Long baseline near measurements: scientific strategy and conceptual design

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4/18/2018

CERN Neutrino Platform general meeting
https://indico.cern.ch/event/718570/

Fundamental issue affecting near detector configuration for accelerator LBL experiments.

- The current set of experimental projects evolved out of the first modern long-baseline experiments that were designed to demonstrate that neutrino oscillations took place. High confidence was needed on the far ***muon neutrino*** spectrum, and this could be satisfied by the selection of a ***near-identical*** detector in the ***far field (as far away as possible)*** of the flux.

- The new problem is having high confidence in the estimate of the electron neutrino flux after oscillations. This is quite different and the problem remains largely unsolved, but incremental progress is being made.

- Having an identical technology detector surely helps, but it is unclear how much. We also do not have complete arguments for the geometrical configuration.

- ***These questions need not be solved immediately; with sufficient flexibility in the key design parameters it could become a long term program.***

Outline

- ***Requirements for DUNE.***
- ***DUNE design status.***
- ***Strategies employed by T2K, MINOS, NOVA.***
- ***Technical issues regarding ND and beam integration.***

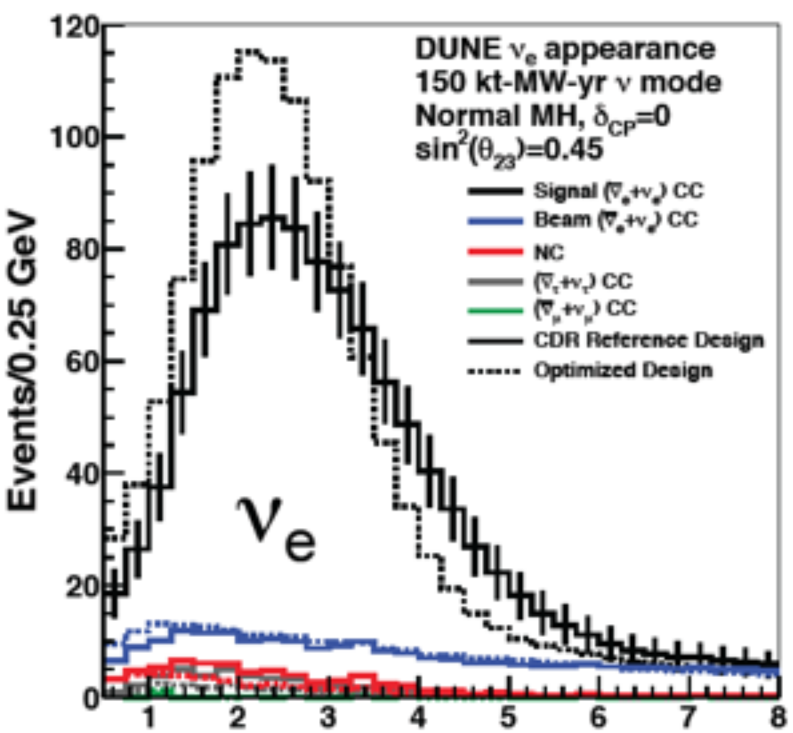
Working groups

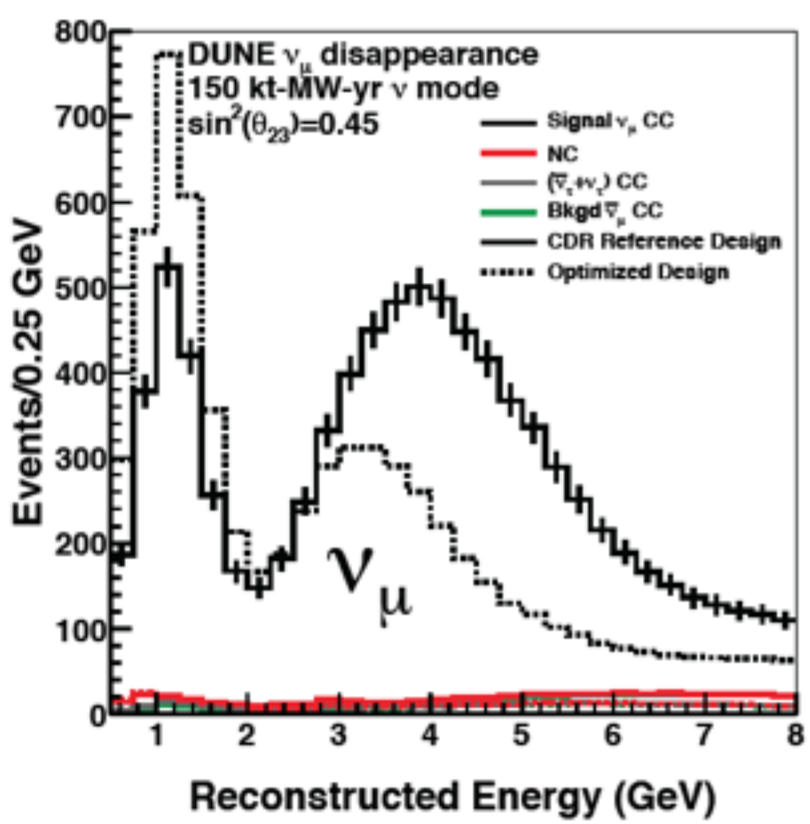
- DUNE near detector working group and physics groups.
  - https://indico.fnal.gov/category/459/ - Kam-biu Luk, M. Kordosky, S. Manly, A. Weber.
  - Weekly meetings. 4 Workshops
- Parallel, but broader working group is being conducted at CERN through the Cern Neutrino Platform. CENF-ND forum.
  - https://twiki.cern.ch/twiki/bin/view/CENF/NearDetector - Forum for the European effort to understand the needs and requirements for the future generation of Near Detectors and in parallel to contribute to improve the existing neutrino event generators.
  - CENF-ND has 5 subgroups spanning neutrino flux to detector requirements and has participation from all current and future LBL experiments.

DUNE big picture

- ***LBNF far site construction has started which implies that the scope of conventional halls and the far detector is well-defined.***
- ***Near site conventional construction in design phase.***
- ***Far detector technical issues have good progress with protoDUNE, but liquid argon is hard.***
- ***Far detector analysis issues in progress. Pattern recognition concepts need to be fully explored.***
- ***Neutrino beam design optimization has made excellent progress, but there are a number of options to consider.***
- ***All of the above impact the near detector choices.***
- ***Near detector analysis issues are still in the works. These will inform the design. This analysis and design must be an integrated approach across the beam -> near -> far detectors because the systematic requirements need careful consideration.***

Near detector numerical science requirements





bin	electron events	% syst req=stat/2
0-0.8 GeV	60	6%
0.8-1.7 GeV	130	4%
1.7-2.6 GeV	540	2%
2.6-5.2 GeV	380	2.5%
5.2-10 GeV	~150	4%

bin	muon events	statistical error
0-0.8 GeV	600	4%
0.8-1.7 GeV	2000	2.2%
1.7-2.6 GeV	670	4%
2.6-5.2 GeV	5500	1.3%
5.2-10 GeV	~2000	2.2%

$$Osc.freq = (1/500) km/GeV$$

$$Sampling > 2 \times Osc.freq$$

- *The appearance and disappearance measurements must be considered simultaneously.*
- *The disappearance measurement provides the "calibration" of atmospheric parameters within the same experimental setup reducing systematic.*
- *The prediction of muon CC events can be obtained by an identical detector.*
- *The prediction of electron CC events cannot be performed by an identical detector alone.*
- *Key issue*
  - ***How do we predict the electron neutrino and antineutrino event spectrum at the far site as a function of CP phase ?***
  - ***How is the neutrino energy in these plots to be calibrated.***

Summary of needed accuracy

- ***Given 1300 km, the broad band nu-e event spectrum will need to be measured with energy resolution better than ~0.5 GeV.***

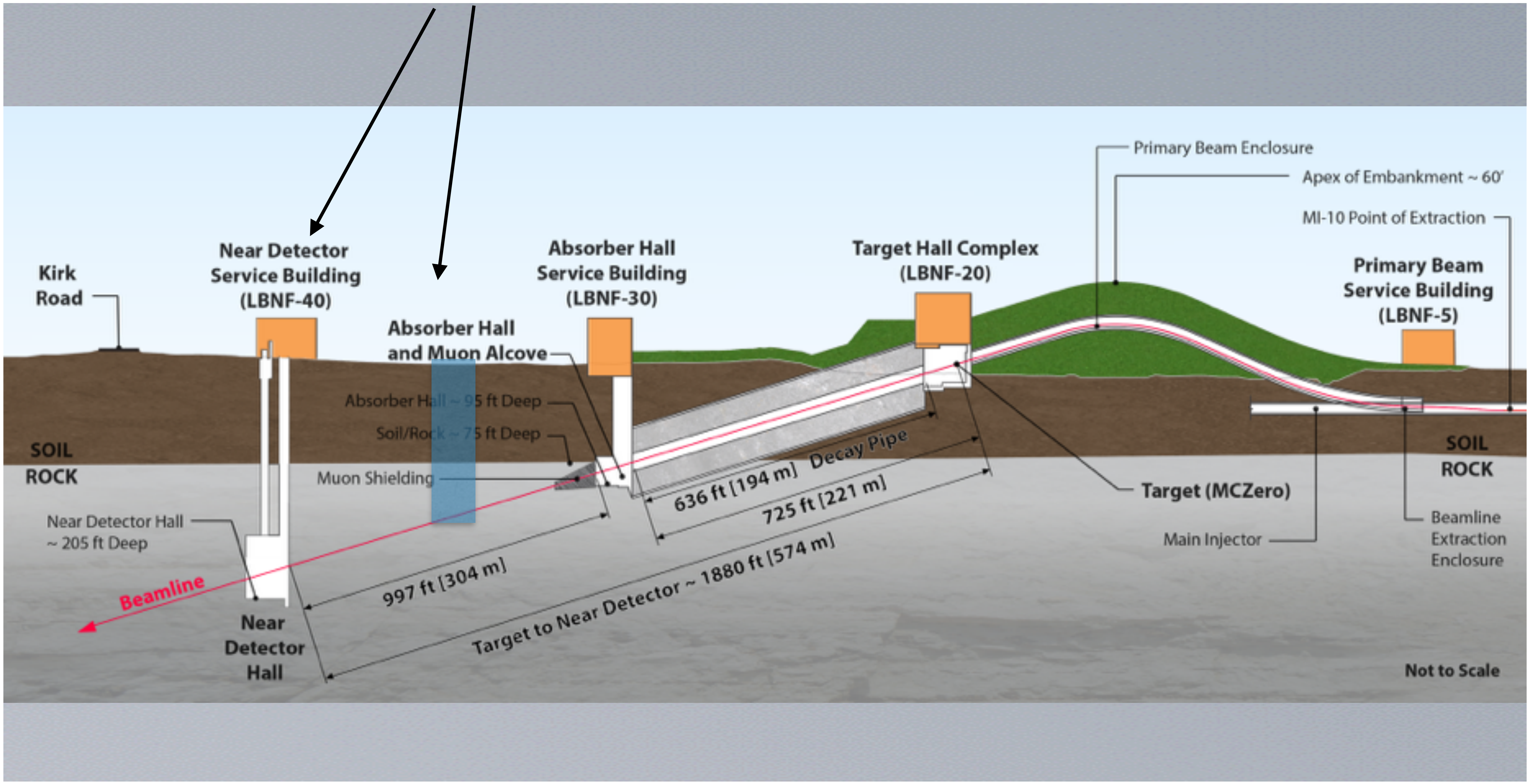
- ***The systematic error on the prediction of electron neutrino spectrum should ultimately be ~2-5% per bin. But this will change over time as 1/Sqrt[exposure].***

- ***The systematical error on the prediction of unoscillated muon neutrino spectrum should be ~2% across all bins.***

- ***Muon energy resolution and scale is very important to determine the Delta-m^2, but the shape allows significant reduction in the requirement. The energy resolution is crucial for mixing angle resolution.***

- ***Both electron and muon spectra have to be analyzed together to perform the CP fits because they depend on the location of the "node" which depends on Delta-m^2 and so both muon and electron systematic errors have to be achieved simultaneously.***

Possible locations are ~360m and 574m; the 360m location could be an open pit with easy access



LBNE DocDB 11180: The near detector location is 574 m from the target station based on the requirement that it be placed as far away as possible to obtain the smaller ND/FD flux ratio.

