Enhancing the DUNE Physics Potential

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PONDD: Physics Opportunities in the Near DUNE Detector hall
Fermilab, December 3, 2018

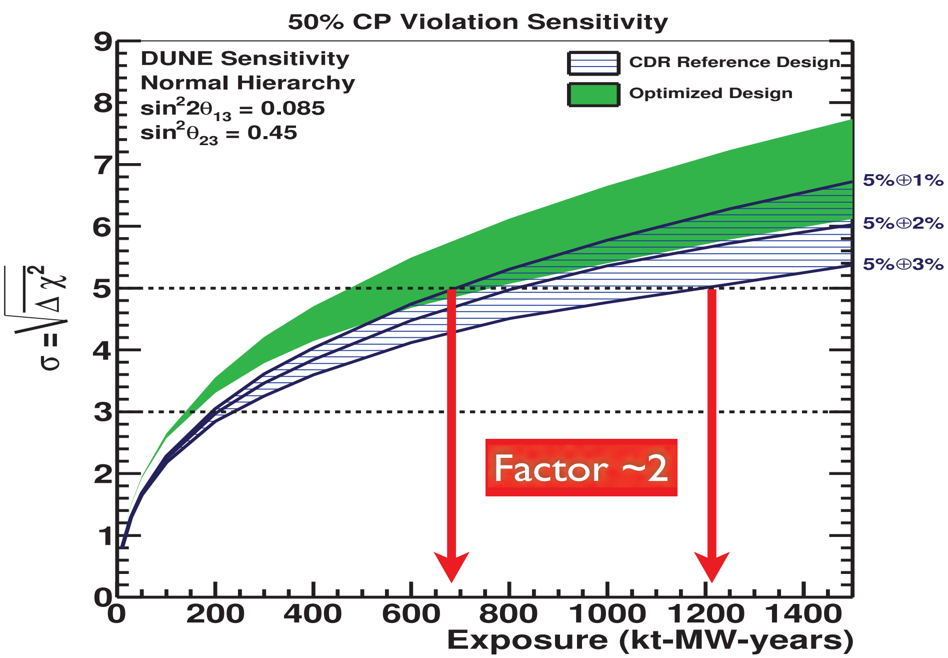
LIMITATIONS OF ND COMPLEX

- *Current ND design: LAr TPC followed by high pressure Ar gas TPC & plastic scintillator.*

- *Intrinsic limitations from the use of (single) Ar nuclear target:*
  - *Ar target not good for* **flux** *measurements due to substantial nuclear effects (n, FSI, etc.);*
  - *Need to understand the nuclear smearing (unfolding in FD), present even for an ideal Ar detector;*
  - *Need to calibrate the reconstructed neutrino energy scale.*

$\Longrightarrow$ *We can not rely entirely on MC/model corrections to control related systematics*

- *Need redundancy & in-situ measurements to constrain systematics from Ar target.*



Cost of systematic uncertainties can be large in DUNE

DUNE CDR [Vol. 2], arXiv:1512.06148 [physics.ins.det]

- *Current ND design cannot perform model-independent measurements of nuclear effects on Ar and relies on MC/model corrections for related systematics.*

- *DUNEprism concept can provide useful information to determine the reconstructed neutrino energy scale, typically at low E_ν, but cannot be the sole handle:*
  - *Dependence from beam model to predict expected "known" spectra;*
  - *Sensitive to possible time variations of beam conditions (& detector) while moving off-axis;*
  - *Off-axis positions cannot yield monochromatic energy for oscillation-relevant 0.5<E_ν<10 GeV.*

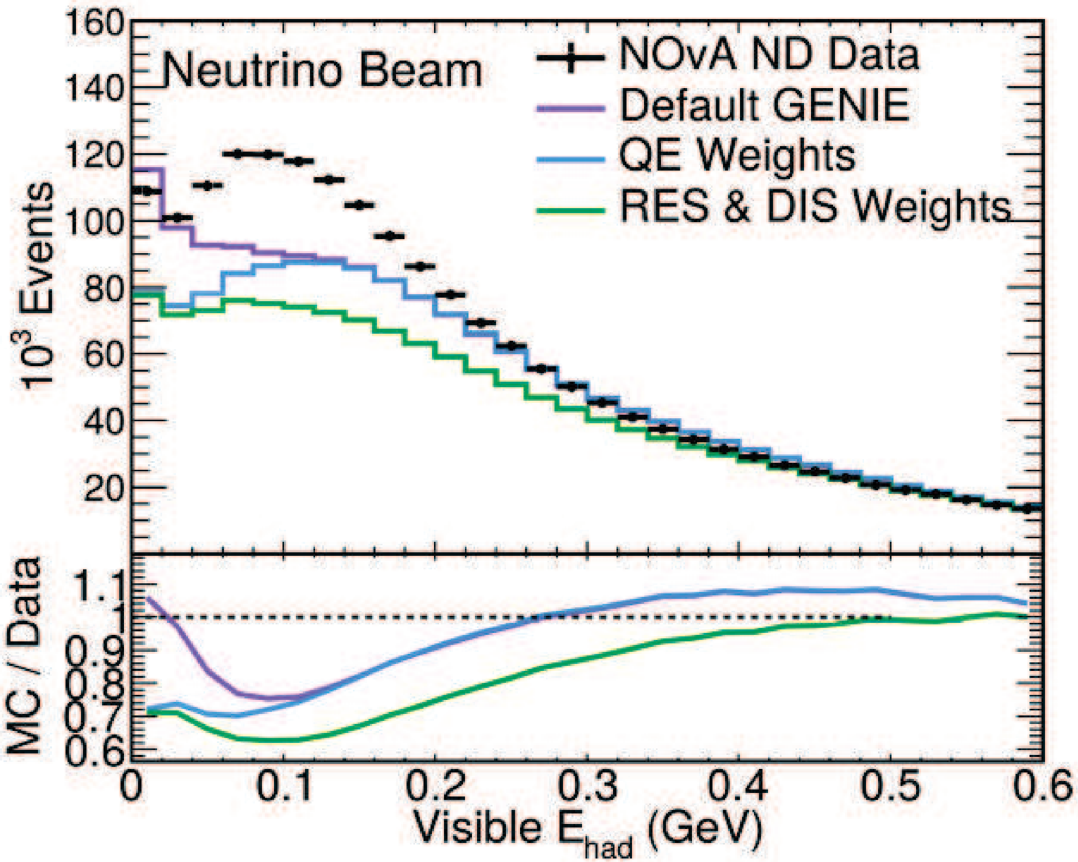
- *Current ND cannot provide accurate measurements of $\bar{\nu}_\mu/\nu_\mu$ flux vs. E_ν.*

- *Current ND cannot provide accurate measurements of $\bar{\nu}_e/\bar{\nu}_\mu$ & $\bar{\nu}_e/\nu_e$ flux vs. E_ν.*

$\Longrightarrow$ *Substantial dependence on MC to estimate systematic uncertainties!*

