near measurements scientific strategy and conceptual design

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Please also see Mary Bishai’s slides

Reminder DUNE ND requirements

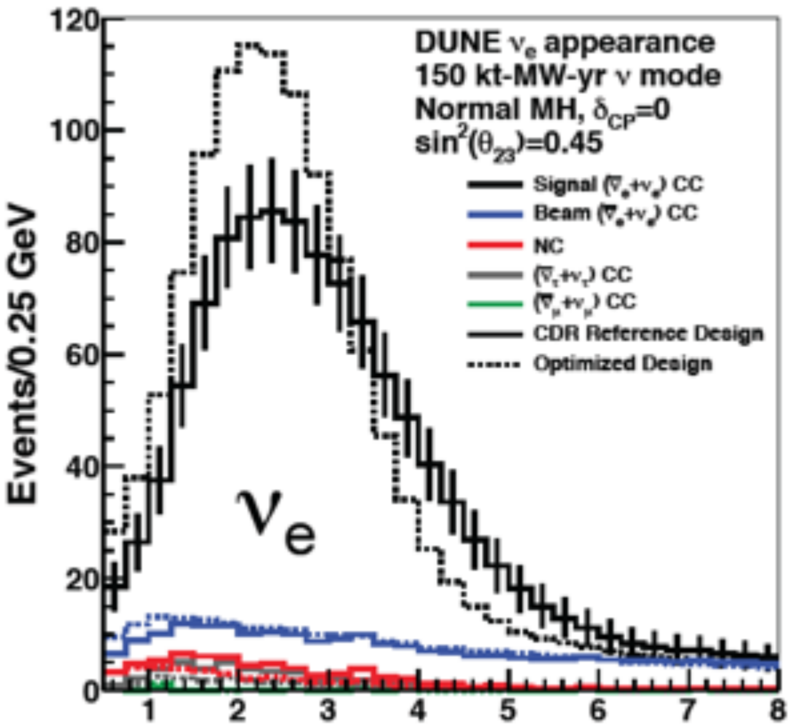
- **The current set of broadly written scientific requirements are in DOCDB-112. This was covered in the CD1(R) and CD3a reviews.**

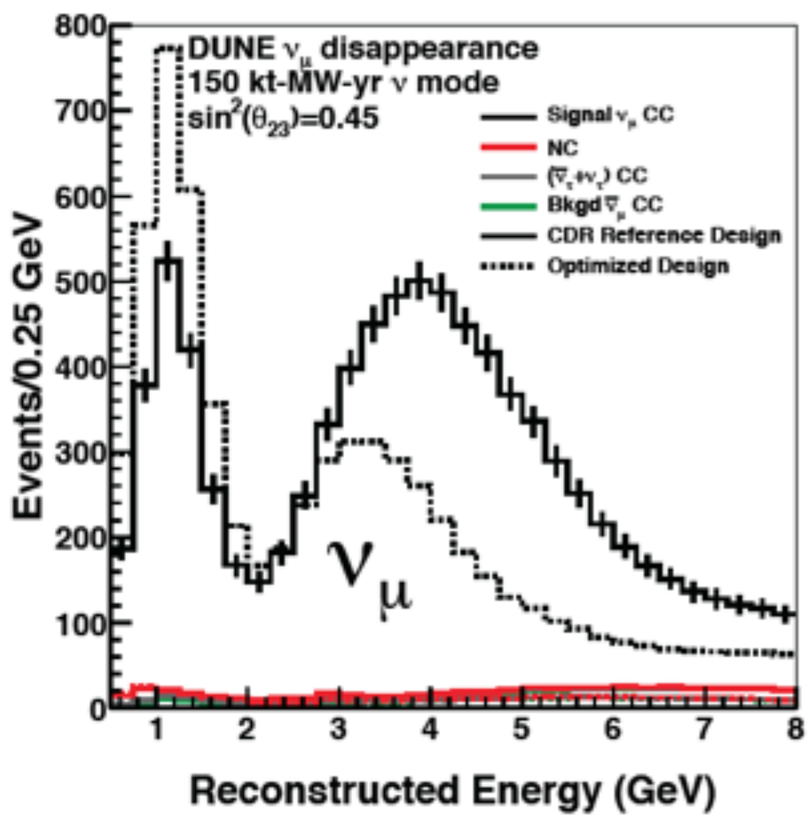
- **The Near Detector Complex measurements shall be sufficiently precise and accurate that the long-baseline neutrino oscillation analysis capability shall be limited by the statistics of the planned exposure and the systematic uncertainties of the far detector.**

- **The near neutrino detector shall be placed on axis with the neutrino beam; it shall be placed sufficiently far to satisfy two conditions: all muon flux from the beam should be absorbed before the neutrino beam reaches the near detector, and the uncertainties due to beam spectrum comparison between far and near should be highly constrained.**

These need to be made numerical with a specific design !
These were adapted with the view towards an evolving facility.

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%

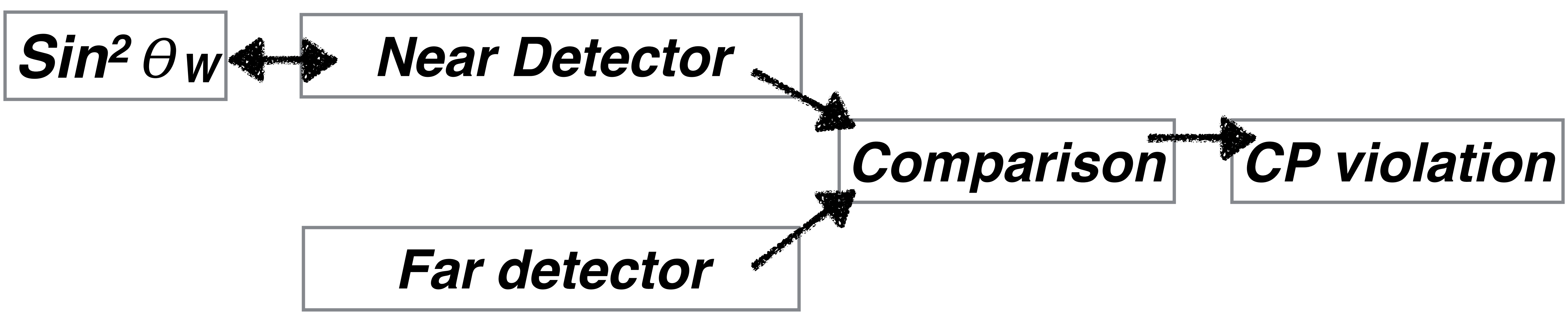
$Osc.\,freq = (1/500)km/GeV$

$Sampling > 2 \times Osc.freq$

- *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.*

Scientific Strategy

To obtain the needed precision for measurement of CP violation, DUNE near detector measurements shall be performed with respect to electro-weak parameters which are the most precise parameters in particle physics.



