A High Resolution Experiment
for Precision Neutrino Physics

R. Petti

University of South Carolina, USA

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OUTLINE

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SUMMARY OF NEUTRINO MASSES AND MIXING

**MIXING**

**KNOWN PARAMETERS:**
- $\theta_{12} \sim 33^0$
  *from SOLAR neutrino oscillations*
- $\theta_{23} \sim 45^0$
  *from ATMOSPHERIC oscillations*

**TO BE DETERMINED:**
- $\theta_{13} < 9^0$ *at 90% CL*
  *from REACTOR experiments*
- $\delta$ *CP phase*
  $\Rightarrow P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- $\nu_2 - \nu_3$ *mixing maximal ($\theta_{23} \equiv 45^0$)?*

**MASSES**

**KNOWN PARAMETERS:**
- $\Delta m_{32}^2 = 2.4 \times 10^{-3}$, $\Delta m_{21}^2 = 8.0 \times 10^{-5}$
- One $\nu$ *has a mass of AT LEAST 0.05 eV*
- Masses must be AT MOST 2.5 eV
  ($m_{\text{electron}} = 511000$ eV!)

**TO BE DETERMINED:**
- *Mass hierarchy* (normal or inverted?)
- *Absolute $\nu$ mass scale*
CORRELATIONS & DEGENERACIES

\[ \nu_\mu \leftrightarrow \nu_e \] and \[ \nu_e \rightarrow \nu_\tau \]

\[ P_{\alpha\beta}^\pm \equiv P_{\alpha\beta}^\pm (\theta_{\alpha\beta}, \delta_{\text{CP}}, \text{sign } [\Delta m_{23}^2], \text{sign } [\tan(2\theta_{23})]) \]

Need independent measurements to solve eightfold degeneracy:

- \( \nu \) and \( \bar{\nu} \);
- Different \( L/E \) values;
- Complementary channels: \( P_{\mu e} \) vs. \( P_{e\tau} \);
- \( \nu_{e,\mu,\tau} \) appearance vs. \( \nu_{e,\mu} \) disappearance.

\[ \downarrow \]

Complex experimental program
Sensitivity to oscillation parameters affected by systematics in backgrounds & signal detection

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USC
REQUIREMENTS FOR LBL EXPERIMENTS

I  PRECISION

♦ Statistics: accelerator, tonnage;
♦ Near detector(s): resolution;
♦ $\sigma_{\nu,\bar{\nu}}$ and $\nu$-induced $\pi^\pm/K^\pm/\pi^0$ & nuclear effects;
♦ $\nu$ Neutral Current (NC) and Charged Current (CC) interactions.

II  REDUNDANCY

♦ Complementary measurements;
♦ Hadro-production ($\pi^\pm, K^\pm, K^0$) data;
♦ Flux measurement $\Phi(\nu_\mu, \bar{\nu}, \nu_e, \bar{\nu}_e)$ as a function of $(E_\nu, \theta_\nu)$. 
What Kind of Near Detectors?

✧ Use of “identical” small detector at a near site insufficient for future LBL experiments:
  ● $\Phi^{\nu,\bar{\nu}}(E_\nu, \theta_\nu)$ different at near & far sites;
  ● Impossible to have really “identical” for $\mathcal{O}(100\text{kt})$ detectors at projected luminosities;
  ● Different compositions of event samples ($\nu_e, \nu_\mu$, NC, CC)
    $\implies$ Coarse resolution dictated by $\mathcal{O}(100\text{kt})$ compromises measurements at near site

✧ Need additional high resolution detector to address systematics affecting LBL:
  ● $\nu_\mu, \bar{\nu}, [\nu_e, \bar{\nu}_e]$ content vs. $E_\nu$ and $\theta_\nu$;
  ● $\nu$-induced $\pi^\pm/K^\pm/p/\pi^0$ in CC and NC interactions;
  ● Quantitative determination of $E_\nu$ absolute energy scale;
  ● Measurement of detailed event topologies in CC & NC.
    $\implies$ Provide an ‘Event-Generator’ measurement for LBL

✧ Fine grained near detectors at future LBL facilities are natural candidates to study neutrino scattering physics.
  Can they achieve a substantial physics potential for non-oscillation physics?

Roberto Petti
USC
### STATUS OF $\nu$ SCATTERING EXPERIMENTS

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass</th>
<th>$\nu_\mu$ CC</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCFR</td>
<td>690 t</td>
<td>$1.0 \times 10^6$</td>
<td>massive calo</td>
</tr>
<tr>
<td>NuTeV</td>
<td>690 t</td>
<td>$1.3 \times 10^6$</td>
<td>massive calo</td>
</tr>
<tr>
<td>CDHS</td>
<td>750 t</td>
<td>$10^7$</td>
<td>massive calo</td>
</tr>
<tr>
<td>CHARM II</td>
<td>547 t</td>
<td>$10^7$</td>
<td>massive calo</td>
</tr>
<tr>
<td>NOMAD</td>
<td>25 t</td>
<td>$1.3 \times 10^7$</td>
<td>Fe calo</td>
</tr>
<tr>
<td>CHORUS</td>
<td>100 t</td>
<td>$1.4 \times 10^7$</td>
<td>Pb calo</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass</th>
<th>$\nu_\mu$ CC</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>E531</td>
<td>91 kg</td>
<td>$3.8 \times 10^4$</td>
<td>emulsions</td>
</tr>
<tr>
<td>BBC</td>
<td>various</td>
<td>$5.7 \times 10^4$</td>
<td>bubble ch.</td>
</tr>
<tr>
<td>CHORUS</td>
<td>700 kg</td>
<td>$4.8 \times 10^5$</td>
<td>emulsions</td>
</tr>
<tr>
<td>NOMAD</td>
<td>2.7 t</td>
<td>$1.3 \times 10^6$</td>
<td>Drift chambers</td>
</tr>
</tbody>
</table>

