Neutrino scattering physics
at future neutrino oscillation facilities

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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
  - $\implies P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- $\nu_2 - \nu_3$ 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 $\nu_e \rightarrow \nu_\tau$

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

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.

_complex experimental program
Sensitivity to oscillation parameters
affected by systematics
in backgrounds & signal detection
Experiments currently running (MINOS, CNGS) or in preparation (off-axis NOνA, T2K) can reach sensitivities down to $\theta_{13} \sim 0.006$.

Going further with conventional neutrino beams requires:

- Megawatt level proton source for HIGH INTENSITY;
- Detectors with effective LARGE MASS $(mass \times efficiency) > 100 kt$ → Water Cherenkov or liquid argon
- $L/E$ optimized to oscillation probability (1st & 2nd maximum).

If $\theta_{13}$ is very small need new beam concepts: neutrino factory or $\beta$ beam

- $\sim 100 kt$ magnetized iron calorimeter & OPERA-like emulsion detector;
- Megaton water Cherenkov or $\sim 100$ kt liquid argon.
**J-PARC facility in Japan:**
- Phase I for T2K (2009): 0.75 MW 30 GeV, $10 \times 10^{20}$ pot/y;
- Phase II upgrade (2015): 4MW 50 GeV, $50 \times 10^{20}$ pot/y

**Project-X at Fermilab:**
- NuMI for NO\(\nu\)A: 400kW, 700kW MI 120 GeV, $6 \times 10^{20}$ pot/y;

*(see talk by D. Harris & A. Jansson)*
Megawatt proton source of few GeV for pion production
Neutrinos produced from decay of 25-50 GeV stored muons

Useful decays achievable $3 \div 5 \times 10^{20}$ per year
Megawatt proton driver of few GeV to produce radioactive ions (ISOL target)

Neutrinos originated from $\beta$ decay of accelerated ions (EURISOL)

$\Rightarrow$ Rates of $2.9 \times 10^{18} \bar{\nu} (^6\text{He})$ and $1.1 \times 10^{18} \bar{\nu} (^{18}\text{Ne})$ per year at $\gamma = 100$
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 projects;
✦ 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 $\mathcal{O}(100\,kt)$ detectors at projected luminosities;
- Different compositions of event samples ($\nu_e, \nu_\mu, \text{NC, CC}$)

$\implies$ *Coarse resolution dictated by $\mathcal{O}(100\,kt)$ 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?*
## 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>
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<tr>
<td>CDHS</td>
<td>750 t</td>
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<td>massive calo</td>
</tr>
<tr>
<td>CHARM II</td>
<td>547 t</td>
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<td>massive calo</td>
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<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 $O(10^7)$ interactions in coarse detectors (sampling).

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

$\Rightarrow$ **Forced choice between statistics & resolution**

$\Rightarrow$ **Physics potential of neutrino probe not fully exploited yet**
Total $\nu$ cross-section known to 2.5% for $E_\nu \geq 10$ GeV and to 4% for $E_\nu > 2.5$ GeV
$\implies$ 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
$\implies$ Need to collect large statistics of anti-neutrino data

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THE DENOMINATOR: FLUX

σ IS A RATIO: \( \sigma = \frac{N}{\Phi} \equiv \frac{\# \text{ Events}}{\text{Flux}} \)

ALL neutrino scattering experiments limited by flux uncertainties so far
\( \Rightarrow \) Flux measurements crucial for conventional neutrino beams
\( \Rightarrow \) Less demanding requirements for \( \nu \)-factory and \( \beta \)-beam

Need input from hadro-production experiments (talk by G. Catanesi):
\[ p + A \rightarrow \pi^\pm, K^\pm, p, K_s^0 \quad \Rightarrow \quad \frac{d^2\sigma}{dx_F dp_T^2}(\pi^\pm, K^\pm, p, K_s^0)\]

- MIPP & upgrade at FNAL;
- HARP & NA61 at CERN
\( \Rightarrow \) Use \( \nu \)-targets and nuclear targets from beam elements

