Next obstacles in precision neutrino oscillations:

\( \nu \)-Nucleus cross-section

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Neutrino oscillations
Similar to quarks, flavour and Lorentz eigenstates of massive neutrinos are not identical.

The two eigenbases are related through the Pontecorvo-Maki-Nakagawa-Sakata matrix ($U_{PNMS}$).

\[
U_{PNMS} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\]
V oscillations

\[ U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta_{CP}} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{21} & \sin \theta_{21} & 0 \\ -\sin \theta_{21} & \cos \theta_{21} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

\[ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \]

- With 3\(\nu\), there are 3 angles and 1 imaginary phase:
- The imaginary phase allows for CP violation similar to the quark sector.
- There are also 2 values of \(\Delta m^2\): traditionally \(\Delta m^2_{12}\) & \(\Delta m^2_{23}\).
LBL concept

Interaction

$V_1$

$V_2$

$V_3$

$V_e$

$V_1$

$V_e$

$V_\mu$

$V_T$

Propagation

pion

muon

neutrino

neutrino

0$^{15}$

electron

0$^{16}$
V oscillations

Particle Data Group neutrino review

Status as of 2014

\[ \Delta m^2_{12} = \]
\[ \lvert \Delta m^2_{23} \rvert = \]
\[ \sin^2 \theta_{12} = \]
\[ \sin^2 \theta_{23} = \]
\[ \sin^2 \theta_{13} = \]
\[ \delta = 1.39^{+0.29}_{-0.33} \pi \]

\[ 7.54^{+0.26}_{-0.22} (10^{-5} eV^2) \]
\[ 2.43 \pm 0.06 (10^{-3} eV^2) \]
\[ 0.308 \pm 0.017 \]
\[ 0.437^{+0.033}_{-0.023} (\Delta m^2 > 0) \]
\[ 0.455^{+0.039}_{-0.021} (\Delta m^2 < 0) \]
\[ 0.0234^{+0.0020}_{-0.0019} (\Delta m^2 > 0) \]
\[ 0.0240^{+0.0019}_{-0.0022} (\Delta m^2 < 0) \]
Next steps

- $\delta_{CP}$ accessible through:
  - comparison of appearance with reactor disappearance.
  - comparison of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- The $\theta_{23}$ octant:
  - The $\theta_{23}$ is close to 45° but, how close?, is $\theta_{23} < 45^\circ$ or $\theta_{23} < 45^\circ$?

- What is the absolute neutrino mass? (Katrin?, Cosmology?,…)

- The mass hierarchy: is $m_3 > m_1$?
Next steps

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LBL concept

30 GeV protons
primary beamline

MR

target station
decay pipe
beam dump

μ

ν

ν

280m detectors

on-axis

off-axis

Super-Kamiokande

110m 120m 280m

Beam
Near site detector
Far side detector
LBL concept

Proton beam

Near detector monitor

Far detector

Invisible: $\nu$’s are not energetic

$\nu_\mu \rightarrow \nu_e$

$\nu_\tau \rightarrow \nu_e$

Materials and Life Science Experimental Facility

Linac 180-400 MeV

Rapid Cycling Synchrotron (3 GeV, 25 Hz, 1MW)

Main Ring (30 GeV, 0.3 Hz, 0.75 MW – 1.66 MW)

J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA
The observable is the disappearance/appearance of events as function of the $\nu$ energy.

We have to reconstruct the energy of the neutrinos!!!!!
• The number of events depends on the cross-section:

\[ N_{\text{events}}(E_\nu) = \sigma_\nu(E_\nu) \Phi(E_\nu) \]

• This is not so critical if we can determine the energy of the neutrino, since at the far detector

\[ N_{\text{events}}^{\text{far}}(E_\nu) = \sigma_\nu(E_\nu) \Phi(E_\nu) P_{\text{osc}}(E_\nu) \]

• and it cancels out in the ratio as function of energy:

\[ \frac{N_{\text{events}}^{\text{far}}(E_\nu)}{N_{\text{events}}(E_\nu)} = P_{\text{osc}}(E_\nu) \]
Cross-section problem

- Since the neutrino energy is not monochromatic, we need to determine event by event the energy of the neutrino.