- **Massive calorimeters** (CDHS, CHARM II, CCFR, NuTeV) collected statistics up to $\mathcal{O}(10^7)$ interactions in coarse detectors (sampling)

- **Precise tracking experiments** (BBC, E531, NOMAD, CHORUS) reached high resolution on smaller data samples up to $\mathcal{O}(10^6)$

⇒ Forced choice between statistics & resolution
⇒ Physics potential of neutrino probe not fully exploited yet
**KNOWLEDGE OF $\nu(\bar{\nu})$ CROSS-SECTIONS**

- **Total $\nu$ cross-section known to 2.5% for $E_\nu \geq 10$ GeV and to 4% for $E_\nu > 2.5$ GeV**
  $\Rightarrow$ Need precision data at $E_\nu < 3.0$ GeV (oscillation peak!!)

- **Large uncertainties on exclusive processes:** quasi-elastic (20%), resonance (40%) and coherent production in CC and NC (100%)

- **Poor knowledge of $\bar{\nu}$ cross-sections and $\bar{\nu}$-induced processes**
  $\Rightarrow$ Need to collect large statistics of anti-neutrino data
REQUIREMENTS FOR NEW DETECTORS

✦ STATISTICS

- Limiting factor for old experiments;
- Need increase \( \times 10 \div \times 100 \) with respect to current experiments;
- Detector mass not critical at new oscillation facilities (large fluxes);

\[ \Rightarrow \text{Shift focus from measurements of cross-sections to precision tests of fundamental interactions & structure of matter} \]

✦ Reduction of systematic uncertainties:

- Flux, energy & momentum scales, backgrounds, theoretical modeling etc.;
- Start to dominate current \( \nu \)-scattering experiments;
- Need fine-grained detectors & REDUNDANCY through multiple measurements

\[ \Rightarrow \text{A major physics program requires HIGH RESOLUTION} \]
Neutral Current Event

Massive Calo (NuTeV)

Precise Tracker (NOMAD)

Hadron Shower

Missing transverse momentum

HiResMν: order of mag. higher segmentation
THE HiResMν DETECTOR

Fiducial Mass
≈ 7.4 tons

Build upon the NOMAD experience:
- Combine high resolution tracking & particle identification inside dipole magnet ($B = 0.4\ T$);
- Low density design with target embedded.

Side coverage of EM calorimeter needed for $\pi^0$ detection

External muon detector based upon Resistive Plate Chambers (RPC)
THE STRAW TUBE TRACKER

✦ Build upon NOMAD experience

✦ The ATLAS TRT technology allows to improve upon limitations of the NOMAD design while keeping all the advantages of a low density - $\rho = 0.1 g/cm^3$ - detector:
  - Small cylindrical drift tubes insensitive to track angles;
  - More sampling points along the track ($\times 6$ $\perp$ beam axis and $\times 2$ along the beam axis) $\implies$ efficient proton reconstruction down to 250 MeV/c
  - $dE/dx$ and Transition Radiation (TR) for particle identification $\implies$ proton and electron identification with little background

✦ Mass of the active target is completely dominated by the radiators (85% of total mass) and can be tuned to achieve desired events & momentum resolution

✦ Basic design for the proposed detector after COMPASS
  - Operate with Xe/CO$_2$ gas mixture;
  - As baseline calculate radiator thickness in order to give same density as in NOMAD ($1X_0 = 5 m$);
  - Arrange radiators and straws in "modules".
Project-X at FNAL (2016): new 8 GeV linac + Recycler + Main Injector: beam power of 2.3 MW at 120 GeV, $30 \times 10^{20} \text{ pot/y}$.

Event rates on axis with the Medium Energy (ME) configuration (default for LBL$\nu$): $6.3 \times 10^6 \nu_\mu \text{ CC/t/y}$ at few 100 m from the neutrino source

$\Rightarrow$ Increase by about a factor of 3 with High Energy configuration
3(4) years $\nu(\bar{\nu})$ run in tandem with the Long Baseline neutrino oscillation experiments (LBL$\nu$) 

$\implies$ No need for a dedicated beam

Required running time reduced by about 3 times with the HE beam
Neutrino radiography of one drift chamber

**NOMAD:** charged track momentum scale known to < 0.2%
hadronic energy scale known to < 0.5%

**HiResMν:** $200 \times$ more statistics and $12 \times$ higher segmentation
THE NEUTRINO PROBE

✦ In $e^+e^-$ collisions it is possible to enhance the weak cross-section by running at the $Z^0$ mass pole:

$$\frac{\sigma_Z}{\sigma_\gamma} \propto \frac{E^4}{[(2E)^2 - (M_Zc^2)^2]^2 + (h\Gamma_Z M_Z c^2)^2}$$

$$\implies$$  High-statistics electroweak measurements at LEP/SLC reached a precision $\sim 10^{-3}$.

