Precision Measurements of Fundamental Interactions with (Anti)neutrinos

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OUTLINE

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

II *Requirements for Precision Physics*

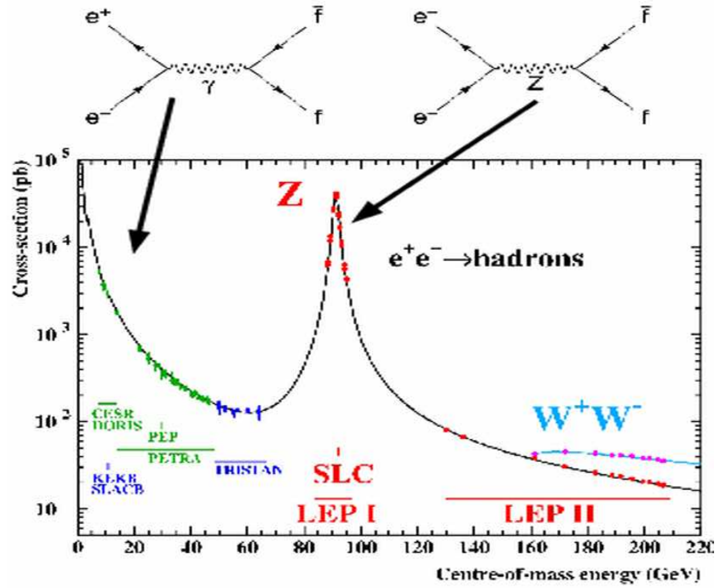
- *Statistics vs. resolution*
- *Control of the targets*
- *Control of the fluxes*

III *Precision Measurements*

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

IV *Summary*

PRECISION PHYSICS: $e^{\pm}$ PROBE



M_Z = 91187.5 (2.1) MeV

N_ν = 2.9841 (83) [-1.9σ]

✦ *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

$\Longrightarrow$ *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.*

$\Longrightarrow$ *Can a modern $\nu(\bar{\nu})$ facility deliver comparable precisions unveiling discovery potential in precision tests of fundamental interactions?*

PRECISION PHYSICS: $\nu/\bar{\nu}$ PROBE

✦ *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 $e^{\pm}$.*

$\Longrightarrow$ *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

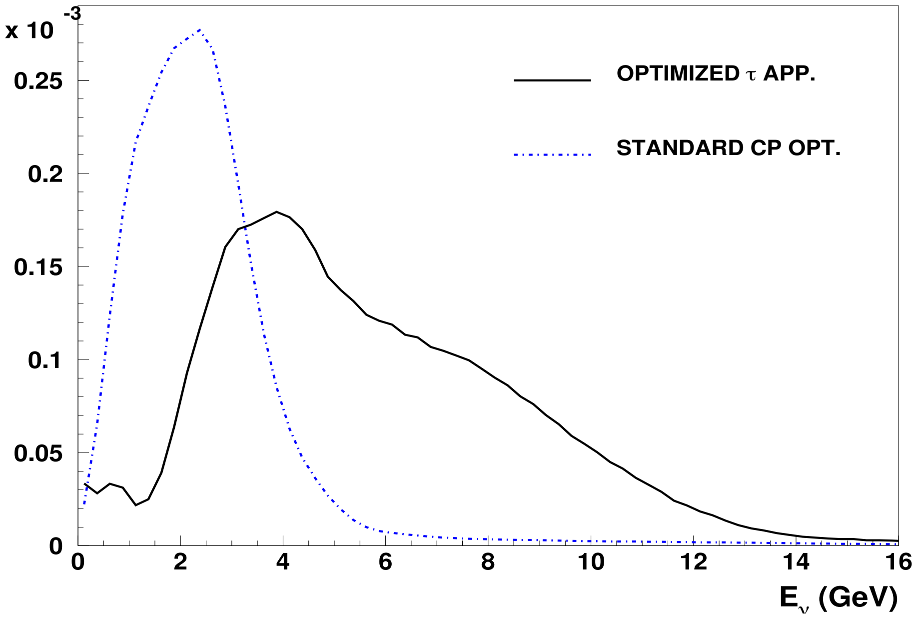
- *Existing detectors compromise between high (low) statistics and high (coarse) resolution are affected by systematics on E_μ, E_H scales, nuclear targets & flux*

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_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*



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	44×10^6

✦ *Available LBNF – Long-Baseline Neutrino Facility – beam optimized for FD ν_τ appearance: Conceivable dedicated run after 5y FHC + 5y RHC with the "standard" beams optimized for CP*

- *LBNF: 120 GeV p, 1.2 MW, 1.1×10^{21} pot/y, ND at 574m;*
- *LBNF upgrade: 120 GeV p,* **2.4 MW (x 2)**, *$\sim3\times10^{21}$ pot/y.*

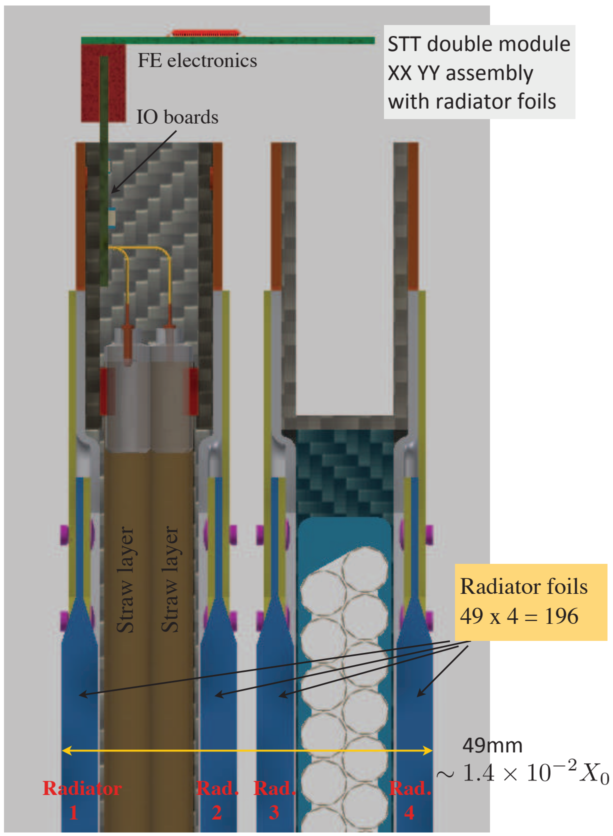
✦ *Assume a modest 2y FHC run with ν_τ optimized beam & LBNF upgrade*

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

CONTROL OF TARGETS

- *Precision EW & QCD measurements require control of 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 $\rho \sim 0.16$ g/cm^3.*

$\Longrightarrow$ *Straw Tube Tracker (STT) in $B \sim 0.6T$ with 4π electromagnetic calorimeter*

