Precision Measurements of Fundametal Interactions with (Anti)neutrinos in DUNE

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Physics seminar
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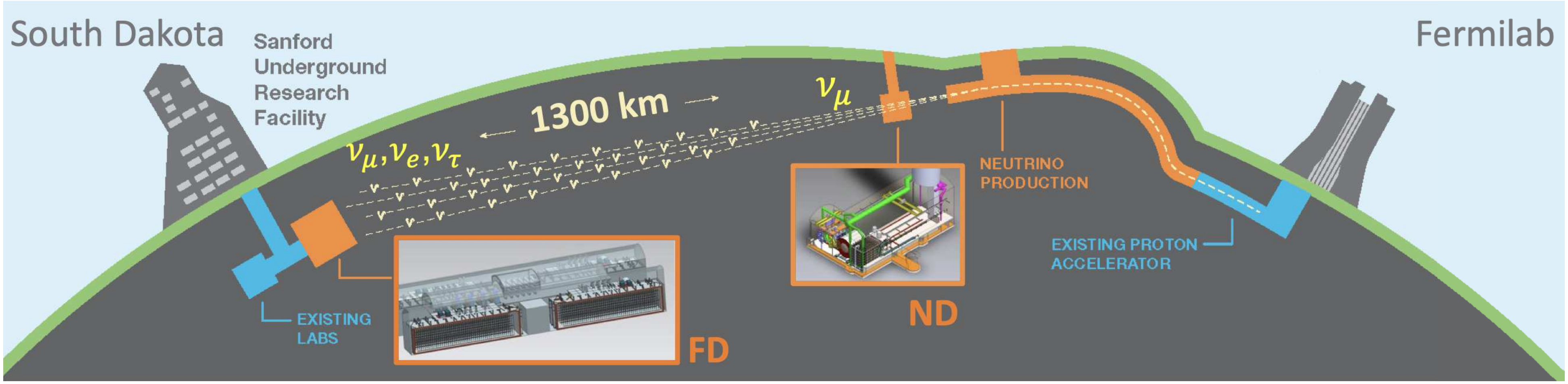
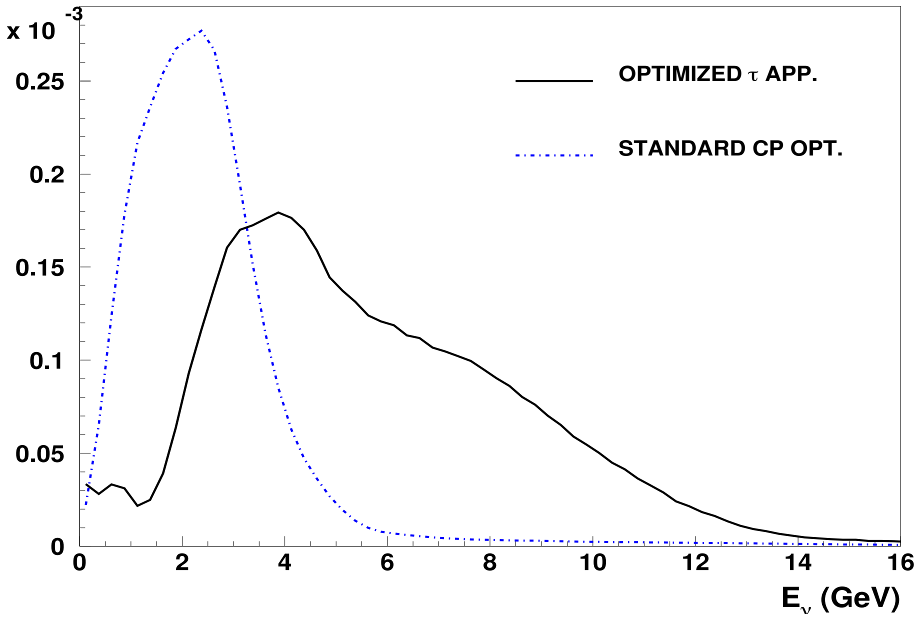
DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE)



- ✦ *Dedicated Long-Baseline Neutrino Facility (LBNF) beamline at Fermilab sending high intensity ν & $\bar{\nu}$ beams to the far site;*
- ✦ *A Far Detector (FD) in South Dakota (1,300 km from Fermilab) located 1.5 km underground and consisting of 4 LAr TPC modules, with a mass of 17 kt each;*
- ✦ *A Near Detector (ND) complex located at 574 m from the ν source at Fermilab.*

$\Longrightarrow$ *Next-generation long-baseline oscillation experiment with broad physics program*

LBNF (ANTI)NEUTRINO BEAMS



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

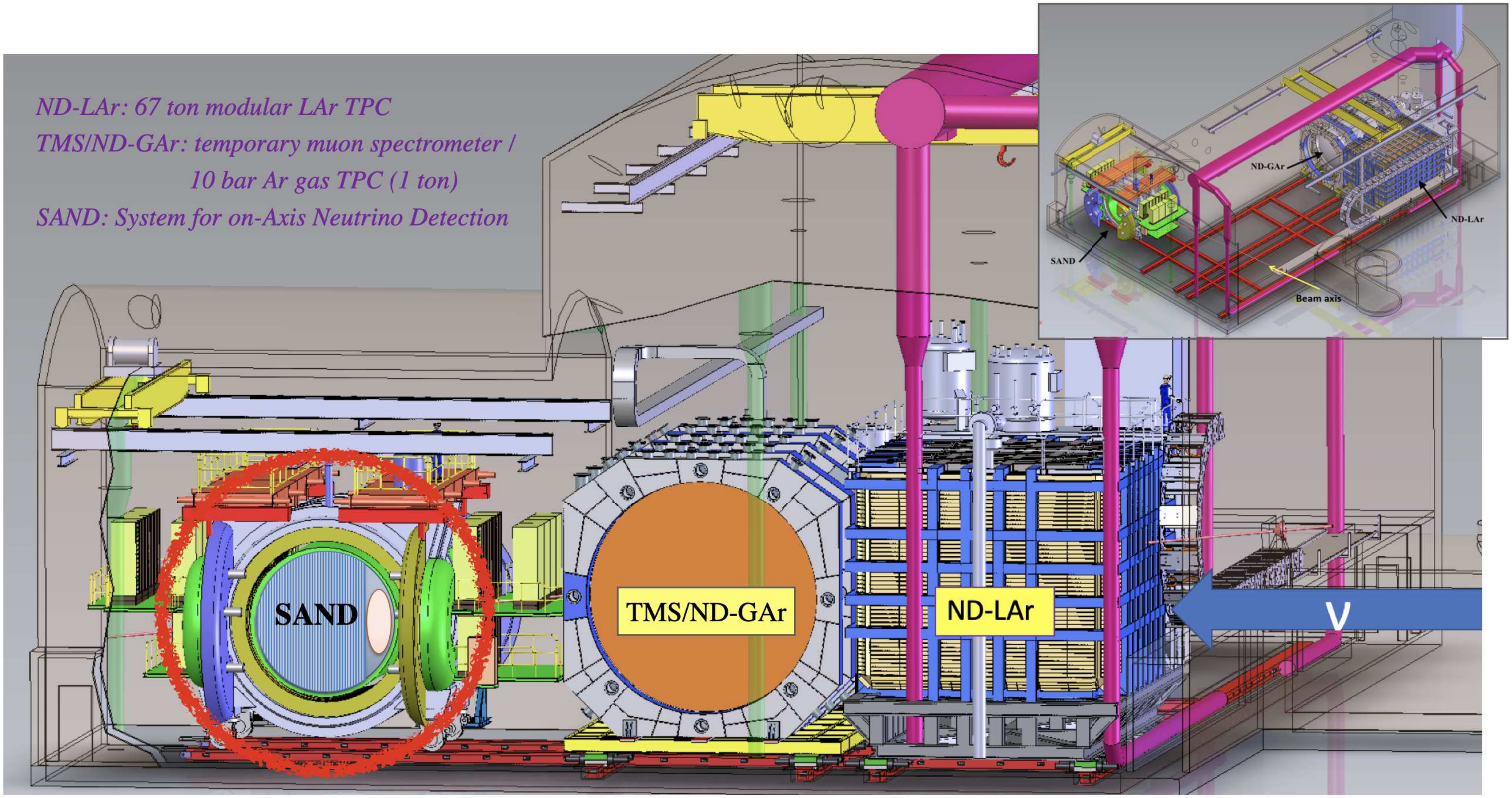
✦ *Two beam options available at LBNF:*

- *Default low-energy beam optimized for LBL search for CP violation: 120 GeV p, 1.1×10^{21} pot/y;*
- *High-energy beam optimized for the detection of ν_τ appearance at FD.*