$\Longrightarrow$ *If physics beyond PNMS – one of main points of DUNE – current design inadequate*

J. Wolcott, NuInt 2018



- *A lesson from NOνA: – 14 mrad off-axis – still has largest systematics from E_ν scale;*
- *Impossible to disentangle CC interaction modeling, initial & final state nuclear effects, etc.*

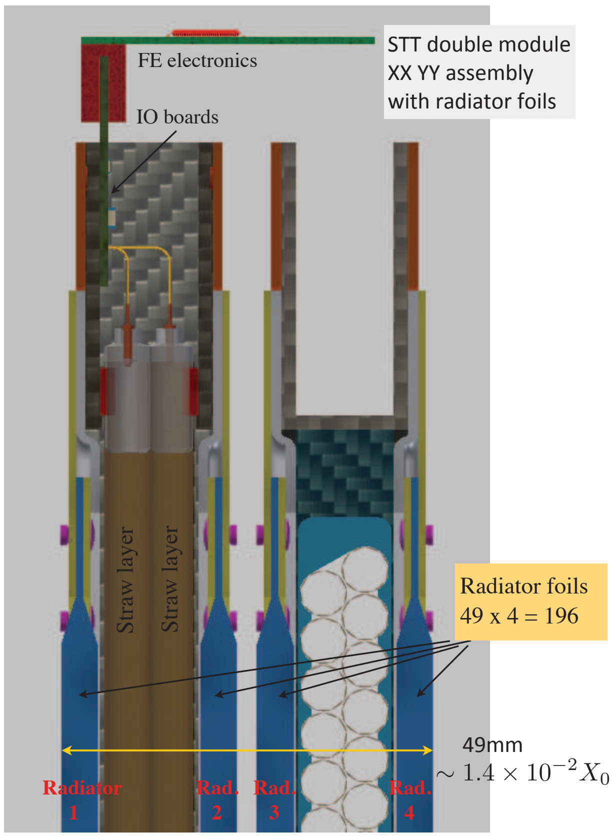
$\Longrightarrow$ *Cannot resolve unexpected discrepancies using MC only*

A TOOL TO REDUCE SYSTEMATICS

✦ *Compact version of Straw Tube Tracker (STT) from DUNE CDR:*

- *Accurate control of various nuclear target(s) by separating target(s) from active tracker;*
- *Thin targets spread out uniformly within tracker by keeping low density* $\rho \sim 0.16$ *g/cm*^{3}*;*
- *Total volume* ~ 49 *m*^{3}*, fiducial mass 5 tons,* $X_0 \sim 3.5$ *m, sampling 0.15 (0.36)%*$X_0 \perp (\parallel)$.

$\Longrightarrow$ *Need* $B \sim 0.6\,T$ *and to be surrounded by* 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.*

$\Longrightarrow$ *High purity/efficiency* $\nu(\bar{\nu})$*-H by subtracting* CH_2 *and C*

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

ADDITION TO ND COMPLEX

- *Compact STT flexible and can be adapted to different detector geometries.*

- *Large statistics $\nu(\bar{\nu})$-H samples are necessary to reduce Ar systematics in DUNE*

  $\Longrightarrow$ *Different options to integrate compact STT into ND complex considered*

- Option I:

  High pressure Ar gas TPC & compact STT within the same magnetic volume.

- Option II:

  Additional self-contained detector including compact STT, magnet, & ECAL

  - *Use extra space available in ND hall either off-axis or on-axis once DUNEprism off-axis;*
  - *Possible low-cost solution by re-using KLOE magnet & ECAL with compact STT.*

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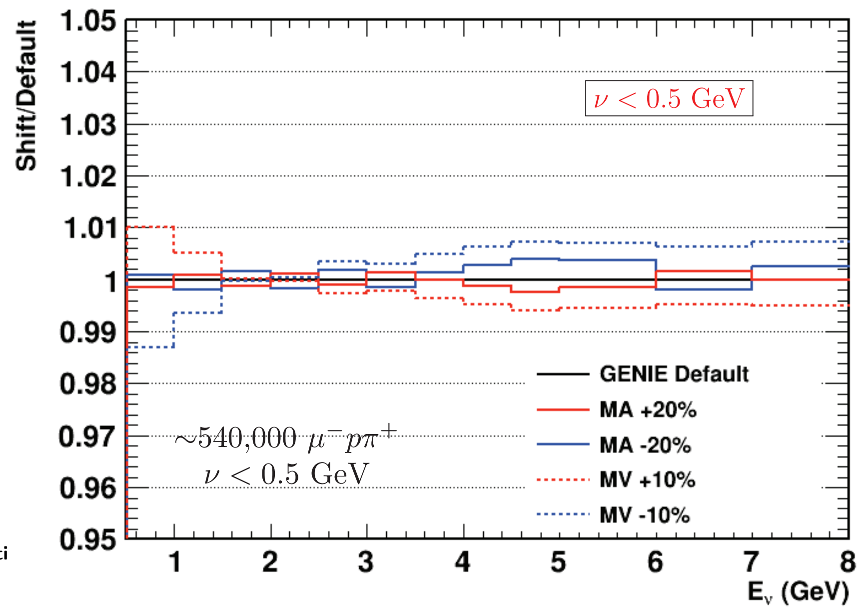
PRECISION FLUX MEASUREMENTS

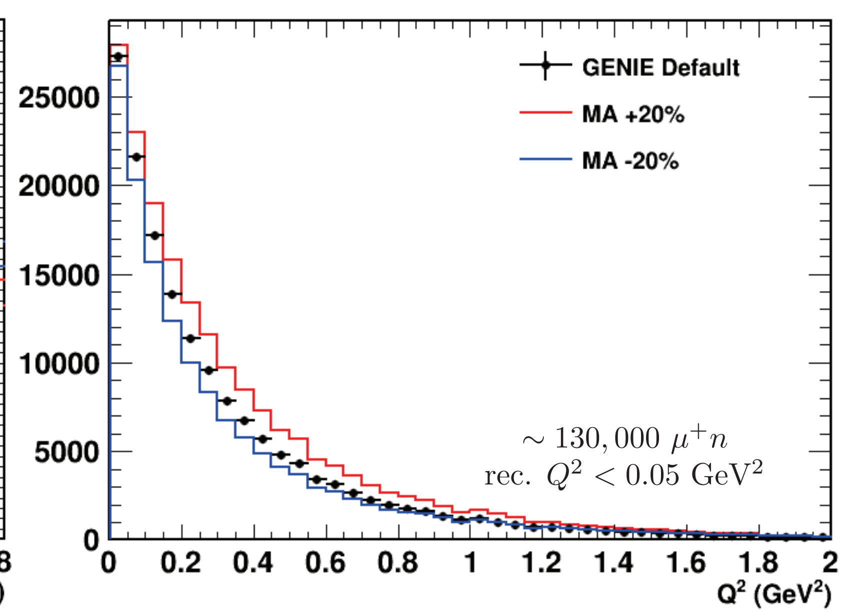
- *Relative ν_μ & $\bar{\nu}_\mu$ fluxes vs. E_ν with exclusive topology on Hydrogen $\nu(\bar{\nu})p \to \mu^\mp p \pi^\pm$:*
  - *Cut* $\boxed{\nu < 0.5 \text{ GeV}}$ *flattens cross-sections reducing uncertainties on E_ν dependence;*
  - *Flux uncertainties dominated by muon energy scale ($\Delta E_\mu \sim 0.2\%$ in low density tracker).*

