ETH zürich

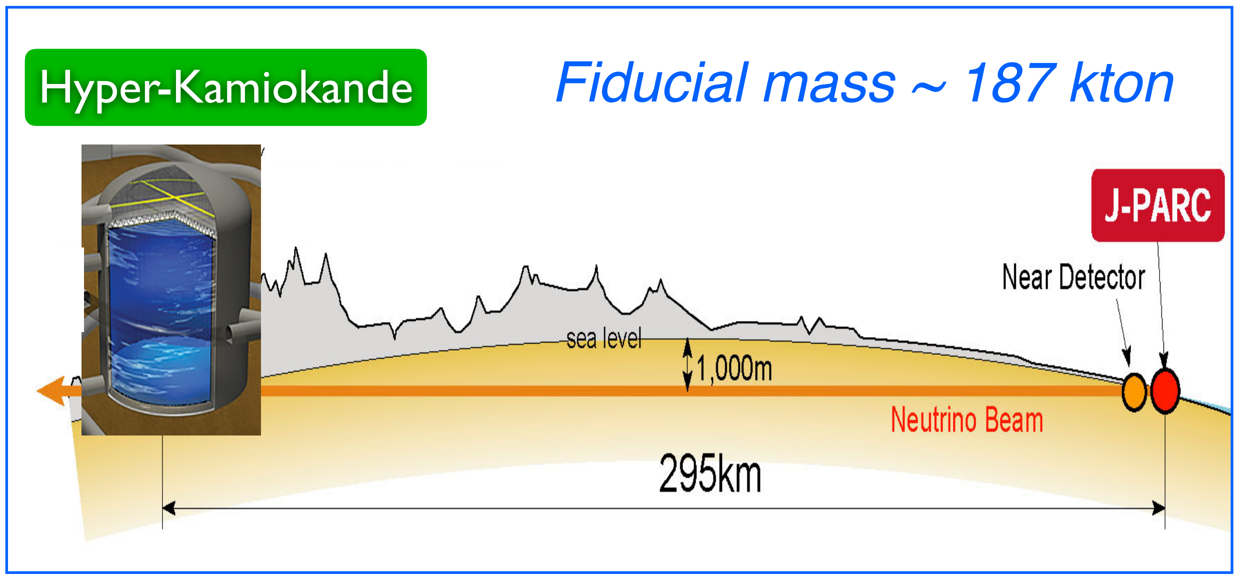
T2HK and DUNE strategy for Near Detectors

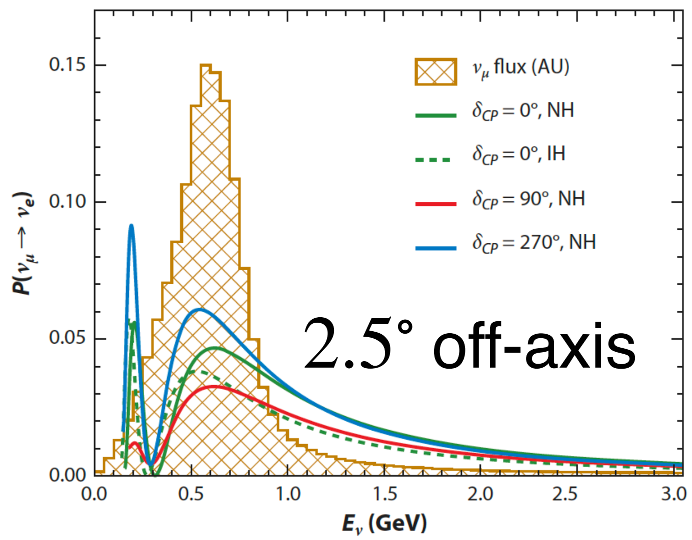
Davide Sgalaberna (ETH Zurich)

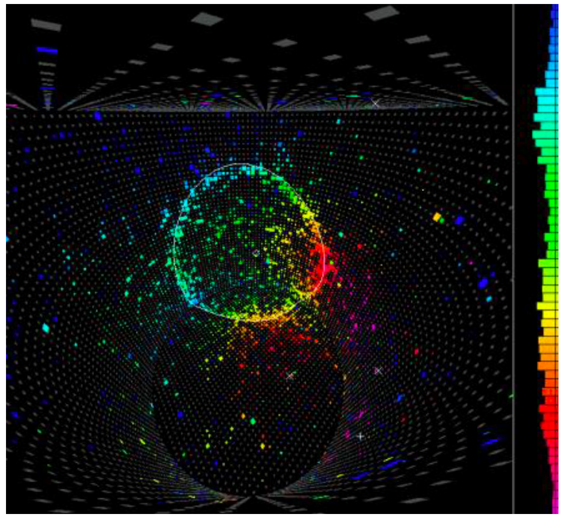
BSMν Workshop 2021

Long-baseline experiments: T2HK and DUNE

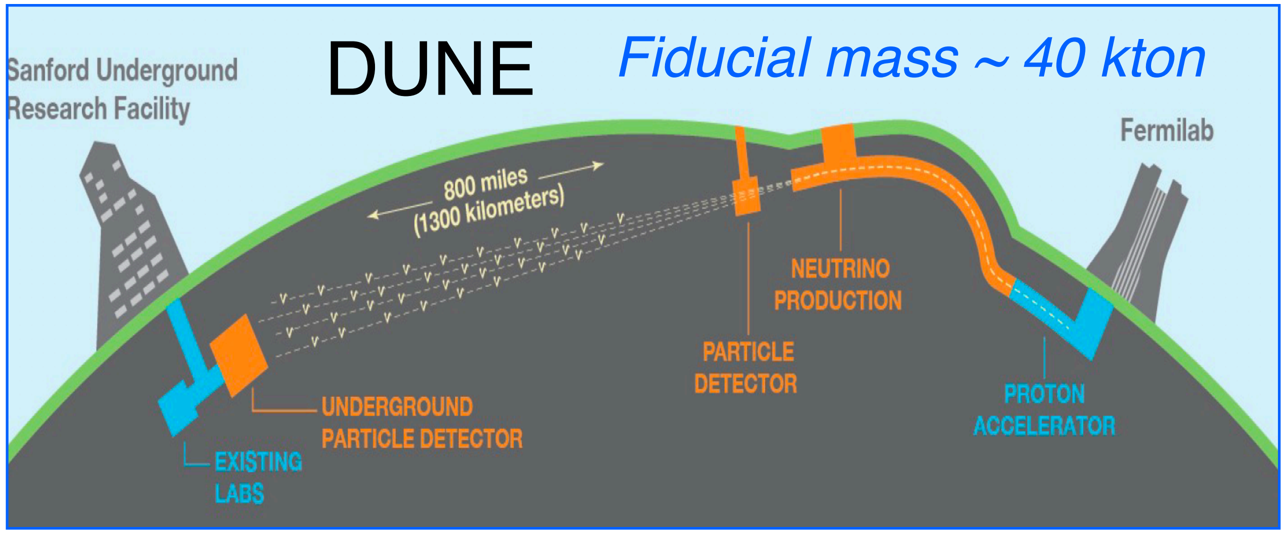
- Towards the measurement of the CP violating phase and Mass Hierarchy
  - ✦ Search for different $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probabilities

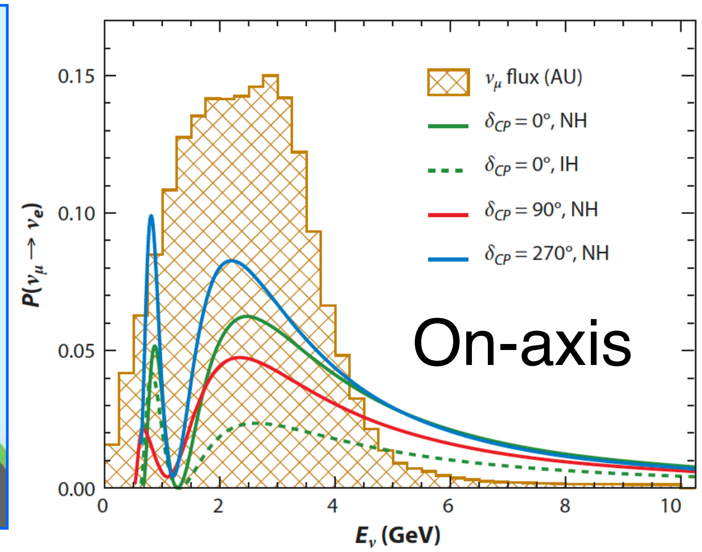


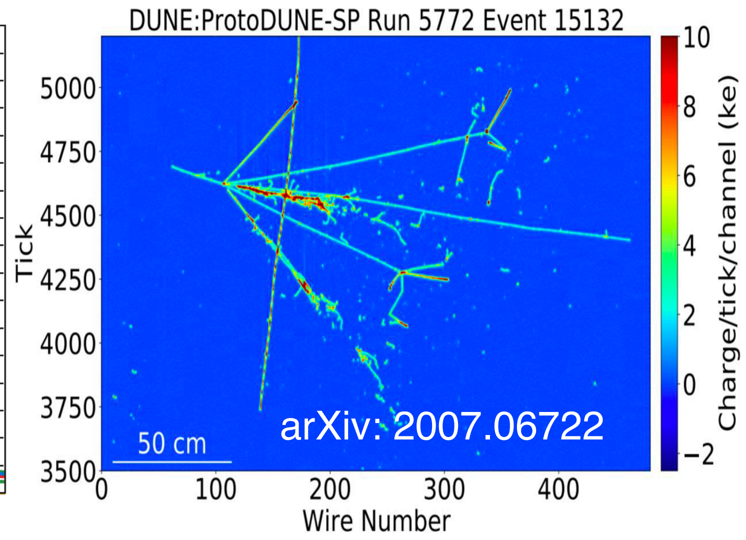




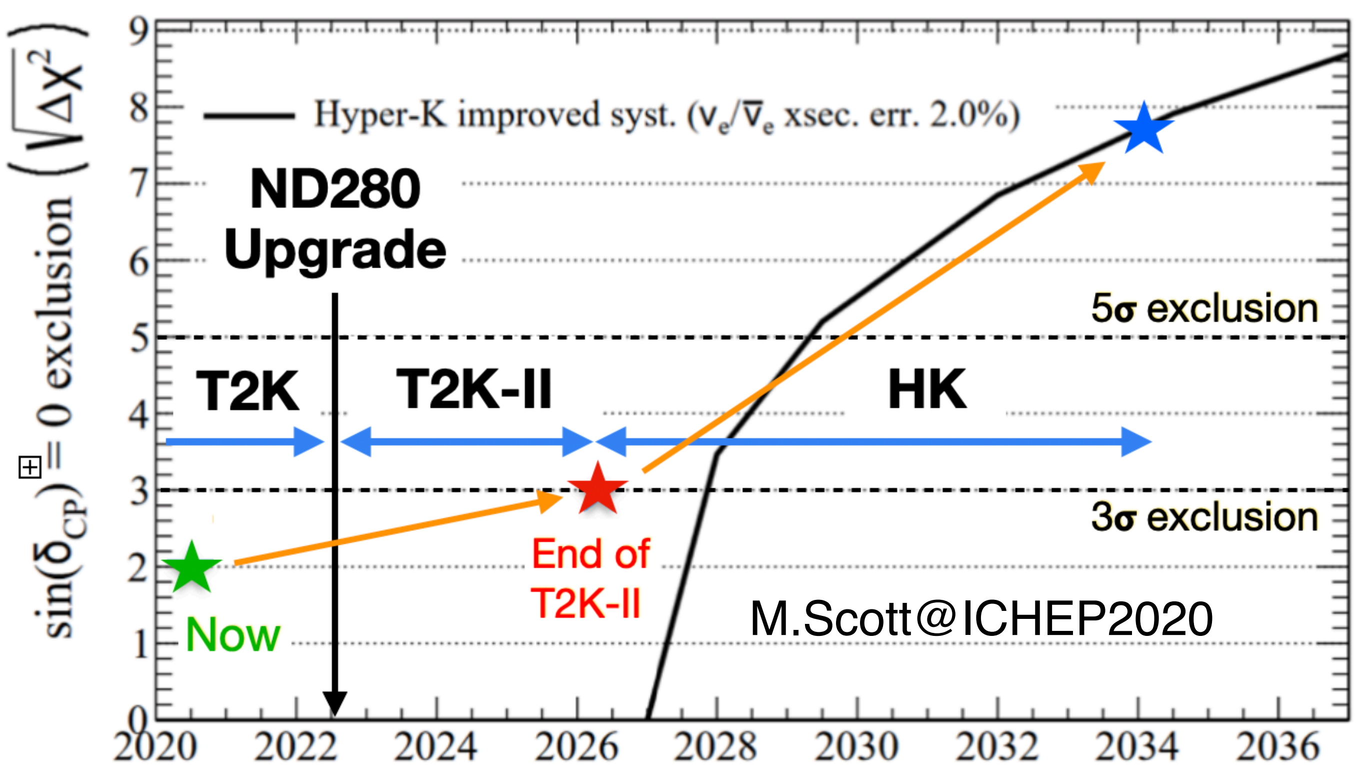
Annu. Rev. Nucl. Part. Sci. 2016. 66:47–71