- This estimation is not perfect, we have the problem that the cross-section does not cancels out in the ratio.

\[
\frac{N_{\text{events}}(E_\nu)}{N_{\text{events}}(E'_\nu)} = \frac{\int \sigma(E'_\nu) \Phi(E'_\nu) P(E_\nu|E'_\nu) P_{\text{osc}}(E'_\nu) dE'_\nu}{\int \sigma(E'_\nu) \Phi(E'_\nu) P(E_\nu|E'_\nu) dE'_\nu}
\]

- The neutrino oscillations introduce differences in the flux spectrum and the ratio does not cancel the cross-sections.

Oscillation experiments require to know both \(\sigma(E_\nu) \& P(E_\nu|E'_\nu)\)

Both are related to cross-sections !!!!
How to measure the neutrino energy?

**Low Energy ν’s (≈ 2GeV)**
- $E_\nu$ relies on the lepton kinematics.
- Channel identification is critical:
  - Final State Interactions
  - Hadron kinematics.
- Fermi momentum, Pauli blocking and bound energy are relevant contributions.

**Medium-high Energy ν’s (≈ 3GeV)**
- $E_\nu = E_l + E_{\text{hadrons}}$ with $E_{\text{hadrons}} \ll E_l$
- Hadronic energy depends on modelling of DIS and high mass resonances.
- Hadronic energy depends on Final State Interactions.
Cross-section problem

**Kinematics**

- Only a fraction of the energy is visible.
- Rely on channel interaction id.

**Calorimetry**

- The visible energy is altered by the hadronic interactions and it depends on hadron nature.
Assume that the **spectator nucleon is at rest** ignoring Fermi Motion which is comparable to neutrino energy (250 MeV vs 600 MeV in T2K) or larger in models like Spectral functions. **Need a good nuclear model.**

Assume that **one of the hadrons is not seen and we know its identity** (proton, pion, Δ, K, …). It can be one out of two or one out of one, **Need to define the interaction channel: final state particles!**

Assume the **neutrino direction** is known (true in far detector, not so at near detector).

Apply conservation of energy and momentum.
Partial summary

- LBL oscillation experiments requires an accurate calculation of the neutrino energy.

- Actually, we call it a cross-section problem but it is caused from our inability to:
  - precisely determine the neutrino energy event by event.
  - generate a mono-energetic neutrino beam.
The problem

Not well defined!

Short range correlations

Long range correlations

Fermi motion & Pauli blocking

FSI
Electron scattering

Initial/final states kinematics under control.

Short range correlations

Well define probe.

FSI

Long range correlations

Fermi motion Pauli blocking

Final state topologies accessible.
Electron scattering

- This is similar to neutrino interactions with known initial conditions.
- But it is not the same:
  - Only Vector current and not Axial current. This is only accessible through neutrinos (or photon scattering in some cases).
  - Initial particle is charged.
  - Initial and final particles are electrons (light with respect to muon in relation to initial/final state radiation).
  - Detector is not full coverage (4π) and normally experiments ignored the hadron production.
Electron scattering

- Control on incident beam kinematics allow to:
  - Identify the channel: Elastic, resonant, etc…
  - Calculate the kinematics of hadronic final state (smeared by fermi-motion).

- This allows to understand the:
  - vector component of interaction.
  - effects of FSI and final state multiplicities.

- It is relevant to analyse electron and neutrino scattering based on the same MC to increase synergies between the two worlds.
The problem

Long range correlations

Short range correlations

V\_1

|±

FSI

Fermi motion & Pauli blocking
The problem

- Present and future oscillation experiments cover a region full of reaction thresholds and sparse data.
The shopping list

- Future CP violation measurements with Long Base Line neutrino beams require “ideally” the measurement of $\nu_\mu$, anti-$\nu_\mu$, $\nu_e$ and anti-$\nu_e$
  - between $\sim 500$ MeV and $\sim 10$ GeV,
  - for (at least!) 4 nuclei: C, O, Fe and Ar. (Not all isoscalars!)
  - for $\sim 10$ exclusive channels:
    - QE, $1\pi^0\pm$, $N\pi^0\pm$, DIS both CC and NC.
    - Require a precise determination of the energy of the neutrino for the dominant(s) channel(s) at each energy.
CCQE + $2p2h$

The most urgent problem!!!
Why CCQE?

- It is the basic channel for neutrino oscillations at low energies (T2K)
- It is a clean signature (no pions produced) with simple neutrino energy reconstruction.
- Regardless its simplicity, the community faced many problems in the past:
  - Description of the axial component.
  - Disagreement among low and high energy experiments.
CCQE problems

\[ F_A(q^2) = \frac{F_A(0)}{(1 - q^2/M_A)^2} \]

- Vector current fixed by electron scattering.
- Axial current parametrised by dipole form factor with mass \( M_A \).
- \( M_A \) increases the cross-section at the high-\( q^2 \) region.
- These effects are observed in \( vA \) experiments.
- Is \( M_A \) an effective parameter?

