Precision (Anti)neutrino scattering off nucleons and nuclei

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

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

- *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

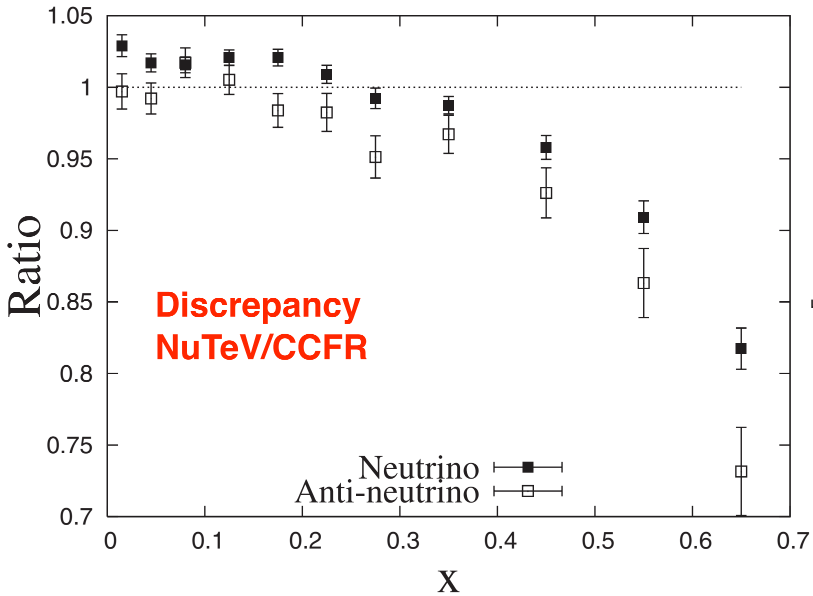
Need of massive nuclear targets does not allow a precise control of the interactions.

✦ FLUXES

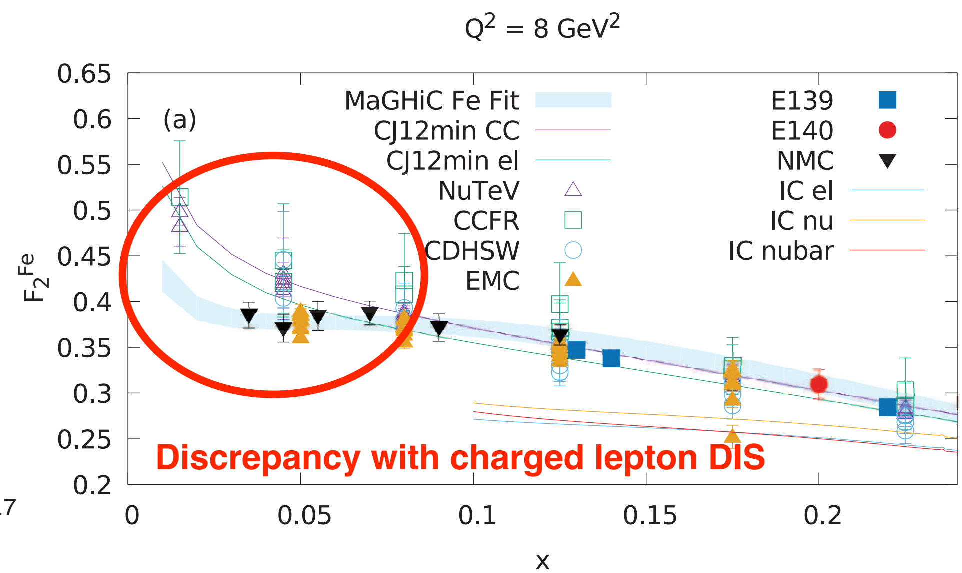
Incoming (anti)neutrino energy unknown implies substantial flux uncertainties.

✦ NUCLEAR EFFECTS

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



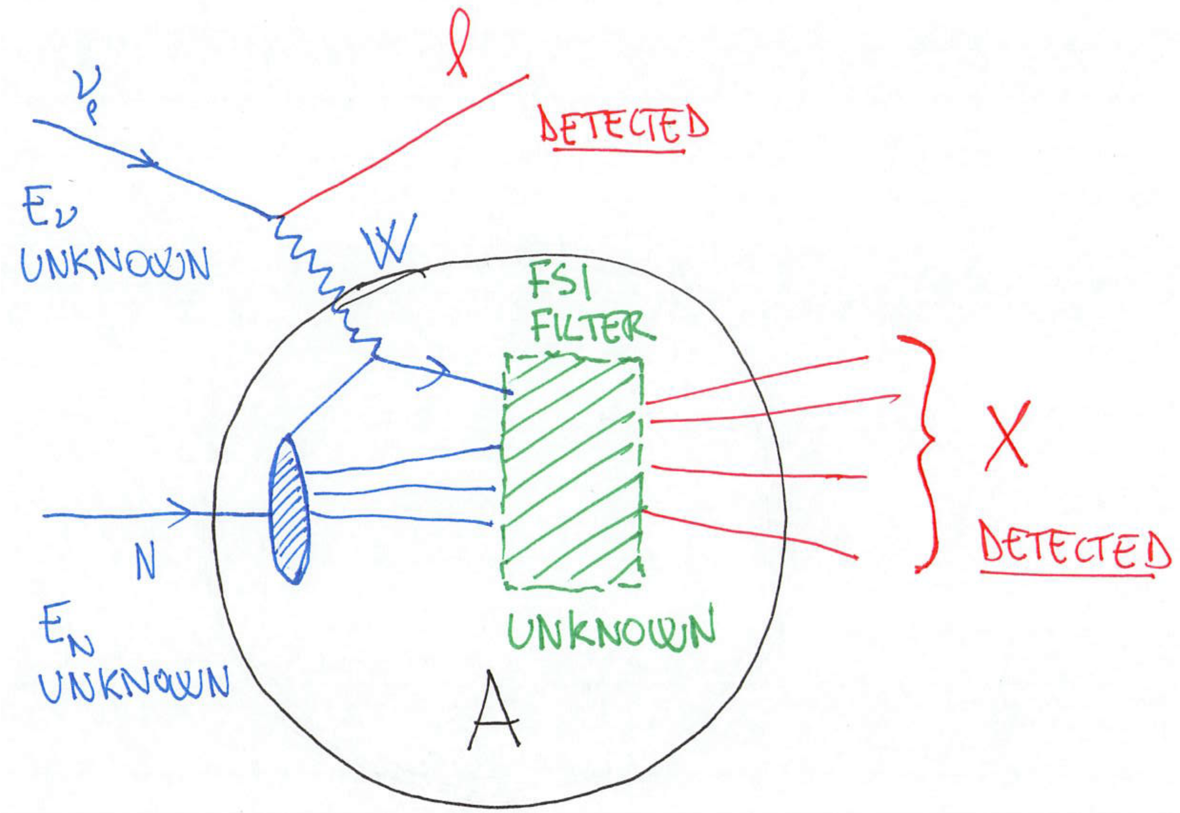
NuTeV Coll., PRD 74 (2006) 012008



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

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

Prog.Part.Nucl.Phys. 100 (2018) 1-68



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

WHY HYDROGEN?

