Precision (Anti)Neutrino Scattering off Nucleons and Nuclei

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Neutrino Platform Week 2019: Hot Topics in Neutrino Physics
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OUTLINE

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*

- *Electroweak measurements*
- *Adler sum rule*
- *Isospin physics*
- *Nuclear modifications of nucleon properties*

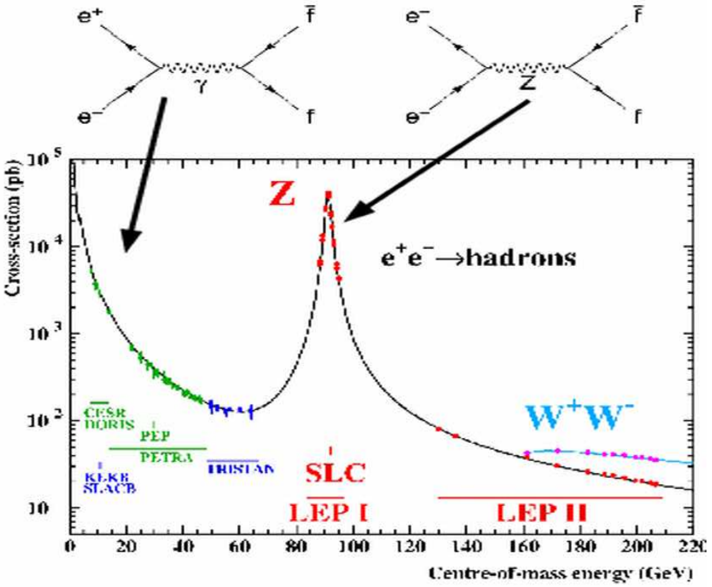
IV *Summary*

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

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



M_Z = 91187.5 (2.1) MeV

N_ν = 2.9841 (83) [-1.9σ]

- ✦ *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 adding insights complementary to planned fixed-target & collider programs?*

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, full polarization;*
- *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) limitations*

✦ 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

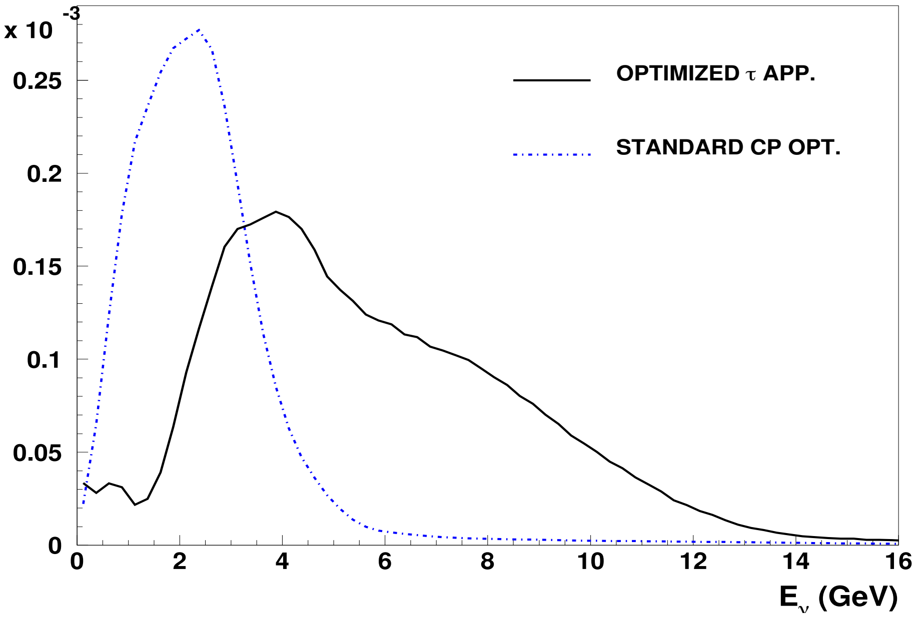
- *Existing detectors compromise between high (low) statistics and coarse (high) resolution: affected by systematics on E_μ, $E_{\rm H}$ scales, nuclear targets & flux*

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	1.5×10^6	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%	

$\Longrightarrow$ *Significant progress requires about 10^8 CC AND high resolution $\Delta E_\mu \leq 0.2\%$*

- *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*

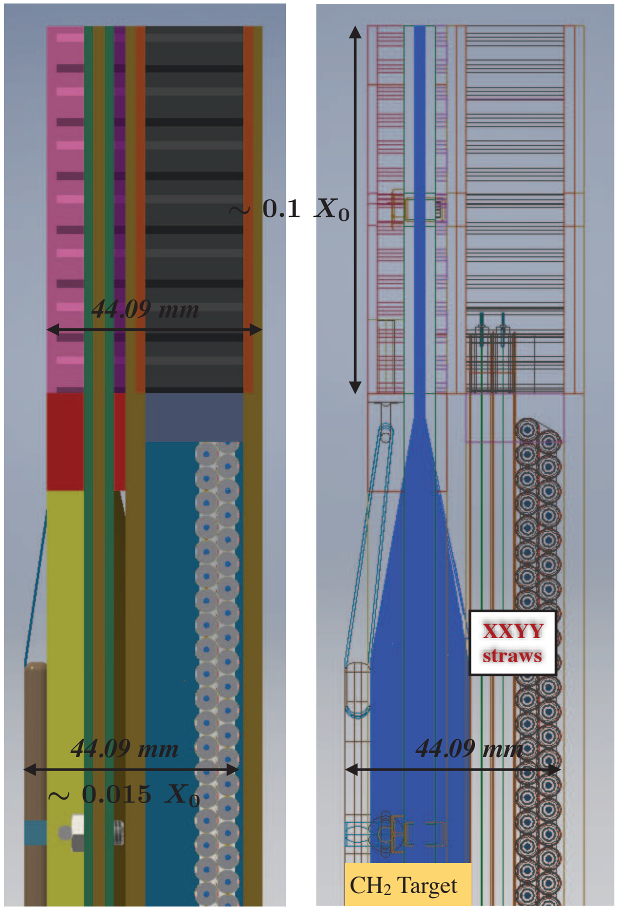
$\Longrightarrow$ *Can afford a high resolution ND of a few tons and still collect desired statistics* $\sim 10^8$

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* $\boxed{0.005 \leq \rho \leq 0.18 \text{ g/cm}^3}$.

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



✦ *Targets (100% purity) account for $\sim 97\%$ of STT mass (straws 3%) and can be tuned to achieve desired statistics & resolutions.*

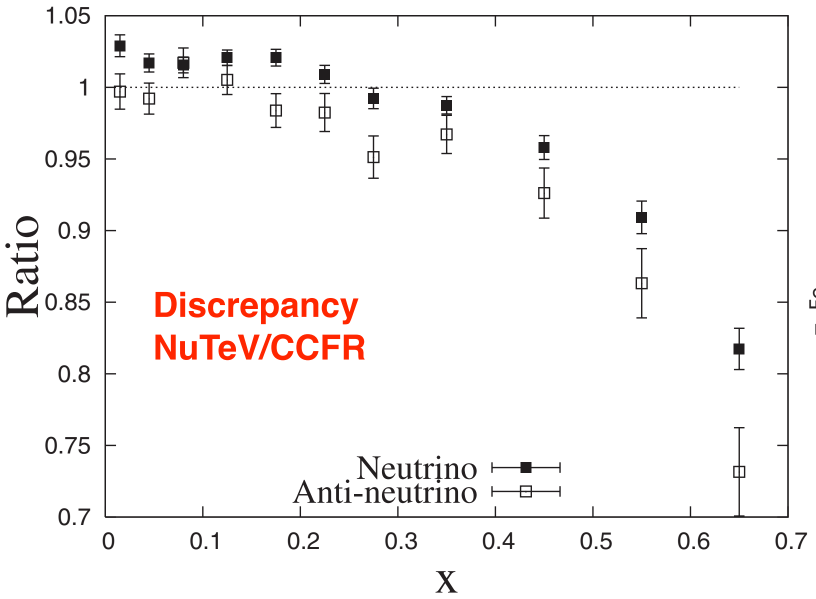
✦ *Separation from excellent vertex, angular & timing resolutions.*