Bernard et al. 2002
CCQE problems

Difficult to concile the low and high energy results.

Experiments define CCQE in different manners (no proton, one proton, etc…) and sometimes develop analysis under certain model paradigm confusing the model comparison.
• MiniBoone published a double differential $\nu$ cross-section for events with no pions in final state (CCQE-like).

• Theorist profited from the clean data to realize that we were missing 20% of the cross-section!

• We need to add a new channel (CC-2p2h)!!!
What is 2p2h?

- 2p2h is basically the exchange of a meson between two close by nucleons in the nucleons with the emission of 2 nucleons.
- The pion can be produced in a contact point or through an intermediate virtual $\Delta^{++}$.

It is possible that the same process happens with the emission of one pion through high mass resonances!
Random Phase Approximation (RPA) is a mathematical approximation to describe the modification of the W self-energy in the presence of high density nuclear media.

RPA alters the cross-section dependency with the $q^2$ (mass of the W propagator)
RPA predicts a deficit at low $Q^2$ and enhancement at large $Q^2$.

2p2h fills the low $Q^2$ to compensate RPA and we see enhancement at low $Q^2$.

The overall effect is that: 2p2h + RPA predicts large QE-like cross-section and enhancement at high $Q^2$. 

• This contribution was known to the electron scattering community for more than a decade.

• We needed double differential \( (p_\mu, \theta_\mu) \) data to observe np-nh with neutrinos.

Data fits equally well to:

\[ \text{CCQE } M_A = 1.31 \]

\[ \text{CCQE } M_A = 1.05 + \text{RPA} + 2p2h \]

If so: what is the problem?
2p2h and $E_v$

Effect of multi-nucleon (2p2h) interactions in the neutrino energy reconstruction.

- Recon values ($E_v$)
- $P(E_v|E'_v)$

The problem is that the $E_v$ is wrongly reconstructed.

PHYSICAL REVIEW D 85, 113008 (2012)
Limits of the model

- The main problem with these models is that they are valid only in certain regions of the available kinematic space. Nominally, the low $q^2$ region.
- Extrapolations to the high $q^2$ region are complex since it implies a different treatment of the nucleus (relativistic, non-relativistic).
- Agreement with experiments might vary with the typical experiment energy.

Proposed to use the momentum transfer to the nucleus as a reference cut and not neutrino energy.

Search for 2 proton

- LiqAr ArgoNeut has bubble chamber imaging capabilities to look into final states.
- It has first indications of correlated final state protons.
  - Spectral functions ? (~Initial state correlations)
  - 2p2h ? (~Final state correlations)
  - Both ?

Low statistics!
CCQE-2p2h partial summary

- Revolution during the last 5 years!
- Model is not yet settled due to nuclear contribution uncertainties.
- Lack of direct evidence (2 proton final state) of the 2p2h.
- Problems with the extension to large neutrino energy.
Final state interactions

$V_1$

$|\pm\rangle$

Long range correlations

Fermi motion & Pauli blocking

FSI

Short range correlations
Problem factorisation

- Example: events with $\mu^- + \pi^+$ in the final state.
- Topology is altered by FSI.

FSI alters the definition of the event

1. CCQE
2. Proton in final state
3. $p + p \rightarrow p + \pi^+

1. CC1 $\pi^+$
2. $\pi^+$ in final state
3. $\pi^+ + p \rightarrow p + p$

1. CC 2$\pi^+$
2. 2$\pi^+$ in final state
3. $\pi^+ + p \rightarrow p + p$
• Hadrons outside the nucleus will keep interacting altering the calorimetry.

• This is already part of the measurement program of WA105 but we need to measure exclusive channels and not only calorimetry.

This is already a dominant systematic @ T2K

Specific experiment (DUET) is being run to reduce it.
Experimental results

- Uncertainties from old experiments are large.
- These cross-sections do not cover the full range of interest in energy.
- Some of the results are inclusive.
- It is not obvious that and interaction of a hadron with a nucleus is the same for hadrons produced outside or inside the nucleus.
FSI partial summary

• Critical to the cross-section problem in nuclei.

• Sparse and non-precise data, it is also not available for all energies and all nuclei.

• Additional πA and pA experiments are needed to reduce uncertainties.

