ОСЦИЛЛЯЦИОННЫЕ ИЗМЕРЕНИЯ С НОВЫМ БЛИЖНИМ ДЕТЕКТОРОМ T2K

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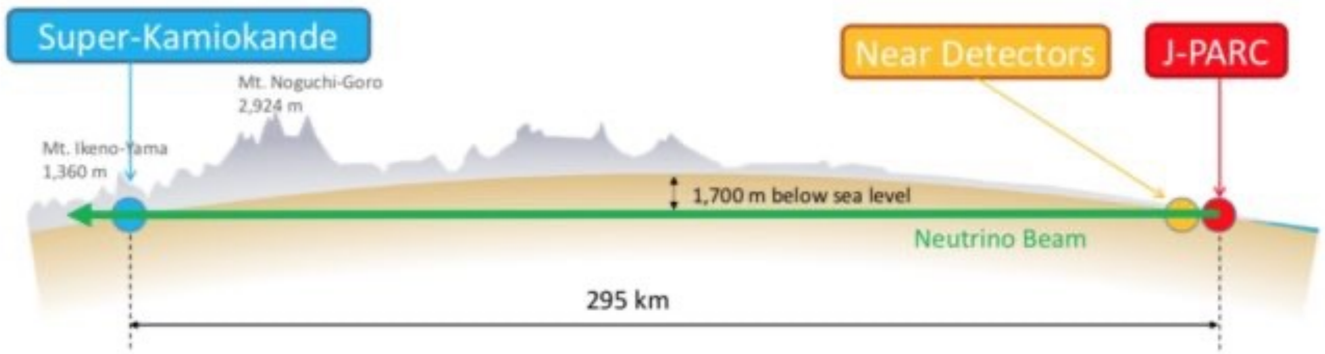
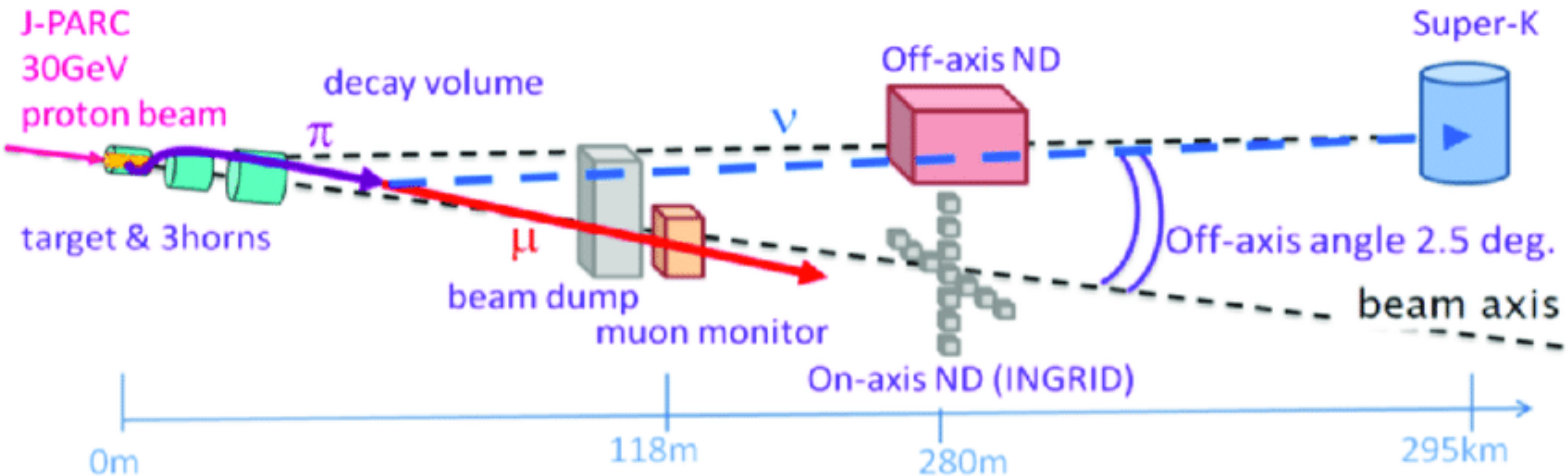
ACCELERATOR NEUTRINO EXPERIMENTS

- Accelerator ν experiments:
  - precisely controlled pure $\overset{(-)}{\nu}_\mu$ beam
  - allow to study:
    - appearance (ν_e) & disappearance (ν_μ) channel
    - neutrino & anti-neutrino oscillations

} CP violation measurements

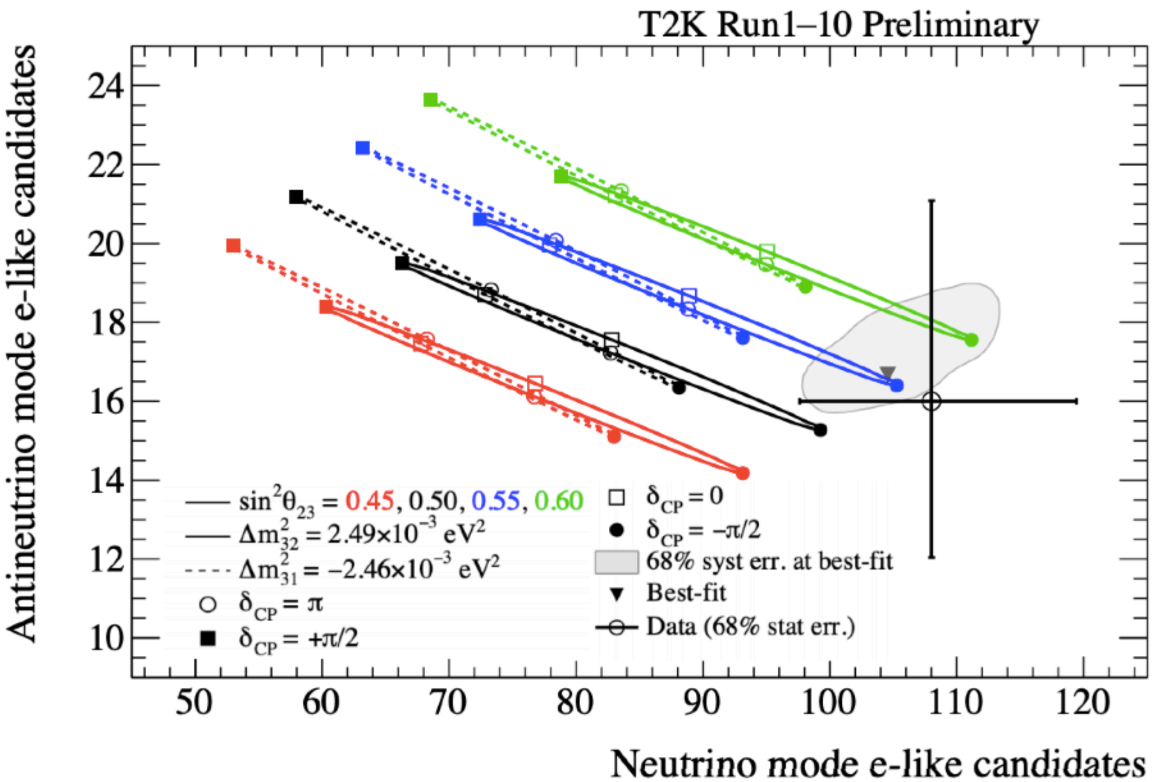


- Beam production:



ND280 UPGRADE MOTIVATION

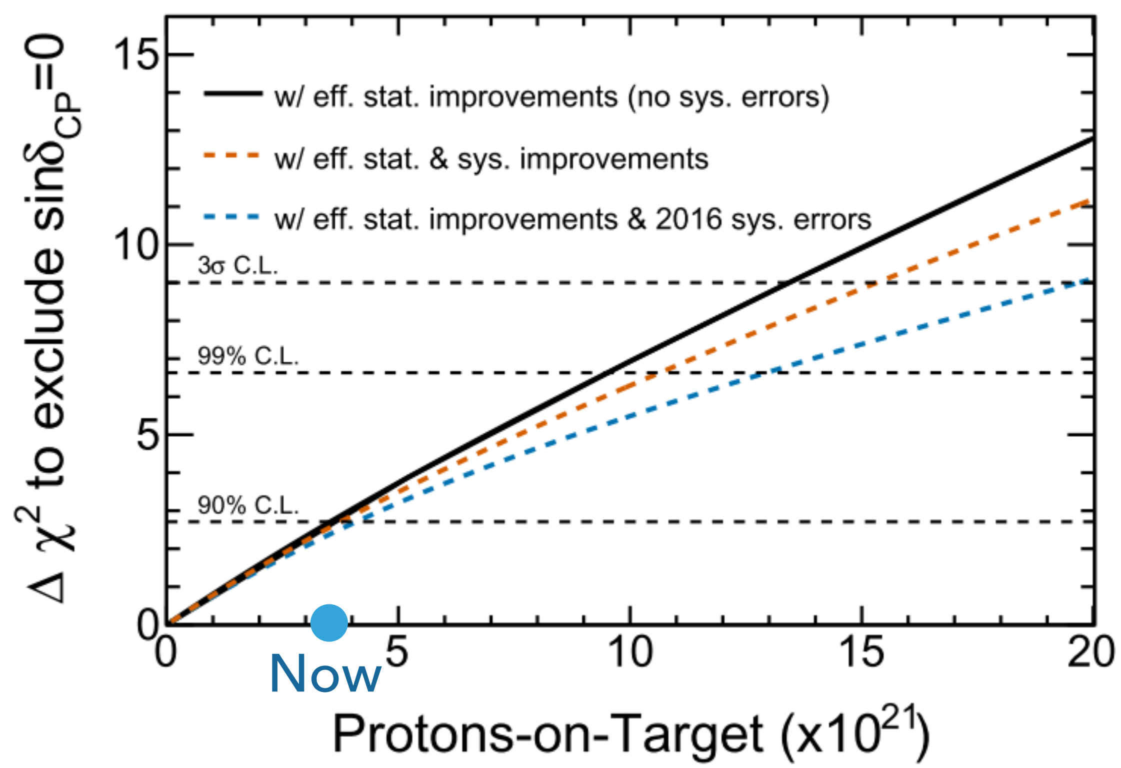
- T2K was approved to collect 20×10^{21} protons on target stat. (T2K-II stage)
  - the main goal is measurements of the δ_{CP}