✦ *Thin targets can be replaced during data taking: C, Ca, Ar, Fe, Pb, etc.*

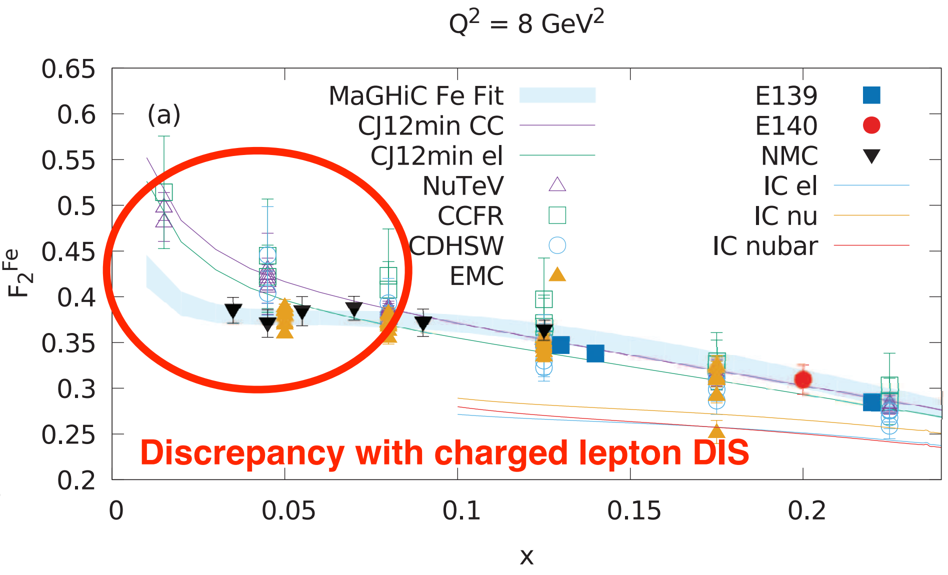
✦ *Need to understand nuclear modifications & corresponding systematic uncertainties*:

- *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*



Discrepancy NuTeV/CCFR



Discrepancy with charged lepton DIS

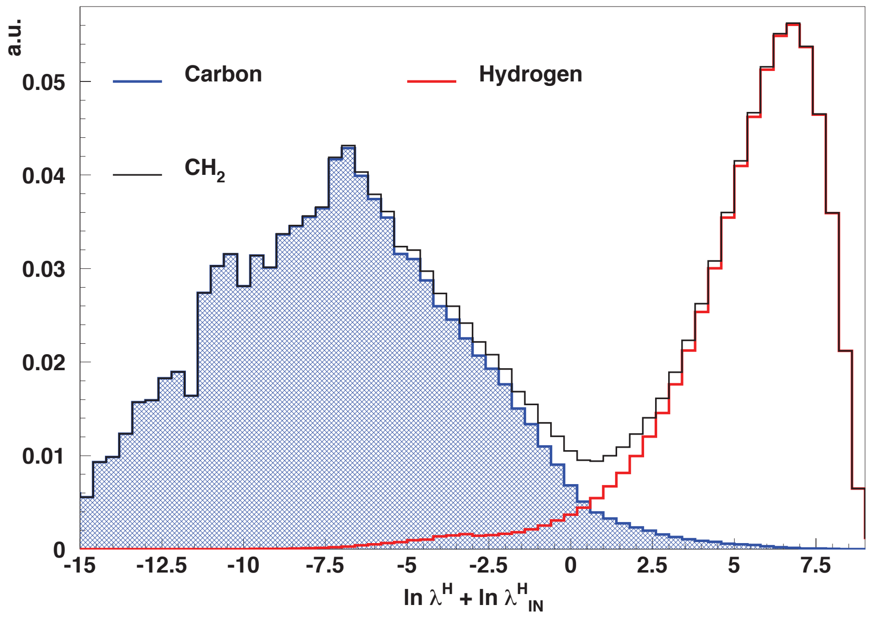
NuTeV Coll., PRD 74 (2006) 012008

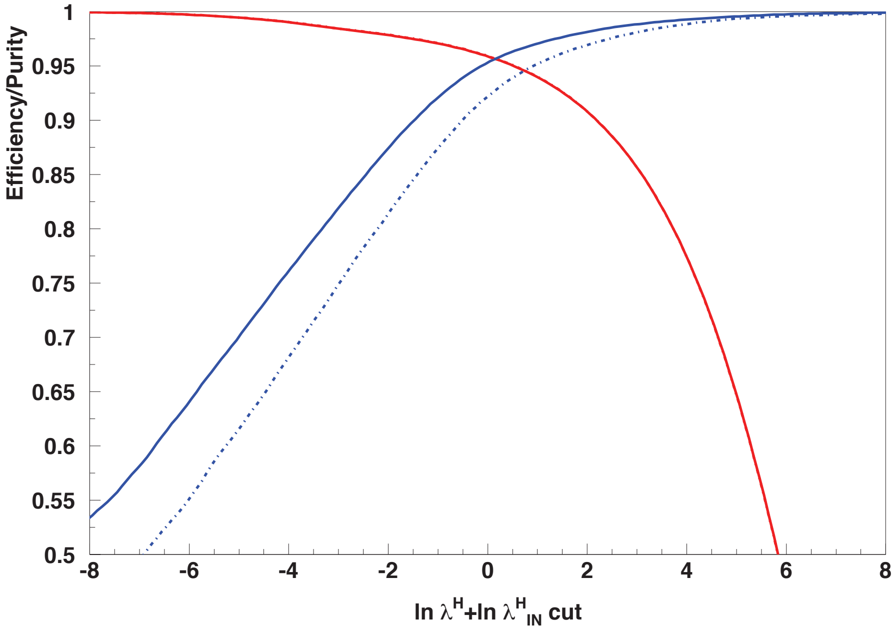
N. Kalantarians, C. Keppel, M.E. Cristy, PRC 96 (2017) 032201

✦ *Novel technique to get $\nu(\bar{\nu})$-Hydrogen by subtracting CH_2 and C targets (solid H):*

- *Exploit high resolutions & control of chemical composition and mass of targets in STT;*
- *Model-independent data subtraction of dedicated C (graphite) target from main CH_2 target;*
- *Kinematic selection provides large H samples of inclusive & exclusive CC topologies with 80-95% purity and >90% efficiency before subtraction.*

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





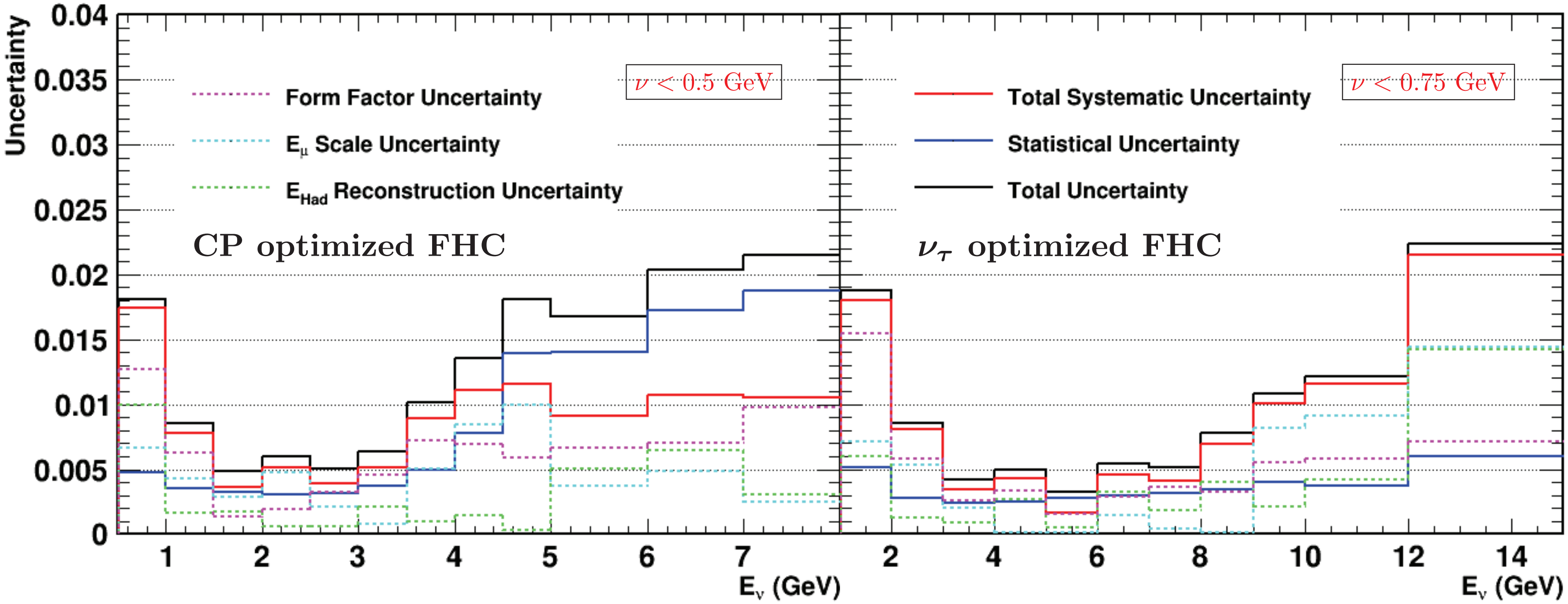
H. Duyang, B. Guo, S.R. Mishra, RP, arXiv:1809.08752 [hep-ph]

