Systematics on (long-baseline) neutrino oscillation measurements

- **Introduction on oscillation measurements**: present results from T2K and NOVA and precision needed for next generation HyperKamiokande, DUNE

- Overview of the systematics:
  - How **neutrino flux and cross-section** affect neutrino oscillation measurements?
  - **Flux** simulation and tuning
  - Main neutrino **cross-section uncertainties** (from an experimentalist point of view)

- Neutrino oscillation analyses and xsec systematics in details: **the T2K and NOVA examples**

S.Bolognesi (CEA Saclay) - T2K
Neutrino oscillation analyses and xsec systematics in details
Long baseline (295 km) neutrino oscillation experiment with off-axis technique:

**Near Detectors:**
- **On-axis:**
  - iron/CH scintillator monitoring of beam angle and position
- **Off-axis:**
  - full tracking and particle reconstruction in near detectors (magnetized TPC!)

**Far Detector:**
- huge water cherenkov detector (50 kTon) with optimal \( \mu/e \) identification to distinguish \( \nu_e, \nu_\mu \)

**Diagram:**
- Super-Kamiokande
- J-PARC
- Far Detector
- Near Detectors
- Off-Axis: ND280
- On-Axis: INGRID
- Clear ring vs. fuzzy ring
- Atmospheric \( \nu_e \) identification

**T2K:** Tokai (JPARC) to Kamioka (SuperKamiokande)
Super-Kamiokande: $\nu_e$ vs $\nu_\mu$

A. Messer INSS 2017

Figures from
http://hep.bu.edu/~superk/atmnu/
Super-Kamiokande: background

CC \(1\pi\) :
if pion above Cherencov threshold 'easy' to reject (ask for 1 only ring)
if below threshold (~150 MeV) look for Michel electrons

NC \(\pi^0\) at high energy very similar to \(\nu_e\)
Still good separation using \(m_{\gamma\gamma}\) and vertex time, position, momentum, direction:
1-ring vs 2-rings hypothesis (90% \(\pi^0\) rejection with 80% \(\nu_e\) efficiency)
Super-Kamiokande spectra

Neutrino CCQE 1 \( \mu \)-like ring

Antineutrino CCQE 1 \( \mu \)-like ring

T2K Preliminary
(not tuned MC)

Neutrino CCQE 1 e-like ring

Antineutrino CCQE 1e-like ring

Neutrino CC1\( \pi \) 1e-like ring
T2K near detector: ND280

Multipurpose detector for full characterization of neutrino interactions:

- **FGD scintillators**: main target for neutrino interaction \((\text{CH} + \text{H}_2\text{O})\)
  - vertex position and energy deposition around the vertex
- **fully magnetized** (0.2 T)
- **TPC** → **good tracking efficiency, resolution** (6% \(p_T<1\text{GeV}\)) and **particle identification**
- **Ecal** all around tracker region to measure \(\gamma\) from \(\pi^0\) and electrons
- **Side Muon Range Detector** in the magnet for escaping particles
- **P0D** scintillator with water target (not yet used for oscillation analysis)
Neutrinos at ND280

Muon reconstruction (same for all CC processes) and particle ID to separate the interaction channels:

- **CCQE event with proton > 500 MeV**
- **CC1π+: particle ID (p vs µ, π vs e) with dE/dx in TPC**
- **DIS event**

**Muon p_T resolution**

**Muon reco efficiency**

**Particle ID in TPC**
ND280 spectra

- **Neutrino beam mode**: selected interactions in FGD1
  
  - $\mu^-$ no pions (CC0$\pi$)
  
  - $\mu^-$ $\pi^+$ (CC1$\pi$)

  Same selection also available for interactions in FGD2 (CH + Water)

- **Antineutrino beam mode**:
  
  - $\mu^+$ no pions (CC1 track)

  Same selection also for $\mu^-$ in antineutrino beam mode to measure the wrong $\nu$ sign background in the flux

Neutrino cross-sections uncertainties measured separately for each process using the muon kinematics

Future: more variables (pion kinematics, protons, $E_{\text{had}}$ ...)

