Please refer to the following two plenary talks together with the presentations in WG2 session

• Summary of Theoretical Challenges Coming from NuInt09 (Luis Alvarez Ruso, Universidad de Murcia)
• Review of Current and Future Neutrino Cross-Section Experiments (David Schmitz, Fermilab)
Outline

• Introduction
  Energy spectrum of various neutrino beams
  ~ Hadron production experiments ~
  Requirements from the experiments

• Quasi-elastic scattering
• Single pion productions
• Coherent pion productions
• Deep inelastic scattering

• New experiments to measure cross-sections
• Flux measurements ~ hadron production ~
• Other related topics
  Deeply virtual neutrino production of $\pi^0$
  Application to the other experiments
  ~ Cross-section of Dark matter ~
Energy spectrum of various neutrino beams

**T2K beam**

- (Flux x x-section)
- OA0°
- OA2°
- OA2.5°
- OA3°

~0.7 (GeV)

**NuMI beam**

- CC Interaction rate
- 2.0 (GeV)

**Beta beam**

- (Flux)
- 0 1 2 3 4 (GeV)

**ν factory**

- μ⁺ → e⁻ + ν_μ + ν_μ
- E_μ = 30 GeV

20 (GeV)
Hadron production experiments

Important to reduce systematic uncertainties in the neutrino oscillation experiments.

Estimate flux at the near and the far detectors.

Also essential input to extract $\nu$ cross-section.

<table>
<thead>
<tr>
<th>Accelerator-based Neutrino Beams</th>
<th>HARP 2-15 GeV/c p, $\pi^+$, $\pi^-$</th>
<th>MIPP 5-120 GeV/c p, $\pi^\pm$, $K^\pm$</th>
<th>NA61 31 GeV/c p</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2K, MiniBooNE</td>
<td>X</td>
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<td>MINOS</td>
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<td>T2K off-axis</td>
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<td>Neutrino Factory</td>
<td>X</td>
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<td>Atmospheric Neutrinos</td>
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<td>Systematic Target Studies</td>
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<td></td>
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<td>H, Be, C, Bi, U</td>
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<td>C</td>
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</table>
Hadron production experiments

- Hadron production knowledge is limiting factor in understanding and optimization of a variety of neutrino sources (accelerator-based neutrino beams, atmospheric neutrinos)

- Search for smaller effects: characterization of actual neutrino beam targets to reduce MC extrapolation to the minimum

- HARP
  - Useful results for conventional ν beams study, NuFact design, EAS, atmospheric ν studies and for general MC tuning (G4, FLUKA, etc.)
  - Data taken with the same detector for a wide range of nuclear target: systematic effects are minimized
  - Lots of results!

- MIPP
  - Multi-GeV neutrinos (MINOS, atmospheric neutrinos, NuMI future: NoVa, MINERvA)
  - Detector performances well understood, physics analysis well underway, first hadron production cross section by september 2009

- NA61
  - Good quality of 2007 data, about to release π⁺ spectra

See also A. Bravar poster contribution for full experiment description and analysis status
Requirements ~ neutrino oscillation experiments ~

Need to understand the neutrino interactions from 0.5 GeV to 30GeV

• Next generation experiments ( $\theta_{13}$ measurements )
  ~10 % ( might be 15~20%? ) of uncertainty is allowed.
  ( depends on the parameter, of course )

• In CP violation studies, error should be less than a few %.

Current understanding of interactions is not sufficient especially to study the CP violation.

