Neutrino energy ($E_\nu$) in GeV

Predominantly:
- $\sim 6\%$ $
u_{\mu}$
- $\sim 0.5\%$ $\epsilon^+$

In MiniBooNE: $\sim 1$ per $1e15$ POT
In SciBooNE: $\sim 0.5$ per $1e15$ POT

$\sim 5x$ closer, $\sim 50x$ smaller

All details of the beamline geometry are modeled in Geant4
- 8 GeV/c p + Be target
- meson production (HARP data**ref)
- Single horn focusing
- 50m decay region, SciBooNE @100m from target
- $0.99 \times 10^{20}$ POT neutrino mode dataset

12/3/2013 K Mahn, INT
Neutrino flux

CC inclusive selection efficiency vs. $E_\nu$

CC inclusive cross section paper

12/3/2013 K Mahn, INT
Electron Calorimeter (EC)
2 plane “spaghetti” calorimeter (scintillating fiber & lead foil)

SciBar vertex detector
32 x-y planes of 14,336 extruded scintillator
(1.3 cm x 2.5 cm x 300 cm)
15ton (10.6ton FV)
WLS fiber and 64ch. MAPMT

Muon range detector (MRD)
362 scintillator counters strapped vertically and horizontally to 12 iron plates

All detectors are recycled from previous experiments

The SciBooNE experiment
Selecting CC interactions in SciBooNE

- Select events with the highest momentum track with a vertex in SciBar fiducial volume which pass data quality, beam timing cuts
- "SciBar contained"
- No MRD matched track
- Muon-like determined from dE/dx with or without decay electron tag
- 1 track mu, 2 track mu+e samples use vertex activity (5x5 charge deposit around vertex)
- 2 track mu+p/\pi uses dE/dx for proton, pion separation
- 2 track mu+p uses CCQE kinematic cut
- Total cross section provided in J. Walding thesis, backward going track data/MC discrepancies
Selecting CC \{ \} interactions in SciBooNE

- Select events with the highest momentum track with a vertex in SciBar fiducial volume which pass data quality, beam timing cuts

- “MRD Stopped”
- 1 track “CCQE-like” (~13k, 66% pure)
- if 2 tracks associated to the same vertex, use dE/dx to separate into
- “mu+p” -> “CCQE like” (~3k, 69% pure)
- “mu+pi” -> “CCnon-QE like” used to constrain backgrounds (~1.5k)
SciBooNE CCQE measurement

- Fit pmu-thetamu distributions for normalizations in true $E_{nu}$ bins
- 2 track mu+pi sample included in fit for background
  - Nuisance parameter allows for 1->2track migration (from pion FSI)

Y. Nakajima, NuInt11
<table>
<thead>
<tr>
<th>characteristics of selected $\nu_\mu$ QE events</th>
<th>SciBooNE values</th>
</tr>
</thead>
</table>
| **QE event selection**                      | 1 muon or 1 muon + proton  
(this selects CC events with no pions and any # of nucleons in the final state) |
| **Nuclear target**                          | $C_8H_8$  
(polystyrene PPO(1%), POPOP(0.03%) coated with TiO$_2$) |
| **Neutrino flux range**                     | $0.6 < E_\nu < 2$ GeV |
| **Sign-selection?**                         | no |
| **Muon angular range**                      | $0 < \theta_\mu < \sim 60^0$ |
| **Muon energy range**                       | $0.2 < p_\mu < 1.2$ GeV/c |
| **Proton detection threshold**              | The minimum reconstructed track length is 8 cm (3 layers), 450 MeV/c proton and 100 MeV/c muon energy thresholds. |
| **How is $E_\nu$ determined?**              | Template fit  
(reported $E_\nu$ is corrected back to true $E_\nu$ from RFG) |
| **How is $Q^2$ determined?**                | Not used in fit |
| **Monte Carlo generator**                   | NEUT (cross check with NUANCE)  
*Used 2 track mu+pi selection to tune nonQE fraction* |
| **QE measurements & associated publications**| $\sigma(E_\nu^{RFG})$: J. Luis Alcaraz Aunion thesis, NuInt2011 proceedings |

12/3/2013 K Mahn, INT
FLUKA/Geant3 beam simulation

- 3 horn focusing system
- 280m from target:
  - INGRID on-axis ND280 off-axis
  - from $\pi^+$, K decay

Prediction and uncertainties determined by external or in-situ measurements of:
- proton beam (30 GeV)
- $\pi$, K production from NA61 experiment
- alignment and off-axis angle
These plots show the effect of the different systematic errors vs. neutrino energy:

- Pion production and kaon production were substantially reduced thanks to NA61 data.
- Proton beam, alignment and off-axis angle uncertainties are constrained from beam monitors, survey data and INGRID.
- Secondary nucleon production (reinteractions of protons, pions within the target which compose ~30% of the flux) will be constrained with new thick target NA61 data.
On-axis Interactive Neutrino GRID (INGRID)

16+1 X-Y iron-scintillator modules arranged in a cross
• 7.1 tons iron / module
• Like SciBar: PPO 1%, POPOP 0.03% polystyrene
• 1cm x 5cm x ~120cm read out with WLS+MPPCs
• 1 “proton” module is all scintillator, located in the center
Off-axis near detectors (ND280)

All detectors located within 0.2T UA1 magnet

- 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))

T2K experiment
NIM A 624, 591 (2010)
Selecting CC $\frac{1}{2}\bar{\mu}$ interactions

Measure unoscillated $\frac{1}{2}$ (CC) rate

1. Neutrino interaction in FGD1
   - Veto events with TPC1 tracks
   - Events within FGD1 fiducial volume

2. Select highest momentum, negative curvature track as $\mu^-$ candidate
   - Energy loss of the track in TPC also consistent with muon hypothesis
Selecting CCQE-enhanced $\frac{1}{2} \mu$ interactions

Measure unoscillated $\frac{1}{2}$ (CC) rate

1. Neutrino interaction in FGD1
   - Veto events with TPC1 tracks
   - Events within FGD1 fiducial volume

2. Select highest momentum, negative curvature track as $\mu^-$ candidate
   - Energy loss of the track in TPC also consistent with muon hypothesis

Select CCQE enhanced based on final state:
   - 1 TPC-FGD matched track
   - no decay electron in FGD1

~6k events, efficiency: 40%, purity 72%

2.6 x $10^{20}$ POT (~5% of T2K goal POT)

*Selection details in:*
*Phys. Rev. D 88, 032002 (2013)*

12/3/2013

K Mahn, INT
Template fit to $p_\mu \cdot \cos(\theta_\mu)$ distributions to determine CCQE cross section

- Relationship from true muon kinematics to $E_\nu$ set from RFG (nominal NEUT)
- Agreement with nominal NEUT MC
- 4th bin in the range 1.0-1.5GeV is 2.1 sigma low, $\chi^2$ test with pseudo experiments gives a p-value of 17%
- Result is similar when other CC inclusive events are used in the fit
- Result is similar when a multinucleon model is considered (Nieves et al)
T2K CCQE enhanced sample: $Q^2(QE)$

- Not used for fit
  - $Q^2(QE)$ according to MiniBooNE paper
    - see backup slides for definition
  - Note not same scale on right and left (sorry!)
<table>
<thead>
<tr>
<th>characteristics of selected $\nu_\mu$ QE events</th>
<th>T2K values (2012 analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QE event selection</strong></td>
<td>1 mu-, no charged pi</td>
</tr>
<tr>
<td></td>
<td><em>using TPC track multiplicity, FGD1 decay electron tag</em></td>
</tr>
<tr>
<td><strong>Nuclear target (FGD)</strong></td>
<td>C$_8$H$_8$ (polystyrene PPO(1%), POPOP(0.03%) coated with TiO$_2$)</td>
</tr>
<tr>
<td><strong>Neutrino flux range</strong></td>
<td>$0.2 &lt; E_\nu &lt; 30$ GeV</td>
</tr>
<tr>
<td><strong>Sign-selection?</strong></td>
<td>yes</td>
</tr>
<tr>
<td><strong>Muon angular range</strong></td>
<td>$0 &lt; \theta_\mu &lt; \sim 80^0$ efficiency &lt;5% above 80$^0$</td>
</tr>
<tr>
<td><strong>Muon energy range</strong></td>
<td>$0 &lt; p_\mu &lt; 30$ GeV/c</td>
</tr>
<tr>
<td></td>
<td><em>At large momentum (&gt;10 GeV?) difficult to determine momentum</em></td>
</tr>
<tr>
<td><strong>Proton detection threshold</strong></td>
<td>N/A</td>
</tr>
<tr>
<td><strong>How is $E_\nu$ determined?</strong></td>
<td>Template fit to muon kinematics</td>
</tr>
<tr>
<td></td>
<td><em>(true m kinematics associated to true $E_\nu$, assuming RFG)</em></td>
</tr>
<tr>
<td><strong>How is $Q^2$ determined?</strong></td>
<td>Not used in fit</td>
</tr>
<tr>
<td></td>
<td>Projections provided vs. $Q2(QE)$ according to MiniBooNE convention</td>
</tr>
<tr>
<td><strong>Monte Carlo generator</strong></td>
<td>NEUT</td>
</tr>
<tr>
<td></td>
<td><em>No tuning applied; cross check with inclusion of other CC inclusive events to constrain background</em></td>
</tr>
<tr>
<td><strong>QE measurements &amp; associated publications</strong></td>
<td>$\sigma(E_\nu^{RFG})$: NuFact2013 proceedings, publication in progress</td>
</tr>
</tbody>
</table>
ND280: expanded selection capabilities with improvements to interdetector timing, reconstruction