Need complementary \( \Phi \) measurement in-situ:
- Magnetized detector (\( \nu, \bar{\nu} \) and momentum measurement);
- Electron identification & reconstruction (\( \nu_e, \bar{\nu}_e \));
- High resolution (\( \Phi \) accuracy).
Results expected in near future

✦ New measurements from a number of existing experiments (talk by T. Nakaya):
K2K, MiniBooNE, SciBooNE, MINOS, NOMAD:

- Quasi-elastic cross-section and axial mass $M_A$ to $\sim 5\%$;
- Coherent NC $\pi^0$ and NC elastic scattering;
- $CC \pi^+, \pi^0$ production

✦ MINER$\nu$A experiment at FNAL planned to start in 2009:

- $16 \times 10^{20}$ pot in 4 years;
- Collect $8.6 \times 10^6 \nu_\mu$ CC in CH ($1.4 \times 10^6$ in C), $2.9 \times 10^6 \nu_\mu$ CC in Fe & Pb;
- Broad physics program: Quasi-elastic, resonance and coherent production, nuclear structure functions, PDFs etc.;
- Measure energy dependence of absolute cross-sections

⇒ Energy range complementary to previous experiments
RESULTS EXPECTED IN NEAR FUTURE (II)

Statistical errors only

Precise determination of $F_A(Q^2)$
Check deviations from dipole form

$\rightarrow$ Access to high $Q^2$ region

Measurement of $\sigma_{coh}$
on various nuclei (He to Pb)
for NC (20%) and CC (7 ÷ 12%)
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);

$\Rightarrow$ 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

$\Rightarrow$ A major physics program requires HIGH RESOLUTION
OPPORTUNITIES AT NEW FACILITIES

Two classes of experiments (complementary):

“High” energy

✦ Project-X at FNAL (2016):
  $6.3 \times 10^6 \nu_\mu$ CC/t/y (ME) at few 100 m
✦ HiResM\(\nu\) proposed
  High resolution spectrometer
  $140 \times 10^6 \nu_\mu$ CC & $50 \times 10^6 \bar{\nu}_\mu$ CC

⇒ Excellent opportunities for $\nu$ scattering physics in the near future
⇒ Knowledge of fluxes possible at the level of $\sim 10^{-2}$

Low energy

✦ J-PARC in Japan (2009):
  $170k \nu_\mu$ CC/t/y at 280m ($2^0$ off-axis)
✦ T2K-ND280 under construction
  High resolution spectrometer
  $7.2 \times 10^6 \nu_\mu$ CC
OPPORTUNITIES AT NEW FACILITIES (II)

\[\nu \times 10^2\]

**High energy**

- Neutrino factory (20xx):
  \[3 \div 5 \times 10^{20} \nu_\mu, \bar{\nu}_e / y\]

\[-\nu / e \]

**Low energy**

- \(\beta\)-beam (20xx)
  \[2.9 \times 10^8 \bar{\nu}_e / y (^6\text{He}) \gamma = 100\]
  \[1.1 \times 10^8 \nu_e / y (^{18}\text{Ne}) \gamma = 100\]

- SPL super-beam (\(\nu_\mu\))

\[\Rightarrow Both\ facilities\ would\ allow\ to\ reach\ ultimate\ precision\ in\ \nu\ scattering\ physics\]
\[\Rightarrow Unique\ beam\ composition\]
\[\Rightarrow Knowledge\ of\ fluxes\ down\ to\ \sim 10^{-3}\]
HiResMv : order of mag. higher segmentation

Missig transverse momentum

Hadron Shower

v

v

Neutral Current Event

MASSIVE CALO (NuTeV)

PRECISE TRACKER (NOMAD)

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USC
$NC\ 1^{\pi^0}$
in T2K-ND280 TPC
THE NEUTRINO PROBE

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

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

⇒ 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

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

♦ The collection of $\mathcal{O}(10^8) \nu(\bar{\nu})$ CC statistics at the new facilities 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>
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</table>
**WEAK MIXING ANGLE MEASUREMENTS**

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

$$R^{-} \overset{\text{def}}{=} \frac{\sigma_{\nu}^{\text{NC}} - \sigma_{\bar{\nu}}^{\text{NC}}}{\sigma_{\nu}^{\text{CC}} - \sigma_{\bar{\nu}}^{\text{CC}}}$$

- HiResM$\nu$ $\delta \sin^{2} \theta_{W} / \sin^{2} \theta_{W} = 2.0 \times 10^{-3}$
- $\nu$-factory $\delta \sin^{2} \theta_{W} / \sin^{2} \theta_{W} = 1.3 \times 10^{-3}$

⇒ Dominated by systematics

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

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

- HiResM$\nu$ $\delta \sin^{2} \theta_{W} / \sin^{2} \theta_{W} = 5.6 \times 10^{-3}$
- $\nu$-factory $\delta \sin^{2} \theta_{W} / \sin^{2} \theta_{W} = 0.9 \times 10^{-3}$

⇒ Dominated by statistics
Independent measurements from matching Collider precision:

- Direct probe of the running of $\sin^2 \theta_W$ within single experiments: elastic $\nu$-e scattering and $\nu N$ DIS have different scales
- Different scales of momentum transfer with respect to LEP/SLC (off $Z^0$ pole)
- Direct measurement of neutrino couplings to $Z^0$
  $\implies$ Only other measurement LEP $\Gamma_{\nu\nu}$

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

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

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

$\implies$ A discrepancy of 3$\sigma$ with respect to SM in the NEUTRINO data
**MEASUREMENT 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 $G_1$:

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

At low $Q^2$ we have $d\sigma/dQ^2 \propto G^2_1$ and the strange axial form factor $G^s_A \to \Delta s$ for $Q^2 \to 0$.

**Measure NC/CC RATIOS** at low $Q^2$ to reduce systematic effects ($\sin^2 \theta_W$ as well):

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

- Need high resolution tracking
- Systematics to address: nuclear effects, form factors ($Q^2$ dependence), neutrons

$\Rightarrow$ T2K-ND280 expect $\sim 120k \nu$ NC events in Fine Grained Detector (FGD)

$\Rightarrow$ HiResM$\nu$ expect $\sim 1.5 \times 10^6 \nu$ NC and $\sim 800k \bar{\nu}$ NC events

$\Rightarrow$ $\beta$-beam ultimate precision (flux and statistics)
CURRENT CONSERVATION

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

● Adler relation for $\nu$ cross-section:

$$\frac{d\sigma^2(\nu T \rightarrow lF)}{dQ^2d\nu} \bigg|_{Q^2=0} \propto \sigma(\pi T \rightarrow F; E_\pi = \nu)$$

● For $Q^2 \rightarrow 0 \ F_2, F_L \neq 0, \ R = \sigma_L/\sigma_T \rightarrow \infty$

$$\Rightarrow \ T2K-ND280 \ & \ HiResM\nu \ can \ do \ precision \ tests \ of \ PCAC \ at \ Q^2 < 0.1 \ GeV^2$$

✦ 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):

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

$$\Rightarrow \ T2K-ND280 \ and \ HiResM\nu \ since \ high \ resolution \ & \ \pi/K \ separation$$

● At low energy $\beta$-beam from tensor form factor $f_2$ (weak magnetism) in $\bar{\nu}_e p \rightarrow e^+n$ (A. Balantekin al.)

$$CVC \rightarrow f_2(0) = \frac{\mu_p - \mu_n}{2m_N}$$
The Adler integral provides the ISOSPIN of the target and is an exact sum rule from current algebra:

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

- At large \( Q^2 \) (quarks) sensitive to \((s - \bar{s})\) asymmetry, isospin violations
- At low \( Q^2 \) cancellation QE, Res, DIS
- Generalize the integral to nuclear targets and test nuclear effects

Physics case for exposing liquid \( H_2 \) and/or \( D_2 \) targets to \( \nu(\bar{\nu}) \) beams, in combination with precision trackers (e.g. HiResM\( \nu \))

\[ \Rightarrow \text{Fluxes at Project-X and } \nu\text{-factory would allow to extract } S_A \text{ at different } Q^2 \]
\[ \Rightarrow \text{Measurement of } \frac{F_{2\nu p}^p}{F_{2\nu p}^\bar{p}} = d/u \text{ at large } (Q^2, x) \text{ free from nuclear uncertainties} \]
STRANGE SEA & CHARM PRODUCTION

Neutrino charm production is a direct probe of the strange quark content of the nucleon:

\[
\frac{d\sigma^{\nu\mu N \to \mu cX}}{d\xi dy} \propto |V_{cs}|^2 s(\xi, Q^2) + |V_{cd}|^2 u(\xi, Q^2) + d(\xi, Q^2)
\]

\(\mu\mu \text{ & } \mu e \text{ in } \nu \text{ and } \bar{\nu} \Rightarrow [s(x) - \bar{s}(x)] \text{ asymmetry}

- HiResM\nu \sim 200k \text{ charm dileptons (}\epsilon=20\%, \delta(s-\bar{s}) \sim 1 \div 5\%
- \nu\text{-factory would reach } \delta(s - \bar{s}) \sim 1\% \text{ or better}

\[\Rightarrow \text{Measurements dominated by systematics}\]

- With high resolution trackers possible to measure exclusive charmed hadrons \((D^0, D^{*+}, D_s, \Lambda_c)\), charmed fractions etc.

\[\Rightarrow \text{HiResM}\nu \text{ expect overall } 6 \times 10^6 \text{ inclusive charm events}\]

- The use of emulsions or silicon trackers at \(\nu\text{-factory}\) would substantially improve the physics potential for charm production
**NUCLEAR EFFECTS**

- **Precision measurements of nuclear effects in \( \nu(\bar{\nu}) \) scattering probe of nuclear structure & reduction of systematics in analysis of \( \nu(\bar{\nu}) \) data (QCD, oscillations etc.)**
  - High statistics \( \mathcal{O}(10^7) \) required for shadowing region at \( x \sim 10^{-3} \)
  - Compare off-shell & nuclear binding with charged leptons at large \( x \) (EMC effect)
  - **Effect of axial-vector current** \( (xF_3, \text{PCAC, shadowing etc.}) \)
  - A dependence of \( \nu(\bar{\nu}) \) cross-sections: quasi-elastic, resonances, coherent production etc.

\[ \implies \text{T2K-ND280 will collect} \]
\[ 4.0 \times 10^6 \text{ CC on plastic (CH), } 2.5 \times 10^6 \text{ CC in } H_2O \text{ and } 700k \text{ CC on Pb} \]
\[ \implies \text{HiResM} \nu \text{ with } 4 \times 1\text{mm Pb sheets in front } 10^7 \text{ CC} \]
\[ \implies \nu\text{-factory ultimate precision (flux & statistics)} \]

- **Low energy \( \beta\)-beam \( (\gamma \sim 14) \) systematic measurements of } \sigma(\nu-A) \text{ (C. Volpe):**}
  - Core-collapse Supernova observatories & physics (nucleosynthesis etc.)
  - Constraints on nuclear uncertainties in \( 0\nu\beta\beta \)-decay searches
Completing our picture of neutrino masses and mixing will require a long and difficult LBL program at future high intensity beam facilities.

Reduction of systematics requires the addition of high resolution near detectors.

The availability of unprecedented neutrino fluxes at new super-beams (T2K and Project-X), coupled with high resolution near detectors for LBL, would finally elevate neutrino physics to the same level of precision of $e^+e^-$ physics (LEP/SLC).

Compelling $\nu$-scattering physics program in the near future!

The new beam concepts of $\nu$-factory and $\beta$-beam would then allow to achieve the ultimate precision required to fully exploit the physics potential of the neutrino probe.

Start from the experience gained with super beams.