The impact of neutrino scattering data for oscillation measurements

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William & Mary

13th International Workshop on Neutrino Factories, Superbeams & Beta Beams

University of Geneva/CERN
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Outline

• A bit of history …
• A few examples
  ◦ muon neutrino disappearance
  ◦ antineutrino disappearance
  ◦ neutrino electron appearance
  ◦ The QE saga as a lesson
• Looking forward
  ◦ Precision disappearance and appearance
  ◦ The roles/needs for the players of the future
• Total cross section -> event totals -> sensitivity
• Oscillations depend on L/E
  ◦ Improved oscillations measurements require better modeling of “E” based on final state
  ◦ FSI/nuclear effects
    • What you see $E_{\text{vis}}$ doesn’t add up to “$\nu$”
  ◦ Angles modified, particles absorbed
    • Can’t always trust kinematic reconstruction
• Backgrounds are need to be modeled with their own cross sections
  ◦ More aggressive signal selection & background suppression can imply more systematics unless one knows the background accurately
• Need to know rates and properties of below-threshold particles
  ◦ Background contributor, resolution killer & systematic bias
We were “here” just after proof of oscillations …


- The first of a long set of productive workshops bringing together the neutrino and electron scattering communities, theory and experiment
  - Recall that Jlab was in its 6th year of beam
  - Their early results were starting to pour in – it was a very exciting time for the hadronic physics community
From S. Zeller’s nufact03 neutrino data summary

**Quasi-Elastic Cross Section**

$$\nu_p \rightarrow \mu^- p \pi^+$$

$$\nu_n \rightarrow \mu^- n \pi^+$$

**CC Single Pion Production**

- ANL, Barish, Phys. Rev. D16, 3103 (1977), D2
- ANL, Barish, Phys. Rev. D19, 2521 (1979), D1
- ANL, Baker, Phys. Rev. D25, 1161 (1982), D1
- SKAT, Brunner, Z. Phys. C45, 551 (1990), CFBr
- GGM, Bonetti, Nuovo Cimento, A38, 260 (1977), CBr
- NEUGE (free nucleon)

**CC \(\nu\mu\) Quasi-Elastic Cross Section**

- ANL, Barish, Phys. Rev. D16, 3103 (1977), D2
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NuFact2011 – scattering & oscillations
From S. Zeller’s nufact03 neutrino data summary

### CC $\nu_\mu$ Total Cross Sections

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Present</th>
<th>Theor.</th>
<th>Knowledge</th>
<th>$\nu$ Data</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS</td>
<td>Excellent</td>
<td>$\star\star\star$</td>
<td>many exps</td>
<td>parton model</td>
<td></td>
</tr>
<tr>
<td>Quasi–Elastic</td>
<td>Good</td>
<td>$\star\star$</td>
<td></td>
<td>bc form factors</td>
<td></td>
</tr>
<tr>
<td>Resonant 1 $\pi$</td>
<td>Fair</td>
<td>$\star$</td>
<td></td>
<td>Rein–Sehgal</td>
<td></td>
</tr>
<tr>
<td>Coherent $\pi$</td>
<td>Poor</td>
<td>$\star\star\star\star$</td>
<td>low $E$ &amp; $\frac{1}{2}$</td>
<td>bc–counter</td>
<td>several</td>
</tr>
<tr>
<td>Combining $\sigma$'s</td>
<td>Poor</td>
<td>$\star$</td>
<td></td>
<td>little</td>
<td>several y</td>
</tr>
<tr>
<td>Nuclear Targets</td>
<td>Poor</td>
<td>$\frac{1}{2}$</td>
<td>very limited</td>
<td></td>
<td>variety</td>
</tr>
</tbody>
</table>

- Program of systematic comparisons of the generators
- Note the correlation Between the different generators
- Spread of generators is not a good error estimate
An example use of scattering data and model/generators

MINOS neutrino disappearance analysis ...
(c.f. J. Hartnell’s talk)
AGKY model of recoil system (2008)

• A hadronization model for few-GeV neutrino interactions
  • Into GENIE

• Tuned on an extensive mining of bubble chamber data

• Developed to try to model the initial differences seen in MINOS ND NC events
Fig. 6 Average π₀ multiplicity \( \langle n_{\pi^0} \rangle \) as a function of the number of negative hadrons \( n^- \) for different intervals of \( W \).

Datapoints are taken from [25].