CONTROL OF FLUXES

✦ *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 ($\delta p/p \sim 3.5\%$);*
- *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).*

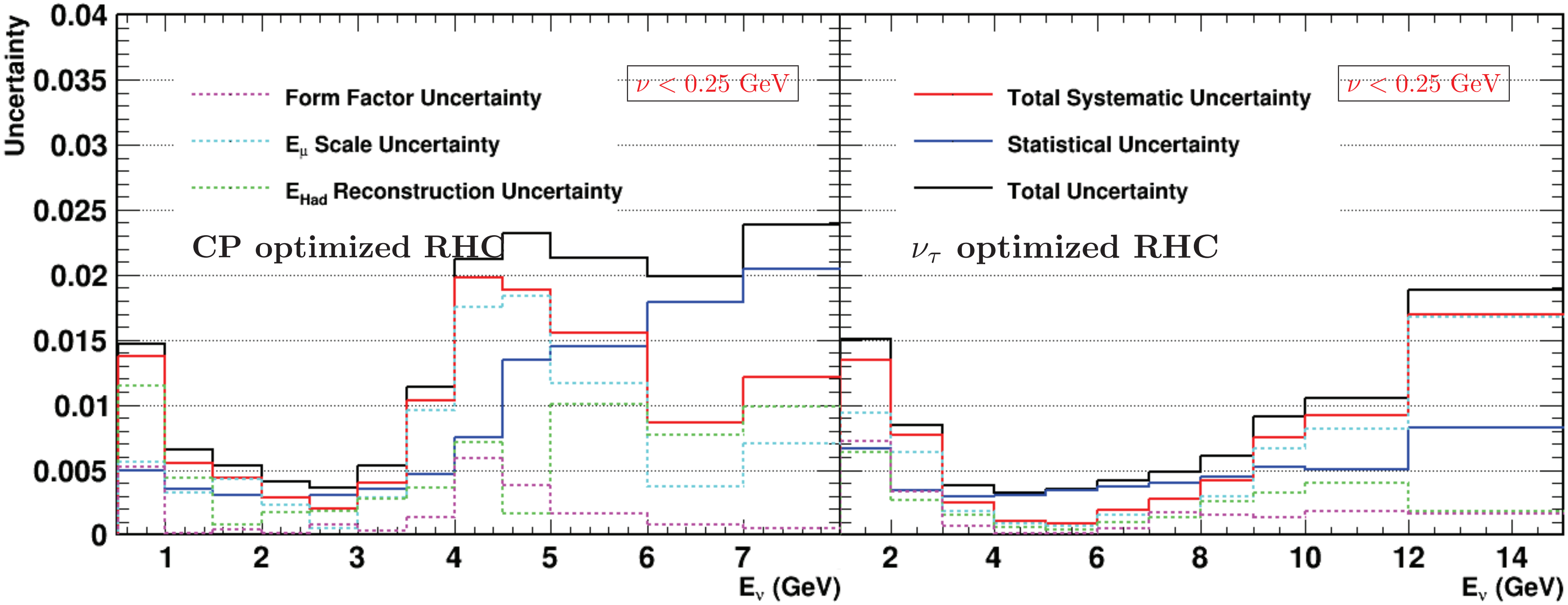
$\Longrightarrow$ *Dramatic reduction of systematics vs. techniques using nuclear targets*



H. Duyang, B. Guo, S.R. Mishra, RP, PLB 795 (2019) 424, 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 reconstructed direction of interacting neutrons (∼80%);*
- *Cut $\boxed{\nu < 0.1(0.25)\ \text{GeV}}$ 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, PLB 795 (2019) 424, arXiv:1902.09480 [hep-ph]

GENERAL PURPOSE PHYSICS FACILITY

✦ *Possible to address the main limitations 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 LBNF ND site into a general purpose $\nu \& \bar{\nu}$ physics facility with broad program complementary to ongoing fixed-target, collider and nuclear physics efforts:*

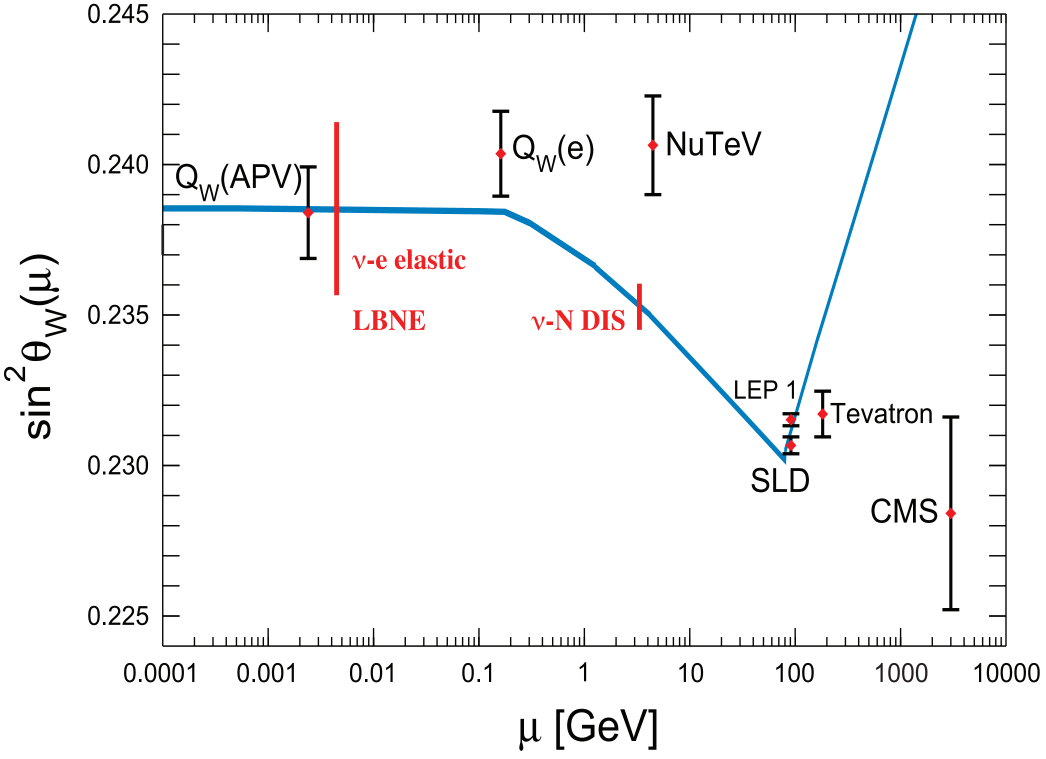
- *Measurement of* $\sin^2\theta_W$ *and electroweak physics;*
- *Precision tests of isospin physics & sum rules (Adler, GLS);*
- *Measurements of strangeness content of the nucleon* $(s(x), \bar{s}(x), \Delta s$*, etc.);*
- *Studies of QCD and structure of nucleons and nuclei;*
- *Precision tests of the structure of the weak current: PCAC, CVC;*
- *Measurement of nuclear physics and (anti)-neutrino-nucleus interactions; etc. .....*
- *Precision measurements as probes of New Physics (BSM);*
- *Searches for New Physics (BSM) .....*

$\Longrightarrow$ *Discovery potential & hundreds of diverse physics topics*

✦ *Same control of targets & fluxes reduces systematics for long-baseline oscillations.*

ELECTROWEAK MEASUREMENTS

- ✦ *Sensitivity expected from ν scattering at LBNF comparable to the Collider precision:*
  - *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 $\Gamma_{\nu\nu}$*
  - *Single experiment to directly check the running of $\sin^2\theta_W$;*
  - *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 ($\sim$0.35%)*
  - *$\mathcal{R}_{\nu e} = \frac{\sigma^{\bar\nu}_{\rm NC}}{\sigma^\nu_{\rm NC}}$ in ν-e^- NC elastic ($\sim$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*