This is inspired by the work of Sanjib Mishra and Roberto Petti as presented in the CD1 review.

Key elements for the strategy

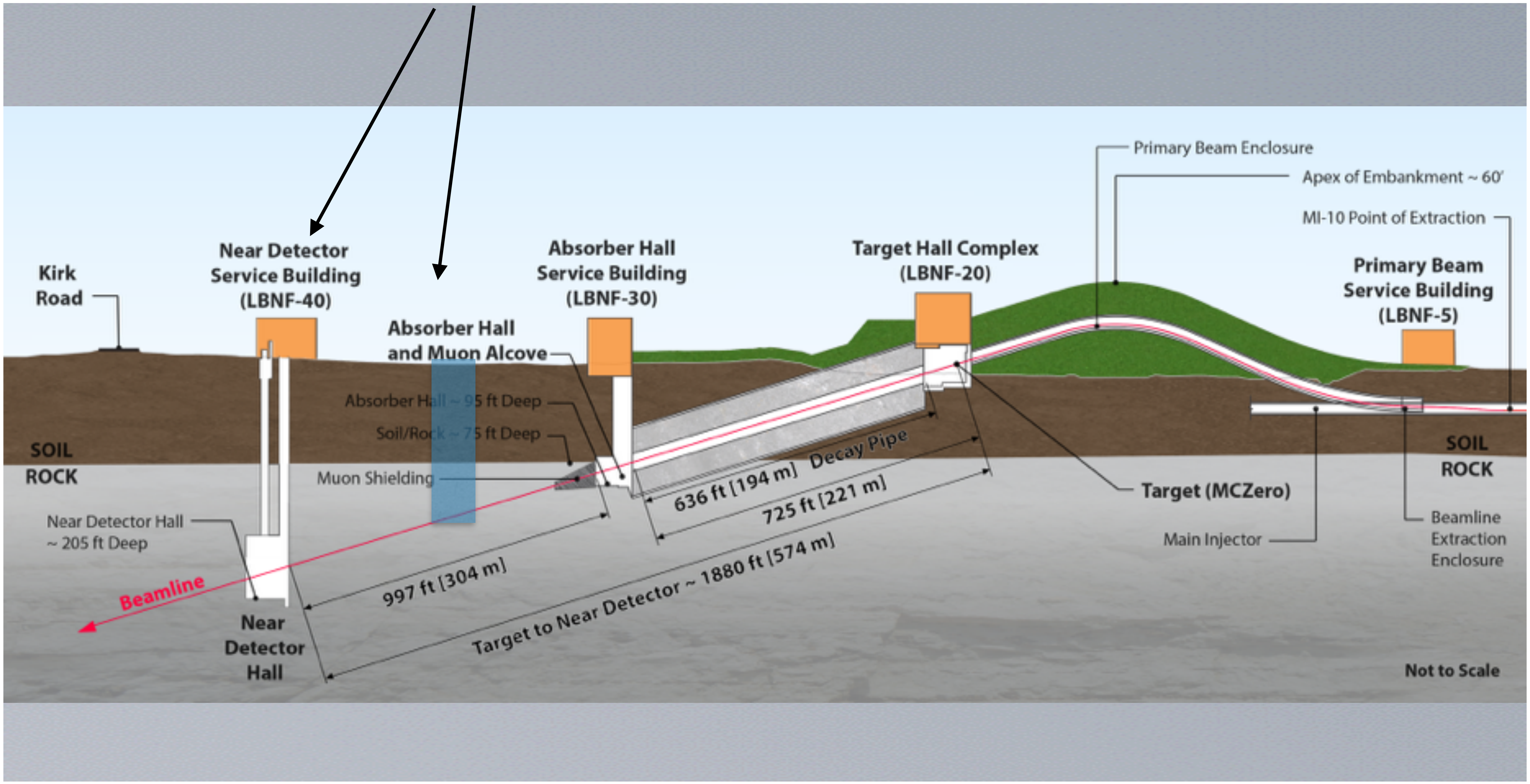
- The near detector complex must measure sufficient number of neutrino electron elastic scattering events — with low backgrounds —to obtain
  - The total neutrino flux.
  - The neutrino spectrum
  - The energy scale of the detector.
- The near detector complex must measure the electron neutrino +Ar CC inclusive events with sufficient purity.
- The near detector complex must measure the muon neutrino+ Ar CC inclusive events with charge separation and excellent purity.

Detector requirements for neutrino electron elastic scattering measurement

- *Angular resolution on the outgoing electron of <10 mrad ~ 0.5 deg. for 1 GeV electron. (must have resolution in both views)*
- *Since angular resolution depends on first scattering at the vertex: sampling must be < 0.1 radiation length*
- *Excellent angular and energy resolution is needed to obtain the neutrino energy spectrum. (This is crucial to obtain the energy scale.)*
- *Excellent dE/dx resolution will reduce gamma (from NC pi0) background.*
- *Good vertex energy resolution needed to veto CC events from nuclear scattering.*
- *Sufficient fiducial mass to obtain ~20000 events.*

