Near detectors in present and future LBL experiments

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Neutrino oscillations

Neutrino mixing described by the PMNS matrix: 3 mixing angles and 1 complex CPV phase

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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Atmospheric and accelerator
$\theta_{23} \sim 50°$
$\Delta m_{32}^2 \sim 2.4\text{x}10^{-3}$ eV^2

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Atmospheric and accelerator
θ_{23} ~ 50°
Δm_{32}^2 ~ 2.4x10^{-3} eV^2

Reactor and accelerator
θ_{13} ~ 8°
Accelerator only δ_{CP} = ??

Solar and reactor
θ_{12} ~ 34°
Δm_{12}^2 ~ 7.4x10^{-5} eV^2

$\Delta m_{ji}^2 = m_j^2 - m_i^2$ $c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

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Inferred from $P(\nu_\alpha \rightarrow \nu_\beta) = P(E, L, \Delta m^2, \theta)$

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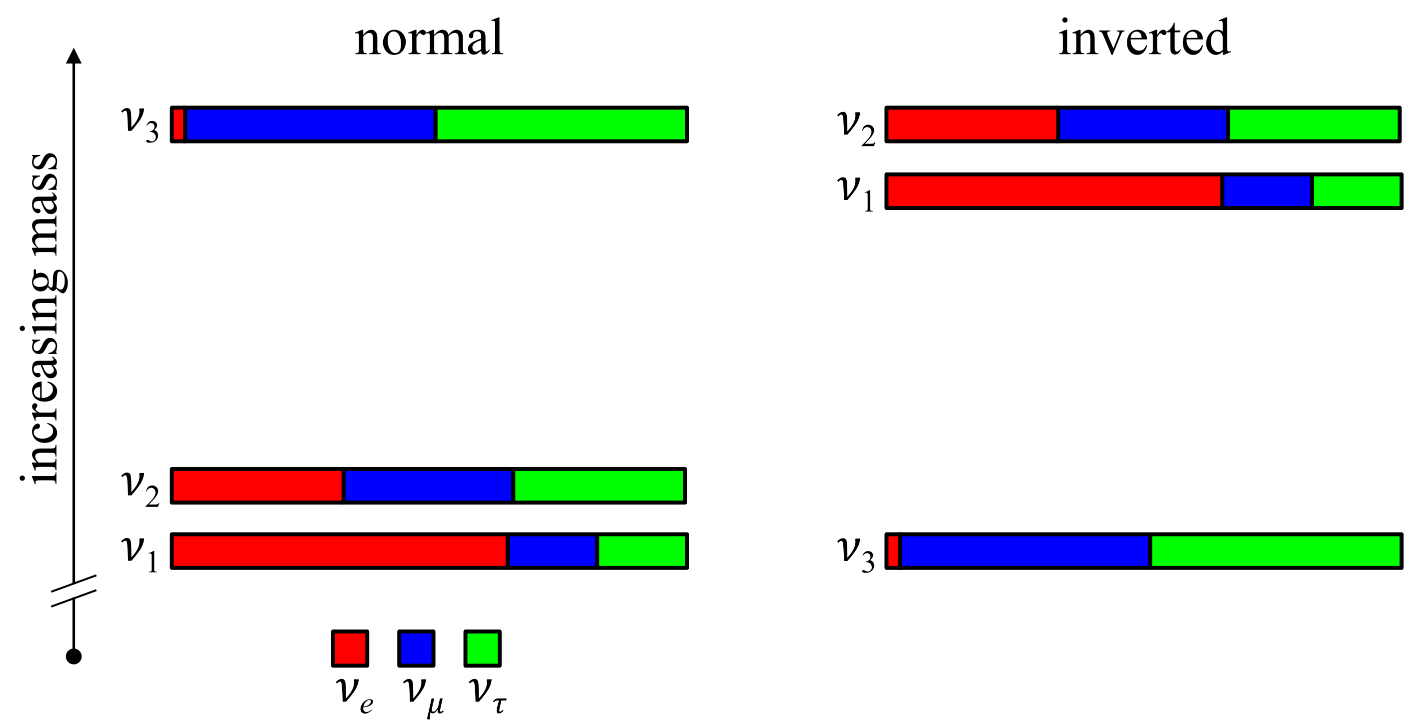
Open questions:
δ_{CP}, θ_{23} octant and mass ordering



$\Delta m_{ji}^2 = m_j^2 - m_i^2 \quad c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$

Oscillations measurements

Long baseline accelerator-based experiments are sensitive to:

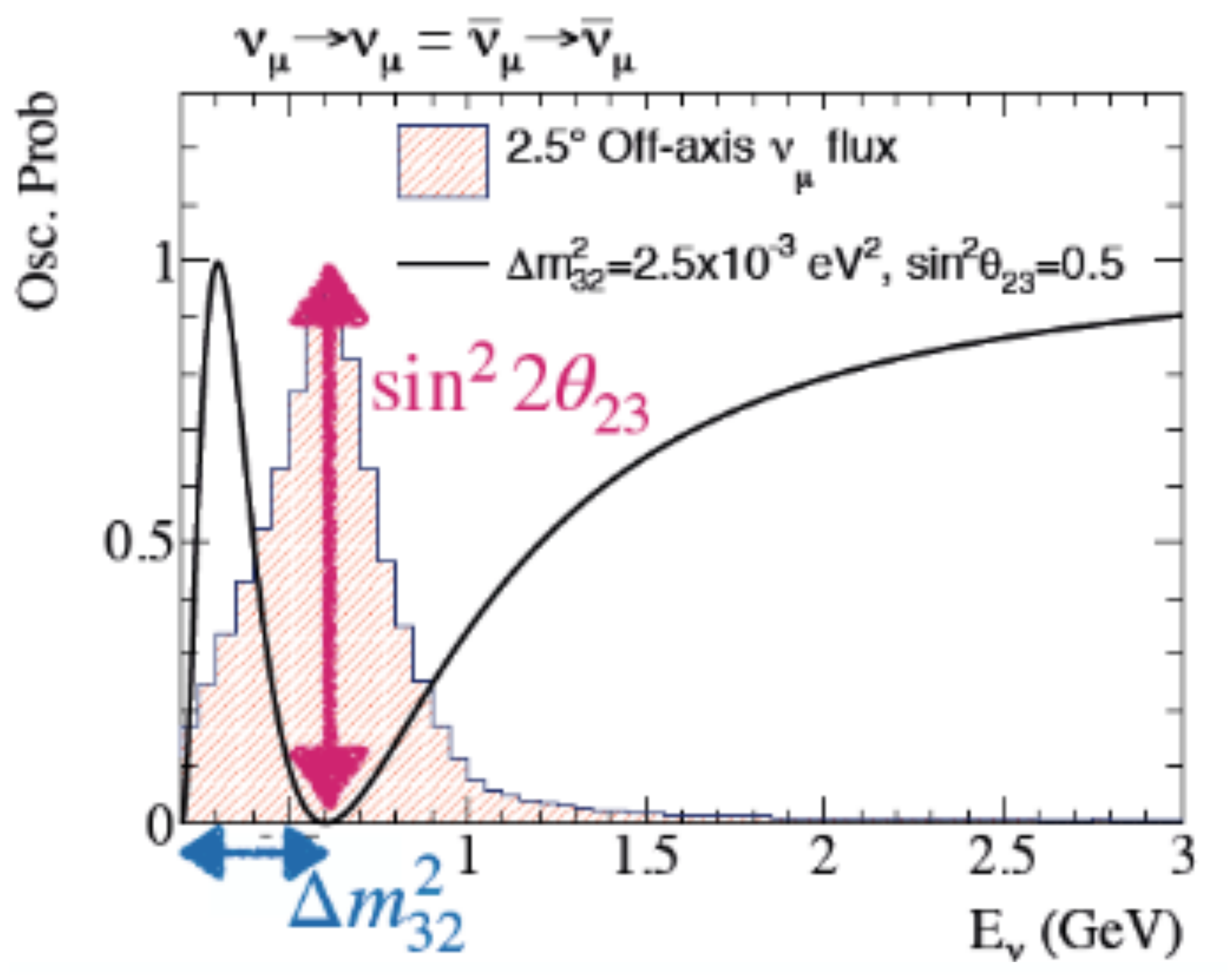
- Atmospheric parameters (θ_{23}, Δm_{32}^2) through ν_μ disappearance

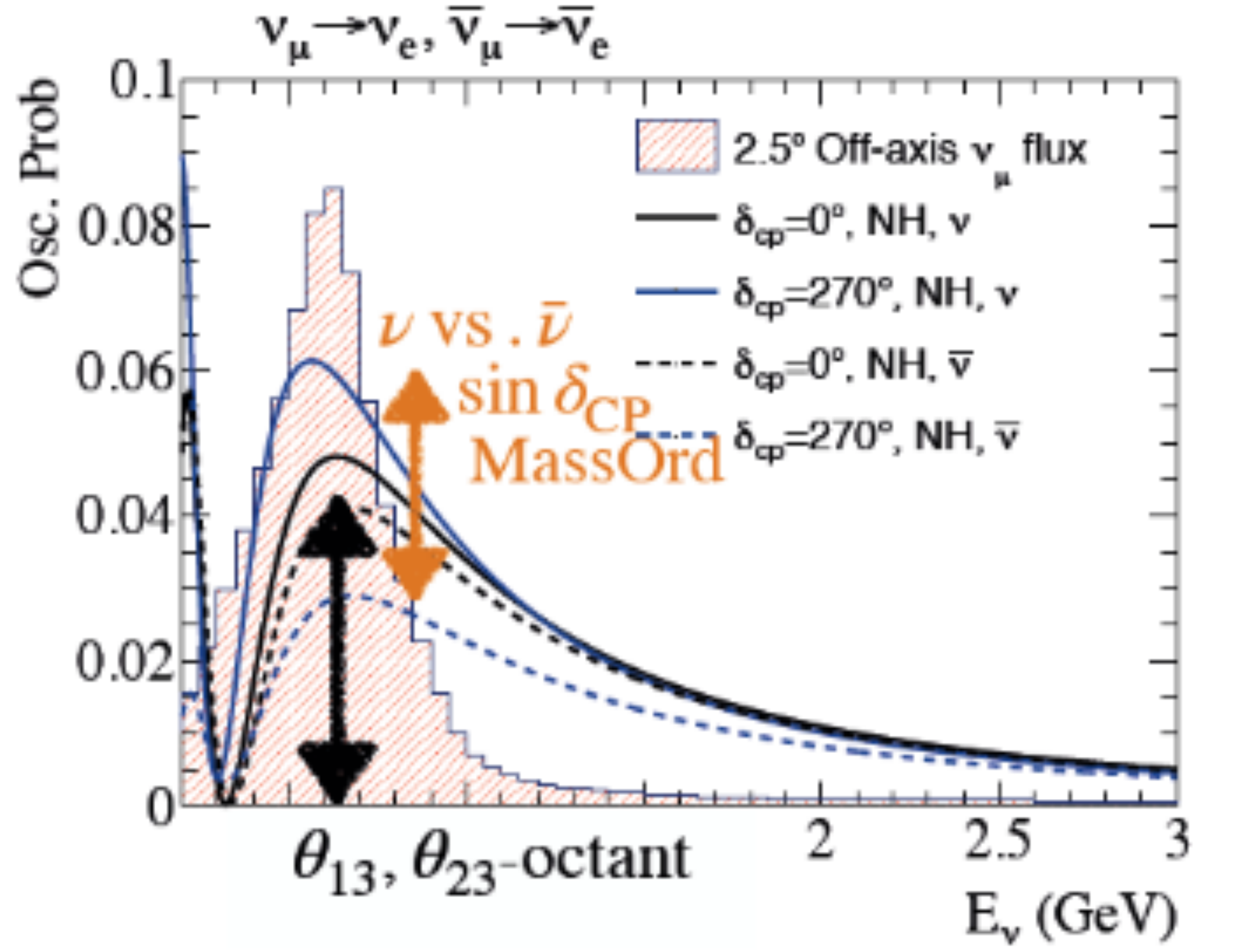
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

- (θ_{13}, δ_{CP}) depends on the $\nu_e/\bar{\nu}_e$ appearance

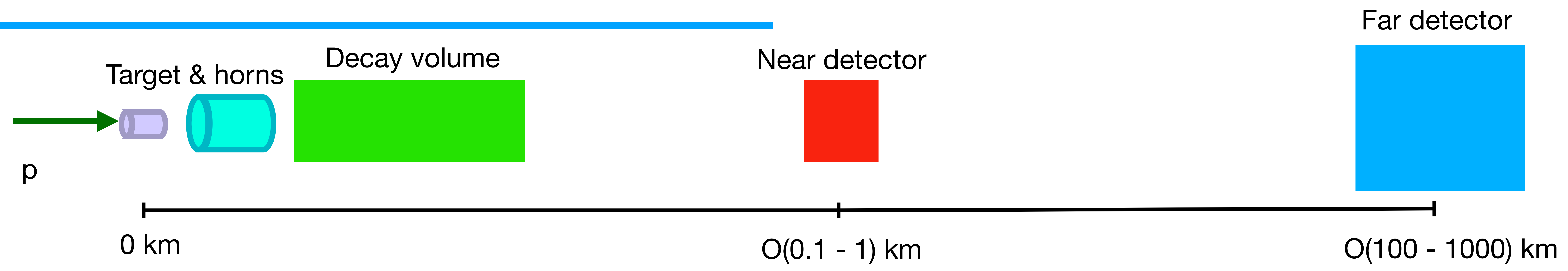
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right) \mp O(\delta_{CP})$$

δ_{CP} change the appearance probability differently for neutrino and antineutrino as well as the mass ordering





LBL experimental setup



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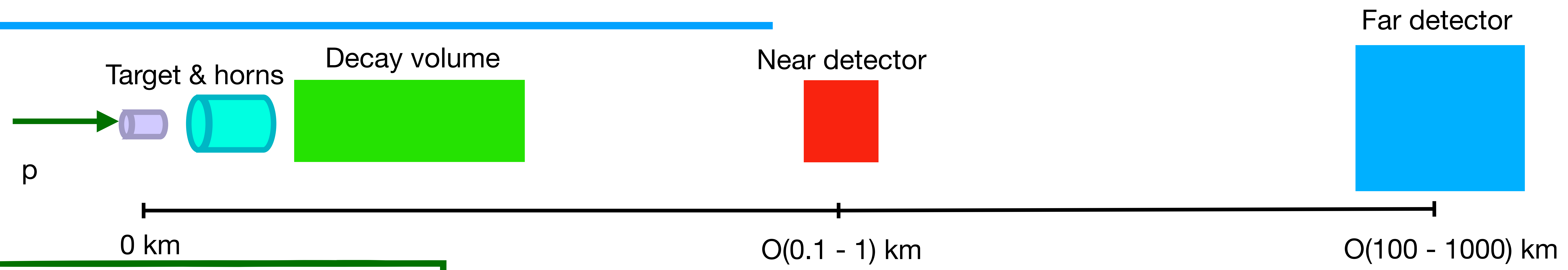
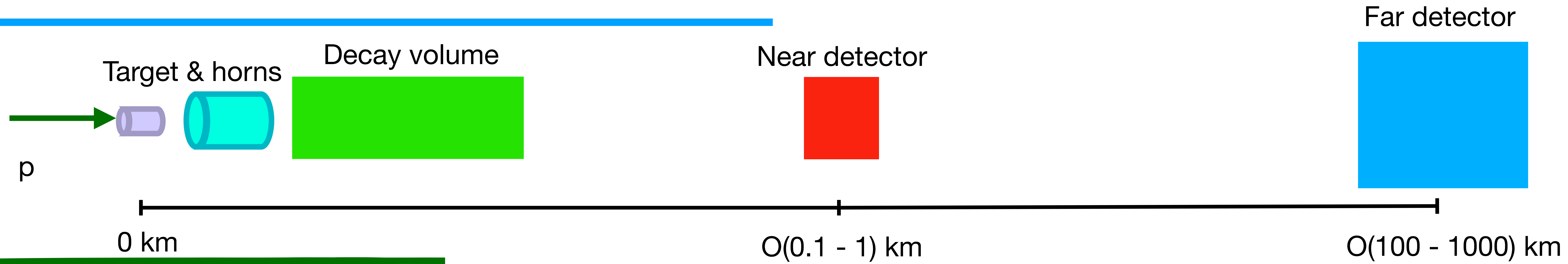


- Proton beam of 10s GeV

LBL experimental setup



- Proton beam of 10s GeV
- Magnetics horns to selection hadrons charge and make a muon neutrino or antineutrino beam

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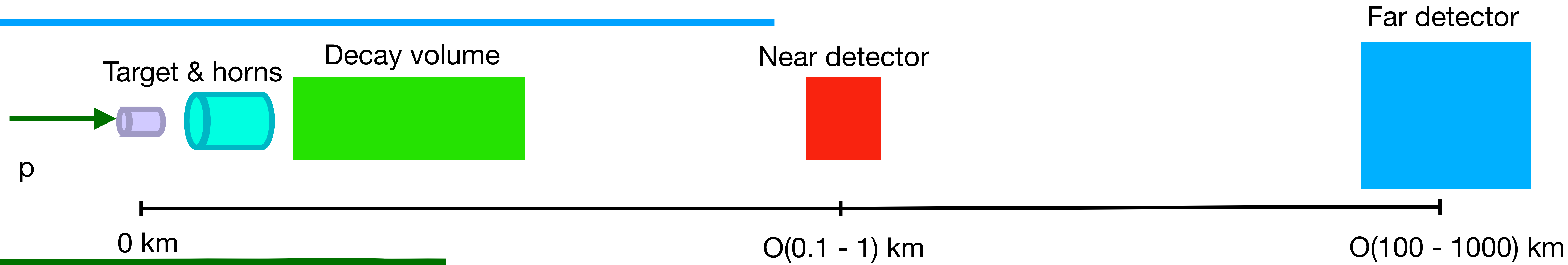

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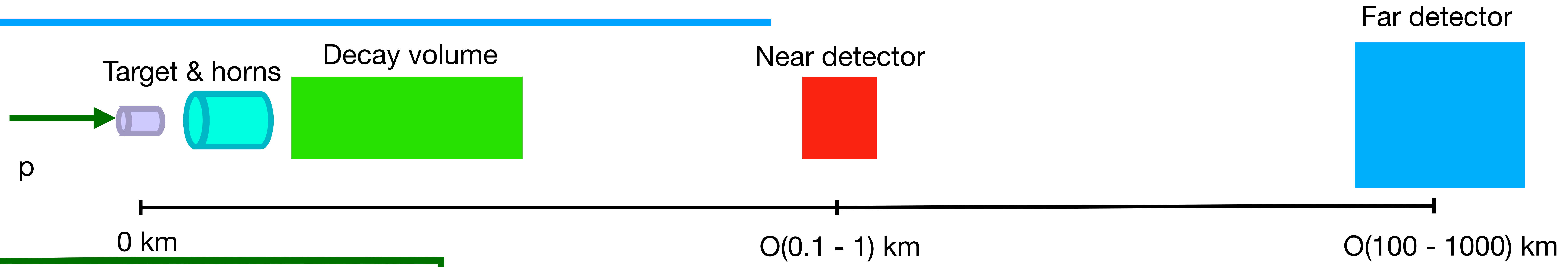

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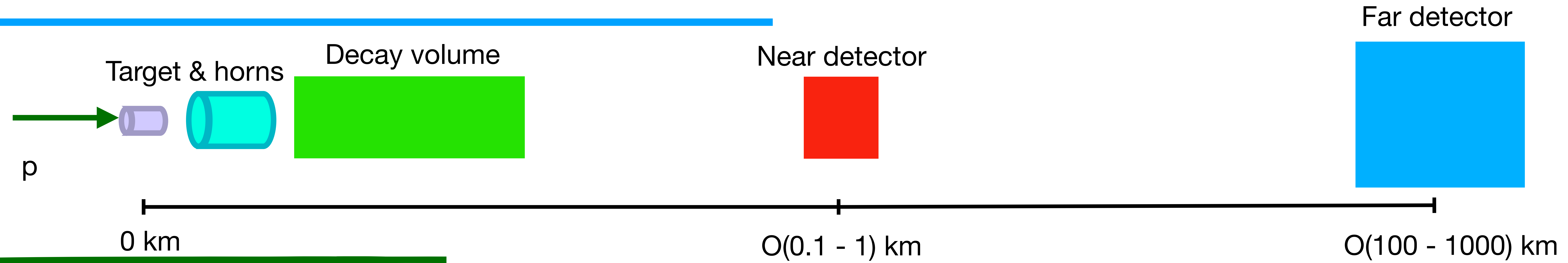

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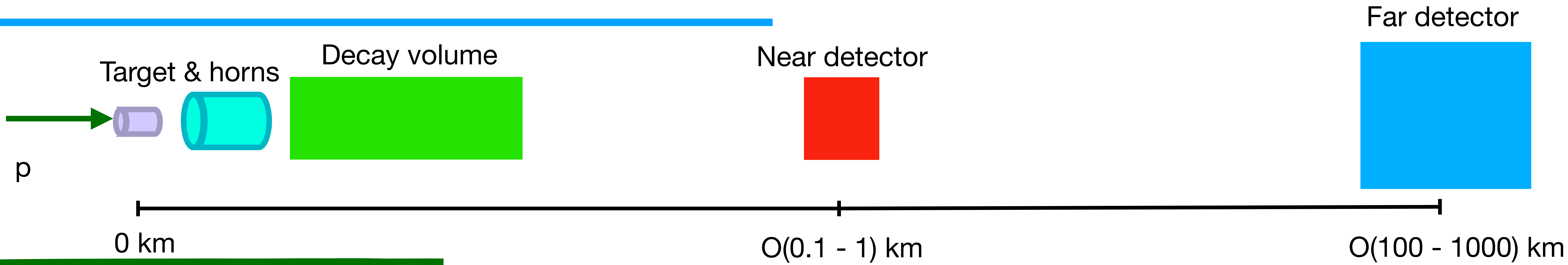

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- Far detector (FD) located at a distance of (100 - 1000) km
- Off-axis strategy: ND and FD are offset compared with beam direction. Maximize oscillation probability and reduce high-energy tail of the flux

LBL measurements

Far detector | Flux | Cross-section | Detector response | Oscillation probability

$$N(E_\nu) = \int \Phi(E_\nu, t) \times \sigma(E_\nu) \times R_{det}(E_\nu, \sigma(E_\nu), \vec{r}) \times P_{osc}(E_\nu, \Theta, L) dE_\nu$$

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Hadron production experiments (e.g. NA61)

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Further constrained by ND

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Often measured through test beam activities. Same if ND and FD use same technology.

