		**1070**	**0.84**

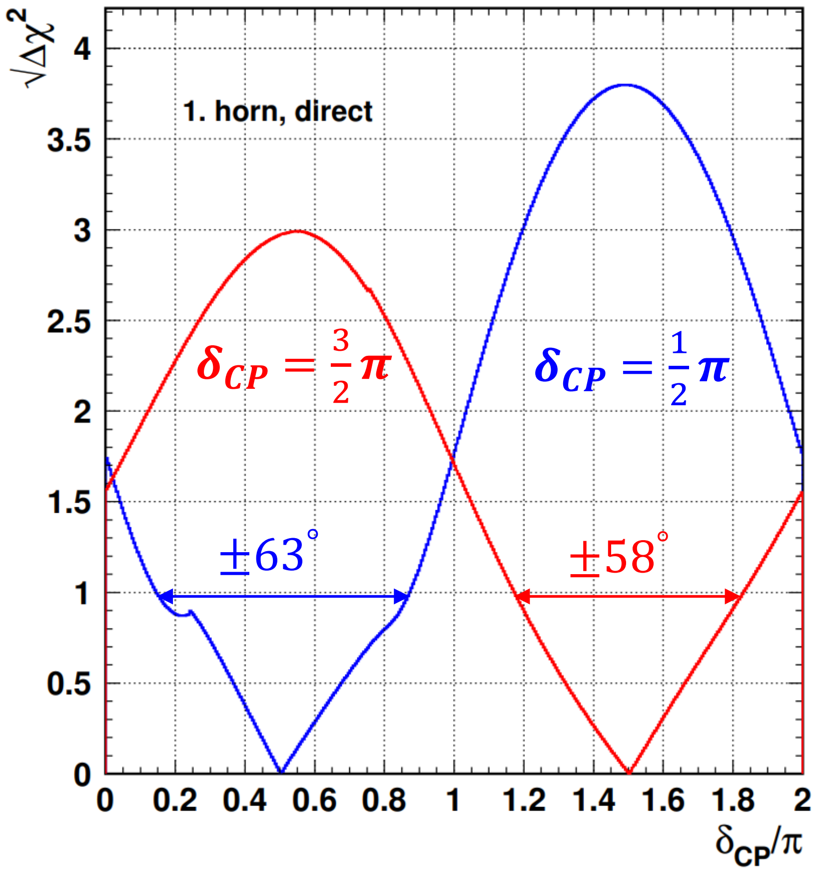
δ_{CP} sensitivity

Phase II 450 kW
3 years
$12 \cdot 10^{20}$ *POT*

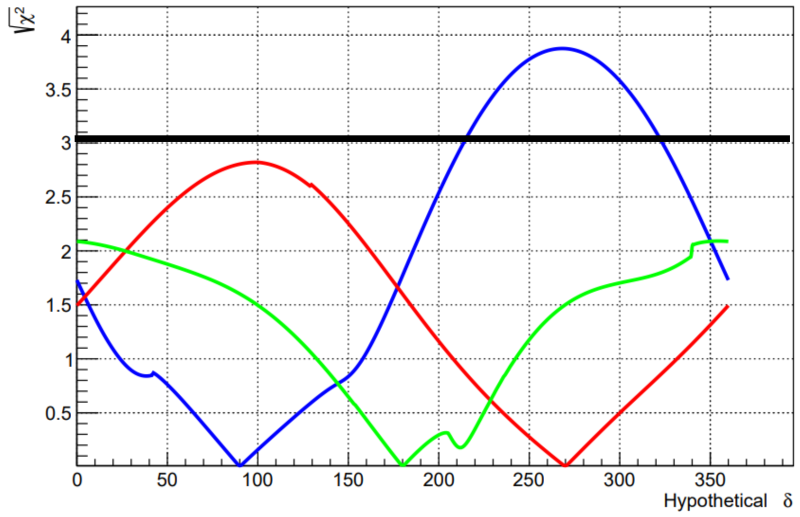
GloBES

Method: χ^2 minimization assuming a test δ_{CP} value and simultaneously fitting oscillation and nuisance parameters





