Precision Measurements of Fundamental Interactions with (Anti)neutrinos

R. Petti

University of South Carolina, USA

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I Introduction

- Electron and $\nu$ probes
- Status of $\nu$ scattering experiments

II Requirements for Precision Physics

- Statistics vs. resolution
- Control of the targets
- Control of the fluxes

III Precision Measurements

- Electroweak measurements
- Adler sum rule
- Isospin physics
- Nuclear modifications of nucleon properties

IV Summary
Reference EW studies in $e^+e^-$ at LEP by enhancing weak $\sigma$ at the $Z^0$ mass pole:

<table>
<thead>
<tr>
<th>LEP</th>
<th>Number of $Z^0$</th>
<th>Number of $W$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$18 \times 10^6$</td>
<td>$80 \times 10^3$</td>
</tr>
</tbody>
</table>

⇒ High-statistics electroweak measurements at LEP/SLC reached a precision $< 10^{-3}$.

Reference QCD studies in $e^p$ at HERA with measurements $\sim 10^{-2}$ of the nucleon structure and fixed target from JLab, COMPASS, SLAC, NMC, BCDMS etc.

⇒ Can a modern $\nu(\bar{\nu})$ facility deliver comparable precisions unveiling discovery potential in precision tests of fundamental interactions?
Neutrinos offer an ideal probe for EW physics and partonic/hadronic structure of matter:

- Clean probe since only weak interaction;
- Complete flavor separation in Charged Current interactions ($d/u$, $s/\bar{s}$, $\bar{d}/\bar{u}$);
- Separation of valence ($xF_3$) and sea ($F_2$) distributions, complementary to $e^\pm$.

Potential so far only partially explored due to 3 (main) issues

**STATISTICS**

Tiny cross-sections with limited beam intensities required massive & coarse detectors.

**TARGETS**

Need of massive nuclear targets did not allow a precise control of the interactions.

**FLUXES**

Incoming (anti)neutrino energy unknown implied substantial flux uncertainties.
STATISTICS vs. RESOLUTION

✦ Existing detectors compromise between high (low) statistics and high (coarse) resolution are affected by systematics on $E_\mu$, $E_H$ scales, nuclear targets & flux

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass</th>
<th>$\nu_\mu$ CC Stat.</th>
<th>Target</th>
<th>$E_\nu$ (GeV)</th>
<th>$\Delta E_\mu$</th>
<th>$\Delta E_H$</th>
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</thead>
<tbody>
<tr>
<td>CDHS</td>
<td>750 t</td>
<td>$10^7$</td>
<td>$p,Fe$</td>
<td>20-200</td>
<td>2.0%</td>
<td>2.5%</td>
</tr>
<tr>
<td>BEBC</td>
<td>various</td>
<td>$5.7 \times 10^4$</td>
<td>$p,D,Ne$</td>
<td>10-200</td>
<td>2.0%</td>
<td>2.5%</td>
</tr>
<tr>
<td>CCFR</td>
<td>690 t</td>
<td>$1.0 \times 10^6$</td>
<td>$Fe$</td>
<td>30-360</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>NuTeV</td>
<td>690 t</td>
<td>$1.3 \times 10^6$</td>
<td>$Fe$</td>
<td>30-360</td>
<td>0.7%</td>
<td>0.43%</td>
</tr>
<tr>
<td>CHORUS</td>
<td>100 t</td>
<td>$3.6 \times 10^6$</td>
<td>Emul., Pb</td>
<td>10-200</td>
<td>0.2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>NOMAD</td>
<td>2.7 t</td>
<td>$1.5 \times 10^6$</td>
<td>C,Fe</td>
<td>5-200</td>
<td>0.2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>MINOS ND</td>
<td>980 t</td>
<td>$3.6 \times 10^6$</td>
<td>Fe</td>
<td>3-50</td>
<td>2-4%</td>
<td>5.6%</td>
</tr>
<tr>
<td>T2K ND</td>
<td>1.9 t</td>
<td>$10^5$</td>
<td>CH,H$_2$O</td>
<td>0.2-5</td>
<td>0.6%</td>
<td>2-4%</td>
</tr>
<tr>
<td>MINER$\nu$A</td>
<td>5.4 t</td>
<td>$10^7$</td>
<td>CH,C,Fe,Pb</td>
<td>1-30</td>
<td>2%</td>
<td></td>
</tr>
</tbody>
</table>