✦ *New precision data from hydrogen target highly desirable:*

- *Scarce (anti)neutrino data on free nucleon (H) from old bubble chambers;*
- *Understanding nucleon-level amplitudes is essential input for (anti)neutrino-nucleus cross-sections*

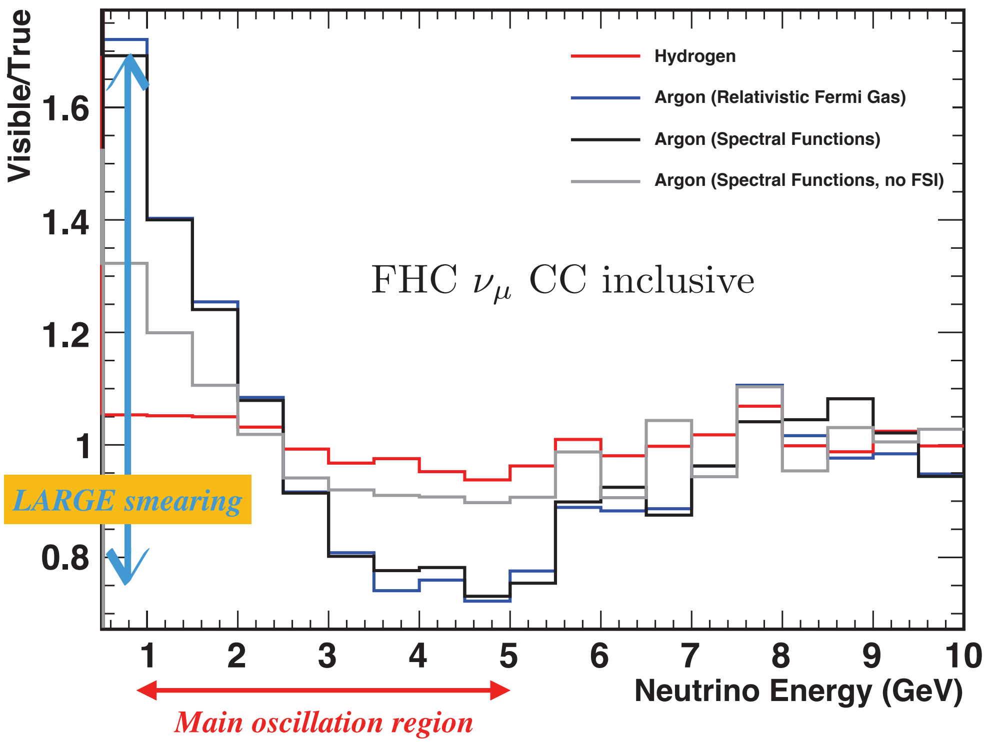
$\Longrightarrow$ *Existing data inadequate for needs of modern neutrino experiments*

✦ *Use of (heavy) nuclear targets necessary evil for neutrino physics.*

✦ *Availability of H target necessary condition for next-generation precision measurements:*

- *Control sample free from nuclear effects to calibrate (anti)neutrino energy scale;*
- *Direct constraints on nuclear effects required to reduce systematics from nuclear targets.*

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



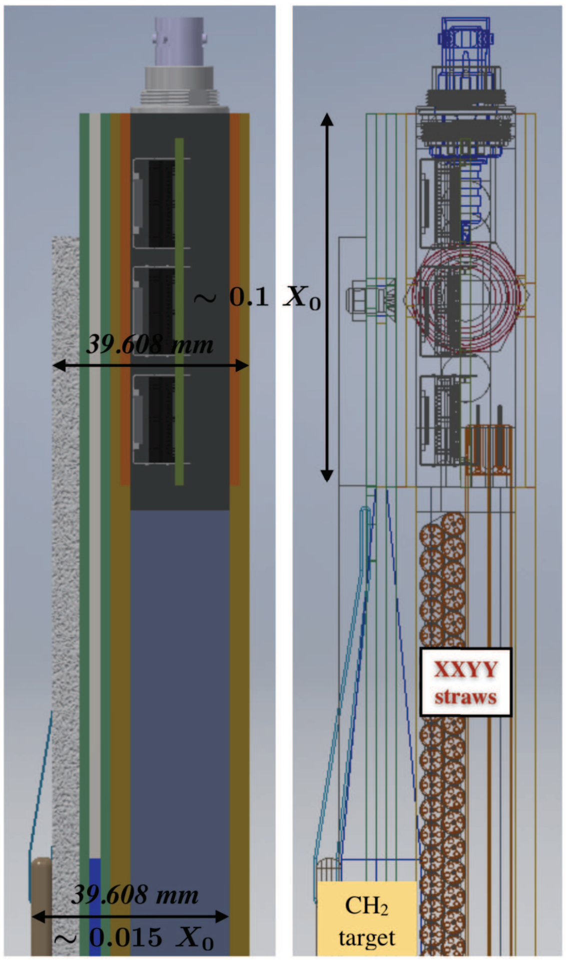
Comparing Ar and H measurements imposes stringent constraints on the nuclear smearing in Ar

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

CONTROL OF TARGETS

- Straw Tube Tracker designed for a control of ν-target(s) similar to $e^{\pm}$ DIS experiments:
  - Thin (1-2% X_0) passive target(s) separated from active detector (straw layers);
  - Target layers spread out uniformly within tracker by keeping low density $0.005 \leq \rho \leq 0.18$ g/cm^3.

$\Longrightarrow$ STT can be considered a precision instrument fully tunable/configurable



- Targets of high chemical purity give ~ 97% of STT mass (straws 3%)
- Separation from excellent vertex, angular & timing resolutions.
- Thin targets replaceable during data taking: CH_2, C, Ca, Fe, Pb, etc.