- **UNTUNED MC**
ND280 spectra

- **Neutrino beam mode**: selected interactions in FGD1
  - $\mu^-$ no pions ($\text{CC0}\pi$)
  - $\mu^-$ $\pi^+$ ($\text{CC1}\pi$)
  - $\mu^-$ multipions ($\text{CCOther}$)

  Same selection also available for interactions in FGD2 (CH + Water)

- **Antineutrino beam mode**:
  - $\mu^+$ no pions ($\text{CC1\ track}$)
  - $\mu^+$ + tracks ($\text{CCN\ track}$)

  Same selection also for $\mu^-$ in antineutrino beam mode to measure the wrong $\nu$ sign background in the flux

Neutrino cross-sections uncertainties measured separately for each process using the muon kinematics

Future: more variables (pion kinematics, protons, $E_{\text{had}}$ ...)

TUNED MC
Muon kinematics (T2K)

Full cross-section model with systematics parametrized with variable parameters → ND data divided in samples to fit cross-section parameters (+flux)

Using only muon kinematics

Prediction at FD: neutrino energy estimated from approximated formula

\[
E_\nu = m_\mu^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu \\
2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)
\]

(valid for 2-body scattering with nucleon at rest + correction for binding energy of nucleon)

Nuclear effects (initial nucleon momentum or additional final state particle) are estimated from MC to correct to true neutrino energy (MC fully tuned to fit to ND data)
Tuning of cross-section model
Main limitations of the far detector in order of importance regarding xsec uncertainties:

- At SK lepton kinematics only accessible in order to measure the energy (no access to nucleons and low momentum pions)
  → multipurpose ND can be used to ping-down the needed xsec inputs for corrections (and $E_{lep} + E_{had}$ at the ND can be measured)

- Signal for oscillation analysis limited to CCQE only
  → in future pion kinematics will be reconstructed at SK as well (Michel electrons can be used below threshold)

- Different near and far detector: different target and acceptance
  → also Oxygen target and some backward efficiency in ND

- No charge separation (need good control of nu intrinsic pollution in nubar flux and viceversa)
  → ND fully magnetized: precise measurement of wrong sign background in the flux
Angular acceptance

- T2K-2: new horizontal target and TPCs to enlarge high angle acceptance

ND280 Upgrade

SuperKamiokande events

Neutrino Mode 1 Electron-like Ring

T2K Preliminary
Multiple targets (C, O) at ND and FD

Phenomenological study neglecting the difference between nuclear model in Carbon and Oxygen:
Treatment of multiple targets

- **Part of ND280 data are on Carbon while SK is on Water**, we need to know how the cross-section change as a function of A (nucleus size)

  We rely on the model (NEUT MC) to predict the cross-section on C and O and when there are effects not well known, we introduce free parameters in the fit

- All the 'physics' is in the estimation of the correlation between the C and O parameters:
  - if we assume to know perfectly how to extrapolate from C to O, then we have one single parameter for C and O
  - if we don't know at all, then two uncorrelated parameters for C and O (we kill our sensitivity because is like using only FGD2 water data for ND constraints)
  - the reality is typically in the middle because C and O have similar A size (large correlation) but the nuclear effects are not well known

  T2K 2017 approach: nucleon-level (MAQE) fully correlated between C and O, BeRPA fully correlated, uncorrelated uncertainty for pF C and O and 20% correlation for 2p2h between C and O (from electron-scattering measurements)
Multiple targets: FSI and SI

FSI and Secondary Interactions: today: 2-3% uncertainty on signal at SuperKamiokande assuming NO correlation between C and O (no ND constraints)

Next analysis: full fit to pion scattering data over multiple targets → tune of NEUT FSI/SI model for all targets

(E. Pinzon, NuINT2017)
Example: 2p2h normalization C vs O

- 2p2h interactions are due to correlated proton-proton and neutron-proton pairs in the initial nucleus: how their number changes with A?