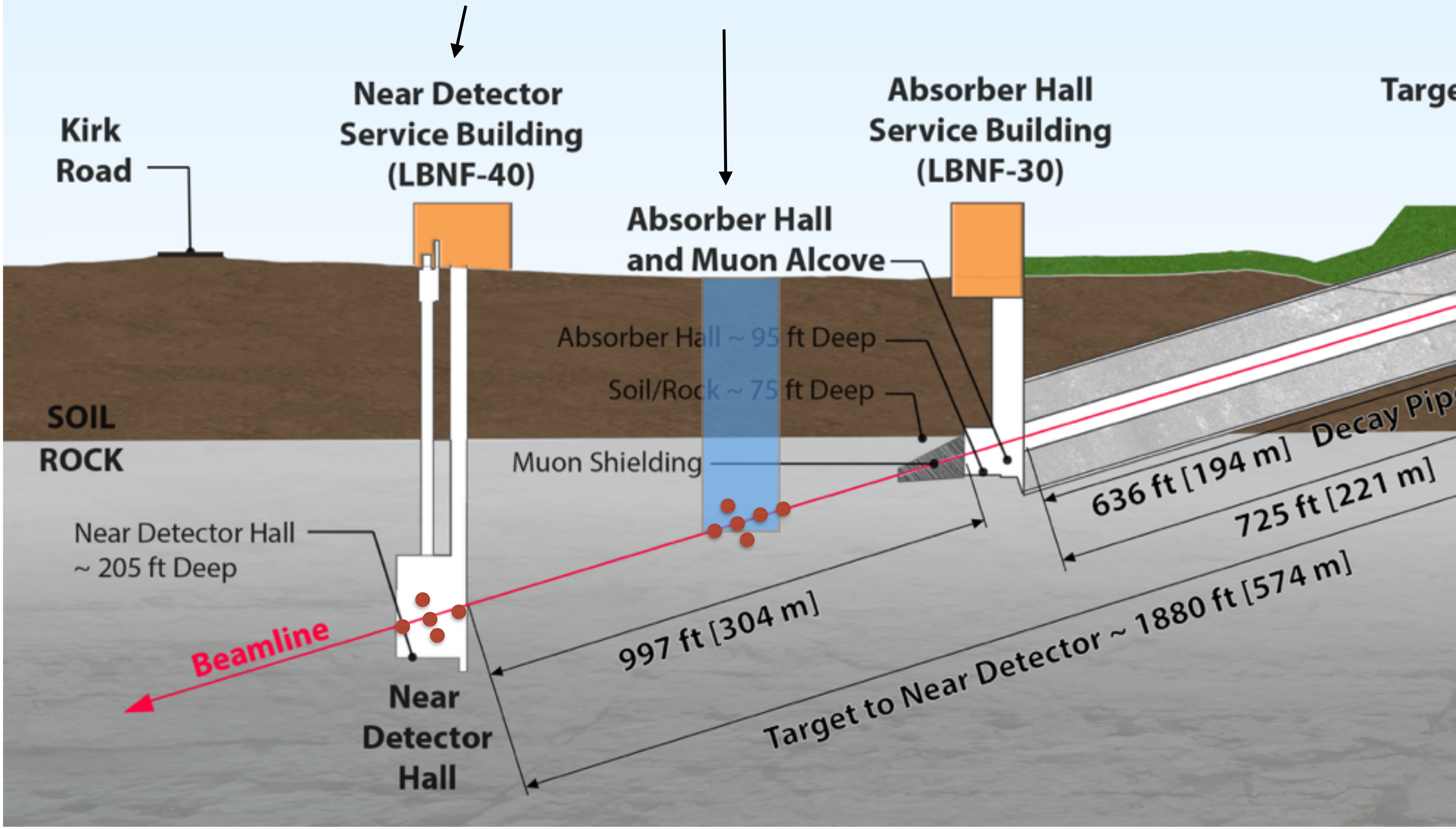
This is all feasible

Possible locations are ~360m and 574m



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.

Possible locations are ~360m and 574m

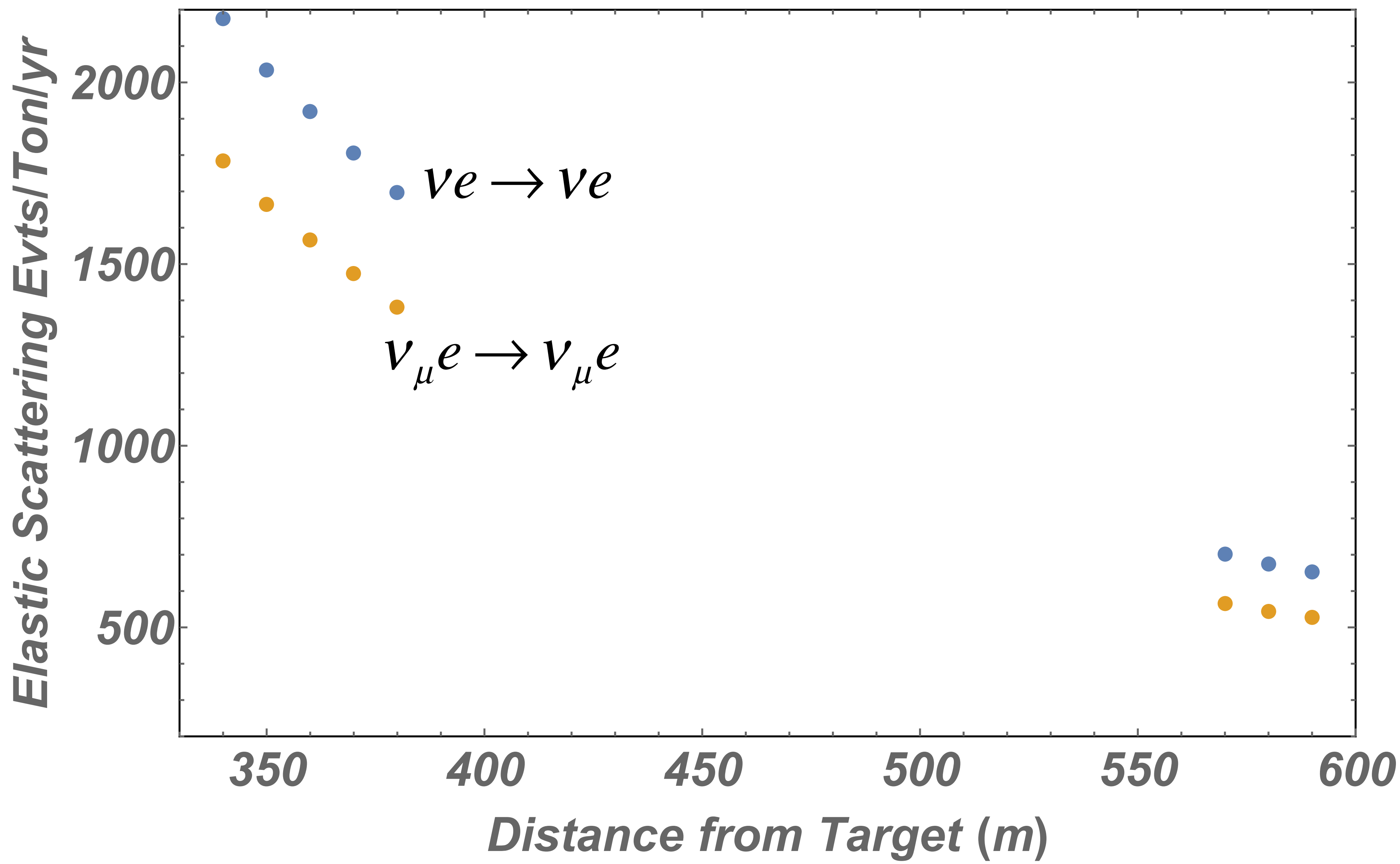


ND flux and spetra have been computed all along the beamline from 340 to 590 m and also off-axis at select locations. This calculation was done by Mary Bishai with geant simulation.

