Precision Measurements of $\nu(\bar{\nu})$-H Interactions at LBNF

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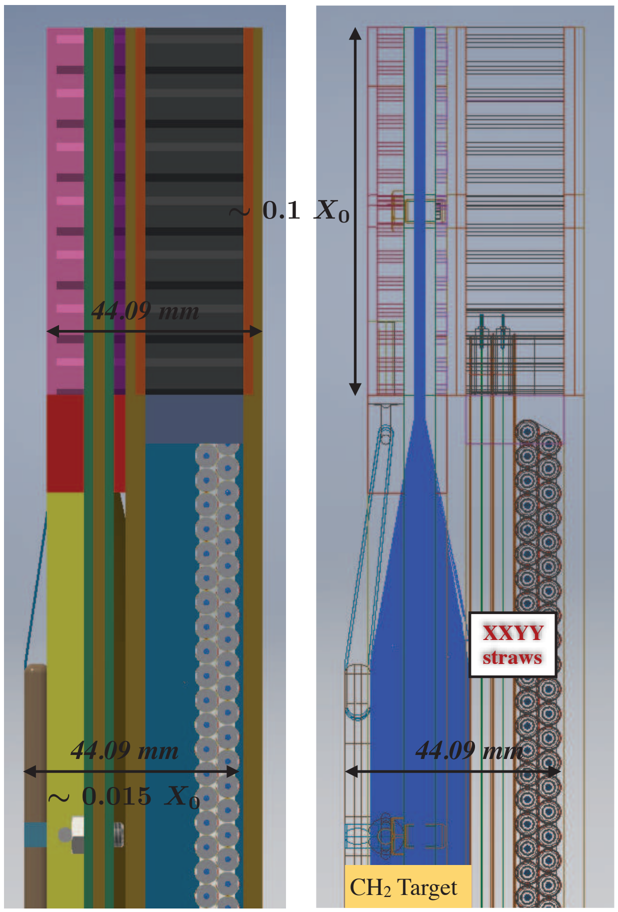
CONTROL OF TARGETS

✦ *High resolution detector providing 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* $0.005 \leq \rho \leq 0.18$ *g/cm^3*.

$\Longrightarrow$ *Straw Tube Tracker (STT) in $B \sim 0.6T$ 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.*

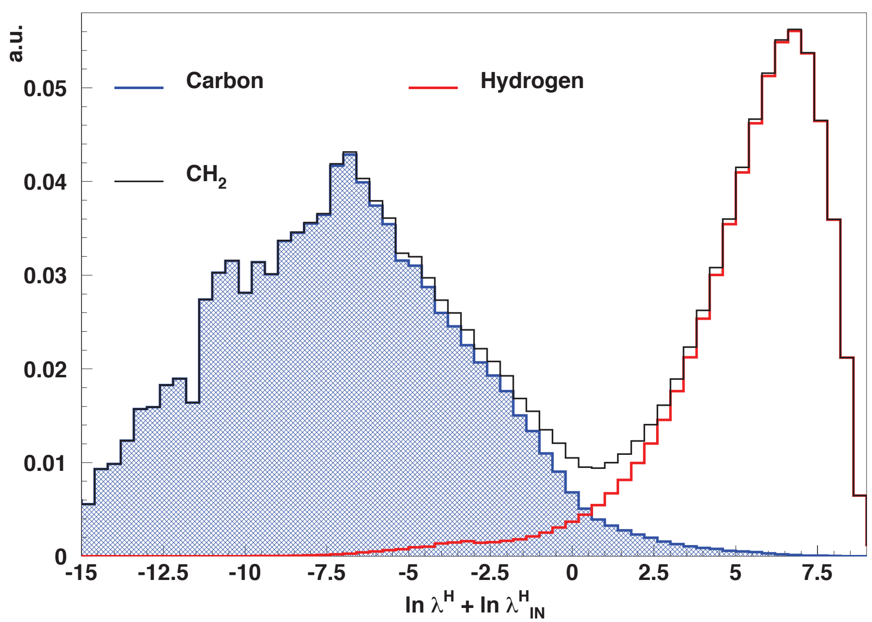
arXiv:1910.05995 [hep-ex]

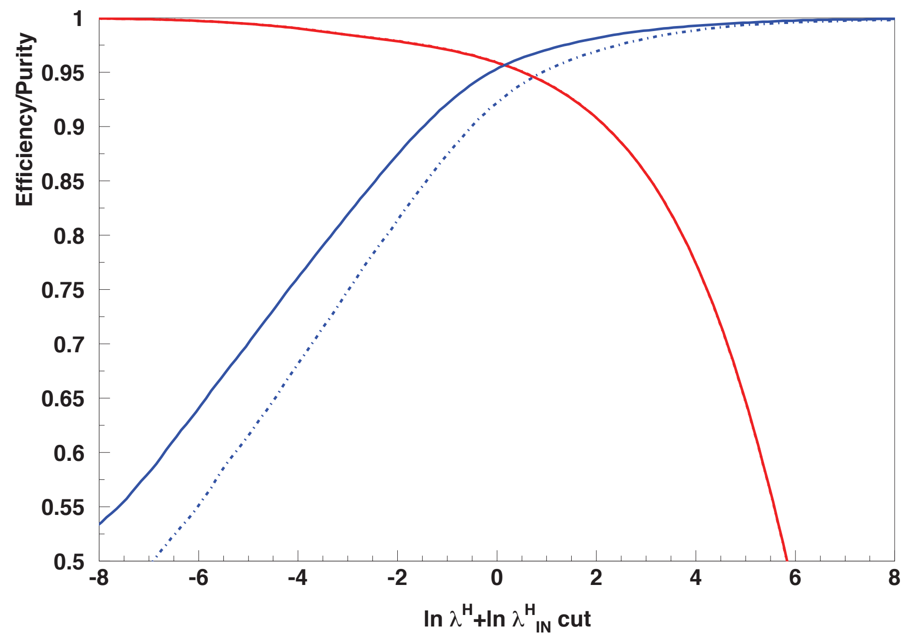
SOLID HYDROGEN TARGET

✦ *$\nu(\bar{\nu})$-Hydrogen by subtracting CH_2 and C targets after kinematic selection:*