δ_{CP} sensitivity (1)



horn, direct

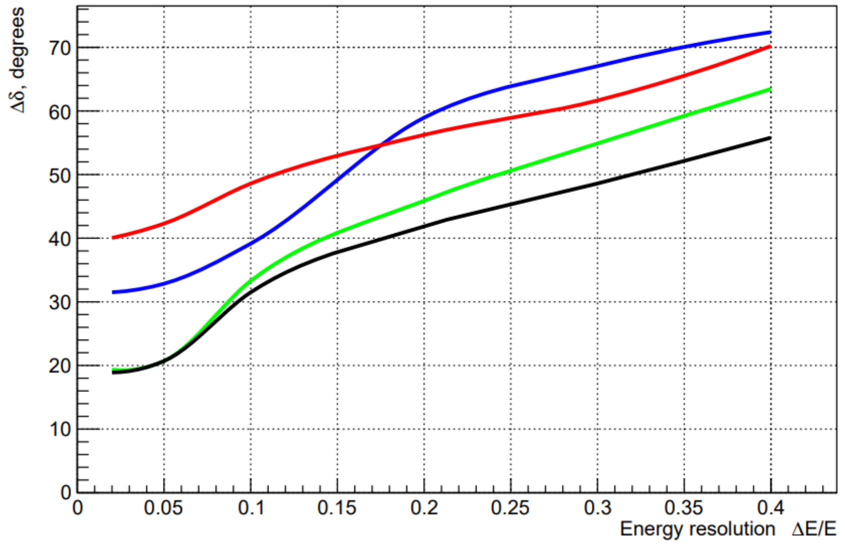
$\delta_{CP} = \frac{1}{2}\pi$

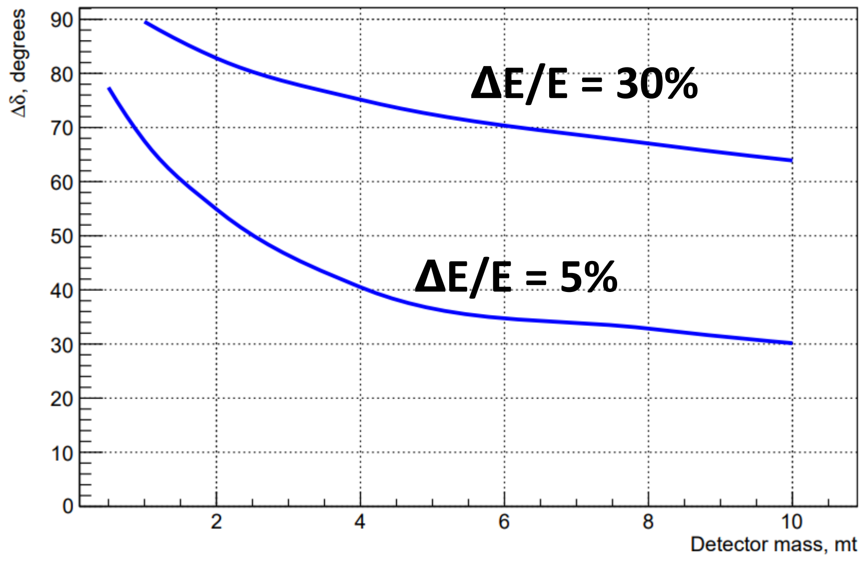
$\delta_{CP} = \pi$

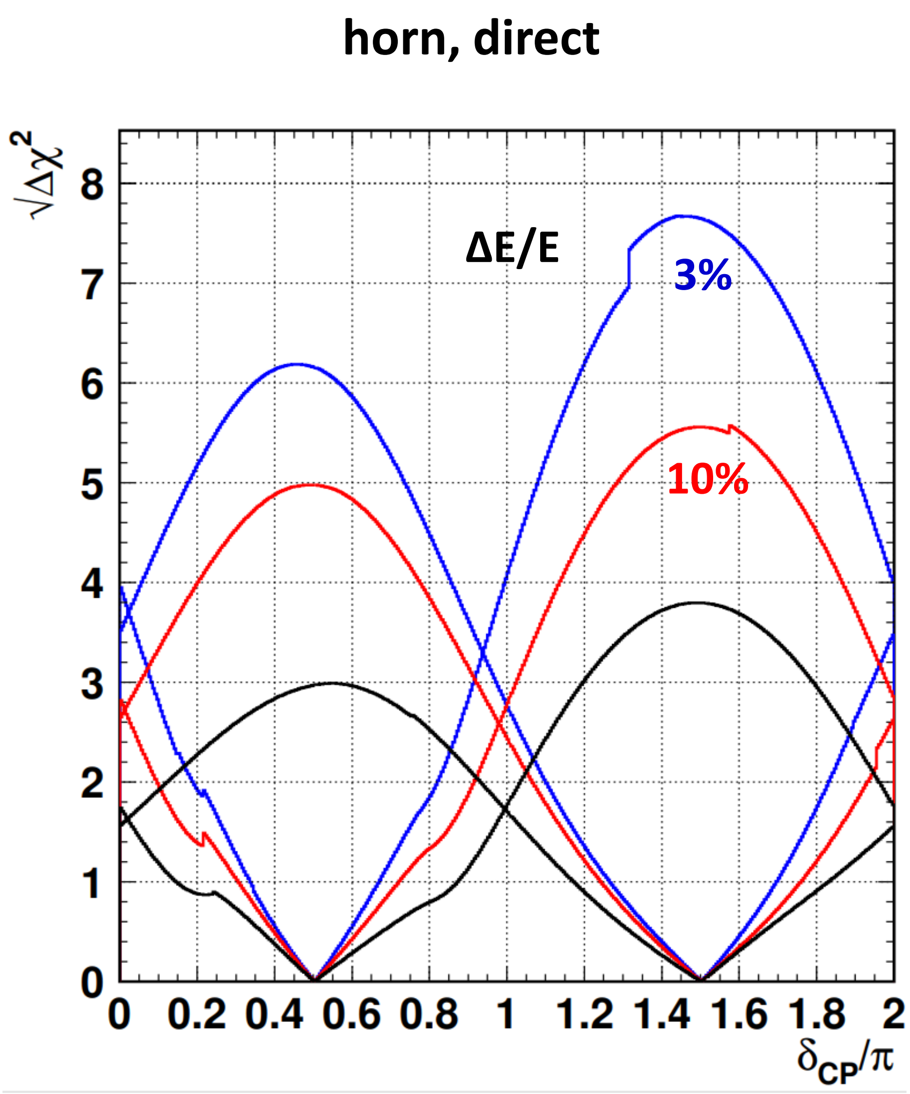
$\delta_{CP} = \frac{3}{2}\pi$

