Near Detector CDR

Alan Bross
LBNC Meeting, CERN
December 8th, 2018
First, a bit of background & Motivation
Main Near Detector Recommendations (EB)

- The recommended concept is a near detector suite consisting of a LArTPC (not in a magnetic field), a Multi-Purpose Detector (MPD) consisting of a HPgTPC, an ECAL and 3D Scintillator Tracker (3DST) in a magnet.
  - 3DST possibly in separate magnet (stand-alone) or in same magnet

- The design of a mobile LAr detector that can make measurements at one or more off-axis positions should go forward (DUNE-PRISM). Study option of moving MPD also

- The experimental floor area should be at least 42.5m x 17m and the hook height must be at least 13m, measured from the floor. The minimum lateral dimension of hall needs further study, and will ultimately be settled in EFIG.

- The option of filling the HPgTPC with hydrogen should also be investigated.
Why do we need near detector(s)

Primary purpose
The significance with which CP violation, defined as $\delta_{CP}$ not equal to zero or $\pi$, as a function of exposure in kt-MW-years, for equal running in FHC and RHC mode. True normal ordering is assumed. The width of the band corresponds to the difference in sensitivity between $\nu_e$ signal normalization uncertainty of 1% and 3% with 5% uncertainty on the $\nu_\mu$ disappearance mode.
Measuring the # of events, near & far

- Oscillation probabilities

\[
P_{\nu_\mu \rightarrow \nu_e}(E_\nu) = \frac{\phi_{\nu_e}^{\text{far}}(E_\nu)}{\phi_{\nu_\mu}^{\text{far, no-osc}}(E_\nu)} = \frac{\phi_{\nu_e}^{\text{far}}(E_\nu)}{\phi_{\nu_\mu}^{\text{near}}(E_\nu) \times F_{\text{far/near}}(E_\nu)}
\]

- Number of events

\[
\frac{dN_{\nu_\mu}^{\text{det}}}{dE_\nu} = \phi_{\nu_\mu}^{\text{det}}(E_\nu) \times \sigma_{\nu_\mu}^{\text{Ar}}(E_\nu)
\]

\[
\nu \text{ flux systematics}
\]

\[
\begin{array}{c}
\text{Limited data on xsec on Ar}
\end{array}
\]

- In reality

\[
\frac{dN_{\nu_\mu}^{\text{det}}}{dE_{\text{rec}}} = \int \phi_{\nu_\mu}^{\text{det}}(E_\nu) \times \sigma_{\nu}^{\text{target}}(E_\nu) \times T_{\nu_\mu}^{\text{det}}(E_\nu, E_{\text{rec}}) \ dE_\nu
\]

Detector systematics

- Flux, cross section, detector smearing are all coupled
  - Needs unfolding
Also extensive program for beyond $\nu$SM physics

- The near detector facility will provide a very powerful tool to study:
  - Boosted dark matter
  - Sterile neutrinos
  - Neutrino tridents
  - Millicharged particles
  - Unknown, unknowns

See: POND²
Physics Opportunities in the Near DUNE Detector Hall
https://indico.fnal.gov/event/18430/overview
Long-Baseline Physics Analysis for the TDR

• CPV sensitivity studies

• Create a set of “test” FD samples with a set of oscillation parameters

• Create another set at the null hypothesis ($\delta_{CP} = [0, \pi]$)

• **Adjust the systematics** on the null hypothesis sample until the $\chi^2$ with the other samples is minimized