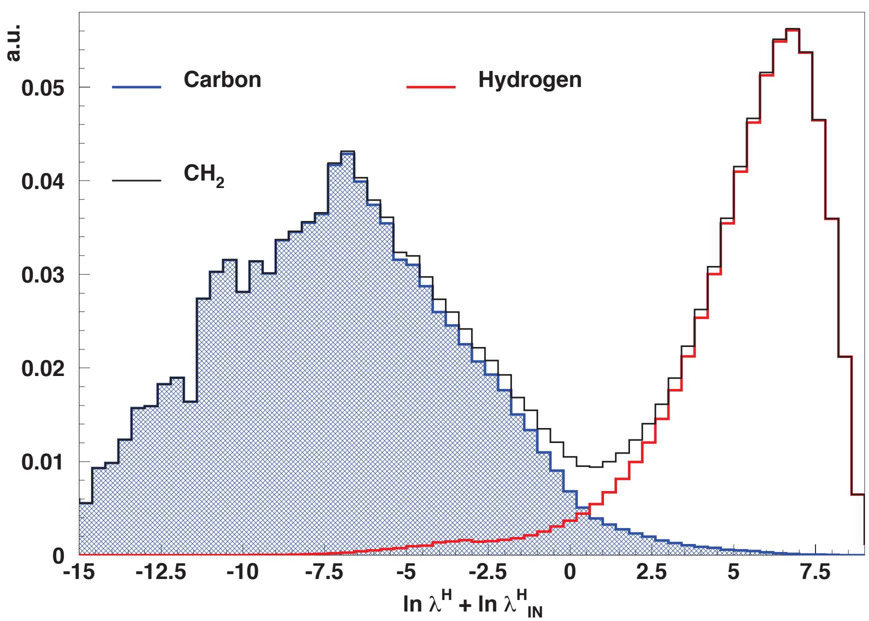
$\Longrightarrow$ Optimized & engineered design, extensive performance studies

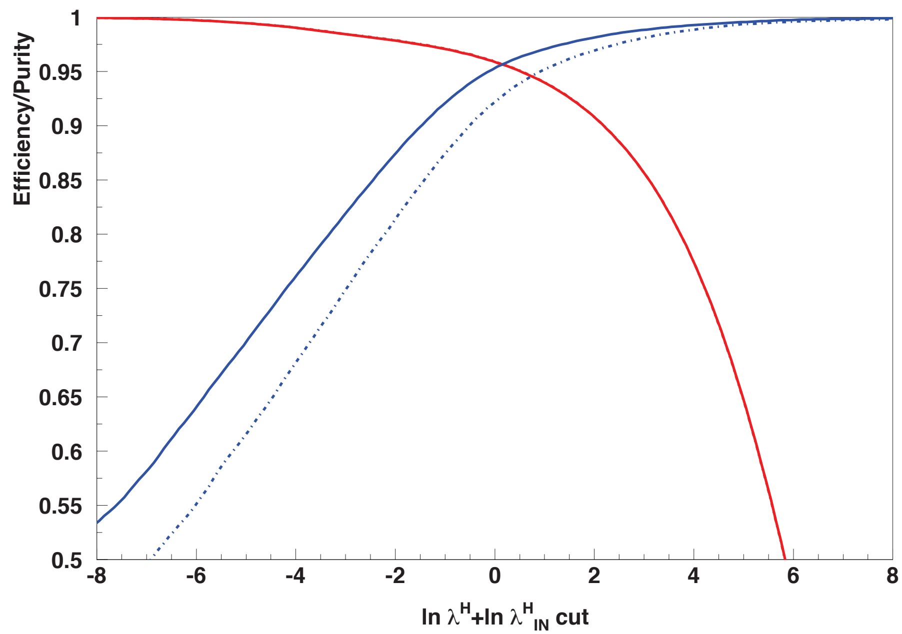
“SOLID” HYDROGEN TARGET

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

- *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 75-96% efficiency before subtraction.*

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





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

CC process (5y+5y)	CH_2 selected	C bkgnd	H selected	
$\nu_\mu p \to \mu^- p \pi^+$	2,148,000	107,000	2,041,000	
$\nu_\mu p \to \mu^- p \pi^+ X$	817,000	57,000	760,000	
$\nu_\mu p \to \mu^- n \pi^+ \pi^+ X$	134,000	41,000	93,000	
ν_μ CC inclusive on H	3,099,000	205,000	2,894,000	~579k / year
$\bar{\nu}_\mu p \to \mu^+ n$	1,078,000	216,000	862,000	
$\bar{\nu}_\mu p \to \mu^+ p \pi^-$	320,000	16,000	304,000	
$\bar{\nu}_\mu p \to \mu^+ n \pi^0$	250,000	41,000	209,000	
$\bar{\nu}_\mu p \to \mu^+ p \pi^- X$	143,000	8,000	135,000	
$\bar{\nu}_\mu p \to \mu^+ n \pi \pi X$	186,000	30,000	156,000	
$\bar{\nu}_\mu$ CC inclusive on H	1,977,000	311,000	1,666,000	~333k / year