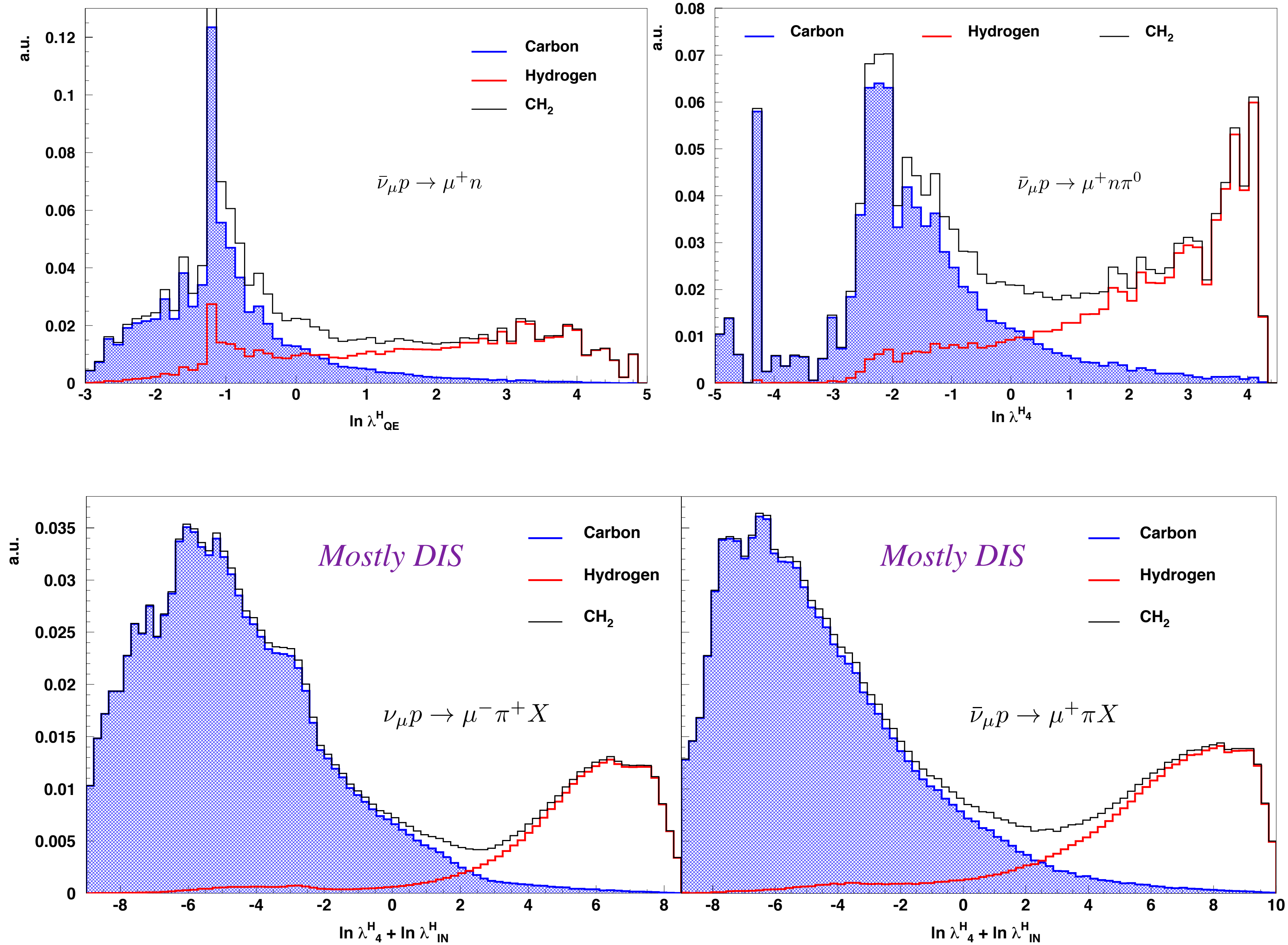
- *Exploit high resolutions & control of chemical composition and mass of targets in STT;*
- *Model-independent data subtraction of dedicated C (graphite) target from main CH_2 target;*
- *Kinematic selection provides large H samples of inclusive & exclusive CC topologies with 80-95% purity and >90%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


a.u.
Carbon
Hydrogen
CH$_2$
$\bar{\nu}_\mu p \rightarrow \mu^+ n$
ln λ^H_{QE}
$\bar{\nu}_\mu p \rightarrow \mu^+ n \pi^0$
ln λ^{H_4}
Mostly DIS
$\nu_\mu p \rightarrow \mu^- \pi^+ X$
$\bar{\nu}_\mu p \rightarrow \mu^+ \pi X$
ln λ^H_4 + ln λ^H_{IN}

Process	ν_μ-H CC				$\bar{\nu}_\mu$-H CC					
	$\mu^- p\pi^+$	$\mu^- p\pi^+ X$	$\mu^- n\pi^+\pi^+ X$	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 $\ln\lambda^{\rm H}+\ln\lambda^{\rm H}_{\rm IN}$ or $\ln\lambda^{\rm H}_4+\ln\lambda^{\rm H}_{\rm IN}$. For the $\mu^+ n$ QE topologies $\ln\lambda^{\rm H}_{\rm QE}$ 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.