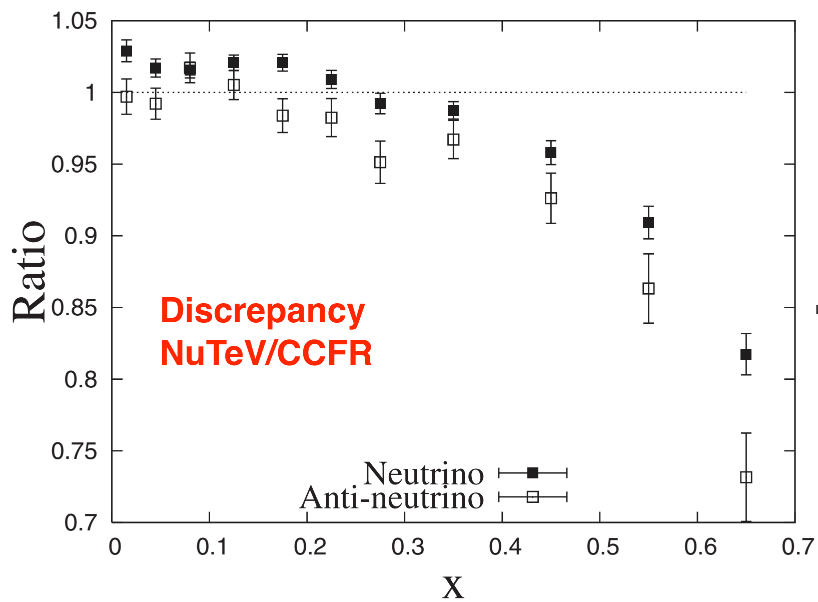


- *Radiator targets (100% purity) account for $> 95\%$ of STT mass and can be tuned to achieve desired statistics & resolutions.*
- *Separation from excellent vertex, angular & timing resolutions.*
- *Radiators can be replaced by thin nuclear targets: C, Ca, Ar, Fe, etc.*

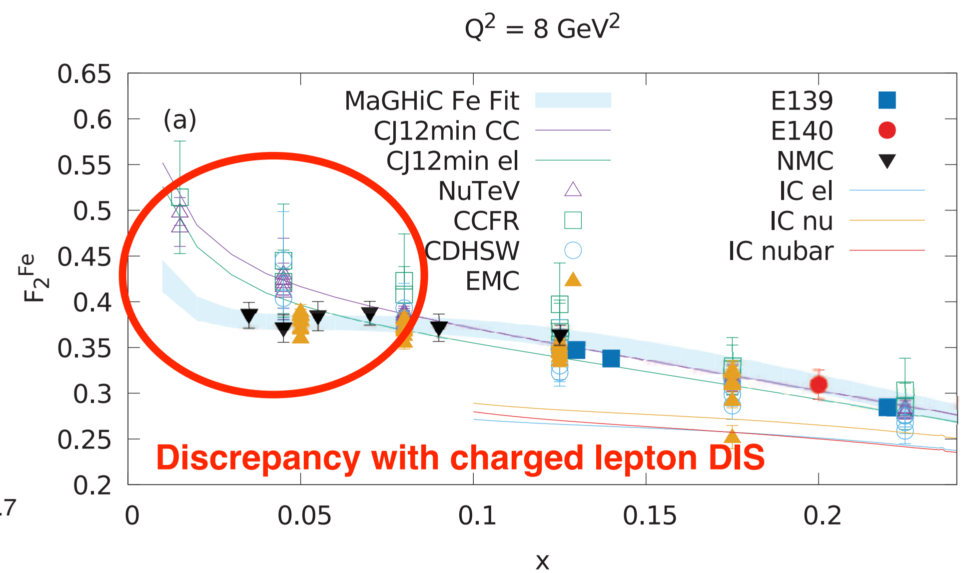
✦ *Need to understand nuclear modifications & corresponding systematic uncertainties*:

- *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.*

$\Longrightarrow$ *Necessary condition availability of (complementary) free nucleon target (hydrogen)*



NuTeV Coll., PRD 74 (2006) 012008

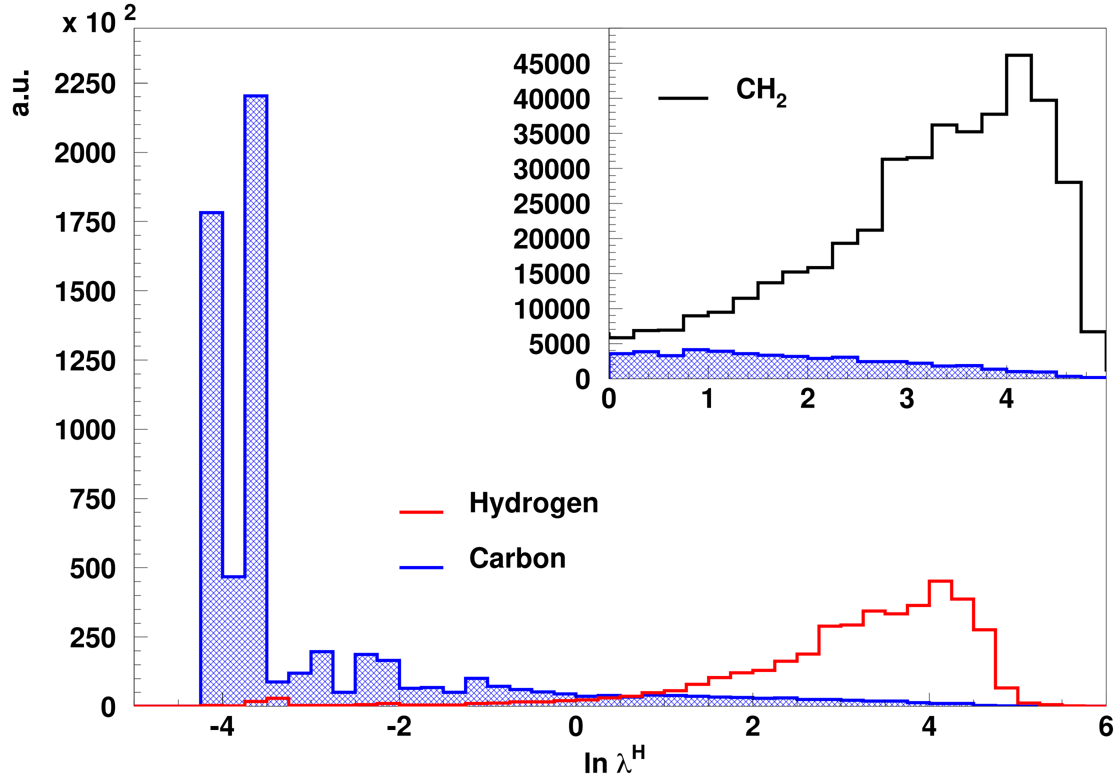


N. Kalantarians, C. Keppel, M.E. Cristy, PRC 96 (2017) 032201

✦ *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.*

$\Longrightarrow$ *Viable and realistic alternative to liquid/gaseous H_2 detectors*



