# Neutrino Scattering Measurements on Hydrogen and Deuterium: A Snowmass White Paper

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NuSTEC discussion, 11 December 2020

RICHARD HILL, U. Kentucky and Fermilab

- The topic spans many different groups and interests:

**NF and related Topical Groups:** (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
■ (NF8) Theory of neutrino physics
■ (NF10) Neutrino detectors
■ (TF05) Lattice Gauge Theory
■ (TF11) Theory of neutrino physics
■ (RF6) Dark sector studies at high intensities

**https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF6_NF3-TF11_TF5_LauraFields_RichardHill_TomJunk-165.pdf**

- Why new H/D data?
    - We have only very imprecise data for neutrino-nucleon interactions
    - Better data would impact many areas of precision measurements in and beyond Standard Model, in and beyond the DUNE era
    - Direct measurements on H/D desirable from both theory and experimental perspectives
- Why NuSTEC?
    - nucleon level interactions are the natural meeting point of **particle and nuclear**
    - important interplay of **theory and experiment** to motivate, collect, analyze, and apply new precision data
    - NuSTEC lives at the particle-nuclear and theory-experiment interfaces

- Mailing list:

  hydrogen_neutrino_detectors@listserv.fnal.gov

- We have had a very stimulating series of talks and discussions

  *(apologies, not an exhaustive list)*

July 29, 2020, **Ryan Plestid**, "*New Physics impact of H/D targets at LBNF*"

tonne-scale H detector can probe new models, e.g. very light and very weakly interacting

- lepto-phobic or hadro-philic, or
- xsec/nucleon larger on free nucleon (e.g. spin/isospin coupling, or absence of Pauli blocking, etc., or
- signal involves small nucleon recoil, or
- …

July 29, 2020, **Xianguo Lu**, "*H from kinematic separation/subtraction versus pure H*"

tonne-scale H detector can probe new models, e.g. very light and very weakly interacting

August 5, 2020, **Luis Alvarez-Ruso**, “*Inelastic processes*”

Many neutrino-induced inelastic processes poorly constrained already at the nucleon level

August 5, 2020, **Roberto Petti**, “*H/D from kinematic separation and subtraction”*

✦ *“Solid” Hydrogen concept: $\nu(\bar{\nu})$-H from subtraction of $CH_2$ and C targets*

- *Exploit high resolutions & control of chemical composition and mass of targets in STT;*
- *Model-independent data subtraction of dedicated C (graphite) target from main $CH_2$ target;*
- *Kinematic selection (transverse plane + energy-momentum conservation) provides large H samples of inclusive & exclusive CC topologies with 80-95% purity and 75-96% efficiency.*

$\Longrightarrow$ *Can be a viable alternative to liquid $H_2$ detectors*

August 5, 2020, **Oleksandr Tomalak**, “*sensitivity of polarization observables to axial and pseudoscalar form factors*”

potential sensitivity to SM and BSM physics from target, beam, recoil asymmetries

August 13, 2020, **Huey-Wen Lin**, “*Lattice QCD and Neutrino-Nucleus Scattering*”

