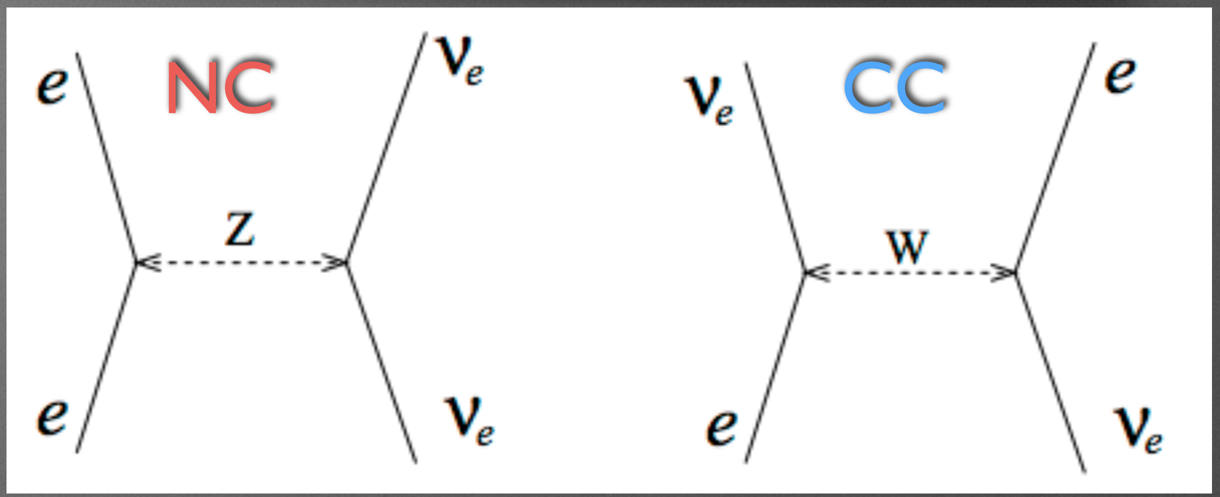
Recent results from T2K and plans for T2K-II and Hyper-K

Claudio Giganti

CPPM Seminar - 08/02/2020

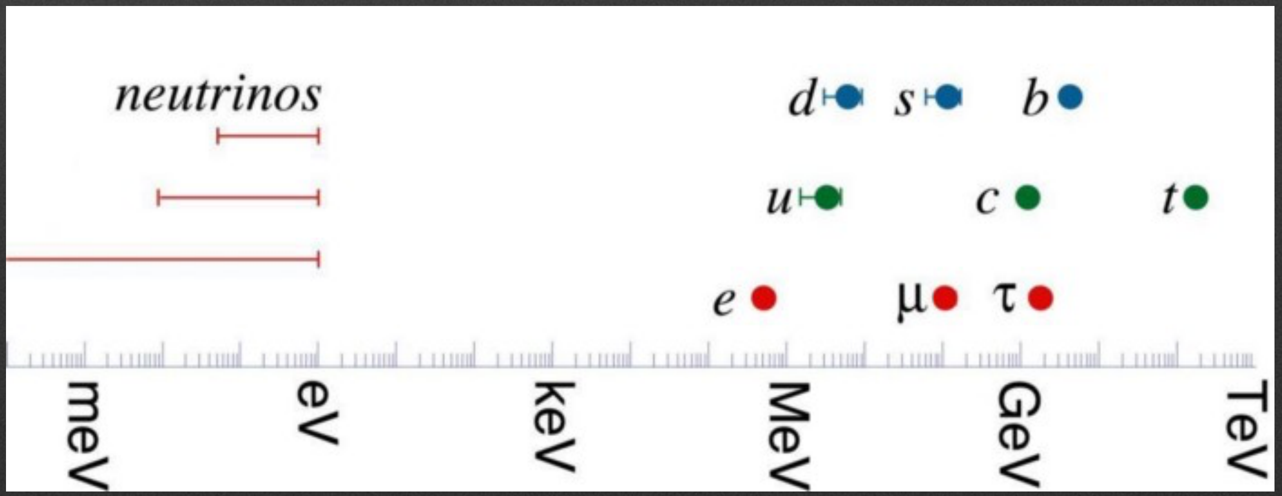
Neutrinos in the SM

Neutrinos are standard model particles → neutral cousin of the electron and of the other charged leptons



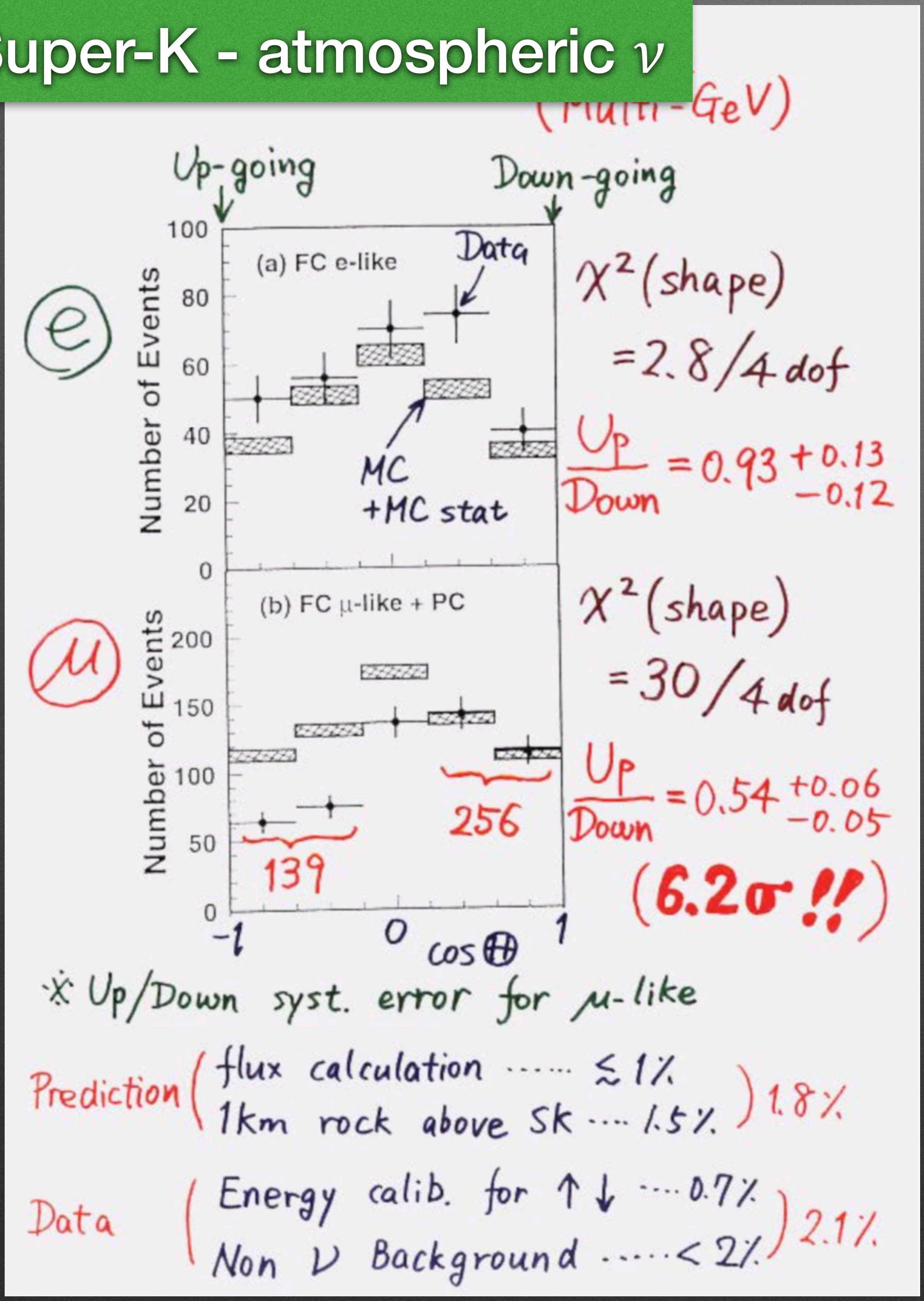
They interact only through weak interactions → Neutral current or Charged current

In the Standard Model neutrinos are massless particles → current limit on the sum of the neutrino masses ~1 eV → order of magnitudes lighter than the other fermions

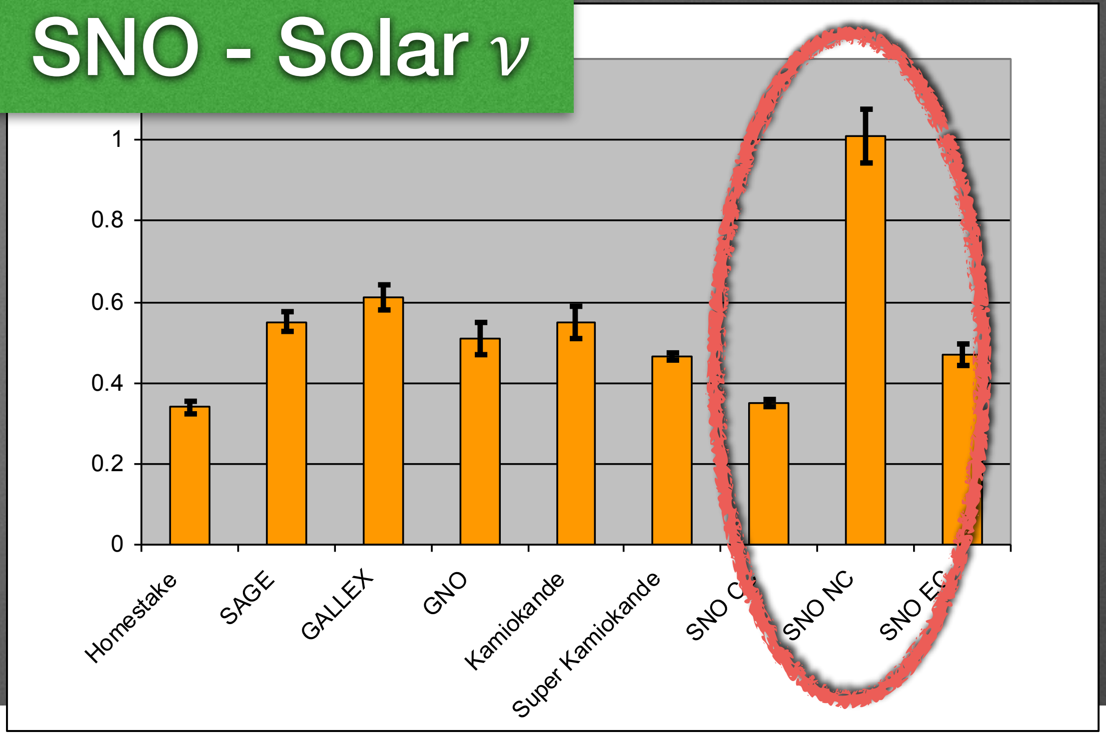


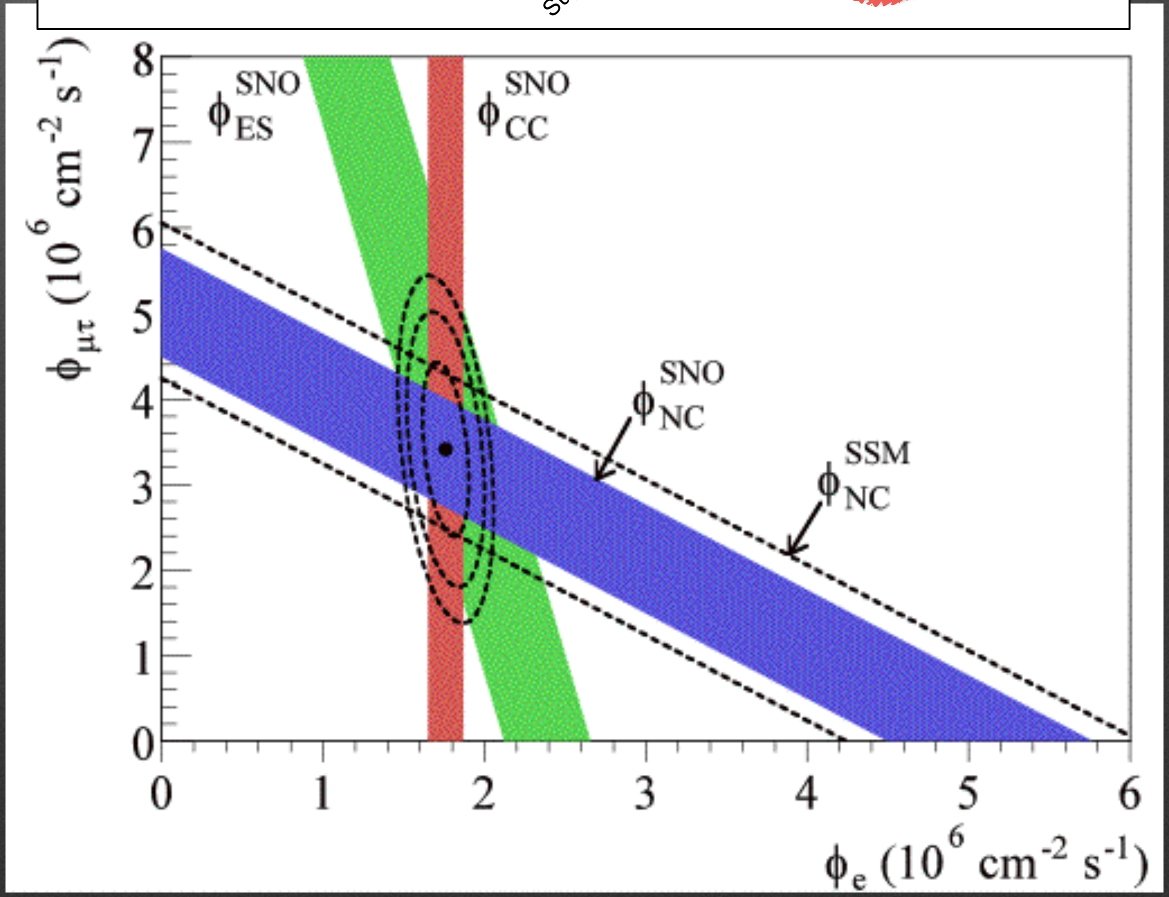
Discovery of ν oscillations

Super-K - atmospheric ν



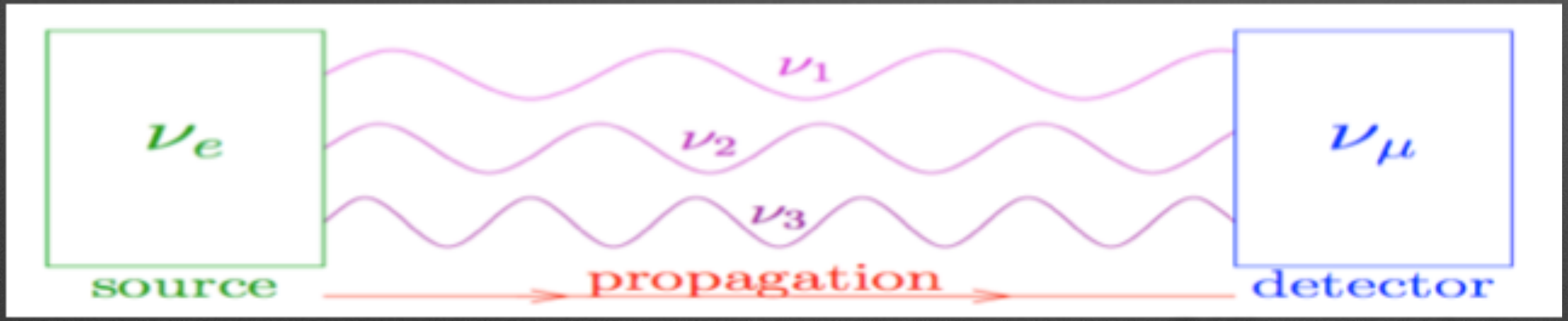
SNO - Solar ν

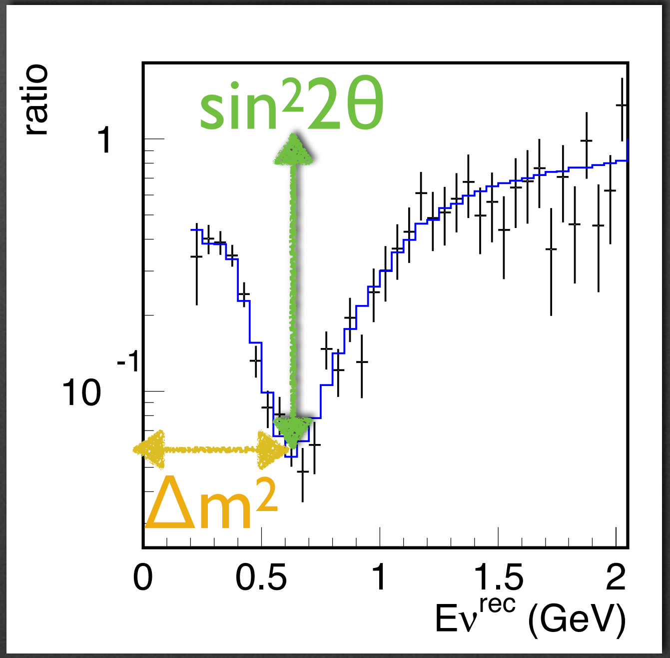




Neutrino oscillations

- First introduced by Bruno Pontecorvo in 1957
- Neutrinos are produced in flavor eigenstates (ν_μ, ν_e, ν_τ) that are linear combination of mass eigenstates (ν_1, ν_2, ν_3)
- Neutrino propagate as mass eigenstates
- At the detection a flavor eigenstate is detected → it can be different from the one that was produced





ν_e produced in a mixture of ν_1, ν_2, ν_3

ν_1, ν_2, ν_3 travel at different speed because they have different masses → interference

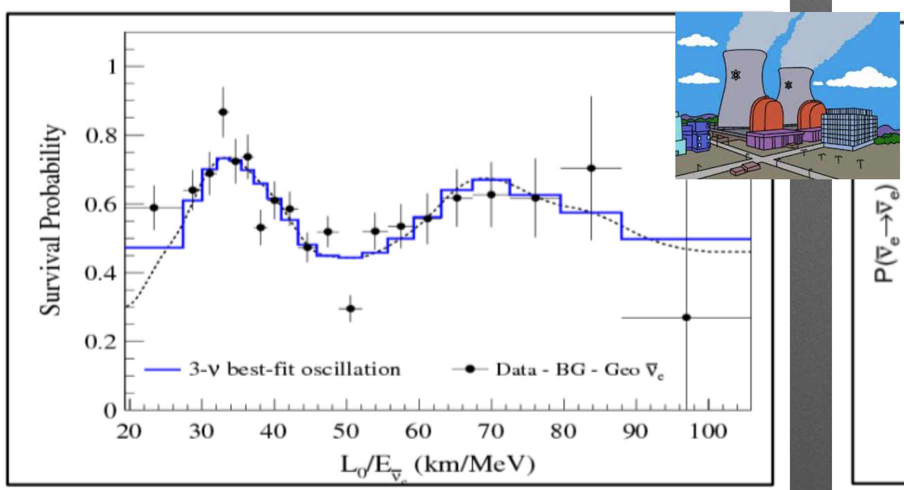
Different mixture of ν_1, ν_2, ν_3 → ν_μ is detected

Neutrino oscillation implies massive neutrinos

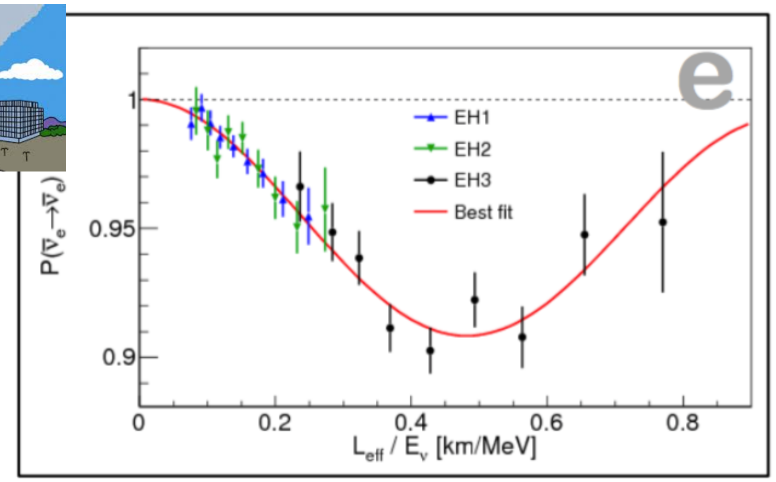
$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2(\Delta m^2_{12} L/E)$$

Neutrino oscillations

e→e (δm^2 , θ_{12})



e→e (Δm^2 , θ_{13})



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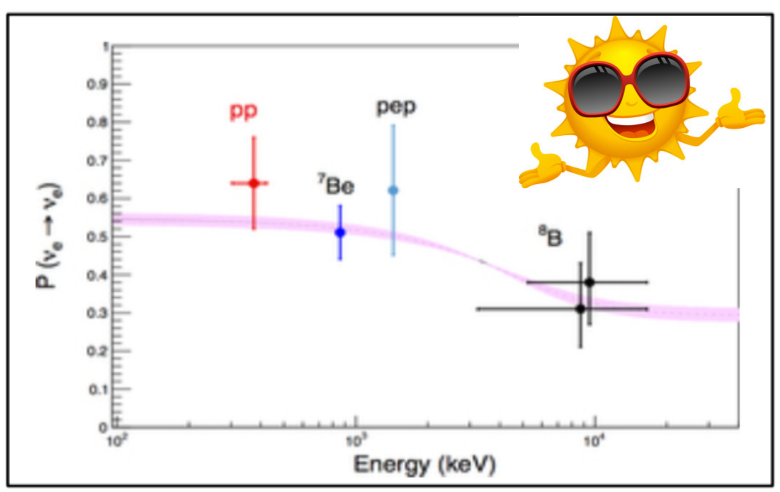
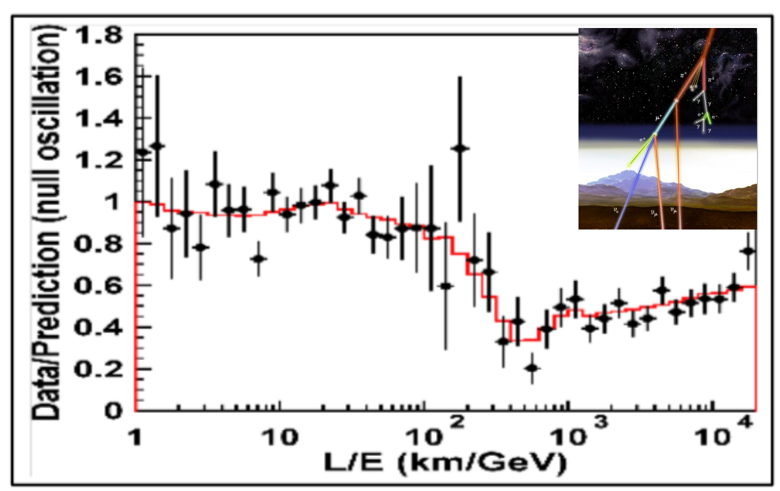
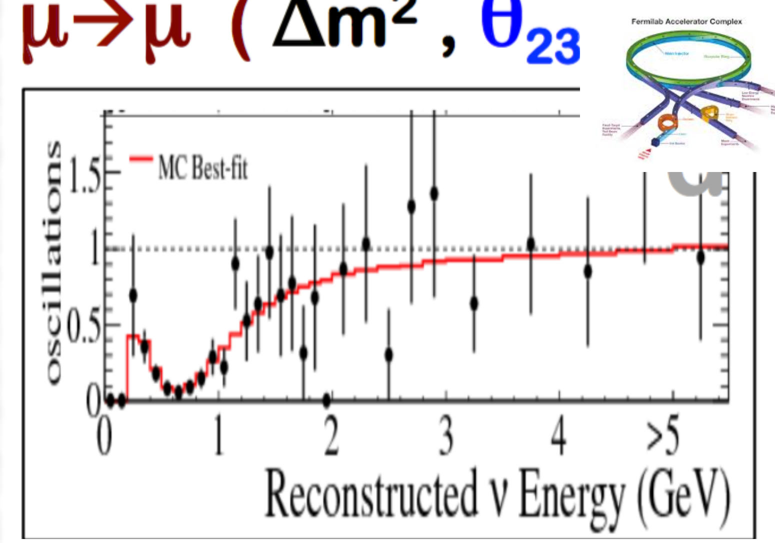


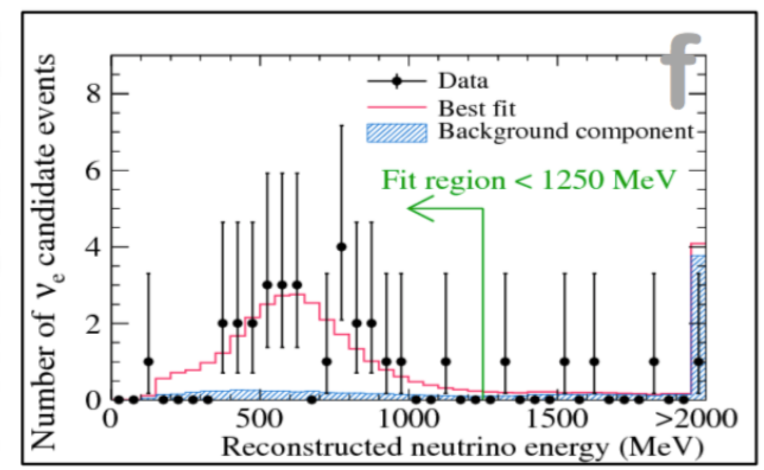
μ→μ (Δm^2 , θ_{23})



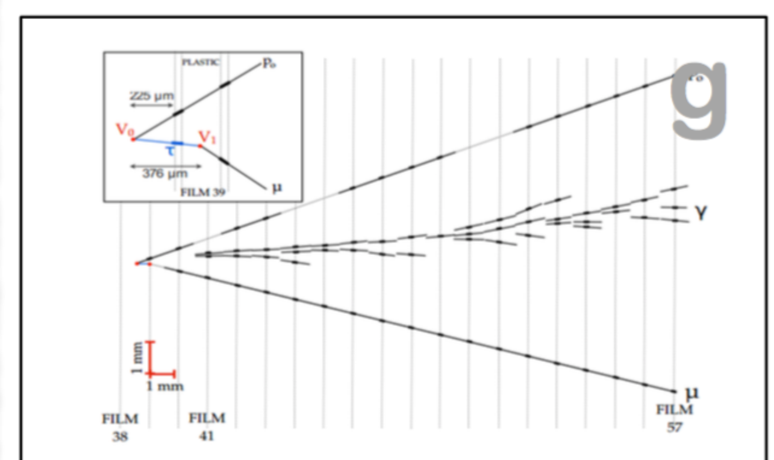
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



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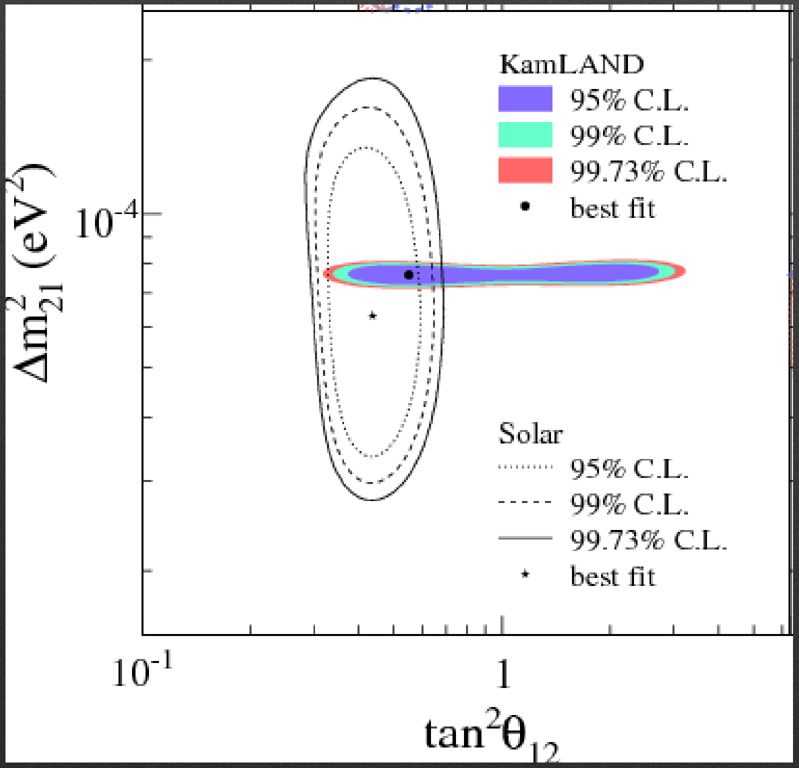
PMNS matrix

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

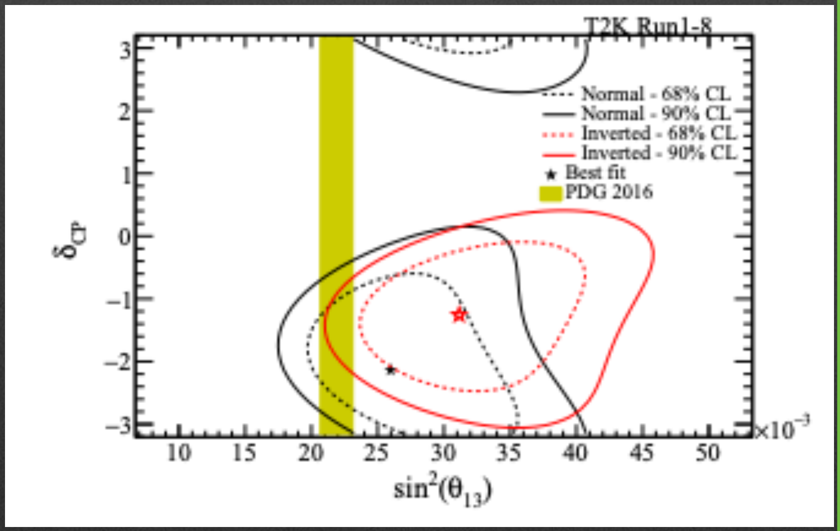
- **3 mixing angles**
- **2 independent mass differences**
- **1 CP violation phase**

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

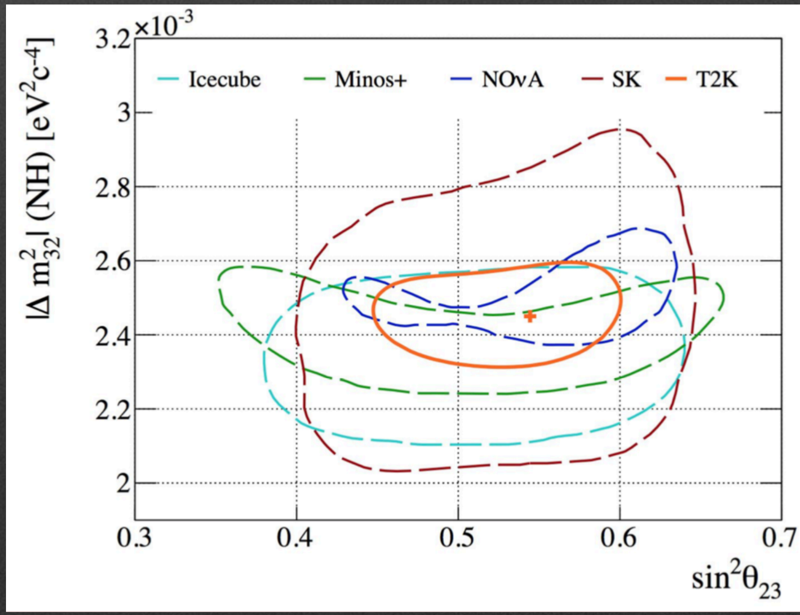
Solar (SNO, KamLand) → θ_{12}, Δm_{12}



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



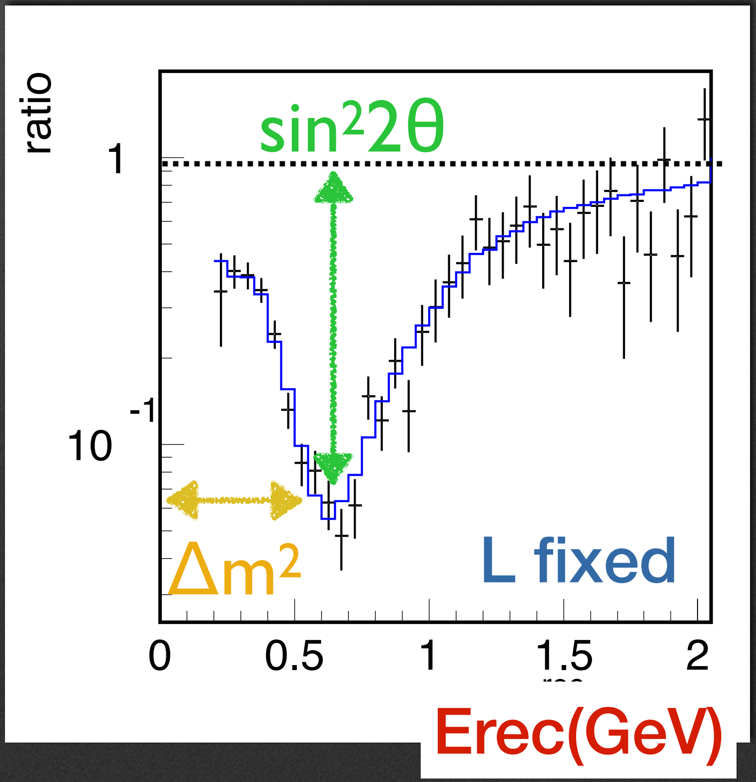
Atmospheric (SK, IceCUBE)
LBL (Minos, T2K, NOνA)
→ θ_{23}, Δm_{32}



Artificial sources of neutrinos

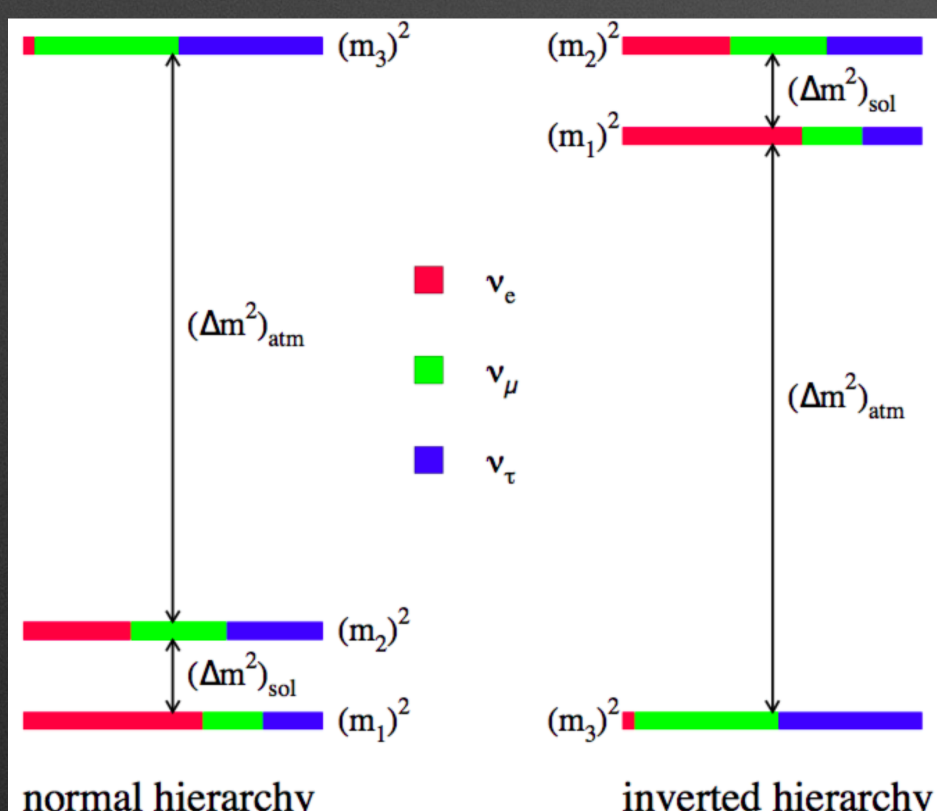
- Oscillations were discovered with solar and and atmospheric neutrinos
- Great sources of neutrinos → they come for free, just need to build a detector
  - Ideal for discoveries (span different ranges of Δm2)
  - Cannot be tuned → not the best sources for precision measurements
- **Reactors** → reactor spectrum is fixed but the distance can be tuned (KamLAND for θ_{12}, DB/DC/RENO for θ_{13}, Juno for mass ordering)
- **Accelerators** → can tune energy and distance
  - Well defined L/E → maximize oscillation probability (knowing Δm2)
  - Sensitive to 5 oscillation parameters (θ_{23}, θ_{13}, Δm^2_{23}, δ_{CP}, and mass ordering)
  - Can produce beam of ν_μ of $\overline{\nu}_\mu$ → study CP violation

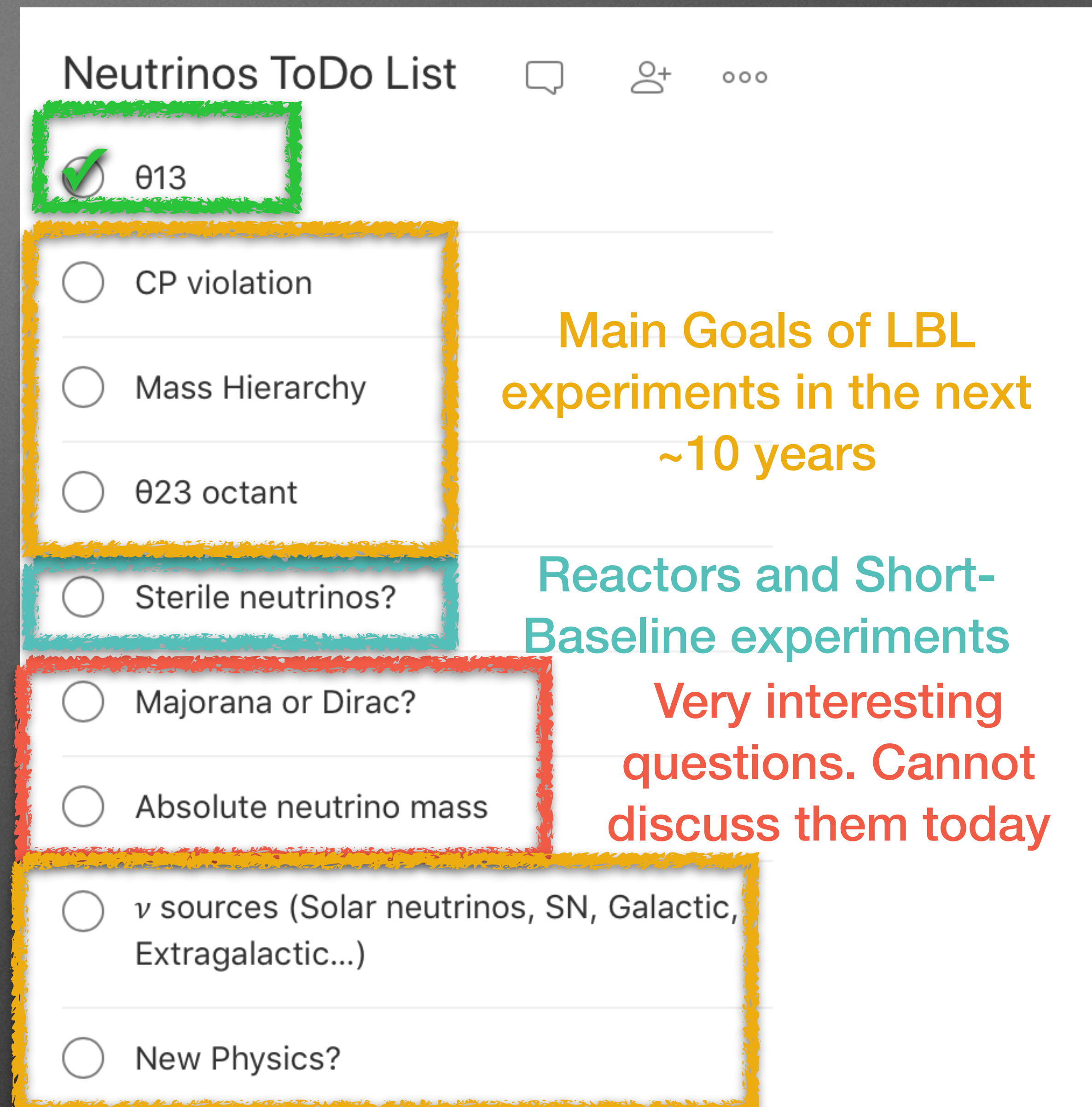
$$P(\nu_\mu \to \nu_x) = \sin^2(2\theta)\sin^2(\Delta m^2_{12} L/E)$$



Open questions

- Still many open questions related to neutrino oscillations → “guaranteed” measurements
- But we also don’t know the nature of neutrinos (Dirac or Majorana) → $0\nu\beta\beta$ experiments
- Absolute mass of neutrinos → Katrin, Project-8, Cosmology
- Multi-messenger astronomy with neutrinos is starting → Far Detectors for LBL experiments

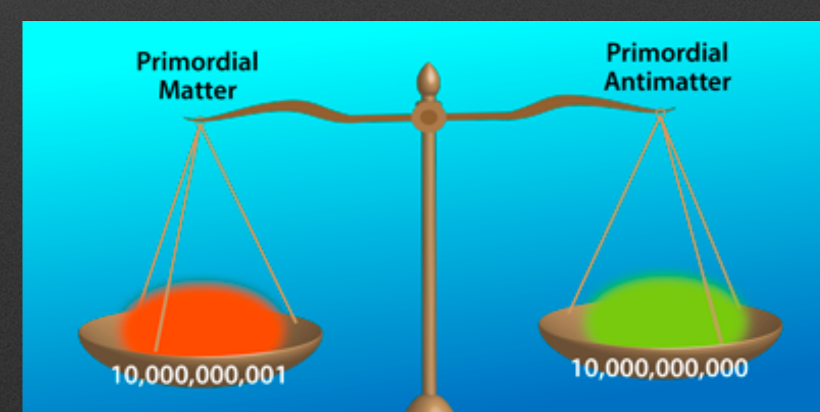




Main Goals of LBL experiments in the next ~10 years

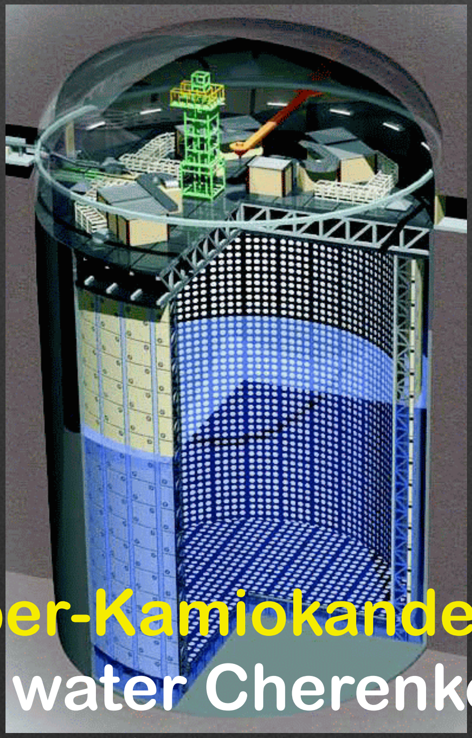
Reactors and Short-Baseline experiments

Very interesting questions. Cannot discuss them today

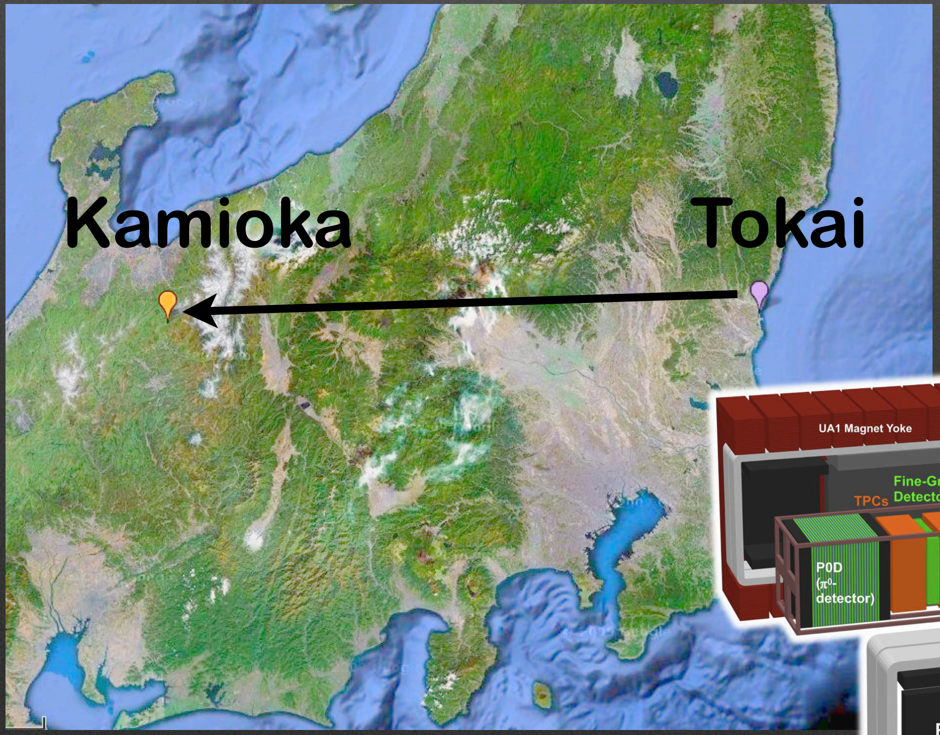


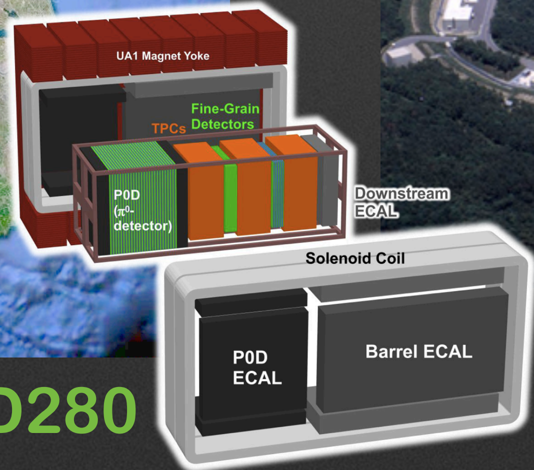
T2K experiment

- High intensity ~600 MeV ν_μ beam produced at J-PARC (Tokai)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande) 295 km from J-PARC
- Run in ν or $\overline{\nu}$ mode by changing the horn polarity
- Physics goals:
  - ν_e and $\overline{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ disappearance → θ_{23} and $|\Delta m^2_{32}|$