- *Absolute & relative $\bar{\nu}_\mu$ fluxes from QE on Hydrogen $\bar{\nu}p \to \mu^+ n$ with $Q^2 \sim 0$:*
  - *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 $\ll 1\%$;*

- *Relative $\bar{\nu}_\mu$ fluxes using QE on Hydrogen $\bar{\nu}p \to \mu^+ n$ with $\nu < 0.5$ GeV (or lower).*

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





- ✦ *Absolute ν_μ flux from ν-e elastic $\sim$ 2%*

- ✦ *Ratio of $\bar{\nu}_\mu/\nu_\mu$ fluxes vs. E_ν from coherent π^-/π^+*
  $\Longrightarrow$ *Within same beam polarity on C (isoscalar) target in radiators*

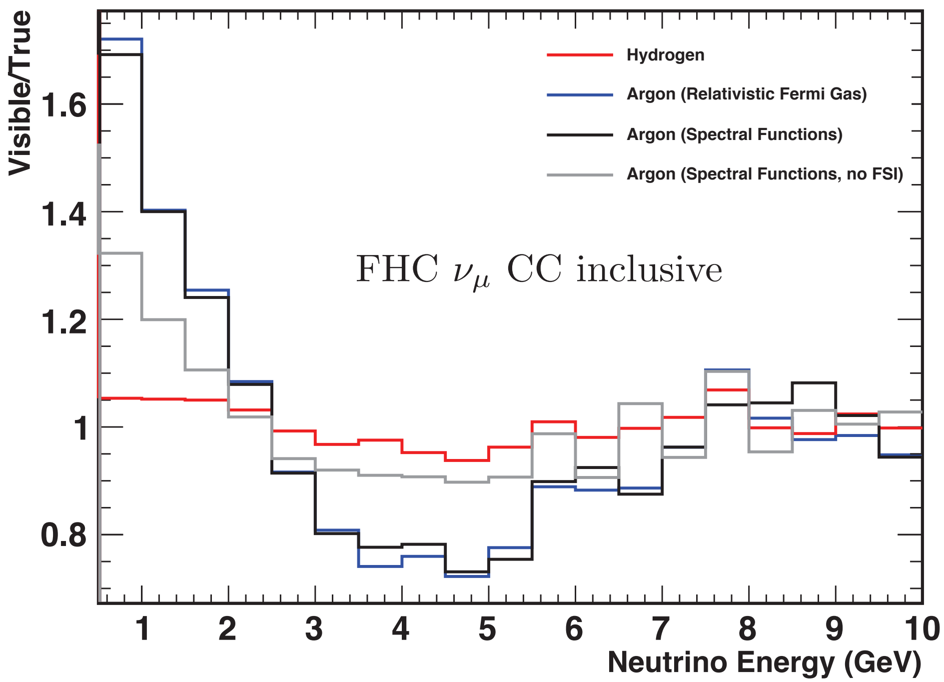
- ✦ *Ratio of ν_e/ν_μ AND $\bar{\nu}_e/\bar{\nu}_\mu$ vs. E_ν from CH_2 radiator targets*
  $\Longrightarrow$ *Effect of difference m_e vs. m_μ negligible in main DUNE energy range*

- ✦ *Ratio of ν_e/ν_μ AND $\bar{\nu}_e/\bar{\nu}_\mu$ from $\nu(\bar{\nu})$-H*
  $\Longrightarrow$ *Constrain integral and independent measurement of shape vs. E_ν*

- ✦ *Determination of parent $\mu/\pi/K$ distributions from $\nu(\bar{\nu})$-H (+ radiators) at low-ν*
  $\Longrightarrow$ *Crucial in-situ measurement for flux extrapolation to FD*

NUCLEAR SMEARING & ENERGY SCALE

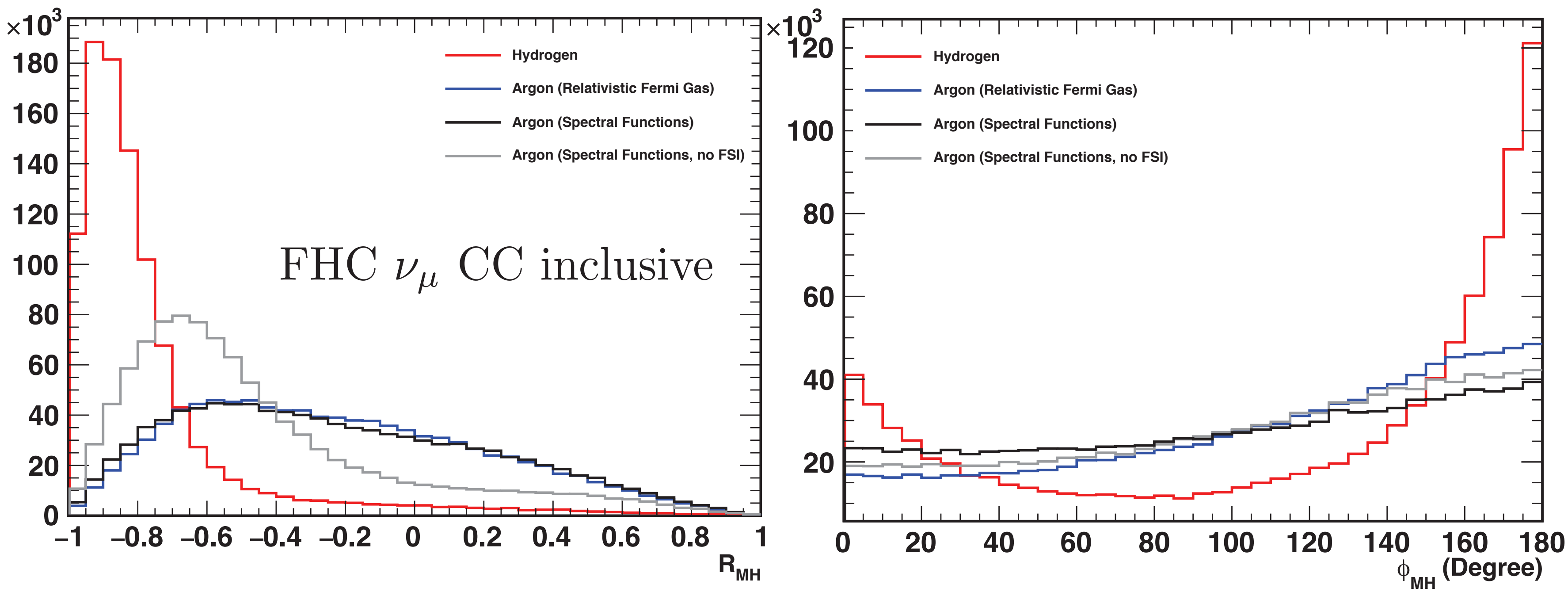
- *For most $\nu(\bar{\nu})$-H topologies (e.g. $\mu p \pi$) response function defined by $\delta p/p$ resolution*
  $\Longrightarrow$ *Unfolding of detector response can be calibrated accurately in low-density STT*
- *Compare inclusive CC distributions of variable X from $\nu(\bar{\nu})$-H and Ar*
  $\Longrightarrow$ *Determine product of nuclear smearing times σ for the particular ND spectrum*
- *H allows model-independent measurement of initial and final state nuclear effects*



Substantial nuclear smearing rapidly varying in oscillation range!

