The design of DUNE near detector

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On behalf of the DUNE collaboration

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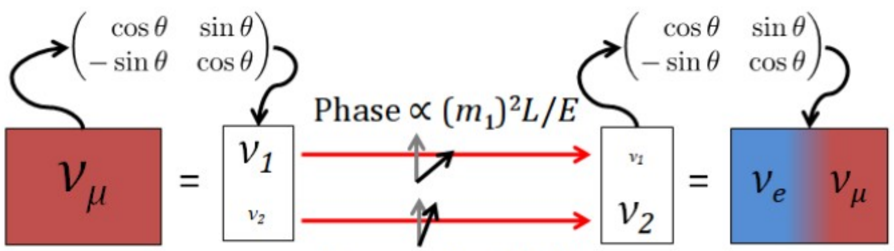
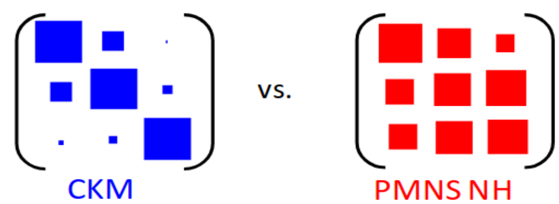
Neutrino Oscillation

- Neutrinos propagate in mass states and interact in flavor states.
- Three generations of neutrino have been found corresponding to lepton flavors.
- Three “Euler” angle has been measured.

  - mixing angles 12, 13 and 23 are measured by various neutrino experiments with different sources, Octant of angle 23 is not clear.





$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

δ

with $s_{ij} = \sin\theta_{ij}\ ;\ c_{ij} = \cos\theta_{ij}$

Neutrino Oscillation

- Non-zero mixing angle 13 measured by Double Chooz, Daya Bay and RENO provides opportunity to measure CP violation phase.
- Matter effect helps on mass hierarchy identification.
- Different appearance probability between neutrino and antineutrino indicates the CP phase. Existing long-baseline experiments are measuring CP phase with a combination of neutrino and antineutrino fluxes.

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$ ← What we measure

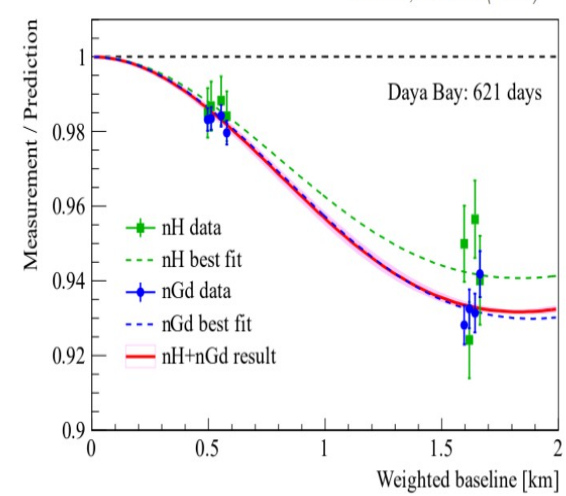
ME $$\frac{16A}{\Delta m_{31}^2} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$$ ← Small

ME $$-\frac{2AL}{E} \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$$ ← Proportional to L

CPV $$-8\frac{\Delta m_{21}^2 L}{2E} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\delta \; s_{13} c_{13}^2 c_{23} s_{23} c_{12} s_{12}$$ ← What we want

with $A = 2\sqrt{2} G_F n_e E = 7.6 \times 10^{-5} \mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$

PRD 93, 072011 (2016)