Also we need appropriate prescriptions to simulate events.
  ( Fast enough to generate millions of simulated events
    in reasonable amount of time. )
Quasi-elastic scattering

M_A from CCQE

- different targets/energies
(also, M_A from π photo-production similar)

- However, recent data from some high-stats experiments not well-described with this M_A and/or the simple model described on previous page

Fig. 18. A summary of existing experimental data on the axial mass M_A as measured in neutrino (left) and antineutrino (right) experiments. Points show results obtained both from deuterium filled BC (squares) and from heavy liquid BC and other experiments (circles). Dashed line corresponds to the so-called world average value M_A = 1.026 ± 0.021 GeV (see review [33]).
Quasi-elastic scattering
Low energy experiments

BNL QE data:
- data on $D_2$
  - $M_A = 1.07 \pm 0.06$ GeV
  - 1,236 $\nu_\mu$ QE events
- curves with diff $M_A$ values, relatively norm'd, overlaid.
- $M_A$ extracted from the shape of this data in $Q^2$

$$F_A(Q^2) = -\frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

from Sam Zeller
Quasi-elastic scattering
Recent results in low energy experiments

K2K SciFi
shape only fits $Q^2 > 0.2 \text{(GeV/c)}^2$
$M_A = 1.20 \pm 0.12 \text{ (GeV/c}^2\text{)}$

MiniBooNE
$M_A^{\text{eff}} = 1.35 \pm 0.17$

Preliminary SciBooNE results also indicates larger $M_A$

( R. Tayloe )
Quasi-elastic scattering
Recent results in high energy experiments

NOMAD

normalization to deep inelastic scattering and inverse muon decay

$M_A = 1.05 \pm 0.02 \text{(stat.)} \pm 0.06 \text{(syst.) (GeV/c}^2\text{)}$

MINOS preliminary

Shape fit (all $Q^2$ region)

$M_A = 1.19 \pm 0.09_{0.10} \text{(fit.)} \pm 0.12_{0.14} \text{(syst.)}$

Shape fit ($Q^2 > 0.3$ (GeV/c$^2$))

$M_A = 1.26 \pm 0.12_{0.10} \text{(fit.)} \pm 0.08_{0.12} \text{(syst.)}$

Results from shape $Q^2$ fit

$M_A = 1.07 \pm 0.06 \text{(stat.)} \pm 0.07 \text{(syst.) (GeV/c}^2\text{)}$
Quasi-elastic scattering

Also, the interaction rate (~ cross-section) seems to be larger for the experiments with larger $M_A$?

Somewhat inconsistent?
Quasi-elastic scattering ~ Theory ~

More careful treatments of nuclear effects is essential
~ Beyond the simple Fermi-gas model ~

- Pauli blocking
  Fermi Gas
- Fermi motion
  Fermi Gas
- Correlations in excited states
  RPA
- Nucleon binding
  Nucleon spectral functions (hole states)
- Final State Interactions
  Nucleon spectral functions (particle states)
- Nucleon rescattering
  MonteCarlo cascade models
  GiBUU
Quasi-elastic scattering ~ Theory ~

RPA is important effect for MiniBoone

Models including spectral functions seem consistent

- Qualitative agreement on which nuclear effects are relevant and how they affect cross sections
- Quantitative agreement between different theoretical models (specially differential cross sections) not so good
Quasi-elastic scattering

To resolve the existing inconsistencies,

- **Need more careful analyses ( of existing data )**
  Need to understand background in the CCQE measurements.
  Need to know ( estimate ) the flux correctly.
- **Need data from 1 GeV to several GeV for various material.**
  \( \rightarrow \) **MINERvA**
- **Need another experiments**
  \( \rightarrow \) **T2K-Near detectors ( Scintillator + TPC )**
  \( \rightarrow \) **Lq. Ar TPCs ( ArgoNeut, MicroBooNE )**

Another important thing ( for the future experiment )
Measurement of the anti-neutrino cross-sections

**Another type of difficulties**

- Final state nucleon is neutral ( neutron )
  Identification is more difficult.
- Usual beam contains fair amount of neutrinos in the anti-neutrino beam.

\( \rightarrow \) **Correct understanding of neutrino cross-section is essential.**
Single pion productions

In the $\theta_{13}$ measurement experiments
  • Background to search for the $\nu_e$ appearance signal.

In the $\Delta m_{23}$ & $\theta_{23}$ precise measurement experiments
  • Bias in the energy estimation using the charged current quasi-elastic scattering.
  • Background in the number of events estimation (energy bin) using the charged current quasi-elastic scattering.