✦ *Additional handles to resolve potential degeneracies in the nuclear smearing:*

- *Comparisons of H and Ar interactions in bins of muon variables (p_μ, θ_μ);*
- *Comparisons of H and Ar interactions in bins of the radial distance from the beam axis & different ND locations provide a variation of the input spectra;*
- *Exclusive topologies ($\mu p \pi$, μn, etc.) in both H and Ar & complete set of kinematic variables;*
- *Simultaneous analysis of ν AND $\bar{\nu}$ to gather information about ν-n (isospin symmetry);*
- *Selection of Ar events with a total charge at the primary vertex $C_{\rm vtx} = 0$ for neutrinos and $C_{\rm vtx} = +1$ for antineutrinos to check the impact of n and p interactions.*



GENERAL PURPOSE PHYSICS FACILITY

✦ *Addition of "compact STT" can address the main issues of neutrino experiments (statistics, control of targets & fluxes) filling precision gap with electron experiments.*

$\Longrightarrow$ *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 $\nu\&\bar{\nu}$ 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, Gross-Llewellyn Smith);*
- *Measurements of strangeness content of the nucleon $(s(x), \bar{s}(x), \Delta s$, etc.);*
- *Studies of perturbative and non-perturbative 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 (Fe, Ar, Ca, C, etc.);*
- *Precision measurements of cross-sections and particle production; etc. .....*
- *Searches for New Physics (BSM): sterile ν, MiniBooNE anomaly, ν_τ search, axion-like particles, dark photons, sub-GeV dark matter, etc. .....*

$\Longrightarrow$ *Significant discovery potential & hundreds of diverse physics topics!*

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STATISTICS vs. RESOLUTION

- *Existing detectors compromise between high (low) statistics and coarse (high) resolution are affected by systematics on E_μ, $E_{\rm H}$ scales, nuclear targets & flux*

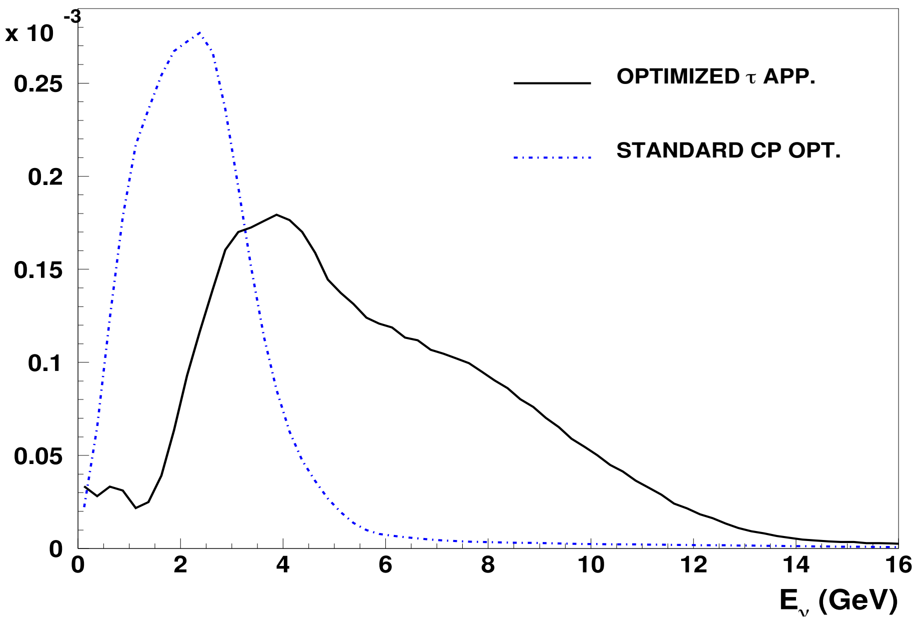
Experiment	Mass	ν_μ CC Stat.	Target	E_ν (GeV)	ΔE_μ	$\Delta E_{\rm H}$
CDHS	750 t	10^7	p,Fe	20-200	2.0%	2.5%
BEBC	various	5.7×10^4	p,D,Ne	10-200		
CCFR	690 t	1.0×10^6	Fe	30-360	1.0%	1.0%
NuTeV	690 t	1.3×10^6	Fe	30-360	0.7%	0.43%
CHORUS	100 t	3.6×10^6	Emul.,Pb	10-200	2.5%	5.0%
NOMAD	2.7 t	1.3×10^7	C,Fe	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_2O	0.2-5	0.6%	2-4%
MINERνA	5.4 t	10^7	CH,C,Fe,Pb	1-30	2%	

$\Longrightarrow$ *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*

  $\Longrightarrow$ *Modern beam facilities optimized at lower energies for detection of oscillations*

DUNE ND



Process	Events (5 t)
Standard CP optimized (1.2 MW):	
ν_μ CC (FHC, 5 y)	34×10^6
$\bar{\nu}_\mu$ CC (RHC, 5 y)	13×10^6
Optimized ν_τ appearance (2.4 MW):	
ν_μ CC (FHC, 2 y)	66×10^6
$\bar{\nu}_\mu$ CC (RHC, 2 y)	24×10^6
TOTAL W^+	100×10^6
TOTAL W^-	37×10^6
TOTAL Z^0	45×10^6