$\Rightarrow$ Precision measurements require close to $10^8$ CC AND high resolution $\Delta E_\mu \sim 0.2\%$

✦ Precision EW and QCD studies prefer high energy (anti)neutrinos

$\Rightarrow$ Modern beam facilities optimized at lower energies for detection of oscillations
<table>
<thead>
<tr>
<th>Process</th>
<th>Events (5 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard CP optimized (1.2 MW):</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu$ CC (FHC, 5 y)</td>
<td>$34 \times 10^6$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ CC (RHC, 5 y)</td>
<td>$13 \times 10^6$</td>
</tr>
<tr>
<td>Optimized $\nu_\tau$ appearance (2.4 MW):</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu$ CC (FHC, 2 y)</td>
<td>$66 \times 10^6$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ CC (RHC, 2 y)</td>
<td>$24 \times 10^6$</td>
</tr>
<tr>
<td>TOTAL $W^+$</td>
<td>$100 \times 10^6$</td>
</tr>
<tr>
<td>TOTAL $W^-$</td>
<td>$37 \times 10^6$</td>
</tr>
<tr>
<td>TOTAL $Z^0$</td>
<td>$44 \times 10^6$</td>
</tr>
</tbody>
</table>

- **Available LBNF – Long-Baseline Neutrino Facility – beam optimized for FD $\nu_\tau$ appearance:**
  - Conceivable dedicated run after 5y FHC + 5y RHC with the "standard" beams optimized for CP
  - **LBNF:** 120 GeV p, **1.2 MW**, $1.1 \times 10^{21}$ pot/y, ND at 574m;
  - **LBNF upgrade:** 120 GeV p, **2.4 MW (x 2)**, $\sim 3 \times 10^{21}$ pot/y.

- Assume a modest 2y FHC run with $\nu_\tau$ optimized beam & LBNF upgrade

\[\rightarrow\text{ Can afford a high resolution ND of a few tons and still collect desired statistics } \sim 10^8\]
**CONTROL OF TARGETS**

- **Precision EW & QCD measurements** require control of $\nu$-target(s) as in $e^\pm$ DIS:
  - Massive $\nu$ detectors intrinsically limited by the knowledge of the target composition & materials;
  - Possible accurate control of target(s) by separating target(s) from active detector(s);
  - Thin targets spread out uniformly within tracker by keeping low density $\rho \sim 0.16 \text{ g/cm}^3$.

$\implies$ *Straw Tube Tracker (STT) in $B \sim 0.6 \text{T with } 4\pi$ electromagnetic calorimeter*

- **Radiator targets (100% purity)** account for $> 95\%$ of STT mass and can be tuned to achieve desired statistics & resolutions.

- **Separation from excellent vertex, angular & timing resolutions.**

- **Radiators can be replaced by thin nuclear targets: C, Ca, Ar, Fe, etc.**
Need to understand nuclear modifications & corresponding systematic uncertainties:

- Use of heavy target material(s) unavoidable to achieve desired statistics;
- Complexity of weak current (vs. EM) + substantial nuclear modifications (primary & FSI);
- Cannot rely only on model corrections for precision EW & QCD studies.

⇒ Necessary condition availability of (complementary) free nucleon target (hydrogen)
Novel technique to measure $\nu(\bar{\nu})$-Hydrogen by subtracting CH$_2$ and C targets:

- Exploit high vertex, angular & time resolutions of STT to locate interactions within targets;
- Model-independent data subtraction of dedicated C (graphite) target from main CH$_2$ target;
- Kinematic selection provides clean H samples of inclusive & exclusive CC topologies with 80-92% purity and $>90\%$ efficiency before subtraction.

⇒ Viable and realistic alternative to liquid/gaseous H$_2$ detectors

CONTROL OF FLUXES

✧ Relative $\nu_\mu$ flux vs. $E_\nu$ from exclusive $\nu_\mu p \rightarrow \mu^- p \pi^+$ on Hydrogen:
  - Select well reconstructed $\mu^- p \pi^+$ topology on H ($\delta p/p \sim 3%$);
  - Cut $\nu < 0.5(0.75) \text{ GeV}$ flattens cross-sections reducing uncertainties on $E_\nu$ dependence;
  - Systematic uncertainties dominated by muon energy scale ($\Delta E_\mu \sim 0.2\%$ in STT from $K_0$ mass).

