Probing Free Nucleons with (Anti)neutrinos

R. Petti

University of South Carolina, Columbia SC, USA

DIS 2022
May 5th, 2022, Santiago de Compostela, Spain

SPLENDORS AND MISERIES OF $\nu/\bar{\nu}$ PROBE

✦ *Neutrinos desirable probe for EW physics and partonic/hadronic structure of matter:*

- *Clean probe (only weak interaction) complementary to $e^{\pm}$;*
- *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, natural spin polarization.*

$\Longrightarrow$ *Potential only partially explored due to various limitations*

✦ STATISTICS

Tiny cross-sections with limited beam intensities requires massive & coarse detectors.

✦ TARGETS

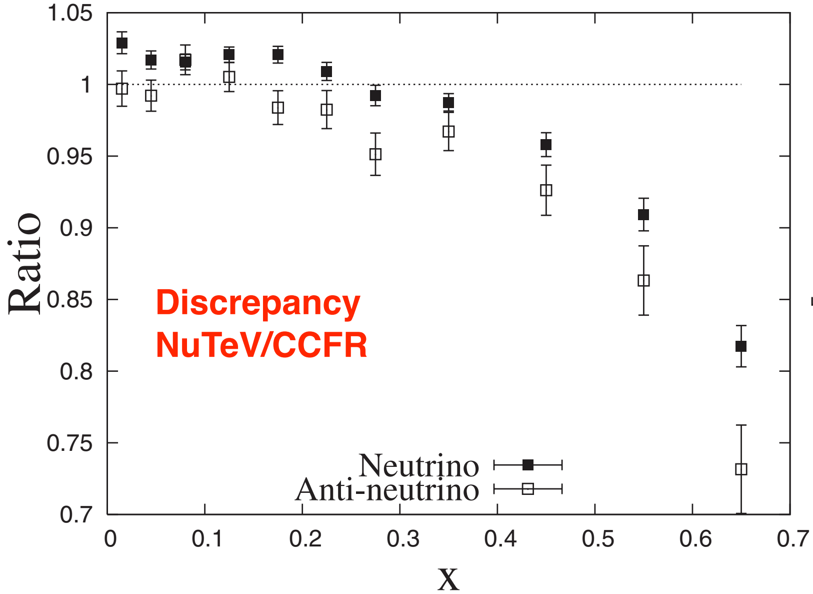
Need of massive nuclear targets does not allow a precise control of the interactions.

✦ FLUXES

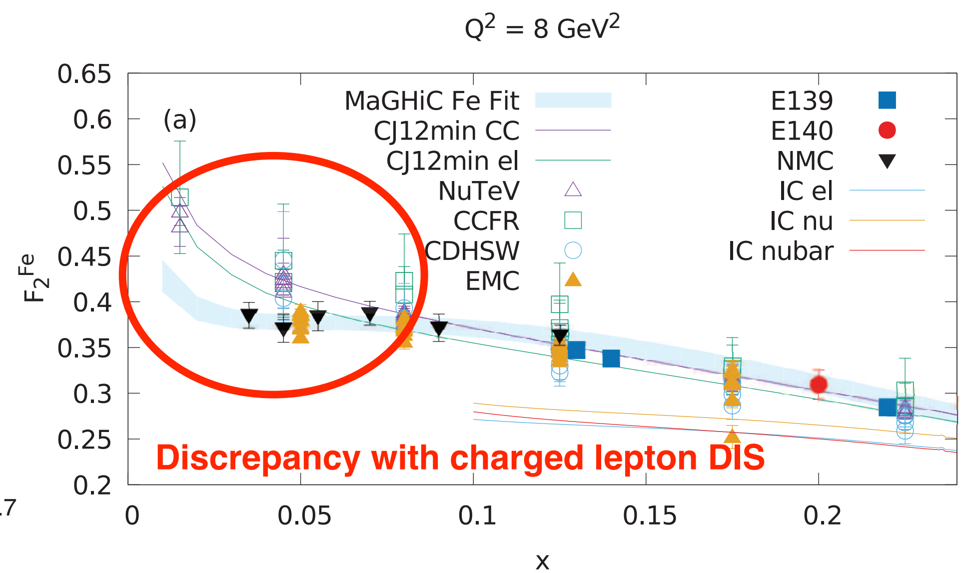
Incoming (anti)neutrino energy unknown implies substantial flux uncertainties.

✦ NUCLEAR EFFECTS

Nuclear smearing affecting data unfolding:
unknown target momentum & measured particles modified by final state interactions.

