INSTITUTE OF PARTICLE PHYSICS

Considerations for Near Detectors at HK

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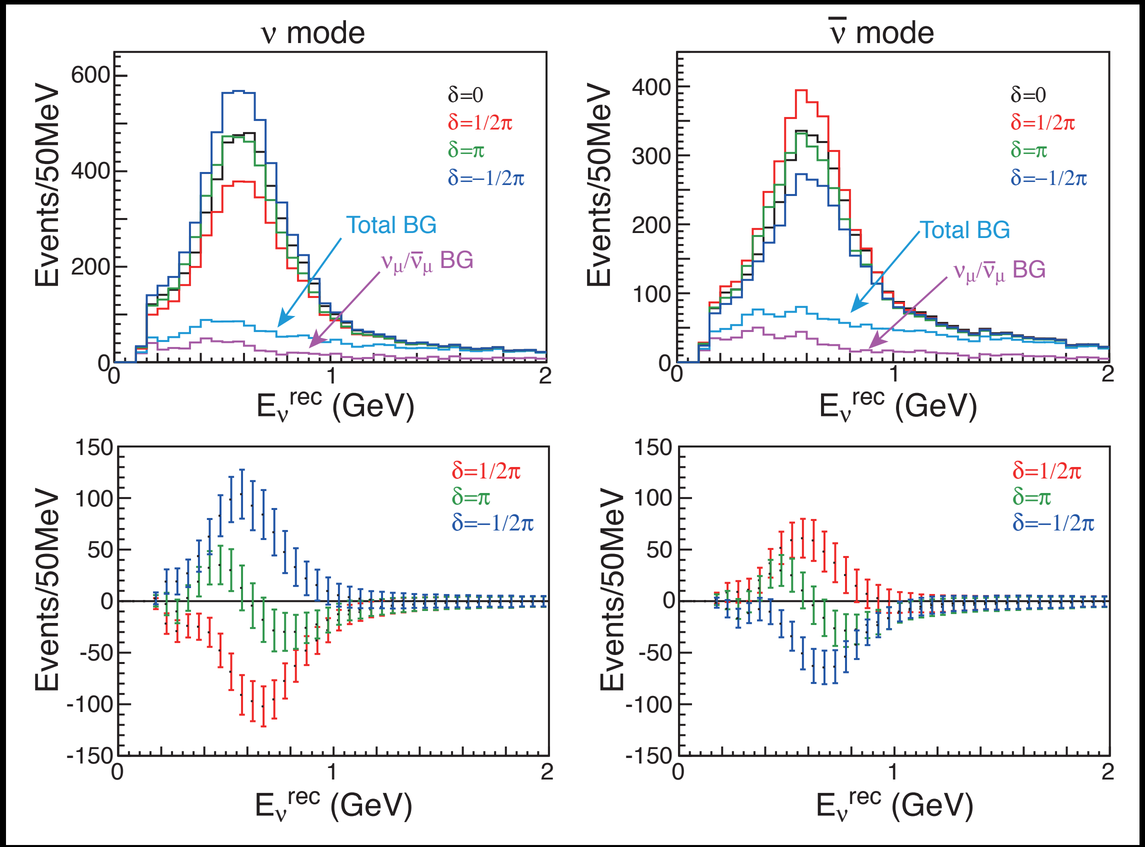
Introduction

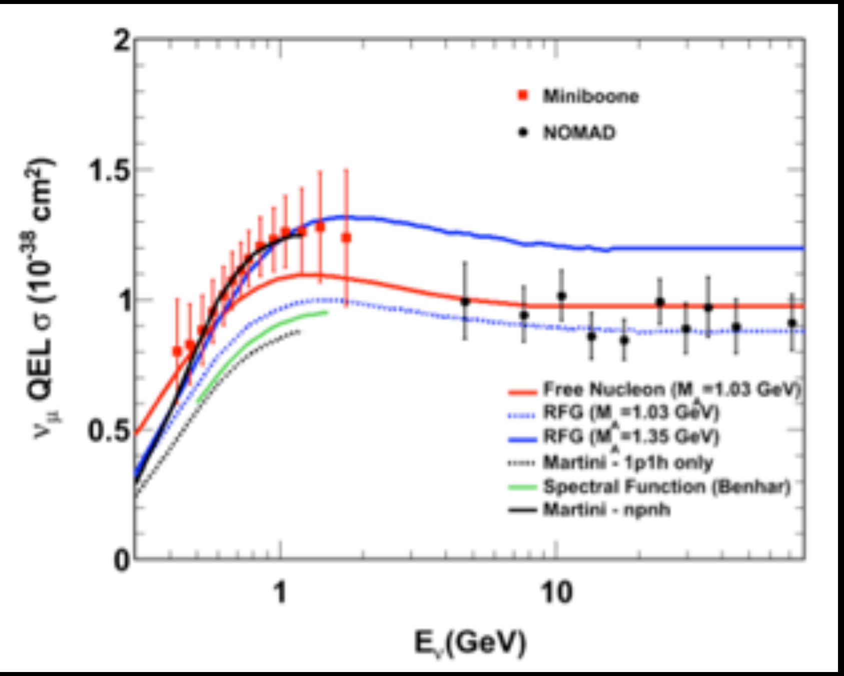
- We have strong evidence that θ_{13} is relatively large
  - Blessing:
    - Door towards 3-flavor mixing (CP violation, mass hierarchy) is open!
    - Large S/B: background (π^0, etc.) issues are smaller
  - Curse:
    - $\nu/\bar{\nu}$ asymmetry is smaller: more sensitivity to cross section and modeling systematics of signal process in $\nu/\bar{\nu}$