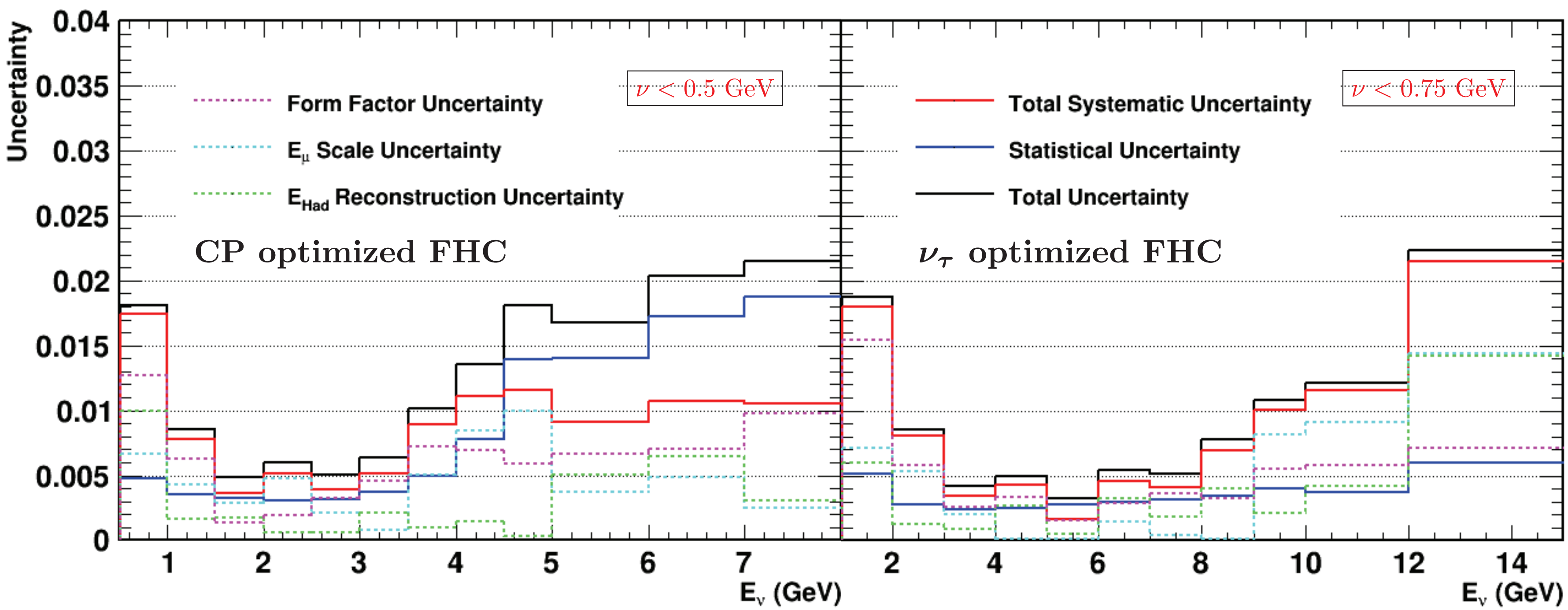
$\Longrightarrow$ *Exclusive and inclusive topologies on H can be selected kinematically in STT*

(largest statistics available about 13k νH and 6k $\bar{\nu} H$)

CONTROL OF FLUXES

- *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

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



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

GENERAL PURPOSE PHYSICS FACILITY

✦ *Possible to constrain main systematics (control of targets, fluxes, & nuclear effects) reducing 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): 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*

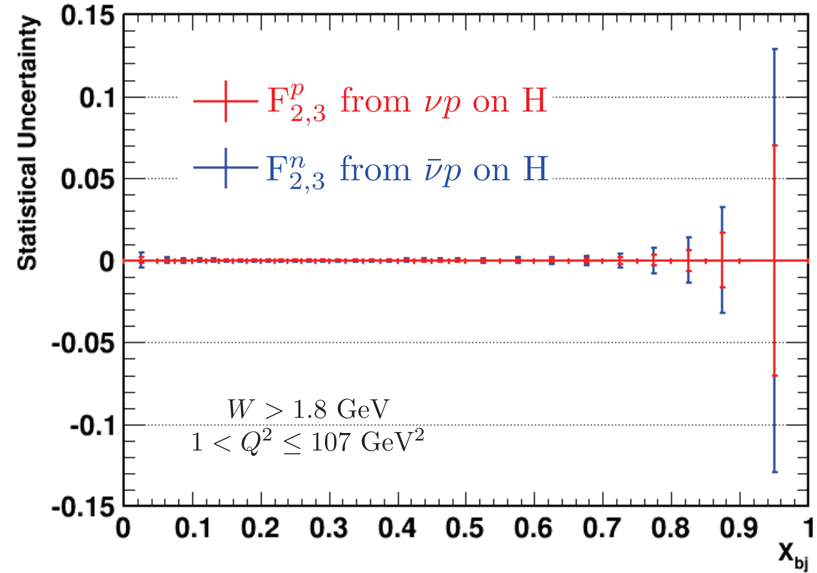
ADLER SUM RULE & ISOSPIN PHYSICS

✦ *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

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 & $\bar{\nu}$ ($W^{\pm}/Z$ helicity, C-parity, Isospin);*
- *Effect of the axial-vector current.*

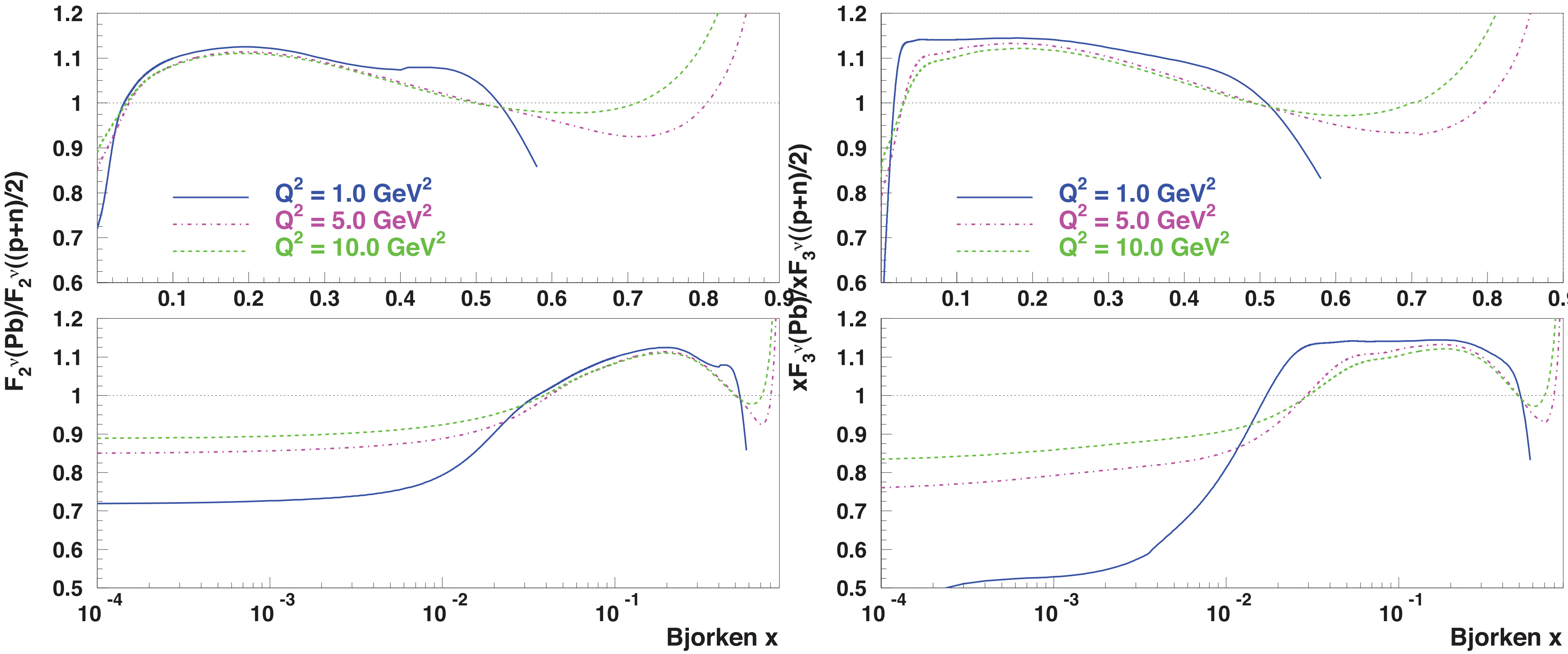
✦ *Study nuclear modifications to parton distributions in a wide range of Q^2 and x.*