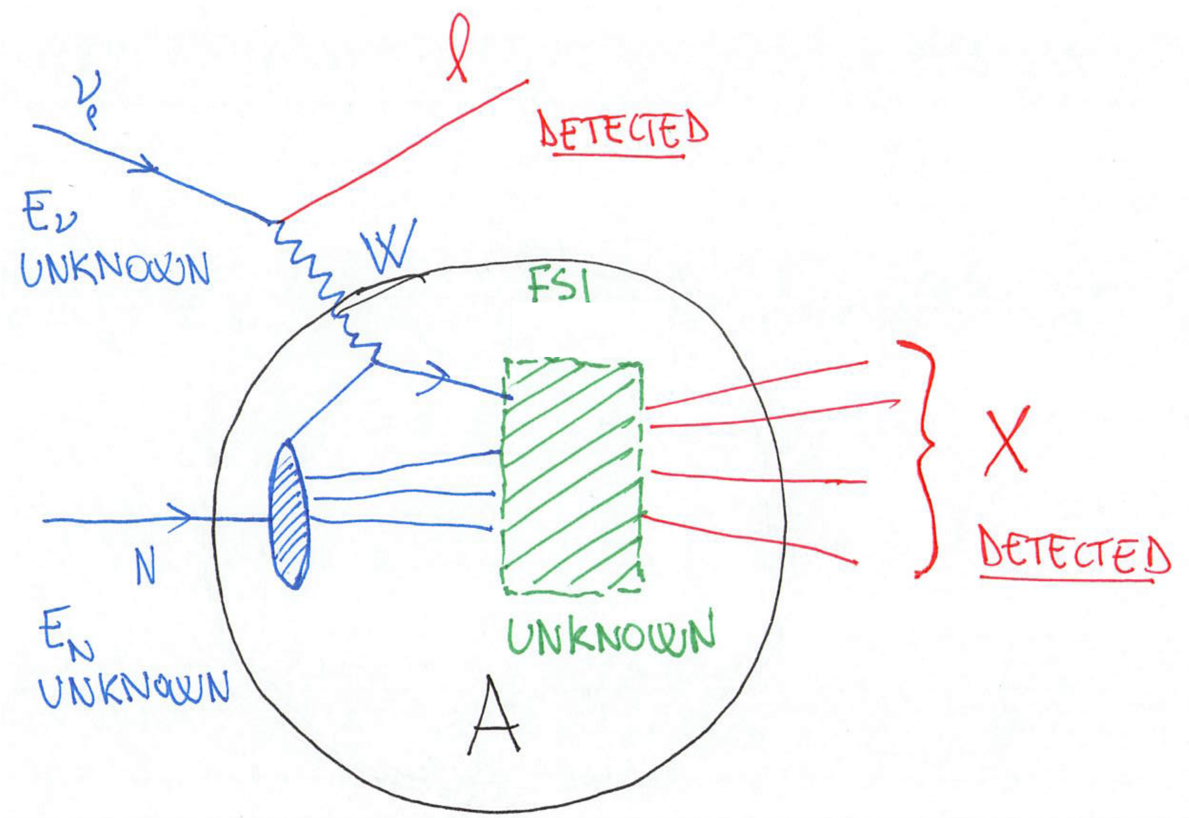


NuTeV Coll., PRD 74 (2006) 012008



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

Many outstanding discrepancies among different measurements and between measurements and existing models



(Anti)neutrino-Nucleus scattering:
projectile of unknown energy hitting target of unknown energy
with outgoing products undergoing unknown smearing

WHY HYDROGEN?

✦ *H target provides valuable physics measurements per se:*

- *Proton structure from flavor-sensitive $\nu(\bar{\nu})$-H CC interactions;*
- *Isospin symmetry provides direct access to free neutron structure without nuclear corrections;*
- *Understanding nucleon-level amplitudes is essential input for (anti)neutrino-nucleus cross-sections.*

$\Longrightarrow$ *Complementary information to charged lepton DIS & colliders*

✦ *H target necessary tool for next-generation precision measurements on nuclei:*

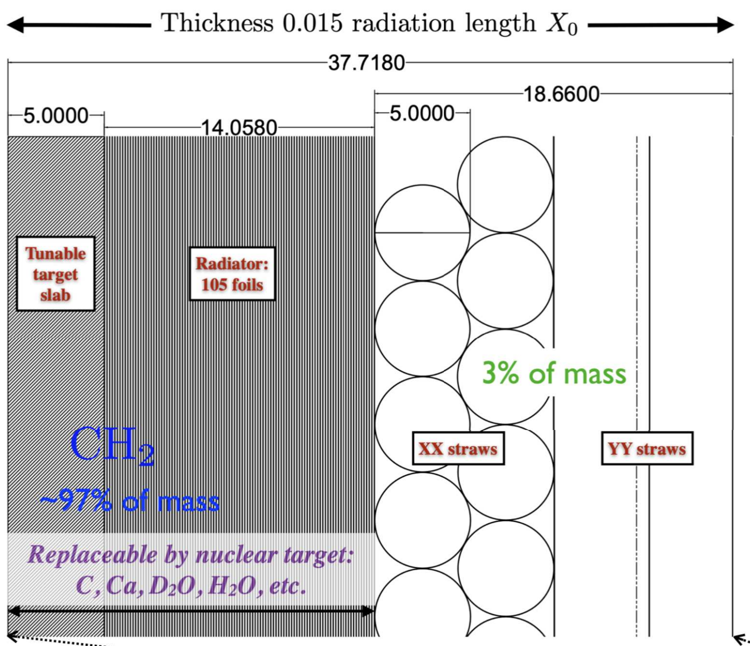
- *Hadronic target of known energy;*
- *Exclusive topologies for precise determination of (anti)neutrino flux;*
- *Control sample free from nuclear effects to calibrate (anti)neutrino energy scale.*

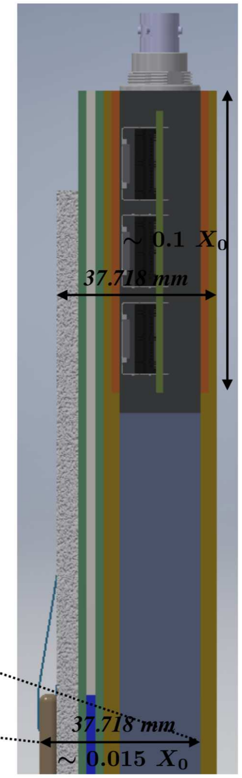
$\Longrightarrow$ *Without H target achievable precisions limited by nuclear smearing*

"SOLID" HYDROGEN TARGET

✦ *"Solid" Hydrogen concept: $\nu(\bar{\nu})$-H from subtraction of* CH_2 & C *targets*

- *Straw Tube Tracker designed for a control of ν-target(s) similar to $e^{\pm}$ DIS experiments;*
- *Thin (1-2% X_0) passive targets spread out within tracker of negligible mass: $\rho_{avg} \leq 0.18$ g/cm^3;*
- *Model-independent data subtraction of dedicated C (graphite) target from main CH_2 target;*