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Goal of LBL investigation

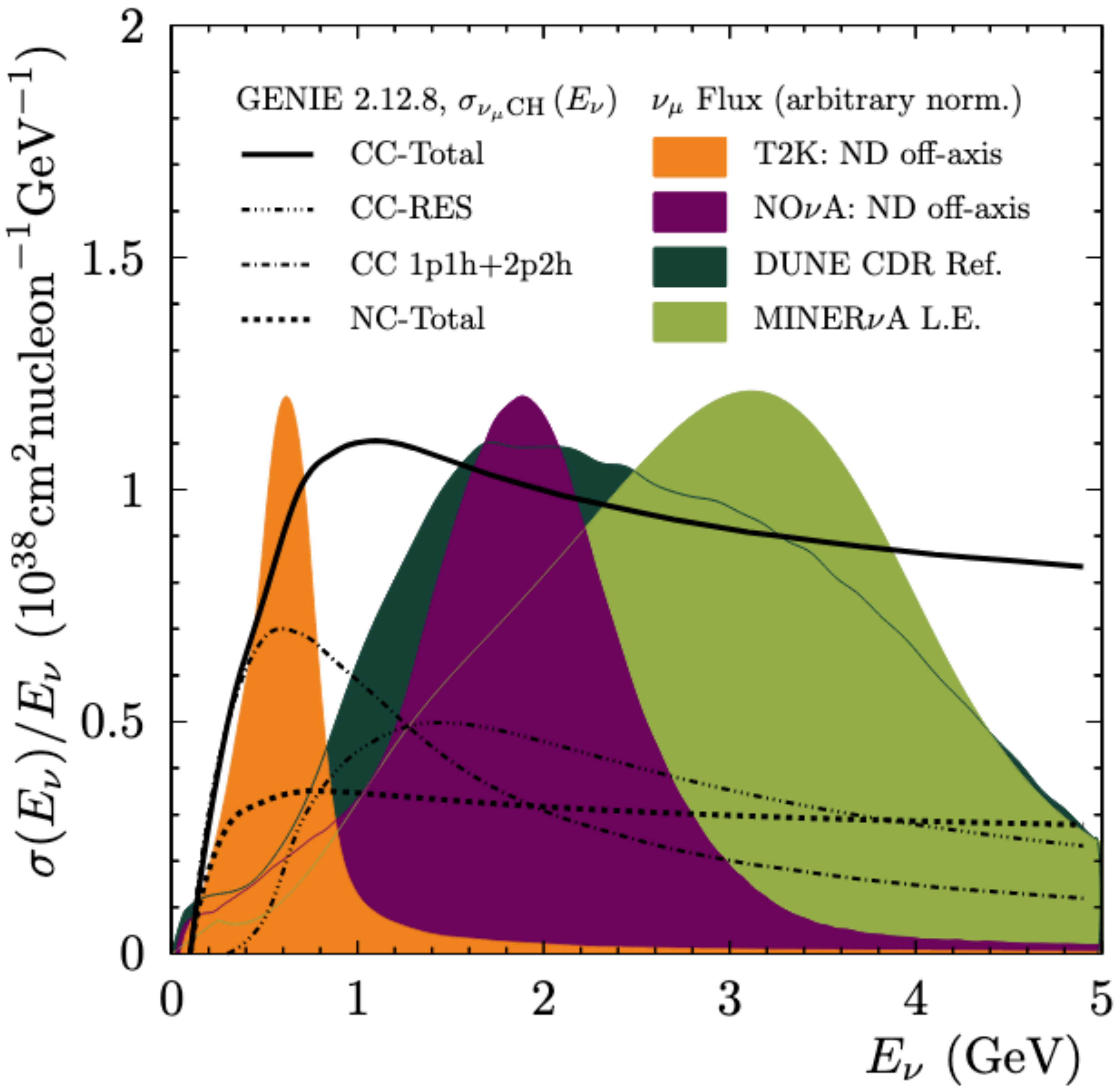
Further constrained by ND

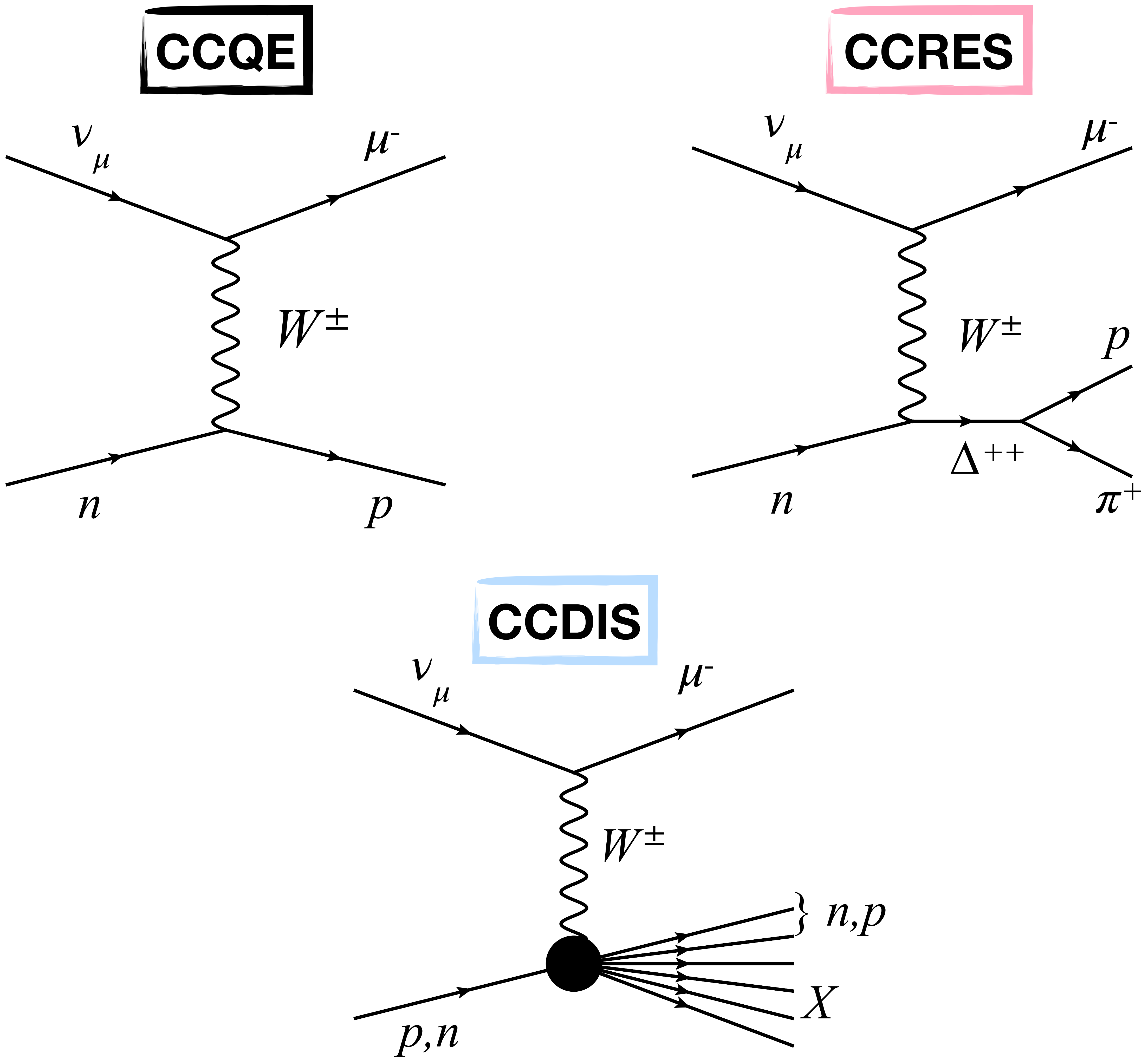
Flux measurements

- Neutrino flux prediction has improved enormously over the LBL era
- Thanks to hadron production experiments (e.g. NA61/SHINE) flux is known now with an uncertainty between ~5-10%
- Relation between flux at ND and FD is nominally well understood
- It can be improved for future LBL:
    - Hadron production experiments using replica target of the LBL experiment
    - Flux measurements at ND can be performed as well: electron neutrino elastic scattering
    - Identify, measure O(1%) “wrong sign” component of the beam

Neutrino interactions

See Anna Ershova's talk



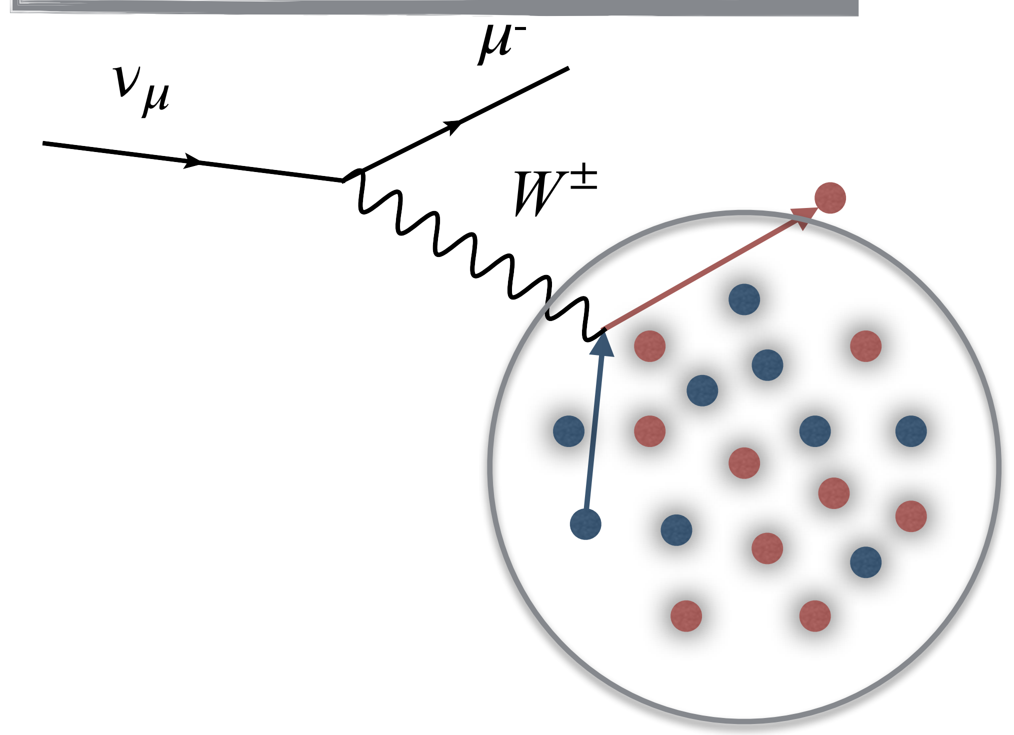


Nuclear effects

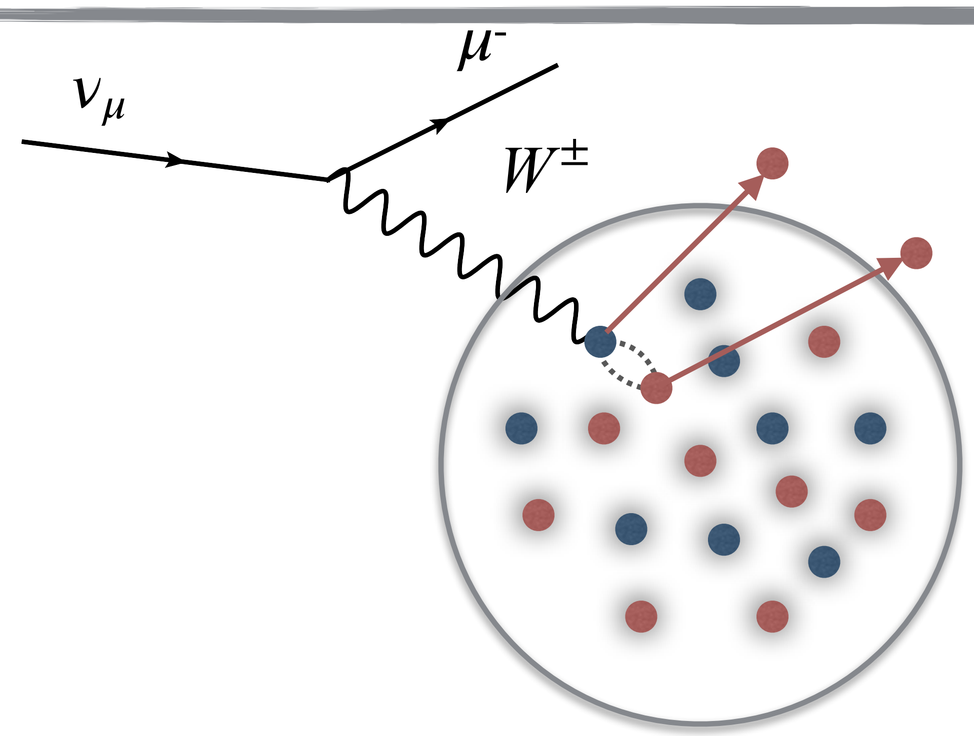
See Anna Ershova's talk

Nucleons bound in the nucleus ⇒ Nuclear effect!

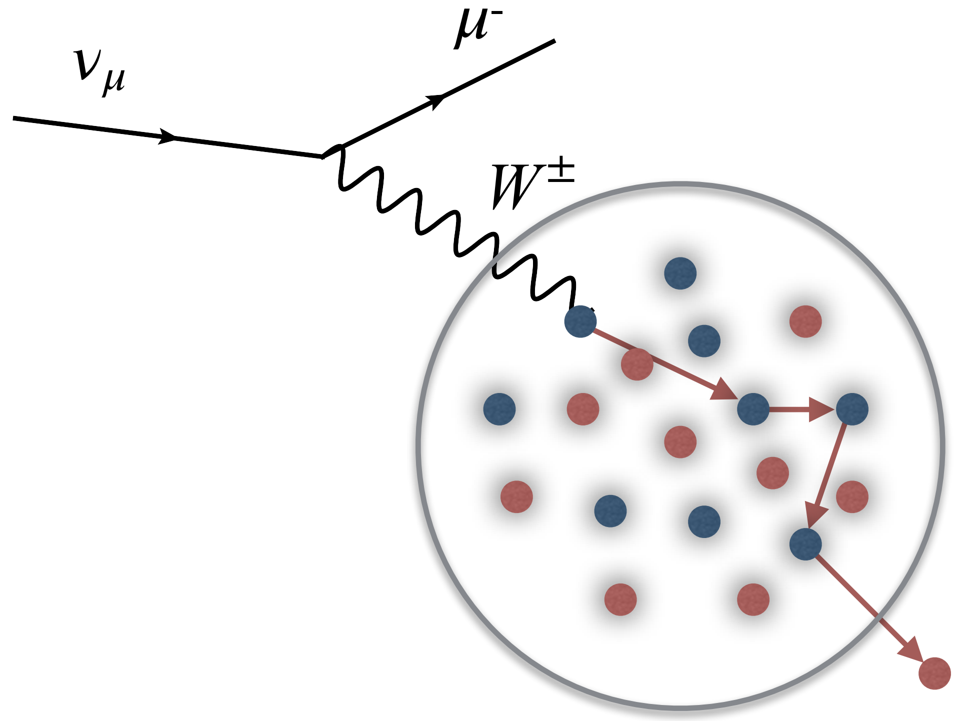
Fermi motion



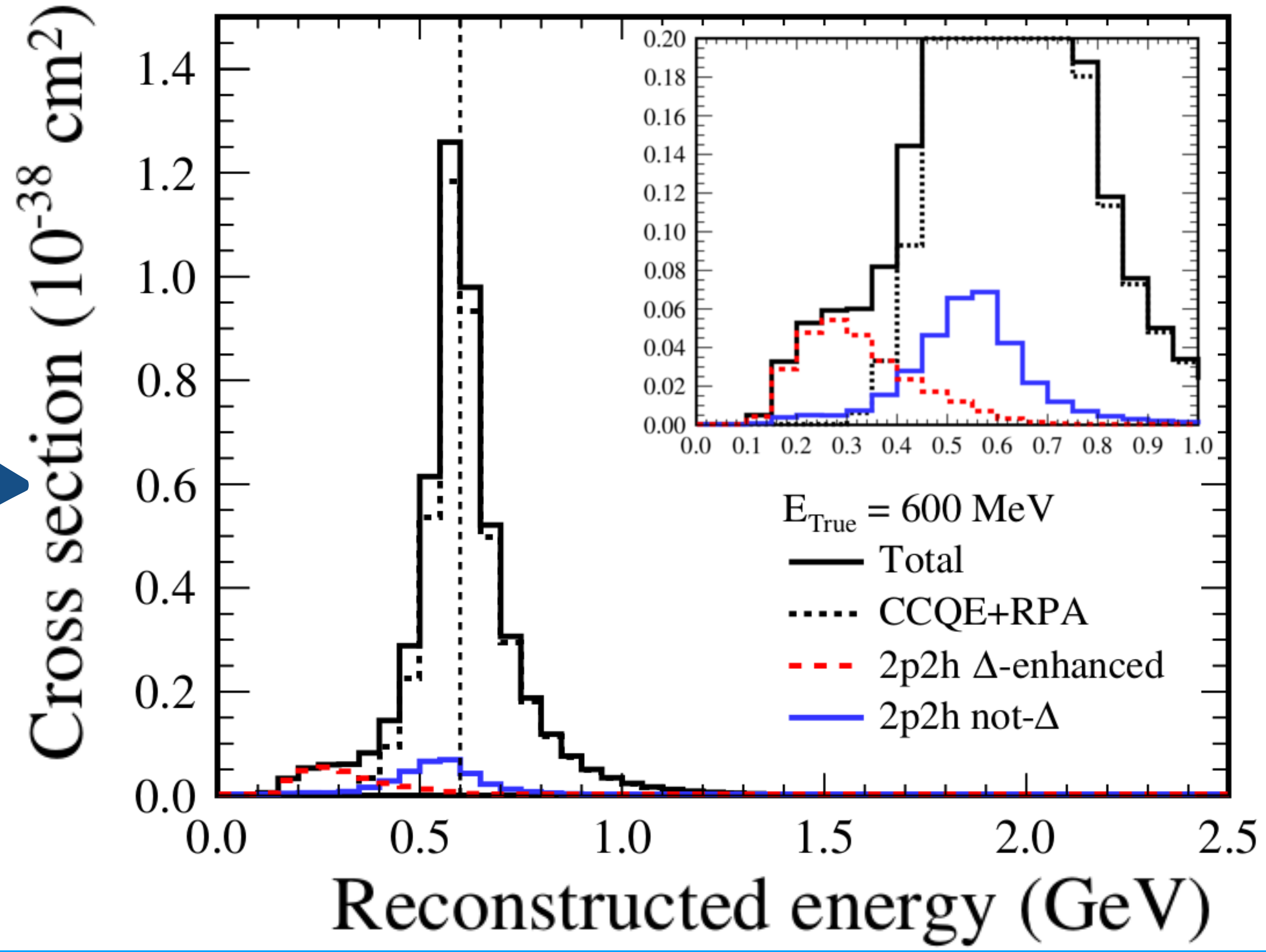
Nucleon correlations



Final State Interaction (FSI)



Nuclear effects introduce a bias in neutrino energy reconstruction



Cross-section modeling

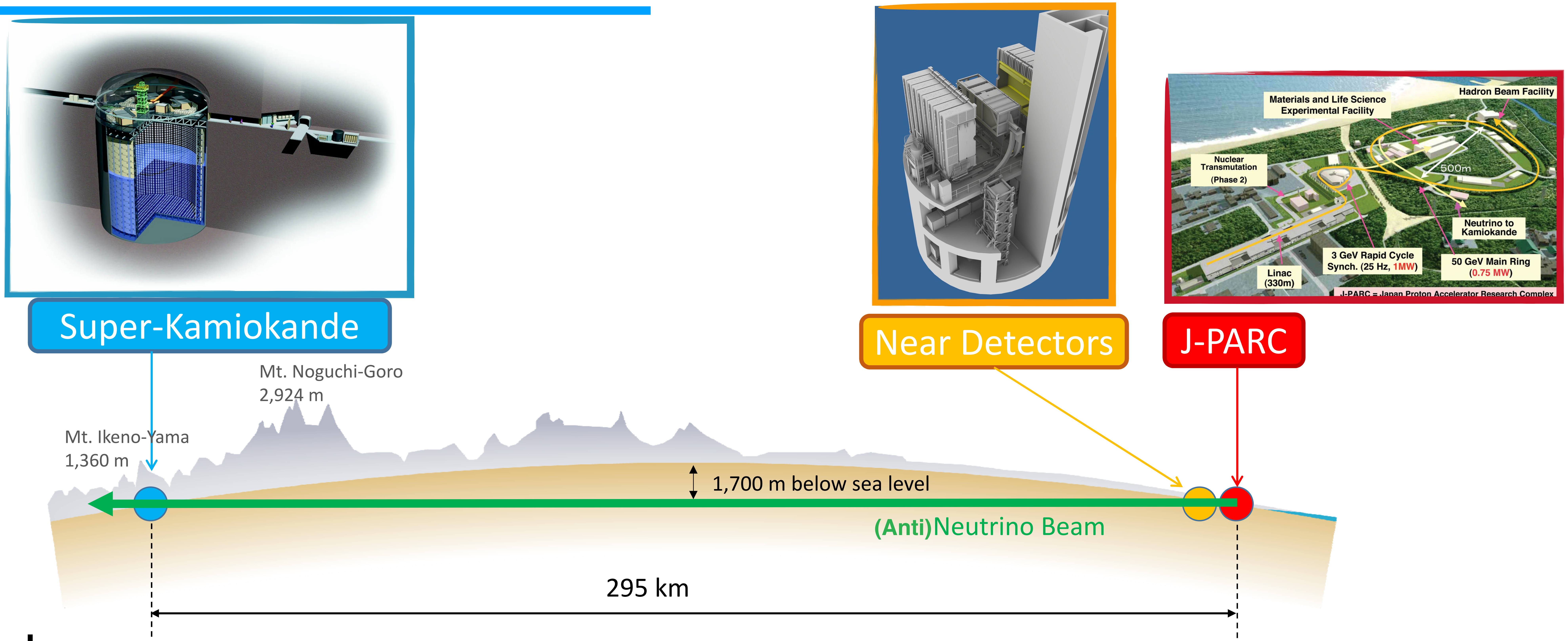
- Modeling of neutrino-nucleus interactions continue to be the most challenging aspect for the LBL program

- It is the largest uncertainty in LBL oscillation analyses, being of the order of 10-15%

- Significant progress: improving theoretical modeling and implementation of variety of models in neutrino event generators

- New and more precise cross-section measurement at ND needed to give direction to the development, ie to help us understand it we are converging on the right physics within our event generators