✦ Neutrinos the most natural probe to investigate both electroweak parameters and hadronic structure of matter since they experience only one interaction

$$\implies$$  Due to limited statistics $\nu$ measurements $\sim 10^{-2}$

✦ The collection of $\mathcal{O}(10^8)$ $\nu(\bar{\nu})$ CC statistics with HiRes$\nu$ could have, for neutrino physics, the same impact LEP had for $e^+e^-$:

<table>
<thead>
<tr>
<th></th>
<th>Number of $Z^0$</th>
<th>Number of $W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP</td>
<td>$18 \times 10^6$</td>
<td>$80 \times 10^3$</td>
</tr>
</tbody>
</table>
MEASUREMENT OF $\sin^2 \theta_W$ FROM $\nu N$ DIS

- Measure ratios of NC and CC in both $\nu$-N and $\bar{\nu}$-N Deep Inelastic Scattering. Paschos-Wolfenstein relation allows a reduction of systematic uncertainties:

$$R^- \equiv \frac{\sigma^\nu_{NC} - \sigma^\nu_{CC}}{\sigma^\nu_{CC} - \sigma^\nu_{NC}}$$

Large statistics available in HiResM$\nu$:
- $19 \times 10^6$ NC events with $E_{\text{had}} > 3.0$ GeV in $\nu$ mode;
- $6 \times 10^6$ NC events with $E_{\text{had}} > 3.0$ GeV in $\bar{\nu}$ mode.

- Expected total uncertainty $\sim 0.2\%$. Model systematics constrained by dedicated measurements:

  - Charm production from both dileptons ($\sim 200k \mu\mu&\mu\epsilon$) and exclusive charmed hadrons ($5 \times 10^6$ charm events);
  - Structure function measurement and QCD analysis of HiResM$\nu$ data (PDFs, High Twists, etc.)

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\delta s^2_W/s^2_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>0.0008</td>
</tr>
<tr>
<td>Experimental systematics</td>
<td>0.0010</td>
</tr>
<tr>
<td>Model systematics</td>
<td>0.0014</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.0019</td>
</tr>
</tbody>
</table>
Relative uncertainties for *NuTeV* (PRL 88 (2002)091802) and expectations for HiResMν:

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\delta X/X$</th>
<th>$\delta R^\nu/R^\nu$</th>
<th>$\delta R^\bar{\nu}/R^\bar{\nu}$</th>
<th>$\delta X/X$</th>
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<tbody>
<tr>
<td>Data statistics</td>
<td>0.00593</td>
<td>0.00176</td>
<td>0.00393</td>
<td></td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>0.00044</td>
<td>0.00015</td>
<td>0.00025</td>
<td></td>
</tr>
<tr>
<td><strong>Total Statistics</strong></td>
<td><strong>0.00593</strong></td>
<td><strong>0.00176</strong></td>
<td><strong>0.00393</strong></td>
<td><strong>0.0008</strong></td>
</tr>
<tr>
<td>$\nu_e, \bar{\nu}_e$ flux ($\sim$ 1.7%)</td>
<td>0.00171</td>
<td>0.00064</td>
<td>0.00109</td>
<td>0.0001</td>
</tr>
<tr>
<td>Energy measurement</td>
<td>0.00079</td>
<td>0.00038</td>
<td>0.00059</td>
<td>0.0004</td>
</tr>
<tr>
<td>Shower length model</td>
<td>0.00119</td>
<td>0.00054</td>
<td>0.00049</td>
<td>n.a.</td>
</tr>
<tr>
<td>Counter efficiency, noise</td>
<td>0.00101</td>
<td>0.00036</td>
<td>0.00015</td>
<td>n.a.</td>
</tr>
<tr>
<td>Interaction vertex</td>
<td>0.00132</td>
<td>0.00056</td>
<td>0.00042</td>
<td>n.a.</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.0008</td>
</tr>
<tr>
<td><strong>Experimental systematics</strong></td>
<td><strong>0.00277</strong></td>
<td><strong>0.00112</strong></td>
<td><strong>0.00141</strong></td>
<td><strong>0.0010</strong></td>
</tr>
<tr>
<td>$d,s\rightarrow c, s$-sea</td>
<td>0.00206</td>
<td>0.00227</td>
<td>0.00454</td>
<td>0.0011</td>
</tr>
<tr>
<td>Charm sea</td>
<td>0.00044</td>
<td>0.00013</td>
<td>0.00010</td>
<td>n.a.</td>
</tr>
<tr>
<td>$r = \sigma^\bar{\nu}/\sigma^\nu$</td>
<td>0.00097</td>
<td>0.00018</td>
<td>0.00064</td>
<td>0.0005</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>0.00048</td>
<td>0.00013</td>
<td>0.00015</td>
<td>0.0001</td>
</tr>
<tr>
<td>Non-isoscalar target</td>
<td>0.00022</td>
<td>0.00010</td>
<td>0.00010</td>
<td>N.A.</td>
</tr>
<tr>
<td>Higher twists</td>
<td>0.00061</td>
<td>0.00031</td>
<td>0.00032</td>
<td>0.0003</td>
</tr>
<tr>
<td>$R_L$</td>
<td>0.00141</td>
<td>0.00115</td>
<td>0.00249</td>
<td>(F_2, F_T, xF_3) 0.0005</td>
</tr>
<tr>
<td><strong>Model systematics</strong></td>
<td><strong>0.00281</strong></td>
<td><strong>0.00258</strong></td>
<td><strong>0.00523</strong></td>
<td><strong>0.0014</strong></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.00711</strong></td>
<td><strong>0.00332</strong></td>
<td><strong>0.00672</strong></td>
<td><strong>0.0019</strong></td>
</tr>
</tbody>
</table>
Available dimuon statistics:

<table>
<thead>
<tr>
<th>Type</th>
<th>NuTeV</th>
<th>CCFR</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$</td>
<td>5012</td>
<td>5030</td>
<td>10042</td>
</tr>
<tr>
<td>$\bar{\nu}$</td>
<td>1458</td>
<td>1060</td>
<td>2518</td>
</tr>
</tbody>
</table>

$\Rightarrow$ NOMAD $\sim 15000$ $\nu$-induced charm dimuon events (ongoing analysis)

✦ Charm production in $\nu$ N DIS is a direct probe of the strange content of the nucleon:

$$\frac{d\sigma_{\mu^+\mu^-}}{dx dy dz} = \frac{d\sigma_{\mu^+e}}{dx dy} \sum_h f_h D_c^h(z) Br(h \rightarrow \mu^\pm X)$$

$D_c(z)$ fragmentation function, $f_h$ fraction of charmed hadrons $h = D^0, D^\pm, D_s^\pm, \Lambda_c^\pm$.

✦ Dimuon $\nu(\bar{\nu})$ cross-section data from NuTeV and CCFR included in global PDF fit of DIS and Drell-Yan data. Charm calculation at NLO in fixed flavour scheme ($n_f = 3$).
Parameterize $s(x)$ and $\bar{s}(x)$ distributions: $x s(x) = A x^\alpha (1 - x)^\beta$ where $A$ and $\beta$ can be different for $s(x)$ and $\bar{s}(x)$, while $\alpha$ is common.

Strange sea suppression factor $\kappa = \frac{\int_0^1 [x s(x) + x \bar{s}(x)] dx}{\int_0^1 [x \bar{u}(x) + x \bar{d}(x)] dx}$ is 0.59 at $Q^2 = 20$ GeV$^2$.

Strange sea asymmetry consistent with zero within errors (arXiv:0810.4893 [hep-ph]): $\int_0^1 x [s(x) - \bar{s}(x)] dx = 0.0011(13)$
Our results indicate that both shape and magnitude of twist-4 contributions to $F_2$ and $F_T$ are comparable.

Twist-6 terms compatible with zero $H_{2,T}^{\tau 6} = 0$. Upper limit on twist-6 terms $\sim 0.02$ GeV$^2$, well below twist-4 terms.

Out of the resonance region the high twist contributions correspond to $\leq 10\%$ of the total structure functions, indicating a convergence of the OPE expansion.
- HT on $F_2$ and $F_T$ from CHORUS $\nu(\bar{\nu})$ cross-section data consistent with charged leptons after charge rescaling.

- Simultaneous extraction of HT in $x F_3$ from neutrino data

The excess in SLAC data for $R = \sigma_L/\sigma_T$ at $x \sim 0.2$ with respect to the QCD predictions was considered as evidence of the large high twist contribution to $R$ and $F_L$ (Miramontes 92).

Our results show instead such excess is connected with the discrepancy between SLAC and BCDMS and can be hardly attributed to the high twist contributions.

Parameters and model uncertainties determined from analysis of charged lepton data.

Predictions for (anti)neutrino scattering consistent with NuTeV (Fe) and CHORUS (Pb) cross-section data over main kinematic range (band in plots ±2.5%).

⇒ NOMAD data on C and Fe targets (prel.) don't support NuTeV excess at large x.
**Tests of Isospin Symmetry**

- **Extraction of** $\sin^2 \theta_W$ **from** $\nu N$ **DIS** sensitive to violations of isospin symmetry in nucleon, $u_p(n) \neq d_n(p)$. *HiResM* $\nu$ with $\nu$ AND $\bar{\nu}$ on isoscalar C TARGET:

$$\frac{F_2^{\nu C}}{F_2^{\bar{\nu} C}}(x, Q^2) - 1$$

- Structure function ratio reduces systematic uncertainties;
- Need to take into account charm quark effects $\propto \sin^2 \theta_C$. Sensitivity to $m_c$;
- A non-vanishing strange sea asymmetry $s(x) - \bar{s}(x)$ would affect the result. Need combined analysis with charm production in $\nu$ and $\bar{\nu}$ interactions;
- Potential effect of nuclear environment e.g. with Coulomb field.

- **Collect $\nu$ and $\bar{\nu}$ interactions on both Ca AND Cu TARGETS** to disentangle nuclear effects from isospin effects in nucleon structure functions.