ν_μ and ν_e CC rates for reference

	Distance m	Numu	Anumu	Nue	Anue	Total	Detector Needed
Rock	340	17.7	0.96	0.32	0.051	19.1	
	350	16.6	0.90	0.30	0.048	17.8	60 kg
Front of hall	360	15.6	0.86	0.29	0.045	16.8	
Back of hall	380	13.7	0.77	0.26	0.041	14.8	
Front of hall	570	5.6	0.34	0.11	0.018	6.1	163 kg
	580	5.4	0.33	0.10	0.017	5.9	
Back of hall	590	5.2	0.32	0.10	0.016	5.6	

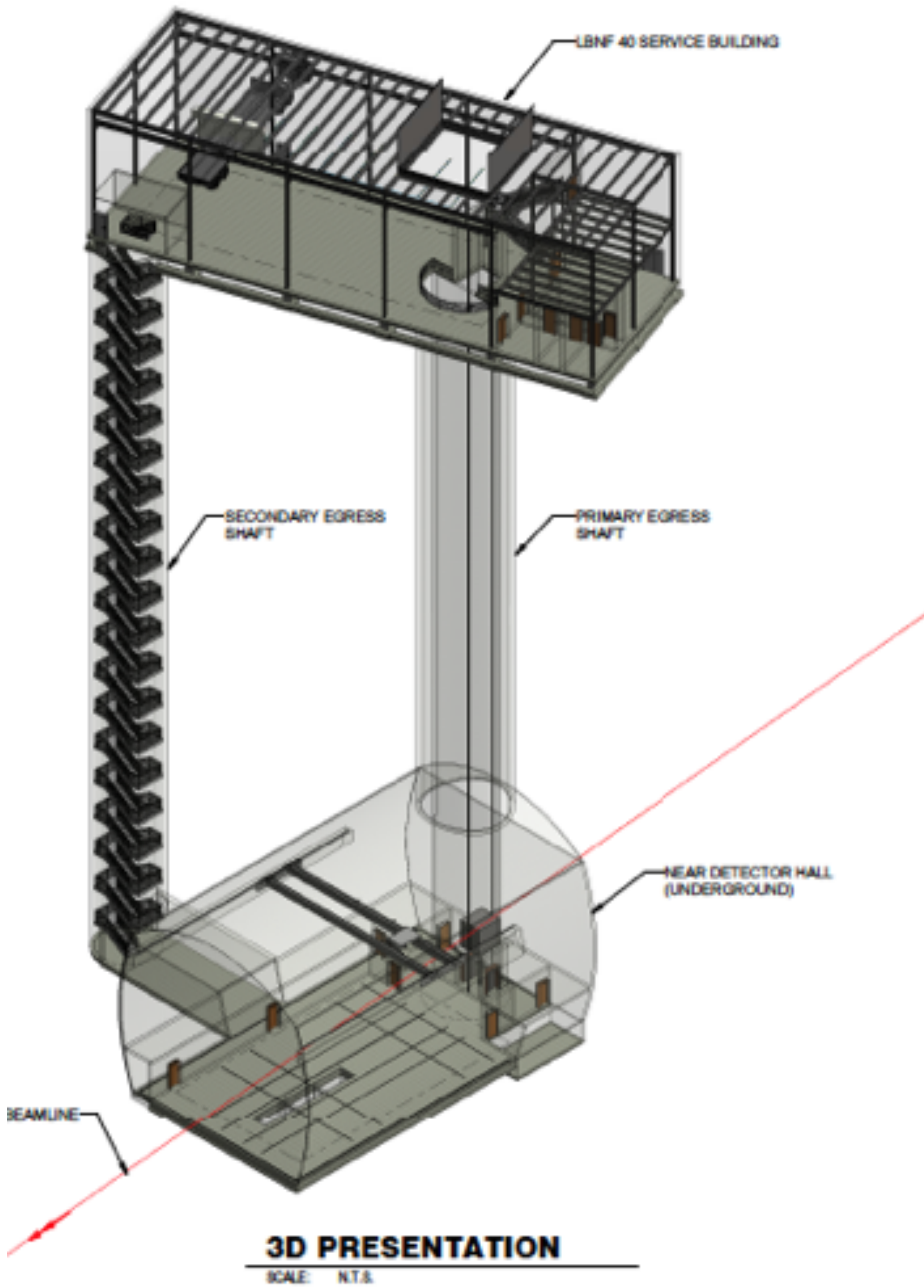
Rate is X10^6 evts/ton/yr.
Acceptance will depend on geometry, but should be high for a small detector needed for 10^6 events/yr

Neutrino electron elastic scattering event rates for reference.

	Distance m	Numu	Anumu	Nue	Anue	Total	Detector Needed
Rock	340	1780	178	185	27	2175	
	350	1665	167	174	26	2033	1 Ton
Front of hall	360	1567	159	168	25	1920	
Back of hall	380	1380	142	149	22	1698	
Front of hall	570	566	62	62	10	701	3 Ton
	580	545	60	60	9.5	676	
Back of hall	590	525	58	58	9.2	652	

Rate is evts/ton/yr. CDR 80 GeV beam. $1.5*10^{21}$ Pot/yr
Typical acceptance is 60%. (not included here)
Notice that r dependence is different for different species. Detector needed for 10000 events/5yrs

ND 570



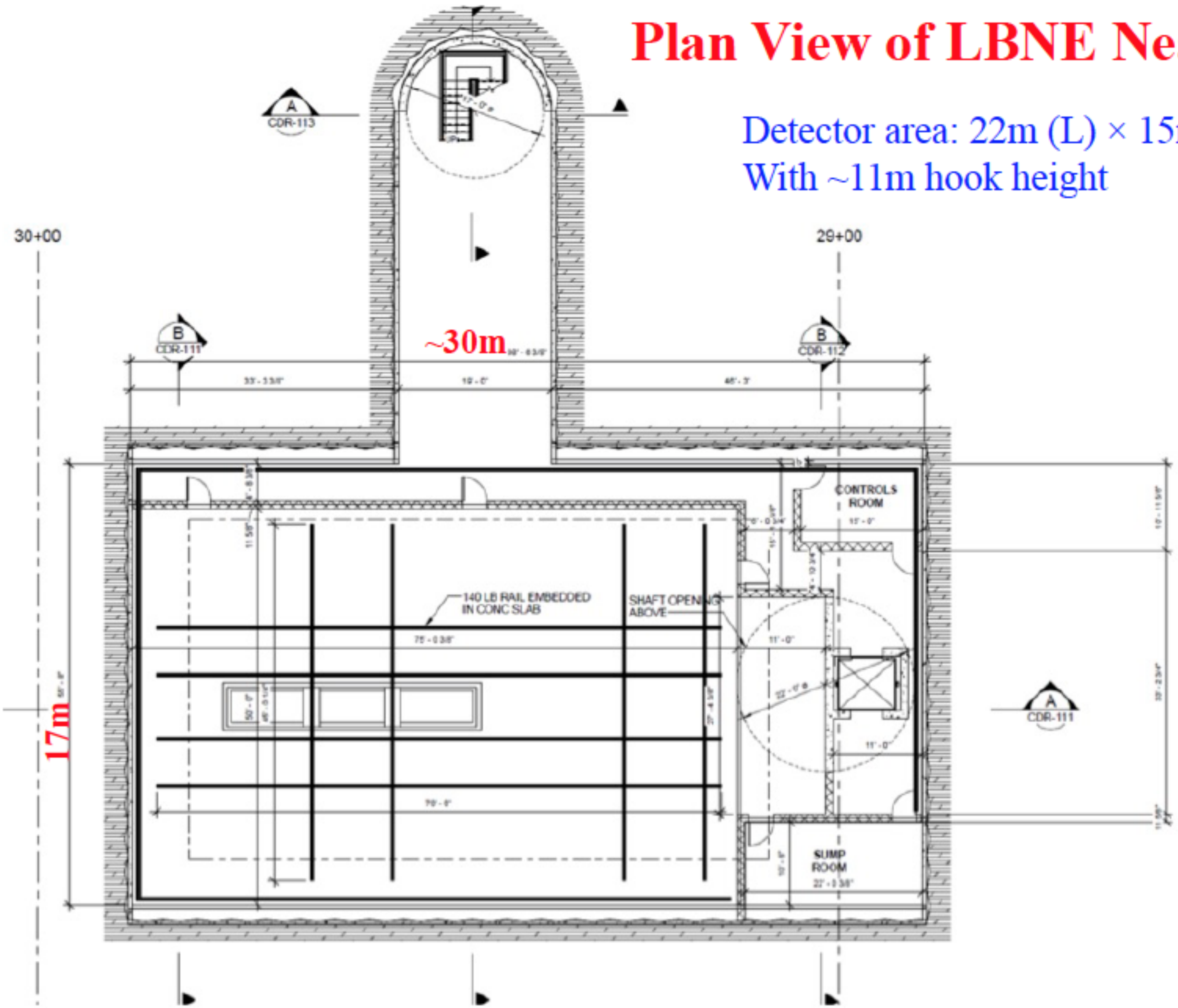
Cost of ND and associated infrastructure with advantages in short and long term need to be considered together.

The ND 360 location would need an open pit construction which would need to be optimized. This requires strong scientific consensus.

Expansion of near hall at 570 under consideration.

