Hybrid Detector Concepts

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Science & Technology Facilities Council
Rutherford Appleton Laboratory
UNIVERSITY OF OXFORD

Introduction

- Oscillation probabilities

$$P_{\nu_\mu \to \nu_e}(E_\nu) = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{far,no-osc}(E_\nu)} = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}\ (E_\nu)}$$

Well known (1-2%)

- Number of events/energy spectrum

$$\frac{dN_\nu^{det}}{dE_\nu} = \phi_{\nu_\mu}^{det}(E_\nu) * \sigma_{\nu_\mu}^{Ar}\ (E_\nu)$$

- In reality

$$\frac{dN_\nu^{det}}{dE_{rec}} = \int \phi_\nu^{det}(E_\nu) * \sigma_\nu^{target}\ (E_\nu) * D_{\nu_\mu}^{det}(E_\nu, E_{rec})\ dE_\nu$$

- Folding of detector effects
  - Prevents (easy) cancellations of many systematic effects
  - Needs unfolding

Are there cancellations?

- Oscillation signal

Small theo. uncertainty or measurement

$$\frac{dN_{\nu_e}^{far}}{dE_\nu} \Big/ \frac{dN_{\nu_\mu}^{near}}{dE_\nu} = P_{\nu_\mu \to \nu_e}(E_\nu) * \frac{\sigma_{\nu_e}^{Ar}(E_\nu)}{\sigma_{\nu_\mu}^{Ar}(E_\nu)} * F_{far/near}\,(E_\nu)$$

1-2% uncertainty

- Near muon/electron ratio

$$\frac{dN_{\nu_e}^{near}}{dE_\nu} \Big/ \frac{dN_{\nu_\mu}^{near}}{dE_\nu} = \frac{\sigma_{\nu_e}^{Ar}(E_\nu)}{\sigma_{\nu_\mu}^{Ar}(E_\nu)} * \frac{\phi_{\nu_e}^{near}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu)}$$

Not so small uncertainty

- Need to know
  - Flux & cross section ratios
  - Far/near extrapolation

But in Reality

$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * D_{\nu_e}^{far}(E_\nu, E_{rec})\ dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * D_{\nu_\mu}^{near}(E_\nu, E_{rec})\ dE_\nu}$$

- No cancellations
  - Unless you unfold
- Need to understand especially
  - Detector effects in near and far detector
  - Relation of visible to neutrino energy
  - Cross section ratios
  - Near to far flux extrapolation
- Flux normalisation cancels
  - Shape is important

Key Measurements

Dan Dwyer

In order of importance:

1) Rate, spectrum of inclusive ν_μ charged-current interactions for near/far comp.
- Provide combined constraint on (flux × cross-section) relevant for oscillation measurement

2a) Spectrum of low-ν (low hadronic energy) ν_μ charged-current interactions
- Provide independent constraint on ν_μ energy spectrum (i.e. flux shape) at near site (~few %)
  → Breaks degeneracy with other shape systematics (e.g. x-section, det. resp., bkgd.)

2b) Rate, spectrum of inclusive ν_μ-CC in magnetized low-density tracker
- Provide independent measurement of (flux × cross-section) via different technique
  → Breaks degeneracy with detector response, background systematics
- Constrain assumptions in underlying model of neutrino-nuclear interactions

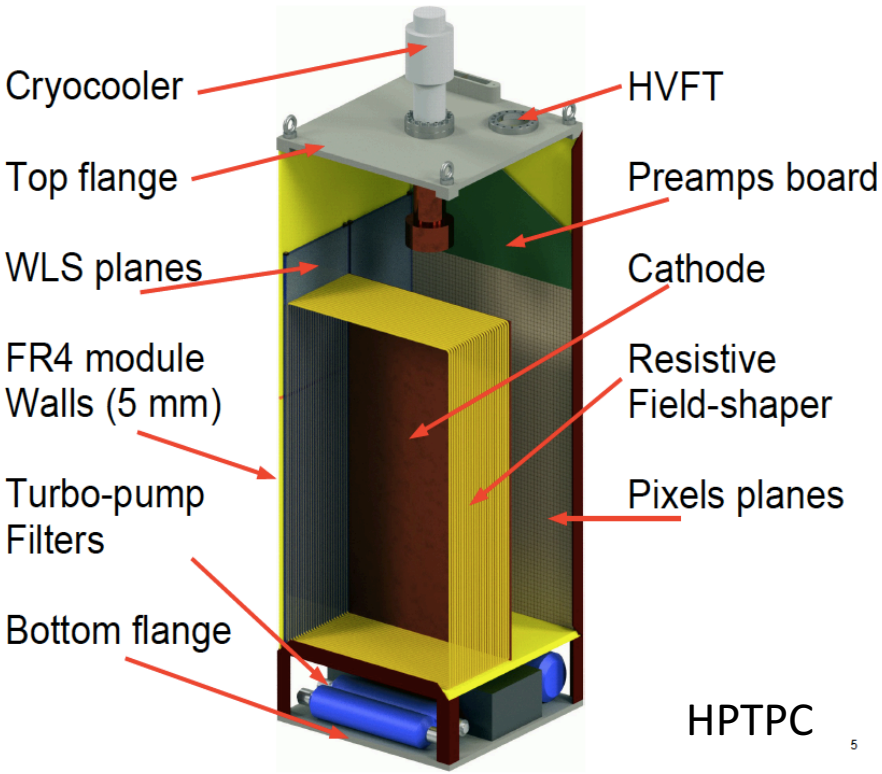
2c) Rate of ν-electron elastic scattering interactions
- Provide independent constraint on absolute flux normalization
  → Breaks degeneracy with other normalization systematics (e.g. bkgd, x-section, det. eff.)