Super-Kamiokande: 50 kt water Cherenkov detector





ND280

J-PARC accelerator: Design power: 750 kW

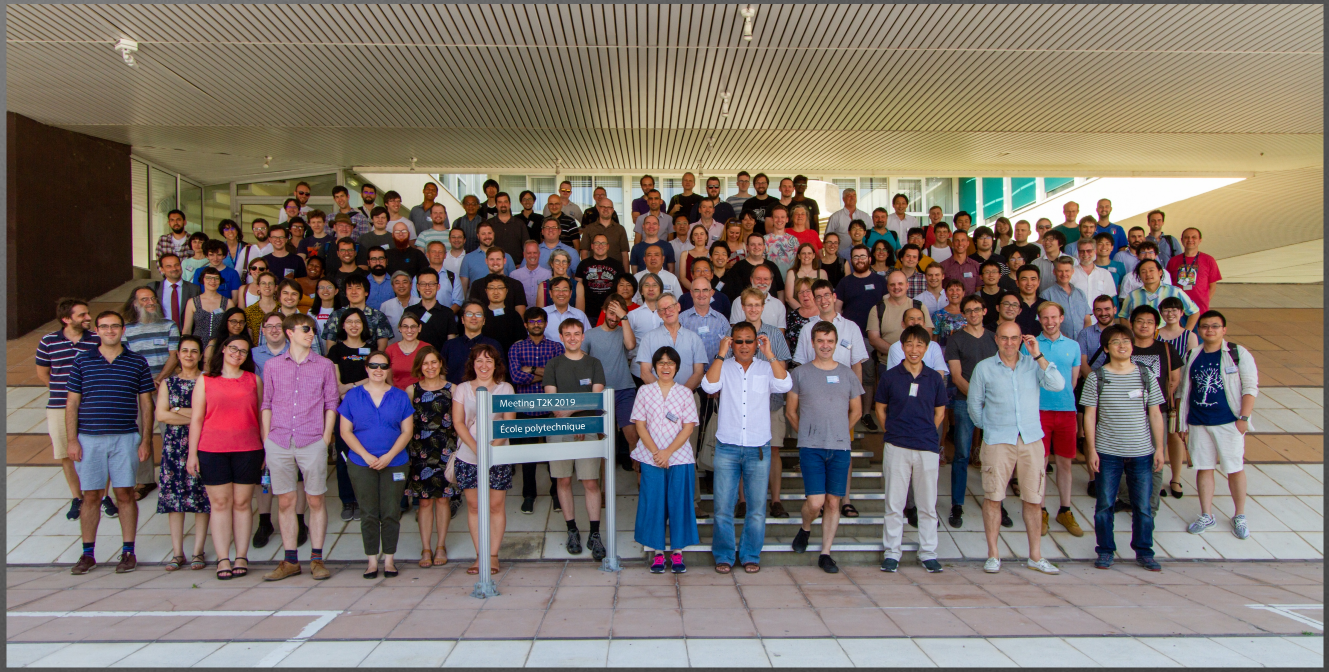
T2K collaboration

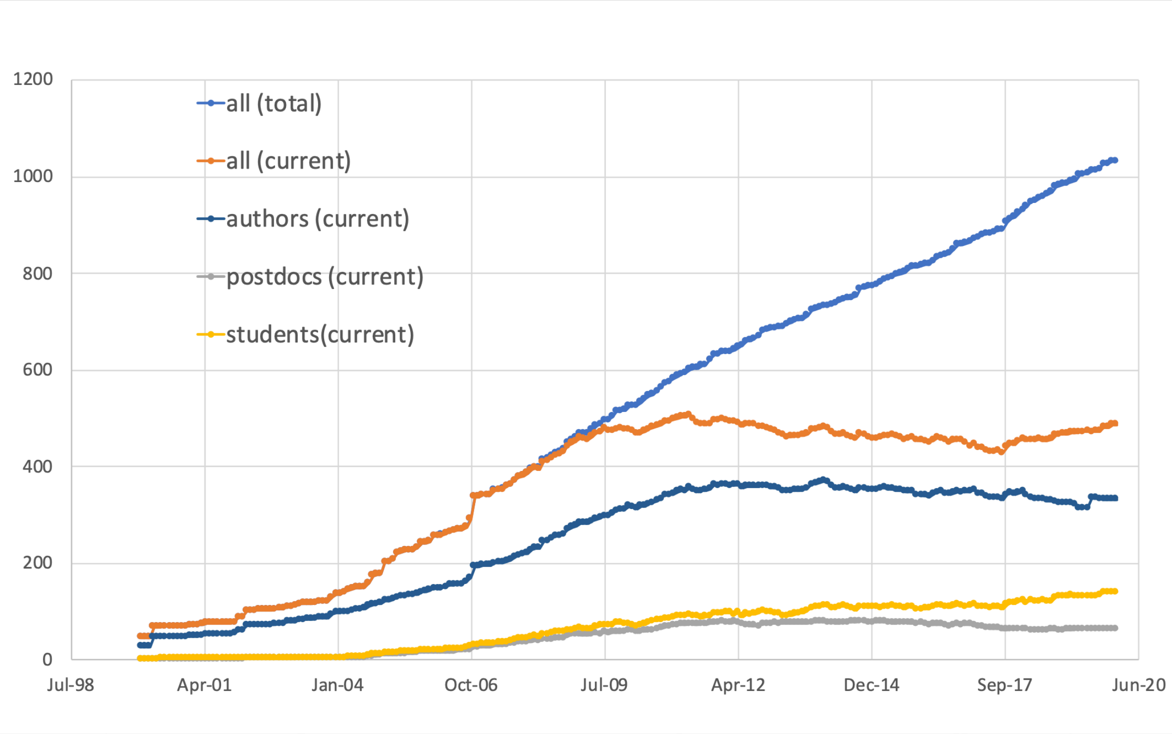
~500 members, 69 institutes, 12 countries

Asia	117
Japan	114
Vietnam	3

Americas	96
Canada	26
USA	70

Europe	262
France	40
Germany	5
Italy	24
Poland	27
Russia	19
Spain	14
Switzerland	34
UK	99





A long journey

T2K starts data taking (2010)

Take data in $\bar{\nu}$-mode (2014)

T2K phase-II + ND280 upgrade (2022)

Hyper-K (2027)

2010 2012 2014 2016 2018 2020 2022 2024 2026 2028

Hints of ν_e appearance ($\theta_{13}\neq0$@2.5σ)

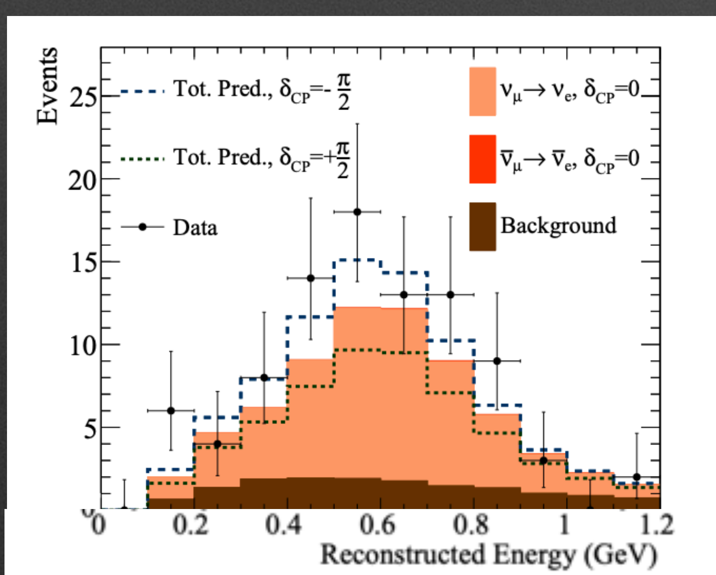
Phys.Rev.Lett. 107 (2011) 041801

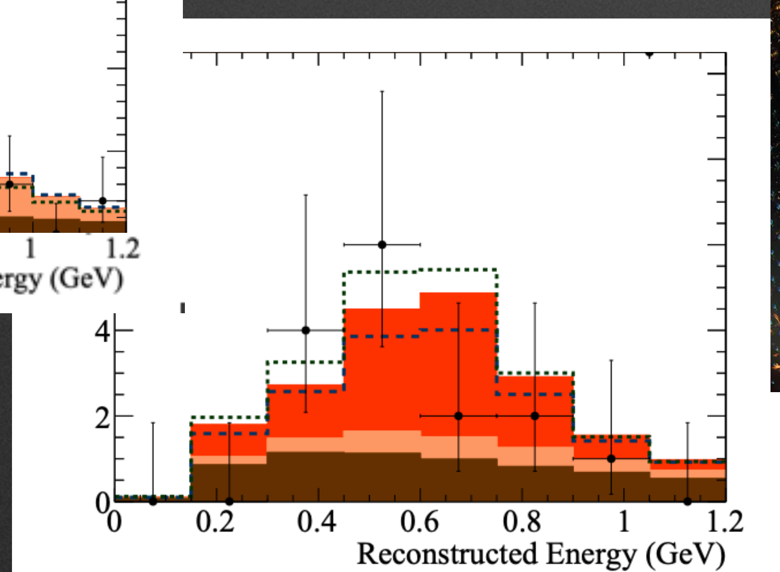
Observation of ν_e appearance ($\theta_{13}\neq0$@7.3σ)

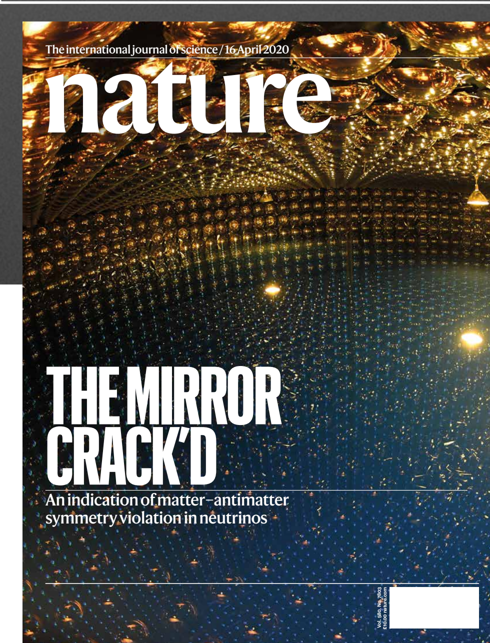
Phys.Rev.Lett. 112 (2014) 061802

Hints of CP violation → $\sin(\delta_{CP})=0$ excluded at 95%

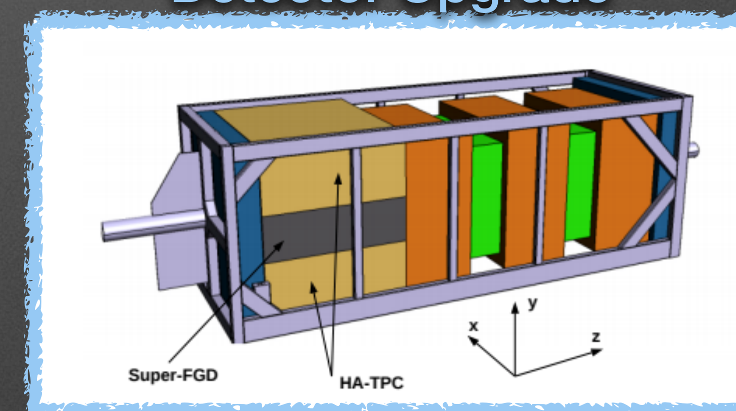
Nature Vol. 580, pp. 339-344



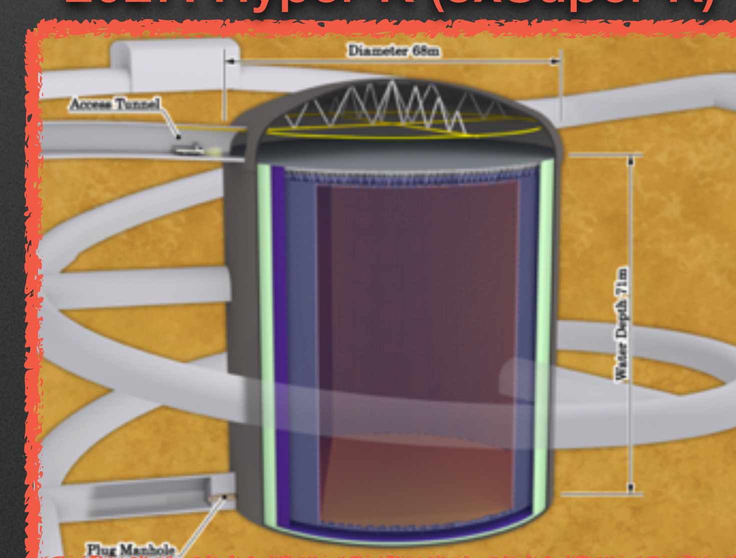




2022: T2K-II + Near Detector Upgrade

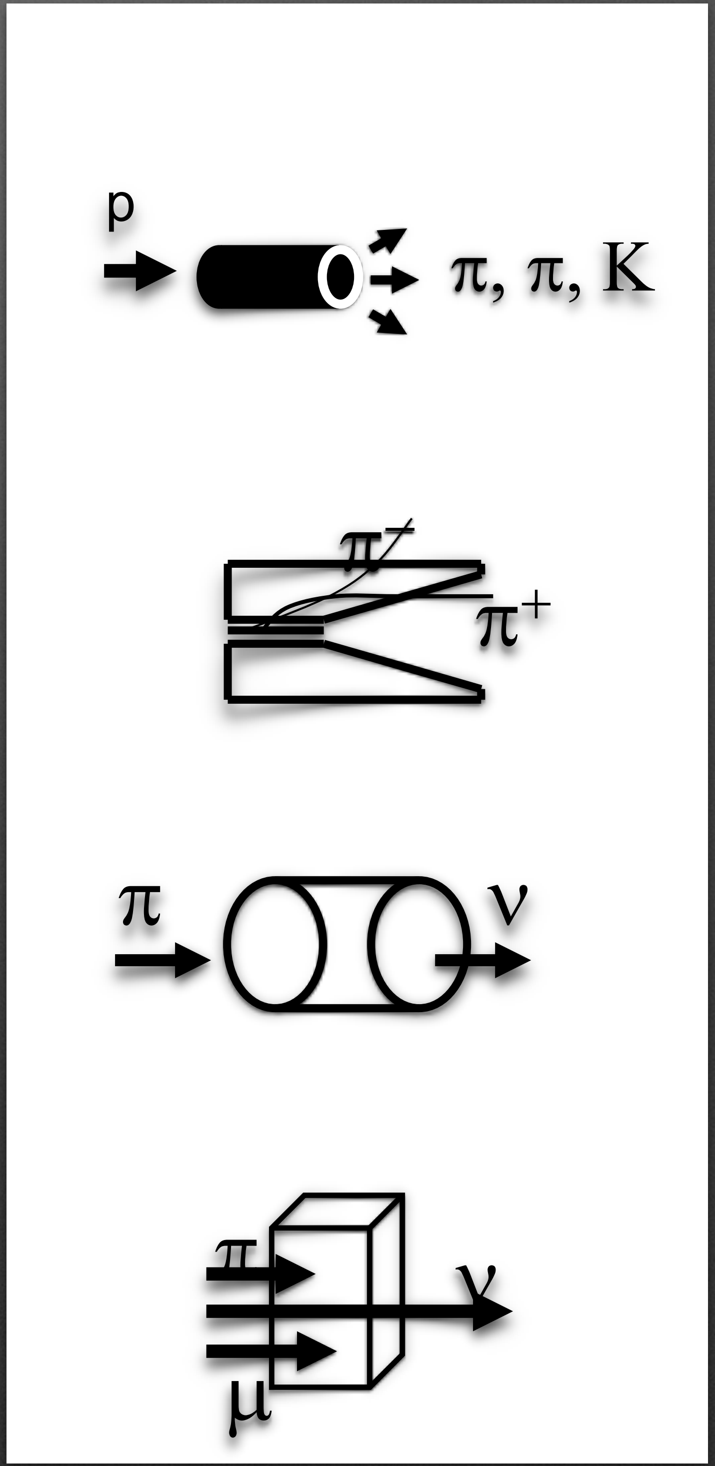


2027: Hyper-K (8xSuper-K)

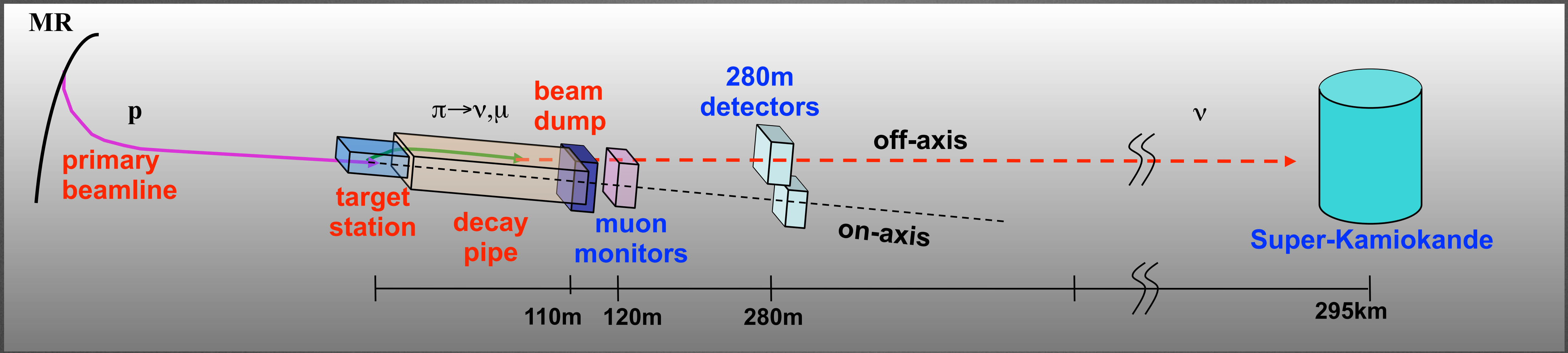


Neutrino beam

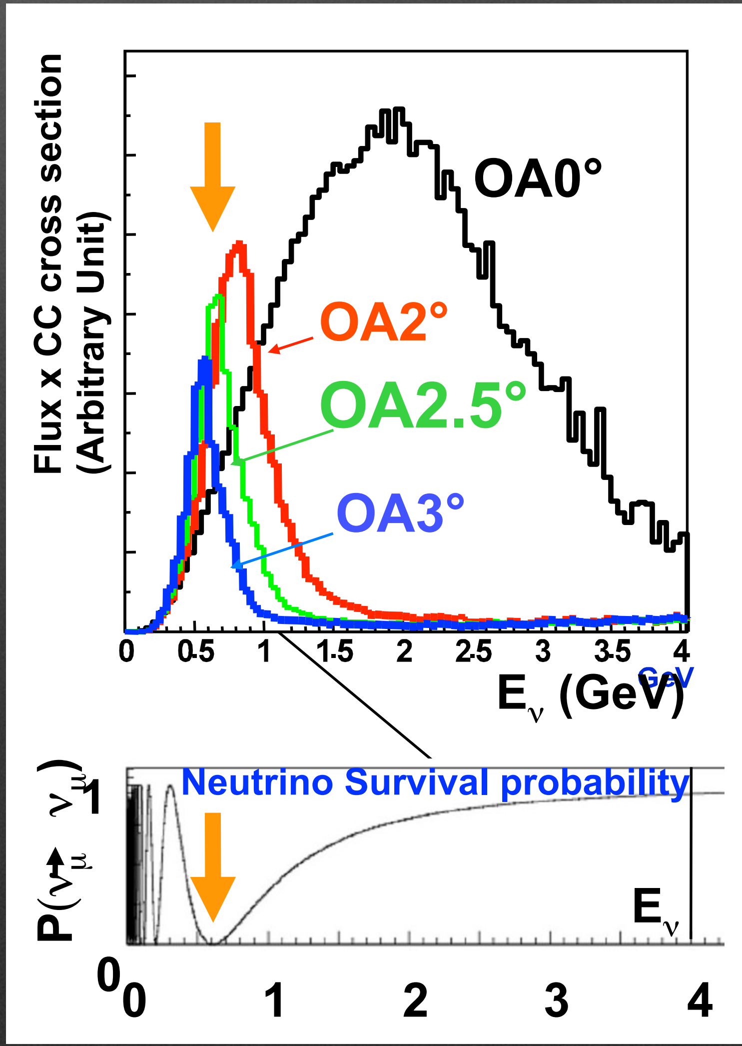
- 30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target
- p+C interactions producing hadrons (mainly pions and kaons)
- Hadrons are focused and selected in charge by 3 electromagnetic horns
- ν_μ mainly produced by pion decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$
    - $\bar{\nu}_\mu$ produced by changing the direction of the horn current
- All charged particles stopped by beam-dump



T2K beamline



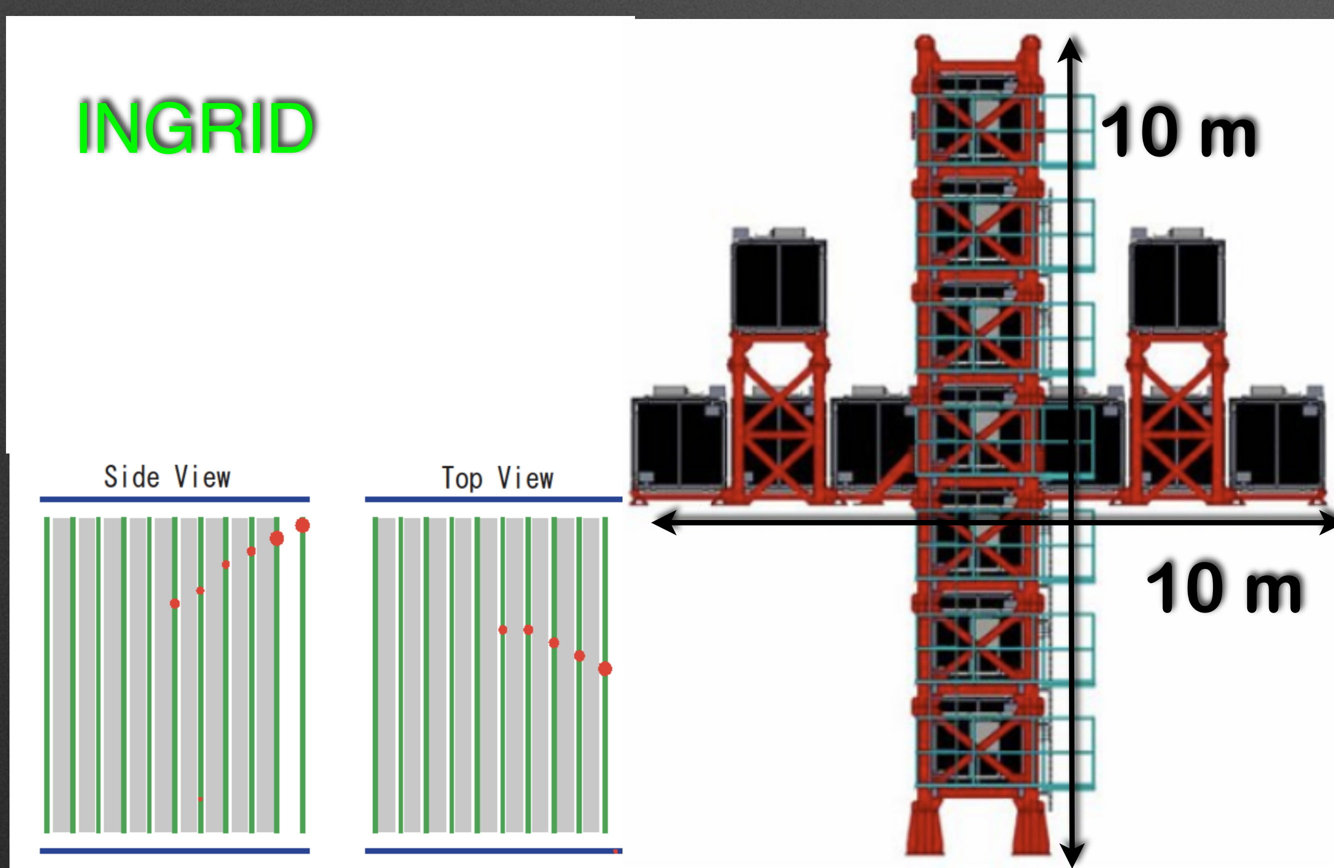
- In the case of T2K we use the off-axis technique
- Detectors are placed off-axis with respect to center of the beam
- Narrow band beam centered at the oscillation maximum

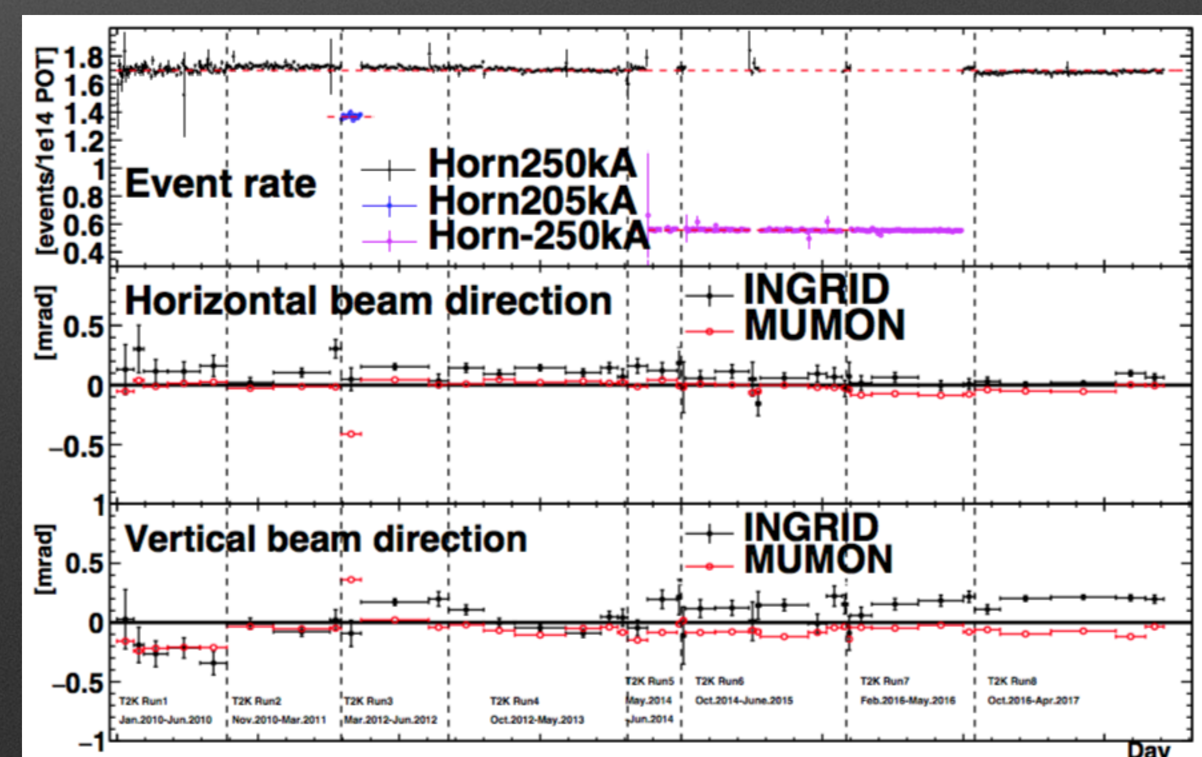


ND280 on-axis (INGRID)

- On-axis Near Detector (INGRID)
  - Monitor the beam stability day-by-day looking at ν ($\overline{\nu}$) interactions
  - 16 cubic modules: 1 module is a sandwich of 10 iron and 11 scintillator layers

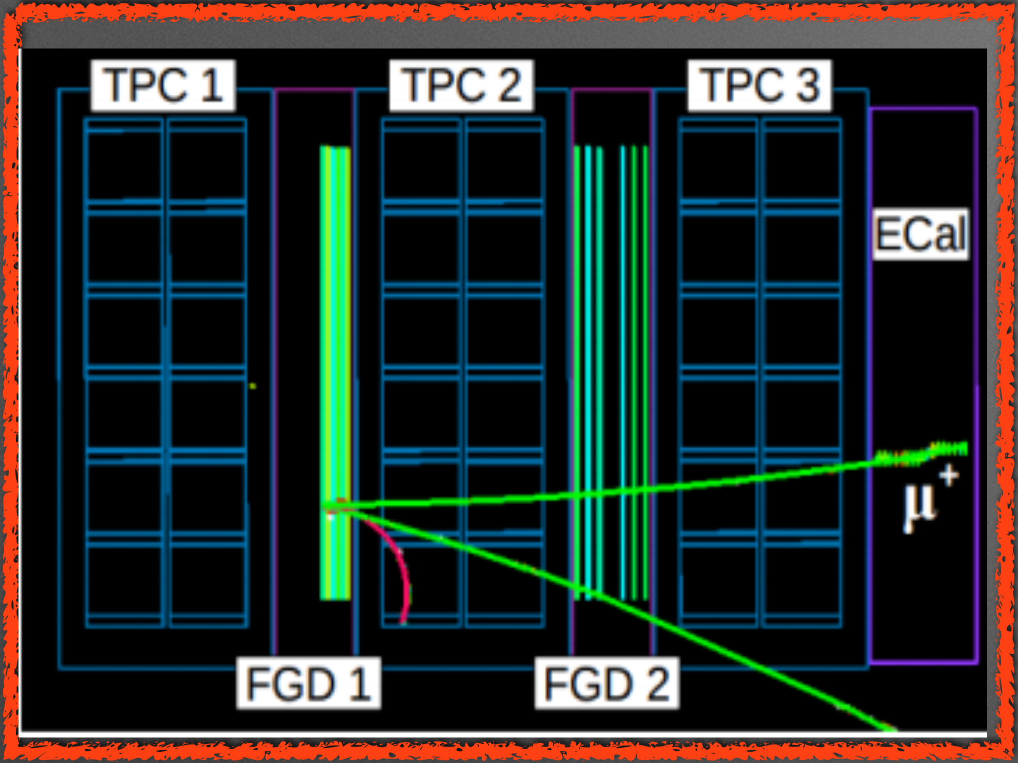
INGRID interaction rate and beam direction

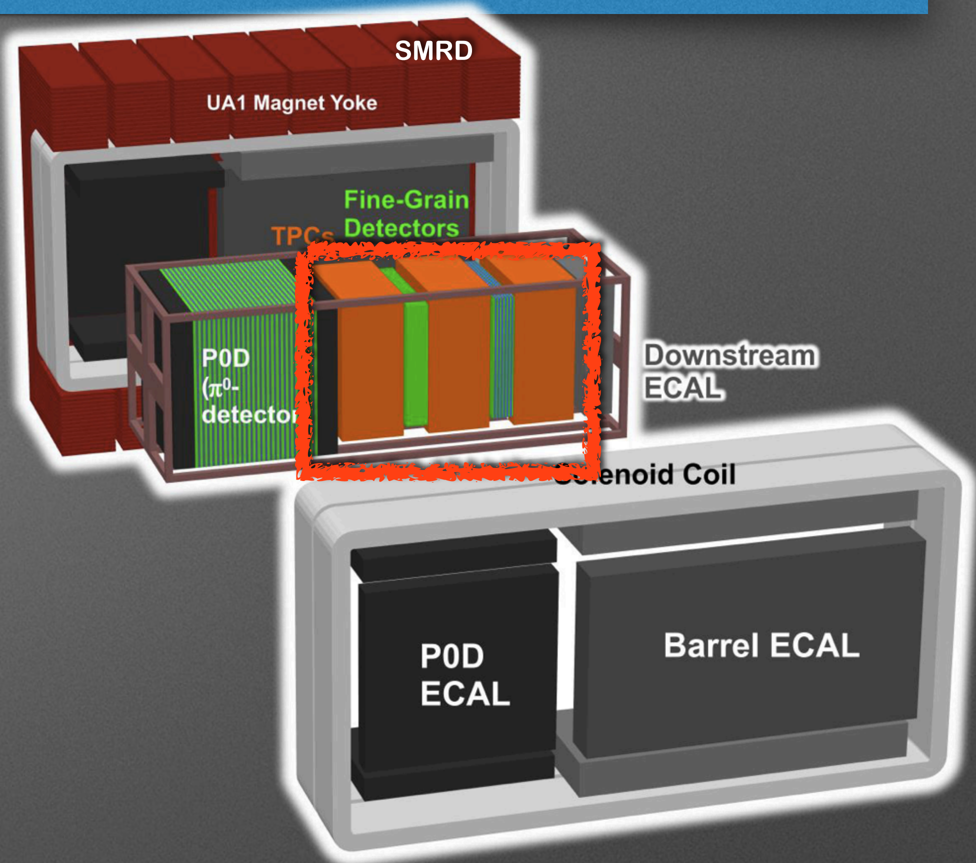




ND280 off-axis

Tracker





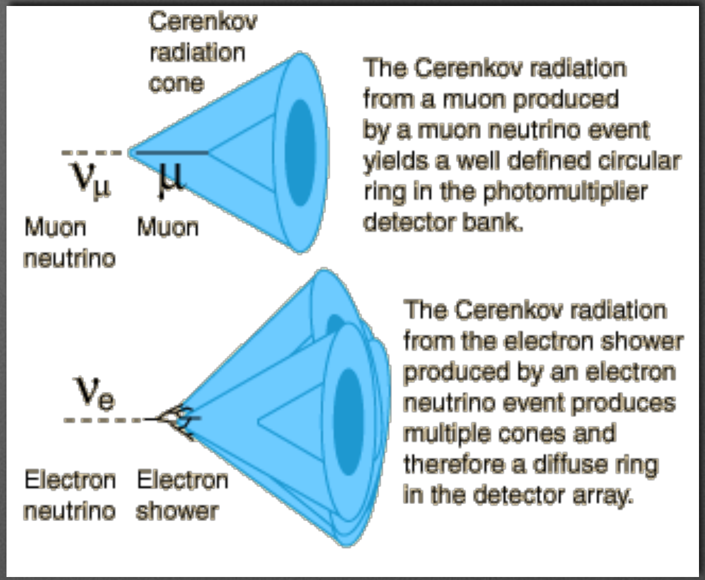
- Detectors installed inside the UA1/NOMAD magnet (0.2 T field)
- Dedicated π^0 detector (P0D)

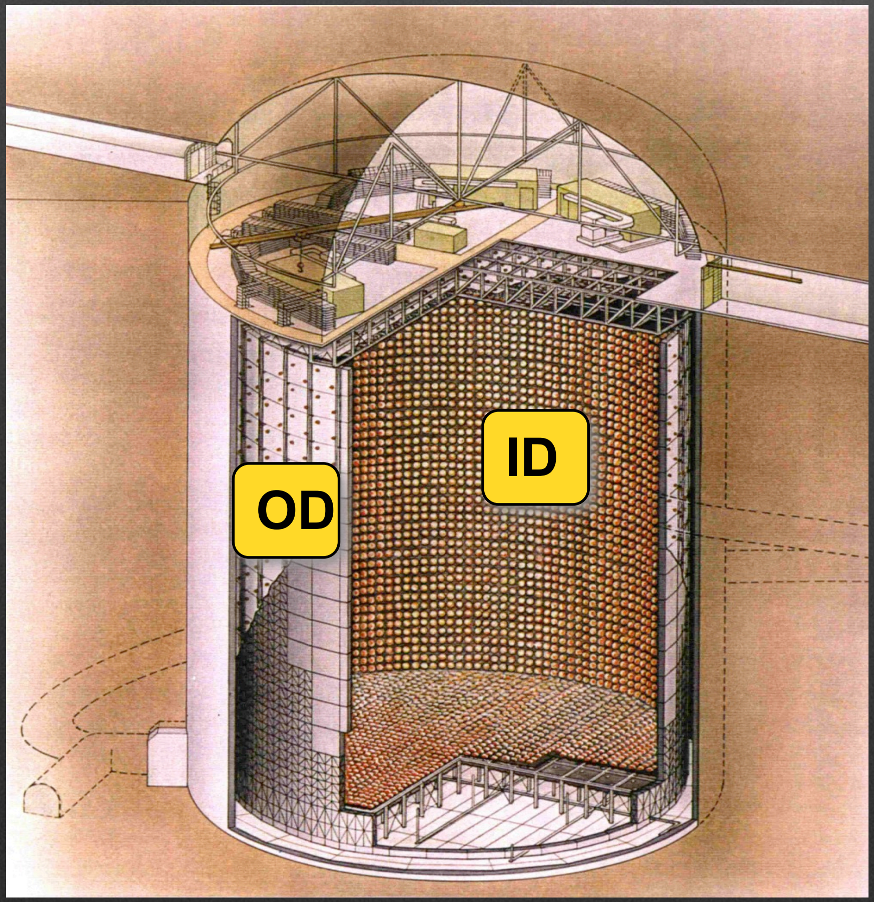
Tracker

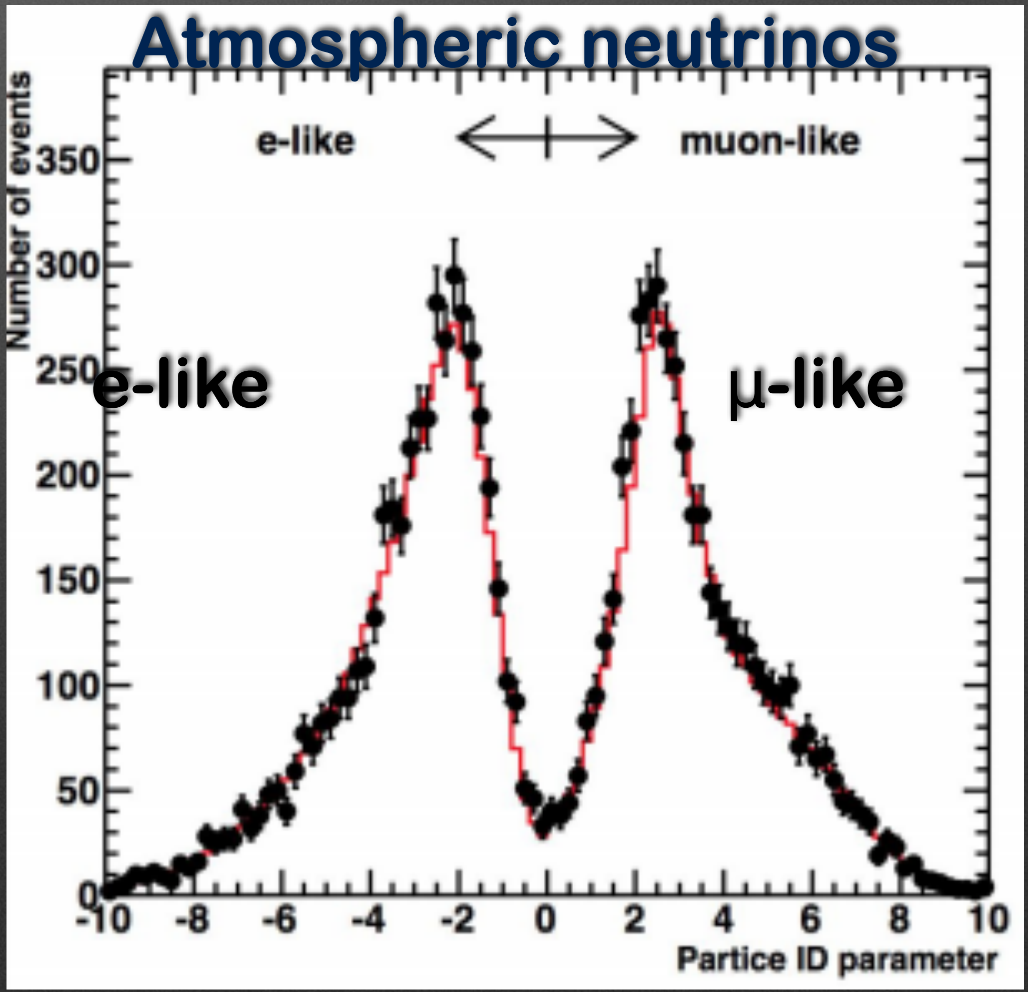
- 2 Fine-Grained Detectors (target for neutrino interactions)
- 3 Time Projection Chambers: reconstruct momentum and charge of the particles produced in ν interactions, PID based on ionization
- Electromagnetic Calorimeter to distinguish tracks from showers
- Side Muon Range Detector (SMRD) installed inside the magnet yokes

Super-Kamiokande

- 50 kton water Cherenkov detector
  - ~11000 20'' PMT inner detector (~2000 8'' PMT outer detector used as veto)
- ~1000 meters underground in the Kamioka mine, operated since 1996
- Very good PID capabilities to distinguish electrons from muons







Neutrinos and 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

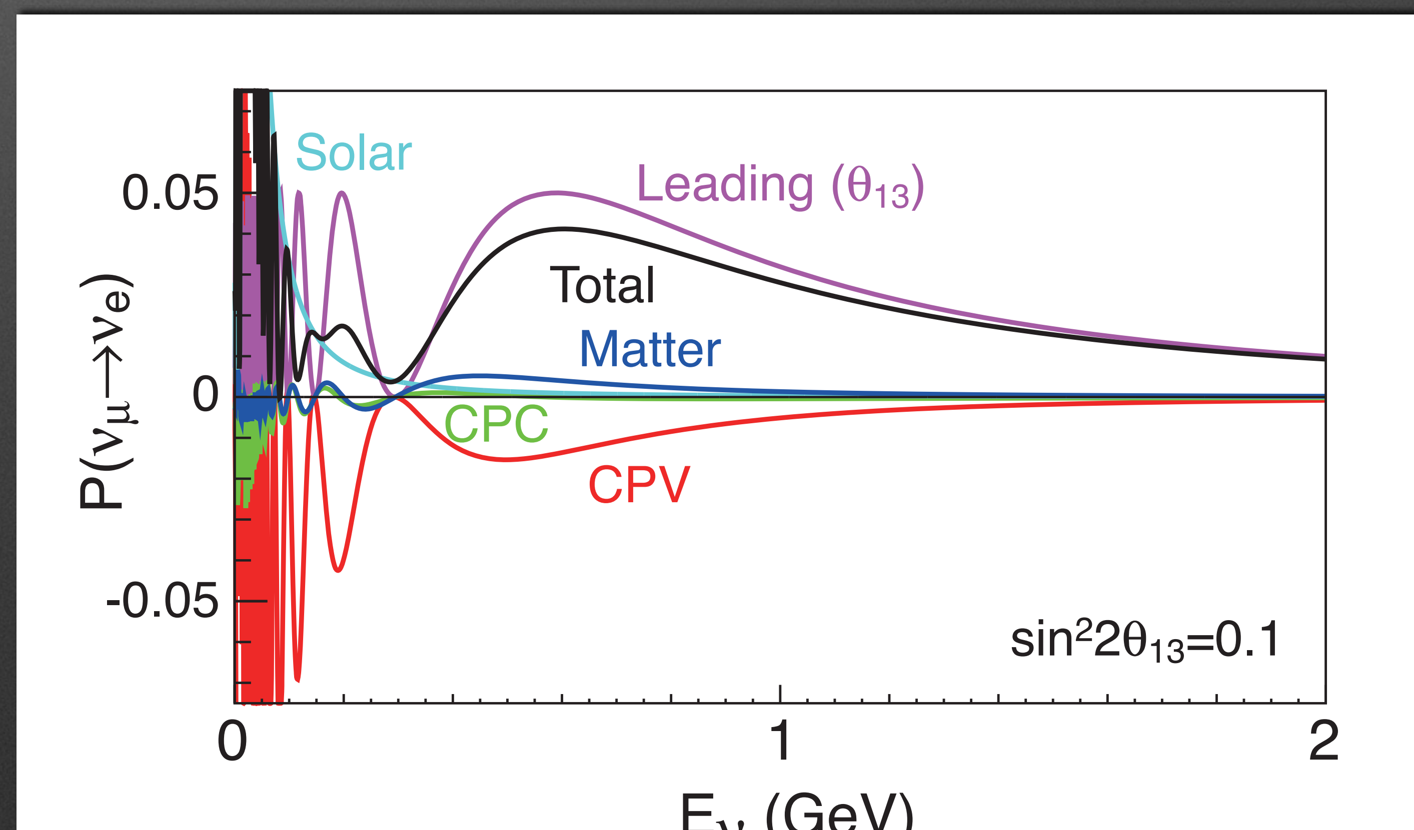
∝ distance

Experimentally we measure an appearance probability

$\sin\delta$ 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%



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& +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} \\
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$$

Leading term → θ_{13}

CPV term

Matter effects

∝ distance

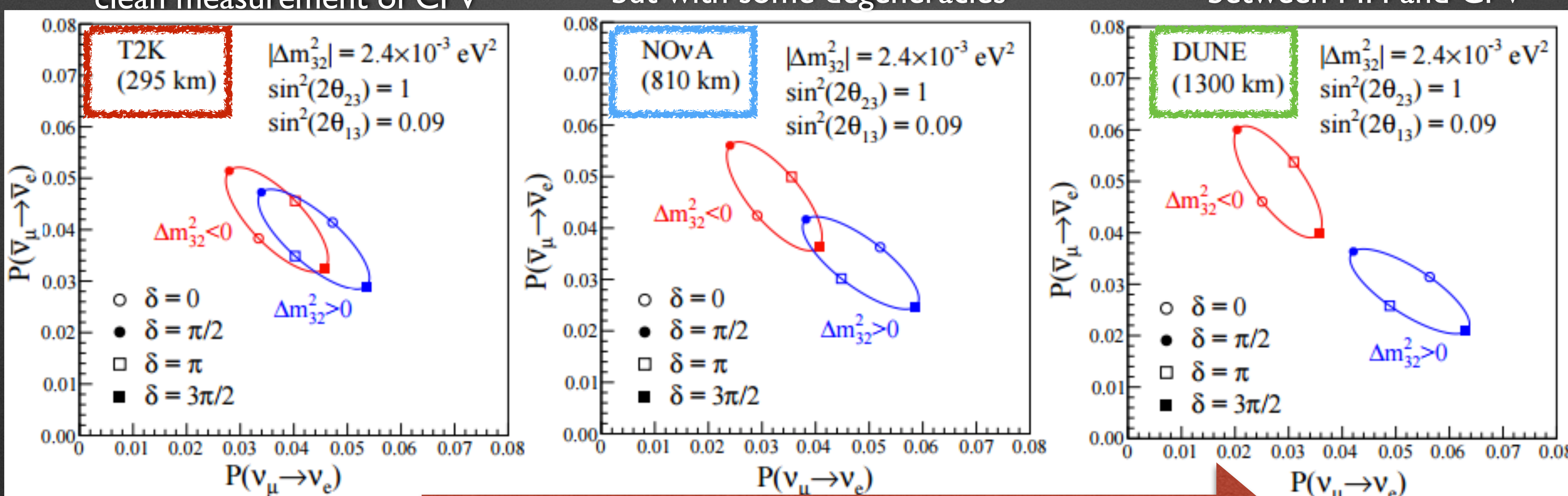
Experimentally we measure an appearance probability

