Long Baseline Neutrino Oscillation Lecture 2

TRISEP 2024
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Blair Jamieson
bl.jamieson@uwinnipeg.ca

THE UNIVERSITY OF WINNIPEG

Lecture 2 Outline

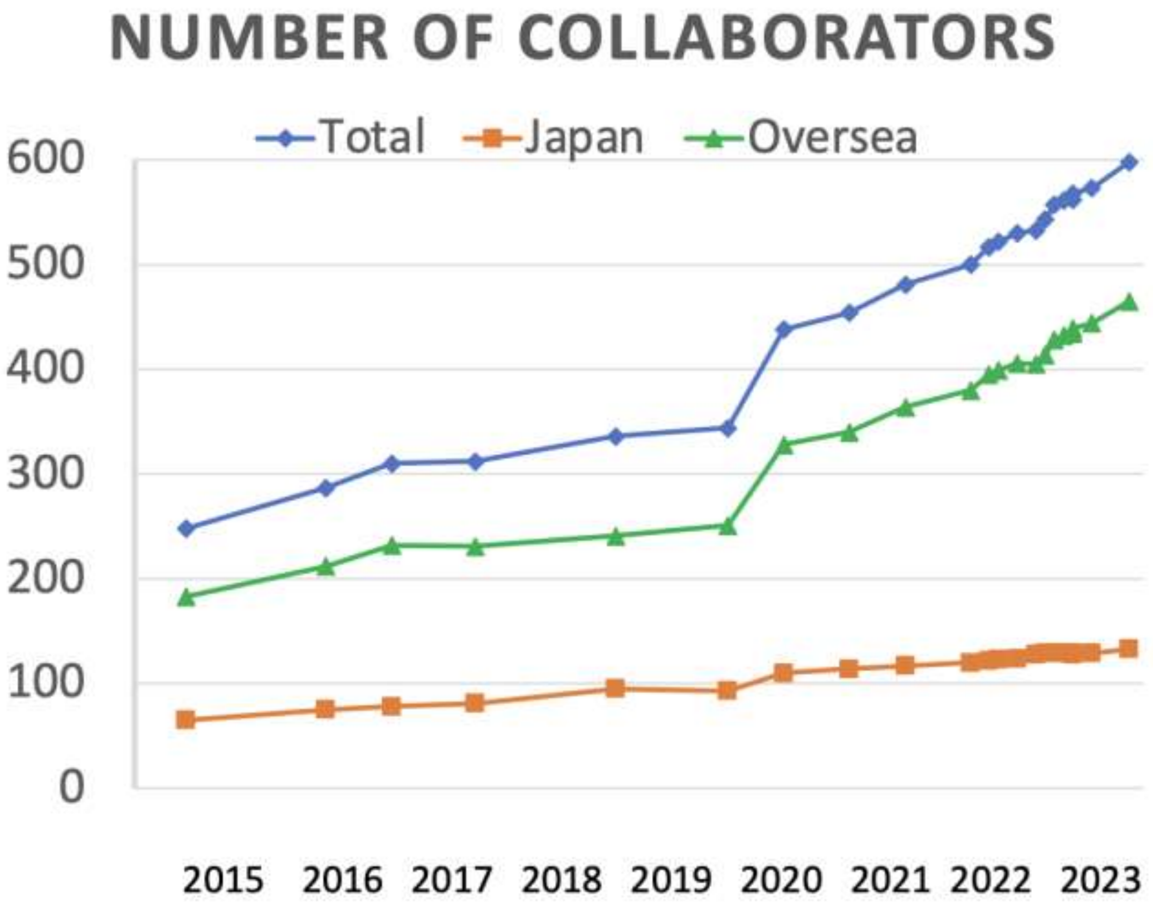
Mar. 19, 2024 excavation to 20 m depth of Hyper-Kamiokande cavern

- Hyper-Kamiokande experiment
  - Physics goals
  - systematic errors at the 1% level
- Beam and flux prediction
  - a bit about NA61
  - a bit about Emphatic
  - The WCTE experiment
- Near detector measurements
  - a little about the neutrino interactions
- Intermediate water Chernkov Detector
  - the PRISM method
- Measurement of electron neutrino cross section
- Other far detector measurement
  - atmospheric neutrinos
  - proton decay
- Other future long baseline measurements
  - DUNE
  - JUNO, etc

Acknowledgements

I want to thank all my collaborators, and physics colleagues from whom many of this slides have been acquired for use in the long baseline neutrino oscillation lectures.

International Hyper-K collaboration and a new UTokyo building at Kamioka



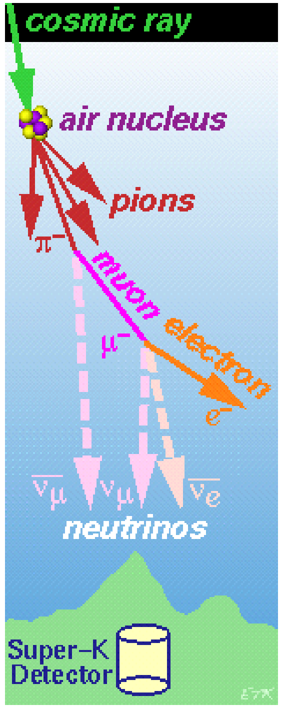
Hyper-K meeting @Kamioka Oct. 2023

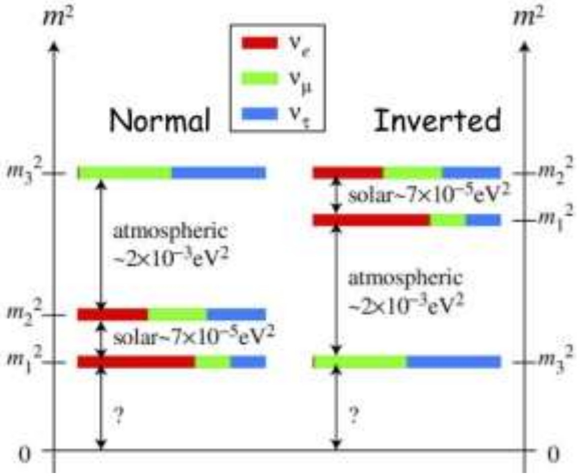
22 countries, 104 institutes, 583 members as of April 1, 2024

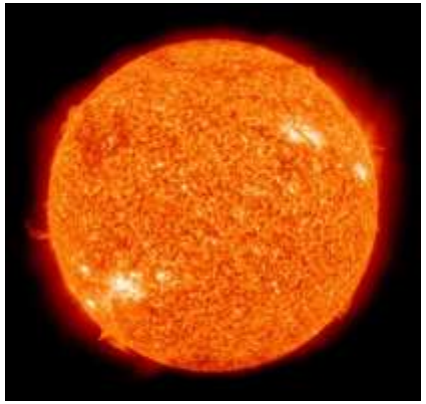
Still linearly increasing

Physics Goals for Hyper-K

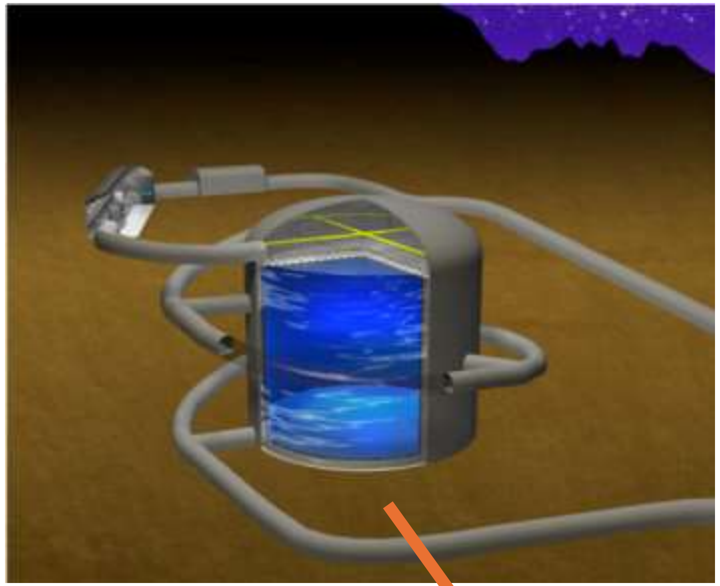
- Search for physics beyond the standard model:
  - CPV in lepton sector
  - Neutrino mass hierarchy
  - Precision oscillation parameter measurement
  - Search for nucleon decay
- Astrophysics Observatory:
  - Precision measurement of solar ν
  - High statistics supernova burst ν
  - Detection of supernova relic ν



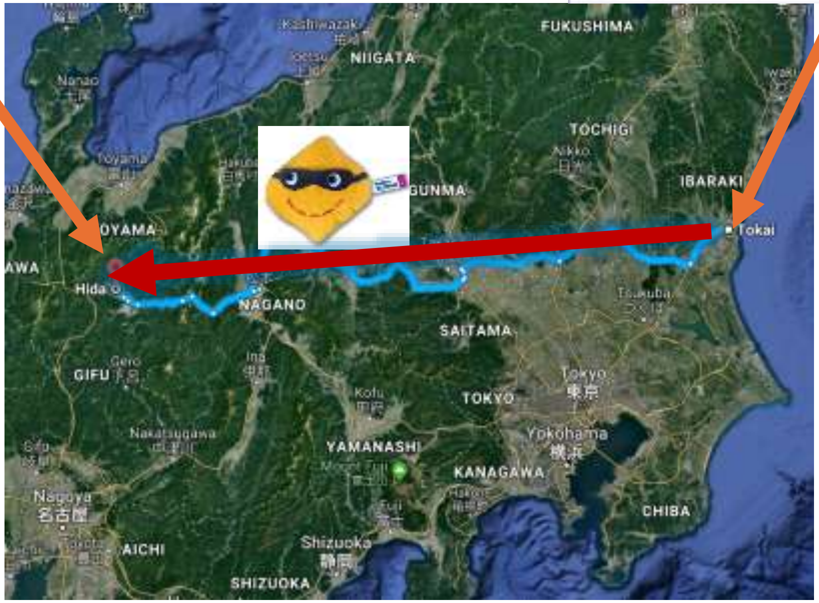




J-PARC to Hyper-K 295 km baseline



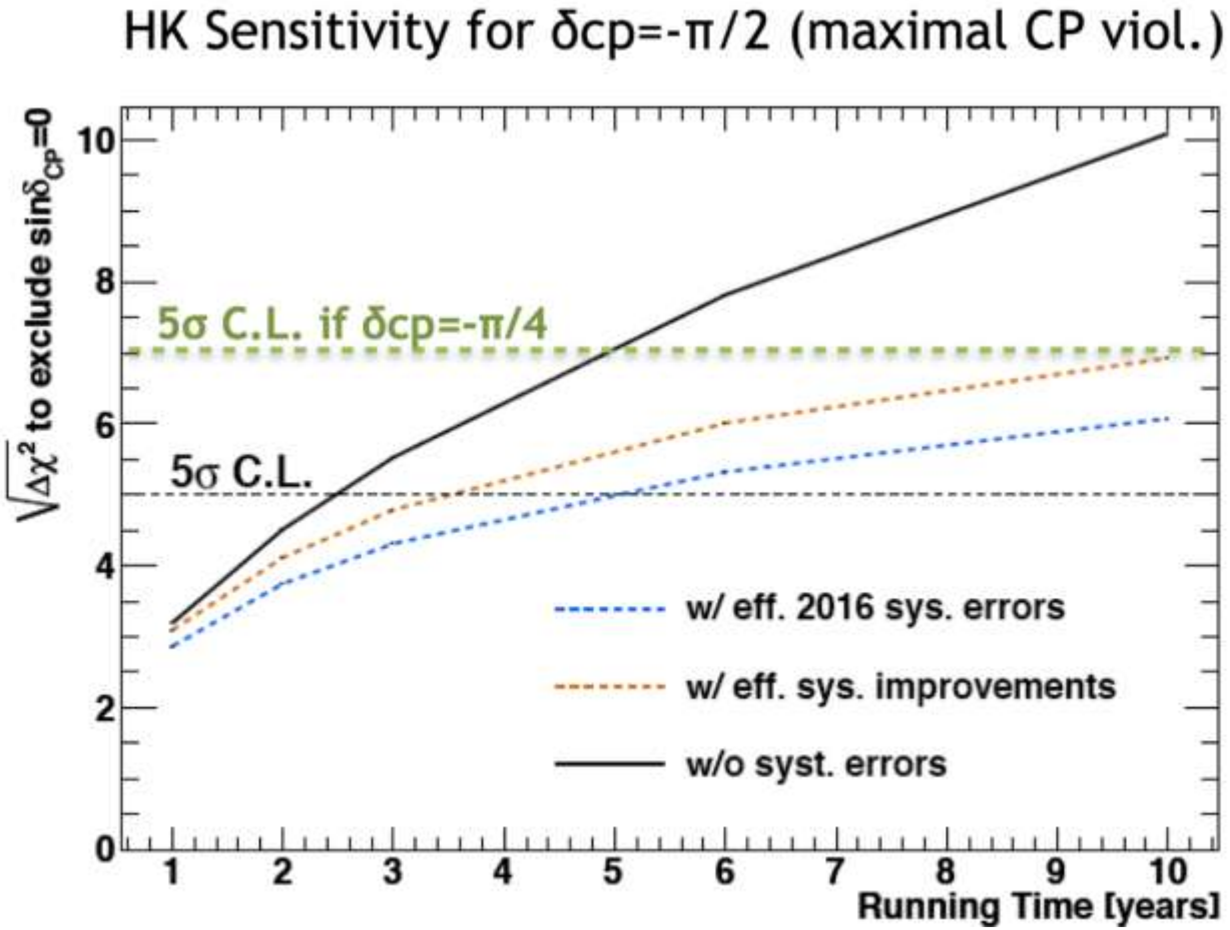
260 kton Water Cherenkov Detector
H = 60 m
ϕ = 74 m
20,000 50 cm PMTs (20% photo-coverage)
High QE box and line



Upgrade J-PARC neutrino beam to 1.3 MW beam power

New/upgraded near detectors

Systematic Uncertainties in HK Era



- Reaching 5σ C.L. for maximal CP will require improved systematic uncertainty estimates
- Will require improved understanding of:
  - Hadron-production distributions
  - ν cross-sections
  - Detection efficiencies

Neutrino beamline upgrades

- Replacement of Main Ring power supplies to allow for higher repetition rate from 2.48s to 1.36s
- Several upgrades done on the neutrino beamline to cope with higher beam power
- Horn being operated at 320 kA instead of 250 kA → ~10% increase in the ν flux

June 2024 – Produced 800 kW Beam

New horn PS for 320 kA/1Hz operation

New horns 1 and 2

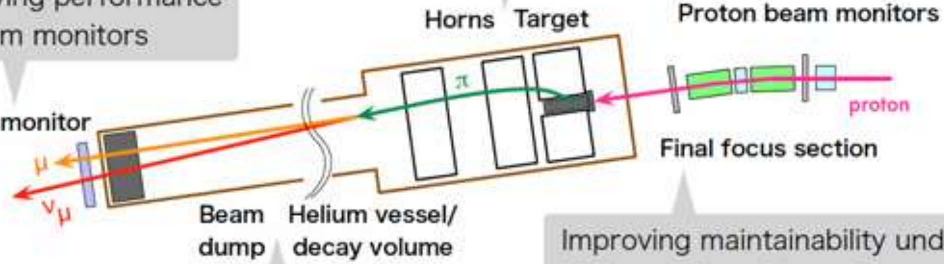
Increasing cooling capability for the heat generated by beam

New OTR

Improving performance of beam monitors

New FVD2 magnet

Improving performance of beam monitors



New target

Improving maintainability under higher radio-active environment

New MUMON Si (Half sensors)

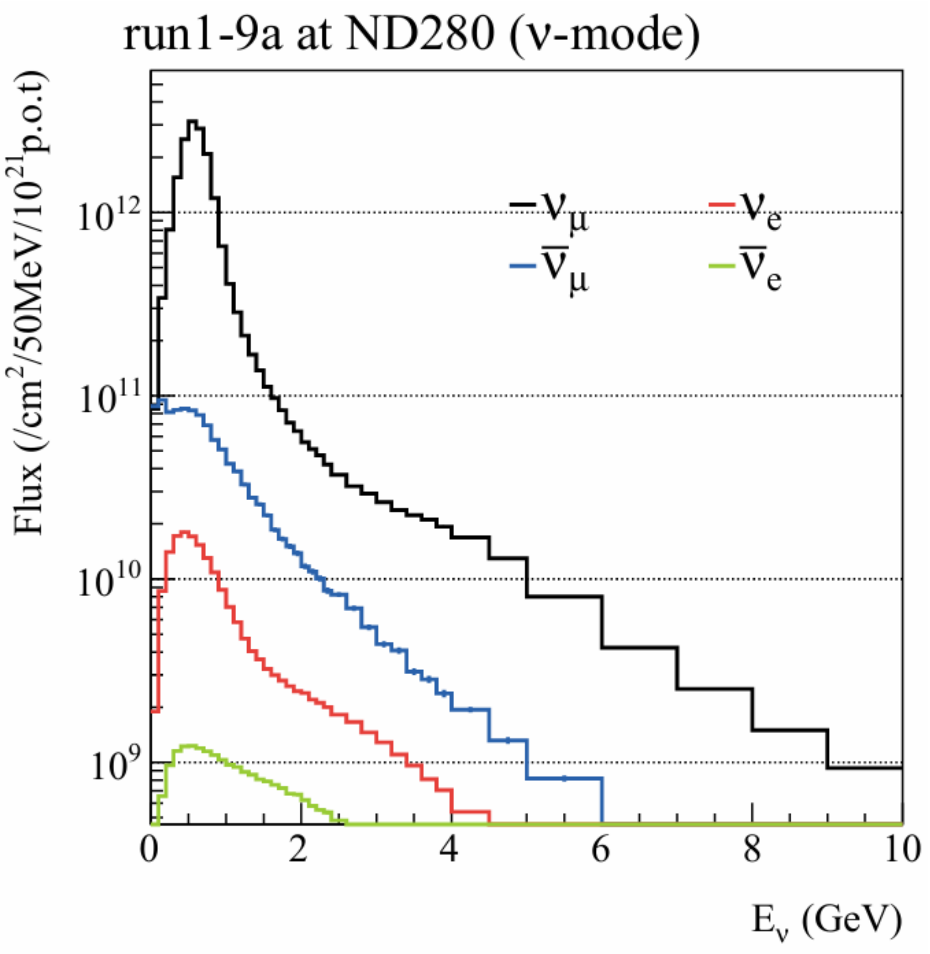
Increasing capability of radio-active waste handling

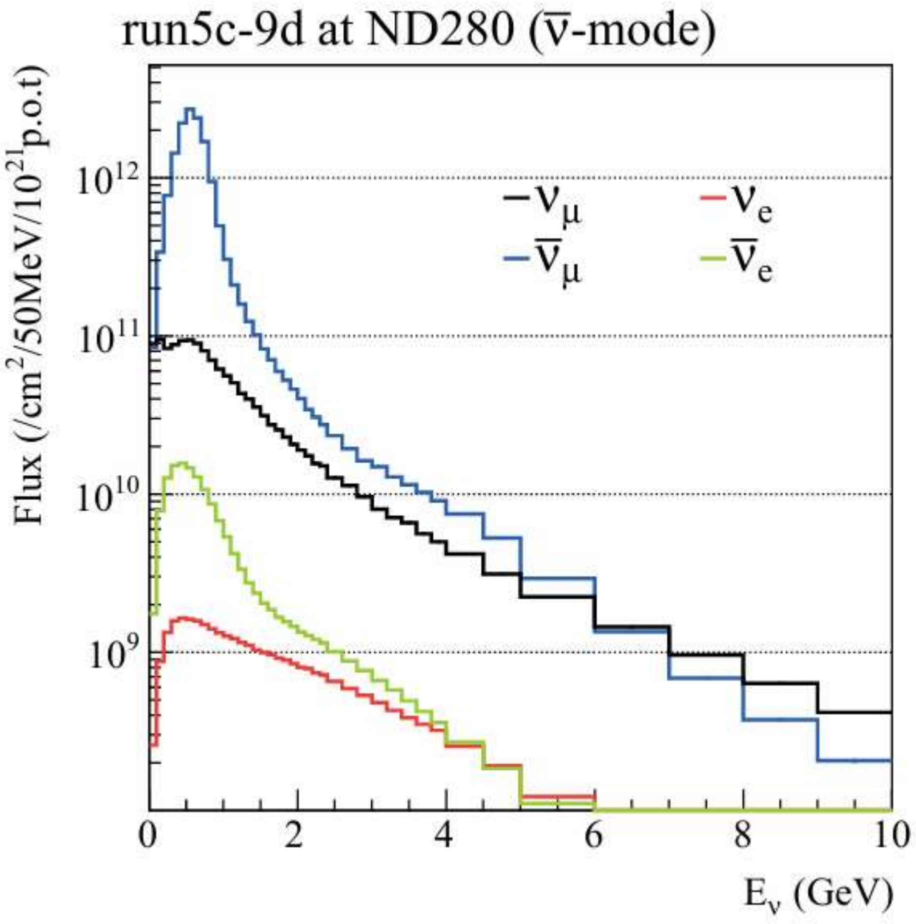
New water tank for radioactive water disposal

New target cooling system

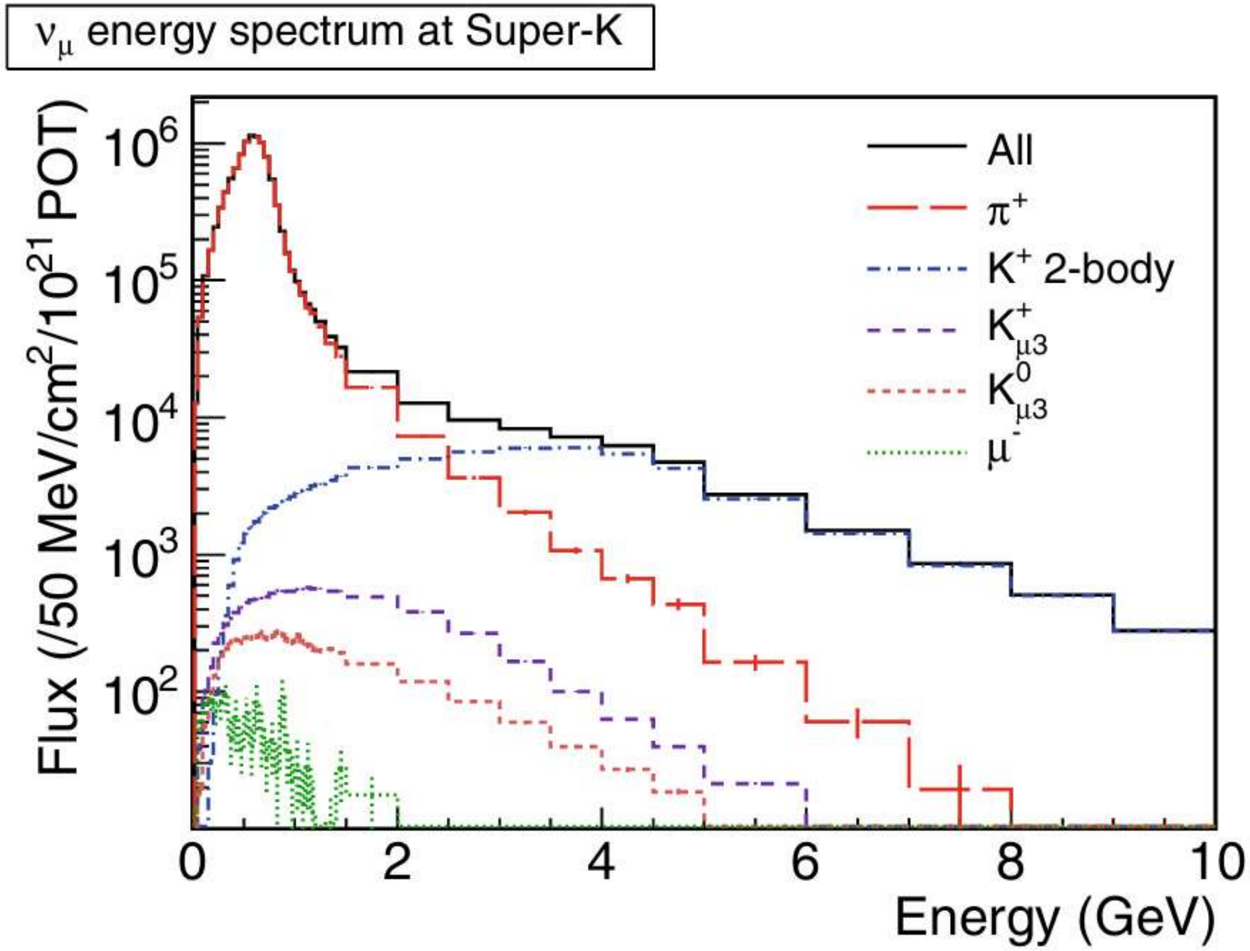
25

The T2K neutrino beam flux



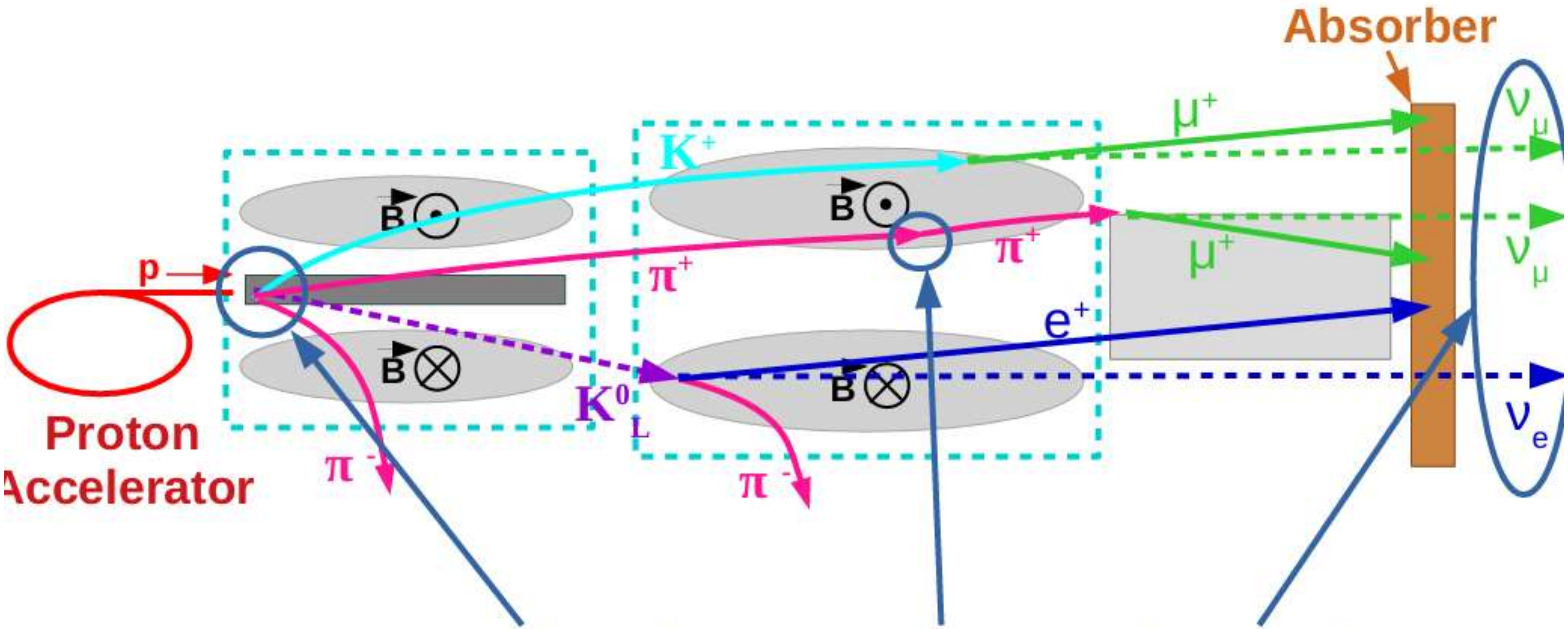


Neutrino flux hadron decay sources



Decays for ν production	Branching ratio
$\pi^+ \to \mu^+\nu_\mu$	99.9877%
$\pi^+ \to e^+\nu_e$	1.23×10^{-4}
$K^+ \to \mu^+\nu_\mu$	63.55%
$K^+ \to \pi^0\mu^+\nu_\mu$	3.353%
$K^+ \to \pi^0 e^+\nu_e$	5.07%
$K_L^0 \to \pi^\pm\mu^\mp\overline{\nu}_\mu(\nu_\mu)$, called $K_{\mu3}^0$	27.04%
$K_L^0 \to \pi^\pm e^\mp\overline{\nu}_e(\nu_e)$, called K_{e3}^0	40.55%
$\mu^+ \to e^+\overline{\nu}_\mu\nu_e$	100%

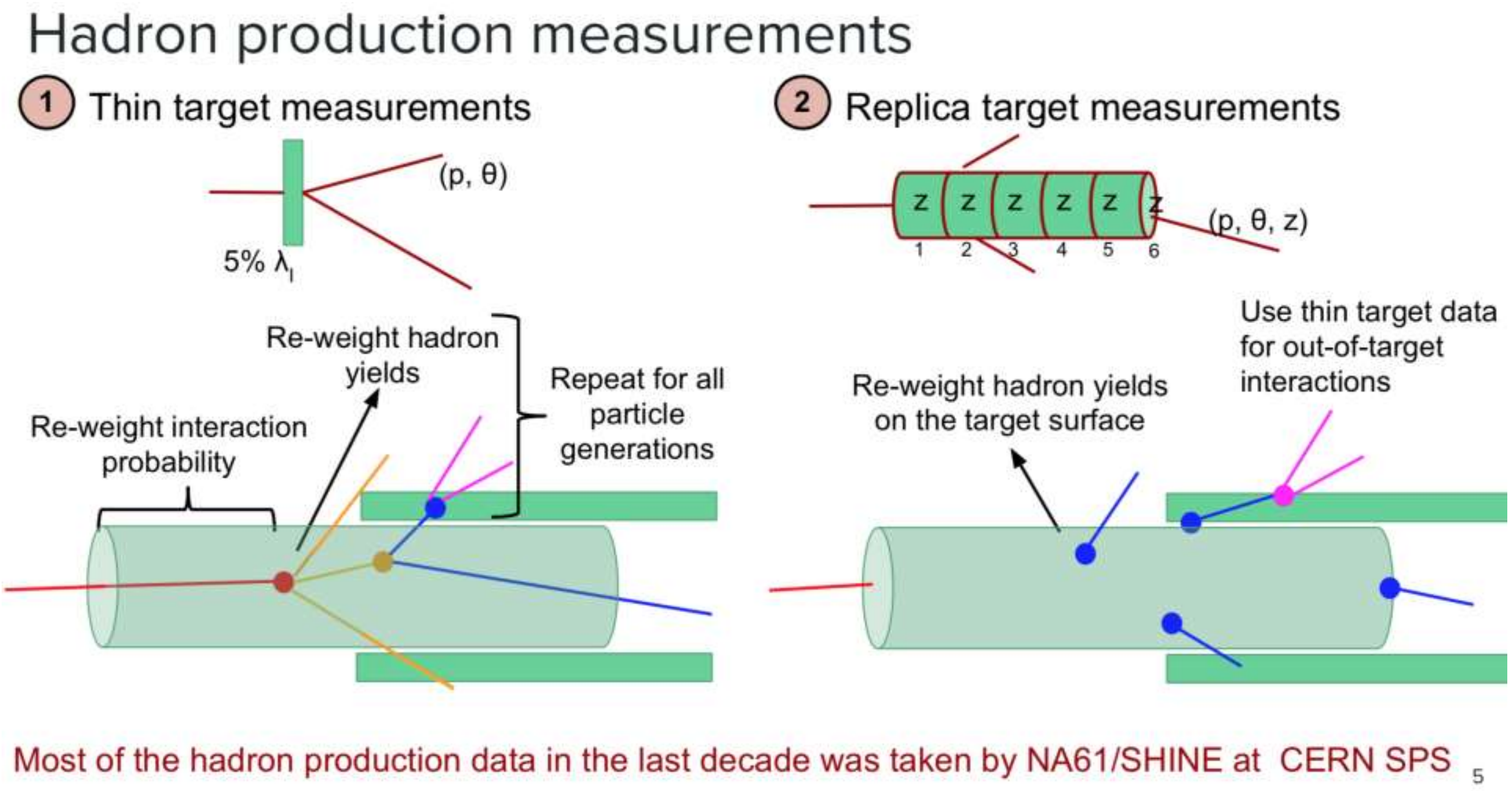
Neutrino Beam Flux Uncertainties



Neutrino beam content depends on primary & secondary hadron production in target & horns

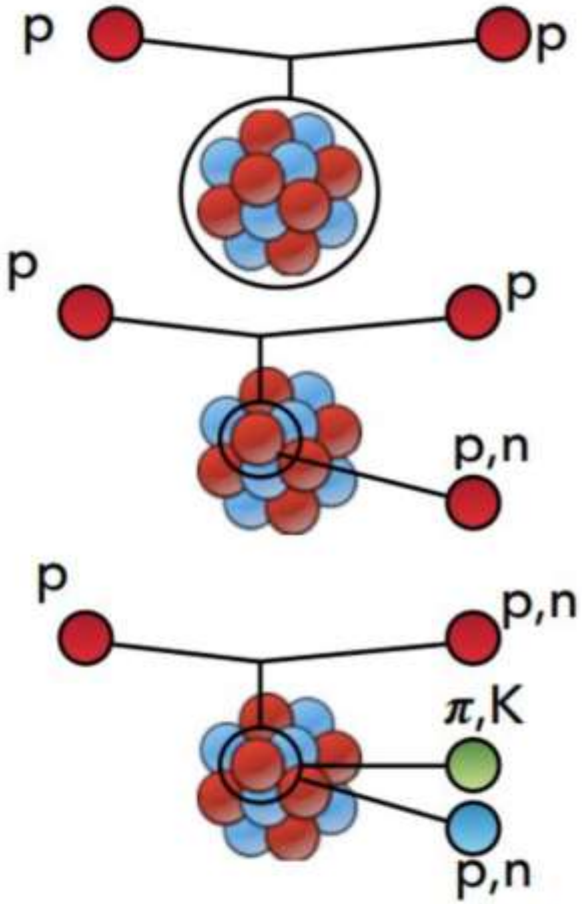
No constraint data:
Large uncertainty!