$\delta_{CP} = 0$

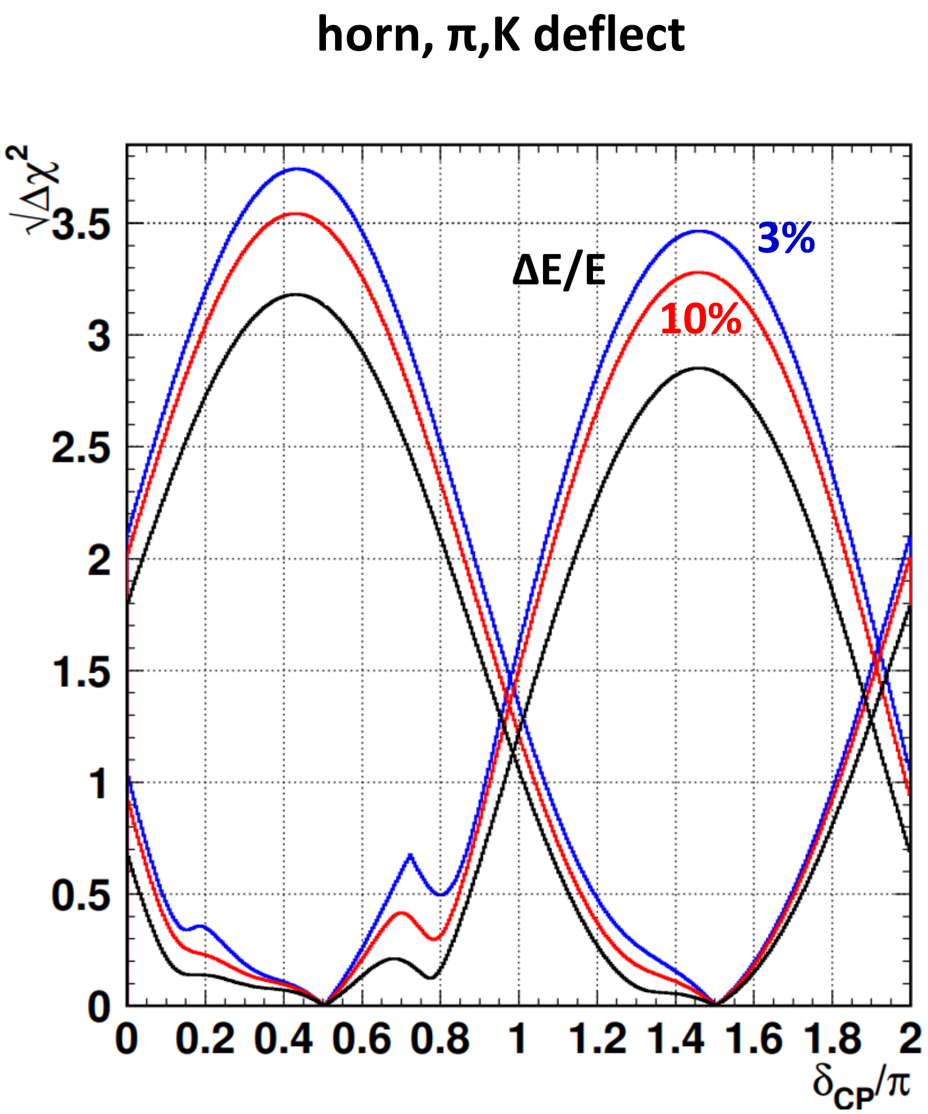
Phase II 450 kW
3 years
$12 \cdot 10^{20}\ POT$







horn, direct
ΔE/E
3%
10%
$\sqrt{\Delta\chi^2}$
δ_{CP}/π



horn, π,K deflect
ΔE/E
3%
10%
$\sqrt{\Delta\chi^2}$
δ_{CP}/π