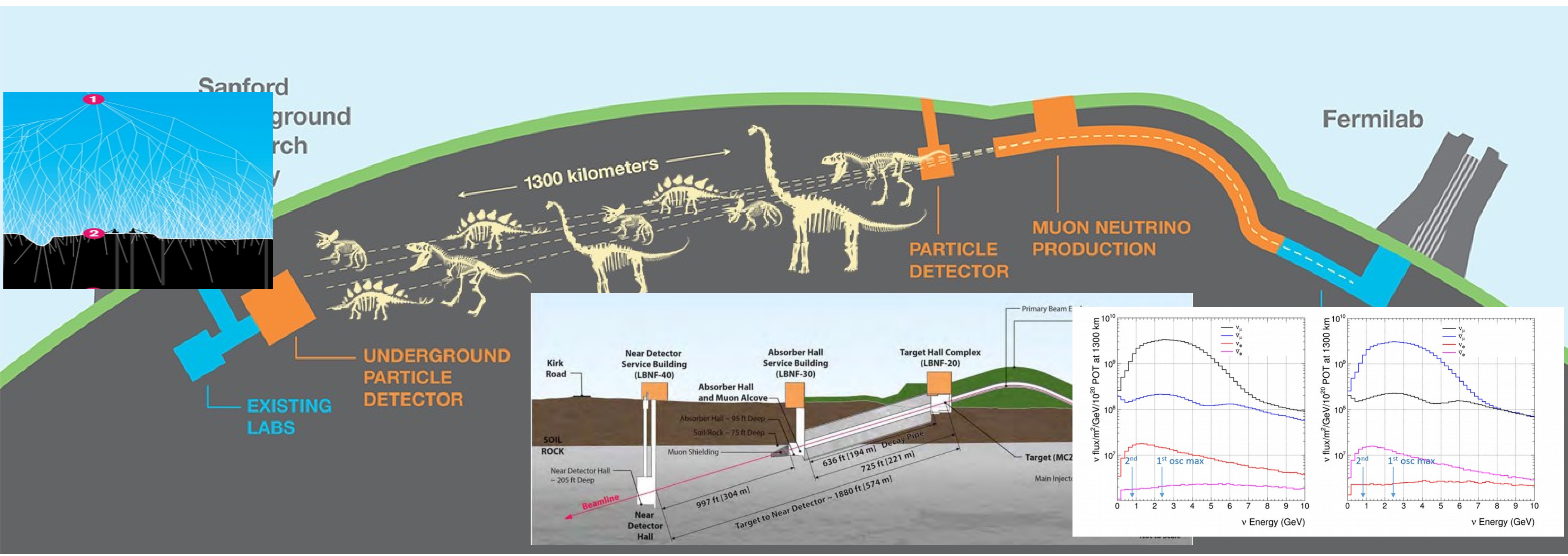
DUNE Collab.