✦ *LBNF upgrade planned doubling beam intensity from initial 1.2 MW to 2.4 MW (× 2)*

$\Longrightarrow$ *Possible to collect a CC statistics $\sim 10^8$ with relatively compact detector at near site*

DUNE NEAR DETECTOR COMPLEX



ND-LAr: 67 ton modular LAr TPC

TMS/ND-GAr: temporary muon spectrometer /
10 bar Ar gas TPC (1 ton)

SAND: System for on-Axis Neutrino Detection

✦ *Measurements to constrain in-situ systematics for LBL oscillation analysis*

✦ *Short-baseline physics program of precision measurements & searches for new physics*

$\Longrightarrow$ *Synergy between both measuremets sharing same requirements*

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

✦ *Neutrinos desirable probe for fundamental interactions:*

- *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

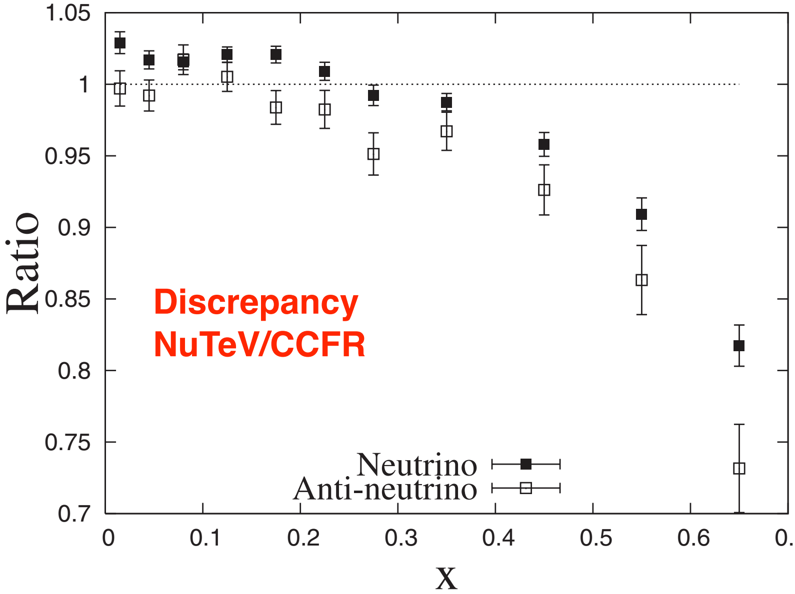
Need of massive nuclear targets does not allow a precise control of the interactions.

✦ FLUXES

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

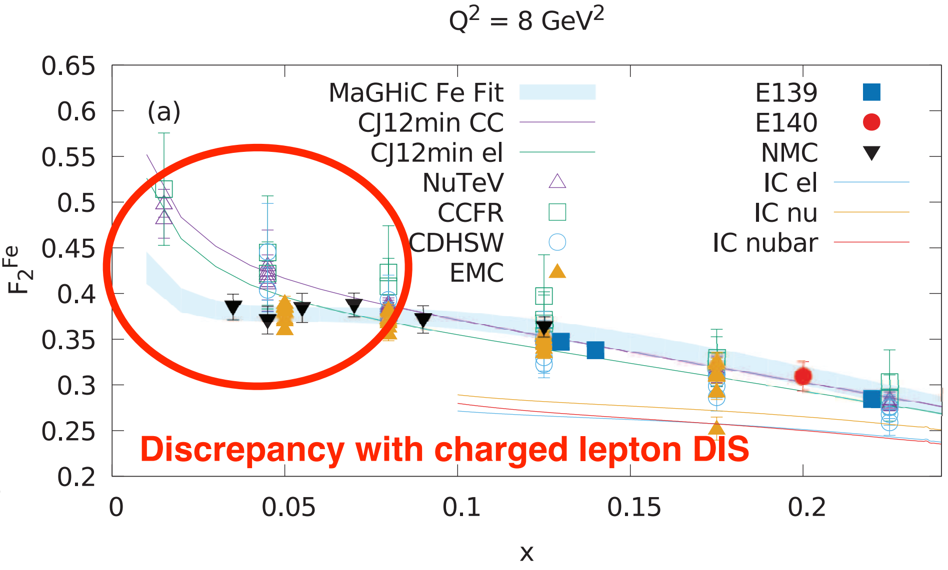
✦ NUCLEAR EFFECTS

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



Discrepancy NuTeV/CCFR

NuTeV Coll., PRD 74 (2006) 012008



Discrepancy with charged lepton DIS

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

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

A TALE OF SYSTEMATICS

$$N_{\mathrm{X}}(E_{\mathrm{rec}}) = \int_{E_\nu} dE_\nu \; \Phi(E_\nu) \; P_{\mathrm{osc}}(E_\nu) \; \sigma_{\mathrm{X}}(E_\nu) \; R_{\mathrm{phys}}(E_\nu, E_{\mathrm{vis}}) \; R_{\mathrm{det}}(E_{\mathrm{vis}}, E_{\mathrm{rec}})$$

Measurements expected to be dominated by systematics given intense LBNF beams.

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

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

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

$\Longrightarrow$ *Same systematics affecting study of* $\nu(\bar{\nu})$ *interactions (*σ_{X}*) in ND also relevant for LBL oscillation analysis (*P_{osc}*)*

A TALE OF SYSTEMATICS

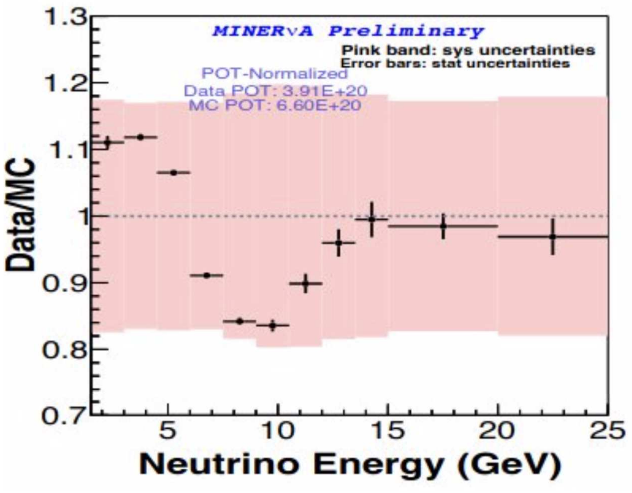
$$N_{\mathrm{X}}(E_{\mathrm{rec}}) = \int_{E_\nu} dE_\nu \; \boxed{\Phi(E_\nu)} \; P_{\mathrm{osc}}(E_\nu) \; \sigma_{\mathrm{X}}(E_\nu) \; R_{\mathrm{phys}}(E_\nu, E_{\mathrm{vis}}) \; R_{\mathrm{det}}(E_{\mathrm{vis}}, E_{\mathrm{rec}})$$