Plan View of LBNE Near Hall

Detector area: 22m (L) × 15m (W)
With ~11m hook height



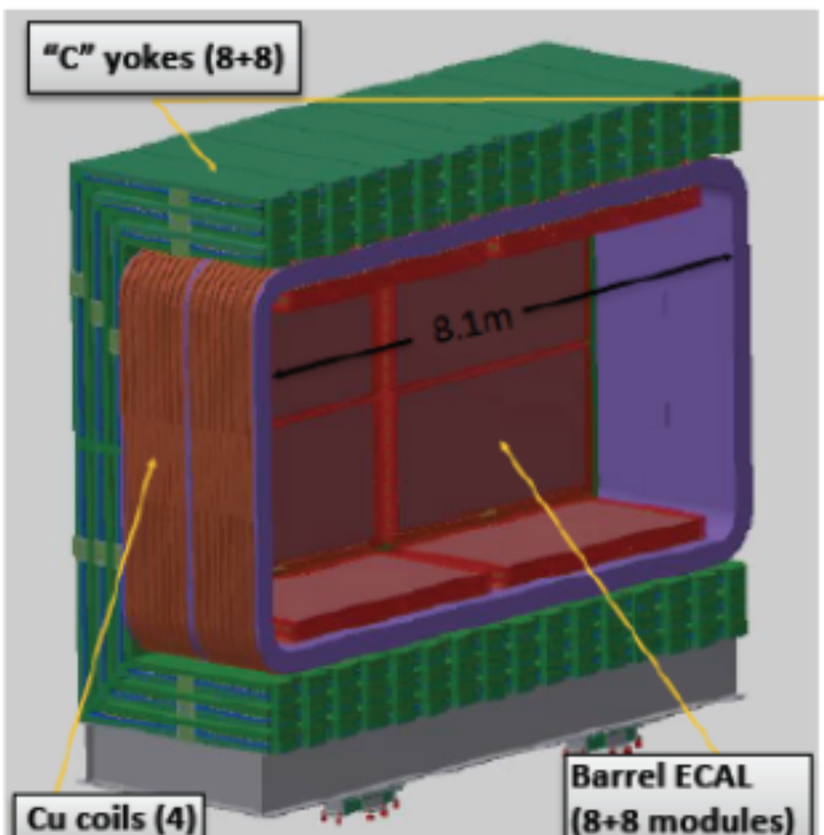
This design was done for 2012

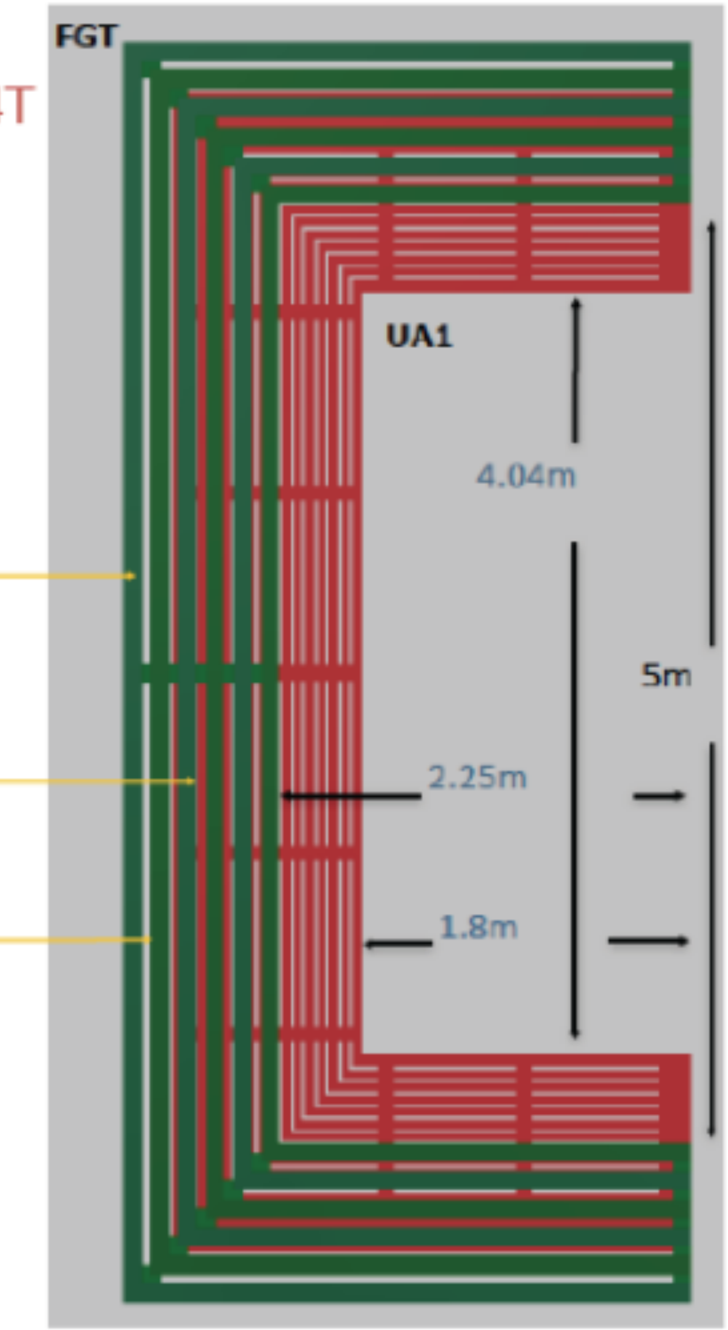
Dimensions of FGT

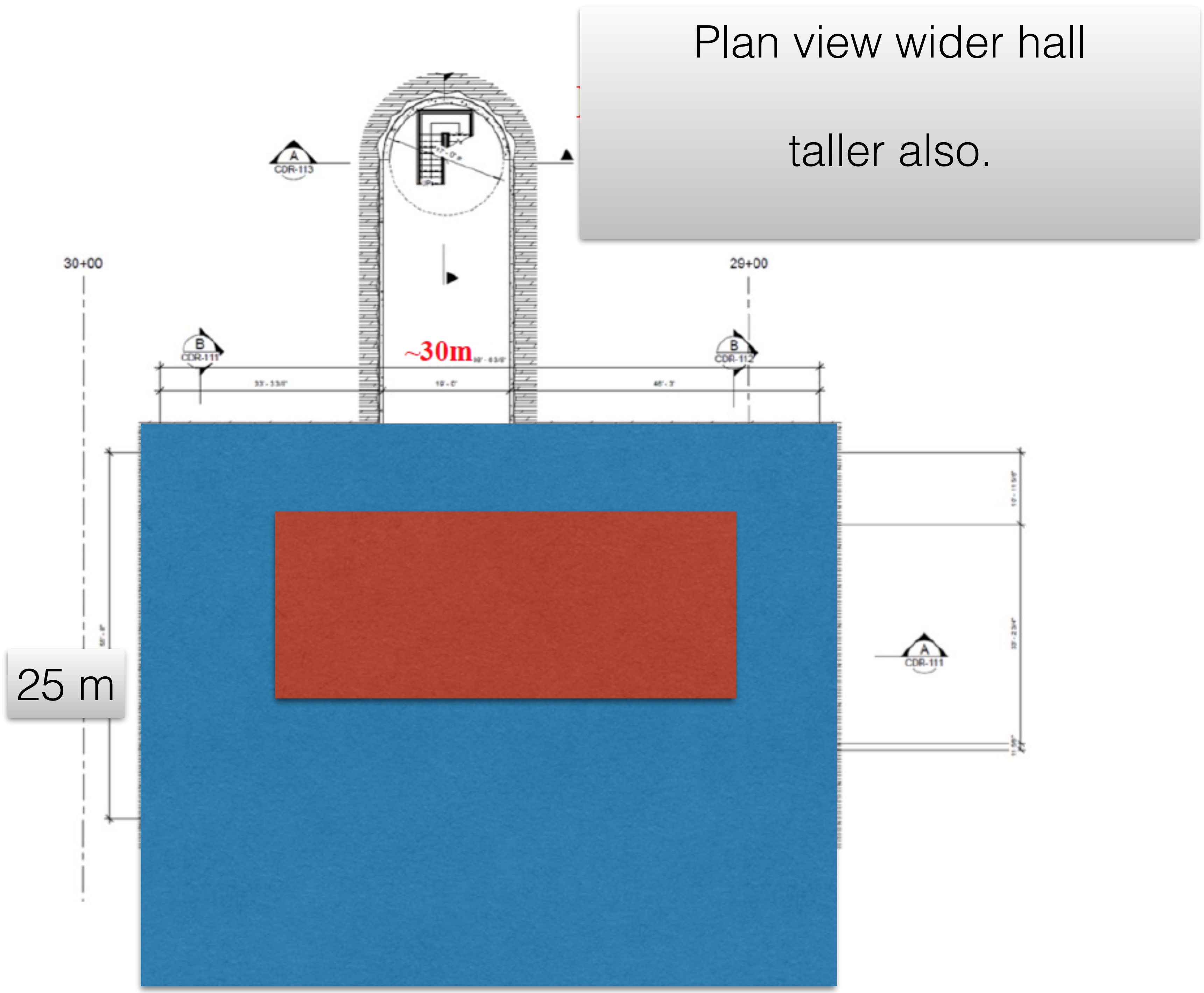
The Dipole Magnet

Outer dimensions: 6m (w) × 6m (h) × 11m (l)

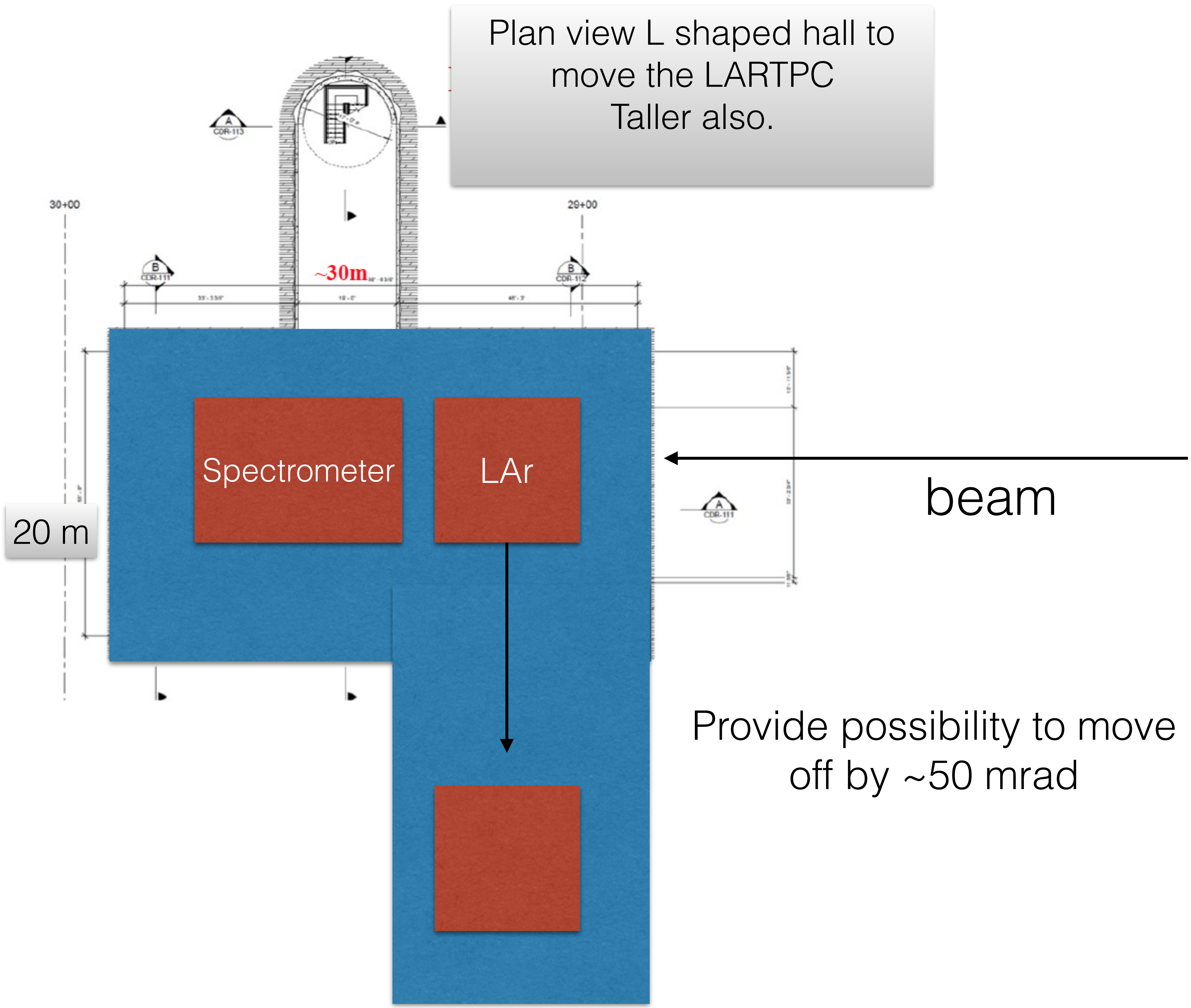
- Design based on UA1/NOMAD/T2K magnet
- Magnetic volume: 4.5 m x 4.5 m x 8.1 m, nominal B = 0.4T
- Return yoke with 8+8 "C" section:
  - 6 x 100 mm steel plates, 50 mm gaps (960 tons)
- 4 vertical Cu coils (168 tons) made of 8 double pancake
- Power requirement for nominal field 2.43 MW, water flow for coil cooling: 20 l/s



