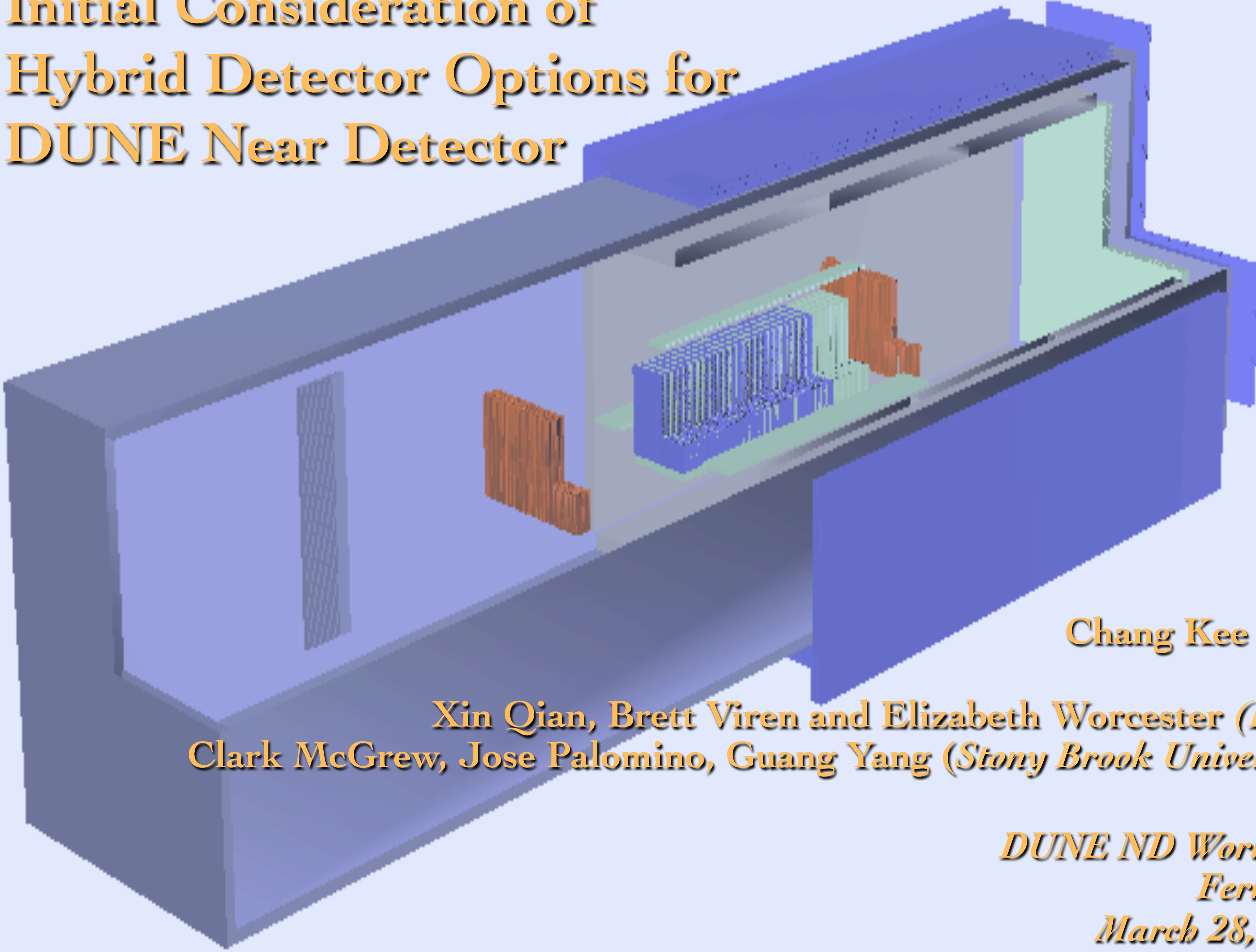
Initial Consideration of Hybrid Detector Options for DUNE Near Detector



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for
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DUNE ND Workshop
Fermilab
March 28, 2017

What do we mean by "Hybrid"?

- Hybrid Near Detector ≡ Same "active" target detector w/ FD + FGD
  - ¬ K2K ND: a hybrid detector
  - ¬ T2K ND: NOT a hybrid detector
    - Lacking active FD target (water) detector
  - ¬ MINOS and NOvA NDs: NOT hybrid detectors
    - Functionally identical/similar ND and FD
    - Lacking FGD elements
- Can we consider a hybrid detector for DUNE ND?
  - ¬ e.g.) LAr TPC + FGD, HPGAr TPC + FGD or LAr TPC + GAr TPC + FGD
  - ¬ What are the pros and cons?

Why go Hybrid?

- Pros: Wider coverage of physics and better handling of systematic uncertainties
  - Active FD target detector can cancel some major syst. errors (cross section and detector)
  - Complementary subdetectors can better address physics requirements and syst. errors
- Pros: More versatile to adopt the advance in the neutrino physics
  - Projecting to the status of our knowledge in 10 years
    - Utilize both the knowledge to be gained from the LAr TPC experiments (ProtoDUNE, CAPTAIN and SBN detectors) and Scintillator detectors (MINERvA, T2K and NOvA)
    - It is likely more robust in dealing with new sources of systematic errors that are unknown today e.g.) 2p2h

Why go Hybrid?

