Neutrino physics with particle beams

EPS HEP 2021 – 29 July

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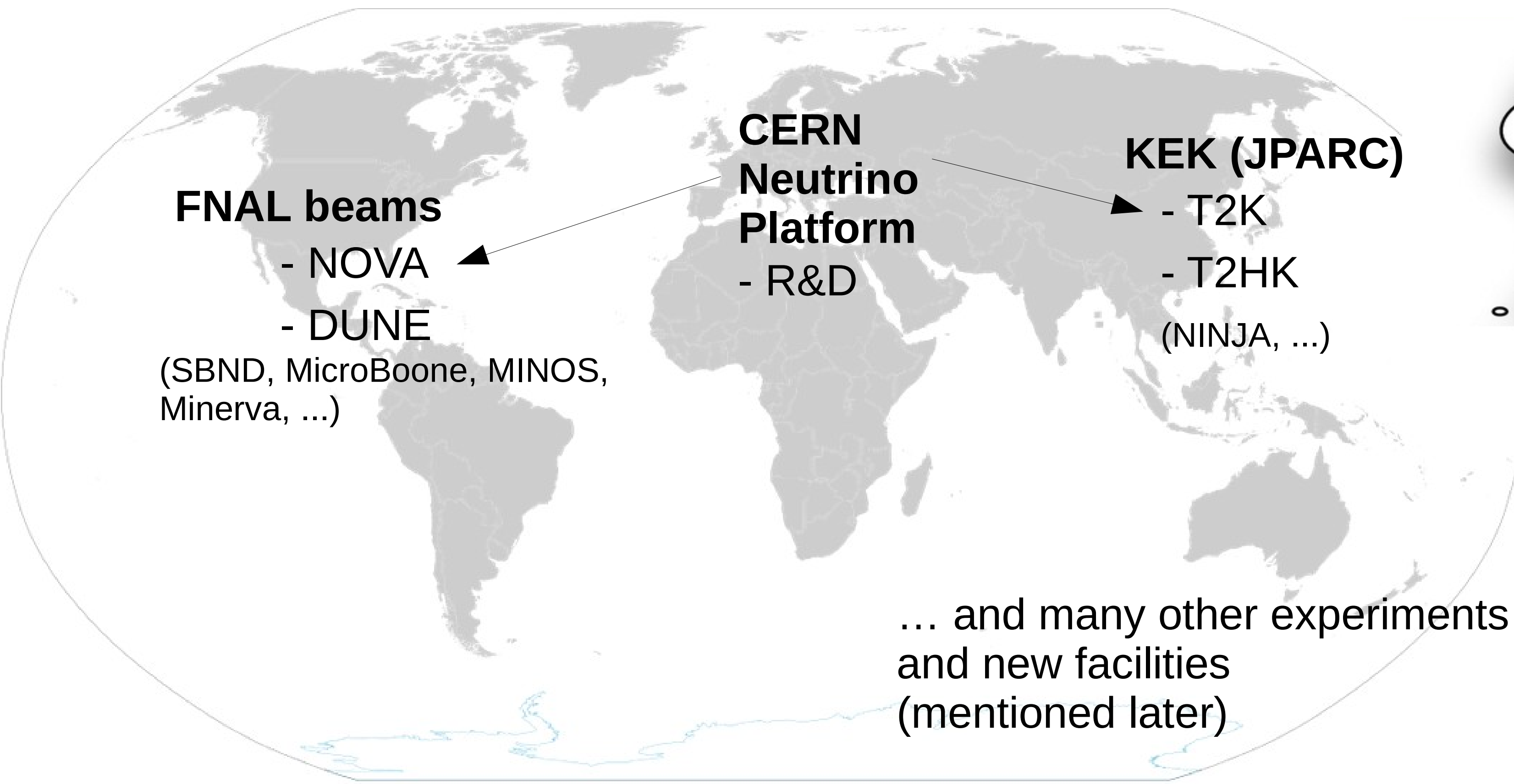
Neutrinos with beams around the world

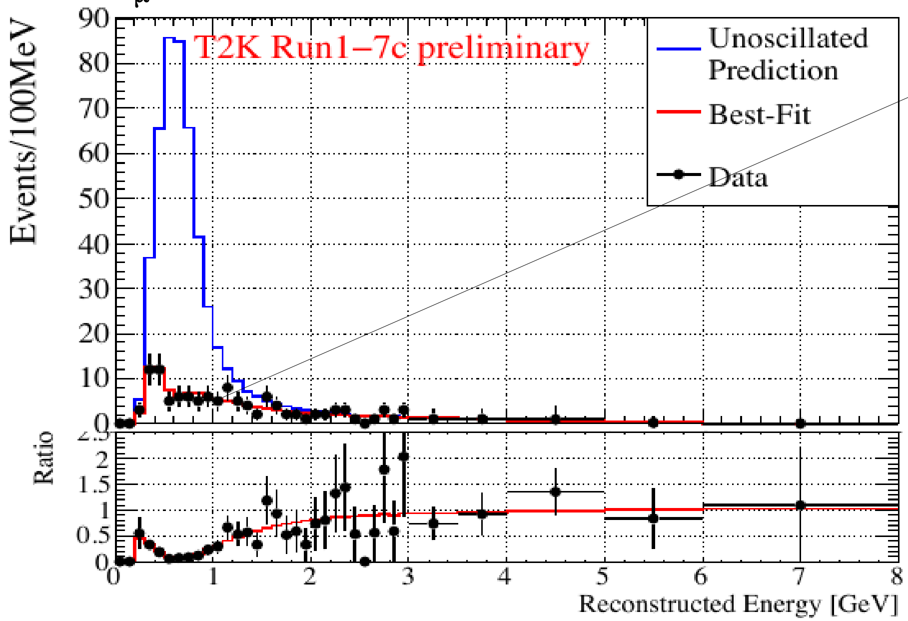
Neutrino oscillation physics with “neutrino beams” entered the precision era with NOVA and T2K → next generation experiments will be worldwide efforts comparable to collider experiments

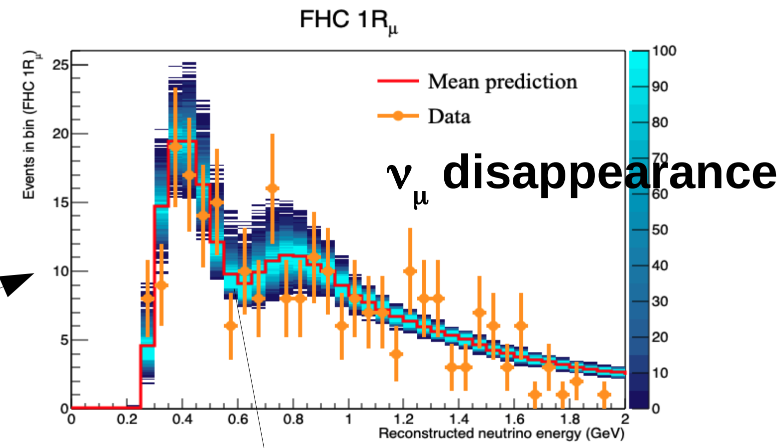


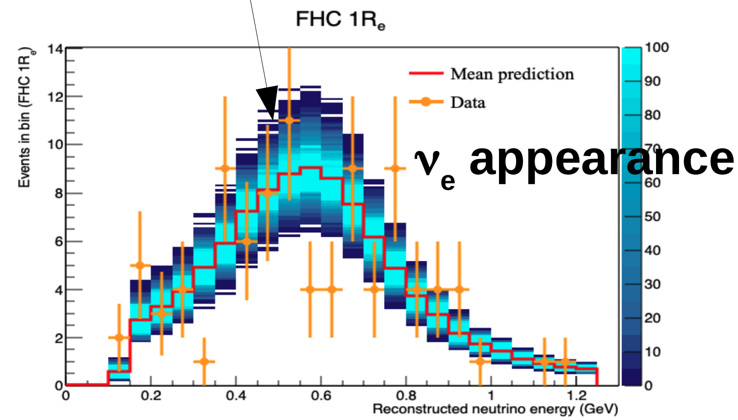
Neutrino physics has a rich present and a bright future!

Neutrino oscillations

ν_μ spectrum at the far detector







T2K preliminary Run1-10

$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\text{amplitude}} \sin^2\left(\underbrace{1.27\frac{\Delta m^2_{ji}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}}_{\text{frequency}}\right)$$

amplitude **frequency**

(simplified 2-flavors approximation)

Full 3-flavors formalism: PMNS matrix

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle \qquad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$U_{\alpha i}$ are expressed in terms of 3 mixing angles (θ_{13}, θ_{23}, θ_{12}) and a phase δ_{CP}

3 mass states → two δm^2: solar (small) and atmospheric (large)

$\nu_e/\bar{\nu}_e$ appearance: δ_{CP} and MH

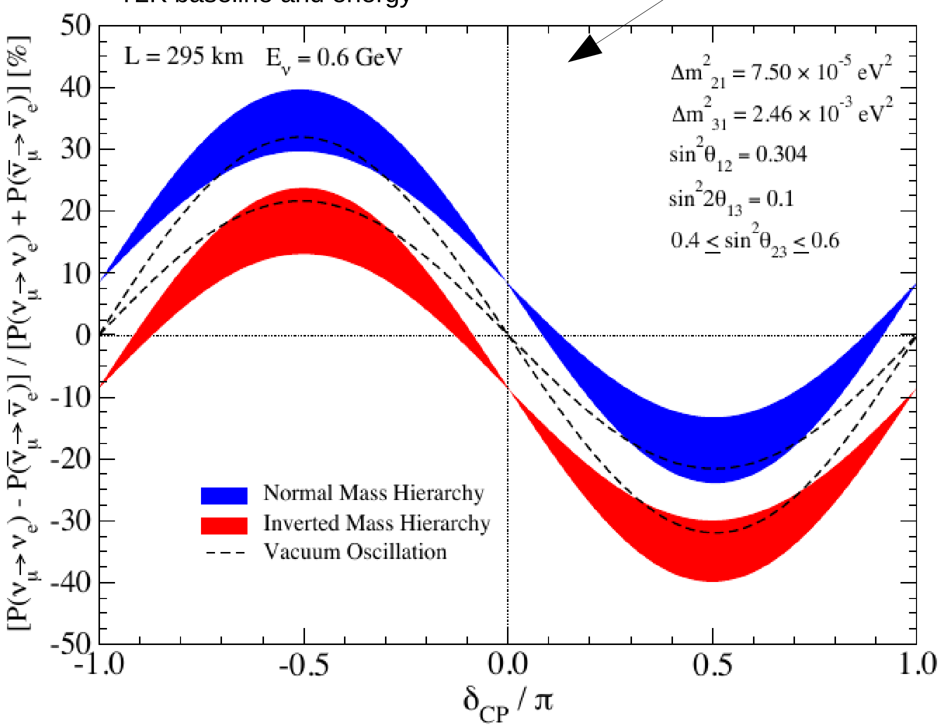
δ_{CP} parametrizes different oscillations for ν and $\bar{\nu}$ → **new fundamental source of CP violation (and first in leptonic sector!)**

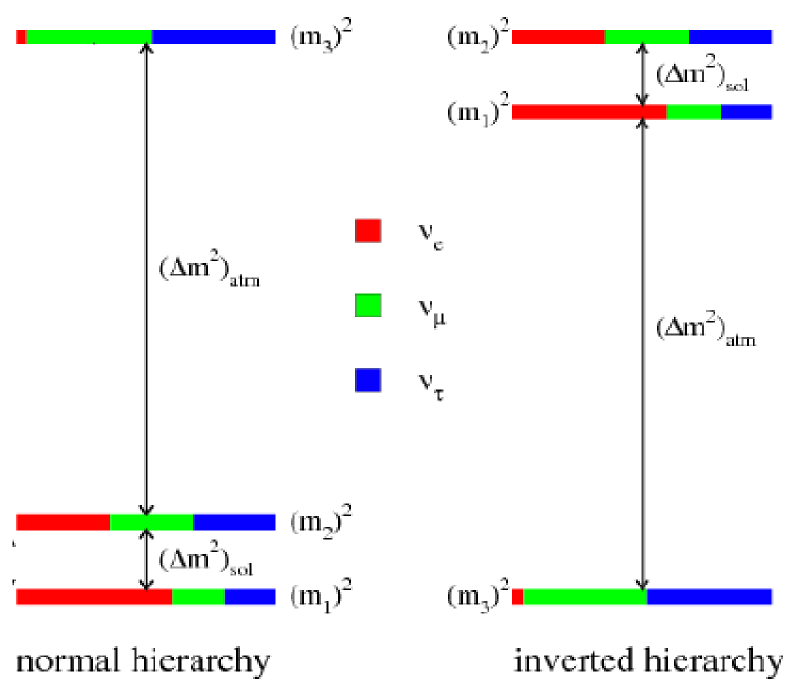
Mass Hierachy : is the mass ordering the same for charged and neutral leptons? **(→what is the fundamental symmetry hidden behind neutrino oscillation)**

$$\mathcal{A}_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \sin\delta}{\sin\theta_{13}\tan\theta_{23}}\Delta_{21} + \text{matter effects},$$

longer the baseline → larger MH sensitivity

T2K baseline and energy



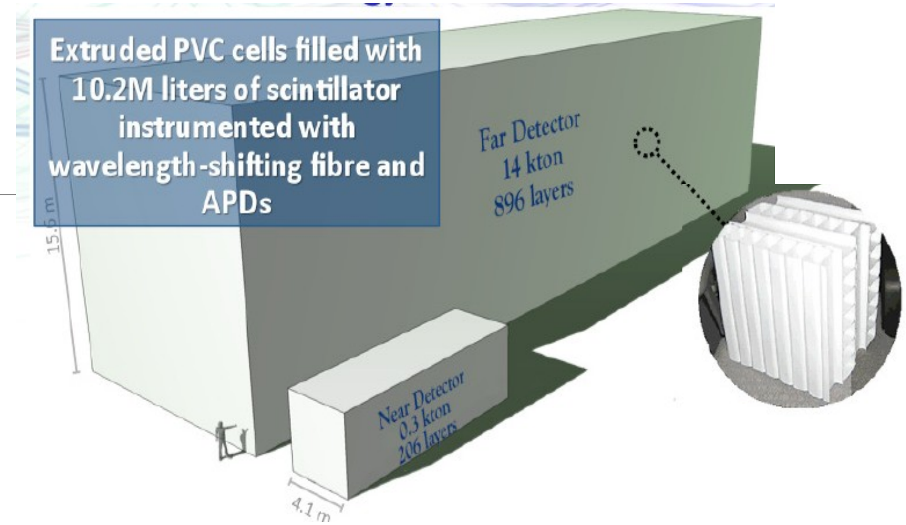


NOVA

Far: 14 kT on the surface

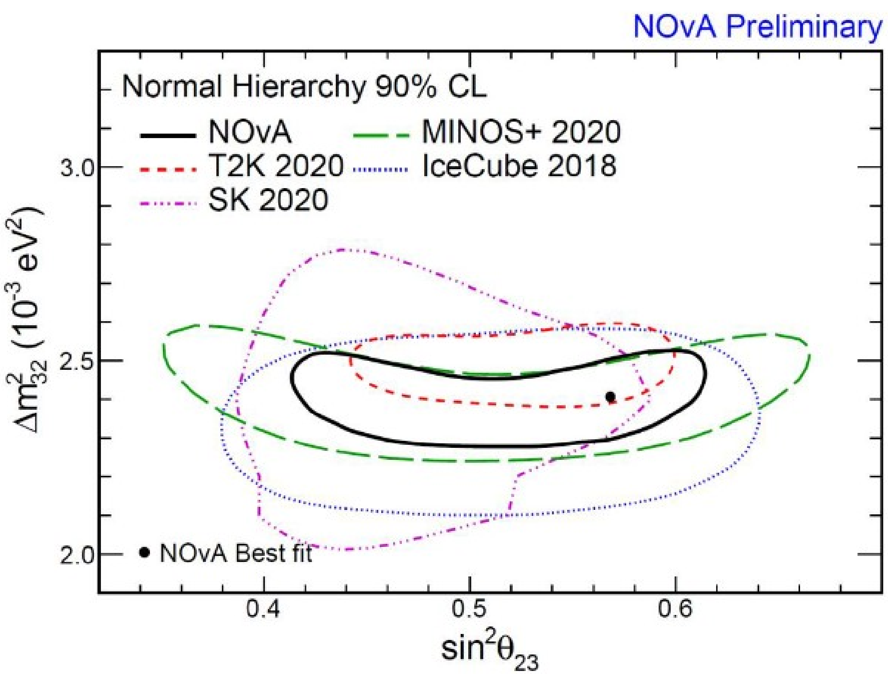
Baseline: 810km

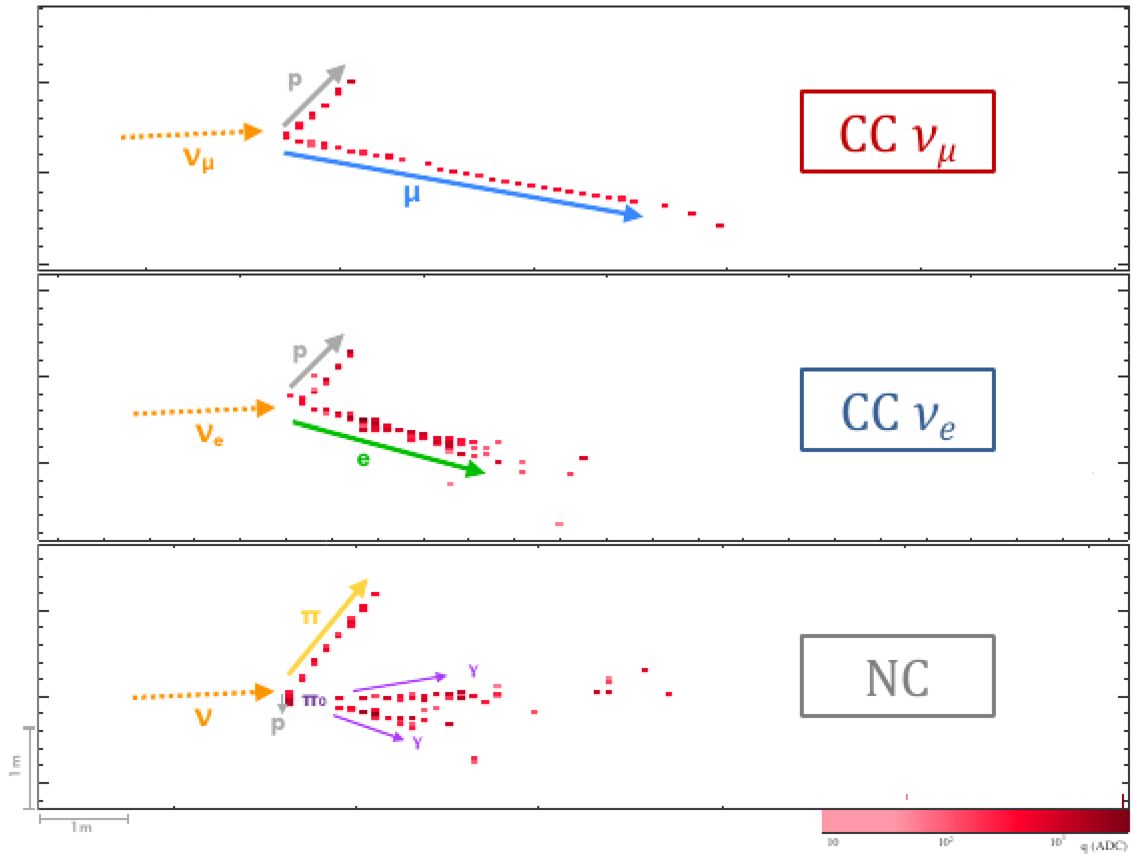
NUMI beam at FNAL
Near Detector: 300T underground



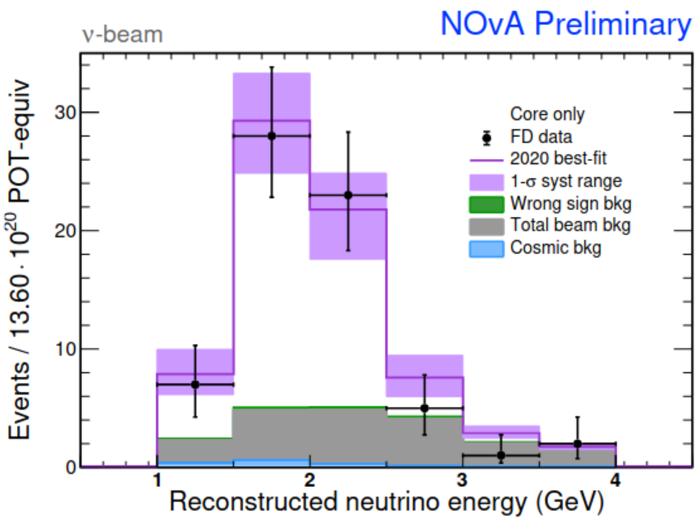
– **Functionally identical near and far detectors**

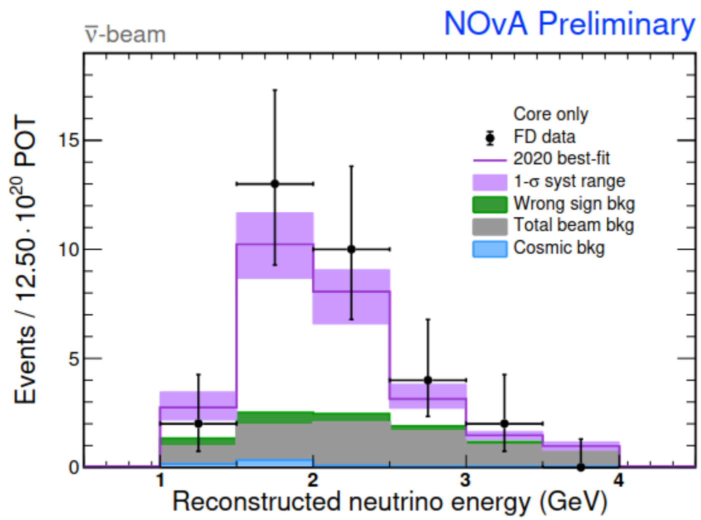
– Placed 14mrad off-axis to produce a narrow-band spectrum



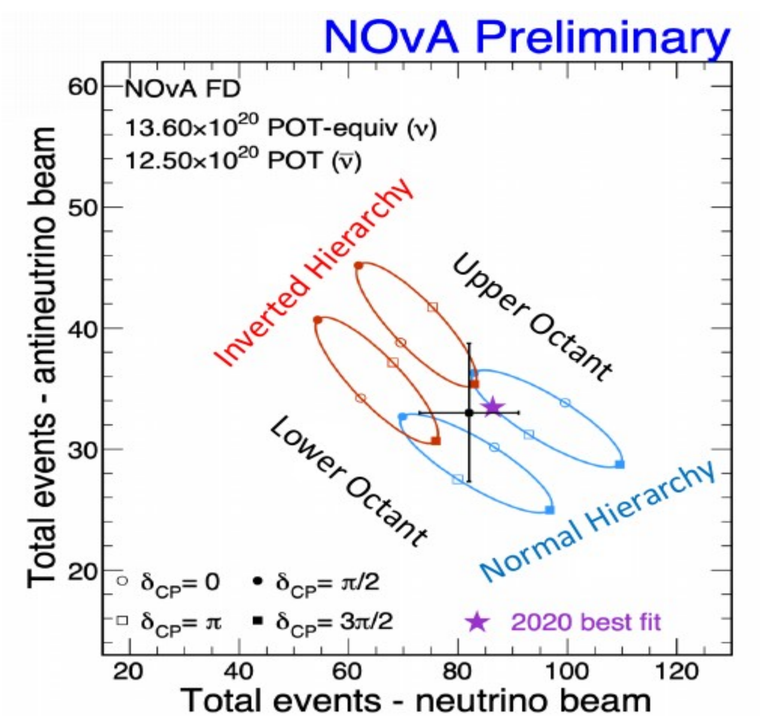


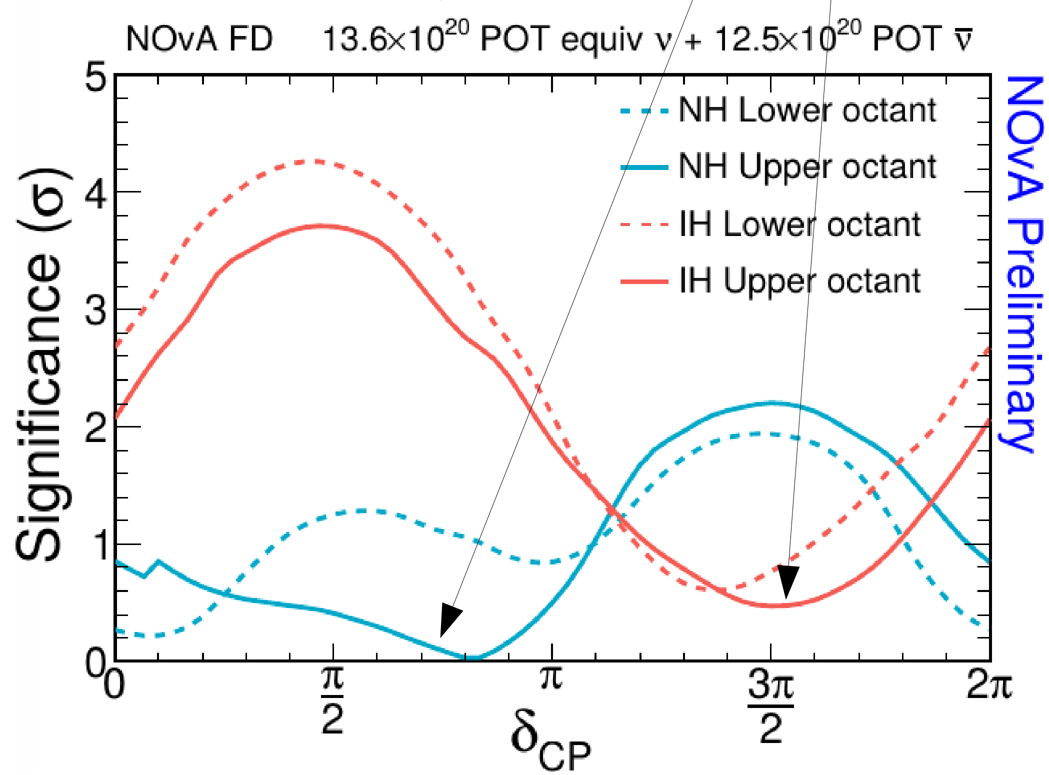
NOVA: δ_{CP} and MH



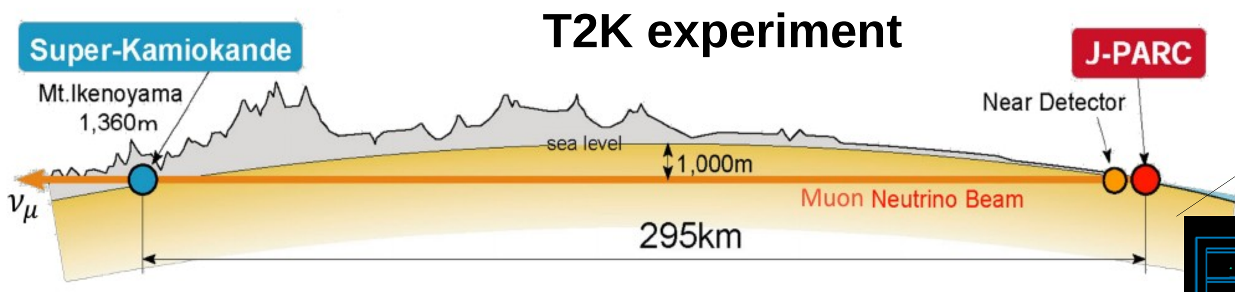


Sensitive to both δ_{CP} and MH with some degeneracies

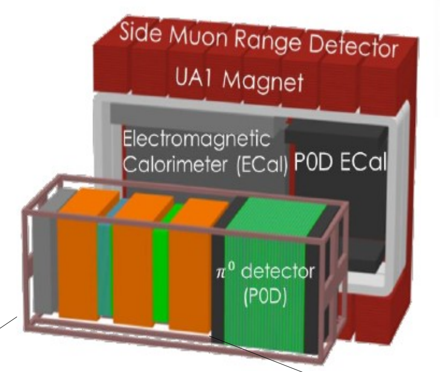


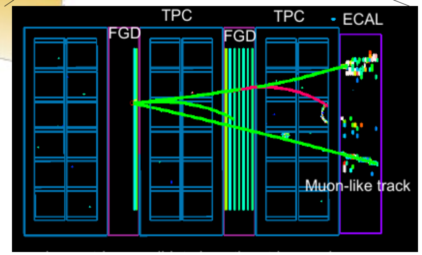


T2K



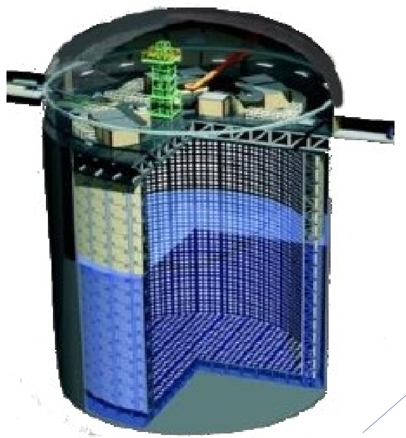
ND280 near detector



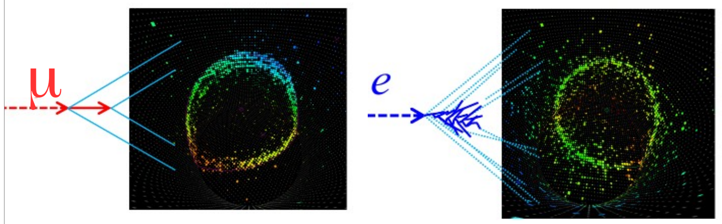


- Full tracking and particle reconstruction (**<u>magnetized!</u>**): measure precisely neutrino and antineutrino rate before oscillation

Super-Kamiokande



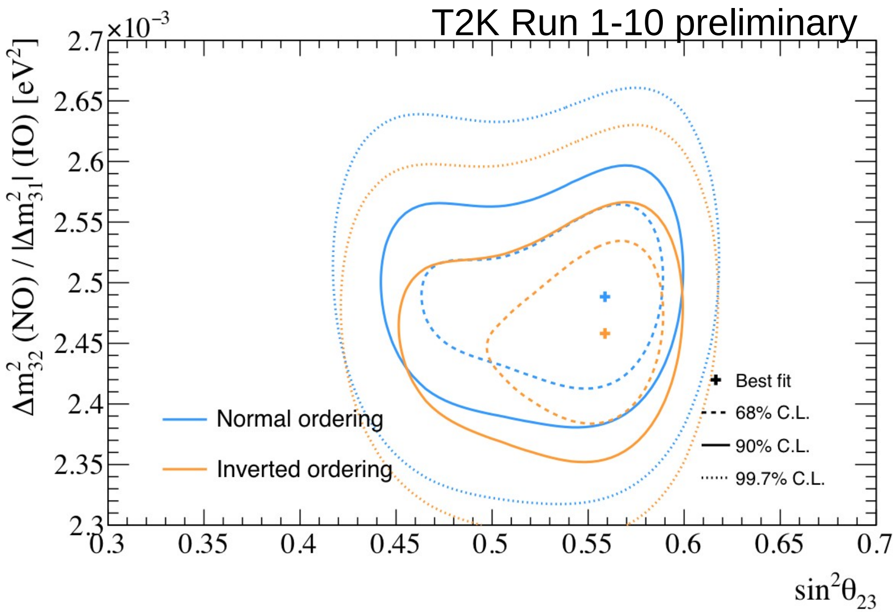
- Huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ



<u>clear ring</u>

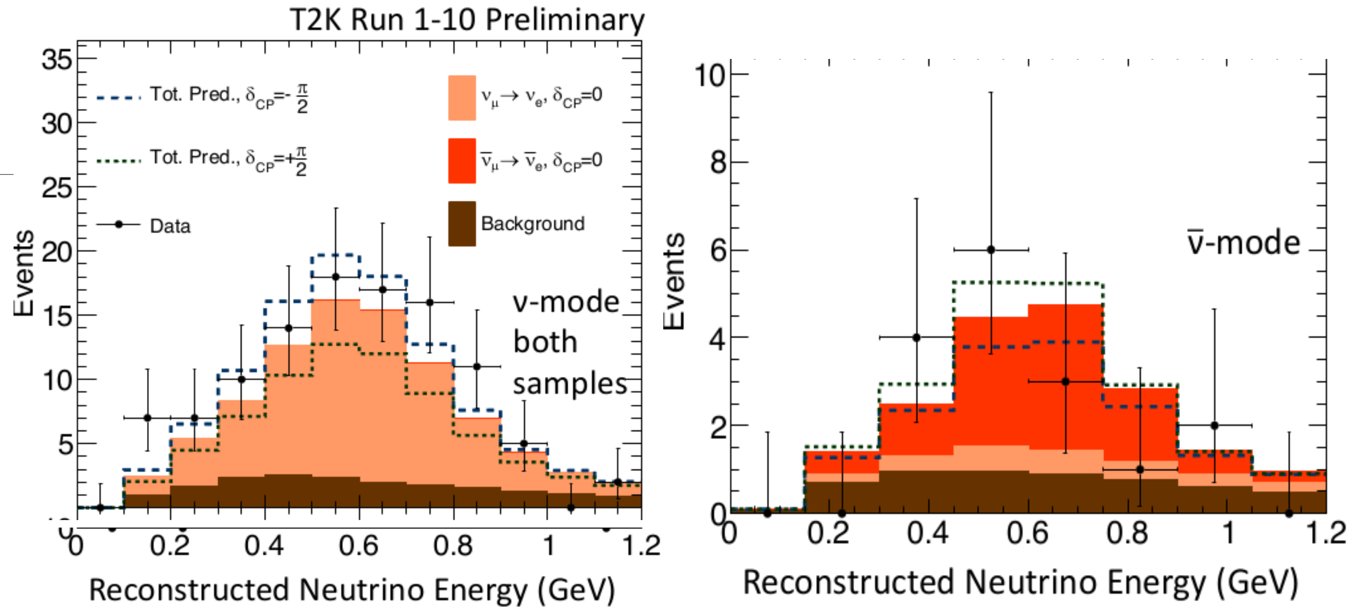
<u>fuzzy ring</u>

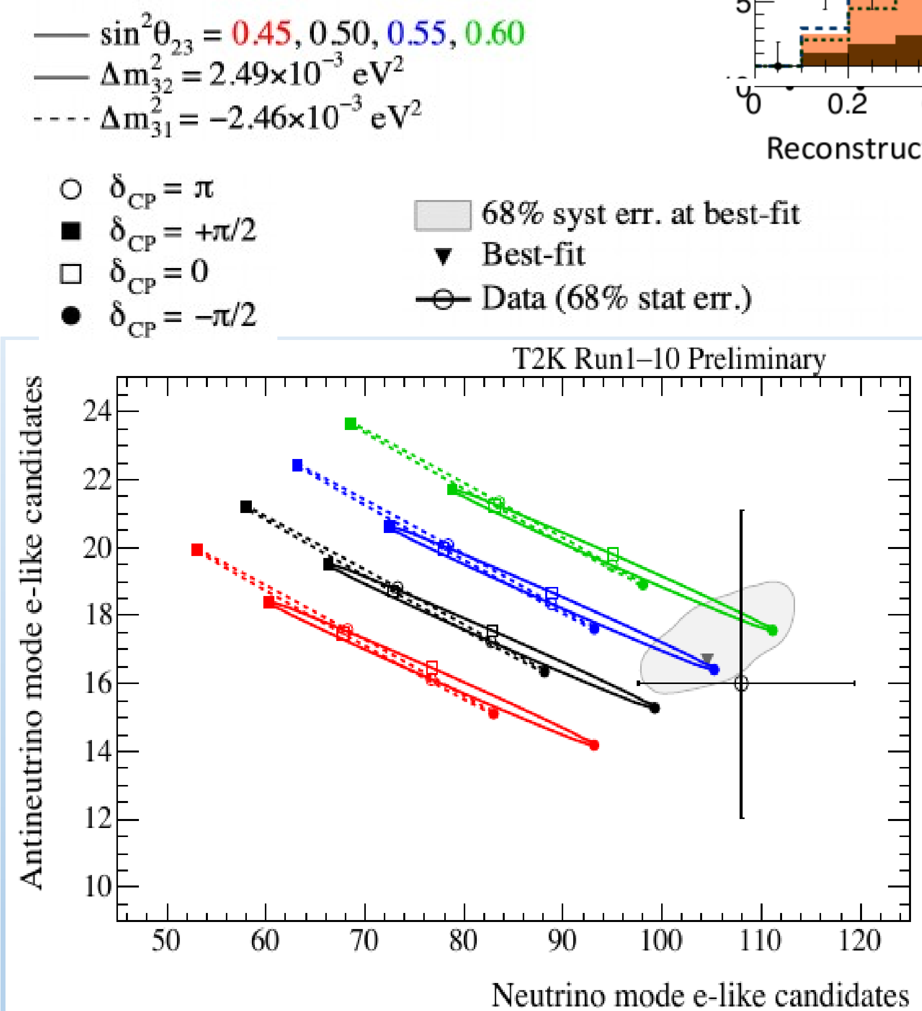
- Placed 2.5deg off-axis to produce narrow-band flux

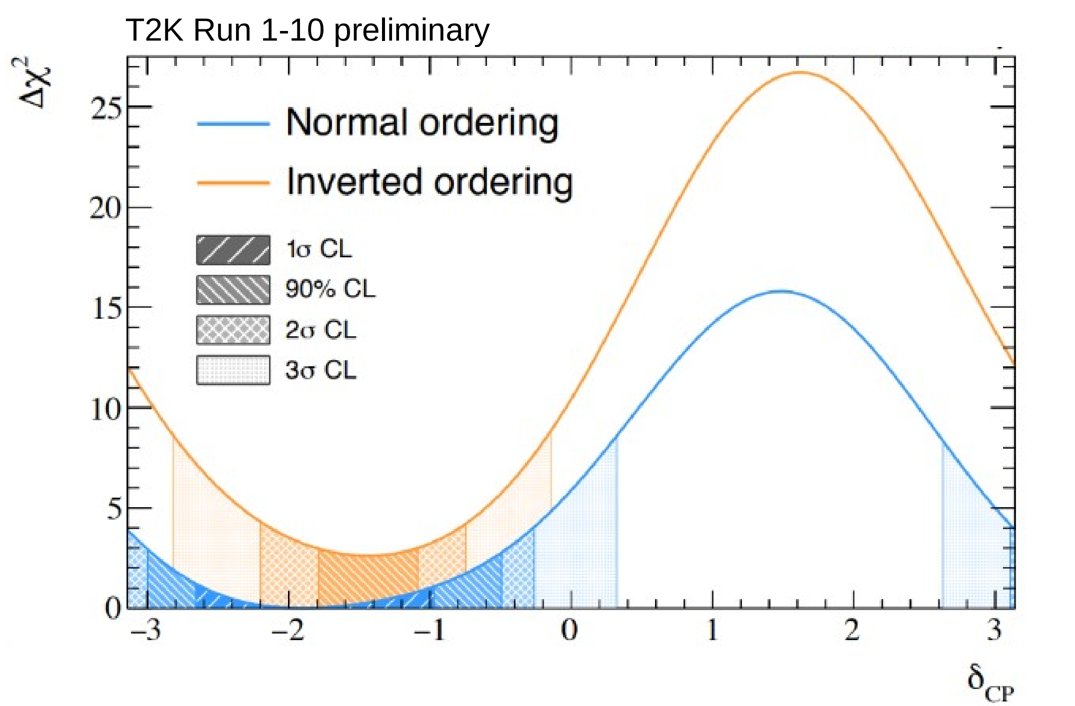


T2K: δ_{CP}

Small MH sensitivity → clean measurement of δ_{CP}

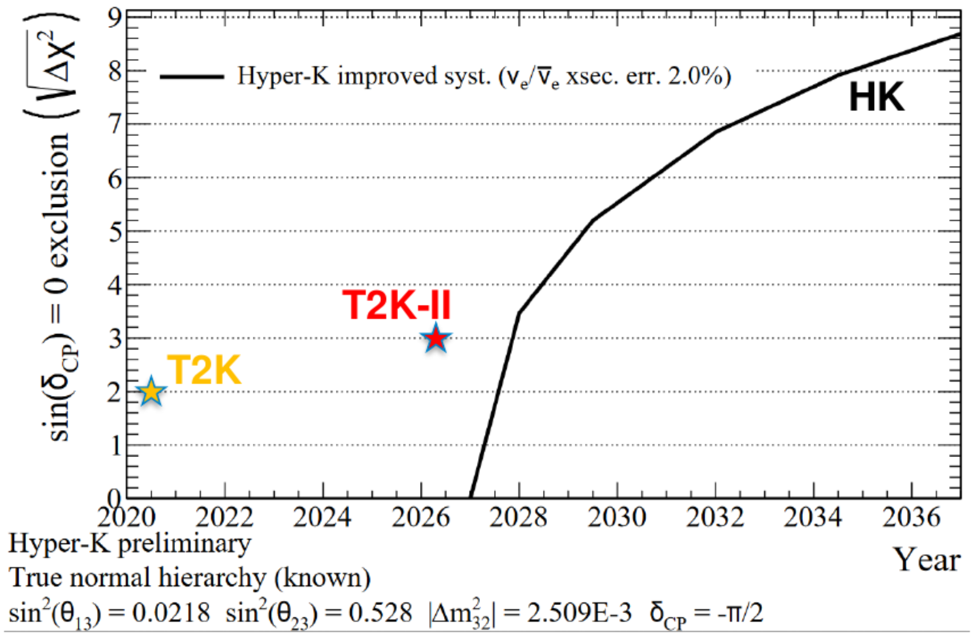


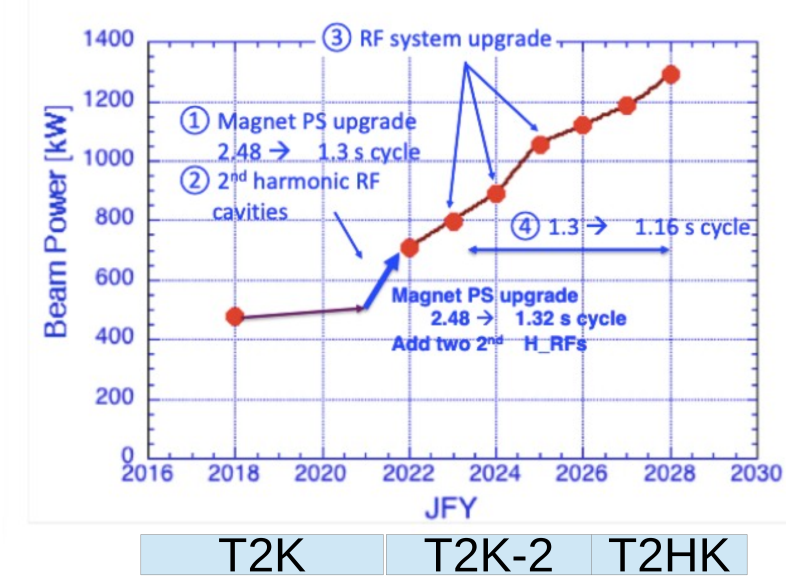




T2K → T2K-"2" → T2HK

- **Beam upgrade from 500kW to 750kW in 2022 for T2K → 1.3MW in HyperKamiokande era**





- **Seamless program of neutrino beam**

- T2K-"2" will push further the study of systematics at % level with upgrade of near detector ND280.

- ND280 upgrade will be ported from T2K to HK: robust path to calibration/systematic understanding from day 1 of HK

- **Hyperkamiokande: huge water cherenkov detector on JPARC beam**

- 190kTon fiducial mass (x8.4 SuperKamiokande)

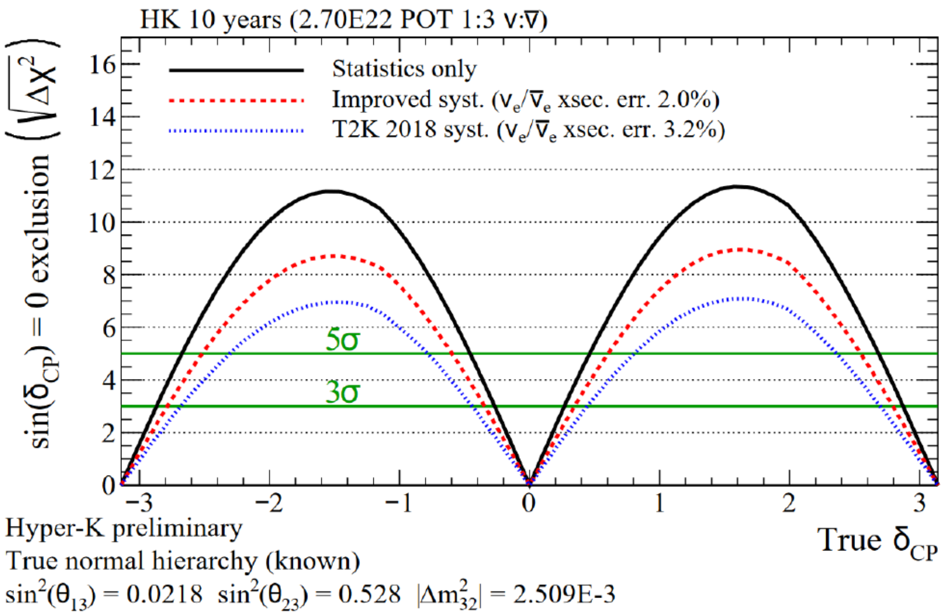
- PMTs with double sensitivity of SuperKamiokande

→ more than x20 SuperKamiokande beam neutrino rate

→ enabling very fast CP-violation discovery

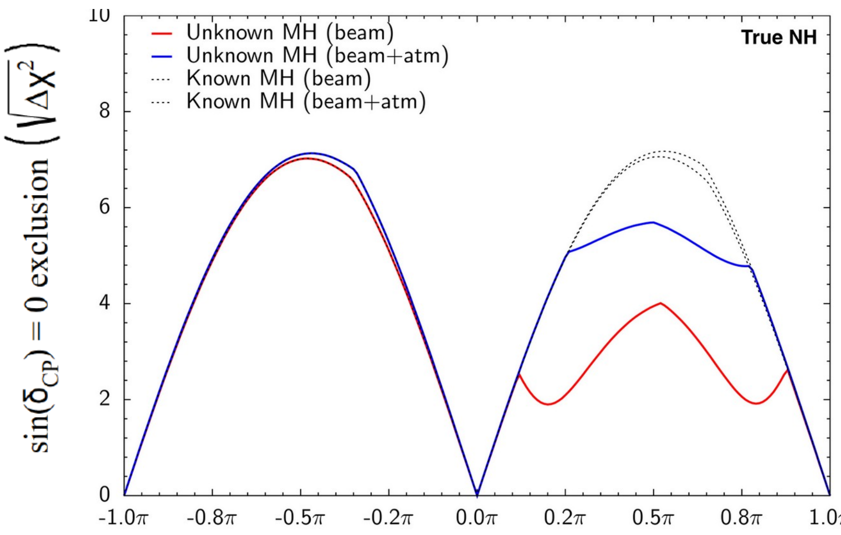
HyperKamiokande sensitivity

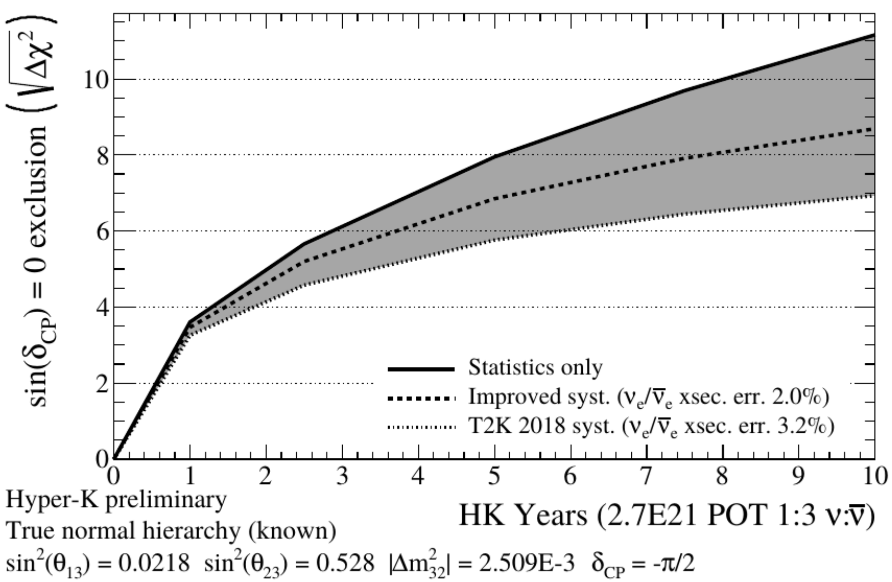
CP-violation sensitivity with known mass hierarchy: →

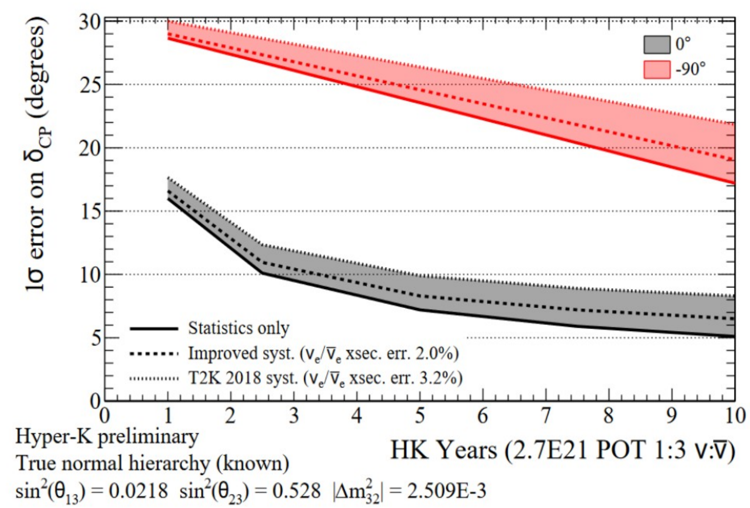


Unknown MH:
Combination of atm and beam neutrinos to measure δCP and MH

→ x8 SuperKamiokande natural neutrino rate

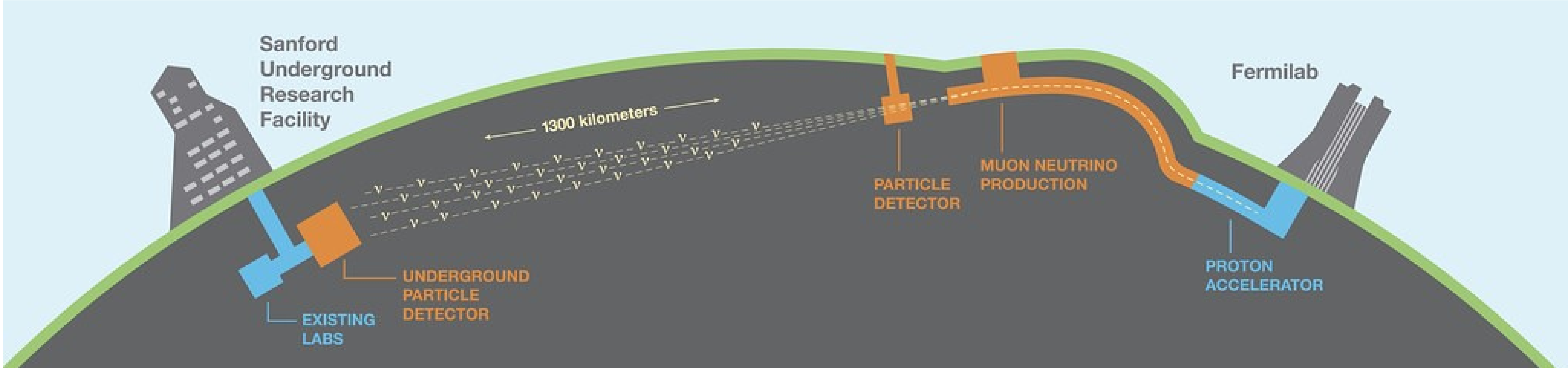


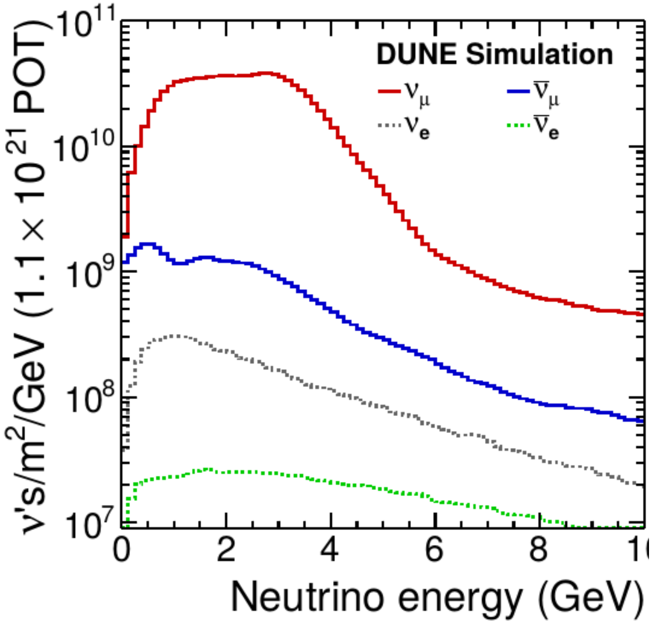


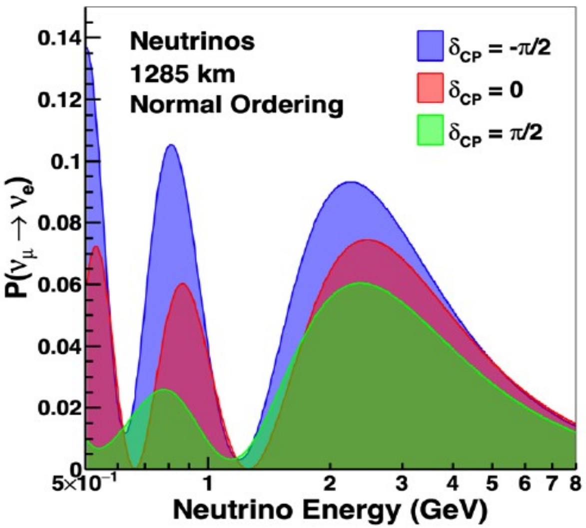


DUNE

New wide-band neutrino beam at Fermilab: 1.2MW → 2.4MW







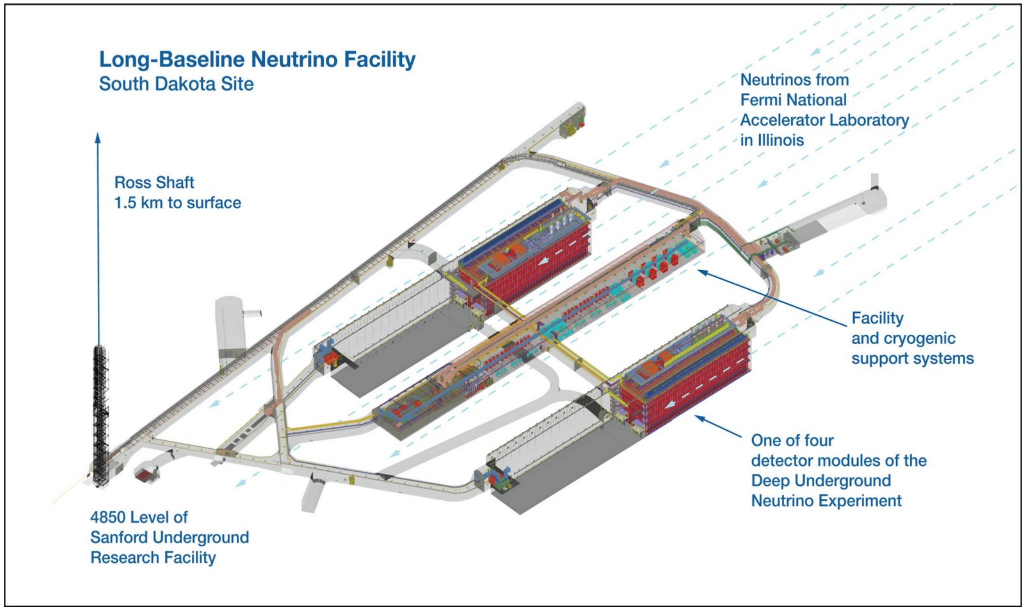
- Cover two oscillation maxima → a lot of shape information to exploit for precision physics on PMNS paradigm

- To exploit full sensitivity a shape analysis is needed **→ need extremely good resolution on neutrino energy reconstruction**

DUNE technology

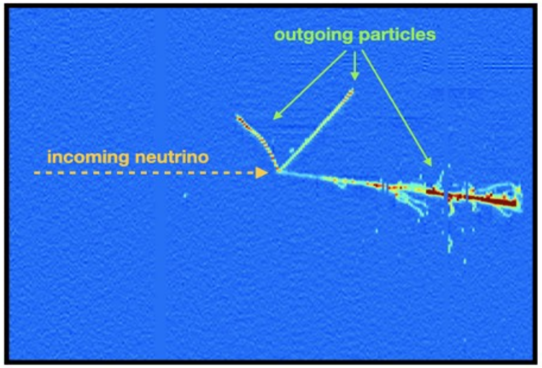
(Relatively) new technology to be deployed to unprecedented scale: huge LAr TPCs with charge readout

- **4 LAr TPC:** 4 x 10kTon fiducial mass with staged approach

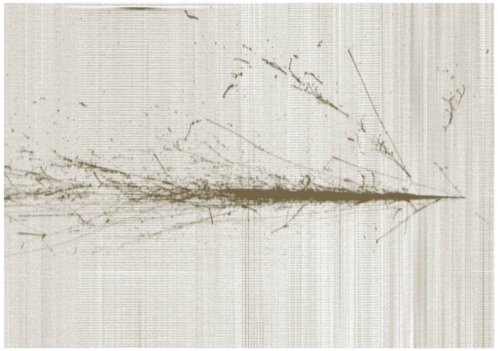


- Full reconstruction of final state particles (~bubble chamber)

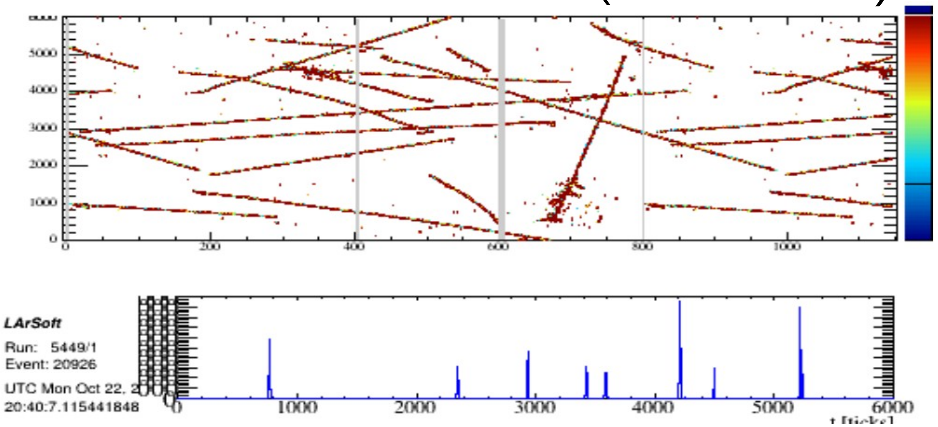
ArgoNeut (~250 kg LAr)



