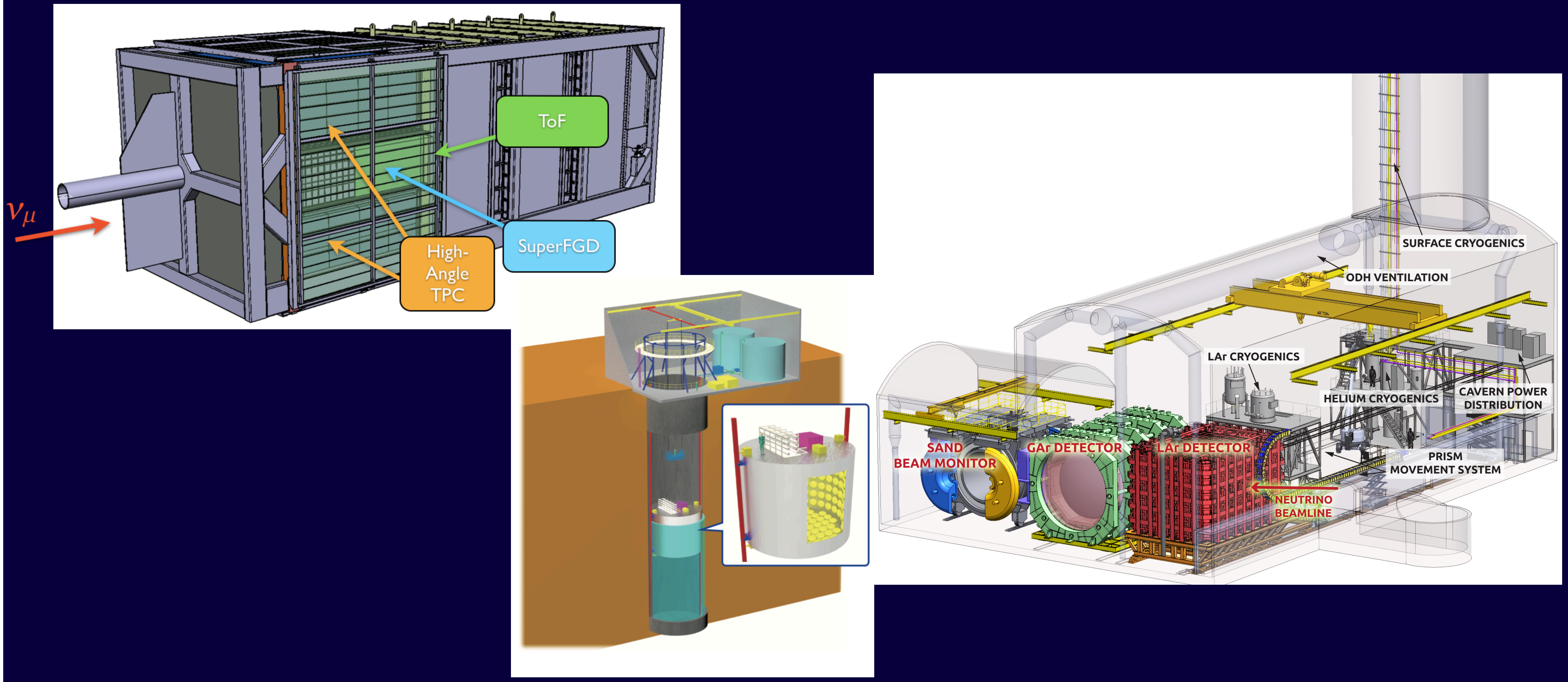
Flux Determination at (*Future*) Near Detectors
(at the Conventional Neutrino Beam Experiments)

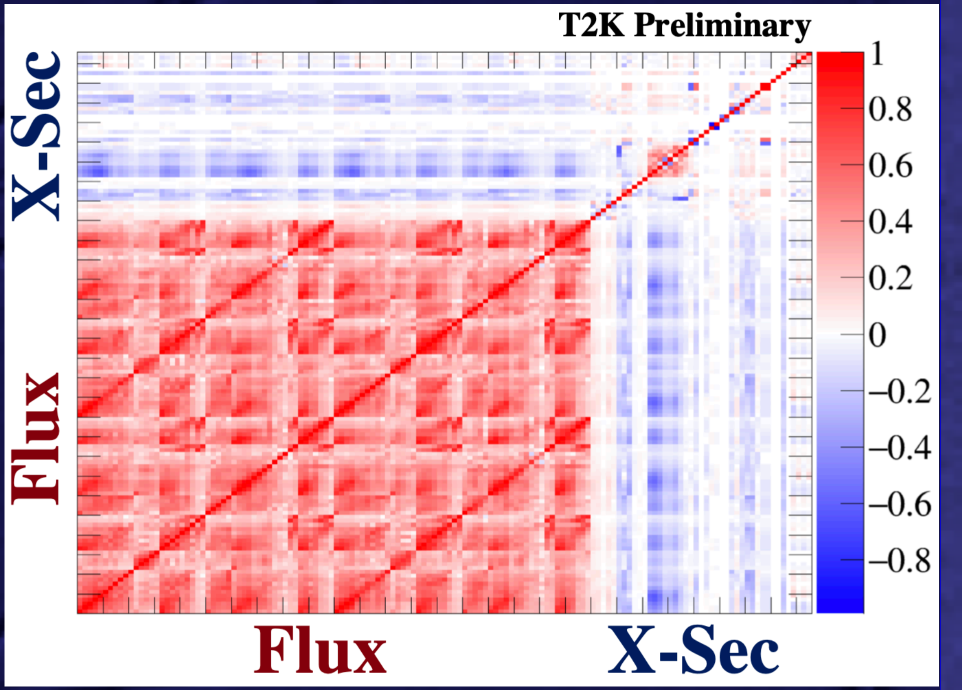


Chang Kee Jung, Stony Brook University

Snowmass21 NF09 Workshop, via video
December 2, 2020

Ways to Determine Neutrino Beam Flux w/ ND

- Canonical "Inclusive" ($\Phi(E)$, $\sigma(E)$) constraint method
  - ¬ Fit simultaneously a variety of data samples including all correlations w/ external inputs (priors)
  - ¬ Full utilization of data/statistics
  - ¬ Unavoidable model dependences → relatively large systematic uncertainties
  - ¬ T2K/T2K-II, HyperK, DUNE



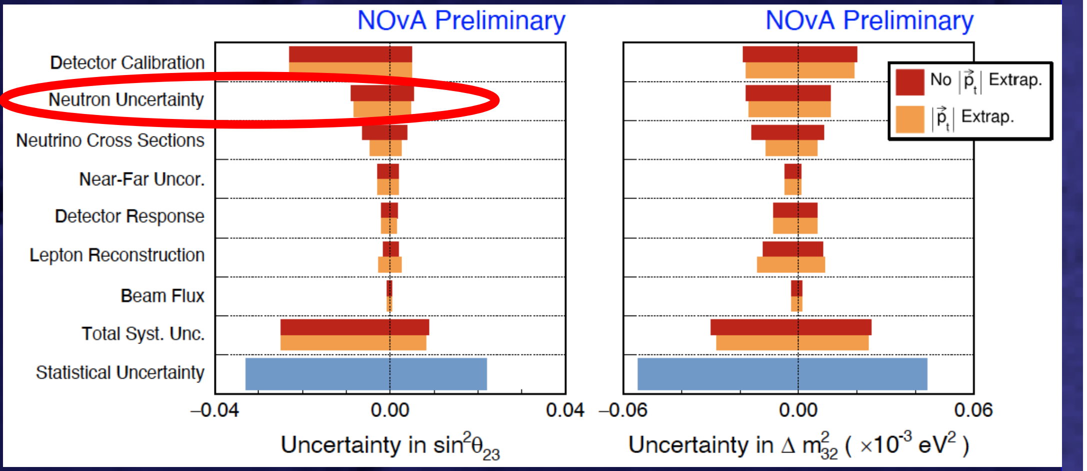
Ways to Determine Neutrino Beam Flux w/ ND

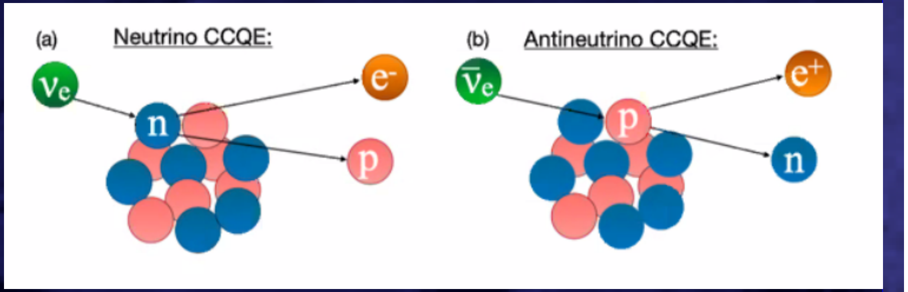
- "Quasi-exclusive" determination methods
  - Attempts to decouple ($\Phi(E)$, $\sigma(E)$) in observables
  - Neutrino – electron elastic scattering
    - The known, pure electro-weak, cross section
    - But small cross section → relatively small sample size
    - Could be a powerful tool for DUNE (higher beam energy and larger ND target size)
  - Low-ν (energy transfer to the target nucleus/nuclear recoil energy) flux method
    - Approximately constant cross section for events with $\nu <$ cutoff ν_0 ($\ll E_\nu$)
    - Extract neutrino flux shape from the shape of the neutrino CC event spectrum for $\nu < \nu_0$
    - Relatively limited sample size
    - Could be a useful tool for DUNE
  - "PRISM" (off-axis flux sampling for linear combination) method
    - Break degeneracies in $\Phi(E)$, $\sigma(E)$ with many off-axis measurements (different flux shapes)
    - Minimize neutrino-nuclear interaction model dependence and possible biases
    - DUNE-PRISM (DUNE), nu-PRISM (HyperK)

Additional Tools for Flux Determinations

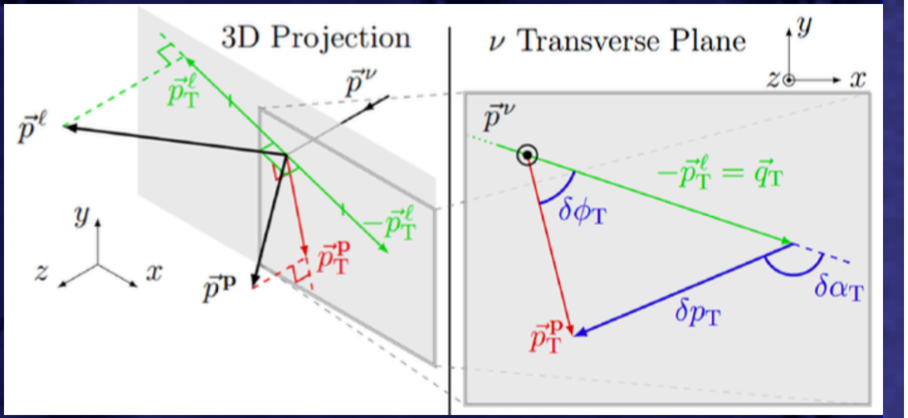
A. Himmel, Neutrino 2020

- Event-by-event **neutron** kinetic energy determination
  - Improve constraints with both canonical and low-ν methods
  - Improve anti-nu flux determination
  - **SuperFGD**/T2K upgrade and **3DST**/DUNE ND SAND

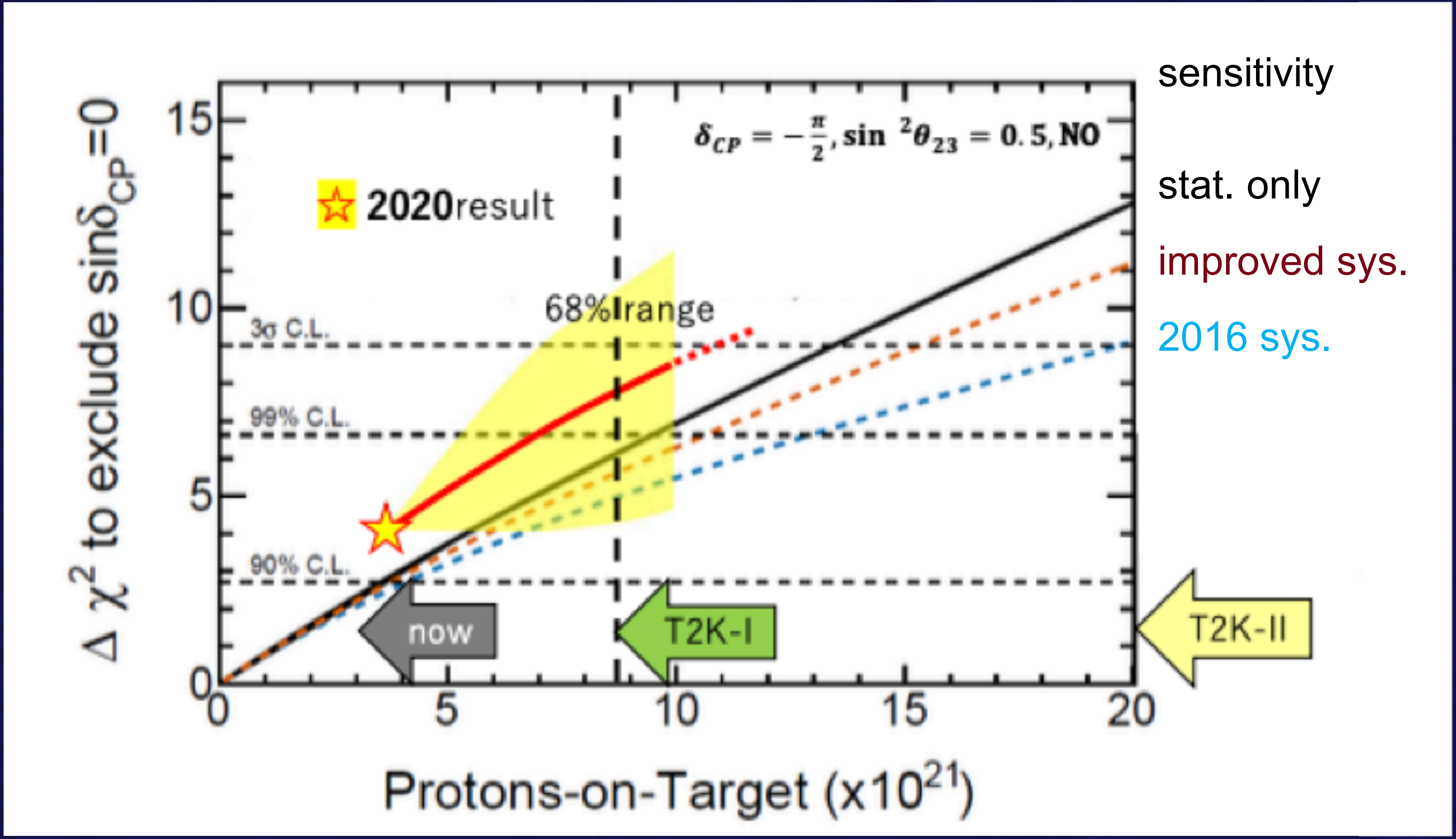




- STV (Single Transverse Variables)
  - Small δp_t cut allows selection of clean sample of neutrino interactions on H and also on C w/ relatively little nuclear effects → stronger constraints on neutrino flux



T2K-I/T2K-II Projected Sensitivities for sinδ_{cp}

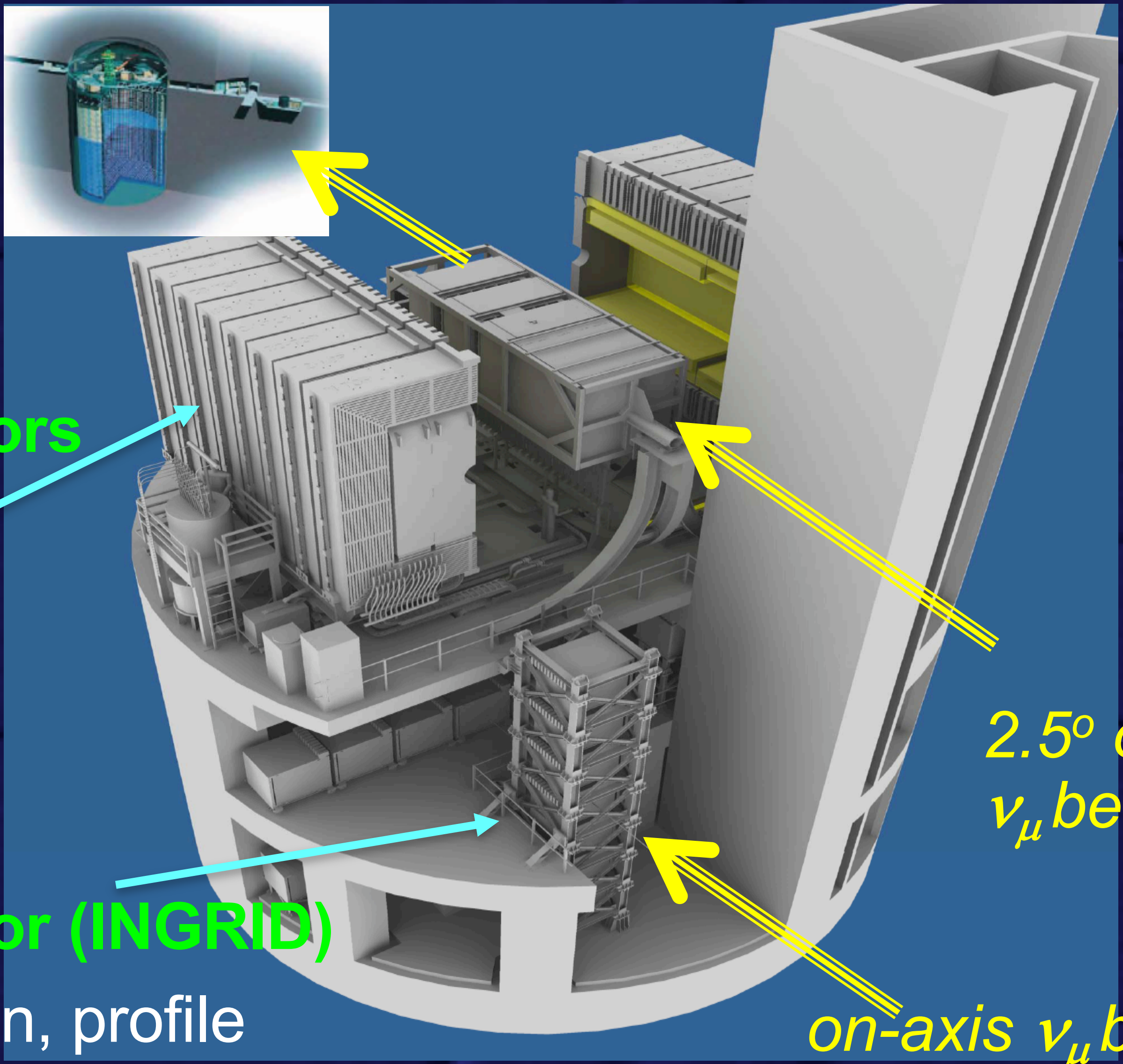


T2K-II Main Goal: search for CPV in neutrinos

~4 months/year data taking runs until the beginning of the HyperK data taking

→ Need to reduce systemtic uncertainties → ND280 upgrade (summer 2022)

T2K Near Detector Complex



Off-Axis Detectors

- 0.2 T magnet
- ν flux/spectrum
- cross-sections

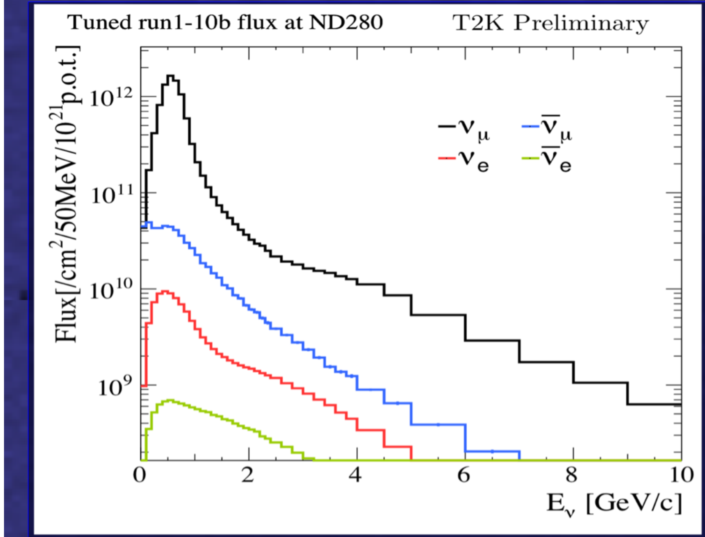
On-Axis Detector (INGRID)

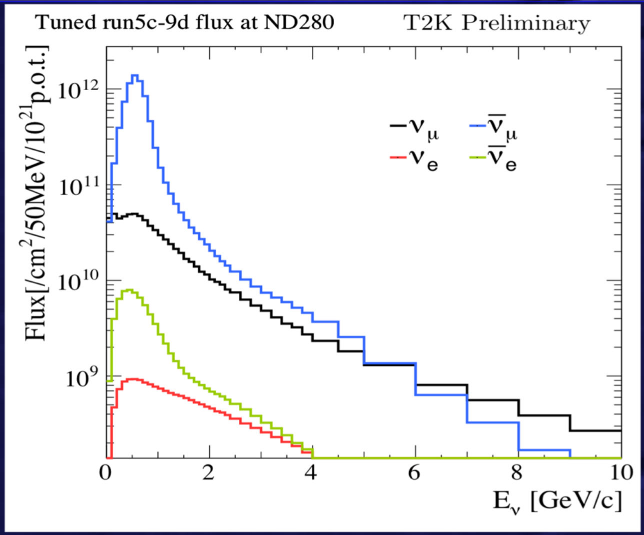
- ν beam direction, profile

2.5^o off-axis ν_μ beam

on-axis ν_μ beam

Neutrino/Antineutrino Flux Predictions and Uncertainties



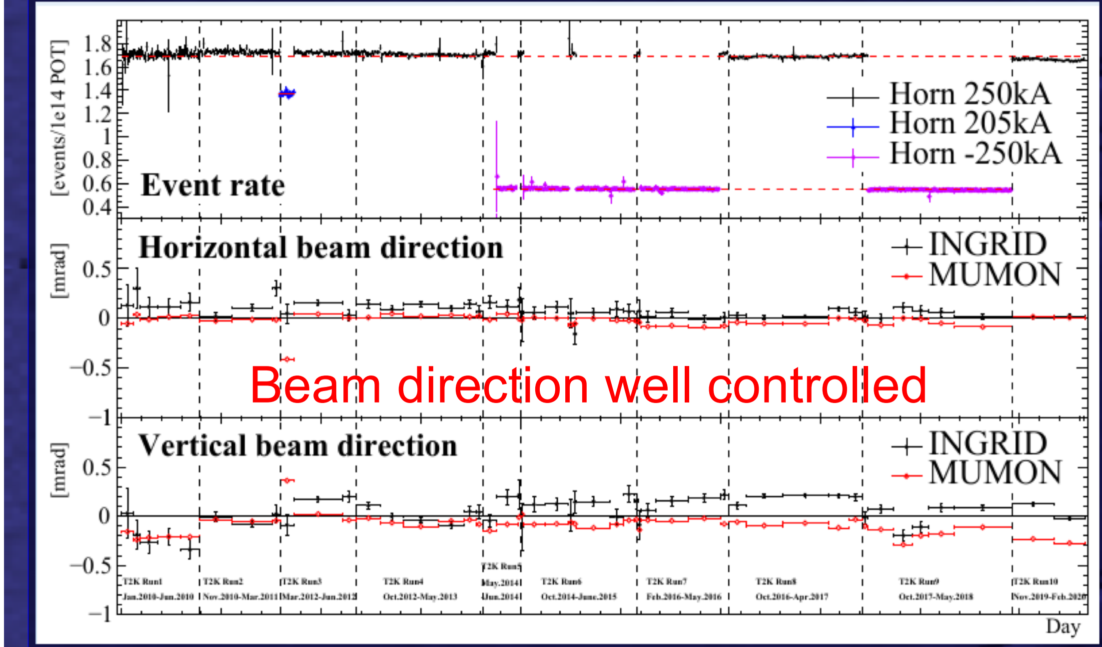


Flux simulation (FLUKA/GEANT3/GCALOR)

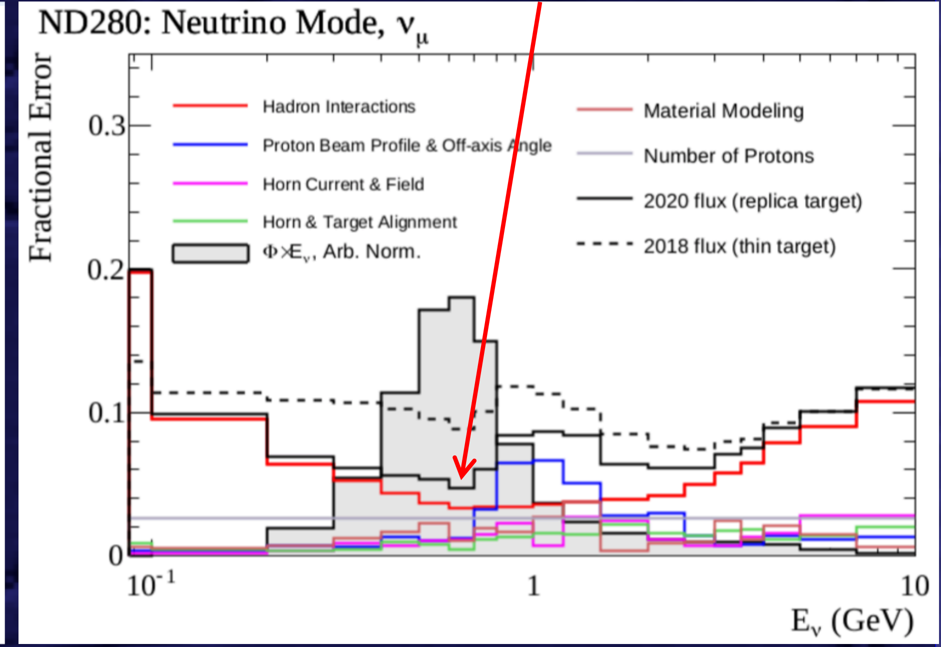
Large neutrino component in antineutrino flux

Intrinsic ν_e component ~0.5% at flux peak

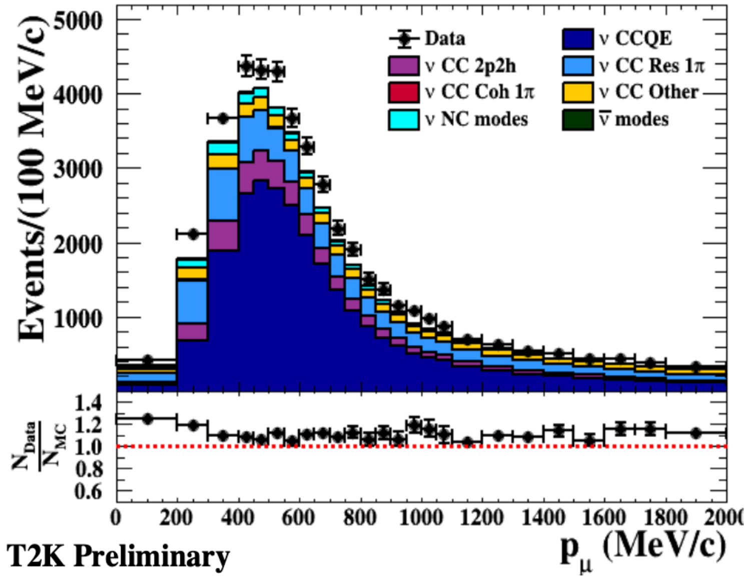
Greatly reduced uncertainty w/ new NA61/Shine data



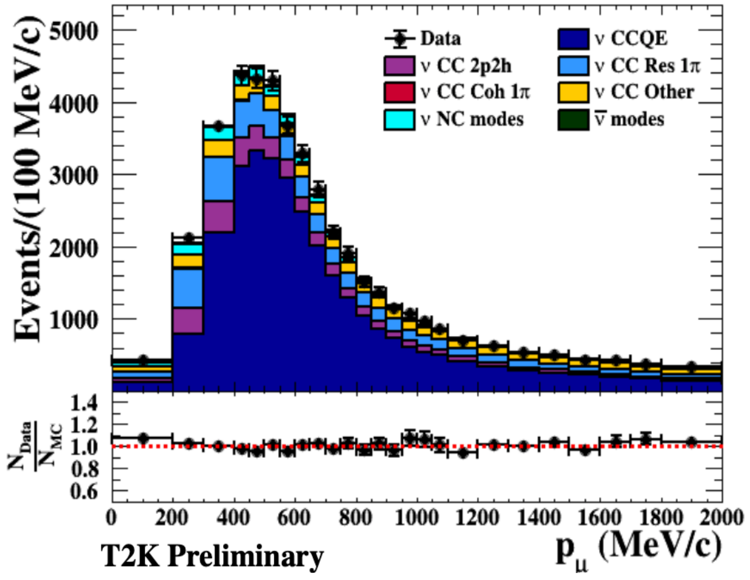
Beam direction well controlled



Flux and X-sec Constraints with ND280

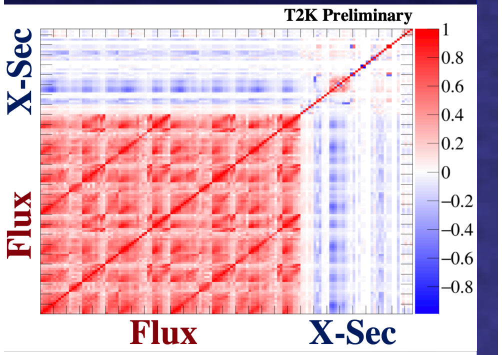


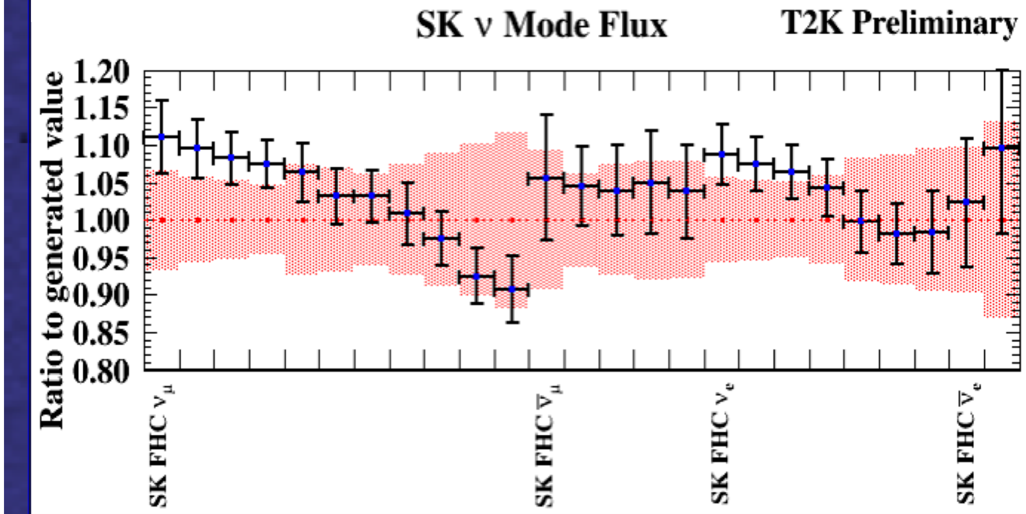
CC0π sample Pre-Fit

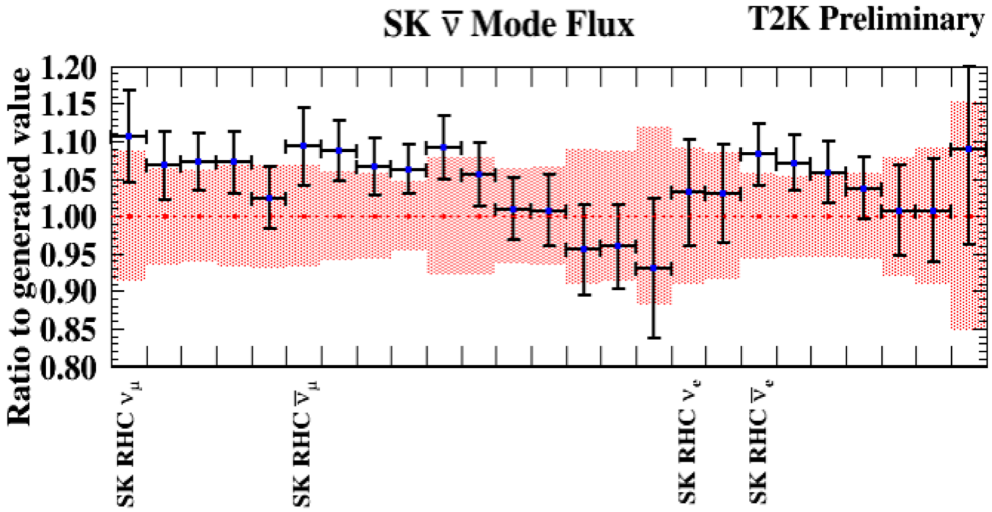


CC0π sample Post-Fit

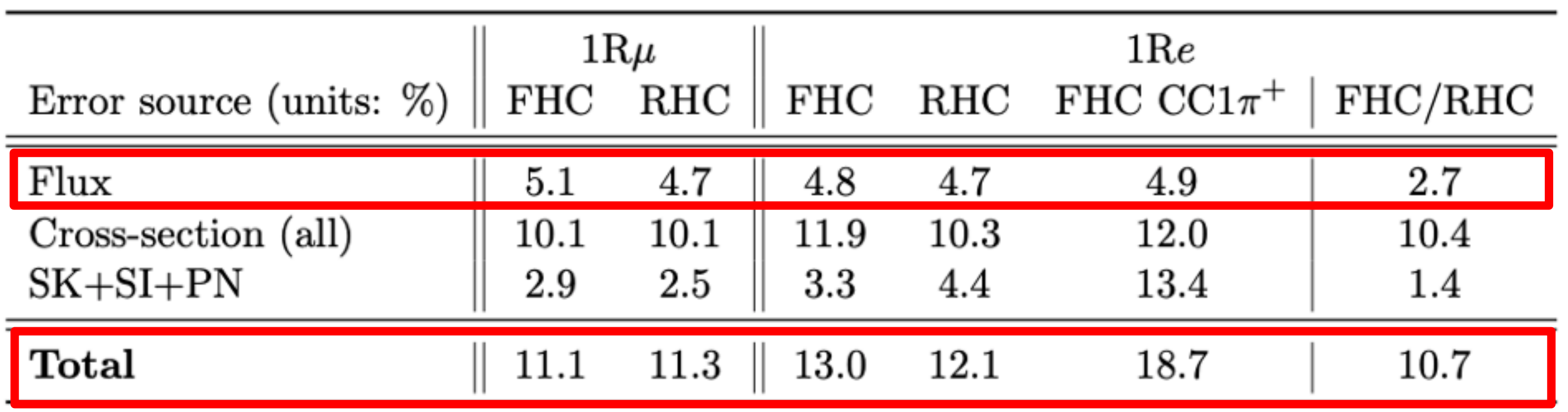
Total of 18 data samples





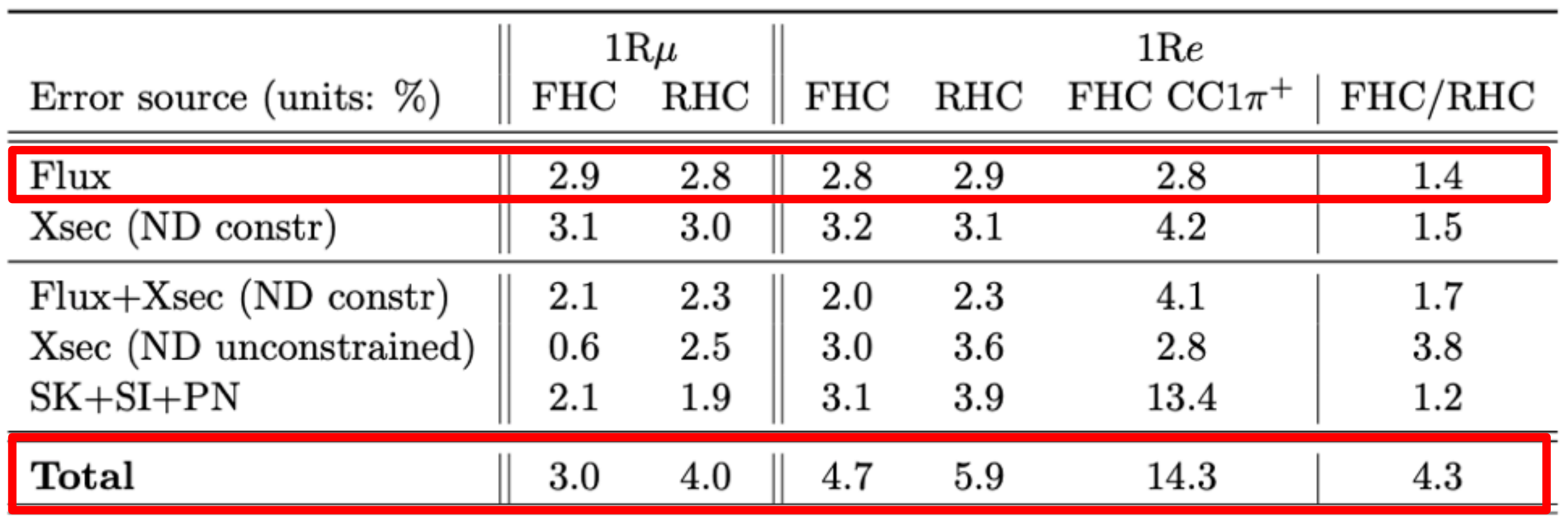


Uncertainty on the Number of Events in each SK Sample



Error source (units: %)	$1R\mu$		$1Re$			
	FHC	RHC	FHC	RHC	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

Pre-ND Fit

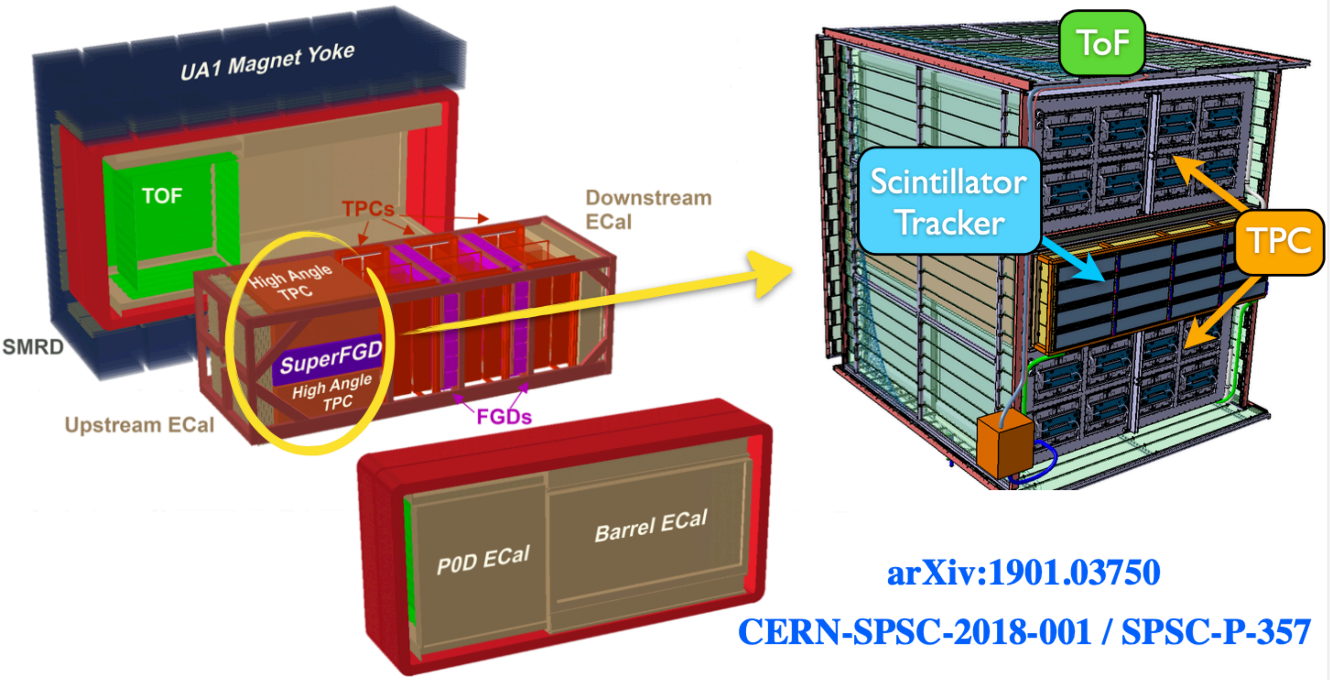


Error source (units: %)	$1R\mu$		$1Re$			
	FHC	RHC	FHC	RHC	FHC $CC1\pi^+$	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

Post-ND Fit

most relevant for extracting CPV effect

ND280 Upgrade



arXiv:1901.03750

CERN-SPSC-2018-001 / SPSC-P-357

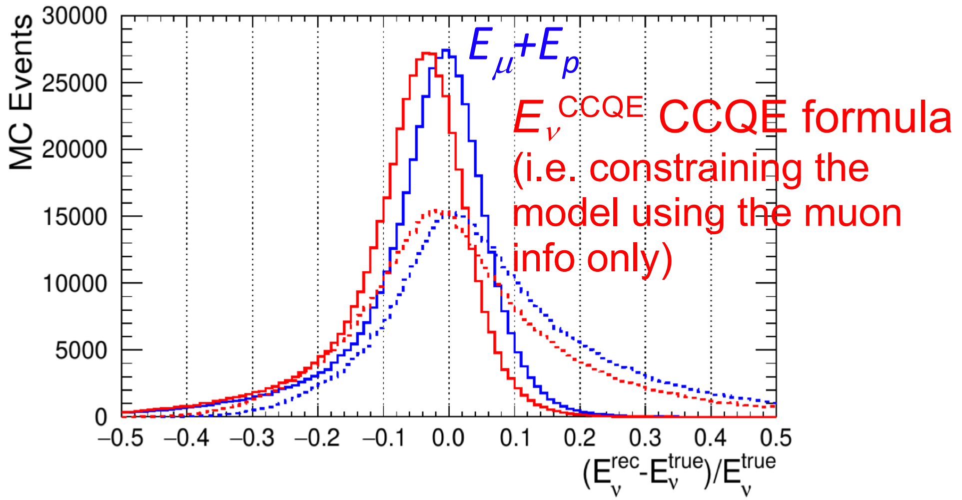
- 6 ToF modules all around the new tracker

→ Reduces background due to confusion of muon direction

- Detectors are being constructed, and will be installed by summer 2022 for beam data taking in fall 2022

- Preliminary studies show a factor 2-3 improvements in the precision of measuring the cross-section uncertainties (and similarly for flux), for the same statistics of ND280

e.g.) better neutrino energy reconstruction using proton information in QE events (TDR addendum)



E_ν^{CCQE} CCQE formula (i.e. constraining the model using the muon info only)

DUNE ND Current Concept Configuration
(A robust system of complementary subsystems)

Scintillator based Spectrometer (SAND)

- 3DST+low den. tracker
- KLOE ECAL & magnet
- On-axis beam monitor
- **High stat on C target**

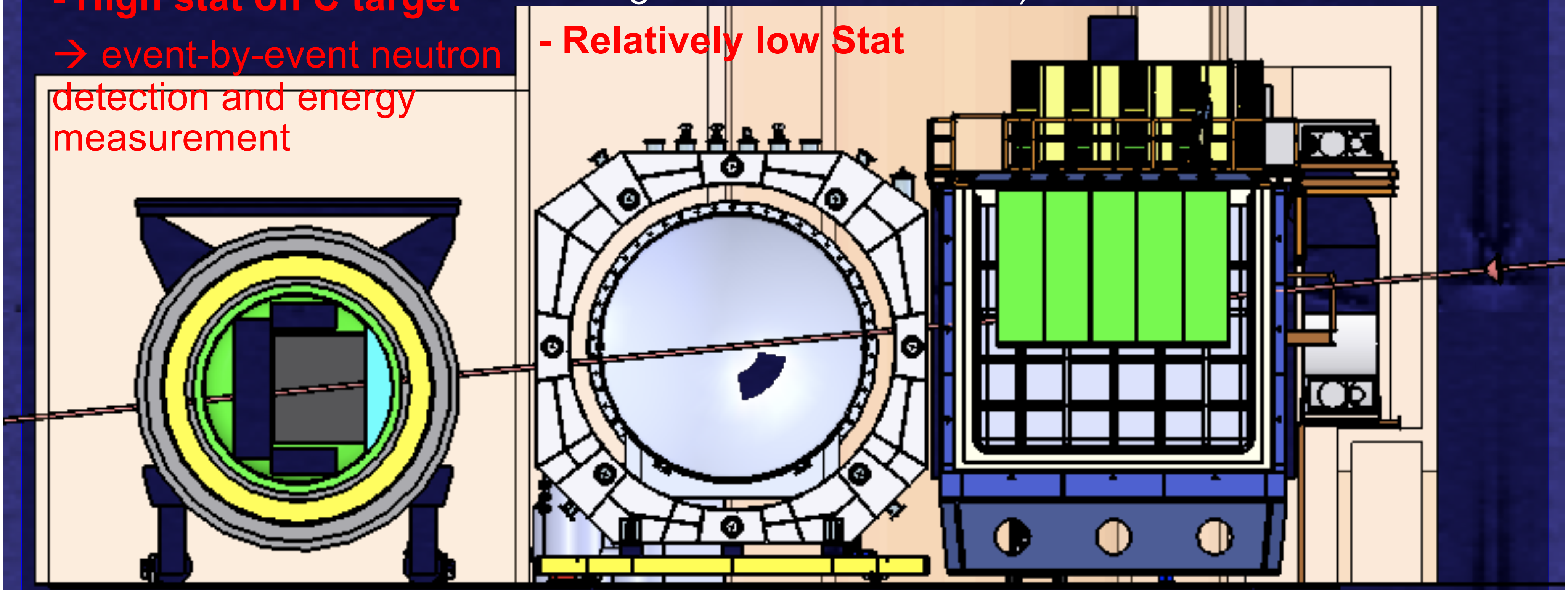
→ event-by-event neutron detection and energy measurement

Multi-Purpose Detector

- HPgTPC (high res. & low E threshold on Ar target)
- ECAL (high performance)
- B-field (spectrometry of the exiting muons from LArTPC)
- **Relatively low Stat**

LArTPC as FD

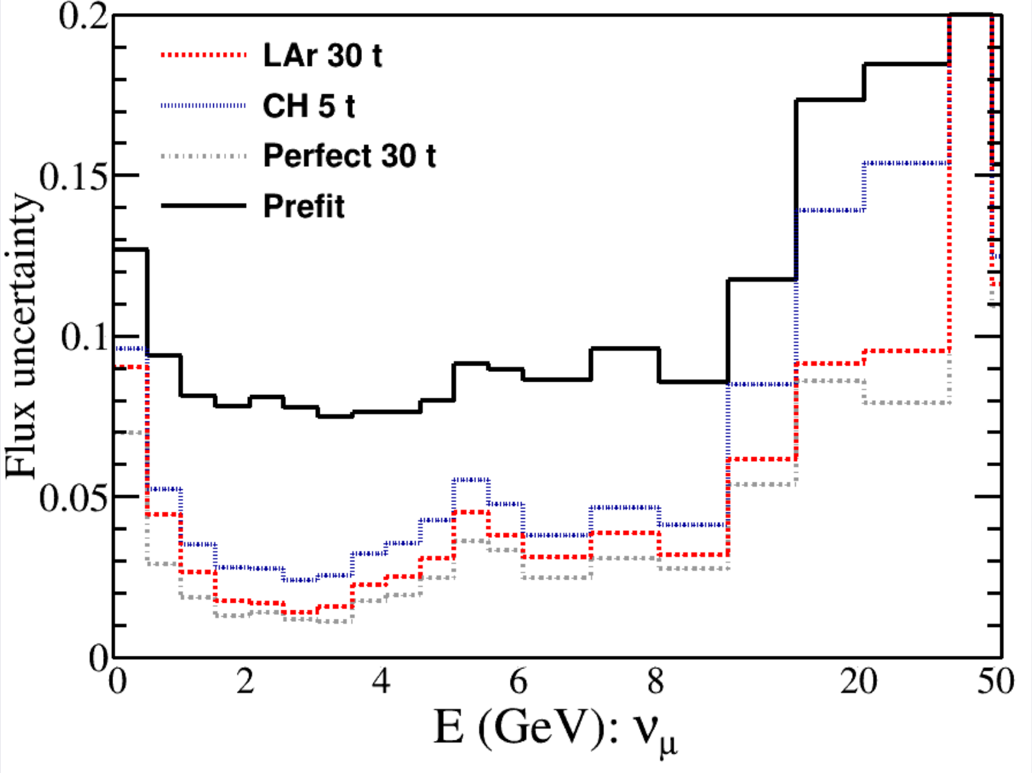
- Modular design w/ pixel readout
- High Stat on Ar target
- No B-field



DUNE Flux Constraint by Neutrino-electron Elastic Scattering in ND-LAr

- ~5000 LAr ND events/year
  - ¬ Reduced stat. under DUNE-PRISM
- A powerful additional tool for achieving DUNE's sensitivities, and resolving flux ↔ cross section ambiguities

5 years, 30 t LAr FV, 1.2 MW beam



$$E_\nu = \frac{E_e}{1 - \frac{E_e(1-\cos\theta)}{m}}$$

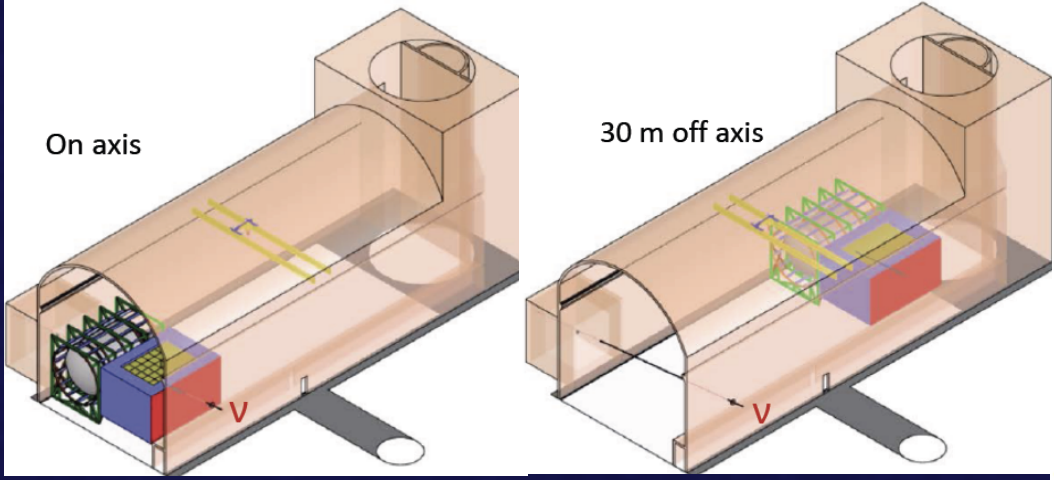
- Strong normalization contraint due to known XSEC

- Weak shape constraint due to detector smearing and beam divergence

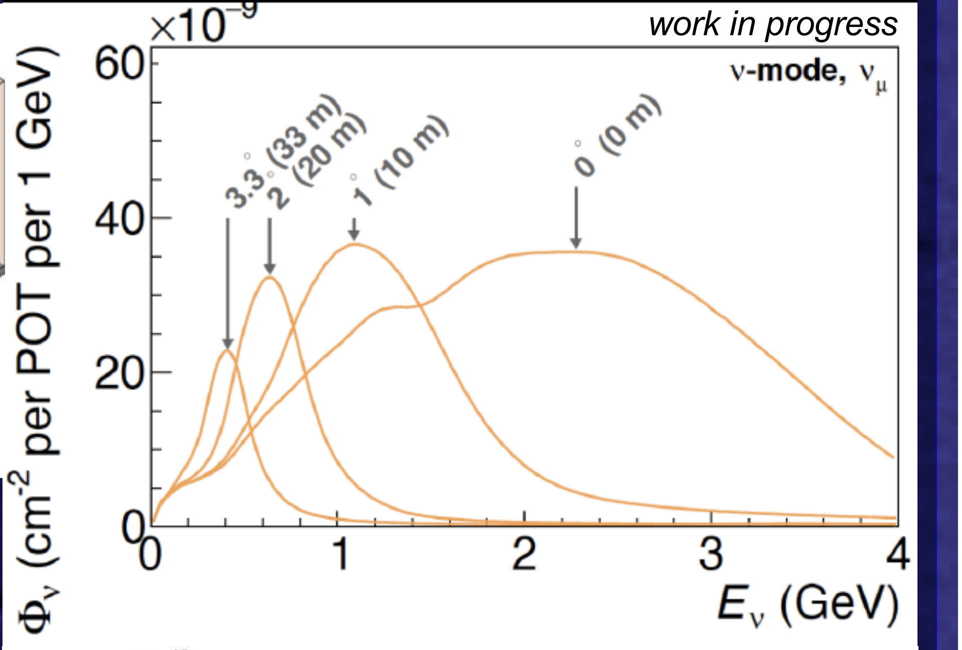
- The prefit uncertainty may need to be updated

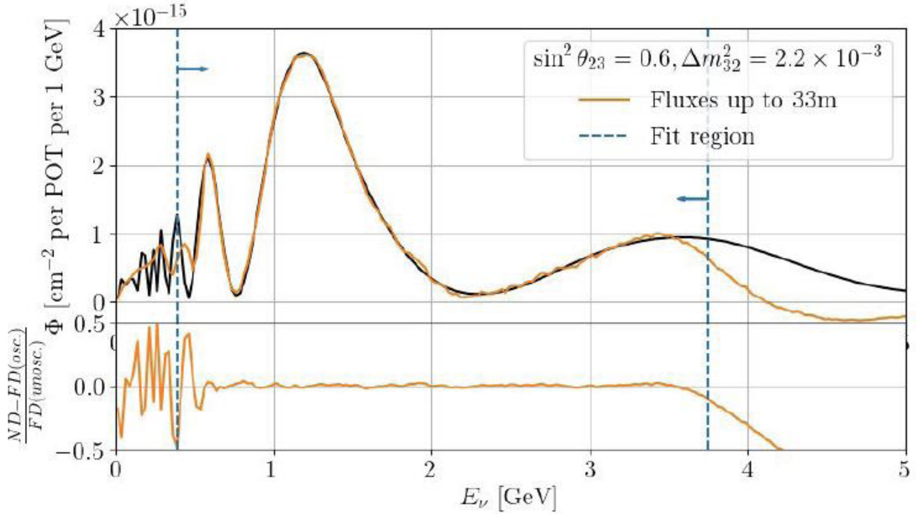
Phys.Rev.D 101 (2020) 3, 032002

DUNE-PRISM



- Move LArTPC&MPD off-axis
  - Sample difference E_ν
- Produce FD oscillated spectra (or any arbitrary spectra) by a linear combination of the off-axis samples
  - Break cross-section model degeneracies
  - Reduce overall dependence on the cross-section model and biases

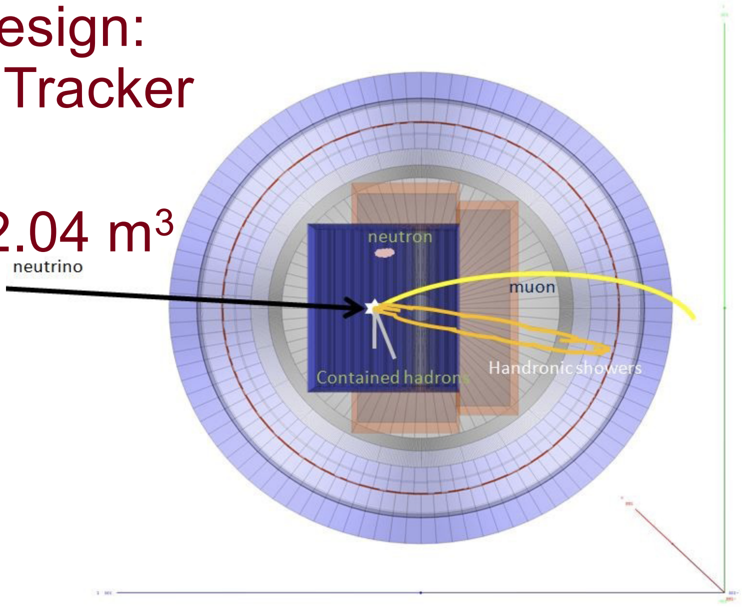


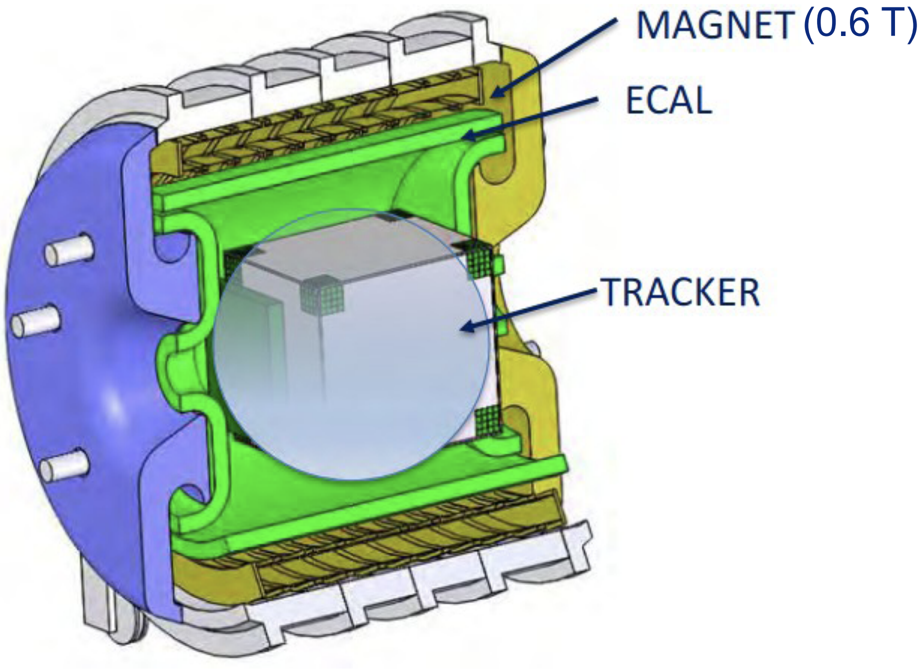


SAND (System of on-Axis Neutrino Detector)

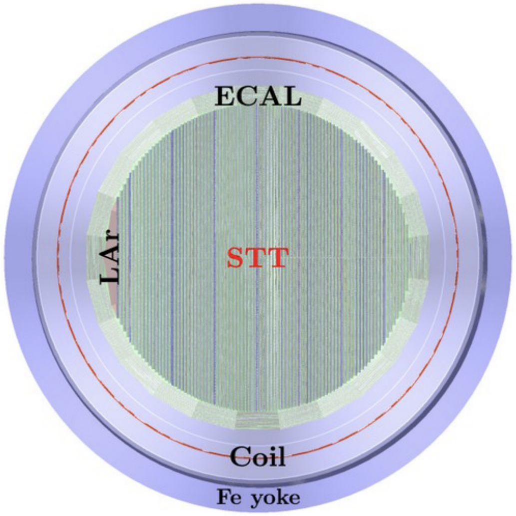
Tracker Reference Design:
3DST + Low Density Tracker
(either TPC or STT)

3DST: 2.53 x 2.36 x 2.04 m^3



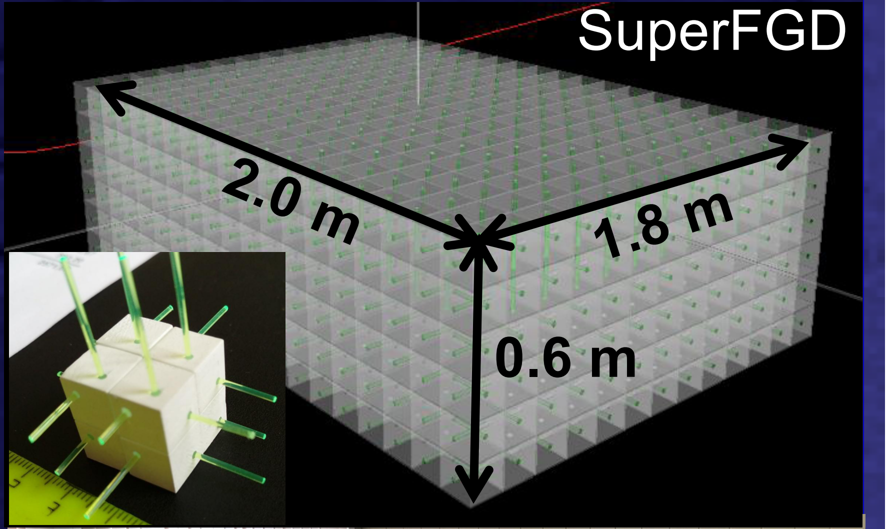


Tracker Alternative Design:
STT + mLAr



Fundamentals of DUNE 3DST & T2K SuperFGD

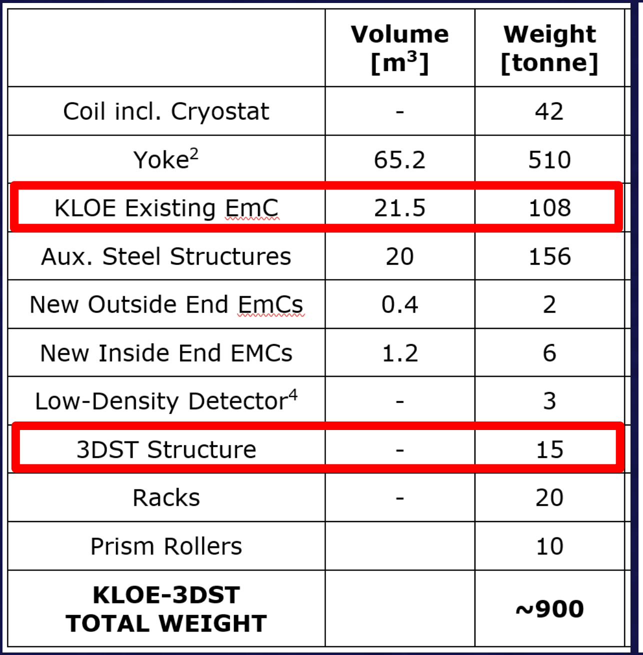
- Plastic scintillator + WLS fiber + MPPC
  - Fully active target
  - 1x1x1 cm^3 scintillator cubes assembled in rows and columns
  - Provide 3D projected views w/ fine segmentation
  - 4π acceptance w/ low momentum threshold for protons (~300 MeV)
  - Momentum-by-range: ~ 2-3% for stopping muons
- High light yield
  - ~50 p.e. for MIP
- Good timing resolution
  - ~0.95 ns for 1 channel, ~0.5 ns for 1 cube
  - Event-by-event neutron KE measurement using TOF



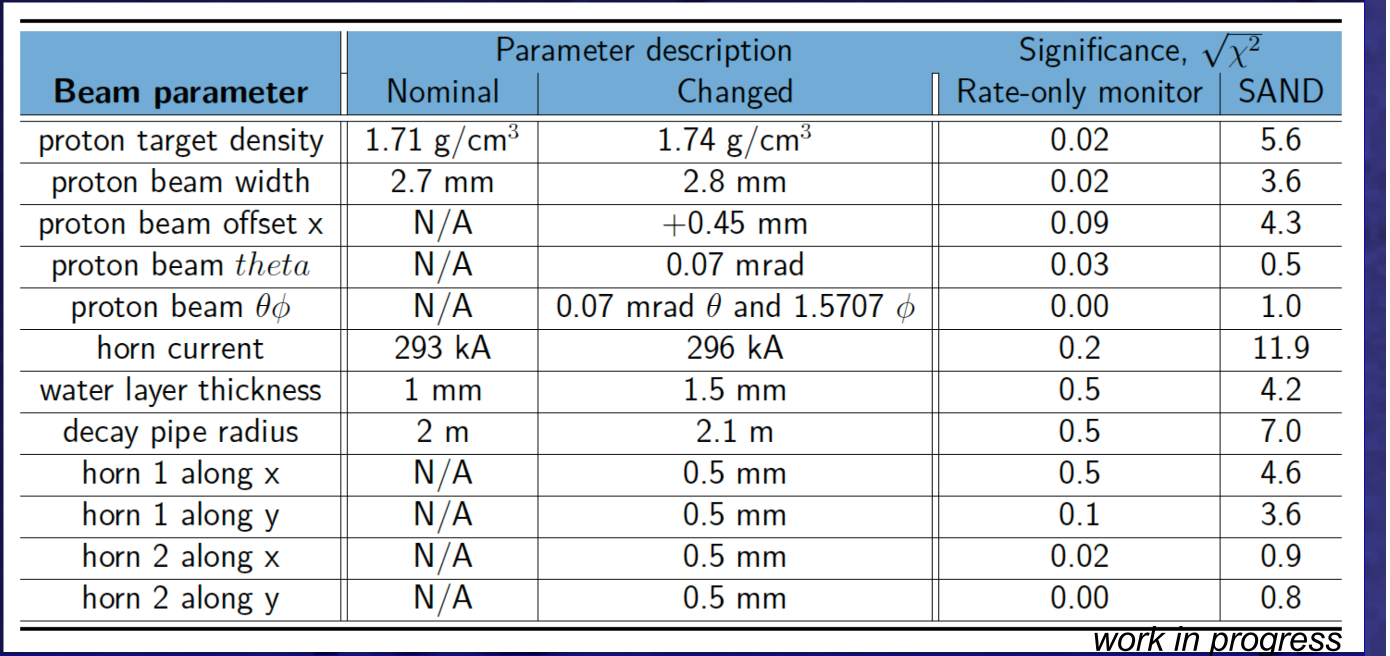

Successful large scale assembly at INR, Russia

Beam Monitoring w/ SAND (Reference Design)

- A good sensitivity to relatively small spectrum variations in one week time scale, afforded by:
  - ¬ High statistics resulting from the large mass of 3DST+ECAL
  - ¬ The excellent energy/momentum resolutions of combined 3DST, ECAL and TPC system
- The sensitivities are compared with those from four 7-ton “INGRID-like” modules placed at 0, 1, 2, 3 meters from the on-axis position



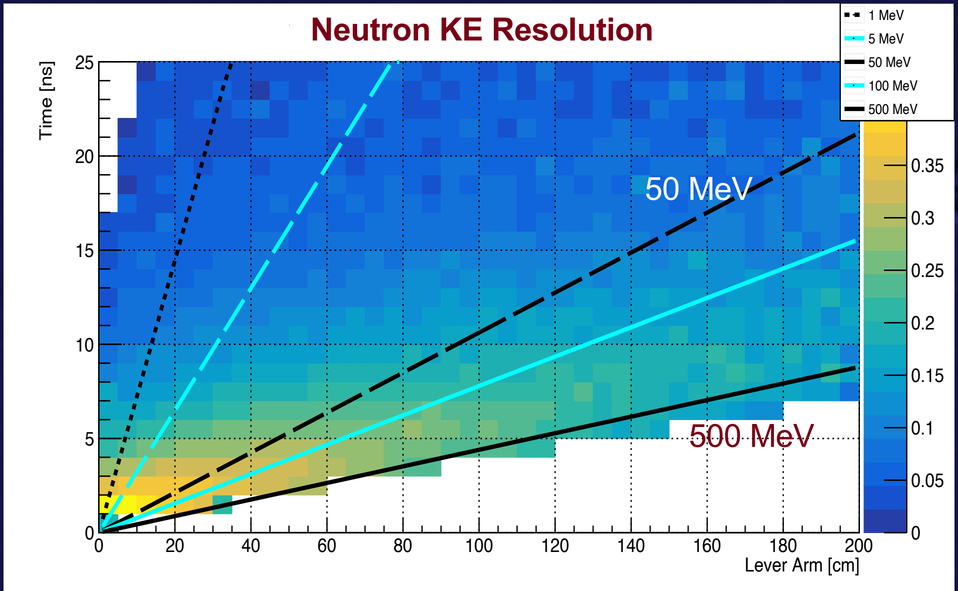
	Volume [m^3]	**Weight [tonne]**
Coil incl. Cryostat	-	42
Yoke[2]	65.2	510
KLOE Existing EmC	21.5	108
Aux. Steel Structures	20	156
New Outside End EmCs	0.4	2
New Inside End EMCs	1.2	6
Low-Density Detector[4]	-	3
3DST Structure	-	15
Racks	-	20
Prism Rollers		10
KLOE-3DST TOTAL WEIGHT		**~900**



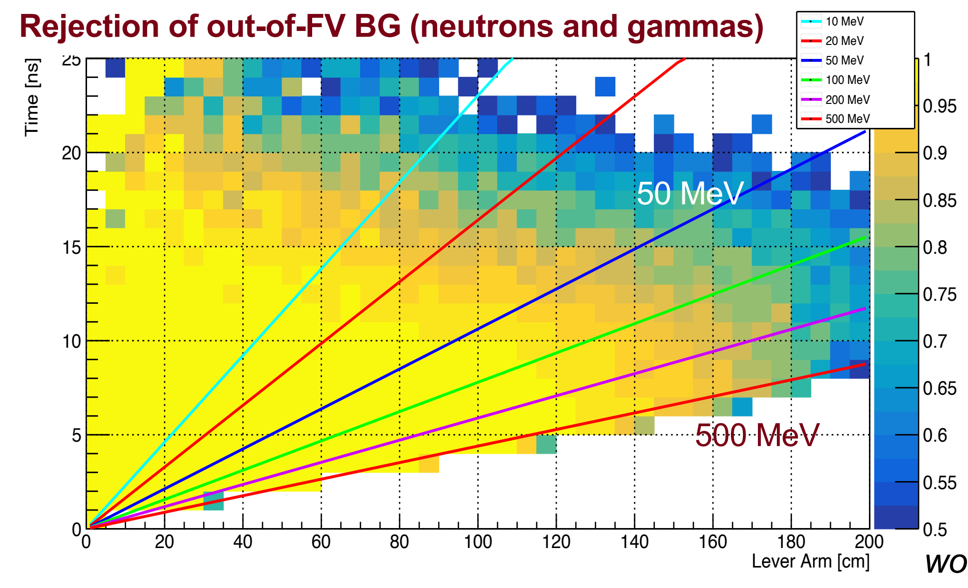
Beam parameter	Parameter description		Significance, $\sqrt{\chi^2}$	
	Nominal	Changed	Rate-only monitor	SAND
proton target density	1.71 g/cm^3	1.74 g/cm^3	0.02	5.6
proton beam width	2.7 mm	2.8 mm	0.02	3.6
proton beam offset x	N/A	+0.45 mm	0.09	4.3
proton beam $theta$	N/A	0.07 mrad	0.03	0.5
proton beam $\theta\phi$	N/A	0.07 mrad θ and 1.5707 ϕ	0.00	1.0
horn current	293 kA	296 kA	0.2	11.9
water layer thickness	1 mm	1.5 mm	0.5	4.2
decay pipe radius	2 m	2.1 m	0.5	7.0
horn 1 along x	N/A	0.5 mm	0.5	4.6
horn 1 along y	N/A	0.5 mm	0.1	3.6
horn 2 along x	N/A	0.5 mm	0.02	0.9
horn 2 along y	N/A	0.5 mm	0.00	0.8

work in progress

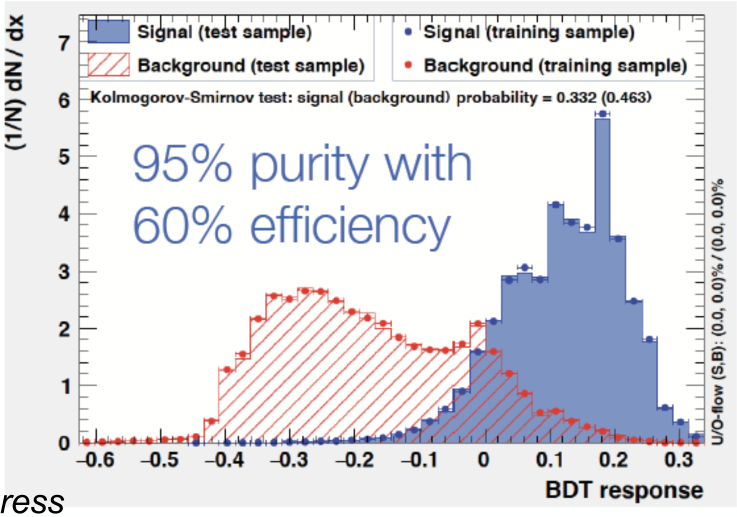
Event-by-event Neutron KE Measurement in DUNE 3DST utilizing TOF


Neutron KE Resolution

- 3DST best suited for neutron KE measurement
  - ¬ Fine granularity and sub-nano sec timing resolution (~.5 ns for 3 fibers)
  - ¬ Large fully active mass for neutron interactions (low-A nuclei & scintillating)
  - ¬ Low energy threshold (1 p.e. ~60 keV)


Rejection of out-of-FV BG (neutrons and gammas)

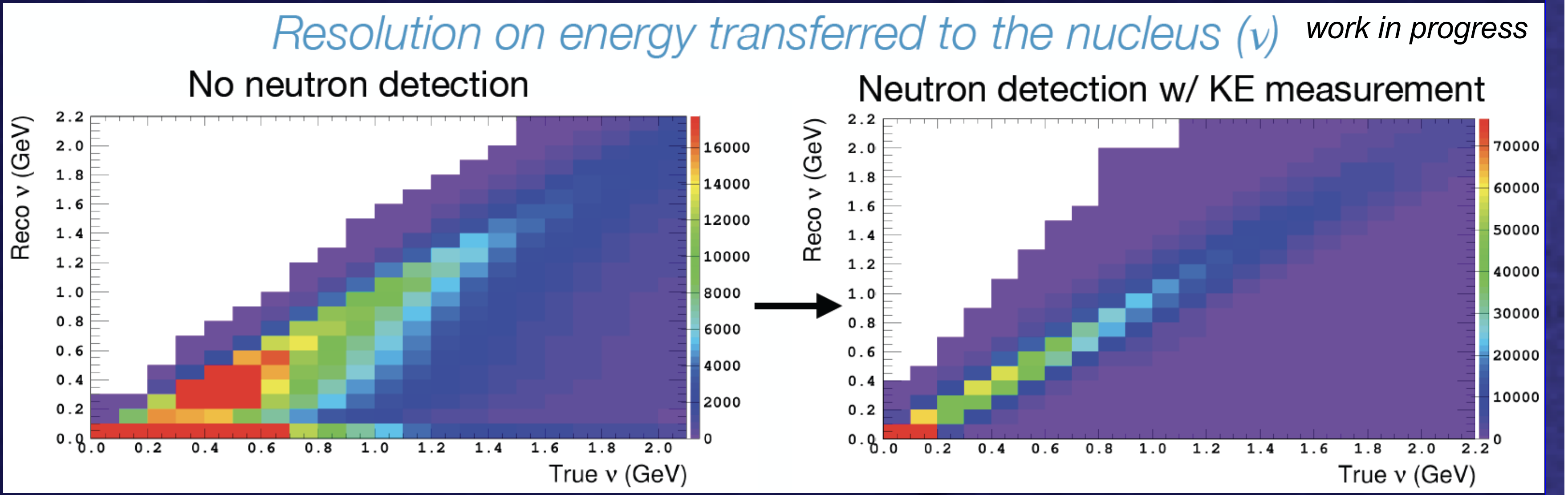
Rejection of gammas / secondary neutrons from 3DST



work in progress

Importance of Event-by-event Neutron KE Measurement

- Event-by-event neutron energy measurement is one of the final, if not the final, frontiers in particle physics experiment
  - ¬ Allows full event reconstruction
    - Detailed studies of neutrino interaction models
    - Measurement of antinu flux, especially using antinu–hydrogen interactions which has limited model dependence (PRD 101, 092003 (2020) → next slide)



Resolution on energy transferred to the nucleus (ν)

work in progress

No neutron detection

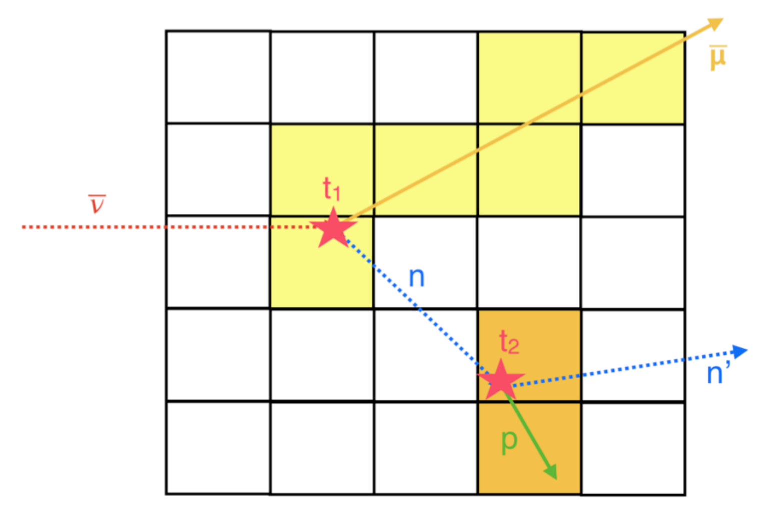
Neutron detection w/ KE measurement

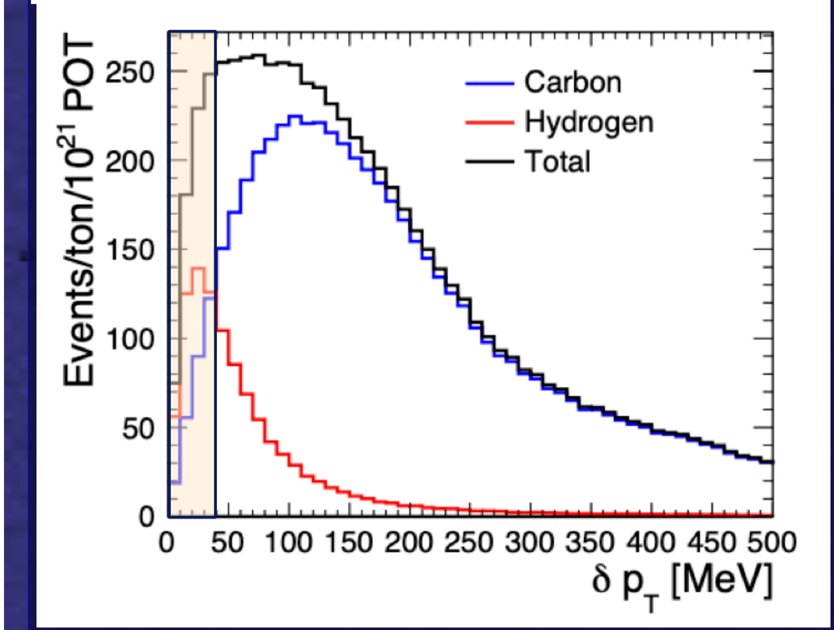
- 3DST
  - ¬ Very good neutron detection efficiency and very low out-FV background
- Recent paper from Minerva (PRD 100, 052002 (2019))

Neutron KE Measurement and Antineutrino Flux Measurement w/ T2K SuperFGD

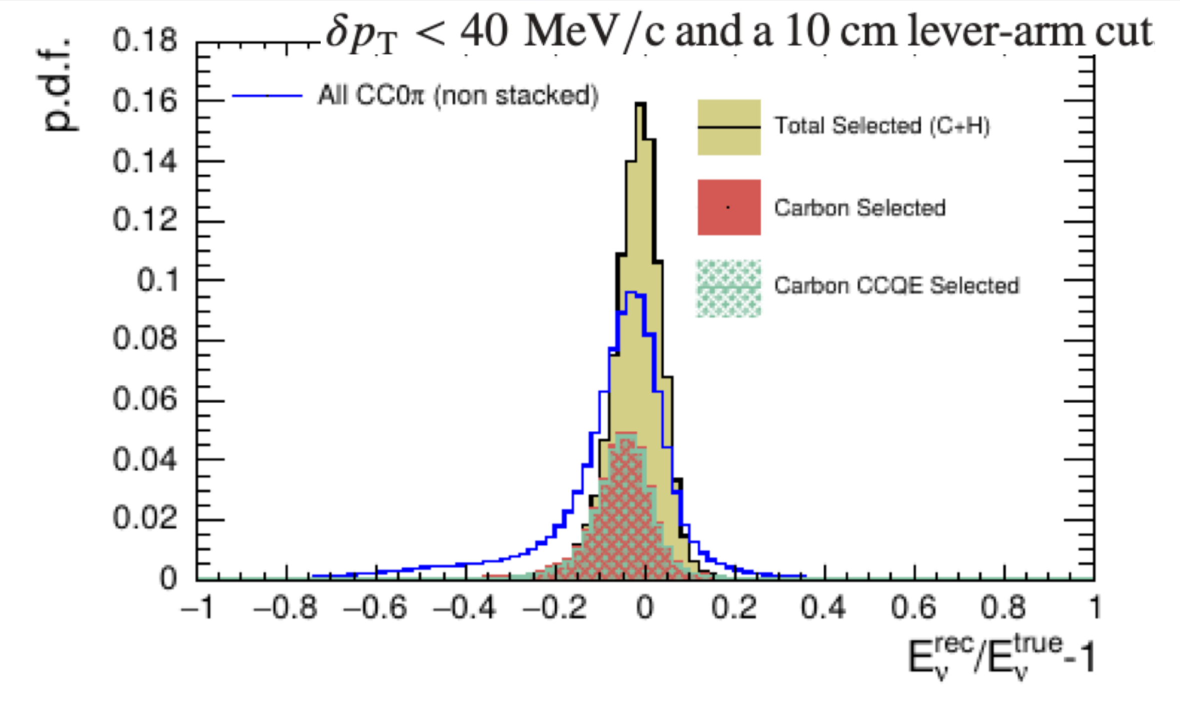
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

PRD.101.092003

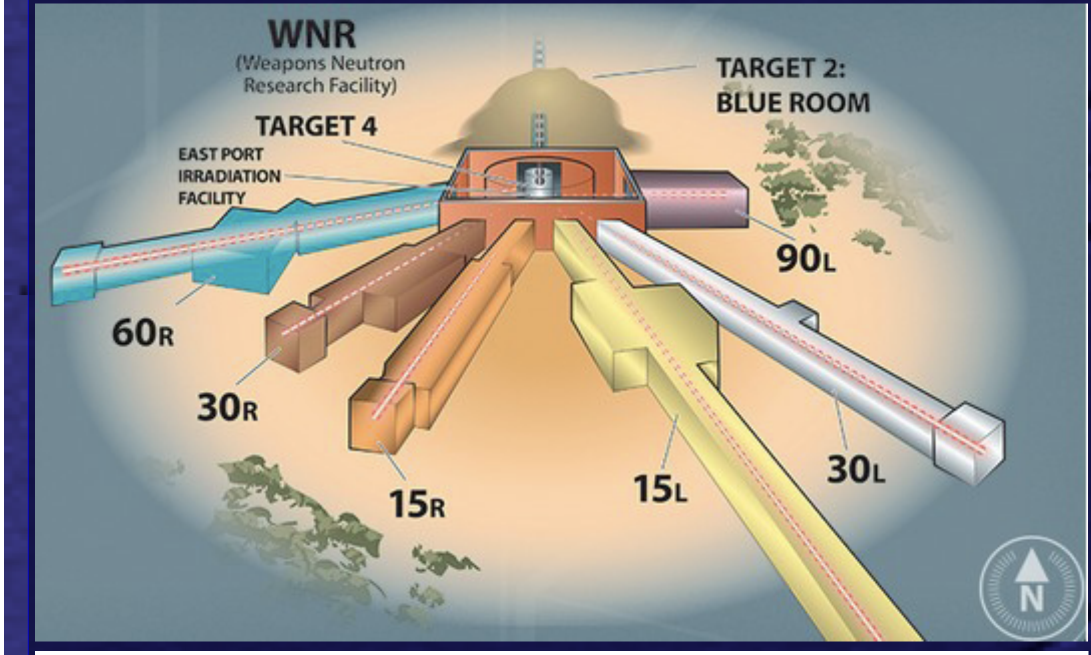


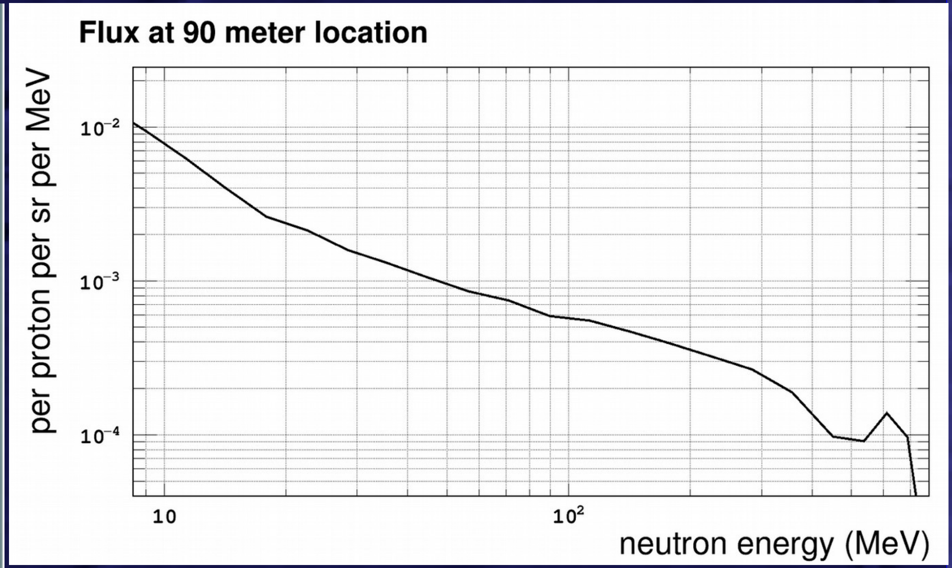


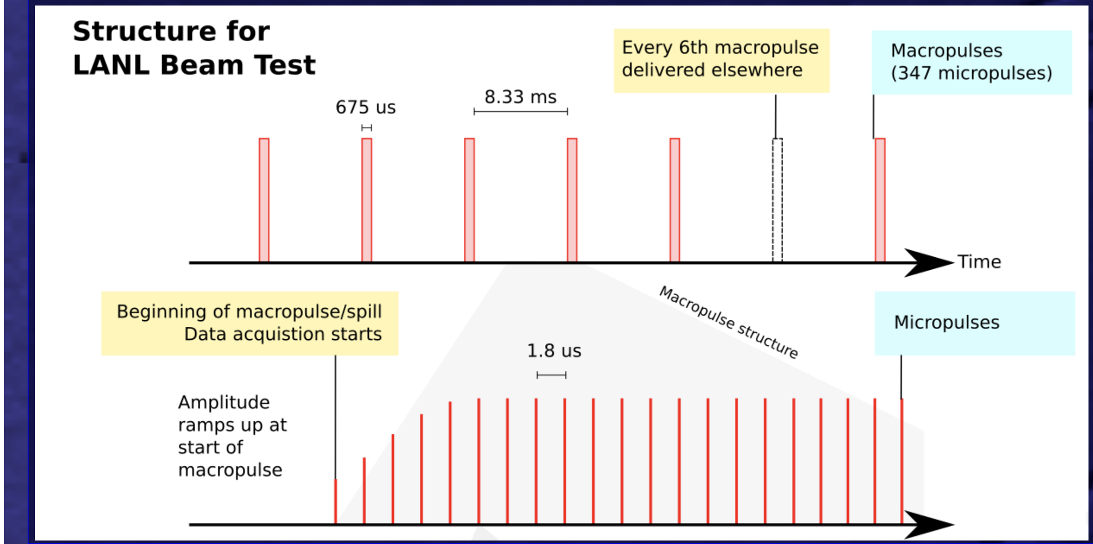
Improved reconstructed antineutrino energy resolution utilizing neutron KE measurement and δp_t (STV)



LANSCE Neutron Beam Test Facility

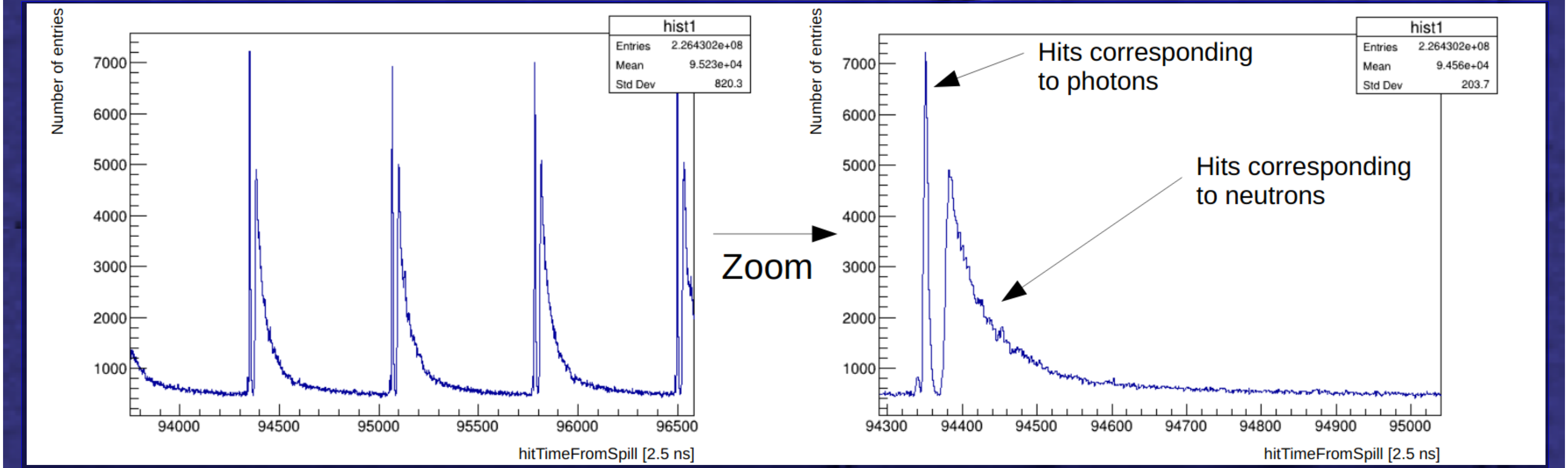






- Collimated neutron beam from 0-800 MeV
- Dec. 2019 data taking
  - ~3 weeks at 15L 90 m location
  - ~3 days at 15R 20 m location
- Dec. 2020 data taking
  - ~3 weeks at 15L 90 m location
  - → **Data taking run started today!!!**

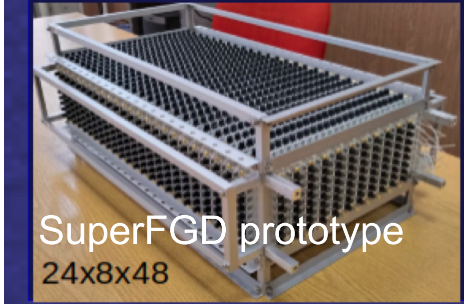
Neutron Beam Test Data

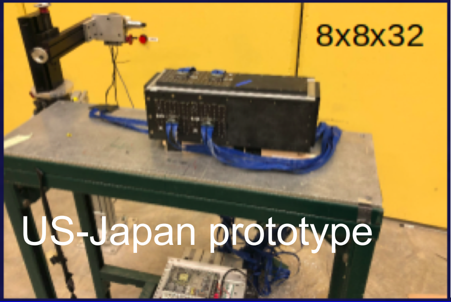


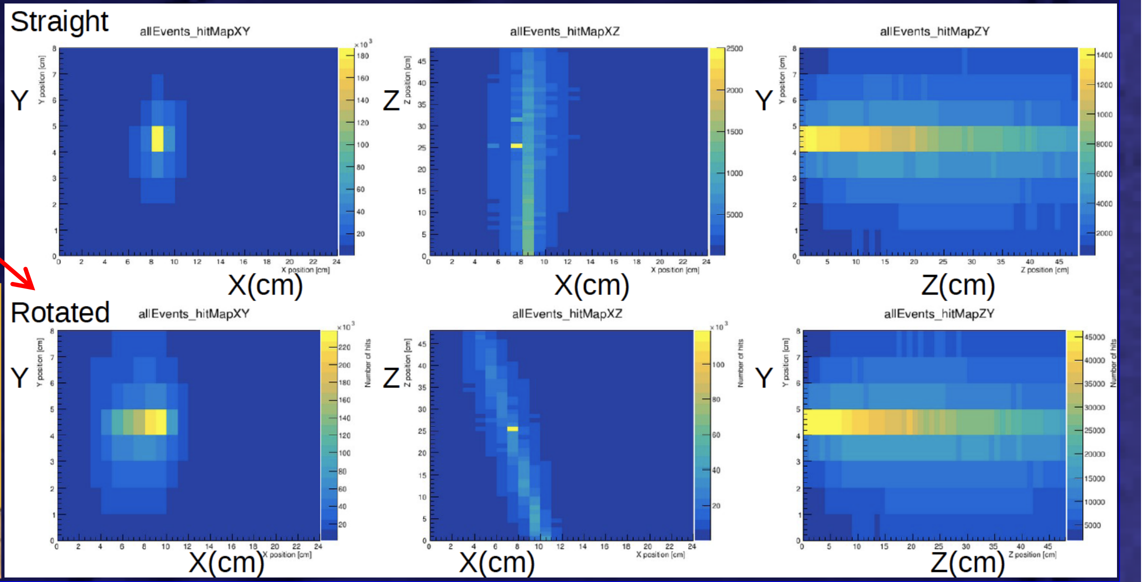
Hits corresponding to photons

Hits corresponding to neutrons

Detector (SuperFGD prototype) was rotated at various angles to characterize the fiber/MPPC responses


SuperFGD prototype
24x8x48

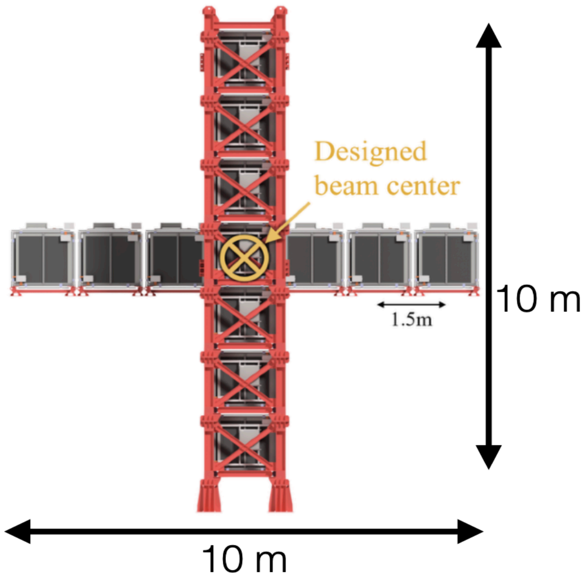

US-Japan prototype
8x8x32



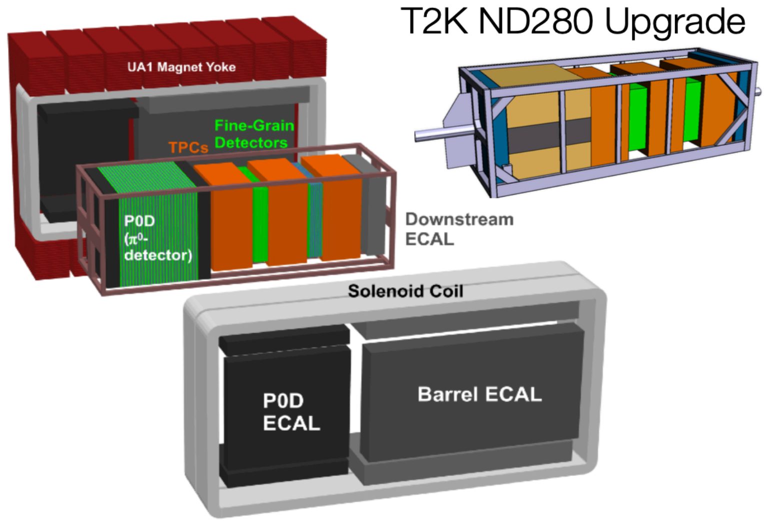
Flux Determinations in HyperK

Input by M. Hartz

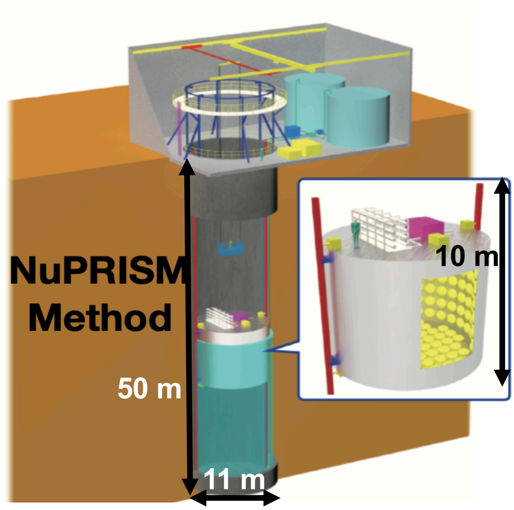
On-axis Detector (INGRID)



Off-axis Magnetized Tracker - T2K is upgrading ND280, expect additional upgrades for HK



Off-axis spanning intermediate water Cherenkov detector (IWCD)

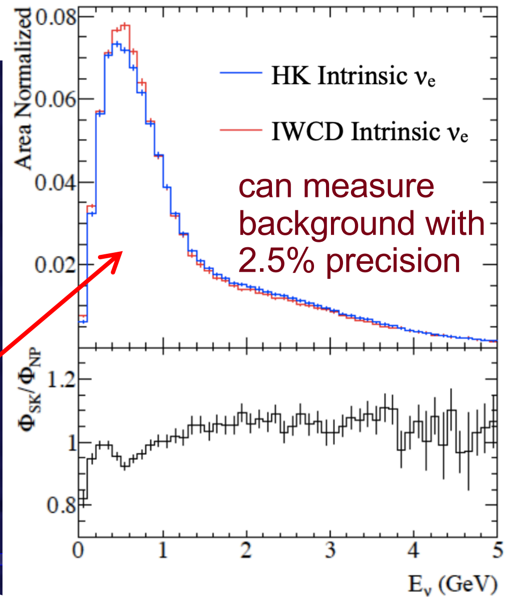


- At HyperK beam energy, methods to constraint flux such as low-ν or neutrino-electron scattering don't work well
- Rely on prior flux model constrained by beam monitors and hadron production data → continue T2K-II canonical method
- Beam direction measured with < 0.25 mrad accuracy

→ Uncertainty on predicted peak *E* of neutrino spectrum < 2 MeV

- Control of intrinsic ν_e and NC background using IWCD

→ Spectrum of electron (anti)neutrinos at IWCD matches HK



can measure background with 2.5% precision

Conclusion

- Needless to say, discovery of CPV in neutrino oscillations will require stringent control of systematic uncertainties, especially if dcp is away from $-\pi/2$
  - It would be prudent to aim to reduce neutrino flux related uncertainties to ~1% level
  - We will need continuing improvement in all aspects of flux determination by ND
    - External inputs (flux predictions and cross-section modeling, …)
    - Detectors (high resolution, full acceptance, …)
    - New methods (neutrino-electron scattering, low-ν, PRISM, …)
    - New tools (neutron, STV, …)

→ **event-by-event determination of neutron KE could be a powerful new tool!**