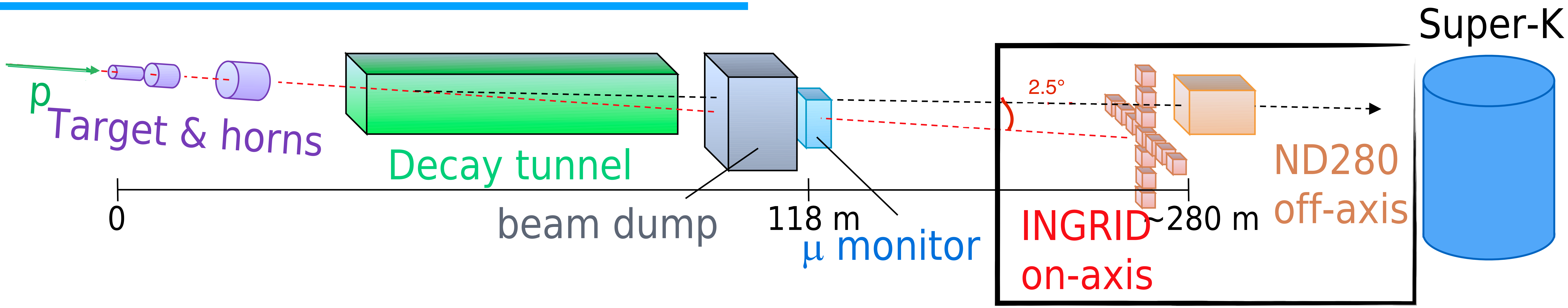
The T2K experiment



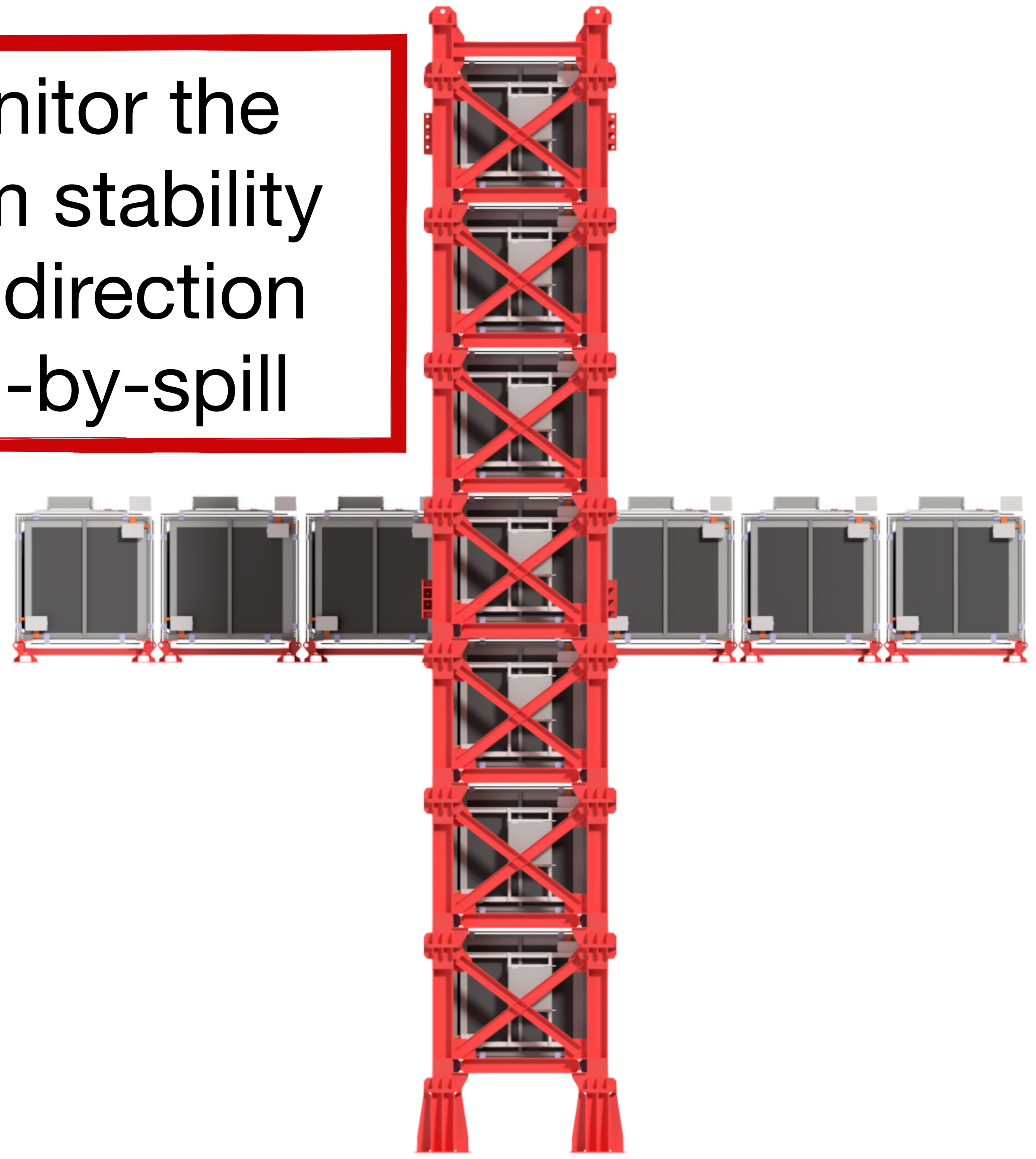
Physics goals:

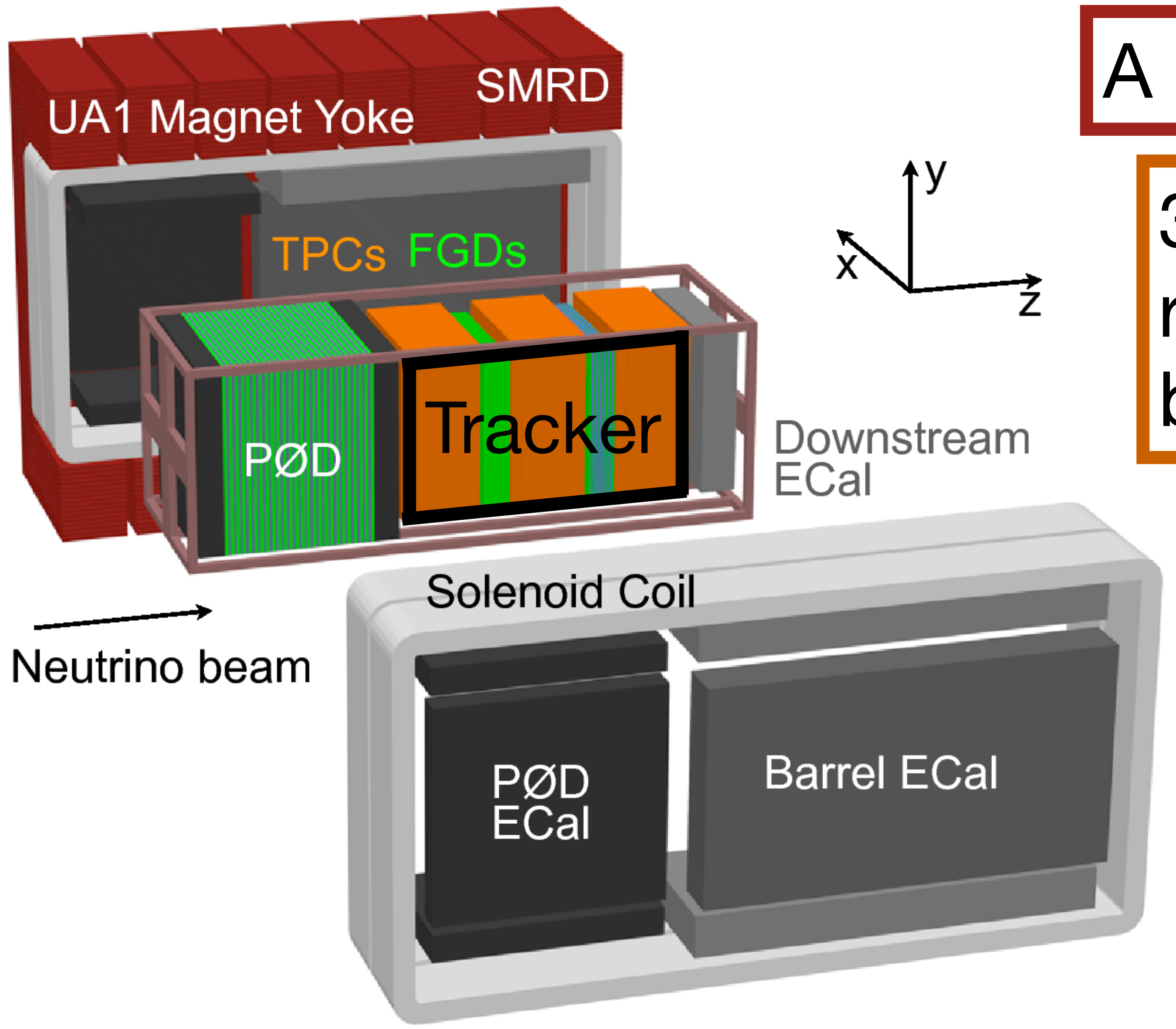
- Precise measurement of θ_{23}, Δm_{32}^2
- Determine θ_{13} and limits on δ_{CP}
- ν cross section measurements at the near detectors

The near detector complex



Monitor the beam stability and direction spill-by-spill





A large dipole magnet (UA1) produces 0.2 T

3 Time projection chambers (TPC): reconstruct momentum and charge, PID based on ionization

2 Fine-grained detectors (FGD): upstream constituted of *xy* layers of plastic scintillator, the other is alternated with water layers

An electromagnetic calorimeter (ECal) is used to distinguish tracks from showers

T2K oscillation analysis strategy

Hybrid-frequentist analysis

Flux prediction:
external hadron production measurements and T2K beam monitors

Neutrino interactions model:
tuned using available cross-sections data

ND280 measurements and model:
select CC ν_μ and $\overline{\nu}_\mu$ interactions to constrain flux and cross sections

Prediction at the Far Detector:
ND280 measurements predict the expected events at SK

SK measurements and model:
Select CC $\nu_\mu/\overline{\nu}_\mu$ and $\nu_e/\overline{\nu}_e$ candidates after the oscillations

Extract oscillation parameters
(θ_{13}, θ_{23}, Δm^2_{32}, δ_{CP})

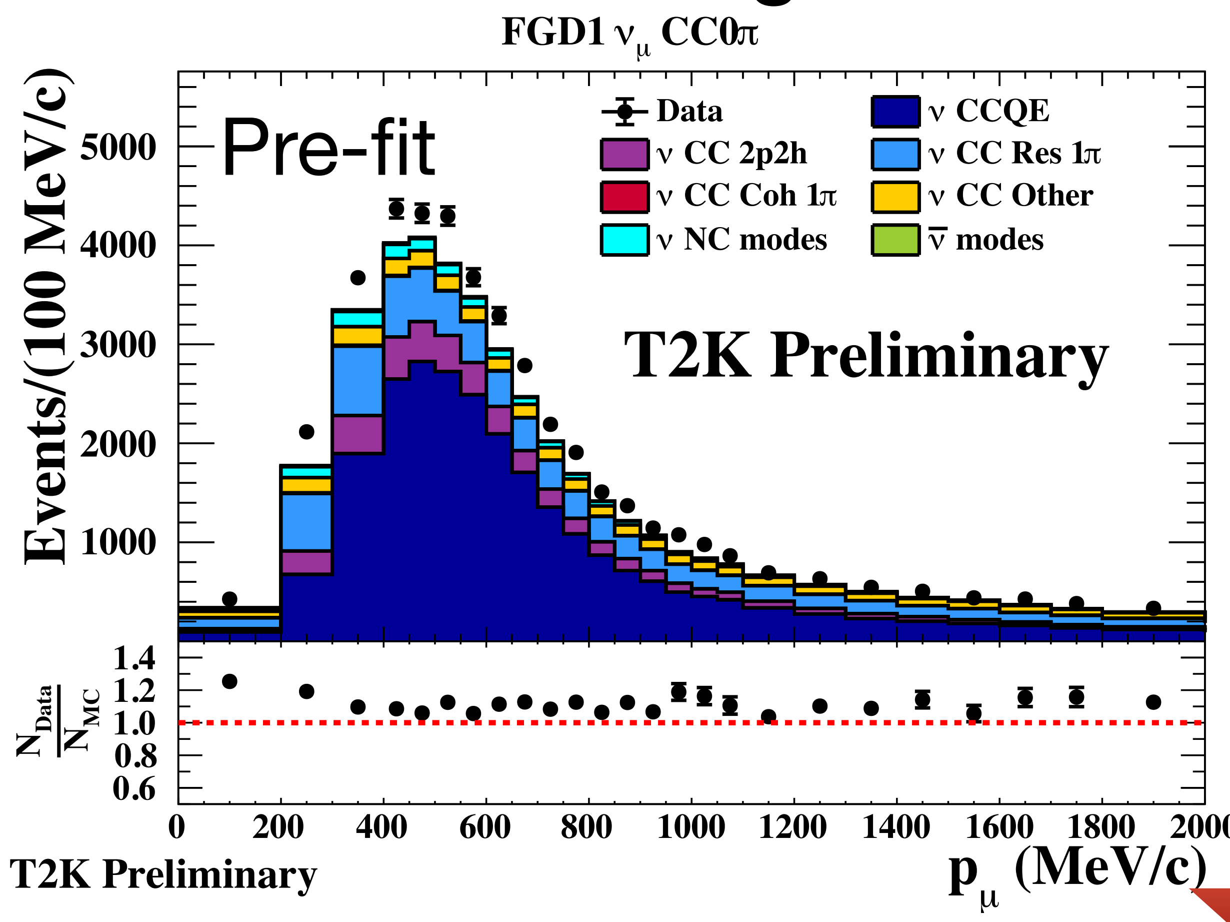
ND280 Fit

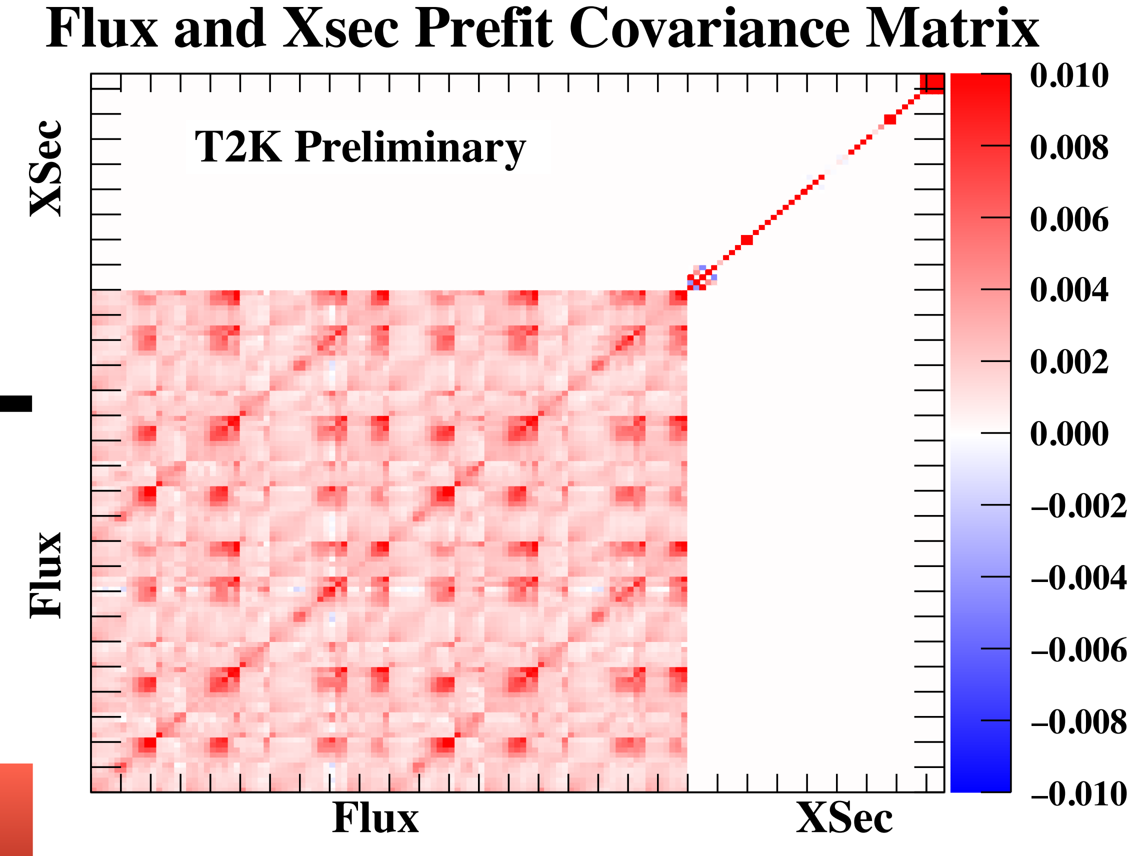
Flux prediction:
external hadron production measurements and T2K beam monitors

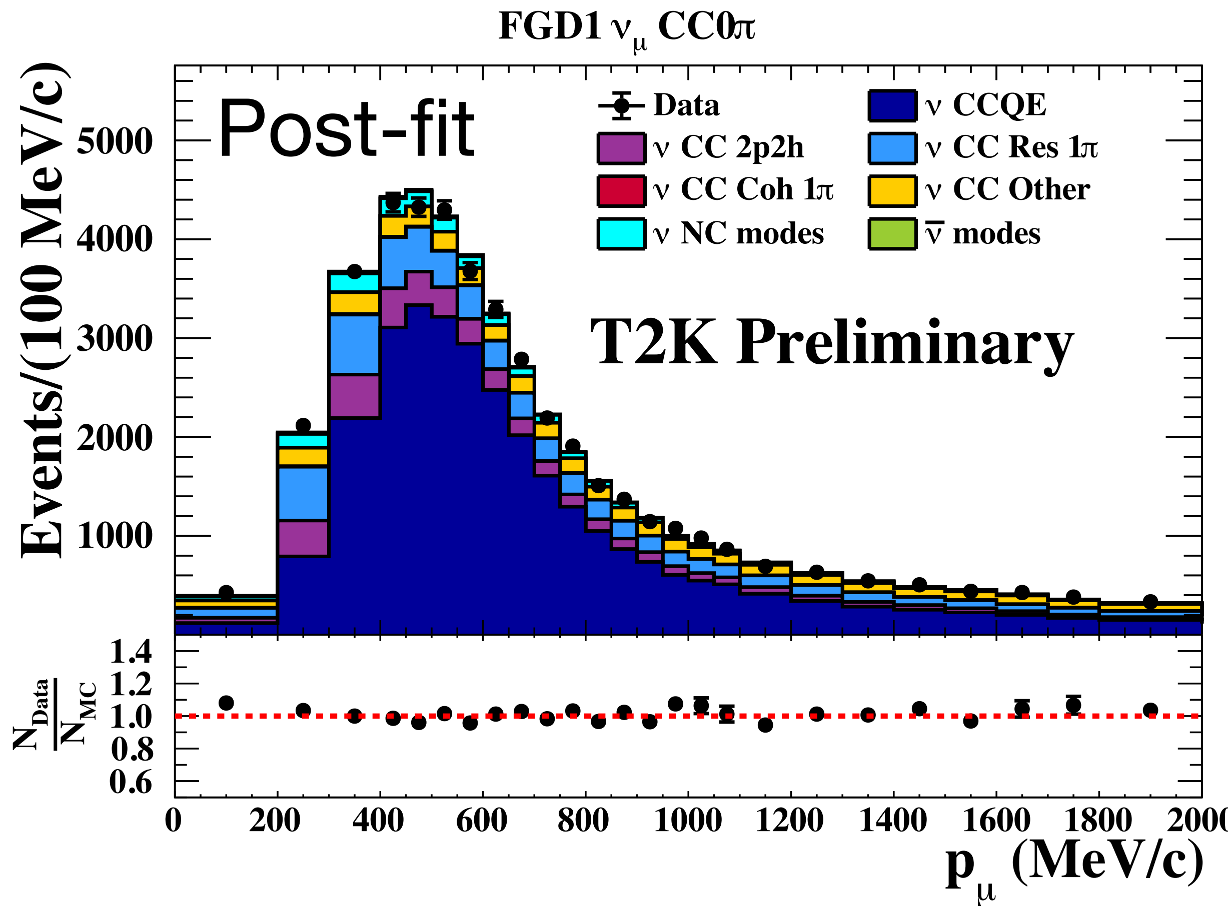
ND280 measurements and model:
select CC ν_μ and $\bar{\nu}_\mu$ interactions to constrain flux and cross sections

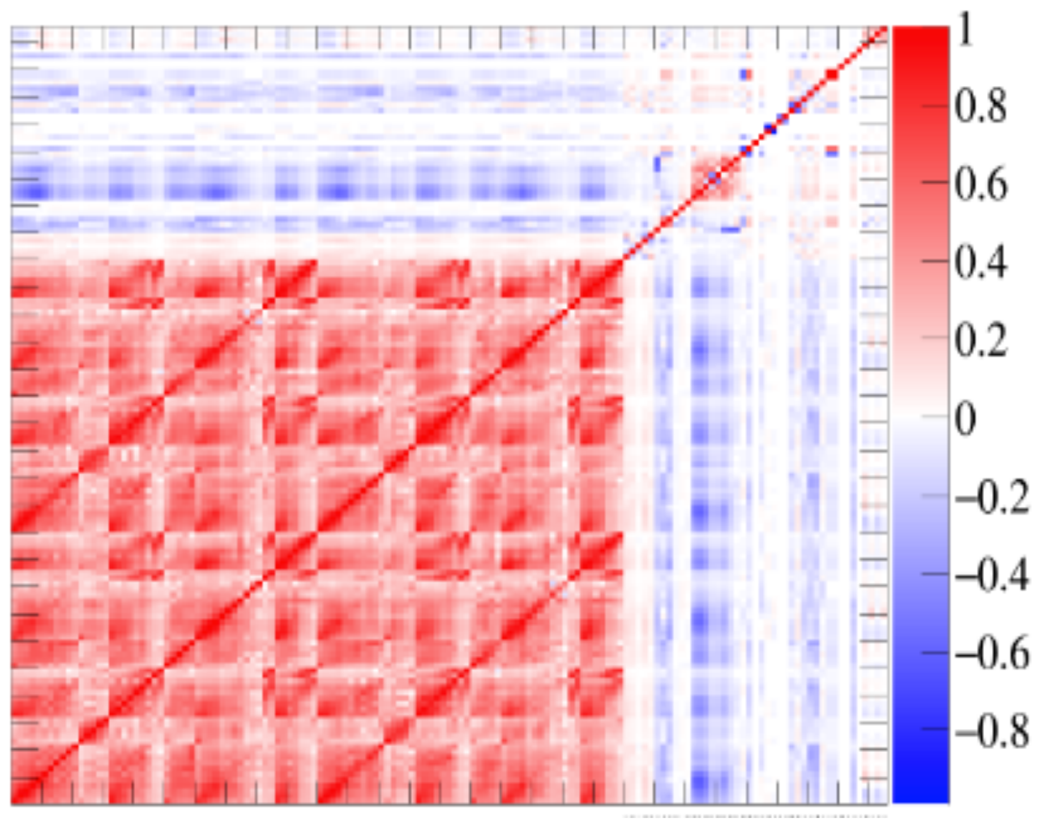
Neutrino interactions model:
tuned using available cross-sections data

Perform an extended binned likelihood fit to the number of selected events in every sample (18 in total) as a function of muon kinematics. Prior model p-value is 74% showing that our model is a good fit to data.







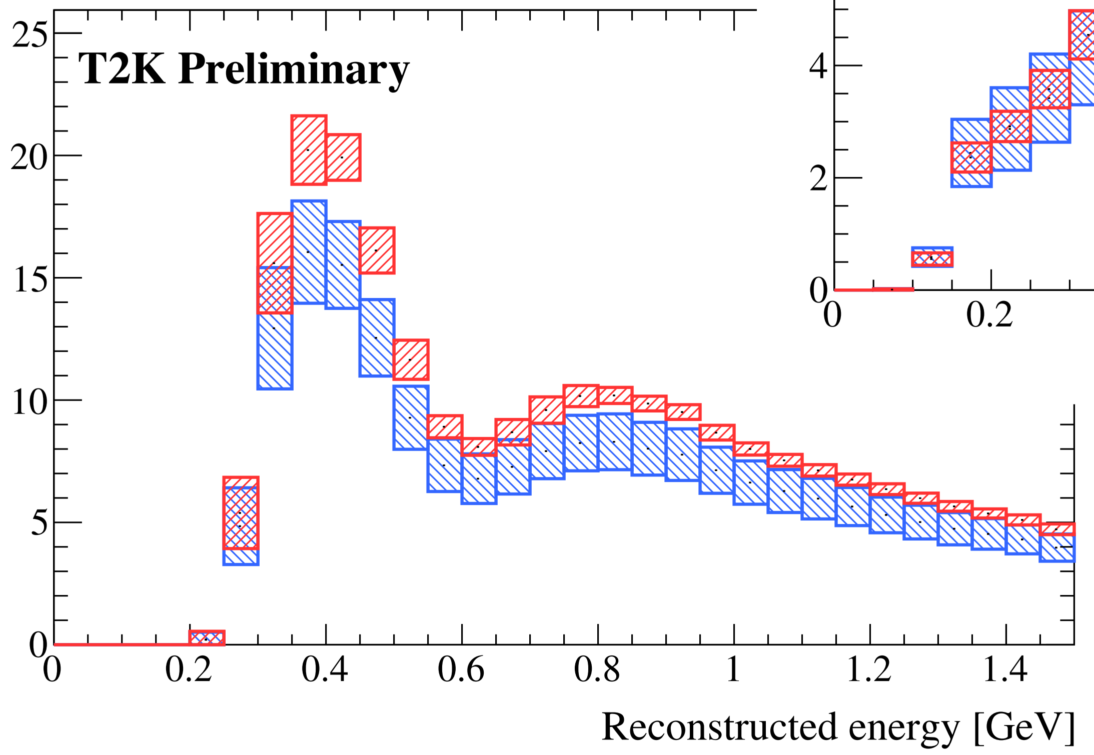


Impact of the ND fit

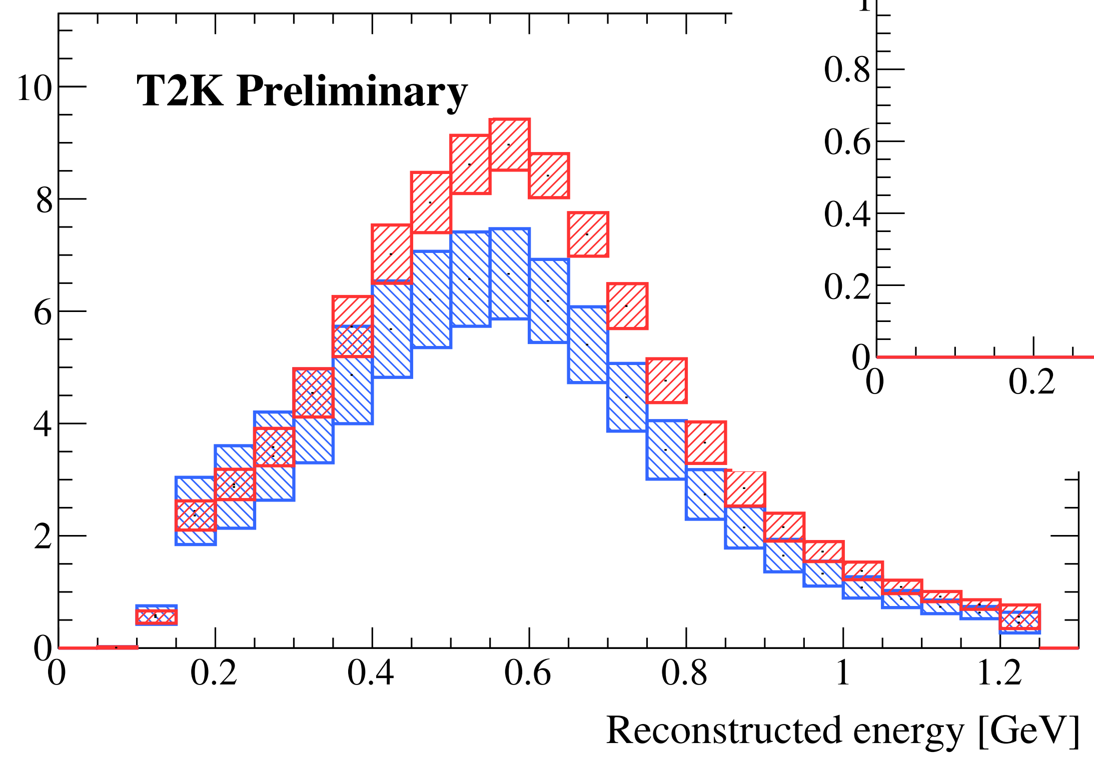
Pre-ND
Post-ND

ν-mode

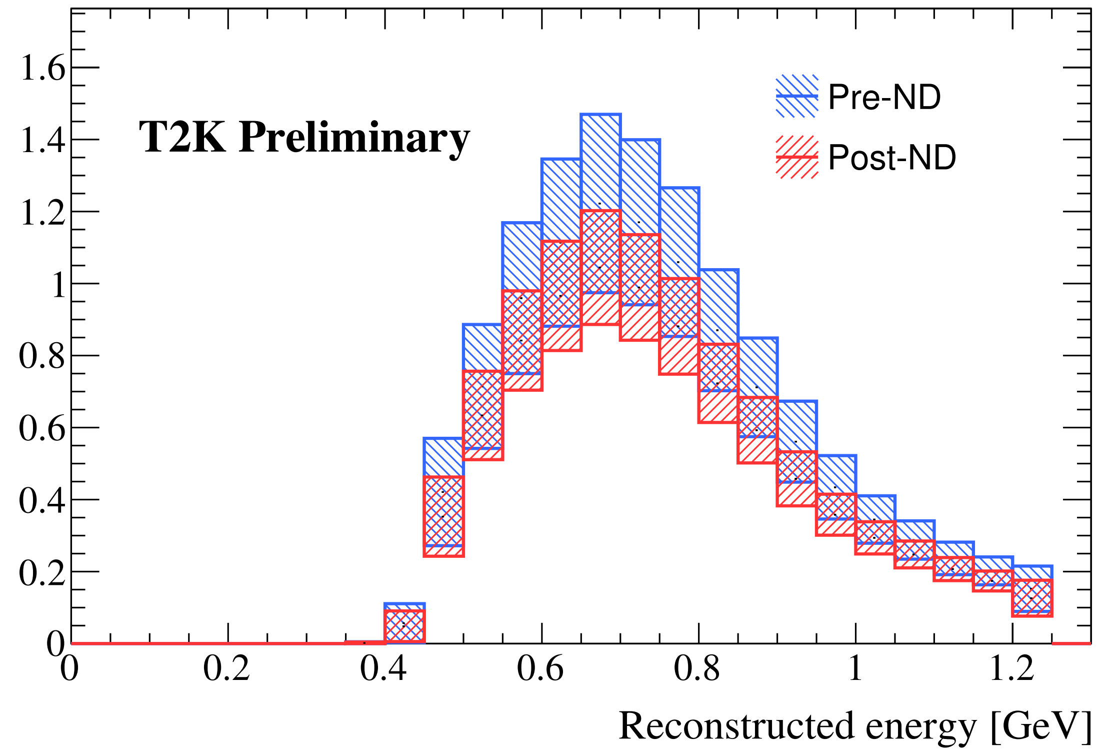
1 Ring μ-like



1 Ring e-like

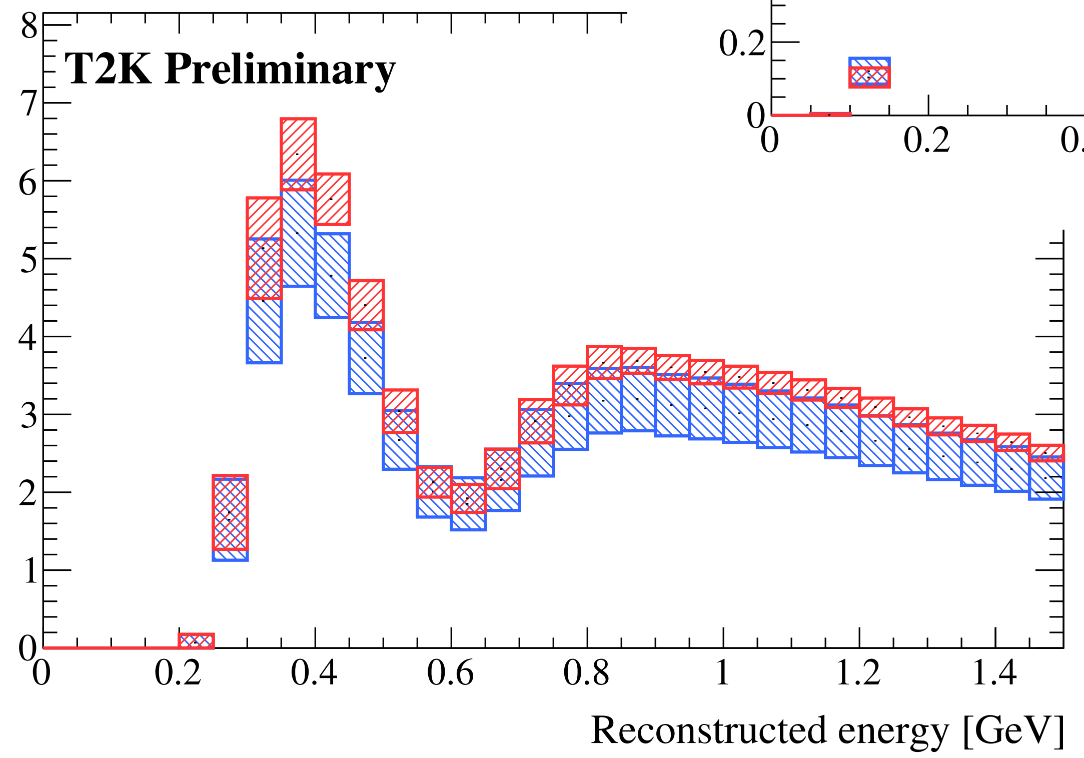


1 Ring e-like 1 decay-e

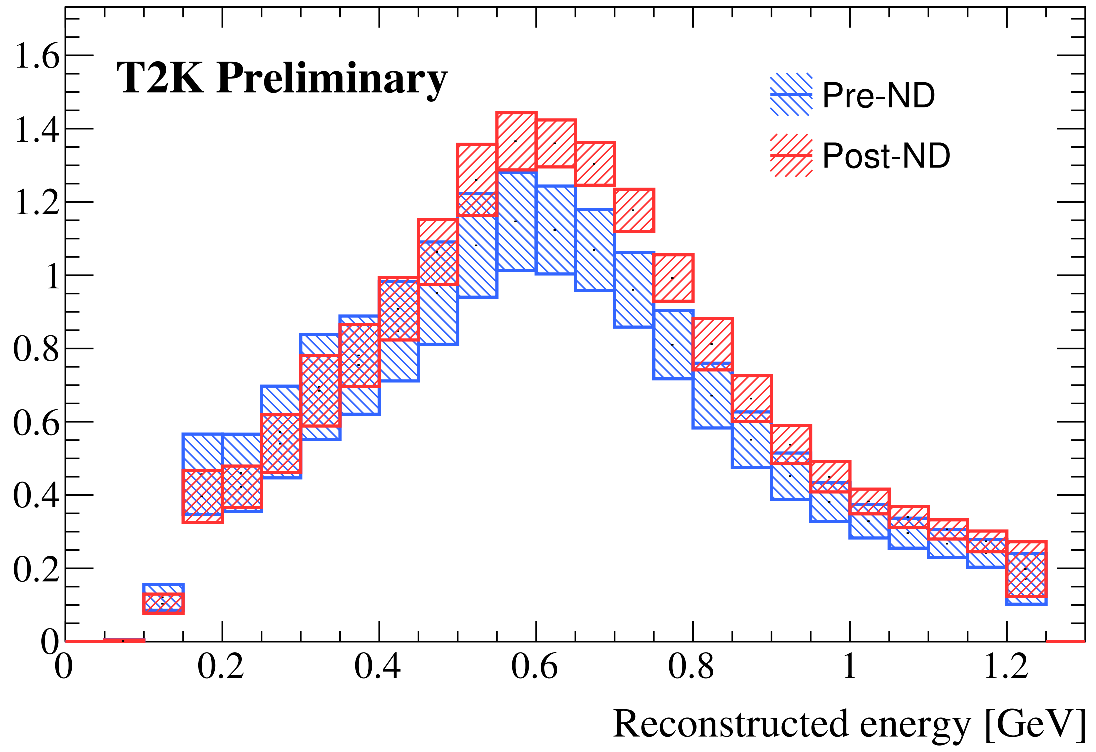


$\bar{\nu}$-mode

1 Ring μ-like



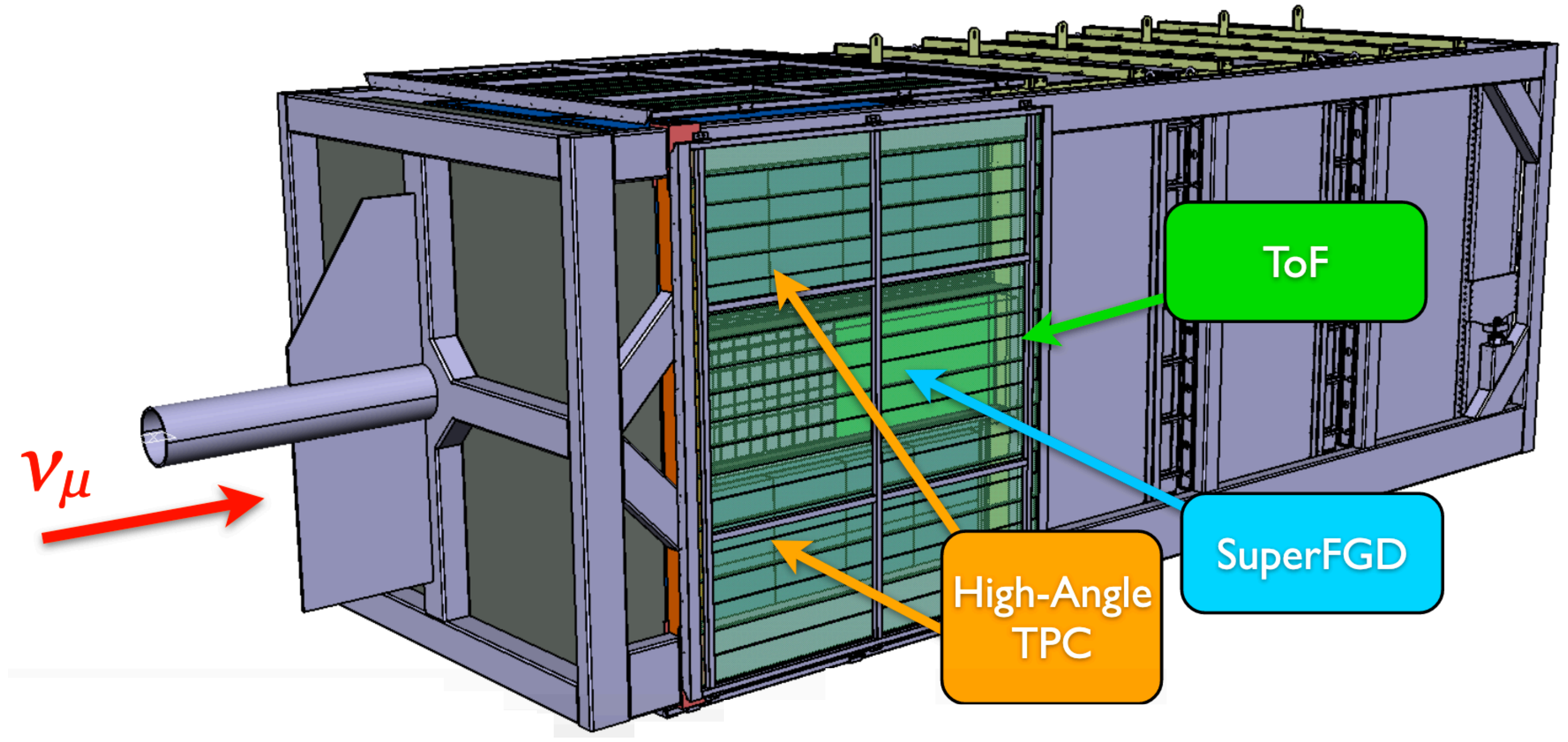
1 Ring e-like



Systematic uncertainties					
Beam mode	**Neutrino**			**Antineutrino**	
SK sample	**1 Ring μ-like**	**1 Ring e-like**	**1 Ring e-like 1de**	**1 Ring μ-like**	**1 Ring e-like**
Before ND280 fit	11.1%	13.0%	18.7%	11.3%	12.1%
After ND280 fit	3.0%	4.7%	14.3%	4.0%	5.9%

ND280 upgrade

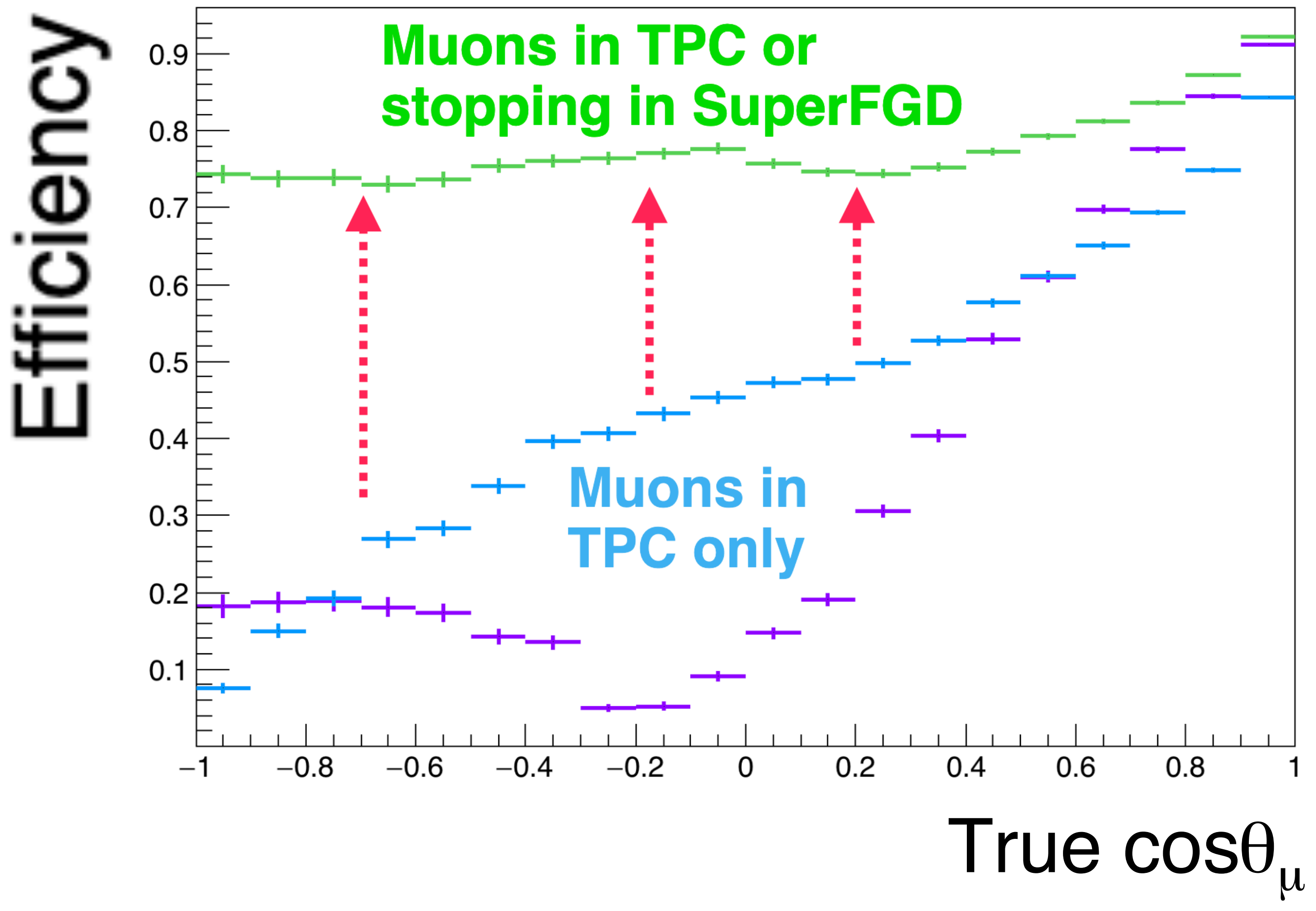
See David Henaff and Jaafar Chakrani's talks

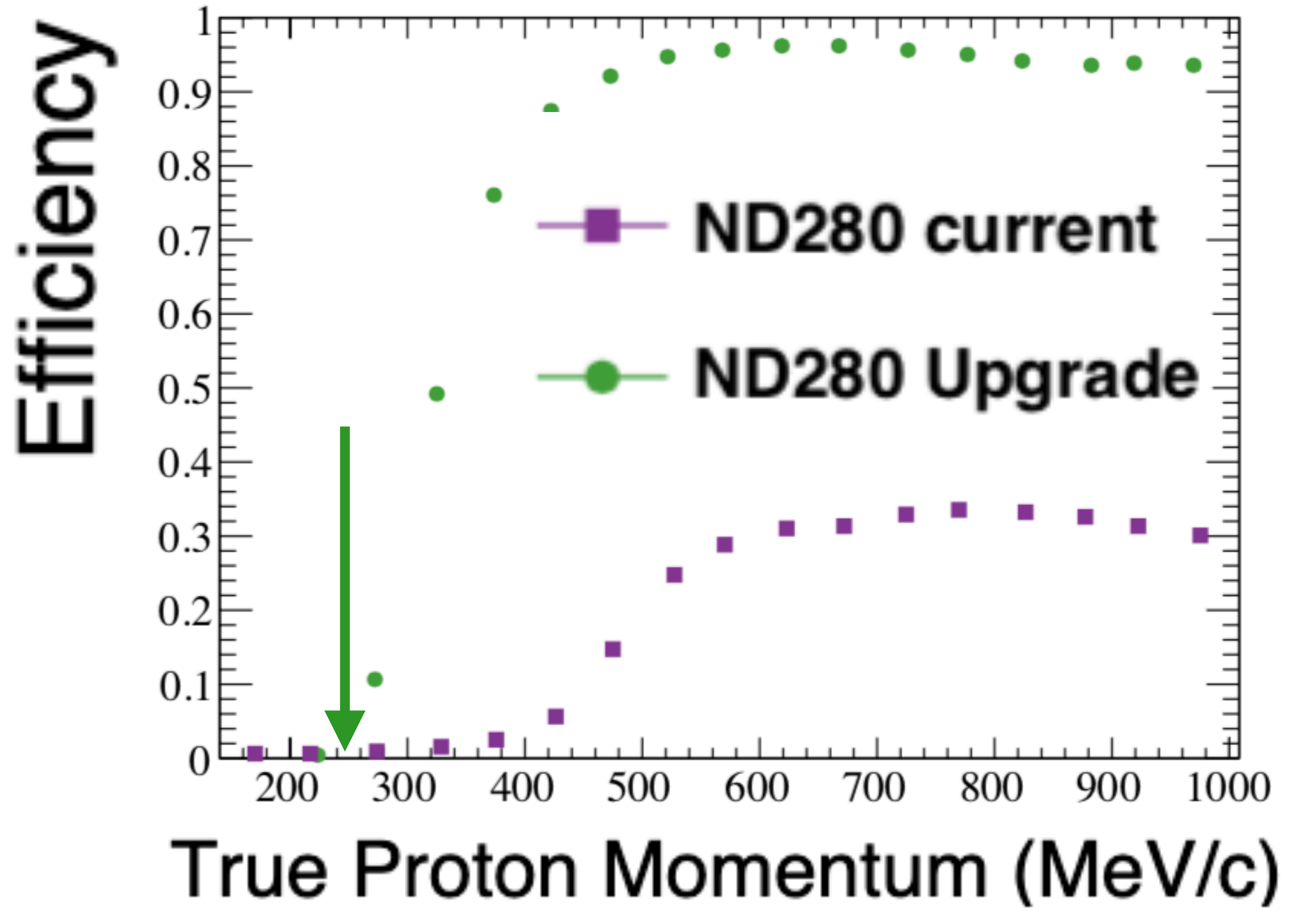


Main ND280 upgrade improvements:

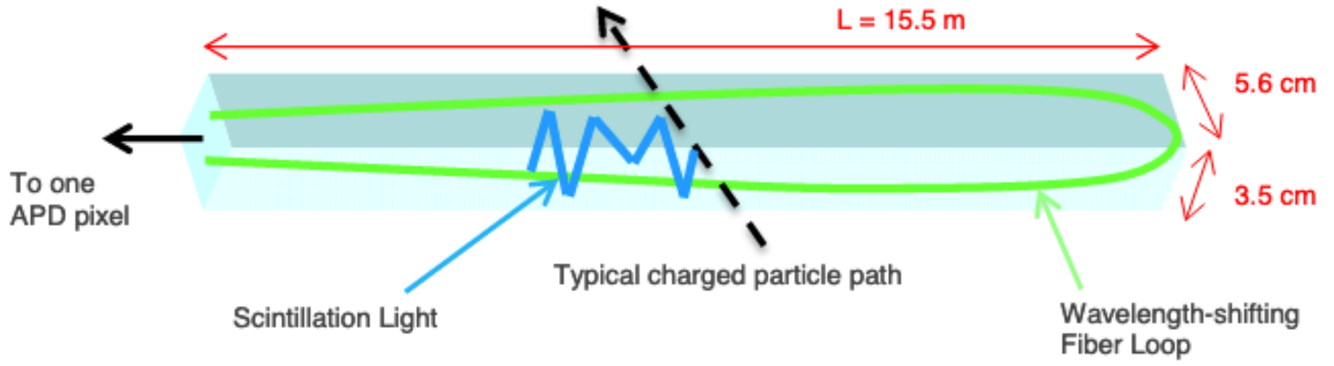
- Improved efficiency
- Lower threshold for protons
- Neutron kinematics
- Increased target mass (2 tons)

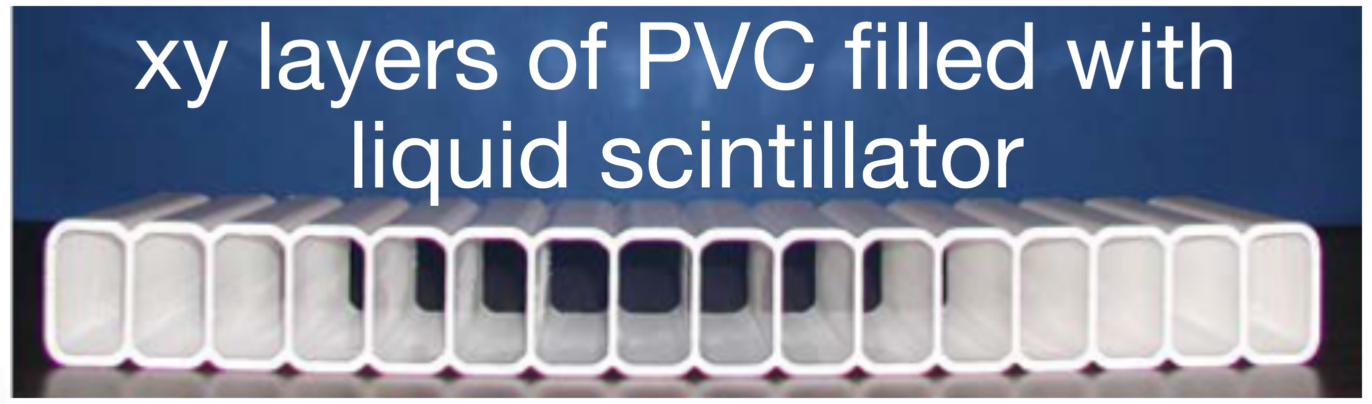
- SuperFGD: 2M 1cm-cubes
- 2 TPCs equipped with resistive MicroMegas
- 6 Time-Of-Flight detectors
- Start construction in Fall 2022 and taking data from April 2023. Then 4 months of running per year until Hyper-K starts

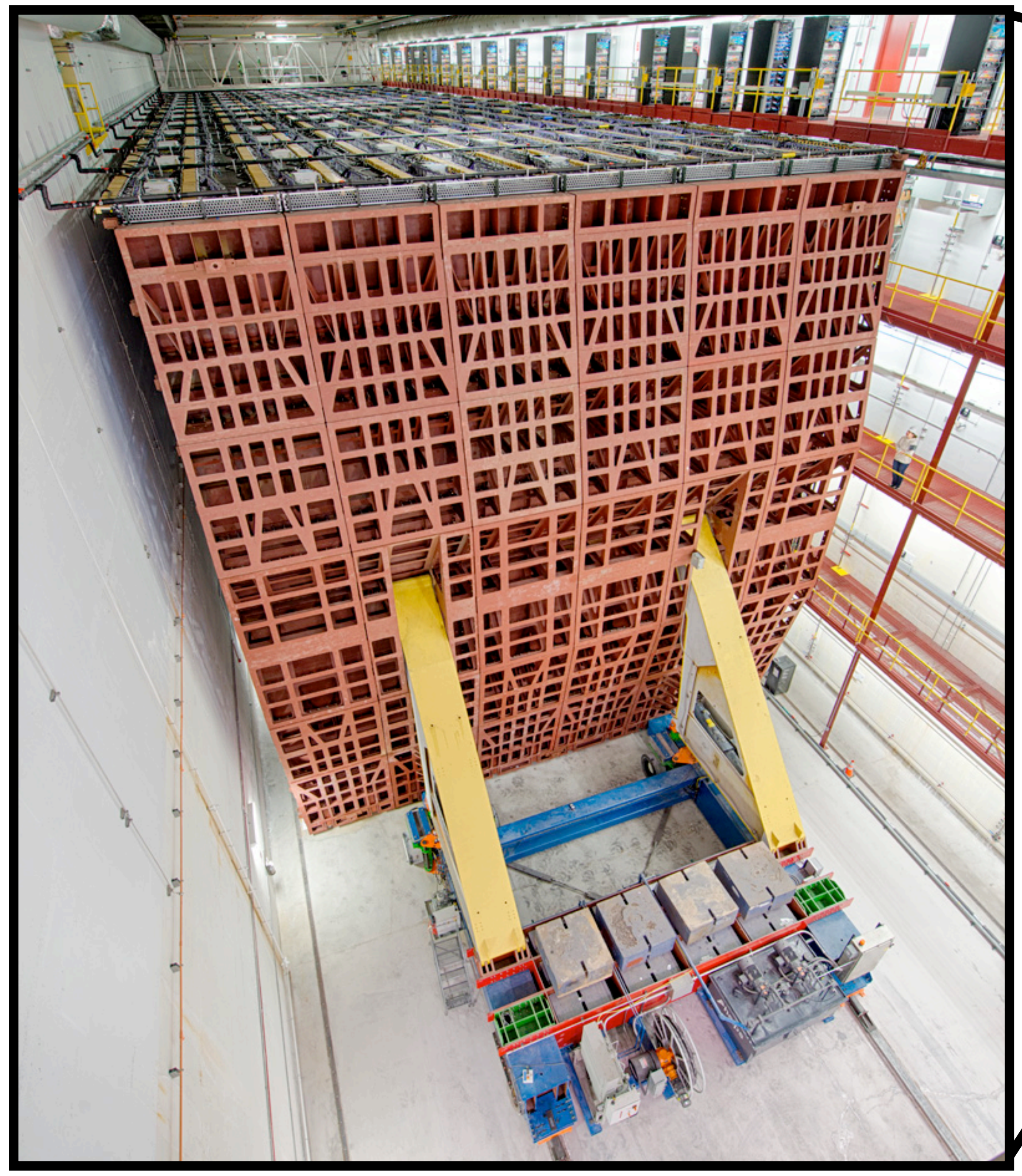




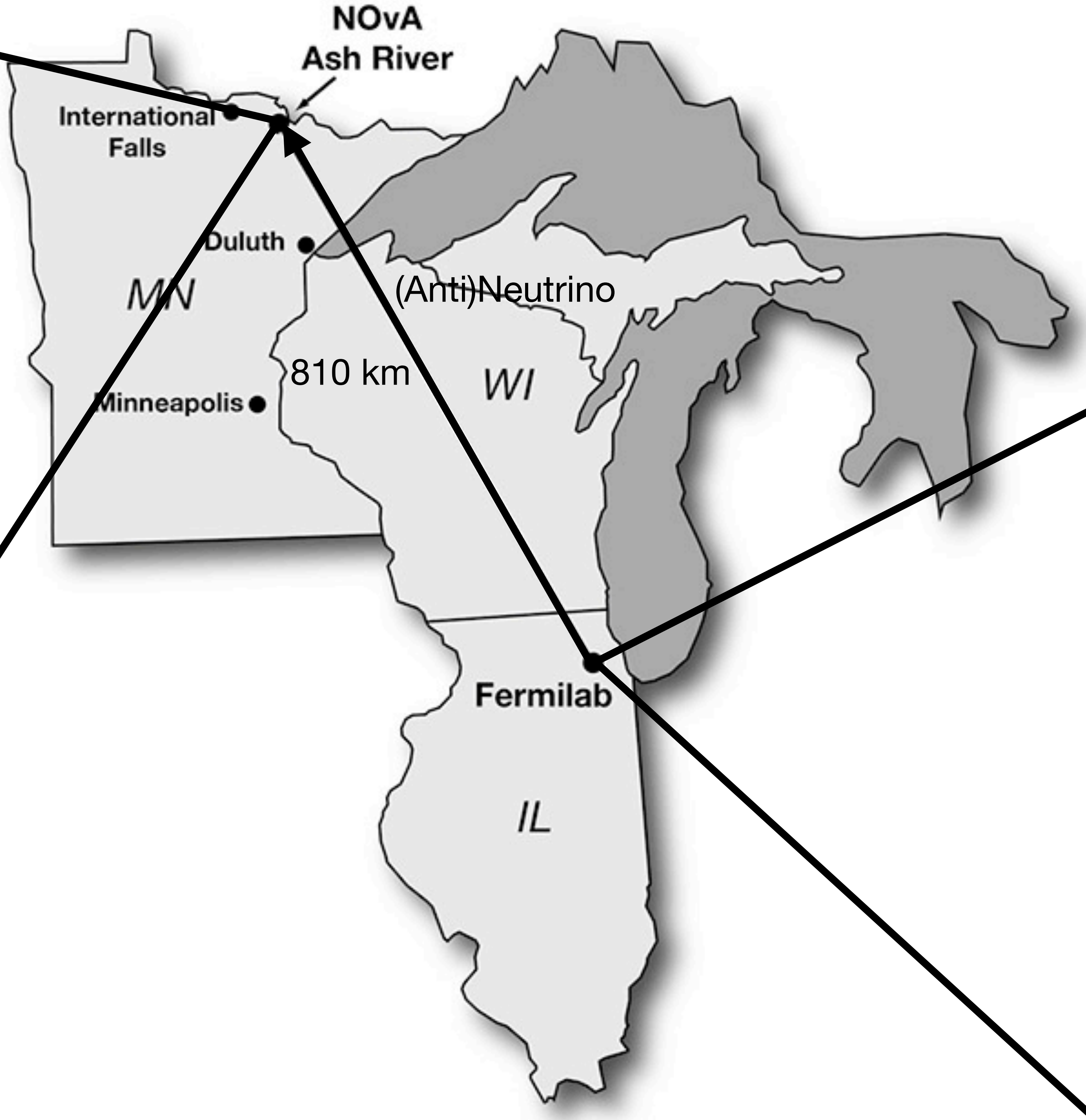
The NOvA experiment



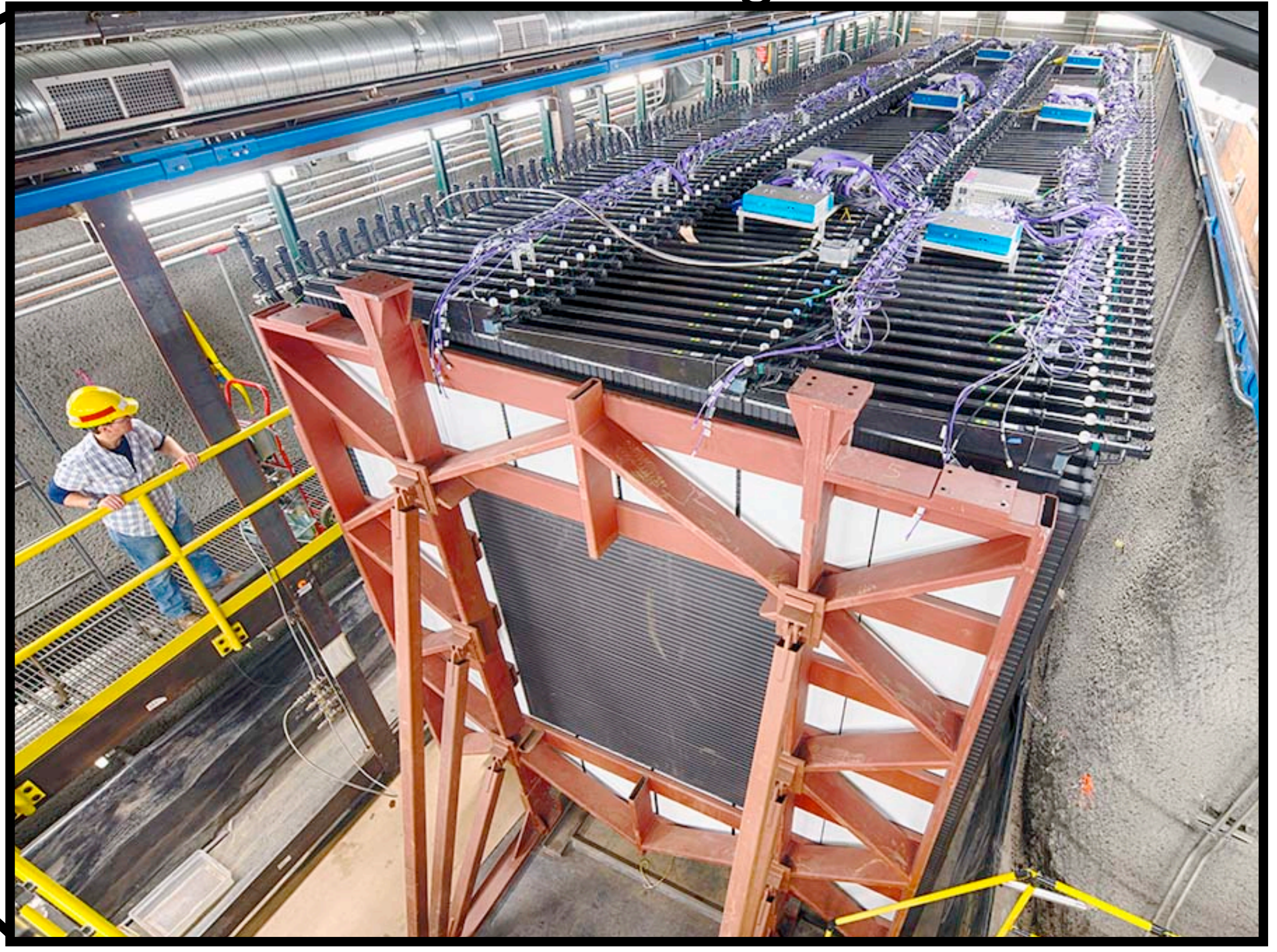




14 kTon FD on surface



0.3 kt ND 105 m underground

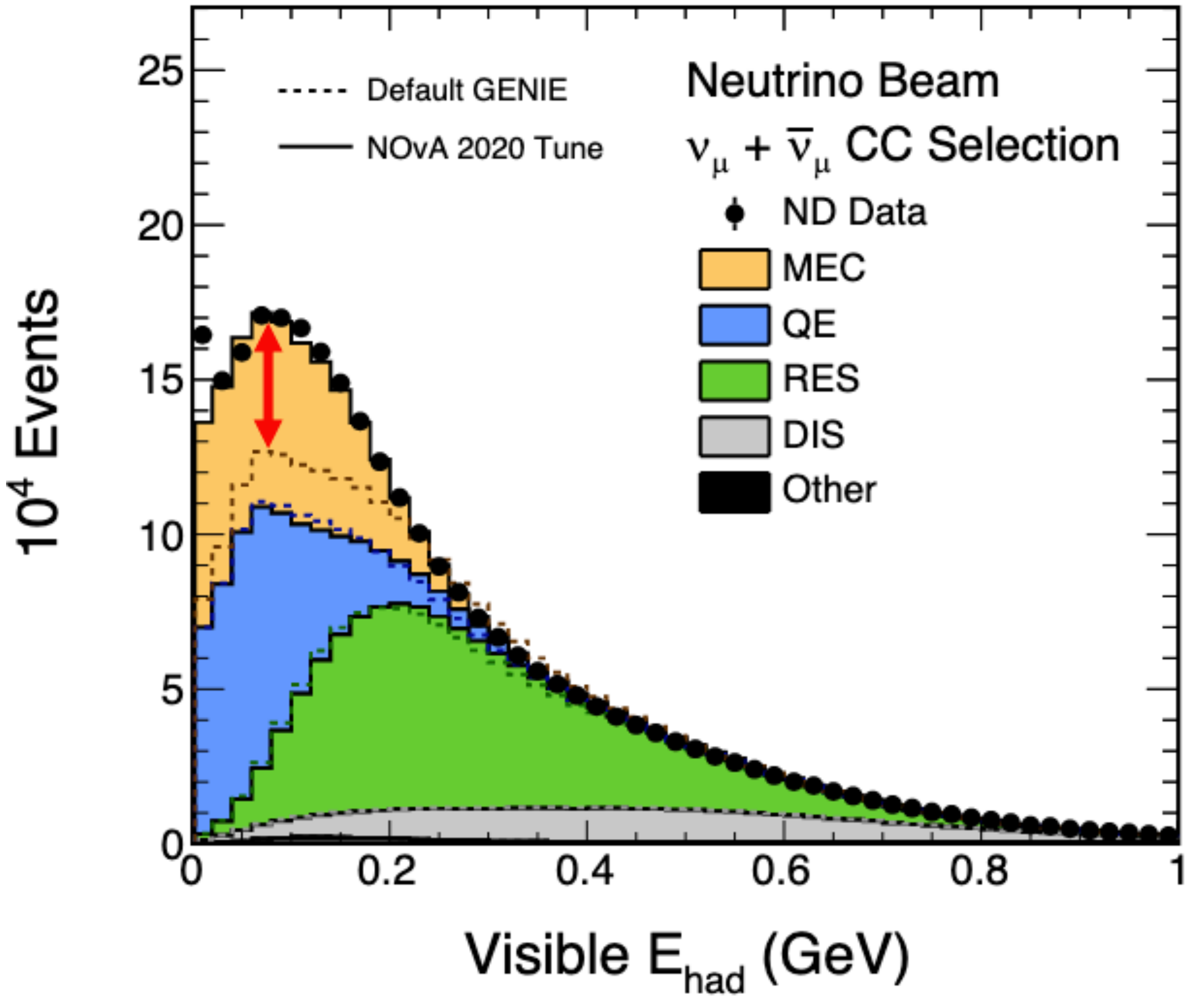


Physics goals:

- Precise measurement of θ_{23}, Δm_{32}^2
- Limits on mass hierarchy and δ_{CP}

NOvA analysis strategy

Neutrino interactions model: tuned using **internal** data ND **measurements**



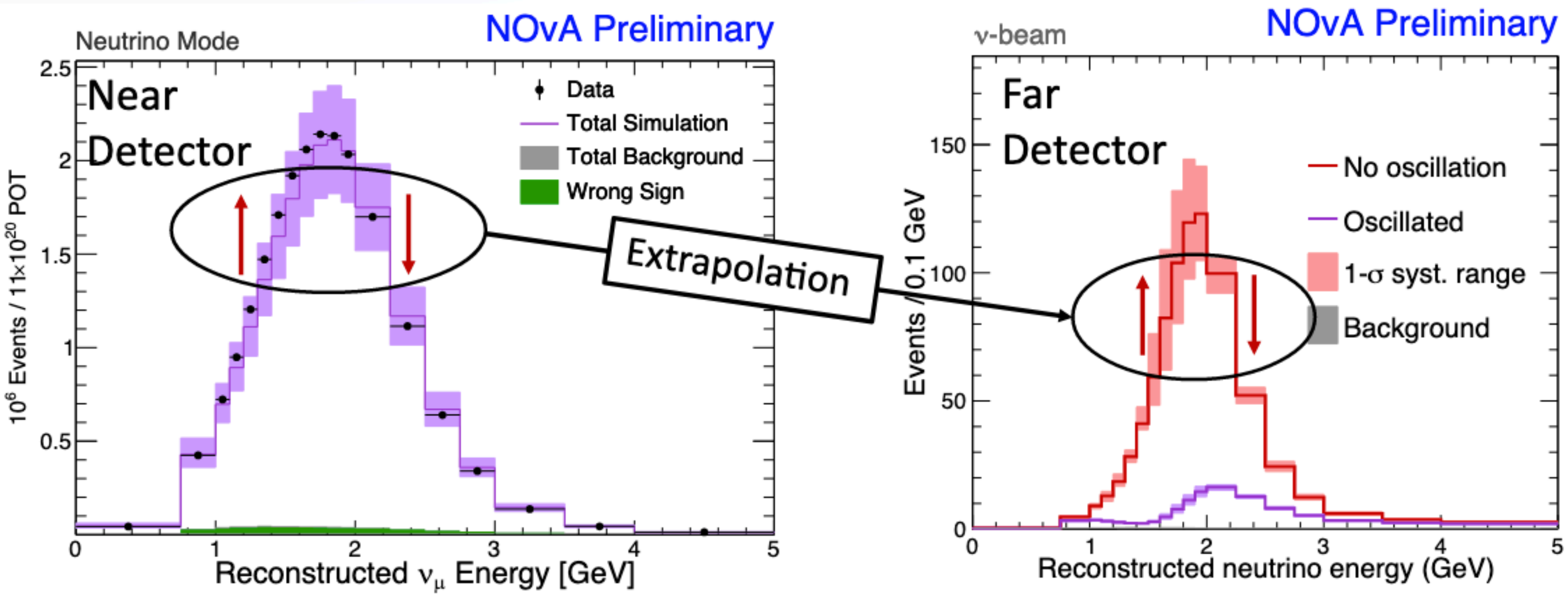
10.1140/epjc/s10052-020-08577-5

ND-FD extrapolation: modify the FD MC from data-MC differences at the ND

FD measurements and model: Select CC $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$ candidates after the oscillations

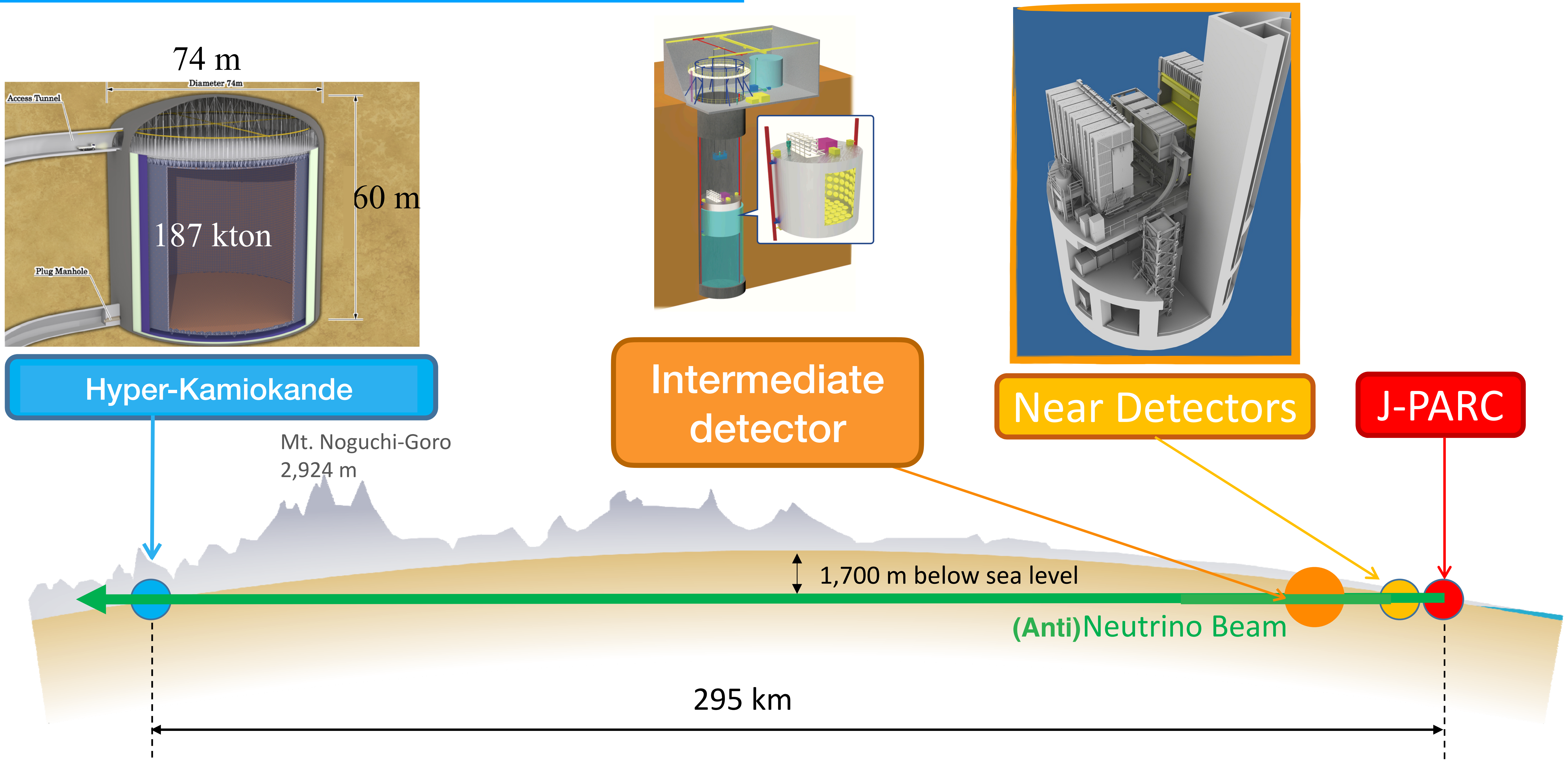
Extract oscillation parameters (θ_{13}, θ_{23}, Δm^2_{32}, δ_{CP})

NOvA ND-FD extrapolation



- Observe data-MC differences at the ND, use them to modify the FD MC
- Significantly reduces the impact of uncertainties correlated between detectors
- Especially effective at reduce uncertainties on cross-section and flux by 20%
- Reduces the size of the systematics most likely to contain “unknown unknowns”

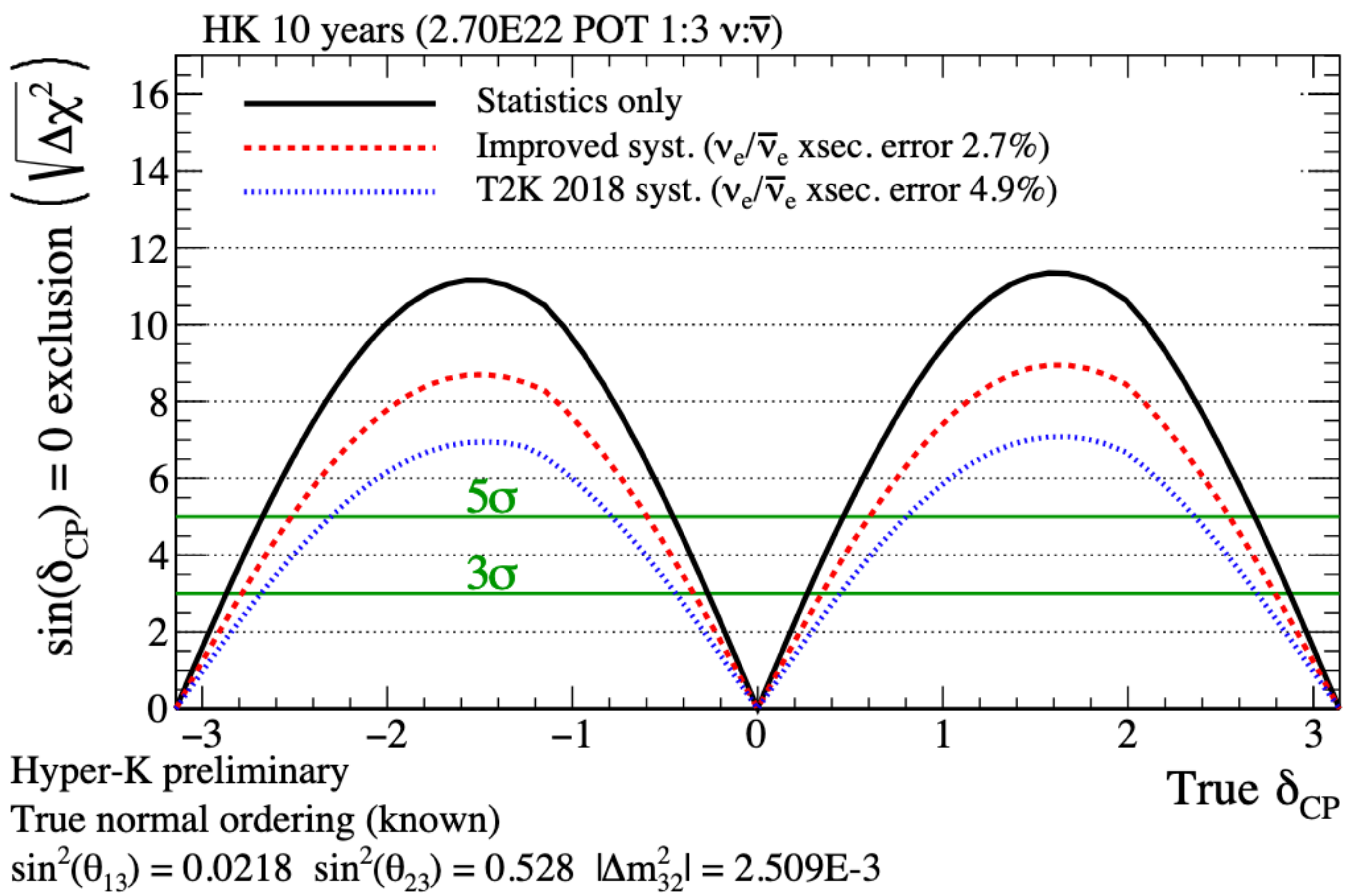
The HYPER K experiment



Physics goals:

- Measure CP Violation and mass ordering
- Atmospheric neutrinos
- Supernova neutrinos, nucleon decay and new physics

sensitivity



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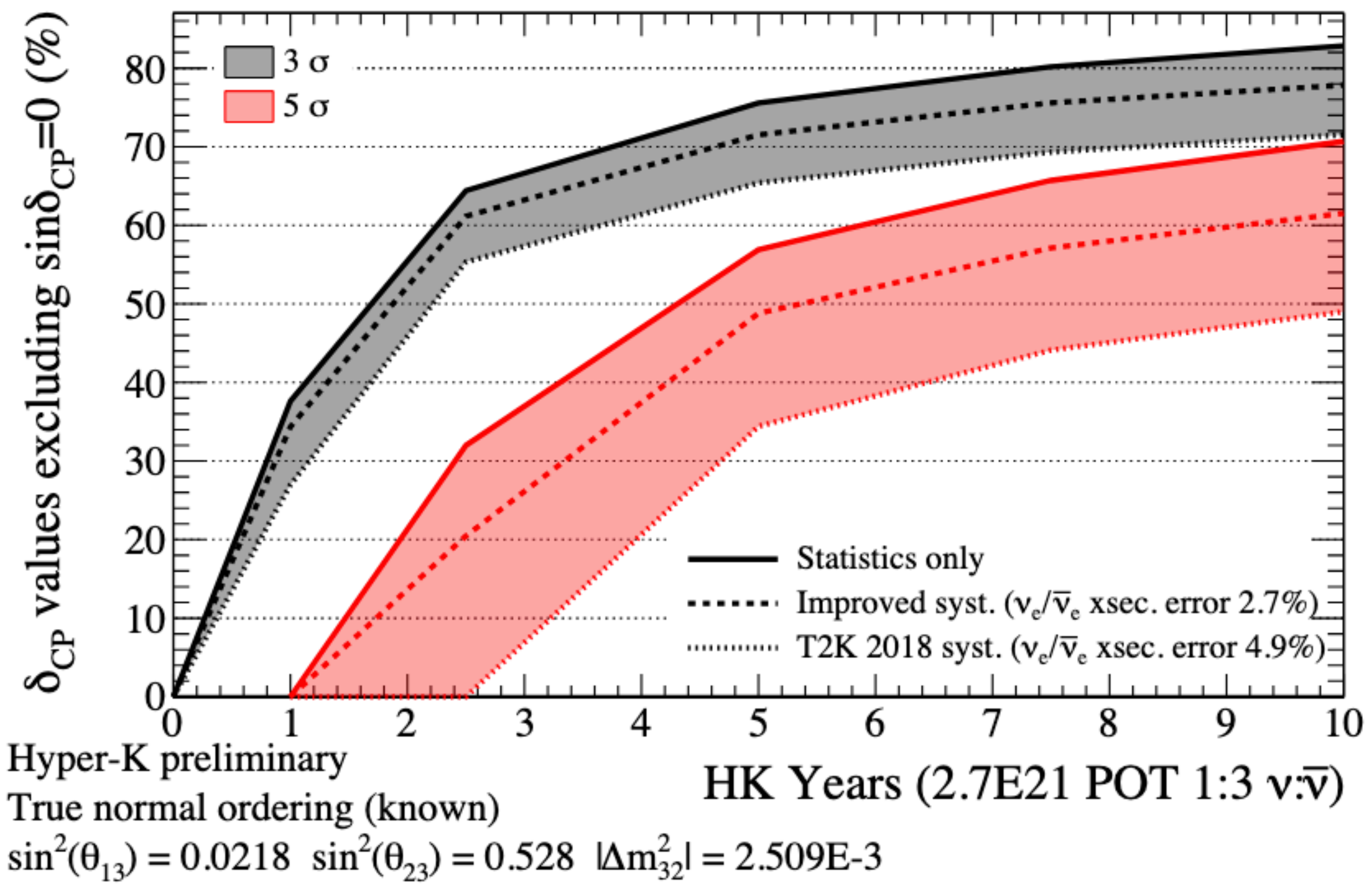
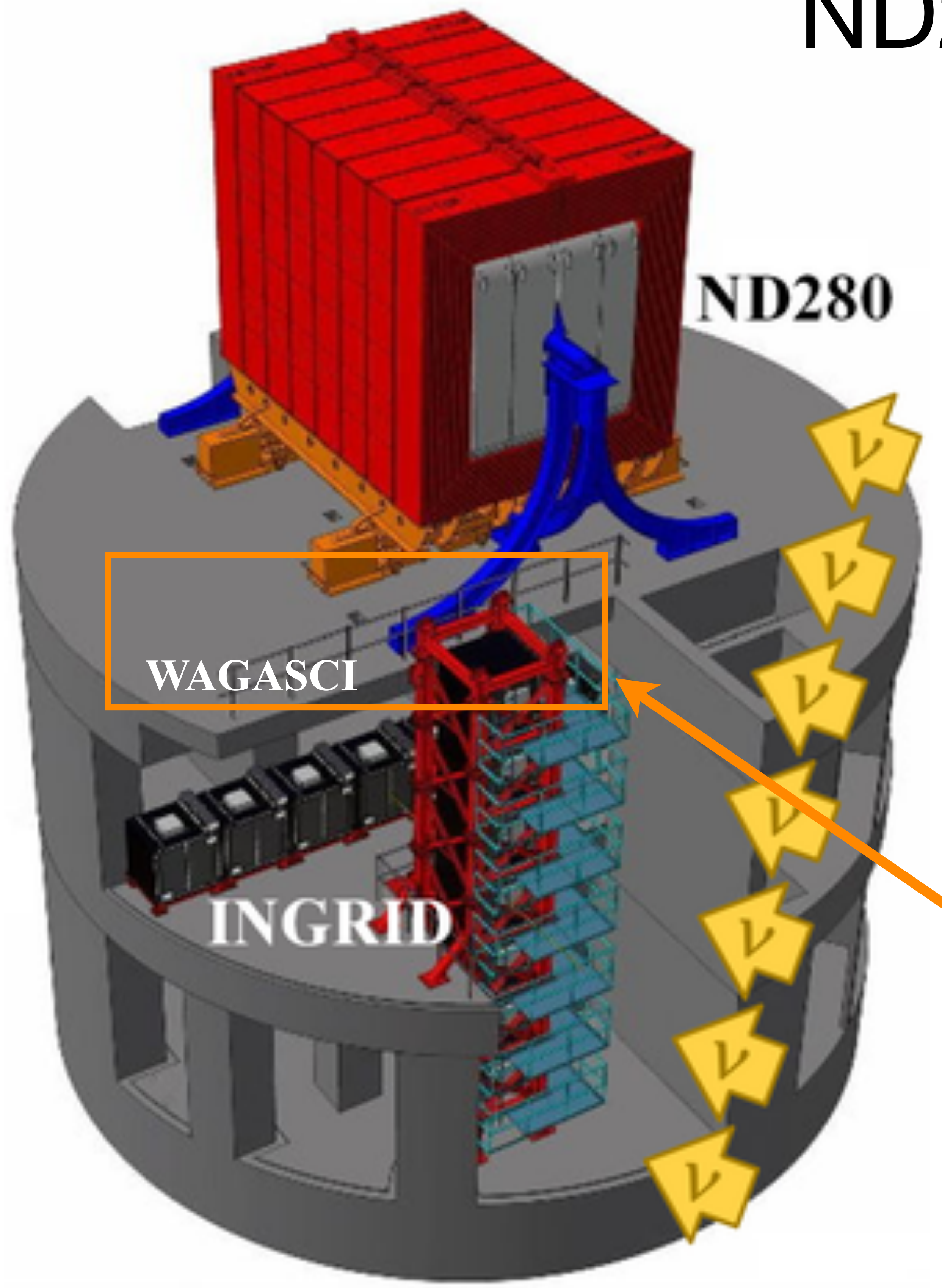


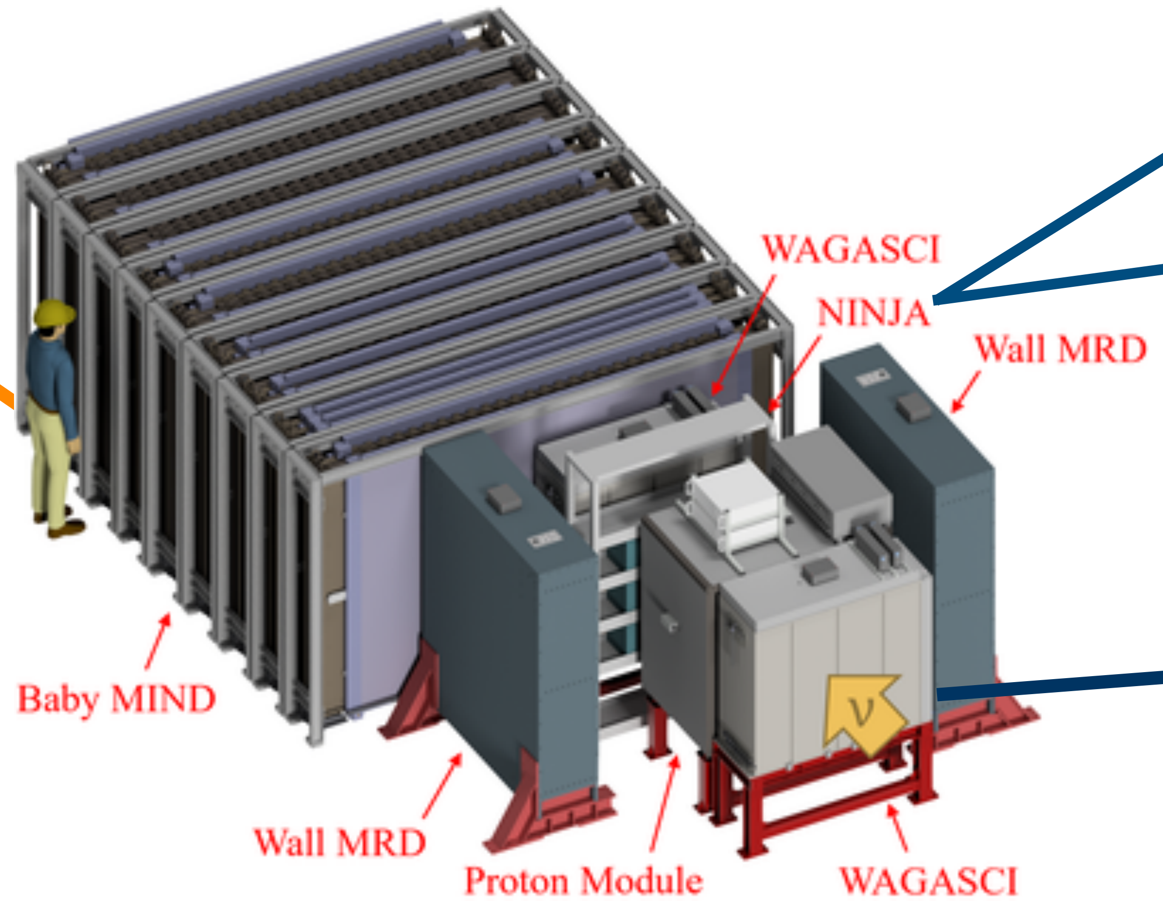
- Sensitivity to CPV is limited by systematics
- CPV discovery at 5σ in 10 years for large fraction (~60%) of δ_{CP} values
- Improving the systematics model will allow for a faster discovery and access to CPV discovery for larger fraction of δ_{CP} values

ND280 for HYPER K

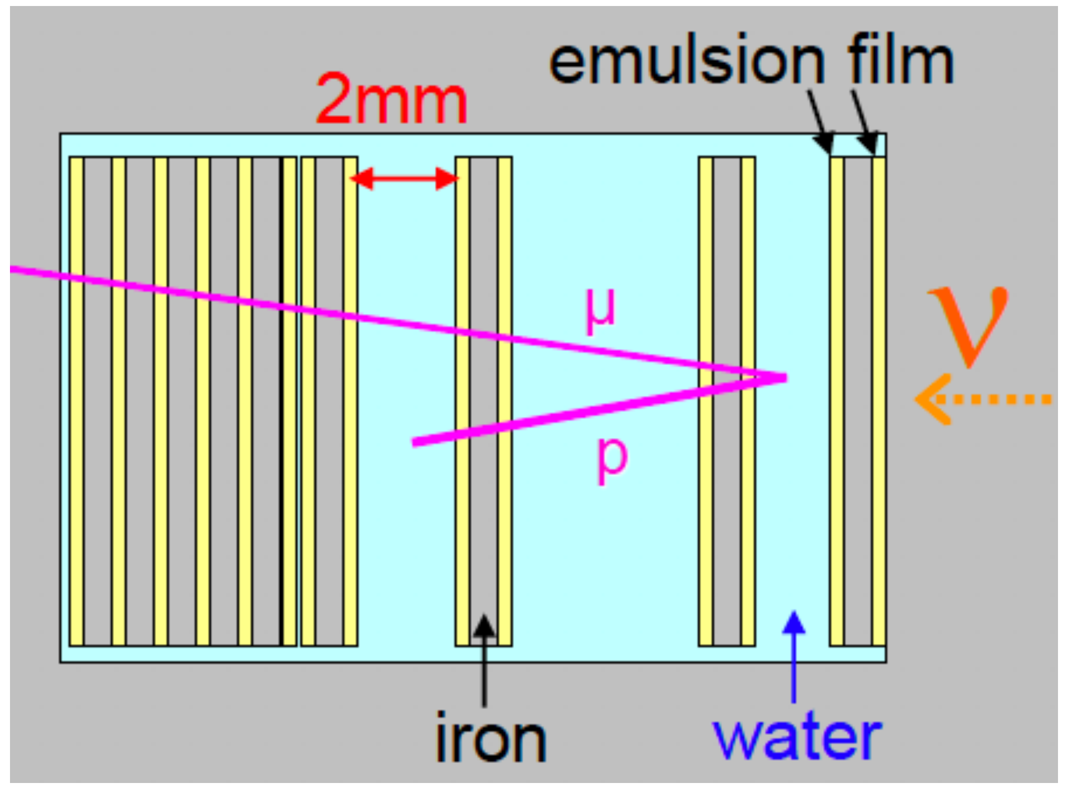
Possible upgrades of ND280?