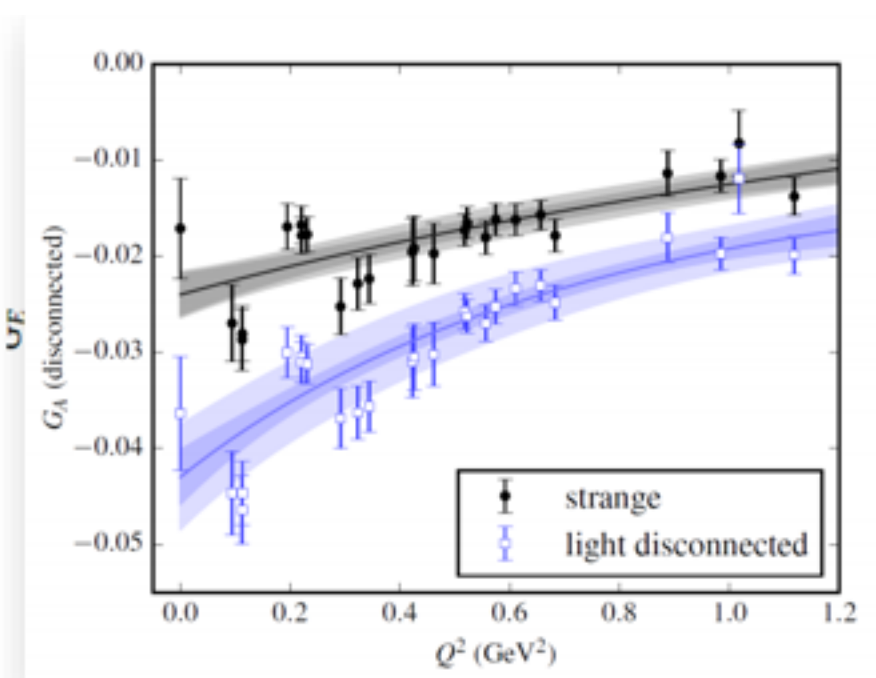
lots of complementarity/positive interference between lattice QCD and experimental measurements

§ Straightforward Calculations (still numerically challenging)

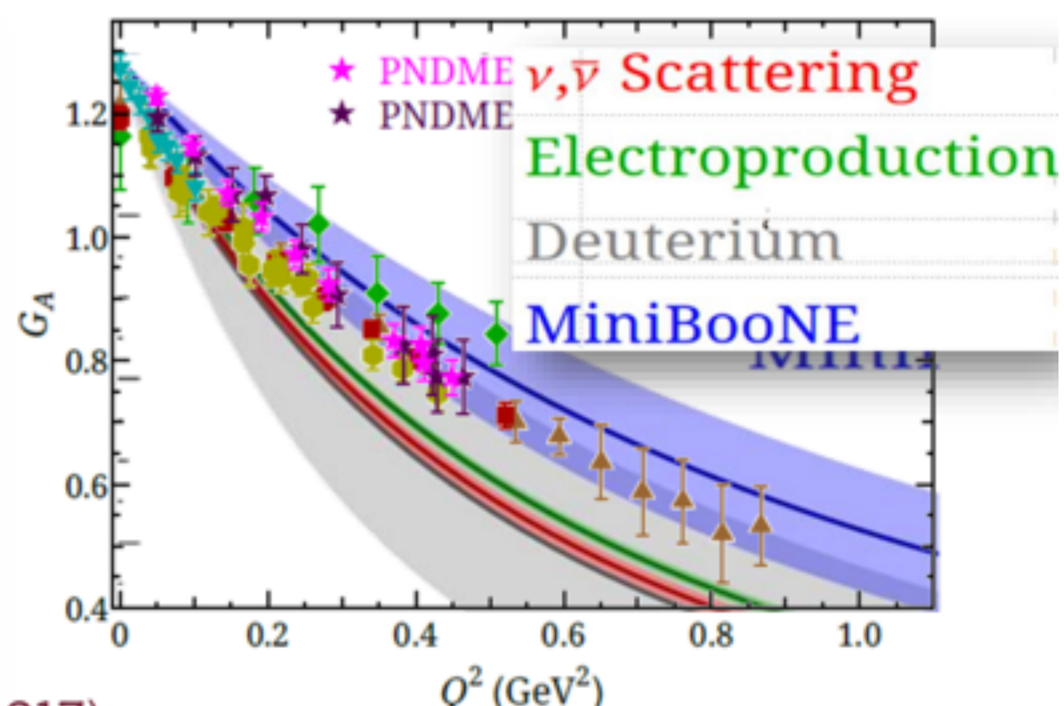
- Nucleon form factors
- Moments of parton distribution functions (PDFs)

§ Challenging Calculations (figuring out how to make it plausible)

- Transition form factors
- Hadronic tensor for shallow and deep inelastic scattering (DIS)
- Parton distribution functions for neutrino DIS
- Axial currents in light nuclei