Neutrino electron elastic scattering event rates

	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*



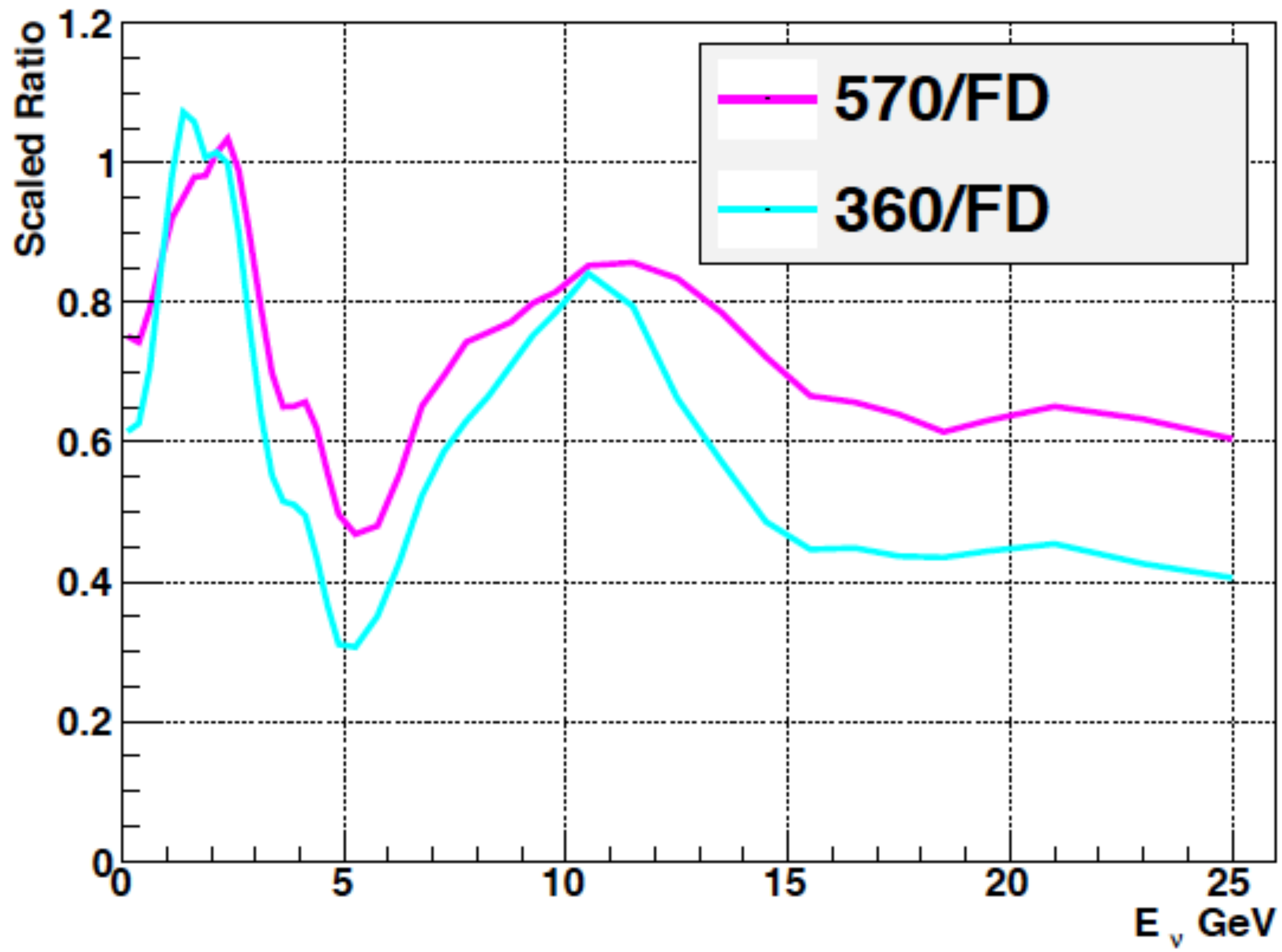
The predominant rate is from the main (ν_μ) species.
The dependence along distance and off-axis has information on how to disentangle the various species.
The dependence is measurable at both locations.

