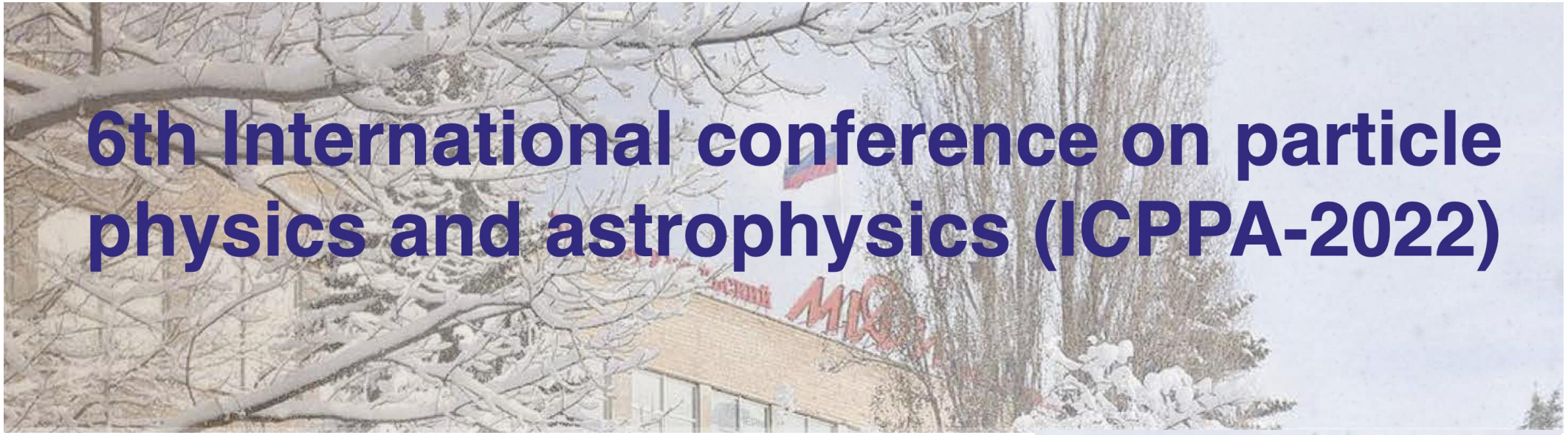
Tagged neutrino beam in the P2O experiment



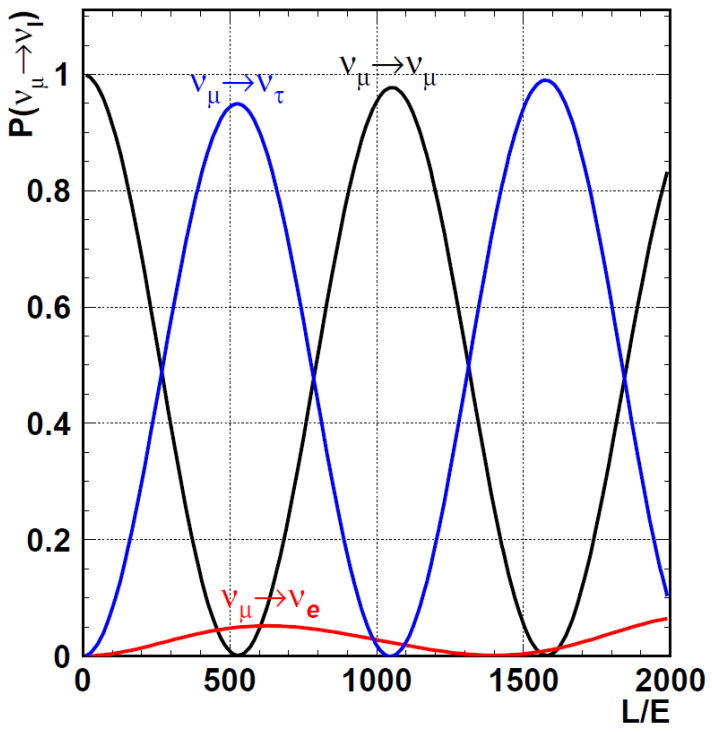
Anatoly Sokolov
NRC "Kurchatov Institute" – IHEP, Protvino

Outline

- Protvino to ORCA (P2O) project
- Neutrino tagging concept
- Neutrino channel project study at U70 (Protvino)
- Summary

NEUTRINO OSCILLATION

Appearance and Disappearance experiments



1st 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**	**4000 km**	**1350 km**
	***E* ~ 4.9 GeV**	**7.5 GeV**	**2.5 GeV**

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

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

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

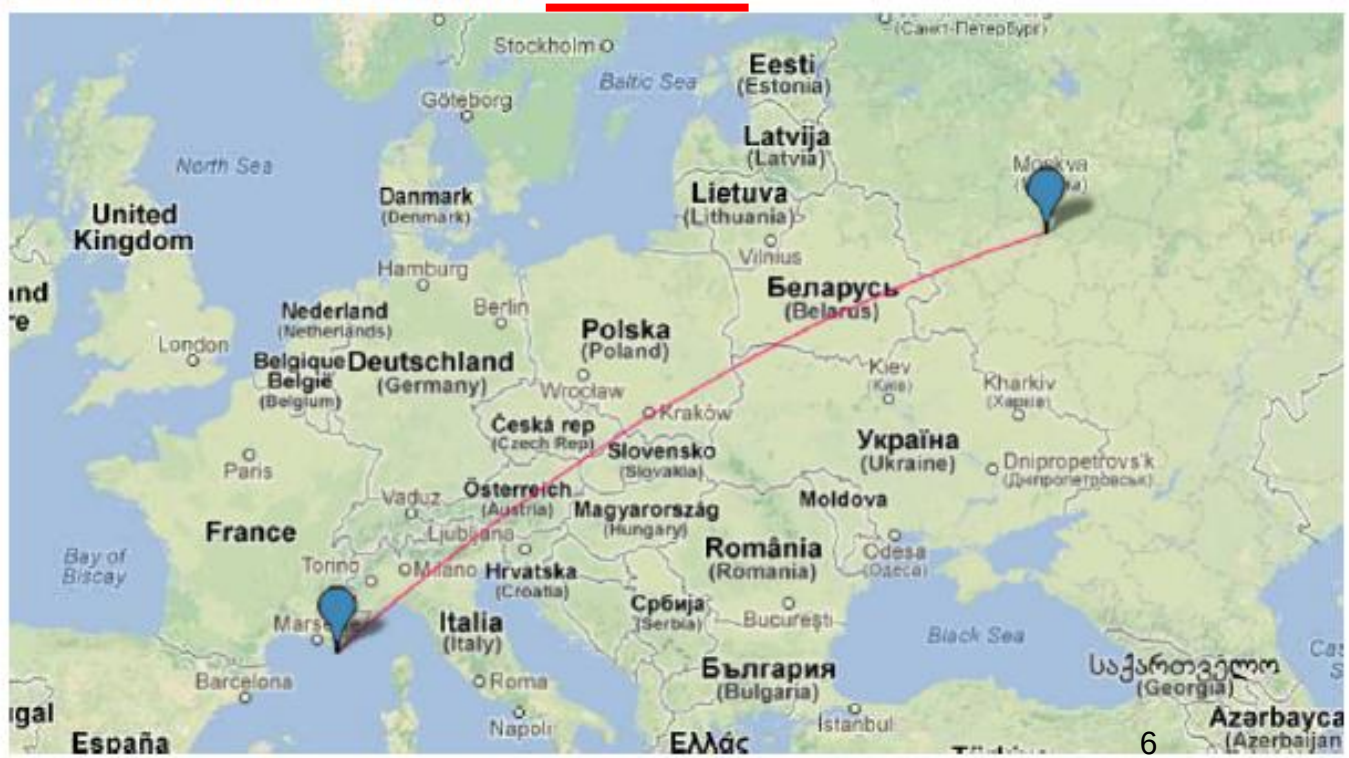
Protvino to ORCA project

P2O

P2O : Protvino to ORCA

- Baseline 2588km ; beam inclination : 11.7° ($\cos\theta = 0.2$)
- ORCA position : 42° 48' 16.28" N , 06° 01' 53.06" E
- Deepest point 134km : 3.3 g/cm^3
- First oscillation maximum 5.1 GeV