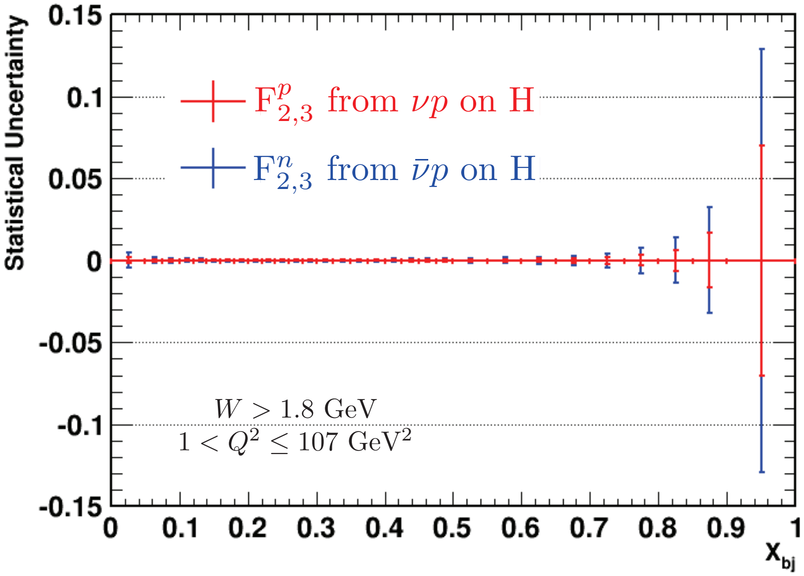
ADLER SUM RULE & ISOSPIN PHYSICS

✦ *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*
- *Apply 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 $F_{2,3}^{\nu n}/F_{2,3}^{\nu p}$ 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

NUCLEAR MODIFICATIONS OF NUCLEON PROPERTIES

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

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

- *Comparison with e/μ DIS results and nuclear models;*
- *Study flavor dependence of nuclear modifications using ν & $\bar{\nu}$ ($W^\pm/Z$ helicity, C-parity, Isospin);*
- *Effect of the axial-vector current.*

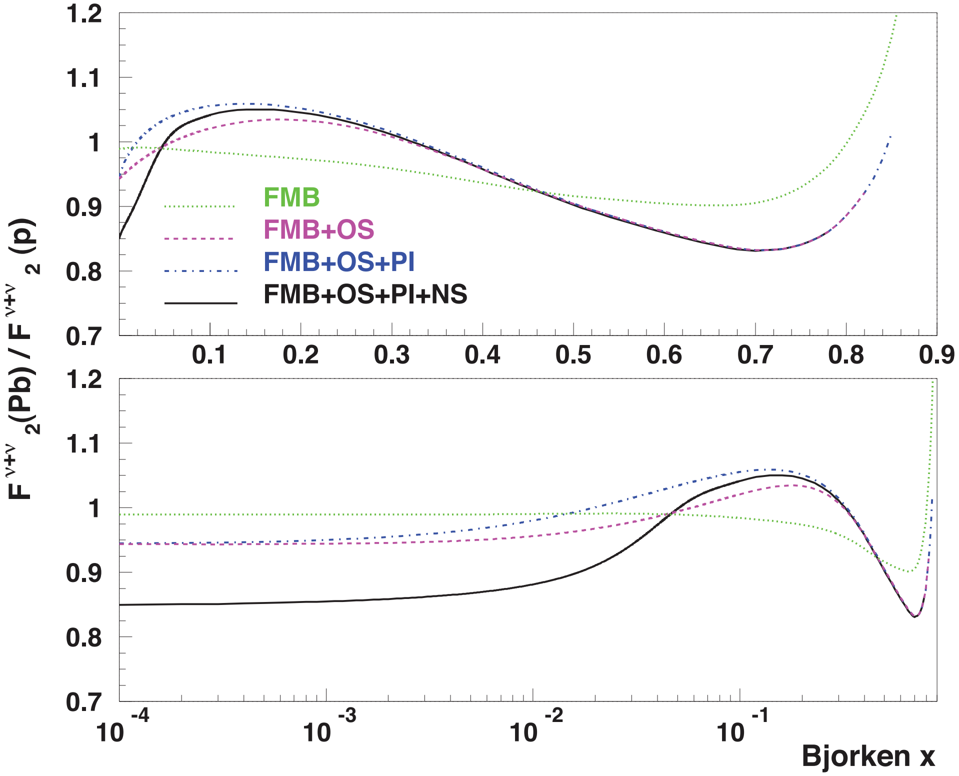
✦ *Study nuclear modifications to parton distributions in a wide range of Q^2 and x.*

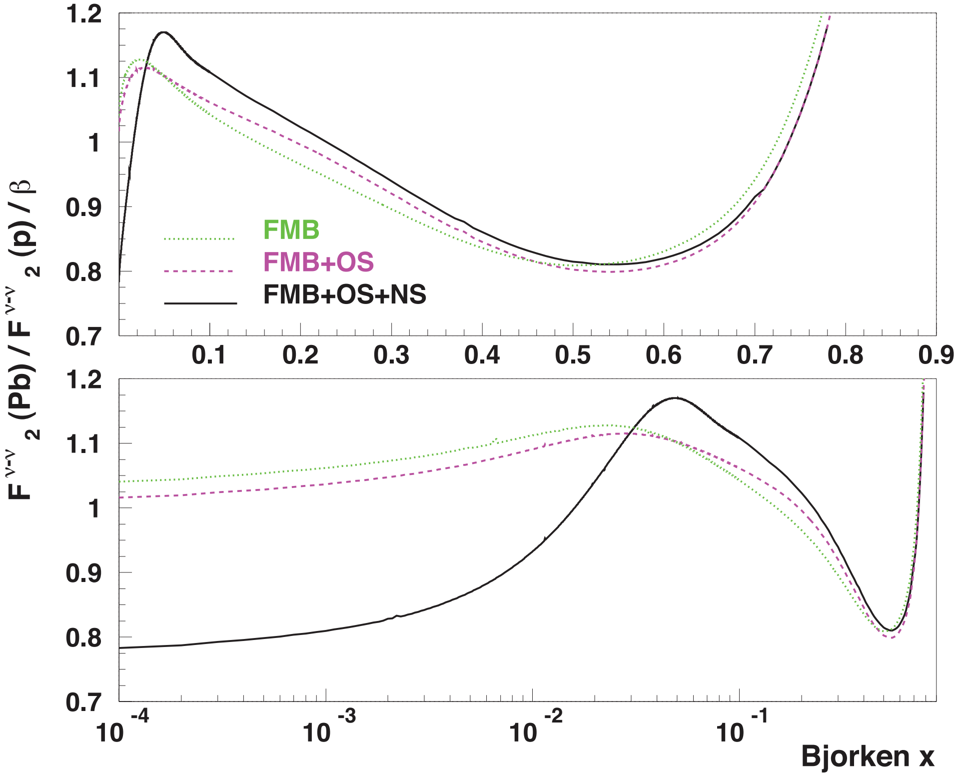
✦ *Study non-perturbative contributions from High Twists, PCAC, etc. and quark-hadron duality in different structure functions $F_2, xF_3, R = F_L/F_T$.*

✦ *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.*

$\Longrightarrow$ *Synergy with Heavy Ion and EIC physics programs for cold nuclear matter effects.*