ν_μ and ν_e CC rates

	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

ND/FD detector extrapolation

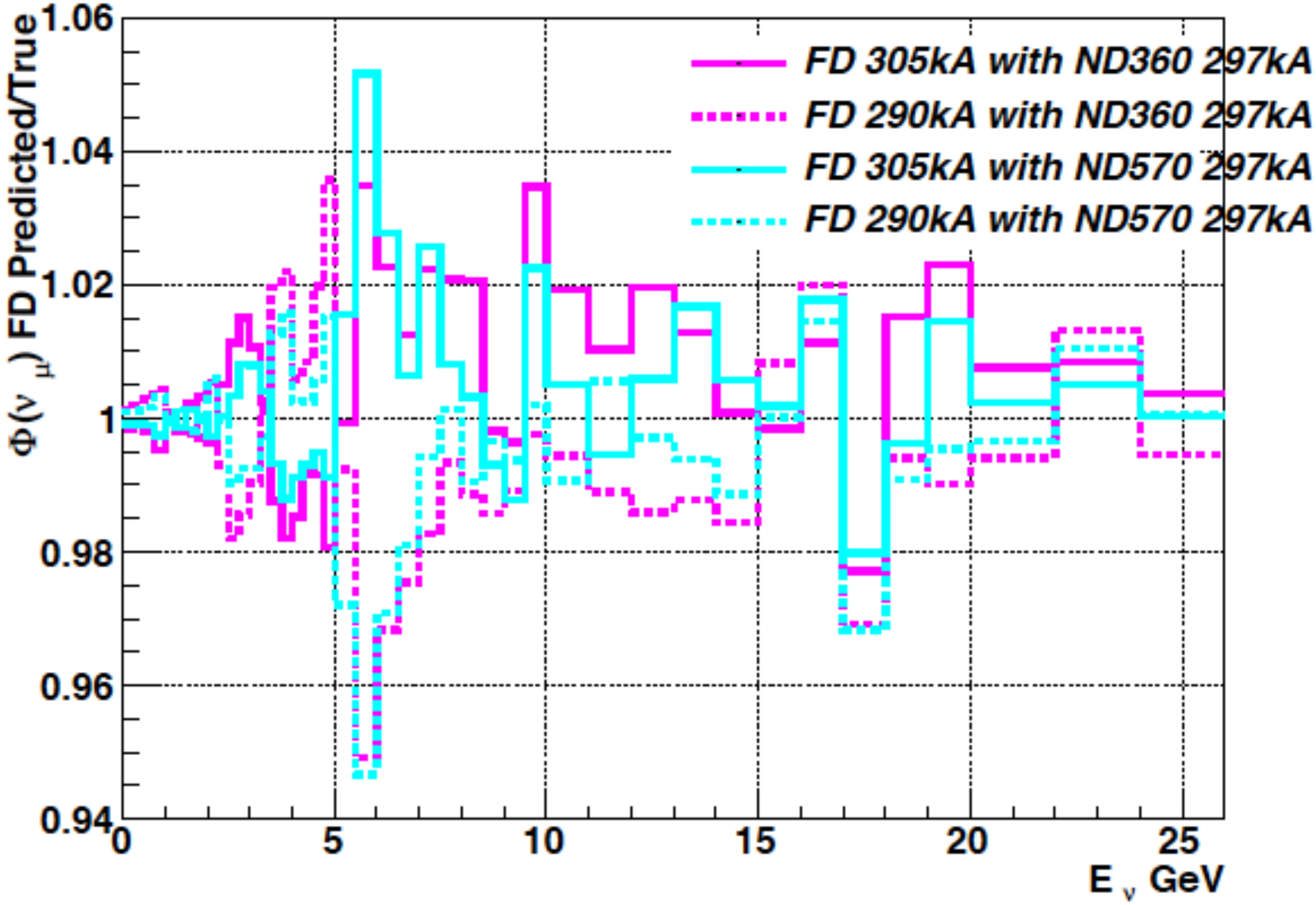


BL scaled from center of decay channel ($\sim$ 110m).

With a proper selection of the origin, the ND/FD extrapolation is not very different for 360 versus 570 m. The extrapolation is mostly governed by pion lifetime and geometric effects.

Bishai

e.g. systematic due to horn current

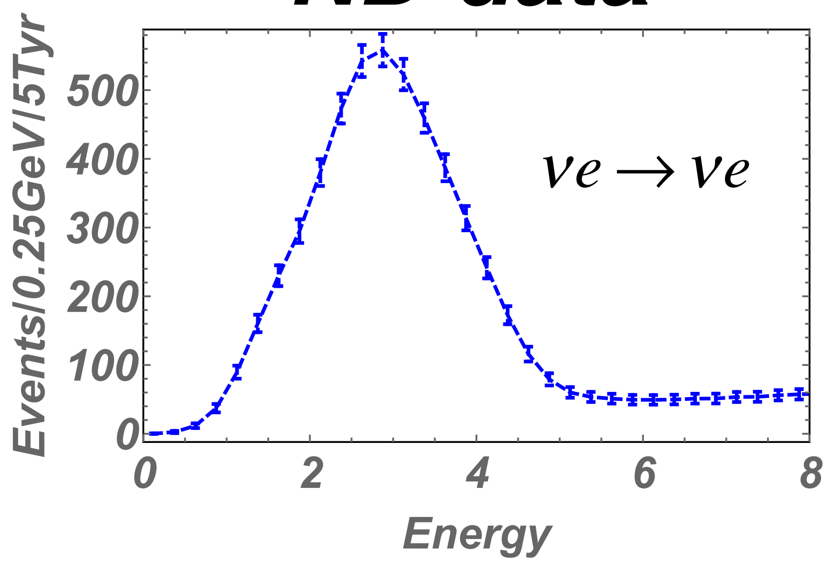


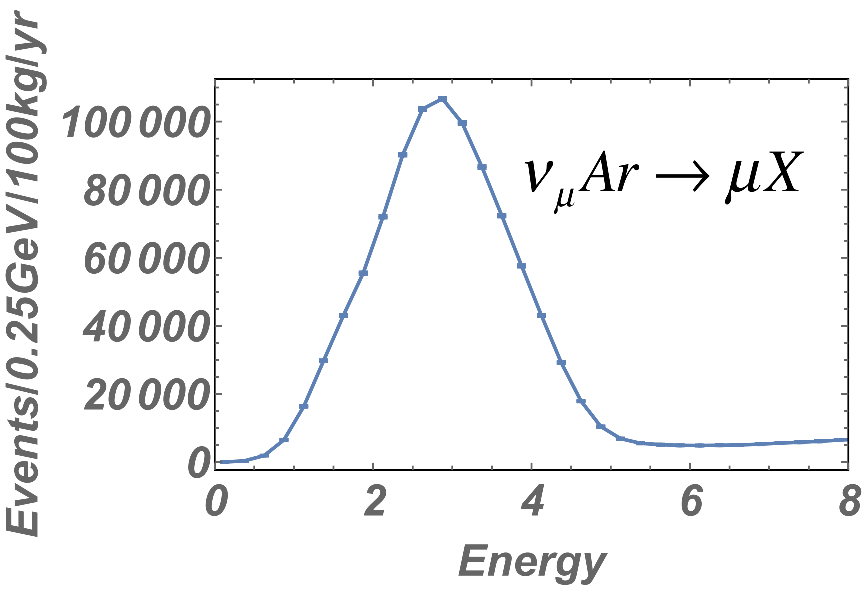
Residual N $\rightarrow$ F discrepancy using matrix extrapolation