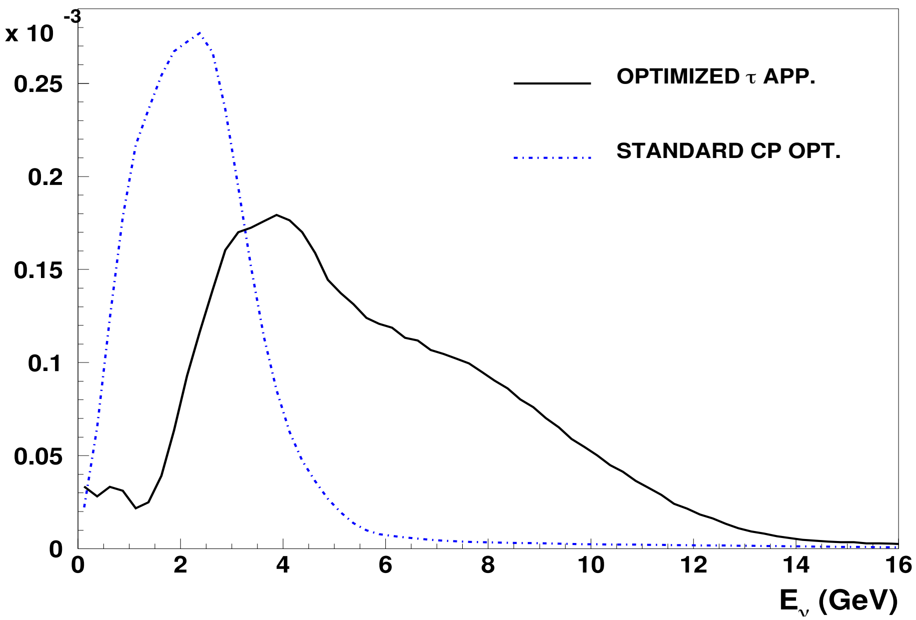
Process	ν_μ-H CC, $\varepsilon \equiv 75\%$				$\bar{\nu}_\mu$-H CC, $\varepsilon \equiv 75\%$					
	$\mu^- p\pi^+$	$\mu^- p\pi^+ X$	$\mu^- n\pi^+\pi^+ X$	Inclusive	$\mu^+ p\pi^-$	$\mu^+ n\pi^0$	$\mu^+ n$	$\mu^+ p\pi^- X$	$\mu^+ n\pi\pi X$	Inclusive
Purity	99%	99%	70%	98%	99%	90%	80%	98%	90%	86%

TABLE II. Purity achieved with the kinematic selection of H interactions from the CH_2 plastic target using a cut on the likelihood ratio $\ln\lambda^{\rm H}+\ln\lambda^{\rm H}_{\rm IN}$ or $\ln\lambda^{\rm H}_4+\ln\lambda^{\rm H}_{\rm IN}$ resulting in the fixed H signal efficiency ε specified. For the $\mu^+ n$ QE topologies $\ln\lambda^{\rm H}_{\rm QE}$ 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.

CC process	CH_2 target	H target	CH_2 selected	C bkgnd	H selected
$\nu_\mu p \to \mu^- p \pi^+$	5,615,000	2,453,000	2,305,000	115,000	2,190,000
$\nu_\mu p \to \mu^- p \pi^+ X$	11,444,000	955,000	877,000	61,000	816,000
$\nu_\mu p \to \mu^- n \pi^+ \pi^+ X$	3,533,000	183,000	158,000	48,000	110,000
ν_μ CC inclusive	34,900,000	3,591,000	3,340,000	224,000	3,116,000
$\bar{\nu}_\mu p \to \mu^+ n$	4,450,000	1,688,000	1,274,000	255,000	1,019,000
$\bar{\nu}_\mu p \to \mu^+ p \pi^-$	827,000	372,000	342,000	17,000	325,000
$\bar{\nu}_\mu p \to \mu^+ n \pi^0$	791,000	366,000	295,000	48,000	247,000
$\bar{\nu}_\mu p \to \mu^+ p \pi^- X$	2,270,000	176,000	153,000	9,000	144,000
$\bar{\nu}_\mu p \to \mu^+ n \pi \pi X$	2,324,000	280,000	220,000	35,000	185,000
$\bar{\nu}_\mu$ CC inclusive	13,000,000	2,882,000	2,284,000	364,000	1,920,000

TABLE III. Number of events expected in the selection of all the various processes on H with the default low energy (anti)neutrino beams available at the LBNF [1, 2], assuming 5+5 years of data taking with the neutrino and antineutrino beams. The first two columns (CH_2 and H targets) refer to the initial statistics, while the last three include all selection cuts described in this paper (Sec. III and Tab. I). For the CH_2 and C targets the numbers refer to the given final state topologies originated from either p or n interactions. The fifth column shows the total residual C background to be subtracted from the corresponding CH_2 selected samples. We use a ratio $M_C/M_{C/CH_2} = 0.12$ to measure the C backgrounds from the graphite targets. See the text for details.

BEAM SPECTRA & EXPOSURES



Process	Events (5t CH_2) CH_2	H
Standard CP optimized (1.2 MW):		
ν_μ CC (FHC, 5 y)	35×10^6	3.6×10^6
$\bar{\nu}_\mu$ CC (RHC, 5 y)	13×10^6	2.9×10^6
Optimized ν_τ appearance (2.4 MW):		
ν_μ CC (FHC, 2 y)	66×10^6	6.5×10^6
$\bar{\nu}_\mu$ CC (RHC, 2 y)	24×10^6	4.3×10^6

✦ *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*

RESOLUTIONS & CALLIBRATIONS

✦ *Excellent angular, momentum & timing resolution:*

- *Low density design for accurate tracking;*
- $\delta\theta \sim$ *1-2 mrad,* $\delta p/p \sim$ *3-5% with default density* $\rho \sim 0.18$ *g/cm*^{3}*;*
- *Time resolution* $\sim 1ns$*, can resolve beam structure & withstand high rates (max. drift* $\sim$ *50* ns*).*

