Probing Nucleons and Nuclei with SAND in Phase II

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DUNE Phase II ND workshop
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MOTIVATIONS

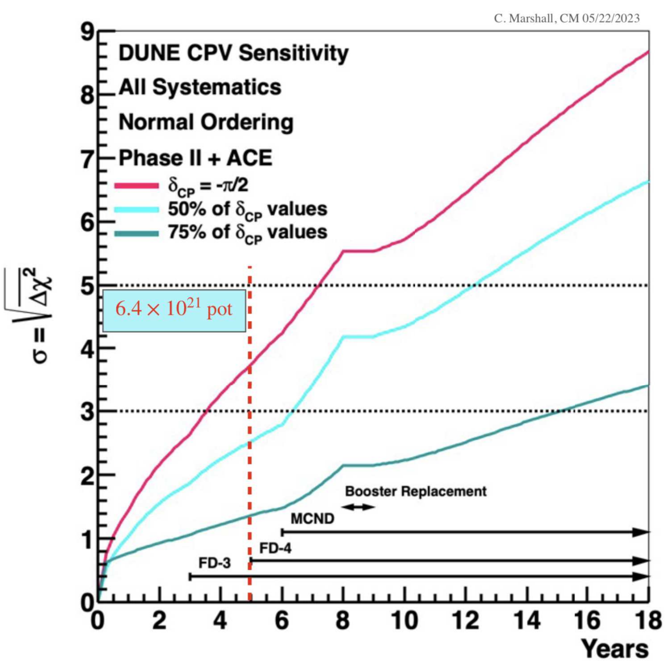
✦ *SAND expected to take data from Day-1 of DUNE Phase I:*

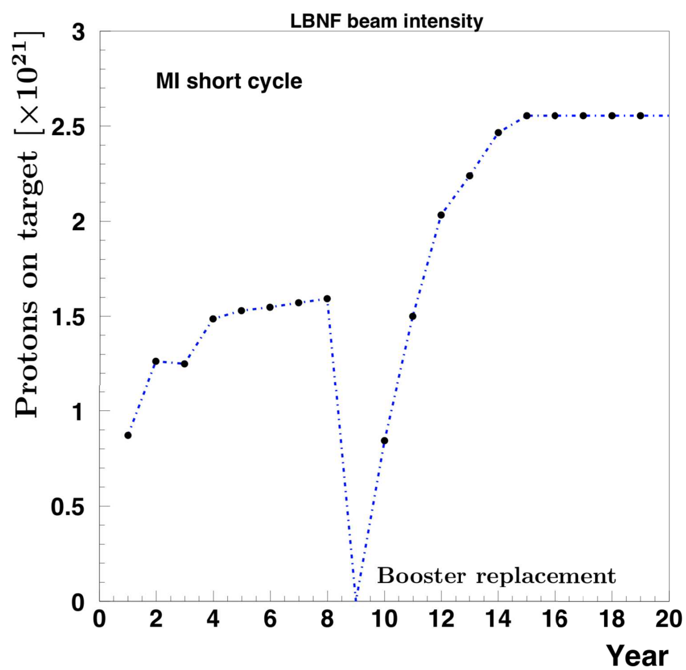
$\Longrightarrow$ *Collect* $\sim 6.4 \times 10^{21}$ *pot of data in 5 years before FD4 operational*

✦ *SAND offers unique opportunities to broaden Phase II physics program:*

- *Reduce LBL systematics from* ν_μ, $\bar{\nu}_\mu$, ν_e, *and* $\bar{\nu}_e$ *flux and nuclear effects in Ar/C/O;*
- *Precision measurements of fundamental interactions & structure of nucleons and nuclei.*

$\Longrightarrow$ *Synergistic programs sharing same requirements*





EXPECTED SAND STATISTICS IN PHASE I

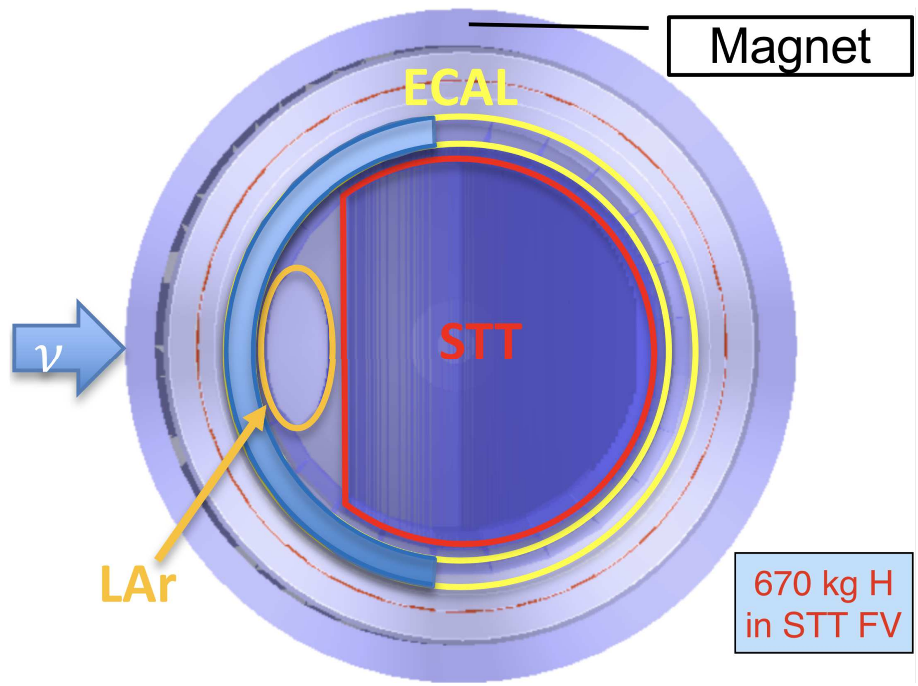
Target	CP optimized FHC (3.2×10^{21} pot)				CP optimized RHC (3.2×10^{21} pot)			
	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC
CH_2	18,924,127	908,116	279,444	46,403	2,961,415	7,084,454	132,369	100,768
H	1,778,292	162,289	26,758	8,083	282,496	1,318,007	12,672	18,986
C	2,250,198	97,882	33,162	5,030	351,578	756,781	15,709	10,851
Ar	4,529,936	176,736	67,468	9,459	699,436	1,362,166	31,901	20,170
Pb	90,367,418	3,647,913	1,342,563	190,080	15,091,491	26,505,018	636,049	385,897

NOTE: Phase I assumed to cover initial 5y with about 3.2×10^{21} pot in FHC and 3.2×10^{21} pot in RHC

STT FV mass:
4.7 t CH_2
557 kg C

GRAIN mass:
1 t LAr

Front ECAL mass:
22.8 t Pb



CONTROL OF SYSTEMATICS

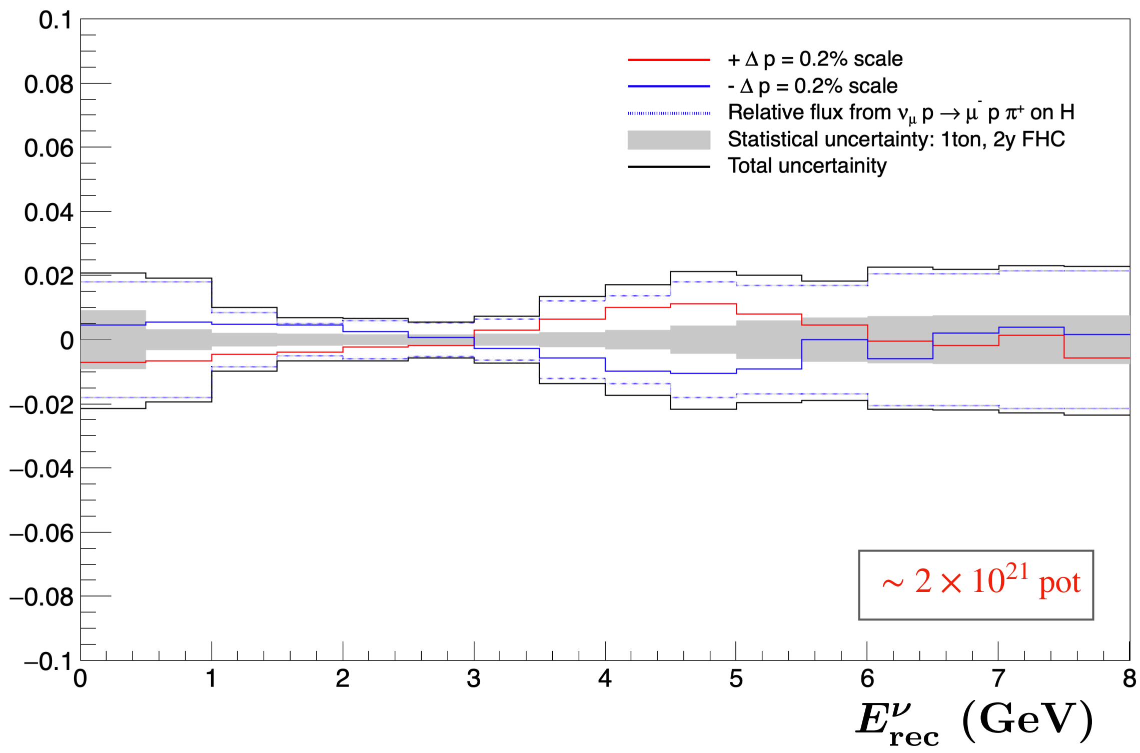
- *STT designed to offer a control of ν-target(s) similar to $e^{\pm}$ DIS experiments:*
  - *"Transparent" target/tracker system with total length* $\sim 1.3 X_0$ *and average* $\rho \leq 0.18$ *g/cm*^{3}*;*
  - *Accurate reconstruction of transverse plane kinematics from particle 4-momenta.*

- *Low-density design & target mass allow accurate in-situ calibrations:*
  - $\Delta p < 0.2\%$ *momentum scale uncertainty from* $K_0 \to \pi^+\pi^-$ *in STT volume (337,000 in FHC);*
  - *p reconstruction and identification, vertex, etc. from* $\Lambda \to p\pi^-$ *in STT volume (506,000 in FHC);*
  - $e^{\pm}$ *reconstruction and identification from* $\gamma \to e^+e^-$ *in STT volume* (8×10^6 *in FHC).*

- *Precise in-situ measurement of (anti)neutrino fluxes:*
  - *Relative* ν_μ *&* $\bar{\nu}_\mu$ *flux vs.* E_ν *from* $\nu_\mu H \to \mu^- p \pi^+$ *&* $\bar{\nu}_\mu H \to \mu^+ n$*:* $\Delta\Phi(E_\nu) \sim 1\%$*;*
  - *Absolute* ν_μ *flux from* $\nu e^- \to \nu e^-$ *elastic scattering:* $< 2\%$*;*
  - *Absolute* $\bar{\nu}_\mu$ *flux from* $\bar{\nu}_\mu H \to \mu^+ n$ *with* $Q^2 < 0.05$ *GeV*^{2}*.*

- *Calibration of (anti)neutrino energy scale* ΔE_ν *from comparison of* $\nu(\bar{\nu})$ *CC interactions on nuclear targets A and on H with similar detector acceptance*

$\Longrightarrow$ *Expected level of total systematic uncertainties* $\lesssim 2\%$ *after Phase I*



For a 1 ton target in SAND uncertainties already dominated by systematics (1-2%) for exposures $\geq 2 \times 10^{21}$ *pot (~1.6y with MI short cycle)*

PHASE II OPPORTUNITIES WITH SAND

- *Increase of statistics for measurements of rare processes (statistics limited in Phase I):*
  - *Exclusive processes with tiny cross-section: ν-e elastic, coherent meson production, etc.*
  - *Searches for new physics: sterile neutrinos, NSI, NHL, etc.*

$\Longrightarrow$ *Extend physics sensitivity of established Phase I analyses*

- *Change of targets in STT:*

  Individual targets in STT can be replaced/removed during data taking allowing the probe of a broad range of different nuclei.

- *Change of STT average density:*

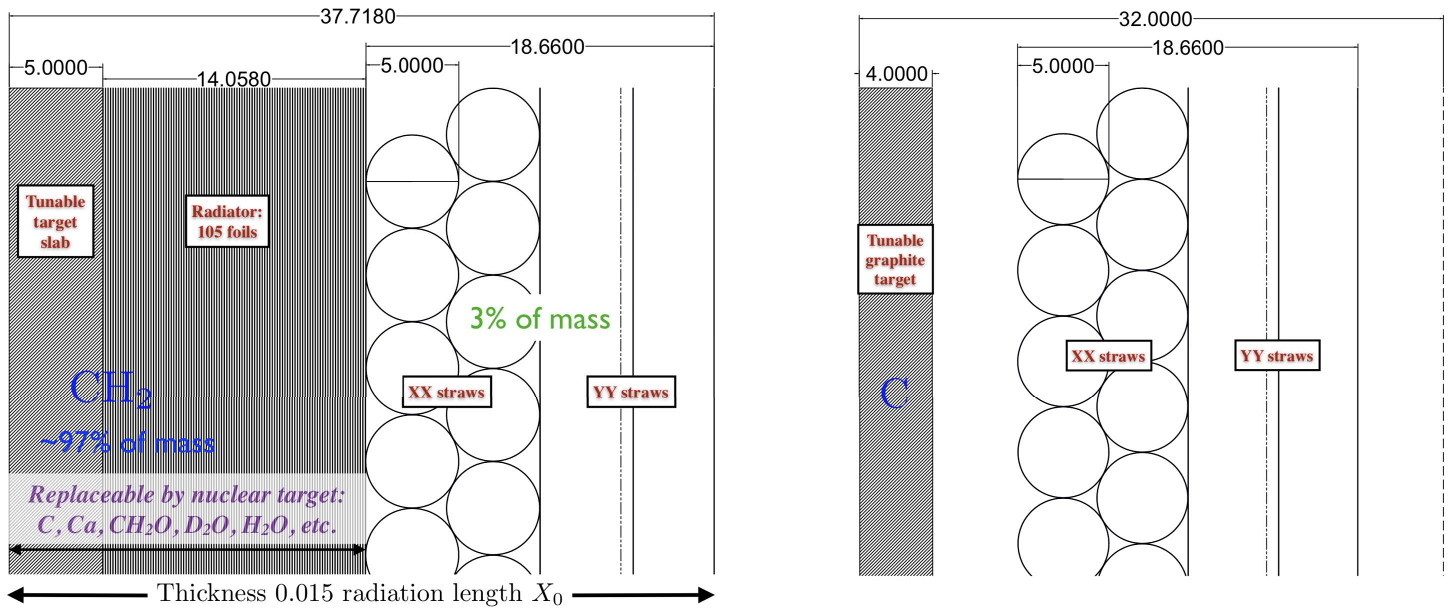
  If unexpected results in Phase I, data with reduced density $0.005 \leq \rho \leq 0.18$ g/cm^3 could provide increased resolutions and/or lower backgrouds for cross-checks.

- *Change of beam spectrum:*

  High-energy beam optimized for ν_τ appearance in FD can substantially expand physics potential of precision measurements (EW, QCD, etc.) & BSM searches in SAND.

STT TARGETS INDIVIDUALLY REPLACEABLE

Phase I targets



- *Total of 78 thin (~1.5% X_0) passive targets* separated from active detector (straw layers);
- *Targets of high chemical purity (~ 97% of mass)* keeping average density $\rho \leq 0.18$ g/cm^3
- *High track sampling*: 0.15 (0.36)%X_0 $\perp$ ($\parallel$) with total detector thickness $\sim 1.3 X_0$;
- *"Solid" hydrogen target* from a subtraction of CH_2 & C targets.

$\Longrightarrow$ *Individual targets can be replaced with planar targets of desired material up to 19mm thick*

CALCIUM TARGET

✦ *Isoscalar nucleus with same A=40 as Ar:*

- *Nuclear modifications & test of isospin symmetry;*
- *Direct comparison with Ar target in SAND probe of flavor dependence of nuclear effects in A=40.*

$\Longrightarrow$ *Relevant both for nuclear physics & for LBL systematics in Ar*

✦ *Integrate a few calcium planes within STT:*

- *Target planes assembled from solid Ca "tiles" ∼4 mm thick:* $\longrightarrow$ *Density 1.55 g/cm*^{3}*, ∼0.038* X_0*;*
- *Calcium targets to be enclosed in thin* CH_2 *shell and possibly oil-coated for safety;*
- *Calcium target planes installed upstream close to Ar target (GRAIN)*

$\Longrightarrow$ *Need to test assembly of calcium tiles and safety*

OXYGEN TARGET

✦ *Cross-sections & related nuclear smearing on "solid" oxygen target:*

$$N_{\mathrm{O}}(\vec{x}) \equiv N_{\mathrm{CH_2O}}(\vec{x}) - \frac{M_{\mathrm{CH_2/CH_2O}}}{M_{\mathrm{CH_2}}} N_{\mathrm{CH_2}}(\vec{x})$$

- *Interactions on oxygen from subtraction between polyoxymethylene (delrin) and default CH_2 targets. Oxygen content by mass within delrin is dominant at 53.3%, excellent mechanical properties.*
- *Direct measurement on oxygen target (NOT water) and separation of water constituents O and H.*

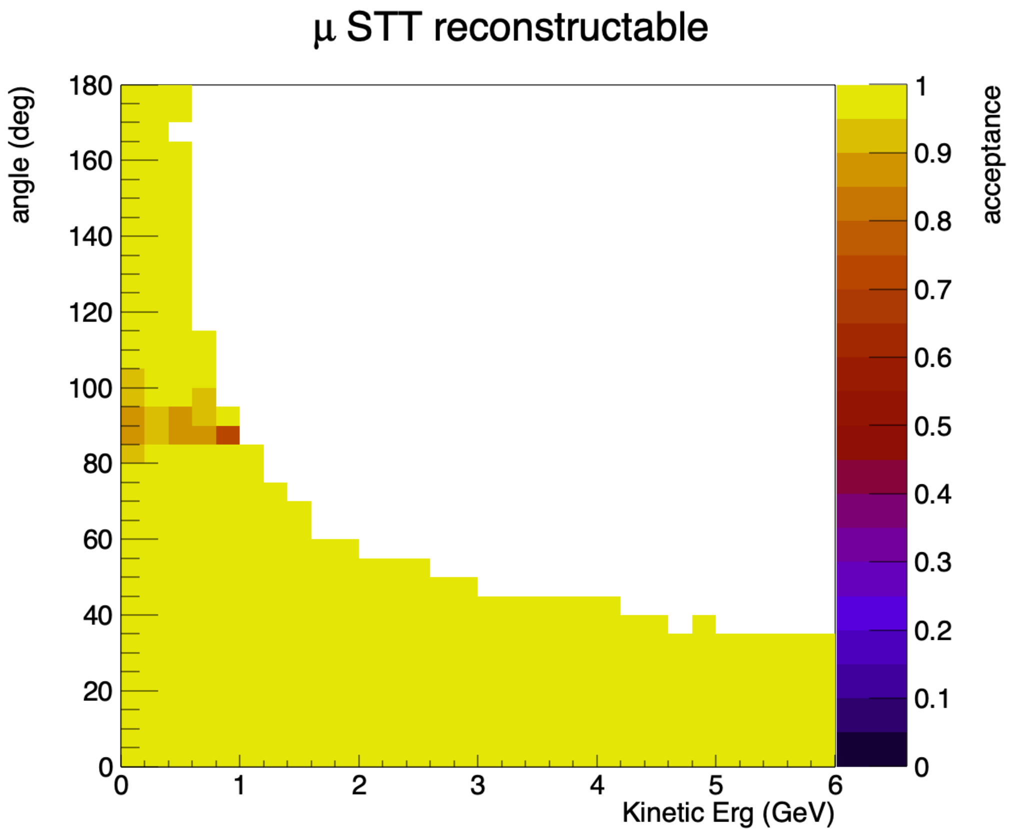
$\Longrightarrow$ *Relevant for nuclear physics & in case of non-Ar FD4 (e.g. Theia)*

✦ *Cross-sections on water target:*

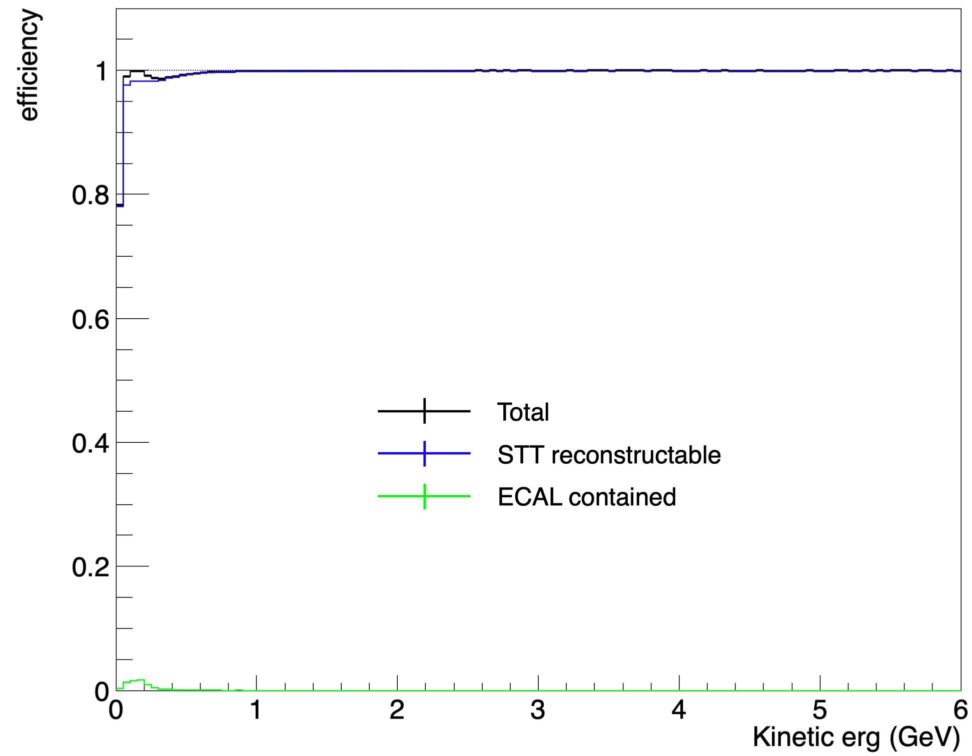
$$N_{\mathrm{H_2O}}(\vec{x}) \equiv N_{\mathrm{CH_2O}}(\vec{x}) - \frac{M_{\mathrm{C/CH_2O}}}{M_{\mathrm{C}}} N_{\mathrm{C}}(\vec{x})$$

- *Exploit simultaneous presence of alternated CH_2, C, and CH_2O targets in STT.*
- *Interactions on water from subtraction between polyoxymethylene (CH_2O) and graphite (C) targets. Water content by mass within delrin is 60%, mass of available C targets larger than C in delrin.*

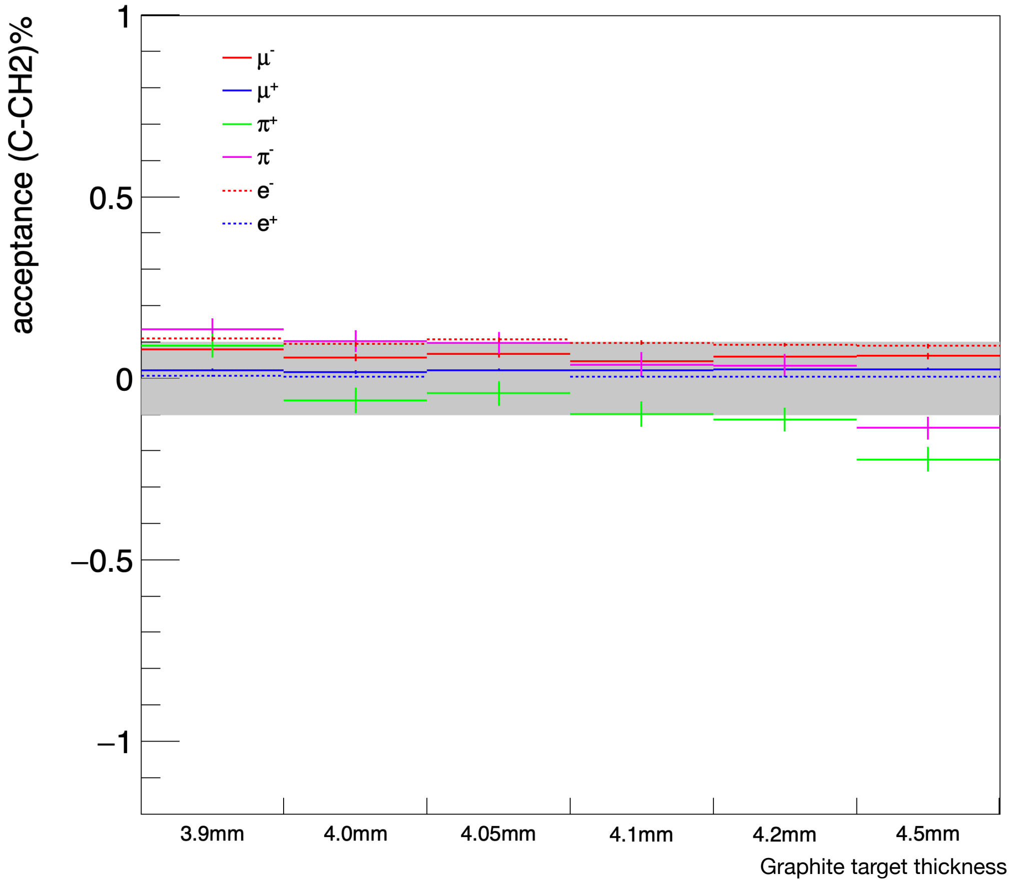
Target material	Composition	Density	Thickness	Rad. length	Nucl. int. length
Polypropylene	CH_2	0.91 g/cm^3	7.0 mm	0.015 X_0	0.008 λ_I
Graphite	C	1.80 g/cm^3	4.0 mm	0.016 X_0	0.008 λ_I
Polyoxymethylene	CH_2O	1.41 g/cm^3	4.5 mm	0.016 X_0	0.008 λ_I



Integrated over all angles



SAND can provide high statistics samples of interactions on H and nuclear targets A with large acceptance over the full 4π angle down to low momenta ($\rho < 0.18$ g/cm³)



Optimization of the ratio between the CH_2 and C thickness shows that we can keep acceptance differences among CH_2, C, CH_2O targets $<10^{-3}$ for all particles

DEUTERIUM TARGET

✦ *Bound np system with significant nuclear modifications*

⟹ *Comparison with H first direct measurement of nuclear modifications in D*

⟹ *Complementary measurement of absolute ν_μ flux from $\nu_\mu n \to \mu^- p$ at $Q^2 \sim 0$*

✦ *Use of CD_2 plastics not feasible due to prohibitive costs.*

✦ *Subtraction between D_2O and H_2O alternated targets:*

$$N_{\mathrm{n/D}}(\vec{x}) \equiv N_{\mathrm{D_2O}}(\vec{x}) - N_{\mathrm{H_2O}}(\vec{x})$$

- *Planes with 12mm thick water layers encapsulated in 1.5mm delrin (CH_2O) shell*
  ⟶ *Overall ∼90% water content, ∼0.044 X_0*
- *Use identical delrin shells for both D_2O and H_2O targets to subtract shells*
  ⟶ *Water filling giving same oxygen mass in both targets*

⟹ *Need to optimize targets, test leaks, etc.*

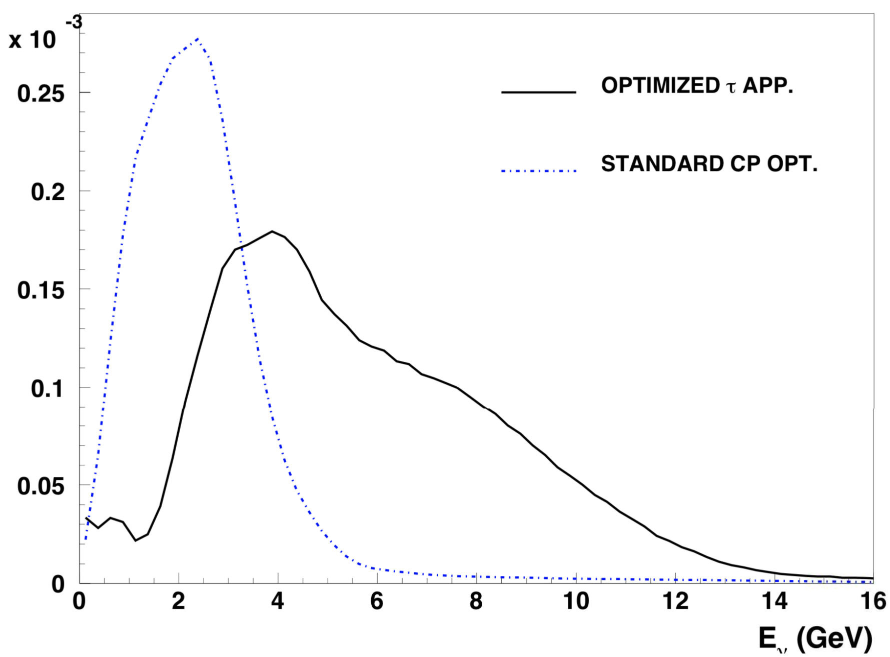
HIGH-ENERGY BEAM OPTION

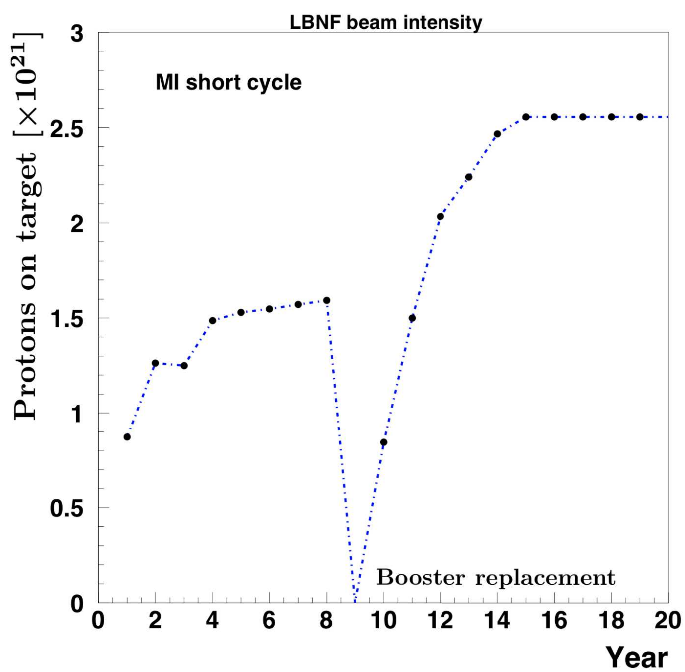
✦ *After Booster replacement in Phase II beam intensity increase up to 2.5×10^{21} pot/year (60% increase from Phase I with MI short cycle)*

✦ *High-energy LBNF beam option optimized for ν_τ appearance in FD:*

- *Conceivable a dedicated run (1-2 years) at a later Phase II stage;*
- *Change of beam spectrum would affect both FD and ND in DUNE.*

$\Longrightarrow$ *High-energy data can significantly expand SAND physics reach*





MINIMAL RUN TIME AFTER TARGET CHANGE

- *"Solid" hydrogen target required at all times to constrain systematics: keep all graphite targets in Phase II (~600 kg)*

- *Replace some of the 70 CH_2 targets in Phase II keeping average density $\leq$0.18 g/cm^3*
  $\Longrightarrow$ *Realistic fiducial mass of new targets from 200 kg to 1 ton*

Mass (isoscalar)	CP optimized beam (2.5×10^{21} pot) ν_μ CC FHC	CP optimized beam (2.5×10^{21} pot) $\bar{\nu}_\mu$ CC RHC	ν_τ optimized beam (2.5×10^{21} pot) ν_μ CC FHC	ν_τ optimized beam (2.5×10^{21} pot) $\bar{\nu}_\mu$ CC RHC
200 kg	666,000	224,000	1,589,000	517,000
500 kg	1,665,000	560,000	3,972,000	1,294,000
1 ton	3,330,000	1,120,000	7,944,000	2,588,000

$\Longrightarrow$ *In less than one year enough statistics for sensible physics measurements*

GENERAL PURPOSE FACILITY

✦ *SAND in Phase II allows to probe a variety of nuclei with excellent control of systematic uncertainties (scales, flux, & nuclear effects)*

$\Longrightarrow$ *General purpose (anti)neutrino physics facility*

✦ *Rich physics program complementary to 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*

✦ *Measurements can concurrently constrain LBL systematics for both Ar and non-Ar FD*

FREE NEUTRON TARGET

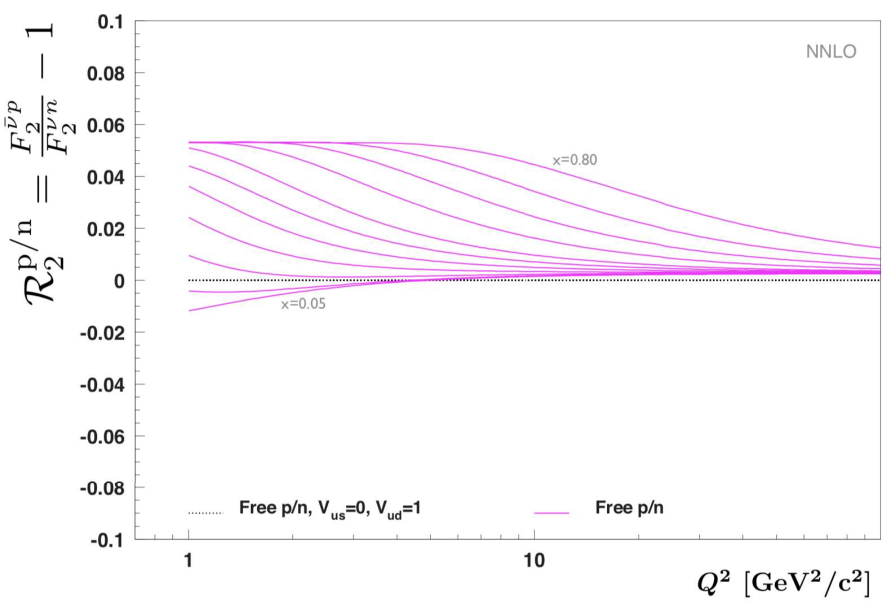
- Structure function $F^{\nu n}$ directly related to $F^{\bar{\nu} p}$ by **ISOSPIN SYMMETRY**

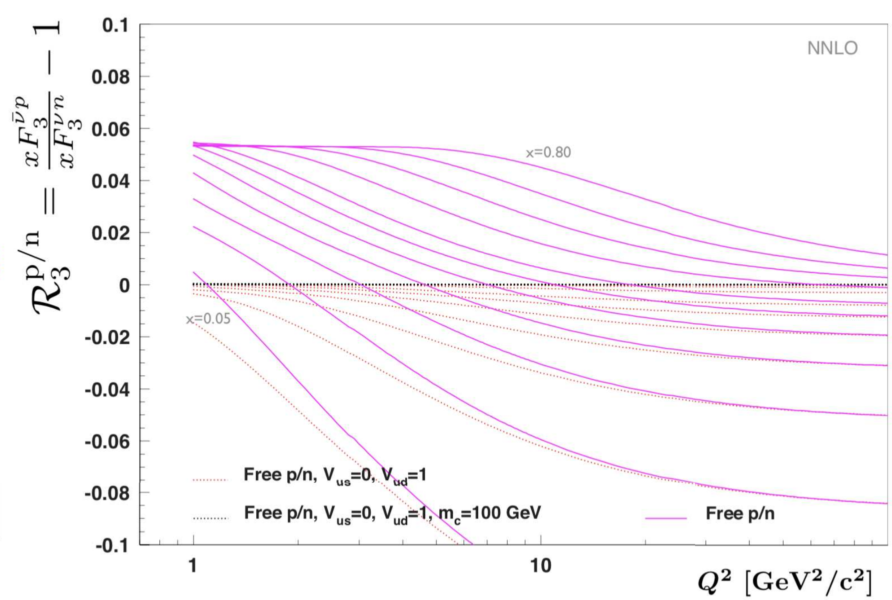
- Correction factors:

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

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

$\Longrightarrow$ Self-determined d/u and s (synergy with 12 GeV JLab program)





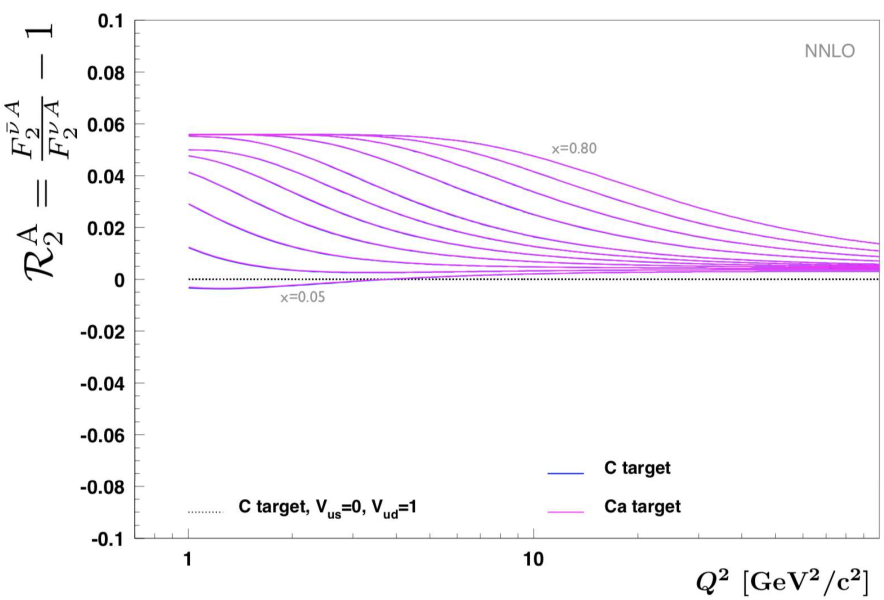
TESTS OF ISOSPIN SYMMETRY

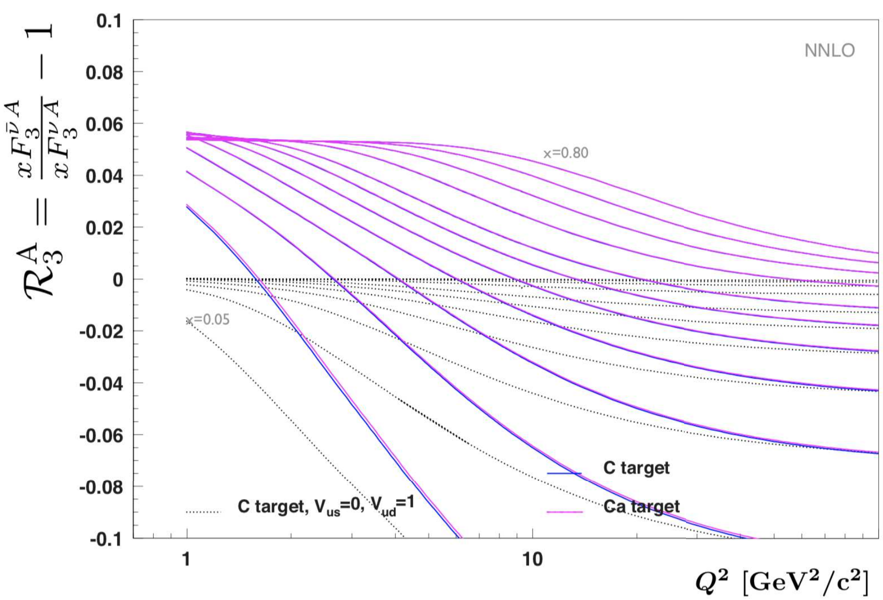
✦ *Isospin symmetry can be verified with* ISOSCALAR TARGET *:*

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

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

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

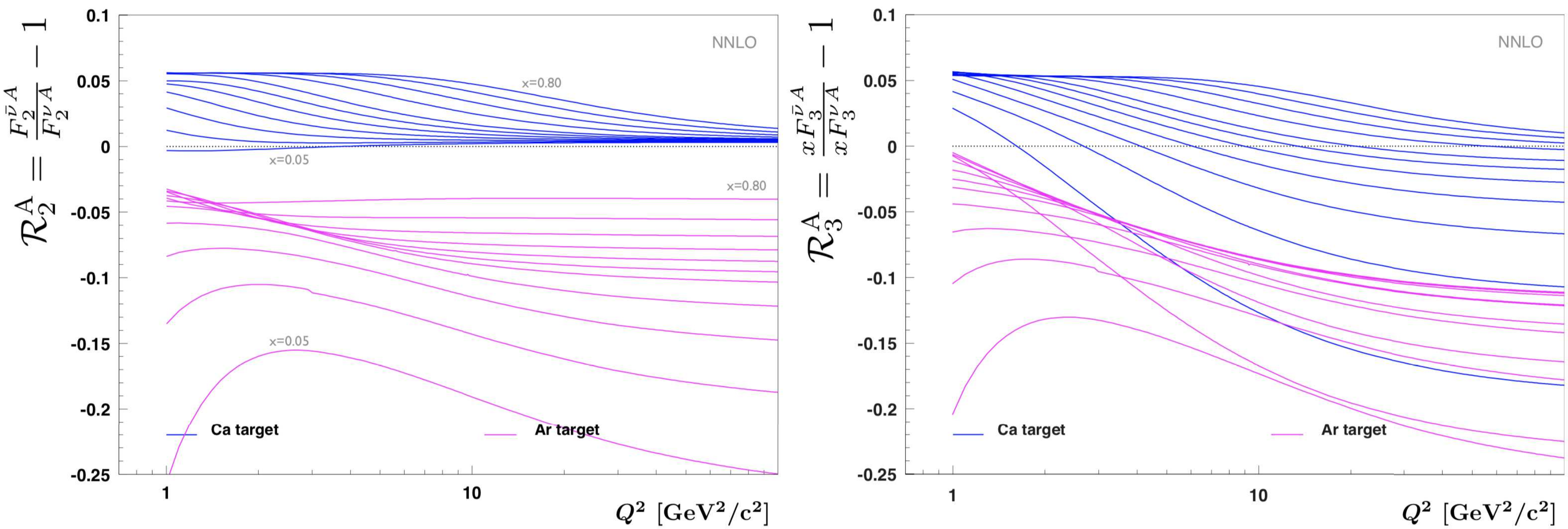




✦ *Comparison of Ca and Ar can probe* **FLAVOR DEPENDENCE** *of nuclear effects:*

- *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 $F_{2,3}$:*

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

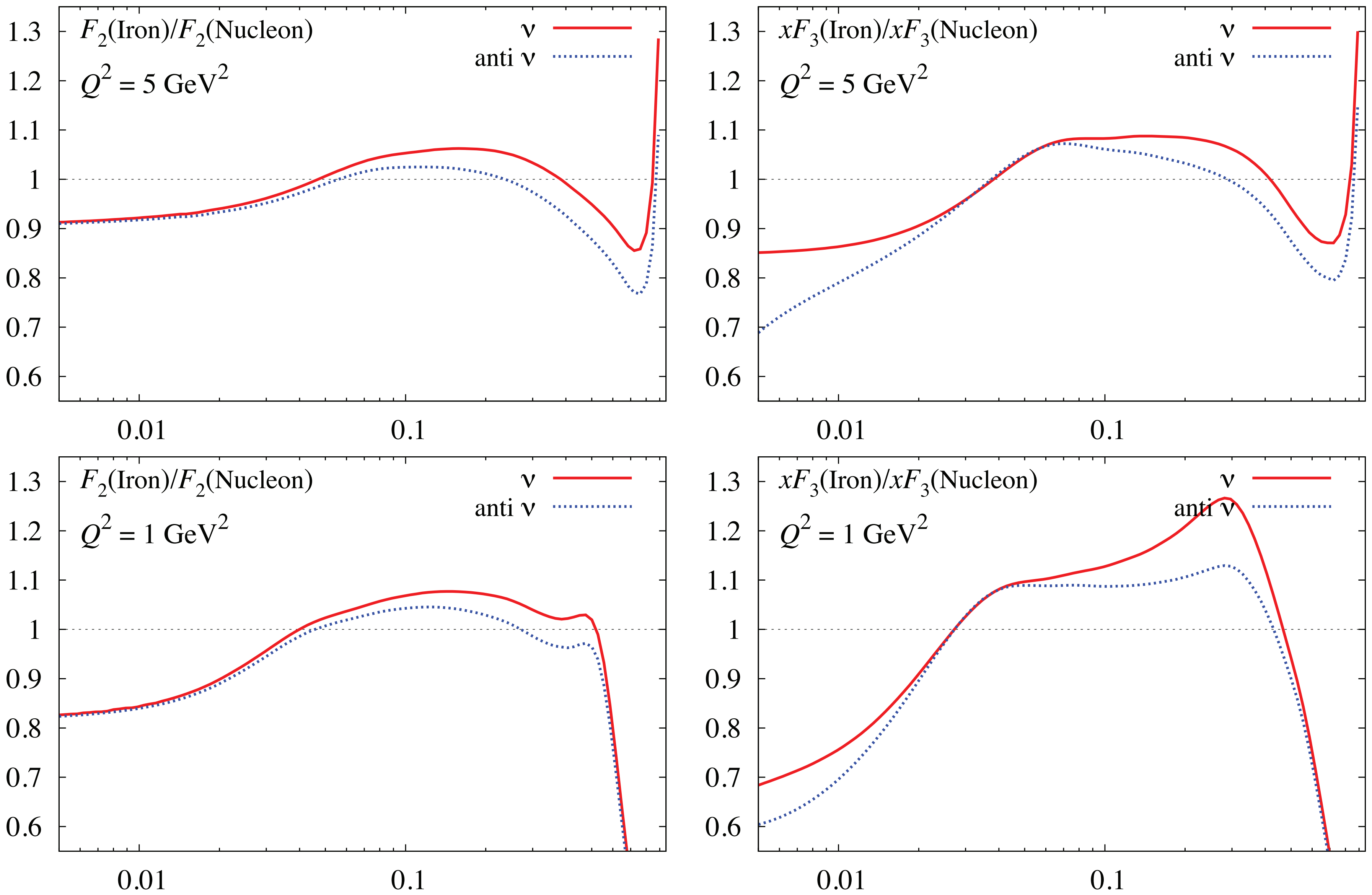
- *Comparison with e/μ DIS results and nuclear models;*
- *Study flavor dependence of nuclear modifications ($W^{\pm}/Z$ helicity, C-parity, Isospin);*
- *Effect of the axial-vector current.*

✦ *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.*

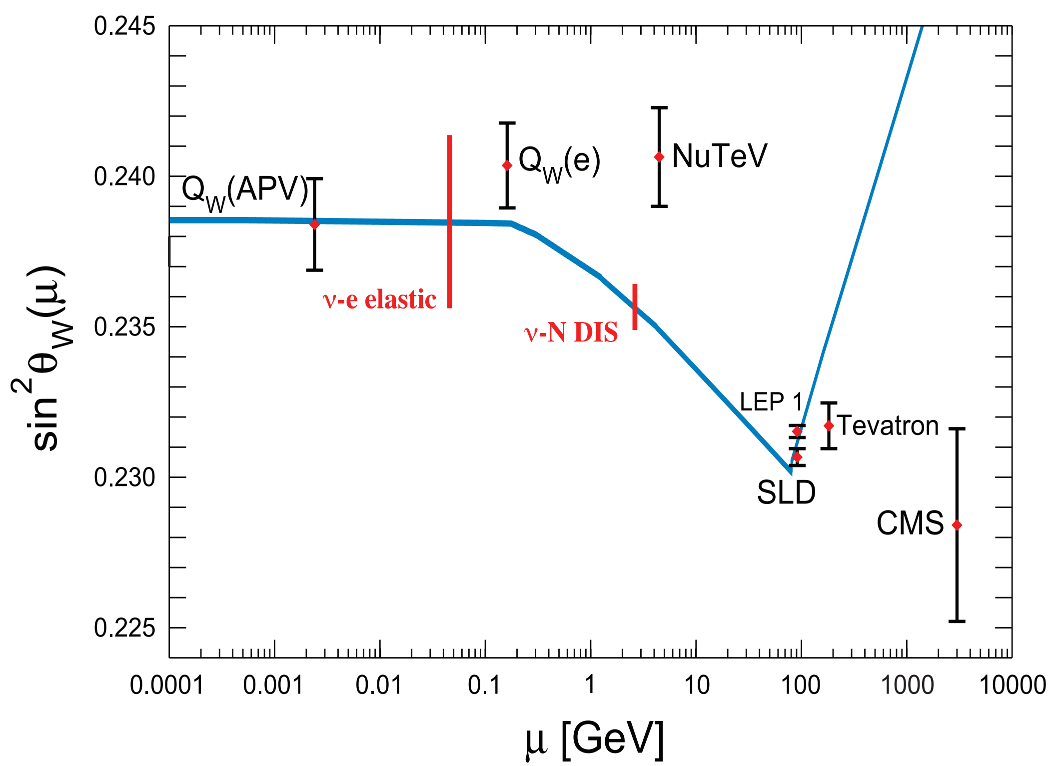
$\Longrightarrow$ *Synergy with Heavy Ion and EIC physics programs for cold nuclear matter effects.*


F_2(Iron)/F_2(Nucleon)
$Q^2 = 5$ GeV^2
ν
anti ν
xF_3(Iron)/xF_3(Nucleon)
$Q^2 = 5$ GeV^2
ν
anti ν
F_2(Iron)/F_2(Nucleon)
$Q^2 = 1$ GeV^2
ν
anti ν
xF_3(Iron)/xF_3(Nucleon)
$Q^2 = 1$ GeV^2
ν
anti ν
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 (~0.35%)*
- $\mathcal{R}_{\nu e} = \frac{\sigma^{\bar\nu}_{NC}}{\sigma^\nu_{NC}}$ *in ν-e^- NC elastic (~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

✦ SAND well understood detector from DUNE Phase I:

- Collect $\sim 6.4 \times 10^{21}$ pot of data from Day-1 in DUNE Phase I;
- Use of data calibration samples (H, V^0, etc.) to constrain systematic uncertainties $\lesssim 2\%$.

✦ Phase II opportunities with SAND:

- Increase of statistics for measurements of rare processes & searches for BSM physics (statistics limited in Phase I);
- Change of targets in STT allowing the probe of a broad range of different nuclei;
- Change of STT average density within $0.005 \leq \rho \leq 0.18$ g/cm^3 for cross-checks;
- Change of beam spectrum with high-energy beam option optimized for ν_τ apperance.

✦ SAND facility for precision measurements of fundamental interactions & structure of nucleons and nuclei complementary to fixed-target, collider, and nuclear physics efforts

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

✦ SAND can constrain LBL systematics for both Ar and non-Ar FD options from $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ fluxes and nuclear effects in Ar/C/O

Backup slides