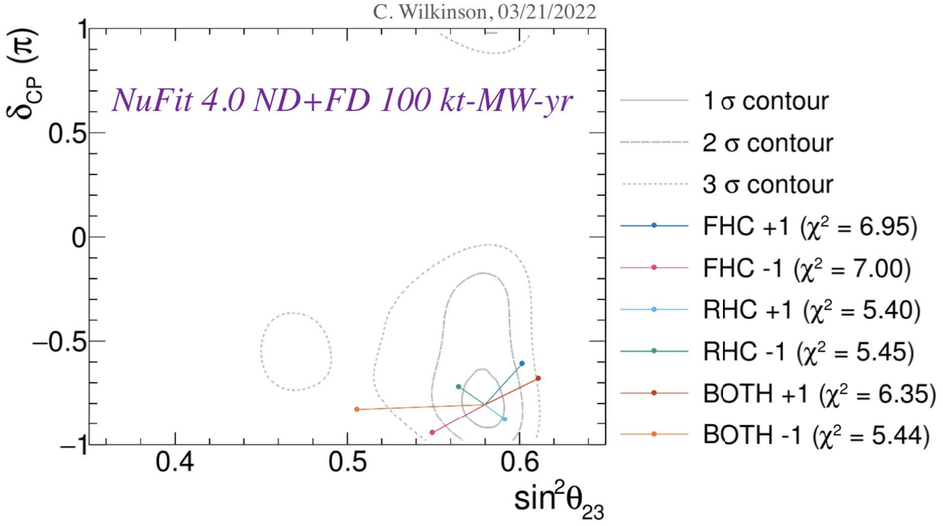
Measurements expected to be dominated by systematics given intense LBNF beams.

$\Phi(E_\nu)$ *Long-baseline oscillation analysis sensitive to spectral changes of on-axis flux*

- *Accurate knowledge of on-axis and off-axis flux required in DUNE;*
- *Flux and related uncertainties folded into all ND observables.*

$\Longrightarrow$ *Only factor which can be easily factored out in ND*




C. Wilkinson, 03/21/2022

A TALE OF SYSTEMATICS

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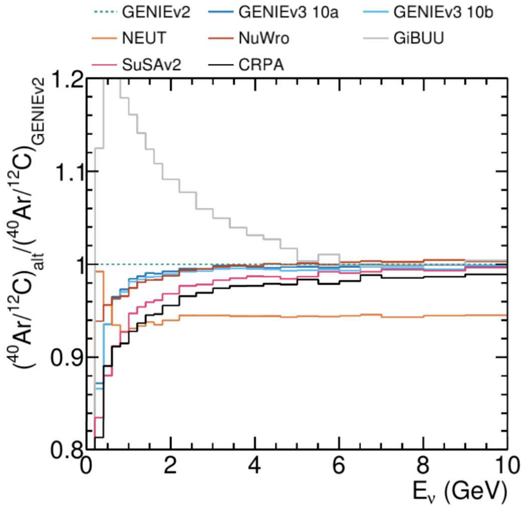
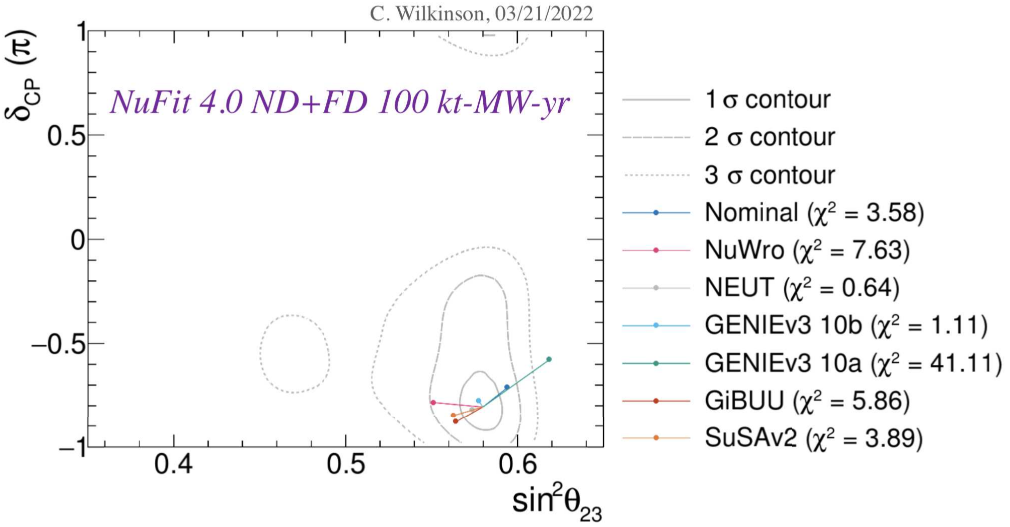
Measurements expected to be dominated by systematics given intense LBNF beams.

σ_{X} *Cross-section on Ar target (nuclear effects) required in DUNE*

R_{phys} *Smearing introduced by nuclear effects on initial and final state particles can result in systematic biases on the oscillation parameters extracted from fits to FD and ND data.*




C. Wilkinson, 03/21/2022

SYSTEM FOR ON-AXIS NEUTRINO DETECTION

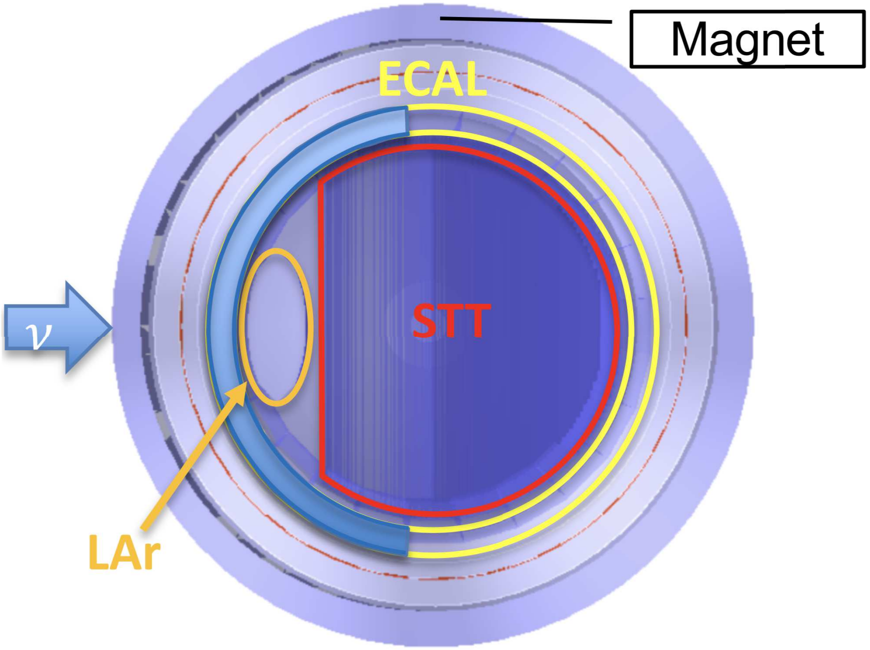
✦ *Multipurpose detector with combined particle ID & tracking:*

- *Superconducting magnet and ECAL refurbished from KLOE experiment;*
- *New low-density inner tracker integrating multiple nuclear targets and preceded by small LAr target.*

✦ *Low-density design & target mass allow accurate in-situ calibrations* $\boxed{\Delta p < 0.2\%}$ *momentum scale uncertainty from* $K_0 \to \pi^+\pi^-$

✦ *Accurate reconstruction of transverse plane kinematics from particle 4-momenta:*

- *"Transparent" target/tracker system with total length* $\boxed{\sim 1.3X_0}$*;*
- *NOMAD concept originally developed for kinematic detection of* ν_τ *[Nucl.Phys.B 611 (2001) 3-39].*