Possible bias in the energy reconstruction (U. Mosel)
Single pion productions ~ experiments ~
MiniBooNE NC $\pi^0$ production

Signal definition:
Neutral Current events with a $\pi^0$ exiting from the target nucleus and no other mesons.

Event selection similar to K2K 1KT one.

First absolute differential xsec measured for NC-pi0 production using neutrinos and antineutrinos.

C. Anderson - NuInt09

$\nu$ - induced $\sigma = (4.54 \pm 0.04_{\text{stat.}} \pm 0.71_{\text{sys.}}) \times 10^{-40} \text{ cm}^2/\text{nucleon}$

$\bar{\nu}$ - induced $\sigma = (1.43 \pm 0.03_{\text{stat.}} \pm 0.23_{\text{sys.}}) \times 10^{-40} \text{ cm}^2/\text{nucleon}$
Single pion productions ~ experiments ~ (J. Catala)
SciBooNE CC & NC $\pi^0$ production ~ Analysis is ongoing

![CC Invariant Mass](image1)

![CC Pi0 Momentum](image2)

![NC MC](image3)

![NC MC2](image4)
Single pion productions ~ experiments ~ (J. Catala)

CC $\pi^+$ cross-sections
ANL, K2K and MiniBooNE

CC $\pi^+$ Q$^2$ distribution from MiniBooNE

MiniBooNE gives rather large $M_A$

$M_A^{1\pi}$ for $Q^2 > 0.2\text{GeV}$

- $M_A^{1\pi} = 1.17 \pm 0.13 \text{ GeV}$

[Graphs and data plots showing experimental results and fits]

arXiv:0904.3159v1 [hep-ex]
Single pion productions ~ Theoretical ~ (U. Mosel)

Take look at the presentation by U.Mosel
Instructive for the experimentalists.

Rein-Segal formfactors bad in vector sector,
but reasonable in neutrino X-sect
⇒ Fortunate cancellation of vector and axial contribs

We (experimentalists) need to use more appropriate models.
Medium modifications

- All cross sections Fermi smeared
- $\Delta$ cross section is further modified in the nuclear medium:
  - $\pi$ decay might be Pauli blocked: decrease of the free width $\Gamma \rightarrow \Gamma_P$
  - additional "decay" channels in the medium: collisional width $\Gamma_{\text{coll}}$

Overall effect: increase of width

$\Gamma \rightarrow \Gamma^{\text{med}} = \Gamma_P + \Gamma_{\text{coll}}$

Collisional broadening

\[ \frac{d^2\sigma}{dE_\mu dQ^2} \text{[10}^{-38} \text{cm}^2/\text{GeV}^3] \]

- elementary
- + Fermi
- + Pauli
- + binding
- + in-medium width

(U. Mosel)
Higher Resonances

Photoabsorption X-section

- $\Delta$ nearly unchanged
- 2nd resonances vanish
- 3rd resonances vanish

3rd resonance region disappears by Fermi-motion
Coherent pion productions

Initially, the K2K experiment gives smaller cross-section for the charged current coherent $\pi$ production compared to the original Rein-Sehgal model.

Correcting the model to apply low energy region, there seems to be a solution.

• Wait for the anti-nu data from SciBooNE together with detailed analysis of neutrino data.
• Another precise measurements from MINERvA.

As for the neutral current cross-section, we need to check the “new” models using the MiniBooNE data.

(Their data indicates the existing of enhancement in the forward going $\pi^0$.)

Of course, correct understanding of resonance production is required.
Coherent pion productions ~ Experiments ~ (H. Tanaka)

Upper limit on cross section

Rein-Sehgal w/ lepton mass correction (Our default model)

Upper limit: 33% of the prediction

SciBooNE 90% C.L.

New coherent $\pi$ models:

Recently proposed CC coherent $\pi$ models predict production of CC coherent $\pi$ events just below our upper limit.