✦ *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.*

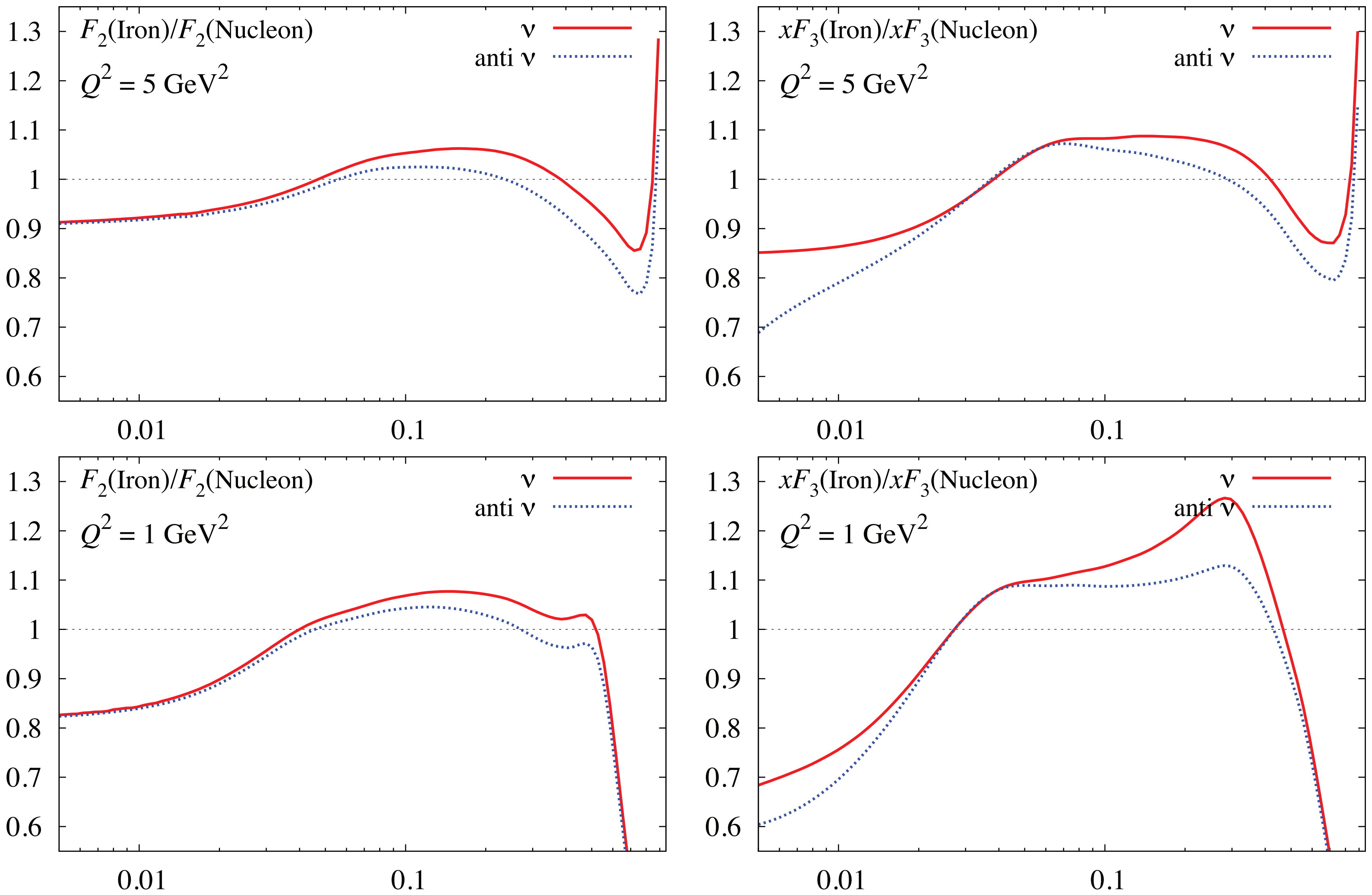
✦ *Coherent meson production off nuclei in CC & NC and diffractive physics.*

