DUNE near detector design for long-baseline neutrino physics

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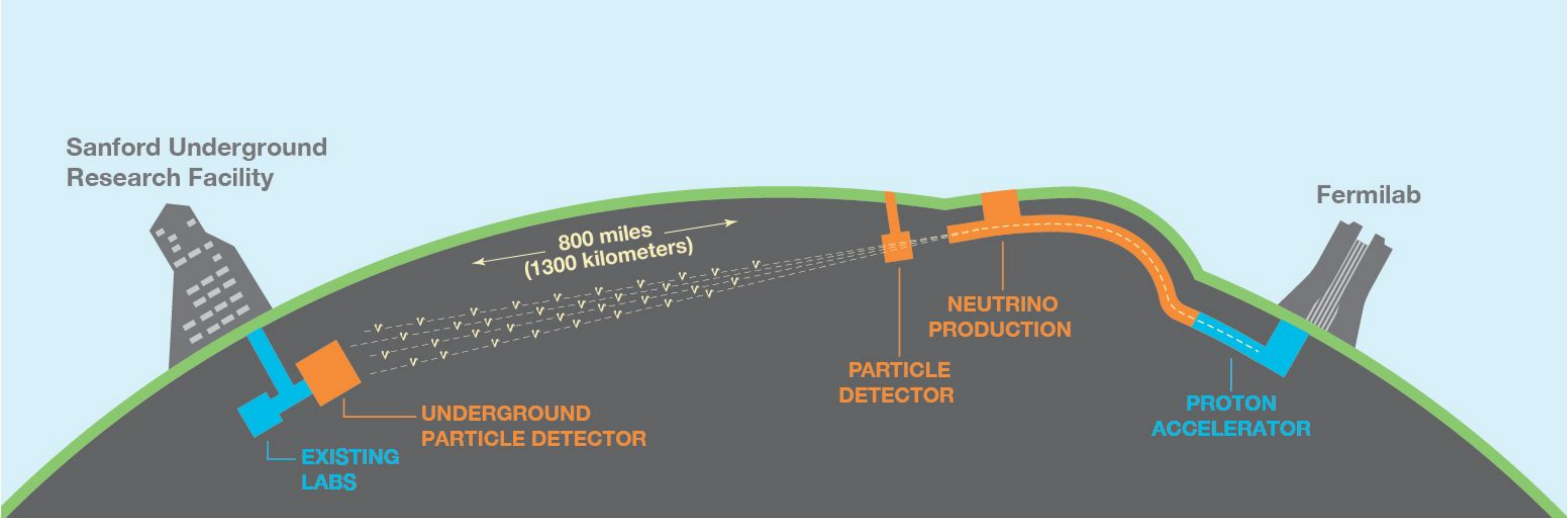
The DUNE near detector facility will be great for...

- Precision measurements of neutrino-nucleus cross sections
- Searches for boosted dark matter
- Searches for sterile neutrinos
- Searches for neutrino tridents
- Searches for millicharged particles
- etc.

But it's day job is being a long-baseline near detector



- Wide-band neutrino beam from LBNF
- Near detector facility at Fermilab with baseline ~ 574m
- Far detector facility at SURF with baseline ~ 1300km

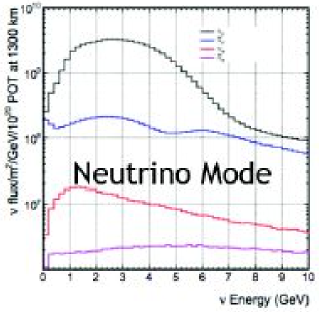
ND design timeline

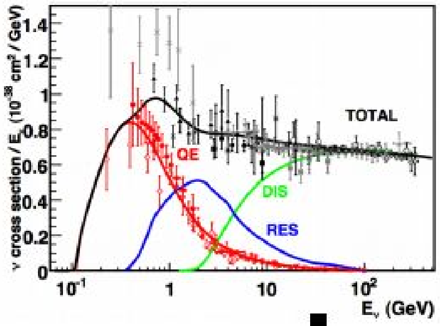
- LBNE era: Reference ND conceptual design (fine-grained tracker)
- 2016-2017: Near Detector Task Force to study FGT, LAr near detector, high-pressure gas TPC
- 2017-2018: Near Detector Concept study
- August 2018: concept study recommendations accepted
- 2018-present: Near Detector Design Group
- Spring 2019: Conceptual design report
- 2020: Technical design report

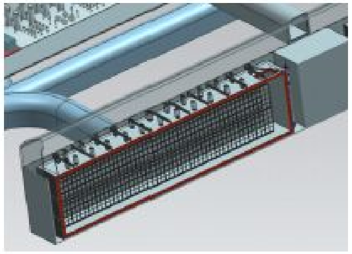
In this talk

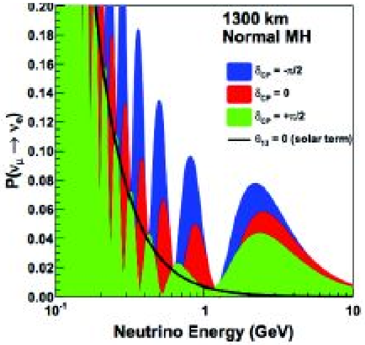
- What does the long-baseline near detector have to do?
- How are we going to do it?

DUNE LBL analysis









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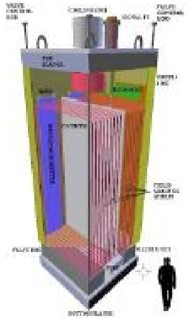
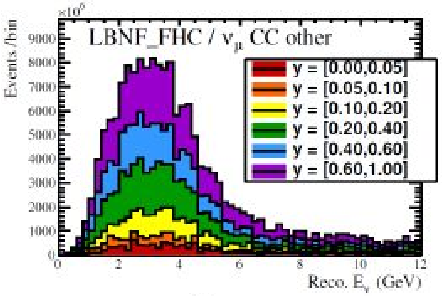
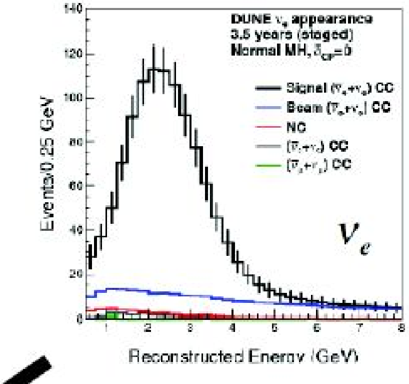
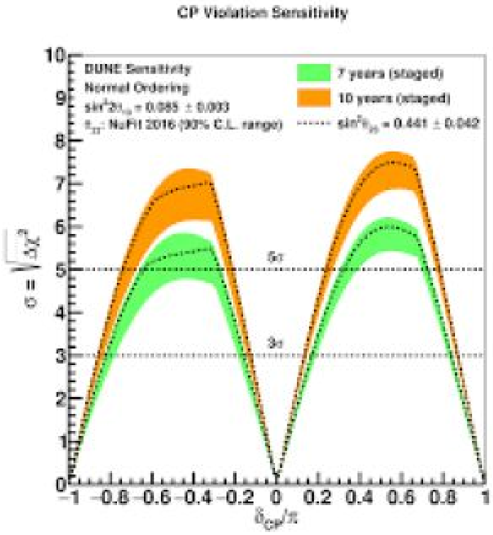
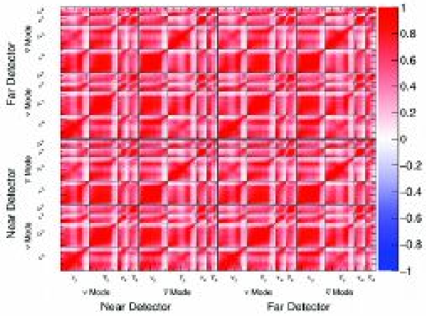




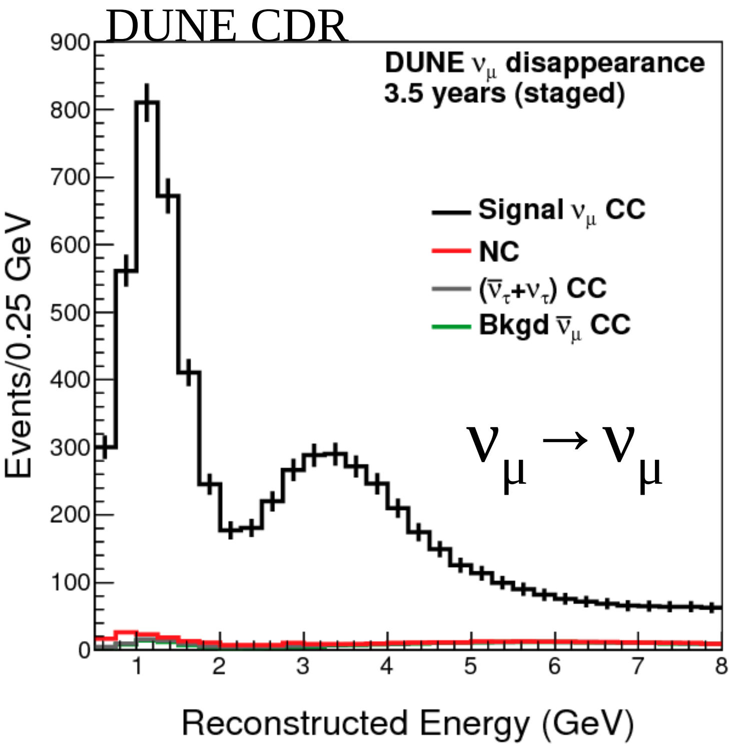


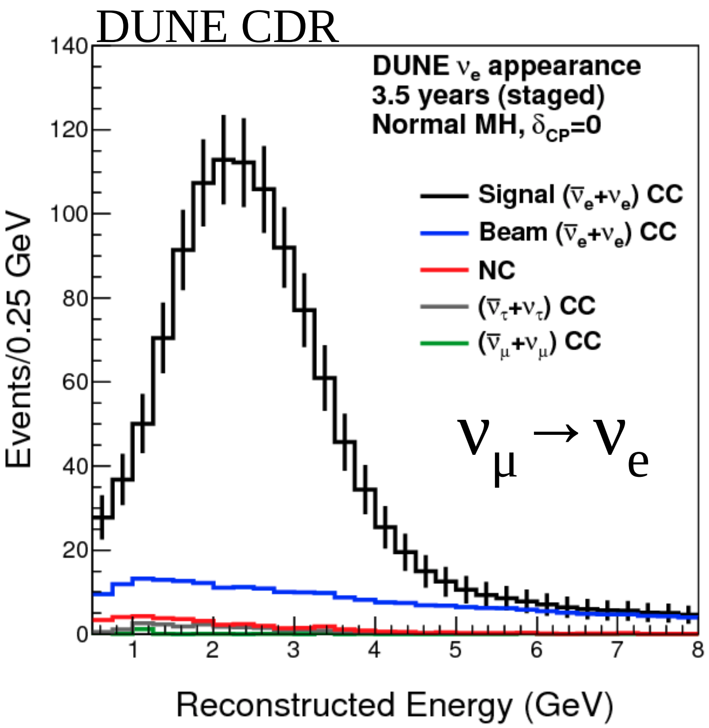


$$\boxed{\sqrt{\Delta\chi^2}}$$



Far detector neutrino spectra





- Wideband neutrino beam peaked at oscillation maximum ~ 2.5 GeV, 2nd maximum at ~0.8 GeV
- Expect O(1000) far detector ν_e → ~3% statistical uncertainty on overall ν_e appearance rate

Observed rate depends on many (uncertain) things...

$$N(E_{reco}) = \Phi(E_{true}) \times \sigma(E_{true}) \times \epsilon(E_{true}) \times \mathbf{D}(E_{true} \rightarrow E_{reco})$$

Observed far detector spectra depend on:

Neutrino flux prediction

Neutrino-Argon interaction cross sections

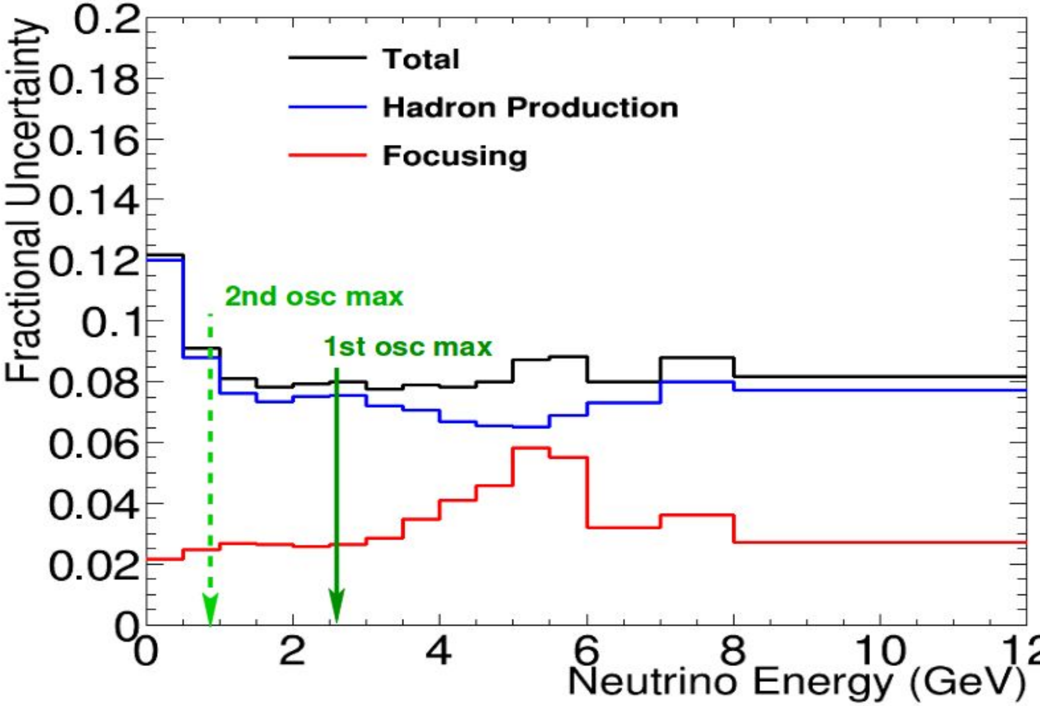
Detector acceptance

True → Reconstructed energy smearing

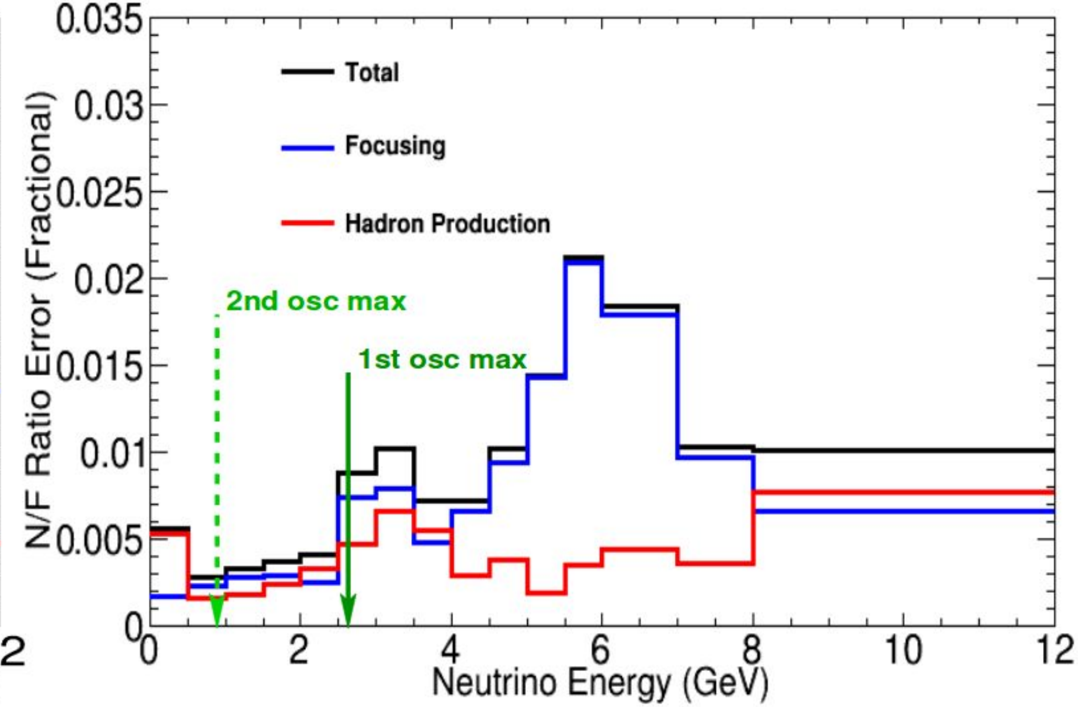
“Out-of-the-box” predictions have 10s% uncertainty → Need highly capable ND to constrain to ~3%