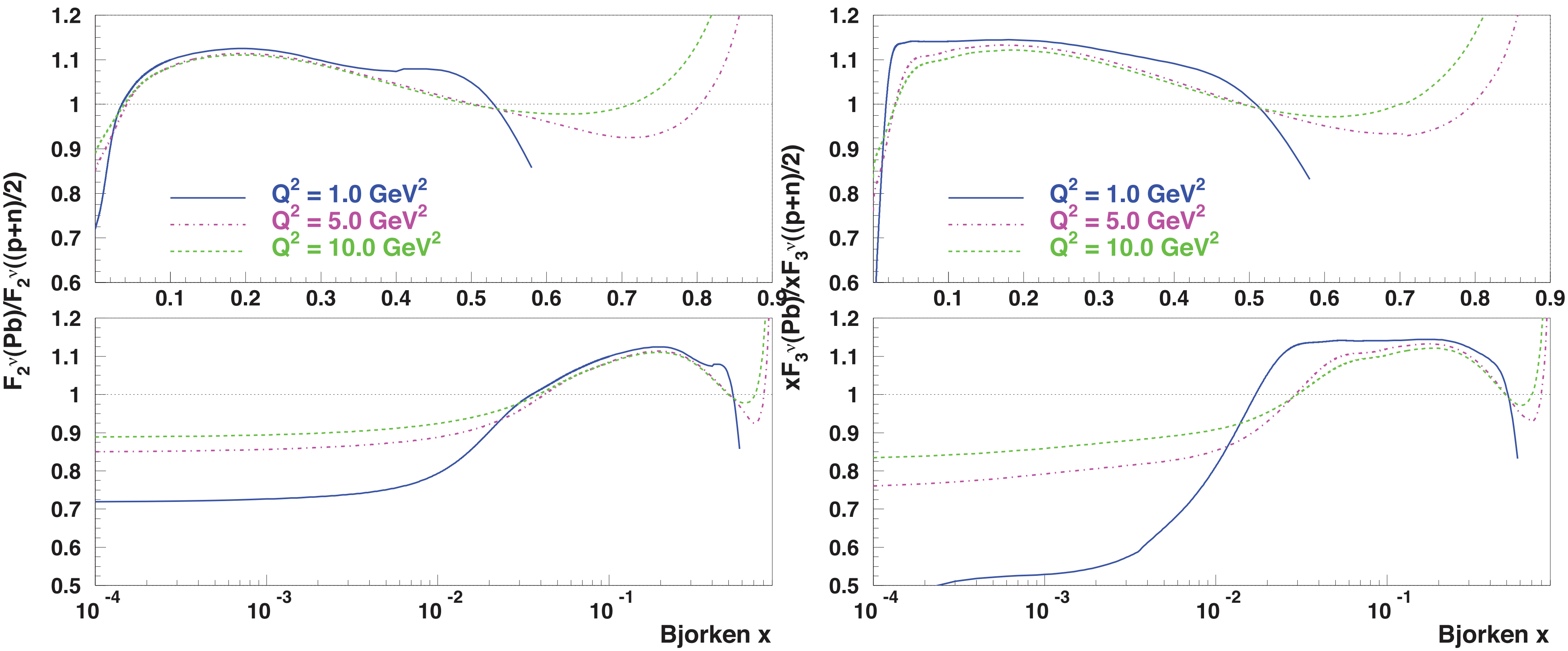




$\frac{1}{A}F_2^{(\nu+\bar{\nu})A}/F_2^{(\nu+\bar{\nu})p}$ for ^{207}Pb
at Q^2=5 GeV^2

$\frac{1}{A}F_2^{(\nu-\bar{\nu})A}/(\beta F_2^{(\nu-\bar{\nu})p})$ for Pb, Q^2=5 GeV^2
$\beta = (Z-N)/A$

S. Kulagin and R.P., NPA 765 (2006) 126; PRD 76 (2007) 094023, PRC 90 (2014) 045204



Ratio of Charged Current structure functions on ^{207}*Pb and isoscalar nucleon* $(p+n)/2$

S. Kulagin and R.P., NPA 765 (2006) 126; PRD 76 (2007) 094023, PRC 90 (2014) 045204

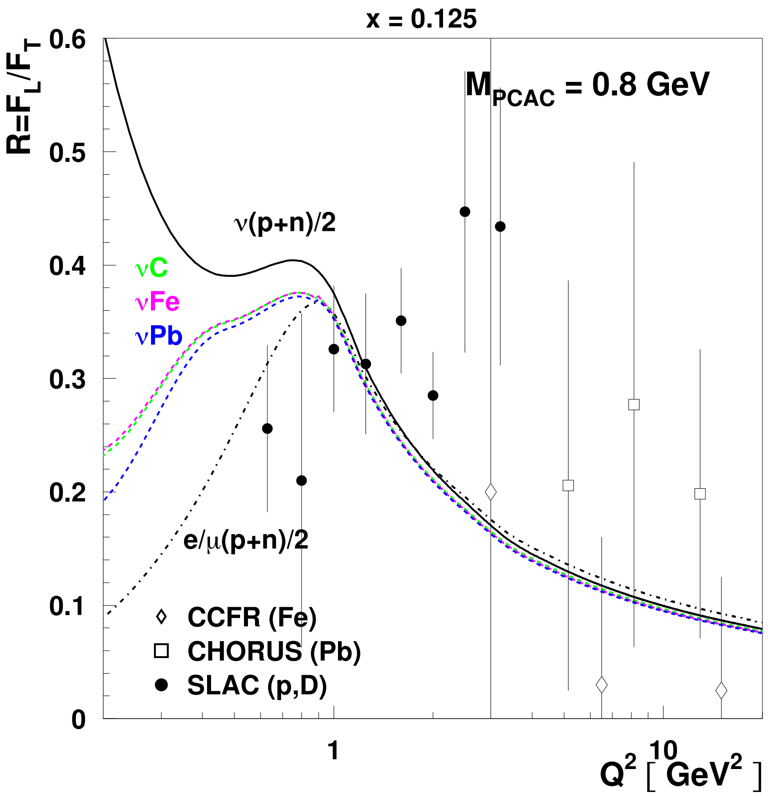
- *Neutrino scattering is characterized by an* AXIAL-VECTOR CURRENT *in addition to the the Vector current.*

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

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

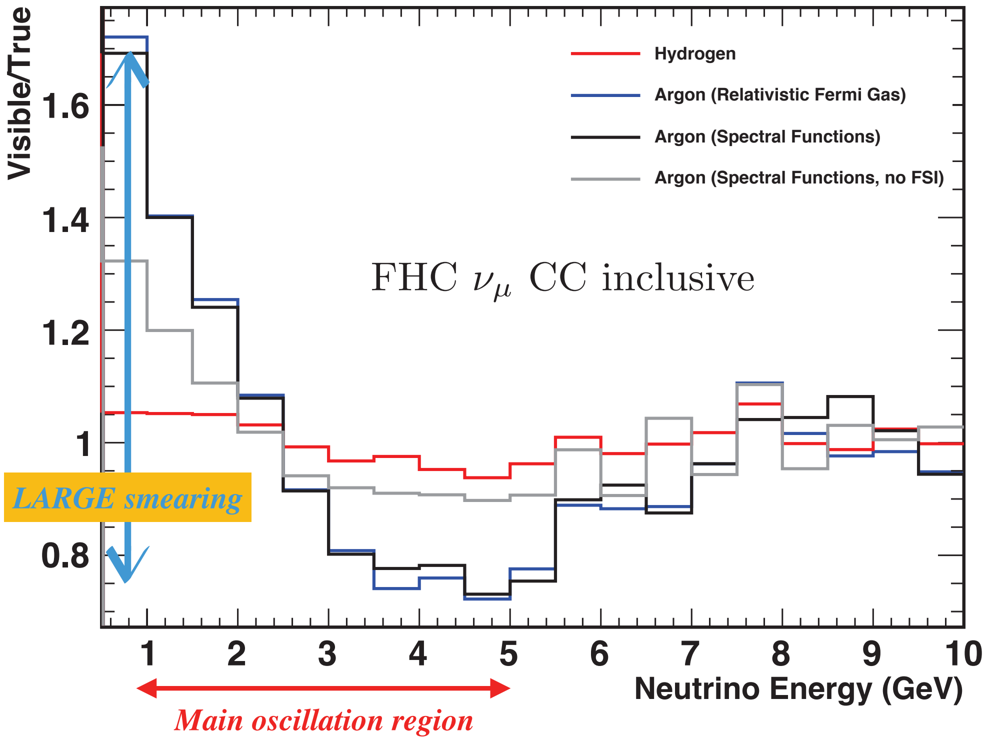
- *The finite PCAC contribution to F_L strongly affects the asymptotic behaviour of $\boxed{R = \sigma_L/\sigma_T}$ for $Q^2 \to 0$:*

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



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

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



LARGE smearing

Main oscillation region

Comparing Ar and H measurements imposes stringent constraints on the nuclear smearing in Ar

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 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**:

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

- *Structure function ratio reduces systematic uncertainties;*
- *Need to take into account charm quark effects $\propto \sin^2\theta_C$. Sensitivity to $\boxed{m_c}$;*
- *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 $R^A_{2,3} = \Delta F^{(\bar{\nu}-\nu)A}_{2,3} / F^{\nu A}_{2,3}(x,Q^2)$;*
- *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.*