$\rightarrow$ Search for $\bar{\nu}$ CC coherent pion production, since $\bar{\nu}$ data is expected to be more sensitive to look at CC coherent $\pi$ production than $\nu$ data.
Coherent pion productions ~ Experiments ~ (H. Tanaka)

Further analysis in SciBooNE

Some excess in the forward going pion?

(K. Hiraide @ NuINT09)
Coherent pion productions ~ Experiments ~

$\bar{\nu}$ CC coherent $\pi$

$\bar{\nu}$ coh-$\pi$, $\theta_\pi < 35^\circ$

Preliminary & stat. error only

**Signal region:** $Q^2 < 0.1$
- 87 events observed
- 31 non-coherent $\pi$ events (BG)

$\rightarrow$ Data - BG: $56\pm11$ (stat)

NEUT (R&S) prediction: 92 ($\nu+\bar{\nu}$)

$\bar{\nu}$ coh-$\pi$, $\theta_\pi > 35^\circ$

**Signal region:** $Q^2 < 0.1$
- 52 events observed
- 49 non-coherent $\pi$ events (BG)

$\rightarrow$ Data - BG: $2.6\pm8.5$ (stat)

NEUT (R&S) prediction: 59 ($\nu+\bar{\nu}$)

CC coherent $\pi$ component at small $\theta_\pi$ region.
More NC-\(\pi^0\) from MiniBooNE

C.E. Anderson at NuInt09

Coherent Production Models

- Models for NC coherent \(\pi^0\) production demonstrate wide variabilities in their predictions.
- Forward angular distribution (particularly for antineutrino mode) is very sensitive to predictions.
- MiniBooNE uses the Rein-Sehgal\(^1\) prediction scaled by 0.65 by default in MC; also incorporated predictions from Hernandez, et al\(^6\), and Alvarez-Ruso, et al\(^7\).

\(^{6}\) arXiv:0903.6208v1; thanks to Juan Nieves for predictions
\(^{7}\) Phys. Rev. C 76, 068501 (2007); thanks to Luis Alvarez-Ruso for predictions

- New NC-\(\pi^0\) results for both \(\nu\) and \(\bar{\nu}\) beam modes.
- Demonstrated comparison between data and models.
- \(\nu\) and \(\bar{\nu}\) data suggest:
  - Clear evidence of non-zero NC coh-\(\pi^0\).
  - Forward angular distribution is sensitive to model predictions.

NOTE: MC distributions are absolutely normalized
Recent models / corrected model seems to have better agreement with data in the directional distribution.
Deep inelastic scattering

Neutrino DIS

\[ Q^2 = 4E_\nu E_\mu \sin^2 \frac{\theta}{2}, \]

Squared 4-momentum transferred to hadronic system

\[ x = \frac{Q^2}{2ME_{\text{HAD}}}, \]

Fraction of momentum carried by the struck quark

\[ y = \frac{\nu}{E_\nu} = \frac{E_{\text{HAD}}}{E_\nu}, \]

Inelasticity

Differential cross section in terms of structure functions:

\[
\frac{1}{E_\nu} \frac{d^2\sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M}{\pi (1 + Q^2 / M_W^2)^2} \left[ \left( 1 - y - \frac{Mxy}{2E_\nu} + \frac{y^2}{2} + \frac{1 + 4M^2x^2/Q^2}{1 + R(x, Q^2)} \right) F_2^{\nu(\bar{\nu})} + \left( y - \frac{y^2}{2} \right)xF_3^{\nu(\bar{\nu})} \right]
\]

Structure Functions in terms of parton distributions

\[
F_2^{\nu(\bar{\nu})} = \sum [xq^{\nu(\bar{\nu})N}(x) + x\bar{q}^{\nu(\bar{\nu})N}(x) + 2xk^{\nu(\bar{\nu})N}(x)]
\]

\[
xF_3^{\nu(\bar{\nu})} = \sum [xq^{\nu(\bar{\nu})N}(x) - x\bar{q}^{\nu(\bar{\nu})N}(x)] = x(d_\nu(x) + u_\nu(x)) \pm 2x(s(x) - c(x)), \text{ } \nu\text{-scattering only}
\]

\[
R = \frac{\sigma_L}{\sigma_T}
\]