- Electron scattering data
  
  number of Short Range Correlated pairs is extracted from the comparison of $\sigma(e \rightarrow e'p)$ and $\sigma(e \rightarrow e'pp)$ measurement +
  
  corrected for FSI effects (large uncertainty)

- Measurements on C, Al, Fe, Pb (→ plot as ratio to C) compared to simple model

- $1\sigma$ uncertainty on the measurements gives 20% uncertainty on O prediction → C to O extrapolation known at 20%
  
  (i.e. 2p2h normalization parameter is correlated at 20%)
$E_\nu$ reconstruction: 2p2h bias

- CCQE formula to reconstruct $E_\nu$ does not hold for 2p2h

$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)}$$

Different 2p2h components give different $E_\nu$ biases

- OA approach: let free in ND fit 2p2h total xsec and Delta/notDelta fraction
Muon kinematics: limitations

- Estimation of neutrino energy from muon kinematics depends on nuclear model
  - Spreading of reconstructed $E_\nu$ for fixed true $E_\nu$ due to nuclear model
  - Some nuclear effects (scattering on correlated nucleon pairs, aka 2p2h) can also give a bias.

Very important to have proper parametrization of such effects at ND to correct for them:

- possible bias if **the model is wrong** and/or underestimation of the uncertainties if **the model is not complete**
  
- remaining **unconstrained uncertainties** from what cannot be measured at ND (eg: different acceptance or $\nu_e$ xsec)
NOVA

Same technology at ND and FD (not same size → different containment)

Scintillator oil → collect light and use topological info for PID
Example of events in NOVA

$\nu_\mu$ CC

$\nu_e$ CC

NC

Long, straight track

Shorter, wider, fuzzy shower

Diffuse activity from nuclear recoil system
Surface far detector, rate is driven by cosmic ray muons. Rate of 148 kHz.

Cosmics
Electrons vs muons and muon containment

- Need the muon to be contained to measure the momentum using the energy range
  → different efficiency for $\mu$ and $e$, different efficiency for ND and FD
  (different size → different $E_\nu$, $Q^2$ phase space for ND and FD)
- $\nu_e$ vs $\nu_\mu$ with visual neural network: not straightforward efficiency and different
  for electron and muons
Energy reconstruction

\[ E_ν = E_μ + E_{\text{had}} \]

Energy resolution and detector effects different for \( ν_μ \) and \( ν_e \) events: different reconstruction and selection.

Response depends on composition of shower (\( π^0/\text{hadrons} \)).

Energy estimator is a quadratic function of \( E_e \) and \( E_{\text{had}} \), with \( \sim 8\% \) resolution.
NOVA spectra

$\nu_\mu$ disappearance  $\nu_e$ appearance
NOVA limitations

Main limitations in order of importance for xsec systematics:

- Calorimetric energy reconstruction: entangling of detector effects (e.g. e/h) and xsec effects: neutrals + nuclear effects (E_b, ...)

- As a consequence: different energy response for \( \nu_e \), \( \nu_\mu \) and \( \nu \) vs \( \bar{\nu} \)

- 'Complicated' muon and electron ID and efficiency: dependence on kinematics of lepton and on topology (multiplicity)

- NC background and wrong flavor (\( \nu_e / \nu_\mu \)) background larger than SK?

The impact of most of these problems are highly suppressed by using the same technology at ND and FD

But... the cancellation is not complete because of

- different neutrino energy spectrum before and after oscillation
  (\( \rightarrow \) eg different fraction of neutrals)
Oscillation analysis in NOVA

- Measurement of all the (visible!) energy in the event to estimate the neutrino energy

Near to Far extrapolation

- Subtract NC expectation in ND, reweight MC in reco energy to match
- Transform to true energy, transport to FD with oscillations
- Transform to reco energy, add FD NC expectation back in
- Dependence on MC for background subtraction and true/reco matrix