  - Measure ratios $F_2^{\nu A}/F_2^{\bar{\nu} A}(x, Q^2)$;
  - Use heavier isoscalar target, $^{20}_{40}Ca$, to verify nuclear effects in $^{6}_{12}C$;
  - Use second target with large isovector component but A comparable to Ca: $^{29}_{63}Cu$;
  - The Ca target has also the same A as argon $^{18}_{40}Ar$.

- **Possibly add external cryogenic target with liquid H or D (see next)**
◆ Measure the A dependence with two points, Ca and Cu, in addition to the main C target in STT:
  ● Ratios of $F_2$ AND $xF_3$ on different nuclei;
  ● Comparisons with charged leptons.

◆ Use 0.15$X_0$ thick target plates in front of three straw modules (providing 6 space points) without radiators. Nuclear targets upstream.
  ● For Ca target consider CaCO$_3$ or other compounds;
  ● Total Cu target ($\sim$ 2mm) mass for one module $\sim$ 220 kg;
  ● **OPTION**: possible to install other materials (Pb, etc.).
MEASUREMENT OF $\sin^2 \theta_W$ FROM $\nu$-e

- **Ratio of** $\nu e \to \nu e$ and $\bar{\nu} e \to \bar{\nu} e$ **NC elastic scattering**, which is free from hadronic uncertainties:

\[
R_{\nu e} \overset{\text{def}}{=} \frac{\sigma(\bar{\nu}e^-)}{\sigma(\nu e^-)}
\]

**Statistics available in HiResM$\nu$:**
- $31 \times 10^3$ NC events in $\nu$ mode;
- $17 \times 10^3$ NC events in $\bar{\nu}$ mode.

- **Expected total uncertainty** $\sim 0.56\%$ **dominated by statistics**. **Systematic uncertainties reduced by** $\nu/\bar{\nu}$ **ratio and detector design:**
  - High resolution $e$ tracking and charge measurement avoid background extrapolation (CHARM II);
  - Electron energy measurement cancel in the ratio;
  - Absolute fluxes determined by inverse muon decay at high energy. Relative fluxes from low-$\nu^0$ method in conjunction with MIPP hadroproduction data.
RELEVANCE OF THE $\sin^2 \theta_W$ MEASUREMENT

✦ Sensitivity expected from $\nu$ scattering in HiResM$\nu$ comparable to the Collider precision:

- **FIRST single experiment to directly check the running of $\sin^2 \theta_W$:**
  elastic $\nu$-e scattering and $\nu$N DIS have different scales
- **different scale** of momentum transfer with respect to LEP/SLD (off $Z^0$ pole)
- direct measurement of neutrino couplings to $Z^0$

  $\Rightarrow$ Only other measurement LEP $\Gamma_{\nu\nu}$

✦ NuTeV measured $\sin^2 \theta_W$ by comparing NC and CC rates for BOTH $\nu$ and $\bar{\nu}$:

$$R^\nu = \frac{\sigma_{NC}}{\sigma_{CC}}$$
$$R^\bar{\nu} = \frac{\sigma_{NC}}{\sigma_{CC}}$$

$\Rightarrow$ A discrepancy of $3\sigma$ with respect to SM in the NEUTRINO data
**ADDITIONAL CHANNELS**

- **Ratio of NC elastic scattering neutrino-nucleus to CC quasi-elastic scattering for both ν and ν̄ (sin^2 θ_W):**

  \[ R_ν = \frac{σ(νp→νp)}{σ(νn→μ^−p)}; \quad R_ν̄ = \frac{σ(ν̄p→ν̄p)}{σ(ν̄p→μ^+n)} \]

  Excellent proton reconstruction and ID in HiResMν. Extract axial form factor \( G_A \) from the CC sample.

  - Expect \( \sim 1.5 \times 10^6 \) ν NC and \( \sim 800k \) ν̄ NC events;
  - Intermediate Q scale between νN DIS and ν-e scattering;
  - Significant reduction of systematics from NC/CC ratios.
  - Systematics to check: nuclear effects, form factors (\( Q^2 \) dependence), neutrons

- Additional constraints to electroweak parameters could be provided by the study of coherent-like NC processes. The statistical precision on NC coherent \( π^0 \) production expected in HiResMν is \( \sim 0.2\% \).

- Perform a global electroweak fit with the various independent measurements similarly to what was done at LEP
Measurment of $\Delta_s$

- **NC Elastic Scattering**
  Neutrino-nucleus is sensitive to the strange quark contribution to nucleon spin, $\Delta_s$, through axial-vector form factor $G_1$:

  $$G_1 = \left[-\frac{G_A}{2} \tau_z + \frac{G_A^s}{2}\right]$$

  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):

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

  - Statistical precision in HiResM$\nu$ will be at the $10^{-3}$ level;
  - High resolution tracking for protons down to momenta of 250 MeV/c in HiResM$\nu$ allows to access low $Q^2$ values and reduce backgrounds;
  - A 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;
  - Nuclear effects are expected to largely cancel in the ratios $R_\nu$ and $R_{\bar{\nu}}$. 