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



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

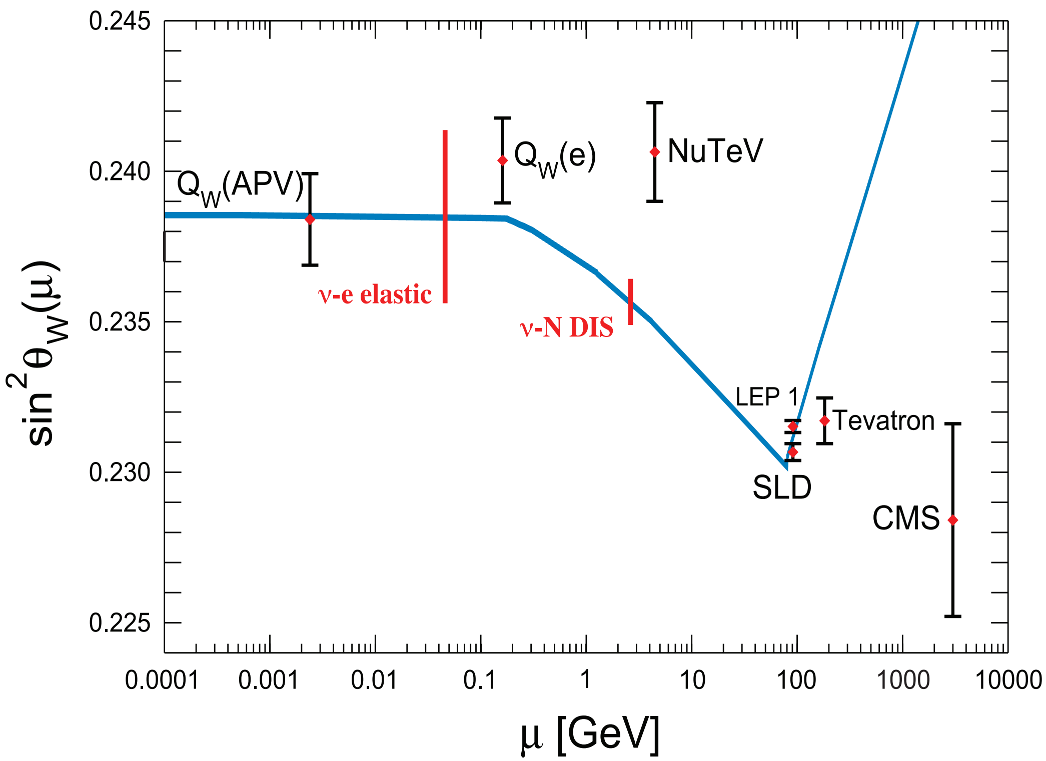


F2(Iron)/F2(Nucleon)
Q2 = 5 GeV2
ν
anti ν
xF3(Iron)/xF3(Nucleon)
Q2 = 5 GeV2
F2(Iron)/F2(Nucleon)
Q2 = 1 GeV2
xF3(Iron)/xF3(Nucleon)
Q2 = 1 GeV2
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.01
0.1

ELECTROWEAK MEASUREMENTS

✦ *Complementarity with colliders & low-energy measurements:*

- *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:*

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

✦ *Achievable sensitivity depending upon HE beam exposure*

SUMMARY

- *Availability of complementary hydrogen targets necessary condition to reduce systematics from nuclear smearing in next-generation precision $\nu(\bar{\nu})$ measurements.*

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

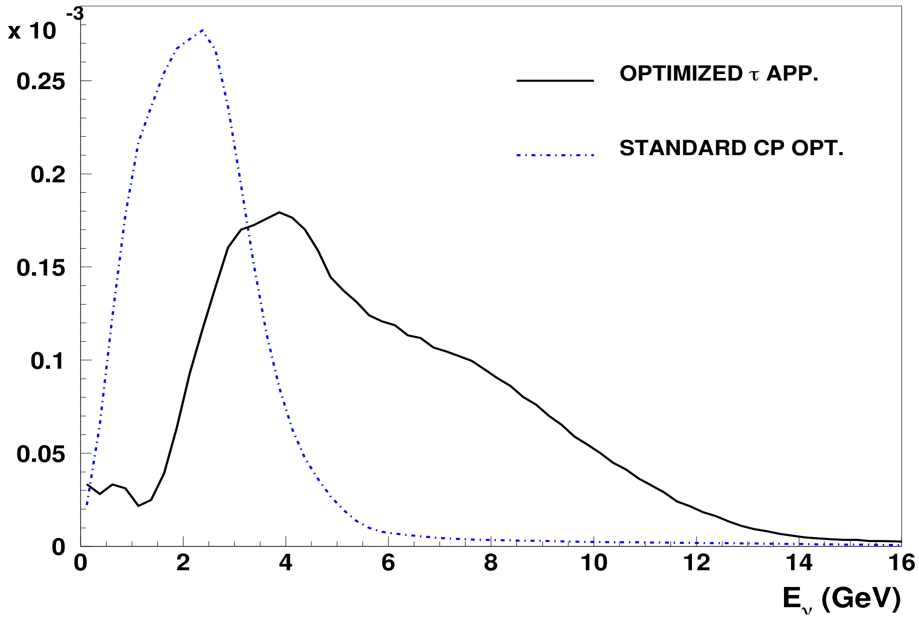
- *"Solid" hydrogen concept can provide high statistics $\mathcal{O}(10^6)$ samples of $\nu(\bar{\nu})$-hydrogen interactions, allowing precisions in the measurement of ν & $\bar{\nu}$ fluxes $< 1\%$.*

