News from T2K, T2K-II and Hyper-K

Claudio Giganti

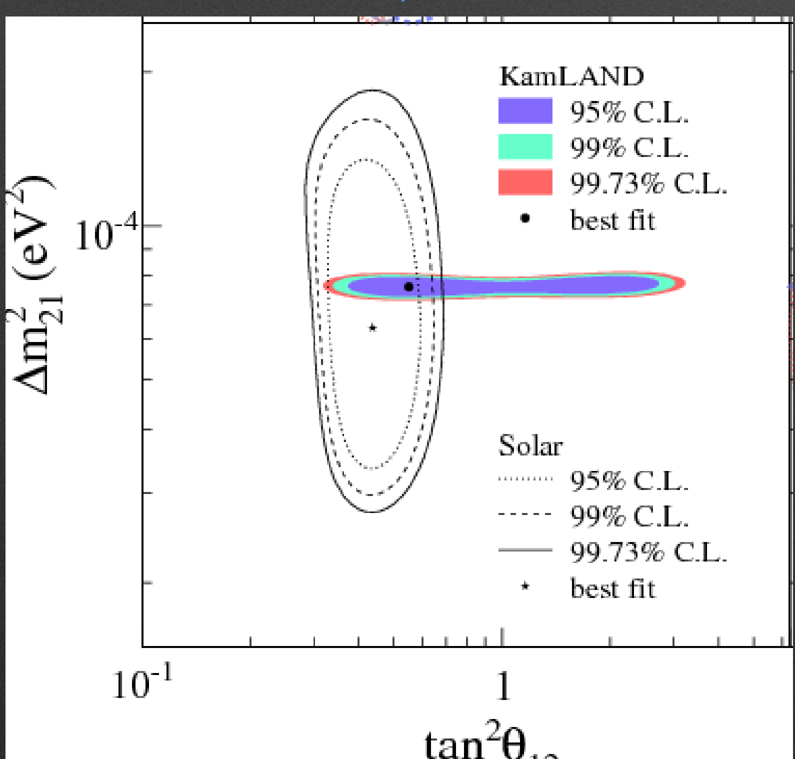
GDR Neutrino
Bordeaux 29/10/2019

Neutrino oscillations

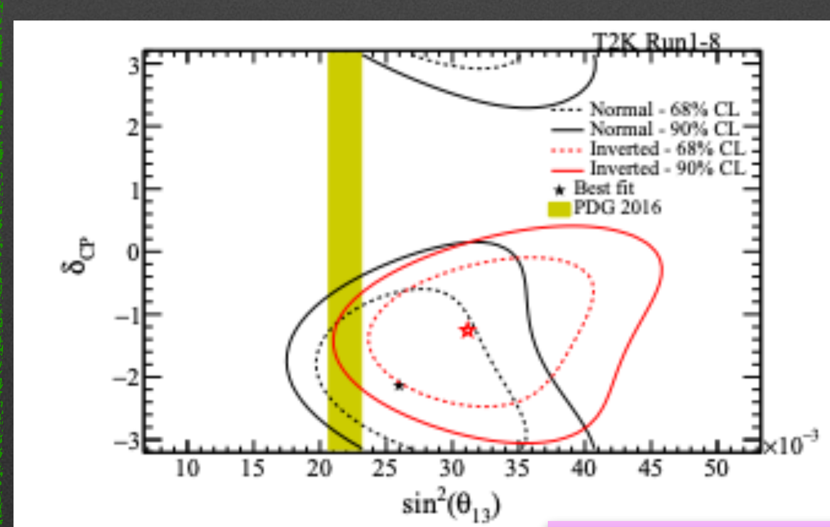
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

* 3 mixing angles
* 2 independent mass differences
* 1 CP violation phase → not yet measured

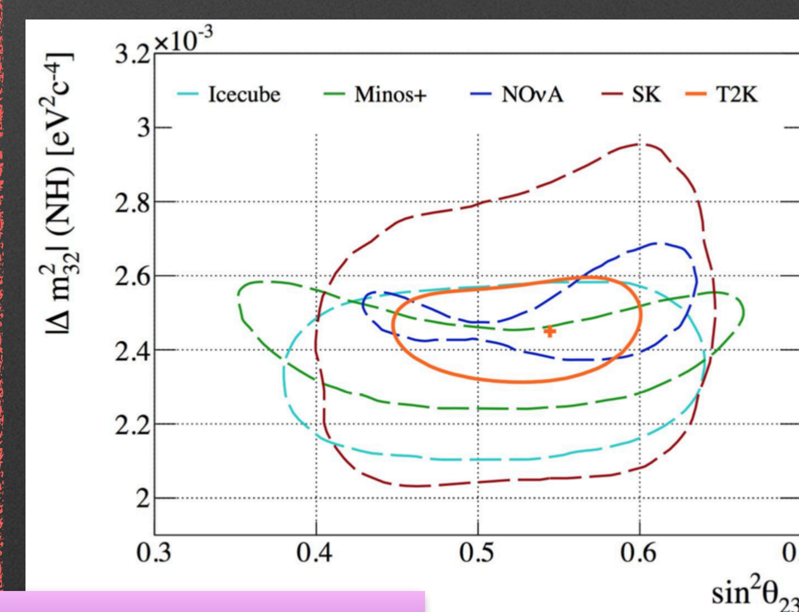
Solar (SNO, KamLand)
→ θ_{12}, Δm_{12}



Reactors (Daya Bay, RENO, DChooz) → θ_{13}
LBL (T2K, NOνA) → θ_{13}, δ_{CP}



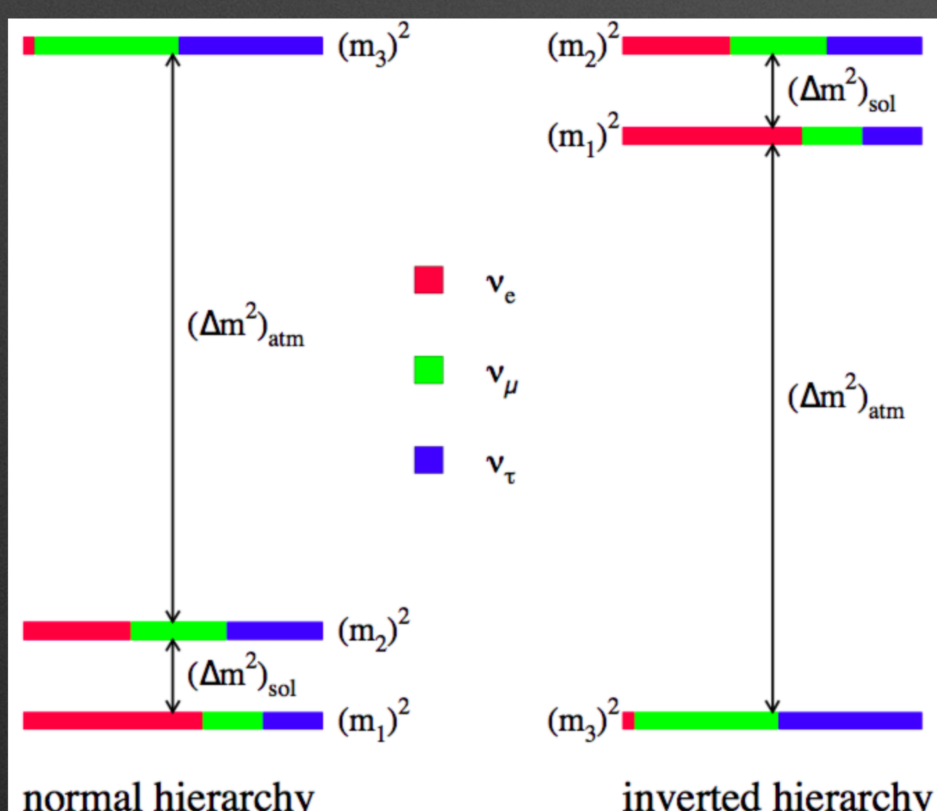
Atmospheric (SK, IceCUBE)
LBL (Minos, T2K, NOνA)
→ θ_{23}, Δm_{32}



LBL experiments

Open questions

- Neutrino oscillations → "guaranteed" measurements for T2K and HK
- Multi-messenger astronomy with neutrinos is starting now → SK, HK
- Nature of neutrinos (Dirac or Majorana) and their mass → not accessible to LBL experiments



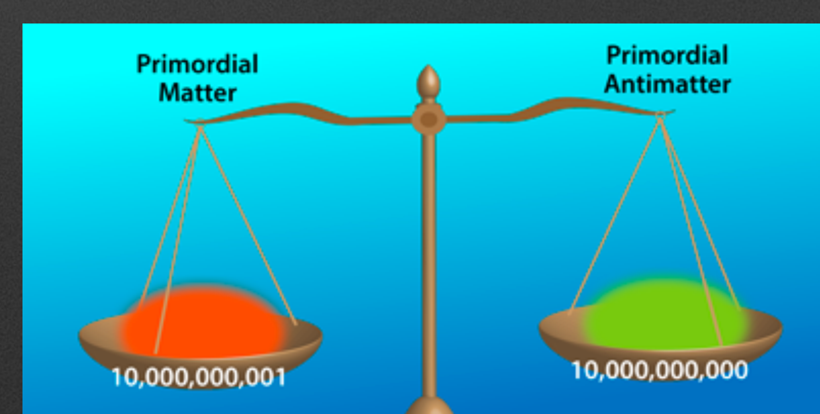
Neutrinos ToDo List

- [x] θ13
- [ ] CP violation
- [ ] Mass Hierarchy
- [ ] θ23 octant
- [ ] Sterile neutrinos?
- [ ] Majorana or Dirac?
- [ ] Absolute neutrino mass
- [ ] ν sources (Solar neutrinos, SN, Galactic, Extragalactic...)
- [ ] New Physics?

Main Goals of LBL experiments in the next ~10 years

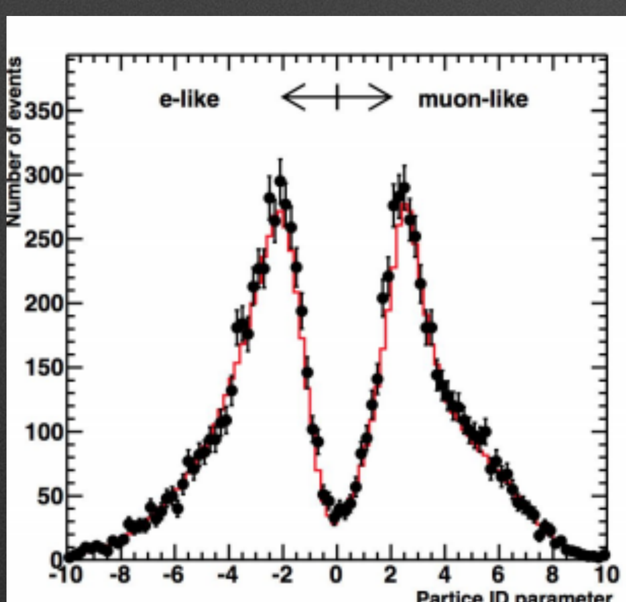
Reactors and Short-Baseline experiments

$0\nu\beta\beta$
Katrin, Project8, cosmology

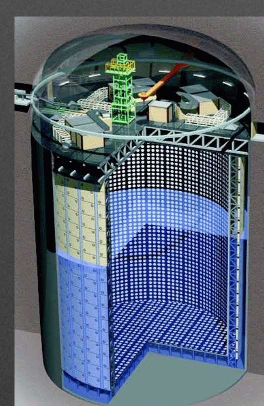


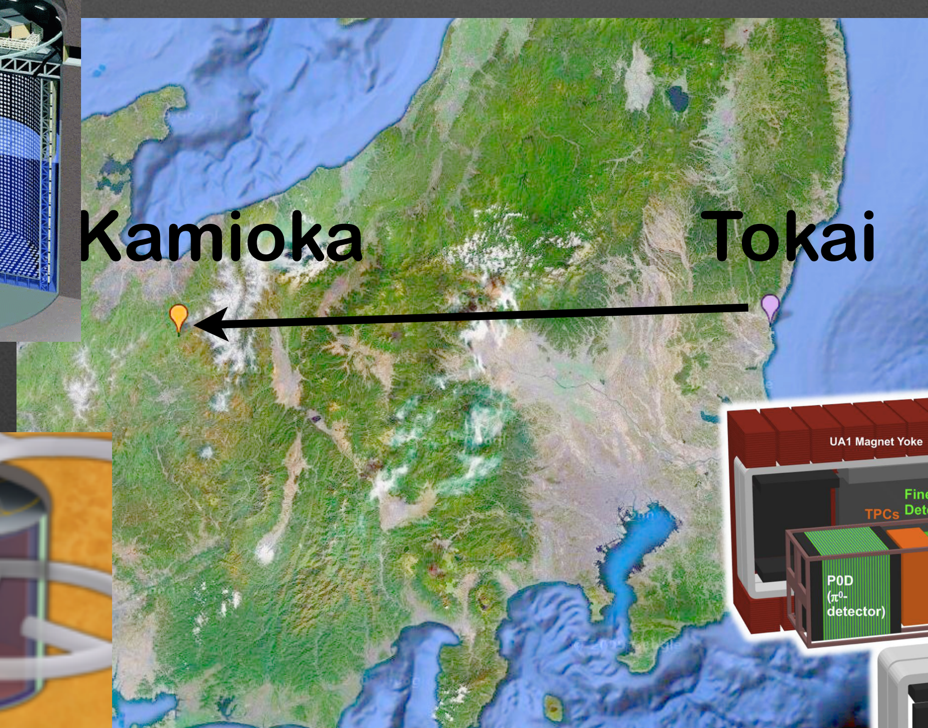
Tokai to Kamioka (SK or HK)

- High intensity ~600 MeV ν_μ beam produced at J-PARC (Tokai, Japan)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector, Super-Kamiokande (Hyper-Kamiokande) 295 km from J-PARC
- Main physics goals:
  - Observation of ν_e and $\overline{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ and $\overline{\nu}_\mu$ disappearance → θ_{23} and Δm^2_{32}



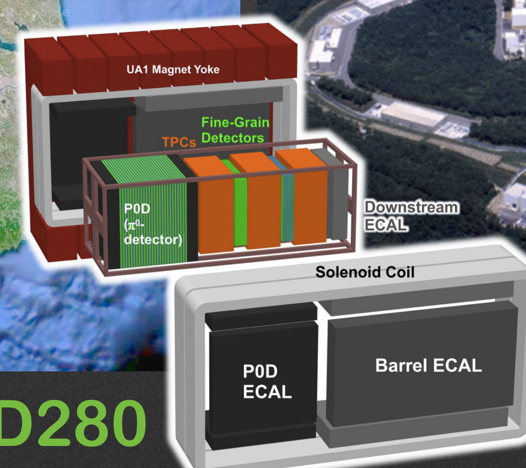
Super-Kamiokande





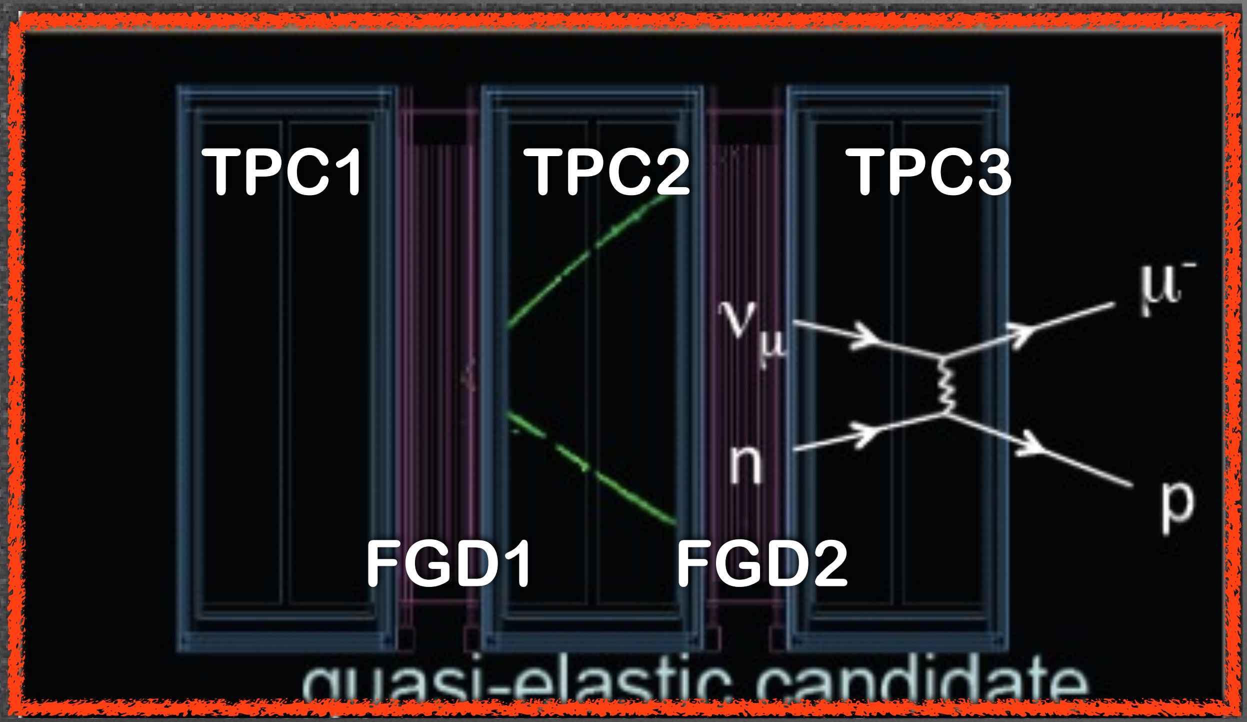
Hyper-Kamiokande

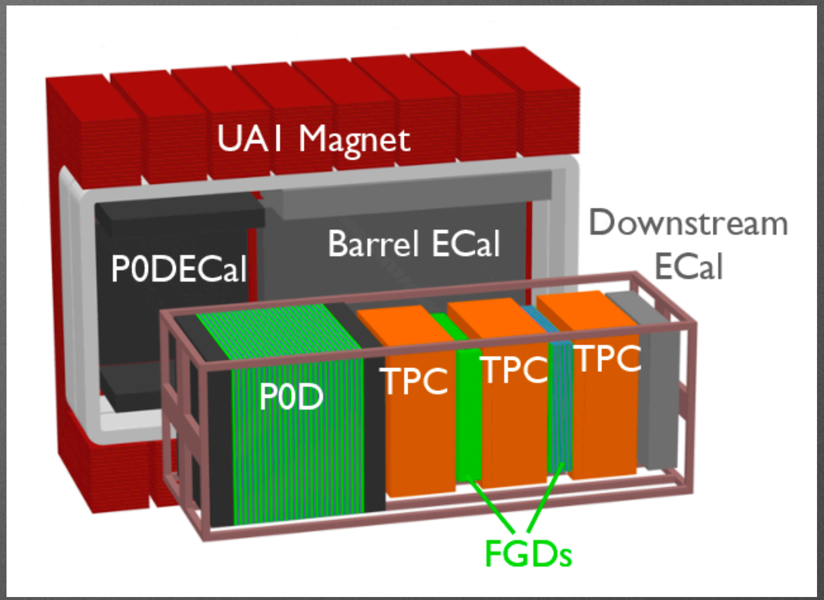
J-PARC accelerator:
Design power: 750 kW
(1.3 MW for HK)



ND280

ND280

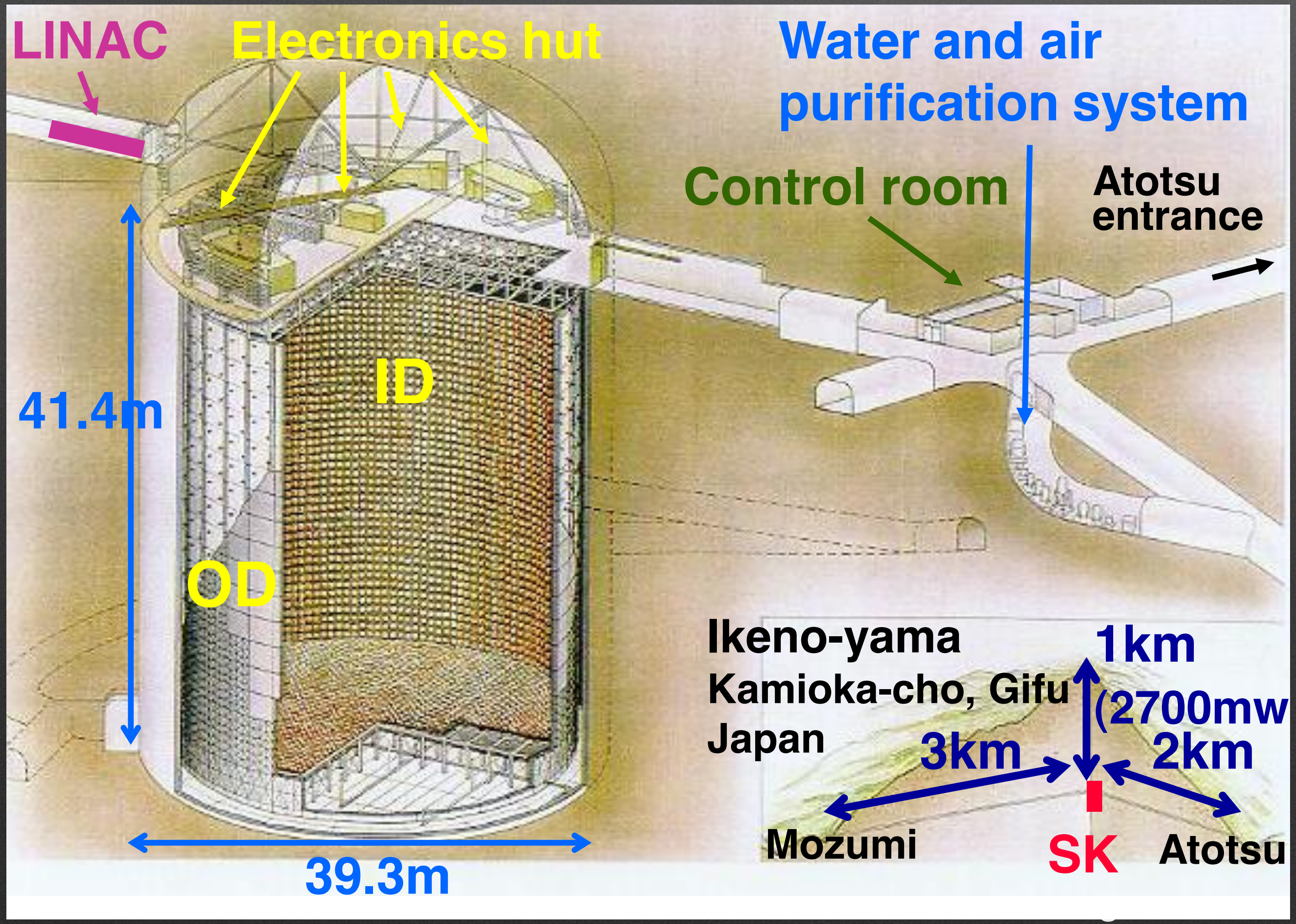




- Detector installed inside the UA1/NOMAD magnet (0.2 T magnetic field)
- A detector optimized to measure π^0 (P0D)
- A tracker system composed by:
  - 2 Fine Grained Detectors (target for ν interactions). FGD1 is pure scintillator, FGD2 has water layers interleaved with scintillator
  - 3 Time Projection Chambers: reconstruct momentum and charge of particles, PID based on measurement of ionization
  - Electromagnetic calorimeter to distinguish tracks from showers

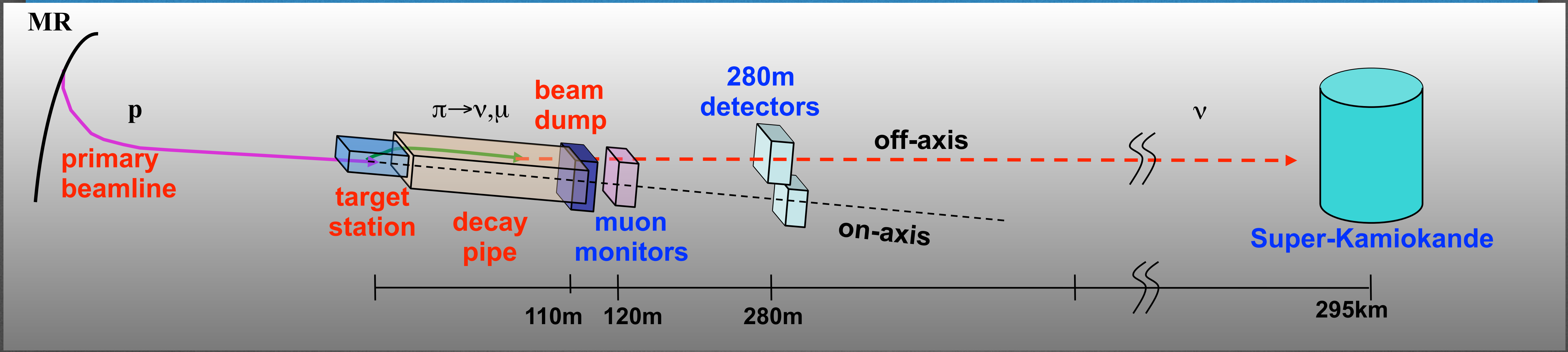
Super-Kamiokande

- 50 kton water Cherenkov detector (22.5 kton FV)
  - ~11000 20’’ PMT inner detector (~2000 8’’ PMT outer detector used as veto) → 40% photocathode coverage
- ~1000 meters underground in the Kamioka mine

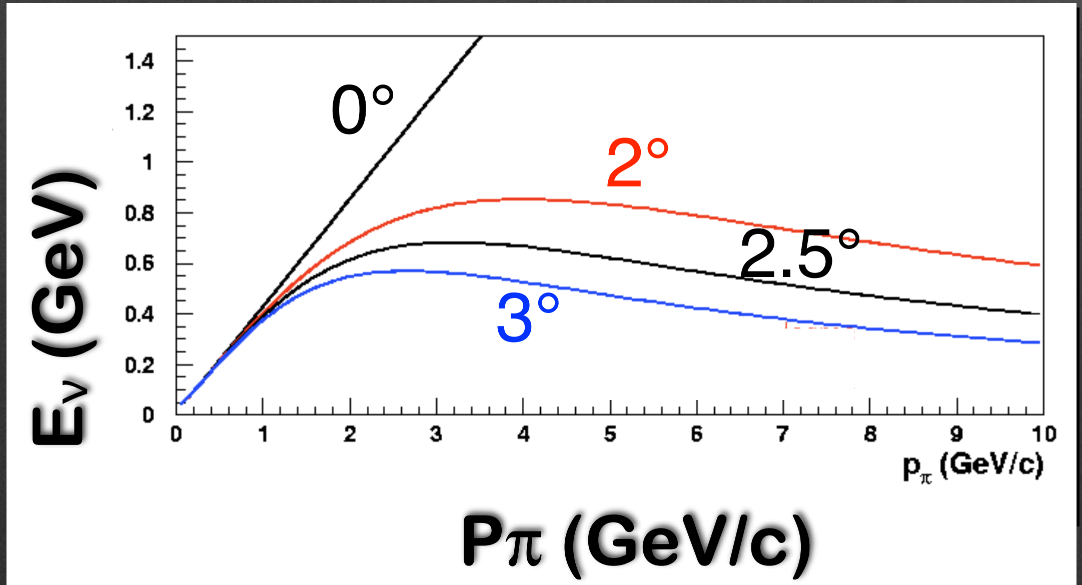


- Operated since 1996 (upgraded for T2K)
- Reconstruct vertex position, charged track direction and energy

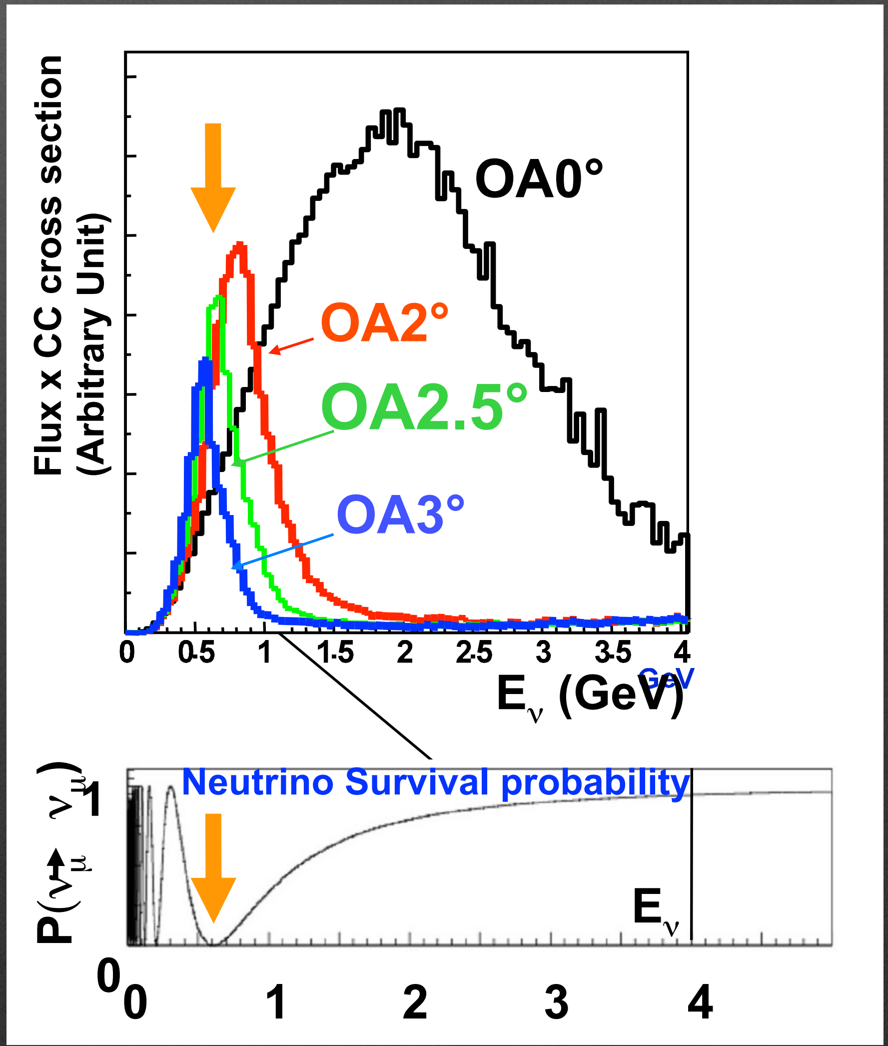
Off-axis beam



- T2K uses an off-axis technique (detectors at 2.5° from the center of the beam)
- Increase the intensity of the beam at the desired L/E → maximize the oscillation probability



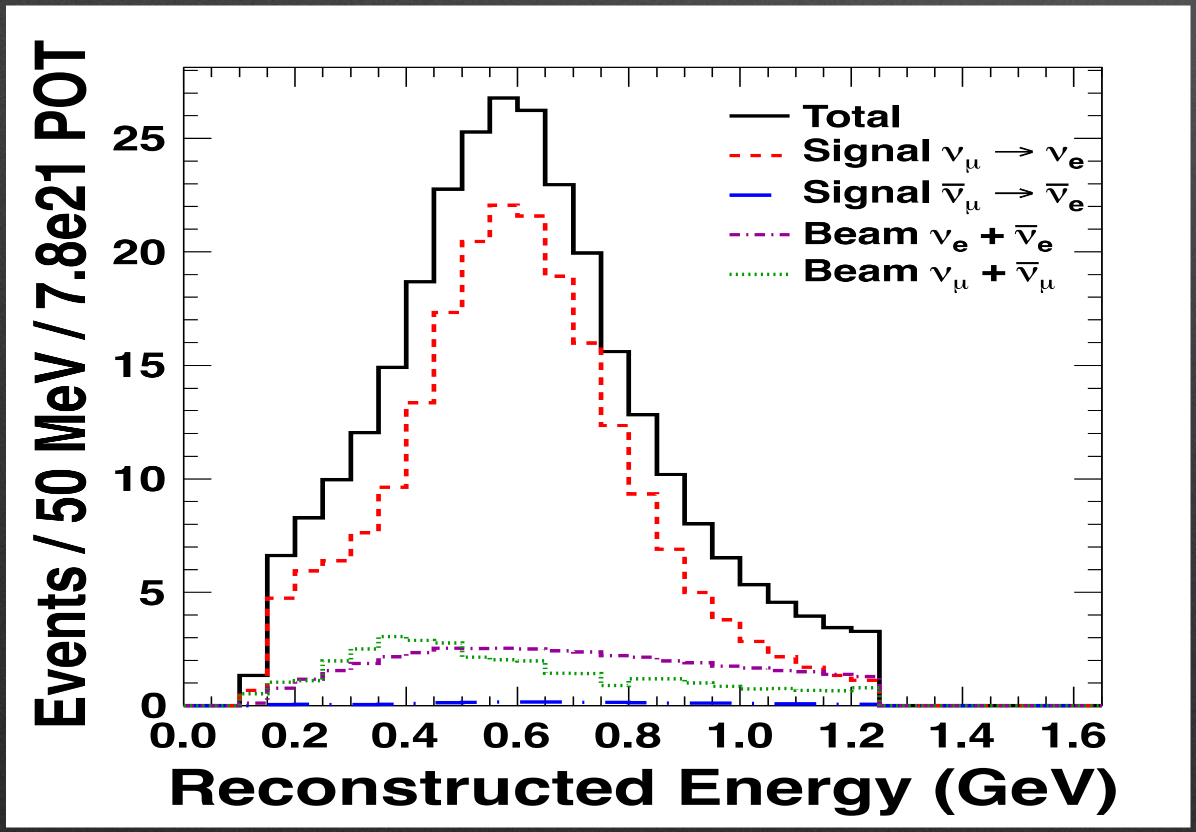
On-axis: E_ν proportional at P_π
Off-axis: different P_π contribute to the same E_ν