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/`

  $\Longrightarrow$ *Discovery potential & hundreds of diverse physics topics*

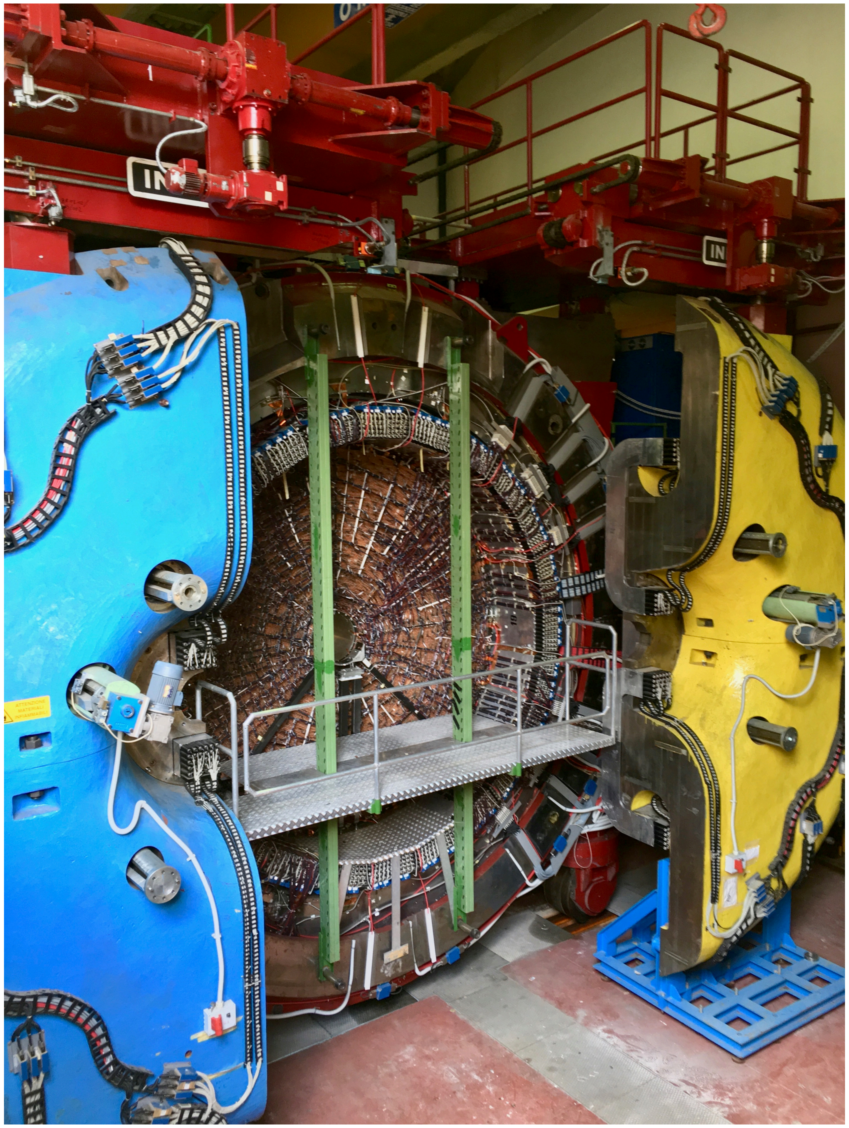
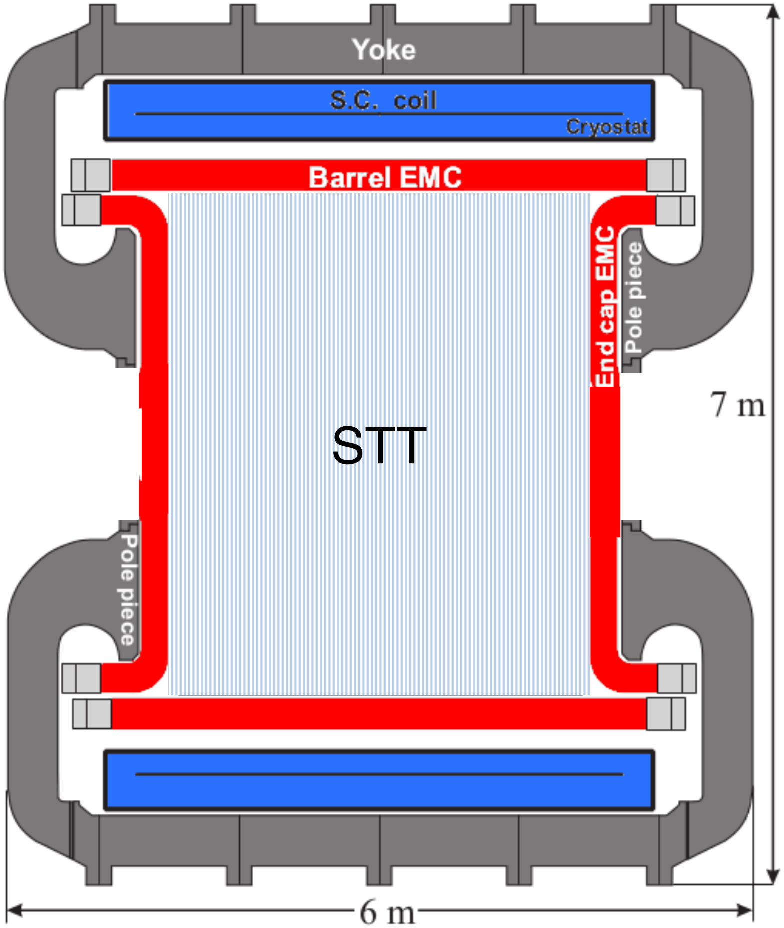


Photo from workshop in Frascati, March 2019

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



A Proposal to enhance the DUNE Near-Detector Complex

G. Adamov[1,10], L. Alvarez Ruso[2], I. Bagaturia[1], P. Bernardini[3,4], S. Bertolucci[5,6], M. Bhattacharjee[7], B. Bhuyan[7], S. Biagi[8], A. Caminata[9], A. Cervelli[5], D. Chokheli[1,10], A. Chukanov[10], S. Davini[9], S. Di Domizio[9,11], C. Distefano[8], L. Di Noto[9,11], M. Diwan[412], H. Duyang[13], A. Falcone[14,15], O. Fedin[16], A. Ferrari[17], F. Ferraro[9,11], A. Gabrielli[5], M. Guerzoni[5], B. Guo[13], M.A. Iliescu[18,19], A.L. Kataev[20], A. Khvedelidze[1,10], B. Kirby[12], U. Kose[5,19], S.A. Kulagin[20], C. Kullenberg[10], C. Kuruppu[13], I. Lomidze[1], G. Laurenti[5], V. Maleev[16], G .Mandrioli[5], N. Mauri[5,6], P. Mehta[21], S.R. Mishra[13], N. Moggi[5,6], A. Montanari[5], S. Movchan[10], S. Nagu[22], F. Olness[23], M. Pallavicini[9,11], R. Papaleo[8], L. Pasqualini[5,6], L. Patrizii[5], R. Petti [13], V. Pia[5,6], F. Poppi[5,6], V.K.S. Potukuchi[24], M. Pozzato[5,6], G. Riccobene[8], P.R. Sala[25], O. Samoylov[10], P. Sapienza[8], F. H. Sawy[26,28], Ja. Singh[22], Jy. Singh[22], V. Singh[27], G. Sirri[5], L. Stanco[26], A. Surdo[4], M. Tenti[5], F. Terranova[14,15], G. Testera[9], M. Torti[14,15], N. Tosi[5], R. Travaglini[26], Z. Tsamalaidze[1,10], N. Tsverava[1,10], and S. Zucchelli[5,6]

Currently 74 physicists from 23 institutions and 7 countries

SUMMARY

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- *Possible to achieve a control of configuration, material & mass of neutrino targets similar to electron experiments & use a suite of various target materials.*

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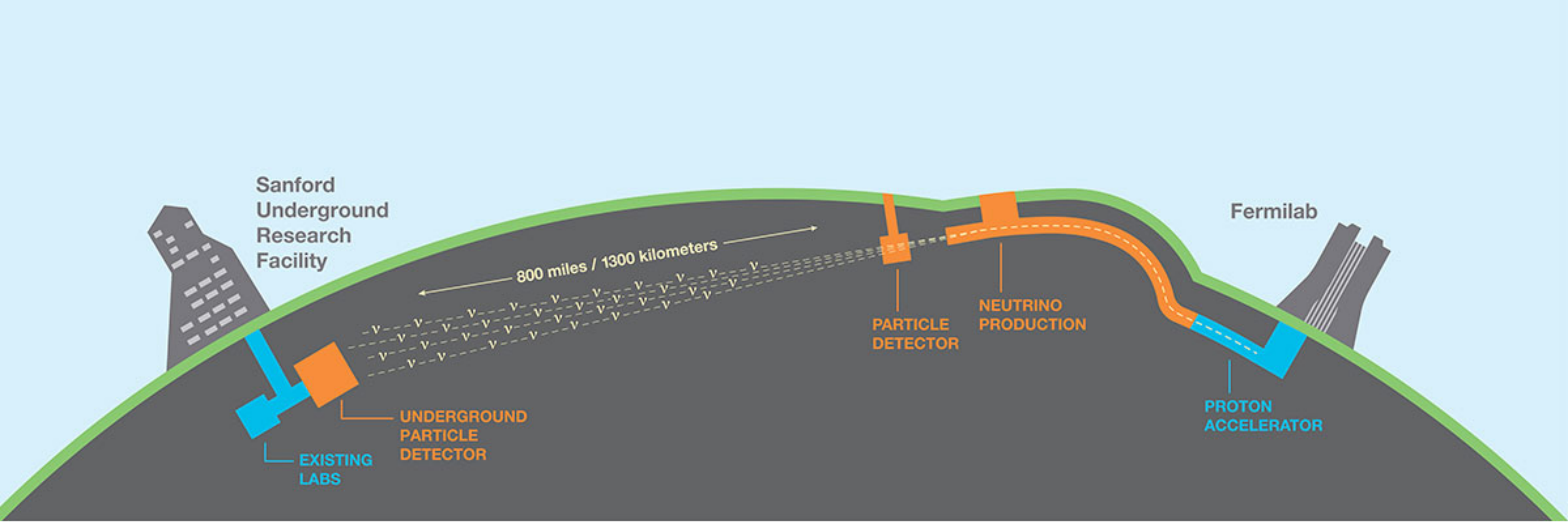
  $\Longrightarrow$ *Discovery potential & hundreds of diverse physics topics*

