

Precision Measurements of Fundamental Interactions with (Anti)neutrinos

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I Introduction

- ◆ *Electron and ν probes*
- ◆ *Status of ν scattering experiments*

II Requirements for Precision Physics

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

III Precision Measurements

- ◆ *Measurements of $\sin^2 \theta_W$*
- ◆ *Model uncertainties*
- ◆ *Relevance of measurements*
- ◆ *The Adler sum rule*
- ◆ *Measurement of Δ_S*
- ◆ *Tests of isospin symmetry*

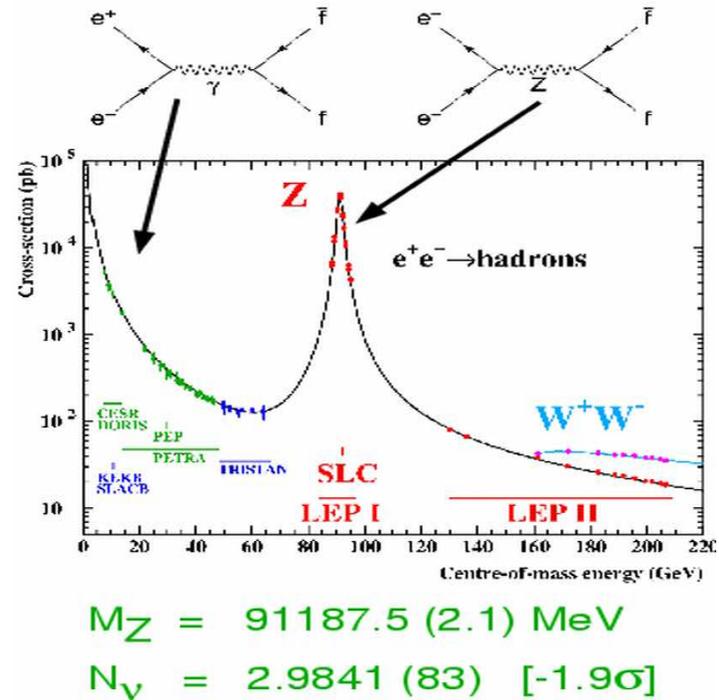
IV Summary

PRECISION PHYSICS: e^\pm PROBE

- ◆ Reference EW studies in e^+e^- at LEP by enhancing weak σ at the Z^0 mass pole:

	Number of Z^0	Number of W
LEP	18×10^6	80×10^3

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



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

⇒ Can a modern $\nu(\bar{\nu})$ facility deliver 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_μ , E_H scales, nuclear targets & flux

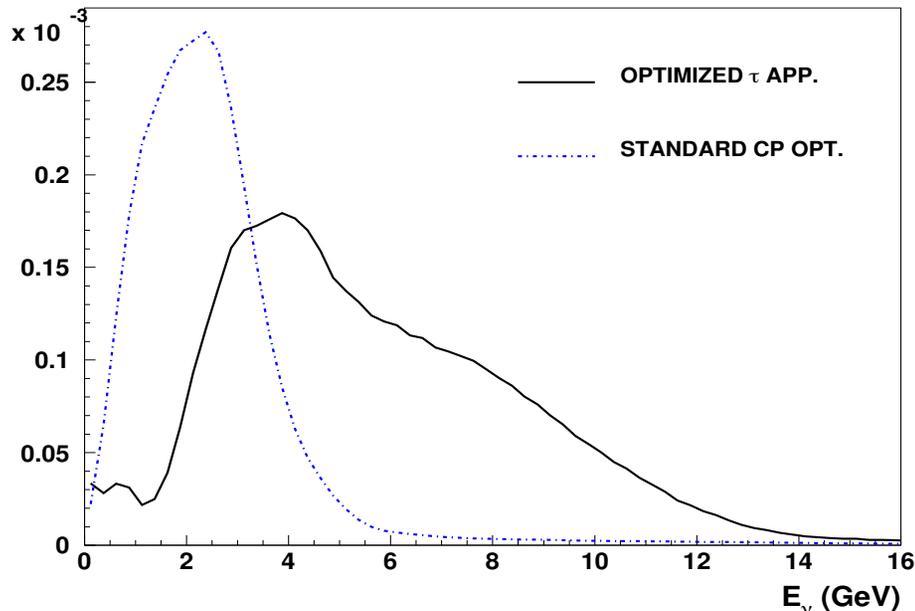
Experiment	Mass	ν_μ CC Stat.	Target	E_ν (GeV)	ΔE_μ	ΔE_H
CDHS	750 t	10^7	p,Fe	20-200	2.0%	2.5%
BEBC	various	5.7×10^4	p,D,Ne	10-200		
CCFR	690 t	1.0×10^6	Fe	30-360	1.0%	1.0%
NuTeV	690 t	1.3×10^6	Fe	30-360	0.7%	0.43%
CHORUS	100 t	3.6×10^6	Emul.,Pb	10-200	2.5%	5.0%
NOMAD	2.7 t	1.3×10^7	C,Fe	5-200	0.2%	0.5%
MINOS ND	980 t	3.6×10^6	Fe	3-50	2-4%	5.6%
T2K ND	1.9 t	10^5	CH,H ₂ O	0.2-5	0.6%	2-4%
MINER ν A	5.4 t	10^7	CH,C,Fe,Pb	1-30	2%	

⇒ 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

⇒ Modern beam facilities optimized at lower energies for detection of oscillations

DUNE ND

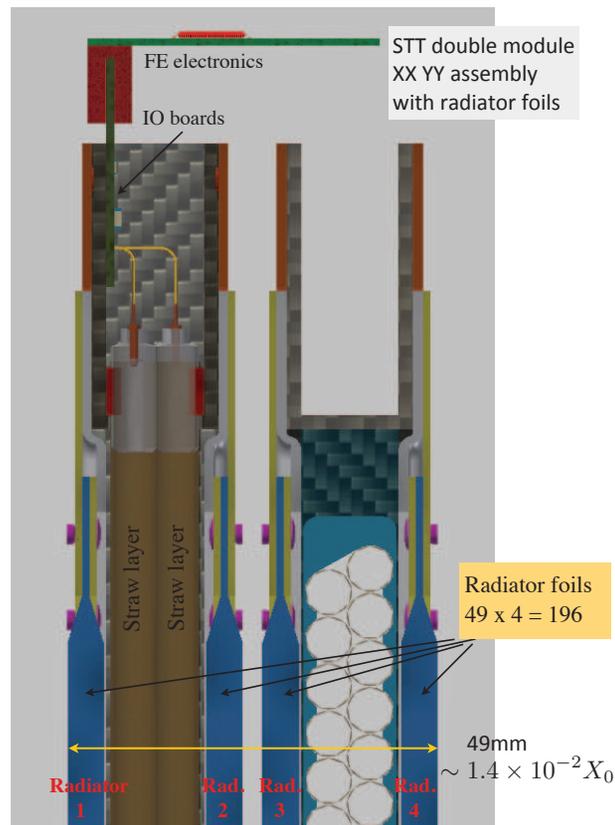


Process	Events (5 t)
<i>Standard CP optimized (1.07 MW):</i>	
ν_μ CC (FHC, 5 y)	34×10^6
$\bar{\nu}_\mu$ CC (RHC, 5 y)	13×10^6
<i>Optimized ν_τ appearance (1.07 MW):</i>	
ν_μ CC (FHC, 2 y)	33×10^6
$\bar{\nu}_\mu$ CC (RHC, 2 y)	12×10^6
TOTAL W^+	67×10^6
TOTAL W^-	25×10^6
TOTAL Z^0	31×10^6

- ◆ Available LBNF beam optimized for FD ν_τ appearance (120 GeV):
Conceivable dedicated run after 5y FHC + 5y RHC with the "standard" beams optimized for CP
 - LBNF & DUNE (202x): 120 GeV p, 1.07 MW, 1.47×10^{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 ν_τ optimized beam (conservative)

⇒ Can afford a high resolution ND of a few tons and still collect desired statistics $\sim 10^8$

- ◆ Precision EW & QCD measurements *require control of ν -target(s) as in e^\pm DIS:*
 - Massive ν 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 $\rho = 0.10\text{-}0.16 \text{ g/cm}^3$.
- ⇒ Straw Tube Tracker (STT) in $B \sim 0.6 T$ with 4π electromagnetic calorimeter

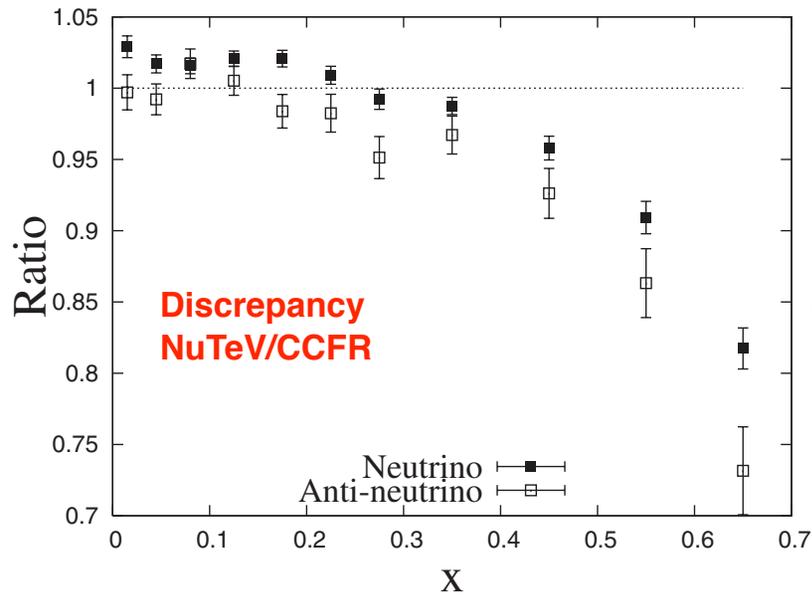


- ◆ Radiator targets (100% purity) account for $> 95\%$ of STT mass and can be tuned to achieve desired statistics & resolutions.
- ◆ Separation from excellent vertex, angular & timing resolutions.
- ◆ Radiators can be replaced by thin nuclear targets: C, Ca, Ar, Fe, etc.