DEEP UNDERGROUND NEUTRINO EXPERIMENT

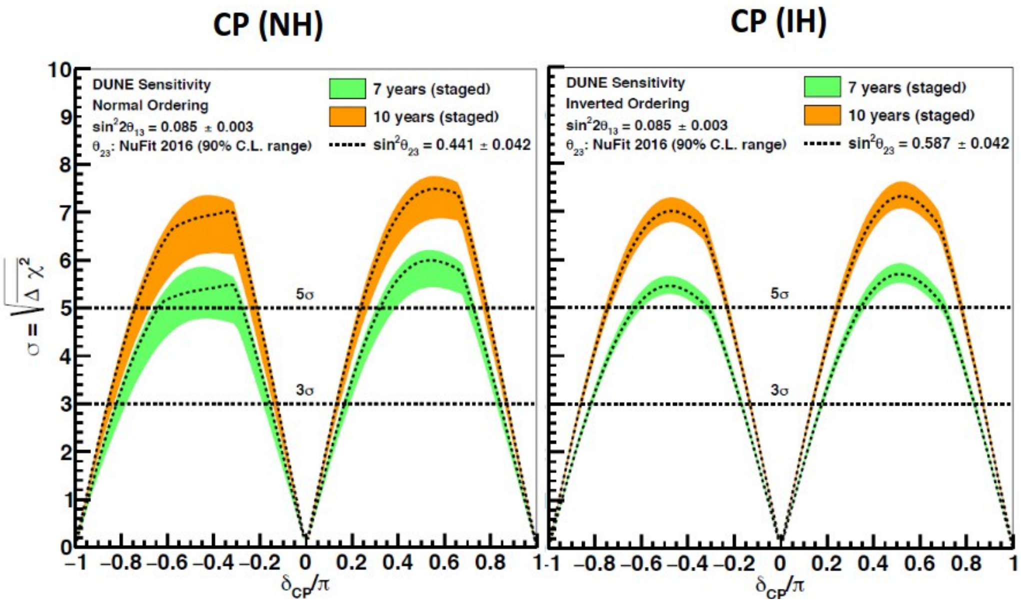
Stony Brook University

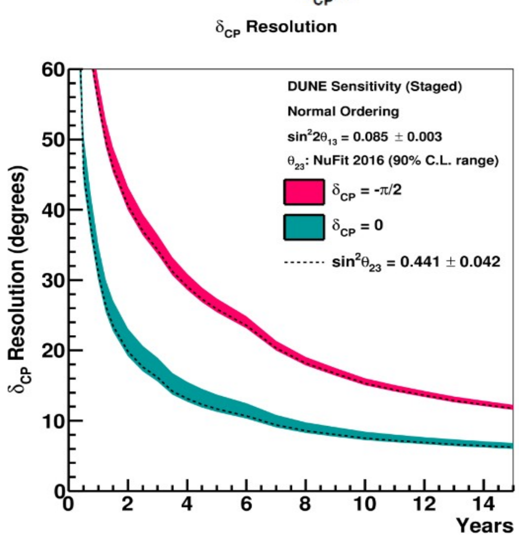
DUNE experiment

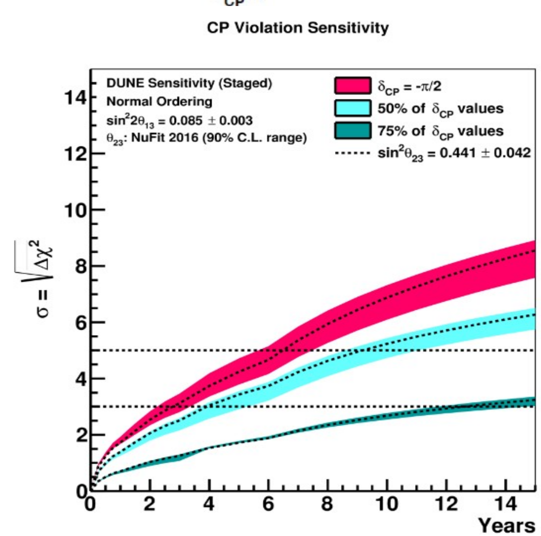
- High-intensity wide-band muon neutrino beam located at Fermilab.
  - Cover at least 2, up to 3 electron neutrino appearance maxima.
  - 1.2 MW proton beam upgradable to 2.4 MW.
- Muon neutrino disappearance and electron neutrino appearance channels will be observed at a high-mass far detector with a baseline of 1300 m.



DUNE Sensitivity







- Aim at 5 sigma CP violation measure after 7 years running of FHC + RHC modes.
- Time plan:

  - Year 1 : 10kt FD mass, 1.07 MV 80-GEV proton beam with no ND.

  - Year 2 : adding 10kt FD.

  - Year 3: adding 10kt FD, with a preliminary ND.

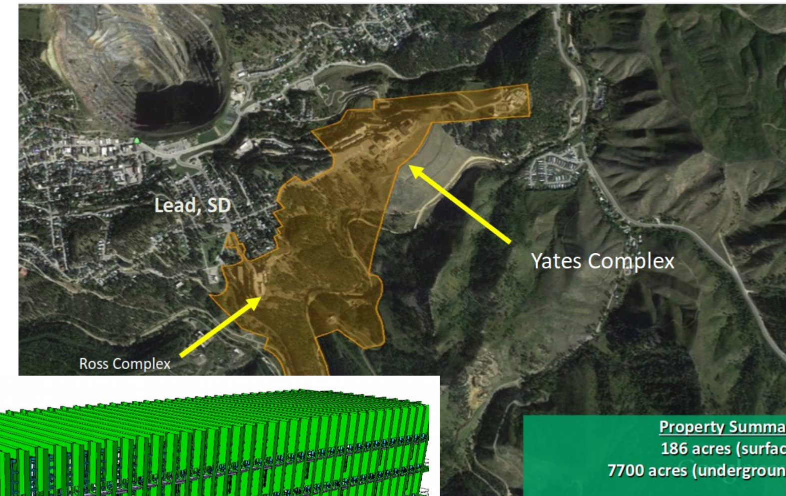
  - Year 4: adding 10kt FD.

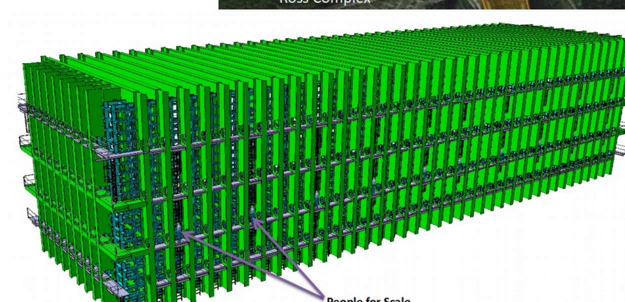
  - Year 5 : a full ND;

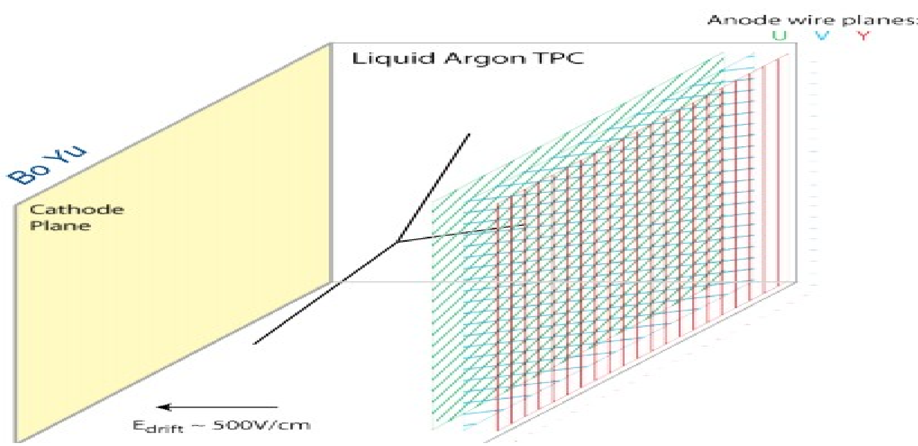
  - Year 7 : upgrade beam to 2.14 MW.