Similar thickness 1-2% X_0 for both CH_2 and C

CH_2 and C targets alternated to guarantee same acceptance

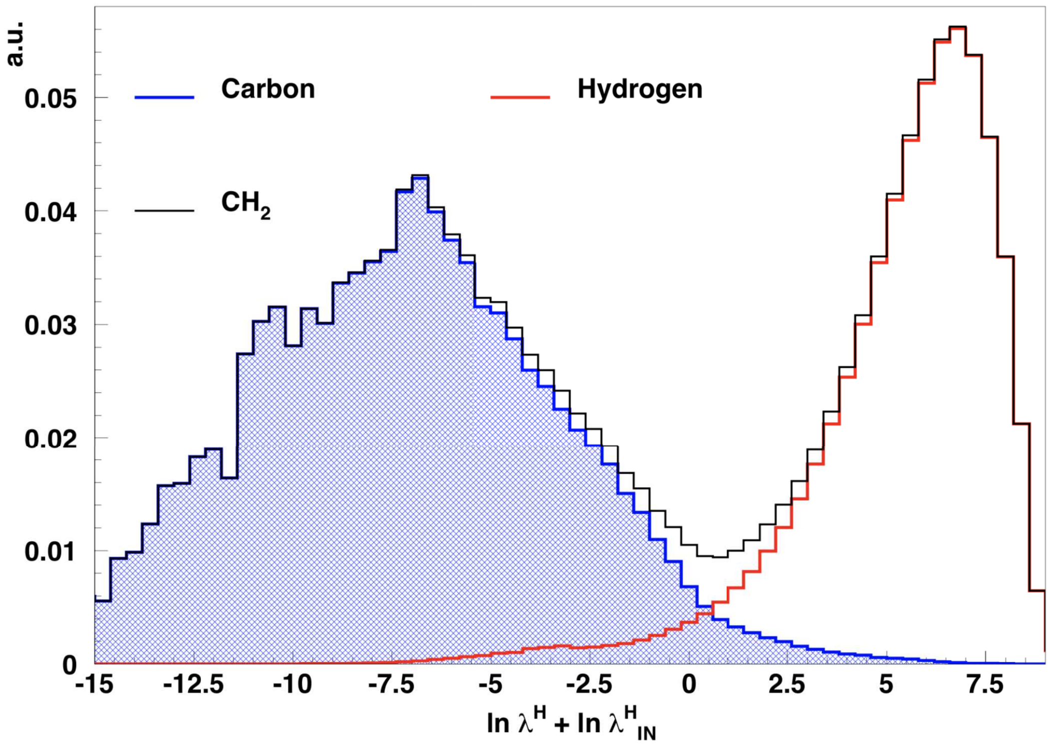
Mass ratio optimized for subtraction

$\Longrightarrow$ *Typical fiducial mass achievable equivalent to about* $10\ \mathrm{m}^3\ \mathrm{LH}_2$

"SOLID" HYDROGEN TARGET

✦ *"Solid" Hydrogen concept: $\nu(\bar{\nu})$-H from subtraction of* CH$_2$ & C *targets*

- *Straw Tube Tracker designed for a control of ν-target(s) similar to $e^{\pm}$ DIS experiments;*
- *Thin (1-2% X_0) passive targets spread out within tracker of negligible mass: $\rho_{\rm avg} \leq 0.18$ g/cm^3;*
- *Model-independent data subtraction of dedicated C (graphite) target from main CH$_2$ target;*



Kinematic selection (transverse plane) can reduce dilution factor for CC

Applicable to all inclusive & exclusive CC topologies with 80-95% purity and 75-96% efficiency before subtraction.

$\Longrightarrow$ *Viable & acceptable approximation to liquid H_2 detectors*

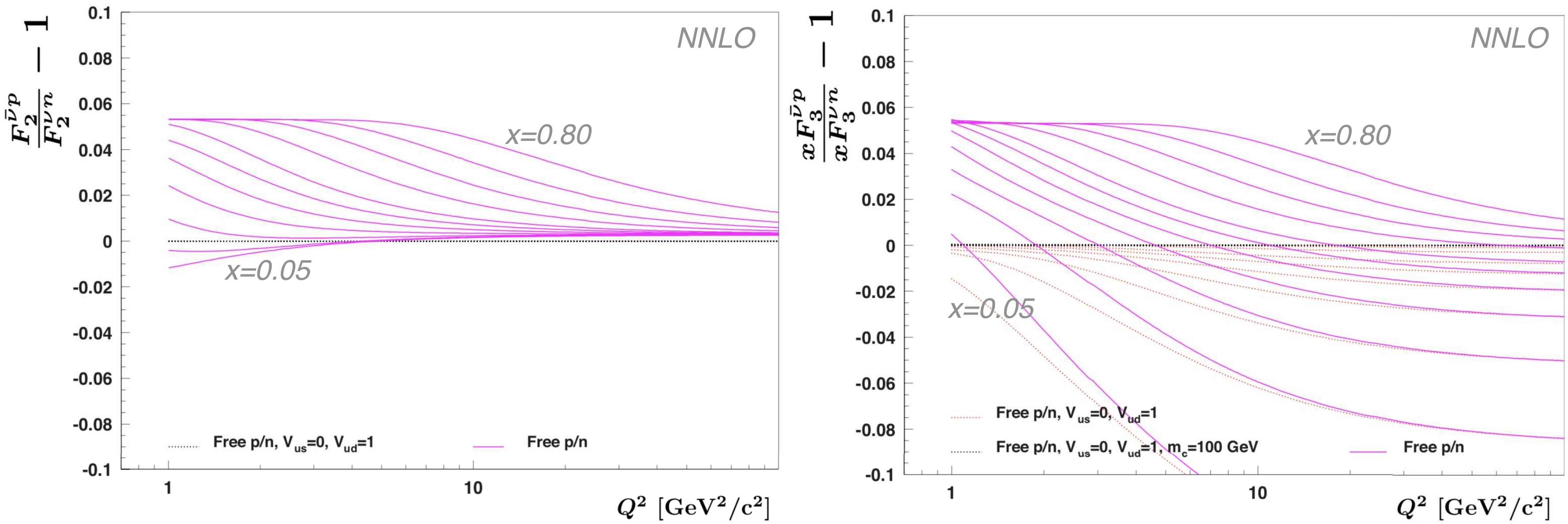
arXiv:1910.05995 [hep-ex], 1809.08752 [hep-ph]

FREE NEUTRON TARGET

- *Structure function $F^{\nu n}$ directly related to $F^{\bar{\nu} p}$ by* ISOSPIN SYMMETRY
- *Correction factors:*

$$\mathcal{R}_2^{\rm p/n}(x,Q^2) = \frac{F_2^{\bar{\nu}p}(x,Q^2)}{F_2^{\nu n}(x,Q^2)} - 1; \qquad \mathcal{R}_3^{\rm p/n}(x,Q^2) = \frac{xF_3^{\bar{\nu}p}(x,Q^2)}{xF_3^{\nu n}(x,Q^2)} - 1$$