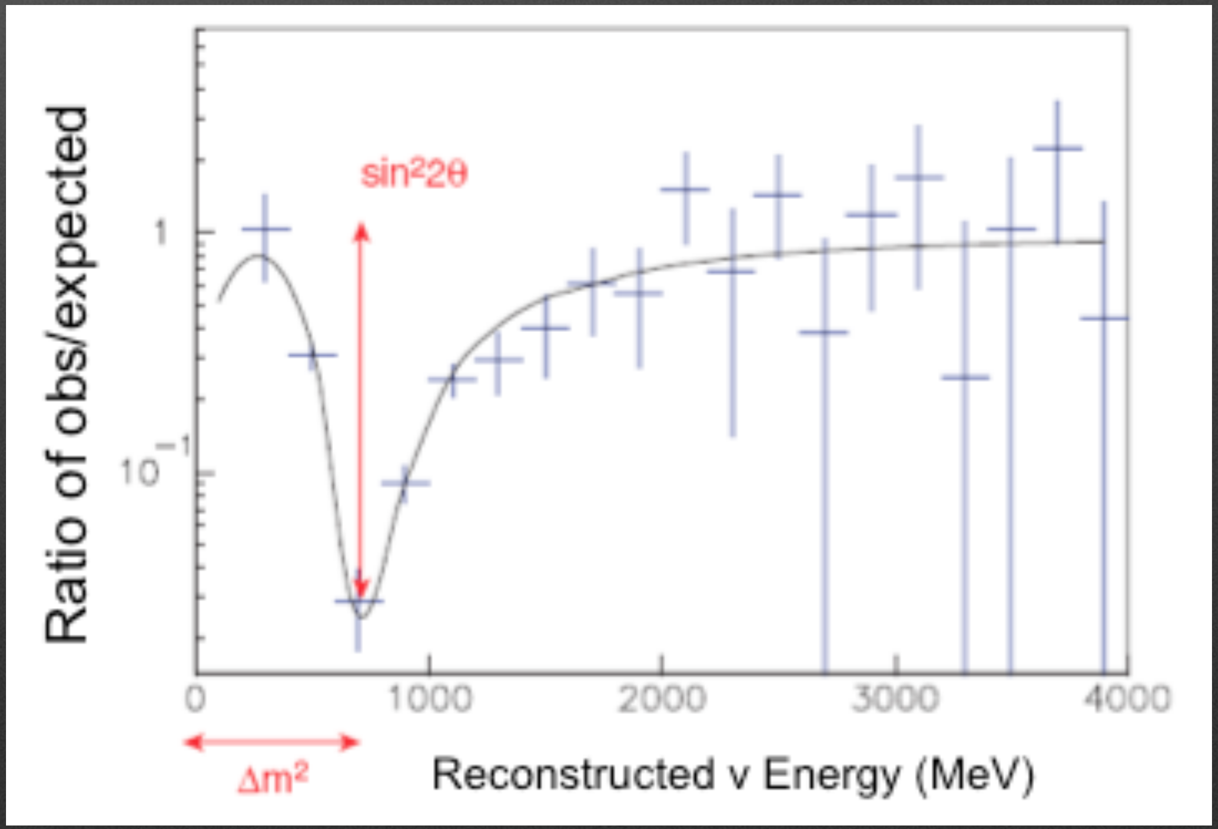
Physics goals

- The T2K experiment was designed to have Super-Kamiokande at the maximum of the oscillation probability
  - Ideal place to look for ν_e appearance (mainly driven by θ_{13} and δ_{CP}) and ν_μ disappearance (θ_{23} and Δm^2_{32})
- If negative pions are focused the beam is predominantly composed of $\overline{\nu}$ and this maximize the δ_{CP} sensitivity

ν_e and $\overline{\nu}_e$ appearance → θ_{13} and δ_{CP}



ν_μ disappearance → θ_{23} and and Δm^2_{32}



Why anti-neutrinos

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

Leading term → θ_{13}

CPV term

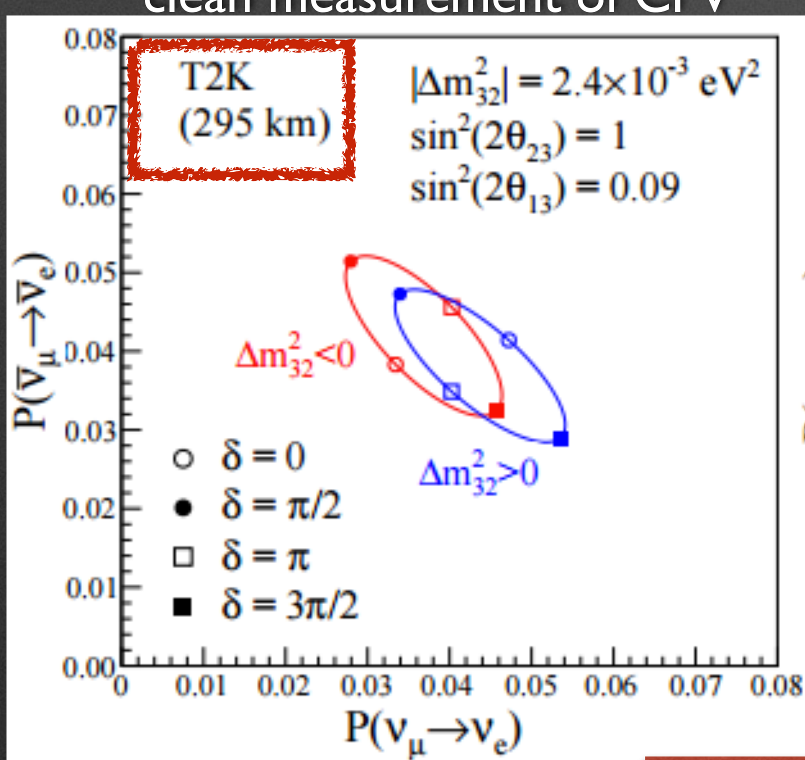
Matter effects

∝ distance

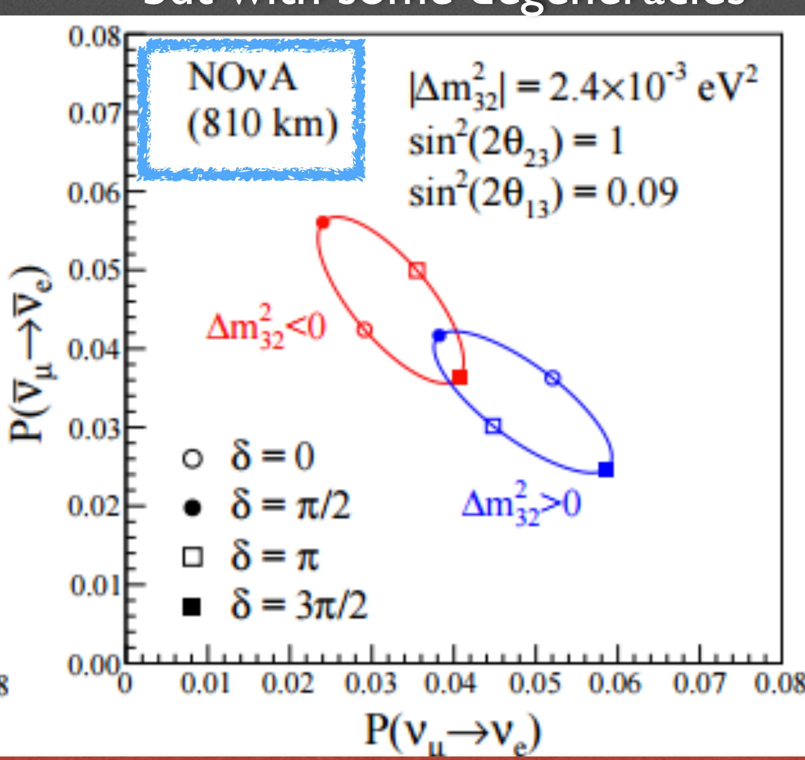
Experimentally we measure an appearance probability

sinδ and **a** change sign from neutrino to antineutrino

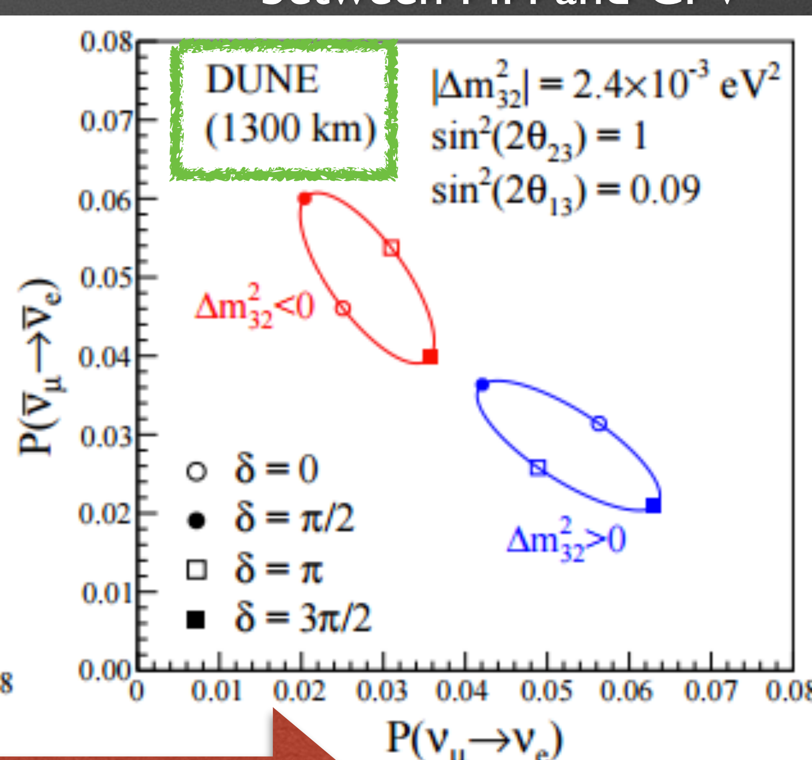
T2K almost no MH —> ~ clean measurement of CPV



NOVA sensitive to MH and CPV but with some degeneracies



DUNE breaks the degeneracy between MH and CPV



increasing baseline

Why antineutrinos

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = {} & 4\boxed{C_{13}^2 S_{13}^2 S_{23}^2} \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \boxed{\sin\delta} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

Leading term → θ_{13}

CPV term

Matter effects

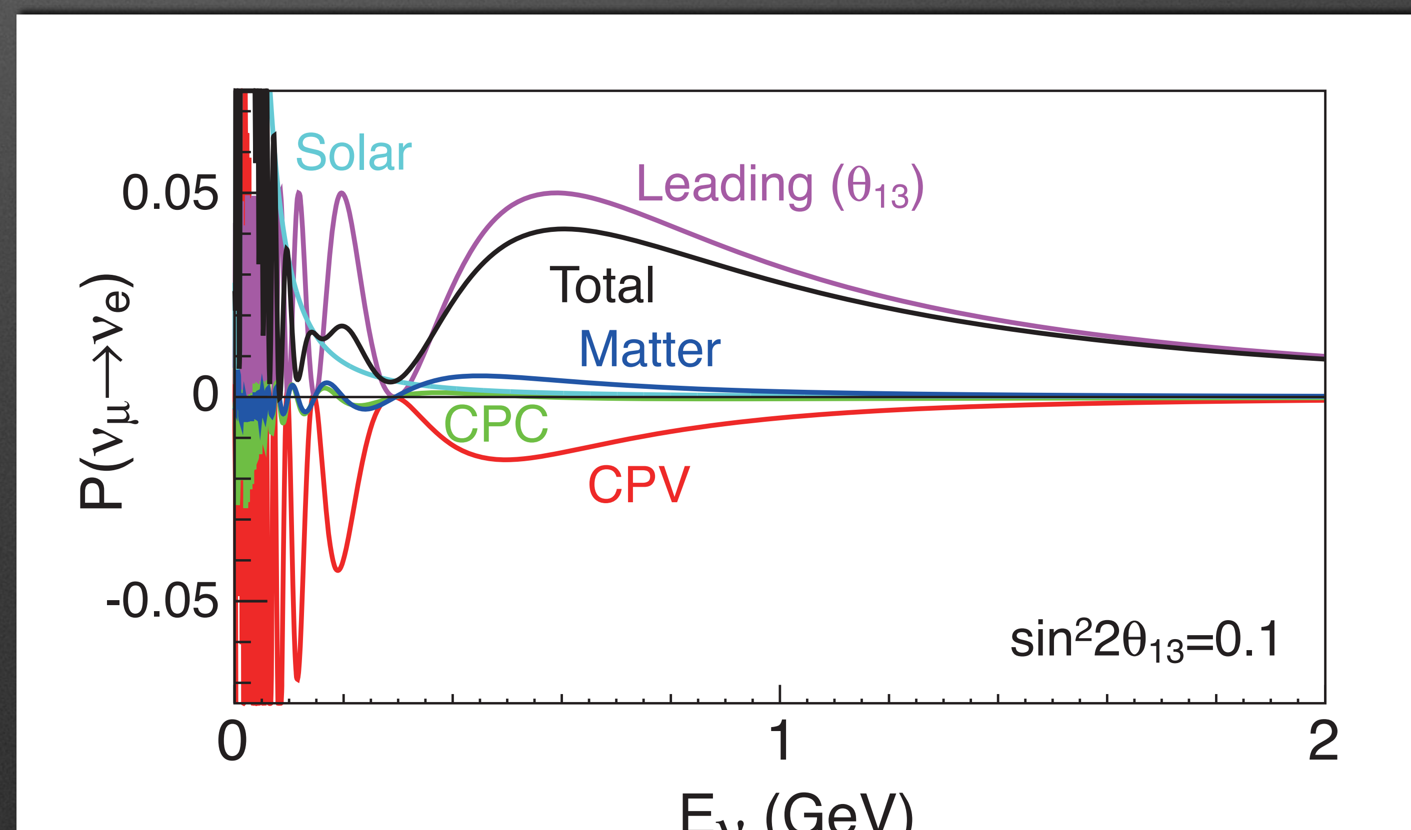
∝ distance

Experimentally we measure an appearance probability

sinδ and **a** change sign from neutrino to antineutrino

In case of T2K where the baseline is short we have:

δ_{CP} effect ±30%
MH effect ~10%



T2K Oscillation Analysis

Flux prediction:
- ✓ Proton beam stability
- ✓ Hadron production (NA61 and others external data)

ND280 measurements:
- ✓ ν_μ selection to constrain flux and cross-sections
- ✓ Measure ν_e beam component

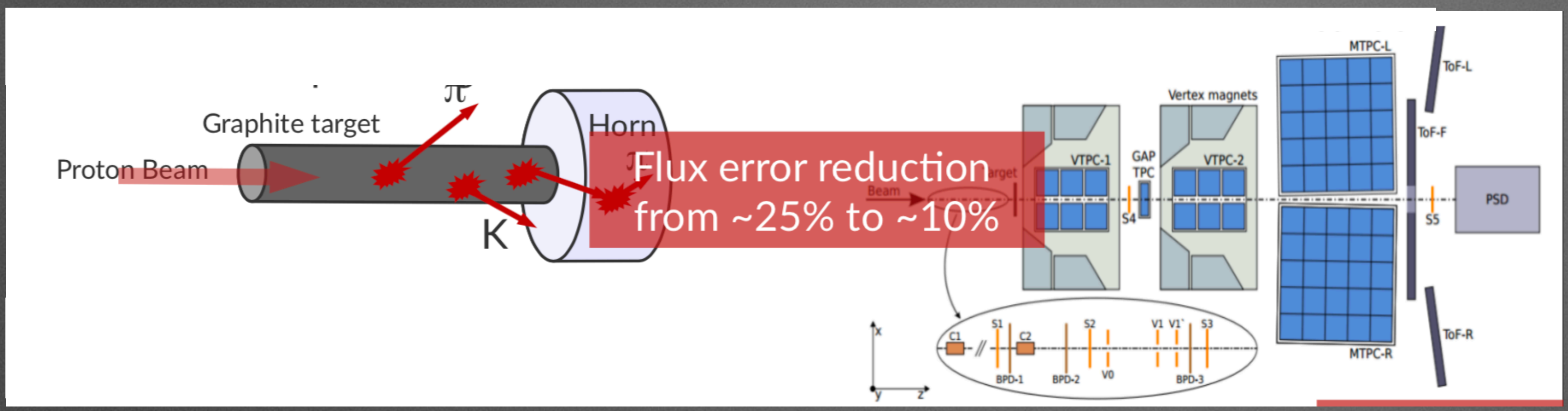
Neutrino interactions:
- ✓ Interaction models
- ✓ External cross-section data

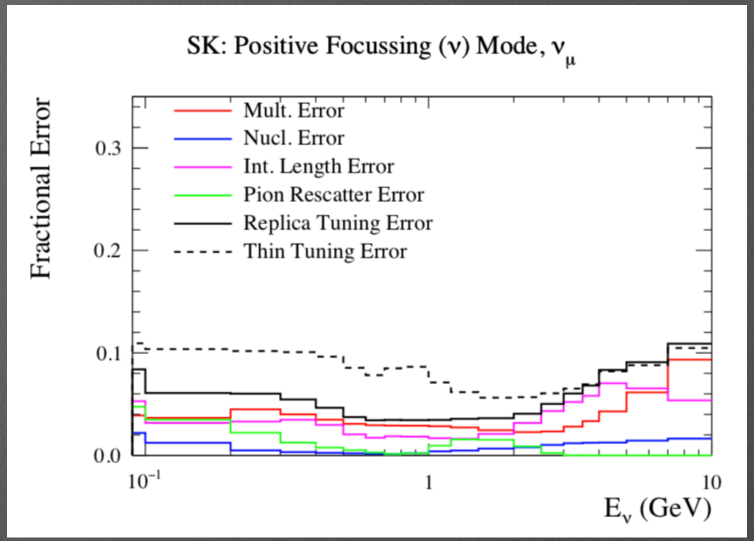
Prediction at the Far Detector:
- ✓ Combine flux, x-section and ND280 to predict the expected events at SK

Extract oscillation parameters!!

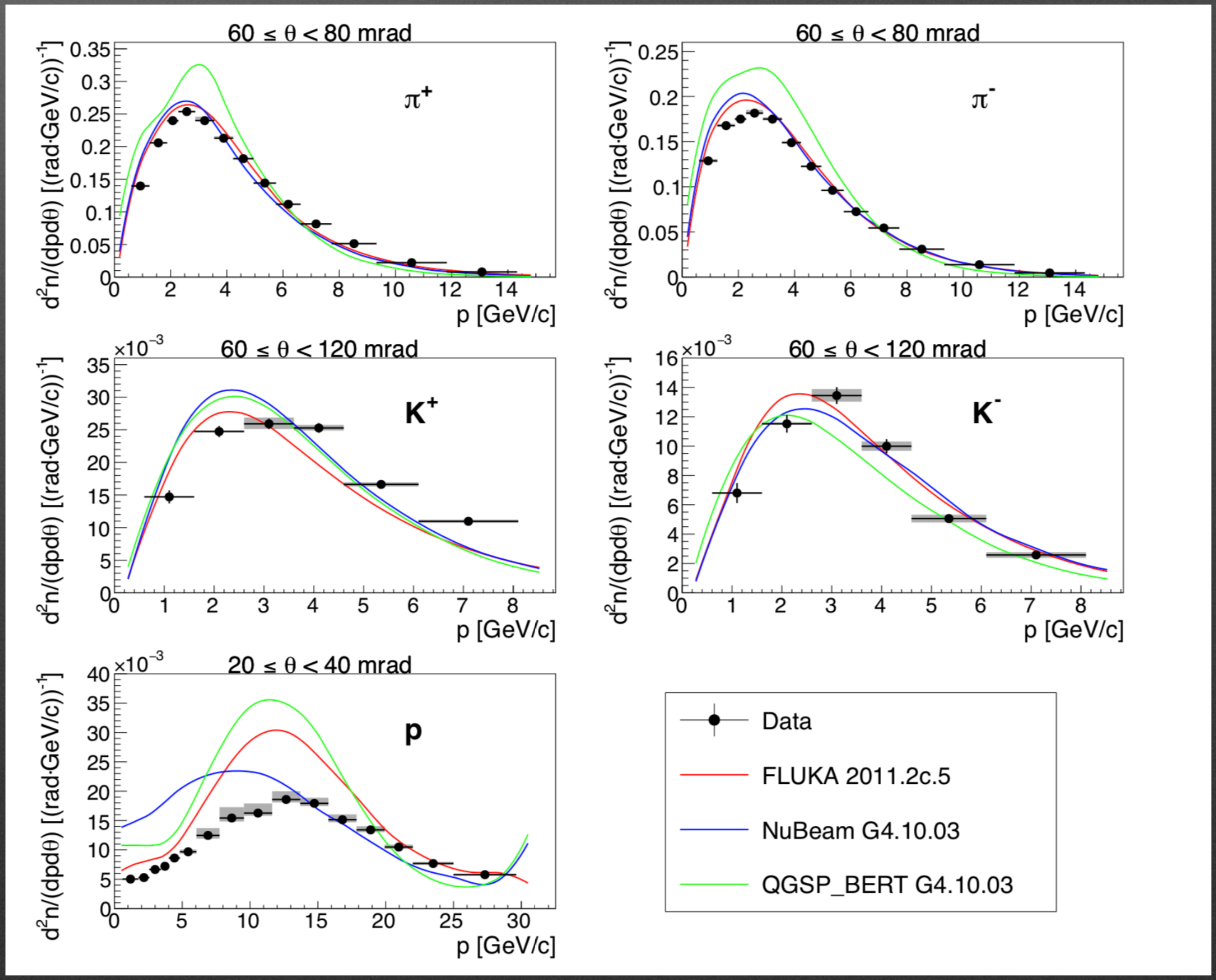
Super-Kamiokande measurements:
- ✓ Select CC ν_μ and ν_e candidates after the oscillations

NA61/SHINE

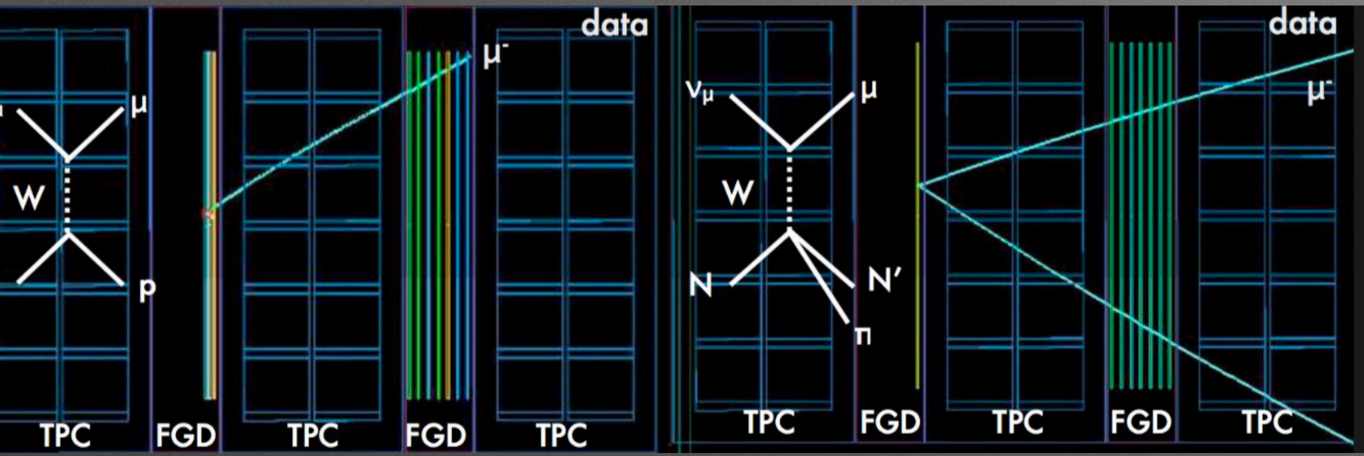


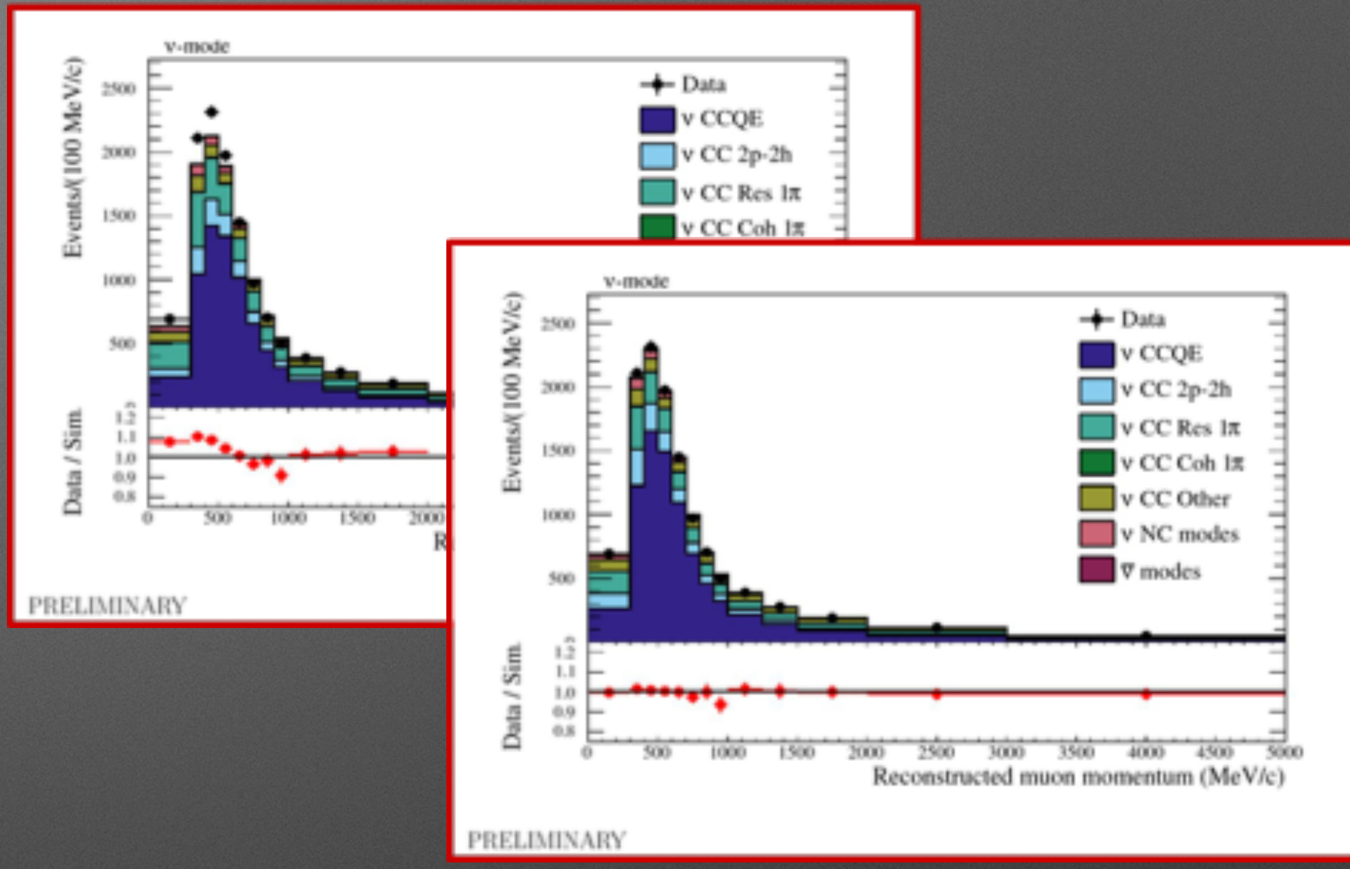


* Multipurpose detector @ CERN → precision hadron production measurements for T2K (and FNAL) neutrino fluxes predictions
* Took data for T2K in 2007, 2009, 2010 with thin and replica target
* Thin target data already used → 10% uncertainties on neutrino fluxes
* Inclusion of 2010 data with replica target will allow to reduce flux uncertainties to ~5% level

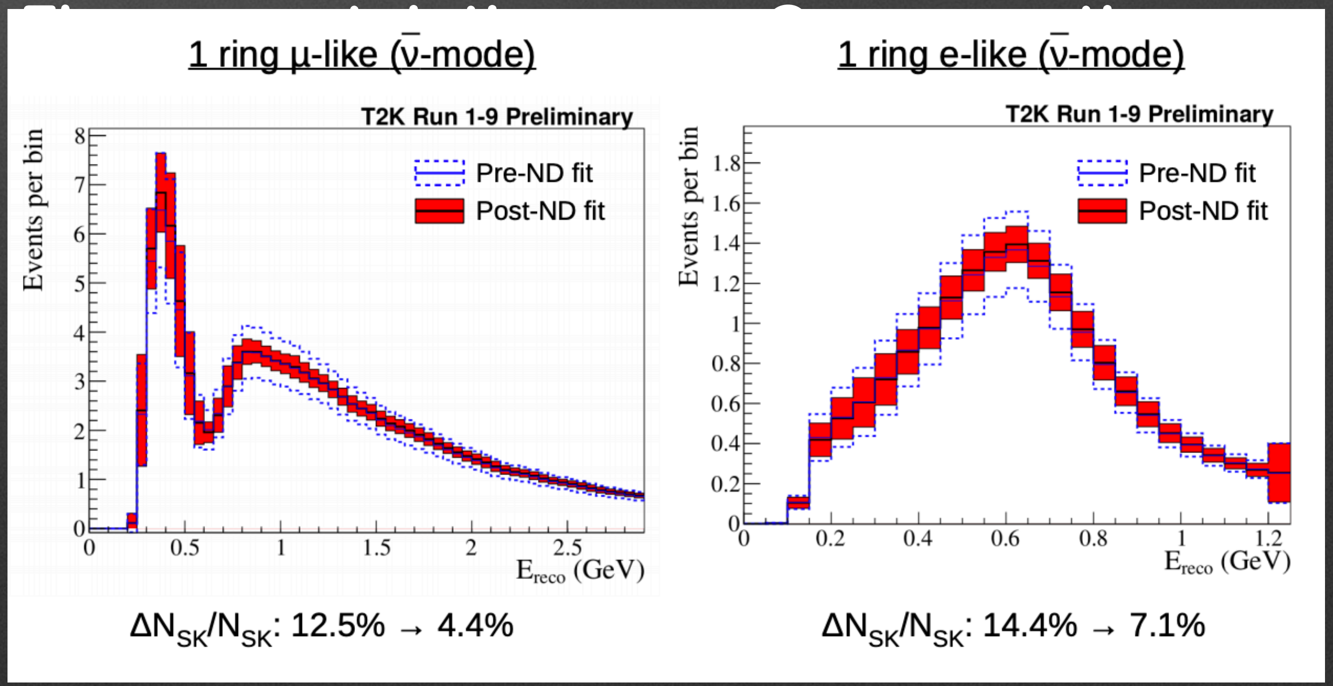


ND280



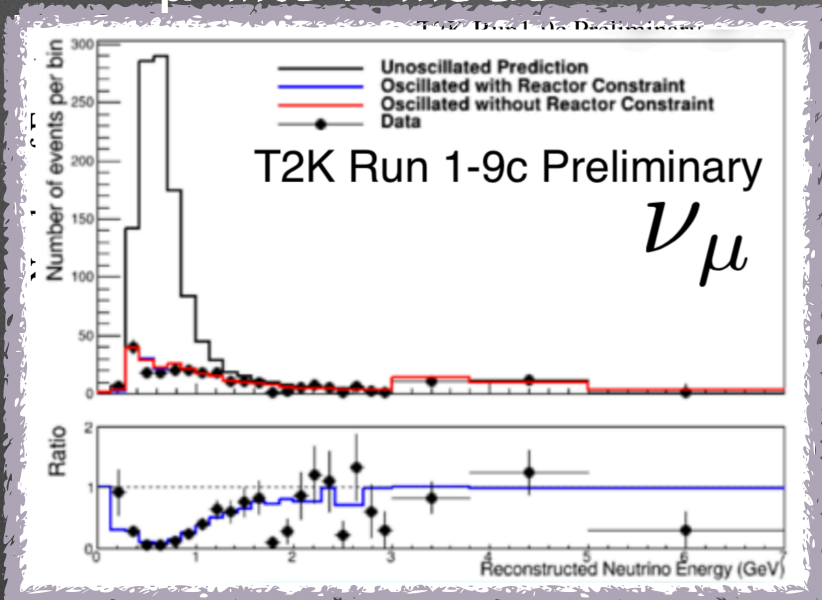


- Select 14 samples of ν_μ and $\overline{\nu}_\mu$ interactions on Carbon and Water with 0,1,>1 π in the final state
- Likelihood fit to constraint flux and cross-section uncertainties for T2K Oscillation Analysis
- Reduce uncertainties from ~15% to ~5%