Fig. 7 Average charged-hadron multiplicity in the forward and backward hemispheres as functions of \( W^2 \): (a) \( \nu p \), forward, (b) \( \nu p \), backward (c) \( \nu n \), forward, (d) \( \nu n \), backward. Data points are taken from [7, 25, 26].
Example distribution
(FHC, CC selected, Near Detector)

Figure 35: ND LE Data/MC Comparison: Reconstructed $y$. 

- Low Energy Beam
- Data
- MC expectation
- NC background

Events / $10^{16}$ PoT

Reconstructed $y$
Example (RHC – antineutrino-tune) distribution after beam tuning

Figure 3: Reconstructed energy distribution of events selected as antineutrinos in the Near Detector. The red histogram represents the Monte Carlo expectation with the systematic error, the blue histogram represents the total (charged and neutral current) background with the background uncertainty. Black points represent data.

MINOS
- Data
- MC Expectation
- Total Background

Near Detector
8.65 × 10^{19} PoT
Antineutrino Running
Far Detector Data

Events / GeV vs. Reconstructed Neutrino Energy (GeV)

Resolution Bin 0
Resolution Bin 1
Resolution Bin 2
Resolution Bin 3
Resolution Bin 4

Negative Curvature
Positive Curvature

Prediction
Best Fit
NC Background
Data

Figure 4. Far Detector events with negative curvature are split into five samples based on energy resolution, with best energy resolution events in Resolution Bin 0 and worst resolution events in Resolution Bin 4. Additionally, Far Detector events with positive curvature are included as a sixth sample. These six spectra are then fit simultaneously.
Genie/NEUGEN moving to more complete error estimates for the MINOS 2008 disappearance analysis (See Gallagher 45th Karpacz School, ’09)

Total Anti-Neutrino CC Cross Section

Total Neutrino CC Cross Section

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NuFact2011 – scattering & oscillations
• Systematic error estimate on the visible (calorimetric) shower energy for the MINOS for disappearance analysis

<table>
<thead>
<tr>
<th>branching ratios</th>
<th>1σ uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>parameter</td>
<td></td>
</tr>
<tr>
<td>π charge-exchange</td>
<td>50</td>
</tr>
<tr>
<td>π elastic</td>
<td>10</td>
</tr>
<tr>
<td>π inelastic</td>
<td>40</td>
</tr>
<tr>
<td>π absorption</td>
<td>30</td>
</tr>
<tr>
<td>π secondary π production</td>
<td>20</td>
</tr>
<tr>
<td>N absorption</td>
<td>20</td>
</tr>
<tr>
<td>N secondary π production</td>
<td>20</td>
</tr>
<tr>
<td>N elastic</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>cross-sections</th>
<th>1σ uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>parameter</td>
<td></td>
</tr>
<tr>
<td>π total cross-section</td>
<td>10</td>
</tr>
<tr>
<td>N total cross-section</td>
<td>15</td>
</tr>
</tbody>
</table>

![Figure 10: Total uncertainty from all sources (solid black). Contributions from intranuke assumptions (blue), INTRANUKE input (dashed red), hadronization model (solid red), and formation zone (dashed black).](image)
Systematics on the MINOS CC result

Includes component due to syst comparing gcalor pion modeling to test beam results – secondary interactions

<table>
<thead>
<tr>
<th>Shift</th>
<th>Amount</th>
<th>7.2 × 10^{20} POT Fiducial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shower Energy</td>
<td>1σ</td>
<td>0.049</td>
</tr>
<tr>
<td>Rel. Shower Energy</td>
<td>1.9%/1.1%</td>
<td>0.008</td>
</tr>
<tr>
<td>Norm.</td>
<td>1.6%</td>
<td>0.030</td>
</tr>
<tr>
<td>NC Bknd.</td>
<td>20%</td>
<td>0.008</td>
</tr>
<tr>
<td>μ Momentum</td>
<td>2%/3%</td>
<td>0.038</td>
</tr>
<tr>
<td>σν (sum in quadrature)</td>
<td>1σ</td>
<td>0.007</td>
</tr>
<tr>
<td>Beam</td>
<td>1σ</td>
<td>0.009</td>
</tr>
<tr>
<td>(\bar{\nu}_\mu) wrong-sign</td>
<td>30%</td>
<td>0.003</td>
</tr>
<tr>
<td>RAF only</td>
<td>1σ</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.071</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>7.2 × 10^{20} POT Fiducial</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta m^2)</td>
<td>0.001</td>
</tr>
<tr>
<td>(\sin^2(2\theta_{23}))</td>
<td>0.000</td>
</tr>
</tbody>
</table>
It is not just neutrino cross sections
They are exposing a small detector to pions at TRIUMF to help better model secondary interactions of muons in T2K data [WG #2 Ikeda, yesterday]
  - MINOS had their test beam run too
This sort of measurement of hadron scattering data needed for better precision results in any neutrino cross section measurement and E reconstruction.
- 4-parameter comparison
  - Track length
  - Mean energy of track hits
  - Energy fluctuations along the track
  - Transverse track profile
The Anti-neutrino Analysis