- Pros: More diverse and rich cross-section measurements and ND physics program
- Pros: Broader participation of the collaborating institutions/countries
  - ¬ Each detector option/subdetector must have a champion who has expertise/ track records and plausible path to acquire funding
    - Better matched projects/component and expertise
    - More manageable construction and operation costs for Identifiable projects

    →Higher probability of getting an approval w/ a more credible proposal
- Pros: Can start with all ideas on the table with participation open to all collaborators
  - ¬ Achieve the final design through a collaboration-wide consensus
- Cons: Larger overall costs, although effective burden per institution could be lower

Factors to be Considered for Final Decision

- Physics requirements
  - Difficult to make apple-to-apple comparisons for preferred FOMs w/ different levels of sophistication in simulation/reconstruction for each option
- Many other factors to be considered
  - Cost
  - Funding sources
  - Risks involved
  - Attractiveness of the technology

→ In practice, some level of intellectual bias and political consideration is inevitable or perhaps necessary

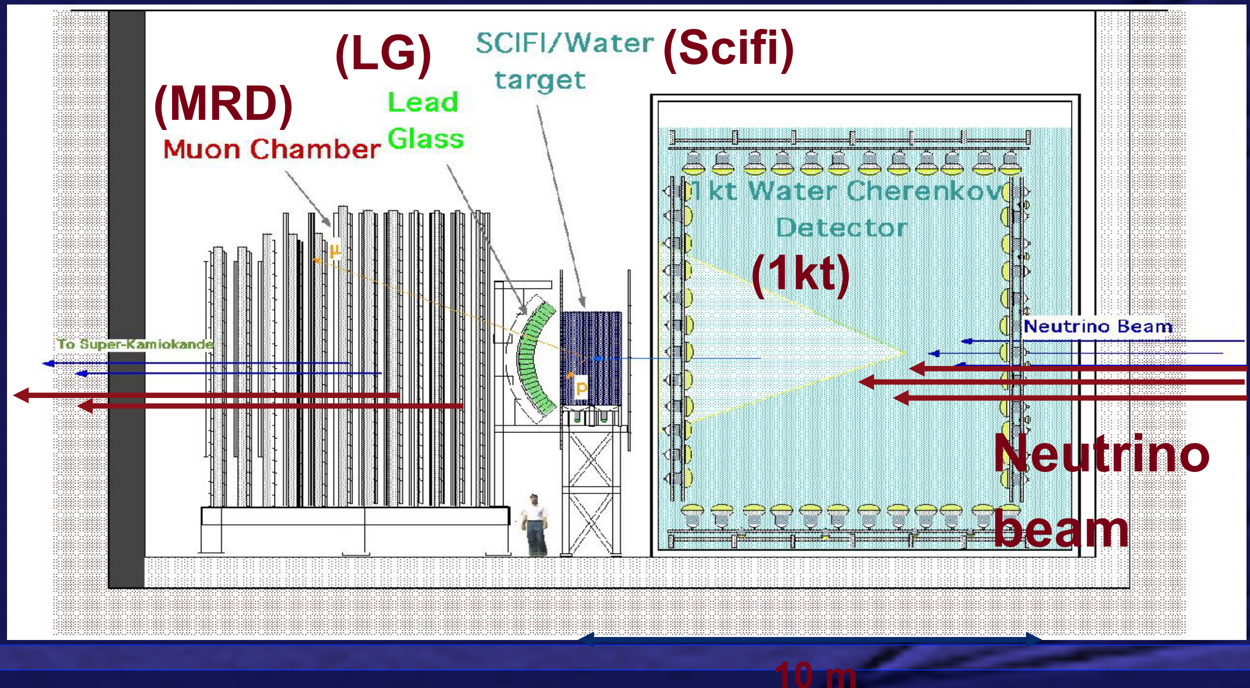
Building Common Denominators towards Decision Making

- Ar target → 100% consensus
- Magnetic Field → 90% (?)
- Active Ar target detector →
- LAr TPC →
- 4π coverage →
- C target →
- ECAL →
- Mu Detector →
- …

Some Insights and Lessons Learned from K2K and T2K ND Designs

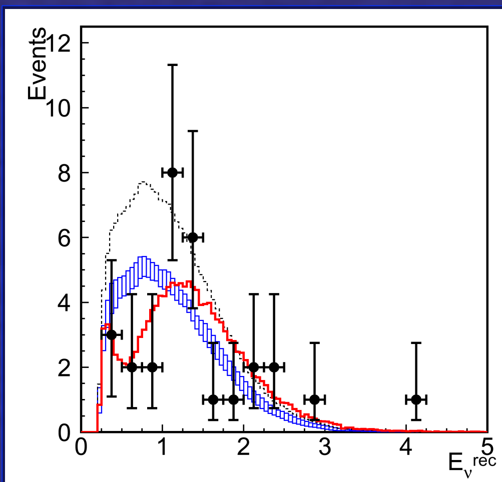
K2K Near Detector – a Hybrid Detector

- 1kt (mini-SuperK): similar systematics as SuperK
- Scifi (scintillating fiber tracker): 19 layers of 6 cm thick water target w/ 20 layers of scifi (x,y), precision tracking
- LG (Lead Glass calorimeter): Measure ν_e contamination
- MRD (muon range detector): 12 layers of iron plates w/ D.C.s