NEUTRINO TAGGING STUDY

ν tagging concept

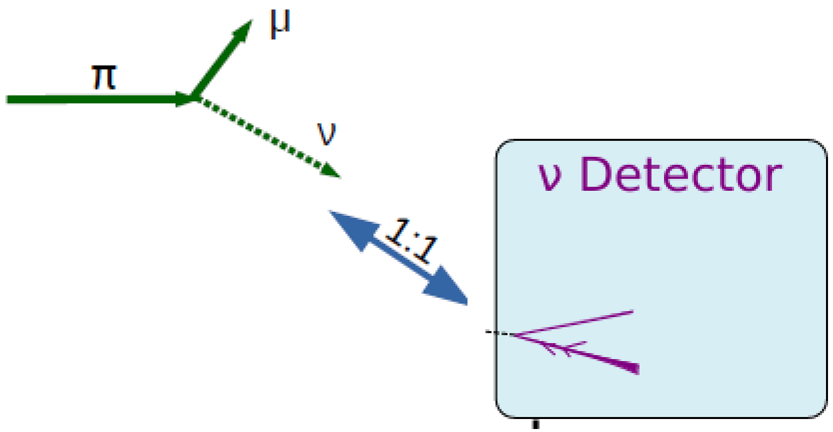
Each neutrino is fully & precisely **characterised from its decay partners**
Similar to old ideas [1] that the **progress on Silicon Trackers** makes now feasible