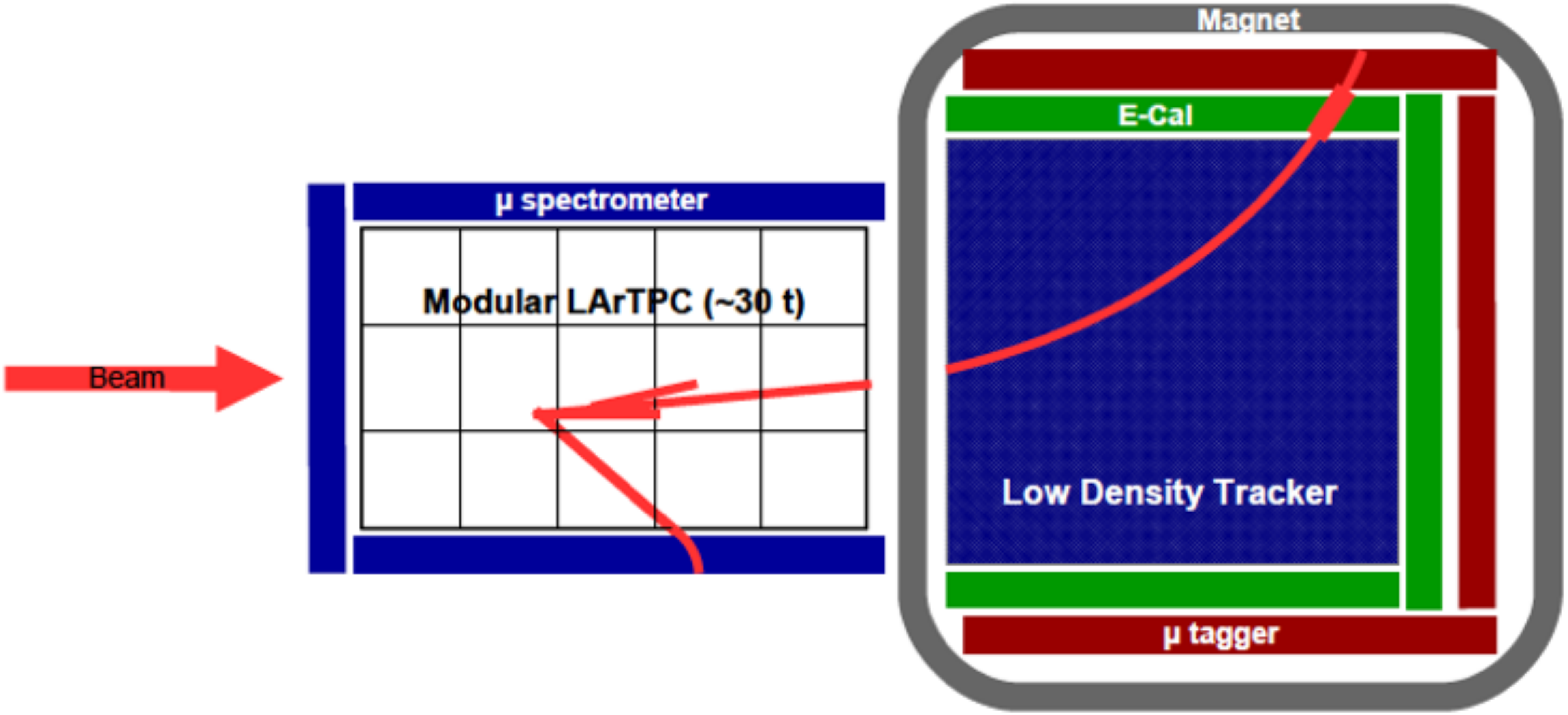




Wider hall to allow more floor space

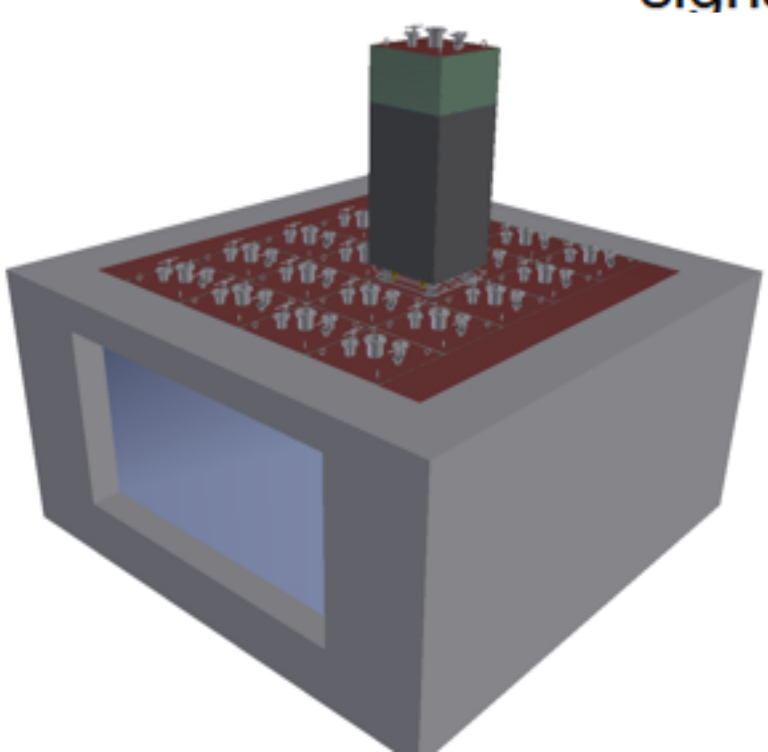

Plan view L shaped hall to
move the LARTPC
Taller also.
~30m
Spectrometer
LAr
20 m
beam
Provide possibility to move
off by ~50 mrad

The current DUNE ND concept is a ‘hybrid’ LArTPC + low density tracker.



Modular LAr-TPC: high statistics ν-Ar interactions, assessment of LArTPC response.

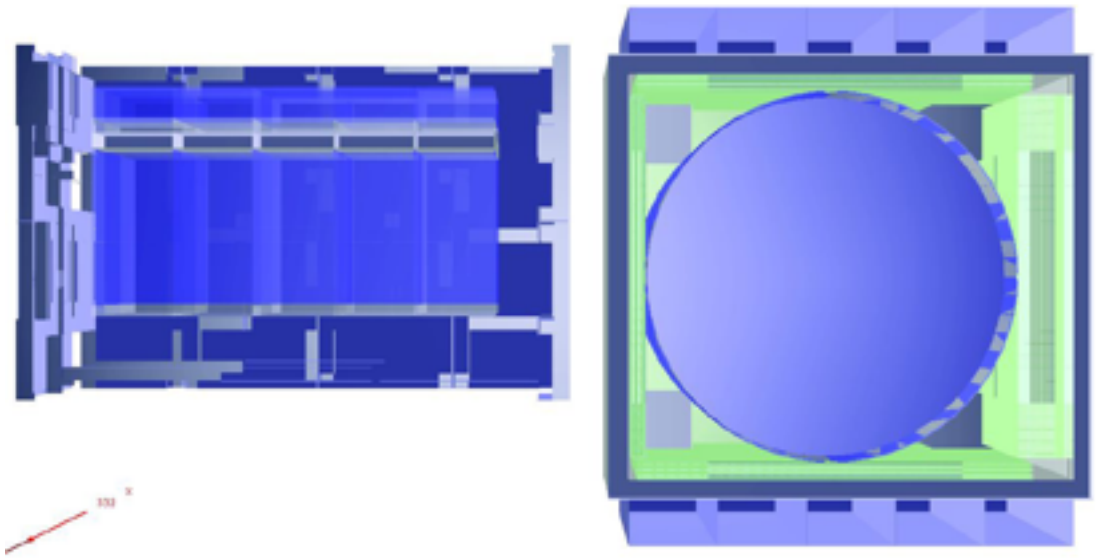
Low Density Tracker: precision characterization of ν-nucleus interactions, complementary signal vs. BG discrimination. Possibly FGT, scintillator or GArTPC.

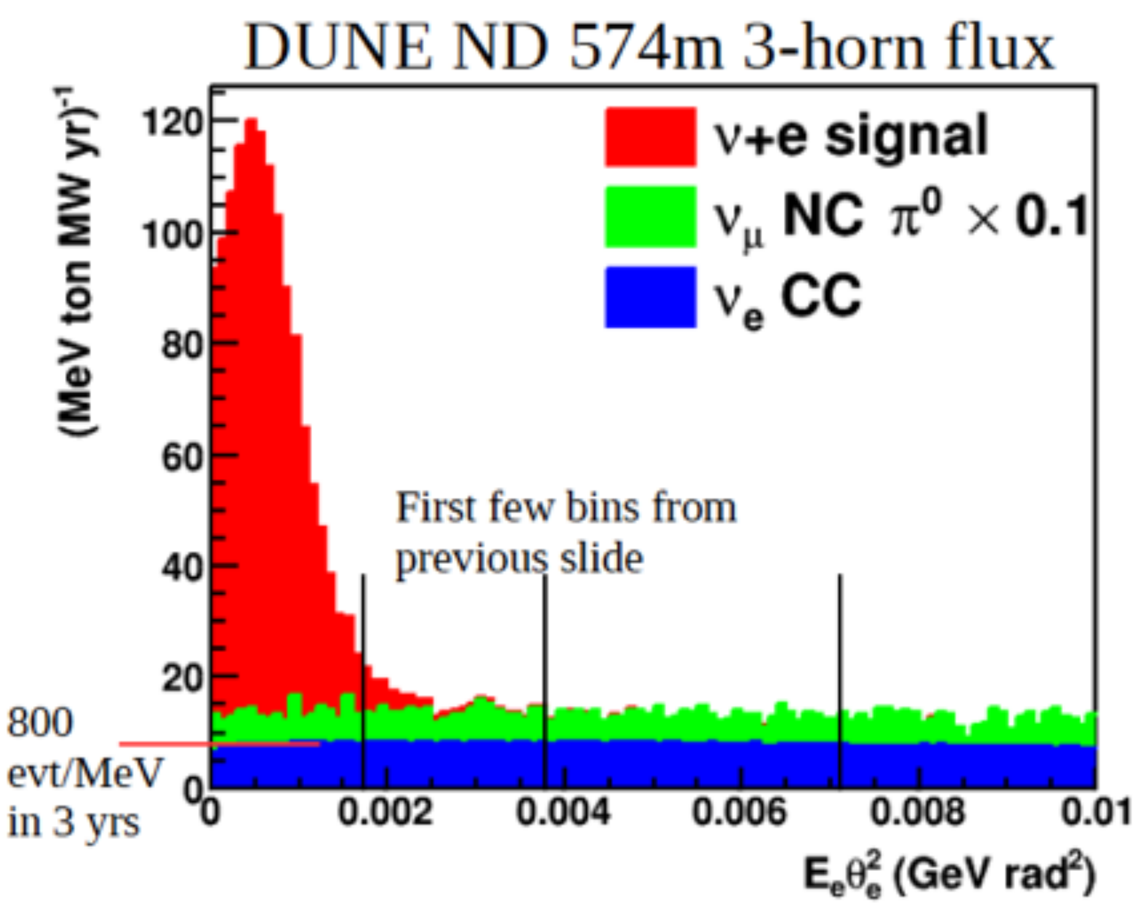


Modular LAR (Bern design)
Individual optically separated
TPCs with pixel readout.