⇒ Dramatic reduction of systematics vs. techniques using nuclear targets

Relative $\bar{\nu}_\mu$ flux vs. $E_\nu$ from exclusive $\bar{\nu}_\mu p \rightarrow \mu^+ n$ QE on Hydrogen:

- $E_\nu$ from QE kinematics on H and detection of interacting neutrons: $\sim 25 \pm 45\%$ in STT (ECAL);
- Cut $\nu < 0.1(0.25) \text{ GeV}$ flattens cross-sections reducing uncertainties on $E_\nu$ dependence;
- Systematics and total uncertainties comparable to relative $\nu_\mu$ flux from $\nu_\mu p \rightarrow \mu^- p \pi^+$ on H.

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Possible to solve the main issues of neutrino experiments (statistics, control of targets & fluxes) largely filling the precision gap with electron experiments.

⇒ Exploit the unique properties of the (anti)neutrino probe to study fundamental interactions & structure of nucleons and nuclei.

Turn the LBNF ND site into a general purpose $\nu\bar{\nu}$ physics facility with broad program complementary to ongoing fixed-target, collider and nuclear physics efforts:

- Measurement of $\sin^2 \theta_W$ and electroweak physics;
- Precision tests of isospin physics & sum rules (Adler, GLS);
- Measurements of strangeness content of the nucleon ($s(x), \bar{s}(x), \Delta s$, etc.);
- Studies of QCD and structure of nucleons and nuclei;
- Precision tests of the structure of the weak current: PCAC, CVC;
- Measurement of nuclear physics and (anti)-neutrino-nucleus interactions;
- Precision measurements of cross-sections and particle production; etc. .....  
- Searches for New Physics (BSM) ......

⇒ Significant discovery potential & hundreds of diverse physics topics

Same control of targets & fluxes reduces systematics for long-baseline oscillations.
**ELECTROWEAK MEASUREMENTS**

- **Sensitivity expected from \( \nu \) scattering at LBNF comparable to the Collider precision:**
  - **FIRST** single experiment to directly check the running of \( \sin^2 \theta_W \);
  - **Different scale** of momentum transfer with respect to LEP/SLD (off \( Z^0 \) pole);
  - **Direct measurement of neutrino couplings to** \( Z^0 \) (\( \rho \))
    
    \[ \Rightarrow \text{Only other measurement} \text{ LEP} \Gamma_{\nu \nu} \]
  - **Independent cross-check of the NuTeV** \( \sin^2 \theta_W \) anomaly (~3σ in \( \nu \) data) in a similar \( Q^2 \) range.

- **Different independent channels:**
  - \( R^\nu = \frac{\sigma_{\nu NC}}{\sigma_{\nu CC}} \) in \( \nu \)-N DIS (~0.35%)
  - \( R_{\nu e} = \frac{\sigma_{\nu NC}}{\sigma_{\nu NC}} \) in \( \nu\rightarrow e^- \) NC elastic (~1%)
  - NC/CC ratio \( (\nu p \rightarrow \nu p)/(\nu n \rightarrow \mu^- p) \) in (quasi)-elastic interactions
  - NC/CC ratio \( \rho^0 / \rho^+ \) in coherent processes
    
    \( \Rightarrow \text{Combined EW fits like LEP} \)

- **Further reduction of uncertainties depending upon beam exposure**
The Adler integral provides the \textbf{ISOSPIN} of the target and is derived from current algebra:

\[ S_A(Q^2) = \int_0^1 \frac{dx}{2x} \left( F_2^{\bar{\nu}p} - F_2^{\nu p} \right) = I_p \]

- At large \( Q^2 \) (quarks) sensitive to \( (s - \bar{s}) \) asymmetry, isospin violations, heavy quark production
- Generalize the integral to nuclear targets and test nuclear effects (S. Kulagin and R.P. PRD 76 (2007) 094023)

\[ \implies \text{Precision test of } S_A \text{ at different } Q^2 \text{ values} \]