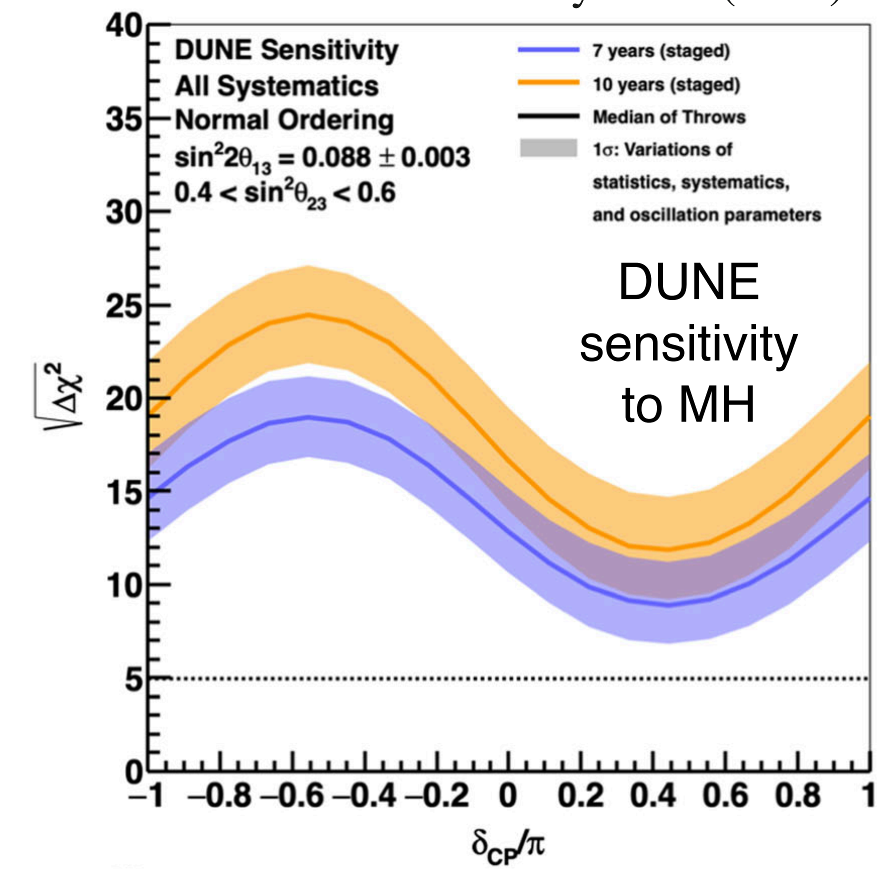


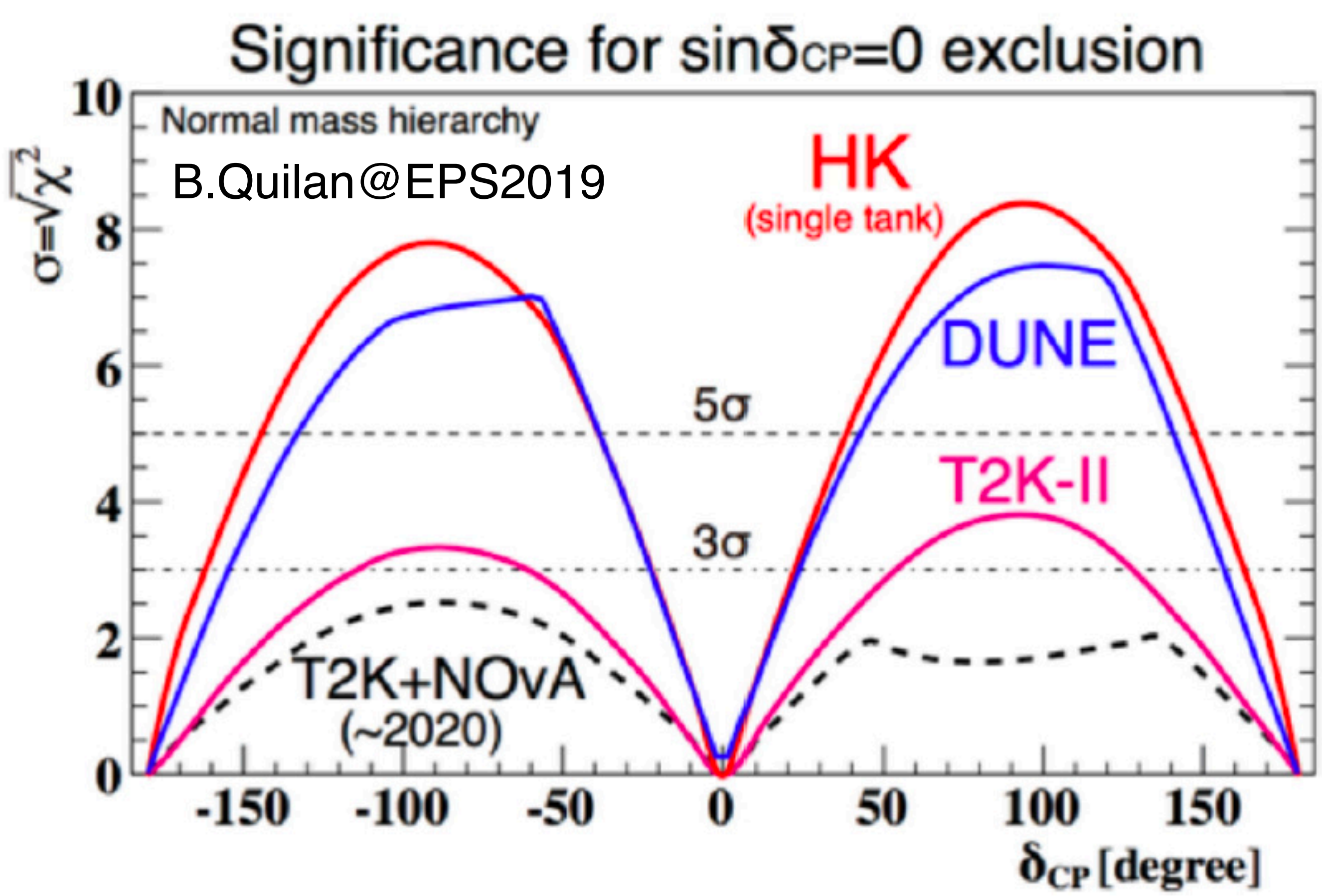


Long-baseline experiments: T2HK and DUNE



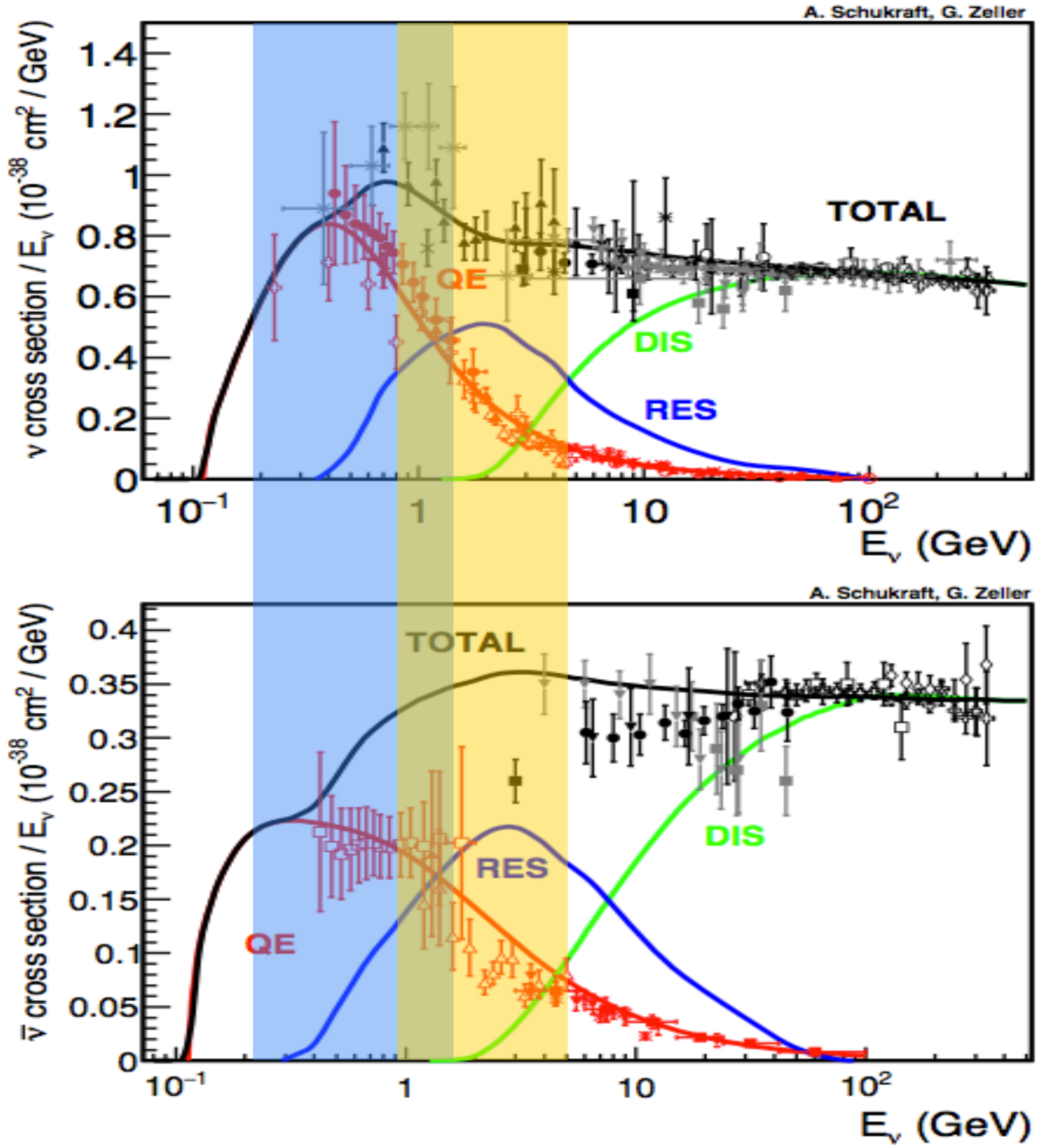
Eur. Phys. J. C (2020) 80:978



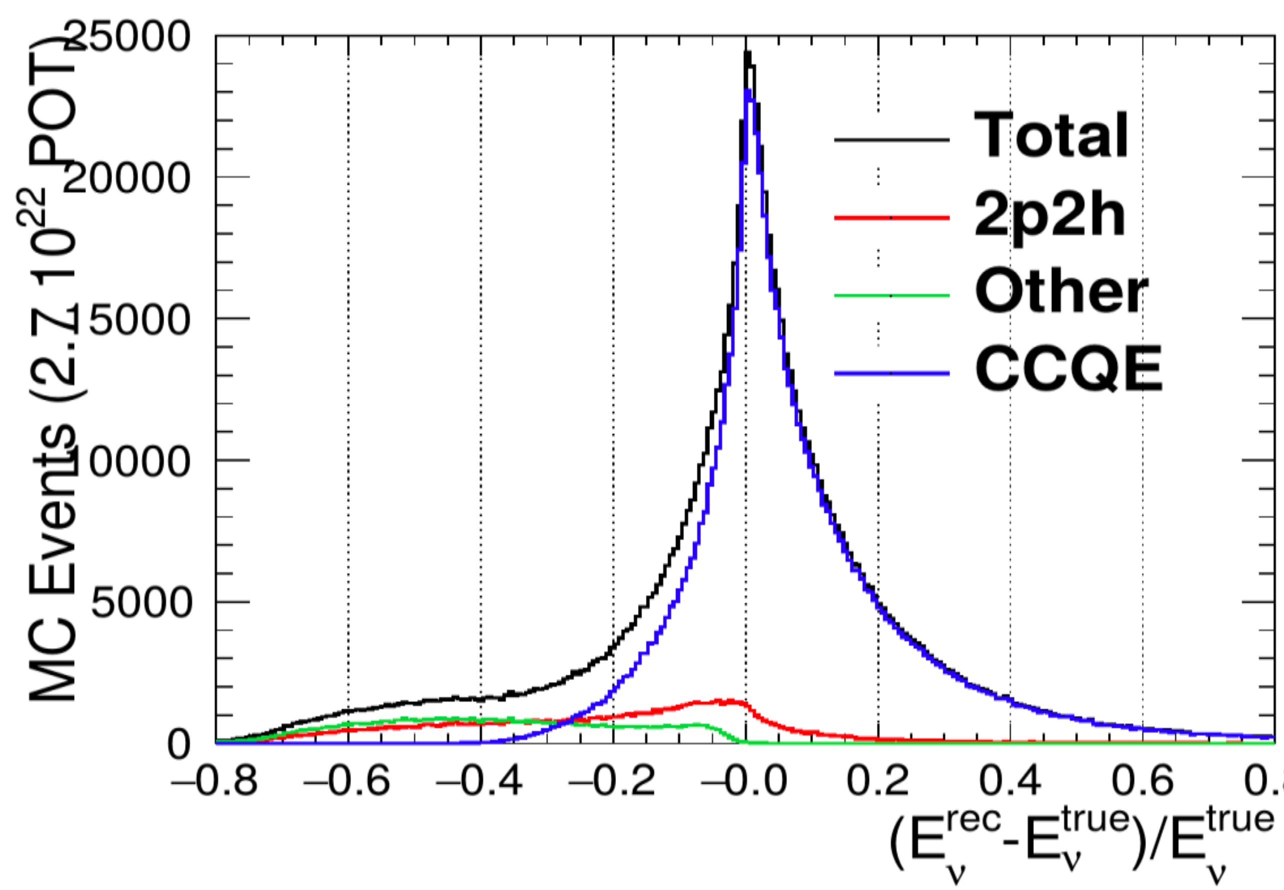


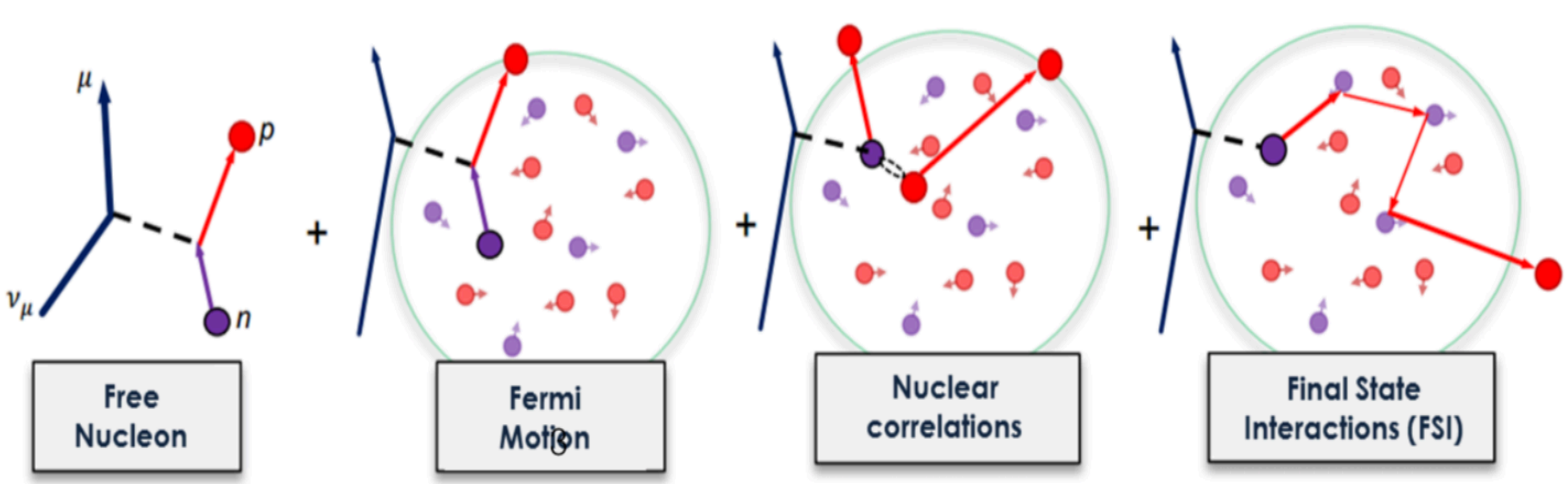
- T2K can give us insights about leptonic CP violation before 2027
- For both HK and DUNE will be important to fully implement the FDs and achieve the target beam intensitities
  - ✦ Search for CP violation requires large-statistic samples

Neutrino interactions at T2HK and DUNE



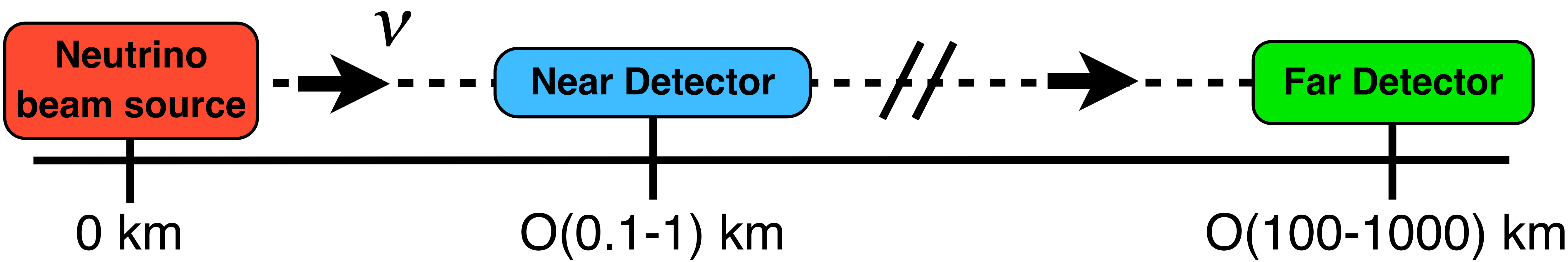
See S.Dolan's talk





Different interactions processes combined with nuclear effects and not-perfect detectors can introduce a large smearing in ν energy reconstruction

Function of Near Detectors and future requirements



Flux — Cross Section — Detector Response — Oscillation Probability

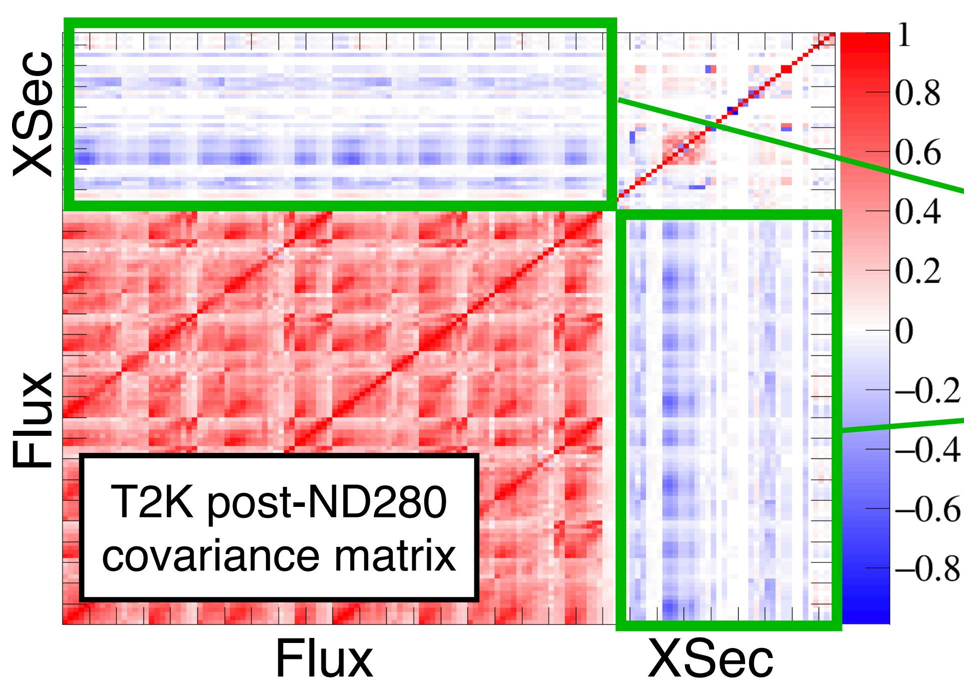
$$N(E_\nu) = \int \Phi(E_\nu, t) \times \sigma(E_\nu) \times R_{det}(E_\nu, \sigma(E_\nu), \vec{r}) \times P_{osc}(E_\nu)$$

Flux: Hadron production experiment (e.g. NA61/SHINE, EMPHATIC)

Flux × Cross Section: Near Detector

Detector Response: ~ same for ND and FD if same technology

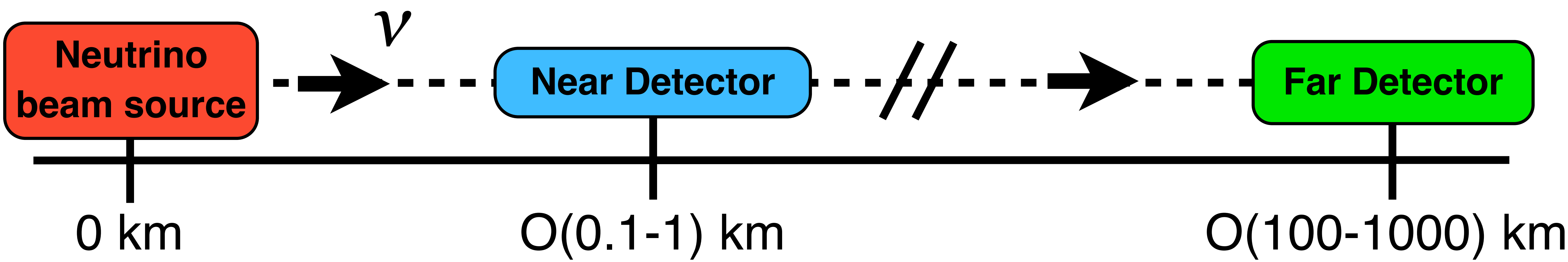
Oscillation Probability: Far Detector



L.Munteanu@ICHEP2020

From fits of Near Detector data strong anti-correlations arise between flux and cross section parameters

Function of Near Detectors and future requirements



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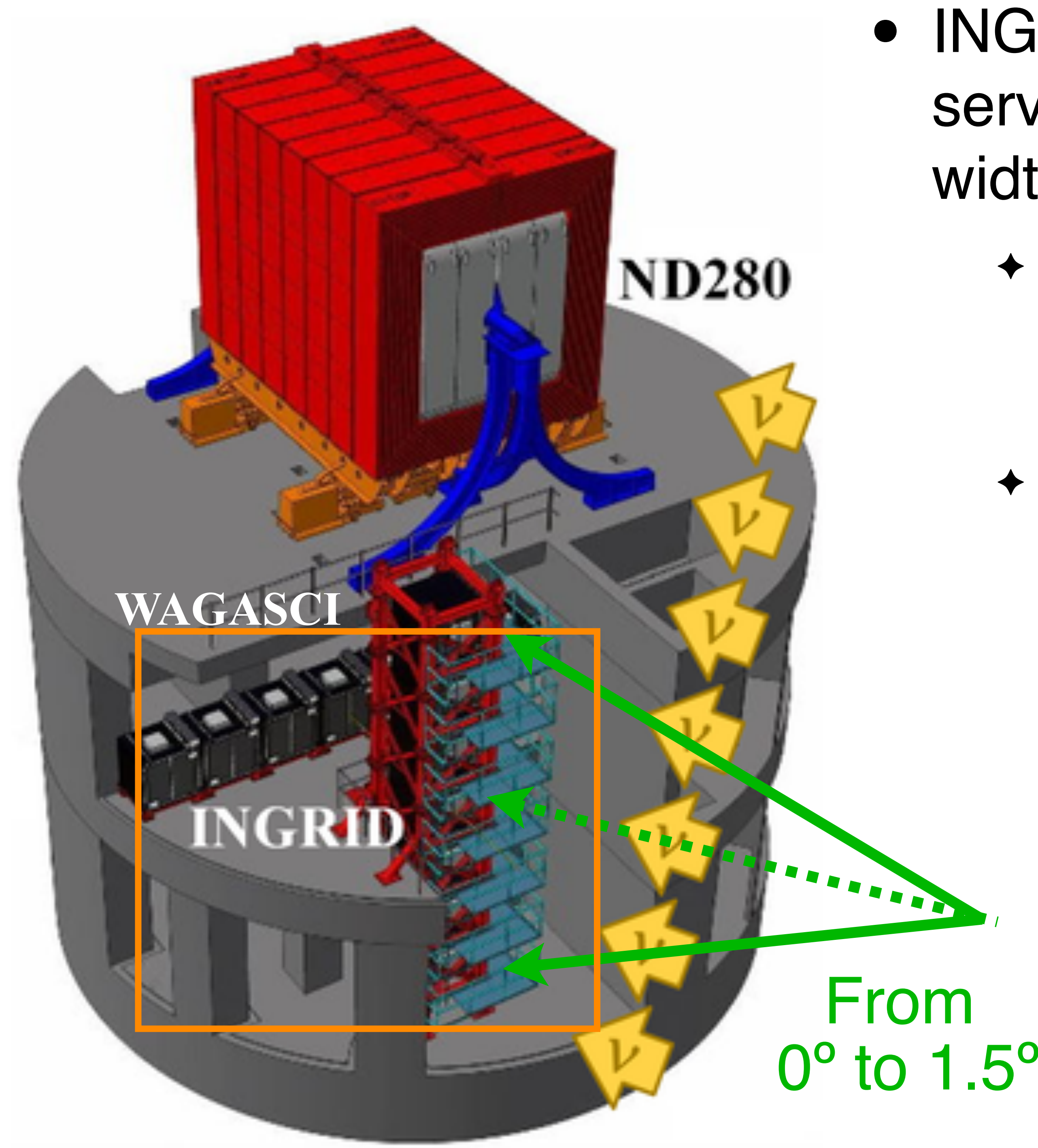
- Oscillation Probability: Far Detector

The Near Detector predicts the FD ν event-rate with different oscillation hypotheses and low systematic uncertainties, thus the main requirements are:

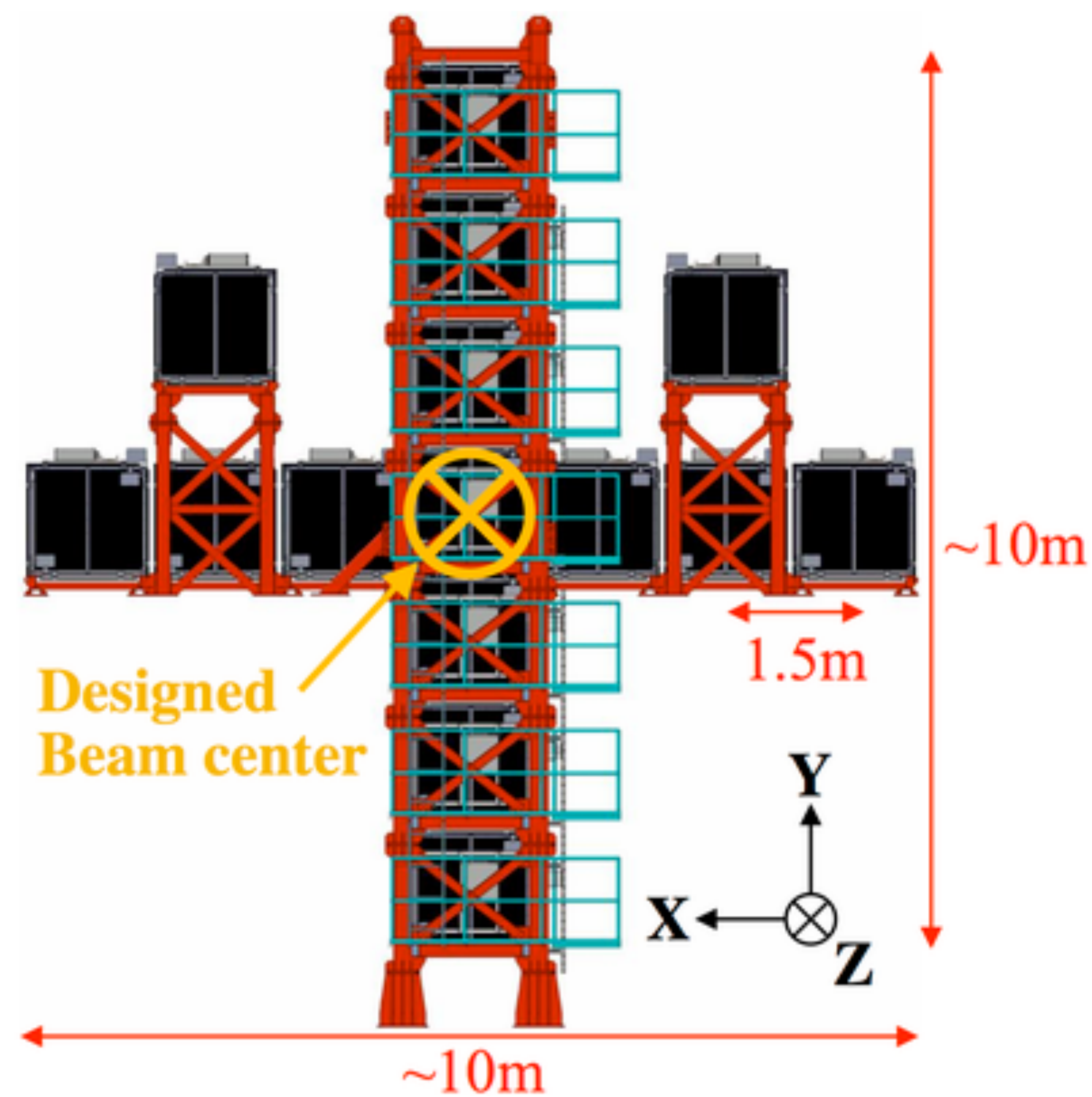
- Monitor the ν beam stability
- Measure ν_e cross section (~3% theoretical uncertainty - Phys.Rev. D86 (2012) 053003)
- Characterise the nuclear effects
- Flux measurements independent from hadron-production data

T2(H)K near detector complex at ~280 m



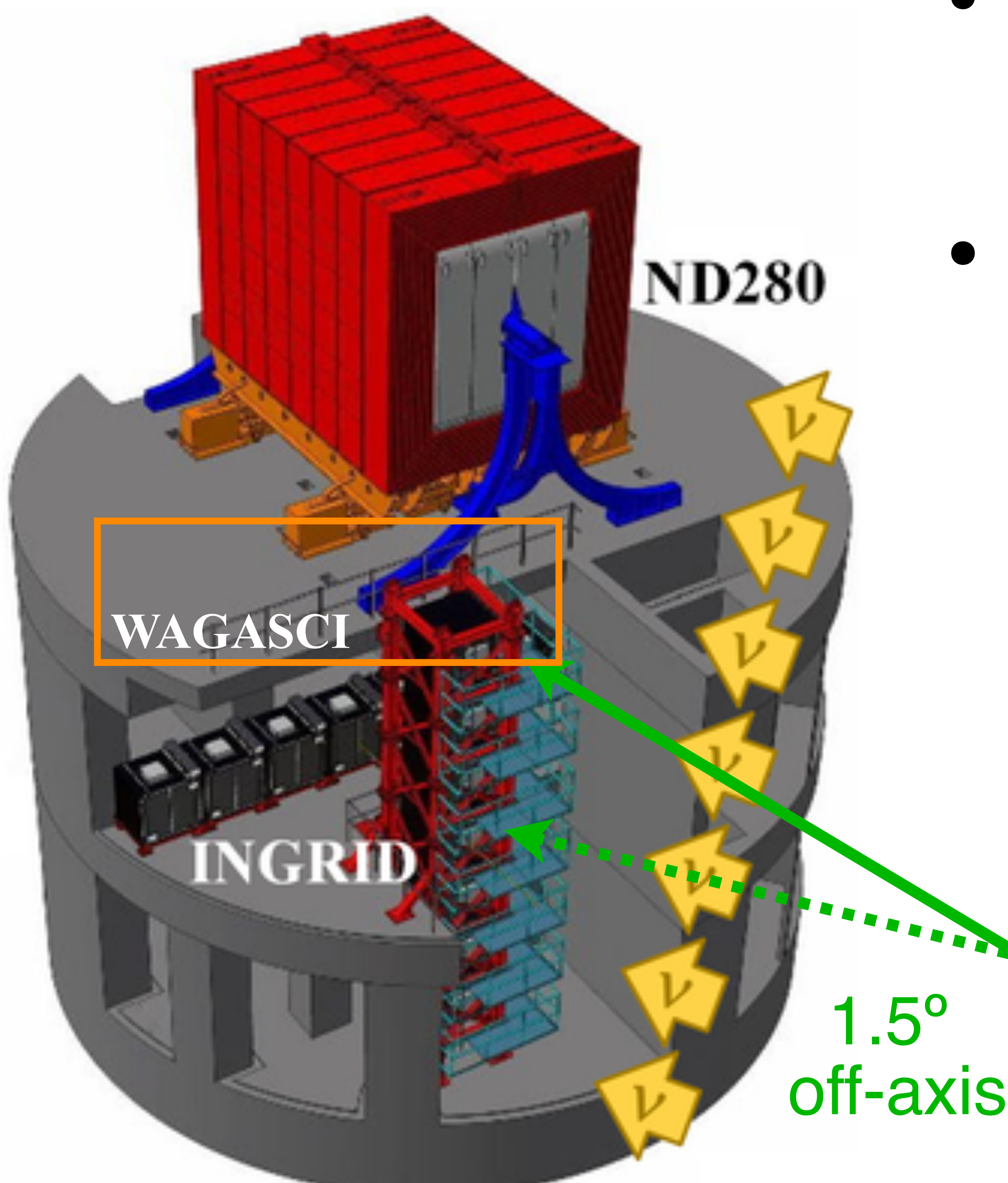
Beam monitor detector also for HK

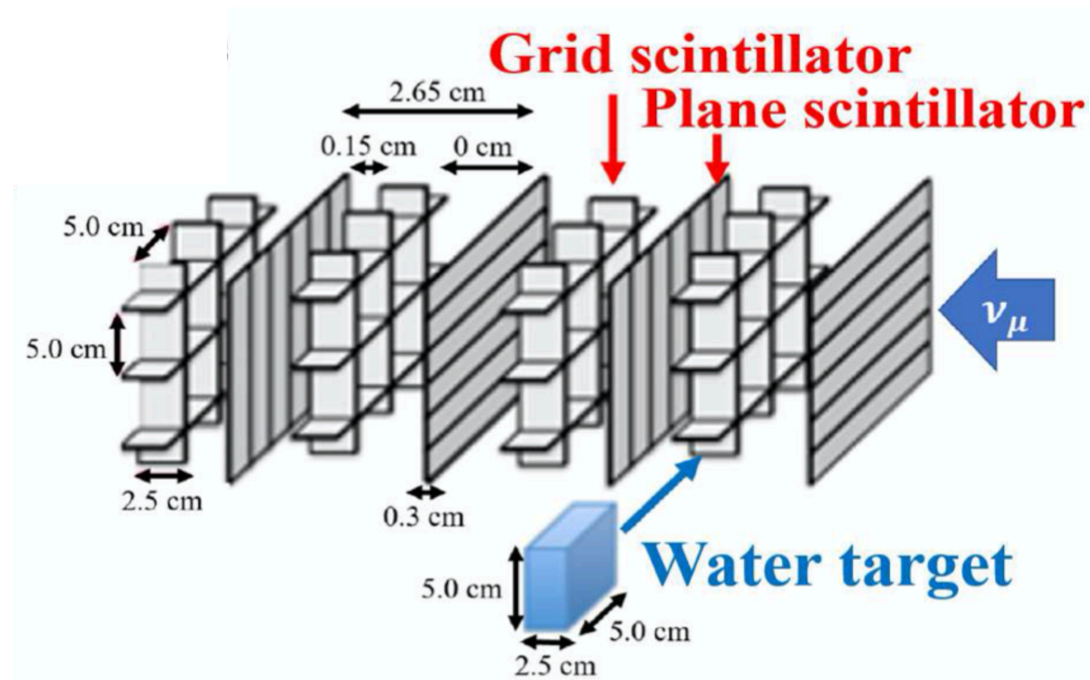
- INGRID detector (7ton of scintillator+iron) serves as beam monitor (beam rate, direction, width), muon range for parasitic detectors
  - ✦ Proton Module (scintillator) + WAGASCI (scintillator + water) - arXiv:2004.13989, Progr.Theor.Exp.Phys. 9 2019 093C02
  - ✦ NINJA (emulsions) - Phys. Rev. D **102**, 072006

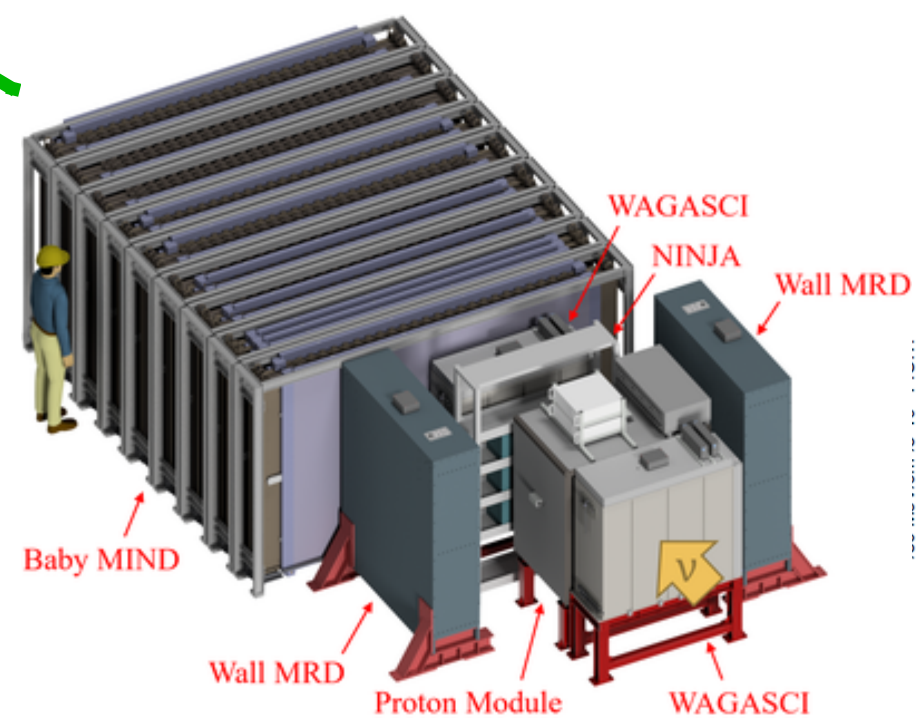


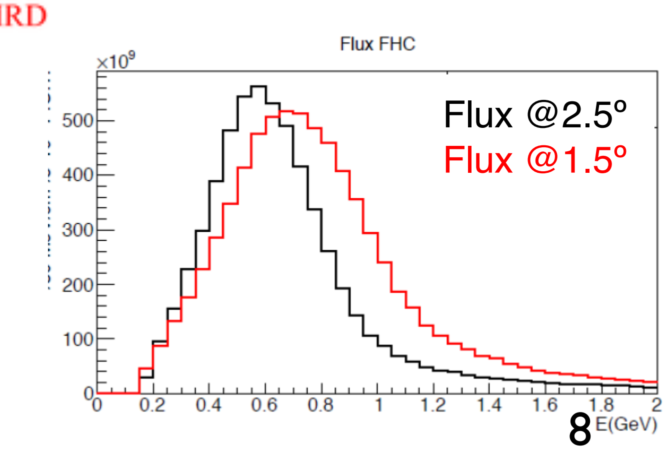
T2(H)K near detector complex at ~280 m

- Baby MIND magnetised spectrometer
  - Range muon dp/p ~ 5% up to 1.5GeV/c
  - Curvature muon dp/p ~20-30% above 1GeV/c
- WAGASCI detector (~0.5 ton water target)



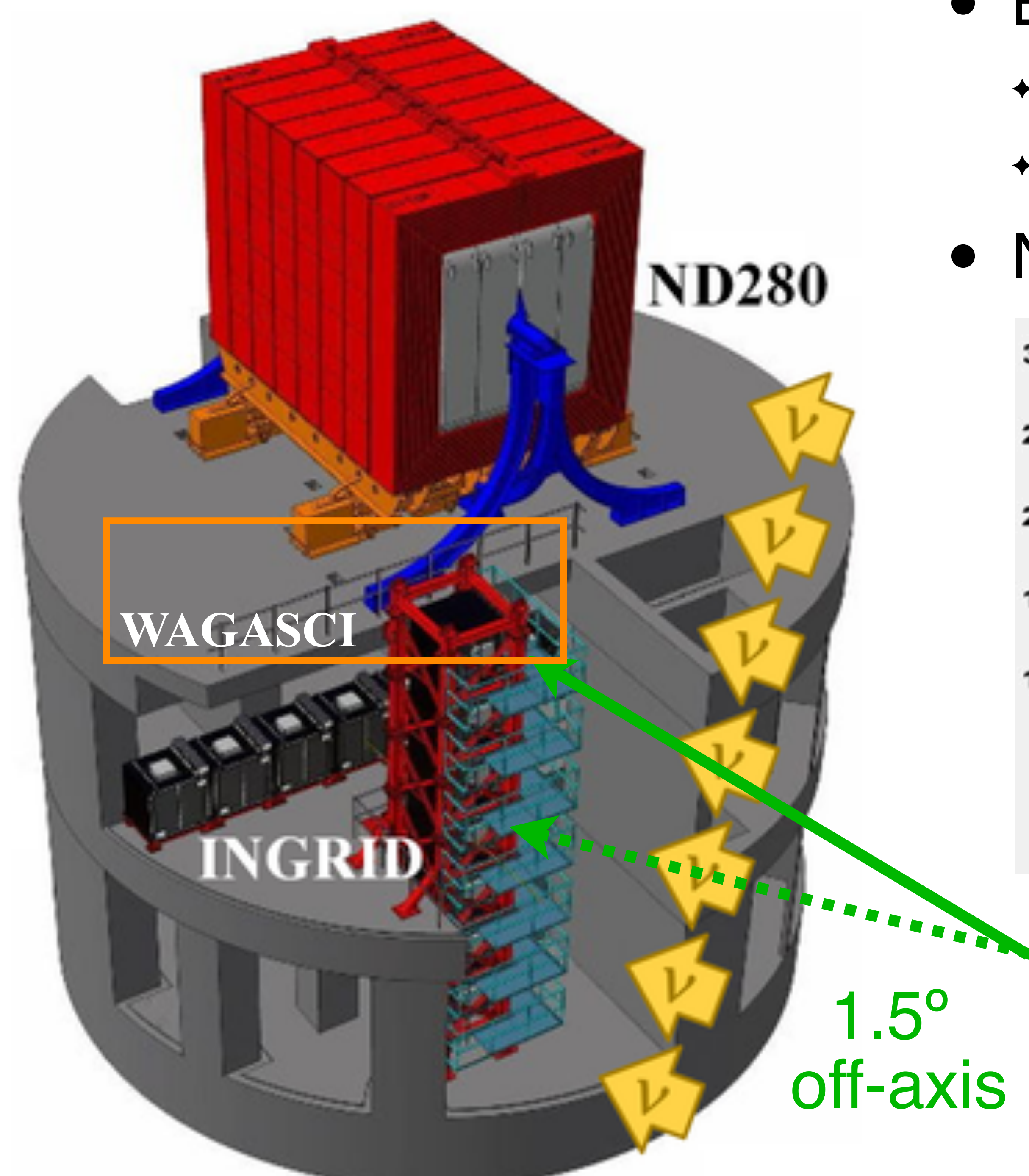




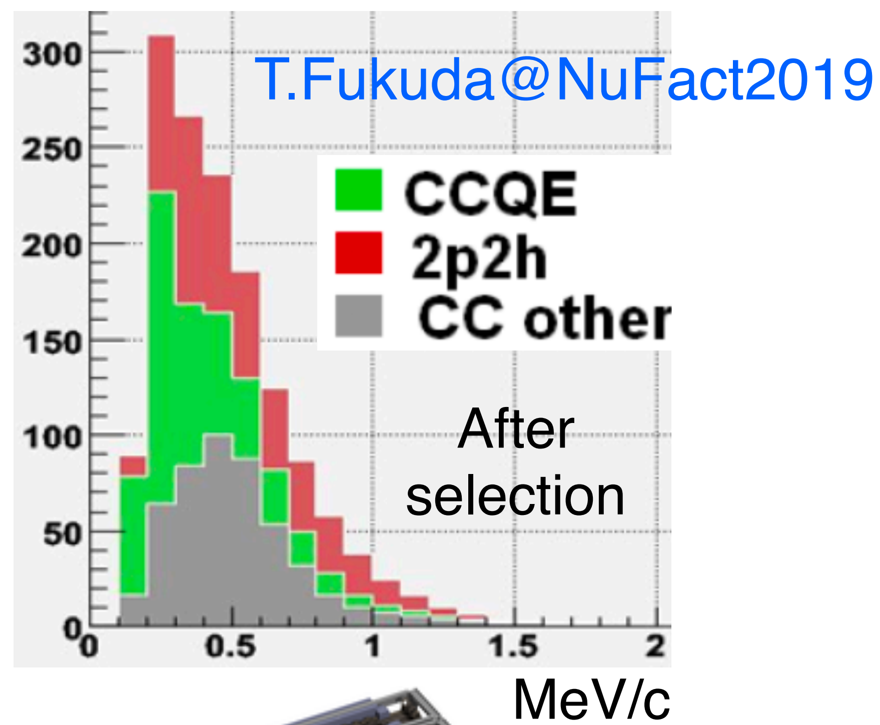


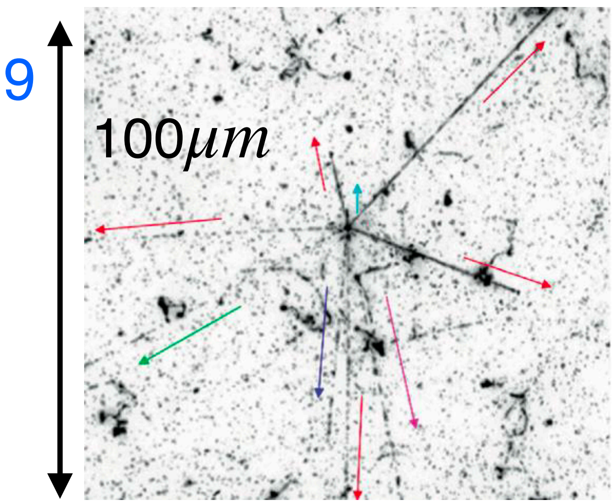
Currently running at the T2K ND site. Useful for systematic reduction also at T2K-II and HyperK