Not only detector systematics but also theoretical uncertainties (FSI, multiplicity in the final state, fraction of neutrons...) do affect the true ↔ reco correspondence
Efficiencies

- **Efficiencies sculpted** by containment and background rejections + muon reconstruction more complicated in a high multiplicity environment
- Need to correct back separately for each process to avoid biases in $E_\nu$ reconstruction: correction depend on xsec of each process, hadron multiplicity, lepton kinematics...
NC background

Quite small background for $\nu_{\mu}$ since easy to disentangle a muon from an hadron

Larger for $\nu_e$:

ND data-driven tuning to correct for 10% discrepancy data-MC

3 regions of electron-classifier with different background fractions
Energy reconstruction

Need to correct from $E_{\text{rec}}$ to $E_{\text{true}}$

Correction depends on detector effects + xsec effects (eg neutrals) through efficiencies and resolution

Each process has different resolution + dependence on multiplicity, $\pi^0$ fraction, kinematics of leptons ...
Smearing and underestimation of neutrino energy due to nuclear effects + detector effects for DIS events

Different response for $\nu$ and $\bar{\nu}$ → possible bias on $\delta_{CP}$
2p2h

- Known mismodeling of hadronic energy in 2p2h (and beyond): important xsec systematics at NOVA for $\nu_\mu$ disappearance

- Another important effect that should be considered is the fraction on neutrons/protons in the final state (depending on the flavor of the correlated pairs in the initial nucleons)

$\nu + nn \rightarrow \mu^- + np$

$\nu + pn \rightarrow \mu^- + pp$

$\bar{\nu} + pp \rightarrow \mu^+ + pn$

$\bar{\nu} + np \rightarrow \mu^+ + nn$

$\rightarrow$ affect $\bar{\nu}/\nu$ differently: important systematics for $\delta_{CP}$
Calorimetric approach: limits

- **Main limitation:**
  - Calibration issues (no sensitivity to neutrons, energy threshold...)
  - Very limited predictivity from models regarding the hadronic final state!

The two problems are tightly convoluted and difficult to disentangle

Example from NOVA:

- **A taste of the future → DUNE:**
  - need to reconstruct precise $E_\nu$ shape for good sensitivity (two oscillation maxima)
  - capability of full reconstruction of tracks and showers down to very low threshold
  - need to reach very good control on detector calibration/uniformity *and* on neutrino interaction modelling which have convoluted effected in $E_\nu$
LAr TPC (MicroBooNE)

- Need to reconstruct muon/electron and hadronic showers to measure the total energy.

- **Muon momentum from multiple scattering**
  (+ correction for Michel electrons)

- **Energy resolution on the hadronic side:**
  - efficiency of shower clustering (vs noise removal)
  - \(\pi^0/e/\gamma\) identification and calibration of EM vs HAD side of the shower ...
  - detection threshold of low energy particle

Full study of these effects to be done: how the xsec uncertainties interplay with all of these effects?
(Test benches: MicroBooNE, LArIAT.. and protoDUNEs!!!)

To correct for these effects and go back to total En → need correct MC estimation of multiplicity and momentum of outgoing hadrons

**Uncertainties:**
- MC needed to correct for these lost protons
- mis-ID protons counted as pions – energy wrong, or muons – event topology wrong
No perfect solution

- Impact of neutrino cross-section uncertainties on oscillation measurements is a complicated problem!

- There is no perfect solution!

- Having two very different detectors (SuperKamiokande and NOVA) where the same systematics gives different effects is very valuable in order to:
  - check for possible bias on the results
  - better understand possible problems in the neutrino interactions

(hopefully this will be true also for HyperKamiokande and DUNE!)
How we are going to improve the xsec model uncertainty for the OA?

- **In a direct way adding new samples:** eg, improve efficiency for high angle and low momentum particles and include those in the ND fit of OA.