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

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

Backup slides

LBNF SPECTRA & STATISTICS

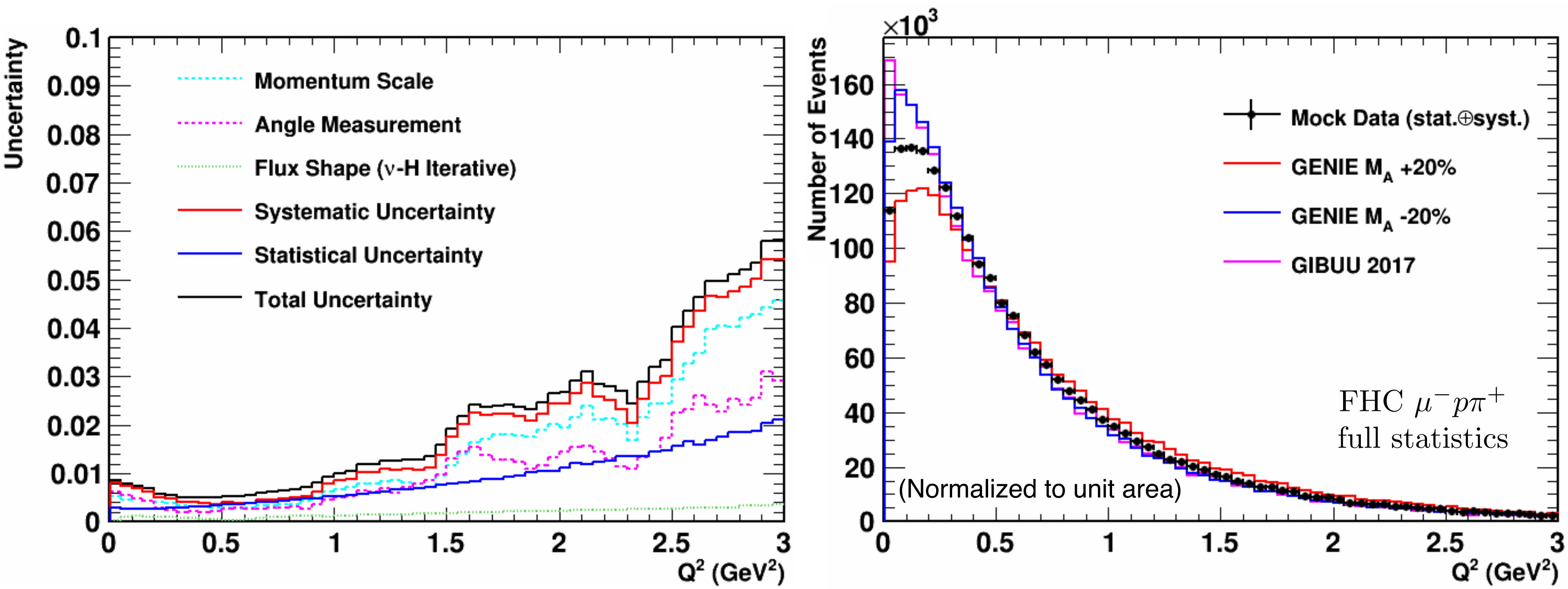


Interactions (5 tons)	CH_2
Standard CP optimized (1.2 MW):	
ν_μ CC (ν beam, 5 y)	33×10^6
$\bar{\nu}_\mu$ CC ($\bar{\nu}$ beam, 5 y)	12×10^6
Optimized ν_τ appearance (2.4 MW):	
ν_μ CC (ν beam, 2 y)	62×10^6
$\bar{\nu}_\mu$ CC ($\bar{\nu}$ beam, 2 y)	22×10^6

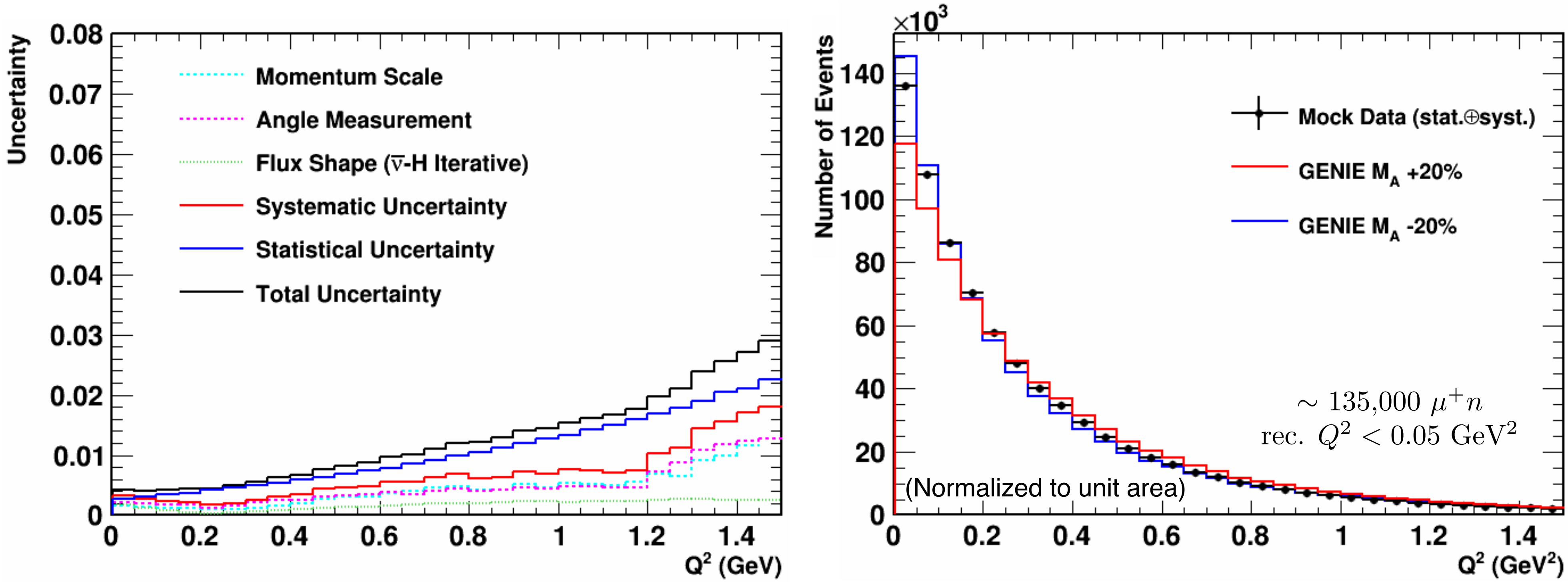
- *Two LBNF beam options: low-energy CP optimized & high-energy for ν_τ appearance*
  - *LBNF: 120 GeV p, 1.2 MW, 1.1×10^{21} pot/y, ND at 574m;*
  - *LBNF upgrade: 120 GeV p,* **2.4 MW (x 2)**, *∼3×10^{21} pot/y.*
- *Conceivable high-energy run after 5y ν + 5y $\bar{\nu}$ with the "standard" beams optimized for CP*

$\Longrightarrow$ *Can collect $\sim 10^8$ CC events with compact high-resolution detector ($\Delta E_\mu \leq 0.2\%$)*