✦ e^+/e^- *& other particle ID over the entire tracking volume:*

- *Electron ID with Transition Radiation (TR) and dE/dx* $\Longrightarrow \pi$ *rejection* $\sim 10^{-3}$*;*
- 4π *detection of* π^0 *from* γ *conversions (*$\sim 50\%$*) within the STT volume;*
- $p/\pi/K$ *ID with dE/dx and range.*

✦ *Accurate in-situ calibrations of momentum & angle reconstruction:*

- *Momentum scale from* $K_0 \to \pi^+\pi^-$ *in STT volume (264,000 in FHC);*
- *p reconstruction and identification, vertex, etc. from* $\Lambda \to p\pi^-$ *in STT volume (293,000 in FHC);*
- $e^\pm$ *reconstruction and identification from* $\gamma \to e^+e^-$ *in STT volume (*8×10^6 *in FHC).*

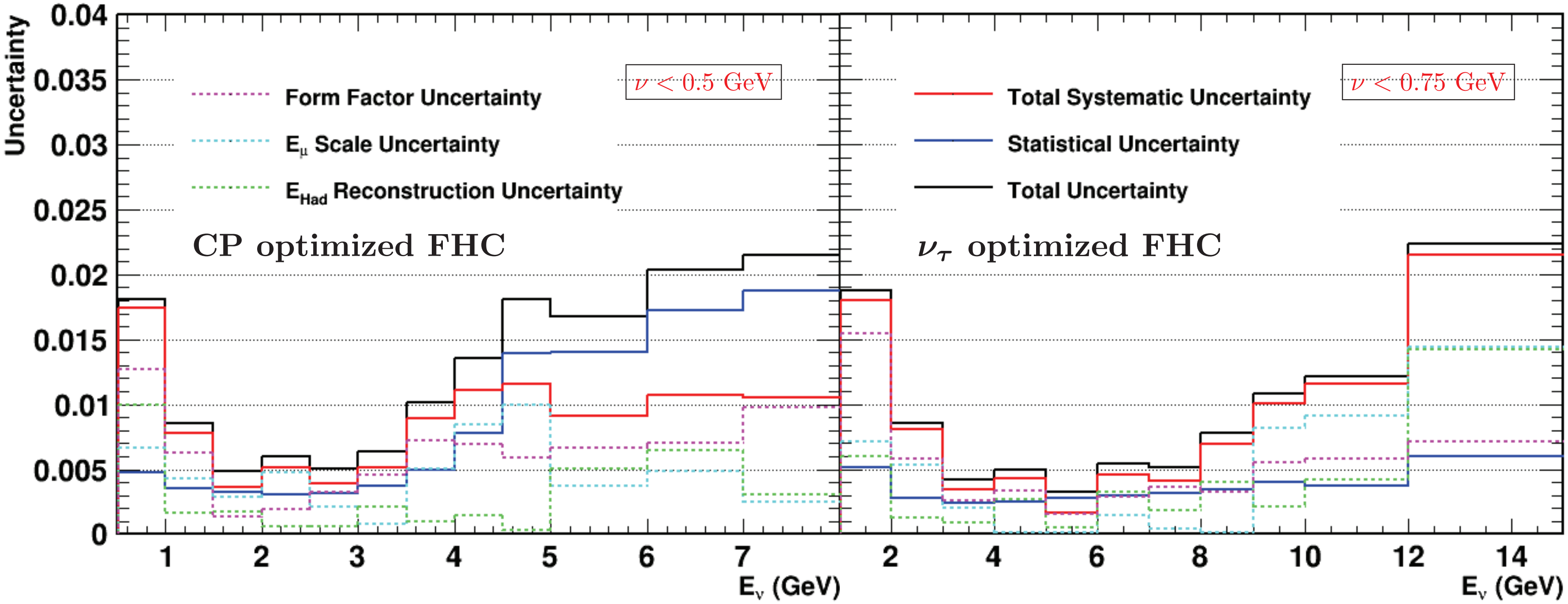
$\Longrightarrow$ *Momentum scale uncertainty* $< 0.2\%$ *(NOMAD)*

CONTROL OF FLUXES

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

- *Well reconstructed tracks for $\mu^- p \pi^+$ 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).*

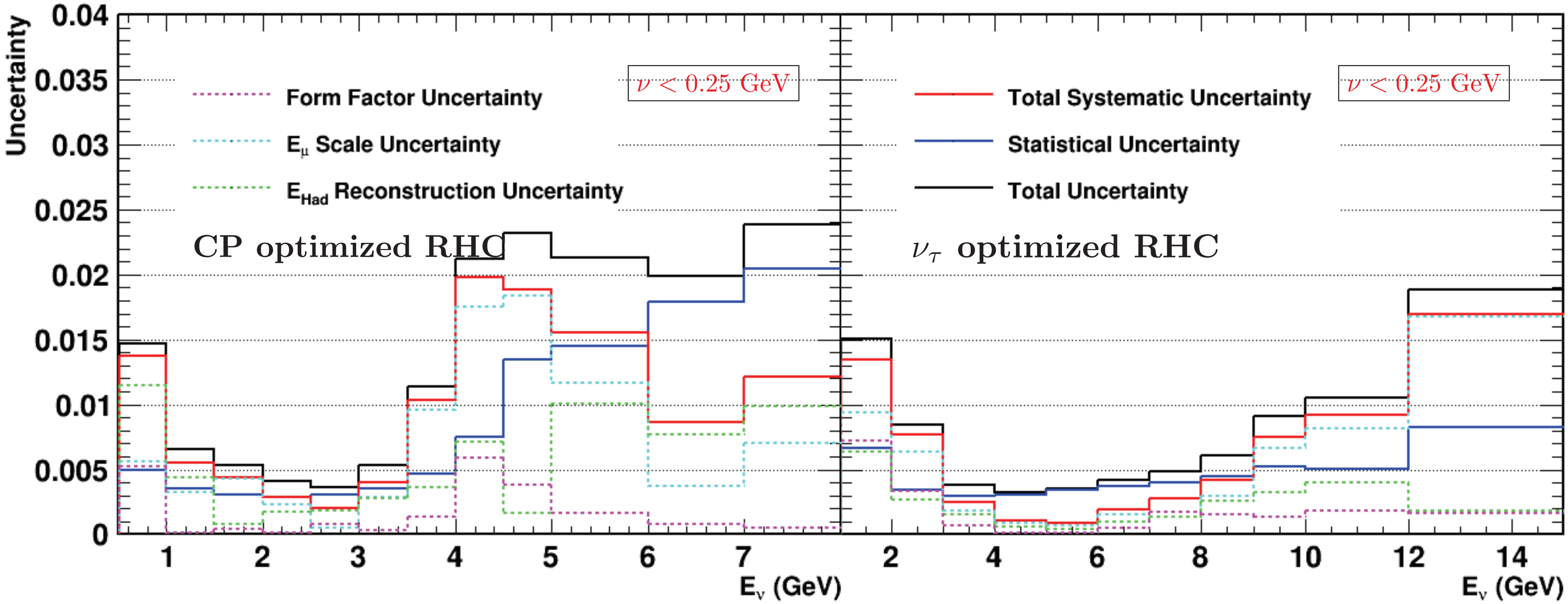
$\Longrightarrow$ *Dramatic reduction of systematics vs. techniques using nuclear targets*