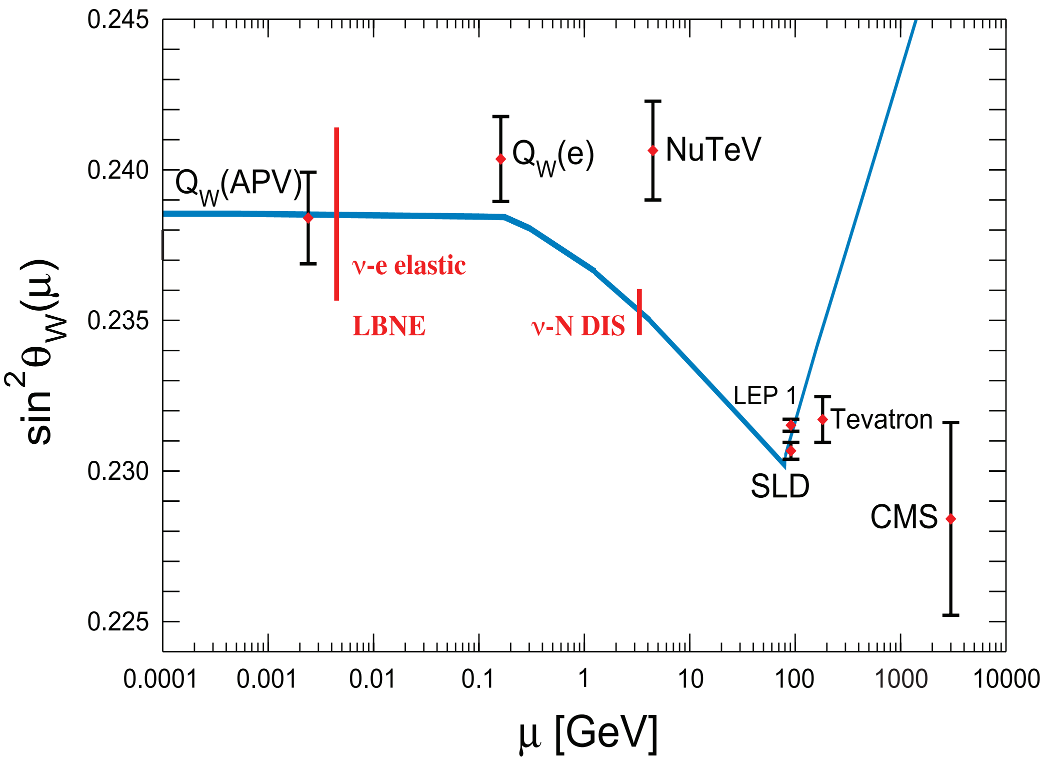
- *Available LBNF beam optimized for FD ν_τ appearance (120 GeV):*
  Conceivable dedicated run after 5y FHC + 5y RHC with the "standard" beams optimized for CP
  - *LBNF & DUNE (202x): 120 GeV p, 1.2 MW, 1.47×10^{21} pot/y, ND at 574m;*
  - *LBNF upgrade: 120 GeV p,* **2.4 MW**, *$\sim3\times10^{21}$ pot/y.*
- *Assume a modest 2y run with ν_τ optimized beam and upgraded intensity.*

$\Longrightarrow$ *Compact STT provides desired statistics $\sim 10^8$ & high resolution*

ELECTROWEAK 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*
  $\Longrightarrow$ *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:*

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

$\Longrightarrow$ *Combined EW fits like LEP*

✦ *Further reduction of uncertainties depending upon beam exposure*

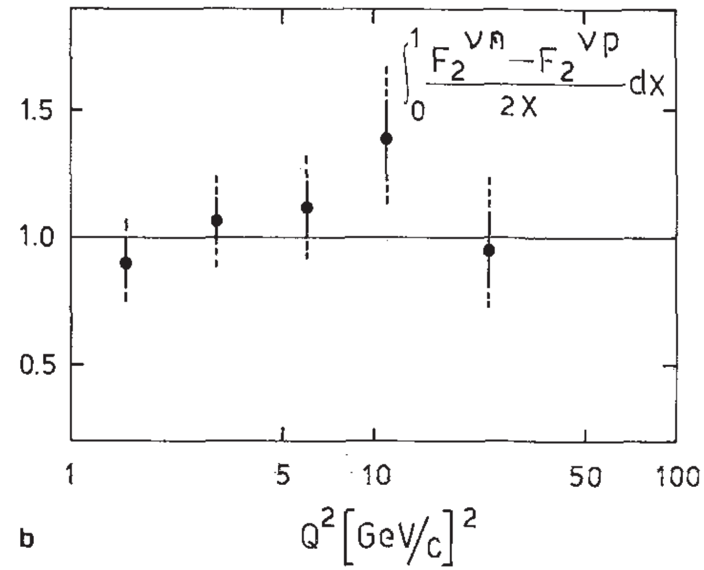
ADLER SUM RULE & ISOSPIN PHYSICS

✦ *The Adler integral provides the* 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)*

$\Longrightarrow$ *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*

$\Longrightarrow$ *d/u at large x and verify limit for $x \to 1$*

Process	$\nu(\bar{\nu})$**-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)**	**6.5×10**^{6}
ν_μ **CC (2 y)**	**4.3×10**^{6}

STRANGENESS CONTENT OF NUCLEON

✦ 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 $Q^2 \to 0$ 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):*

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

- *Compare axial current charge radius r_A^2 with muon capture in muonic hydrogen (discrepancies);*
- *Expect $\sim$ 2 $\times 10^6$ 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.*

✦ *Direct probe of $s(x)$ & $\bar s(x)$ content of nucleon from charm production in both dilepton ($\sim 100k$ $\mu\mu$&μe) and exclusive charmed hadrons (e.g. D^{*+}, D_s, Λ_c).*

TESTS OF ISOSPIN (CHARGE) SYMMETRY

- *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:

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

  - *Structure function ratio reduces systematic uncertainties;*
  - *Need to take into account charm quark effects $\propto \sin^2\theta_C$. Sensitivity to $\boxed{m_c}$;*
  - *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, $^{20}_{40}$Ca, to verify nuclear effects in $^{6}_{12}$C;*
  - *Use second target with isovector component but same A as Ca: $^{18}_{40}$Ar.*

NUCLEAR MODIFICATIONS OF NUCLEON PROPERTIES

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

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

  - *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.*

SUMMARY

✦ *To overcome limitations from Ar target in DUNE necessary to have a hydrogen target, which offers unique handle on 3 important systematics for LBL analyses:*

- *Determination of the neutrino and antineutrino fluxes as a function of E_ν;*
- *Constraint of the response function associated to the nuclear smearing (unfolding);*
- *Calibration of the reconstructed neutrino energy scale.*

