Precision Measurements with (Anti)Neutrinos at LBNF

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LoI: SNOWMASS21-NF5-NF6-EF6-EF4-RF1-RF6-122

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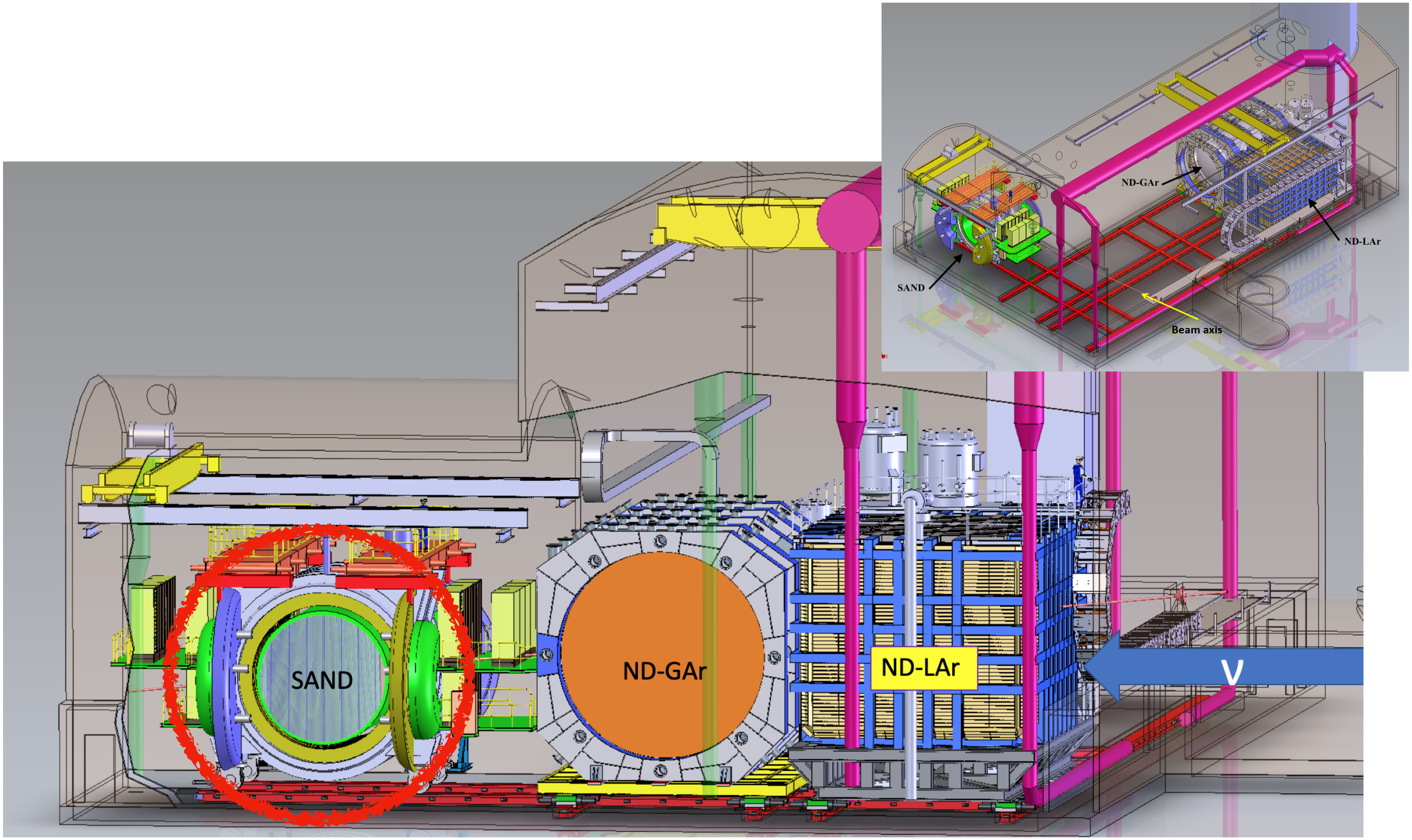
NEAR DETECTOR COMPLEX IN DUNE



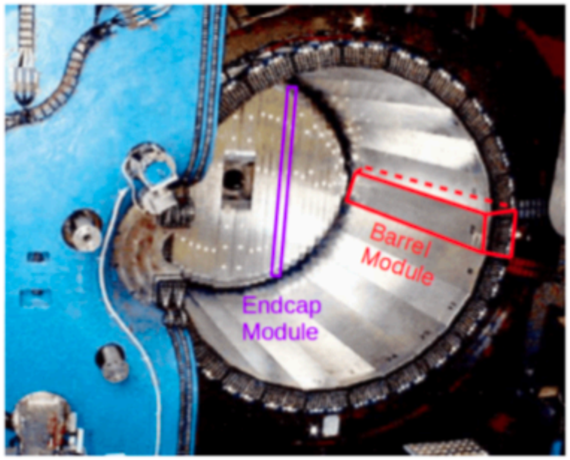
TRACKER FOR ON-AXIS ND IN DUNE

✦ *System for on-Axis Neutrino Detection (SAND) part of reference Near Detector (ND) complex in Deep Underground Neutrino Experiment (DUNE) at LBNF:*