STT FV mass:
4.7 t CH_2
557 kg C

GRAIN mass:
1 t LAr

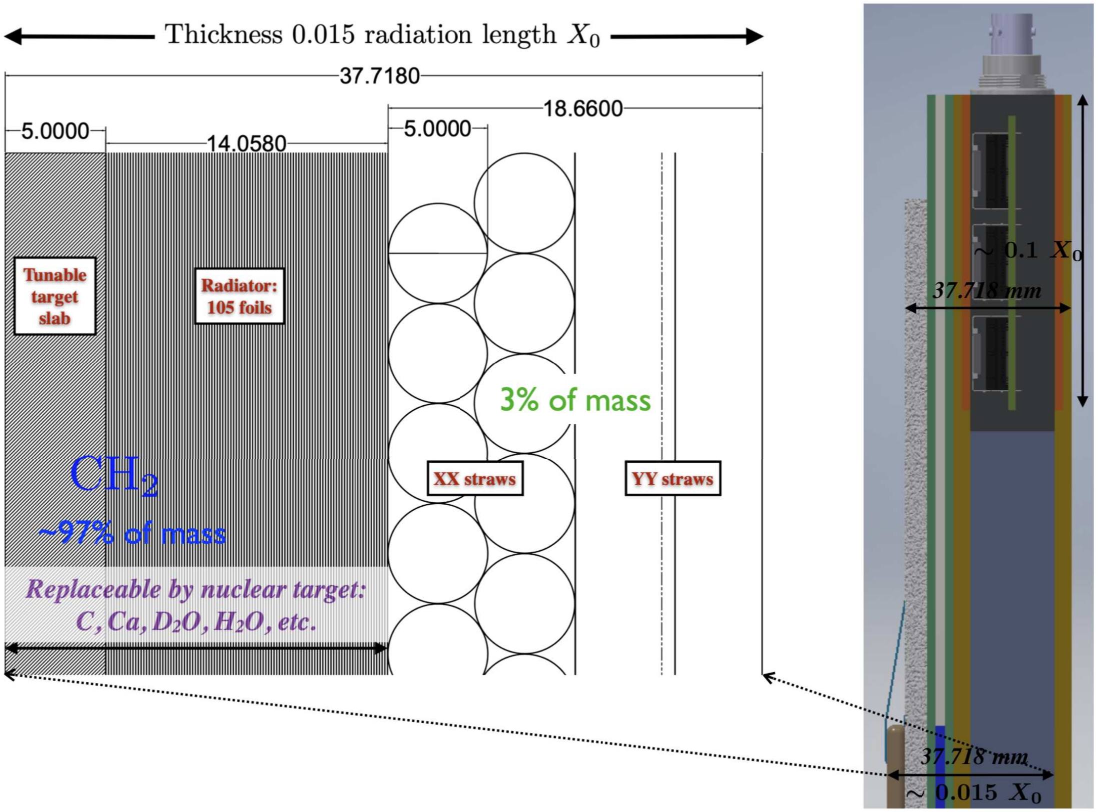
Front ECAL mass:
22.8 t Pb

A TOOL TO REDUCE SYSTEMATICS

✦ *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 of negligible mass (straw layers);*
- *Many target layers dispersed within tracker by keeping low density* $\boxed{0.005 \leq \rho \leq 0.18\ g/cm^3}$.

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



✦ *Targets of high chemical purity $\sim 97\%$ of total STT mass (straws 3%)*

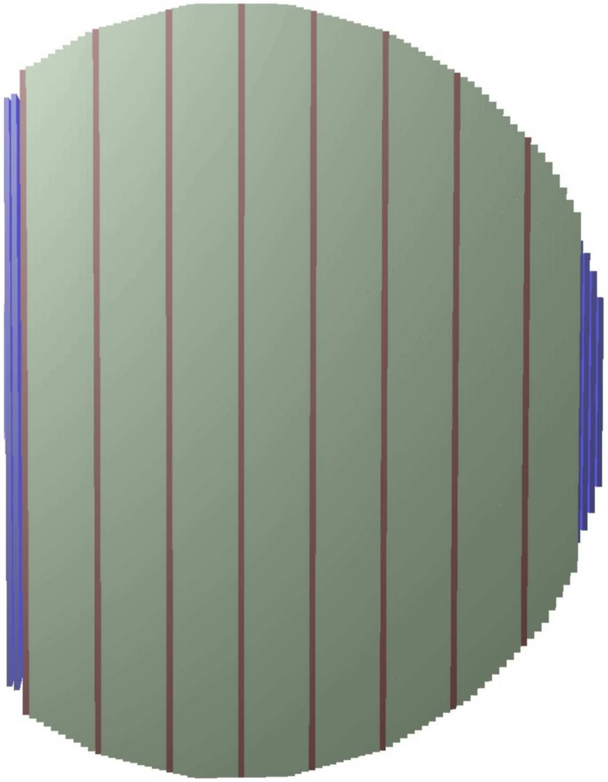
✦ *Separation from excellent vertex and angular resolutions*

✦ *Thin targets replaceable during data taking: CH$_2$, C, Ca, Fe, Pb, etc.*

"SOLID" HYDROGEN TARGET

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

- *Exploits 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;*



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

CH_2 and C targets alternated in FV
to guarantee same acceptance

Mass ratio optimized for subtraction

$\Longrightarrow$ *Equivalent to about* $\boxed{10 \text{ m}^3 \text{ LH}_2}$

Green: CH_2 *Brown: C*

"SOLID" HYDROGEN TARGET

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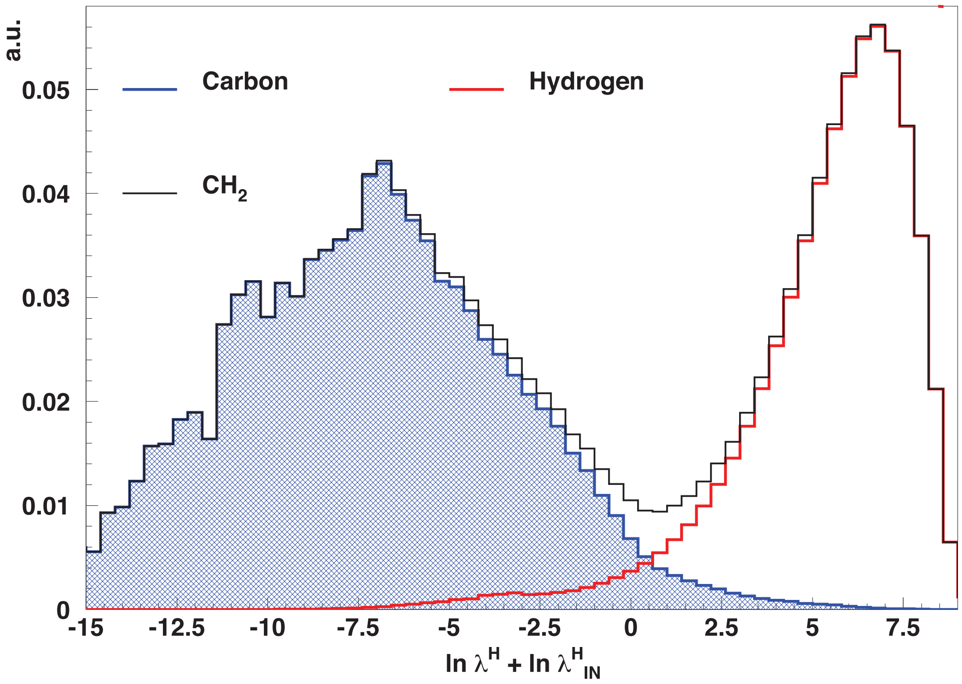
- *Exploits high resolutions & control of chemical composition and mass of targets in STT;*
- *Model-independent data subtraction of dedicated C (graphite) target from main CH_2 target;*
- *Kinematic selection can reduce dilution factor for inclusive & exclusive CC topologies with 80-95% purity and 75-96% efficiency before subtraction.*

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



CC process (1y+1y)	H selected Evts/year
$\nu_\mu p \to \mu^- p \pi^+$	*408,000*
$\nu_\mu p \to \mu^- p \pi^+ X$	*152,000*
$\nu_\mu p \to \mu^- n \pi^+ \pi^+ X$	*19,000*
ν_μ CC inclusive on H	*579,000*
$\bar{\nu}_\mu p \to \mu^+ n$	*172,000*
$\bar{\nu}_\mu p \to \mu^+ p \pi^-$	*61,000*
$\bar{\nu}_\mu p \to \mu^+ n \pi^0$	*42,000*
$\bar{\nu}_\mu p \to \mu^+ p \pi^- X$	*27,000*
$\bar{\nu}_\mu p \to \mu^+ n \pi \pi X$	*31,000*
$\bar{\nu}_\mu$ CC inclusive on H	*333,000*

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

WHY HYDROGEN?