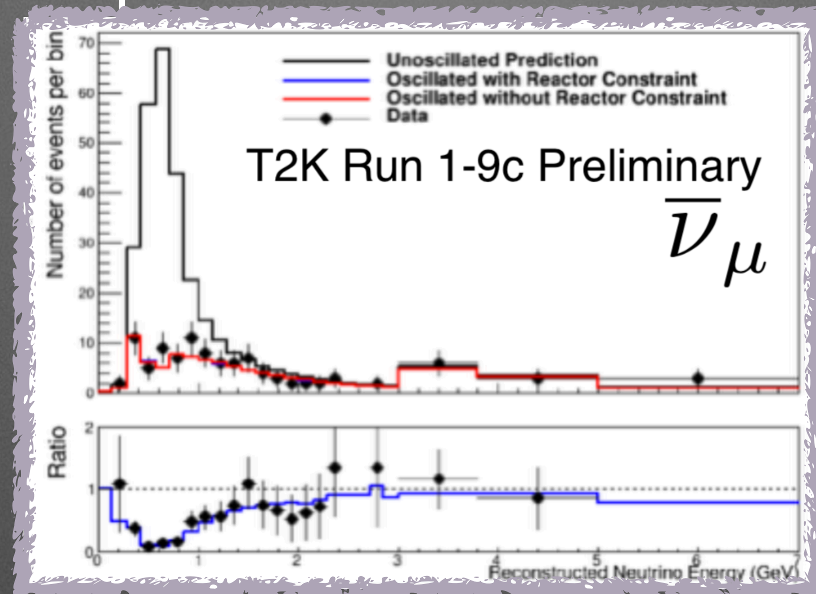


Super-K

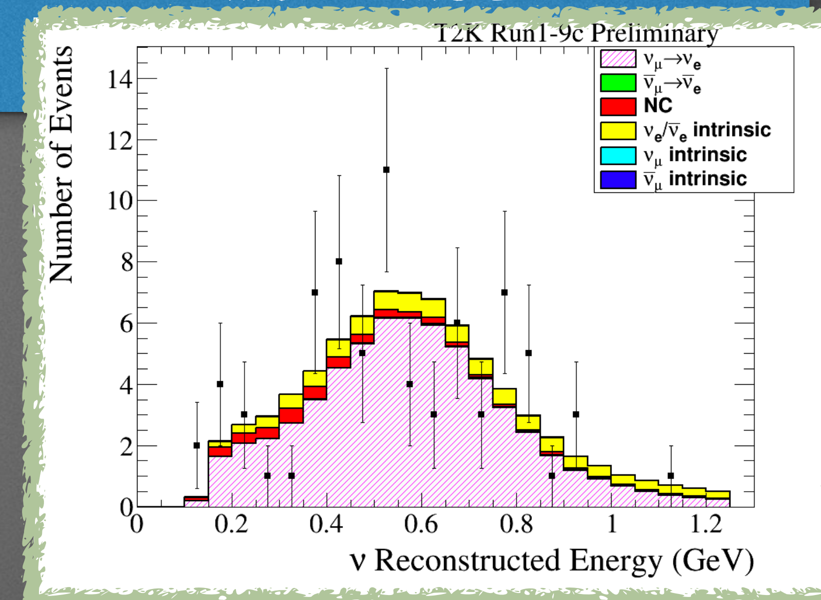
μ-like ν-mode

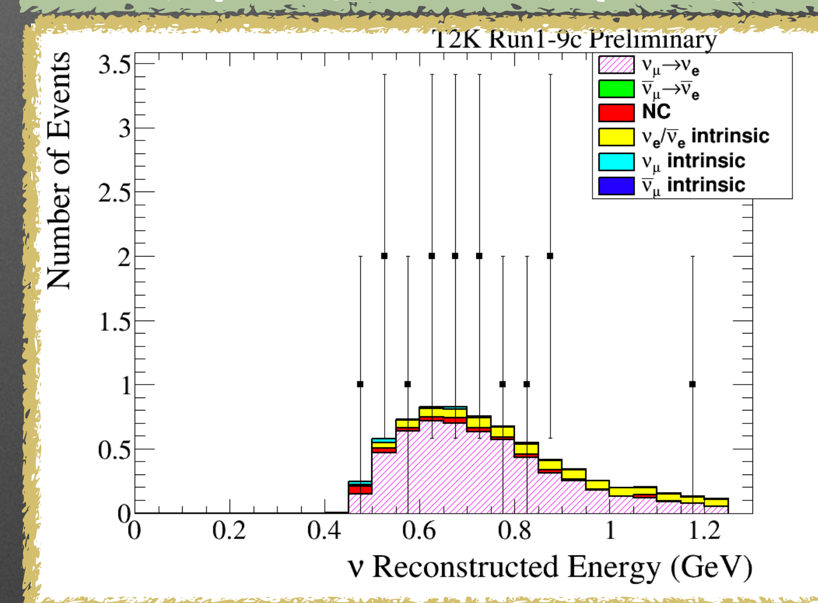


μ-like $\bar{\nu}$-mode

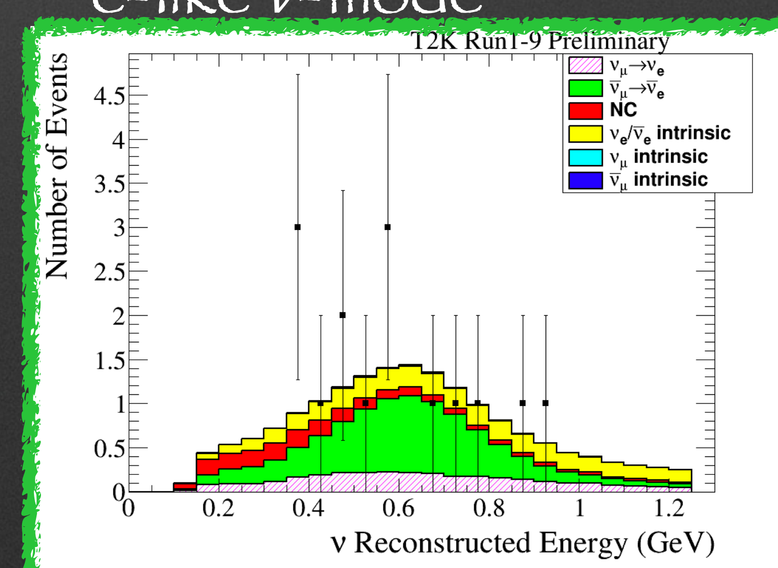


e-like ν-mode



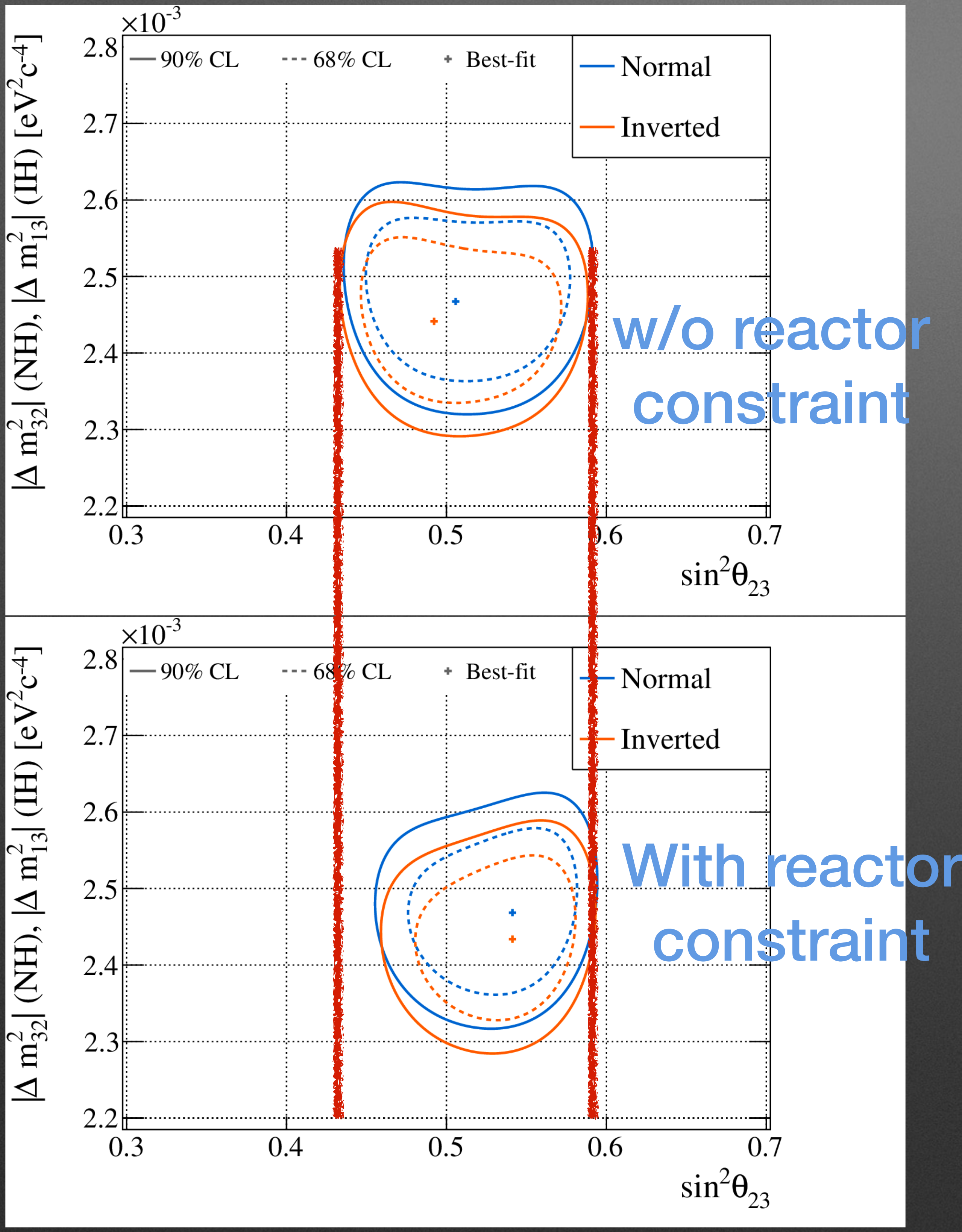


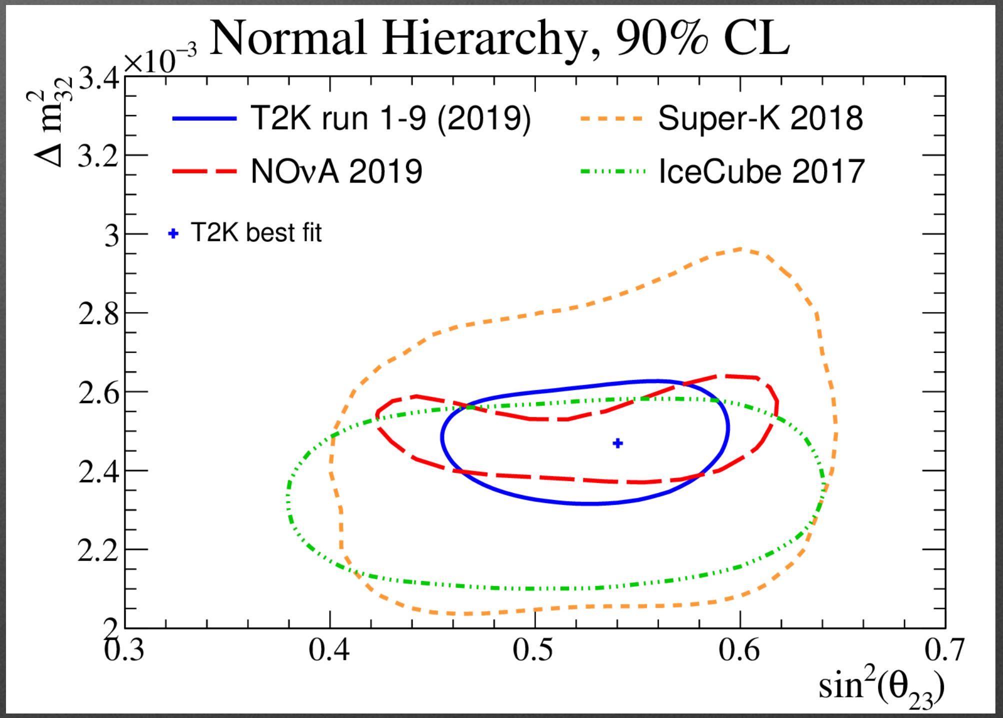
e-like $\bar{\nu}$-mode



	Data	MC expected Number of events			
		$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$
ν-mode μ-like	243	272.3	272.0	272.3	272.7
$\bar{\nu}$-mode μ-like	140	139.5	139.1	139.5	139.8
ν-mode e-like	75	74.5	62.3	50.6	62.8
$\bar{\nu}$-mode e-like	15	17.1	19.6	21.7	19.3
ν-mode e-like+1π	15	7.0	6.1	4.9	5.9

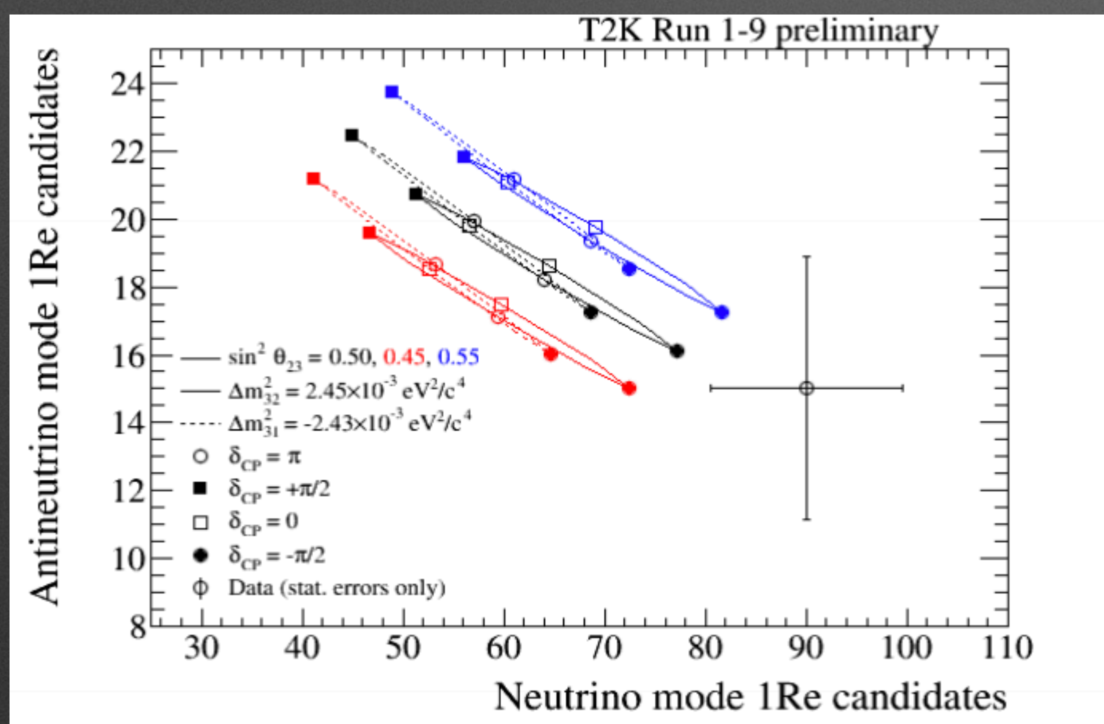
Δm^2_{32} and θ_{23}



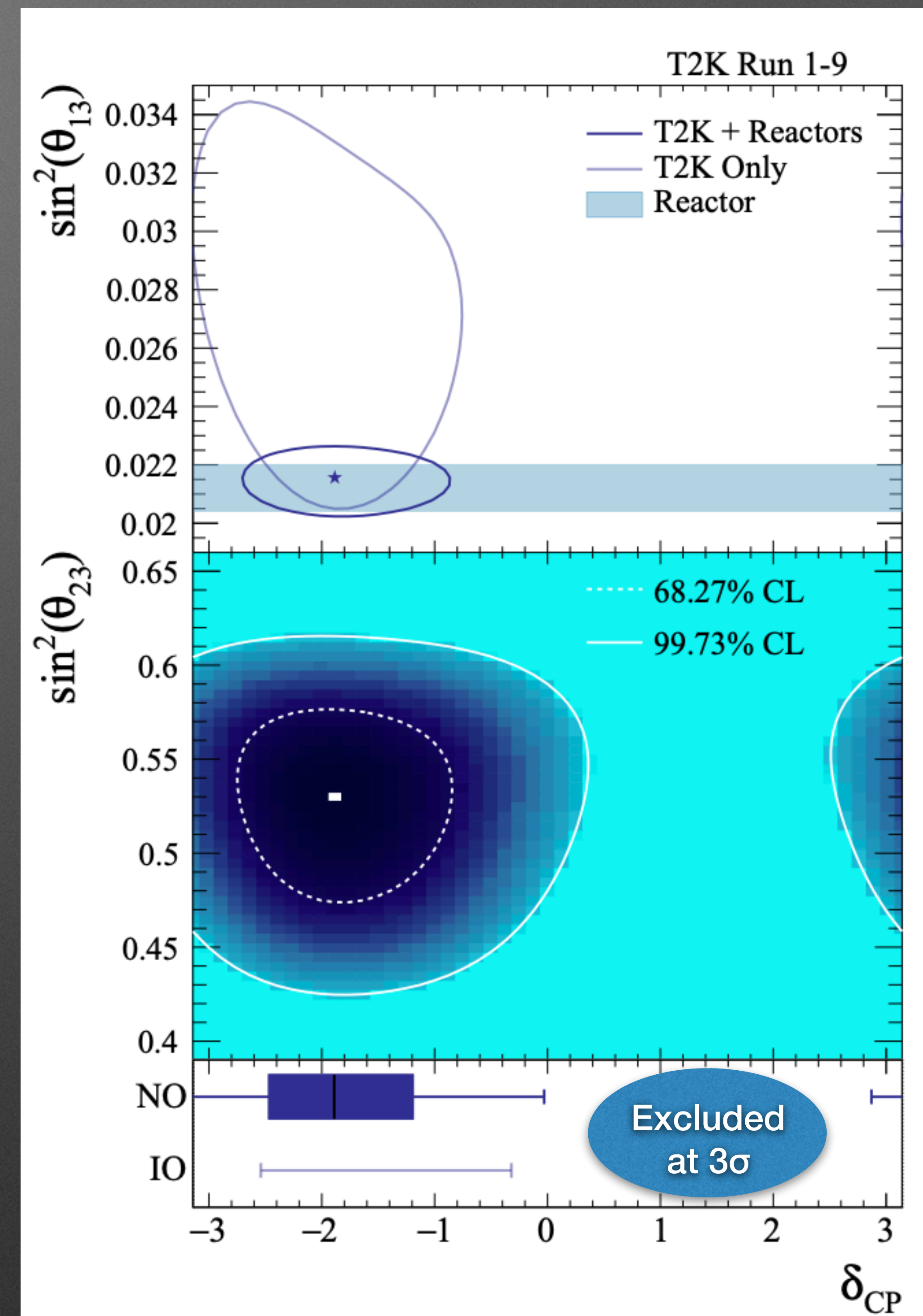


Search for CP violation

- Paper submitted to Nature: Constraint of the matter-antimatter symmetry violating phase in Neutrino oscillations
- First 3σ exclusion for 46% (65%) of the δ_{CP} values in NO (IO)
- Need more data (and smaller systematics)!

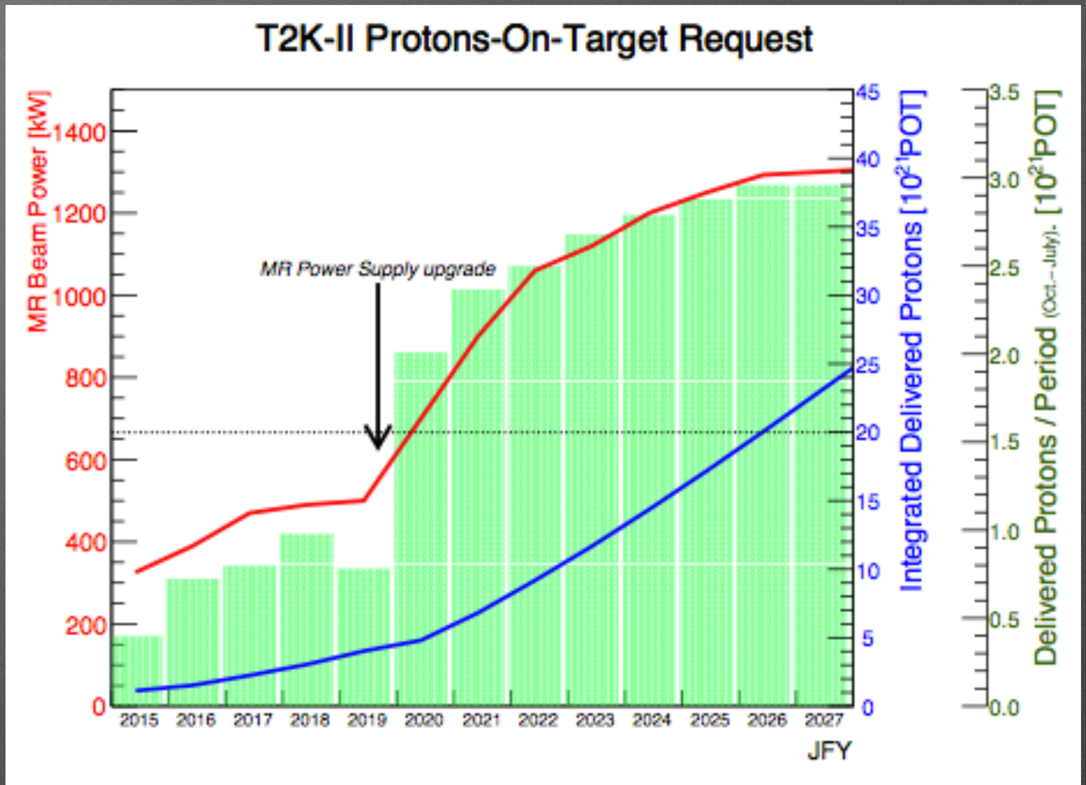


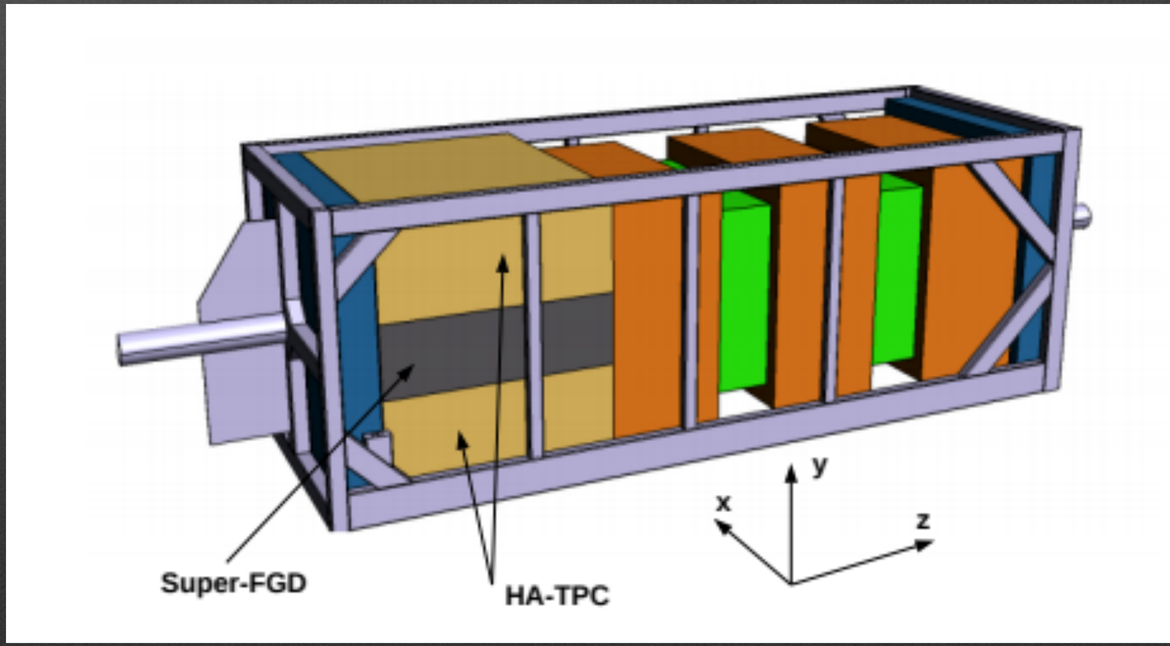
	ν-mode	$\bar{\nu}$-mode
Observed	**90**	**15**
Exp ($\delta_{CP}=-\pi/2$)	81.7	17.2
Exp ($\delta_{CP}=0$)	68.4	19.6



T2K phase-II

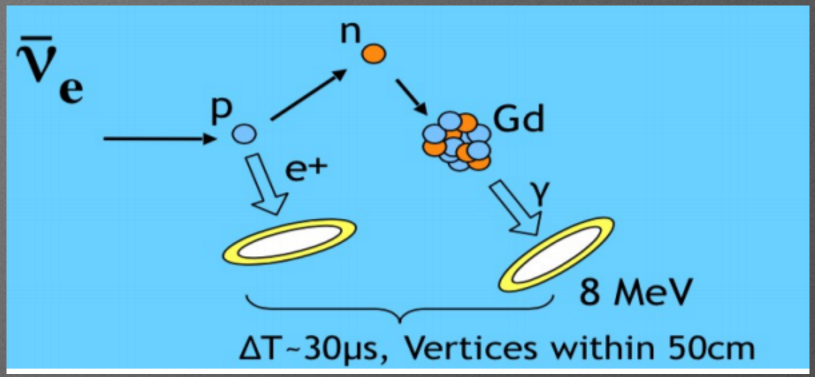
- Upgrade of J-PARC Main Ring (1.3 MW beam)
    - Approved and funded, will be done in 2021
- Goal: collect >10x10^{21} POT by 2026 → 3σ measurement of CP violation if δ_{CP}~-π/2
- Near Detector upgrade to reduce systematics from ~7% to ~4%
    - We will install the new detectors in 2021
    - Use the ND280 Upgrade detector also as initial Near Detector for HK
- Improvements of the Far Detector thanks to the SK-Gd project

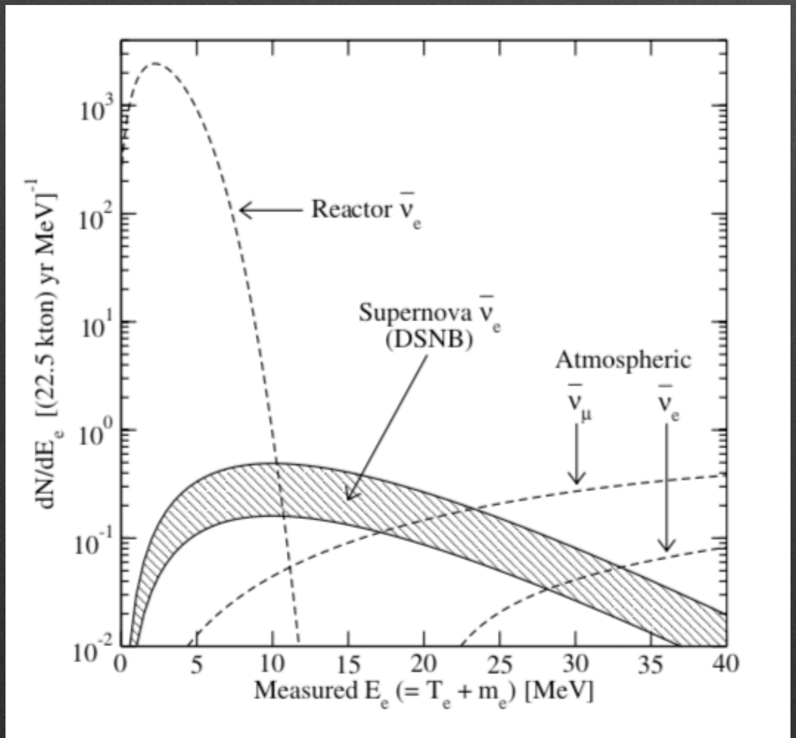


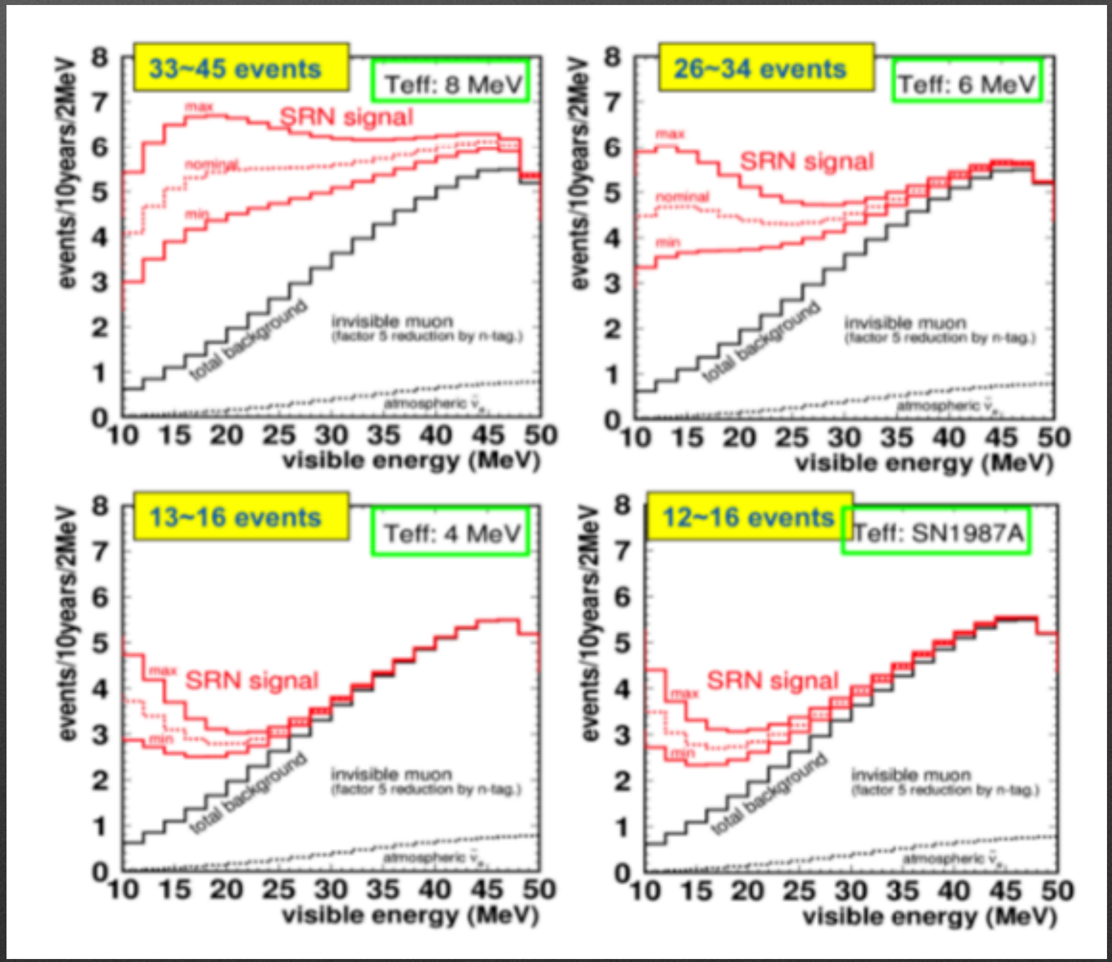


SK-Gd

- Huge repair work in 2018 to prepare the loading of SK with Gadolinium
- SK ready to be loaded with Gd in 2020 (0.02% → 0.2% in a second phase)
- Enhance neutron tagging capability → crucial to distinguish ν from $\bar{\nu}$ → detect SN-relic antineutrinos from IBD (3-5 events per year are expected)
- The Gd loading will also be useful for T2K