- *Quark mixing (CKM): sensitivity to V_{us} and V_{ud};*
- *Strange sea quarks and charm production: sensitivity to m_c and strange sea asymmetry.*



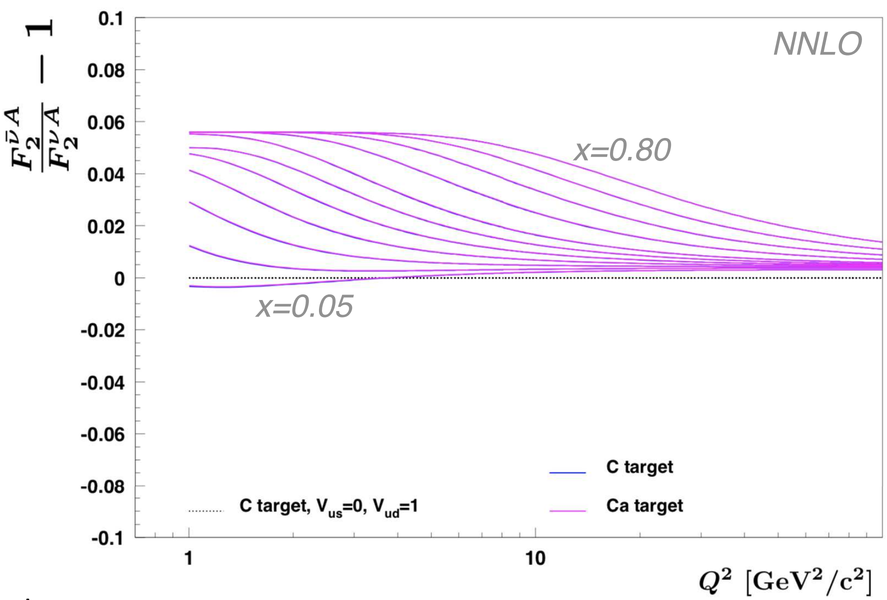
TESTS OF ISOSPIN SYMMETRY

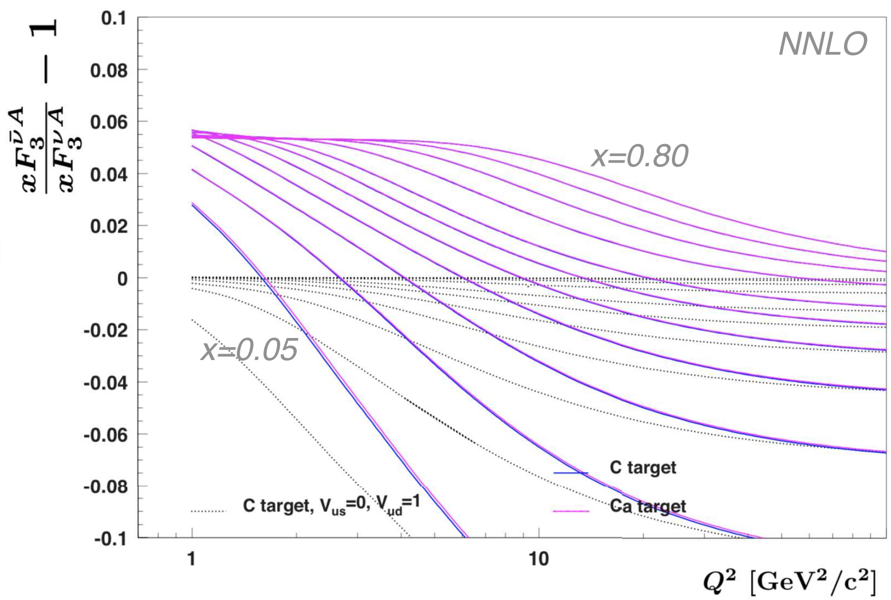
- *Isospin symmetry can be verified with* ISOSCALAR TARGET :

$$\mathcal{R}_2^{\rm A}(x,Q^2) = \frac{F_2^{\bar\nu A}(x,Q^2)}{F_2^{\nu A}(x,Q^2)} - 1; \qquad \mathcal{R}_3^{\rm A}(x,Q^2) = \frac{xF_3^{\bar\nu A}(x,Q^2)}{xF_3^{\nu A}(x,Q^2)} - 1$$

  - *Exploit C target in "solid" hydrogen: validation of $\mathcal{R}_{2,3}^{\rm p/n}$ corrections to free neutrons;*
  - *Search for direct violations of the isospin (charge) symmetry from deviations in $\mathcal{R}_{2,3}^{\rm A}$.*

- *If anomalous deviations in $\mathcal{R}_{2,3}^{\rm A}$ independent measurement with isoscalar ^{40}Ca target*