Predecessor to EMPHATIC experiment



NA61 and EMPHATIC experiments

Hadron interactions



Coherent elastic interactions (σ_{el})

Quasi-elastic interactions (σ_{qel})

Particle production (σ_{prod})

$$\sigma_{tot} = \sigma_{el} + \sigma_{qel} + \sigma_{prod}$$

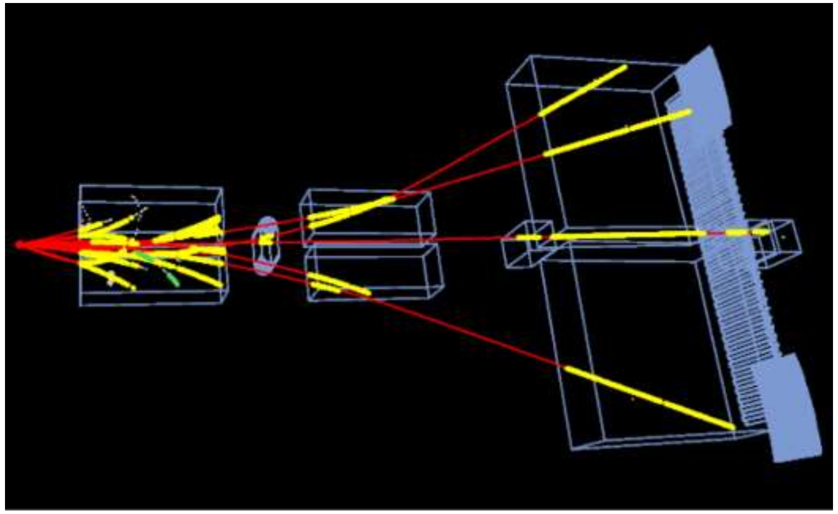
$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$$

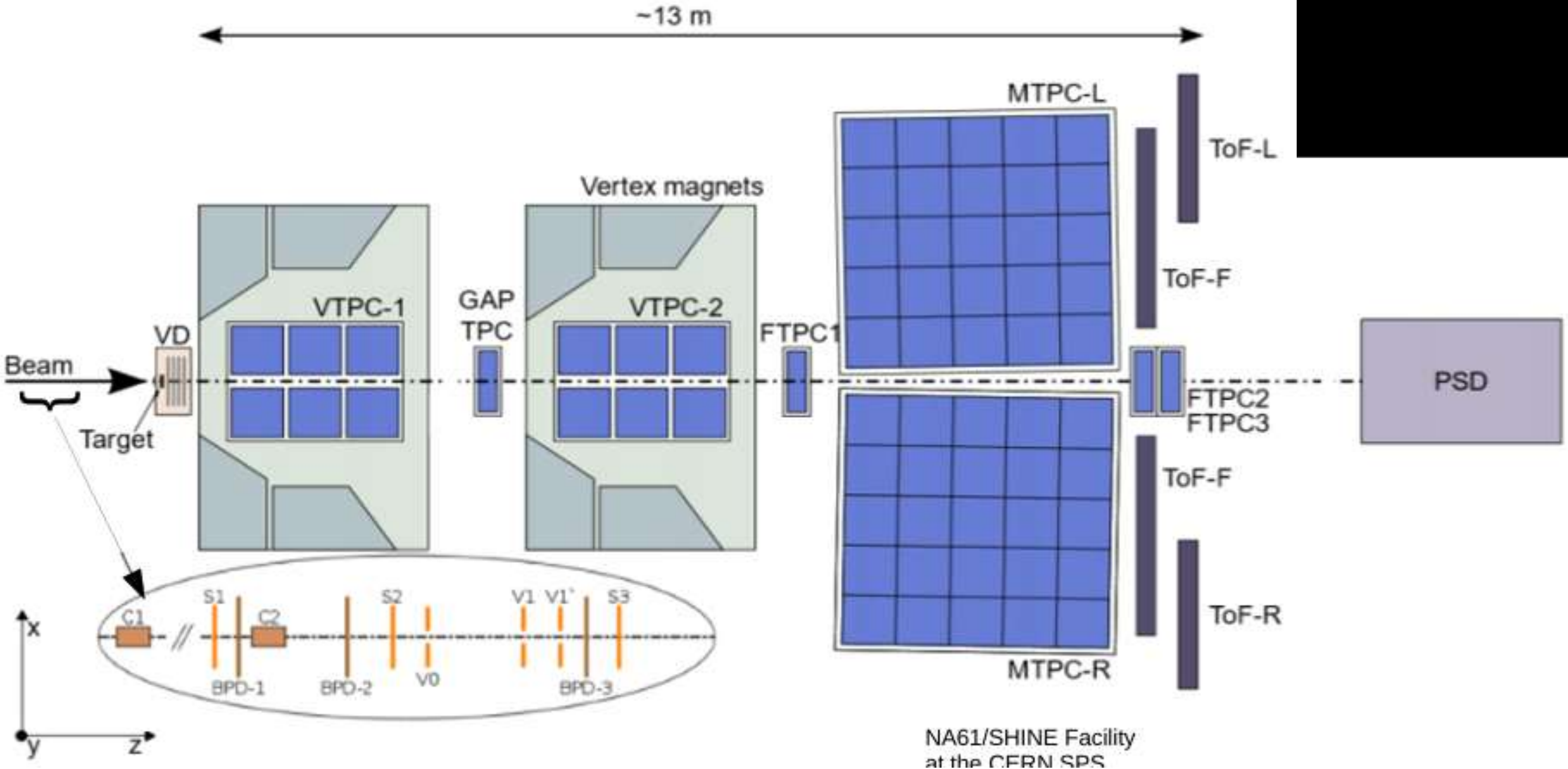
Inelastic interactions (σ_{inel})

Old measurements used mixed notation → it is hard to understand what was measured.

NA61/SHINE Detector

- 8 Time Projection Chambers: 3D tracking, dE/dx measurement (5 + 3 new)
- 2 superconducting magnets: momentum determination
- Cerenkov detectors: beam particle identification
- 3 Time-Of-Flight walls: mass determination
- 3 beam position detectors
- Projectile Spectator Detector (PSD): forward calorimeter



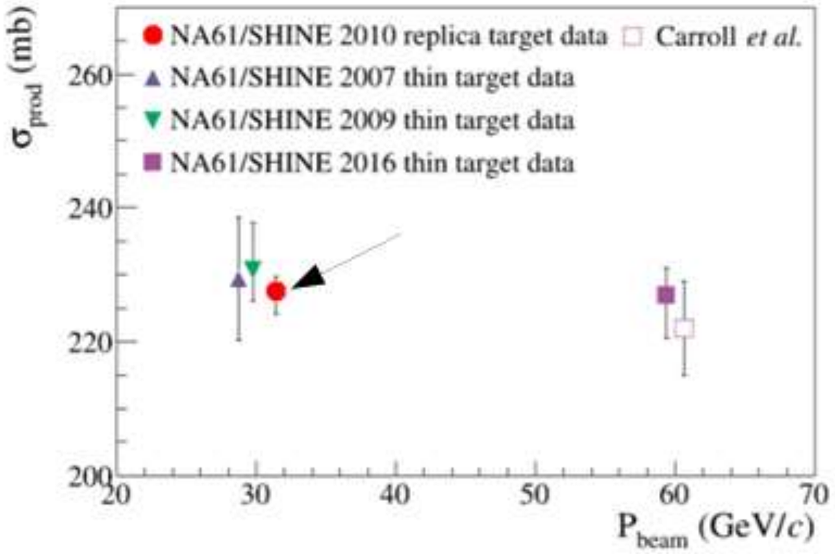


NA61/SHINE Facility
at the CERN SPS

T2K Replica Target Production Cross-Section

- Production cross-section measured via beam attenuation in 90-cm T2K Replica Target
- Full magnetic field setting used for improved measurement of elastic and quasi-elastic protons
- Result consistent with 31 GeV/c proton-carbon thin-target measurement
  - Improved overall precision
- Will help reduce T2K flux prediction uncertainty

T2K Replica Target



Phys. Rev. D 103, 012006 (12 Jan. 2021)

A snippet of the NA61 T2K replica target data *Eur. Phys. J. C 79 (2019) 100*

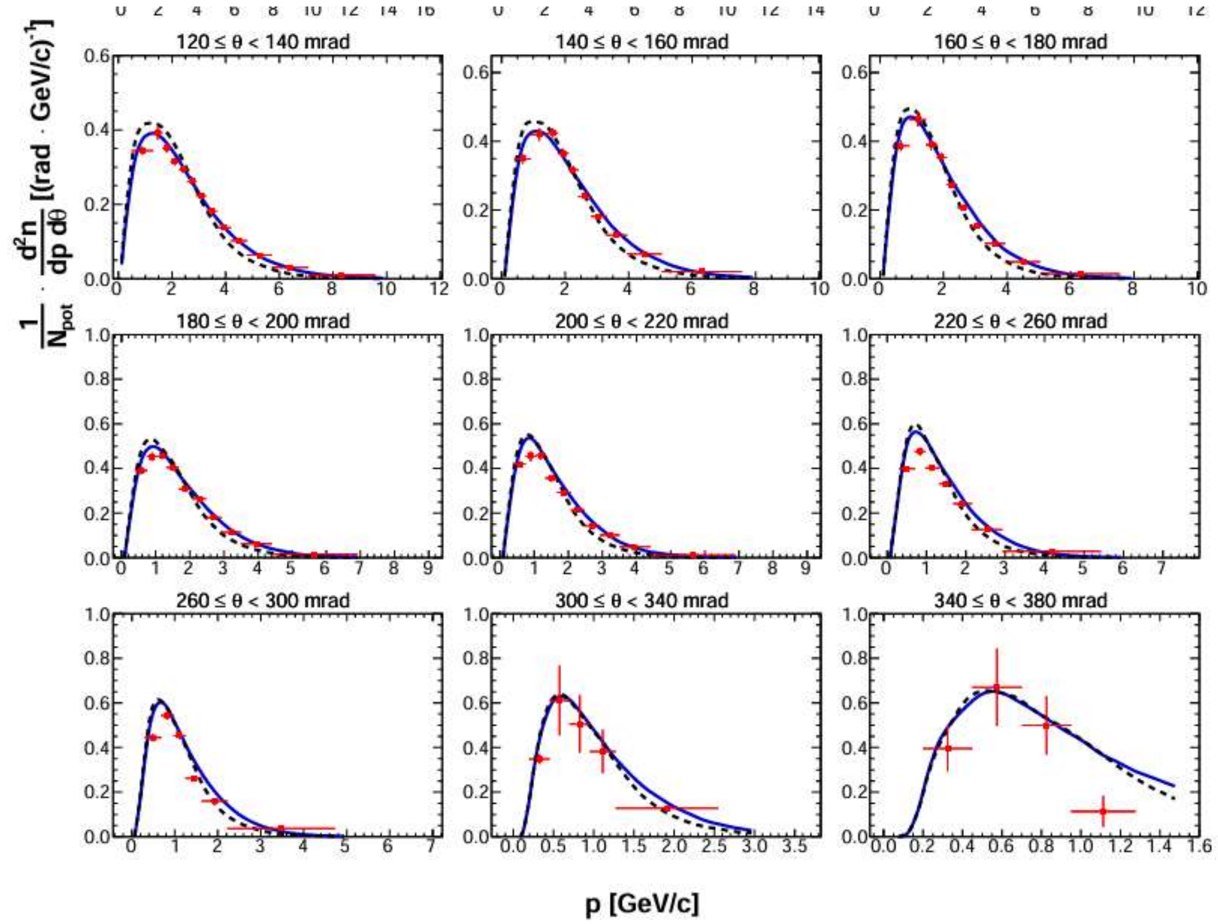


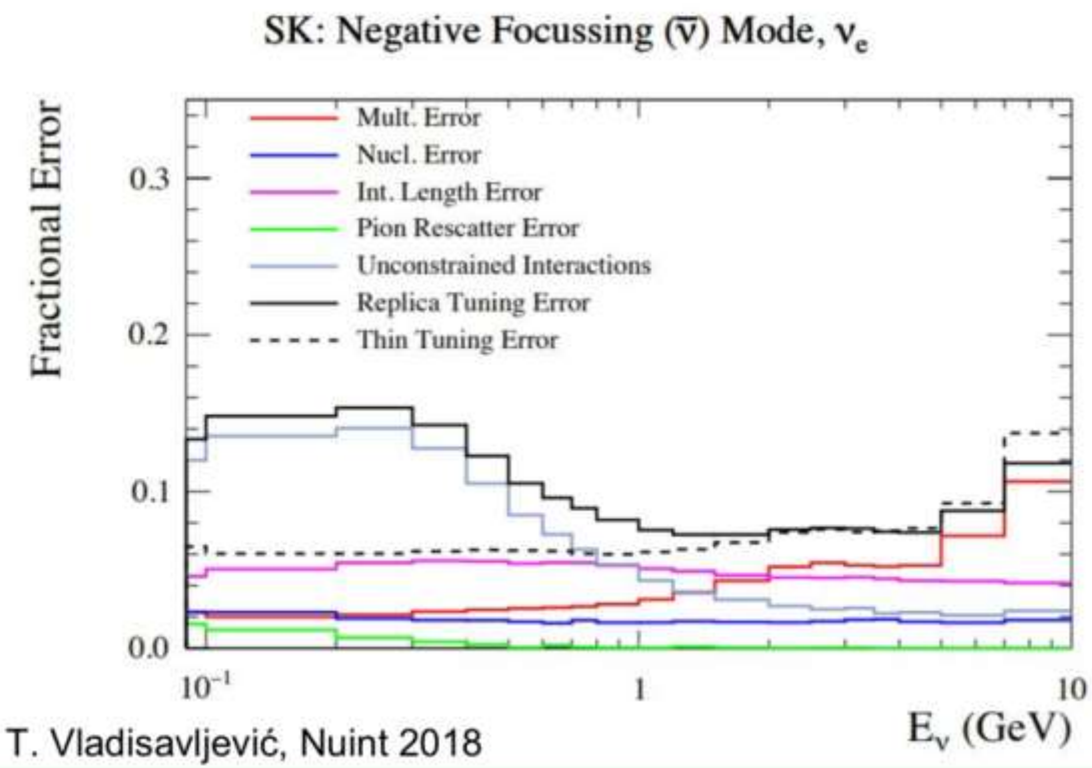
Fig. 30: Double differential yields of negatively charged pions for the second upstream longitudinal bin ($18 \leq z < 36$ cm). Vertical bars represent the total uncertainties. Predictions from the NuBeam (solid blue line) and QGSP_BERT (dashed black line) physics lists from Geant4.10.03 [27, 28] are overlaid on top of the data.

- About 24 pages of plots
  - Broken down by section along target
  - Each panel covering 20 mrad
  - Broken down by particle production (pion, kaon)
  - Compared to Geant4 NuBeam (solid) and QGSP_BERT (dashed)

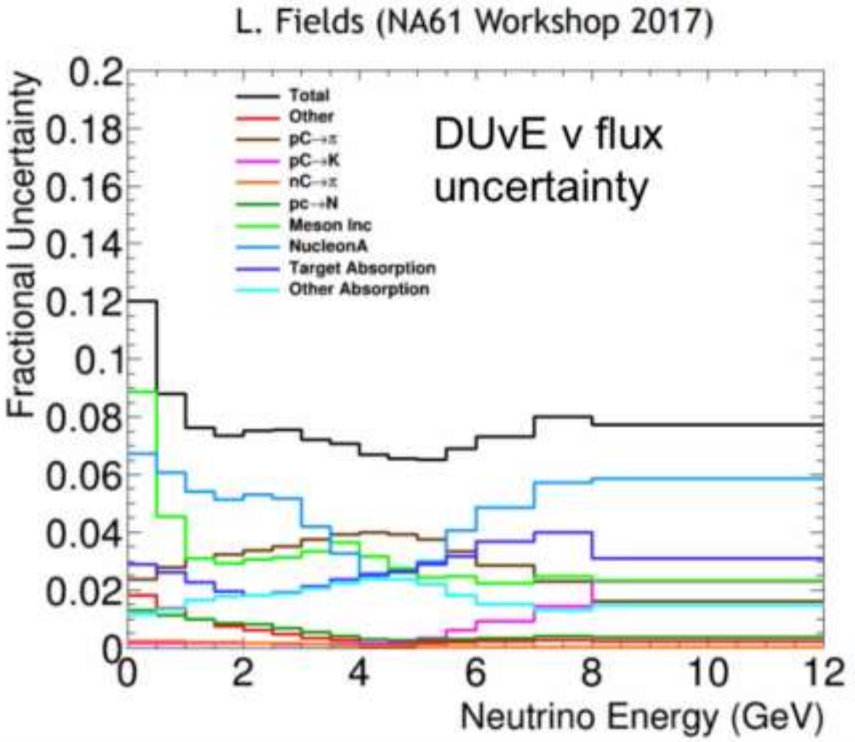
Motivation for EMPHATIC

Flux uncertainty at T2K(T2HK) and DUNE

- T2K flux uncertainty at low energies is limited by the interactions outside of the target
- Nearly 50% of wrong-sign neutrinos come from interactions outside of the target ($\pi^{\pm}$+Al→$\pi^{\pm}$, $K^{\pm}$+Al→$K^{\pm}$)

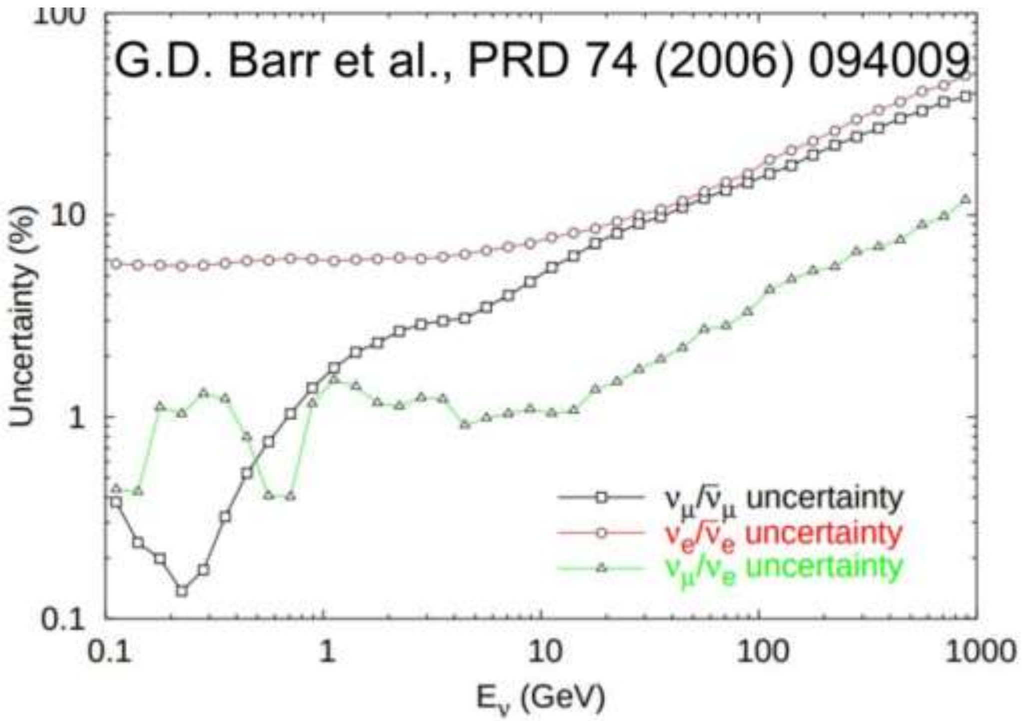


T. Vladisavljević, Nuint 2018

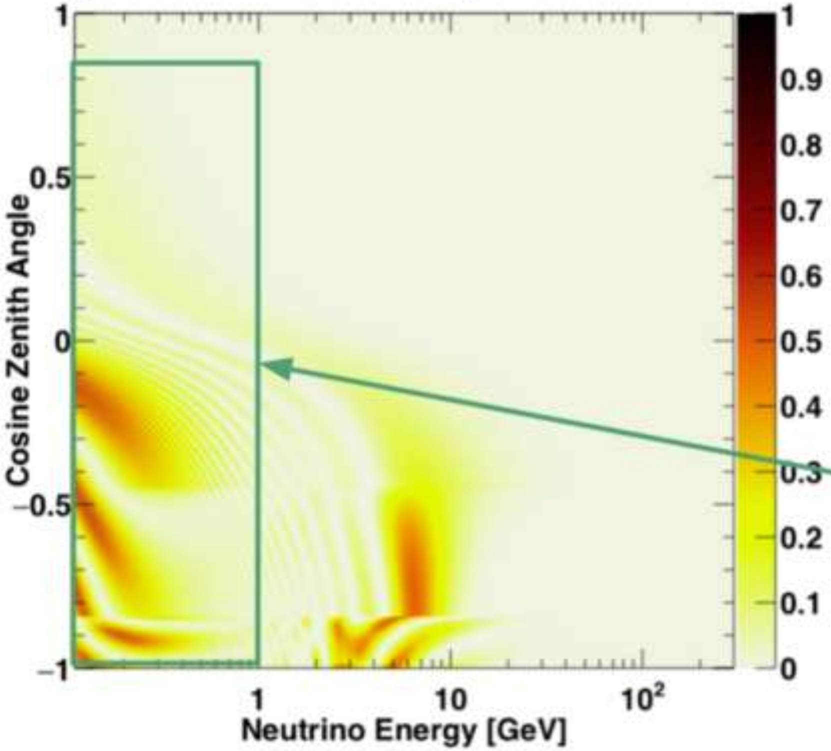


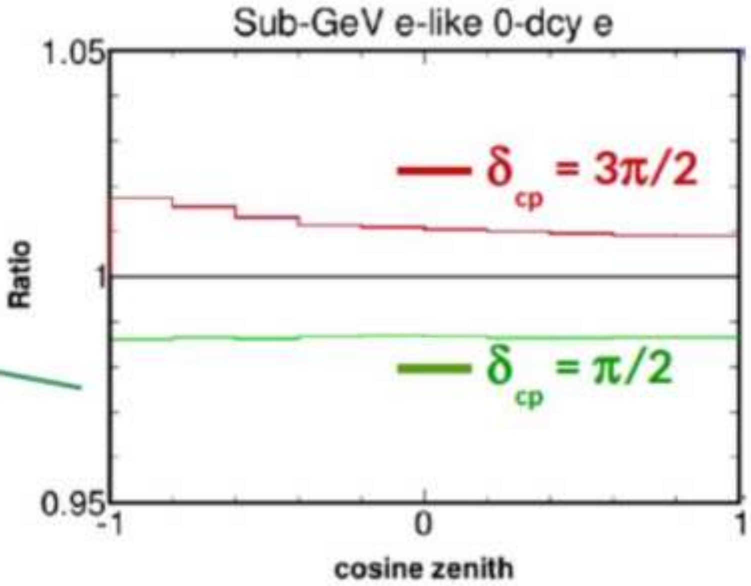
CP violation in atmospheric neutrino oscillations

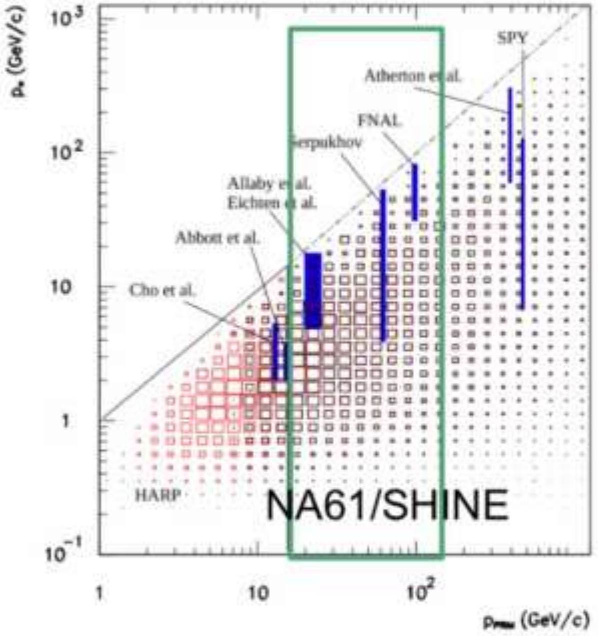
- uncertainty is dominated by pion production at low energies (π^+/π^-)
- proton interactions 3-30 GeV/c



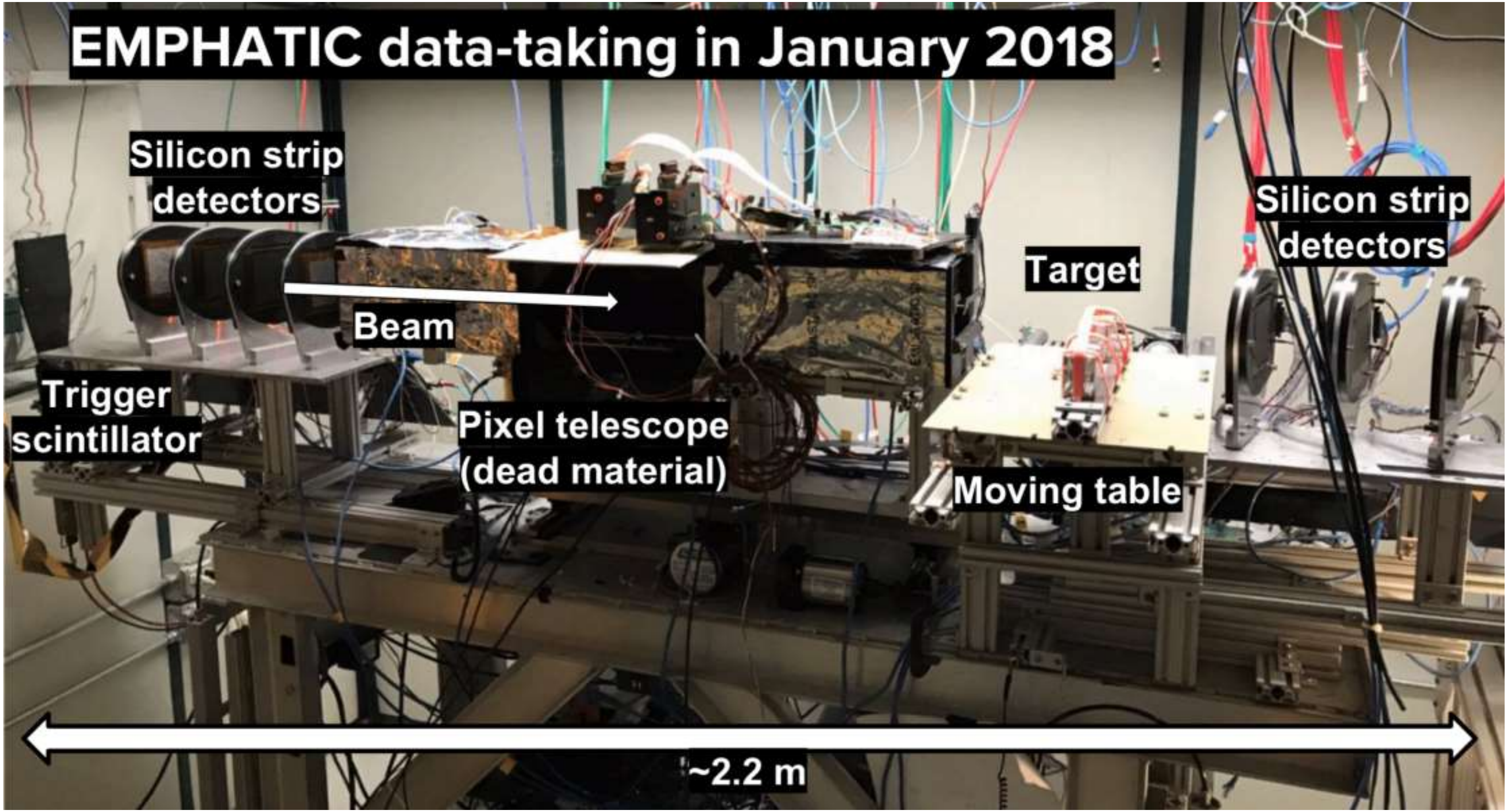
Roger Wendell, Hadron production workshop, RCNP



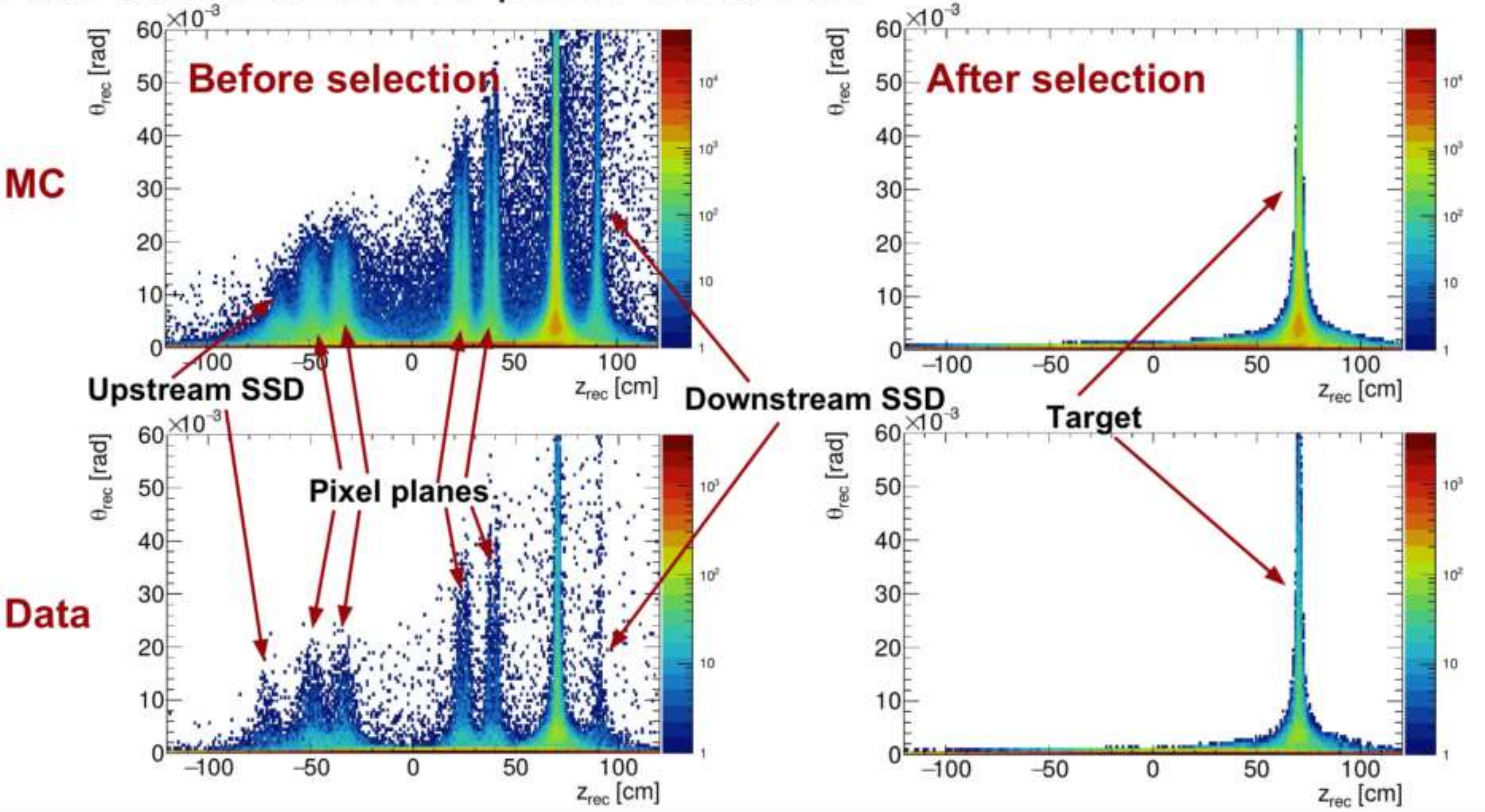




EMPHATIC first experiment



Interactions in the pixel detector



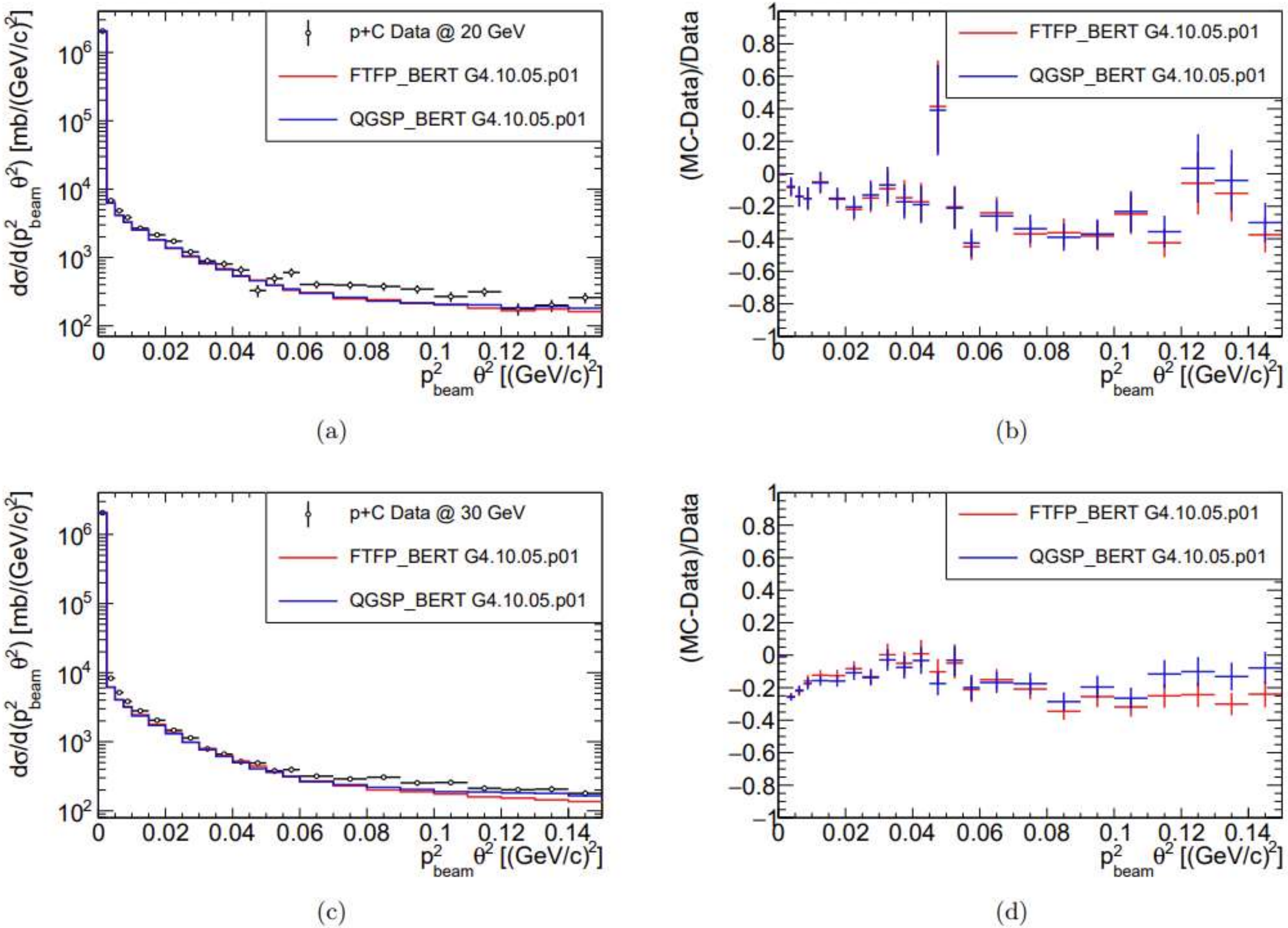
Differential cross-section

$$\left(\frac{d\sigma}{dt}\right)_i = \frac{1}{nd}\frac{1}{\Delta t}\frac{N_i}{N_{pot}} \cdot C$$

- i - bin number
- n - number density
- d - target thickness
- N_i - number of tracks in a bin i
- N_{pot} - number of protons on target
- Δt - momentum transfer bin size
- C - total correction factor

EMPHATIC first experiment

M. Pavin *et al.* (EMPHATIC Collaboration)
Phys. Rev. D **106**, 112008 – Published 23 December 2022

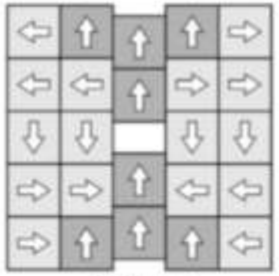


EMPHATIC phase 1b

Upgrade of the detector

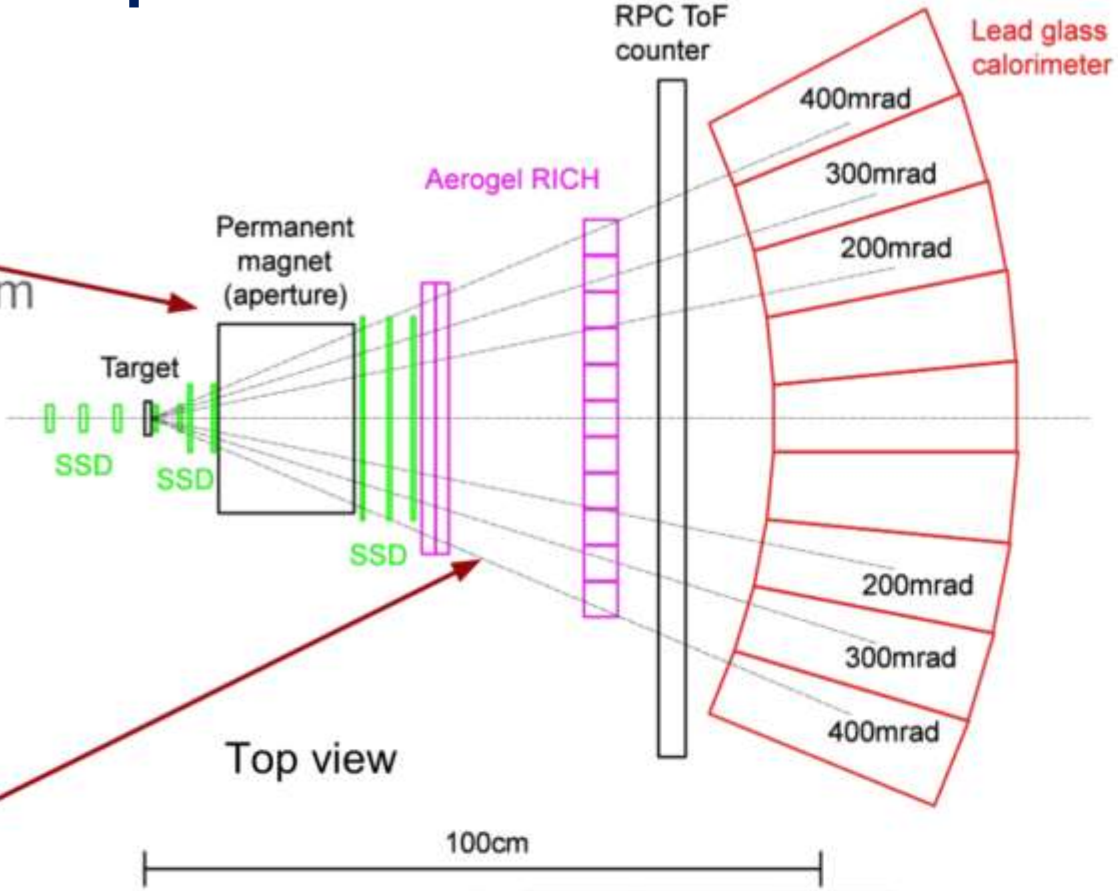
Compact permanent magnet

- Halbach array → 20 cm long with ~10 cm gap → field strength > 1T

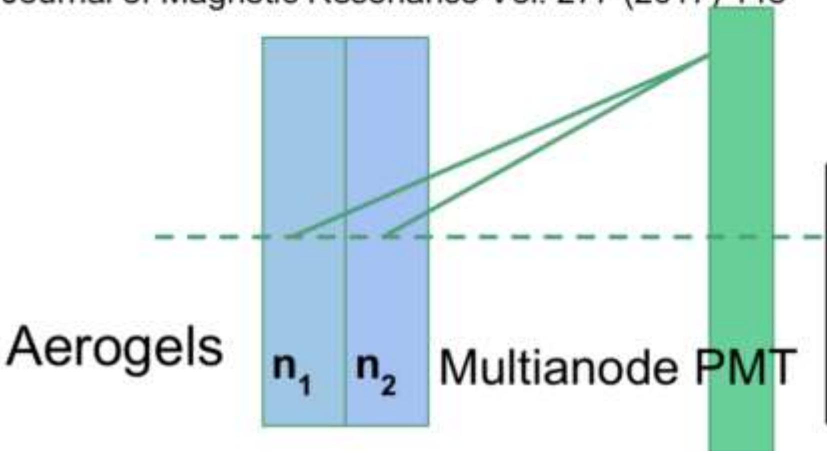


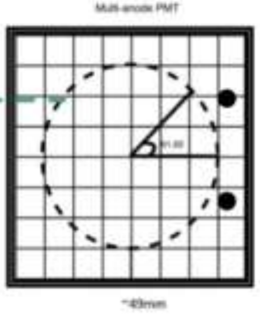
24 blocks

Journal of Magnetic Resonance Vol. 277 (2017) 143



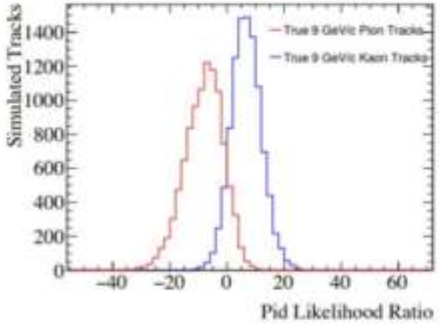
ARICH



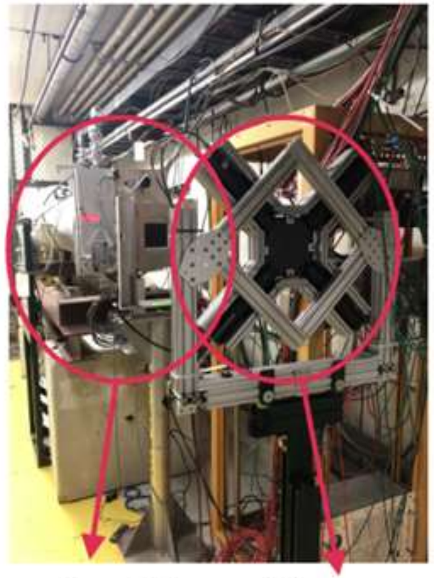


2σ π/K separation < 7 GeV/c

1σ π/K separation < 11 GeV/c



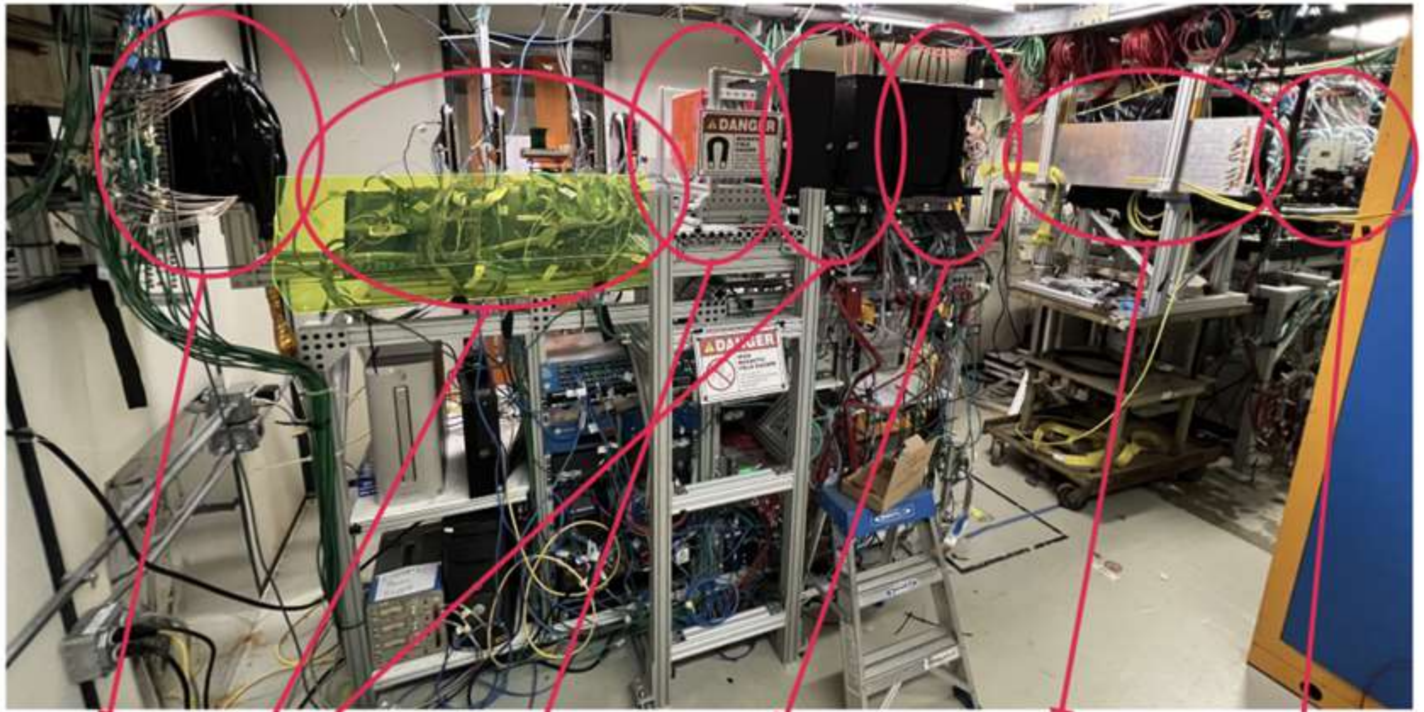
EMPHATIC Spectrometer – In Photos



Gas Ckov + Trigger

Beam aerogel Ckov

~1.5m



T0 SSDs Magnet Aerogel RICH RPC Lead-glass Calorimeter

EMPHATIC Phase 1 Run

- Now taking Phase 1 data in several periods during 2022~2023
  - Low and high momentum hadron production data (with 100 mrad acceptance) + elastic/quasi-elastic scattering data
  - ±2, 4, 8, 12, 20, 31, 60, 120 GeV/c proton, pion(+kaon) beams
  - On C, CH_2, Al, Fe, Be, Ti, Ca, H_20 targets
- Run 1a: January 2022
  - 100 mrad acceptance spectrometer (w/out ARICH)
  - Graphite, Aluminum, Iron, CH_2 targets with ±2, 4, 8, 12, 20, 30, 60, 120 GeV/c proton, pion, kaon beams
- Run 1b: June~July 2022
  - 100 mrad acceptance spectrometer (w/ ARICH)
  - Graphite, Aluminum, Iron, CH_2 targets with ±2, 4, 8, 12, 20, 31, 120 GeV/c proton, pion, kaon beams
- Run 1c: March~April 2023
  - Configuration still under preparation, but at least full spectrometer from Run 1b will be available

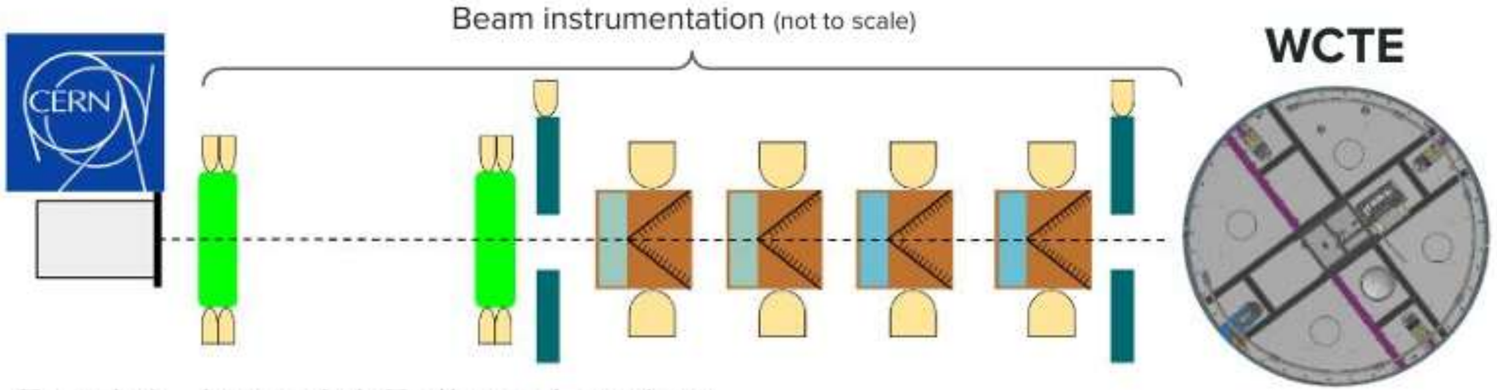
The Water Cherenkov Test experiment at CERN

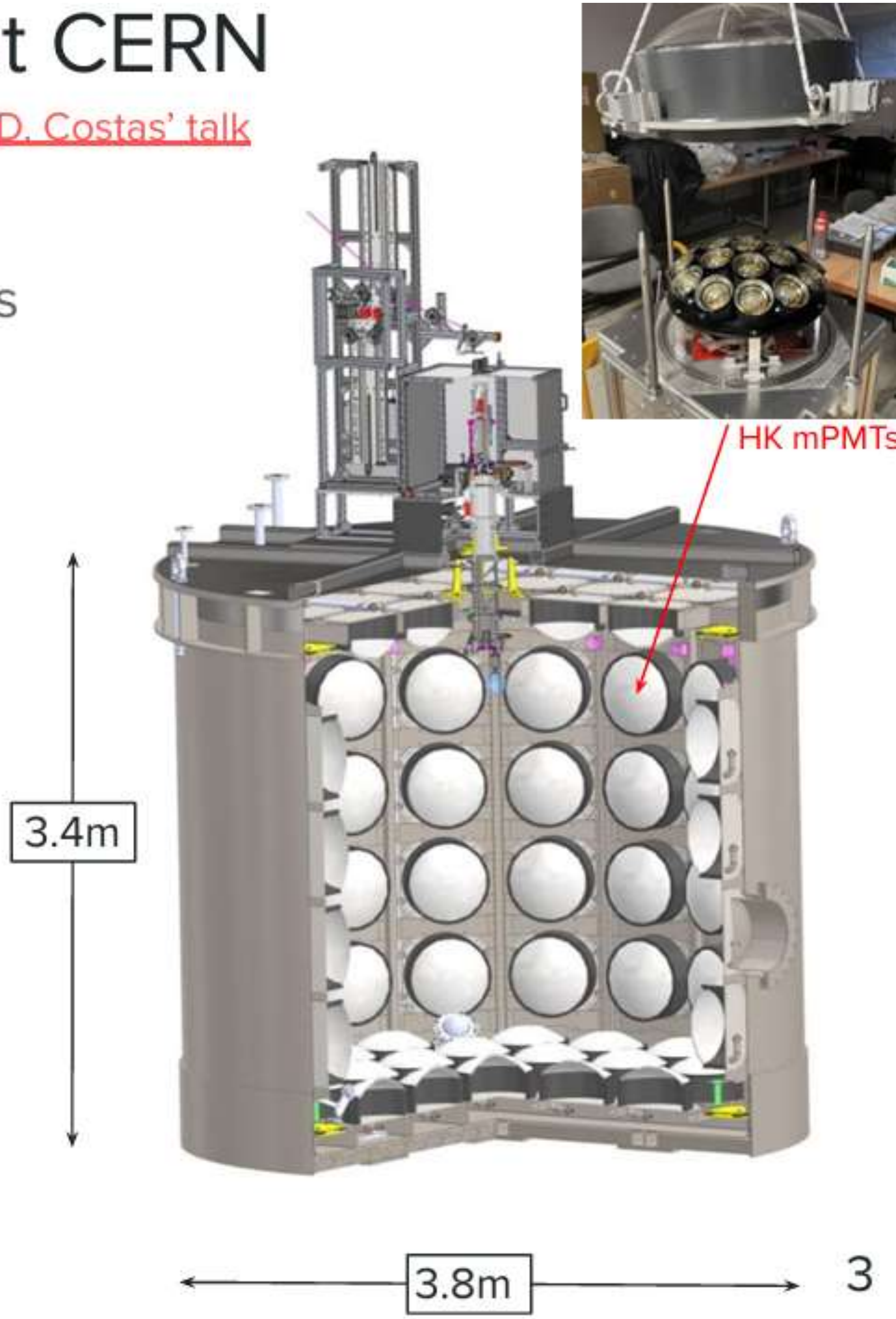
See D. Costas' talk

- The Water Cherenkov Test Experiment (WCTE) will
    - develop and test hardware and calibration techniques
    - study the interaction of π, p, e, μ and γ in ultra-pure and Gd-doped water

  to help Hyper-Kamiokande reach its targeted precision.

- WCTE be installed in summer 2024 at CERN in the newly refurbished T9 beamline (East Area) and receive a beam of charged particles (π, p, e, μ) with momenta 200 MeV/c to 1.2 GeV/c.





WCTE beamline and July 2023 beam test

- WCTE uses two beamline set-ups:
    - one low momentum set-up,
        - charged particle identification
        - momentum measurement
    - one tagged photon set-up,
        - produce γ of known energy

- Set-ups tested at CERN in July 2023. Over a 3-week long beam test, the collaboration achieved :
    - Development and test of DAQ and detectors
    - Demonstration of high purity PID and good photon production rates
    - First measurement of the T9 beam composition

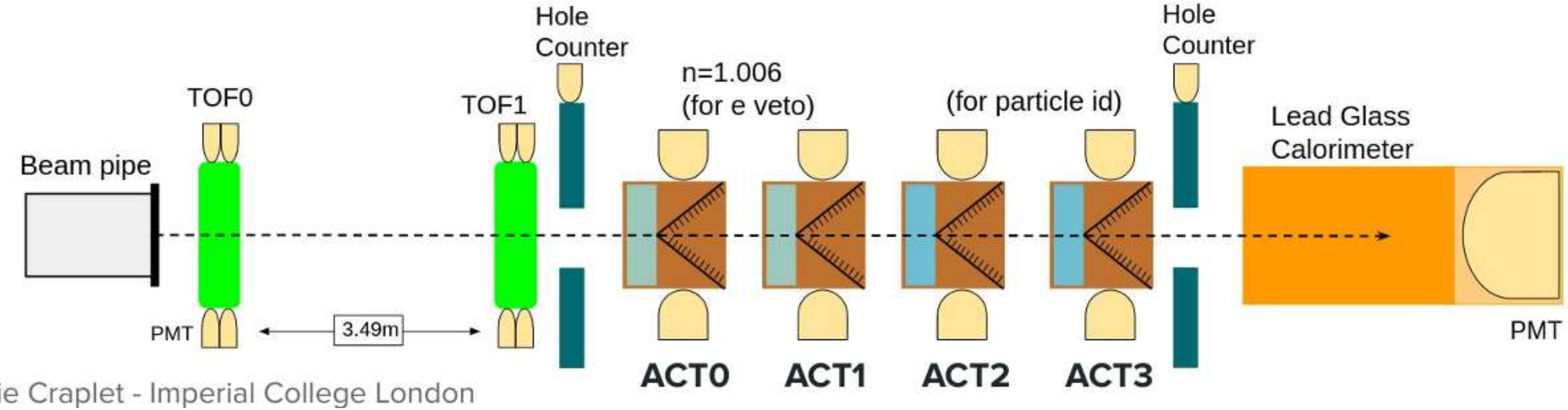
Set-up for Sub-GeV particle identification

Trigger scintillators : • provide time of flight and beam momentum measurement

Hole counters : • provide beam halo veto

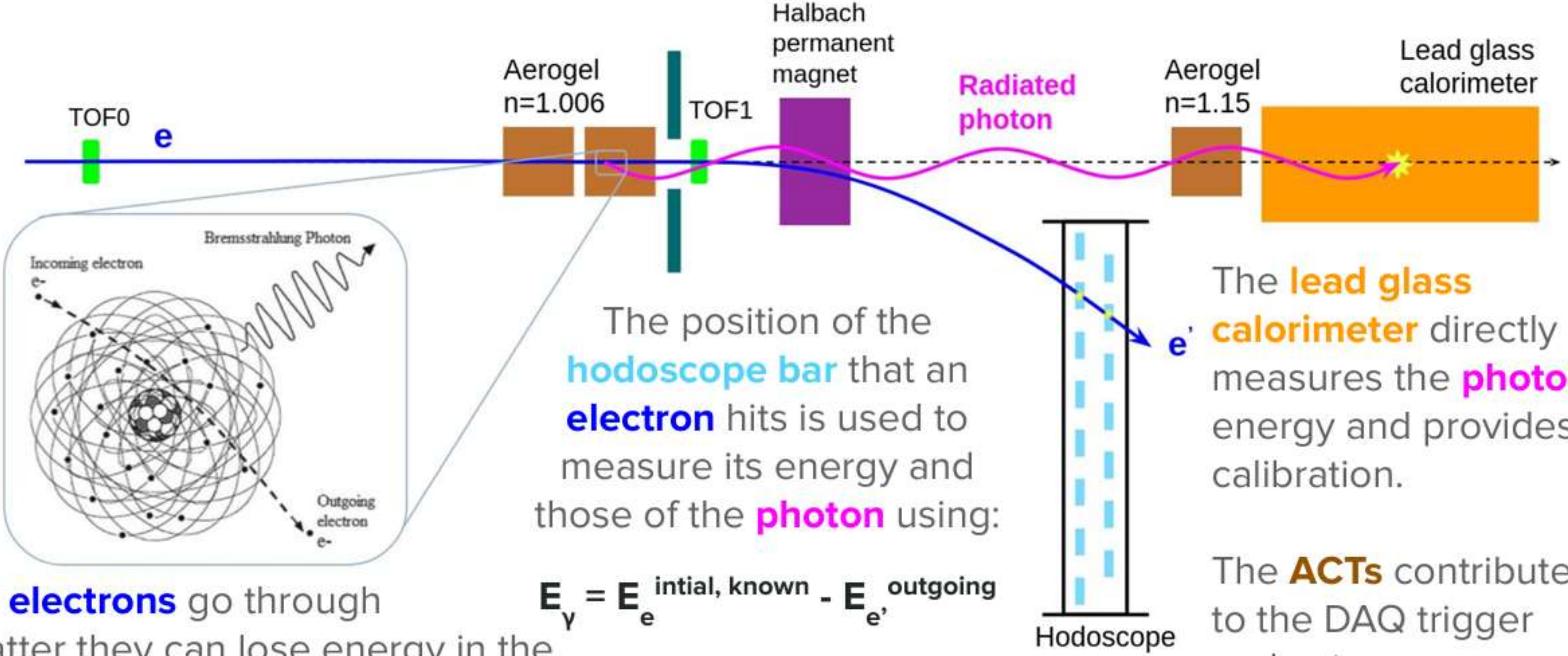
Aerogel Cherenkov Threshold (ACTs) detectors: • upstream **ACTs** used for e veto
• downstream **ACTs** refractive index tailored to the beam momentum • **e** and **μ** above Cherenkov threshold • **π** and **p** below threshold

Lead-glass calorimeter : • provides momentum measurement and additional particle ID information.
• The water Cherenkov detector will replace the calorimeter in 2024



Set-up for tagged photon production

Electrons are deflected by the **permanent magnet**, depending on their energy.



The position of the **hodoscope bar** that an **electron** hits is used to measure its energy and those of the **photon** using:

$$E_\gamma = E_e^{\text{intial, known}} - E_{e'}^{\text{outgoing}}$$

The **lead glass calorimeter** directly measures the **photon** energy and provides calibration.

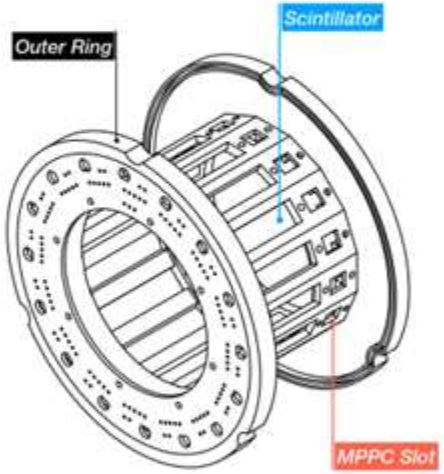
The **ACTs** contribute to the DAQ trigger and veto.

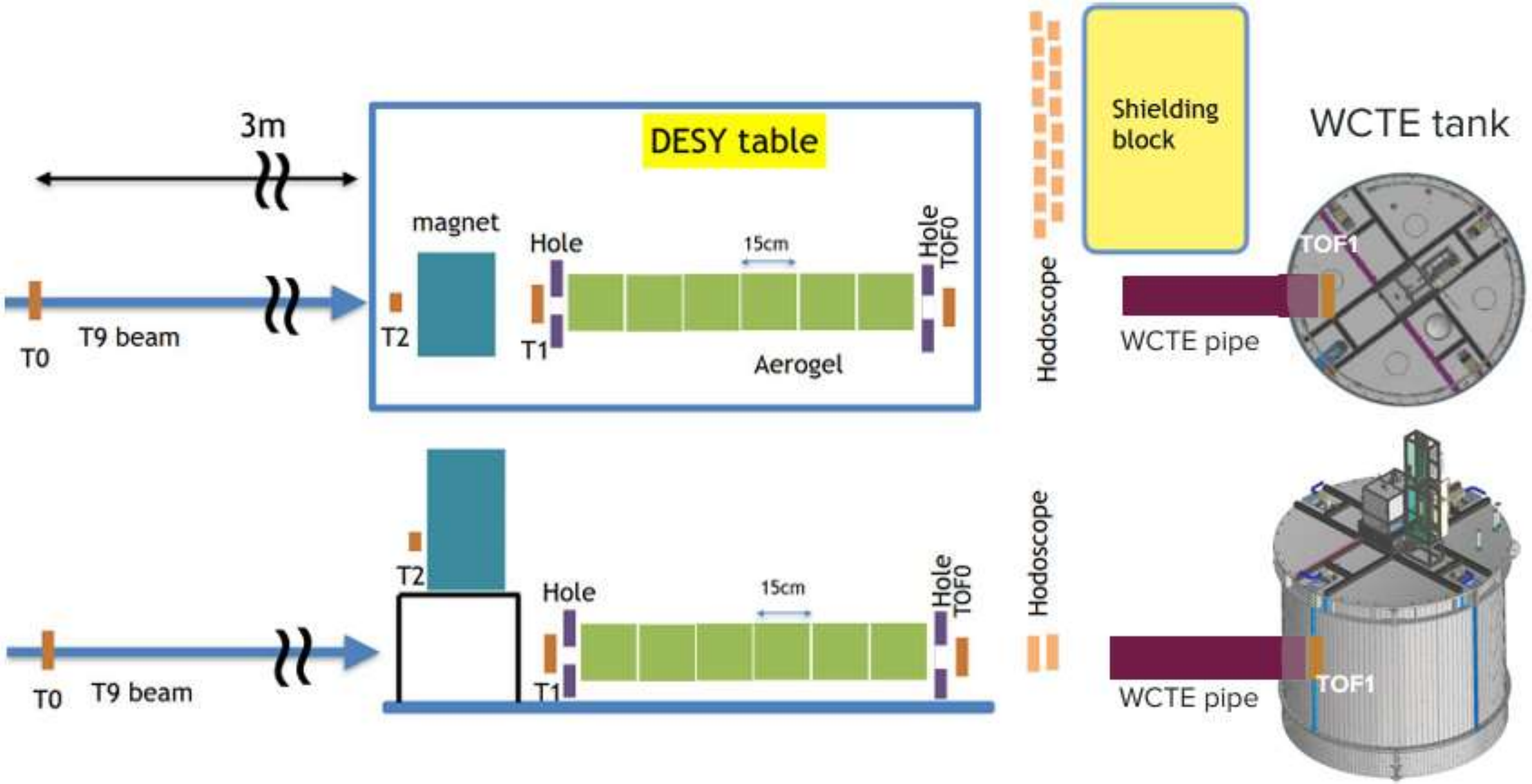
As **electrons** go through matter they can lose energy in the form of **Bremsstrahlung photons**.

Beam line developments for 2024 WCTE operation

- The PID and tagged photons set-ups are combined into a single set-up.

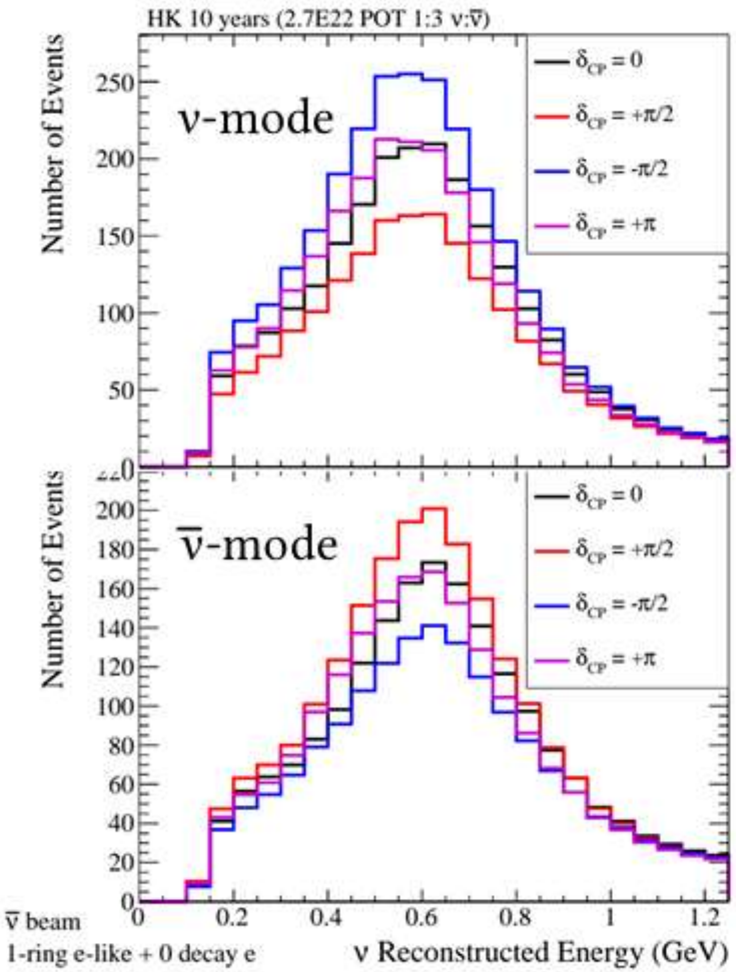
- A new TOF detector will improve PID and trigger.

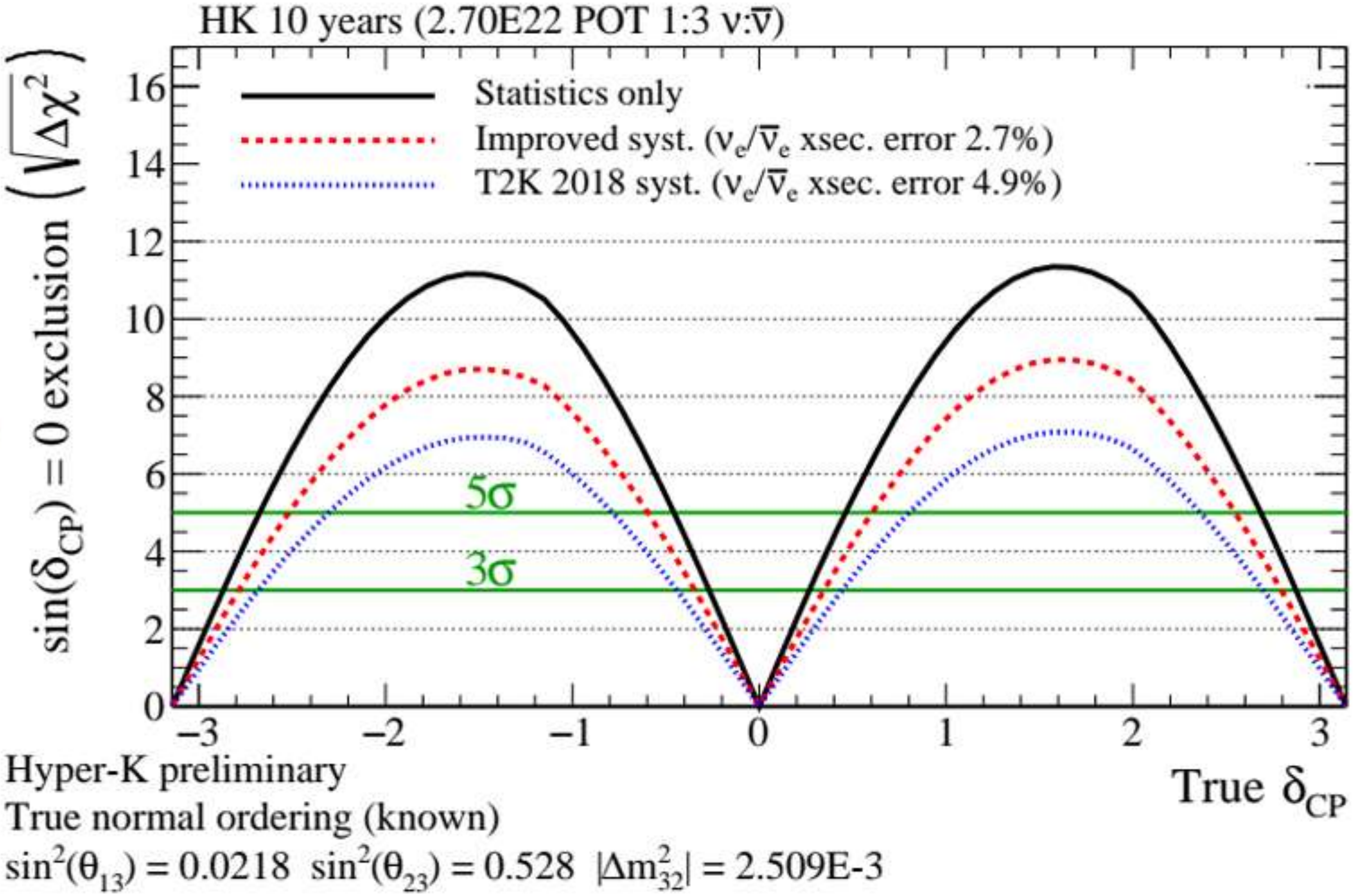




- Number of ACTs will be increased from 4 to 6 and reflective film exchanged for non-scintillating Mylar to improve electron veto and PID.

ν_e and $\overline{\nu}_e$ cross-section uncertainties

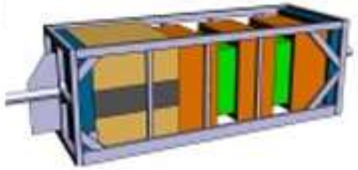




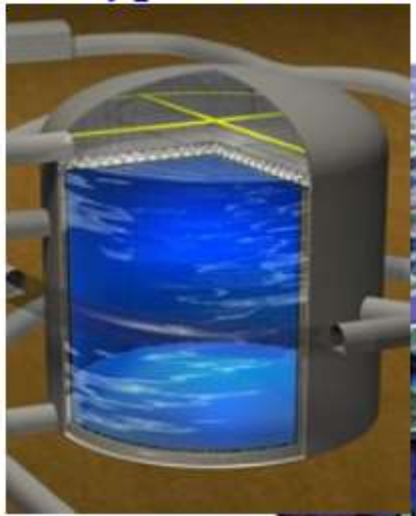
- The CP violation will be studied by essentially comparing observed ν_e and $\overline{\nu}_e$ event rates
- ν_e and $\overline{\nu}_e$ cross-section uncertainties will be dominant

Intermediate Water Cherenkov Detector

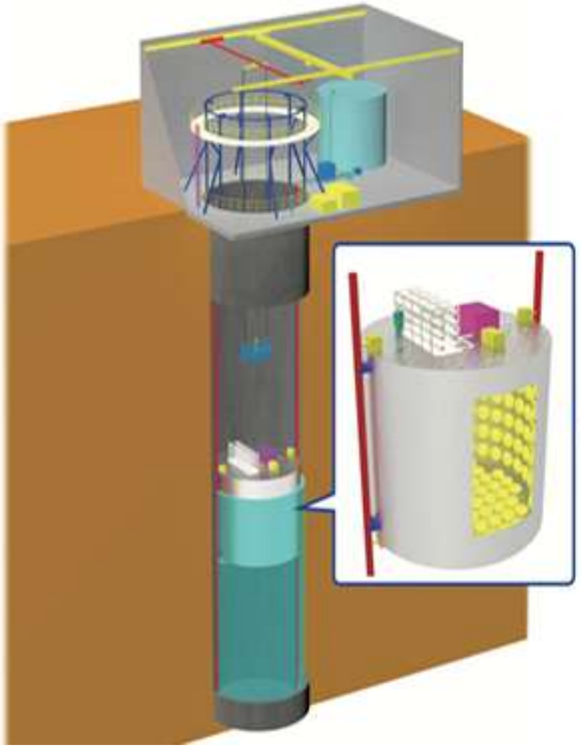
Other near detectors @ 280m
- INGRID
- Upgraded ND280



The Hyper-K detector



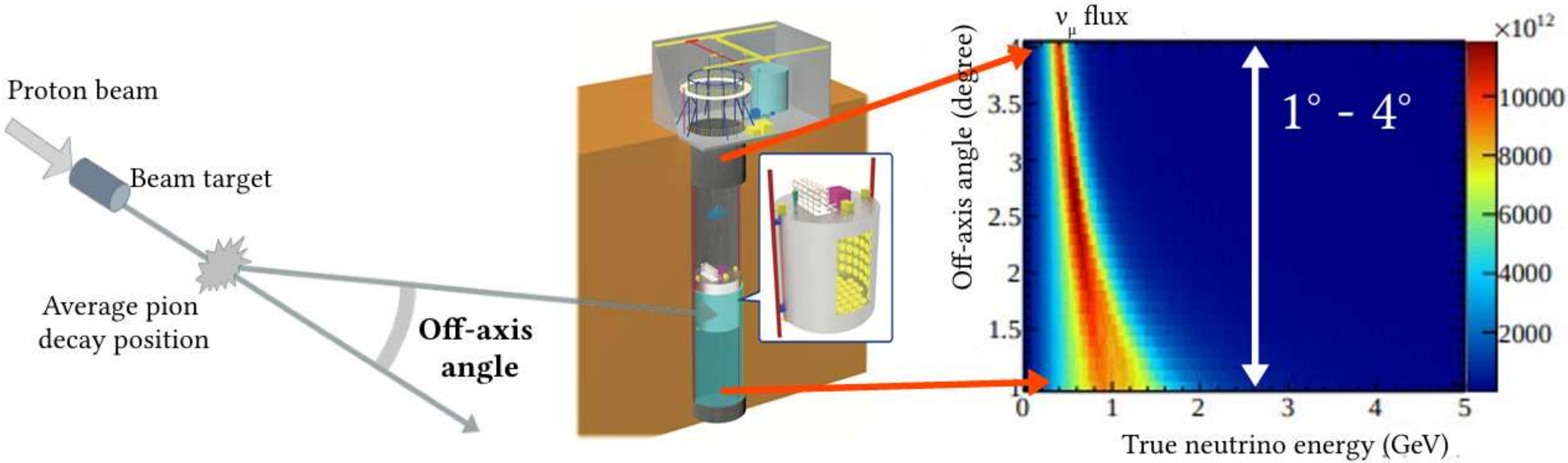
IWCD



@ ~1km

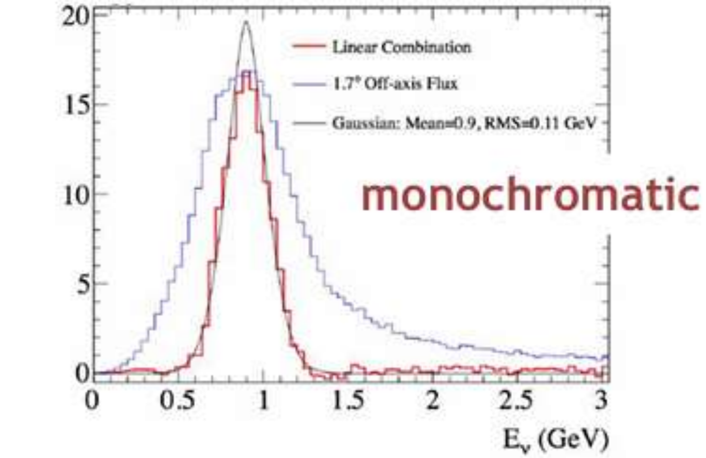
- ◆ Sub-kiloton scale water Cherenkov detector (Φ8m x 6m)
  - ⟹ 480 photosensor modules inside the tank
  - ⟹ 60 ton of fiducial volume
- ◆ Gadolinium loading option to add neutron detection capability

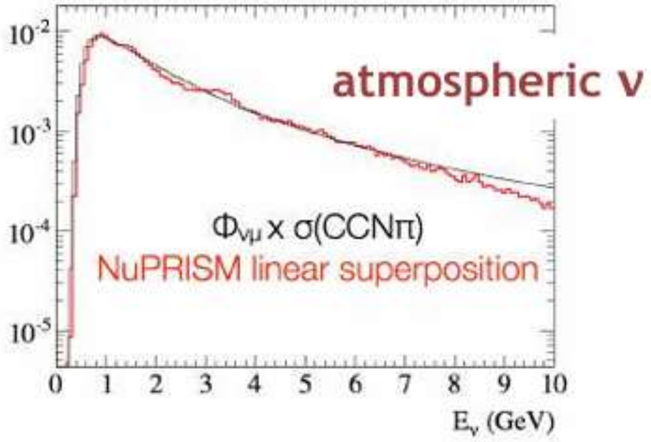
The vertically movable detector

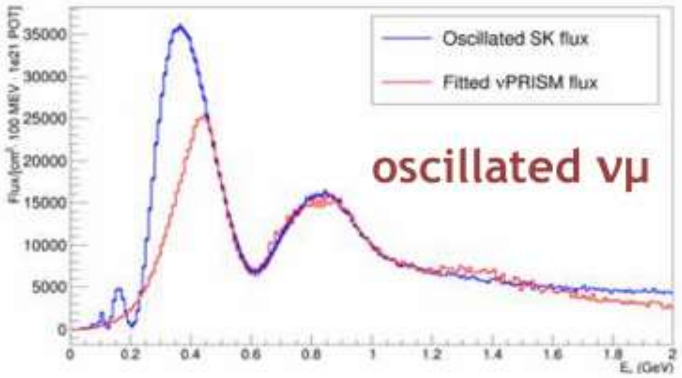


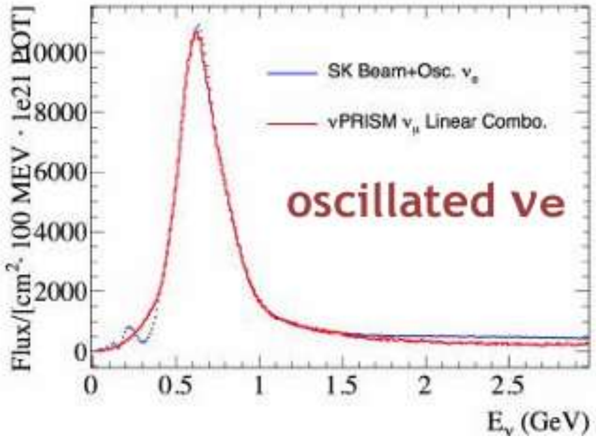
- Neutrino energy spectrum depends on off-axis angle
- Taking data at different vertical positions provides true energy information

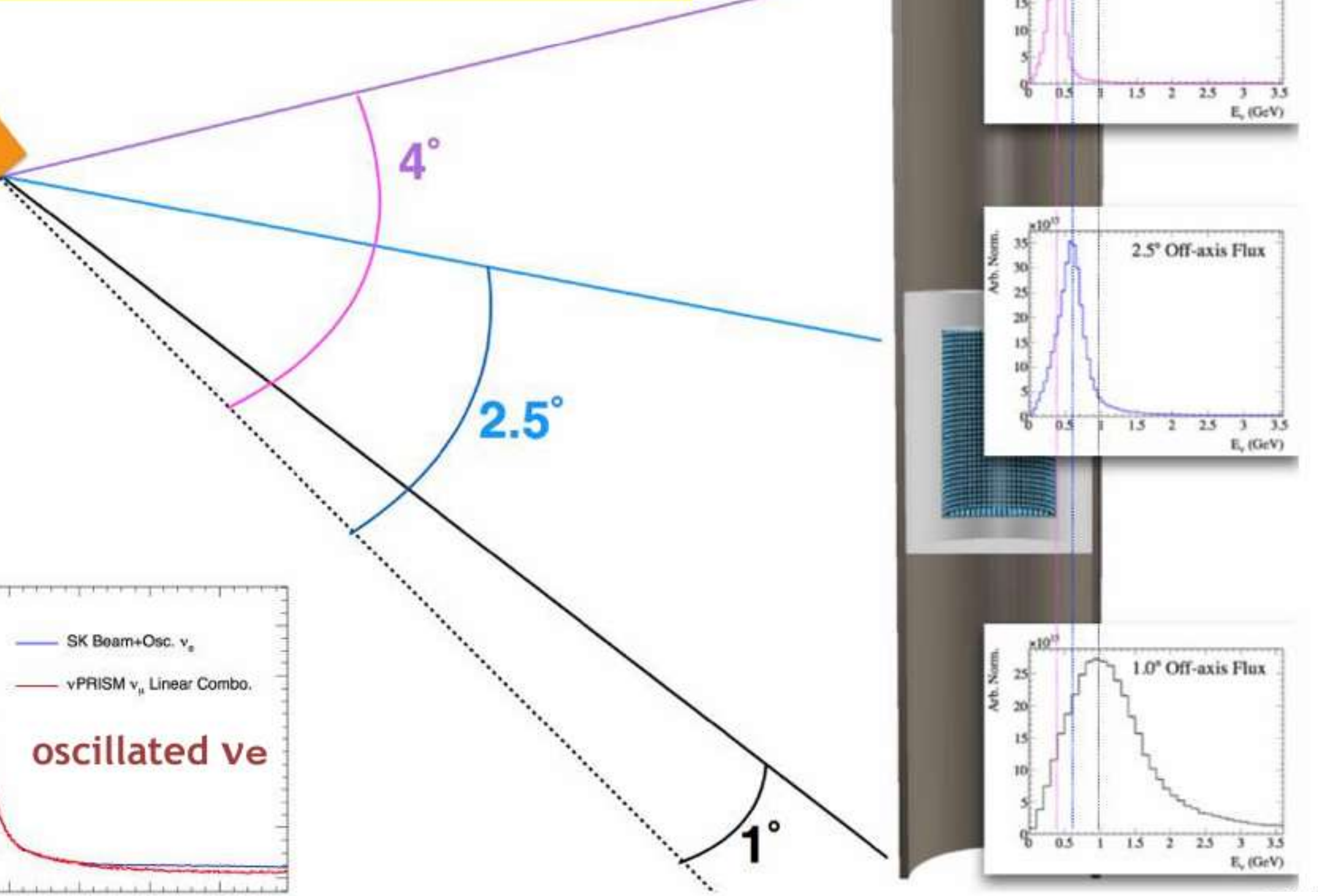
emulate the far spectrum using near detector spectra





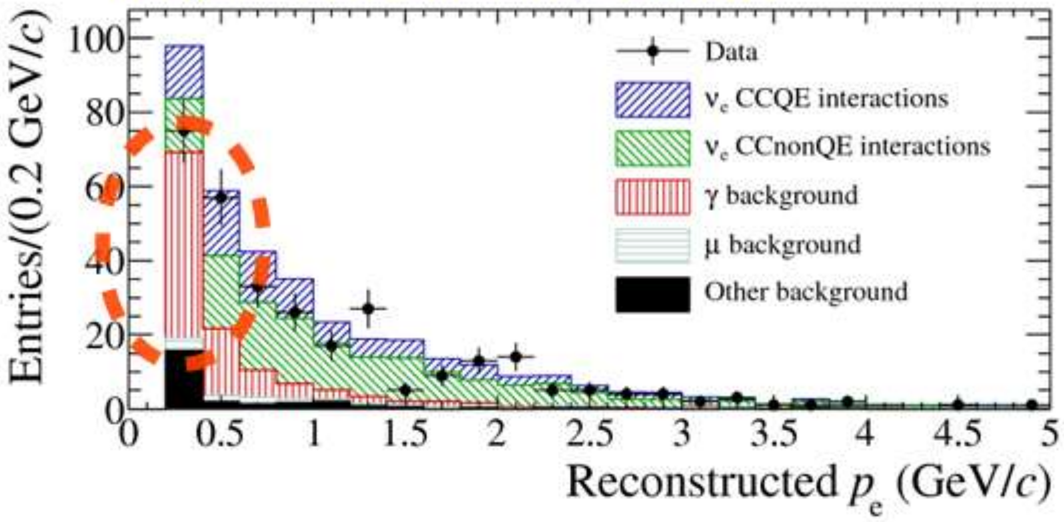






Active water shielding

Phys. Rev. Lett. 113, 241803



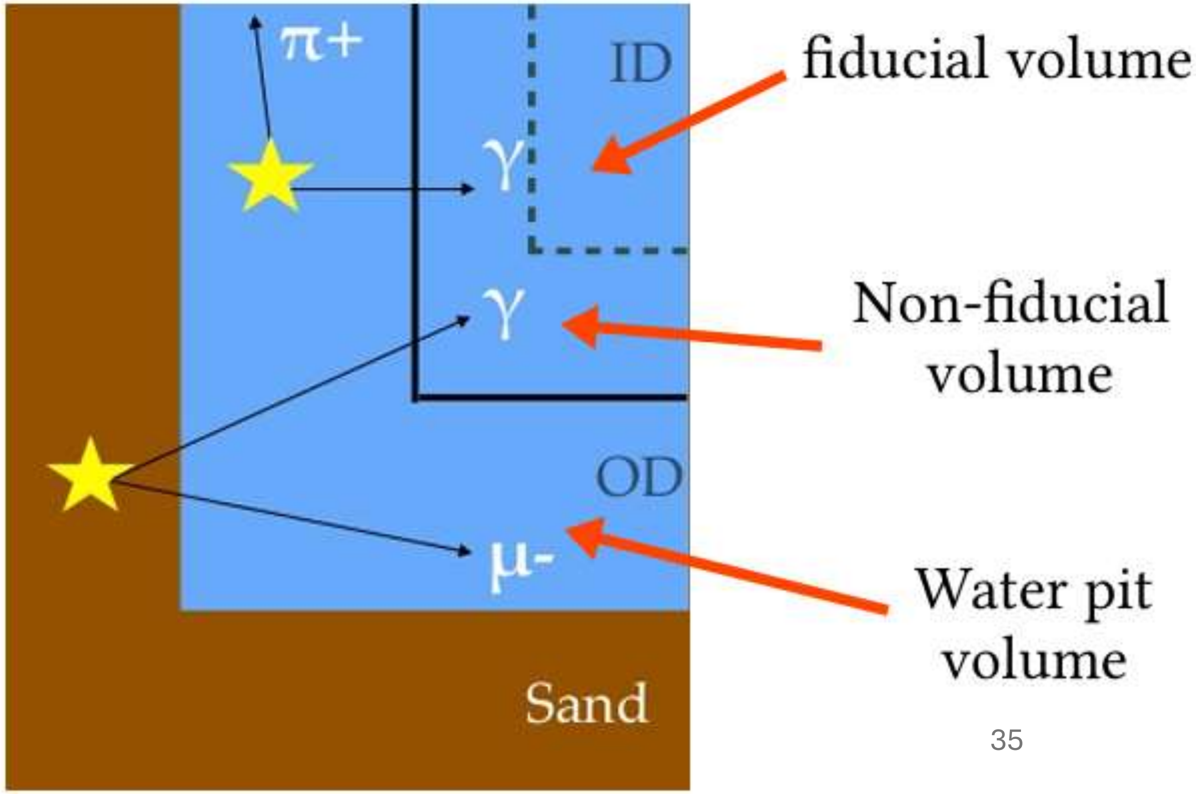
◆ T2K results are suffering from large background events induced by external high energy γs

⇒ Reduction of this background is important

◆ IWCD has two regions that can serve as active shield for protecting the γ background

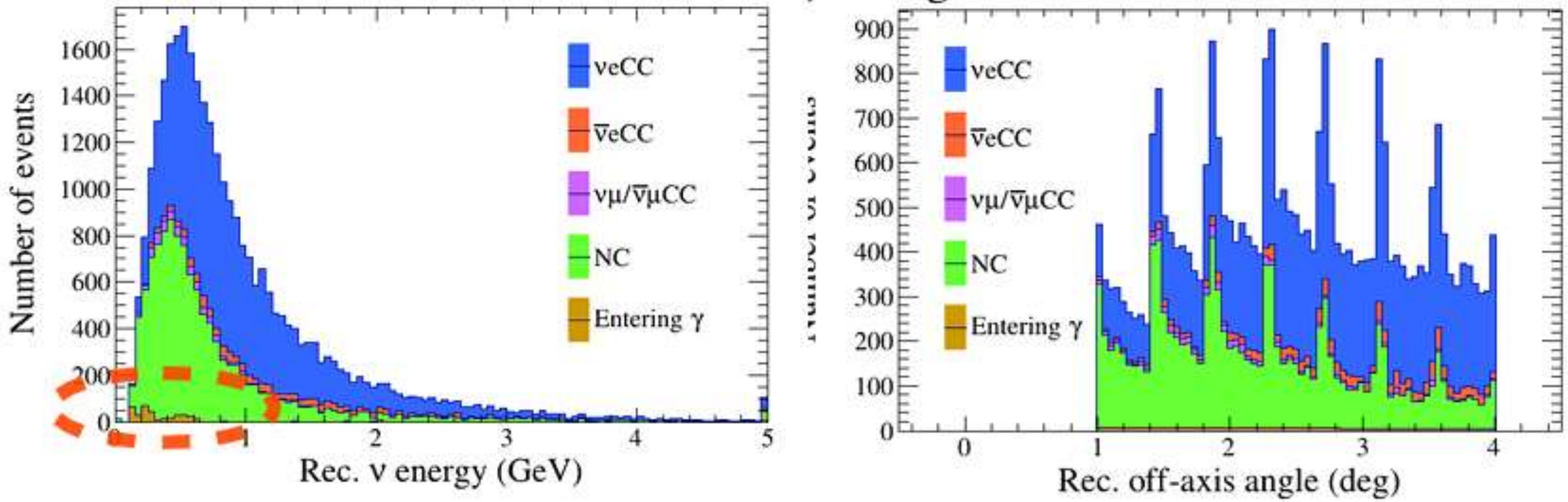
⇒ water volume in the pit

⇒ non-fiducial volume inside the detector

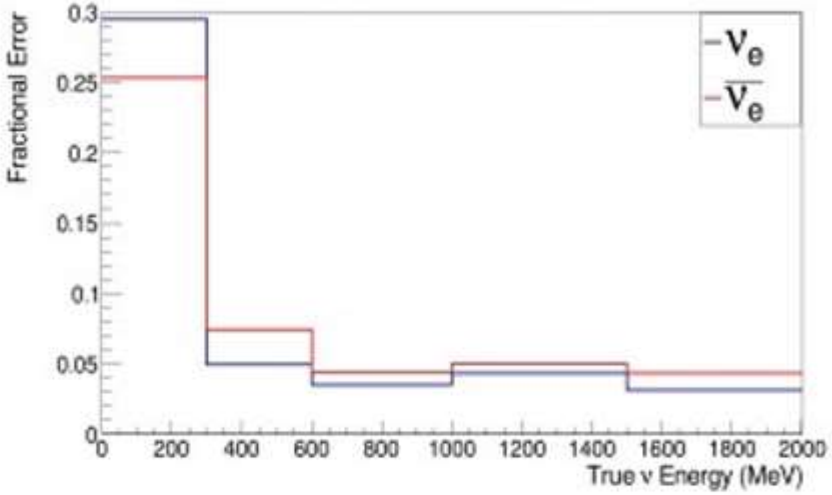


ν_e and $\bar{\nu}_e$ cross-section measurements

ν-mode single-ring e-like events

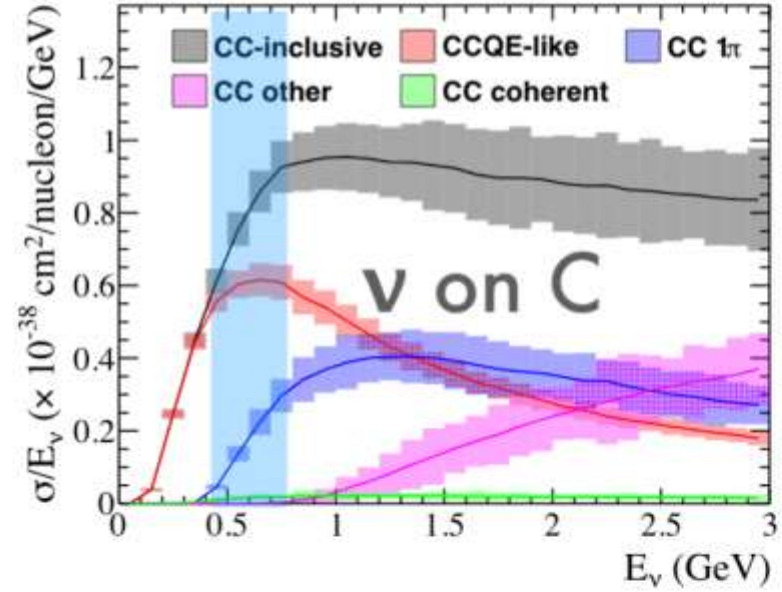


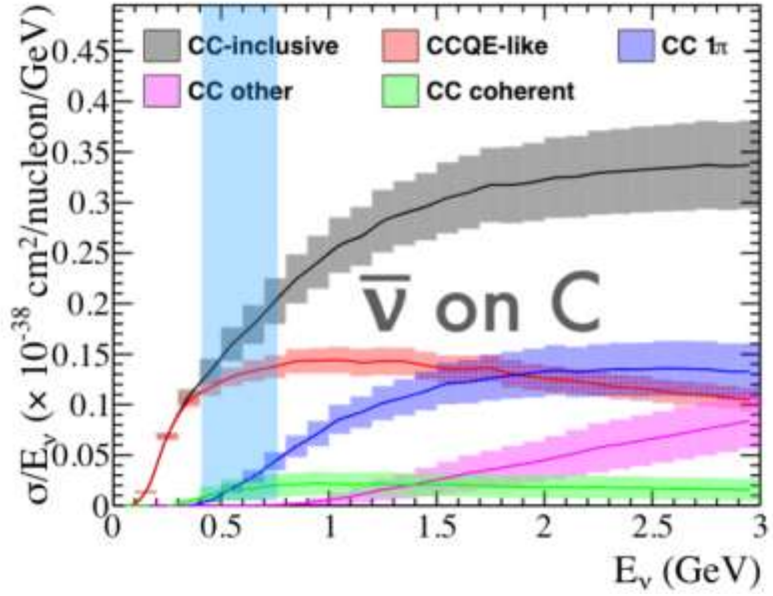
νe/ν̄e cross-section errors



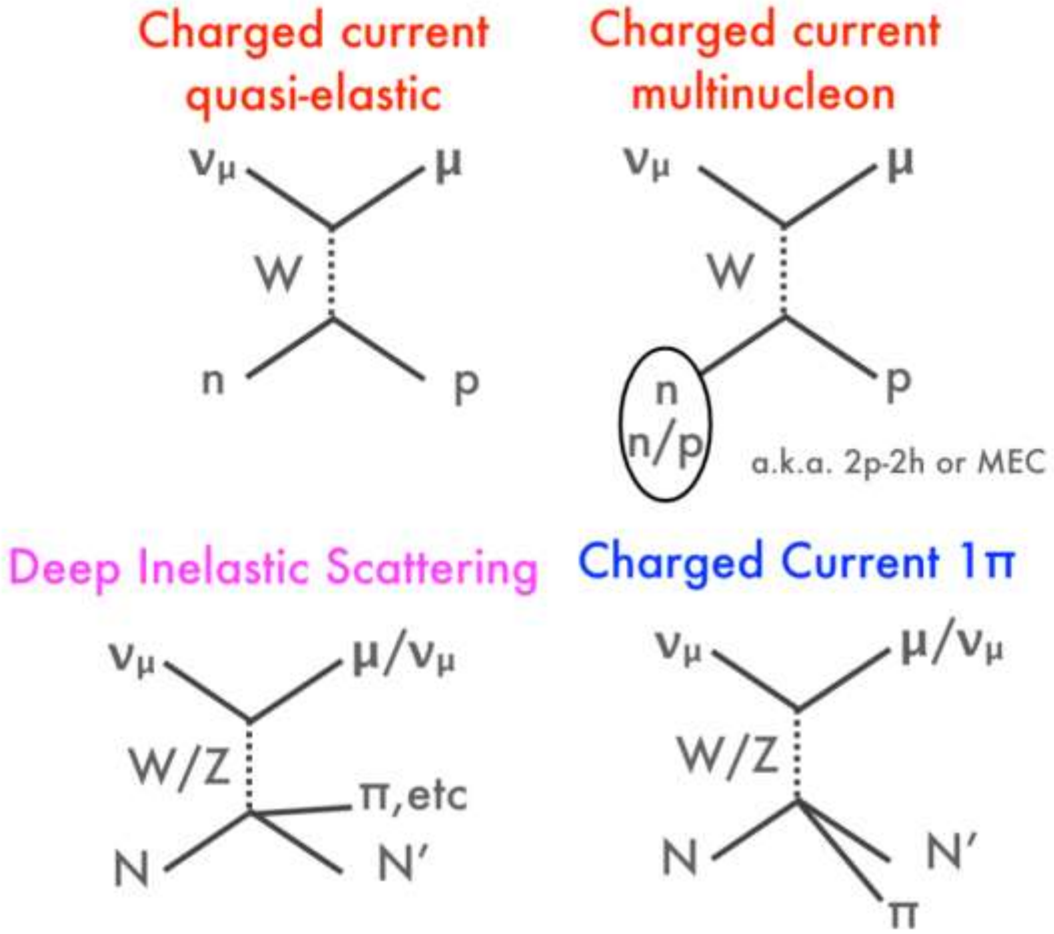
- About 1% of ν_e and $\bar{\nu}_e$ components in the beam can be identified
- Over 18,000 ν_e CC events enable a cross-section measurement binned in true energy
- Improved error on the ratio between the ν_e and $\bar{\nu}_e$ event rates at the far detector
  - ⇒ The true energy dependent constraints: **3.7%**
  - ⇒ T2K's theory based constraints: **5.0%**
  - } ⇔ Statistical error: **1.4%**

ν-N Cross Section Model





Uncertainties come from underlying model parameters and normalizations

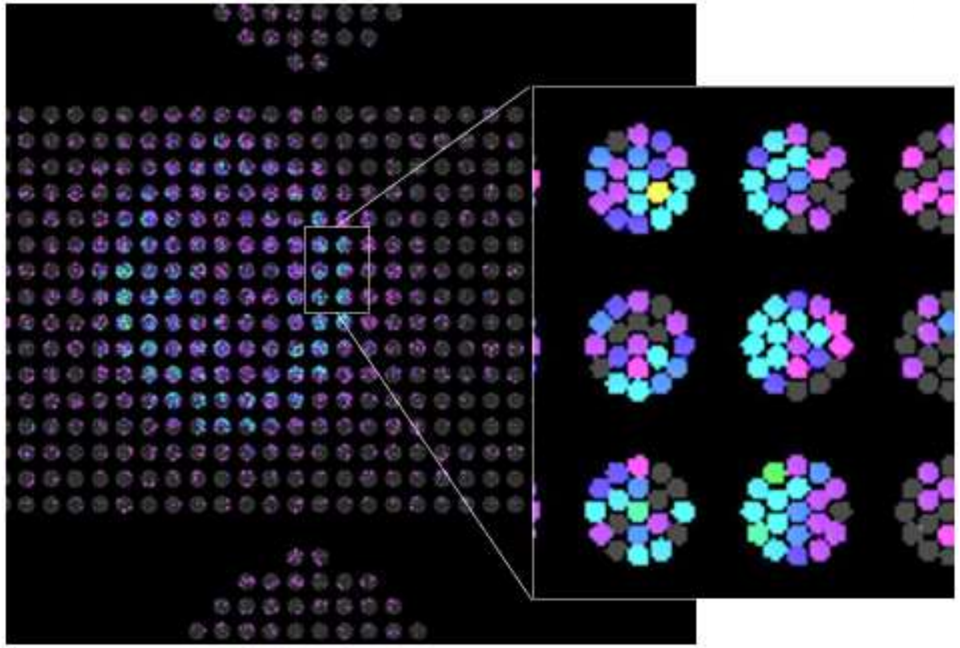


IWCD measurements
Of muon-neutrino
Interactions also
Important!

Photosensor module

◆ The detector size is much smaller than the far detector

⇒ Higher granularity and better timing resolution needed to utilize off-axis angle information



◆ 19 3-inch diameter photomultiplier tubes integrated in a water-tight module

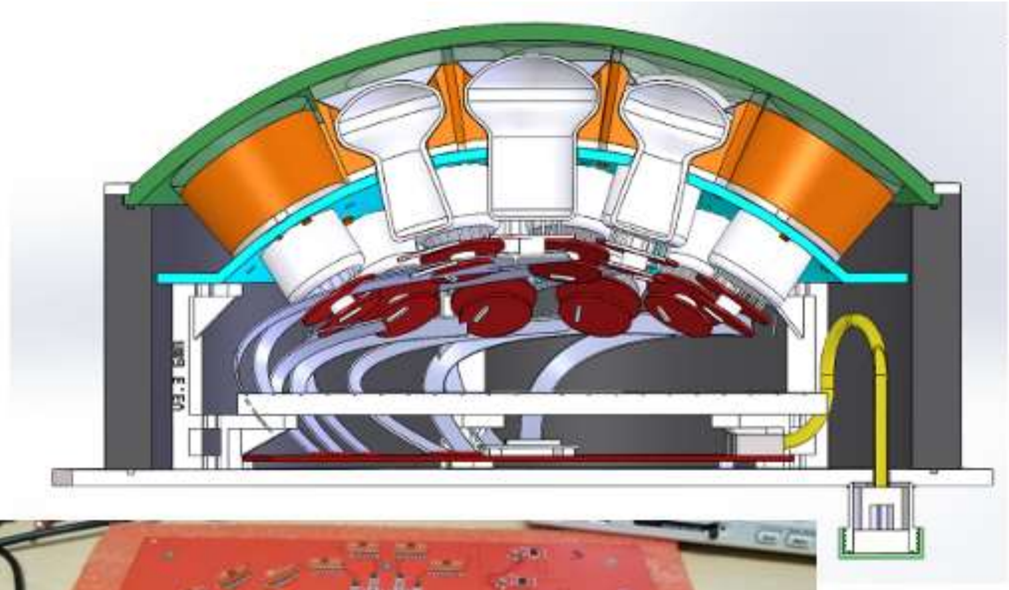
⇒ Acrylic dome, PVC cylinder, and stainless steal backplate used

⇒ Each tube optically coupled to the acrylic dome by a gel, in order to enhance light collection

⇒ Tube placement being able to gain directional information

Electronics and photosensor

◆ High voltage circuits and readout electronics mainboard are inside



◆ 20-channel 125 MSPS FADC mainboard developed

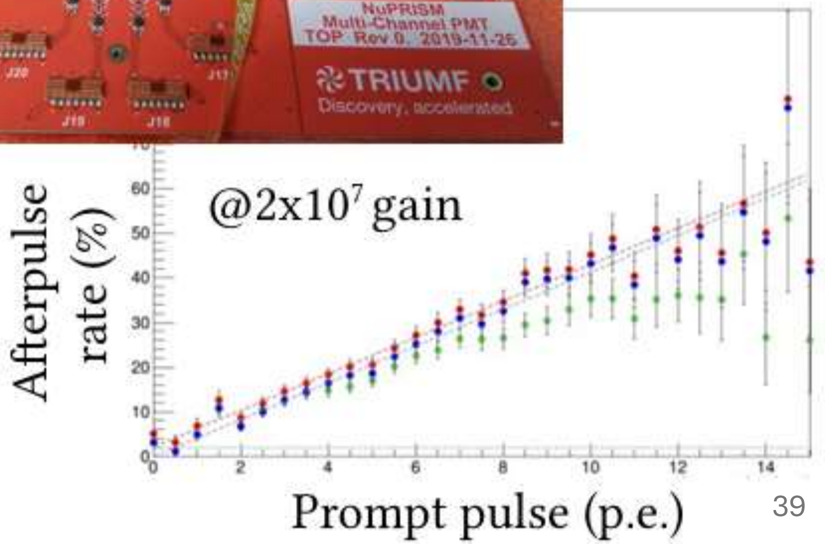
⇒ Full waveform can be readout, allowing better pile-up event identification

⇒ Digitization and pulse-finding are done

⇒ LEDs mounted for detector calibration

◆ Characteristics of Hamamatsu R14374 3-inch PMT measured with the mainboard

⇒ TTS: ~1.5ns, Dark rate: <1kHz, Afterpulse rate: <5%/P.E.



Detector calibrations

- The moving detector needs to be precisely calibrated at each vertical position

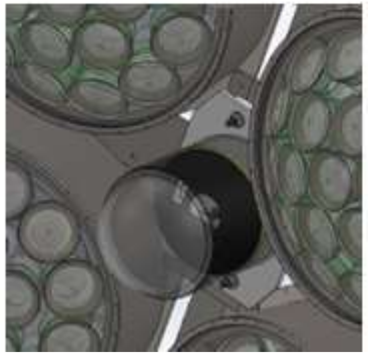
- An accurate calibration source deployment is essential to understand the position dependent detector response

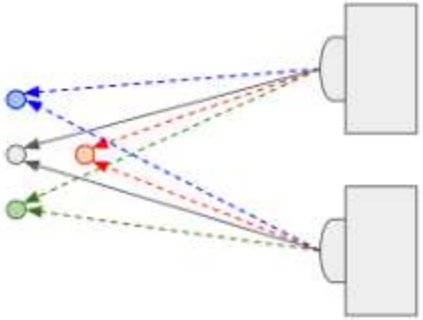
  ⇒ Auto 3D-depolyment system being developed

- For the small detector size, the positions of photosensor modules need to be understood precisely

  ⇒ Taking photos of the modules by cameras inside the detector

  ⇒ Using photogrammetry technique used for measuring the positions from the photos



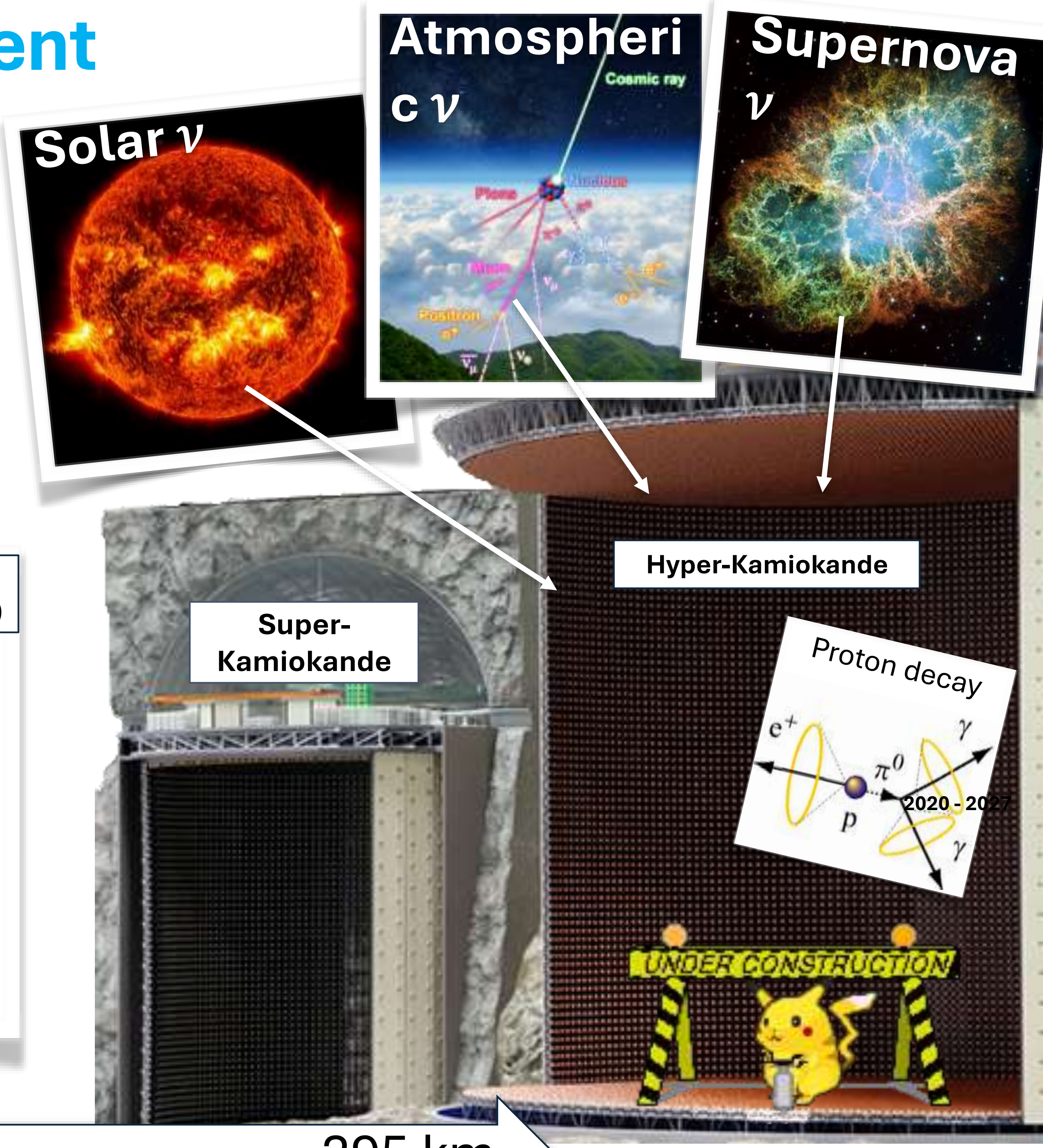


The Hyper-Kamiokande Experiment

Hyper-Kamiokande (Hyper-K) is a world-leading neutrino experiment, building on success of Super-Kamiokande & T2K.

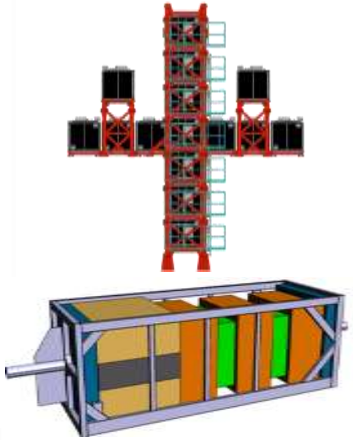
Broad & ambitious physics programmes covering many neutrino sources as well as proton decay measurements.

Water Cherenkov detector technology provides huge target mass with excellent particle ID and reconstruction capabilities.

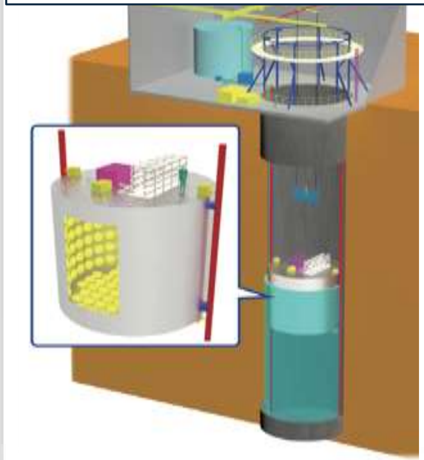


Water Cherenkov Test-beam Experiment (WCTE) at CERN

Near detectors



Intermediate Water Cherenkov Detector (IWCD)

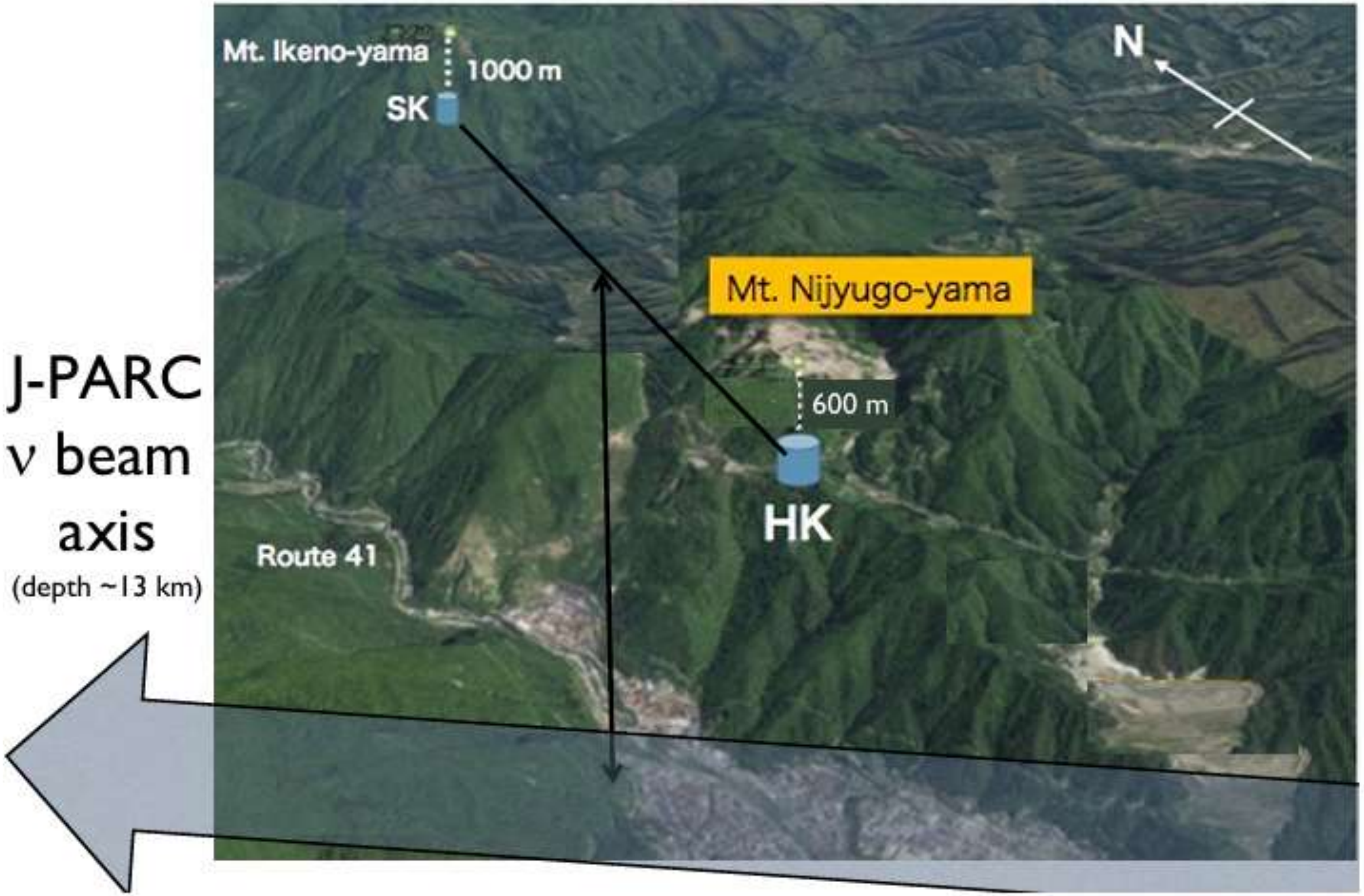


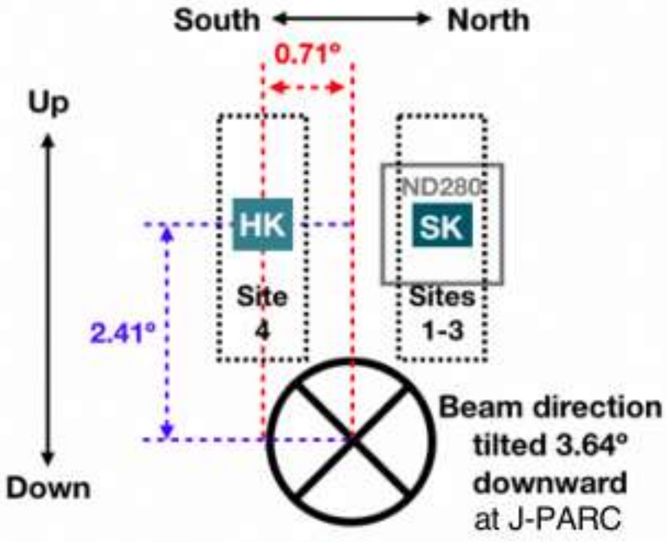
280 m → ~ 1 km → ~ 295 km

Detector Location and J-PARC ν beam

- 8 km south of Super-K
- 295 km from J-PARC and 2.5 deg. off-axis beam (same as Super-K)
- 600 m rock overburden

J-PARC
ν beam
axis
(depth ~13 km)





Hyper-K Detector

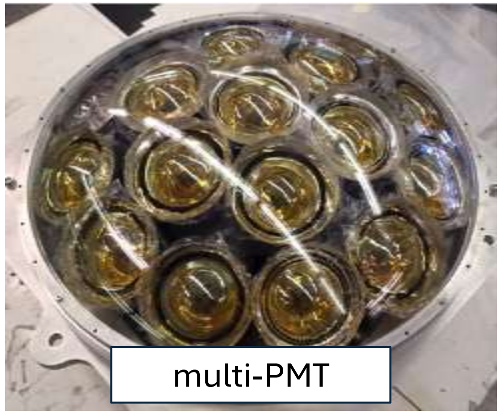
8 x increase in fiducial mass over Super-K

- 71 m tall x 68 m diameter = 258 kt total mass
  188 kt fiducial mass
- Outer detector region for active veto of incoming particles
  - 1 m wide around barrel, 2 m at top & bottom

New photo-detector technology for increased sensitivity

- 20,000 B&L 50 cm PMTs = 20% photo-coverage
  - 1.5 ns timing resolution (half that of SK PMTs)
  - Double quantum efficiency of SK PMTs
- Additional photo-coverage from multi-PMT modules
  - 8 cm PMTs grouped in modules of 19 PMTs
  - Improved position, timing, direction resolution
  - Also used for in-situ calibration of 50cm PMTs

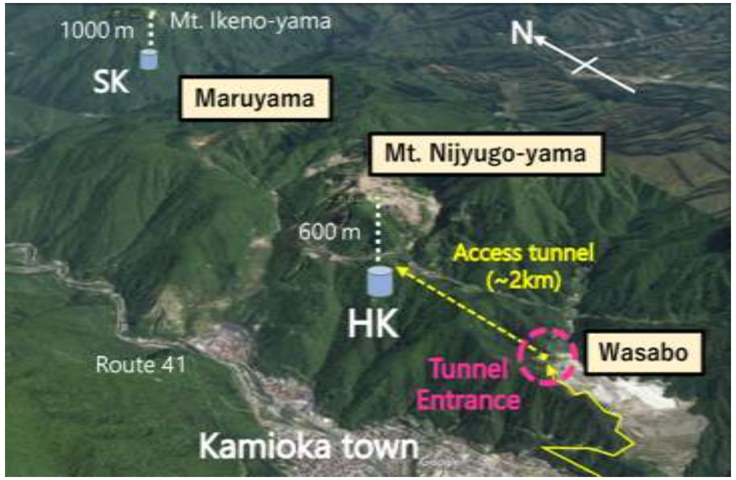

50cm B&L PMT


multi-PMT

Detector Construction

Access tunnel completed well!

Cavern excavation to 20 m depth!

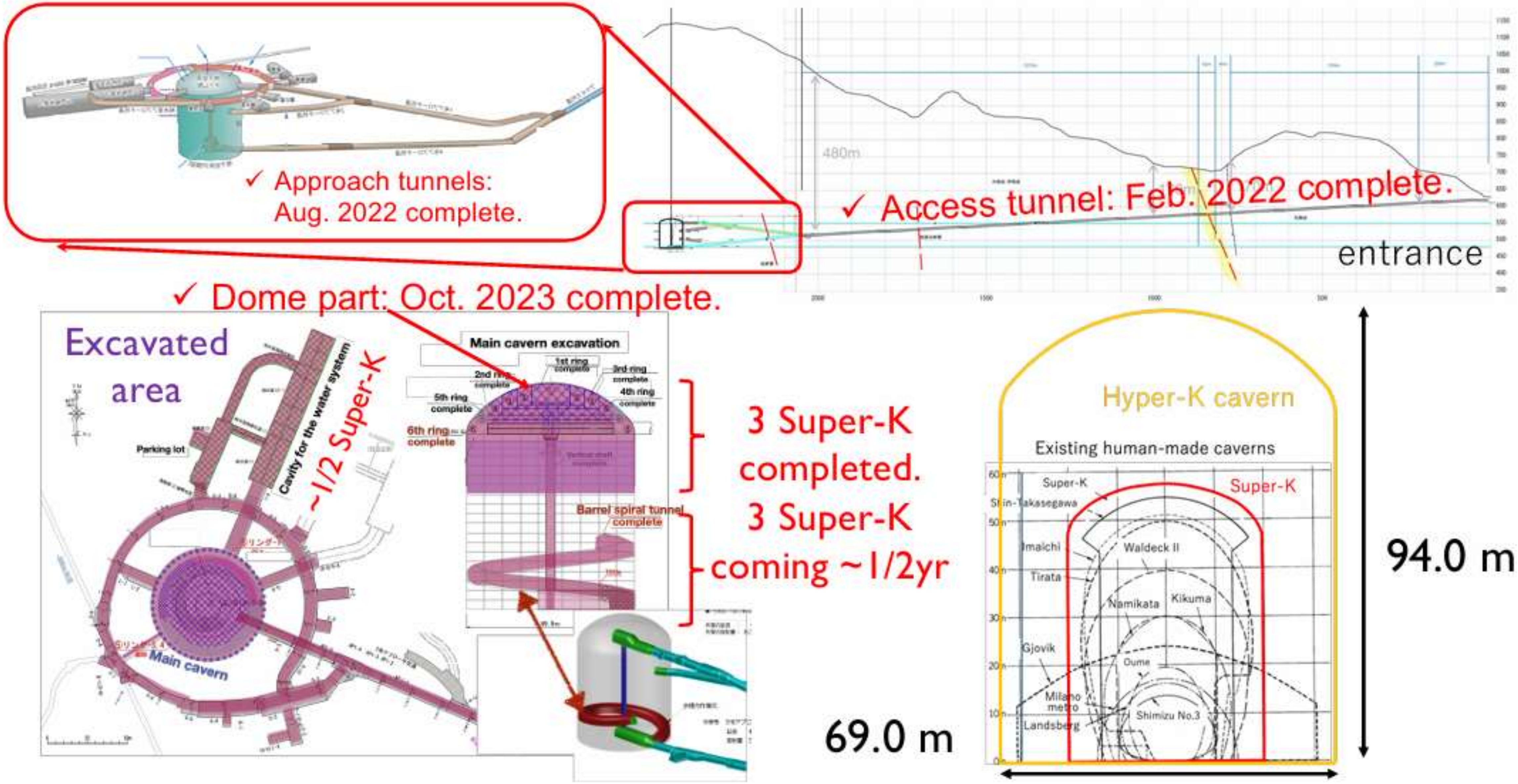


PMT production on schedule

Inspection and testing is ongoing

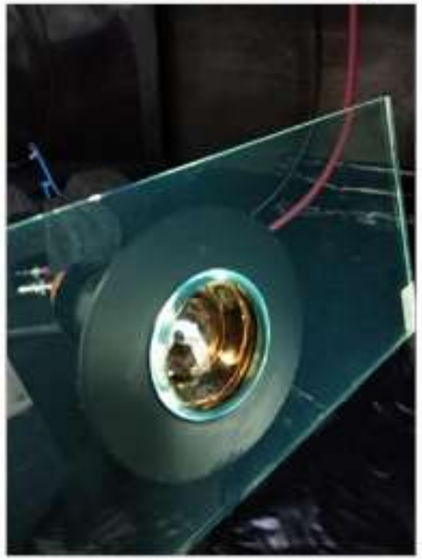
Half of PMTs delivered

Excavating the world's largest human-made cavern



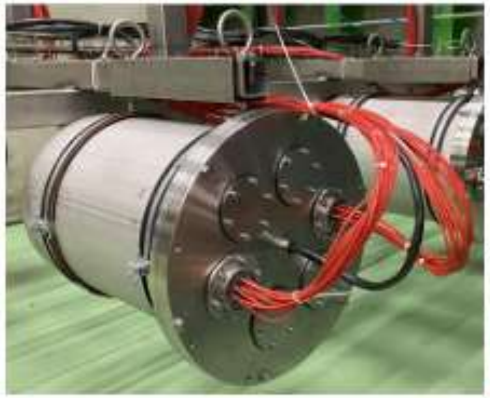
Photosensors and underwater electronics

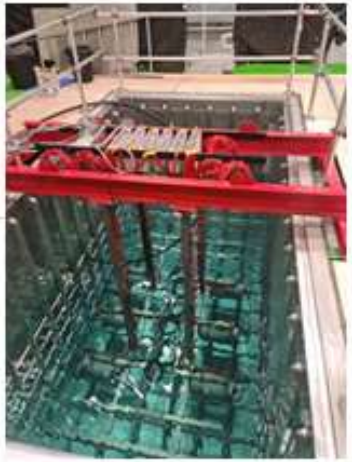
Outer detector: PMT+WLS plate



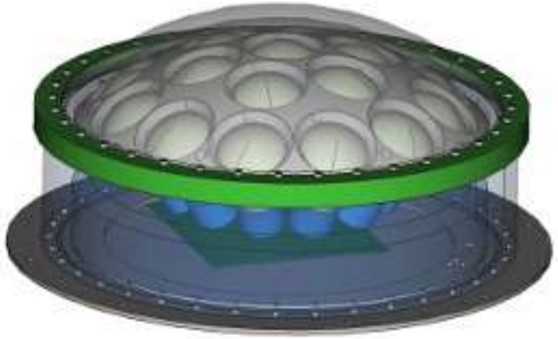
Photosensors/elec. mockup

Underwater electronics: Case design and feedthrough

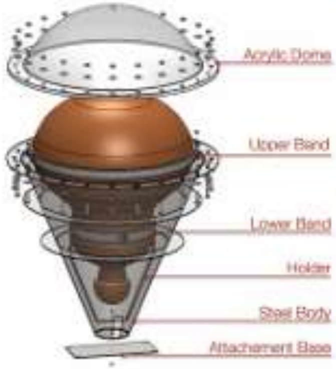




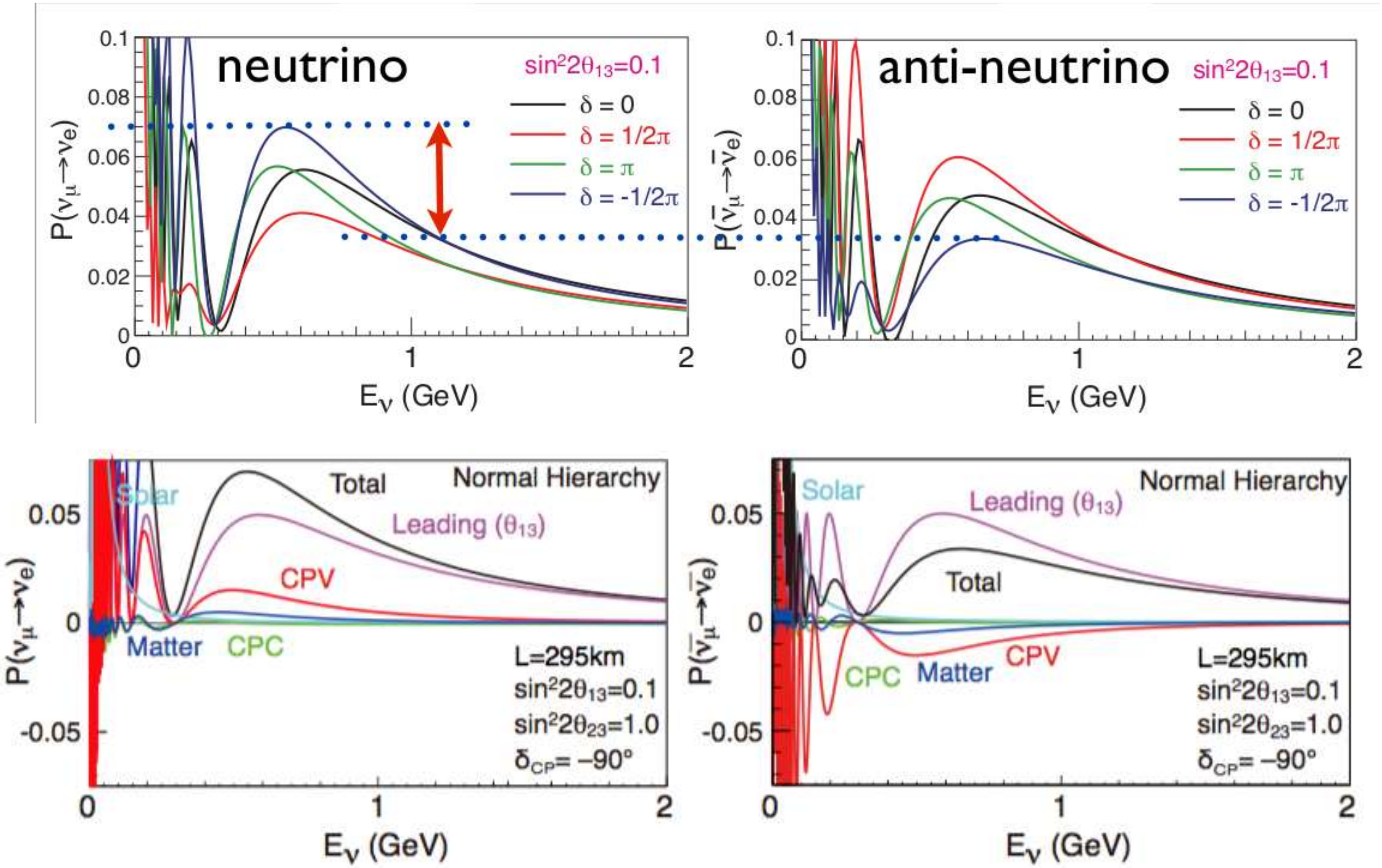
Multi-PMT module:



PMT cover

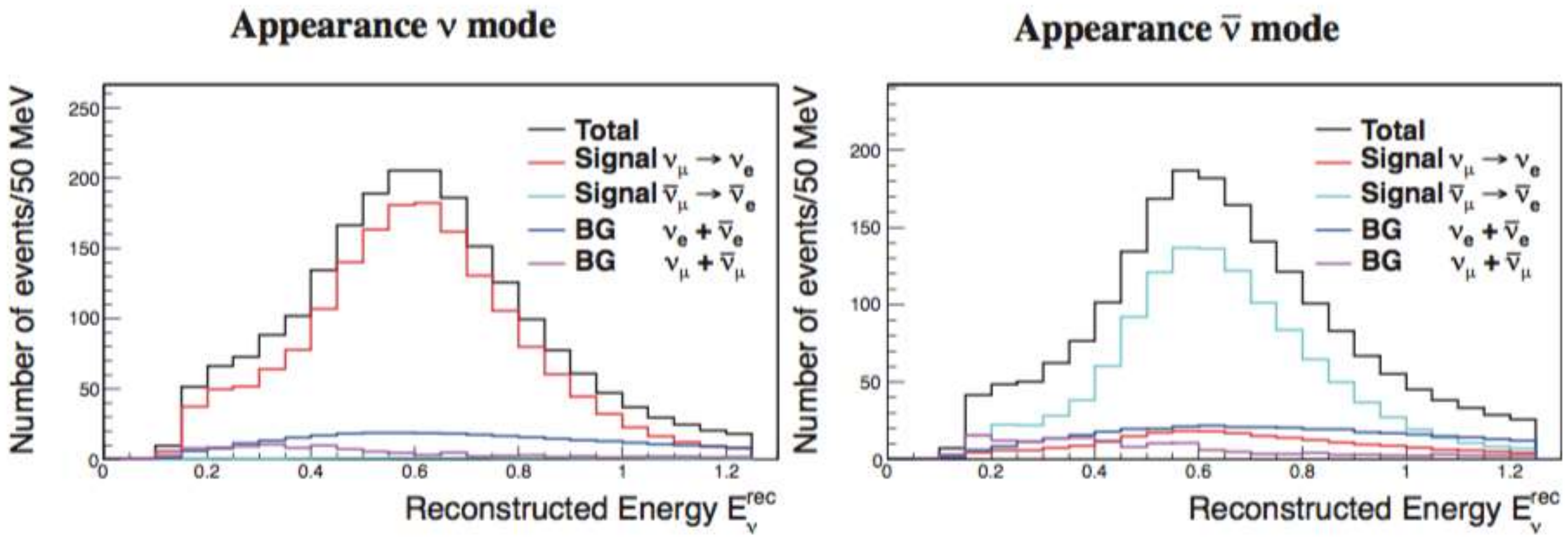


Long baseline physics -- At 295 km CPV dominates



Appearance event rates

10 years operation with 1.3 MW beam 3:1 ν to $\bar{\nu}$ ratio



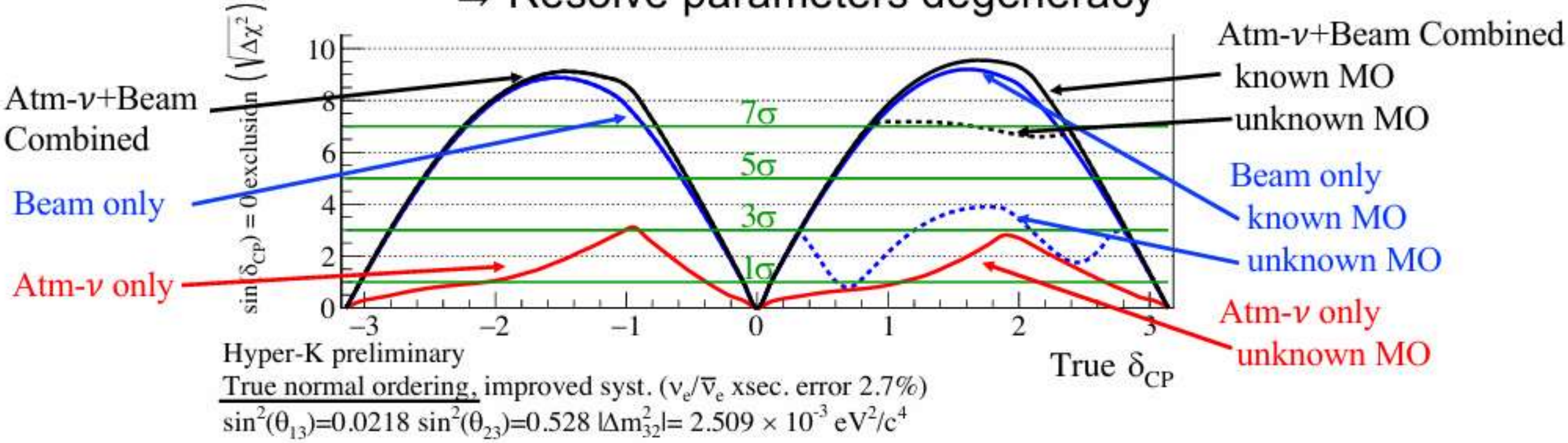
		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	BG Total	
ν mode	Events	1643	15	7	0	248	11	134	400	2058
	Eff.(%)	63.6	47.3	0.1	0.0	24.5	12.6	1.4	1.6	—
$\bar{\nu}$ mode	Events	206	1183	2	2	101	216	196	517	1906
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

Oscillation Measurements - Search for CP Violation

Strategy of oscillation measurement at Hyper-K

Combination of long-baseline and atm. ν observations

⇒ Resolve parameters degeneracy



	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ	→ 3.8 σ
	0.60	4.9 σ	→ 6.2 σ
θ_{23} octant	0.45	2.2 σ	→ 6.2 σ
	0.55	1.6 σ	→ 3.6 σ

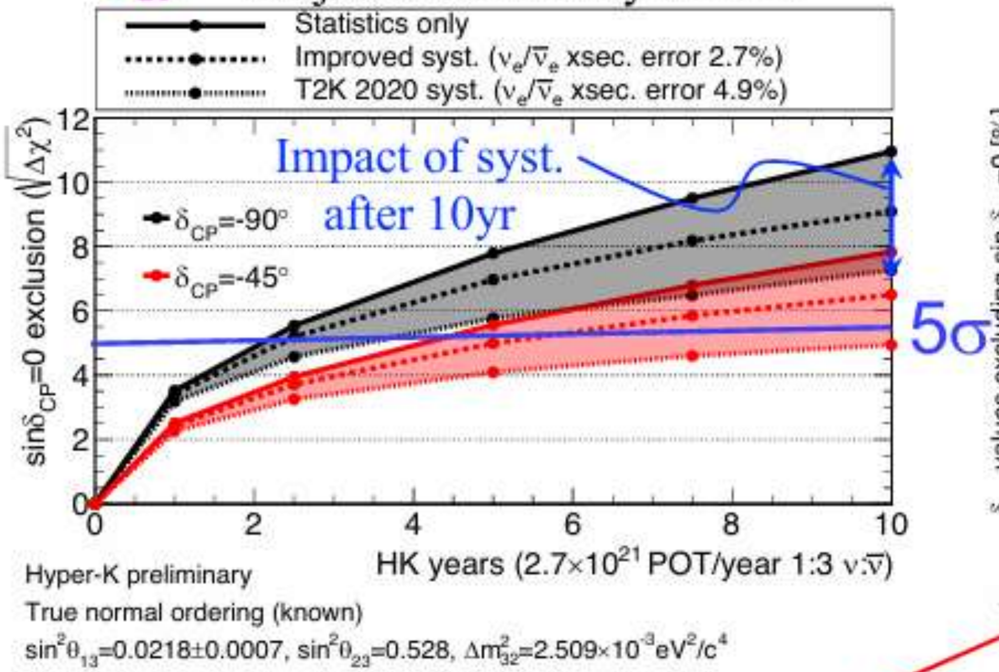
10 years with 1.3MW, normal mass ordering is assumed

Atmospheric neutrino:
sensitive to mass ordering by the earth matter effects
→ Constraints on mass ordering enhance sensitivity to CP violation by long-baseline

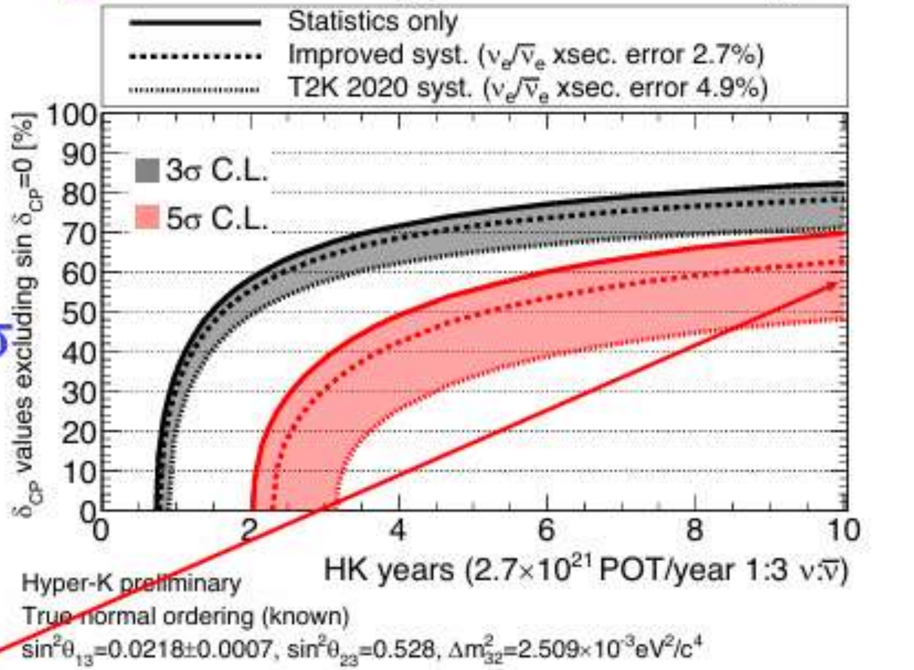
6

Precision measurement of neutrino oscillations

δ_{CP} Projected sensitivity to CPV



δ_{CP} Fraction of δ_{CP} to exclude $\sin\delta_{CP} = 0$



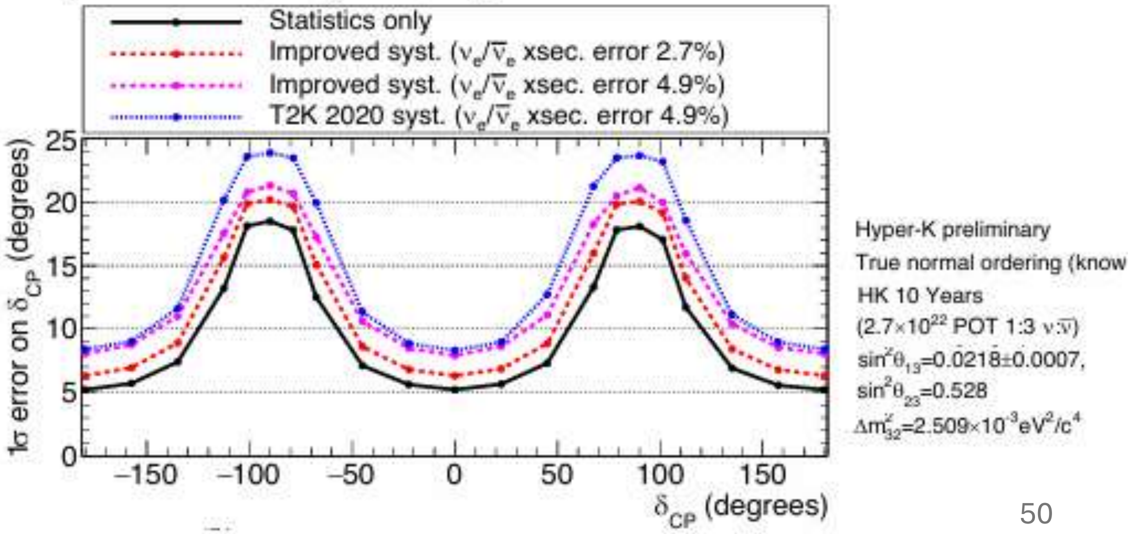
Discovery of CP violation at >5 σ for >60% of δ_{CP}

1σ resolution of δ_{CP} in 10 yrs

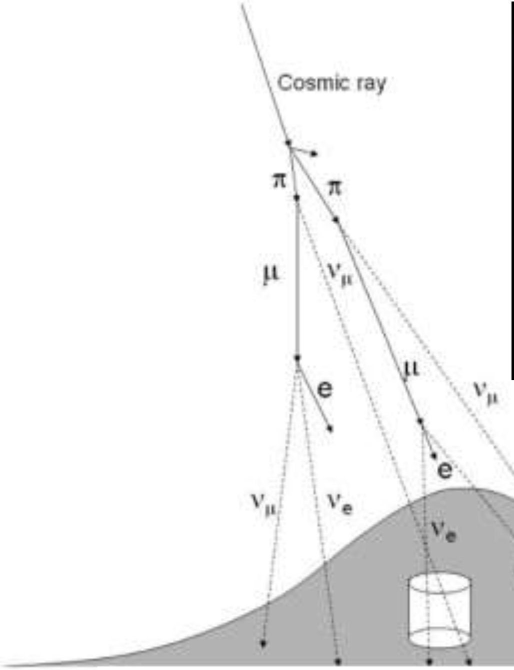
~20° for $\delta_{cp} = -90°$ / ~6° for $\delta_{cp} = 0°$

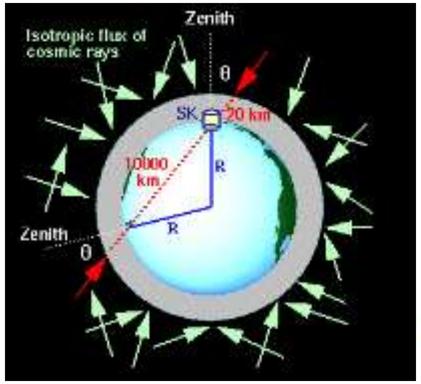
Reduction of systematic uncertainty has sizable impact:

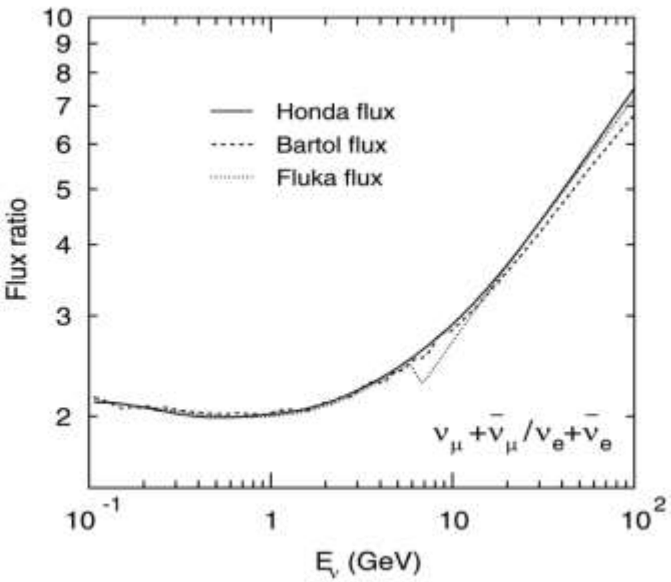
- Upgrade of ND280 + ~600 ton Intermediate Water Cherenkov detector (IWCD)
- Aim to suppress detector error below 1%



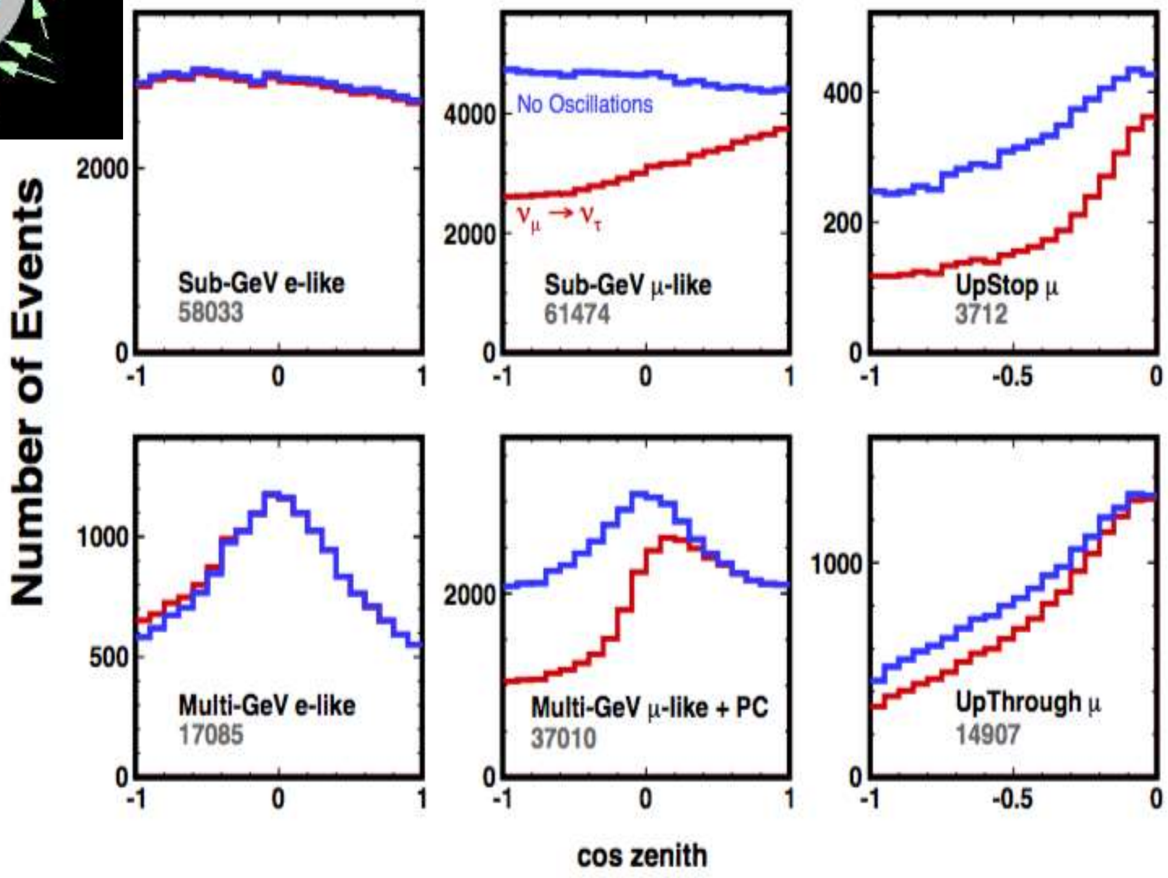
Atmospheric neutrino sample







Red is expected event rate for
10 years running, normal hierarchy and maximal mixing

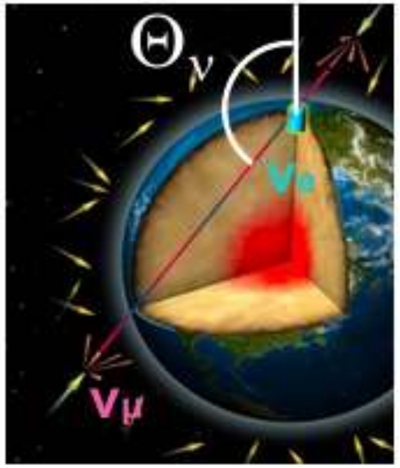


Atmospheric 3-flavor ν beam (0.1-10^3 GeV, 10-13,000 km)

- The wide range of E (0.1~10^3 GeV) and L (10 km ~13,000 km) provide an excellent opportunity to study various properties of ν.
- Study of the earth matter effect to determine neutrino mass ordering
- Unique tests of exotic properties

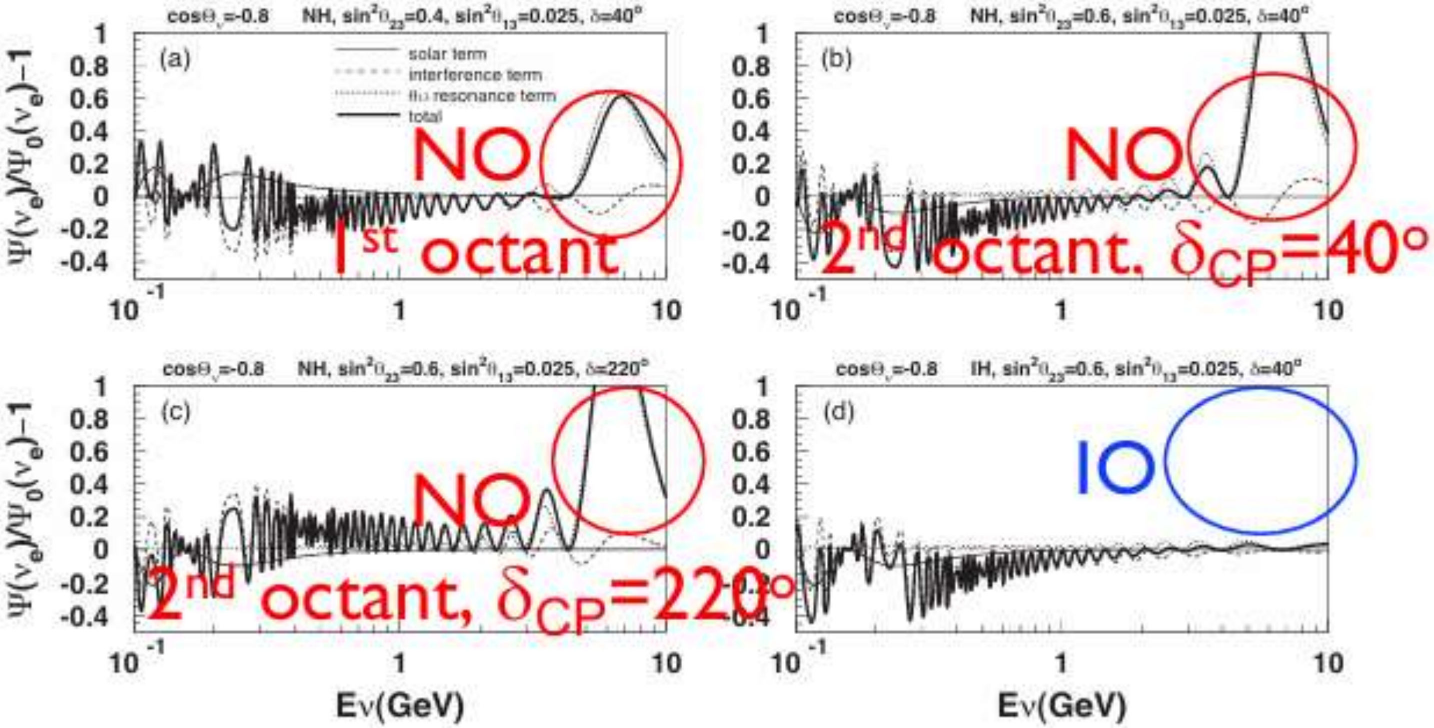
~80 events/day

Oscillation studies with wide range of E and L. The matter effect solves MO.



In case of $\cos\Theta_\nu$=-0.8, the effect of MO can be observed.

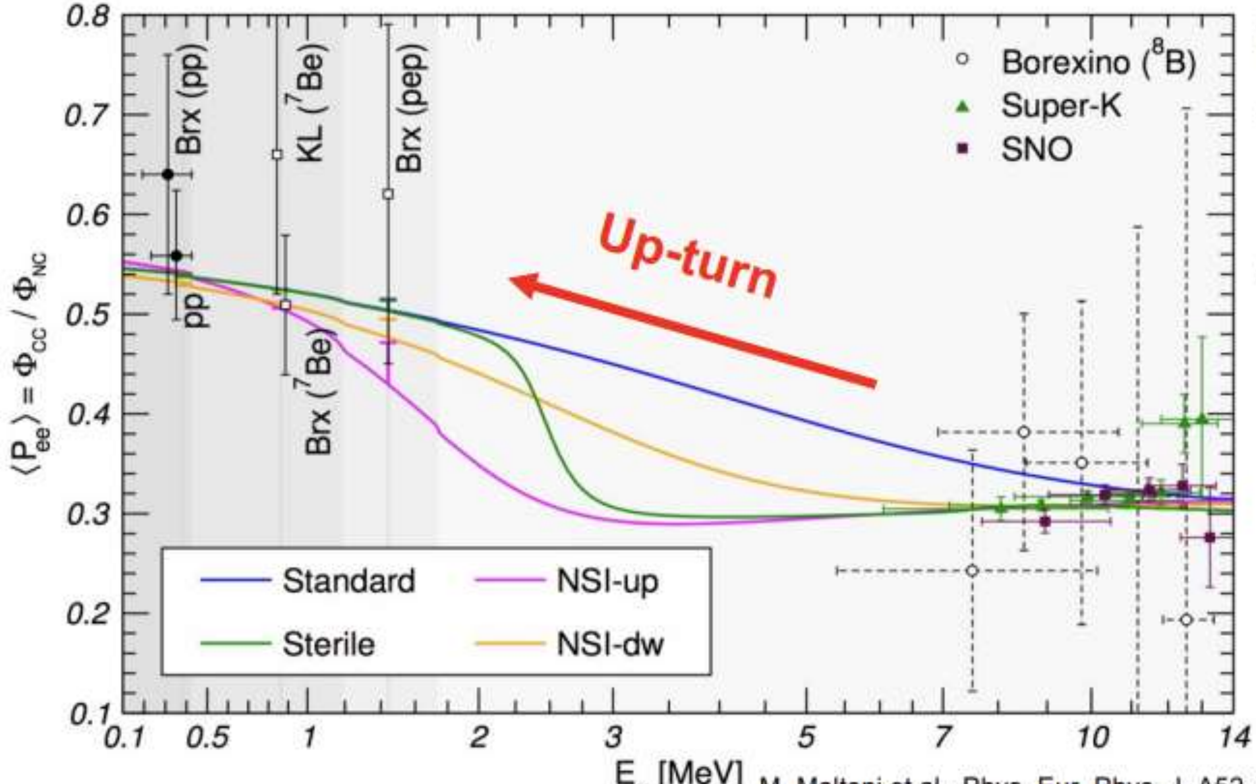
Effect of Mass Ordering (MO) and CP on ν_e flux



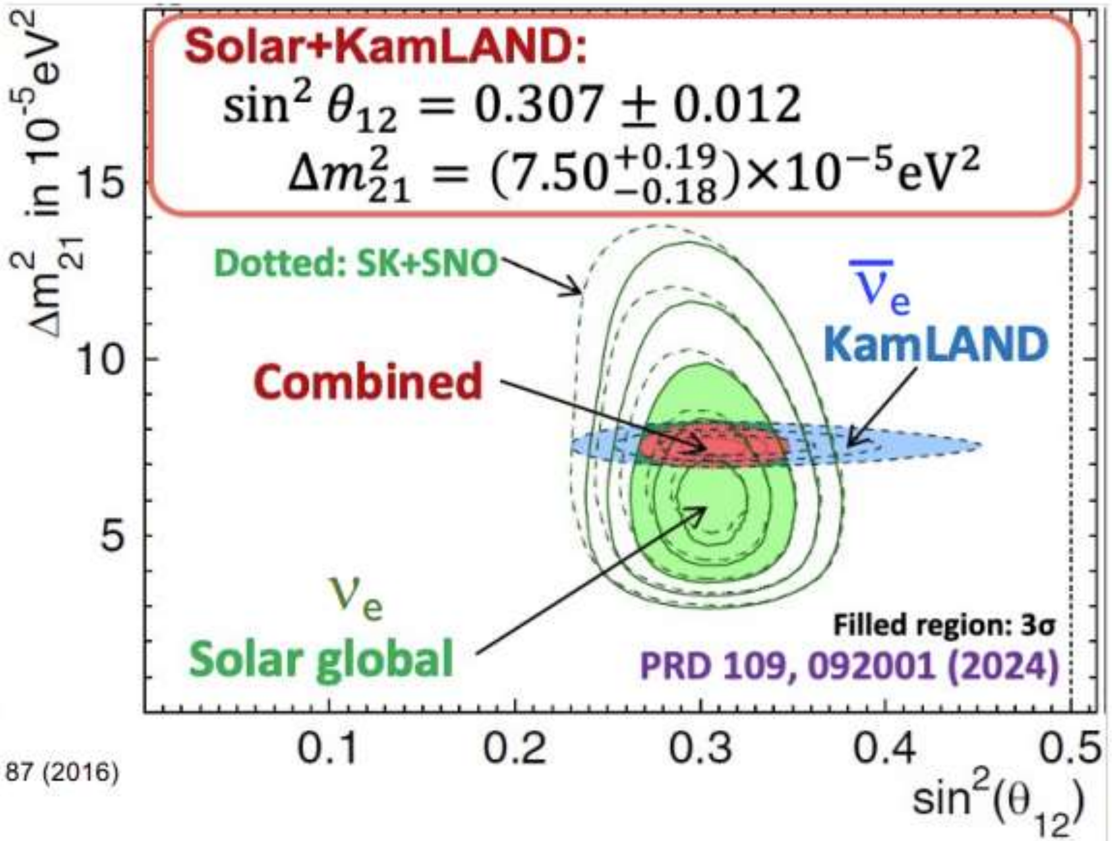
Solar ν spectrum & possible differences in $\nu_e/\overline{\nu}_e$ oscillation

Confirm MSW effect by observing spectrum distortion "up-turn"

Compare ν_e, $\overline{\nu}_e$ oscillation (currently ~1.5σ tension in solar/reactor ν)



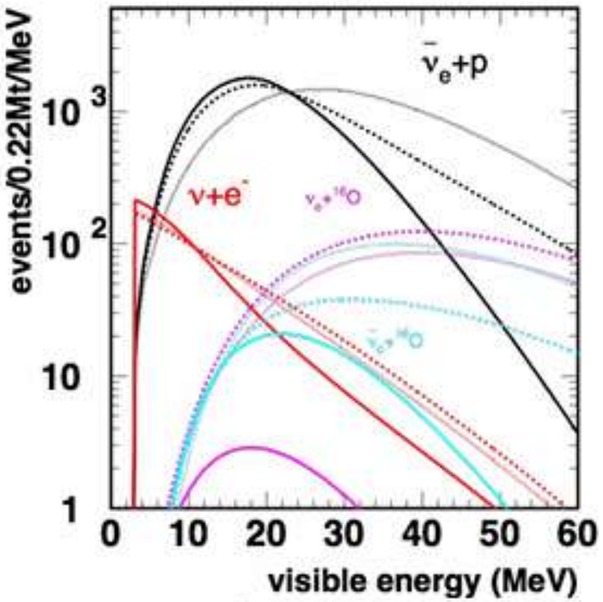
M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)

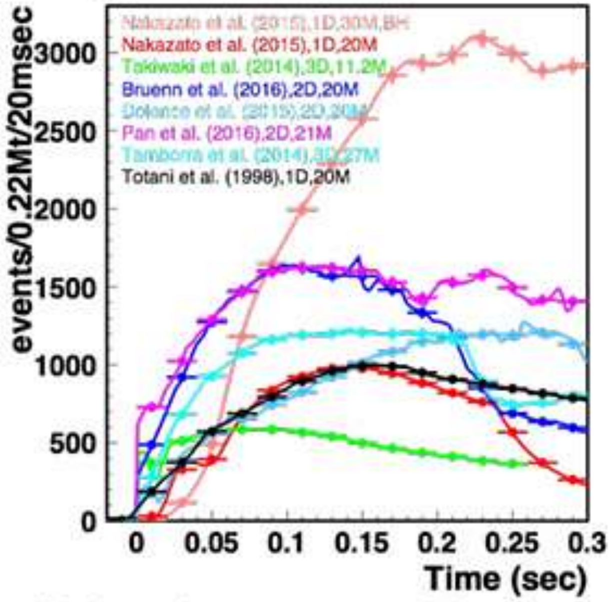


~130 events/day

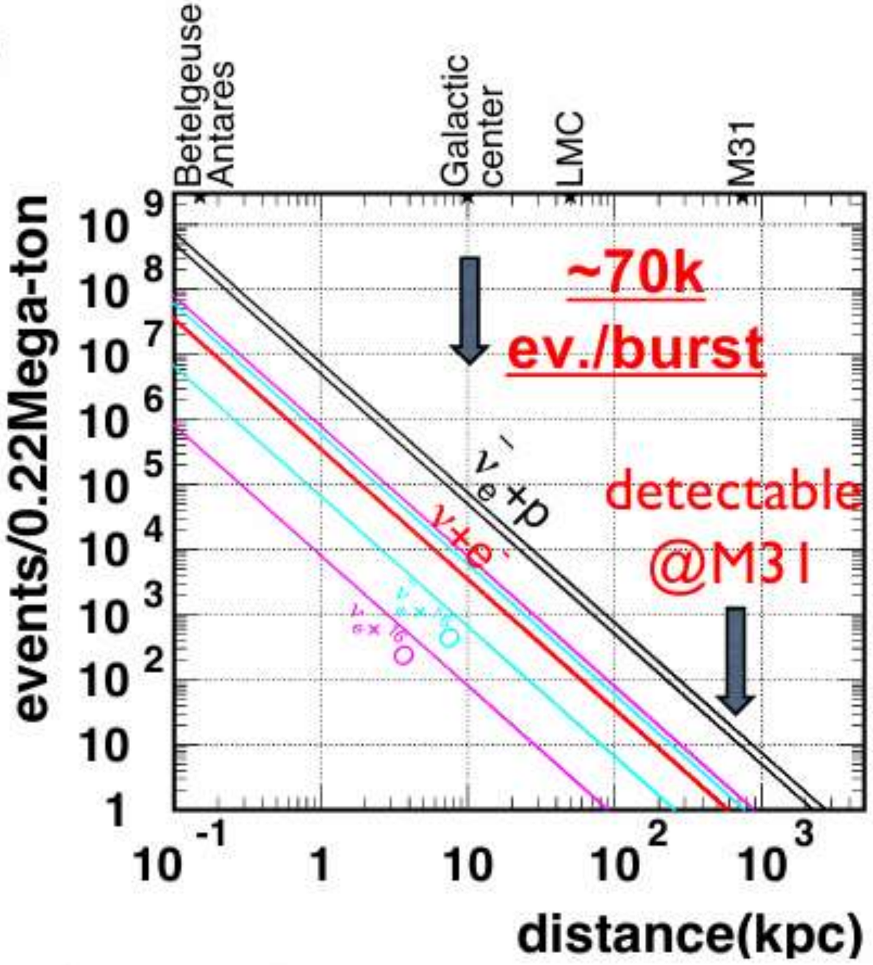
- > 3σ sensitivity for the spectrum up-turn in 10 yrs (E_{th}=4.5 MeV).
- ~2σ day/night sensitivity expected for the difference in $\nu_e/\overline{\nu}_e$ osc. in 20 yrs.

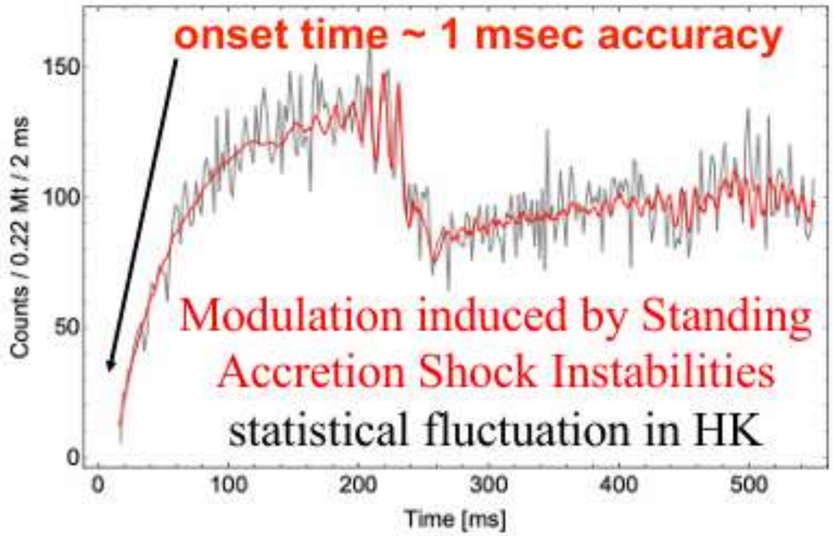
Astrophysics: Supernova burst ν

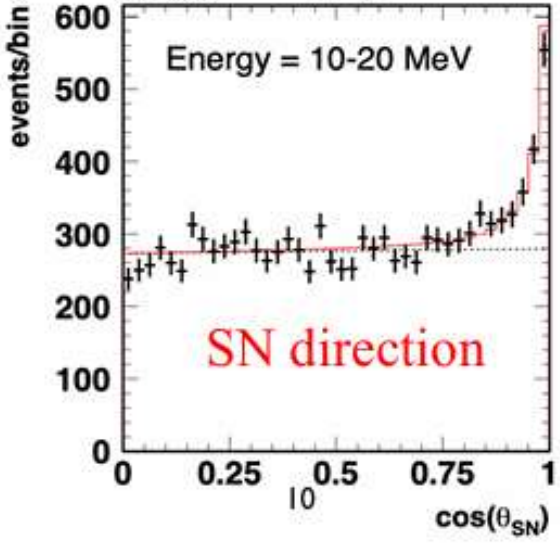




galactic supernova at 10 kpc (our r_{galaxy}= 8 kpc)





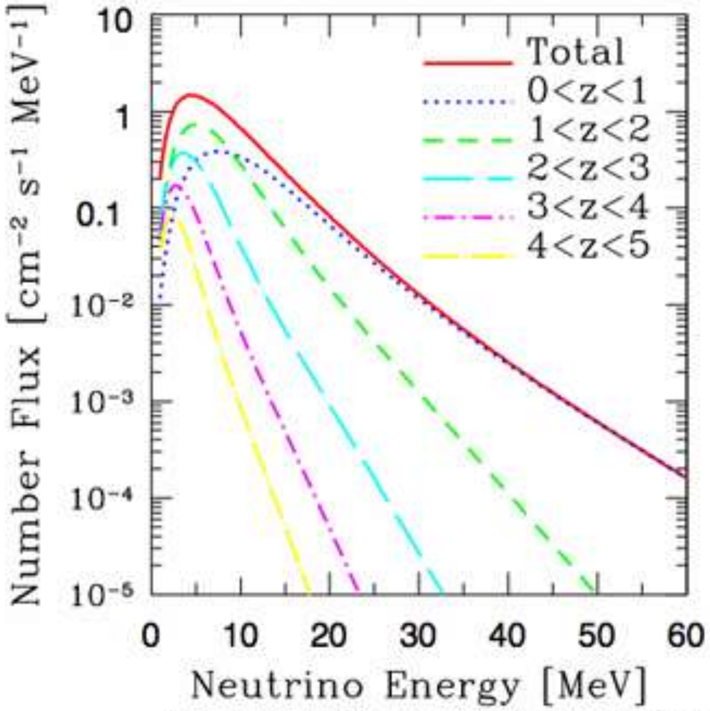


~70k events/burst at 10 kpc

- explosion mechanism,
- BH/NS formation,
- alert with 1° pointing

Diffuse Supernova Neutrino Background (DSNB)

DSNB energy spectrum including red shift



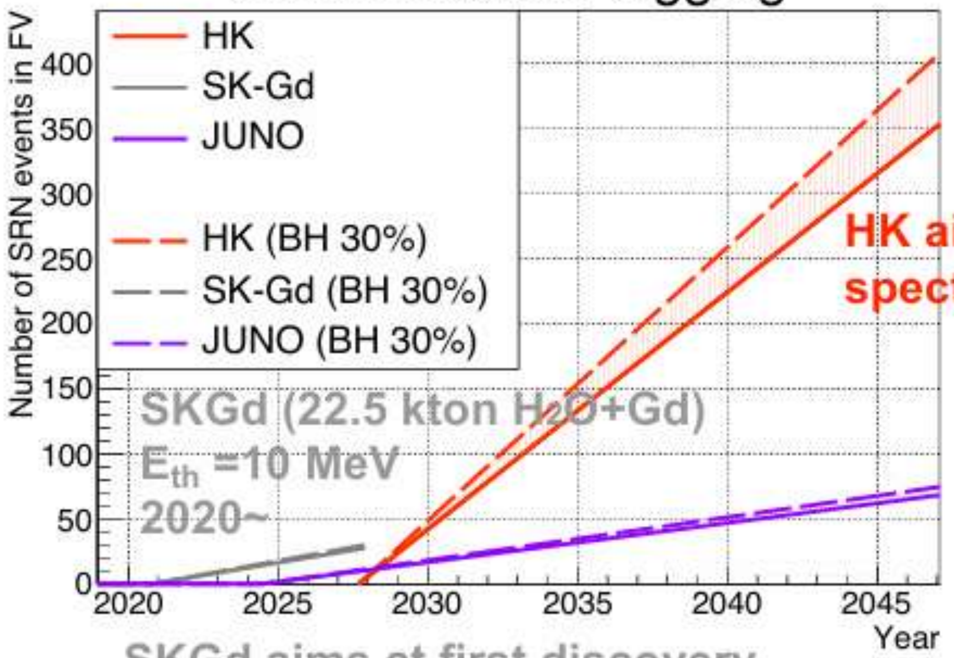
S. Ando and K. Sato, New J. Phys. 6, 170 (2004)

$$\frac{dF_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{\max}} R_{SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}\frac{dz}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}},$$

Neutrinos from supernova explosions in the early universe to the present day

integrated flux ~10 $cm^{-2}sec^{-1}$

Number of DSNB events before neutron tagging



HK (187 kton H_2O)
E_{th} =16 MeV
2027~

HK aims for precise flux & spectrum measurement.

JUNO (20 kt LS)
E_{th} =12 MeV
2024~

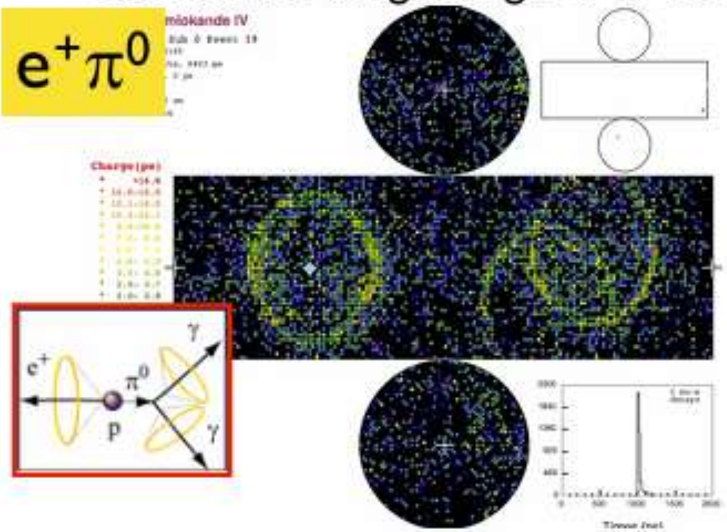
SKGd aims at first discovery.

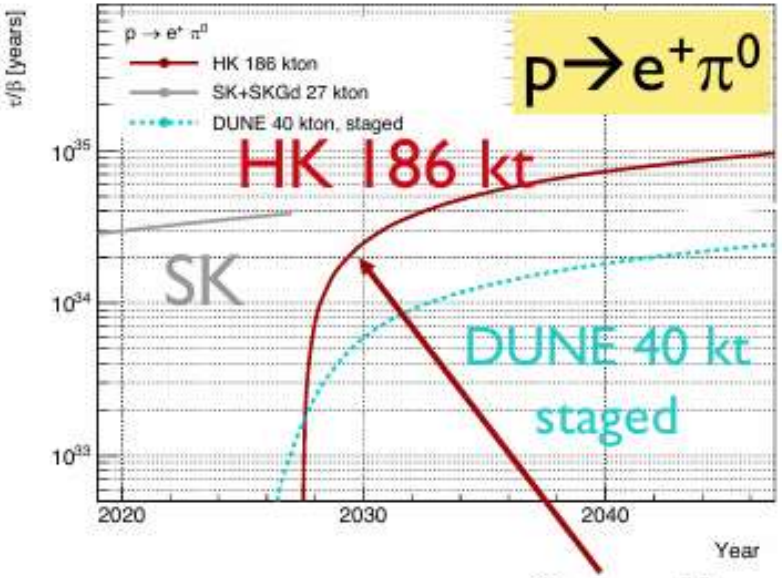
~4 ev/yr after neutron tagging w/ H_2O

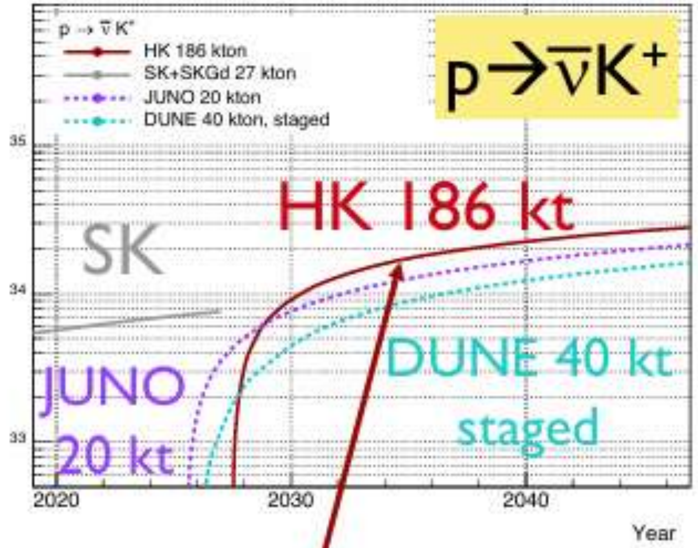
- Stellar collapse
- Star formation rate
- Heavy element synthesis

Proton decay searches (note: FV ~8 x Super-K)

Cherenkov ring image $e^+\pi^0$ in SK

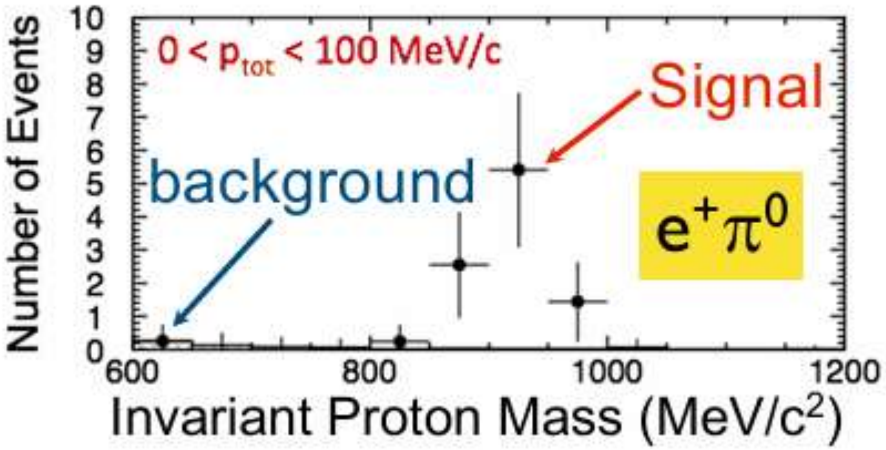






3σ discovery potential

Hyper-K 10 years operation assuming $\tau_{proton}=1.7\times10^{34}$ years (~Super-K limit)



HK 10 years

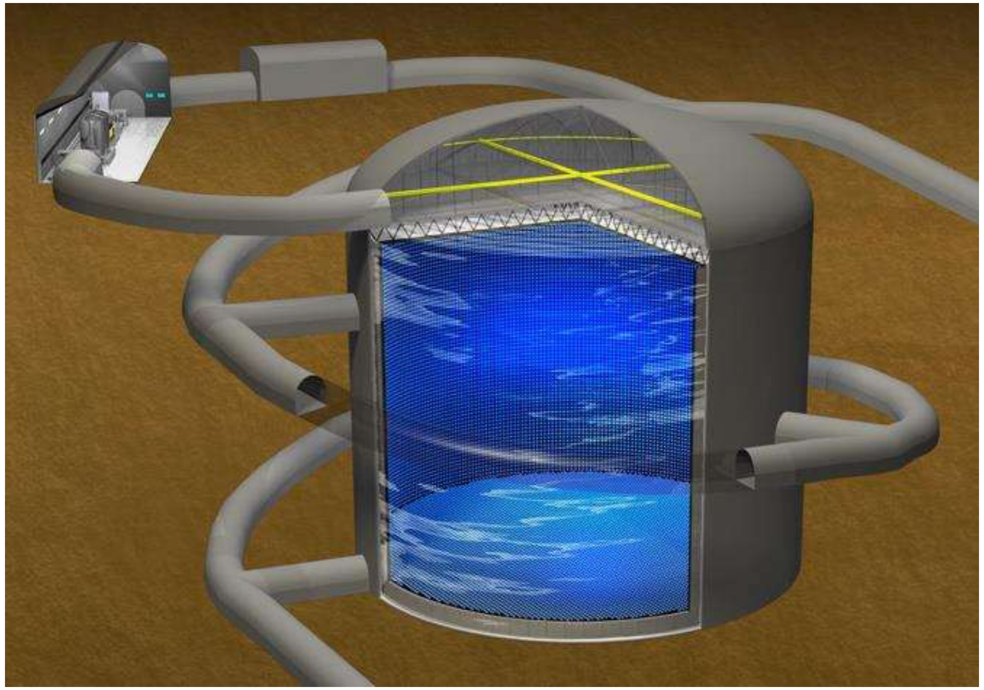
- $p\rightarrow e^+\pi^0$: ~6×10^{34} yrs
- $p\rightarrow \nu K^+$: ~2×10^{34} yrs
- …

Hyper-K will play a leading role in the next-generation proton decay search

Hyper-K Summary

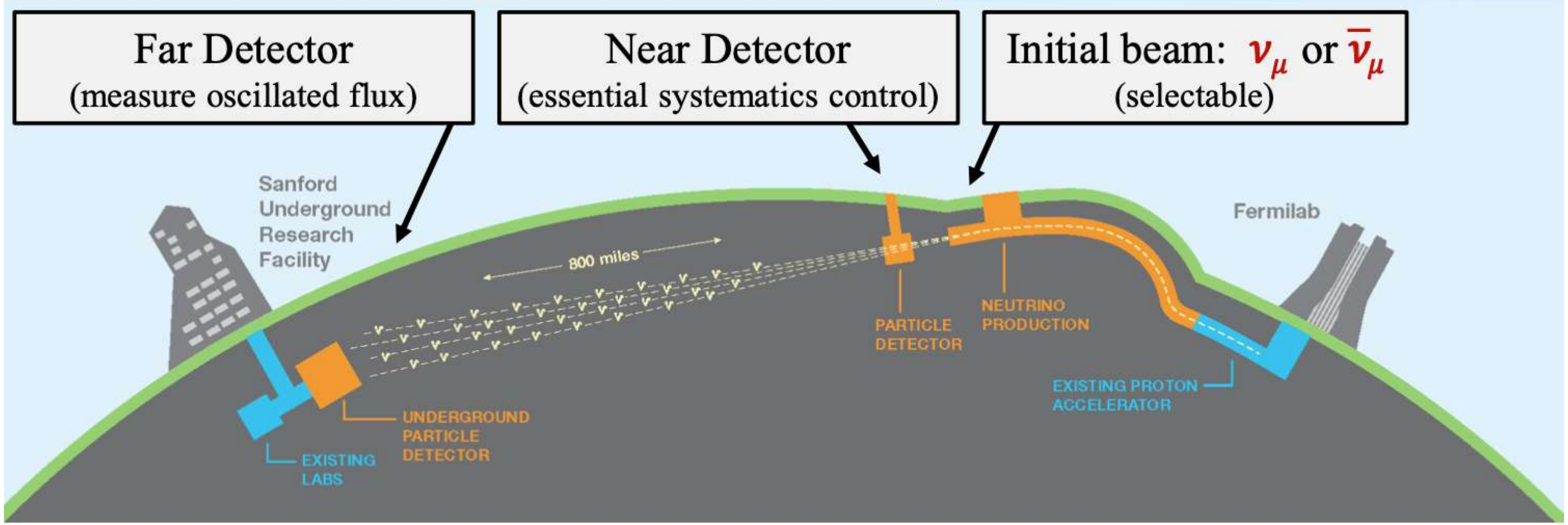
Hyper-Kamiokande construction has begun, with first data taking planned for 2027!