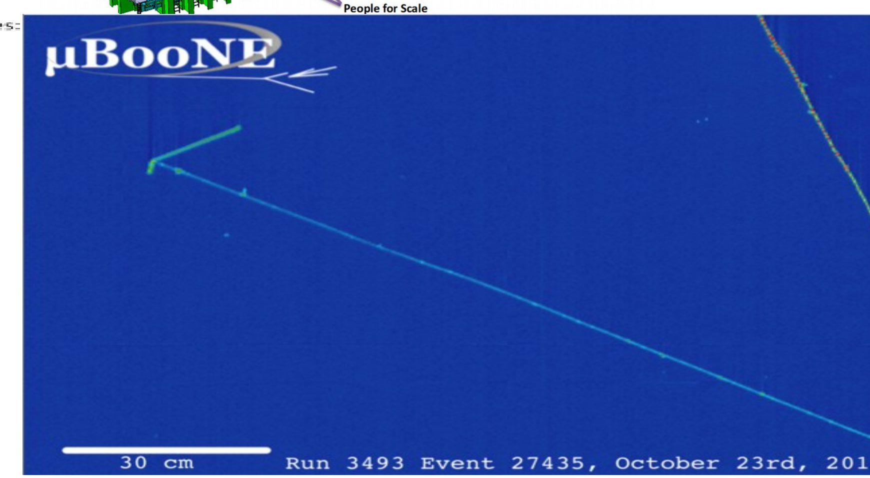
DUNE Far Detector

- FD is located at Homestake in South Dakota
  with a number of 10 kt liquid argon TPC modules.
- Each module has 3 Anode Plane Assemblies (APA).
  - 384,000 cold electronics channels
- Cathode planes (CPA) operate at 180 kV.
  - 3.6 m max drift length
- Photon detection system to provide T0.









What ND must do?

Ideally:

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

Event spectrum:

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

However…

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

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

Just make them Canceled??

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

It turns out...

Ambiguities need to be resolved:

- Detection effects in near and far detector
- Cross section
- Reconstructed energy to true energy mapping
- Near to Far flux extrapolation

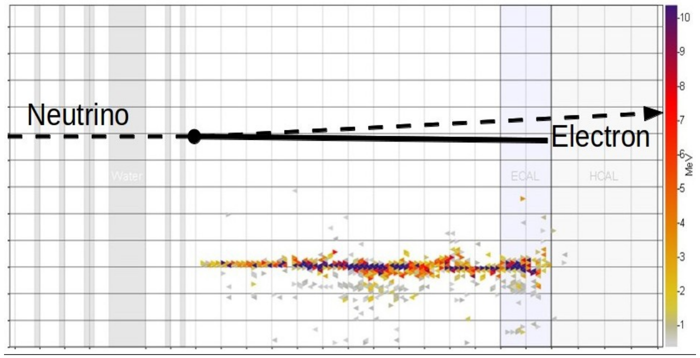
DUNE ND : flux measurement

- Target independent
- Better use channels that cross section well known.

  \- Neutron-electron scattering: Pure weak interaction; signature is very straightforward electron.

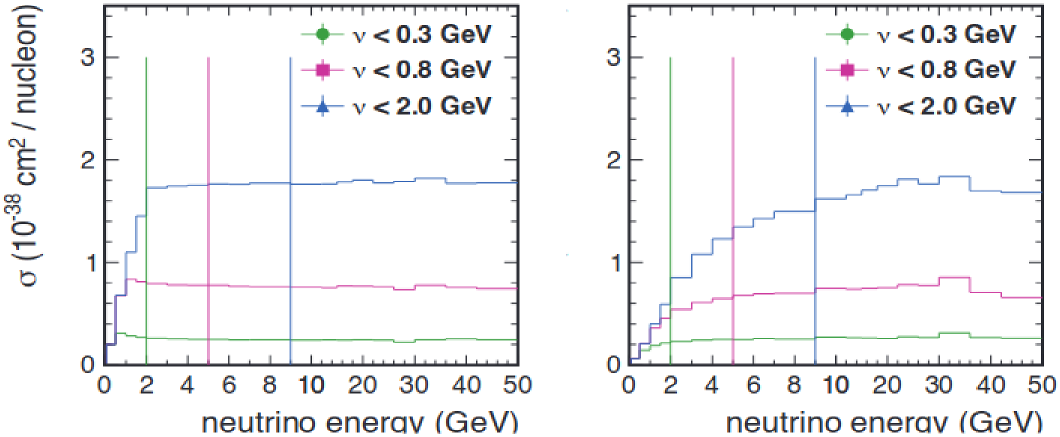
  \- low-nu channel: Very low energy transferring from neutrino to nuclear system; Cross section is independent of energy; Cross section depends on ability to measure all hadronic energy including neutrons.