[1] S. P. Denisov et al., preprint IHEP 80-158, Serpukhov, 1980. Tagged Neutrino Facility at Protvino.

$$\vec{p}_{\nu} = \vec{p}_{\pi} - \vec{p}_{\mu}$$

- Reconstruct **each and all π ➔ μν** decays
  - ✓ ν **energy, direction** and **chirality** precisely known
    - ➢ ν **flux** perfectly determined

Challenge 1
RATE

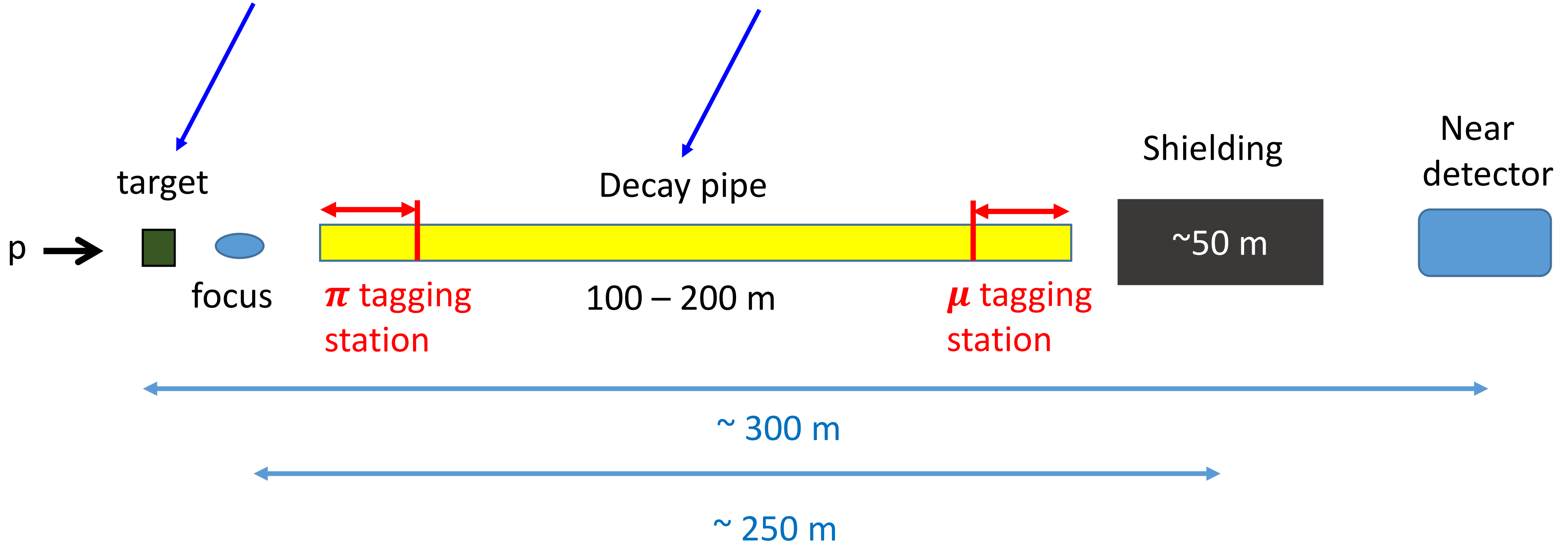


- **Associate each ν seen in ν-detector to its π ➔ μν genitor**
  - ✓ Association done based on time and angular matching
    - ➢ **<1% energy resolution** can be used at ν interaction
    - ➢ **ν and anti-ν** can be **collected together**