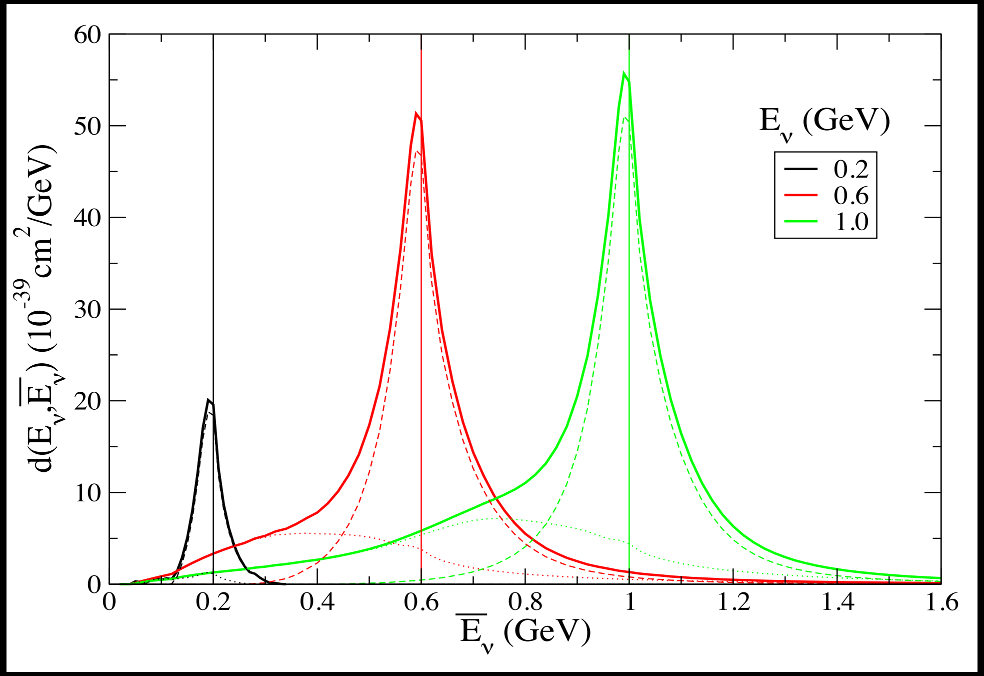


- Exploit spectral information regarding $\nu/\bar{\nu}$ oscillations
- What impact does this have on near detector design and capabilities?

CCQE

- Recent studies of the “CCQE” process have raised some questions





cf.
A. V. Butkevich
Phys.Rev. C78 (2008) 015501

Martini, Ericson, Chanfray
arXiv:1211.1523

NuInt 2009
http://indico.cern.ch/getFile.py/access?contribId=134&sessionId=1&resId=0&materialId=slides&confId=47248

and many others.

- Emerging picture:
  - additional process contribute to “CCQE” (MEC/NN correlations)
  - Enlarges cross sections for “CCQE”, different kinematics
- For HK, we must understand for $\nu/\bar{\nu}$:
  - “CCQE” cross section for vs. neutrino energy (ν_μ, ν_e)
  - relation between outgoing lepton momentum and incoming neutrino energy for whatever we call “CCQE”

Status

- We may hope for a resolution to this issue in the future. Requires:
  - theoretical consensus (qualitative → quantitative)
  - experimental input and verification (possibly from multiple sources)
- We should have some capability to address this within HK
  - need a new "standard candle" with better handle on the underlying kinematics and nuclear physics than ($\nu/\bar{\nu}$)-^{16}O CCQE
  - Possibilities:
    - leptonic scattering (IMD, ν-e elastic) **X** (threshold too high, statistics)
    - deep inelastic scattering **X** (energy range too high)
    - free nucleon CCQE (i.e. unbound protons, neutrons)
      - practically, there are no "free neutrons". Closest thing is deuterium
- How to introduce/extract ν-scattering from free protons/deuterium?
  - how well do we understand ν-scattering on p/d?

D_2 Theoretical Status

PHYSICAL REVIEW C **86**, 035503 (2012)