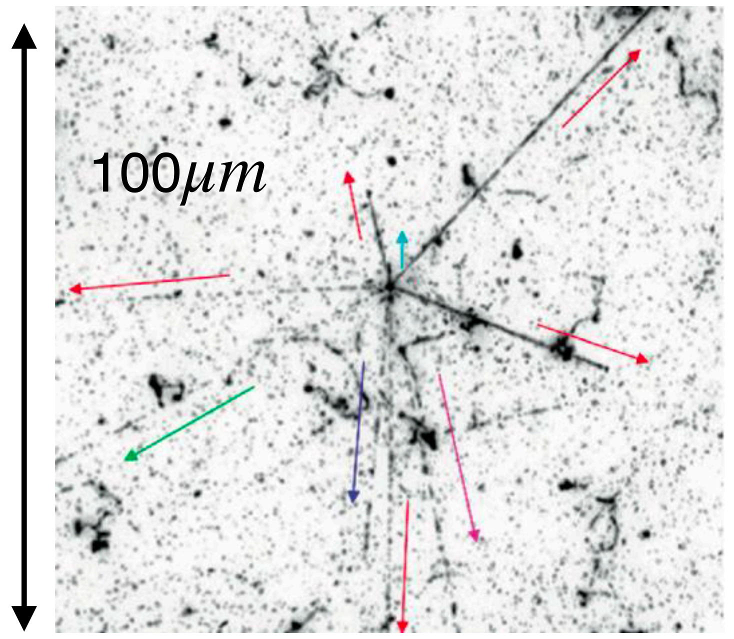


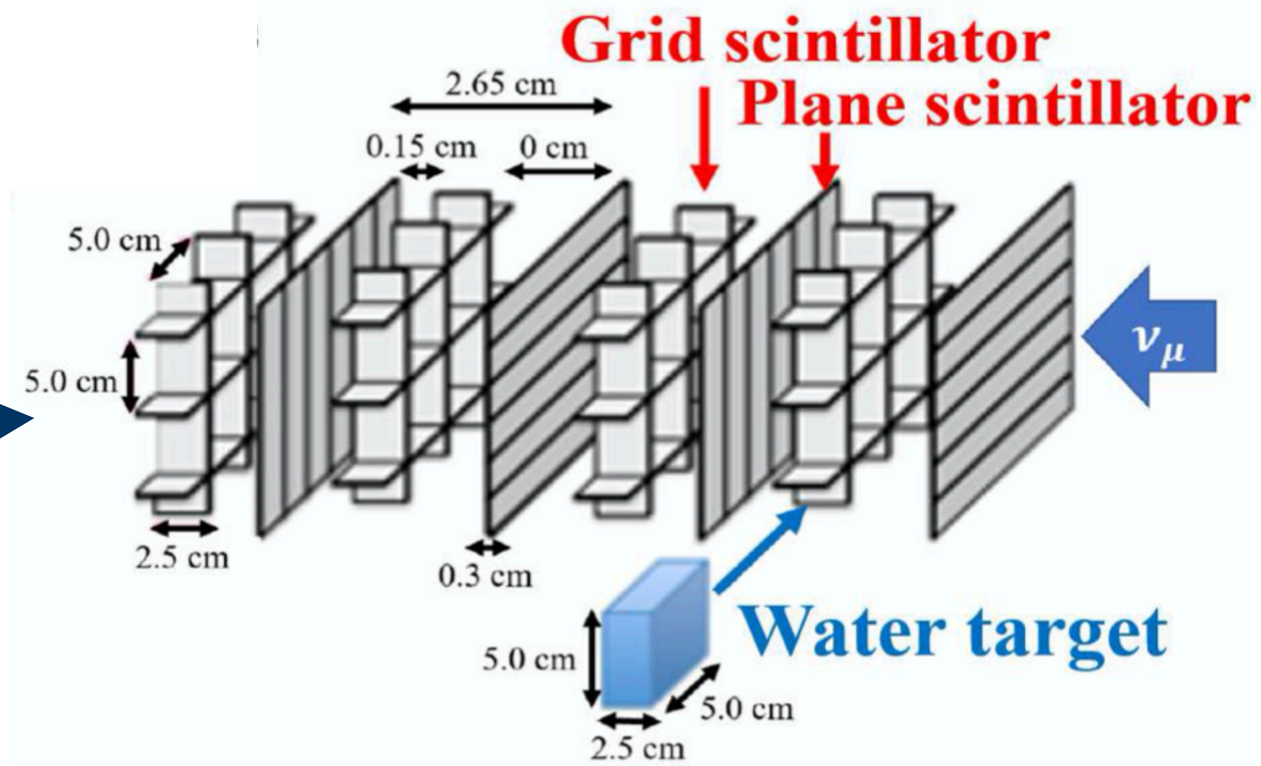
WAGASCI+BabyMind already in operation since 2019



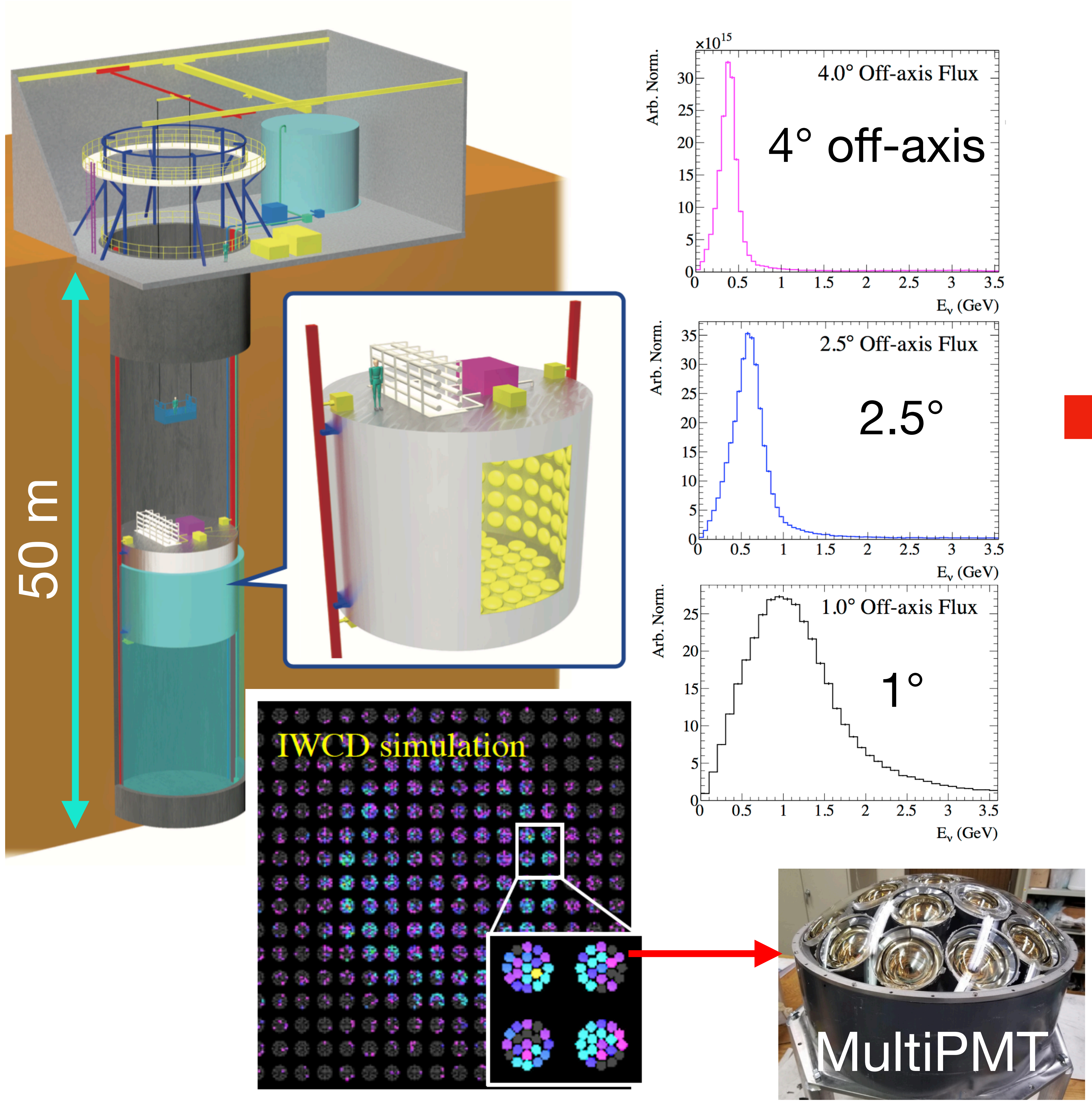
NINJA in operation but still statistically limited. Interesting since has very low proton threshold (200 MeV)



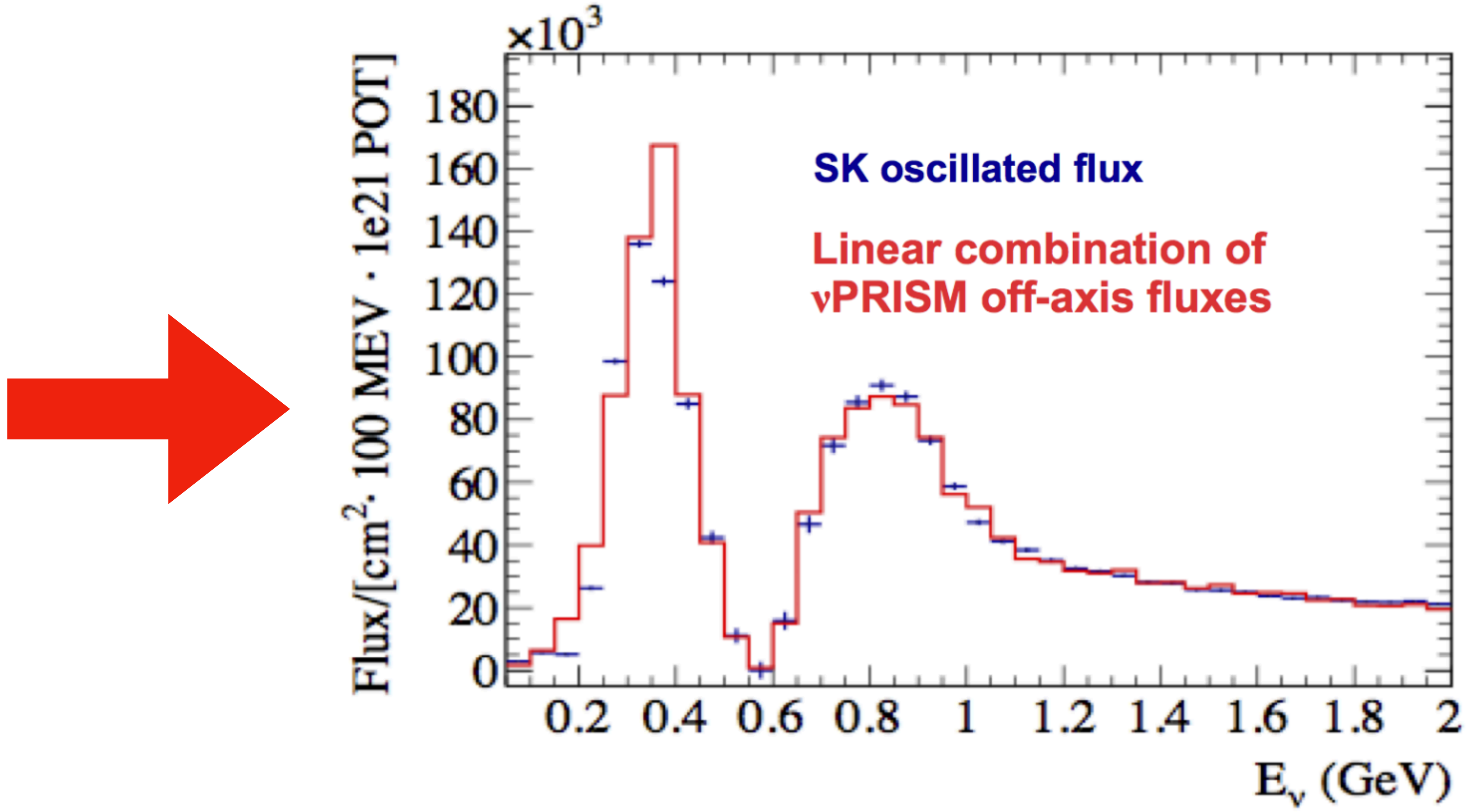




Intermediate Water Cherenkov



- 600 ton water loaded with Gd located ~1 km



- The flux predictions at each off-axis position can be linearly combined to match flux at the FD. Break degeneracies between flux and cross-section.
- Low statistical uncertainty in ν_e cross section (3.5-7% precision) because higher flux fraction more off-axis

The DUNE experiment

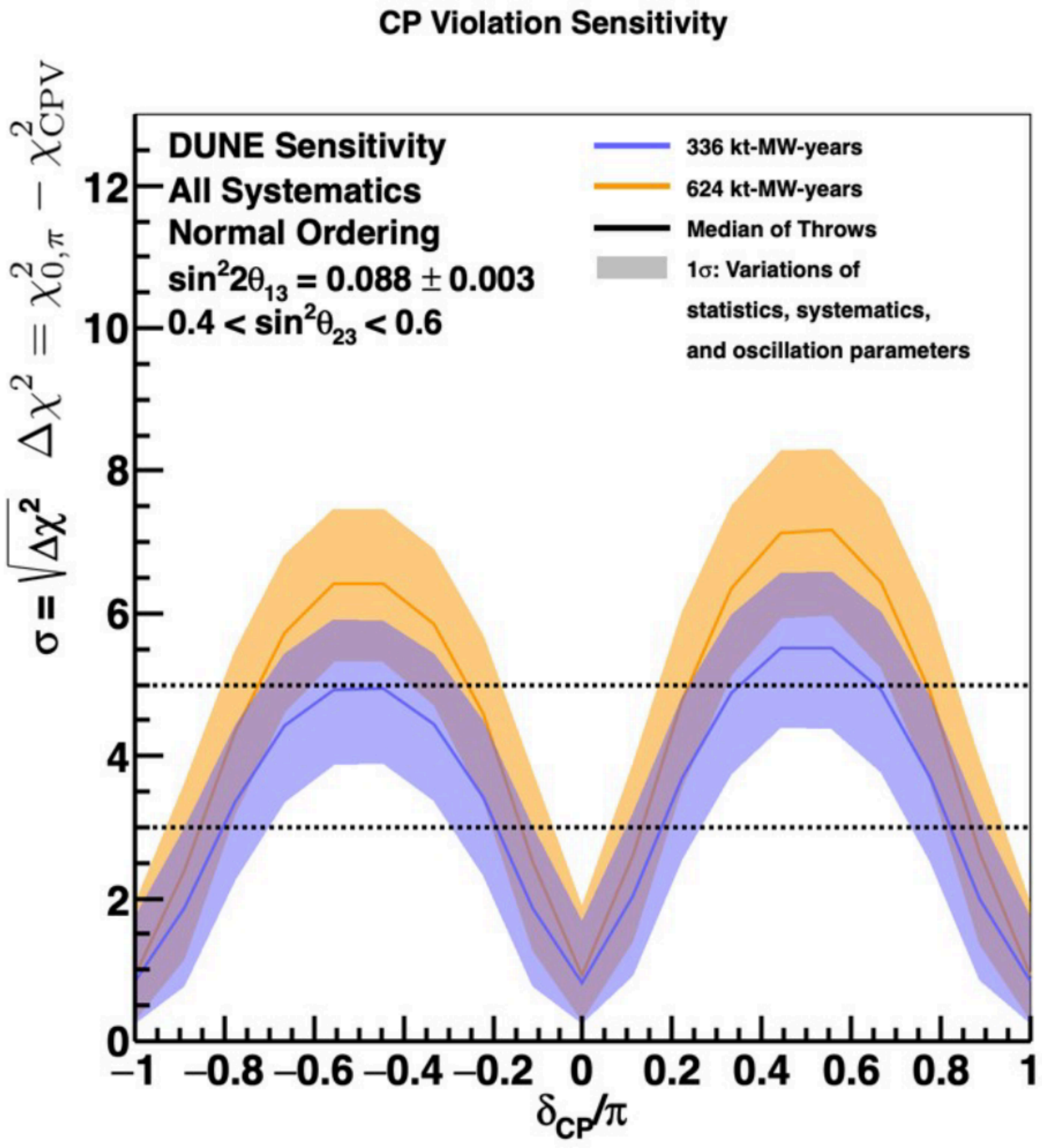
Physics goals:

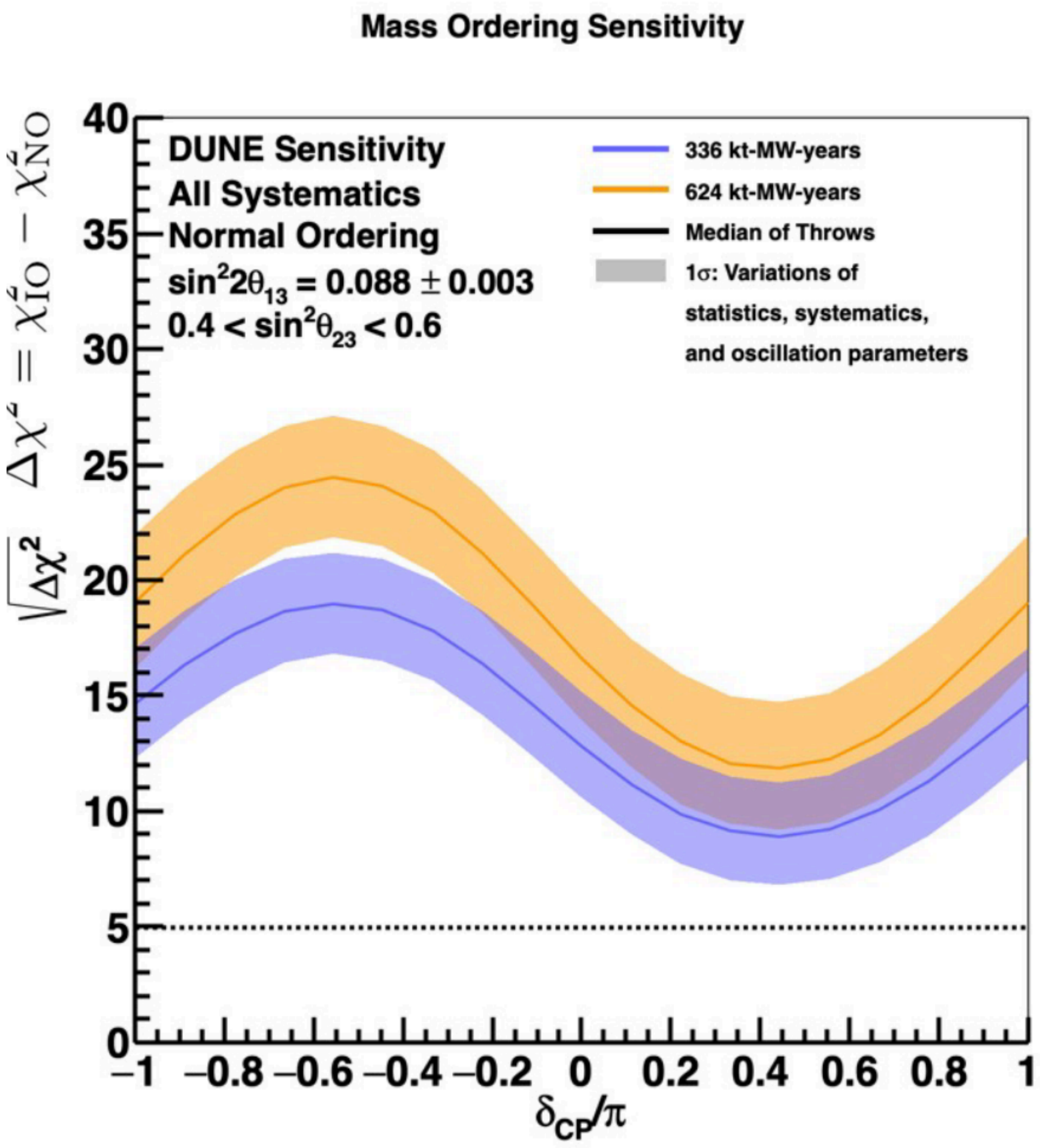
- Measure CP Violation and mass ordering
- Supernova neutrinos
- Nucleon decay
- New Physics

Two options for the far detector: LAr single phase with horizontal an vertical drift