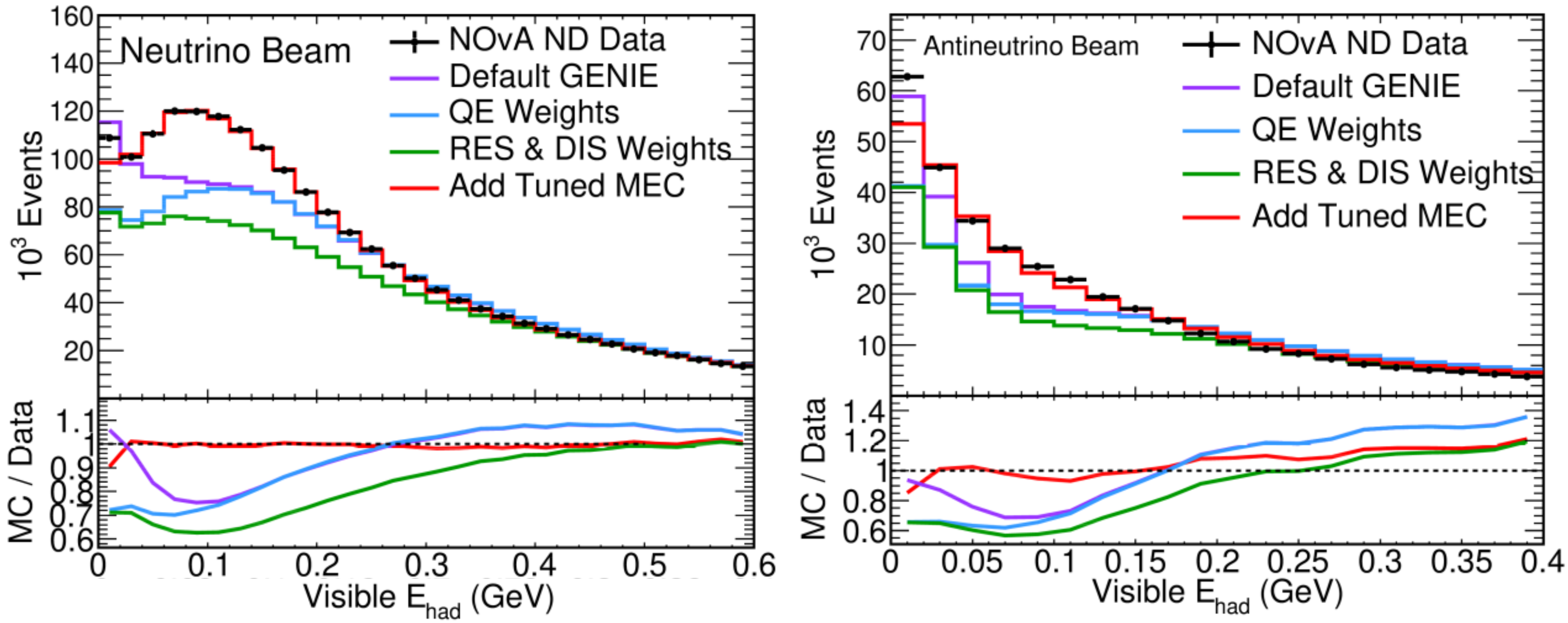
✦ *All $\nu(\bar{\nu})$-H CC topologies can be selected in a compact STT with high efficiency & purity via a data-driven background subtraction with high statistics*
$\Longrightarrow$ *Various options to implement within ND complex with minimal design changes*

✦ *Addition of compact STT addresses the limitations of current ND design, providing the required redundancy and direct in-situ constraints of relevant systematics*

✦ *Compact STT additionally offers a rich physics program, with hundreds of diverse topics, complementary to ongoing fixed-target, collider and nuclear physics efforts.*

We welcome, and need, your support to help build the DUNE ND to precisely measure processes that would ultimately allow DISCOVERIES at Fermilab

Backup slides


Neutrino Beam
NOvA ND Data
Default GENIE
QE Weights
RES & DIS Weights
Add Tuned MEC
10^3 Events
MC / Data
Visible E_had (GeV)
Antineutrino Beam
NOvA ND Data
Default GENIE
QE Weights
RES & DIS Weights
Add Tuned MEC
10^3 Events
MC / Data
Visible E_had (GeV)

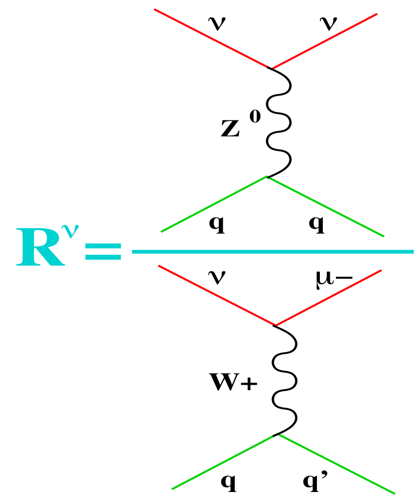
MEASUREMENT OF $\sin^2\theta_W$ FROM νN DIS

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

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

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**
Standard CP optimized:	
ν_μ **CC (5 y)**	**3×10^6**
Optimized ν_τ appearance:	
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:*

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

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

$\Longrightarrow$ *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 $R^{\bar\nu}$:*

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

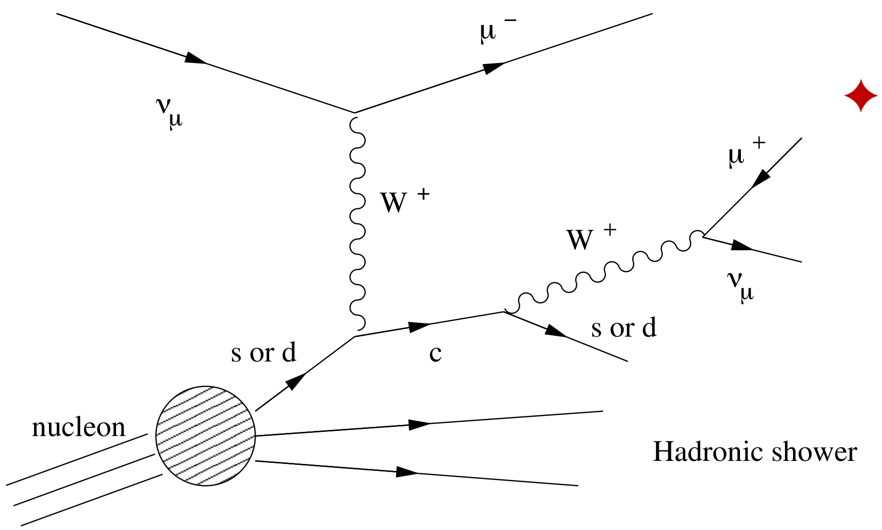
$$\text{SM from LEPEWWG} = 0.2227 \pm 0.00037$$

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

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

$\Longrightarrow$ *A discrepancy of 3σ with SM in the NEUTRINO data*

A DIRECT PROBE OF STRANGE SEA



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

$$\frac{d^2\sigma_{\mu\mu}}{dxdydz} = \frac{d^2\sigma_c}{dxdy} D_c(z) B_\mu; \qquad z = \frac{P_L(h_c)}{P_L^{\max}}$$