- **2013**: “CC0π” selection explicit tests on additional tracks for pions
  - using decay electron tag, π-ρ dE/dx in FGD and TPC
  - Electron-like TPC tracks identify π⁰ (often from DIS events)
  - see backup slides
- **2014+**: Backward going tracks, high angle tracks, ECAL photon information

Measurements (currently have ~10% of total POT for experiment taken)

- CCQE double differential measurement
- water and carbon targets (FGD2/P0D/INGRID proton module)
- Searches for multinucleon events using: high momentum protons, proton multiplicity, backward vs. forward going events, vertex activity
  - Need to consider multiple multinucleon models
- Comparisons to GENIE, NEUT (updated with a multinucleon model, spectral function)
- INGRID CC inclusive vs. $E_\nu$ using varying flux across detector

http://inspirehep.net/record/812790/files/
- “The Birk’s constant for the SciBar scintillator is measured to be 0.0208\(+/-0.0023\) cm/MeV [90], using a prototype of SciBar in a proton beam (Figure 5.6).” Ref 90 is: M. Hasegawa, Ph.D. thesis, Kyoto University (2006)

**Measurement of the absolute $\nu_\mu$-CCQE cross section at the SciBooNE experiment** - Aunion, Jose Luis Alcaraz FERMILAB-THESIS-2010-45
http://inspirehep.net/record/876786/files/

**A sub-GeV charged-current quasi-elastic $\nu_\mu$ cross-section on carbon at SciBooNE** - Walding, Joseph James FERMILAB-THESIS-2009-57
http://inspirehep.net/record/855292/files/

Y. Nakajima NuINT2011 talk:

\[ E_{\nu}^{\text{rec}} = \frac{1}{2} \frac{(m_p^2 - m_{\mu}^2) - (m_n^2 - V^2) + 2E_{\mu}(m_n - V)}{(m_n - V) - E_{\mu} + p_{\mu} \cos \theta_{\mu}}, \] (8.3)

where \( m_p, m_n \) and \( m_{\mu} \) correspond to the proton, neutron and muon mass respectively. \( V \) is the nuclear potential set to 27 MeV[62]. In similar way, one can derive the expression of the reconstructed momentum transfer, expressed as follows:

\[ Q_{\text{rec}}^2 = 2E_{\nu}^{\text{rec}}(E_{\mu} - p_{\mu}\cos \theta_{\mu}) - m_{\mu}^2, \] (8.4)
SciBooNE 2 track (μ+p, QE) selection

Enu(QE)

Q2(QE)

Postfit (black)
Prefit (red)

pmu

thetamu
SciBooNE 2 track (mu+pi, nonQE) selection

Enu(QE)

Q2(QE)

Postfit (black)
Prefit (red)

pmu

thetamu
Protons out of CC1pi absorption not simulated in NEUT (and simulated in NUANCE)

These events contributed to low vertex activity

Should revisit with DUET/Piano data?

2 Track (mu+p, QE) NUANCE
CCQE results (Dave Hadley @ NuFact2013)

- Talk: http://indico.ihep.ac.cn/getFile.py/access?contribId=138&sessionId=6&resId=0&materialId=slides&confId=2996
- Proceedings


T2K flux information: http://t2k-experiment.org/publication_category/flux-predictions/
structured $Q^2$. The reconstructed neutrino energy, $E_{QE}^\nu$, was calculated assuming QE kinematics,

$$E_{QE}^\nu = \frac{m_p^2 - m_\mu^2 + 2E_\mu m_n - m_n^2}{2(m_n - E_\mu + p_\mu \cos(\theta_\mu))}. \quad (10)$$

The reconstructed $Q^2$, $Q_{QE}^2$, was calculated assuming QE kinematics,

$$Q_{QE}^2 = (p_\mu^2 + E_{QE}^\nu)^2 - 2p_\mu E_{QE}^\nu \cos(\theta_\mu) + (E_\mu - E_{QE}^\nu)^2. \quad (11)$$
T2K CCQE analysis backups
CCQE-enhanced efficiency, purity