• Electron scattering might help to tune the “cascade” Monte Carlo models since the initial condition and energy is known.
CC $\pi^\pm$

$\nu_\mu$ $\rightarrow$ $\mu^\pm$

Background to CCQE if $\pi$ is missed!
Final state interactions alters the final state hadrons.

Experiments make measurements for pion production:

- @ nucleon level.
- theoretically easy.
- FSI correction by experiments, difficult to undo.

- leaving the nucleus.
- theorist need FSI model.
- no experimental modelling bias.
**CCπ⁺,⁰ data**

- Old deuterium data is inconsistent (probably flux)
- Difficult to tune MC models if the basic νp(νn) interaction is imperfect.
- FSI+nucleon model need to be tuned together (Large uncertainties in FSI!)

- Models are not able to describe CC π⁺ π⁰ and NCπ⁰ together.
• It is more complex than CCQE and is not well understood:
  • $C_A^5(0)$ (interaction strength)
  • resonant + non-resonant + interference,
  • transition to the forest of high mass resonances.
• Final state interactions
  • Problem, poor agreement with MC predictions:
  • Data “seems” to prefer no nuclear absorption of pions!.

O.Lalakulich et al, NuInt12 Proceedings
Courtesy of S. Dytman

GIBUU MC
Genie MC
Minerva results

- Preliminary results show agreement with MC predictions & disagreement with MiniBoone data.

- Minerva and MiniBoone are in a different energy region: backgrounds from large mass resonances?, ....

- Minerva and MiniBoone detection technique is very different: Signal definition?
The CC1π coherent has been an issue in neutrino interactions since a decade:

- Low cross-section but concentrated at low $q^2$ !!!
- The experiments were not able to find evidence at low energies.
- Some microscopic models predict that the coherent might help to understand the CC1π signal.

Low nuclear recoil (t)

No nuclear breakup and no proton (vertex activity)
CC $\pi^\pm$ coherent

- Minerva from vertex activity & nuclear recoil energy

Good agreement with models except in the shape of nuclear recoil!

- ArgoNeut from vertex activity.
Cross-section problem

**CC1π partial summary**

- CC1π is a difficult channel but it is the main background to other channels.
- Not well understood even at the nucleon level (old sparse data):
  - Nowadays it is almost impossible to make an active hydrogen(deuterium) active target detector.
- Large effects from FSI (π reinteractions!).
CC-Nππ

$\nu_\mu \rightarrow \mu^\pm$
This is a complex region with contributions from high mass $\Delta$ resonances and low $\omega$ DIS.

There is no new data since ANL and BNL back to the 80’s.

No data in nuclei: difficult measurement due to FSI.

No detailed pion kinematics available.

Critical for LBNE and LBNO!
Inclusive CC $\nu_e$
The $\nu_e$ problem

- Calculations show significant differences in the ratio of $\nu_e$ to $\nu_\mu$ cross-sections due to:
  - form factors.
  - radiative corrections.
  - lepton mass.

Dominantes @ low $E_\nu$ (T2K)
• Despite the relevance of the measurement, there are very little results (Gargamelle 1978):

• Conventional beams provide small $\nu_e$ flux:
  
  • excellent PID.
  
  • large sample.

• Two main flux contributions: $\mu$ decays and $K$ decays.

• The signal is masked by a large $\pi^0$ background from NC $\nu_\mu$. (~24% in the T2K selection)
CC inclusive $\nu_e$

First measurement in 36 years!

low statistics & large background!

Preliminary
$\nu_e$ partial summary

- Expected differences between $\nu_e$ and $\nu_\mu$ cross-sections at threshold.
- Critical for future experiments and CP violation search.
- Very difficult to make a pure $\nu_e$ beam although there are some new ideas popping up.
NC $\nu_{\mu}$
• 30 years old and sparse data & MiniBoone (2009).

• No new results in Nuint’14.

• Important background for $\nu_\mu$ disappearance (NC$\pi^+$) $\nu$ appearance. (NC$\pi^0$)

• $\nu$ sterile searches!
Recent results

2010 SciBoone NCT\(\pi^0\)/CC


2008 MiniBoone NCT\(\pi^0\) Coherent.


arXiv:0806.2347

2014 T2K NC-QE from nuclear de-excitation \(\gamma\) rays.

arXiv:1403.3140

2014 T2K NC \(\pi^0\)

2010 SciBoone NCT\(\pi^0\) coh.

2011 MiniBoone NC elastic.

arXiv:1110.6574
NC partial summary

- Sparse and non precise measurements.
- NC-$\pi$ is a background to oscillations ($\pi$ mistaken for an electron or a muon).
- There is no way to make a neutrino energy prediction because the outgoing neutrino is not detectable.
- Modelling will rely on CC since this is a simple modification of the lepton current.
Monochromatic beam?
Monochromatic beam

- Many of the problems in neutrino cross-section and neutrino oscillations comes from the reconstruction of the energy.