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

CONTROL OF FLUXES

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

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

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

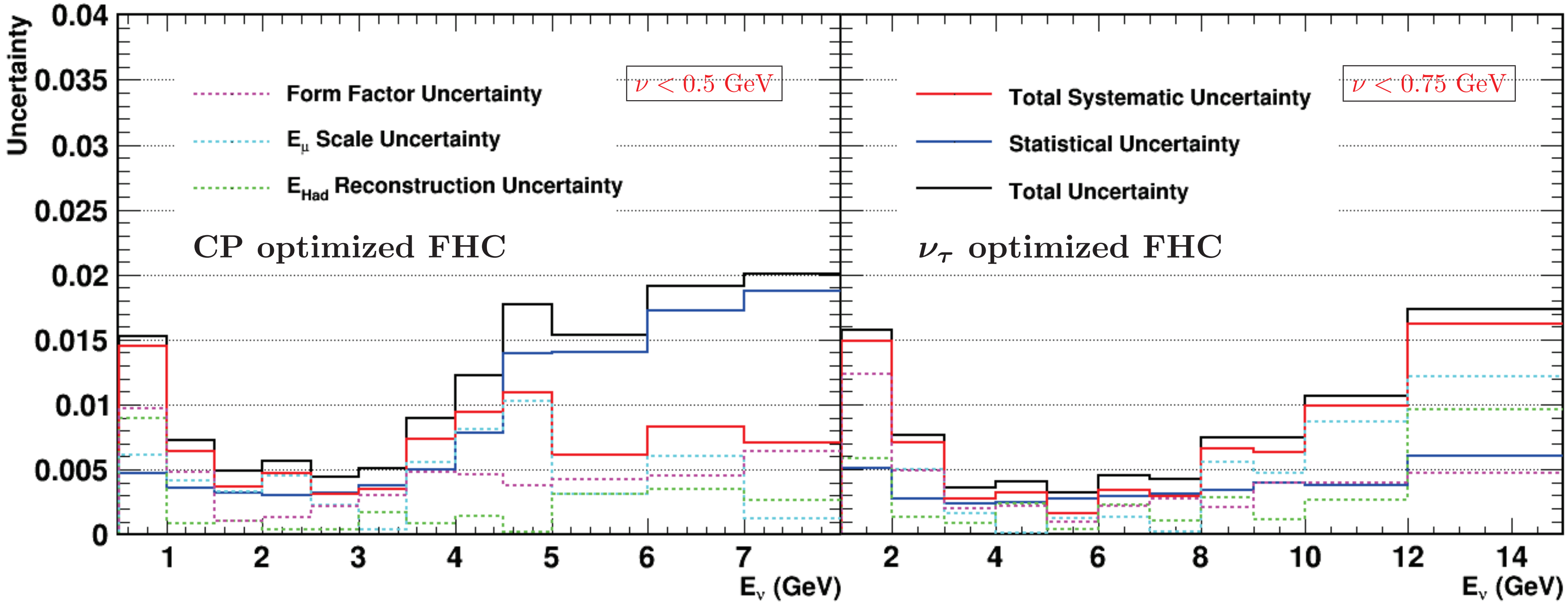
- *Used by past and current experiments with nuclear targets from C to Pb:*
  - *For $\nu_0 \leq 1$ GeV sample dominated by inclusive QE+RES interactions;*
  - *Need precise muon energy scale and good resolution at low ν values;*
  - *Nuclear effects on f_c, $E_{\rm Had}$ reconstruction & acceptance of cut $\nu < \nu_0$.*

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

- *Exclusive $\nu(\bar{\nu})$-Hydrogen topologies dramatically reduce hadronic uncertainties:*
  - *Well defined cross-section for single exclusive process on H;*
  - *Remove bottleneck from nuclear smearing.*

✦ *Relative ν_μ flux vs. E_ν from exclusive $\nu_\mu p \to \mu^- p \pi^+$ on Hydrogen:*

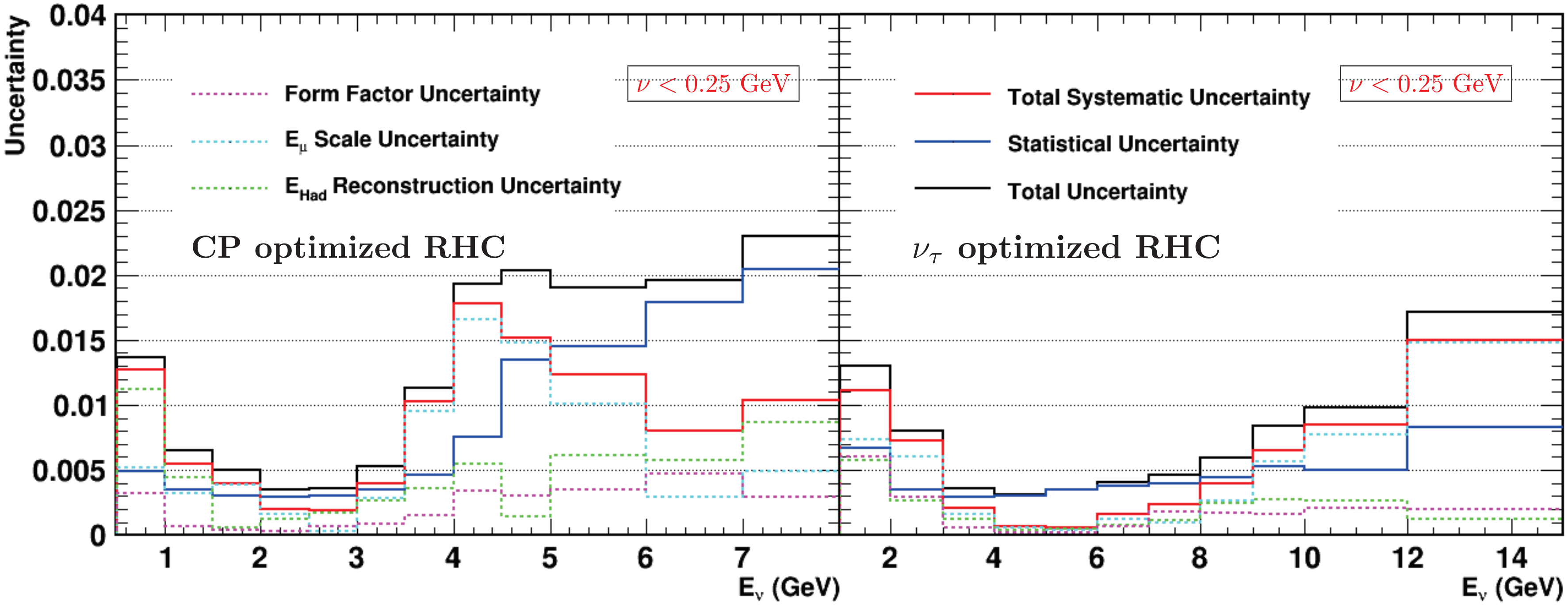
- *Select well reconstructed $\mu^- p \pi^+$ topology on H ($\delta p/p \sim 3\%$);*
- *Cut $\boxed{\nu < 0.5(0.75)\ \text{GeV}}$ flattens cross-sections reducing uncertainties on E_ν dependence;*
- *Systematic uncertainties dominated by muon energy scale ($\Delta E_\mu \sim 0.2\%$ in STT from K_0 mass).*



H. Duyang, B. Guo, S.R. Mishra, RP, arXiv:1902.09480 [hep-ph]

✦ *Relative $\bar{\nu}_\mu$ flux vs. E_ν from exclusive $\bar{\nu}_\mu p \to \mu^+ n$ QE on Hydrogen*:

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



H. Duyang, B. Guo, S.R. Mishra, RP, arXiv:1902.09480 [hep-ph]

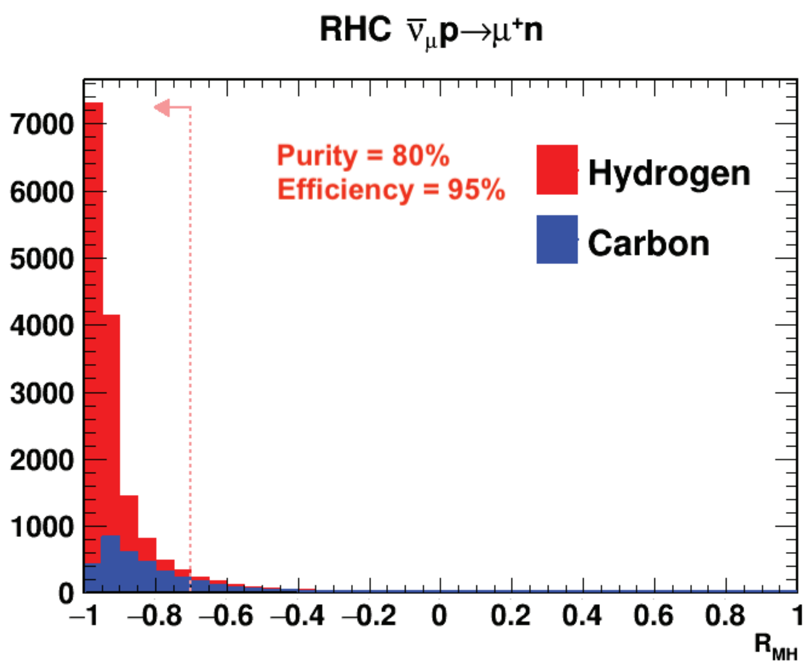
✦ *Absolute $\bar{\nu}_\mu$ flux from QE on Hydrogen $\bar{\nu}_\mu p \to \mu^+ n$:*

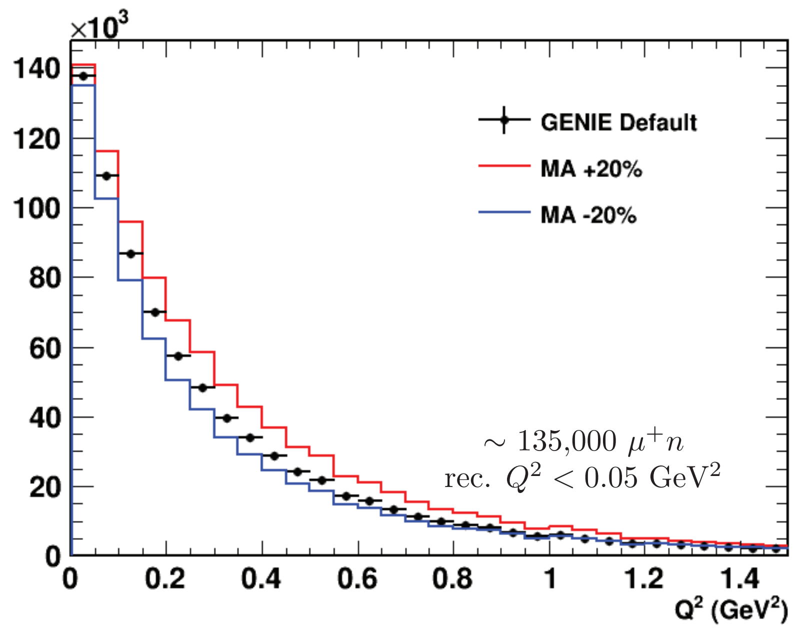
$$\frac{d\sigma}{dQ^2}\,|_{Q^2=0} \;=\; \frac{G_F^2 \cos^2\theta_c}{2\pi}\,[F_V^2(0) + G_A^2(0)]$$

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

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

$\Longrightarrow$ *Calibrate absolute n detection efficiency with dedicated irradiation of STT & ECAL*





GENERAL PURPOSE PHYSICS FACILITY

- *Possible to solve the main issues of neutrino experiments (statistics, control of targets & fluxes) largely filling the 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, GLS);*
  - *Measurements of strangeness content of the nucleon ($s(x), \bar{s}(x), \Delta s$, etc.);*
  - *Studies of QCD and structure of nucleons and nuclei;*
  - *Precision tests of the structure of the weak current: PCAC, CVC;*
  - *Measurement of nuclear physics and (anti)-neutrino-nucleus interactions;*
  - *Precision measurements of cross-sections and particle production; etc. .....*
  - *Searches for New Physics (BSM) .....*

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

- *Synergy with PNPI scientific program in High Energy Physics & Nuclear Physics*

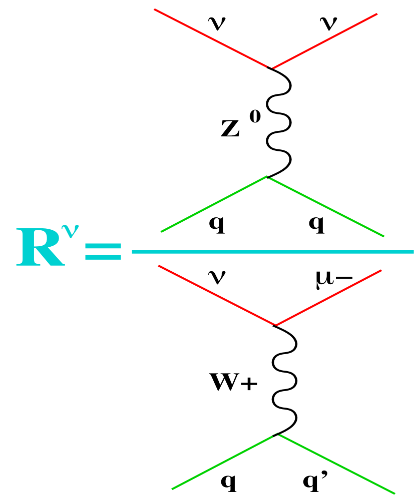
MEASUREMENT OF $\sin^2\theta_W$ FROM νN DIS

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

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

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

- *Events with $E_{\rm had} > 5$ 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 (~ 100k $\mu\mu$&μe) 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	$E_{\rm had} > 5$ GeV
Standard CP optimized:	
ν_μ CC (5 y)	3×10^6
Optimized ν_τ appearance:	
ν_μ CC (2 y)	19×10^6
TOTAL W^+	22×10^6
TOTAL Z^0	7×10^6

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

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

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

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

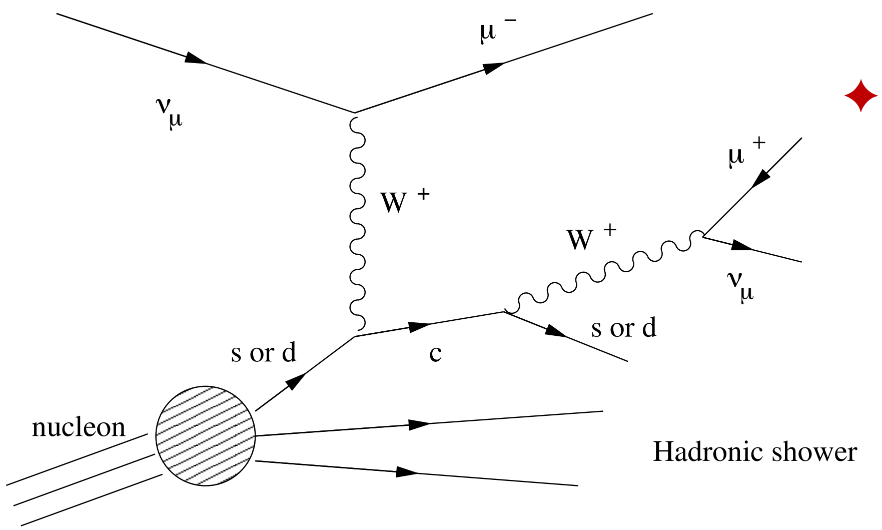
$$\text{SM from LEPEWWG} = 0.2227 \pm 0.00037$$