Minerva neutrino-electron scattering event



Phys. Rev. D 93, 112007 (2016)

Minerva low-nu cross section



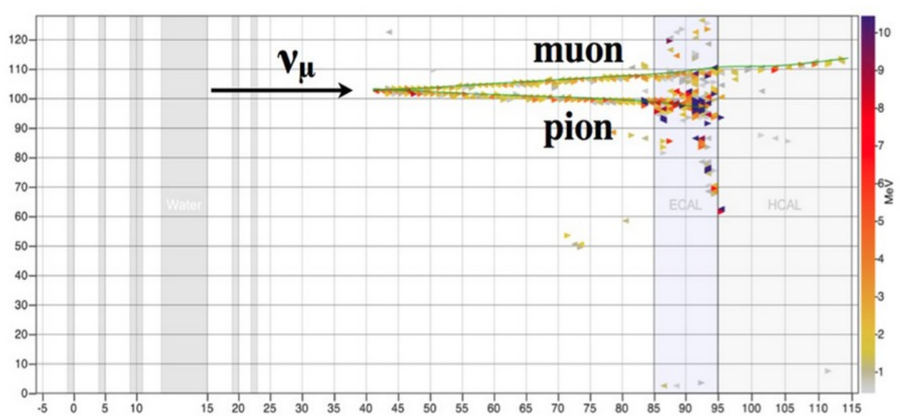
Phys. Rev. D 94, 112007 (2016)

DUNE ND : flux measurement

- Coherent channel: No Long/short range correlations and no final state interaction; Cross section not well known and small; Pretty forward-going lepton and pions.

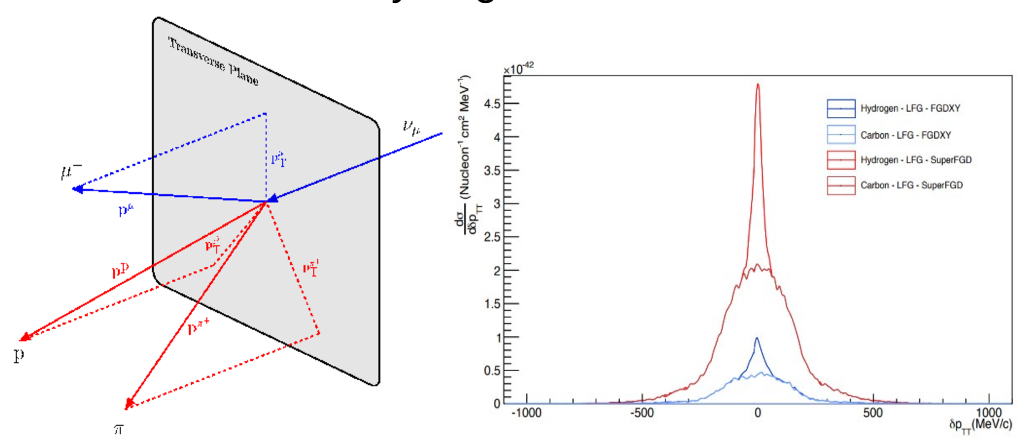
- Hydrogen interaction: No final state interaction; No initial state transverse momentum→ identify by transverse momentum balance; Neutron measurements may be needed for this.

Minerva Coherent interaction event



Phys. Rev. Lett. 113, 261802 (2014)

T2K transverse momentum
→ extract hydrogen interaction



arXiv. 1901.03750

DUNE ND : Cross section and smearing

- Unknown initial state: neutrino energy and nucleon momentum
- Unknown final state: Neutron, protons below threshold
- Unknown detector smearing
- Very model dependent

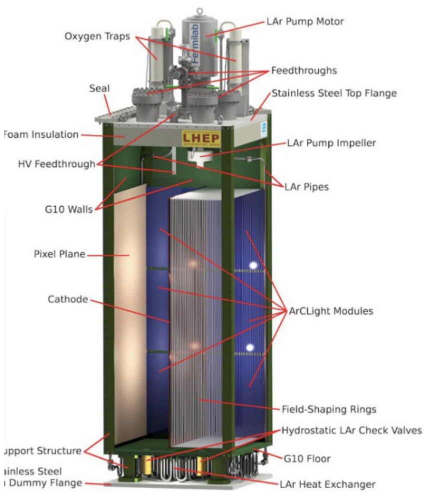
--→ ND philosophy:

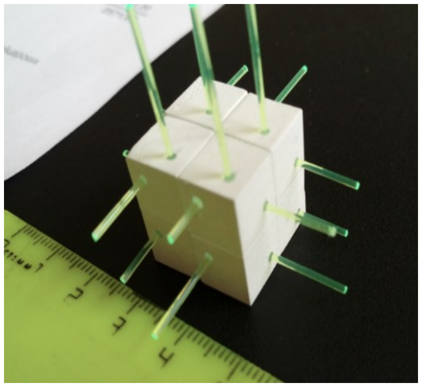
- Measure as many exclusive differential cross sections as possible.
- Tune model.
- Extract cross section and smearing from simulation.

