A modest proposal for a DUNE Near Detector System and measurement strategy

Dan Dwyer (LBNL)

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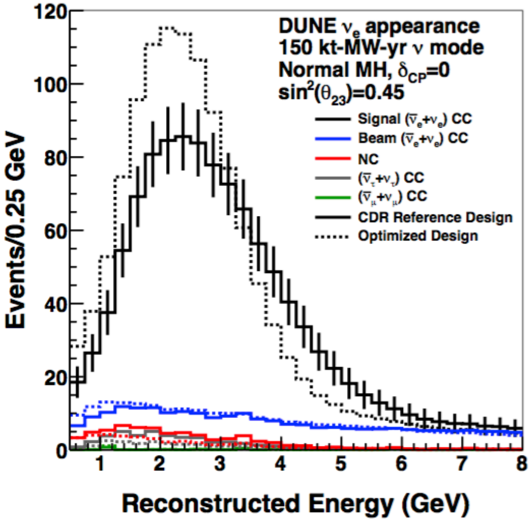
Purpose

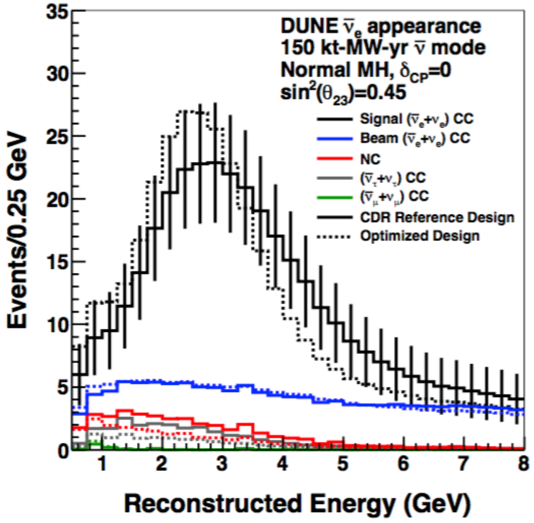
Purpose of this talk:

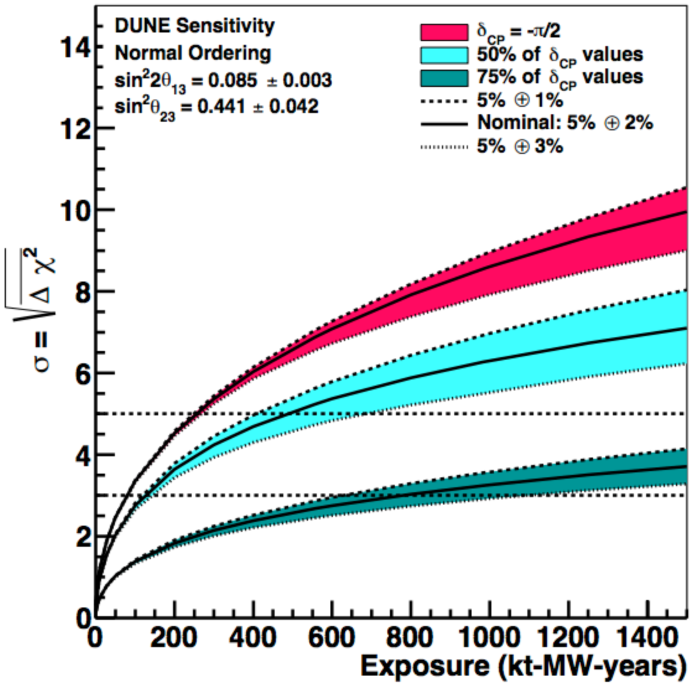
Describe a potential route for Near Detector System to provide the necessary systematic constraint to the CP-violation measurement.

Basic Assumption:

Following CDR, assume NDS constraint is substantially more precise than statistical precision of Far Detector ν_e and $\overline{\nu}_e$ appearance measurement (~3%).







See E. Worchester's talk from yesterday.

Preview of Conclusions

Near Detector Requirement:

Constrain systematics in far detector ν_e and $\overline{\nu}_e$ appearance signal at CDR level (2%).

Compare with 5-6% uncertainty for Nova & T2K, as shown in yesterday's talks by M. Sanchez and K. Mahn.