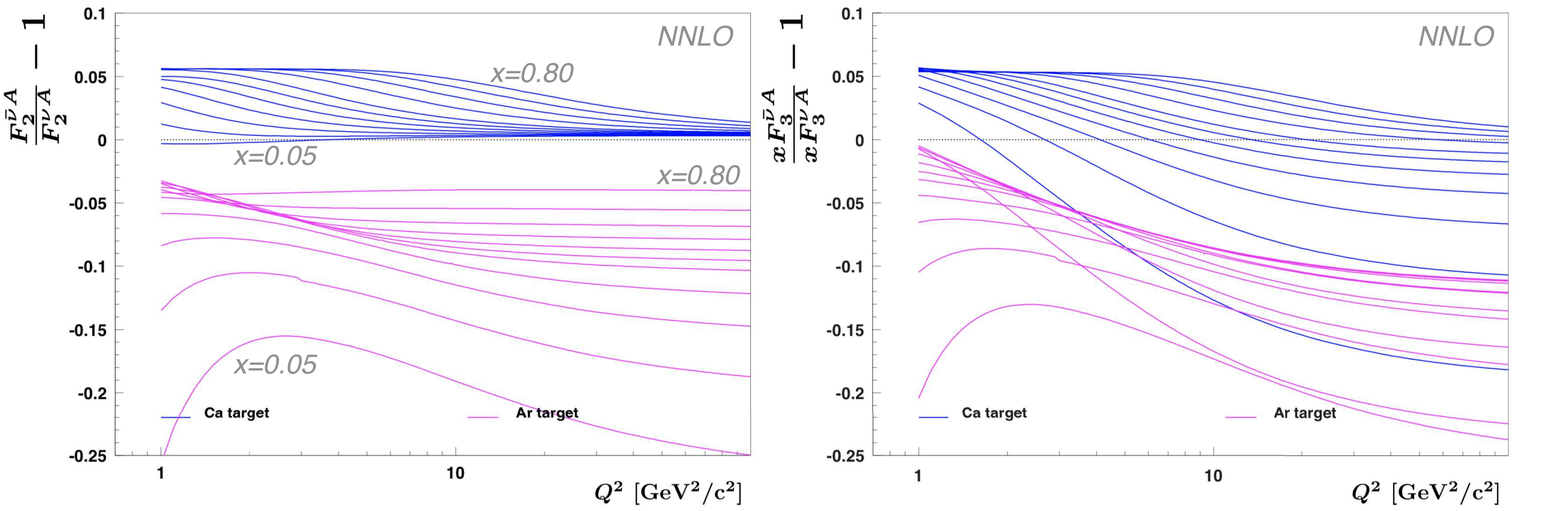




✦ *Comparison of Ca and Ar can probe* **ISOSPIN DEPENDENCE** *of nuclear effects:*

- *Same $A = 40$: neutron excess in Ar $\beta = (Z - N)/A \sim -0.1$, Ca mostly isoscalar $\beta \sim -2.6 \times 10^{-3}$;*
- *Insights on physics mechanisms responsible for isovector effects at both nucleon and nuclear level.*

✦ *Isovector effects relevant for LBL oscillation measurements with non-isoscalar nuclei: e.g. DUNE exploits tiny differences between ν and $\bar{\nu}$ CC on ^{40}Ar*



NUCLEAR MODIFICATIONS OF BOUND NUCLEONS

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

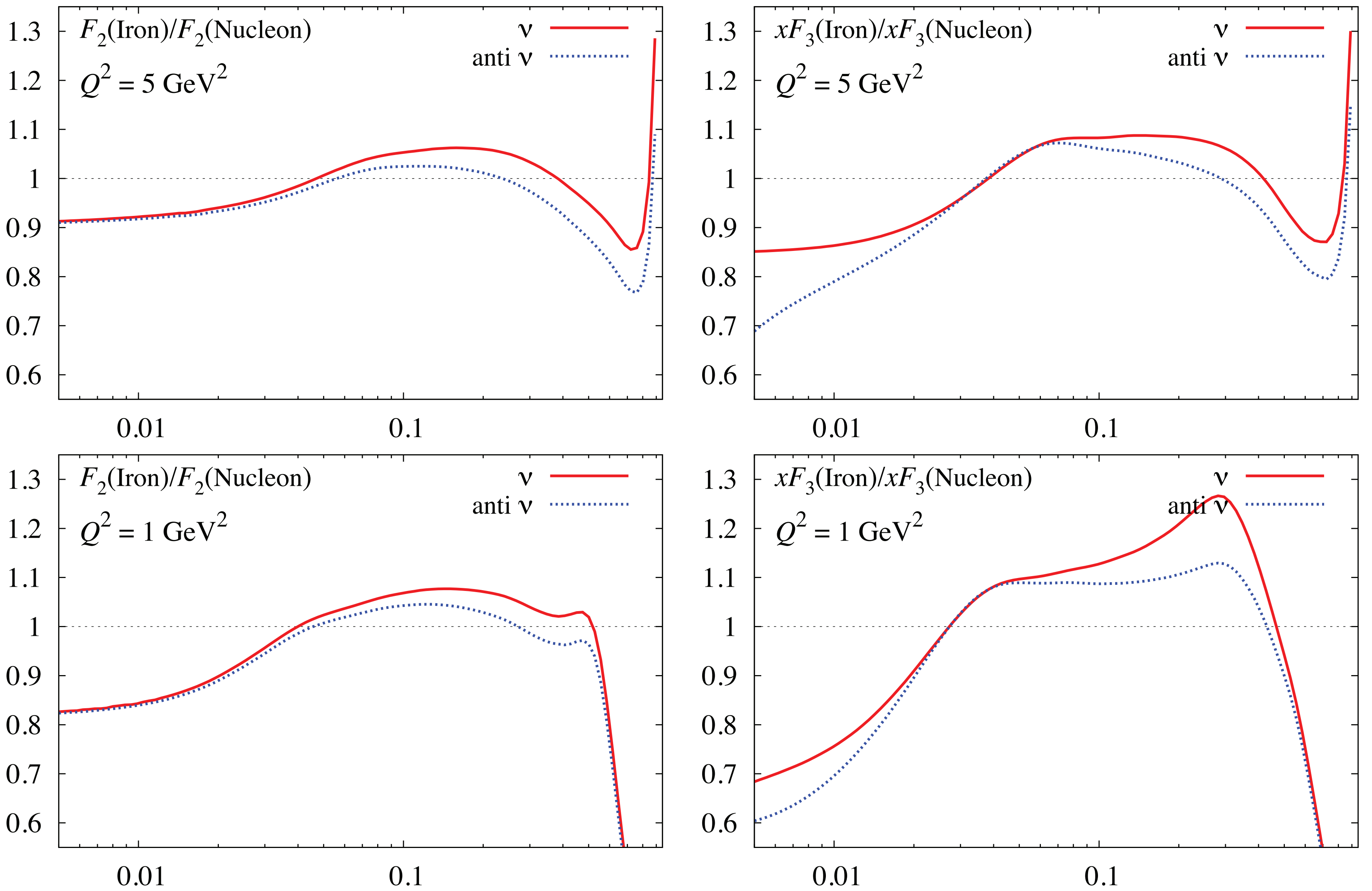
$$R^A_{2,3}(x,Q^2) \;=\; \frac{F^{\nu A}_{2,3}}{ZF^{\nu p}_{2,3}+(A-Z)F^{\nu n}_{2,3}} \sim \frac{F^{\nu A}_{2,3}}{ZF^{\nu H}_{2,3}+(A-Z)F^{\bar{\nu} H}_{2,3}}(x,Q^2)$$