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

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

$\Longrightarrow$ *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 $\bar{s}(x)$*

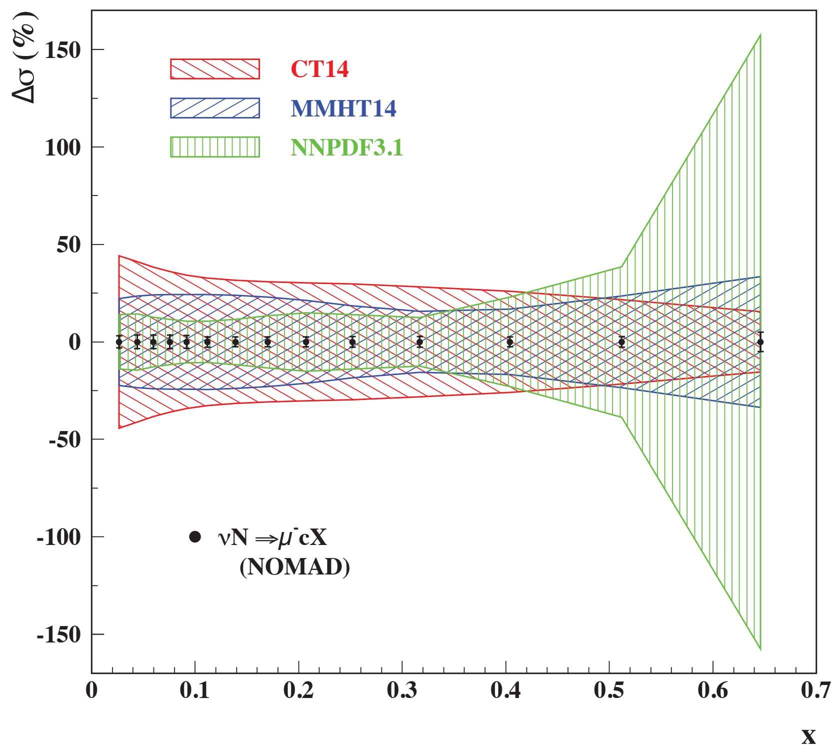
$$F_{2,c}(x,Q) = 2\xi \left[|V_{cs}|^2 s(\xi,\mu) + |V_{cd}|^2 \frac{u(\xi,\mu) + d(\xi,\mu)}{2} \right]$$

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

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

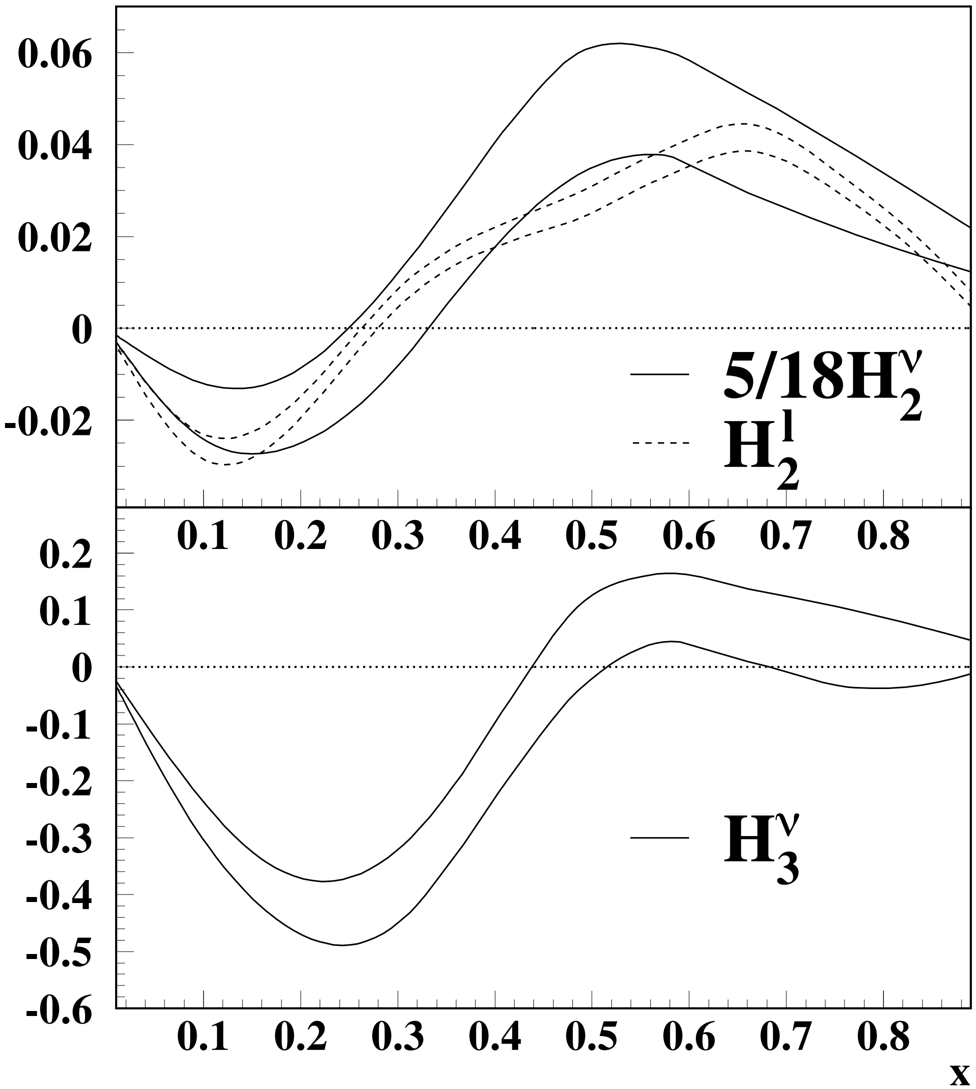


- *NOMAD measurement allows reduction of $s(x)$ uncertainty down to $\sim 3\%$:*
  $\kappa_s = \int_0^1 x(s+\bar{s})dx / \int_0^1 x(\bar{u}+\bar{d})dx = 0.591 \pm 0.019$ *(NPB 876 (2013) 339)*

- *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

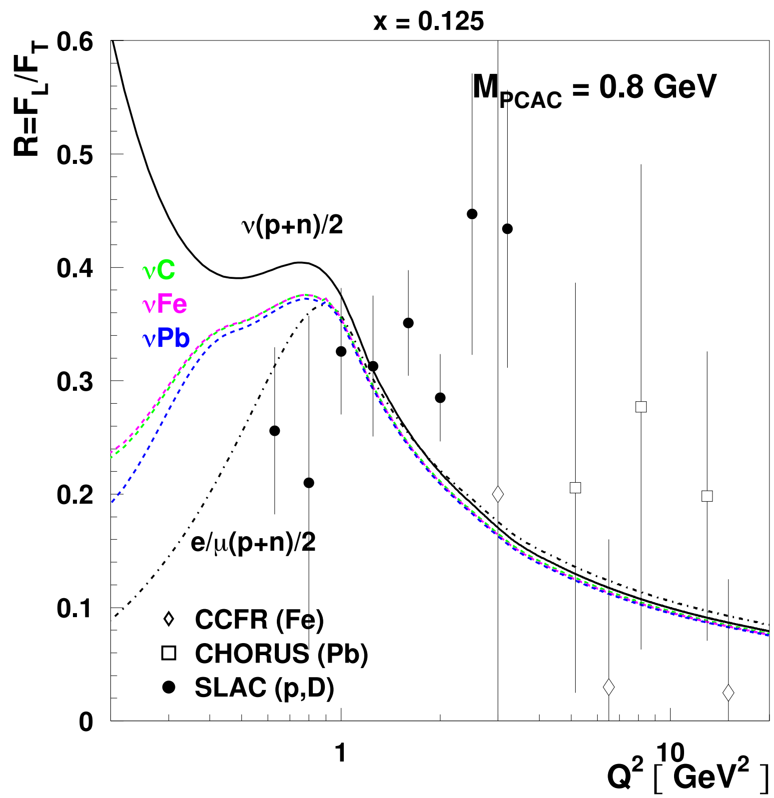
- *Neutrino scattering is characterized by an* AXIAL-VECTOR CURRENT *in addition to the the Vector current.*