- Essentially the neutrino analysis of 2008
  - No resolution binning, shower estimator, new selector
  - Only stopped taking antineutrino data on March 22nd

- What’s different with antineutrinos?
  - Lower statistics ~1/12th events
  - Larger wrong-sign component
  - Interactions are less hadronic
Data/MC agreement comparable to neutrino running
Electron appearance in MINOS

- Electrons leave a compact core of high pulse height hits
- Contamination
  - NC: can be mistaken for EM shower (e.g. if there is a $\pi^0$ in the recoil or unlucky collection of unassociated depositions)
  - $\nu_\mu$ CC: Hard to eliminate if track is small/embedded
  - $\nu_e$ CC: the 1.3% beam $\nu_e$ CC events
• The electron identification variable
• MC based on tuned flux and GENIE
• LHS: NC-like
• RHS: electron-enhanced
• Some residual issues after hard cuts to removed background

MINOS 2011
nue discriminant variable
## Systematics

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>Uncertainty on background events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event energy scale</td>
<td>4.0%</td>
</tr>
<tr>
<td>$\nu_\tau$ background</td>
<td>2.1%</td>
</tr>
<tr>
<td>Relative FD/ND rate</td>
<td>1.9%</td>
</tr>
<tr>
<td>Hadronic shower model</td>
<td>1.1%</td>
</tr>
<tr>
<td>All others</td>
<td>2.0%</td>
</tr>
<tr>
<td>Total</td>
<td>5.4%</td>
</tr>
</tbody>
</table>
FD data and best fit for each LEM PID bin

Counting experiment results (LEM PID > 0.7)

Observe 62 events
Background 50 ± 7 (stat.) ± 3 (syst.)

MINOS Far Detector Data

0.6 < LEM < 0.7

Best Fit: \( \sin^2(2\theta_{13}) = 0.041 \)
\( \Delta m^2_{32} > 0 \), \( \delta_{\text{CP}} = 0 \), \( \theta_{23} = \frac{\pi}{4} \)

0.7 < LEM < 0.8

LEM > 0.8

Bins Merged for Fit

Reconstructed Energy (GeV)

Events

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NuFact2011 – MINOS Elec
Some systematics from MINOS cross section measurements

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NuFact2011 – scattering & oscillations
A example of NC-like systematic in MINOS

\[ \Delta m^2 = 2.38 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 \theta_{23} = 1.00 \]
\[ \theta_{13} = 0.00 \]
A step lower in energy -> MiniBooNE
Charged-Current $\pi^+$


• Crucial channel for $\nu_\mu$ disappearance measurements
  ◦ can bias CCQE signal if $\pi^+$ lost

▶ First tracking of charged pions in a Cherenkov detector!

▶ Measured quantities:
  ▶ $\sigma(E_\nu)$, $d\sigma/dQ^2$, $d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$,
    $d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$, $d^2\sigma/dT_\mu d\theta_\mu$,
    $d^2\sigma/dT_\pi d\theta_\pi$ (many firsts)

WG #2: Louis


Charged-Current $\pi^0$


- Custom 3 Cherenkov-ring fitter developed to reconstruct both $\mu$, $\pi^0$
  - Resonant-only process
  - Measured quantities:
    - $\sigma(E_\nu)$, $d\sigma/dQ^2$, $d\sigma/dT_\mu$, $d\sigma/dp_\pi$, $d\sigma/d\theta_\mu$, $d\sigma/d\theta_\pi$
      (many firsts)


Examples of recent data: SciBooNE

  - No evidence of CC coh-$\pi$

- $\nu$ NC-$\pi^0$: Phys.Rev.D81, 033004 (2010)
  - Cross section and $\pi^0$ kinematics, MC agree with data

- $\nu$ NC coh-$\pi^0$: Phys.Rev.D81, 111102 (2011)
  - Clear evidence of coh-$\pi$, R-S model agrees with data

- $\bar{\nu}$ CC coh-$\pi$: preliminary results
  - Cross section ratio $\sim 2\sigma$ away from zero
  - Data hint that non-zero CC coh-$\pi$ events in very forward region (than R-S model)

- $\nu$ CC-$\pi^0$: preliminary results
  - Absolute cross section, working on syst. uncertainties