Rather well understood compared to the other interactions. (at least to me)
Deep inelastic scattering

• Several high stat. & high precision measurements

  NuTeV, NOMAD, CHORUS, MINOS

NuTeV & MINOS: \( \text{Fe} \)
NOMAD: \( \text{C, Al, Fe} \)
CHORUS: \( \text{Pb, Fe, Ca, C} \)
Deep inelastic scattering

CHORUS, NuTeV and CCFR Comparison

- not as precise,
- agrees well with NuTeV over the whole range,
- hint of a different $Q^2$ shape at low-x
- assuming nuclear corrections similar for Fe and Pb.

D. Naples – NuInt07
Deep inelastic scattering

How do Neutrino Scattering Results Influence Parton Distribution Function Fits?

Summary

- Neutrino scattering could be a powerful tool to determine PDFs particularly the strange and high-x valence quarks.
- \((d - u)/(d + u)\) reasonably constrained out to \(x \approx 0.4\).
- \(\kappa = (s + s)/(u + d)\) seems to be increasing with \(x\).
- \((s - s)/(s + s)\) and heavy quarks need further clarification.
- The valence u-quark is reasonable out to \(x = 0.5\), while the d-quark uncertainty blows up around \(x = 0.3\).
- \(d/u\) at high-x still uncertain due to spread in deuteron correction.
- There is a serious need for new input to global QCD fits at HIGH X.
- The Cleanest Way To Measure \(d/u\): \(\nu + p\) Scattering.
- UNKNOWN nuclear corrections in neutrino scattering are keeping the special abilities of neutrinos out of global fits for PDFs.
Deep inelastic scattering

How do Neutrino Scattering Results Influence Parton Distribution Function Fits?

$F_2$ Structure Function Ratios: NuTeV $\nu$-Iron

See NuFact08 Proceedings for Details

Estimated nuclear effects differences $\mu/e-A$ vs $\nu-A$
Deep inelastic scattering ~ duality

There have been some difficulties in handling the transition region from resonance to safe DIS.

Fit existing charged lepton scattering data and obtain correction factors for the neutrino scattering.

Bodek -Yang Effective LO PDF model - 2003

1. Start with GRV98 LO ($Q^2_{min}=0.80$ GeV$^2$)
   - dashed line: describe $F_2$ data at high $Q^2$
2. Replace the $Xbj$ with a new scaling, $\beta_w$
3. Multiply all PDFs by $K$ factors for photo prod.
   - limit and higher twist
     \[ \frac{\alpha_s}{4\pi \alpha/Q^2} \times F_2(x, Q^2) \]
   - $K_{sea} = Q^2/[Q^2+C_{sea}]$
   - $K_{val} = [1-\sigma_s^2(Q^2)]^2$ \[ [Q^2-C_{2V}]/[Q^2+C_{1V}] \]
     - motivated by Adler sum rule
     - where $\sigma_s^2(Q^2) = \frac{1}{[1+Q^2/0.71]^4}$
4. Freeze the evolution at $Q^2 = Q^2_{min}$
   - $F_2(x, Q^2 \times 0.8) = K(Q^2) \times F_2(xw, Q^2=0.8)$

- Fit to all DIS $F_2$ P/D (with low x HERA data)
  \[ A=0.418, B=0.222 \]
  \[ C_{sea} = 0.381, C_{1V} = 0.604, C_{2V}=0.485 \]
  \[ \chi^2/DOF = 1268 / 1200 \text{ Solid Line} \]

2004 update: Separate $K$ factors for $uv, dv, us, ds$

A : initial binding/TM effect+ higher order
B : final state mass $m_f^2$, $\Delta m^2$
K Factor: Photo-prod limit ($Q^2=0$), Adler sum rule

\[ W = \frac{Q^2+m_f^2+O(m_2^2-m_3^2) + A}{Mv \frac{(1+Q^2)^{1/2}}{B}} \]