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

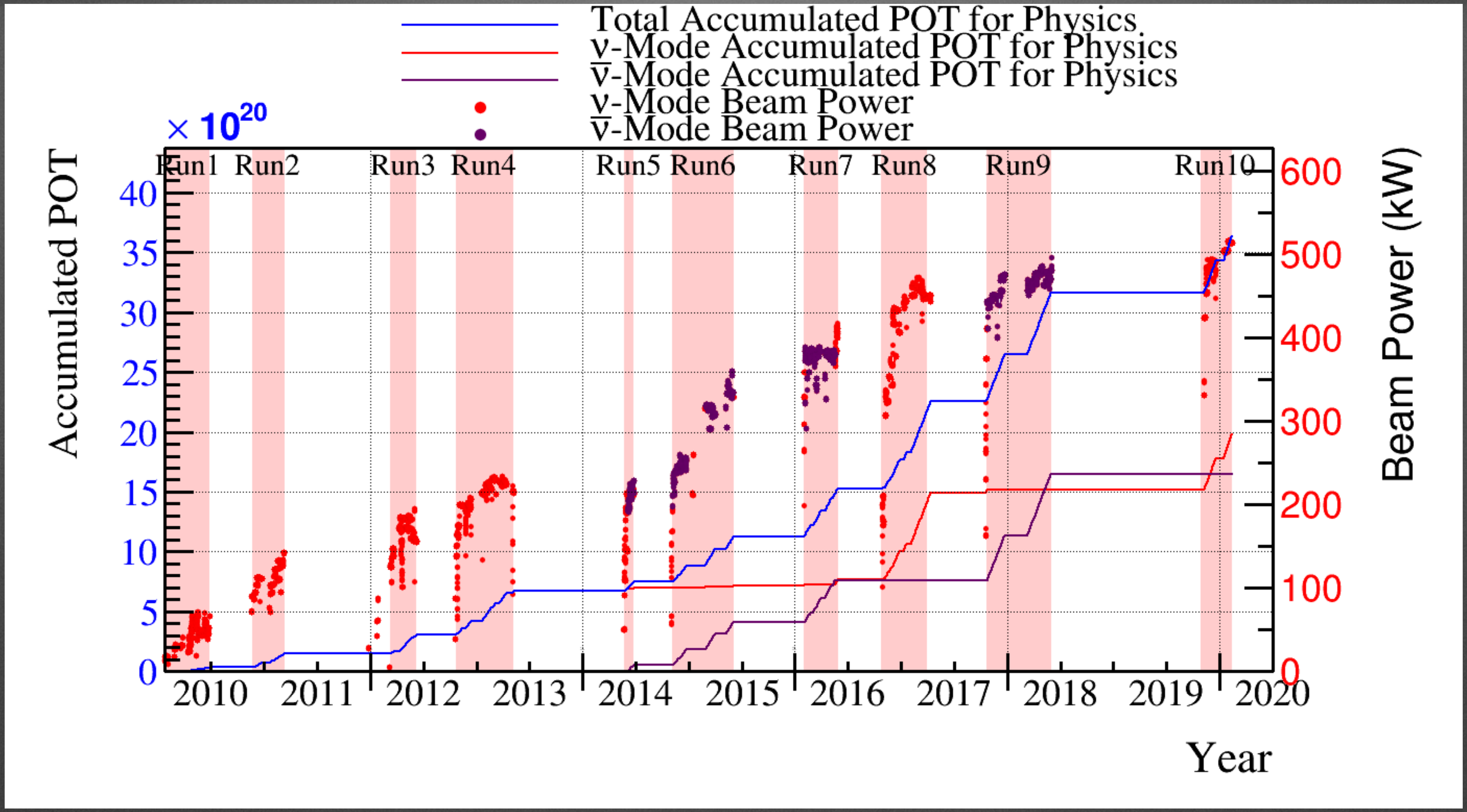
DUNE breaks the degeneracy between MH and CPV



increasing baseline

Recent T2K results

Data Set



- Beam power up to 500 kW
- 1.97E21 POT in ν-mode, 1.63E21 POT in $\bar{\nu}$-mode

T2K Oscillation Analysis

Flux prediction:
Proton beam measurement
Hadron production (NA61 2009 replica target data)

Neutrino interactions:
Cross-section models
External data

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ND280 measurements:
ν_μ and $\bar{\nu}_\mu$ selections to constrain flux and cross-sections

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Combine flux, cross section and ND280 to predict the expected events at SK

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SK measurements:
Select CC ν_μ, $\overline{\nu}_\mu$, ν_e, $\overline{\nu}_e$ candidates after the oscillations

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Cross-section models
External data

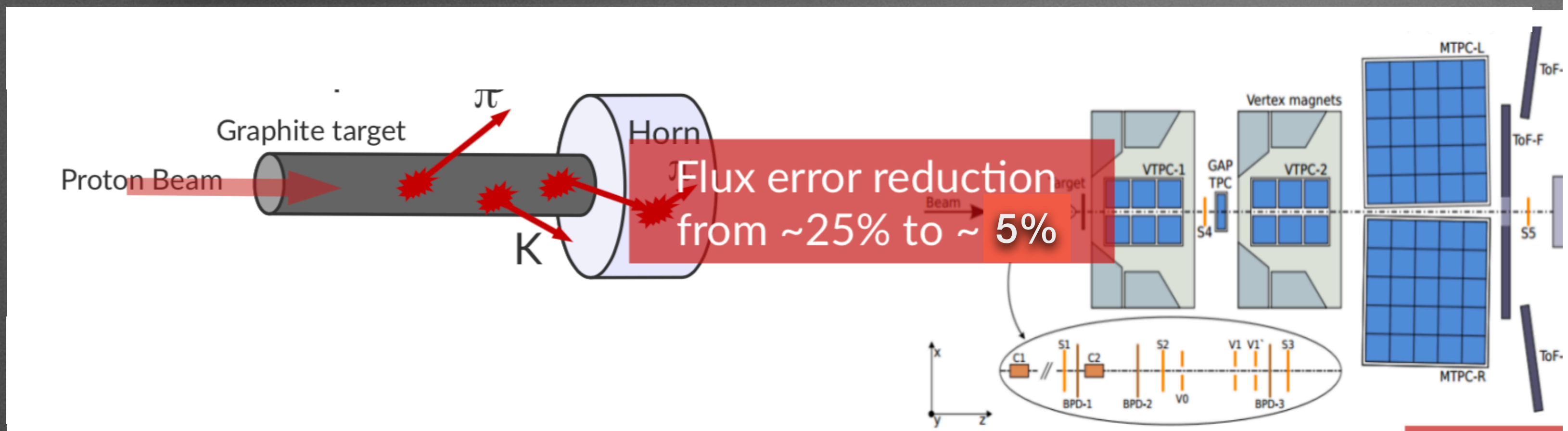
ND280 measurements:
ν_μ and $\bar{\nu}_\mu$ selections to constrain flux and cross-sections

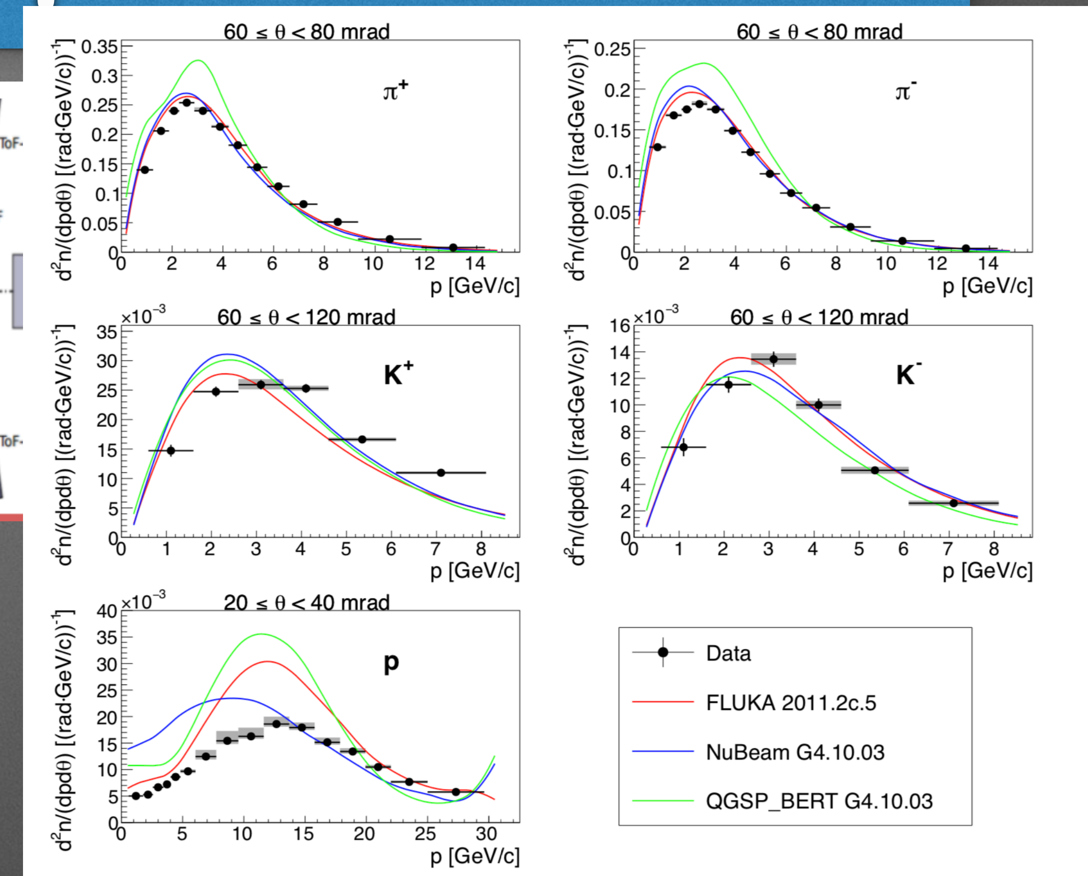
Prediction at the Far Detector:
Combine flux, cross section and ND280 to predict the expected events at SK

Extract oscillation parameters!

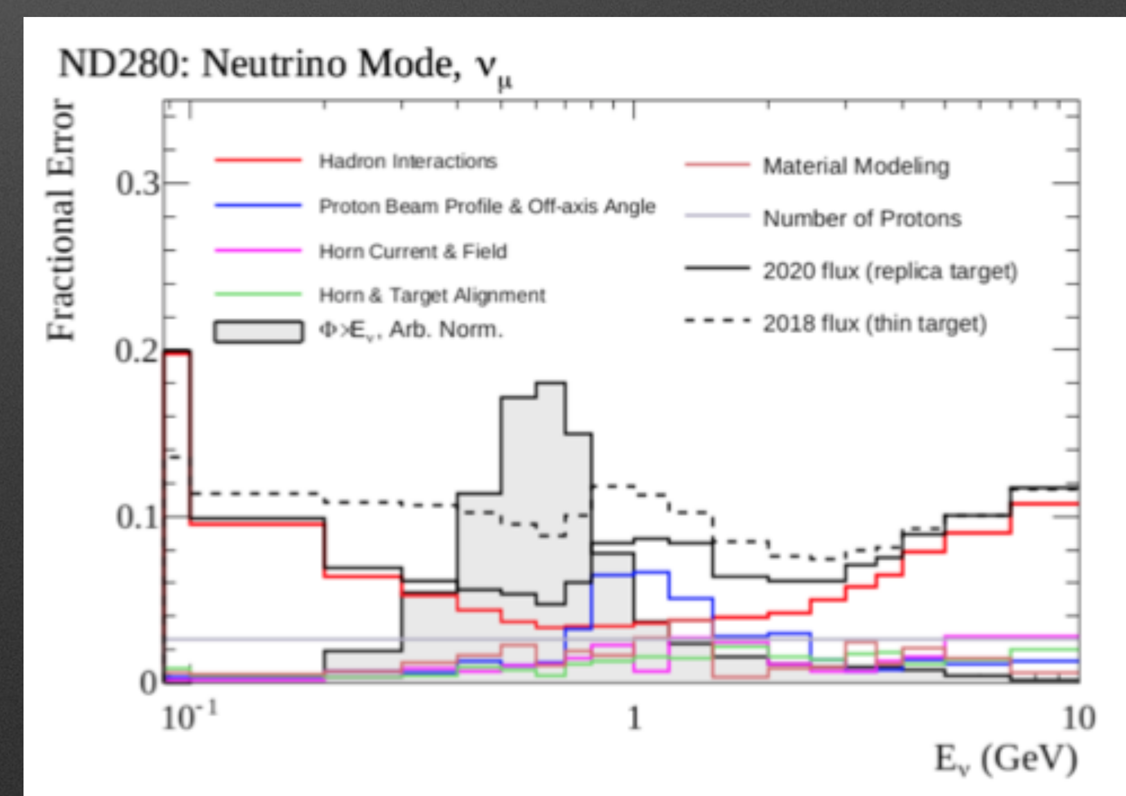
SK measurements:
Select CC ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ candidates after the oscillations

NA61/SHINE - flux prediction

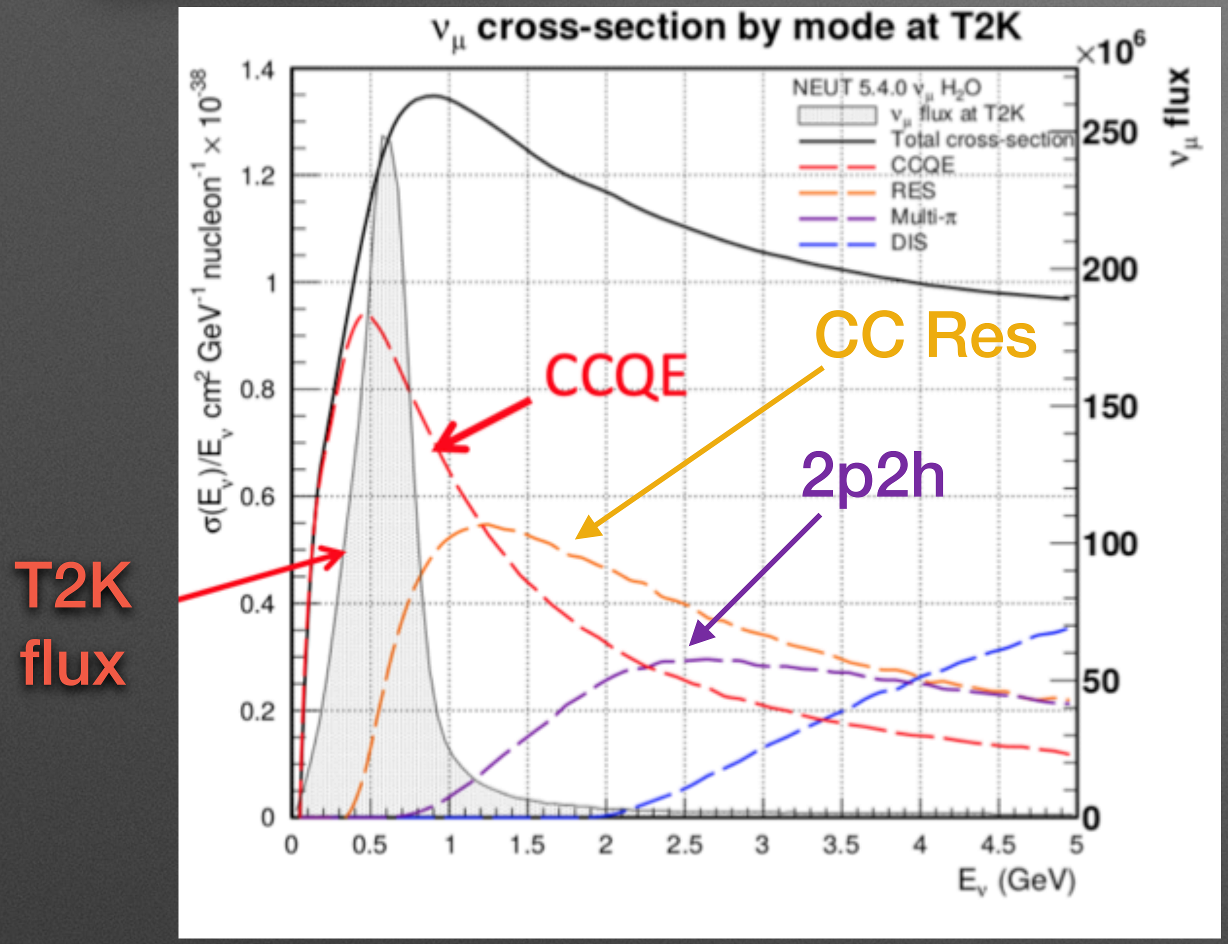


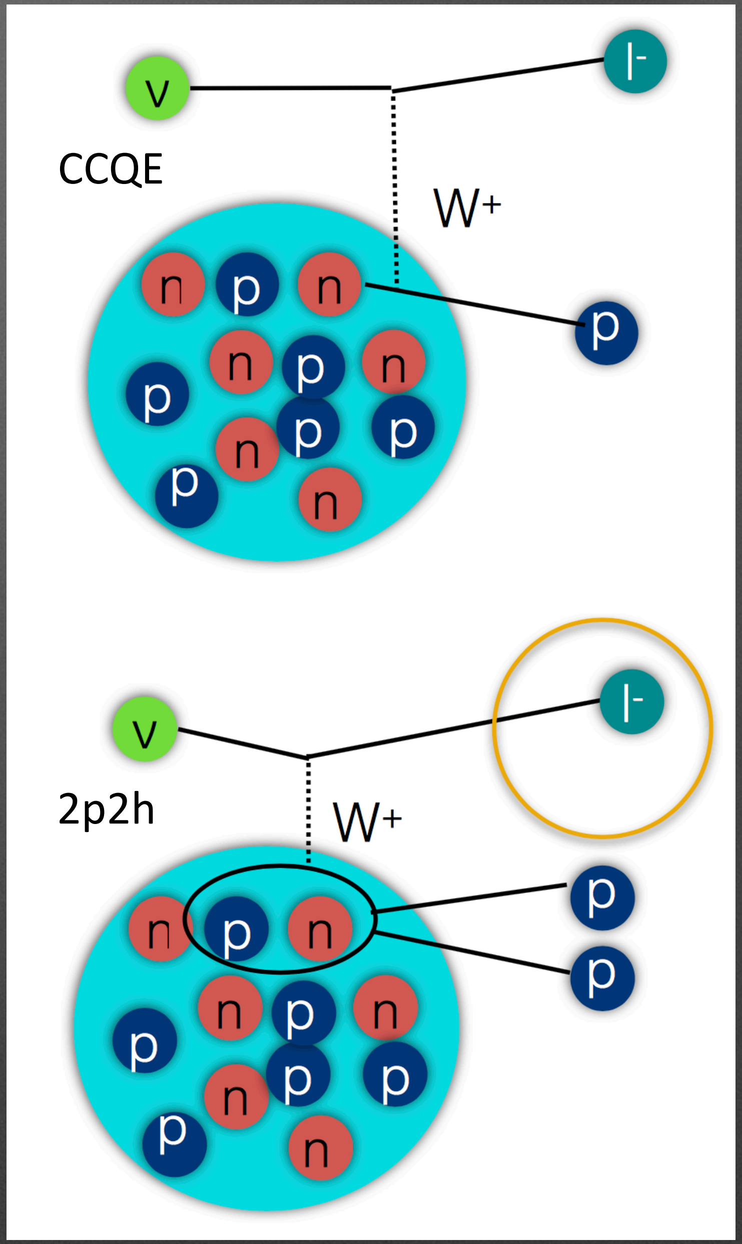


- Multipurpose detector @ CERN → precision hadron production measurements for T2K (and FNAL) neutrino fluxes predictions
- Took data for T2K in 2007, 2009, 2010 with thin and replica target
- Inclusion of data with replica target allowed to reduce flux uncertainties to ~5%



Neutrino interaction modelling





- T2K mean energy 0.6 GeV → CCQE dominates but significant multinucleon (2p2h) and resonant production

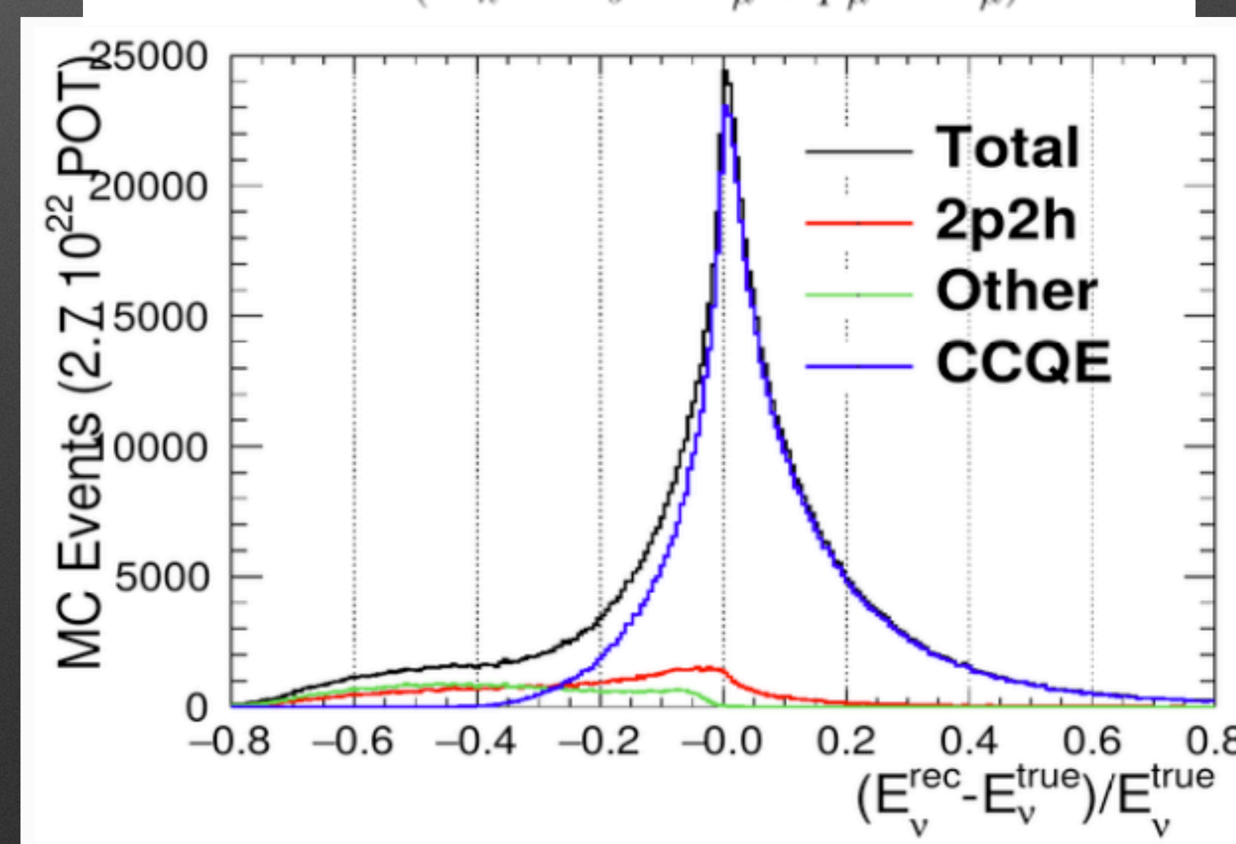
- Neutrino interaction modelling has been updated to use Spectral function, better treatment of binding energy, 2p2h contributions, …

Why this matter…

- Oscillations depends on L/E → L is fixed so only E matters
- E is the true neutrino energy but in experiments we have access to the reconstructed one
- At SK only the lepton is visible and we reconstruct the energy with the quasi-elastic formula based on reconstructed lepton momentum and angle

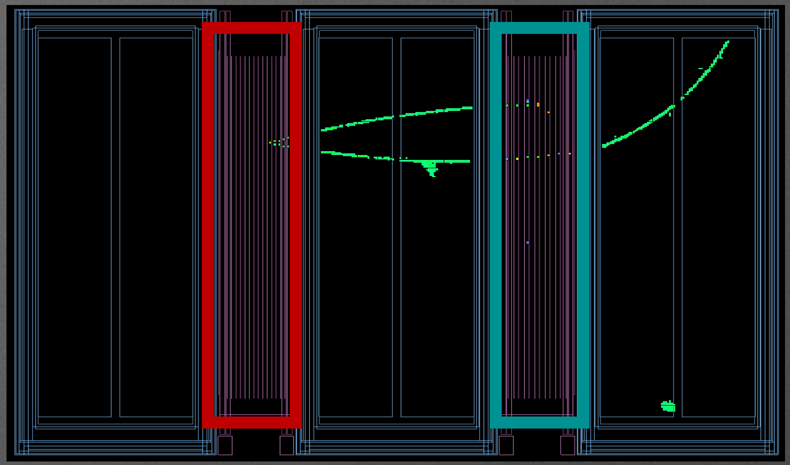
$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

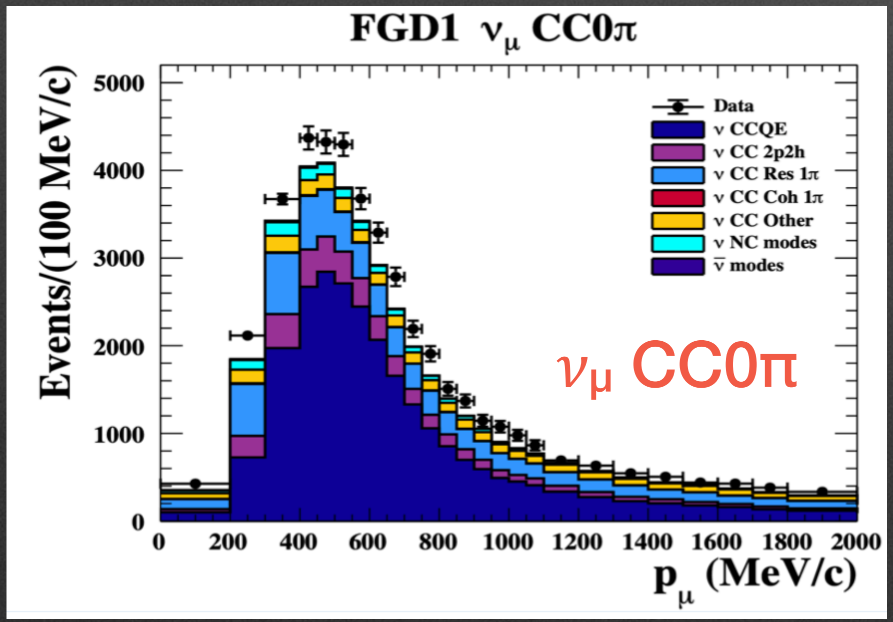
- Erec is a good proxy for Etrue for CCQE interactions
- For 2p2h (or any other interaction) Erec underestimates Etrue → if that's not taken into account it will bias the extraction of oscillation parameters
- Need to characterize these channels as well as possible or find new ways to reconstruct the neutrino energy

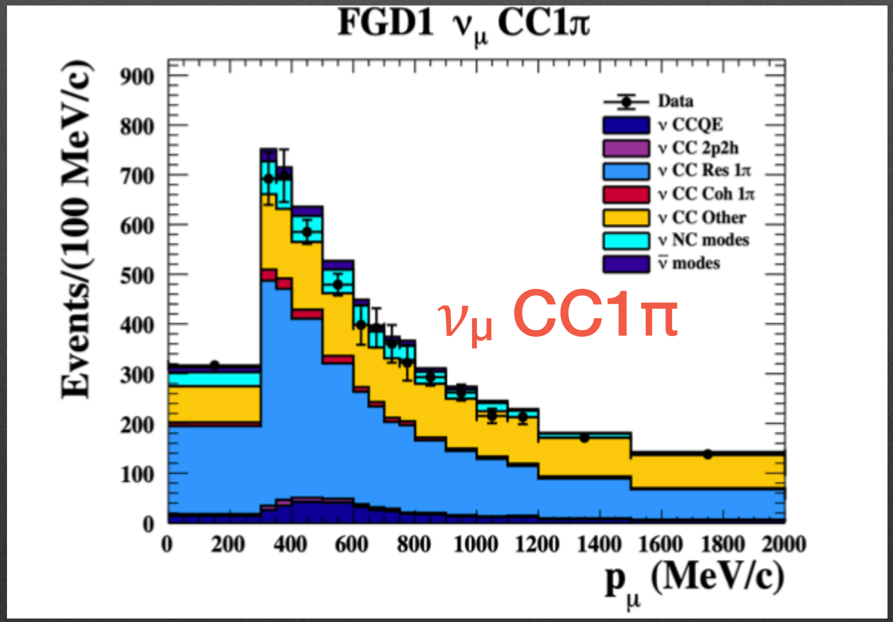


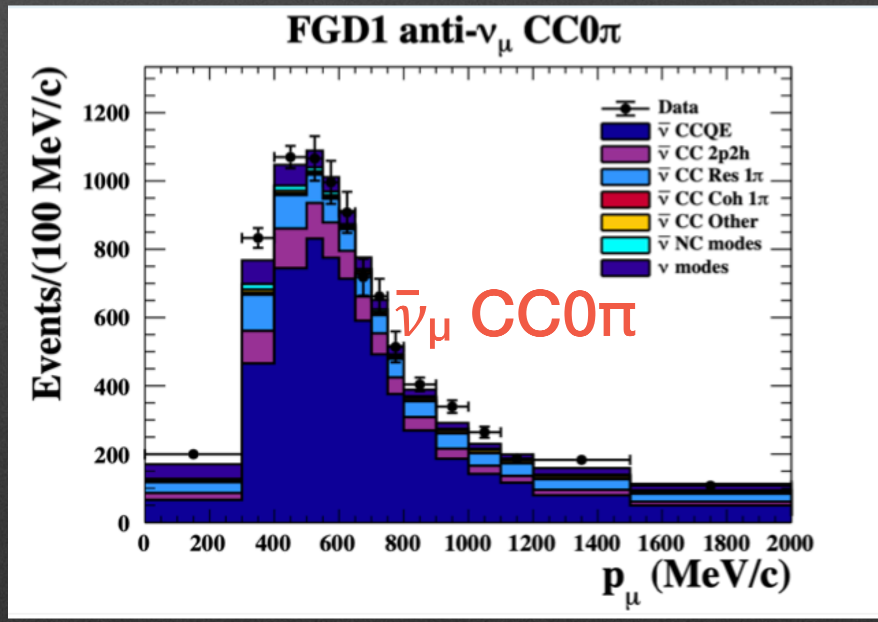
ND280 selections

- ND280 magnetized detector
- Select interactions on CH (FGD1) and CH/Water (FGD2)
- Precise measurement of Pμ and θμ with the TPCs
- Distinguish ν from $\bar{\nu}$ interactions thanks to the reconstruction of the charge of the lepton
- Separate samples based on number of reconstructed pions (CC0π, CC1π, CCNπ)
    - Total of 18 samples





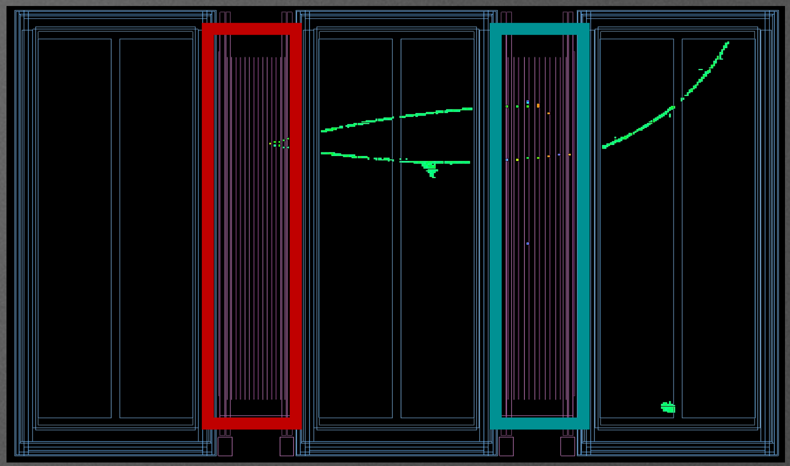


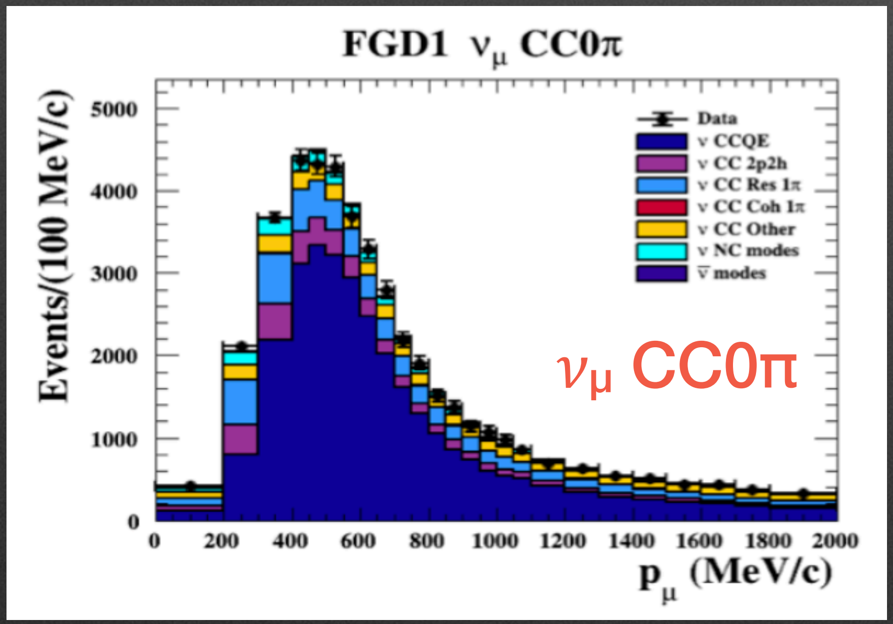


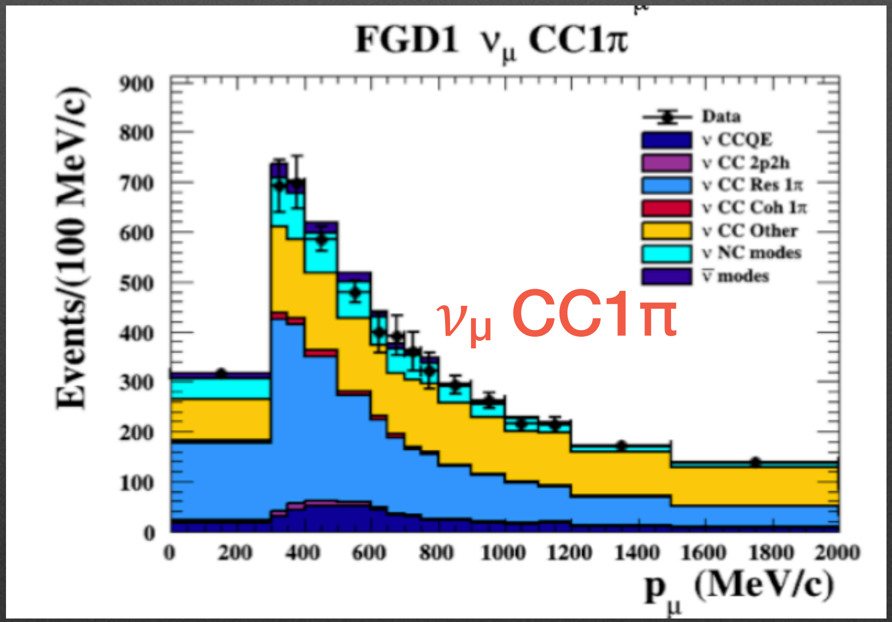
Prefit systematics uncertainties on the rate of single ring e-like events at SK ~14%

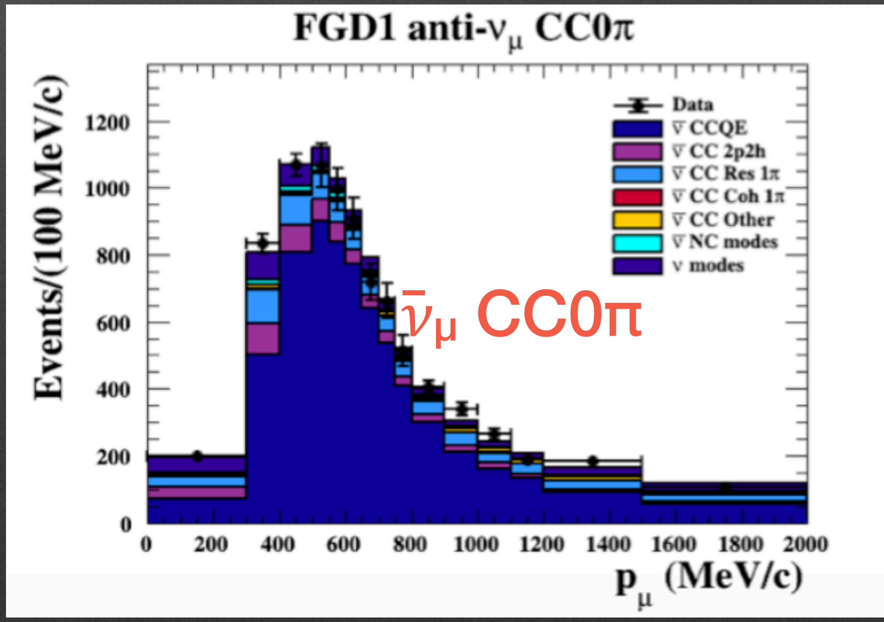
ND280 selections

- ND280 magnetized detector
- Select interactions on CH (FGD1) and CH/Water (FGD2)
- Precise measurement of Pμ and θμ with the TPCs
- Distinguish ν from $\bar{\nu}$ interactions thanks to the reconstruction of the charge of the lepton
- Separate samples based on number of reconstructed pions (CC0π, CC1π, CCNπ)
  - Total of 18 samples



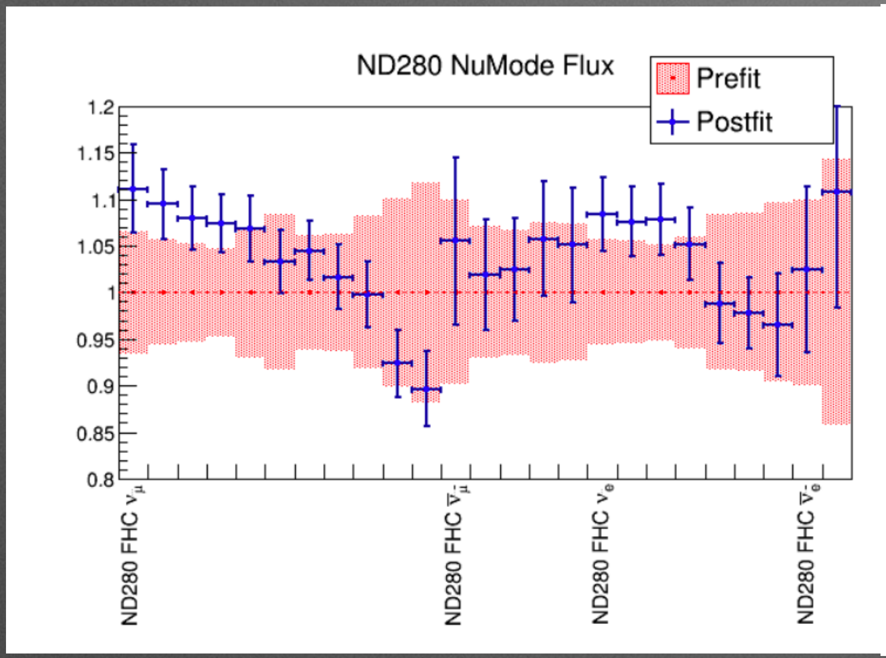


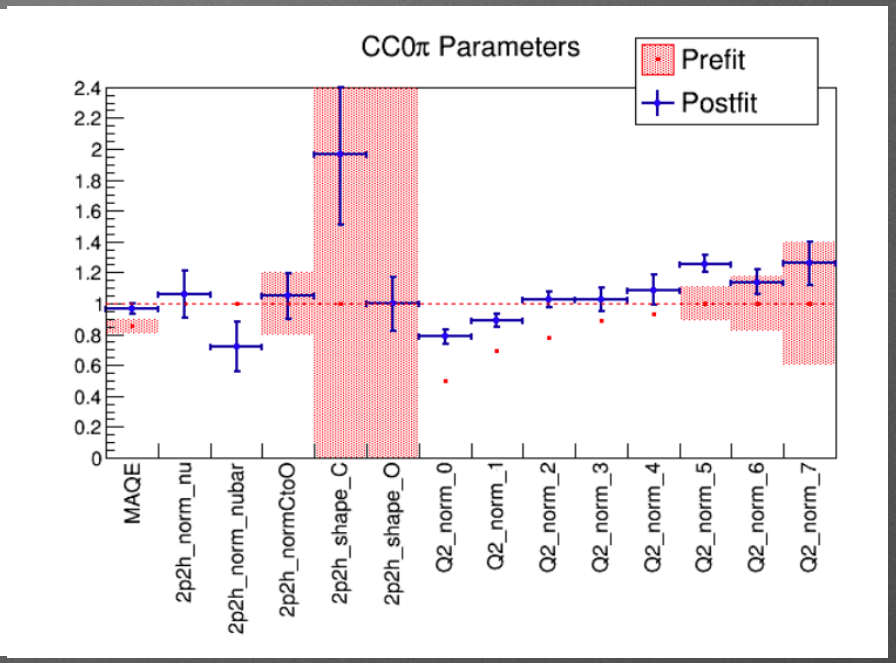




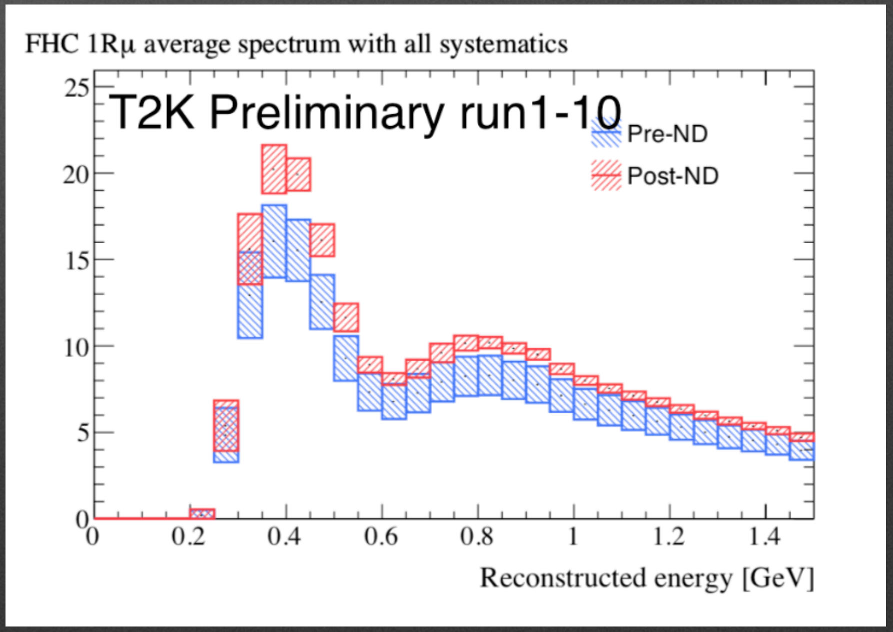
Postfit systematics uncertainties on the rate of single ring e-like events at SK ~4.7%

Flux and x-sec constraint



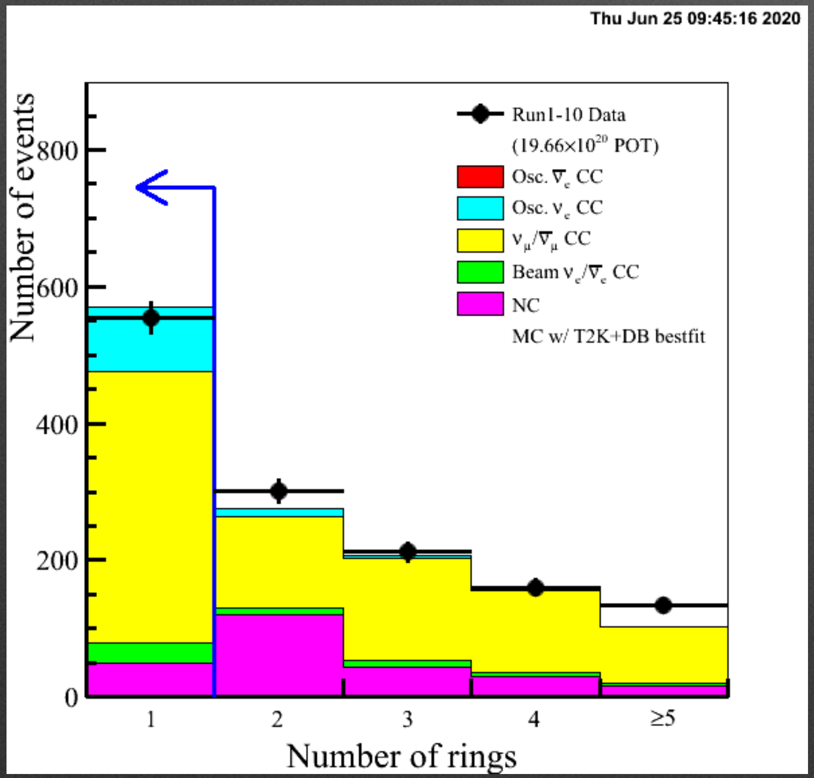


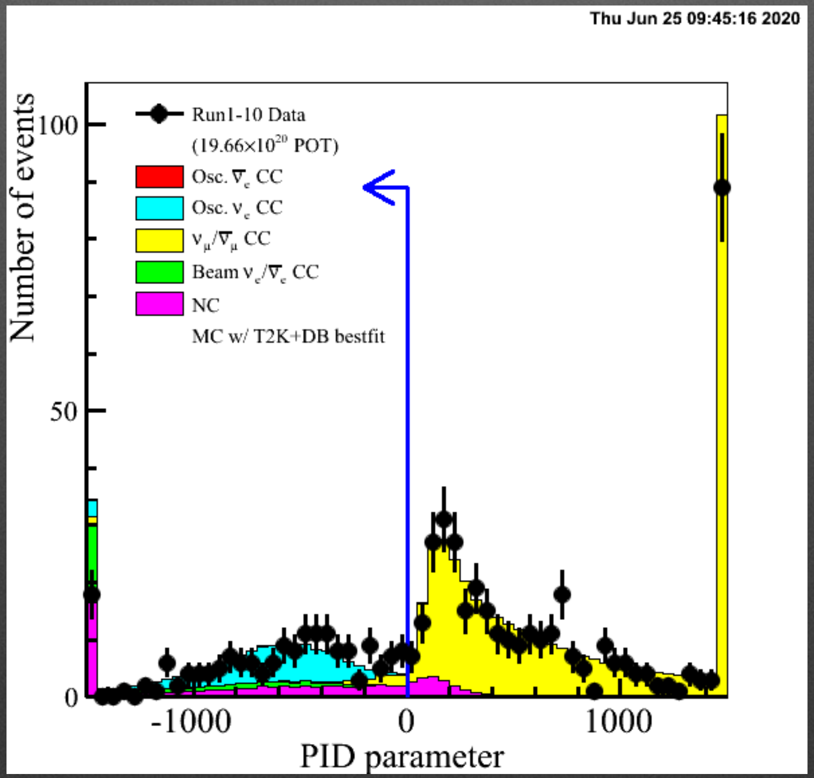
Sample	Pre-ND FIT error	Post-ND FIT error
FHC 1Rμ	11.1%	3.0%
RHC 1Rμ	11.3%	4.0%
FHC 1Re	13.0%	4.7 %
RHC 1Re	12.1%	5.9%
FHC 1Re 1d.e.	18.7%	14.3%