Inclusive neutrino scattering off the deuteron from threshold to GeV energies

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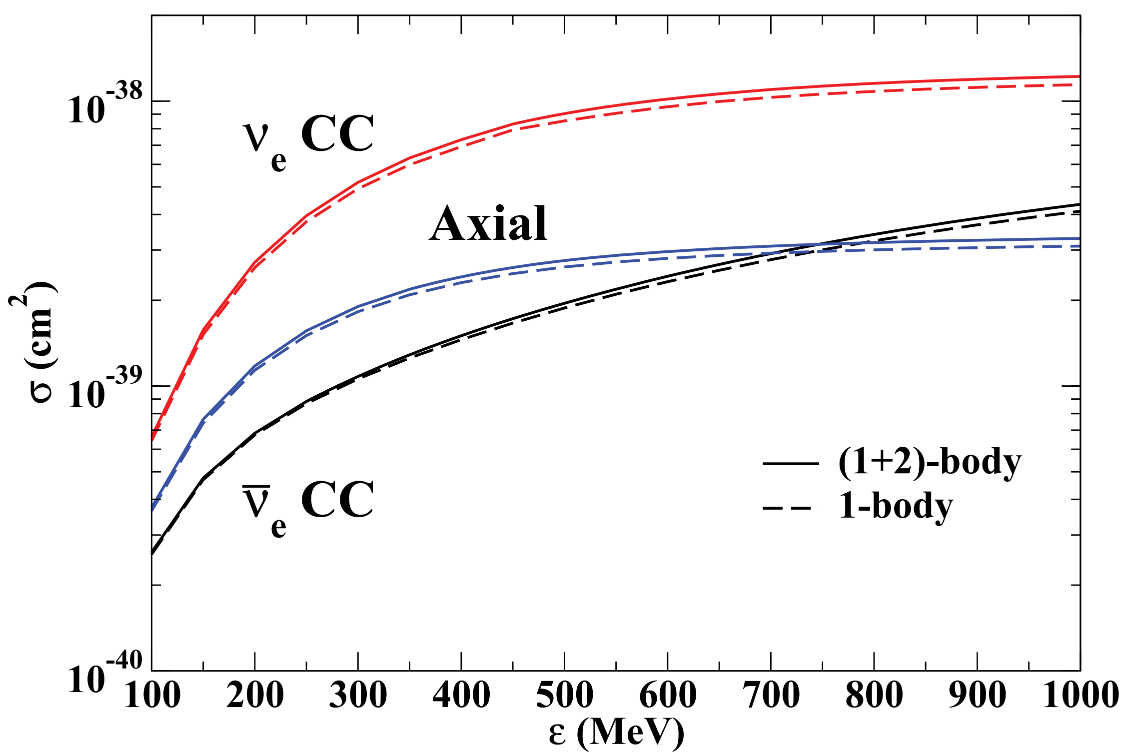
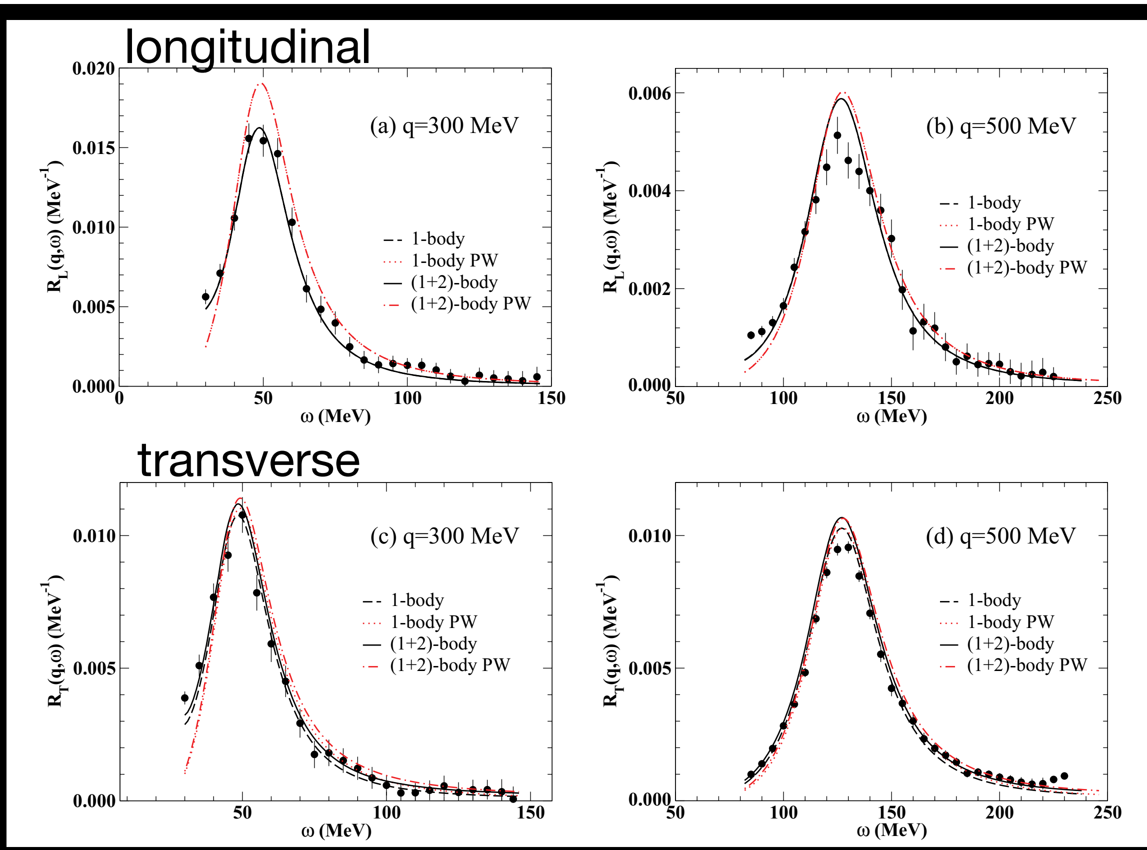


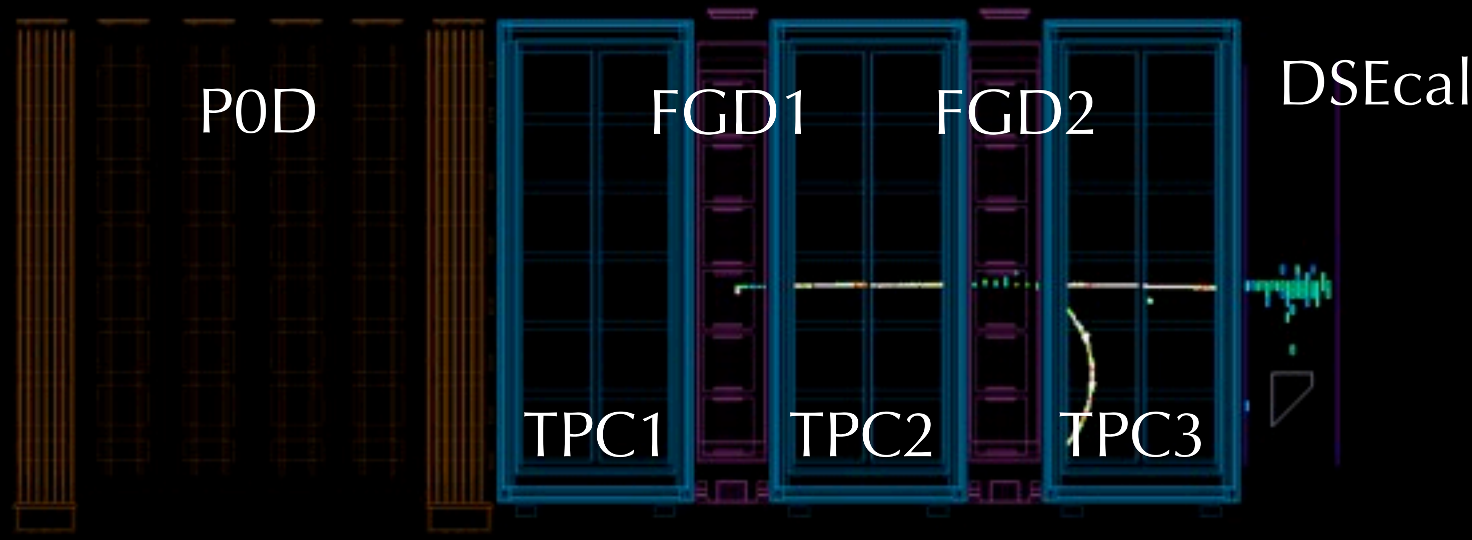
- 2-body contributions to ν-D scattering "<10%" at all energies
  - difference with PWIA "negligible" for >500 MeV
  - sensitivity to modeling of 2-nucleon potential/weak current "weak".
- Supports naive expectation that D_2 is "simpler"



e-scattering kinematics

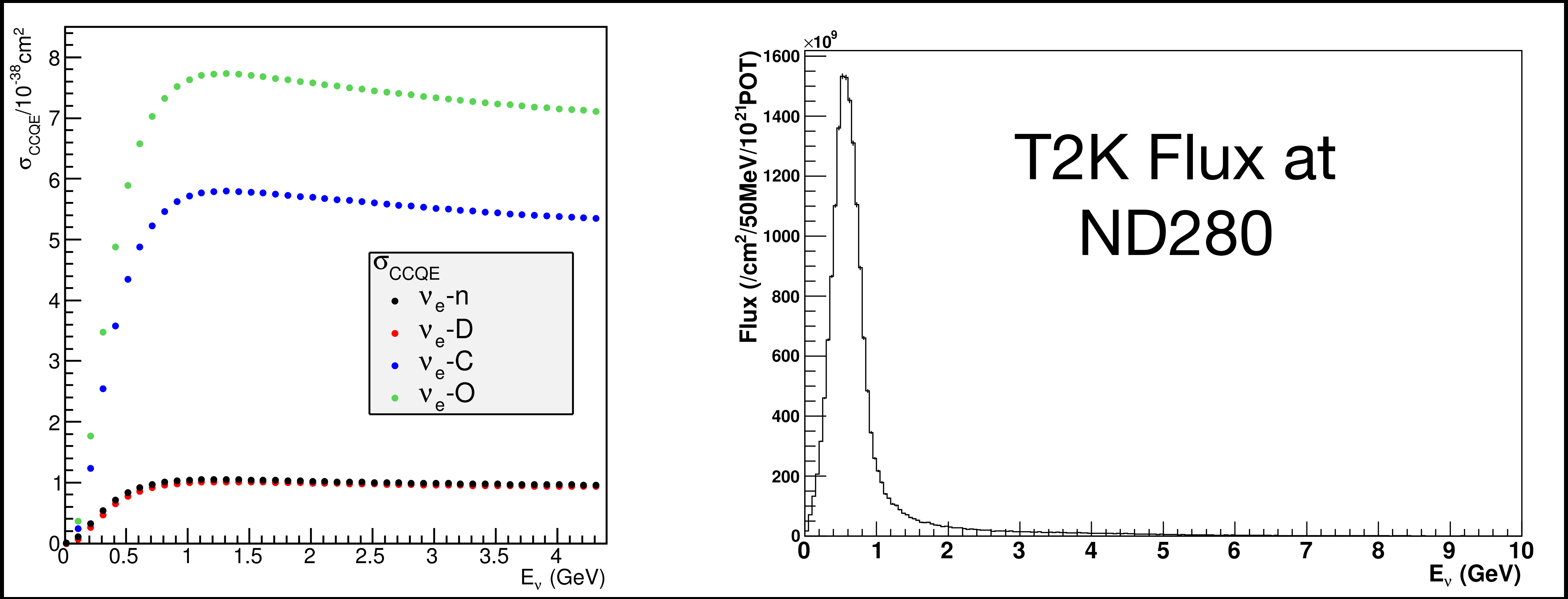
Detector Possibilities

- Liquid D_2/H target
  - technical/safety issues in maintaining combustible cryogenic target
  - what is the detector? (passive target? bubble chamber?)
- Heavy water (D_2O)
- Deuterated plastic, liquid scintillator C(H/D), $C(H/D)_2$



- In ND280, interactions on ^{16}O are extracted by subtraction of:
  - events in FGD1 (all CH) and FGD2 (CH + H_2O)
  - events in P0D with H_2O in/out
- A similar approach can may allow us to isolate ν-(p/D) events

Properties of CCQE on D_2



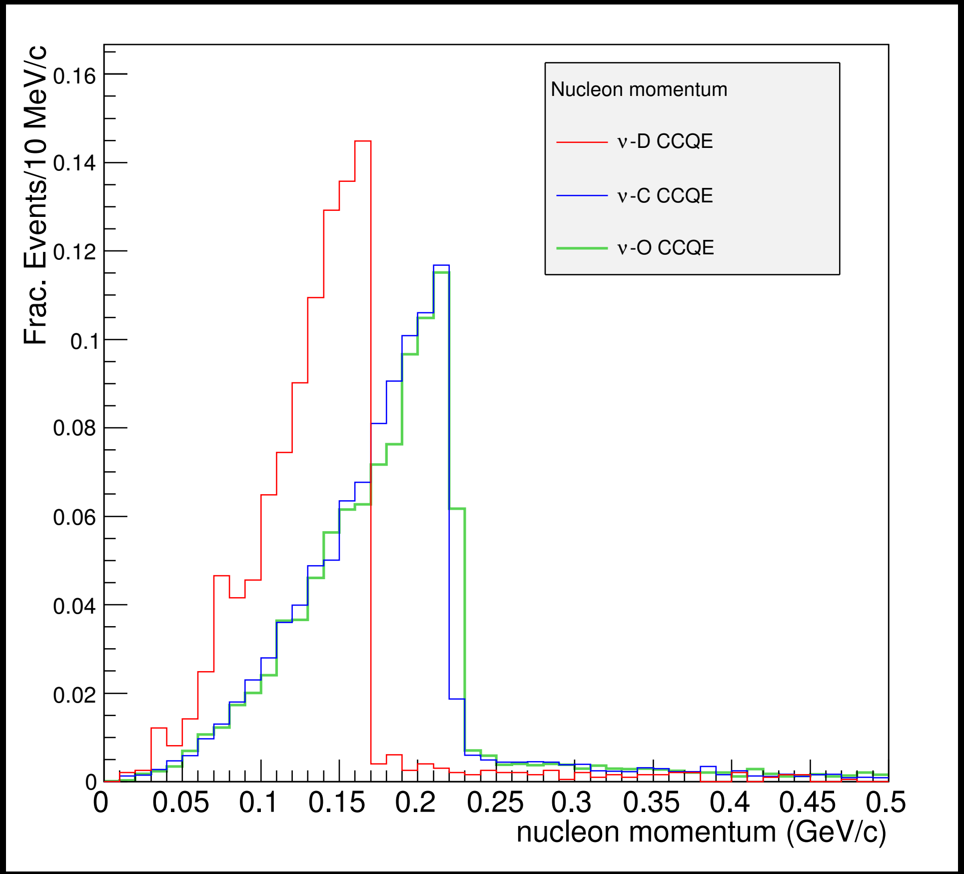
- σ_{CCQE} in Genie
  - RFG model (like other nuclei)
  - $\sigma(\nu\text{-D}) < \sigma(\nu\text{-n})$ due to nuclear effects

Target	CCQE/10^{21} POT (with 10^6 x N_A targets*)
D	4062
^{12}C	23045
^{16}O	30965

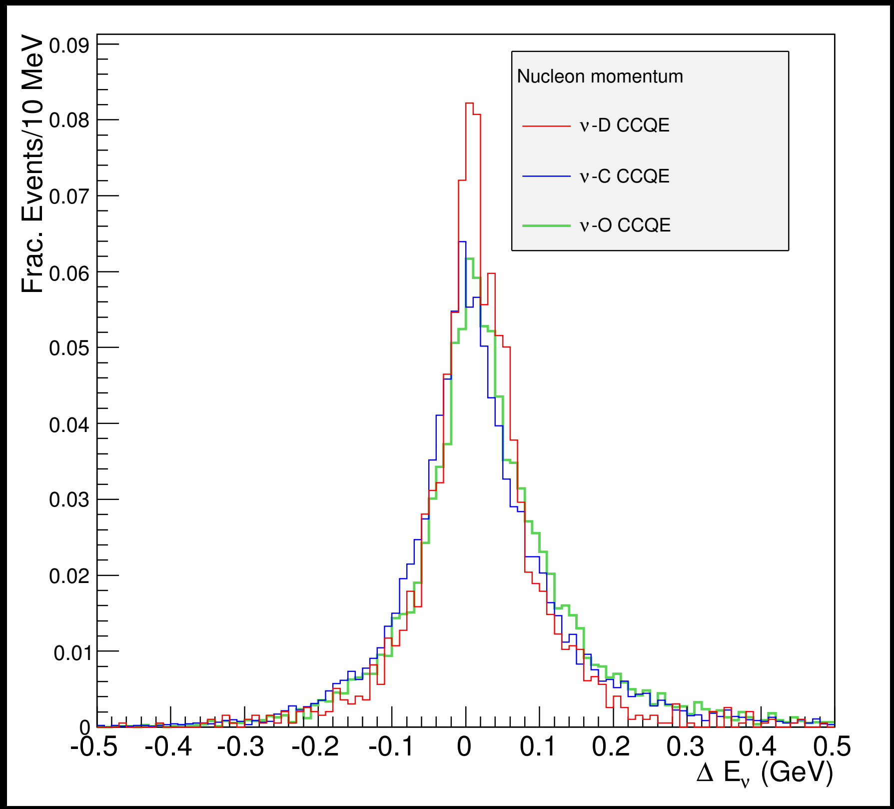
* = 1 ton H_2O
1.11 ton D_2O
0.72 ton CH

N.B. 700 kW $\cdot 10^7$ sec = 1.46 x 10^{21} POT
1.66 MW $\cdot 10^7$ sec = 3.46 x 10^{21} POT

Kinematics of Genie ν-D events



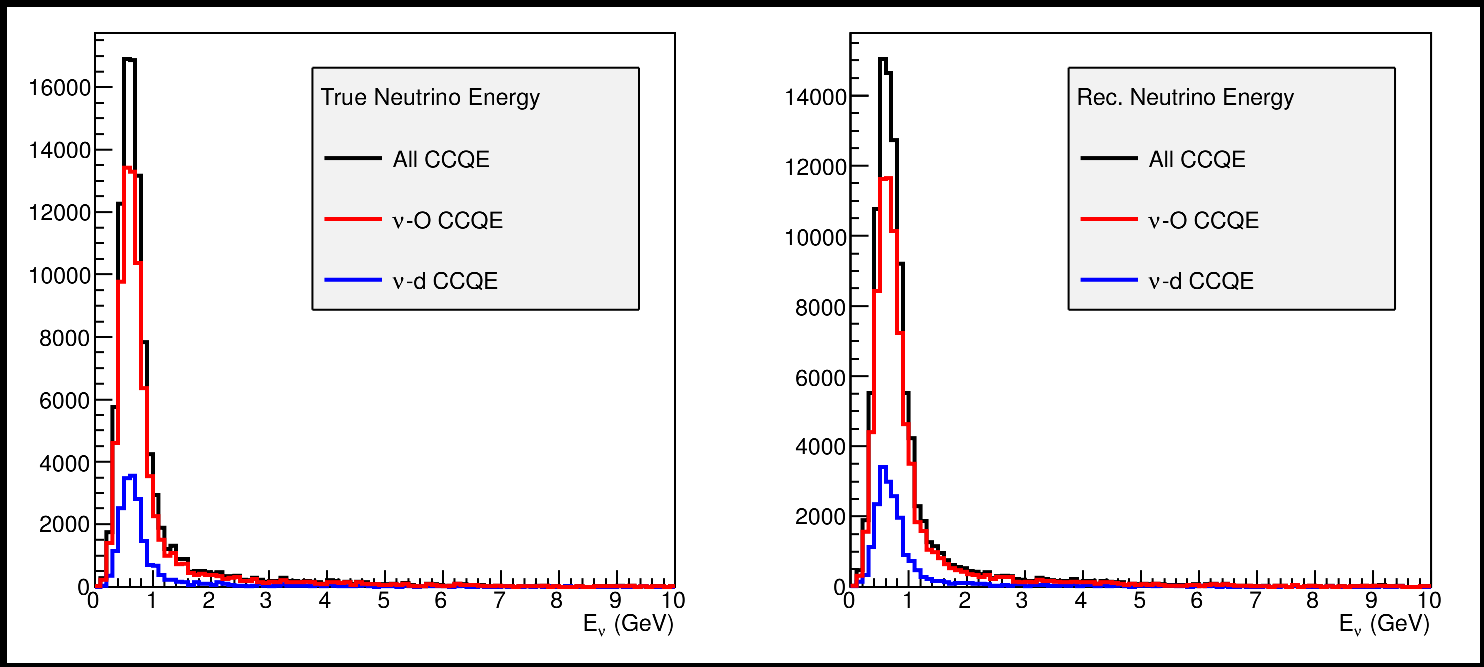
- Fermi momentum still affects energy reconstruction significantly
  - whether this is theoretically understood is critical to whether this is worthwhile
  - **reconstructing the recoil proton** would provide a check within the detector



- Valid theoretical modeling (experimental verification) is critical
  - Provides "foundation" from which to extrapolate to more complex nuclei (^{12}C, ^{16}O)
- Reconstruction of recoil proton may be a large factor in the detector design

