Physics studies for the ND280 upgrade

ND280 Upgrade Workshop
- May 2017 Tokai -

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Reproducing the oscillation analysis

- **Well known and quantitative approach** (Simon's talk)

- **Results depend on the xsec model we use**...
  (Eg: larger angular acceptance is beneficial proportionally to the size of the $Q^2$-dependent uncertainty we assume)

  ... and we know that our xsec model does not describe our ND280 data (and the external data) well (yet?)

**ND280 BANFF 2016**
**prefit CC0π sample**

**MINERVA q3,ω measurement**
More wide approach

More basic studies: **how well can we measure a given physical effect in the upgrade?**

- **C/O** study → is an oxygen target beneficial?
- $\nu_e/\nu_\mu$ uncertainty → what do we need to measure $\nu_e$ well enough to be useful for the oscillation analysis?
- threshold for low momentum particles (eg: protons) and vertex activity → would a 'more light' target give us useful information?

Less model-dependent studies

but also less straightforward... we are still learning about these issues in T2K:

- we have not yet the statistics in OA to be limited by these issues but we need to anticipate what will happen at much larger statistics in T2K-2
- we don't know yet how to exploit such measurements to improve the model

Not clear if something is feasible in the available timeline of the upgrade studies... but at least we may use these studies to setup same fake-data studies for the BANFF fits
The uncertainties we are including in our OA are relatively small → **will be ever capable of measuring C/O well enough at ND280 upgrade to be useful?**

- The C/O uncertainty is due to different nuclear structure/size → most of the effect at very low transferred energy to the nucleus ($\omega$)
  Typically parametrized as a function of Fermi momentum and binding energy

- The best way I found to estimate this uncertainty is to use the latest CCQE+2p2h model from SuSa which tuned the A-dependency from electron scattering data

T2K uses:
- Carbon $p_F$ 223 MeV
- Oxygen $p_F$ 225 MeV

**sorry, this is not public yet :)**
Looking into more details

- 2p2h and CCQE have opposite C/O behavior! \( \rightarrow \) 2p2h \( \sim \) \( A^*p_F^2 \), CCQE \( \sim \) \( A/p_F \)

Some cancellation: C/O difference 5% goes down to \( \sim \) 1-2%

- Most of the effect in the very low muon momentum region (very difficult to measure muons in water at \( \sim \) 100MeV)

- A large effect also at \( p_\mu \sim 600 \) GeV but this is due to change in 2p2h/CCQE ratio \( \rightarrow \) quite model dependent effect...

PRIVATE MODEL PREDICTIONS FROM SUSA GROUP (PLEASE, DO NOT CIRCULATE)

sorry, this is not public yet :)
How well can we measure C/O?

Only statistical uncertainty considered!

Compare simplified simulation of ND280 with real analysis (TN305)

\[
\frac{\delta R_{O/C}}{R_{O/C}} = \sqrt{\frac{1}{N_{\text{events on C}}^{\text{Target 1}}} + \frac{1}{N_{\text{events on C}}^{\text{Target 2}}} + \frac{1}{N_{\text{events on O}}^{\text{Target 1}}} + \frac{1}{N_{\text{events on O}}^{\text{Target 2}}}}
\]

\[6 \times 10^{20} \text{ POT}\]

| Configuration            | \(N_{\text{events}}^{C}\) | \(N_{\text{events}}^{O}\) | \(\frac{\delta R}{R}|_{\text{inc}}\) (%) | \(\frac{\delta R}{R}|_{0\pi}\) (%) |
|--------------------------|-----------------------------|-----------------------------|------------------------------------------|-----------------------------------|
| current-like             | 40842                       | 11756                       | 1.047                                    | 1.303                             |
| current-like (FGD2)      | 14333                       | 11748                       | 1.908                                    | 2.391                             |
| upgrade ref.             | 22932                       | 25280                       | 0.912                                    | 1.109                             |
| upgrade alt. Target → TPC| 58623                       | 51394                       | 0.604                                    | 0.746                             |
| upgrade alt. TPC → Target| 58257                       | 48574                       | 0.614                                    | 0.754                             |