$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu} - \sin 2\theta_{12}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}\sin\frac{\Delta m^2_{21}L}{4E_\nu}$$

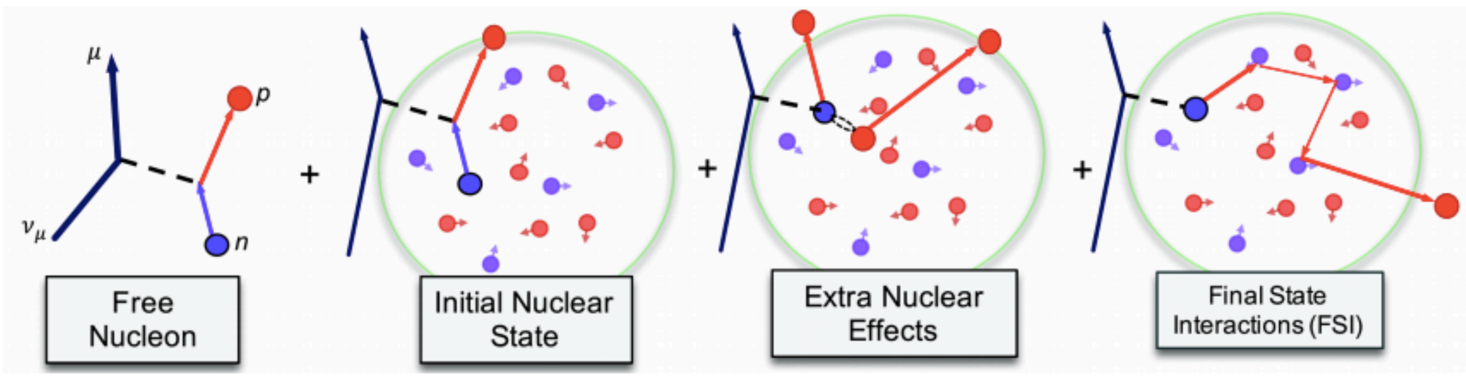
- e-like candidate observed:
  16 in $\bar{\nu}$-mode and **109** in ν-mode

- Now we are limited by statistics
- For T2K-II systematic is critical for search for CPV
  - *CPV sensitivity with current and improved systematics vs statistics*



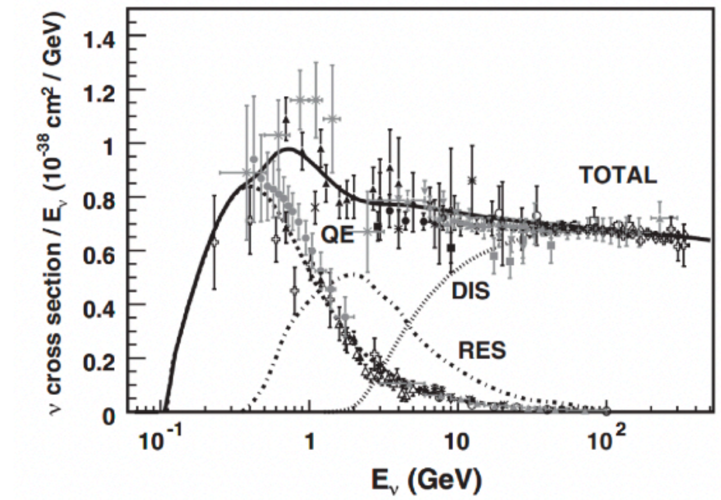
T2K SYSTEMATIC IMPROVEMENTS

- Oscillation analysis systematic is dominated by the ν interaction models uncertainties
  - Precise measurements are complicated because of poorly studied nuclear effects



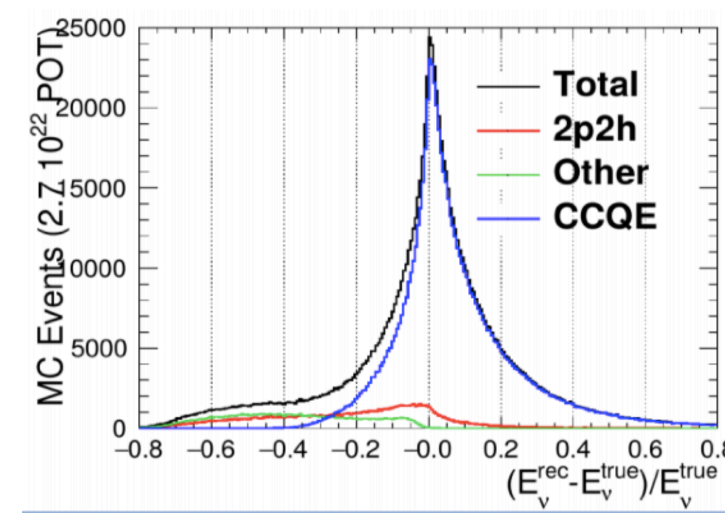
Fermi motion

e.g. 2p2h
2 nucleon interaction



- Example: Neutrino energy reconstruction in Super-Kamiokande:
  - Charge Current Quasi Elastic (CCQE) interaction on the nucleon at rest is assumed
  - E_ν is reconstructed based on the lepton kinematics only

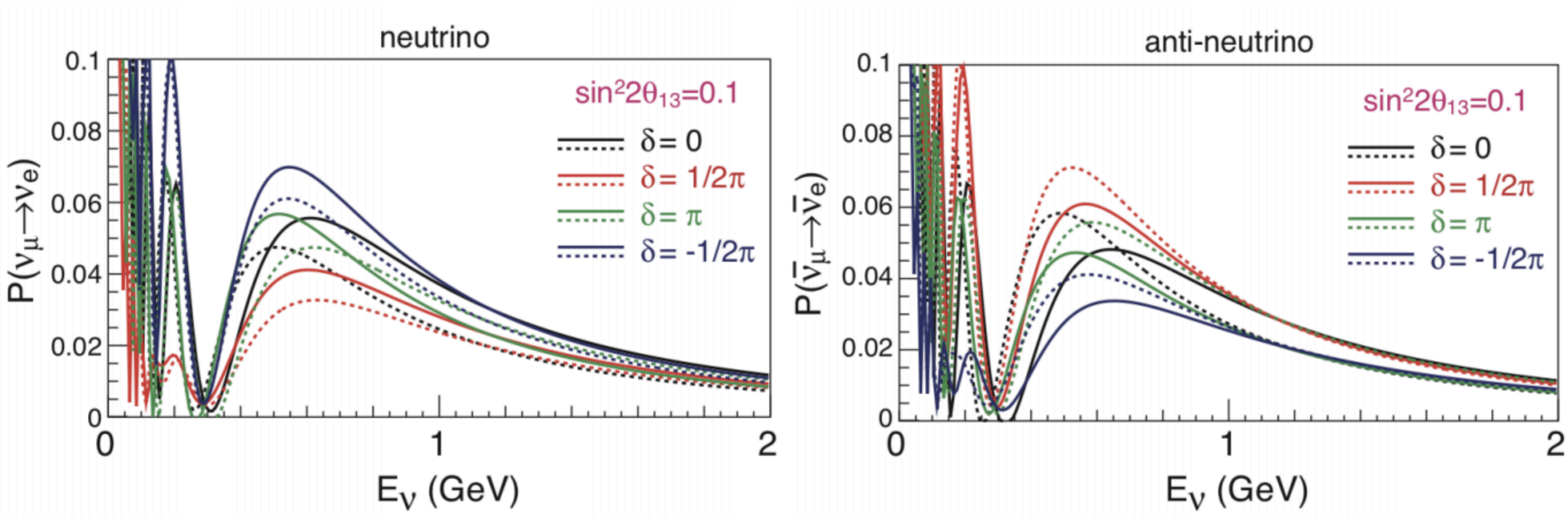
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$



- To perform more precise measurements of ν interaction:
  - new detector configuration
  - new analysis technique

ND280 UPGRADE MOTIVATION

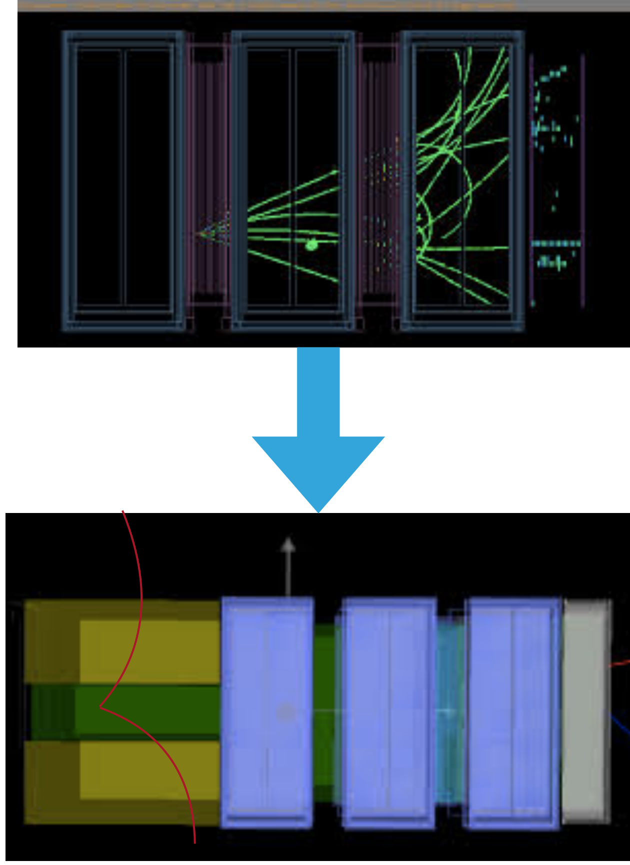
- The effect of interest:

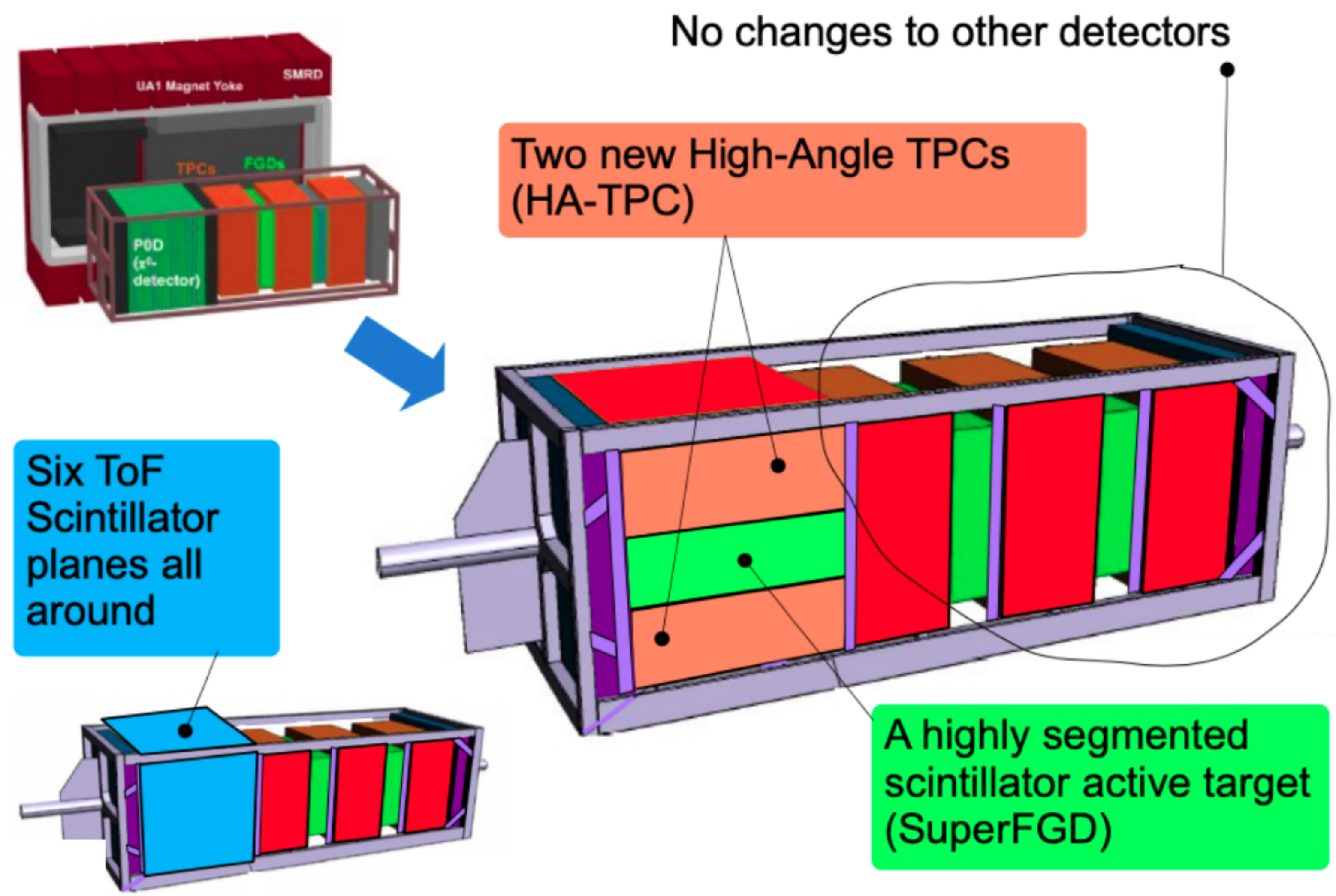


	Now $(1.97\nu + 1.63\overline{\nu}) \times 10^{21}$ POT	T2K-II $(10\nu + 10\overline{\nu}) \times 10^{21}$ POT	
ν-mode, ν_e sample	109 *limited by statistics*	$\delta_{CP} = 0$ 467.6 $\delta_{CP} = -\pi/2$ 558.7	difference we want to measure
$\overline{\nu}$-mode, $\overline{\nu}_e$ sample	16	$\delta_{CP} = 0$ 133.9 $\delta_{CP} = -\pi/2$ 115.8	

ND UPGRADE CONCEPT

- Near detector upgrade project was started aiming:
  - full phase space coverage
    –> same angular acceptance as far detector
  - lower thresholds for muon, pion, proton
  - neutron detection from $\overline{\nu}$ interactions
  - e/γ conversion separation (ν_e measurements)



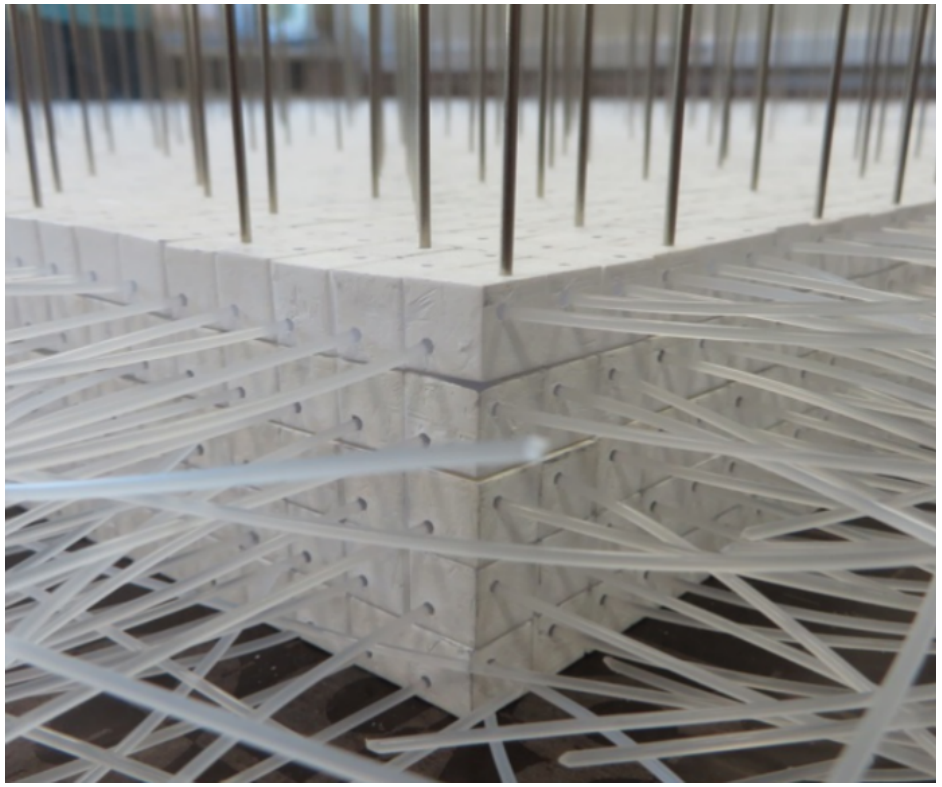


- A novel highly segmented scintillator detector
- Two new TPCs with resistive anode
- 6 time of flights panels around new sub-detectors

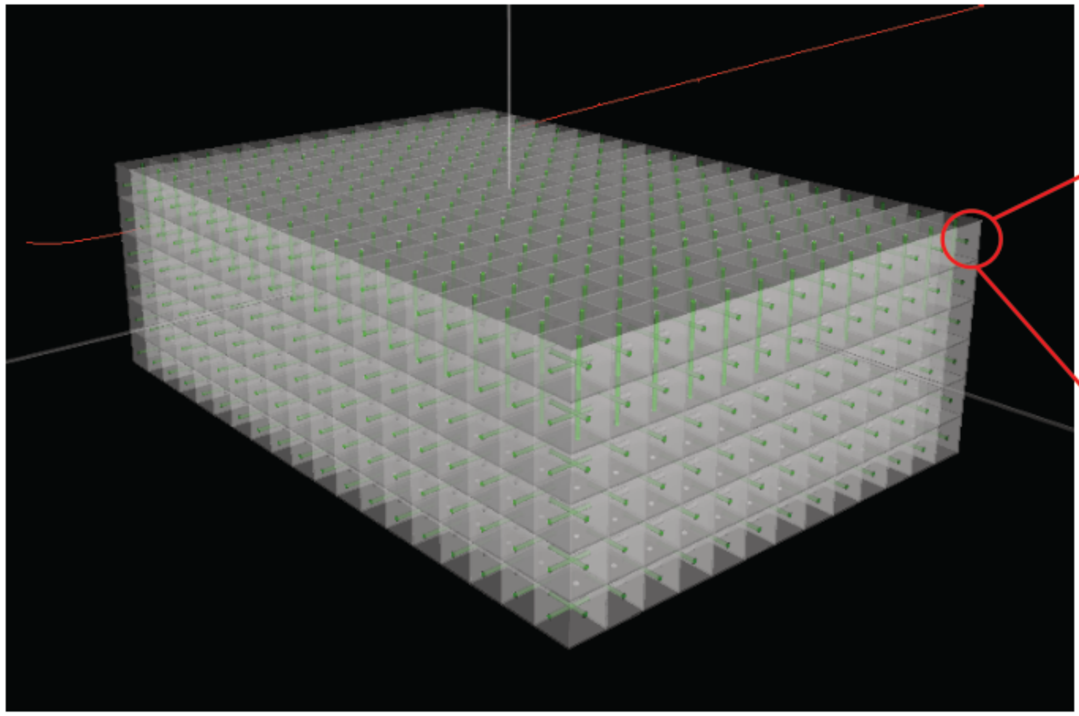
NEW SCINTILLATOR DETECTOR (SUPER FGD)

