DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

A Near Detector System in DUNE

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Dec. 26 2019

Conclusion

- DUNE will give the Korean neutrino community a fun time

Outline

- dCP measurement
- T2K
- DUNE, DUNE FD, Proto-DUNE
- DUNE ND
- PRISM
- 3DST

DCP measurement

- Non-zero mixing angle theta13 measured by Double Chooz, Daya Bay and RENO provides opportunity to measure CP violation phase.
- Matter effect helps on mass hierarchy identification.
- Different appearance probability between neutrino and antineutrino indicates the CP phase. Existing long-baseline experiments are measuring CP phase with a combination of neutrino and antineutrino fluxes.

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$ ← What we measure

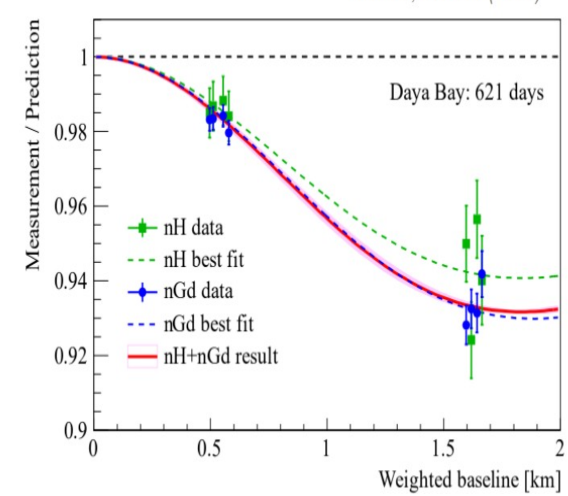
ME: $$\frac{16A}{\Delta m^2_{31}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) c^2_{13} s^2_{13} s^2_{23} (1 - 2s^2_{13})$$ ← Small

ME: $$- \frac{2AL}{E} \sin\left(\frac{\Delta m^2_{31} L}{4E}\right) c^2_{13} s^2_{13} s^2_{23} (1 - 2s^2_{13})$$ ← Proportional to L

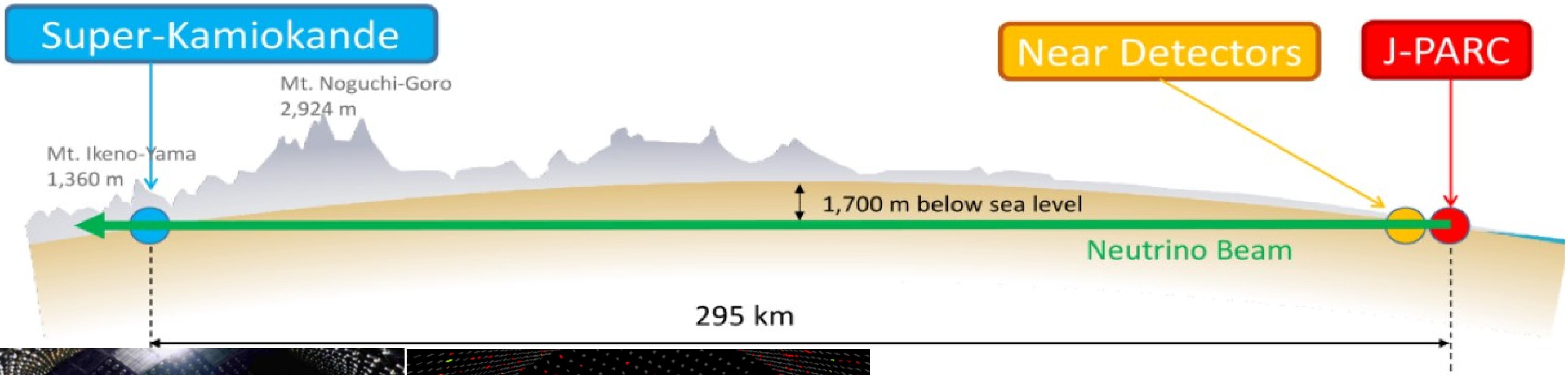
CPV: $$- 8 \frac{\Delta m^2_{21} L}{2E} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \sin\delta \; s_{13} c^2_{13} c_{23} s_{23} c_{12} s_{12}$$ ← What we want

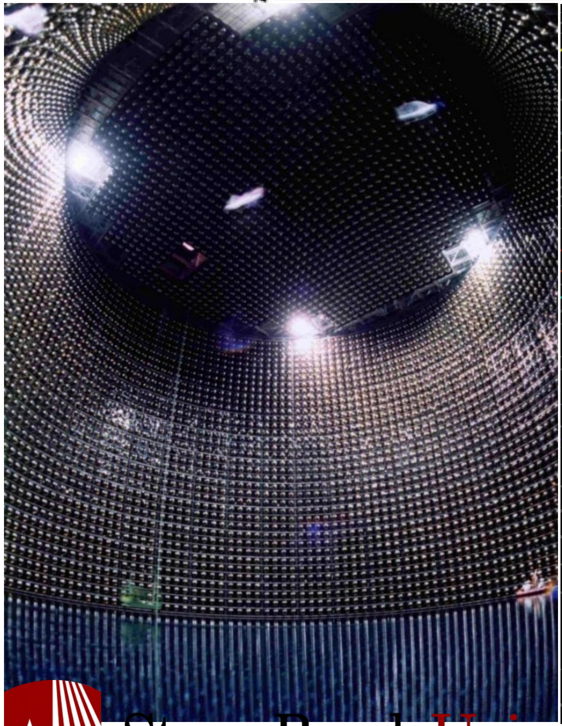
with $A = 2\sqrt{2} G_F n_e E = 7.6 \times 10^{-5} \mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$

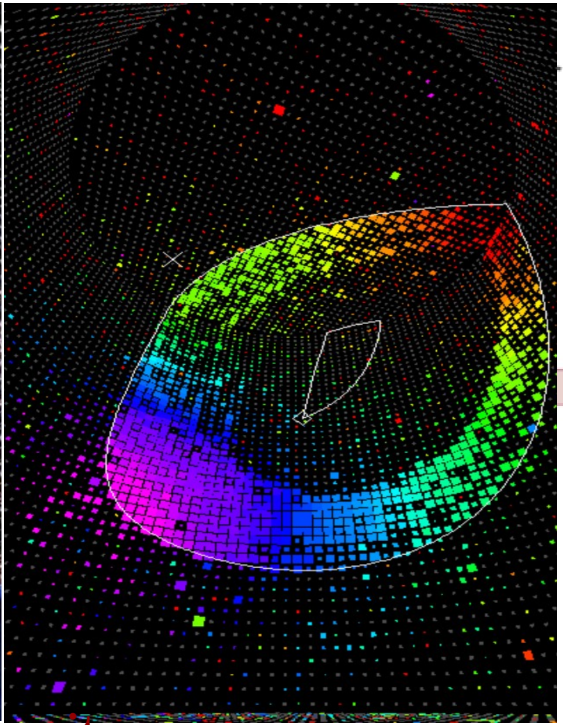
PRD 93, 072011 (2016)

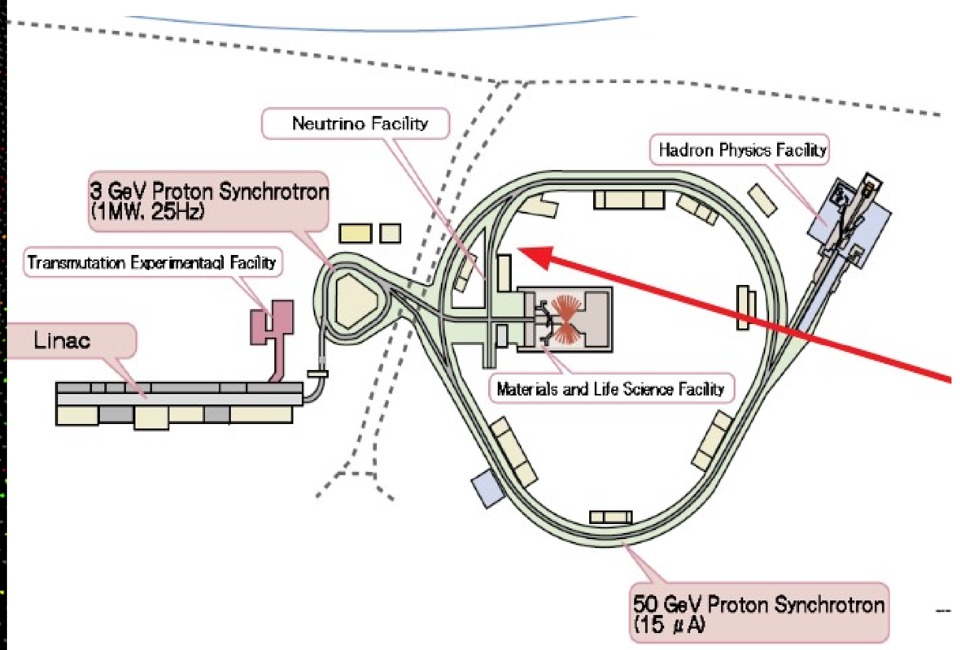


T2K experiment









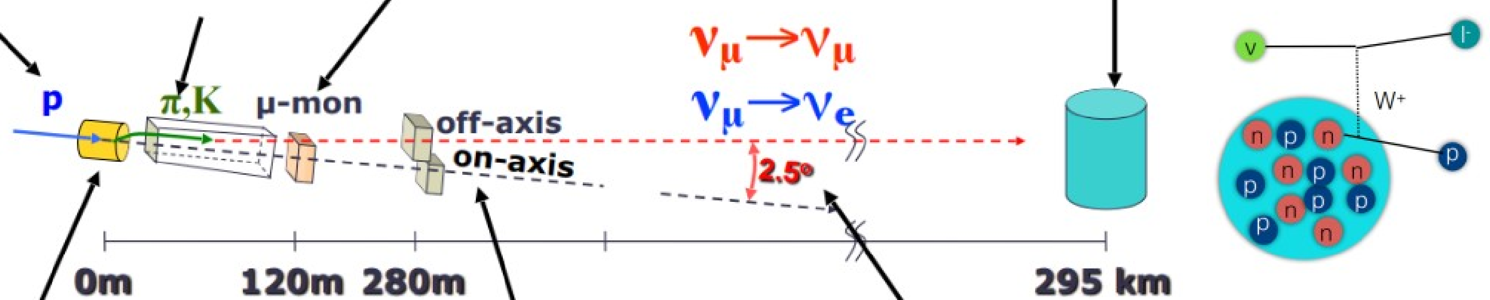
T2K in one slide

30 GeV proton beam

Decay volume:
$\pi^+ \rightarrow \mu^+ + \nu_\mu$
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

MUMON measures muons from pion decay

Off-axis **far detector** at 295 km: SK Cherenkov detector measures event rates after oscillations



Off-axis = narrow band beam

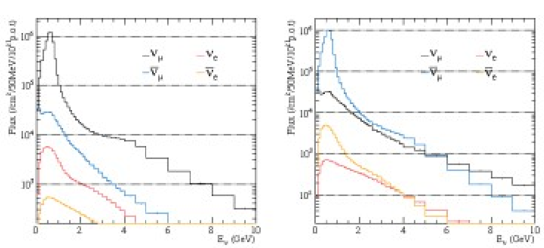
Beam on graphite target

3 magnetic horns focus:
π^+ for neutrino mode

π^- for antineutrino mode

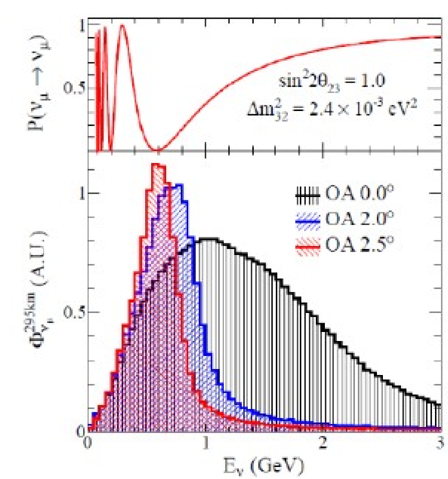
Off-axis **near detector**: ND280 detector measures spectra interactions

INGRID on-axis detector monitors beam direction and neutrino rate



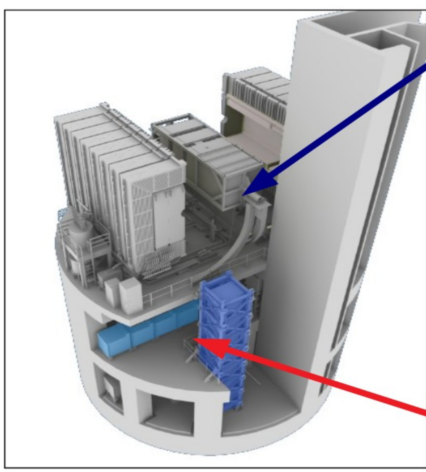
(a) FHC

(b) RHC



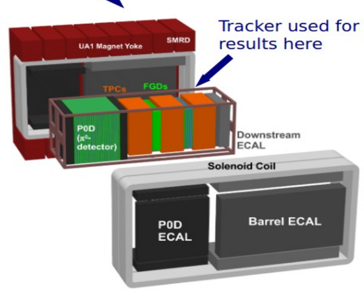
T2K off-axis near detector

- Overall point: obtain non-oscillation flux and constrain cross section
- P0D: measure the pi0 and nue production from the beam
- FGD: Carbon target (close enough to water) to constrain flux and cross section in the numu(bar) beam
- TPCs: fine resolution and low threshold for muons
- ECAL: contain showers
- Magnet: Measure muon/pi+- momentum



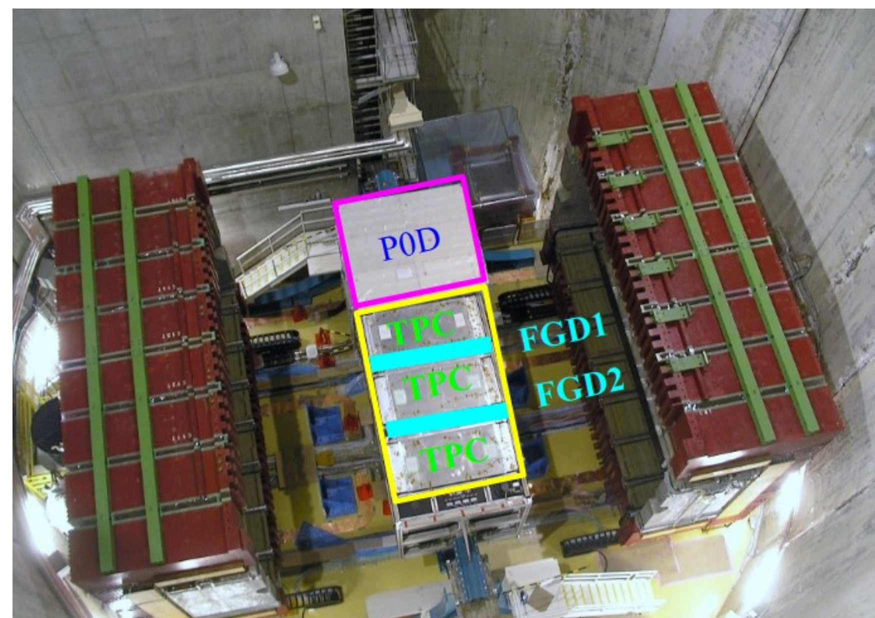
Off-axis (2.5°)
ND280

On axis
(INGRID)

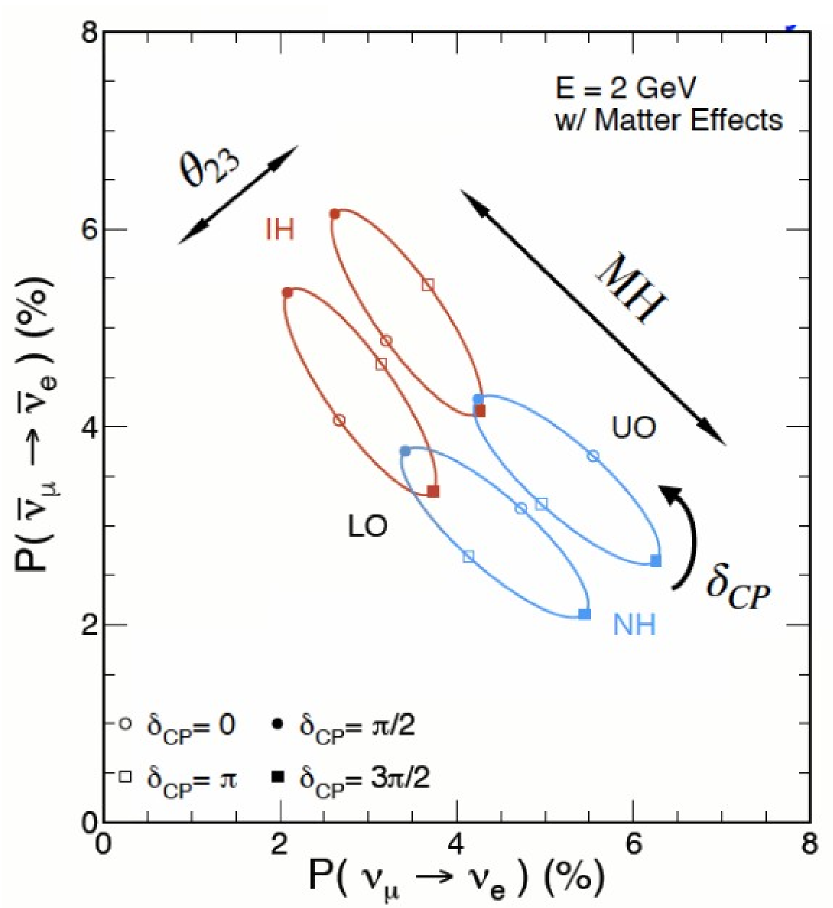


Tracker used for results here

See Xianguo Lu's talk for ND280 details

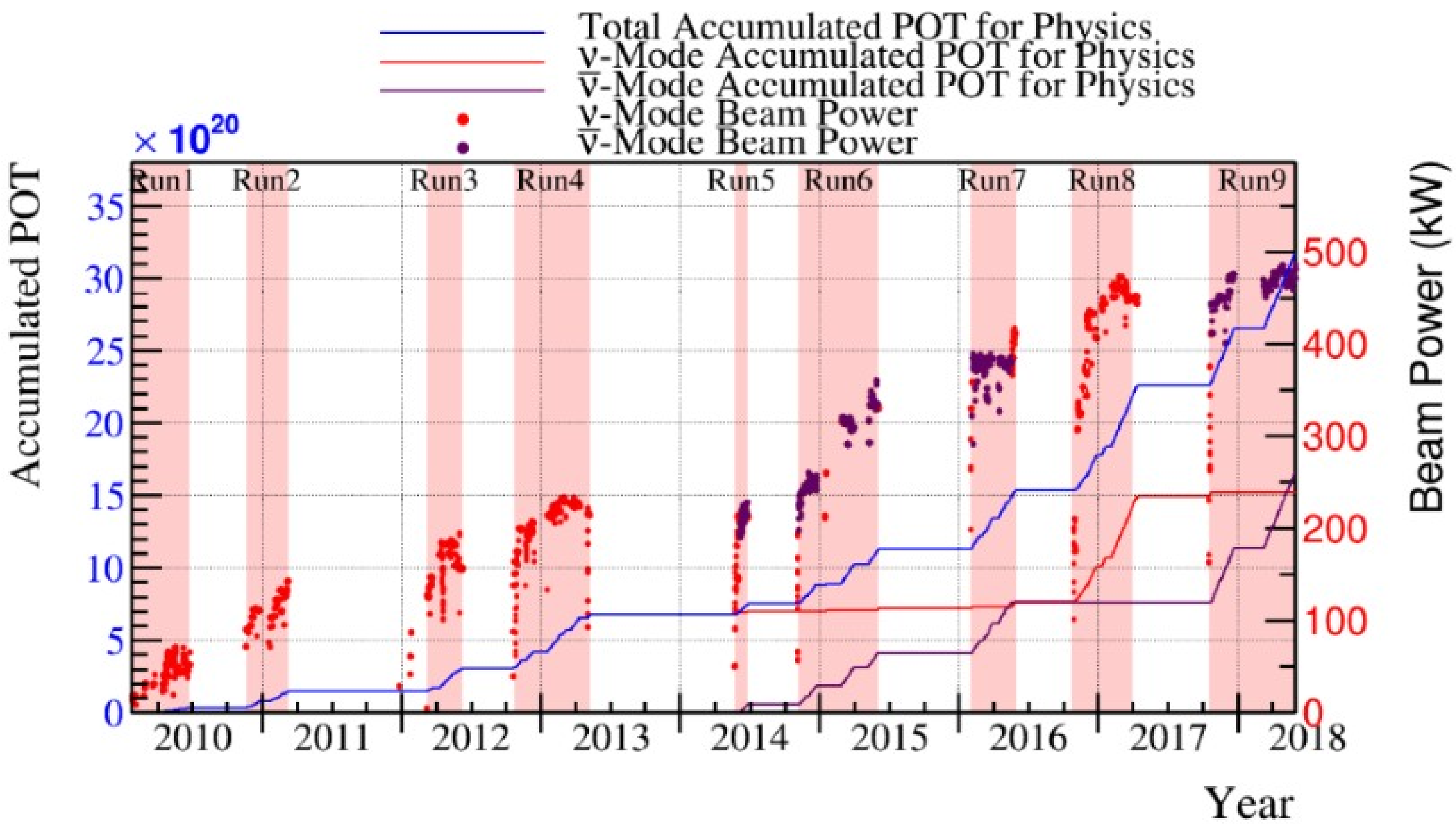


Oscillation analysis



- Long-baseline experiment is to measure disappearance and appearance channels
- Experiment setup: constrain on numu in ND and obtain survived numu and oscillated nue in FD
- Nu mode and antinu mode needed: at least 4 samples needed in total
- Three effects are convoluted : 23, dcp and MH
- We need precision measurement to disentangle them.

T2K run time



23 Jan. 2010 – 31 May 2018

POT total: 3.16×10^{21}

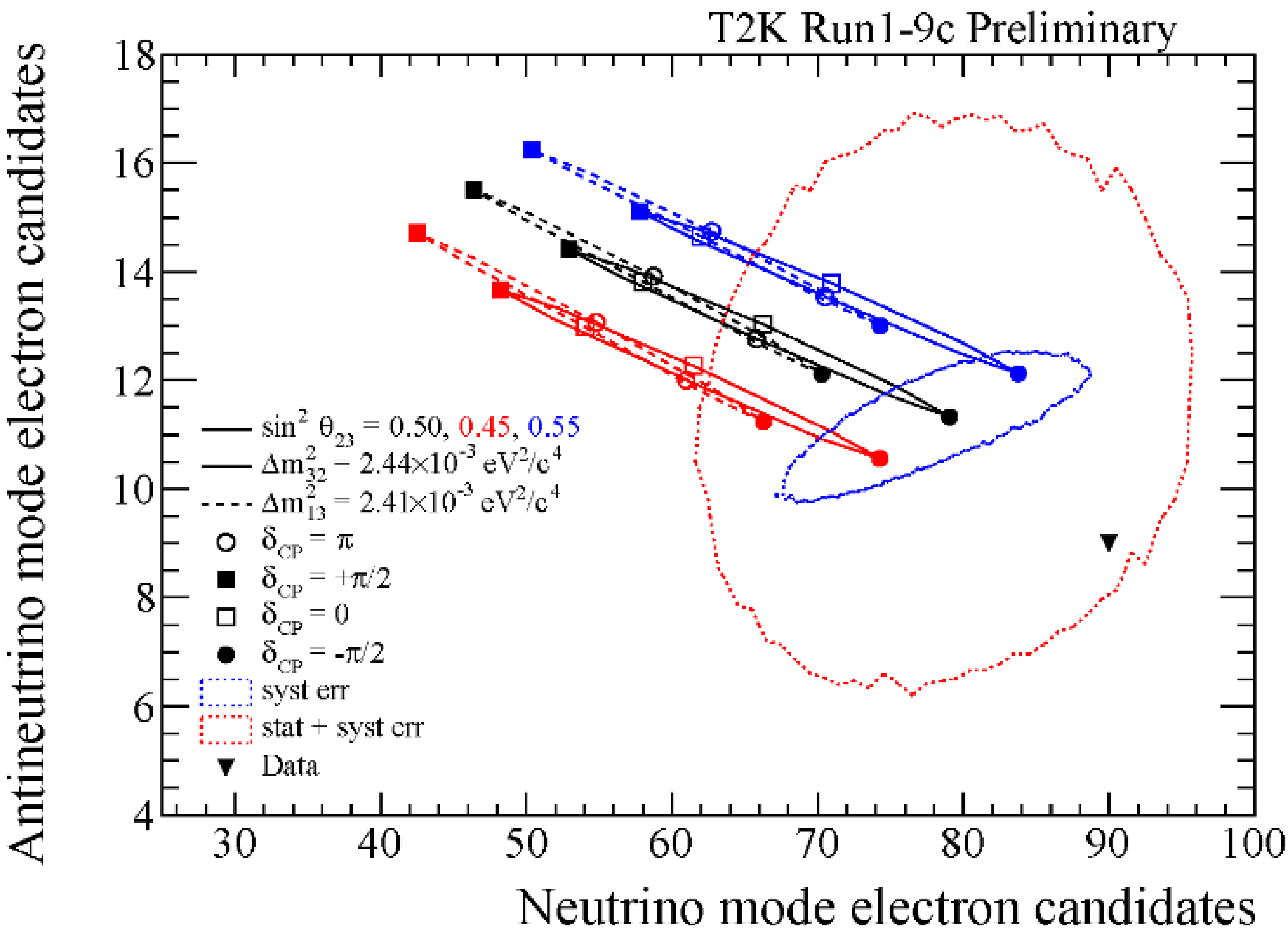
ν-mode 1.51×10^{21} (47.83%)

$\bar{\nu}$-mode 1.65×10^{21} (52.17%)

T2K oscillation results

	Predicted				Observed
δ_{CP} =	-π/2	0	+π/2	π	
FHC 1Rμ	268.5	268.2	268.5	268.9	243
RHC 1Rμ	95.5	95.3	95.5	95.8	102
FHC 1Re No decay e	73.8	61.6	50.0	62.2	75
FHC 1Re 1 decay e	6.9	6.0	4.9	5.8	15
RHC 1Re 0 decay e	11.8	13.4	14.9	13.2	9

T2K results



T2K Run1-9c Preliminary
Antineutrino mode electron candidates
Neutrino mode electron candidates
sin² θ23 = 0.50, 0.45, 0.55
Δm²32 = 2.44×10⁻³ eV²/c⁴
Δm²13 = 2.41×10⁻³ eV²/c⁴
δCP = π
δCP = +π/2
δCP = 0
δCP = -π/2
syst err
stat + syst err
Data

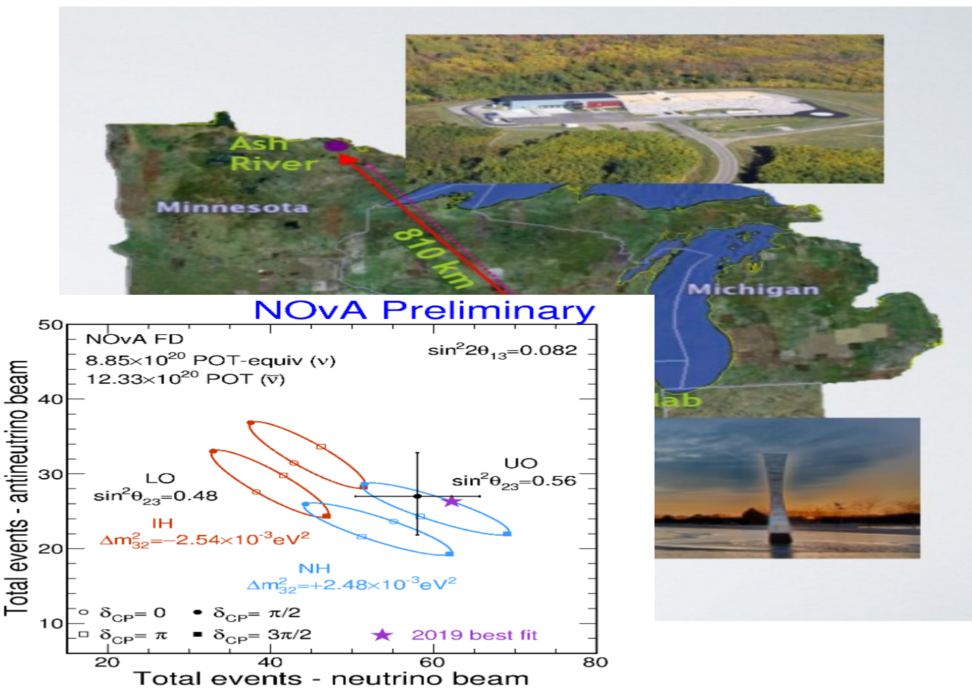
How to improve?

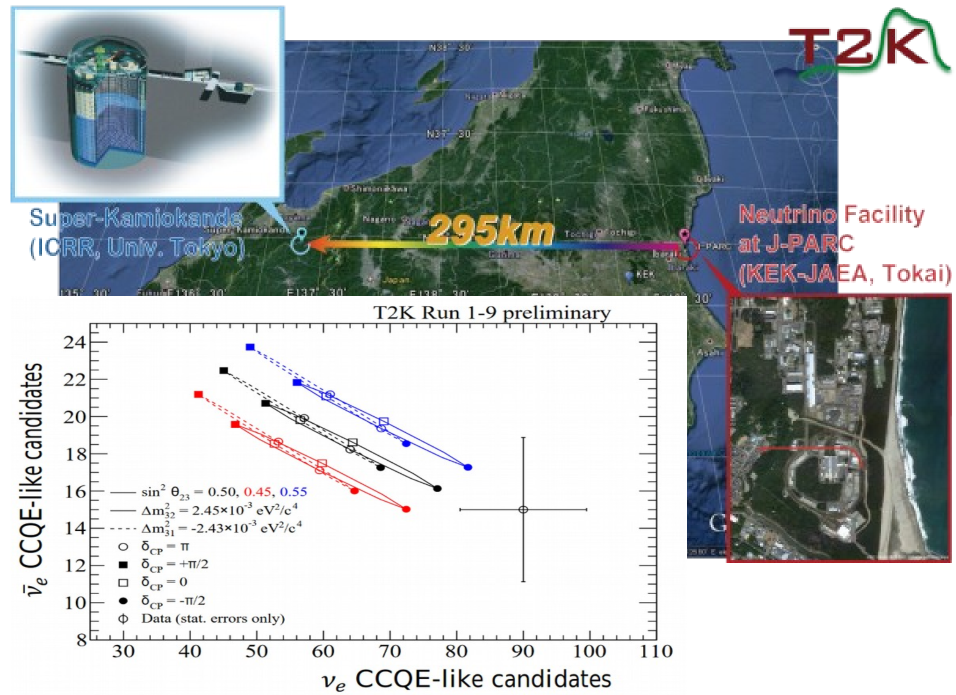
- SK detector cannot be largely reduced
- Sk FSI+SI+PN cannot be largely reduced
- ND280 contain the flux and xsec at few percent level
- Improvements:
  - Detector: better topology, lower threshold
  - Shape: broad band beam
  - baseline: longer!

	% Errors on Predicted Event Rates, Osc. Parameter Set A					
	1R μ-Like		1R e-Like			
Error Source	FHC	RHC	FHC	RHC	FHC CC1π	FHC/RHC
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI+SI+PN	2.20	1.98	3.01	2.31	11.43	1.57
ND280 const. flux & xsec	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.08	2.59	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Total Systematic Error	**4.40**	**3.76**	**6.10**	**6.51**	**20.94**	**4.77**

T2K vs. NOvA

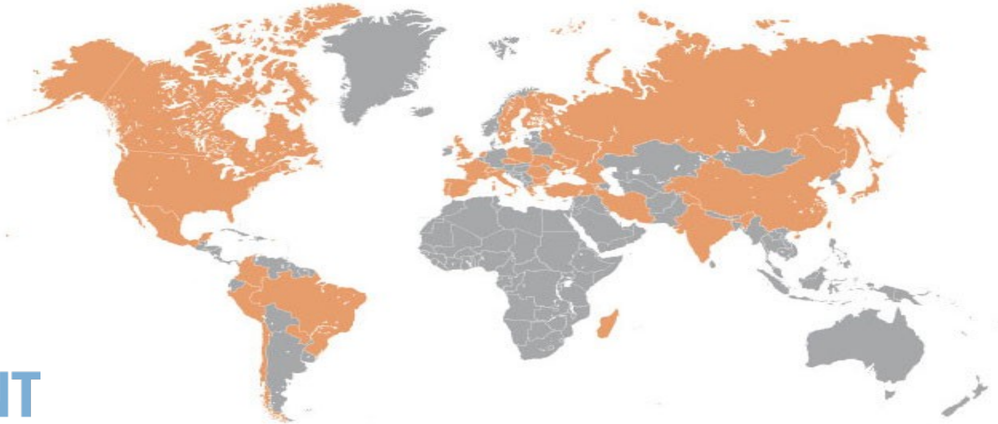
- T2K in Japan with 295 km baseline and 0.6 GeV peaked neutrino beam
- NOvA in USA with 810 km baseline and 2 GeV peaked neutrino beam





- T2K observed CP violation > 2 sigma. If NOvA goes to the same direction (not yet), a combination of them could reach 3 sigma in the near future.
- Five sigma measurement needs a newly built wide-band beam, longer baseline experiment, like DUNE.

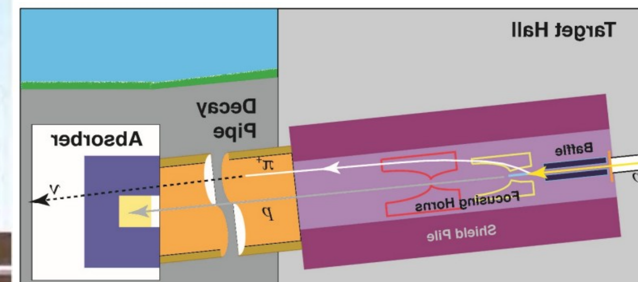
DUNE Collab.

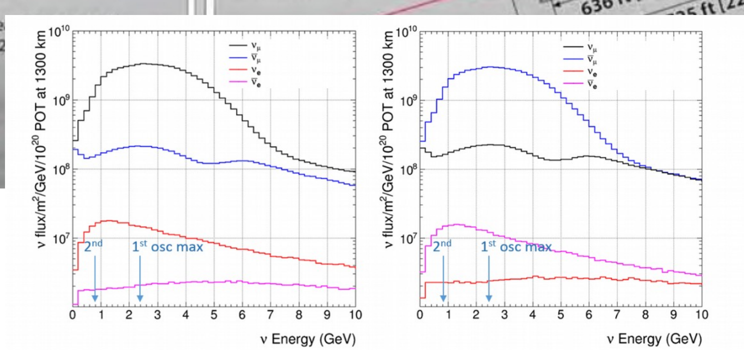


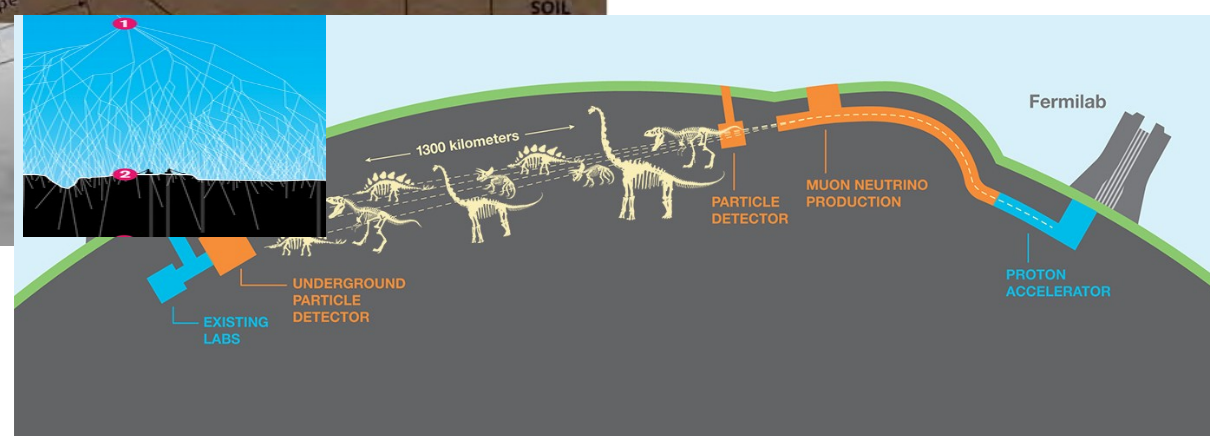
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

DUNE experiment

- High-intensity wide-band muon neutrino beam located at Fermilab.
  - Cover at least 2, up to 3 electron neutrino appearance maxima.
  - 1.2 MW proton beam upgradable to 2.4 MW.
- Muon neutrino disappearance and electron neutrino appearance channels will be observed at a high-mass far detector with a baseline of 1300 m.







Physics goals in DUNE

- Precision measurements of the parameters that govern muon neutrino to electron neutrino and anti-muon neutrino to anti-electron neutrino oscillations

  - measuring CP violation phase

  - Determine neutrino mass ordering

- Search for proton decay in several decay modes, for example p→ kaon and antineutrino.
- Detection of the electron neutrino flux from a core-collapse supernova within our galaxy.
- Ancillary goals:

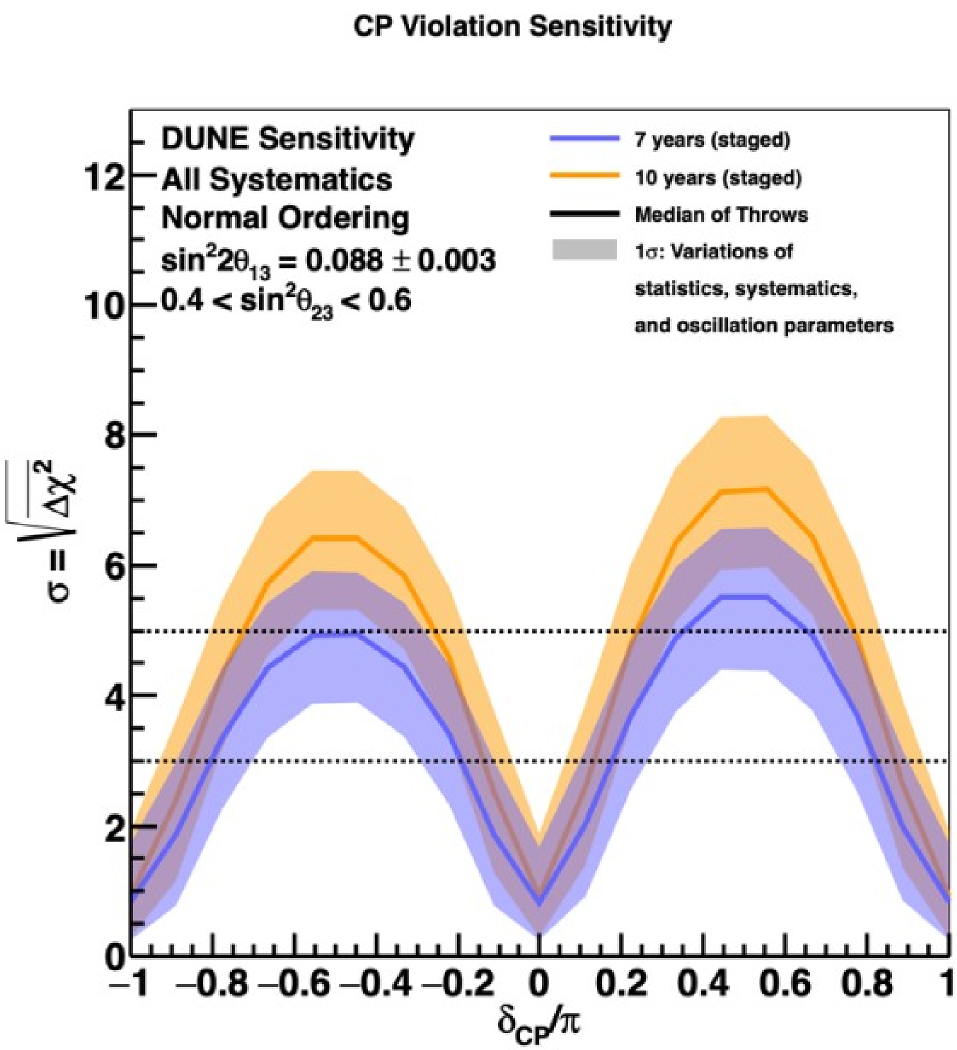
  - Beyond standard model physics: NSIs, sterile neutrinos..

  - Atmospheric neutrino oscillation

  - A rich neutrino interaction physics program utilizing DUNE near detector such as cross section measurements, studies of the nuclear effects and nuclear structure..

  - Dark matter...

DUNE Sensitivity



- Aim at 5 sigma CP violation measure after 7 years running of FHC + RHC modes.
- Time plan :

  - July 2017: Far detector site ground breaking

  - 2018-2022 ProtoDUNE single phase and dual phase

  - Late 2019: FD TDR approval

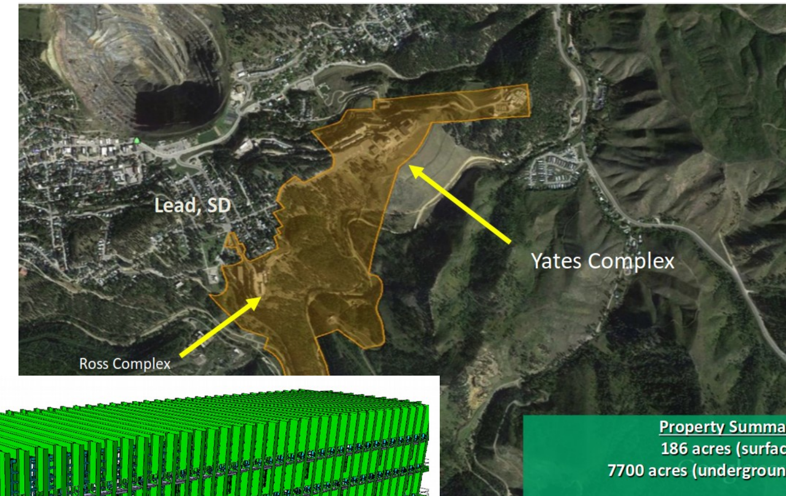
  - Aug. 2024 – May. 2025: 1st 10 kt FD installation

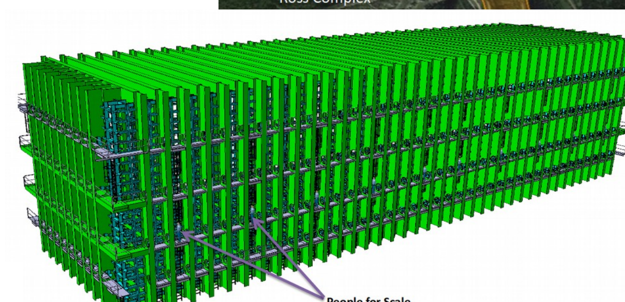
  - Aug. 2025 – May. 2026: 2nd 10 kt FD installation

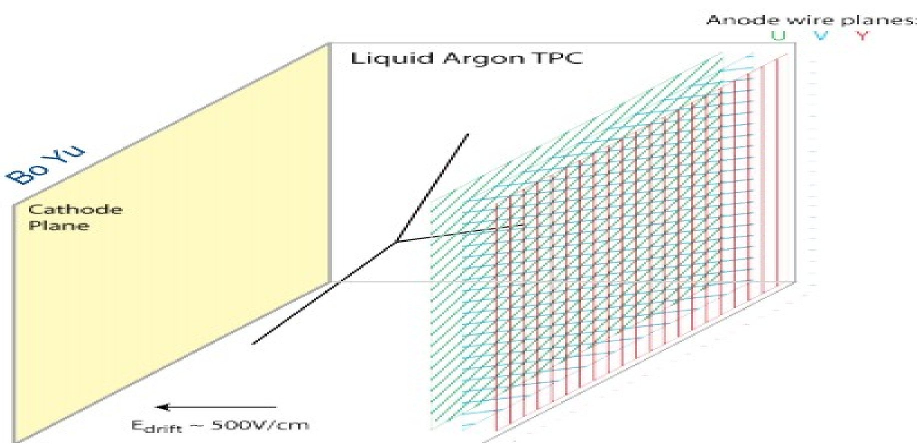
  - 2027: ND and LBNF beam ready

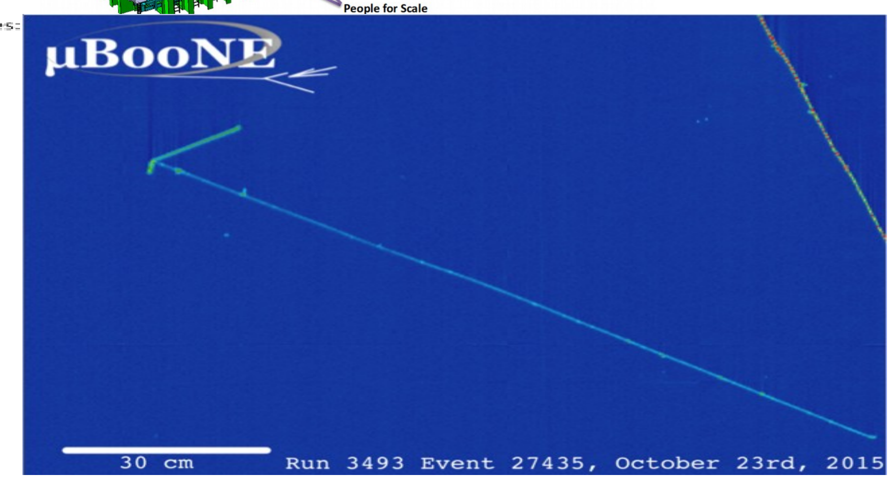
DUNE Far Detector

- FD is located at Homestake in South Dakota
  with a number of 10 kt liquid argon TPC modules.
- Each module has 3 Anode Plane Assemblies (APA).
  - 384,000 cold electronics channels
- Cathode planes (CPA) operate at 180 kV.
  - 3.6 m max drift length
- Photon detection system to provide T0.









Proto-DUNE

- Active 6m x 7m x 7.2m volume with 0.77 kt LAr,

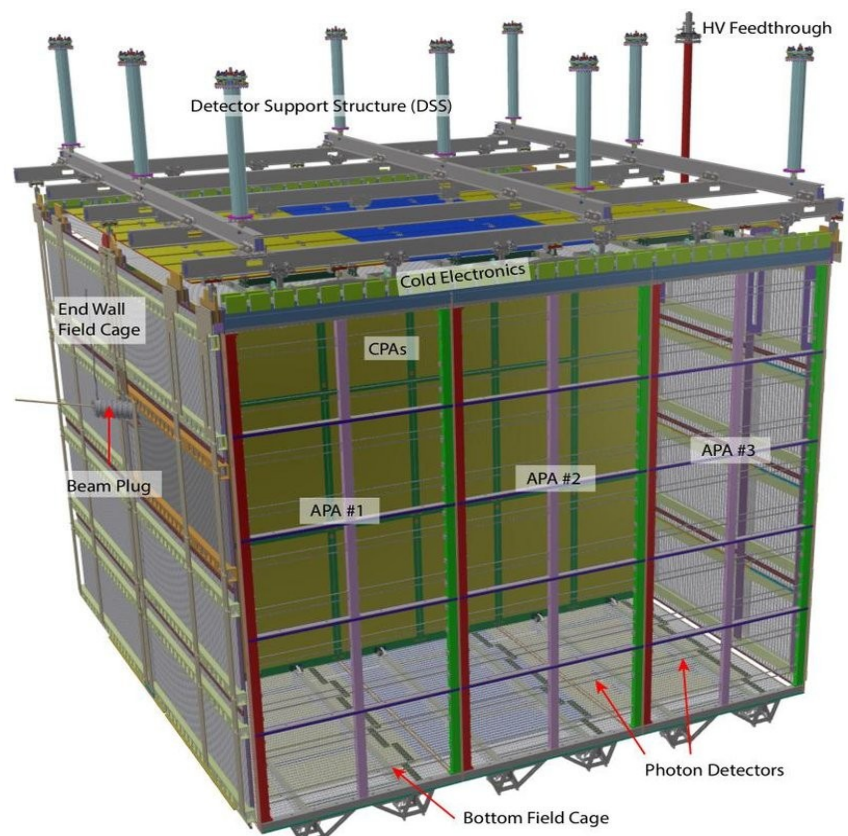
  ~3520 wires per APA.
- Goals of protoDUNE:

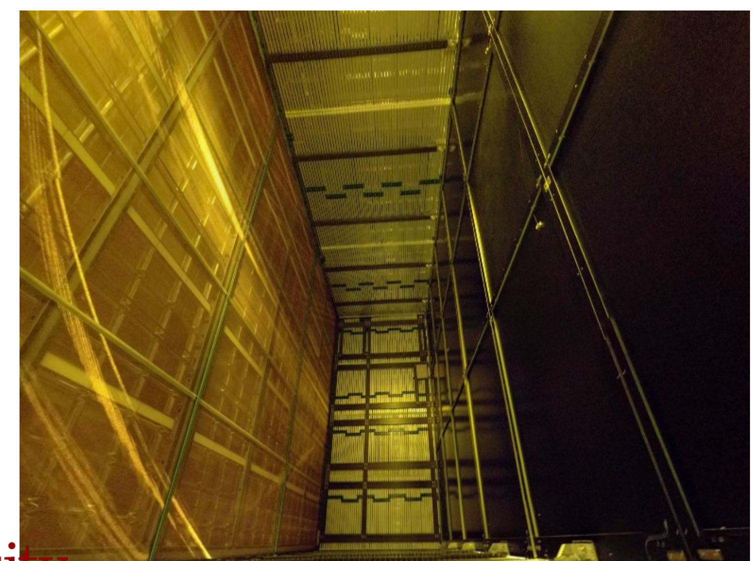
  - Prototype the production and installation.

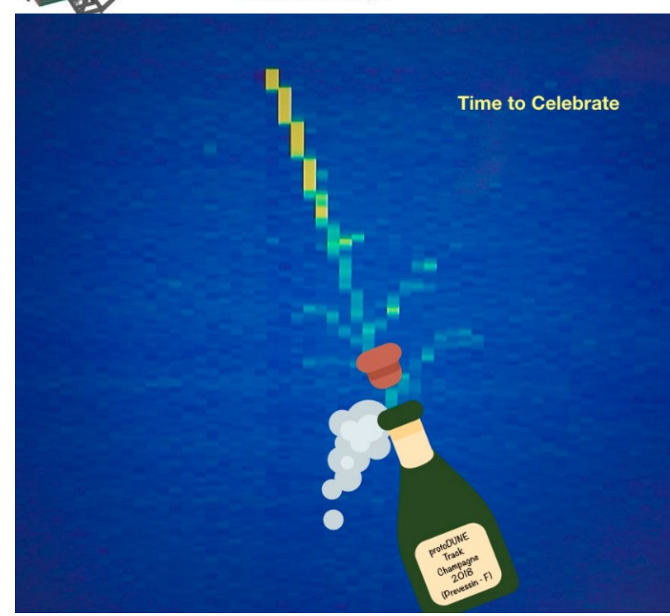
  - Validate the design and performance.

  - Accumulate test-beam data to calibrate detector.

  - Demonstrate operational stability.
- Taking data in CERN!!







What should ND do?

Ideally:

$$P_{\nu_\mu\to\nu_e}(E_\nu) = \frac{\phi^{far}_{\nu_e}(E_\nu)}{\phi^{far,no-osc}_{\nu_\mu}(E_\nu)} = \frac{\phi^{far}_{\nu_e}(E_\nu)}{\phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu)}$$

$$\frac{dN^{det}_{\nu}}{dE_\nu} = \phi^{det}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu)$$

Event spectrum:

$$\frac{dN^{det}_{\nu}}{dE_{rec}} = \int \phi^{det}_{\nu}(E_\nu) * \sigma^{target}_{\nu}(E_\nu) * T^{det}_{\nu_\mu}(E_\nu, E_{rec})\ dE_\nu$$

However…

$$\left.\frac{dN^{far}_{\nu_e}}{dE_\nu}\right/\frac{dN^{near}_{\nu_\mu}}{dE_\nu} = P_{\nu_\mu\to\nu_e}(E_\nu) * \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * F_{far/near}(E_\nu)$$

Just make them Canceled??

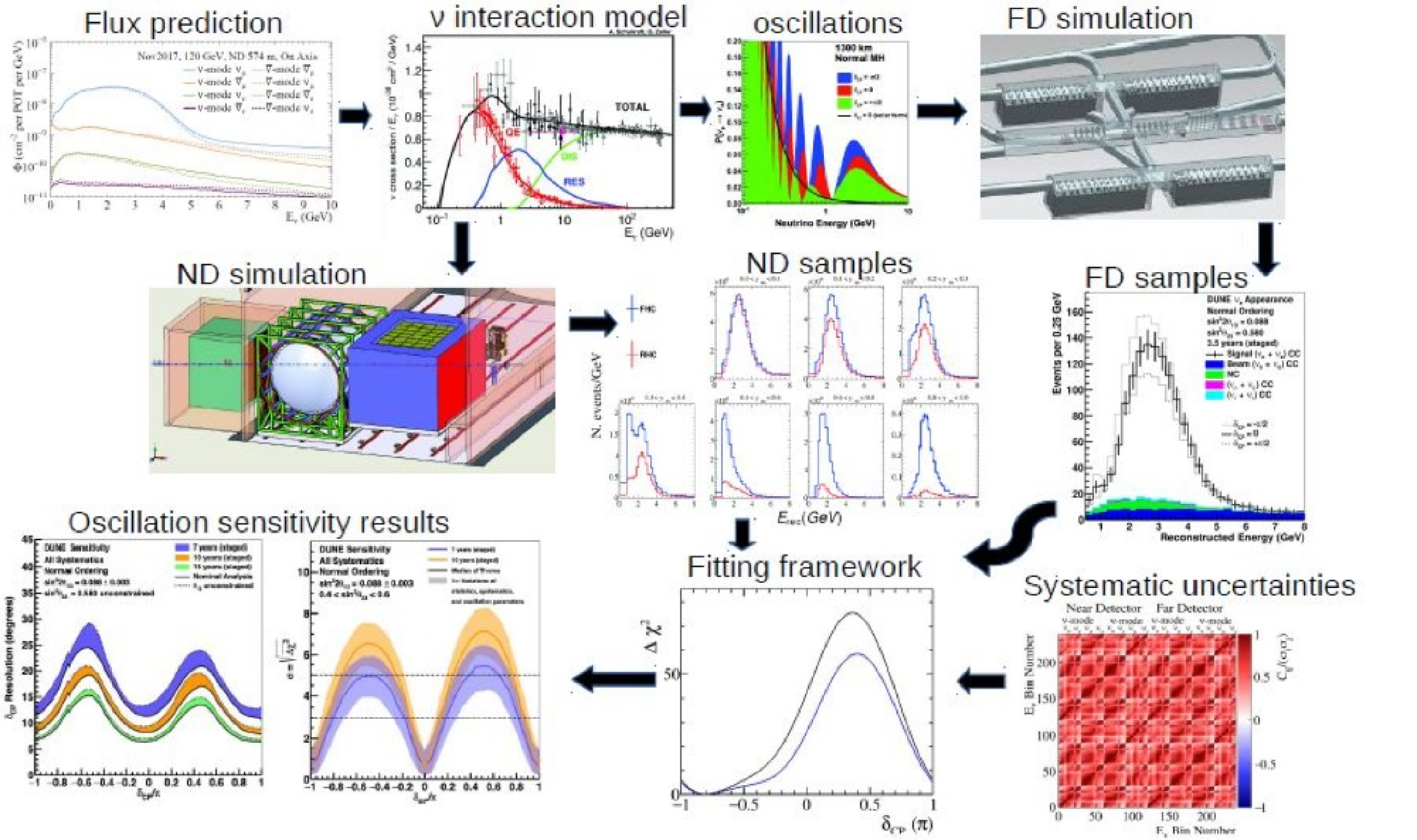
$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu\to\nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * T^{far}_{\nu_e}(E_\nu, E_{rec})\ dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * T^{near}_{\nu_\mu}(E_\nu, E_{rec})\ dE_\nu}$$

It turns out...

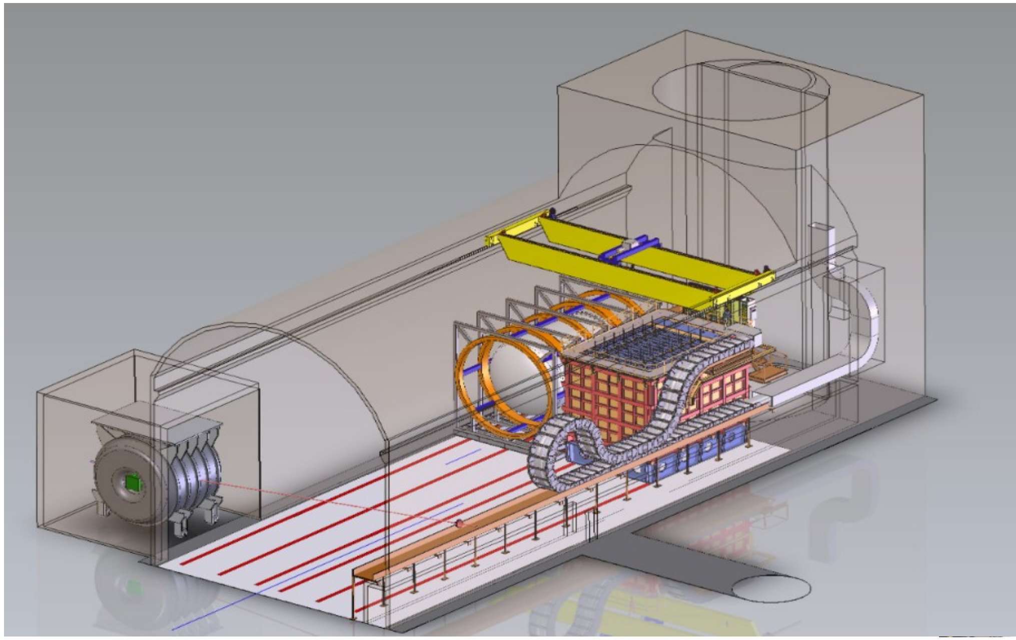
Ambiguities need to be resolved w/:
- Independent flux measurement
- Good cross section modelings
- Reconstructed energy to true energy mapping
- Near to Far flux extrapolation

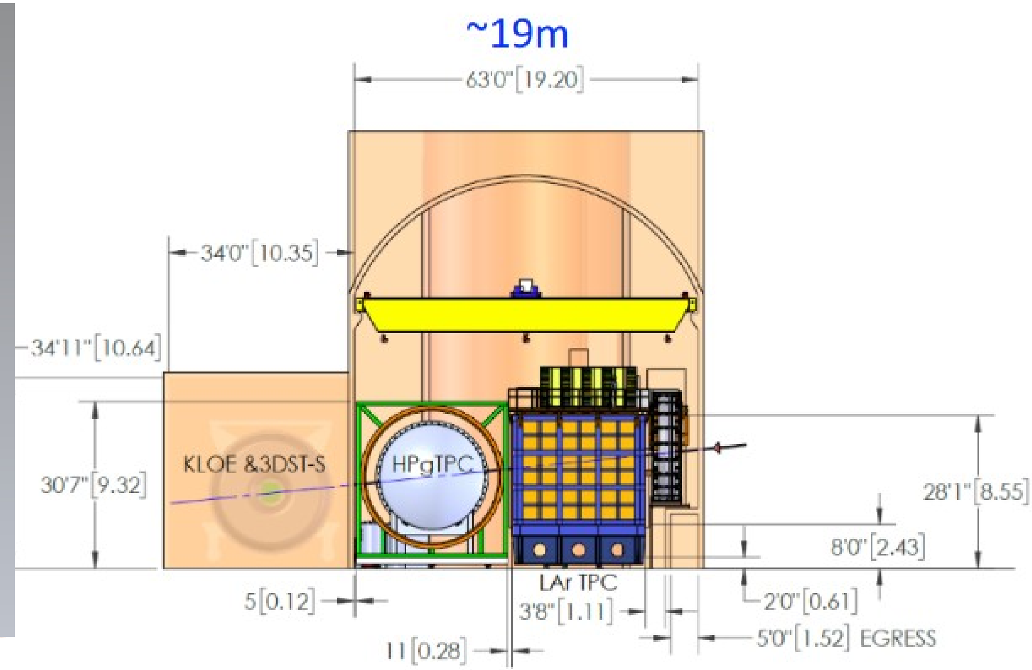
DEEP UNDERGROUND NEUTRINO EXPERIMENT

What should ND do?



DUNE ND hall

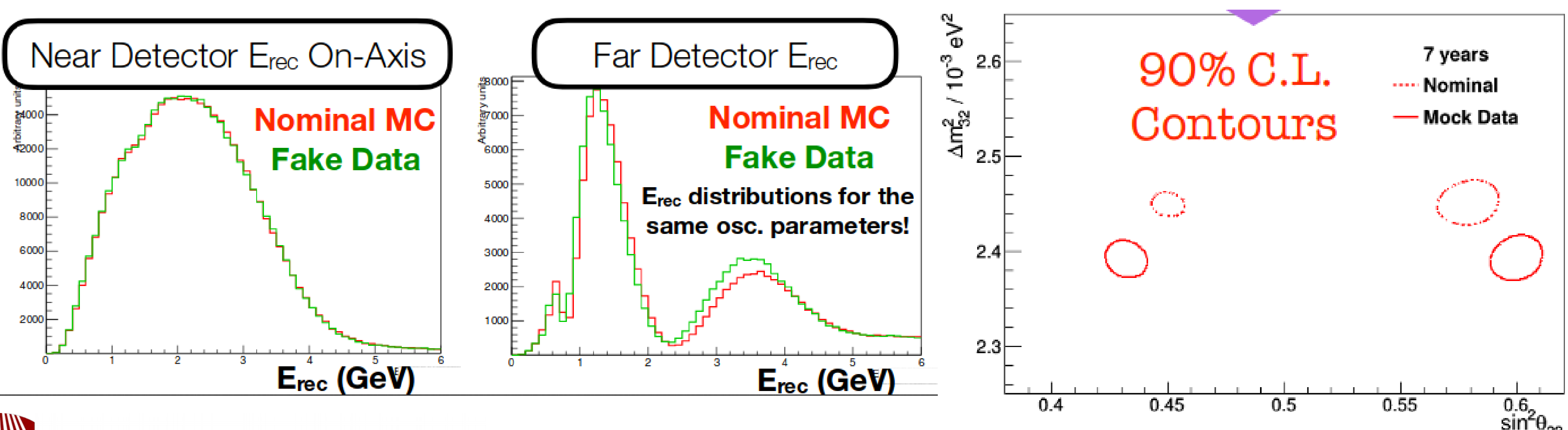




- There is a liquid argon detector
- There is a magnetized gas argon TPC system
- There is a magnetized 3D projection scintillator tracker.
- Part of the ND system will be movable.

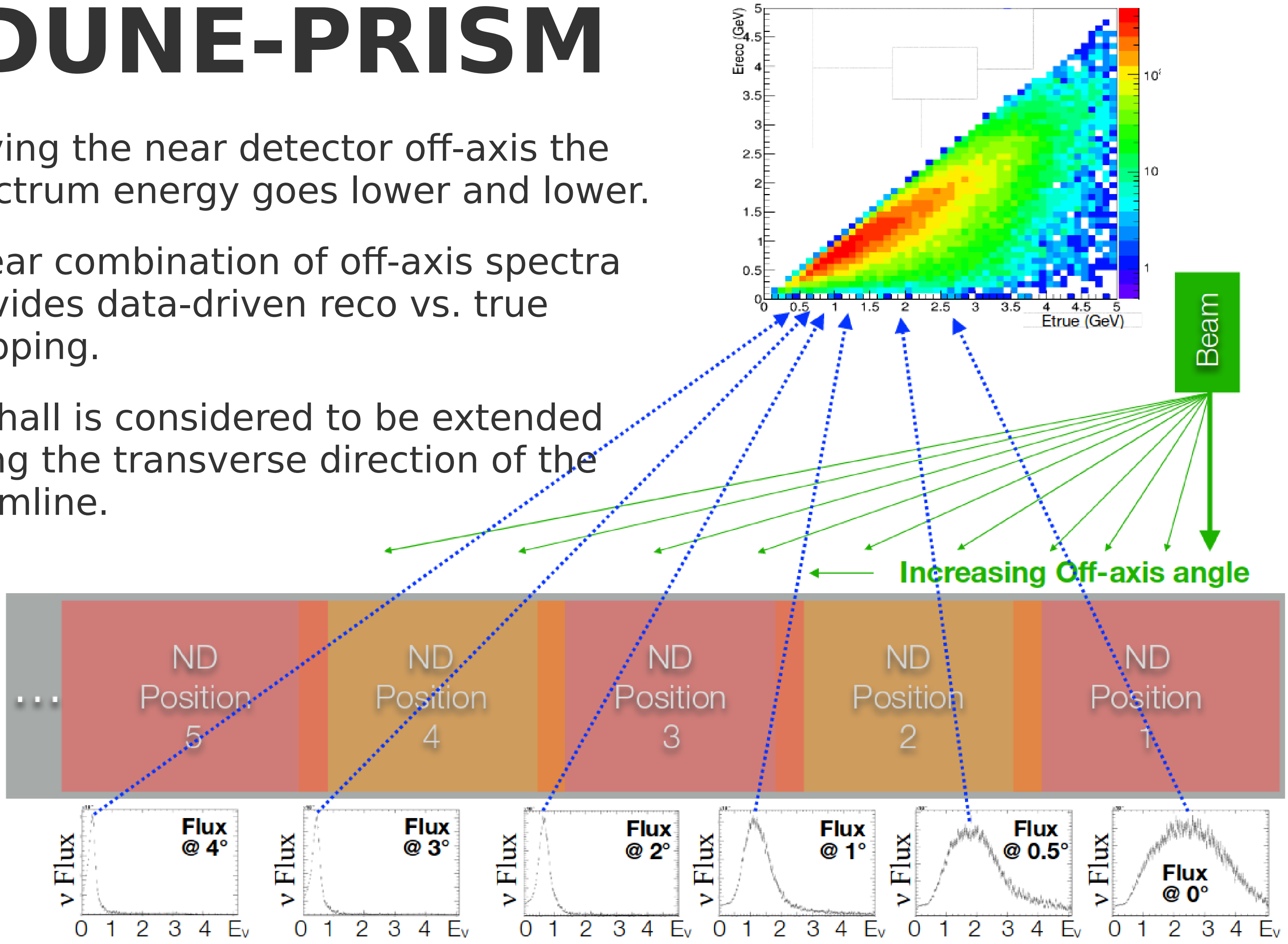
Neutrino interaction bias

- A fake data example:
  - 20% proton kinetic energy transferred to unseen neutrons.
  - Adjust other parts of cross section model to make ND observation look good.
  - This is the way to do oscillation analysis in reality with only an on-axis ND.
  - Incorrect way to “fix” the ND data and prediction agreement causes wrong CP.
- A clear way out → “Calibrate” reco. vs. true energy map.



DUNE-PRISM

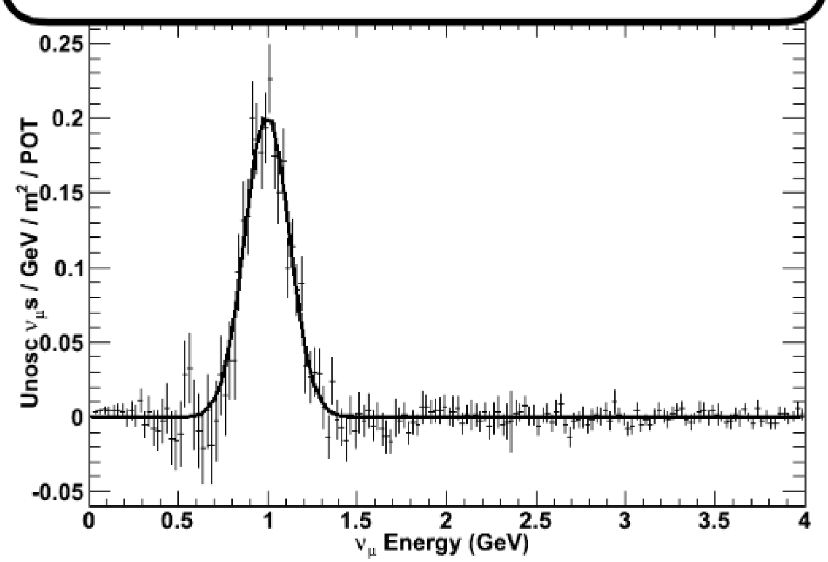
- Moving the near detector off-axis the spectrum energy goes lower and lower.
- Linear combination of off-axis spectra provides data-driven reco vs. true mapping.
- ND hall is considered to be extended along the transverse direction of the beamline.



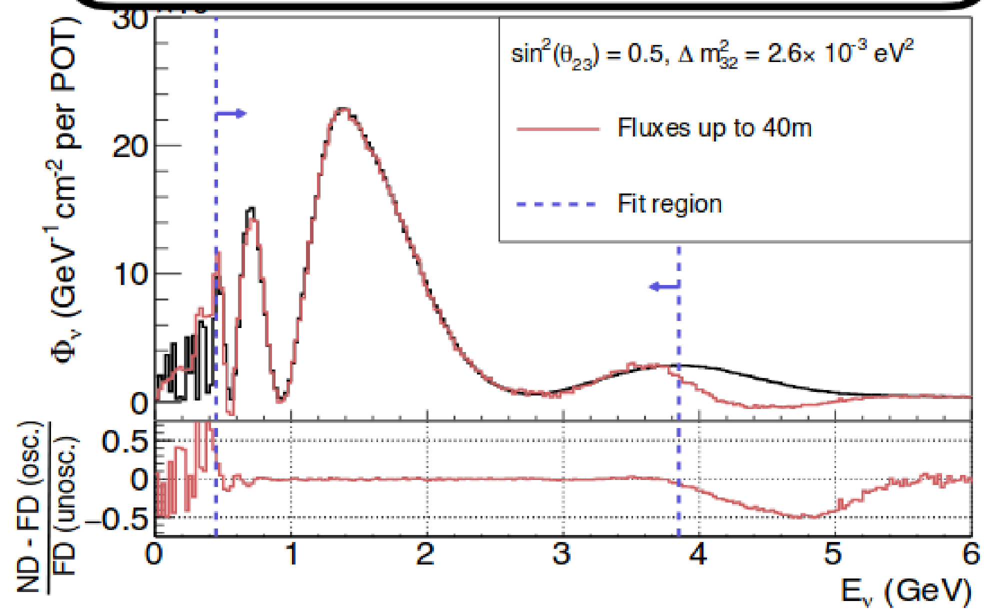
DUNE-PRISM : What to do?

- We are able to directly measure oscillated observables at ND with a wide energy range
- Mono-energetic beam can be formed as well to obtain reco. vs. true mapping.

Pseudo-Monoenergetic Beams

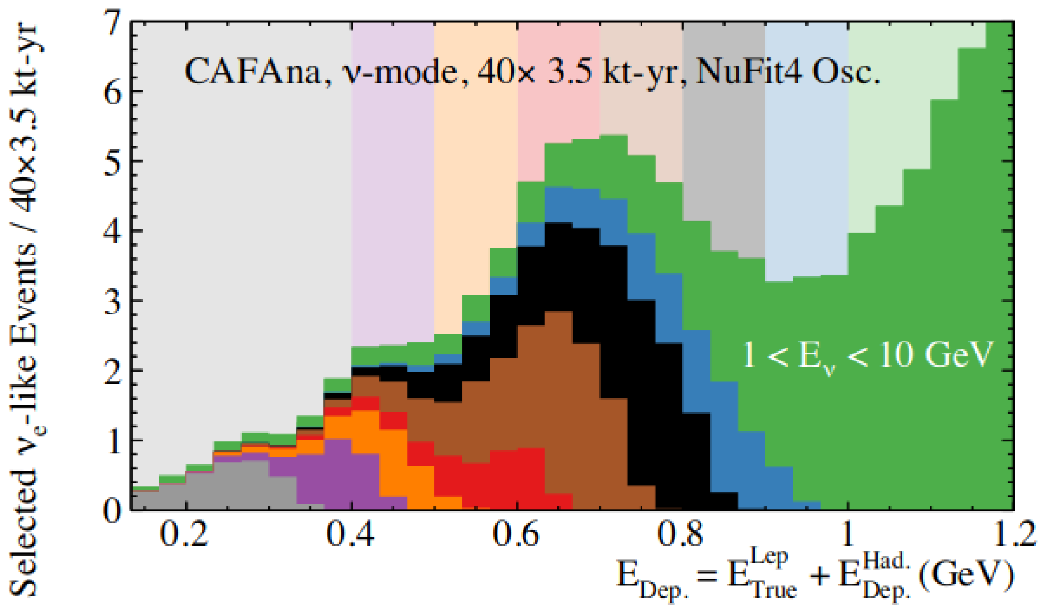


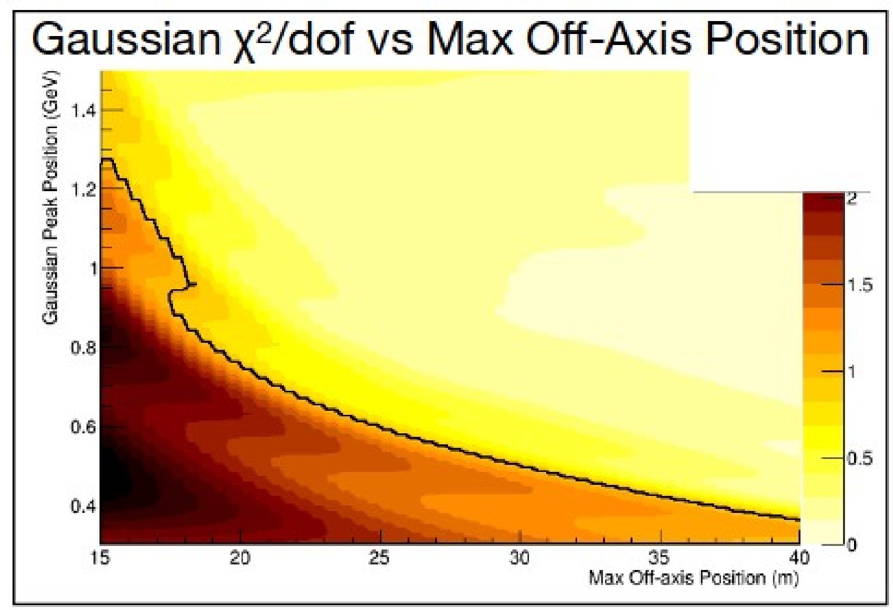
Oscillated Fluxes at the ND!



DUNE-PRISM : How off-axis?

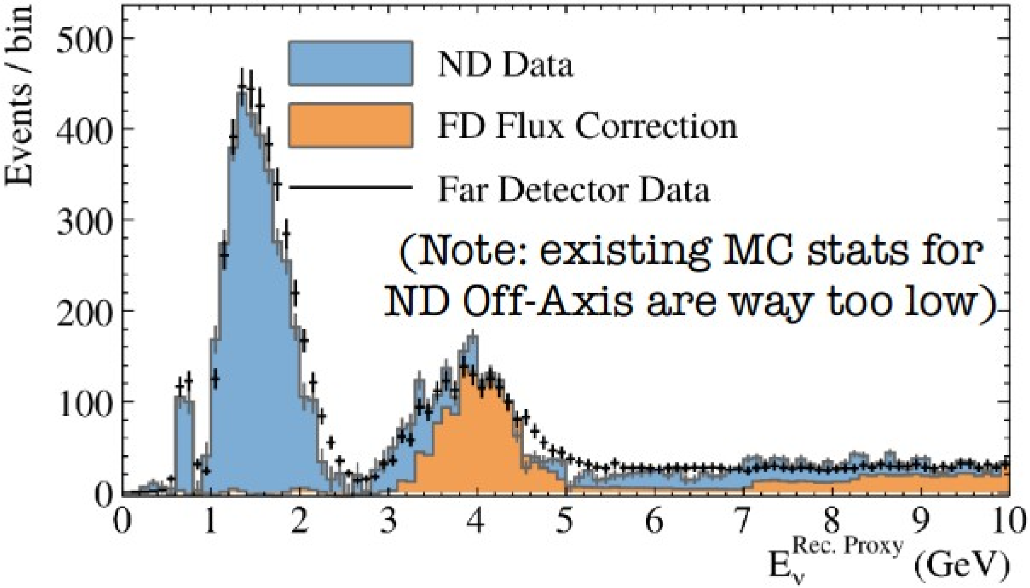
- The main reason for DUNE to use a wide-band beam is “The difference in probability amplitude for different values of CP is larger at higher oscillation nodes, which correspond to energies less than 1.5 GeV.” An observed spectrum down to 500 MeV is desired.
- To fully utilize the power of DUNE-PRISM, we should fit Gaussian peak down to 500 MeV, which corresponds to > 30 meters off-axis.





DUNE-PRISM : procedure

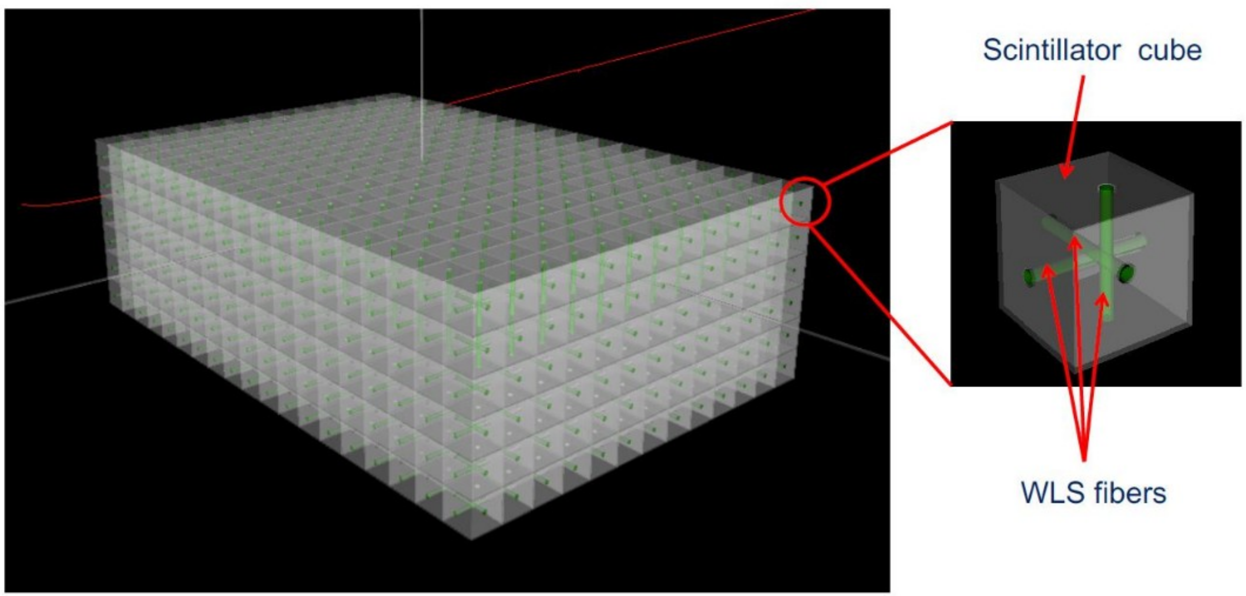
- Defining reconstructed energy
- Doing linear combination of ND off-axis flux to match oscillated FD flux
- Apply the linear combination coefficients to the ND off-axis data to match FD data
  - Apply flux fit correction and efficiency correction
- Repeat for all oscillation parameters
- Based on the best linear combination, find best fit oscillation parameters

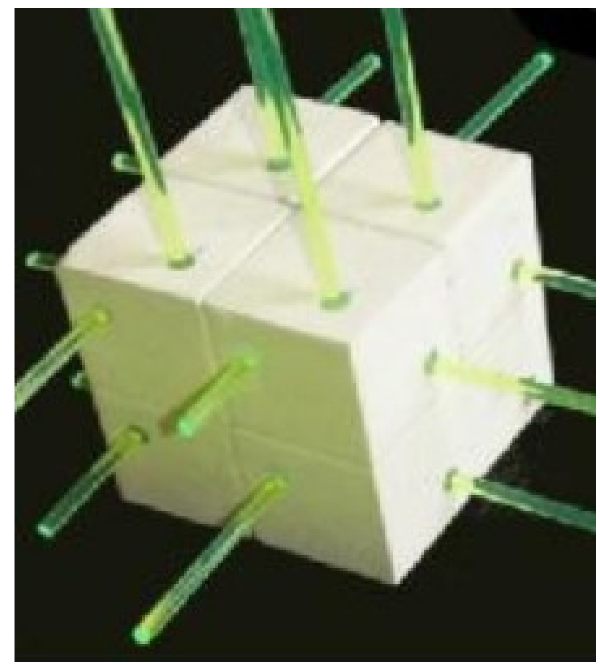


- Now, with a movable LAr + GAr:
  - No beam stability monitoring
  - Largely blind to neutrons
  - Only one nuclear target, hard to test model

3D projection scintillator tracker (3DST): a handle for Flux systematics

- Plastic scintillator detector with 1 cm x 1 cm x 1cm cubes → Fully active
- Light collected by 3 wavelength shifting fibers
- Each cube coated with TiO2 to keep light entrapped inside the cube
- Read out by MPPC at 3 faces
- Combining with TPC and ECAL, it is named 3DST-S (3DST spectrometer).

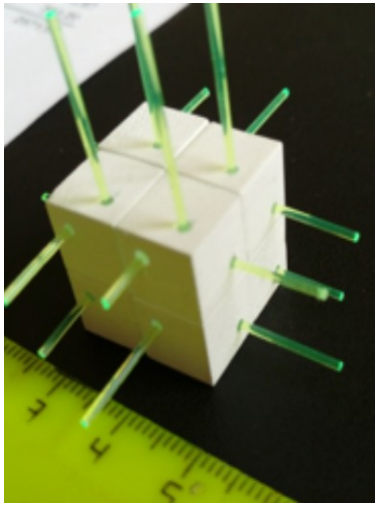


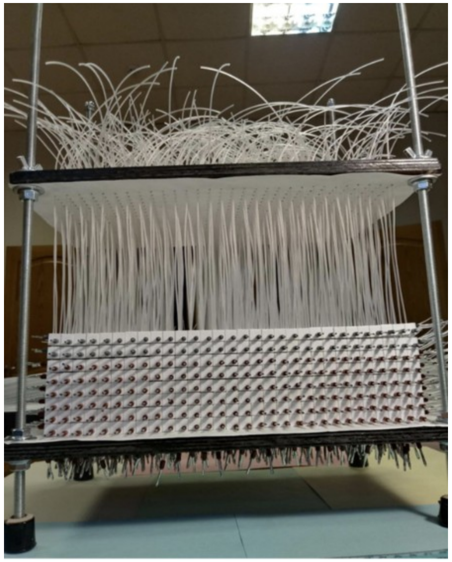


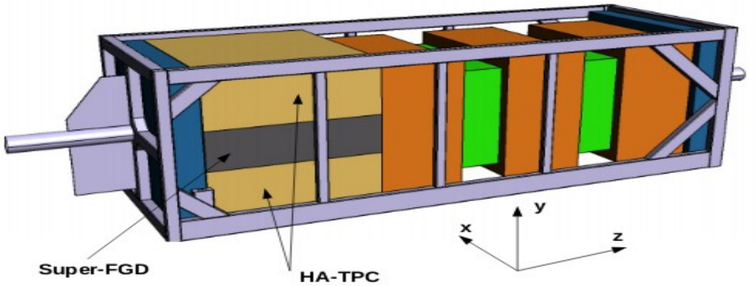
3DST: Synergy with T2K upgrade

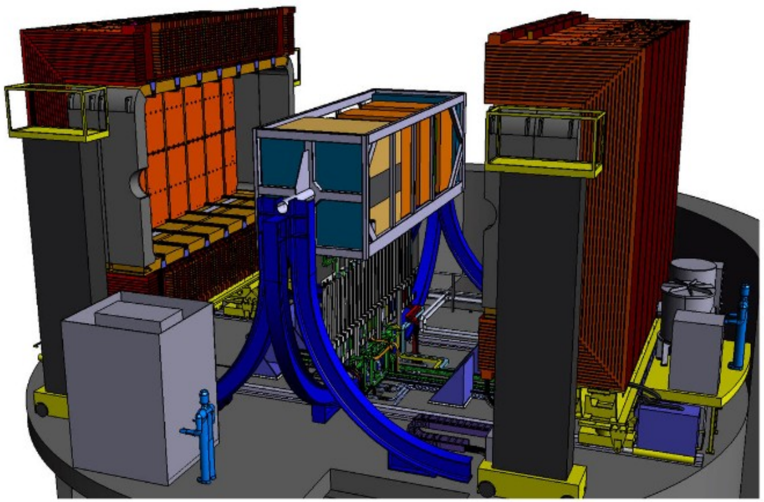
- Functionally identical to the T2K super-FGD in T2K ND280
- Share the effort including hardware and software such as parts production, R&D, neutrino event reconstruction etc.
- Stony Brook in both working groups

Super-FGD proto-type
by T2K upgrade group







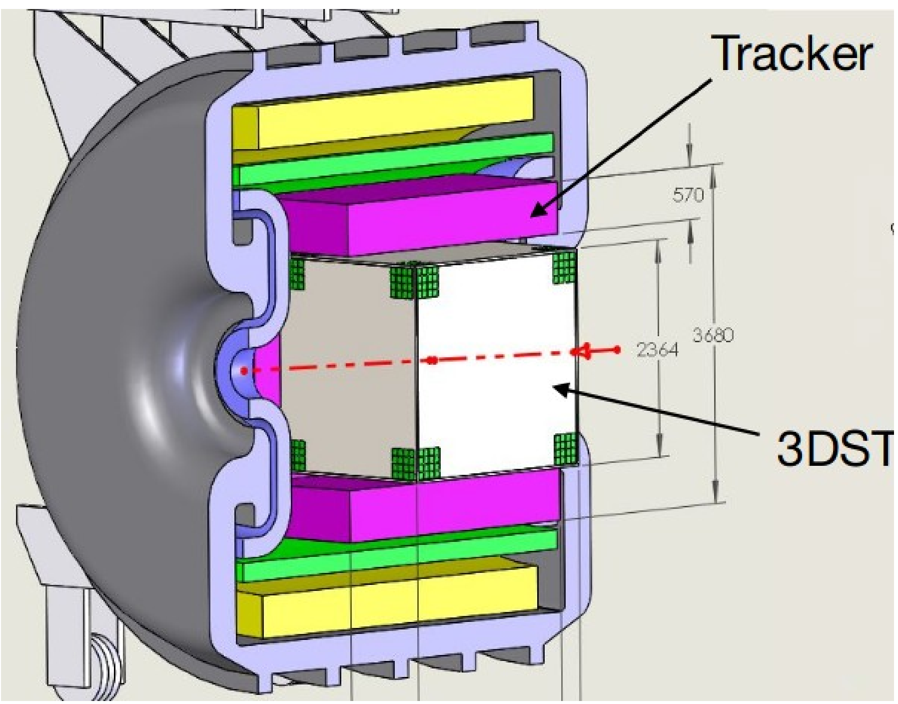


arXiv. 1901.03750

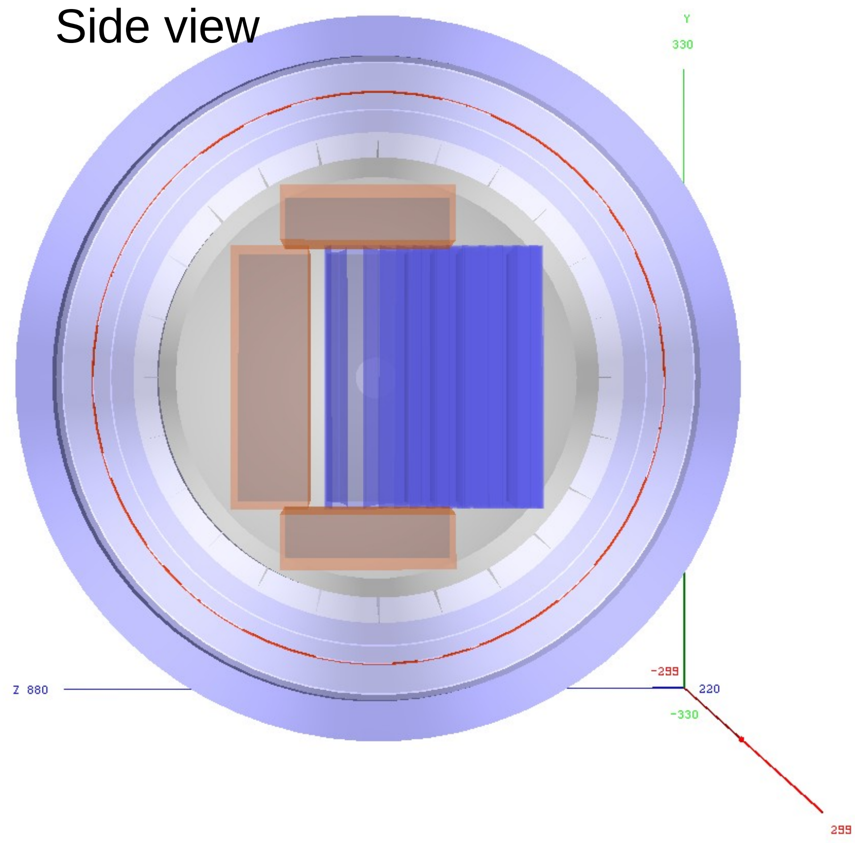
3DST-S/K

- 3DST-S containing 3DST, TPC and ECAL inside a magnetic field (>0.6 T)
- The magnet could be the KLOE magnet

Beam view



Side view

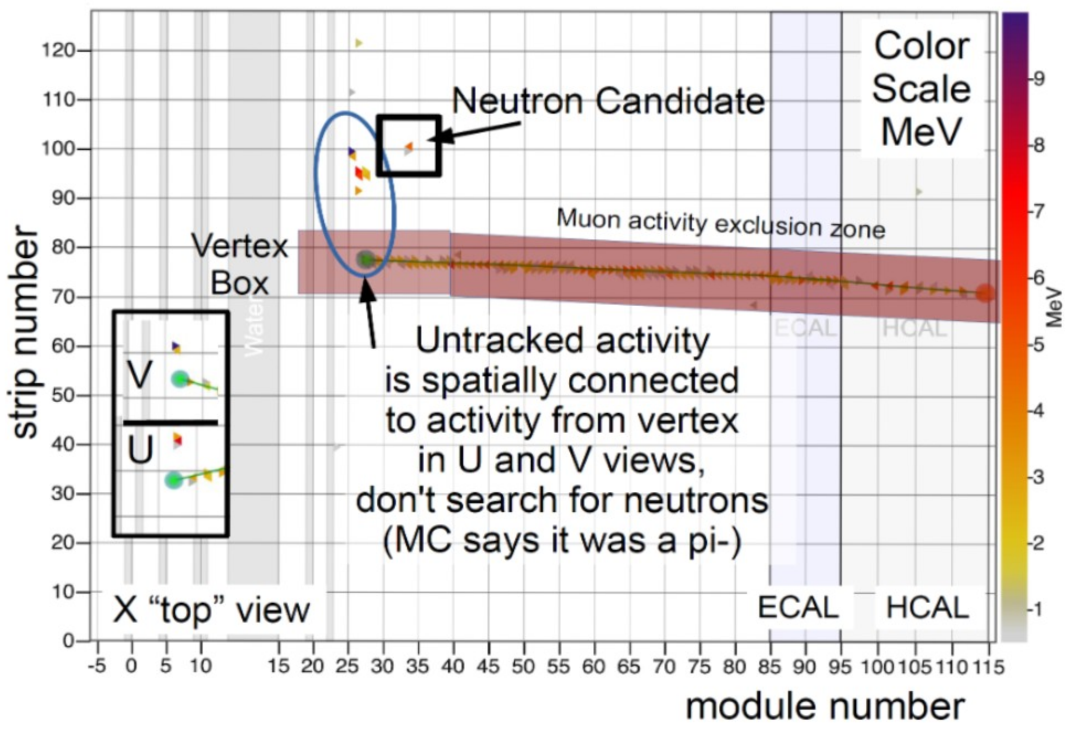


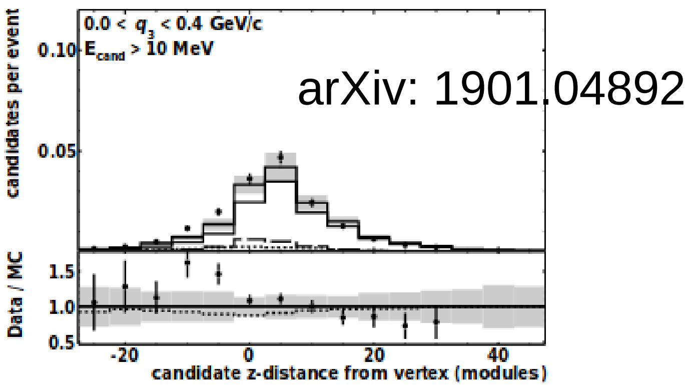
Purposes of 3DST-S/K

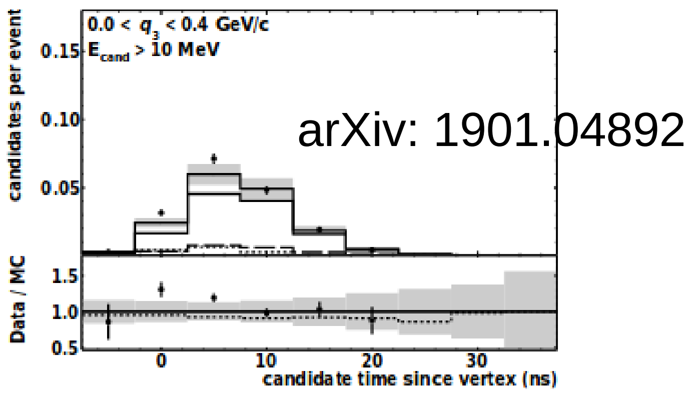
- Beam monitoring:
  - A 2.4m x 2.4m x 2m 3DST can provide daily event rate monitoring with <1% statistical error.
  - As a spectrometer, 3DST is sensitive to all major beam condition changes which would give neutrino spectrum distortions.
- Neutron tagging and energy measurement: Fast timing, high light yield, low thresholds and fine granularity give good ability for neutron detection.
- Measuring the neutrino flux (via neutron detection):
  - Single transverse variable can be used to select H-enriched sample.
  - Channels such as low-nu can be used for flux shape constraint.
- Scintillator (CH) cross section measurement:
  - DUNE is model dependent, thus A-dependency may be important.
  - 3DST scintillator measurement can provide us a bridge to the world scintillator cross-section measurements.

3DST neutron detection

- Minerva sees neutrons.
- Neutron multiplicity, energy and spatial distributions, timing all fairly well described by simulation in Minerva.

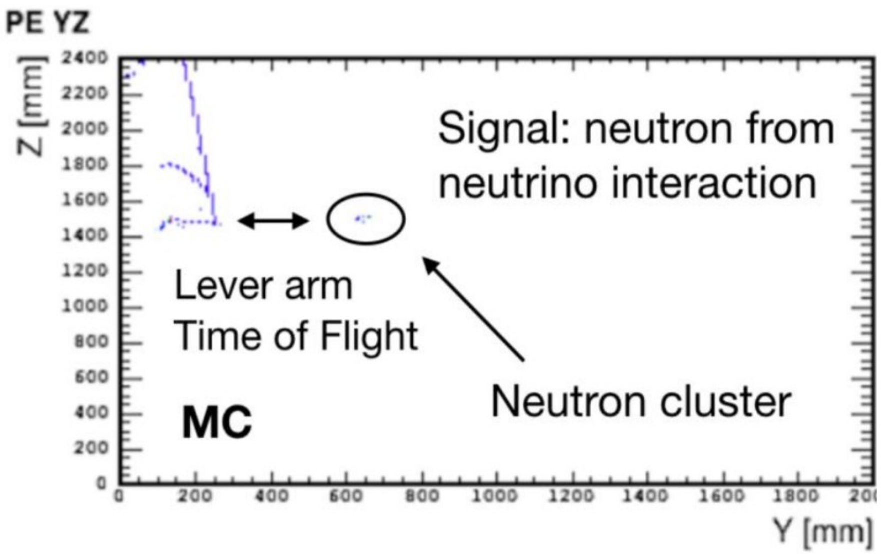


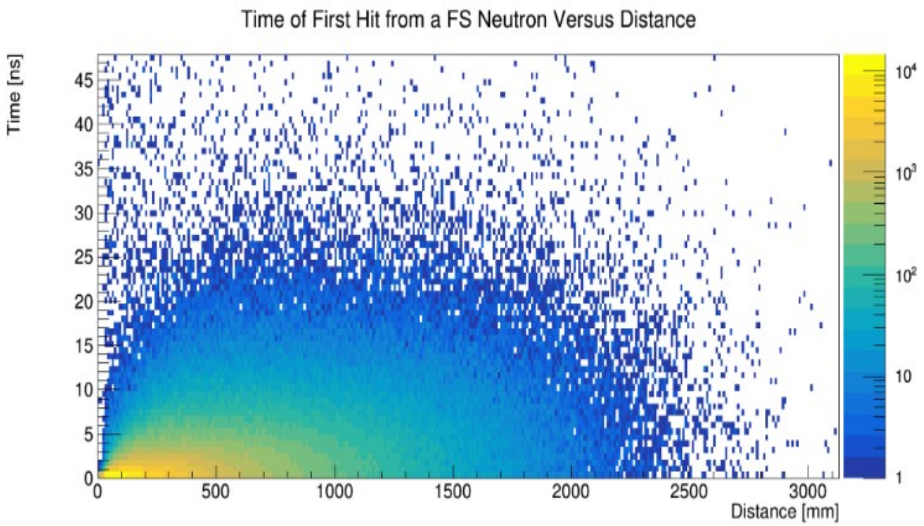




3DST neutron detection

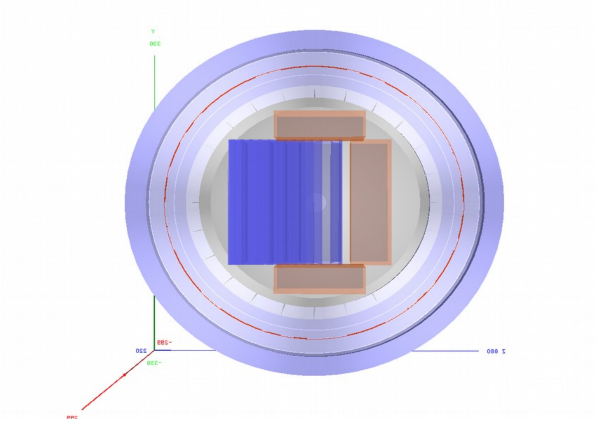
- Antineutrino mode is crucial for DUNE.
- Neutron is the last piece to fully reconstruct the neutrino energy for the antinu. Mode.
- Thus, we can do flux constraint and cross section model tuning with neutrons.



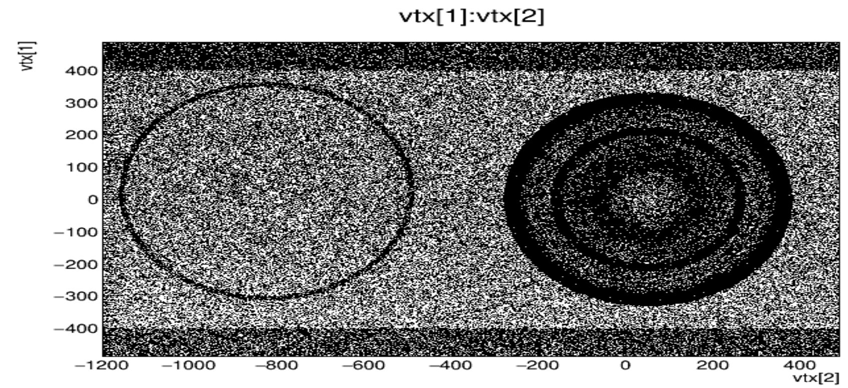


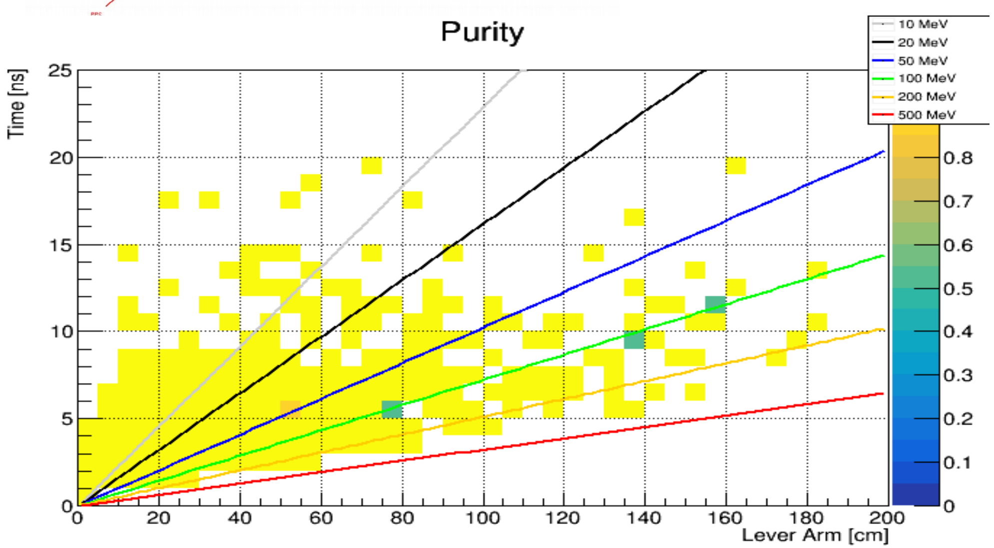
3DST neutron detection

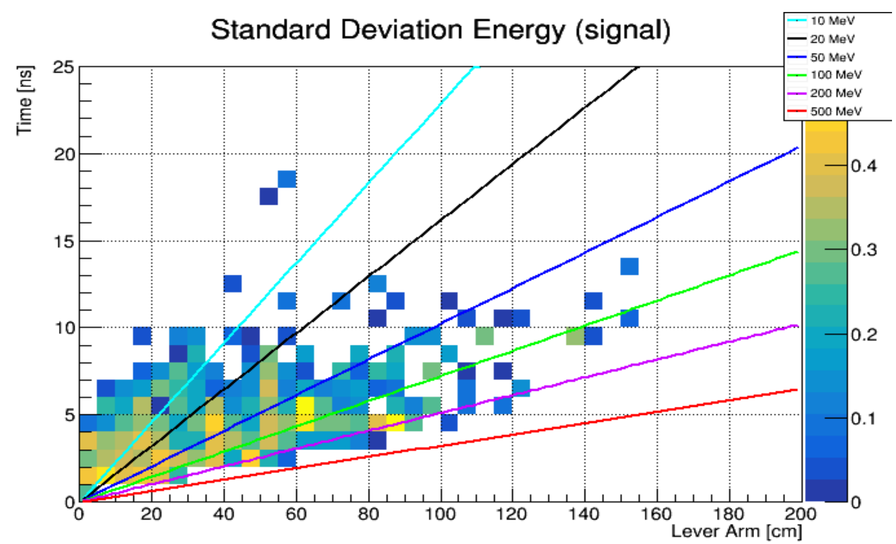
- Neutron energy can be measured with fast timing.
- Out-of-FV (fiducial volume) background can be controlled.



Rock +
Upstream detector
+ magnet
Give neutron
background



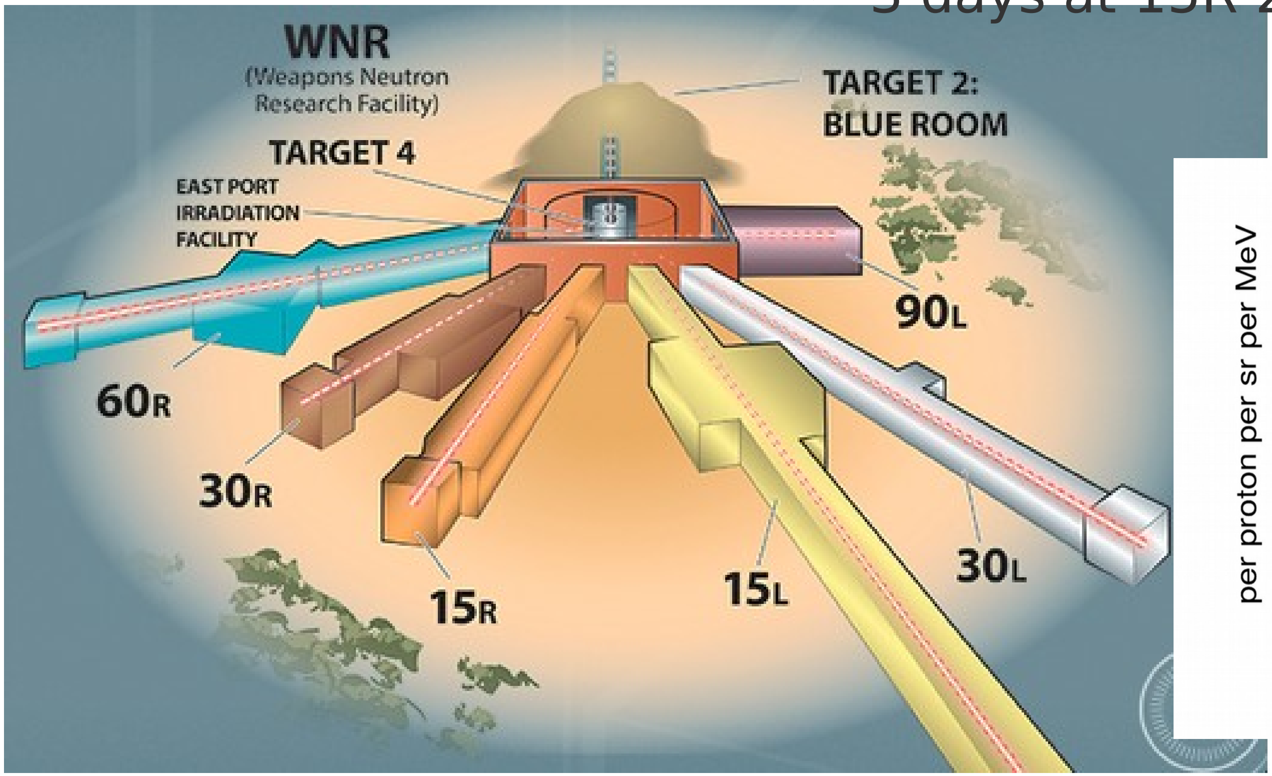


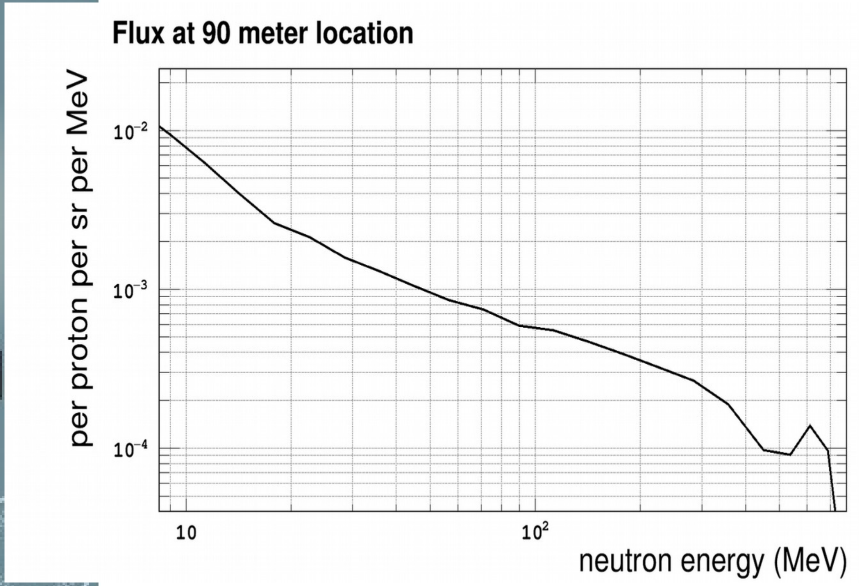


Neutron beam test in LANL

- LANL (Los Alamos National Lab) provides neutron beam ranged from 0 -800 MeV
- We have two run time: ~ 3 weeks at 15L 90 m location

  ~ 3 days at 15R 20 m location

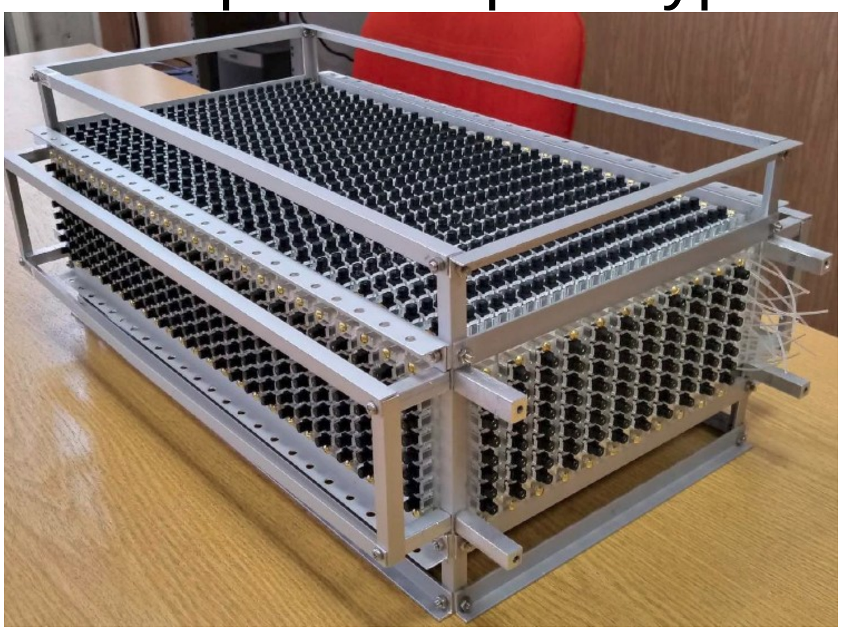




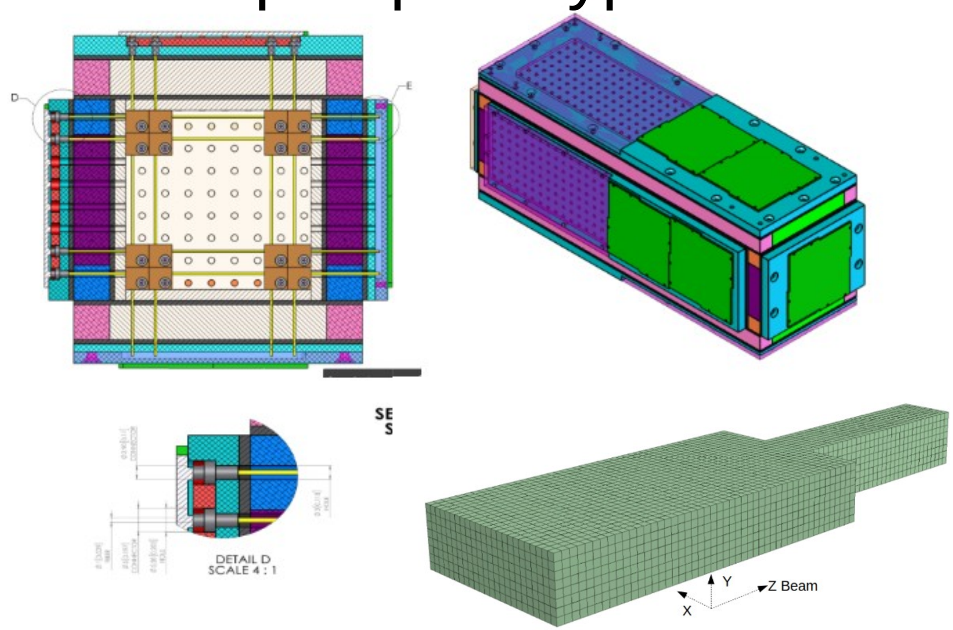
Two prototypes

- SuperFGD prototype being used for the charged particle beam test in CERN (24x8 48)
- US-Japan prototype uses some new designs that will be used in the T2K upgrade, probably 3DST (8x8x32)
- They can be combined in a number of ways

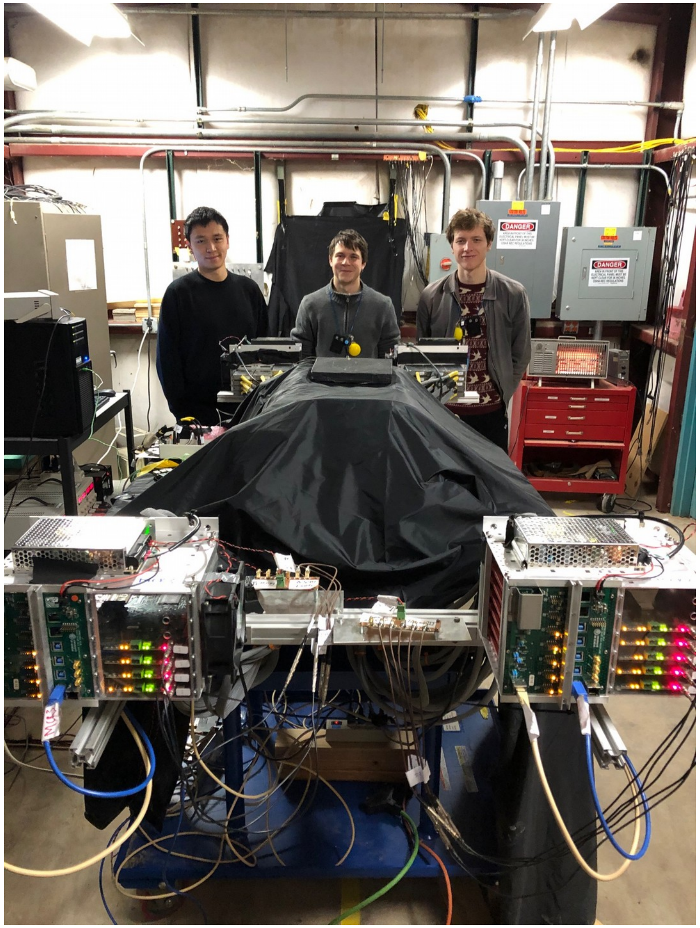
SuperFGD prototype



US-Japan prototype

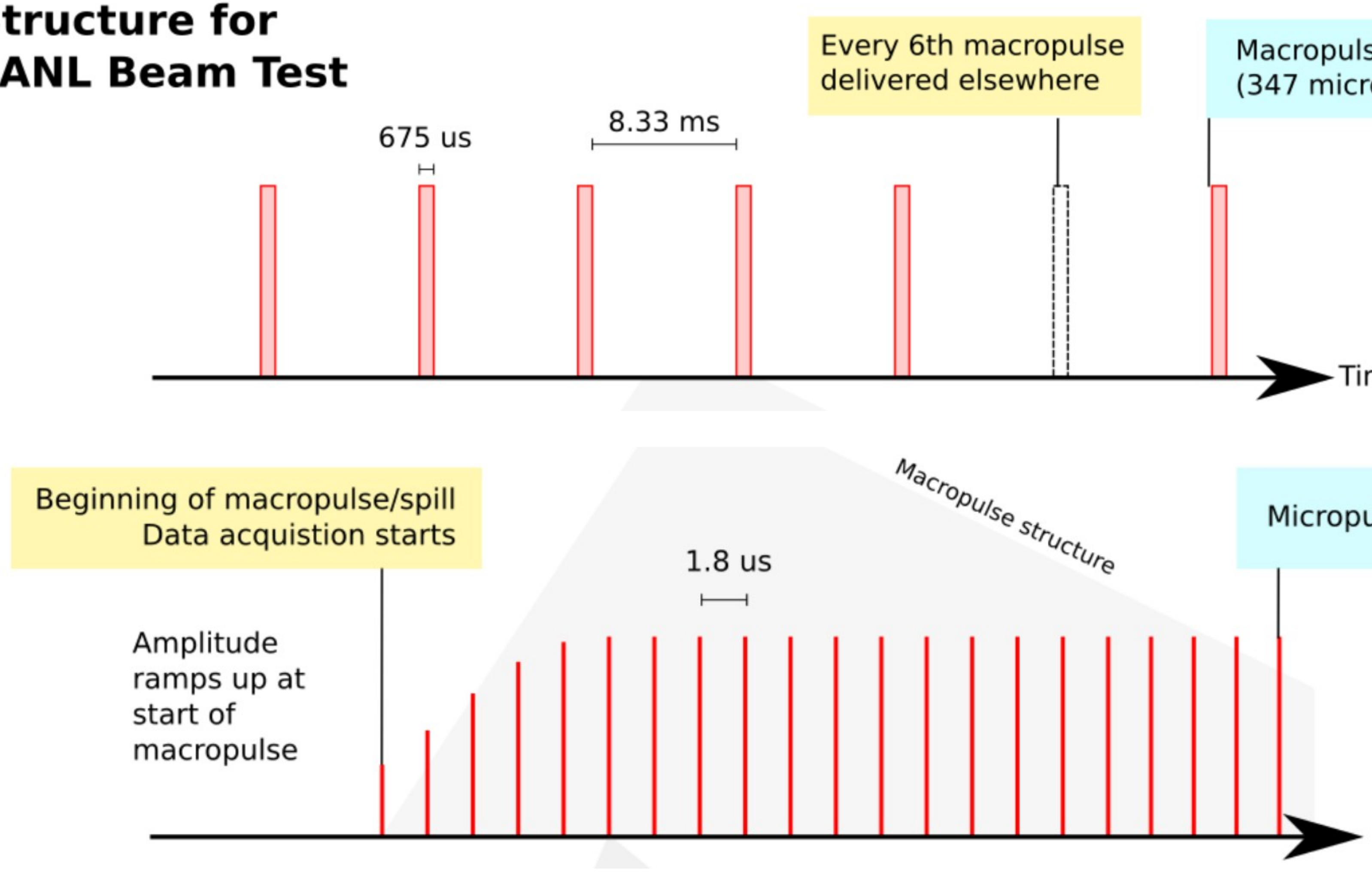


Detector with run-coordinators



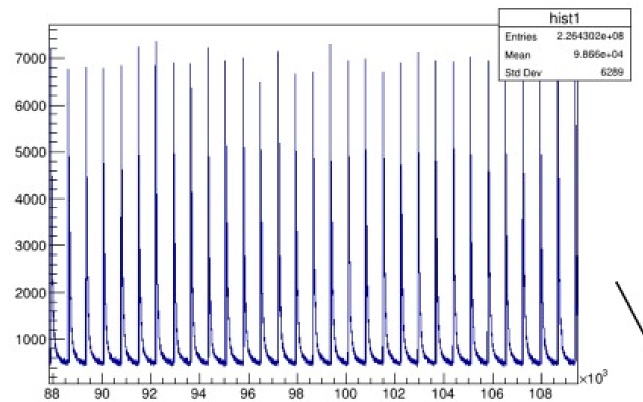
Time structure 1

Proton Beam Structure for LANL Beam Test



Time structure 2

What we see in the detector:

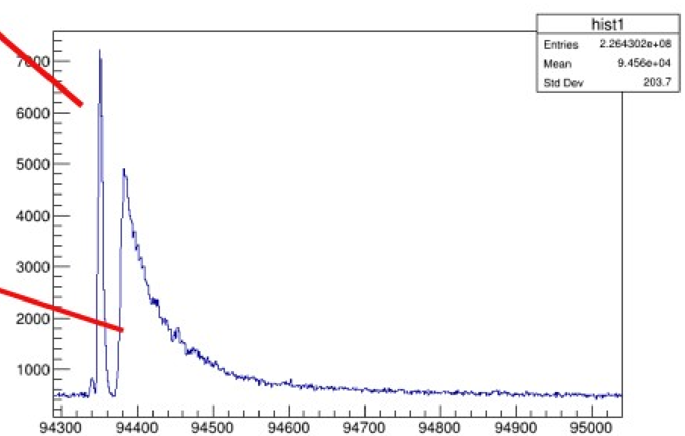


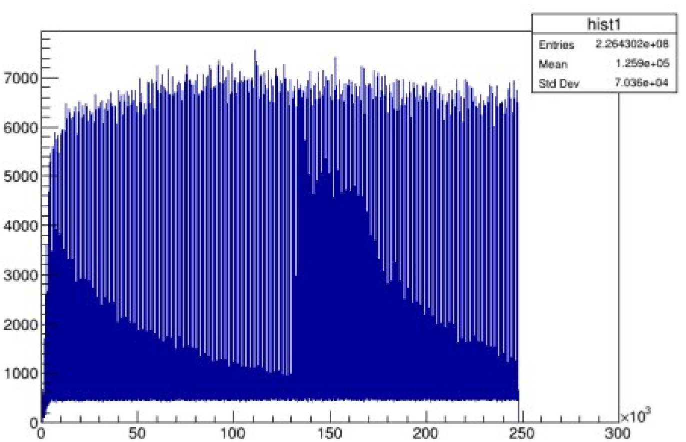
Zoom in

Zoom out

Hits produced by gamma flash which reaches detector before neutrons

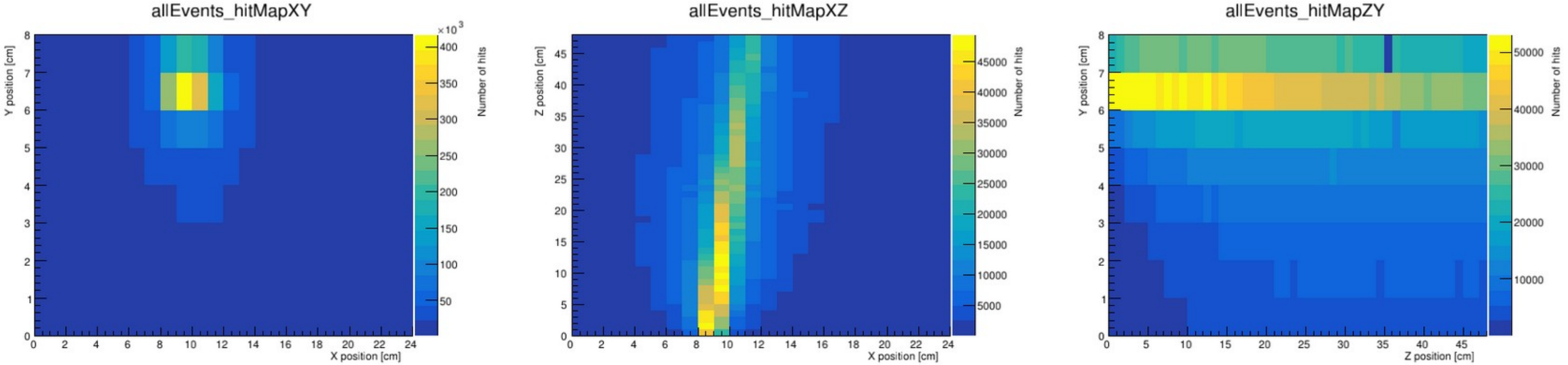
Hits produced by neutrons. Could be high energy neutrons with slightly longer TOF than gammas or low energy neutrons that have a TOF longer than the micropulse separation





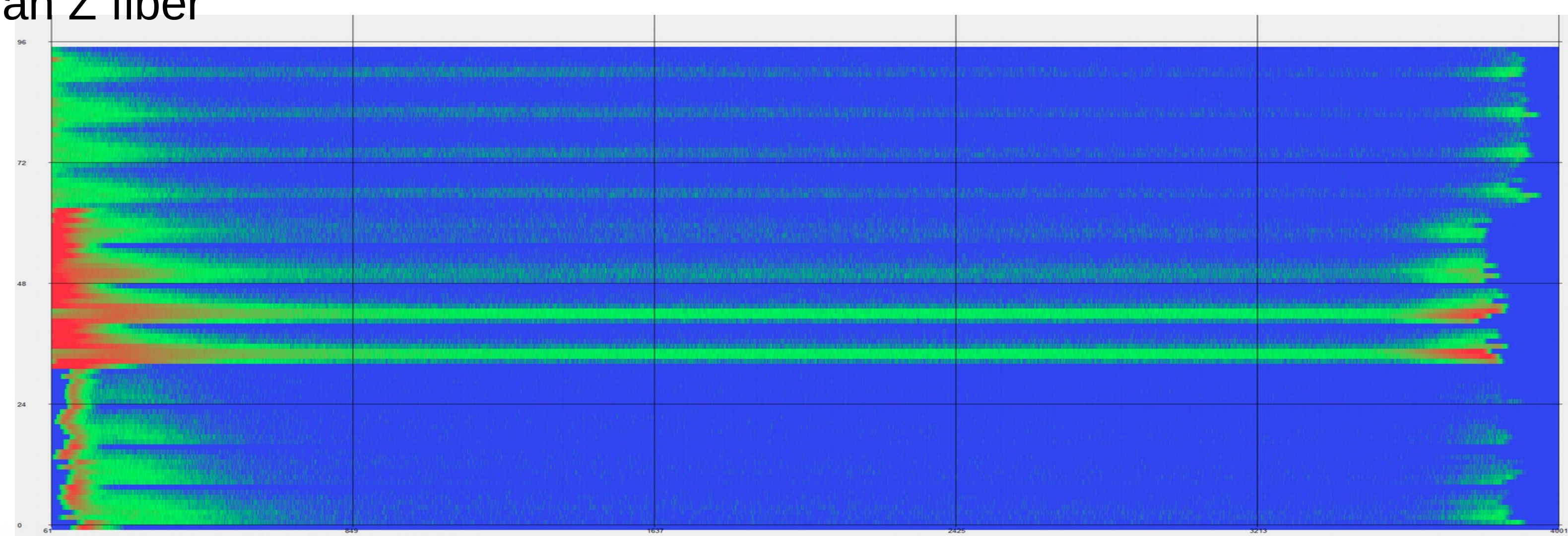
LANL test: Event topology

Super FGD prototype



US-Japan Z fiber

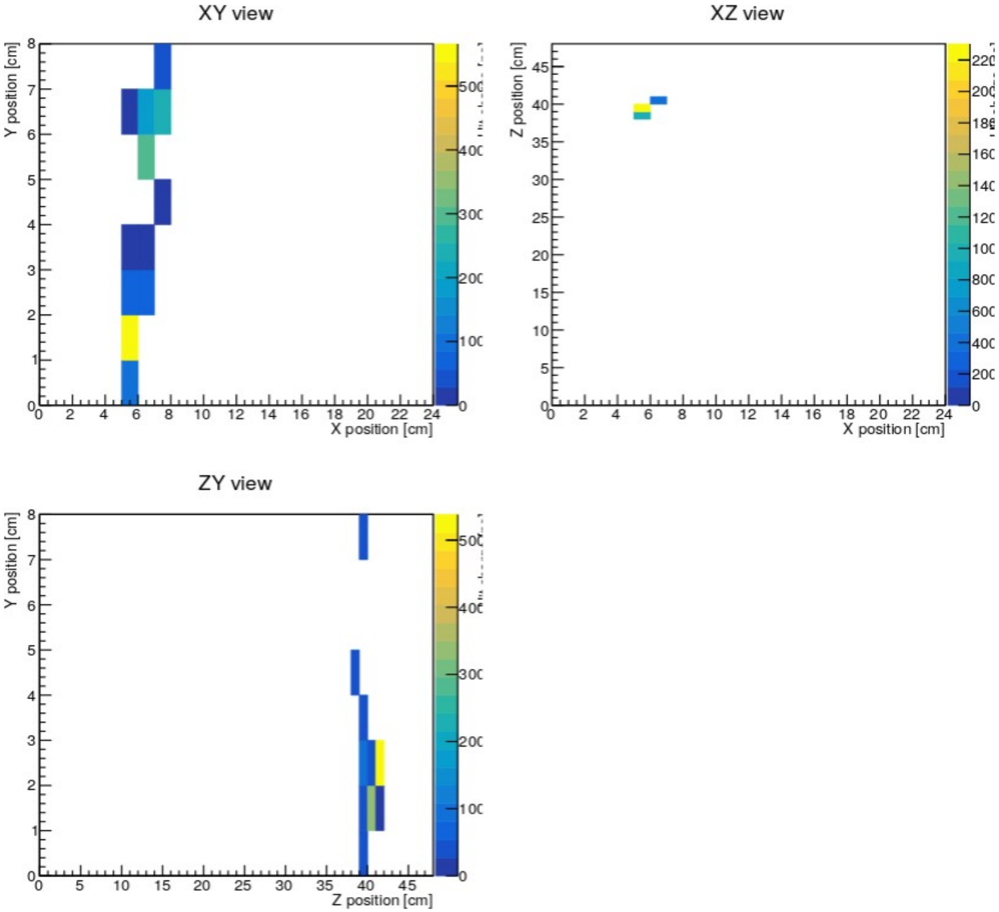
Channel

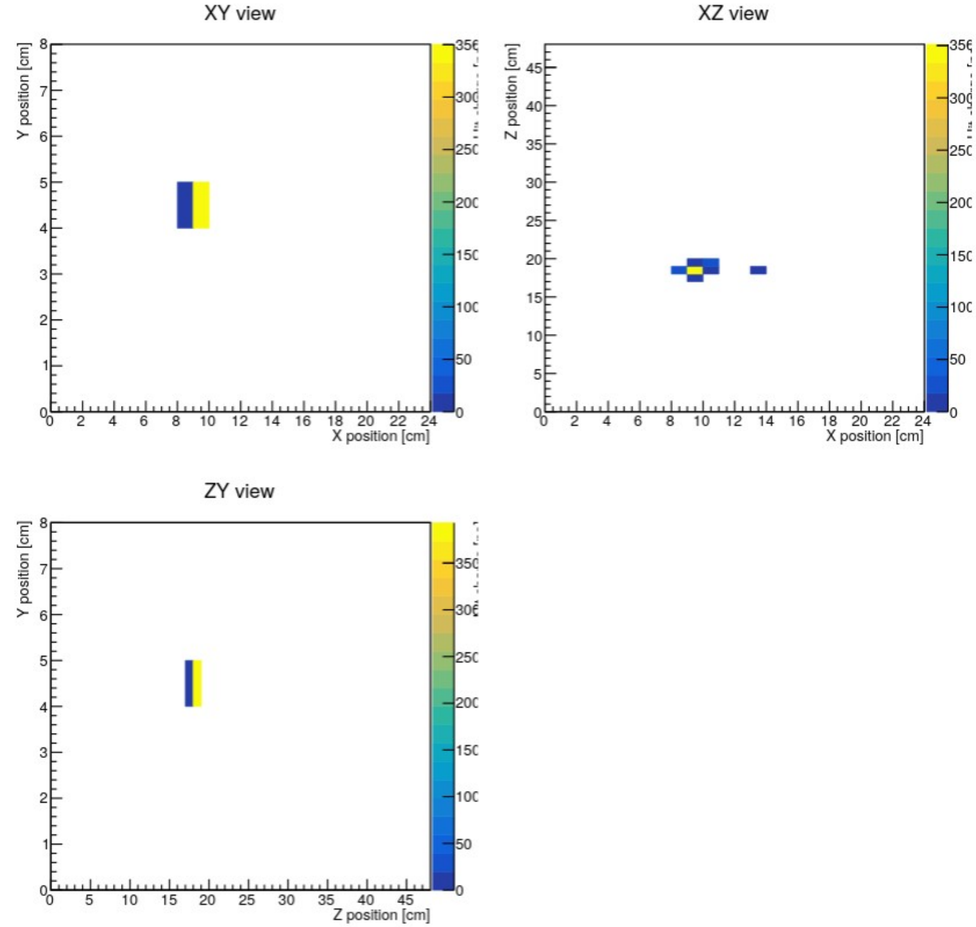


ADC counts

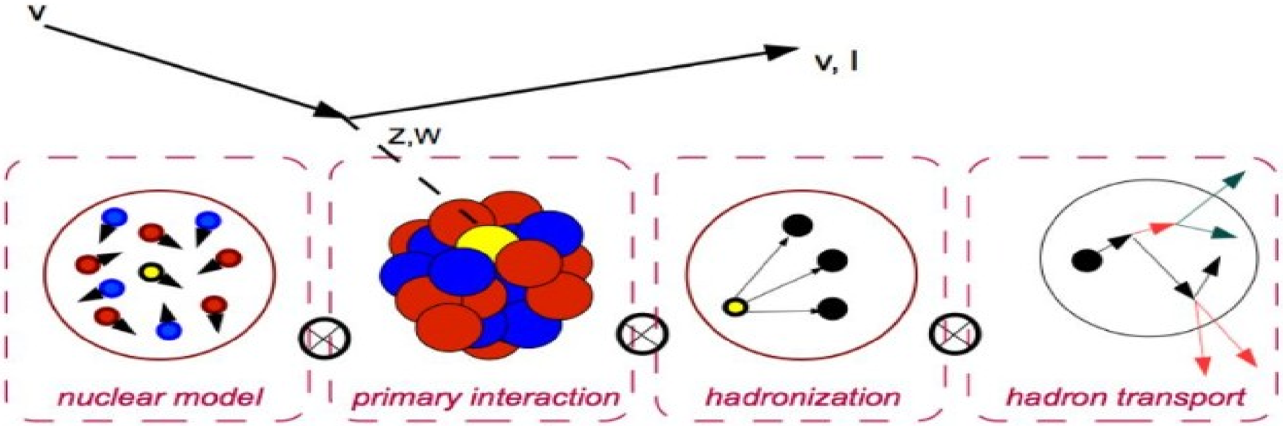
LANL test: Some event displays

Super FGD





3DST : A CH target



- There will always be model-dependent thing in the analysis. With current model, we are missing something fundamental: scaling
- Having a simultaneous measurement on neutrino CH interaction offers a unique lever-arm for model validation and discrimination
- Unrealistic to expect a model for oscillation analysis without proper validation and tuning informed by the near detector and external data

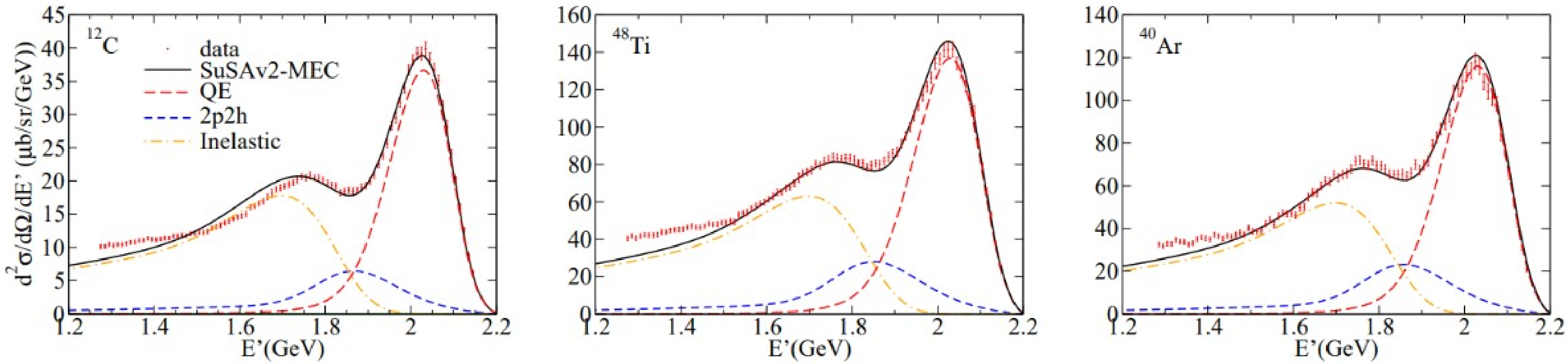
3DST : tuning Ar model

- Models that moves beyond simple Fermi-gas approximations on the timescale of DUNE are expected:
  An example is the Relativistic Mean Field (RMF) model

  https://arxiv.org/pdf/nucl-th/9905060.pdf

- RMF calculates interaction cross section on different nuclear targets in the same framework using the same physics

- Working great with electron scattering data



Conclusion (the real one)

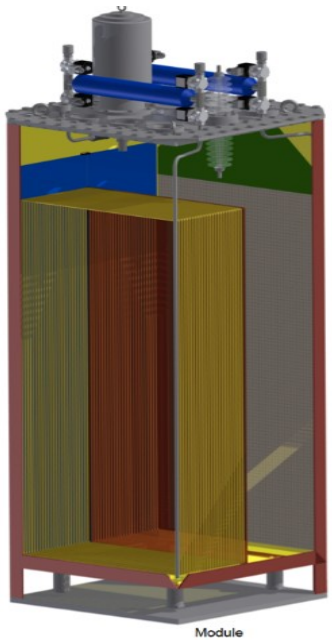
- DUNE near detector baseline:
  - A liquid argon detector
  - A gaseous argon detector
  - DUNE PRISM
  - The most interesting: SAND (3DST + KLOE magnet)

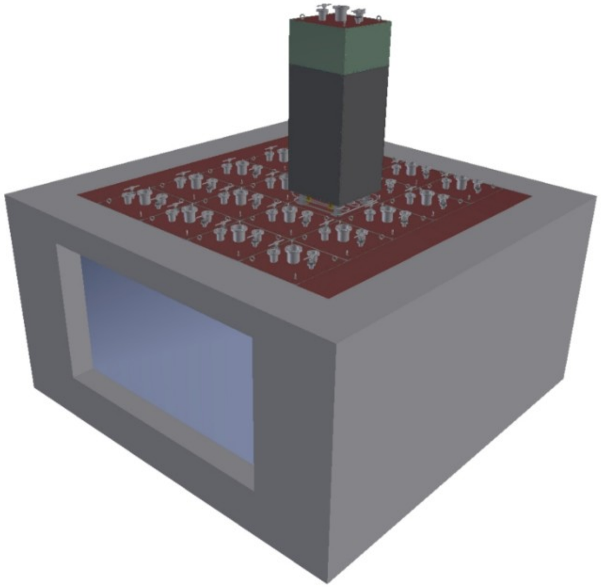
Backups

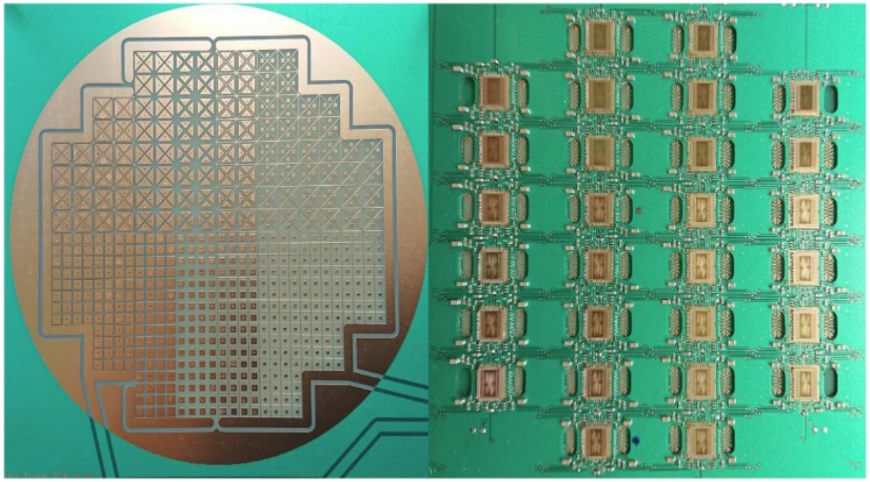
Detection systematics

- We must have a same-target-as-far detector :

  ArgonCube : A modular detector with short drift volume
- Covering same neutrino interaction phase space as far detector.
- Pixelated readout developed by LBNL (arXiv: 1808.02969)

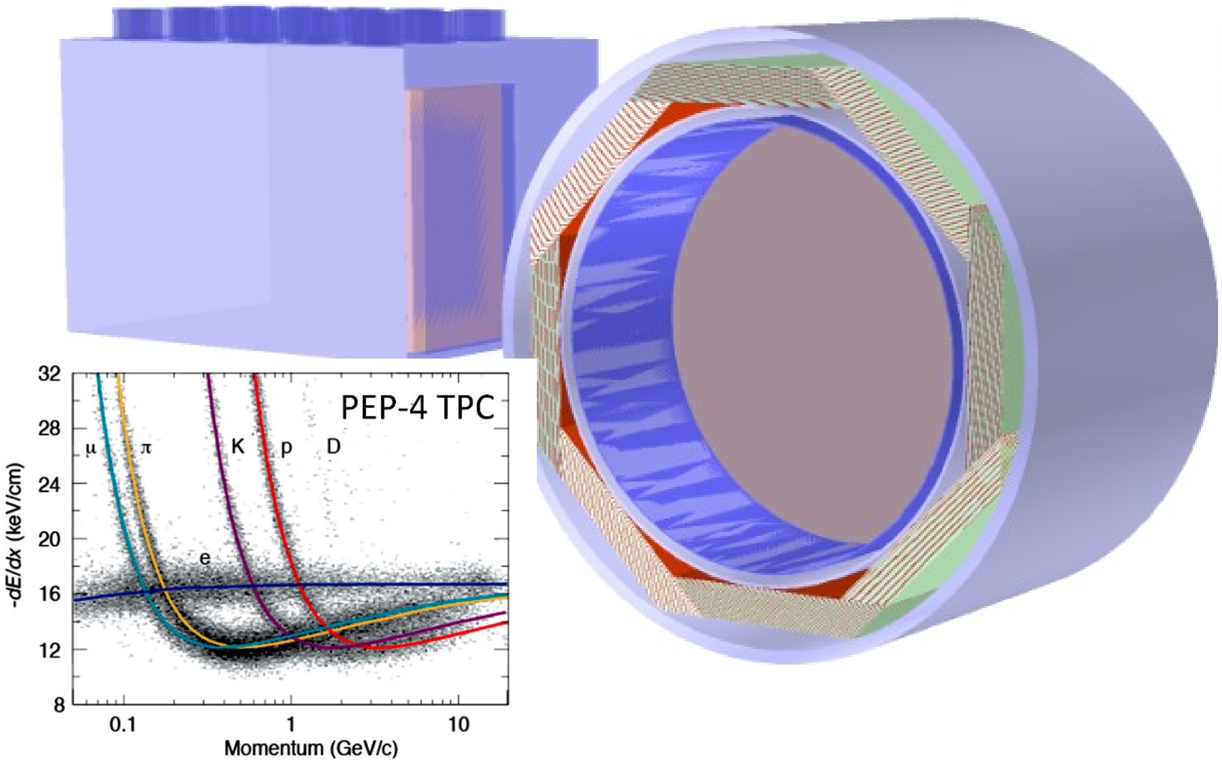


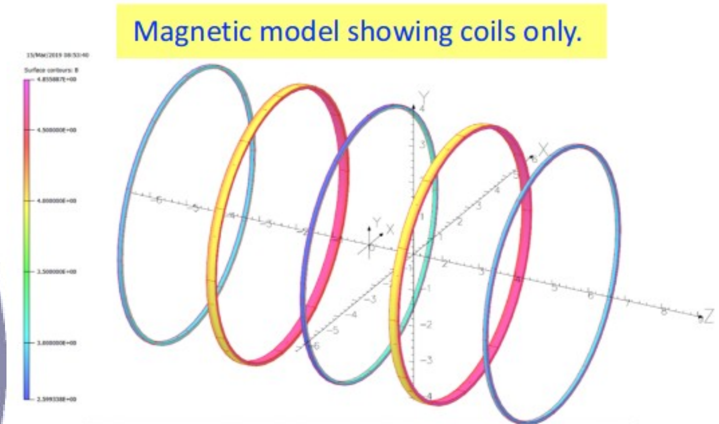


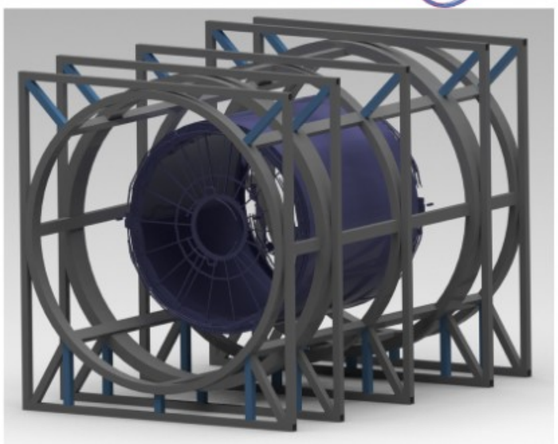


Detection systematics

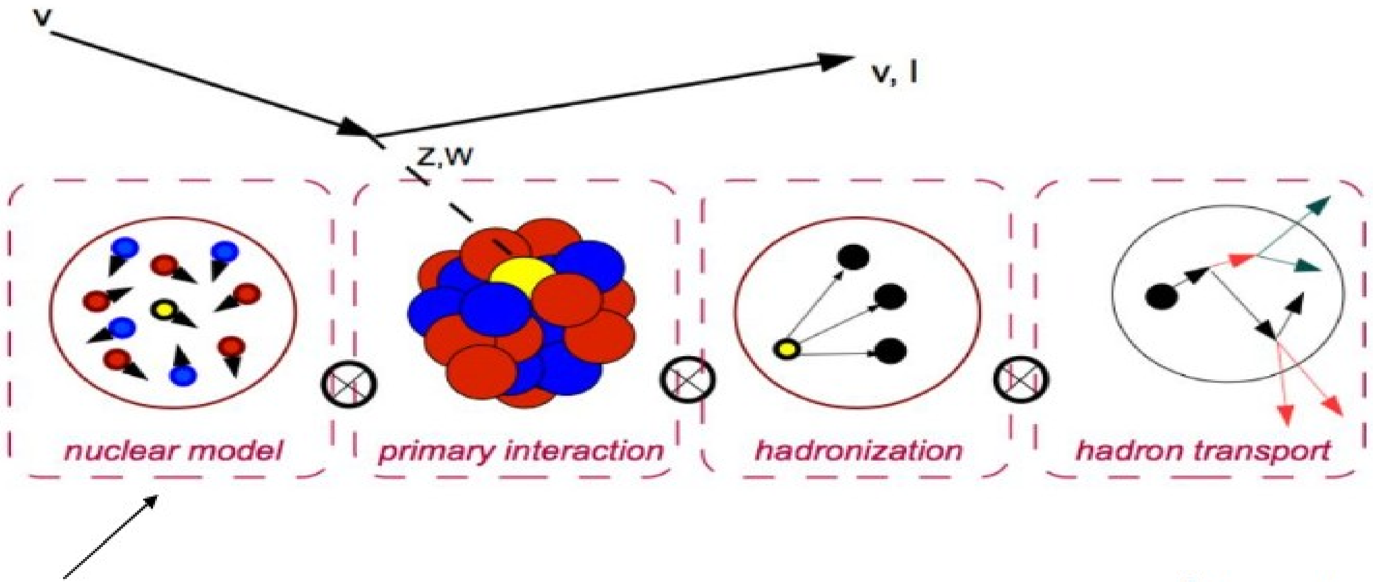
- A finer resolution Ar target is useful for better understanding of the neutrino-Ar interaction and final state particle detection.
- First test-stand will be ALICE inner readout chamber







Cross section systematics

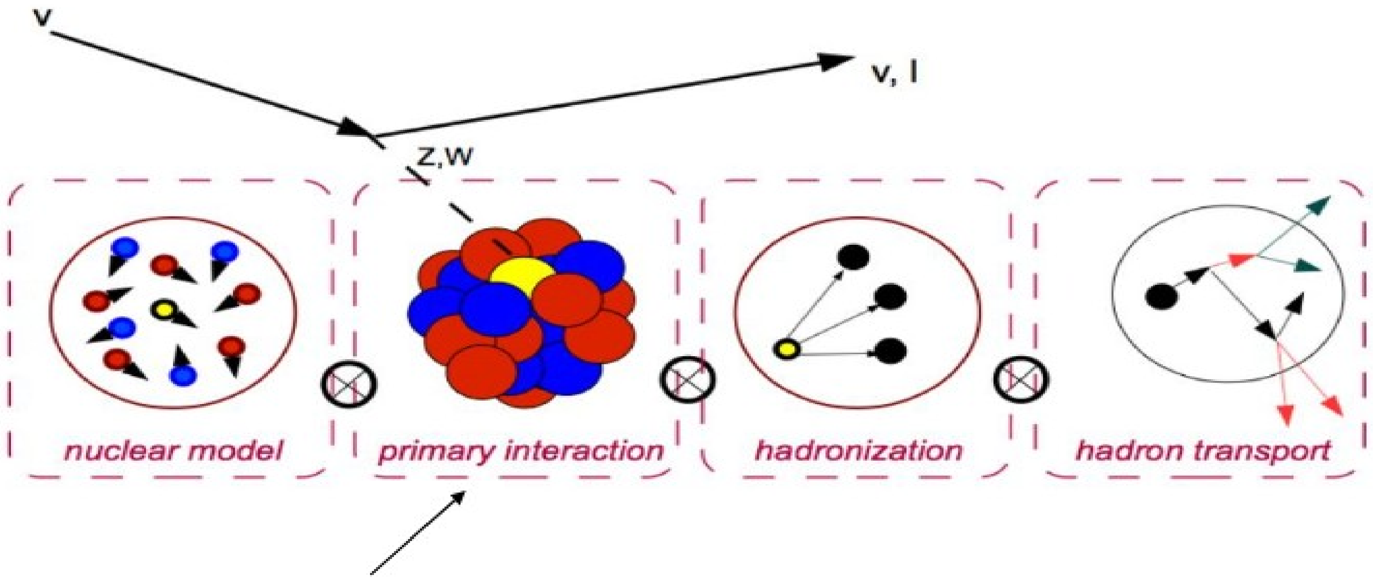


- The initial nuclear model often based on Fermi gas
- Known to be overly simplistic, not suitable for exclusive scattering predictions

From Nieves et al. (Phys. Rev. C **83**, 045501)

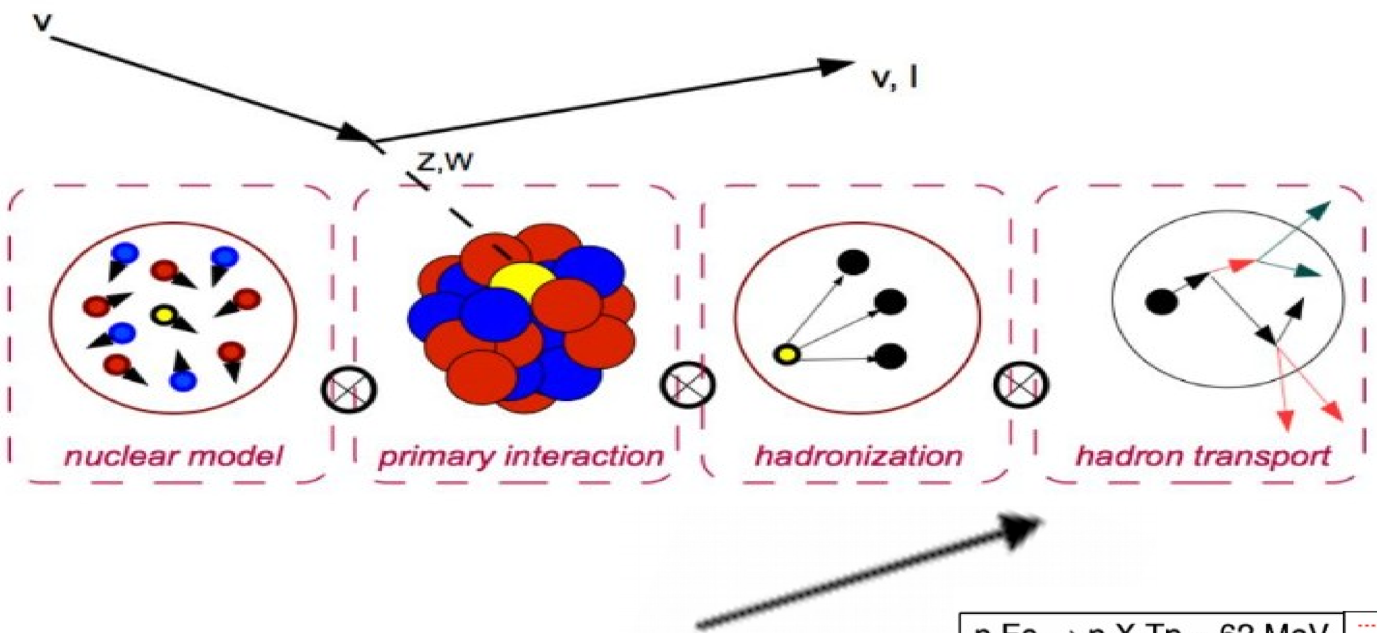
> The LFG description of the nucleus has been shown to be well suited for inclusive processes and nuclear excitation energies of around 100 MeV or higher [1,37–42]. The reason is that in these circumstances one should sum up over several nuclear configurations, both in the discrete and in the continuum. This inclusive sum is almost insensitive to the details of the nuclear wave function,[5] in sharp contrast to what happens in the case of exclusive processes

Cross section systematics

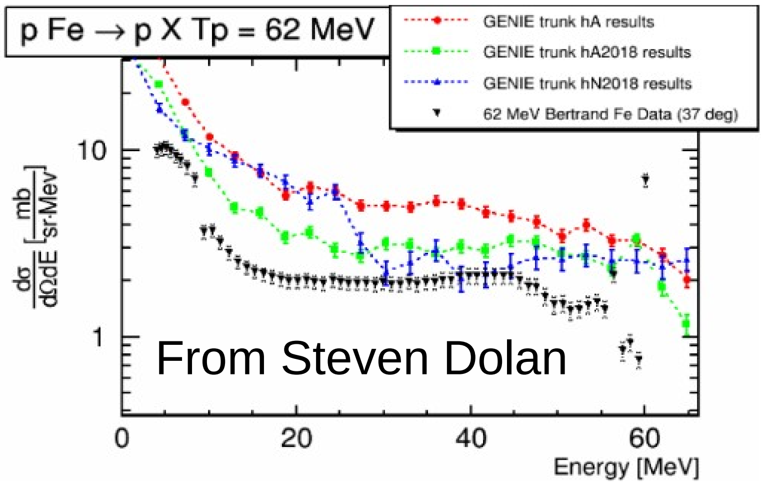


- In principle, we need an exclusive input
  - for example, for CCQE, $\frac{d^6\sigma}{d\omega dq_3 dE_m d\boldsymbol{p_m}}$
- However, what we usually have is an inclusive cross section, with only part of the required kinematics:
  $\frac{d^2\sigma}{d\omega dq_3}$ or even just $\frac{d\sigma}{dQ^2}$

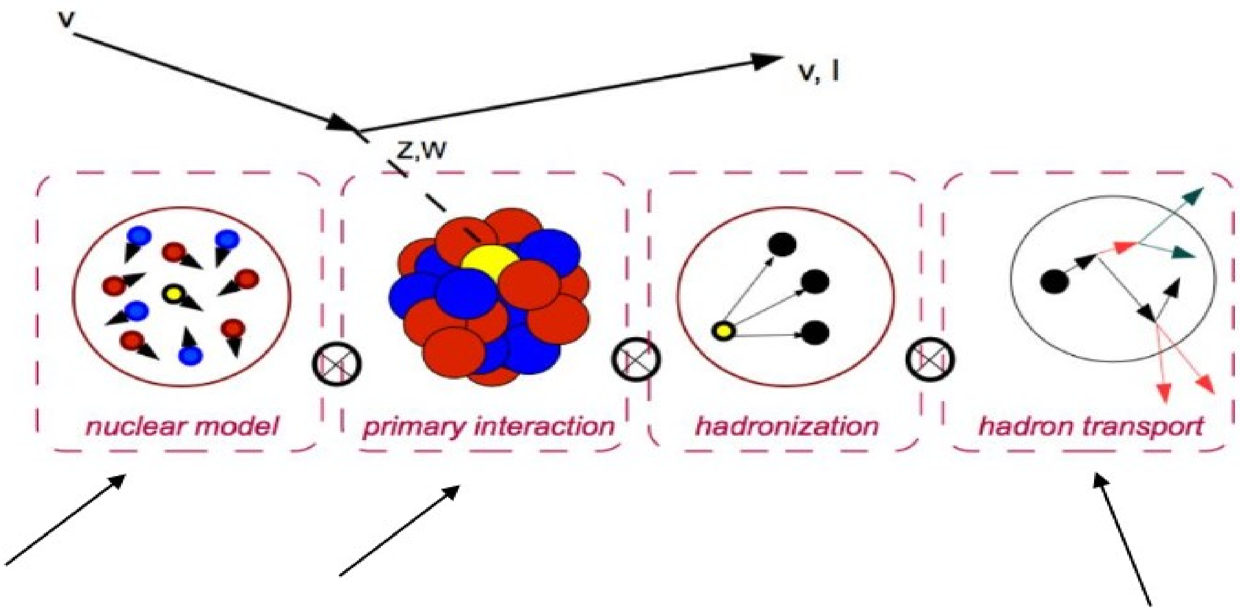
Cross section systematics



- We usually use cascade model to describe final state interaction
- The model has been carefully tuned to hadron scattering data, but still struggling



Cross section systematics

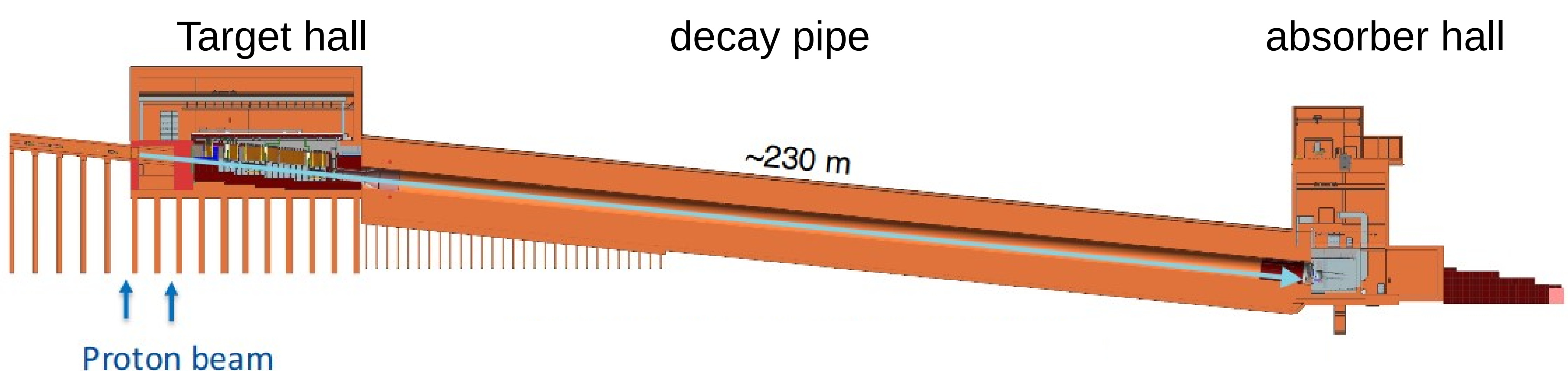


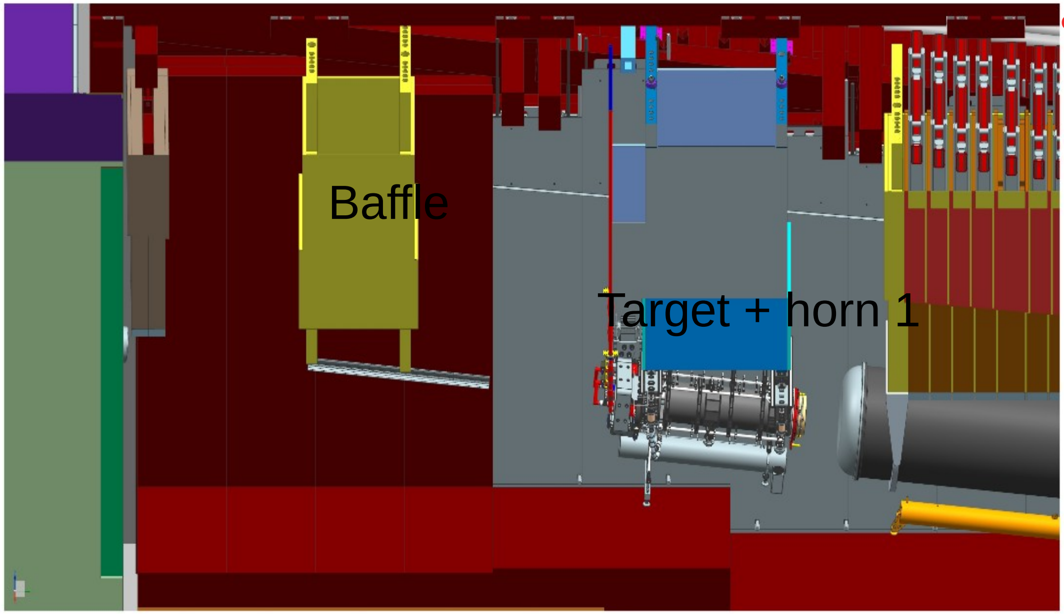
- All these components are independent and not linked :

  - The nuclear potential in FSI may not be the one in the nuclear model

  - The primary interaction may not be affected by the nucleon sampled from the nuclear model

Neutrino beam



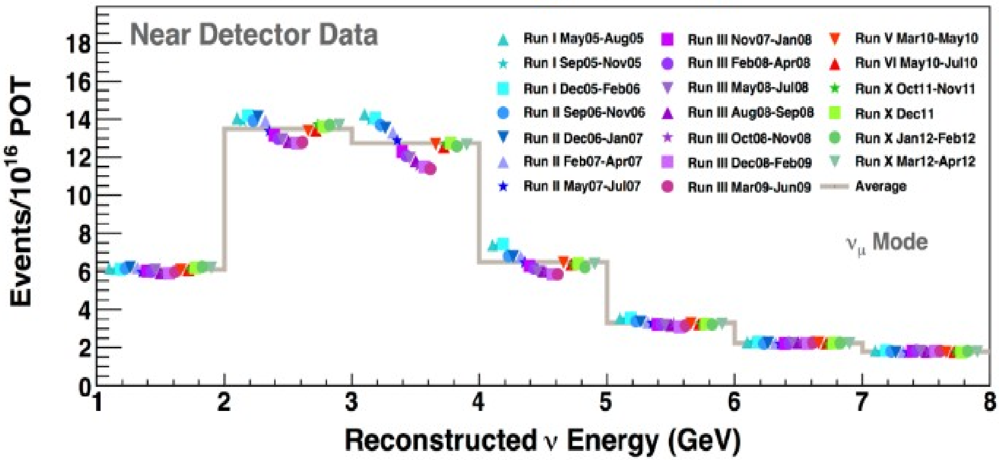


- Beam-related uncertainty sources:
  - Proton beam direction, width
  - Target density, location
  - Horn alignment: there are three horns
  - Horn current
  - Decay pipe

Beam instability

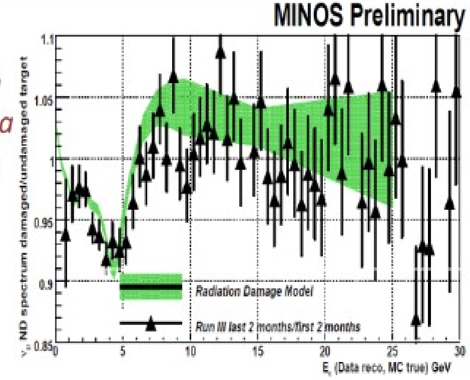
- Beam accidents happened before.

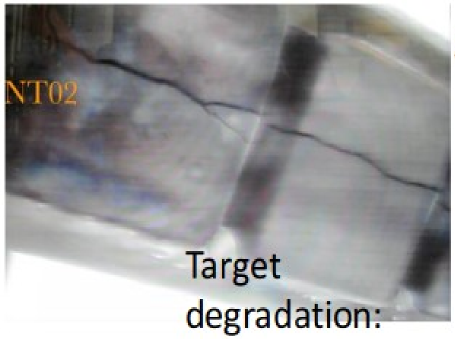
MINOS ND low energy running



Target damage model in FLUKA08

Target degradation modeled by ND data M. Bishai (Neutrino 2010)



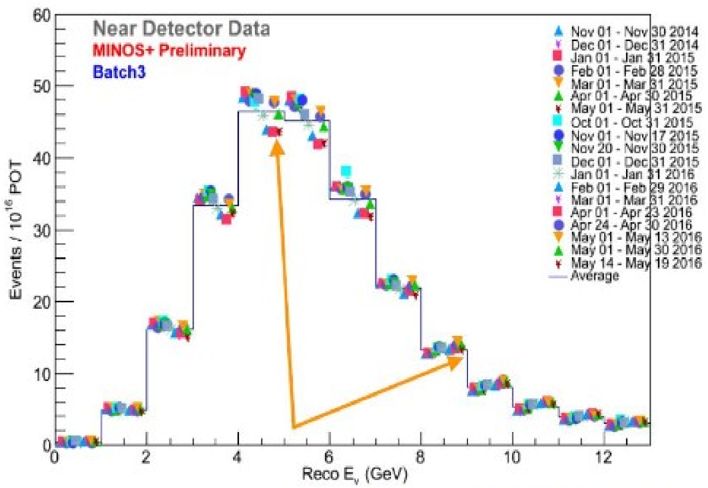


A. Holin, CERN CENF-ND meeting, Nov 2017

Target degradation: Broken upstream target fins

Unexpected horn Tilt discovered by Change in ND flux (due to corroded part)

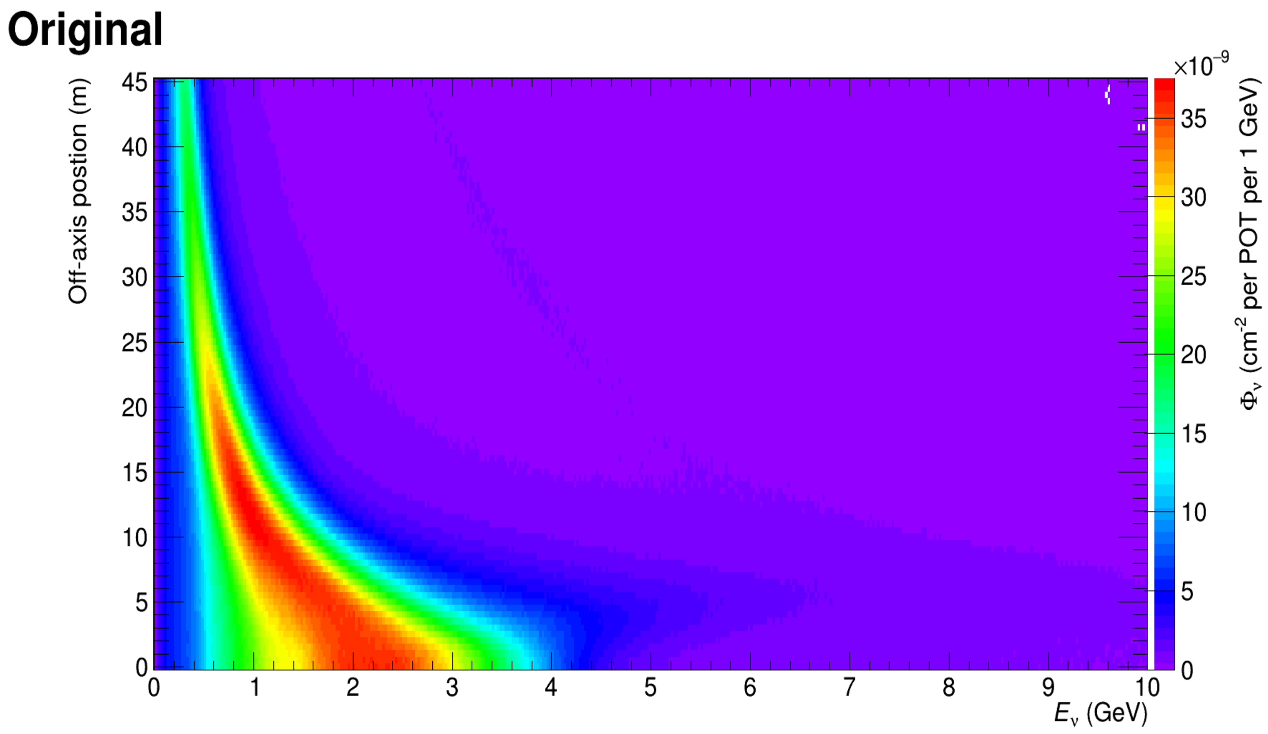
Neutrino Selected Batch Energy Spectrum Stability (PQ and NQ)

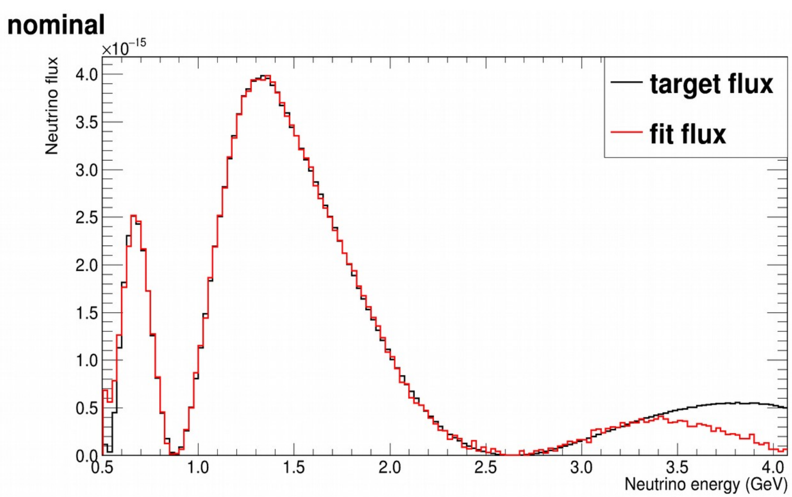


Jim Hylen, NuMI OPS, Nov 2016

Beam instability

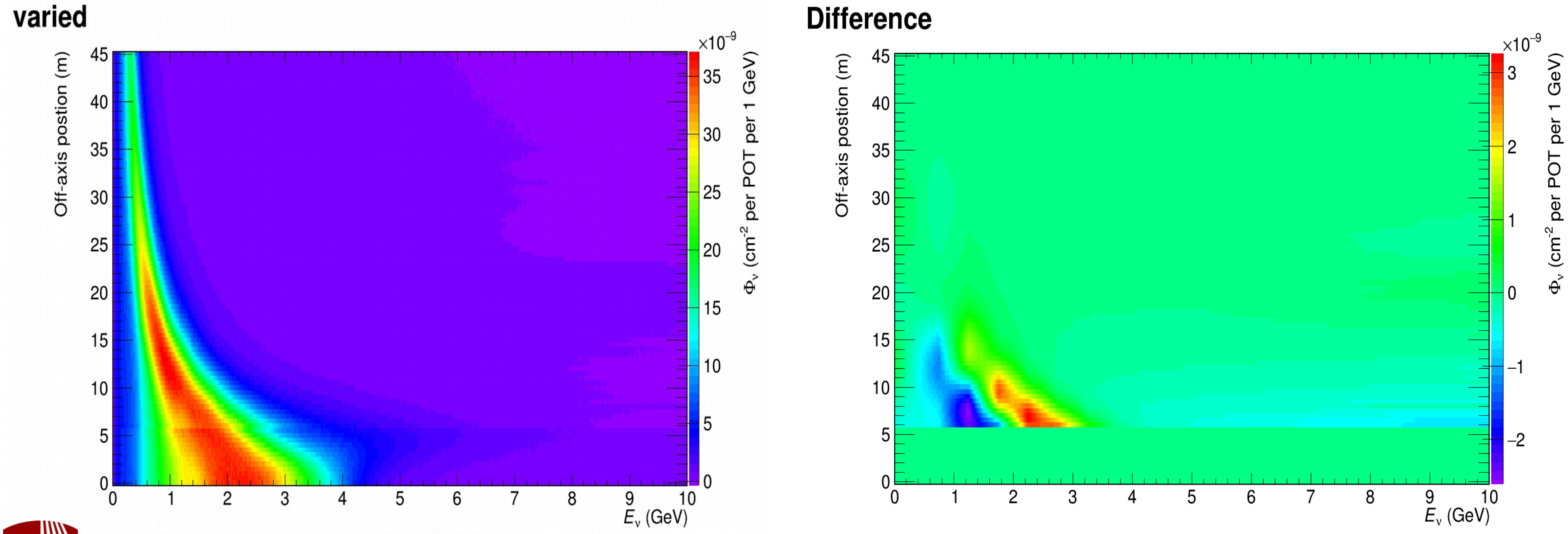
- Use off-axis ND flux to match FD oscillated flux





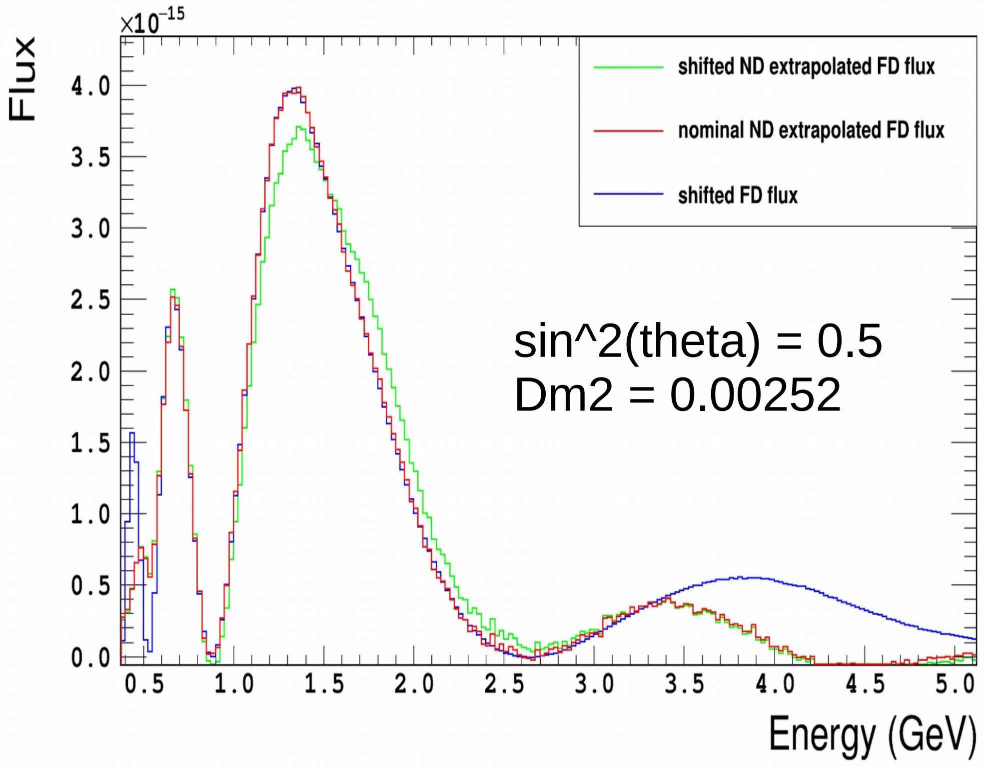
Beam instability

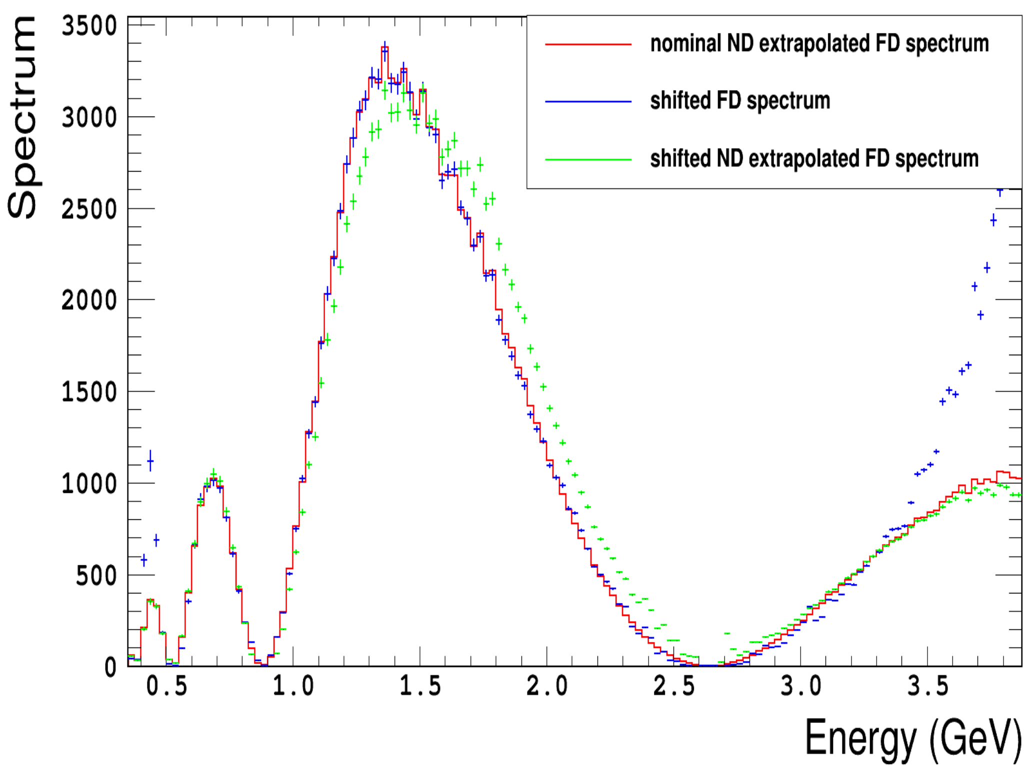
- The system on-axis 50% of the time while 50% off-axis
- When detector goes off-axis at 6 meters, beam changes in shape.
- Total rate over energy not changed
- This case was made with ~ 6 mm horn 1 X shift + overall rate compensation.



Beam instability

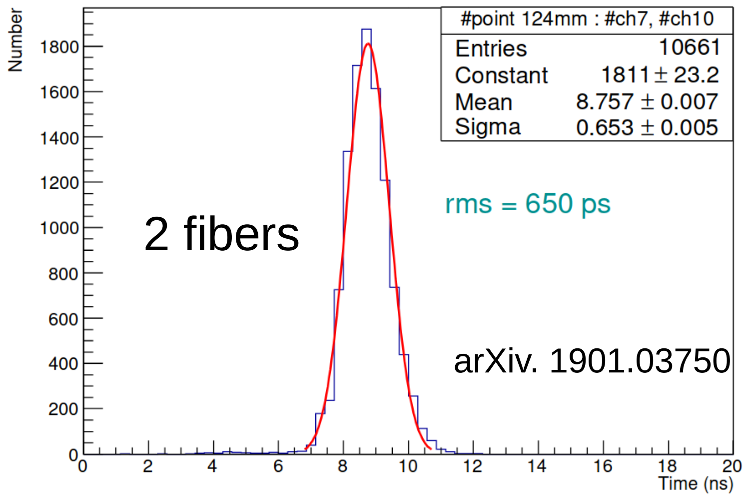
- Applying the linear combination coefficients to the changed ND; FD shifted as well (50% of time)

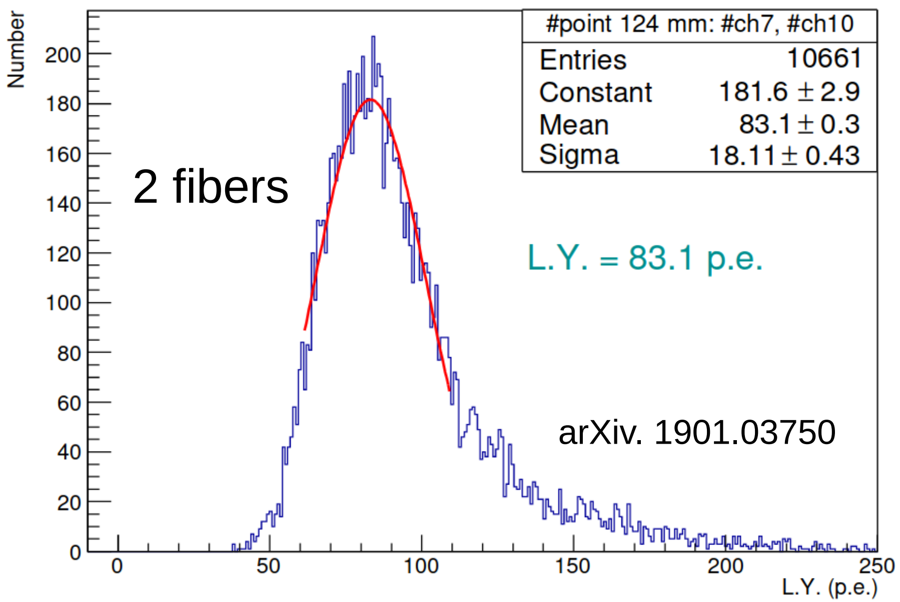


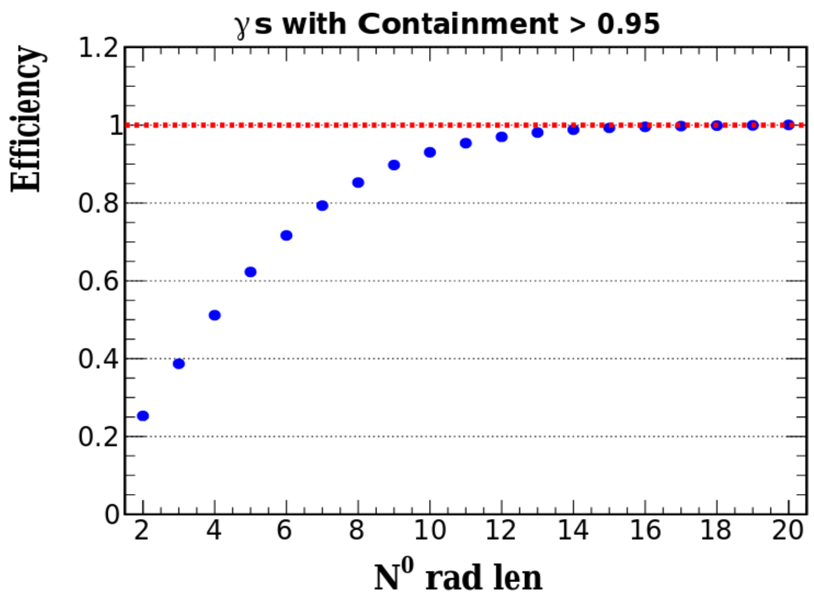


3DST performance

- Super fast and high light yield
- Radiation length ~ 40 cm, TPC and ECAL needed in addition to 3DST
- ~100% charge ID for tracks below 3 GeV

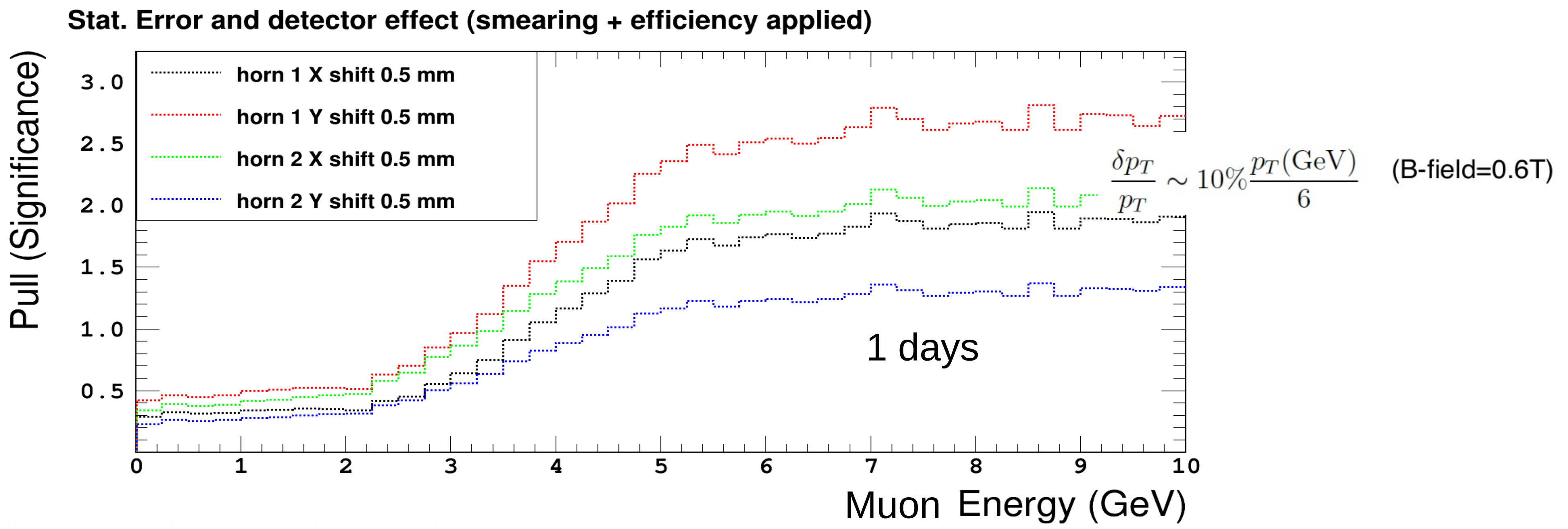






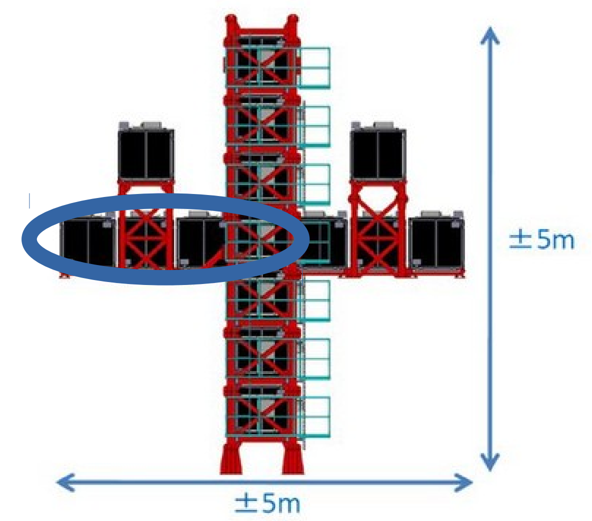
3DST-S/K: Beam spectrum monitor

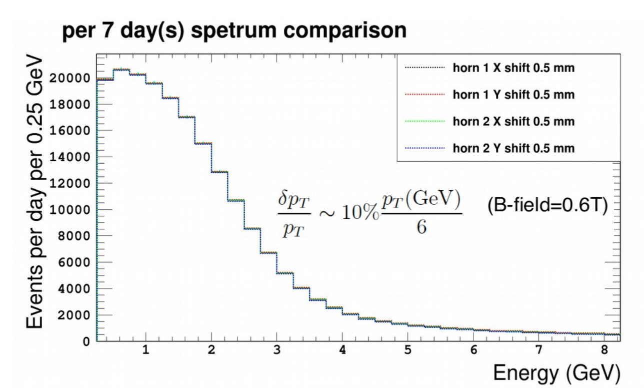
- The 3DST has the ability to detect FS particles.
- With the shape measurement over a time period, 3DST is sensitive to beam parameters.
- An example: With only muon energy measurement, 3DST provide good sensitivity to the beam condition changes.
- Major beam variations have been tested.



Rate monitor → 7 ton each module
Spectrometer → 8.7 FV in total

sqrt(chi2)	4 modules One-side rate One week	Muon Spectrometer One day
Beam targ. dens.	1.9	7.8
Beam offset x	0.7	6.7
Beam theta	0.2	19.9
Horn 1 X 0.5 mm	1.9	8.8
Horn 1 Y 0.5 mm	0.7	12.8
Horn 2 X 0.5 mm	0.2	9.9
Horn 2 Y 0.5 mm	0.4	6.3





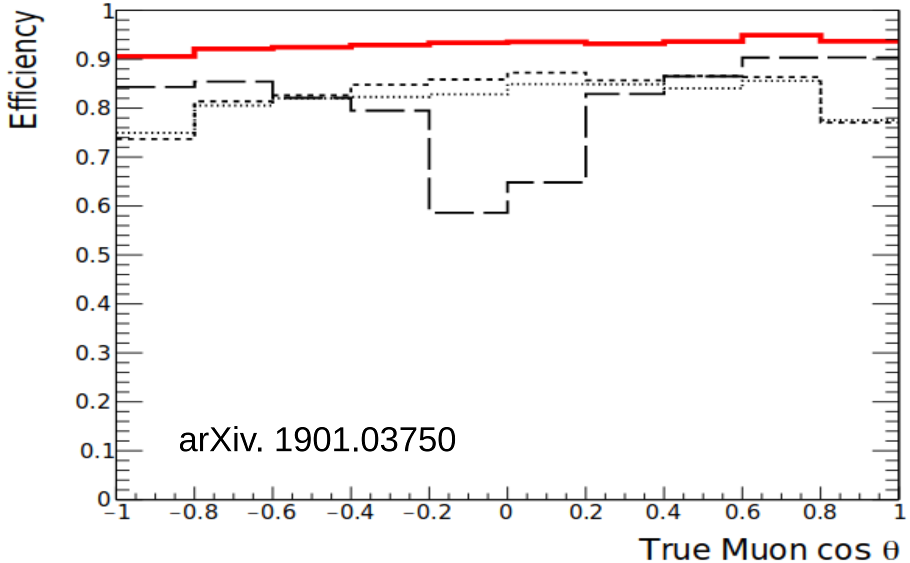
- Summary of the cases that rate-only measurements are not sensitive enough

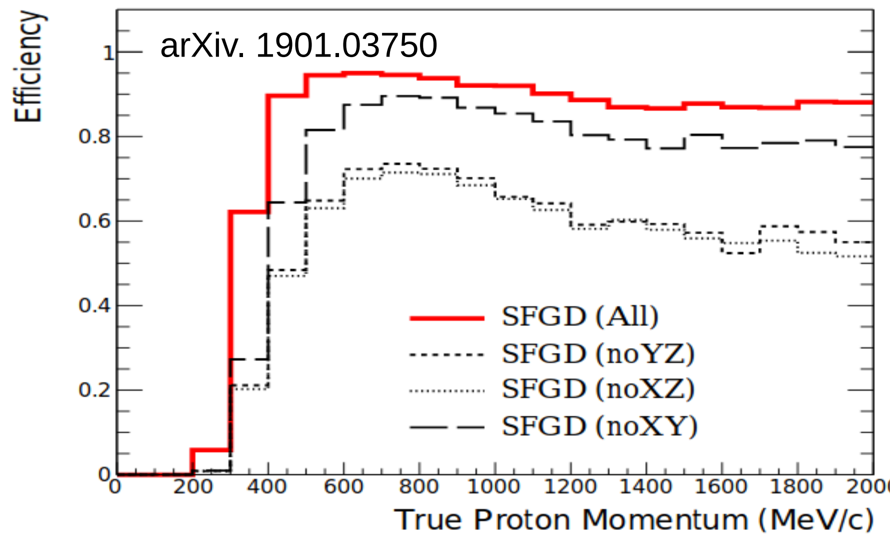
3DST performance

- Relatively high statistics with HydroCarbon target
- Tracking particles over 4pi space
- Low proton threshold

For one year

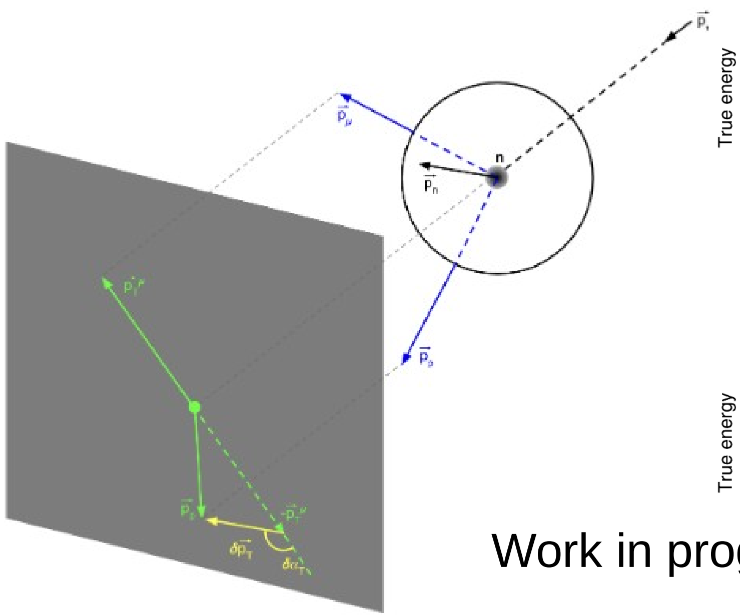
Channel	ν mode	$\bar{\nu}$ mode
ν_μ CC inclusive	13.6×10^6	5.1×10^6
CCQE	2.9×10^6	1.6×10^6
CC π° inclusive	3.8×10^6	0.97×10^6
NC total	4.9×10^6	2.1×10^6
ν_μ-e$^-$ scattering	1067	1008
ν_μ CC coherent	$1.26\ \times10^5$	$8.6\ \times10^4$
ν_μ CC low-ν (ν <250 MeV)	1.48×10^6	$8.8\ \times10^5$
ν_e CC coherent	2.1×10^3	719
ν_e CC low-ν (ν <250 MeV)	2.1×10^4	$4.7\ \times10^3$
ν_e CC inclusive	2.5×10^5	0.56×10^5

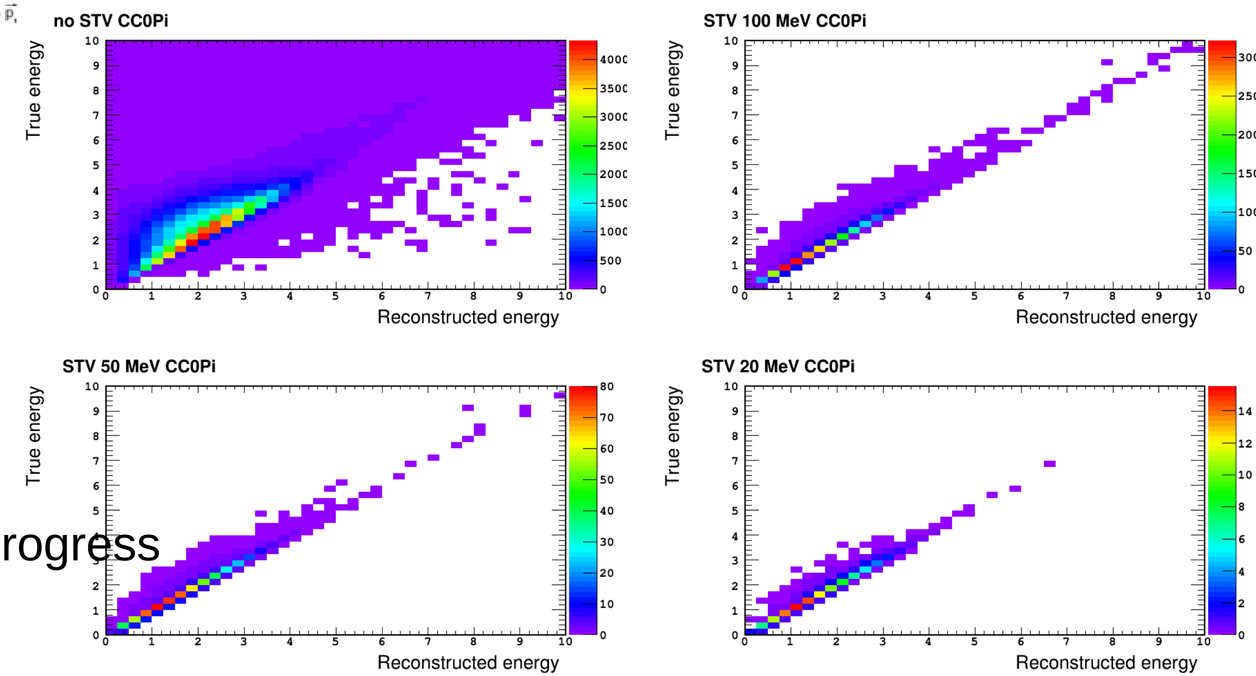




Flux constraint – Single transverse variable

- STV cut provides a less-FSI sample.
- Selecting CC0pi as a demonstrator; can potential do single pion channels as well.



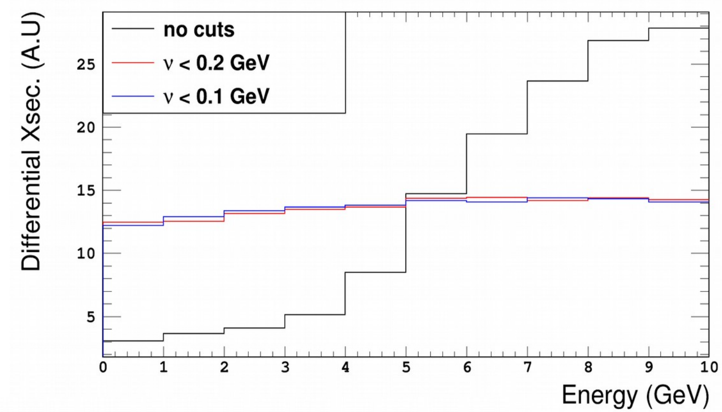


Work in progress

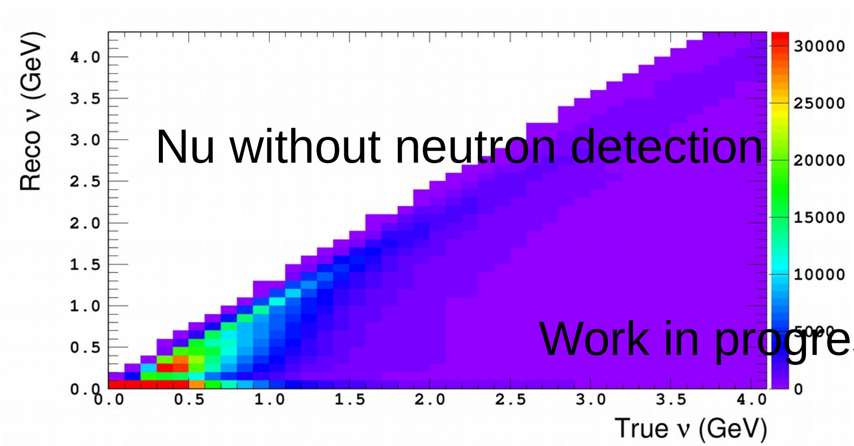
Flux constraint – low nu

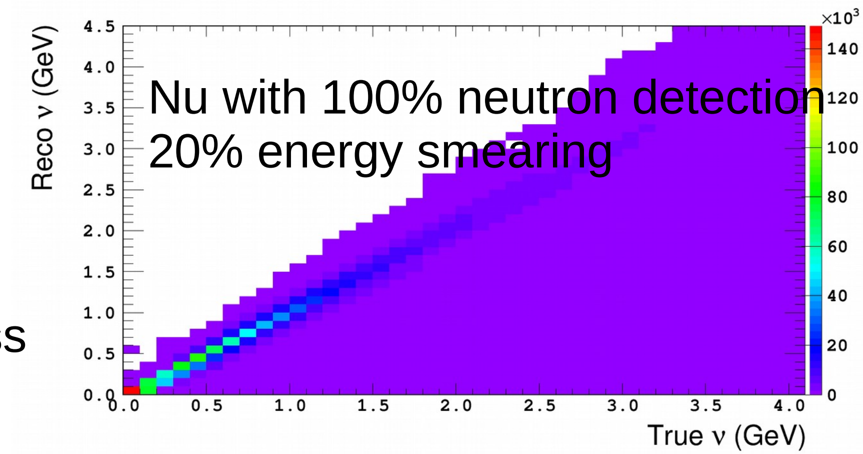
- Low nu cross section is flat along neutrino energy → flux shape info. can be constrained.

$$\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi} \int_0^1 \left(F_2 - \frac{\nu}{E_\nu}\left[F_2 \mp xF_3\right] + \frac{\nu}{2E_\nu^2}\left[\frac{Mx(1-R_L)}{1+R_L}F_2\right] + \frac{\nu^2}{2E_\nu^2}\left[\frac{F_2}{1+R_L} \mp xF_3\right]\right) dx$$



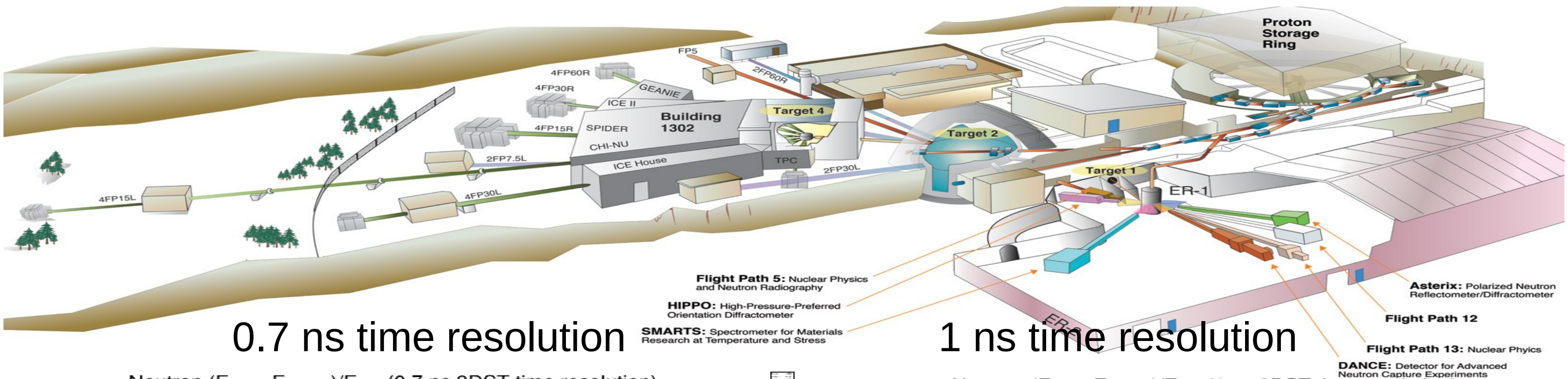
- True nu : neutrino energy – muon energy
- RHC only as a demonstrator for neutron detection ability



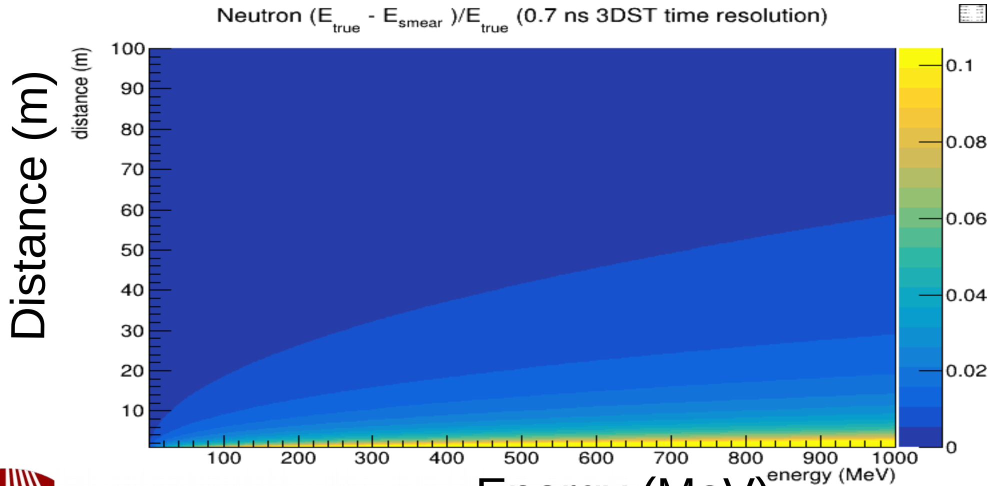


3DST neutron beam test

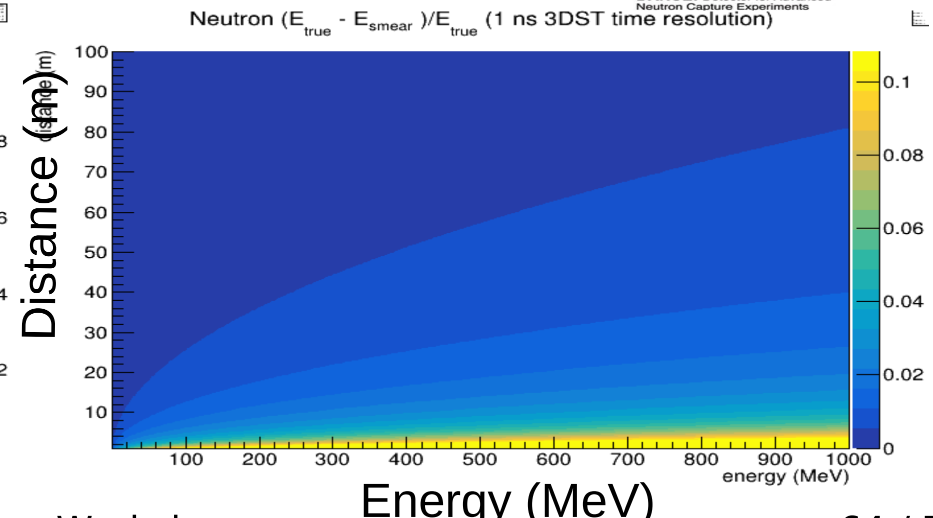
- LANL is our target facility for the beam test.
- With TOF, we have good neutron energy resolution in LANL.



0.7 ns time resolution

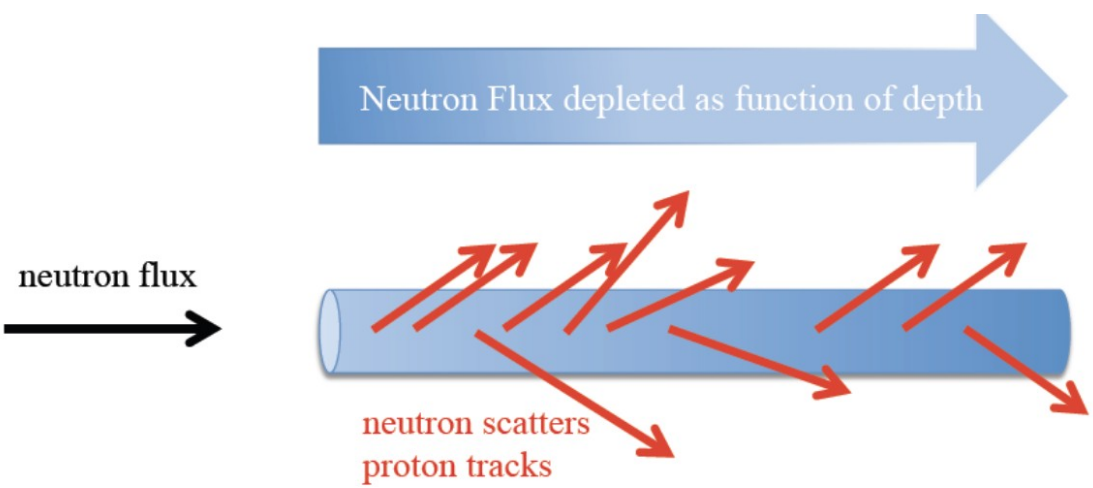


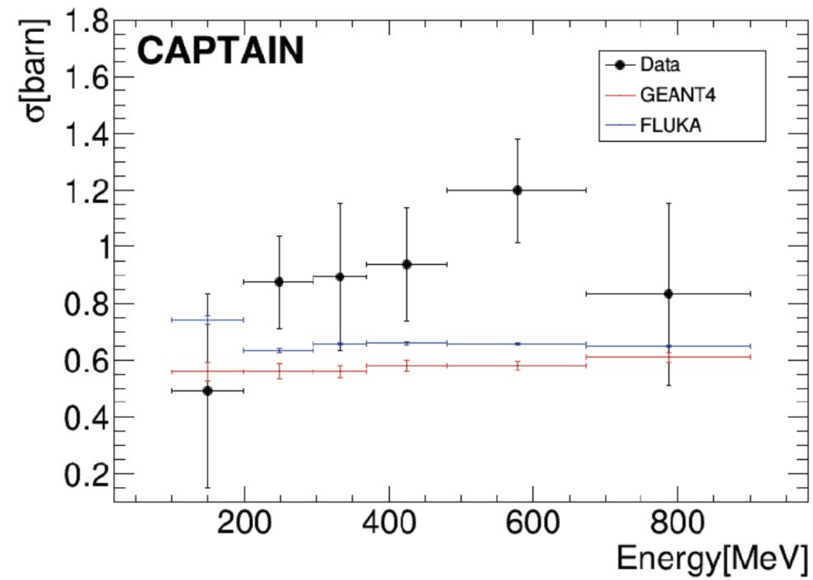
1 ns time resolution



3DST neutron beam test

- We can study the detector response as a function of neutron kinetic energy up to 800 MeV – mostly via n-p scattering
- Can also look at charged pion production
- Measurement of the absolute cross section should be possible via attenuation of events as function of depth in the detector

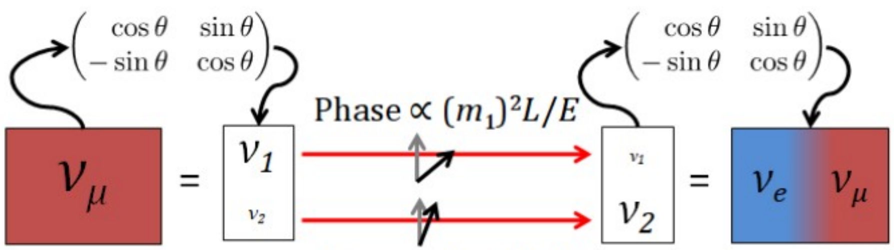


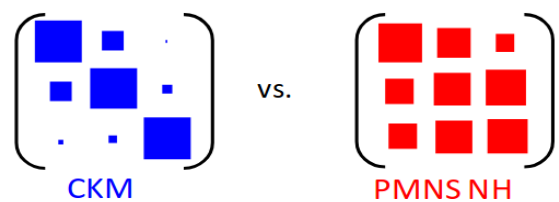


Neutrino Oscillation

- Neutrinos propagate in mass states and interact in flavor states.
- Three generations of neutrino have been found corresponding to lepton flavors.
- Three "Euler" angle has been measured.

  - mixing angles 12, 13 and 23 are measured by various neutrino experiments with different sources, Octant of angle 23 is not clear.





$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

δ

with $s_{ij} = \sin\theta_{ij}$; $c_{ij} = \cos\theta_{ij}$

Current/Past neutrino oscillation experiments

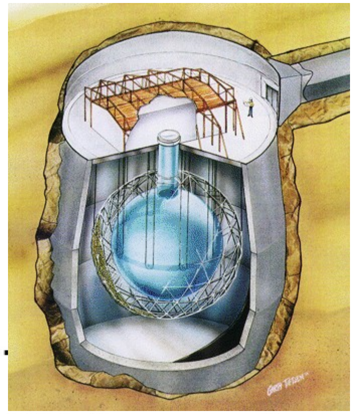
Solar: BOREXINO, SNO...

Atmospheric: Super-K...

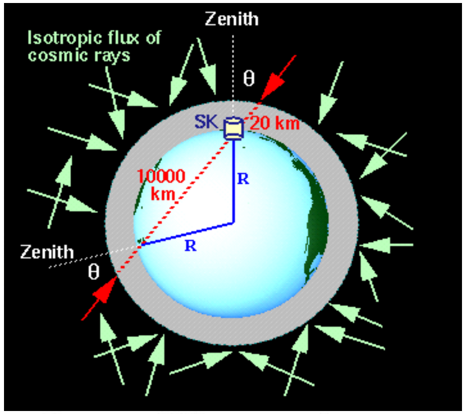
Accelerator: MINOS, NOvA, T2K...

Reactor: Daya Bay, Double Chooz, RENO, KamLAND...

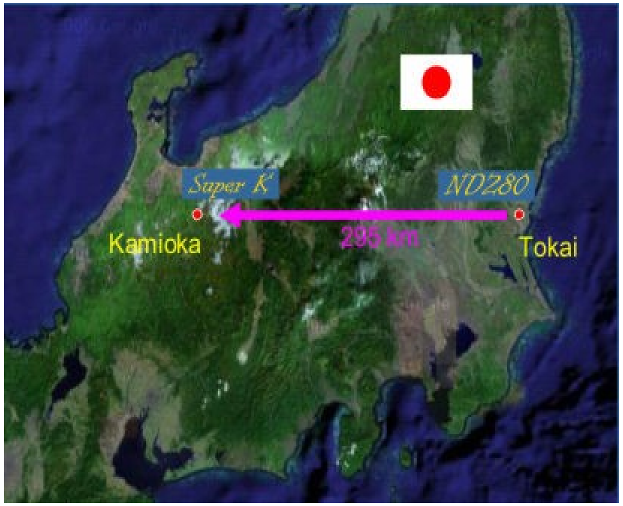
Cosmic: IceCube...



SNO ($\nu_e \to \nu_{\mu,\tau}$)

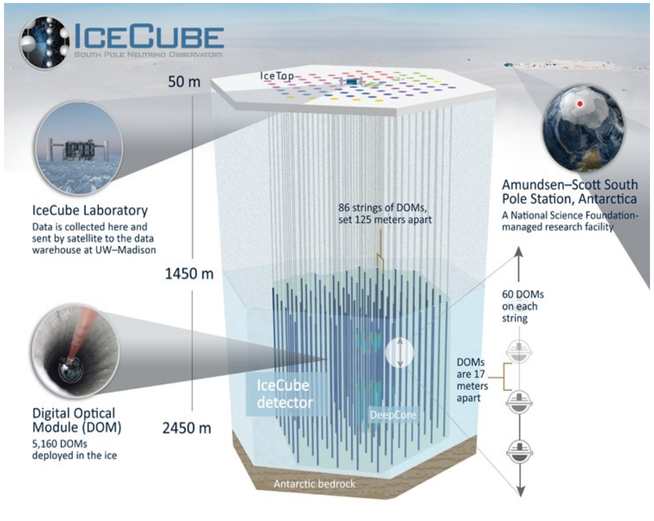


Super-K($\nu_\mu \to \nu_\tau$)



T2K

Double Chooz ($\bar{\nu}_e \to \bar{\nu}_e$)

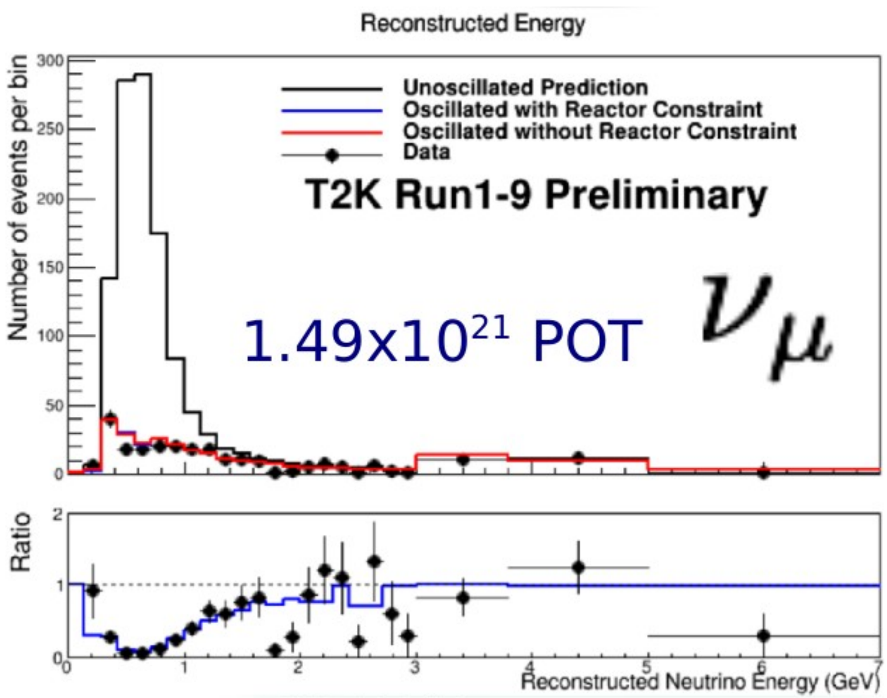


IceCube

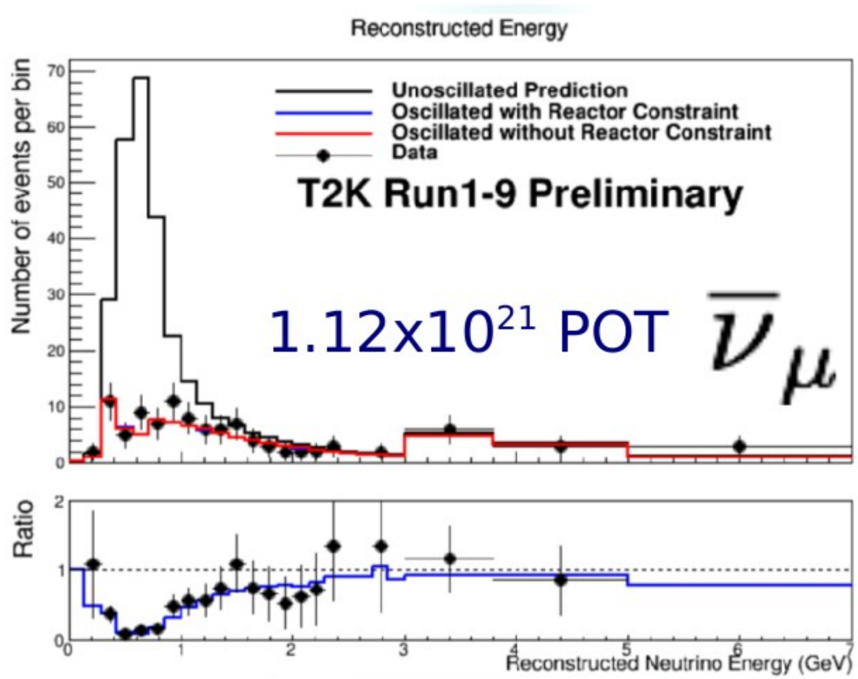
Known unknown questions

- Why are neutrino mass so small?
  - Is there a connection to GUT scale?
  - What is the mass?
- Is neutrino Majorana or Dirac particle? Neutrino-less double beta decay?
- Are there light sterile neutrino states?
  - Some anomalies need explanations.
- What is the mass hierarchy?
  - solving along with CP (DUNE) or measure very good energy resolution (JUNO).
- Is CP violated in leptonic sector?
  - Is this the key to matter-antimatter asymmetry?
  - Long-baseline experiments aim at resolving it.

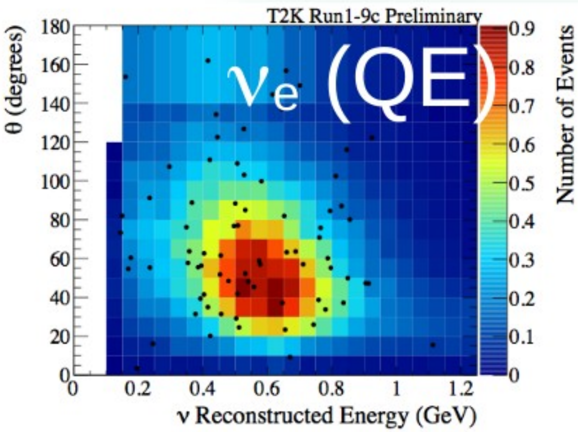
SK samples



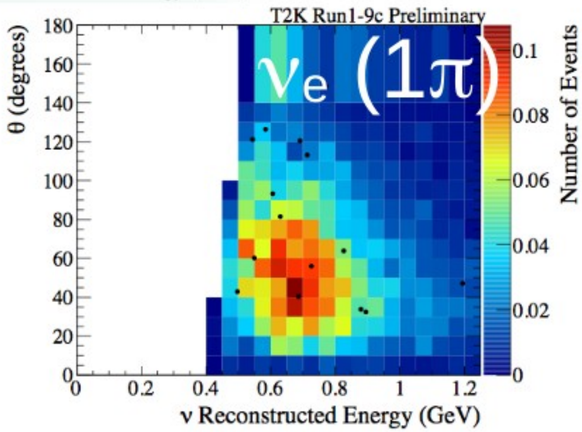
Reconstructed Energy
Unoscillated Prediction
Oscillated with Reactor Constraint
Oscillated without Reactor Constraint
Data
T2K Run1-9 Preliminary
1.49x10^21 POT
Number of events per bin
Ratio
Reconstructed Neutrino Energy (GeV)



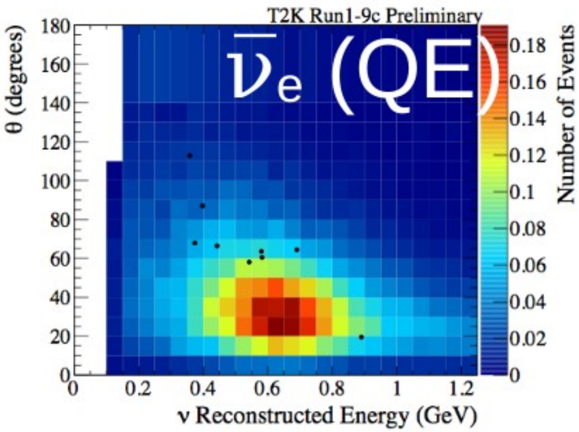
Reconstructed Energy
Unoscillated Prediction
Oscillated with Reactor Constraint
Oscillated without Reactor Constraint
Data
T2K Run1-9 Preliminary
1.12x10^21 POT
Number of events per bin
Ratio
Reconstructed Neutrino Energy (GeV)



T2K Run1-9c Preliminary
νe (QE)
θ (degrees)
Number of Events
ν Reconstructed Energy (GeV)



T2K Run1-9c Preliminary
νe (1π)
θ (degrees)
Number of Events
ν Reconstructed Energy (GeV)

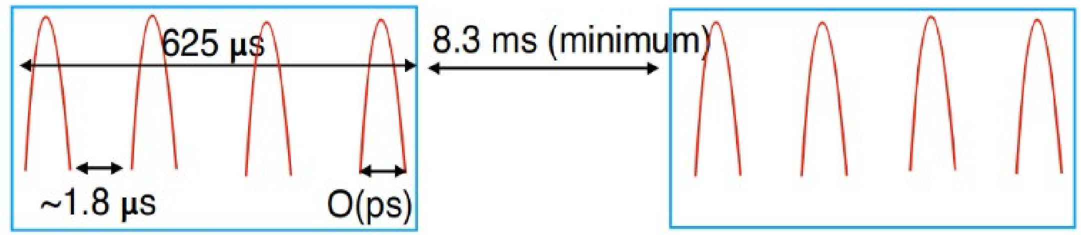


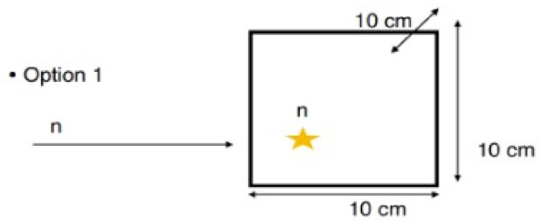
T2K Run1-9c Preliminary
θ (degrees)
Number of Events
ν Reconstructed Energy (GeV)

3DST neutron beam test

Beam structure of LANCSE →

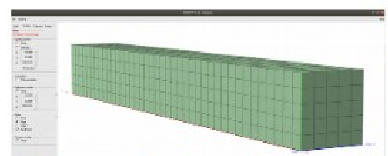
- Intensity can be adjusted to very low
- Neutron energy can be determined precisely using TOF



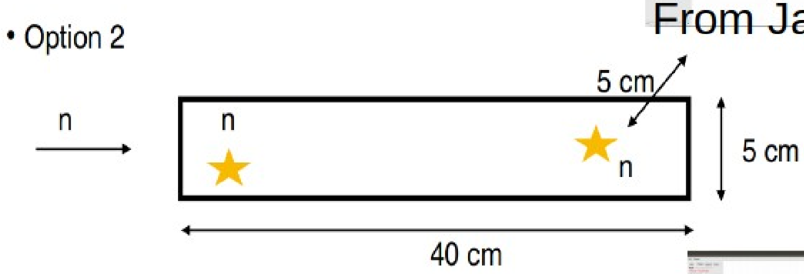


Original proposed 3DST prototype:

Study the basic neutron hit detection efficiency

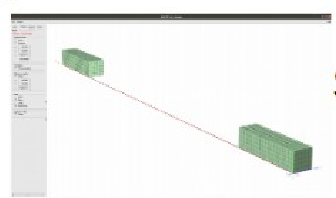


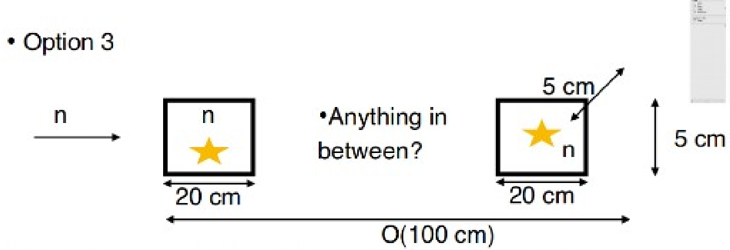
From Jairo (SDSMT)



Re-shaped 3DST prototype:

Better containment of neutron scattering in 3DST





Separated 3DST prototypes:

Study the neutron scattering kinematics.
Second module can be in different angles
3DST module is small, easy to move.

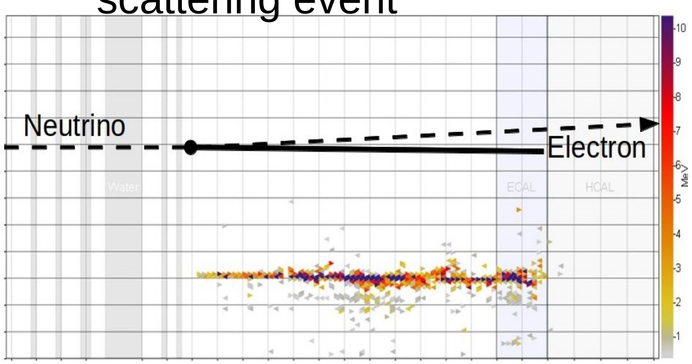
DUNE ND : flux measurement

- Target independent
- Better use channels that cross section well known.

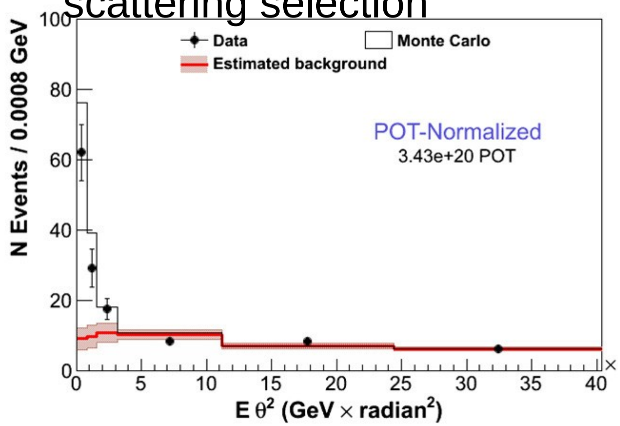
  - Neutron-electron scattering: Pure weak interaction; signature is very straightforward electron.

  - low-nu channel: Very low energy transferring from neutrino to nuclear system; Cross section is independent of energy; Cross section depends on ability to measure all hadronic energy including neutrons.

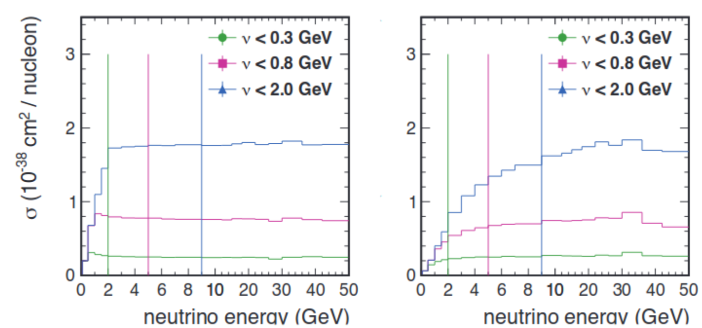
Minerva neutrino-electron scattering event



Minerva neutrino-electron scattering selection



Minerva low-nu cross section

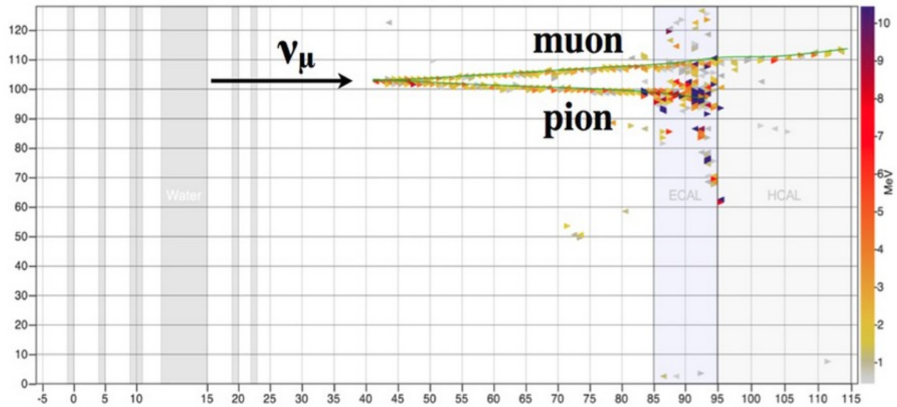


DUNE ND : flux measurement

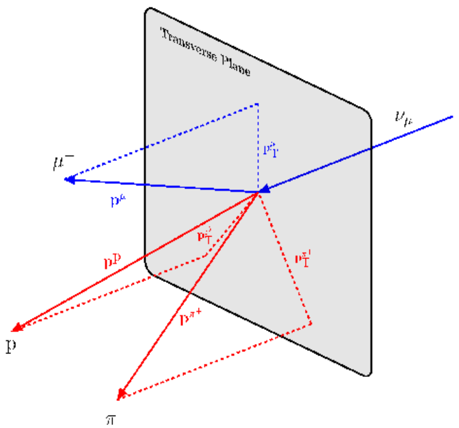
- Coherent channel: No Long/short range correlations and no final state interaction; Cross section not well known and small; Pretty forward-going lepton and pions.

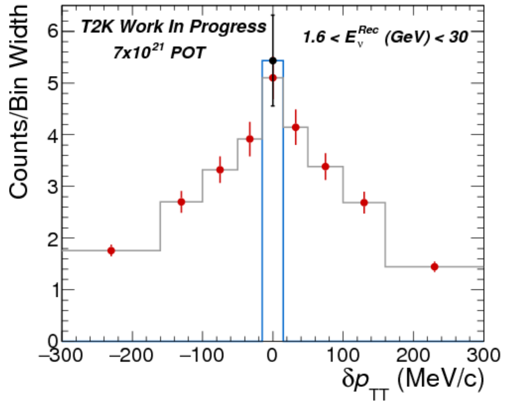
- Hydrogen interaction: No final state interaction; No initial state transverse momentum→ identify by transverse momentum balance; Neutron measurements may be needed for this.

Minerva Coherent interaction event



T2K transverse momentum
→ extract hydrogen interaction





DUNE ND : Cross section and smearing

- Unknown initial state: neutrino energy and nucleon momentum
- Unknown final state: Neutron, protons below threshold
- Unknown detector smearing
- Very model dependent

--→ ND philosophy:

- Measure as many exclusive differential cross sections as possible.
- Tune model.
- Extract cross section and smearing from simulation.

--→ We start to consider detector configuration based on the ideas above