- **In a indirect way measuring neutrino interactions at ND (and elsewhere):**
  measure protons, vertex energy, … which are not directly included in OA but help us understanding the goodness of our models and/or constrain the prior uncertainties

→ **worldwide effort of cross-section measurements!**

*Effects on the cross-section which are very small (eg different neutrino flavours or carbon versus oxygen difference) will be very difficult to constrain directly from the data (need very large statistics and/or complex experimental setup/analysis)*

But if we do **high precision measurements in \( \nu_\mu \) on a given target** to better constrain the nuclear model then we will know **how to extrapolate to different target and neutrino species**

*(ie... we will never get rid of our models... better to have good ones !!)*
BACK-UP
Near detector constraints

Near detector is used to tune the xsec model but...

- some nuclear effects can be degenerate (indistinguishable) with near detector data but still give you different spectrum at far detector

- detector effects (calibration and threshold) can also be degenerate with nuclear effects

- anticorrelation between the xsec and the flux → difficult to constrain them separately (and they propagate differently at FD)

you can perfectly describe ND data and still be wrong in FD prediction

Impact of such problems on the oscillation analysis depends on the detector and how the analysis is done
What we need to control?

Uncertainties in ND→FD extrapolation:

- different $E_\nu$ distribution (because of oscillation)
  - $\nu$ flux has typically a wrong sign component
  - measure all particles in the final state: threshold and calibration at low energy (neutrons? FSI?)

- different target
  - A-scaling: measure cross-sections on different targets (and/or on the same target of FD)

- different acceptance
  - measurement of cross-section in the larger possible phase-space: increase angular acceptance and containment at ND

- different neutrino flavor (because of oscillation)
- $\nu$ ($\bar{\nu}$) flux has typically a wrong sign component
  - 'control' cross-section asymmetries between different neutrino species
The 'wrong sign' background comes from high $p_L$ pions (kaons) which cannot be defocused properly because they miss the horns.
Question from yesterday (2)

When proton hits the target it is more probable to create positive charged hadrons than negative ones.
Cross-section normalization

\[ \sigma_{\text{hadroprod}} = \sigma_{\text{tot}} - \sigma_{\text{el}} - \sigma_{\text{qe}} \]

\( \sigma_{\text{tot}} \) can be extracted from beam instrumentation in anti-coincidence with S4 (normalized to number of carbon nuclei in the target)

Need to correct for events with actual interactions in S4 using model

\( \sigma_{\text{el}} \) elastic scattering on carbon nucleus (from previous measurements compared to GEANT → largest uncertainty)

\( \sigma_{\text{qe}} \) quasi-elastic scattering on single nucleon in the carbon nucleus which get ejected (from GEANT)

\[ \sigma_{\text{prod}} = 230.7 \pm 2.8(\text{stat}) \pm 1.2(\text{det})^{+6.3}_{-3.5}(\text{mod}) \text{mb} \]
**Random Phase Approximation** is a non-perturbative method to describe microscopic quantum mechanical interactions in complex systems of many bodies.

The many-body system constituted by the mutual interactions of nucleons inside the nucleus cannot be resolved exactly → approximated calculation which parametrize the impact of such collective effects on the ν-N cross-section

- $Q^2 < 0.5 \text{ GeV}^2$ screening: nucleons embedded in nuclear potential
- $Q^2 \rightarrow \infty$ no RPA effect: if high energy transferred to nucleus than nucleons (→ quarks) ~ free
C-RPA

RPA is an \textit{approximation} → a more sophisticated computation Continuum-RPA describes the very reach details of the nuclear structure

Resonances at low energy transferred to the nucleus ($\omega$), ie low $E_\nu$ or very forward muon
Additional process: 2 particles-2 holes (only in nuclei)

CCQE (aka 1p1h) + 2p2h: interaction with correlated nucleons

Meson Exchange Currents (MEC)

Nucleon-Nucleon correlations

Pion in flight  Contact  Delta

Dominant in MEC

+ interference

Experimentally difficult to disentangle: final state can be pn or pp with low energy protons

CCQE + CC1pi (+DIS)

from Gran (Minerva) at 2p2h Saclay workshop

2p2h (Nieves)