DUNE flux uncertainties

ND flux uncertainty

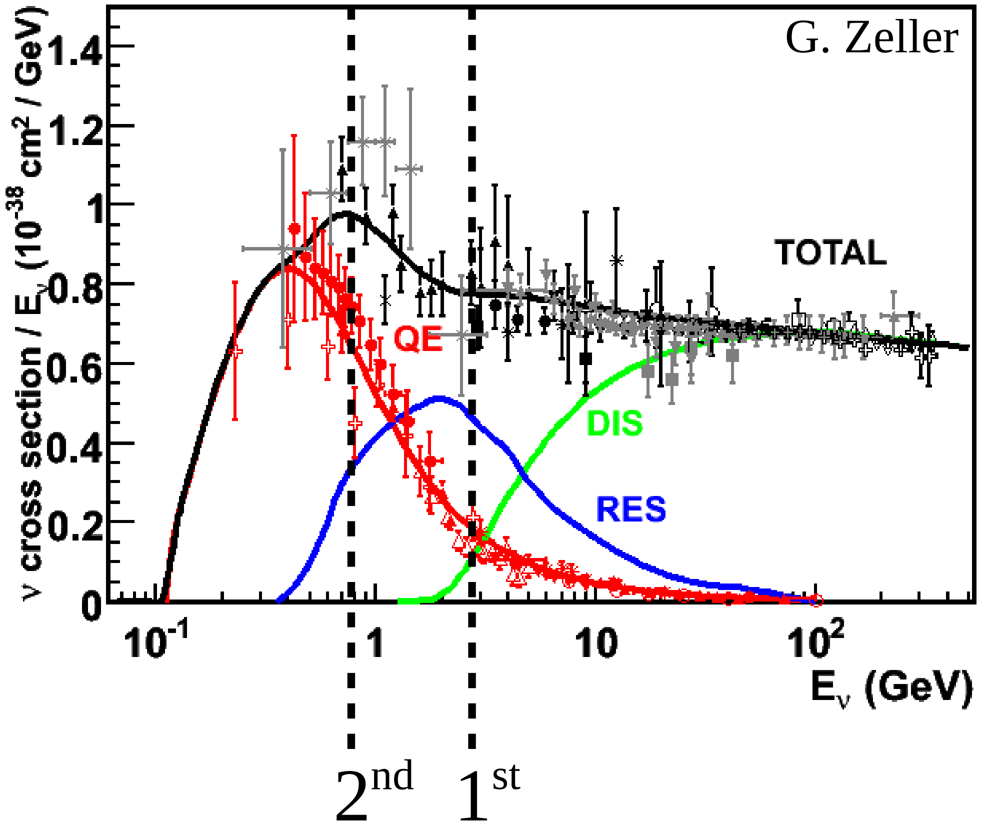


ND/FD flux uncertainty



- Based on current hadron production data, and simulation of focusing system
- ~8% uncertainty on overall flux, and ~0.5% uncertainty on flux differences at ND and FD
- There is room for improvement, i.e. DUNE spectrometer, EMPHATIC

Cross sections:
2.5 GeV is a challenging energy



DUNE oscillation peaks where 0π, 1π, DIS reactions are all relevant!

- Due to oscillations, the fluxes are different at ND and FD
- Sensitive to different mix of neutrino cross sections
- Different reactions give different relationship between E_ν and detector observable, $E_\nu \to E_{rec}$

Flux, cross section, detector smearing are all coupled

$$\frac{N^{far}_{\nu_e}(E_{reco}) = \int \boxed{\Phi_{\nu_e}(E_\nu, L)} \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \mathbf{D}^{far}_{\nu_e}(E_\nu \rightarrow E_{reco})dE_\nu}{N^{near}_{\nu_\mu}(E_{reco}) = \int \boxed{\Phi_{\nu_\mu}(E_\nu, 0)} \times \sigma_{\nu_\mu}(E_\nu) \times \epsilon^{near}(E_\nu) \times \mathbf{D}^{near}_{\nu_\mu}(E_\nu \rightarrow E_{reco})dE_\nu}$$

ND and FD flux differences mainly due to oscillations
→ couples to cross sections, energy reconstruction

Flux, cross section, detector smearing are all coupled

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Cross sections at different energy, and (for disappearance measurement) different lepton mass

Flux, cross section, detector smearing are all coupled

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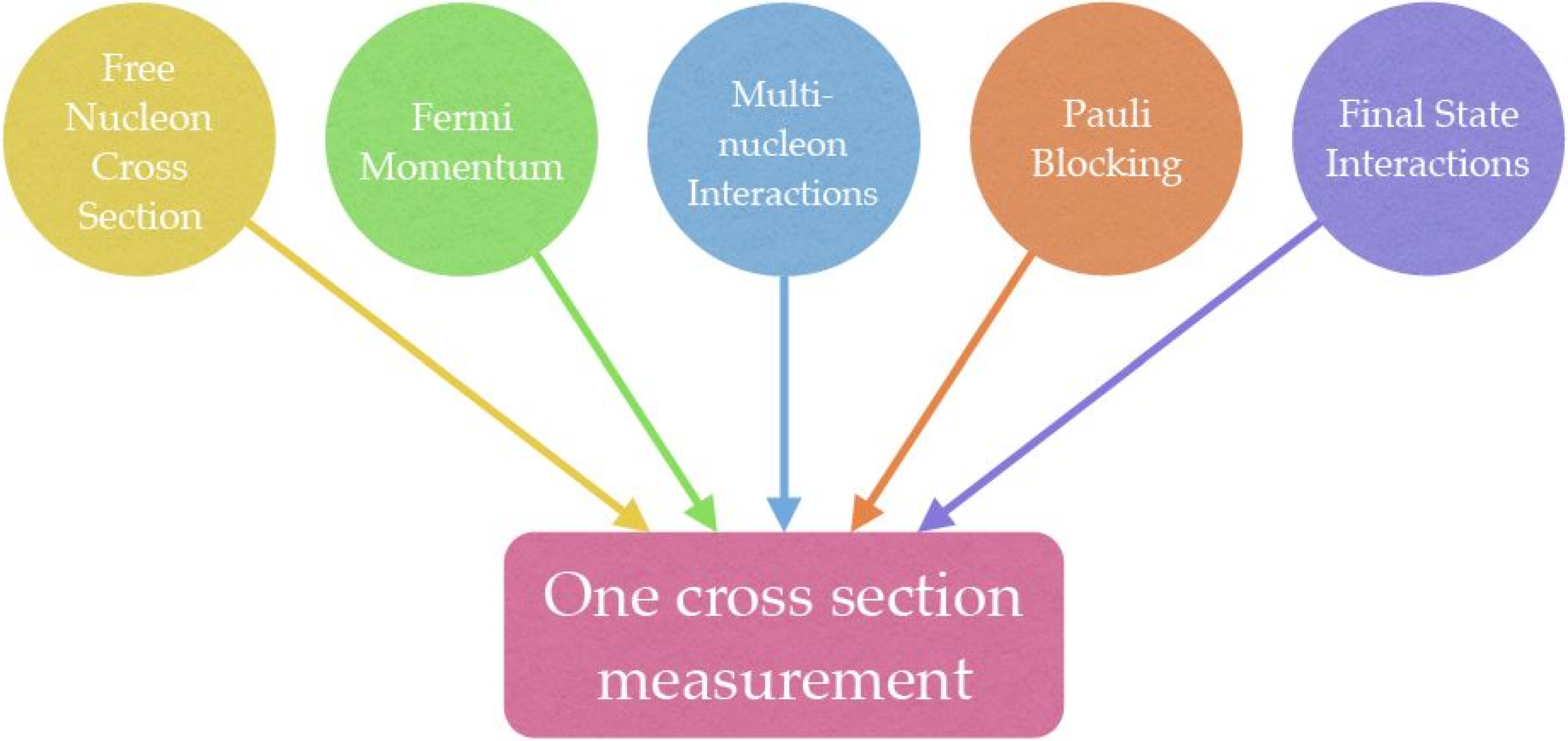
ND and FD flux differences mainly due to oscillations
→ couples to cross sections, energy reconstruction

Cross sections at different energy, and (for disappearance measurement) different lepton mass

Energy reconstruction is highly sensitive to final-state composition, and depends critically on cross sections

Neutrino-argon interactions are sensitive to a lot of physics...



Free Nucleon Cross Section

Fermi Momentum

Multi-nucleon Interactions

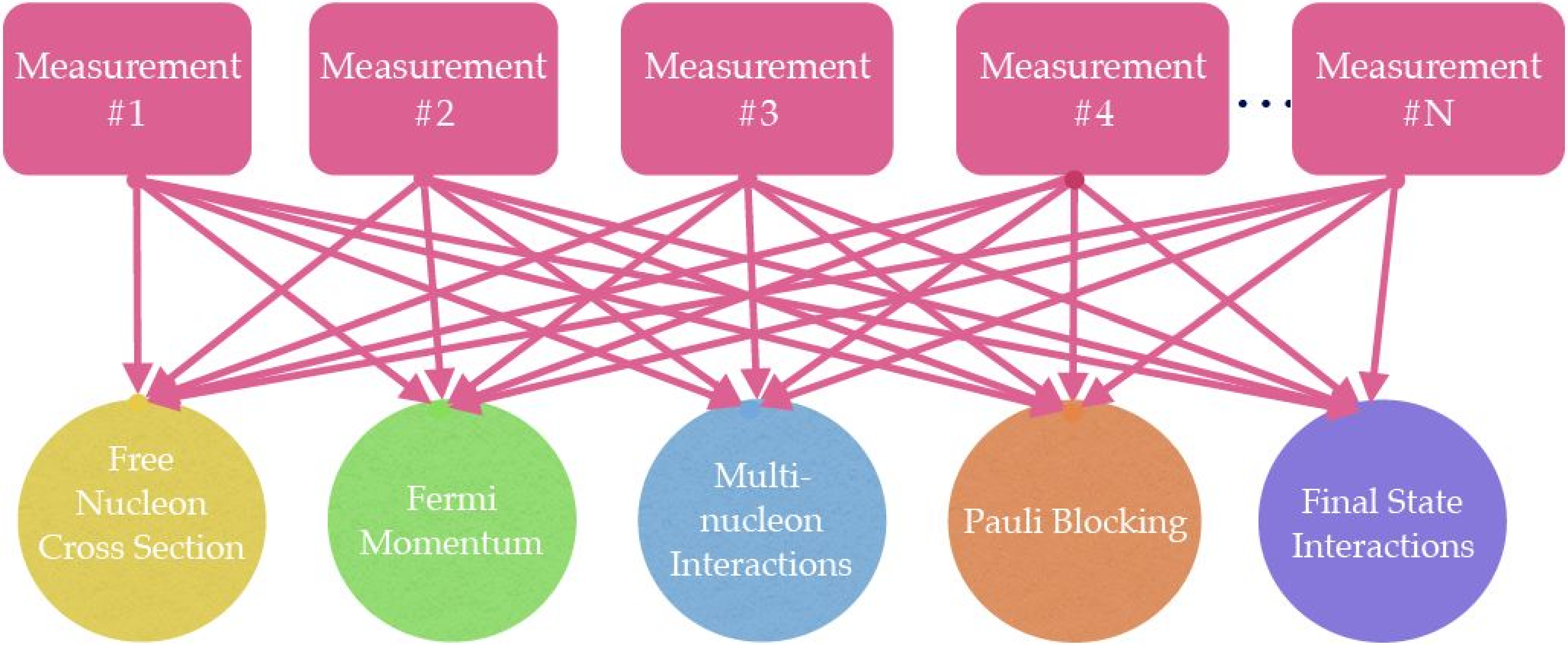
Pauli Blocking

Final State Interactions

One cross section measurement

graphic by L. Fields

We need near detector capable of making a lot of measurements

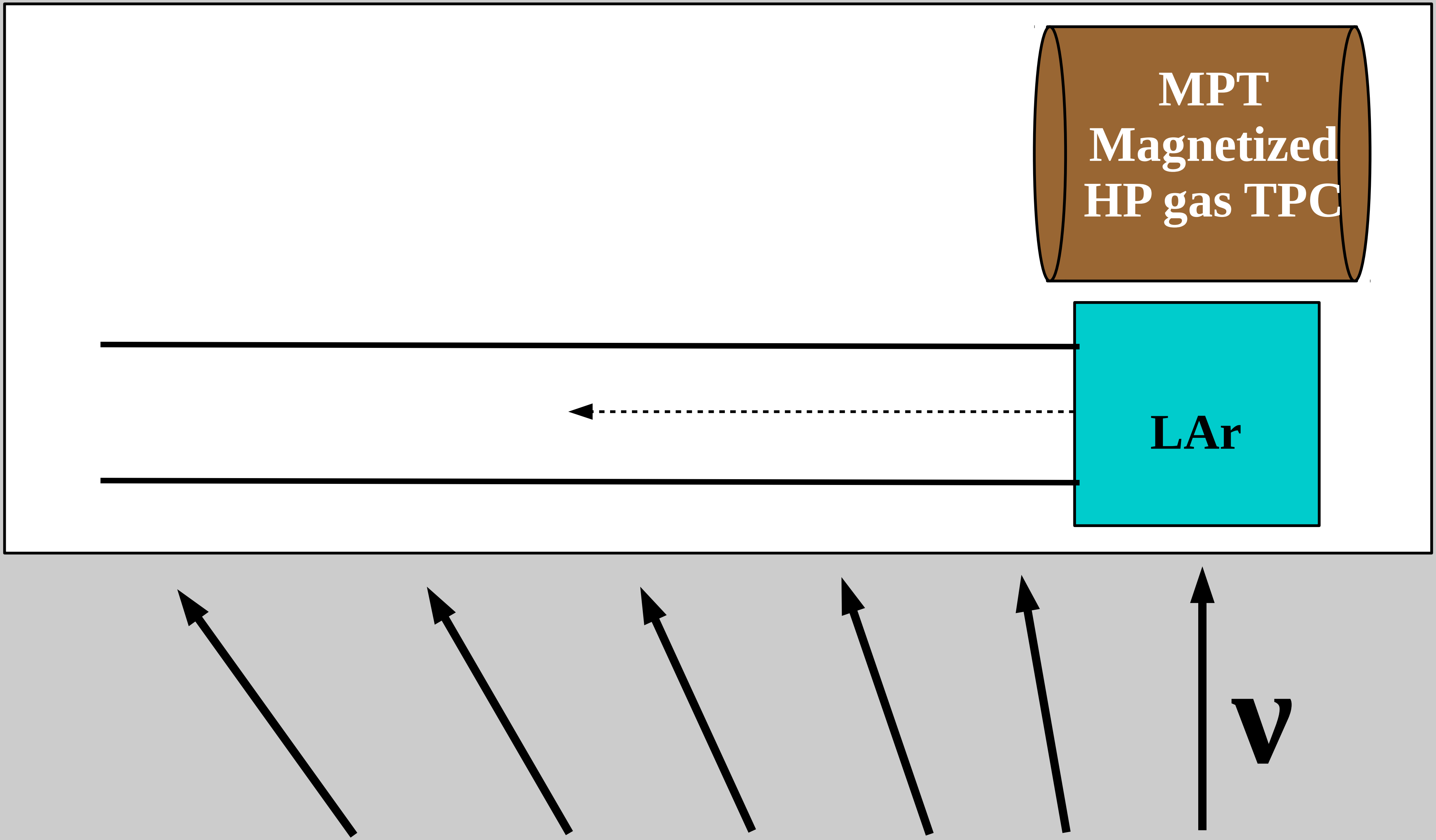


graphic by L. Fields

ND needs for LBL physics

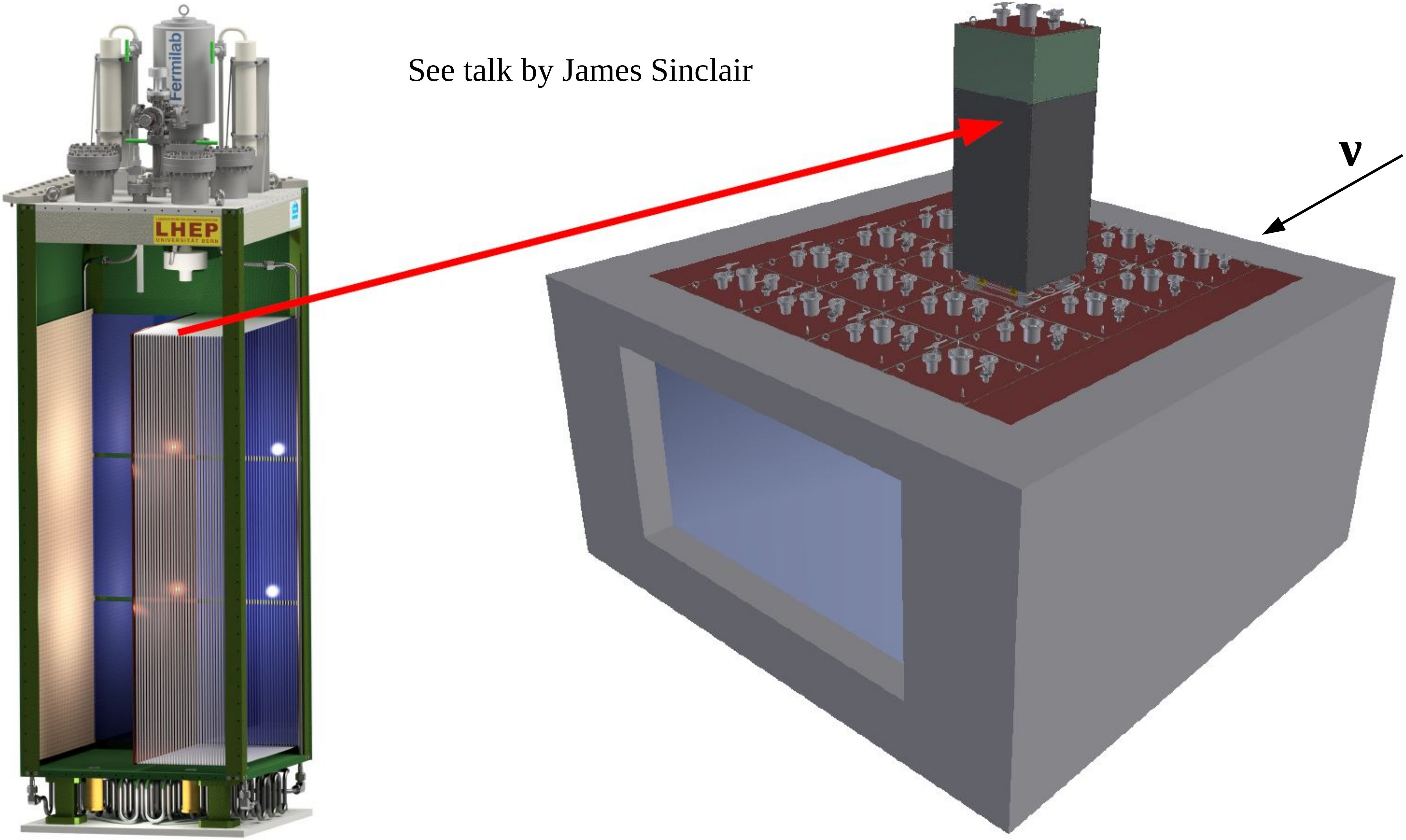
- High-statistics measurements of ν-Ar interactions
- Measurements of ν-Ar exclusive final states
- Direct measurement of neutrino flux
- Ability to measure $E_\nu \rightarrow E_{rec}$ in liquid Argon
- Ability to monitor neutrino beam and detect changes in flux on relatively short timescale

Near detector complex



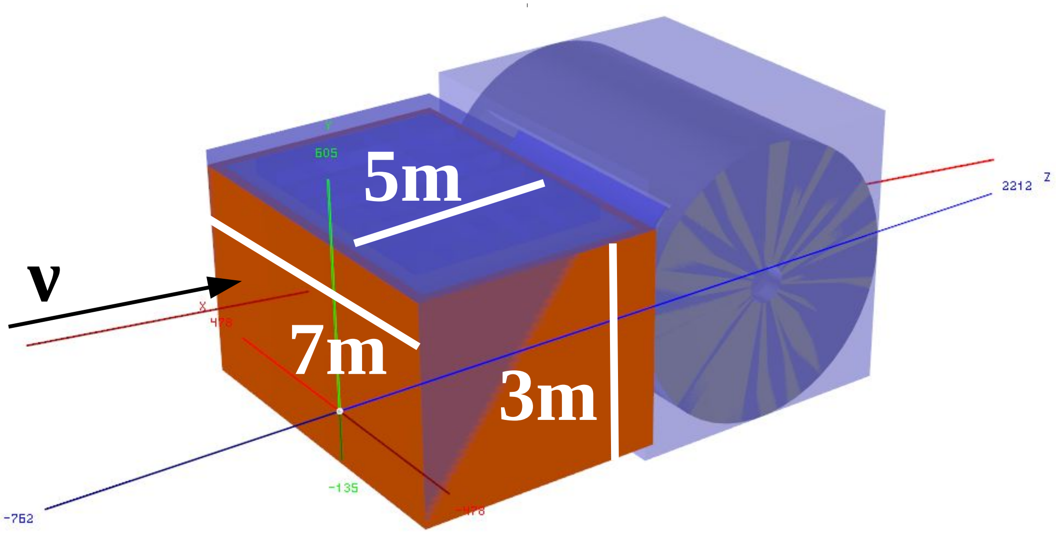
LAr TPC for ND: ArgonCube

See talk by James Sinclair



LAr size driven by containment, not rate

- Goal: Containment in LAr of hadronic showers in neutrino interactions up to ~8 GeV
    - Need ~5m in beam direction, ~4m in transverse direction
- Goal: Containment of high-angle muons in LAr
    - Can be achieved by widening detector to ~7m
- Per year at 1M, fiducial CC ν_μ rates for 7x3x5m LAr with good containment, muon acceptance
    - 0π: 12.8M
    - $1\pi^+$: 6.0M
    - $1\pi^0$: 2.4M
    - 2 pions: 2.2M
    - 3 pions: 0.6M

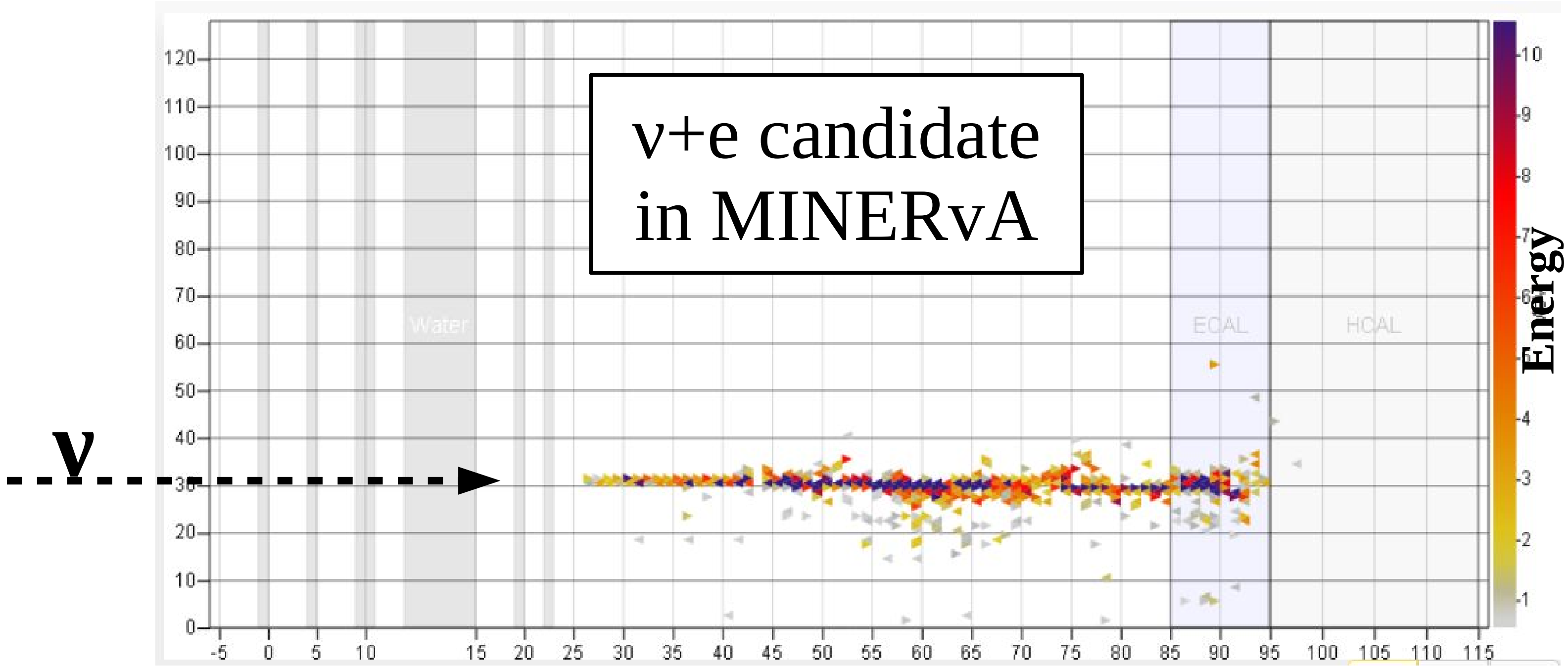


Direct flux measurement: ν+e elastic scattering

- Pure EW process with known* cross section:

$$\frac{d\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{dy} = \frac{G_F{}^2 m_e E_\nu}{2\pi}\left[\left(\frac{1}{2} - \sin^2\theta_W\right)^2 + \sin^4\theta_W (1-y)^2\right]$$

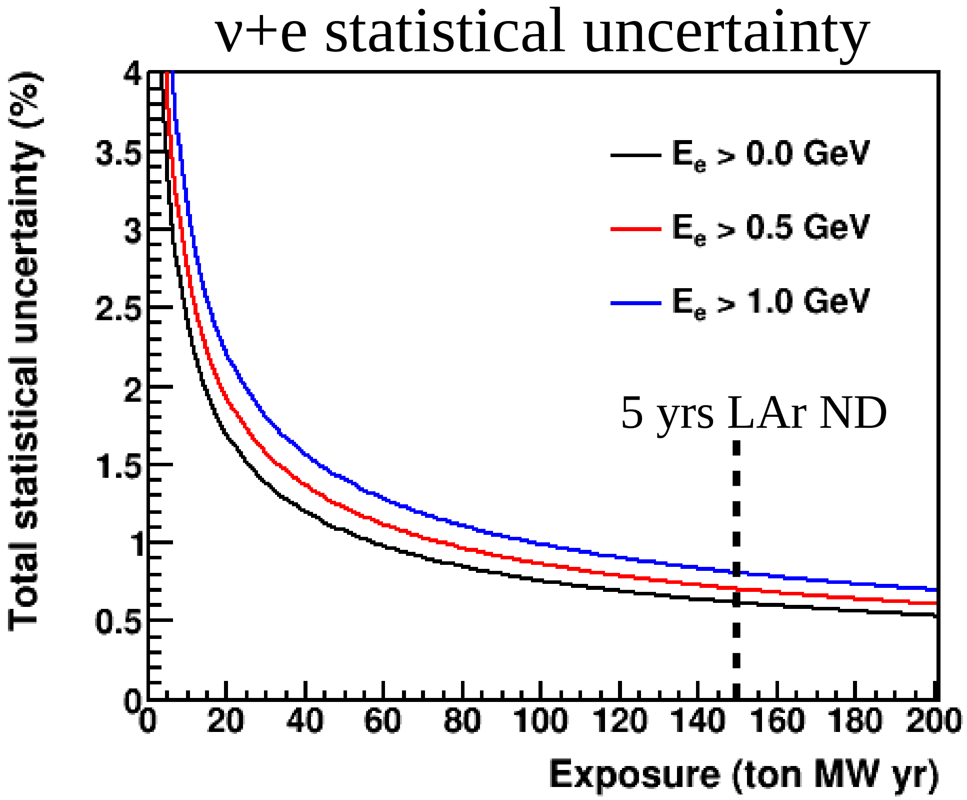
- Signal is single electron, with kinematic constraint $E_e\theta^2 < 2m_e$ – very forward electron



ν+e candidate in MINERνA

*at tree level

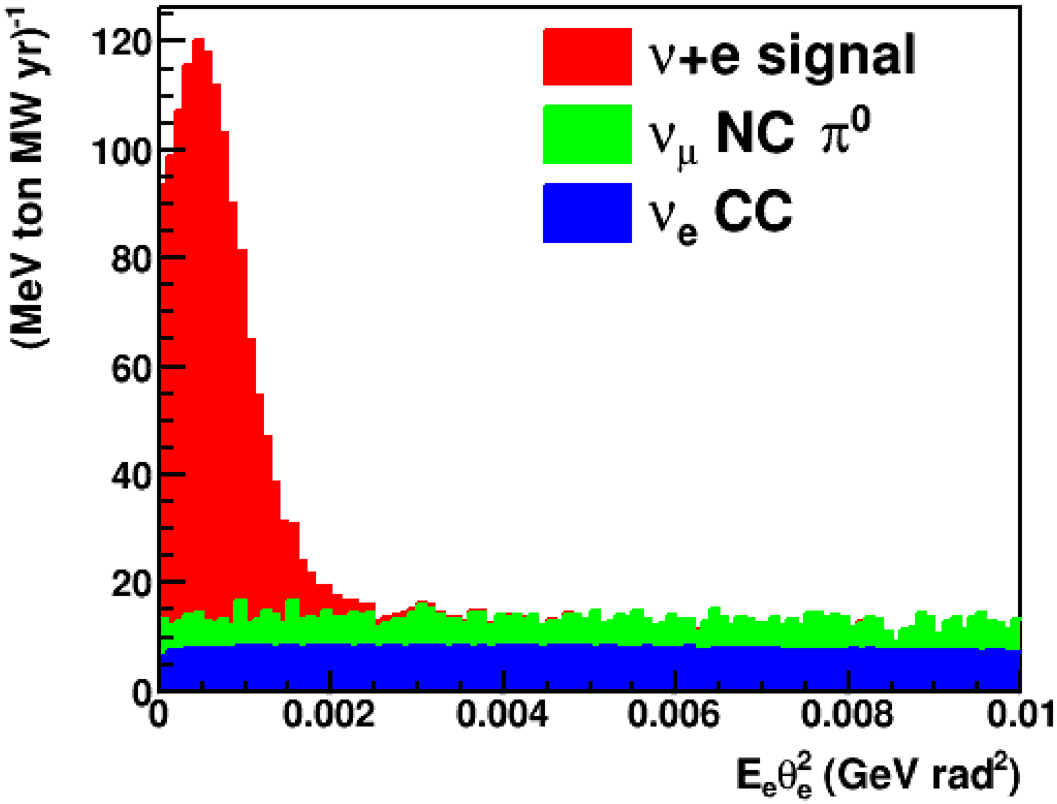
ν+e potential in DUNE: huge stats



- Even with conservative reconstruction assumptions, DUNE LAr ND can select over 3,000 ν+e events per year at initial intensity
- <1% statistical uncertainty
- Very powerful *in situ* constraint on absolute flux normalization

Expected ν+e purity in LAr is ~85%

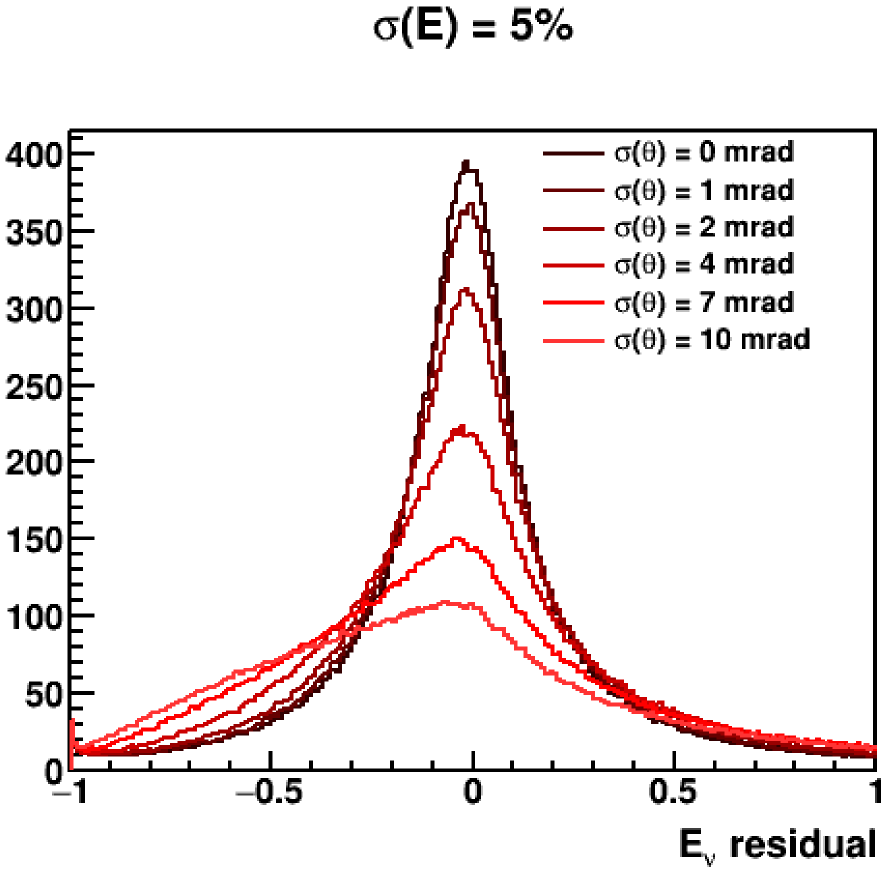
Preliminary LAr simulation:
- 1 electromagnetic shower
- No charged hadrons >1 pad size
- No other particles
- electron-like shower dE/dx



- Backgrounds due to:
  - ν_e CC at very low Q^2
  - NC π^0 with only 1 detected γ
- Sideband at moderate $E\theta^2$ will give excellent background normalization constraint
- But shape at very low Q^2 is uncertain, and will give at least ~1% overall systematic
- Challenge: constrain reconstruction systematics to 1% level
- Larger LAr TPC not beneficial

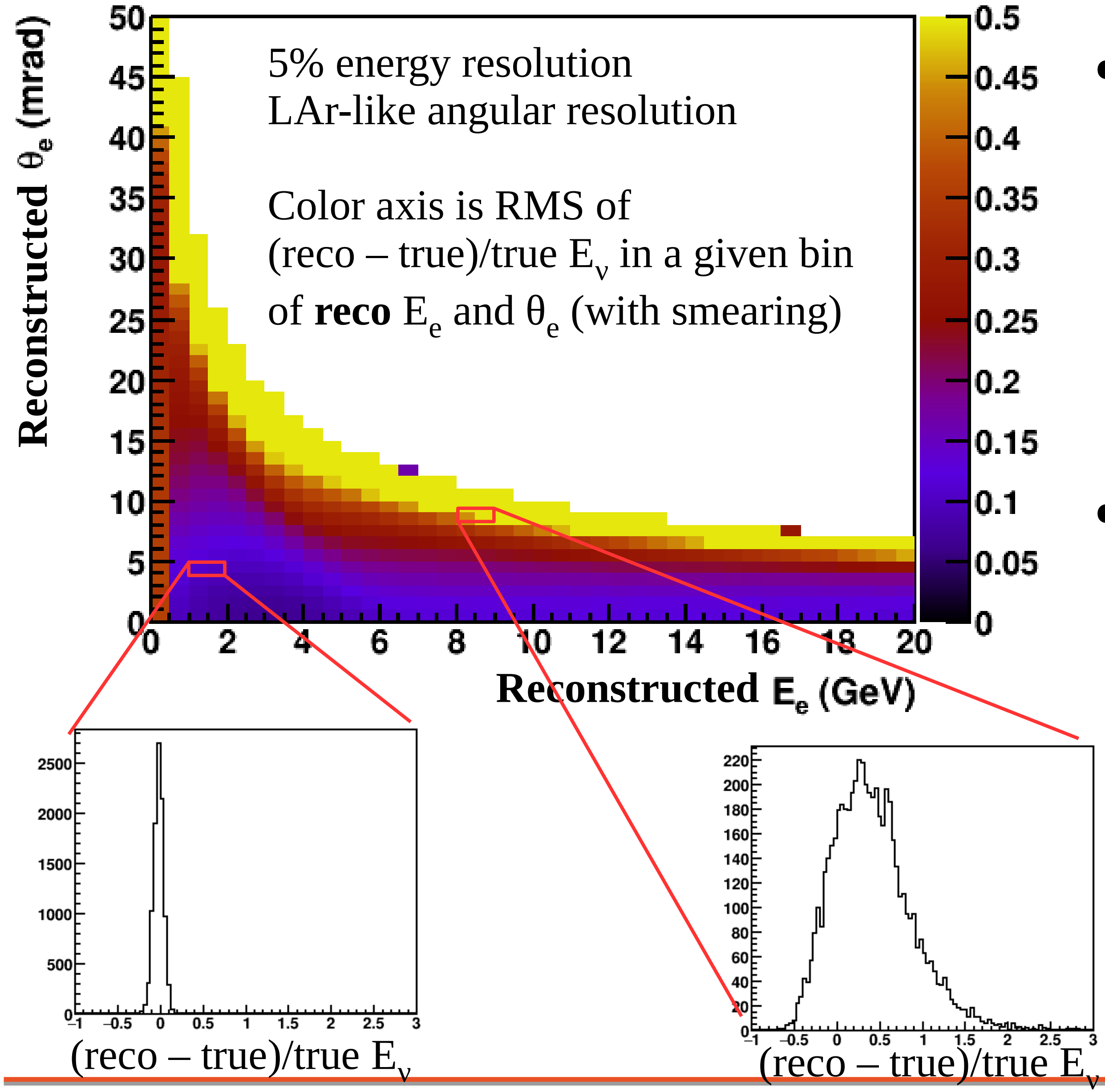
Direct neutrino energy measurement

$$E_\nu = \frac{E_e}{1 - \frac{E_e(1-\cos\theta)}{m}} \approx \frac{E_e}{1 - \frac{E_e\theta^2}{2m}}$$



- In principle, one can measure neutrino energy event by event
- Extremely sensitive to electron kinematics, especially angle
- Beam divergence alone gives ~20% resolution

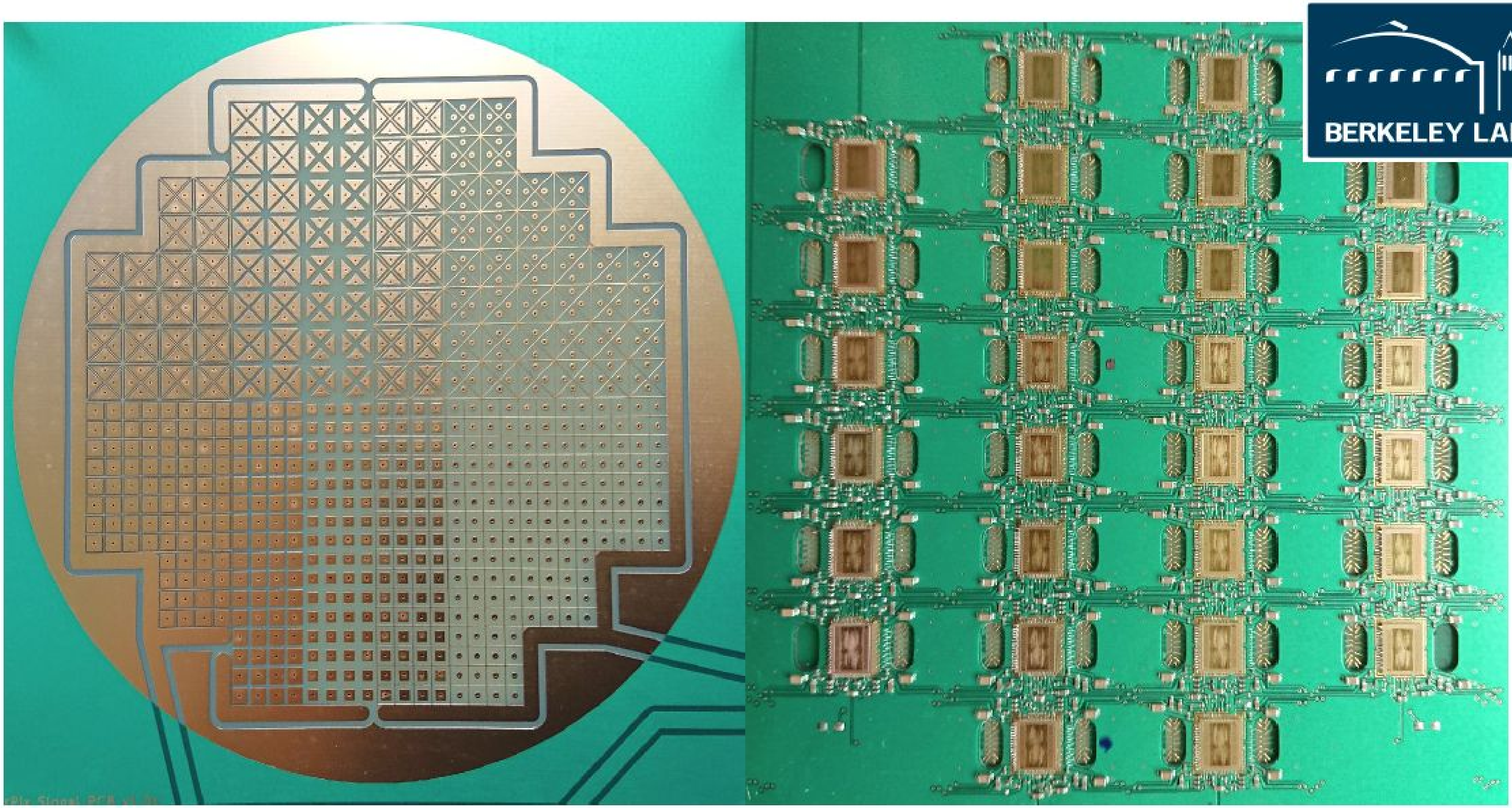
E_ν resolution vs. (E_e, θ_e)


5% energy resolution
LAr-like angular resolution

Color axis is RMS of
(reco – true)/true E_ν in a given bin
of **reco** E_e and θ_e (with smearing)

- Energy resolution is quite good in a region of (E,θ), basically where Eθ² is very small
- Effectively, select a subsample of good, and unbiased energy resolution and measure shape from it
- Requires very high statistics

Triangular pad readout?



- 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

LAr strengths & limitations

Strengths

- High statistics ν-Ar, with sufficient resolution for many exclusive channels
- Ability to measure flux via ν+e elastic scattering
- An excellent calorimeter, with good π^0 reconstruction ability
- Similar to far detector

Limitations

- No **B** field → no e^+/e^-, π^+/π^-, low-energy $\mu^+/\ \mu^-$
- Relatively high thresholds for charged hadrons
- Hadrons will shower → PID challenging
- Does not range out muons above ~1 GeV

GAr strengths & limitations

Limitations

- Moderate statistics ν-Ar interactions
- Insufficient rate to measure ν+e scattering

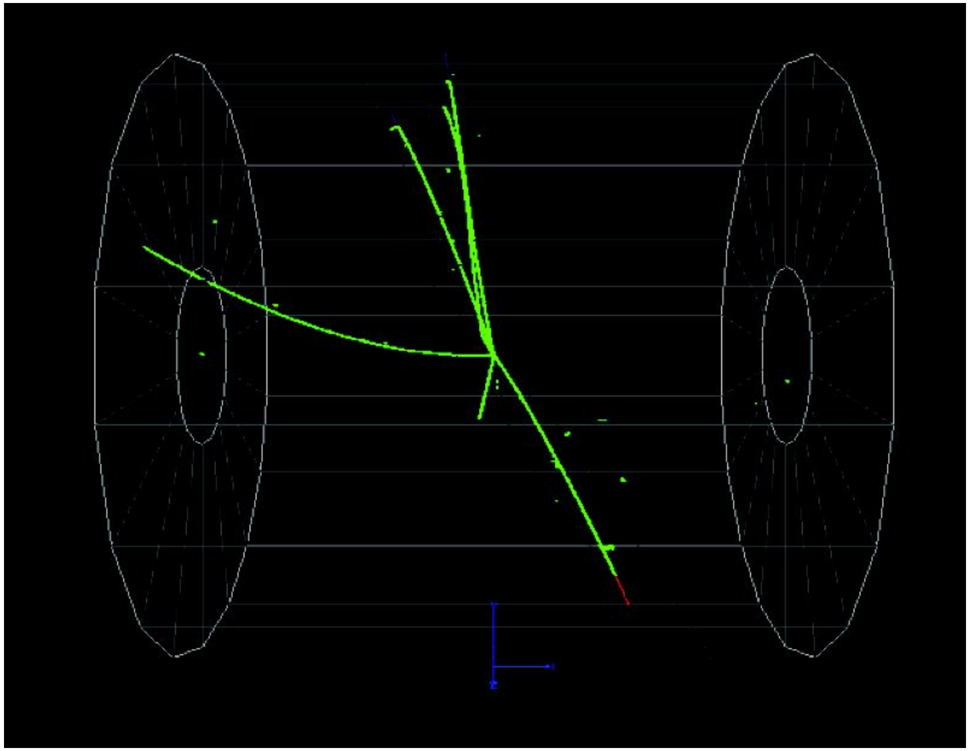
Strengths

- **B** field → excellent e^+/e^-, π^+/π^-, low-energy $\mu^+/\ \mu^-$ over 4π phase space
- Very low thresholds for charged hadrons
- Clean hadron tracks → excellent PID
- Catches high-energy muons from LAr interactions

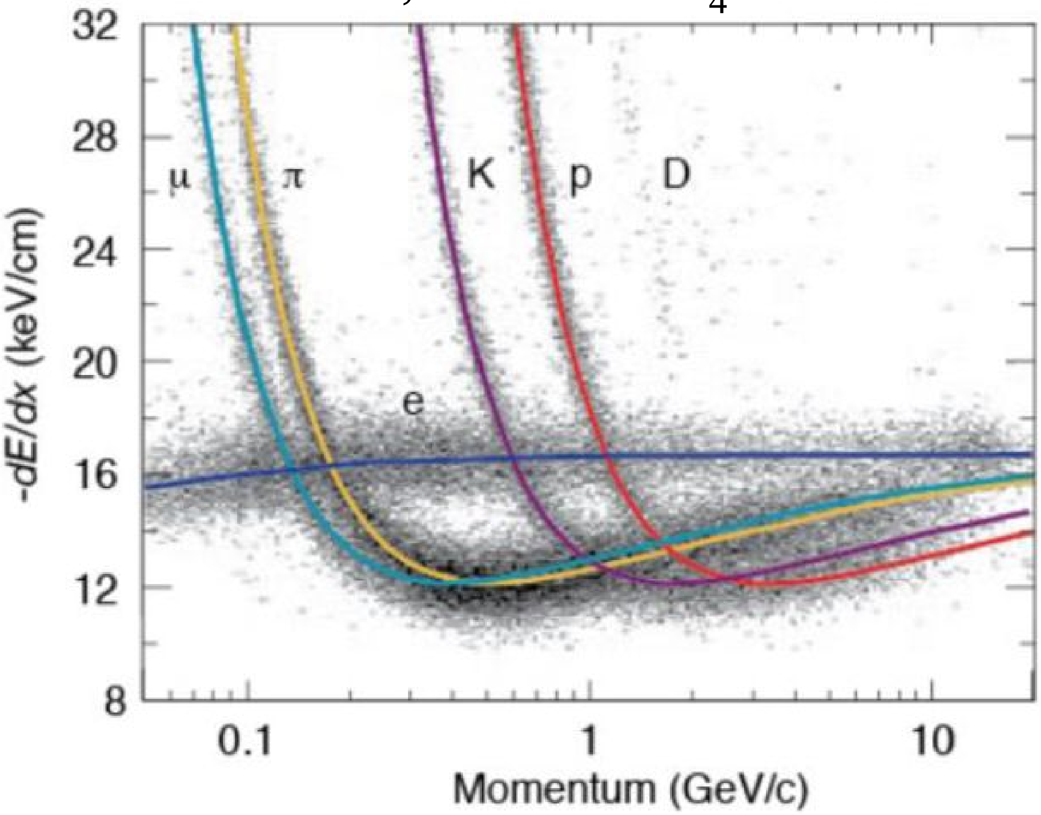
High-pressure gas TPC: more than a muon spectrometer

- Same ν-Ar interactions with very different measurement technique, very different systematic uncertainties

See talk by Tanaz Mohayai



PEP-4, 80/20 Ar-CH_4 at 8.5 atm



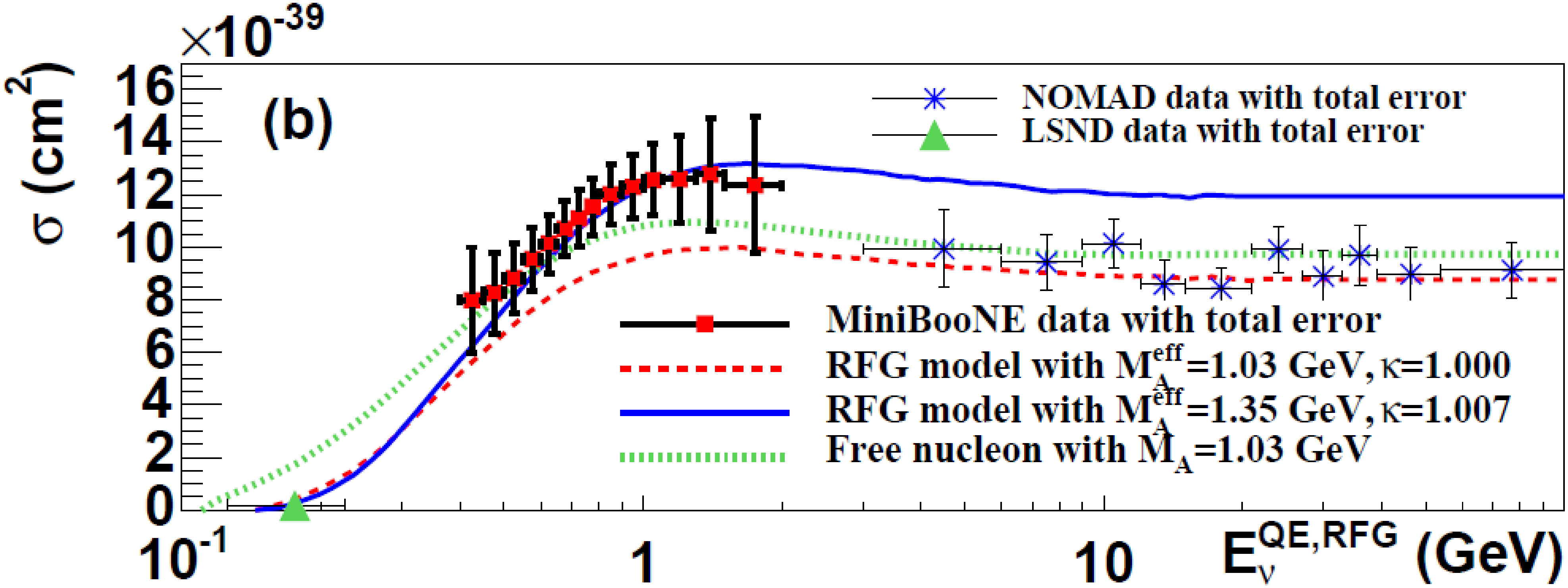
Cross section modeling is complicated: possible degeneracies

MaCCQE
VecFFCCQEshape
MaNCEL
EtaNCEL
MaCCRES
MvCCRES
MaNCRES
MvNCRES
RDecBR1gamma
RDecBR1eta
Theta_Delta2Npi
AhtBY
BhtBY
CV1uBY
CV2uBY
FormZone
MFP_pi
FrCEx_pi
FrElas_pi
FrInel_pi
FrAbs_pi
FrPiProd_pi
MFP_N
FrCEx_N
FrElas_N
FrInel_N
FrAbs_N
FrPiProd_N
CCQEPauliSupViaKF
Mnv2p2hGaussEnhancement
MKSPP_ReWeight
E2p2h_A_nu
E2p2h_B_nu
E2p2h_A_nubar
E2p2h_B_nubar

NR_nu_n_CC_2Pi
NR_nu_n_CC_3Pi
NR_nu_p_CC_2Pi
NR_nu_p_CC_3Pi
NR_nu_np_CC_1Pi
NR_nu_n_NC_1Pi
NR_nu_n_NC_2Pi
NR_nu_n_NC_3Pi
NR_nu_p_NC_1Pi
NR_nu_p_NC_2Pi
NR_nu_p_NC_3Pi
NR_nubar_n_CC_1Pi
NR_nubar_n_CC_2Pi
NR_nubar_n_CC_3Pi
NR_nubar_p_CC_1Pi
NR_nubar_p_CC_2Pi
NR_nubar_p_CC_3Pi
NR_nubar_n_NC_1Pi
NR_nubar_n_NC_2Pi
NR_nubar_n_NC_3Pi
NR_nubar_p_NC_1Pi
NR_nubar_p_NC_2Pi
NR_nubar_p_NC_3Pi
BeRPA_A
BeRPA_B
BeRPA_D
BeRPA_E
C12ToAr40_2p2hScaling_nu
C12ToAr40_2p2hScaling_nubar
nuenuebar_xsec_ratio
nuenumu_xsec_ratio
SPPLowQ2Suppression

- At left is an *partial* list of cross section parameters in the current DUNE oscillation analysis
- There are a lot of moving parts
- We may be able to adjust these parameters to fit our ND data, but how do we know we've made the *right* adjustment?

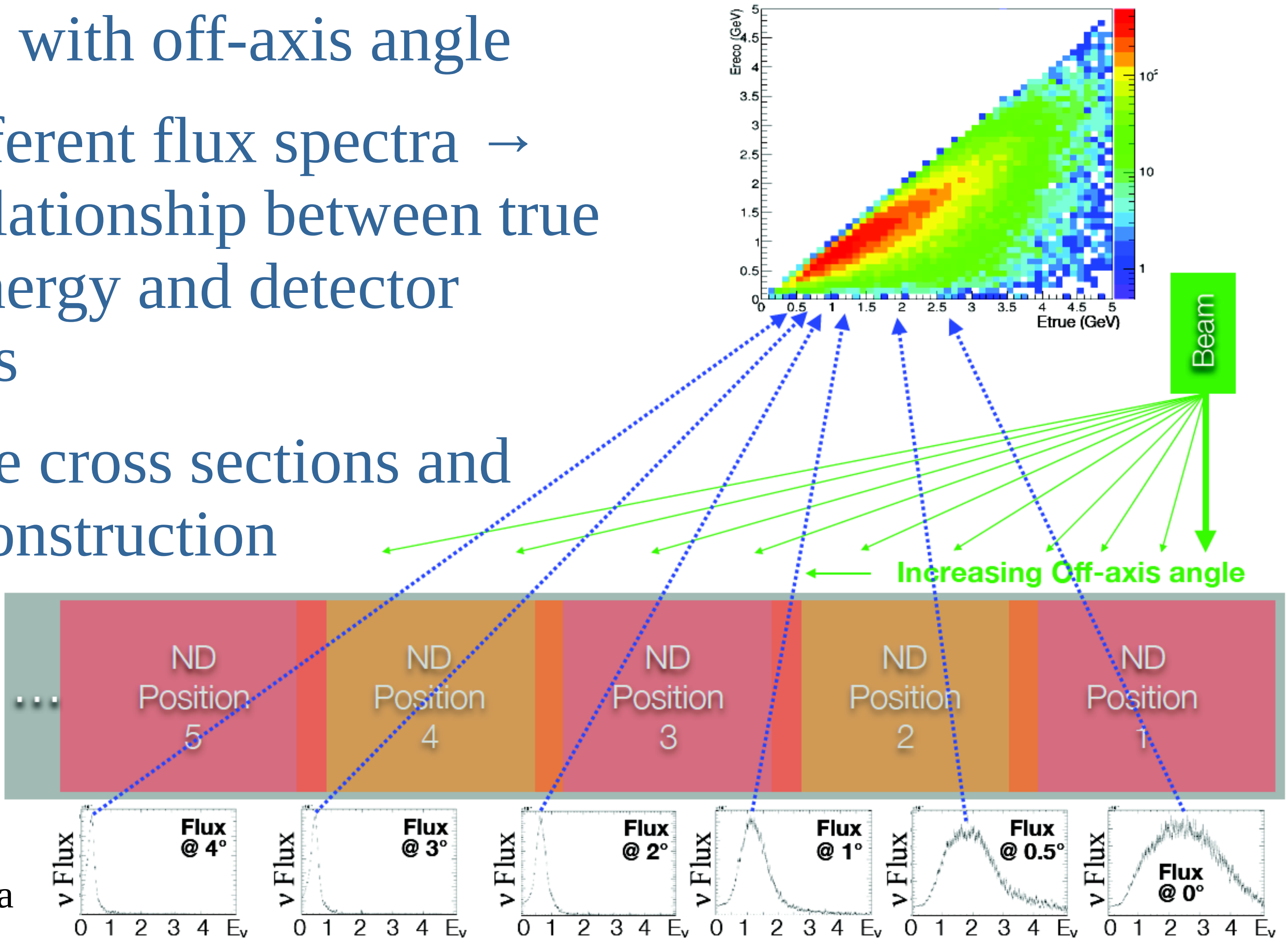
A simple example of fitting ND data with the wrong adjustment



- Setting M_A to 1.35 gives a good fit to the MiniBooNE CC0π data, but does not capture the correct physics, extrapolate well in neutrino energy, etc.