CCQE selection Efficiency vs Neutrino Energy (MeV)

CC selection Purity vs Neutrino Energy (MeV)

CC selection Efficiency vs Cos (muon angle)
CCQE-enhanced distributions, prior to fit

(a) Reconstructed $E_{\nu}$

(b) Reconstructed $Q_{QE}^2$

(c) Reconstructed $p_\mu$

(d) Reconstructed $\theta_\mu$
CCQE-enhanced distributions, after fit

(a) Reconstructed $E_{\nu}$

(b) Reconstructed $Q_{QE}^2$

(c) Reconstructed $p_{\mu}$

(d) Reconstructed $\theta_{\mu}$
Measurement of the CCQE Cross Section

The Log Likelihood Ratio is minimised,

\[-2\ln\lambda(\theta) = \frac{p_\mu - \cos(\theta_\mu)}{\text{bins}} \sum_{i=1}^N \left[ \frac{N_i^{\text{predicted}}(\theta)}{N_i^{\text{observed}}} - \frac{N_i^{\text{observed}}}{N_i^{\text{predicted}}(\theta)} \right] + \ln \frac{\pi_d(d)}{\pi_d(d_{\text{nominal}})} + \ln \frac{\pi_f(f)}{\pi_f(f_{\text{nominal}})} + \ln \frac{\pi_x(x)}{\pi_x(x_{\text{nominal}})} \]

which includes,

- standard Poisson statistical terms
- penalty terms for the systematics

Analysis Method

- Simulated template histograms were fit to the observed $p_\mu - \cos(\theta_\mu)$ distribution.
- The CCQE cross section was extracted by weighting 5 template histograms in bins of $E_\nu$.
- Systematic uncertainties were accounted for by varying bin contents with nuisance parameters.
- A maximum likelihood fit was used to find the best fit parameters.
T2K CCQE enhanced sample: $E_{\nu}(QE)$

Not used for fit

- $E_{\nu}(QE)$ according to MiniBooNE paper
- Note not same scale on right and left (sorry!)
The best-fit MAQE when fitting with normalisation (left) and shape only (right). Both fit results are consistent with the nominal value used in NEUT. It is possible to fit different values of depending on which effects are included in the model and which effects the input data samples are sensitive to. One should avoid interpreting this result as a measurement of a fundamental parameter. As the meaning of this effective parameter depends on the details of the QE model, comparison with results from other experiments should be done with care.
T2K supplemental plots
We collected $6.63 \times 10^{20}$ protons on target (p.o.t.) so far

**Data for the CCQE analysis** = $2.6 \times 10^{20}$ p.o.t. (till Jul 2012)

* Including $0.21 \times 10^{20}$ p.o.t. with 205kA horn operation (13% flux reduction at peak) in Run3 (250kA horn current for nominal operation)
Fine Grained Detectors (FGDs)

Scintillation light (from charged particles) is sent down a wavelength shifting fibre connected to a multi-pixel-photon-counter (MPPC)

- MPPCs function in a magnetic field

X and Y scintillator layers can be used for 3D tracking

1cm² bar size provides detailed vertex information

“FGD1” is only scintillator, “FGD2” has alternating water layers
Charged particle ionizes 95% Ar, 3% CF4, 2% isobutane (iC4H10) gas
Electrons drift to readout plane ($E \sim 25kV$, max distance 897mm)
``Wireless” TPC: Use of bulk micromegas detectors in readout

3D tracks are reconstructed provided drift velocity in the gas and timing of entry from other subdetectors

Momentum of the particle can be determined from curvature

- 0.2T B field; $p_\mu \sim 1$ GeV/c has <10% momentum resolution
Performance: spatial, momentum resolution

Spatial resolution:

Momentum resolution (B = 0.2T)

Simulation of muons from neutrino interactions which cross at least 50 / 72 pad columns

Associate charge deposited in time slices into clusters. Group pads into:
columns (horizontal tracks)
or rows (vertical tracks)

Compare position of a fitted track to location of single cluster
2013 Selection: FGD-Only Tracks

- **FGD-only tracks** = short tracks that do not reach a TPC
- Particle identification based on dE/dx
- **Pion tag** = at least 1 FGD-only track with a charge deposit consistent with a pion
  - Allow at most 1 pion to be tagged in this way
    - FGD-only tracks can break into more than 1 piece due to hadronic interactions and high-angle reconstruction failures
2013 Selection: Michel Tagging

- A Michel electron indicates a short stopped pion near the event vertex
- **Pion tag:**
  - $>200$ p.e. of “delayed” charge
  - “delayed” means $>100$ ns after the $\mu^-$ track time
Tag particle based on the most probable particle type

Positive particle in TPC
- Track compatible with the most probable de/dx positive type.
- If identified as electron and $p > 900$ MeV/c then change to proton.