What does the ND need to measure?

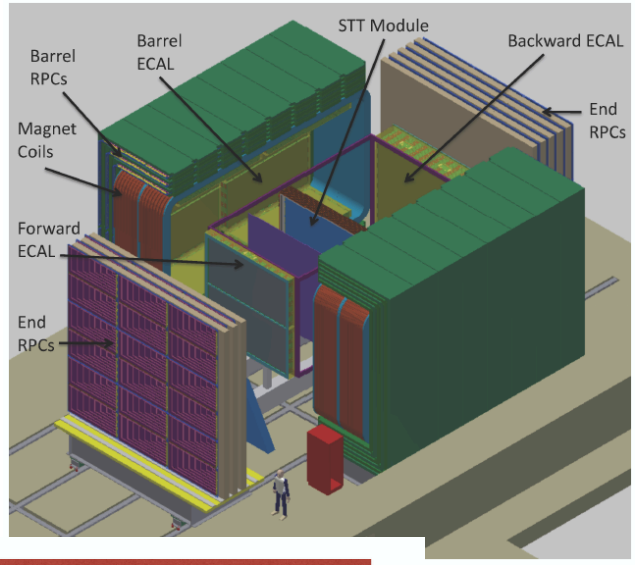
- Constrain systematics in far detector ν_e /anti-ν_e appearance signal
  - CDR level (2%)
- Measurement Strategy
  - Understand detector response and model dependence
    - electron & muon neutrino interactions (LAr TPC)
    - inclusive & exclusive ν_μ CC interactions
      - in Ar and (other materials) in a low-density tracker
  - Understand flux shape
    - low-nu method (little hadronic energy)
  - Understand near-to-far extrapolation
    - ND can help to constrain hadron production & focussing uncertainties
    - measure energy spectrum/flux of all neutrino flavours