One solution: make ND measurements with many different fluxes

- Flux varies with off-axis angle
- Access different flux spectra → map out relationship between true neutrino energy and detector observables
- Disentangle cross sections and energy reconstruction



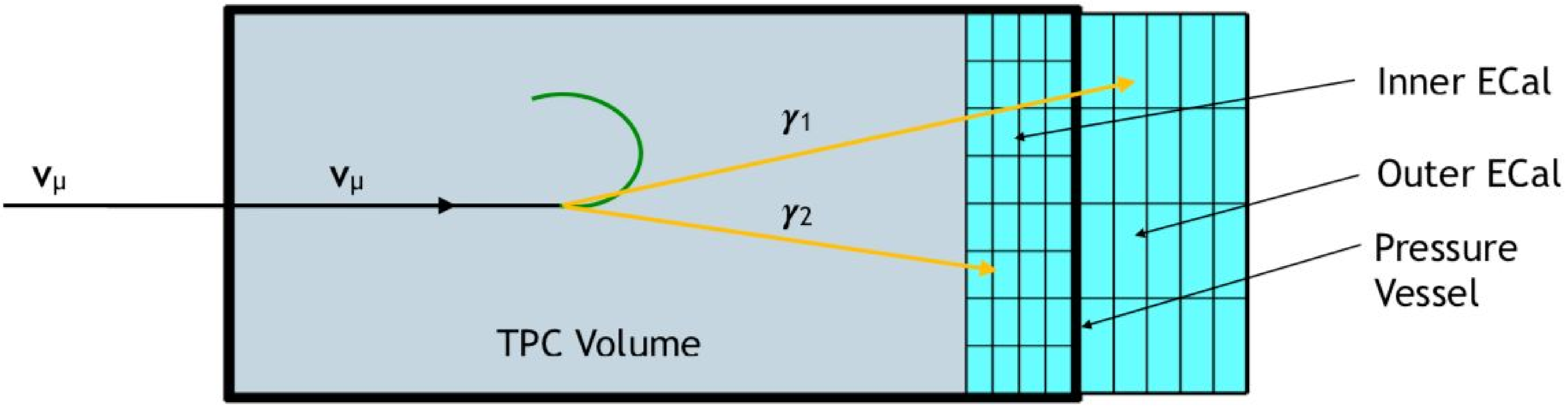
See talk by Cris Viela

Summary

- The DUNE near detector must solve a very challenging problem: simultaneously constraining flux, cross section, and energy smearing
- Our solution is to build a network of highly-capable near detectors
  - Modular, optically segmented, movable LAr TPC
  - High-pressure gas Ar TPC
  - Not mentioned: 3D scintillator tracker

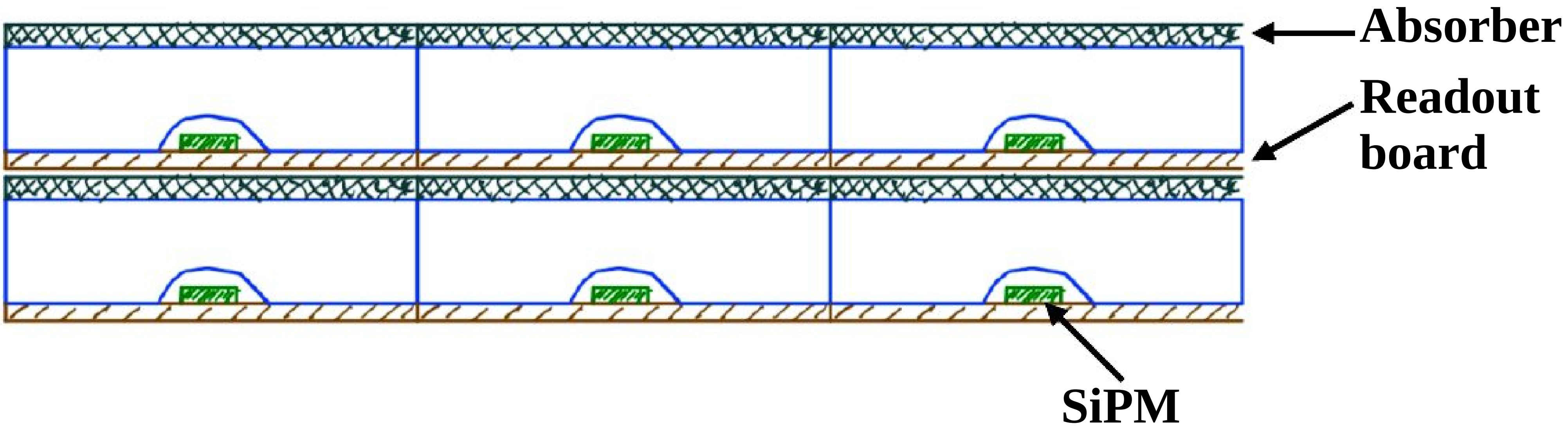
Backups

High-performance ECal



- Gas TPC provides exquisite resolution for charged tracks, including electrons
    - But photons will rarely convert in gas volume
- π^0 reconstruction requires high-performance ECal, with excellent energy and angular resolution for photon conversions

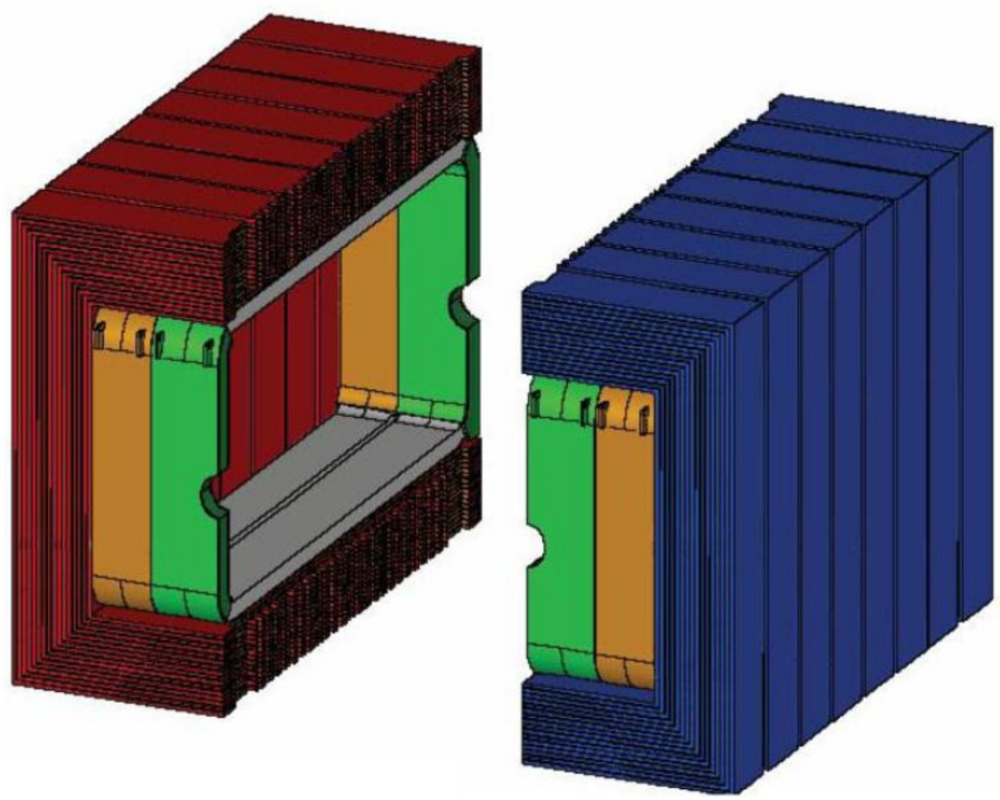
DUNE ND ECal concept

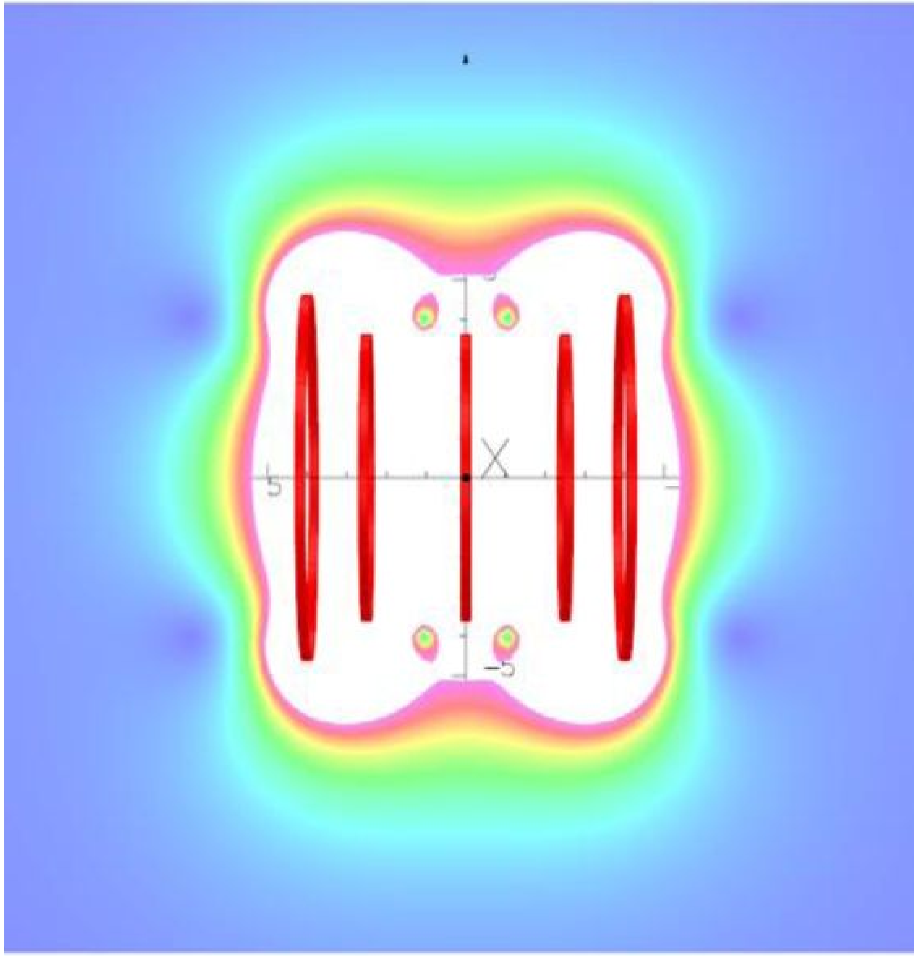


- Based on CALICE AHCAL concept
- Layers of scintillator tiles read out by SiPM
- Optimizations being performed at MPI-Munich, Mainz, DESY

Magnet

CDR reference design is UA1-like warm dipole with central field of ~0.4T, but superconducting designs are also being considered

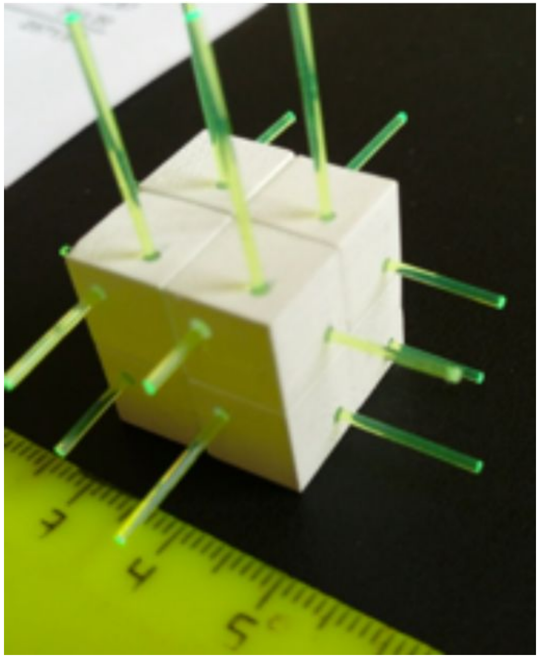




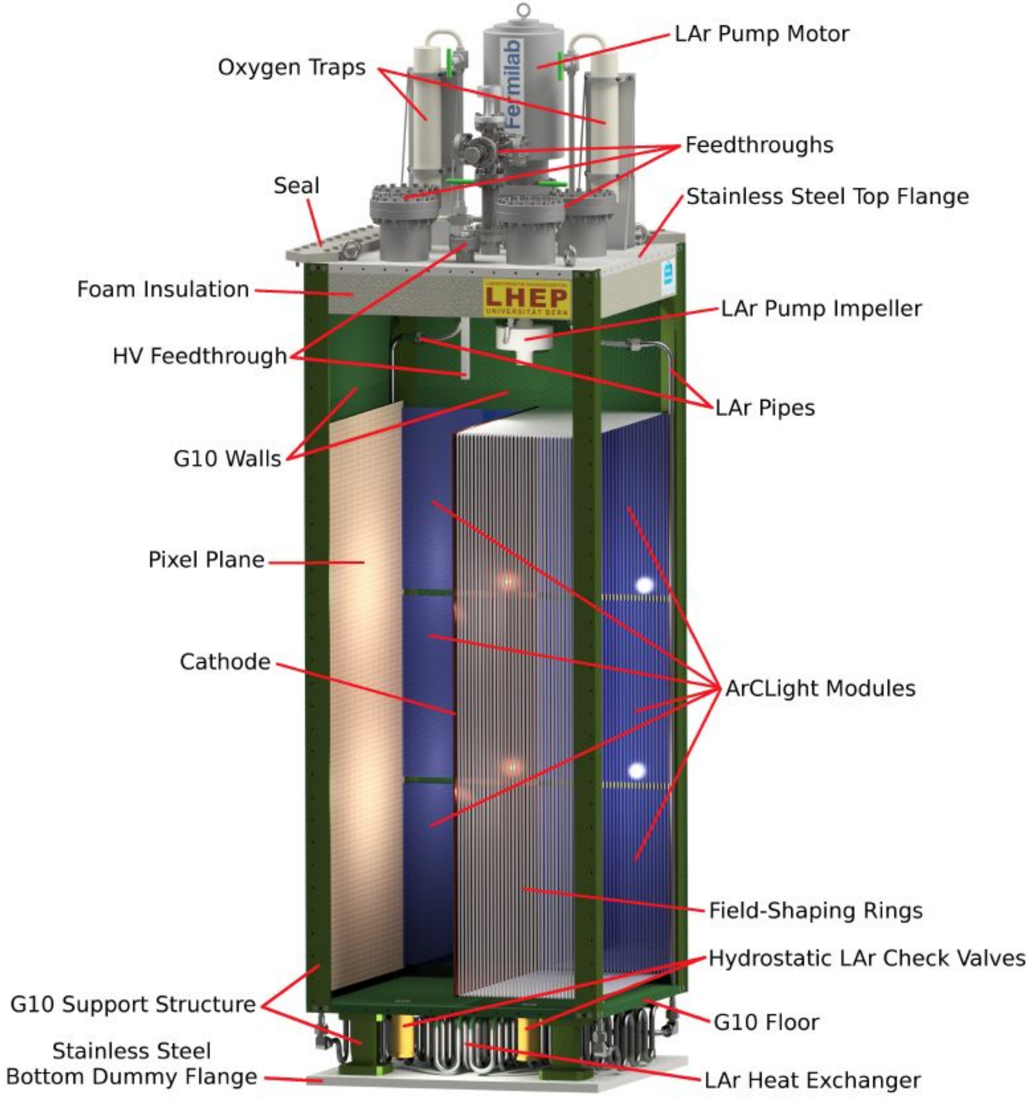
3 superconducting coils with 2 bucking coils to actively cancel stray fields to ~50 gauss

3D scintillator tracker (3DST)