Sinclair

Liquid argon physics





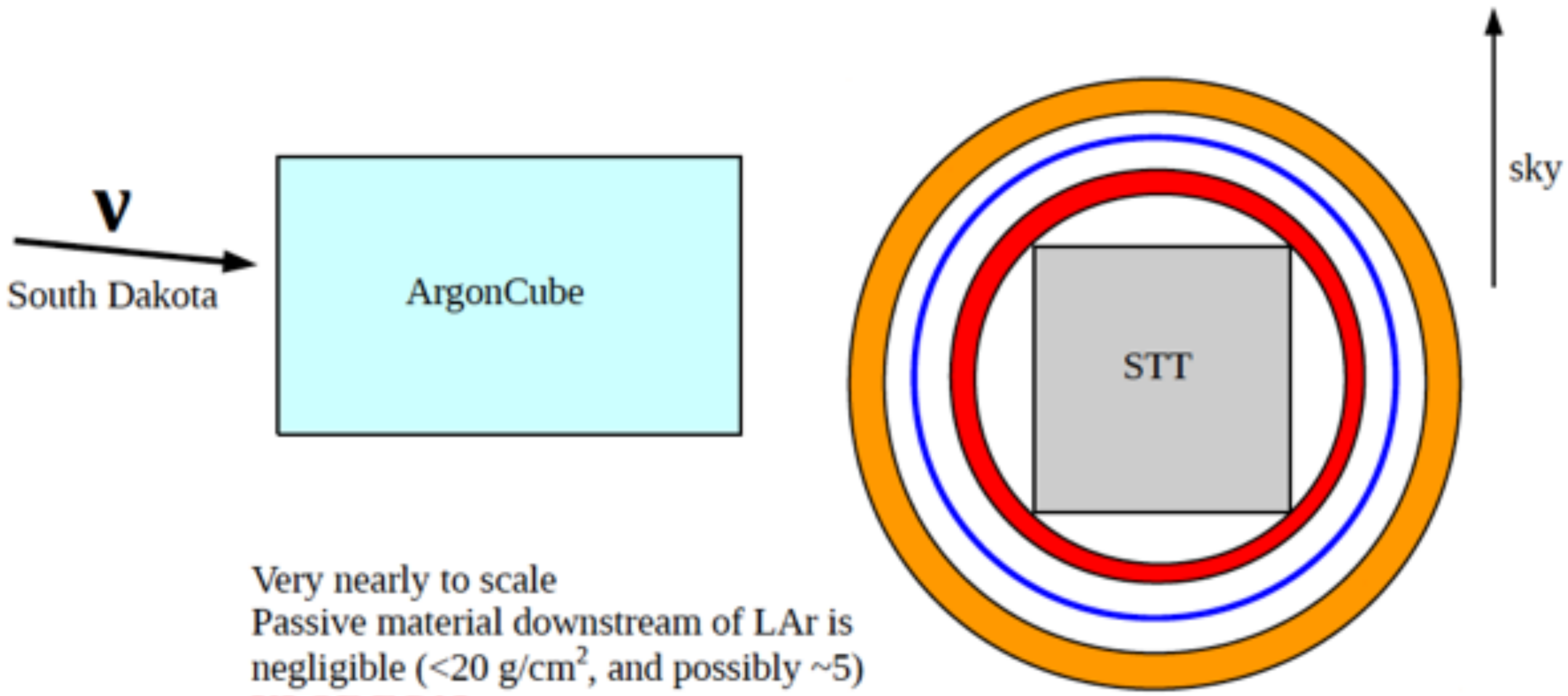
- *LrTPC ~4x3x5m, with 5m in ~beam direction*
- *For 3x2x3m F.V. (25t), 37M vμ CC events per year at 1.07 MW*
- *Muon acceptance in the magnet is a complicated issue*
  - *A magnet with coils/yoke in the way will absorb muons from the peak of the flux.*
  - *Spectrometer on the sides of LAR may be needed.*
- *Pile up of unrelated extra energy in showers is manageable (~1%) up to 2 MW*
- *Hadron containment is good.*
- *Nu- e elastic scattering appears to be in decent control with the pixellated readout. ~10k events in 3 yrs for nu.*
- *The systematic error on background due to shape uncertainty is manageable to ~10% using current data on CCQE.*

Chris Marshall

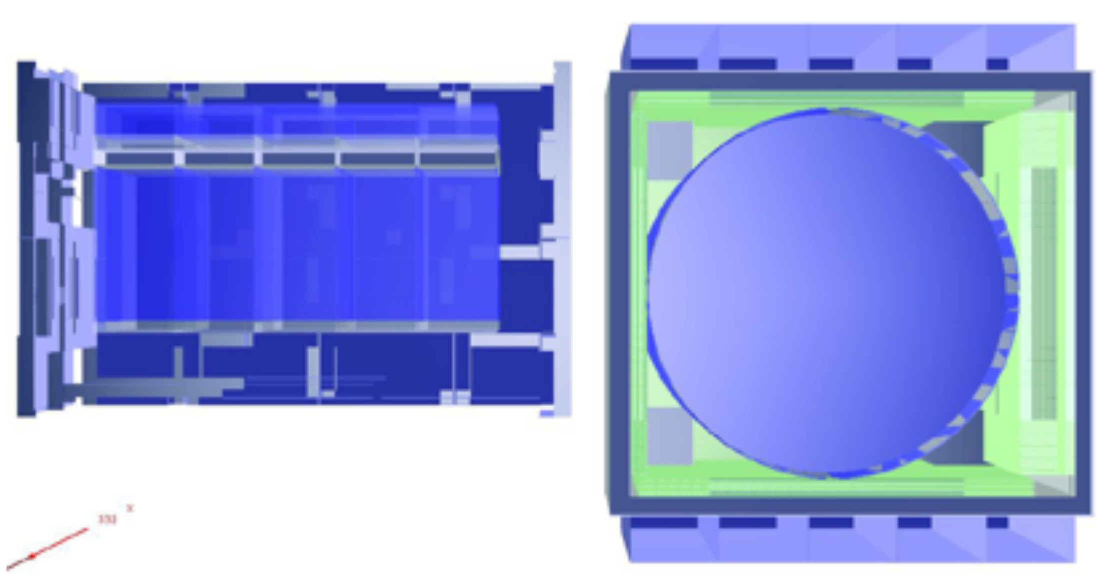
Key elements from the interim DUNE ND report

- *Default geometry @ND570 for near detector conventional construction.*
- *There are important options for geometry that will significantly enhance science, but are costly such as ND360.*
- *Include a hybrid design for a LARTPC and a magnetized multipurpose fine grained detector.*
- *Hall size needs to be optimized.*
- *Magnet design to be optimized to allow high acceptance for muons from the LAR.*
- *To be decided - tracker technology, 3D scintillator technology, liquid argon optimization and readout design.*
    - *Various detector options: 3DST, GasArTPC, optical liquid argon readout with the KLOE magnet, Straw tube tracker.*
    - *There are important arguments for choosing STT versus High pressure gas TPC.*

Spectrometer Magnet



Very nearly to scale
Passive material downstream of LAr is negligible (<20 g/cm^2, and possibly ~5)
KLOE ECAL
Magnet coil (inside cryostat)
KLOE yoke



- ***An interesting option is the reuse of the KLOE SC magnet with straw tube tracker.***
- ***But the KLOE Yoke and ECAL are quite thick and reduce muon acceptance.***

- ***New magnet may have to be built for the spectrometer to increase muon acceptance.***

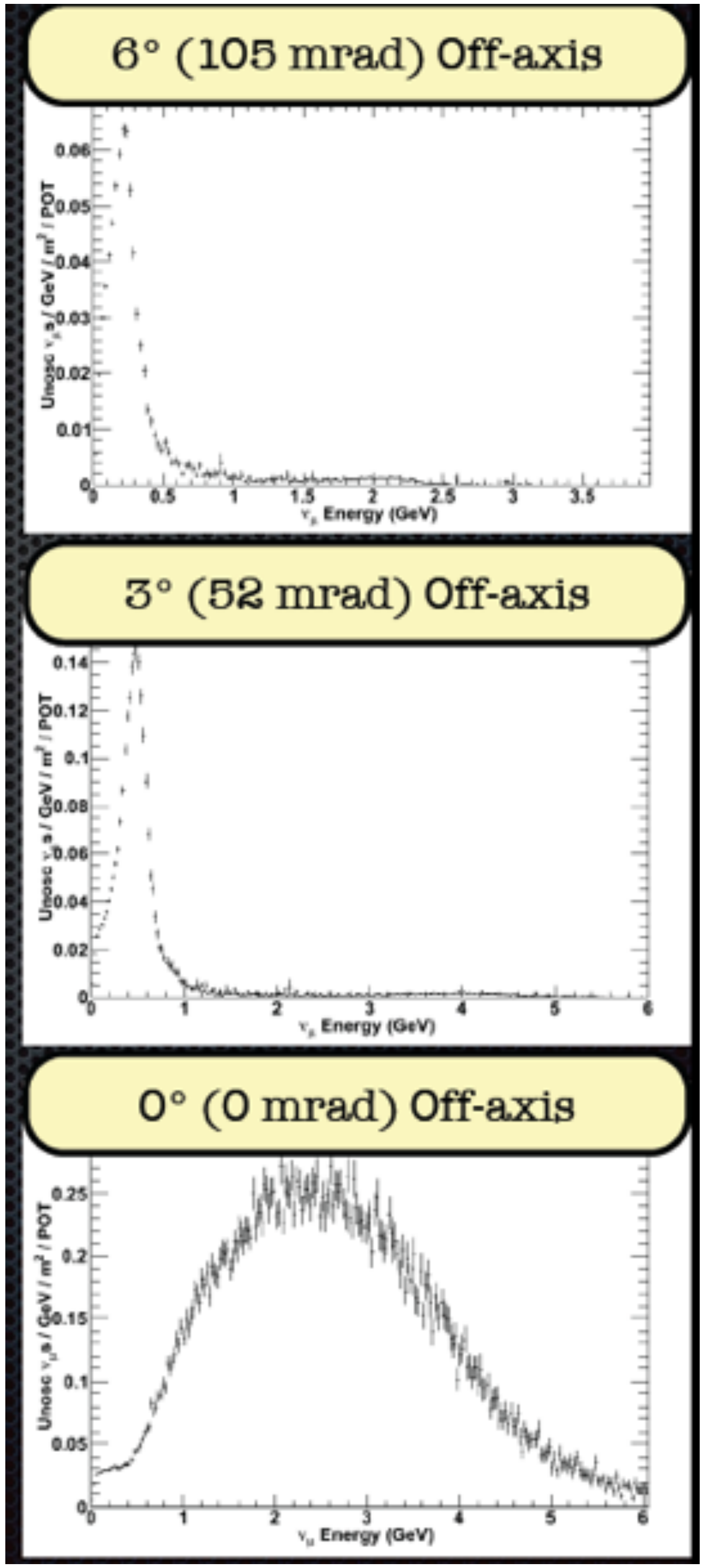
- ***In either case, is highly likely that additional muon measurement will be needed around the LAR TPC.***

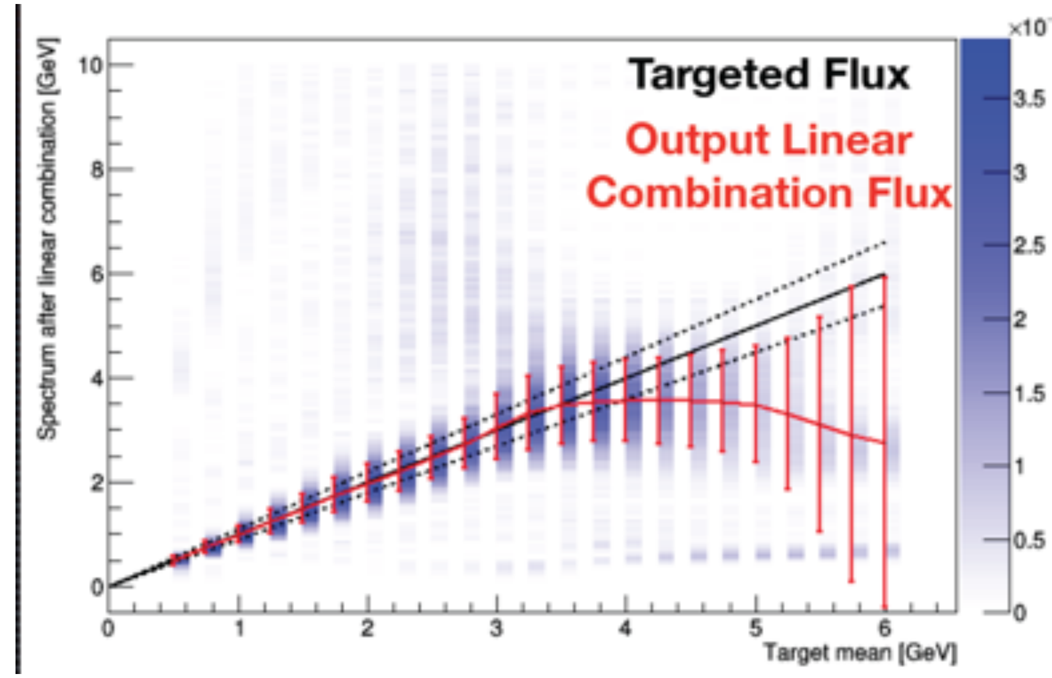
DUNE ND Evaluation Sheet

Photon conversion in tracker
Fast timing (nsec)
Sign selected low Pmu included in flux constraint
Larger angular acceptance (good Pmu) in flux constraint
Acceptance/eff even over 4 pi
High stats when LAr off axis
neutrino-electron scattering with different systematics
low-nu flux determination with sample independent of LAr CC
Sign separate pions for xsec
High stats connection to plastic data
nu-Ar xsec measurement with different systematics
CC coherent-pi measurement (specified CC)
sensitivity to low energy protons
potential to usefully measure scattering on hydrogen
potential to usefully measure scattering on other nuclear tar
potential to measure NC pizeros
ability to tag neutrons
ability to tag neutrons from Argon
ability to measure primary neutron energy
transverse variables on Argon
measuring multiplicity
energy scale
calibrations
control sample

Is having multiple nuclear targets an important criteria ?