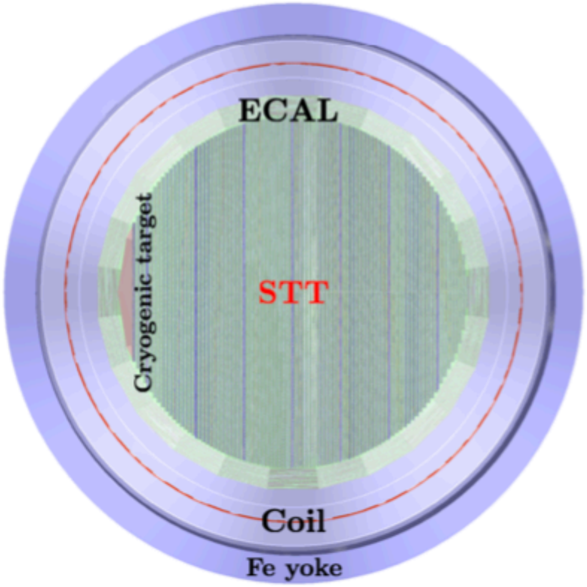
- *Repurposed superconducting magnet (0.6 T) & electromagnetic calorimeter from KLOE experiment;*
- *STT + upstream thin cryogenic target option considered for inner tracker (fiducial mass ~5 tons).*

✦ *Proposal with design, simulations, reconstruction, physics sensitivity studies, etc. (DUNE DocDb # 13262)*

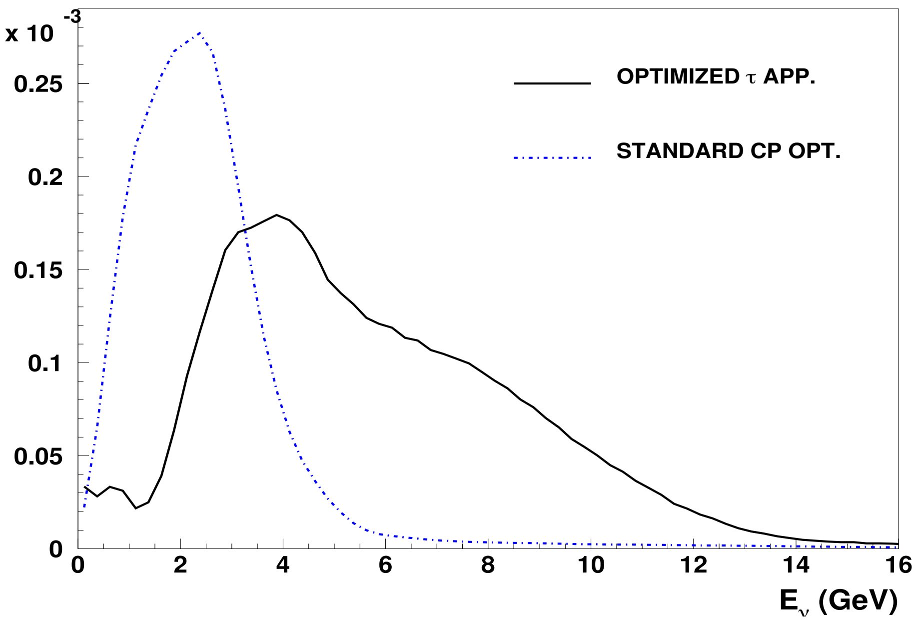
LoI submitted to Snowmass 2021, contribution 122 to neutrino physics frontier, European Particle Physics Strategy Update 2018-2020, contribution 131.



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



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 (HE) 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 , $\sim3\times10^{21}$ pot/y,* **HE EVTS $\times5$**.
- *Conceivable high-energy run after 5y ν + 5y $\bar{\nu}$ with the "standard" beams optimized for CP*

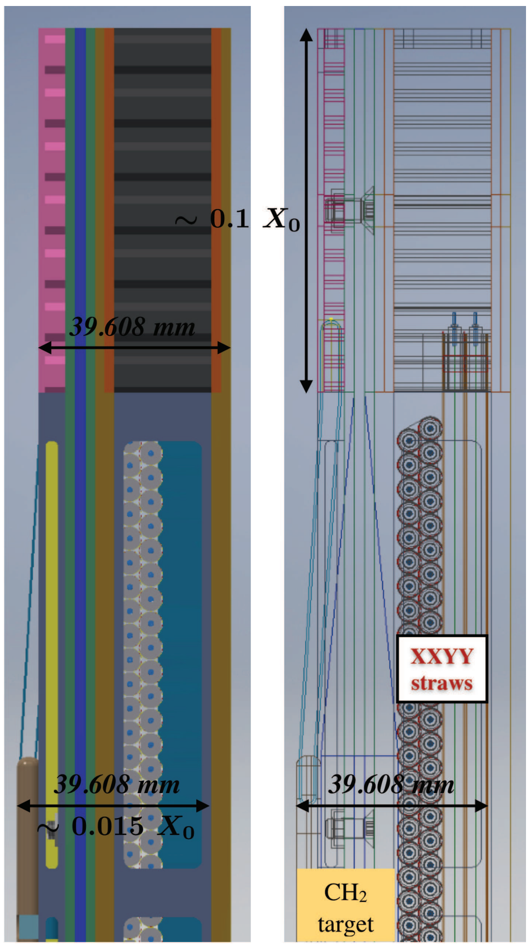
$\Longrightarrow$ *Proposed detector can collect $\sim 10^8$ CC events with high-resolution $\Delta E_\mu \leq 0.2\%$*

CONTROL OF TARGETS

✦ *Straw Tube Tracker designed for a control of ν-target(s) similar to $e^{\pm}$ DIS experiments:*

- *Typical ν-detectors: systematics from target composition & materials, limited target options;*
- *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 can be replaced during data taking: C, Ca, Ar, Fe, Pb, etc.*