Measurement Strategy:

Critical measurements:

1) Measure ν-e^- elastic scattering in low-density tracker
2) Measure low-ν ν_μ charged-current interactions on Ar in a LAr-TPC
3) Measure inclusive ν_μ charged-current interactions on Ar in a LAr-TPC
4) Measure inclusive ν_μ charged-current interactions on Ar in a low-density tracker

Near Detector System:

Preliminary studies of these measurements suggest Hybrid detector system:

a.) Moderately-sized (~10s ton) upstream LAr-TPC module

b.) Downstream magnetized low-density tracker (~5 ton total mass, ~0.1 ton Ar mass) with 4π electromagnetic calorimeter and muon system

The rest of this presentation will motivate these conclusions.

Requirements: Rate and Spectrum

Appearance Rate:

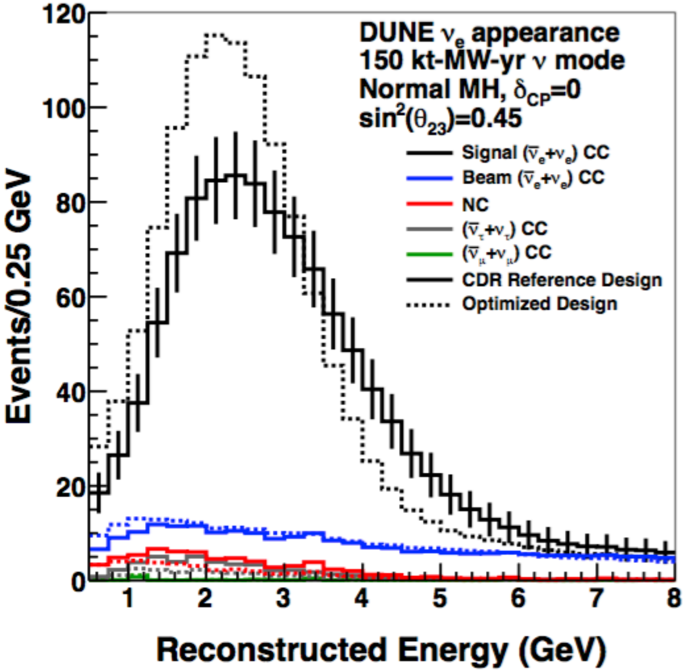
At CDR exposure: 300 kt-MW-yrs (~7 yrs)

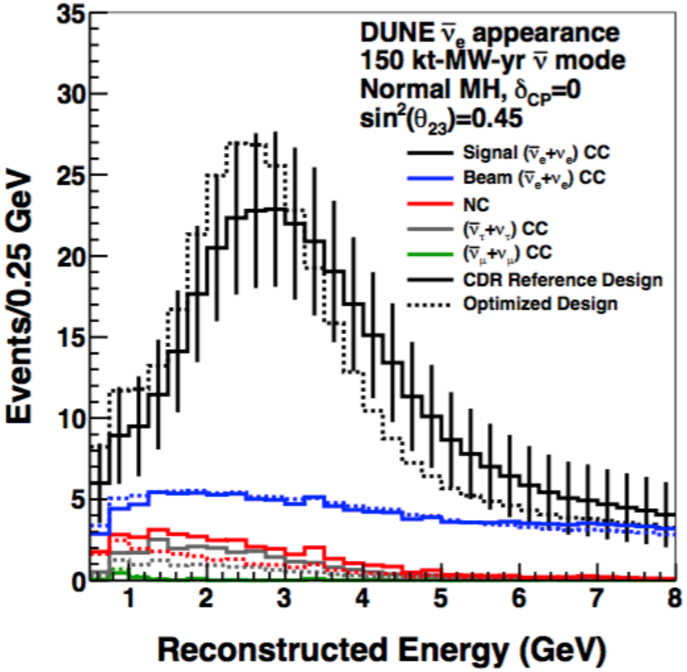
ν_e: 400 to 1600 events $\sigma_{\text{stat,rate}} \approx 2.5\%$ to 5%

$\bar{\nu}_e$: 150 to 500 events $\sigma_{\text{stat,rate}} \approx 4.5\%$ to 8%

Statistical Precision of Spectrum:

Considering 0.5 GeV bins: $\sigma_{\text{stat,per bin}} \approx 5\%$ (in peak, ν_e) to 20% (in tails, $\bar{\nu}_e$)





To meet CDR sensitivity, targeting NDS constraints of:

$\sigma_{\text{syst,rate}} \approx 2\%$

$\sigma_{\text{syst,per bin}} \approx 3\%$ (in peak)