Negative particle in TPC
- Track compatible with the most probable de/dx negative type

Same TPC quality track as muon

Particle types = electron, proton, pion
Particle types = electron, proton, pion
Particle types = electron, pion
Negative tracks in the TPC.

Energy loss of the particle \( \frac{dE}{dx} \) can be used to separate particle type. 

\( \frac{dE}{dx} \) resolution for MIPs is 8%.

Probability for a muon between 0.2 and 1.0 GeV to be identified using \( \frac{dE}{dx} \) as an electron is less than 0.2%.

Positive tracks in the TPC.
FGD only tracks

Tracks with segment in the FGD1 and no segments in any TPC

Pion candidate

Fully contained in FGD1
Selection based on FGD de/dx pion-like

Pion pull before cut selection in FGD

Pion pull after positive pion selection in FGD
2013 selection: muon momentum

<table>
<thead>
<tr>
<th></th>
<th>CC0</th>
<th>CC1</th>
<th>CCother</th>
</tr>
</thead>
<tbody>
<tr>
<td>purities</td>
<td>72.6%</td>
<td>6.4%</td>
<td>5.8%</td>
</tr>
<tr>
<td>CC0 events</td>
<td>17352 events</td>
<td>4110 events</td>
<td>4119 events</td>
</tr>
<tr>
<td>CC1 events</td>
<td>4110 events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCother events</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bkg(NC + anti-nu)</td>
<td>2.3%</td>
<td>6.8%</td>
<td>8.7%</td>
</tr>
<tr>
<td>Out FGD1 FV</td>
<td>5.1%</td>
<td>6.5%</td>
<td>3.9%</td>
</tr>
</tbody>
</table>
2013 selection: muon angle

<table>
<thead>
<tr>
<th>Category</th>
<th>CC0</th>
<th>CC1</th>
<th>CCother</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC0 purities</td>
<td>72.6%</td>
<td>6.4%</td>
<td>5.8%</td>
</tr>
<tr>
<td>CC1 purities</td>
<td>8.6%</td>
<td>49.4%</td>
<td>7.8%</td>
</tr>
<tr>
<td>CCother purities</td>
<td>11.4%</td>
<td>31%</td>
<td>73.8%</td>
</tr>
<tr>
<td>Bkg(NC +anti-nu)</td>
<td>2.3%</td>
<td>6.8%</td>
<td>8.7%</td>
</tr>
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<td>Out FGD1 FV</td>
<td>5.1%</td>
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<td>3.9%</td>
</tr>
</tbody>
</table>
Many sources of systematic error have been evaluated for the ND280 constraint

- All errors are assigned using data control samples
Pion Secondary Interactions

- Several datasets have been compiled for $\pi^+$ interactions on Carbon
  - Absorption
  - Charge exchange
  - Quasi-elastic scattering
- The default GEANT4 prediction is adjusted to the measured values
- The systematic uncertainty is set to the error on the data
  - In regions without data, the assumed error is inflated
    - This has a small effect since these regions contain very few pions
Detector systematics

- B Field distortion (0.3%)
- TPC Tracking efficiency (0.6%)
- TPC-FGD matching efficiency (1%)
- TPC Charge confusion (2.2%)
- TPC Momentum scale (2%)
- TPC Momentum resolution (5%)
- TPC Quality cut (0.7%)
- Michel electron efficiency (0.7%)
- FGD Mass (0.65%)
- Out of Fiducial Volume (10%)
- Pile-up (0.07%)
- Sand muon (0.02%)
- TPC PID (3.5%)
- FGD PID (0.3%)
- FGD tracking efficiency (1.4%)
- Pion secondary interaction (8%)

Largest relative error in all momentum bins in all categories
Detector systematics

- B Field distortion (0.3%)
- TPC Tracking efficiency (0.2%)
- TPC-FGD matching efficiency (1.8%)
- TPC Charge confusion (5.0%)
- TPC Momentum scale (2%)
- TPC Momentum resolution (5%)
- TPC Quality cut (0.7%)
- Michel electron efficiency (0.7%)
- FGD Mass (0.65%)
- Out of Fiducial Volume (22%)
- Pile-up (0.07%)
- Sand muon (0.02%)
- TPC PID (9.0%)
- FGD PID (0.3%)

Largest relative error in all angle bins in all categories