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

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

- *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.*



NPA 765 (2006) 126; PRD 76 (2007) 094023, PRC 90 (2014) 045204

H CALIBRATION TOOL FOR $\nu(\bar{\nu})$-A SYSTEMATICS

$$N_X(E_{rec}) = \int_{E_\nu} dE_\nu \, \Phi(E_\nu) \, [P_{osc}(E_\nu)] \, \sigma_X(E_\nu) \, R_{phys}(E_\nu, E_{vis}) \, R_{det}(E_{vis}, E_{rec})$$

Measurements expected to be dominated by systematics with modern intense beams

$\boxed{\Phi(E_\nu)}$ *Flux uncertainties affect virtually the measurement of every observable and are usually one of the leading systematics in neutrino scatterig experiments.*

$\Longrightarrow$ *Exclusive* $\nu_\mu p \to \mu^- p \pi^+$ *and* $\bar{\nu}_\mu p \to \mu^+ n$ *on H provide calibration samples*

R_{det} *Detector smearing controlled by* $\boxed{\Delta p \text{ SCALE}}$ *and reconstruction efficiencies.*

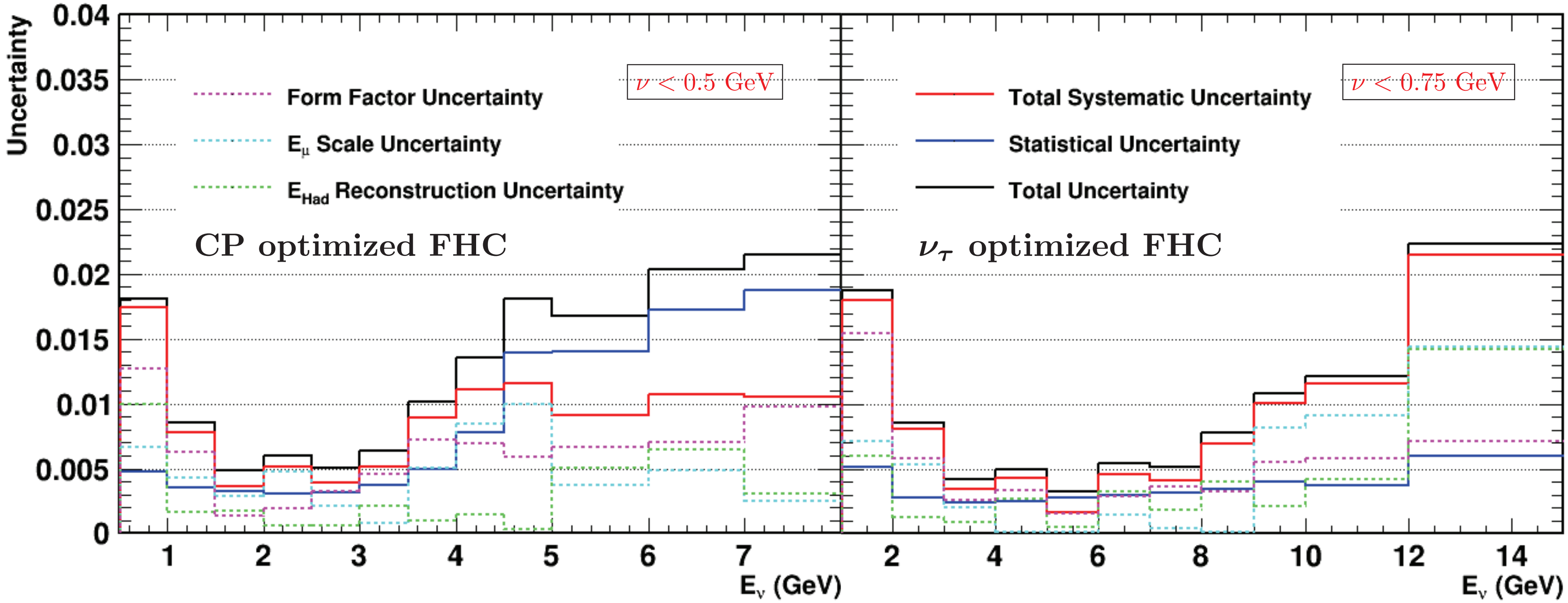
R_{phys} *Smearing introduced by nuclear effects on initial and final state particles results in systematics on* $\boxed{\Delta E_\nu \text{ SCALE}}$ *since* E_ν *unknown on event-by-event basis.*

$\Longrightarrow$ *Inclusive* ν_μ *CC &* $\bar{\nu}_\mu$ *CC interactions on H provide calibration sample*

FLUX MEASUREMENTS WITH H

- *Relative ν_μ flux vs. E_ν from exclusive $\nu_\mu p \to \mu^- p \pi^+$ on H:*
  $\nu < 0.5$ GeV *flattens cross-sections reducing uncertainties on E_ν dependence.*
- *Relative $\bar{\nu}_\mu$ flux vs. E_ν from exclusive $\bar{\nu}_\mu p \to \mu^+ n$ QE on H:*
  $\nu < 0.25$ GeV*: uncertainties comparable to relative ν_μ flux from $\nu_\mu p \to \mu^- p \pi^+$ on H.*
- *Absolute $\bar{\nu}_\mu$ flux from QE $\bar{\nu}_\mu p \to \mu^+ n$ on H* with $Q^2 < 0.05$ GeV^2

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



PLB 795 (2019) 424, arXiv:1902.09480 [hep-ph]

CALIBRATION OF E_ν ENERGY SCALE WITH H

$$N_X(E_{rec}) = \int_{E_\nu} dE_\nu \, \boxed{\Phi(E_\nu)} \, [P_{osc}(E_\nu)] \, \boxed{\sigma_X(E_\nu)} \, \boxed{R_{phys}(E_\nu, E_{vis})} \, \boxed{R_{det}(E_{vis}, E_{rec})}$$