$\approx 13\%$ (in tail)

Long-baseline Oscillation

What we want to measure:

Oscillation appearance probability at far detectors

ν_e spectrum at the far detectors

$$P_{\mu e}(E_\nu) = \frac{\Phi^{\rm far}_{\nu_e}(E_\nu)\big|_{l=l_{\rm far}}}{\Phi^{\rm far}_{\nu_\mu}(E_\nu)\big|_{l=0}}$$

ν_μ spectrum at source, emitted toward the far detectors

What we get to measure:

Reconstructed spectrum

Detector response, including efficiencies

Charged-current inclusive cross section on argon

$$\frac{dN^{\rm far}_{\nu_e}}{dE_{\rm rec}} = \int_{E_\nu} D^{\rm far,inclus.}_{\nu_e-{\rm CC}}(E_{\rm rec};E_\nu)\;\sigma^{\rm inclus.,Ar}_{\nu_e-{\rm CC}}(E_\nu)\;\Phi^{\rm far}_{\nu_e}(E_\nu)\big|_{l=l_{\rm far}}\,dE_\nu$$

$$= P_{\mu e}(E_\nu)\,\Phi^{\rm far}_{\nu_\mu}(E_\nu)\big|_{l=0}$$

$\sigma_{\rm stat,rate} \approx 3\%$

$\sigma_{\rm stat,per\ bin} \approx 5\%$ (in peak)

$\approx 20\%$ (in tail)

Caveat: For now, assume backgrounds have been assessed and accurately subtracted.

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$$\Vert$$

$$\underline{P_{\mu e}(E_\nu)\ \Phi^{\rm far}_{\nu_\mu}(E_\nu)\Big|_{l=0}}$$

$\sigma_{\rm syst,rate} \approx 2\%$
$\sigma_{\rm syst,per\ bin} \approx 3\%$ (in peak)
$\approx 13\%$ (in tail)

NDS must determine

← *in order to provide constraint*

Caveat: For now, assume backgrounds have been assessed and accurately subtracted.

Constraining the Flux

Flux Normalization:

1) Measure ν-e⁻ elastic scattering in low-density tracker

$\sigma_{\text{stat,rate}} \approx 1.5\%$ for ~5000 events

Cross-section known to better than 1%

$$\frac{dN^{\text{near}-\text{LDT}}_{\nu-\text{e}}}{dE_{\text{rec}}} = \int_{E_\nu} D^{\text{near}-\text{LDT}}_{\nu-\text{e}}(E_{\text{rec}};E_\nu)\,\sigma_{\nu-\text{e}}(E_\nu)\;\Phi^{\text{near}}_{\nu}(E_\nu)\Big|_{l=l_{\text{near}}}\,dE_\nu$$

Need detector with well-understood response to single e⁻.

Can potentially reach ~1-2% precision.

Key Issues:

- Most important: detector e⁻ angular resolution
- Moderately important: Understanding of detector e⁻ energy threshold
- Angular dispersion of LBNF beam at near site

Needs:

Detector with good e⁻ angular resolution (~<5 mrad), reasonable e⁻ energy resolution (~<10%), and a total fiducial mass sufficient to reach ~<1% statistical precision.

→ *~5-ton low-density tracker*

Might also provide some spectral constraint, though limited in quality.

See details in talk by Chris Marshall

Constraining the Flux

Flux Spectrum:

2) Measure low-ν ν_μ charged-current interactions on Ar in a LAr-TPC

$\sigma_{\text{stat,per bin}} \approx$ 3% for ~1000 events in peak

Energy dependence of cross-section known to few-%

$$\frac{dN^{\text{near-LDT}}_{\nu-\text{e}}}{dE_{\text{rec}}} = \int_{E_\nu} D^{\text{near-LDT}}_{\nu-\text{e}}(E_{\text{rec}};E_\nu)\,\sigma_{\nu-\text{e}}(E_\nu)\;\Phi^{\text{near}}_{\nu_\mu}(E_\nu)\Big|_{l=l_{\text{near}}} dE_\nu$$

Detector with well-understood response to single μ, and moderate neutron containment.

Can potentially reach ~<3% precision in shape.