- *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

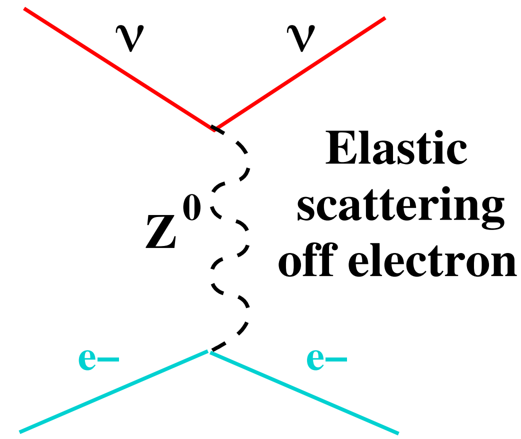
MEASUREMENT OF $\sin^2\theta_W$ FROM ν-e

- *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;*
  - *Small backgrounds in STT: ν_e QE (3%) & NC π^0 (2%).*



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

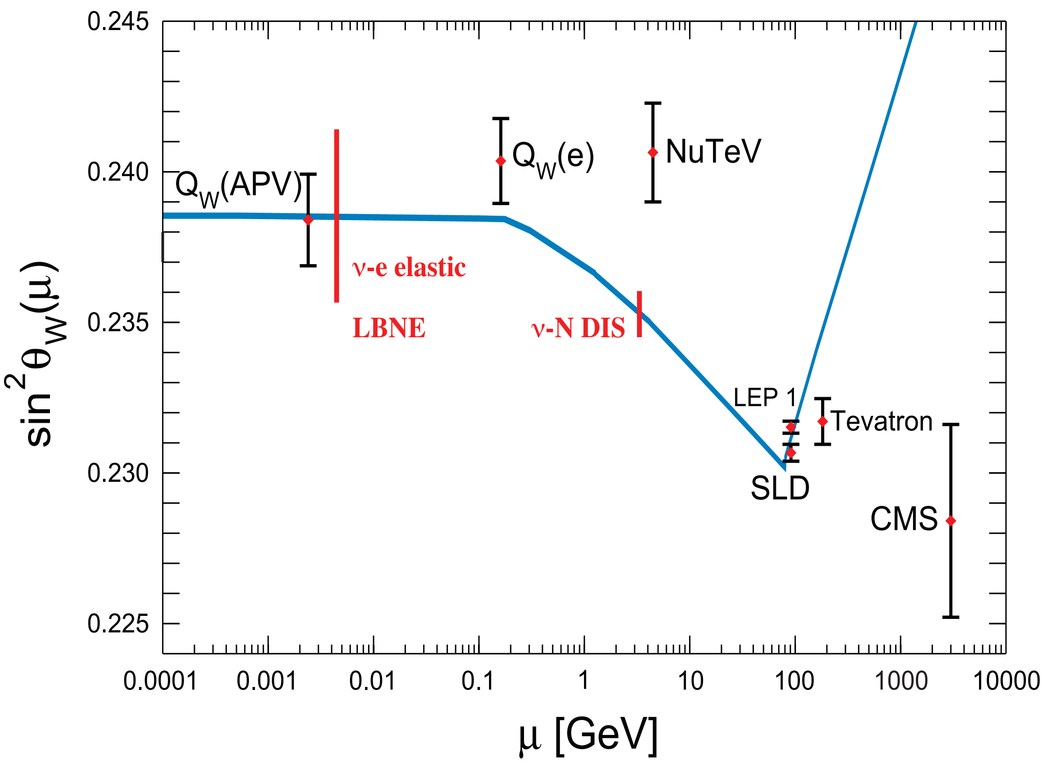
- *Dominated by statistics. Need high resolution detectors & accurate flux measurements:*
  - *Electron systematics cancel in the ratio;*
  - *Background rejection & calibration ($e^{\pm}$ ID, resolution);*
  - *ν and $\bar{\nu}$ flux measurements from $\nu(\bar{\nu})$-H.*

Process	Evts (5 t)
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)	10×10^3
$\bar{\nu} e$ NC (2 y)	6×10^3

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*
  $\Longrightarrow$ *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:*

- $\mathcal{R}^\nu = \frac{\sigma^\nu_{\rm NC}}{\sigma^\nu_{\rm CC}}$ *in ν-N DIS (~0.35%)*
- $\mathcal{R}_{\nu e} = \frac{\sigma^{\bar\nu}_{\rm NC}}{\sigma^\nu_{\rm NC}}$ *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*

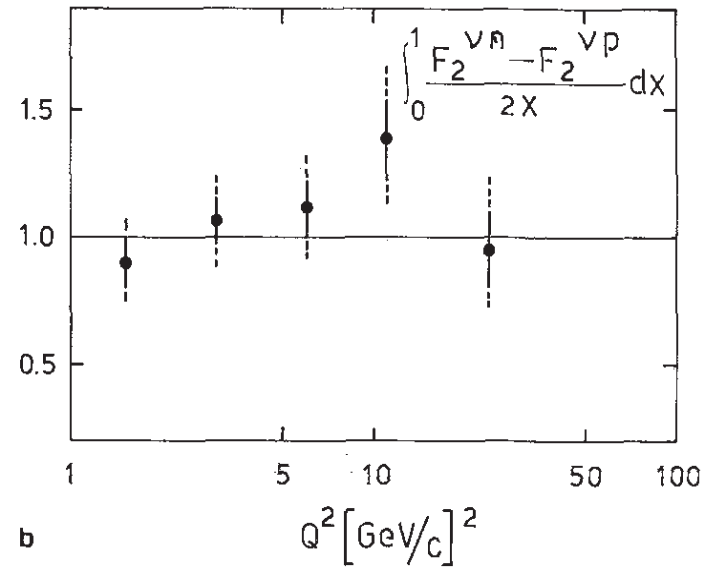
ADLER SUM RULE & ISOSPIN PHYSICS

✦ *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*



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✦ *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**

MEASUREMENT OF Δs

✦ 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 $G_A^s \to \Delta s$.