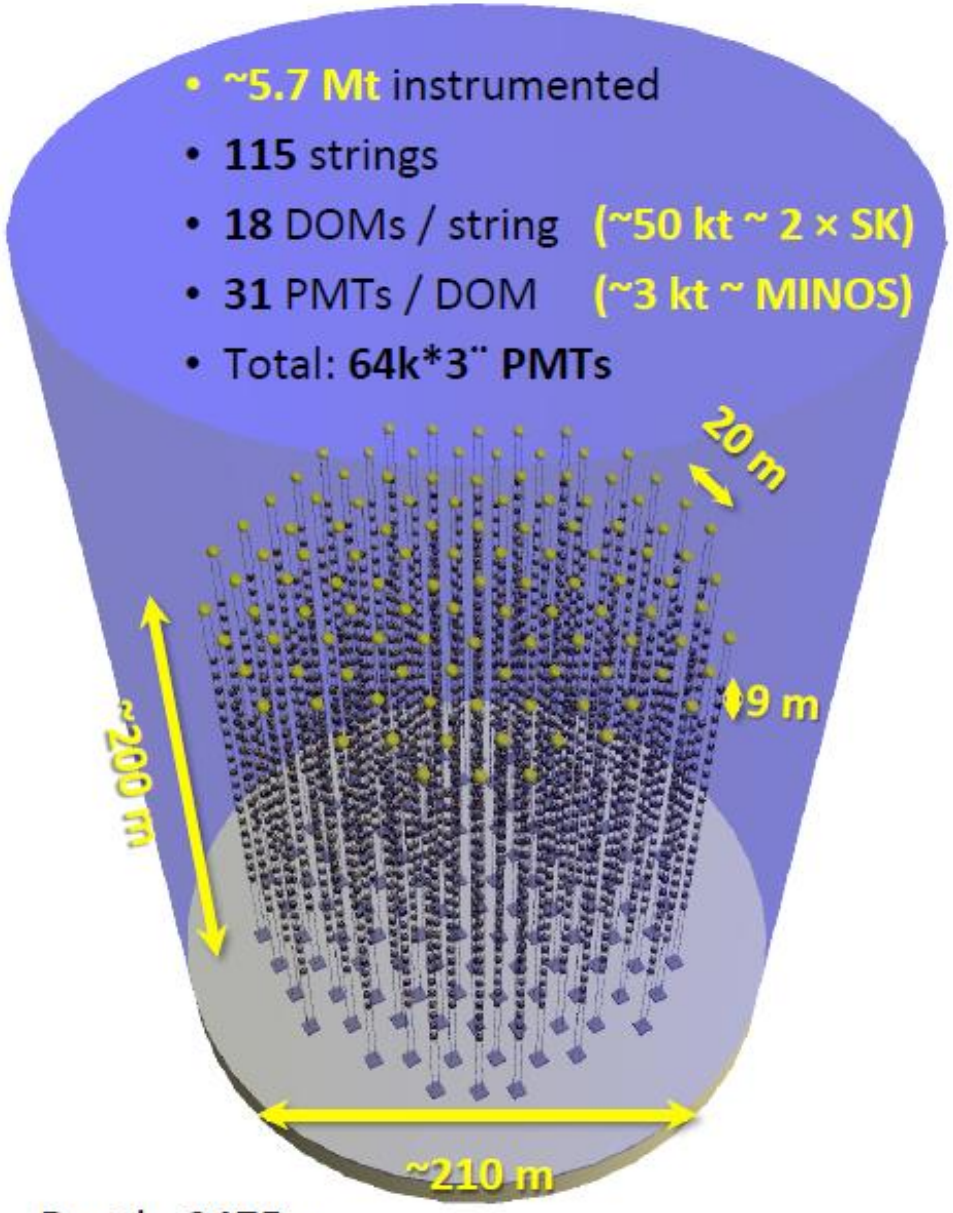
ORCA: Oscillation Research with Cosmics in the Abyss



Letter of interest for a neutrino beam from Protvino to KM3NeT/ORCA
Eur. Phys. J. C (2019) 79:758

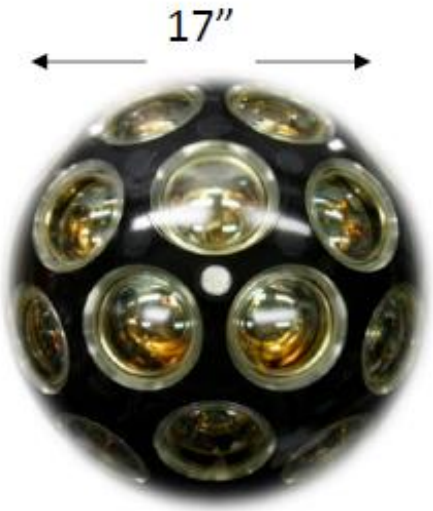
(~100 participants, 27 Institutes)

The ORCA Detector



Depth=2475m

Digital Optical Module

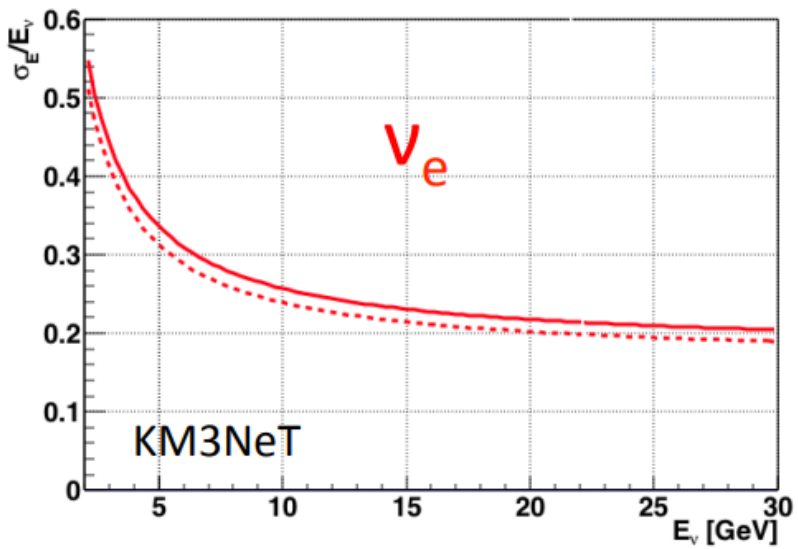


- 31 x 3" PMTs
- Uniform angular coverage
- Directional information
- Digital photon counting
- Background rejection
- All data to shore

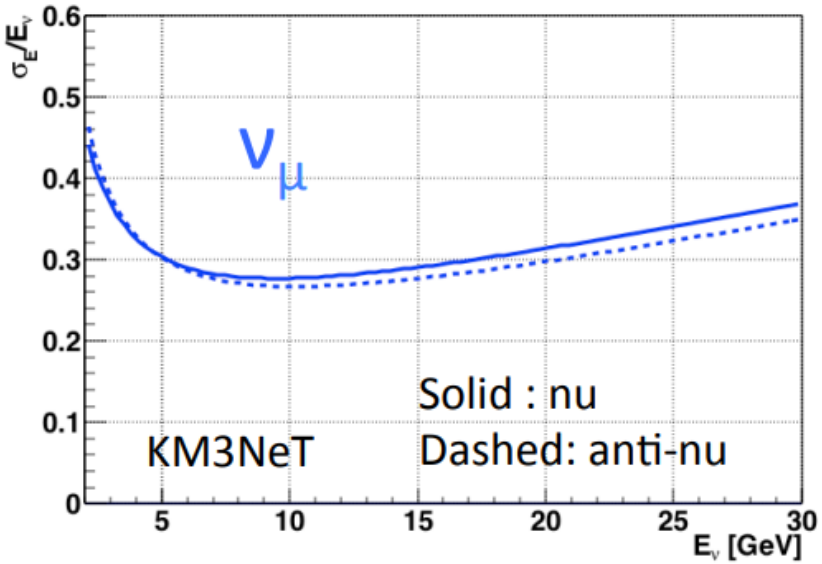
See P1.095: R. Bruijn, The KM3NeT DOM

Energy Resolutions

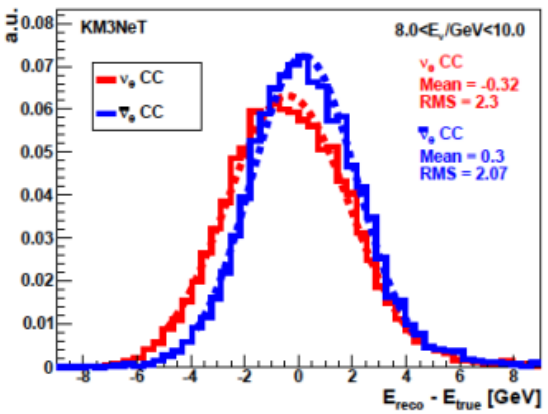
Shower



Track



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



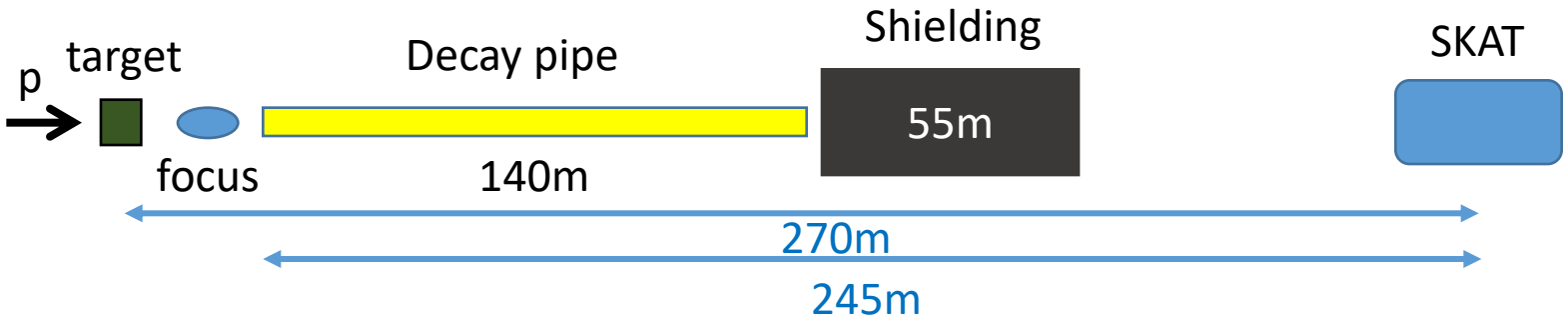
Федеральное государственное бюджетное учреждение

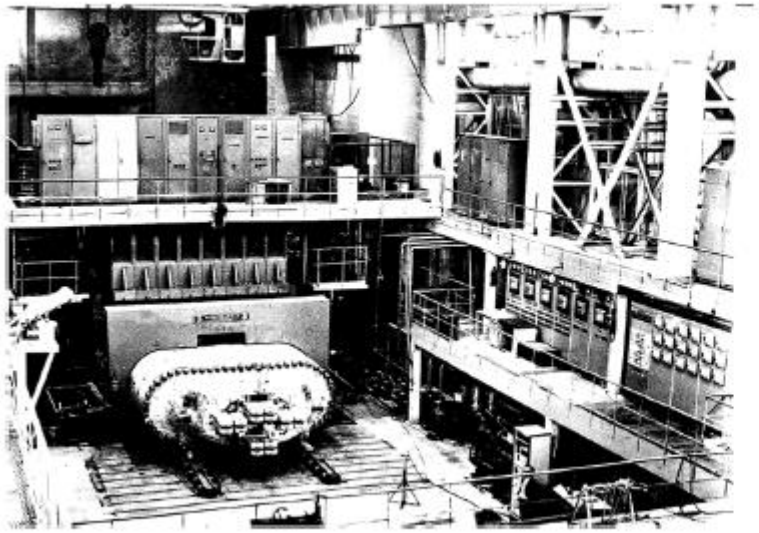
«ИНСТИТУТ ФИЗИКИ ВЫСОКИХ ЭНЕРГИЙ имени А.А.Логунова

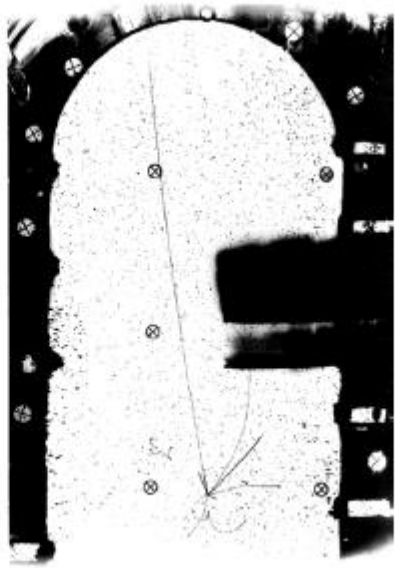
Национального исследовательского центра «Курчатовский институт»

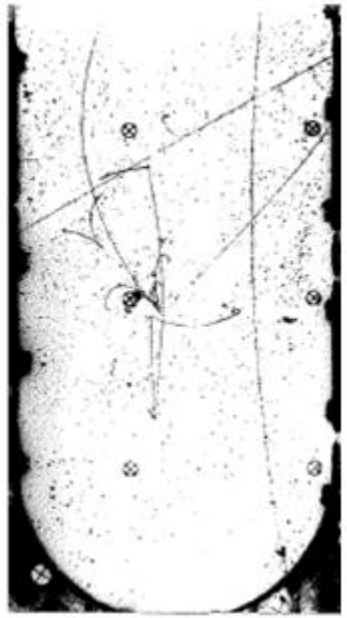
IHEP neutrino experiment (1975 - 2000)

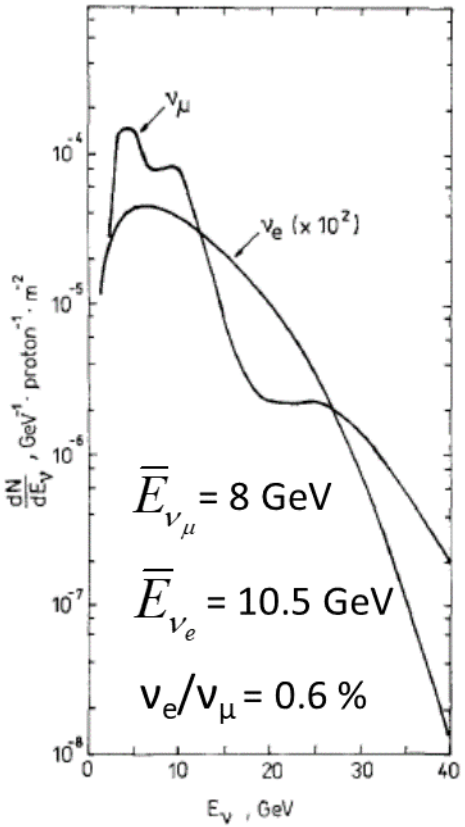
$$p + A \rightarrow \pi(K) + X \qquad \pi(K) \rightarrow \nu_\mu(\nu_e, \bar{\nu}_\mu, \bar{\nu}_e)...$$









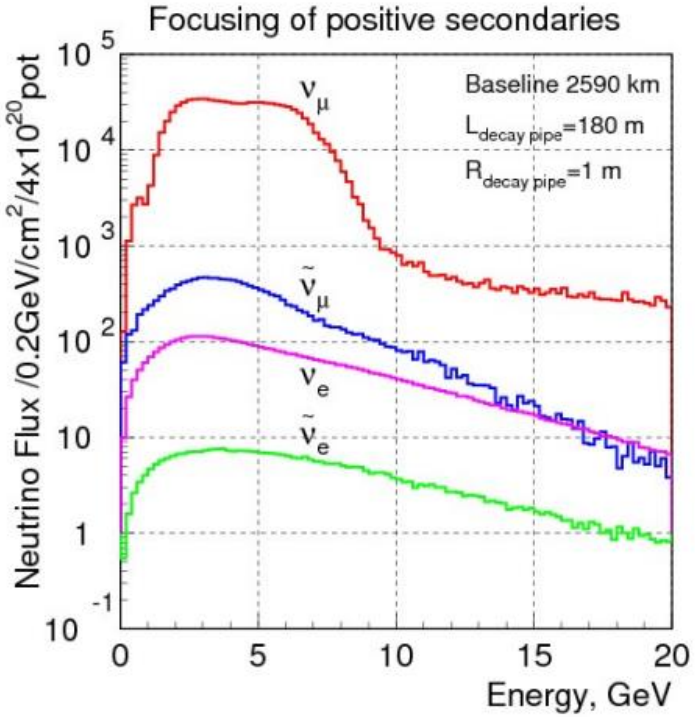


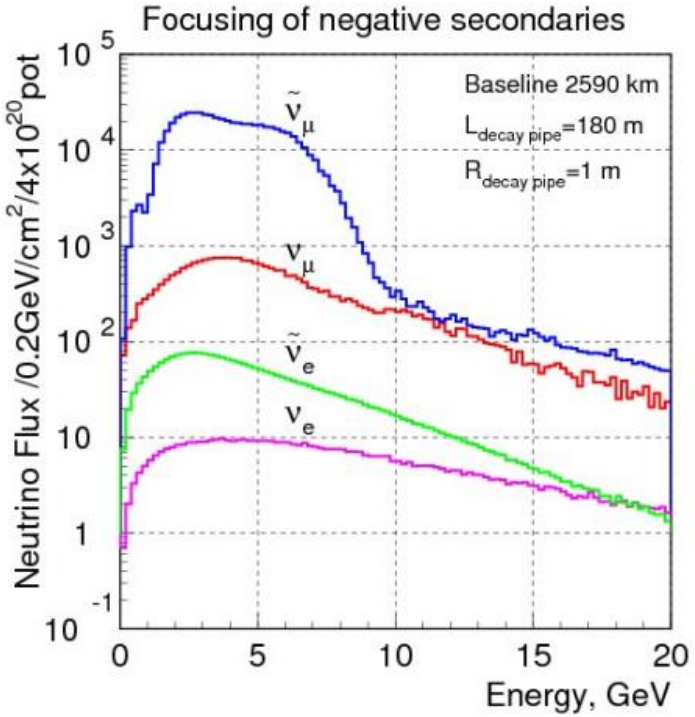
Neutrino Flux at the Far Detector Location

for 4×10^{20} Protons on Target

Phase I I = 90 kW

T = 5 year

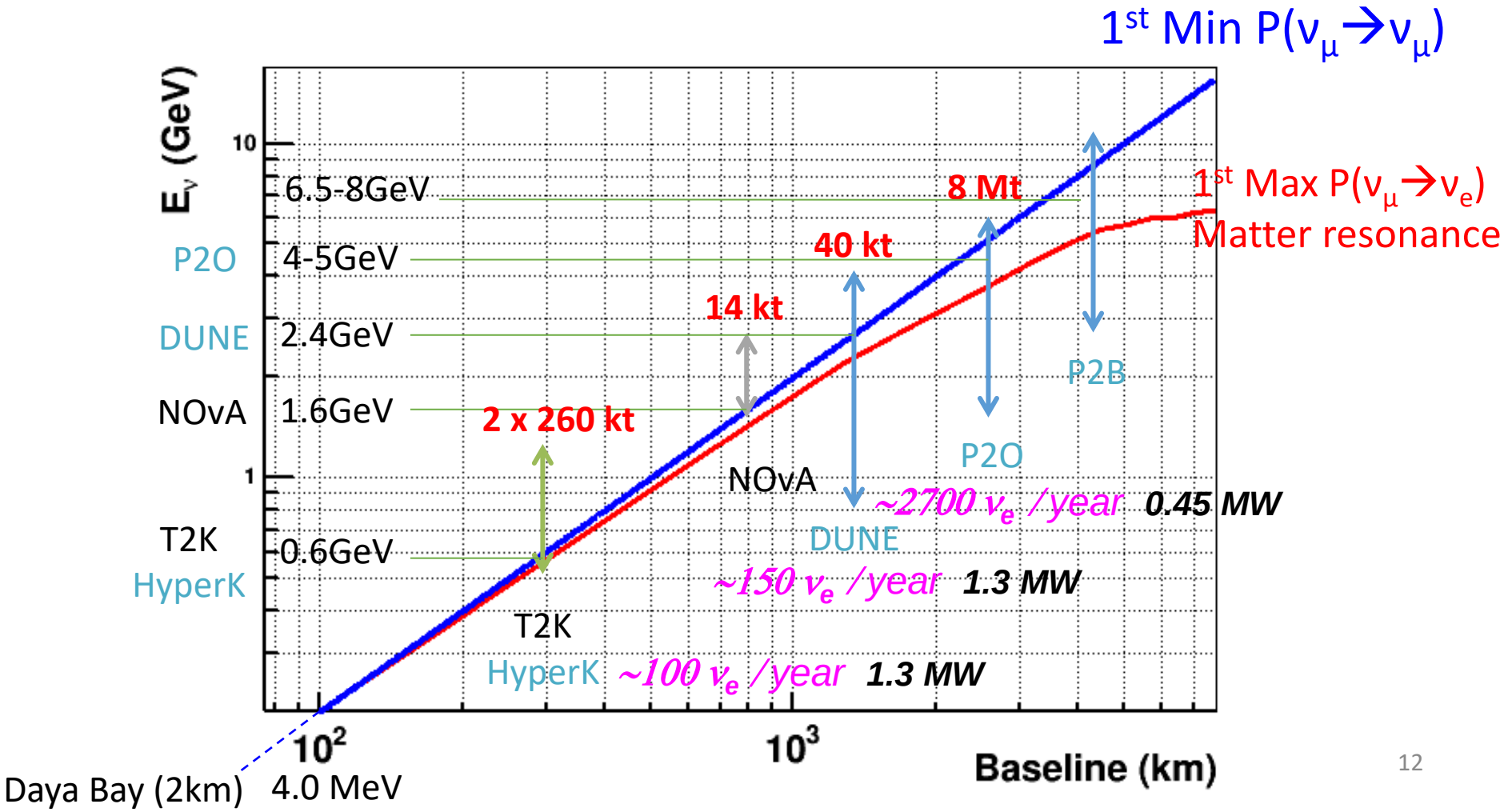




$Np = I/T \times t \times \varepsilon = 2 \cdot 10^{13}/5\ c \times 9\ \text{months} \times 0{,}85 = 0{,}8 \cdot 10^{20}$ p/year

Comparison of LBL Projects

- Energy versus baseline



NEUTRINO TAGGING CONCEPT

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.

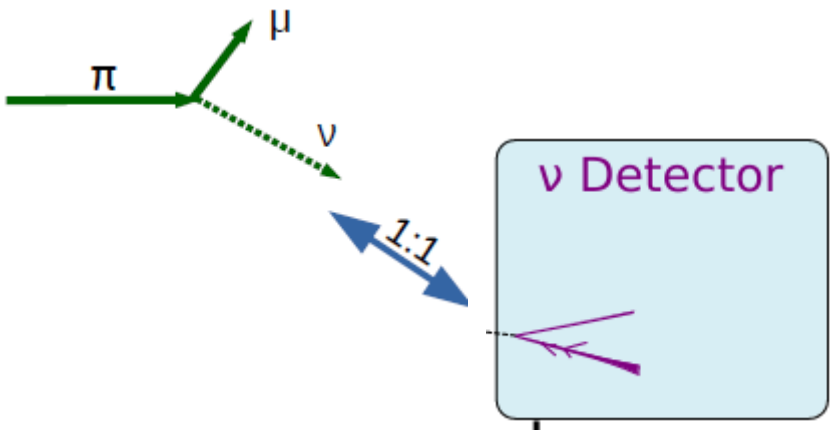
$$\vec{p}_\nu = \vec{p}_\pi - \vec{p}_\mu$$

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

Challenge 1
RATE

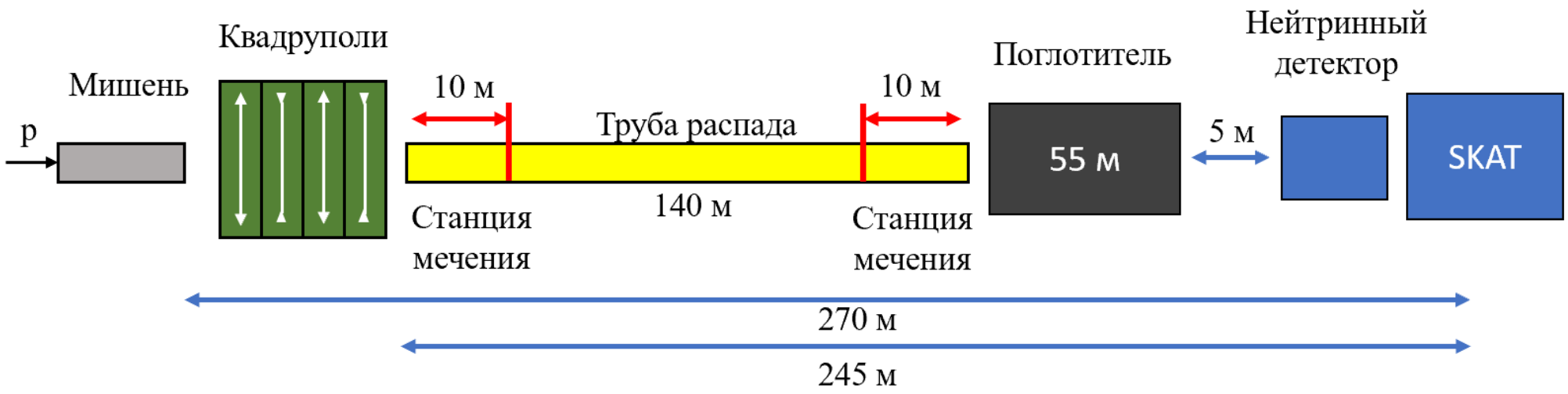
- **Associate each ν seen in ν-detector to its π → μν genitor**
  - ✓ Association done based on time and angular matching
    - ➢ **<1% energy resolution** can be used at ν interaction
    - ➢ **ν and anti-ν** can be **collected together**

Challenge 2
MATCHING



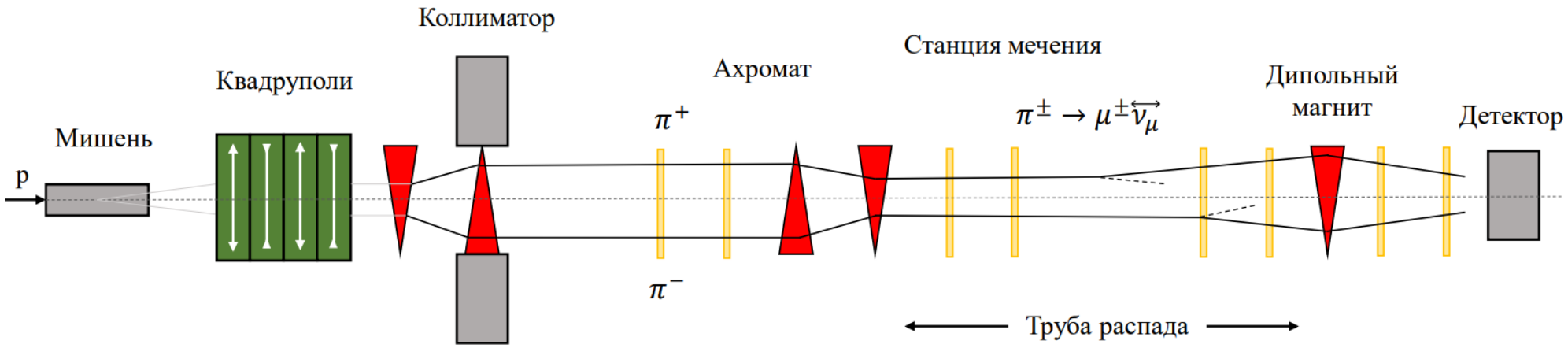
Neutrino channel scheme

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



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

Tagged neutrino channel scheme



Green rectangles - quadrupole magnets, red triangles - dipole magnets, vertical yellow lines - coordinate planes of tagging stations.

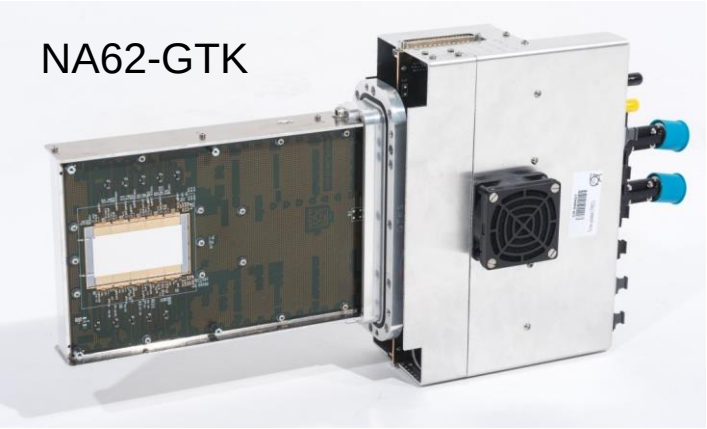
Feasibility: NA62 as demonstrator

- ***ν* tagging implemented at NA62 (rare *K* decays)** as a by-product
- **Calorimeters act also as ν detectors** and with O($10^{12\text{-}13}$) *K* decays /y: ~1400ν/y from $K \rightarrow \mu\nu + K_{\mu 3}$ interact in Lkr+MUV (20 + 66 ton)
- *K* and *μ* properties precisely measured thanks to GTK (Si-Pixel) and STRAW trackers
- Dedicated **trigger line** will collect these events from July 2021

Toward a Dedicated Tagged Neutrino Beam

- Difference between NA62 and a ν-beam: **beam particle rate**
- Rate is limited **by trackers irradiation and occupancy**

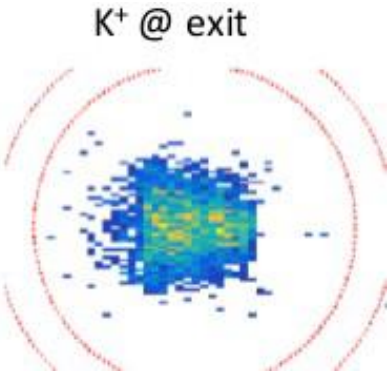
	Available Max.	Radiation Max.	Flux Time
NA62-GTK	since 2015	$10^{14\text{-}15}$ n_{eq} /cm²	200 MHz/cm²
HL-LHC	before 2028	$10^{16\text{-}17}$ n_{eq} /cm²	2000 MHz/cm²



- Handles to **limit particle flux**:
  - ➢ spread particles in **time** (slow extraction) and **space** (beam size)
  - ➢ select only relevant π **momentum range**

- **ENUBET** beam line was optimized with **~similar concerns**

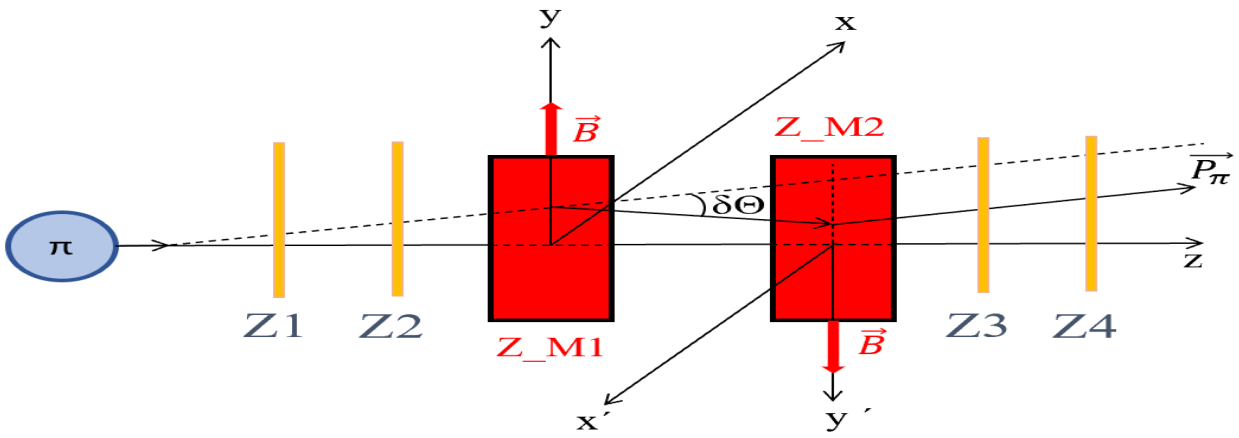
➢ expected rate [1] is ~10^{12} part/s on ~1m radius surf. at pipe end:
➔ already matches the capabilities of the GTK technology!



1 m radius

[1] Pupilli, NeuTel 2019

π-meson kinematics at the tagging station



Θ_{π_xz} angle measuring in the xz plane

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

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

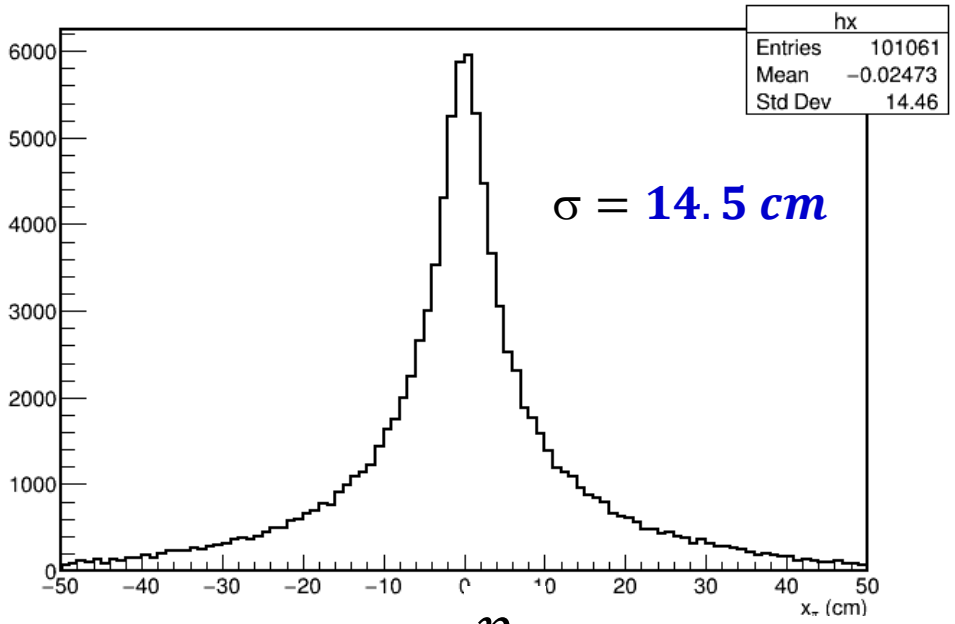
$$\delta\Theta_{\pi_{xz}} = \frac{30\vec{B}L_B}{P_{\pi_{xz}}}$$

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

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

π meson beam parameters

x_π



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

Geant4

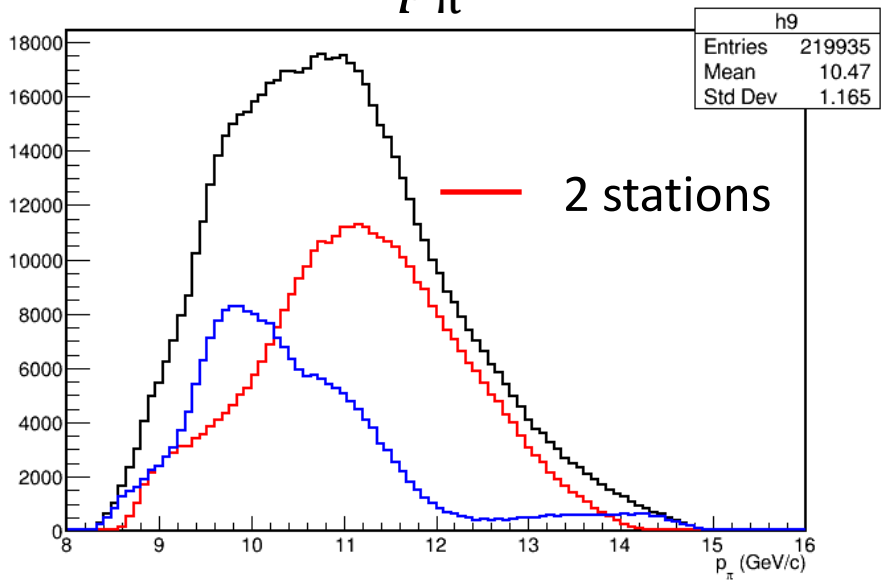
Coordinate planes - **50x50 cm² (Si, d ~ 0.5 *mm*)**

10^9 π/s/cm²

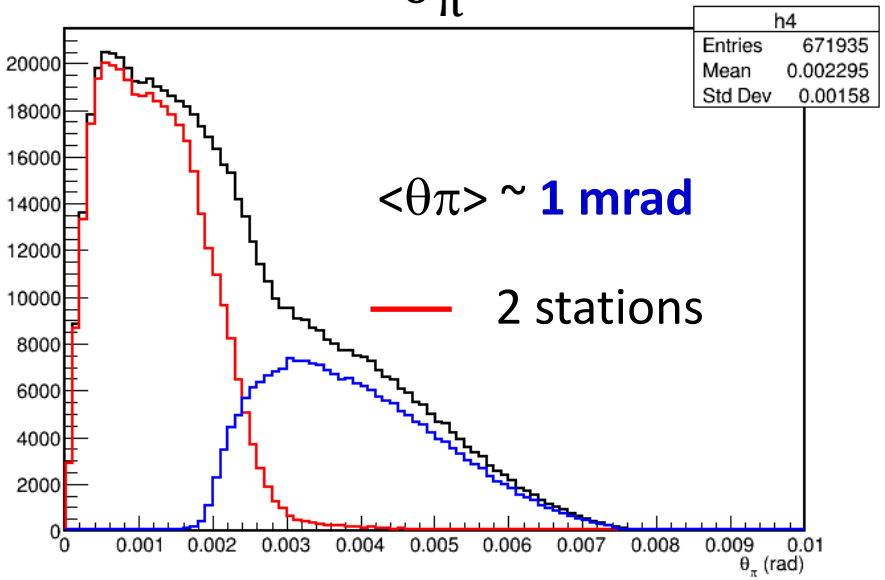
Errors in coordinate planes

- coulomb scattering - $X/X_0 = 0.5\%$
- cell structure of the plane **0.1 x 0.1 *mm*²**

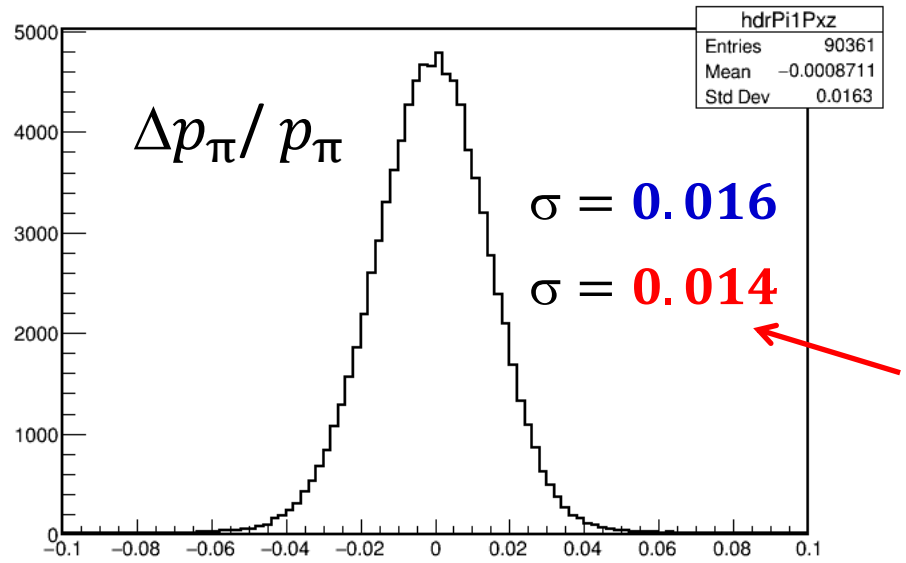
p_π



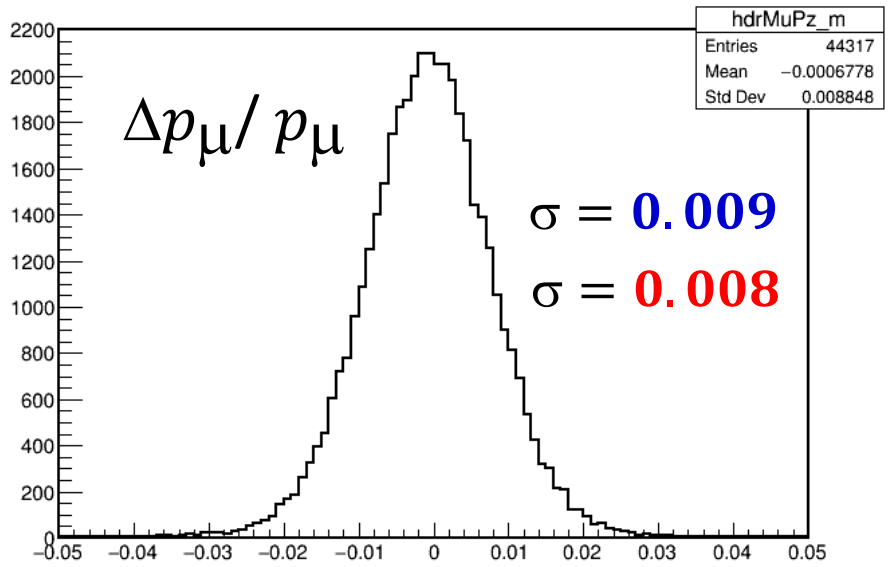
θ_π

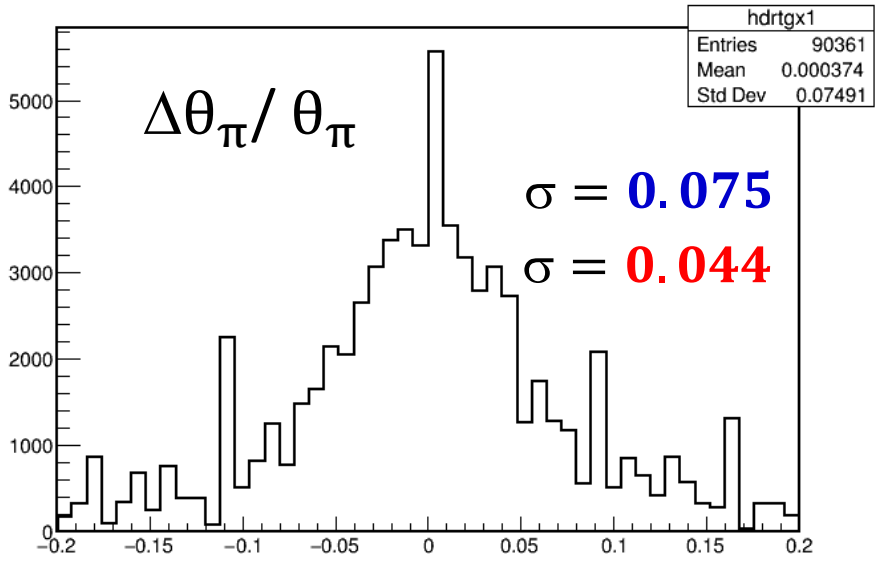


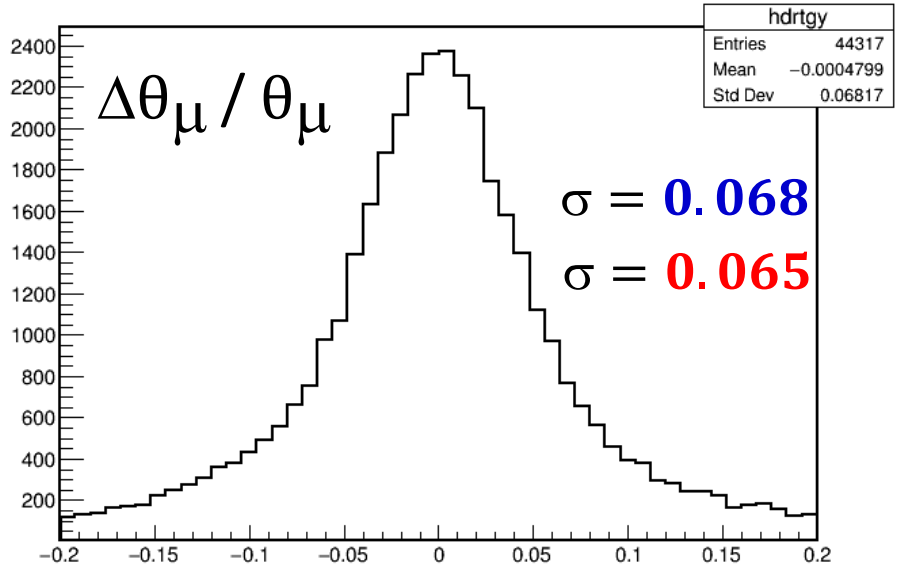
π, μ momenta measurement



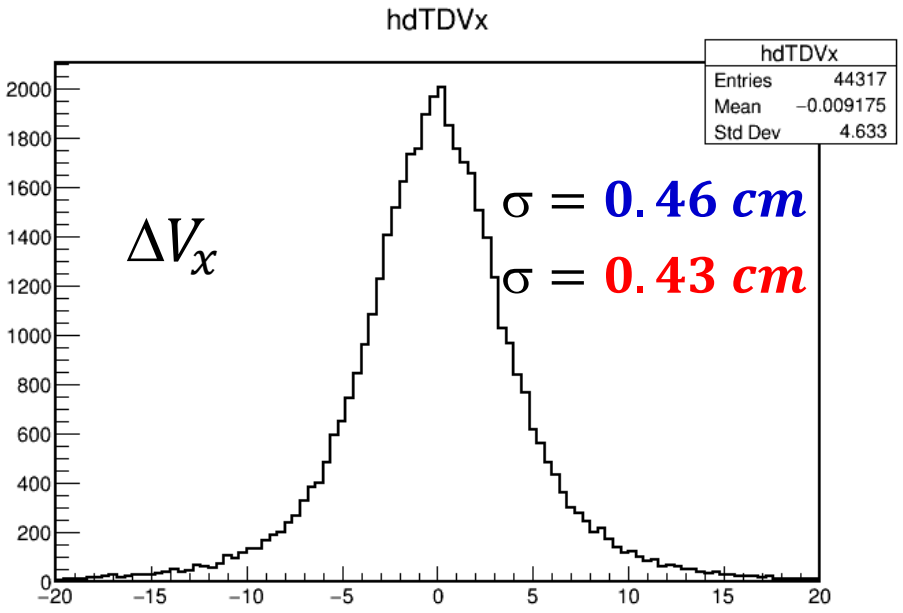
No cell structure



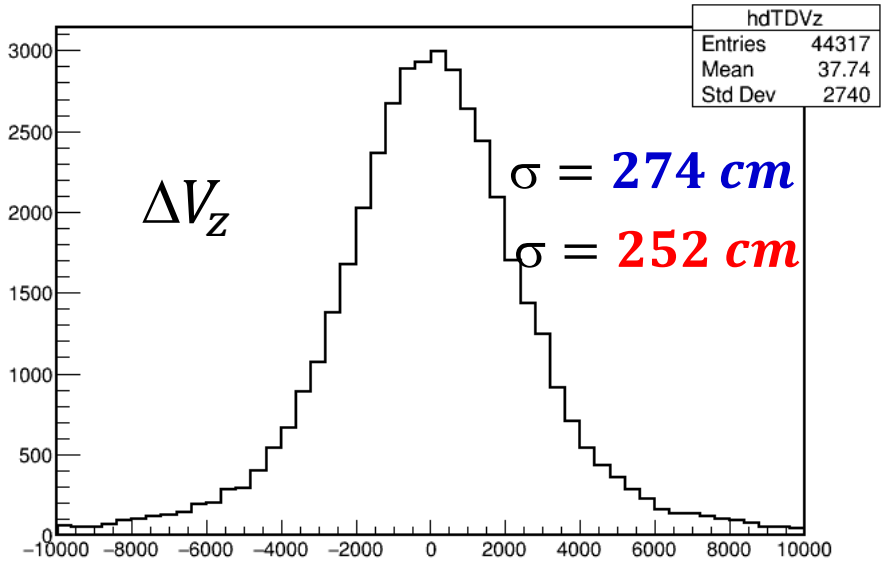




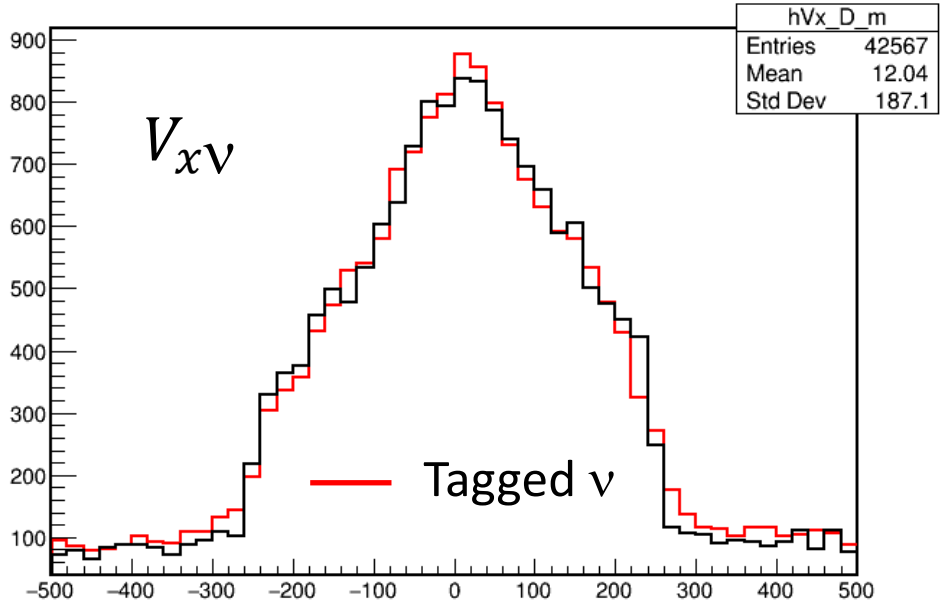
π decay vertex measurement

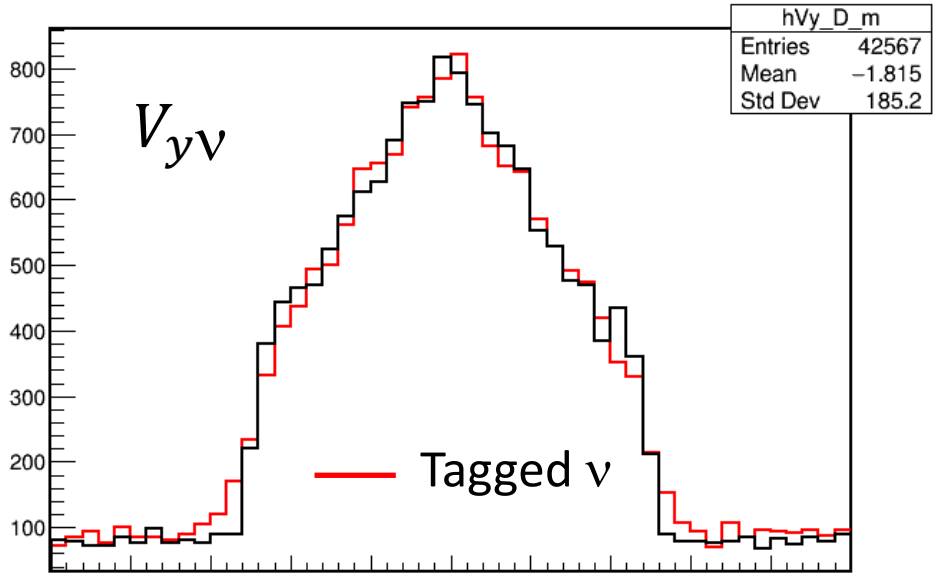


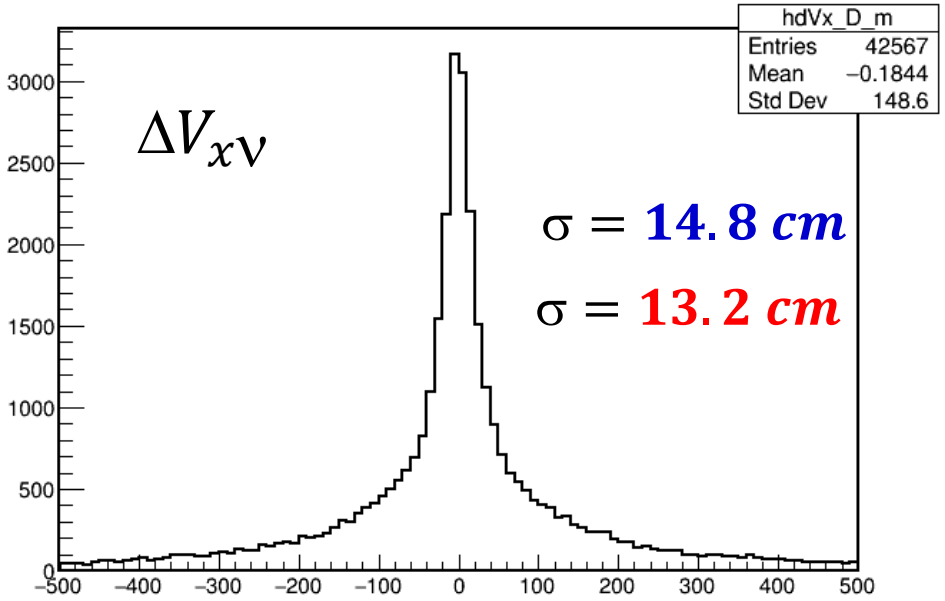
No cell structure

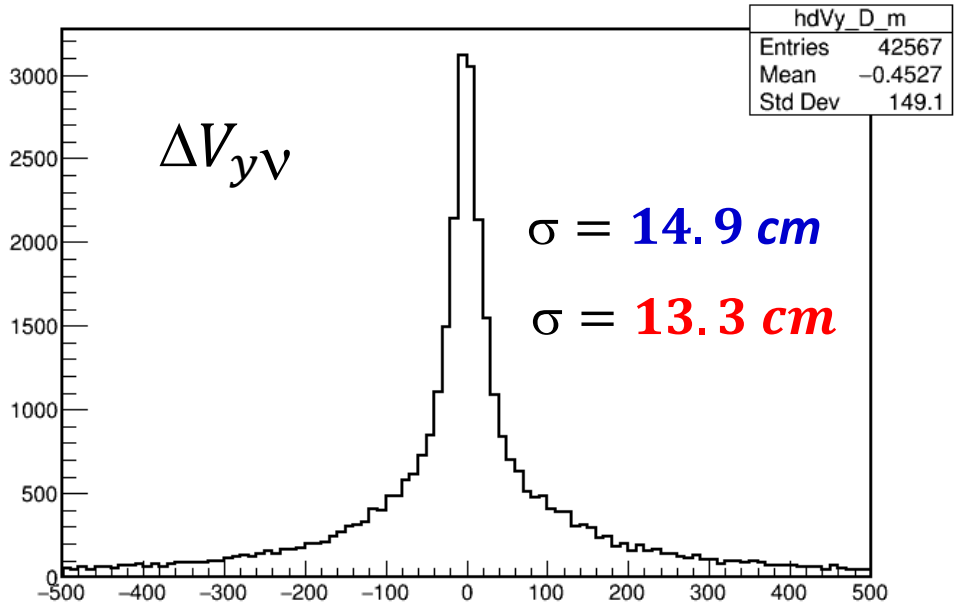


Neutrino vertex in a detector

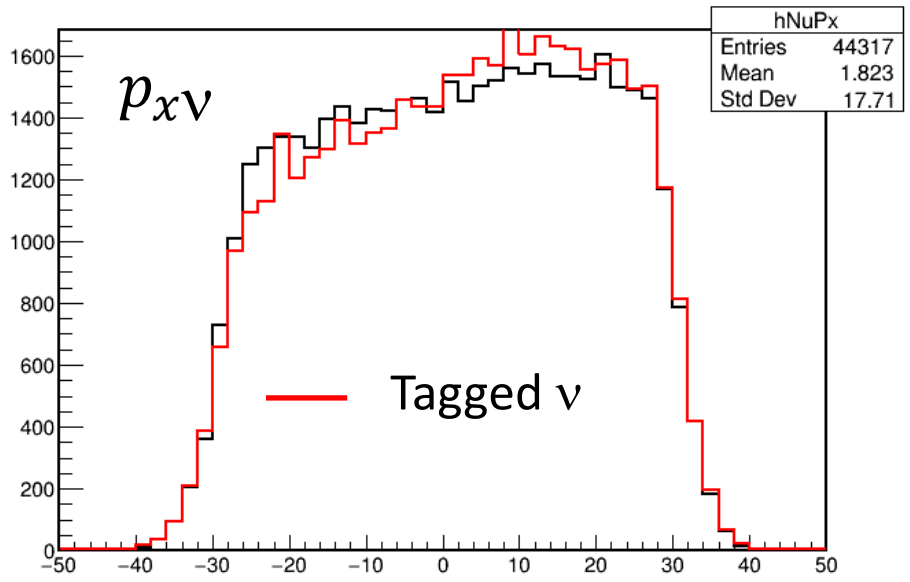


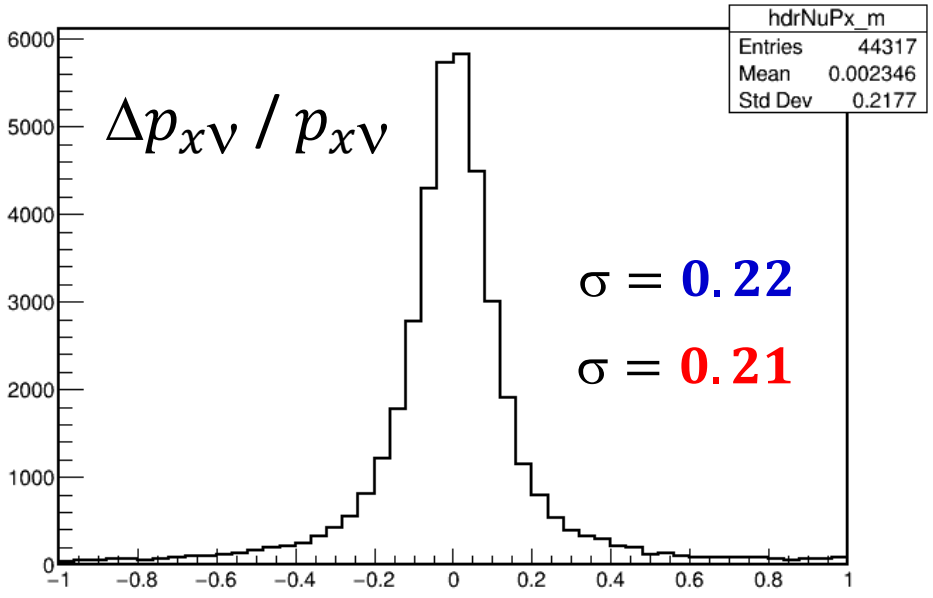


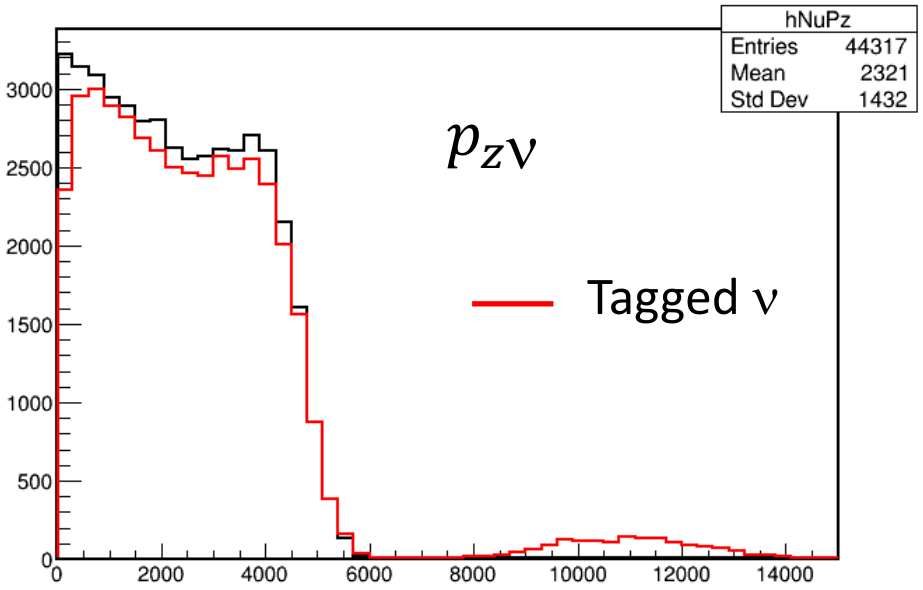


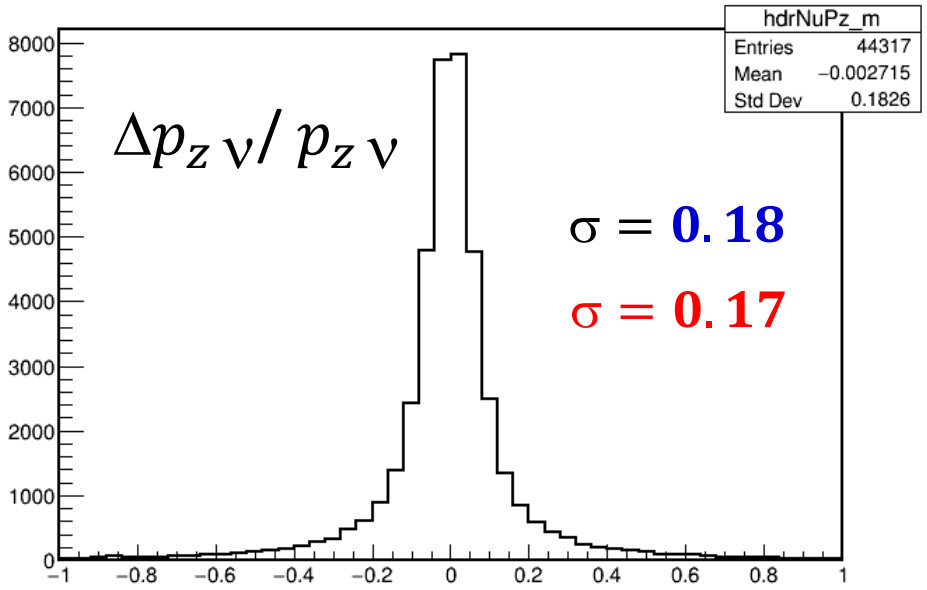


Neutrino momentum measurement

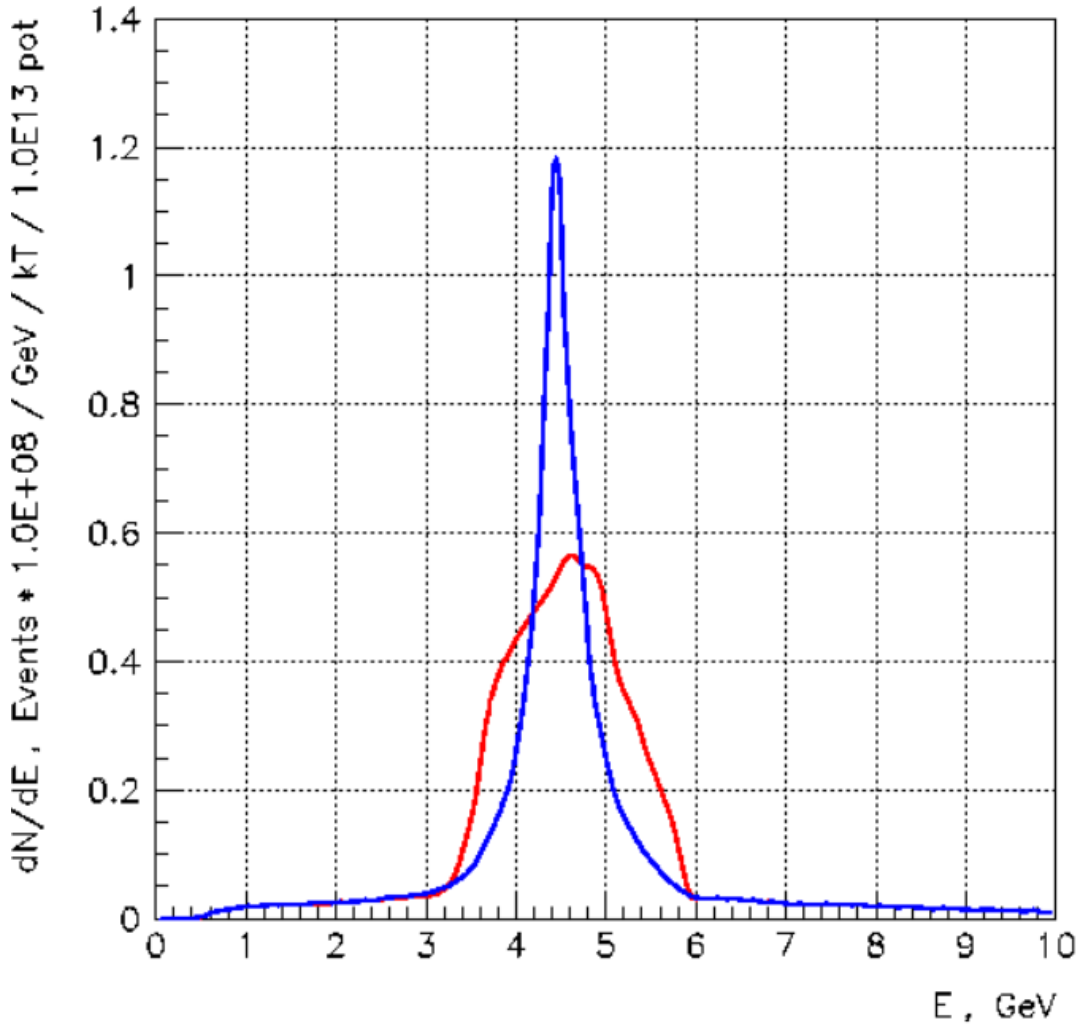








Neutrino at the far detector



L_{det} = 2595 km

$N(\nu_\mu)$(ev) (E_ν = 3 ÷ 6 GeV, 10^{13} protons,

$M_{det} = 1\ kt$, $Z_{dec\ tube}$ = 150 m,

$R_{dec\ tube}$ = 75 cm)

$= 0.955 \cdot 10^{-8}$ ev

Phase I **I = 90 kW** **~ 610 ν_μ ev/year**

Np = $0{,}8 \cdot 10^{20}$ p/year

$M_{det} = 8\ Mt$ **~ 130 ν_e ev/year**

HK, DUNE *~ 100, 150 ν_e /year* ***1.3 MW***

Results for the 1st step of the beam line optimization

Summary

- **Neutrino tagging**: follow ν from creation to detection
  - ✓ reconstruct each and **every π ➔ μν decay** to precisely characterize ν
  - ✓ **associate** ν seen in ν-detector to its πμν genitor
- **Technological** challenge is the beam particle rate and addressed by
  - ✓ **beam line studies** (efficient static focusing, large beam)
  - ✓ **high intensity trackers**

- **Applications: ν oscillation LBNE** with **NuTAG** and mega-ton **natural water Cerenkov** ν detector
  - ✓ large **statistic** obtain from detector mass
  - ✓ **lower beam intensity** allows ν tagging
  - ✓ tagging brings **high energy resolution** and **low systematics**

- **Beam line studies are in progress**