Key Issues:

- Most important: Missed neutron energy limits precision of spectrum measurement
- Biases in muon energy measurement result in next largest systematic uncertainty
- Theory & exp. systematic corrections likely overwhelm measurement for E_ν ~< 1 GeV

Needs:

Detector with reasonable μ energy resolution (~<6 %), good muon energy calibration (~1%), and a mass sufficient to recover a reasonable fraction of neutron energy.

→ *~10s ton LAr-TPC with downstream μ-spectrometer*

See details in talk by Chris Marshall

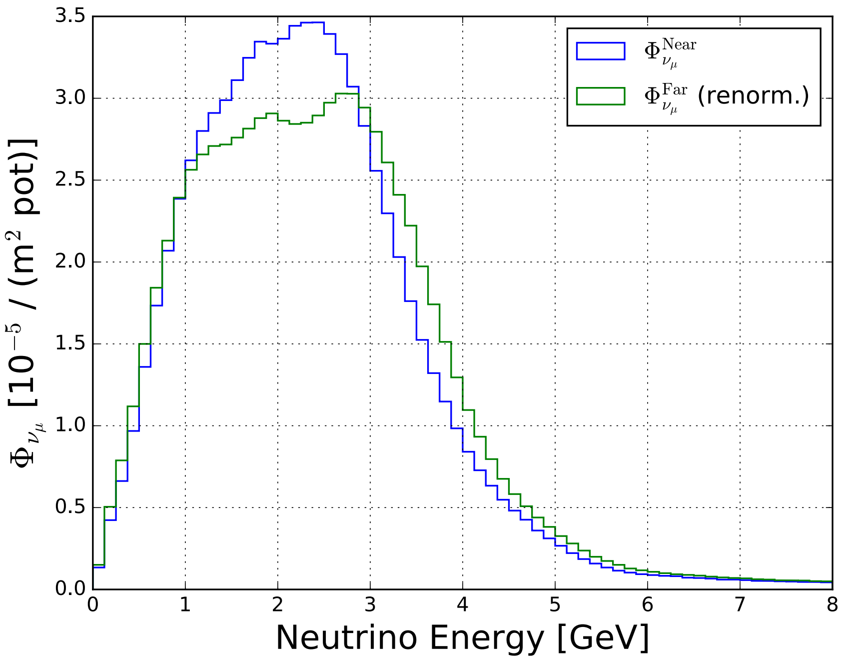
Constraining the Flux

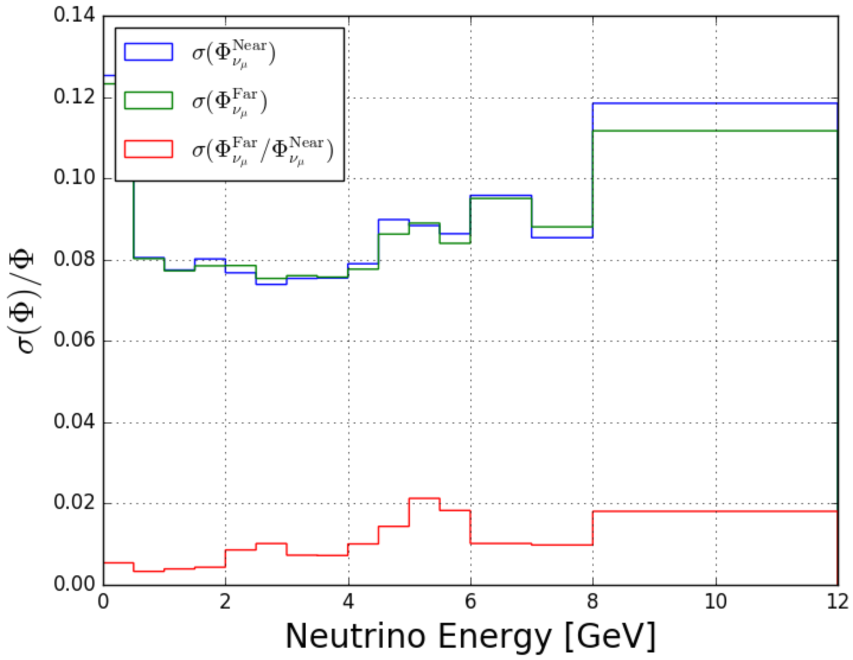
80 GeV, 3 horn optimized flux
http://home.fnal.gov/~ljf26/DUNEFluxes/

Flux Extrapolation:

According to LBNF beam group:

Near-site flux substantially different from far-site flux.
Absolute flux uncertainties: ~8%
Far/Near flux ratio uncertainty: ~1-2%





Initial Conclusion:

- Precise near-site flux measurement is sufficient to constrain far-site flux.