✦ *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):*

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

- *Compare axial current charge radius r_A^2 with muon capture in muonic hydrogen [Rept.Prog.Phys. 81 (2018) 096301];*
- *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.*

NUCLEAR MODIFICATIONS OF NUCLEON PROPERTIES

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

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

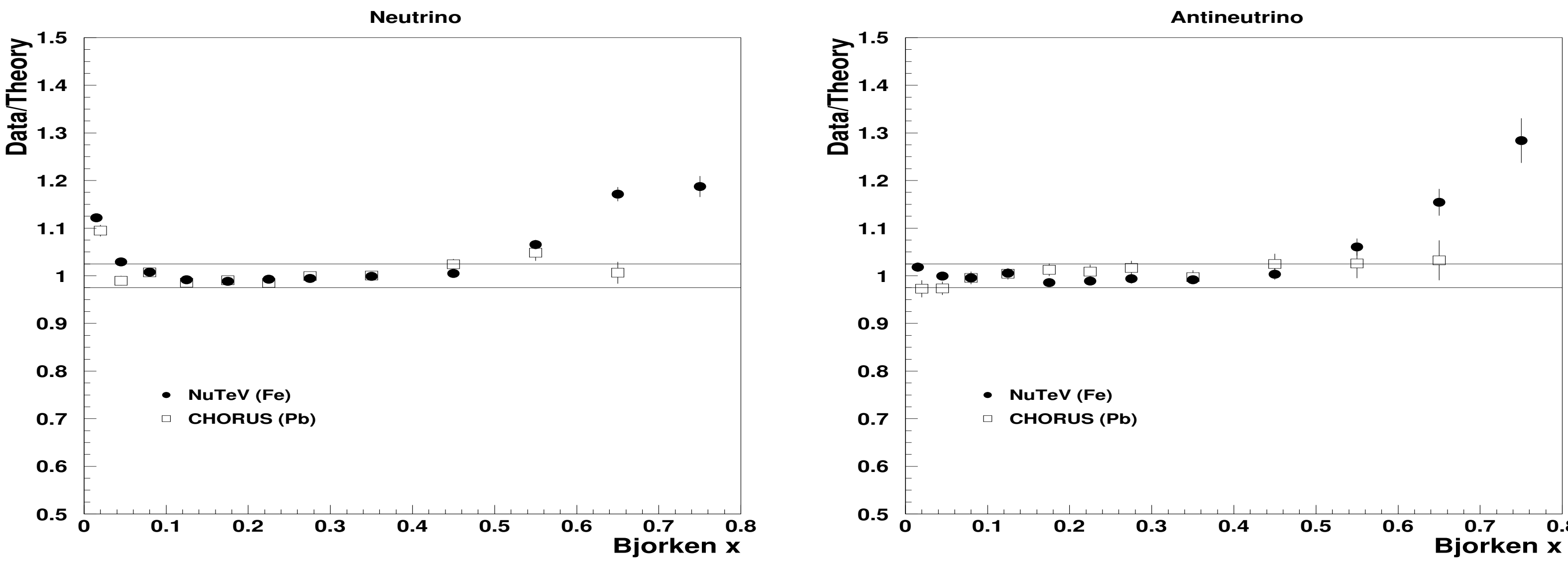
- *Comparison with e/μ DIS results and nuclear models;*
- *Study flavor dependence of nuclear modifications using ν & $\bar{\nu}$;*
- *Effect of the axial-vector current.*

✦ *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.*

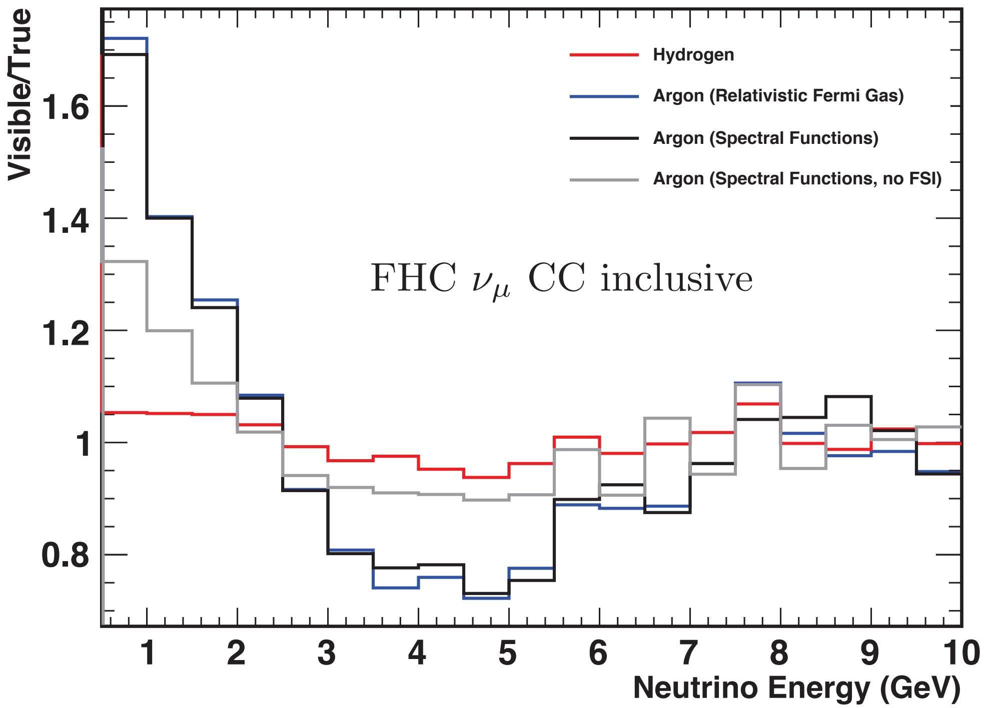
✦ *Coherent meson production off nuclei in CC & NC and diffractive physics.*



✦ *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 $\bar{\nu}$*



Substantial nuclear smearing rapidly varying in oscillation range

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

TESTS OF ISOSPIN (CHARGE) SYMMETRY

✦ *Extraction of* $\sin^2\theta_W$ *from* ν*N 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:

$$R^H_{2,3} \stackrel{\text{def}}{\equiv} \frac{F^{\bar{\nu}p}_{2,3}}{F^{\nu p}_{2,3}}(x,Q^2) = \frac{F^{\nu n}_{2,3}}{F^{\nu p}_{2,3}}; \qquad R^C_{2,3} \stackrel{\text{def}}{\equiv} \frac{F^{\bar{\nu}C}_{2,3}}{F^{\nu C}_{2,3}}(x,Q^2) - 1 = \frac{\Delta F^{\bar{\nu}-\nu}_{2,3}}{F^{\nu}_{2,3}}$$