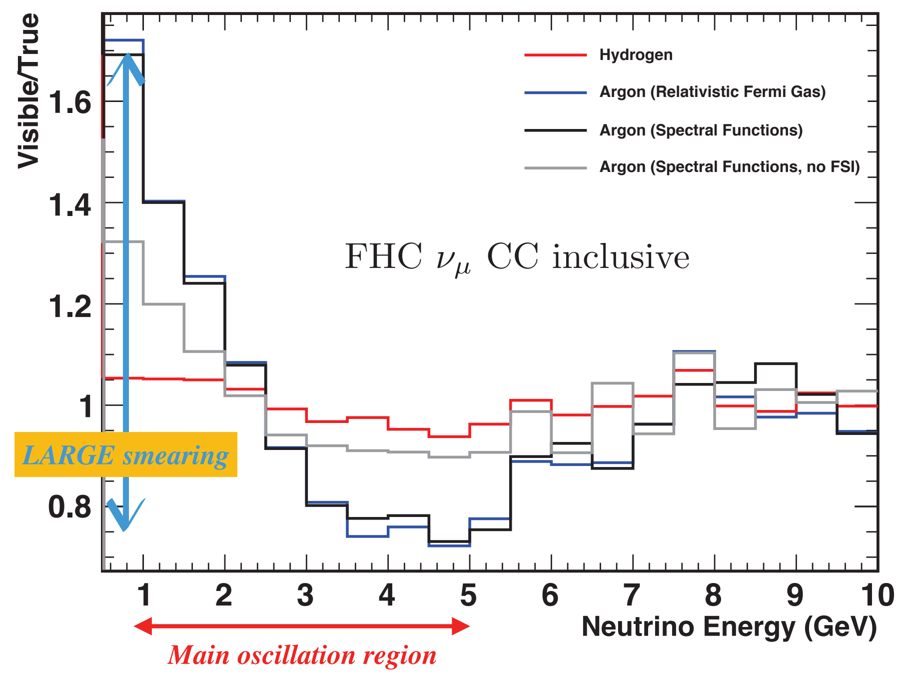
$\sim$1% in H $F_i(Q^2)$ $R_{phys} \equiv I$ K_0, Λ, γ

✦ *Combination of ν-H & $\bar{\nu}$-H CC calibration sample for (anti)neutrino energy scale* $\boxed{\Delta E_\nu}$

✦ *Compare with CC inclusive interactions on nuclear target A*
$\Longrightarrow$ *Similar detector acceptance*

✦ *Calibration using y distribution (minimal nuclear effects on σ)*

✦ *Understanding nuclear smearing required to reduce unfolding systematics*

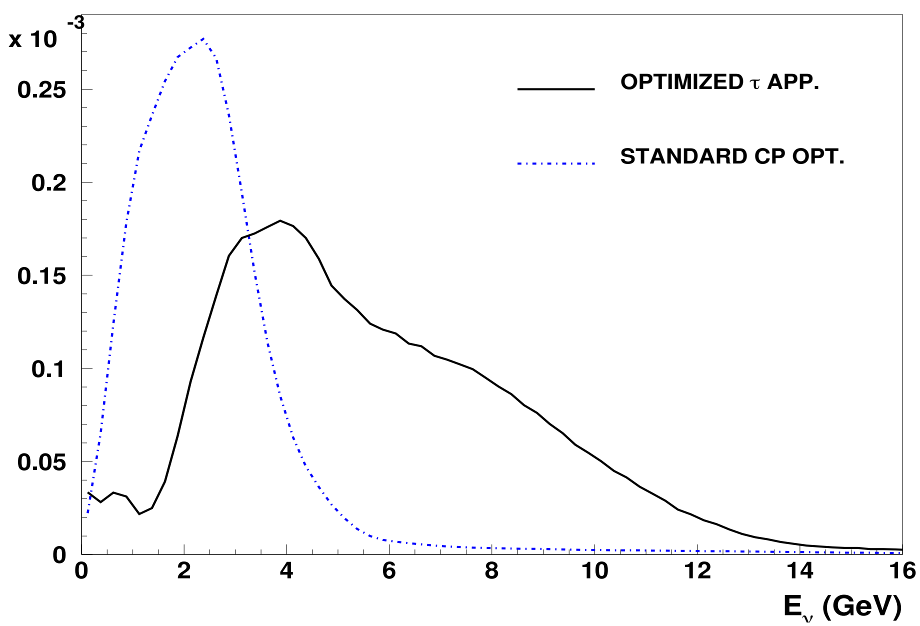


EXPECTED MEASUREMENTS IN DUNE

- *STT inner tracker of SAND in DUNE ND and expected to take data from Day 1: default low-energy CP optimized beam and CH_2, C, & Ar targets.*

- *Various possibilities after initial run:*
  - *Replace some of the main CH_2 targets in STT with different materials;*
  - *High-energy beam optimized for ν_τ appearace & upgraded intensity (x 2).*

$\Longrightarrow$ *General purpose ν & $\bar{\nu}$ physics facility with broad physics program*



Interactions	CH_2	H
Standard CP optimized (1.2 MW):		
ν_μ CC (FHC, 5 y)	32×10^6	3.1×10^6
$\bar{\nu}_\mu$ CC (RHC, 5 y)	12×10^6	2.3×10^6
Optimized ν_τ appearance (2.4 MW):		
ν_μ CC (FHC, 2 y)	62×10^6	6.0×10^6
$\bar{\nu}_\mu$ CC (RHC, 2 y)	22×10^6	4.0×10^6

SUMMARY

- *Availability of complementary hydrogen target necessary to reduce systematics from nuclear smearing and flux in next-generation precision measurements.*

- *"Solid" hydrogen concept can provide high statistics $\mathcal{O}(10^6)$ samples of ν-H & $\bar{\nu}$-H interactions, giving access to the flavor content of free protons and neutrons.*

- *A combination of H and various nuclear targets within the same detector allows precision tests of isospin (charge) symmetry and a study of nuclear modifications of parton distributions and their flavor dependence.*

- *STT in SAND within the DUNE ND complex can enable a broad physics program complementary to ongoing fixed-target, collider and nuclear physics efforts*