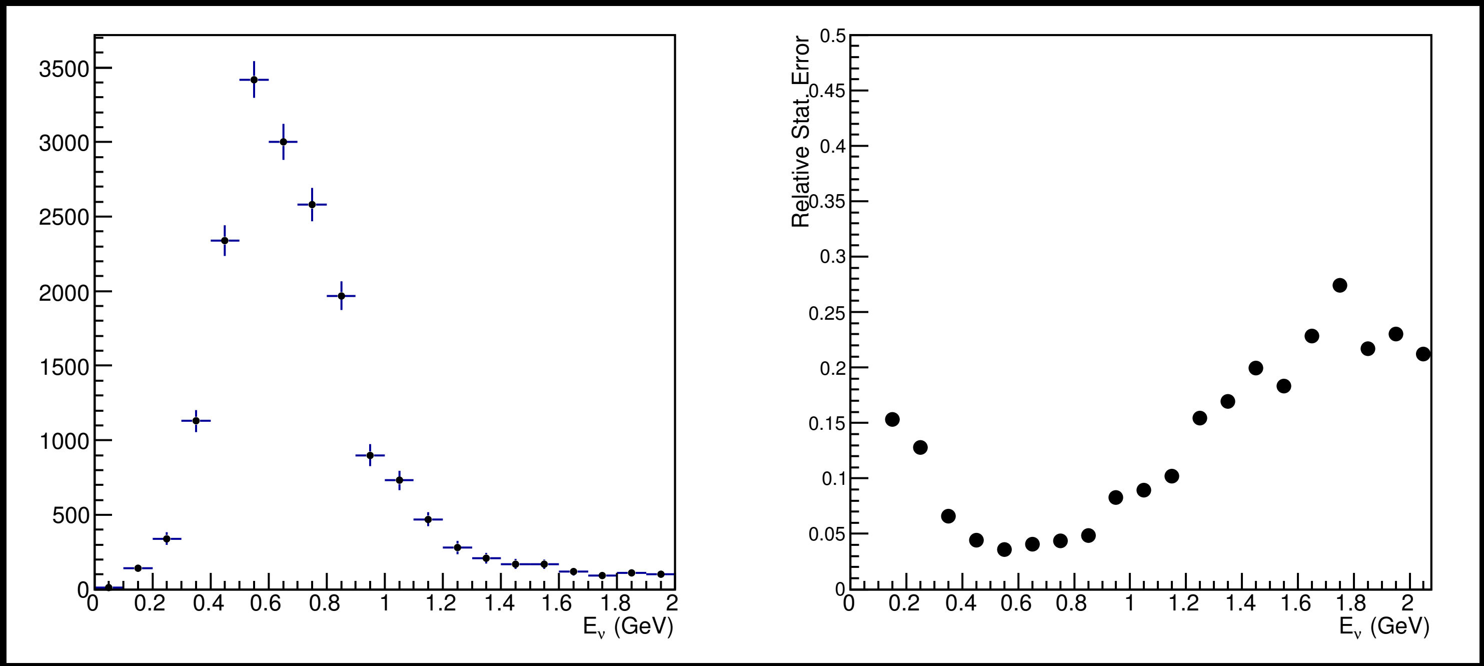
Current state of $(\nu/\bar{\nu})$-D modeling. Should update to latest knowledge

Statistics



- true and reconstructed neutrino energy distribution for ~100k CCQE events
- Approximately 1 ton-year at 1.66 MW (not accounting for efficiency)

- Expected statistical error following subtraction of ^{16}O component
- ~5% statistical error in off-axis peak region



- Obviously, better statistical precision can be obtained by larger target mass (>1 ton) or more running (> 1 year)

Physics/Analysis

- Following subtraction, one has the reconstructed neutrino energy distribution from ν-(p/D) CCQE scattering
  - (hopefully) minimal neutrino cross-section/modeling uncertainties
  - should agree with observed ν-(^{12}C/^{16}O) CCQE if modeling is correct.
- If proton kinematic reconstruction is available:
  - E_ν reconstruction on D can be directly tested by comparing kinematic reconstruction using p_μ with the "fully-reconstructed" events summing E_μ and E_p event-by-event
- Will provide a strong anchor for neutrino xsec/interaction studies
  - any "complex" detector will need a strong ν-int program
  - extend into low energy (<1 GeV) range below MINERvA.

Materials:

- Is ND280 FGD approach sensible?
  - in principle we can have targets consisting of:
    - CH/CH_2 (plastic/liquid scintillator)
    - H_2O (passive, or possibly with liquid scintillators)
    - + deuterated counterparts
  - this would allow extracting $\nu/\bar{\nu}$ scattering off p/D
  - We need to learn from ND280 experience as it evolves
- Availability:
  - D_2O:
    - O(1 ton) is needed for near detector.
    - **Does not need to be high purity**
    - Small compared to SNO (1kT) but where to get it?
  - Deuterated plastic (CD)
    - Available, though very expensive in small quantities