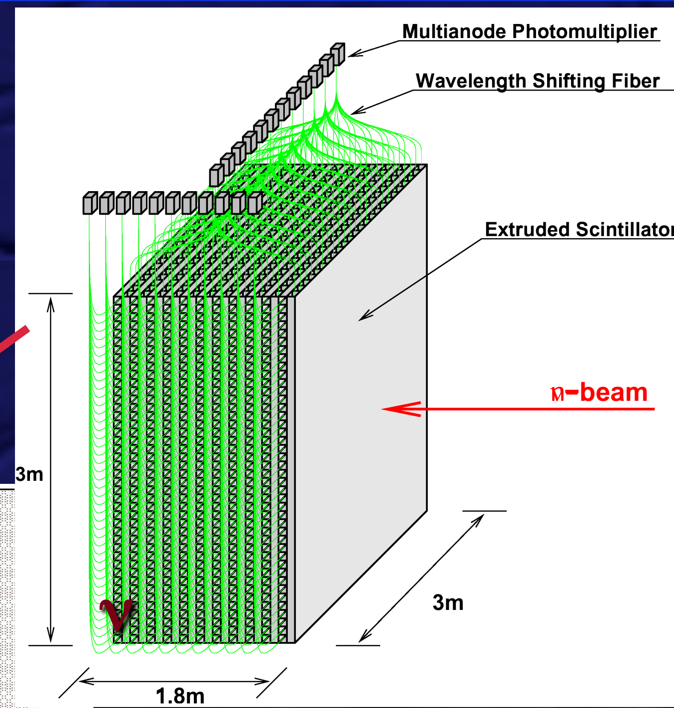


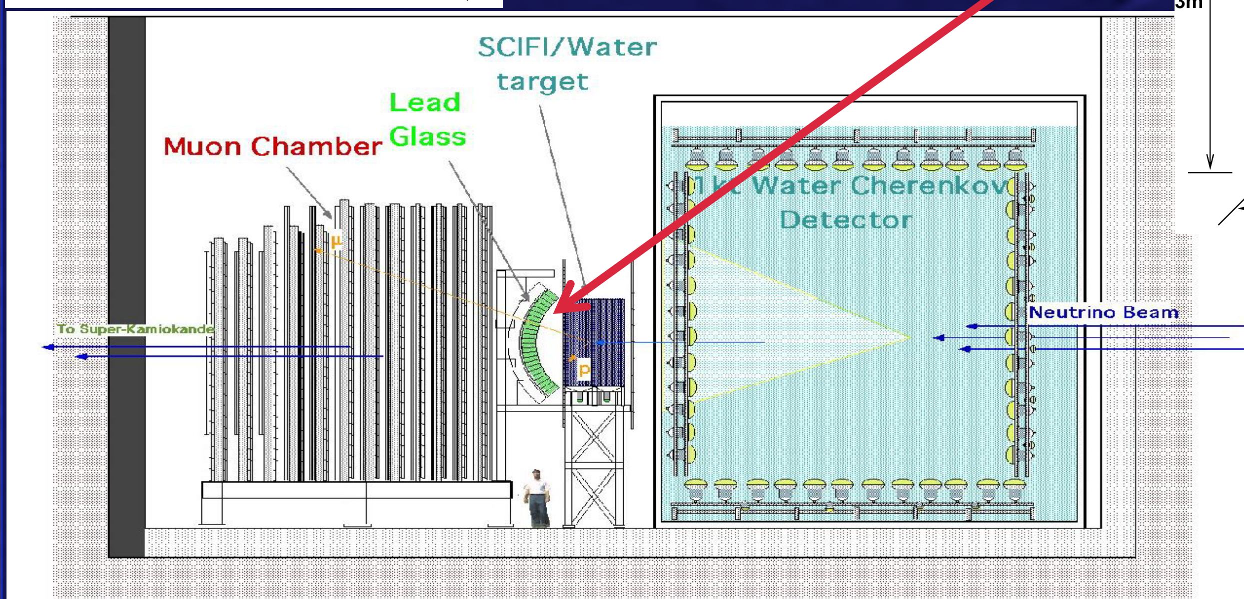
1kt, LG and MRD were all recycled from other experiments

K2K Scibar Detector



The LG (ECAL) detector energy threshold was too high to be useful.





Lessons Learned from K2K

- Employing the same detector technology for Near and Far detectors (1kt and SuperK) does not necessarily produce the full intended benefit, namely, canceling the detector systematic errors
  - ¬Different detector size, granularity, calibration …
  - ¬Something to pay attention for the ND LAr TPC option
- Merits of the reverse configuration (1 kt behind FGD) was debated
  - ¬In the end, 1 kt and FGD were used independently
  - ¬Something to pay attention for the ND hybrid design

Lessons Learned from K2K

- Recycling a detector system (LG ECAL) has obvious cost benefits but actual utilization must be made based on the scientific needs
- A detector at an intermediate distance was considered in order to avoid the uncertainties associated with the neutrino "line" source, and was abandoned
  - ¬ This was the correct decision considering the limited statistics
- Overall, the K2K near detector system was sufficient for the original K2K physics goals

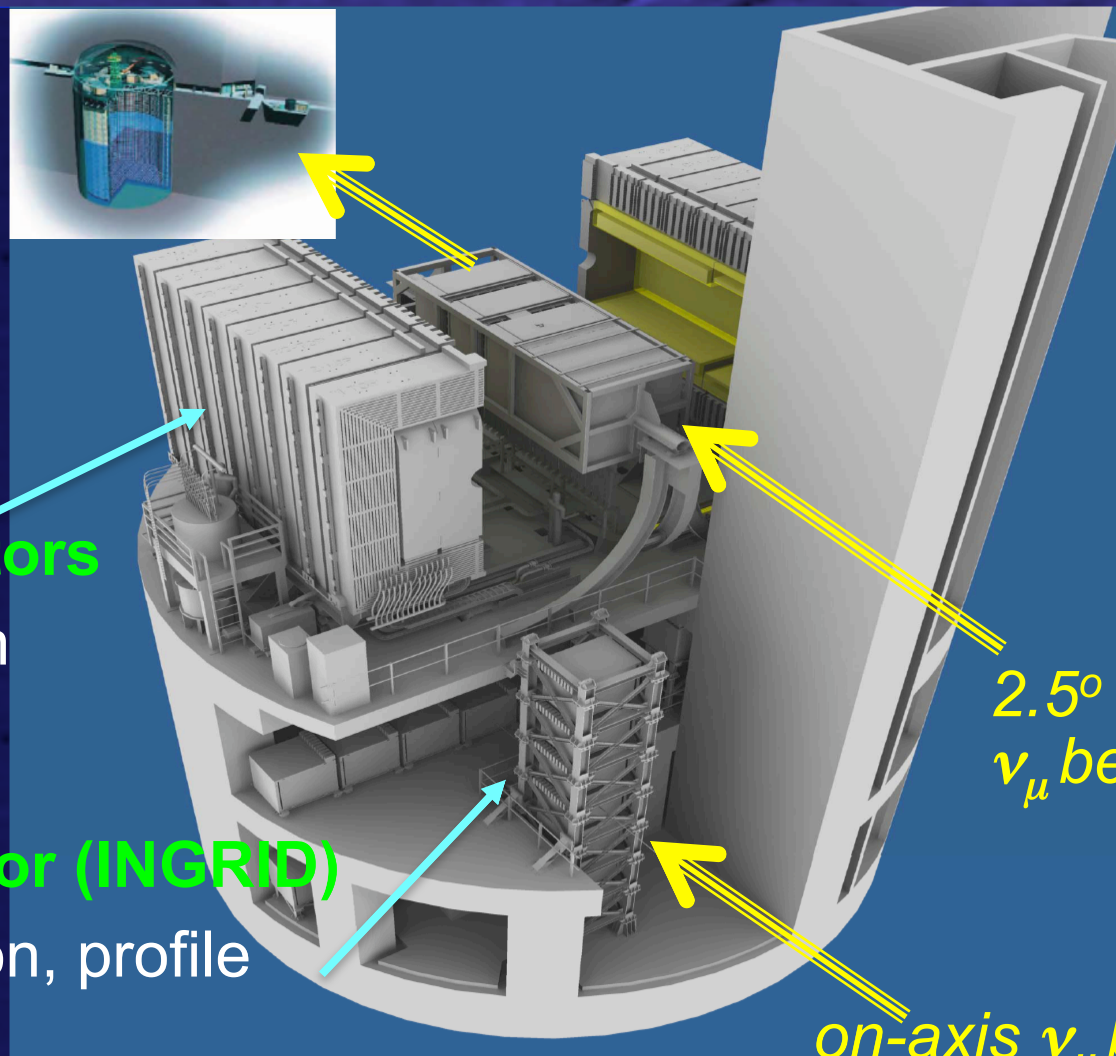
Development of T2K ND

- Japanese government approved funding for T2K beamline and ND
  - ¬160 okuyen (in 2004) ~ $160M
    - Less than the amount needed for the beamline and ND facility (only)
    - No available funds for ND
    - → Call for international contributions to ND and beamline components
    - → Reduced decay pipe length, ND hall diameter, variable off-axis angle, etc.
    - → Does this sound familiar?

Development of T2K ND

- Initially a Hybrid detector a la K2K ND (WC + FGD) was considered
  - A WC detector was not possible within the J-PARC boundary due to too high rate of multiple interactions (pile-up)
    - → Led to a FGD ND with passive water target **
      - ** Note that this was not a choice made based on an ideological belief on oscillation analysis method
    - → Employed magnet for charge separation and muon *p* measurement (forced by the limited pit size)
    - → Contributions from 12 countries to the ND construction
  - A hybrid detector (WC+MRD+LAr TPC) proposal at 2 km site
    - Not approved

T2K Near Detector Complex



Off-Axis Detectors

- ν flux/spectrum
- cross-sections

On-Axis Detector (INGRID)

- ν beam direction, profile

(France, Japan)

2.5^o off-axis ν_μ beam

on-axis ν_μ beam

T2K ND280 Off-axis Detector

P0D: U.S.

TPC: Canada, France, Germany, Italy, Spain

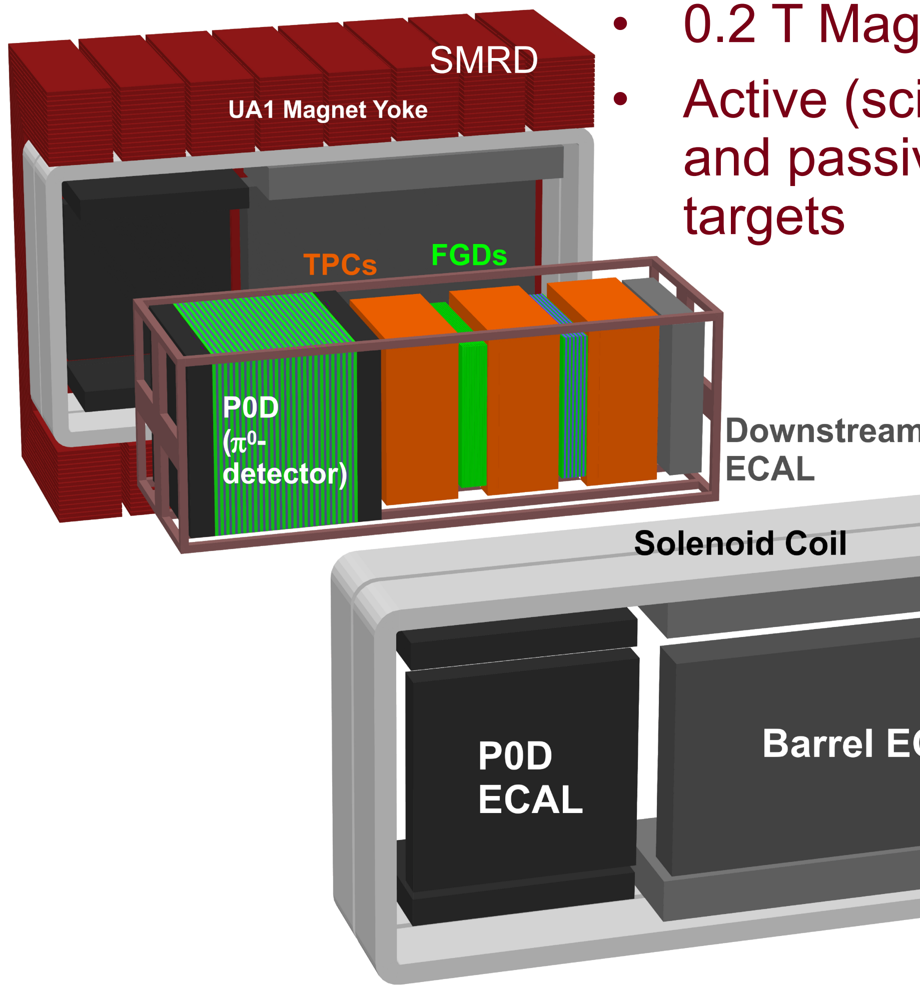
FGD: Canada, Japan

ECAL: U.K.

SMRD: Poland, Russia, U.S.

DAQ: U.K.

2.5° off-axis ν_μ beam



- 0.2 T Magnet
- Active (scintillator) and passive (water) targets

UA1 Magnet:

Donated by CERN

Refurbished by an EU consortium led by Switzerland

Magnet Mover: DESY

T2K Systematic Uncertainty on the Predicted Event Rate @ Far Detector by Source

Source [%]	ν_μ	ν_e	$\overline{\nu}_\mu$	$\overline{\nu}_e$
ND280-unconstrained cross section	0.7	3.0	0.8	3.3
Flux and ND280-constrained cross section	2.8	2.9	3.3	3.2
SK detector systematics	3.9	2.4	3.3	3.1
Final or secondary hadron interactions	1.5	2.5	2.1	2.5
Total	5.0	5.4	5.2	6.2

"First combined analysis of neutrino and antineutrino oscillations at T2K" arXiv:1701.00432 [hep-ex] 2 Jan 2017

The T2K's overall systematic uncertainties has now reached far lower than the original goal (~10%) for ν_e appearance but to pursue CPV at 3 σ level much more improvement is needed

Lessons Learned from T2K

- Difficult to overcome the different active nuclear targets for near (mostly C) and far (mostly H_2O) detectors
  - Passive (H_2O) targets results in large systematic errors stemming from statistical subtraction methods
  - T2K could not build a water Cherenkov detector at the near detector site due to the expected multiple interactions (pile-up) in the detector
  - However, the resulting comprehensive ND design in lieu of a WC detector brought a very broad participation of collaborating institutions/ countries
    - The membership in the T2K ND working group was larger than that in the T2K-SK and SuperK collaboration combined
    - Developed "collaboration blessed" credible regional proposals that matched well with the proponent's expertise and interests

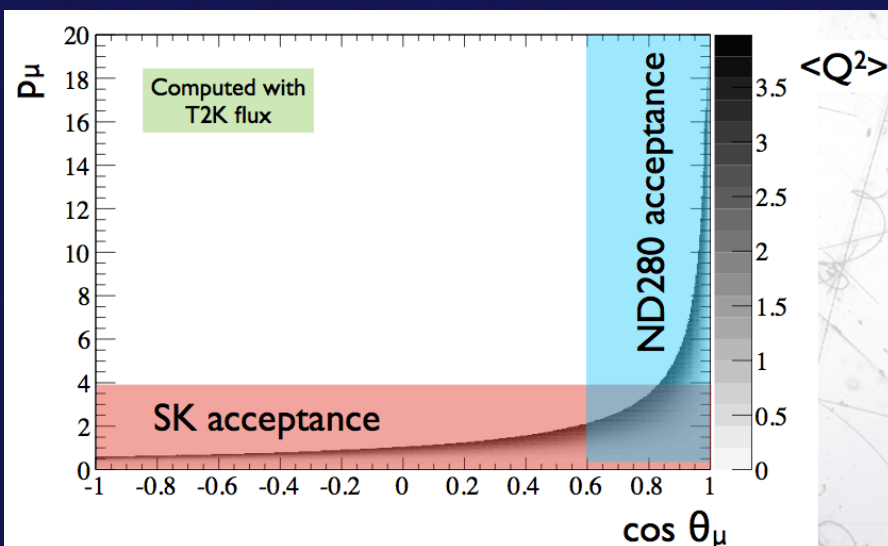
    → Led to successful approvals of all regional proposals

Lessons Learned from T2K

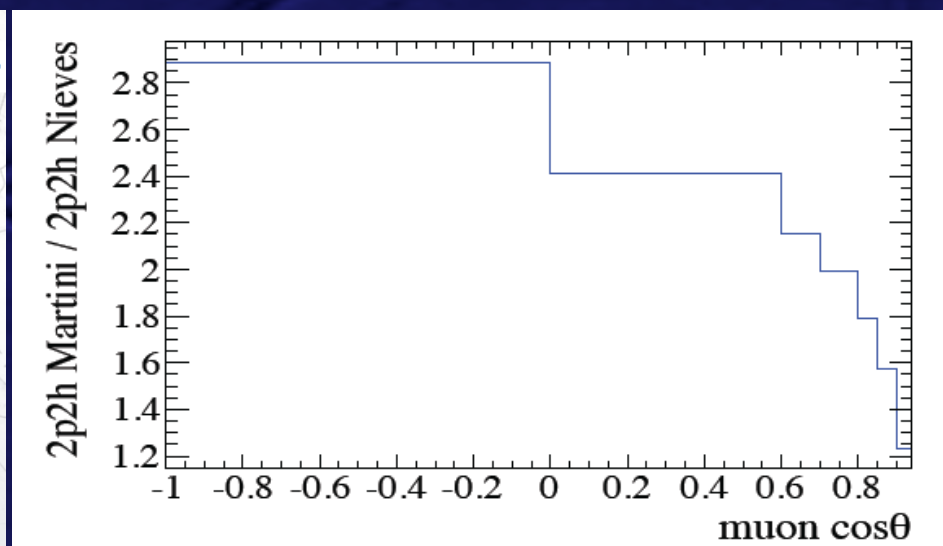
- Recycling the UA1 magnet (operating at 0.2 T) was highly cost effective and the magnet performed satisfactorily
- The kinematic phase space covered by the ND280 (mostly forward region) was quite different from that by SuperK (4π)
  - ¬This became a substantial source of systematic error
- Difficult to handle new source of systematic error stemming from multi-nucleon (2p2h) interactions → NuPRISM proposal
- Nonetheless, overall, the T2K near detector system was sufficient for the original T2K physics goals (ν_e appearance and ν_μ disappearance)

T2K Upgrade Proposal

- Improve the ND280 kinematic acceptance to cover the full cosθ range, especially the high angle region, of the far detector
  - ¬ Current ND280 covers approximately 20~30% of the cosθ region
- Improve the event vertex determination in the passive water target
  - ¬ Localized "cell" structure water target

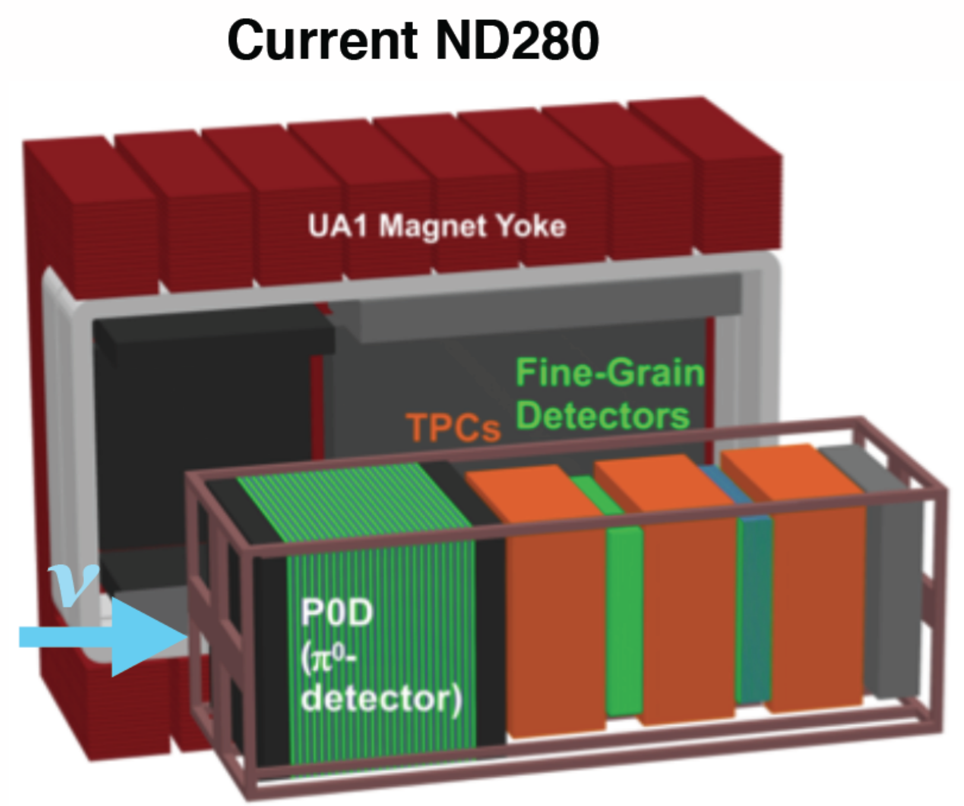


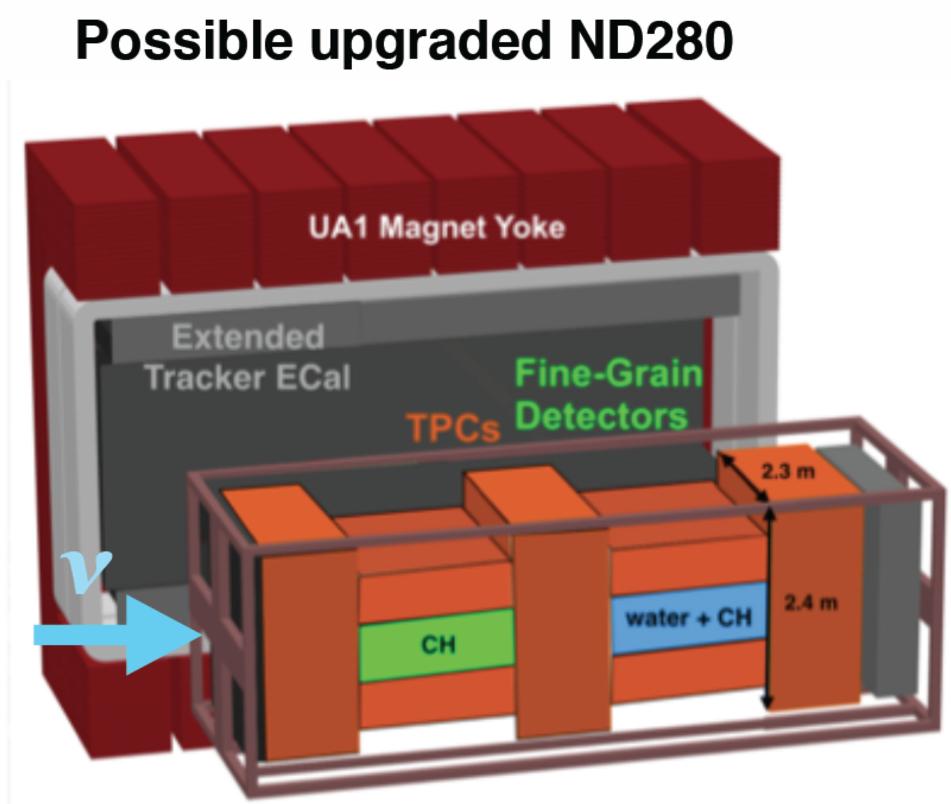
Kinematic acceptance



2p2h modeling

Possible T2K ND280 Upgrade

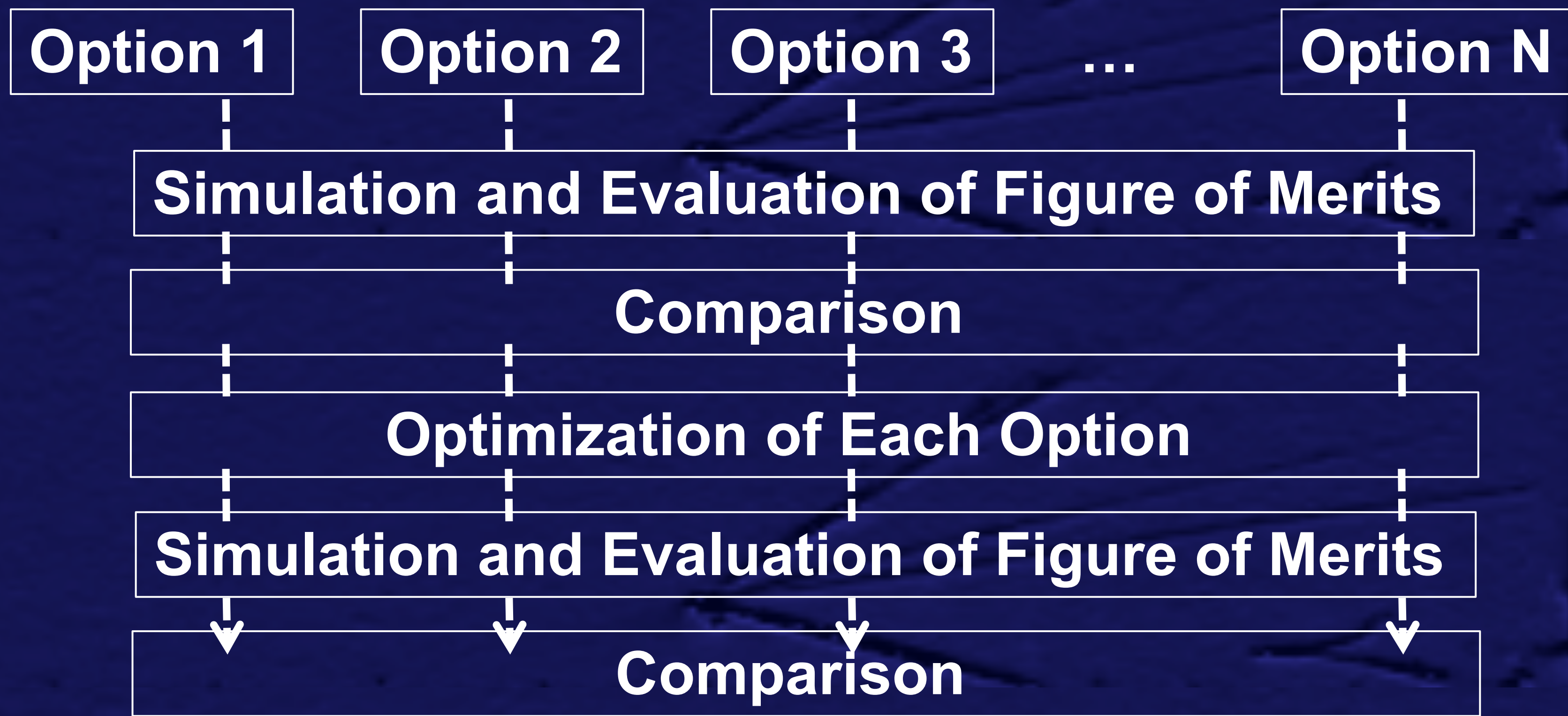




Initial Thoughts on DUNE ND

- To control the overall systematic errors (other than normalization) to few percent on ν_e, It is likely that we will need a hybrid detector
  - ¬w/ a magnetic field
  - ¬An active Ar target detector (likely LAr TPC) + a FGD with an excellent kinematic phase-space coverage (~4π) employing scintillator (C) target as well as other targets.

Process of Making Decisions on Detector Options



→ A time consuming process with high demand for resources

→ Can weed out some options that do not meet the minimum physics requirements. However, difficult to make a decision w/o considering the costs, risks and funding sources

Alternative Process of Making Decisions on Detector Options

All options on the table and all interested parties at the table

↓

Brainstorming Sessions

↓

"Straw-Person" Design based on consideration of all relevant factors including costs, risks and possible funding sources

↓

Fast Simulation and Evaluation of Figure of Merits

↓

Optimization and Reconfiguration

↓

Initial Conceptual Design

↓

Full Simulation and Evaluation

Development of General Design Tool for DUNE ND (for the study of hybrid detector configurations and designs)

Clark McGrew, Jose Palomino, Guang Yang and Brett Viren

General Software Packages Developed for the Hybrid Detector Design Studies

- dunendggd
  - The Hybrid detector geometry definition package
  - based on a general geometry producing package GeGeDe by Brett Viren (BNL)
  - GeGeDe (General Geometry Description):
    - Generates a description of a constructive solid geometry, specifically as used by Geant4 or ROOT applications as represented in GDML files
    - Implemented as a pure Python module "gegede”

General Software Packages Developed for the Hybrid Detector Design Studies

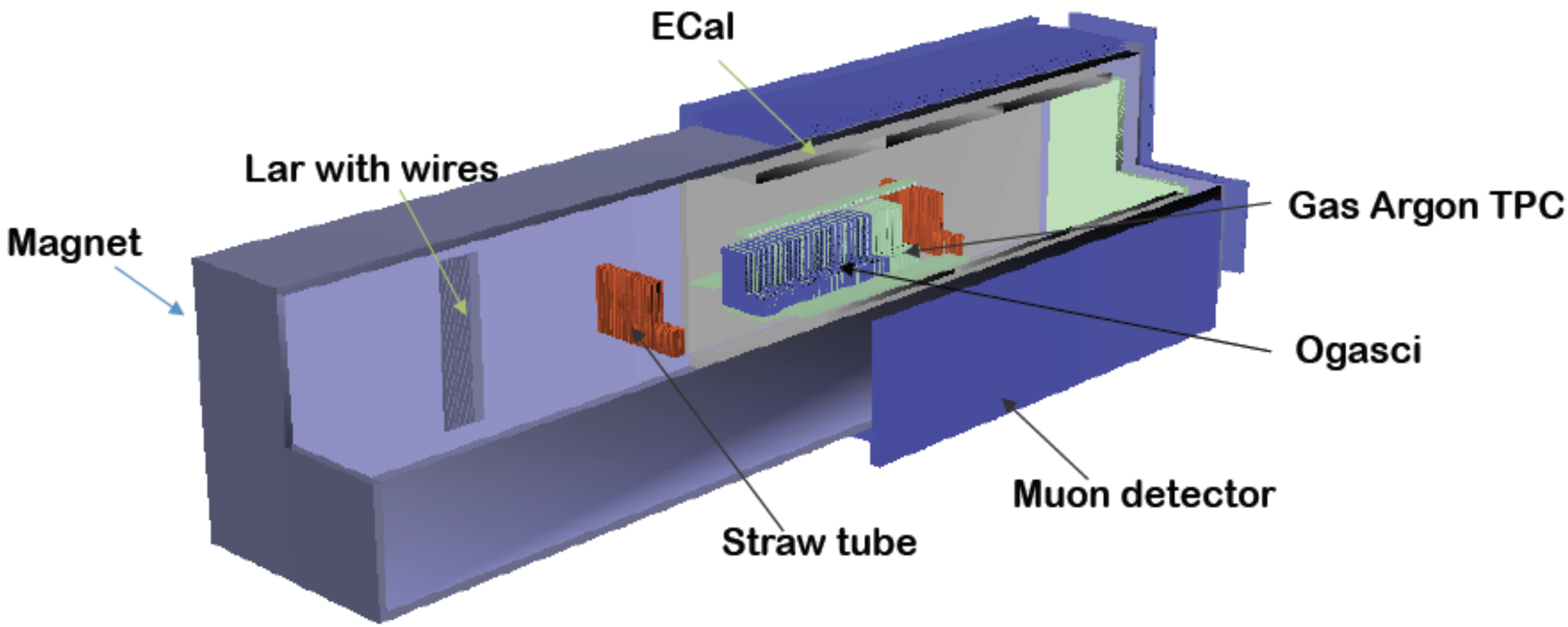
- dune-ndx
  - ¬A spack based the Hybrid detector design software bundling package. For now includes:
    - ROOT, Geant, the detector simulation and GeGeDe

→ detailed presentations on these packages will be made in the future ND working group weekly meetings

https://github.com/gyang9/dunendggd

https://github.com/brettviren/gegede

Example Design w/ dunendggd

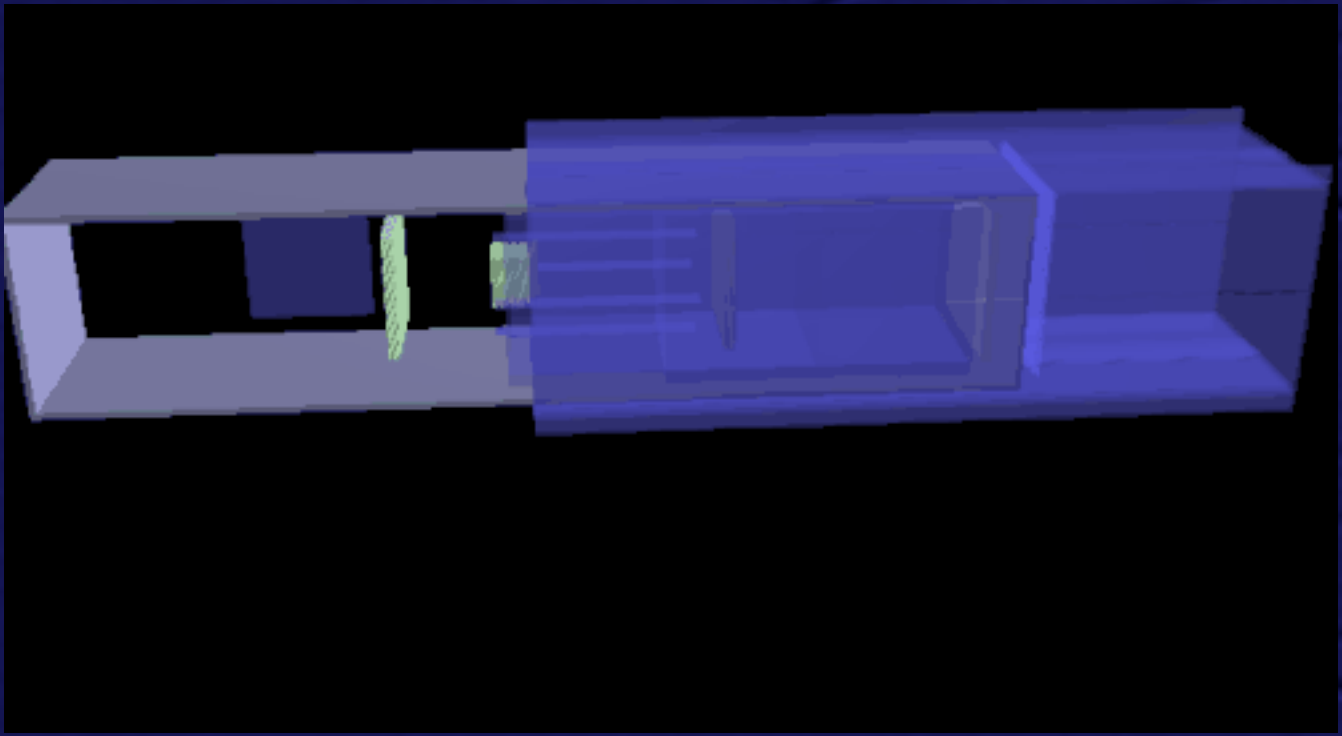


To build complex detector as the example shown, just check out:

https://github.com/brettviren/gegede

https://github.com/gyang9/dunendggd

Example Design in dune-ndx



Closing Thoughts…

- A hybrid detector design:
  - ¬will be a robust system that is less subject to specific deficiencies of a particular detector technology
  - ¬can be optimized to meet all critical physics/FOM requirements
  - ¬will bring a broader participation of collaborators
- Cost is an issue only if no one wishes to pay for it
- There is a strong and urgent need for a centralized ND software working group

The End