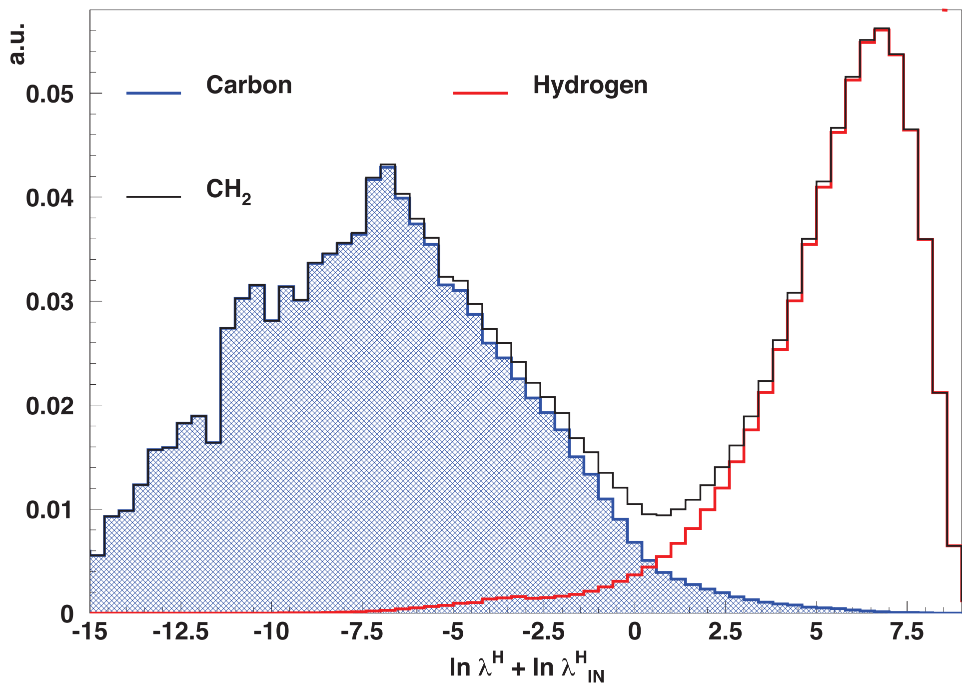
$\Longrightarrow$ *Optimized & engineered design, extensive performance studies*

"SOLID" HYDROGEN TARGET

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



CC process (5y+5y)	*H selected*
$\nu_\mu p \to \mu^- p \pi^+$	2,041,000
$\nu_\mu p \to \mu^- p \pi^+ X$	760,000
$\nu_\mu p \to \mu^- n \pi^+ \pi^+ X$	93,000
ν_μ *CC inclusive on H*	2,894,000
$\bar{\nu}_\mu p \to \mu^+ n$	862,000
$\bar{\nu}_\mu p \to \mu^+ p \pi^-$	304,000
$\bar{\nu}_\mu p \to \mu^+ n \pi^0$	209,000
$\bar{\nu}_\mu p \to \mu^+ p \pi^- X$	135,000
$\bar{\nu}_\mu p \to \mu^+ n \pi \pi X$	156,000
$\bar{\nu}_\mu$ *CC inclusive on H*	1,666,000

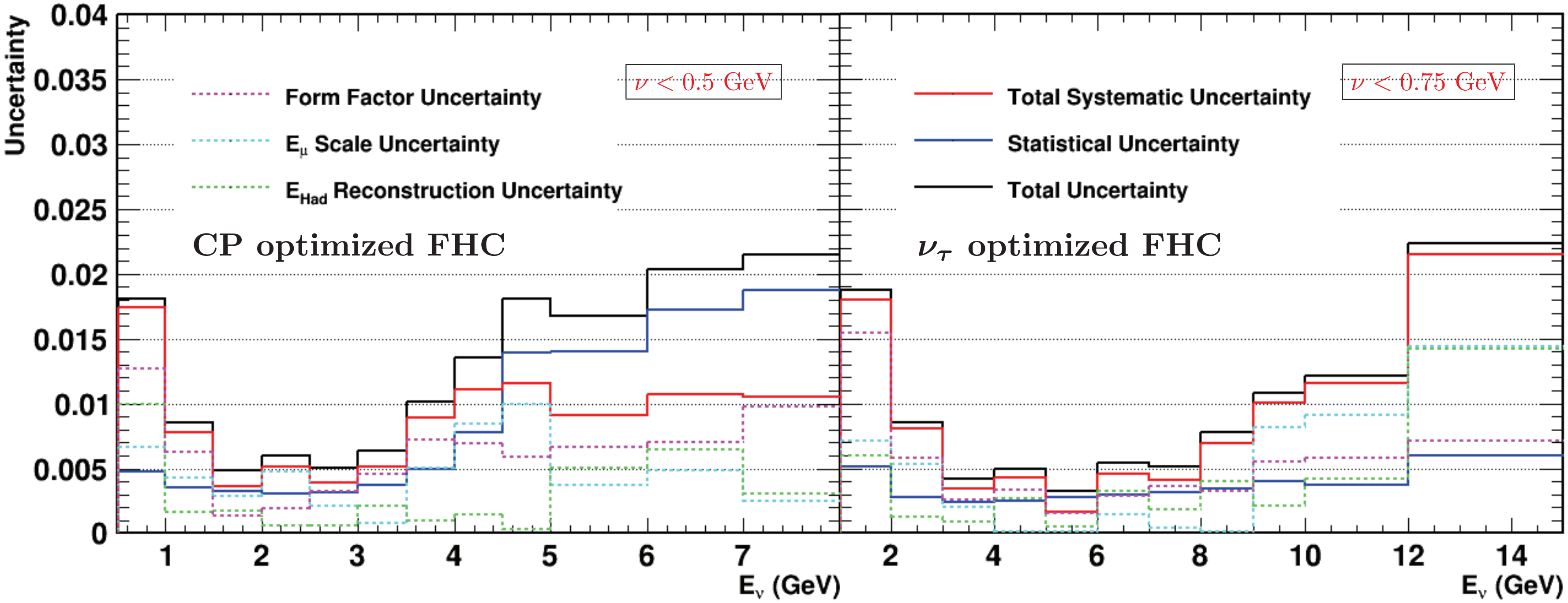
arXiv:1809.08752 [hep-ph], arXiv:1910.05995 [hep-ex]