Challenge 2
MATCHING

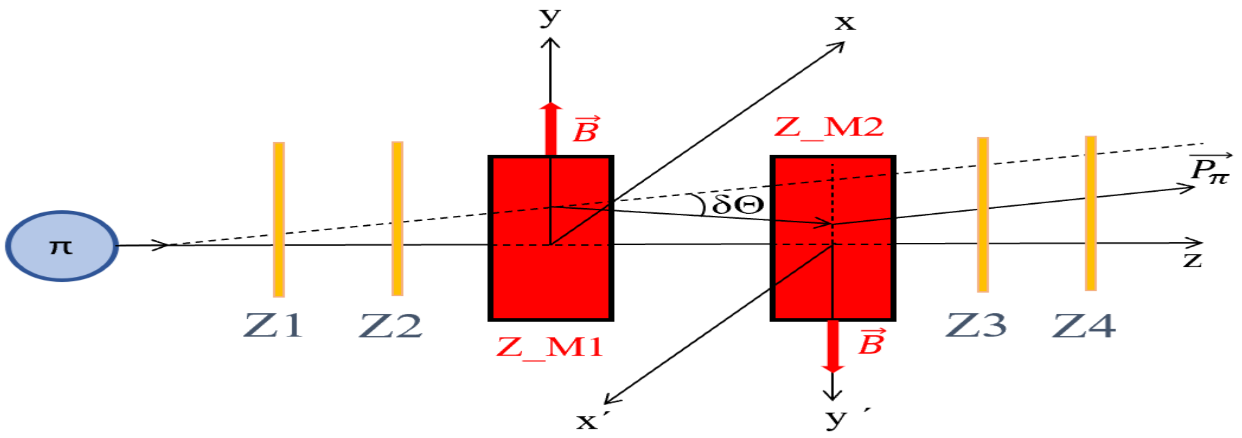
Neutrino channel

$$p + A \to \pi(K) + X \qquad \pi(K) \to \nu_\mu(\nu_e, \bar{\nu}_\mu, \bar{\nu}_e)\ldots$$