Looking for suggestions, feedback and/or potential interest

Backup slides



LBNF: Long-Baseline Neutrino Facility

DUNE: Deep Underground Neutrino Experiment

	ν_μ-H CC				$\bar{\nu}_\mu$-H CC					
Process	$\mu^- p \pi^+$	$\mu^- p \pi^+ X$	$\mu^- n \pi^+ \pi^+ X$	Inclusive	$\mu^+ p \pi^-$	$\mu^+ n \pi^0$	$\mu^+ n$	$\mu^+ p \pi^- X$	$\mu^+ n \pi \pi X$	Inclusive
Eff. ε	96%	89%	75%	93%	94%	84%	75%	85%	82%	80%
Purity	95%	93%	70%	93%	95%	84%	80%	94%	84%	84%

TABLE I. Efficiency ε and purity for the kinematic selection of H interactions from the CH_2 plastic target using the likelihood ratio $\ln \lambda^{\mathrm{H}} + \ln \lambda^{\mathrm{H}}_{\mathrm{IN}}$ or $\ln \lambda^{\mathrm{H}}_4 + \ln \lambda^{\mathrm{H}}_{\mathrm{IN}}$. For the $\mu^+ n$ QE topologies $\ln \lambda^{\mathrm{H}}_{\mathrm{QE}}$ is used instead. The cuts applied for each channel are chosen to maximize the sensitivity defined as $S/\sqrt{S+B}$, where S is the H signal and B the C background. The CC inclusive samples are obtained from the combination of the corresponding exclusive channels.

	ν_μ-H CC, $\varepsilon \equiv 75\%$				$\bar{\nu}_\mu$-H CC, $\varepsilon \equiv 75\%$					
Process	$\mu^- p \pi^+$	$\mu^- p \pi^+ X$	$\mu^- n \pi^+ \pi^+ X$	Inclusive	$\mu^+ p \pi^-$	$\mu^+ n \pi^0$	$\mu^+ n$	$\mu^+ p \pi^- X$	$\mu^+ n \pi \pi X$	Inclusive
Purity	99%	99%	70%	98%	99%	90%	80%	98%	90%	86%

TABLE II. Purity achieved with the kinematic selection of H interactions from the CH_2 plastic target using a cut on the likelihood ratio $\ln \lambda^{\mathrm{H}} + \ln \lambda^{\mathrm{H}}_{\mathrm{IN}}$ or $\ln \lambda^{\mathrm{H}}_4 + \ln \lambda^{\mathrm{H}}_{\mathrm{IN}}$ resulting in the fixed H signal efficiency ε specified. For the $\mu^+ n$ QE topologies $\ln \lambda^{\mathrm{H}}_{\mathrm{QE}}$ is used instead. For illustration purpose, the value of the efficiency is chosen as the lowest among the ones listed in Tab. I for individual topologies. The CC inclusive samples are obtained from the combination of the corresponding exclusive channels.

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:

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

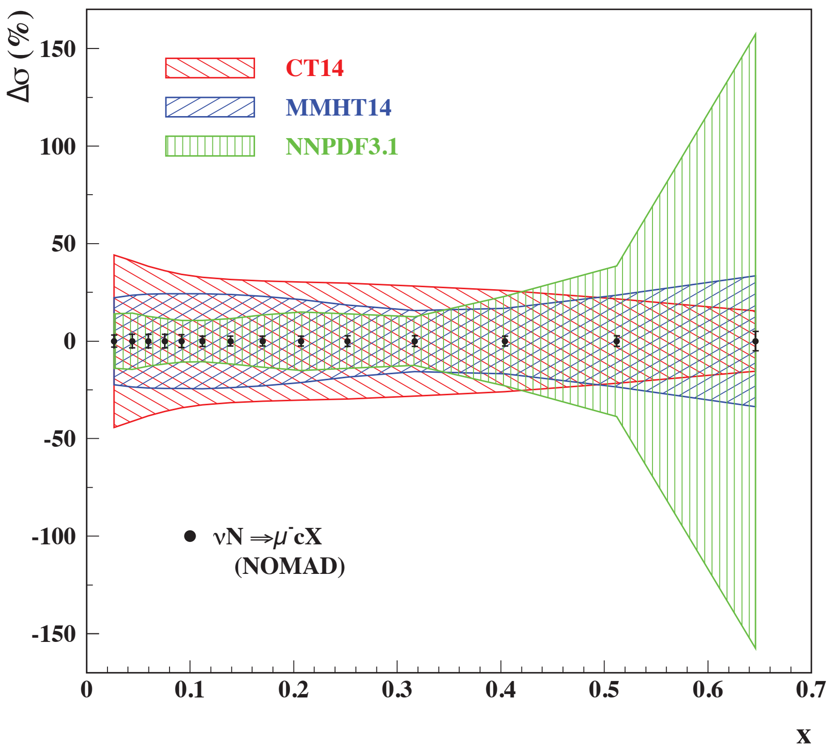
At $Q^2 \to 0$ *we have* $d\sigma/dQ^2 \propto G_1^2$ *and the strange axial form factor* $G_A^s \to \Delta s$.

✦ *Measure* NC/CC RATIOS *as a function of* Q^2 *to reduce systematics* ($\sin^2\theta_W$ *as well)*:

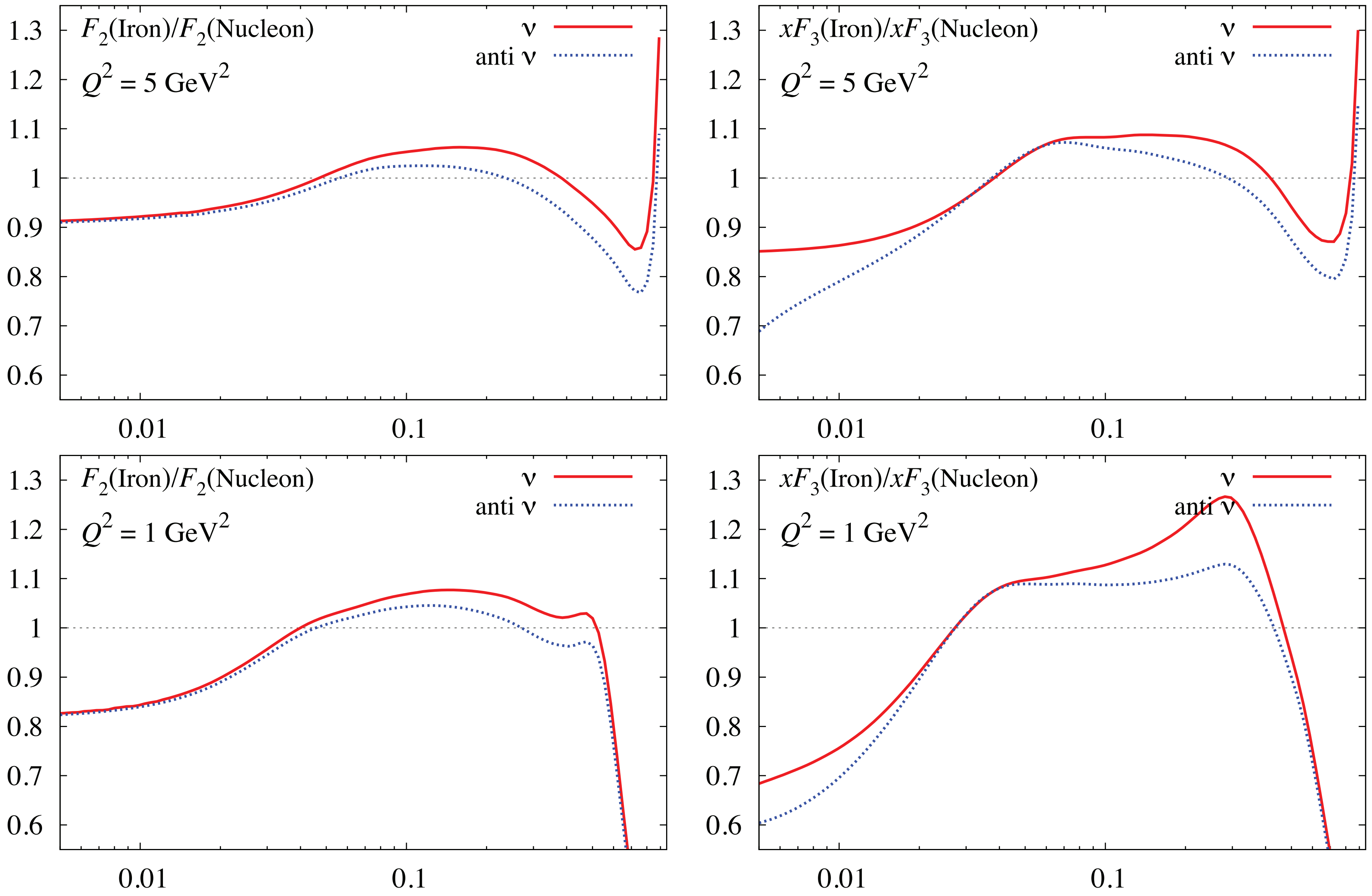
$$R_\nu = \frac{\sigma(\nu p \to \nu p)}{\sigma(\nu n \to \mu^- p)}; \qquad R_{\bar\nu} = \frac{\sigma(\bar\nu p \to \bar\nu p)}{\sigma(\bar\nu p \to \mu^+ n)}$$