- Only measurement available from BEBC based on 5,000 \( \nu p \) and 9,000 \( \bar{\nu} p \) (D. Allasia et al., ZPC 28 (1985) 321)

- Direct measurement of \( F_2^{\nu n}/F_2^{\nu p} \) free from nuclear uncertainties and comparisons with \( e/\mu \) DIS

\[ \implies d/u \text{ at large } x \text{ and verify limit for } x \to 1 \]

\begin{tabular}{ |c|c|c| } 
\hline
\textbf{Process} & \textbf{\( \nu(\bar{\nu})-H \)} & \\
\hline
\textit{Standard CP optimized}: & & \\
\( \nu_\mu \) CC (5 y) & 3.4 \times 10^6 & \\
\( \bar{\nu}_\mu \) CC (5 y) & 2.5 \times 10^6 & \\
\hline
\textit{Optimized }\nu_\tau \text{ appearance}:

\( \nu_\mu \) CC (2 y) & 6.5 \times 10^6 & \\
\( \nu_\mu \) CC (2 y) & 4.3 \times 10^6 & \\
\hline
\end{tabular}
Availability of $\nu$-H & $\bar{\nu}$-H allows direct measurement of nuclear modifications of $F_{2,3}$:

$$R_A \equiv \frac{2F_{2,3}^{\nu A} + F_{2,3}^{\nu p}}{F_{2,3}^{\nu A} + F_{2,3}^{\nu p}} (x, Q^2) = \frac{F_{2,3}^{\nu A}}{F_{2,3}^N}$$

- Comparison with $e/\mu$ DIS results and nuclear models;
- Study flavor dependence of nuclear modifications using $\nu$ & $\bar{\nu}$;
- Effect of the axial-vector current.

Study nuclear modifications to parton distributions in a wide range of $Q^2$ and $x$.

Study non-perturbative contributions from High Twists, PCAC, etc. and quark-hadron duality in different structure functions $F_2, xF_3, R = F_L/F_T$.

Nuclear modifications of nucleon form factors e.g. using NC elastic, CC quasi-elastic and resonance production.

Coherent meson production off nuclei in CC & NC and diffractive physics.

$\implies$ Synergy with Heavy Ion and EIC physics programs for cold nuclear matter effects.
Substantial nuclear smearing rapidly varying in oscillation range

Understanding of nuclear smearing (response function for unfolding) crucial for systematics in DUNE oscillation analyses
The intensity and $\nu(\bar{\nu})$ spectra available at the LBNF offer a unique opportunity for neutrino physics, if coupled with a high resolution ND of a few tons.

Possible to achieve a control of configuration, material & mass of neutrino targets similar to electron experiments & use a suite of various target materials.

A novel technique can provide high statistics $\mathcal{O}(10^6)$ samples of $\nu(\bar{\nu})$-hydrogen interactions, allowing unprecedented precisions in the measurement of $\nu$ & $\bar{\nu}$ fluxes.

Turn the DUNE ND site into a general purpose $\nu$ & $\bar{\nu}$ physics facility with broad program complementary to ongoing fixed-target, collider and nuclear physics efforts.

European Particle Physics Strategy Update 2018-2020 (proposal 131):
https://indico.cern.ch/event/765096/contributions/3295805/

$\Rightarrow$ Significant discovery potential & hundreds of diverse physics topics
Reuse existing KLOE magnet + ECAL and fill it with STT & nuclear targets
The intensity and $\nu(\bar{\nu})$ spectra available at the LBNF offer a unique opportunity for neutrino physics, if coupled with a high resolution ND of a few tons.

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⇒ Significant discovery potential & hundreds of diverse physics topics

New ideas or suggestions to further broaden physics scope welcomed
Looking for feedback and/or potential interest

Roberto Petti
USC
Backup slides
STRANGENESS CONTENT OF NUCLEON

✦ **NC ELASTIC SCATTERING** 

Neutrino-nucleus is sensitive to the *strange quark* contribution to nucleon spin, $\Delta s$, through axial-vector form factor $G_1$:

$$ G_1 = \left[ -\frac{G_A}{2} T_z + \frac{G_s}{2} \right] $$

At $Q^2 \to 0$ we have $d\sigma/dQ^2 \propto G_1^2$ and the *strange axial form factor* $G_A^s \to \Delta s$.