CONTROL OF FLUXES

✦ *Relative ν_μ and $\bar{\nu}_\mu$ flux vs. E_ν from exclusive processes on H at small energy transfer:*

- *Use simplest topologies on H: $\nu_\mu p \to \mu^- p \pi^+$ and $\bar{\nu}_\mu p \to \mu^+ n$;*
- *Cut $\boxed{\nu < \nu_0}$ 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).*

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



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 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*

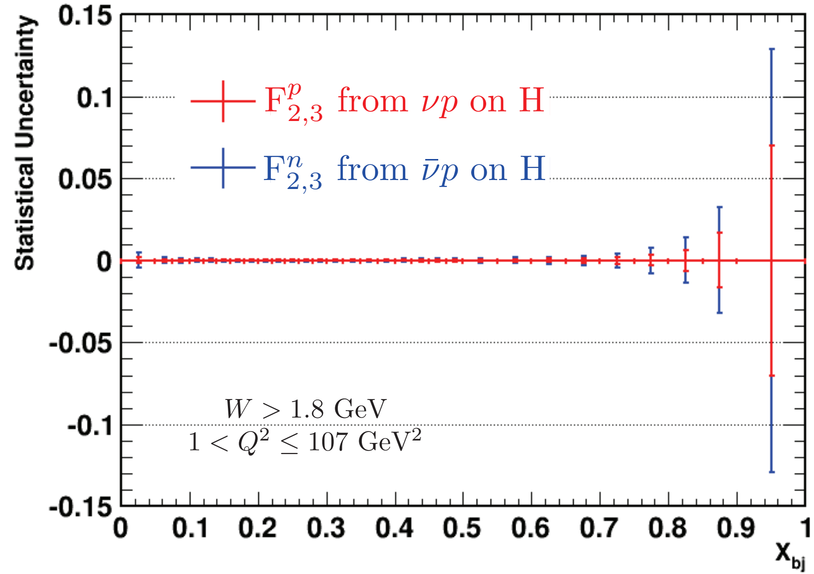
ADLER SUM RULE & ISOSPIN PHYSICS

- 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 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 $x \rightarrow 1$

(Synergy with 12 GeV JLab program)

Process	$\nu(\bar{\nu})$-H
Standard CP optimized:	
ν_μ CC (5 y)	3.1×10^6
$\bar{\nu}_\mu$ CC (5 y)	2.3×10^6
Optimized ν_τ appearance:	
ν_μ CC (2 y)	6.0×10^6
ν_μ CC (2 y)	4.0×10^6

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.*

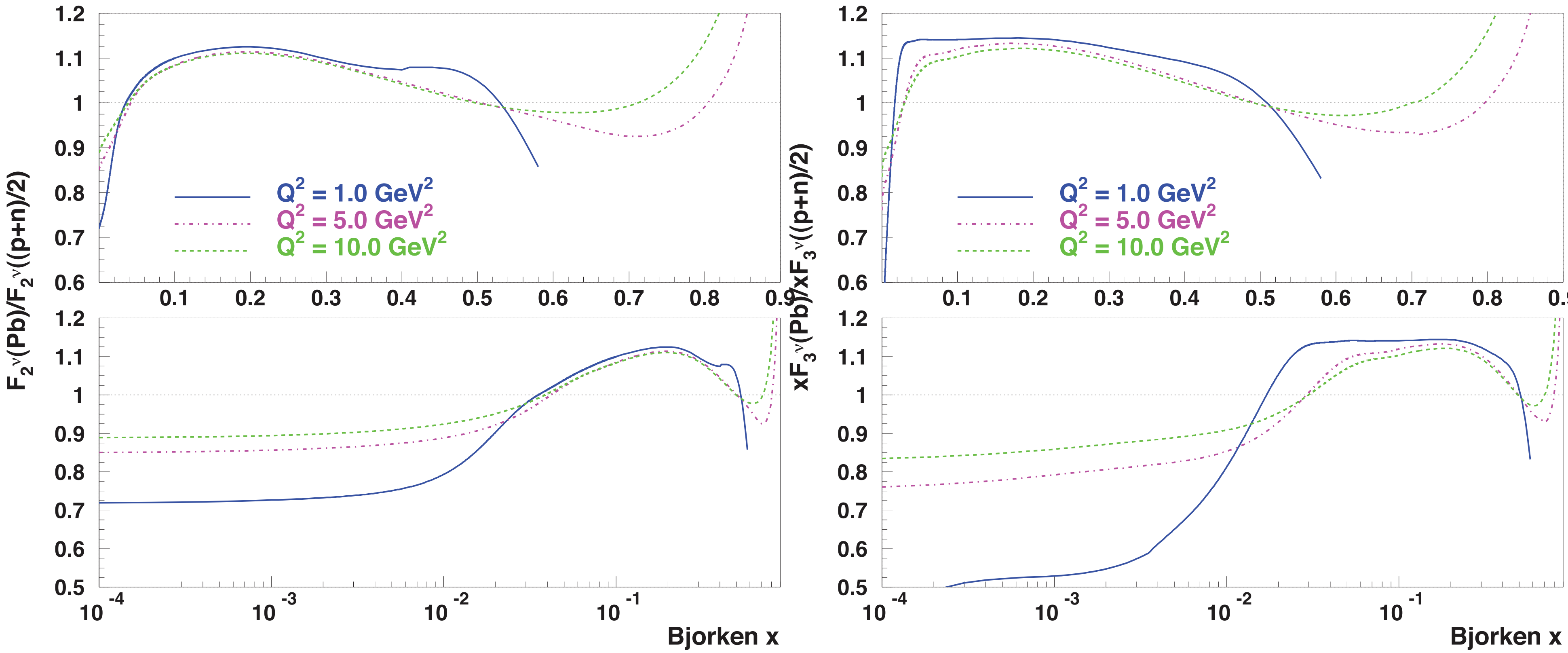
- *Study nuclear modifications to parton distributions in a wide range of Q^2 and x.*