- 1 cm^3 scintillator cubes in a large array, read out with orthogonal optical fibers in three dimensions
- Same concept being pursued by T2K ND280 upgrade, called "Super-FGD"
- Excellent 4π acceptance –no hole at 90°
- Very fast timing: capable of tagging neutrons from recoils, and measuring energy from time-of-flight
- Could be placed in front of (or inside?) gas TPC, or operated in its own magnet with muon spectrometer

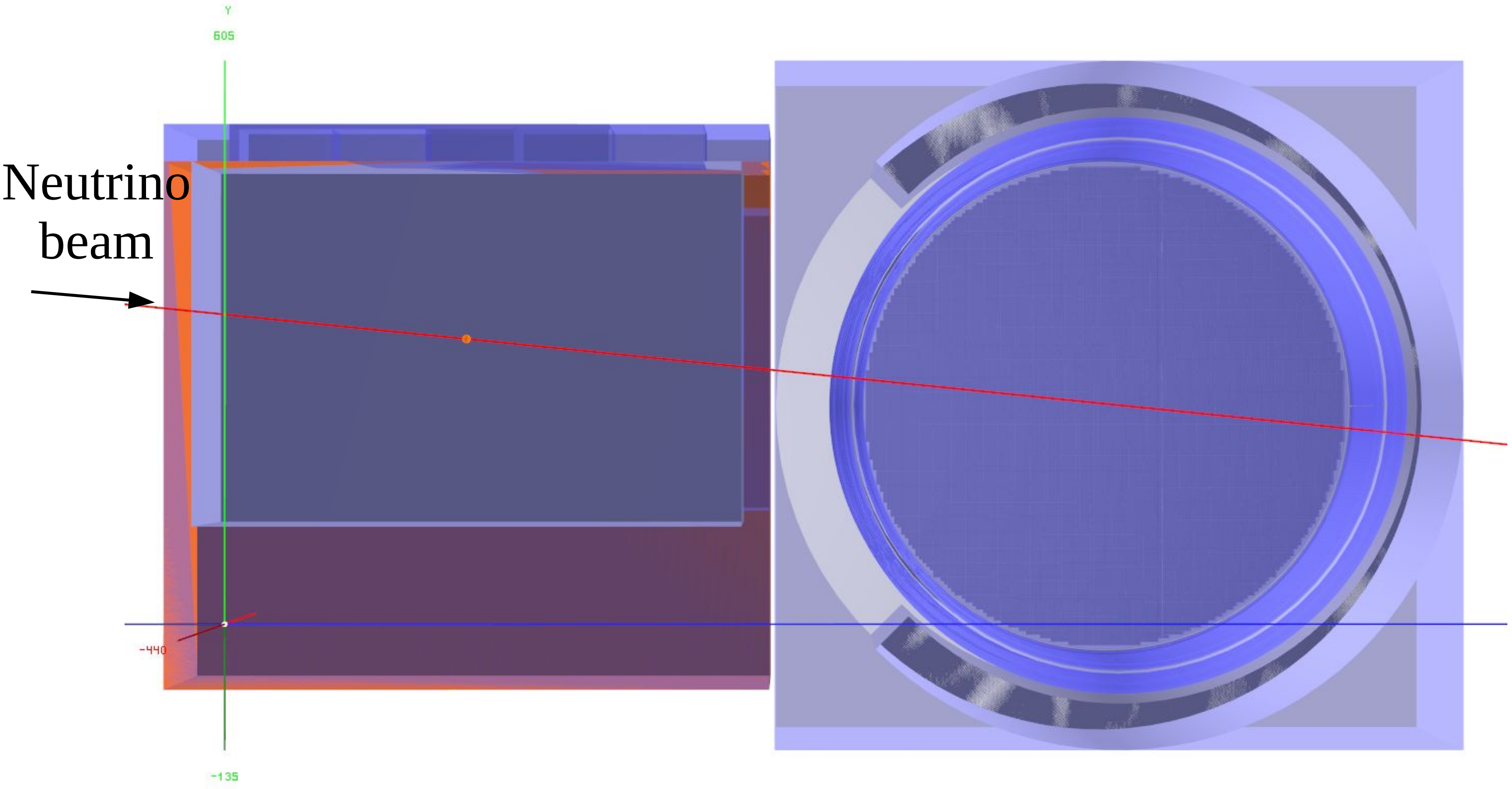


ArgonCube module

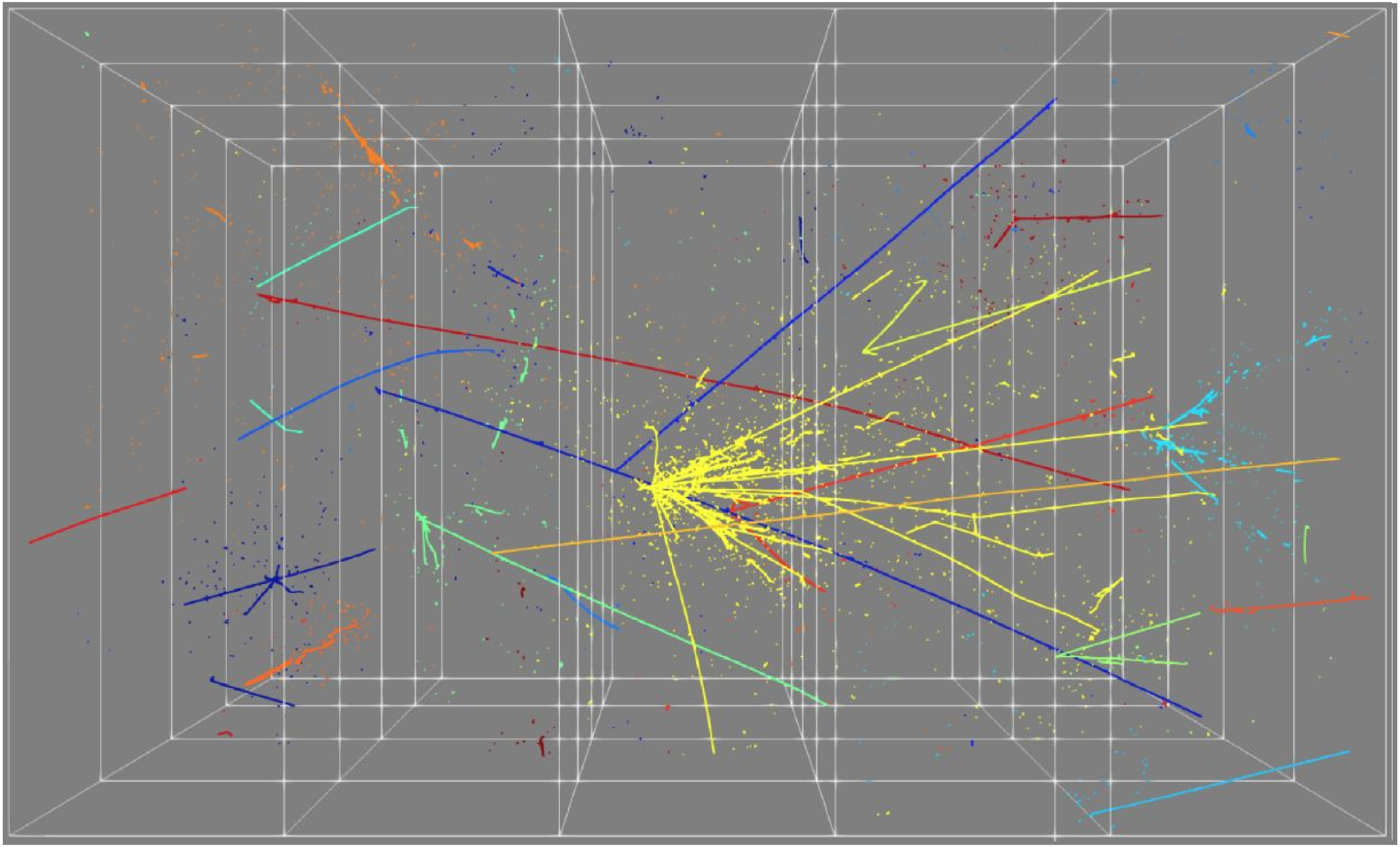


2x2 Demonstrator module.
Note, ND modules will not have individual pumps & filters

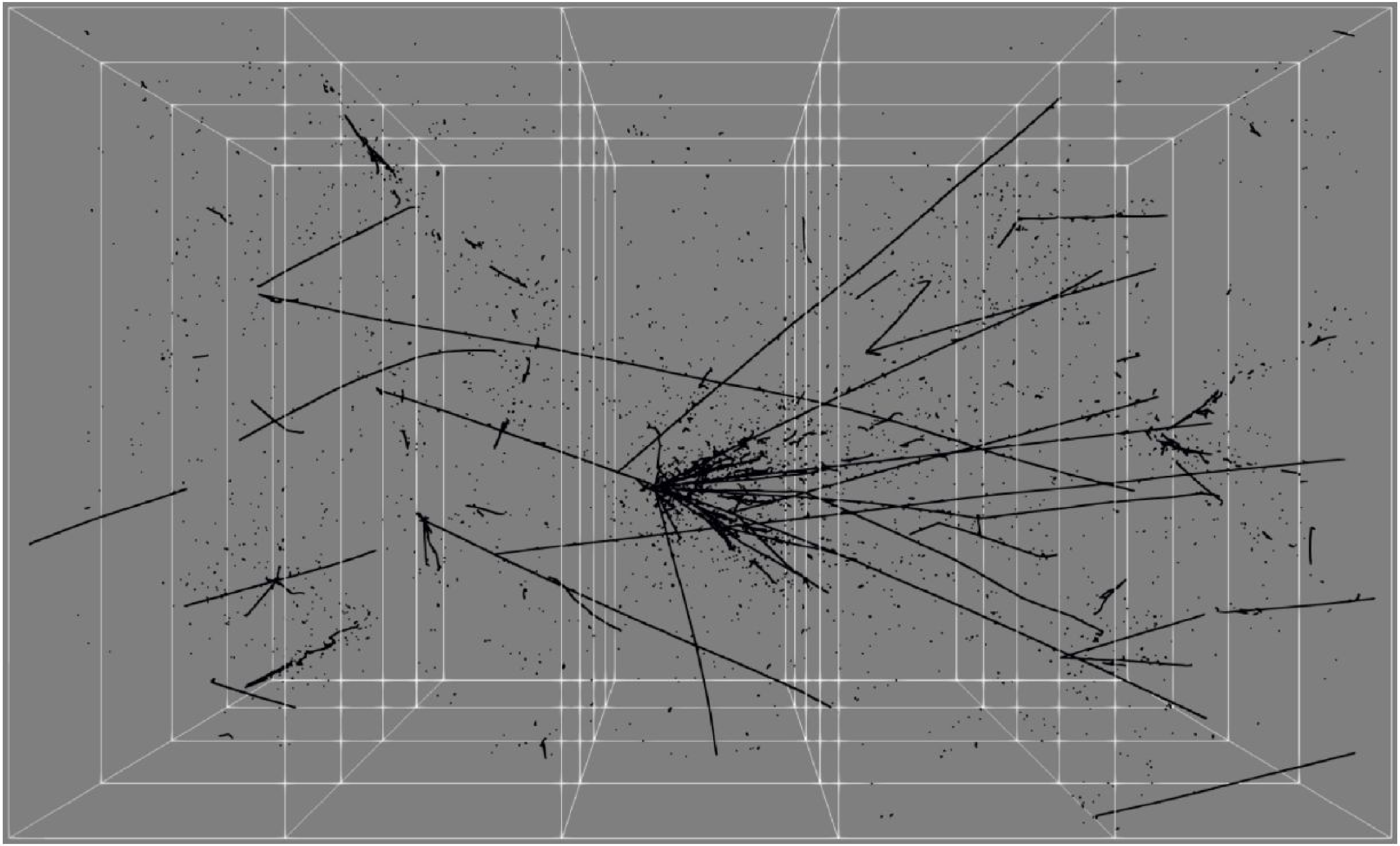
Near detector concept: Modular LAr TPC & Magnetized high-pressure gas Ar TPC


Neutrino beam

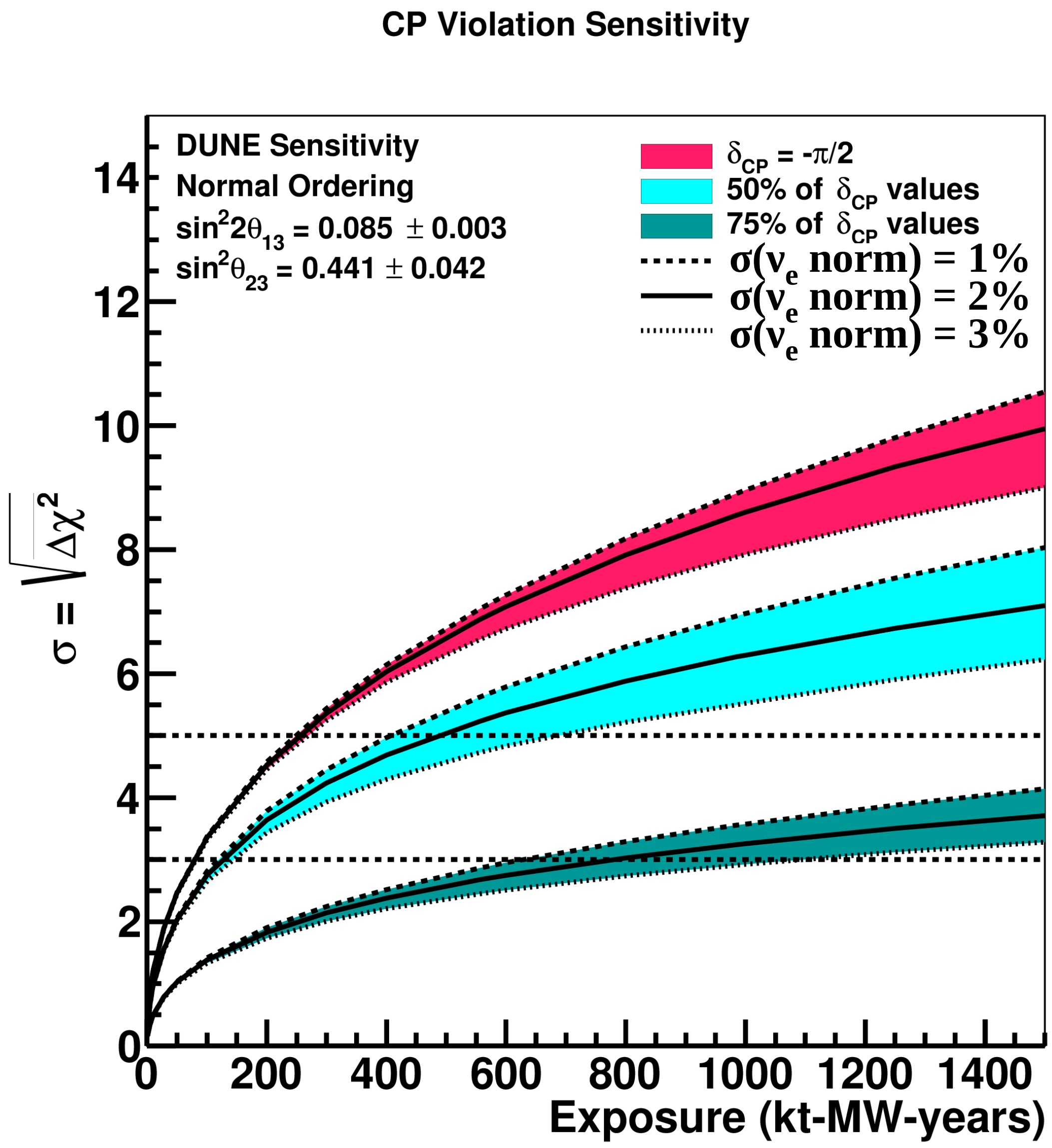
One beam spill at 1MW in LAr ND...