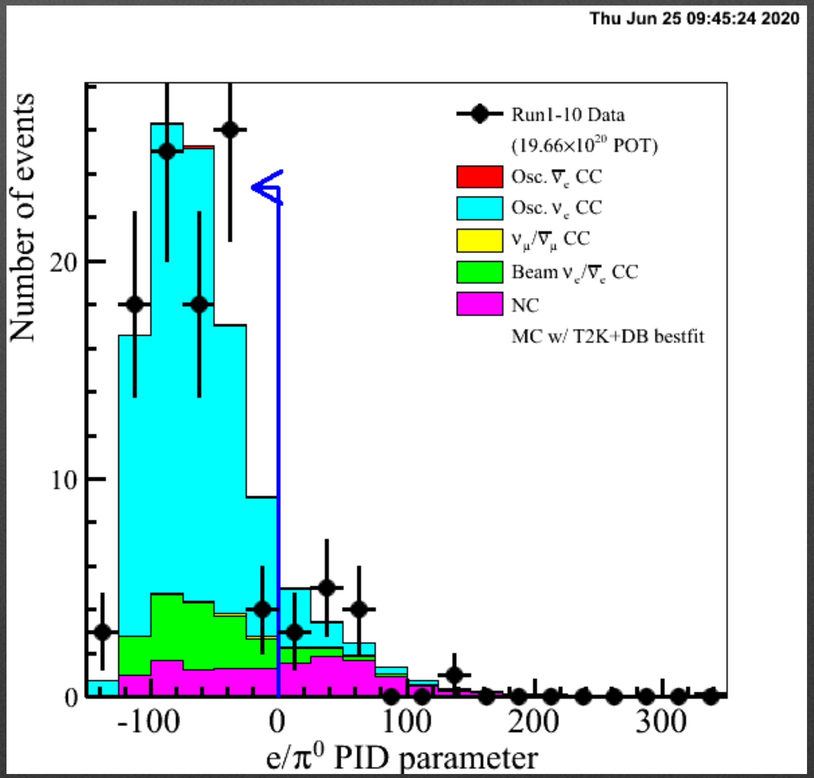


Super-Kamiokande

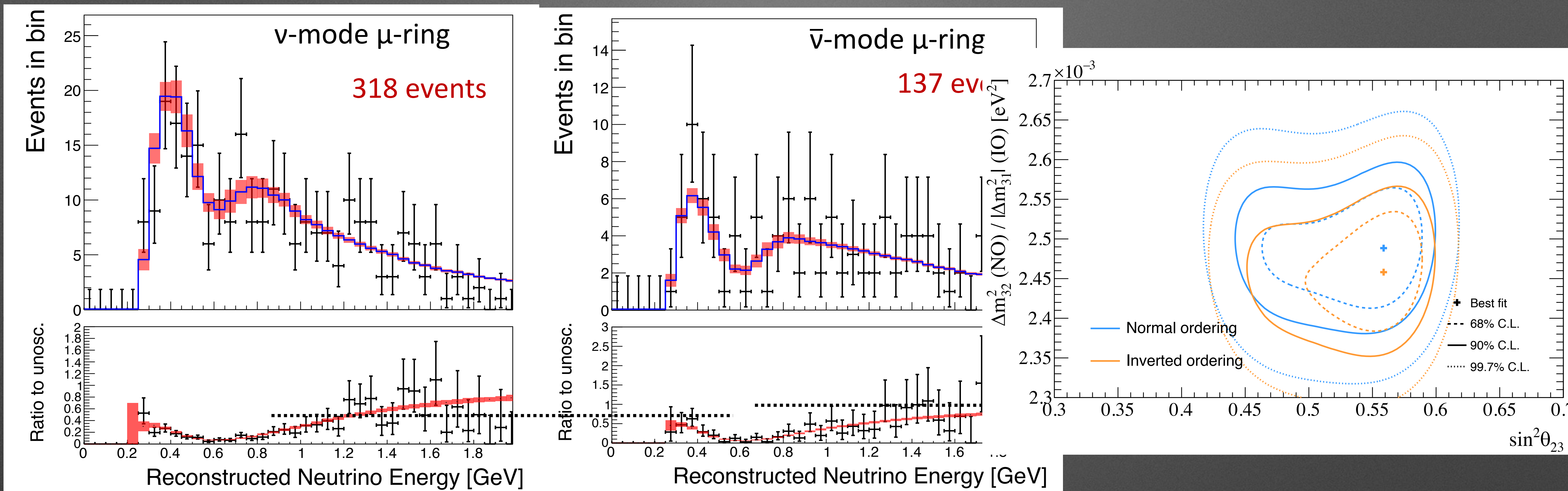
- Single ring events selected at SK
- Separated between e-like and μ-like according to the PID
- Additional cuts to reject NC producing π0 → γγ background





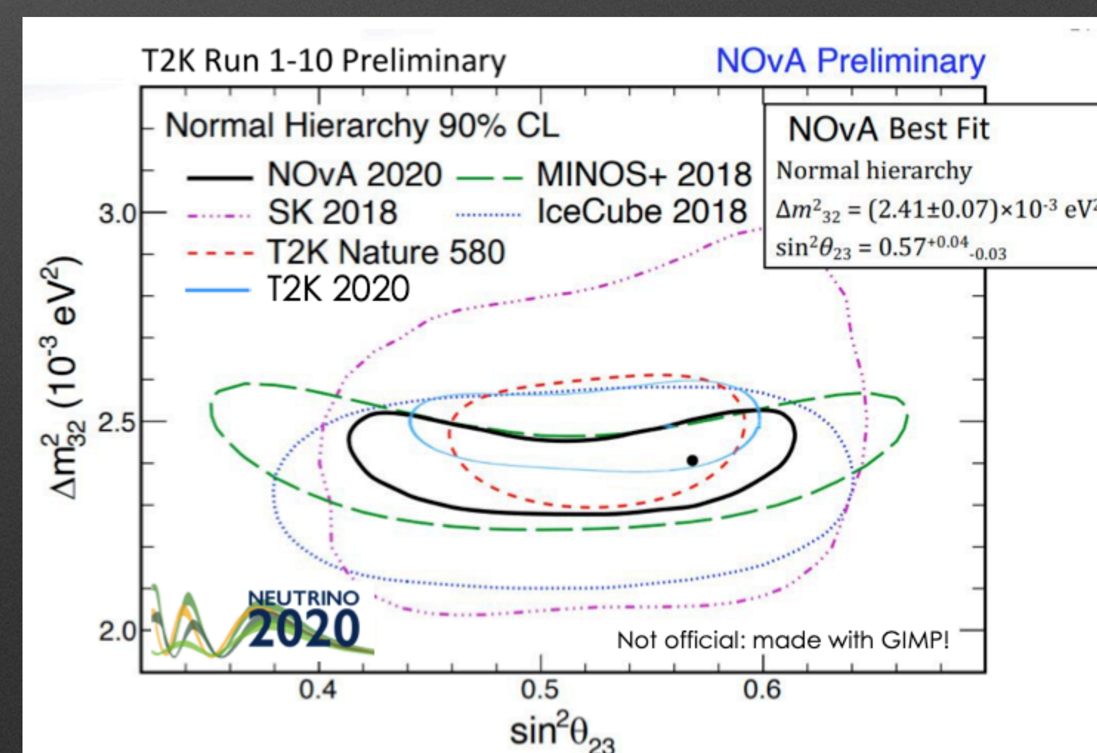


θ_{23} and Δm^2_{23}

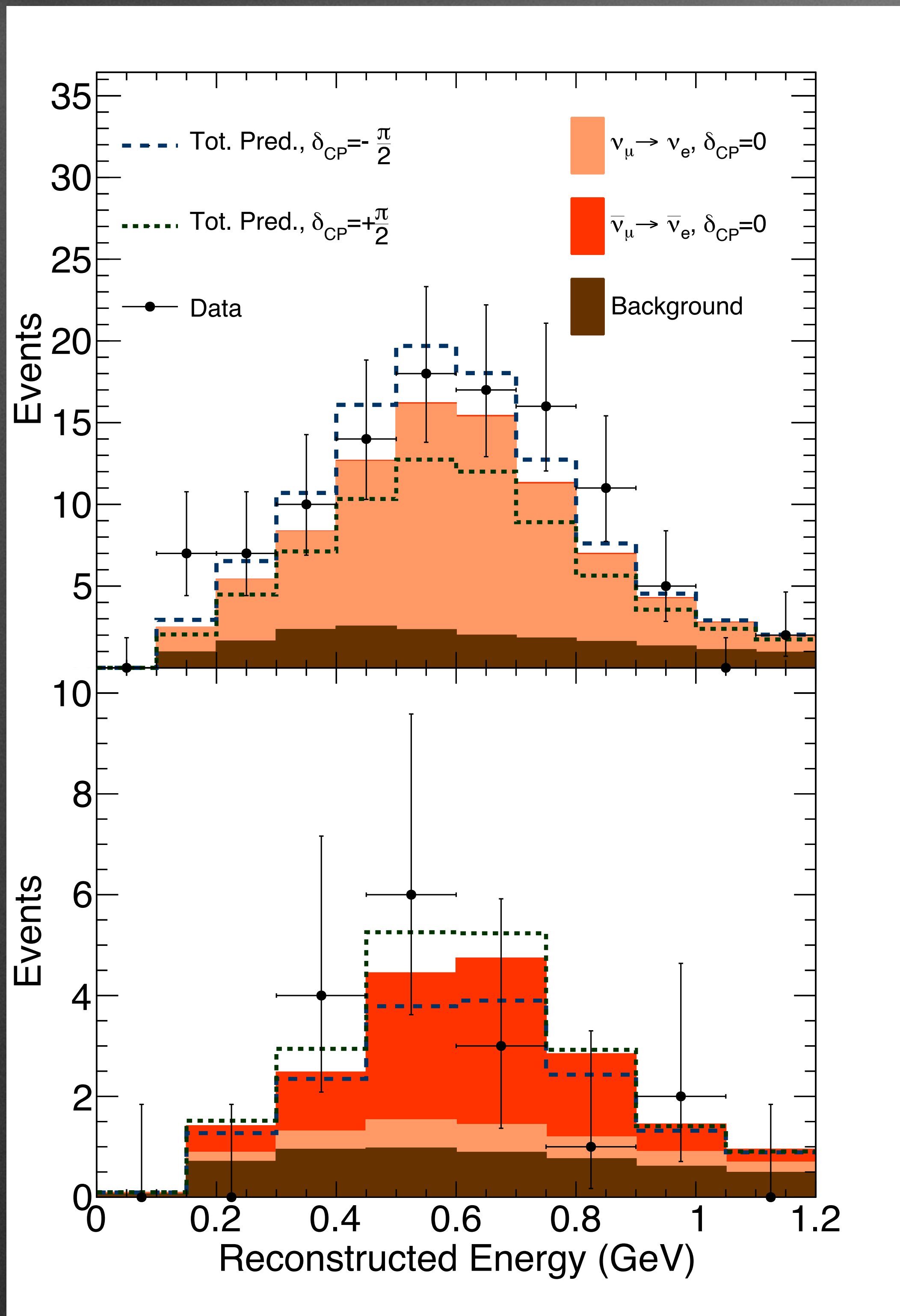


- Slight preference for non maximal mixing with θ_{23} in the second octant

- Still compatible with maximal mixing

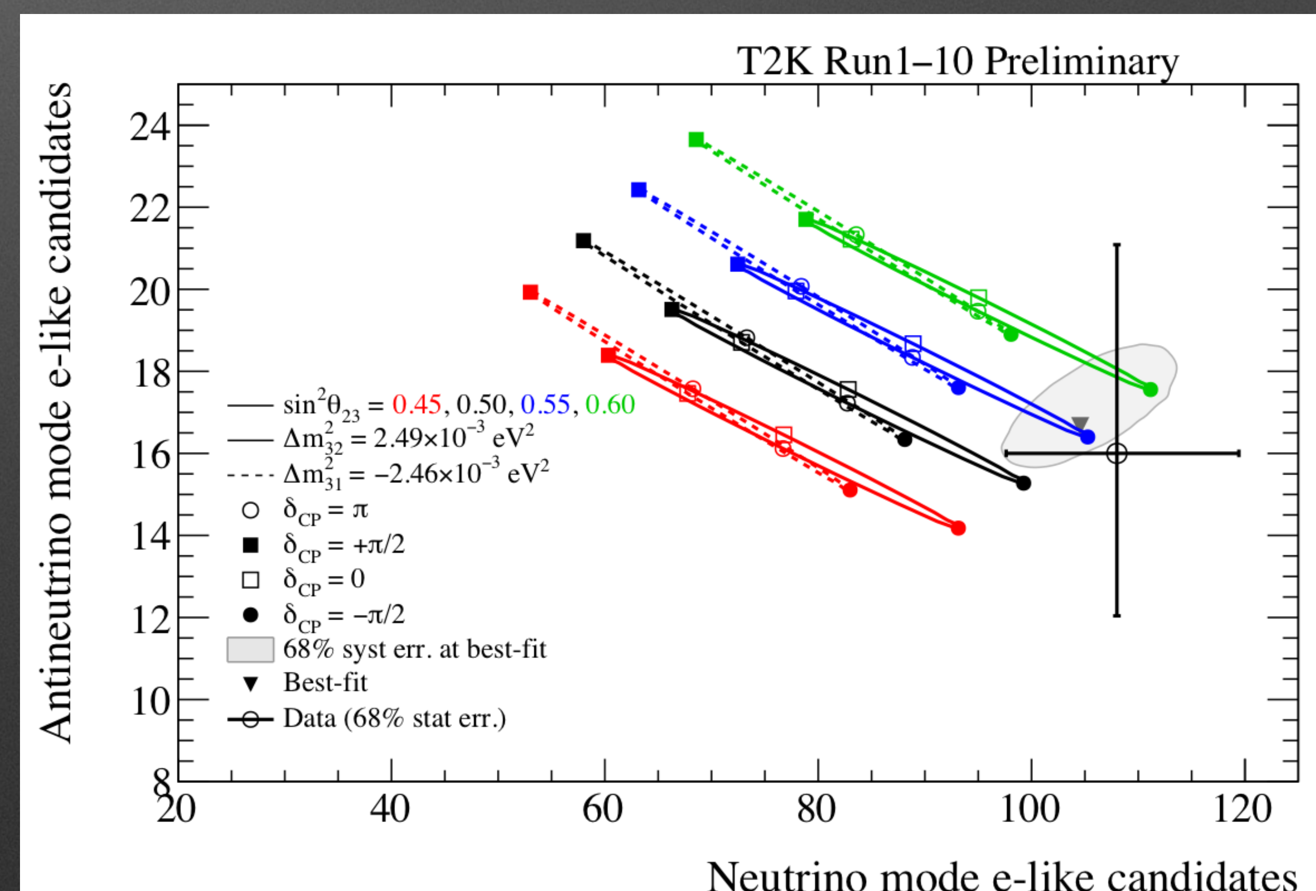


ν_e and $\bar{\nu}_e$ appearance



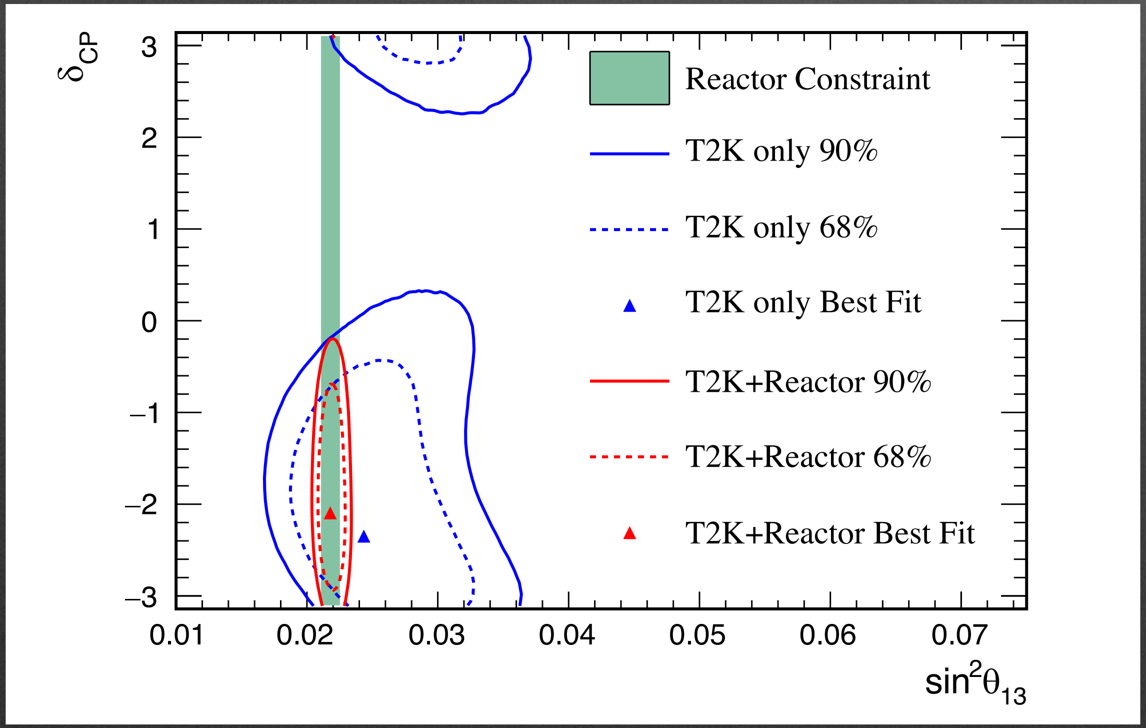
$\sin^2(\theta_{23})$=0.5, Normal Hierarchy

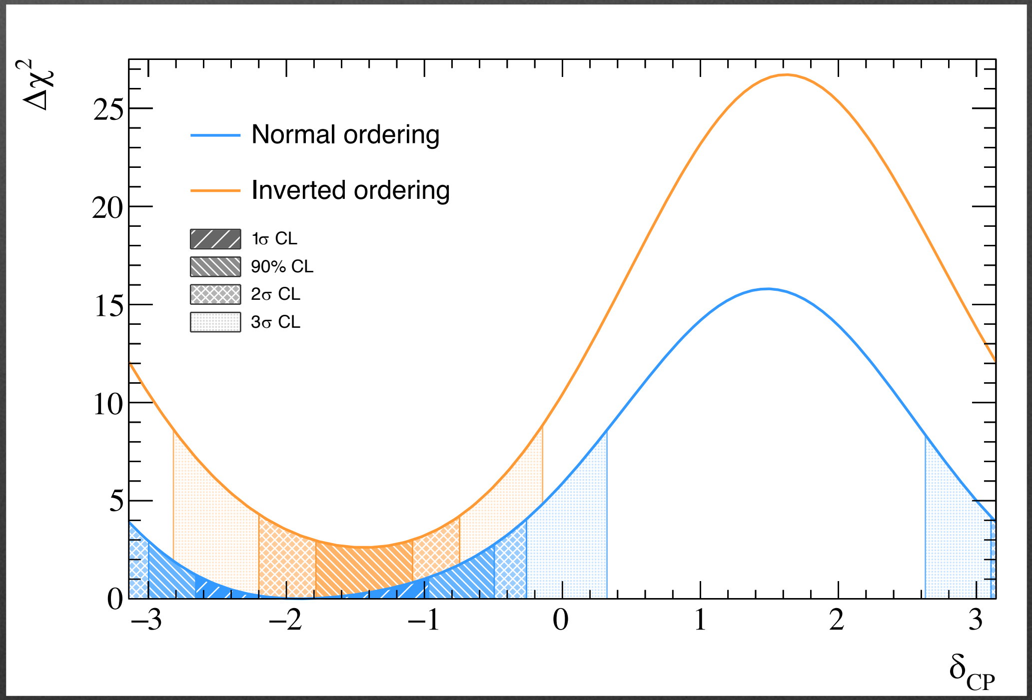
	ν-mode	ν̄-mode
Data	**108**	**16**
$\delta_{CP}=-\pi/2$	106.8	16.7
$\delta_{CP}=0,\pi$	90.4	19.0
$\delta_{CP}=+\pi/2$	74.1	20.9



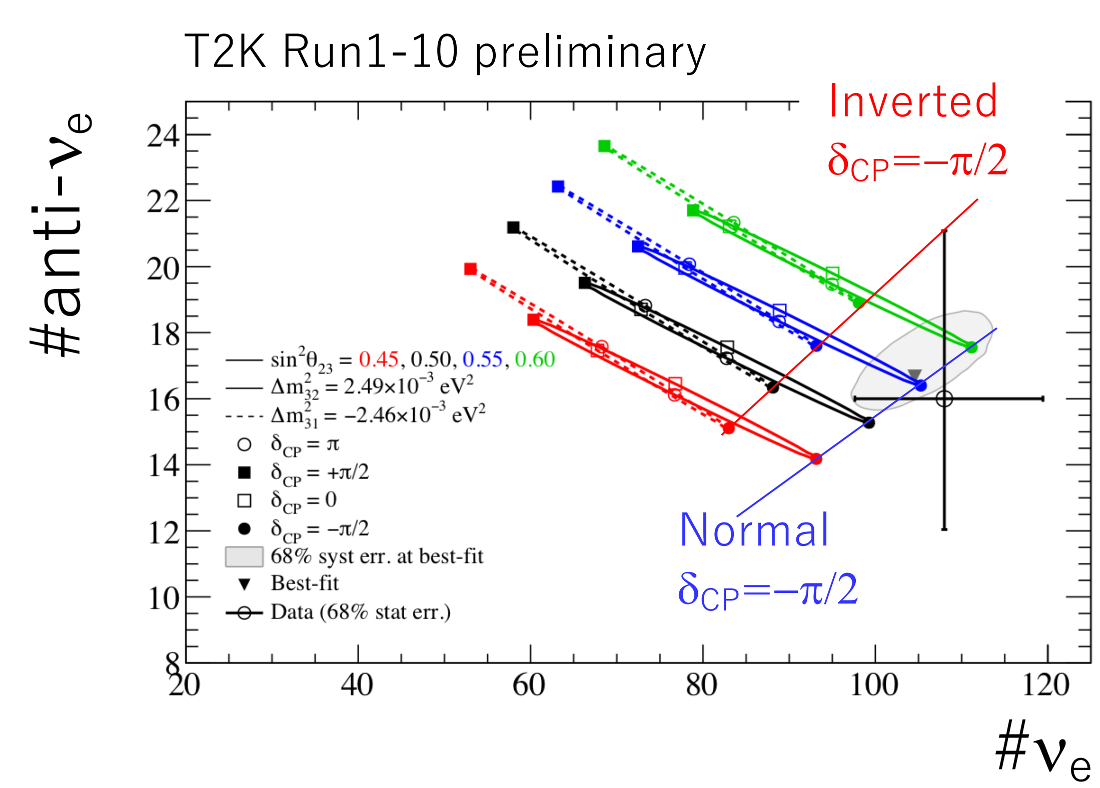
θ_{13} and δ_{CP}

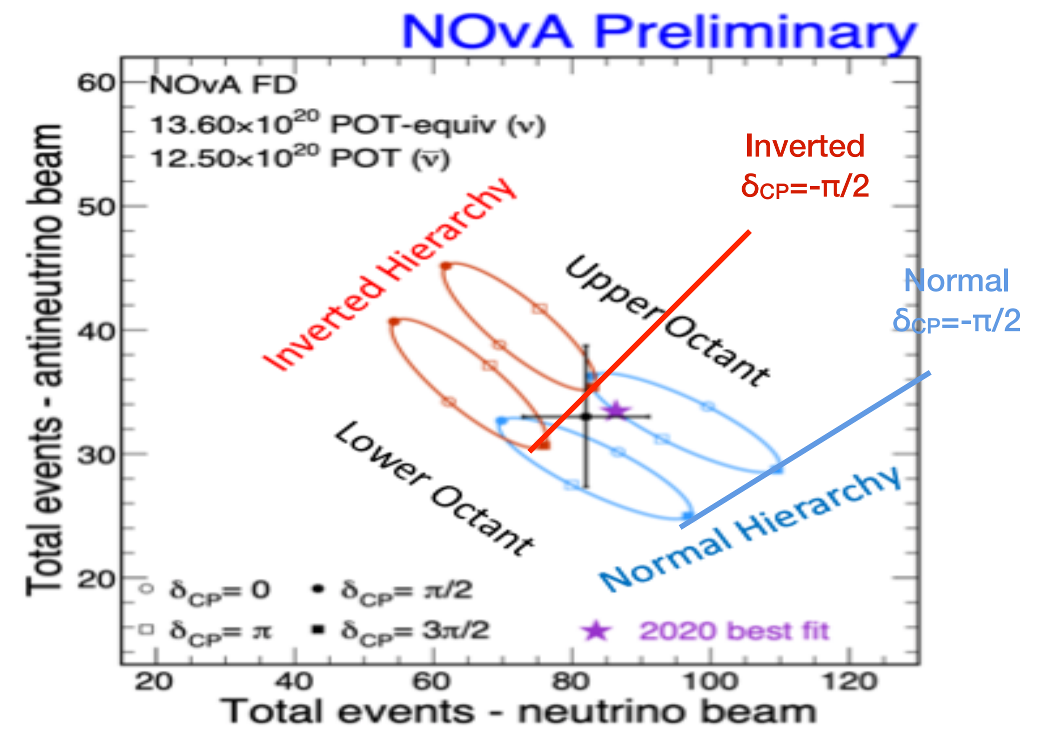
- T2K only data compatible with reactor measurements of θ13
- When the reactor constraint is used 35% of the values of δ_{CP} are excluded at >3σ
- CP conserving values (0,π) excluded at 90% CL



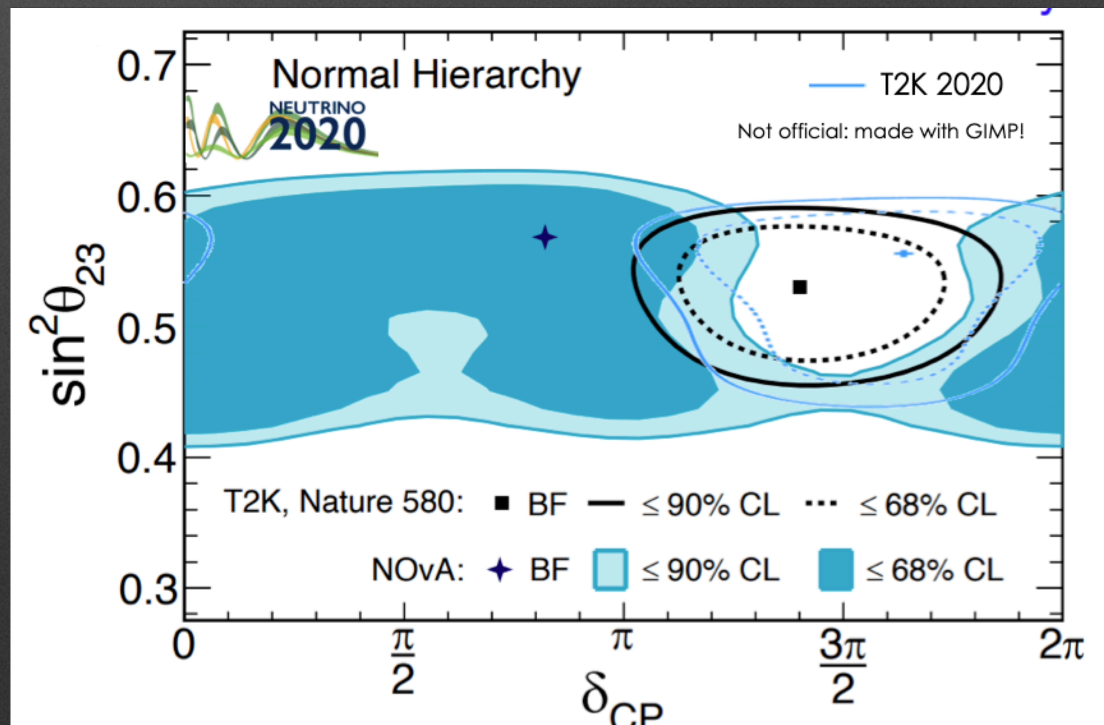


T2K/NOvA comparison





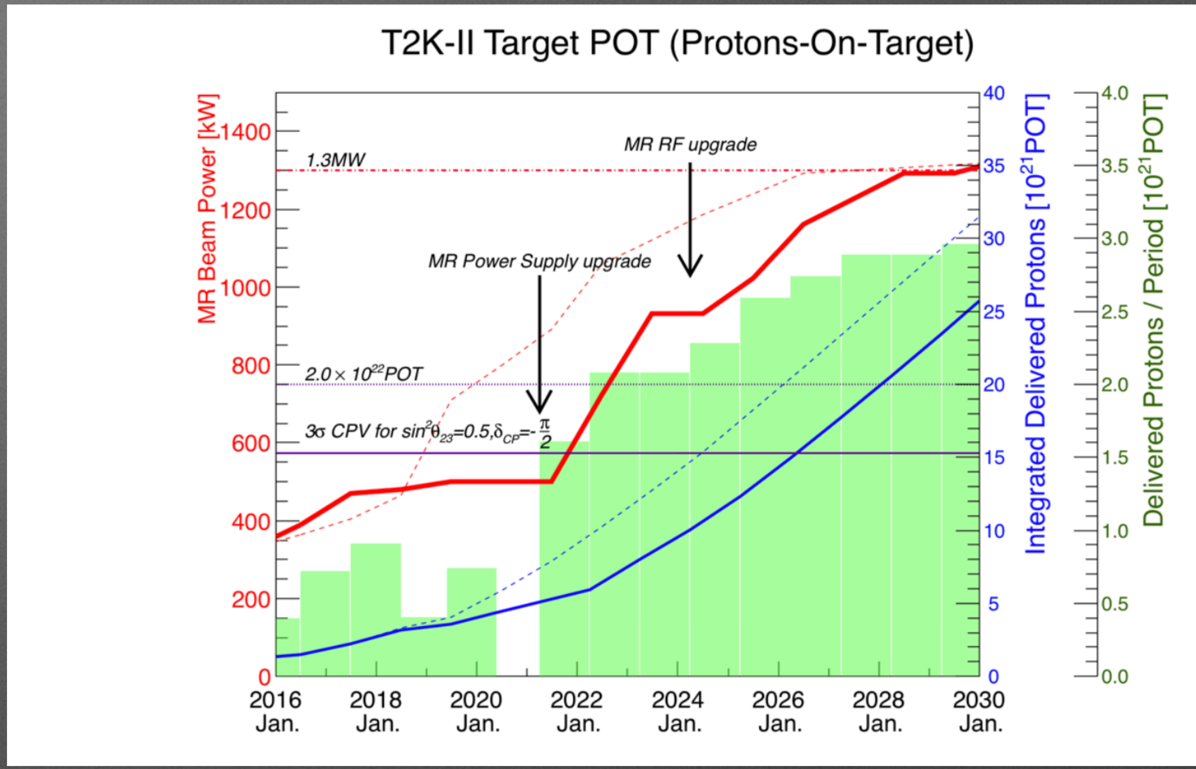
- T2K and NOvA both released new results at Neutrino 2020
- Mild tension on δ_{CP}
  - Reinforce the need of collecting more data for both experiments!

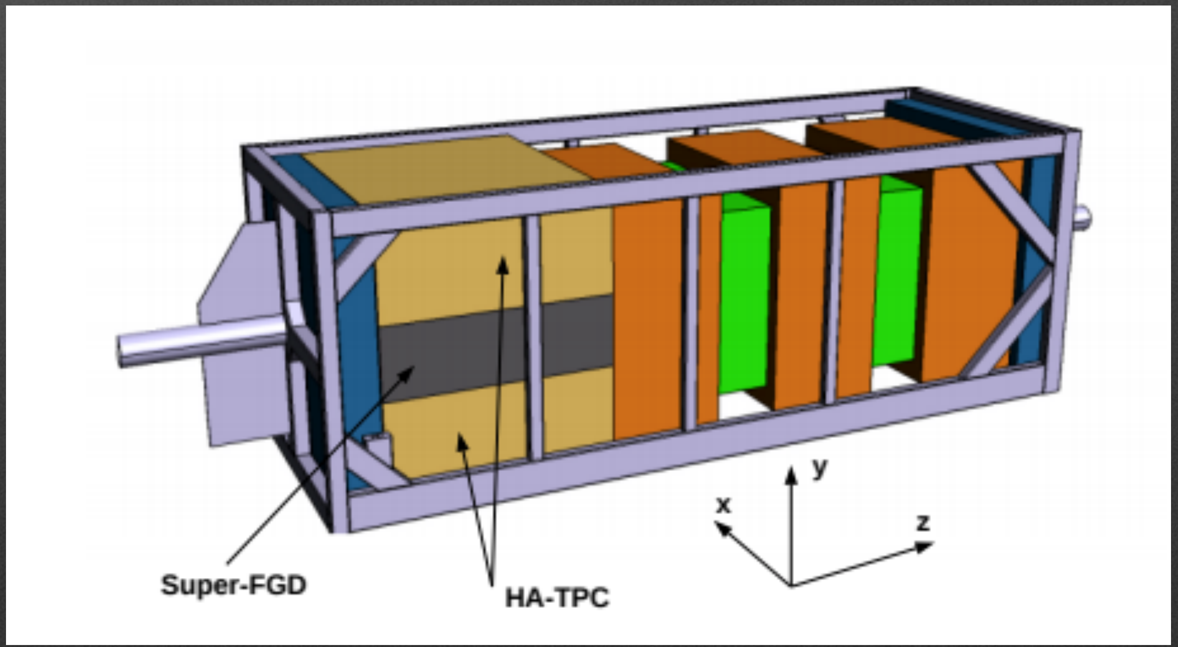


The future: T2K-II and Hyper-K

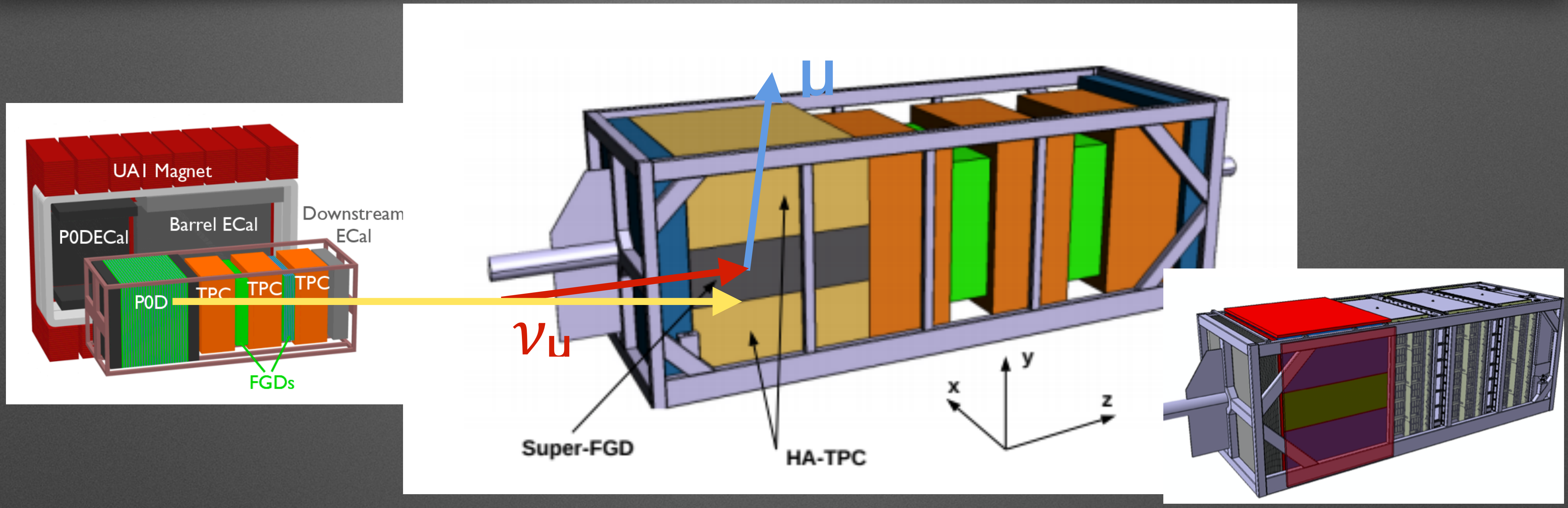
T2K phase-II

- Upgrade of J-PARC Main Ring (1.3 MW beam)
  - Approved and funded, will be ready for beam in Fall 2022
- 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 2022
  - Use the ND280 Upgrade detector also as initial Near Detector for HK
- Improvements of the Far Detector thanks to the SK-Gd project





ND280 Upgrade



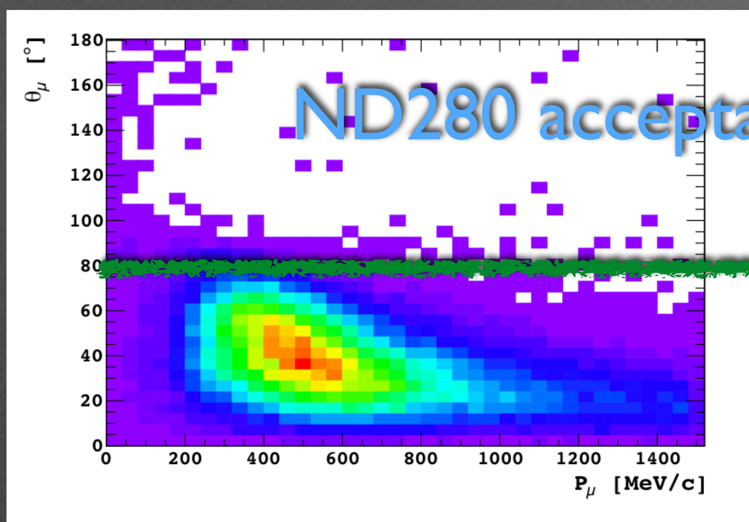
- One horizontal highly segmented target (Super-FGD) → Improve reconstruction of hadronic part of the interaction and of low momentum leptons

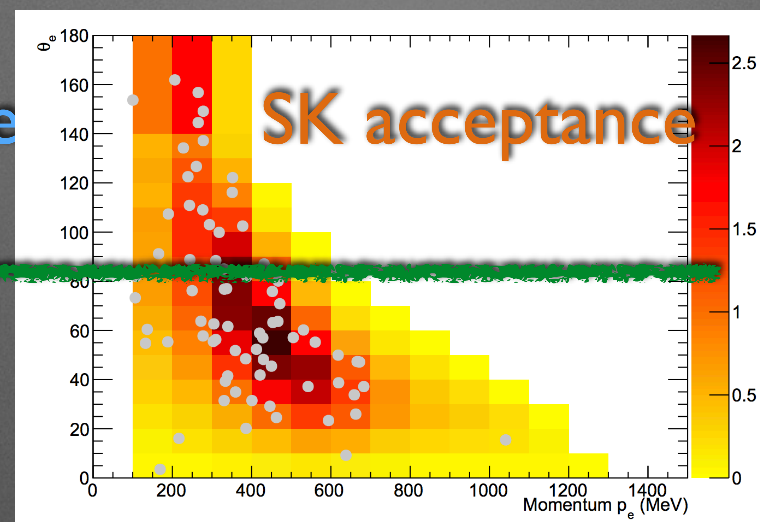
- Two new High Angle TPCs → Improve reconstruction of high angle leptons

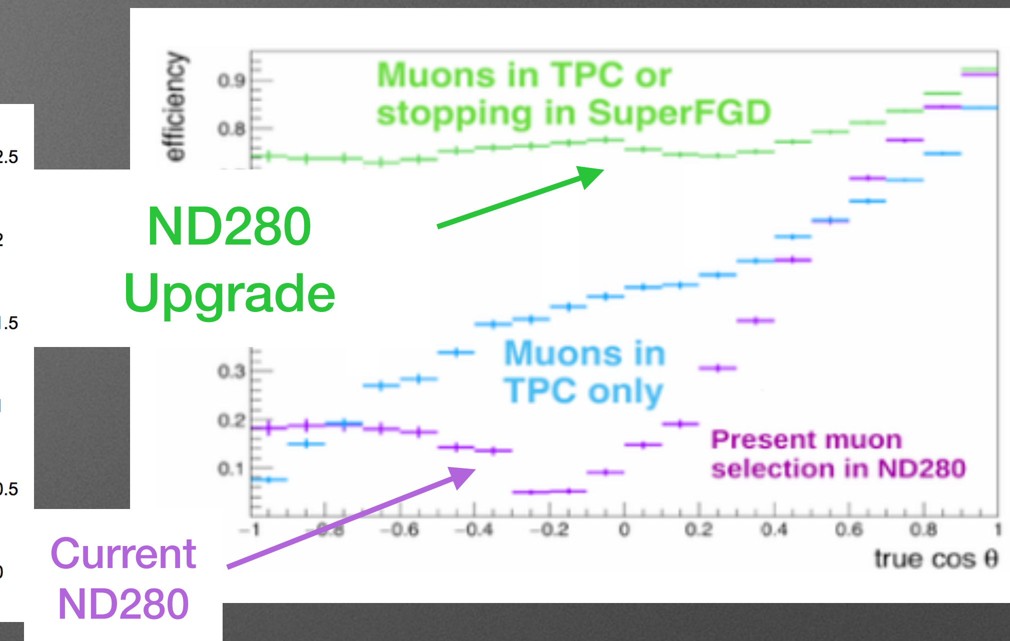
- 6 Time Of Flight planes → Reduce backgrounds entering from outside the Super-FGD

- After the upgrade ND280 will be a full acceptance fine grained detector with magnetic field → Measure momentum and charge of all leptons emitted in neutrino and antineutrino interactions

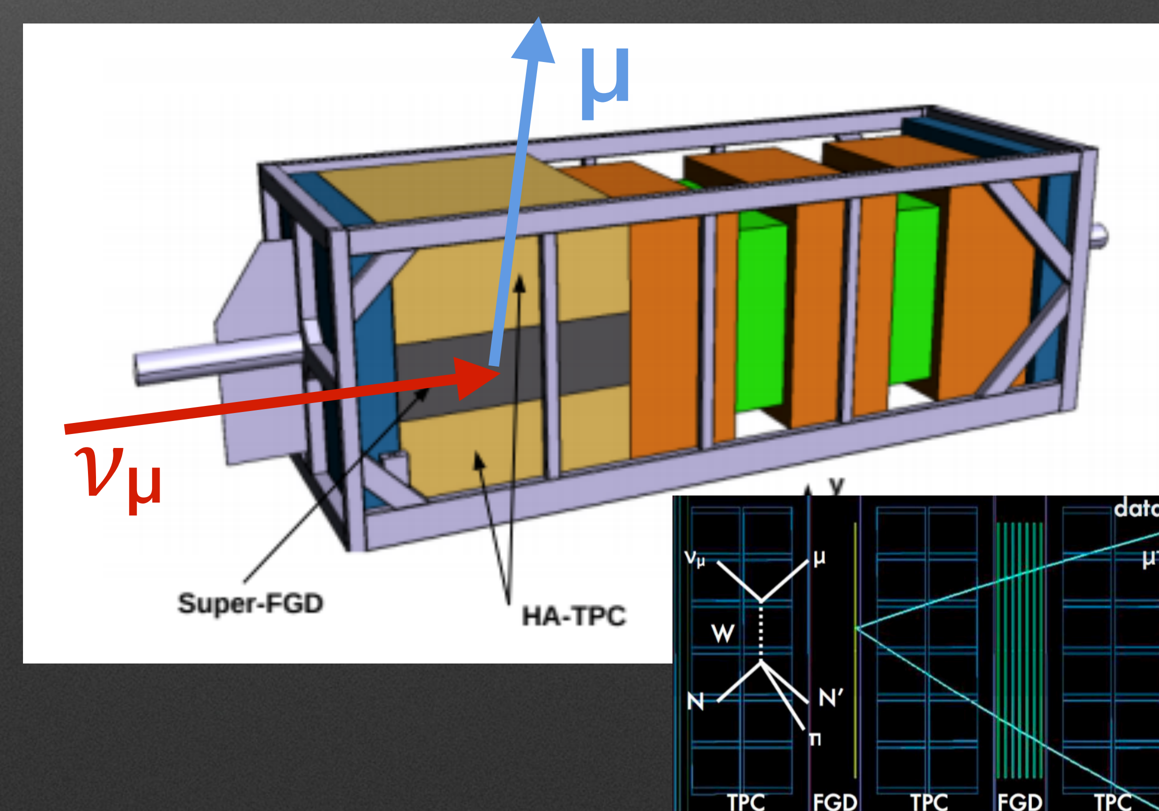
Improved angular acceptance





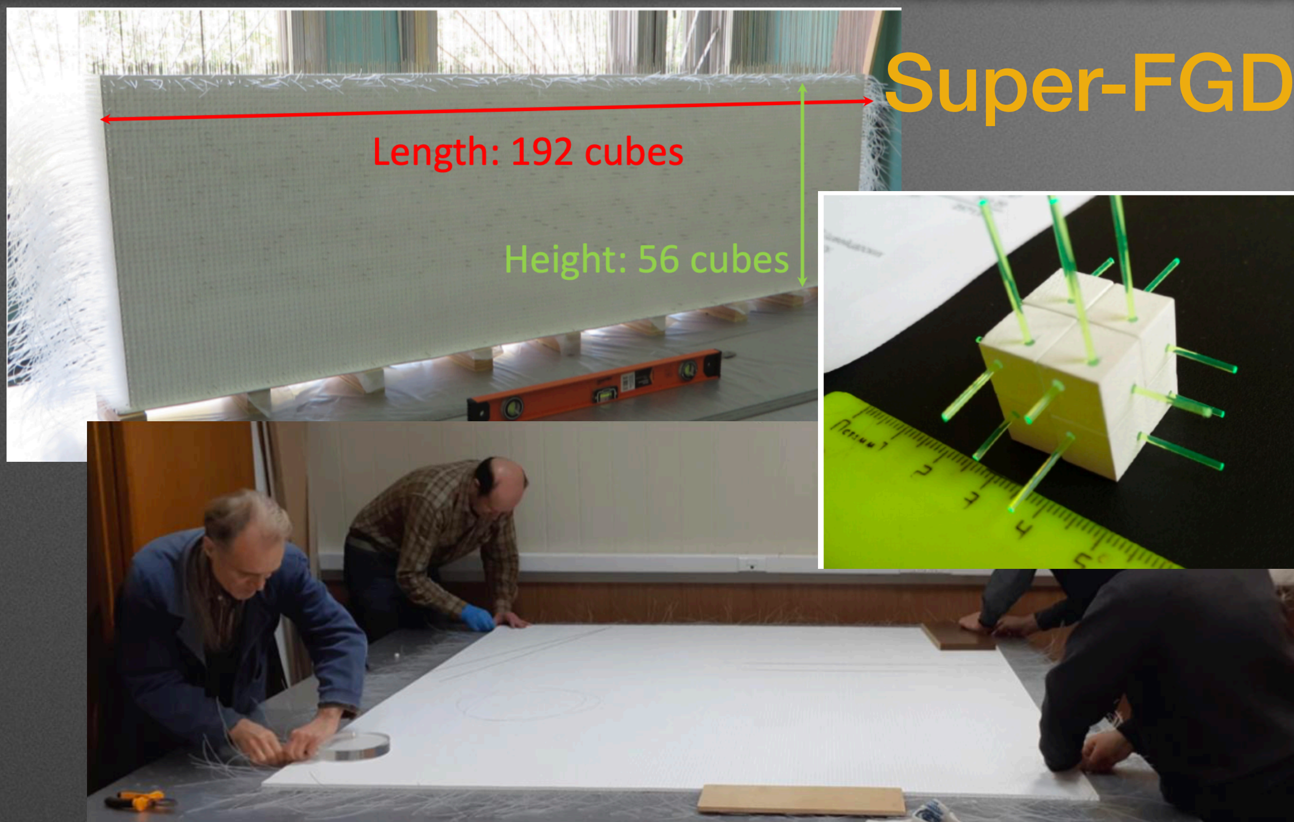


- Main strength of ND280 : magnetized detector → separate ν from $\overline{\nu}$ (cannot be done in SK or HK)
- Main limitation of ND280 : reduced angular acceptance → only forward going muons are selected with high efficiency
- An analysis dedicated to select tracks with high polar angles → 20% efficiency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