Prism

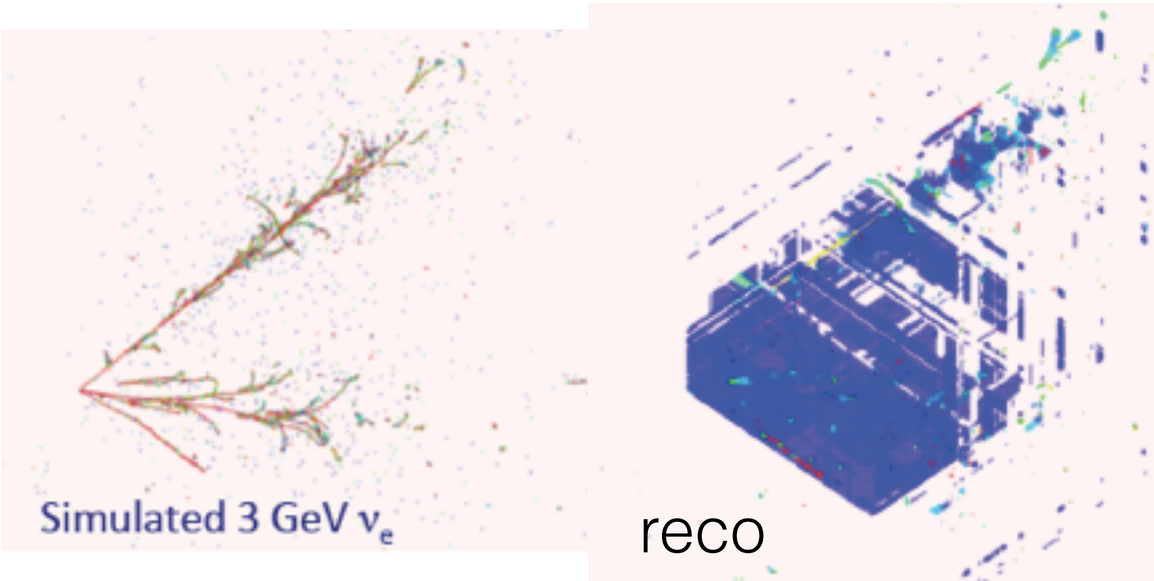


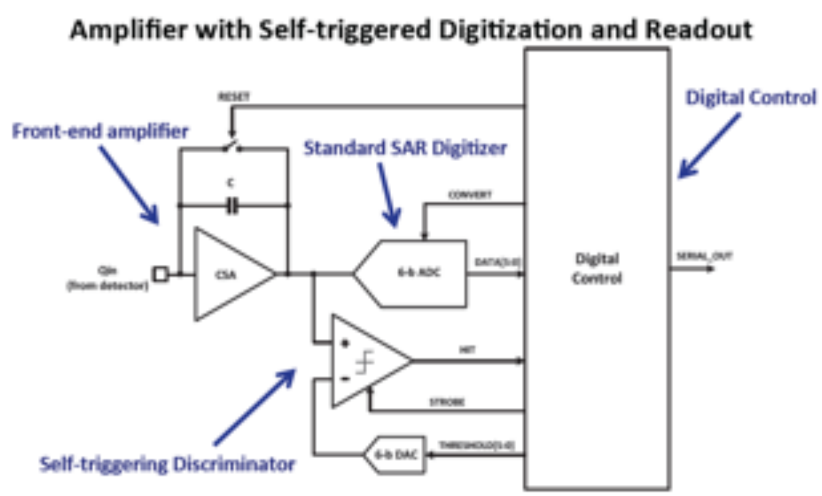


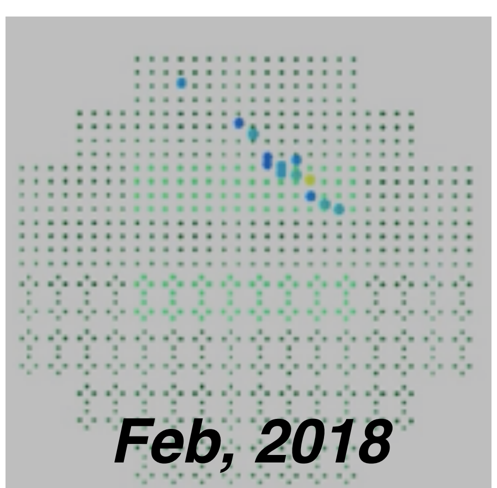
- ***Off axis placement of detectors yields data with effectively narrow band beams.***
- ***A linear combination of these beams will yield measurement of detector response as a function of energy.***
- ***A far detector oscillated spectrum can be reproduced with near data.***
- ***does this help the nue systematic errors and what is the technical feasibility ?***

M. Wilking

Pixel readout



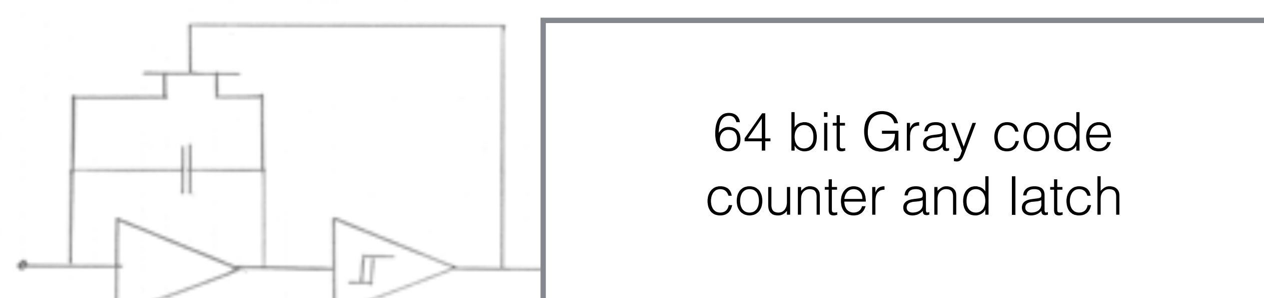




- ***A high multiplicity event with isochronous tracks is very difficult to reconstruct a wire readout LAR. See recent: Qian, Zhang, Viren, Diwan***
- ***For a true 3D readout we need pixel readout. But the electronics power and noise need to be extremely low.***
- ***Several efforts are underway to provide an ultra-low power solution.***

LBL: LARPIX has some encouraging results. See: Dan Dwyer's talk in FNAL indico.

UTA: A radical new thinking on how to digitize by preamplifier reset pulses by D. Nygren. This needs examination.



MINOS and NOVA beam

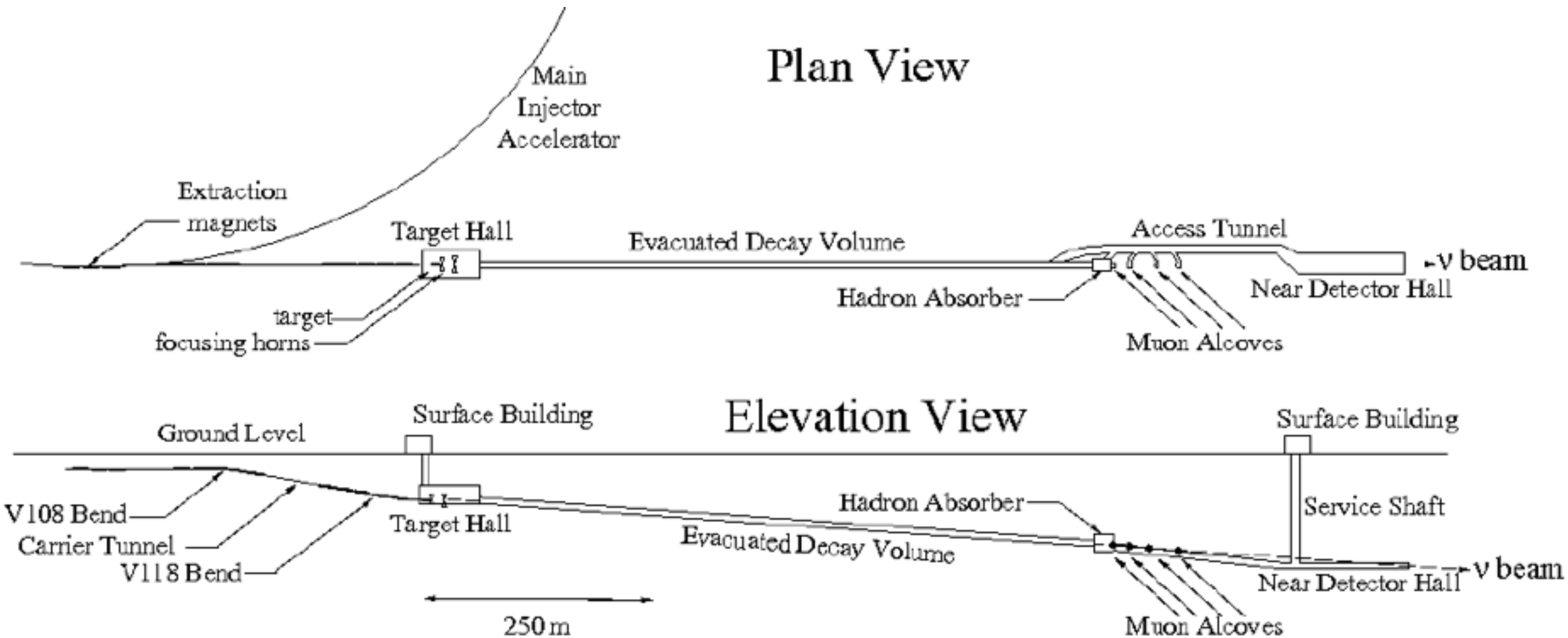


Figure 3: Plan and Elevation Views of the NuMI Beam Facility. The proton beam is directed onto a target, where subsequently the secondary pions and kaons are focused into an evacuated decay volume (later filled with helium) via magnetic horns. Ionization chambers at the end of the beam line measure the secondary hadron beam and tertiary muon beam.