- Imaging you know precisely the response function of a detector:

\[ P(p_\mu, \theta_\mu | E_\nu) \]

- The oscillation result of the oscillation would be:

\[ \int P(p_\mu, \theta_\mu | E_\nu) \times P_{osc}(E_\nu) \times \phi(E_\nu) dE_\nu \]

- and the cross-section problem is reduced/vanished.
• The proportion of electron neutrinos to muon neutrinos increase for high off-axis angles.

• It needs careful study but it looks like an affordable option to get a rather pure $\nu_e$ beam.
Beam systematics

- I did not have time to talk about the importance of beam prediction systematics.
- Total flux and flux shape are crucial for precise cross-section measurements.
- Hadro-production experiments: NA61 / MIPP. (talk A.Korzenev on Friday)
- clean beam: NuStorm including electron neutrinos. (poster by D.Adey)
New Ideas: HPTPC

- TPC imaging capabilities.
- Interactions in the same gas (no passive material).
- Low momentum detected inside the TPC. Large momentum done with tracker chambers or range detector.
- Calorimeter for neutral energy containment.
- High pressure (~10 bars) to increase particle containment and # interactions.

A moving detector ("a la NuPrism") or tuneable beam will help to reduce systematics.

A dream (?) : A HPTPC filled with hydrogen and deuterium.
New Ideas: HPTPC

CCQE

$p_p = 365 \text{ MeV/c}$

$p_\mu = 483 \text{ MeV/c}$

CC$\pi$

$p_p = 250 \text{ MeV/c}$

$p_\pi = 115 \text{ MeV/c}$

$p_\mu = 690 \text{ MeV/c}$
• If the cross-section model is incomplete or incorrect, the fitting of free parameter does not solve the problem (like $M_A$).

• There are two “convolved” contributions to the exclusive cross-sections:
  • free-nucleon cross-section (all reference data still from BNL and ANL).
  • effects of nucleon inside high density nuclear matter (from pion & nucleon cross-sections).

• Axial, scalar and pseudo-scalar form factors are based on models.
  • $e^-$ scattering has no axial component, need $\nu$ data to derive them!.

• Better underlying theory. Theorist are requesting improvements in these measurements to be able to advance:
  • We need to repeat measurements in deuterium !!!!
Personal view

- If the cross-section model is incomplete or incorrect, the fitting of free parameter does not solve the problem (like $M_A$).

- There are two “convolved” contributions to the exclusive cross-sections:
  - free-nucleon cross-section (all reference data still from BNL and ANL).
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  **The problem is not the precise measurement of few parameters.**

- Axial, scalar and pseudo-scalar form factors are based on models.

- $e^-$ scattering has no axial component, need data to derive them!.

- The problem is the validity of the cross-section model itself.

- Better underlying theory. Theorist are requesting improvements in these measurements to be able to advance:

  - We need to repeat measurements in deuterium !!!!
Shopping list

- I believe (and I am not the only one!) the community needs, parallel to the LBL oscillation, a consistent program of neutrino interaction cross-sections involving:

1. Experiments with several targets nuclei and/or low proton thresholds: ~100 MeV/c.

- Monochromatic or changeable neutrino beam (off-axis?) & hadro-production experiments.

2. Clean electron neutrino beam: NuStorm, off-axis NuPrism...

3. Common MC tools and consistent models developed in close interaction with theorists.

4. Electron and photon scattering experiments needs to be integrated in the process.

5. Need of a deuterium target measurement.
Shopping list

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4. Electron and photon scattering experiments needs to be integrated in the process.
5. Need of a deuterium target measurement.

We need

1. better theoretical models.
2. data of better quality.
3. new detector concepts.
4. new beam concepts.
Backup and supporting slides
Neutrino Event Generators

- Coordinate theorist-experimentalist collaborative efforts to improve generators

Workshops: Organize Community-wide Workshops when needed

- Organization beginning on workshop to investigate np-nh/MEC nuclear effects

Training Programs: Organize and run training programs.