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CURRENT CONSERVATION

✦ **PCAC**: Axial Current is only Partially Conserved. Axial-vector contributions dominate at low $Q^2$:

- Adler relation for $\nu$ cross-section:
  \[
  \frac{d^2\sigma(\nu T \rightarrow lF)}{dQ^2 d\nu} \bigg|_{Q^2=0} \propto \sigma(\pi T \rightarrow F; E_\pi = \nu)
  \]
- For $Q^2 \rightarrow 0$, $F_2, F_L \neq 0$, $R = \sigma_L/\sigma_T \rightarrow \infty$

$\implies$ HiResM$\nu$ can perform precision tests of PCAC at $Q^2 < 0.1$ GeV$^2$

✦ The Vector Current is Conserved, **CVC**. Vector contributions vanish for $Q^2 \rightarrow 0$

Test CVC from momenta & polarization ($\Lambda$) in exclusive channels (S. Adler):

$\nu A \rightarrow l A' \pi \pi$; $\nu A \rightarrow l A' \Lambda K$

$\implies$ HiResM$\nu$ can access such channels thanks to high resolution & $\pi/K$ separation
TEST OF ADLER SUM RULE

- The Adler integral provides the isospin of the target and is derived from current algebra:

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

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

- Physics case for exposing liquid \( H_2 \) and/or \( D_2 \) targets to \( \nu(\bar{\nu}) \) beams, in combination with the HiRes\( \nu \) precision tracker

\[ \rightarrow \text{Fluxes at Project-X would allow to extract } S_A \text{ at different } Q^2 \]
\[ \rightarrow \text{Measurement of } \frac{F_{2p}^{\nu}}{F_{2p}^{\bar{\nu}}} = \frac{d}{u} \text{ at large } (Q^2, x) \text{ free from nuclear uncertainties} \]
SUMMARY

✦ The Project-X with HiRes$\nu$ offers a unique opportunity to do neutrino physics: for oscillation studies and for standard model physics

● Well established technologies (no R&D required) based upon ATLAS and COMPASS designs;
● Dipole design based upon NOMAD and LHCB;
● Calorimetry and Muon Range Detector based on conventional detectors.

✦ Outstanding Physics potential for HiRes$\nu$ at Project-X:

● Ultimate Near Detector for Long Baseline Neutrino Oscillation experiments;
● Precise measurement of $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, $\bar{\nu}_e$ as a function of $E_\nu$ & detailed topology;
● Measurement of $\sin^2 \theta_W$ in neutrino interactions to a precision comparable to LEP/SLC & check of NuTeV anomaly. Direct probe of running of $\sin^2 \theta_W$;
● Precision tests of isospin symmetry;
● Measurement of strange sea contribution to the nucleon spin $\Delta s$;
● Precision tests of the structure of the weak current: PCAC, CVC;
● Strange sea and charm production;
● Measurement of Nuclear effects in neutrino interactions;
● Precision measurements of cross-sections and particle production;
● Studies of QCD and hadron structure of nucleons and nuclei;
● Search for weakly interacting massive particles and other exotic phenomena;
● etc., etc. …..
Backup slides
Compact design combining tracking & particle identification in the same detector:

- Radiator foils for Transition Radiation (TR) for electron identification ($\gamma > 1000$);
- Drift straw tubes for tracking (400k channels with 4mm diameter filled with Xe/CO$_2$/O$_2$);
- Low density $1X_0 \sim 5\ m$.

Electronic readout chain developed to match the challenging rate & radiation problems in ATLAS:

- Drift time measurement;
- Signal pulses are fed to discriminators with Low (tracking) and High (electron ID) Thresholds (no analog readout of charge).

Standard resolution achieved on space points 130 $\mu m$ at testbeam.

Straw Tracker also built for the COMPASS detector, where only the drift time information is used (tracking without particle identification).
Use the same global mechanics as in COMPASS (established and well tested design). The design of the tracking modules would be the following:

- Straw diameter 1 cm;
- Straw walls 60\(\mu\)m Kapton or Mylar (one wall \(2 \times 10^{-4} X_0\));
- Gas in each straw \(9 \times 10^{-5} X_0\);
- Wire W gold plated 30\(\mu\)m diameter;
- Wire tension around 90g;
- Default radiator thickness \(\sim 3\)mm (foils for TR);
- Straws are arranged in double layers glued together (epoxy glue) and inserted within Al mechanical frames (or C-fibre);
- Thickness of frames 4 cm (2 straws / 4 cm);
- Total of 125 modules to cover 5 m, arranged by alternating vertical and horizontal orientation;
- Analog readout at both ends of straws to solve ambiguities in the association of hits.
**EXPECTED PERFORMANCE**

✦ **Space point resolution** better than 200 µm (in ATLAS 130 µm).

✦ **Momentum resolution** for \( \rho = 0.1 \text{g/cm}^3 \) and \( B = 0.4T \):
  - Multiple scattering contribution \( 0.05 \) for \( L = 1m \) (\( B = 0.4T \), default radiator)
  - Measurement error (\( B = 0.4T \))

\[
\frac{\sigma(p)}{p} = \frac{\sigma(x)p}{0.3BL^2} \sqrt{\frac{720}{N + 4}}
\]

which gives \( 0.006 \) for \( L = 1m \) and \( p = 1 \) GeV/c (\( N = 50 \) if along beam direction)

✦ **Full reconstruction of charged particles and γ’s**

✦ **Identify e, π, K, p from \( dE/dx \). Use Transition Radiation for electron identification with Xe filling. Full reconstruction and ID of protons down to 250 MeV/c.**