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

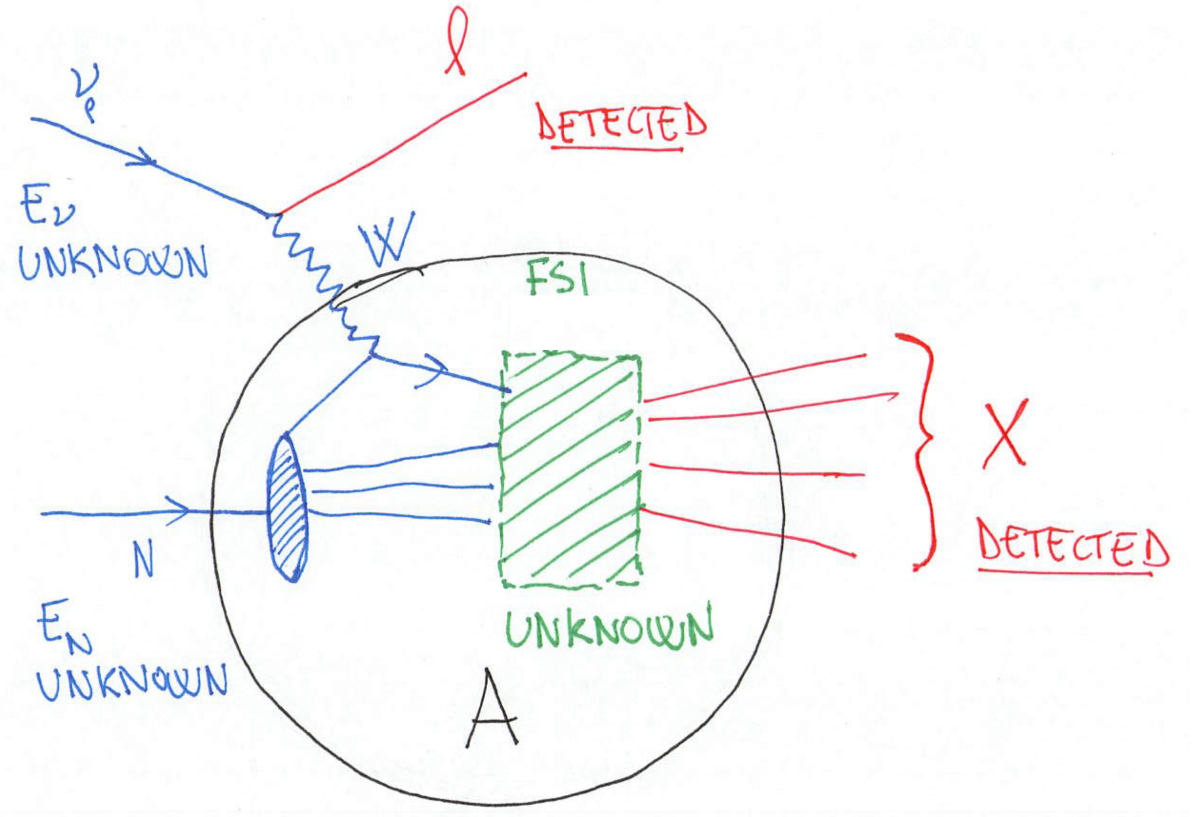
- *Proton structure from flavor-sensitive $\nu(\bar{\nu})$-H CC interactions;*
- *Isospin symmetry provides direct access to free neutron structure without nuclear corrections;*
- *Understanding nucleon-level amplitudes is essential input for (anti)neutrino-nucleus cross-sections.*

$\Longrightarrow$ *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*



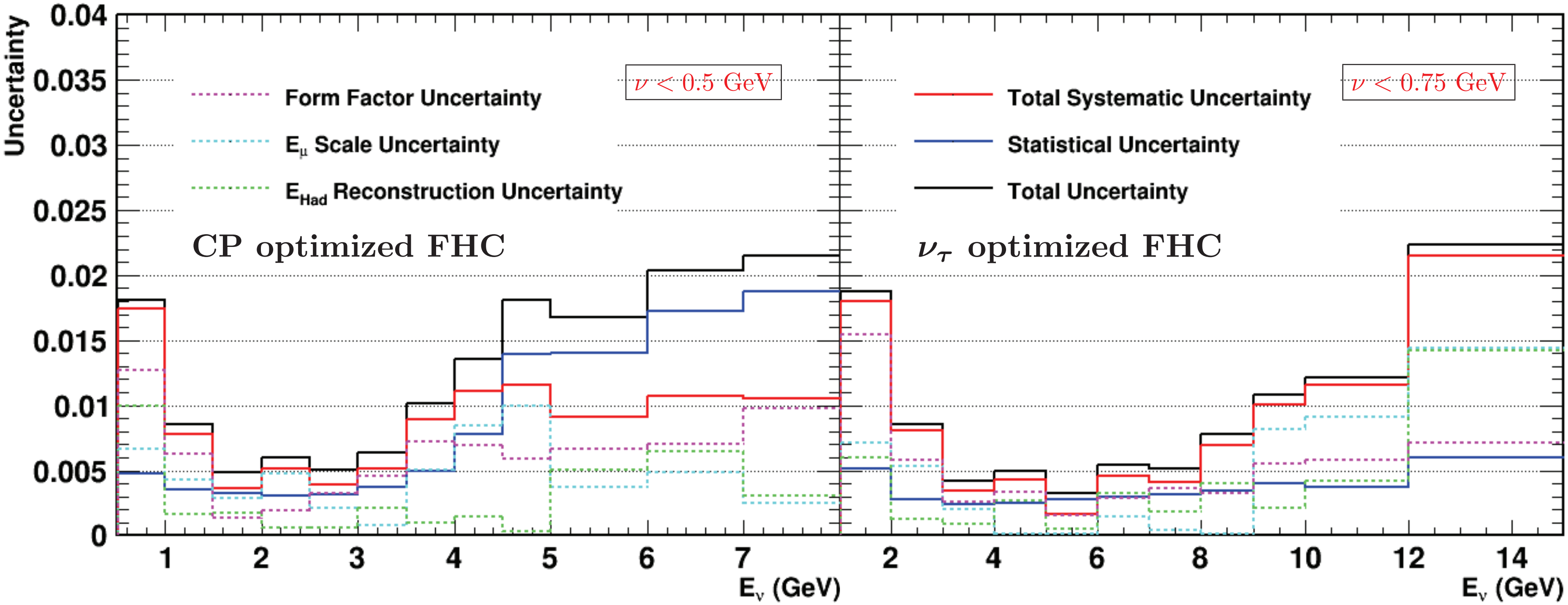
<u>(Anti)neutrino-Nucleus scattering</u>:
projectile of unknown energy hitting target of unknown energy
with outgoing products undergoing unknown smearing

FLUX MEASUREMENTS WITH H

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

- *Select well reconstructed $\mu^- p \pi^+$ topology on H ($\sim 93\%$ p reconstructable);*
- *Cut $\boxed{\nu < 0.5 \text{ GeV}}$ flattens cross-sections reducing uncertainties on E_ν dependence;*
- *Systematic uncertainties dominated by momentum scale ($\Delta p \sim 0.2\%$ from $K_s^0 \to \pi^+\pi^-$).*