Questions:

- Are the existing beam modeling uncertainties comprehensive?
- Do we need an independent constraint on the near-far flux extrapolation?

Constraining the CC-Inclusive Signal

Charged-Current Inclusive Signal:

3) Measure inclusive ν_μ charged-current interactions on Ar in a LAr-TPC

$$\frac{dN^{\mathrm{near-LAr}}_{\nu_\mu-\mathrm{CC}}}{dE_{\mathrm{rec}}} = \int_{E_\nu} D^{\mathrm{near-LAr}}_{\nu_\mu-\mathrm{CC,inclus.}}(E_{\mathrm{rec}};E_\nu)\ \sigma^{\mathrm{inclus.,Ar}}_{\nu_\mu-\mathrm{CC}}(E_\nu)\ \Phi^{\mathrm{near}}_{\nu_\mu}(E_\nu)\Big|_{l=l_{\mathrm{near}}}\ dE_\nu$$

Related by data-driven μ,e swap

~1% by theory

Constrained by e⁻-scat., low-ν msmts.

$$\frac{dN^{\mathrm{far}}_{\nu_e}}{dE_{\mathrm{rec}}} = \int_{E_\nu} D^{\mathrm{far,inclus.}}_{\nu_e-\mathrm{CC}}(E_{\mathrm{rec}};E_\nu)\ \sigma^{\mathrm{inclus.,Ar}}_{\nu_e-\mathrm{CC}}(E_\nu)\ \Phi^{\mathrm{far}}_{\nu_e}(E_\nu)\Big|_{l=l_{\mathrm{far}}}\ dE_\nu$$

Key Issues:

- Similarities of near versus far detector responses?
- Uncertainty introduced by impurities in CC inclusive samples?
- Precision of data-driven μ,e swap in detector response?
- Bias introduced by differences in near ν_μ vs. far ν_e spectra?

These issues require further study.

Needs:

Detector of similar nature to far LAr-TPCs, with a total fiducial mass sufficient for CC-inclusive shower containment and reasonable μ energy resolution.

→ *~10s ton LAr-TPC with μ-spectrometer*

Constraining the CC-Inclusive Signal

Charged-Current Inclusive Signal:

4) Measure inclusive ν_μ charged-current interactions on Ar in a low-density tracker

$$\frac{dN^{\text{near}-\text{LDT}}_{\nu_\mu-\text{CC}}}{dE_{\text{rec}}} = \int_{E_\nu} D^{\text{near}-\text{LDT}}_{\nu_\mu-\text{CC,inclus.}}(E_{\text{rec}};E_\nu)\ \sigma^{\text{inclus.,Ar}}_{\nu_\mu-\text{CC}}(E_\nu)\ \ \Phi^{\text{near}}_{\nu_\mu}(E_\nu)\Big|_{l=l_{\text{near}}}\ dE_\nu$$

Face different systematics in efficiency, background

Identical

Identical, and constrained by e^--scat., low-ν msmts.

$$\frac{dN^{\text{near}-\text{LAr}}_{\nu_\mu-\text{CC}}}{dE_{\text{rec}}} = \int_{E_\nu} D^{\text{near}-\text{LAr}}_{\nu_\mu-\text{CC,inclus.}}(E_{\text{rec}};E_\nu)\ \sigma^{\text{inclus.,Ar}}_{\nu_\mu-\text{CC}}(E_\nu)\ \ \Phi^{\text{near}}_{\nu_\mu}(E_\nu)\Big|_{l=l_{\text{near}}}\ dE_\nu$$

Key Issues:

- Required size of argon target in low-density tracking detector?
- Level of correlation in backgrounds, detector responses?
- Size of differences in acceptance and efficiencies?

Breaks degeneracy between detector response/background uncertainties and cross-section.

Needs:

Hybrid detector: one module of similar nature to far LAr-TPCs, and one module of low-density tracker with sufficient Ar target to achieve necessary statistical precision.

Measurement requires further study.