NUMI target hall chase: ~40 m
Decay volume: 2 m diameter, 675 m long
Near detector location: 1045 m from target

1507.06690

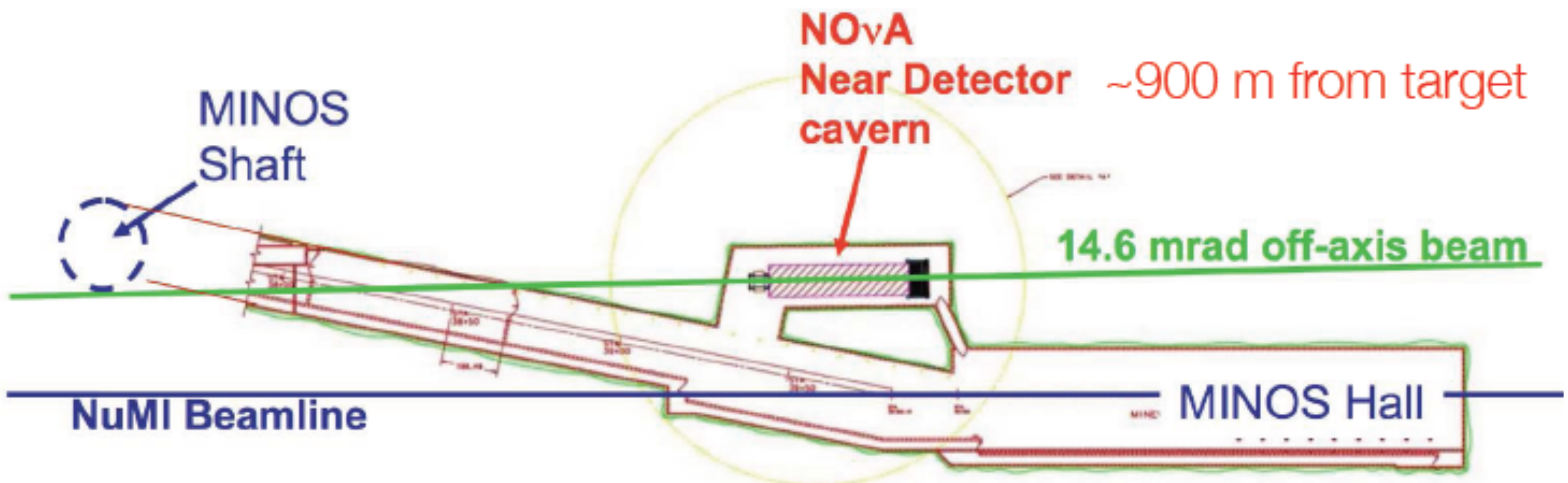
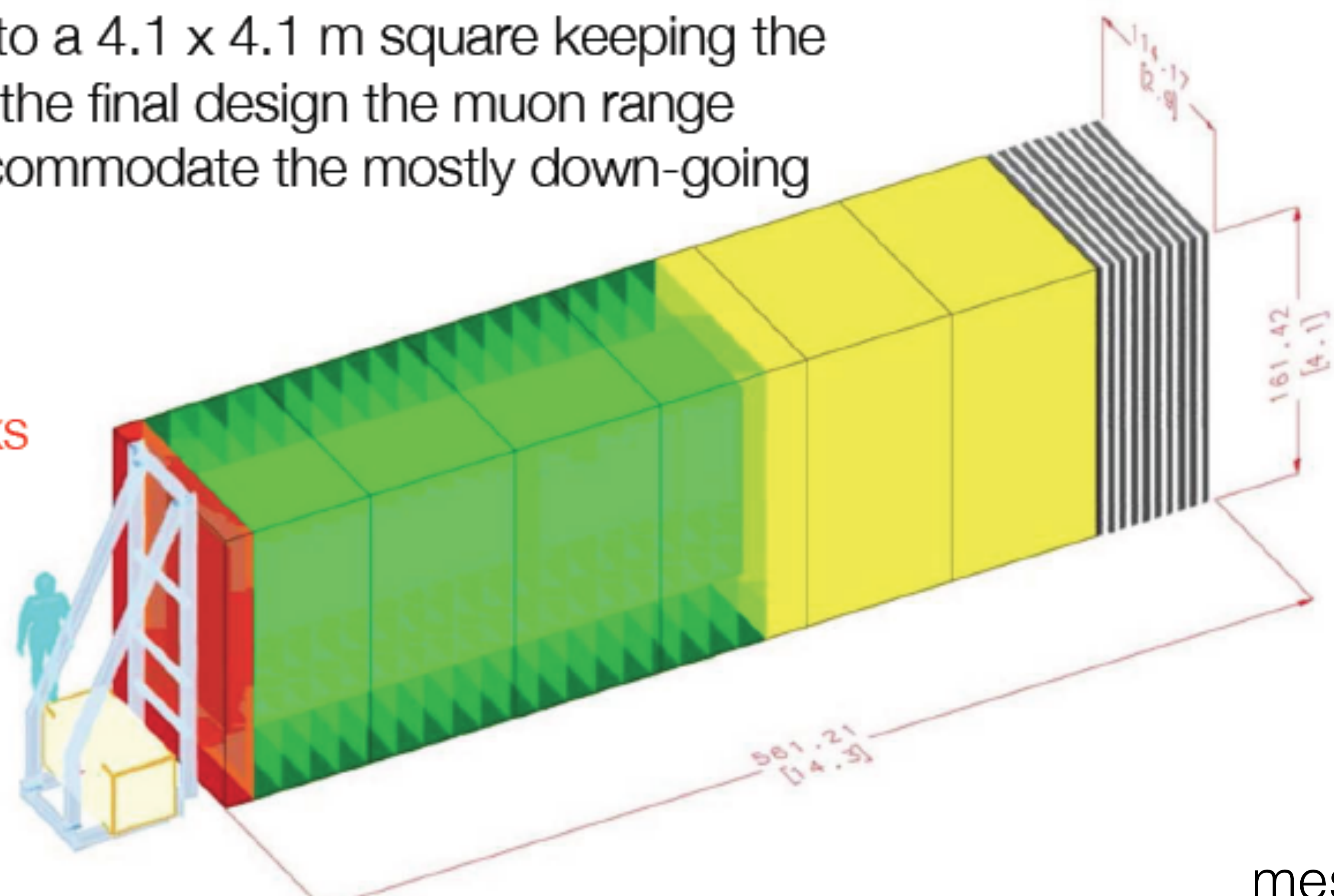


Fig. 5.9: A detailed plan view of the MINOS access tunnel from the vertical MINOS shaft to the MINOS hall. The new NOνA cavern is indicated.

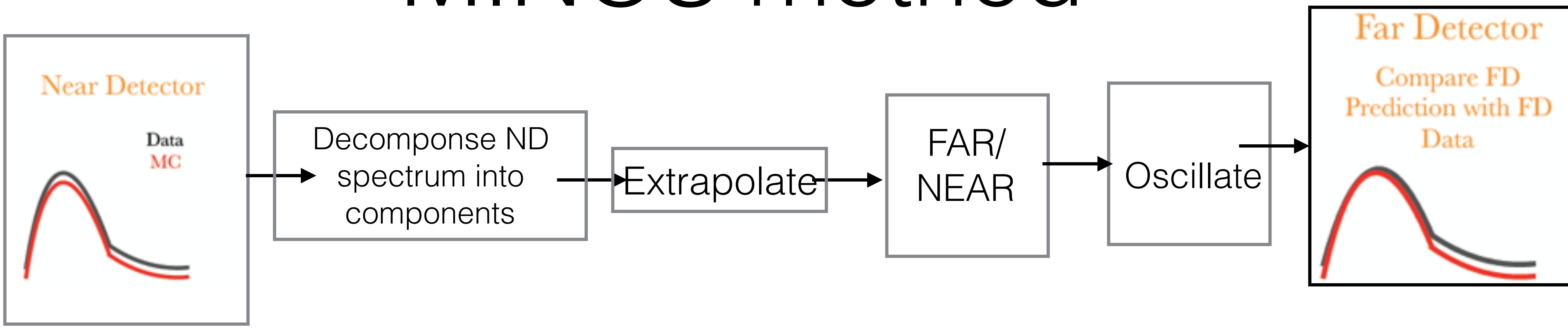
Original design of the NOvA near detector.
Final design widened the profile to a 4.1 x 4.1 m square keeping the cavern dimensions the same. In the final design the muon range stack was built on its side to accommodate the mostly down-going beam muons.

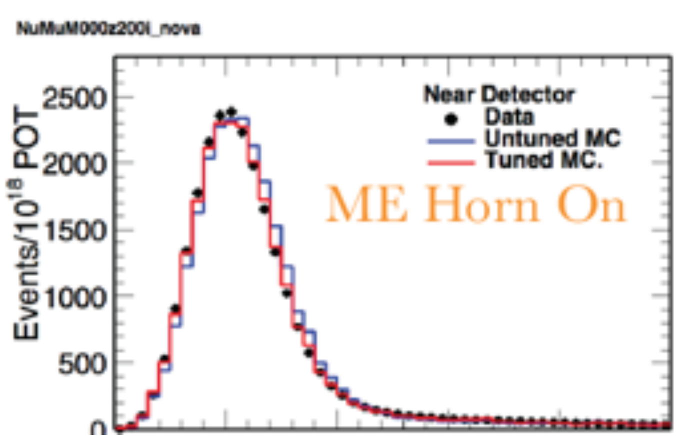
Basic units are:
Red : veto against entering tracks
Green: Target volume.
Yellow: Shower containment
Black/white: Muon ranger.