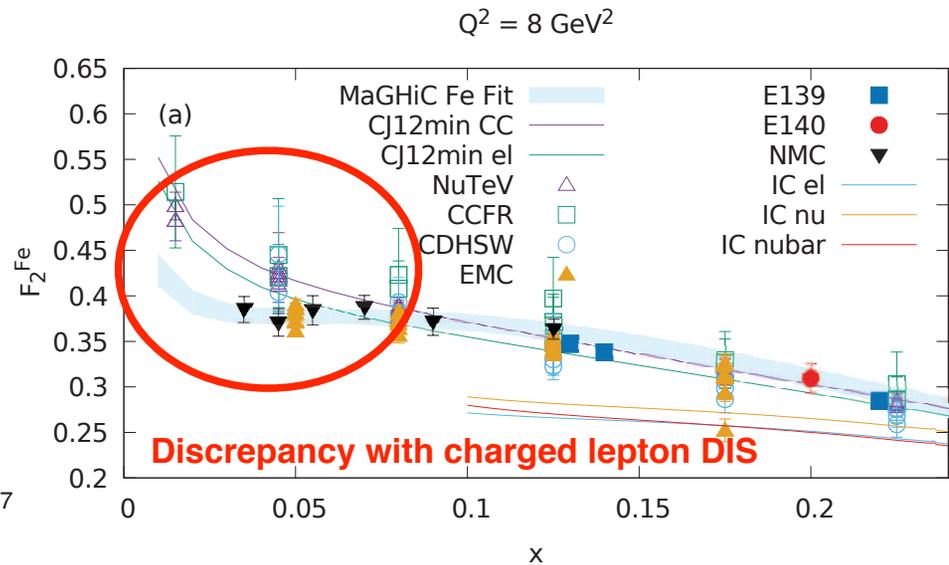
◆ *Need to understand nuclear modifications & corresponding systematic uncertainties:*

- 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)*



NuTeV Coll., PRD 74 (2006) 012008

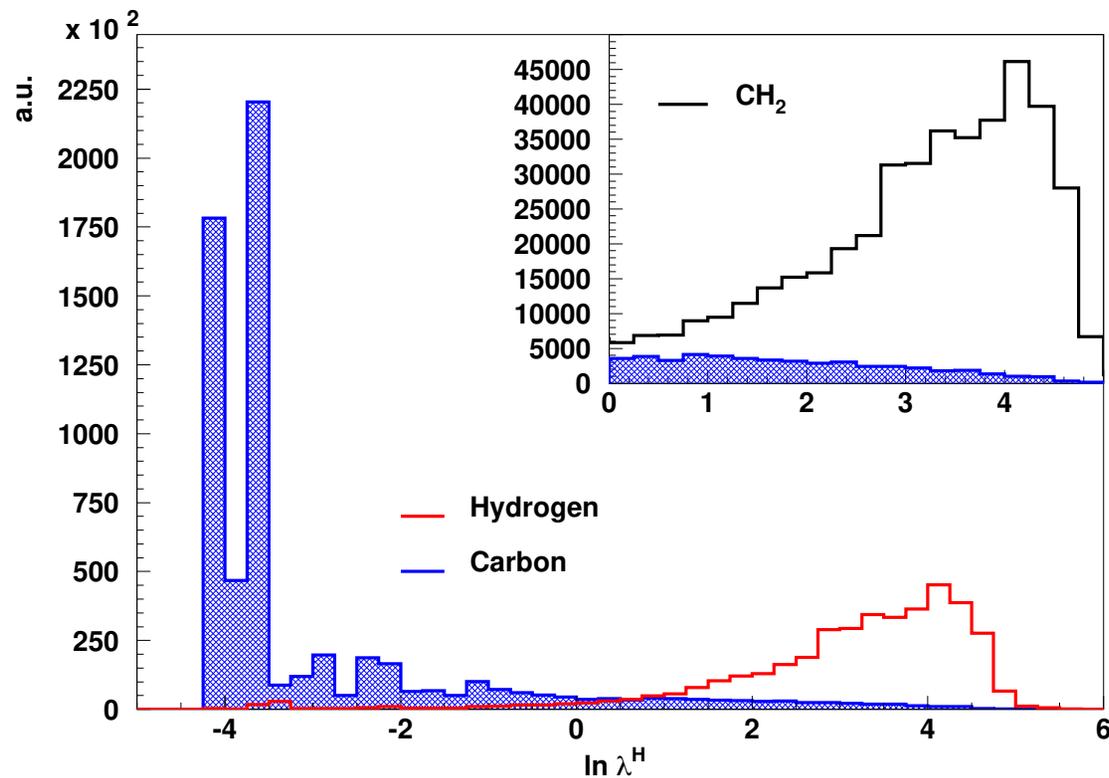


N. Kalantarians, C. Keppel, M.E. Cristy, PRC 96 (2017) 032201

◆ *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.*

⇒ *Viabile and realistic alternative to liquid H_2 bubble chambers*



*H. Duyang, B. Guo,
S.R. Mishra, R. P.,
arXiv:1809.08752 [hep-ph]*

- ◆ *Relative $\nu_\mu, \bar{\nu}_\mu$ flux vs. energy from low- ν_0 method:*

$$N(E_\nu, E_{\text{Had}} < \nu_0) \propto \Phi(E_\nu) f_c\left(\frac{\nu_0}{E_\nu}\right)$$

the correction factor $f_c(\nu_0/E_\nu) \rightarrow 1$ for $\nu_0 \rightarrow 0$.

- ◆ *Used by past and current experiments with heavy (nuclear) targets:*

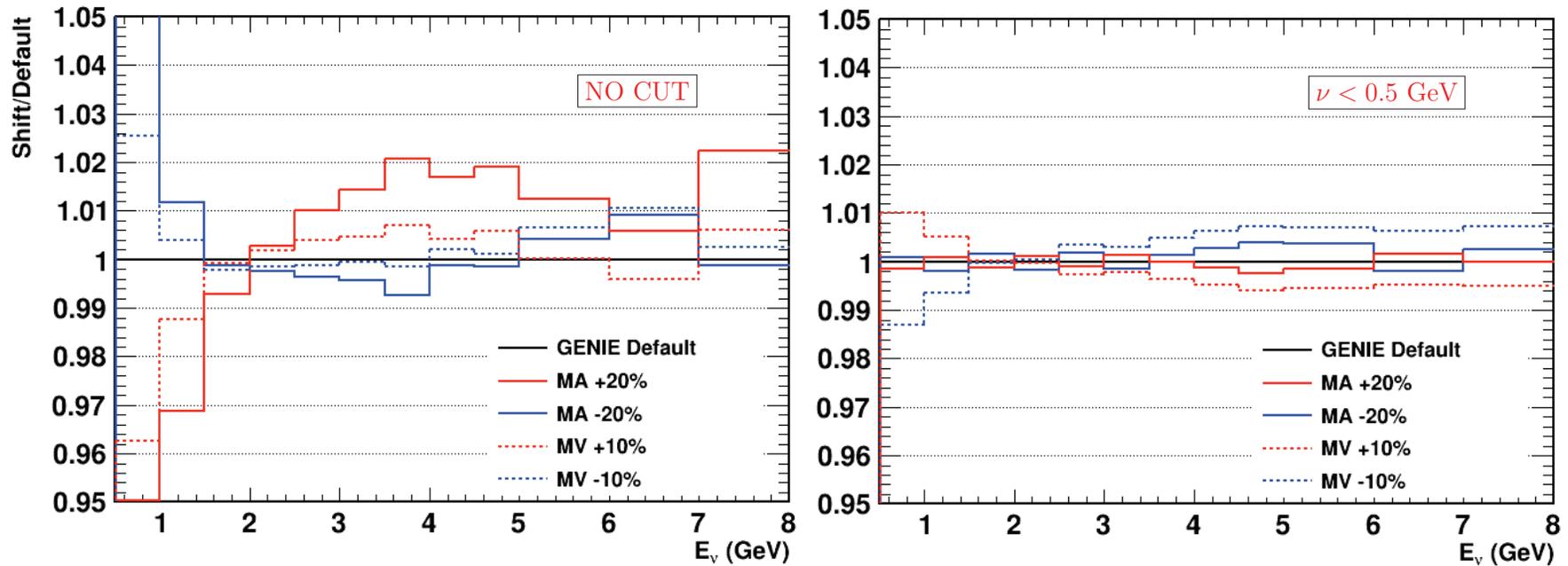
- *For $\nu_0 \leq 1$ GeV sample dominated by inclusive QE+RES interactions;*
- *Need precise muon energy scale and good resolution at low ν values;*
- *Nuclear smearing affects hadronic energy reconstruction & acceptance of cut $\nu < \nu_0$.*

\implies *Intrinsically limited by the (large especially in Ar like DUNE) uncertainties from nuclear smearing (neutrons, FSI, etc.)*

◆ *Use of $\nu(\bar{\nu})$ -Hydrogen interactions dramatically reduces hadronic uncertainties:*

- Select exclusive $\mu p \pi$ 3-track topology on Hydrogen;
- Cut $\nu < 0.5 \text{ GeV}$ flattens cross-sections reducing uncertainties on E_ν dependence;
- Flux uncertainties dominated by muon energy scale ($\Delta E_\mu \sim 0.2\%$ in low density tracker).