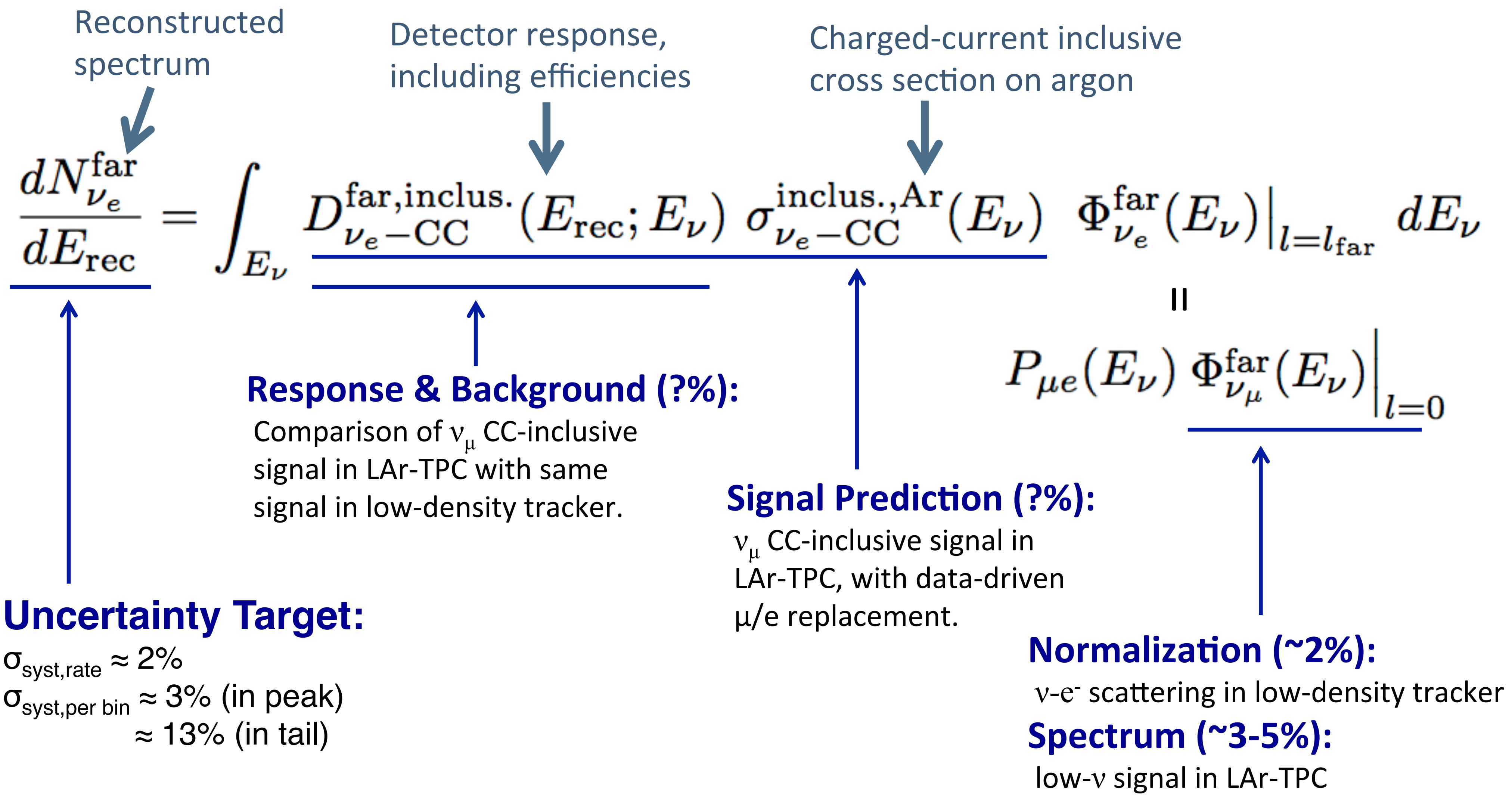
→ *~10s ton LAr-TPC with magnetized low-density tracker including ~0.1-ton Ar*