H. Duyang, B. Guo, S.R. Mishra, RP, PLB 795 (2019) 424, arXiv:1902.09480 [hep-ph]

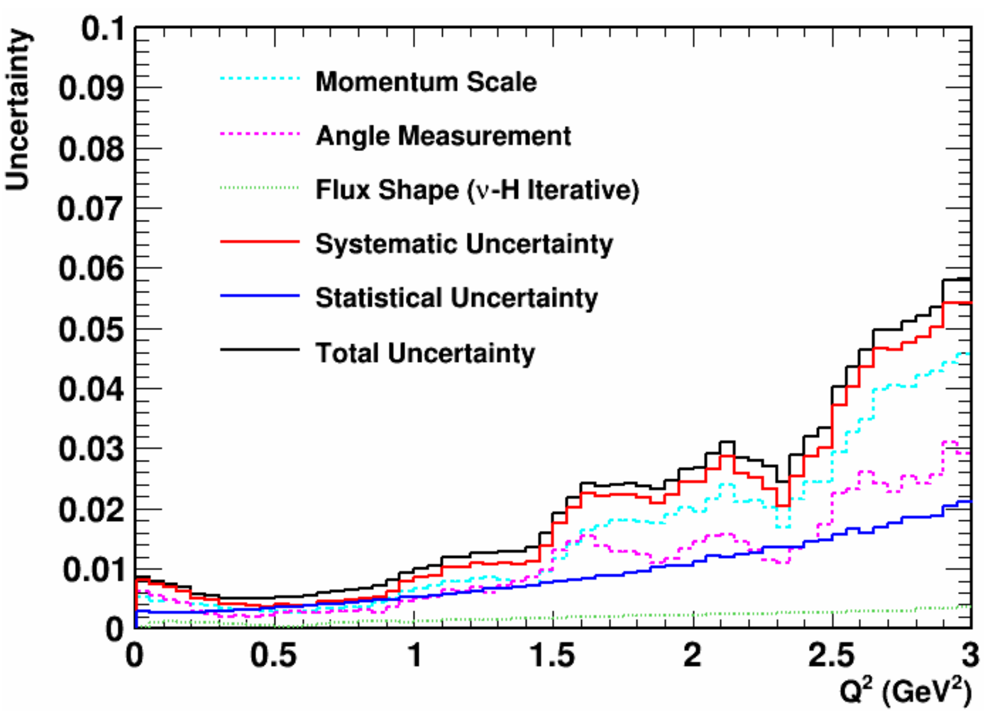
✦ *Relative $\bar{\nu}_\mu$ flux vs. E_ν from exclusive $\bar{\nu}_\mu p \to \mu^+ n$ QE on Hydrogen*:

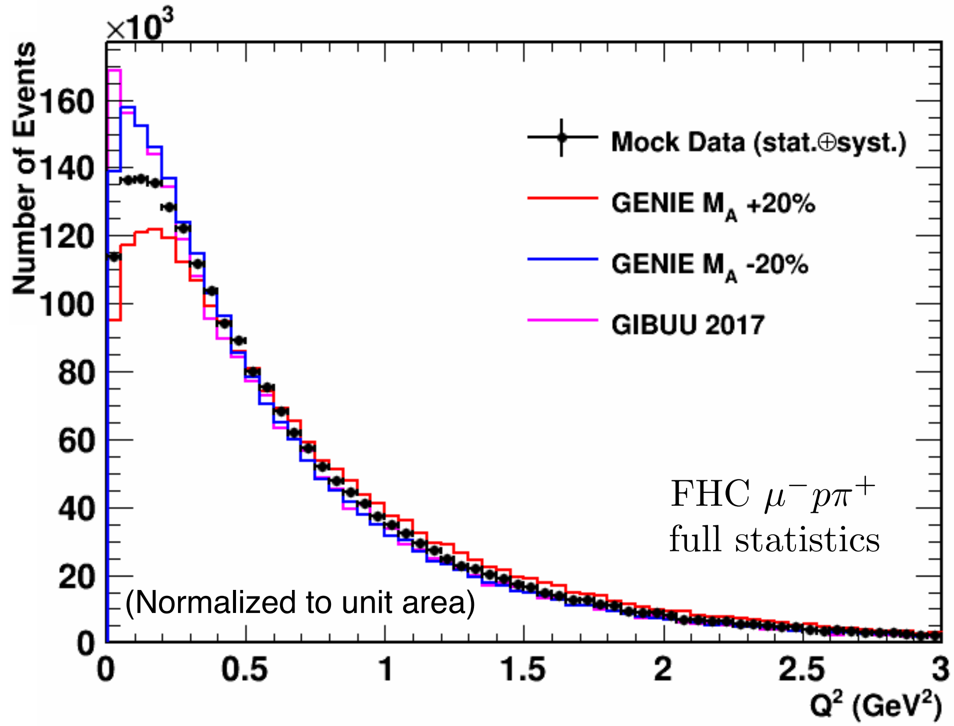
- E_ν *from QE kinematics on H and reconstructed direction of interacting neutrons;*
- *Cut* $\boxed{\nu < 0.1(0.25)\ \text{GeV}}$ *flattens cross-sections reducing uncertainties on* E_ν *dependence;*
- *Systematics and total uncertainties comparable to relative* ν_μ *flux from* $\nu_\mu p \to \mu^- p \pi^+$ *on H.*