✦ **Reconstruction of electrons down to 80 MeV from curvature in magnetic field (\( B = 0.4T \))**
Reconstruction of $\pi^0$:

- 50% of $\pi^0$ with at least one converted $\gamma$;
- 25% of $\pi^0$ with both photons converted.

\[ \Rightarrow \text{Use events with at least one converted } \gamma \text{ to reconstruct the pointing direction}\]

Electromagnetic calorimeter surrounding the STT:

- Compact 15-20 $X_0$ in 50 cm;
- Fine grained longitudinal segmentation ($\gamma$ direction);
- Transverse segmentation not so critical for $\pi^0$ reconstruction if we require one converted $\gamma$;
- Energy resolution about $10\%/\sqrt{E}$;

\[ \Rightarrow \text{Sampling calorimeter with Pb as absorber}\]

The Muon Range Detector (MRD), outside of the magnetic field, provides a coverage of forward and side regions. Resistive Plate Chambers (RPC) for muon detection.
The maximum drift time for a Xe/CO$_2$ gas mixture is 125 ns for a distance of 5mm (lower for Ar), as measured in testbeam.

The STT can resolve individual beam bunches

Possible a self-triggering scheme in which hits are stored in pipelines (can use FE ADC - e.g. 8 bit - to operate in digital domain) waiting a later decision:

- ATLAS FE has pipeline 256 × clock;
- Avoid trigger based upon geometrical acceptance (problem in NOMAD).

Depending upon the background rate, it should be possible to read and timestamp everything within one spill and to take a decision later in the cycle.

In addition, calorimetric trigger (complementary)
Perform global fit to the charged lepton DIS and Drell-Yan data samples with $Q^2 > 1.0$ GeV$^2$ and $W > 1.8$ GeV is used. The leading twist is calculated in the NNLO approximation, with parton distributions evolved from $Q^2_0 = 9$ GeV$^2$.

The dynamical twist-4,6 terms, $H^\tau_4,\tau_6(x)$, are parameterized in a model-independent way by cubic splines with values at $x = 0.1, 0.3, 0.5, 0.7, 0.9$ which are fitted from data.

Few external constraints are imposed:
- $H^{\tau_4,\tau_6}_{2,T}(0) = 0$ since no clear evidence for saturation effects is found at HERA;
- $H^{\tau_6}_{2,T} = 0$ at $x > 0.5$ due to the impossibility to extract them out of the resonance region.
Detailed phenomenological model describing nuclear corrections to structure functions

- Introduce 3 general parameters, common to all nuclei
- Extract parameters from e and \(\mu\) DIS data on He, Li, Be, C, Al, Ca, Fe, Cu, Ag, Sn, Au, Pb from BCDMS, EMC, E139, E140, E665, NMC
- Shadowing at small \(x\) (coherent) with meson dominance + leading twist
- Off-shell, binding energy, Fermi motion at large \(x\) in convolution approach
- Nuclear pion excess
- Non-isoscalarity (isovector) correction
- Independent correction for \(F_T\), \(F_2\) and \(xF_3\)

\[\Rightarrow\] Data from charged lepton scattering bound uncertainties
PHYSICS POTENTIAL

✦ About NuMI and Service to LBLν
1: The energy scale and relative flux of $\nu_\mu$ Flux in NuMI
2: The $\bar{\nu}_\mu$ relative to $\nu_\mu$ as a function of $E_\nu$ in NuMI
3: Relative abundance of $\nu_e$ and $\bar{\nu}_e$ -vs- $\nu_\mu$ and $\bar{\nu}_\mu$ in NuMI
4: An empirical parametrization of $K_L^0$ yield in NuMI using the $\bar{\nu}_e$ data
5: Redundancy check on the MIPP $\pi^+, K^+, \pi^-, K^-$, and $K_L^0$ yields in NuMI using the $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$ , and $\bar{\nu}_e$ induced charged current interactions

✦ Neutral-Pion Production in $\nu$-Interactions
6: Coherent and single $\pi^0$ production in $\nu$-induced neutral current interactions
7: Multiplicity and energy distribution $\pi^0$ production in neutral current and charged current processes as a function of hadronic energy
8: The cross section of $\pi^0$ production as a function of $X_F$ and $P_T$ in the $\nu$-CC interactions

✦ Charged-Pion, Kaon and Proton Production in $\nu$-Interactions
9: Coherent and single $\pi^\pm$ production in $\nu$-induced charged current interactions
10: Charged $\pi/K/p$ production in the the NC and CC interactions as a function of hadronic energy
11: Cross section of $\pi^\pm/K^\pm/p$ production as a function of $X_F$ and $P_T$ in the $\nu$-CC interactions

✦ Neutrino-Electron Scattering
12: Measurement of inverse muon decay and absolute normalization of the NuMI flux above $E_\nu > 11$ GeV with $\leq 1\%$ precision
13: The $\nu_\mu-e^-$ and $\bar{\nu}_\mu-e^-$ neutral current interaction and determination of $\sin^2\theta_W$
14: Measurement of the chiral couplings, $g_L$ and $g_R$ using the $\nu_\mu-e^-$ and $\bar{\nu}_\mu-e^-$ NC interactions
\обрашенный \-Nucleon Neutral Current Scattering
15: Measurement of NC to CC ratio, $R_{\nu}$, as a function of hadronic energy $0.25 \leq E_{\text{Had}} \leq 20$ GeV
16: Measurement of NC to CC ratio, $R_{\nu}$ and $R_{\bar{\nu}}$, for $E_{\text{Had}} \geq 3$ GeV and determination of the electroweak parameters $\sin^2 \theta_W$ and $\rho$.