Xbj = $Q^2/2Mv$
Deep inelastic scattering

Summary and Discussions

- We updated our Effective LO model with $\xi_w$ and $K(Q^2)$ factors.
- (1) Updated to include a low nu $K$ factor to describe all charged lepton inelastic continuum as well as resonance data including photo-production data. The vector part of the neutrino cross section is now modeled very well. Note: By Gauge Invariance, the vector structure functions must go to zero at $Q^2=0$ for both resonances and inelastic continuum.
- (2) Updated to account for the difference in the higher order QCD corrections between $F_2$ and $X_{F3}$. This is accounted for with a $H(x)$ factor. Therefore, the axial part is also well described for $Q^2>1$ GeV2, where axial and vector are expected to be the same.
- (3) Updated to use $K_{axial}(Q^2)=1$ for both the resonance and inelastic continuum region. This is expected since we know that neutrino quasielastic and resonance production form factor are not zero at $Q^2=0$.
- The lowest $Q^2$ bins in the neutrino and antineutrino measured differential cross sections favor $K_{axial}(Q^2)=1$. Needs to be studied in more detail.
- The total cross section as measured in high energy neutrino scattering favors $K_{axial}(Q^2)=1$. 
the Bloom-Gilman duality is confirmed experimentally for the electron scattering off nucleon and nucleus
  - BG duality is violated below $Q^2=0.3$ GeV$^2$

- BG duality can help to fine tune the magnitude of nonresonant contribution

- Neutrino-nucleon
  - phenomenological models suggest appearance of the duality in neutrino scattering off deuteron-like target
  - for charged current and neutral current structure functions with $W < 1.6/1.8$ GeV
    - $x_F1$ and $x_F3$ (with $1\sigma$ level of accuracy), for the $F2$ (with $2\sigma$ level of accuracy)
    - violation below $Q^2=0.3$ GeV
    - the experimental verification is required (waiting for Minerva measurements)

- duality in neutrino scattering off nucleus waits for more comprehensive studies
Use MINOS beamline to measure cross-sections with various target material

- Scintillator Region: 8.3 tons (~3 tons fiducial)
- Solid Nuclear Target Region: 6.2 tons (40% scintillator)
MINERνA

- If assume a standard run:
  - $4 \times 10^{20}$ POT LE
  - $12 \times 10^{20}$ POT ME

- Results in $\sim 14$ million CC events
  - $\sim 9$ million on scintillator
  - $\sim 5$ million on nuclear targets

<table>
<thead>
<tr>
<th>CC Process Type (on scint.)</th>
<th>Number of Events</th>
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<tbody>
<tr>
<td>Quasi-elastic</td>
<td>0.8M</td>
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<tr>
<td>Resonance Production</td>
<td>1.7M</td>
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<tr>
<td>Res-DIS Transition Region</td>
<td>2.1M</td>
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<td>DIS Low Q2 &amp; Structure Functions</td>
<td>4.3M</td>
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<tr>
<td>Coherent Pion</td>
<td>89k CC, 44k NC</td>
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<td>Charm/Strange</td>
<td>230k</td>
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<table>
<thead>
<tr>
<th>Nuclear Target</th>
<th>Number of Events</th>
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</thead>
<tbody>
<tr>
<td>He</td>
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<tr>
<td>C</td>
<td>0.4M</td>
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<tr>
<td>Fe</td>
<td>2.0M</td>
</tr>
<tr>
<td>Pb</td>
<td>2.5M</td>
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Aiming to reduce cross-section uncertainties

- QE 5%
- Resonance 5% (CC) / 10% (NC)
- DIS 5%
- Coherent 20%
ArgoNeuT
Lq. Ar detector in the MINOS beamline
170 L active volume (~235kg)

- ArgoNeuT will address some of the hardware and physics R&D issues on the way toward massive LAr TPC detectors (MicroBooNE, LAr20 etc.) in terms of:
  - Argon purity, electronics, detector design and construction, etc.
  - Development of MC Simulation and off line reconstruction
- Demonstrate **particle ID** capabilities of LArTPCs with **dE/dx and Range** measurements