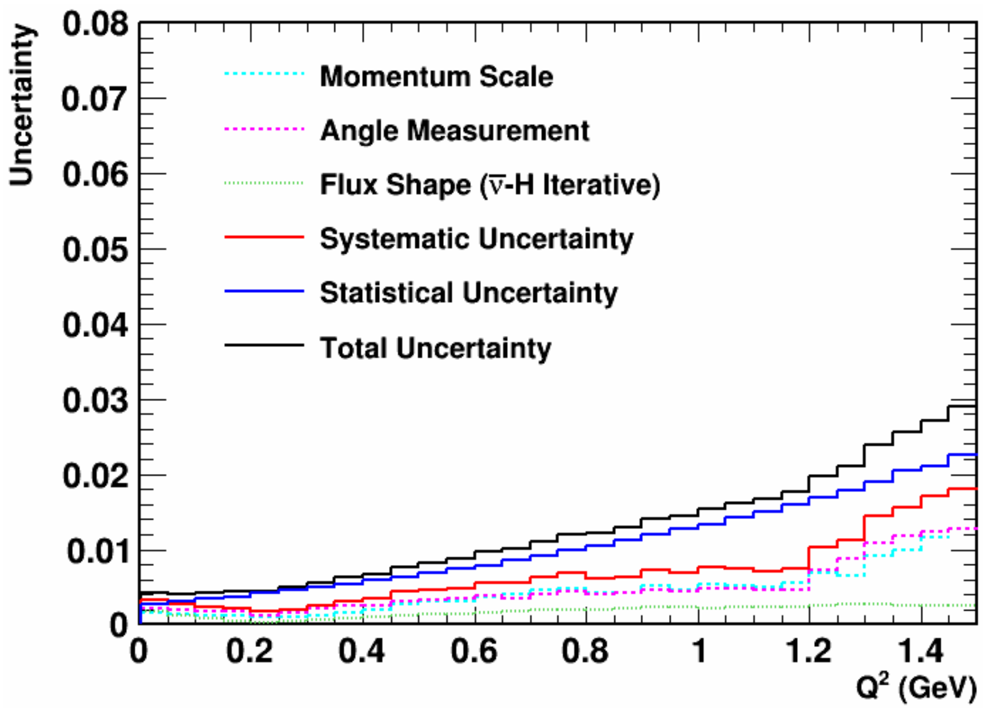
H. Duyang, B. Guo, S.R. Mishra, RP, PLB 795 (2019) 424, arXiv:1902.09480 [hep-ph]