- Building on the success of Super-K & T2K with a next generation neutrino experiment
  - New far detector with 8 x fiducial mass of Super-K
  - Improved photosensors with 2 x detection efficiency & timing resolution reduced by half
  - Upgraded near detectors and new intermediate detector
  - Beam upgrade from 750 kW to 1.3 MW
- Wide range of physics measurements
  - Search for CP violation with precision oscillation measurements
  - Neutrino astrophysics through solar and supernova neutrinos
  - Searches for proton decay and other new physics

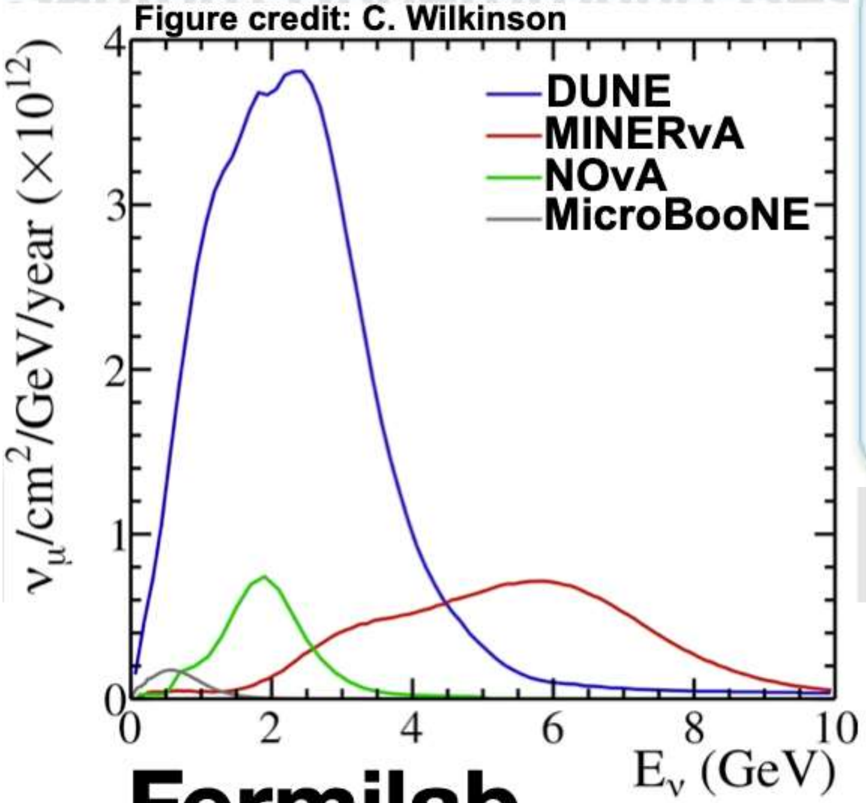


DUNE Overview

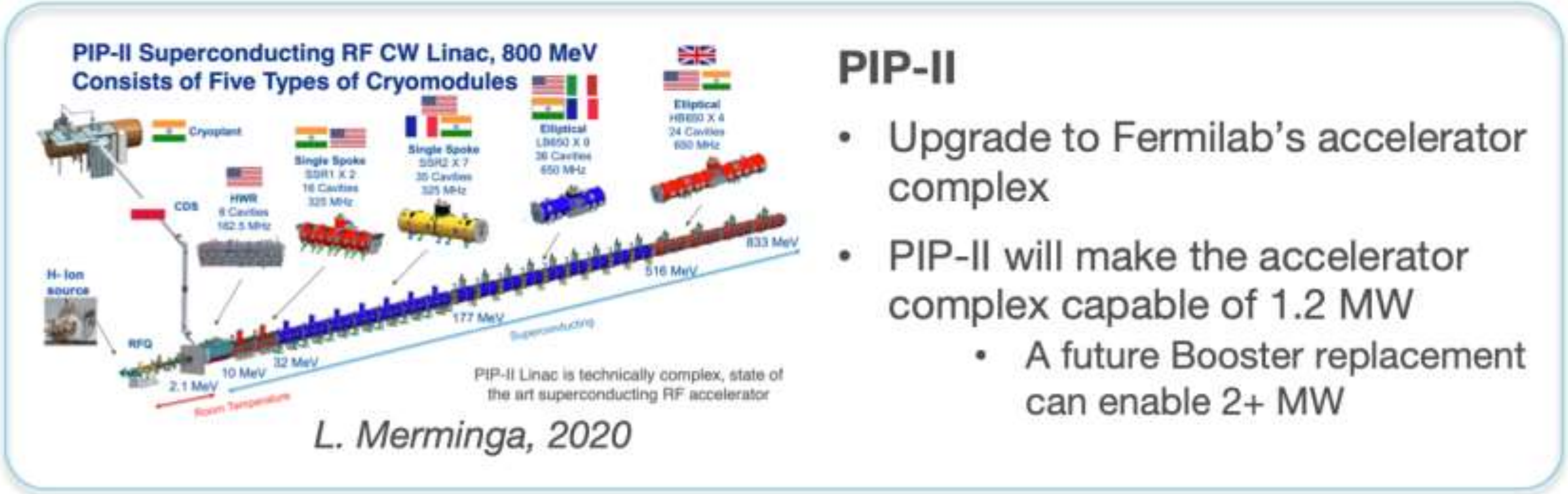
A next generation experiment for **neutrino science, supernova physics,** and **physics beyond the Standard Model**



DUNE Beam



Fermilab neutrino fluxes

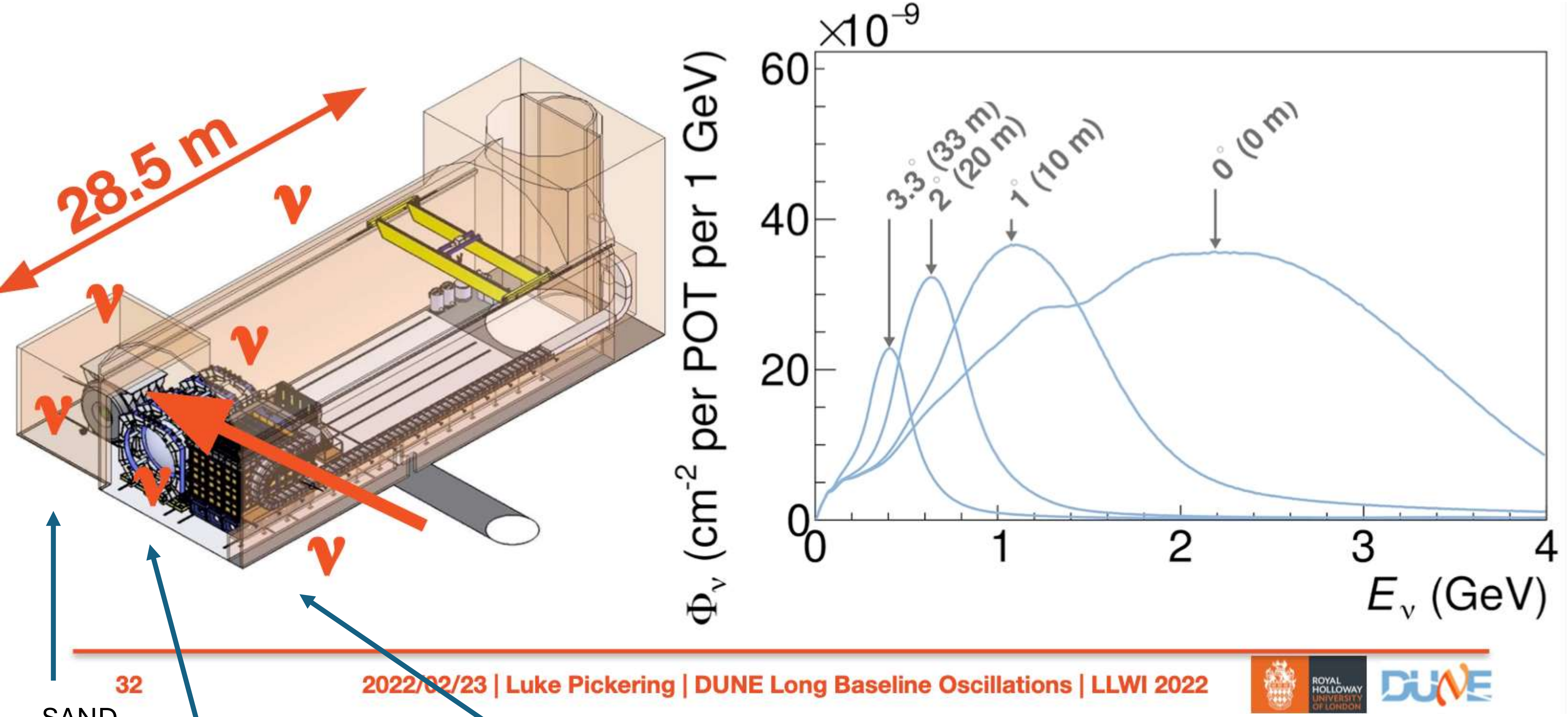


Accelerator

The DUNE Neutrino Beam

- 1.2 MW neutrino beam
- Optimized for CPV sensitivity

DUNE Near Detectors (DUNE PRISM)

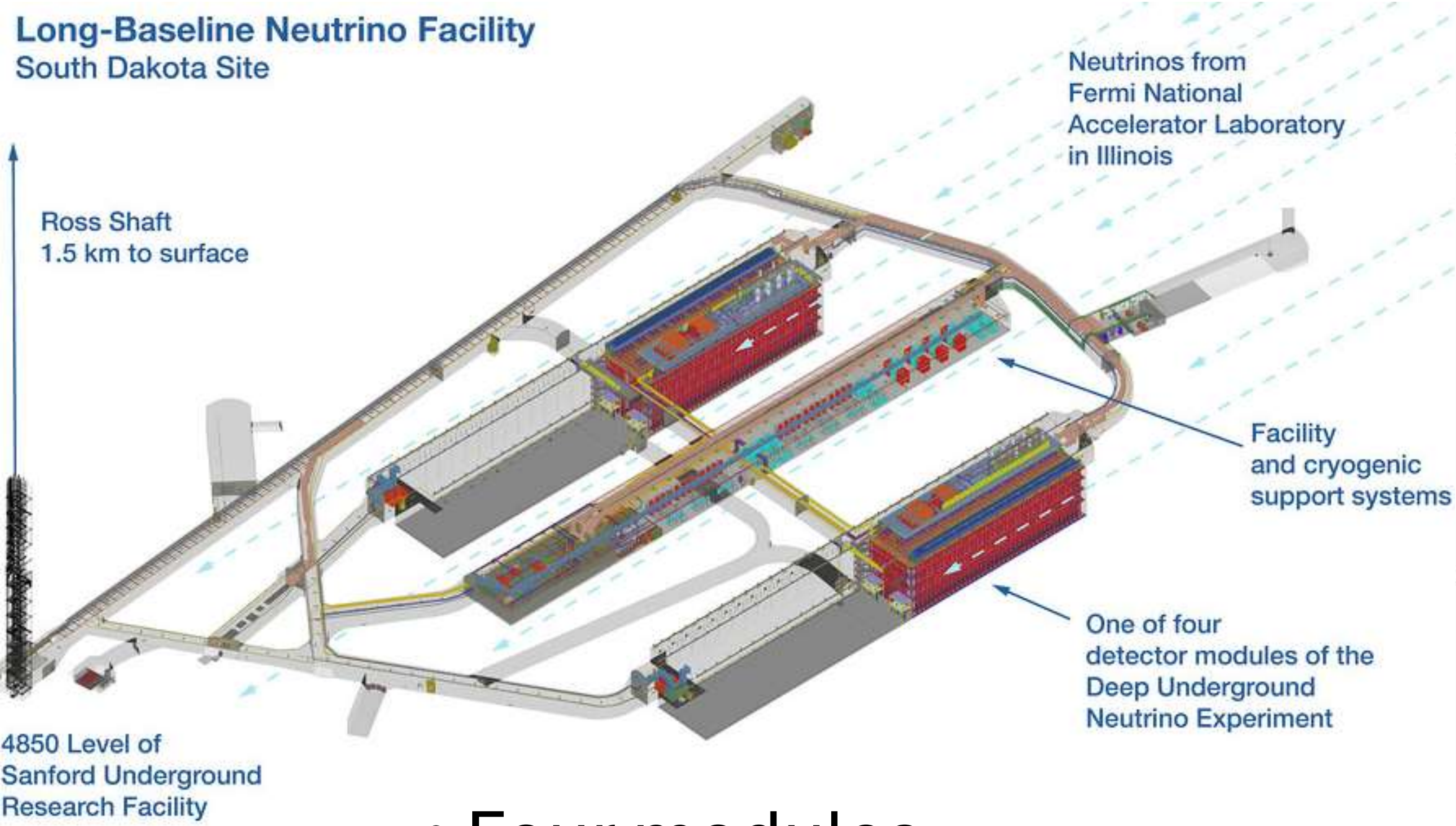


SAND

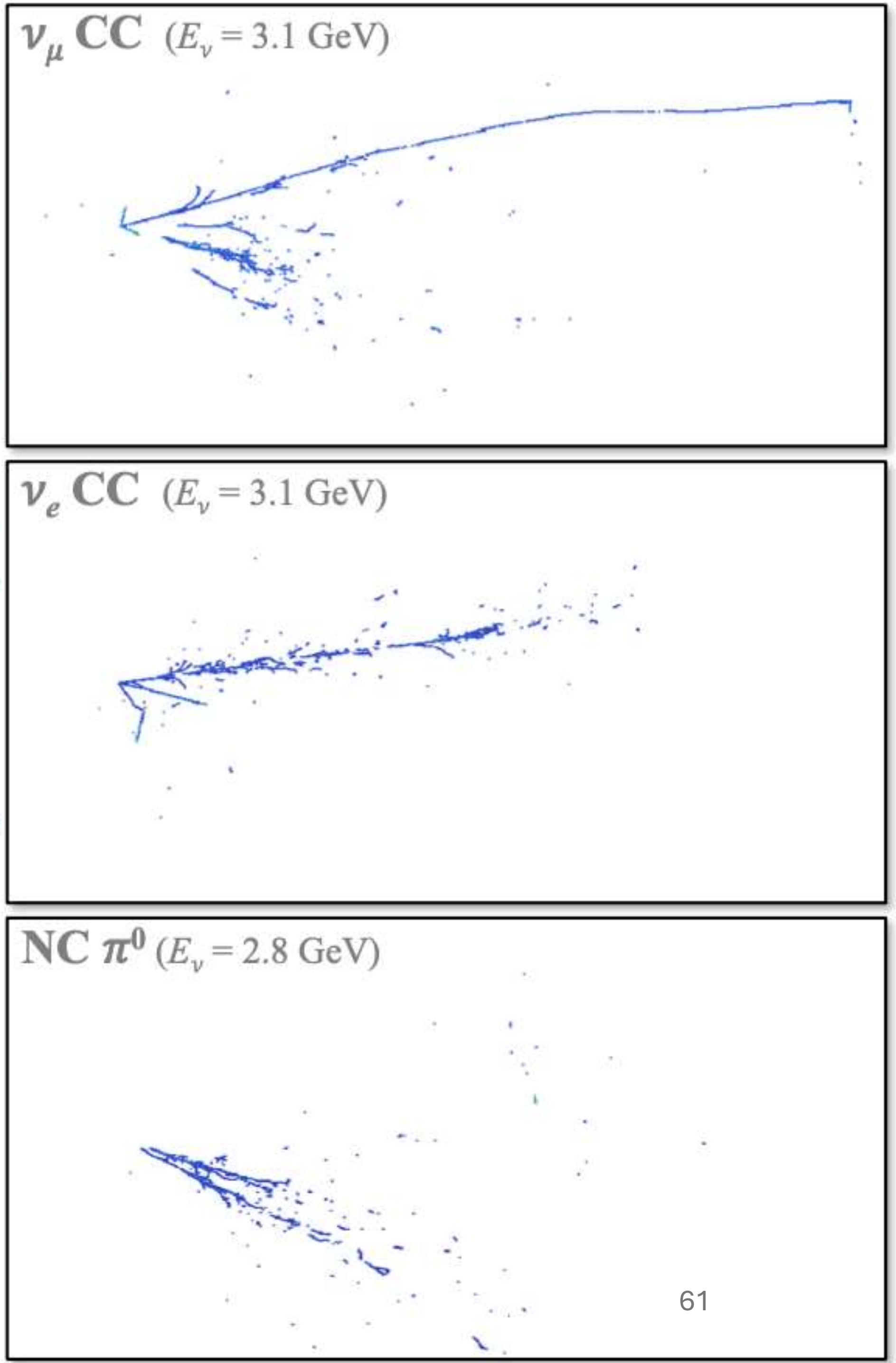
Muon spectrometer

Liquid Argon

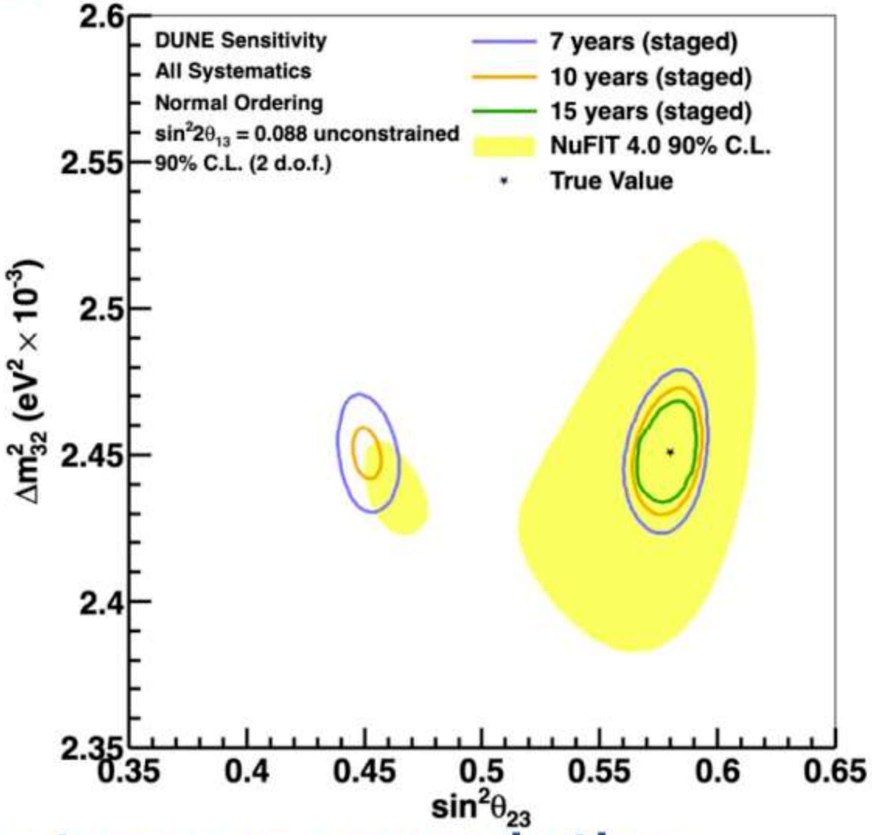
DUNE far detector



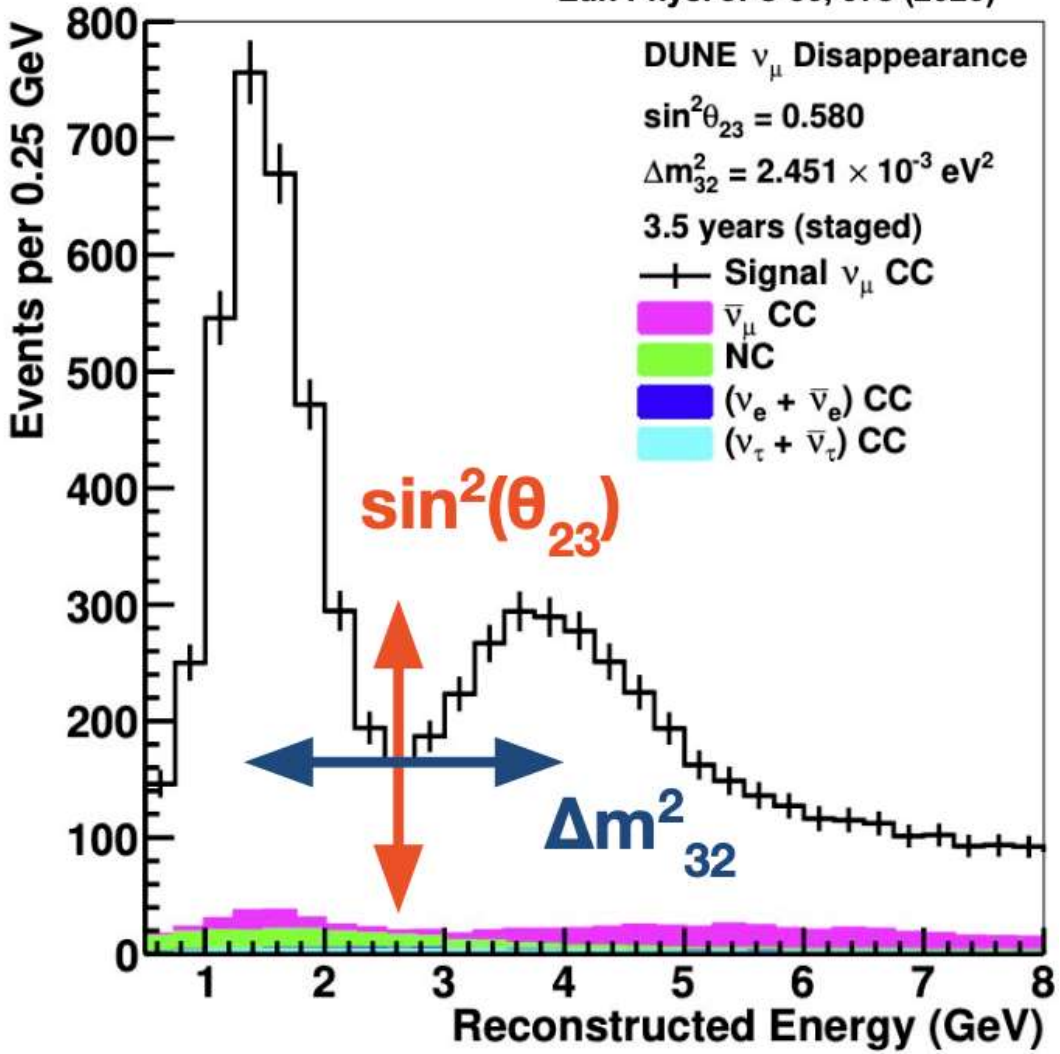
- Four modules
- Each 17 kT Ar TPC



Disappearance Sensitivity

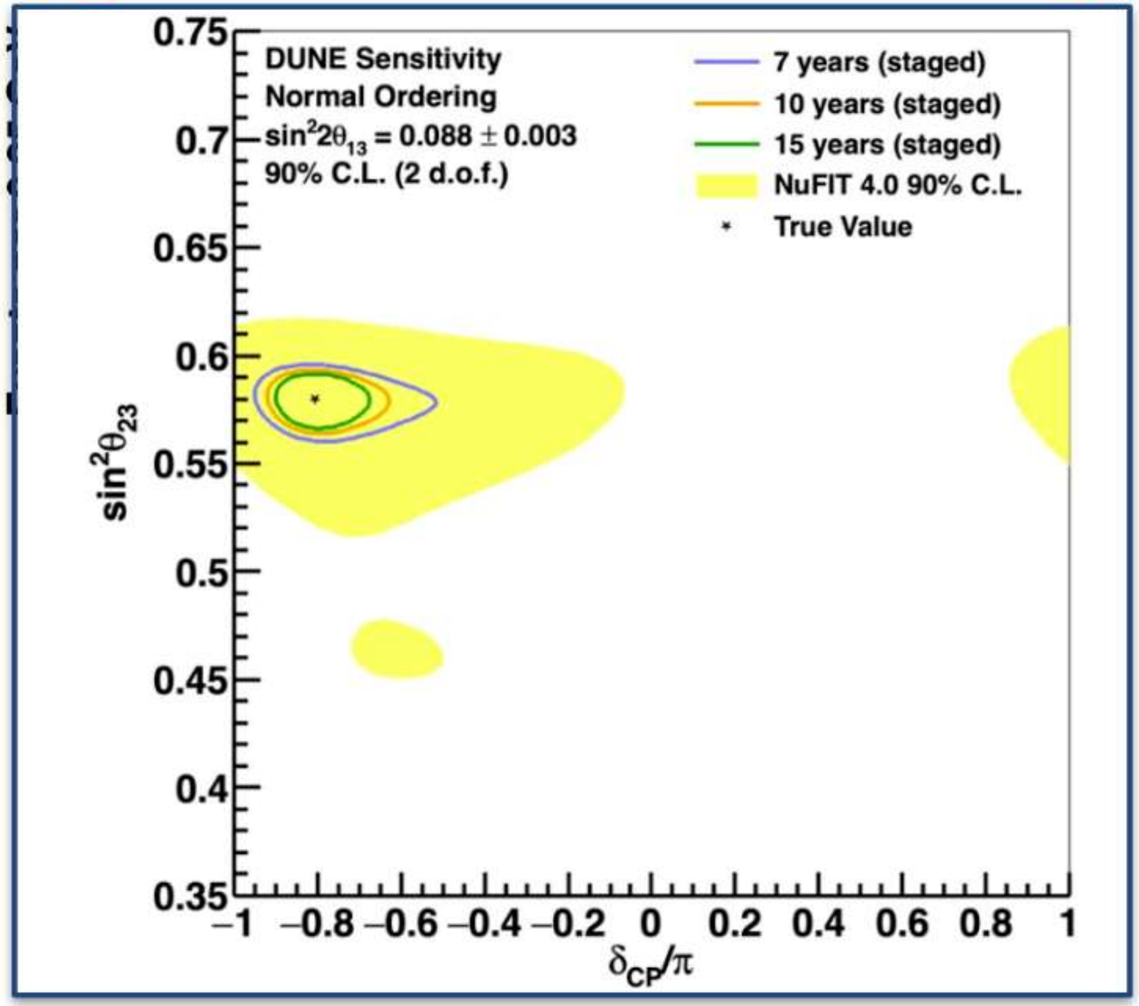


Eur. Phys. J. C 80, 978 (2020)

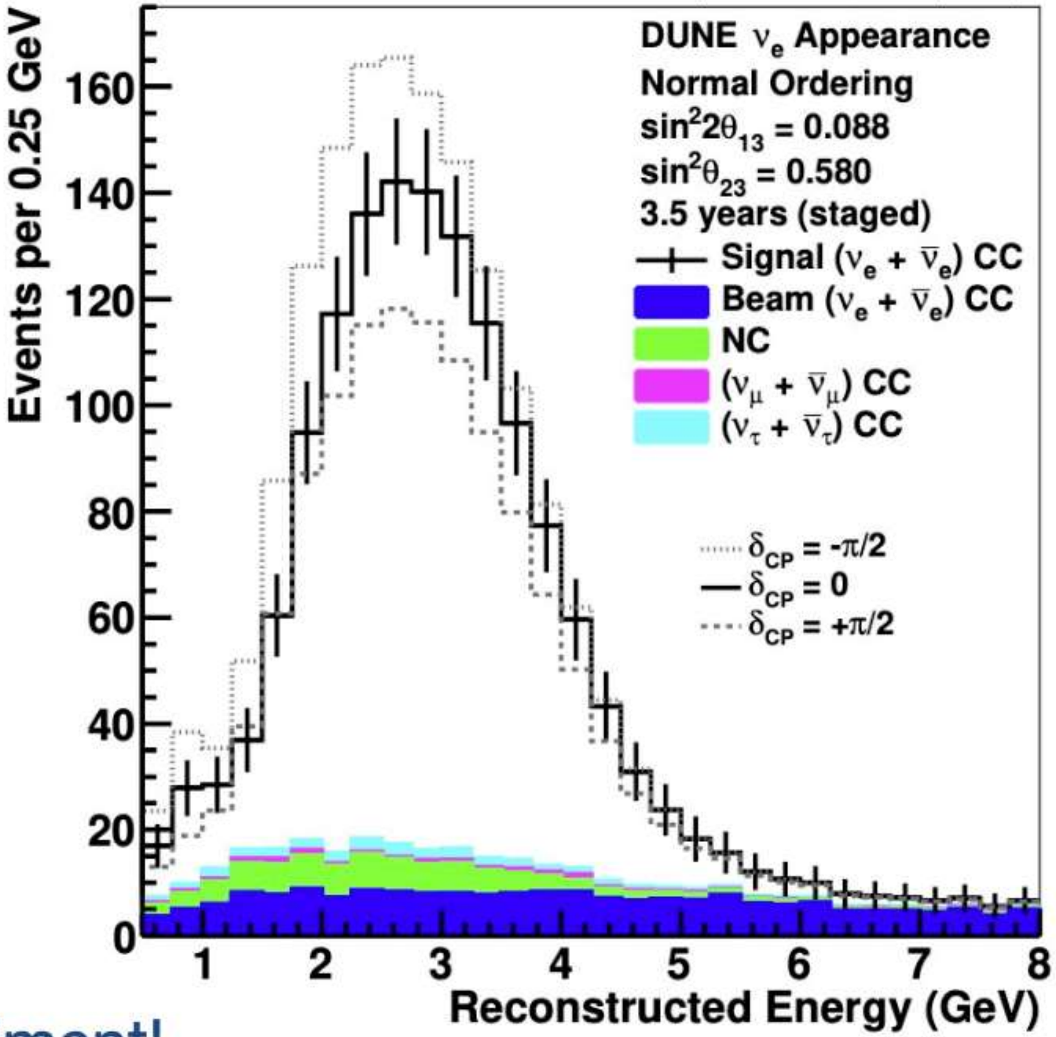


- Excellent energy resolution
- Massive far detector event rate
- Unprecedented oscillation parameter sensitivity

Appearance Sensitivity

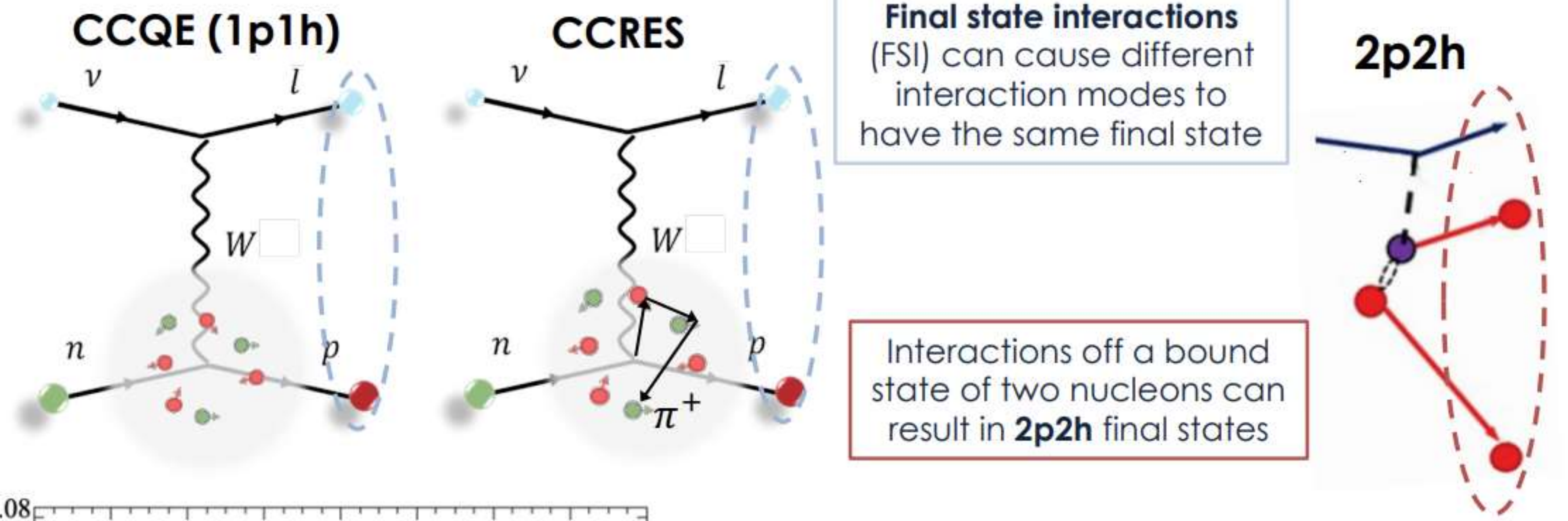


Eur. Phys. J. C 80, 978 (2020)



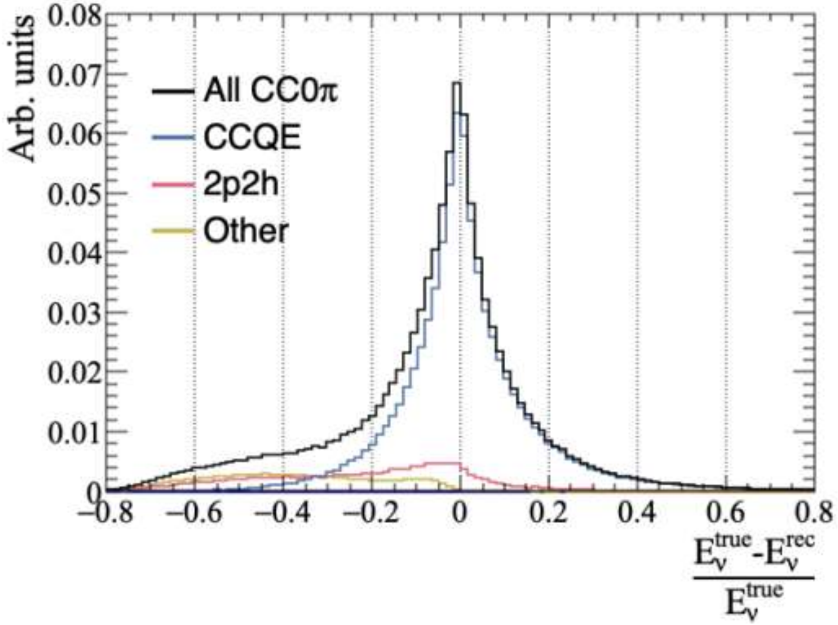
- Unique access to MO + CPV in one experiment!

Neutrino energy reconstruction



Final state interactions (FSI) can cause different interaction modes to have the same final state

Interactions off a bound state of two nucleons can result in **2p2h** final states



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

First-order effects

Fermi motion causes a **smearing** on E_ν^{QE}

Nuclear removal energy effects introduce a **bias**

2p2h and pion abs. *FSI* cause further **bias**

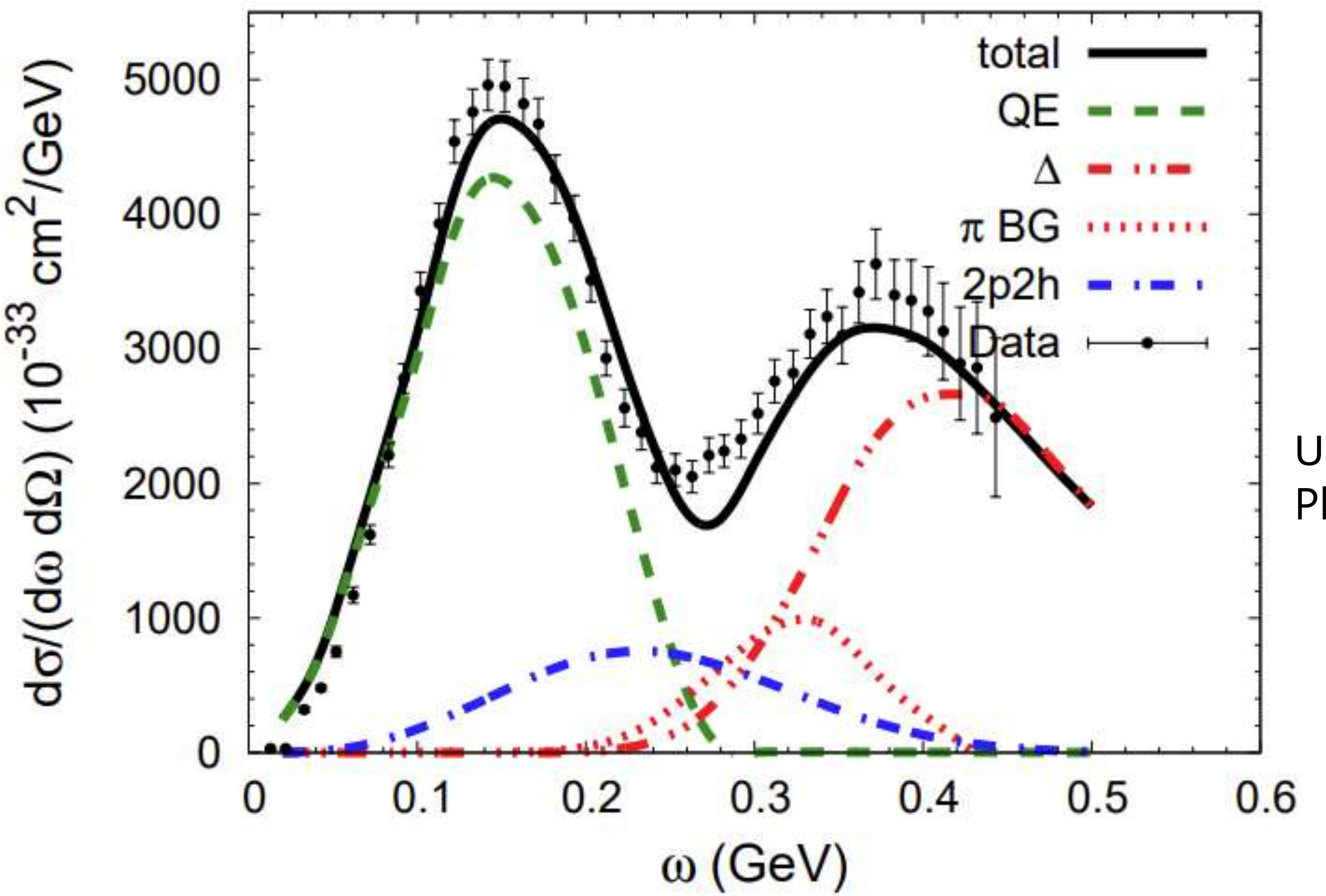
Neutrino energy reconstruction problem – nuclear interactions

"Neutrino interactions in the energy range of interest to current and near-future experiments (1 to 10 GeV), pose particular problems. In this energy range, bridging the perturbative and nonperturbative pictures of the nucleon, a variety of scattering mechanisms are important.