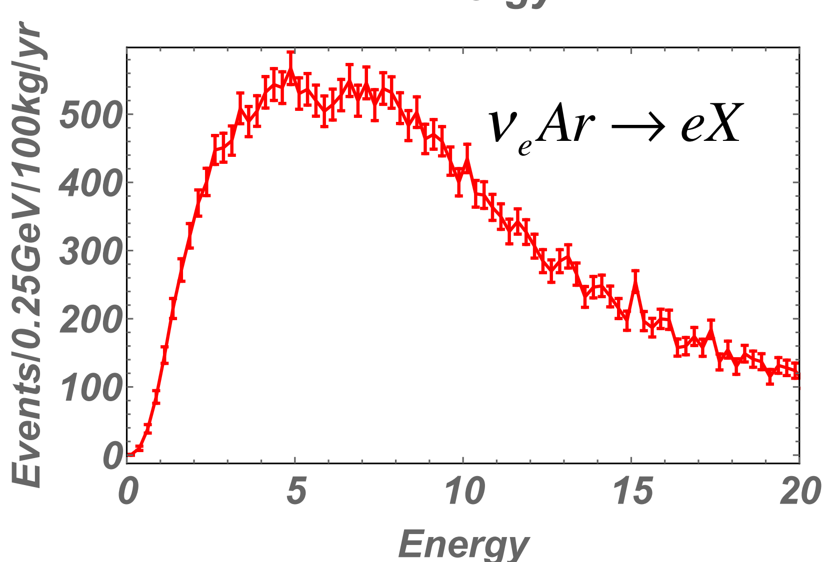
Using the beam matrix method predict the FD (at 290, 305 kA) using ND spectra at 297 kA. There is not much difference in ND located at 360 versus 570.

Analysis big picture

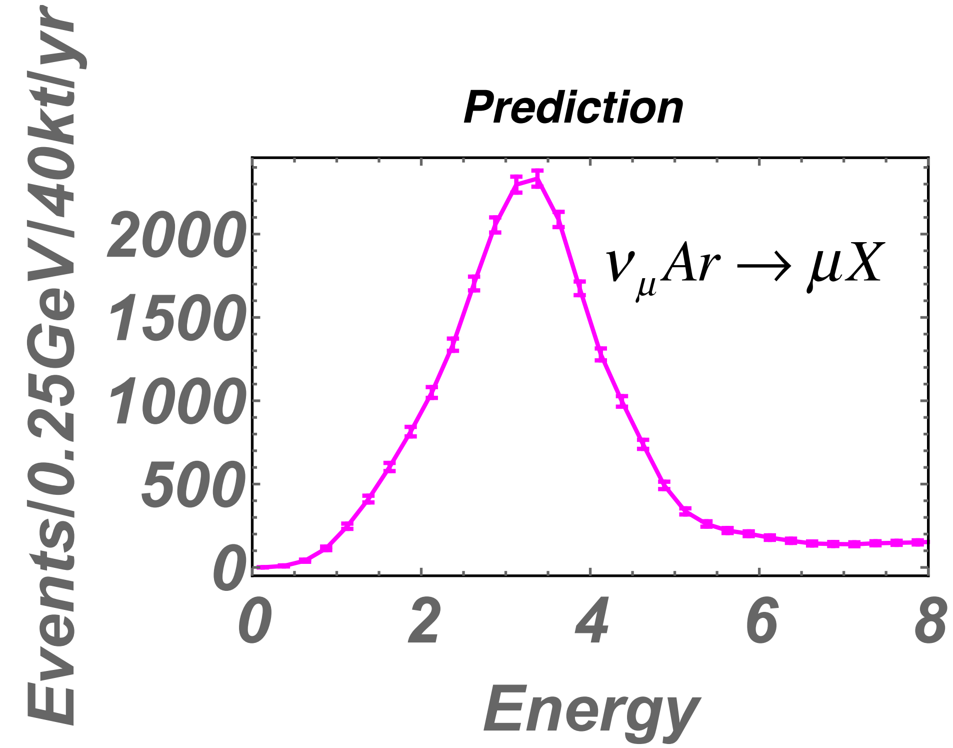
ND data



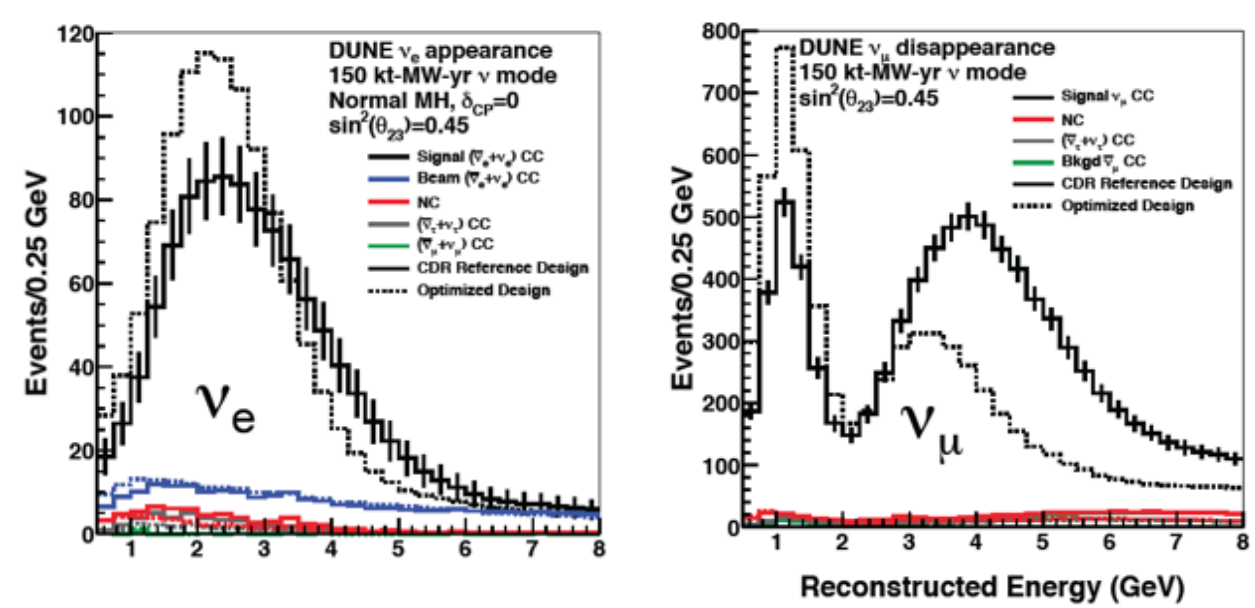




ND/FD Covariance (Xin Qian)



