Towards a Near Detector CDR

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DUNE ND general meeting
December 19th, 2018
Introduction

• This talk is meant to be an introduction to a discussion on how we move forward with the near detectors

• It follows some of the structure of my recent presentation to the Long Baseline Neutrino Committee (LBNC) meeting held at CERN

• And includes some of the committee’s feedback which will be useful in considering our path forward
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
  \[ P_{\nu_\mu \to \nu_e}(E_\nu) = \frac{\phi_{\nu_\mu}^{\text{far}}(E_\nu)}{\phi_{\nu_\mu}^{\text{far, no-osc}}(E_\nu)} = \frac{\phi_{\nu_\mu}^{\text{near}}(E_\nu) * F_{\text{far/near}}(E_\nu)}{\phi_{\nu_\mu}(E_\nu)} \]

- Number of events
  \[ \frac{dN_{\nu_\mu}^{\text{det}}}{dE_\nu} = \phi_{\nu_\mu}^{\text{det}}(E_\nu) * \sigma_{\nu_\mu}^{\text{Ar}}(E_\nu) \]
  \[ \text{flux systematics} \]
  \[ \text{Limited data on xsec on Ar} \]

- In reality
  \[ \frac{dN_{\nu_\mu}^{\text{det}}}{dE_{\text{rec}}} = \int \phi_{\nu_\mu}^{\text{det}}(E_\nu) * \sigma_{\nu}^{\text{target}}(E_\nu) * T_{\nu_\mu}^{\text{det}}(E_\nu, E_{\text{rec}}) \, dE_\nu \]
  \[ \text{Detector systematics} \]

- 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
  - Mono-$\nu_s$
  - Unknown, unknowns

See: POND²
Physics Opportunities in the Near DUNE Detector Hall
https://indico.fnal.gov/event/18430/overview
Also powerful program for $\nu$SM (interactions) physics @ ND574

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>$\nu_\mu$ 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>

Plus unique opportunities with the high-energy tune ($\tau$)
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
Neutrino Mode

Dan Cherdack

$\sqrt{\Delta \chi^2}$
Beam systematics

- Work continues on understanding beam
- Hadron production measurements
  - NA61/SHINE
  - EMPHATIC
    - 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:
    - DUNErwt
    - 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:
    - DUNErwt
    - Fitting software (cafana)
  - Needed:
    - “Reconstruction”
    - Analysis samples
    - Sample generation
    - Detector systematics
Our 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)**
  - ≥ 6t 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 ($\nu_\mu/\nu_\mu$-bar, $\nu_e/\nu_e$-bar)

Prong 2

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

Prong 3

- Large sample (~0.5M/yr) $\nu$ interactions on H
- Remain on-axis when Ar detectors move off-axis
  - Very-high quality beam monitor
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 $\nu$SM)

- 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: 2nd half of 2020
LBNC meeting at CERN (12/7-9)

Informed them on the move to the NDDG and details of our “baseline” plan:

- Powerful, high-precision, full capability (calorimetric, spectrometer, PID, multiple target nuclei, off-axis measurements) detector systems
  - LAr, MPD (HPgTPC+ECAL+Magnet+$\mu$ 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.
  - $\sim$1.5M $\nu_\mu$CC events/yr-ton (FHC)

- Aggressive 3-pronged approach to CPV
- Opportunities to study physics beyond the $\nu$SM are extensive
LBNC meeting: Comments

• The strength of what we propose was appreciated, but the scale raised many concerns and questions

• The thrust of the questions pertained to what was really needed (minimum?) to reach CPV goals (P5 mandate – 50% coverage at 5\sigma). Some provocative:
  – Do you really need near detector(s)?
  – What if you only get LAr?
  – What if you only get LAr + MPD (no DUNE-PRISM)?
  – What does an active scintillator target add to the CPV reach?

• **Connection between detector performance spec and physics achievable (quantifiable)**
  – This is being stressed for the Far Detector

• In the CDR, they would like to see a table where each component of the facility (including the width of the Hall), is enumerate in such a way that its impact on the CP Violation ultimate systematic uncertainty can easily be understood
Moving forward

• There will certainly be hard decisions to make in the coming months in order to produce the CDR

• Quantifying how each decision impacts our physics achievable will be required from us

• Although at this time, we are not required to provide costing data, we must keep costs in mind

An Example
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