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

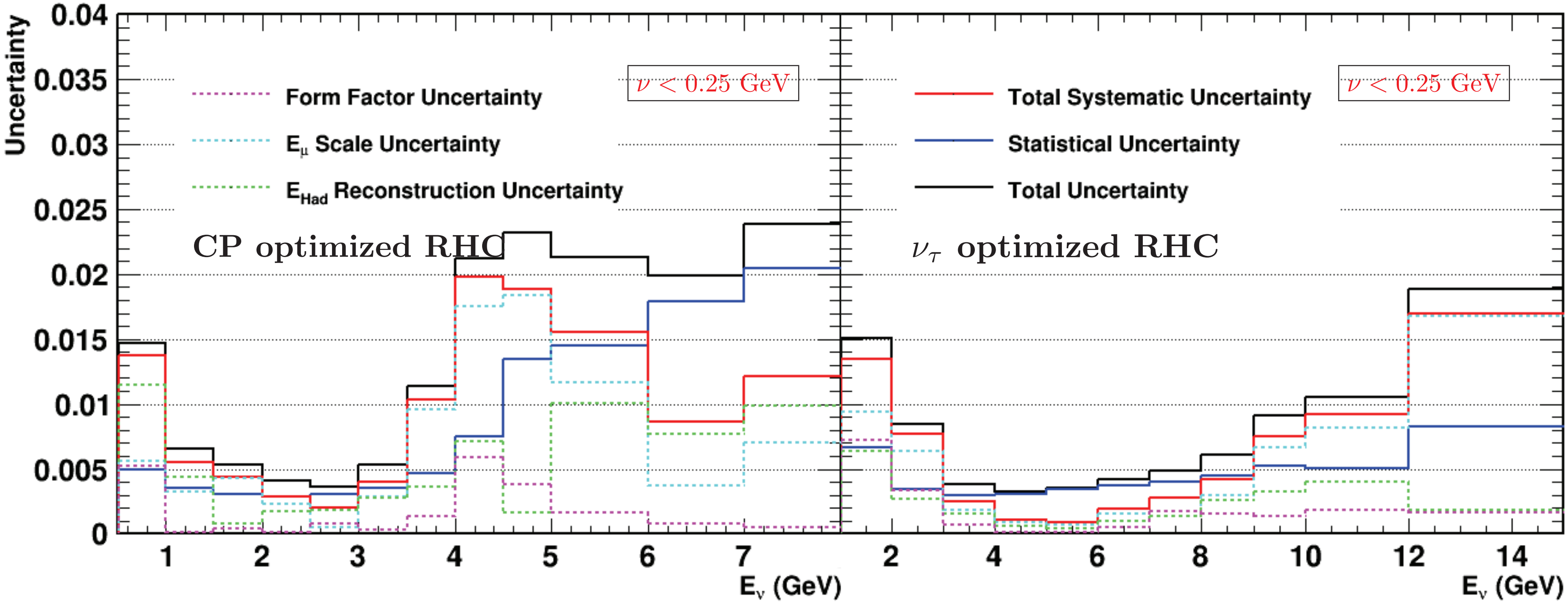


PLB 795 (2019) 424, arXiv:1902.09480 [hep-ph]

✦ *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 + reconstructed direction of neutrons detected in STT+ECAL ($\sim 80\%$);*
- *Cut $\boxed{\nu < 0.25 \text{ GeV}}$ 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*

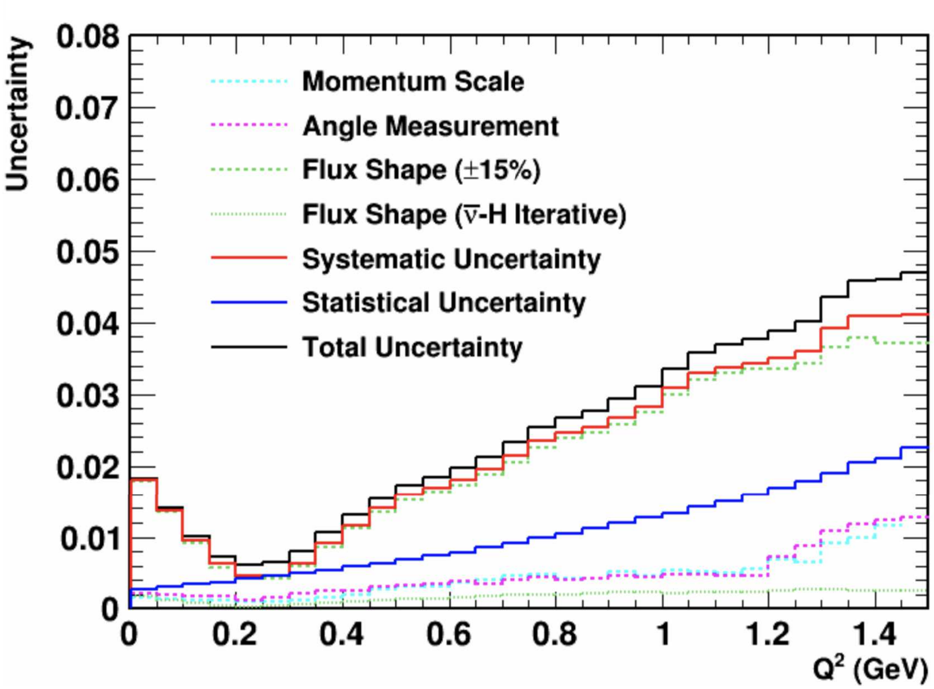


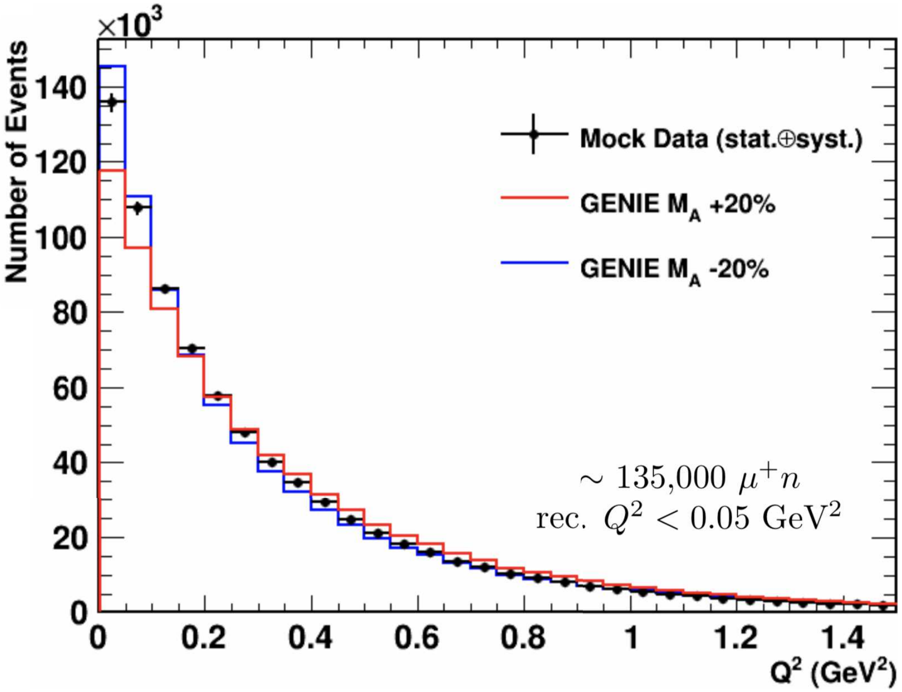
✦ *Absolute $\bar{\nu}_\mu$ flux from QE on Hydrogen $\bar{\nu}_\mu p \to \mu^+ n$:*

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

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

$\Longrightarrow$ *Calibrate absolute n detection efficiency with dedicated irradiation of STT & ECAL*