Neutrino channel scheme for the formation of "tagged" neutrino beam

π-meson kinematics at the tagging station



Θ_{π_xz} angle measuring in the xz plane

$$\Theta_{\pi_{xz}} = \arctan\left(\frac{x_2 - x_1}{z_2 - z_1}\right)$$

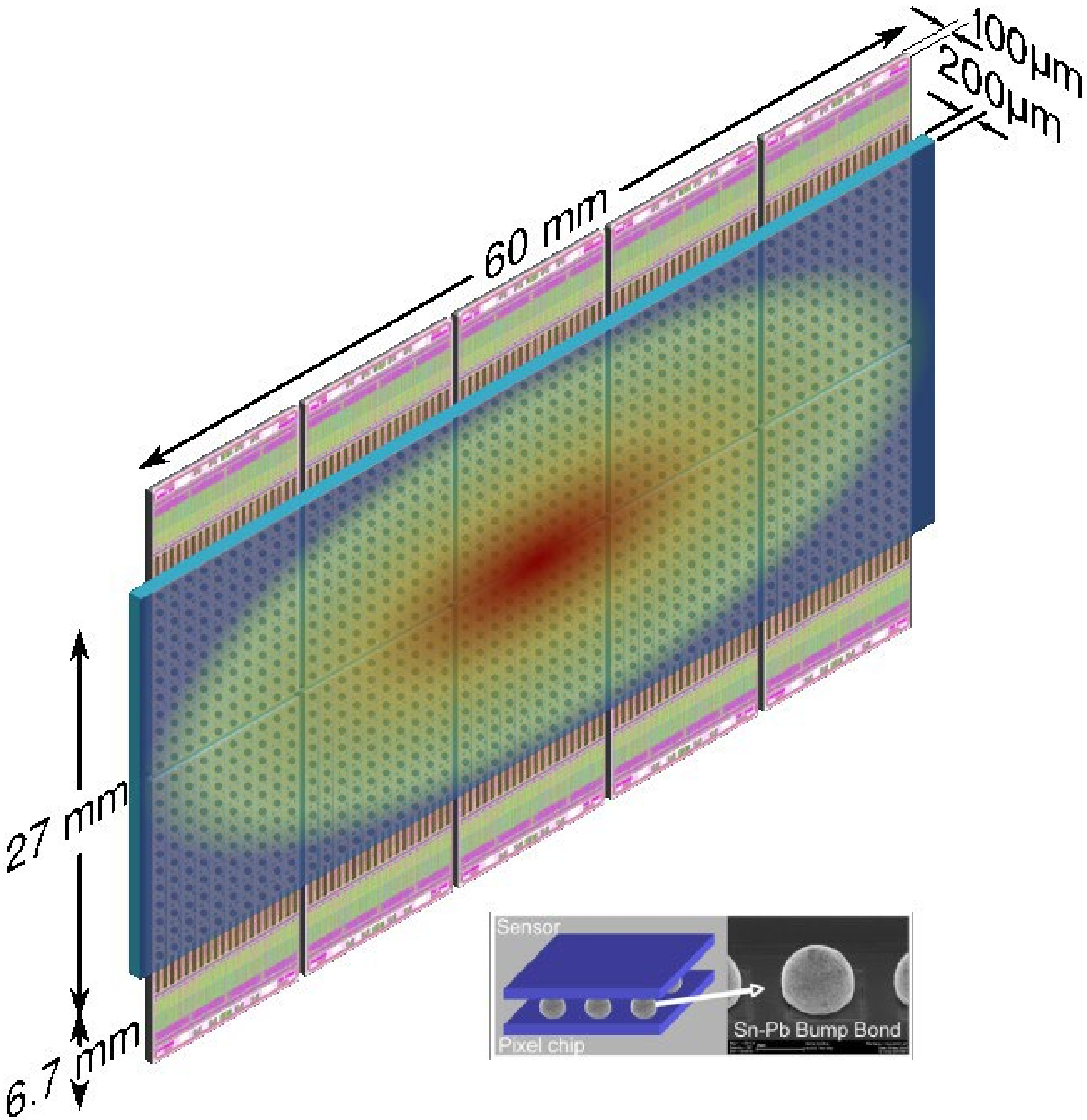
π-meson deflection angle in the xz plane when passing through a magnet

$$\delta\Theta_{\pi_{xz}} = \frac{30\vec{B}L_B}{P_{\pi_{xz}}}$$

The angle shift $\delta\Theta_{\pi\_xz}$ can be determined by measuring the shift in the direction of the π-meson

$$\tan\left(\Theta_{\pi_{xz}} + \delta\Theta_{\pi_{xz}}\right) = \frac{\left(x_3 - \left(\frac{x_2 - x_1}{z_2 - z_1}\right)(z_3 - z_1) + x_1\right)}{L_B} + \tan\left(\Theta_{\pi_{xz}}\right)$$

NA62 at CERN: $K^+ \to \pi^+ \nu\nu$



The sensor

Sensitive region of 27 x 60 mm^2

18000 pixels

n-in-p type

200 µm thick (0.2% X_0)

Bump bonded to 10 ROC

Tagging system occupancy

Geant4

$N_P = 10^{13}\ ppp$ $\quad 6 \cdot 10^{10}\ \pi^+/s$

~ PHASE I

Coordinate planes - **50x50 cm²** **(Si, d ~ 0.5 *mm*)**

Errors in coordinate planes

- coulomb scattering - $\boldsymbol{X/X_0 = 0.5\%}$
- cell structure of the plane **0.1 x 0.1 *mm²***

Time resolution of silicon pixels of coordinate detectors 100 ps (10^{-10} sec). Beam stretch 1 sec.

Loading of π tagging station coordinate planes ~ **6.0 · 10¹⁰** particles / plane /sec.