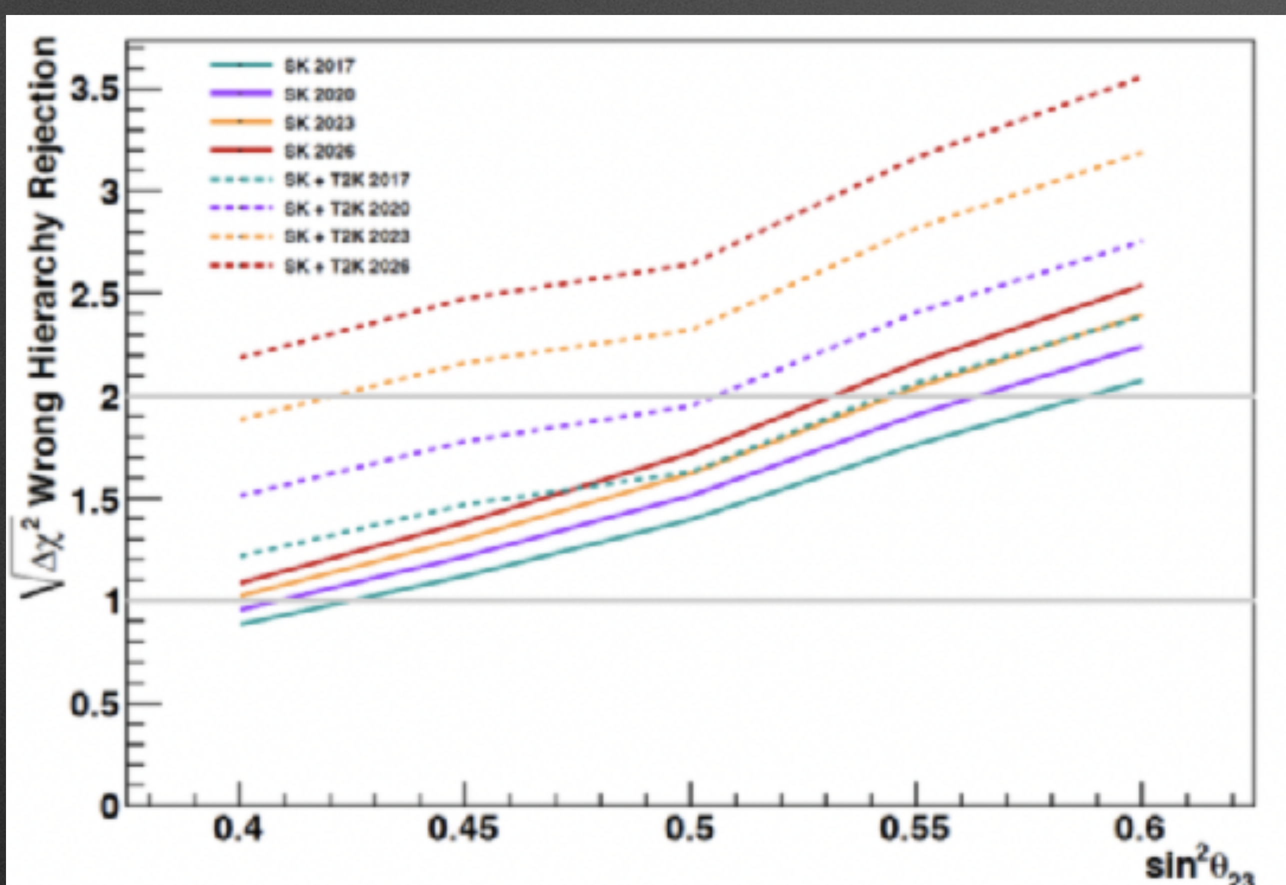


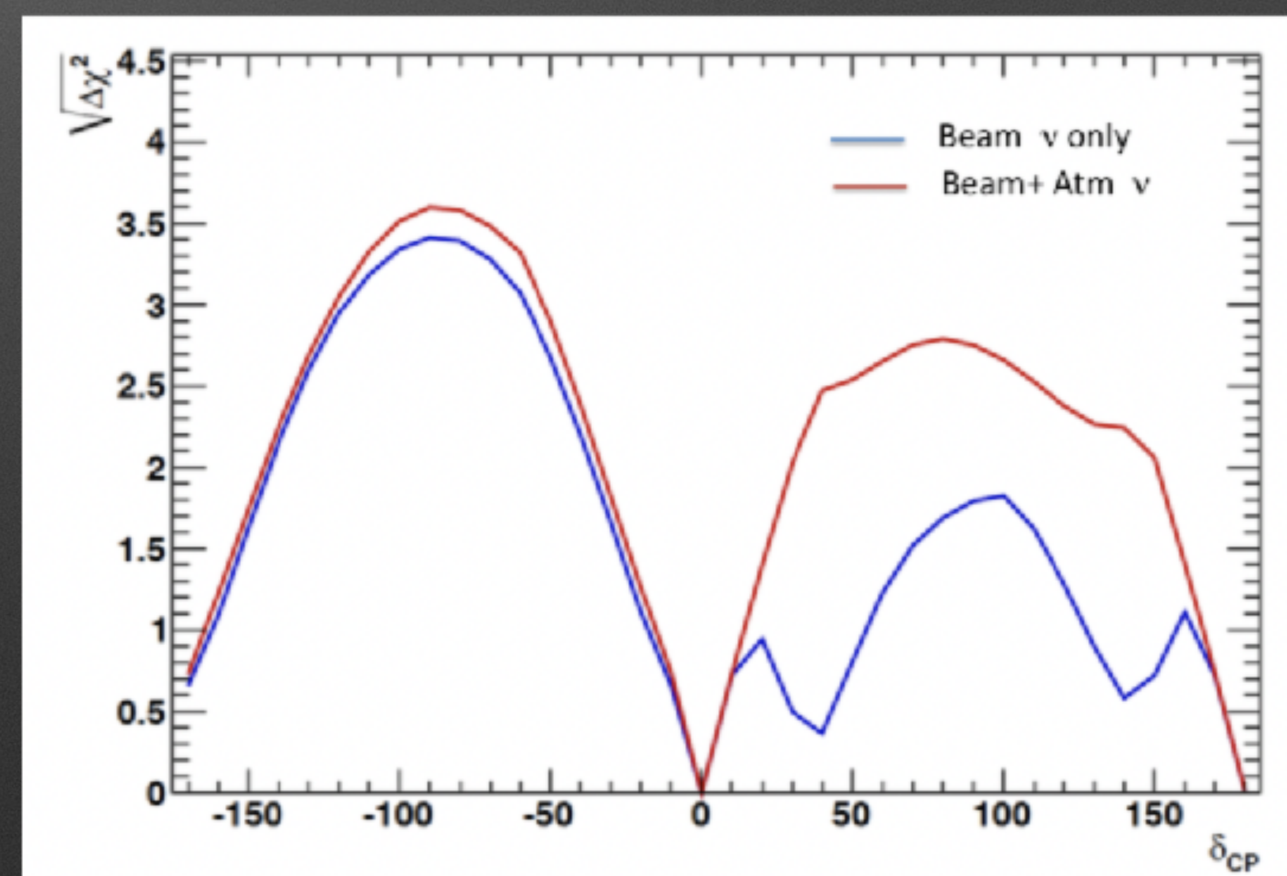




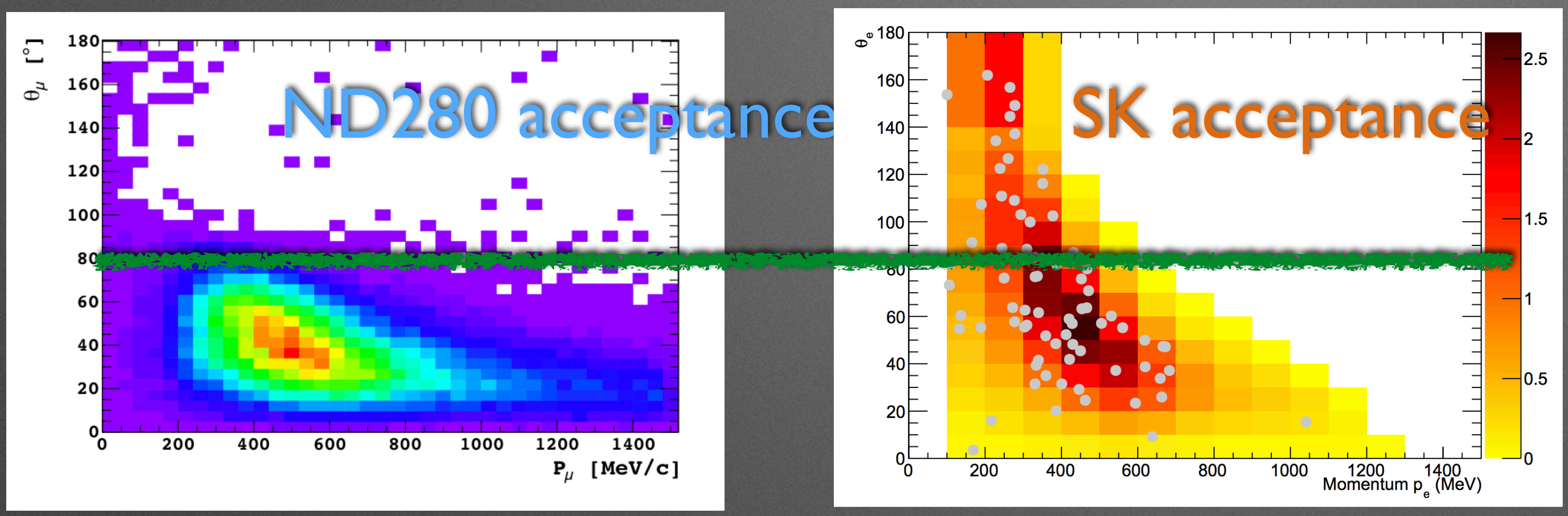
Combinations of oscillation analyses

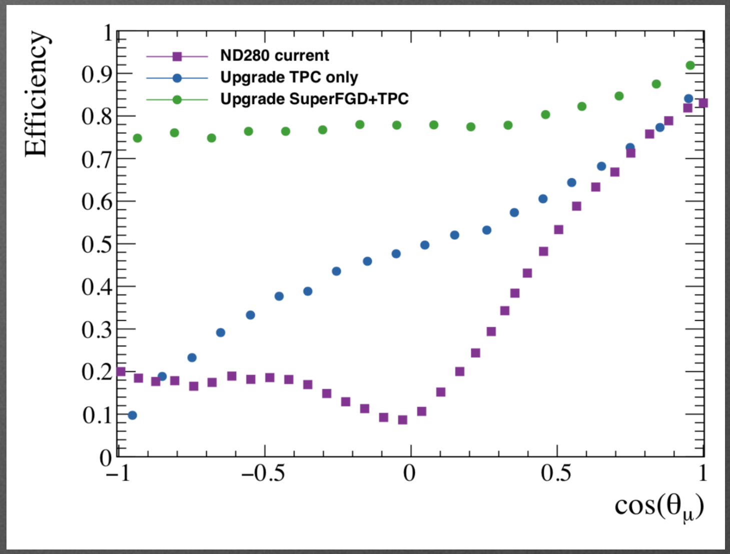
- Discussion on-going with NOvA to produce combined oscillation analysis
- Recently an MoU between T2K and SK collaborations has been signed in order to produce an official T2K/SK combined analysis
  - Already done by SK collaboration using public T2K data as external constraints (Phys. Rev. D 97, 072001 (2018))
  - Use Near Detector data to improve SK atmospheric model
  - Combine T2K and SK samples to improve sensitivity to mass ordering and to δCP (by breaking some degenaracies)



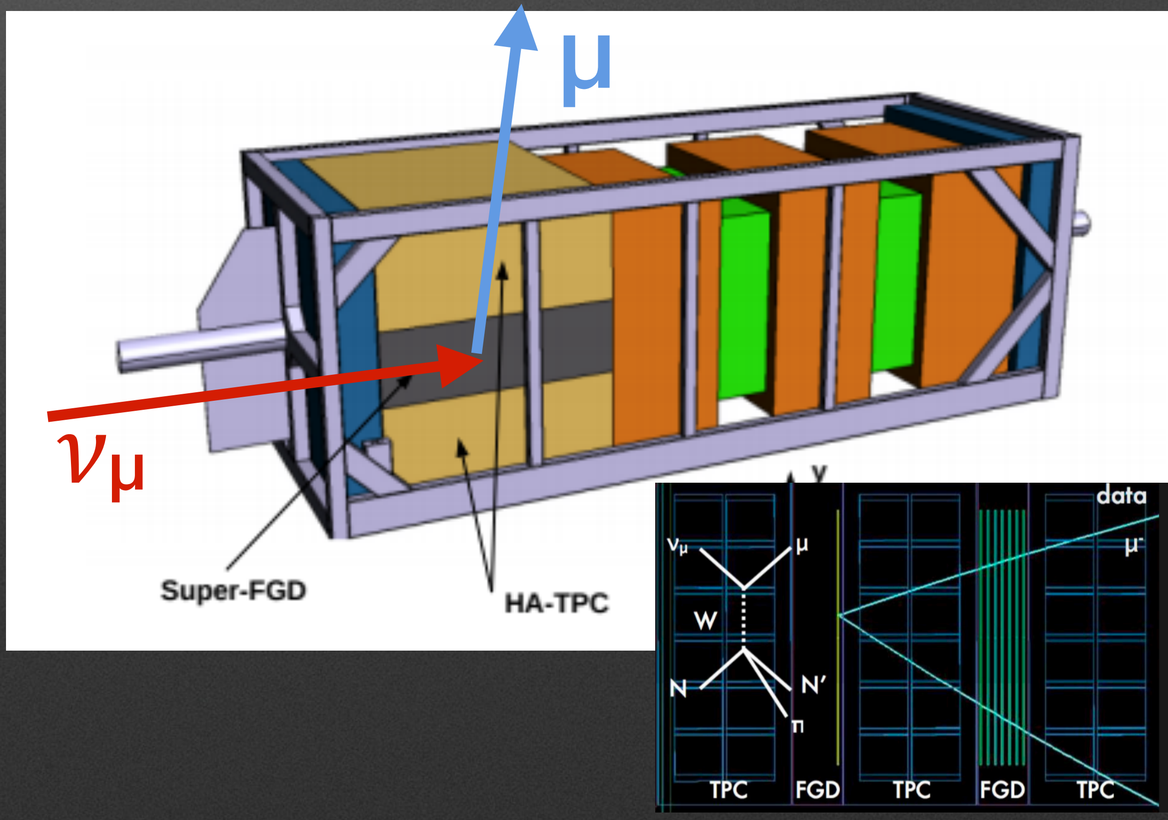


ND280 upgrade

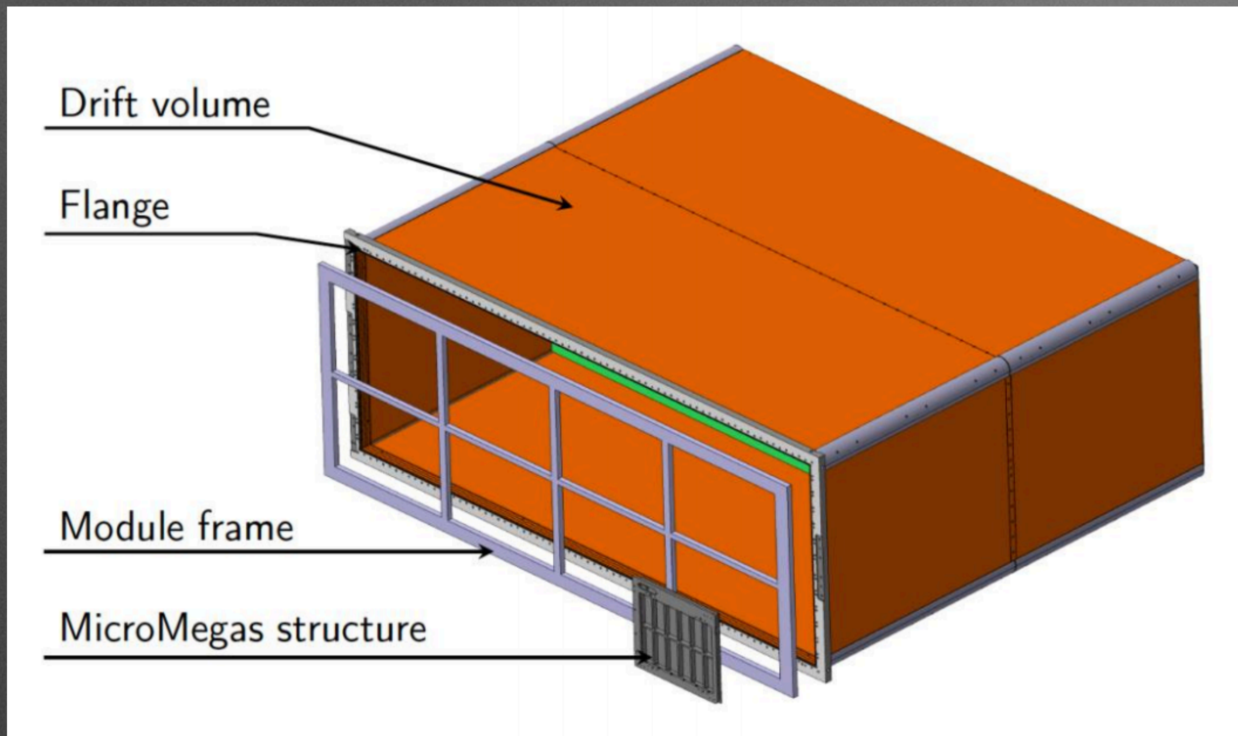


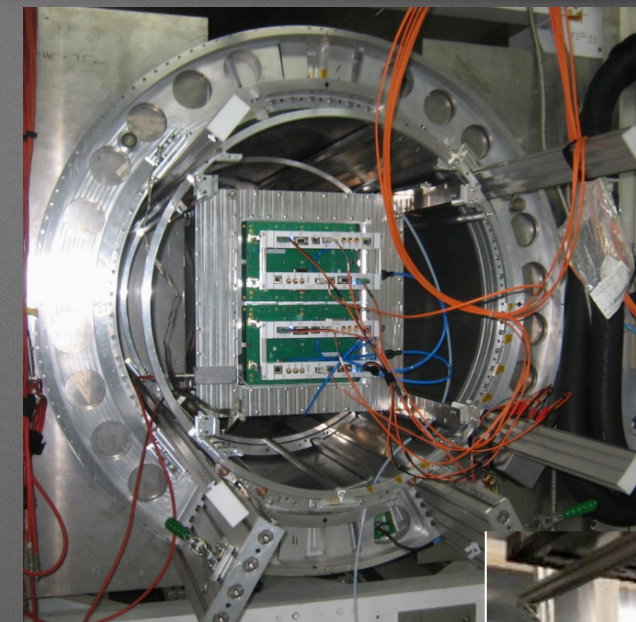


- Main strength of ND280 : magnetized detector → separate ν from $\bar{\nu}$ (cannot be done in SK or HK)
- Main limitation of ND280 : reduced angular acceptance → only forward going muons are selected with high efficiency
- An analysis dedicated to select tracks with high polar angles → 20% efficiency
- We can do better with an upgrade → Horizontal target and horizontal TPCs

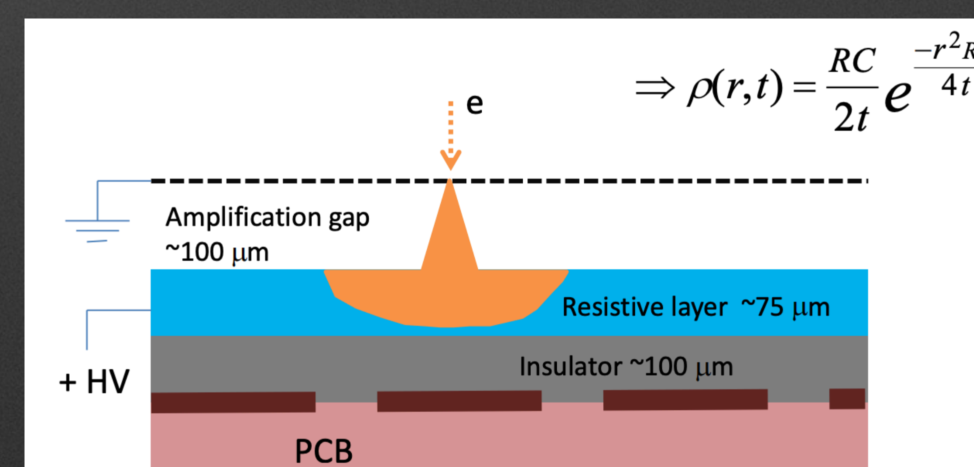


HA-TPC





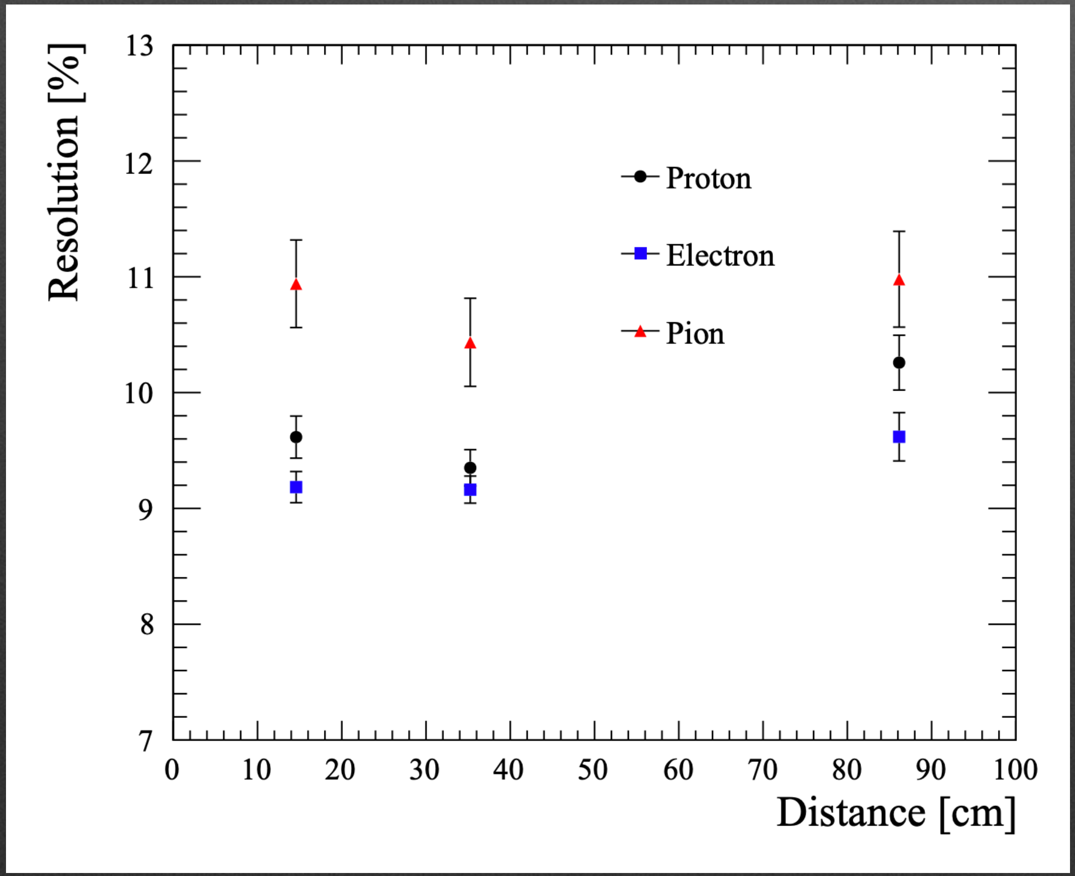
- 2 rectangular TPCs
- Instrumented with resistive MicroMegas modules (8 on each side, 32 in total)
- Require momentum resolution of 10% at 1 GeV, dE/dx resolution better than 10%

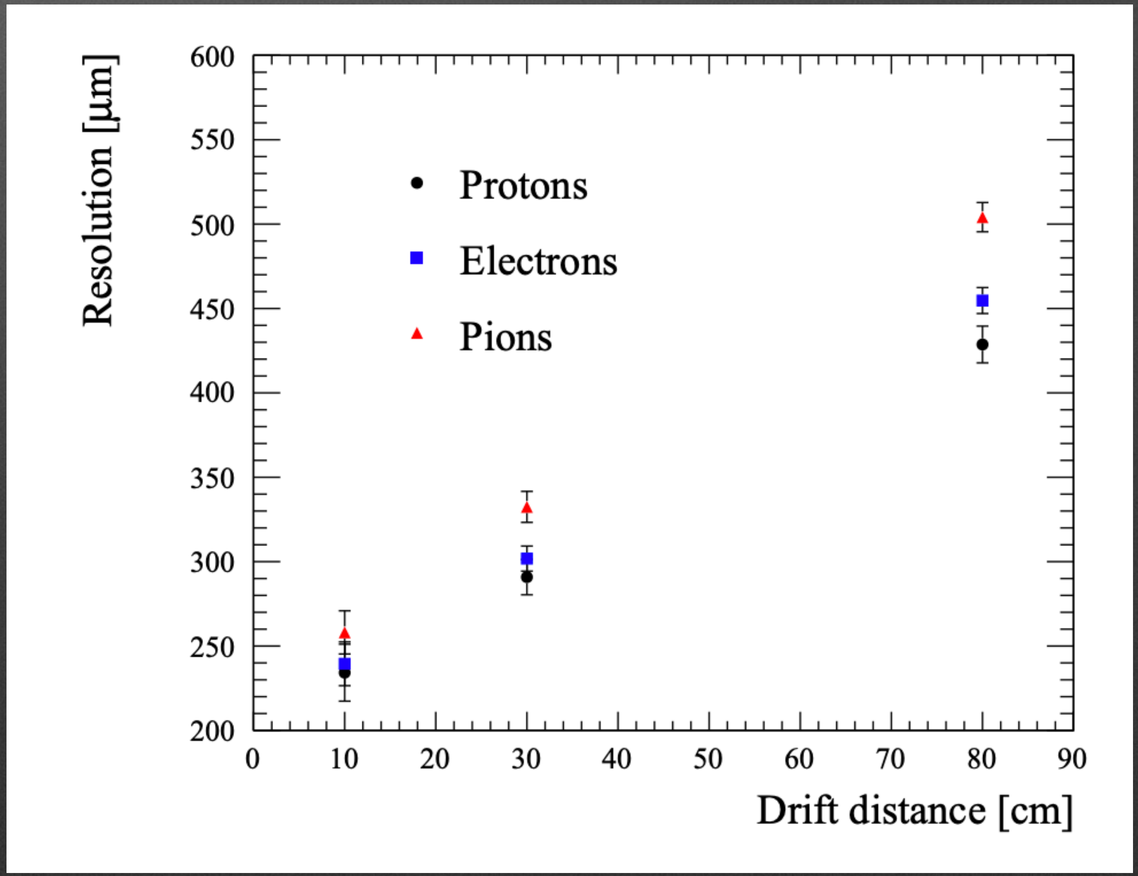


Test Beam results

- Resistive MM modules exposed at test beams at CERN (2018) and DESY (2019)

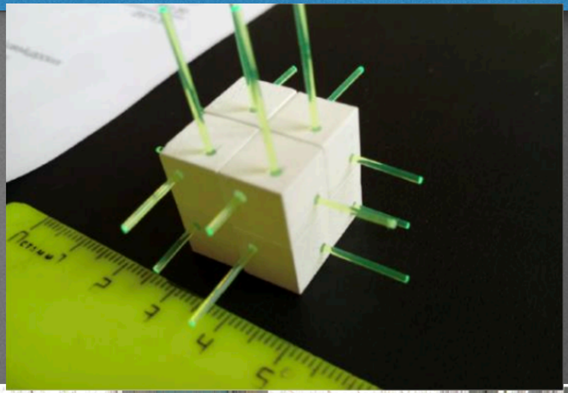
  - Spatial resolution ~200 µm for horizontal tracks
  - dE/dx resolution ~10% → 7% for 70 cm tracks

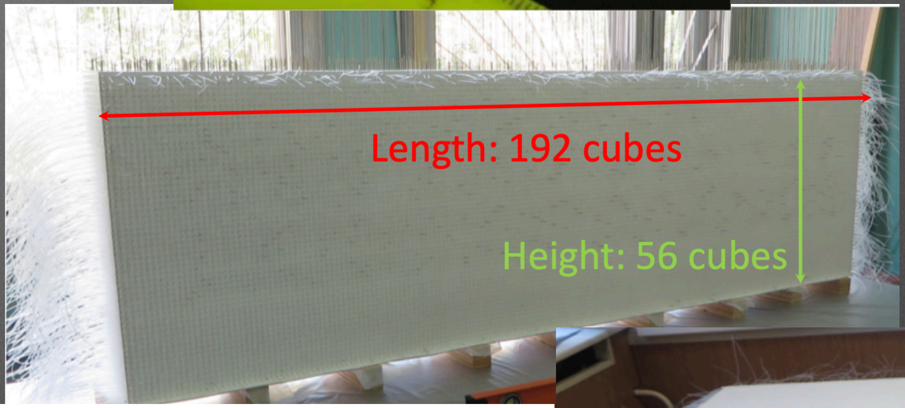


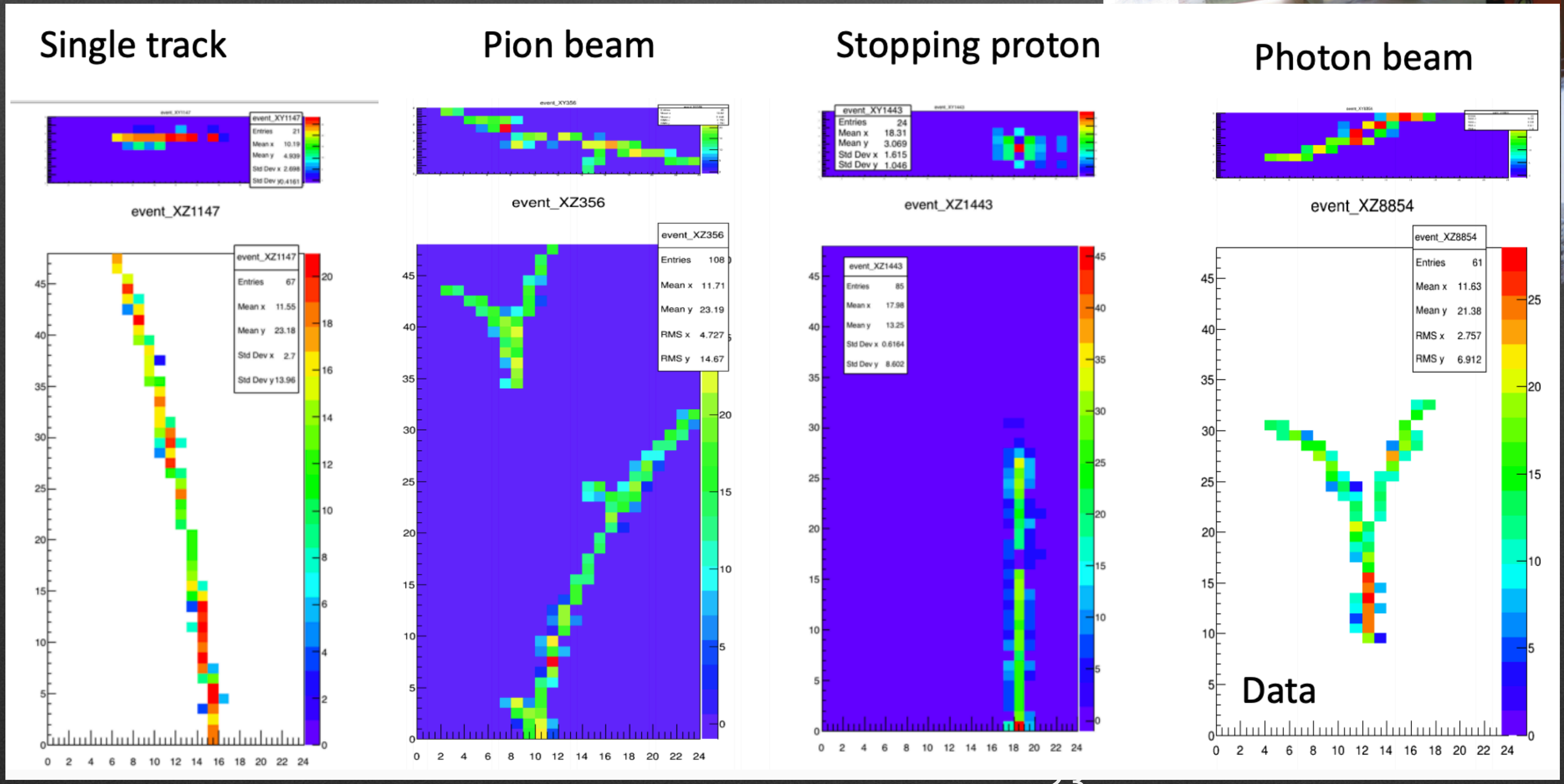


Super-FGD

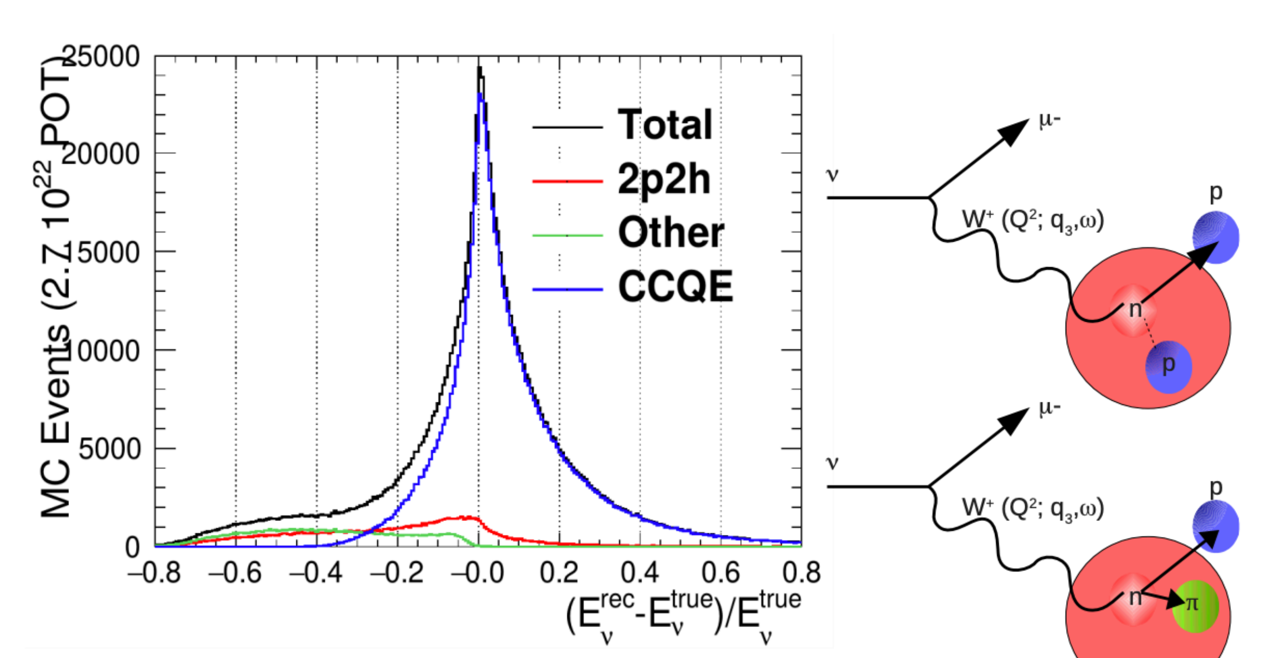
- New concept of detectors, 2×10^6 $1 cm^3$ cubes
  - 25% of the cubes already built
  - All produced by Dec 2020
- Each read by 3 WLS
- Improve reconstruction of the hadronic part of the interactions







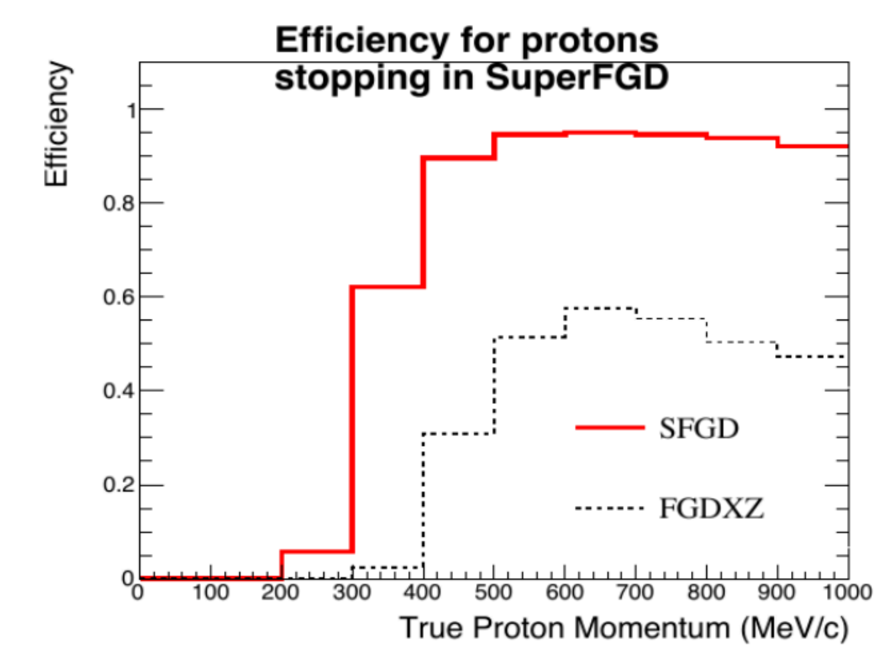
Physics impact

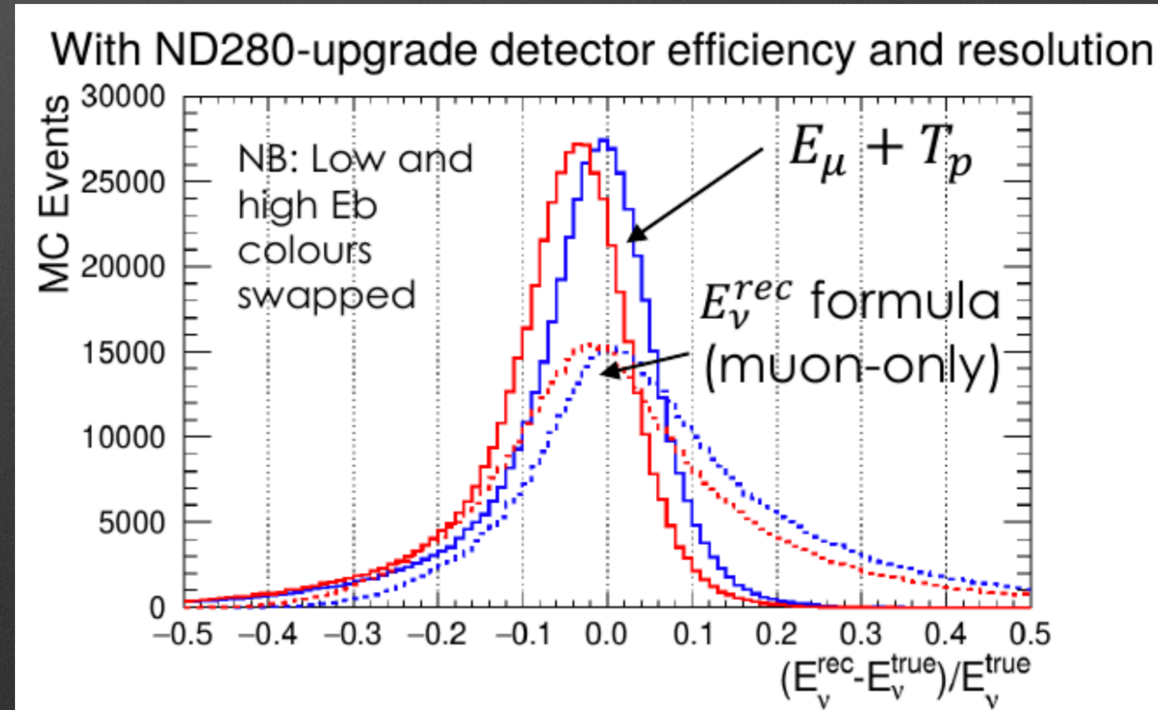


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Posc depends on L/E_{true}
We reconstruct the energy
in the QE assumption

By reconstructing the hadronic
part of the interaction we would
be able to recunstruct the energy
in calorimetric way

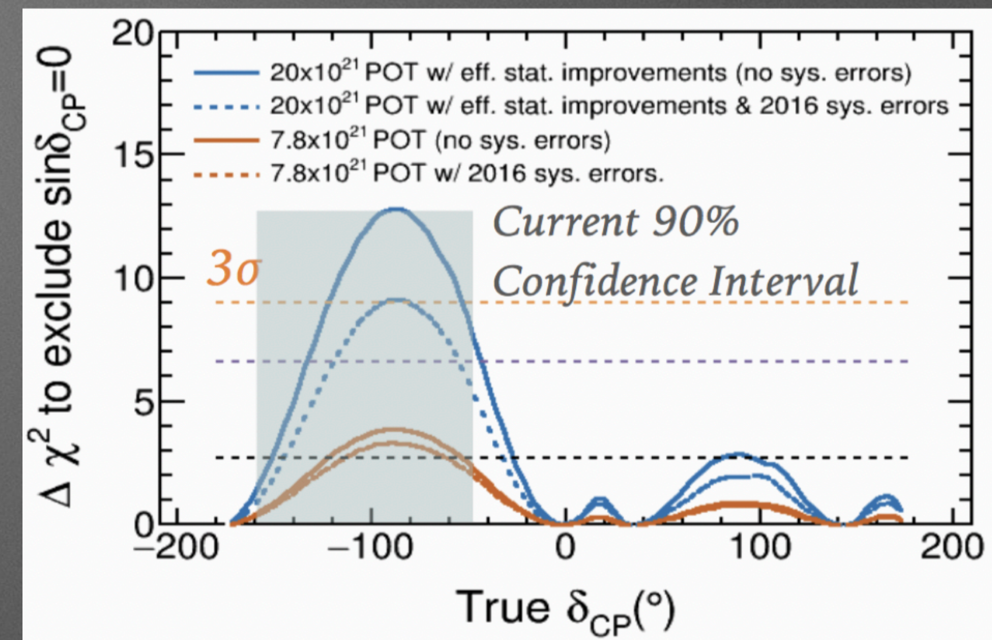




Sensitivity of T2K-II

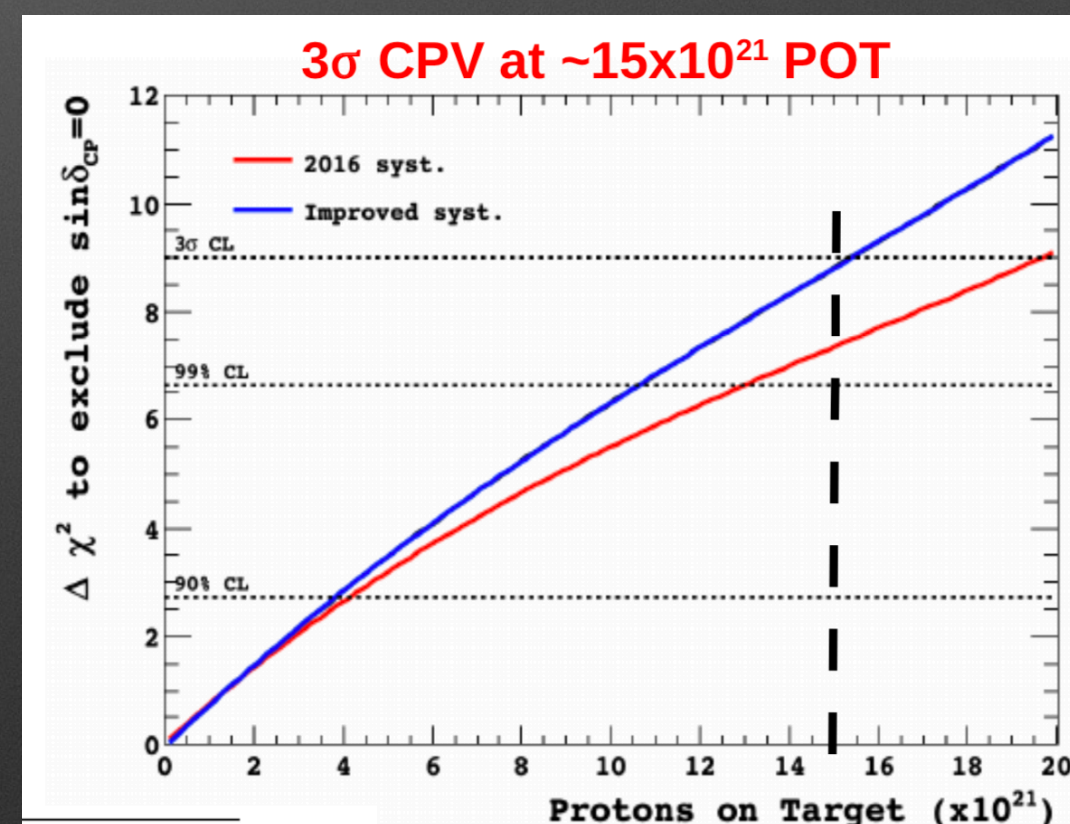
T2K-II Expression of Interest (10E21 POT for nu and 10E21 POT for an

	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode	0	454.6	346.3	3.8	72.2	1.8	30.5
ν_e sample	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$-mode	0	129.2	16.1	71.0	28.4	0.4	13.3
$\bar{\nu}_e$ sample	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3



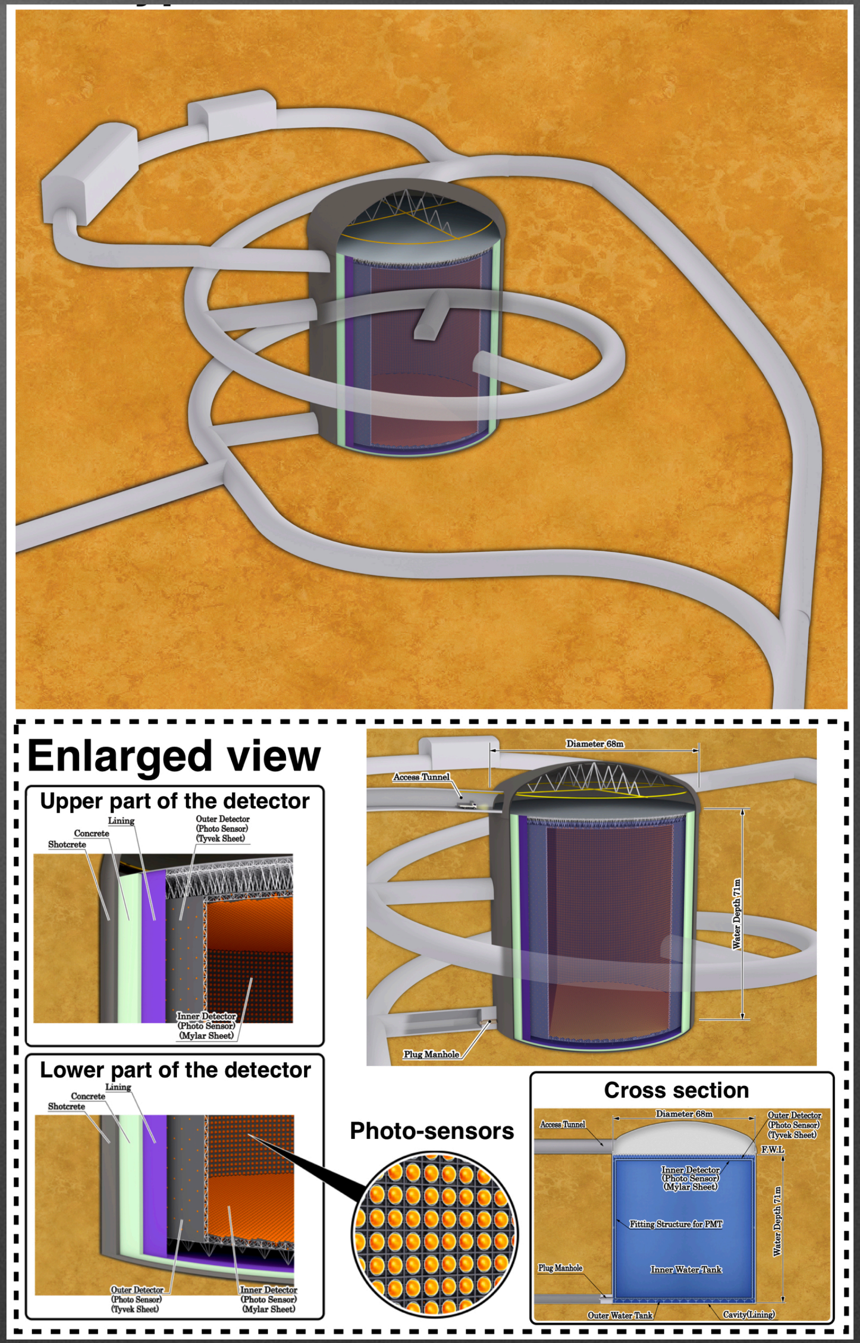
- The upgrade will help reducing systematics uncertainties in oscillation analysis → earlier sensitivity to δ_{CP}

- Necessity to collect enough proton-on-target!



Hyper-Kamiokande

- Extremely well established Water Cherenkov technology
    - 190 kton FV (SK 22.5), instrumented with up to 40k PMTs
- HK will be the most sensitive observatory for rare events (proton decay, SN neutrinos, …)
- Search for CP violation in lepton sector
    - Upgrade of J-PARC neutrino beam (1.3 MW)
    - Near and Intermediate detector complex
- August 2019 → MEXT approved HK and required budget for construction to the Ministry of Finance
- Begin construction in 2020, start operation in 2027



MEXT Statement

In addition to the ongoing 13 large-scale projects, the next-generation neutrino research project Hyper-Kamiokande, will be newly launched in FY2020

Release by MEXT on Aug. 29, 2019

(MEXT) will start the next-generation neutrino research project "Hyper-Kamiokande" in JFY2020.

○ 日本学術会議において科学的観点から策定したマスタープランを踏まえつつ、専門家等で構成される文部科学省の審議会において戦略性・緊急性等を加味し、ロードマップを策定。

○ ロードマップの中から大規模学術フロンティア促進事業として実施するプロジェクトを選定の上、国立大学法人運営費交付金等の基盤的経費により戦略的・計画的に推進。原則、10年間の年次計画を策定し、審議会における厳格な評価・進捗管理を実施。

○ 現行の13プロジェクトに加え、令和2年度より、ニュートリノ研究の次世代計画である「ハイパーカミオカンデ計画」に新たに着手。

主な成果

○ ノーベル賞受賞につながる画期的研究成果
（受賞歴：H14小柴昌俊氏、H20小林誠氏、益川敏英氏、H27梶田隆章氏）

○ 年間約1万人の共同研究者が集結し、国際共同研究を推進。このうちの半数以上が外国人

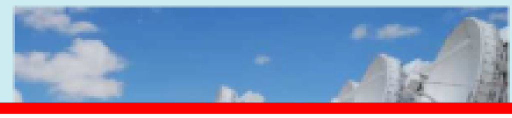
Next generation of neutrino project with a 260 kton detector and the J-PARC upgrade. The project will reveal the mysteries in elementary particles and the Universe by the observation of proton decays and the neutrino researches including CP violation.

天文学・宇宙物理学分野	論文数	Top10%割合	国際共著割合
すばる望遠鏡	644	18.5%	86.3%
アルマ望遠鏡	878	27.3%	89.0%
日本全体	8,938	12.9%	68.0%
世界全体	103,445	9.6%	50.6%

※ 大学共同利用機関法人自然科学研究機構が「InCites」（Web of Science）に基づき、2013–2017の5か年に出版された天文学・宇宙物理学分野の論文（article,review）を分析（2019年7月）。「日本全体」は、著作住所に日本を含む論文を抽出。

大規模学術フロンティア促進事業等の主な事業

大型電波望遠鏡「アルマ」による国際共同利用研究の推進
〔自然科学研究機構国立天文台〕



巨大ブラックホールの「影」の撮影に世界で初めて成功した国際プロジェクトに参加し、高い感度の観測機能により、その成果に大きく貢献。

新しいステージに向けた学術情報ネットワーク(SINET)整備
〔情報・システム研究機構国立情報学研究所〕

等を高速通信回線ネットワークで究の基盤を提供。全国900以上機関、約300万人の研究者・学我が国の教育研究活動に必須の学術情報基盤。

NEW

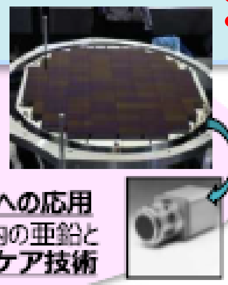
ハイパーカミオカンデ(HK)計画の推進
〔東京大学宇宙線研究所〕
〔高エネルギー加速器研究機構〕

日本が切り拓いてきたニュートリノ研究の次世代計画として、超高感度光検出器を備えた総重量26万トンの大型検出器の建設及びJ-PARCの高度化により、ニュートリノの検出性能を著しく向上。素粒子物理学の大統一理論の鍵となる未発見の陽子崩壊探索やCP対称性の破れなどのニュートリノ研究を通じ、新たな物理法則の発見、素粒子と宇宙の謎の解明を目指す。【ロードマップ2017掲載事業】

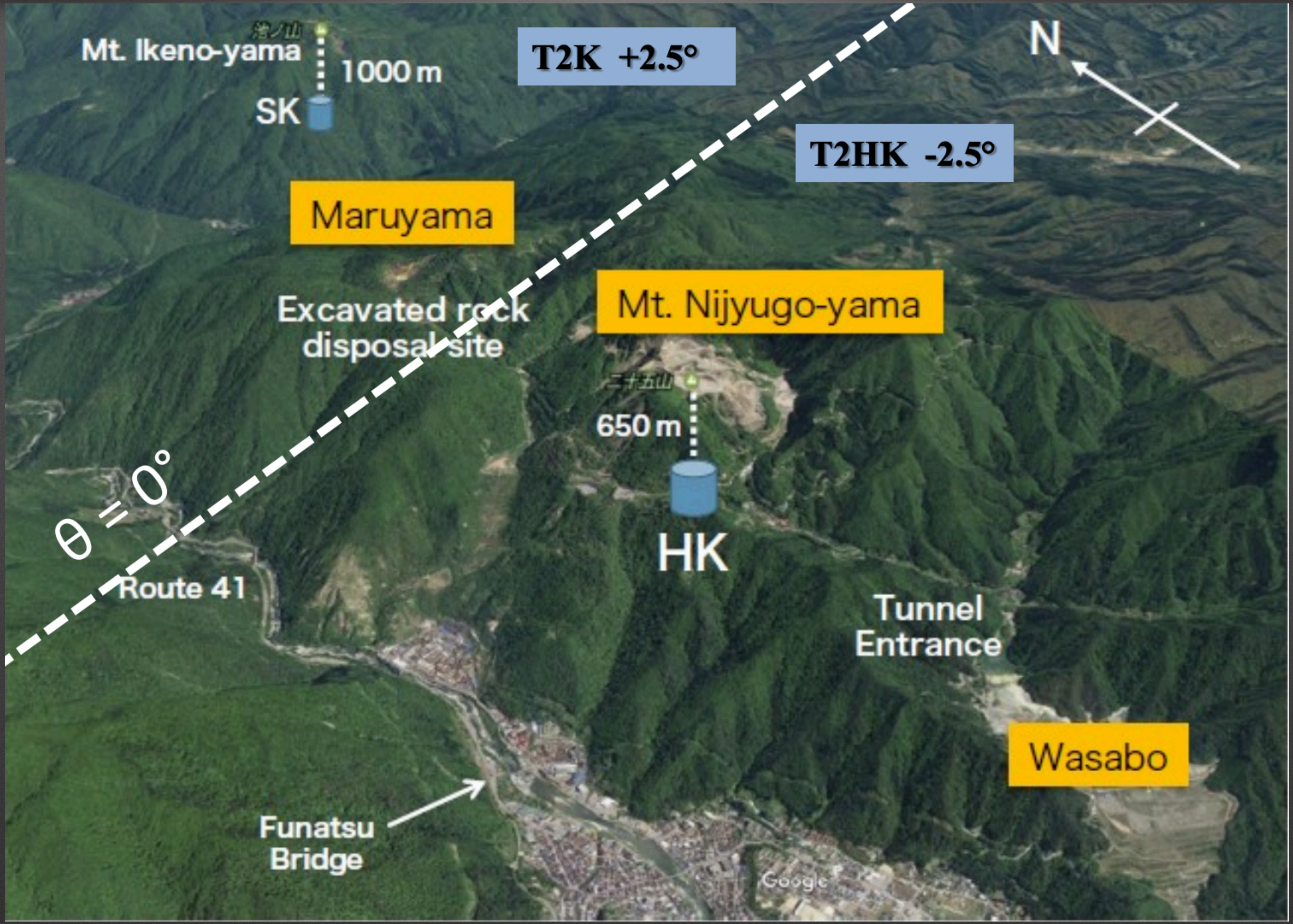
<産業等への波及>

○ 産業界と連携した最先端の研究装置開発により、イノベーションの創出にも貢献

（事例）・【すばる望遠鏡】超高感度カメラ技術⇒医療用X線カメラへの応用
・【放射光施設】加齢による毛髪のハリ・コシの低下が毛髪内の亜鉛と関係性を解明⇒亜鉛を毛髪に浸透させる新しいヘアケア技術の開発・製品化に成功

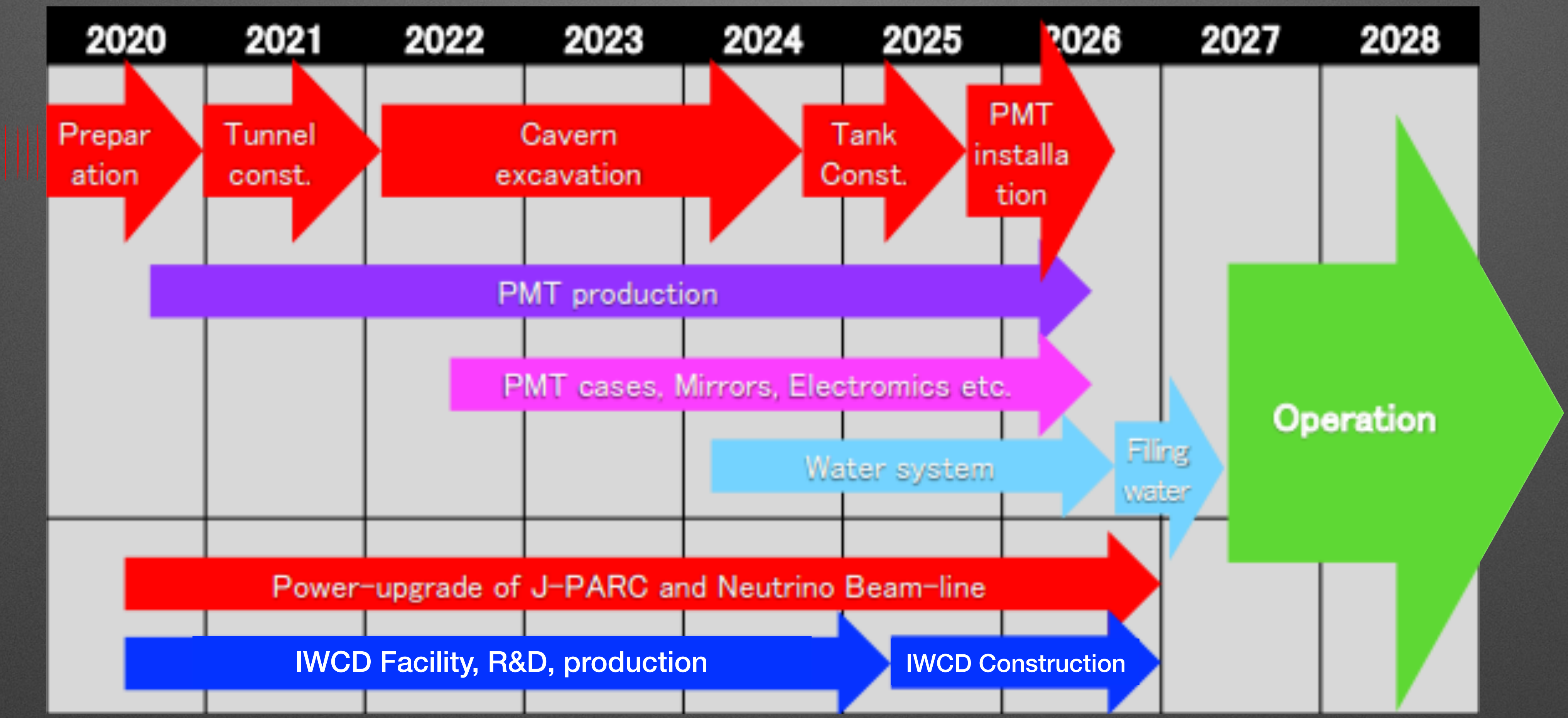


HK : Where



* Possibility for a 2nd detector in Korea being explored

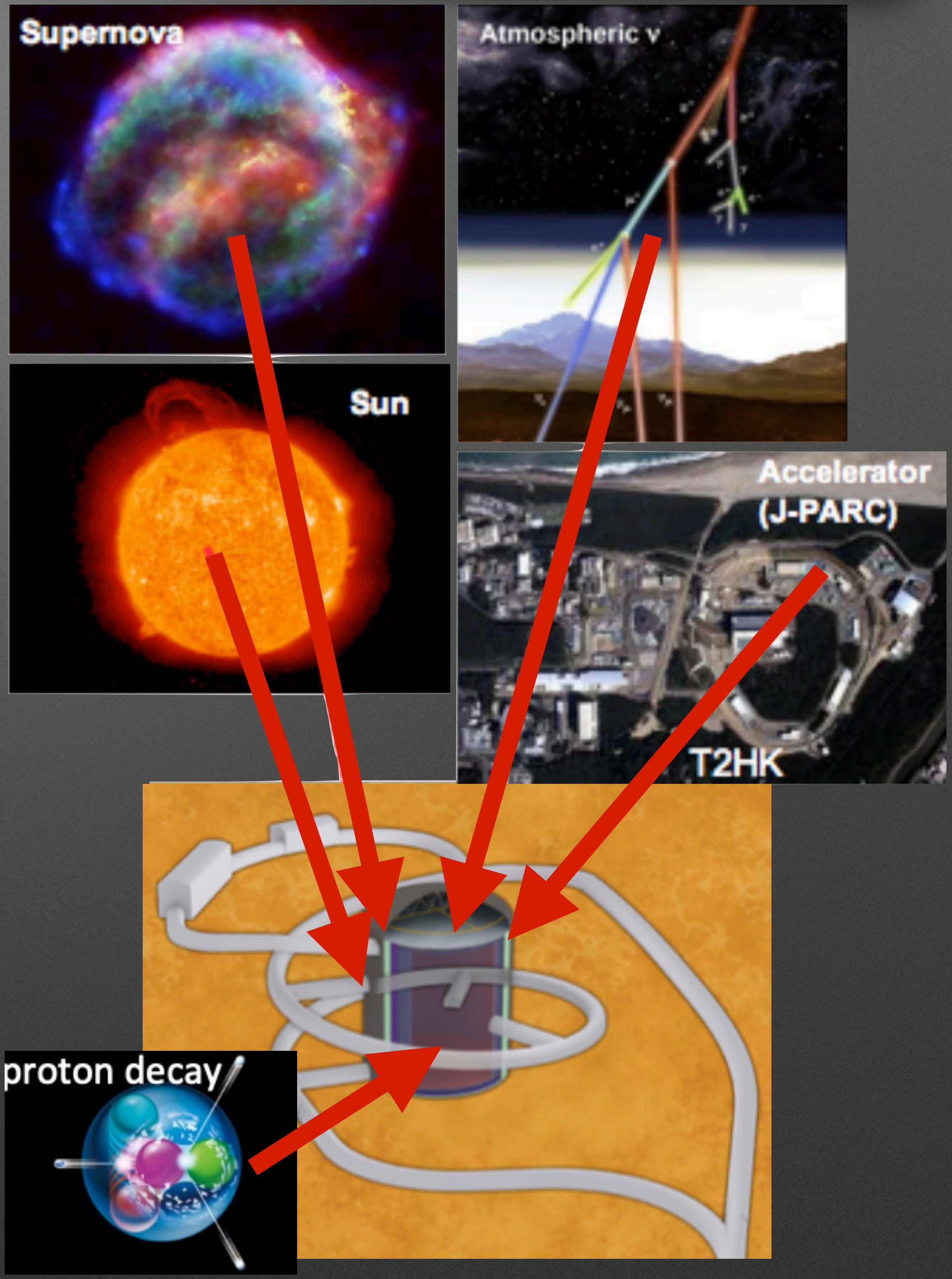
HK : When



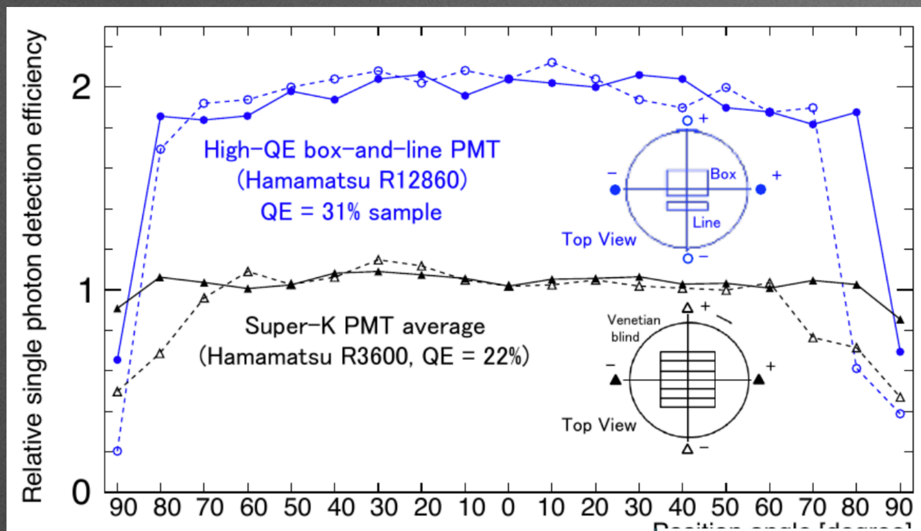
- Start Construction in 2020 (some preparatory work already started)
- Start data taking in JFY 2027
- Budget requested by MEXT to Ministry of Finance for Japanese part (~80% of the total cost of the experiment)
- International contributions being formalized

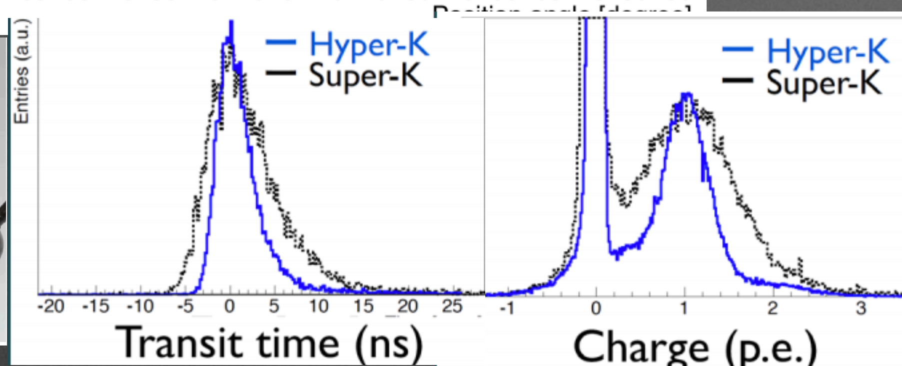
Physics case

- Neutrino oscillation physics
  - Combination of beam and atmospheric neutrinos
- Search for nucleon decay
  - ~10 times better sensitivity than SK
- Neutrino astrophysics
  - Solar ν
  - Atmospheric ν
  - SuperNovae burst
  - Relic SN neutrinos
- Geophysics
- Surprises



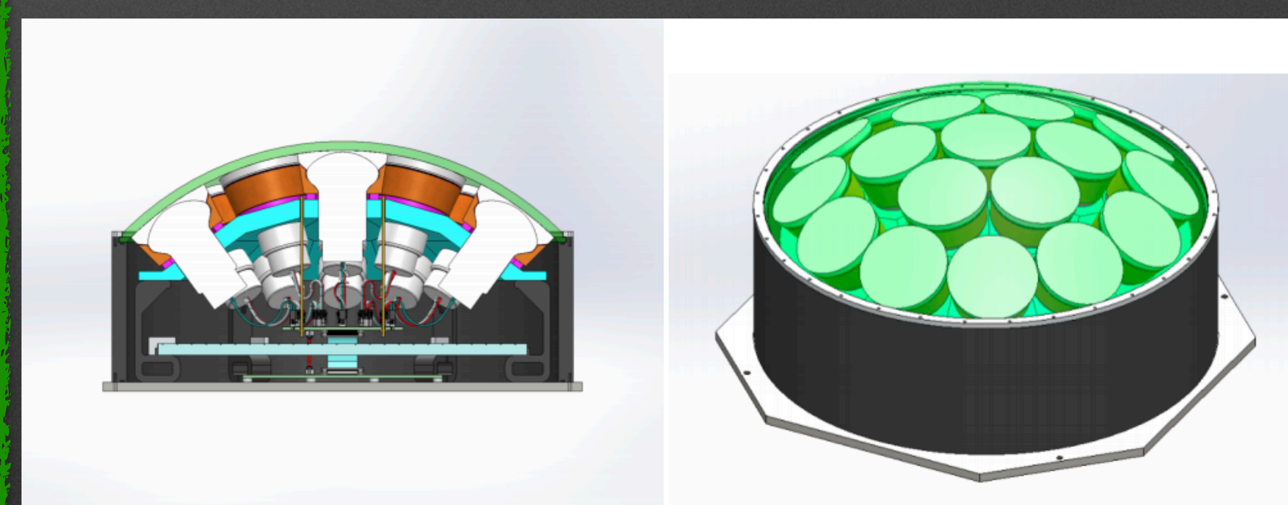
Hyper-K photo-detection system





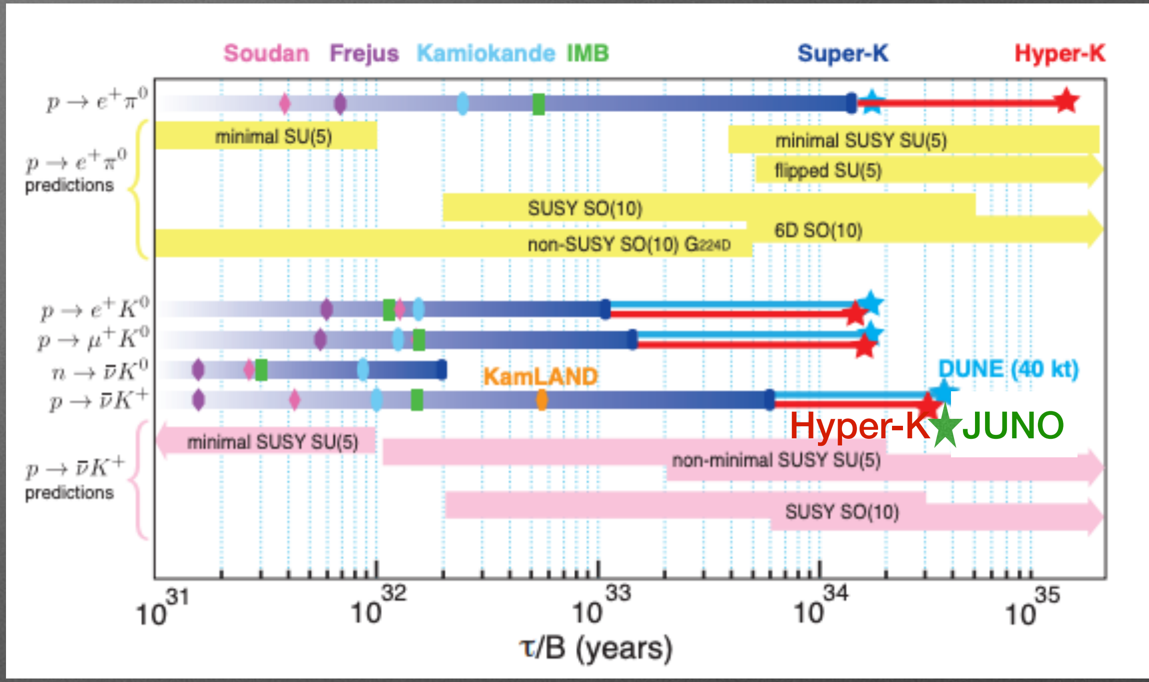
- HK will be instrumented with "box-and-line" 20'' PMTs
- At least 20k modules
- 31% QE (2 times better than SK)
- Better transit time spread

- Array of 19 3" PMTs
- Baseline option for IWCD
- Possibility to add 5k or 10k m-PMTs in HK (depending on funding)
  - Would improve vertex reconstruction and energy resolution at low energy
- Good opportunity for France
  - Synergies with KM3Net and with JUNO small PMTs

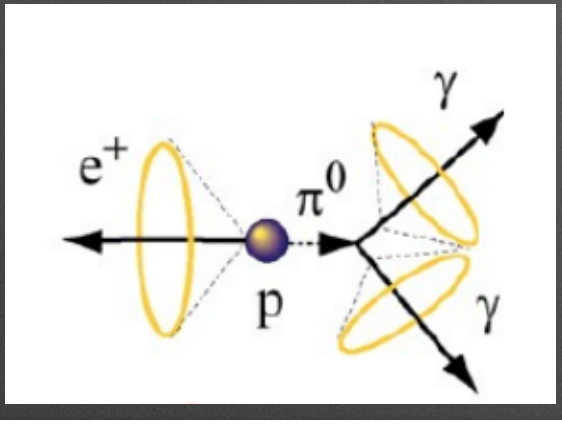


Proton-decay

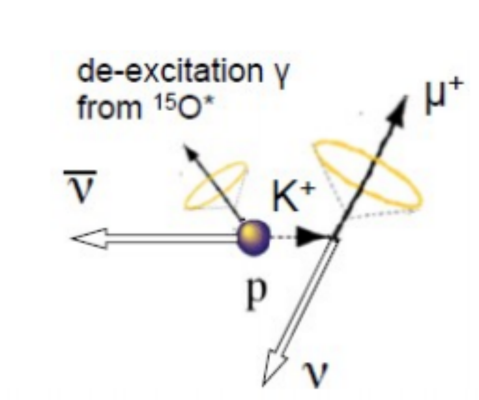
Sensitivity to many different modes
Surpass SK by ~1 order of magnitude in the leading $p \to e^+ + \pi^0$

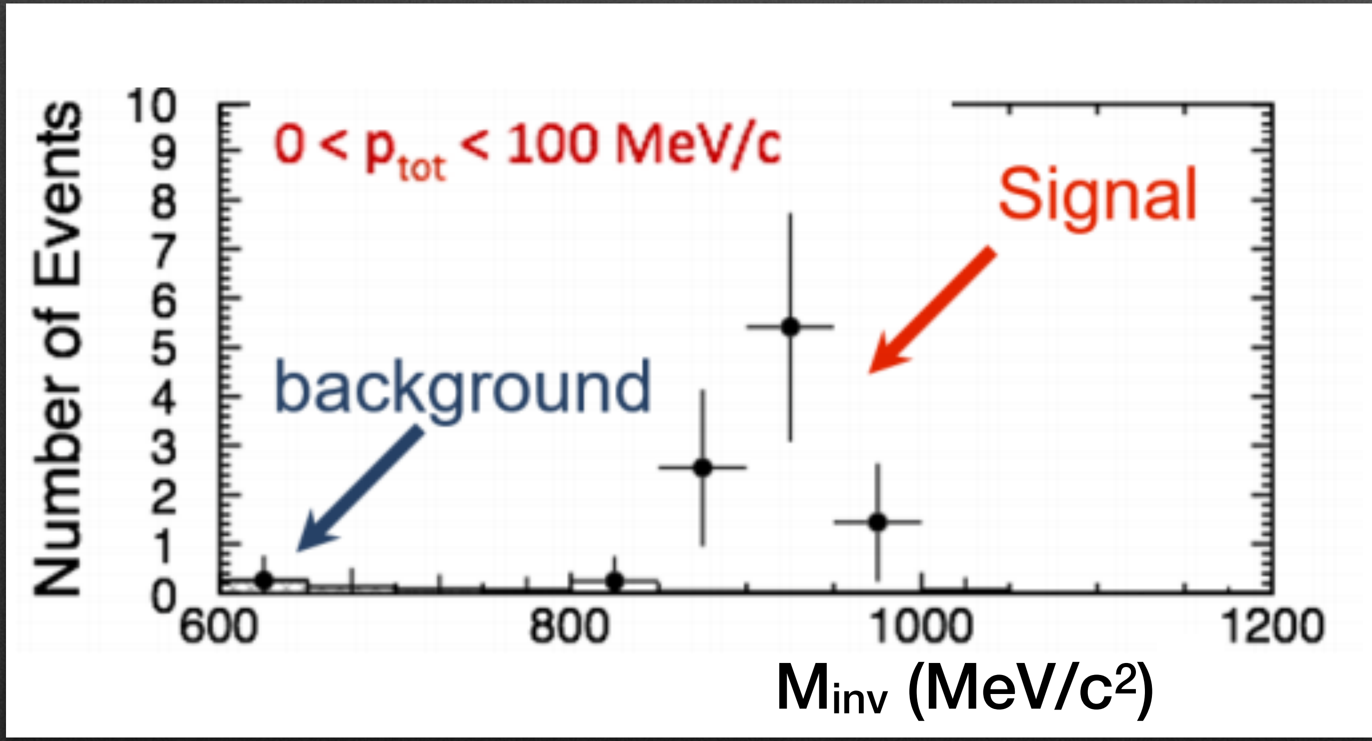


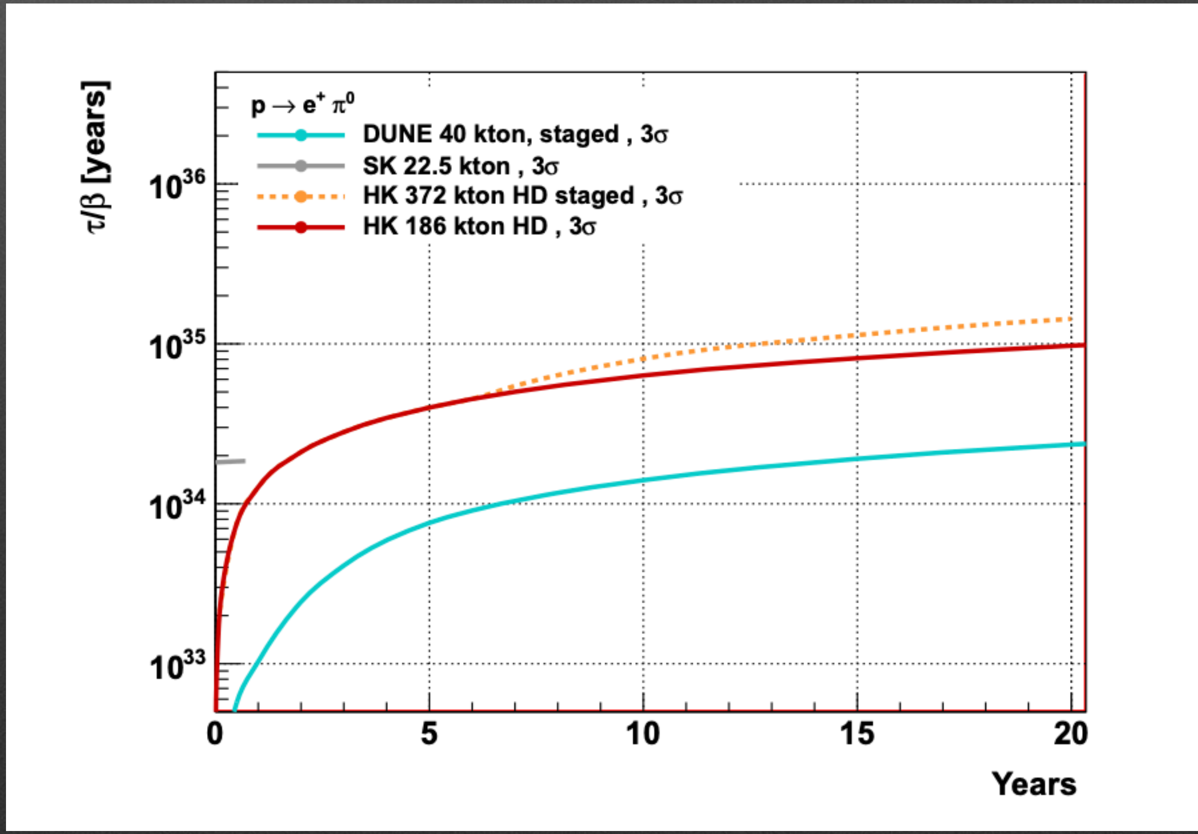
$p \to e^+ + \pi^0$



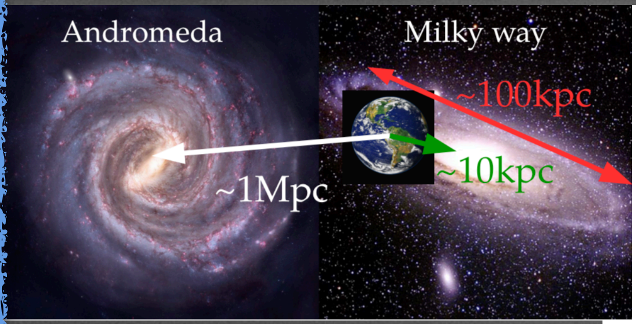
$p \to K^+ + \nu$

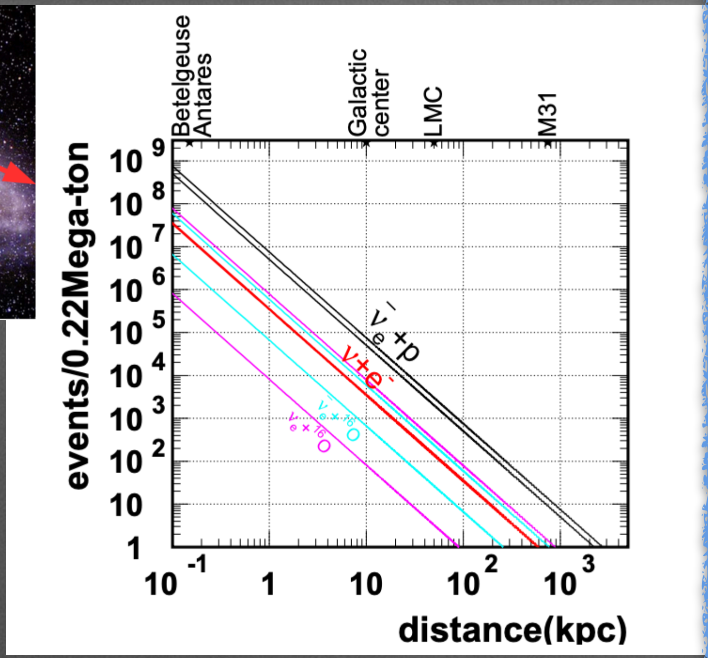




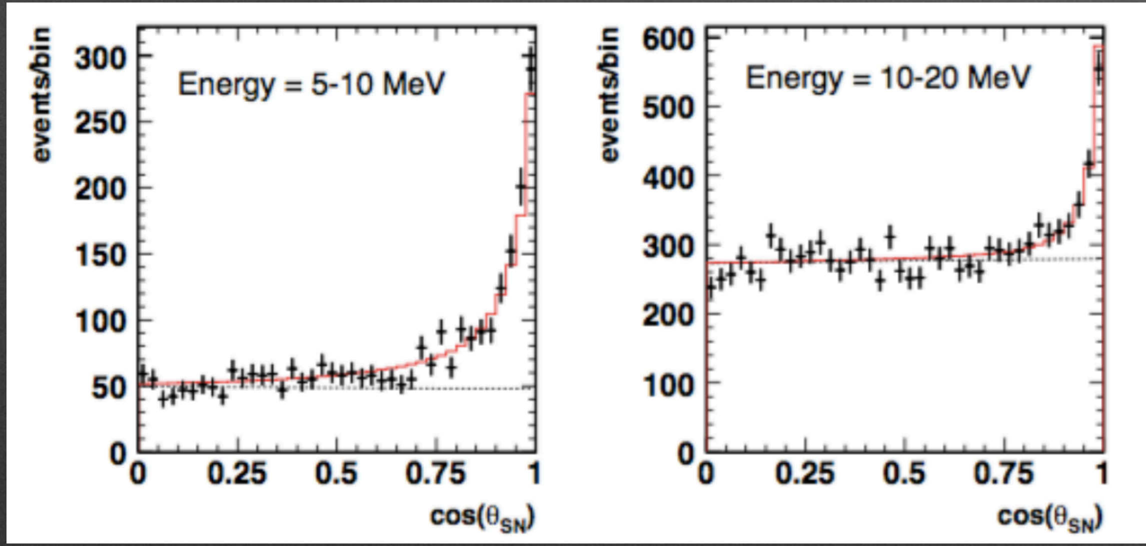


Supernovae neutrinos

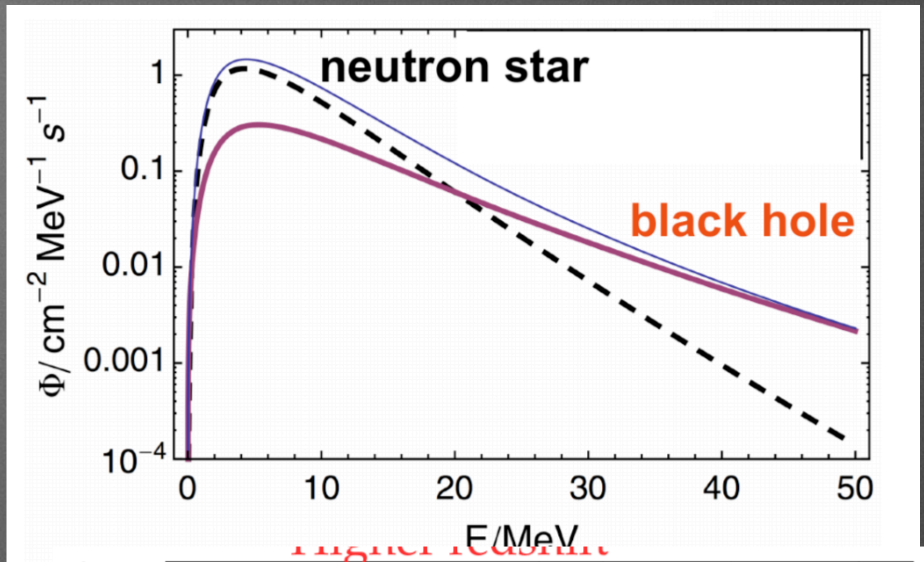


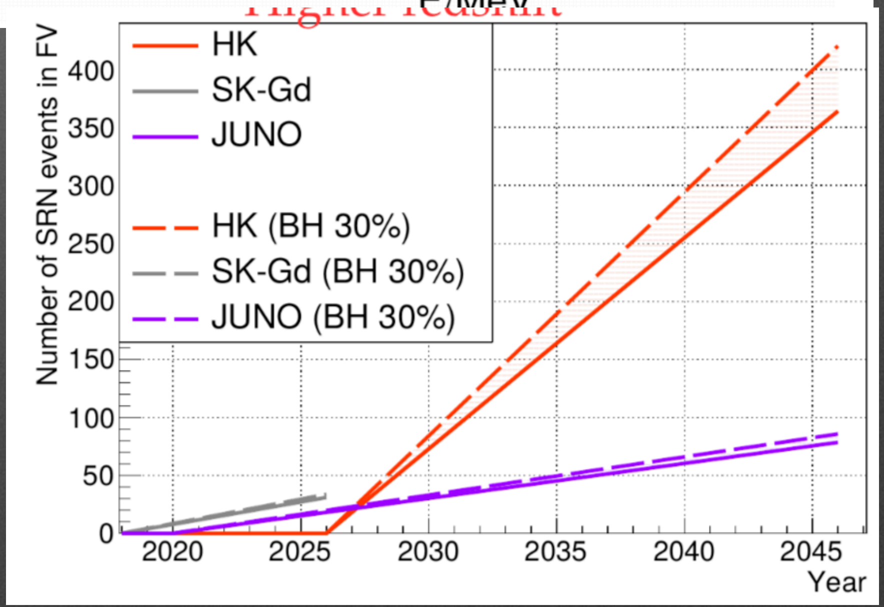


- IBD: huge statistics → SN model
- ES: directionality



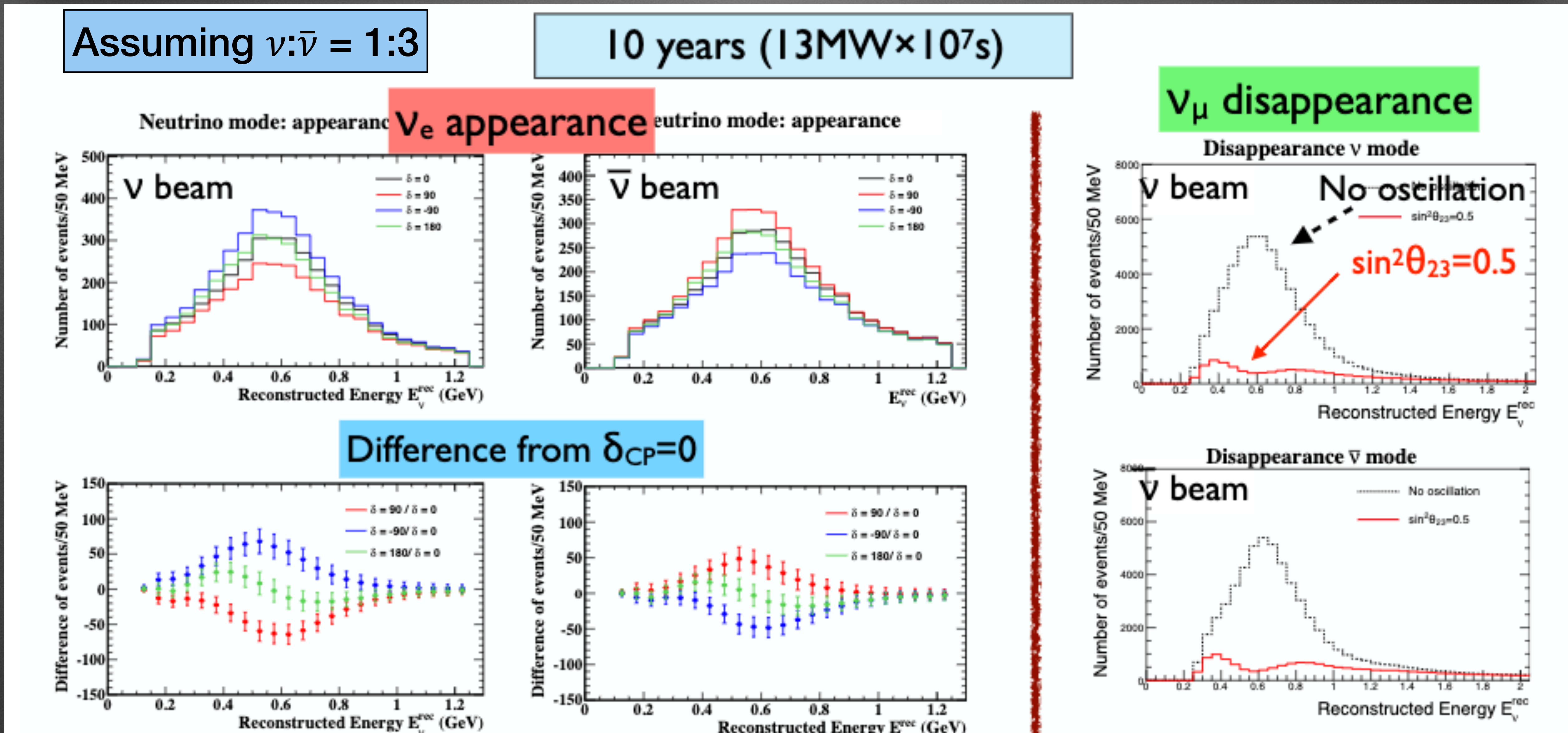
- ~80k IBD and ~3k ES for SN explosions in the galactic center
- Sensitive also to SN explosions in Andromeda





- SRN not yet observed → could be observed before 2025 by SK-Gd or JUNO
- HK will make a high statistics measurement → Constraints on cosmic star history

Long-baseline physics

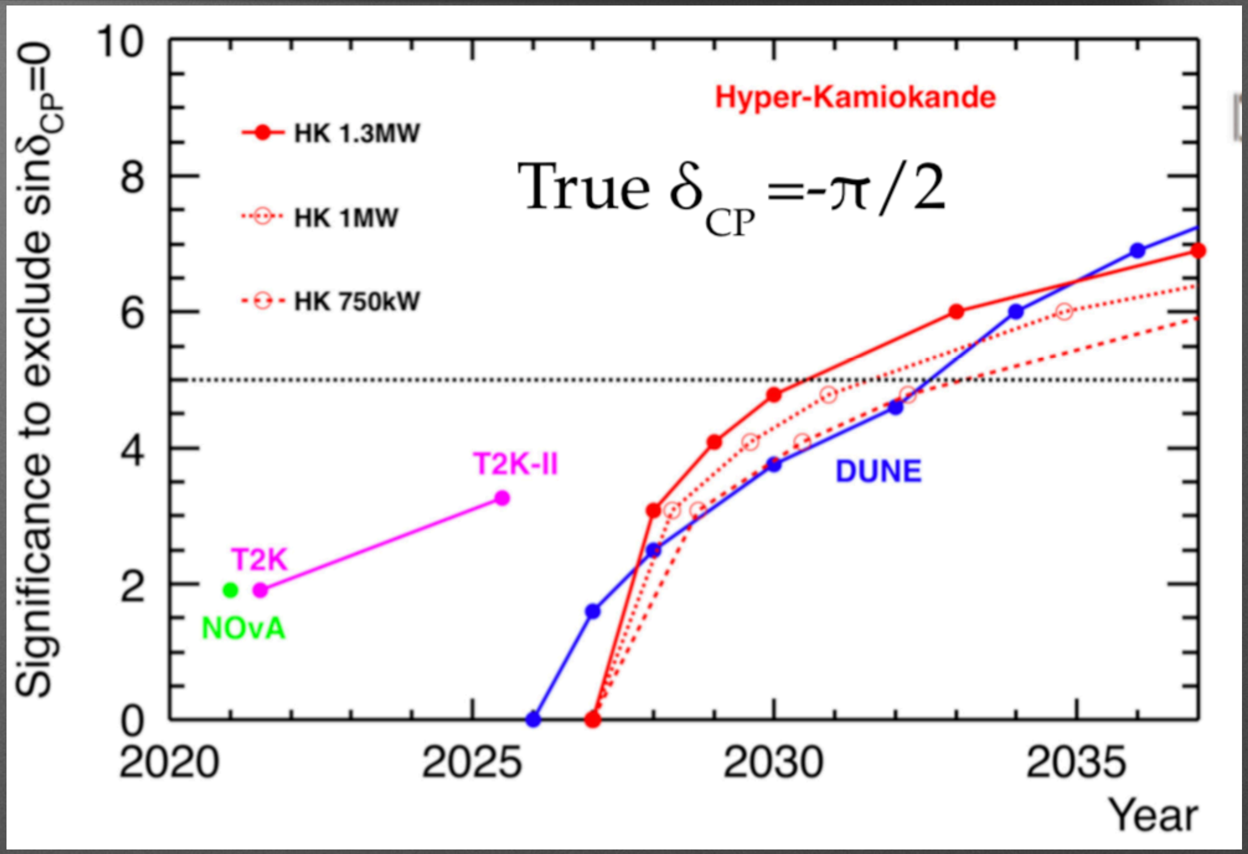


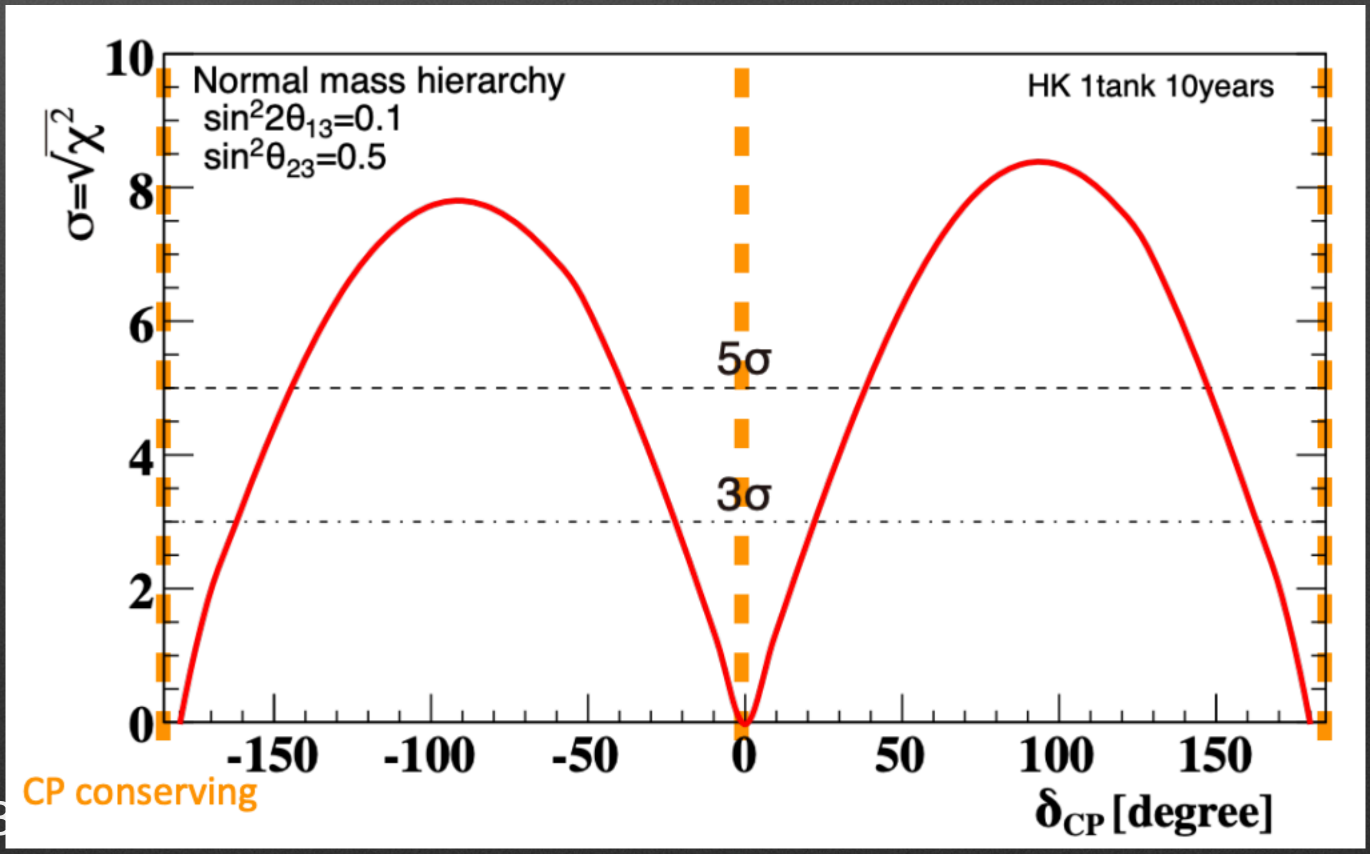
$\delta CP=-\pi/2$	Signal $\nu_\mu \rightarrow \nu_e$	Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	BCG	Total
ν-mode	**1643**	15	400	2058
$\bar{\nu}$-mode	206	**1183**	517	1906

Huge statistics → sensitivity to CP violation
Need to control systematics!

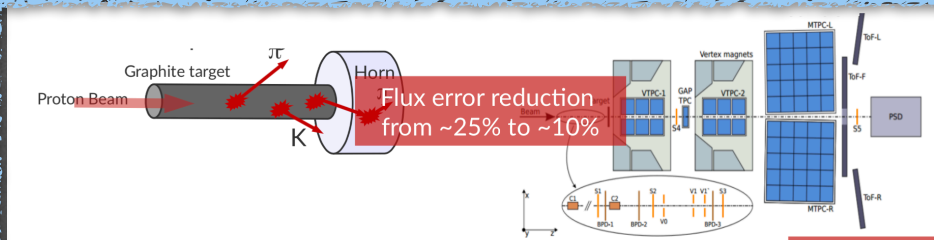
CP Violation

- Exclusion of sin(δCP)=0
  - 8σ for δCP ~ ± π/2
  - >3σ (5σ) significance for 76% (57%) of δCP space
  - Precision on δ_{CP} between 7° and 20°
- Sensitivity will be further enhanced by combination with atmospheric neutrinos
- Assume systematics uncertainties of ~4% (currently 7% for T2K)

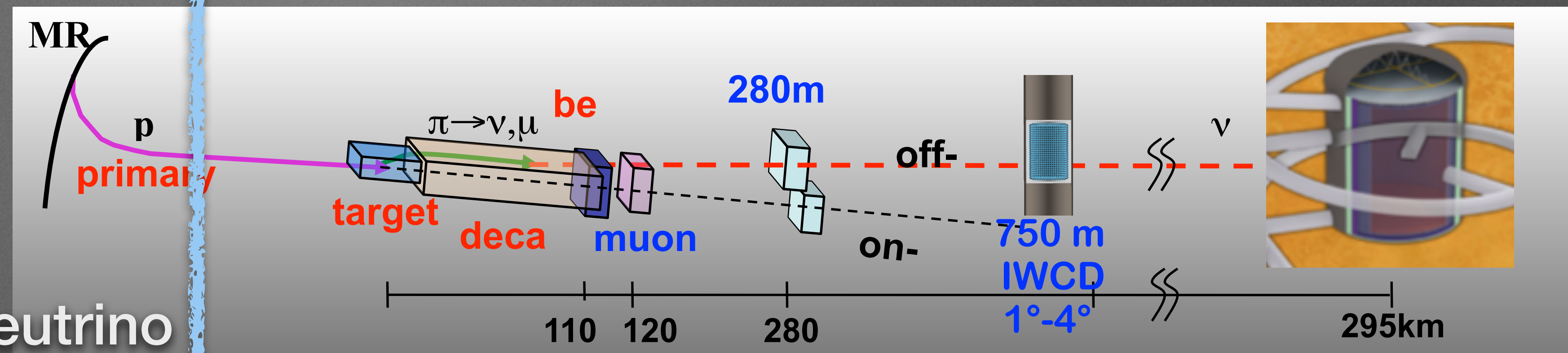


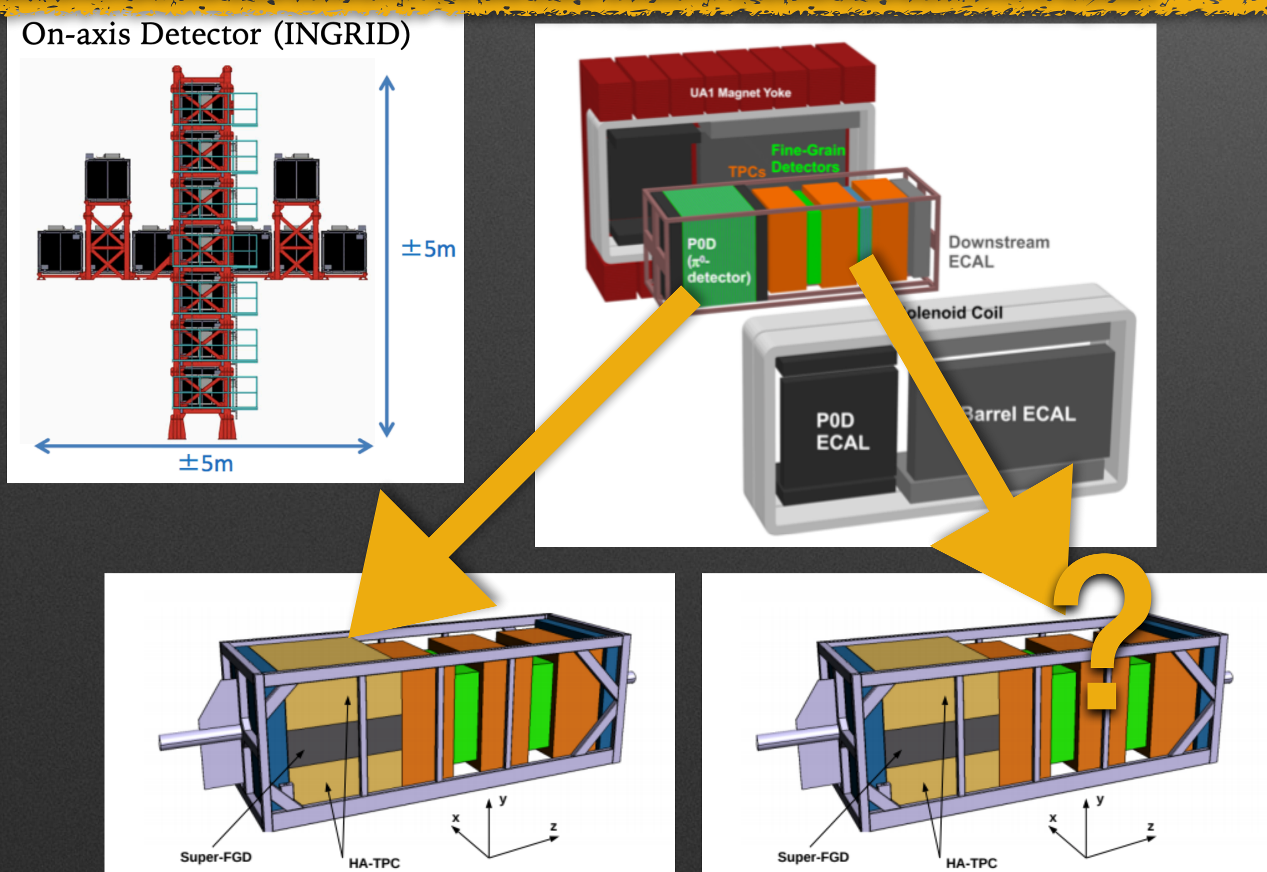


Systematics and Near Detectors



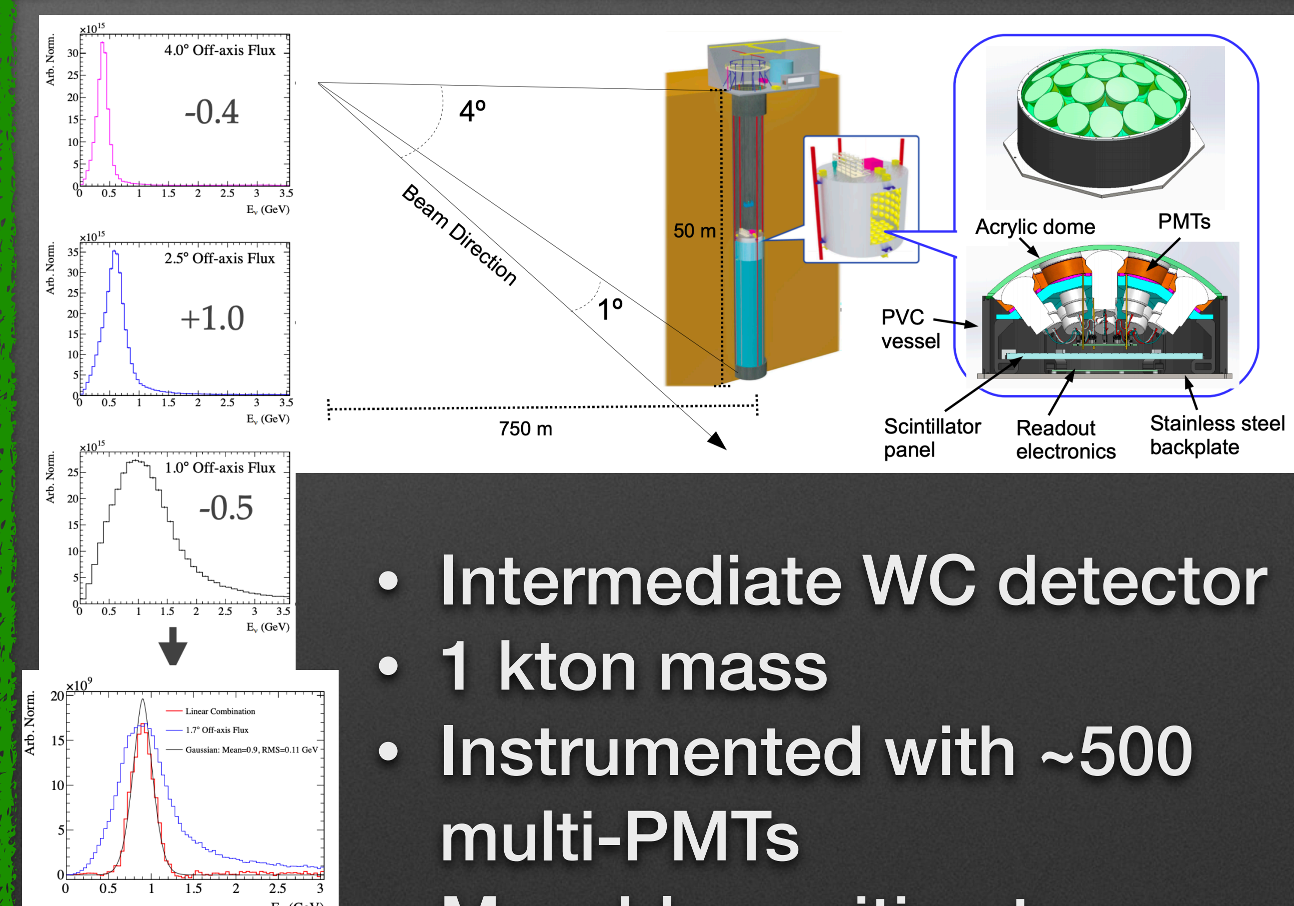
- NA61 hadron-production experiment @CERN
- T2K → uncertainties on the neutrino flux ~5% thanks to NA61
- New measurements planned for HK





2021

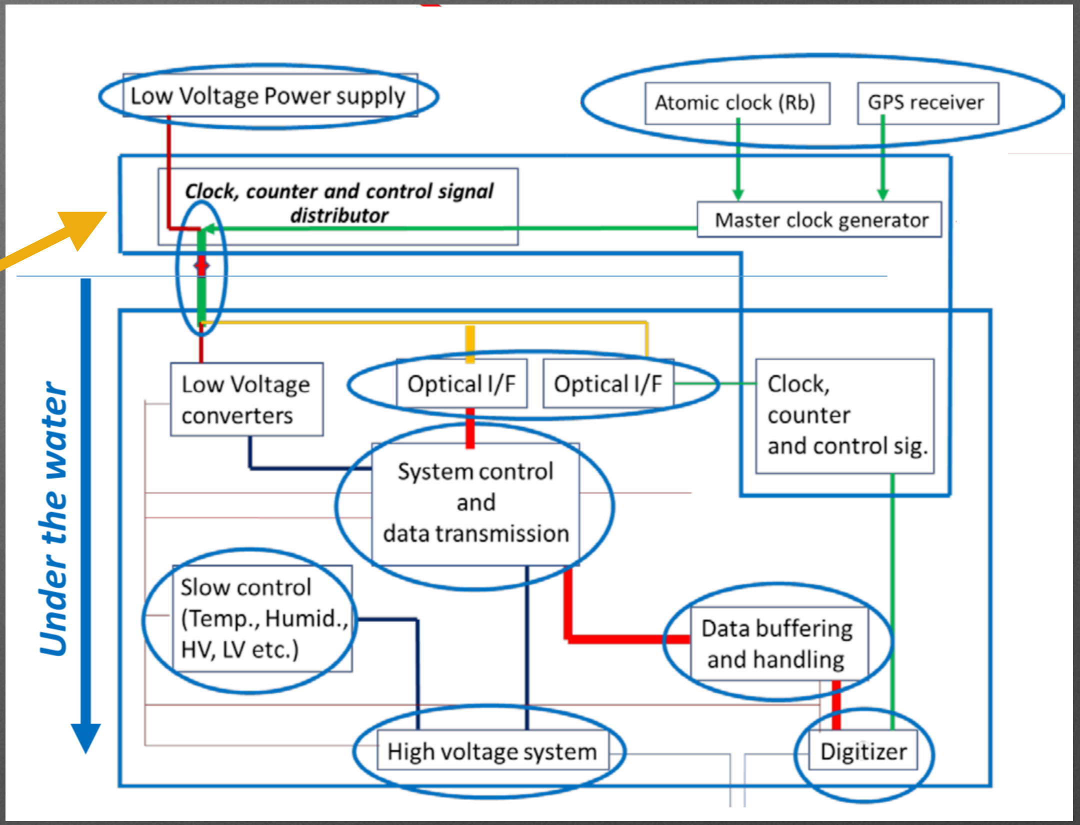
2030?

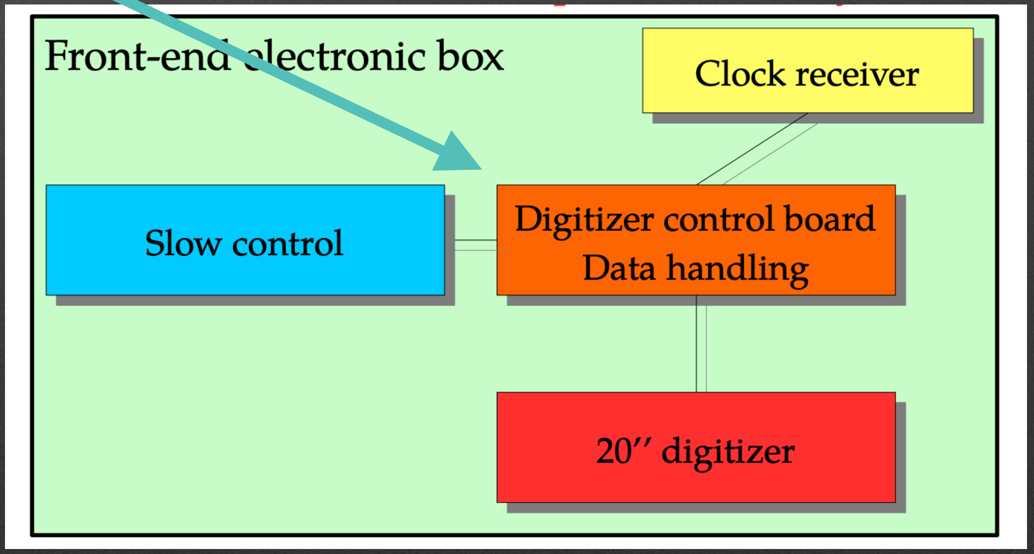


- Intermediate WC detector
- 1 kton mass
- Instrumented with ~500 multi-PMTs
- Movable position to scan different off-axis angles

French contributions

* NA61/SHINE hadron-production measurements for HK and further ND280 upgrades
* Contribution to the Far Detector centered around the electronics for the 20’’ PMTs
  * Design and procurement of the clock distribution and time synchronization system for the 20’’ PMTs (White Rabbit or Custom Made solution)
  * Front End digitizers (OMEGA chips) and front end boards for the 20’’ PMTs
* Such contributions can eventually be extended to the Multi-PMTs in HK
  * Testing one prototype in Memphyno@APC
  * Test Beam experiment @CERN (LOI submitted to SPSC, ~100 mPMTs, data taking in 2022) → provide synchronization system, deploy few 20’’ PMTs
* Computing → CC Lyon Tier-1 for HK





Conclusions

* Most recent results from T2K show hints that CP might be violated in the leptonic sector
* To confirm this hints more statistics and reduction of the systematics is needed
    * T2K phase II and ND280 Upgrade → CP violation at 3σ by 2026
    * Combination of T2K/SK/NOvA oscillation analyses
* Excellent news for Hyper-Kamiokande, the next generation neutrino observatory
    * Experiment approved by MEXT
    * Start data taking in 2027
    * Leading experiment in the search for CP violation in the leptonic sector
    * Most sensitive detector for proton decay
    * Observatory for neutrinos from different sources (Supernova, Sun, Atmosphere, Gravitational Waves,…)
* Our contributions are being defined → let's join us to build HK!

Back-up

Release by MEXT on Aug. 29, 2019

(MEXT) will start the next-generation neutrino research project "Hyper-Kamiokande" in JFY2020.

○ 日本学術会議において科学的観点から策定したマスタープランを踏まえつつ、専門家等で構成される文部科学省の審議会において戦略性・緊急性等を加味し、ロードマップを策定。

○ ロードマップの中から大規模学術フロンティア促進事業として実施するプロジェクトを選定の上、国立大学法人運営費交付金等の基盤的経費により戦略的・計画的に推進。原則、10年間の年次計画を策定し、審議会における厳格な評価・進捗管理を実施。

○ 現行の13プロジェクトに加え、令和2年度より、ニュートリノ研究の次世代計画である「ハイパーカミオカンデ計画」に新たに着手。

主な成果

○ ノーベル賞受賞につながる画期的研究成果（受賞歴：H14小柴昌俊氏、H20小林誠氏、益川敏英氏、H27梶田隆章氏）

○ 年間約1万人の共同研究者が集結し、国際共同研究を推進。このうちの半数以上が外国人

Next generation of neutrino project with a 260 kton detector and the J-PARC upgrade. The project will reveal the mysteries in elementary particles and the Universe by the observation of proton decays and the neutrino researches including CP violation.

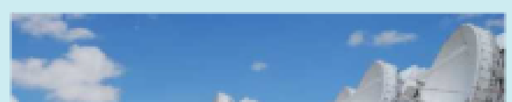
天文学・宇宙物理学分野	論文数	Top10%割合	国際共著割合
すばる望遠鏡	644	18.5%	86.3%
アルマ望遠鏡	878	27.3%	89.0%
日本全体	8,938	12.9%	68.0%
世界全体	103,445	9.6%	50.6%

※ 大学共同利用機関法人自然科学研究機構が「InCites」（Web of Science）に基づき、2013-2017の5か年に出版された天文学・宇宙物理学分野の論文（article,review）を分析（2019年7月）。「日本全体」は、著作住所に日本を含む論文を抽出。

大規模学術フロンティア促進事業等の主な事業

大型電波望遠鏡「アルマ」による国際共同利用研究の推進

〔自然科学研究機構国立天文台〕



巨大ブラックホールの「影」の撮影に世界で初めて成功した国際プロジェクトに参加し、高い感度の観測機能により、その成果に大きく貢献。

新しいステージに向けた学術情報ネットワーク（SINET）整備

〔情報・システム研究機構国立情報学研究所〕

…等を高速通信回線ネットワークで…究の基盤を提供。全国900以上…機関、約300万人の研究者・学…我が国の教育研究活動に必須の学術情報基盤。

NEW ハイパーカミオカンデ(HK)計画の推進

〔東京大学宇宙線研究所〕
〔高エネルギー加速器研究機構〕

日本が切り拓いてきたニュートリノ研究の次世代計画として、超高感度光検出器を備えた総重量26万トンの大型検出器の建設及びJ-PARCの高度化により、ニュートリノの検出性能を著しく向上。素粒子物理学の大統一理論の鍵となる未発見の陽子崩壊探索やCP対称性の破れなどのニュートリノ研究を通じ、新たな物理法則の発見、素粒子と宇宙の謎の解明を目指す。【ロードマップ2017掲載事業】

＜産業等への波及＞

○ 産業界と連携した最先端の研究装置開発により、イノベーションの創出にも貢献

（事例）・【すばる望遠鏡】超高感度カメラ技術⇒医療用X線カメラへの応用
・【放射光施設】加齢による毛髪のハリ・コシの低下が毛髪内の亜鉛と関係性を解明⇒亜鉛を毛髪に浸透させる新しいヘアケア技術の開発・製品化に成功

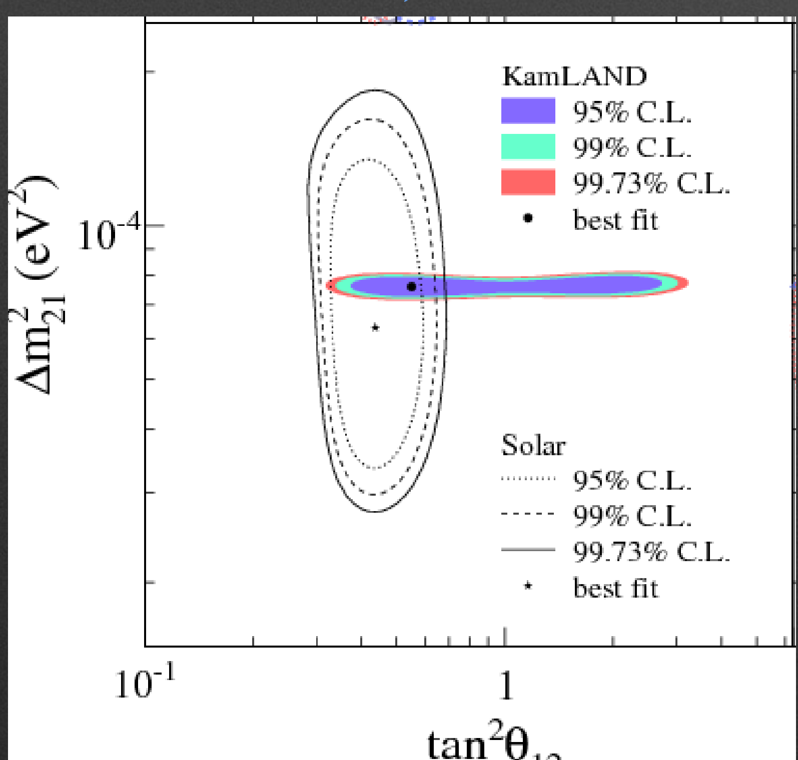
PMNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

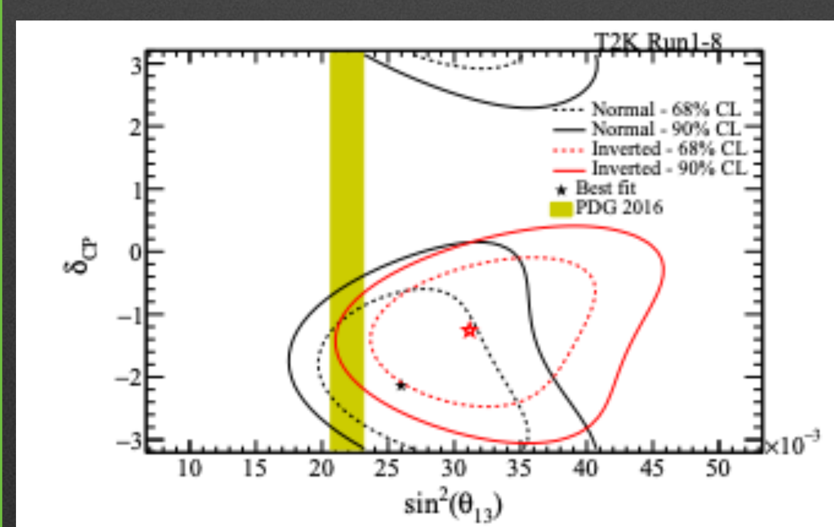
- 3 mixing angles
- 2 independent mass differences
- 1 CP violation phase

θ_{13} is precisely known, some indications also for δ_{CP}

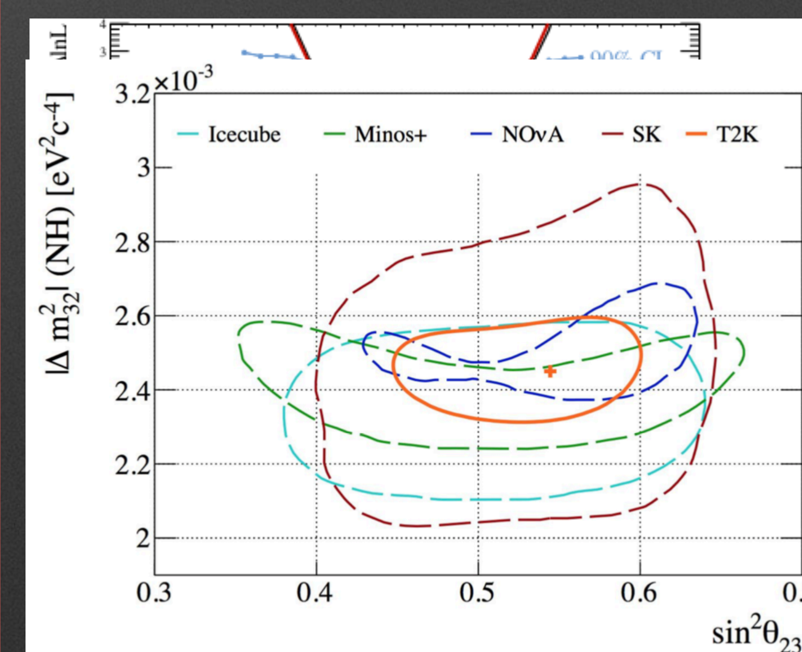
Solar (SNO, KamLand) → θ_{12}, Δm_{12}



Reactors (Daya Bay, RENO, DChooz) → θ_{13}
LBL (T2K, NOνA) → θ_{13}, δ_{CP}

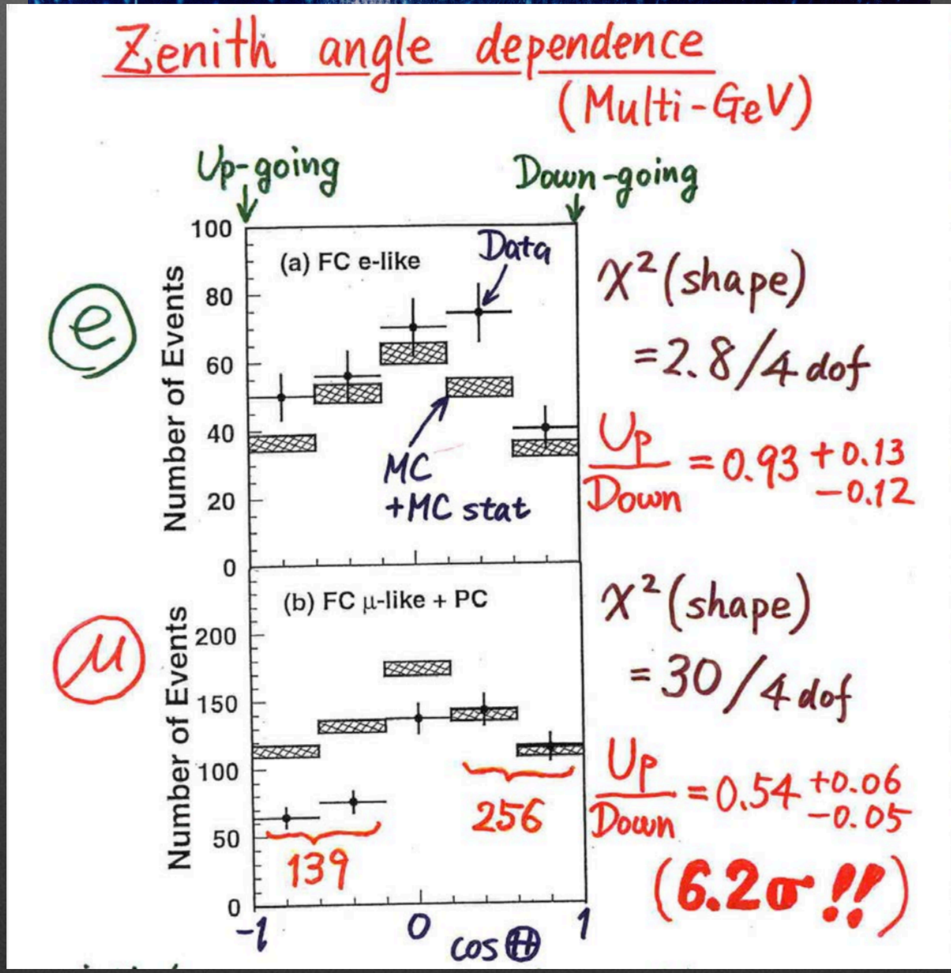


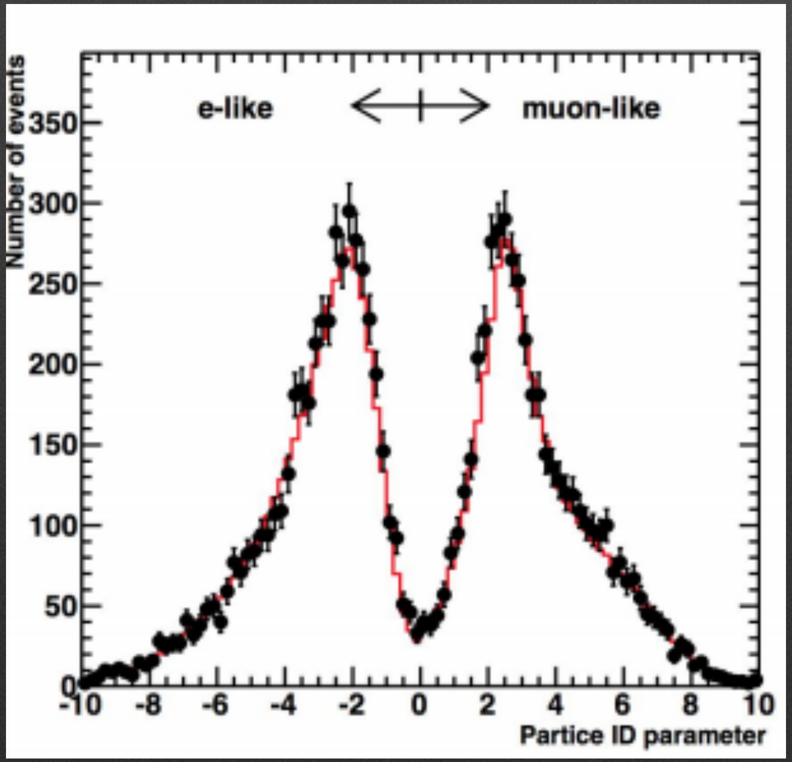
Atmospheric (SK, IceCUBE)
LBL (Minos, T2K, NOνA)
→ θ_{23}, Δm_{32}



Super-Kamiokande

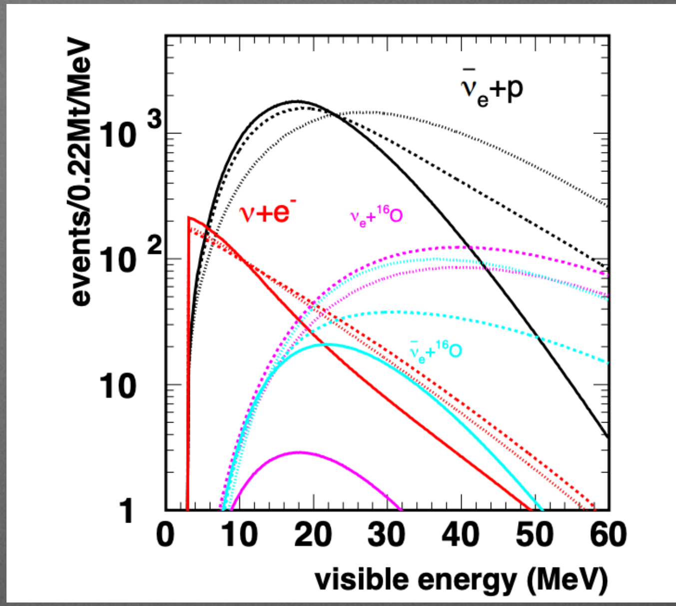
- 50 kton Water Cherenkov detector
  - ~11000 PMTs for ID, ~2000 for OD
- 1000 m underground at Kamioka mine operated since 1996
- Very good PID capabilities to distinguish between ν_e and ν_μ thanks to shape of Cherenkov ring → <1% misidentification probability

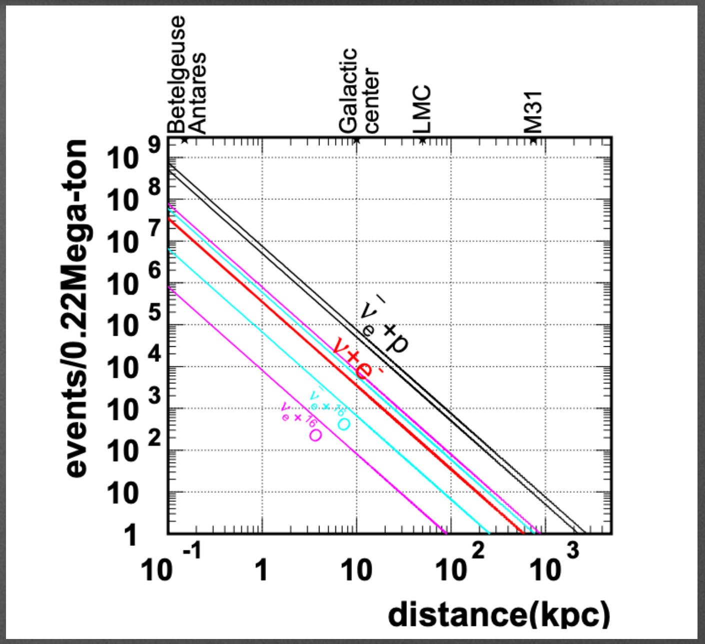




Supernovae Explosions

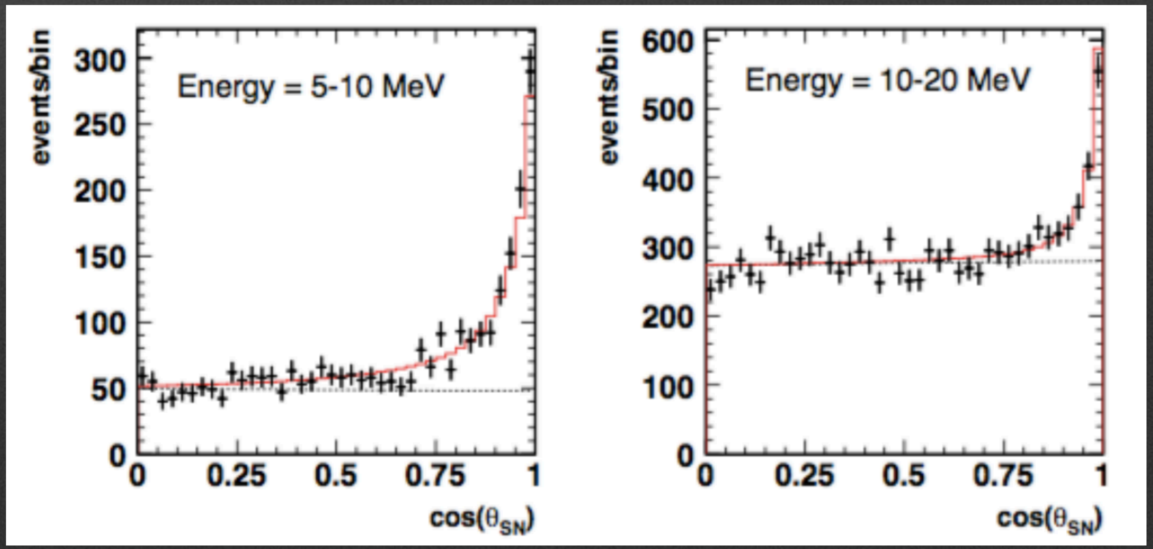
- Neutrinos carry out ~99% of the total energy released in a SN burst
- HK will mostly sensitive to $\overline{\nu}e$ through inverse β-decay, but also other channels can be inspected
- Point to the SN
- Study energy spectrum and time profile → distinguish between different models for SN explosions
- Neutrino mass hierarchy determination?