  $\Longrightarrow$ *Hundreds of diverse physics topics providing insights on various fields*

Backup slides

BROAD PHYSICS POTENTIAL

✦ *SAND can constrain main systematics from targets, scales, flux, & nuclear effects*

$\Longrightarrow$ *Exploit the unique properties of the (anti)neutrino probe to study fundamental interactions & structure of nucleons and nuclei*

✦ *SAND can contribute to create a ND complex with a broad physics 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): sterile neutrinos, NSI, NHL, etc.....*

$\Longrightarrow$ *Hundreds of diverse physics topics offering insights on various fields*

✦ *No additional requirements: same control of targets & fluxes to study LBL systematics*

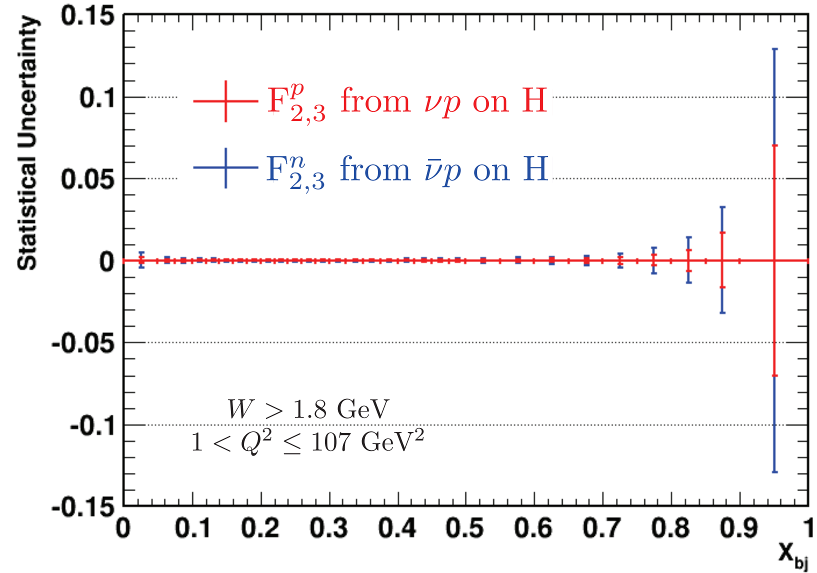
ADLER SUM RULE & ISOSPIN PHYSICS

✦ *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 RP, PRD 76 (2007) 094023)*

$\Longrightarrow$ *Precision test of S_A at different Q^2 values*



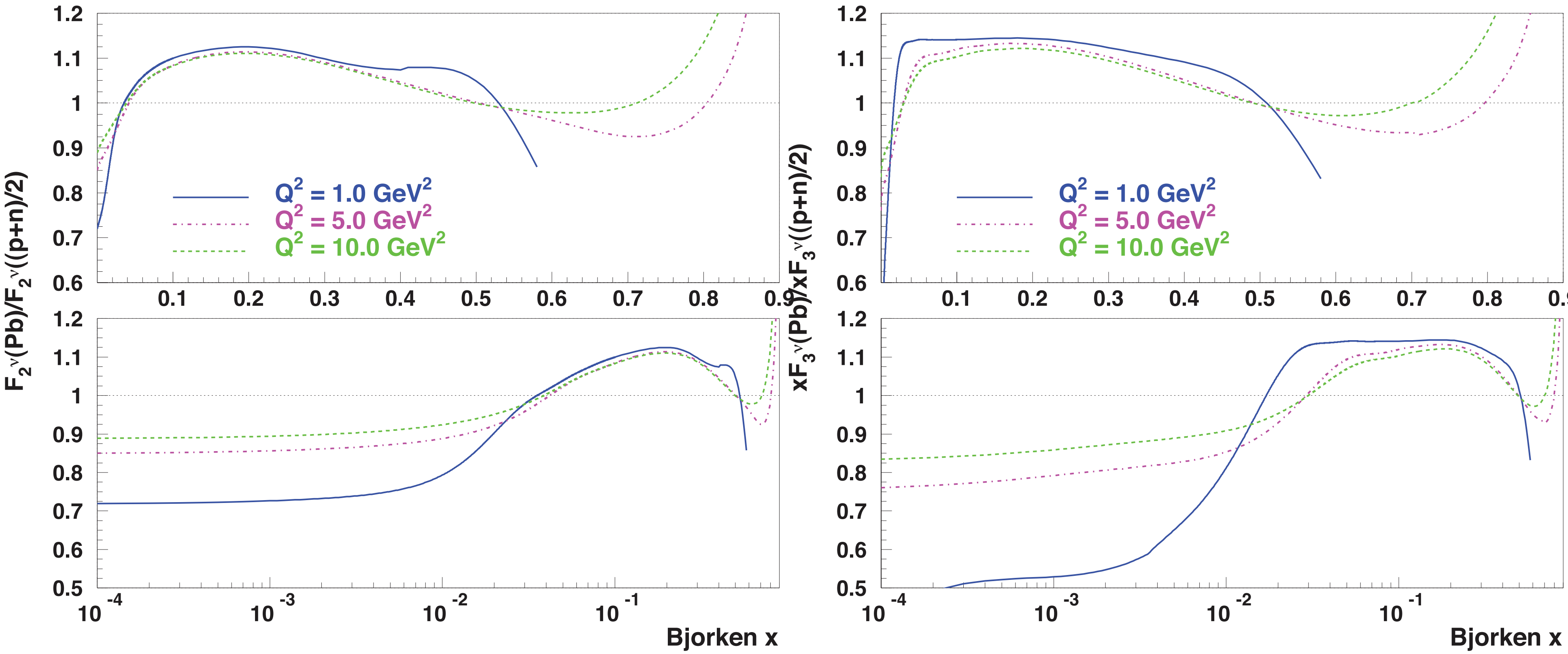
✦ *Only measurement available from BEBC based on 5,000 νp and 9,000 $\bar{\nu}p$ (D. Allasia et al., ZPC 28 (1985) 321)*

✦ *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 $x \to 1$*

(Synergy with 12 GeV JLab program)

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



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

NPA 765 (2006) 126; PRD 76 (2007) 094023, PRC 90 (2014) 045204