- *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.*



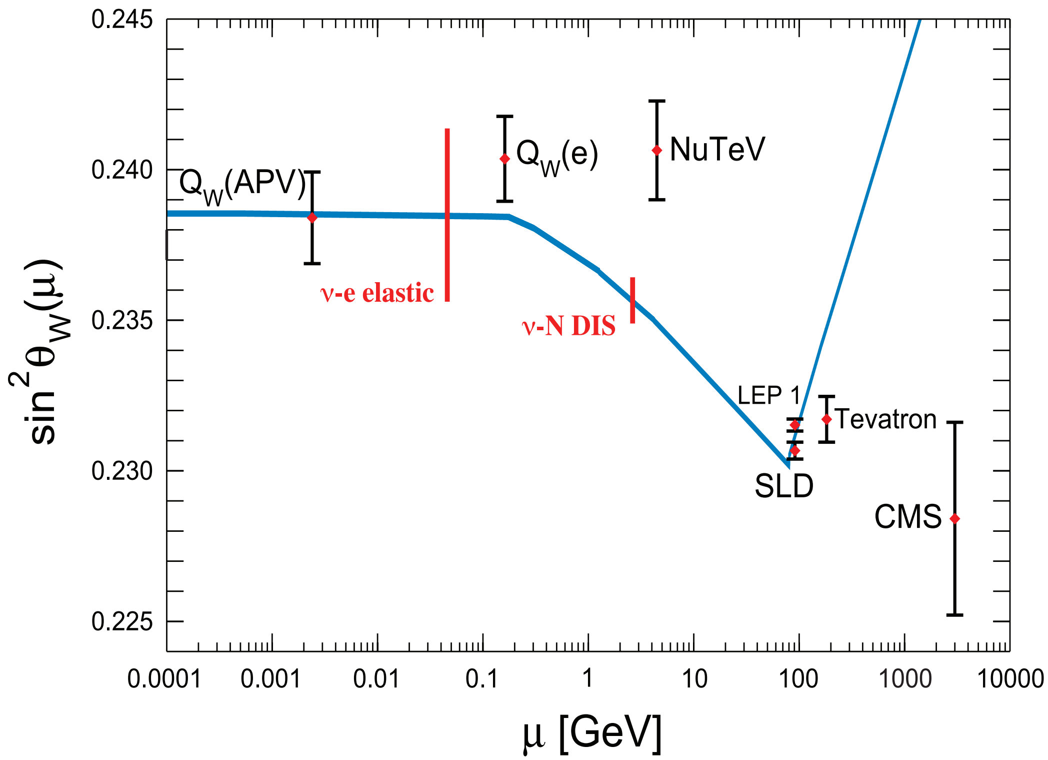
Ratio of Charged Current structure functions on ^{207}*Pb and isoscalar nucleon* $(p+n)/2$

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

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:*

- $\mathcal{R}^\nu = \frac{\sigma^\nu_{\rm NC}}{\sigma^\nu_{\rm CC}}$ *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*

✦ *Achievable sensitivity depending upon HE beam exposure*

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*

- *Proposed STT offers 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*

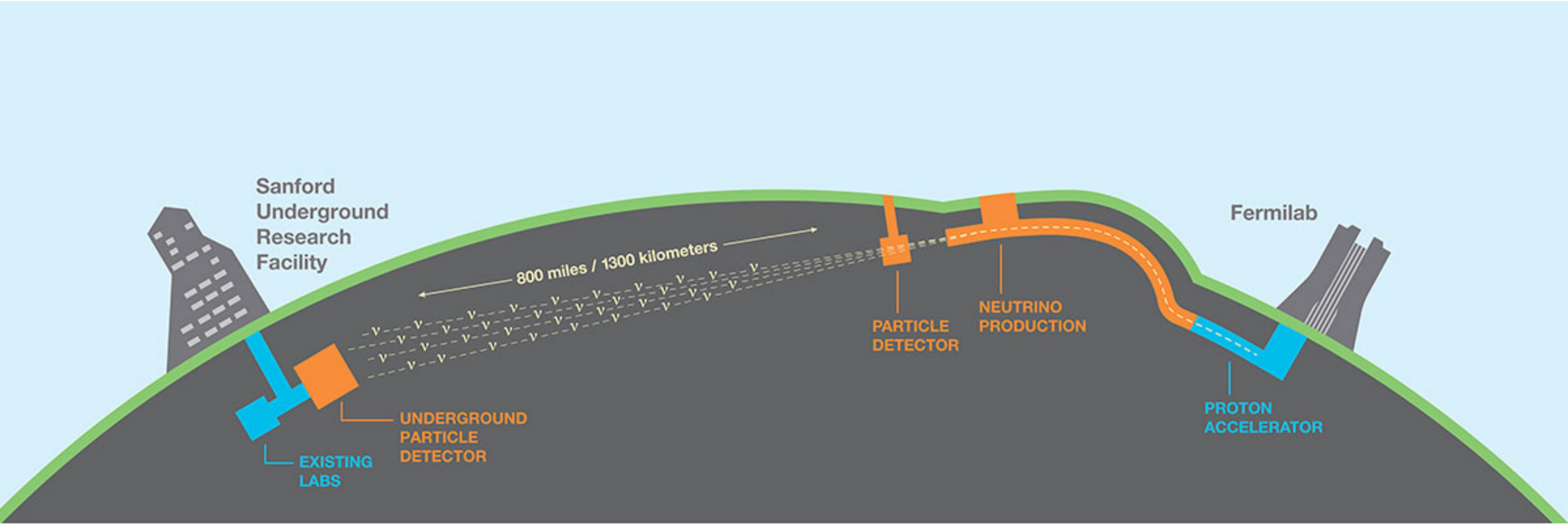
Welcome suggestions, feedback and/or potential interest