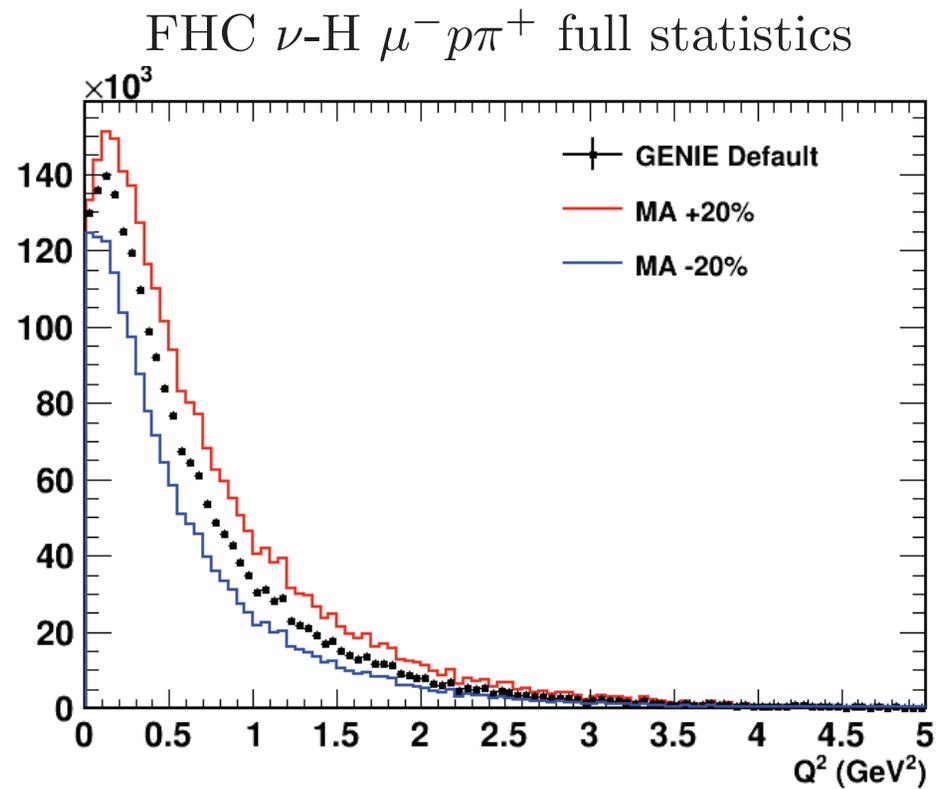
⇒ *Potentially achieve unprecedented precision on fluxes $\sim 1\%$*



◆ *Direct determination/constraint of H form factors from observed Q^2 distribution:*

- *Use the full $\mu p \pi$ event sample without ν cut (25% overlap);*
- *Fit to measured (Q^2, θ) distributions;*

⇒ *Theoretical E_ν uncertainties not manifesting in differential distributions (Q^2, θ) ?*



◆ *Measure relative $\bar{\nu}$ fluxes using QE on Hydrogen $\bar{\nu}p \rightarrow \mu^+n$ with $\nu < 0.5$ GeV (or lower), similar to complementary $\mu^+p\pi^-$ exclusive topology.*

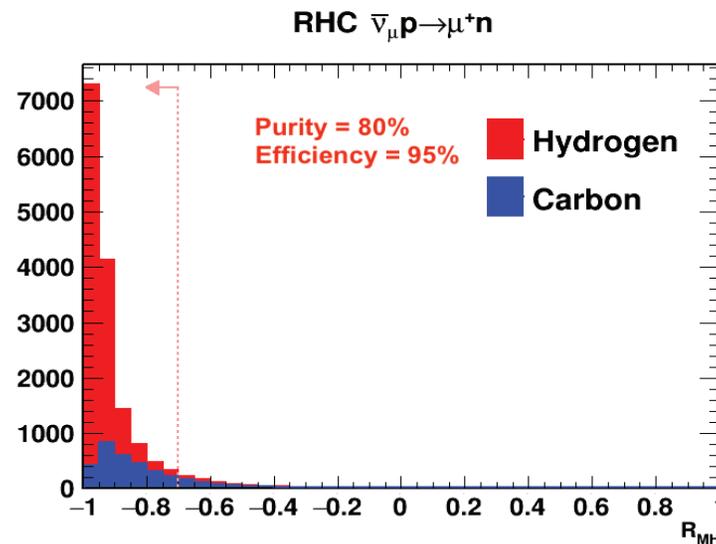
◆ *Measure absolute $\bar{\nu}$ fluxes from QE on Hydrogen $\bar{\nu}p \rightarrow \mu^+n$:*

$$\frac{d\sigma}{dQ^2} \Big|_{Q^2=0} = \frac{G_F^2 \cos^2 \theta_c}{2\pi} [F_1^2(0) + G_A^2(0)]$$

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

- Cross-section independent of neutrino energy for $\sqrt{2E_\nu M} > m_l$;
- At $Q^2 = 0$ QE cross-section determined by neutron β -decay to a precision $\ll 1\%$;

\implies *Additional theoretical E_ν uncertainties to consider?*



- ◆ Possible to solve the main issues of neutrino experiments (statistics, control of targets & fluxes) *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 DUNE ND site into a general purpose ν & $\bar{\nu}$ 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 ($s(x)$, $\bar{s}(x)$, Δs , 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!*

- ◆ *Synergy with JLab physics program and mutual benefits for both communities.*

MEASUREMENT OF $\sin^2 \theta_W$ FROM νN DIS

◆ **NC/CC RATIO** in ν -N Deep Inelastic Scattering:

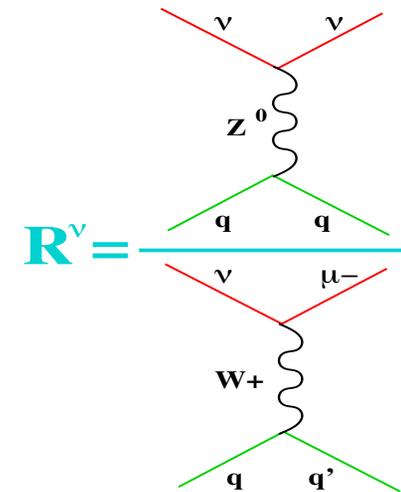
$$R^\nu \stackrel{\text{def}}{=} \frac{\sigma_{\text{NC}}^\nu}{\sigma_{\text{CC}}^\nu} = \rho^2 \left[\frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \sin^4 \theta_W \left(1 + \frac{\sigma_{\text{CC}}^{\bar{\nu}}}{\sigma_{\text{CC}}^\nu} \right) \right]$$

sensitivity $\delta \sin^2 \theta_W / \sin^2 \theta_W \sim 1.5 \delta R^\nu / R^\nu$

- Events with $E_{\text{had}} > 5$ GeV for higher Q^2 (CHARM used 4 GeV);
- High purity NC sample with NC/CC kinematic selection (NOMAD).

◆ Dominated by systematics. *Model systematics constrained by dedicated in-situ measurements:*

- Charm production from both dileptons ($\sim 100k \mu\mu \& \mu e$) and exclusive charmed hadrons (e.g., D^{*+}, D_s, Λ_c);
- Structure function measurement and QCD analysis of ND data (PDFs, High Twists, R_L , nuclear effects, etc.)



Process	$E_{\text{had}} > 5$ GeV
<i>Standard CP optimized:</i>	
ν_μ CC (5 y)	3×10^6
<i>Optimized ν_τ appearance:</i>	
ν_μ CC (2 y)	10×10^6
TOTAL W^+	13×10^6
TOTAL Z^0	4×10^6

- ◆ Possible to reduce theoretical uncertainties with *Paschos-Wolfenstein relation*:

$$R^- \stackrel{\text{def}}{=} \frac{\sigma_{\text{NC}}^\nu - \sigma_{\text{NC}}^{\bar{\nu}}}{\sigma_{\text{CC}}^\nu - \sigma_{\text{CC}}^{\bar{\nu}}} = \rho^2 \left(\frac{1}{2} - \sin^2 \theta_W \right)$$

assumptions: isospin (charge) symmetry, $s(x) = \bar{s}(x)$, cancellation of nuclear effects.

⇒ Requires dedicated ν AND $\bar{\nu}$ beams with small contaminations

- ◆ R^- experimentally challenging:

ν and $\bar{\nu}$ beams NOT simultaneous & different spectra and acceptances for ν and $\bar{\nu}$.

- ◆ NuTeV measured $\sin^2 \theta_W$ to 0.7% by measuring separately R^ν and $R^{\bar{\nu}}$:

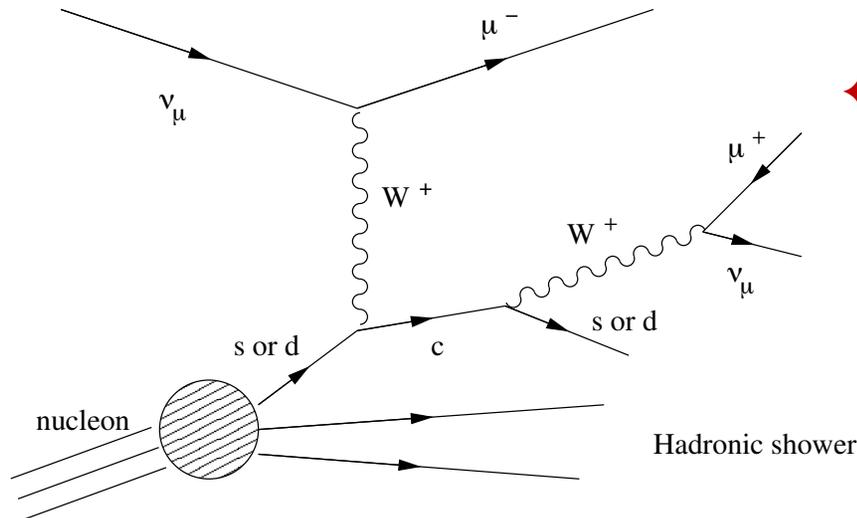
$$\sin^2 \theta_W^{\text{on-shell}} \equiv 1.0 - \frac{M_W^2}{M_Z^2} = \boxed{0.2277 \pm 0.0013(\text{stat.}) \pm 0.0009(\text{syst.})}$$

$$\text{SM from LEPWWG} = 0.2227 \pm 0.00037$$

$$R^\nu = \frac{\sigma_{\text{NC}}^\nu}{\sigma_{\text{CC}}^\nu} = 0.3916 \pm 0.0013 \quad (\text{SM } 0.3950)$$

$$R^{\bar{\nu}} = \frac{\sigma_{\text{NC}}^{\bar{\nu}}}{\sigma_{\text{CC}}^{\bar{\nu}}} = 0.4050 \pm 0.0027 \quad (\text{SM } 0.4066)$$

⇒ A discrepancy of 3σ with SM in the NEUTRINO data



◆ Charm dimuon production in $\nu(\bar{\nu})$ DIS

$$\frac{d^2\sigma_{\mu\mu}}{dx dy dz} = \frac{d^2\sigma_c}{dx dy} D_c(z) B_\mu; \quad z = \frac{P_L(h_c)}{P_L^{\max}}$$

$$B_\mu = \sum_h f_h Br(h \rightarrow \mu^+ X); \quad h = D^0, D^+, D_s^+, \Lambda_c^+$$

$D_c(z)$ average fragmentation function

◆ Charm production in ν and $\bar{\nu}$ DIS provides a *clean and direct access to $s(x)$ and $\bar{s}(x)$*