✦ **Measure NC/CC RATIOS** as a function of $Q^2$ to reduce systematics ($\sin^2 \theta_W$ as well):

$$ R_\nu = \frac{\sigma(\nu p \to \nu p)}{\sigma(\nu n \to \mu^- p)}; \quad R_{\bar{\nu}} = \frac{\sigma(\bar{\nu} p \to \bar{\nu} p)}{\sigma(\bar{\nu} p \to \mu^+ n)} $$

- Compare axial current charge radius $r_A^2$ with muon capture in muonic hydrogen (discrepancies);
- Expect $\sim 2 \times 10^6 \nu$ NC and $\sim 1 \times 10^6 \bar{\nu}$ NC events (BNL E734: 951 $\nu p$ and 776 $\bar{\nu} p$);
- Precision measurement over an extended $Q^2$ range reduces systematic uncertainties from the $Q^2$ dependence of vector ($F_{1,2}^s$) and axial ($G_A^s$) strange form factors.

✦ **Direct probe of $s(x) \ & \bar{s}(x)$ content of nucleon from charm production in both dilepton ($\sim 100k \mu\mu \& \mu e$) and exclusive charmed hadrons (e.g. $D^*, D_s, \Lambda_c$).**
Absolute $\bar{\nu}_\mu$ flux from QE on Hydrogen $\bar{\nu}_\mu p \rightarrow \mu^+ n$:

$$\frac{d\sigma}{dQ^2} \bigg|_{Q^2=0} = \frac{G_F^2 \cos^2 \theta_C}{2\pi} \left[ F_V^2(0) + G_A^2(0) \right]$$

where terms in $(m_l/M)^2$ are neglected.

- Select reconstructed QE events with small $Q^2$ values: $\sim 135,000$ events with $Q^2 < 0.05$ GeV$^2$;
- At $Q^2 = 0$ QE cross-section determined by neutron $\beta$-decay to a precision $\ll 1$;  

Calibrate absolute $n$ detection efficiency with dedicated irradiation of STT & ECAL
<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>( \delta R^\nu / R^\nu )</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NuTeV</td>
<td>DUNE</td>
</tr>
<tr>
<td>Data statistics</td>
<td>0.00176</td>
<td>0.00057</td>
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<tr>
<td>Monte Carlo statistics</td>
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<tr>
<td>Total Statistics</td>
<td><strong>0.00176</strong></td>
<td><strong>0.00057</strong></td>
</tr>
<tr>
<td>( \nu_e, \bar{\nu}_e ) flux</td>
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</tr>
<tr>
<td>Energy measurement</td>
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<td>Shower length model</td>
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<td>Counter efficiency, noise</td>
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<td>Interaction vertex</td>
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<td>Kinematic selection</td>
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<tr>
<td>Experimental systematics</td>
<td><strong>0.00112</strong></td>
<td><strong>0.00100</strong></td>
</tr>
<tr>
<td>( d, s \rightarrow c, s )-sea</td>
<td>0.00227</td>
<td>0.00140</td>
</tr>
<tr>
<td>Charm sea</td>
<td>0.00013</td>
<td>n.a.</td>
</tr>
<tr>
<td>( r = \sigma^\bar{\nu} / \sigma ^\nu )</td>
<td>0.00018</td>
<td>n.a.</td>
</tr>
<tr>
<td>Radiative corrections</td>
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</tr>
<tr>
<td>Non-isoscalar target</td>
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<tr>
<td>Higher twists</td>
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<td>0.00070</td>
</tr>
<tr>
<td>( R_L \ (F_2, F_T, xF_3) )</td>
<td>0.00115</td>
<td>0.00140</td>
</tr>
<tr>
<td>Nuclear corrections</td>
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<td>Model systematics</td>
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<td><strong>0.00210</strong></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.00332</strong></td>
<td><strong>0.00239</strong></td>
</tr>
</tbody>
</table>

\( \Rightarrow \) Non-perturbative effects (High Twists, \( R_L \), etc.) & nuclear corrections?
Kinematic NC/CC separation successfully used by the NOMAD experiment:

No radiative corrections applied