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

$D_c(z)$ *average fragmentation function*

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

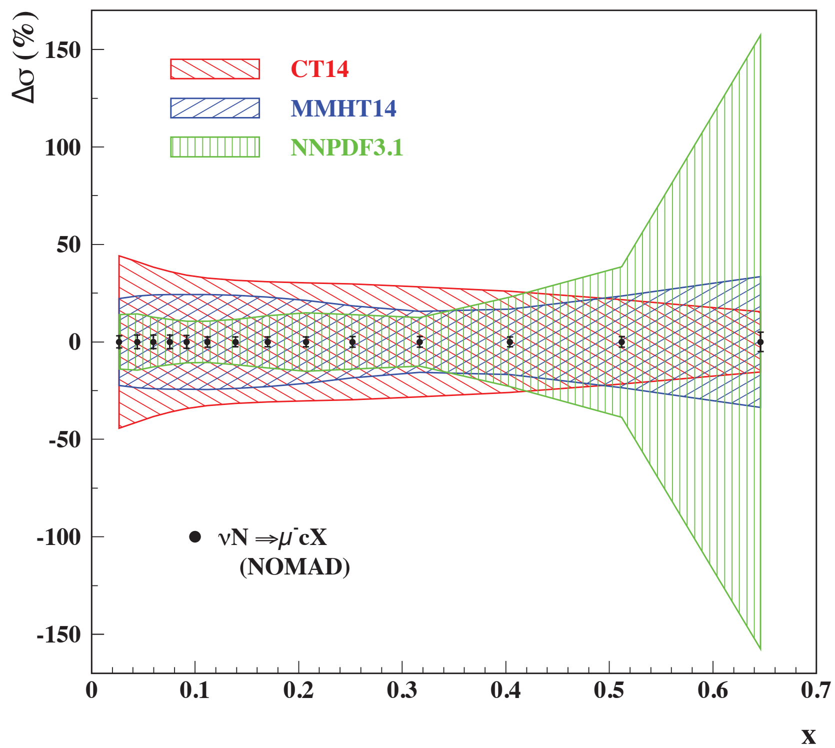
$$F_{2,c}(x,Q) = 2\xi \left[|V_{cs}|^2 s(\xi,\mu) + |V_{cd}|^2 \frac{u(\xi,\mu) + d(\xi,\mu)}{2} \right]$$

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

where simple LO approximations are given for illustration purpose

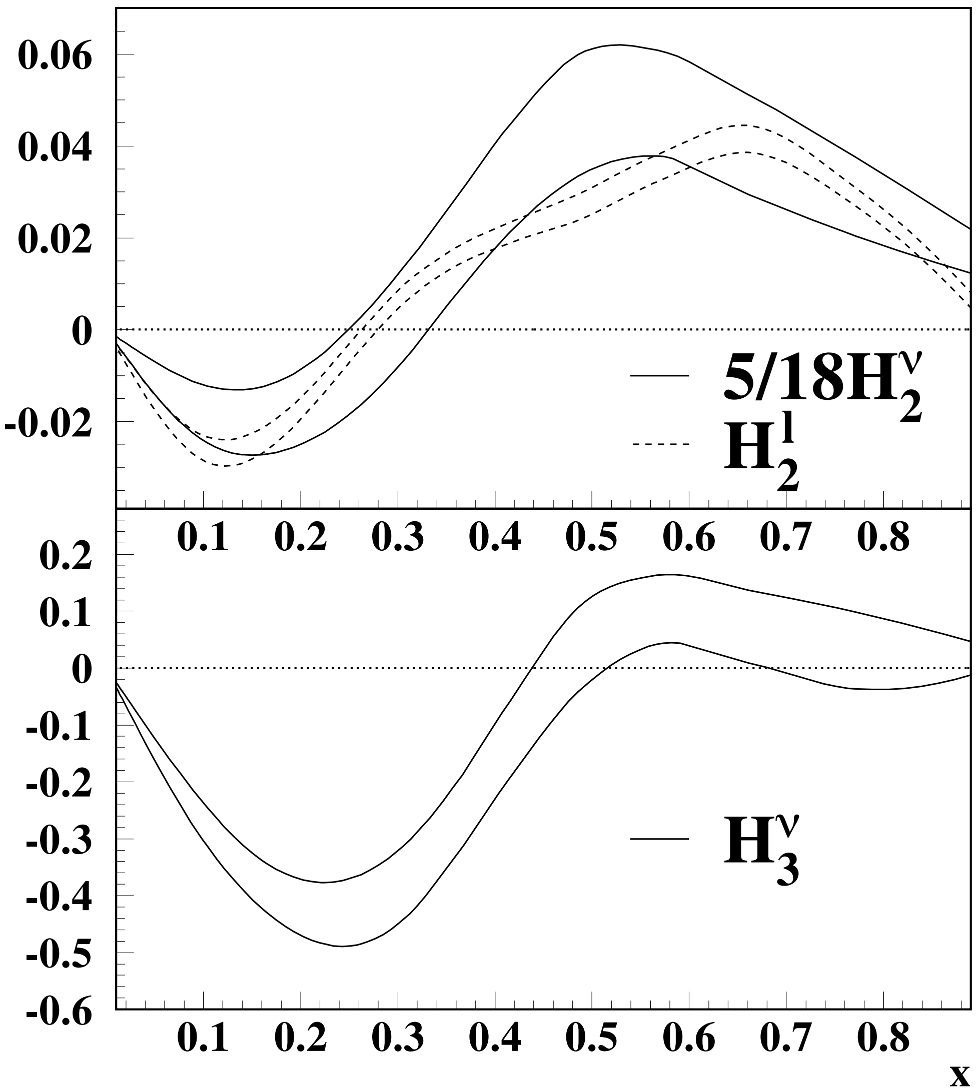
$$\begin{cases} \nu: & s/(d_v + d_s) \to c & \simeq 50\% \\ \bar{\nu}: & \bar{s}/\bar{d}_s \to \bar{c} & \simeq 90\% \end{cases}$$

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 $\overline{\mathrm{MS}}$ 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)*

HIGH TWIST CONTRIBUTIONS



- *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

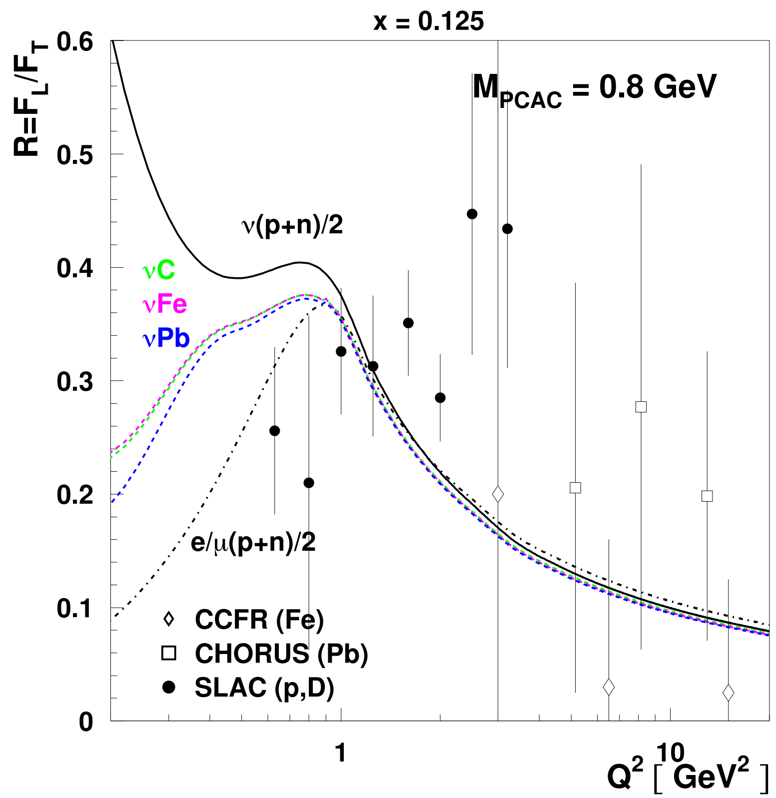
- *Neutrino scattering is characterized by an* AXIAL-VECTOR CURRENT *in addition to the the Vector current.*