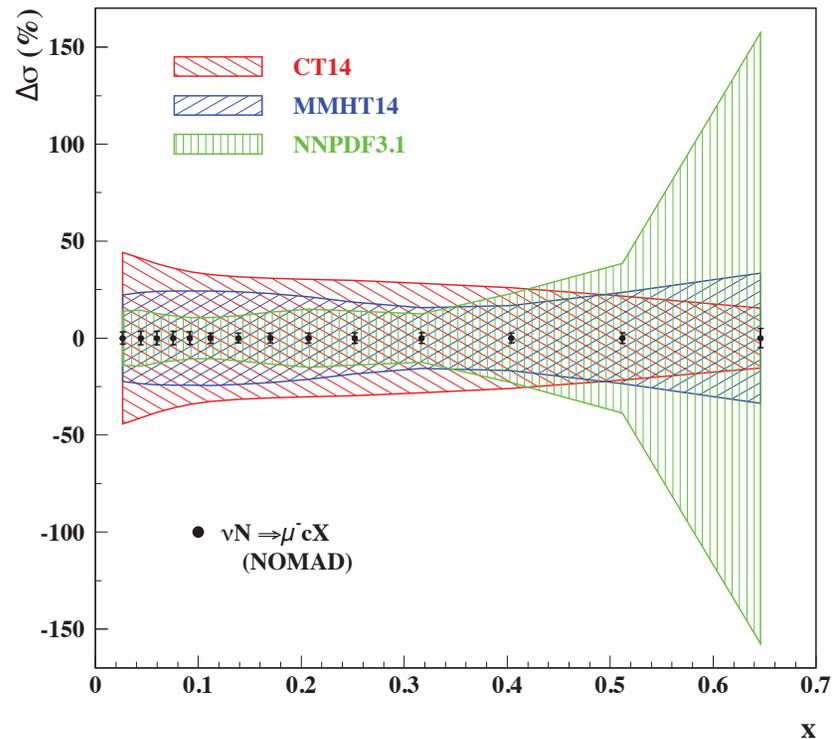
$$F_{2,c}(x, Q) = 2\xi \left[|V_{cs}|^2 s(\xi, \mu) + |V_{cd}|^2 \frac{u(\xi, \mu) + d(\xi, \mu)}{2} \right]$$

$$\xi = x \left(1 + \frac{m_c^2}{Q^2} \right), \quad \mu = \sqrt{Q^2 + m_c^2}$$

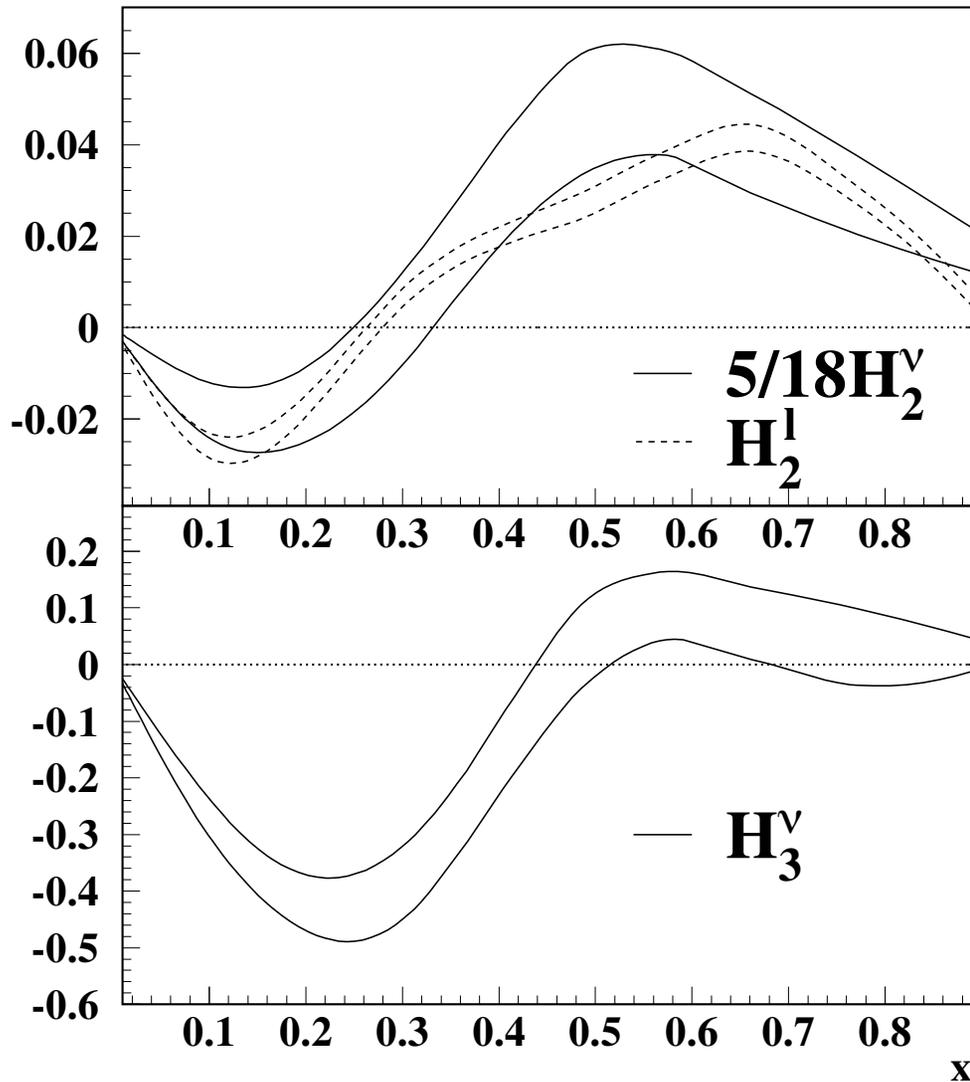
where simple LO approximations are given for illustration purpose

$$\begin{cases} \nu : s/(d_v + d_s) \rightarrow c & \simeq 50\% \\ \bar{\nu} : \bar{s}/\bar{d}_s \rightarrow \bar{c} & \simeq 90\% \end{cases}$$

NOMAD: 15k
DUNE ND: 100k



- ◆ *NOMAD measurement allows reduction of $s(x)$ uncertainty down to $\sim 3\%$:*
 $\kappa_s = \int_0^1 x(s + \bar{s})dx / \int_0^1 x(\bar{u} + \bar{d})dx = 0.591 \pm 0.019$ (NPB 876 (2013) 339)
- ◆ *Improved determination of the \overline{MS} mass from global PDF fits:*
 $m_c(m_c) = 1.252 \pm 0.018 \pm 0.010(QCD)$ (S. Alekhin et al., PRD 96 (2017) 014011)
- ◆ *Recent ATLAS claims of enhanced $s(x)$ seems related to overconstrained PDF parameterization* (S. Alekhin et al., PLB 777 (2018) 134, PRD 91 (2015) 094002)



- ◆ No evidence for sizeable twist-6 terms from global fit to e, μ DIS and DY data (upper limit ~ 0.02 well below twist-4)
- ◆ HT similar in F_T and F_2 indicate HT contributions to F_L very small
- ◆ 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 xF_3 from neutrino data

S. Alekhin, S. Kulagin and R.P.,
 arXiv:0710.0124 [hep-ph],
 arXiv:0810.4893 [hep-ph]

PECULIARITY OF THE WEAK CURRENT

- ◆ Neutrino scattering is characterized by an **AXIAL-VECTOR CURRENT** in addition to the the Vector current.

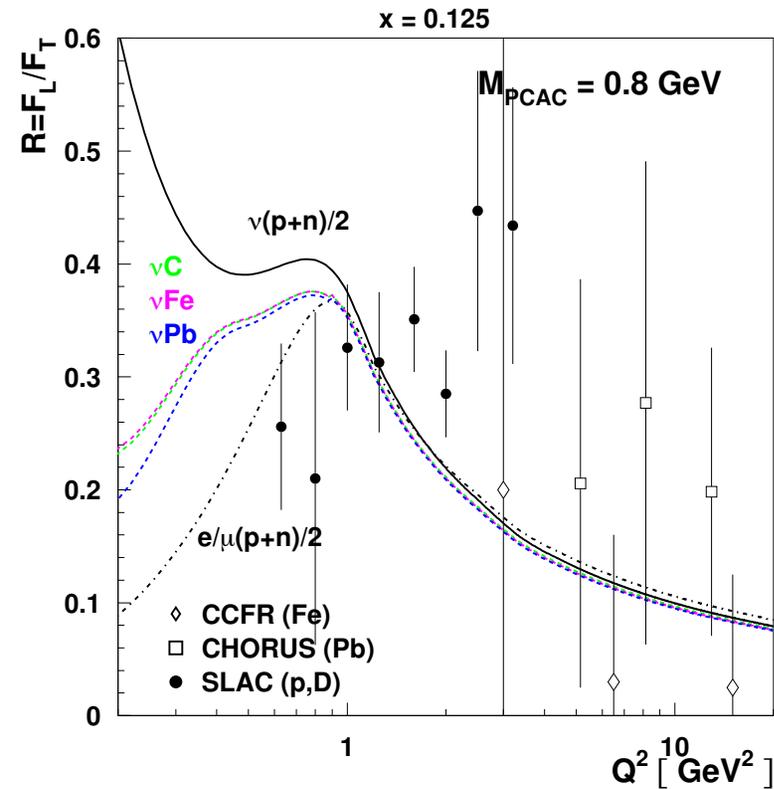
- ◆ Axial Current is only Partially Conserved (PCAC) and dominates SFs at low Q^2 :

$$F_2 \rightarrow F_L = \frac{f_\pi^2 \sigma_\pi}{\pi} \quad Q^2 \rightarrow 0$$

- ◆ The finite PCAC contribution to F_L strongly affects the asymptotic behaviour of **$R = \sigma_L/\sigma_T$** for $Q^2 \rightarrow 0$:

$$F_T \sim Q^2 \quad F_L \sim \frac{f_\pi^2 \sigma_\pi}{\pi} > 0$$

⇒ Substantial difference with respect to charged lepton scattering.