Global Fits: Combine results from multiple experiments to compare with and then, if necessary, modify a theory/model framework.
Near Minos

- Iron target.
- Magnetised.
- Large statistics.

<table>
<thead>
<tr>
<th>Principal: $0 &lt; Q^2 &lt; 1.2$</th>
<th>$M_A^{OE}$ (GeV)</th>
<th>$E_\nu$ Scale</th>
<th>$M_A^{RES}$ (GeV)</th>
<th>$K_{QE}^{Fermi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.21 $\pm$ 0.18</td>
<td>0.996 $\pm$ 0.007 &amp; -0.015</td>
<td>1.10 $\pm$ 0.15 &amp; -0.16</td>
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</tr>
<tr>
<td>Alternative: $0.3 &lt; Q^2 &lt; 1.2$</td>
<td>1.19 $\pm$ 0.19 &amp; 0.995 $\pm$ 0.008 &amp; -0.016</td>
<td>1.13 $\pm$ 0.17 &amp; -0.18</td>
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</tbody>
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CCInclusive

CCQE

F. Sánchez, Kavli IPMU, March 3rd 2015
MiniBoone

- 800 tons mineral oil Cherenkov detector.
- Boone neutrino line with sharp edge at 3 GeV.
- Flux constrained from HARP hadro-production experiment.
- ~450 MeV/c proton threshold.
- Excellent pion detection and tagging.
- Very large statistics.
MiniBoone

NC Elastic

$\nu_\mu$ CC$\pi^+$

$\nu_\mu$ CC$\pi^0$

$\nu_\mu$ CCQE

$\bar{\nu}_\mu$ CCQE
SciBoone

- Boone beam ($< 3$ GeV)
- Carbon target.
- Low proton tagging threshold ($p > 450$ MeV/c)
- Low statistics.
- Forward acceptance ($> 60^\circ$)

CC$_\pi$ coherent scattering.

Y. Nakajima, NuInt11
All detectors located within 0.2T UA1 magnet (charge sign determination):

- 3 Ar - time projection chambers (TPC) NIM A 637, 25 (2011)
- Electromagnetic calorimeters (ECALs JINST 8 P10019 (2013))
- Muon range detectors (scintillator in magnet, sMRD Nucl. Instrum. Meth. A 698, 135 (2013))
Nova ND

- Fully active target.
- Carbon target.
- Momentum by range.
- ND under construction.
- NDOS preliminary results.

New results expected in the future.
MicroBoone

- 60 ton fiducial volume LiqAr.
- Boone neutrino beam.
- Search for sterile neutrinos and study the low energy MiniBoone excess.
- Low momentum threshold for protons.
- Large mass!
- No muon catcher!

New results expected in the future
Relatively low proton threshold.
Reduced forward acceptance for leptons in Minos
Other CCQE

T2K off-axis

T2K on-axis

Preliminary

Nuint’14

Minerva
ArgoNeut

- LiqAr detector demonstrator: 240 kg.
- Boone neutrino beam.
- Low proton threshold.
- Operation: ~5 months.
Inclusive CC $v_\mu$
Why inclusive?

- Inclusive is a nice way for experiments to publish their data:
  - small theoretical bias.
  - “easy” to interpret from theorists.
  - easy to compare across experiments.
- The double differential \((p_{\mu}, \theta_{\mu})\) can be used to isolate reaction channels like CCQE and CC\(1\frac{1}{2}\). (Martini et al. \textit{arXiv:1404.1490})

It should be accompanied by the flux prediction + full covariance matrix.
Near detector (ND280) double differential CC inclusive measurement and check with the Martini et al. model of CCQE and CC1π


Martini et al. arXiv:1404.1490
MiniBoone antineutrinos

- Models with RPA+nph also predicts anti-neutrino CCQE-like selection in MiniBoone.

CC inclusive ArgoNeut

![Graphs showing the comparison of ArgoNeut Data, GENIE Expectation, and NUWRO Expectation for neutrino and antineutrino interactions.](image)
Problem with models appear $E_{\nu} \sim 1\text{ GeV}$:
- CC-coh not seen this energy.
- Broken isospin relation prediction
- $\text{CC-coh/NC-coh} \sim 2$.

Large systematic errors from bck x-section modelling.

New T2K data with vertex activity

Nuint'14
Minerva A dependencies

- Minerva made the first CC inclusive measurement for neutrinos comparing **different nuclear targets** for different kinematic variables.

- This is very model independent and a nice input to model builders.

- See P. Rodrigues talk.