Precision Measurements with (Anti)Neutrinos at LBNF

G. Adamov[1,10], L. Alvarez Ruso[2], I. Bagaturia[1], B. A. Bambah[30], P. Bernardini[3,4], S. Bertolucci[5,6], M. Bhattacharjee[7], B. Bhuyan[7], S. Biagi[8], B. Brahma[31], A. Caminata[9], A. Cervelli[5], A. Chatla[30], D. Chokheli[1,10], A. Chukanov[10], S. Davini[9], S. Di Domizio[9,11], C. Distefano[8], L. Di Noto[9,11], M.V. Diwan[13], H. Duyang[12], P. Evtoukhovitch[10], A. Falcone[14,15], O. Fedin[16], A. Ferrari[17], F. Ferraro[9,11], A. Gabrielli[5], Z. Ghorbani Moghaddam[9], A. Giri[31], M. Guerzoni[5], B. Guo[12], M.A. Iliescu[18,19], A. Jha[30], I. Kakorin[10], A.L. Kataev[20], A. Khvedelidze[1,10], B. Kirby[13], U. Kose[5,19], S.A. Kulagin[20], C. Kullenberg[10], C. Kuruppu[12], R. Lalnuathunga[31], I. Lomidze[1], G. Laurenti[5], R. Majhi[30], V. Maleev[16], S. Malhotra[24], G .Mandrioli[5], N. Mauri[5,6], P. Mehta[21], S.R. Mishra[12], N. Moggi[5,6], R. Mohanta[30], A. Montanari[5], S. Movchan[10], S. Nagu[22], A. Nandi[7], A. Nath[7], F. Olness[23], M. Pallavicini[9,11], R. Papaleo[8], L. Pasqualini[5,6], L. Patrizii[5], R. Petti[12], V. Pia[5,6], F. Poppi[5,6], 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], K. Singh[24], L. Singh[27], V. Singh[27], G. Sirri[5], L. Stanco[26], S. Sundar Rajan[24], A. Surdo[4], N. Talukdar[7], M. Tenti[5], V. Teotia[24], 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], S. Vasina[10], M. Vicenzi[9,11], S. Zucchelli[5,6], and B. Wonsak[29]

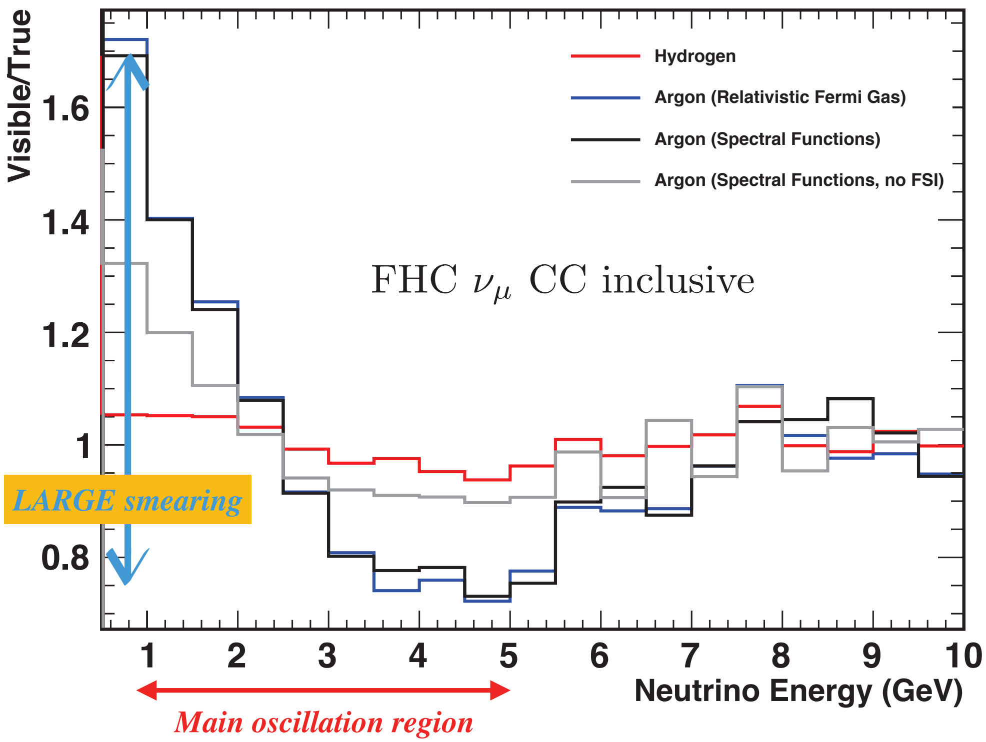
LoI: SNOWMASS21-NF5-NF6-EF6-EF4-RF1-RF6-122, DUNE DocDb # 13262

Backup slides



LBNF: Long-Baseline Neutrino Facility

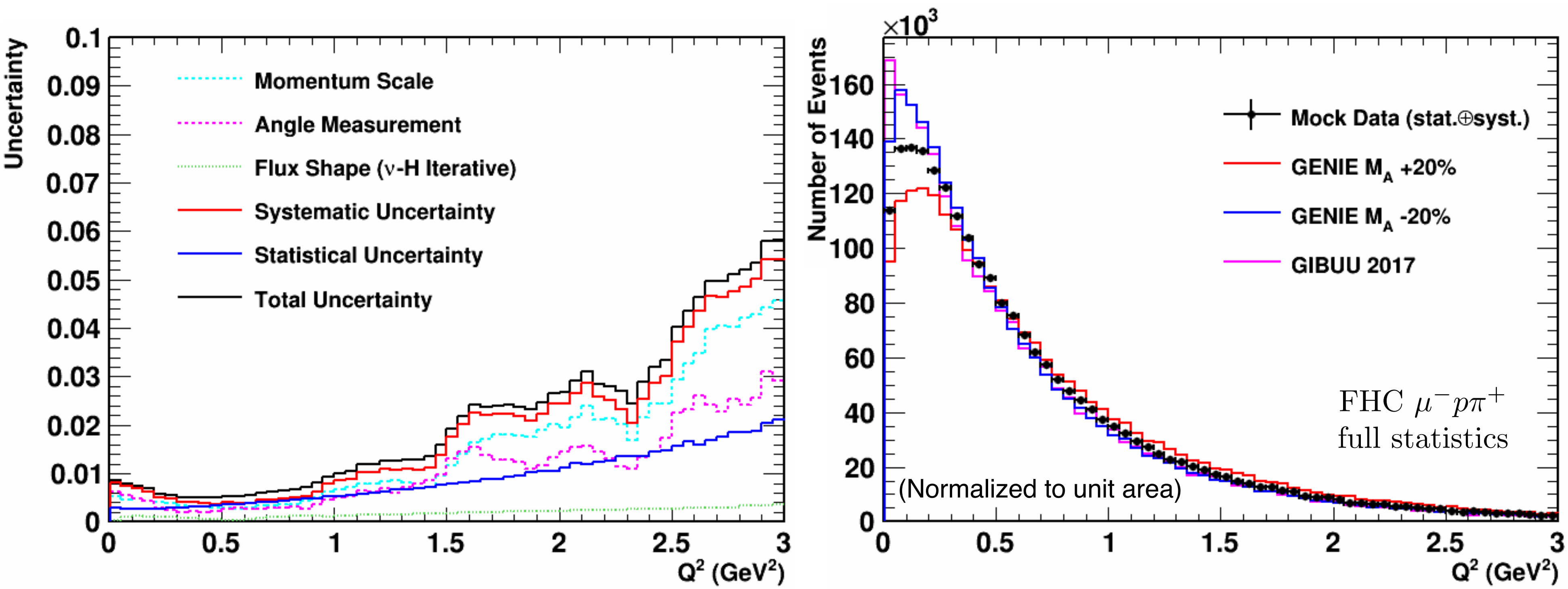
DUNE: Deep Underground Neutrino Experiment



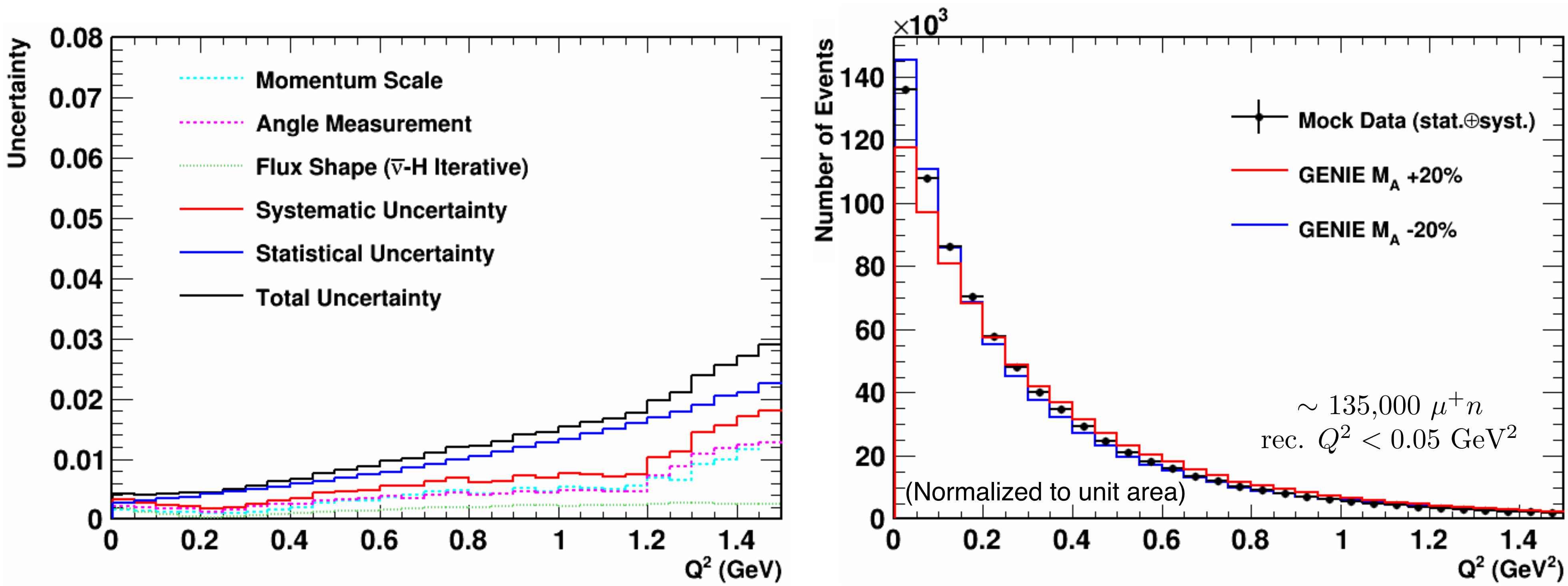
Comparing Ar and H measurements imposes stringent constraints on the nuclear smearing in Ar