S. Kulagin and R.P., PRD 76 (2007) 094023

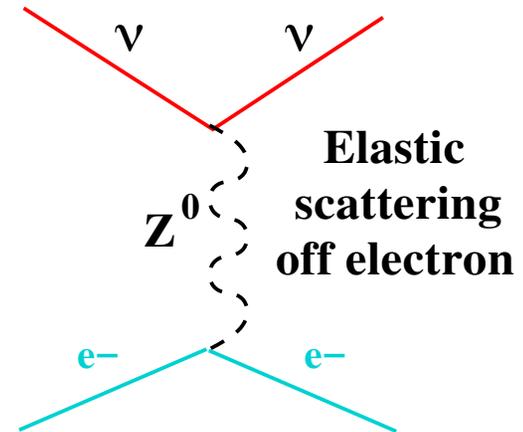
MEASUREMENT OF $\sin^2 \theta_W$ FROM ν -e

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

$$R_{\nu e} \stackrel{\text{def}}{=} \frac{\sigma(\nu e^-)}{\sigma(\bar{\nu} e^-)} = 3 \frac{1-4 \sin^2 \theta_W + 16/3 \sin^4 \theta_W}{1-4 \sin^2 \theta_W + 16 \sin^4 \theta_W}$$

sensitivity $\delta \sin^2 \theta_W / \sin^2 \theta_W \sim 0.6 \delta R_{\nu e} / R_{\nu e}$.

- Signal sharply peaked at small $E_e \theta_e^2$ of electron;
 - Backgrounds from ν_e QE & NC π^0 .
- ◆ Benefits from combination of light high resolution (5 t) and massive LAr ND detectors (25 t)
 - ◆ Dominated by statistics. Need high resolution detectors & accurate flux measurements:
 - Electron systematics cancel in the ratio;
 - Background rejection & calibration (e^\pm ID, resolution);
 - ν and $\bar{\nu}$ flux measurements from $\nu(\bar{\nu})$ -H.

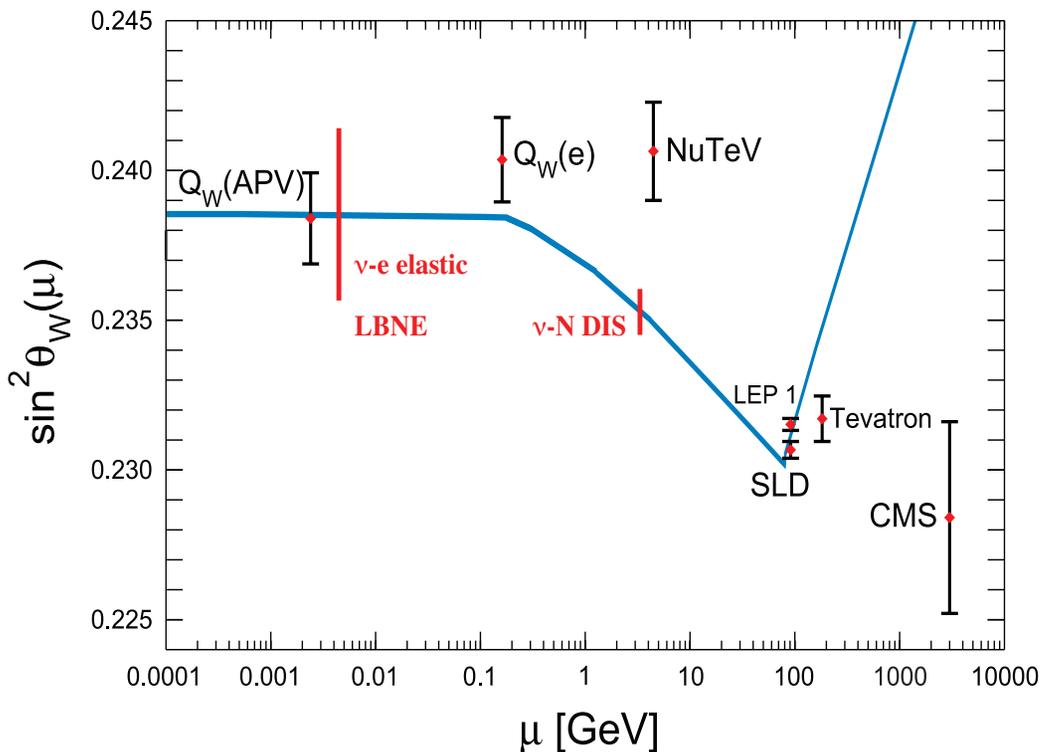


Process	Evts (5 t)
<i>Standard CP optimized:</i>	
νe NC (5 y)	5×10^3
$\bar{\nu} e$ NC (5 y)	3×10^3
<i>Optimized ν_τ appearance:</i>	
νe NC (2 y)	5×10^3
$\bar{\nu} e$ NC (2 y)	3×10^3

RELEVANCE OF $\sin^2 \theta_W$ MEASUREMENTS

◆ Sensitivity expected from ν scattering in DUNE 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
 \implies Only other measurement LEP $\Gamma_{\nu\nu}$
- Independent cross-check of the NuTeV $\sin^2 \theta_W$ anomaly ($\sim 3\sigma$ in ν data) in a similar Q^2 range.



◆ Different independent channels:

- $\mathcal{R}^\nu = \frac{\sigma_{\text{NC}}^\nu}{\sigma_{\text{CC}}^\nu}$ in ν -N DIS ($\sim 0.35\%$)
- $\mathcal{R}_{\nu e} = \frac{\sigma_{\text{NC}}^{\bar{\nu}}}{\sigma_{\text{NC}}^\nu}$ in ν - e^- NC elastic ($\sim 1\%$)
- NC/CC ratio ($\nu p \rightarrow \nu p$)/($\nu n \rightarrow \mu^- p$) in (quasi)-elastic interactions
- NC/CC ratio ρ^0/ρ^+ in coherent processes

\implies Combined EW fits like LEP

◆ Further reduction of uncertainties depending upon beam exposure

MEASUREMENT OF ADLER SUM RULE

◆ The Adler integral provides the **ISOSPIN** of the target and is derived from current algebra:

$$S_A(Q^2) = \int_0^1 \frac{dx}{x} (F_2^{\bar{\nu}p} - F_2^{\nu p}) = 2$$

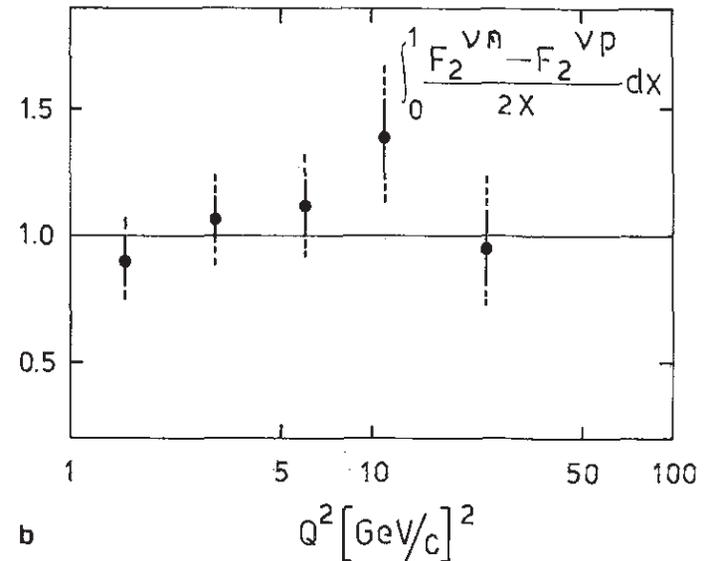
- At large Q^2 (quarks) sensitive to $(s - \bar{s})$ asymmetry, isospin violations, heavy quark production
- Generalize the integral to nuclear targets and test nuclear effects (S. Kulagin and R.P. PRD 76 (2007) 094023)

⇒ Precision test of S_A at different Q^2 values

◆ Only measurement available from BEBC based on 5,000 νp 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/μ DIS

⇒ d/u at large x and verify limit for $x \rightarrow 1$



Process	$\nu(\bar{\nu})\text{-H}$
Standard CP optimized:	
ν_μ CC (5 y)	3.4×10^6
$\bar{\nu}_\mu$ CC (5 y)	2.5×10^6
Optimized ν_τ appearance:	
ν_μ CC (2 y)	3.3×10^6
ν_μ CC (2 y)	2.2×10^6

- ◆ **NC ELASTIC SCATTERING** neutrino-nucleus is sensitive to the *strange quark contribution to nucleon spin, Δs* , through axial-vector form factor G_1 :

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

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

- ◆ Combined *analysis with parity-violating electron scattering data (HAPPEX, G0, A4)* allows an accurate determination of all three strange form factors G_E^s, G_M^s, G_A^s .
- ◆ Measure **NC/CC RATIOS** as a function of Q^2 to reduce systematics ($\sin^2 \theta_W$ as well):

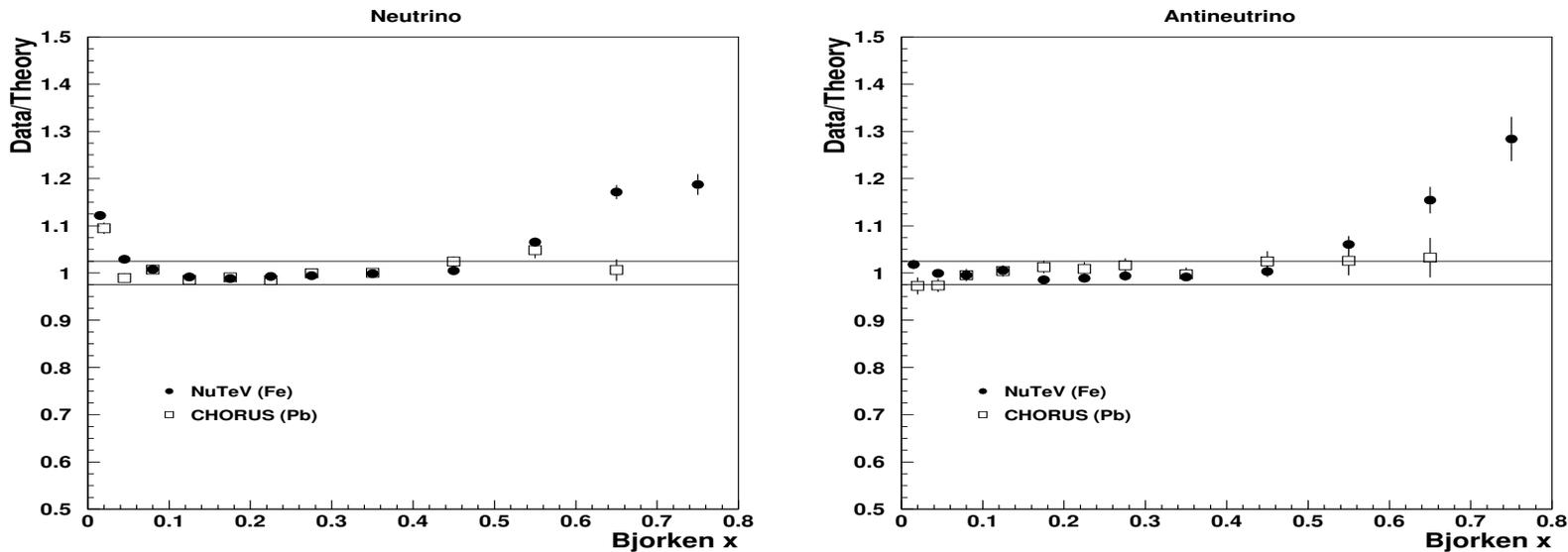
$$R_\nu = \frac{\sigma(\nu p \rightarrow \nu p)}{\sigma(\nu n \rightarrow \mu^- p)}; \quad R_{\bar{\nu}} = \frac{\sigma(\bar{\nu} p \rightarrow \bar{\nu} p)}{\sigma(\bar{\nu} p \rightarrow \mu^+ n)}$$