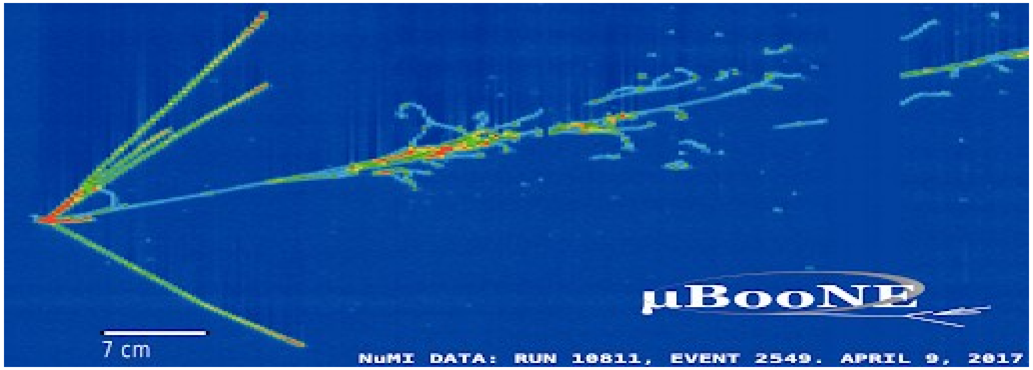
ICARUS (~500 Ton LAr)



ProtoDUNE-SP demonstrator (17.5 kTon LAr)

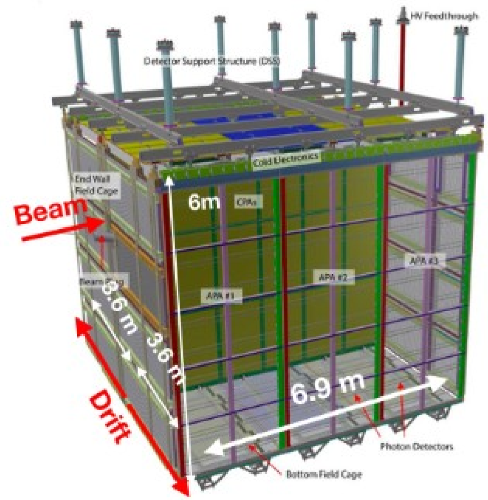


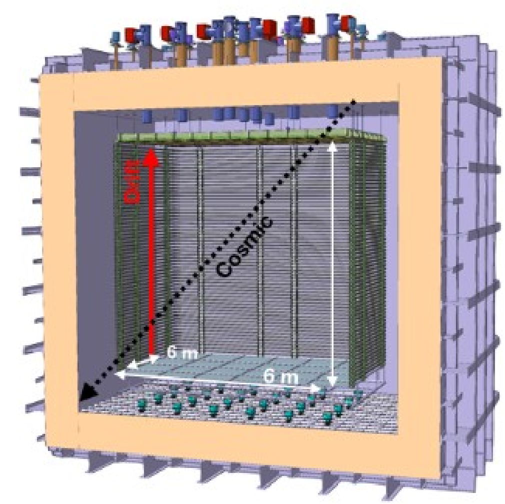
MicroBoone (~170 Ton LAr)



LAr measurements

Proto-DUNE: Single-Phase validation and tuning,
Double-Phase → Vertical Drift

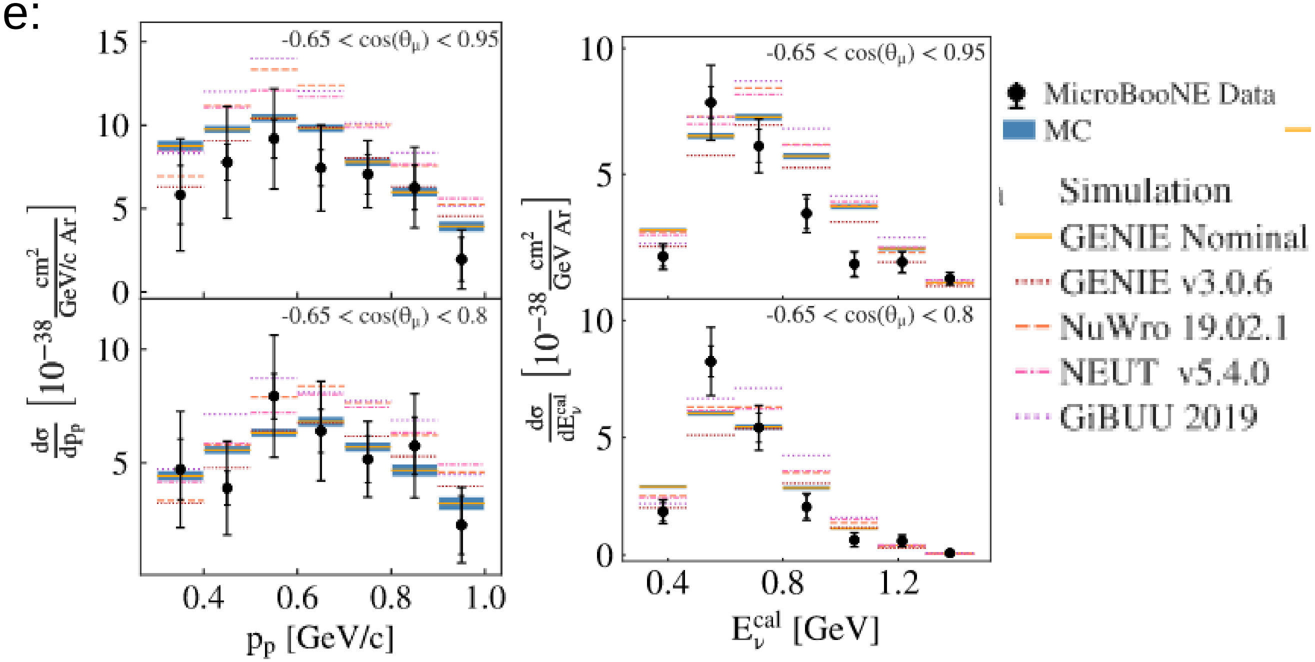


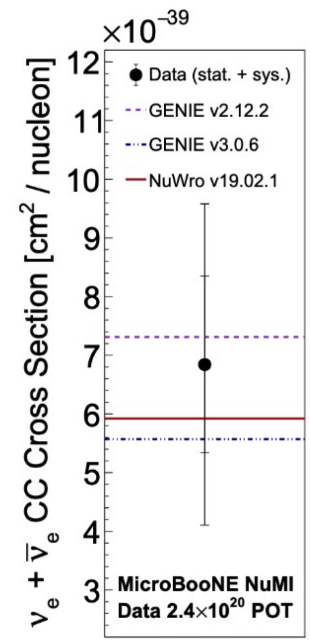


Not only R&D for technology but also measurements to control nuclear model in Argon

- MicroBoone:

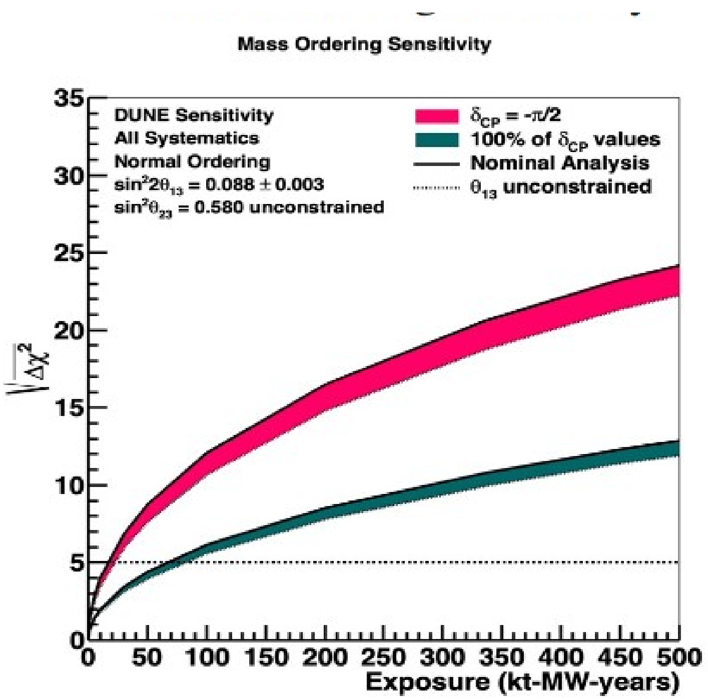
PHYSICAL REVIEW LETTERS125,201803 (2020)

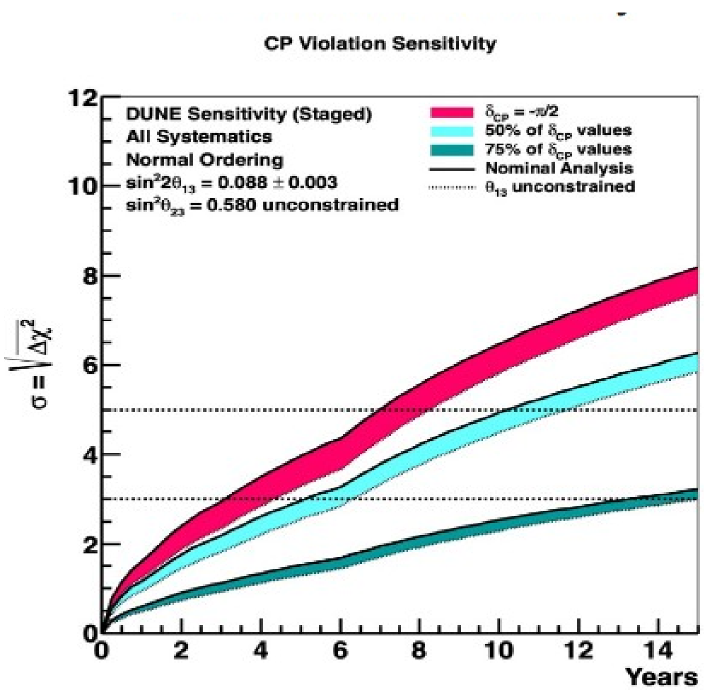




arXiv:2101.04228 [hep-ex]

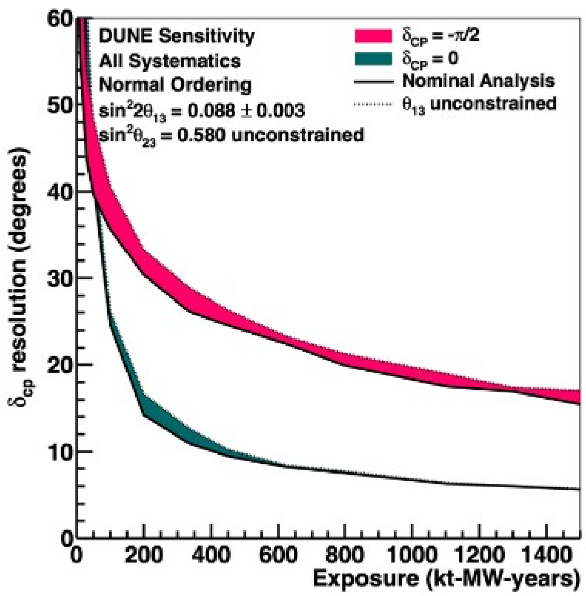
DUNE sensitivity

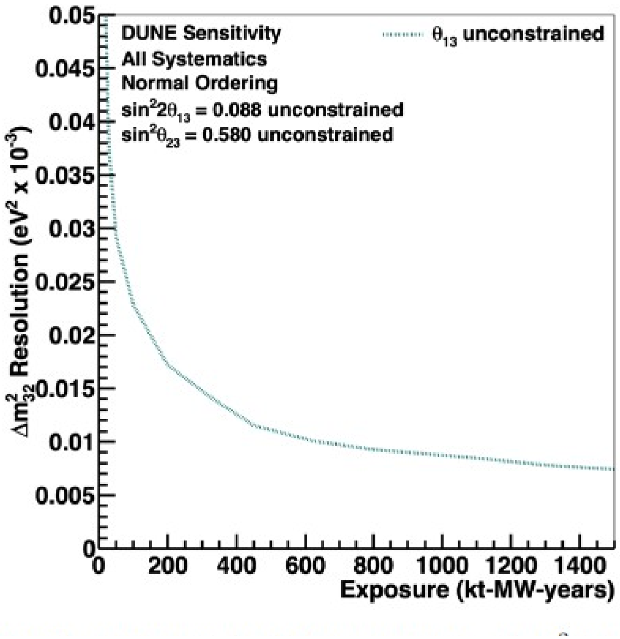




- **Very fast MH determination at 5σ**

- **Precision physics: prospects for δ_{CP}, Δm^2 resolution**





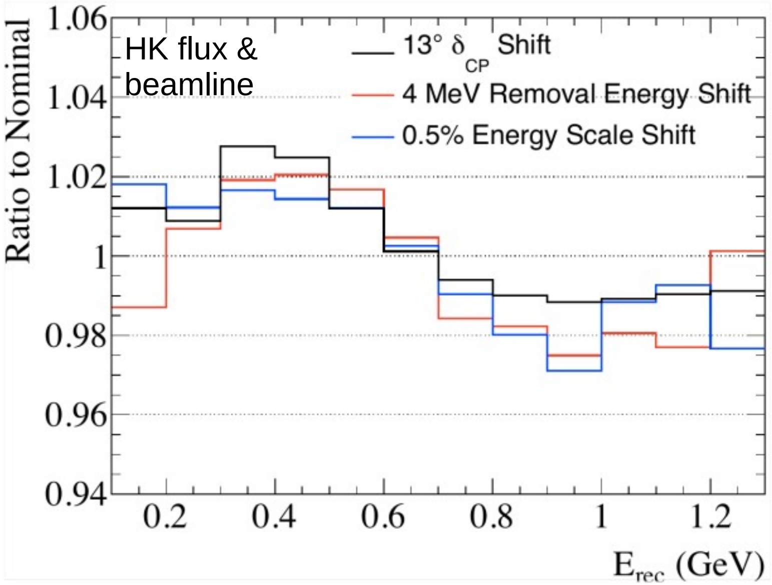
Importance of systematics

- Precision physics will be dominated by systematics

  - ~2000 of ν_e ($\bar{\nu}_e$) and ~10000 events ν_μ ($\bar{\nu}_\mu$)

  → **first order systematic is the normalization of ν_e / $\bar{\nu}_e$ for CPV and MH**

  → precision measurements require very good control of **neutrino energy spectrum shape**



Measurement of δ_{CP} <15deg and of Δm^2 ~ 1% require control of energy scale (calibration + nuclear effects) <1%

- Crucial role of **present experiments (T2K – NOVA) to open the road to % systematics** and indicating analysis strategies and detector design enabling such precision

- Crucial role of **near detectors**

  Without forgetting crucial ancillary measurements like EMPHATIC, ANNIE, electron-scattering at JLab...

Near detectors and nuclear theory

ND measures rate vs neutrino energy before oscillation
→ characterize flux and xsec

$$R_{ND}^{\nu'} = \int \Phi^{\nu}(E_{\nu}) \frac{d\sigma^{\nu'}}{dE_{\nu}} dE_{\nu}$$

$$R_{FD}^{\nu'} = \int \Phi^{\nu}(E_{\nu}) P_{osc}^{\nu \to \nu'}(E_{\nu}) \frac{d\sigma^{\nu'}}{dE_{\nu}} dE_{\nu}$$

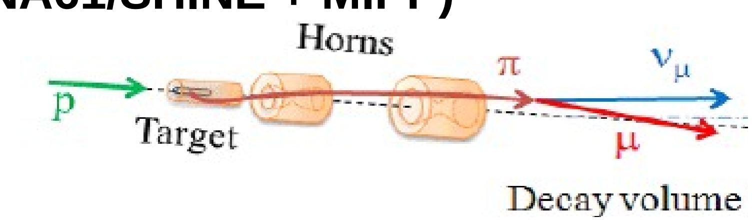
~same flux at ND and FD

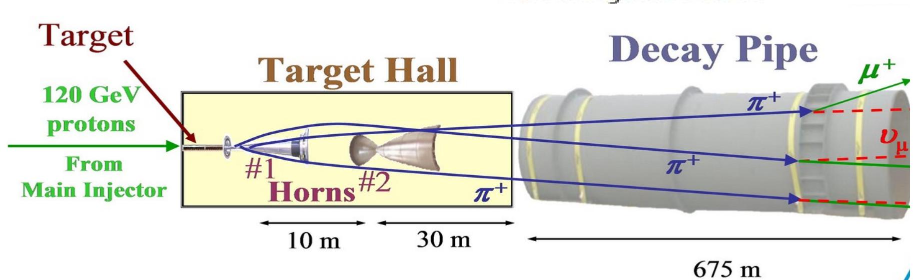
what we want to measure:
oscillation probability

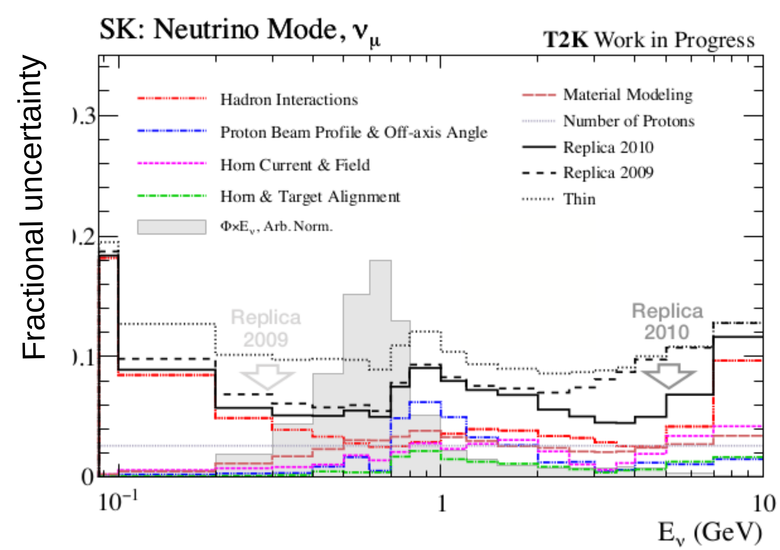
cross-section must be extrapolated from ND to FD:
- different neutrino energy distribution
- ND measure flux times xsec

Need nuclear theory models!

Flux simulation and tuning (NA61/SHINE + MIPP)







Near detectors and nuclear theory

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$$R_{ND}^{\nu'} = \int \Phi^{\nu}(E_\nu) \frac{d\sigma^{\nu'}}{dE_\nu} dE_\nu$$

$$R_{FD}^{\nu'} = \int \Phi^{\nu}(E_\nu) P_{osc}^{\nu\rightarrow\nu'}(E_\nu) \frac{d\sigma^{\nu'}}{dE_\nu} dE_\nu$$

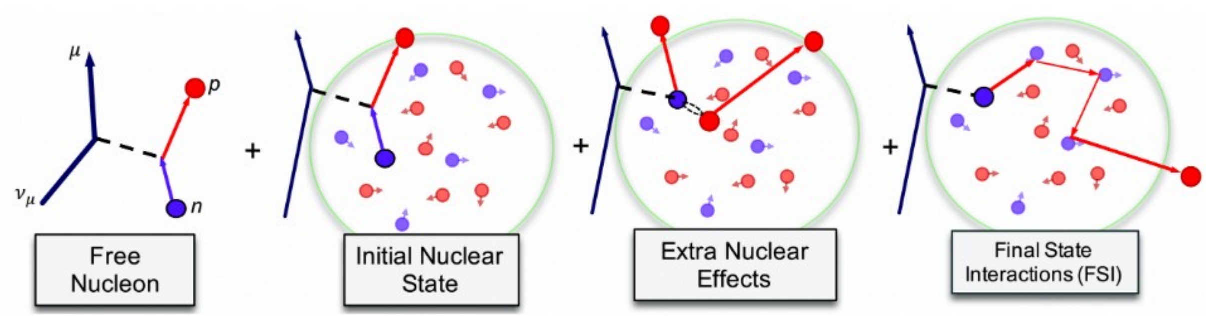
~same flux at ND and FD

what we want to measure: oscillation probability

cross-section must be extrapolated from ND to FD:
- different neutrino energy distribution
- ND measure flux times xsec

Need nuclear theory models!

ν-nucleus interaction modeling and tuning



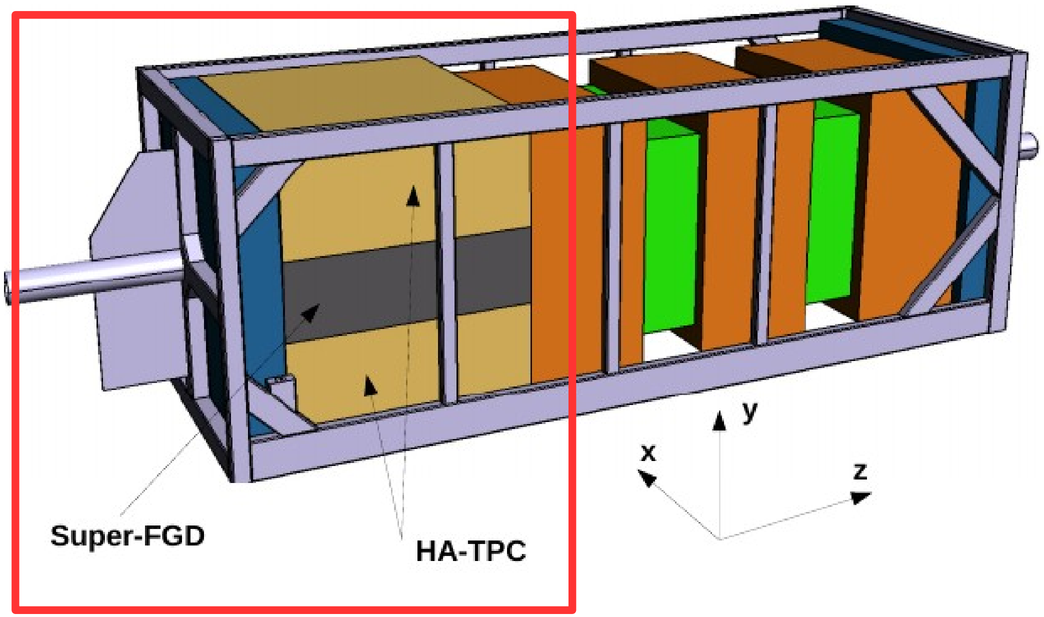
(and similarly for pion(s) production)

- Nuclear theory
- External data (eg e-scattering)
- ν-nucleus xsec measurements at near detectors and dedicated experiments (Minerva, ArgoNeuT, ..)

→ fundamentally the name of the game: precise Eν reconstruction

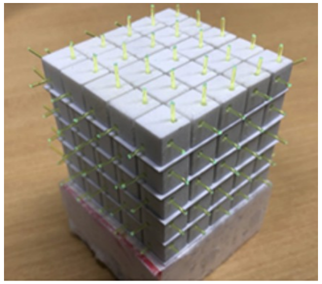
New generation of near detectors

- T2K is preparing an **upgrade of ND280** to be installed in 2022 to cope with increased statistics after beam upgrade and for HyperKamiokande



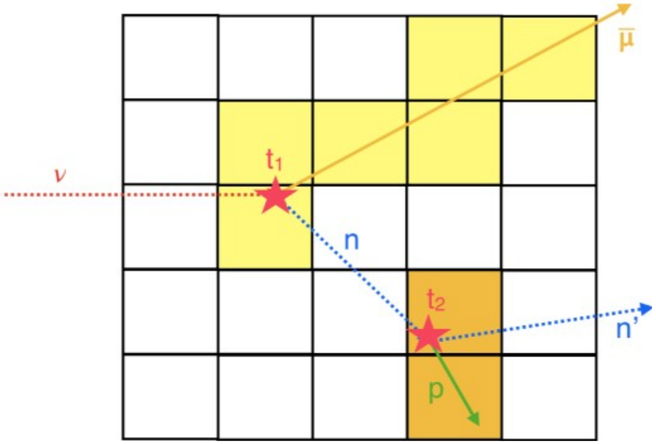
Horizontal TPCs to enlarge angular acceptance

Scintillator with 3D track reconstruction capabilities



→ low threshold on proton, pion momentum

→ measurement of neutrons with ToF



- Full **exclusive reconstruction of final state for best neutrino energy 'reconstruction'** from outgoing interaction particles

→ for the first time neutron reconstruction event by event!

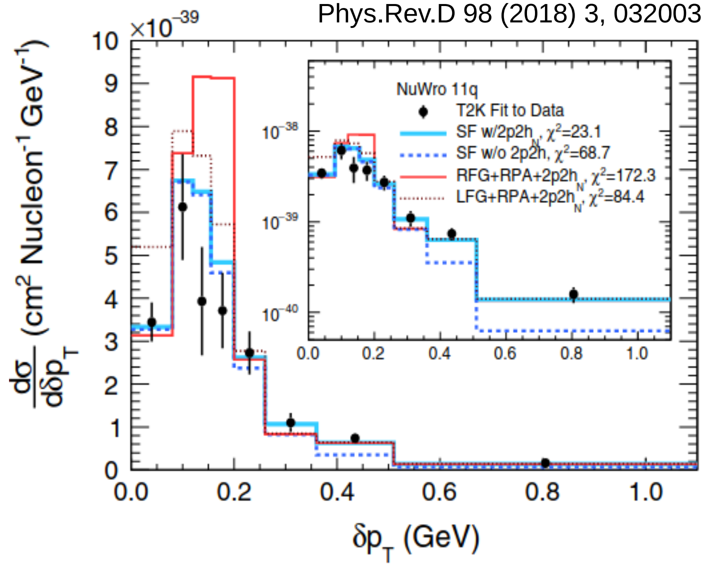
- **Similar design also under consideration for SAND DUNE near detector:**

→ enabling to exploit complementarity of HK/DUNE beams and comparisons/combinations for model tuning

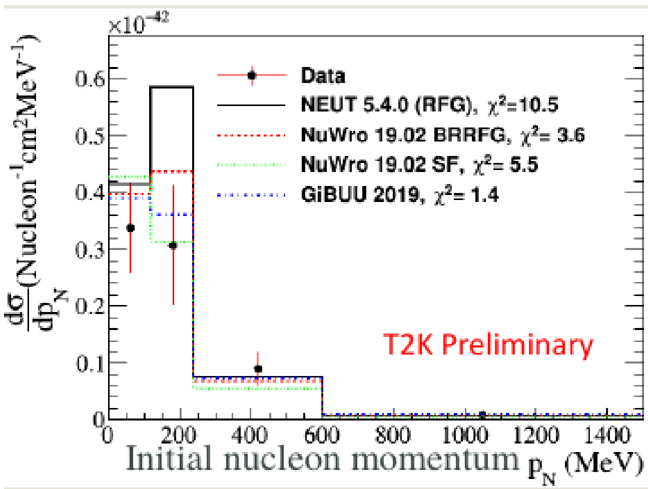
Opening the road...

- Hadron-muon transverse momentum unbalance for 'direct' measuring of nuclear effects
(ND280)

Phys.Rev.D 98 (2018) 3, 032003

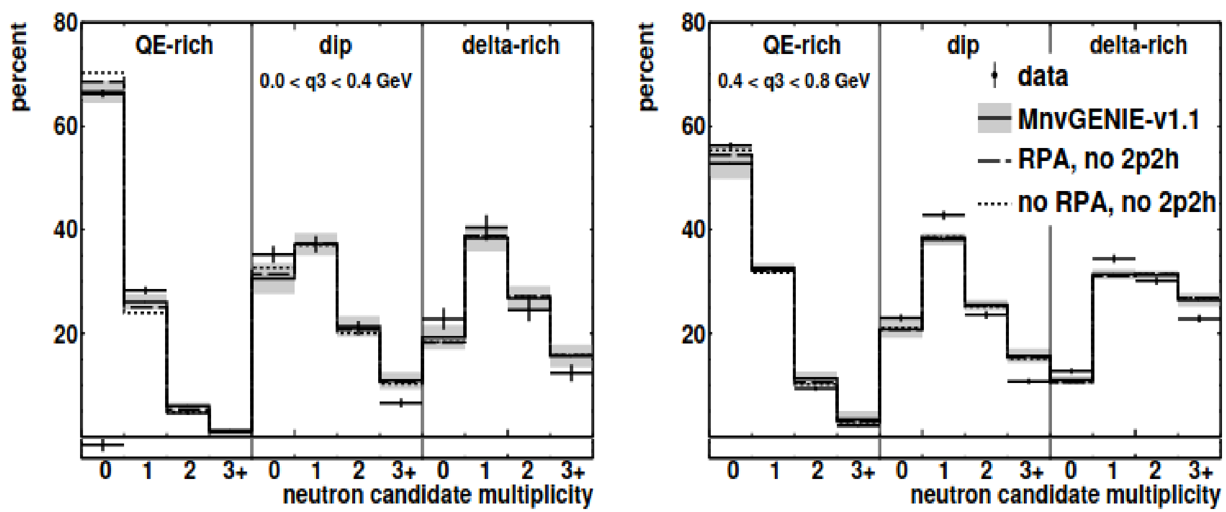


Phys.Rev.D 103 (2021) 11, 112009



- First usage of neutrons in neutrino-nucleus scattering
(Minerva)

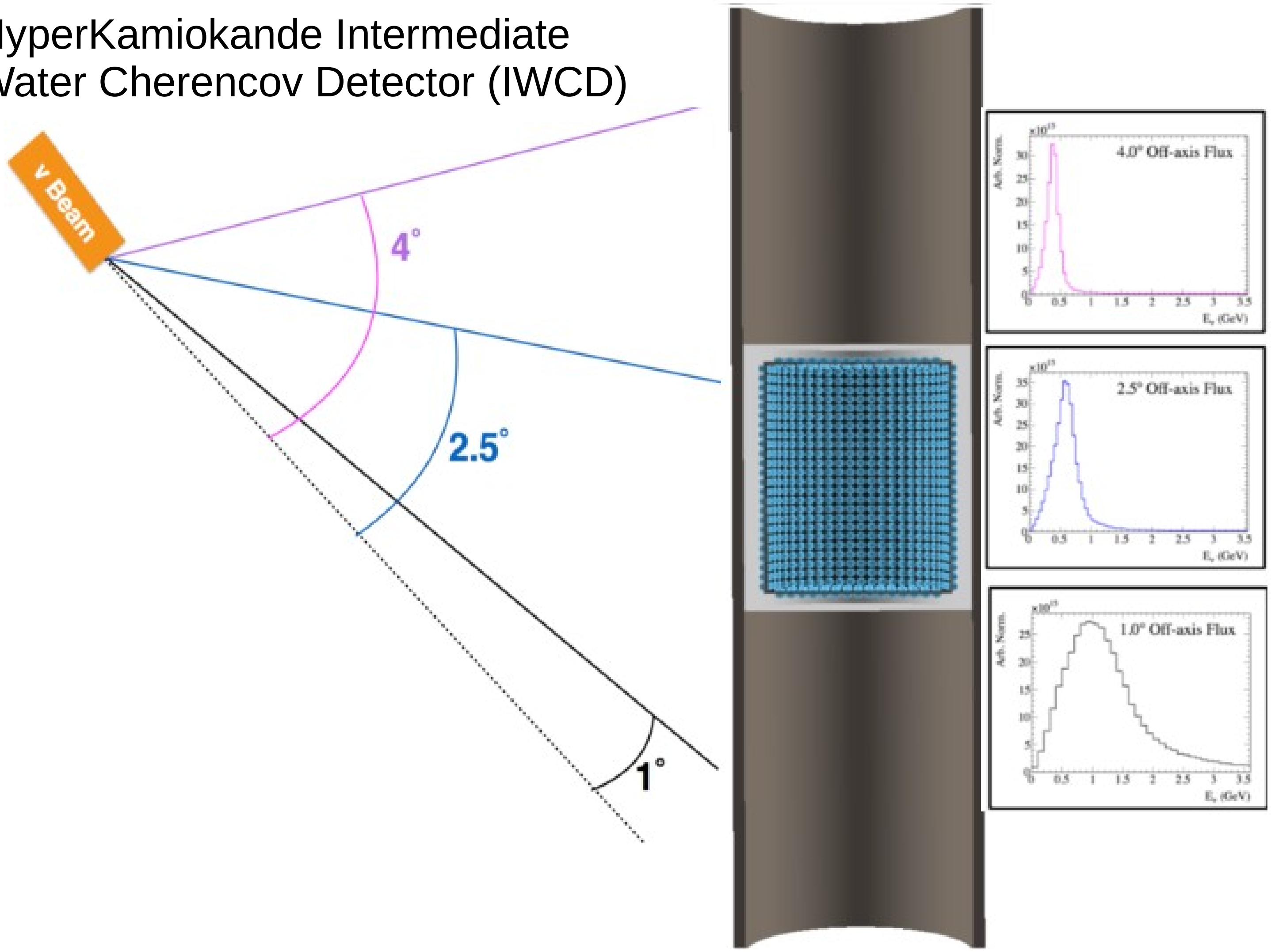
Phys. Rev. D 100, 052002 (2019)



New approach
to near to far extrapolation

Extract Eν dependence from off-axis angle

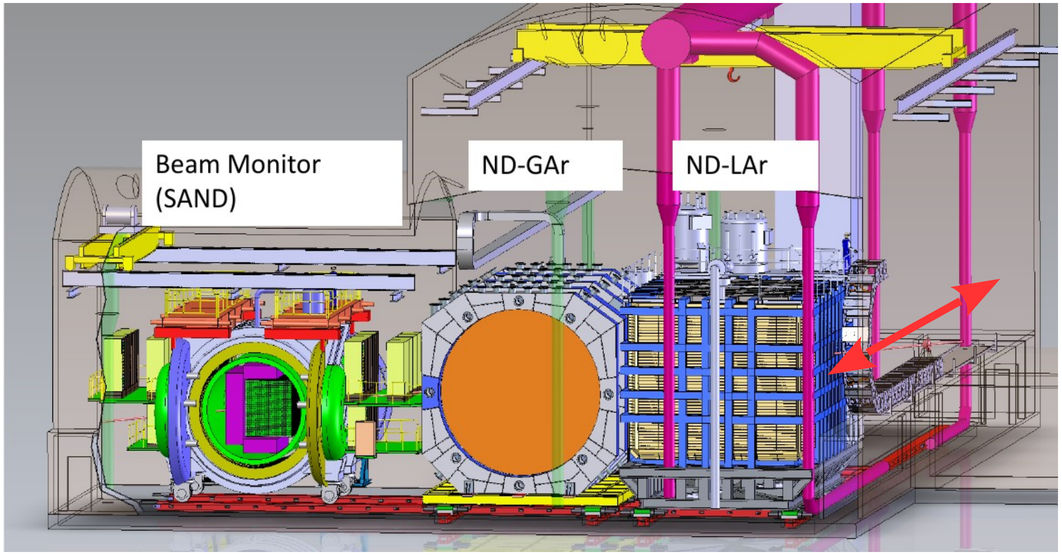
HyperKamiokande Intermediate
Water Cherencov Detector (IWCD)

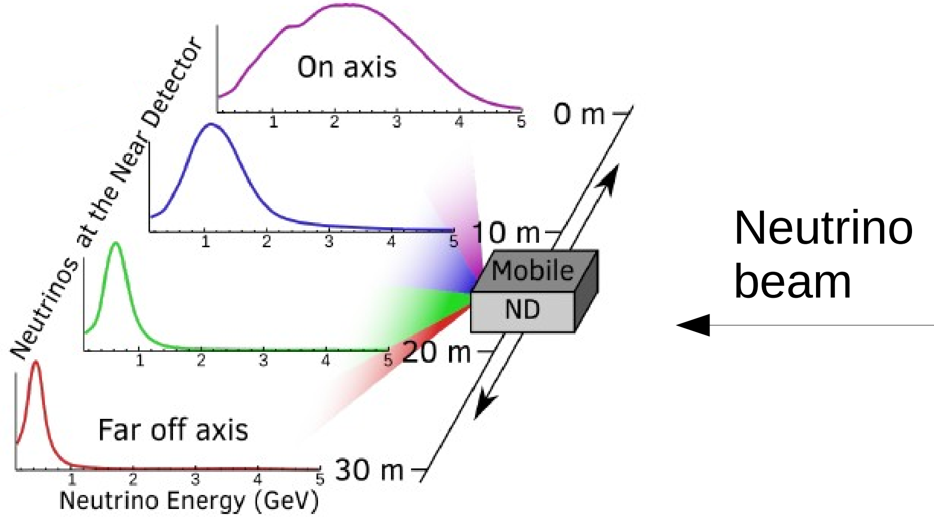


New approach to near to far extrapolation

Extract Eν dependence from off-axis angle

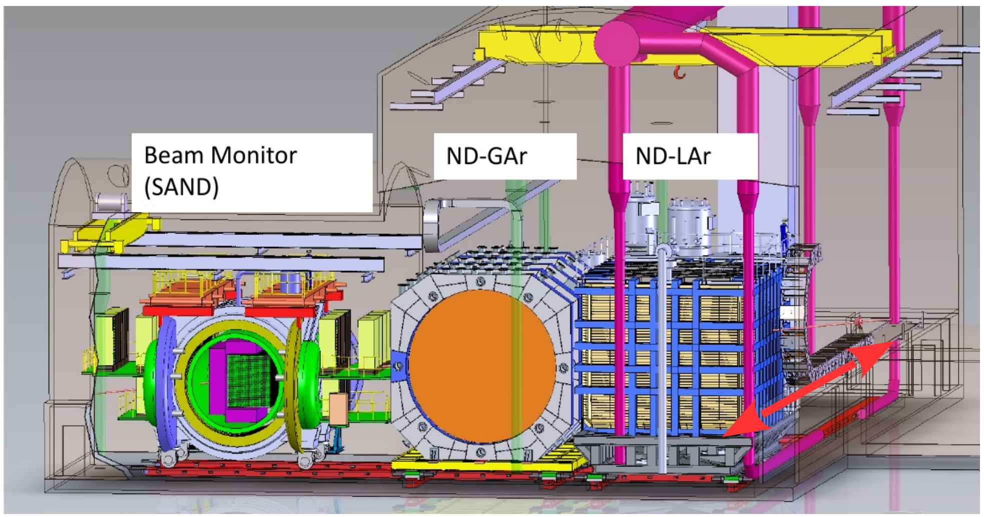
DUNE LAr and GAr TPCs as movable near detectors: DUNE-Prism

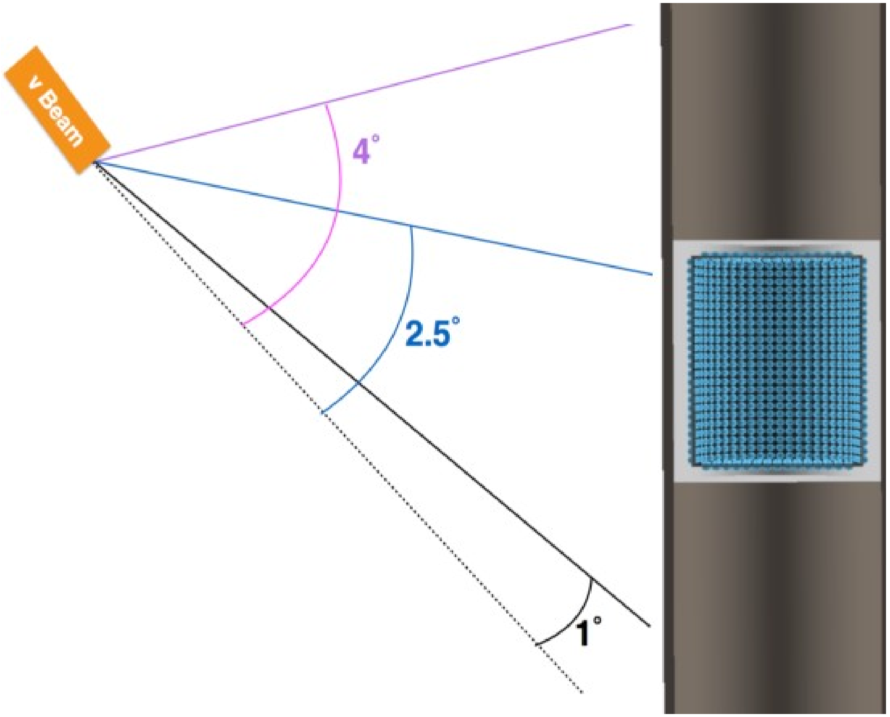




New approach
to near to far extrapolation

Extract Eν dependence from off-axis angle





- Nuclear-level systematics becomes 'second order'
→ quantification on-going (acceptance, finite statistics, ...)

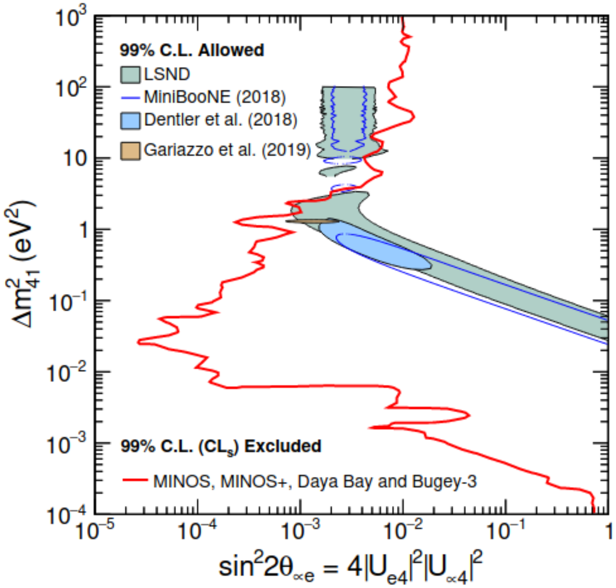
- Need to control well flux systematic uncertainties vs angle and flux stability vs time (DUNE SAND, T2(H)K INGRID)

- Movable ND are also **extremely useful measurement for ν_e cross-section** (first order systematics for CPV and MH) since ν_e / ν_μ change vs angle

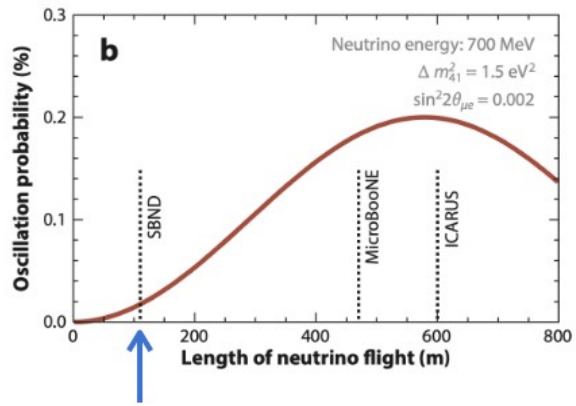
BSM surpises?

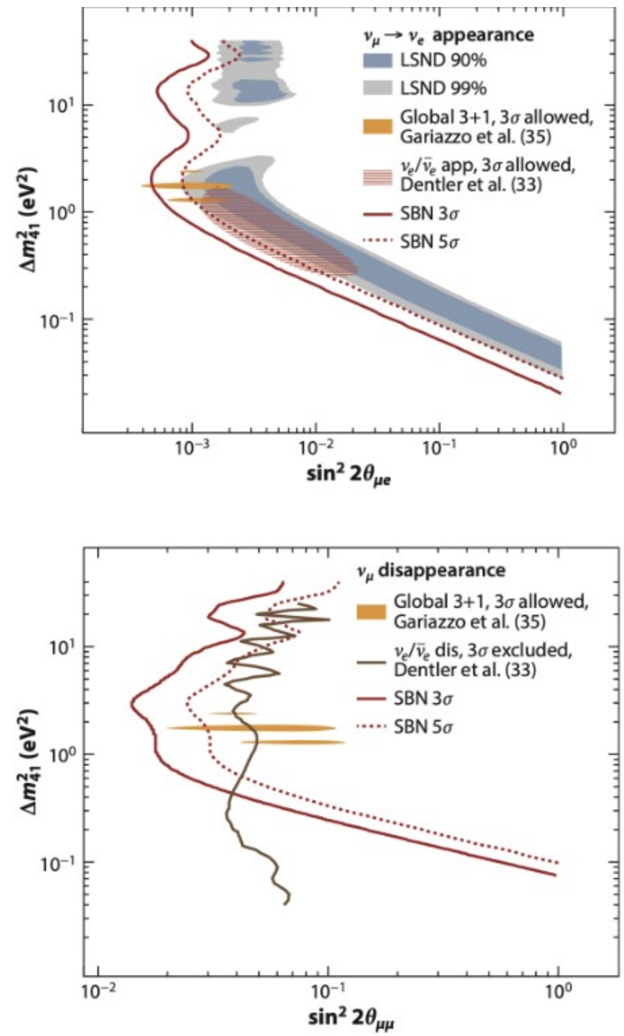
Steriles

MINOS/MINOS+/reactors results



Short Baseline Neutrino program at FNAL.
Sensitivity:



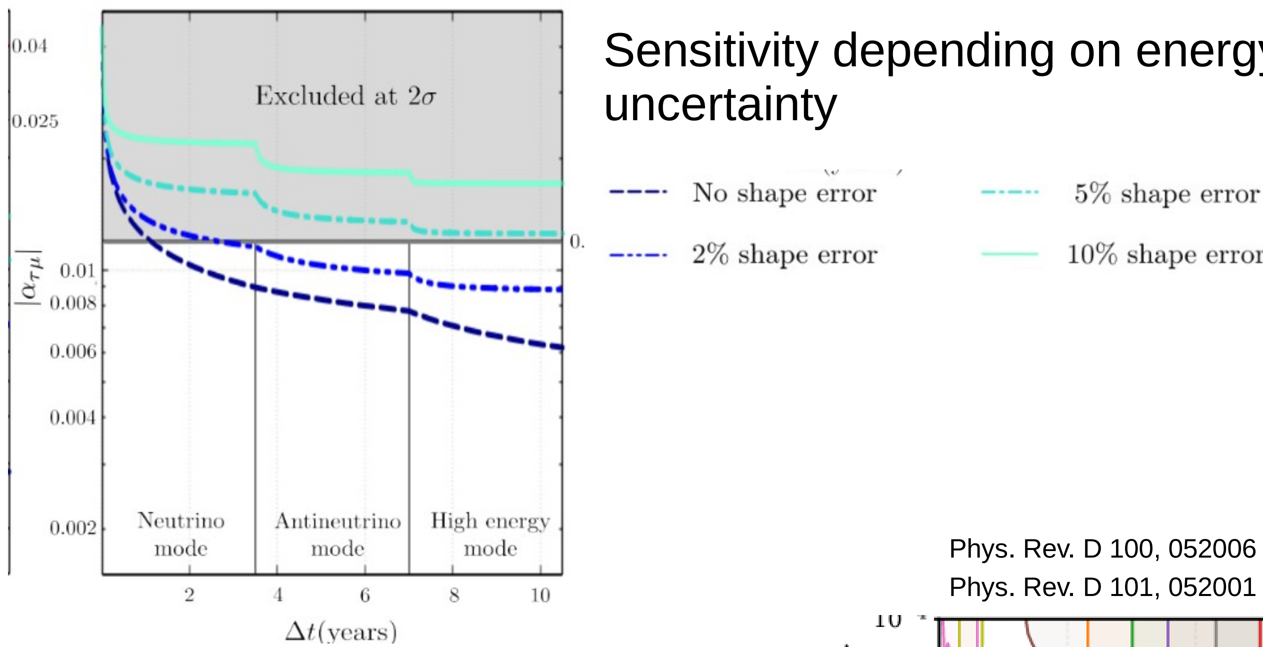


Annu. Rev. Nucl. Part. Sci. 2019 DOI 10.1146
(Reproduced from SBN Proposal assuming 6.6 E20 POT)

BSM surpises?

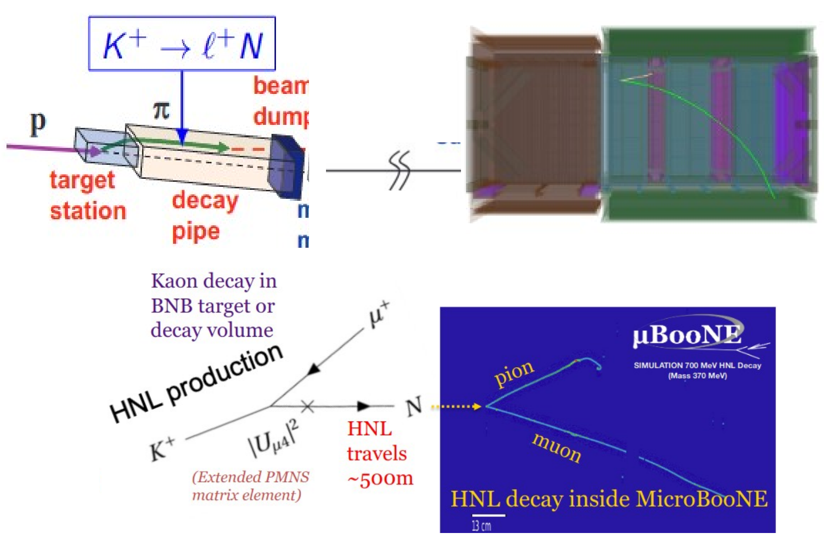
Steriles (of many different types) → inventive ways of use near detectors

- DUNE tau ν appearance at near detectors



Sensitivity depending on energy shape uncertainty

- HNL from K decays in the beam

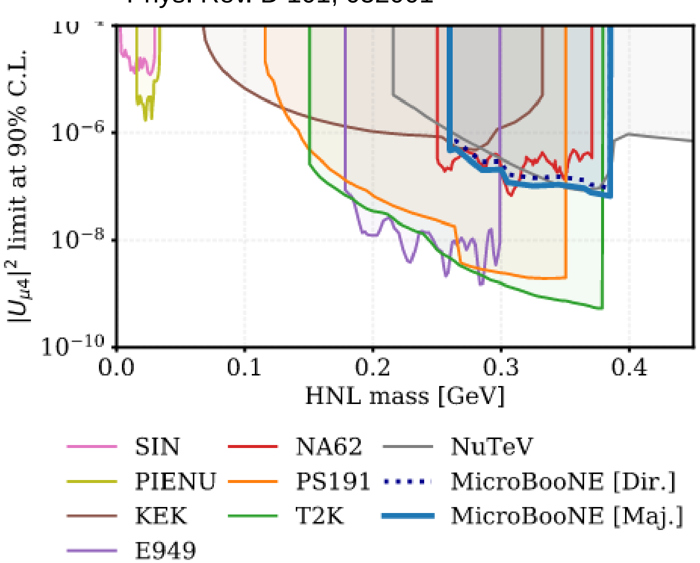


- ND280: decay of N in TPC gas volume (~no background)

- MicroBooNE: delayed N decays

Phys. Rev. D 100, 052006 (2019)

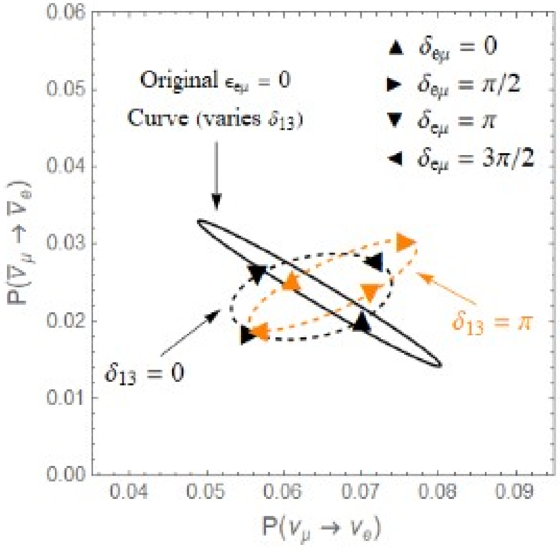
Phys. Rev. D 101, 052001



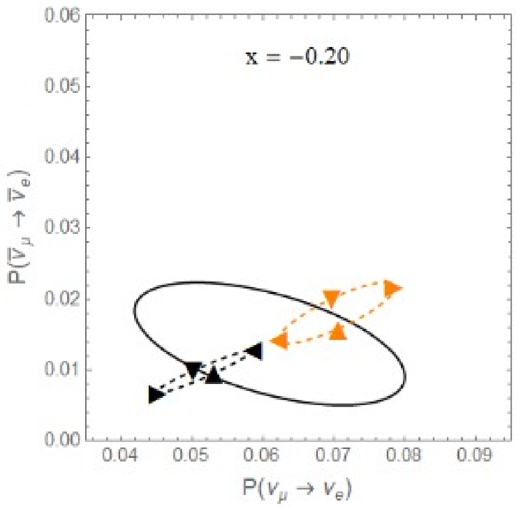
BSM surpises?

Non Standard Interactions: a door to new physics. (And more: CPT-violation, ...)
Need to able to disentangle from “standard” oscillation effects

Eg: new sources of CP-violation in NSI from non-diagonal terms in matter potential



moving to different (L/)E



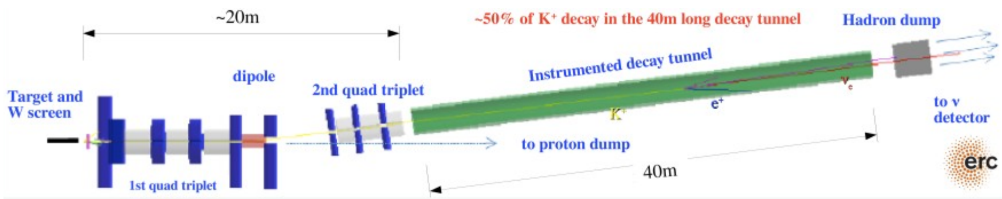
CIPANP 2018, Print:1809.11128 [hep-ph]

- **complementarity of DUNE and HK: different baselines, different energy** (atmospherics vs beam)
  - should be investigated more even in the framework of control of systematic uncertainties in “standard” oscillation measurements!

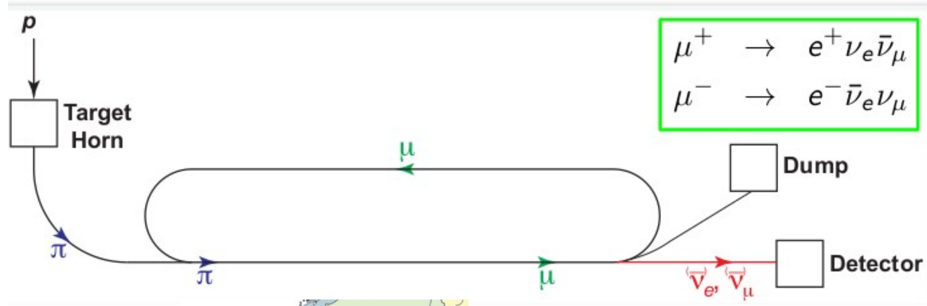
New ideas and new facilities

- **Improved beams for more precise control of neutrino flux**

  - EνBET: instrumented decay tunnel for precise (1%) measurement of ν_e from K decays



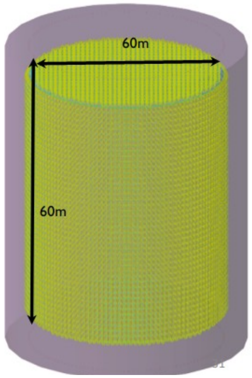
  - νSTORM: muon storage ring giving very well known ν_e and ν_μ fluxes (R&D toward Neutrino Factories)



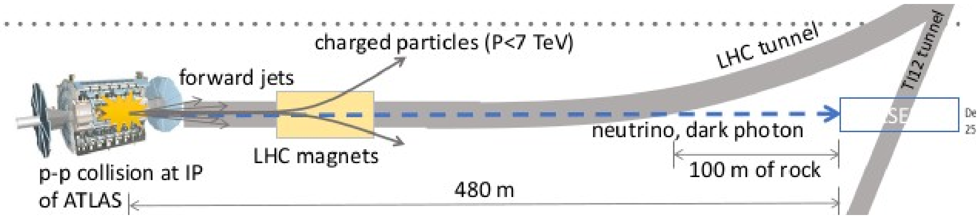
  - ESSνSuperBeam: 2nd oscillation + HIFI (demonstrator for low energy νSTORM)

- **Next-to-next generation detectors:**

  - THEIA: water based (doped) optical detector for comprehensive neutrino program (scintillation + Cherenkov)



- **Neutrinos at LHC: FASER** in forward region after defocusing charged particles → Eν~TeV



Summary

- Oscillation measurements made the cover of Nature in April 2020 with a statistically limited measurement: join us for interesting physics ahead!

- Neutrino oscillation physics with "neutrino beams" entering the precision era with NOVA and T2K → next generation experiments are worldwide efforts comparable to collider experiments

- Next generation of experiments (DUNE, HK) relies on control of systematics at % level → crucial role of near detectors: a new generation coming

  - **T2K and NOVA** are opening to road to exercise new near detectors, new analyses techniques, …

  - … long term work in collaboration with **nuclear theory community**

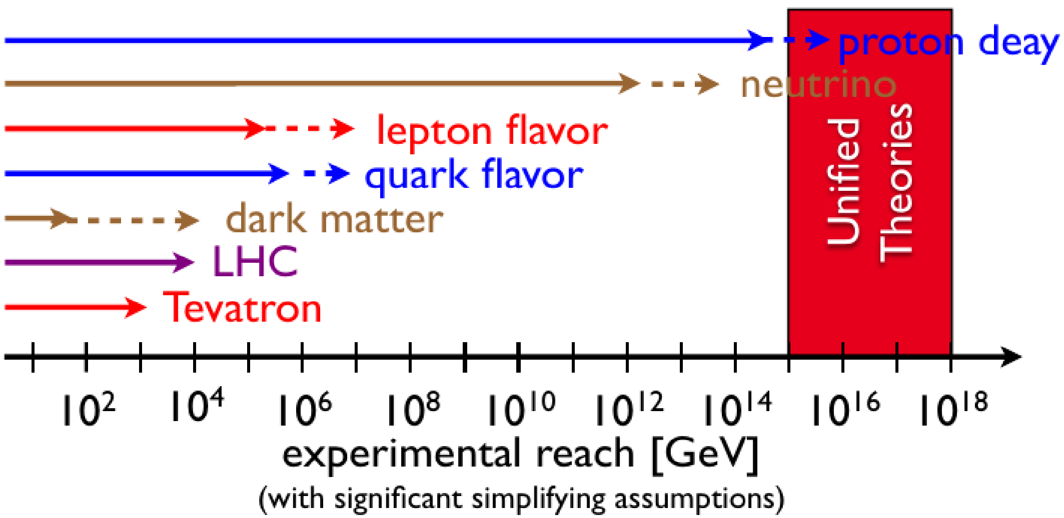
  - Important **R&D** involved (CERN Neutrino Platform)

- A vibrant community ready to react to the 'unexpected': new systematics and/or BSM signs → **inventive in the usage of near detectors and in the exploration of complementarity between HK and DUNE**

BACK-UP

Why?

+ Similarly, to the discovery of Fermi scale with nuclear β-decays, we are now on a **fishing expedition to the next energy scale of the (necessary!) New Physics:**



H.Murayama @
Higgs workshop 2013
(arXiv:1401.0966)

Neutrino oscillation are sensitive to very tiny effects similarly to interferometry.
Unique tool to study very high energy scale (today $\Lambda \sim 10^{14}$GeV)

+ Search of **CP violation in the leptonic sector** (related with matter/antimatter asymmetry in the Universe)

Independently on model: a new fundamental source of CP violation!
→ **Major next discovery of HEP**

+ What is the **New Symmetry hidden behind the mass and flavour mixing?**

Neutrinos as door to New Physics

- **Expansion of Lagrangian in terms of NP energy scale (Λ_{UV}):** $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{UV}}\mathcal{L}_5 + \ldots$

  $\mathcal{L}_{SM}$ SM as effective theory valid until UV cutoff

$$\frac{1}{\Lambda_{UV}}\mathcal{L}_5 = \frac{v^2}{\Lambda_{UV}}\nu\nu. \qquad \frac{246^2}{10^{15}} GeV \approx 10^{-2} eV$$

The only 5th order operator possible according to fundamental symmetries: neutrino (Majorana!) mass is the first order effect of NP

→ **New type of fundamental particle**

→ Discovery of **lepton number violation** (accidental conservation in SM: no symmetry supporting it)

→ Naturally emerging in **leptogenesis scenarios to create matter/antimatter asymmetry**

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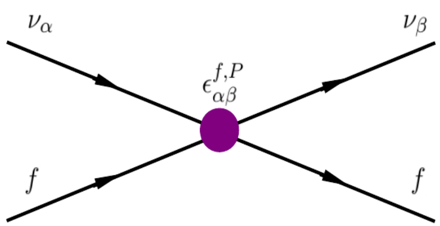
→ Discovery of **lepton number violation** (accidental conservation in SM: no symmetry supporting it)

→ Naturally emerging in **leptogenesis scenarios to create matter/antimatter asymmetry**

- Peculiar nature of n and being in direct contact with L_{UV}: natural to expect new type of interactions for neutrinos: Non Standard Interactions

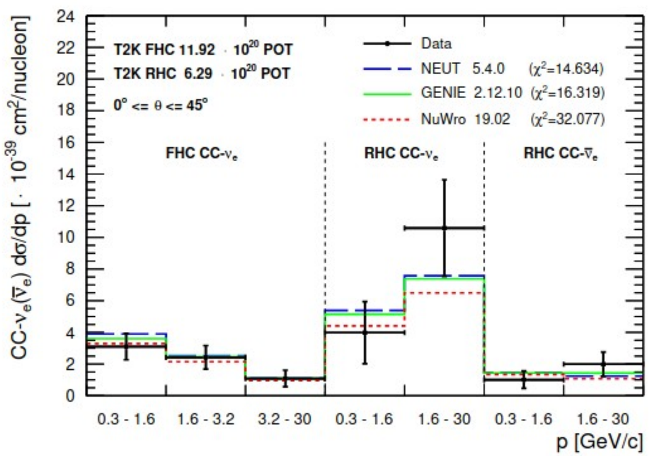


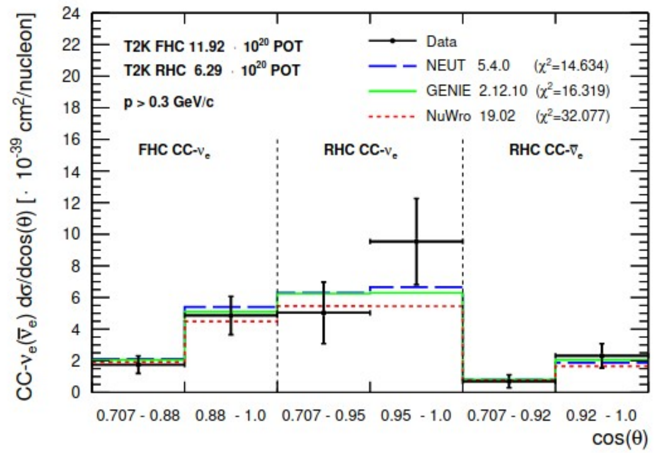
$$G_F \epsilon_{NSI} (\bar{\nu}\nu)(\bar{f} f)$$

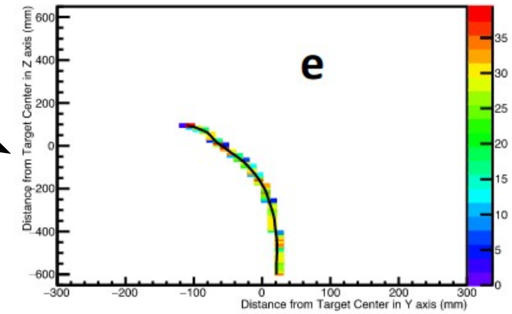
ν_e, $\bar{\nu}_e$ cross-section

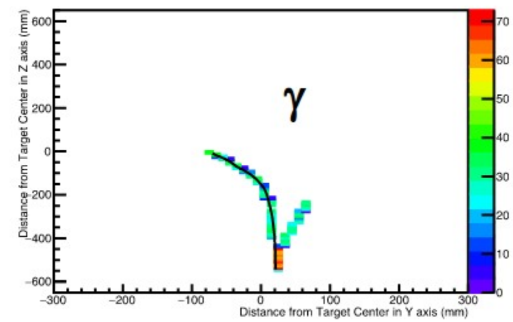
ND280 measurement → improvement with ND280 upgrade

JHEP 10 (2020) 114









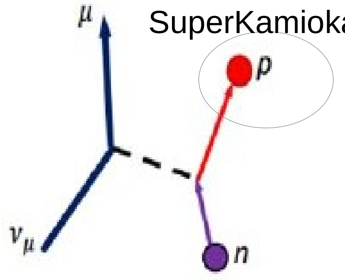
- Movable ND are also **extremely useful measurement for ν_e cross-section** (first order systematics for CPV and MH) since ν_e / ν_μ change vs angle

Neutrino energy reconstruction

T2K approach: evaluate neutrino energy from muon kinematics

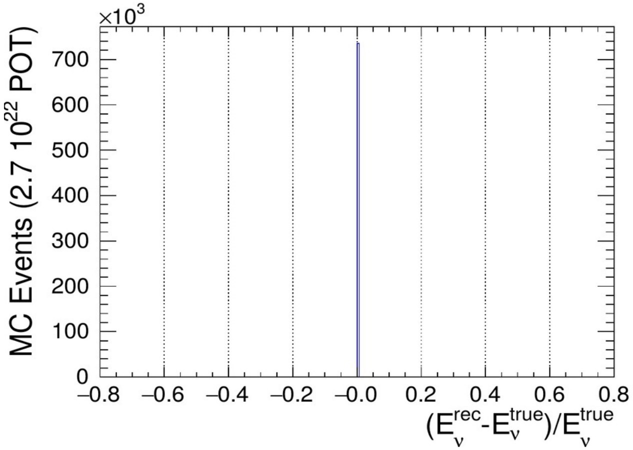
Charged Current Quasi-Elastic

Not observable at SuperKamiokande



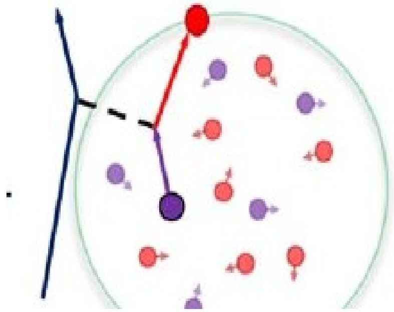
$$\overline{E_\nu} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Encalculated from muon only kinematics is a perfect estimator for elastic scattering on a free nucleon at rest



Neutrino energy reconstruction

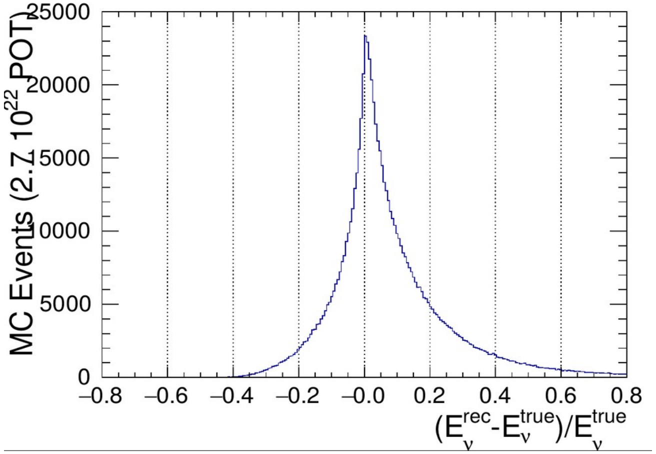
T2K approach: evaluate neutrino energy from muon kinematics



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

The motion of nucleons inside the nucleus (Fermi momentum) induces a smearing on E_n^{rec}

The energy lost in the nucleus (needed to extract the nucleon from its shell) induces a bias on E_n^{rec}



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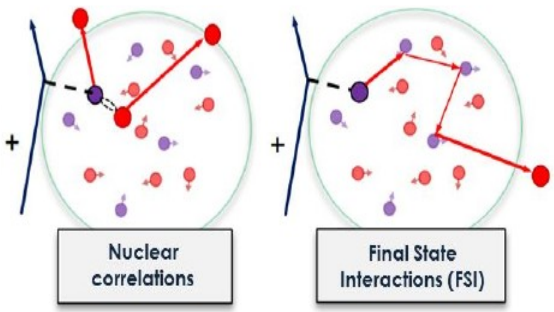
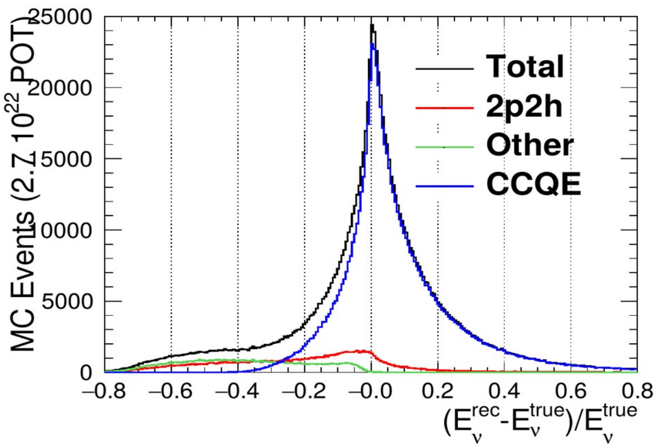


$$\overline{E_\nu} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

E_ν^{rec} is not a good estimator of true E_ν for non-CCQE events:

2p2h

Pion produced and reabsorbed



Present strategy: use inclusive measurements (muon only) at ND280 to constrain such effects

$$R_{ND}^{\nu'}(E_\nu) = \Phi^{\nu}(E_\nu)\frac{d\sigma^{\nu'}}{dE_\nu} = F(p_\mu, \cos\theta_\mu; \alpha_{ND}, \alpha_{model})$$

nuisances = parametrization of (detector systematics), flux and nuclear physics uncertainties

Reconstruction of energy at the far detector

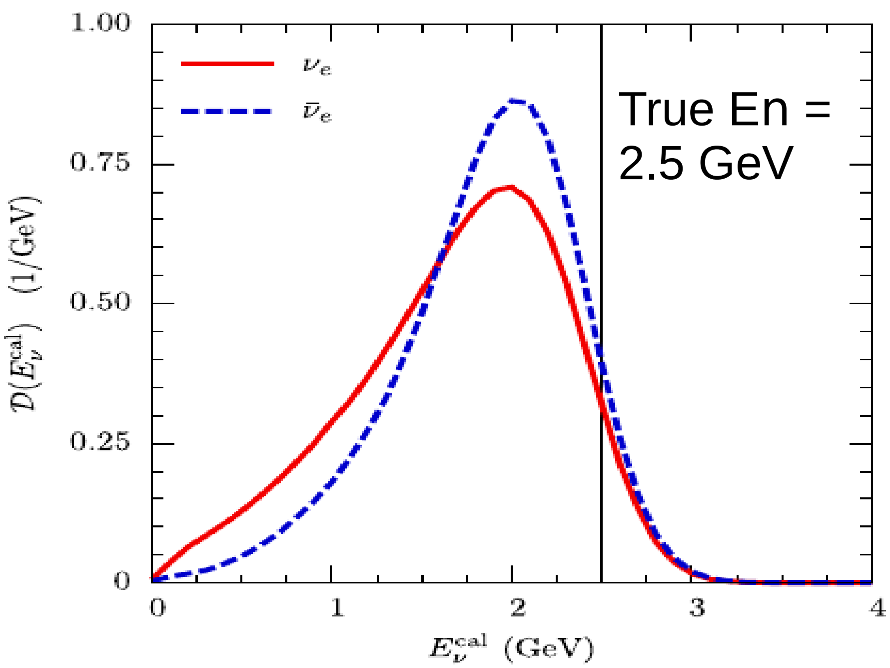
$$E_\nu = R(p_\mu, \cos\theta_\mu; \alpha_{FD}, \alpha_{model})$$

DUNE oscillation analysis

- Require very precise **shape** analysis of oscillated and unoscillated energy spectrum of neutrinos

- crucial to have good resolution on energy at near and far detector, especially for neutrinos and antineutrinos ($\nu/\bar{\nu}$ at core of δCP measurement)

J. Phys. G: Nucl. Part. Phys. **44** (2017) 054001



- Impact of missing energy on DUNE-like calorimetric energy reconstruction

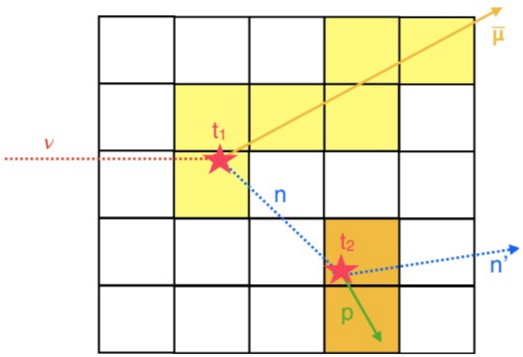
- Large contribution from nuclear effects (neutrons!) and entangled with detector calibration

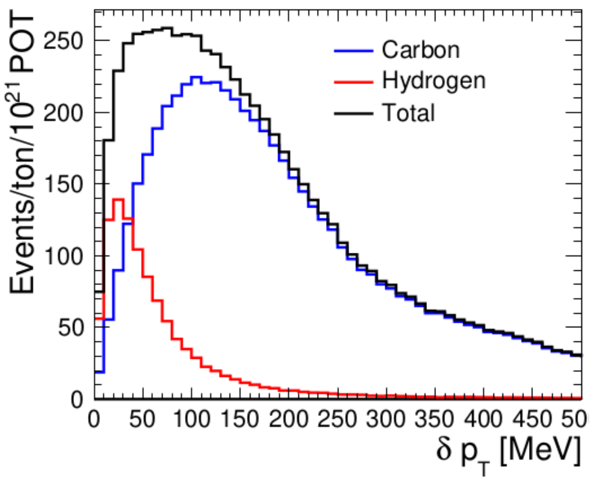
- Neutrons can bias $\nu/\bar{\nu}$ E_ν reconstruction since different neutron rate for $\nu/\bar{\nu}$ interactions

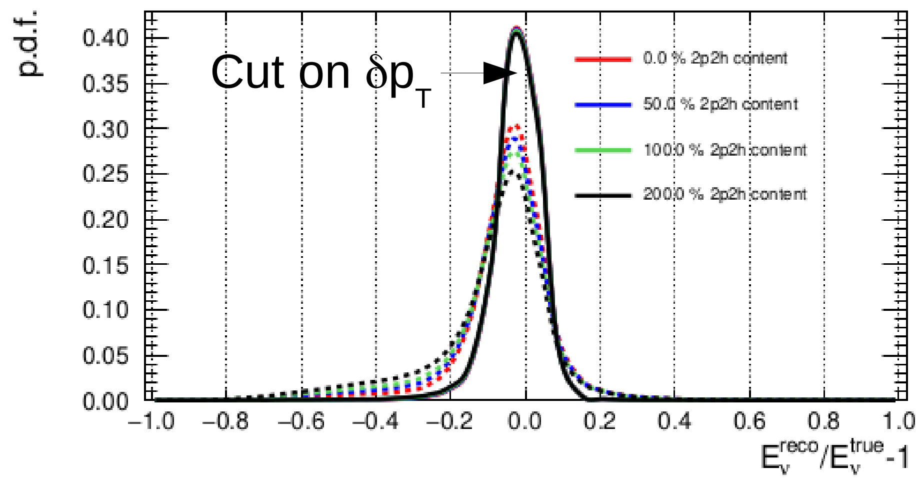
Isolating ν-H interactions

Measurement of neutrons from CH interactions inside the target of the main neutrino interactions

Phys.Rev.D 101 (2020) 9, 092003

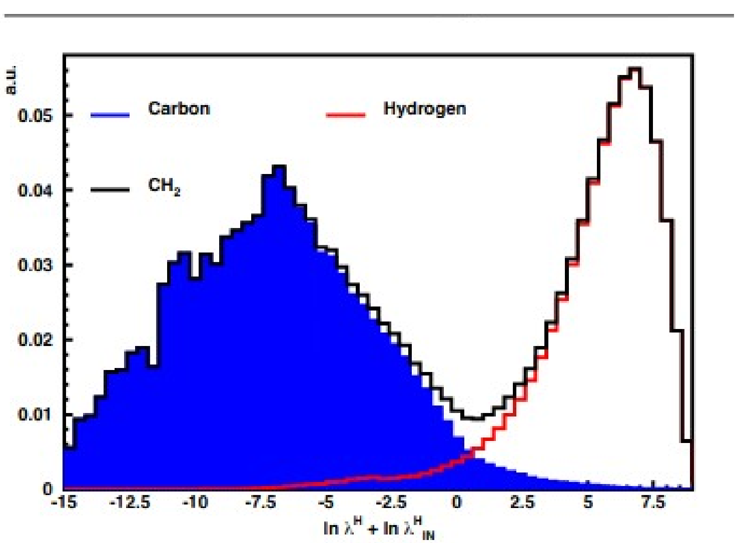


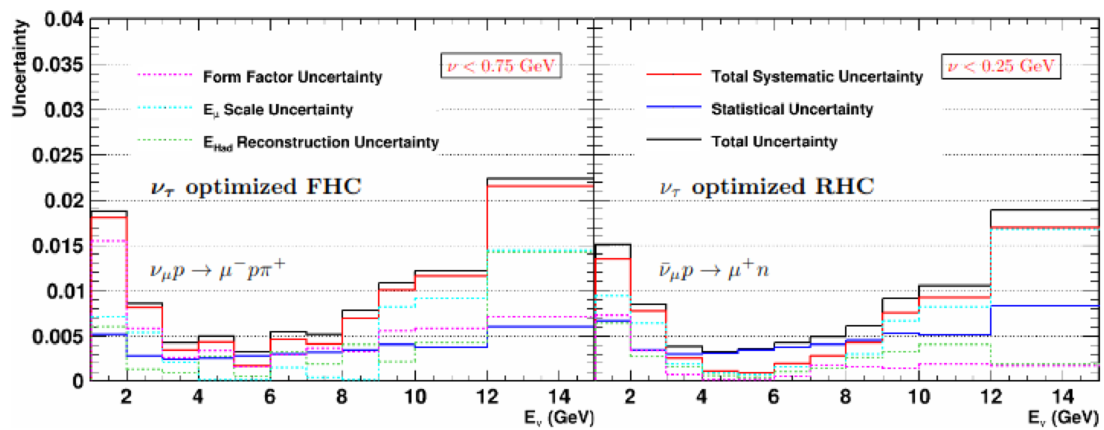




Subtractions analysis in C and CH with neutrino interactions on passive targets → neutron measurement in external electromagnetic calorimeter

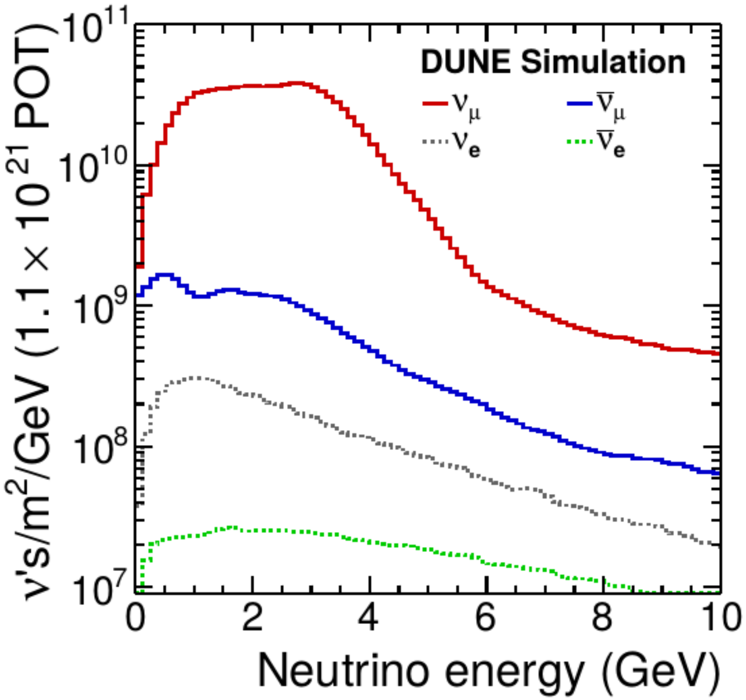
Phys.Lett.B 795 (2019) 424-431



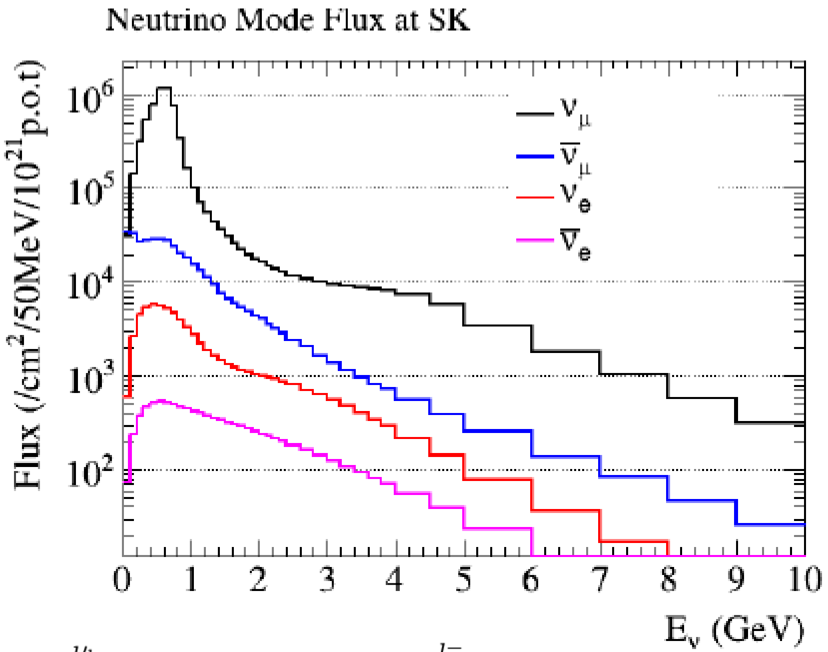


DUNE: beam

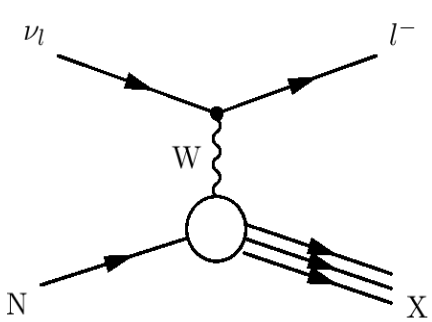
New wide-band neutrino beam at Fermilab: 1.2MW → 2.4MW

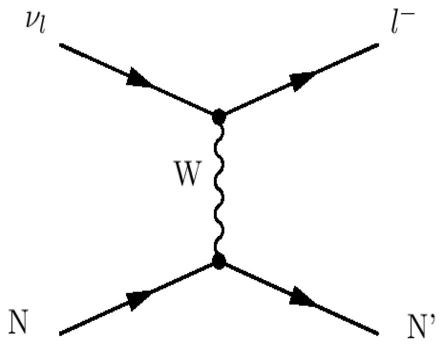


Comparison with T2K flux



Largest contribution from single and multiple pion production
→ **less known region in terms of nuclear physics modeling**



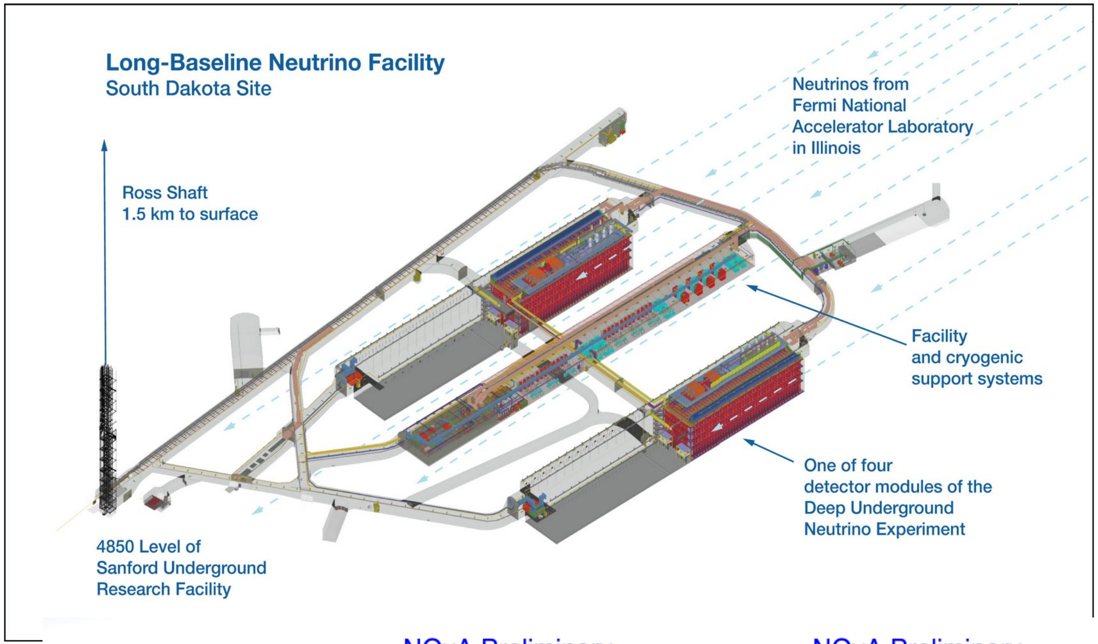


Dominated by 'simple' Quasi-Elastic interactions

Crucial role of near detectors !

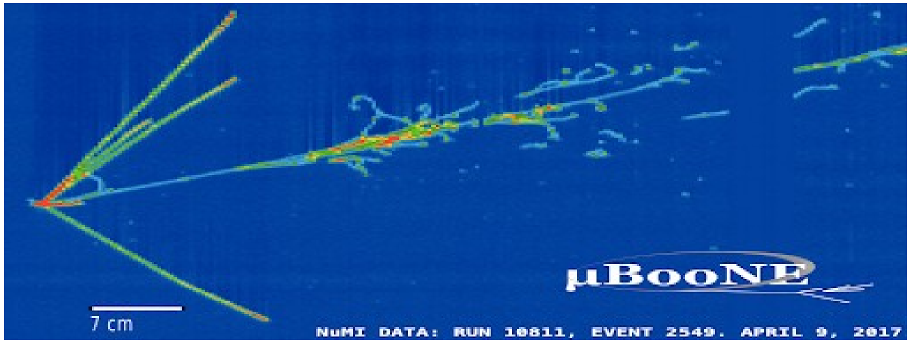
DUNE: far detectors

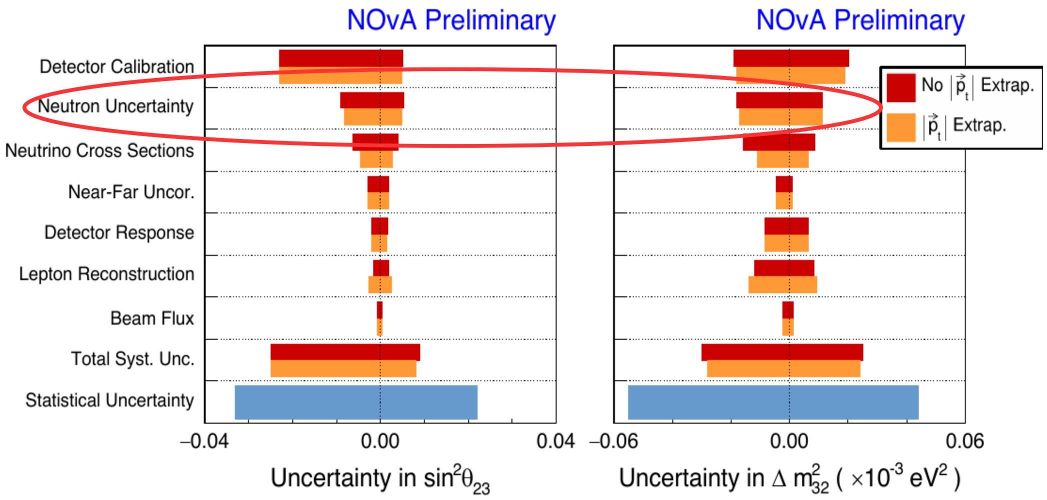
(Relatively) new technology to be deployed to unprecedented scale: huge LAr TPCs with charge readout



- **4 LAr TPC:** 4 x 10kTon fiducial mass. Staged approach (from 2029 to 2035)

- Full reconstruction of final state particles (~bubble chamber)



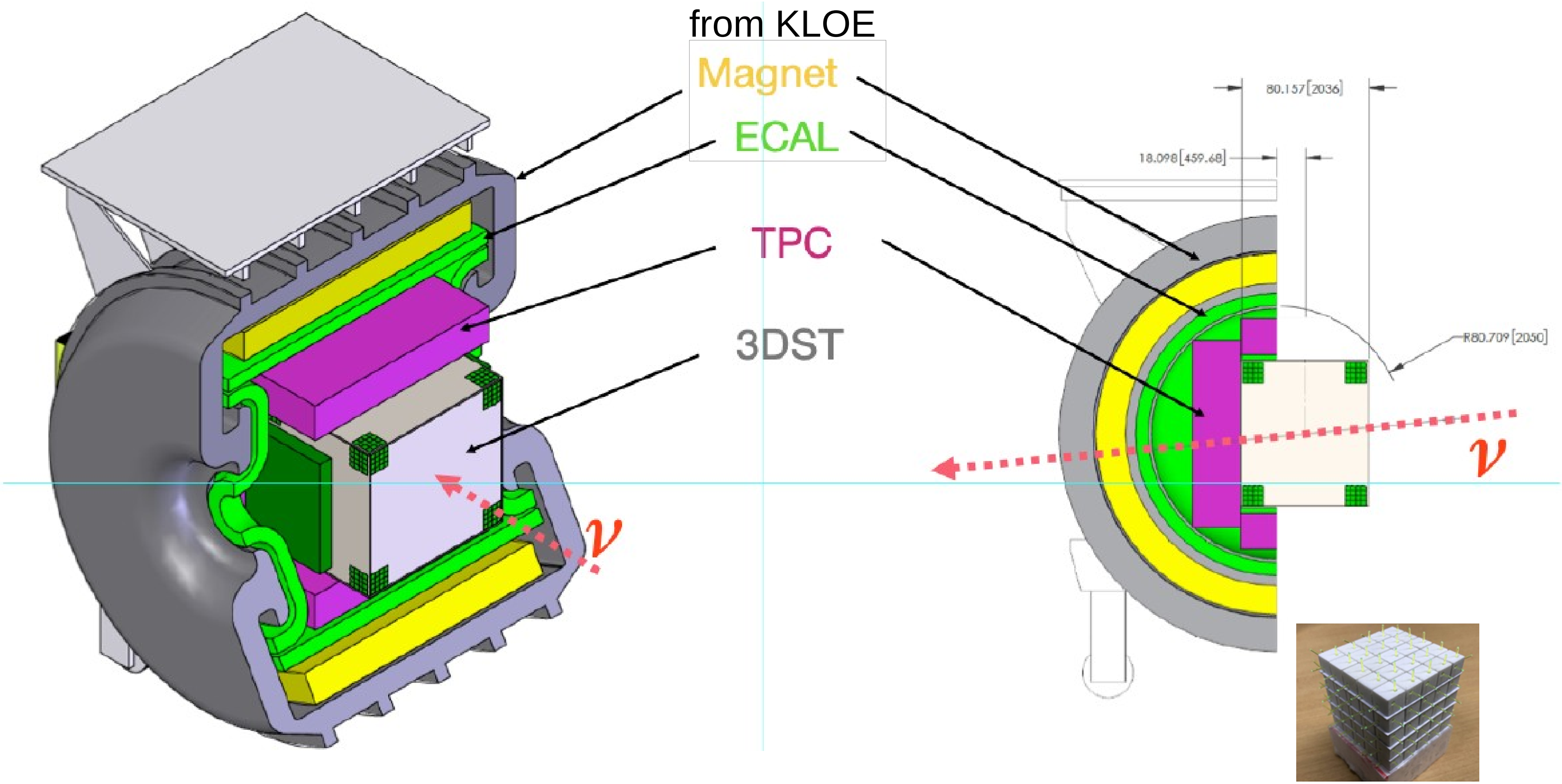


Except neutrons!

- **Argon target**: 'heavy' target with complex nuclear effects (eg nuclear transparency to protons 50%)

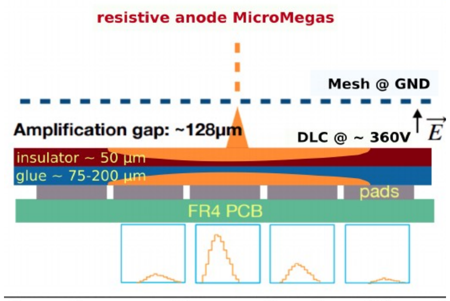
Crucial to measure new beam at "new" energy with known/"easy" nucleus (C)

SAND design: baseline

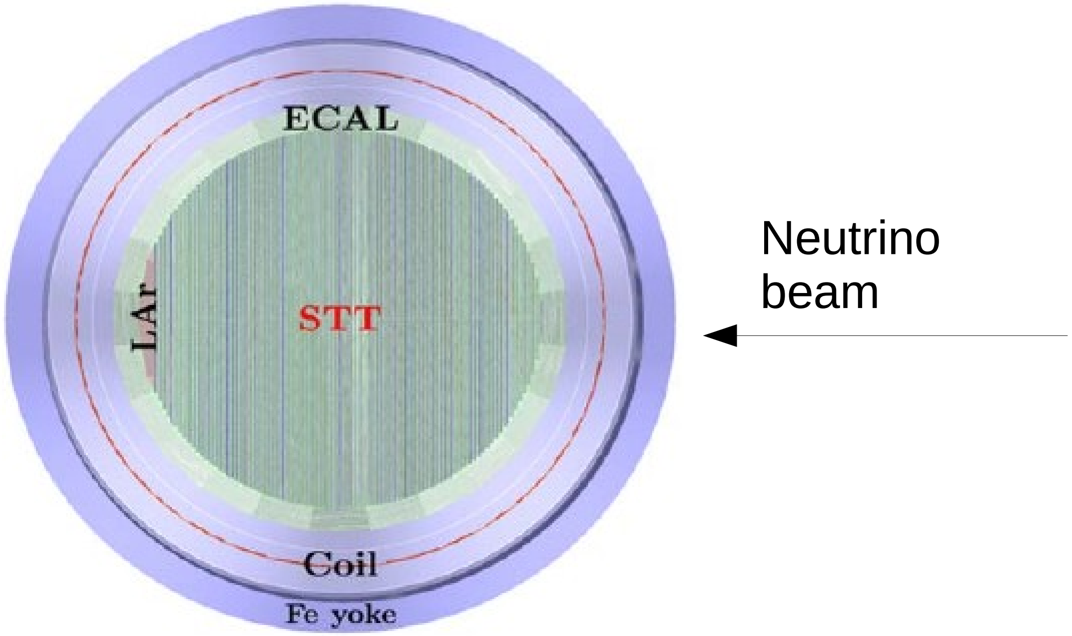


The ND280 upgrade design adapted to KLOE magnet+calorimeter:

- 3DST = 3D scintillator target composed of cubes with optical readout fibers (as superFGD)
- 3TPCs all around the 3SDT (top, bottom, downstream) based on resistive Micromegas technology



SAND design: alternative option

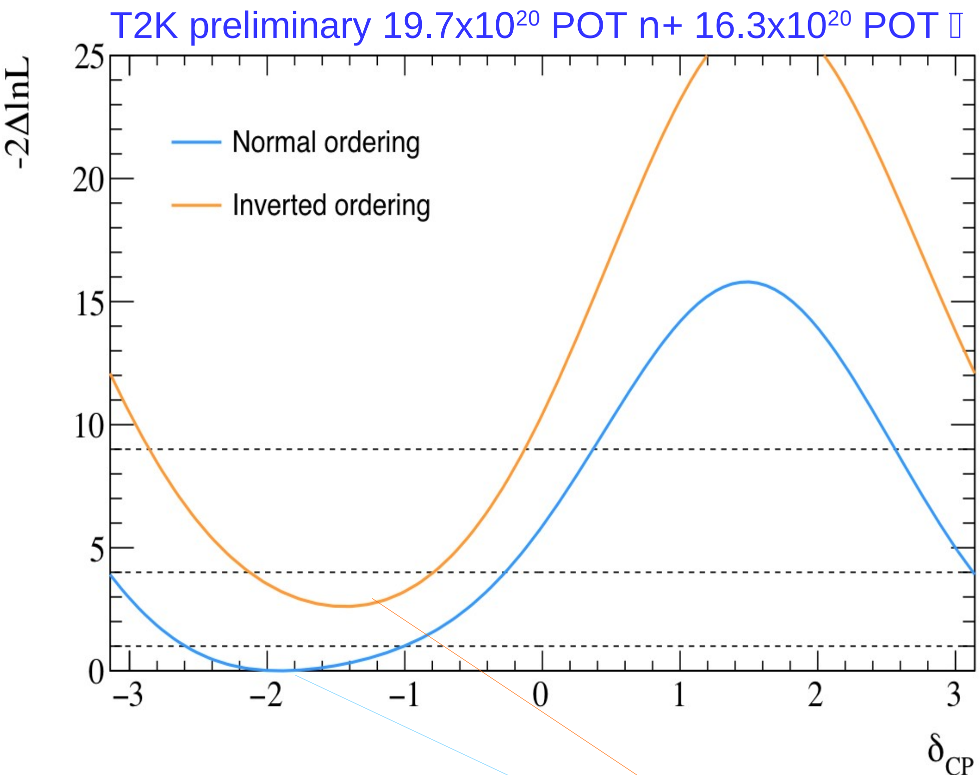


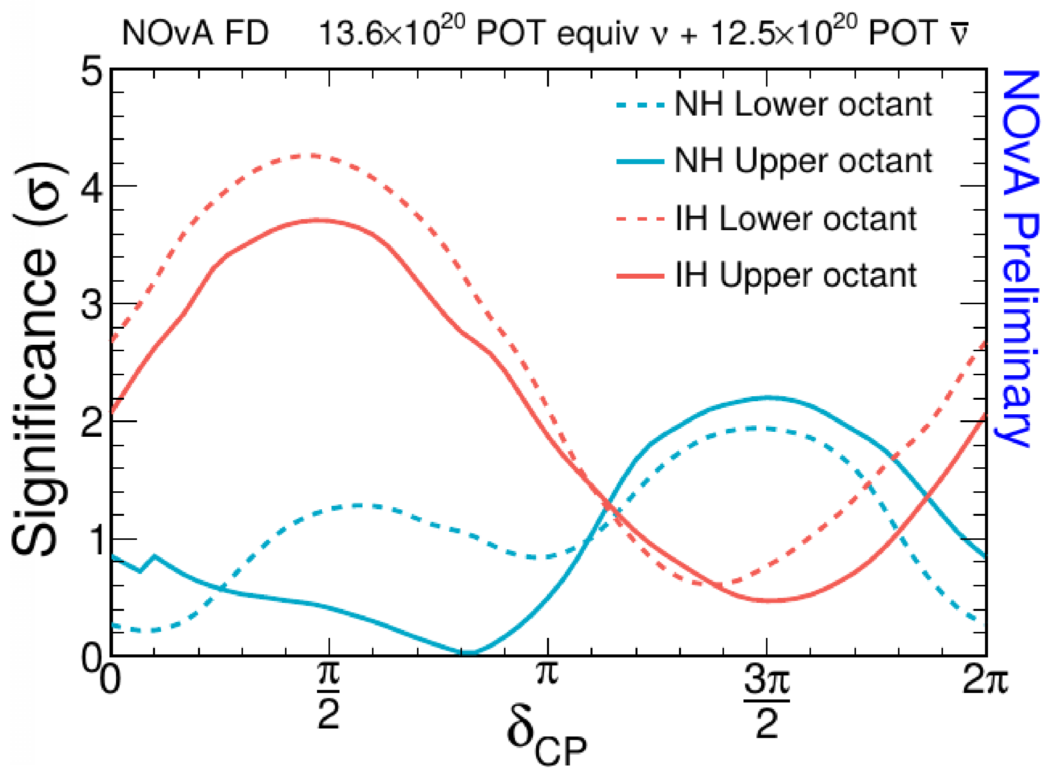
- **StrawTubes alternating with passive targets:**

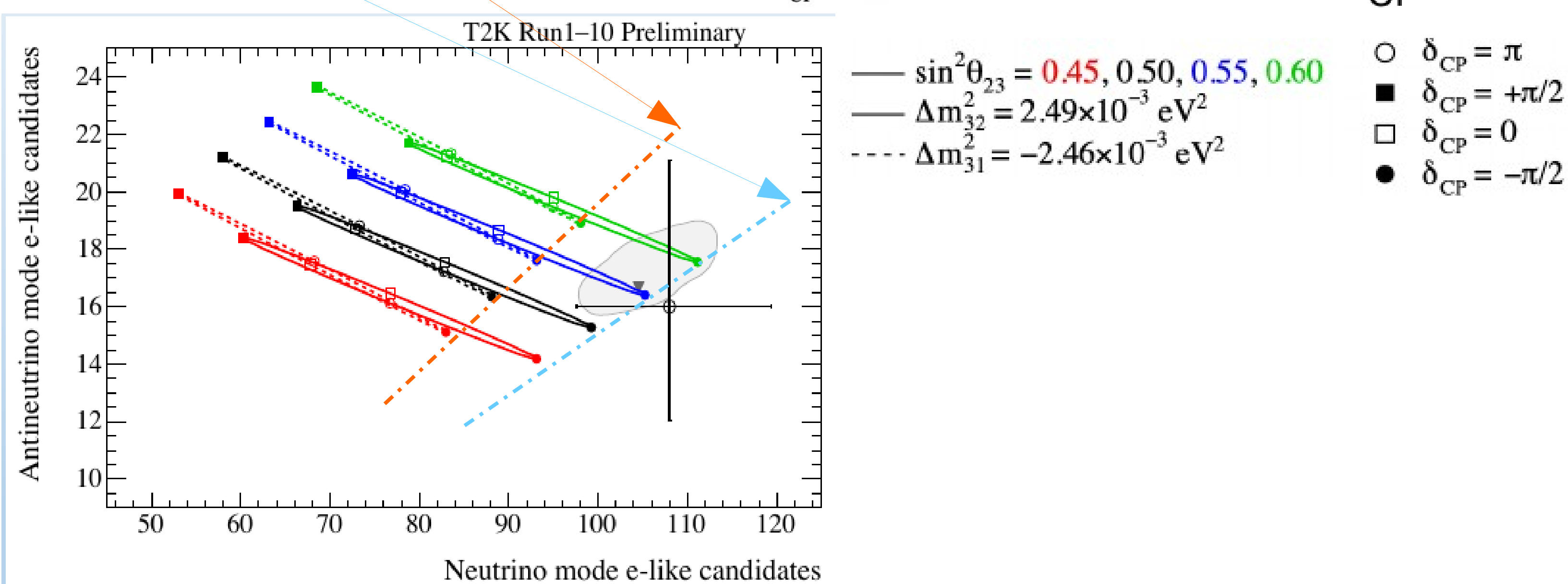
  - possibility to change nuclear targets to study nuclear effects (eg C, Fe,...)

  - possibility to compare C and C_8H_8 targets to extract events on H → measurement of flux with smaller nuclear effects

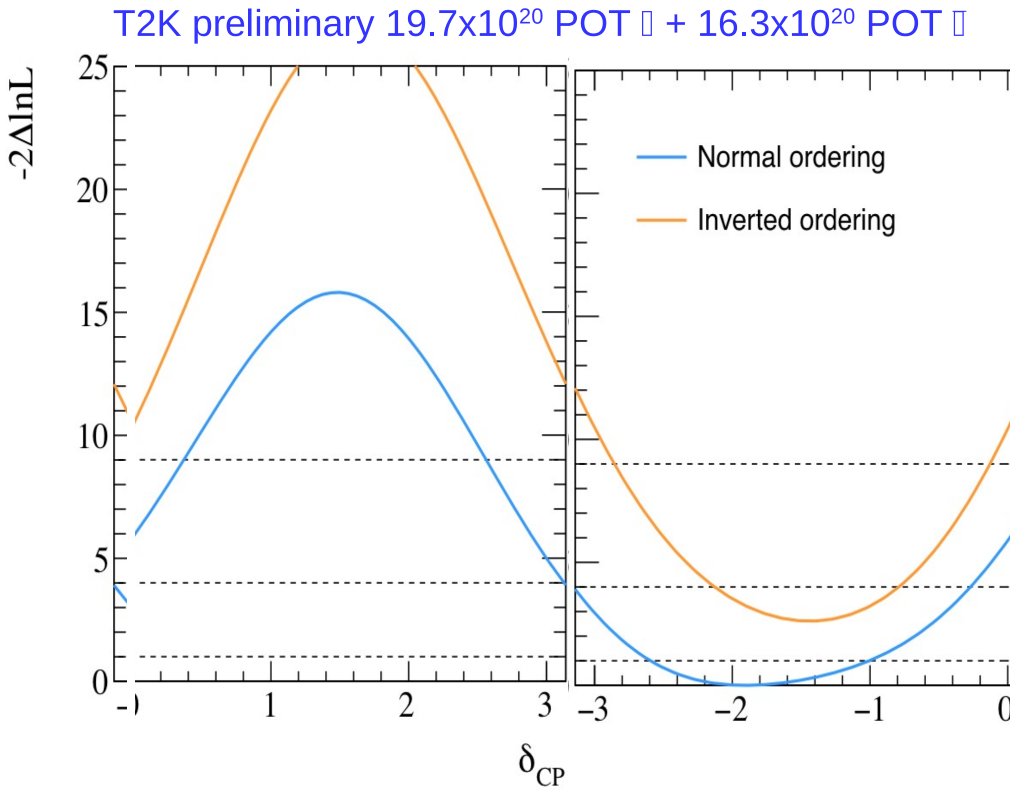
Results

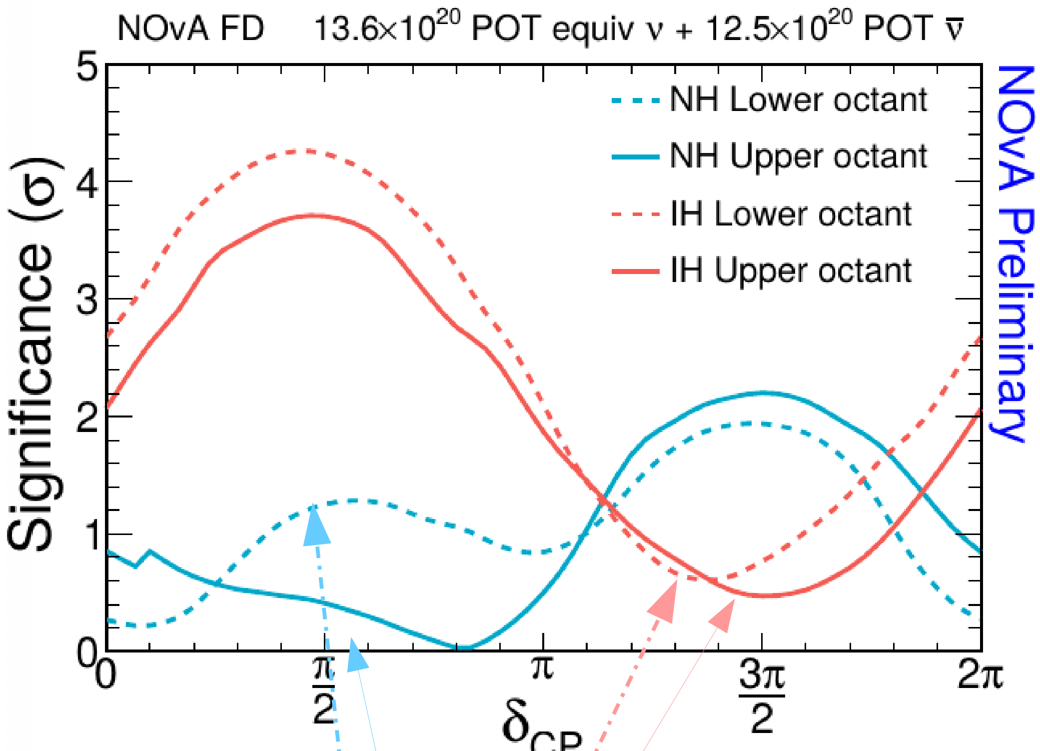

T2K preliminary 19.7x10^20 POT n+ 16.3x10^20 POT
-2ΔlnL
Normal ordering
Inverted ordering
δCP

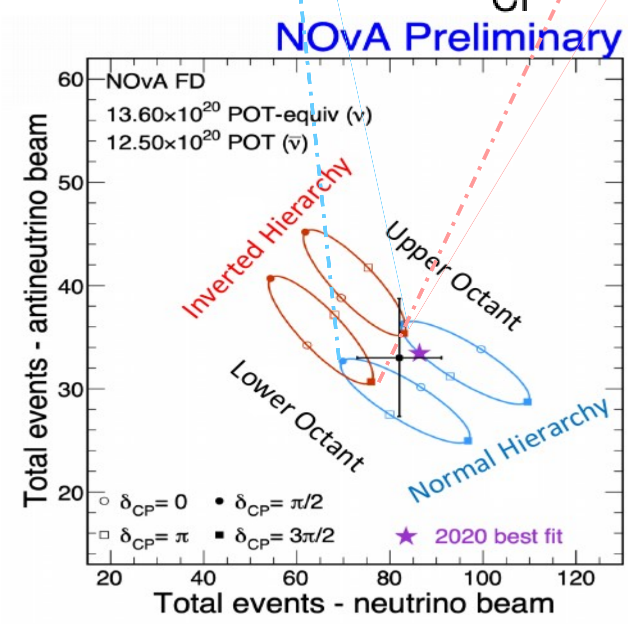

NOvA FD 13.6×10^20 POT equiv ν + 12.5×10^20 POT ν̄
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
NOvA Preliminary
Significance (σ)
δCP


T2K Run1–10 Preliminary
Antineutrino mode e-like candidates
Neutrino mode e-like candidates
sin²θ23 = 0.45, 0.50, 0.55, 0.60
Δm²32 = 2.49×10⁻³ eV²
Δm²31 = −2.46×10⁻³ eV²
δCP = π
δCP = +π/2
δCP = 0
δCP = −π/2

Results

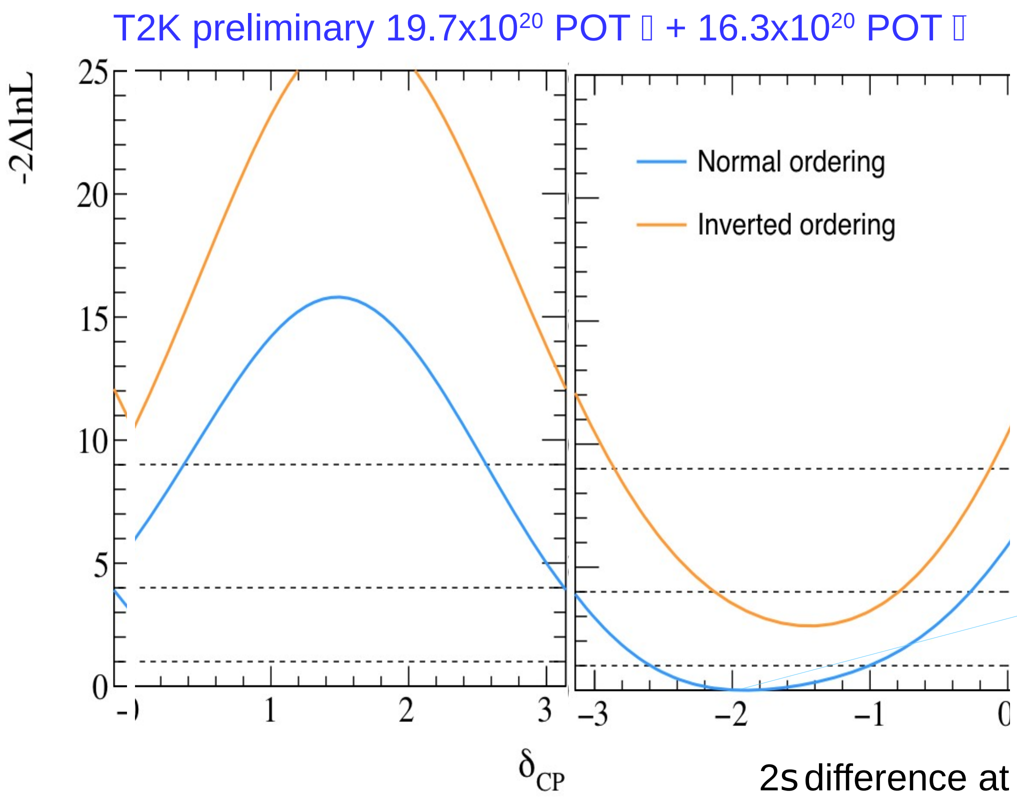


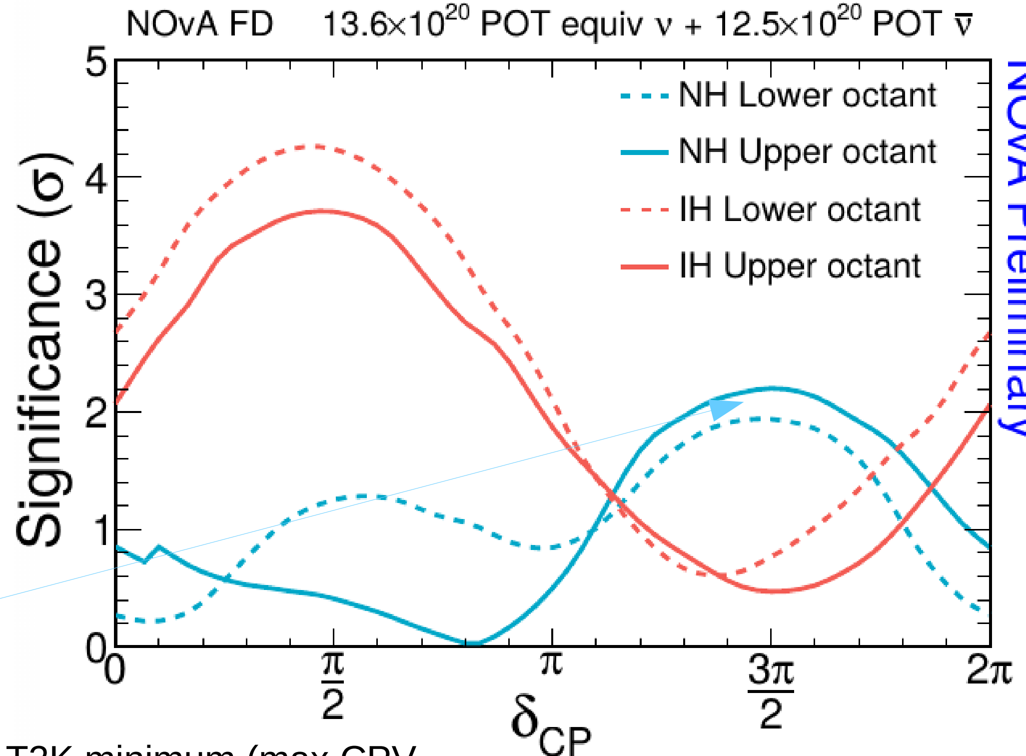




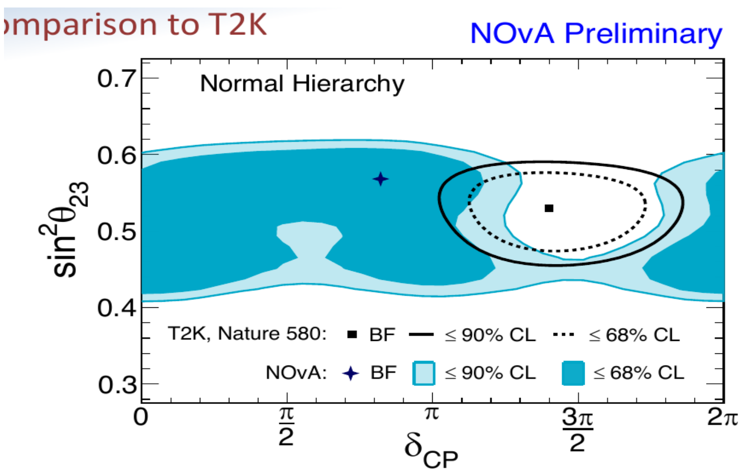
all these possibilities inside 1s

Results

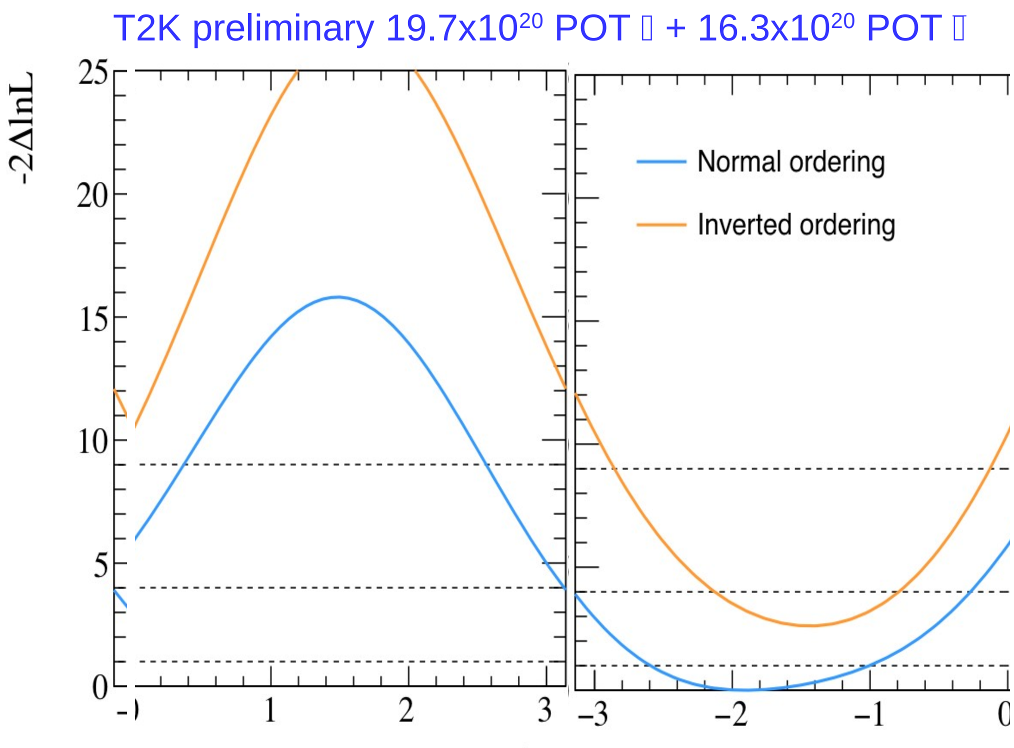


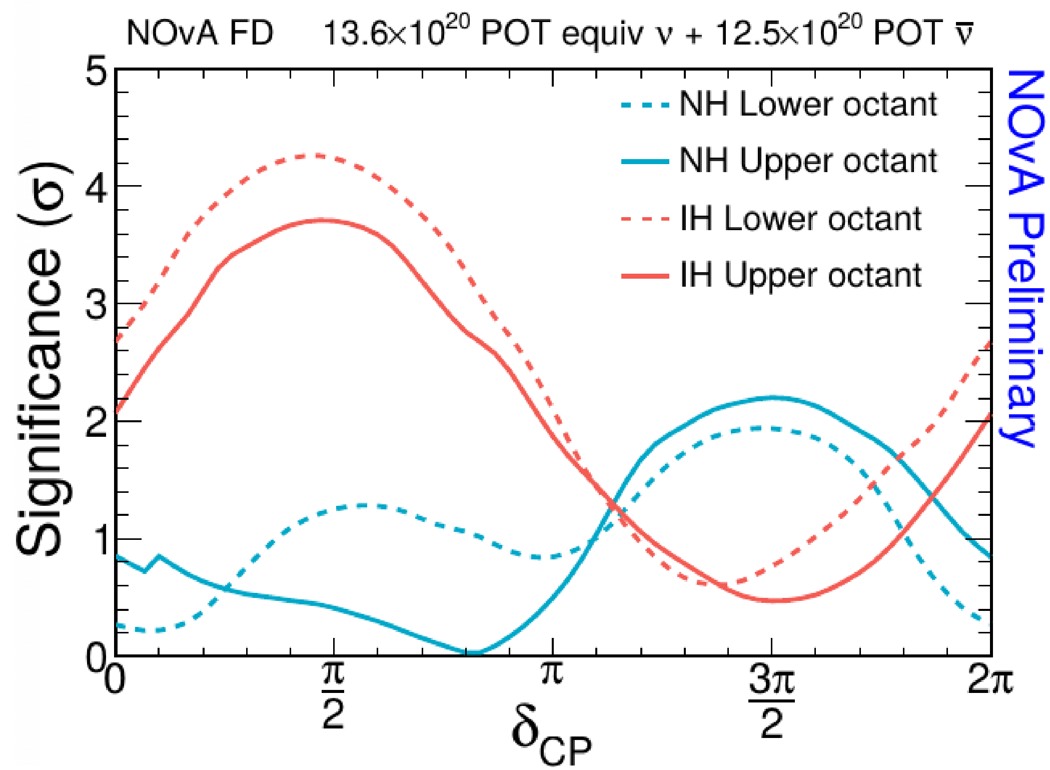


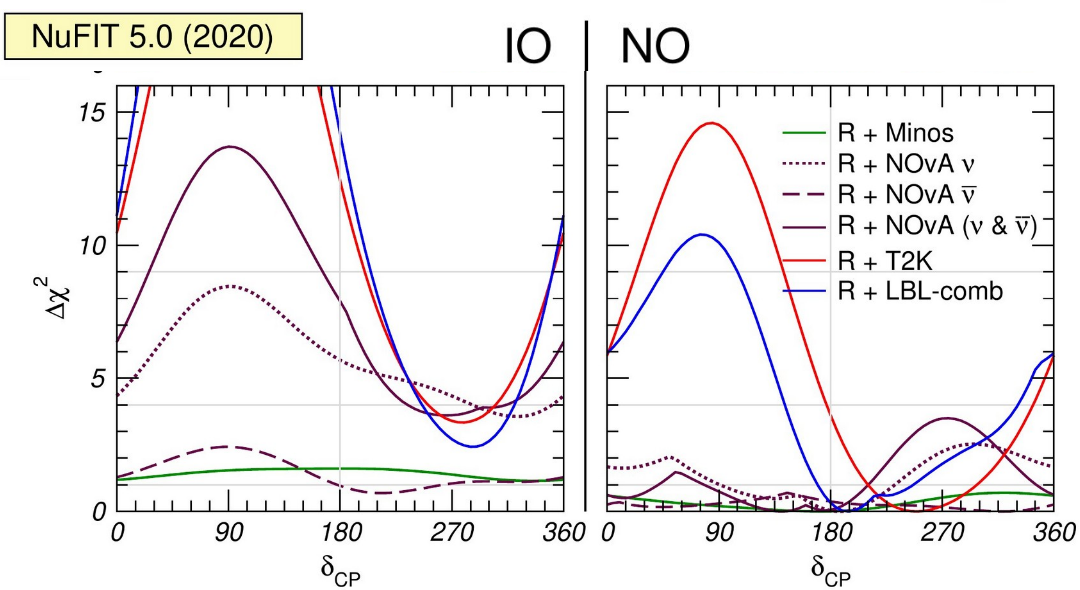
2s difference at T2K minimum (max CPV, NH) but still common regions at 1

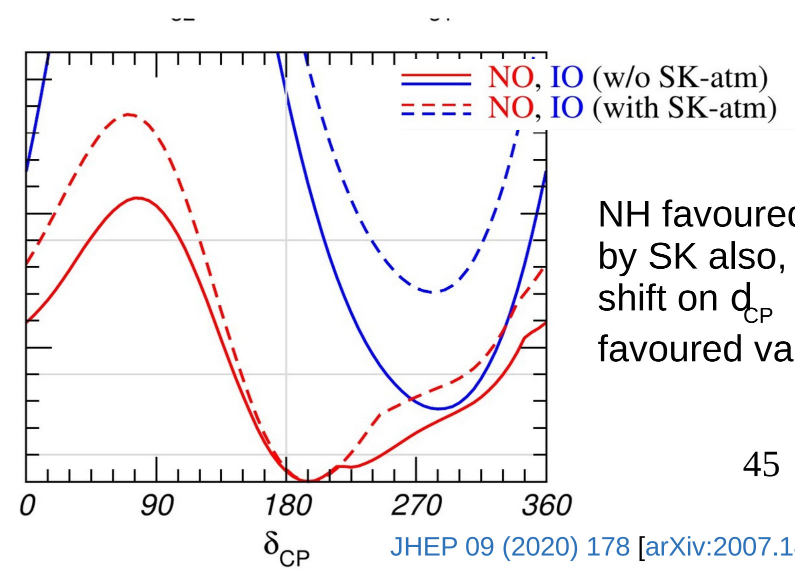


Results





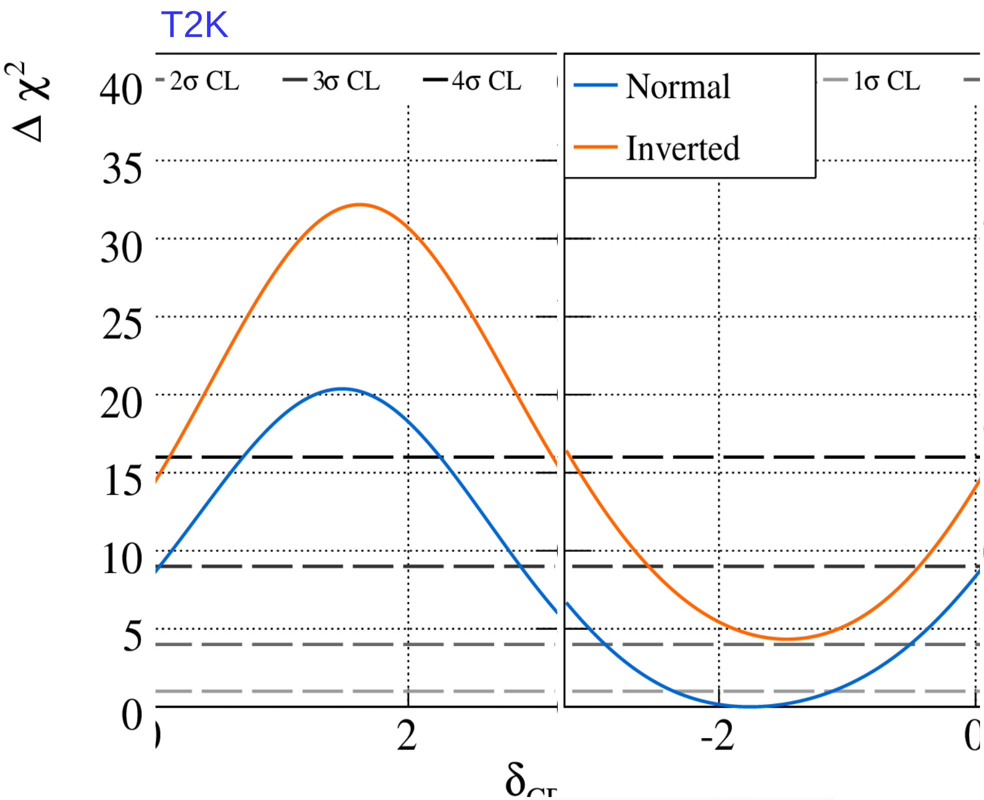


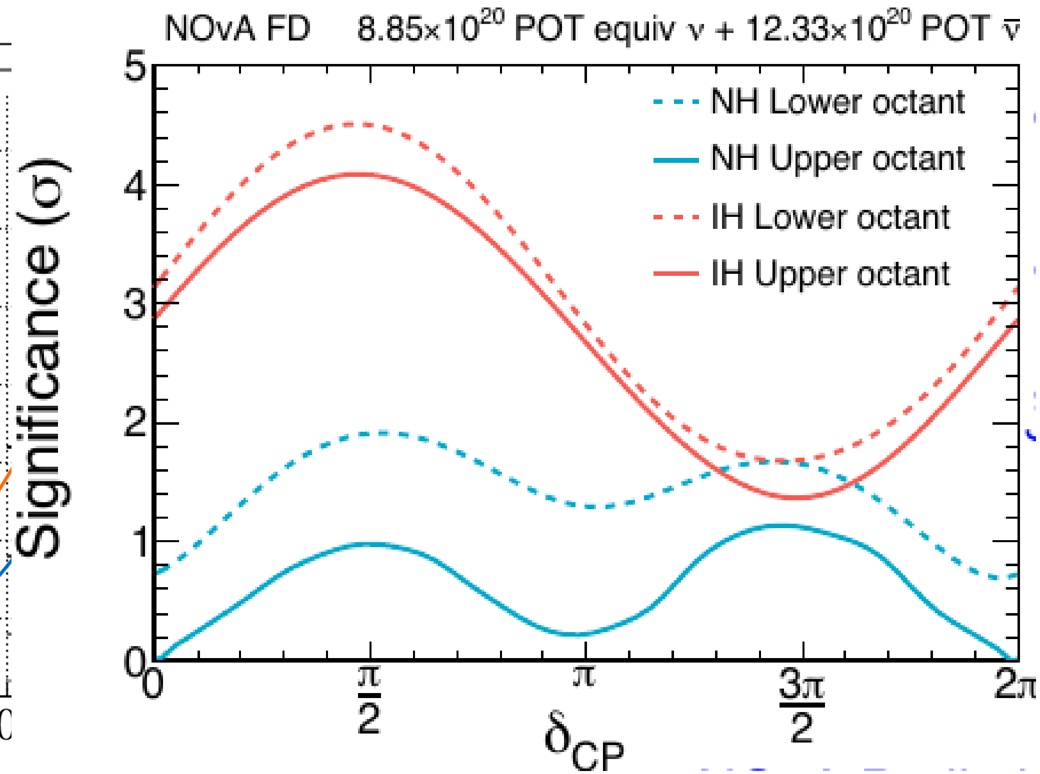


NH favoured by SK also, shift on d_{CP} favoured value

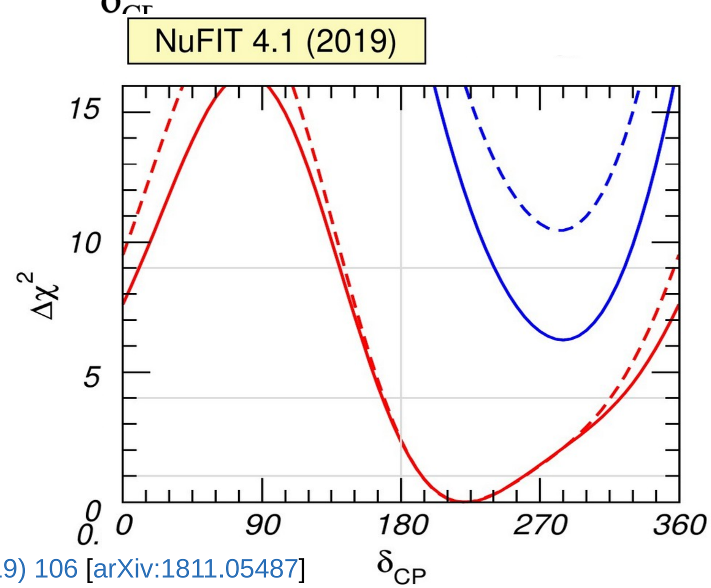
JHEP 09 (2020) 178 [arXiv:2007.14792]

Results ***2019***

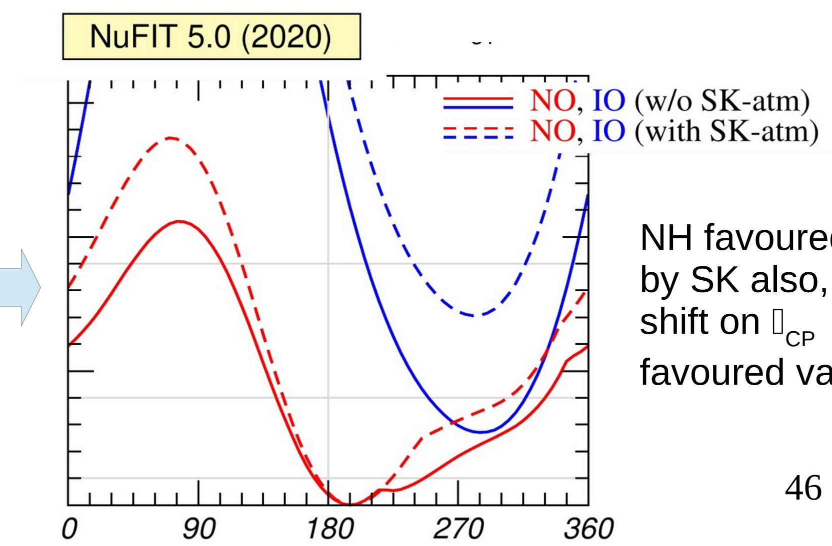




Something similar already visible last year



JHEP 01 (2019) 106 [arXiv:1811.05487]

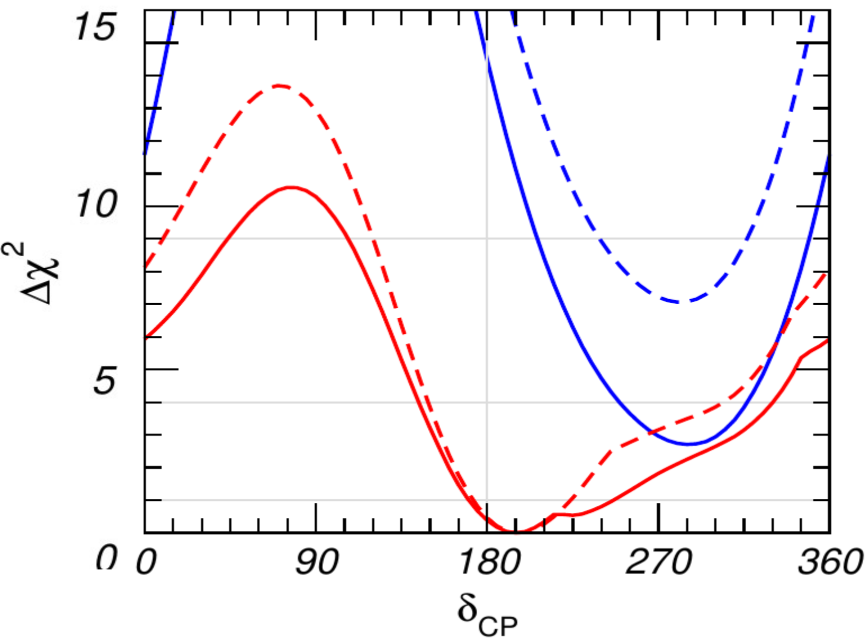


NH favoured by SK also, shift on δ_{CP} favoured value

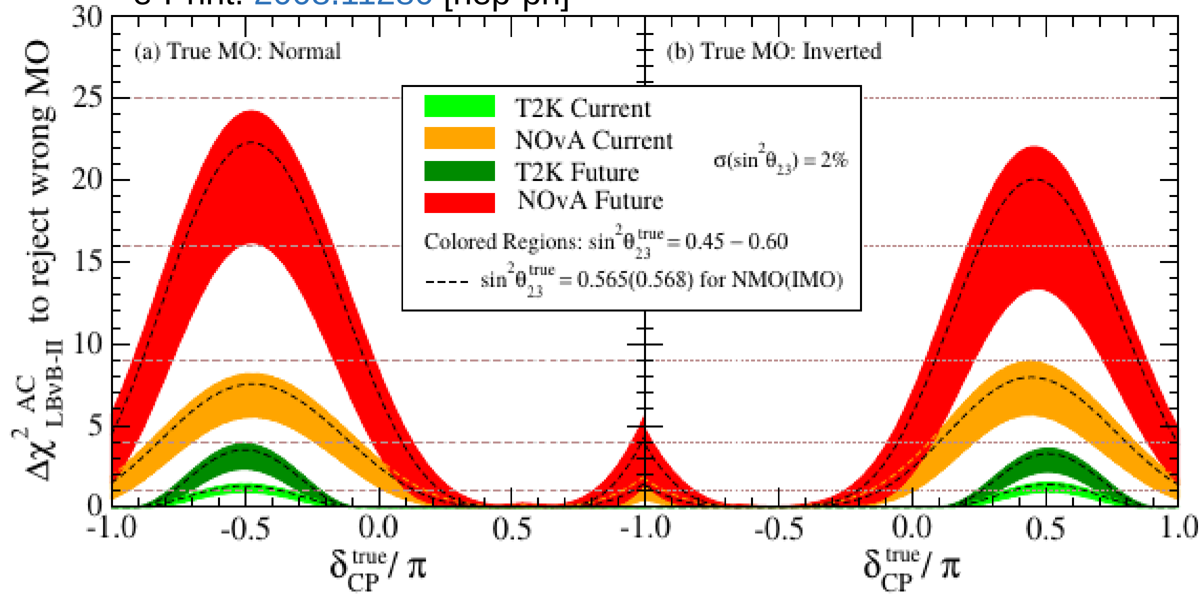
JHEP 09 (2020) 178 [arXiv:2007.14792]

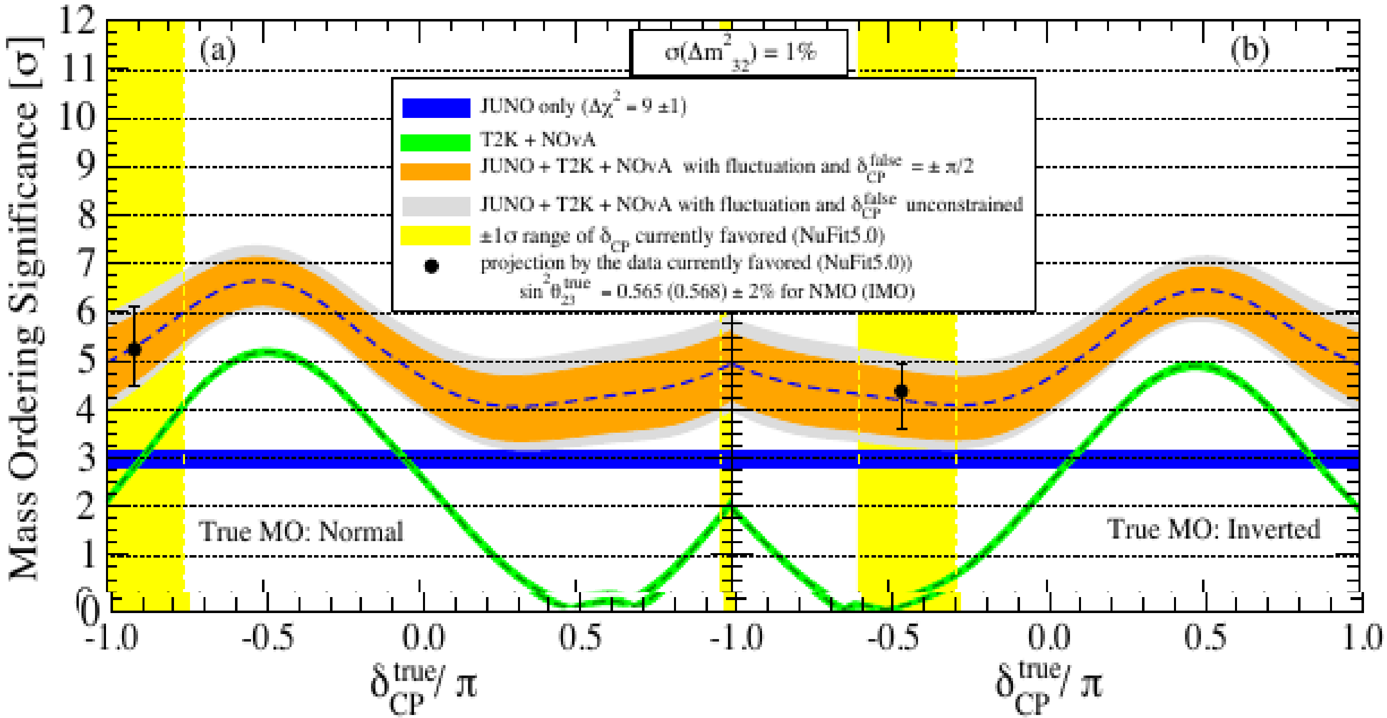
Mass hierachy

NuFit 2020 results



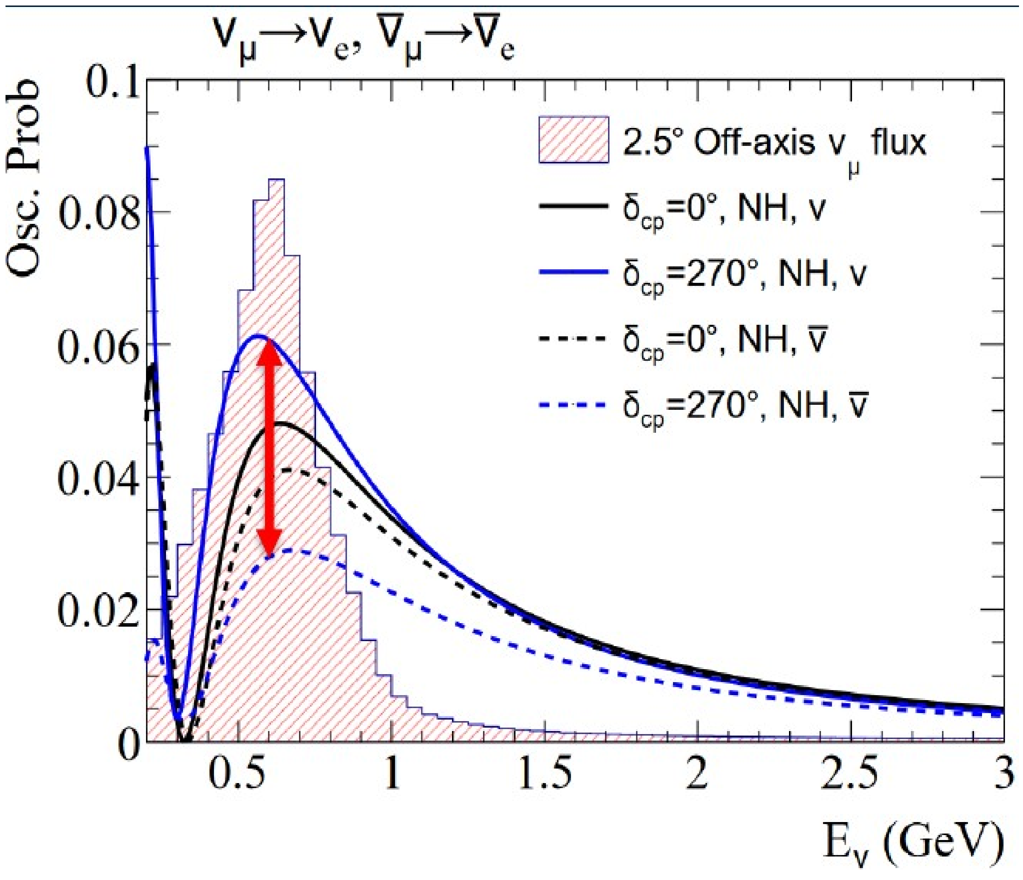
e-Print: 2008.11280 [hep-ph]



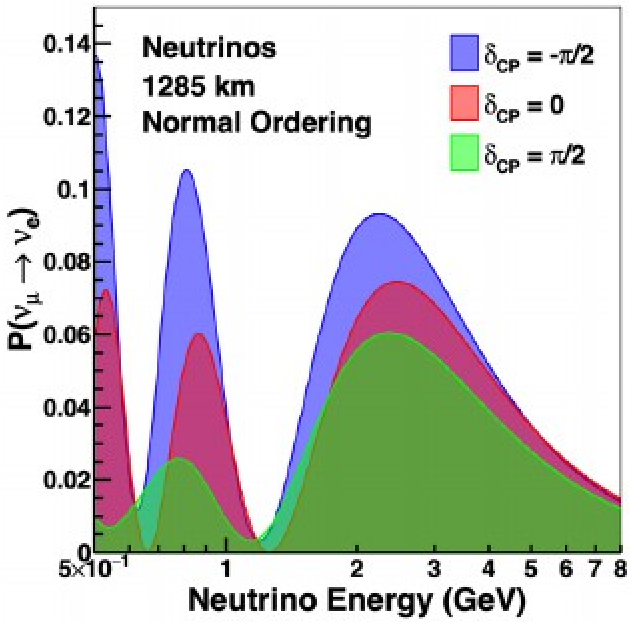


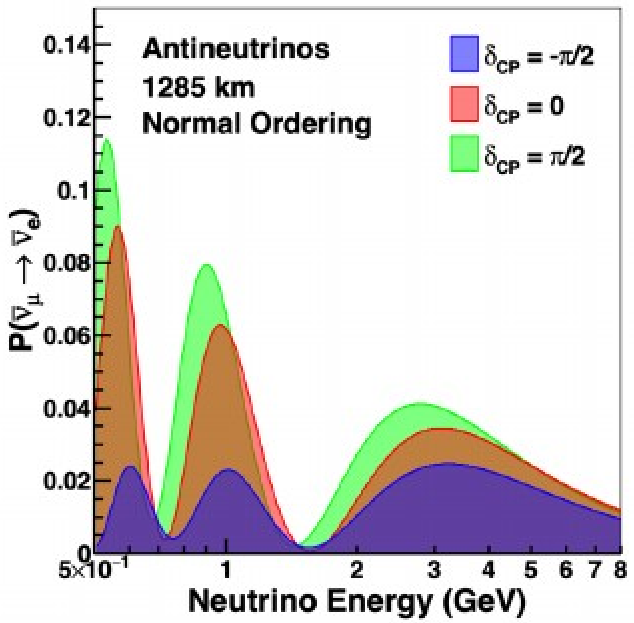
Impact of δ_{CP} on ν_e, $\bar{\nu}_e$ samples

Hyperkamiokande



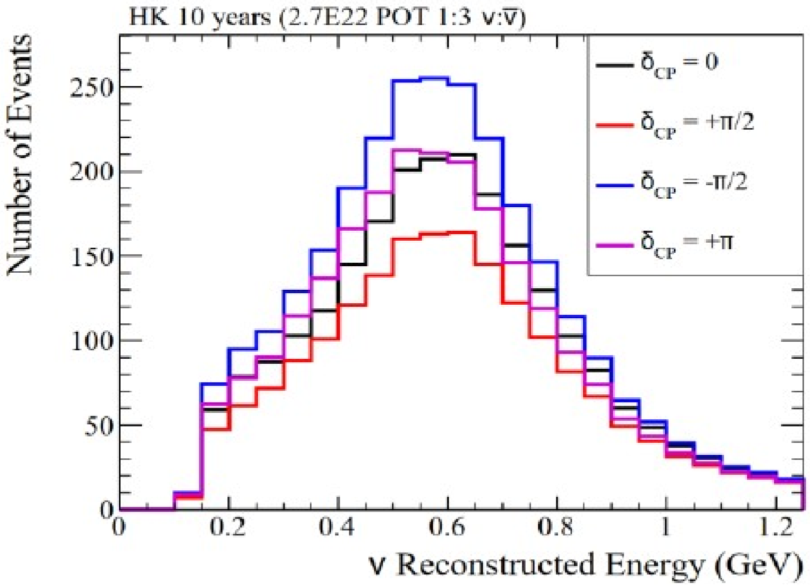
DUNE:



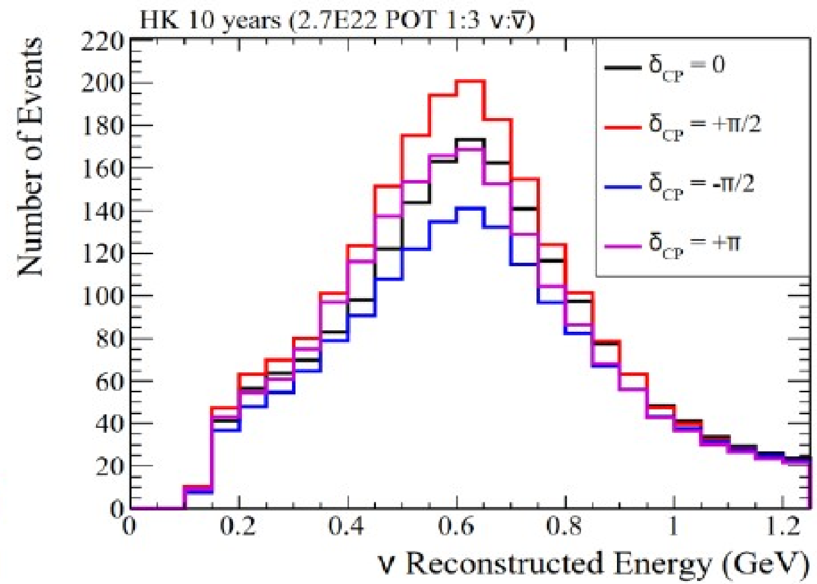


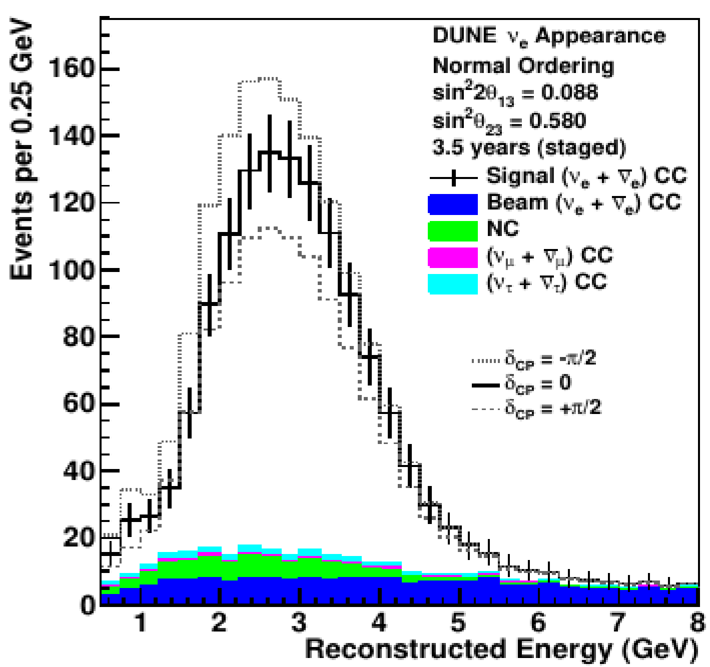
Impact of δ_{CP} on ν_e, $\bar{\nu}_e$ samples

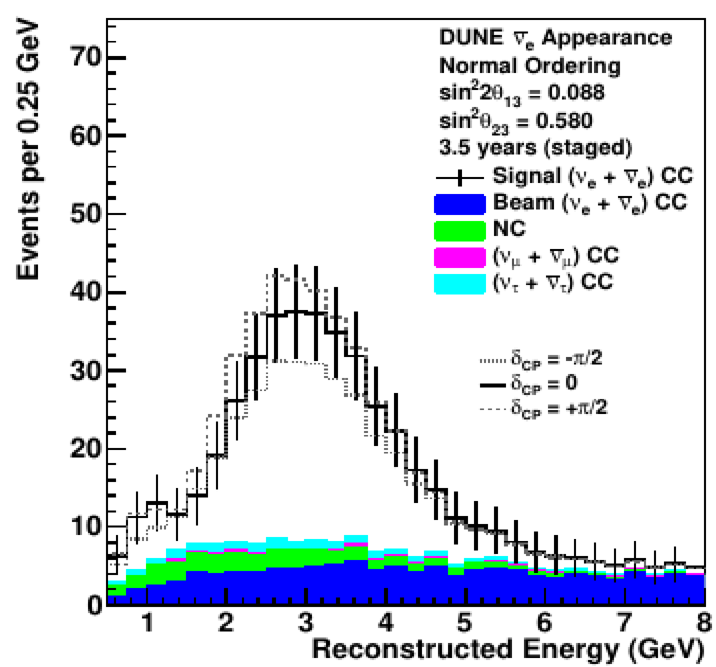
Neutrino beam



Antineutrino beam





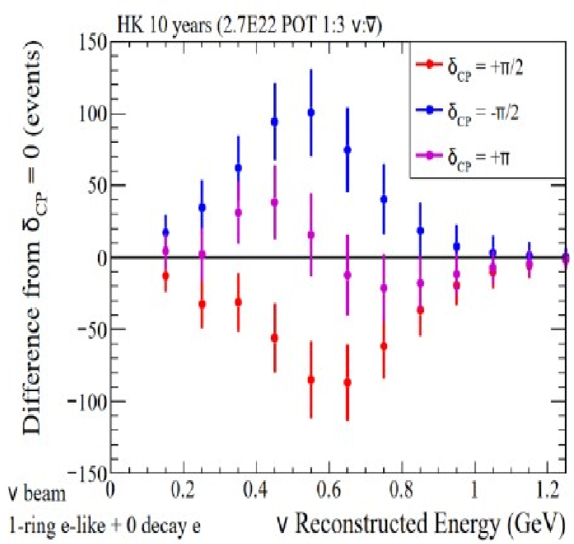


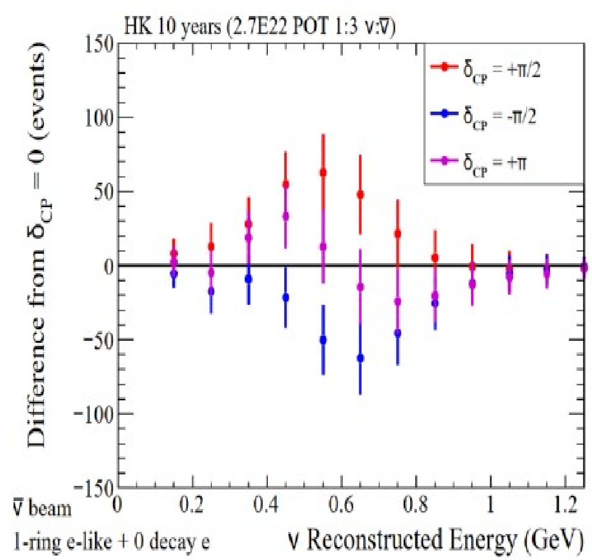
δ_{CP} resolution

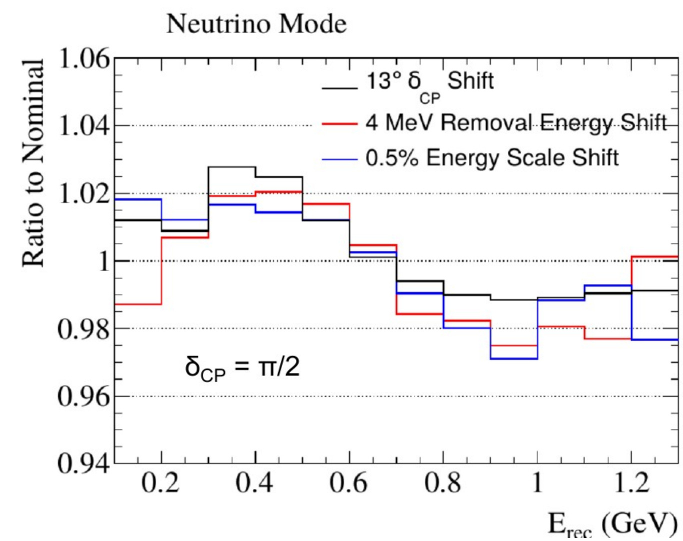
$$
\begin{aligned}
P_{long-baseline} \simeq\ & \boxed{\sin^2 2\theta_{13}}\,\boxed{\sin^2 \theta_{23}} \sin^2 \Delta \\
& \mp\ \alpha\ \sin 2\theta_{13} \boxed{\sin \delta_{CP}} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta \\
& +\ \alpha\ \sin 2\theta_{13} \boxed{\cos \delta_{CP}} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin^2 \Delta \\
& +\ \alpha^2\ \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta
\end{aligned}
$$

with $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$ and $\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$.

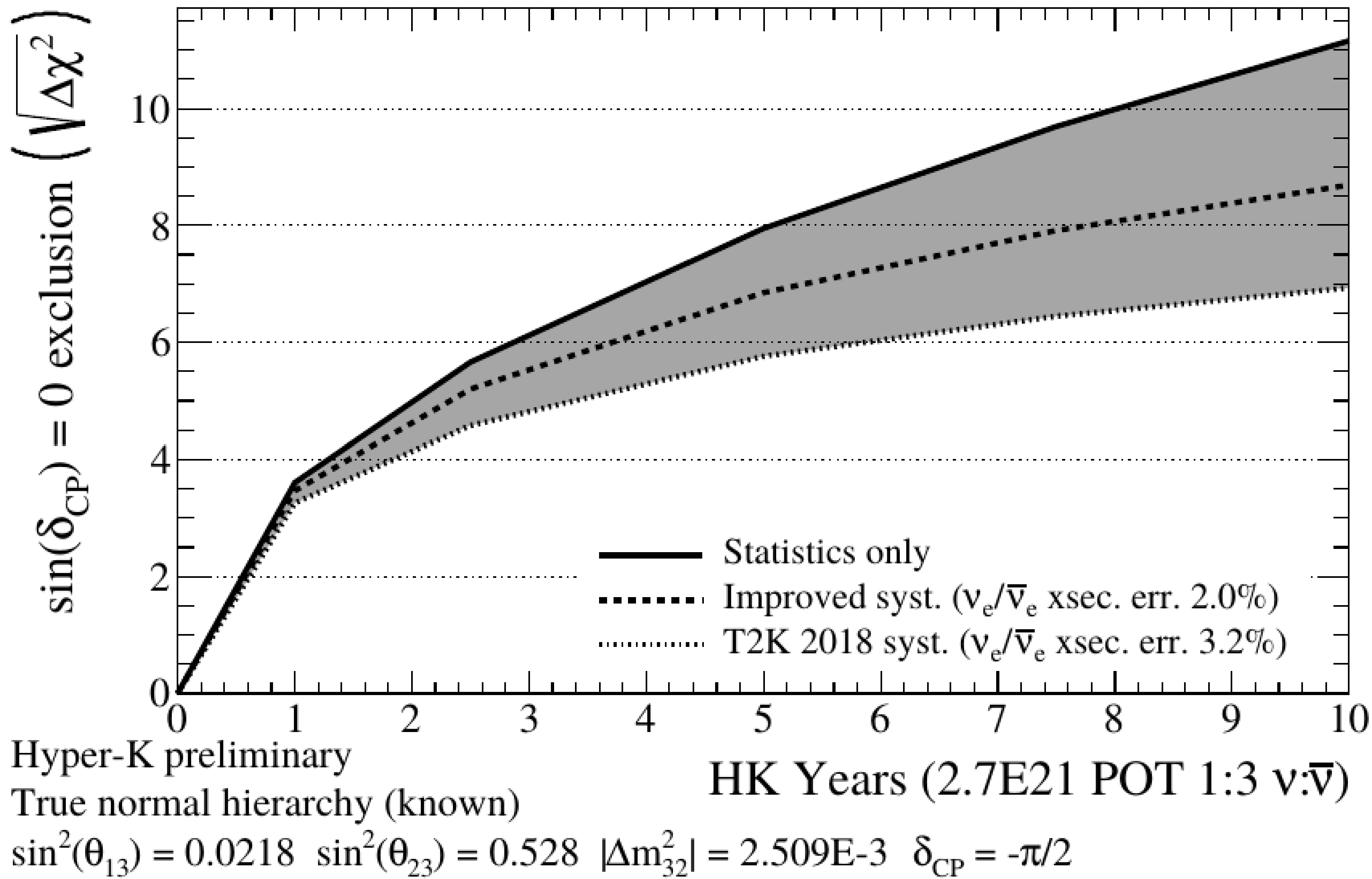
Change sign for $\nu/\bar{\nu}$ $\rightarrow$ CP violation







HK sensitivity vs time (systematics)



Single phase vs double phase

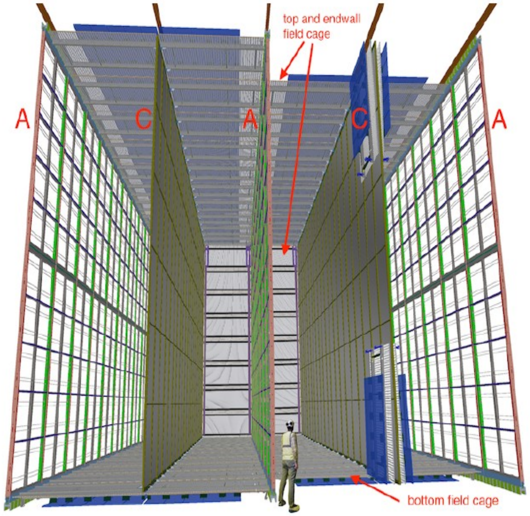
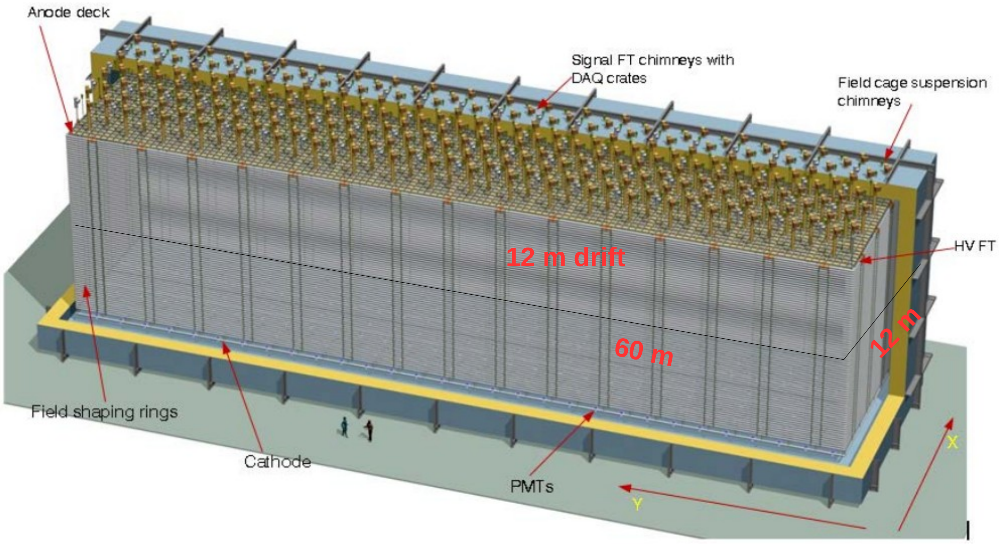
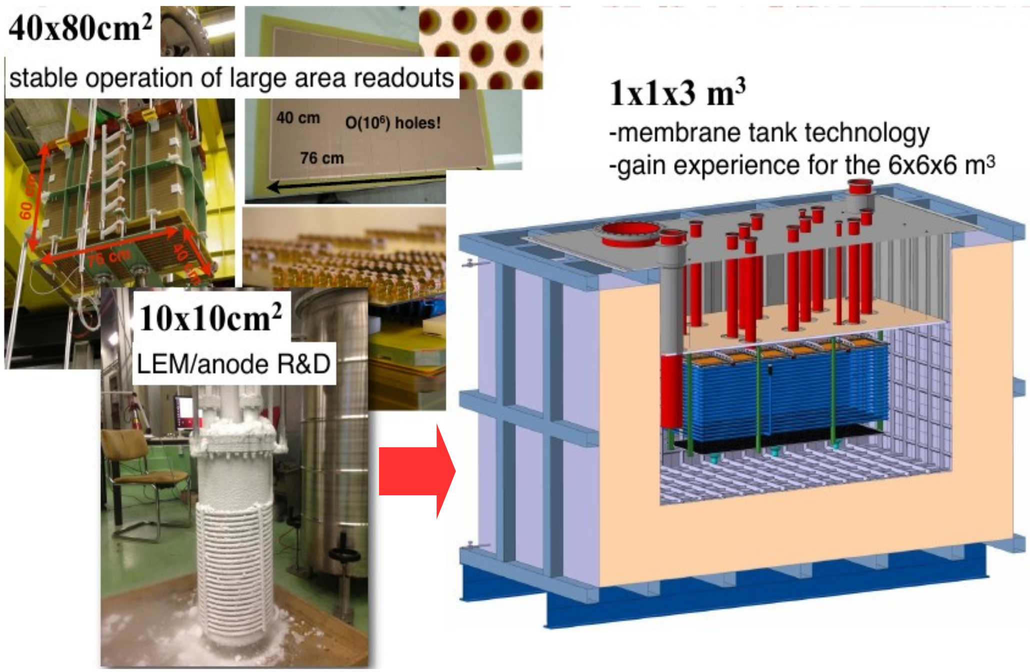


Figure 1.7: A 10 kt DUNE FD SP module, showing the alternating 58.2 m long (into the page), 12.0 m high anode (A) and cathode (C) planes, as well as the field cage (FC) that surrounds the drift regions between the anode and cathode planes. On the right-hand cathode plane, the foremost portion of the FC is shown in its undeployed (folded) state.

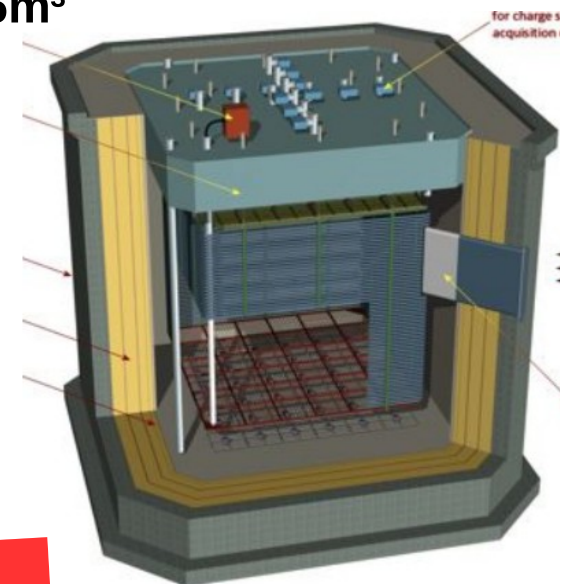


From double-phase to vertical-drift

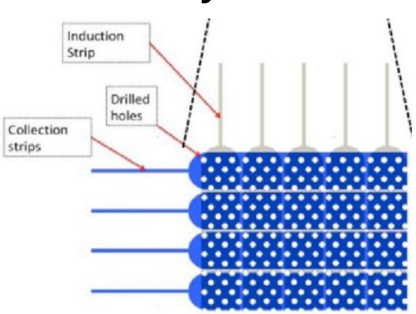
Problems of stability due to irregular gas/liquid interface (bubble/waves) + coupling of grid-LEM can cause dangerous sparks

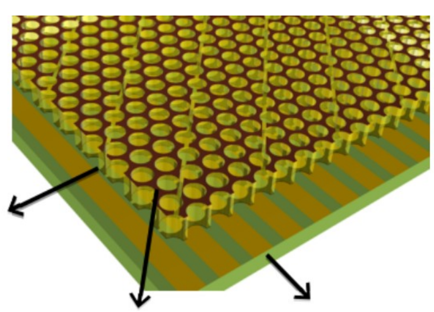


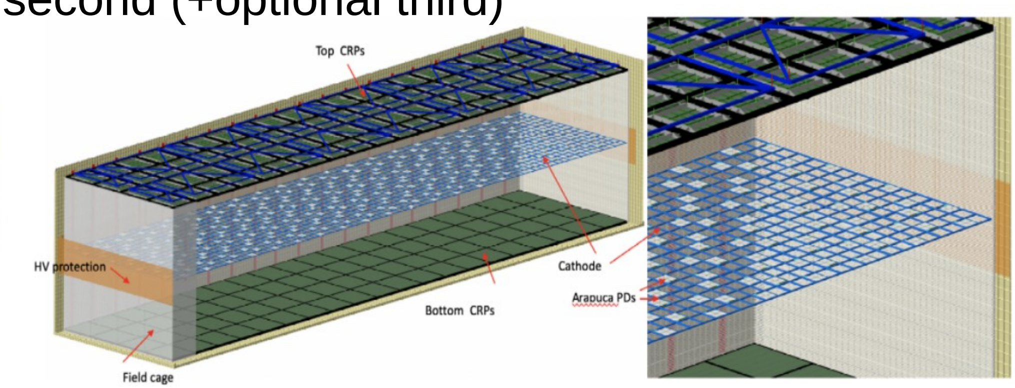
ProtoDUNE-DP (ex LBNO-DEMO)
6x6x6m³



"Vertical drift": no charge multiplication and second (+optional third) readout by induction



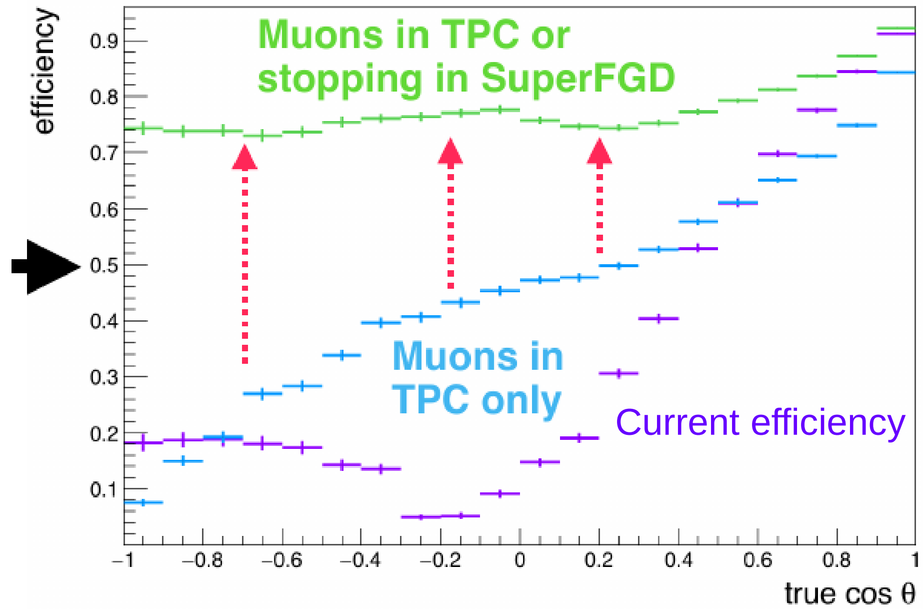




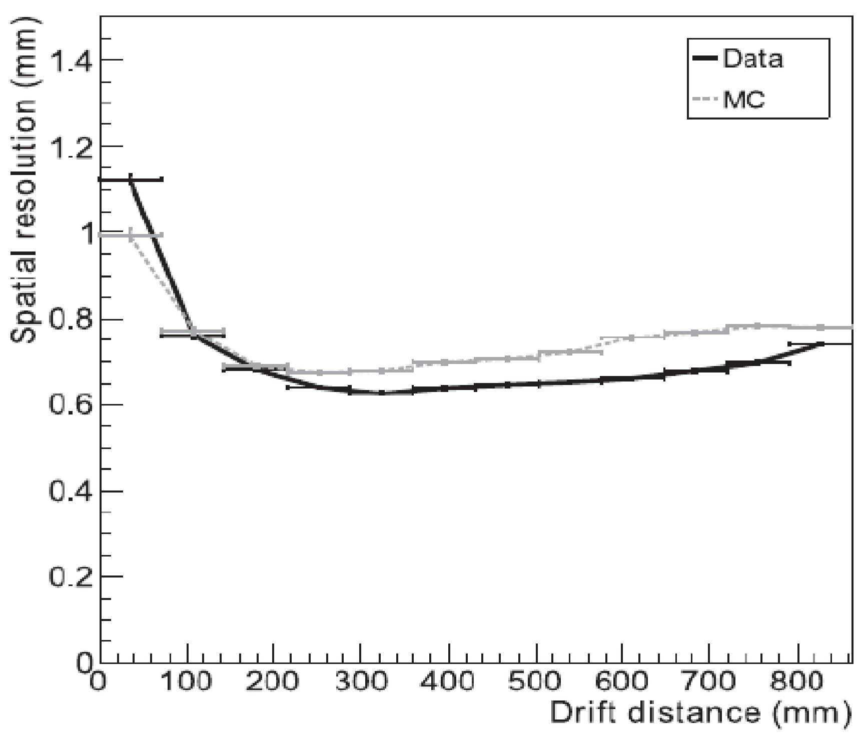
ND280 Upgrade improvements

- **Improvement of angular coverage** for charged particles

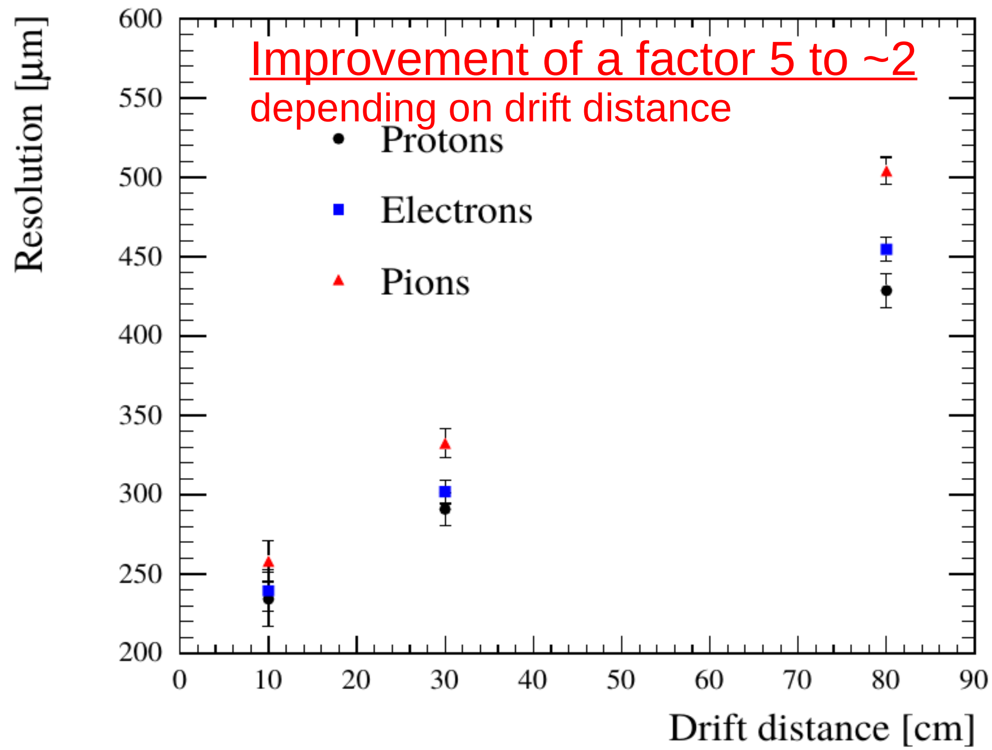
- **Improved TPC spatial resolution** → improved momentum resolution (10% in previous TPCs)

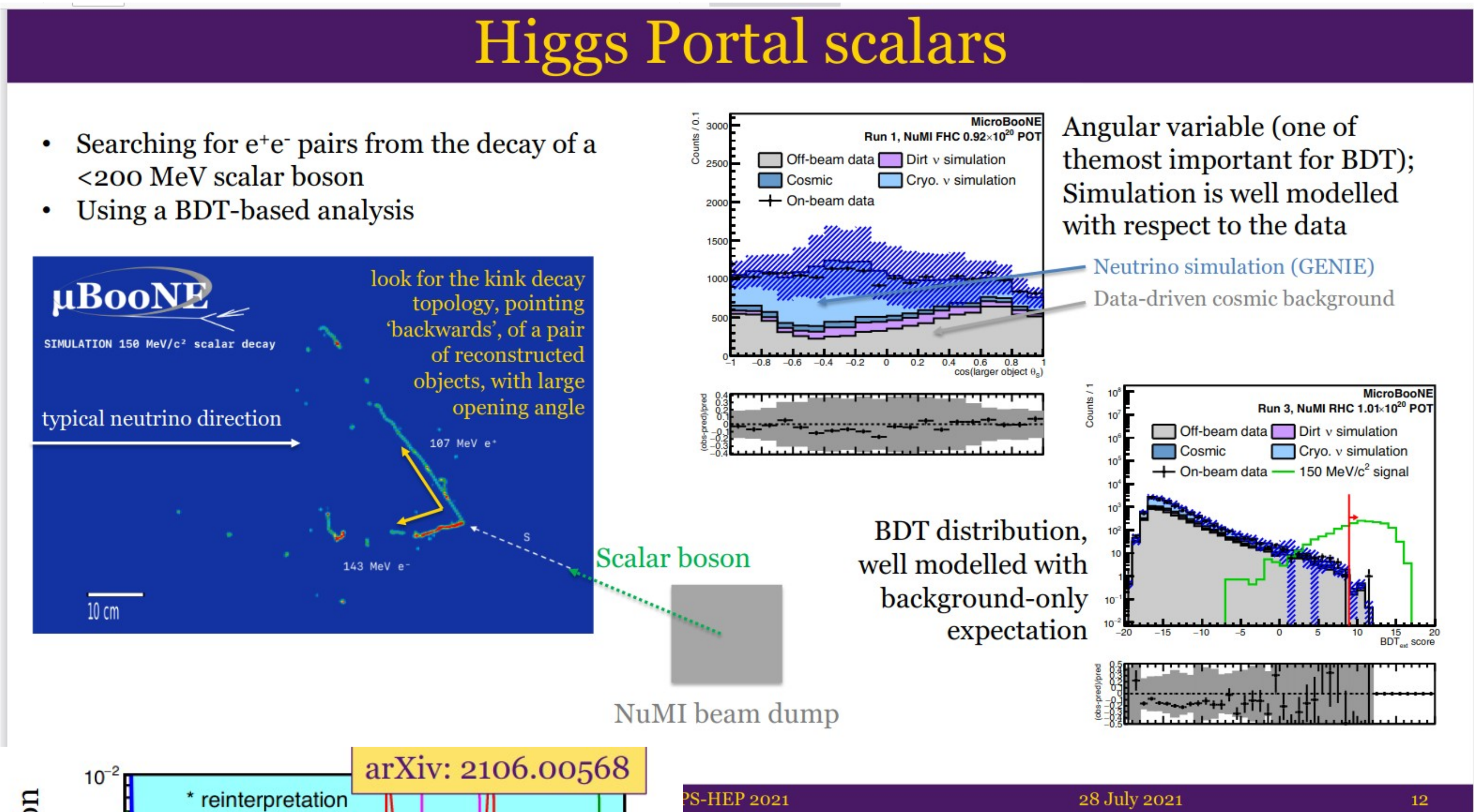


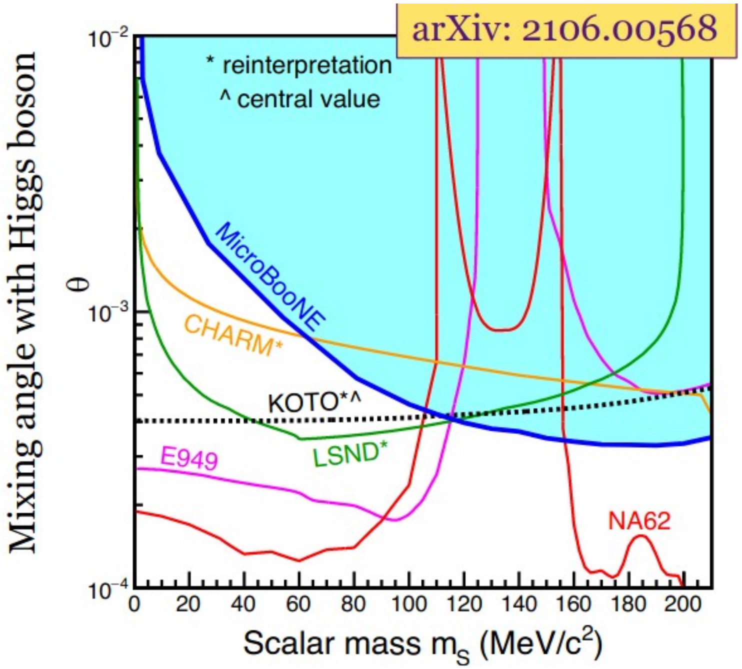
ND280 vertical TPCs



Resistive Micromegas prototype for ND280 upgrade at 2018 CERN test beam







- We observe 5 events in signal region, with 2.0±0.8 expected

- Can exclude model central value parameters required to explain KOTO anomaly

- This was with 10% of our NuMI dataset; further search results to come!

Pawel Guzowski - EPS-HEP 2021

Dark prospects

- Further BSM models being explored with e^+e^- final states
- Dark neutrino portal, with dark Z' decay
  - could explain MiniBooNE: if e^+e^- resolved as single shower
- Dark matter produced in beamline; inelastic scattering off argon
  - MicroBooNE has excellent sensitivity