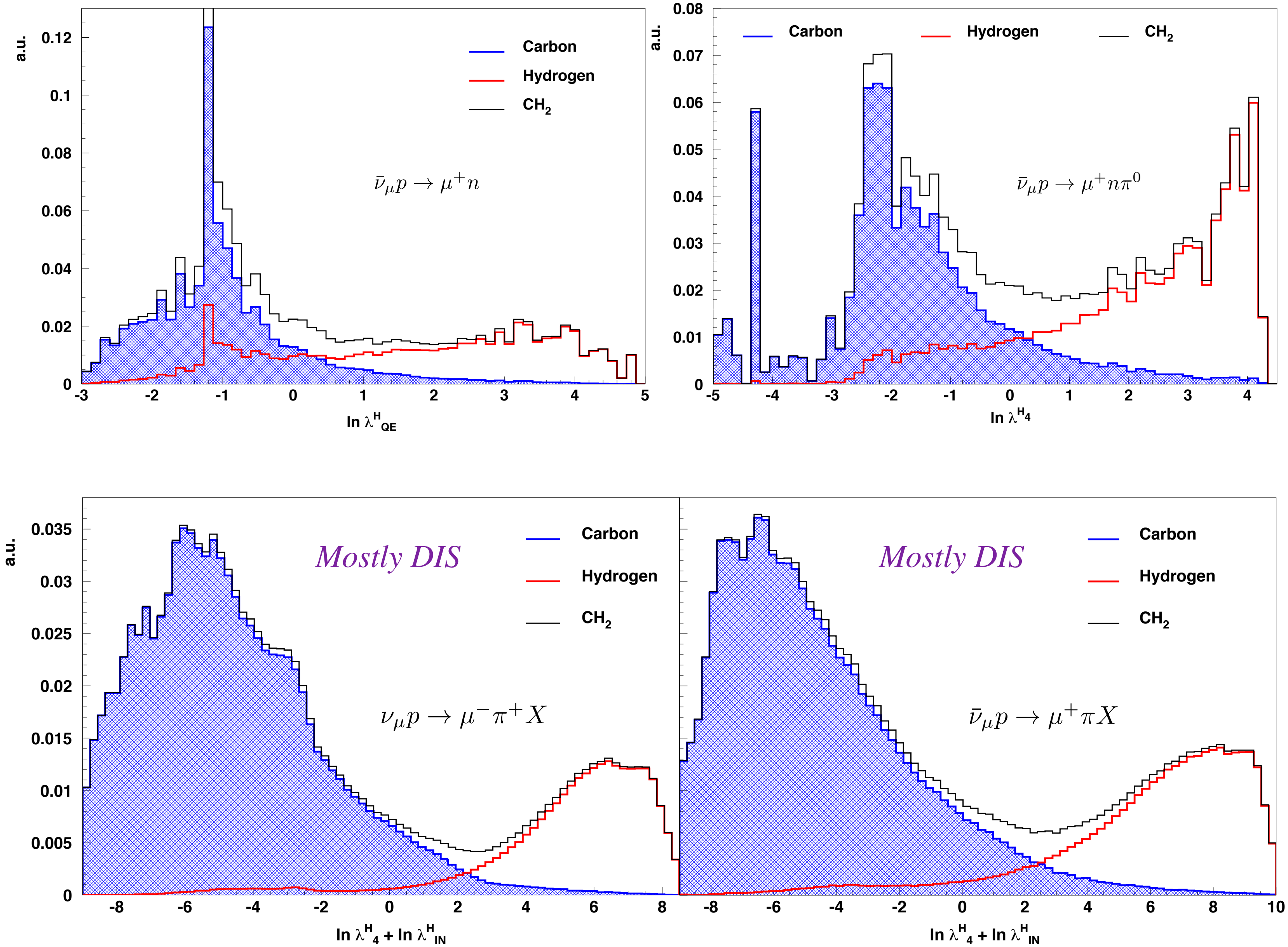
MEASUREMENT OF NUCLEON FORM FACTORS



Expected Q^2 distribution for $\nu_\mu p \to \mu^- p \pi^+$ on H (5y low-energy beam)



Expected Q^2 distribution for $\bar{\nu}_\mu p \to \mu^+ n$ QE on H (5y low-energy beam)

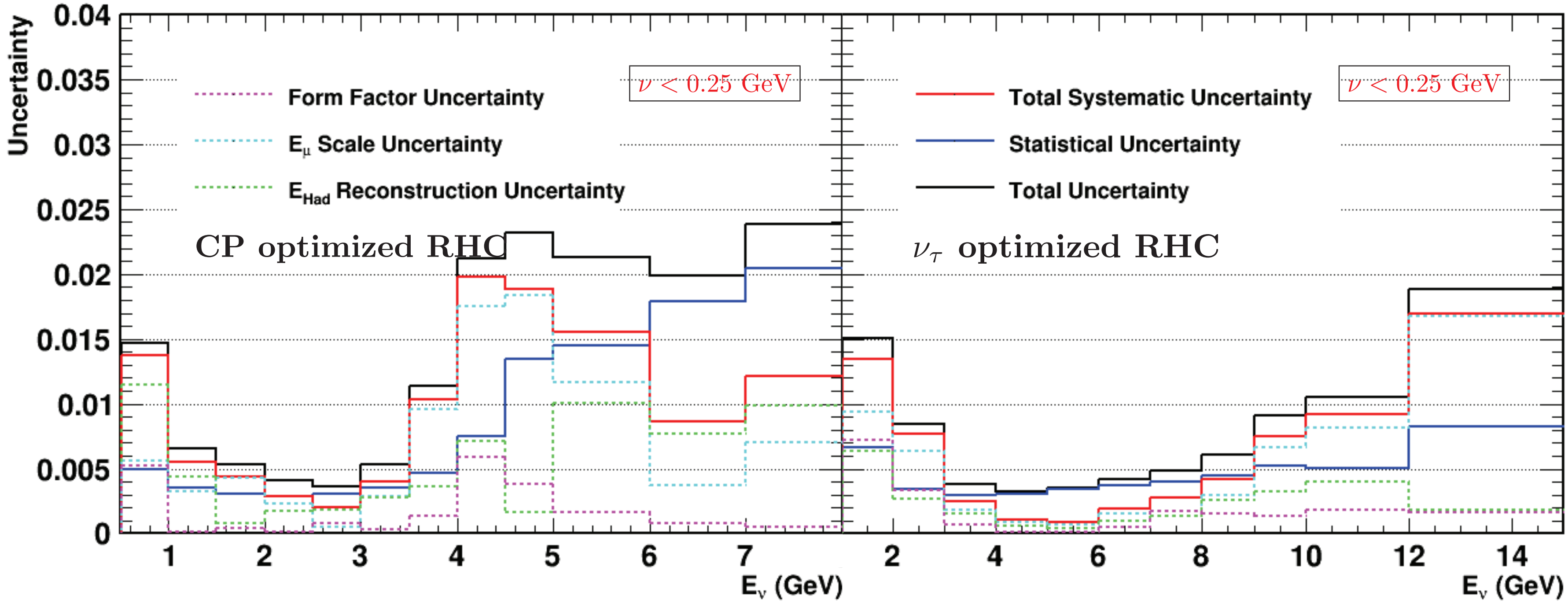


arXiv:1809.08752 [hep-ph]

✦ *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 + reconstructed direction of neutrons detected ($\sim 80\%$);*
- *Cut* $\nu < 0.25$ *GeV flattens cross-sections reducing uncertainties on* E_ν *dependence;*
- *Efficient rejection of random neutrons from external interactions (rocks, magnet) within the spill.*

$\Longrightarrow$ *Uncertainties comparable to relative ν_μ flux from $\nu_\mu p \to \mu^- p \pi^+$ on H*



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

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

- *At $Q^2 = 0$ QE cross-section determined by neutron β-decay to a precision $\ll 1\%$;*
- *Select reconstructed QE events with $Q^2 < 0.05$ GeV^2: ∼27,000 events/year with default RHC.*

$\Longrightarrow$ *Calibrate absolute n detection efficiency with dedicated irradiation of detector*