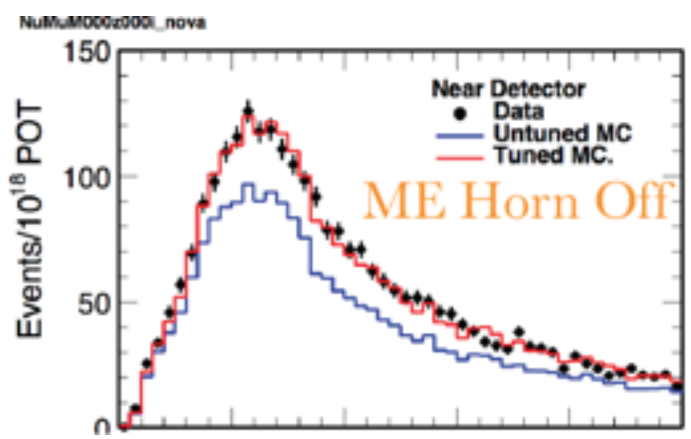


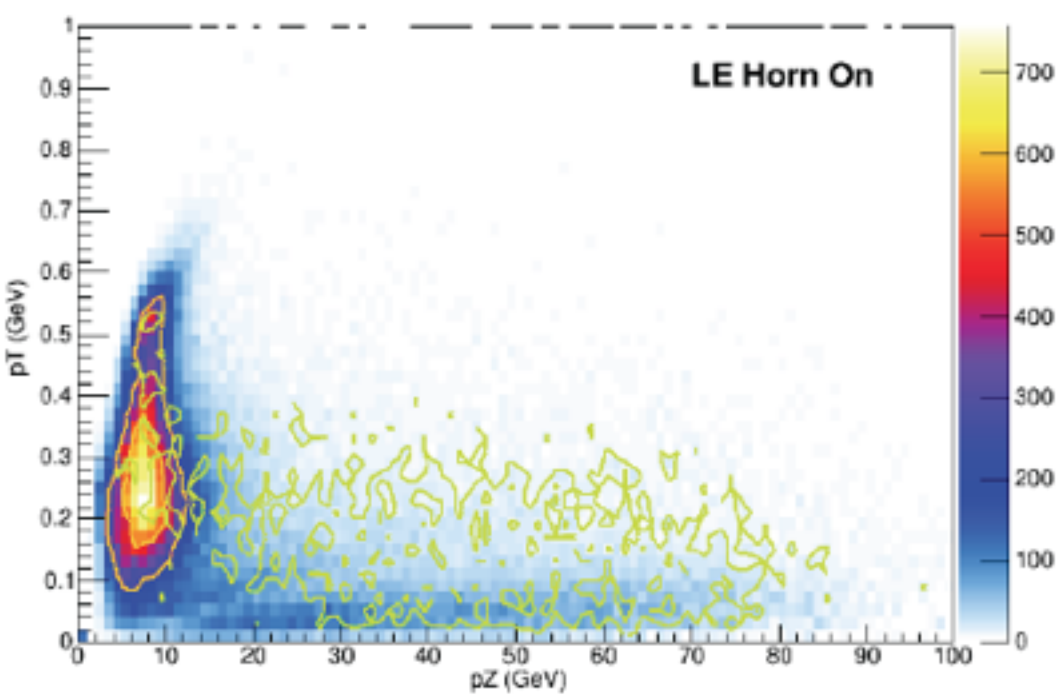
messier

MINOS method









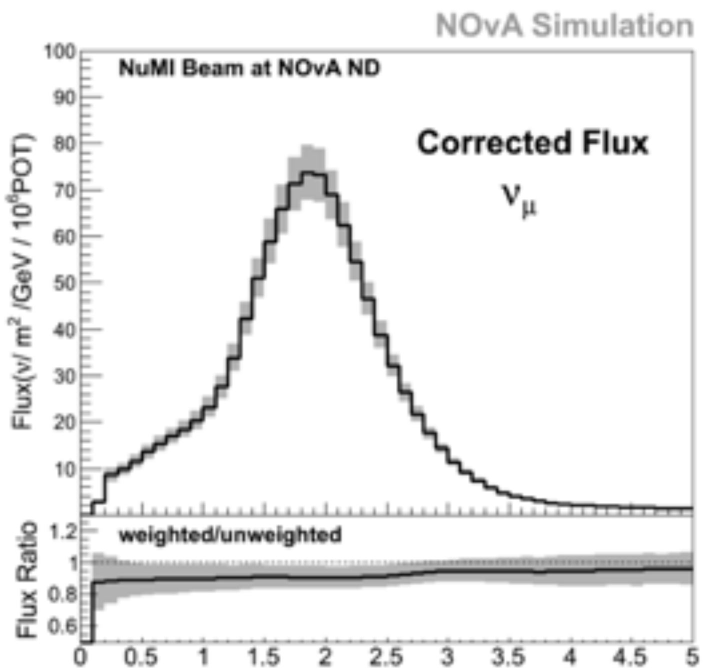
- *The method is aided by knowledge of two detector geometry and identical detectors.*
- *Fitting of different ND spectra can produce the decomposition needed.*
- *The ab-initio fits are not great, and the magnet focusing correction is poorly understood.*
- *BUT for MINOS disappearance this did not matter*
- *For advanced analysis, we need better knowledge of the spectra.*

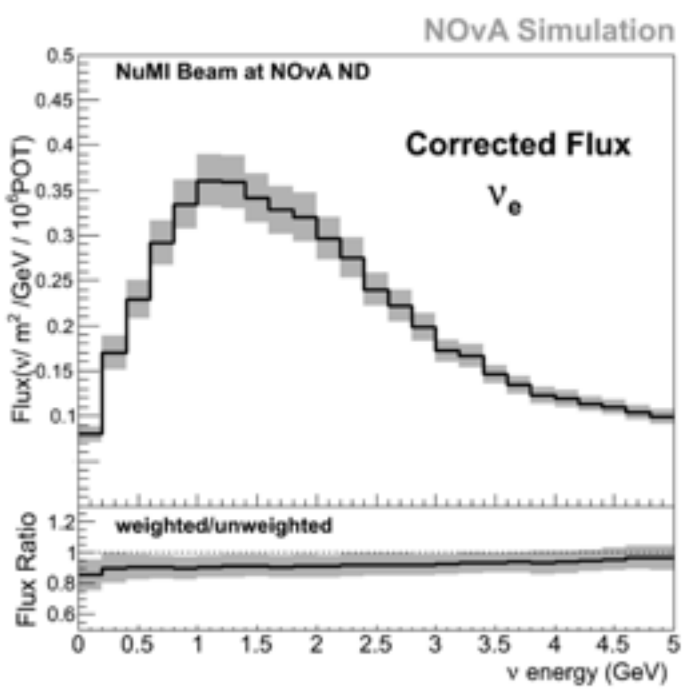
Detailed fit in pt,pz is being performed to get much better understanding

Holin

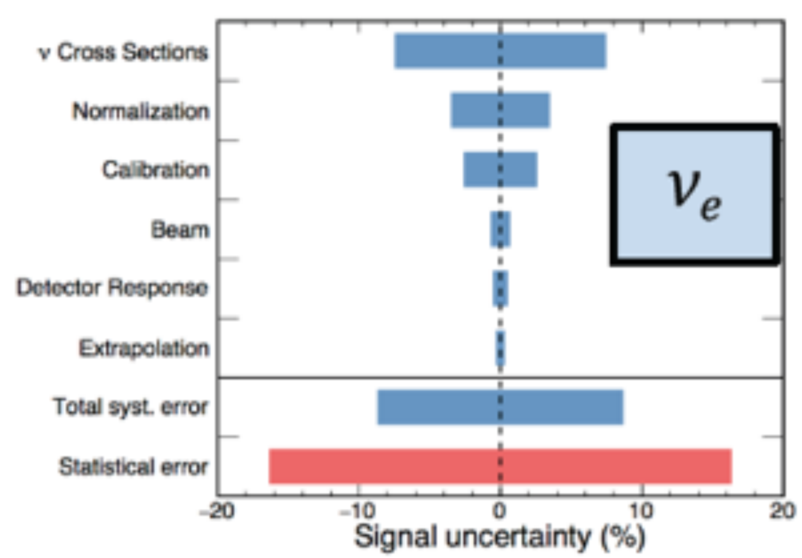
NOVA method

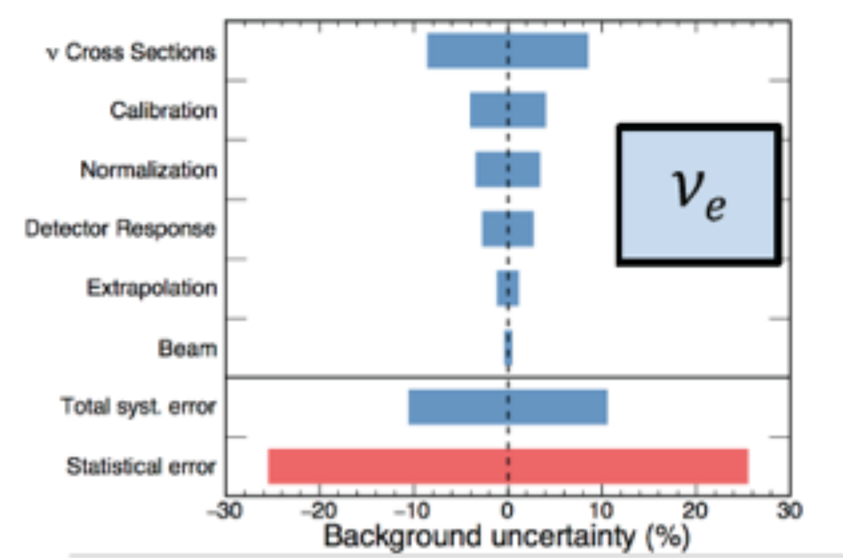
PPFX calculation of flux





- ***NOVA does not use the ND for flux constraints. It is used to tune cross section and detector performance.***
- ***The flux comes from PPFX which is a calculation using constraints from (Barton, NA61,NA49, MIPP)***
- ***Systematic error <10% is achieved.***





Messier

T2K method

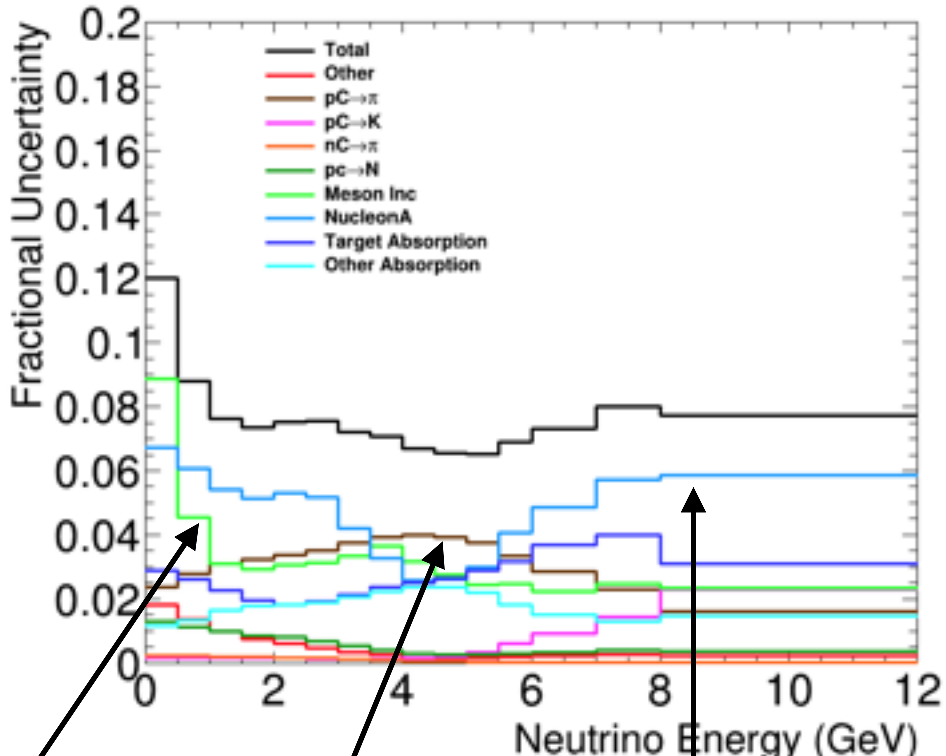
- ***T2K cannot easily constrain flux with near detector due to low energy: cannot use DIS events and too much model dependence on low energy methods.***
- ***Nu-e elastic scattering rate is too small.***
- ***T2K uses PRD 87 012001 to calculate the flux using simulation constrained by hadron prod. data.***
- ***Flux X cross sec is constrained by ND280 off-axis tracker/ spectrometer***
- ***This method manages to get to ~5% relative systematic error.***

	% 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

Harz

What beam progress to expect that could impact scope of DUNE near detector.

Current DUNE flux errors without ND



reinteractions

existing pC data.

interactions not covered by data.

- *NA61 at CERN will perform DUNE target production measurements to reduce errors.*
- *At 60, 90, 120 GeV with much improved forward hadron coverage.*
- *Better secondary production*
- *Additional large data set is expected to reduce total uncertainties in the peak to ~3%.*
- *This program implies*
  - ➡ *Larger physics scope for the Near Detector is possible.*
  - ➡ *Must be prepared to take advantage of such extreme precision.*

from: Aliaga, A. Marino

How does all this come together in a coherent plan for a high precision experiment?

$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * D_{\nu_e}^{far}(E_\nu, E_{rec})\ dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * D_{\nu_\mu}^{near}(E_\nu, E_{rec})\ dE_\nu}$$

Weber

- ***There is no satisfactory answer yet.***
- ***If energy is considered the random variable to be measured then this is a convolution of many effects: target-> horn->hadrons->nubeam->oscillations -> detector interactions -> Spectra***
- ***NOVA and T2K have chosen similar methods so far (with important differences, NOVA has identical det) to separate the convolutions into target-> beam flux, and beam flux -> detected spectra.***
- ***If DUNE chooses the NOVA/T2K approach then the systematic floor will likely be the hadron production errors.***
- ***DUNE has important advantages: huge near flux will allow nu-e elastic and low-nu measurements. This combined with a properly configured ND could allow this analysis.***
- ***The problem of controlling the eCC and muCC detector efficiency could remain and will need enormous work.***

Conclusion

- ***If DUNE gets the intended far detector mass of 40kton and 2 MW intensity, this could turn into a very high precision experiment. We need to think big about how to exploit this.***
- ***DUNE ND working group is charged to produce a pre-conceptual design soon. Conceptual design is to be followed within a year.***
- ***CENF ND working groups are looking at a broader picture including T2K and ancillary measurements.***
- ***Many options for hybrid technology detector under discussion.***
- ***Other important options include 2-Near Detector stations, and the PRISM concept. In both options, additional neutrino detectors (either at 360 m or further off axis) provide further constraints to reduce systematics.***
- ***It is important to preserve options as much as possible since physics is likely to change and higher precision will become both feasible and necessary.***
- ***Near detector should be expected to evolve and the facility should be designed to easily accommodate changes to the near detector systems.***