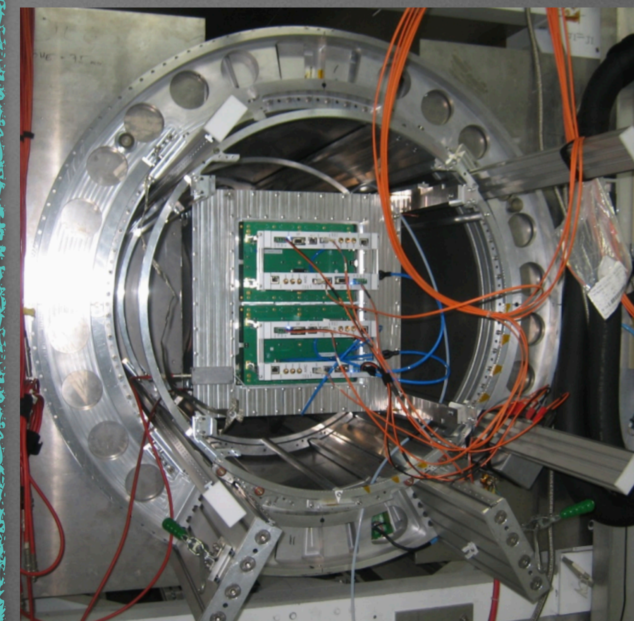
New detectors

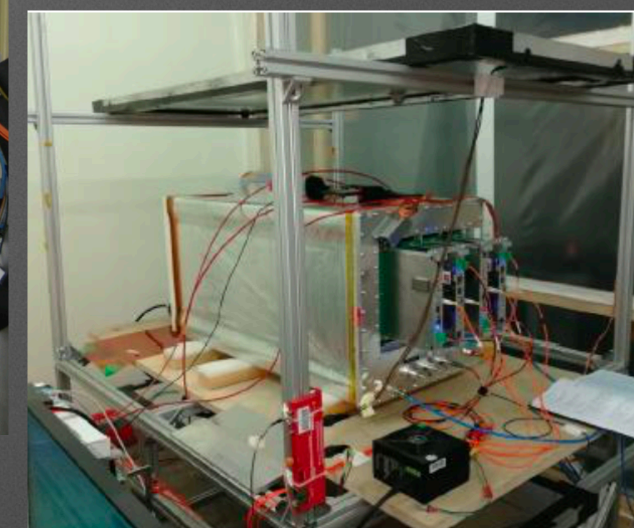
Super-FGD



- New concept of detectors, 2×10^6 $1 cm^3$ cubes
  - $>1 \times 10^6$ cubes already delivered
  - All cubes will be produced by Dec 2020
- Each cube is read by 3 WLS

High-Angle TPCs

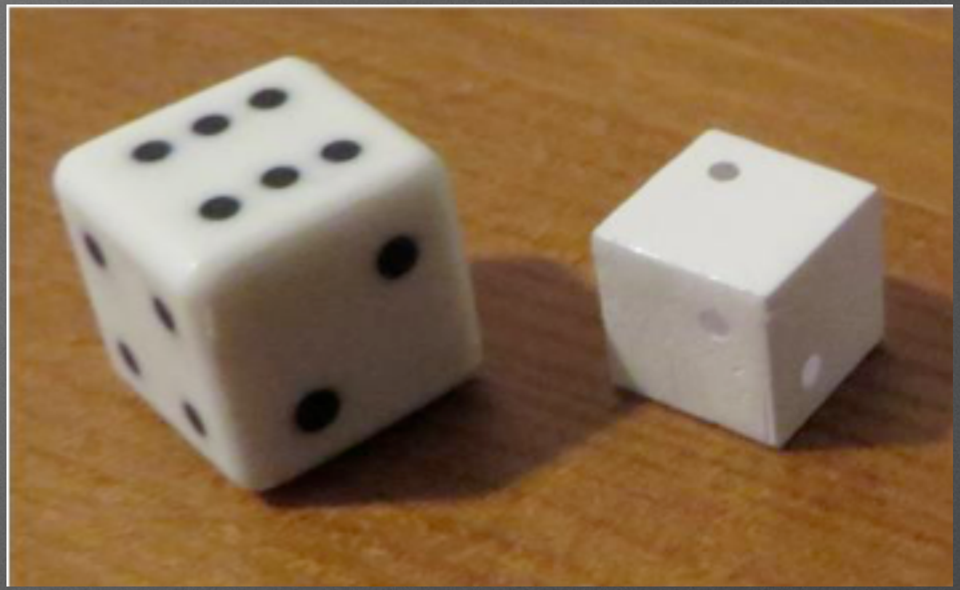


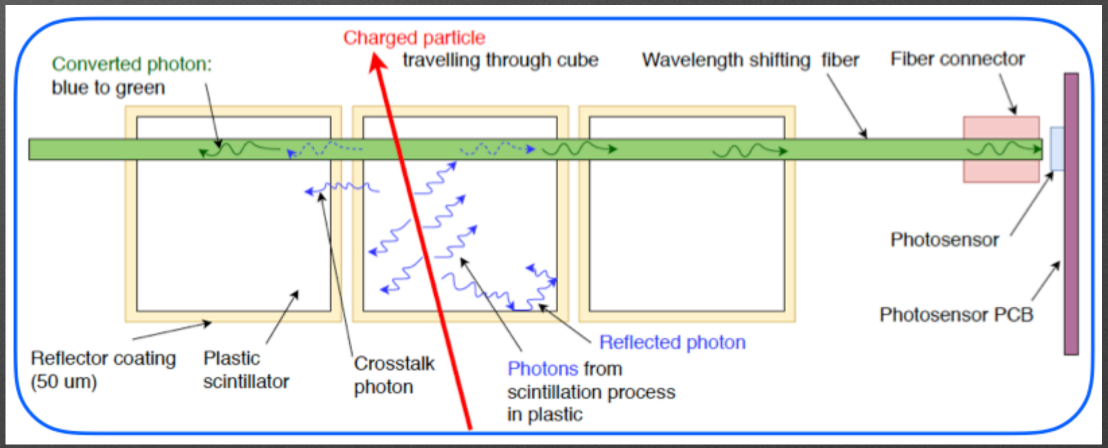


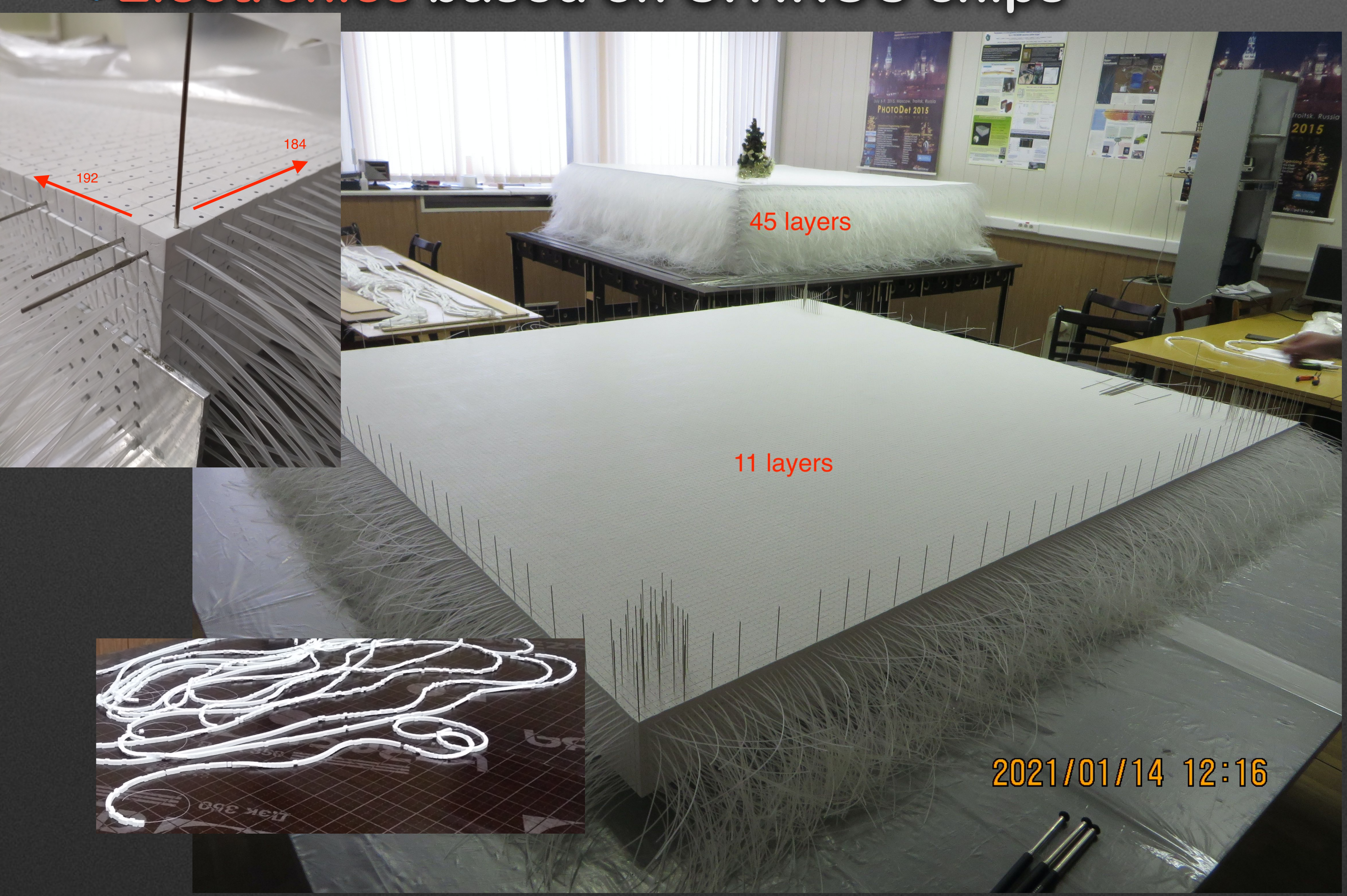
- New TPCs instrumented with Encapsulated Resistive Anode MicroMegas (ERAM)
- Design validated with first prototype
- DESY and CERN Test beams results
  - Spatial resolution ~200 μm
  - dE/dx resolution ~7% for 70 cm tracks

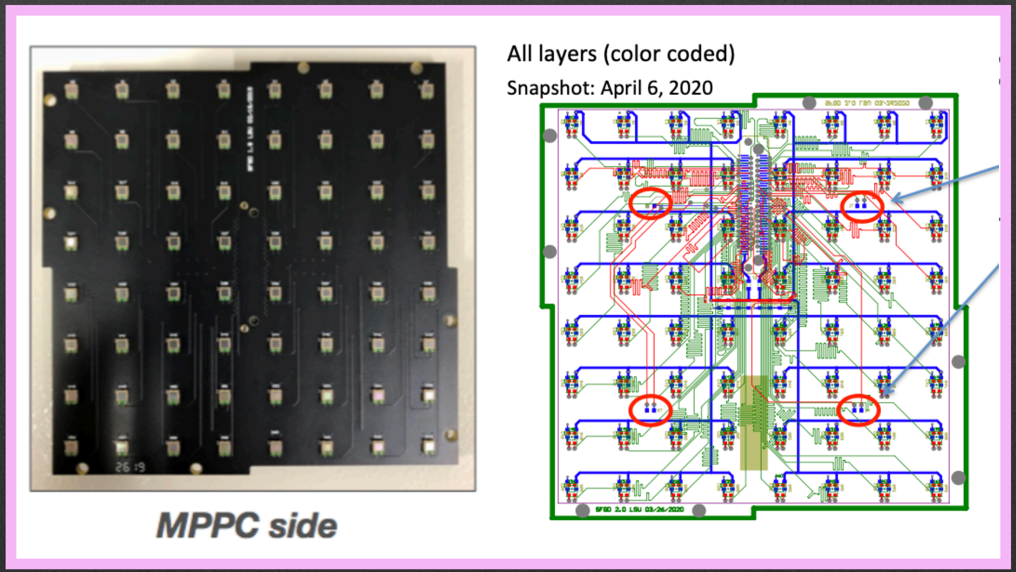
Super-FGD

- 2 millions 1cm^3 cubes → **assembled in 56 x-y layers** at INR
- Light in each cube is collected by 3 WLS (3 views)
- Light carried by the WLS is read by **56k MPPCs** mounted on PCB
- **Electronics** based on CITIROC chips

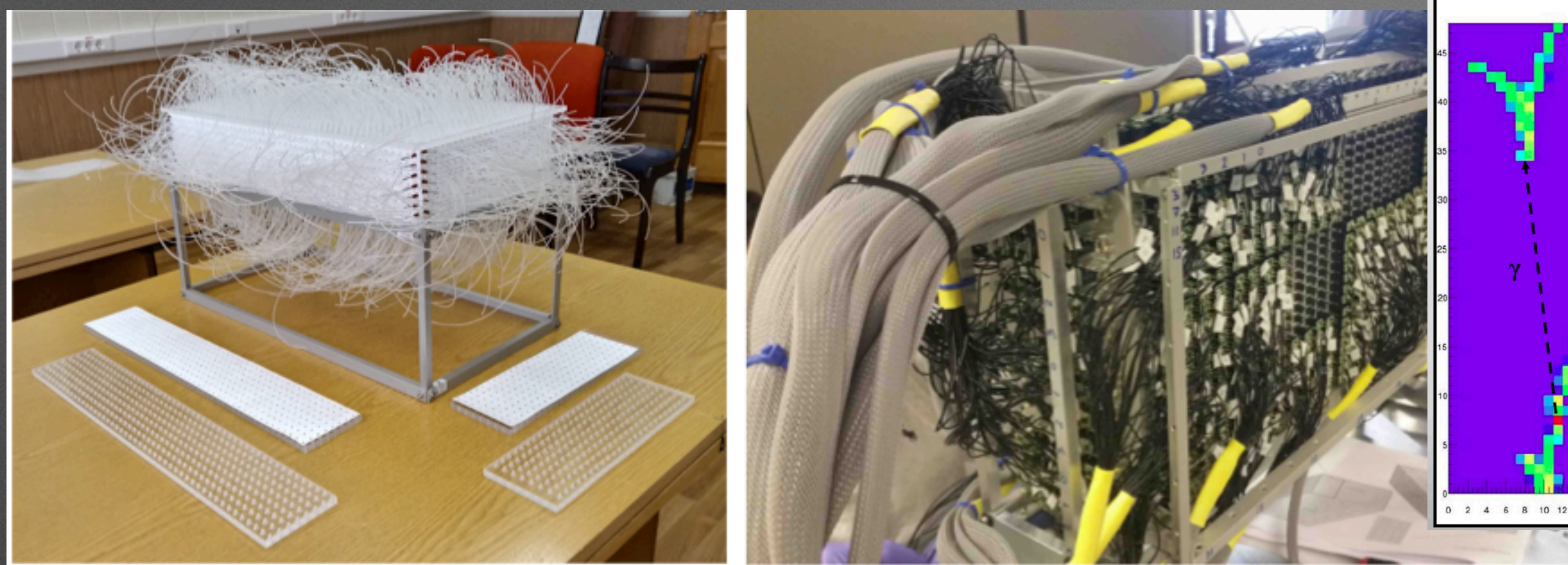


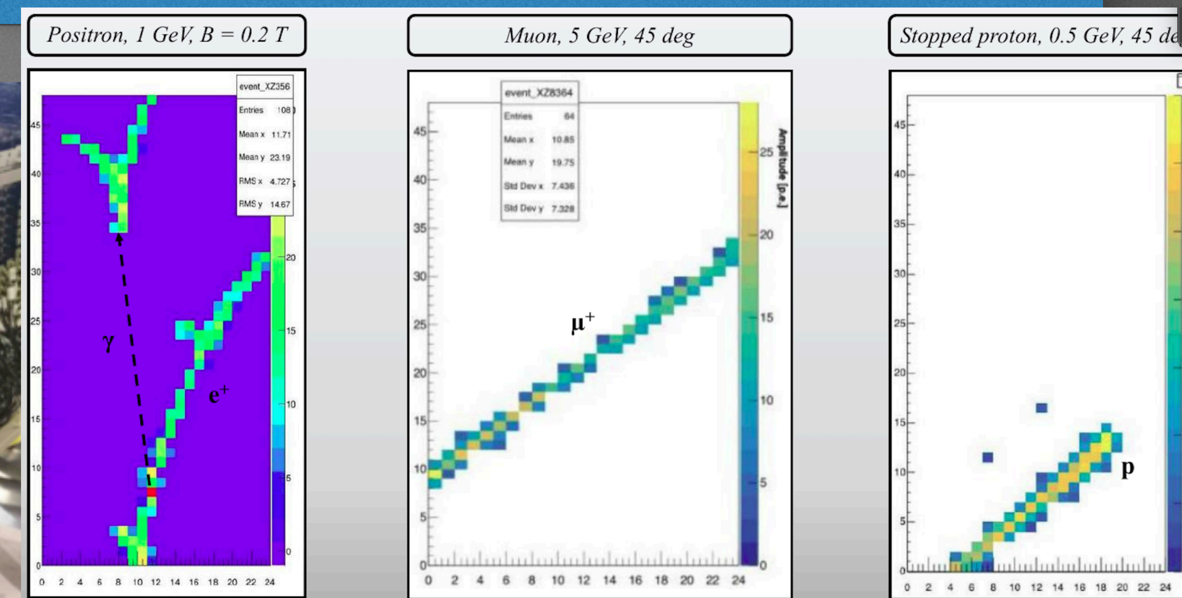


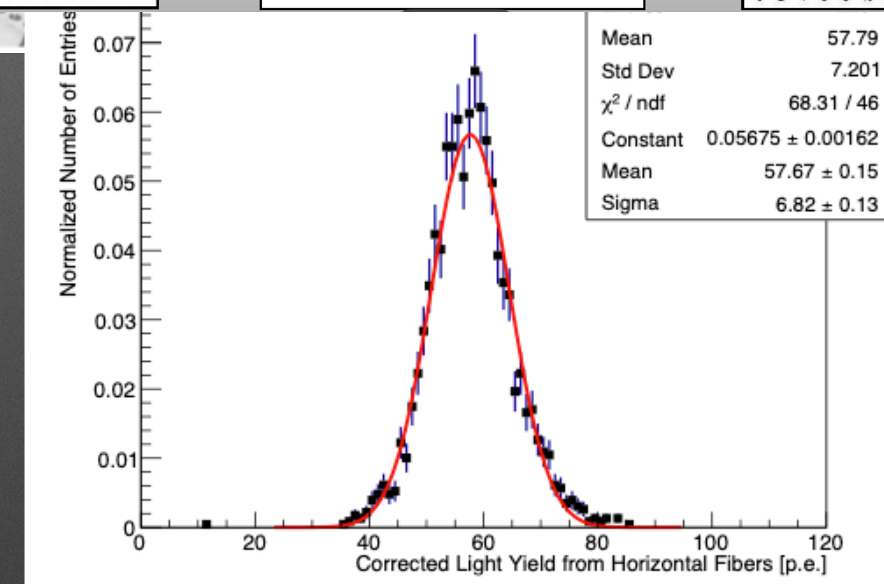


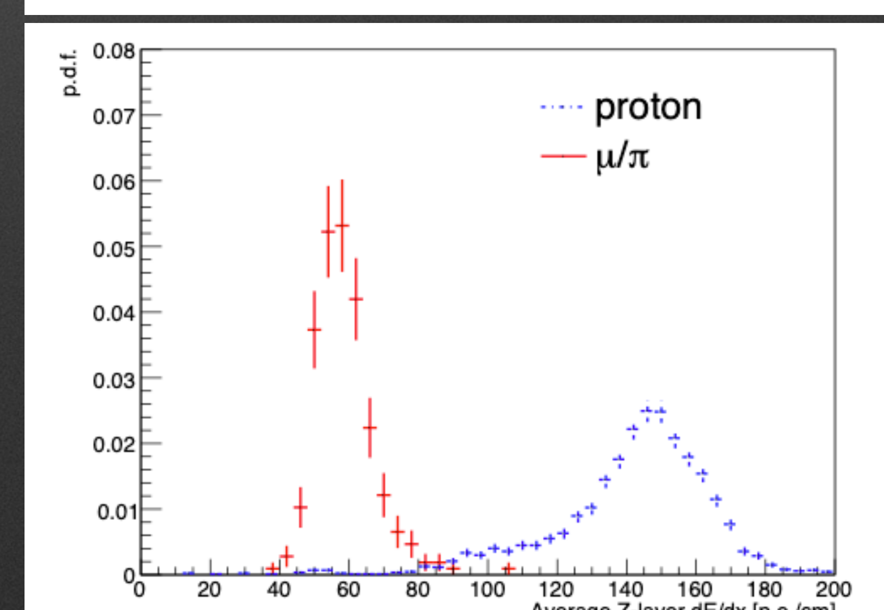


sFGD Test Beam





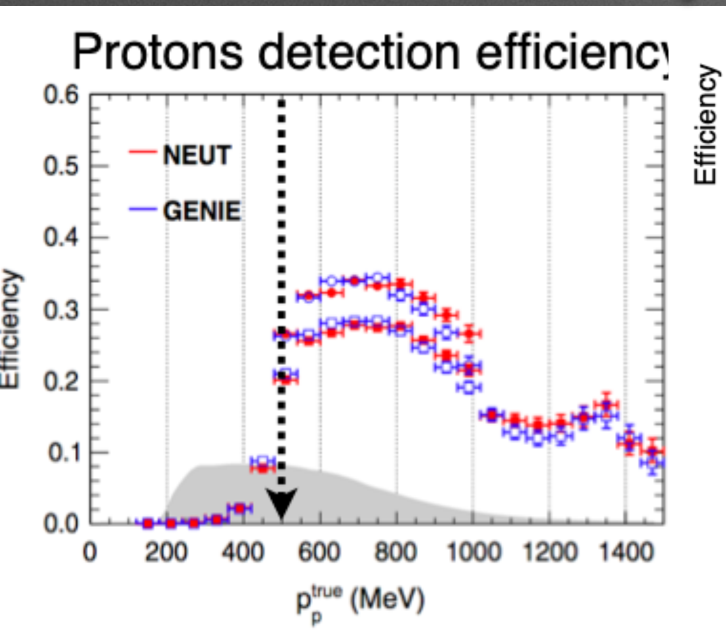


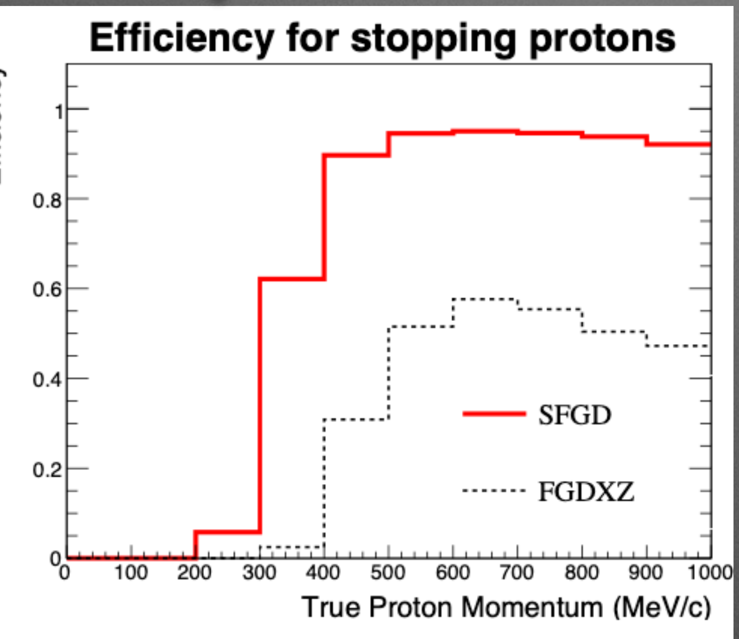


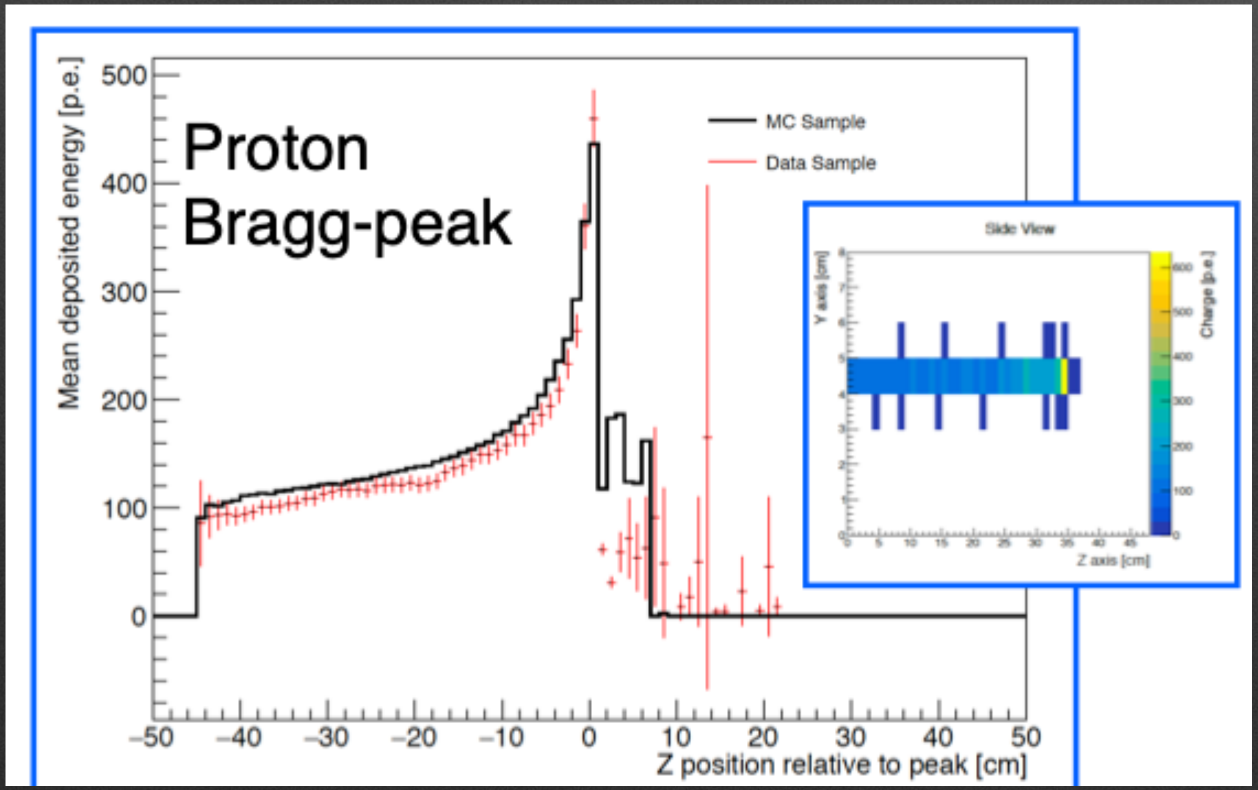
- CERN Test Beam with a prototype in 2018
- Published on 2020 JINST 15 P12003
- Excellent performances for light yield and particle separation

Super-FGD protons and neutrons

Reduce threshold from ~500 to ~300 MeV → access to most of the protons produced in ND280







$\bar{\nu}$ + p → μ+ + n

Reconstructing neutrons would open a new window to exploit nuclear effect

Measurements on-going with a test beam at LANL

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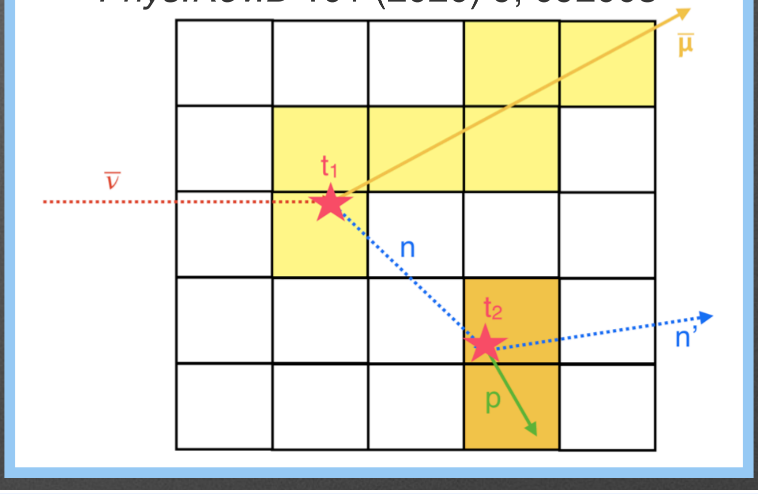
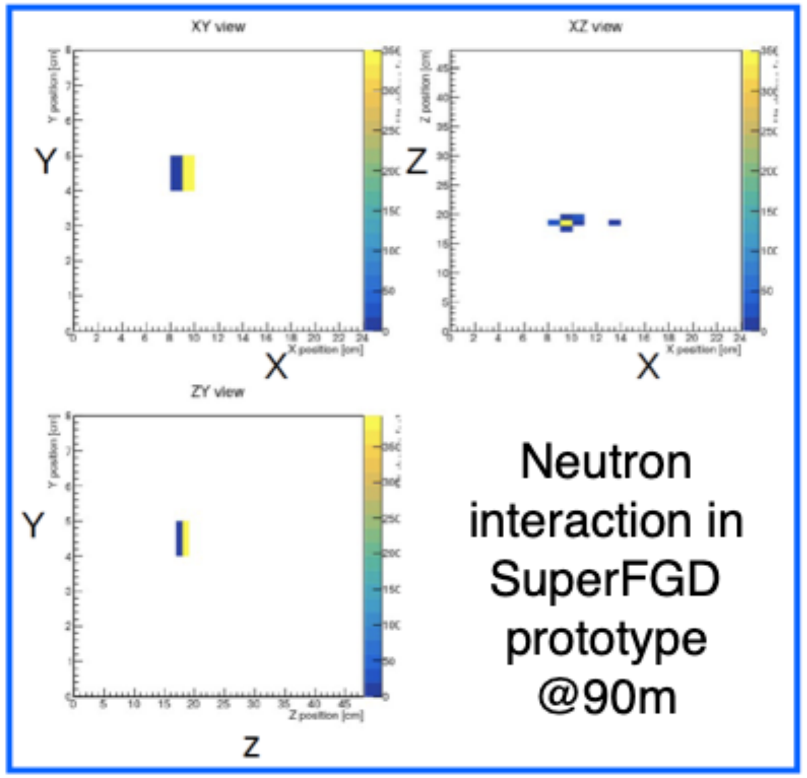




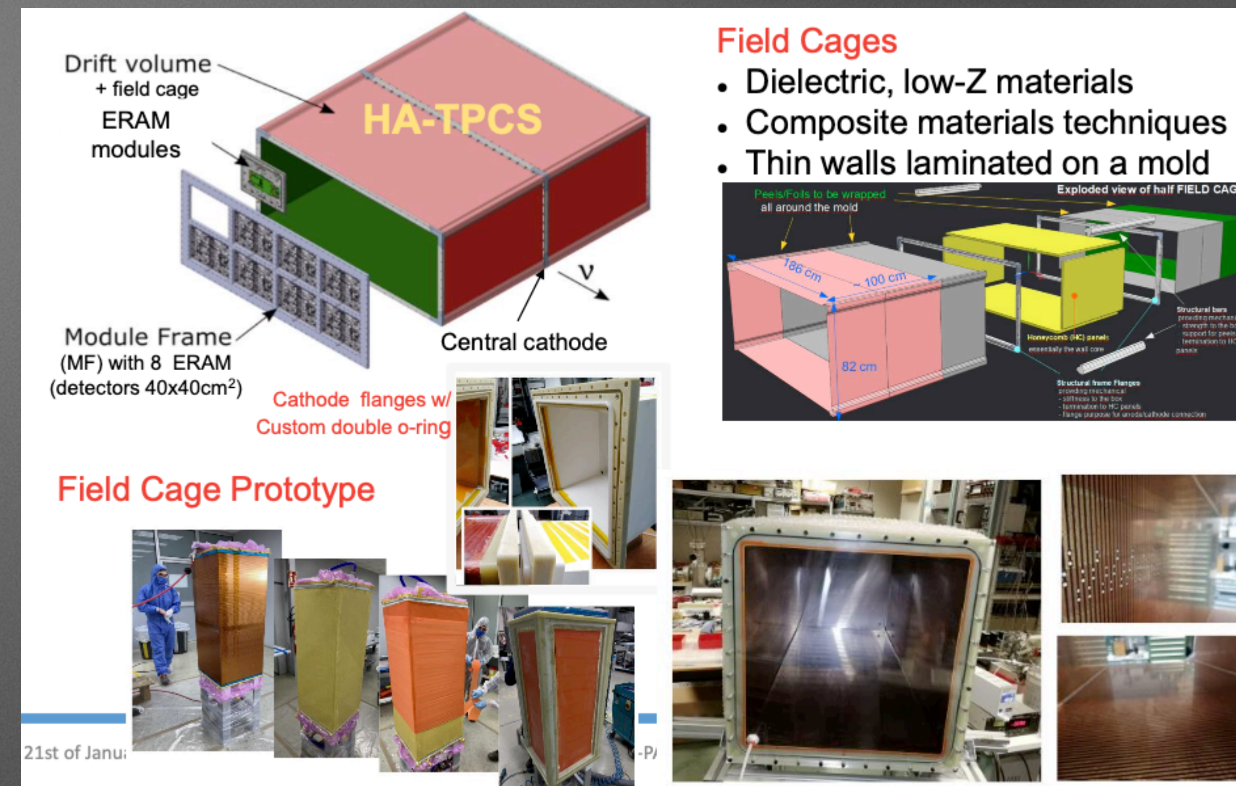
Neutron interaction in SuperFGD prototype @90m

HA-TPC

- Two field cage prototypes tested → first field cage expected in May 2021

- Resistive MM modules have been satisfactory tested and production started

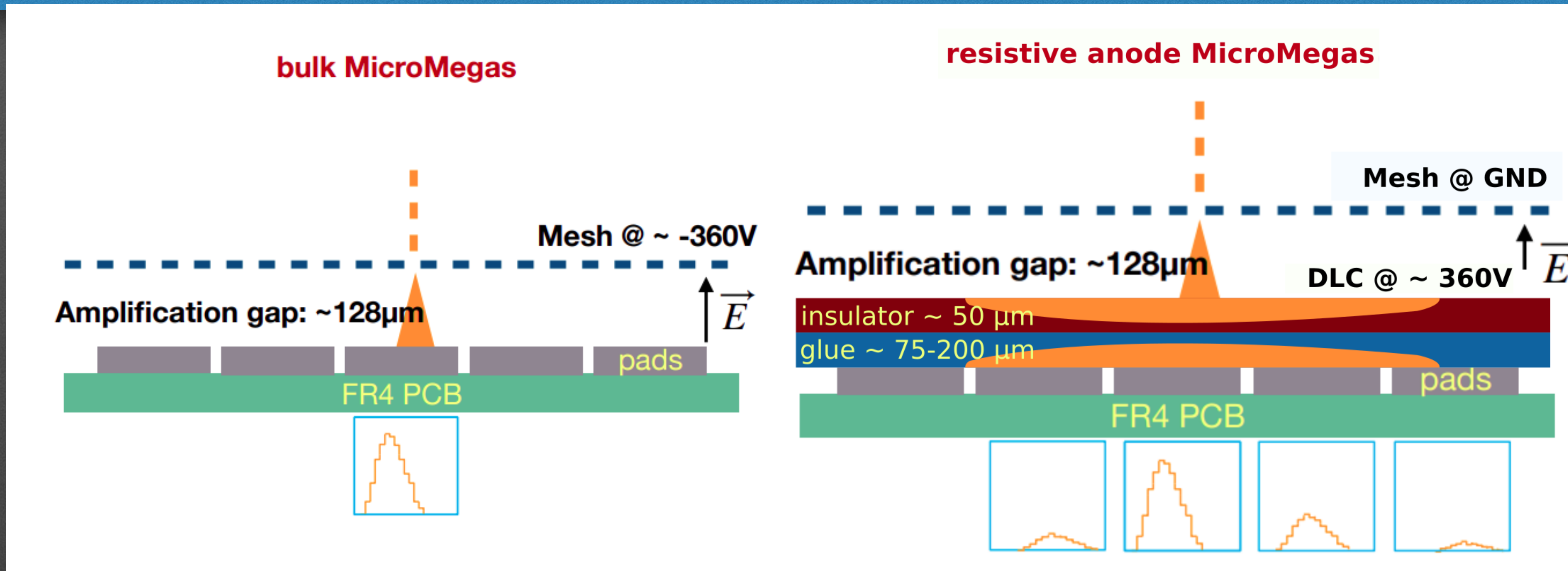
- Front End electronics (FEC+FEM) prototypes have been validated → production of the cards have been launched



Bulk-micromegas side

Connector side

Resistive MM principles



$$\rho(r,t) = \frac{RC}{2t}\exp[-\frac{-r^2RC}{4t}]$$

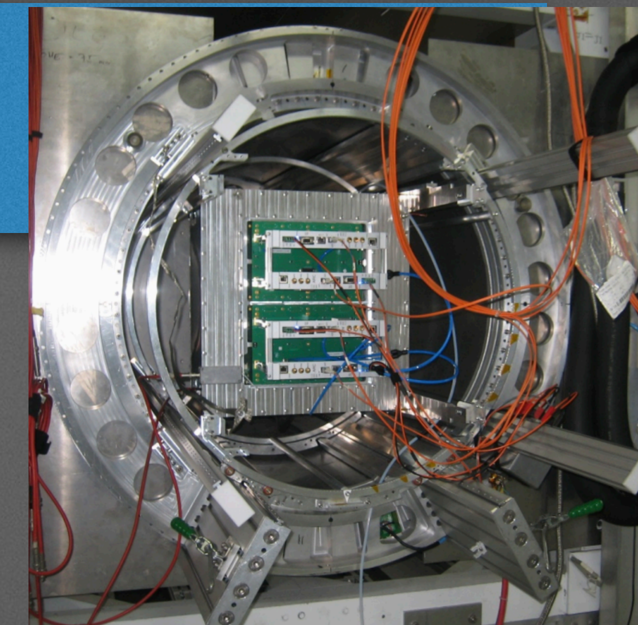
R- surface resistivity
C- capacitance/unit area

Gaussian spreading as a function of time with :

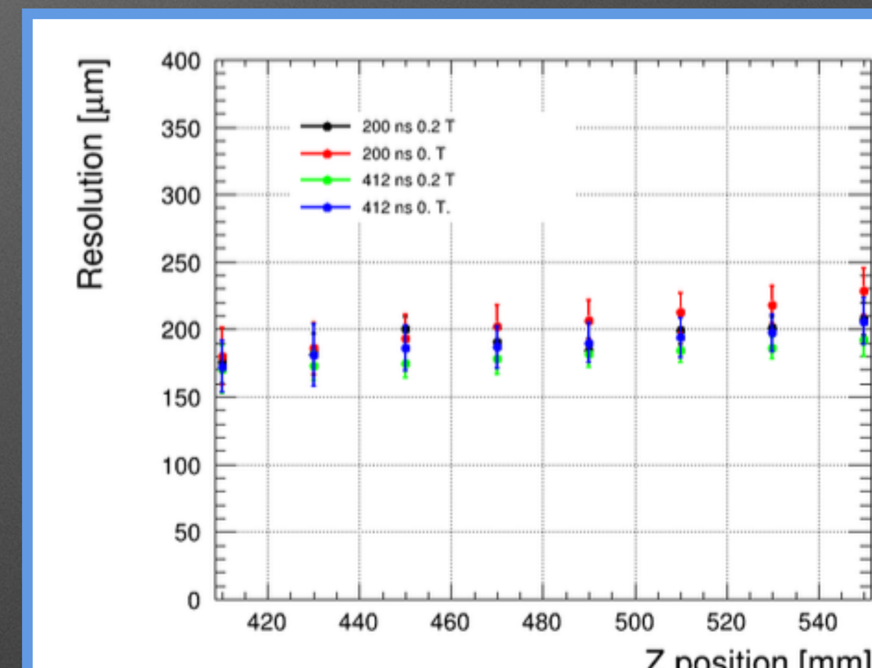
$$\sigma_r = \sqrt{\frac{2t}{RC}} \quad \begin{cases} t \approx \text{shaping time (few 100 ns)} \\ RC_{[ns/mm^2]} = \dfrac{180\, R_{[M\Omega/\blacksquare]}}{d_{[\mu m]}/175} \end{cases}$$

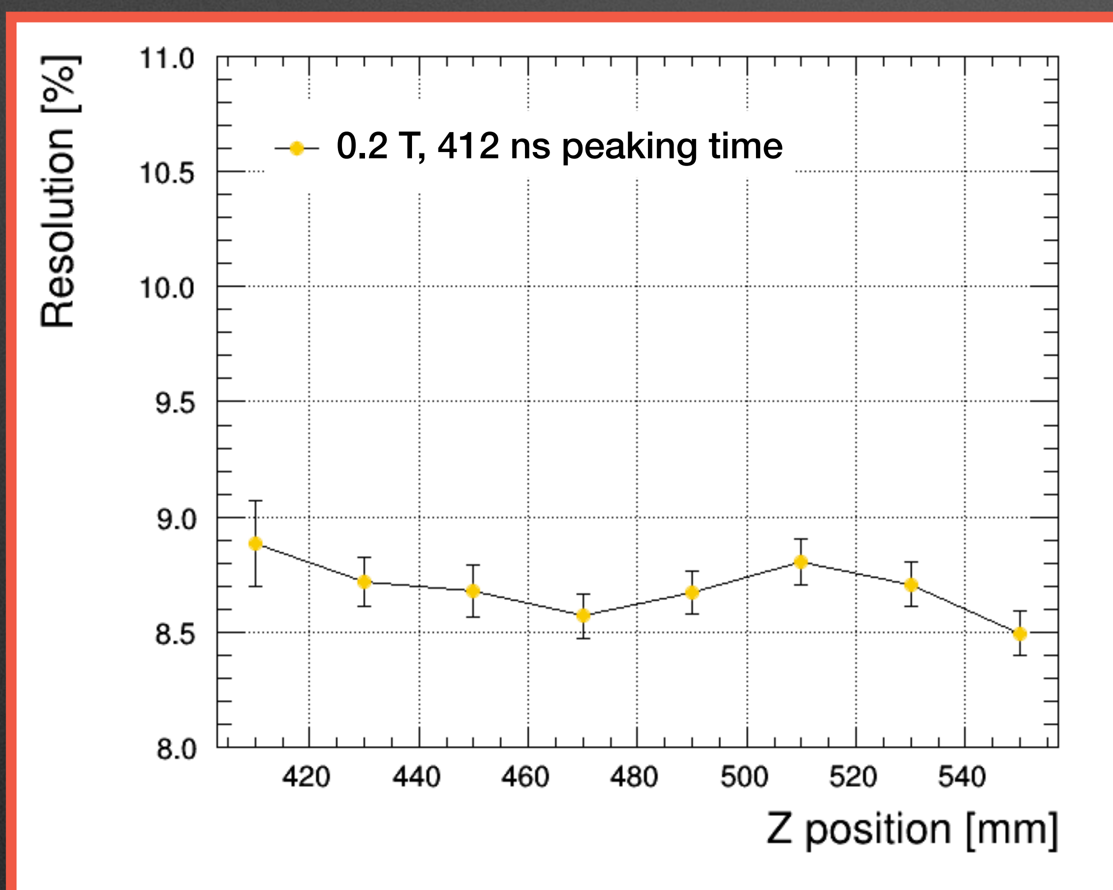
- Encapsulated Resistive Anode Micromegas (ERAM)
- Charge spread over several pads
  - Spreading depends on RC value
- Main advantages:
  - Better spatial resolution (even with larger pads)
  - Reduced risk of sparks
  - Mesh at Ground → better electrostatic integration with TPC drift volume

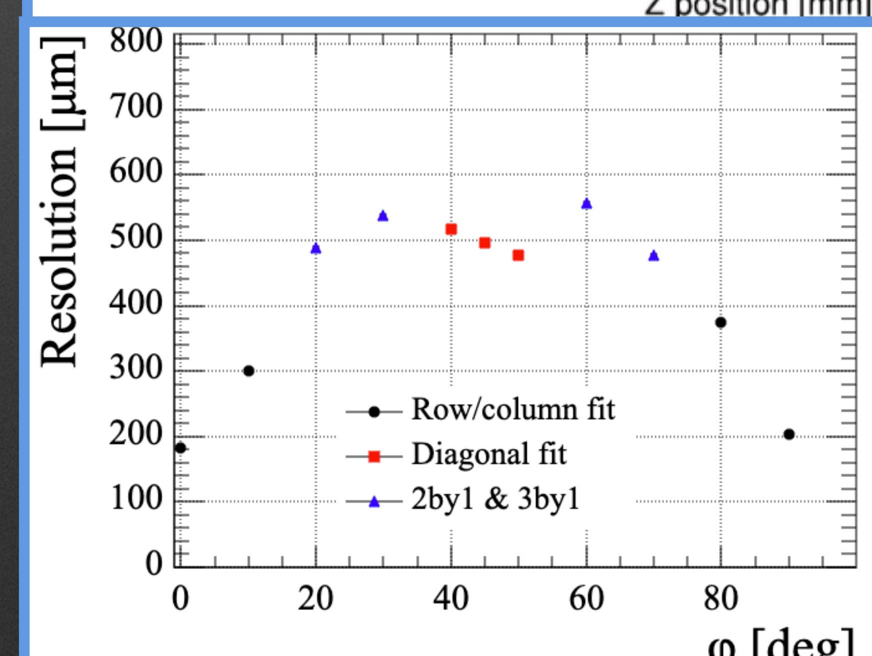
HA-TPC Test Beams



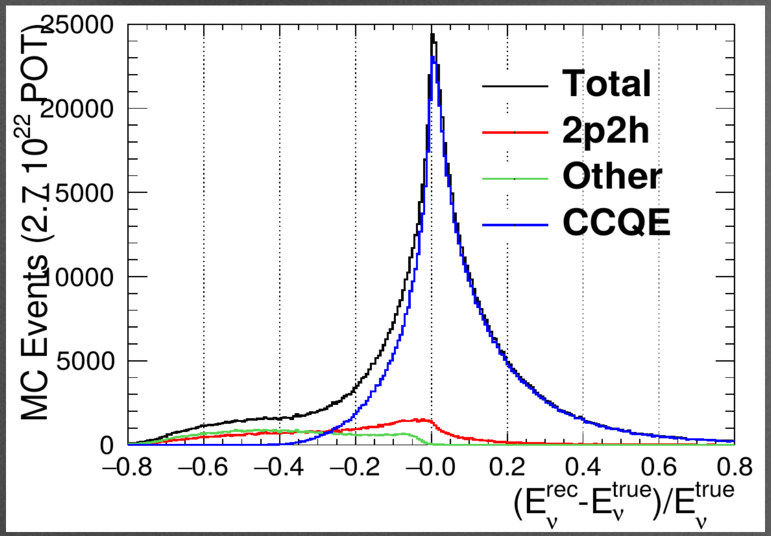
- 2 Test beam campaigns (CERN in 2018, DESY in 2019)
- Spatial resolution:
  - ~200 µm for horizontal tracks (vs 600 µm for existing TPCs)
  - <600 µm for all angles (vs 1 mm for existing TPCs)
- dE/dx resolution < 9% for one module (<7% expected for tracks crossing 2 modules)