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

$$F_2 \to F_L = \frac{f_\pi^2 \sigma_\pi}{\pi} \qquad Q^2 \to 0$$

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

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



$\Longrightarrow$ *Substantial difference with respect to charged lepton scattering.*

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

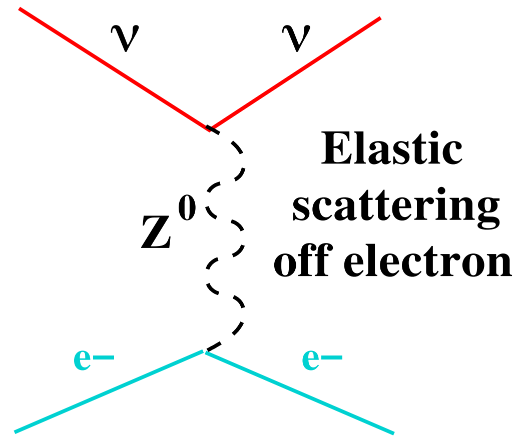
MEASUREMENT OF $\sin^2\theta_W$ FROM ν-e

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

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

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.*

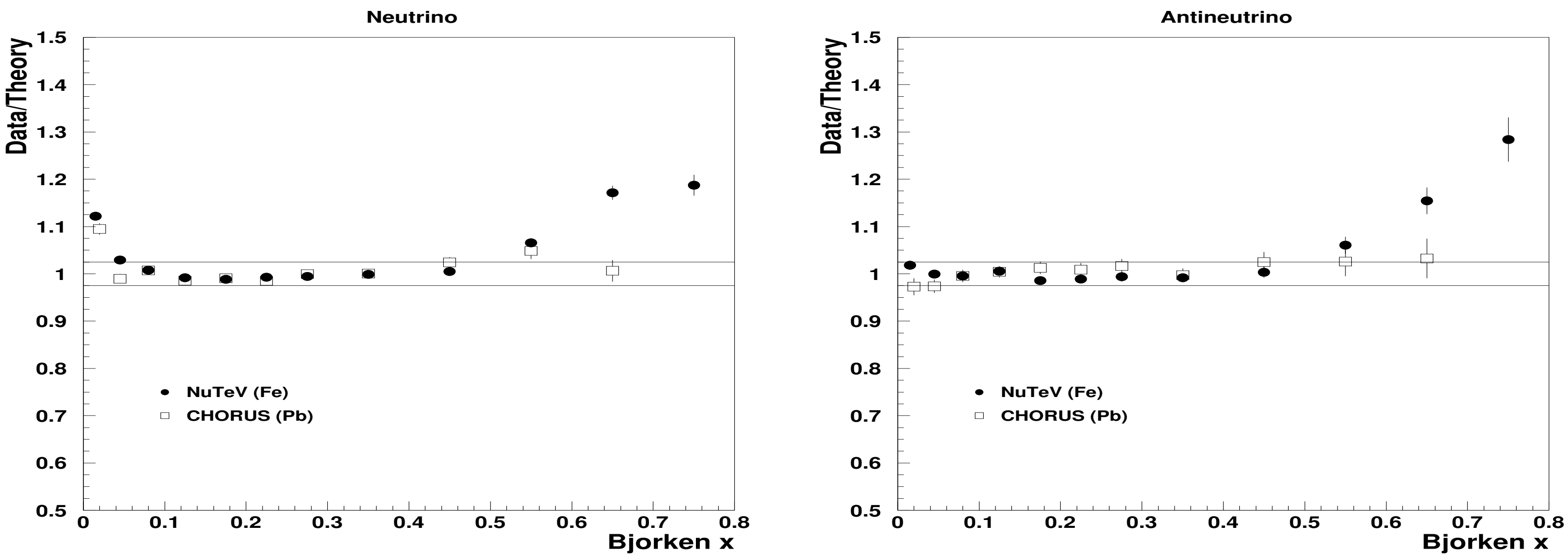


✦ *Benefits from combination of light high resolution (5 t) and massive LAr ND detectors (25 t)*

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

✦ *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.*



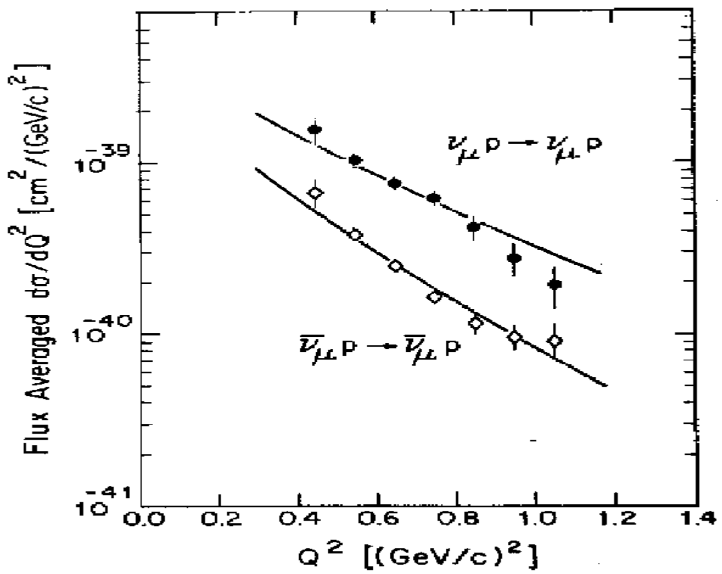
- *Limited $\nu(\bar{\nu})$ data on ratios $\sigma^{A'}/\sigma^{A}$ (BEBC, MINERνA) and differential cross-sections $d\sigma^2/dxdy$ (NuTeV, CCFR, CHORUS)*

- *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).*

  $\Longrightarrow$ *Need new precision measurements with both ν AND $\bar{\nu}$*

ADDITIONAL CHANNELS

BNL E734



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

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

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.*

$\Longrightarrow$ *Systematics from FF, neutrons, nuclear effects?*

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

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

expect $\sim$ 30k coherent ρ^0 and 200k coherent ρ^+ in ND.

$\Longrightarrow$ *Systematics from background subtraction in the coherent ρ^0 selection?*

Source of uncertainty	$\delta R^\nu/R^\nu$ NuTeV	DUNE	Comments
Data statistics	0.00176	0.00057	*With "standard" CP 0.00115*
Monte Carlo statistics	0.00015		
Total Statistics	**0.00176**	**0.00057**	*Depending upon beam exposure*
$\nu_e, \bar{\nu}_e$ *flux*	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**	
d,s→c, s-sea	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*
Higher twists	0.00031	0.00070	*Lower* Q^2 *values*
R_L (F_2, F_T, xF_3)	0.00115	0.00140	*Lower* Q^2 *values*
Nuclear corrections	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*

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

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