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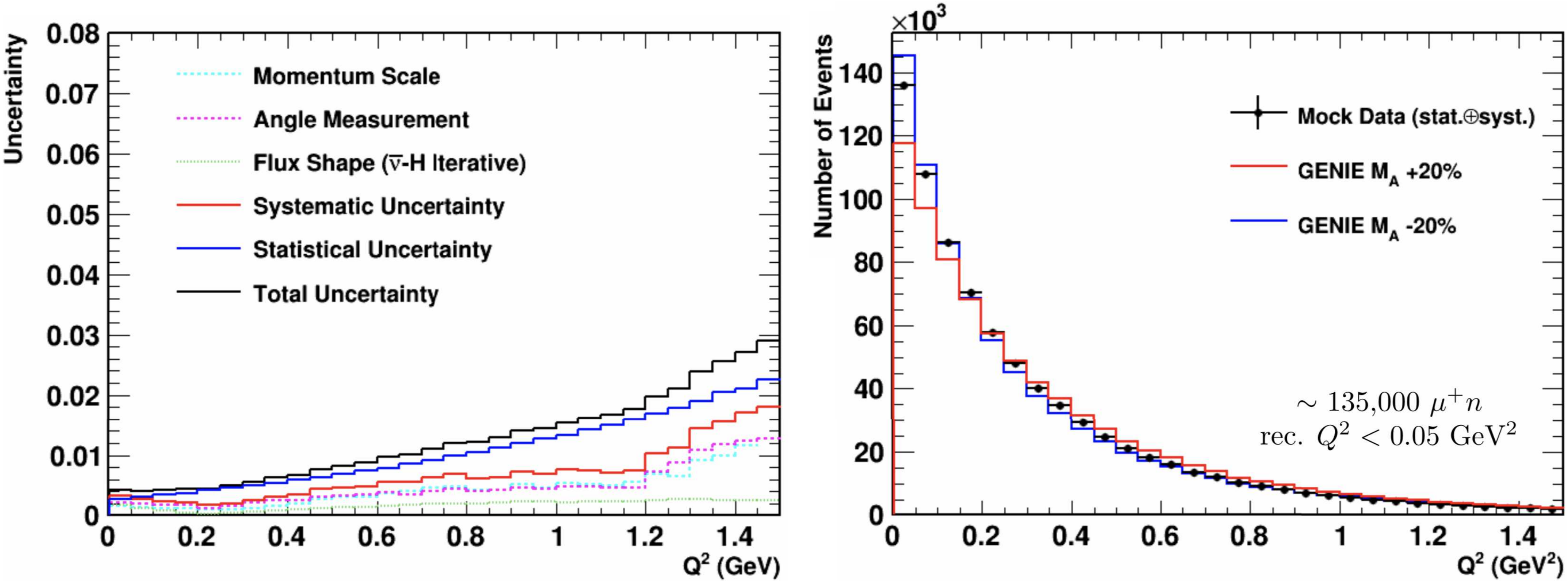
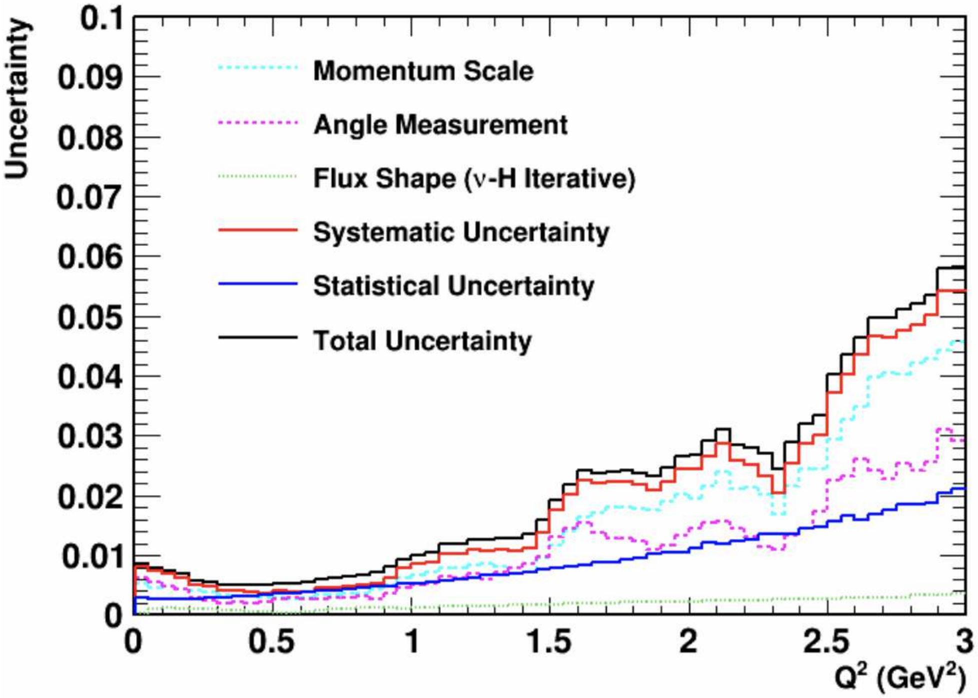
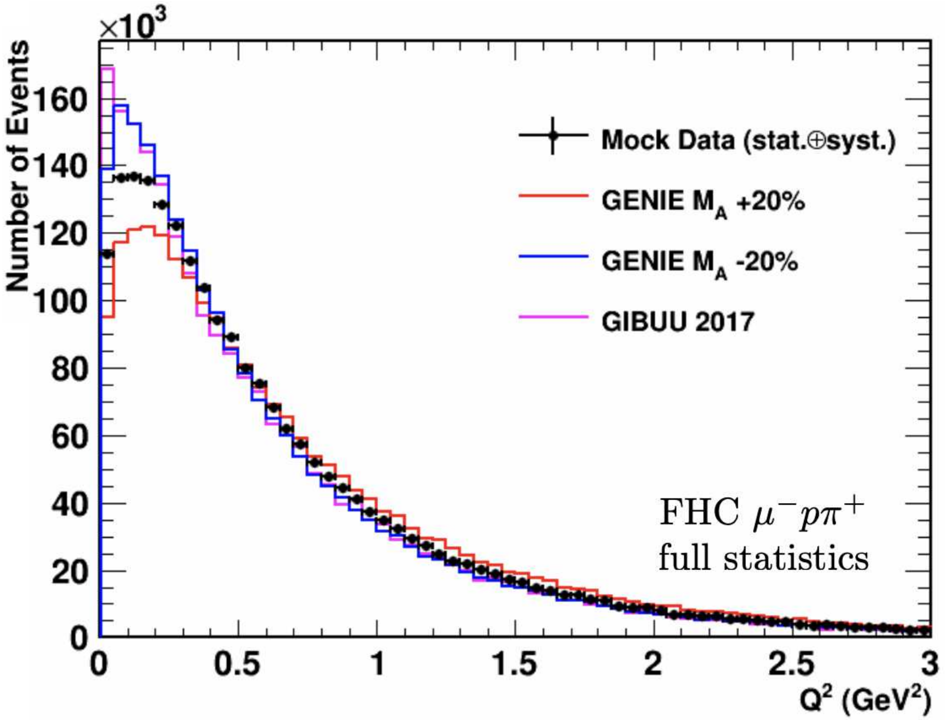