- The value in blue is to be compared with current ND280 simulation results: \(\delta R/R \sim 2.5\%\).
- Current analysis (TN-305) has: \(\delta R/R \sim 4.5\%(\text{stat}) \oplus 2\%(\text{sys})\)
  (taking all effects of migration... into account)
Results for $8 \times 10^{21}$ POT (upgrade reference)

Not much gain with respect to ND280 current because of smaller mass of the new targets.

sorry, this is not public yet :)

M.Lamoureux
Clear improvements with respect to current ND280

Still not obvious that we can measure it if we include 2% systematics and in a real analysis ~factor 2 larger statistical error (eg, from background fluctuation)

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M. Lamoureux
Results for $8 \times 10^{21}$ POT (upgrade alternative 2)

alt. TPC $\rightarrow$ Target upgrade configuration

alt. TPC $\rightarrow$ Target upgrade configuration

sorry, this is not public yet :)

muon cost
Pion FSI in C and O

- We constrain the probability of pion rescattering in the nucleus from $\pi$-N scattering data → uncertainty from data +
  → large uncertainty extrapolation from nucleus surface to inside the nucleus fully based on (not well known) nuclear physics model

- The correlation between C and O FSI uncertainty is actually very large (for what we know... see backup)
  - ND280 fit use fully correlated FSI uncertainty between C and O

- In any case measuring low momentum pions in water target is not feasible...
  - not much an issue of ND design, more useful to have external data on $\pi$-nucleus scattering measured on O
\( \nu_e / \nu_\mu \)

- This is considered the **dominant systematics** for oscillation measurements at very large statistics (eg DUNE and HyperKamiokande)

- Measure of CPV relies on the rate of \( \nu_e \) and \( \bar{\nu}_e \) appearance after oscillation

\[
\sin (\delta_{CP}) \approx \frac{(\nu_\mu \rightarrow \nu_e) - (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{(\nu_\mu \rightarrow \nu_e) + (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}
\]

\( \rightarrow \) difference between \( \nu_\mu \) and \( \nu_e / \bar{\nu}_e \) xsec has a direct impact on \( \delta_{CP} \)

- In present OA we assume an uncertainty of **2% uncorrelated between \( \nu_e \) and \( \bar{\nu}_e \)**
  + **2% anticorrelated**

\[
V_{\nu_e, \bar{\nu}_e} = V_{rad. corr.} + V_{SCC} = \begin{pmatrix}
\sigma_{\nu_e}^2 & \sigma_{\nu_e} \sigma_{\bar{\nu}_e} \\
\sigma_{\bar{\nu}_e} \sigma_{\nu_e} & \sigma_{\bar{\nu}_e}^2
\end{pmatrix} = \begin{pmatrix}
2 \times 0.02^2 & -0.02^2 \\
-0.02^2 & 2 \times 0.02^2
\end{pmatrix}
\]

(more discussion about where this uncertainty comes from in backup)
$\nu_e/\nu_\mu$ : extrapolating from present status

- **Measurement of intrinsic $\nu_e$ component in the flux**

$$R(\nu_e) = 1.01 \pm 0.06({\text{stat.}}) \pm 0.06({\text{flux }+ x.\text{sec}}) \pm 0.05({\text{det. }+ FSI}) = 1.01 \pm 0.10$$

  (in Phys.Rev. D89 (2014) 099902, $6 \times 10^{20}$ POT)

  but it assumes same $\nu_e$ and $\nu_\mu$ cross-section model (i.e. measuring the rate knowing the xsec shape from $\nu_\mu$)

- A **measurement of $\nu_e$ cross-section** give instead:

$$\langle \sigma \rangle_\phi = 1.11 \pm 0.09 \, \text{(stat)} \pm 0.18 \, \text{(syst)} \times 10^{-38} \, \text{cm}^2/\text{nucleon.}$$

  (in Phys.Rev.Lett. 113 (2014) no.24, 241803, $6 \times 10^{20}$ POT)

  **systematics uncertainty**: 13% flux, 8% detector (let's optimistically assume to be fully correlated between $\nu_e$ and $\nu_\mu$) → remaining 6% uncertainty (2% OOFV $\gamma$ background)

→ **to get to $\sim 2\%$ $\nu_e/\nu_\mu$ measurement we need to gain a factor $>3$ in systematics**
\( \nu_e \) statistics at low energy

OA electron events are below 1 GeV but, due to efficiency, ND280 electron events are mostly above 1 GeV

\[ \text{Stat error below 1 GeV (eg from } \mu \text{ decay only) is 4 times larger than total:} \]

\[ R(\nu_e(\mu)) = 0.68 \pm 0.24(\text{stat.}) \pm 0.11(\text{flux } \oplus x.\text{sec}) \]

\[ \pm 0.14(\text{det. } \oplus FSI) = 0.68 \pm 0.30 \]

35% → 8% with \( 10^{21} \text{ POT} \)

Need to improve by a factor \( \sim 16 \) the stat (larger mass, better efficiency and purity)
• Present ND280 proton measurements limited by efficiency → in practice only the protons with momentum > 500 MeV can be reconstructed

phase space: muon angle vs proton momentum

µ+p efficiency vs proton momentum

µ+p efficiency vs muon angle

• Interesting ND280 upgrade: a much larger angular acceptance on muons (horizontal TPC) coupled with a light CH target for low momentum protons

→ big improvements in muon+proton(s) measurements

Example for empty WAGASCI-like target
Example: transverse variables

Official T2K results from TN278 (S. Dolan)

Proton rate dependent on FSI due to $p_p > 500$ MeV cut

→ interpretation of other experiments with lower threshold (Minerva, ArgoNEUT) is not conclusive...
Example: proton multiplicity

2p2h signature gives 'often' 2 protons but most of the time they are low momentum → present multiplicity measurement also limited by high momentum threshold

- We can certainly learn 'a lot' from a light target … can we be more quantitative? Is the gain large enough to compensate the lost of mass in the target?

- Difficult to answer since even the results from present low-threshold experiments did not produce (yet?) a flourish of theoretical interpretation
A more complete picture is emerging... (much less 'demanding'/difficult variable for the detector and for the model predictions)

MINERvA:

- **comparison** $\nu - \bar{\nu}$: systematics highly correlated (70%)

possible 2p2h signature:

- $\nu_\mu$ **data**: suggest additional proton with $E<225$MeV in $25 \pm 1$(stat) $\pm 9$(syst) % of events

- $\bar{\nu}_\mu$ **data**: no additional proton (2p2h would produce neutrons)
Conclusions

- We have well-known quantitative assessment of physics gain from the upgrade using the BANFF fits and reproducing the OA results

- Less model-dependent studies are also useful even if difficult to quantify

Need manpower!
Eg, for proton variables and vertex activity, study the gain in sensitivity to separate the models with a new light target with lower threshold

- Need to find the best compromise and/or prioritize between:
  
  large mass target (beneficial for $\nu_e$) and/or large water target (for C/O) against
  light target for low momentum protons (and pions)
Pion scattering on C, O, Cu

Elder Pinzon
Pion FSI fit results

Normalization Parameters

- C only
- O only
- All nuclei

χ² / N_{DOF}:
- C only: 18.16/27
- O only: 7.02/1
- All nuclei: 53.10/59
\[ \delta_{CP} \text{ and } \nu_e/\bar{\nu}_e \text{ xsec} \]

- Measure of CPV relies on the rate of \( \nu_e \) and \( \bar{\nu}_e \) appearance after oscillation

\[
\sin(\delta_{CP}) \approx \frac{\left( \nu_\mu \rightarrow \nu_e \right) - \left( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \right)}{\left( \nu_\mu \rightarrow \nu_e \right) + \left( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \right)}
\]

\( \rightarrow \) difference between \( \nu_\mu \) and \( \nu_e/\bar{\nu}_e \) xsec has a direct impact on \( \delta_{CP} \)

- Very low statistics of \( \nu_e \) in 'standard' beam \( \rightarrow \) cannot be constrained at ND

\( \nu_e/\bar{\nu}_e \) largest systematics for DUNE and HyperKamiokande

- For future long baselines what matter are the uncorrelated uncertainty between different neutrino flavors and 'charge':

\[ 5\% \pm 1\% \]
\[ 5\% \pm 2\% \]
\[ 5\% \pm 3\% \]

\( \rightarrow \) equivalent to factor 2 in exposure!
In principle, if $\nu_\mu$ xsec is perfectly known, the model can be easily used to extrapolate to $\bar{\nu}_\mu$ and $\nu_e$ (lepton universality and CP symmetry hold in neutrino interactions).

In practice, large uncertainty on $\nu_\mu$ due to nuclear effects, may affect differently $\nu_\mu$, $\bar{\nu}_\mu$ and $\nu_e$.

→ Uncorrelated uncertainty between $\nu_\mu$, $\bar{\nu}_\mu$ and $\nu_e$ are just a product of our limited knowledge on $\nu_\mu$ interactions.

Correction to the CC inclusive cross-section due to nuclear effects for different model with theoretical uncertainty band:

Need to control $\nu_\mu$ *very* precisely (or find a way to produce a high stat beam of $\nu_e$.)
An important missing piece for $\nu_e$

Different radiative corrections for $\nu_e \rightarrow e$ and $\nu_\mu \rightarrow \mu$ (because of different lepton mass)

- The only approximated calculation available is:

That formalism has been recently applied to QE cross-section computation:

$\sim 10\%$ effect on the difference between $\nu_\mu$ and $\nu_e$ cross-section!

$\rightarrow$ need less approximated calculation?
Protons in Minerva (1)

- Track in scintillator with dE/dx compatible with proton: **threshold $E_{\text{kin}}^p > 110$ MeV** with ~ 50% efficiency

**CC0pi analysis: effect of proton ID cut:**
Proton-muon correlations

Angle between $\nu$-$\mu$ and $\nu$-$p$ planes

Large FSI effects

$Q^2$ estimation affected by:
- proton threshold
- initial nucleon momentum
- large FSI effects

$Q^2$ from proton kinematics

$Q^2$ estimation affected by:
- proton threshold
- initial nucleon momentum
- large FSI effects
**Protons in LAr**

- **ArgoNEUT**: small statistics but powerful Ar technology → waiting for MicroBooNE!

- 30 events with 2 protons: some of them back-to-back in LAB frame ('hammer events')

- significative measurement of proton multiplicity
Future prospects

- **ND280 interactions on TPC cathode** (very low proton threshold)

  ![FGD1 (for comparison)](image)

- **High Pressure TPC**

  Threshold kinetic energy to have 1cm track in Ar TPC

  ![Momentum threshold](image)

  - Atm pression: ~30 MeV
  - 10 bar: ~70 MeV
  - Liquid Ar: ~200 MeV
Are we able to interpret the results?

What do we learn from the kinematics of such low energy protons?

- Limited predictivity on outgoing nucleon(s) kinematics of the most advanced models (e.g., proton kinematics in 2p2h?)
  Outgoing nucleons are strongly affected by initial nucleons kinematics in the target nucleus (exclusive measurements in electron scattering may help)

- Main problem: measured protons depend on the convolution of nuclear effects in the interactions and Final State Interaction

Need to measure proton scattering and improve proton FSI modeling!

~40% of protons undergo FSI

Nuclear transparency in electron scattering data

Cross-section for proton knock-out in GiBUU

FSI effects change the outgoing proton kinematics

\[
\text{Cross-section for proton knock-out in GiBUU:}
\]

\[
\text{Nuclear transparency in electron scattering data:}
\]

\[
\text{Physics Letters B 351(1995) 87-92}
\]

\[
\text{FSI effects change the outgoing proton kinematics}
\]
Varying no. of tpc tracks

Neut

Vertex Activity for Numu Sample

Genie

Vertex Activity for Numu Sample

Pratiksha Paudyal