- $K^+$ production measurement at the BNB: Phys. Rev. D84, 012009

- CC inclusive production measurement: Phys. Rev. D83, 012005

NuFact2011 – scattering & oscillations
$\nu_\mu$ CCQE Scattering


![Graph showing the cross-section $\sigma$ as a function of $E_{\nu}^{QE,RFG}$ (GeV)]
New data and modeling being brought to address this problem

Can’t put it all on one plot any more
Comparisons to MB Double Diff’l $\sigma$

Nieves, Simo, & Vacas, arXiv:1106.5374

2p, 2h effects

Accounts for long range nuclear correlations & Multi-nucleon scattering with $M_A = 1.049$ GeV

Implications for resolution in QE energy reconstruction with muon
Examples of recent data: SciBooNE

NuFact2011 – scattering & oscillations

A step even lower in energy
beta beam & 2\textsuperscript{nd} maximum in super beam

Saw here that “2p, 2h processes”
significantly change overall cross sections

WG #1 Meloni
Moving up in energy: NF & MINOS+

In general the situation is better as DIS becomes dominant …
Improved total cross section data (MINOS ND)
Ratio of cross sections

Could well need to know these better depending in nature and the machine we decide to build for CP / CPT tests
• Examples in SK & present in MINOS
• In low energy super-beam experiments they are not so significant
• In neutrino factory or higher energy atmospheric neutrinos they become significant

Paschos and Yu,

Take difference between two models as additional systematic:

GENIE 2.4.0
Moving onward
Current landscape ($\approx$GeV)

- SciBooNE and MiniBooNE mature and transforming our knowledge of neutrinos interaction physics near 1 GeV
  - Strong interplay with neutrino experiments, theory & electron scattering data critical
- T2K ND-280 getting into the game (WG #2 Mccauley)
- MicroBooNE coming in a couple years

- Critical regime for precisions oscillations physics and sterile neutrino searches
Current landscape (<<GeV)

• Needed for super beam experiments looking for 2\textsuperscript{nd} peak
• Needed for LE beta beam
• Not currently in the world’s program ???
  ◦ MicroBooNE might help ???
  ◦ Address low energy excess in MiniBooNe
• Note to self: FS radiative corrections for e’s not in current generators
  ◦ Will be needed for precision work
• MINERvA is collecting data
  ◦ Running in NuMI low energy for next year
  ◦ Running in NuMI medium energy during the NOvA
  ◦ Good prospects, initial physics distributions
• Proposal for a LD/LH target for precision studies in low-density nuclei
  ◦ Recall He nucleus is dense
Why so good at high energies?
Narrow band beams
LE NBB scattering experiments …

- T2K ND280 exists and collecting data
- NOvA is considering an off-axis fine-grain ND
  - SciNOvA Working Group within NOvA
    - Costing and optimizing detector Scibar-like detector in front of NOvA ND & muon stack
- Off-axis gives a 1+ GeV NBB
  - Allows detailed studies for NOvA particle ID development
  - NBB measurement centered above the T2K oscillation dip
    - Study feed down into T2K oscillation minimum
Use these event generators …

- Scattering and oscillation experiments use the generators to make exclusive final states that can be propagated through a detector simulation
  - We need fully detailed descriptions or at least prescriptions to get there ourselves
- For interactions between theorists and experimenters we generally work with specific distributions
- Goal
  - The scattering experiments need to hear from theorists what distributions and conditions will give them the best ability to tune/test their models
  - Of course, we have to tell them what we can actually do
  - This has been on going
Moving forward …

- Need precision neutrino scattering data in the energy regime of the experiment and on the correct targets
  - To squeeze the best sensitivity from an experiment need to have good modeling of the physics in the near detector
    - More than just feel-good physics
  - This means that theory needs to be melded with event generator design to make sure that predictions can be turned into detailed event kinematics
  - Look forward to seeing the details of the T2K systematics analysis

- Ingredients for precision & discovery
  - Precise flux determination by beam component by multiple methods, e.g.
    - Hadron production (dedicated session in WG2)
    - Muon flux measurement
    - Low-v/w method
    - A chance for common goals addressed collaboratively
  - Absolute shower energy scale
    - High quality test beams
    - Tests of secondary scattering (general & specific to experiment)
    - Measurements of nuclear effects / FSI
    - Seems like a good chance for common goals addressed collaboratively
  - Tight collaboration with experimenters in the electron scattering community
  - Theory & experiment talking the same language
    - Making sure to our data measures the same thing the theorist computed