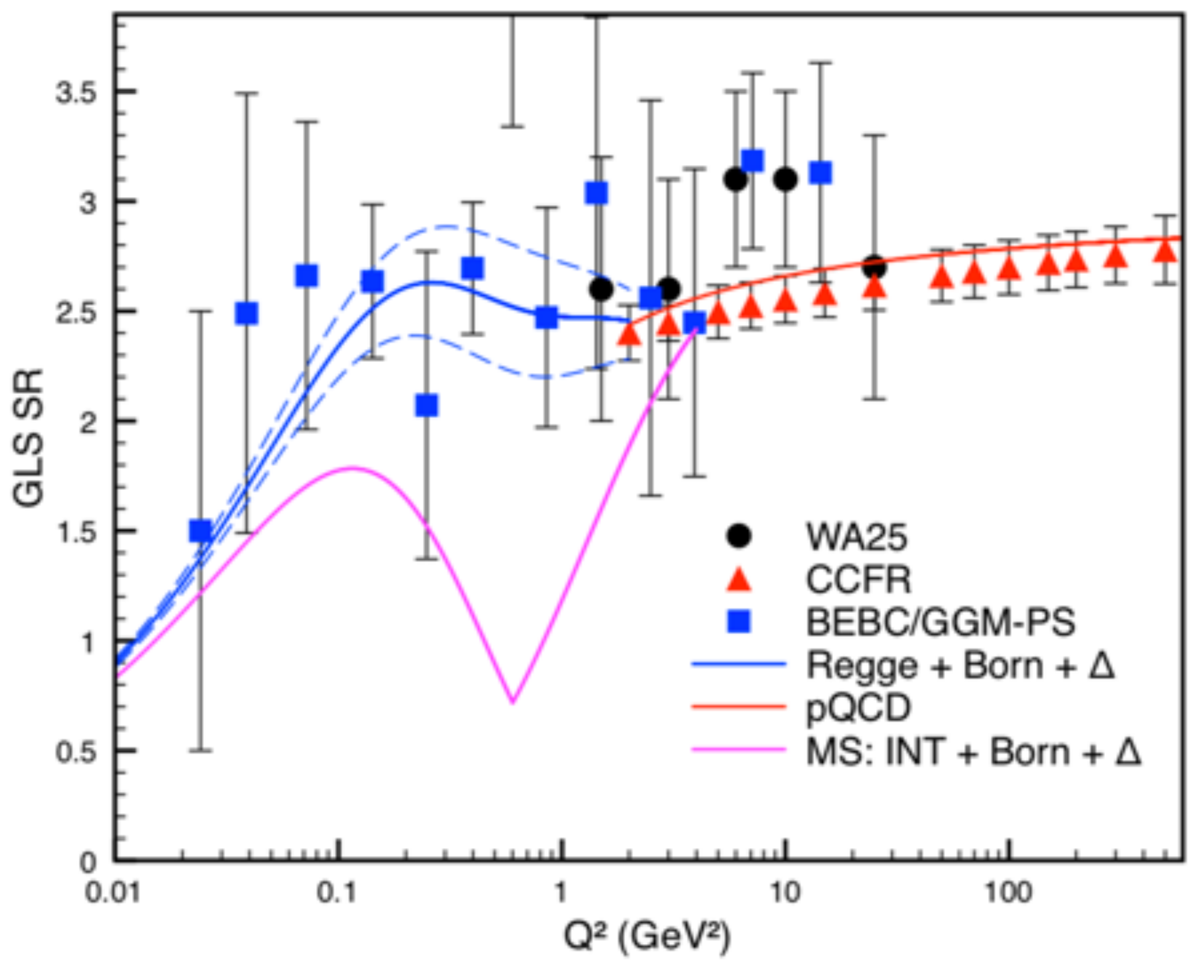

Green et al., Phys. Rev. D 95, 114502 (2017)



August 19, 2020, **Mikhail Gorshteyn**, “*Vud and CKM unitarity*”

≳ 3 sigma unitarity violation from Vud

reanalysis of radiative corrections, sensitivity to F3 structure function for inclusive neutrino scattering



August 19, 2020, **Jorge Morfin**, "*Inelastic Processes/Bubble Chamber Detectors*"

- On the left, Gargamelle mainly using heavy liquids like $CF_3Br$
- BEBC, on right, followed for ν + H, ν + D and ν + Ne/H scattering.

**Total analyzed sample ($E_\nu > 20$ GeV) : 250 $\bar{\nu}$ and 517 ν CC events!**

**No BIG concern for details of systematic errors!**

Table 1
Neutrino and antineutrino cross sections

| | Gargamelle [4] | BEBC (this experiment) | | | |
|---|---|---|---|---|---|
| Energy range (GeV) | 2–10 | 20–60 | 60–100 | 100–150 | 150–200 |
| | | $\nu_\pi$ | $\nu_\pi$ | $\nu_K$ | $\nu_K$ |
| $\sigma^\nu/E$ | 0.72 ± 0.05 | 0.67 ± 0.06 | 0.56 ± 0.05 | 0.61 ± 0.05 | 0.51 ± 0.05 |
| $N$(events) | – | 136 | 123 | 161 | 97 |
| $\sigma^{\bar{\nu}}/E$ | 0.25 ± 0.02 | 0.26 ± 0.03 | 0.25 ± 0.03 | 0.32 ± 0.04 | |
| $N$(events) | – | 90 | 87 | 73 | |
| $R = \sigma^{\bar{\nu}}/\sigma^\nu$ | 0.40 ± 0.02 | 0.39 ± 0.05 | 0.45 ± 0.06 | 0.56 ± 0.07 | |
| $\int F_2(x)\,dx$ | 0.48 ± 0.04 | 0.45 ± 0.04 | 0.39 ± 0.04 | 0.43 ± 0.04 | |
| $\int xF_3(x)\,dx$ | 0.41 ± 0.06 | 0.39 ± 0.08 | 0.30 ± 0.08 | 0.24 ± 0.08 | |
| $B = \int xF_3/\int F_2$ | 0.86 ± 0.04 | 0.86 ± 0.10 | 0.77 ± 0.11 | 0.56 ± 0.12 | |

Cross sections (in units of $10^{-38}$ $cm^2$ $nucleon^{-1}$ $GeV^{-1}$) are corrected to those for an isoscalar target. Errors quoted for the BEBC experiment are statistical. Systematic errors on all cross sections are estimated to be < 7%. Systematic errors drop out in the ratio $R$, except for the $\nu_K$ point, where an uncertainty of ±10% in the $K^+/K^-$ ratio should be included.

August 26, 2020, **Bryan Ramson** “*Bubble chamber R&D*”

ideas for bubble chamber R&D

December 7, 2020, **Dustin Keller**, “*Polarized Target*”

potential for asymmetry measurement e.g. on NH3/ND3 target, analogous to Spinquest

novel way to extract certain nucleon-level (H,D) information

Draft white paper exists, discussions ongoing to determine which studies to pursue/include

draft table of contents: (rough and a bit out of date)

## Contents

# Some discussion of particular nucleon-level amplitudes

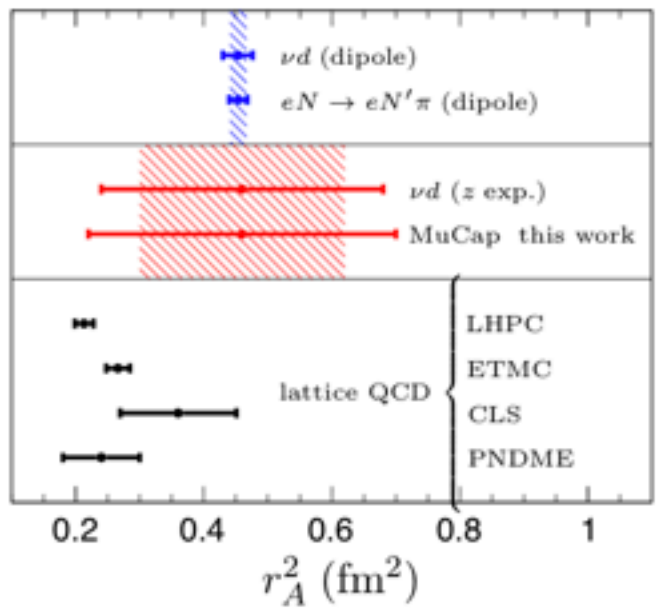



Figure 2: (From Ref. [64]) Squared axial radius determined by different processes. Top: Dipole fits to $\nu d$ and $eN \to eN'\pi$ data employed before 2016 resulted in an average $r_A^2$ with small uncertainty (hatched blue band) [35]. Middle: Replacing the unjustified dipole assumption with the $z$ expansion allowed a model independent extraction of $r_A^2$ from $\nu d$ data and increased the uncertainty. The hashed red region represents the best average from this work combining the new determination from MuCap with the $\nu d$ result. Bottom: Early lattice QCD results denoted by their collaboration acronyms. Several calculations tend towards lower values of $r_A^2$ compared to the historical dipole average.

Some discussion of reusing Fermilab 15 foot chamber

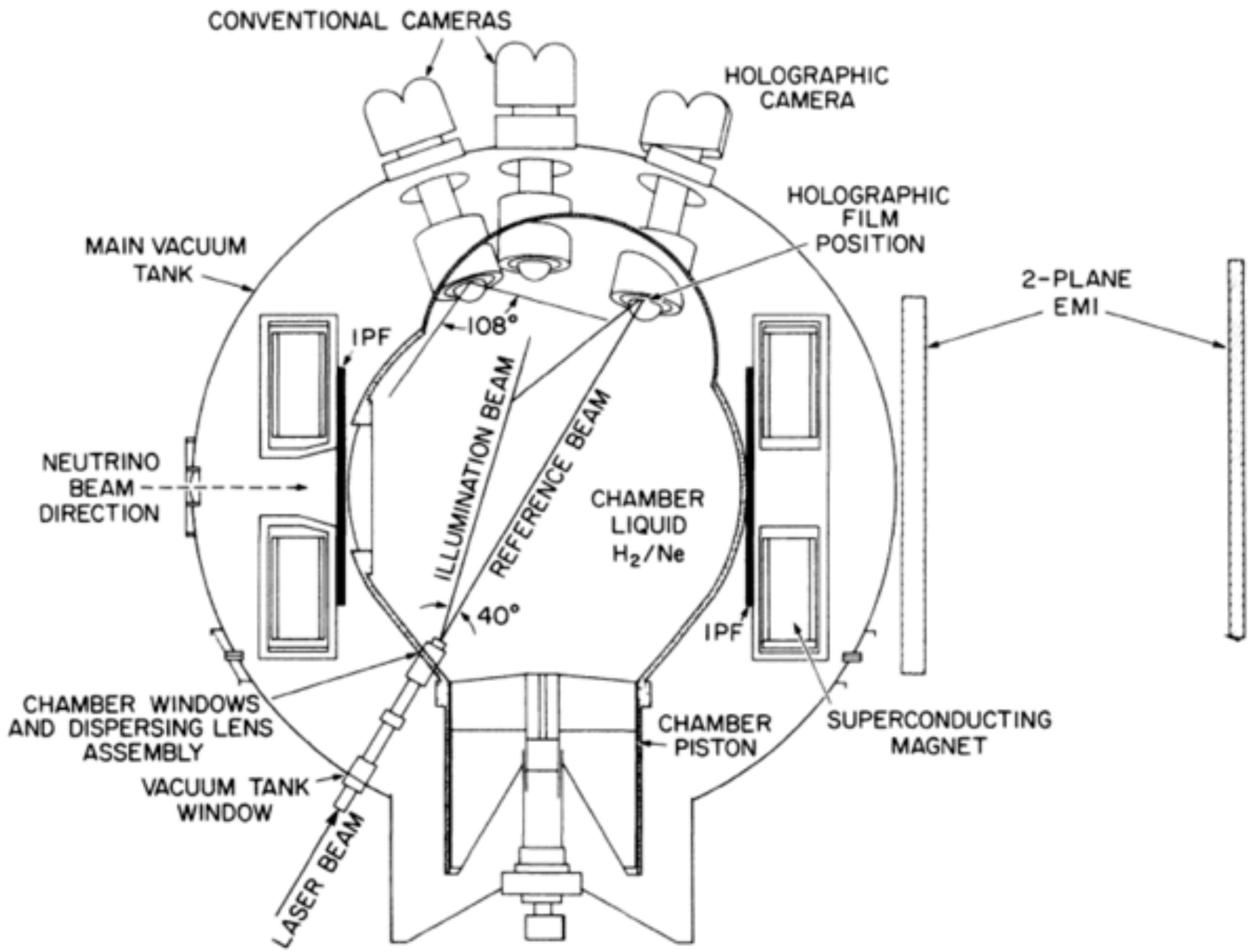



Figure 4: Line drawing of the Fermilab 15 foot bubble chamber.