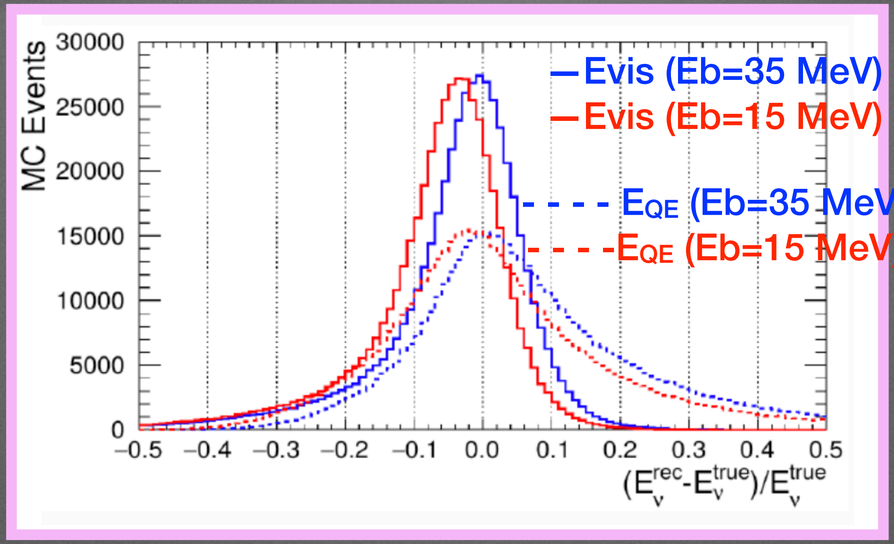


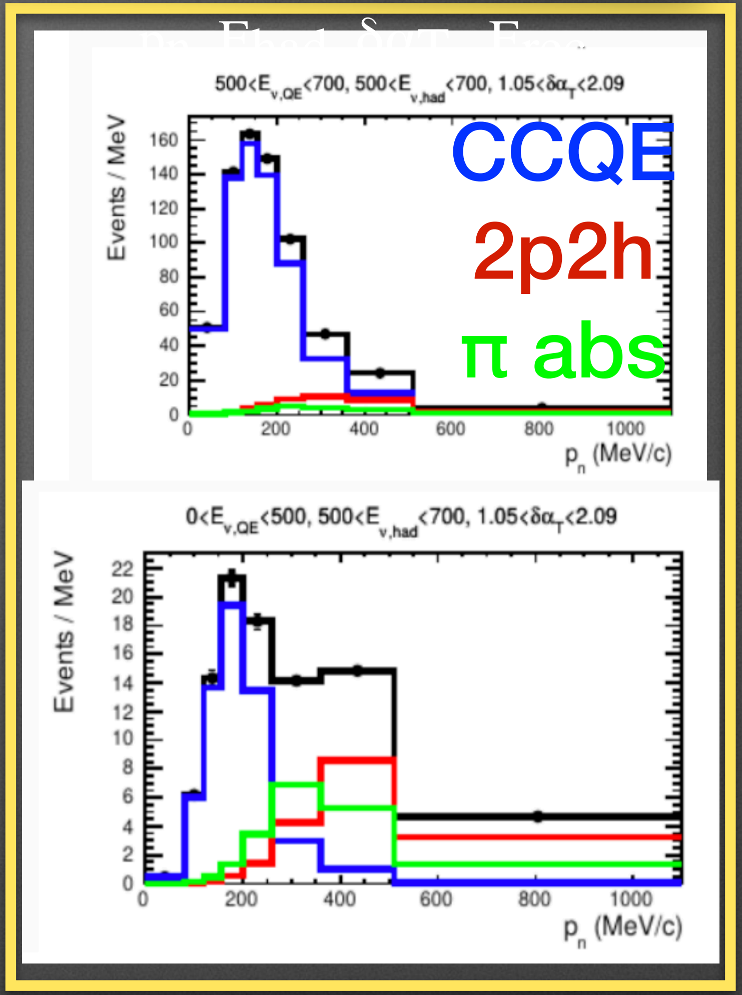




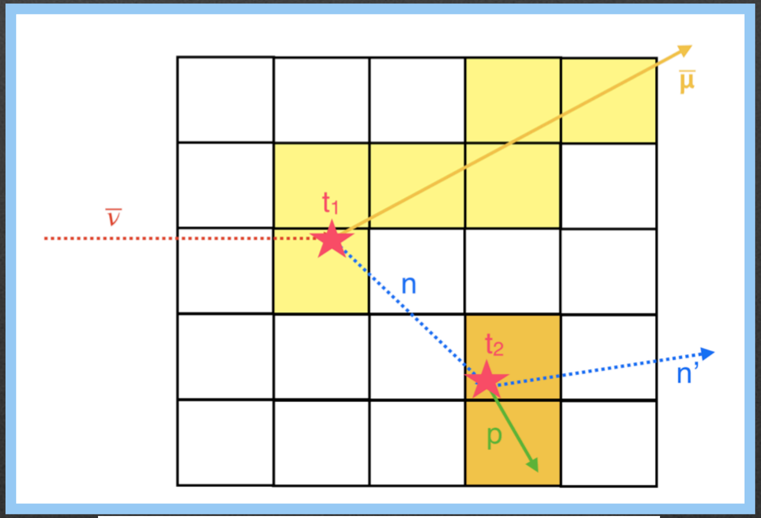
ND280 Upgrade motivations







- Thanks to the reconstruction of muons and protons we will exploit new variables and multidimensional fits in order to improve ND280 constraints
  - Exploit μ + p to reconstruct the ν energy in a complementary way (E_{had})
  - Exploit lepton-nucleon correlations to isolate kinematic regions dominated by non-QE interactions (2p2h, π abs)
  - Reconstruct neutrons using time of flight between neutrino interaction and neutron scattering in the SFGD



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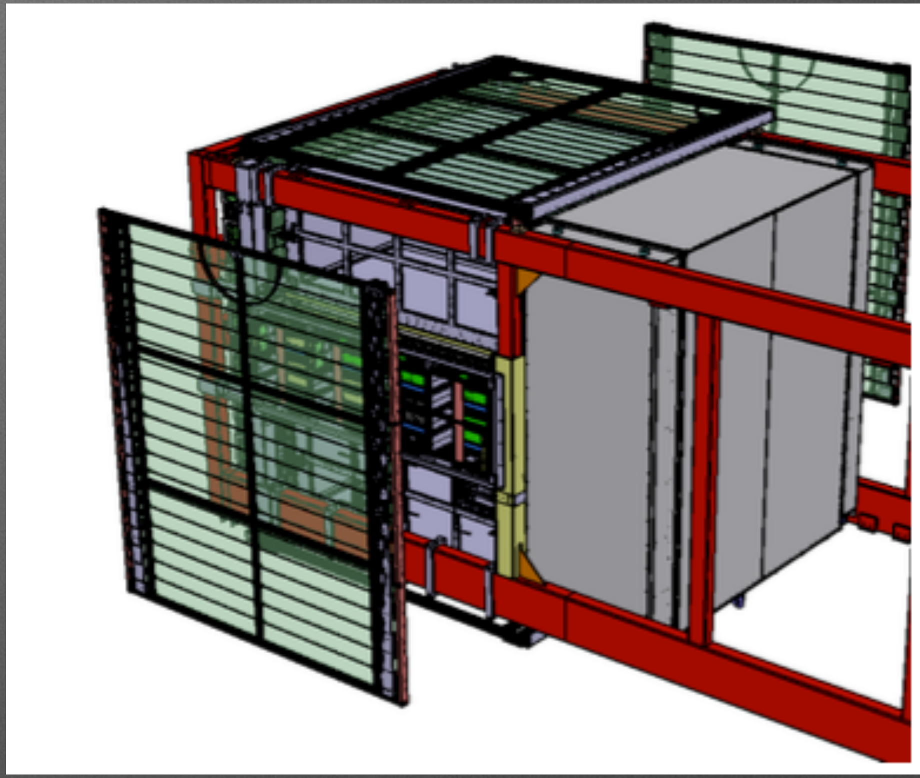
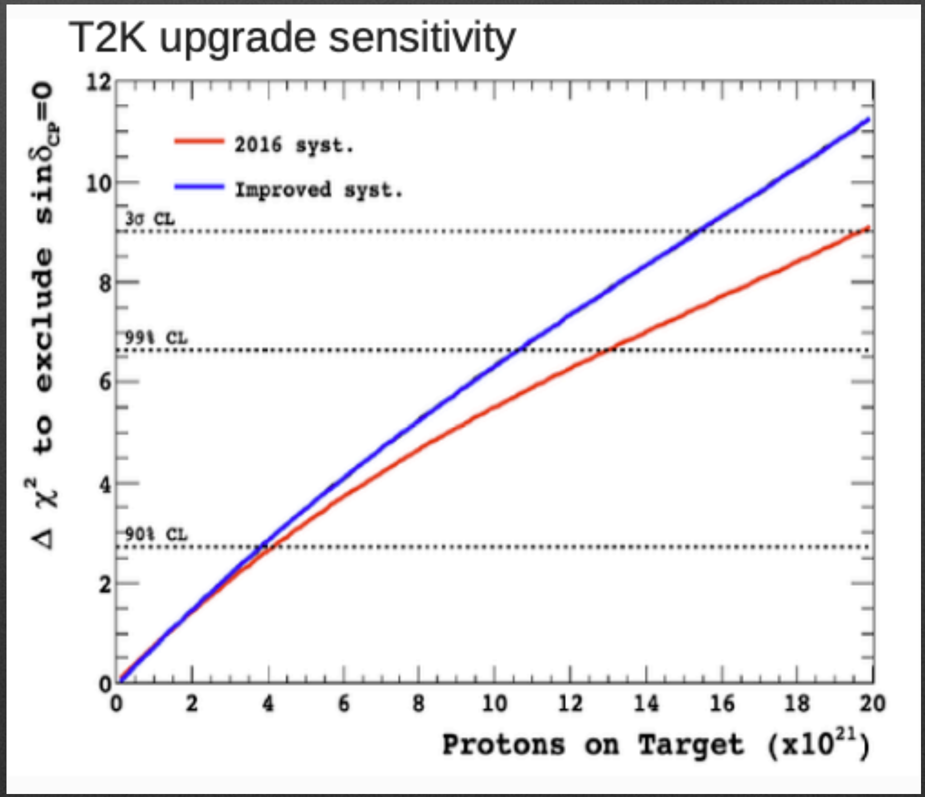
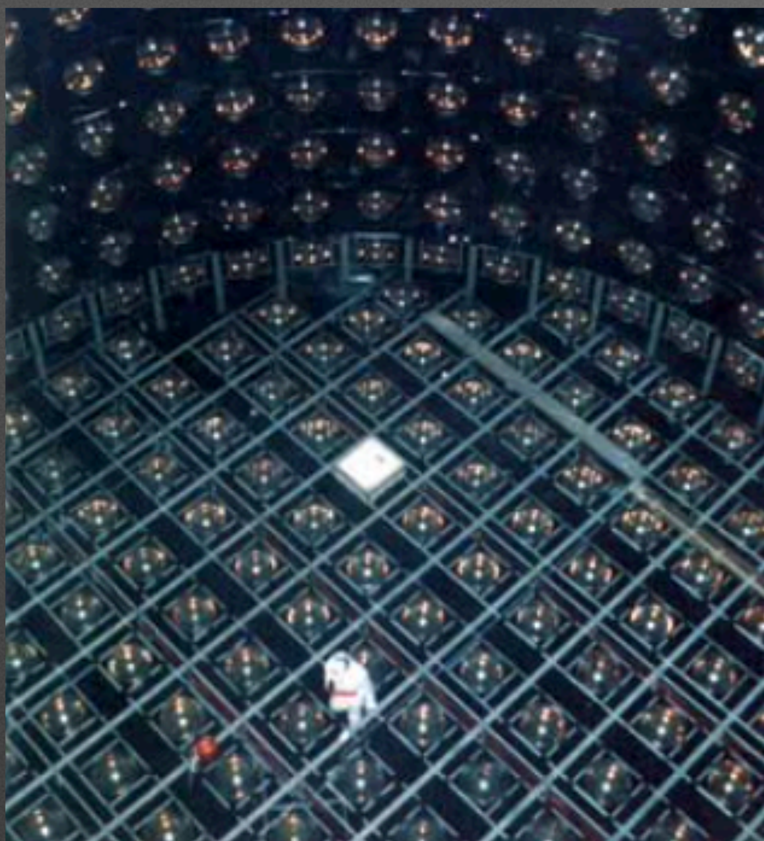
T2K-II

- ND280 Upgrade will be installed at J-PARC in Summer 2022
- At the same time the J-PARC neutrino beam will be upgraded to reach a beam power of 1.3 MW (500 kW today)
- This will allow to collect > 10e21 POT by the beginning of HK (3 times more than the statistics we have today)
  - CP violation > 3σ @ $\delta_{CP}=-\pi/2$
  - $\delta\theta_{23}<1.7°$ (for maximal mixing)
  - $\delta(\Delta m^2_{32})/\Delta m^2_{32} < 1\%$
- Bridge to Hyper-K





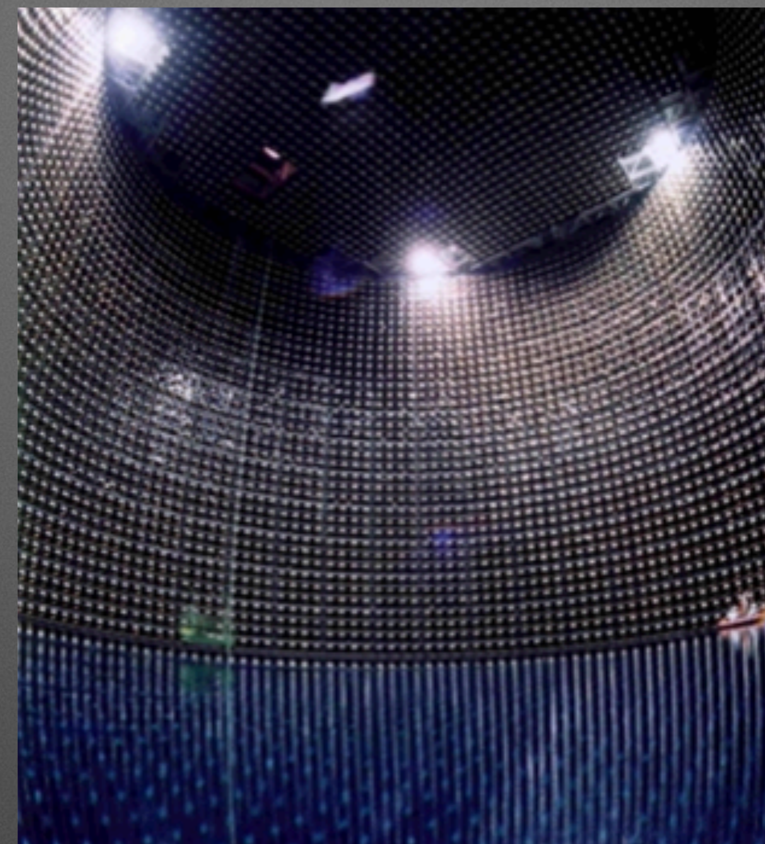
Water Cherenkov Detectors



Kamiokande
(1983-1996)

- Atmospheric and solar ν anomaly
- Supernova 1987A

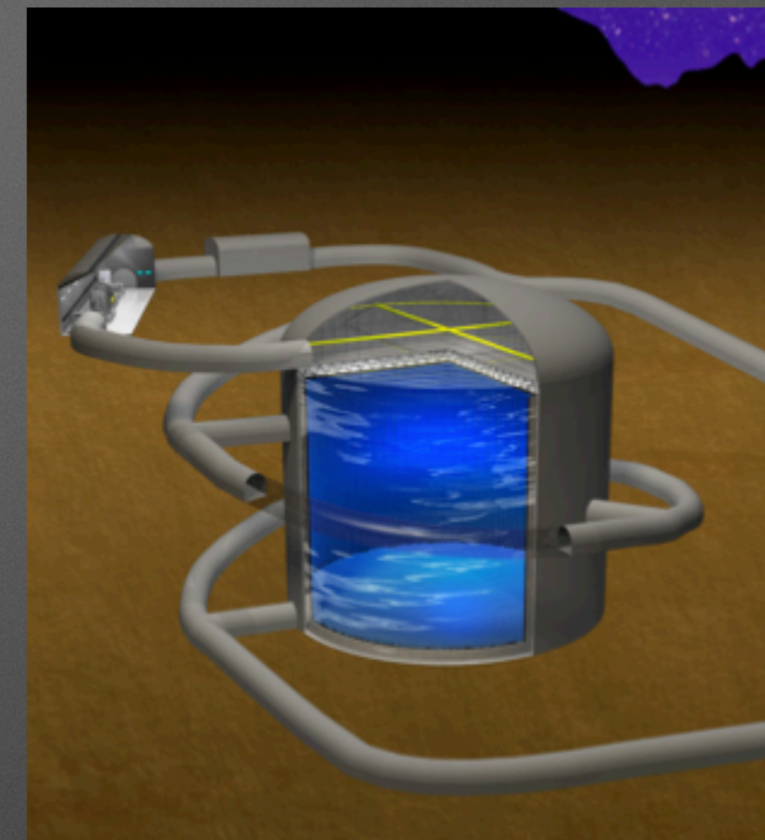
2002 



Super-Kamiokande
(1996-ongoing)

- World best limit on proton decay
- Discovery of ν oscillations
- Measurement of oscillations (atm/solar/LBL)

2015 



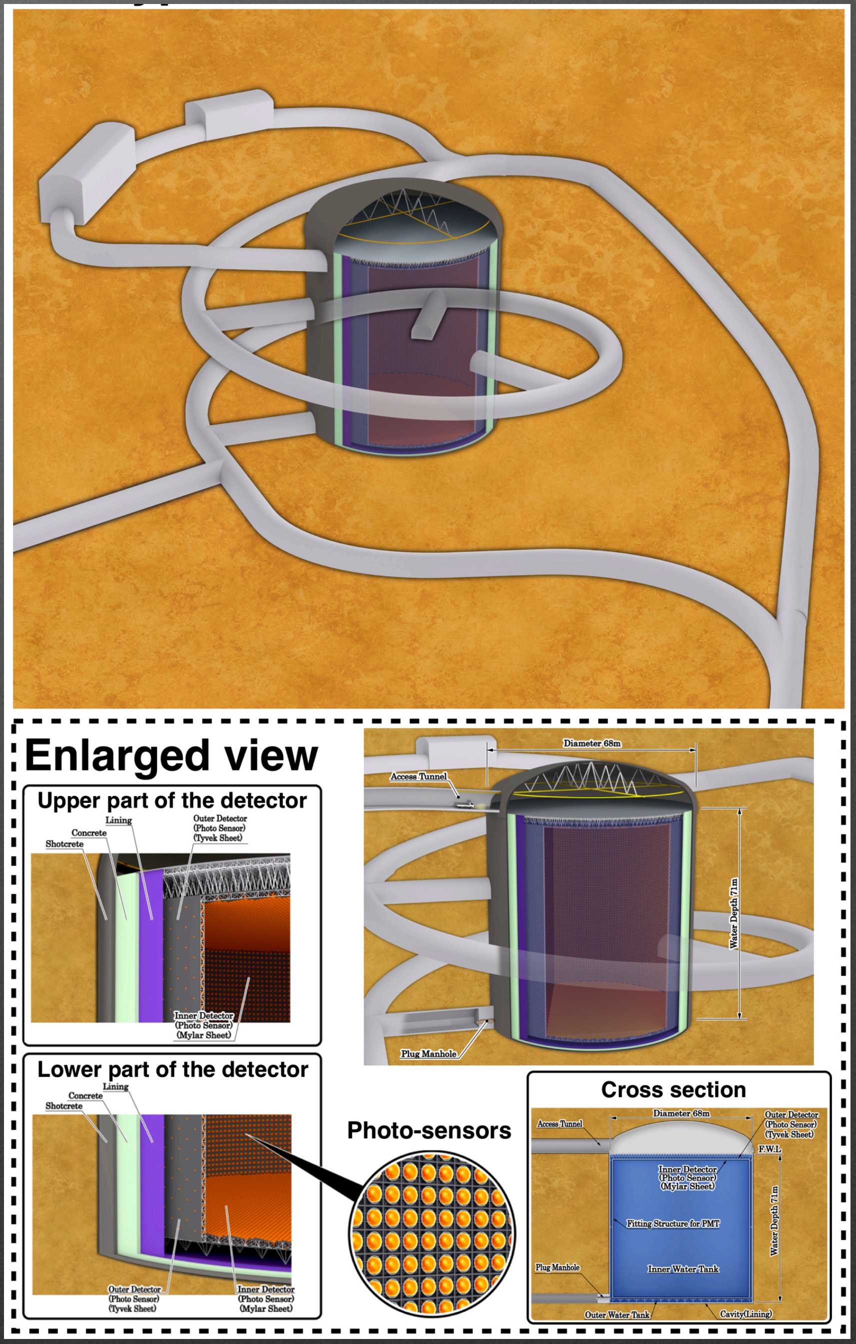
Hyper-Kamiokande
(Start in 2027)

- Extended search of proton decay
- Search for CPV in leptonic sector
- Neutrino astrophysics

203? 

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
- February 2020 → HK budget approved by Japanese governement (~500 M€, 80% of the total cost with 40k PMTs)
  - ~20% of the budget expected to be covered by international contributions
- Construction started in April 2020 → start operation in 2027

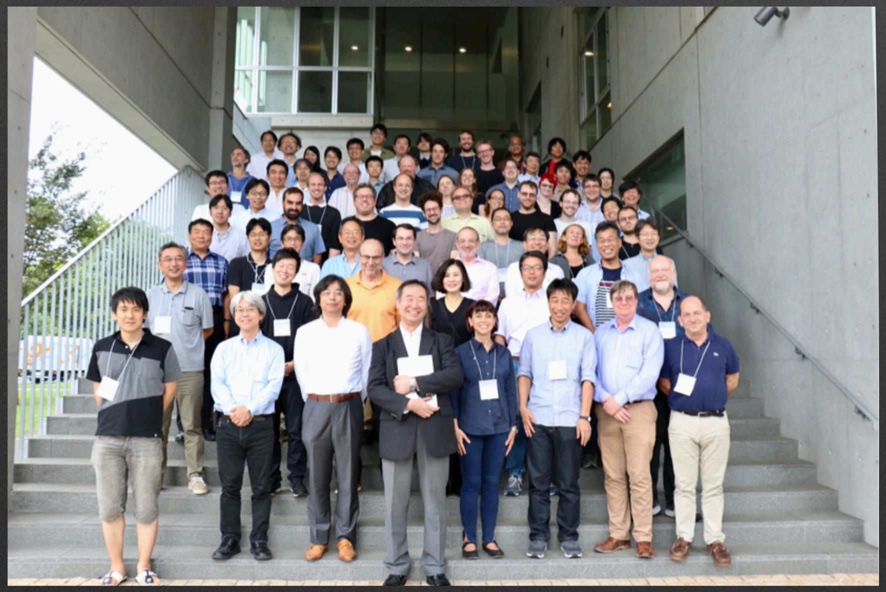


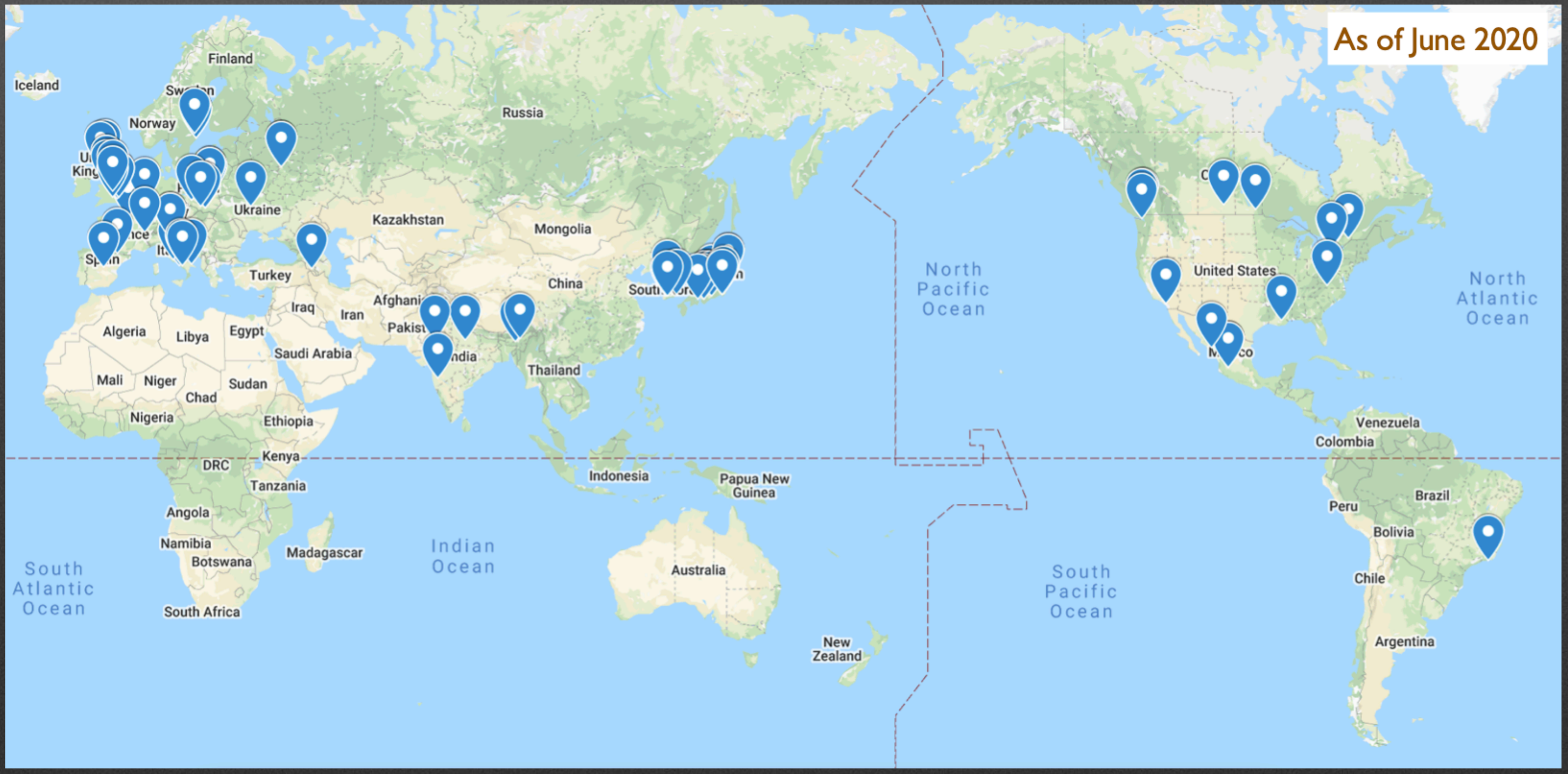
Hyper-Kamiokande proto-collaboration

18 countries, 82 institutes, ~390 people
Currently transitioning to HK collaboration

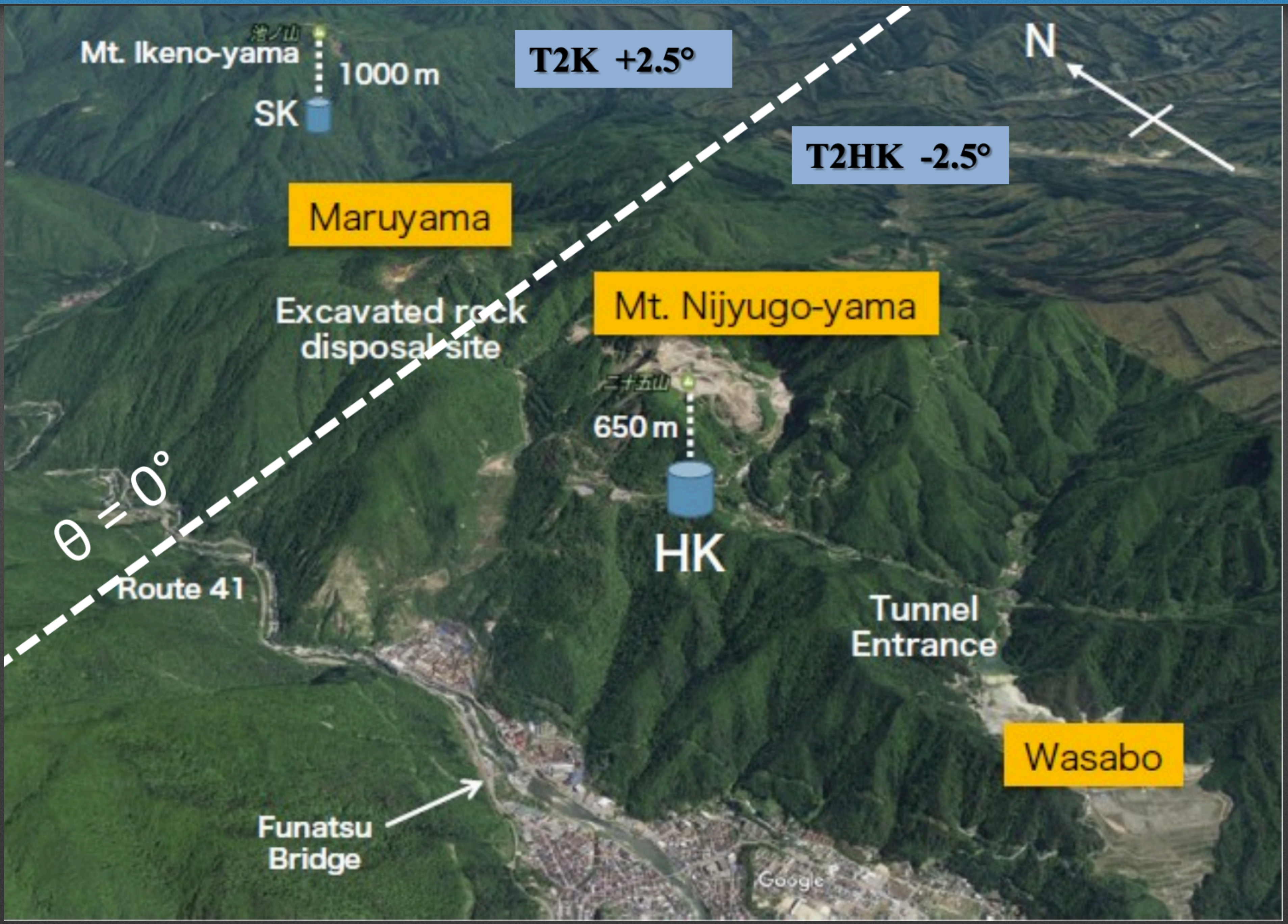
IRFU
LLR
LPNHE
OMEGA

Hyper-Kamiokande



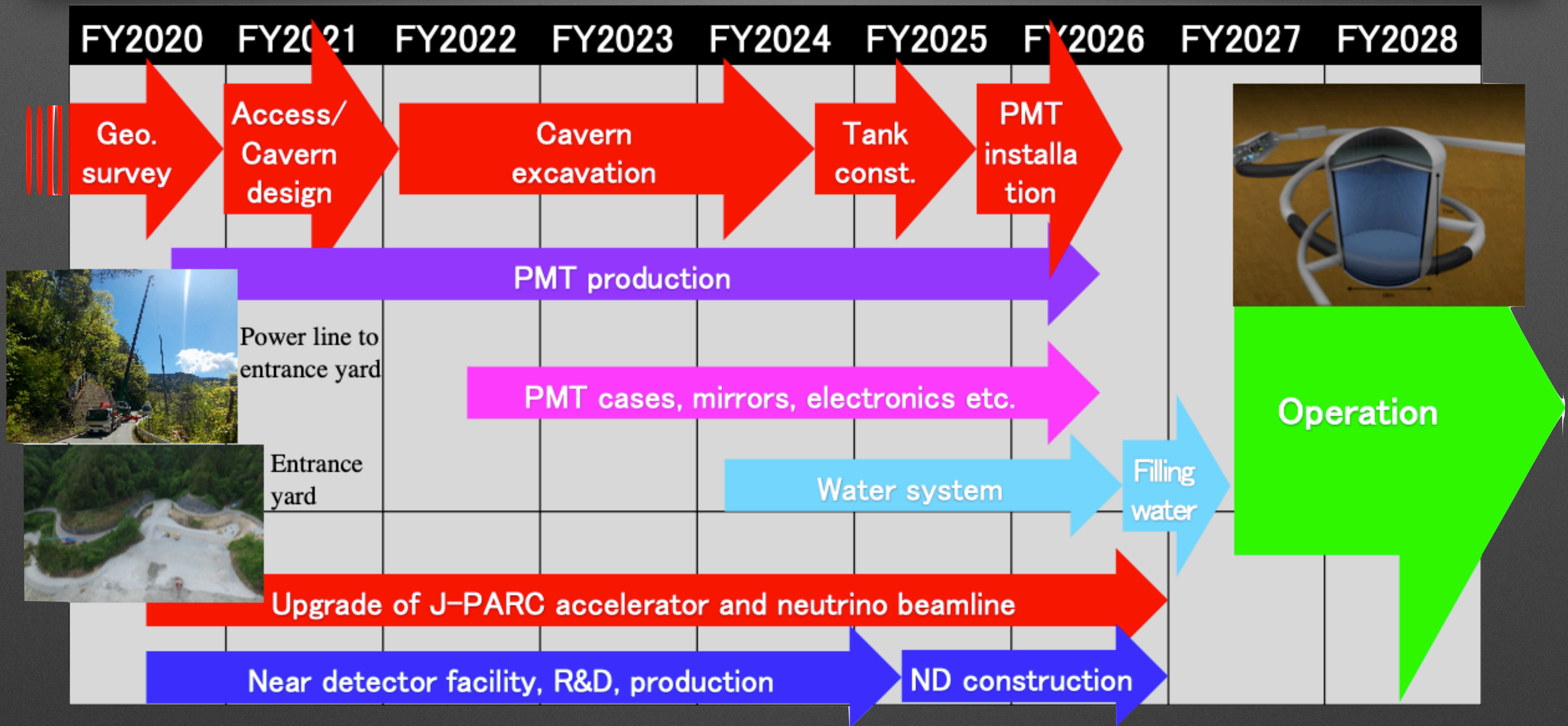


HK : Where



- Same off-axis angle as SK but at different location (10 km away)
- Possibility for a 2nd detector in Korea being explored

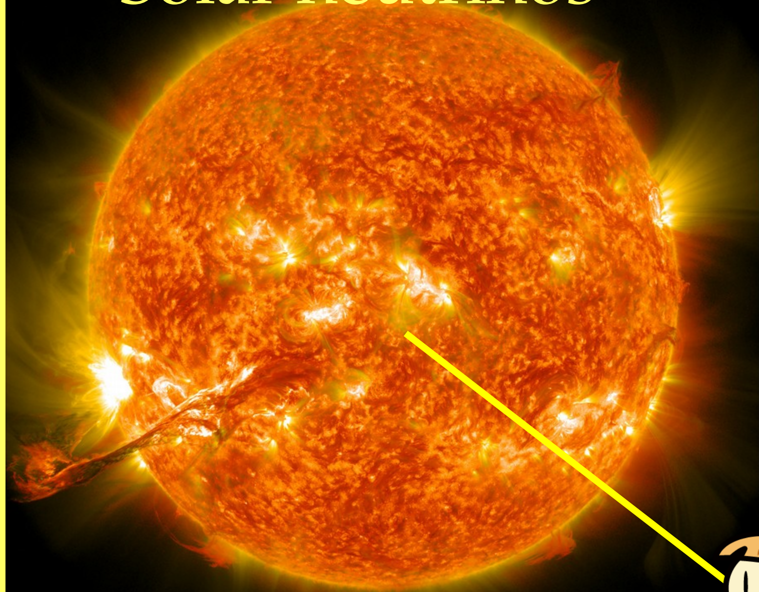
HK : When



- Started Construction in 2020
- Start data taking in JFY 2027
- Japanese part of the budget approved
  - International contributions being formalized

Physics case

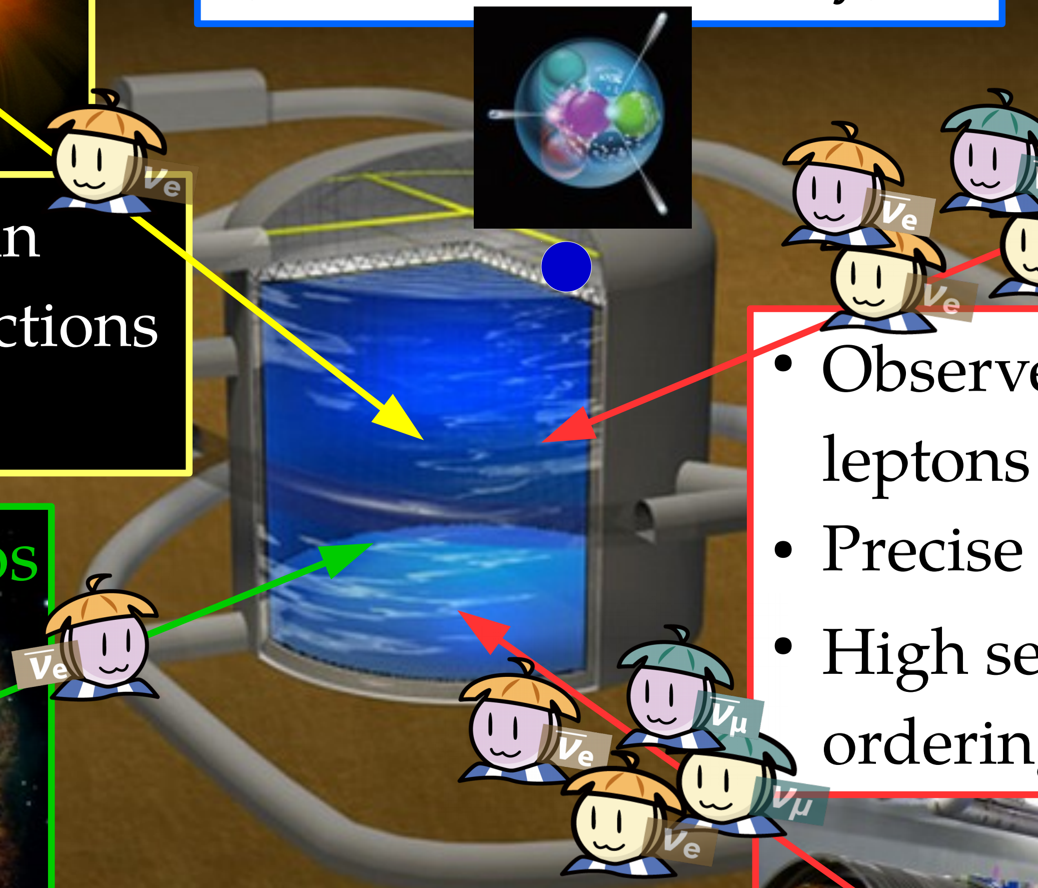
Solar neutrinos



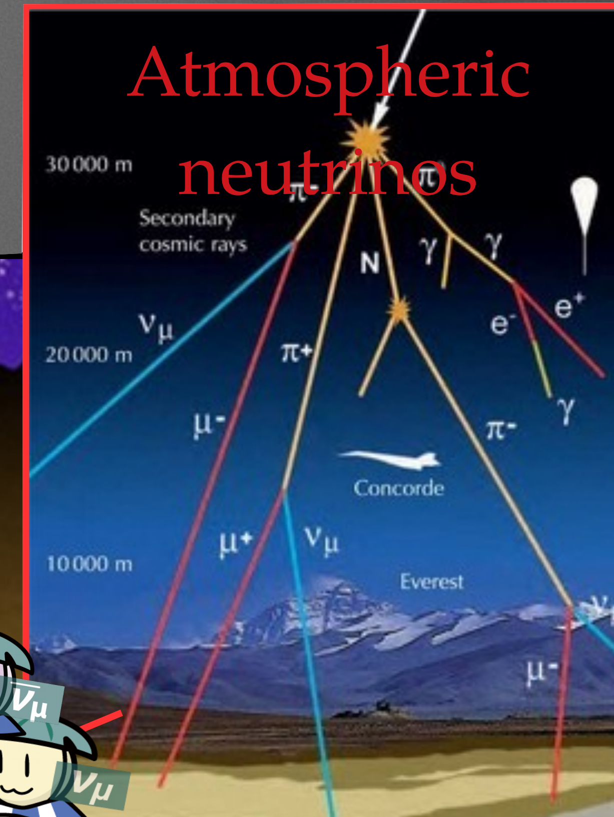
- MSW effect in the Sun
- Non-standard interactions in the Sun.

Proton decay

Probe Grand Unified Theories through p-decay (world best sensitivity)

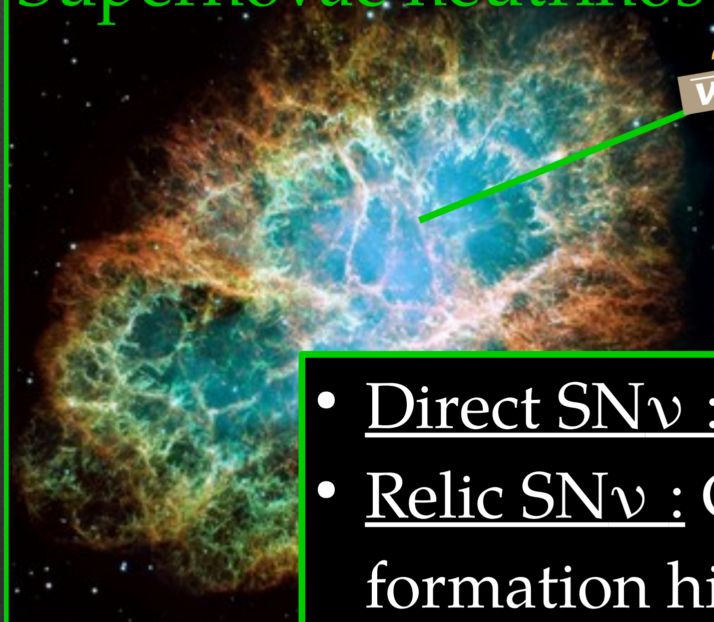


Atmospheric neutrinos



- Observe CP violation for leptons at 5σ
- Precise measurement of δ_{CP} .
- High sensitivity to ν mass ordering.