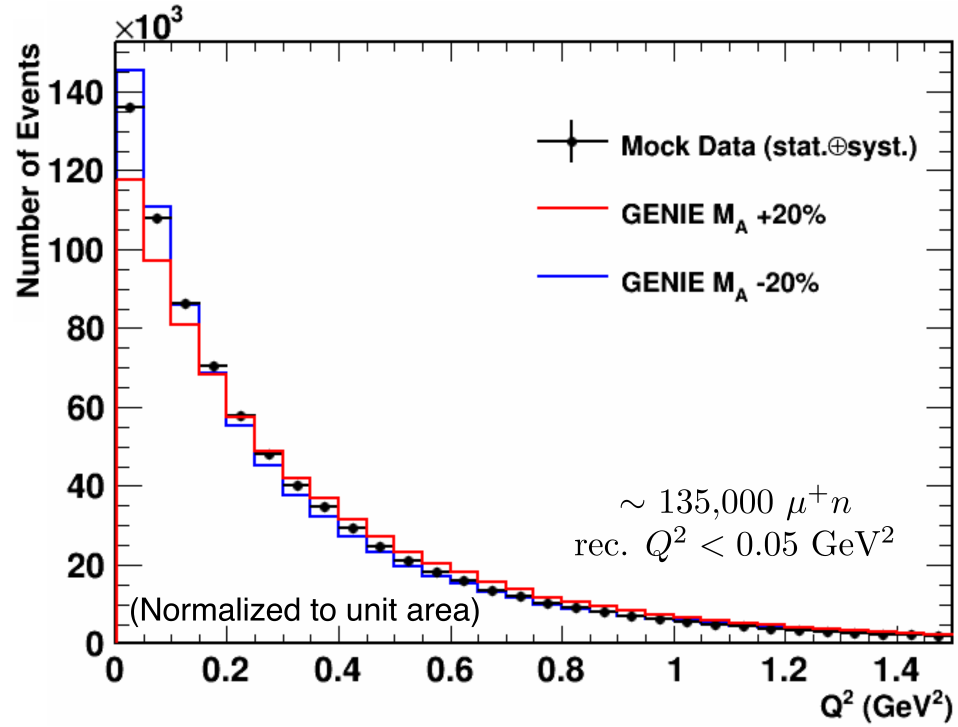
MEASUREMENT OF NUCLEON FORM FACTORS





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





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

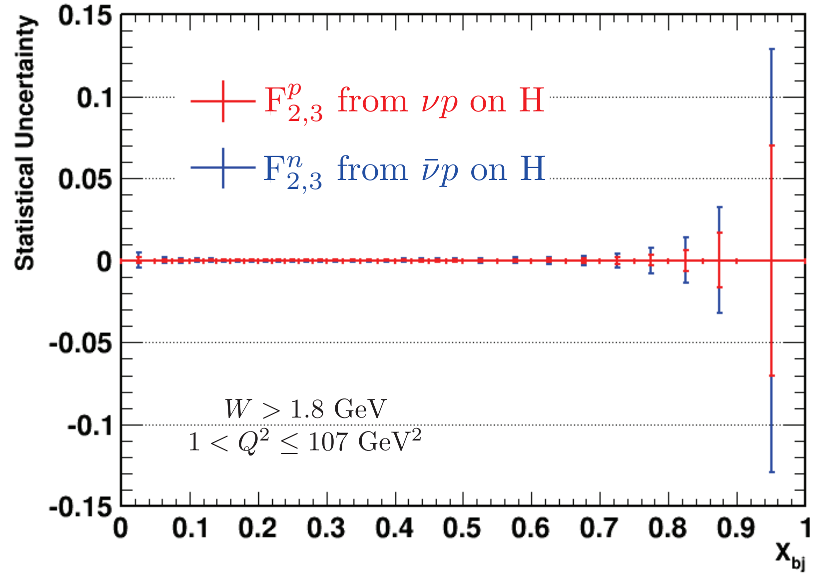
ADLER SUM RULE & ISOSPIN PHYSICS

- 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 $F_{2,3}$:*

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

- *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.*

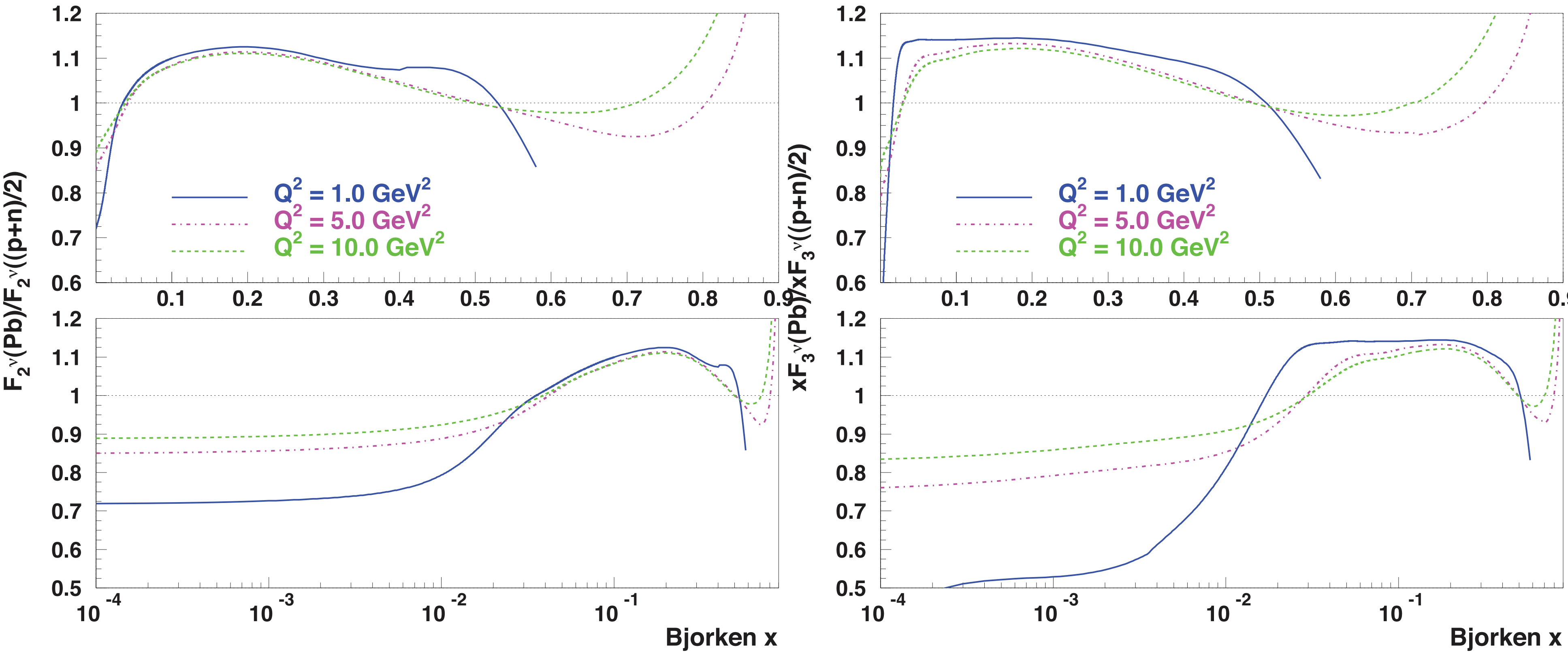
✦ *Study nuclear modifications to parton distributions in a wide range of Q^2 and x.*

✦ *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* $(p+n)/2$

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

SUMMARY

- *The intensity and $\nu(\bar{\nu})$ spectra available at the LBNF offer a unique opportunity for neutrino physics, with a detector offering a control of configuration, material & mass of neutrino targets similar to electron experiments & a suite of target materials.*

- *The solid hydrogen target 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 $< 1\%$.*