--→ We start to consider detector configuration based on the ideas above

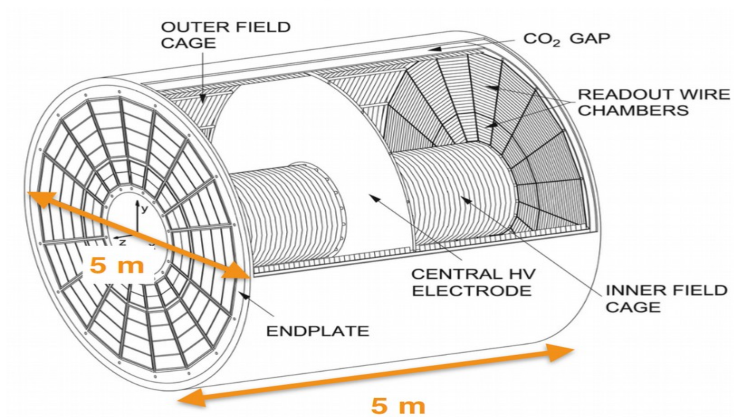
Current DUNE ND design

- Each components can take over one specific task and there are redundancies to ensure the success.
- The following talks will describe these components in detail.





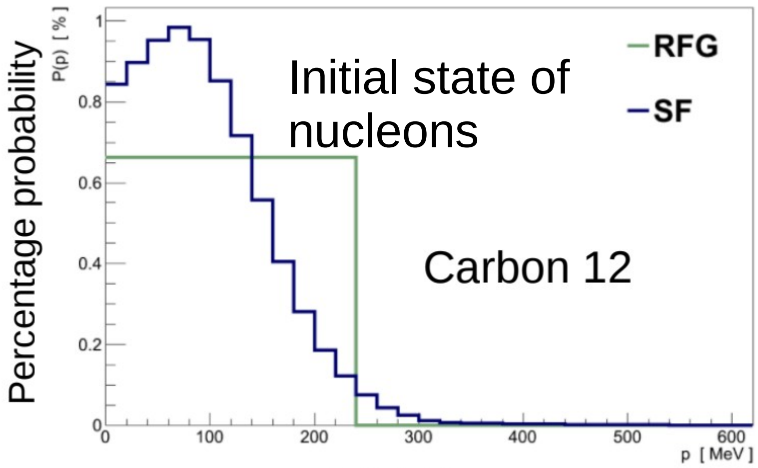
Component	Essential Characteristics	Primary function	Select physics aims
LArTPC (ArgonCube)	Mass	Experimental control for the Far Detector	$\nu_\mu(\overline{\nu}_\mu)$ CC
	Target nucleus Ar	Measure unoscillated E_ν spectra	ν-e$^-$ scattering
	Technology FD-like	Flux determination	ν_e+$\overline{\nu}_e$ CC Interaction model
Multipurpose detector (MPD)	Magnetic field	Experimental control for the LArTPCs	$\nu_\mu(\overline{\nu}_\mu)$ CC
	Target nucleus Ar	Momentum analyze liquid Ar μ	ν_e CC, $\overline{\nu}_e$
	Low density	Measure exclusive final states with low momentum threshold	Interaction model
3D scintillator tracker spectrometer (3DST-S)	On-axis	Beam flux monitor	On-axis flux stability
	Mass Magnetic field CH target	Neutrons	Interaction model A dependence ν-e$^-$ scattering



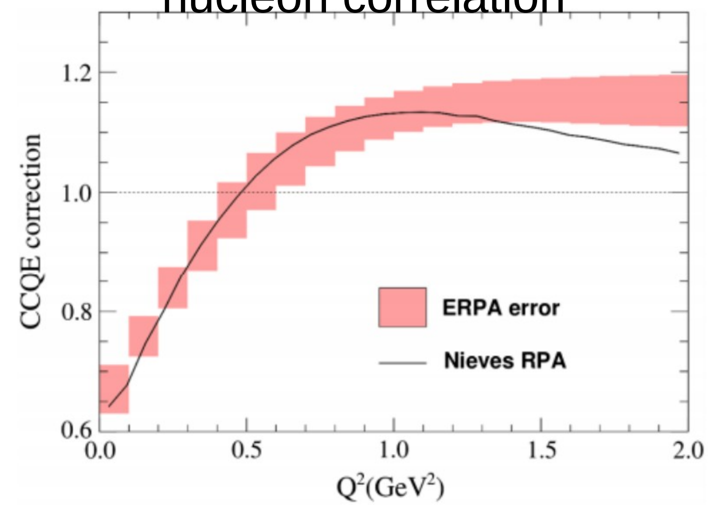
But, it is hard in reality

- Following things all need models, we are too model dependent.