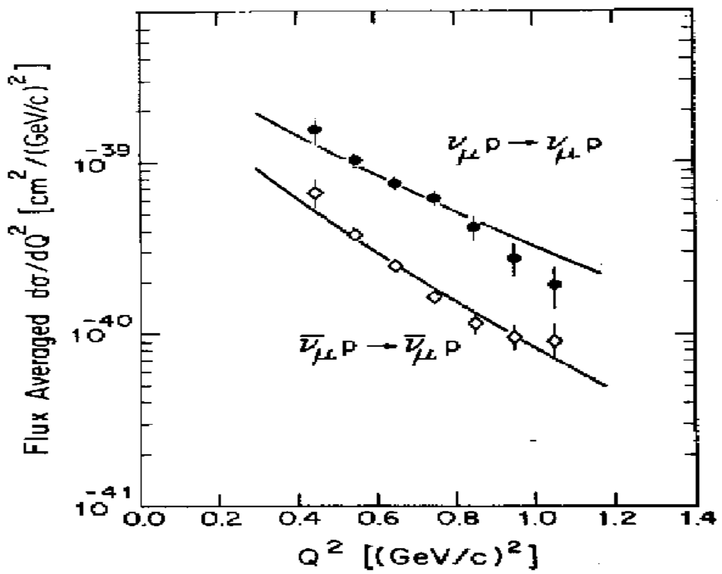
- *Structure function ratio reduces systematic uncertainties;*
- *Need to take into account charm quark effects* $\propto \sin^2\theta_C$. *Sensitivity to* m_c;
- *A non-vanishing strange sea asymmetry* $s(x) - \bar{s}(x)$ *would affect the result. Need combined analysis with charm production in* ν *and* $\bar{\nu}$ *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* $R^A_{2,3} = \Delta F^{(\bar{\nu}-\nu)A}_{2,3} / F^{\nu A}_{2,3}(x,Q^2)$;
- *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.*

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?*

SUMMARY

- *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.*

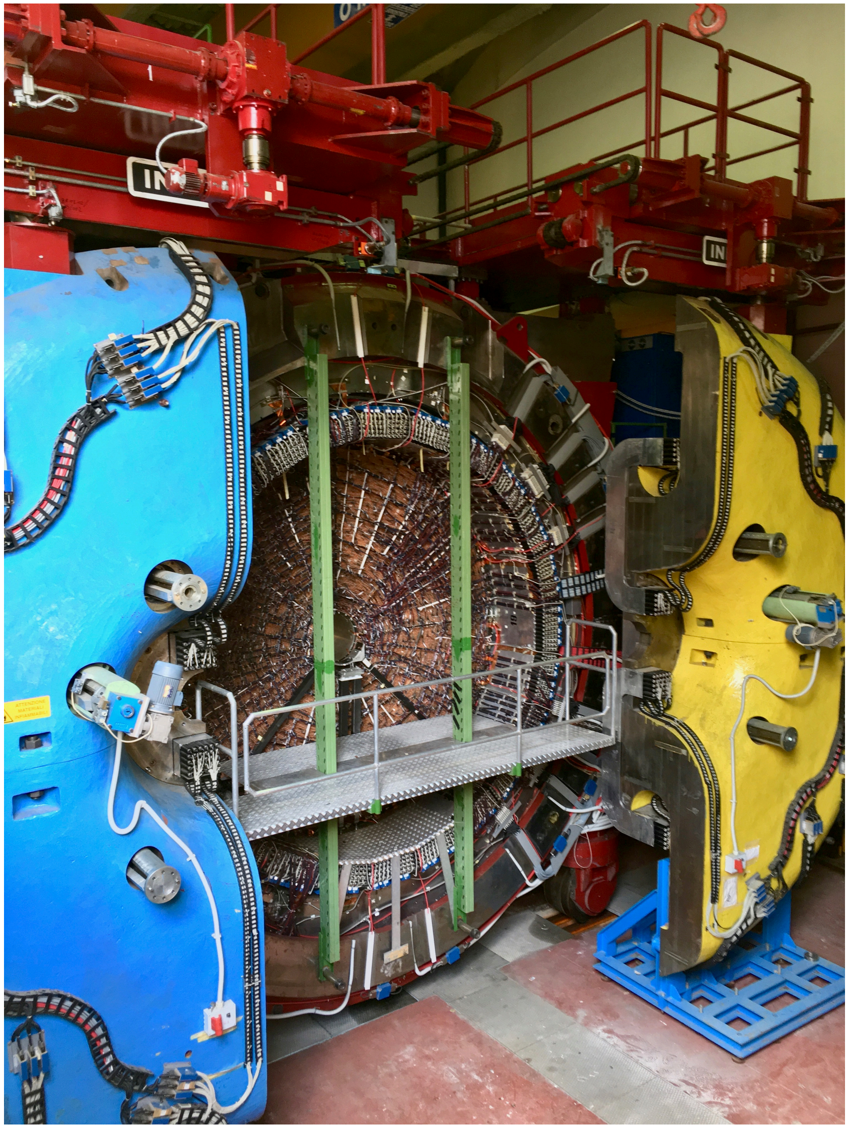
- *A novel technique can provide high statistics $\mathcal{O}(10^6)$ samples of $\nu(\bar{\nu})$-hydrogen interactions, allowing precisions in the measurement of ν & $\bar{\nu}$ fluxes $< 1\%$.*

- *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*

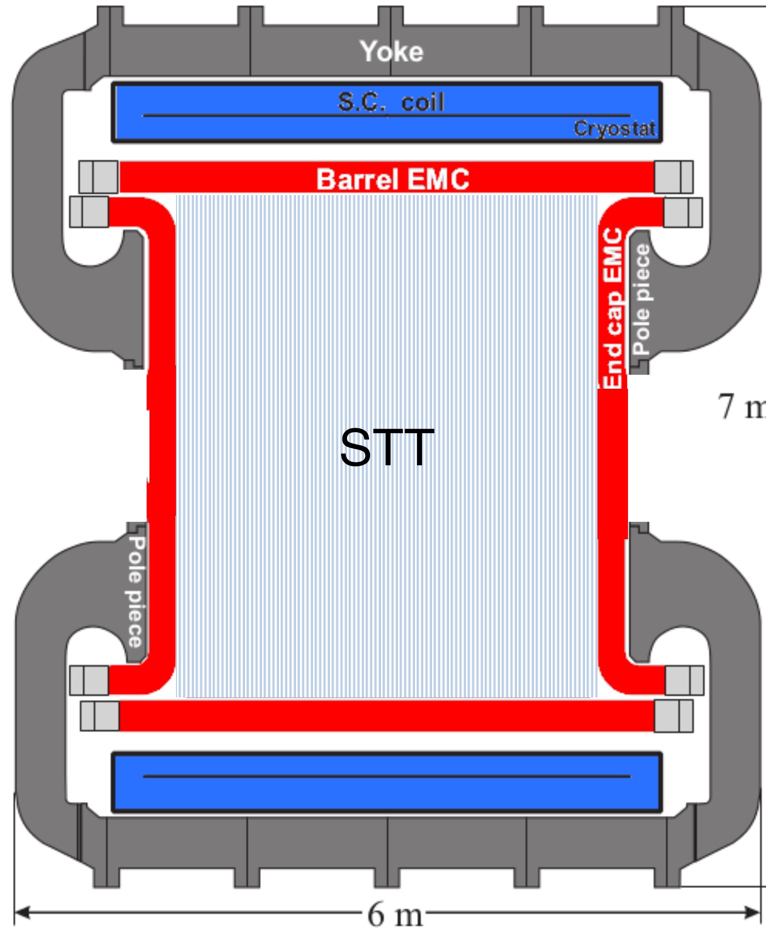
  European Particle Physics Strategy Update 2018-2020:

  `https://indico.cern.ch/event/765096/contributions/3295805/`

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



Reuse existing KLOE magnet + ECAL and fill it with STT & nuclear targets



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

Backup slides

Source of uncertainty	$\delta R^\nu / R^\nu$ NuTeV	$\delta R^\nu / R^\nu$ 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: