Institute for High Energy Physics

Near Detector Technologies

(A WG6 Teaser Talk)

Thorsten Lux

Why do we need Near Detectors?

See talk by S. Dolan

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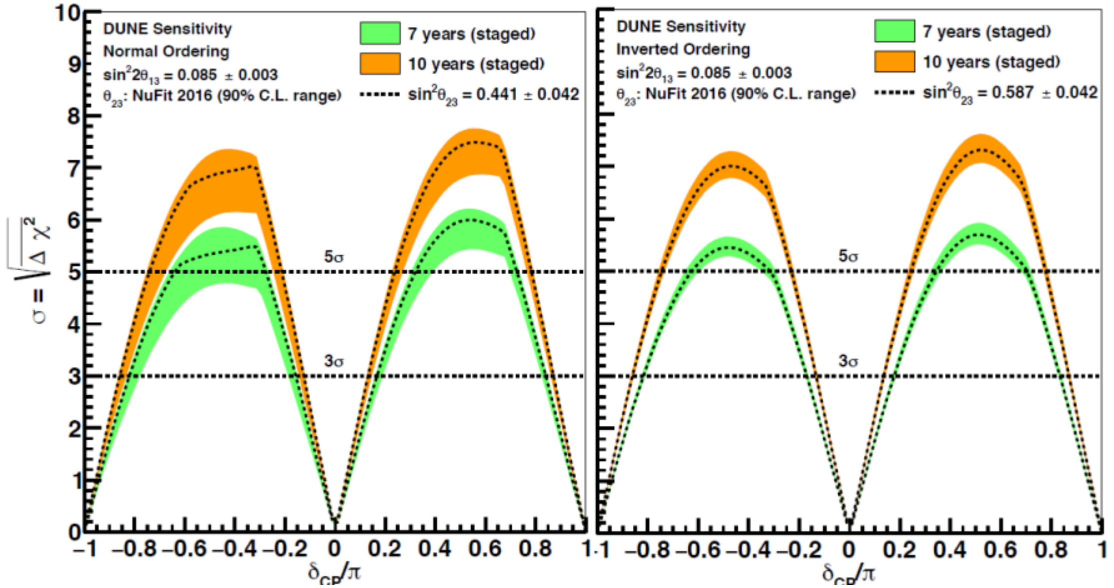
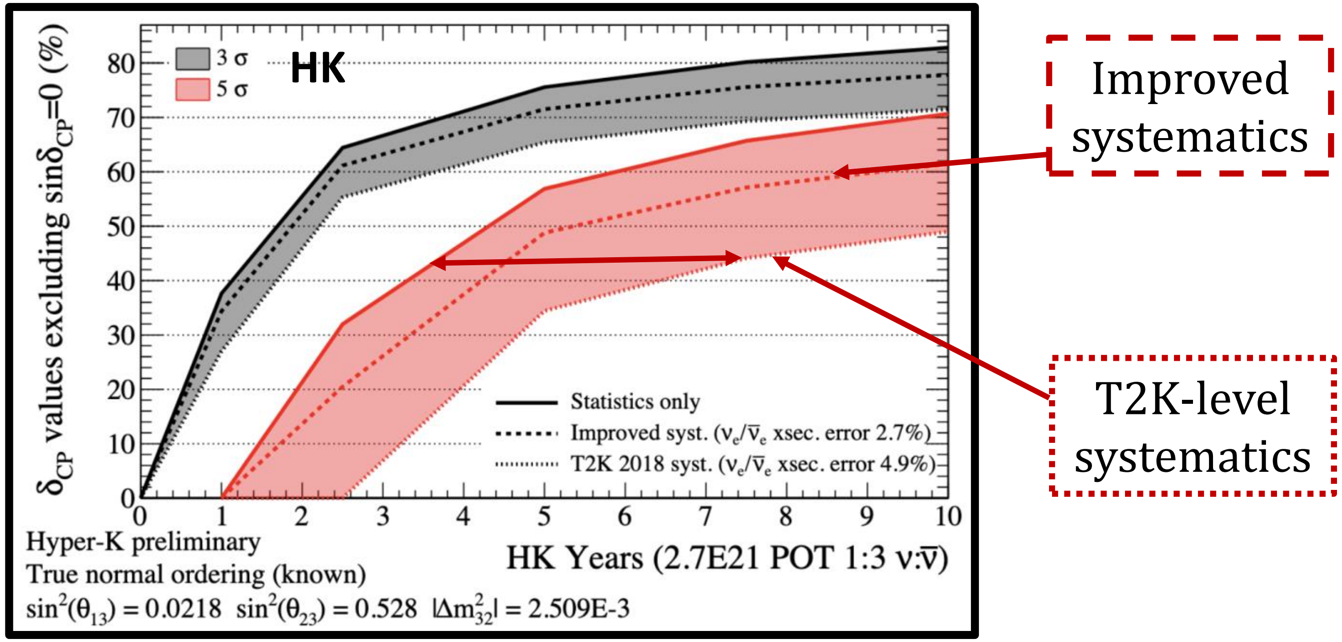
Objective of current and future LBNO experiments is to measure with precision δ_{CP} phase
$\Rightarrow$ Systematic uncertainties are the big enemy!

DUNE





Sensitivity to exclude CP conserving values for δ_{CP}

Can delay physics results **by several years. Or prevent them altogether!**

But we luckily have Near Detectors!

LBNO Concept

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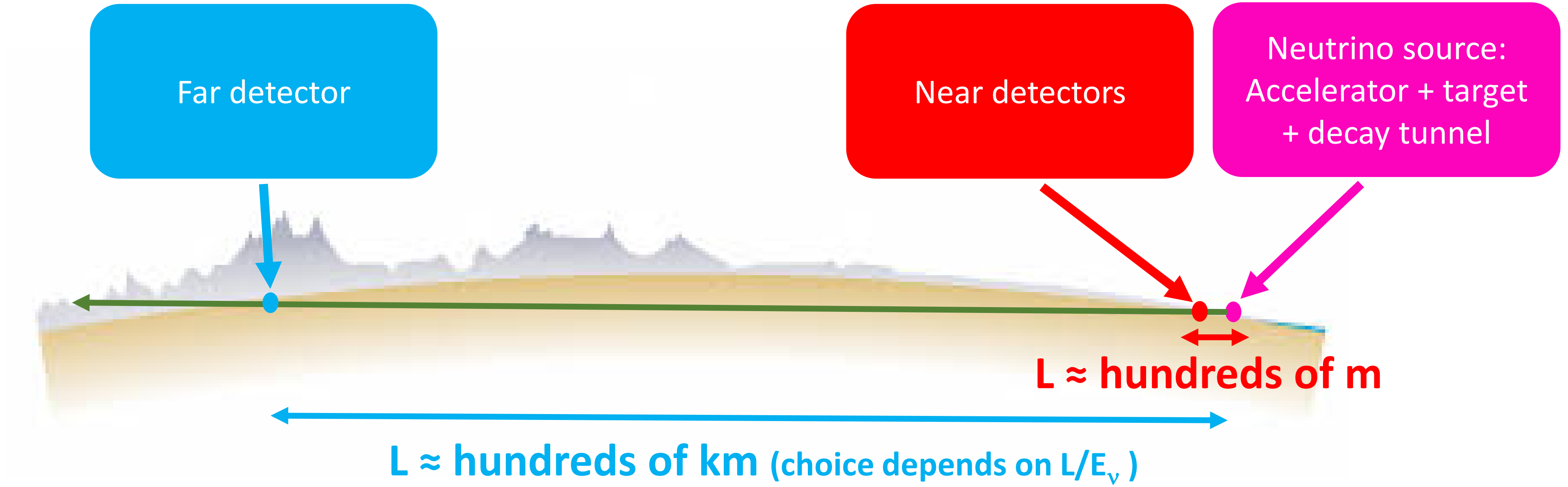

- Huge masses of 10s of ktons
- Often underground
- Oscillated neutrino spectrum

- Constraints on neutrino flux before oscillation
- Neutrino cross sections
- Direction of neutrino beam

- Proton synchrotron (30-120 GeV)
- Target to produce mesons
- Magnetic system to select polarity
- Decay tunnel to let mesons decay and produce neutrinos

LBNO Concept

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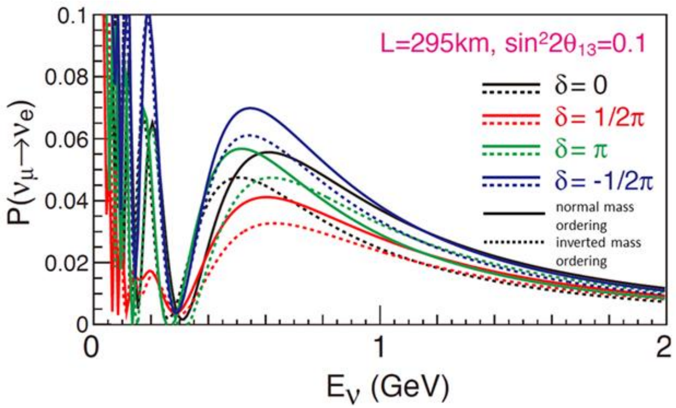
Detectors provide event rates in bins of reconstructed neutrino energy:



ND: $$\frac{dN_\beta^{ND}}{\Delta E_\upsilon^{reco}} = N_{target}^{ND} \sum_i \phi^{ND}(E_\upsilon)\sigma_i^{ND}(E_\upsilon)T_i^{ND}(E_\upsilon, E_\upsilon^{reco})\epsilon_i^{ND}(E_\upsilon, E_\upsilon^{reco})dE_\upsilon$$

FD: $$\frac{dN_\beta^{FD}}{\Delta E_\upsilon^{reco}} = N_{target}^{FD} \sum_i \phi^{FD}(E_\upsilon)\sigma_i^{FD}(E_\upsilon)T_i^{FD}(E_\upsilon, E_\upsilon^{reco})\epsilon_i^{FD}(E_\upsilon, E_\upsilon^{reco})P_{\upsilon_\alpha\to\upsilon_\beta}(E_\upsilon)dE_\upsilon$$

Neutrino flux | **Cross-sections for *i*th interaction mode** | **Energy migration tensor** | **Efficiency/ acceptance** | **Oscillation probability**

We need the **oscillation probability** from event rates with high precision

⇒ From the **oscillation probability** we extract then the oscillation parameters

LBNO Concept

See talk by E. Miller

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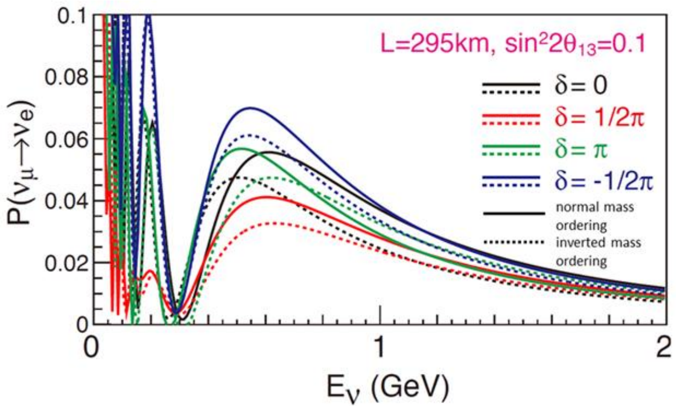
Detectors provide event rates in bins of reconstructed neutrino energy:



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Neutrino flux | Cross-sections for *i*th interaction mode | Energy migration tensor | Efficiency/ acceptance | Oscillation probability

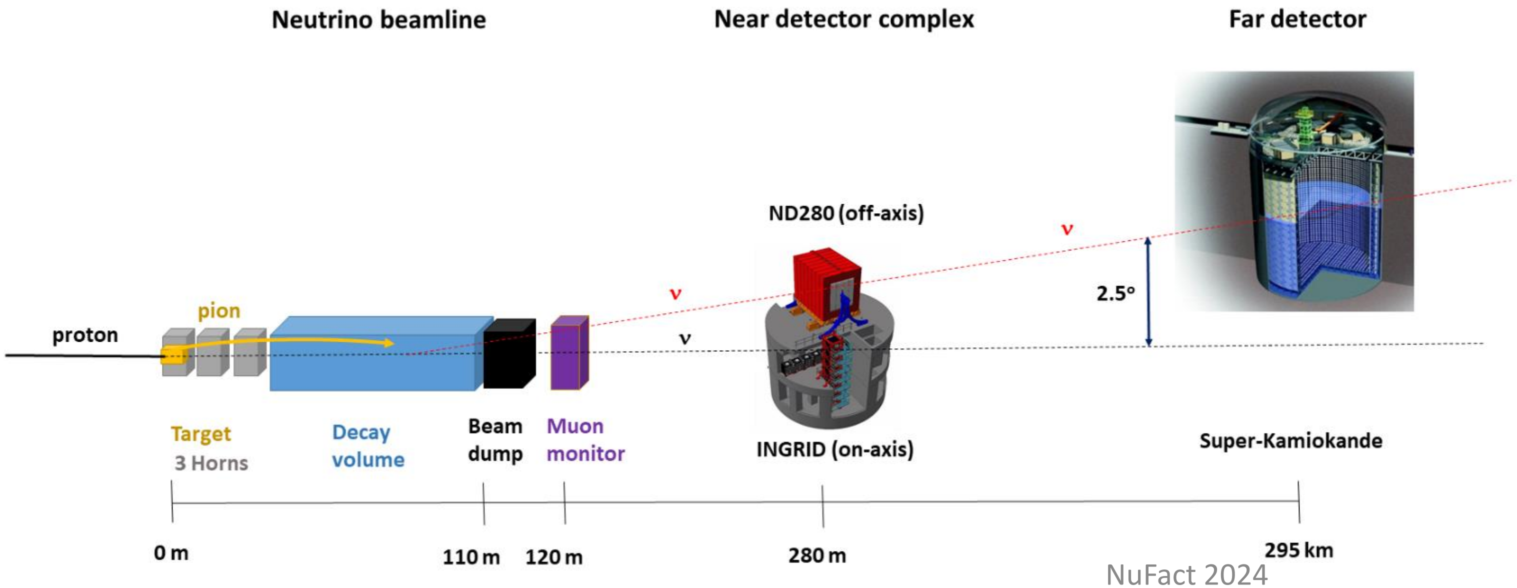
- Near Detector contributes to reduce uncertainty from neutrino flux and cross-sections
- σ^{ND} and σ^{FD} (ideally by measurement) from ND
- Crucial to understand relation between reconstructed and true neutrino energy

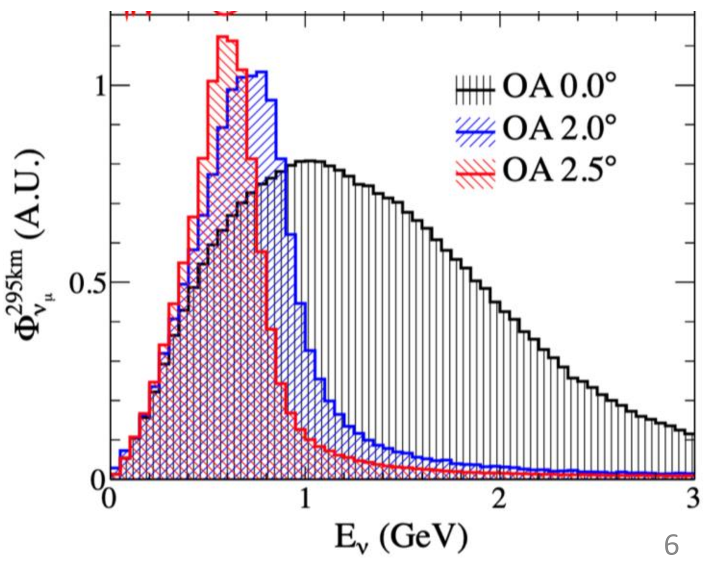
Neutrino Fluxes: Energy Spectrum

- Important to understand what neutrino fluxes one can expect
- Are the detectors on-axis or off-axis?
- On-axis: Wide neutrino energy spectrum
- Off-axis: Narrower neutrino energy spectrum peaking at lower energies

⇒ Neutrino beams are very wide and covering the whole experimental area

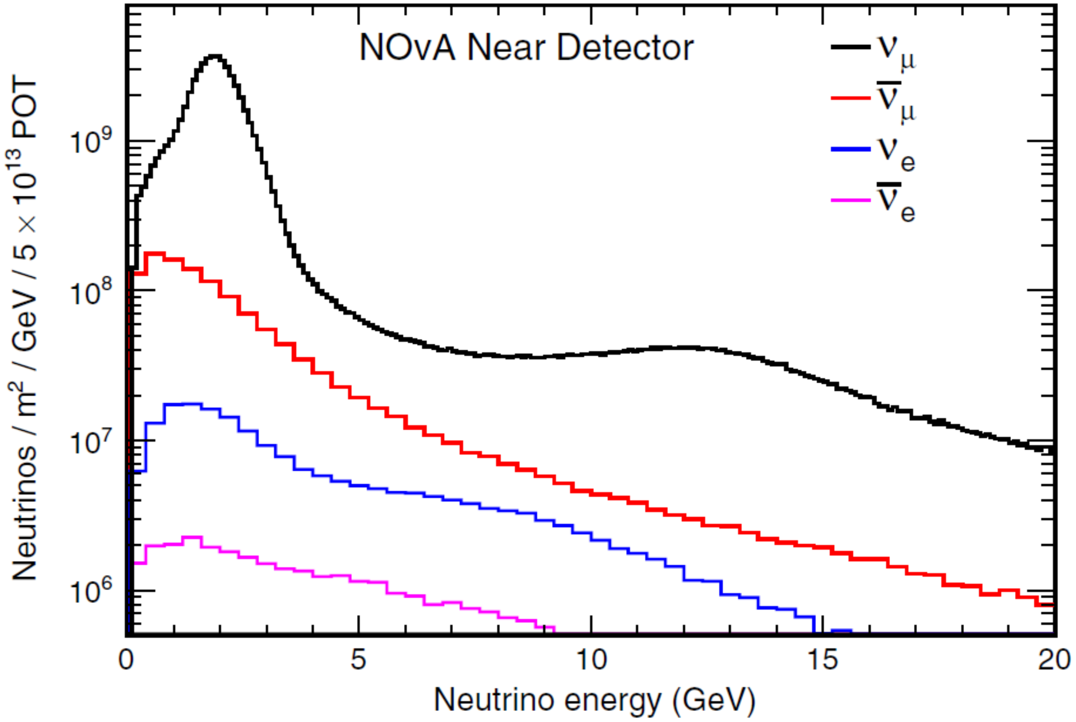
⇒ Measuring at different angles helps to deconvolute flux and cross-section





Neutrino Fluxes: Composition

- Naïve picture: Start with pure ν_μ beam characterized at ND and measure oscillated beam containing ν_μ and ν_e at FD
- Reality: Production process of neutrino beam results in contamination
- Fractions depends on several experimental aspects: proton energy, target geometry, horn system, beam angle, …
- Knowledge important for experiment sensitivity
- Enables to measure cross-sections also for ν_e

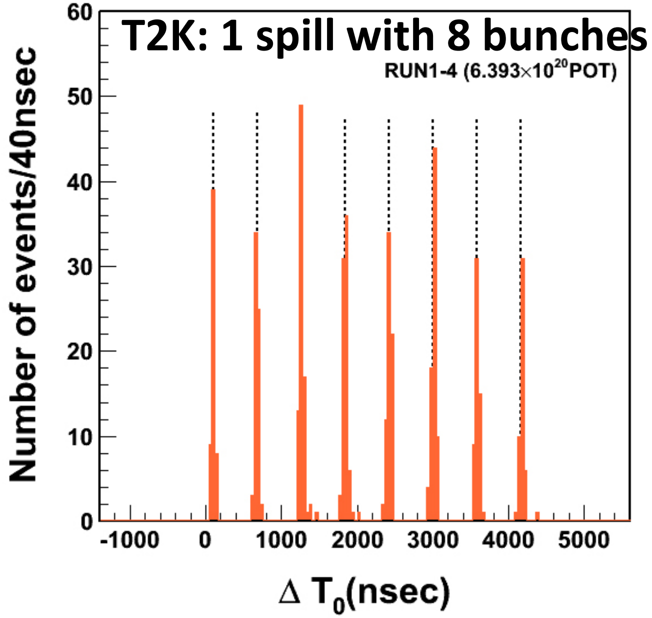


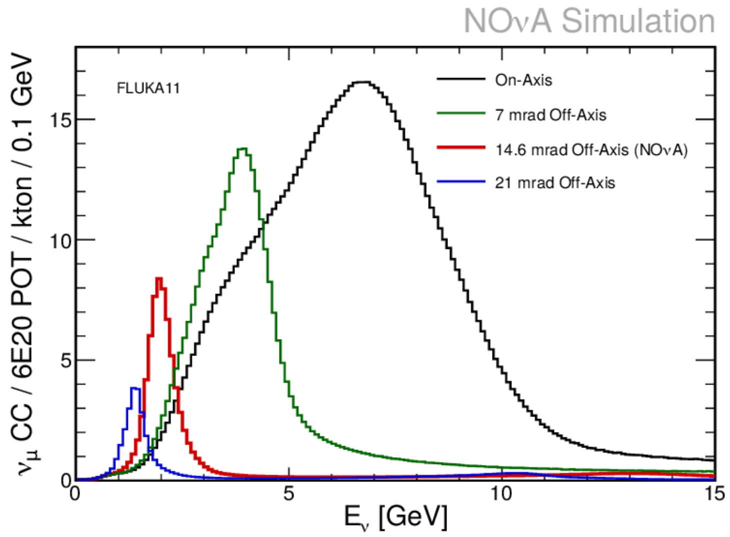
Neutrino fluxes: Intensity/Beam Power

- Intensity of neutrino flux impact on ND design
- Higher flux means more statistics opening new opportunities
- Beam power can be increased by more spills or more neutrinos per spill
- More neutrinos per spill implies more pile up background (also from out of fiducial volume interactions)
- Impressive increase in intensity and neutrinos per spill over last decades:
  - Past: K2K => 1.4 x 10^{12} p.o.t.
  - Current: T2K => 2.65 x 10^{14} p.o.t.
  - Next generation: DUNE => 7.5 x 10^{13} p.o.t.
    HK => 3.2 x 10^{14} p.o.t.

⇒ ND technologies with smaller N_{target} become interesting!

See talk by T. Sekiguchi and A. Burleigh





Cross-Sections

See talk by L. Munteanu and S. Dolan

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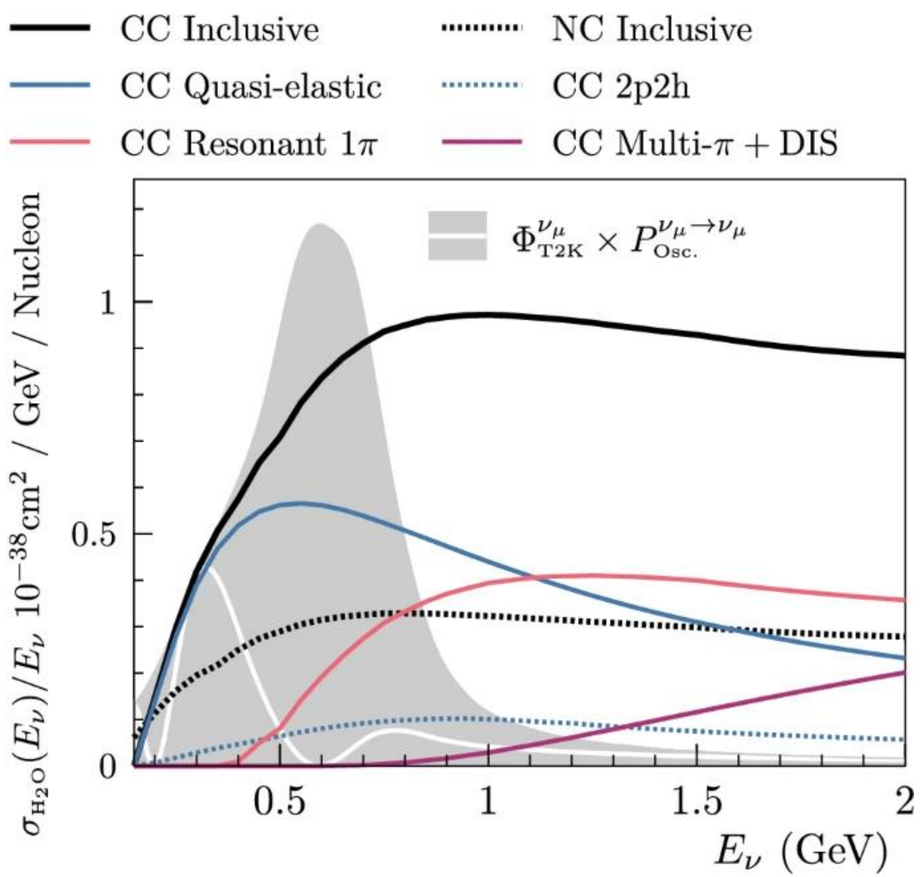
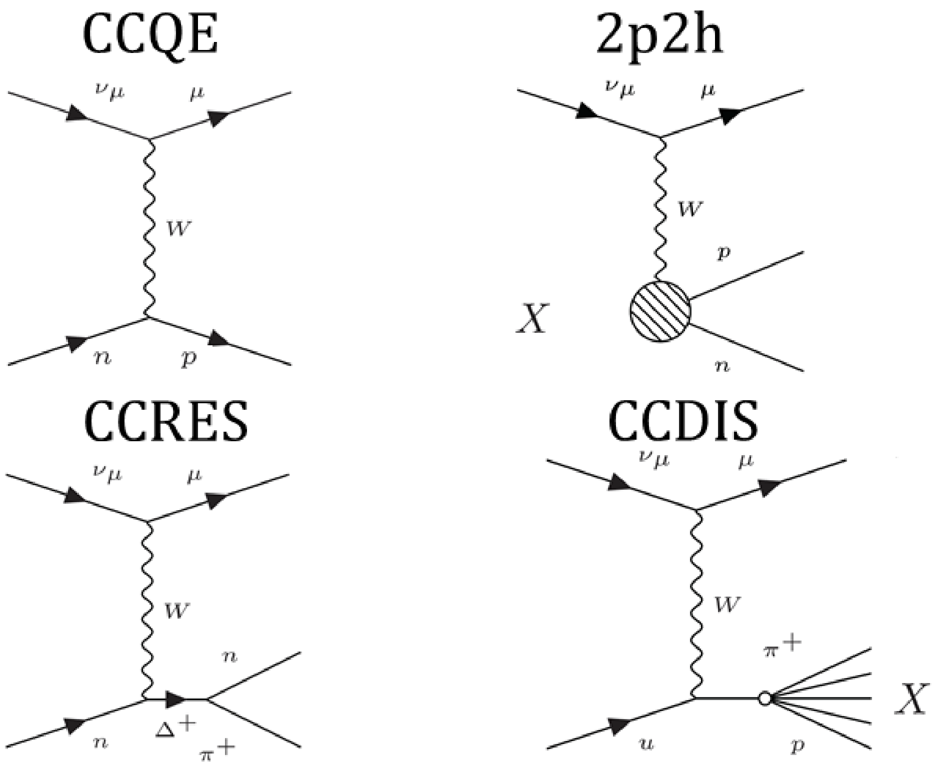
At neutrino energies relevant for LBNO, there are 4 interaction modes:





Depend on target material => ND should provide cross-sections for FD target!

Event Topologies

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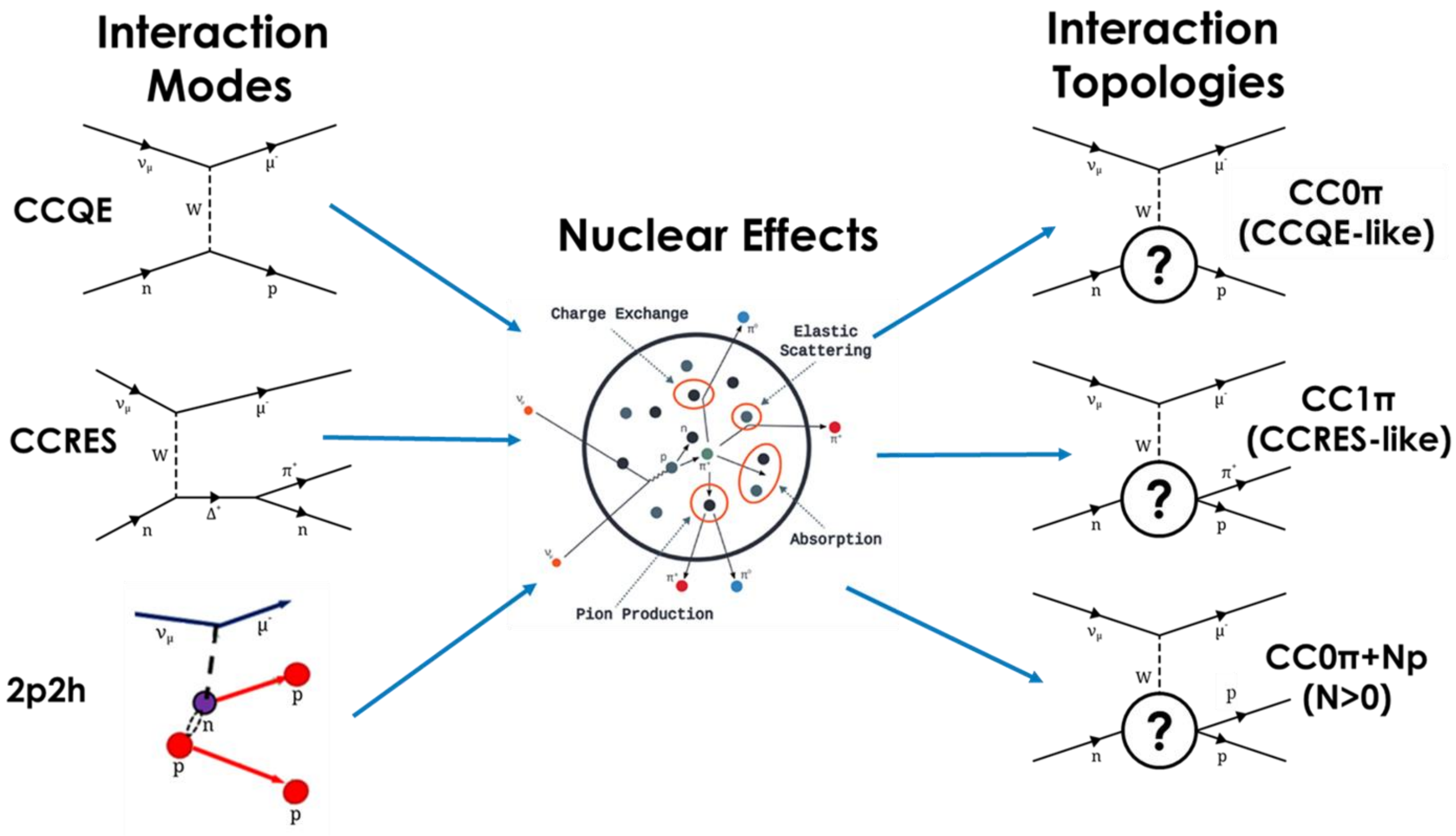
- Interaction not on free nucleons
- Nuclear effects/ Final State Interactions (FSI) can alter the event observables
- Effects depend on target material
- More relevant for low neutrino energies
- **ND provides insight in FSI**



Neutrino Energy Reconstruction

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The oscillation parameters depend on the true neutrino energy => precise knowledge of energy response function **T(E$_{rec}$, E$_{true}$)** crucial.

1) Kinematic energy reconstruction (suitable for true QE events):

$$E_{QE} = \frac{m_p^2 - m_\mu^2 - (m_n - E_B)^2 + 2E_\mu(m_n - E_B)}{2(m_n - E_B - E_\mu + p_\mu^z)}$$

Requires only kinematics of outgoing muon

2) Calorimetric energy resolution:

$$E_\nu^{\mathrm{cal}} = \epsilon_n + E_\ell + \underbrace{\sum_i (E_{\mathbf{p}'_i} - M)}_{\text{Kinetic energy of outgoing nucleons}} + \underbrace{\sum_j E_{\mathbf{h}'_j}}_{\text{Total energy of outgoing mesons}}$$

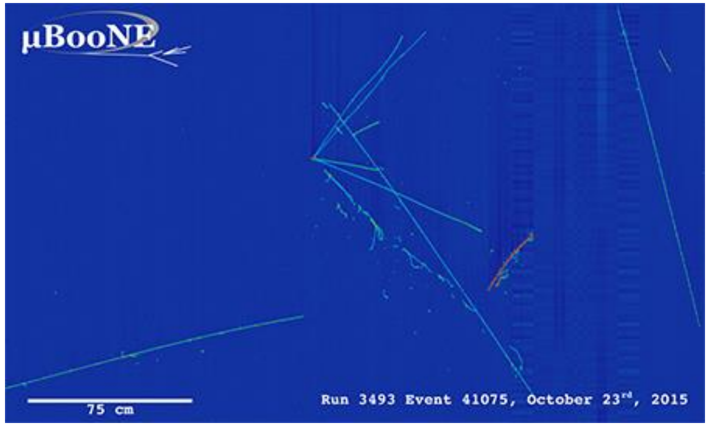
Kinetic energy of outgoing nucleons

Total energy of outgoing mesons

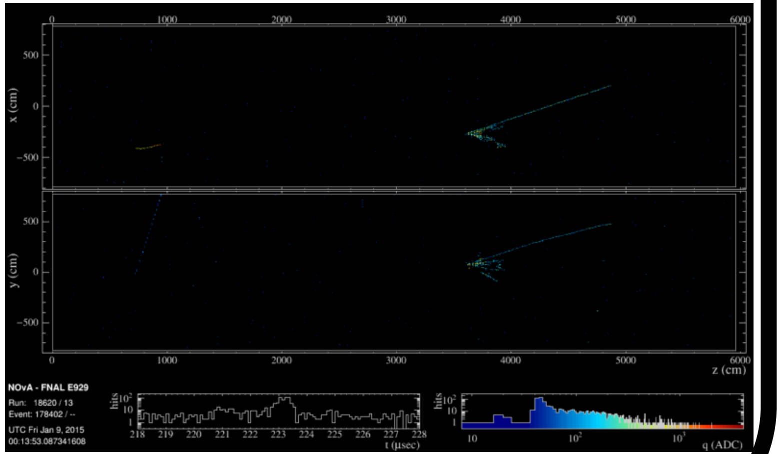
Problem: Sums include neutral particles (neutrons, π0) which might escape undetected

Far Detector Technologies

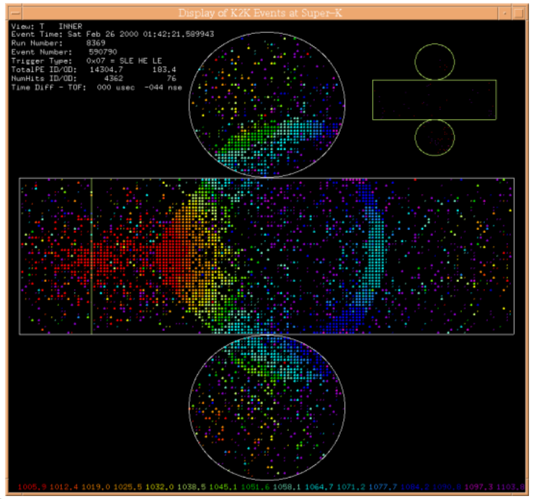
Liquid Argon
- LAr TPCs
- DUNE
- 10 kton per module (up to 4 in total)
- Baseline: 1300 km
- Target: Ar



Scintillator
- Bar tracker
- NOvA
- 14 kton
- Baseline: 810 km
- Target: CH



Water
- Water Cherenkov detectors
- SK and HyperK
- 22.5 and 190 kton
- Baseline: 300 km
- Target: H_2O



Many Expectations on Near Detectors

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What we want:

- $(\nu_e / \nu_\mu) / (\bar{\nu}_e / \bar{\nu}_\mu)$ cross-section ratio
- Understanding the nuclear effects
- Energy response function $T(E_{rec}, E_{true})$
- FD target cross-section
- Flux+cross-sections at various off-axis positions with the same detector
- Wrong-sign contamination in the beam
- Total intensity and direction of the neutrino beam

What we need:

- Large target mass
- Fine granularity
- Magnet
- Same target as in FD
- Low detection threshold
- Good PID and momentum reconstruction
- Detect neutral particles
- Moveable
- 4π acceptance with high efficiency

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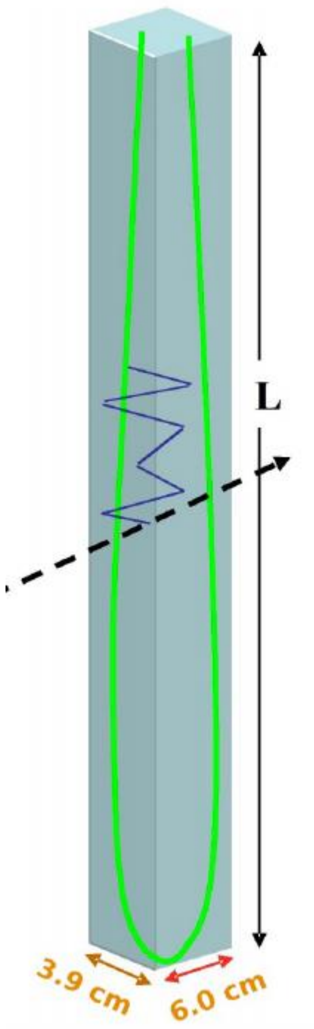
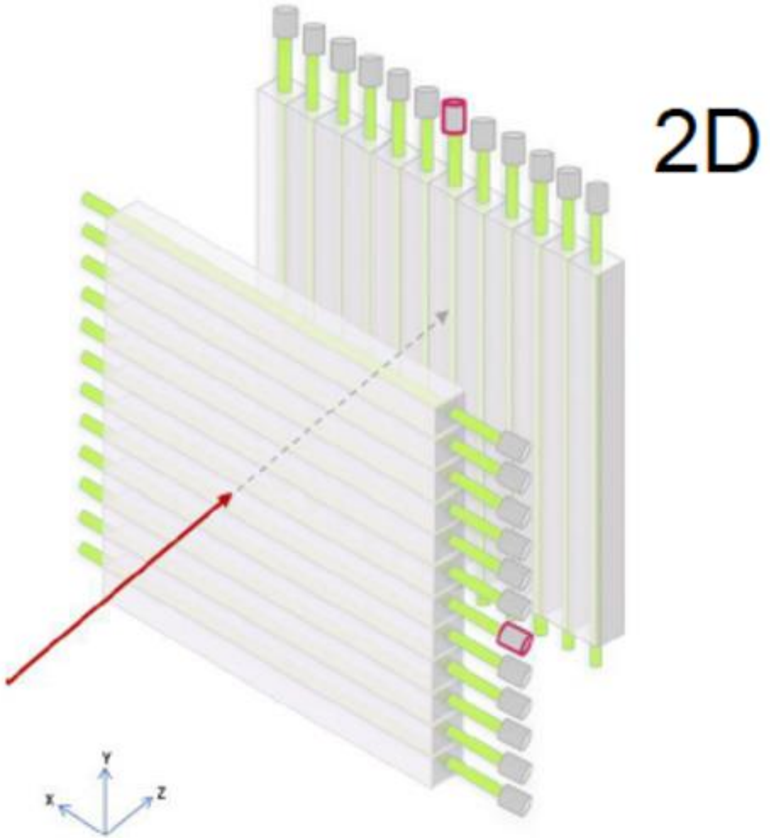
Hardly possible that one ND technology provides all this!

⇒ Selection of target detector technologies on the next slides

2D Scintillator Tracker

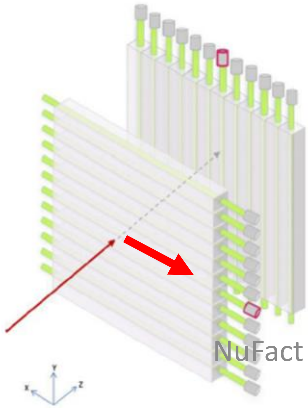


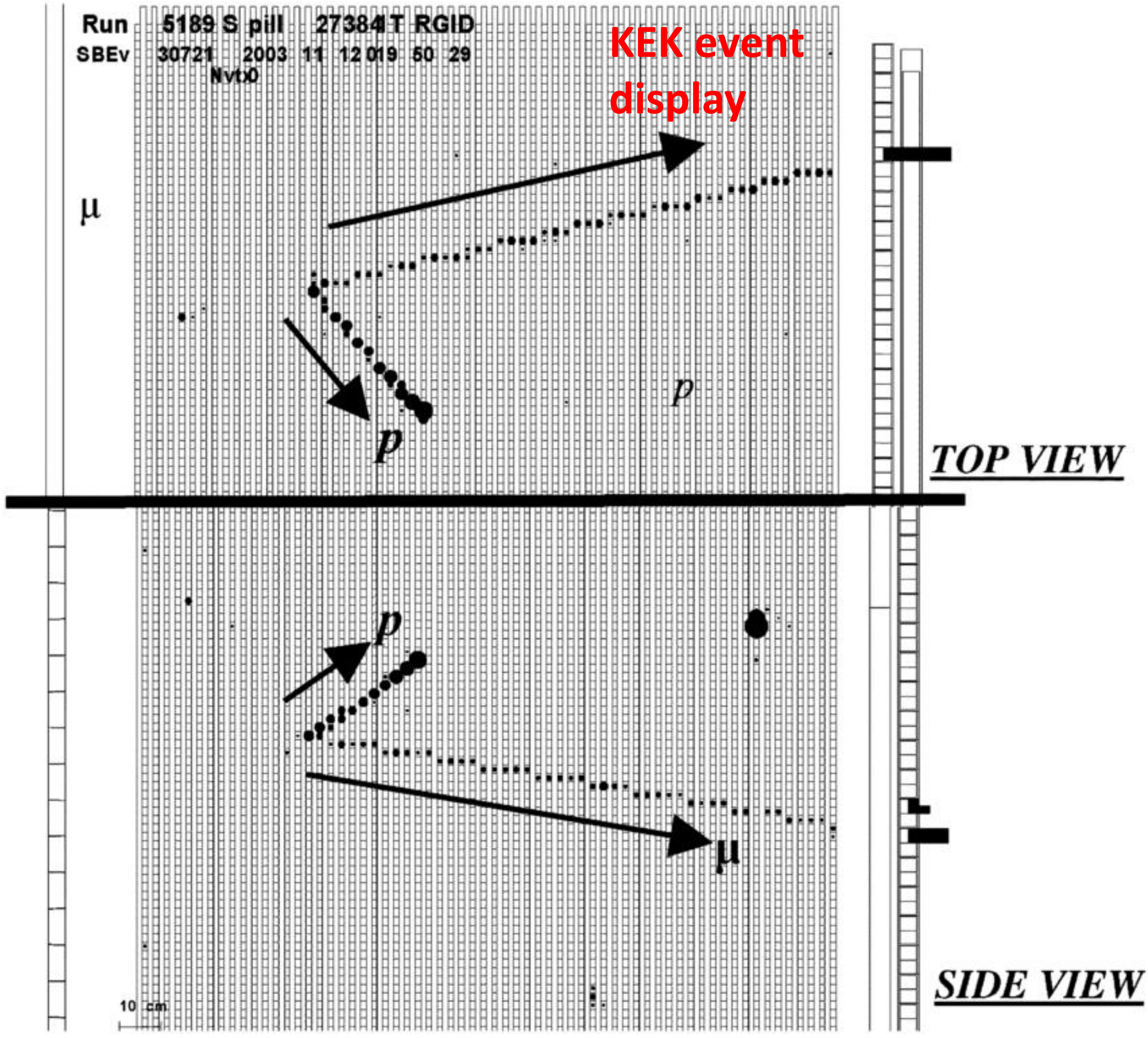
- Plastic/liquid scintillator excellent choice as target (several tons)
- Good light yield
- Excellent timing information
- Classical approach:
  - Scintillator bars with WLS fiber
  - Signal read by MPPC provides information about deposited charge
  - Alternating layers provide either xz or yz information of tracks
  - Freely choosable bar dimensions



2D Scintillator Tracker

- Very successfully used in K2K, T2K and NOvA
- Easy to construct
- Drawbacks:
  - Both views are independent and 3D reconstruction might be ambiguous
  - Relative high track detection threshold (at least 3 hits in each view)
  - High angle tracks (along one bar) not/badly reconstructed





3D Scintillator Tracker

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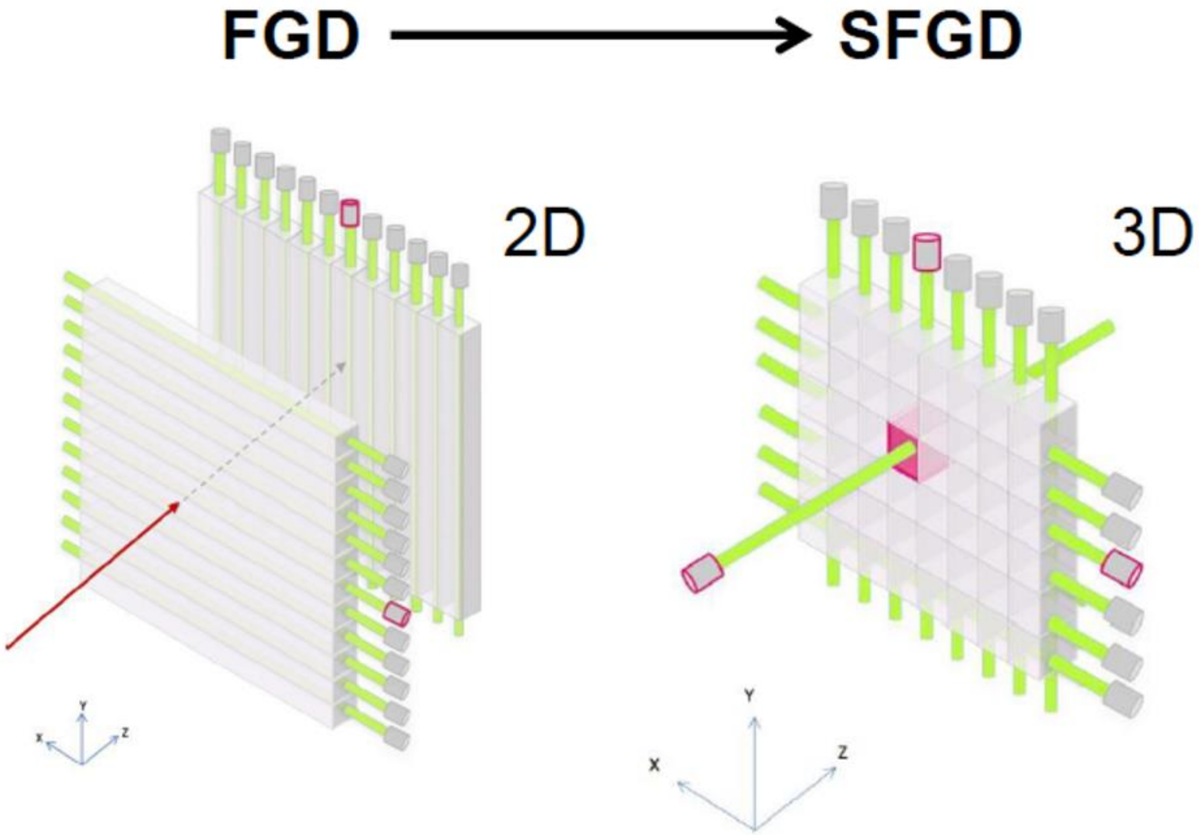
- How to overcome the drawbacks of the 2D tracker?
- Go 3D using cubes instead of bars and 3 WLS fibers per cube!
- “Minor” issues (for 2 ton detector):
  - Instead of 10,000 bars (1x1x200 cm^3), one needs 2,000,000 cubes (1x1x1cm^3)!
  - Readout channels go up from 10,000 to about 60,000!
  - Very stringent requirements on tolerances and alignment of the different components
- But impressive advantages as ND target



3D Scintillator Tracker: SuperFGD

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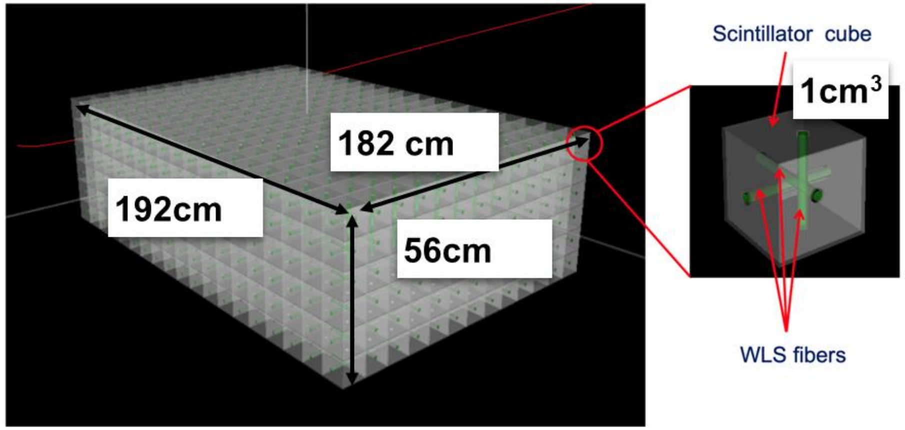
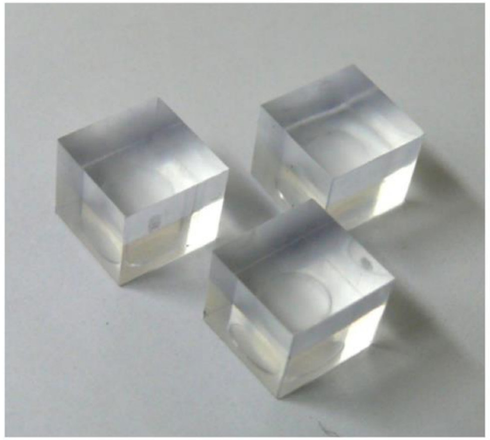
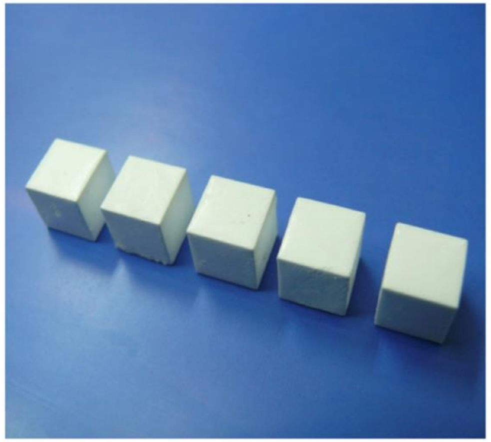
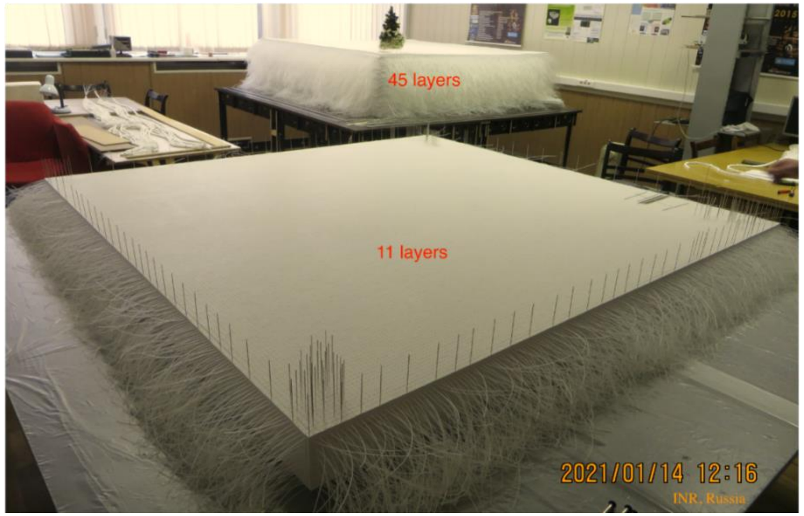
- Built for T2K ND280 Upgrade and installed in October 2023
- 2M optically isolated cubes produced and 6M holes precisely drilled
- Assembled in 56 layers with fishing lines
- Final assembly in box with WLS fibers









SuperFGD: Production + Assembly

IFAE Institute for High Energy Physics

- Production of cubes: ~100k per month
- Cube preparation:
  - 190 cubes for one string
  - 182 strings mounted to 1 layer (40k cubes)
  - ~20 months for all layers

(i) Support system assembly

(ii) First cube layer assembly

(iii) All 56 layers assembled

(iv) Stop panels removed

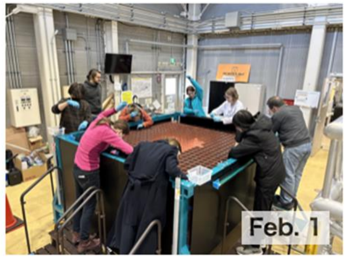
(v) Box closure

(vi) Transfer to new support

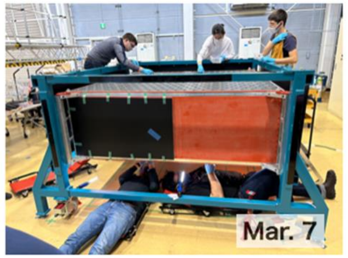
(vii) Horizontal fibers assembly

(viii) Wall MPPCs assembly

(ix) Vertical fibers assembly



(x) Top MPPCs assembly



(xi) LED calib. modules assembly

(xii) Light barrier/cables assembly

- Layer by layer installed carefully aligned with 56k holes in box
- Very slow and labour intensive assembly work
- ~6 months to complete assembly

SuperFGD: Performance

See talk by T. Doyle

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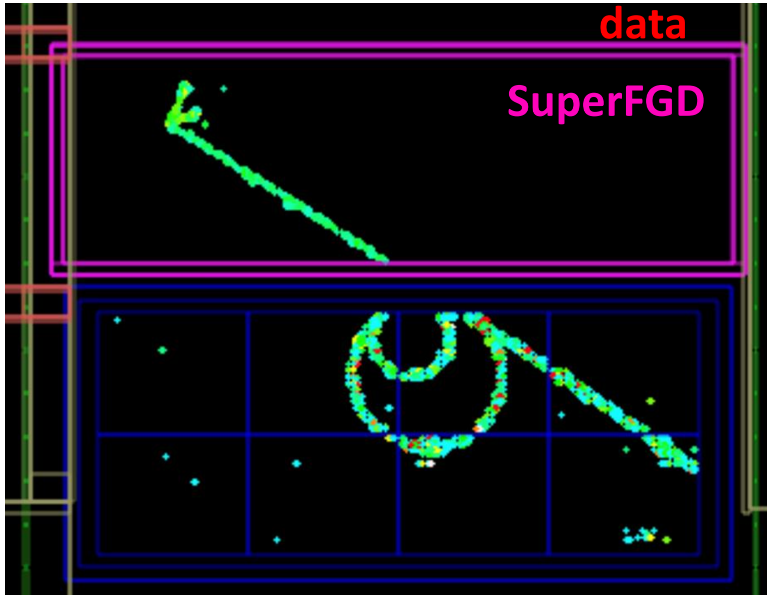
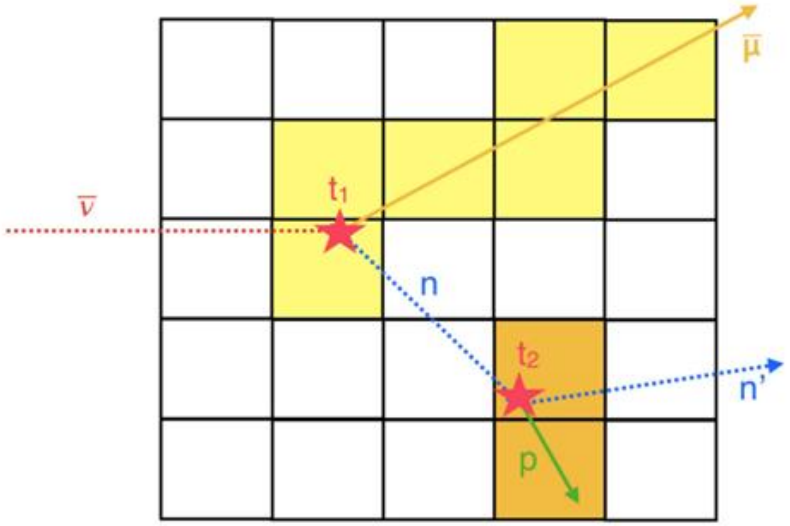
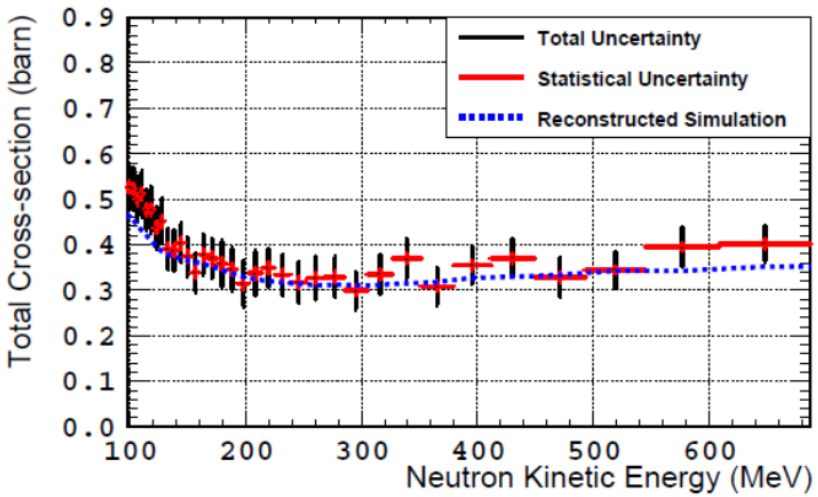
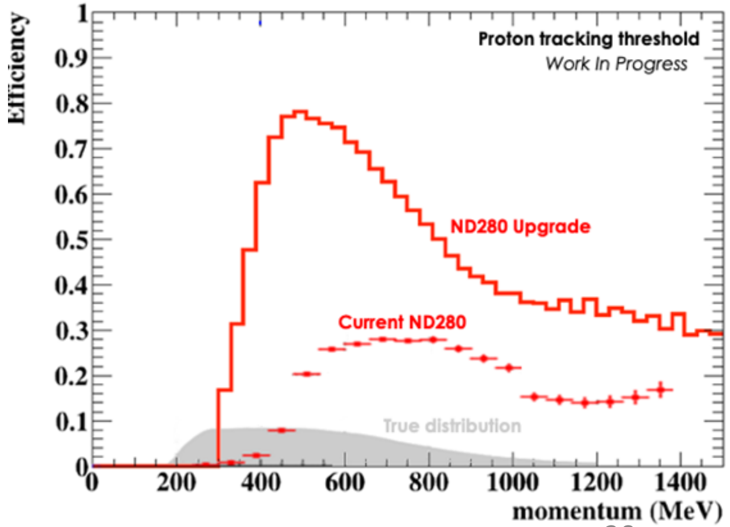
- First data with neutrino beam taken
- Much lower threshold for protons and much higher efficiency
- Allows detecting neutrons (tested with neutron testbeam) with about 50% efficiency
- Neutron energy reconstruction via TOF measurement possible









HyperFGD R&D

See talk by Umut Kose

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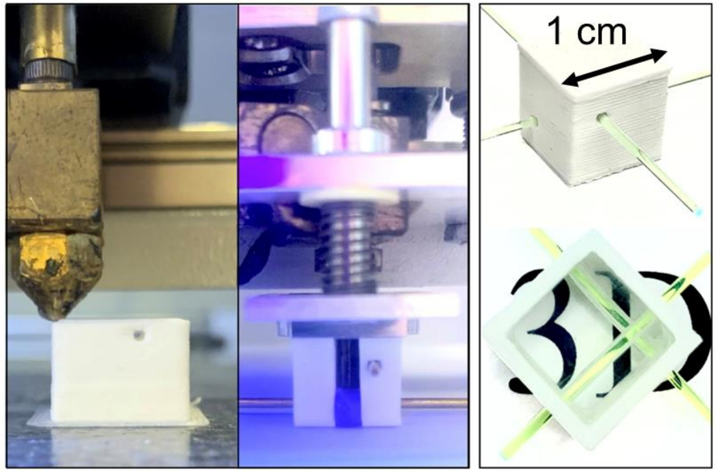
How to build HyperFGDs (SuperFGD++)?

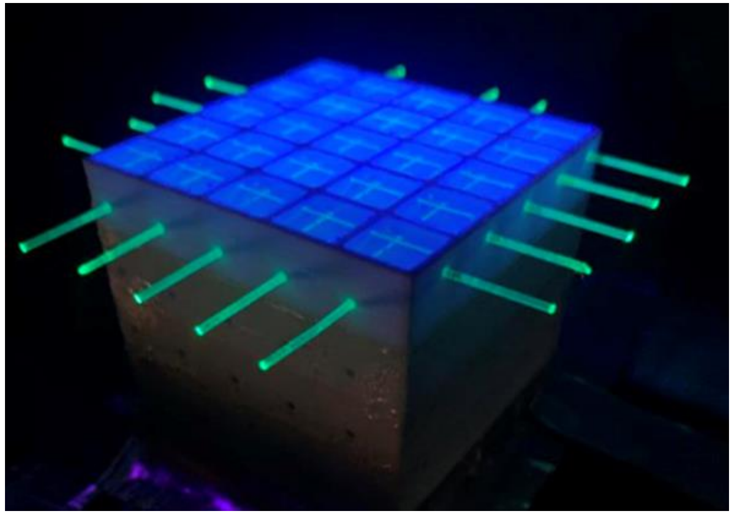
⇒ You do not want to handle 10M cubes and drill 30M holes by hand …

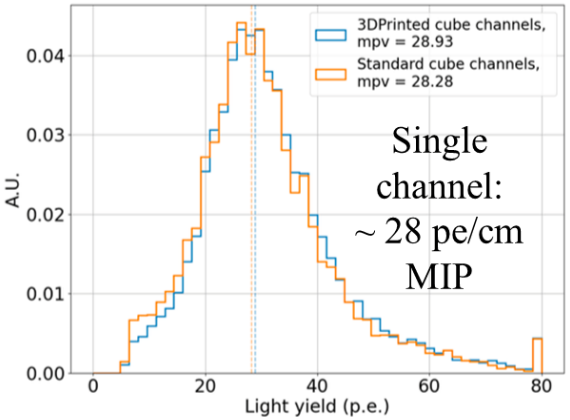
⇒ 3DET collaboration is developing 3D printing of plastic scintillator

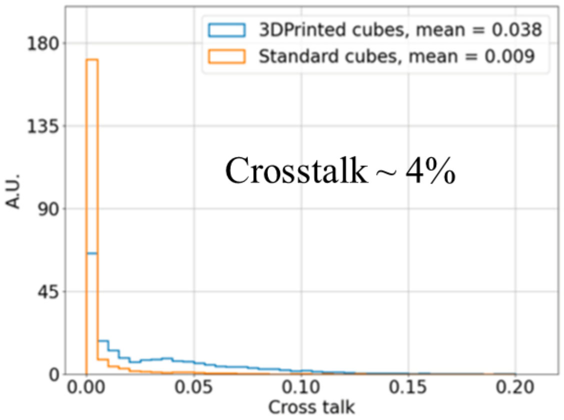
⇒ Prototype has been printed

⇒ Performance similar to standard cube production



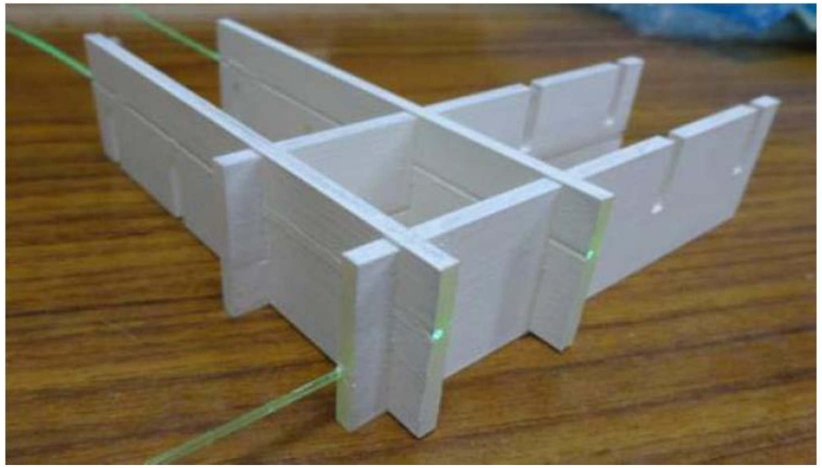


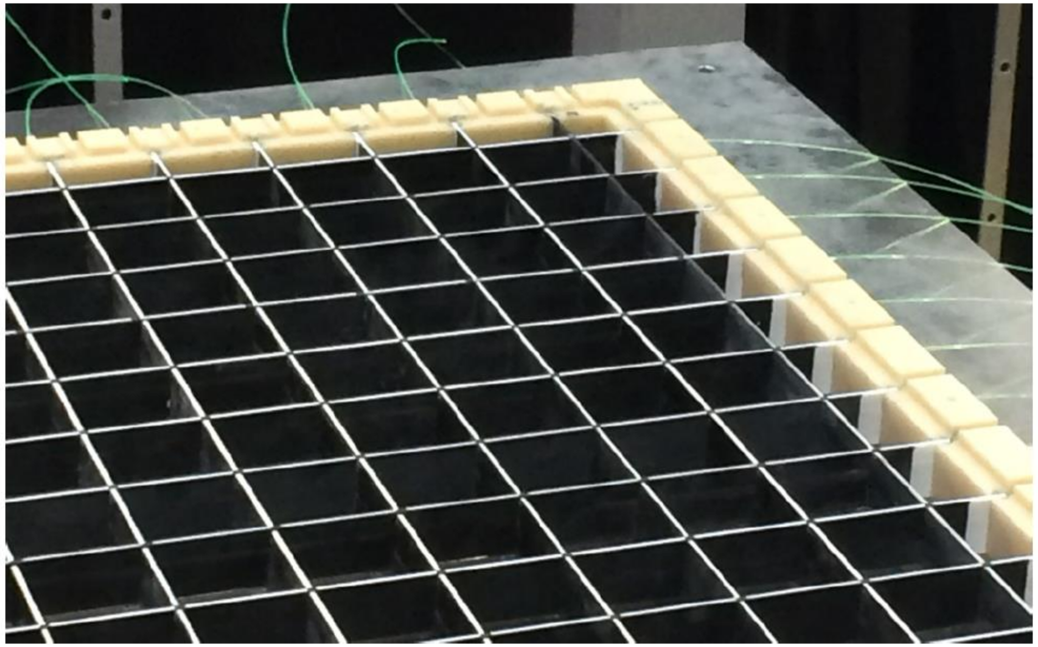


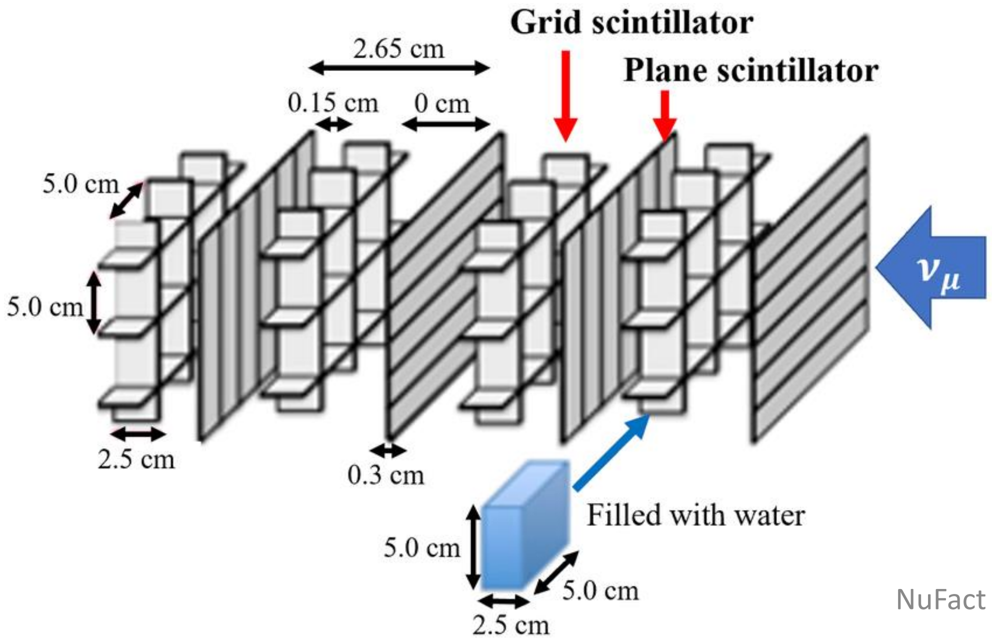


Plastic Scintillator Detector: WAGASCI

- Scintillators and WLS fibers to surround a voxel filled with water
- 80% H_2O and 20% CH as target
- Approach allows to measure cross-section on H_2O by subtracting known CH cross section (or to run without water for some runs)

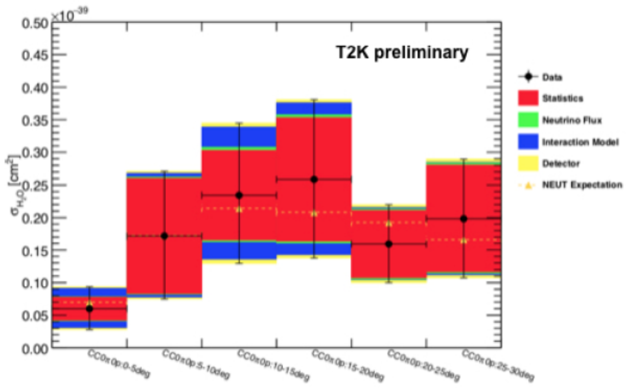


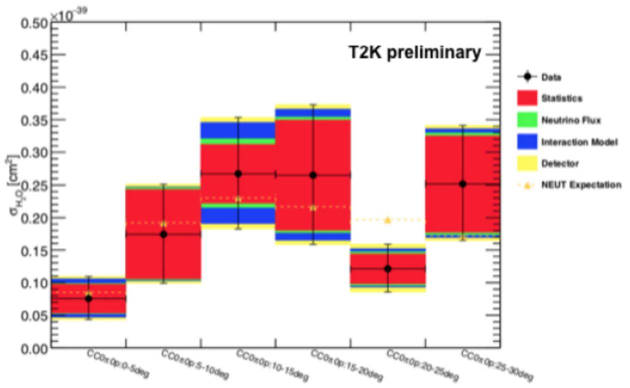




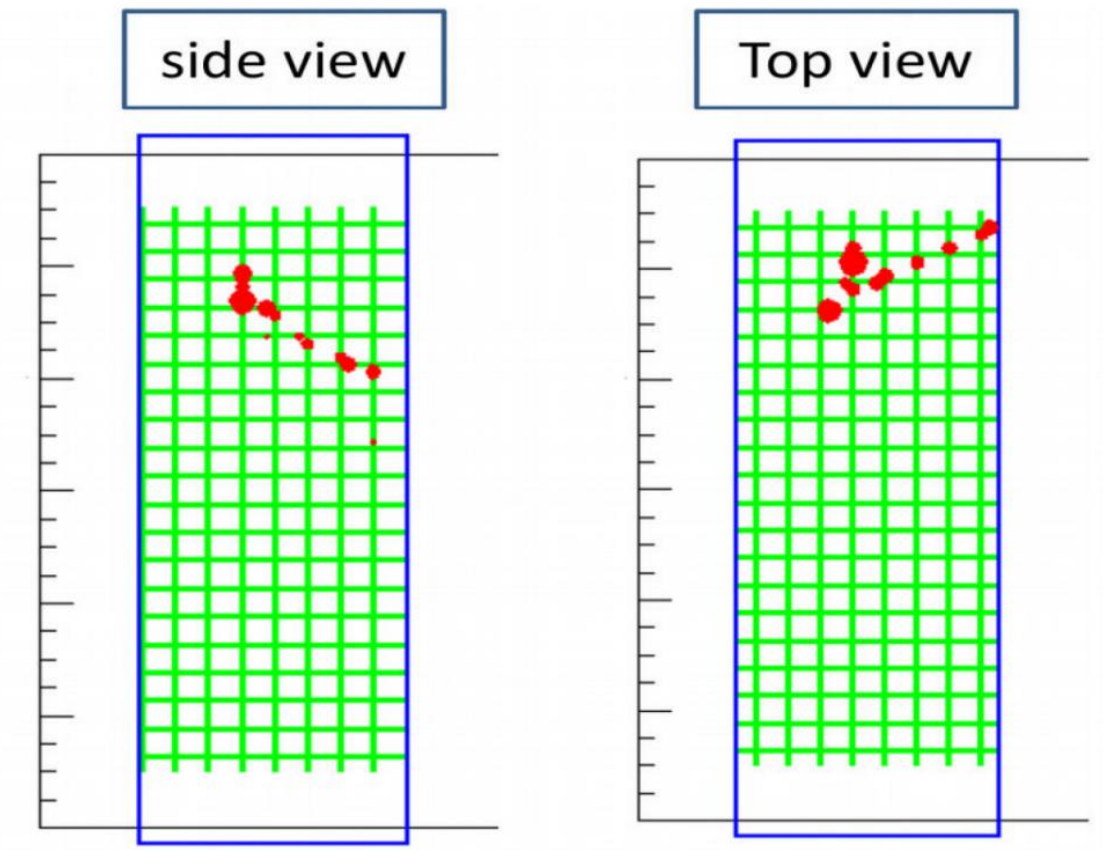
Plastic Scintillator Detector: WAGASCI

- Drawbacks:
  - Light yield limited
  - Smaller voxel size, imply smaller fraction of H_2O
- Detector of 700 kg operated at J-PARC at 1.5 degree off-axis
- First physics results presented in 2020
- R&D on similar concepts using fibres instead of scintillator panels ongoing



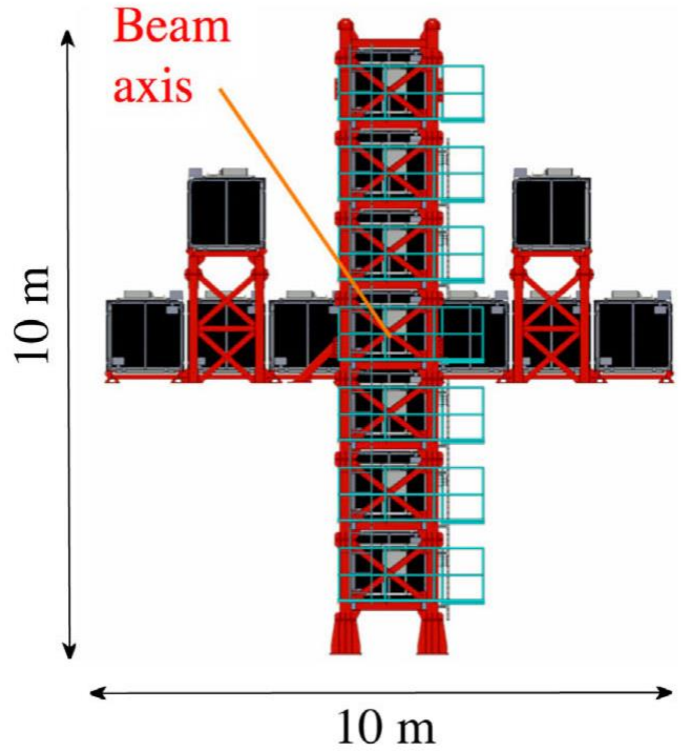


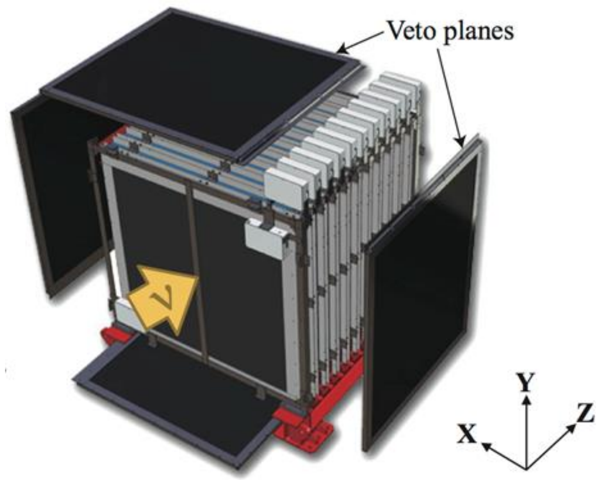
First event

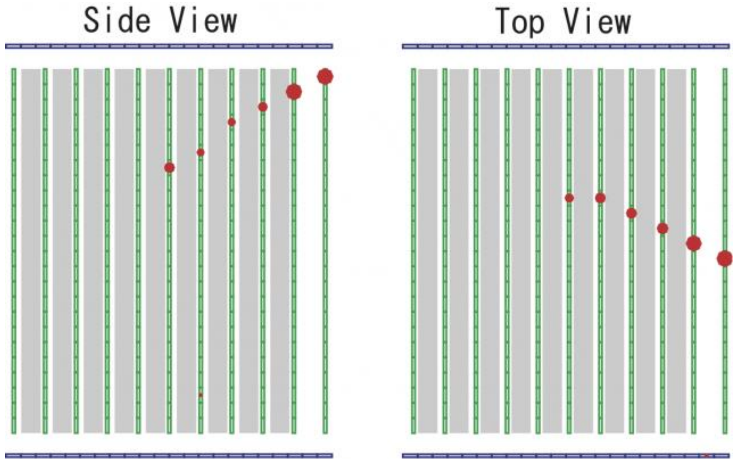


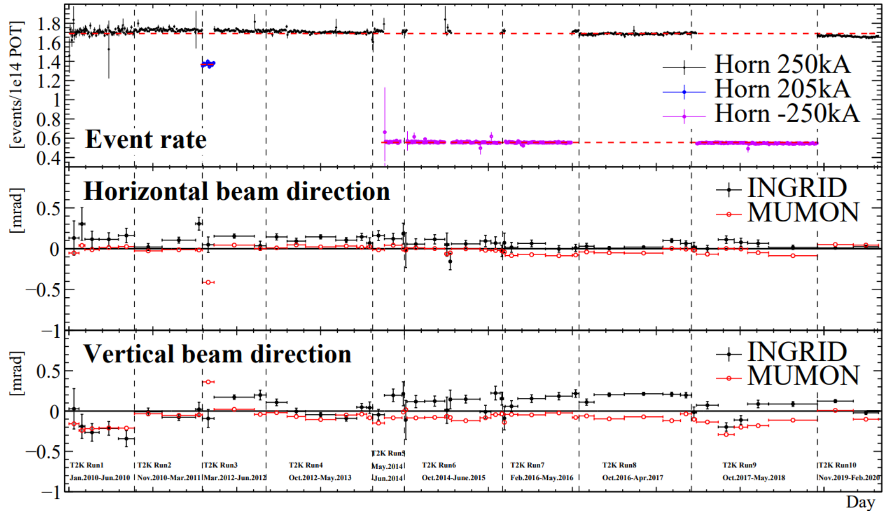
Plastic Scintillator Detector: INGRID

- Neutrino beam stability and direction crucial to control systematic uncertainties
- Simple but efficient approach: Sandwich of a lot of iron interleaved with tracking layers
- Oriented as cross allows reconstructing distribution of interaction horizontally and vertically $\Rightarrow$ beam profile
- No vertex activity information but crucial for data taking in T2K









Plastic Scintillator Detector R&D

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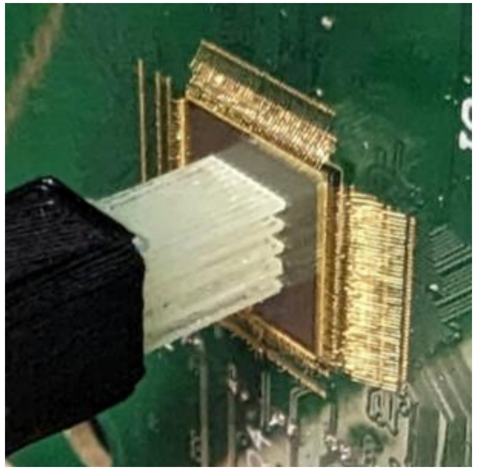
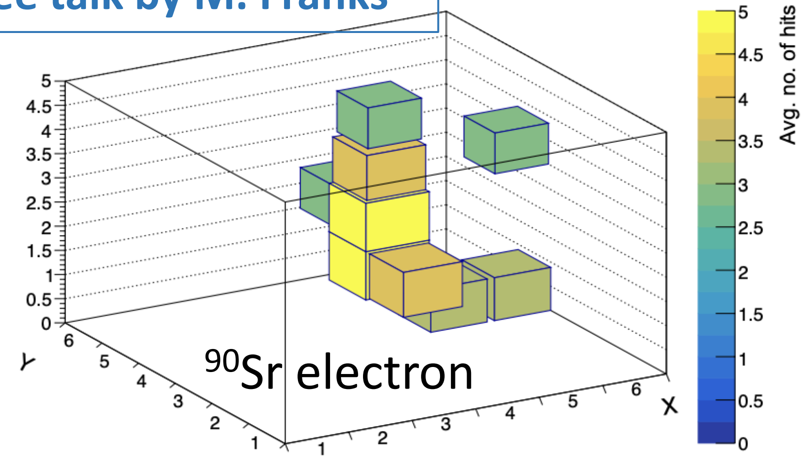
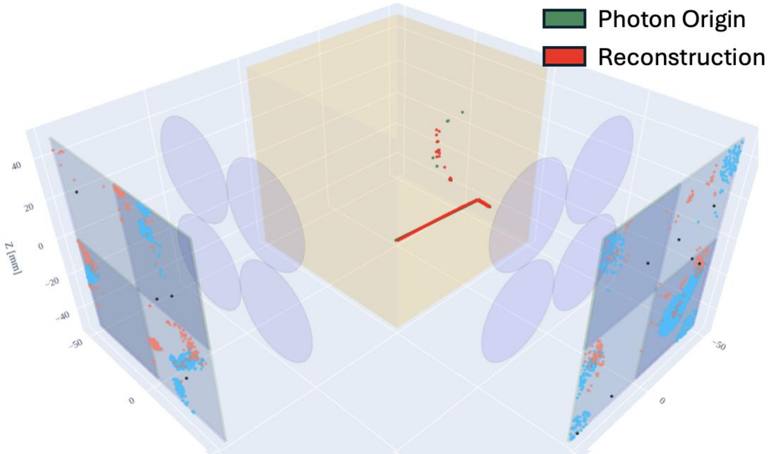
- Development at ETH Zurich of CMOS SPAD array imaging sensors (goal: 1 cm^2)
- Each pixel is a readout channel
  - Position of each pixel (20 µm)
  - Single pixel sub-ns resolution
  - Monolithic: digitization on chip

See talk by M. Franks





Cheap solution for read out scintillating fibres → reconstruct protons ≥150 MeV/c



See talk by T. Dieminger

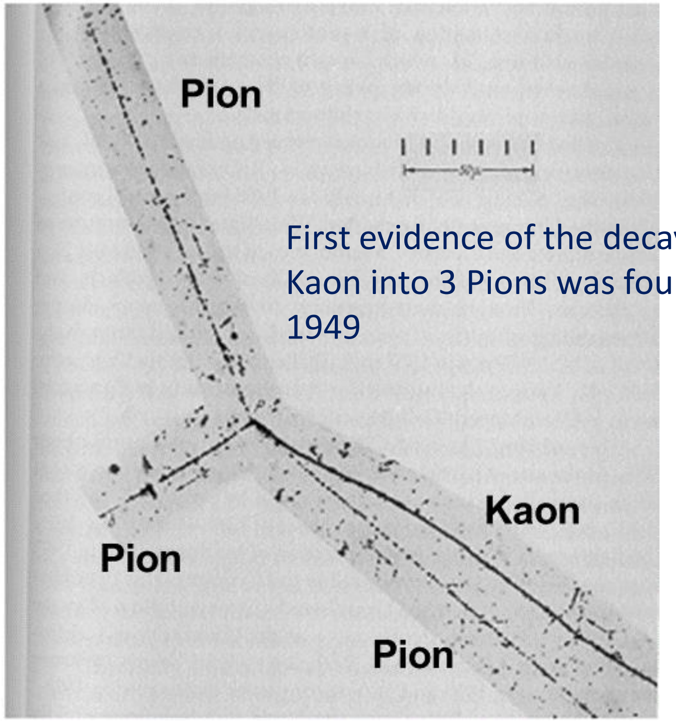
PLATON:

- 3D photographs of ν interactions in scintillator
- Potential for sub-mm spatial resolution

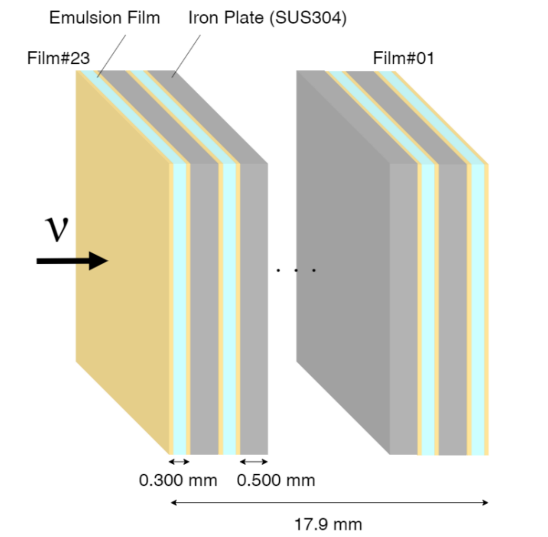
Nuclear Emulsion Detector: NINJA

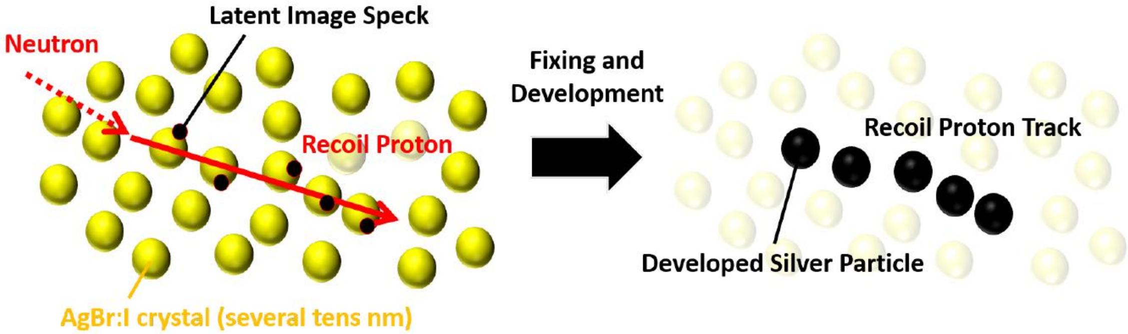
Institute for High Energy Physics

- Historical detector providing e.g. first evidence of Kaon into 3 pion decay
- Adaptation of classical photography $\Rightarrow$ biggest drawback: film needs to be extracted, developed and scanned
- Biggest advantage: excellent point resolution defined by grain size (< μm resolution)
- Sampling approach: emulsion films interleaved with target material



First evidence of the decay of the Kaon into 3 Pions was found in 1949

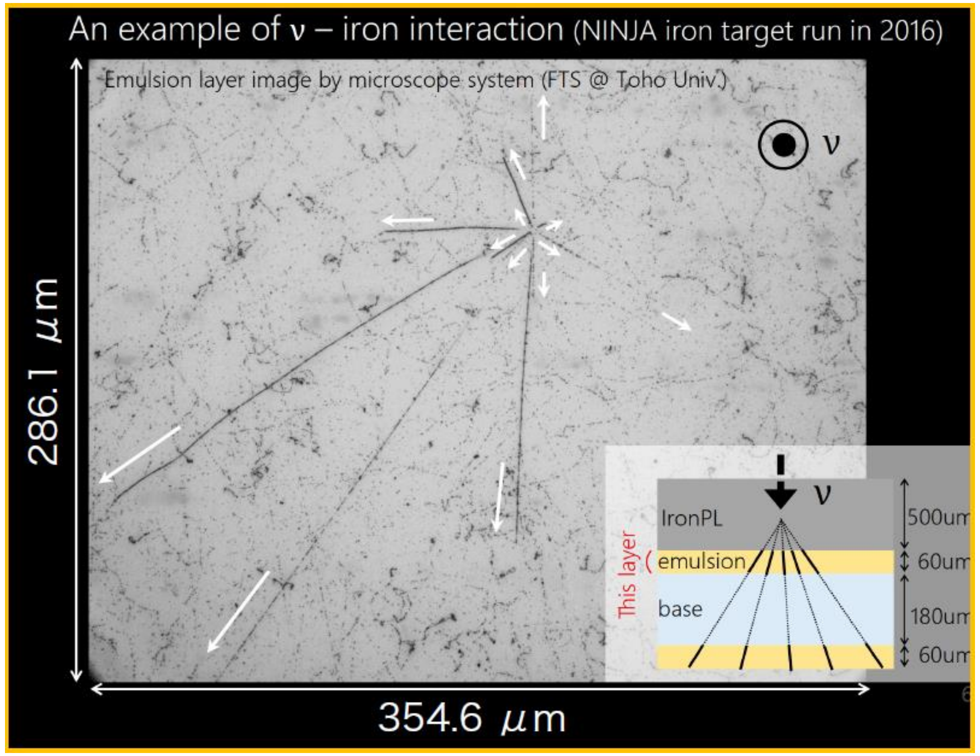




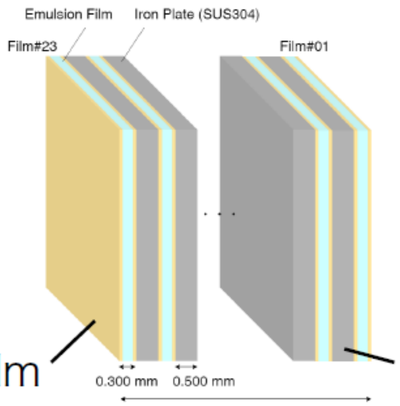
Nuclear Emulsion Detector: NINJA

Institute for High Energy Physics

- Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator (NINJA)
- Operated at T2K beamline (next to WAGASCI)
- Started with Fe target, more recently with H_2O
- Excellent spatial resolution allows to distinguish if interaction happened in emulsion or target
- Low detection threshold
- R&D ongoing to improve performance => e.g. thicker emulsion layer to improve angular resolution



Iron ECC

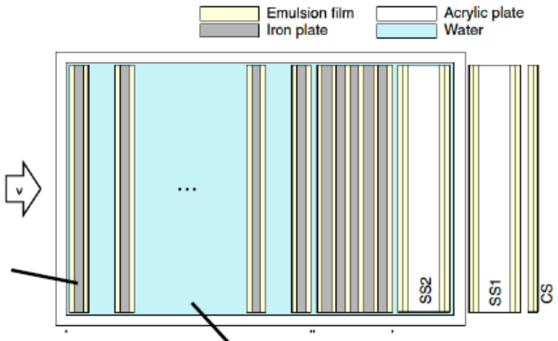


Emulsion film

Iron plate

Water ECC

Emulsion film + Iron plate



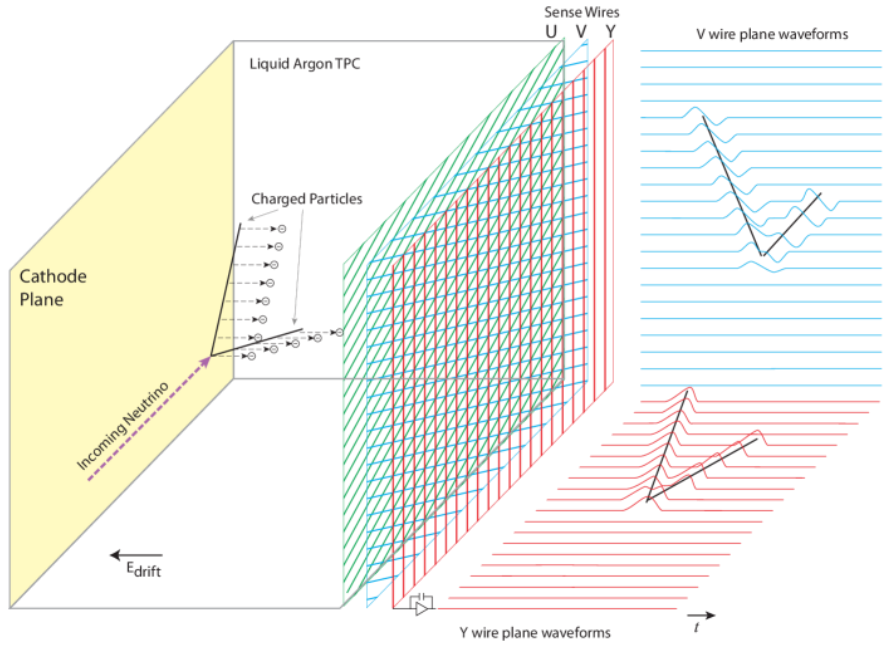
Water

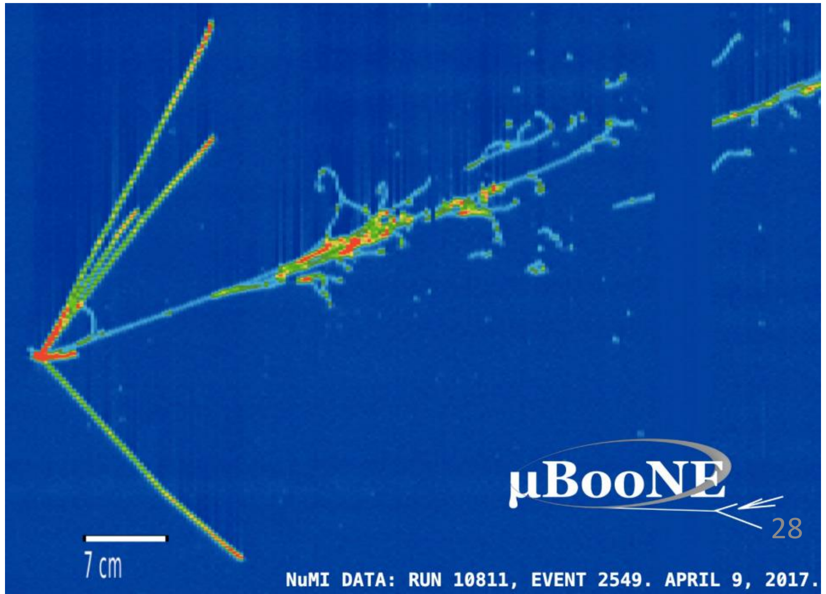
See talk by T. Hayakawa
See poster by N. Otani

Liquid/Gaseous Detectors: LAr TPC

Institute for High Energy Physics

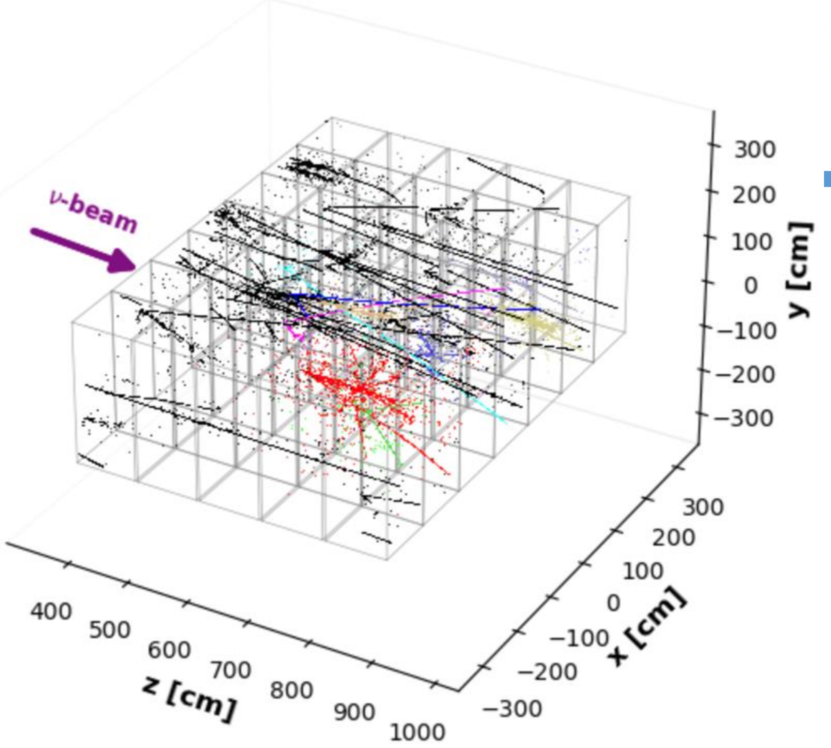
- LAr TPC technology has been developed for more than 20 years
- Provides bubble chamber like images of event with low detection threshold
- Possible to have large, completely sensitive detection volumes
- Very interesting technology for ND if FD also used this technology (DUNE)
- But some drawbacks:
  - Very slow detector with readout windows of about 500 μs per m of drift
  - Cryogenic system and electronics needed
  - Challenging to have magnetized/moveable detector

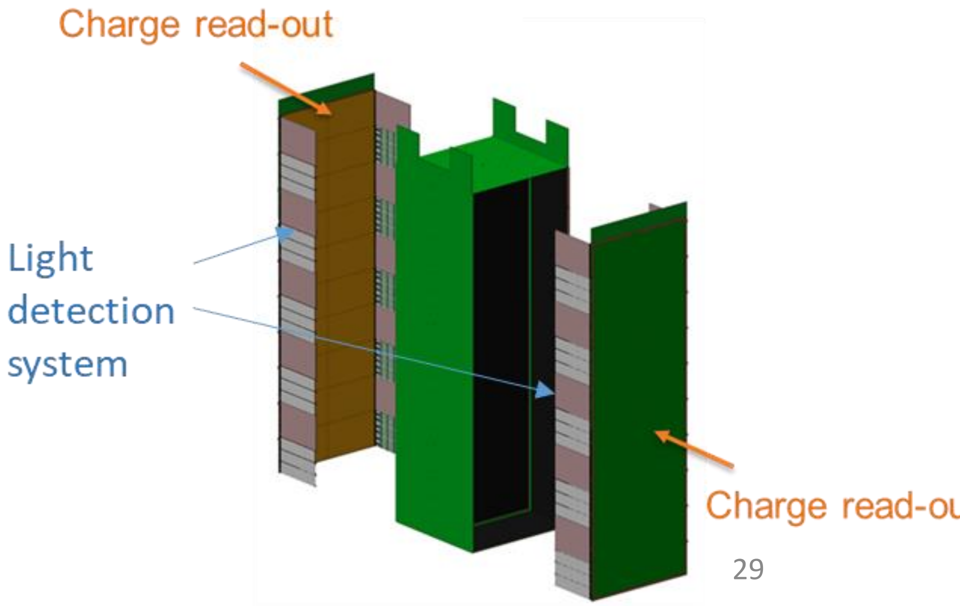




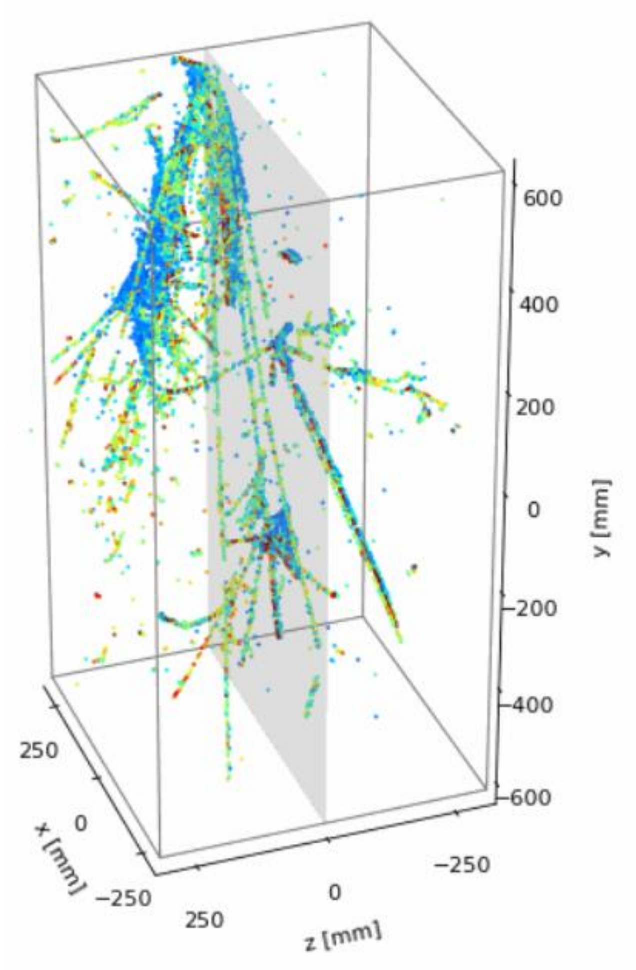
Liquid/Gaseous Detectors: LAr TPC

- Impressive R&D work towards a LAr TPC for ND ongoing since many years
- Biggest Challenge to overcome: Pile-up!
- For DUNE with 130 ton of LAr and 1.2 MW beam, about 50 events are expected during one spill
- Complicates event reconstruction
- Collaboration works on interesting ideas:
  - Pixel instead of classical wire readout including development of dedicated ASIC for LAr
  - Independent modules each with photon detection system



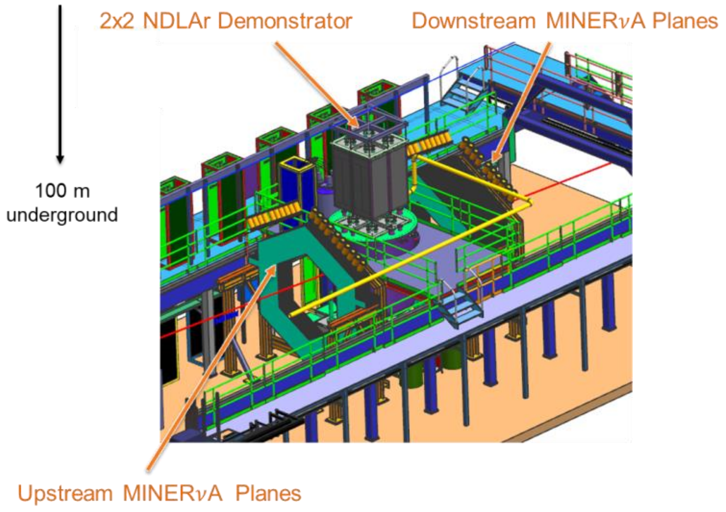


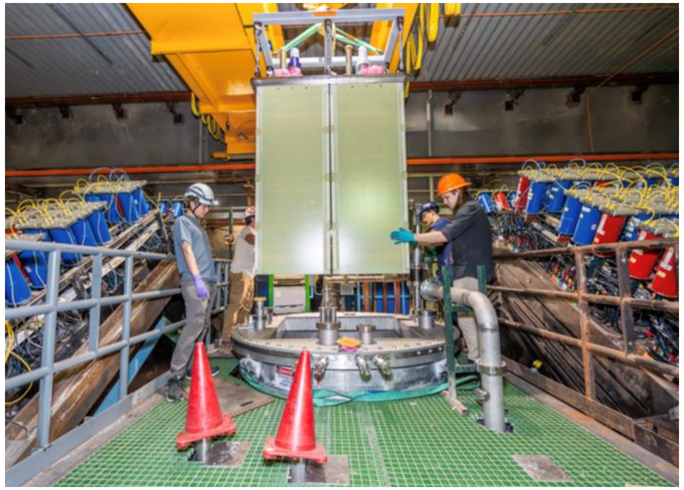
Liquid/Gaseous Detectors: LAr TPC



- Several prototypes were built
- Millions of cosmics taken with large module 0 from 2021 to 2023
- 2x2 NDLAr demonstrator currently taking neutrino data in MINERvA pit (330k pixels charge readout + light detection system)
- Important step towards final NDLAr TPC

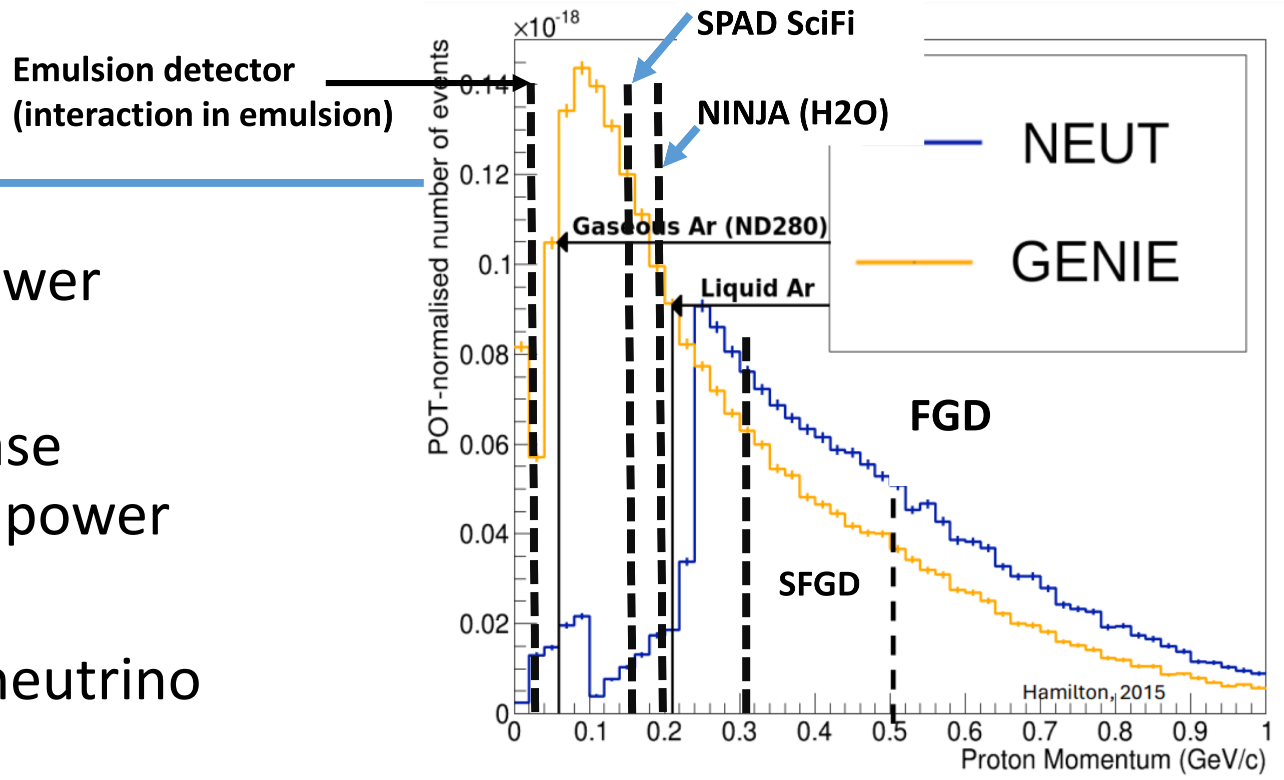
See talks by A. Cudd and S. Kumaran

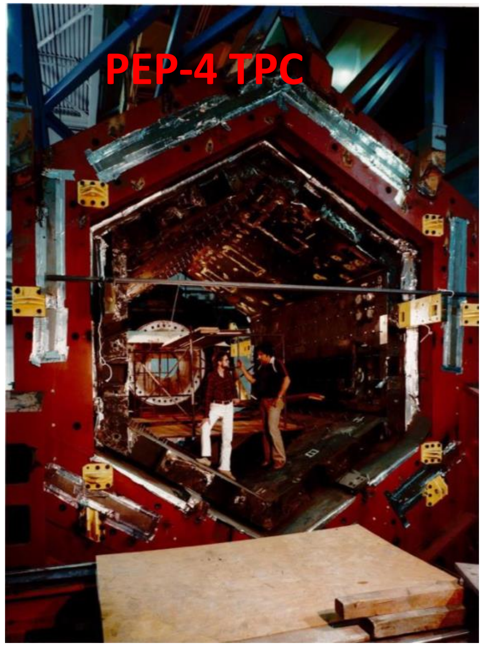




Liquid/Gaseous Detectors: HP TPC

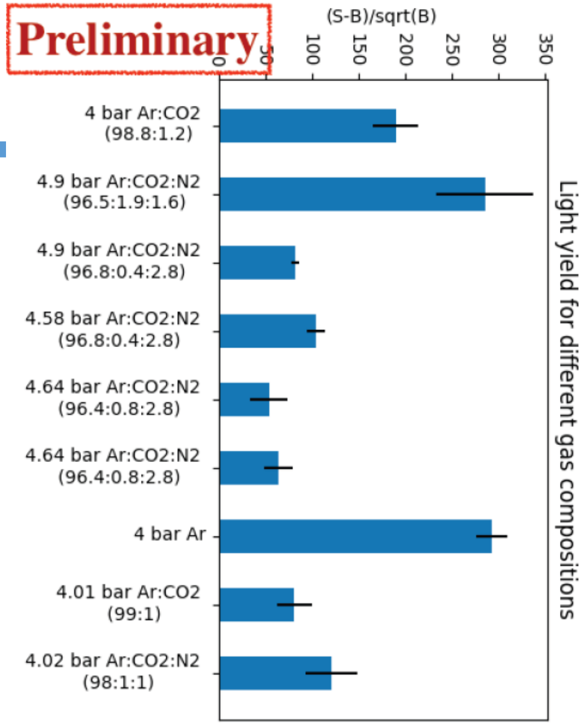
- Gaseous TPCs would allow to go to even lower detection thresholds than LAr
- Low density implies low statistics => increase pressure to 10 to 15 bar + profit from high power beams
- Ideal to study nuclear effects relevant for neutrino interactions
- Possibly same detector could be used with different gases => different targets
- HP TPC R&D ongoing since many years for several applications (first TPC in 1979 was a HP TPC)
- HP TPC R&D is also part of the DRD1 collaboration
- Atm TPC also used for PID $\Rightarrow$ see talk G. Collazuol



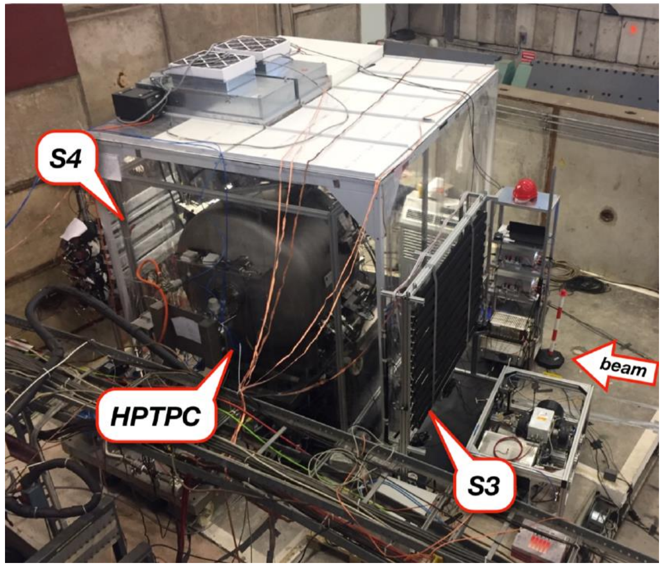


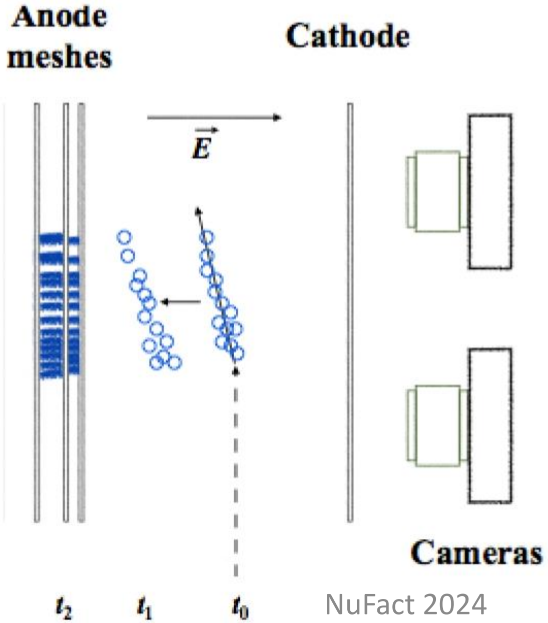
Liquid/Gaseous Detectors: HP TPC

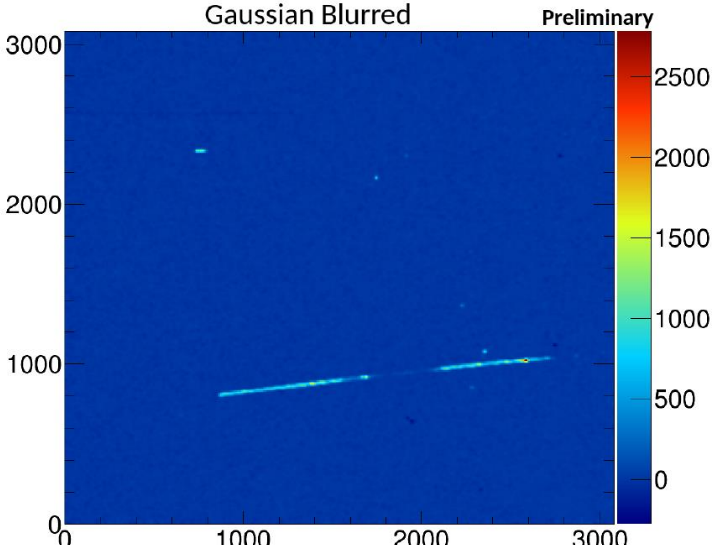
- R&D carried out at many institutes
- UK-led collaboration built large prototype and tested at T10 beamline at CERN
- Images of events taken by 4 CCD cameras behind the cathode
- Tested light yield with various gas mixtures



Instruments 2021, 5(2), 22



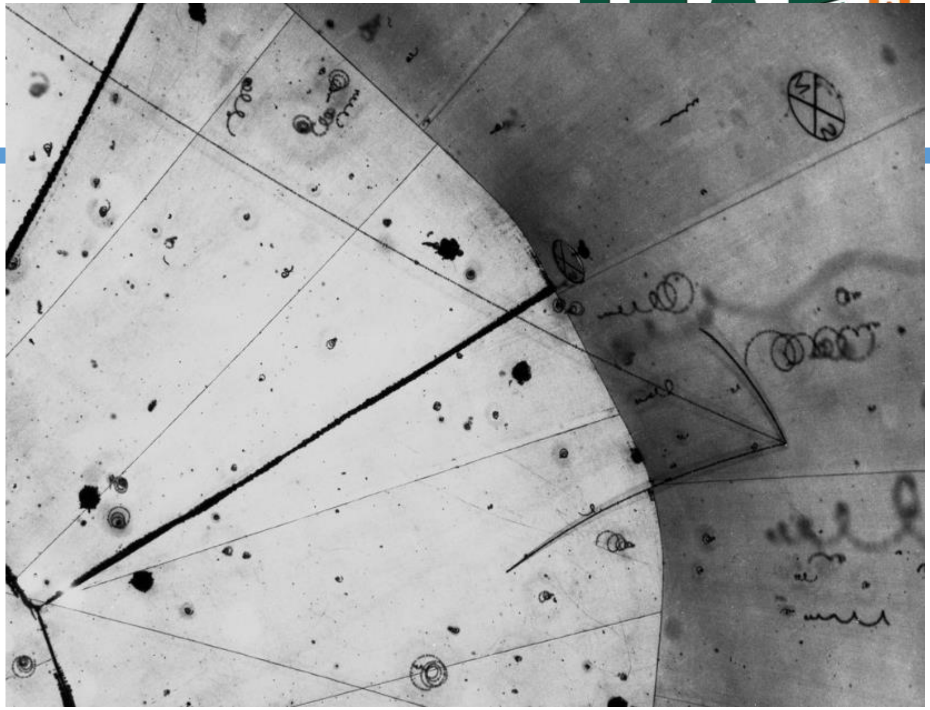


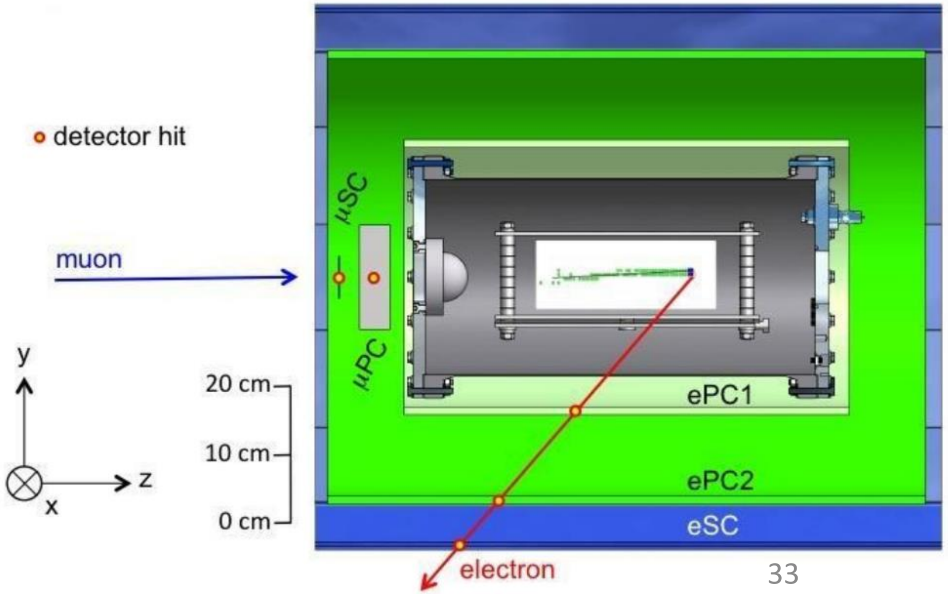


Liquid/Gaseous Detectors: HP Hydrogen TPC

- Neutrinos were studied in hydrogen bubble chambers
- Pure hydrogen TPC would be interesting
- First was built 1984 (Nuclear Instruments and Methods in Physics Research 225 (1984) 550-556)
- More recently the MuCap experiment at PSI uses a hydrogen TPC at 10 bar to study muon capture
- Several challenges:
  - Safety
  - Scaling to larger volumes
  - Low density of H2 => 20 times less statistics than Ar
  - Few electrons per cm for MIPs => small signals

$\Rightarrow$ Lots of interesting R&D possible (could be also for other technologies allowing H as target)

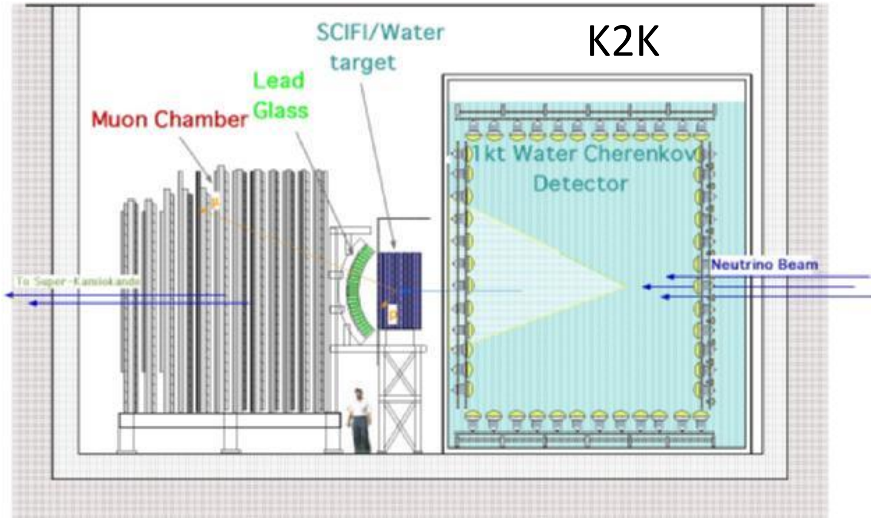




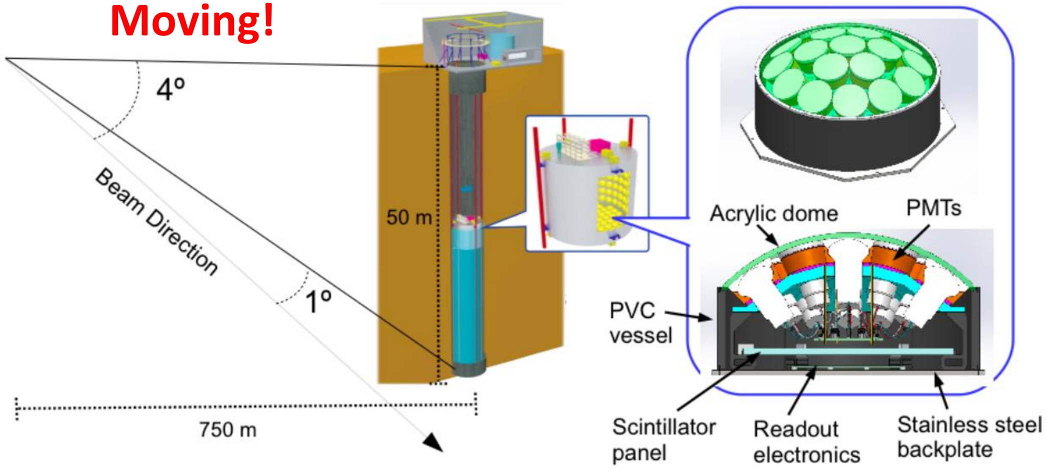
Water Cherenkov Detectors

Institute for High Energy Physics

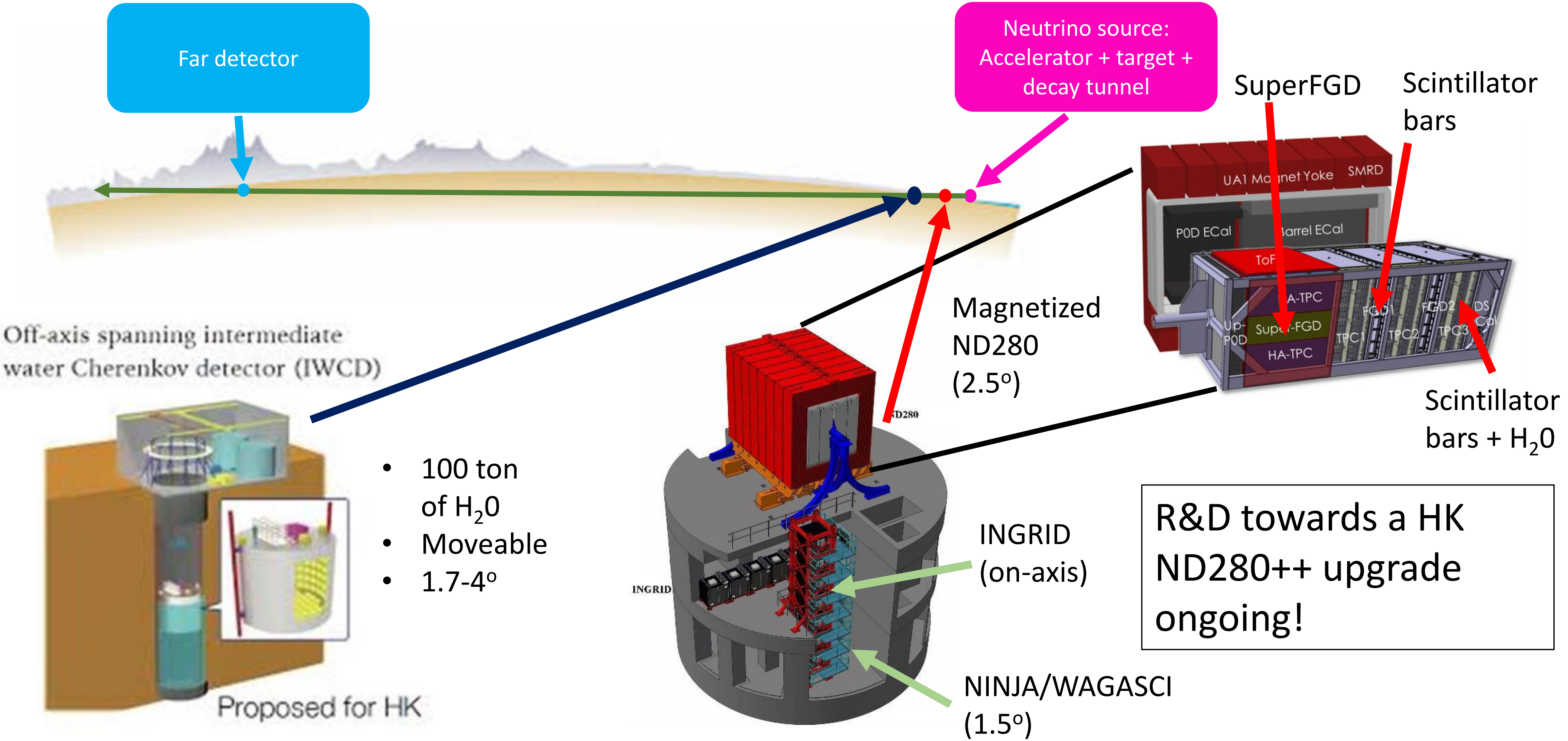
- Water Cherenkov detectors are excellent as FD (SK/HK)
- Some drawbacks as ND:
    - High detection threshold
    - No vertex activity information
    - Particles often not contained (much smaller than FD)
    - Limited size affects ring development
- But also advantages:
    - Cost effective for large masses => interesting for ν_e measurements
    - Same target material
- K2K had 1 kton WC detector
- Significant R&D work ongoing for Intermediate Water Cherenkov Detector (IWCD) for HK including testbeam at CERN (WCTE)



Moving!



T2K/HK Case



- 100 ton of H_20
- Moveable
- 1.7-4°

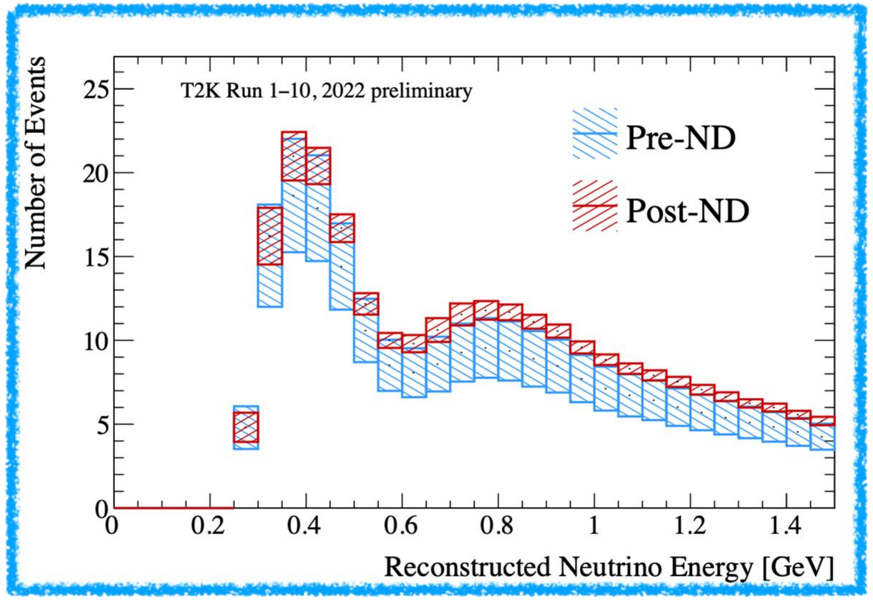
R&D towards a HK ND280++ upgrade ongoing!

Conclusions

Institute for High Energy Physics

- Near detectors are crucial for success of LBNO experiments
- Especially true for DUNE and HK which will be systematic uncertainties limited
- Reduction of systematic uncertainties from about 15-20% to about 3-6%
- Achieved by development of large variety of excellent ND technologies
- There is not “the-one-and-only” ND technology but the combination of different ones is the key
- Possibly opens possibilities for new BSM studies
- Still room for a lot of R&D and new ideas!
- Join the WG6 sessions for much more detailed talks

SK Single ring μ-like sample



C. Giganti talk at Neutrino 2024

NuFACT 2024 Talks and Posters

- NINJA:
  - Tomohiro Hayakawa, Sep 18, 2024, 12:22 PM, WG2
- SuperFGD:
  - Tristan Doyle, Sep 19, 2024, 2:05 PM, WG6
- LAr TPC:
  - Sindhujha Kumaran, Sep 19, 2024, 4:35 PM, WG6
  - Andrew Cudd, Sep 19, 2024, 4:39 PM
- TPC:
  - Gianmaria Collazuol, Sep 19, 2024, 5:15 PM
- Plastic Scintillators:
  - Matthew Franks, Sep 20, 2024, 3:25 PM
  - Till Dieminger, Sep 20, 2024, 3:05 PM

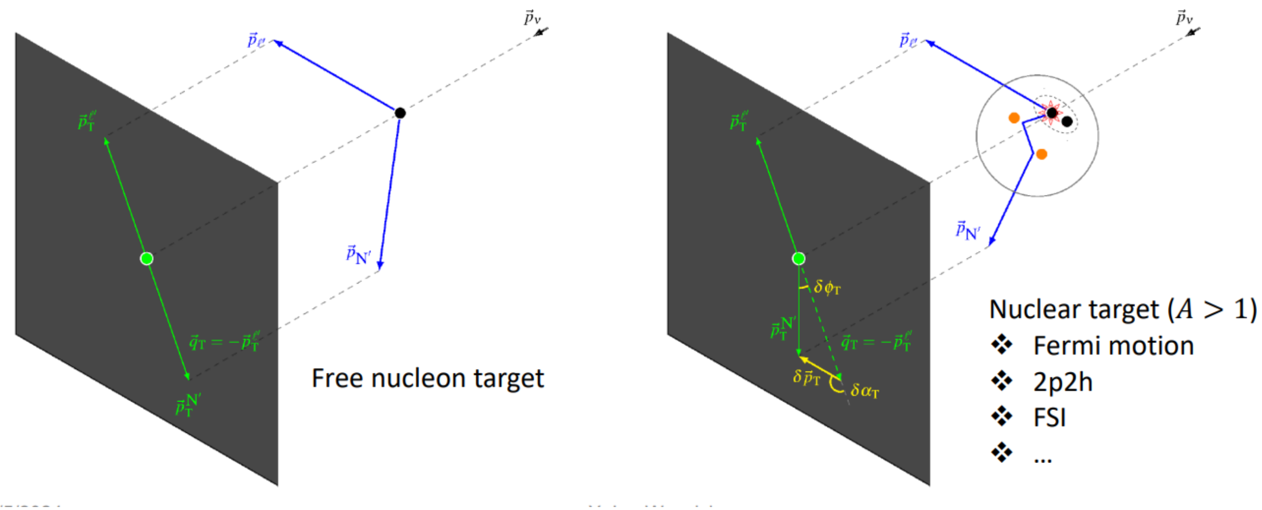
Publications

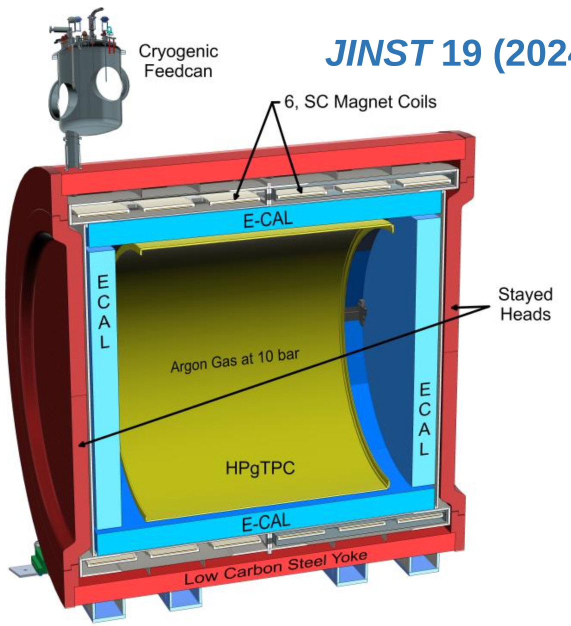
- HP-TPC:
  - Instruments 2021, 5(2), 22
  - JINST 19 (2024) 06, P06018
  - Phys. Rev. D 102, 033005
  - arXiv:1910.06422v1 [physics.ins-det] 14 Oct 2019
  - CERN-SPSC-2017-030 / SPSC-P-355
- MuCap:
  - *Nucl.Instrum.Meth.A* 628 (2011) 199-203
  - SciPost Phys. Proc. 5, 017 (2021)
- Plastic Scintillators:
  - IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 52, NO. 6, DECEMBER 2005
  - 2020 *JINST* **15** P12003
  - Physics Letters B, Volume 840, 10 May 2023, 137843
- NINJA:
  - https://j-parc.jp/researcher/Hadron/en/pac_1801/pdf/P71_2018-4.pdf
  - Prog. Theor. Exp. Phys. **2022** 063H01
- WAGASCI:
  - Journal of Physics: Conference Series 1468 (2020) 012152
  - arXiv:1610.06367v1 [physics.ins-det] 20 Oct 2016
- ND LAr TPC:
  - arXiv:1808.02969v3 [physics.ins-det] 16 Sep 2018

Small selection …

Liquid/Gaseous Detectors: HP TPC R&D

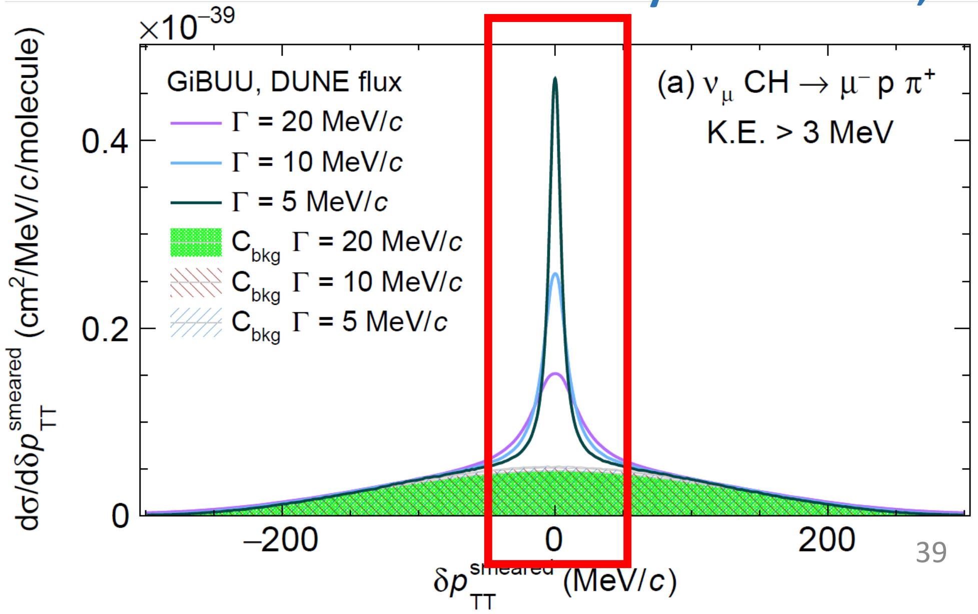
- Aim: gas mixture enriched in hydrogen
- Transverse Kinematic Imbalance analysis to select events on free protons => no nuclear effects
- Problem is pressure vessel: all detectors (HP TPC, ECAL, …) must be inside => conceptual design for DUNE





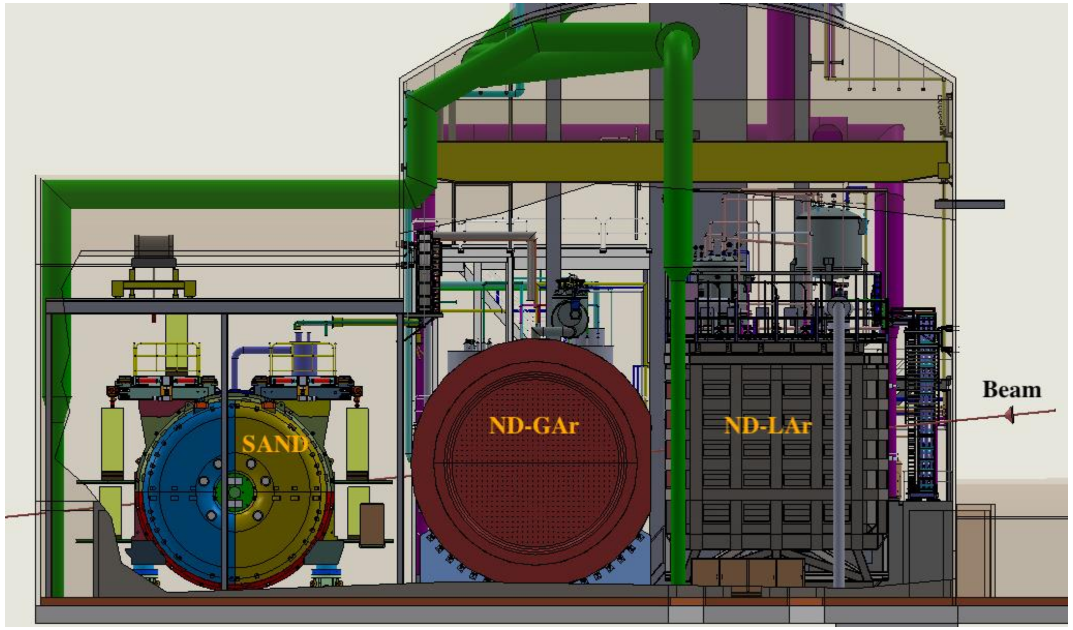
JINST **19 (2024) 06, P06018**

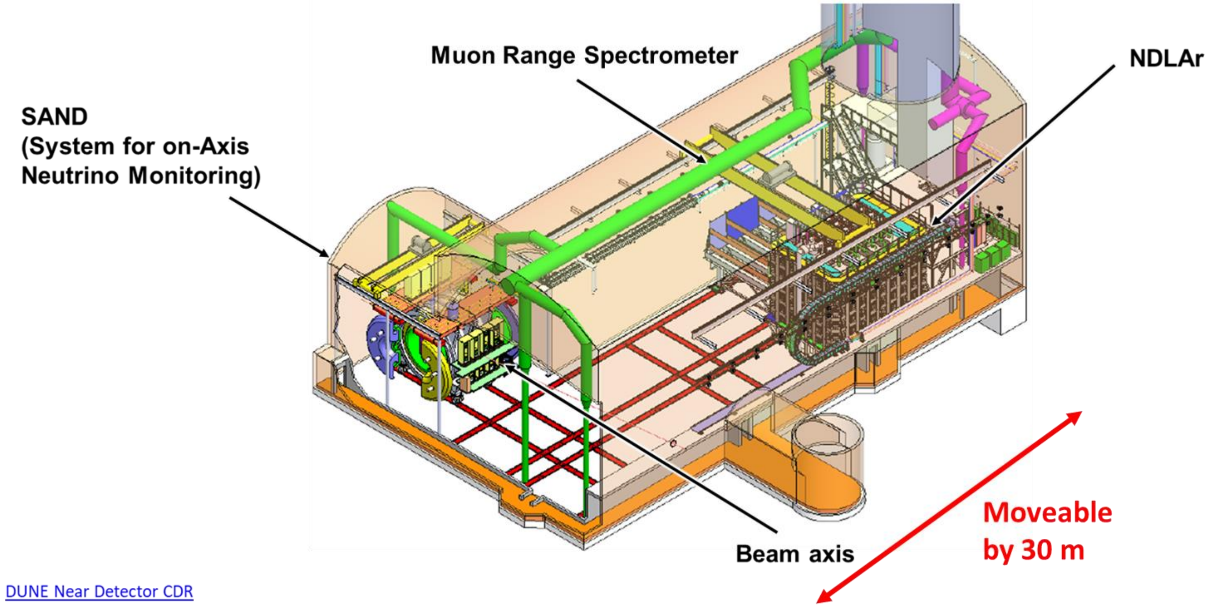
Phys. Rev. D 102, 033005



There is not “the one” ND Technology

- One technology is not covering the full wish list
- ND complexes normally consist of set of complementary detector technologies
- Plans for DUNE ND complex good example





DUNE Near Detector CDR