...

The models incorporated into neutrino simulations at these energies have been tuned primarily to this bubble chamber data. This data is not sufficient to completely constrain the models, particularly with regards to the simulation of nuclear effects. **A logical place to turn for guidance are electron scattering experiments.**"

H. Gallagher, AIP Conf. Proc. 698, 153 (2004)

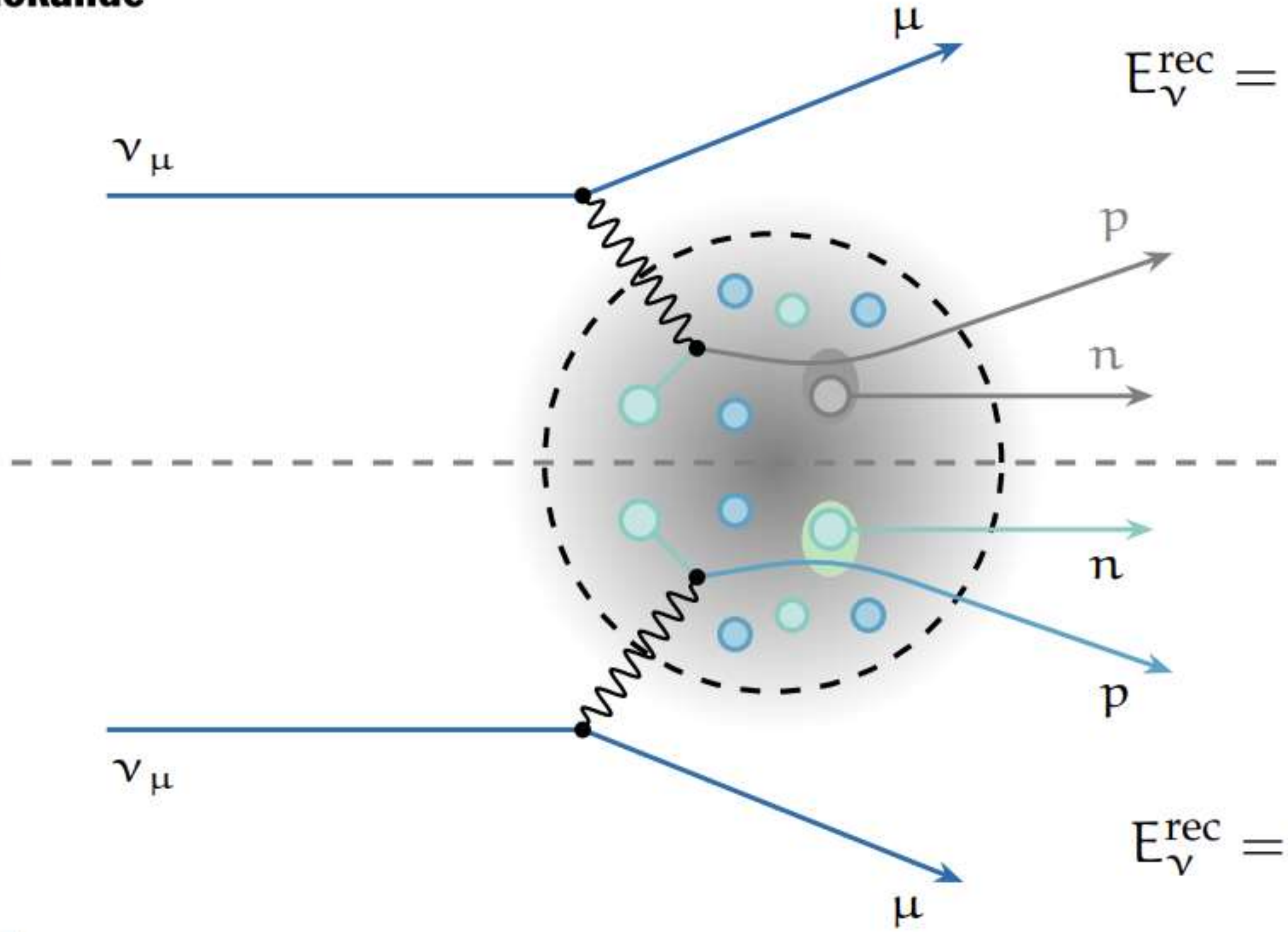


U. Mosel
Phys. Rev. C 94, 035502 (2016)

Figure 1: Inclusive cross section for scattering of electrons on carbon at 560 MeV and 60 Deg ($Q^2 = 0.24$ GeV^2 at the QE peak), obtained with a free Δ spectral function. The leftmost dashed curve gives the contribution from true QE scattering, the dash-dotted curve that from 2p-2h processes, the dashed-dotted-dotted curve that from Δ excitation and the dotted curve that from pion background terms. From [2].

Kinematical energy reconstruction

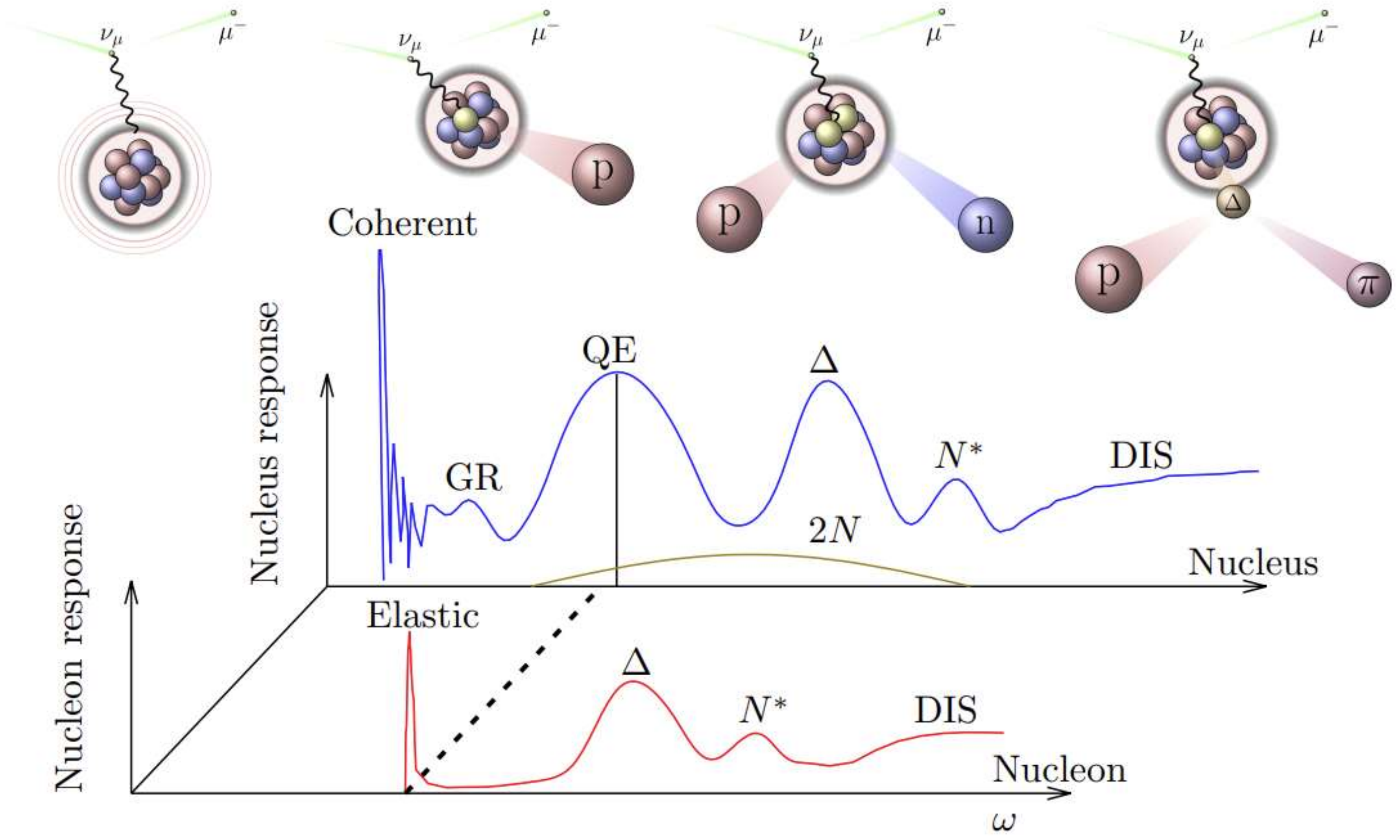
$$E_\nu^{rec} = \frac{2M_N E_\mu - m_\mu{}^2 + M_{N'}^2 - M_N^2}{2(M_N - E_\mu + p_\mu \cos\theta)}$$



$$E_\nu^{rec} = E_\mu - E_B + \sum\nolimits_{nucl.} T_i + \sum\nolimits_{mes.} E_j$$

Calorimetric energy reconstruction

Nuclear response



Intranuclear cascade

→ implement **realistic density profiles** and **cross sections**

→ add the **kinematics** of each interaction

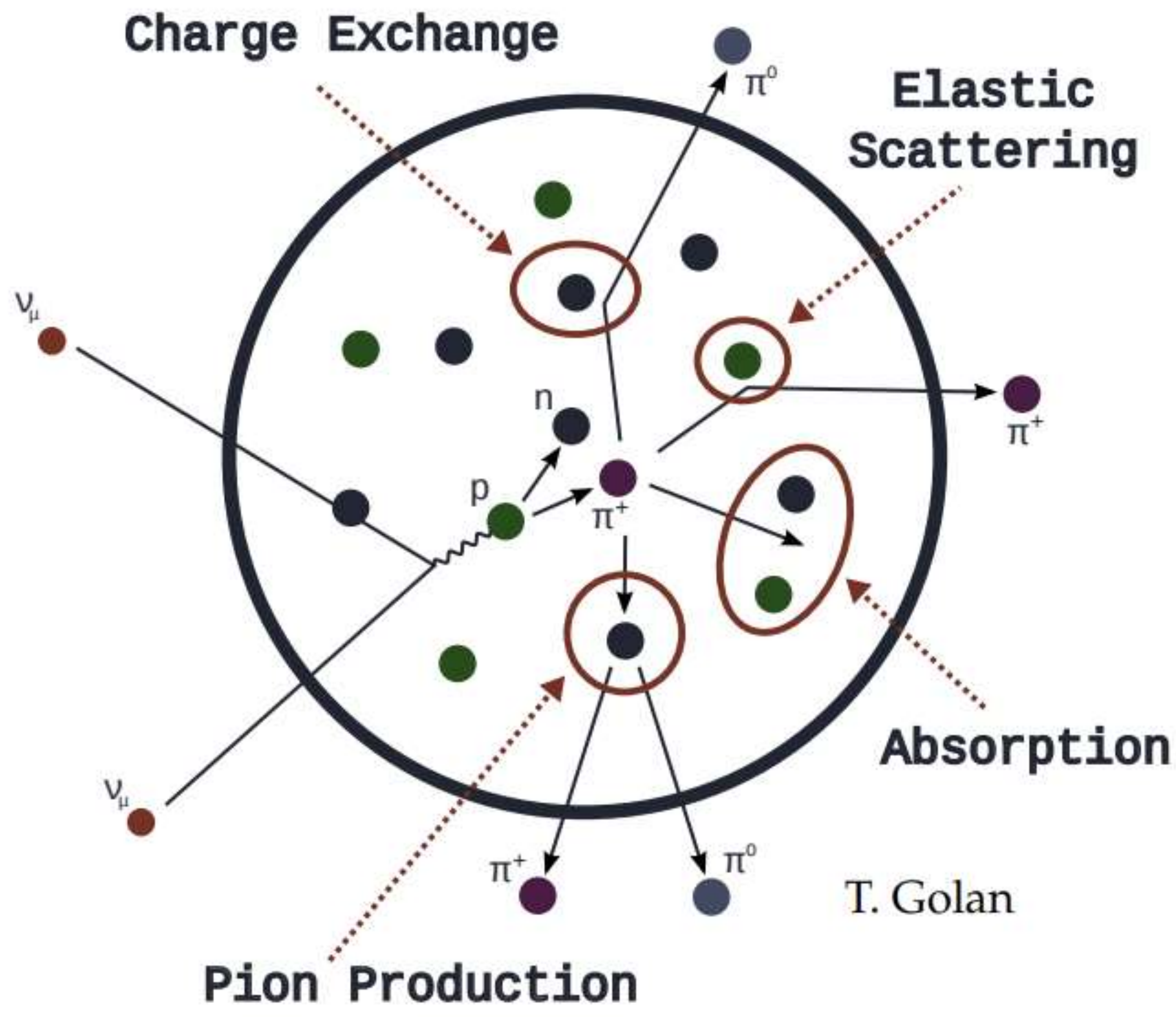
→ respect **Pauli blocking**

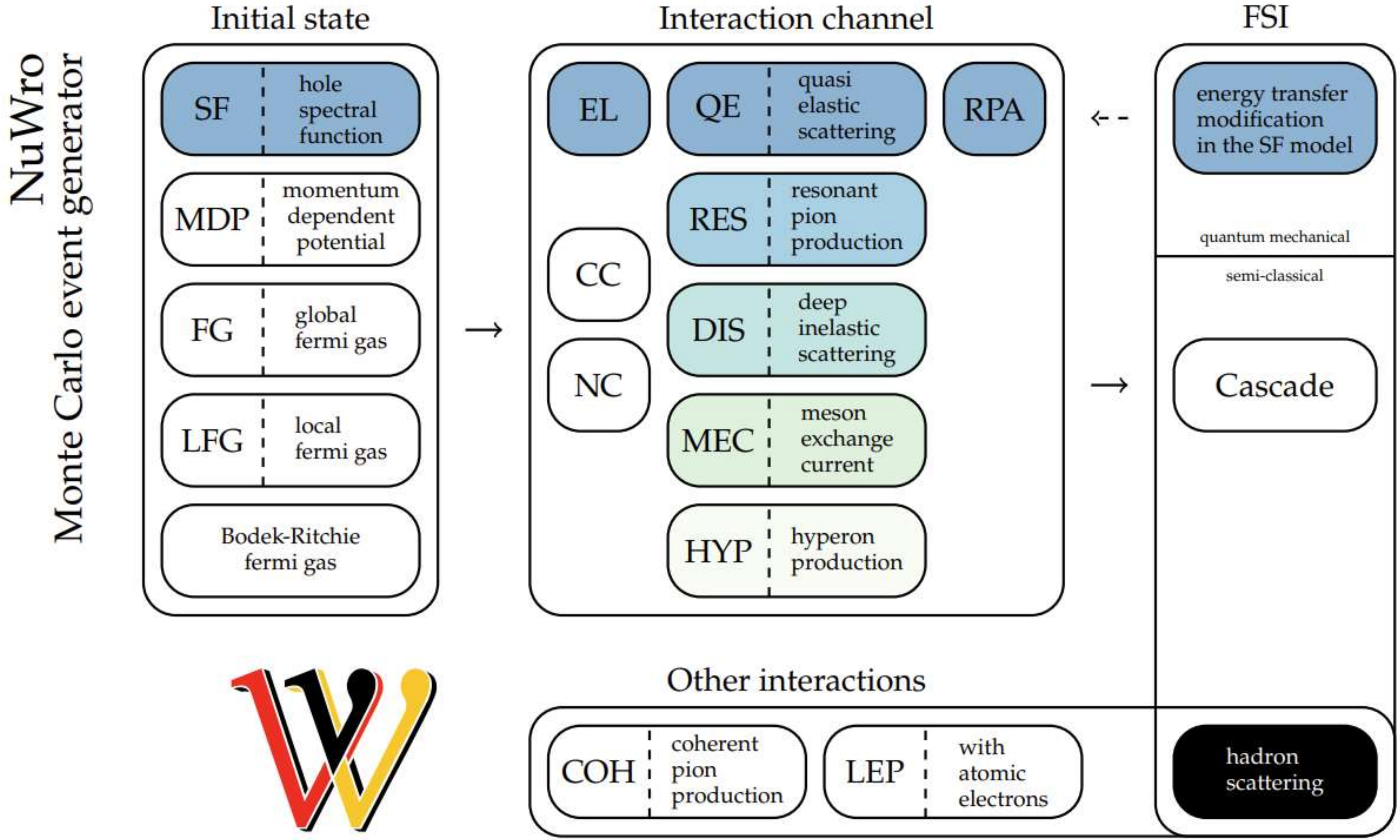
→ make sure that **scattered particles also propagate**

→ introduce **branching ratios** of different channels

→ track also **other hadrons**

→ add **other nuclear effects**...





NuWro
Monte Carlo event generator
Initial state
SF
hole spectral function
MDP
momentum dependent potential
FG
global fermi gas
LFG
local fermi gas
Bodek-Ritchie fermi gas
Interaction channel
EL
QE
quasi elastic scattering
RPA
CC
NC
RES
resonant pion production
DIS
deep inelastic scattering
MEC
meson exchange current
HYP
hyperon production
FSI
energy transfer modification in the SF model
quantum mechanical
semi-classical
Cascade
hadron scattering
Other interactions
COH
coherent pion production
LEP
with atomic electrons

Medium baseline

JUNO experiment

JUNO Experiment: Layout

- A multi-purpose liquid scintillator experiment in China:
  - **Reactor $\bar{\nu}_e$ ~ 60/day**
  - **Atmospheric ν's: several/day**
  - **Solar ν_e ~ 10-1000/day**
  - Supernova ν's ~ 10^4 in 10 s for 10 kpc
  - DSNB 2-4 IBD/year
  - Geo-ν's 1-2/day

This talk

See also Giulio Settanta's talk: "JUNO Non-oscillation Physics"

- Optimized baseline for neutrino mass ordering determination with reactor $\bar{\nu}_e$

Jiangmen Underground Neutrino Observatory

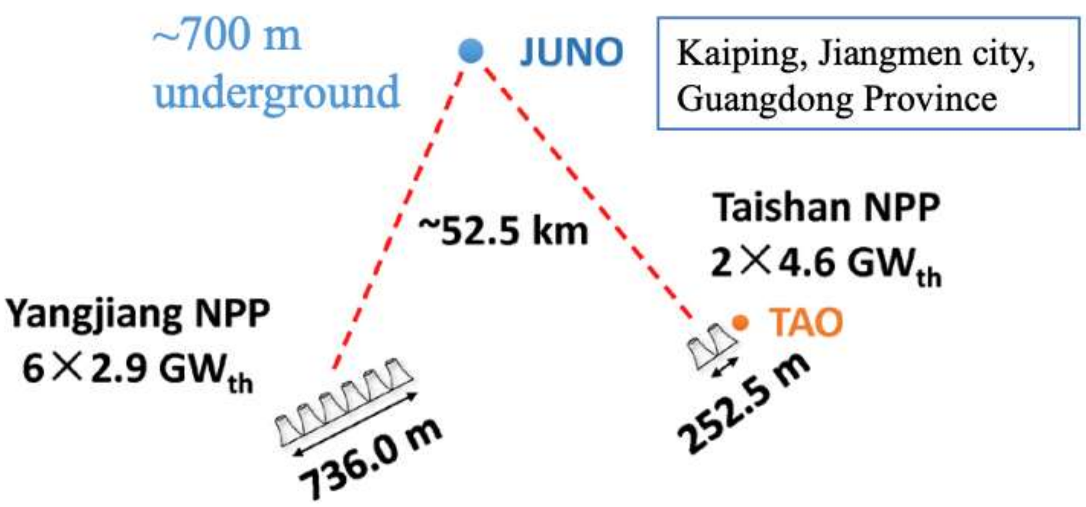
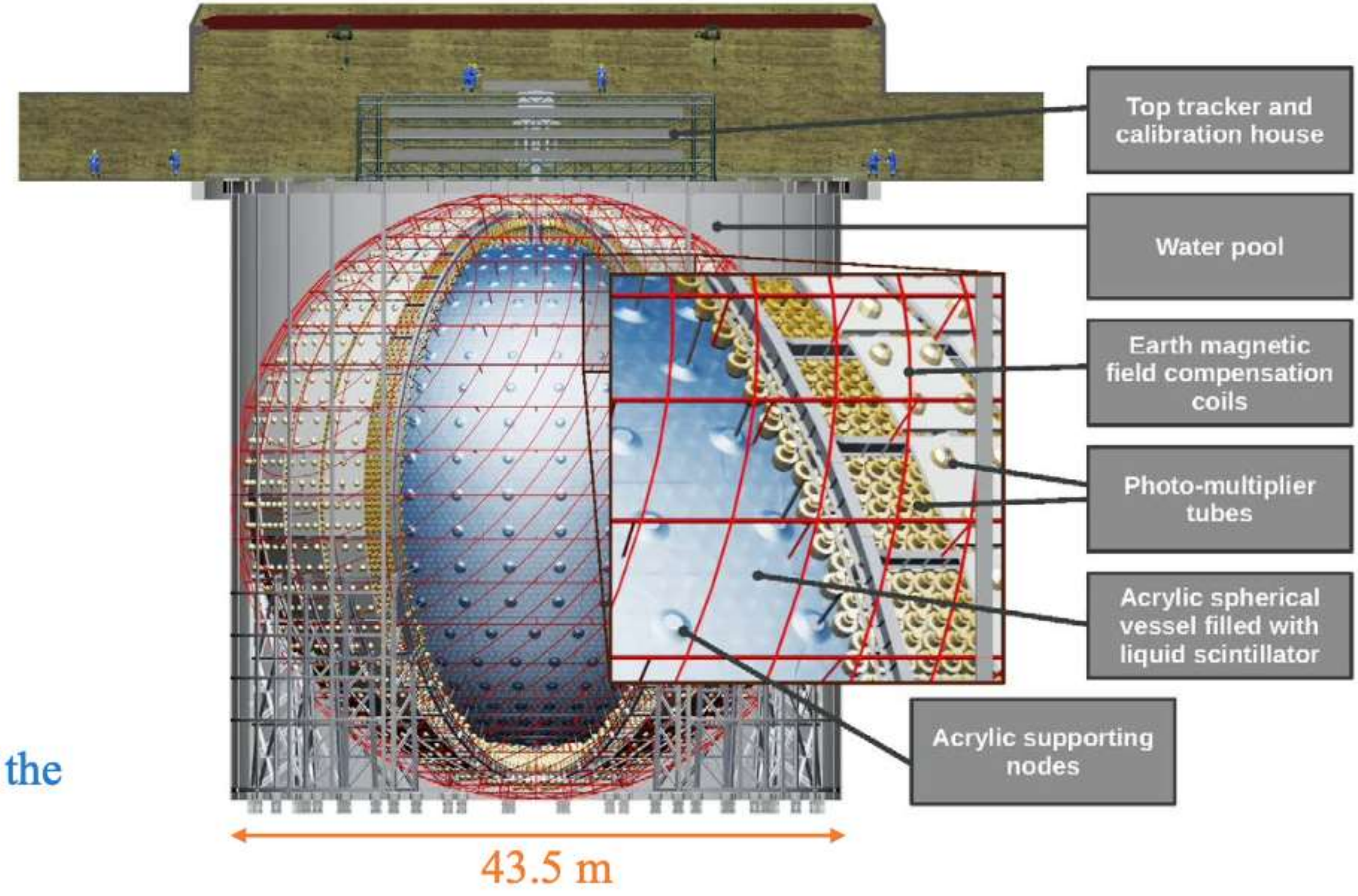


Figure: Setup of JUNO experiment, with the main 20-kton **JUNO detector** and satellite 2.8-ton **TAO detector**.

JUNO Experiment: Detector

- A multi-purpose liquid scintillator experiment.
- **Energy resolution < $3\%/\sqrt{E(\mathrm{MeV})}$:**
  - ~78% PMT coverage, ~1350 PE/MeV:
    - 5000 Hamamatsu 20″ dynode-PMTs
    - 12612 NNVT 20″ MCP-PMTs
    - 25600 HZC 3″ PMT
- **Large target volume:**
  - 20-kton LAB-based liquid scintillator
- **Energy scale uncertainty <1%**
  - JHEP03(2021)004: "Calibration strategy of the JUNO experiment"
- **Background control**
  - arXiv:2107.03669: "Radioactivity control strategy for the JUNO detector"



See also Zhimin Wang's talk: "JUNO Detector Design & Status"

Status of JUNO

Jun Cao (IHEP)

On behalf of the JUNO collaboration, Neutrino 2024, Milan

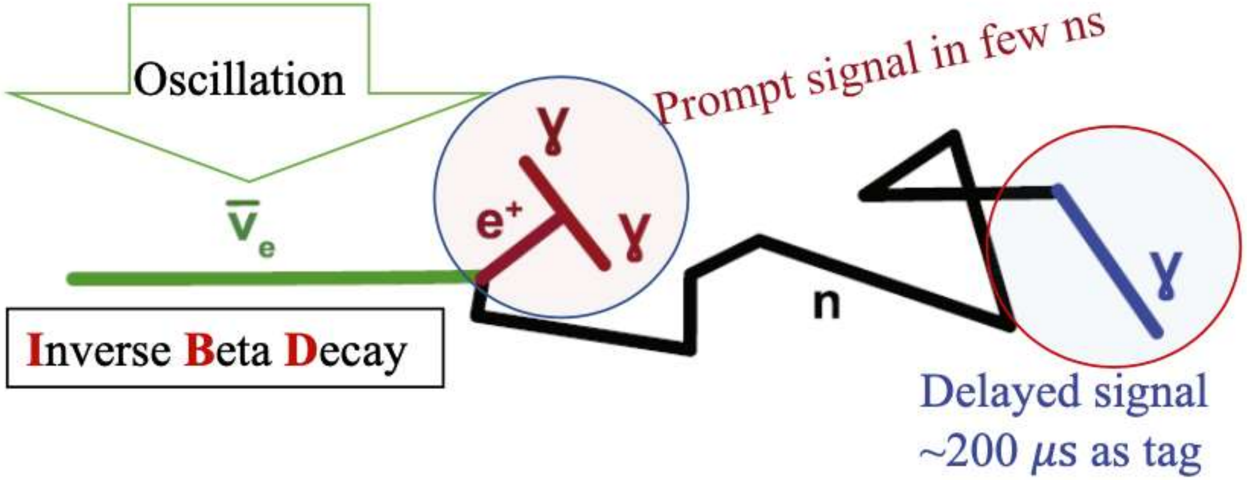
Reactor $\bar{\nu}_e$: Source and Oscillation

- **Source**: reactor antineutrino from fission of four isotopes:
  - ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu
  - Major: 6 YJ cores, ~~4~~ → 2 TS cores

J. Phys. G43:030401 (2016) → arXiv:2104.02565

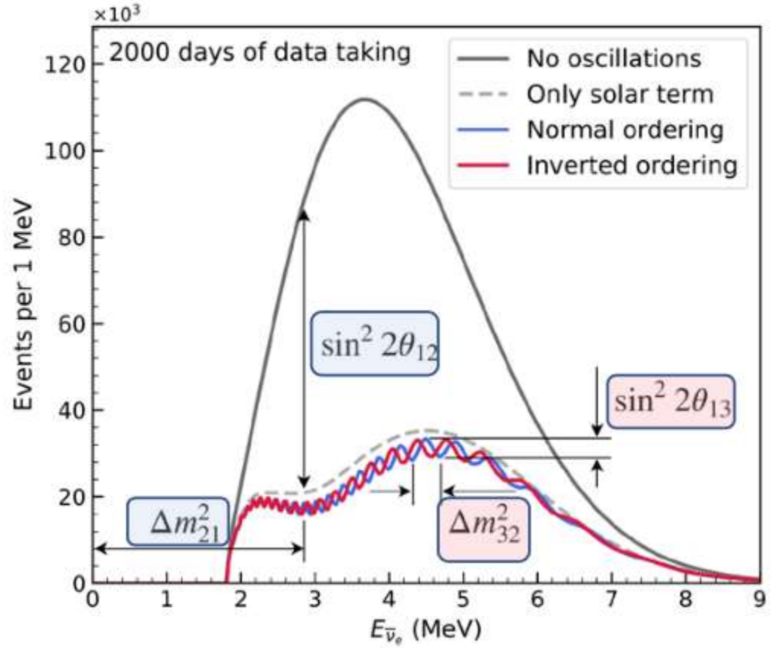
Table: Thermal power and baseline to the JUNO detector for the Yangjiang (YJ), Taishan (TS), Daya Bay (DYB), and Huizhou (HZ) reactor cores.

Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265



- **Oscillation**: $\bar{\nu}_e$ survival probability in vacuum[1]:

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{12}L}{4E} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right).$$



The energy resolution is one of the key factors for determining neutrino mass ordering (NMO).

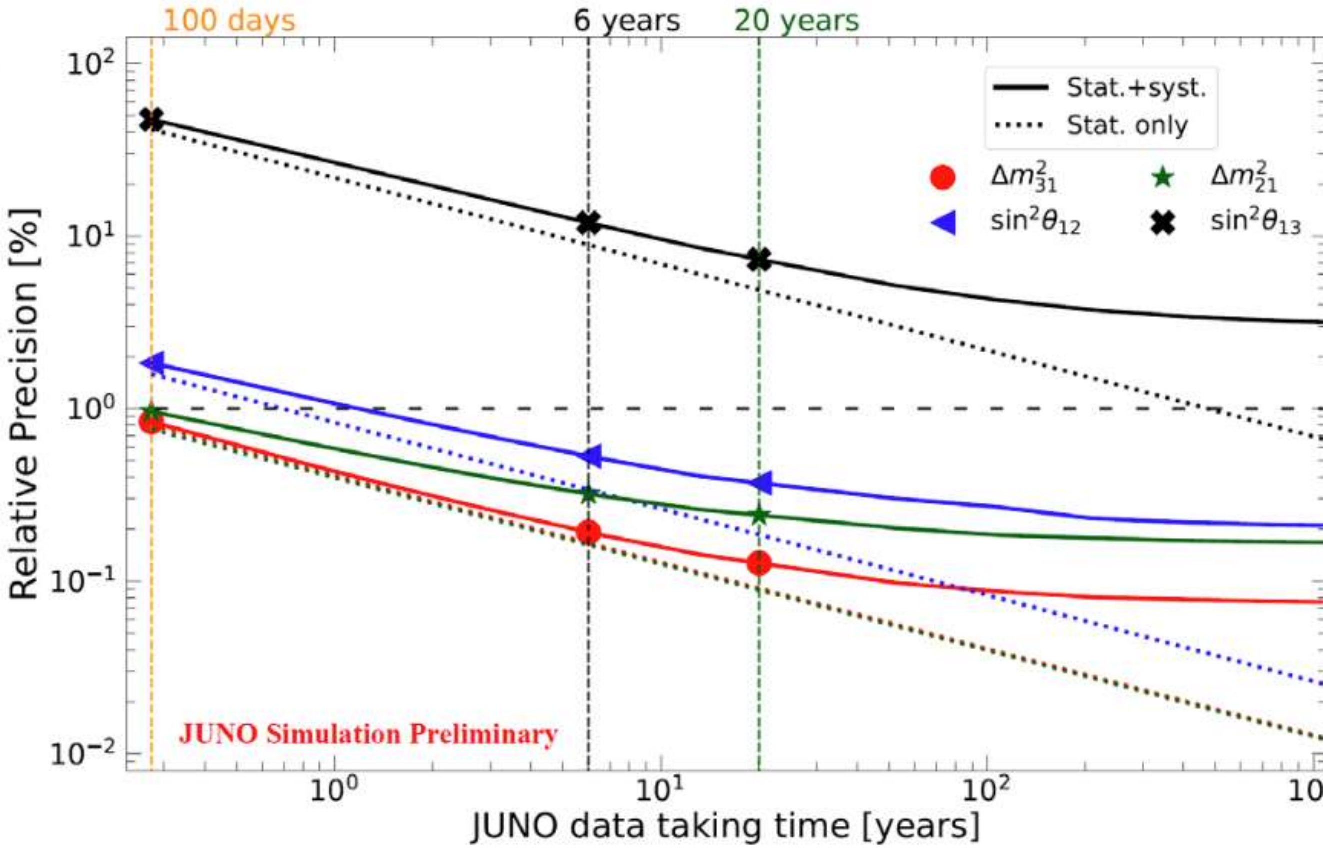
[1]. Oscillation in matter with effective oscillation parameters (j.physletb.2020.135354).

Reactor $\bar{\nu}_e$: Precision Measurement of Oscillation Parameters

- Precision measurement of oscillation parameters:

Relative Precision (%)	$\sin^2\theta_{12}$	Δm^2_{21}	$\sin^2\theta_{13}$	$\Delta m^2_{31}/\Delta m^2_{32}$
Current global fit (Nufit 5.0) [1]	**4.0**	**2.8**	**2.8**	**1.1**
PDG2020 [2]	**4.2**	**2.4**	**3.2**	**1.4**
JUNO 6 years	**0.5**	**0.3**	**12**	**0.2**

JUNO Simulation Preliminary



- JUNO will dominant the precision of $\Delta m^2_{31}/\Delta m^2_{32}$, Δm^2_{21}, and $\sin^2\theta_{12}$ in 1 year
- To sub-percent level in 1-2 years

A publication on the precision measurement of the oscillation parameters is coming soon.

[1]. JHEP09(2020)178 [2]. PTEP 2020 (2020) 8, 083C01

JUNO Physics Summary

- **Multipurpose experiment JUNO**:
- Neutrino mass ordering determination:
  - $> 3\sigma$ in 6 years with only reactor $\bar{\nu}_e$
  - $> 1\sigma$ with JUNO atmospheric neutrinos
- Precision measurement of oscillation parameters
  - Sub-percent for $\Delta m^2_{31}/\Delta m^2_{32}, \Delta m^2_{21}$, and $\sin^2\theta_{12}$ with reactor $\bar{\nu}_e$
  - θ_{23} octant with atmospheric neutrinos
  - Independent Δm^2_{21} and $\sin^2\theta_{12}$ measurement with solar ^8B neutrino
- TAO detector
  - High precision reactor neutrino spectrum
  - Sterile neutrino exploration
- JUNO will start operation in 2024

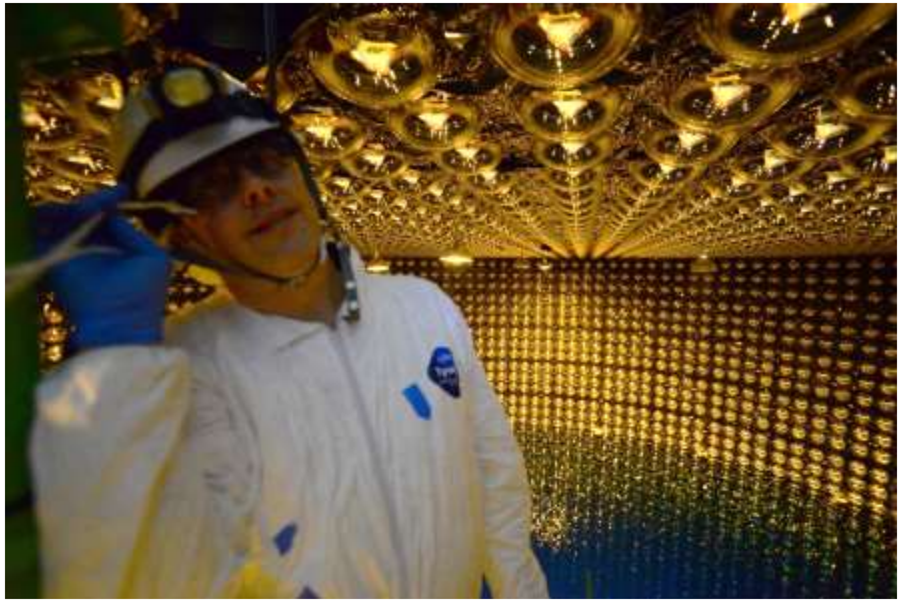
Conclusion

- There are many exciting neutrino experiments planned and under construction around the world
- The next decade of measurements will see us
  - Determine if there is CP violation in neutrinos
  - Determine the mass ordering of neutrinos
  - Make progress on understanding neutrino interactions on nuclei
  - Get closer to measuring the absolute neutrino masses
  - Discover new puzzles related to neutrino properties

Me at J-PARC (Tokai)

Thank you for your attention!

Me at Super-Kamiokande



Me at T2K ND280 near detector