...without timing resolution

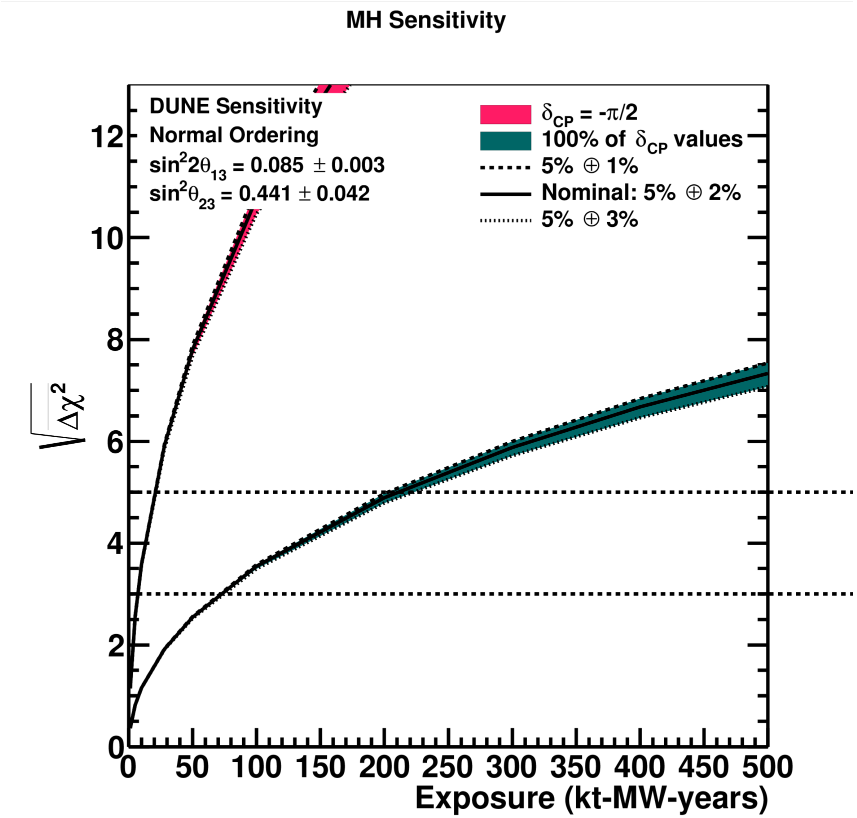


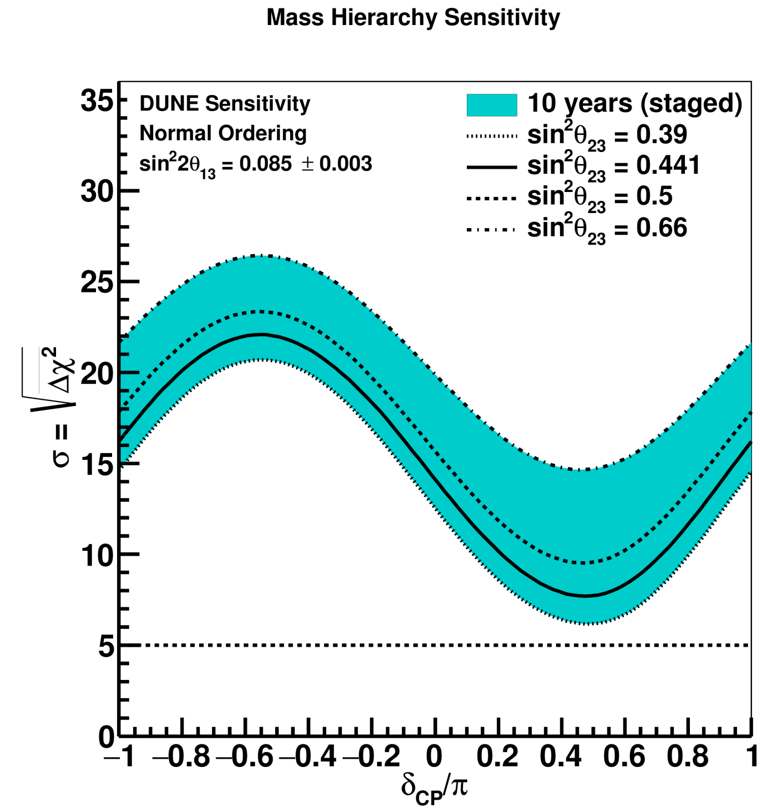
CP violation sensitivity



- 5% normalization uncertainty on ν_e sample fully correlated with ν_μ
- Shown: additional 1, 2, or 3% uncertainty on ν_e sample uncorrelated
- Going from 1% to 3% ~doubles the exposure required for 5σ measurement over 50% of δ values

Effect of systematics on MH





- Systematics have much smaller impact on mass ordering sensitivity
- CP violation is much tougher constraint – any ND that meets CP sensitivity requirements will also easily support MH measurement

Oscillation measurements

You would like to measure:

$$P(\nu_\mu \rightarrow \nu_e) = \frac{\Phi_{\nu_e}(E_{true}, L)}{\Phi_{\nu_\mu}(E_{true}, 0)}$$

$$N_{\nu_e}^{far}(E_{reco}) = \int dE_{true} \Phi_{\nu_e}(E_{true}, L) \times \sigma_{\nu_e}(E_{true}) \times \epsilon^{far}(E_{true}) \times \mathbf{D}_{\nu_e}^{far}(E_{true}, E_{reco})$$

$$N_{\nu_\mu}^{near}(E_{reco}) = \int dE_{true} \Phi_{\nu_\mu}(E_{true}, 0) \times \sigma_{\nu_\mu}(E_{true}) \times \epsilon^{near}(E_{true}) \times \mathbf{D}_{\nu_e}^{near}(E_{true}, E_{reco})$$

Oscillation measurements

You would like to measure:

$$P(\nu_\mu \to \nu_e) = \frac{\Phi_{\nu_e}(E_{true}, L)}{\Phi_{\nu_\mu}(E_{true}, 0)}$$

But what you actually see in the far detector is:

$$N_{\nu_e}^{far}(E_{reco}) = \int dE_{true} \Phi_{\nu_e}(E_{true}, L) \times \sigma_{\nu_e}(E_{true}) \times \epsilon^{far}(E_{true}) \times \mathbf{D}_{\nu_e}^{far}(E_{true}, E_{reco})$$

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But what you actually see in the far detector is:

$$N^{far}_{\nu_e}(E_{reco}) = \int dE_{true}\Phi_{\nu_e}(E_{true}, L)\times\sigma_{\nu_e}(E_{true})\times\epsilon^{far}(E_{true})\times\mathbf{D}^{far}_{\nu_e}(E_{true}, E_{reco})$$

The flux you want is only part of the equation...

Oscillation measurements

You would like to measure:

$$P(\nu_\mu \rightarrow \nu_e) = \frac{\Phi_{\nu_e}(E_{true}, L)}{\Phi_{\nu_\mu}(E_{true}, 0)}$$

But what you actually see in the far detector is:

$$N_{\nu_e}^{far}(E_{reco}) = \int dE_{true} \Phi_{\nu_e}(E_{true}, L) \times \sigma_{\nu_e}(E_{true}) \times \epsilon^{far}(E_{true}) \times \mathbf{D}_{\nu_e}^{far}(E_{true}, E_{reco})$$

σ is the neutrino-Argon interaction cross section

Oscillation measurements

You would like to measure:

$$P(\nu_\mu \rightarrow \nu_e) = \frac{\Phi_{\nu_e}(E_{true}, L)}{\Phi_{\nu_\mu}(E_{true}, 0)}$$

But what you actually see in the far detector is:

$$N^{far}_{\nu_e}(E_{reco}) = \int dE_{true} \Phi_{\nu_e}(E_{true}, L) \times \sigma_{\nu_e}(E_{true}) \times \epsilon^{far}(E_{true}) \times \mathbf{D}^{far}_{\nu_e}(E_{true}, E_{reco})$$

ε is the detector acceptance

Oscillation measurements

You would like to measure:

$$P(\nu_\mu \to \nu_e) = \frac{\Phi_{\nu_e}(E_{true}, L)}{\Phi_{\nu_\mu}(E_{true}, 0)}$$

But what you actually see in the far detector is:

$$N_{\nu_e}^{far}(E_{reco}) = \int dE_{true} \Phi_{\nu_e}(E_{true}, L) \times \sigma_{\nu_e}(E_{true}) \times \epsilon^{far}(E_{true}) \times \mathbf{D}_{\nu_e}^{far}(E_{true}, E_{reco})$$

And you have to correct your observed reconstructed energy spectrum to the true energy, using a model of your detector performance

Oscillation measurements

You would like to measure:

$$P(\nu_\mu \rightarrow \nu_e) = \frac{\Phi_{\nu_e}(E_{true}, L)}{\Phi_{\nu_\mu}(E_{true}, 0)}$$

But what you actually see in the far detector is:

$$\frac{N_{\nu_e}^{far}(E_{reco}) = \int dE_{true}\Phi_{\nu_e}(E_{true}, L)\times\sigma_{\nu_e}(E_{true})\times\epsilon^{far}(E_{true})\times\mathbf{D}_{\nu_e}^{far}(E_{true}, E_{reco})}{N_{\nu_\mu}^{near}(E_{reco}) = \int dE_{true}\Phi_{\nu_\mu}(E_{true}, 0)\times\sigma_{\nu_\mu}(E_{true})\times\epsilon^{near}(E_{true})\times\mathbf{D}_{\nu_\mu}^{near}(E_{true}, E_{reco})}$$

The near detector partially cancels many uncertainties by measuring the same beam on the same target

Systematics on the differences between ND and FD remain

ND/FD differences

$$\frac{N^{far}_{\nu_e}(E_{reco}) = \int dE_{true} \Phi_{\nu_e}(E_{true}, L) \times \sigma_{\nu_e}(E_{true}) \times \epsilon^{far}(E_{true}) \times \mathbf{D}^{far}_{\nu_e}(E_{true}, E_{reco})}{N^{near}_{\nu_\mu}(E_{reco}) = \int dE_{true} \Phi_{\nu_\mu}(E_{true}, 0) \times \sigma_{\nu_\mu}(E_{true}) \times \epsilon^{near}(E_{true}) \times \mathbf{D}^{near}_{\nu_\mu}(E_{true}, E_{reco})}$$

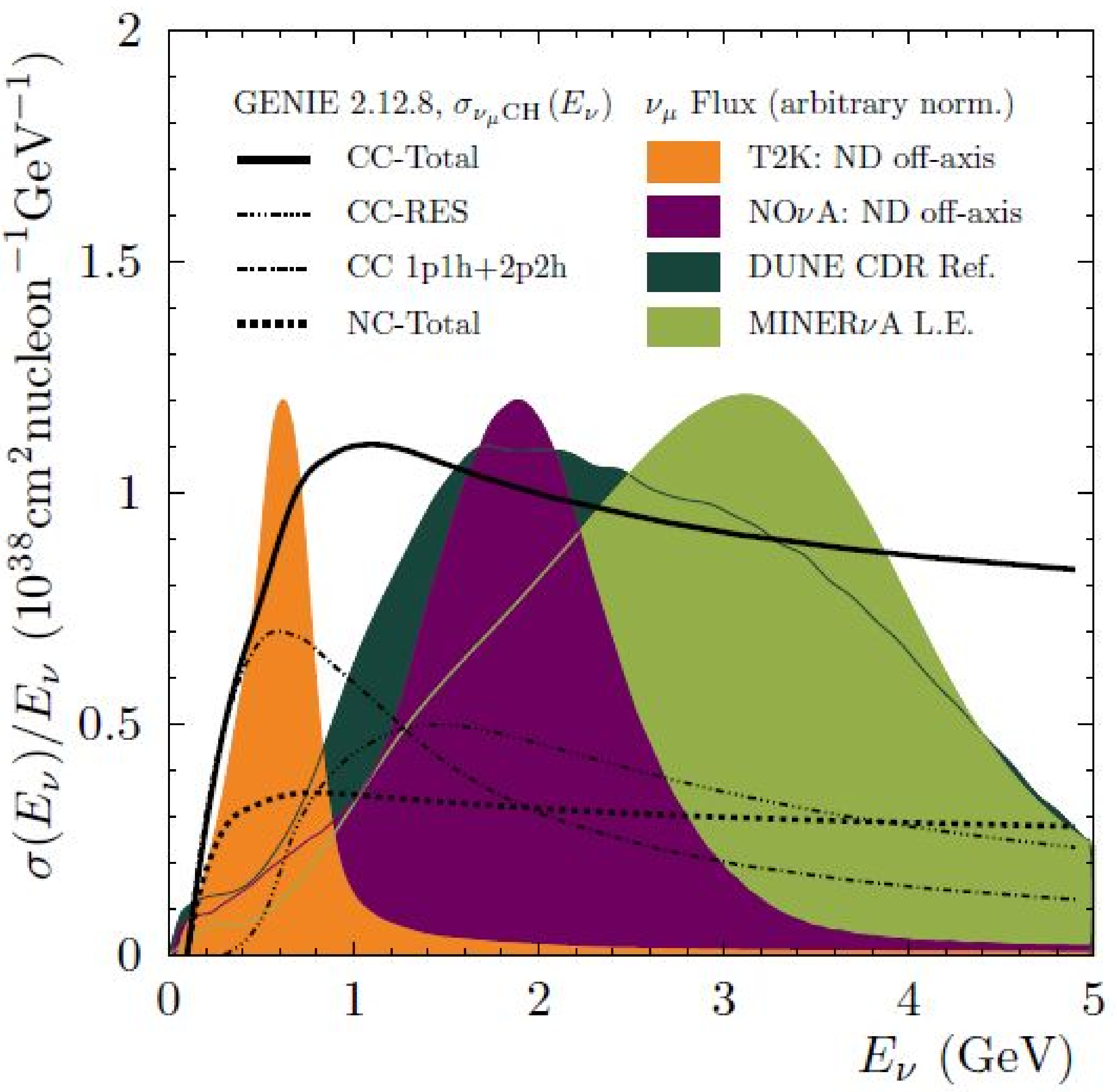
Solid angle effects make the flux different at ND and FD

ND measures ν_μ cross sections, FD measures ν_e scattering
Lepton mass differences give different allowed phase space

ND is smaller, so acceptance may be less than at FD, and acceptance may be different for μ and e

Reconstruction differences may give rise to differences in the reco → true energy relationship

Fluxes and cross sections



L. Pickering