Measurement Overview

Component	Measurement	Criteria	Potential Detector
$\Phi_{\nu}^{\text{near}}(E_\nu)\Big\vert_{l=l_{\text{near}}}$ *(normalization)*	ν-e^- elastic scattering	Detect very-forward 0.5-8 GeV single e^- - energy resolution: ~<5% - ang. resolution: ~<4 mrad	Magnetized low-density tracker, O(5) ton mass.
$\Phi_{\nu_\mu}^{\text{near}}(E_\nu)\Big\vert_{l=l_{\text{near}}}$ *(spectrum)*	low-ν ν_μ charged-current interactions	Detect very-forward 1-8 GeV single μ. Reject signals with signif. hadronic energy. - requires reasonable neutron tagging, energy containment	O(10) ton LAr-TPC, backed by low-density detector to determine μ energy and sign
$\sigma_{\nu_\mu-\text{CC}}^{\text{inclus.,Ar}}(E_\nu)$ × $D_{\nu_\mu-\text{CC,inclus.}}^{\text{near}-\text{LAr}}(E_{\text{rec}};E_\nu)$	Inclusive ν_μ charged-current interactions on Ar, in LAr-TPC	Efficiently detect 0.5-8 GeV ν_μ charged-current signals on Ar, and measure LAr-TPC response. - requires reasonable ν_μ CC TPC shower containment	O(10) ton LAr-TPC, with low-density tracker to determine μ energy and sign
$\dfrac{D_{\nu_\mu-\text{CC,inclus.}}^{\text{near}-\text{LAr}}(E_{\text{rec}};E_\nu)}{D_{\nu_\mu-\text{CC,inclus.}}^{\text{near}-\text{LDT}}(E_{\text{rec}};E_\nu)}$	Compare inclusive ν_μ charged-current interactions on Ar, in low-density tracker vs. LAr-TPC	Efficiently detect 0.5-8 GeV ν_μ charged-current signals on Ar in low-density tracker.	Magnetized low-density tracker with ~0.1 ton Ar mass.

Measurement Summary

Constraining the Appearance Signal:



Reconstructed spectrum

Detector response, including efficiencies

Charged-current inclusive cross section on argon

$$\frac{dN^{\text{far}}_{\nu_e}}{dE_{\text{rec}}} = \int_{E_\nu} D^{\text{far,inclus.}}_{\nu_e-\text{CC}}(E_{\text{rec}};E_\nu)\;\sigma^{\text{inclus.,Ar}}_{\nu_e-\text{CC}}(E_\nu)\;\Phi^{\text{far}}_{\nu_e}(E_\nu)\Big|_{l=l_{\text{far}}}\,dE_\nu$$

$$\Phi^{\text{far}}_{\nu_e}(E_\nu)\Big|_{l=l_{\text{far}}} = P_{\mu e}(E_\nu)\;\Phi^{\text{far}}_{\nu_\mu}(E_\nu)\Big|_{l=0}$$

Response & Background (?%):
Comparison of ν_μ CC-inclusive signal in LAr-TPC with same signal in low-density tracker.

Signal Prediction (?%):
ν_μ CC-inclusive signal in LAr-TPC, with data-driven μ/e replacement.

Uncertainty Target:

$\sigma_{\text{syst,rate}} \approx 2\%$

$\sigma_{\text{syst,per bin}} \approx 3\%$ (in peak)

$\approx 13\%$ (in tail)

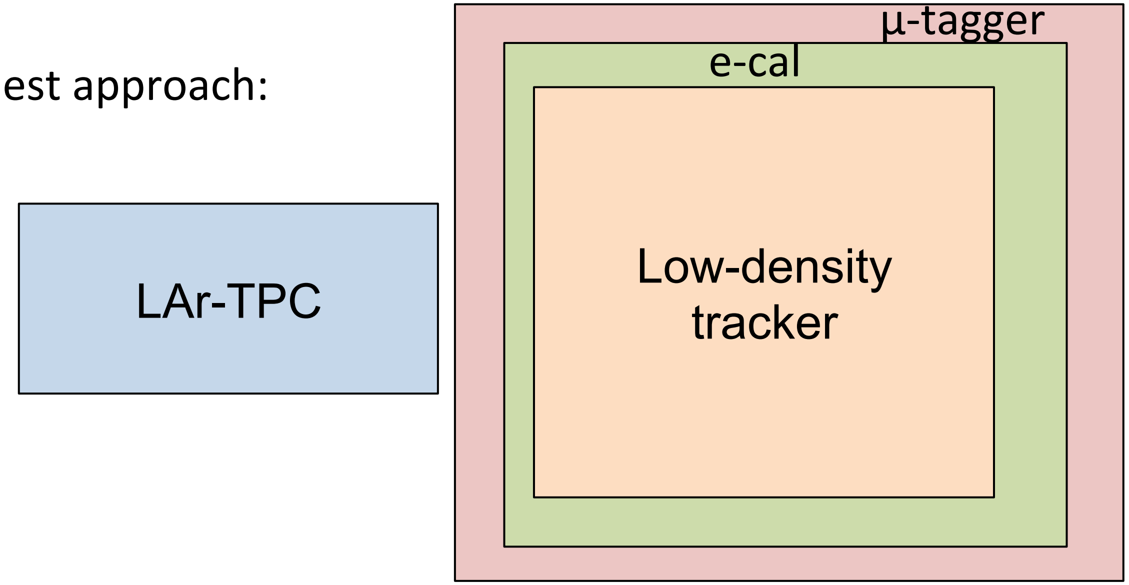
Normalization (~2%):
ν-e$^-$ scattering in low-density tracker