Prototype @CERN Neutrino Platform

DUNE sensitivities



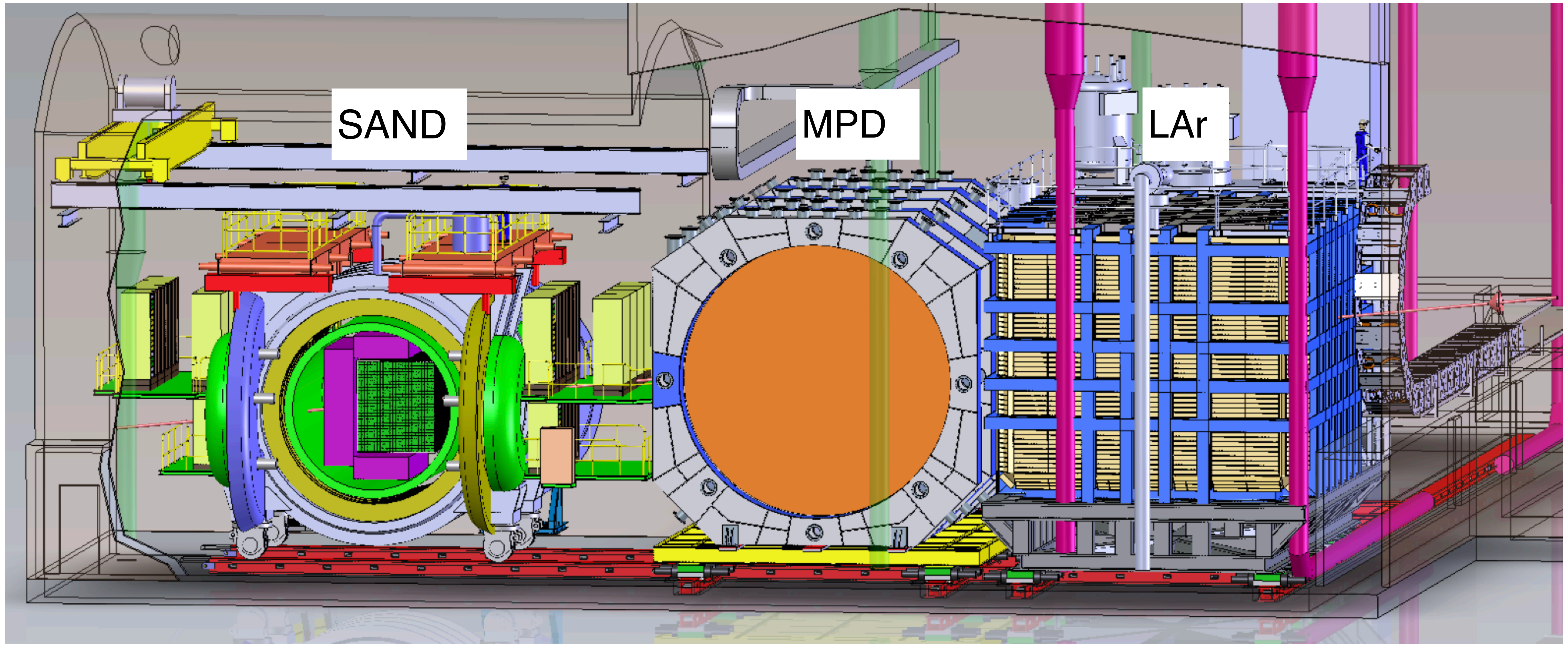


- Assume 4FD+2ND, equal FHC:RHC running, flux uncertainty ~0.5% at peak
- δ_{CP} measured at 5sigma with 624 kt-MW-years
- Already with 336 kt-MW-yr exposure, mass ordering sensitivity is >> 5σ independent of other parameters

Years	kt-MW-years
7	336
10	624
15	1104

Eur. Phys. J. C 80, 978 (2020)

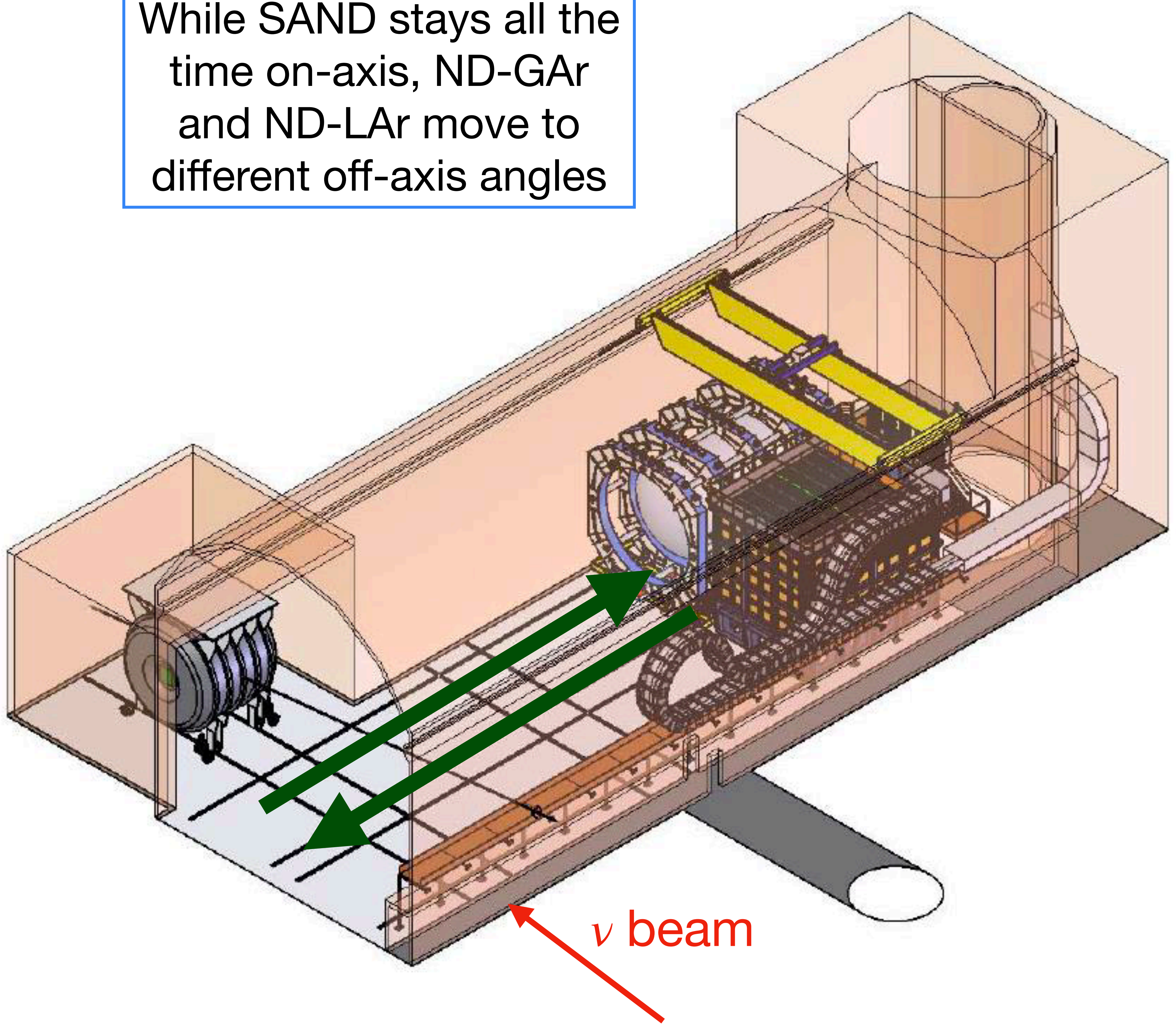
The DUNE ND

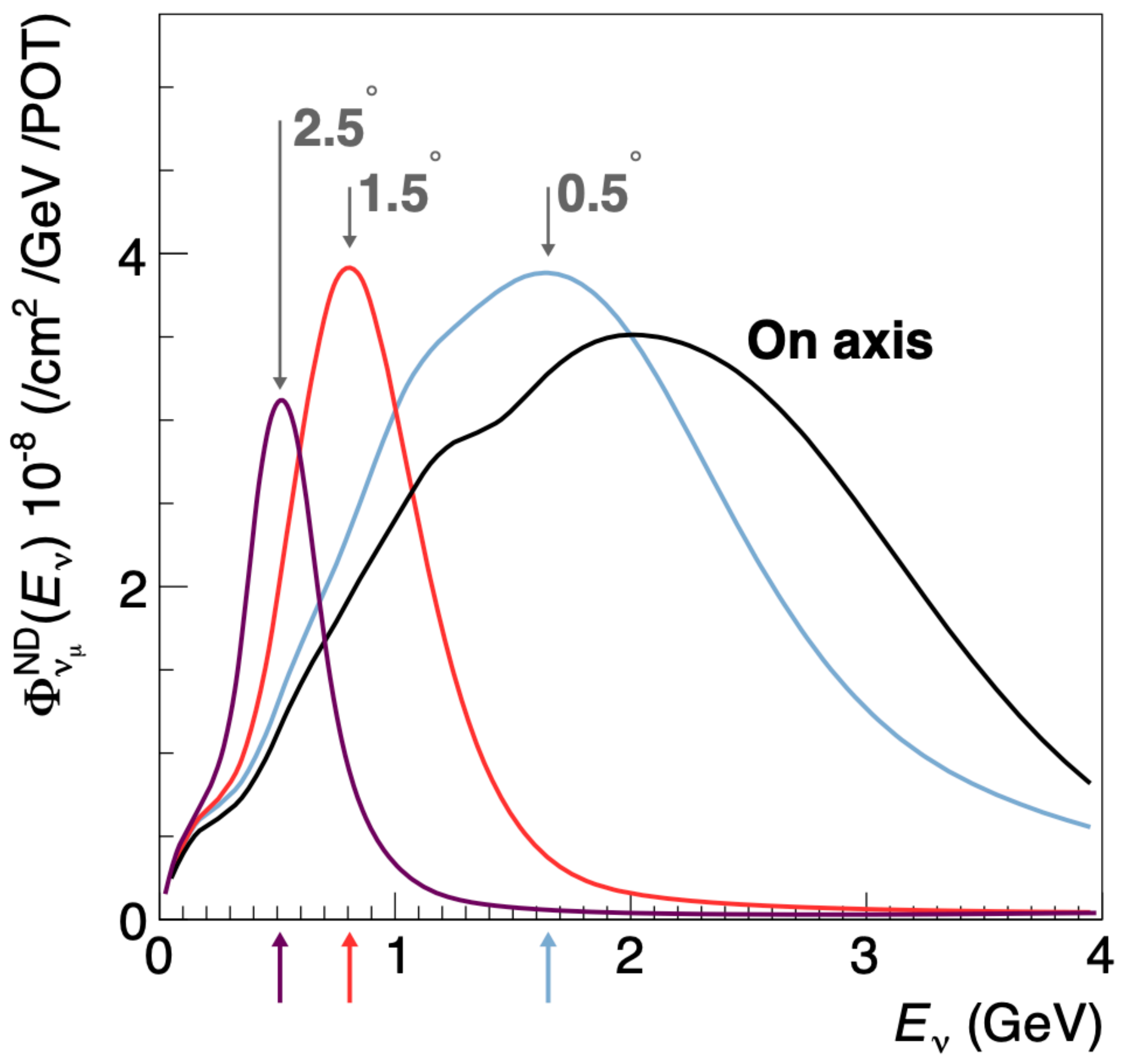


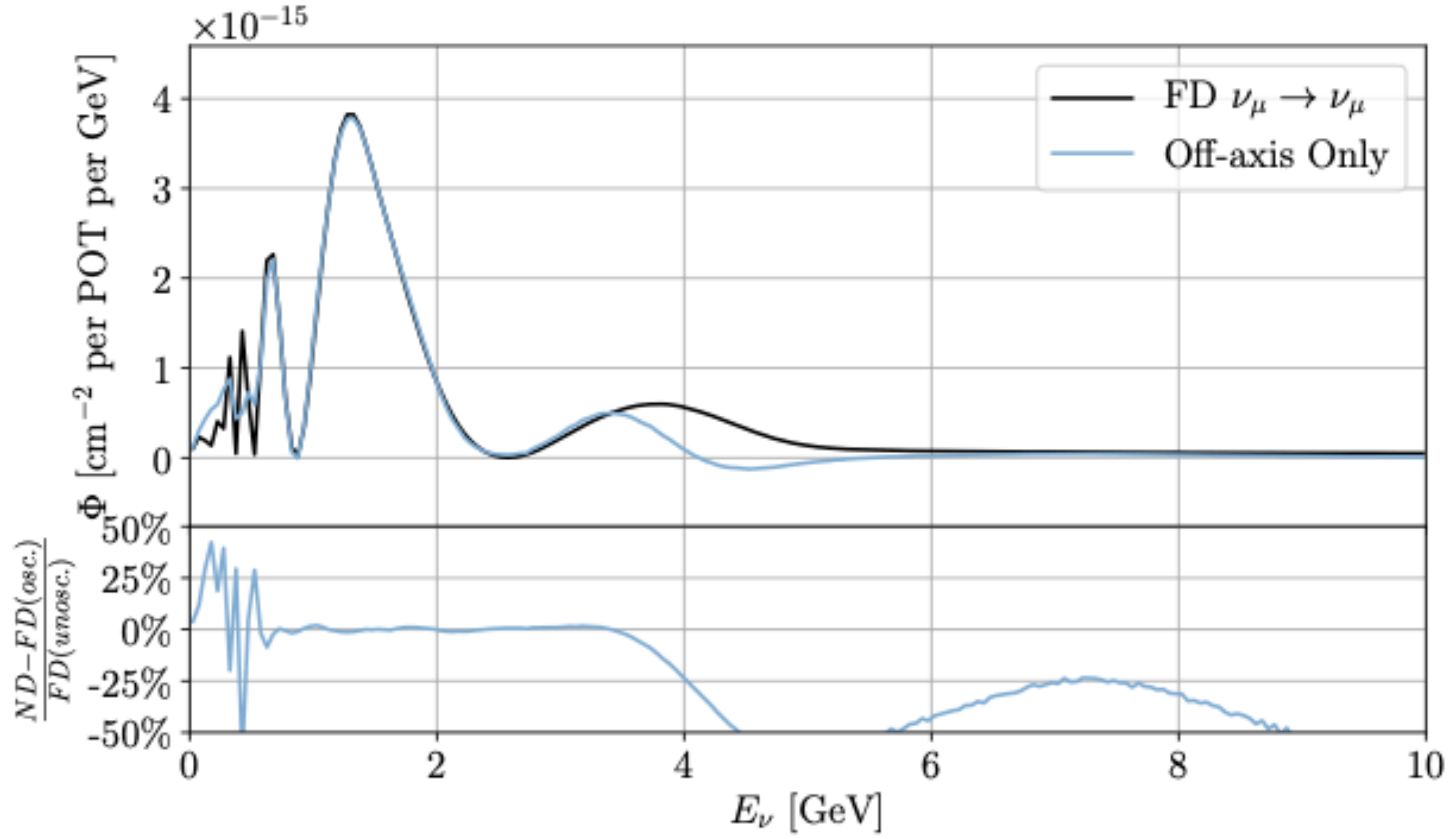
- ND-LAr: 50t FV of LAr with Modular design with 7x5 array of LArTPCs and pixel readout for “native” 3D charge response
- ND-GAr: magnetized GAr TPC + calorimeter with rich cross-section physics program, also muon spectrometer of ND-LAr
- SAND: On-axis beam monitor + magnetized LAr target + STT tracker with rich cross-section physics program

PRISM

While SAND stays all the time on-axis, ND-GAr and ND-LAr move to different off-axis angles







Same method as the IWCD for HK. Promise to break flux and cross-section degeneracies: any out-of-model effects are naturally present in the ND data, and thus will mostly cancel when compared to FD data.

Conclusions

- Neutrino flux and cross-section are the important systematics to keep under control in LBL experiments
- Near detectors in LBL experiments have improved dramatically the precision of oscillation parameters thanks to their simultaneous measurements of flux and cross-section
- Future LBL experiments have to push the precision even further to reach their goal: improve cross-section and flux constraints
- Plan for future LBL is to try as much as possible to measure the final state particles and break the degeneracy between cross-section and flux

Backup

Fractional errors

Fractional errors on ratio of e-like ν-mode/anti-ν-mode total event rates

Error source	T2K 2018 (%)	Improved HK (%)
Flux+cross-section (ND constrained)	4.23	0.74
NC1γ	1.46	0.66
NC Other	0.14	0.04
Nucleon Removal Energy	-	0.01
$\sigma(\nu_e)$ & $\sigma(\text{anti-}\nu_e)$	3.22 (theory)	2.03 (measured)
Detector+Final State Interactions (FSI)	2.05	0.95
All Systematics	**4.99**	**2.45**

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Current systematics for HK studies

T2K (PRD 103, 112008, 2021)

ND: near detectors

FD: far detectors

Source	Error for CPV search (%)
Φ x σ (ND constrained)	2.7
Φ x σ (ND unconstrained)	1.2
Nucleon removal energy	3.6
FD π re-scattering + PN	1.6
σ(ve) / σ($\bar{\nu}$e)	3.0
NC γ + other	1.5
FD detector	1.5
Total	**6.0**

Imperfect extrapolation from ND to FD → Φ x σ (ND constrained)

Uncorrelated processes between ND and FD → Φ x σ (ND unconstrained), Nucleon removal energy, FD π re-scattering + PN

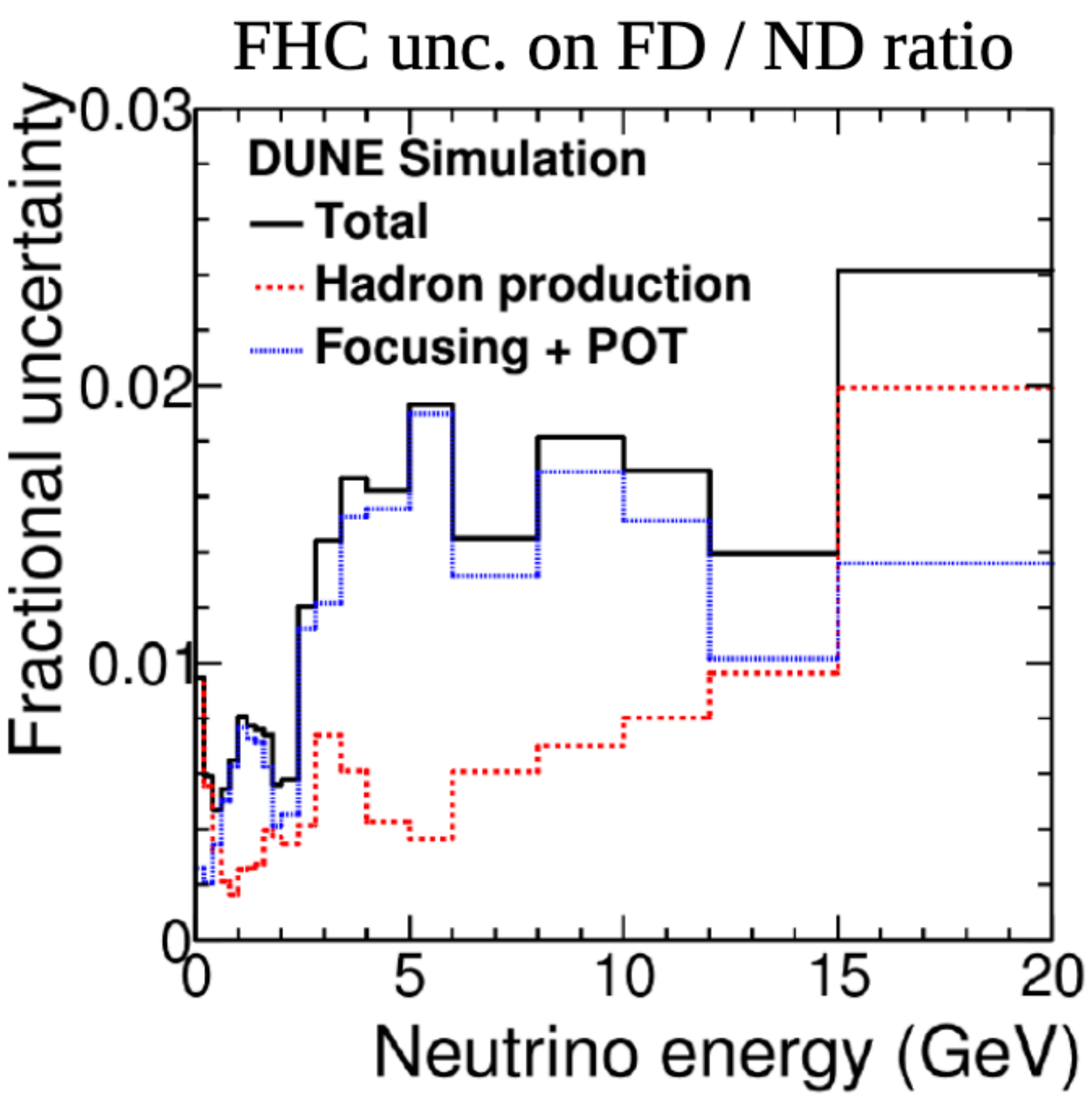
Estimation based on theory → σ(ve) / σ($\bar{\nu}$e)

No data driven constraint → NC γ + other

Detector modeling & calibration → FD detector

- Need to achieve <3 % systematic uncertainties for Hyper-K

DUNE studies



Description	1σ
Quasielastic	
Axial mass for CCQE	$^{+0.25}_{-0.15}$ GeV
CCQE vector form factors (BBBA05 ↔ Dipole)	N/A
Fermi surface momentum for Pauli blocking	±30%
Low W	
Axial mass for CC resonance	±0.05 GeV
Vector mass for CC resonance	±10%
Branching ratio for $\Delta \rightarrow \eta$ decay	±50%
Branching ratio for $\Delta \rightarrow \gamma$ decay	±50%
θ_π distribution in Δ rest frame (isotropic → RS)	N/A
High W	
A_{HT} higher-twist in BY model scaling variable ξ_w	±25%
B_{HT} higher-twist in BY model scaling variable ξ_w	±25%
C_{V1u} valence GRV98 PDF correction in BY model	±30%
C_{V2u} valence GRV98 PDF correction in BY model	±40%
Other neutral current	
Axial mass for NC elastic	±25%
Strange axial form factor η for NC elastic	±30%
Axial mass for NC resonance	±10%
Vector mass for NC resonance	±5%
Misc.	
Vary effective formation zone length	±50%

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Description	1σ
Nucleon charge exchange probability	±50%
Nucleon elastic reaction probability	±30%
Nucleon inelastic reaction probability	±40%
Nucleon absorption probability	±20%
Nucleon π-production probability	±20%
π charge exchange probability	±50%
π elastic reaction probability	±10%
π inelastic reaction probability	±40%
π absorption probability	±20%
π π-production probability	±20%

~20% reduction