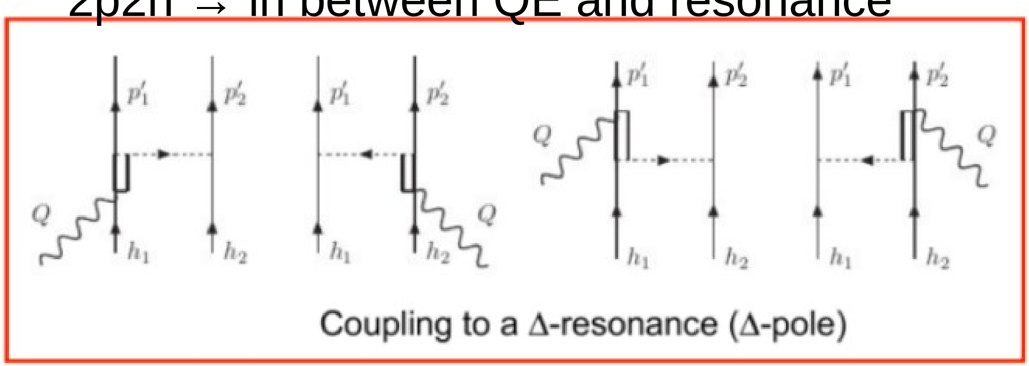
  - Parameterizations may be very wrong.