Spectrum (~3-5%):
low-ν signal in LAr-TPC

Near Detector Proposal

Hybrid Detector System:

Simplest approach:

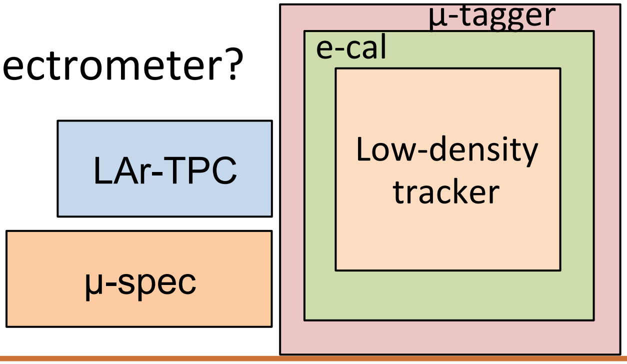


Question:

How important are energy and sign of high-p_T μ from ν_μ CC-inclusive interactions in LAr-TPC?

Alternative:

Sampling μ-spectrometer?



Rough design:

LAr-TPC:

O(10) tons:

Containment of low-ν neutrons, and ν_μ CC-inclusive showers

B-field:

Not preferred?

Low-density tracker:

O(5) tons (e-):

Sufficient stats for ν-e^- scat.

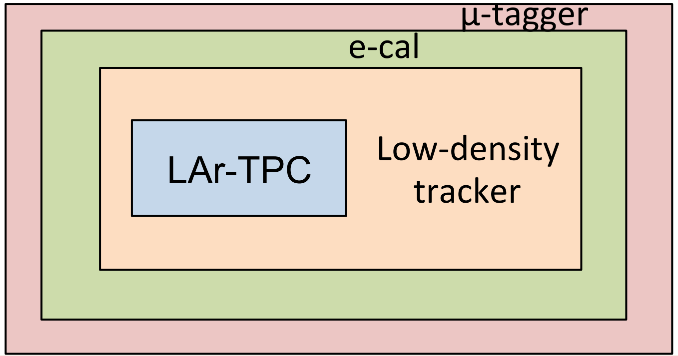
O(0.1) tons (Ar):

Sufficient stats for ν_μ CC-incl.

B-field:

Yes, need sign discrimination and μ energy.

Alternative: ~4π tracker?



Comments and Questions

Near Detector Constraint:

- Achieving a 2% rate and 3%-5% spectrum systematic uncertainty in ν_e appearance signal: very hard.
- My opinion: Robust result more likely achieved by a small set of specific targeted measurements as outlined in this talk, as opposed to 'kitchen sink' approach.
- Targeting a specific set of precision measurements can more clearly guide near detector design.

Detector deployment:

- Near detector constraints need only match current far detector stat. sensitivity (i.e. improve with time)
- LAr-TPC measurements not statistics limited, so module could be deployed at a later date
- ν-e^- scattering measurement is likely statistics limited, so LDT should be ready at start of experiment

Some Questions:

- How quickly does CP sensitivity decline as systematics increase beyond CDR targets?
- Are there other measurements which provide better constraints than those suggested here?
- How can we confirm the uncertainty of projecting the measured near site ν_μ flux to the far site?
- How accurately can we model LAr-TPC response to ν_e CC-inclusive signal via μ/e data-driven swapping?
- How critical is measurement of high-p_T μ energy & sign from ν_μ CC-inclusive interactions in near LAr-TPC?
- How well does comparison of LAr-TPC vs. LDT ν_μ CC-inclusive signal resolve detector response and background systematics? What factors in comparison of these measurements are most critical?
- How does sensitivity of these measurements vary with near hall location?