- **Physics:**
  - Study CC and NC neutrino events in the “few GeV range” in LAr
  - Precise CC QE $\nu_\mu$ cross section measurement in Argon

<table>
<thead>
<tr>
<th>Event Type</th>
<th># of events in 180 days (1.4x10^{20} POT)</th>
<th># of events in 180 days (1.4x10^{20} POT)</th>
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<td>$\nu_\mu$CC</td>
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<td>6109</td>
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<tr>
<td>anti-$\nu_\mu$CC</td>
<td>1692</td>
<td>5490</td>
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<tr>
<td>$\nu_e$CC</td>
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<td>118</td>
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<tr>
<td>NC</td>
<td>6526</td>
<td>4015</td>
</tr>
<tr>
<td>Total</td>
<td><strong>27917</strong></td>
<td><strong>15732</strong></td>
</tr>
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</table>

*Already in operation!*
ArgoNeuT: Reconstructed CC $\nu$ Event

This event reconstruction is still preliminary. A full and detailed MC simulation including nuclear effects is required for validation. A preliminary FLUKA MC simulation support the possibility to detect such nuclear effects in LAr TPC.
MicroBooNE

- MicroBooNE is a proposed LArTPC detector to run in the on-axis Booster and off-axis NuMI beam on the surface at Fermilab.

- MicroBooNE intend to combine hardware R&D with a relevant physics program in the way toward massive LAr TPC detectors.

- Hardware goals:
  - Cold electronics
  - Long Drift (high level purity required)
  - Purity through detector purging with GAr before filling (without evacuating)

- Physics goals
  - Investigate the MiniBooNE low energy excess
  - Measure low energy Cross-section

- Software goals:
  - Develop automated 3D and calorimetric reconstruction and Particle ID

Jun 2008 → Fermilab Directorate Stage I approval
NSF MRI and DOE funded
MicroBooNE

MicroBooNE Design

- Cryostat (170 Tons LAr) as large as can be built commercially and trucked to site; Single wall, mechanically insulated (glass and polyurethane foam)
- TPC parameters:
  - 100 (70) Tons active (fiducial) volume
  - 2.6 m drift @ 500V/cm → 1.6ms drift time
  - ~10,000 channels (using cold preamplifier)
  - 3 Readout planes (±60° Induction, vertical Collection planes)
- ~30 PMT for triggering;
- Purification/Recirculation system

<table>
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<tr>
<th></th>
<th>BNB</th>
<th>NuMI</th>
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<tr>
<td>POT</td>
<td>$6 \times 10^{20}$</td>
<td>$8 \times 10^{20}$</td>
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<tr>
<td>$\nu_\mu$ CCQE</td>
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<td>25k</td>
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<tr>
<td>NC $\pi^0$</td>
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<td>3k</td>
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<td>$\nu_e$ CCQE</td>
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</tbody>
</table>
LAr TPC can separate e/gamma through topological analysis and calorimetric measurement of the first cm of track (1mip for e, 2 mip’s for gamma) (MC$\rightarrow$efficiency>90%)

This allows to reject BG events like $\nu_\mu$ NC$\pi^0$ from signal ($\nu_e$ CC)

very important for $\nu_\mu \rightarrow \nu_e$ oscillation experiments

1GeV $e^-$'s vs 1GeV $\gamma$'s

Monte Carlo

M.Antonello LNGS
Importance of the neutrino scattering experiments

Measuring $\Delta s$ in Elastic $\nu N$ Scattering in Liquid Ar

$R_{NC/CC} \equiv \sigma(\nu_F \rightarrow \nu_F) / \sigma(\nu_n \rightarrow \mu_F)$

Numerator sensitive to $\Delta s$
- Contribution to proton spin from strange quarks
- From DIS: $\Delta s = -0.09 \pm 0.03$
  - Indirect measurement
  - Some model uncertainty

Requires measurement at very low $Q^2$

Uncertainty affects direct searches for supersymmetric cold dark matter

Neutralino-nucleon elastic-scattering cross section very sensitive to $\Delta s$

Will affect choice of detector material
**NuSOnG**

High energy neutrino beam to study new physics and for the high precision measurements.