Loading of μ tagging station coordinate planes:

2.7 · 10¹⁰ particles / plane /sec (1st plane) (~π^+),

2.45 · 10¹⁰ particles / plane /sec (last plane) (~π^+),

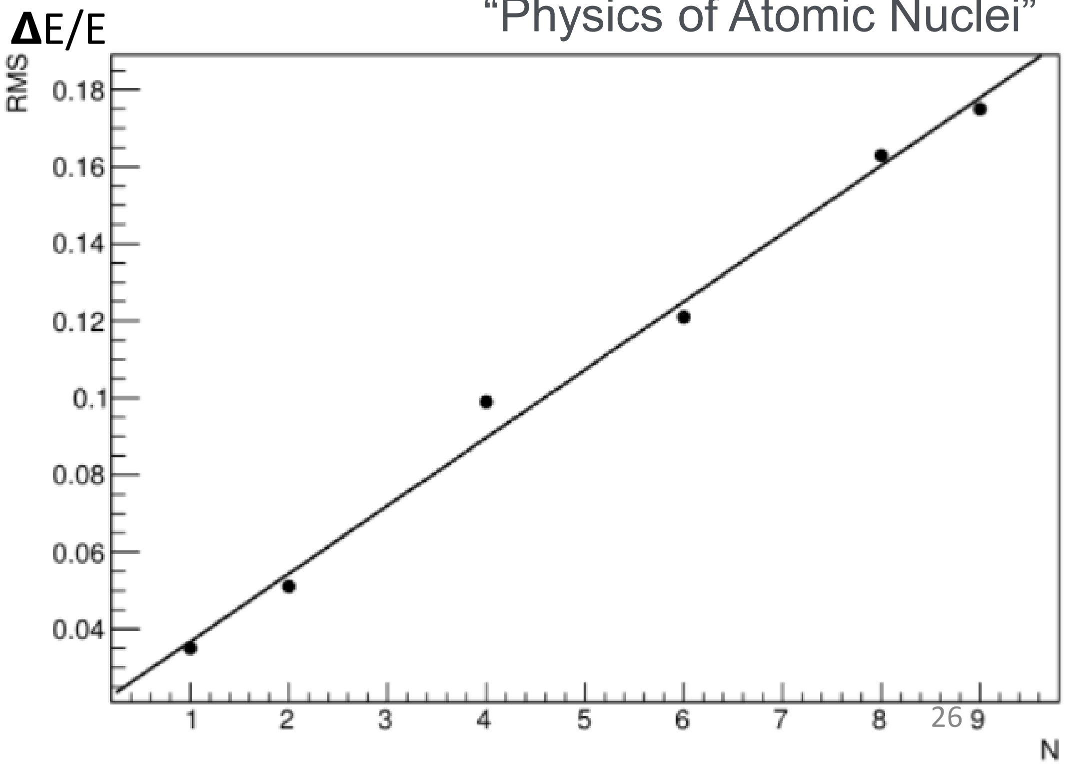
~3.4 · 10⁹ particles / plane /sec (~μ^+) .

Number of tracks merging in time:

in π tagging station planes ~6 tracks/time cycle of coord. det.

in μ tagging station planes ~3 tracks/time cycle of coord. det.

will be pub.
“Physics of Atomic Nuclei”



Conclusion

- Comparative analysis of channels forming neutrino beams for the P2O experiment, namely:
  - direct channel with parabolic lenses - “intense” beam (1);
  - channel with parabolic lenses with parent particles deflection - “intense dichromatic” beam (2);
  - direct channel with quadrupole lenses - “continuous narrow-band” beam (3);
  - channel with quadrupole lenses with parent particles deflection - “continuous dichromatic beam with a low background level” (4).
- The optimal beam to maximize the sensitivity for measurement of the CP violation phase δ_{CP} phase in the P2O experiment is the **“intense” beam (1)**.
- To form a tagged neutrino channel that works effectively in the P2O experiment, it is necessary to use “ high intensity” trackers .

This work was funded by the grant from the Russian Science Foundation no. 22-12-00107, https://rscf.ru/project/22-12-00107/

Благодарю за внимание