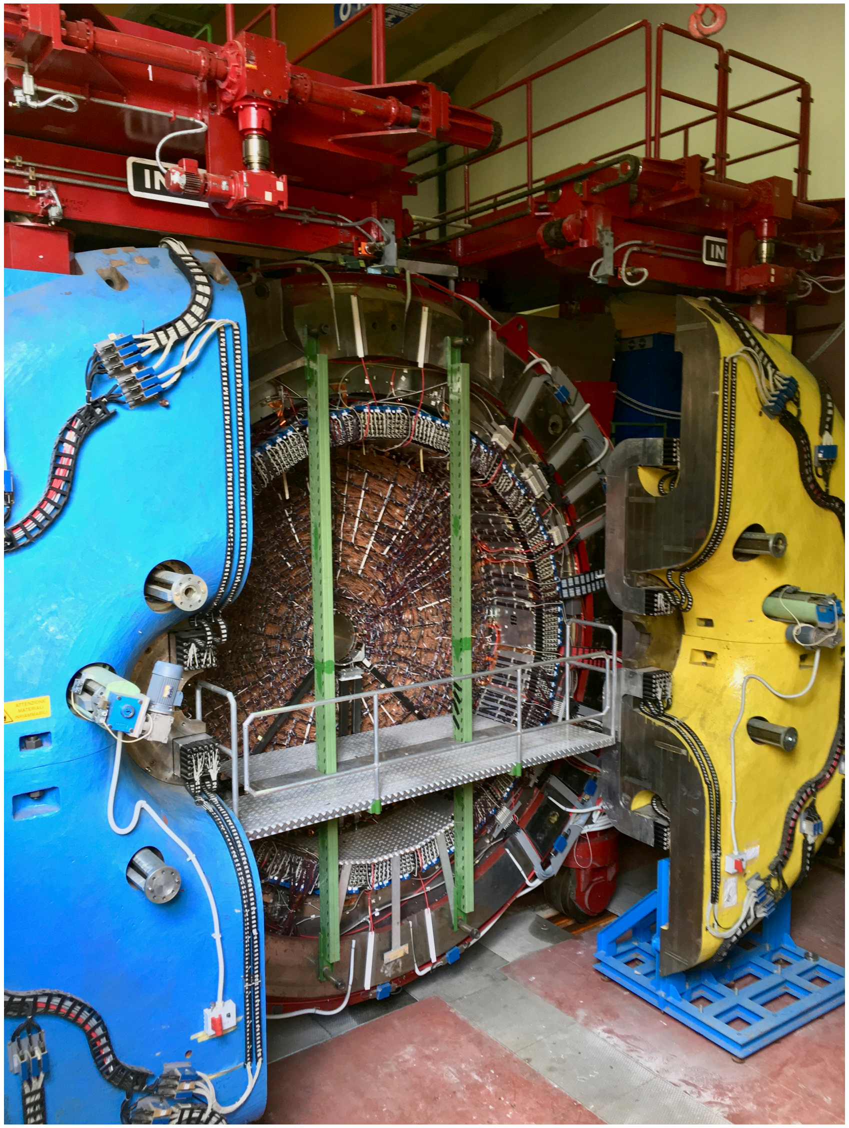
- *Turn the DUNE ND site into a general purpose ν & $\bar{\nu}$ physics facility with broad program complementary to ongoing fixed-target, collider and nuclear physics efforts*

  European Particle Physics Strategy Update 2018-2020 (# 131):

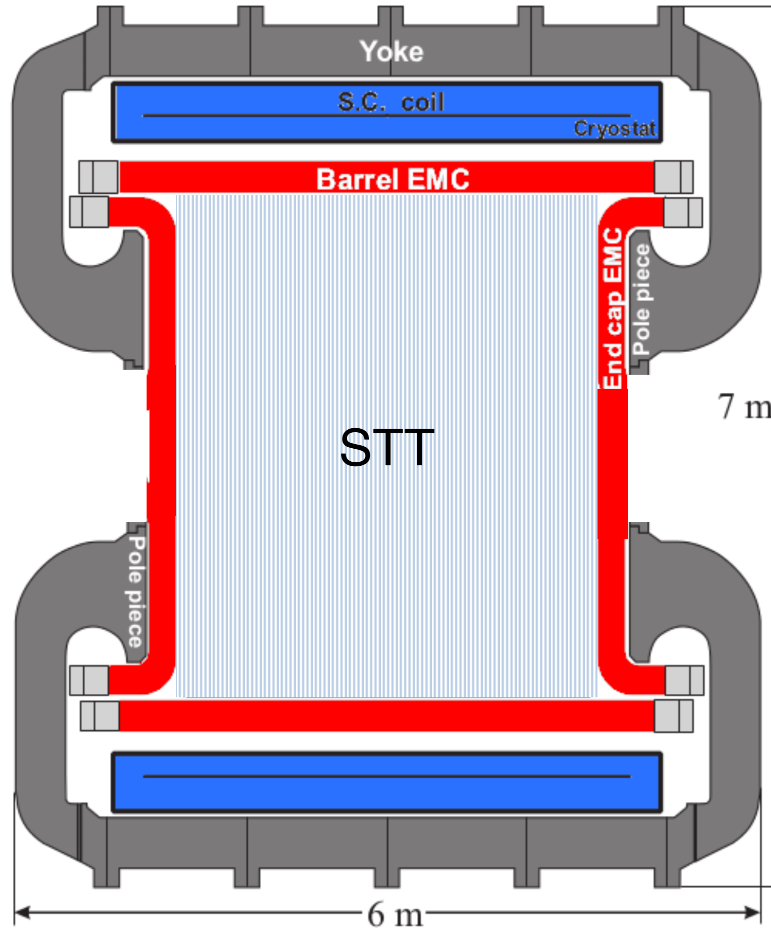
  `https://indico.cern.ch/event/765096/contributions/3295805/`

  $\Longrightarrow$ *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

[DUNE docdb #13262]

- *Interest & support from the community important to pursue the existing opportunity of precision measurements of $\nu(\bar{\nu})$-H at LBNF.*

- *Need to quantify the potential impact of the new $\nu(\bar{\nu})$-H samples on models and/or our understanding of various physics quantities.*

- *Expand the list of physics measurements enabled by the new $\nu(\bar{\nu})$-H samples.*

- *Experimental effort: prototypes, tests and detector construction.*

Welcome suggestions, feedback and/or potential interest

Backup slides