## Some discussion of site selection outside DUNE ND Hall

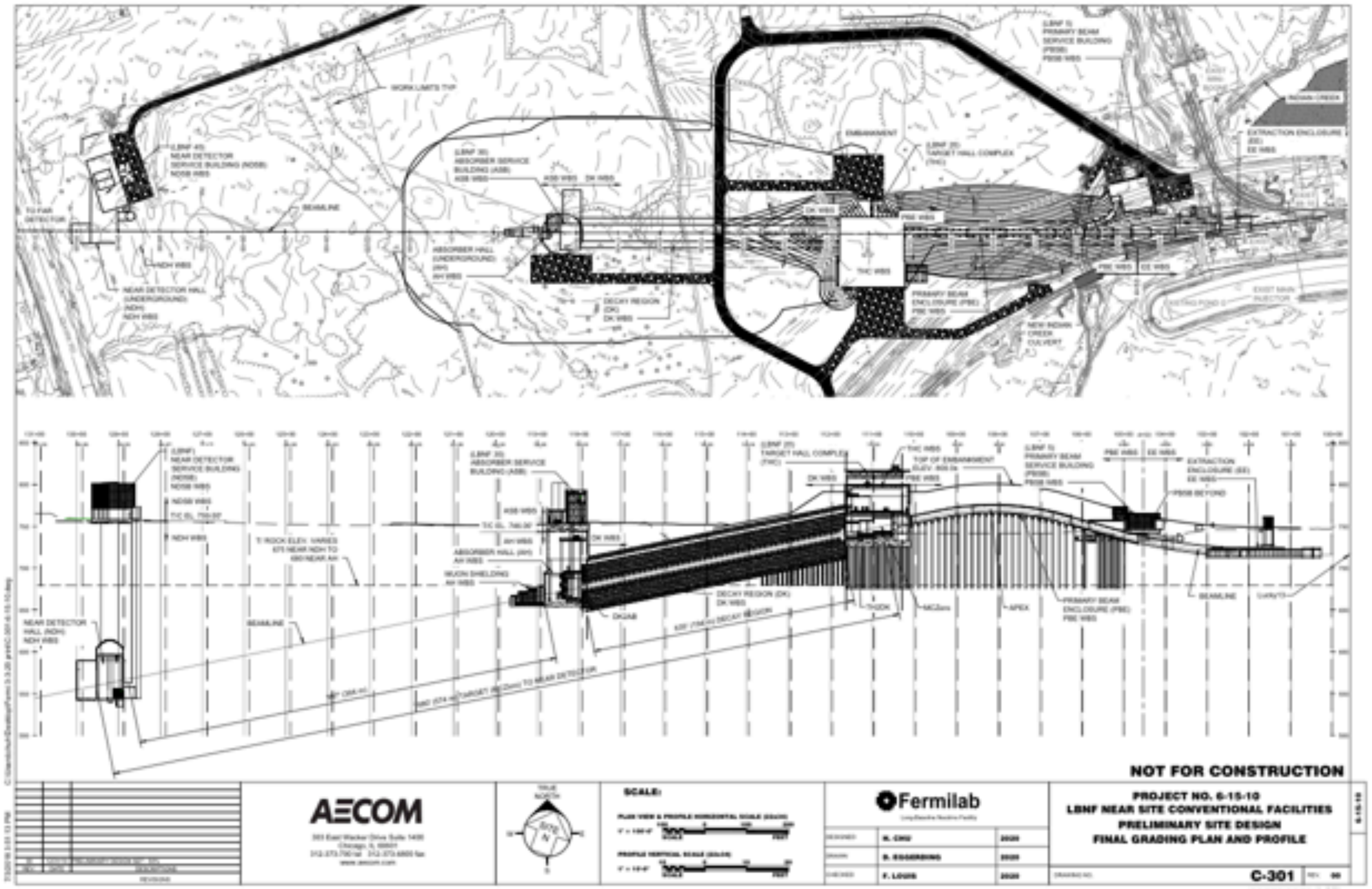



Figure 5: Elevation of the LBNF near site, showing the target hall, decay pipe, and the near detector hall. The boundary between soil and rock is shown. The vertical scale is expanded by a factor of two with respect to the horizontal scale. Both scales are measured in feet.

# Some event number estimates

Table 1: Predicted events per metric ton per year for the LBNF beam ($1.1 \times 10^{21}$ POT) on Hydrogen, FHC.

| process | $\nu_e$ | $\nu_\mu$ | $\bar{\nu}_e$ | $\bar{\nu}_\mu$ |
|---|---|---|---|---|
| Total CC | 14213.7 | 928810 | 4531.34 | 89068.1 |
| CCQE | 0 | 0 | 1012.17 | 27519.9 |
| CCRES | 5501.28 | 527079 | 890.43 | 18136.4 |
| CCDIS | 8052 | 359419 | 2414.98 | 38695.2 |
| CC charm | 166.254 | 4630.46 | 40.1165 | 615.716 |
| CCDFR | 438.431 | 35326.6 | 128.317 | 2912.18 |
| Total NC | 7304.3 | 508419 | 1355.4 | 27230 |
| NCQE | 1115 | 110667 | 186.152 | 5333.75 |
| NCRES | 2035.49 | 191061 | 365.144 | 8141.04 |
| NCDIS | 3932.28 | 188098 | 739.391 | 12229.4 |
| NCDFR | 221.542 | 18304.2 | 64.7119 | 1499.32 |

Table 2: Predicted events per metric ton per year for the LBNF beam ($1.1 \times 10^{21}$ POT) on Deuterium, FHC.

| process | $\nu_e$ | $\nu_\mu$ | $\bar{\nu}_e$ | $\bar{\nu}_\mu$ |
|---|---|---|---|---|
| Total CC | 21492.1 | 1.40822e+06 | 3287.95 | 62378.9 |
| CCQE | 2896.18 | 291186 | 427.559 | 11349.7 |
| CCRES | 5589.25 | 520539 | 862.322 | 18219.7 |
| CCDIS | 12391.1 | 562500 | 1842.94 | 29442.9 |
| CC charm | 233.94 | 6438.96 | 38.9266 | 597.785 |
| CC coh | 288.401 | 23078.3 | 80.5561 | 1824.57 |
| Total NC | 7516.23 | 519739 | 1329.63 | 26500.7 |
| NCQE | 1105.11 | 109954 | 182.843 | 5169.28 |
| NCRES | 2122.27 | 199389 | 371.05 | 8221.84 |
| NCDIS | 4145.86 | 197752 | 735.862 | 12125.6 |
| NC coh | 142.984 | 12500.5 | 39.8791 | 970.796 |

*preliminary*

- Next steps

    - Draft white paper exists.  May be useful to decouple from extended Snowmass timescale

    - A really interesting group of people and discussions

    - Please get in touch if you are interested to join the mailing list, meetings, and/or catch up on slides and reading material

    - Choose an existing or new topic to contribute