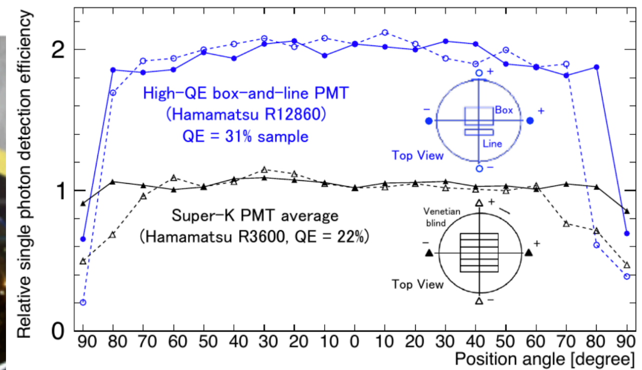
Supernovae neutrinos



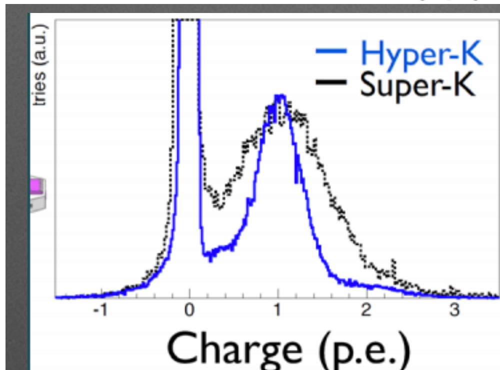
- Direct SNν : Constrains SN models.
- Relic SNν : Constrains cosmic star formation history

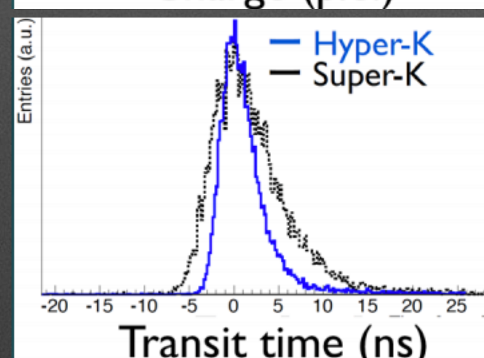
JPARC accelerator neutrinos

Hyper-K photo-detection system



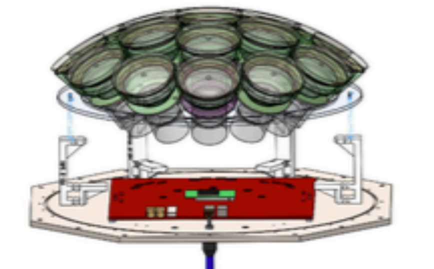
Box&Line PMT in Super-K



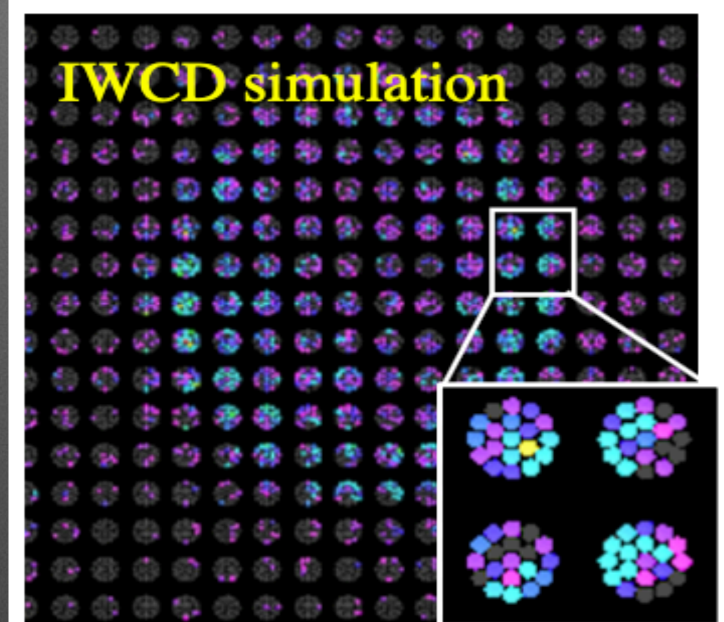


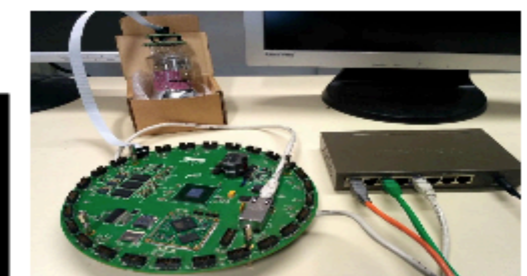
- HK will be instrumented with "box-and-line" 20'' PMTs
- At least 20k modules
- 31% QE (2 times better than SK)
- Better transit time spread and charge resolution

Multi-PMT module:
(ref. KM3NeT)
High resolution Cherenkov ring imaging essential for IWCD
Consider to use for part of HK



Prototype at TRIUMF





Electronics at INFN

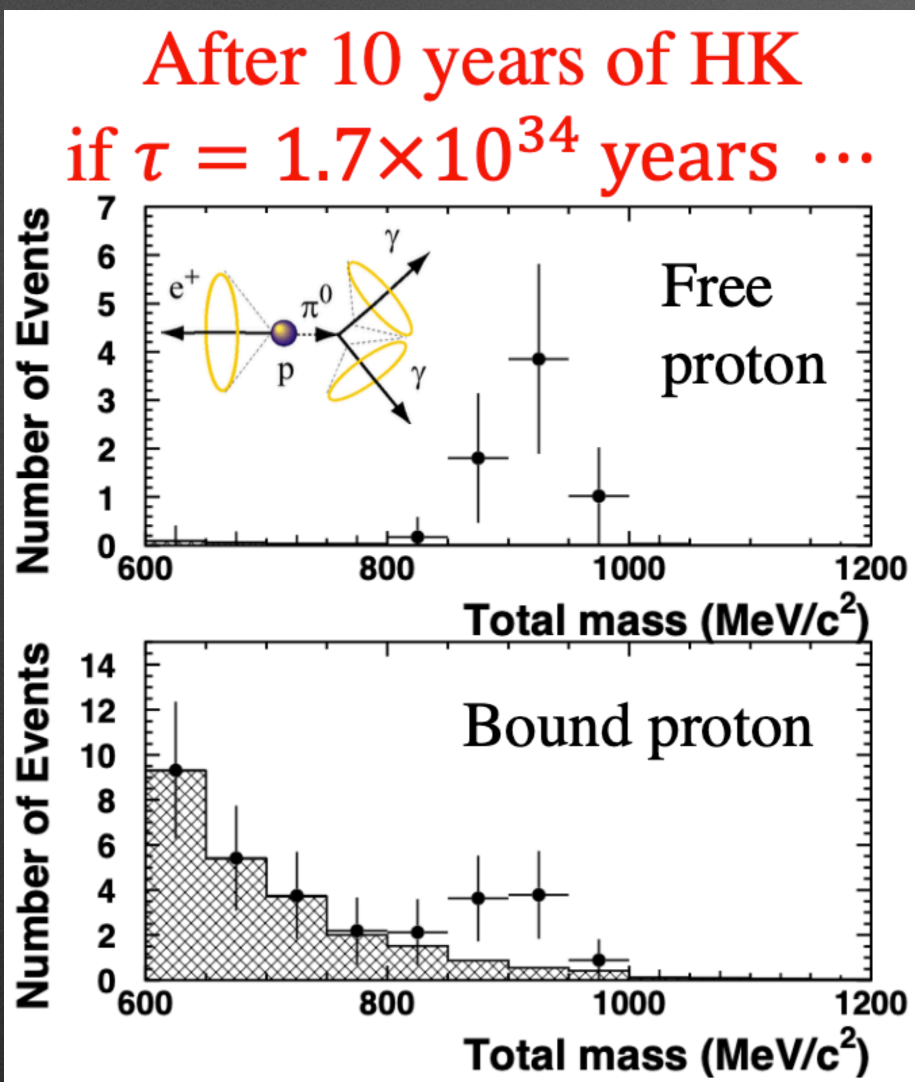
- Array of 19 3" PMTs
- Add 5k or 10k m-PMTs in HK (depending on funding) to improve vertex and energy resolution
- Synergies with KM3Net and with JUNO small PMTs

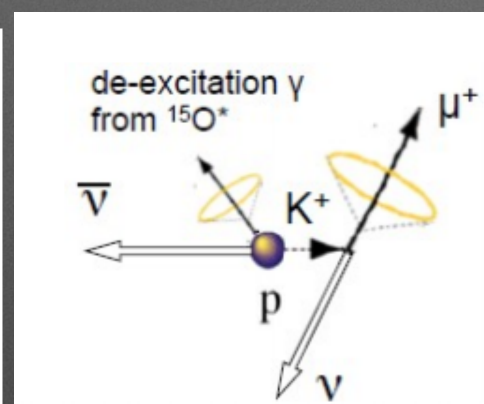
Proton-decay

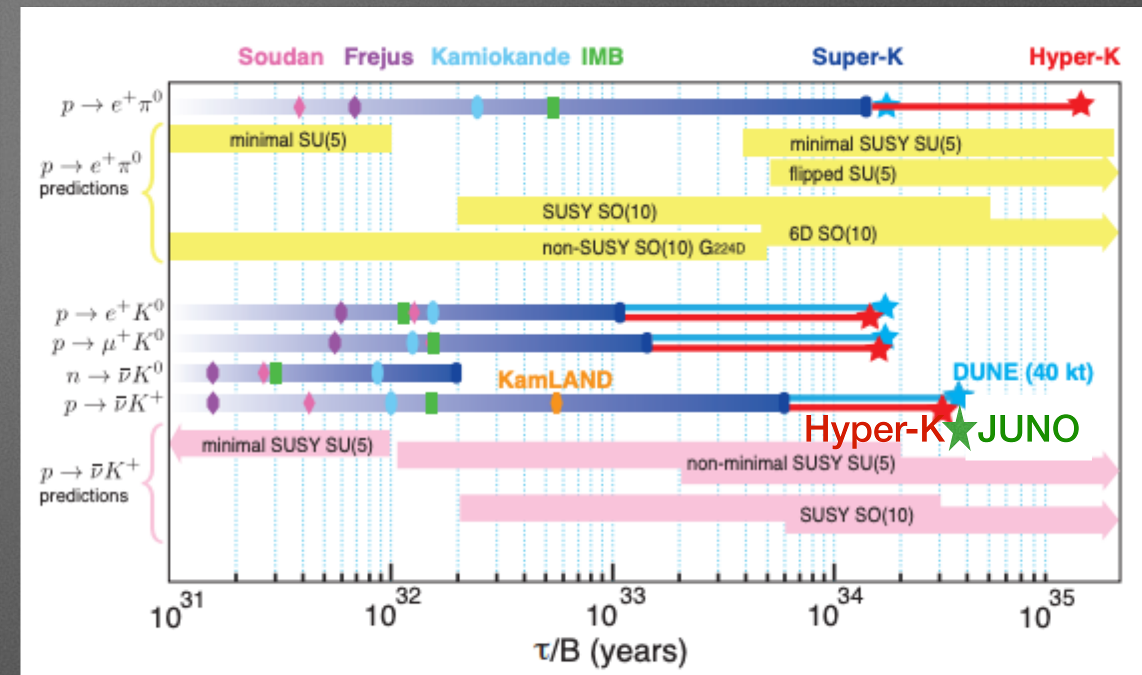
Sensitivity to many different modes
Surpass SK by ~1 order of magnitude in
the leading $p \rightarrow e^+ + \pi^0$

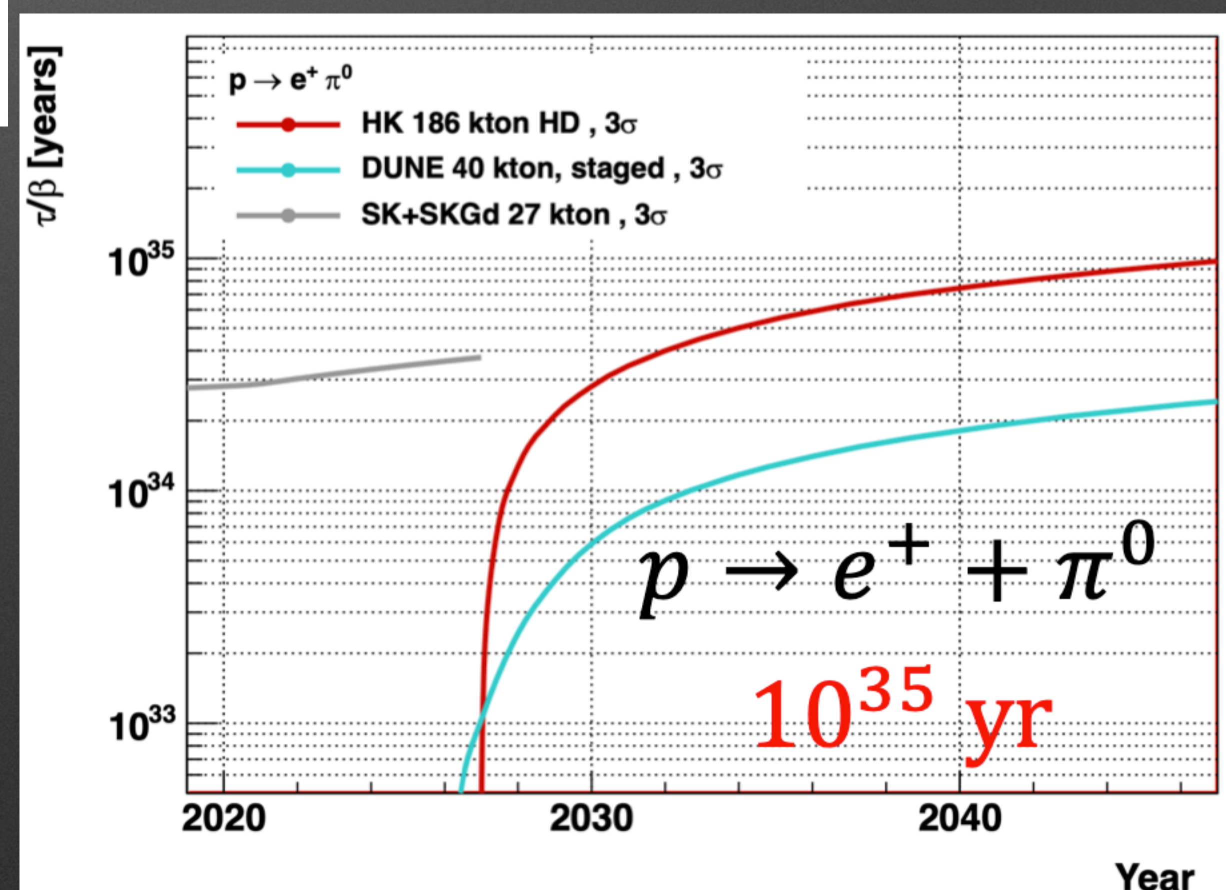
$p \rightarrow e^+ + \pi^0$

$p \rightarrow K^+ + \nu$

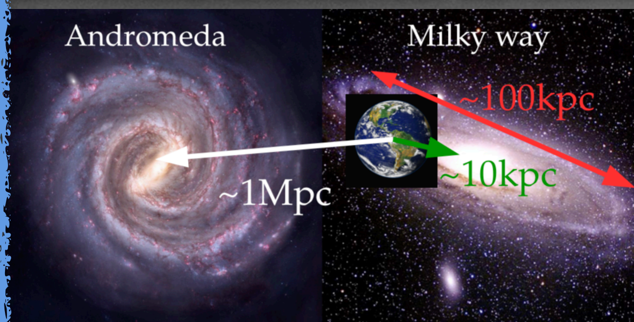


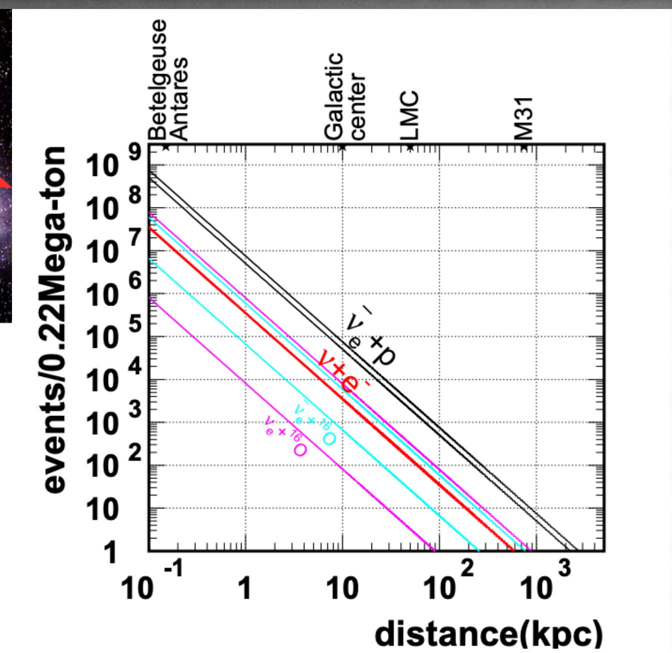




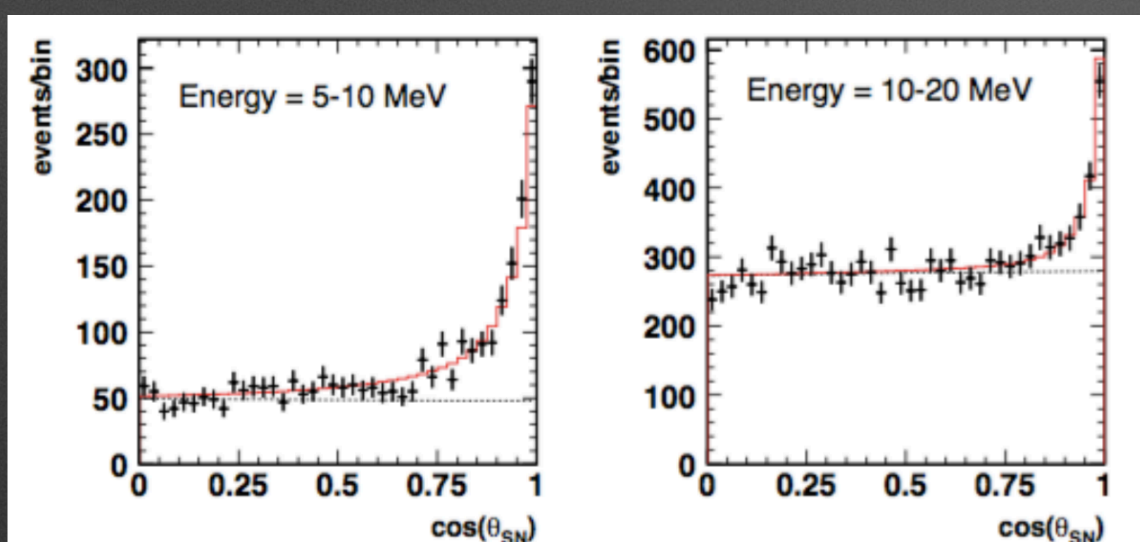


Supernovae neutrinos

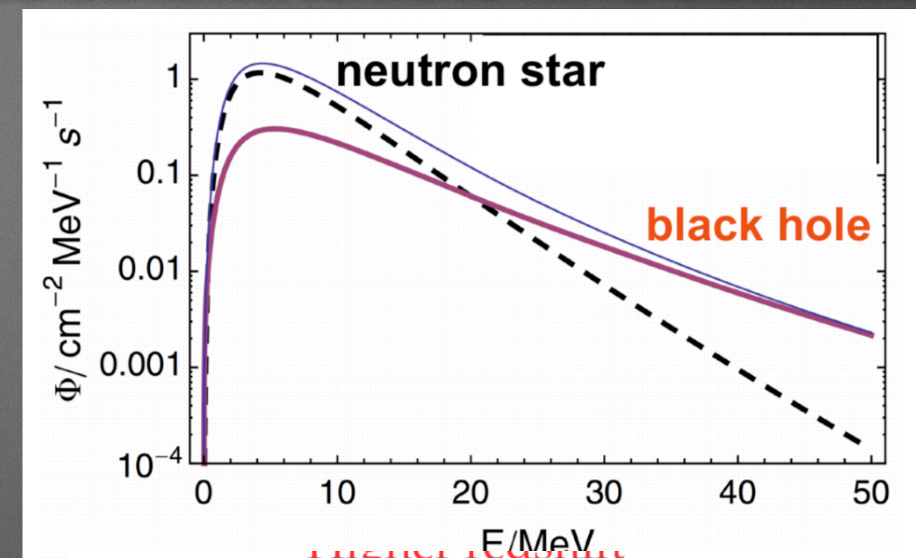


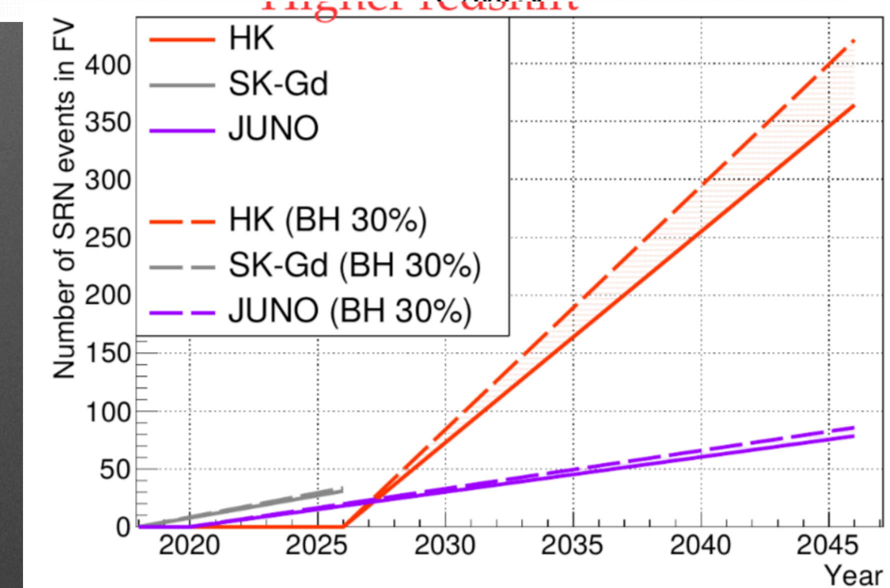


- IBD: huge statistics → SN model
- ES: directionality



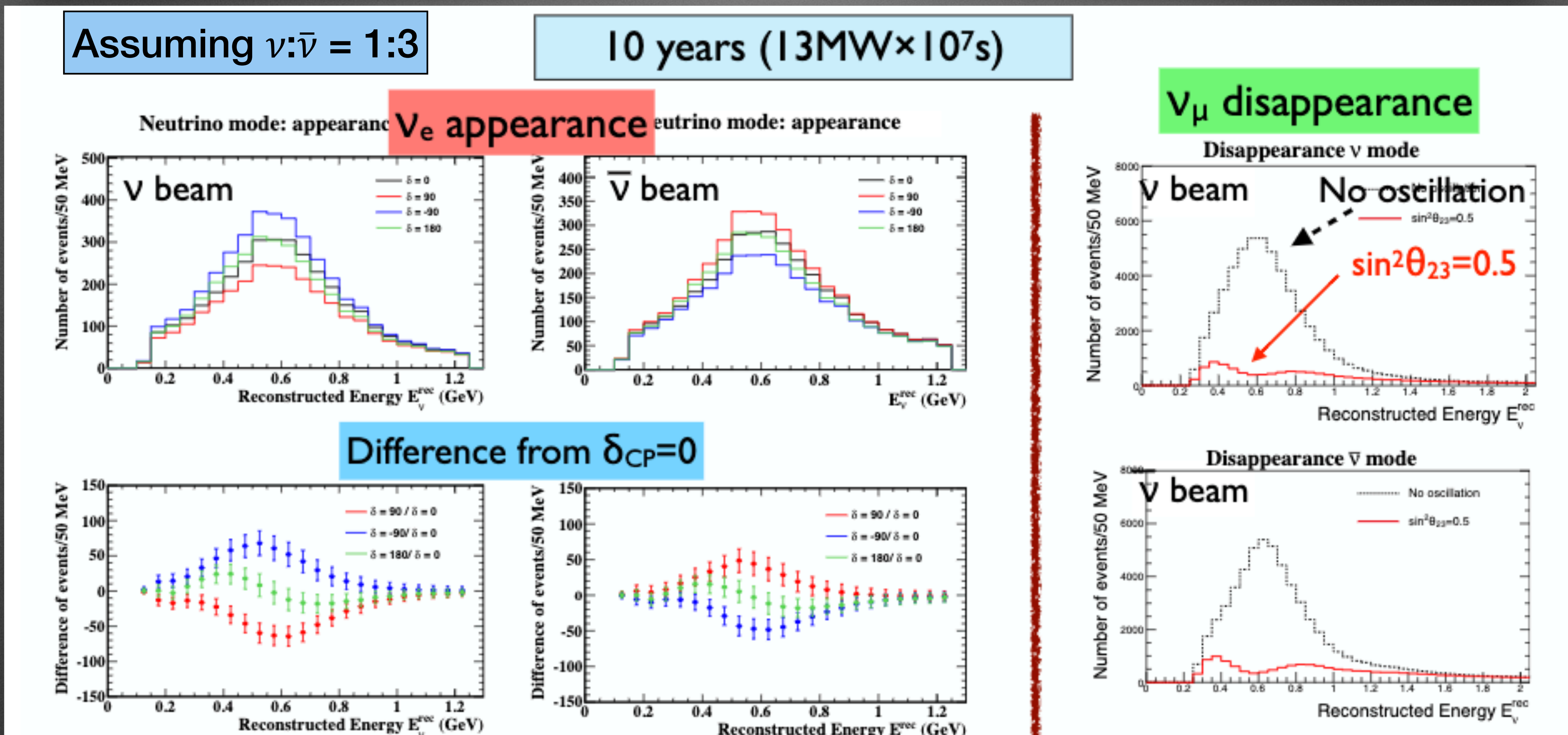
- ~80k IBD and ~3k ES for SN explosions in the galactic center
- Sensitive also to SN explosions in Andromeda





- 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

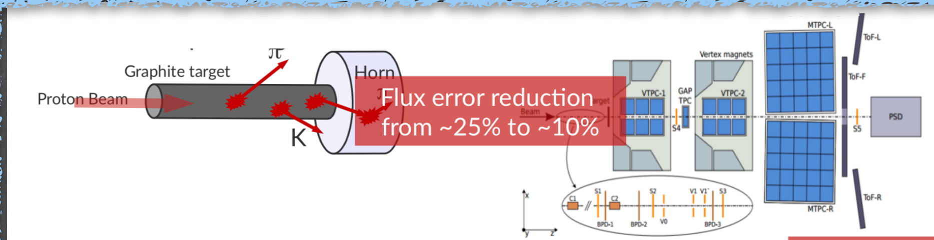
Long-baseline physics



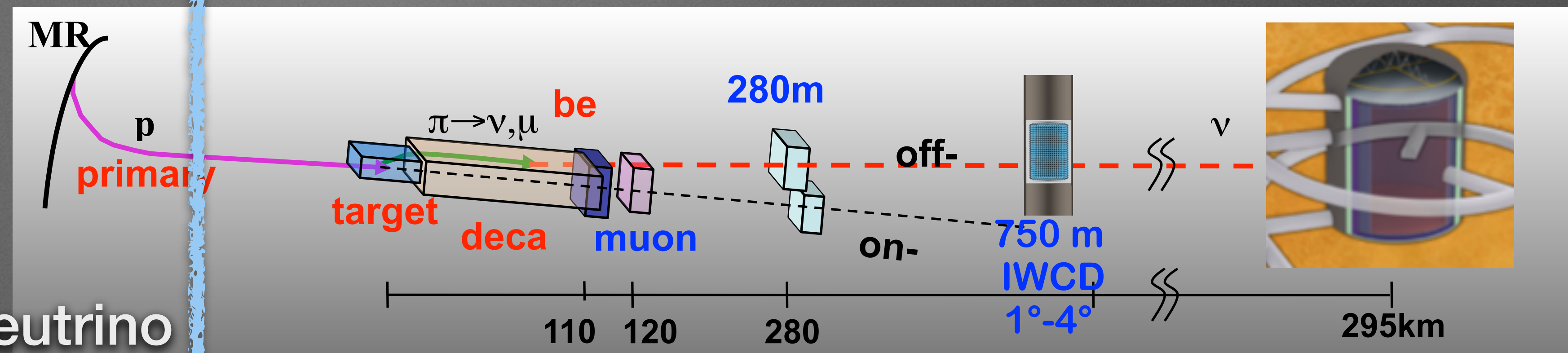
δCP=-π/2	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	BCG	Total
ν-mode	**1643**	15	400	2058
$\bar{\nu}$-mode	206	**1183**	517	1906

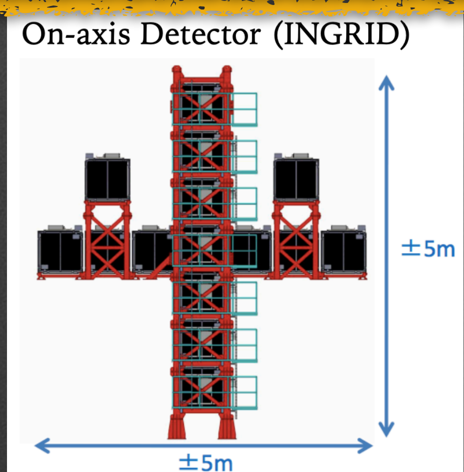
Huge statistics → sensitivity to CP violation
Need to control systematics!

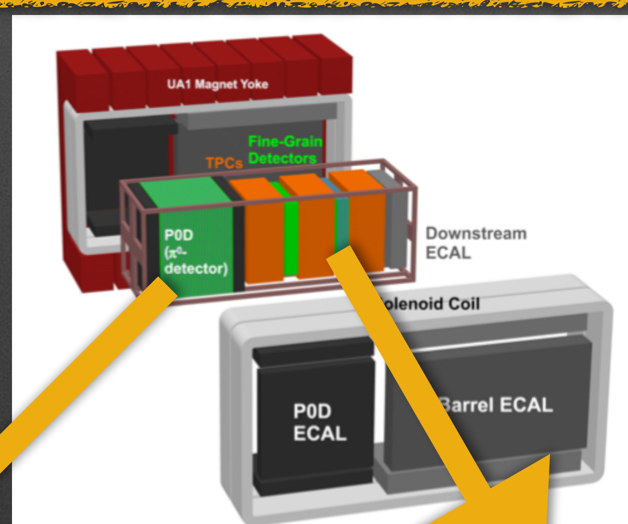
Systematics and Near Detectors

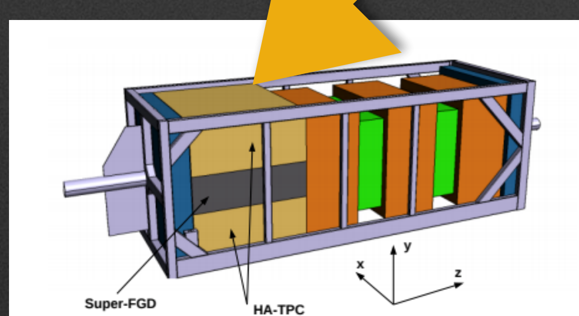


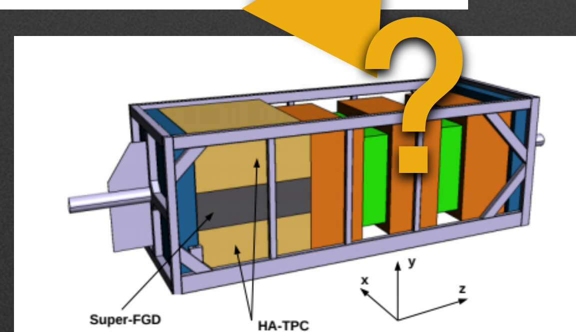
- NA61 hadron-production experiment @CERN
- T2K → uncertainties on the neutrino flux ~5% thanks to NA61
- New measurements planned for HK



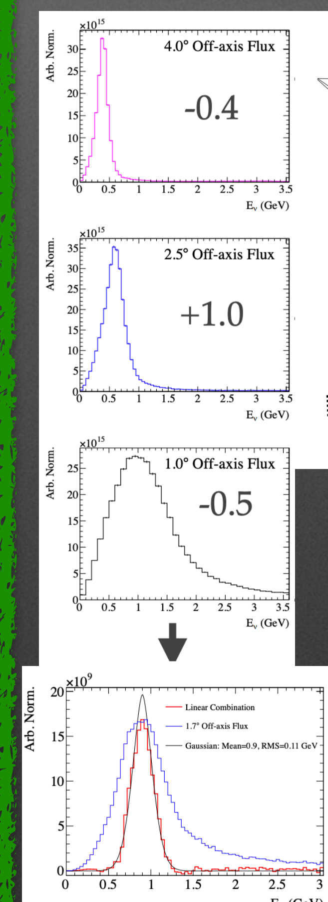


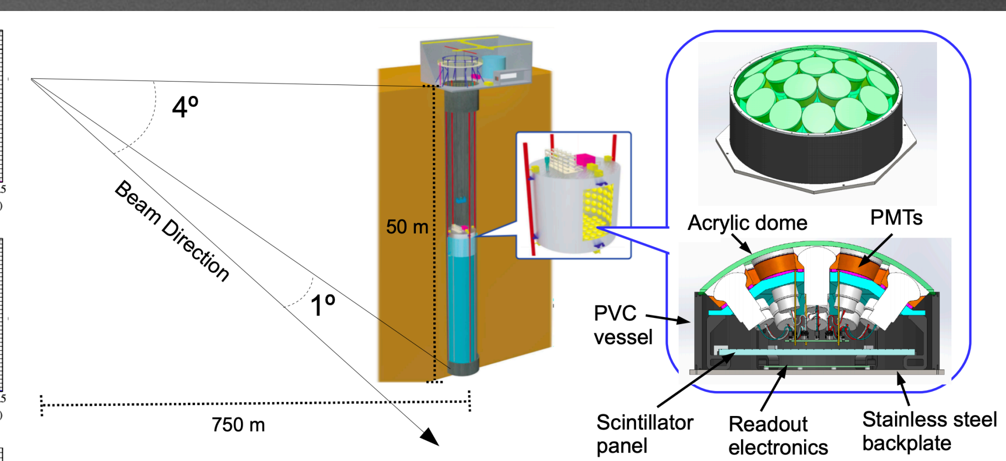






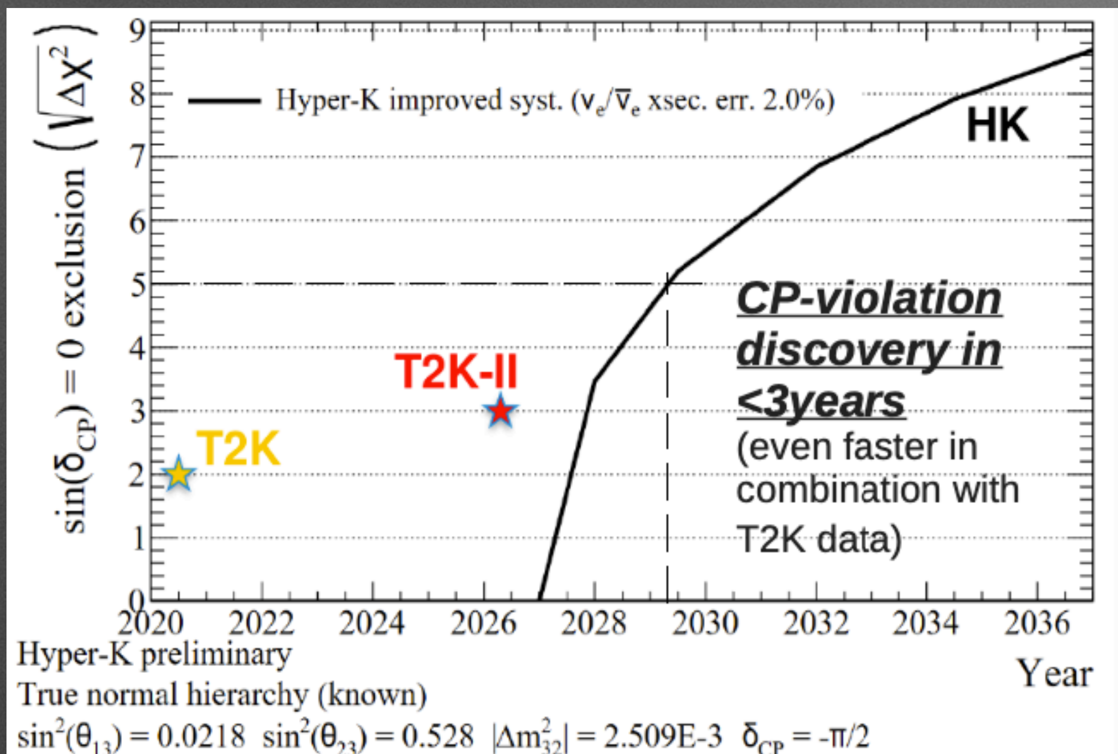
2021 2030?

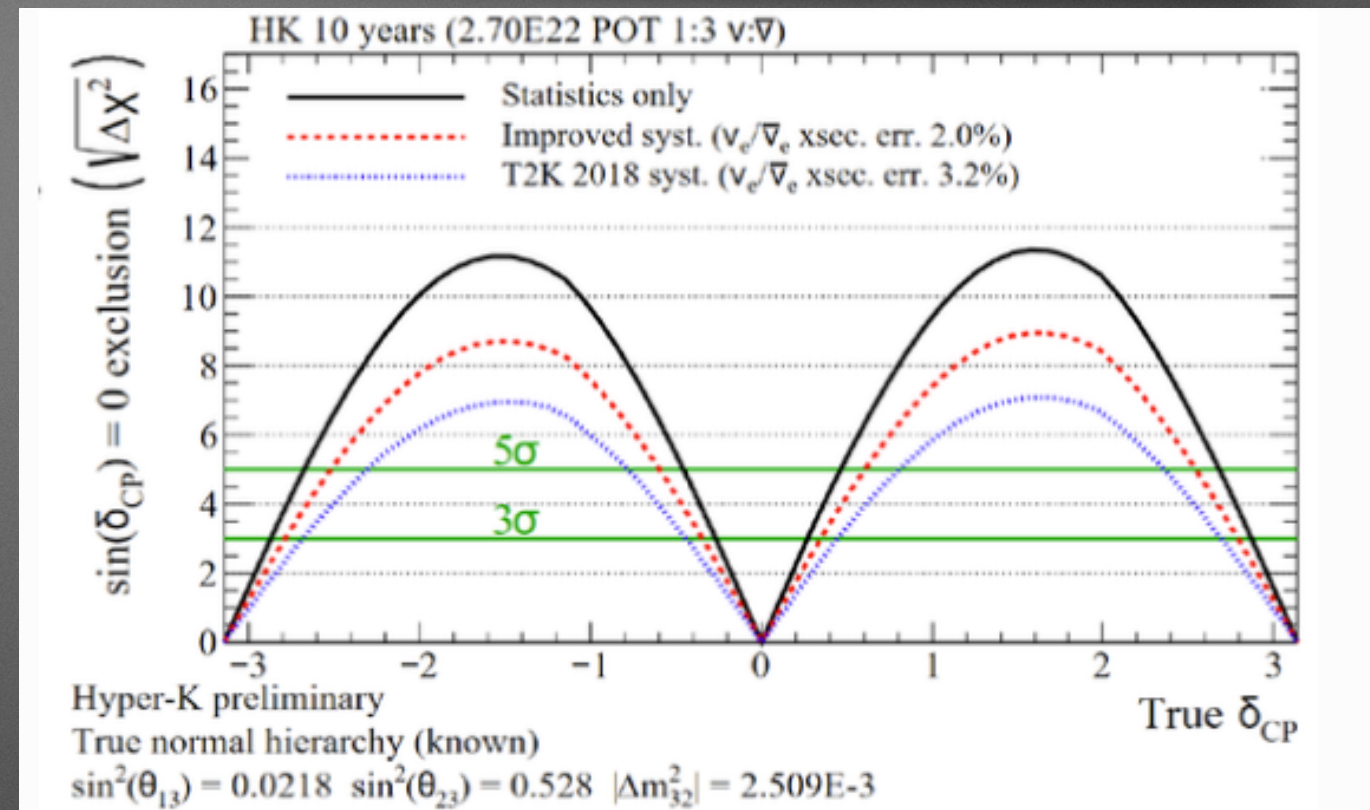




- Intermediate WC detector
- 1 kton mass
- Instrumented with ~500 multi-PMTs
- Movable position to scan different off-axis angles

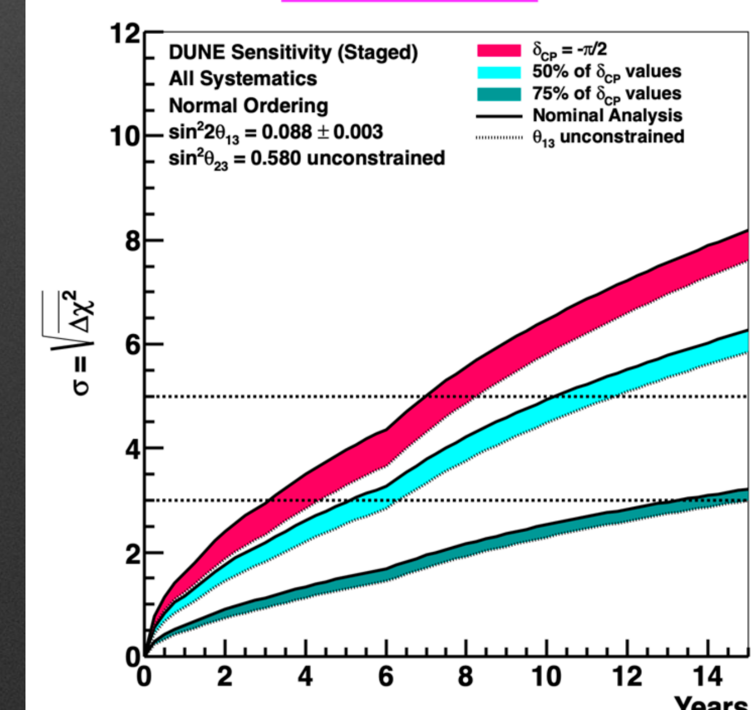
Hyper-K sensitivity



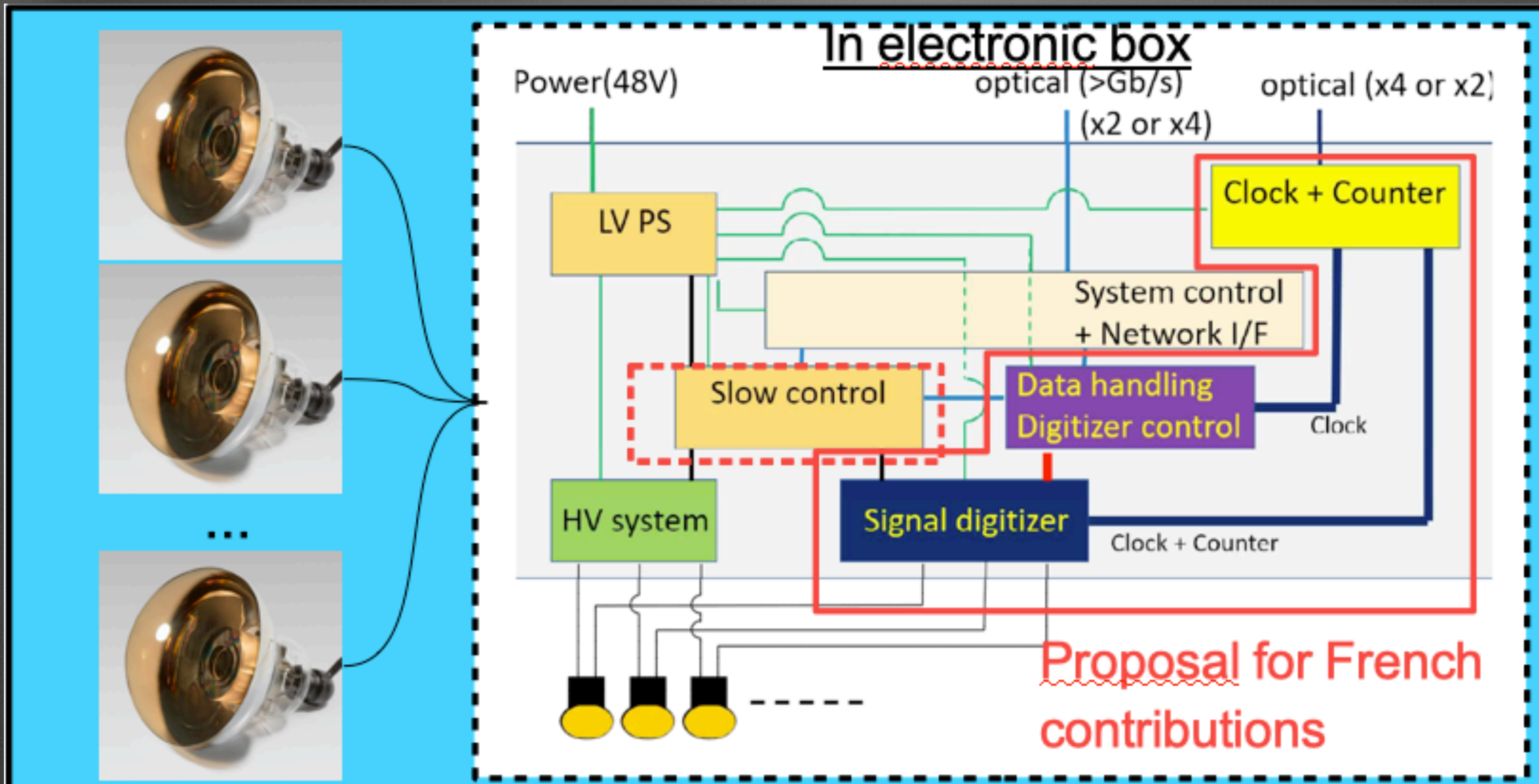


- Great discovery potential : 5σ observation of CP violation if δCP=-π/2 in <3y (4y if systematics are not improved with respect to today)
  - DUNE will require 8y for the same CP value
- 5σ sensitivity for 60% of the CP values assuming MH known
  - If MH not known it can be determined by HK by combining beam and atmospheric ν

DUNE



French contributions in HK



IRFU
LLR
LPNHE
OMEGA

- French groups working on the electronics for the large PMTs
  - Clock distribution and PMT synchrohnization
  - PMT readout (new chip being developed by OMEGA)
- ND280 Upgrade (and interest in further upgrades for HK)

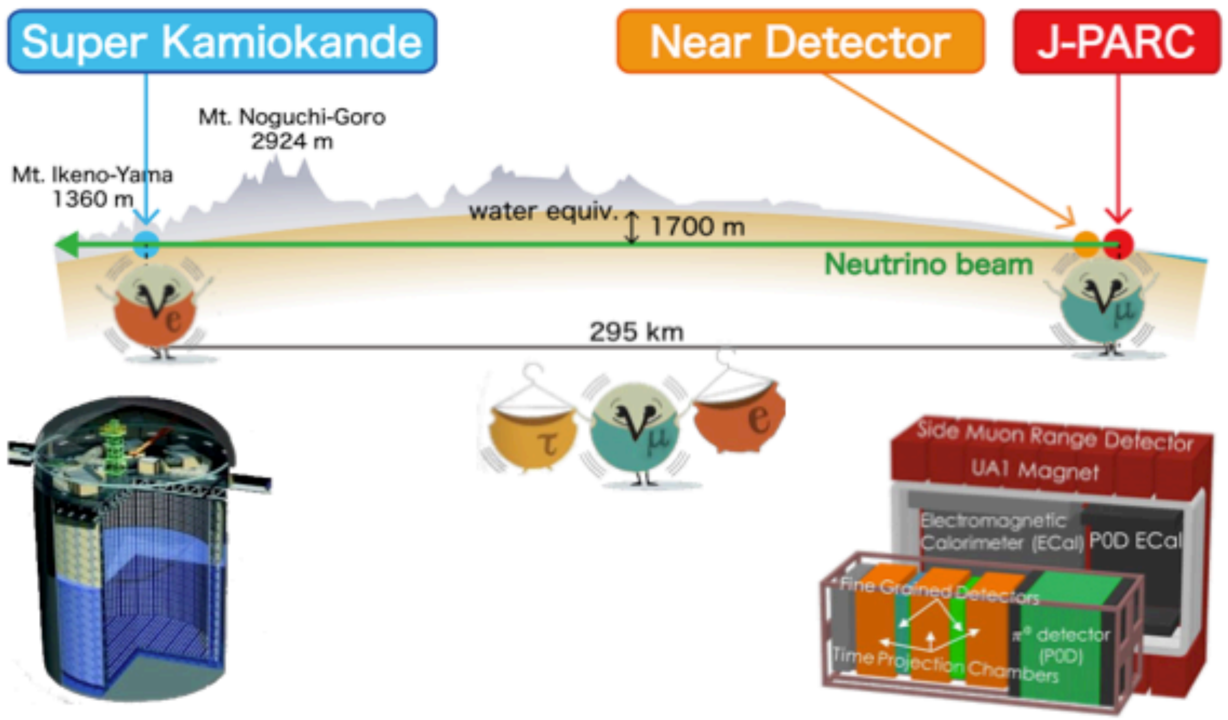
Conclusions

- Neutrino physics is an extremely active field of research
- Japan is engaged to host a seamless ~30y program of LBL experiments T2K → T2K-II → Hyper-K
  - Discovery of νe appearance
  - Most precise measurement of θ23 and Δm232
  - First hints of CP violation in the leptonic sector
- We hope to confirm these hints with T2K-II → 5σ discovery of CPV in the first years of Hyper-K
- Hyper-K will also be the most sensitive detector for rare events (proton decay) and an observatory of ν from different sources (Sun, SN, …)
  - Data taking in 2027, little risk of delays thanks to the use of a well known techonology
- French groups are fully involved in this programme
  - R&D for front-end electronics and time synchronization system
  - More contributions and new collaborators are welcome!