- Compare axial current charge radius r_A^2 with muon capture in muonic hydrogen (discrepancies);
- Expect $\sim 2 \times 10^6$ ν NC and $\sim 1 \times 10^6$ $\bar{\nu}$ NC events (BNL E734: 951 νp 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.

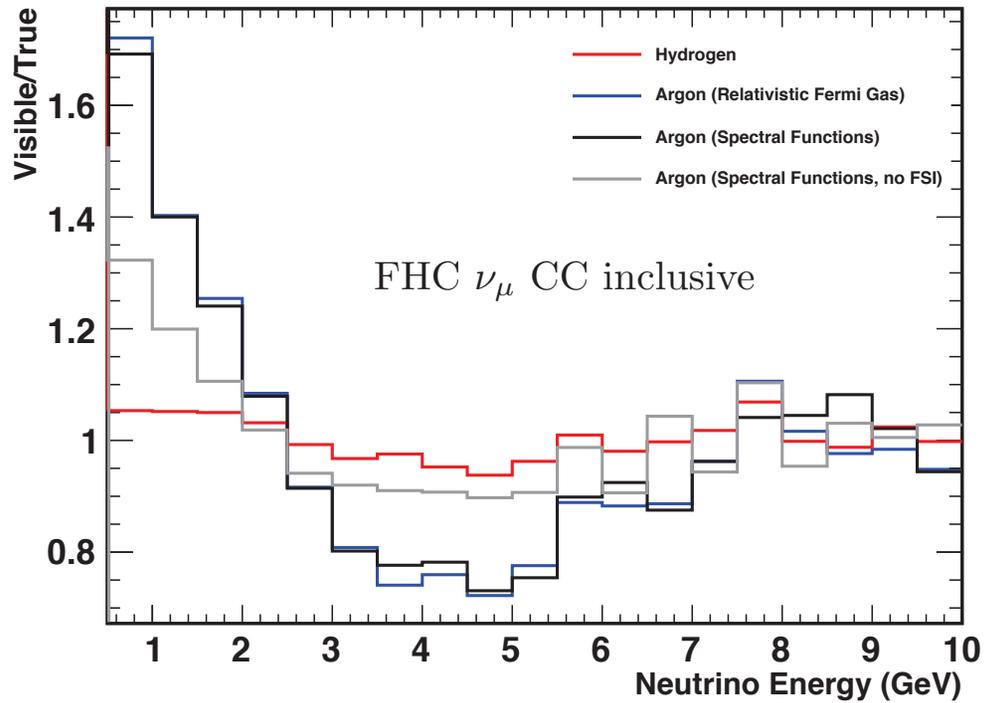
- ◆ Availability of ν -H & $\bar{\nu}$ -H allows direct measurement of nuclear modifications of $F_{2,3}$:

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

- Comparison with e/μ DIS results and nuclear models;
 - Study flavor dependence of nuclear modifications using ν & $\bar{\nu}$;
 - 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.



- ◆ Limited $\nu(\bar{\nu})$ data on ratios $\sigma^{A'}/\sigma^A$ (BEBC, MINER ν A) and differential cross-sections $d\sigma^2/dx dy$ (NuTeV, CCFR, CHORUS)
- ◆ Model predictions agree with data in the bulk of phase space but show discrepancies at $x < 0.05$ and $x > 0.5$ (S. Kulagin and R.P., NPA 765 (2006) 126; PRD 76 (2007) 094023).
 \implies Need new precision measurements with both ν AND $\bar{\nu}$



Substantial nuclear smearing rapidly varying in oscillation range!

Understanding of nuclear smearing (response function for unfolding) crucial for systematics in DUNE oscillation analyses

- ◆ Extraction of $\sin^2 \theta_W$ from νN DIS sensitive to violations of isospin symmetry in nucleon, $u_{p(n)} \neq d_{n(p)}$. Measure ν AND $\bar{\nu}$ on **H AND C TARGETS**:

$$R_{2,3}^H \stackrel{\text{def}}{=} \frac{F_{2,3}^{\bar{\nu}p}}{F_{2,3}^{\nu p}}(x, Q^2) = \frac{F_{2,3}^{\nu n}}{F_{2,3}^{\nu p}}; \quad R_{2,3}^C \stackrel{\text{def}}{=} \frac{F_{2,3}^{\bar{\nu}C}}{F_{2,3}^{\nu C}}(x, Q^2) - 1 = \frac{\Delta F_{2,3}^{\bar{\nu}-\nu}}{F_{2,3}^{\nu}}$$

- 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 ν and $\bar{\nu}$ interactions;
 - Potential effect of nuclear environment e.g. with Coulomb field.
- ◆ Collect ν and $\bar{\nu}$ interactions on both **Ca AND Ar TARGETS** to disentangle nuclear effects from isospin effects in nucleon structure functions.
- Measure ratios $R_{2,3}^A = \Delta F_{2,3}^{(\bar{\nu}-\nu)A} / F_{2,3}^{\nu A}(x, Q^2)$;
 - Use heavier isoscalar target, ${}^{20}_{40}\text{Ca}$, to verify nuclear effects in ${}^6_{12}\text{C}$;
 - Use second target with isovector component but same A as Ca: ${}^{18}_{40}\text{Ar}$.

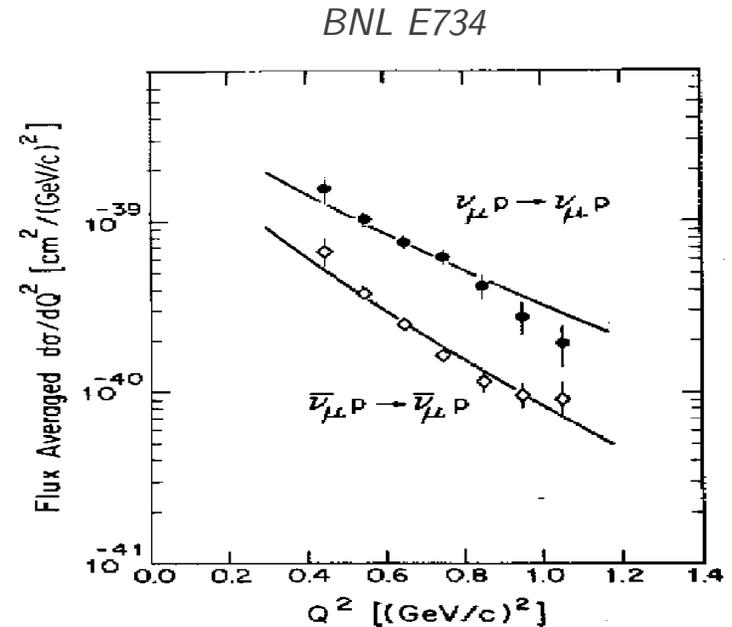
- ◆ Ratio of *NC elastic scattering neutrino-nucleus* to CC quasi-elastic scattering for both ν and $\bar{\nu}$ ($\sin^2 \theta_W$):

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

Determine axial form factor G_A from the CC sample.

- Significant reduction of systematics from NC/CC ratios.
- Estimate Q^2 values in NC from 2-body kinematics;
- $\sin^2 \theta_W$ sensitivity in vector $F_{1,2}$ form factors.

⇒ Systematics from FF, neutrons, nuclear effects?



- ◆ Additional sensitivity from the *NC/CC ratio of coherent ρ meson production*:

$$R_\rho = \frac{\sigma(\nu_\mu A \rightarrow \nu_\mu \rho^0 A)}{\sigma(\nu_\mu A \rightarrow \mu^- \rho^+ A)} = \frac{1}{2} (1 - 2 \sin^2 \theta_W)^2$$

expect ~ 30k coherent ρ^0 and 200k coherent ρ^+ in ND.

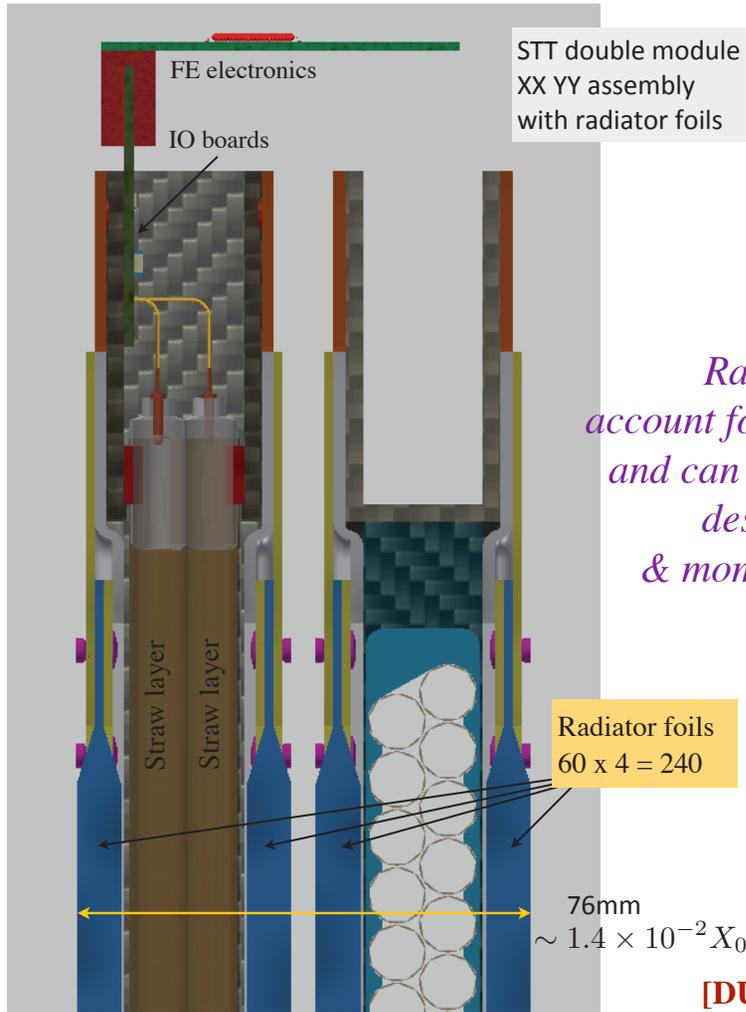
⇒ Systematics from background subtraction in the coherent ρ^0 selection?

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

Backup slides

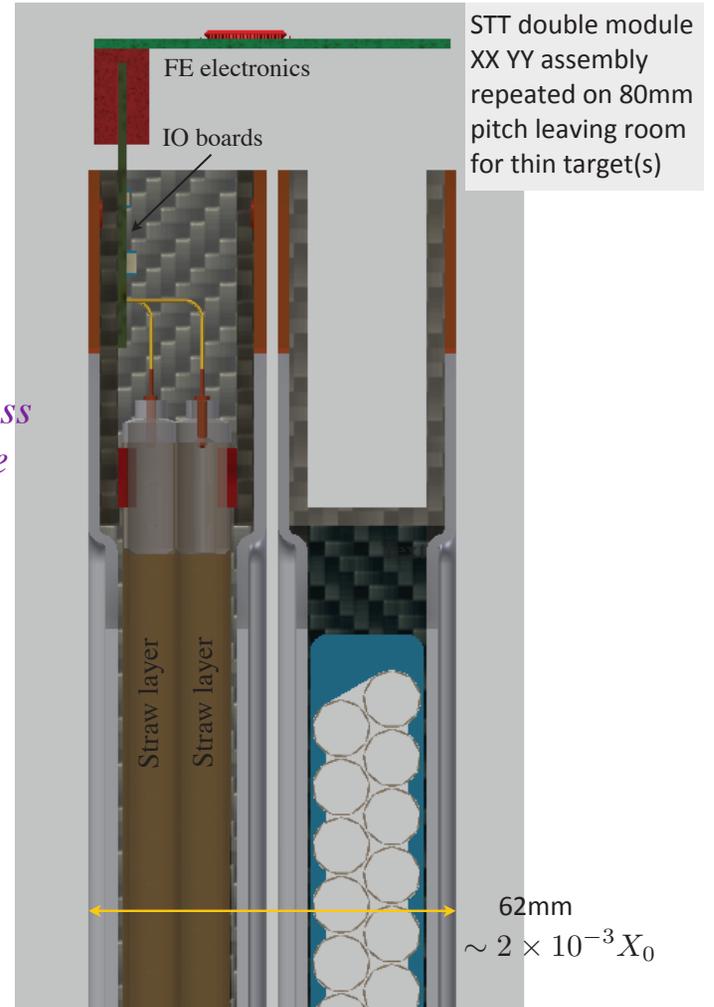
STT module with radiators



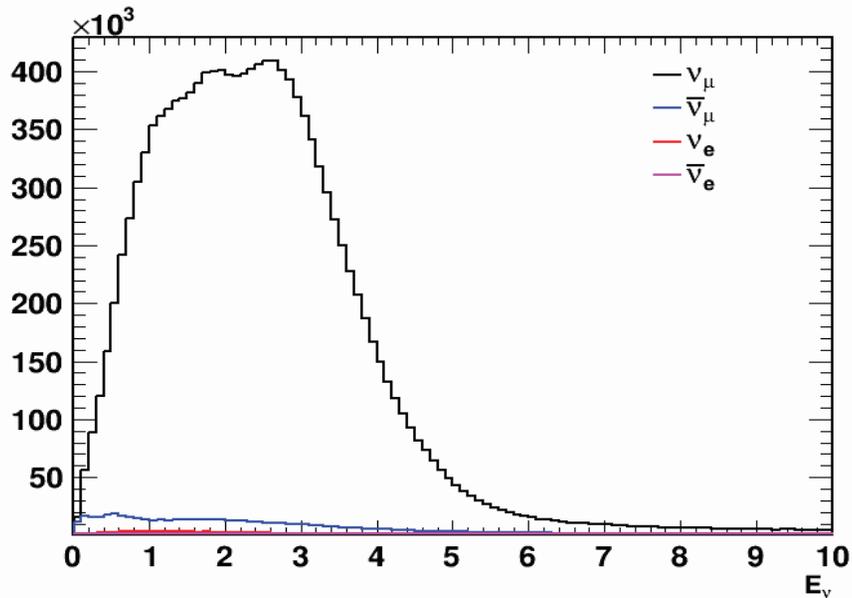
*Radiator targets
account for ~95% of STT mass
and can be tuned to achieve
desired statistics
& momentum resolution*

[DUNE CDR Volume 4]

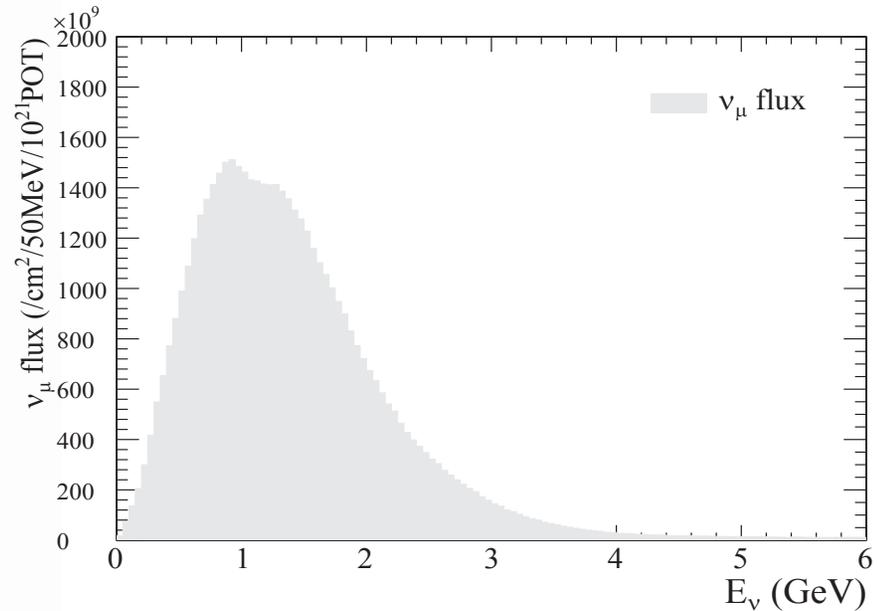
STT module for nuclear targets



DUNE ND



T2K ND on-axis



- ◆ **LBNF & DUNE (202x):**
80 GeV p, 1.47×10^{21} pot/y, ND at 574m
- ◆ **LBNF upgrade**
80-120 GeV p, 2.4 MW, $\sim 3 \times 10^{21}$ pot/y

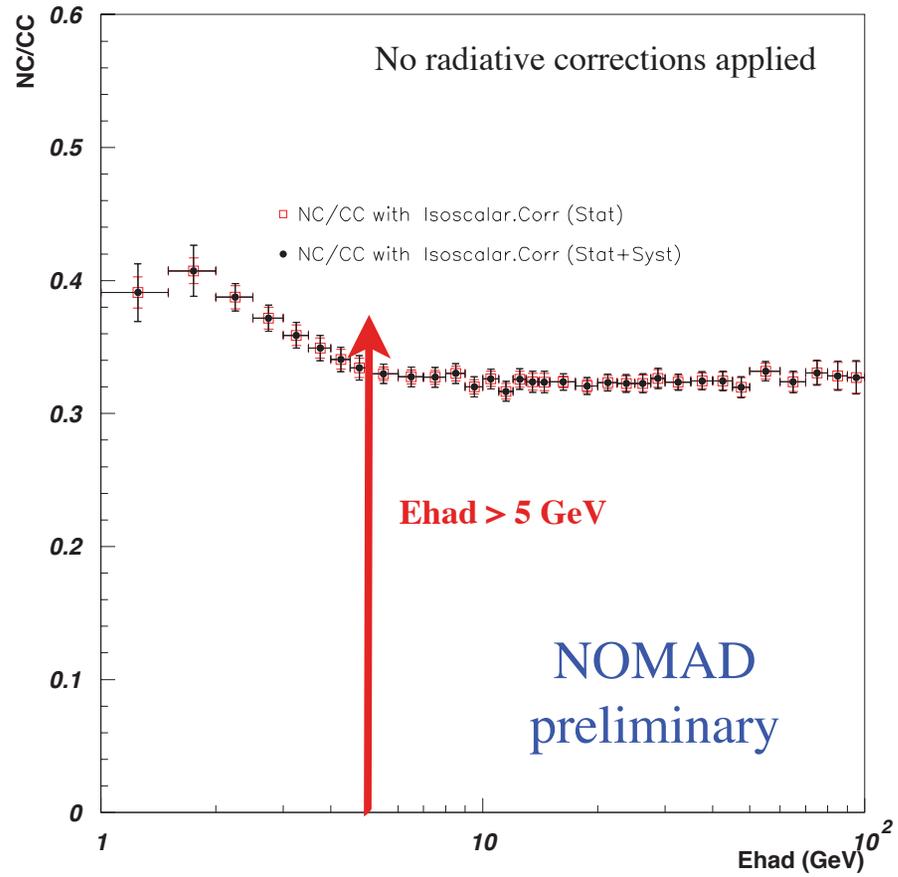
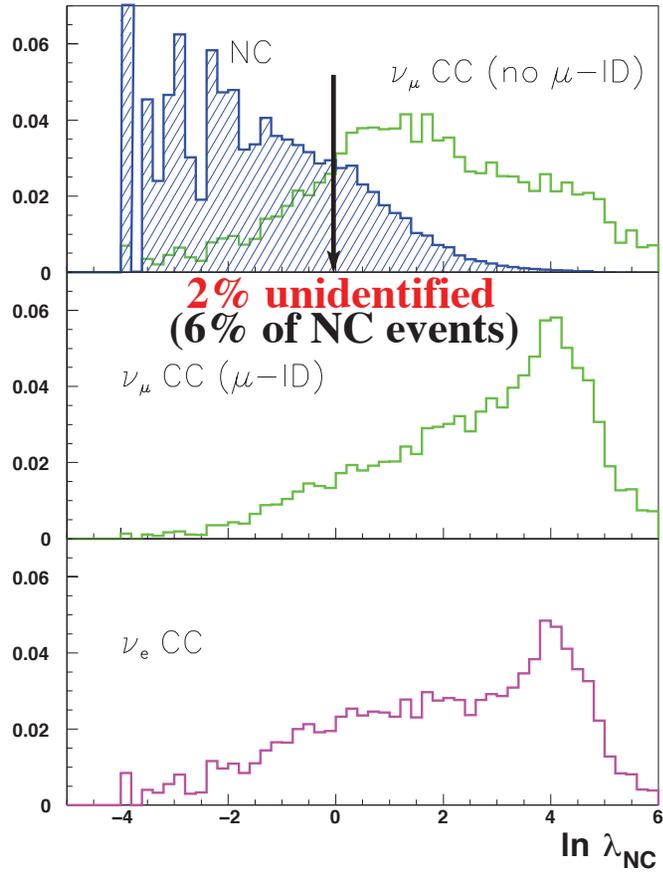
- ◆ **T2K (current):**
30 GeV p, 3×10^{20} pot/y, ND at 280m
- ◆ **T2K-II and T2HK**
30 GeV p, $1-2 \times 10^{21}$ pot/y

⇒ *Modern high intensity beams reduce mass requirements to a few tons, allowing use of higher resolution detectors with reduced systematics*

Source of uncertainty	$\delta R^\nu / R^\nu$		Comments
	NuTeV	DUNE	
<i>Data statistics</i>	0.00176	0.00057	With "standard" CP 0.00115
Monte Carlo statistics	0.00015		
Total Statistics	0.00176	0.00057	Depending upon beam exposure
<i>$\nu_e, \bar{\nu}_e$ flux</i>	0.00064	0.00010	e^\pm identification
Energy measurement	0.00038	0.00040	
Shower length model	0.00054	n.a.	
Counter efficiency, noise	0.00036	n.a.	
Interaction vertex	0.00056	n.a.	
Kinematic selection	N.A.	0.00090	NC/CC separation like NOMAD
Experimental systematics	0.00112	0.00100	
<i>$d,s \rightarrow c, s$-sea</i>	0.00227	0.00140	Based on current knowledge
Charm sea	0.00013	n.a.	
$r = \sigma^{\bar{\nu}} / \sigma^\nu$	0.00018	n.a.	
Radiative corrections	0.00013	0.00013	
Non-isoscalar target	0.00010	0.00010	Constrained by H measurements
<i>Higher twists</i>	0.00031	0.00070	Lower Q^2 values
$R_L (F_2, F_T, xF_3)$	0.00115	0.00140	Lower Q^2 values
<i>Nuclear corrections</i>	n.a.	0.00020	Constrained by H measurements
Model systematics	0.00258	0.00210	Reducible with in-situ measurements
TOTAL	0.00332	0.00239	28% improvement over NuTeV

\Rightarrow *Non-perturbative effects (High Twists, R_L , etc.) & nuclear corrections?*

Kinematic NC/CC separation successfully used by the NOMAD experiment:



- ◆ Neutrino scattering is characterized by the

AXIAL-VECTOR CURRENT (V-A):

$$VV, AA \implies F_{1,2} \quad (\text{or } F_L, F_T)$$

$$VA \implies F_3$$

- ◆ Conservation of Vector Current (CVC), in analogy to the charged leptons, implies:

$$F_2, F_T \sim Q^2 \quad F_L \sim Q^4 \quad \text{for } Q^2 \rightarrow 0$$

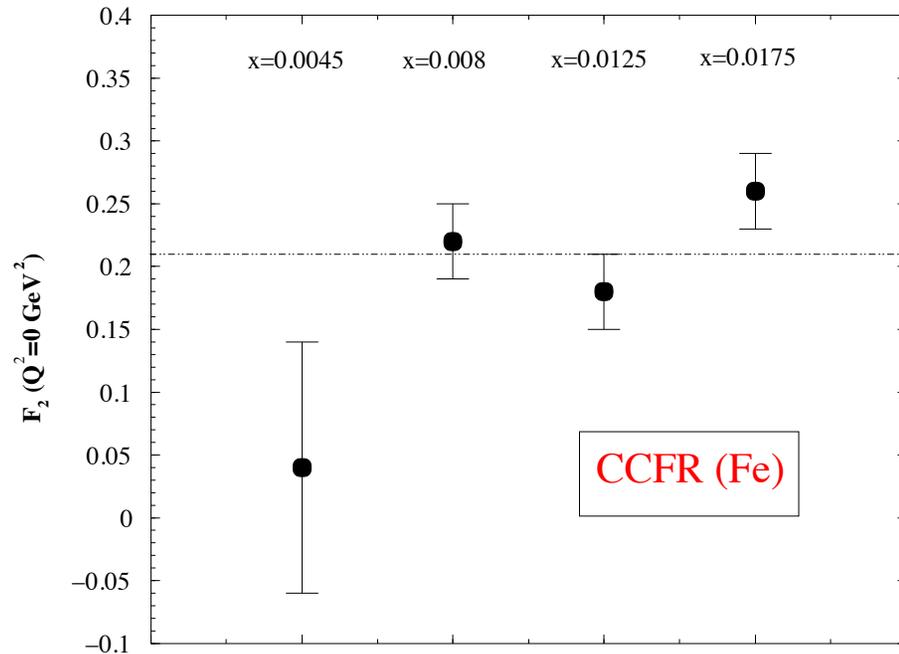
- ◆ Axial Current is only Partially Conserved (PCAC) and dominates F_L at low Q^2 :

$$\partial A = f_\pi m_\pi^2 \varphi \implies F_L = \frac{f_\pi^2 \sigma_\pi}{\pi}$$

- ◆ Transition scale between low and high Q^2 is **NOT m_π^2** but rather $M_{\text{PCAC}} \sim 1 \text{ GeV}^2$, since direct pion contribution $\partial_\mu \varphi$ cancels out. *Non vanishing contribution to F_2 :*

$$F_2 = (F_L + F_T)/(1 + 4x^2 M^2/Q^2) \rightarrow (f_\pi^2 \sigma_\pi)/\pi \quad Q^2 \rightarrow 0$$

\implies CCFR determination on Fe target 0.210 ± 0.02 (CCFR Coll., PRL 86 (2001) 5430).



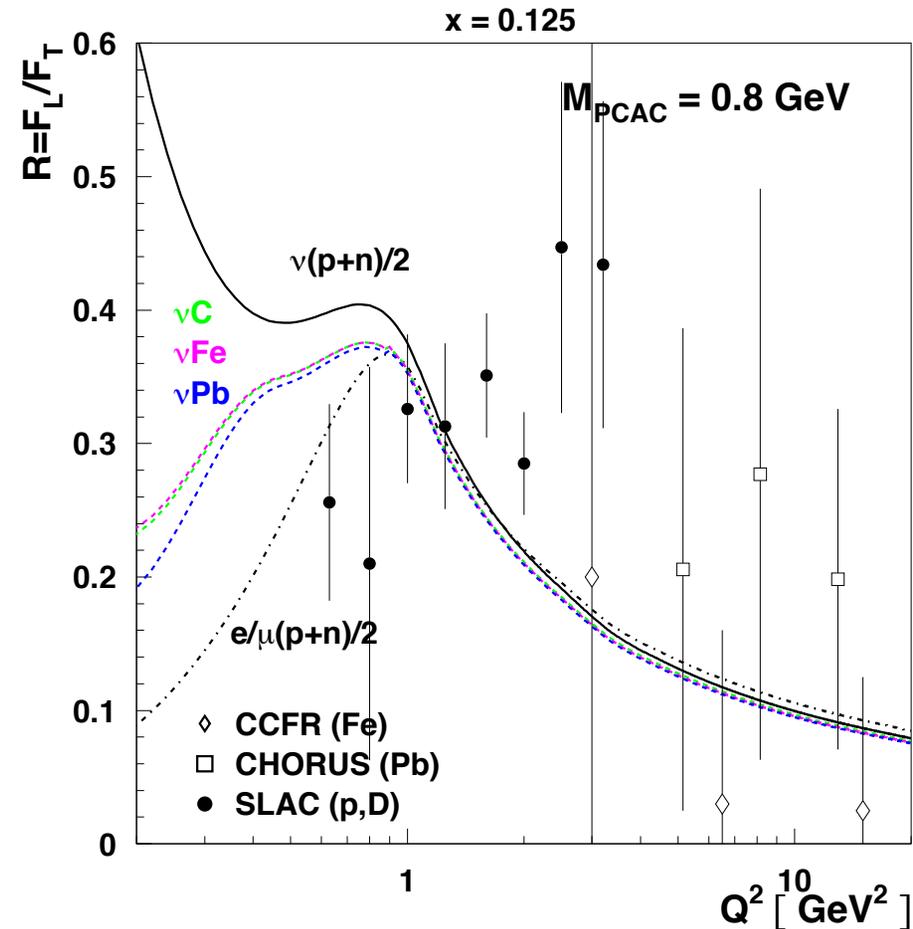
◆ The finite PCAC contribution to F_L strongly affects the asymptotic behaviour of $R = \sigma_L/\sigma_T$ for $Q^2 \rightarrow 0$:

$$F_T \sim Q^2$$

$$F_L \sim \frac{f_\pi^2 \sigma_\pi}{\pi} > 0$$

so that R is divergent for vanishing Q^2

⇒ Substantial difference with respect to charged lepton scattering.



S. Kulagin and R.P., PRD 76 (2007) 094023