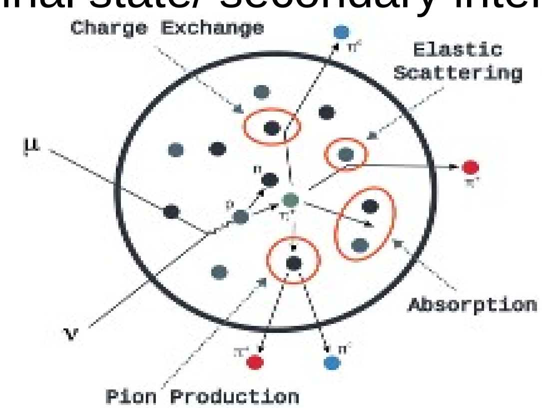
Long-range nucleon-nucleon correlation



2p2h → in between QE and resonance

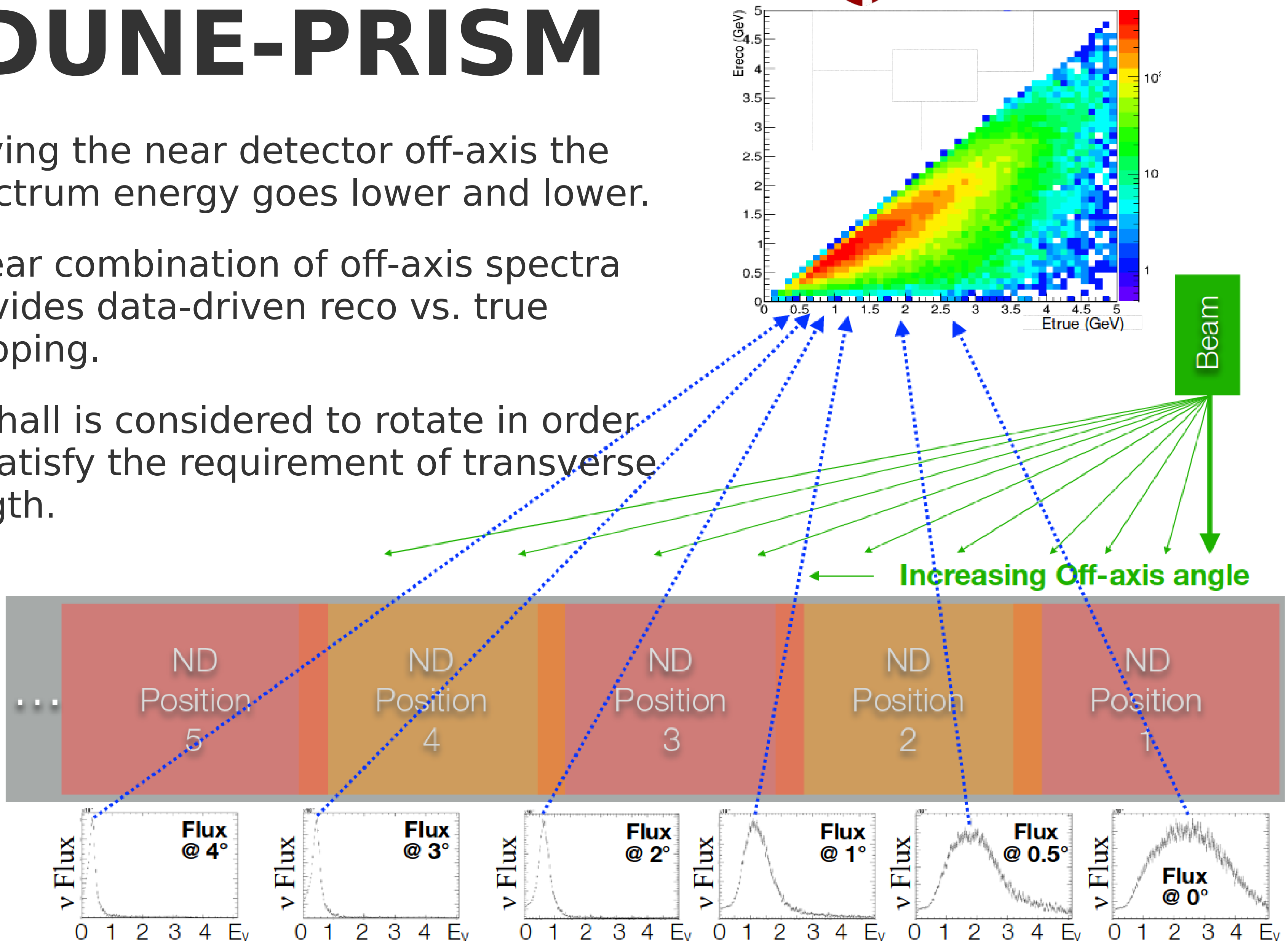


Final state/ secondary interaction

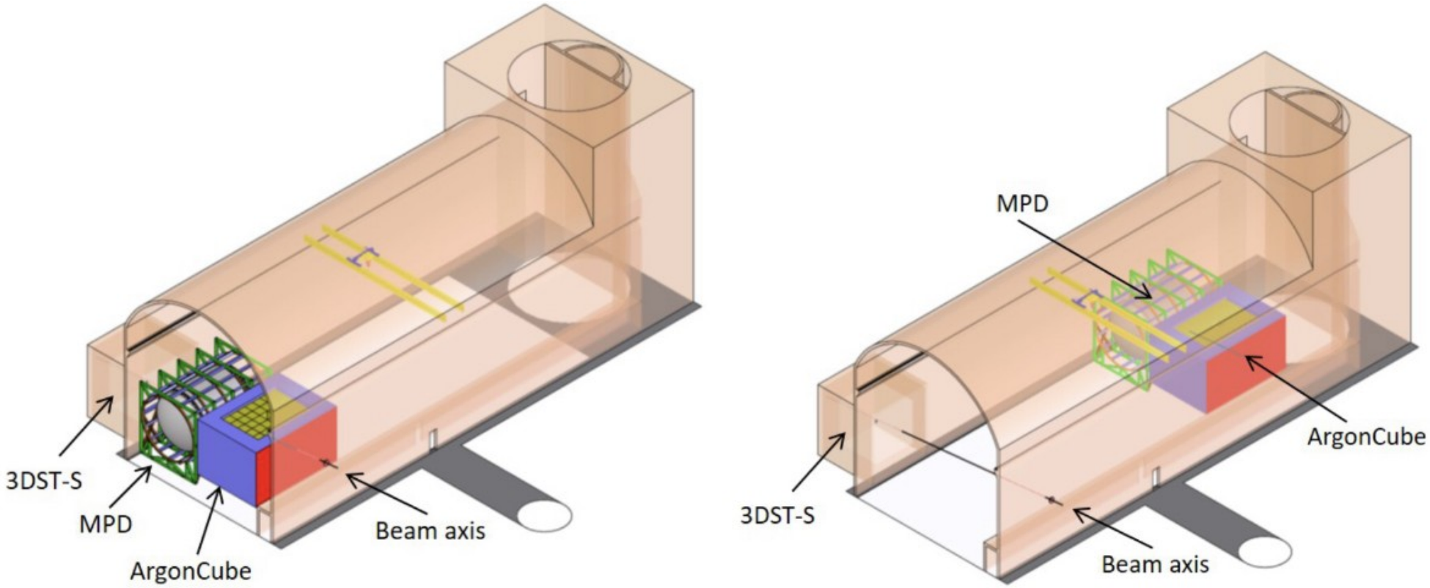


DUNE-PRISM

- Moving the near detector off-axis the spectrum energy goes lower and lower.
- Linear combination of off-axis spectra provides data-driven reco vs. true mapping.
- ND hall is considered to rotate in order to satisfy the requirement of transverse length.



DUNE ND hall and conclusion



- DUNE ND will consist of a liquid argon detector, a gas argon TPC system which will be surrounded by ECAL and inside a magnetic volume and a 3D projection scintillator tracker.
- DUNE-PRISM is the baseline design.
- DUNE aims at measuring CP violation at five sigma with this wonderful ND system.