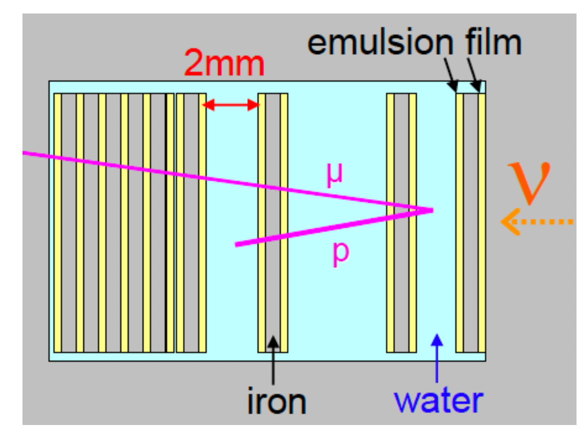
T2(H)K near detector complex at ~280 m

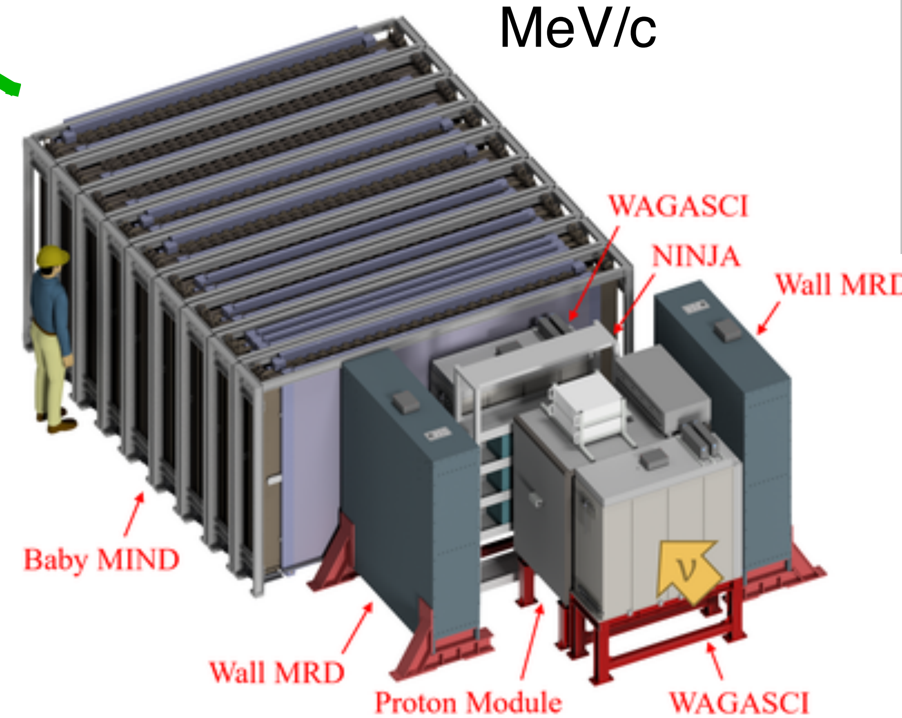


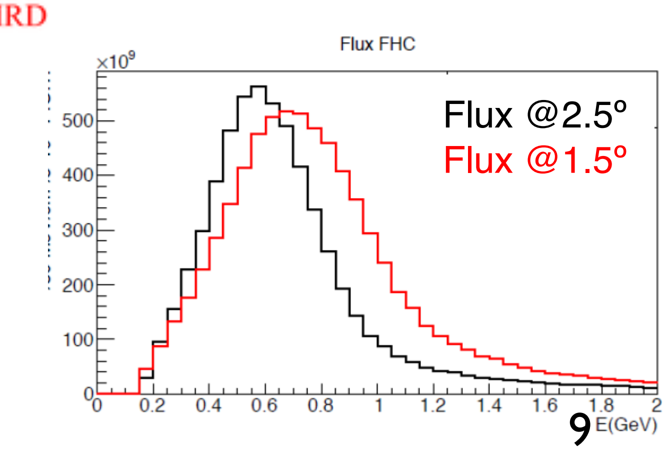
- Baby MIND magnetised spectrometer
  - Range muon dp/p ~ 5% up to 1.5GeV/c
  - Curvature muon dp/p ~20-30% above 1GeV/c
- NINJA: very low momentum in 75kg H_2O





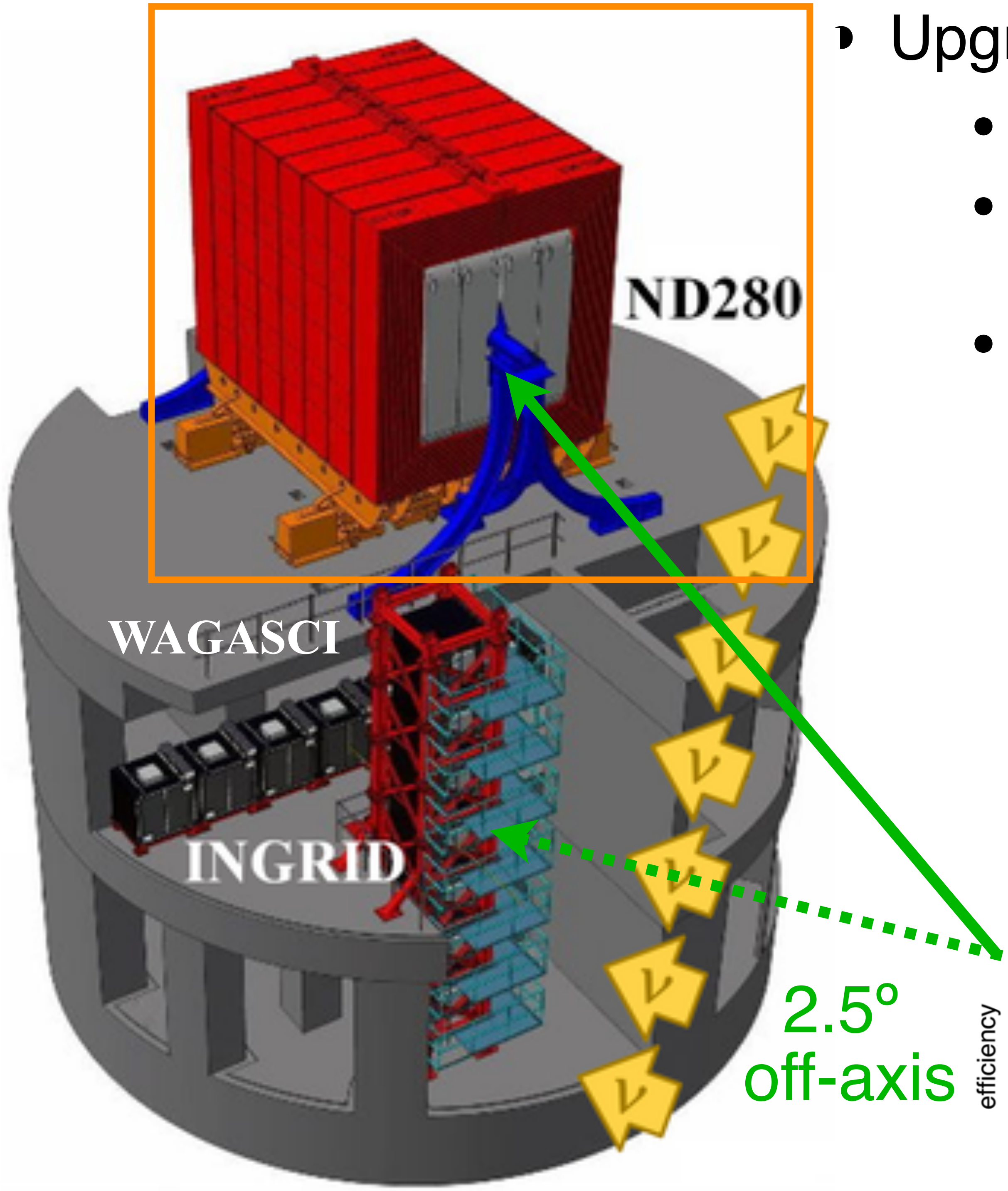






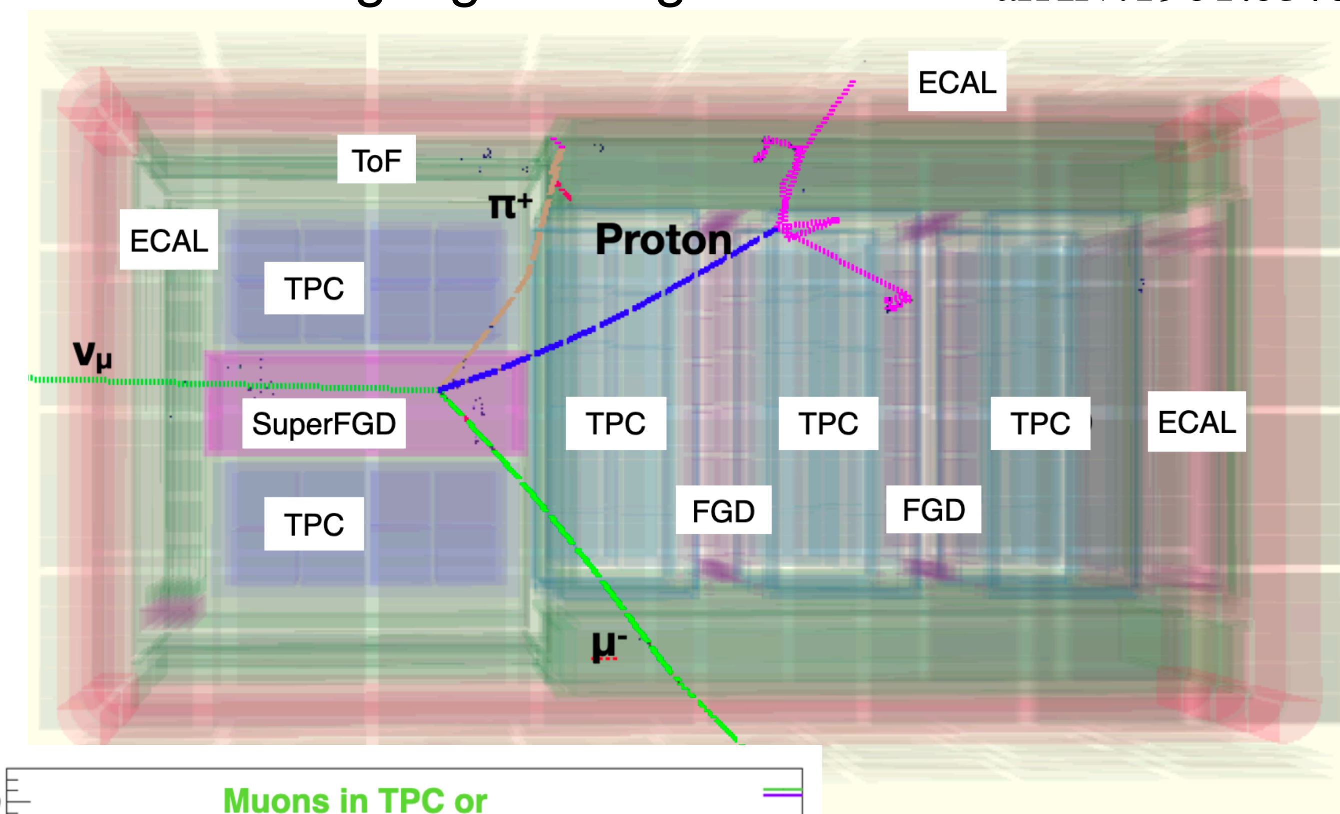
Currently running at the T2K ND site. Useful for systematic reduction also at T2K-II and HyperK

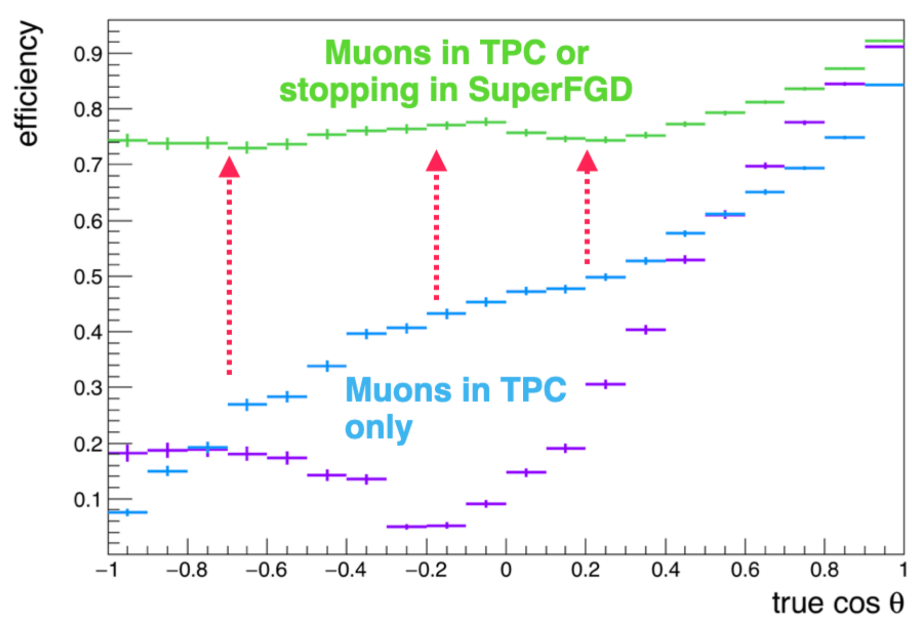
T2(H)K near detector complex at ~280 m

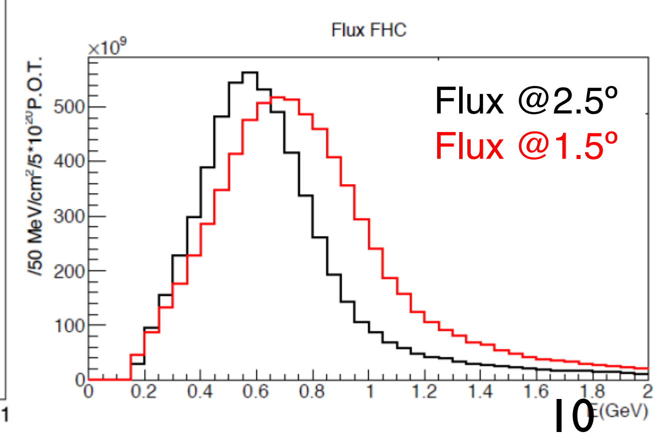


- Upgrade of ND280 ready in 2022 for T2K phase II
  - Fine granularity scintillator and water target (~4 ton)
  - Surrounded by TPCs based on resistive MicroMegas (See C.Giganti's talk), ECAL in 0.2T B-field
  - Measure wrong-sign background

arXiv:1901.03750

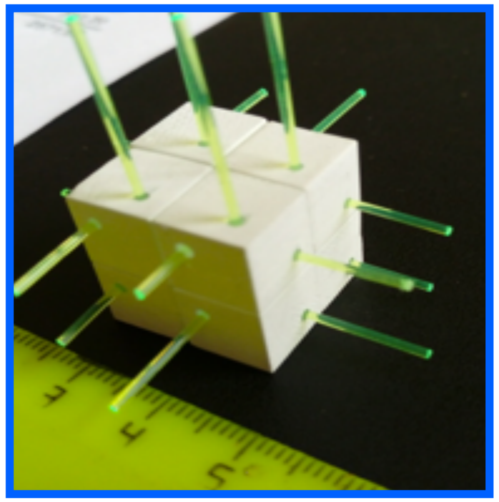






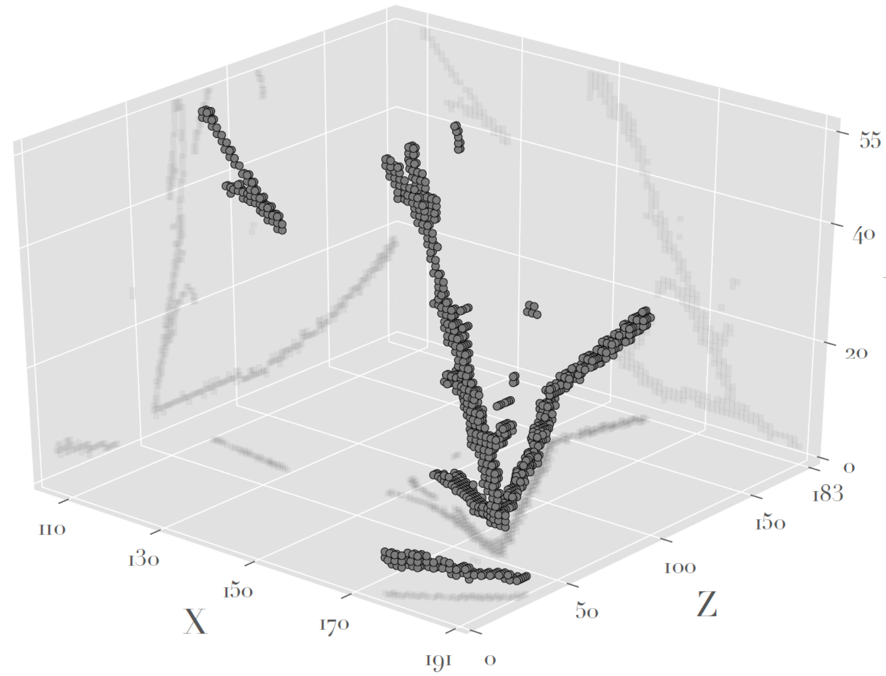
Magnetised ND in T2K-II and HK

The Super Fine-Grained Detector @T2(H)K



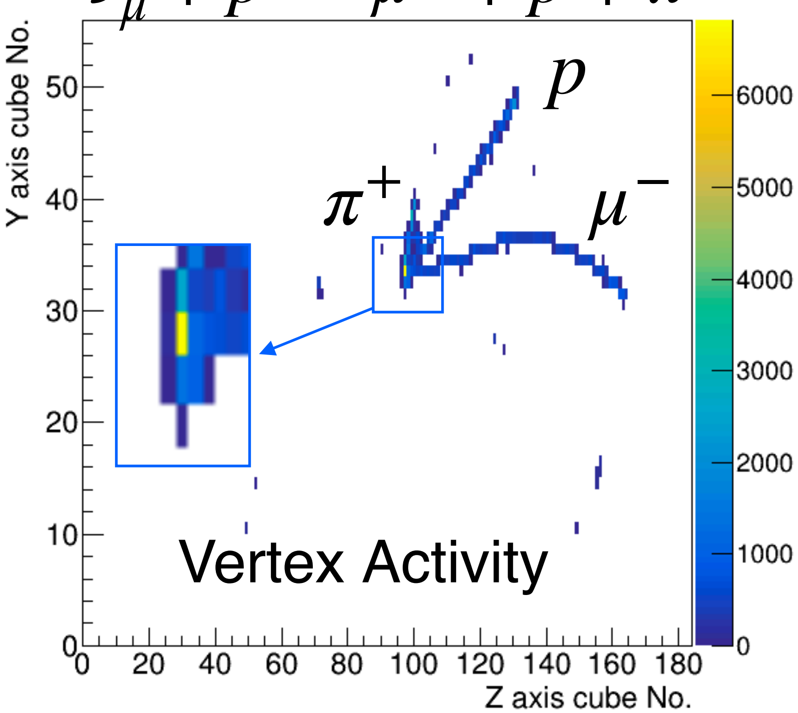
2018 JINST 13 P02006

NIM A936 (2019) 136-138

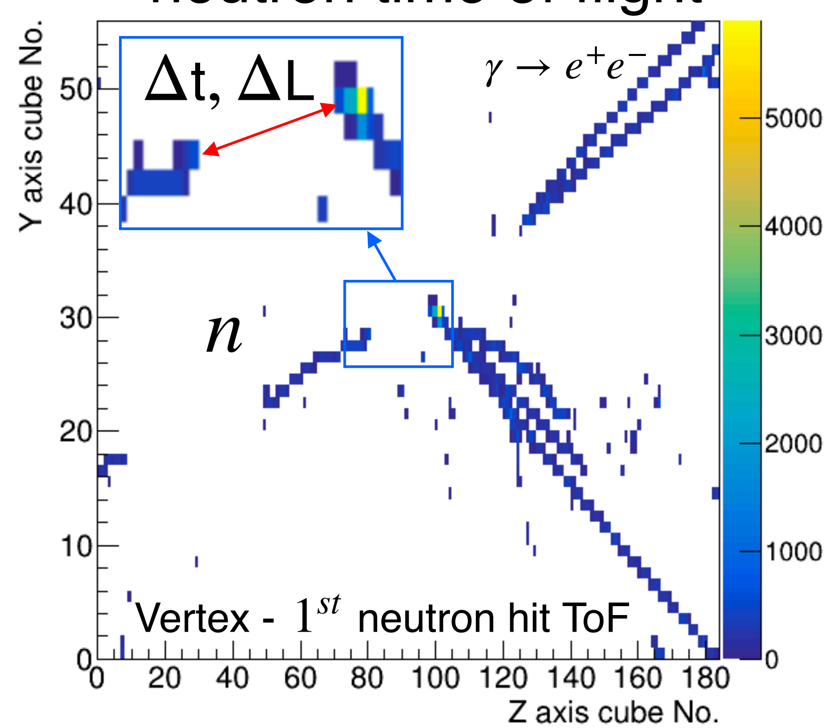


- 3D tracking with 4π acceptance
  - Muon δp/p ~ 2% by range
  - Proton momentum threshold ~300 MeV/c
- Excellent PID (dE/dx,decay-e+)
- SiPM with high-dynamic range
  - "Vertex Activity" and Bragg peak measurements
- ν_e interactions ($\gamma \rightarrow e^+e^-$ rejection)
- Neutron detection with kinetic energy (PRD 101, 092003 (2020))