• Sensitivity $= \sqrt{\chi^2_{\text{min}}}$

• Include ND samples to constrain systematics

• **Results input to NDDG**
LBL physics analysis

Dan Cherdack
Flux, event rates @ ND570

Optimized CPV tune

FHC, Events/ton_Ar-year

<table>
<thead>
<tr>
<th>Event class</th>
<th>Number of events per ton-year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ CC Total</td>
<td>$1.64 \times 10^6$</td>
</tr>
<tr>
<td>$\nu_\mu$ NC Total</td>
<td>$5.17 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ CC Coherent</td>
<td>$8.35 \times 10^3$</td>
</tr>
<tr>
<td>$\nu_\mu$ NC Coherent</td>
<td>$4.8 \times 10^3$</td>
</tr>
<tr>
<td>$\nu_\mu$ - electron elastic</td>
<td>135</td>
</tr>
<tr>
<td>$\nu_\mu$ CC $\pi^0$ inclusive</td>
<td>$4.47 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ NC $\pi^0$ inclusive</td>
<td>$1.96 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ Low $\nu$ (250 MeV)</td>
<td>$2.16 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ Low $\nu$ (100 MeV)</td>
<td>$7.93 \times 10^4$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ CC Coherent ($\bar{\nu}$ mode)</td>
<td>$6.90 \times 10^3$</td>
</tr>
<tr>
<td>$\nu_e$ CC Total</td>
<td>$1.89 \times 10^4$</td>
</tr>
<tr>
<td>$\nu_e$ NC Total</td>
<td>$5.98 \times 10^3$</td>
</tr>
<tr>
<td>$\nu_e$ CC Coherent</td>
<td>93</td>
</tr>
<tr>
<td>$\nu_e$ NC Coherent</td>
<td>52</td>
</tr>
</tbody>
</table>
Beam systematics

- Work continues on understanding beam
- Hadron production measurements
  - NA61/SHINE
  - EMPAHTIC
    - Uses the FNAL Test Beam Facility (FTBF), either MTest or Mcenter
  - Flux spectrometer
    - Exact mock up of LBNF target horn system with multiparticle spectrometer, PID, etc.
- Beam line instrumentation development continues
LBL Physics Study: ND Geometry

- 7m x 3m x 5m LAr Active Volume (ArgonCube)
- Downstream magnetized HPgTPC
- New geometry, ND Task Force style “reconstruction”
Generating ND Samples for Fits

- LArTPC
  - Geometry set
  - GAr TPC acts as downstream spectrometer
  - NDTF style “Reconstruction”
  - Integrated with:
    - DUNErt
    - Fitting software (cafana)
  - Event samples have been generated
  - Needed:
    - Analysis sample breakdowns
    - Detector systematics
    - Off-axis sample generation

- GAr TPC
  - Geometry set
  - Lower thresholds/lower rates
  - NDTF style “Reconstruction”
  - Integrated with:
    - DUNErt
    - Fitting software (cafana)
  - Needed:
    - “Reconstruction”
    - Analysis samples
    - Sample generation
    - Detector systematics
Current concept for Near Detectors

Following EB recommendations
Multi-pronged approach

**Prong 1: State-of-the-art Ar detectors:**
- LAr - non-magnetized
  - ~75t fiducial target mass
  - Pixelated (raw 3D data), Optically segmented modules
- Multi-purpose Detector (MPD)
  - High-Pressure (10ATM) gas TPC (HPgTPC)
    - 1t fiducial target mass
  - In ~0.5T field (magnetic spectrometer)
  - Surrounded by high-performance ECAL and muon tagger

**Prong 2: DUNE-PRISM**
- Move LAr and possible MPD off axis

**Prong 3: Three-dimensional scintillator (CH) tracker (3DST)**
- 4t fiducial target mass
- Magnetized
- With external tracking and ECAL
Justification/Motivation

Prong 1

- **LAr**
  - Very large (100M/yr) sample of $\nu$ interactions on Ar: Precision measurements of cross section on Ar in many exclusive channels
  - Flux normalization via $\nu$ – electron elastic
- **MPD**
  - High-resolution containment of tracks leaving LAr
  - Large (1.5M/yr) sample of $\nu$ interactions on Ar with very-low track threshold
  - Sign analysis ($\nu_\mu/\nu_\bar{\mu}$-bar, $\nu_e/\nu_{e\text{-bar}}$)

Prong 2

- Move detectors off-axis to disentangle flux and x-section effects using different fluxes

Prong 3

- Large sample (1M/yr) $\nu$ interactions on H
- Remain on-axis when Ar detectors move off-axis
  - Very-high quality beam monitor
LAr: ArgonCube

**Underlying principles**
- True Raw 3D readout – in a sense, the first true LArTPC
  - Pad readout, no wires
  - S/N > than in conventional LAr TPCs
  - Potentially better energy resolution and better pointing resolution
- Modular, highly segmented
  - Short drift ⇒ little diffusion, low high voltage, less sensitive to impurities
  - Optically isolated modules ⇒ more effective use of scintillation light

**Strengths**
- High statistics (~100M evts/yr) ν-Ar interactions, with sufficient resolution for many exclusive channels
- Ability to measure flux via ν+e elastic scattering (1%)
- An excellent calorimeter, with good π⁰ reconstruction ability
- Similar to far detector
Pixel Demonstration TPC

- 60 cm drift pixel demonstration TPC in Bern, first operated 2016 (arXiv:1801.08884).
- LBNL (Dan Dwyer) has lead the development of LArPixV1 ASIC (arXiv:1808.02969).
LAr: ArgonCube design

2x2 Demonstrator module.
Note, ND modules will not have individual pumps & filters
Status of mechanical design

Cryostat Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat Internal Dimension (between Flat Surfaces)</td>
<td>9000 (W) x 6000 (L) x 4500 (H)</td>
</tr>
<tr>
<td>Thickness of Insulation (including Membrane Liner and Secondary Barrier)</td>
<td>602</td>
</tr>
<tr>
<td>Thickness of Support Structure (including Vapor Barrier): Concrete or Steel</td>
<td>310</td>
</tr>
</tbody>
</table>
LAr (ArgonCube) 2X2 prototype

4 modules. Initial tests at Bern, fully instrumented then brought to Fermilab (NuMI) in 2020
Multi-purpose detector

- Central component is a large gas TPC operating at 10 Atm (HPgTPC) provide **1t fiducial target mass**
  - Copy of ALICE TPC (5m in diameter X 5m long active)
  - Re-use the ALICE readout chambers were are being replaced during the current long shutdown (& engineering)
- HPgTPC surrounded by high-performance ECAL surrounded by high performance ECAL system, such as concepts developed by the CALICE collaboration
- ~0.5T B field
  - Superconducting design looks most promising
  - Open geometry
- Muon tagger outside coils
- MPD is essentially a Collider Detector design
MPD

ALICE being lowered into Hall

Magnet concept

HPgTPC in pressure vessel & LAr upstream
Strengths

- B field $\rightarrow$ excellent $e^+/e^-, \pi^+/\pi^-$, low-energy $\mu^+/\mu^-$ over $4\pi$ phase space
- Very low thresholds for charged hadrons
  - 5 MeV for protons
- Clean hadron tracks $\rightarrow$ excellent PID
- Catches high-energy muons from LAr interactions
  - Possibly hadronic component also
  - Integrated Ar detector
GArSoft

- Full HPgTPC reconstruction framework
  - Ionization, drift, pattern recon., trk finding, etc
- Well along
3DST (stand-alone)

- Magnetized system complementary to MPD/HPgTPC
  - Different target nucleus
  - High statistics tests of neutrino models
  - Connection to the existing catalog of cross section measurements on scintillator (K2K, MiniBooNE, SciBooNEne, MINERvA, T2K, NOVA)
- Can remain on-axis when other detectors move off-axis
  - Accurate determination of the flux
  - High statistics measurement of the beam electron neutrino component
3DST

**Strengths**

- Large target mass, Fully active, Fine grained, Neutron tagging
- Since in B field
  - Charge identification
DUNE-PRISM

Use linear combinations to disentangle flux and x-section effects using different fluxes.

Narrow fluxes at off-axis near detector positions, can provide understanding of $E_{\text{rec}} \to E_{\text{true}}$ mis-modelling.

Cross-section parameters in a fake model fitted to on-axis data didn’t move much from nominal values, as intended.

By moving the near detector off-axis, we can measure different $E_y$ spectra.

The provides a new degree of freedom over which we can constrain $E_{\text{rec}}$ vs $E_{\text{true}}$.

Goal is to make measurements as similar as possible in all off-axis positions.

~30m
Fake Data Analysis: IMPACT ON OSC. ANALYSIS

- Hypothetical: Assume 20% of $E_{\text{proton}}$ is lost
- A good fit is achieved at the on-axis near → far detectors analysis, but significant biases are seen in the estimation of oscillation parameters.
- However, narrow fluxes at off-axis near detector positions identify the $E_{\text{true}}$ → $E_{\text{rec}}$ mis-modelling.
- Mock-up a far detector oscillated flux using linear combinations of flux predictions at different off axis positions.
Gaussian Flux Study

- Using linear combinations of a variety of off-axis fluxes, we can construct a Gaussian $E_\nu$ spectrum
  - i.e. we can directly measure $E_{\text{rec}}$ for a given, mono-energetic (10% width) $E_{\text{true}}$

- As the off-axis range is truncated, the lower-energy Gaussian fits begin to degrade
  - The following study assumes $E_{\text{true}} \to E_{\text{rec}}$ can only be determined when at least a marginal Gaussian fit can be performed
Near Detector Hall
Hall: Reference design III

• As Chris mentioned yesterday, the hall reference design does not accommodate our current detector designs and run plan (off-axis measurements)
Near Detector Hall: June 2018 Update

Reference ND Detector Cavern Concept:
100ft x 56ft Cavern with
75ft x 50ft Detector Hall

June 2018 ND Collaboration Proposal:
165ft x 61ft Cavern with
140ft x 56ft Detector Hall
Primary access shaft: Reference design

22’ Ø baseline
Need 38’
Larger cavern – cost savings?

- Although LBNF, DUNE and Fermilab management understands the benefits of the larger cavern and access shaft for the DUNE physics program
- Trying to see if some costs can be saved while keeping the larger hall footprint and larger access shaft
- Bring Down the Roof
Near Detector CDR overview

- Executive Summary
- Overview
- Oscillation Physics
  - Flux constraints / measurements
  - Detector systematics
  - Cross-section systematics / model tuning
  - Beam monitoring
- Non-oscillation physics (beyond νSM)

- Facility
  - Hall
  - LAr Detector
  - Multi-Purpose Detector (MPD)
    - HPgTPC, ECAL, Magnet, Muon tagger
  - 3DST
- Engineering integration
  - Detector motion concept (PRISM)

**Timeline:**
ND Executive Summary for Physics TDR: March 2019
CDR: December 2019
TDR: 2\textsuperscript{nd} half of 2020
New Organization: Near Detector Design Group (NDDG)

• The ND Concept study/Task Force is now replaced by the Near Detector Design Group (NDDG)
  – Tasked with producing an integrated detector design for the CDR next year & then delivering the CDR.

• The conveners of the NDDG are Hiro Tanaka (SLAC), Alfons Weber (Oxford/RAL) and AB.

• In addition, Mike Kordosky and Steve Manly have agreed to serve as editors for the CDR and will continue to advise on the physics requirements and work on the performance evaluation of the CDR design
Conclusions and outlook

- The DUNE Near Detector Design Group (NDDG) has been formed whose primary task is to deliver a CDR for the near detectors & the facility
  - I have outlined the basic approach that is being studied and which will form the bases of the input to the CDR, to a large extent

- Powerful, high-precision, full capability (calorimetric, spectrometer, PID, multiple target nuclei, off-axis measurements) detector systems
  - LAr, MPD (HPgTPC+ECAL+Magnet+μ tagger), 3DST
    - Basic technical/engineering foundations in place for most

- With these detectors and the LBNF beam, we will accumulate enormous statistics in all channels, including neutrino-electron elastic scattering.
  - ~1.5MνμCC events/yr-ton (FHC)

- Aggressive 3-pronged approach to CPV

- Opportunities to study physics beyond the νSM are extensive
THANK YOU

And many thanks to my colleagues for allowing me to steal their slides: Alfons Weber, Chris Marshall, James Sinclair, Dan Dwyer, Clark McGrew, Tanaz Mohayai, Michael Wilking, Chris Vilela, Tom Junk, Tom Hamernik, Bob Flight
BACKUPS
Near site
NDDG activities

• We will organize 1 or 2 workshops to support the CDR effort and assume the various subgroups will continue with their current meeting schedules

• NDDG bi-weekly meetings starting October 10th

• Bi-weekly engineering coordination meetings began October 18th
Near Detector needs to measure:

- **ND Fluxes**
  \[ \phi_{\nu_x}^{\text{near}} (E_{\nu}) \]
  - Prior constrained 5-10%

- **Total and differential cross sections on Argon**
  \[ \frac{d^n \sigma_{\nu_x}^{\text{Ar}}}{da \, db \, dc \, \ldots} (E_{\nu}) \] (Largely unknown)

- **True to reconstruction “matrix”**
  \[ T_{\nu_x}^{\text{far}} (E_{\nu}, E_{\text{rec}}) \] and \[ T_{\nu_x}^{\text{near}} (E_{\nu}, E_{\text{rec}}) \]
  - Depends on: Detector effects, xsections, nuclear effects

- **Approach**
  - Measure as many exclusive differential cross sections with as much precision as possible

\[ \frac{dN}{dX_{\text{rec}}} = \int \phi_{\nu_{\mu}}^{\text{near}} (E_{\nu}) \frac{d\sigma_{\nu_{\mu}}^{\text{Ar}}}{dX} (E_{\nu}) T_{\nu_{\mu}}^{\text{near}} (E_{\nu}, X, X_{\text{rec}}) \, dE_{\nu}, dX \]
High $E_\nu$ tune
Unique capabilities of LBNF beam

High energy tune

Nu mu Flux

<table>
<thead>
<tr>
<th>hnumu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Std Dev</td>
</tr>
</tbody>
</table>

Flux (per POT m² * GeV)

- Numu flux
- Numu optimized flux for nutau appearance
$\nu_\tau$ Appearance

- No other planned experiment/facility can study tau neutrino appearance in a neutrino beam
- What physics topics can be studied with this beam at the near site?

~10X increase in $\nu_\tau$ evts in Far detector
LArPix
Pad readout for LAr

- Possible to use triangular pad shape to enable charge-sharing between adjacent pads to improve angular resolution for forward-going tracks
- Testing and prototyping underway, LArPix citation
Pixels in a Test Beam

Pixel anode was fitted to LArIAT, operated winter 2017, analysis lead by UTA is ongoing.
Pixel ASIC Development - LArPix

LBNL (Dan Dwyer) has lead the development of LArPixV1 ASIC (arXiv:1808.02969).

Cold amplification and digitisation demonstrated with.

Self-triggering & pulsed reset is not zero suppression! But, it does make for very low data rates

60 cm TPC, 512 pixels, ~0.3 Hz
~3 kB/s

DUNE ND, 8M pixels, ~0.01 Hz
~2 MB/s

Achieve low power: avoid digitization and readout of mostly quiescent data.

Approach: Amplifier with Self-triggered Digitization and Readout

Front-end amplifier

Standard SAR Digitizer

Digital Control

Self-triggering Discriminator
LArPix provides direct access to unambiguous 3D space points; drastically simplifying event reconstruction!

See https://goo.gl/AdVC9s for interactive events.
LArPix - Gain, Noise, Power

- Demonstrated low-noise low-power cryogenic amplification, digitization, and readout:
  - **Low Power:**
    - Average power for 128-channel readout:
      - Analog: 24 μW/channel
      - Digital: 38 μW/channel
      - Total: 62 μW/channel
    - Performance exceeds design targets:
      - < 500 e- ENC
      - < 100 μW/channel
Pixelated LAr

Pixel Readout System

Working concept for a detector-scale pixel readout system

- DAQ Computer
- Ethernet Switch
- Control Electronics (1 per 4 tiles?)
- Isolation Electronics?
- Feedthrough

Cabling:
- Ground
- Power (~1.8V)
- Clock (~2.5 to ~40 MHz)

Per tile:
- ~6 Digital I/O (~2.5 to ~40 MHz)
- Tile reset
- External trigger
- Analog monitor
- ADC test input
- ?

Pixel Tiles,
32cm x 32cm
~6.4k pixels each
~100 ASICs each

Anode Frame,
with tile and cabling attachments

Preliminary Concept:
Have designs for:
- LArPix ASIC
- Pixel Tile (partial)
- Control Electronics
Other components are currently fictional.

Sep. 29, 2018
LArPix Cost Model
## Pixelated LAr

### Cost Model: Summary

Current cost estimates for production of Pixel Tiles

<table>
<thead>
<tr>
<th></th>
<th>ArgonCube 2x2</th>
<th>Near Det.</th>
<th>Far Det.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readout Area [m²]</td>
<td>6.4</td>
<td>120</td>
<td>2880</td>
</tr>
<tr>
<td># Pixels (4mm pitch)</td>
<td>4.02E+05</td>
<td>7.50E+06</td>
<td>1.80E+08</td>
</tr>
<tr>
<td># ASICs</td>
<td>6,282</td>
<td>117,188</td>
<td>2,812,500</td>
</tr>
<tr>
<td># Tiles (32x32cm)</td>
<td>63</td>
<td>1,172</td>
<td>28,125</td>
</tr>
<tr>
<td>Cost, Wafer Production</td>
<td>$100,780</td>
<td>$280,807</td>
<td>$4,660,018</td>
</tr>
<tr>
<td>Cost, Die Preparation</td>
<td>$1,571</td>
<td>$29,297</td>
<td>$703,125</td>
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<tr>
<td>Cost, Packaging</td>
<td>$6,910</td>
<td>$128,907</td>
<td>$3,093,750</td>
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<tr>
<td>Cost, PCB Production</td>
<td>$3,735</td>
<td>$52,806</td>
<td>$1,267,200</td>
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<tr>
<td>Cost, PCB Components</td>
<td>$2,073</td>
<td>$38,672</td>
<td>$928,125</td>
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<tr>
<td>Cost, PCB Assembly</td>
<td>$1,176</td>
<td>$15,690</td>
<td>$376,509</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>$116,245</strong></td>
<td><strong>$546,178</strong></td>
<td><strong>$11,028,727</strong></td>
</tr>
<tr>
<td><strong>Total Cost (+20% Ovhd)</strong></td>
<td><strong>$139,494</strong></td>
<td><strong>$655,414</strong></td>
<td><strong>$13,234,473</strong></td>
</tr>
<tr>
<td><strong>Cost, per square meter</strong></td>
<td><strong>$21,796</strong></td>
<td><strong>$5,462</strong></td>
<td><strong>$4,595</strong></td>
</tr>
</tbody>
</table>

*Pixel tile production ≠ total system cost*

~$2.9k @ 5mm  
~$8.2k @ 3mm
HPgTPC
Expected Physics Performance

- A $4\pi$ coverage & excellent **tracking efficiency** (based on ALICE performance)
- High multiplicity in HPgTPC will not be an issue – hint: take a look at the ALICE events

**Tracking Efficiency**

HPgTPC Test Stand @ FNAL

- **Gaseous-Argon Operation of the ALICE TPC, GOAT**
  - Test ALICE readout chambers at 10 atm and in various gas mixture (currently 90-10 Ar-CO₂)
  - Develop full front-end electronics chain
- **Various components in GOAT:**
  - Signal readout with ALICE IROC
  - Field cage
  - Front-end with preamps and CAEN digitizers
- **Upgrades to components underway; stay tuned!**
MAGNET
Conceptual Design – HPgTPC Magnet

- 3 superconducting Helmholtz & a pair of trim (added for field uniformity) coils
- Parameters affecting its design:
  - Uniformity in central field + fringe field (should be minimized)

Largest field non-uniformity: ~ 12%
An example
Re-analysis of NC (UA1 type) magnet

- Split-Solenoid having spaces for pedestals for supporting HPgTPC
- Each of the three parts contains about 17 double pan cake coils (Total number of pan cakes will be 52)
# Summary of Electrical Design

<table>
<thead>
<tr>
<th>SN</th>
<th>Parameter</th>
<th>Value (Copper)</th>
<th>Value (Aluminum)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Coils Type</td>
<td>Double Pancake</td>
<td>Double Pancake</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>Number of Double pancakes</td>
<td>52 turns per pancake</td>
<td>52 turns per man</td>
<td>-</td>
</tr>
<tr>
<td>3.</td>
<td>Conductor Type</td>
<td>Hollow conductor</td>
<td>Hollow conductor</td>
<td>-</td>
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<tr>
<td>4.</td>
<td>Conductor Dimensions</td>
<td>80 x 80</td>
<td>80 x 80</td>
<td>mm</td>
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<tr>
<td></td>
<td>Hole dia : 36</td>
<td></td>
<td>Hole dia : 40</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>MMF</td>
<td>4,600,000</td>
<td>4,600,000</td>
<td>At</td>
</tr>
<tr>
<td>6.</td>
<td>Current density</td>
<td>1.65</td>
<td>1.08</td>
<td>A/mm sq</td>
</tr>
<tr>
<td>7.</td>
<td>Power dissipation per pancake</td>
<td>57.5</td>
<td>61.8</td>
<td>kW</td>
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<tr>
<td>8.</td>
<td>Total Power dissipation</td>
<td>3</td>
<td>3.24</td>
<td>MW</td>
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<tr>
<td>9.</td>
<td>Chilling power consumption</td>
<td>1</td>
<td>1.08</td>
<td>MW</td>
</tr>
<tr>
<td>10.</td>
<td>Pumping motor power consumption (gross estimate)</td>
<td>0.25</td>
<td>0.23</td>
<td>MW</td>
</tr>
<tr>
<td>11.</td>
<td>Water velocity</td>
<td>2.5</td>
<td>2</td>
<td>m/s</td>
</tr>
<tr>
<td>12.</td>
<td>Total pressure drop</td>
<td>5</td>
<td>4.5</td>
<td>bar</td>
</tr>
<tr>
<td>13.</td>
<td>Water temperature rise</td>
<td>5.38</td>
<td>5.87</td>
<td>C</td>
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<td>Weight per coil</td>
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<td>15.</td>
<td>Magnet OD</td>
<td>8</td>
<td>9</td>
<td>Meter</td>
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<tr>
<td>16.</td>
<td>Total power dissipation</td>
<td>~4.25</td>
<td>~4.55</td>
<td>MW</td>
</tr>
</tbody>
</table>
NEUTRONS!
Neutron Detection in LAr

\[ E_{\nu,\text{reco}} = E_\mu + \sum_{i=p,\pi^\pm} E_i + \sum_{i=\pi^0,e,\gamma} E_i + \sum E_n \]

Secondary Particles

- Neutron
- Argon
- Proton
- Gamma

ArCLight Threshold

Number of Energy Deposits Related to Protons

Primary Neutron Kinetic Energy [MeV]

Secondary Particle Kinetic Energy [MeV]
ArCLight – Spatial Resolution

• Neutron study: define light readout requirements
  - Pileup $\rightarrow$ need spatial and timing resolution

• Distance from a recoiling proton to any activity above 0.1 MeV from other interactions?
  - Spatial resolution of $\sim$30 cm needed
  - Can we do this with ArCLight?
Neutron Detection in MPD

- Advantages of using ECAL:
  - Very long lever arm due to lack of interactions in gas
  - Measure neutrons from Ar interactions
MPD capabilities for n detection

HPgTPC

Neutron detection efficiency (%) in 10 Atm Ar-Ch4

- Neutron detection efficiency (%), p
- Eff. with p and d
- Neutron detection efficiency (%), d

2 mm Cu absorber, 80 layers
Neutron Detection in MPD III

- Most of the rock → ECAL neutrons are actually charged particles interacting in the magnet and producing neutrons
- Signal events are more likely to be forward
- Background events are more likely to occur in outer ECAL, since they are coming mostly from interactions in the magnet
- SC Magnet design – low mass!
FLUX MEASUREMENTS
Flux measurements

• Primary thrust within DUNE near detector suite is to do measurements on Ar (Liquid and gas)
• Proposed measurements
  – Extensive campaign to measure cross-sections
  – Neutrino-electron scattering (LAr)
  – Low- method (liquid and gas)
  – Coherent Scattering(liquid and gas)
    • $\nu_l + N \rightarrow l^- + N + \pi^+$
    • $\bar{\nu}_l + N \rightarrow l^+ + N + \pi^-$
• Measurements on hydrogen (CH and gas)
  • $\nu_l + p \rightarrow l^- + \Delta^{++} \rightarrow l^- + p + \pi^+$
  • $\bar{\nu}_l + p \rightarrow l^+ + \Delta^0 \rightarrow l^+ + p + \pi^-$
$\nu$ – electron elastic scattering

- Even with conservative reconstruction assumptions, DUNE LAr ND can select over 3,000 $\nu$+e events per year at initial intensity
- <1% statistical uncertainty
- Very powerful \textit{in situ} constraint on absolute flux normalization
Hall: Reference design (2015 CDR)

~56'

75'

72
Hall: Reference design II
Larger Shaft – Size

• Reference shaft is 22ft ID

• Considered shaft diameters ranging from 32ft to 43ft ID

• Now looks like a 38ft ID shaft provides a minimum of 0.5m clearance around HPgTPC and preserves lift/utility segment
Alternate MPD configuration

Not shown: Possible TOF counters around GTPCs
DUNE-PRISM
Fluxes Up to 40 m Off-Axis

Can even somewhat resolve the peak below the 3rd oscillation maximum for all values of $\Delta m^2_{32}$.
Fluxes Up to 33 m Off-Axis

$\Delta m^2 = 3.0 \times 10^{-3}$

$\Delta m^2 = 2.6 \times 10^{-3}$

$\Delta m^2 = 2.2 \times 10^{-3}$
Fluxes Up to 28 m Off-Axis

$\sin^2 \theta_{23} = 0.4$

$\Delta m^2 = 3.0 \times 10^{-3}$

$\Delta m^2 = 2.6 \times 10^{-3}$

$\Delta m^2 = 2.2 \times 10^{-3}$
The sensitivity gain in moving from 600 MeV to 500 MeV in $E_{\nu}$ reach corresponds to an increase in far detector exposure of:

- 10% to get the same $5\sigma$ coverage of $\delta_{CP}$ in the $-\pi/2$ (non-T2K excluded) region
- 7% to get the same $5\sigma$ coverage over all values of $\delta_{CP}$
- 5% to match the peak $\Delta\chi^2$
IS AN ON-AXIS MPT SENSITIVE TO THIS TYPE OF MISMODELLING?

- The proposed multi-purpose tracker will be able to measure tracks precisely down to low thresholds.
- Are we able to reweight kinematic-balance distributions measured by a MPT and still get a biased $E_{\text{rec}}$ model?
- Add the following variables to the list of observables to be reweighted:
  - Number of protons and charged pions above tracking threshold.
  - For events with exactly one tracked proton and no tracked pions:
    - Single transverse kinematics: $\delta p_T$, $\delta \alpha_T$, and $\delta \phi_T$
  - For events with exactly one pion and one proton:
    - Double transverse variable: $\delta p_{\text{TT}}$

**Tracking thresholds:**
- Protons: 200 MeV/c
- Pions: 130 MeV/c
Momentum resolution: 5%
Angular resolution: 2 mrad
From STT document at ND workshop
LBL Physics Analysis
# DUNEerwt Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Mode</th>
<th>Description</th>
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<tbody>
<tr>
<td>$M_A^{QE \rightarrow z}$ exp.</td>
<td>1p1h/QE</td>
<td>D$_2$ constraint</td>
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<tr>
<td>BeRPA</td>
<td>1p1h/QE</td>
<td>RPA/nuclear model suppression</td>
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<tr>
<td>$E_b$</td>
<td>1p1h/QE</td>
<td>Shift in nuclear model removal energy</td>
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<tr>
<td>MnvaTune1</td>
<td>2p2h</td>
<td>Strength into (nn)pp only</td>
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<tr>
<td>MnvaTune2</td>
<td>2p2h</td>
<td>Strength into np pairs only</td>
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<tr>
<td>MnvaTune3</td>
<td>1p1h/QE+2p2h</td>
<td>Strength into 1p1h vs. 2p2h</td>
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<td>ArC2p2h</td>
<td>2p2h Ar/C scaling</td>
<td>Electron scattering SRC pairs</td>
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<td>$E_{2p2h}$</td>
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<tr>
<td>$M_A^{res, C_5^{TA}}$</td>
<td>RES</td>
<td>Single pion form factors</td>
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<td>$I_{1/2}$ bkg</td>
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<td>Non-resonant background</td>
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<td>Low $Q^2$ 1\pi</td>
<td>RES</td>
<td>Low $Q^2$ (empirical) suppression</td>
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<td>MK model</td>
<td>RES</td>
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<td>Nominal FSI</td>
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<td>$E_{avail}/q_0$</td>
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<td>Extreme FSI-like variations</td>
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<tr>
<td>NC/multi-\pi 50% CC/NC with &gt; 1 pion</td>
<td>Increased uncertainty</td>
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<tr>
<td>$\nu_e/\nu_\mu$</td>
<td>$\nu_e$</td>
<td>Large uncertainty since $\nu_e$ unique phase space</td>
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<tr>
<td>$\nu_e/\bar{\nu}_e$ norm</td>
<td>$\nu_e, \bar{\nu}_e$</td>
<td>McFarland&amp;Day, PRD86 053003</td>
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