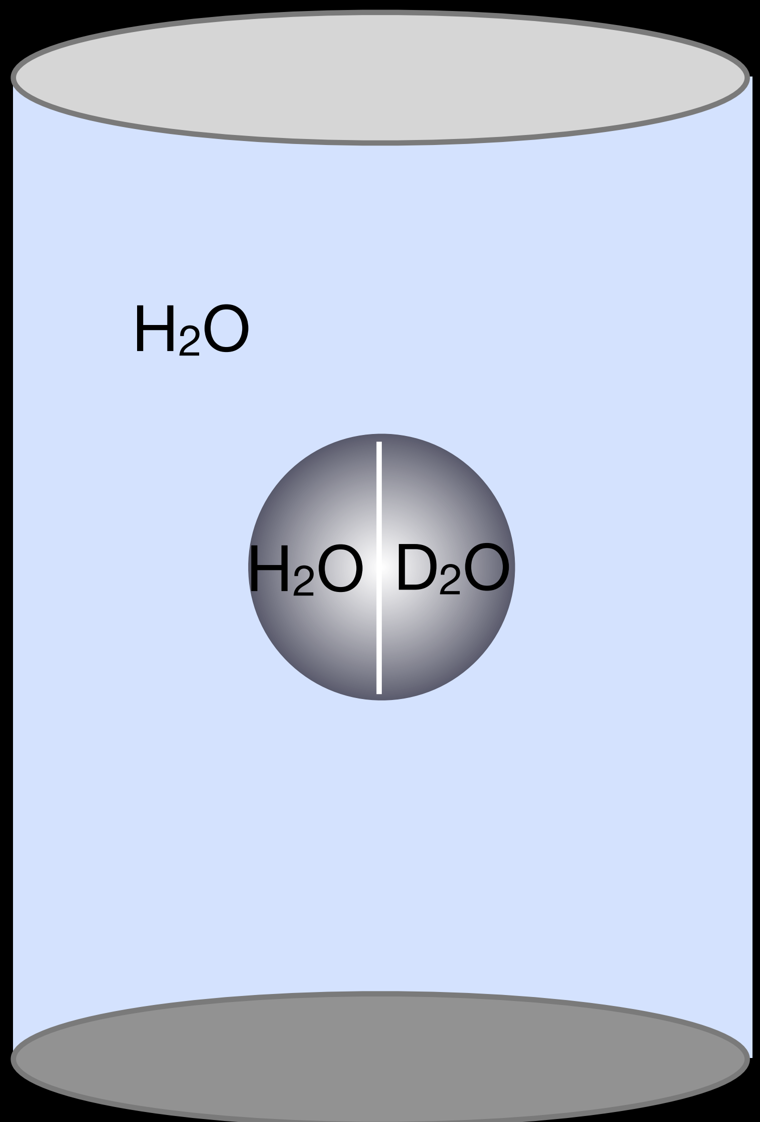
Further thinking/study:

- How important is proton reconstruction/tagging?
  - This will probably be the driving issue in detector design
  - if “FGD” style detector is sufficient, H_2O scintillator, deuterated scintillator might enhance short-track reconstruction
  - if not, then we may need to consider new detector concept
    - also if better/full angular acceptance is needed
- Theoretical understanding of e/ν/$\bar{\nu}$-D scattering
  - if this is too weak, the whole approach may not be worthwhile
    - then we need to consider another option
  - if very solid, proton reconstruction requirements may be less stringent.
- We should consider other detector concepts anyways
  - those mentioned thus far are the most straightforward extension of existing near detector at T2K (ND280)

CO_2 TPC?

- Considered in early days of TPC project with GEM readout
  - large gain needed
- Study ν-^{16}O interactions in great detail with full kinematic coverage
  - detailed reconstruction of hadronic final state
  - "calorimetric" reconstruction of E_ν in addition to "kinematic"
- Possible issues:
  - Statistics: $\rho \sim 2$ kg/m^3 at STP
    - three 2x2x1 m^3 TPCs → ~700 interactions/10^{21} POT
    - 1500 interactions/year at 1.66 MW
    - bigger TPCs may be desirable if gas is the target (2x2x2m^3?)
  - how to isolate the oxygen interactions?
  - backgrounds?

Water Cherenkov?



- Central fiducial volume of O(1 kt) H_2O Č detector segmented using an acrylic vessel
  - One contains H_2O, the other D_2O
  - segmentation should be symmetric
    - possible L/R configuration shown, where ν-D events are extracted by L/R subtraction.
    - If circulation is possible:
      - H_2O/D_2O swapped for systematic studies
      - single vessel with alternating fills.
    - removable vessel to study systematics?
- Possibility for intermediate (~1km) detector?
  - simultaneously cancel detector + neutrino interaction uncertainties more effectively?

Conclusions

- HK needs a near detector
  - even continuing to use existing ND280 needs planning/resources
  - design should be informed by physics
    - large θ_{13} may alter priorities of signal/background issues
    - experience from ND280 (and other experiments)
- Minor extensions to ND280 allow introduction of p/d targets
  - isolate their interaction by subtraction
  - study ($\nu/\bar{\nu}$)-(p/d) interactions in a better controlled nuclear environment
  - address issues with "CCQE" interactions important for CPV studies
  - foundation for a broad neutrino interaction program
  - could happen before HK in the context of T2K?
- If significantly better performance (angular coverage, proton reconstruction) is required, a more radical departure is needed
  - we should think broadly in any case to find the best solution(s)