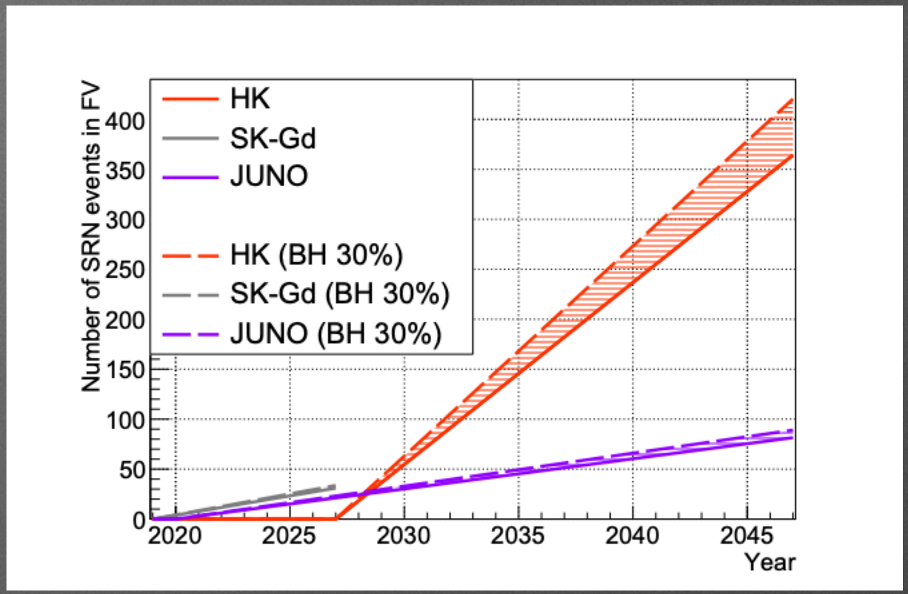
10 kpc

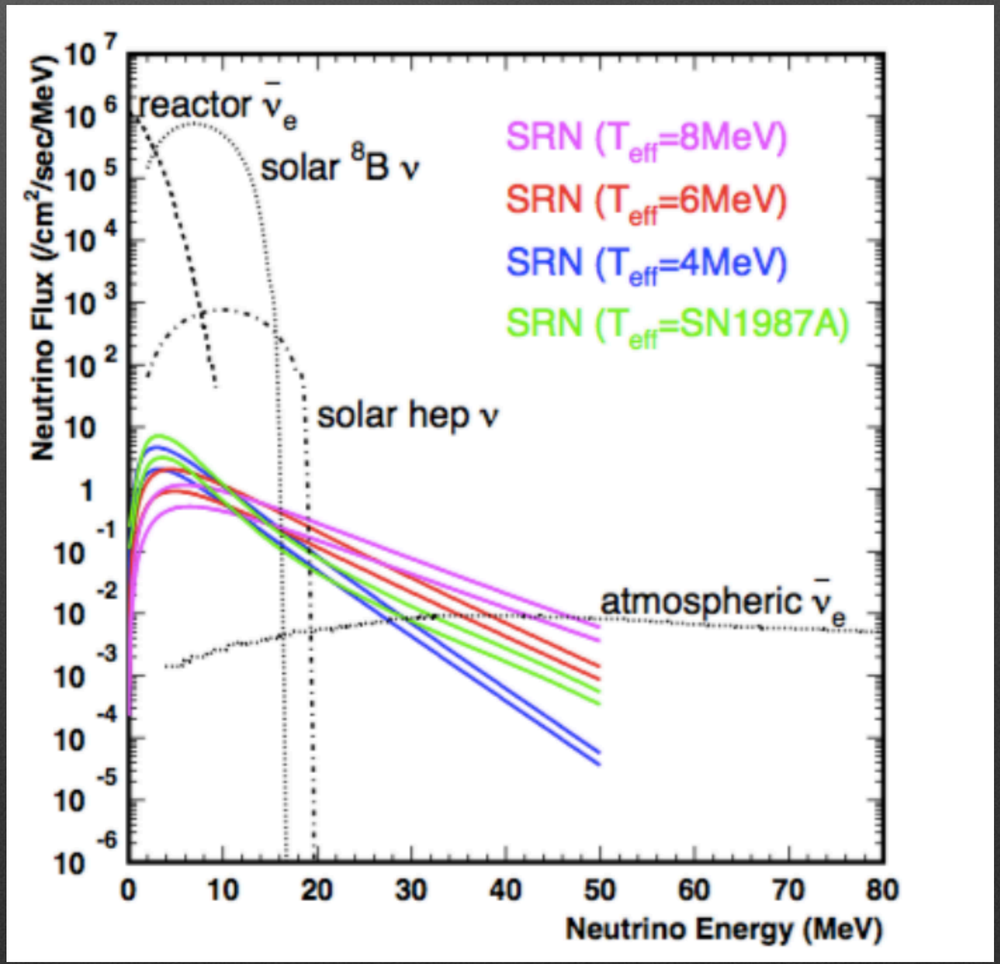
Neutrino source	Single Tank (220 kt Full Volume)	2 Tanks (440 kt Full Volume)
$\bar{\nu}_e + p$	50,000 - 75,000 events	100,000 - 150,000 events
$\nu + e^-$	3,400 - 3,600 events	6,800 - 7,200 events
$\nu_e +^{16} O$ CC	80 - 7,900 events	160 - 11,000 events
$\bar{\nu}_e +^{16} O$ CC	660 - 5,900 events	1,300 - 12,000 events
$\nu + e^-$ (Neutronization)	9 - 55 events	17 - 110 events
Total	54,000 - 90,000 events	109,000 - 180,000 events



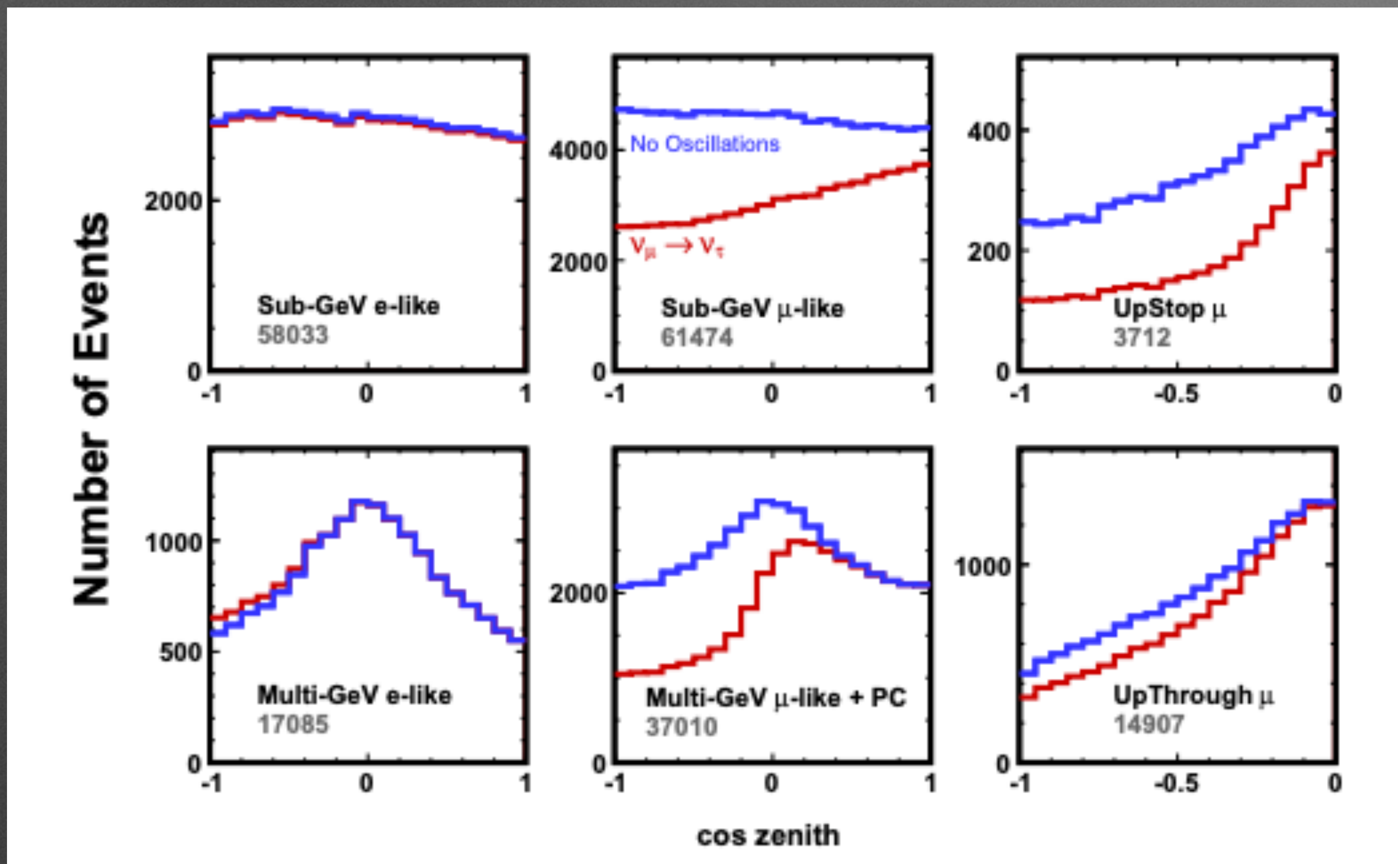
Supernovae Relic Neutrinos

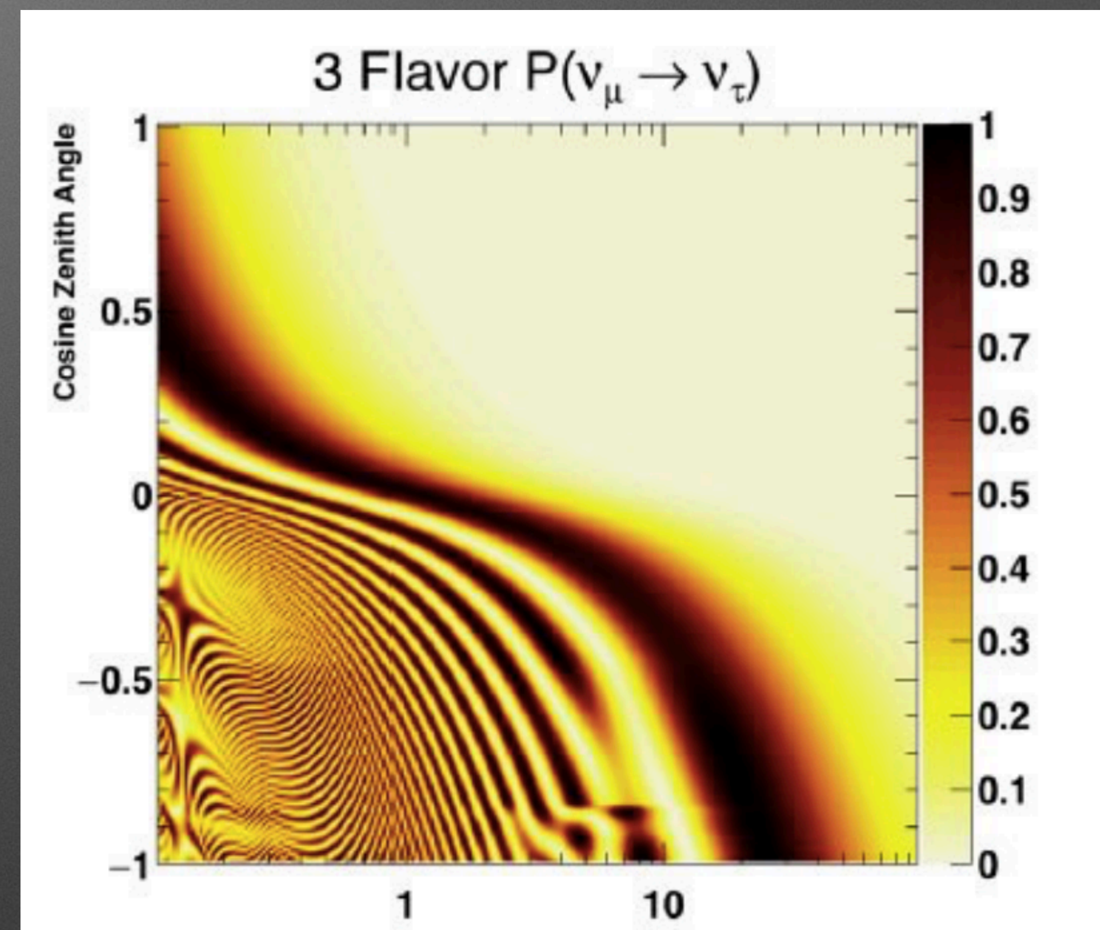
- Neutrinos produced by all the SN since the beginning of the Universe (SRN)
- Their detection is the main goal of the Super-Kamiokande upgrade (SK-Gd)
  - Addition of Gd in SK to tag the neutrons and distinguish $\overline{\nu}_e + p \rightarrow e^- + n$
- If SRN will be discovered by SK, the large size of HK will allow a detailed study of the history of the Universe through SRN

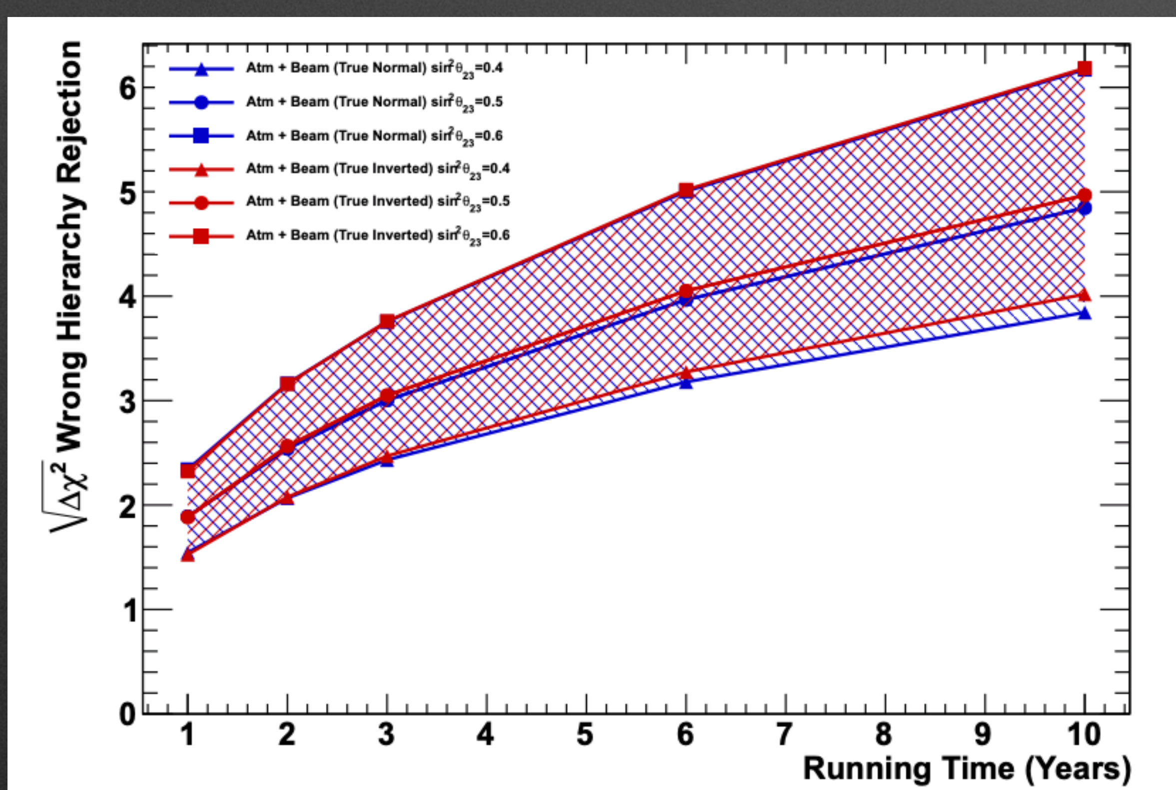


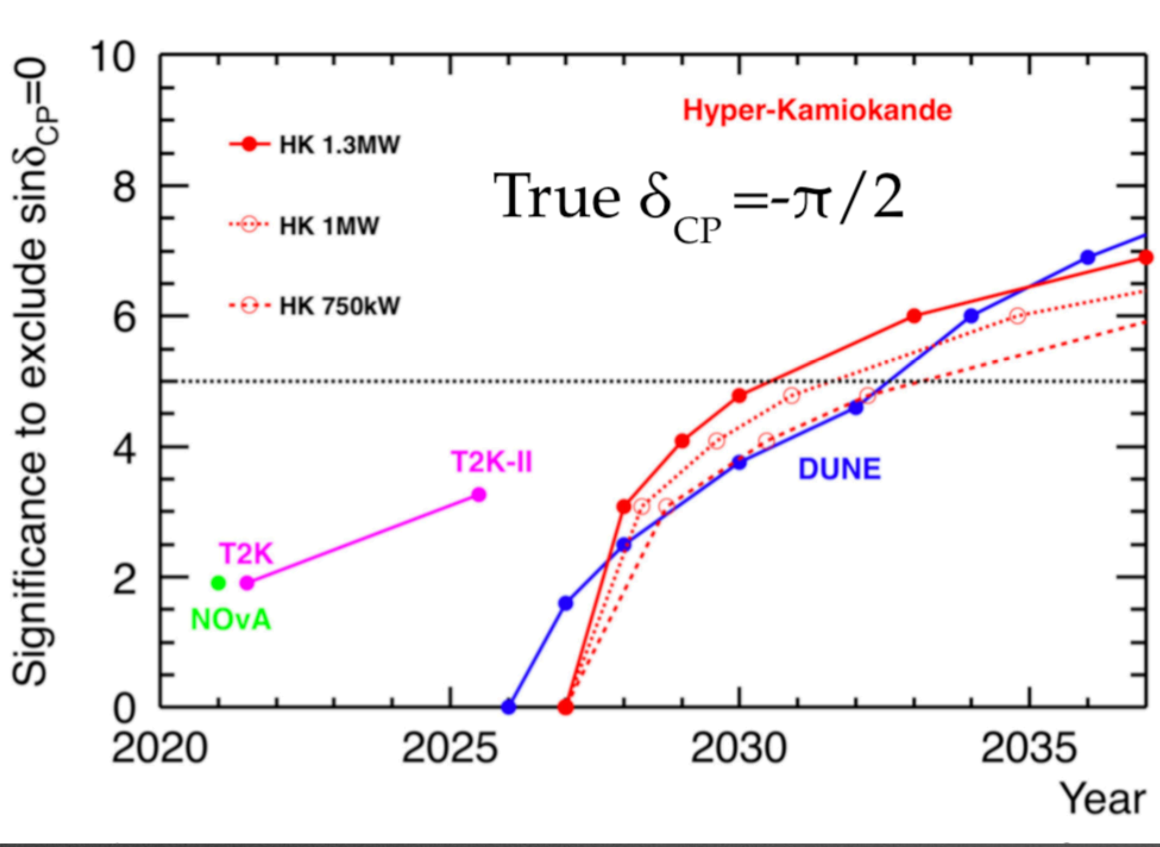


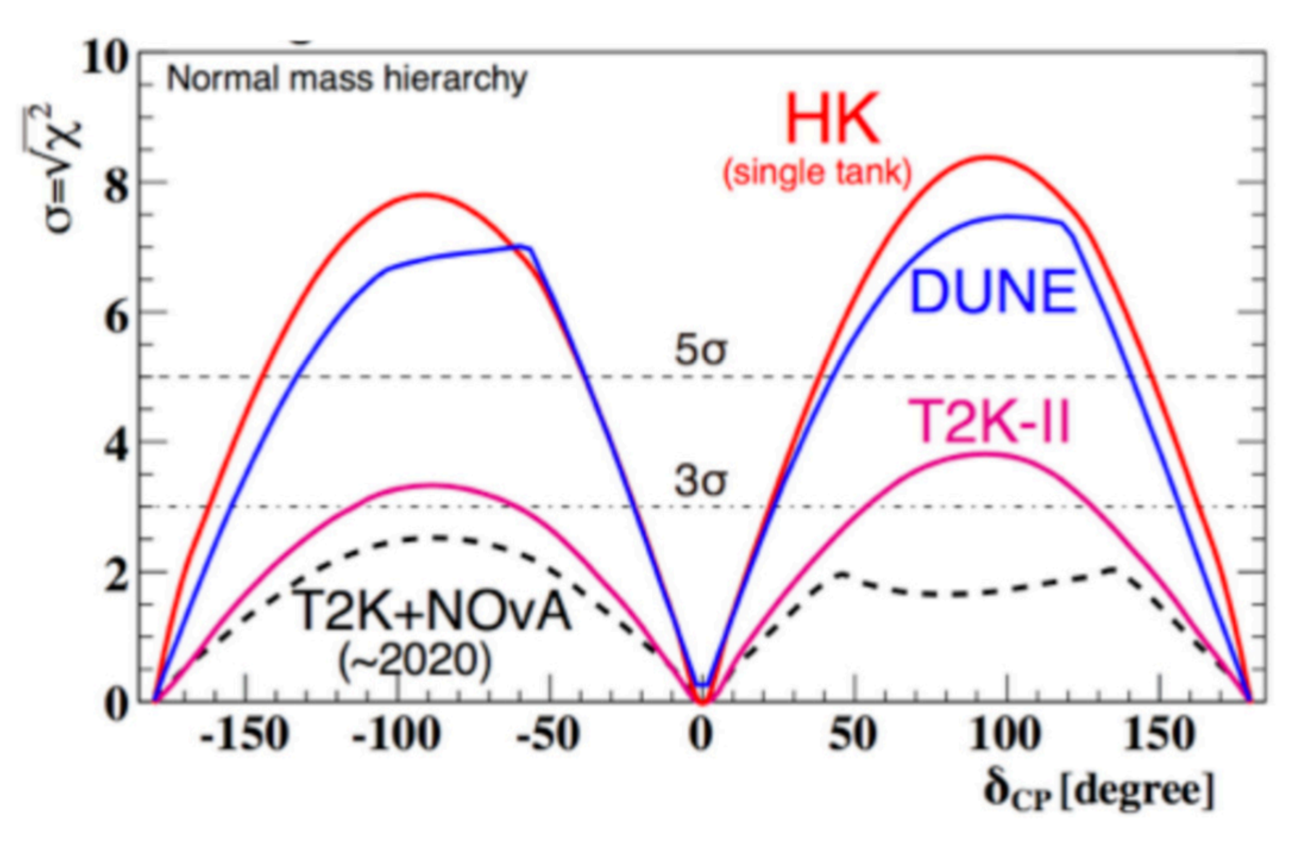
Atmospheric neutrinos

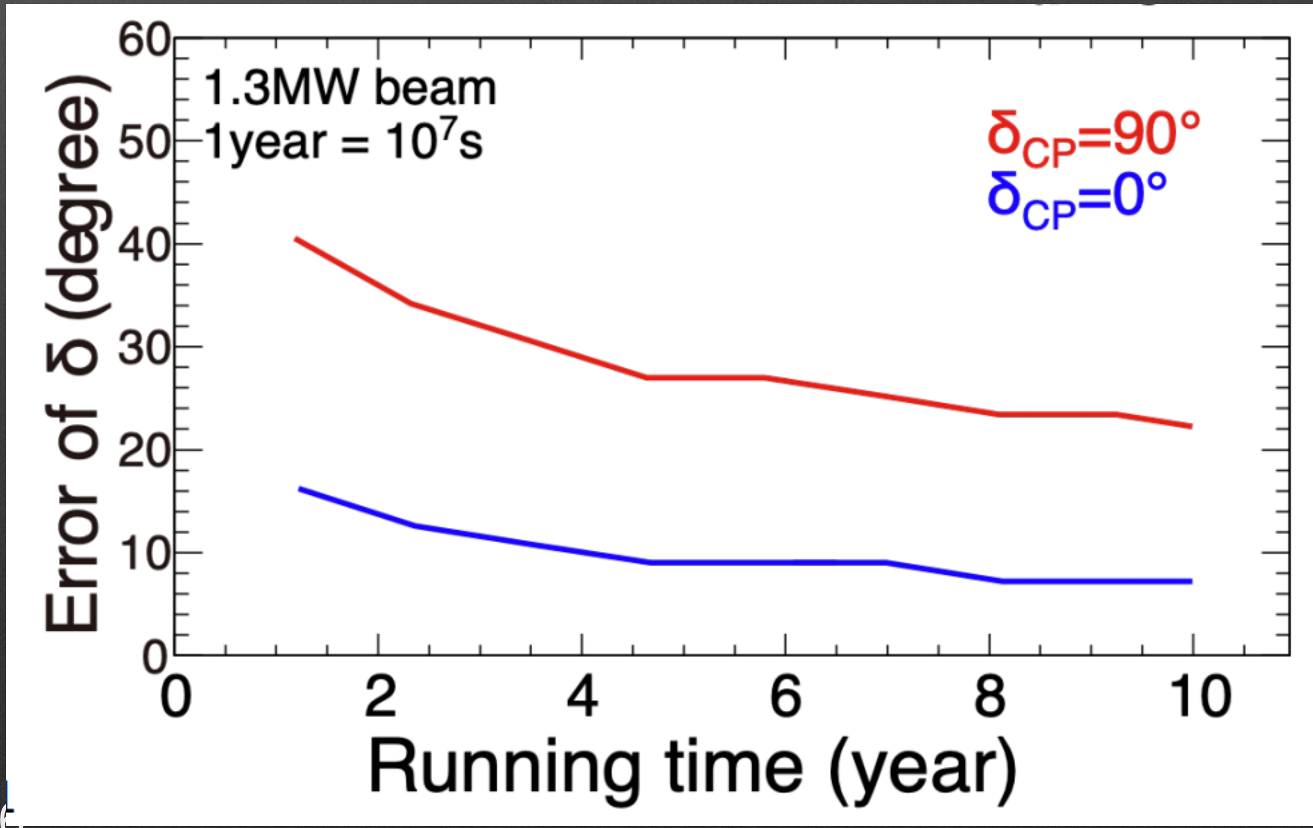


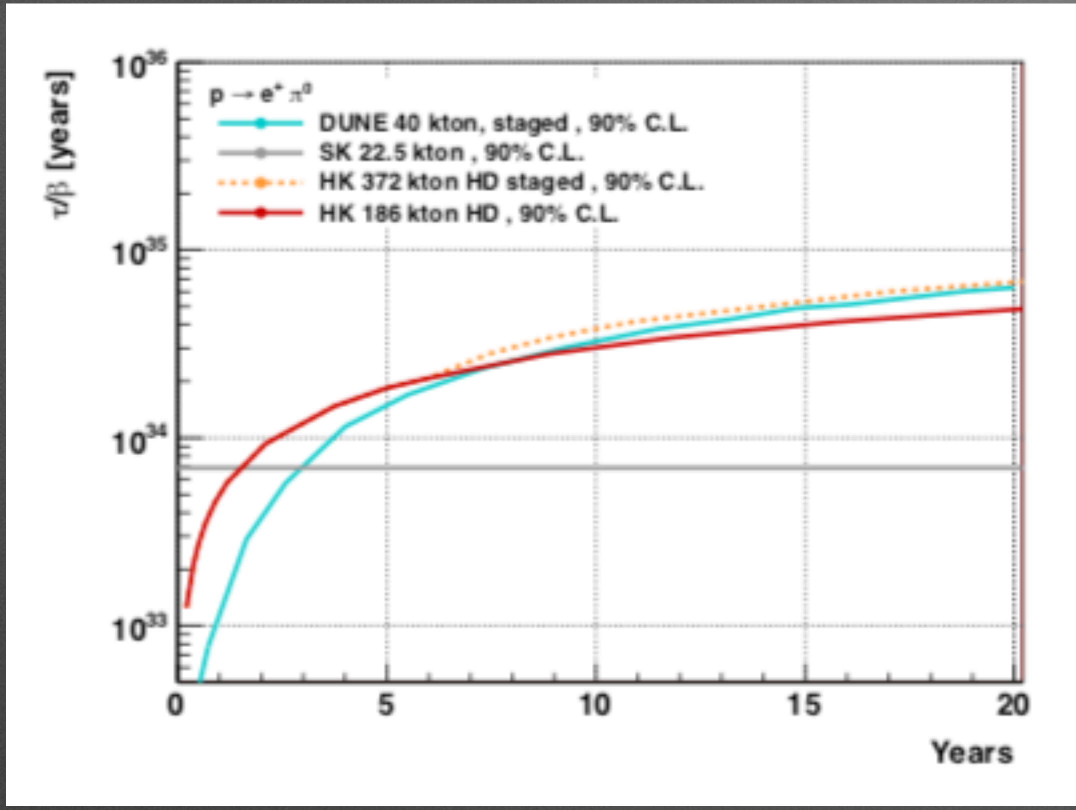


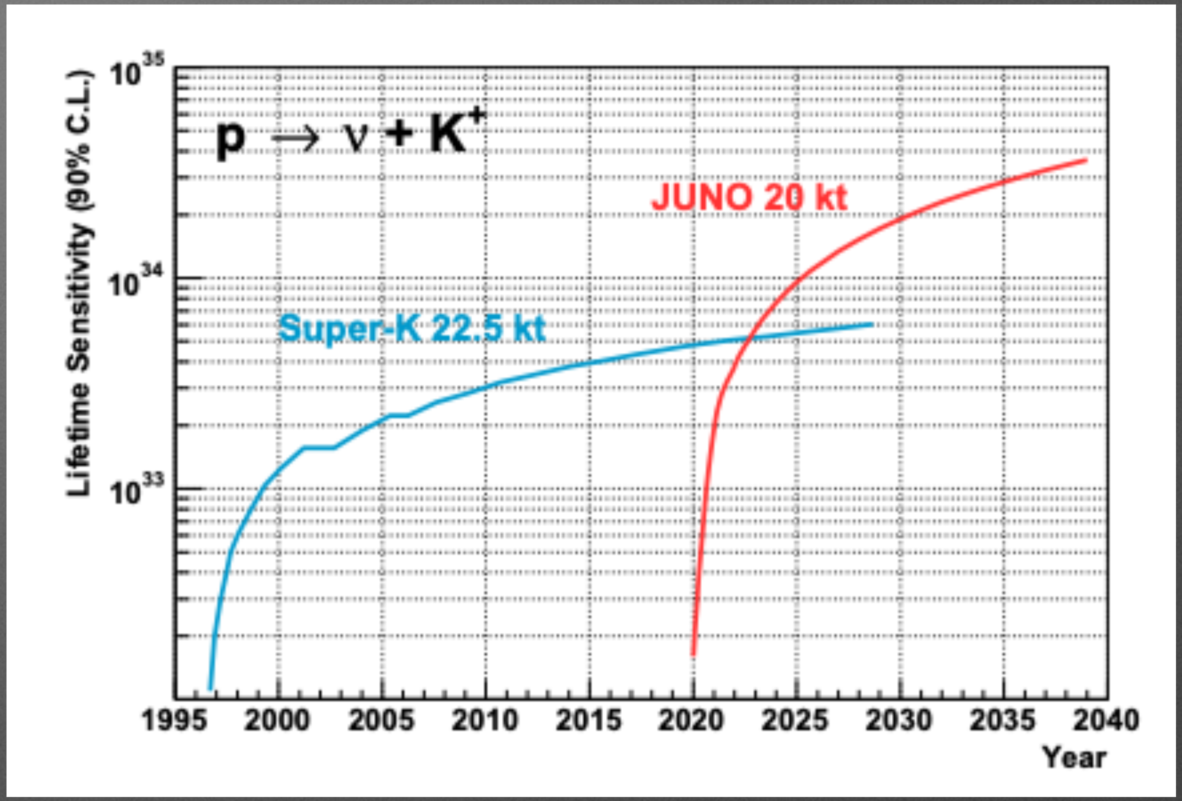



Significance to exclude $\sin\delta_{CP}=0$
Hyper-Kamiokande
HK 1.3MW
HK 1MW
HK 750kW
True $\delta_{CP}=-\pi/2$
T2K-II
DUNE
T2K
NOvA
Year


Normal mass hierarchy
$\sigma=\sqrt{\chi^2}$
HK
(single tank)
DUNE
5σ
T2K-II
3σ
T2K+NOvA
(~2020)
δ_{CP} [degree]


1.3MW beam
1year = 10^7s
$\delta_{CP}=90°$
$\delta_{CP}=0°$
Error of δ (degree)
Running time (year)


τ/β [years]
p → e⁺ π⁰
DUNE 40 kton, staged , 90% C.L.
SK 22.5 kton , 90% C.L.
HK 372 kton HD staged , 90% C.L.
HK 186 kton HD , 90% C.L.
Years


Lifetime Sensitivity (90% C.L.)
p → ν + K⁺
JUNO 20 kt
Super-K 22.5 kt
Year

Trigger	self triggering for each channel
PMT impedance	$50\,\Omega$
Signal reflection	<0.1%
Discriminator threshold	<0.25PE (well below 1PE)
Processing speed/hit (channel dead time)	$<1\,\mu s$
Maximum hit rate	>1 MHz for each channel
Charge dynamic range	0.1 to 1250PE (0.2 to 2500 pC)
Charge resolution	RMS 0.05PE for signals below 25PE
Timing LSB	<0.5 ns
Timing resolution	RMS <0.3 ns at 1PE RMS <0.2 ns for signals above 5PE
Power consumption	<1 W per channel