Analysis can be firmly based on the best known process of elastic scattering



FD data

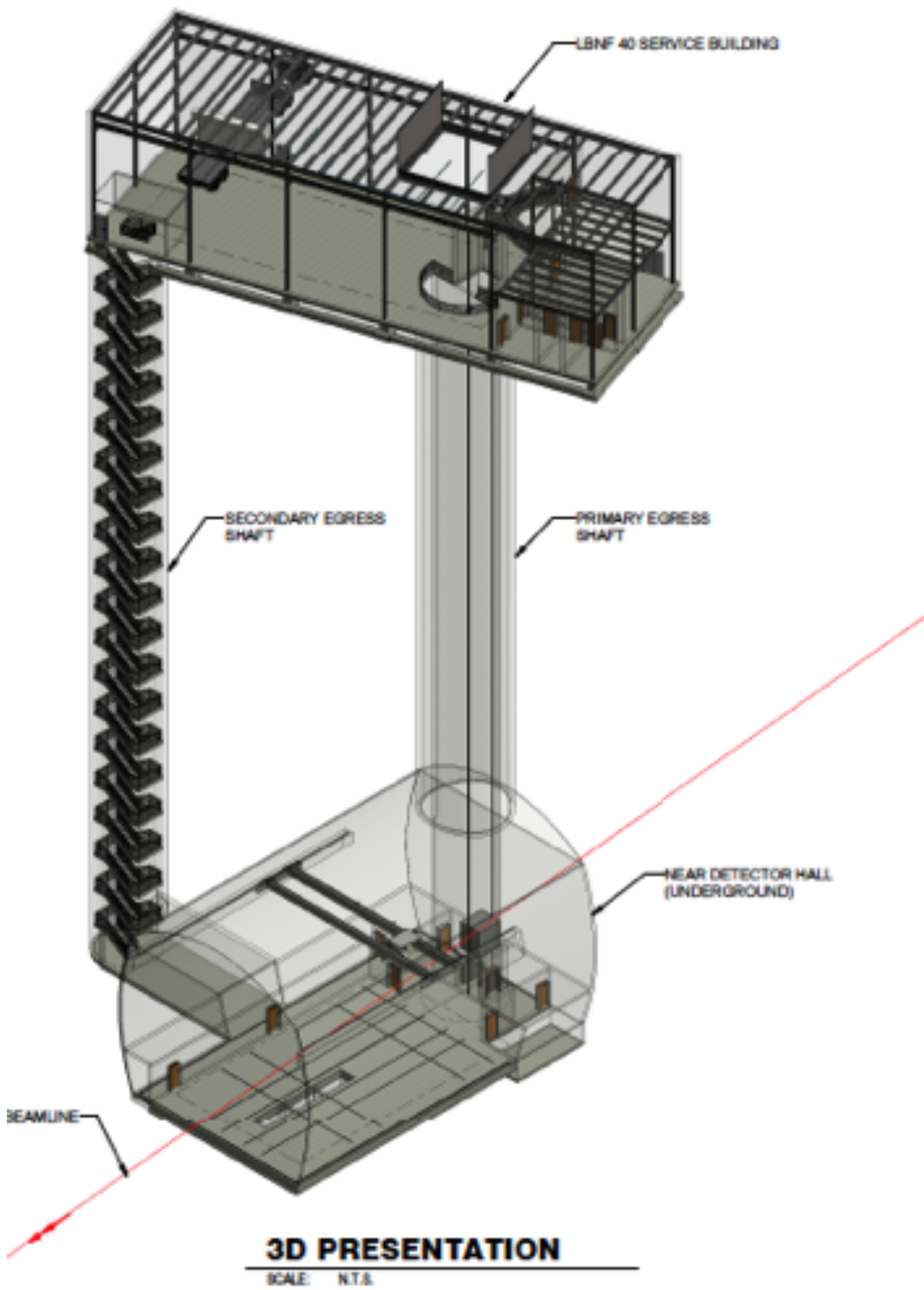
Other Important Elements

- ***High energy flux determination should be made using Inverse Muon Decay (>11 GeV).***
- ***The FD background to the electron neutrino event spectrum should be calibrated using the near detector.***
- ***Nuclear effects will cause the total CC energy to be shifted. The near detector should allow unfolding of nuclear effects.***
- ***Near detector should be expected to evolve and the facility should be designed to easily accommodate changes to the near detector systems.***