\obraшенный Non-Scaling Charged and Neutral Current Processes
17: Measurement of $\nu_\mu$ and $\bar{\nu}_\mu$ quasi-elastic interaction and determination of $M_A$
18: Measurement of the axial form-factor of the nucleon from quasi-elastic interactions
19: Measurement of $\nu_\mu$ and $\bar{\nu}_\mu$ induced resonance processes
20: Measurement of resonant form-factors and structure functions
21: Study of the transition between scaling and non-scaling processes
22: Constraints on the Fermi-motion of the nucleons using the 2-track topology of neutrino quasi-elastic interactions
23: Coherent $\rho^\pm$ production in $\nu$-induced charged current interactions
24: Neutral current elastic scattering on protons $\nu(\bar{\nu})p \rightarrow \nu(\bar{\nu})p$
25: Measurement of the strange quark contribution to the nucleon spin $\Delta s$
26: Determination of the weak mixing angle from NC elastic scattering on protons

\obraшенный Inclusive Charged Current Processes
27: Measurement of the inclusive $\nu_\mu$ and $\bar{\nu}_\mu$ CC cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV
28: Measurement of the inclusive $\nu_e$ and $\bar{\nu}_e$ CC cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV
29: Measurement of the differential $\nu_\mu$ and $\bar{\nu}_\mu$ CC cross-section as a function of $x_{bj}$, $y_{bj}$ and $E_\nu$.
30: Determination of $xF_3$ and $F_2$ structure functions in $\nu_\mu$ and $\bar{\nu}_\mu$ CC and the QCD evolution
31: Measurement of the longitudinal structure function, $F_L$, in $\nu_\mu$ and $\bar{\nu}_\mu$ charged current interactions and test of QCD
32: Determination of the gluon structure function, bound-state and higher twist effects

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33: Precise tests of sum-rules in QPM/QCD
34: Measurement of $\nu_\mu$ and $\bar{\nu}_\mu$ charged current differential cross-section at large-$x_{bj}$ and $-y_{bj}$
35: Measurement of scaled momentum, rapidity, sphericity and thrust in (anti)neutrino CC
36: Search for rapidity gap in neutrino charged current interactions.
37: Verification of quark-hadron duality in (anti)neutrino interactions
38: Verification of the PCAC hypothesis at low momentum transfer
39: Determination of the behavior of $R = \sigma_L/\sigma_T$ at low momentum transfer
40: Precision tests of the Conservation of the Vector Current

♦ Nuclear Effects
41: Measurement of nuclear effects on $F_2$ in $\nu(\bar{\nu})$ scattering from ratios of Pb,Fe and C targets
42: Measurement of nuclear effects on $xF_3$ in $\nu(\bar{\nu})$ scattering from ratios of Pb,Fe and C targets
43: Study of (anti)shadowing in $\nu$ and $\bar{\nu}$ interactions and impact of axial-vector current
44: Measurement of axial form-factors for the bound nucleons from quasi-elastic interactions on Pb, Fe and C targets
45: Measurement of hadron multiplicities and kinematics as a function of the atomic number

♦ Semi-Exclusive and Exclusive Processes
46: Measurement of charmed hadron production via dilepton ($\mu^-\mu^+$, and $\mu^-e^+$) processes
47: Determination of the nucleon strange sea using the (anti)neutrino charm production and QCD evolution
48: Measurement of $J/\psi$ production in neutral current interactions
49: Measurement of $K^0_S$, $\Lambda$ and $\bar{\Lambda}$ production in (anti)neutrino CC and NC processes
50: Measurement of exclusive strange hadron and hyperon production in (anti)neutrino CC and NC
51: Measurement of the $\Lambda$ and $\bar{\Lambda}$ polarization in (anti)neutrino charged current interactions
52: Inclusive production of rho0(770), f0(980) and f2(1270) mesons in (anti)neutrino charged current interactions
53: Measurement of backward going protons and pions in neutrino CC interactions and constraints on nuclear processes
54: D*+ production in neutrino charged current interactions
55: Determination of the D^0, D^+, D_s, Λ_c production fractions in (anti)neutrino interactions
56: Production of K*(892)+ vector mesons and their spin alignment in neutrino interactions

Search for New Physics and Exotic Phenomena
57: Search for heavy neutrinos using electronic, muonic and hadronic decays
58: Search for eV (pseudo)scalar penetrating particles
59: Search for the exotic Theta+ resonance in the neutrino charged current interactions
60: Search for heavy neutrinos mixing with tau neutrinos
61: Search for an anomalous gauge boson in pi0 decays at the 120 GeV p-NuMI target
62: Search for anomaly mediated neutrino induced photons
63: Search for the magnetic moment of neutrinos
64: A test of ν_μ–ν_e universality down to 10^{-4} level

⇒ More than 100 physics papers on a broad range of topics