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

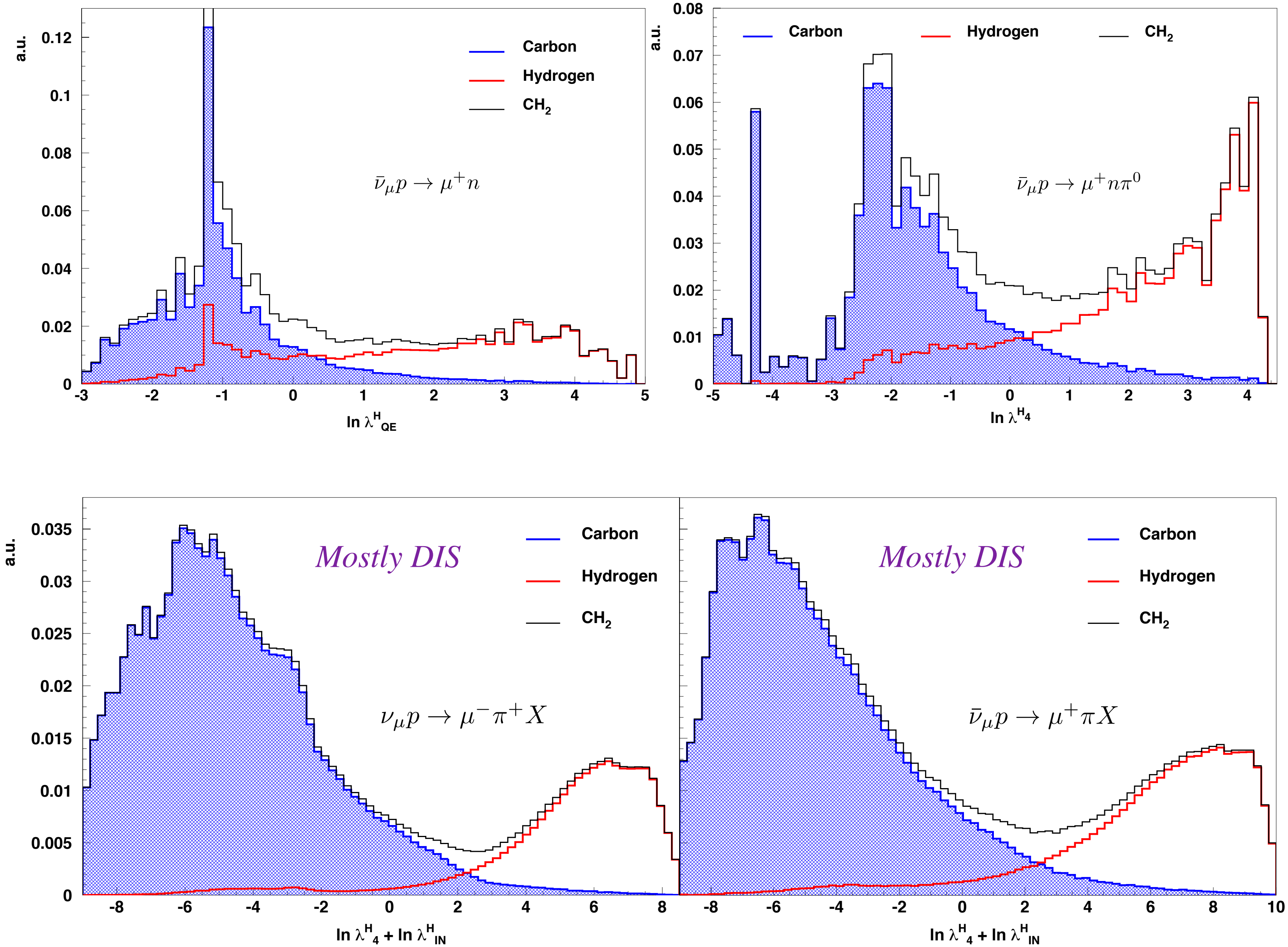
MEASUREMENT OF NUCLEON FORM FACTORS



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)


a.u.
Carbon
Hydrogen
CH2
$\bar{\nu}_\mu p \to \mu^+ n$
ln λ^H_QE
Carbon
Hydrogen
CH2
$\bar{\nu}_\mu p \to \mu^+ n \pi^0$
ln λ^H_4
Mostly DIS
Carbon
Hydrogen
CH2
$\nu_\mu p \to \mu^- \pi^+ X$
ln λ^H_4 + ln λ^H_IN
Mostly DIS
Carbon
Hydrogen
CH2
$\bar{\nu}_\mu p \to \mu^+ \pi X$
ln λ^H_4 + ln λ^H_IN