Traditional Detector Concepts

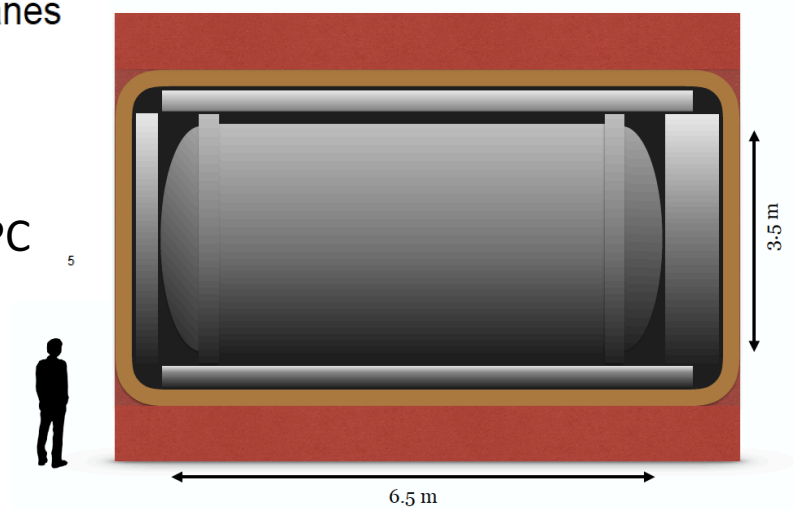
ArgonCube



FGT

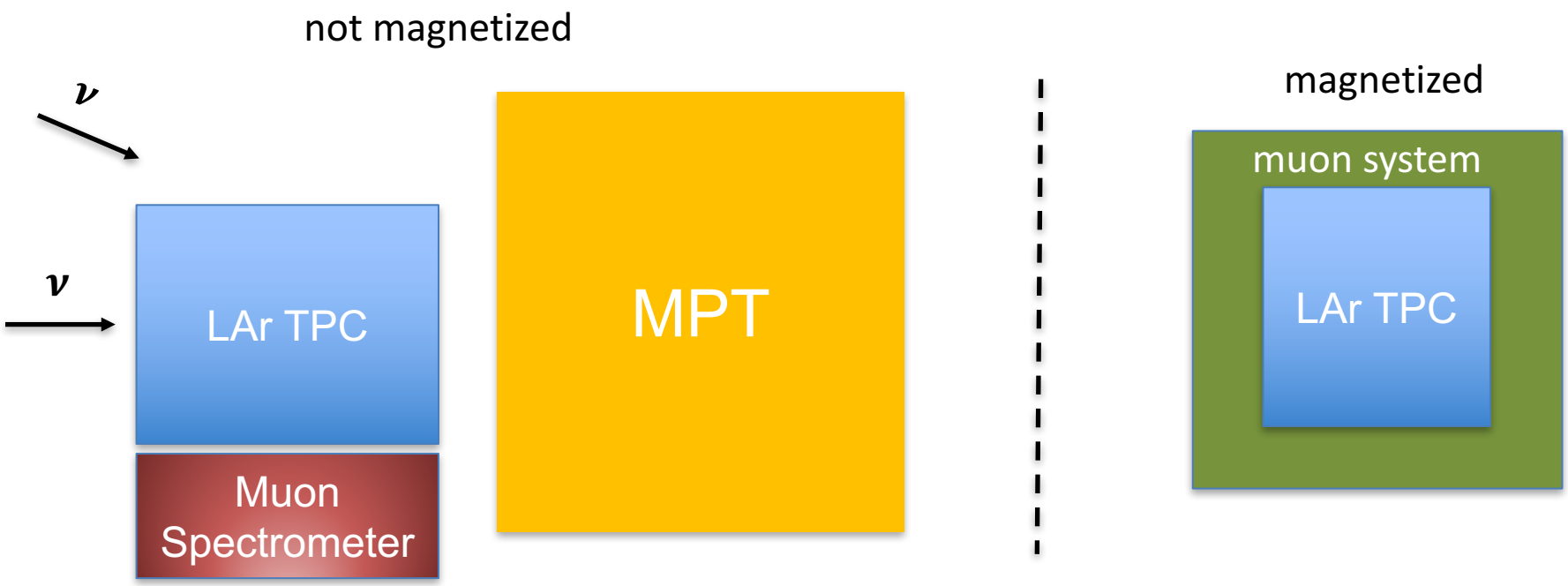


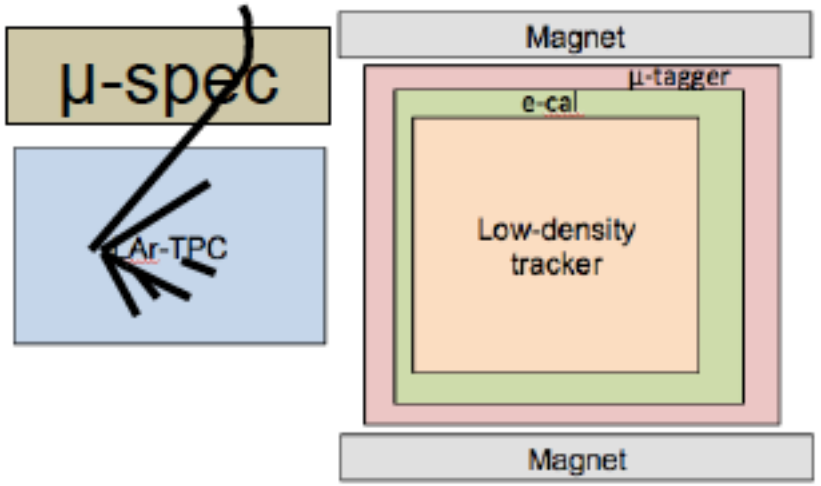
HPTPC

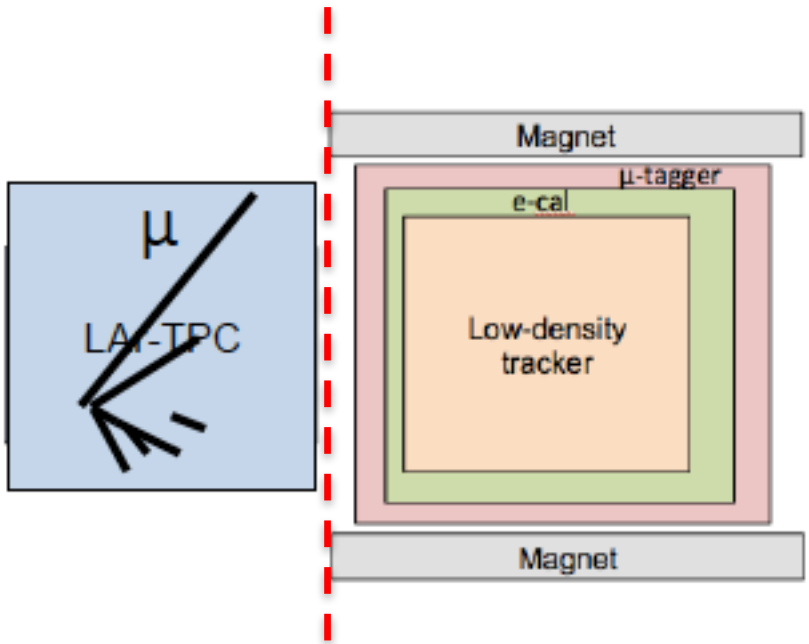


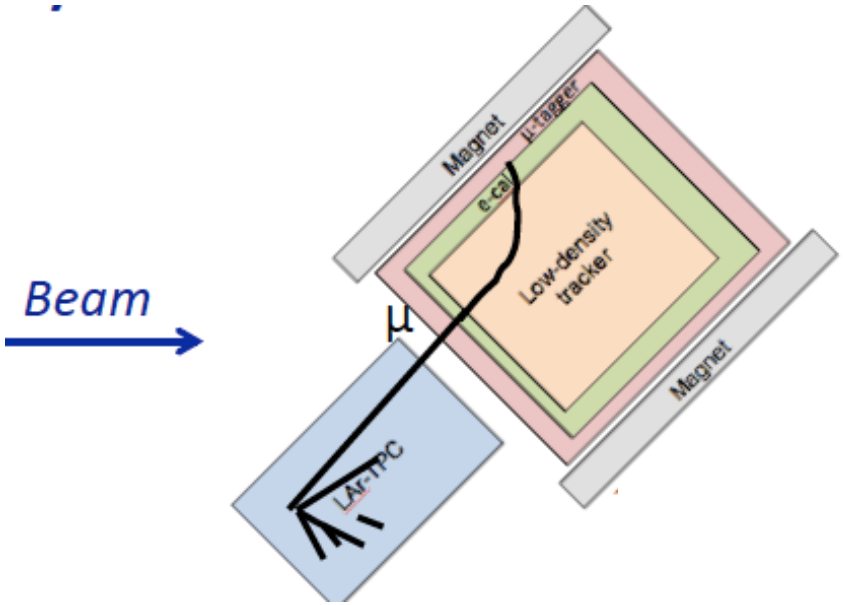
Hybrid Concepts (LAr)

- LAr TPC
  - Agreed “should have” at last Workshop
- Questions
  - Size, location, w/o or w/ magnetic field




μ-spec
Magnet
μ-tagger
e-cal
LAr-TPC
Low-density
tracker
Magnet


Magnet
μ-tagger
e-cal
μ
LAr-TPC
Low-density
tracker
Magnet


Beam
Magnet
μ-tagger
e-cal
Low-density
tracker
μ
Magnet
LAr-TPC

Hybrid Concepts (MPT)

- Measure details of neutrino interactions as much as needed
  Multi-Purpose Tracker
  - Inclusive and exclusive reaction
  - Particle ID
  - Momentum measurements
- Reduce cross section/flux systematics
- Understand relations between visible and neutrino energy
- Several detector options
  - (high pressure) (argon) gas TPC
  - straw-tube tracker
  - (3D) scintillator tracker

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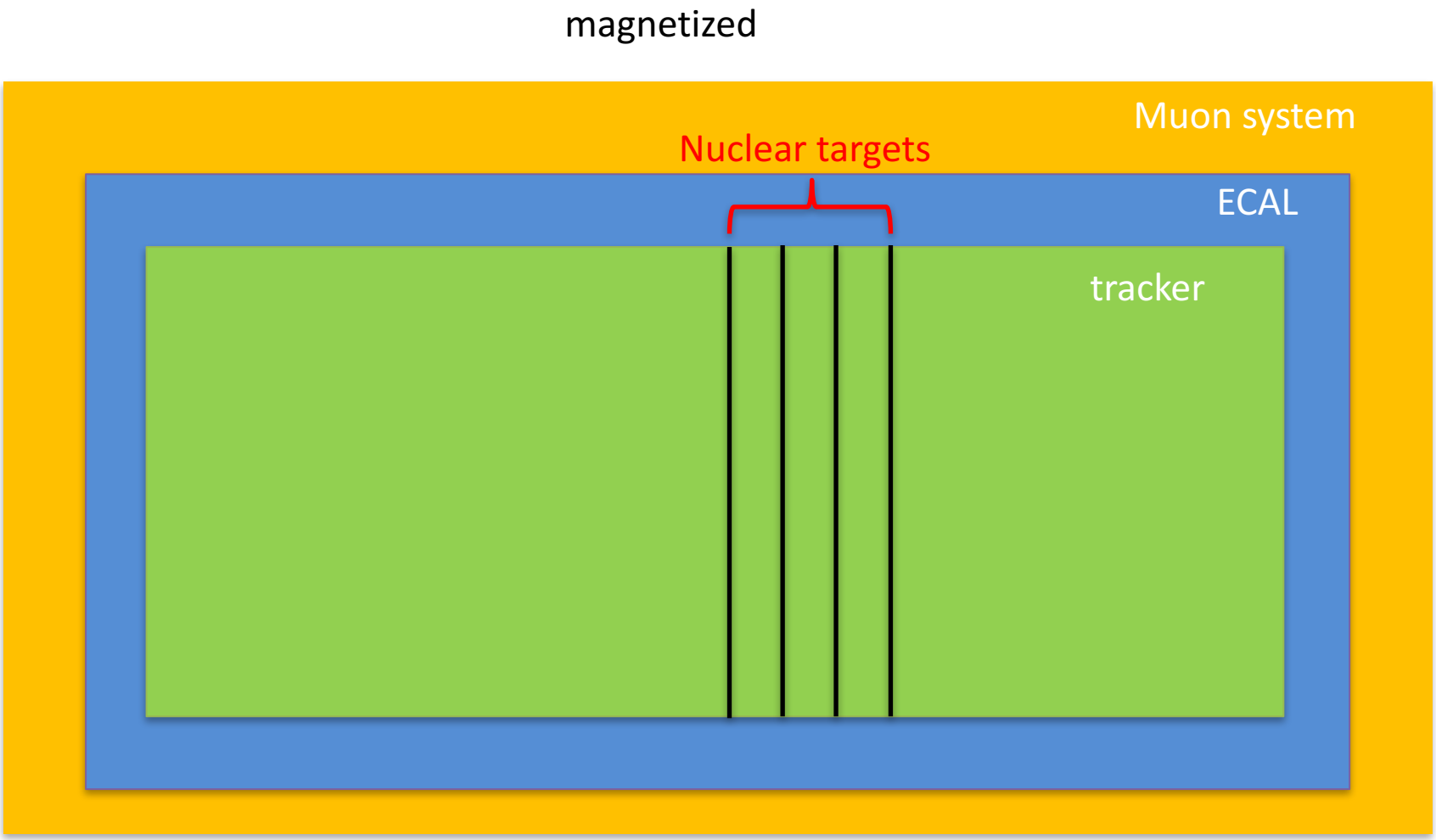
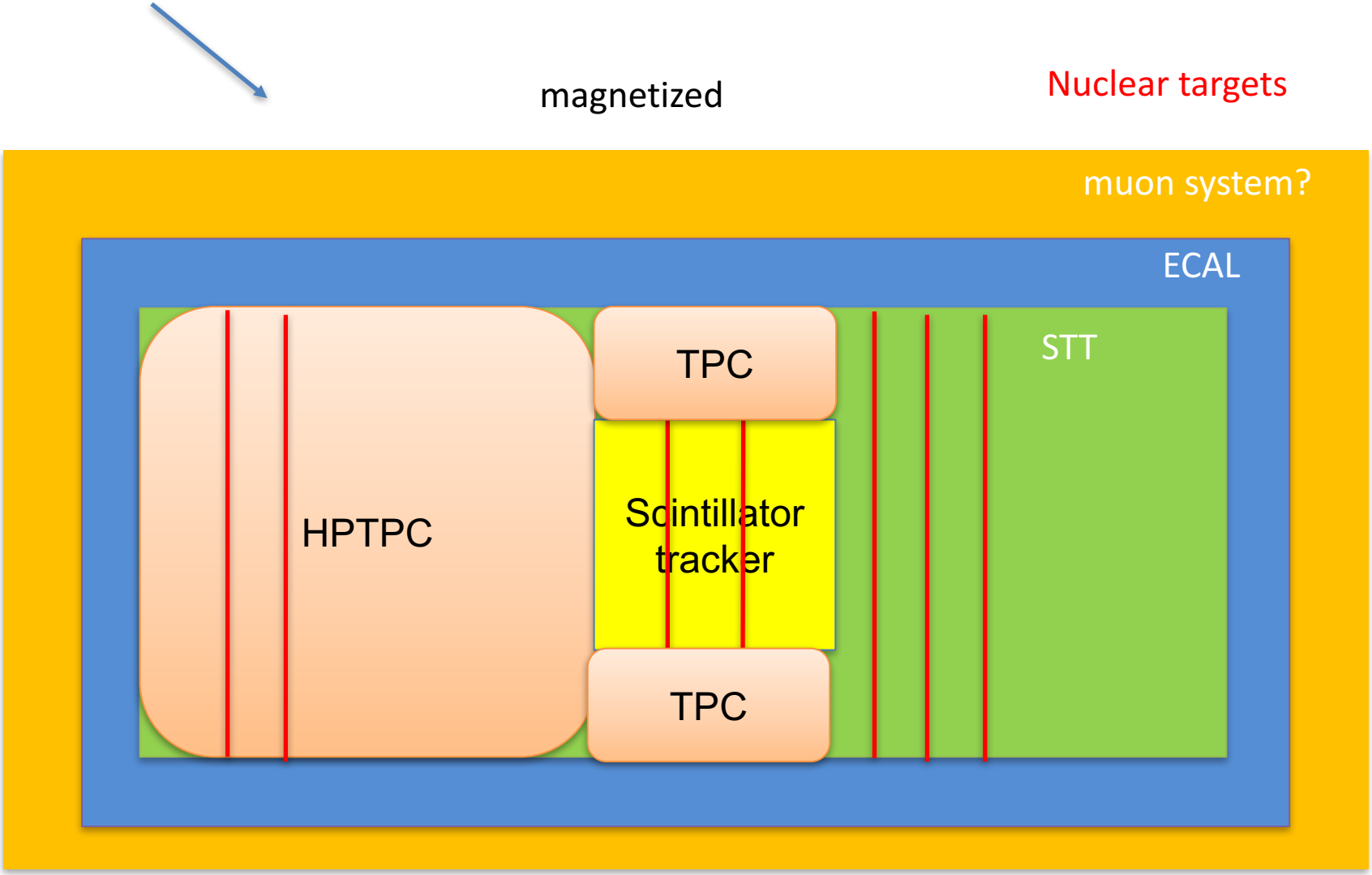
Multi-Purpose Tracker System

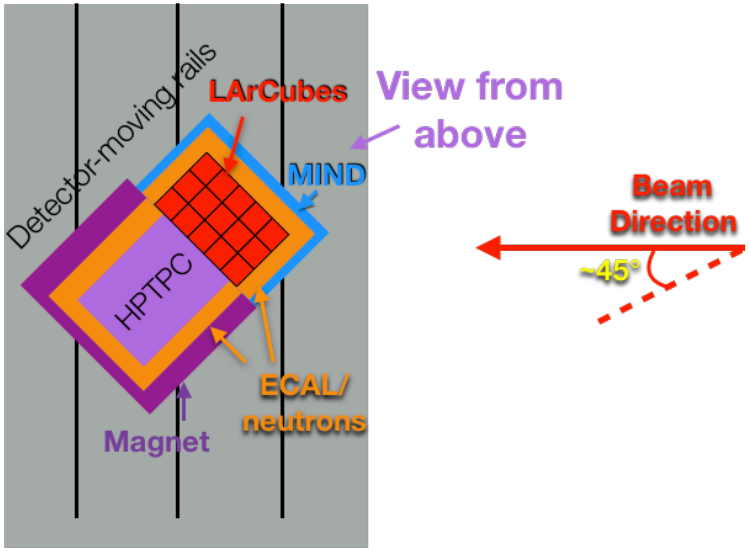


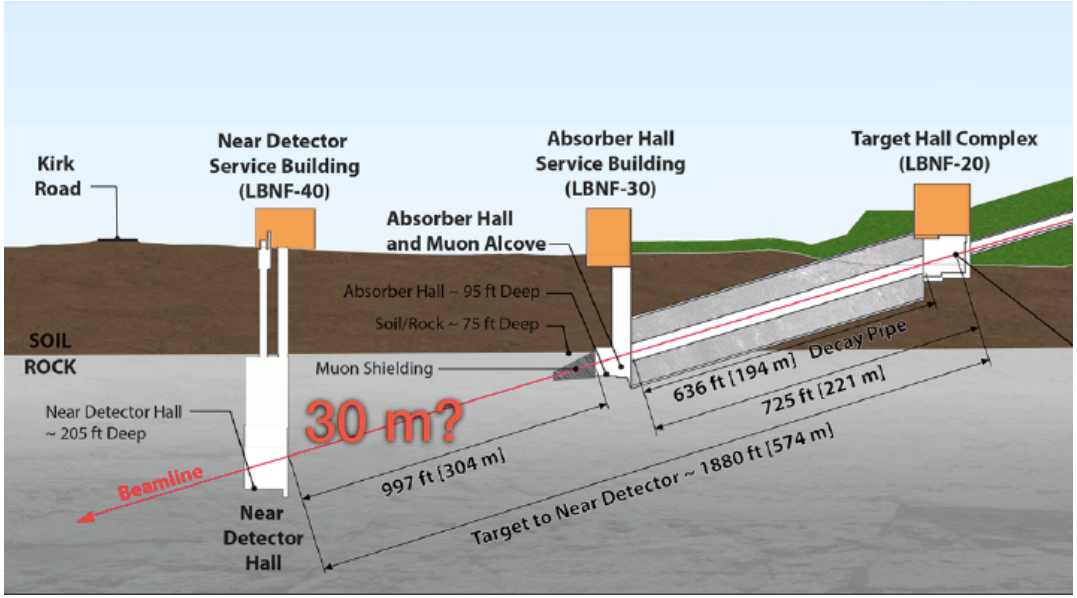
Multi-Purpose Tracker



DUNE-PRISM

- Alternative approach
  - Vary flux by changing off axis angle
  - Only ever measure product of xsec and detector response
- Move detectors along different off-axis angles





Questions (Ia)

- Do we need a LAr detector?
  - Yes! Get handle on detector effects.
- Do we need a B-field
  - Pro
    - Allows momentum measurement of non-contained particles
    - Separate μ^+ from μ^-
  - Cons
    - Can't be done anytime soon
    - Expensive
    - Would make ND-LAr quite different from FD-LAr
- **Conclusion**
  - **We want a non-magnetised LAr detector**

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Questions (Ib)

- Will be smaller than FD (Containment!)
- Important
  - What should the size be?
    - Large enough for shower (& muon) containment
  - Can it handle the rate?
    - Size of drift space (dead space)
  - Does it need a muon spectrometer?
    - No, just containment is enough
    - Yes, dedicated system
    - Yes, MPT can do this

Questions (IIa)

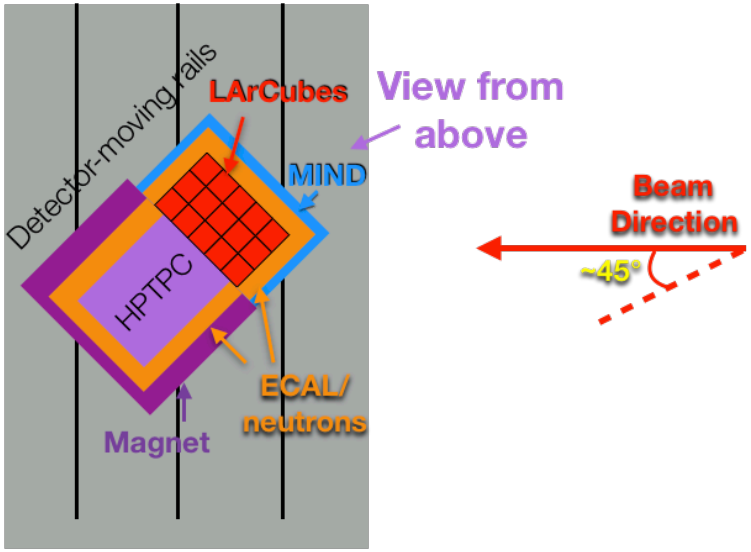
- Need to understand neutrino interactions in as much detail as possible.
  - Study Model dependencies $D_{\nu_\mu}^{det}(E_\nu, E_{rec})$
  - Understand beam flux & extrapolation
  - backgrounds
- Clear physics case for multi-purpose Tracker (MPT) with B-field
- Decoupled
  - Different nuclear targets
  - Tracking technology
  - ECAL technology
  - Muon tagger (do we need one?)

Questions (IIb)

- Tracking technology
  - Can it be built & funded
  - Does it have the required performance
    - Momentum resolution/scale (?/1%) & charge
    - Angular resolution (<5 mrad)
    - Particle ID/ multiplicity
    - neutrals
  - Can it handle
    - Rate
    - Different nuclear targets

Question (IV)

- DUNE-PRISM
  - Interesting option
    - Maybe construct mono-energetic beams
    - **Certainly change energy spectrum**
  - Will provide additional information
- Main questions
  - What is the physics gain?
  - What is the cost?
  - Move the LAr detector
  - Move the non-LAr detector



Preliminary Conclusions

- Detector 1: LAr
  - LAr no B-field (study adding it later)
  - (maybe add spectrometer)
- Detector 2: MPT
  - tracking technology
    - STT, (HP)TPC, scintillator tracker
  - nuclear targets (yes)
  - ECAL (yes)
  - Muon system (yes)
  - Magnet (yes)
- Location
  - 574 m
- DUNE-PRISM
  - Consider option of moving LAr detector by up to 30 m
  - Engineering requirements & cost

Different Technologies (I)

Personal view

High Pressure TPC

- Pro
  - Ar (and other) active target
  - Very low threshold
  - Good particle ID
  - cheap
- Contra
  - Low target mass ⇔ rate
  - Limited number of gas targets
  - Very high external BG
  - Rel. slow

Straw Tube Tracker

- Pro
  - Many (passive) different targets
  - Low threshold on H/C
  - Good particle ID
  - fast
- Contra
  - High threshold on Ar
  - Technology and Cost

Different Technologies (I)

Personal view

Scintillator tracker

- Pro
  - Well established technology (2D)
  - Active H/C target
  - Cheap
  - Very fast
  - Neutrons(?)
- Contra
  - 3D structure needed
  - Higher detection threshold
  - Limited granularity/unit mass
  - Passive nuclear targets

Explore Hybrid Option

- There are pros and cons for all detector options
- Consider combining them
  - Want: the best of all worlds
  - But: could get the worst of all worlds

- For the rest of the workshop
  - Explore what a combination can do
  - What are the gains/losses

Backup

Strategy

1) Complete zeroth-order studies (i.e. Fast-MC-like) of the four measurements outlined (Dan)

→ Coarsely refine near detector design (size, acceptance, materials, etc.)

→ Use overall ~2% rate, ~3% shape systematic uncertainty target as guide

2) Perform first-order (i.e. initial Geant4 MC) of Hybrid Design

→ Use in combination with cheated reconstruction for studies of background, pile-up, etc.

→ Revise uncertainty estimates of four key measurements. Use as input to studies of CP-violation.

→ Fine-tune detector design.

3) Perform second-order (i.e. full Geant4 MC) of Hybrid Design

→ Implement initial reconstruction algorithms. Perform 'realistic' study of 4 key measurements.

From D. Dwyer

Next Steps (I)

- LBL group needs to provide performance “requirements” Does CP-sensitivity depend on
  - Angular and momentum resolution
  - Proton tracking threshold
  - Particle ID
  - Particle counting
  - measure neutrals (π^0, neutron)
- Check relevant parameters for detector concepts
- Magnet/field requirements
  - Existing magnets?

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Next Steps (II)

- From Accelerator & Beam Interface Group
  - What is the error on the ND electron/muon-neutrino flux ratio?
  - What is the uncertainty on neutrino/anti-neutrino flux ratio?
  - Does it matter?
- More …

- Workshop is very soon
  - Need to get some answers soon
  - Don't sleep
  - Buy your tickets now

Event Rates

$$\frac{dN_{\nu_\mu}^{near}}{dE_{rec}} = \int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * D_{\nu_\mu}^{near}(E_\nu, E_{rec})\ dE_\nu$$

$$\frac{dN_{\nu_e}^{near}}{dE_{rec}} = \int \phi_{\nu_e}^{near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * D_{\nu_e}^{near}(E_\nu, E_{rec})\ dE_\nu$$

$$\frac{dN_{\nu_\mu}^{far,no-osc}}{dE_{rec}} = \int \phi_{\nu_\mu}^{far}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * D_{\nu_\mu}^{far}(E_\nu, E_{rec})\ dE_\nu$$

$$\phi_{\nu_\mu}^{far,no-osc}(E_\nu) = \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu)$$

$$\phi_{\nu_e}^{far}(E_\nu) = P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{far,no-osc}(E_\nu)$$

$$\frac{dN_{\nu_\mu}^{far}}{dE_{rec}} = \int \phi_{\nu_\mu}^{far}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * D_{\mu}^{far}(E_\nu, E_{rec}) * P_{\nu_\mu \to \nu_\mu}(E_\nu)\ dE_\nu$$

$$\frac{dN_{\nu_e}^{far}}{dE_{rec}} = \int \phi_{\nu_\mu}^{far}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * D_{\nu_e}^{far}(E_\nu, E_{rec}) * P_{\nu_\mu \to \nu_e}(E_\nu)\ dE_\nu$$

CC interactions

1) Rate, spectrum of inclusive ν_μ charged-current interactions for near/far comp.