- *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*).*



- *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)*


F2(Iron)/F2(Nucleon)
Q2 = 5 GeV2
ν
anti ν
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.01
0.1
xF3(Iron)/xF3(Nucleon)
Q2 = 5 GeV2
ν
anti ν
F2(Iron)/F2(Nucleon)
Q2 = 1 GeV2
ν
anti ν
xF3(Iron)/xF3(Nucleon)
Q2 = 1 GeV2
ν
anti ν

HELICITY, C-PARITY AND ISOSPIN

- *The amplitude controlling nuclear shadowing depends on the helicity of boson* $(\pm1, 0)$

$$\begin{aligned} a_0 &\rightarrow F_L \\ a_T &= (a_{+1} + a_{-1})/2 \rightarrow F_1 \\ a_\Delta &= (a_{+1} - a_{-1})/2 \rightarrow F_3 \end{aligned}$$

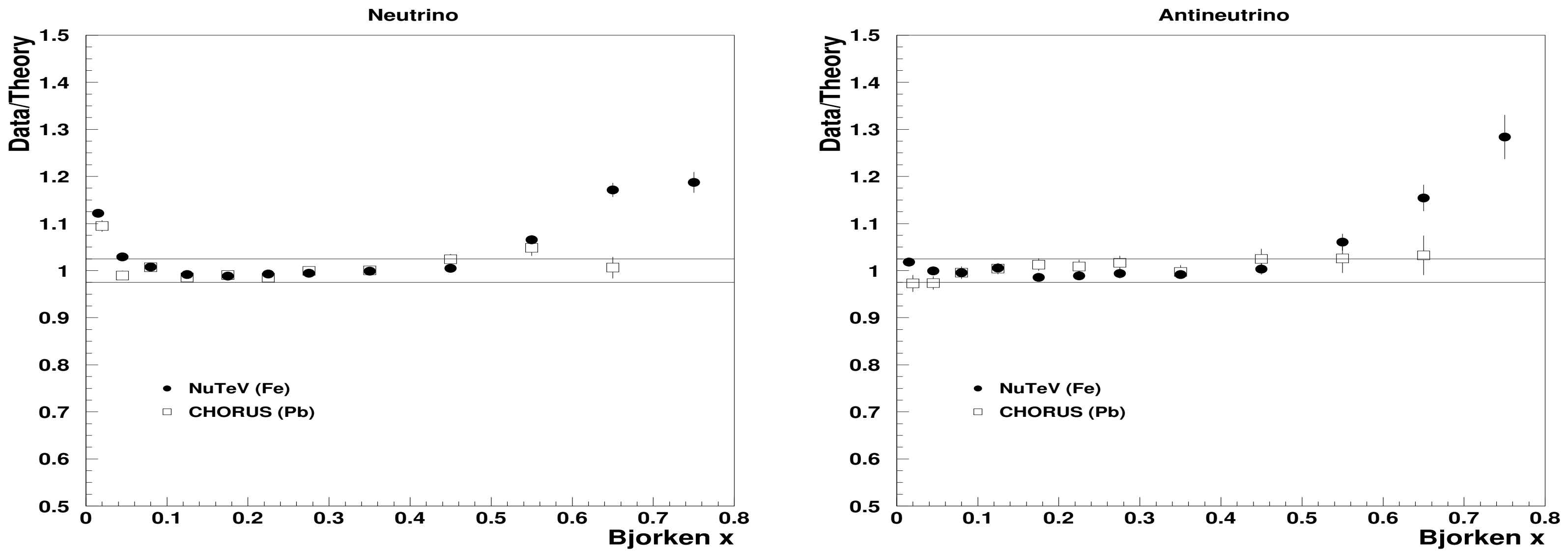
- *The amplitude depends on the isospin I (proton and neutron dependence) and on the C-parity (ν and $\bar{\nu}$ dependence),* $\boxed{a_h^{(I,C)}}$*:*

$$\begin{aligned} a_T^{(0,+)} &\rightarrow F_1^{e/\mu(p+n)} \text{ and } F_1^{(\nu+\bar{\nu})(p+n)} & a_\Delta^{(0,-)} &\rightarrow F_3^{(\nu+\bar{\nu})(p+n)} \\ a_T^{(1,+)} &\rightarrow F_1^{e/\mu(p-n)} \text{ and } F_1^{(\nu+\bar{\nu})(p-n)} & a_\Delta^{(1,-)} &\rightarrow F_3^{(\nu+\bar{\nu})(p-n)} \\ a_T^{(0,-)} &\rightarrow F_1^{(\nu-\bar{\nu})(p+n)} & a_\Delta^{(0,+)} &\rightarrow F_3^{(\nu-\bar{\nu})(p+n)} \\ a_T^{(1,-)} &\rightarrow F_1^{(\nu-\bar{\nu})(p-n)} & a_\Delta^{(1,+)} &\rightarrow F_3^{(\nu-\bar{\nu})(p-n)} \end{aligned}$$

$\Longrightarrow$ *Virtual photon γ^* C-even only, (anti)neutrino interactions both C-even and C-odd*

- *Isoscalar and Isovector spectral functions,* $\boxed{\mathcal{P}_0 \text{ and } \mathcal{P}_1}$*, enter nuclear convolution*

$$F_2^A/A = \langle \frac{F_2^p + F_2^n}{2} \rangle_0 + \frac{\beta}{2} \langle F_2^p - F_2^n \rangle_1 \qquad \beta = (Z-N)/A$$



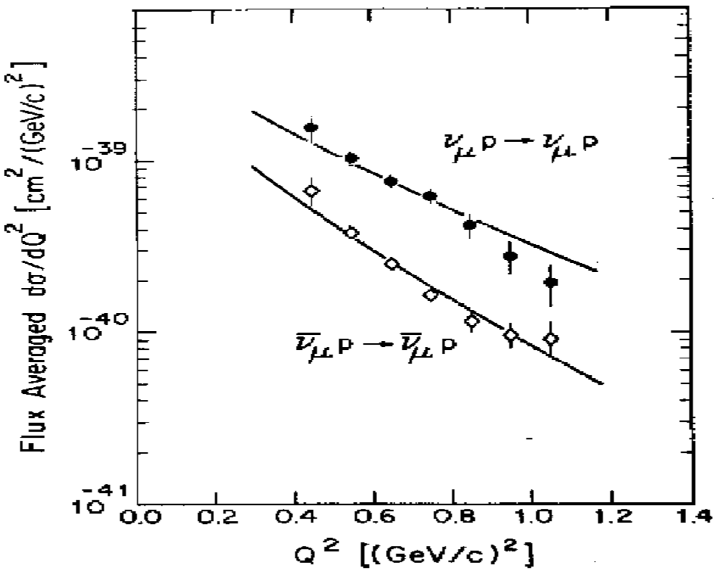
- ✦ *Limited $\nu(\bar{\nu})$ data on ratios $\sigma^{A'}/\sigma^{A}$ (BEBC, MINERνA) and differential cross-sections $d\sigma^2/dxdy$ (NuTeV, CCFR, CHORUS)*

- ✦ *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?*