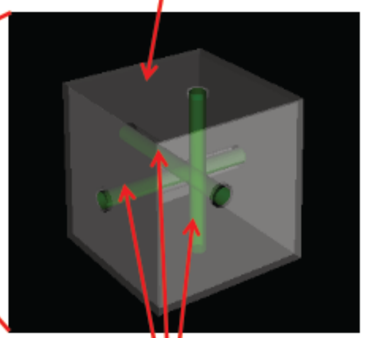
- A **novel detector** made from scintillator cubes
  - 1x1x1 cm^3 cube
    - *low energy thresholds*
    - *high spatial resolution*
    - *3D reconstruction*

    } *Unique for scintillator detector!*
  - fully active plastic detector –> no track distortions



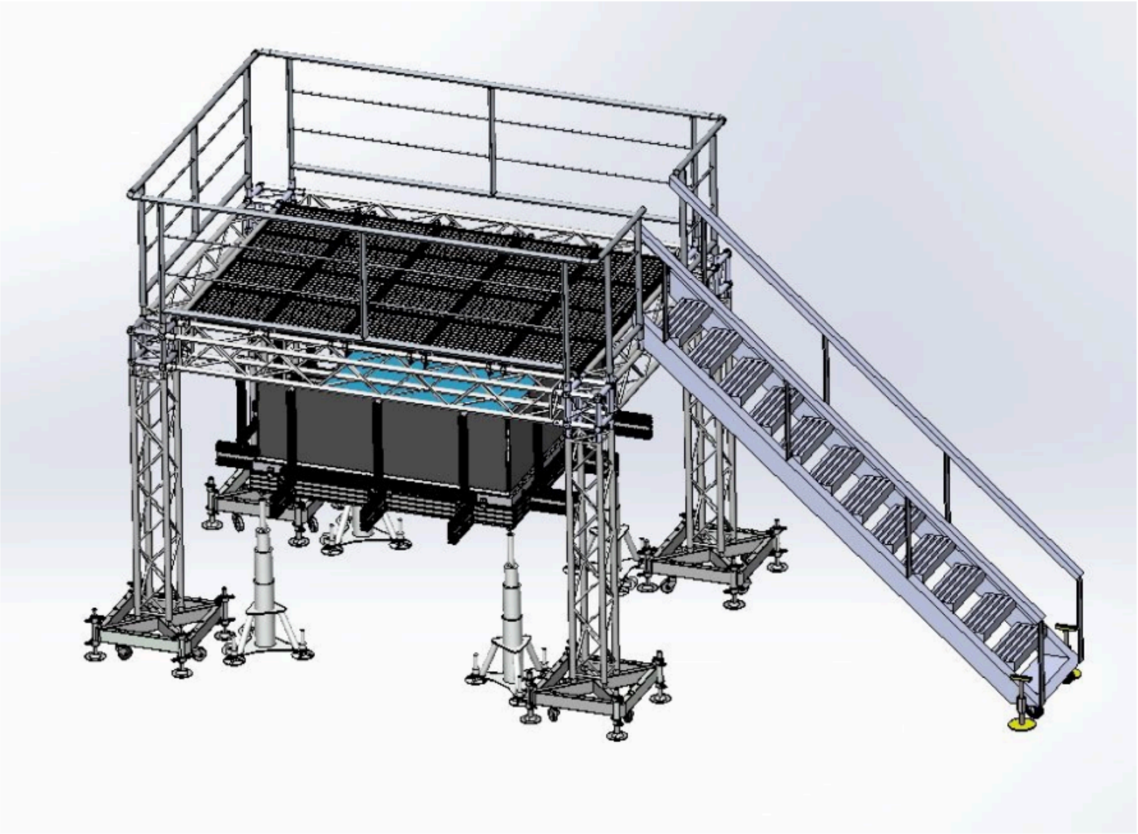
- Adds 2 tons of fiducial volume to current FGDs
- We are pioneering R&D of such a neutrino detector
  - there are proposals to use similar detector in other experiments (e.g. DUNE)





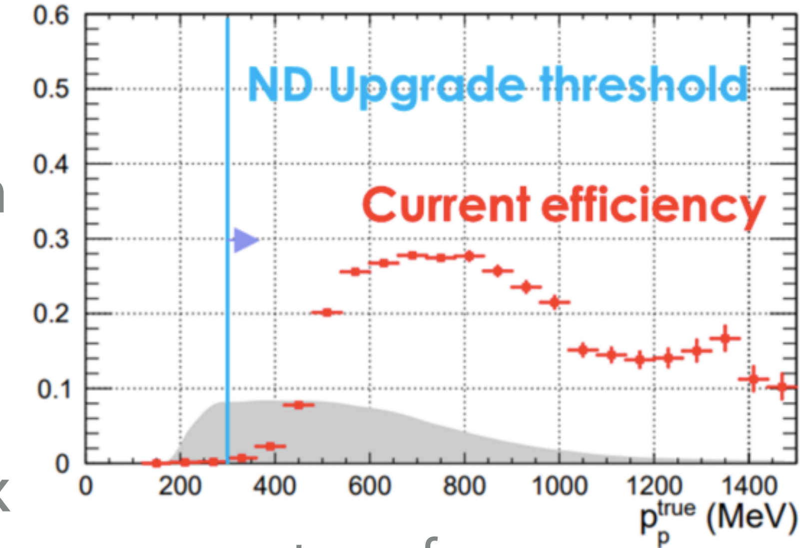
SUPERFGD PRODUCTION

- Major milestone is achieved in the detector production
- Detector production at Uniplast (Vladimir) is finalised
- Planes of scintillator cubes are assembled at INR
- Assembly & Integration procedures are under severe development in collaboration with Dubna and CERN

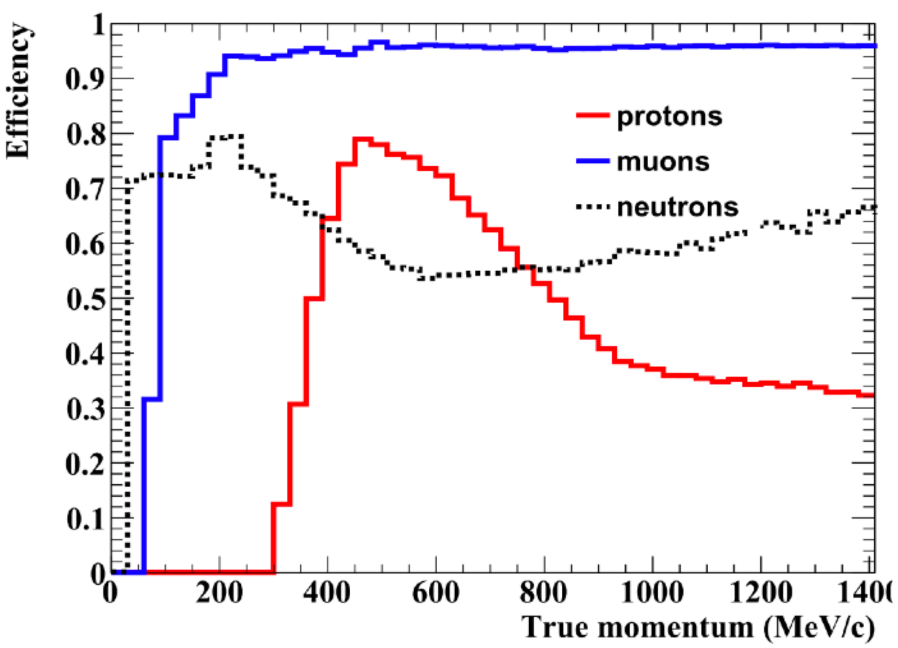


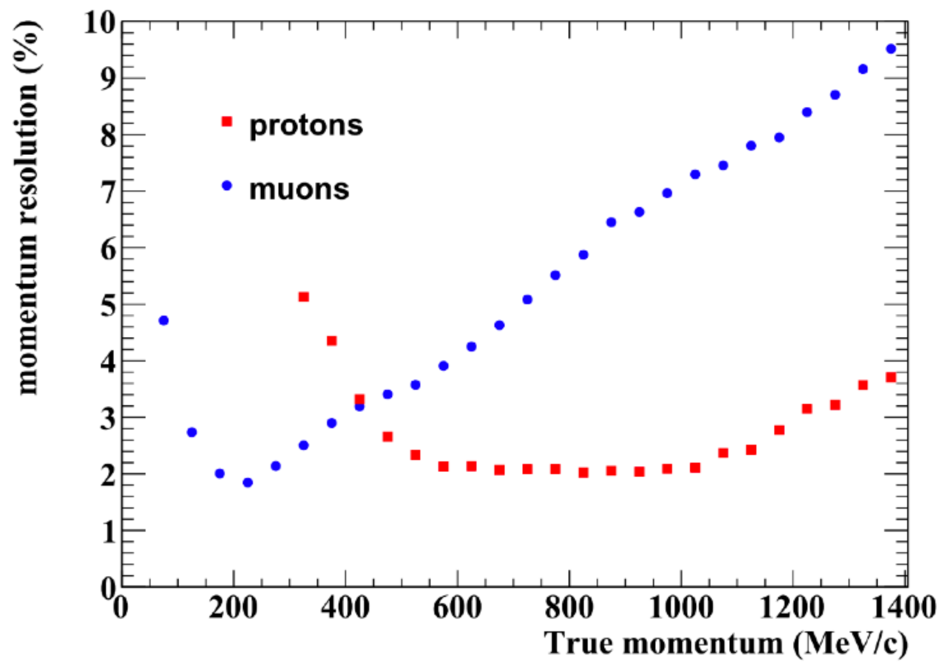
SUPERFGD PERFORMANCE

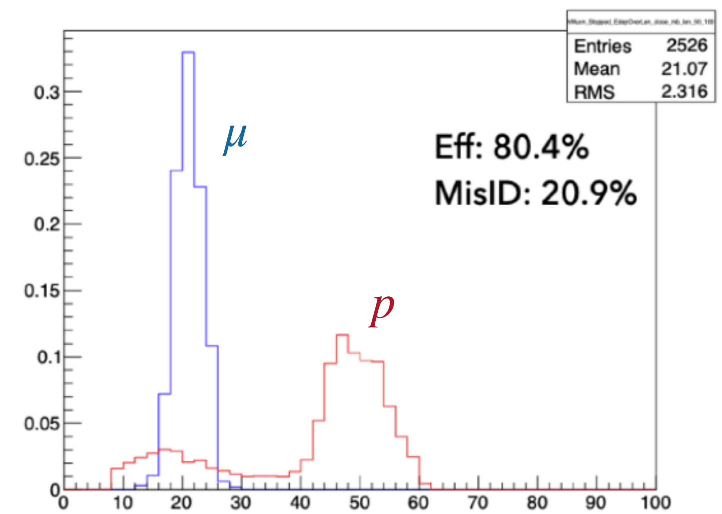
- Fine granularity allows reconstruction of low momentum protons, thus more accurate neutrino interaction measurements
- SuperFGD can perform particle identification with dE/dx



p spectrum from
ν interactions at ND280



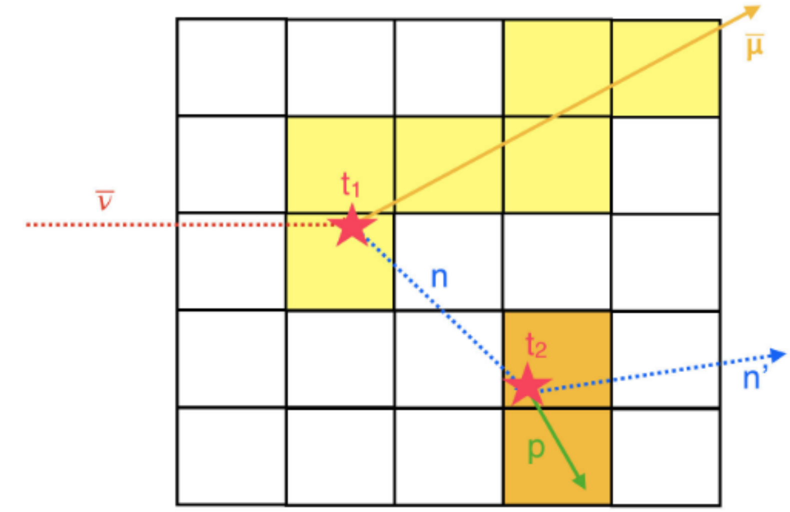




Light yield (p.e.) / cm

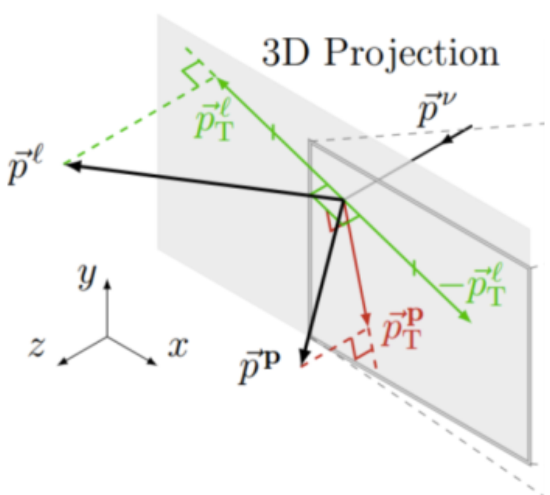
- Expected gain on ν cross-section measurements - arXiv:2108.11779

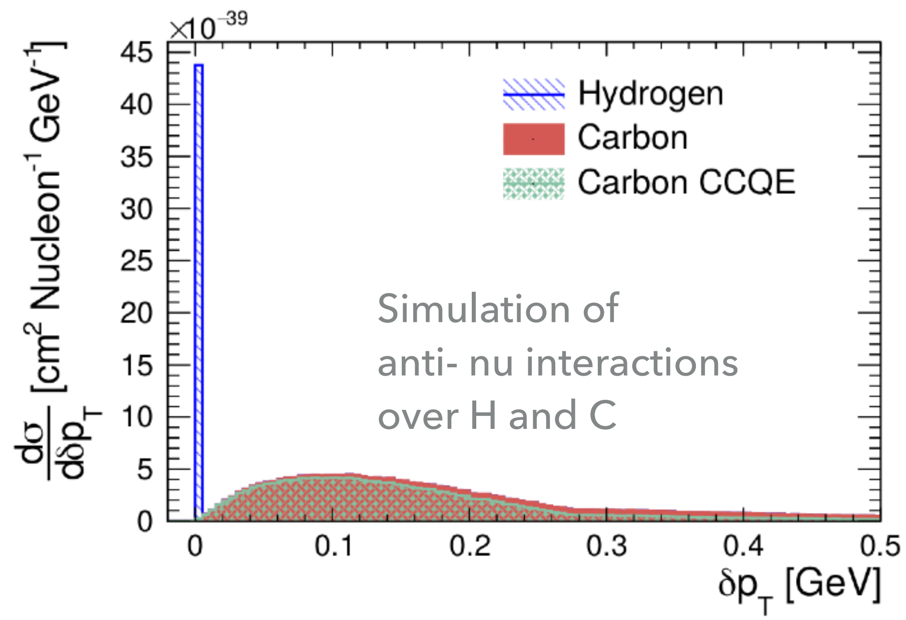
NEUTRONS IN SUPERFGD



- In SuperFGD neutron can be reconstructed with a scattering
  - neutron detection from $\overline{\nu} + p \rightarrow \mu^+ + n$
  - neutron energy can be measured with Time of Flight (ToF)

- Transverse momentum imbalance can be studied
  - neutrino interaction kinematics in plastic detector (C_8H_8) is different for Carbon and Hydrogen





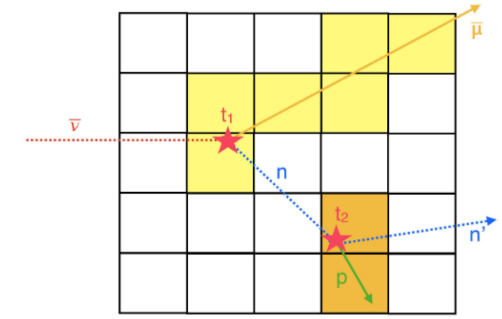
momentum imbalance is completely different!

–> Hydrogen sample can be selected

–> **precise $\overline{\nu}$ energy measurements free from nuclear effects**

- Such an analysis was performed for ν ($\nu + n \rightarrow \mu^- + p$). with both μ and p detection
  - neutron detection is not possible in current ND280 configuration
- Simulation shows high neutron cluster detection efficiency ~ 90%

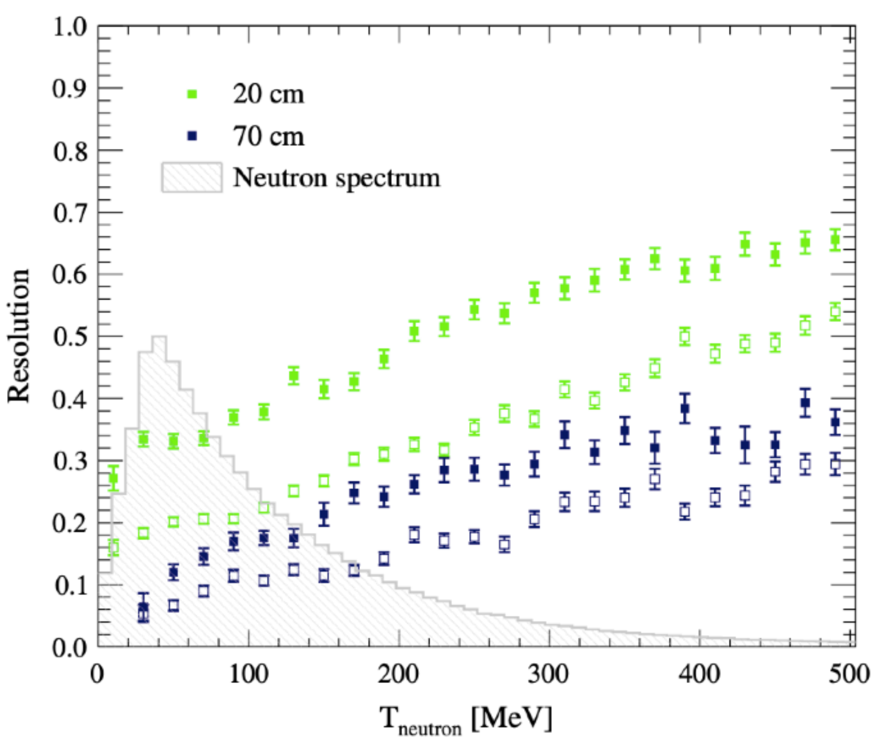
NEUTRONS IN SUPERFGD



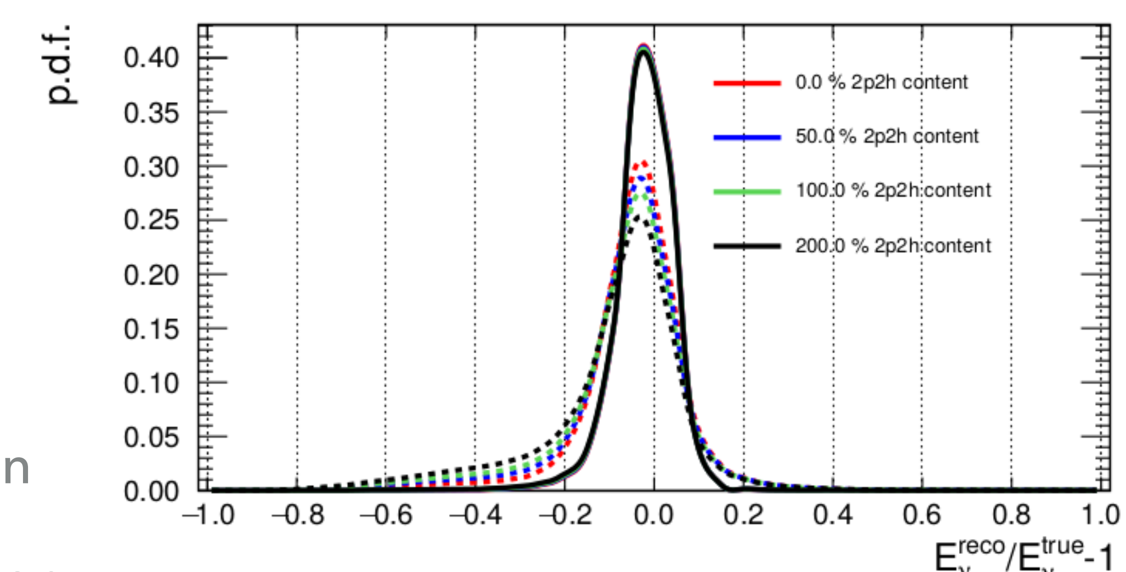
- SuperFGD time resolution ~0.95 ns (from beamtests with MIP)

Phys. Rev. D 101, 092003 (2020)

- Improve the neutron energy reconstruction accuracy:
  - lever-arm cut selects neutrons that travel longer distance
  - l.y. cut select neutron clusters with more light then a MIP
- Reasonable neutron energy resolution was observed:



- Neutron kinematics measurements eliminate dependence from poorly studied nuclear effects in $E_{\overline{\nu}}$ measurements

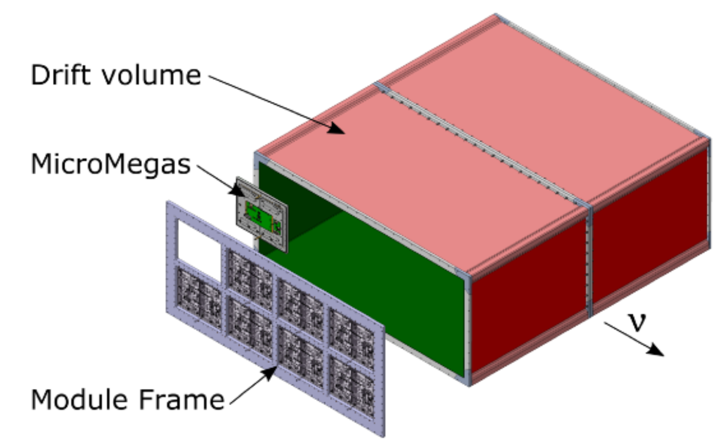


w/ neutron information

w/o neutron information

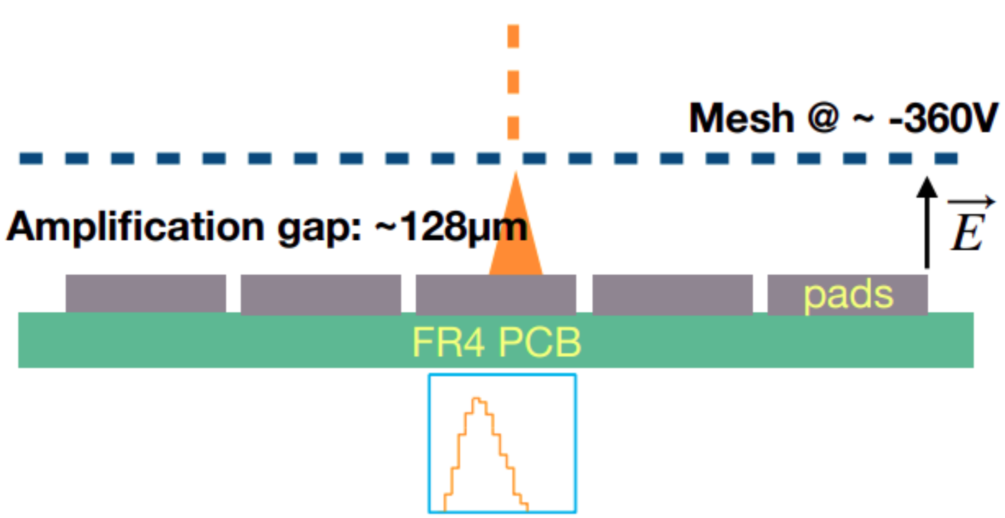
NEW TIME PROJECTION CHAMBERS

- High angle tracks from the target are tracked with 2 new TPCs
  - low material budget –>
    minimal track distortion at SFGD-TPC passage
  - Resistive MicroMegas (MM) modules significantly improve spatial resolution keeping pad size the same

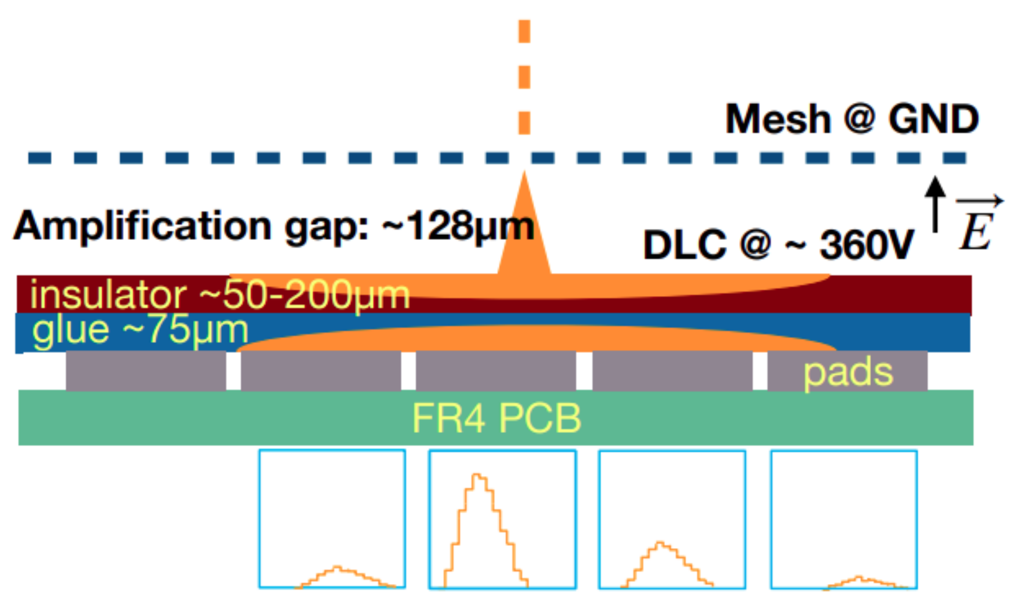


- A resistive layer on top of sensitive pads
  - charge spreading –> avalanche position is reconstructed based on information from several pads --> gain accuracy
  - charge measurements are correlated --> concerns about dE/dx resolution

bulk MicroMegas



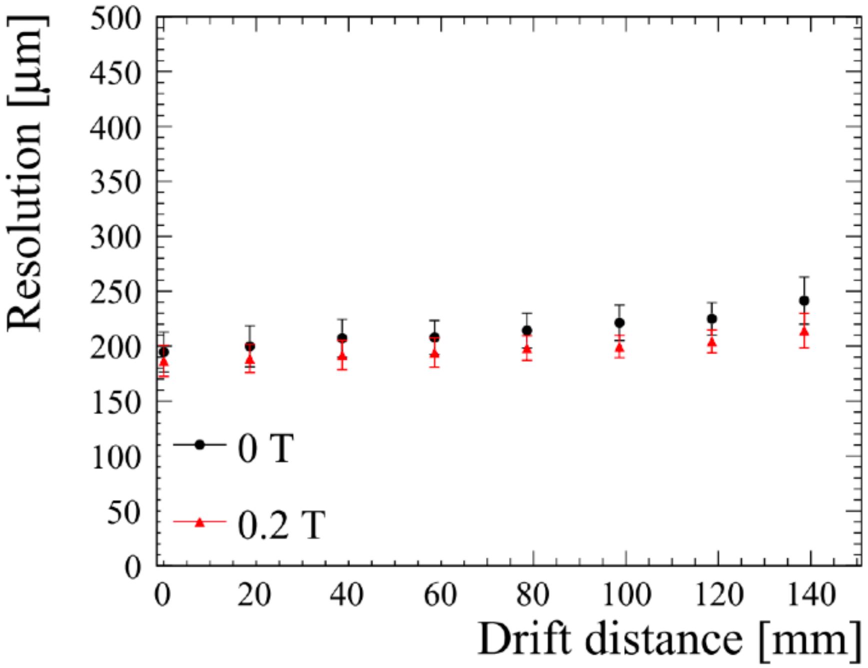
resistive anode MicroMegas



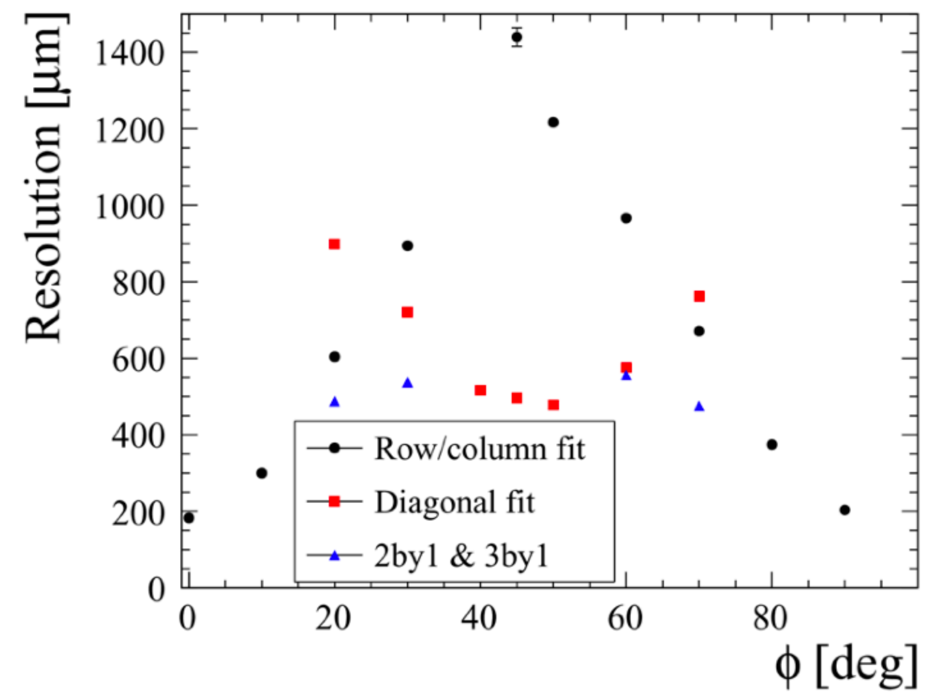
Originally designed for:

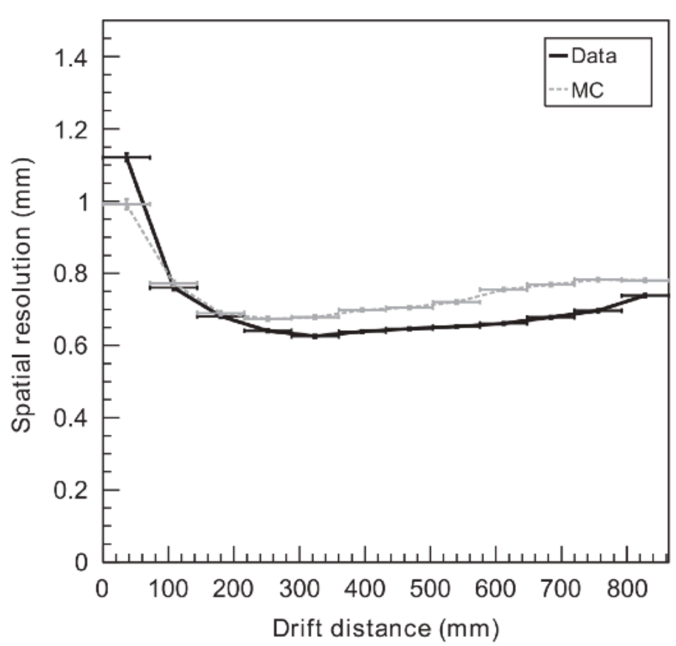
PHYSICS BENEFITS OF THE NEW TPC

- The main advantage of the resistive MM is improved spatial resolution
- ND280 is a magnetised detector
  –> momentum resolution is going to be improved

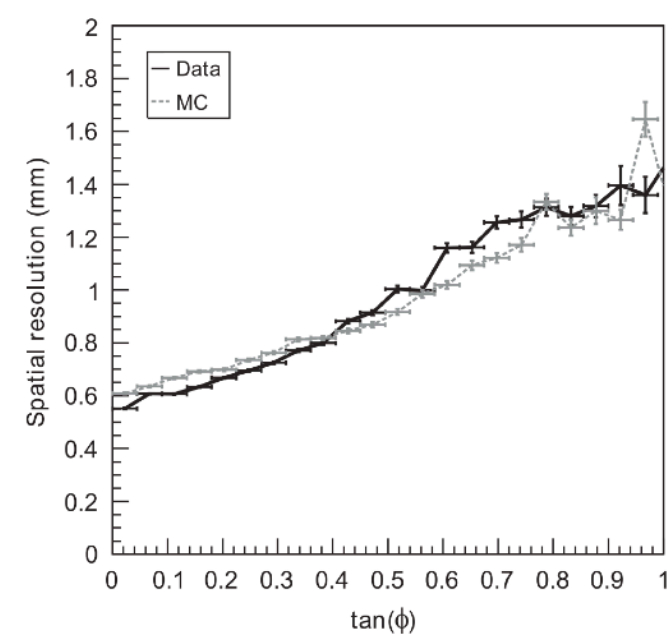


Upgraded TPC performance





Current TPC performance

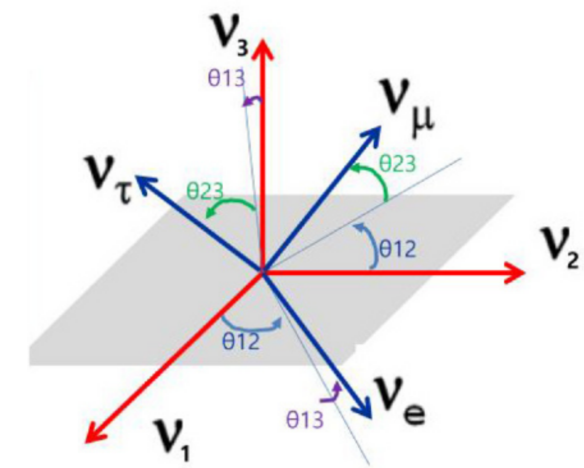


SUMMARY

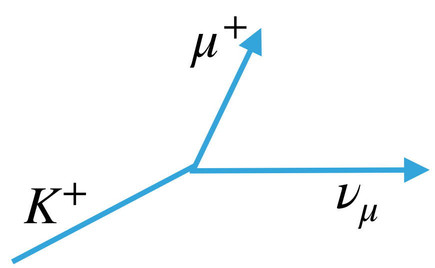
- Precise measurements of CP-violation in T2K experiment requires significant systematics reduction
- Near detector upgrade program aims to reduce uncertainties in oscillation measurements 5% –> 3%
- Brand new detectors R&D are under development
  - Strong contribution of the INR group to the R&D and production of the brand new scintillator neutrino target
- Detector assembly is scheduled in 2022
- Rich physics program is awaited with the new setup
  - Precise measurements of the neutrino cross section
  - Search for CP violation with sensitivities ~3σ in the wide range of δ_{CP}
  - Exotic models constrain (e.g. 10.1016/j.physletb.2021.136641)

BACK UP

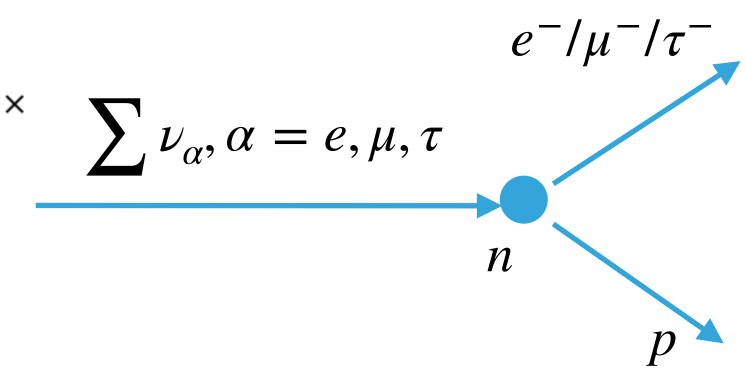
NEUTRINO OSCILLATIONS



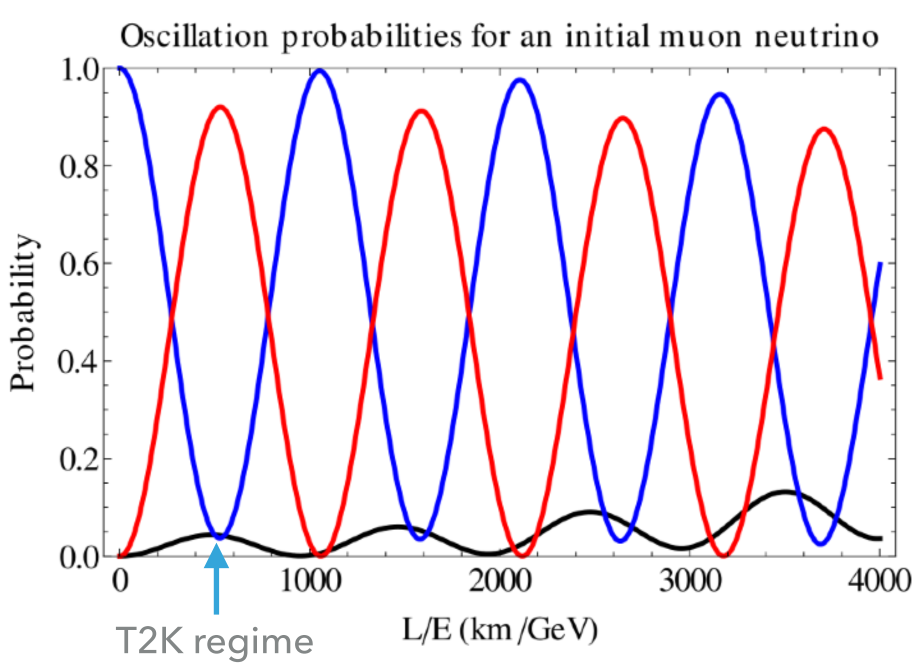
- Neutrino production and detection –> flavor states: e, μ, τ
- Propagation –> mass states ν_1, ν_2, ν_3 $\quad exp\,(-i\Delta E t) \approx exp\left(-i\frac{\Delta m^2}{2E}L\right)$
- Relation of the flavor and mass states –> mixing matrix (3 angles, 3 phases)



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{+i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times$$
$$\times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \exp\frac{i\alpha_1}{2} & 0 & 0 \\ 0 & \exp\frac{i\alpha_2}{2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- Probability of the particular flavor detection oscillates along L/E_ν
- muon neutrino –> electron neutrino, tau neutrino



Two channels to study ν oscillations:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\frac{\Delta m^2_{31}L}{4E_\nu}$$

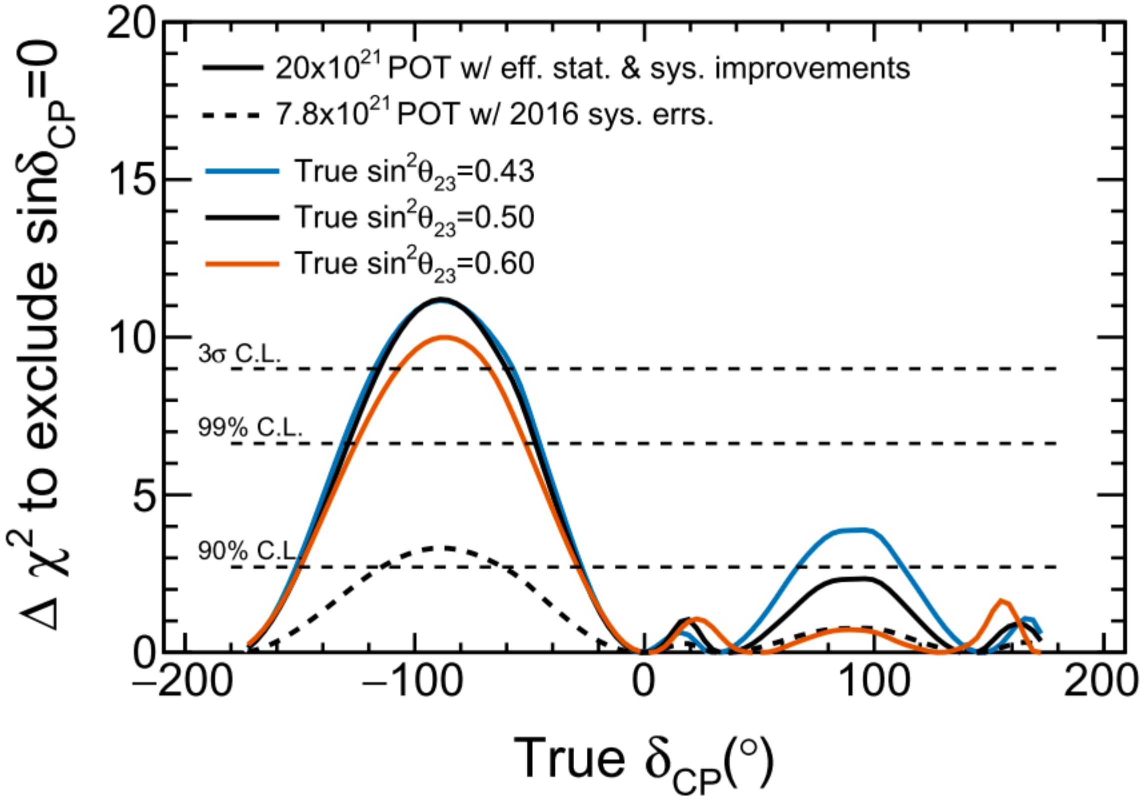
$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}$$
$$-\sin 2\theta_{12}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}\sin\frac{\Delta m^2_{21}L}{4E_\nu}$$

Only appearance channel is sensitive to CP violation phase δ_{CP}

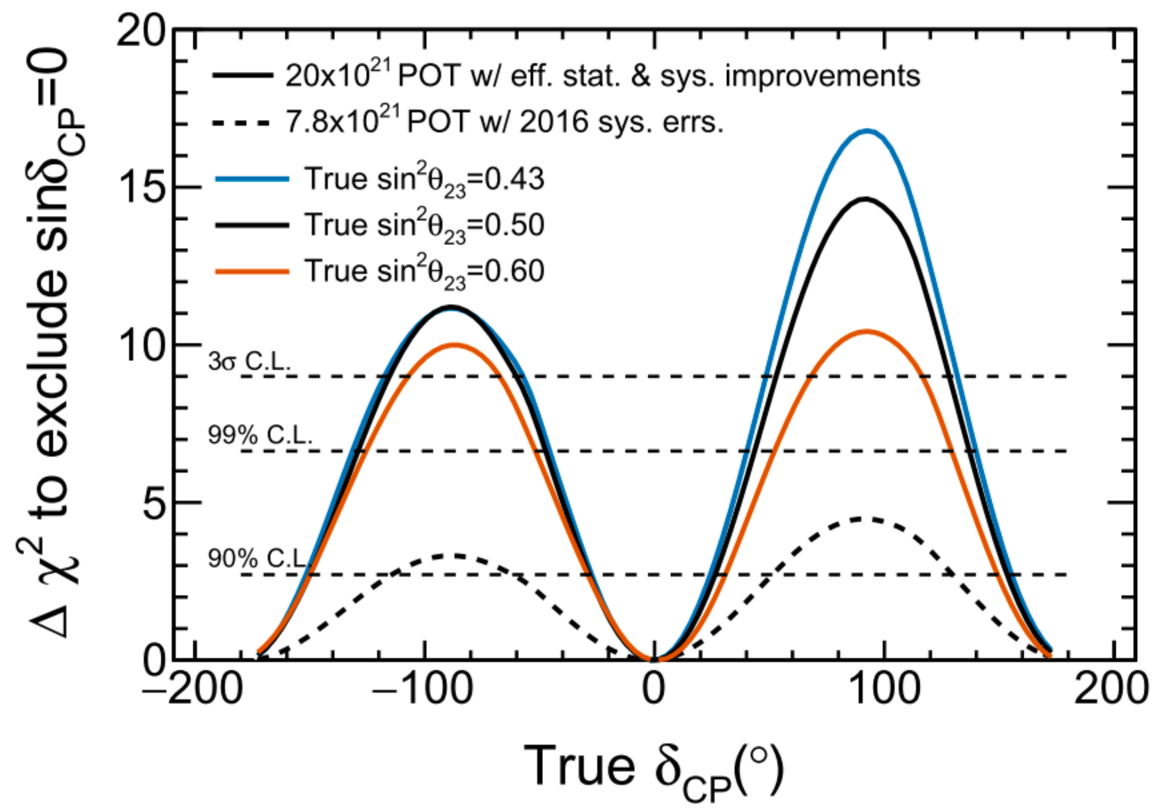
	Pre-BANFF			Post-BANFF		
Group	Mean	1σ	%	Mean	1σ	%
SK Detector	-	-	-	273.06	6.56	2.40
SK FSI+SI+PN	-	-	-	272.36	6.01	2.21
Flux+Xsec constrained	259.08	36.84	14.22	270.71	8.86	3.27
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	-	-	-	272.40	0.00	0.00
NC1γ	-	-	-	272.40	0.00	0.00
NC Other	-	-	-	272.40	0.69	0.25
E_b	-	-	-	272.31	6.48	2.38
Osc	-	-	-	272.44	0.07	0.03
All	258.96	37.96	14.66	271.33	13.88	5.12
All with osc	258.99	37.97	14.66	271.36	13.89	5.12

Table 20: Uncertainty on the number of event in each SK sample broken by error source after the BANFF fit.

	1-Ring μ		1-Ring e		
Error source	FHC	RHC	FHC	RHC	FHC CC1π
Beam	4.3%	4.1%	4.4%	4.2%	4.4%
Cross-section (constr. by ND280)	4.7%	4.0%	4.8%	4.1%	4.1%
Cross-section (all)	5.6%	4.4%	8.4%	6.2%	5.6%
Beam + Cross-section (constr. by ND280)	3.3%	3.3%	3.3%	3.1%	4.0%
Beam + Cross-section (all)	4.4%	2.9%	7.7%	5.7%	5.6%
New E_b fake data parameter	3.2%	1.3%	7.2%	4.1%	2.8%
SK+FSI+SI	3.3%	2.9%	4.1%	4.3%	16.6%
Total	5.5%	4.4%	8.8%	7.3%	17.8%



(a) Assuming the MH is unknown.



(b) Assuming the MH is known – measured by an outside experiment.

NEUTRONS IN SFGD

$\sigma_t^{ly} = 0.95\ \mathrm{ns}/\sqrt{3} \cdot \sqrt{40\ \mathrm{PE/LY}},$ $\sigma_t^{ly} > 200\ \mathrm{ps}$ optimistic

$\sigma_t^{ch} = 0.95\ \mathrm{ns}/\sqrt{\#\mathrm{channels}},$ $\sigma_t^{ch} > 200\ \mathrm{ps}$ conservative