Back up Slides

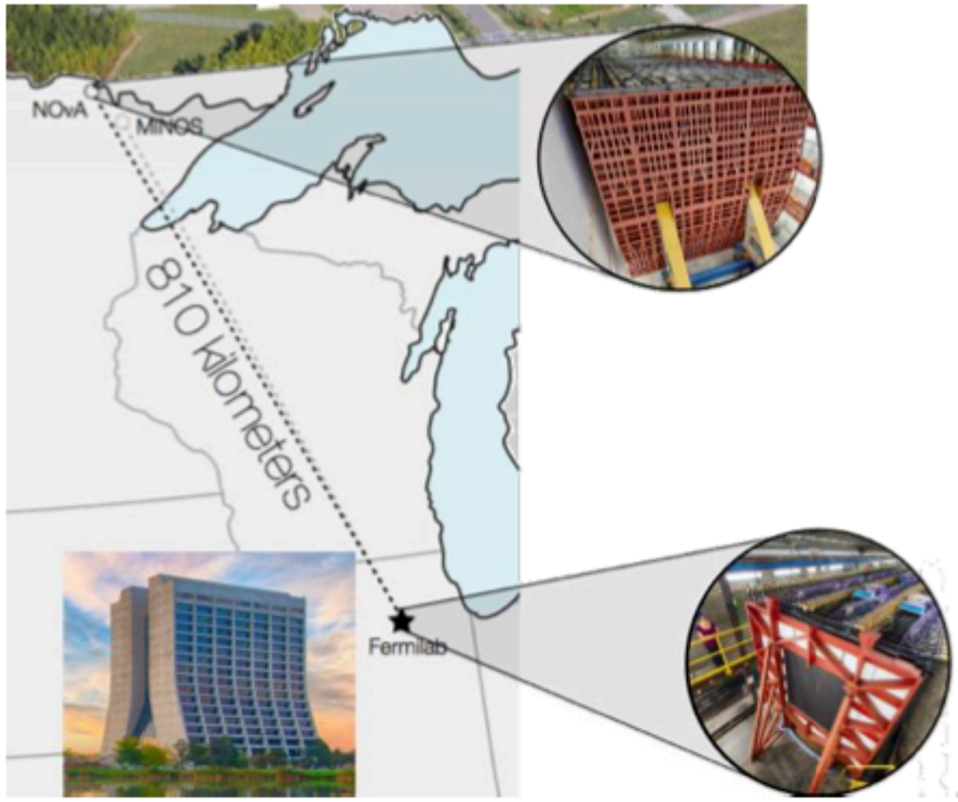
The Experiments

T2K



- Baseline: 295 km
- Peak E_ν: ~0.6 GeV (off-axis)
- Near detector: ND280 (~2 T C/O targets, TPC tracking, magnetised)
- Far detector: Super-K, 50 kT, Water-Cherenkov

NOvA

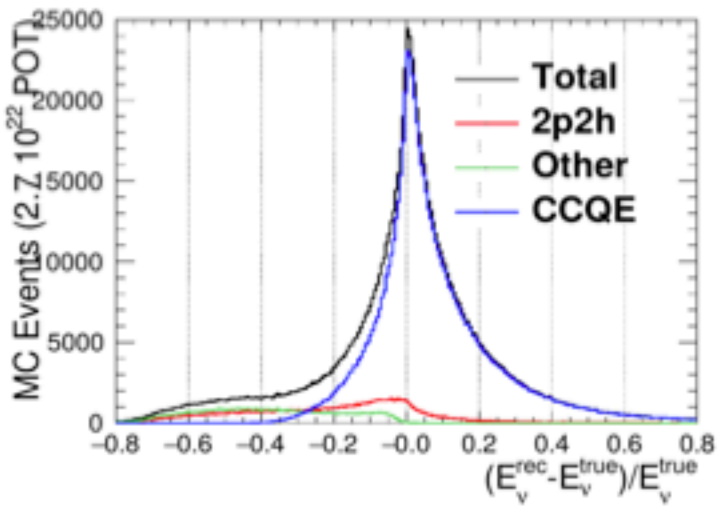


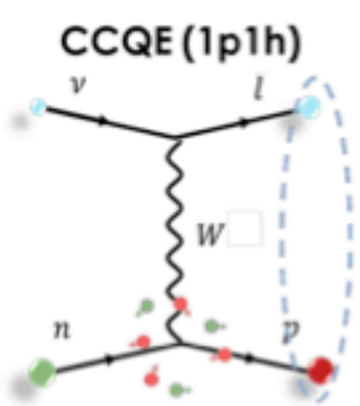
- Baseline: 810 km
- Peak E_ν: ~2 GeV (off-axis)
- Near detector: Scintillator tracker (300 T)
- Far detector: Scintillator tracker (14 kT)

T2K

- Identify neutrino interactions without any mesons observed in the final state
- Reconstruct E_ν assuming the interaction is CCQE on a stationary nucleon with fixed nuclear binding energy
  - Only use lepton kinematics to get E_ν!
- Bias from nuclear effects (e.g. Fermi motion) and from nonQE backgrounds (e.g. 2p2h, π abs. FSI)

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

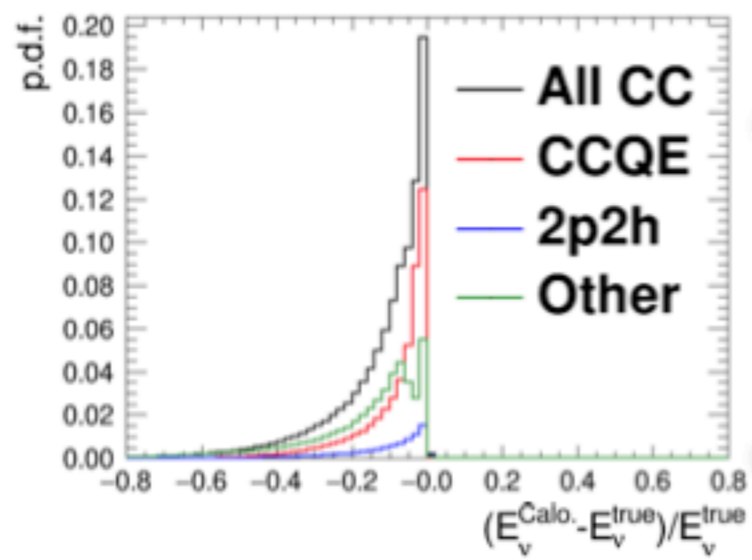


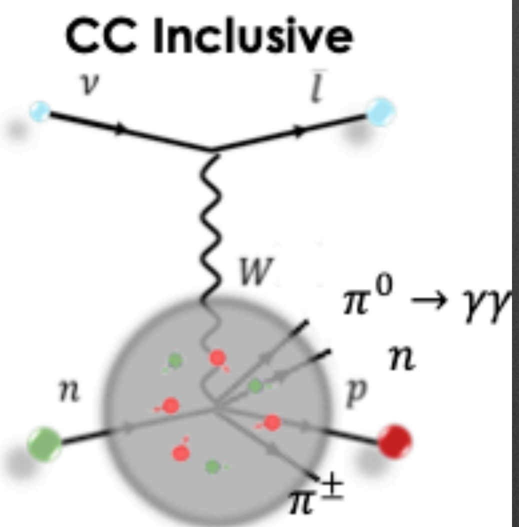


NOvA

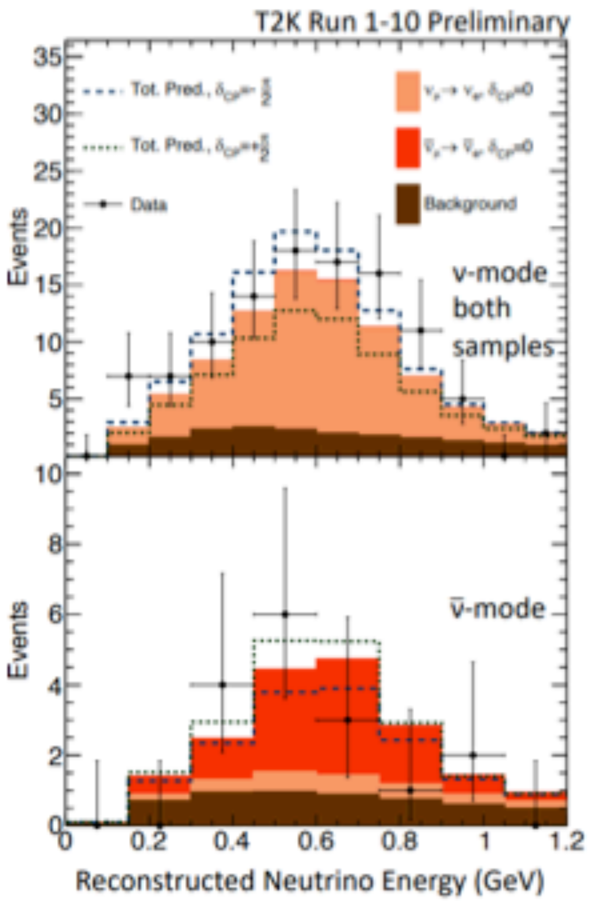
- Identify all CC interactions
- Reconstruct E_ν by summing the lepton and extra calorimetric energy deposits
  - Use all particles to get E_ν!
- Bias mostly from FSI and neutron multiplicity mis-modelling
  - Significantly harder to model

$$E_\nu^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$



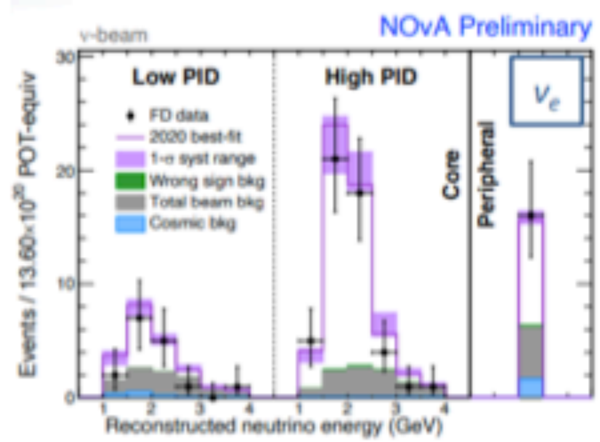


T2K

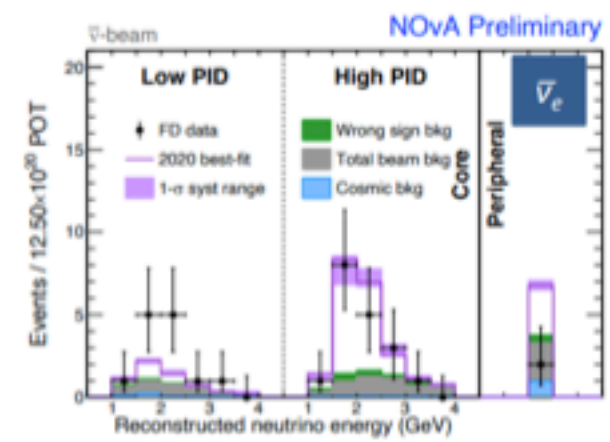


	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Data
FHC 1Re	97.62	82.44	67.56	82.74	94
RHC 1Re	16.69	18.96	20.90	18.63	16
FHC 1R ν_e CC1π^+	9.20	8.01	6.51	7.71	14

NOvA



Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28



Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

>4σ evidence of $\bar{\nu}_e$ appearance

T2K

Note: these show the uncertainty on the event rate, this is not the same as uncertainty on the oscillation parameters (which isn't easy to make for T2K)

After ND constraint

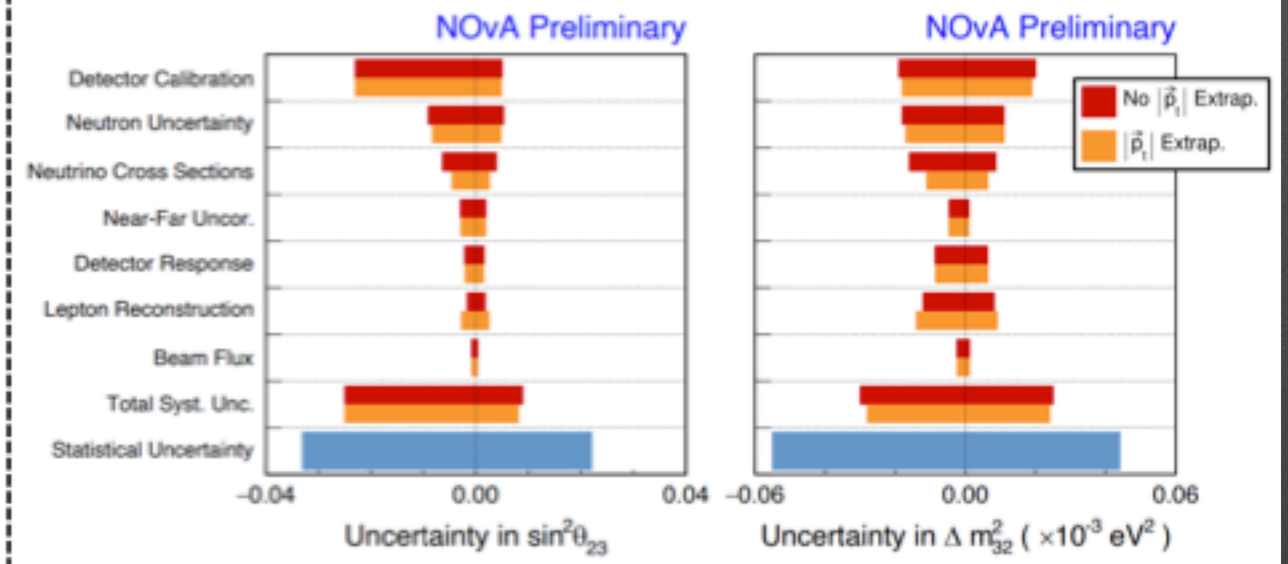
Error source	$1R\mu$ FHC	$1R\mu$ RHC	$1Re$ FHC	$1Re$ RHC	$1Re$ FHC $CC1\pi^+$	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
2p2h Edep	0.4	0.4	0.2	0.2	0.0	0.2
BG_A^{RES} low-p_π	0.4	2.5	0.1	2.2	0.1	2.1
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.7	3.0
NC γ	0.0	0.0	1.4	2.4	0.0	1.0
NC Other	0.2	0.2	0.2	0.4	0.8	0.2
SK	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

Large reduction of previously dominant binding energy uncertainty thanks to updated nuclear model

Before ND constraint

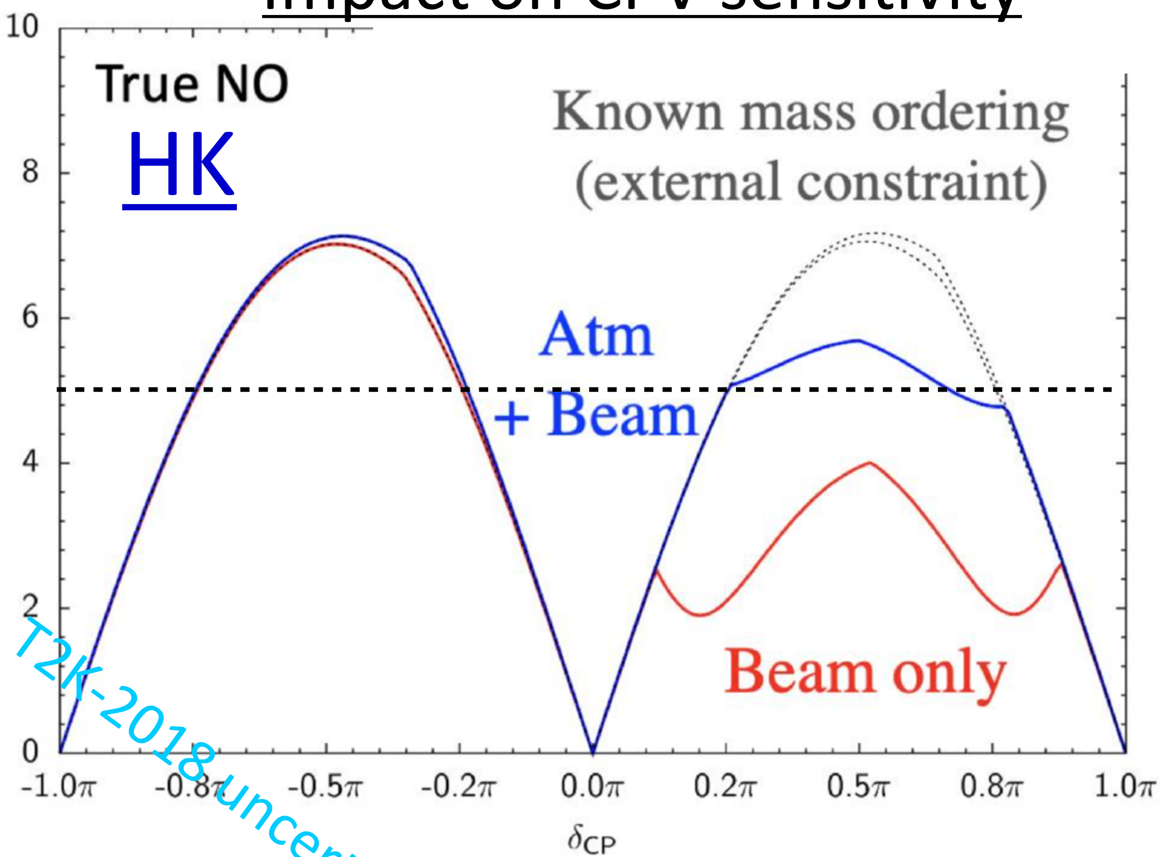
Error source	$1R\mu$ FHC	$1R\mu$ RHC	$1Re$ FHC	$1Re$ RHC	$1Re$ FHC $CC1\pi^+$	FHC/RHC
Flux	5.1%	4.7%	4.8%	4.7%	4.9%	2.7%
Cross-section (all)	10.1%	10.1%	11.9%	10.3%	12.0%	10.4%
SK+SI+PN	2.9%	2.5%	3.3%	4.4%	13.4%	1.4%
Total	11.1%	11.3%	13.0%	12.1%	18.7%	10.7%

NOvA

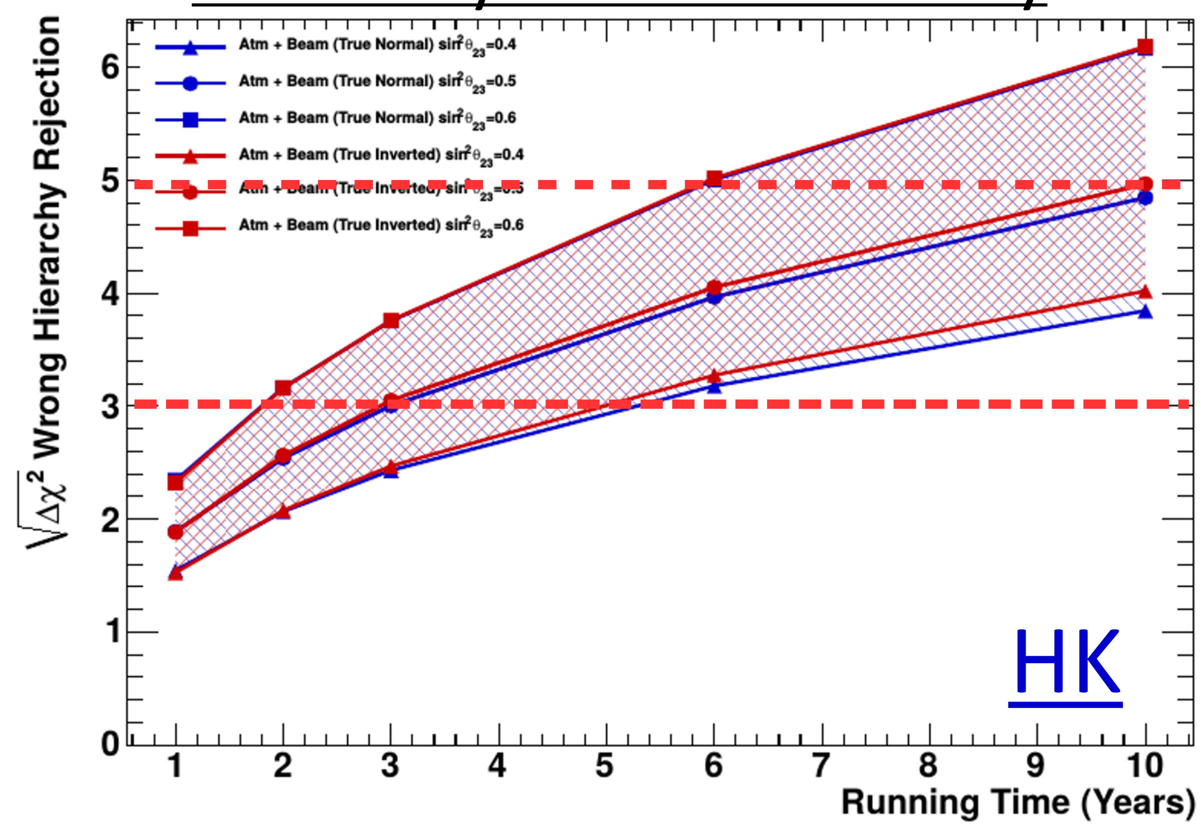


Combination of atmospheric + beam ν

Impact on CPV sensitivity



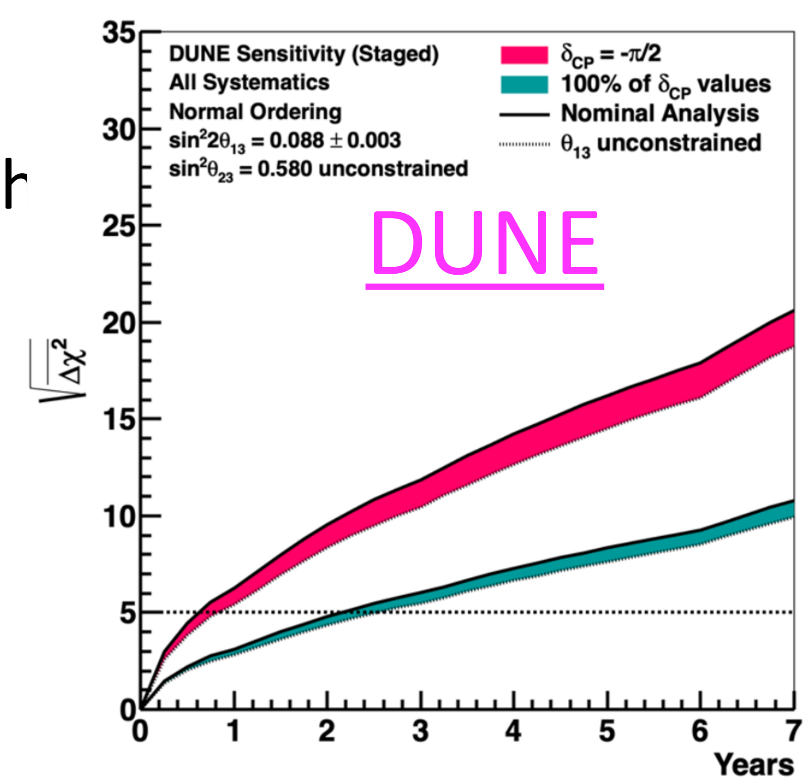
Sensitivity to mass hierarchy



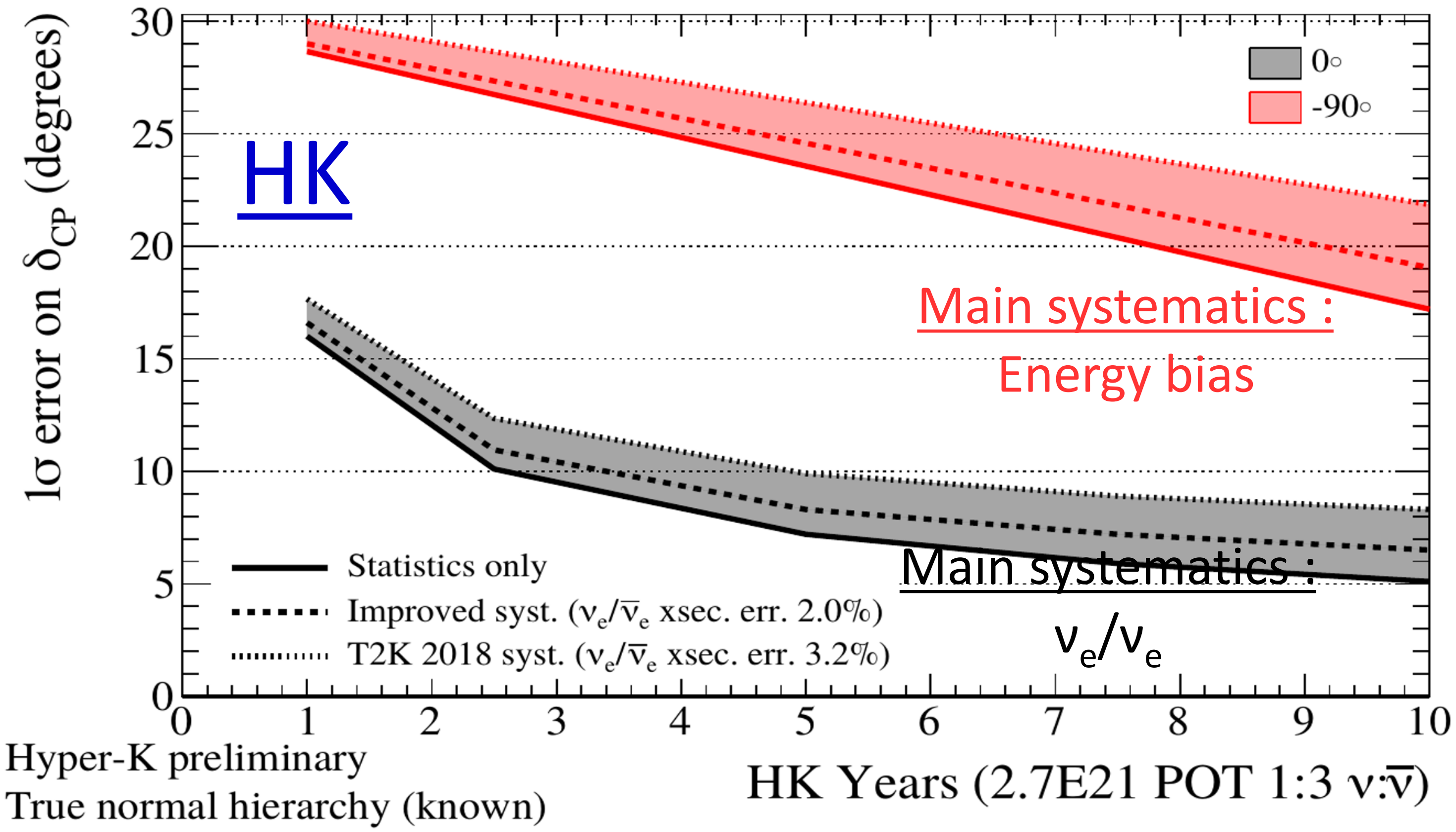
- Even if MH is not known when HK starts

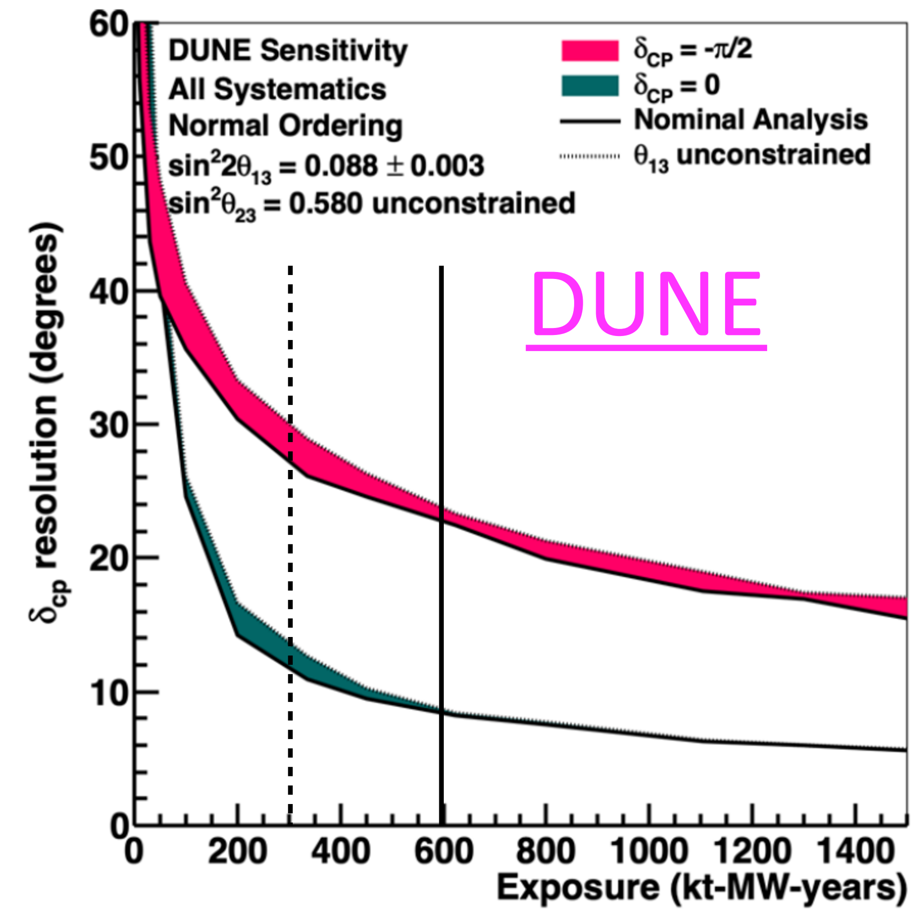
→ Sensitivity to CPV is little affected if we add atmosph

- MH would be determined by :
- → HK after ≥ 6-10 years via atmospheric.
- → DUNE : after 1-2 years.



Precision of δ_{CP} measurement





	5 years HK & DUNE	10 years HK & DUNE
CP conserved $\delta_{CP} = 0$	8° & 13°	6° & 9°
δ_{CP} = -π/2	25° & 29°	19° & 24°

- HK sensitivity δ_{CP} highly improved with syst. error updates.

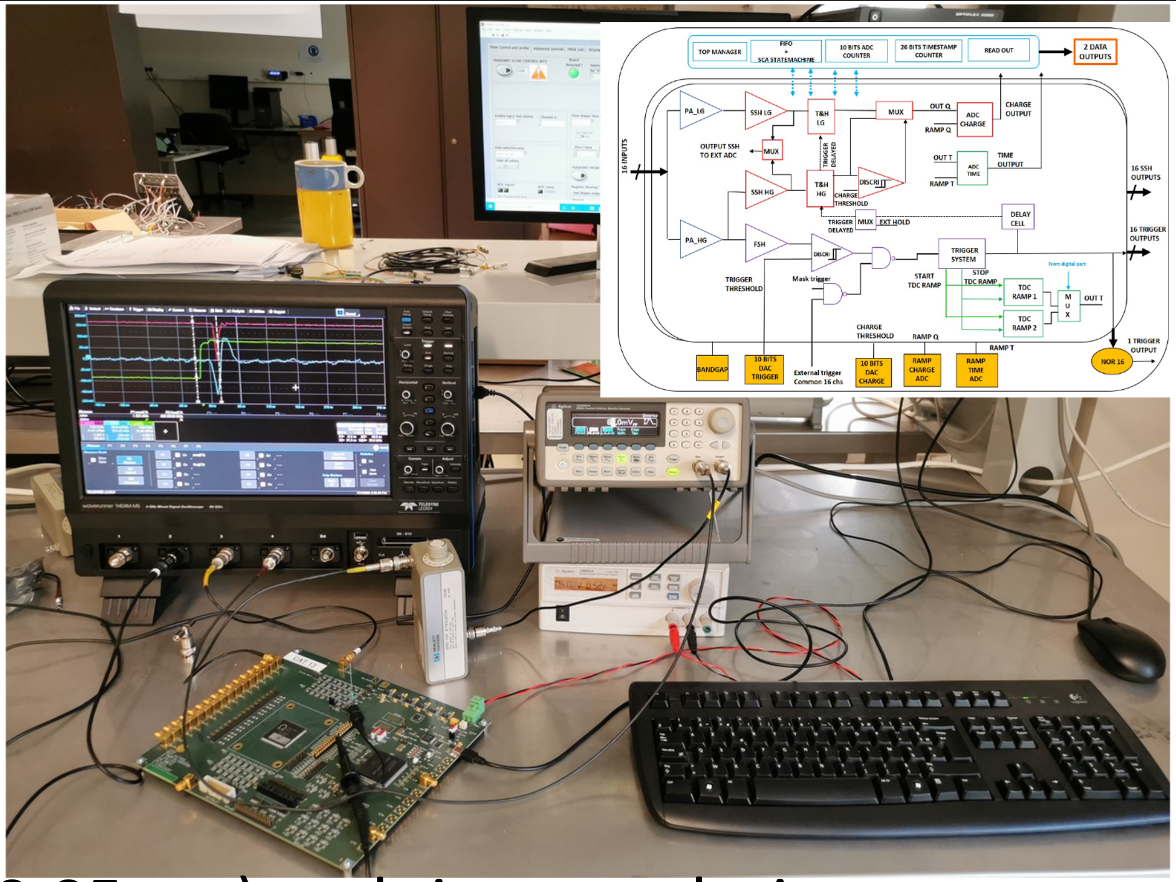
→ World-leading sensitivity together with DUNE full config.

Front-end development

- <u>Propose a new Front-end for HK</u>

→ Start from existing Ω CATIROC.

- <u>Installed test bench at LLR in July.</u>



<u>Charge linearity</u>

High-gain
Low-gain

- Charge (<0.05 p.e) and time resolution (<300ps) comply w/ HK requirements.

<u>Time linearity</u>

High-gain
Low-gain

- <u>Major issues :</u>

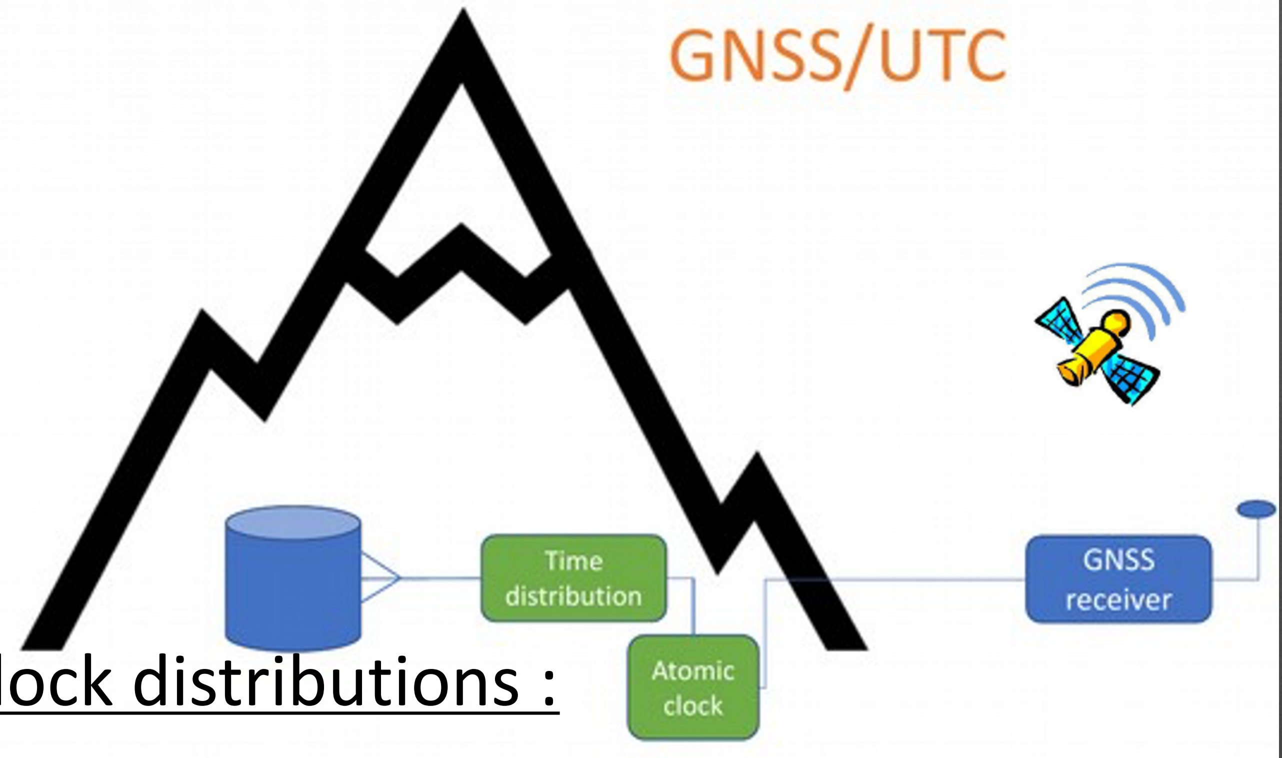
1. Chip deadtime : 3μs → 9μs
2. Charge dynamic range smaller by factor 5 : developed for 3'' PMTs operating at 10^6 gain

→ HK PMT will likely operate at gain = 10^7 .

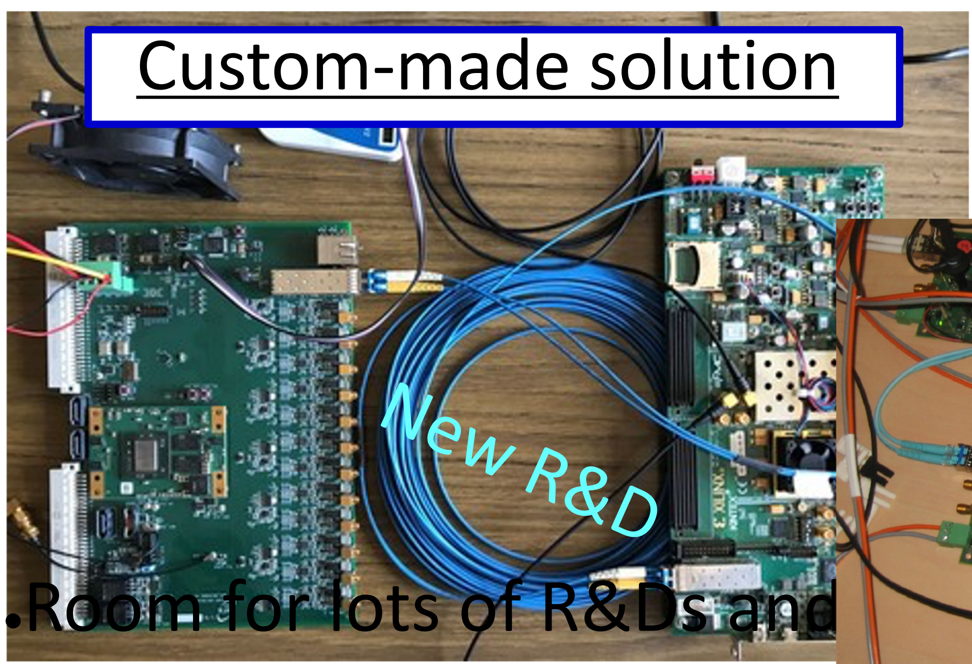
The GNSS and clock distribution system

- <u>France is working both on :</u>

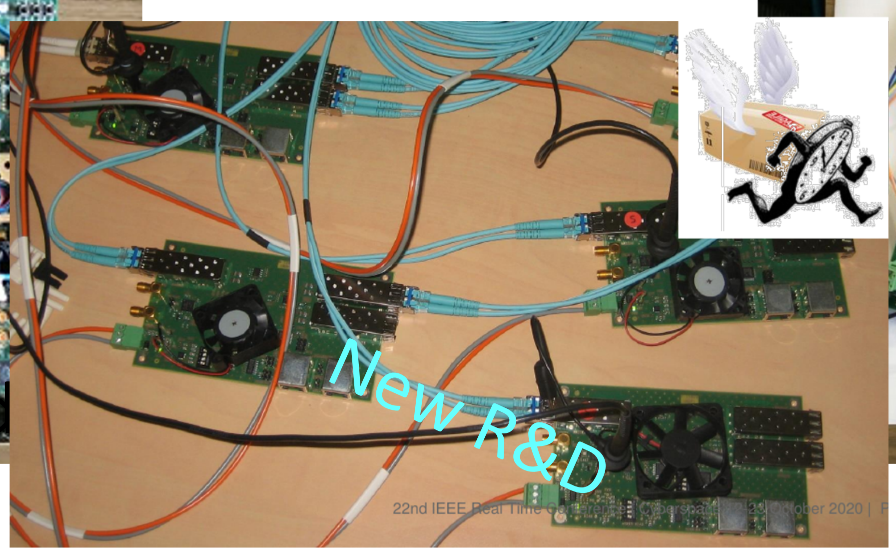
<u>1. GNSS system :</u> Provides local time to synchronize w beam / other detectors.
→ Is being developed with SYRTE.
<u>2. Full clock distribution chain</u> (down to PMT Front-End) → Focus of today.

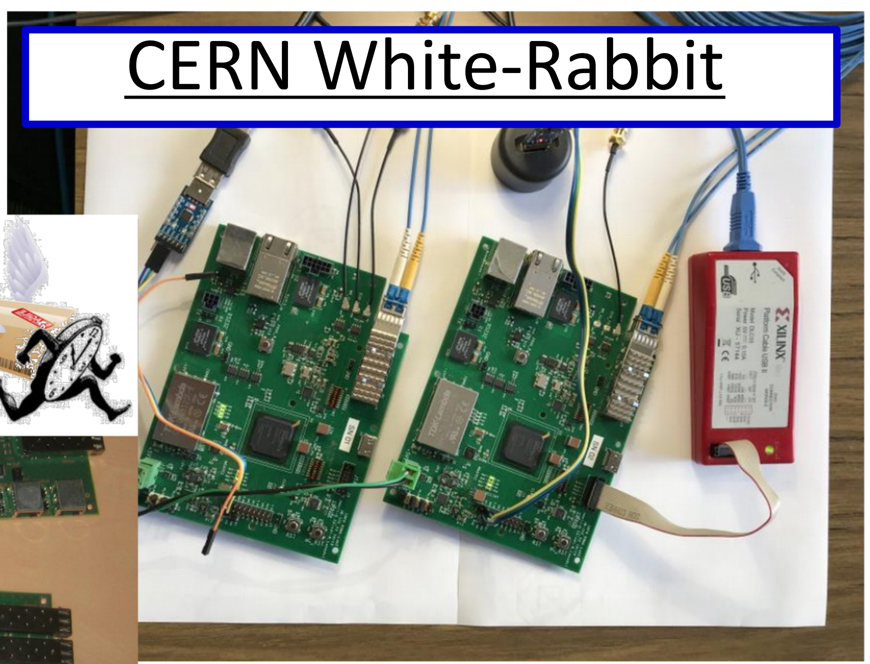


- <u>Several options are being studied for clock distributions :</u>



Clock-centric scheme

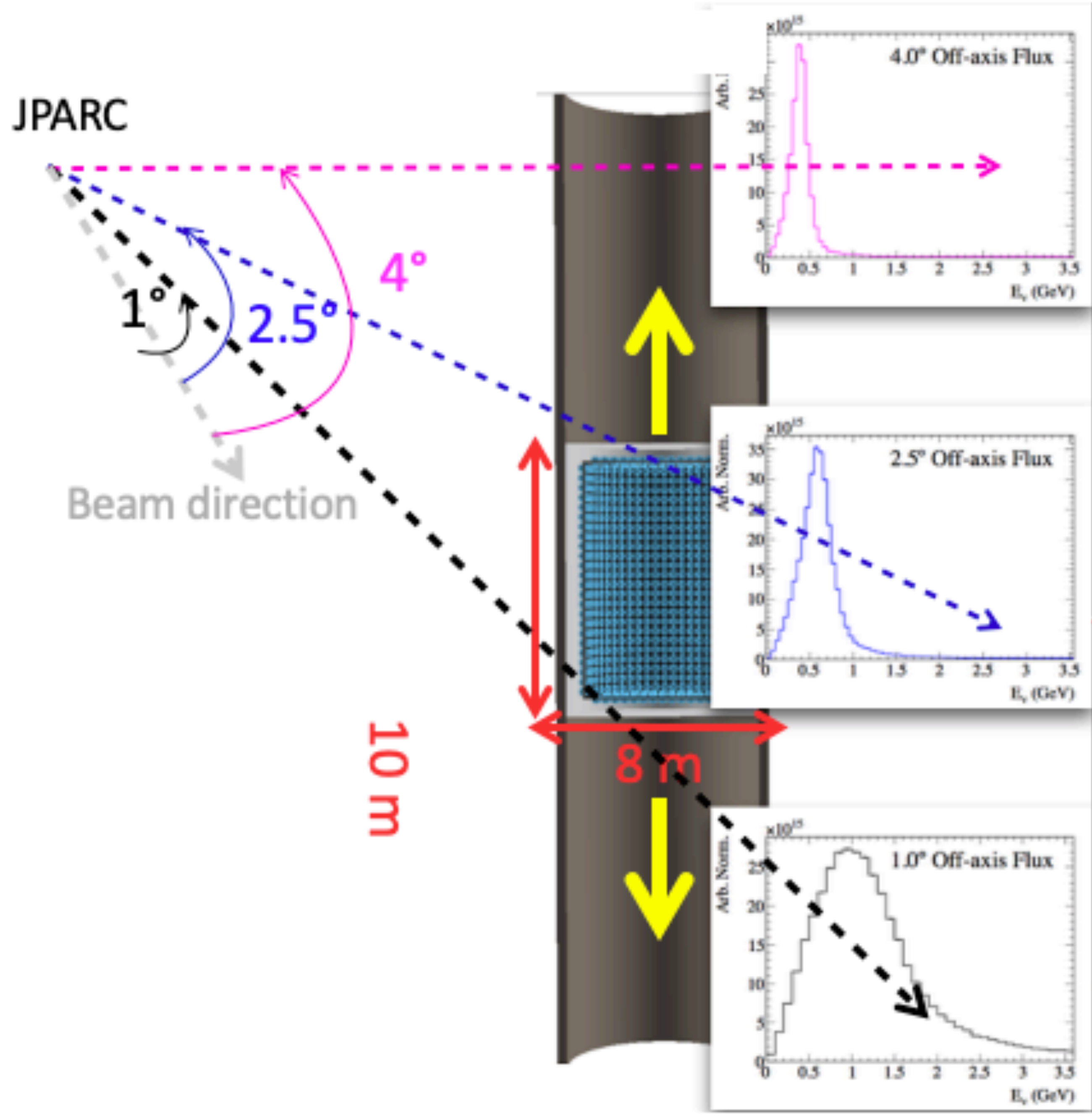




- Room for lots of R&Ds and

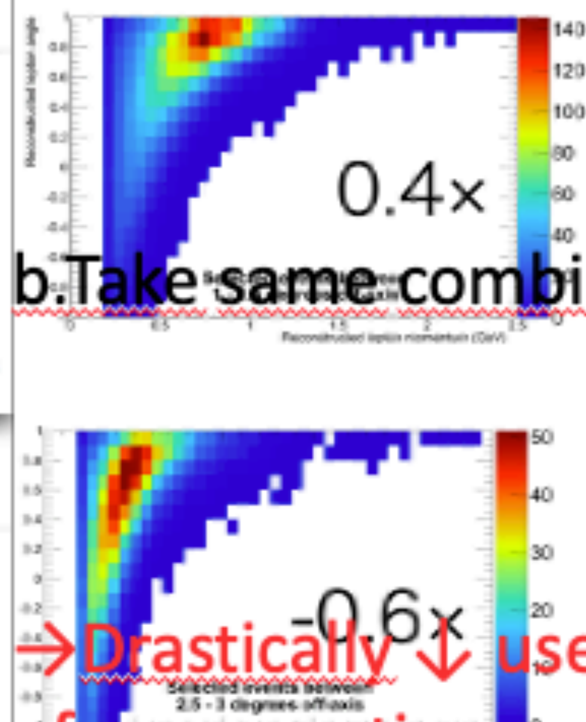
Intermediate Water Cherenkov Detector

- 2.b. New Intermediate Water Cherenkov Detector located @750m - 2km:



1. Same technology far / near.

2. a. HK flux = linear combination of different off-axis angles.



b. Take same combination of

→ Drastically ↓ use (so systematics) of cross-section models !

3. WC => Excellent ν_e / ν_μ separation => $(\nu_e / \nu_\mu) / (\nu_e / \nu_\mu)$.

→ ND280&IWCD necessary & complementary to reach systematics ≤ 3 %.

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