- Provide combined constraint on (flux × cross-section) relevant for oscillation measurement

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

Constrained by detector model

Constrained by theory

Constrained by beam model

$$\frac{dN^{\text{far}}_{\nu_e}}{dE_{\text{rec}}} = \int_{E_\nu} D^{\text{far,inclus.}}_{\nu_e-\text{CC}}(E_{\text{rec}};E_\nu)\ \sigma^{\text{inclus.,Ar}}_{\nu_e-\text{CC}}(E_\nu)\ P_{\mu e}(E_\nu)\ \Phi^{\text{far}}_{\nu_\mu}(E_\nu)\Big|_{l=0}\ dE_\nu$$

Signal: Muon + anything

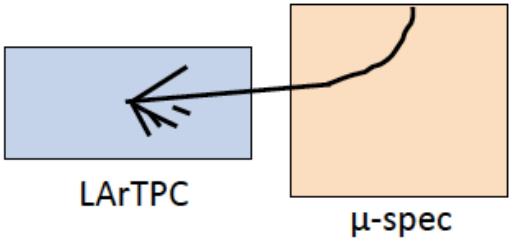
Corrections:

a.) Precision of projection of near site flux to far site (current est.: ~1% on ~50% diff)
b.) Ratio of ν_μ to ν_e inclusive CC cross-section (current est.: ~1-2%, assuming Ar)
c.) Differences in near detector ν_μ-CC response vs. far detector ν_e-CC response (?)
d.) Differences in near site ν_μ-CC vs. far site ν_e-CC backgrounds (?)

→ *Combined uncertainties in these corrections must be <2% in rate, <3%-5% in shape*

Near Detector Options:

- ~~Very large LArTPC~~
- Small (~30 ton) LArTPC w/muon spectrometer
- Magnetized LArTPC



Low ν

2) Spectrum of low-ν (low hadronic energy) ν_μ charged-current interactions

- Provide independent constraint on ν_μ energy spectrum (i.e. flux shape) at near site (~few %)
  → Breaks degeneracy with other shape systematics (e.g. x-section, det. resp., bkgd.)

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

~Response to single μ ~Flat by theory Identical flux

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

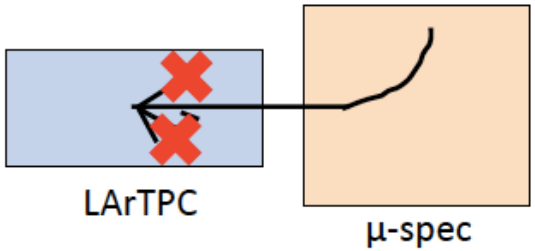
Signal: Energetic very-forward μ, nothing else

Corrections:

a.) Theoretical uncertainty of low-ν cross-section (current est: < 5% above 1 GeV)
b.) Bias in energy measurement of single muons (current est: 4% for 1% μ energy scale unc.)
c.) Most critical: background from high-ν interactions, where neutron missed (det.-dependent)
→ Moderate energetic neutron tagging efficiency (~70%) is sufficient to suppress bkgd.

Near Detector Options:

- Scintillator tracker w/muon spectrometer
- Small (~30 ton) LArTPC w/muon spectrometer
- (~fully active dense detector)



Inclusive and exclusive interactions

3) Rate, spectrum of inclusive ν_μ-CC in magnetized low-density tracker

- Provide independent measurement of (flux × cross-section) via different technique
  → Breaks degeneracy with detector response, background systematics
- Constrain assumptions in underlying model of neutrino-nuclear interactions

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

Very different, test of det. model

Identical

Identical

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

Other nuclei?

$$\sigma^{\text{inclus.Oth.}}_{\nu_\mu-\text{CC}}(E_\nu)$$

→ *Powerful cross-check of potential errors in:*
- detector model
- ν interaction model

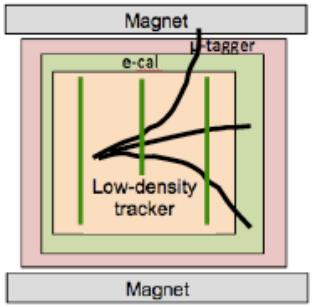
Signal: Muon + anything else

Corrections:

a.) Isolation of interactions on argon, other nuclei (?)
b.) Energy containment (?)
c.) Background from ν interactions outside detector (?)

Near Detector Options:

- FGT-like (straw-tube, e-cal, μ-tagger)
- HPAr-like (HPArTPC, e-cal, μ-tagger)
- ?



ν-e elastic

4) Rate of ν-electron elastic scattering interactions

- Provide independent constraint on absolute flux normalization
  → Breaks degeneracy with other normalization systematics (e.g. x-section, det. eff., bkgd.)

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

~Response to single e⁻ ↓ Known by theory ↓ ↕ ~Identical flux

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

Signal: Energetic very-forward e^-, nothing else

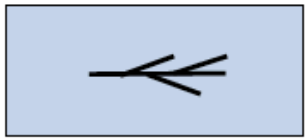
Corrections:

a.) Theoretical uncertainty of ν-e^- cross-section (<1%)
b.) At least ~5 ton target mass to achieve <1% statistical uncertainty
c.) Background rejection requires good angular resolution (≤ 5 mrad)

→ *ν-e^- also carries spectral information, but msmt. looks very difficult.*

Near Detector Options:

- Fine-grained scintillator tracker
- Small (~30 ton) LArTPC
- Straw-tube tracker with radiators
- ?



LArTPC

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
$\sigma_{\nu_\mu-\text{CC}}^{\text{inclus.,Ar}}(E_\nu) \times D_{\nu_\mu-\text{CC,inclus.}}^{\text{near}-\text{LAr}}(E_{\text{rec}};E_\nu)$	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.