Conclusion

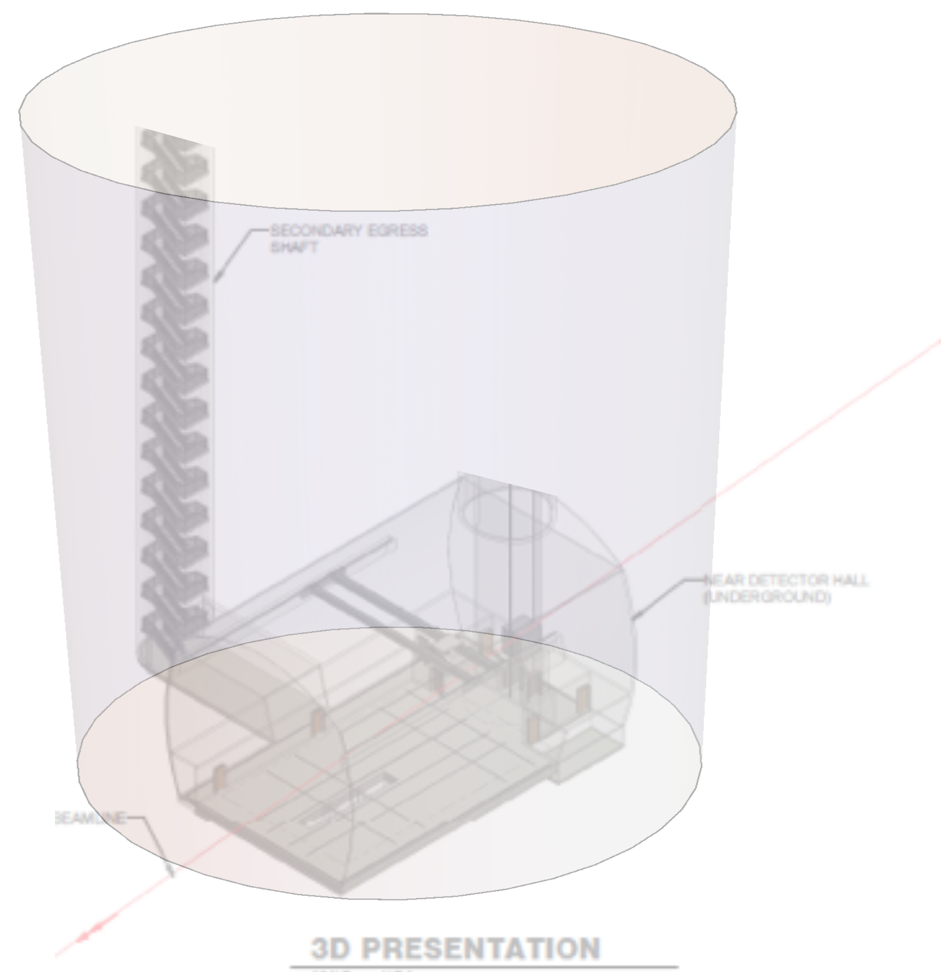
- ***Performing the measurement of CP violation with respect to the precision electroweak parameters appears feasible.***
- ***Both the flux and energy scale can be measured using neutrino electron elastic scattering events.***
- ***The main challenge is obtaining sufficient number of neutrino electron elastic scattering events with excellent kinematic resolution.***
- ***The neutrino muon CC and the electron CC event distributions are highly constrained through pion decay kinematics.***
- ***It is extremely important to optimize the ND, Civil Construction, and the beam in an integrated manner at this time.***

ND 570



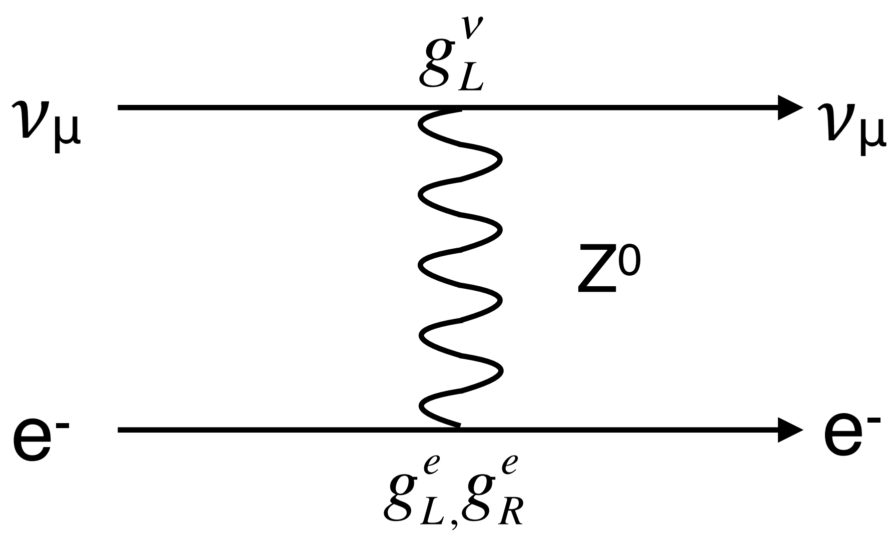
ND 360

A deep cylindrical well that allows ease of construction. (This construction could also be considered at ND570)



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

Neutrino Electron Elastic Reference



Fermion	gL	gR
Neutrino	+1/2	0
electron, muon, tau	$-1/2+\mathrm{Sin}^2\theta_W$	$\mathrm{Sin}^2\theta_W$
up type quarks	$+1/2-2/3\mathrm{Sin}^2\theta_W$	$-2/3\mathrm{Sin}^2\theta_W$
down type quarks	$-1/2+1/3\mathrm{Sin}^2\theta_W$	$+1/3\mathrm{Sin}^2\theta_W$

$$\mathrm{Sin}^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = 0.223$$

$$g_V = 2g_L^\nu(g_L^e + g_R^e)$$

$$g_A = 2g_L^\nu(g_L^e - g_R^e)$$

J = 0 term

J = 1 term

$$\frac{d\sigma}{dy}(\nu_\mu e) = \frac{m_e G_F^2 E_\nu}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2(1-y)^2 - (g_V^2 - g_A^2)\frac{m_e y}{E_\nu}\right]$$

$$\frac{d\sigma}{dy}(\bar{\nu}_\mu e) = \frac{m_e G_F^2 E_\nu}{2\pi}\left[(g_V - g_A)^2 + (g_V + g_A)^2(1-y)^2 - (g_V^2 - g_A^2)\frac{m_e y}{E_\nu}\right]$$

- In neutral current scattering both Left and Right charged particles contribute. The contribution of the Right is proportional to the weak mixing: $\mathrm{Sin}^2\theta_W$.
- Here y is now defined as the fraction of energy lost to the electron.
- Most important observable to reduce backgrounds ($\theta^2 < 2m_e/E_e$) ~ 10^{-3}

$$\nu_e + e^- \rightarrow \nu_e + e^- \Rightarrow \frac{1}{4} + \sin^2\theta_W + \frac{4}{3}\sin^4\theta_W = 0.54$$

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^- \Rightarrow \frac{1}{12} + \frac{1}{3}\sin^2\theta_W + \frac{4}{3}\sin^4\theta_W = 0.22$$

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^- \Rightarrow \frac{1}{3}$$

$$\nu_\mu + e^- \rightarrow \nu_e + \mu^- \Rightarrow 1$$

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^- \Rightarrow \frac{1}{4} - \sin^2\theta_W + \frac{4}{3}\sin^4\theta_W = 0.093$$

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^- \Rightarrow \frac{1}{12} - \frac{1}{3}\sin^2\theta_W + \frac{4}{3}\sin^4\theta_W = 0.075$$

$$\sigma_0 = \frac{2G_F^2 m_e E_\nu}{\pi} = 1.72\times 10^{-41}\ \mathrm{cm}^2\mathrm{GeV}^{-1} \times (E_\nu / GeV)$$

The cross sections are small due to the target mass of the electron, but for the purposes of DUNE these are exactly known.
The first two cross sections have both charged and neutral current components.