---

<table>
<thead>
<tr>
<th>Process</th>
<th>Rate</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ [IMD]</td>
<td>700k</td>
<td>normalization, “WSIMD”, non-standard interactions</td>
</tr>
<tr>
<td>$\nu_\mu + e^- \rightarrow \mu^- + \bar{\nu}_e$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu + e^- \rightarrow \bar{\nu}</em>\mu + e^-$ [ES]</td>
<td>75k</td>
<td>new “heavy” physics ($Z'$, $\nu$ mixing with heavy singlets), new “light” physics, modified couplings, $\sin^2 \theta_w$, $\rho$, $R$-parity, extended Higgs</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu + q \rightarrow \bar{\nu}</em>\mu + X$ [DIS]</td>
<td>190M</td>
<td>$\nu$-$q$ non-standard interactions, $\sin^2 \theta_w$, $\Delta x F_3$, $F_2$, isospin violation, heavy quarks, nuclear effects</td>
</tr>
<tr>
<td>$\nu_\mu + q \rightarrow \nu_\mu + X$</td>
<td>12M</td>
<td></td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu + q \rightarrow \bar{\nu}</em>\mu + X$</td>
<td>600M</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu + q \rightarrow \mu^- + X$</td>
<td>33M</td>
<td></td>
</tr>
<tr>
<td>$\bar{\nu}_\mu + q \rightarrow \mu^- + X$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>decays in low density decay regions</td>
<td>$60??$</td>
<td>new long-lived heavy neutral particles</td>
</tr>
</tbody>
</table>
What makes NuSOnG special?

1) We have an accurate flux measurement! (via IMD events)
2) We have an enormous number of DIS events!

Method: Pick an x and Q^2 bin
Plot the data as a function of y
Vary the structure functions to get the same y-distribution

\[
\frac{d^2\sigma^{\nu(\bar{\nu})N}}{dxdy} = \frac{G_E^2 M E_\nu}{\pi (1 + Q^2/M_W^2)^2} \left[ F_2^{\nu(\bar{\nu})N}(x, Q^2) \left( \frac{y^2 + (2Mxy/Q)^2}{2 + 2R_L^{\nu}(\bar{\nu})N(x, Q^2)} + 1 - y \frac{Mxy}{2E_\nu} \right) + \pm x F_3^{\nu(\bar{\nu})N} y \left( 1 - \frac{y}{2} \right) \right]
\]

Bin-by-bin,
minimize:

\[
\chi^2 = \sum_{\nu, \bar{\nu}} \sum_{y-bins} \left( \frac{N_{data}^{\nu(\bar{\nu})} - N_{MC, pred}^{\nu(\bar{\nu})} (SF_{fit})}{N_{data}^{\nu(\bar{\nu})}} \right)^2
\]
Deeply Virtual Neutrino Production of $\pi^0$ from Nucleon & Nuclear Targets

Spin dependent GPDs upon insertion of T product into nucleon matrix elements

( G. Goldstein, S. Liuti )

Chiral even

Chiral odd

Parity violating V-A coupling doubles the number of helicity amplitudes from 6 to 12

Neutrino (antineutrino) cross section

$$\frac{d^3\sigma}{d\Omega d\varepsilon_2 d\phi dt} = \Gamma \left\{ \frac{d\sigma_T}{dt} + \varepsilon_2 \frac{d\sigma_L}{dt} + \varepsilon \cos 2\phi \frac{d\sigma_{LT}}{dt} + \sqrt{2} \varepsilon_2 (\varepsilon + 1) \cos \phi \frac{d\sigma_{LT}}{dt} \right\}$$

Measure $\phi$ dependence using $\bar{\nu}N \rightarrow \mu^- \pi^+ N$
I’d like to thank all the speakers and the participants in WG2.