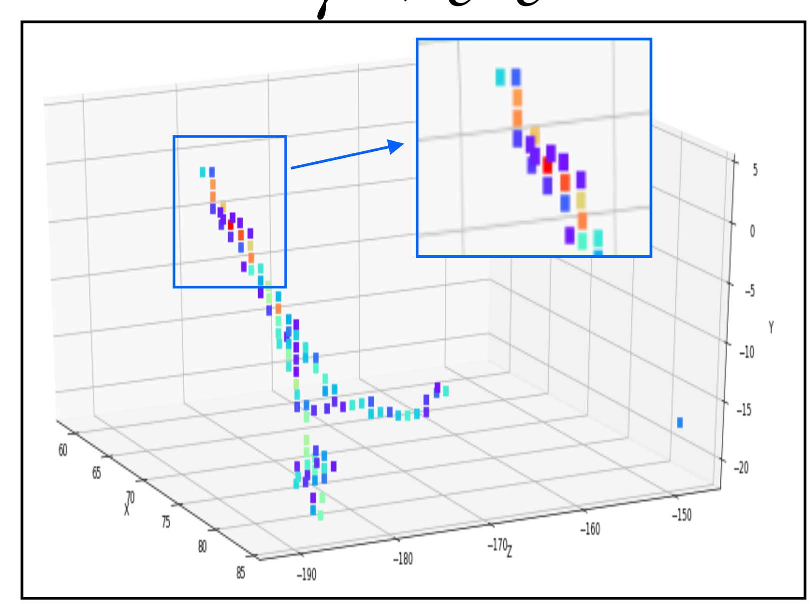
$\nu_\mu + p \rightarrow \mu^- + p + \pi^+$



neutron time of flight



$\gamma \rightarrow e^+e^-$

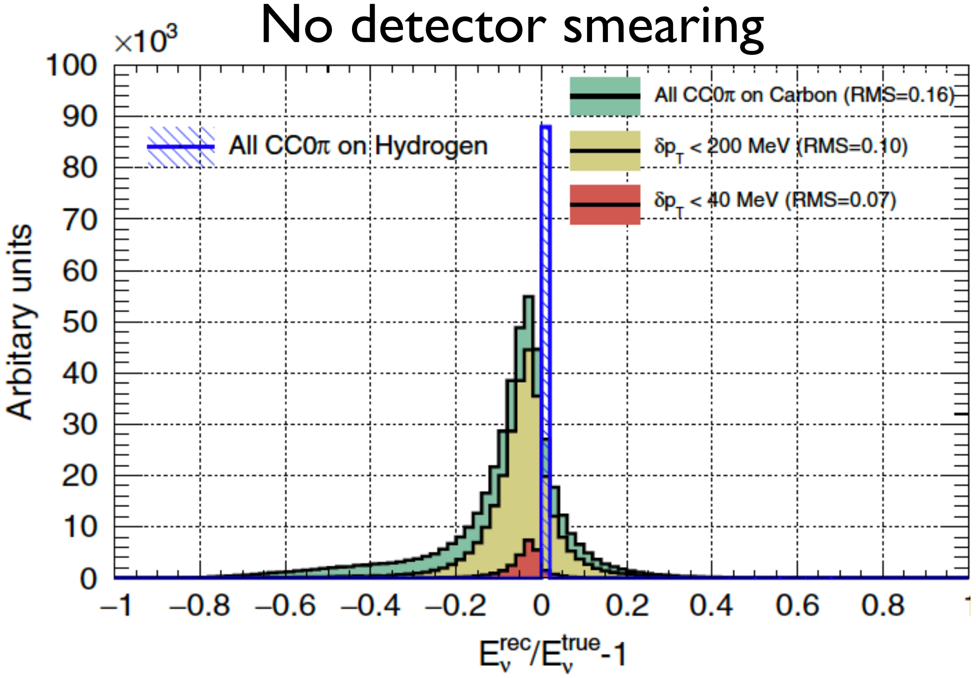


Excellent performance and large statistics are necessary to perform multi-dim analyses to gain more sensitivity to ν interaction models (see S.Dolan's talk)

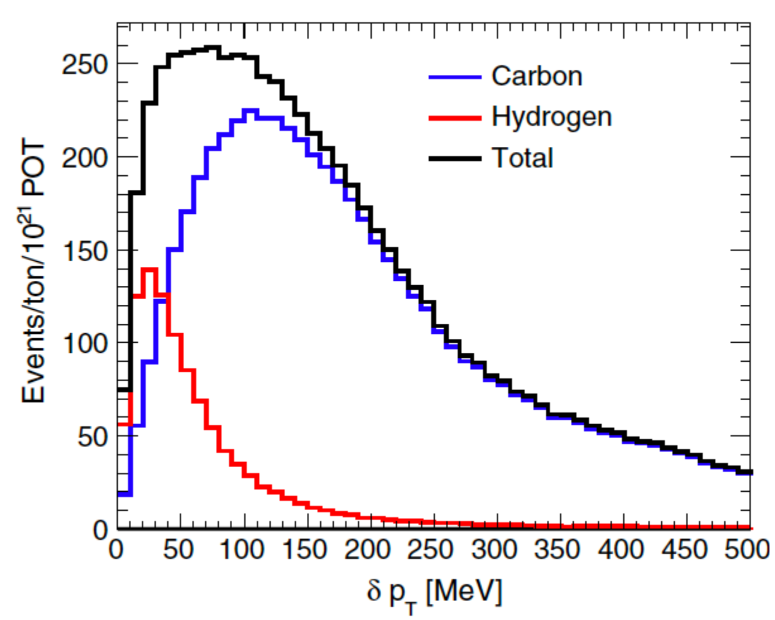
Independent flux measurement @T2HK

- Improve flux prediction with independent methods δ_{CP} precision measurement
- Typical methods tested at neutrino experiments but not optimal for T2HK
  - ✦ ν − e scattering for flux normalisation - Minerva, *Phys.Rev.D* 100 (2019) 9, 092001
  - ✦ Low-ν interactions for flux shape - Minerva, *Phys.Rev.D* 94 (2016) 11, 112007
- Measure the transverse momentum imbalance to isolate $\bar{\nu}$-hydrogen events

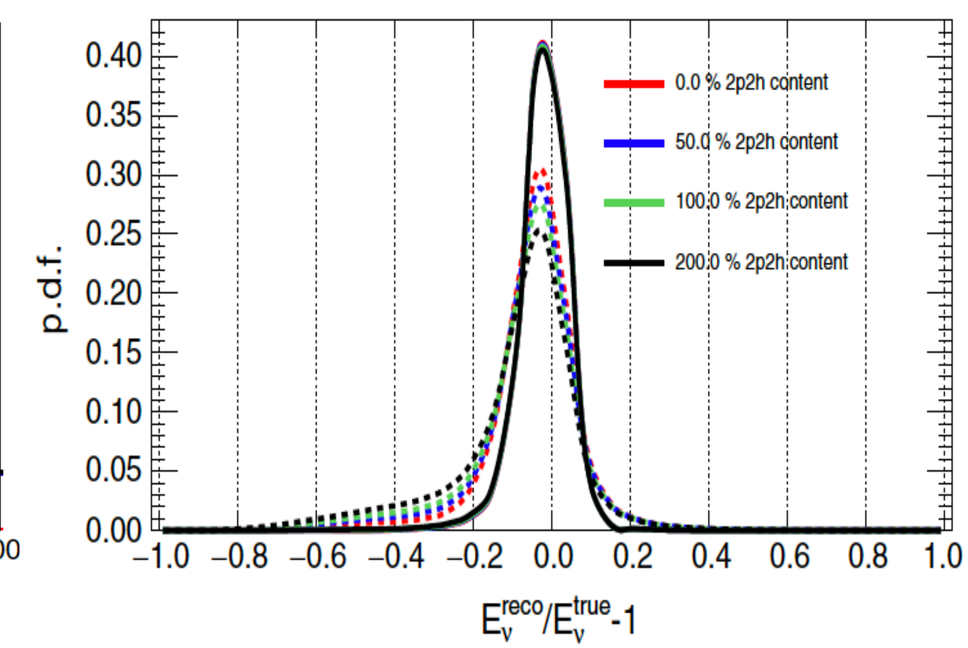
No detector smearing



Phys.Rev.D 101, 092003 (2020)



$\bar{\nu}$ energy resolution



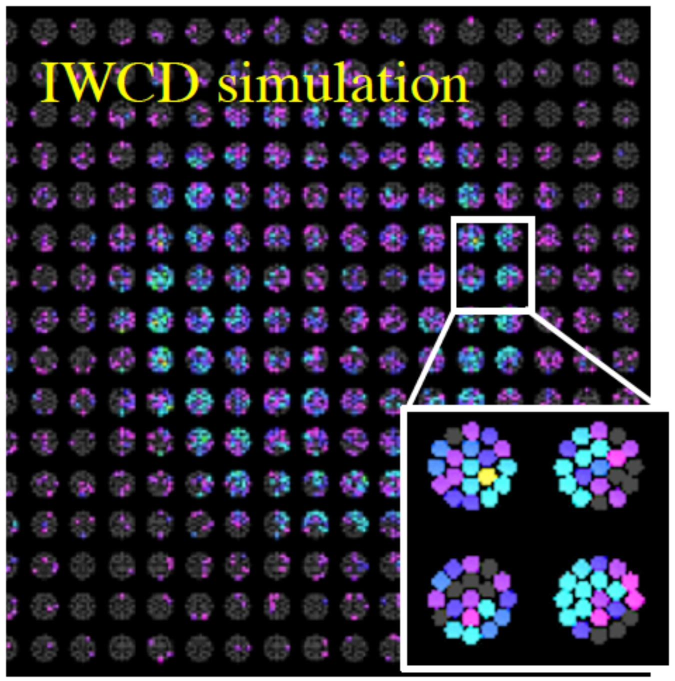
Resolution on δp_T strongly depends on the muon momentum resolution and neutron ToF resolution → fast, fine granularity and large mass scint. detector

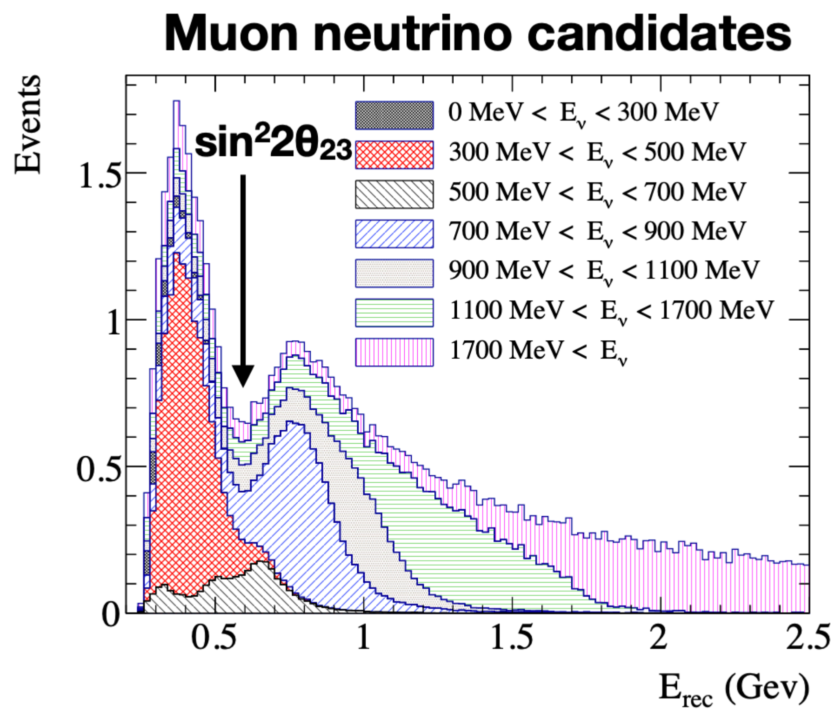
- ✦ ~1,000 $\bar{\nu}$ interactions per ton per 10^{21} POT

See S.Dolan's talk

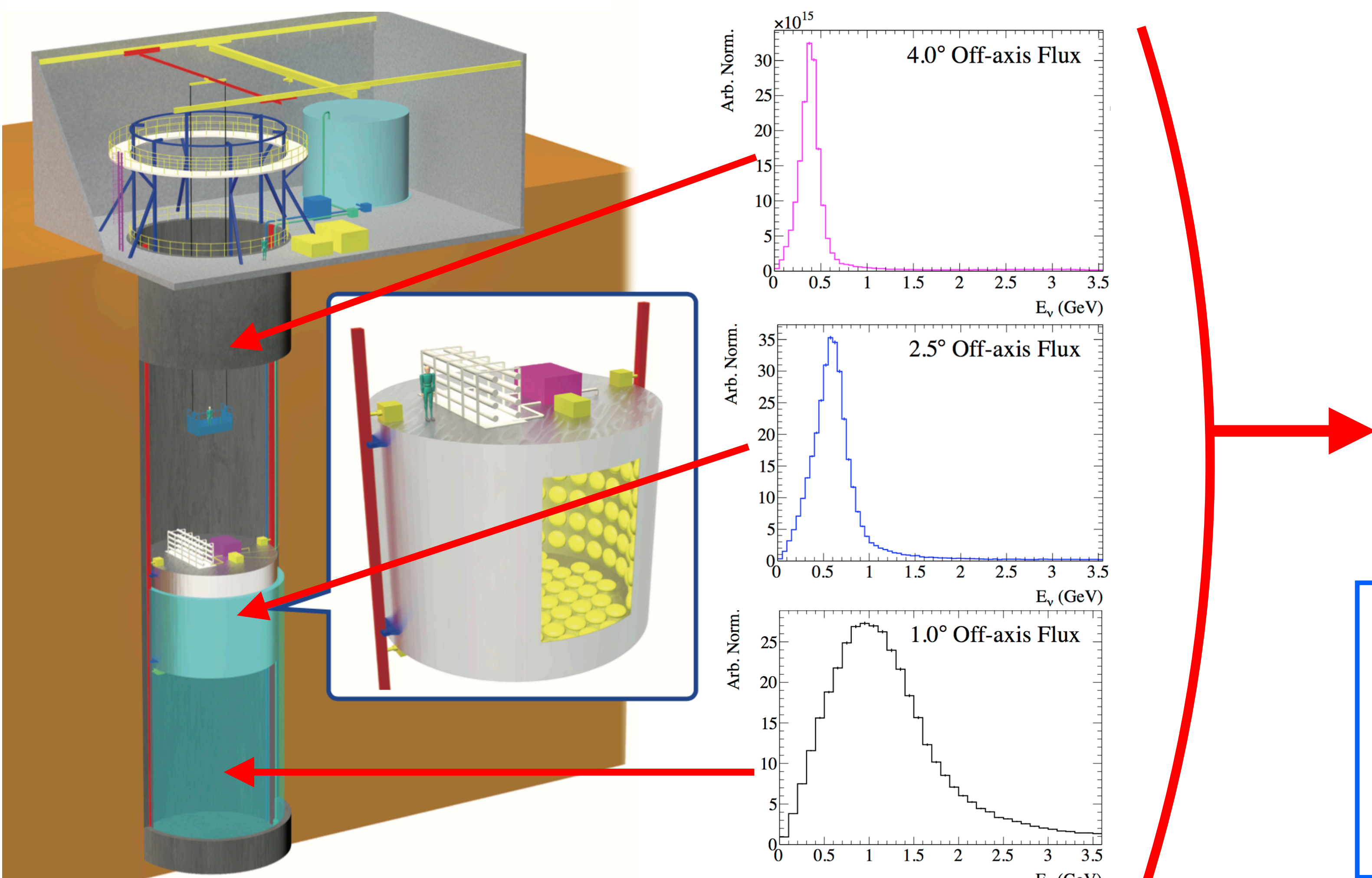
PRISM @Intermediate Water Cherenkov Detector

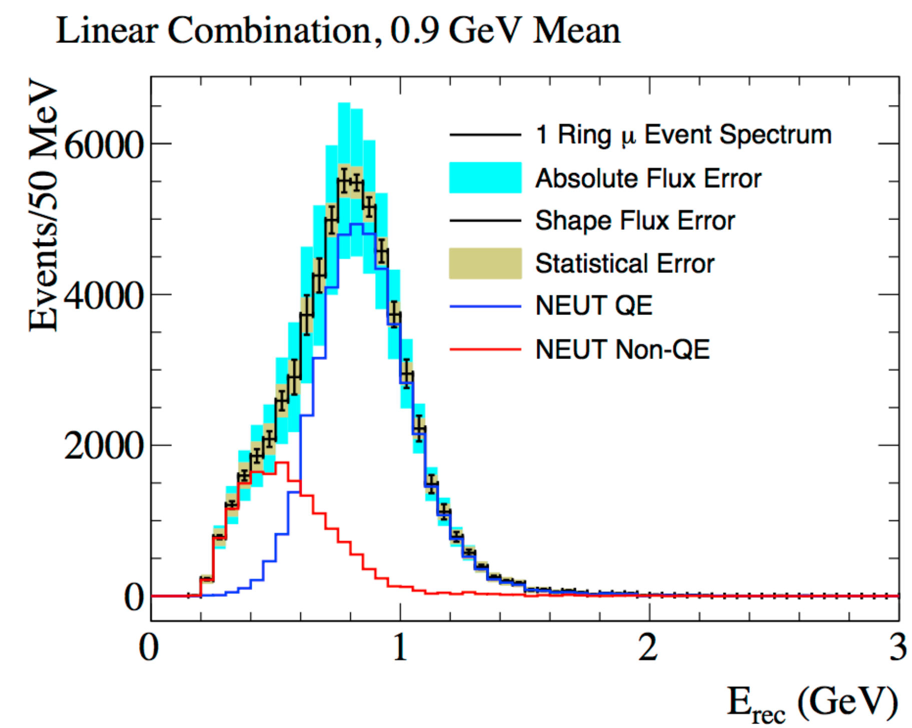
M.Hartz@ICHEP2020





- At 0.75 km from ν source, ~600 ton
- Contain muons up to ~1 GeV/c
- Gd-loading for neutron tagging
- Low statistical uncertainty in ν_e cross section (3.5-7% precision) - higher flux fraction more off-axis





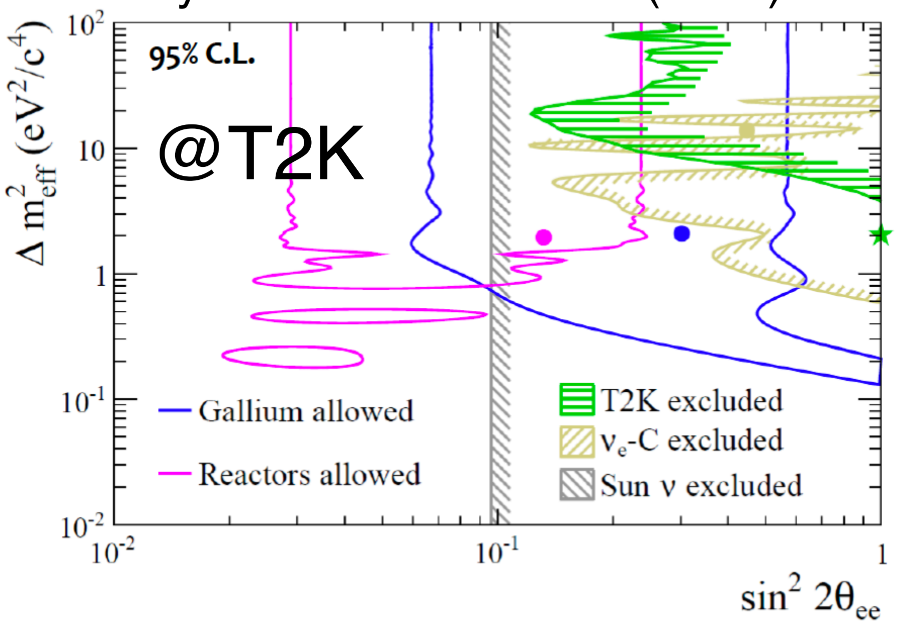
Subtract off low energy and hit energy tails of flux → probe relation between neutrino energy and observed final state in water cherenkov

Beyond Standard Model at T2HK Near Detectors

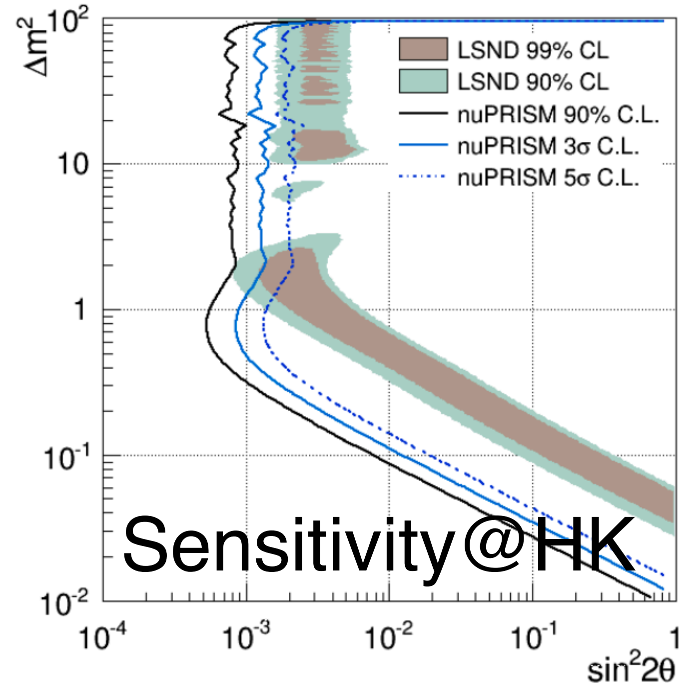
- Sterile neutrinos (short-baseline oscillations)

P.Litchfield@NuFact19

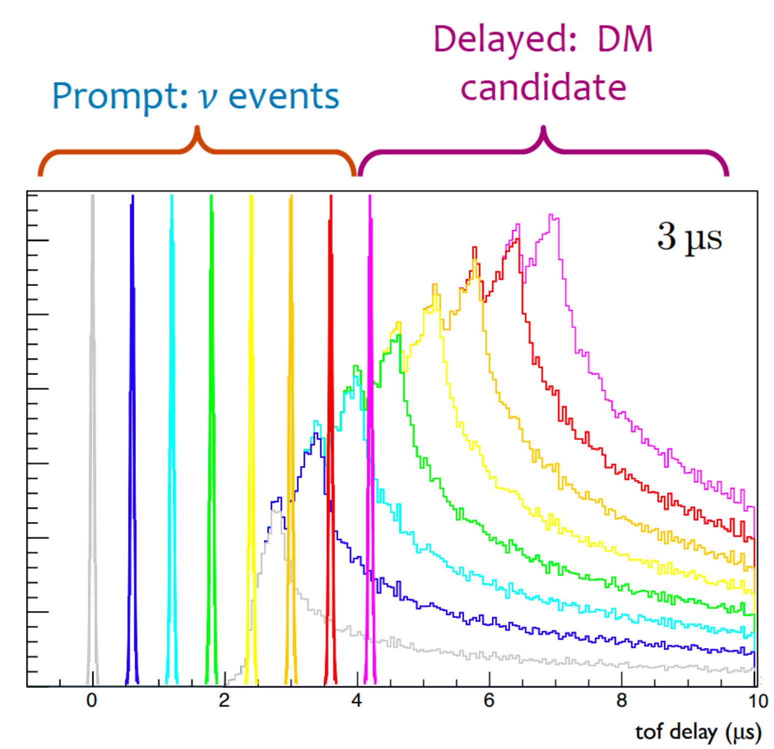
Phys. Rev. D 91 051102 (2015)



At HK it can also profit of detectors at different baselines

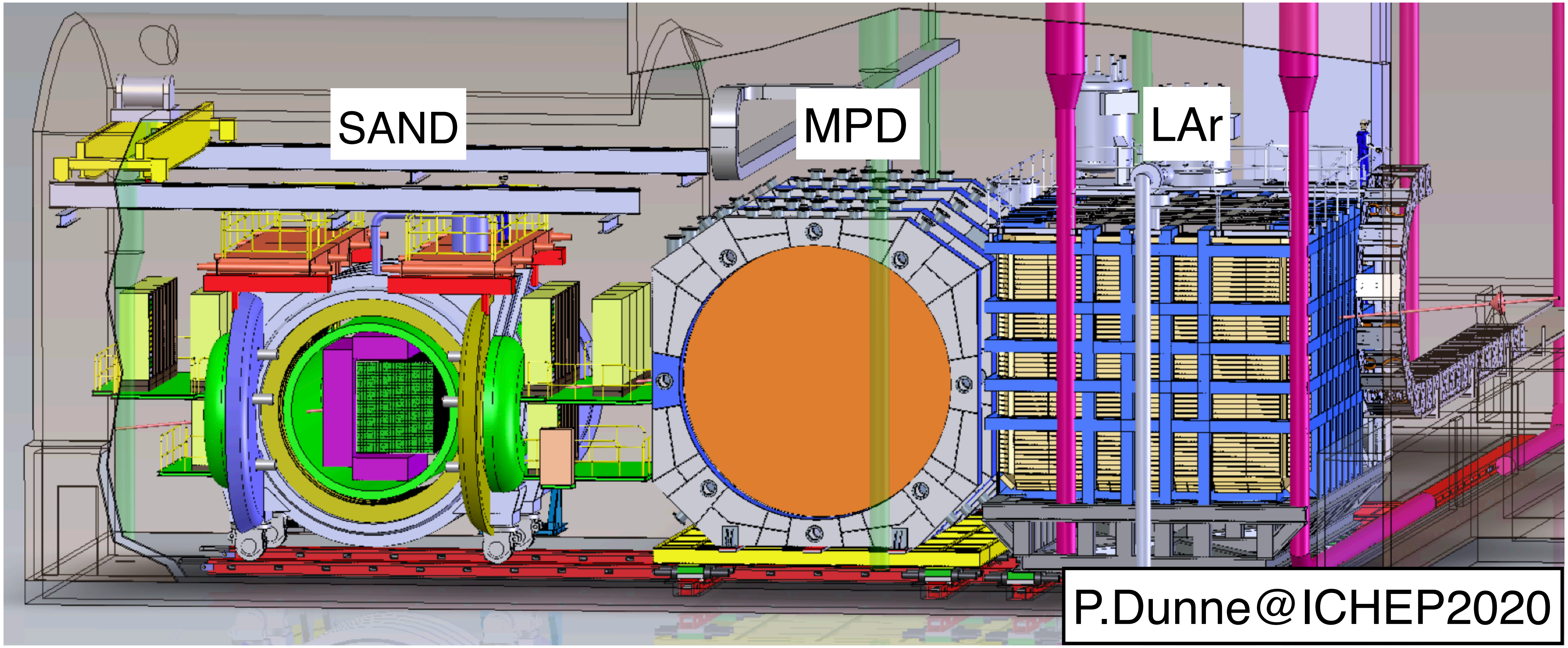


- Search for heavy neutrinos in ND280 TPCs
  - ✦ Already performed at T2K (*Phys.Rev.D* 100 (2019) 5, 052006) and can profit of higher statistics at HK (and more TPCs…)
- Tests for Lorentz and CPT invariance at INGRID (PRD 95, 111101(R) (2017))
- Search for low-mass dark matter produced in ν beams (analyses being developed at T2K)



T2HK will profit of higher beam intensity, mass and more performant detectors

The DUNE Near Detector



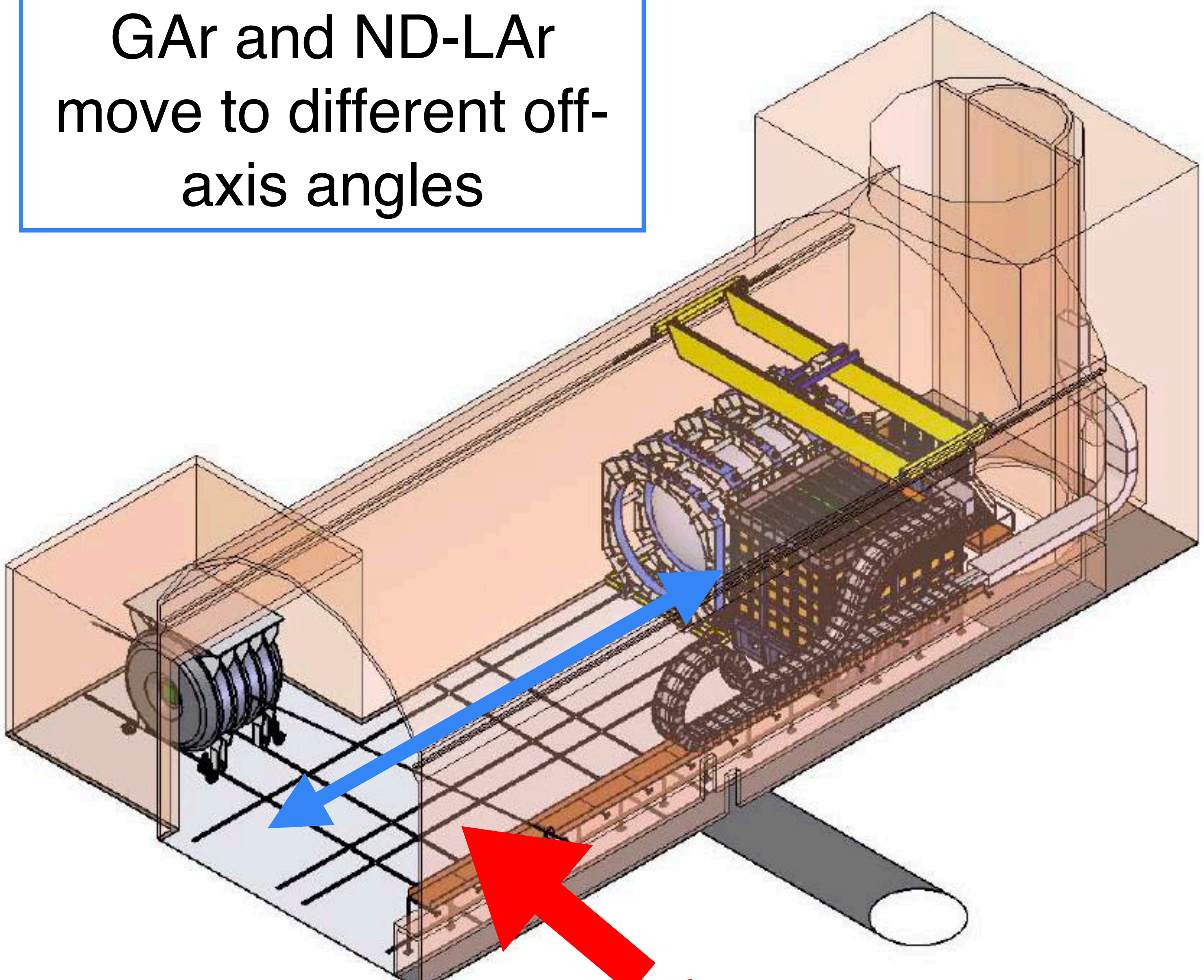
- Three main near detector complexes:
  - System for on-Axis Neutrino Detection (SAND)
  - HpTPC+ECAL (ND-GAR)
  - Liquid Argon (ND-LAr)
- Complementarity necessary to achieve:
  - Detection of ν interactions in argon nucleus, Low-momentum threshold for protons, Neutron detection, Beam monitor, ν flux estimation

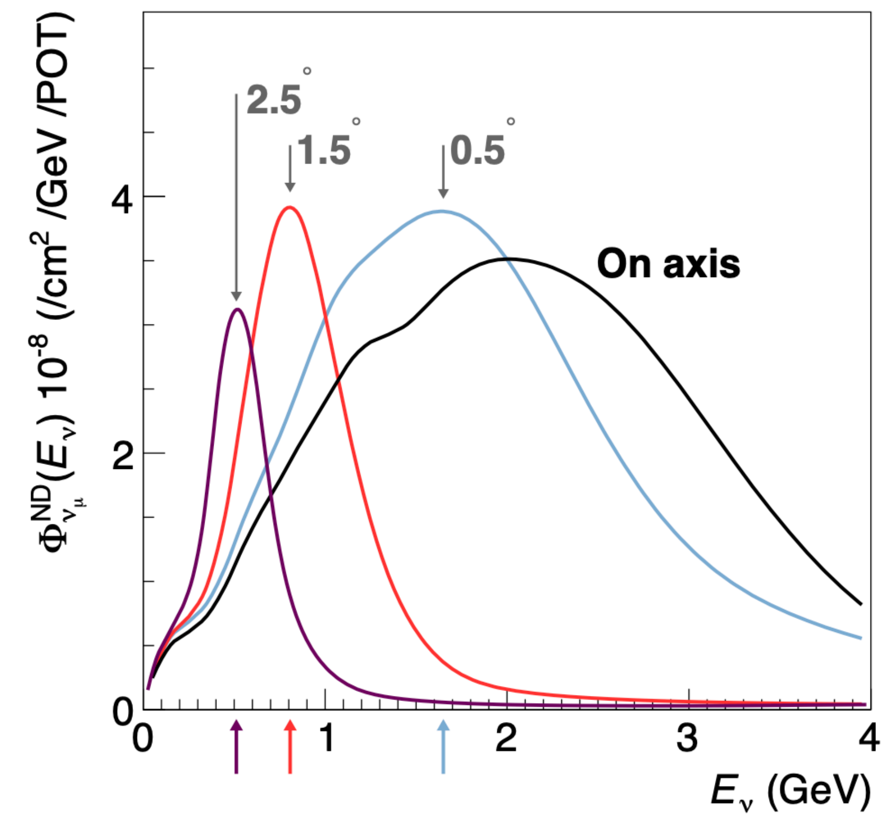
Detector	Target (Fid. mass t)	# ν_μ CC (X10^6)
LAr	Ar (50)	80
HPgTPC	Ar (1)	1.5
SAND	CH (8)	12

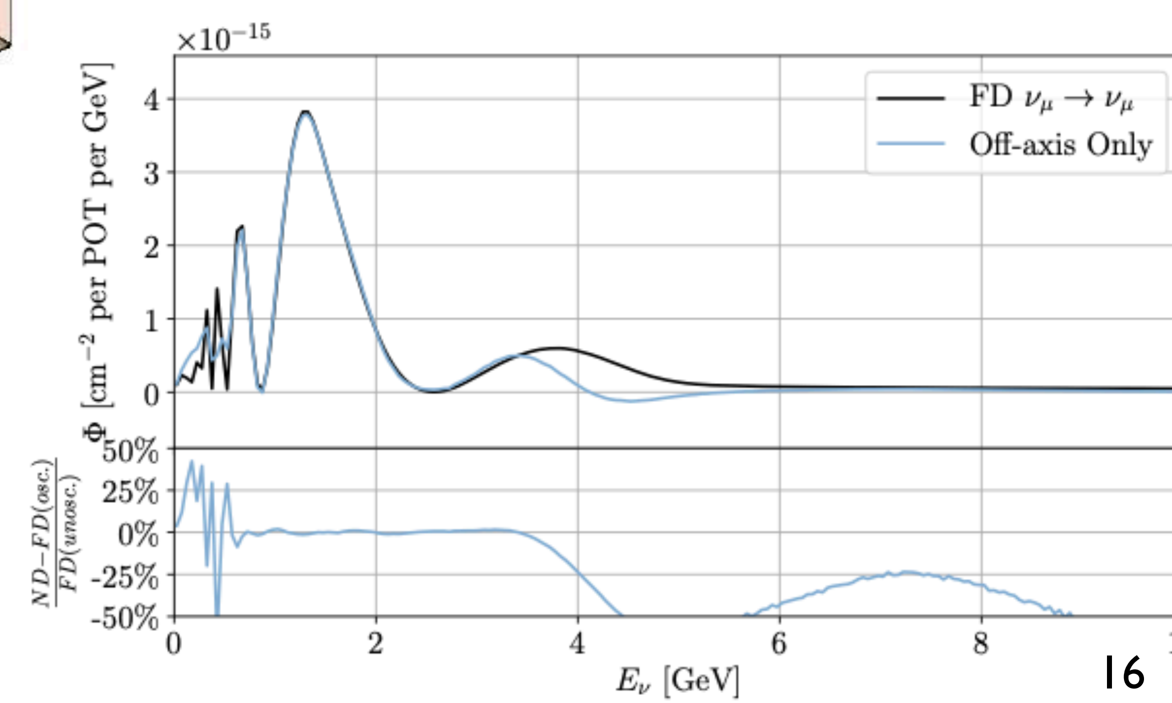
PRISM @DUNE ND

- Same method as PRISM@HK but DUNE is On-Axis, while HK is Off-Axis

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





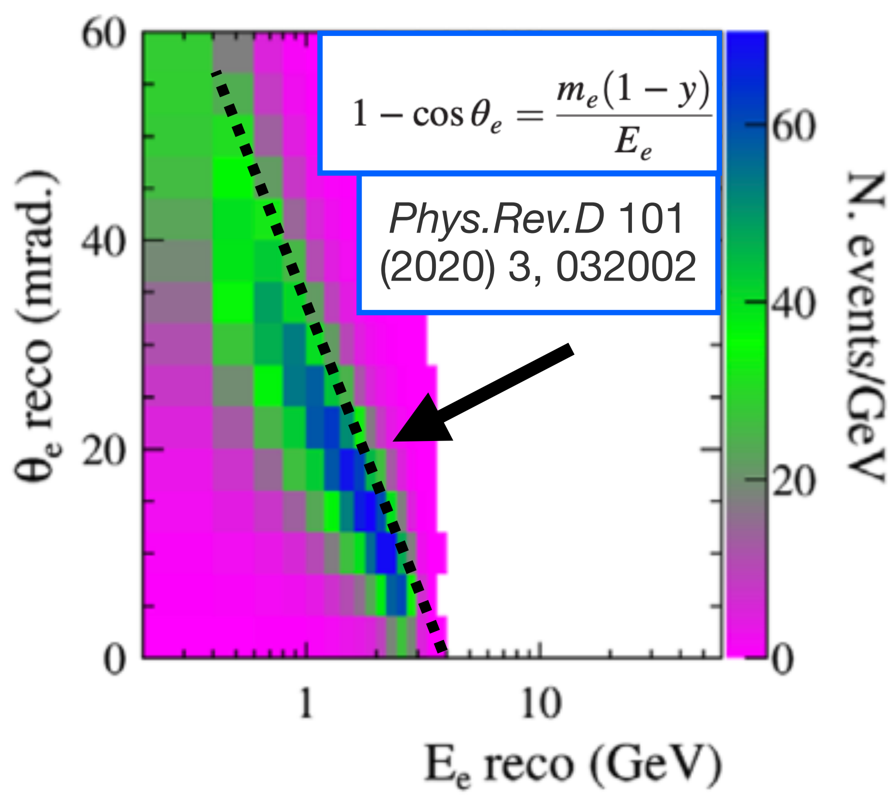


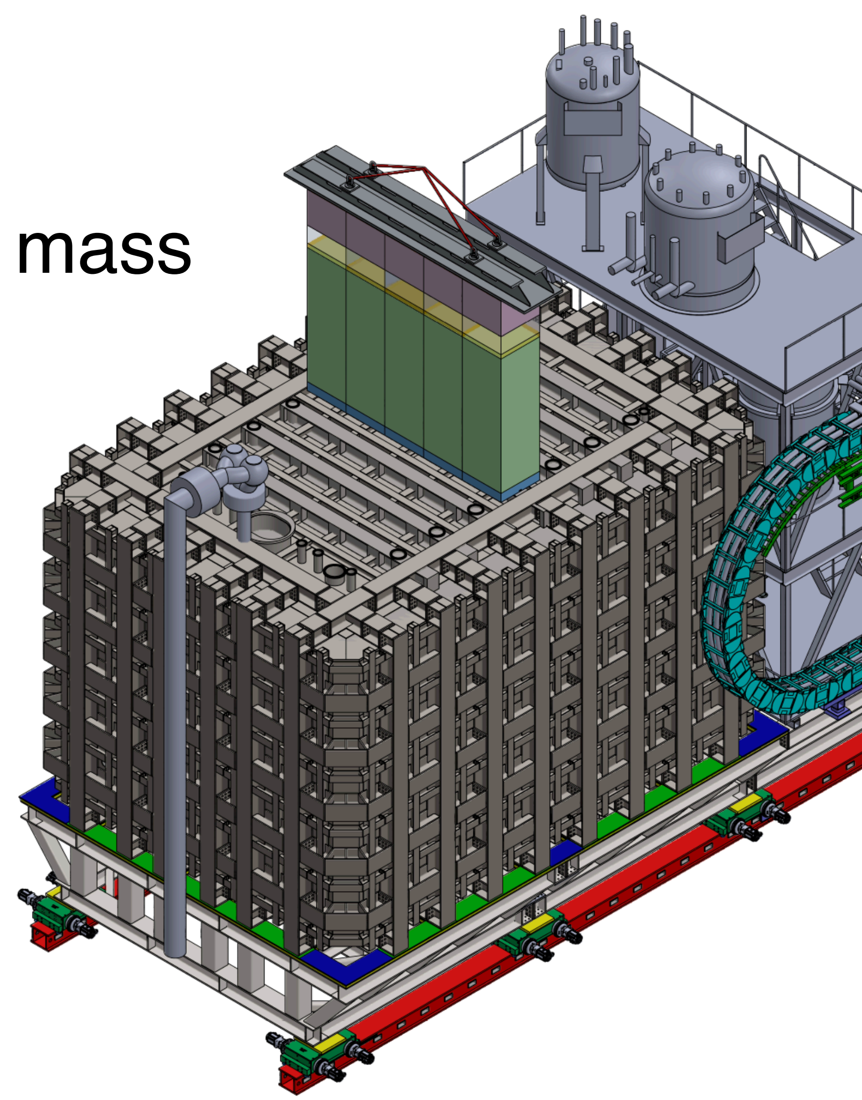
Near Detector Liquid Argon (ND-LAr)

- Liquid-argon TPC with >50 ton fiducial mass
  - ✦ Same target as the far detector
  - ✦ Pixelated charge readout suitable for high event rate environment and 3D localisation of light signal
- Relatively low threshold (<300 MeV/c for protons)
- Particle tracking + excellent EM calorimetry + large mass
  - ✦ Precise measurement of ν_e-Ar cross section

$\nu + \bar{\nu}$ flux normalization from $\nu - e$ interactions:

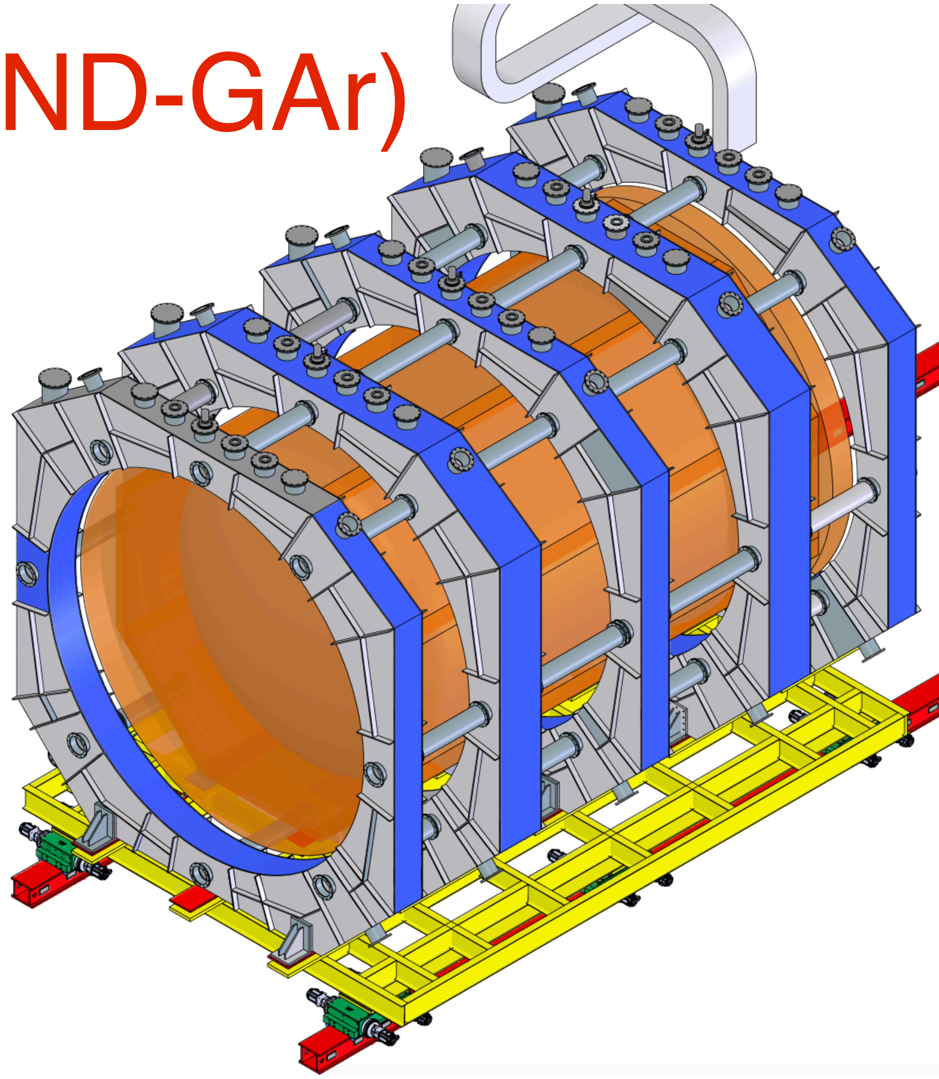
- ✦ known with per-mil precision
- ✦ ~8,300 events per year are expected

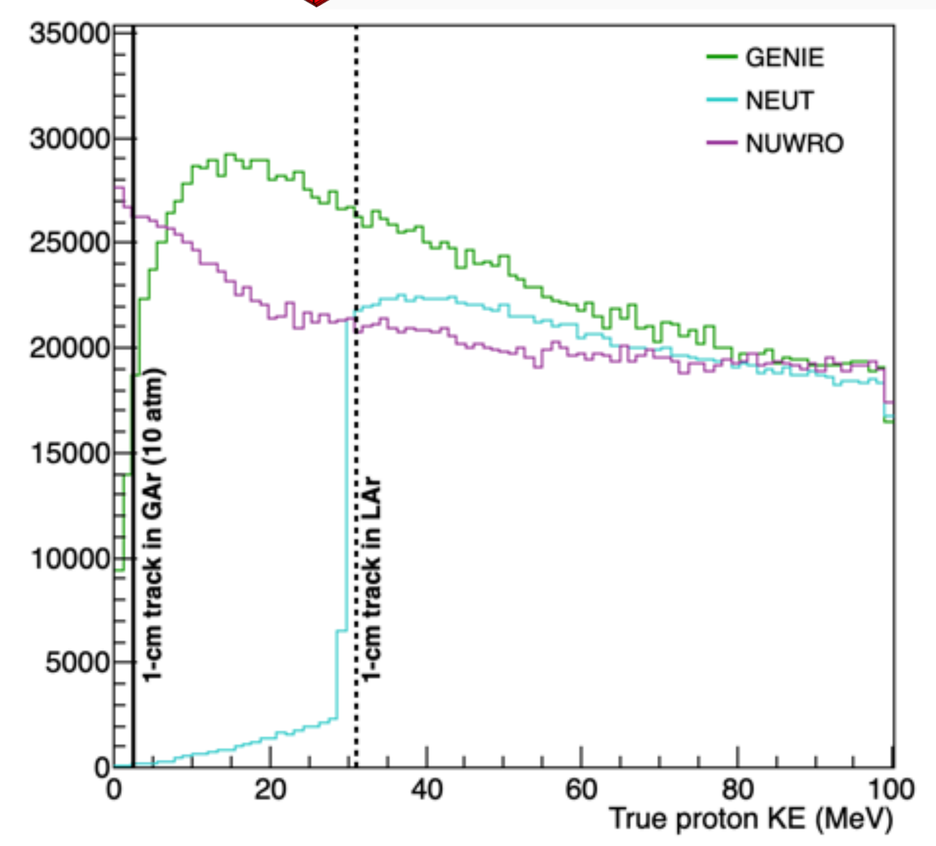




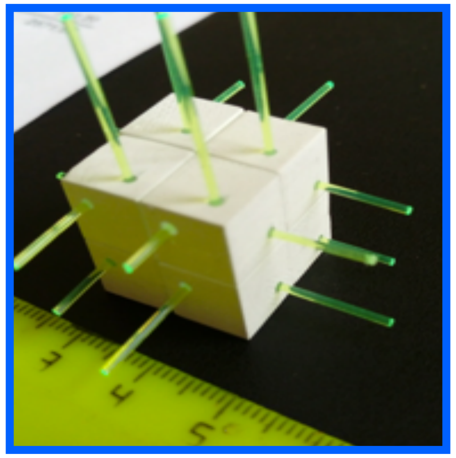
Near Detector Gas Argon (ND-GAr)

- High-Pressure TPC (10 bar) surrounded by an ECAL and Superconducting magnet
  - ✦ 1 ton fiducial mass, measurement of the wrong-sign background
- Also used as spectrometer for ND-LAr
- Very low-momentum threshold for protons
- Also precise reconstruction of charged pions, that may be harder in ND-LAr
- If running with different gases with high hydrogen content (not easy), ν flux could be inferred with either δp_T method with CCQE-like (slide 13) of δp_{TT} with CC-resonance (PRD 102, 033005 (2020))





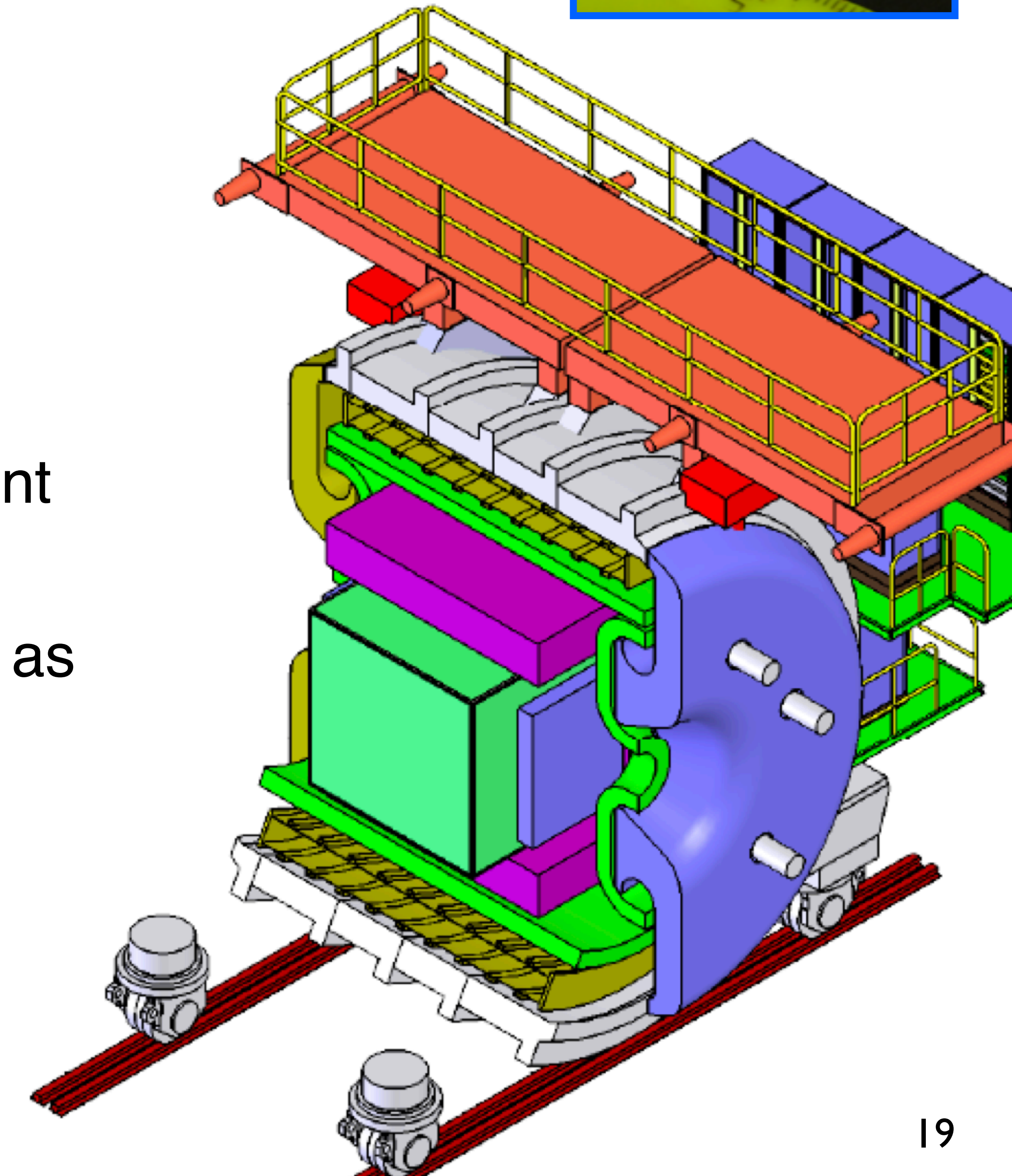
System for on-Axis Neutrino Detection (SAND)



- Beam and ν spectrum monitoring
- Flux measurement from ν-hydrogen interactions
- Cross section in nuclei other than argon with precise neutron detection (ToF measurement)

It's a Tracker + 1ton LAr module surrounded by ECAL in a superconducting magnet (from KLOE experiment)

- Reference design:
  - 3D Scintillator Tracker (3DST): same as T2K SuperFGD but ~12 ton → neutron containment and high-statistics beam monitoring
  - TPCs based on Resistive MicroMegas: same as T2K (see C.Giganti's talk)
- Alternative design:
  - Straw Tubes (XXYY) alternated with 5mm inactive plates
- The Tracker design still to be finalised

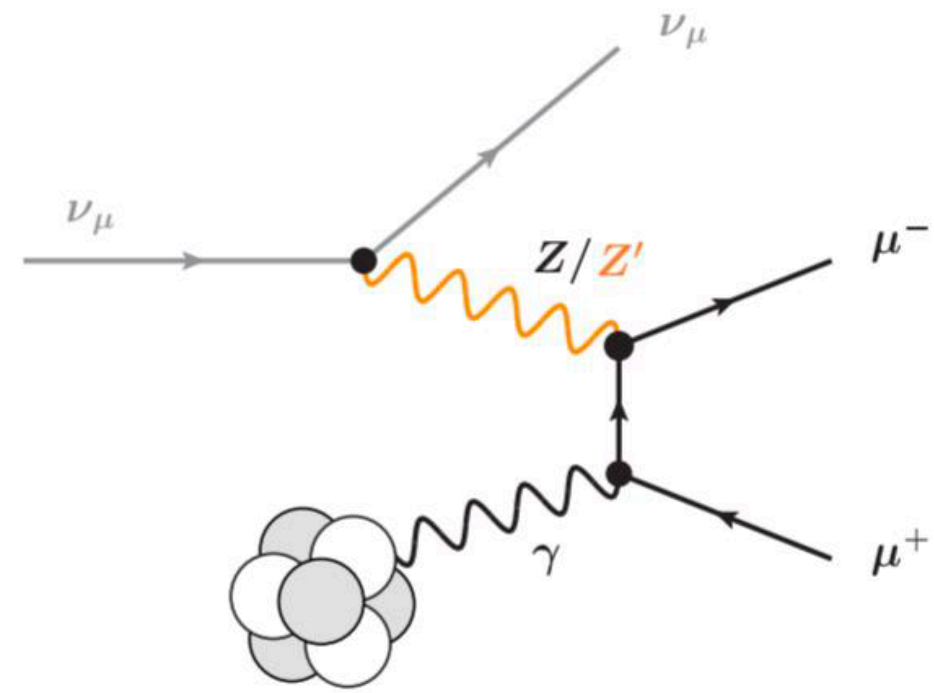


Beyond Standard Model at DUNE Near Detectors

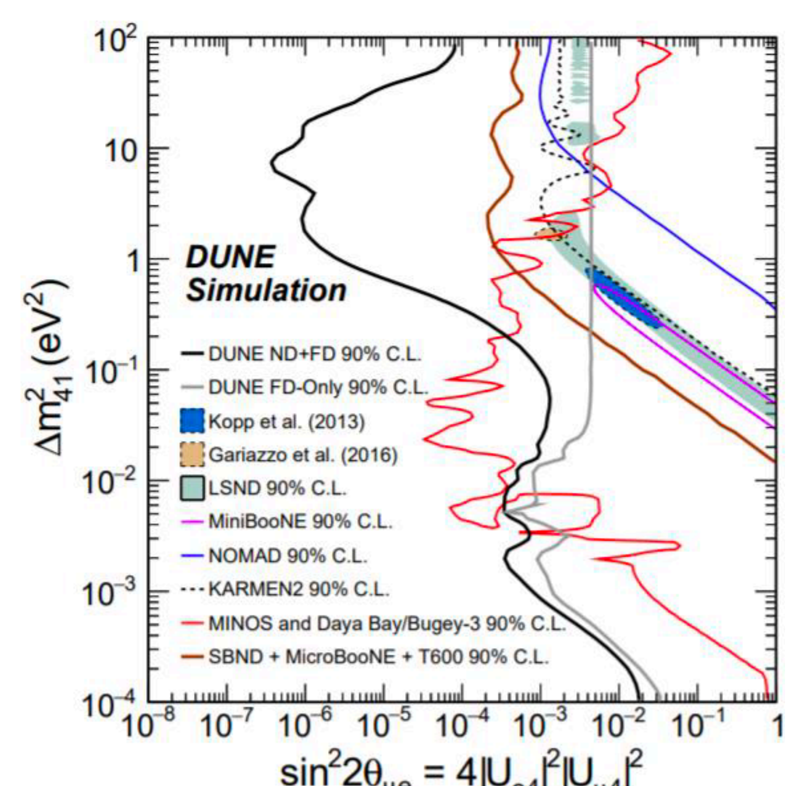
More details in arXiv:2008.12769

- Tests for Lorentz and CPT invariance

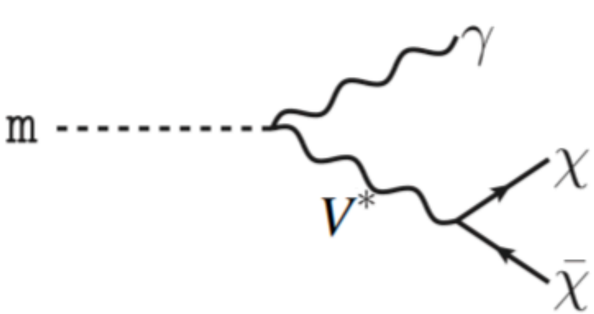
- Neutrino Trident (interaction with nucleus Coulomb field generates two muons)

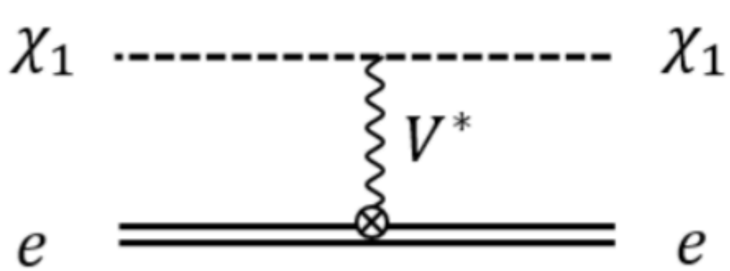


- Sterile neutrinos (short-baseline $\nu_\mu \to \nu_e$)



- Low-energy Dark Matter generated with ν accelerator beam





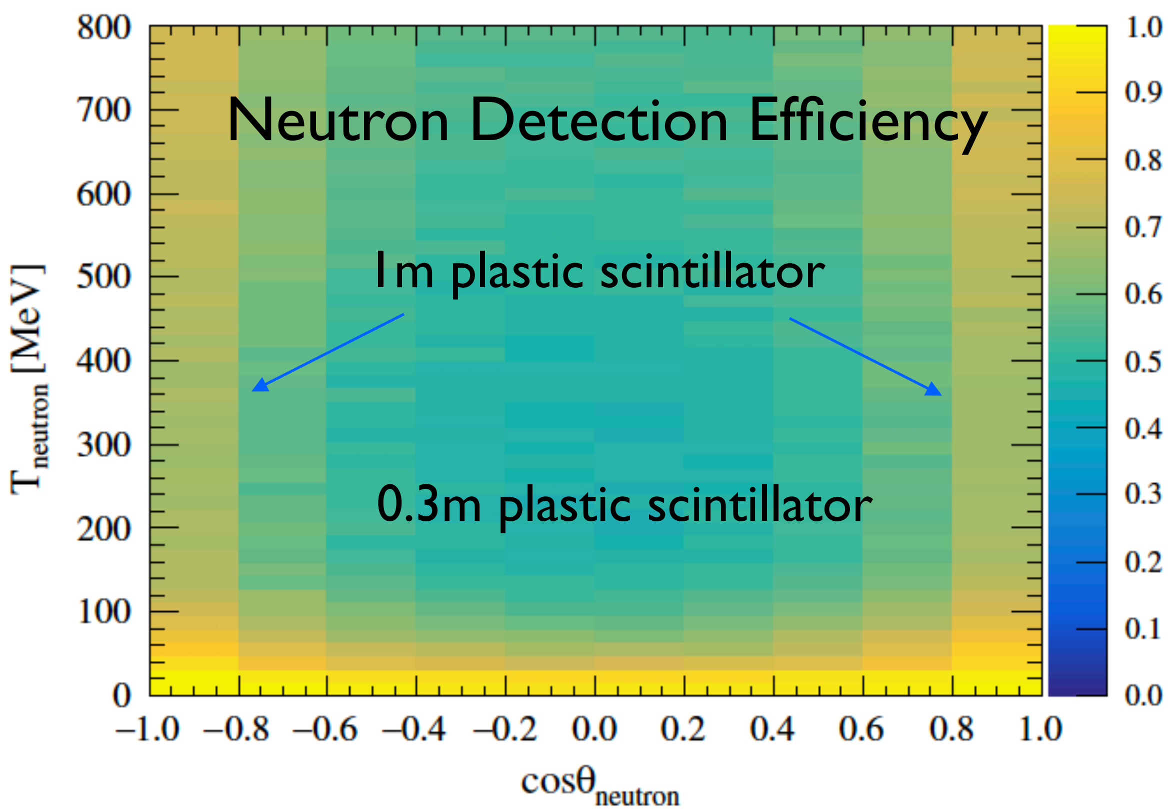
- Search for heavy neutrinos in HpTPC

Conclusions

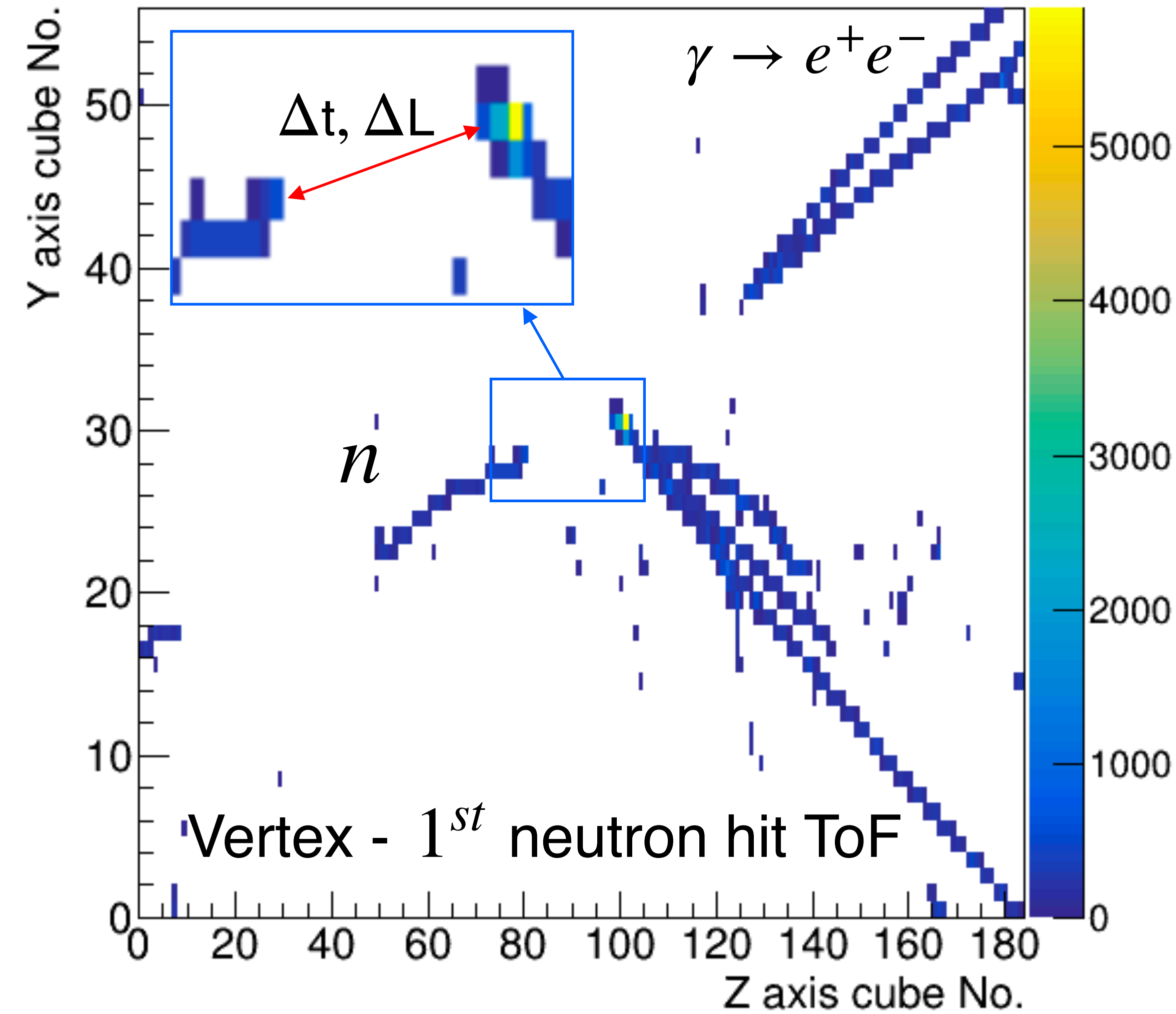
- Near Detectors with excellent performance and large mass are needed to constrain the systematic uncertainties and measure δ_{CP} and MH
  - ✦ Designs are very demanding because they shall be "as big as possible" and, at the same time, with granularities "as small as possible"
- The main goals are:
  - ✦ Precise measurement of ν interactions and Characterisation of nuclear effects
  - ✦ ν_e cross section
  - ✦ Independent ν flux measurement
- However, by design, they have most of the features necessary for searches beyond Standard Model from a neutrino beam

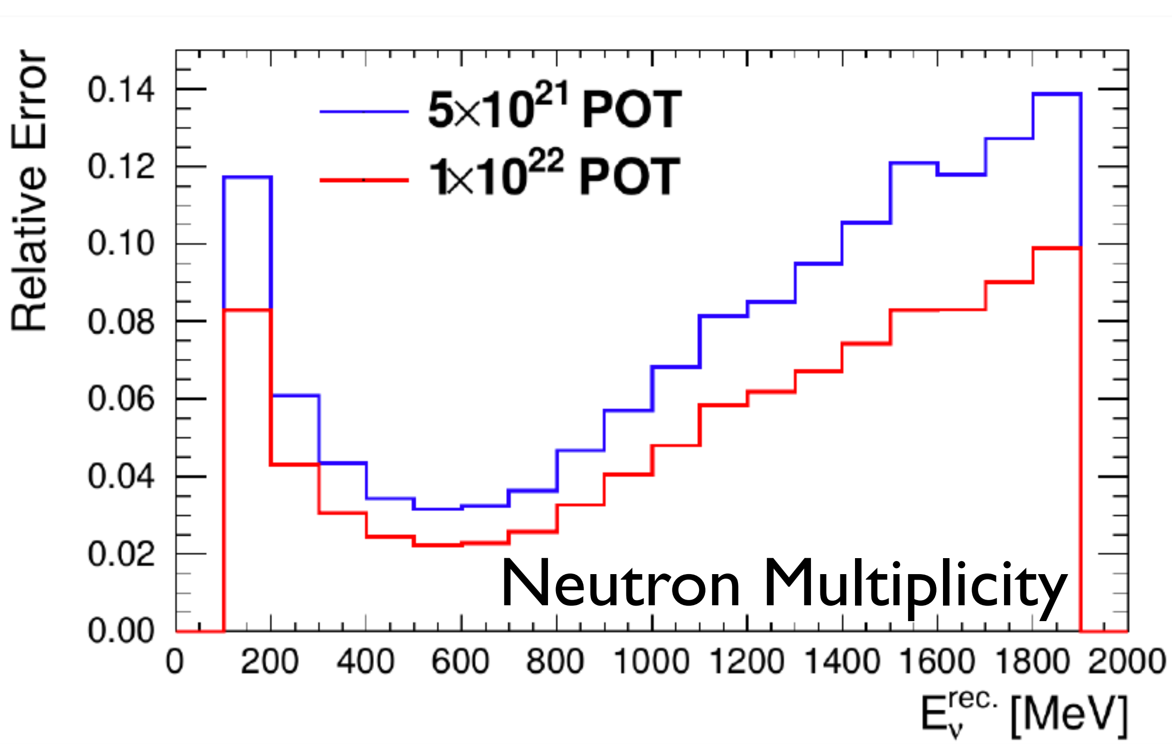
BACKUP

The Super Fine-Grained Detector @T2(H)K

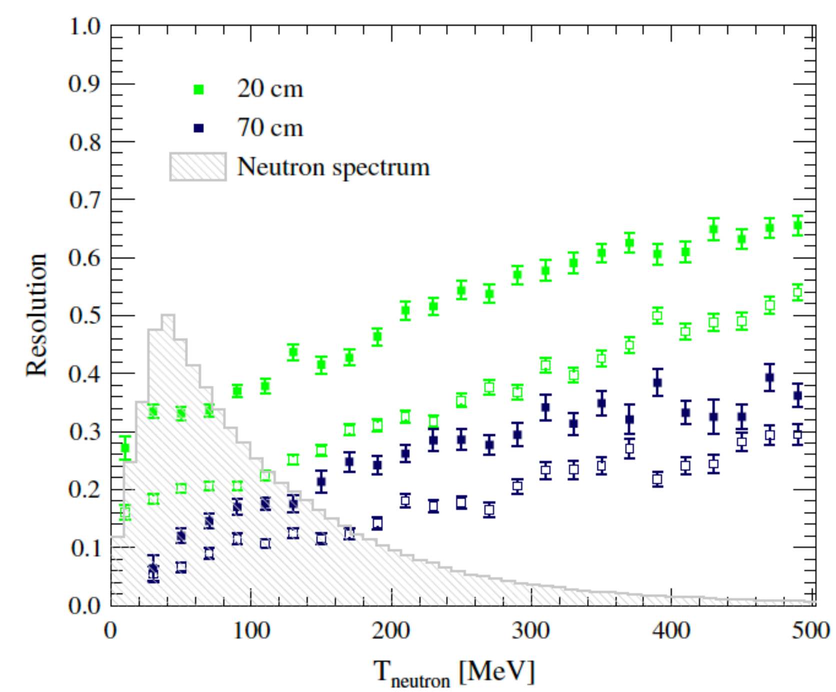


High content of light nuclei (C_8H_8) ensures high neutron detection efficiency





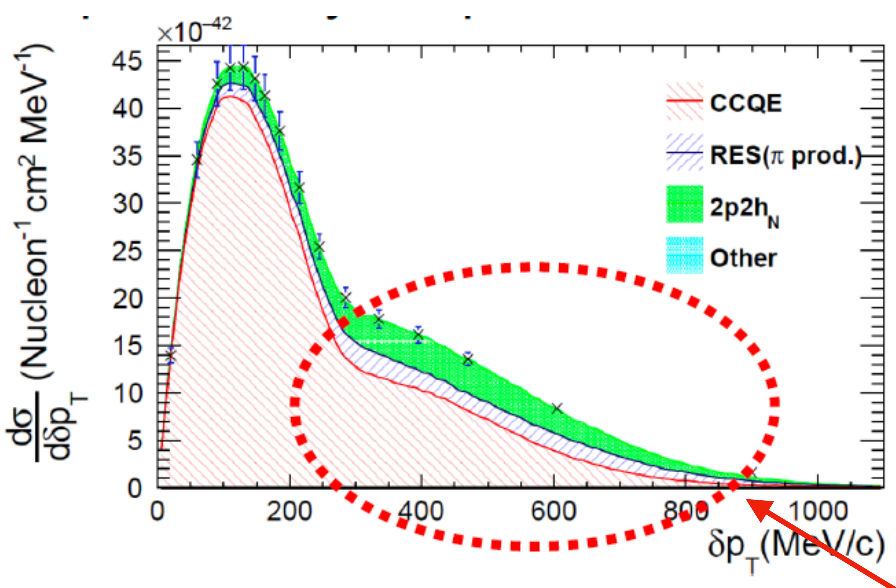
Neutron kinetic energy from ToF thanks to the sub-ns time resolution



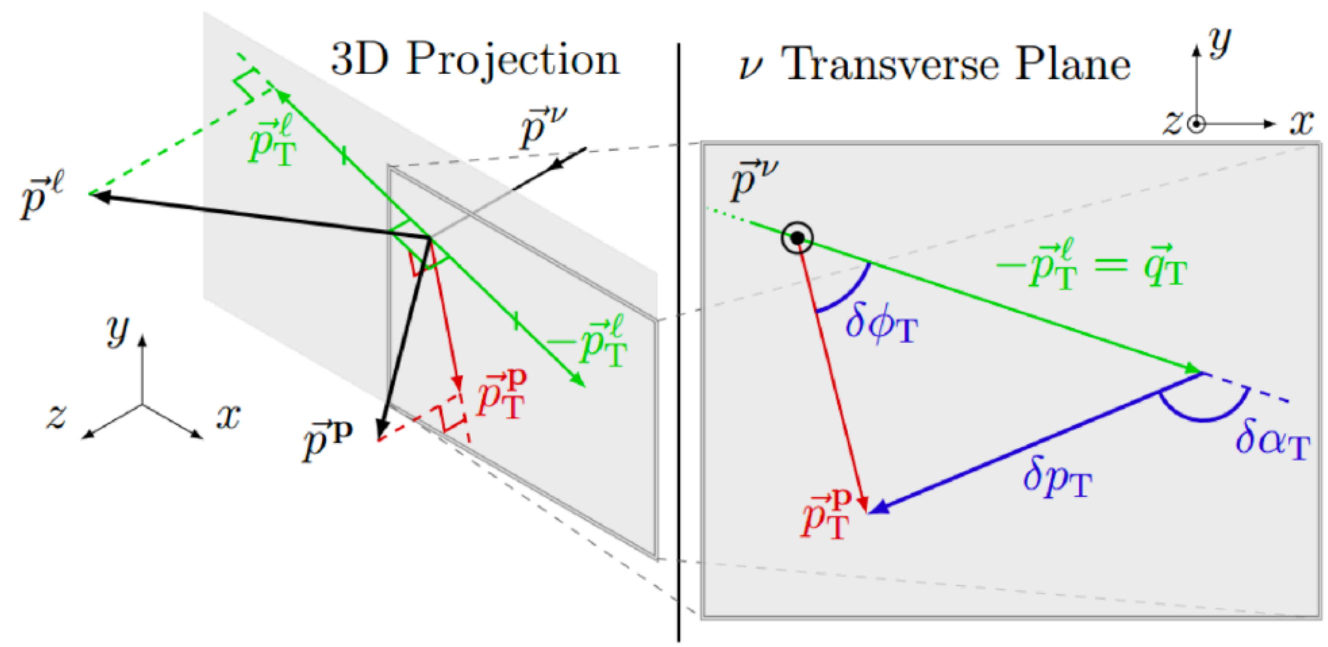
Neutron Kinetic Energy resolution

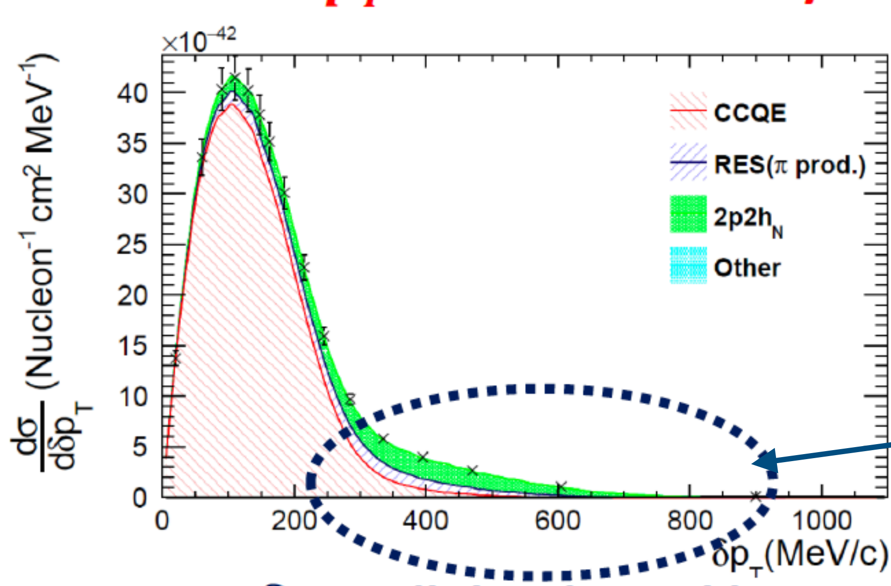
Multidimensional analyses with nucleon informations

- Full angular acceptance and fine 3D granularity is ideal for looking at the transverse plane to probe nuclear effects (PRC 94,015503 2016)
  - ✦ **δp_T** (sensitive to "invisible" processes) and **$\delta\alpha_T$** (system acceleration)
- Other variables: initial nucleon momentum, calorimetric energy, CCQE energy

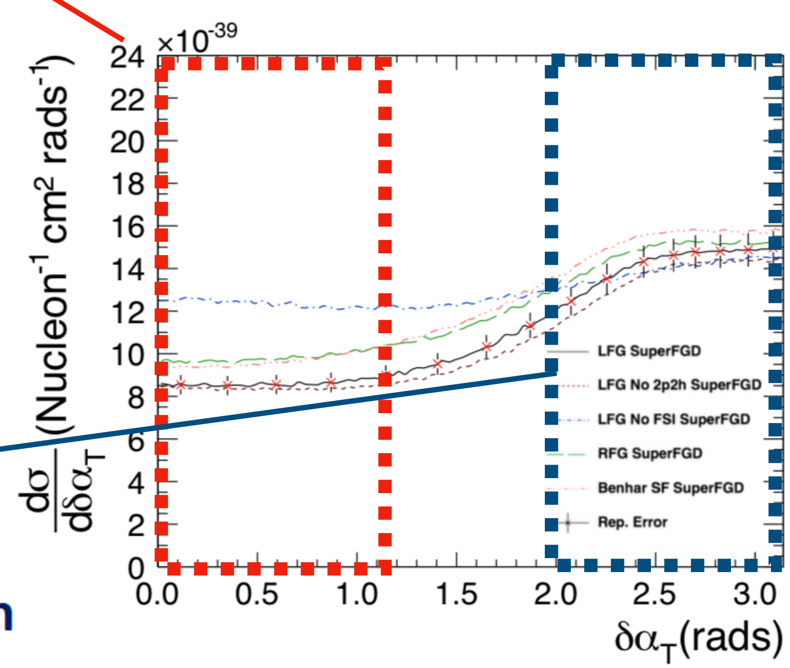


δp_T tail dominated by FSI





δp_T tail dominated by 2p2h



- Able to distinguish nuclear effects from flux normalization
- 2p2h can be constrained to ~2-3% and binding energy to ~1 MeV @T2K-II