STRUCTURE OF FREE PROTON





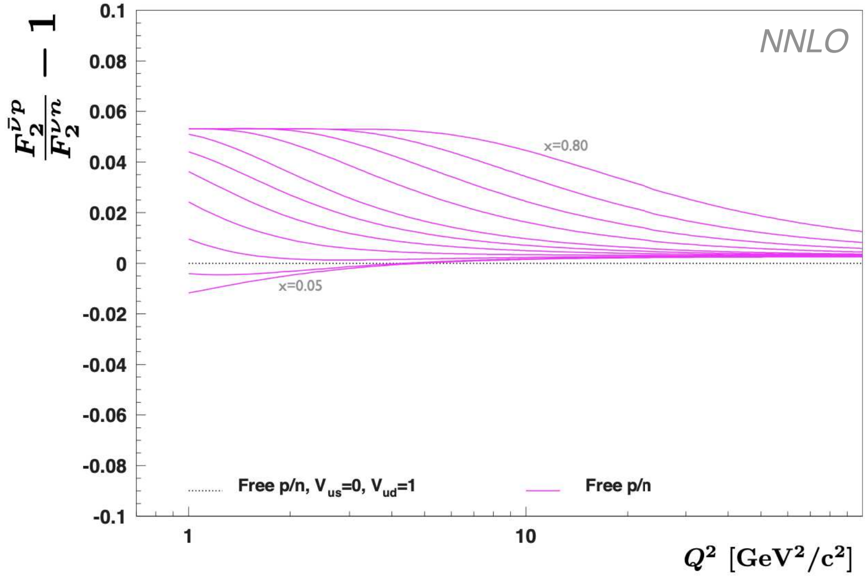
Form factors and structure functions can be constrained from Q^2 and x distributions

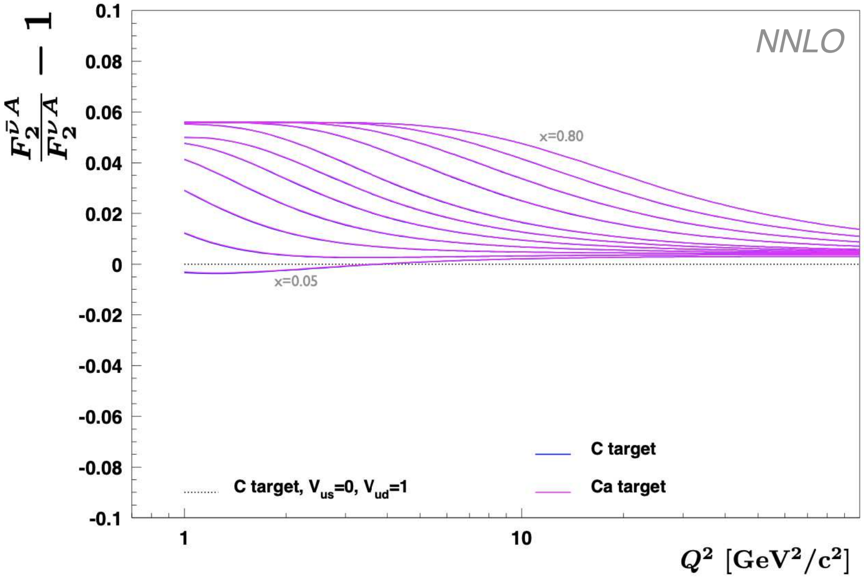
FREE NEUTRON TARGET

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

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

- *Quark mixing (CKM): sensitivity to V_{us} and V_{ud};*
- *Strange sea quarks and charm production: sensitivity to m_c and strange sea asymmetry;*
- *Exploit C target in "solid" hydrogen: validation of $\mathcal{R}_{2,3}^{\mathrm{p/n}}$ corrections to free neutrons.*





arXiv: 2205.10396 [hep-ph]

CALIBRATION OF E_ν ENERGY SCALE WITH H

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

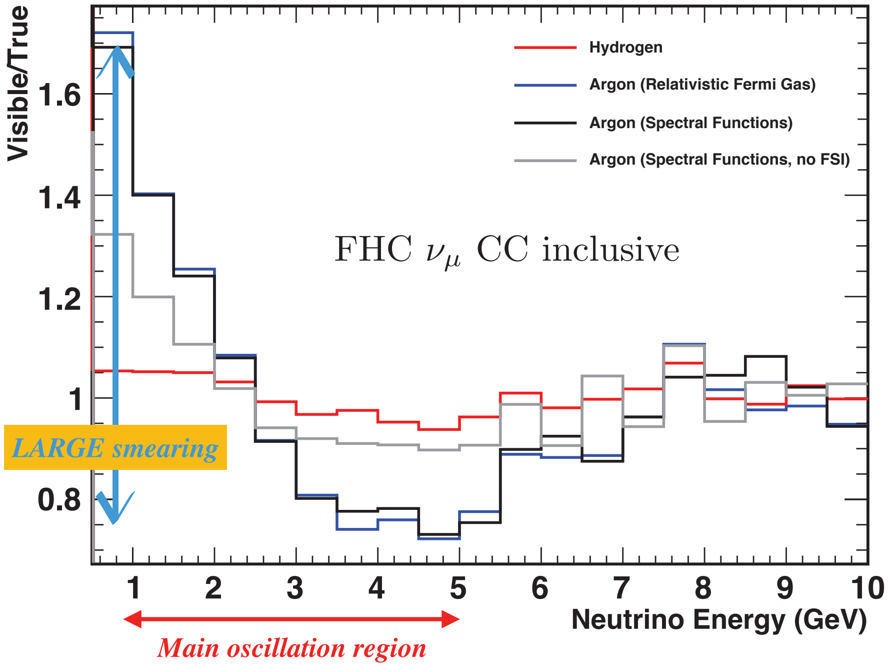
∼1% in H **$F_i(Q^2)$** **$R_{\rm phys} \equiv I$** **K_0, Λ, γ**

✦ *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*



RICH 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

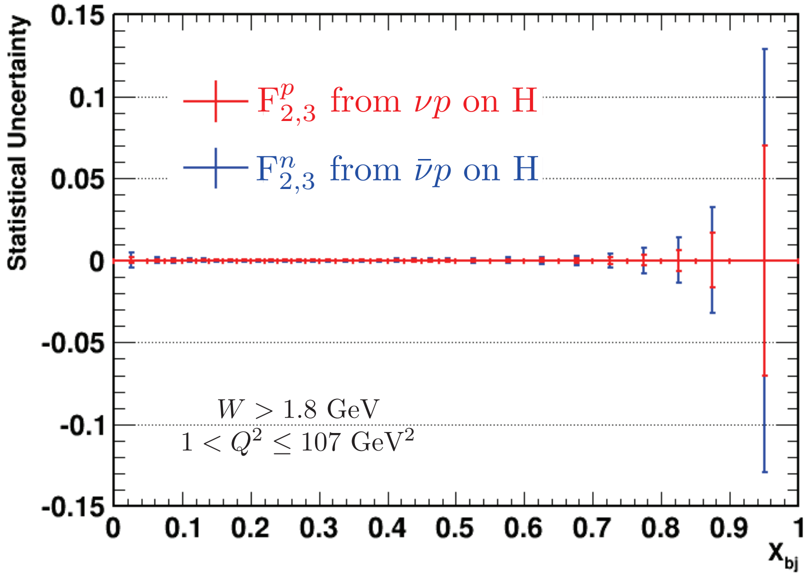
- *The Adler integral provides the* ISOSPIN *of the target and is derived from current algebra:*

$$S_A(Q^2) = \int_0^1 \frac{dx}{2x} \left(F_2^{\bar{\nu}p} - F_2^{\nu p}\right) = I_p$$

  - *At large Q^2 (quarks) sensitive to $(s - \bar{s})$ asymmetry, isospin violations, heavy quark production*
  - *Apply to nuclear targets and test nuclear effects*

  [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 and EIC programs)

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 BOUND NUCLEONS

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

$$R_{2,3}^{A}(x,Q^2) \; = \; \frac{F_{2,3}^{\nu A}}{ZF_{2,3}^{\nu p}+(A-Z)F_{2,3}^{\nu n}} \sim \frac{F_{2,3}^{\nu A}}{ZF_{2,3}^{\nu H}+(A-Z)F_{2,3}^{\bar{\nu} H}}(x,Q^2)$$

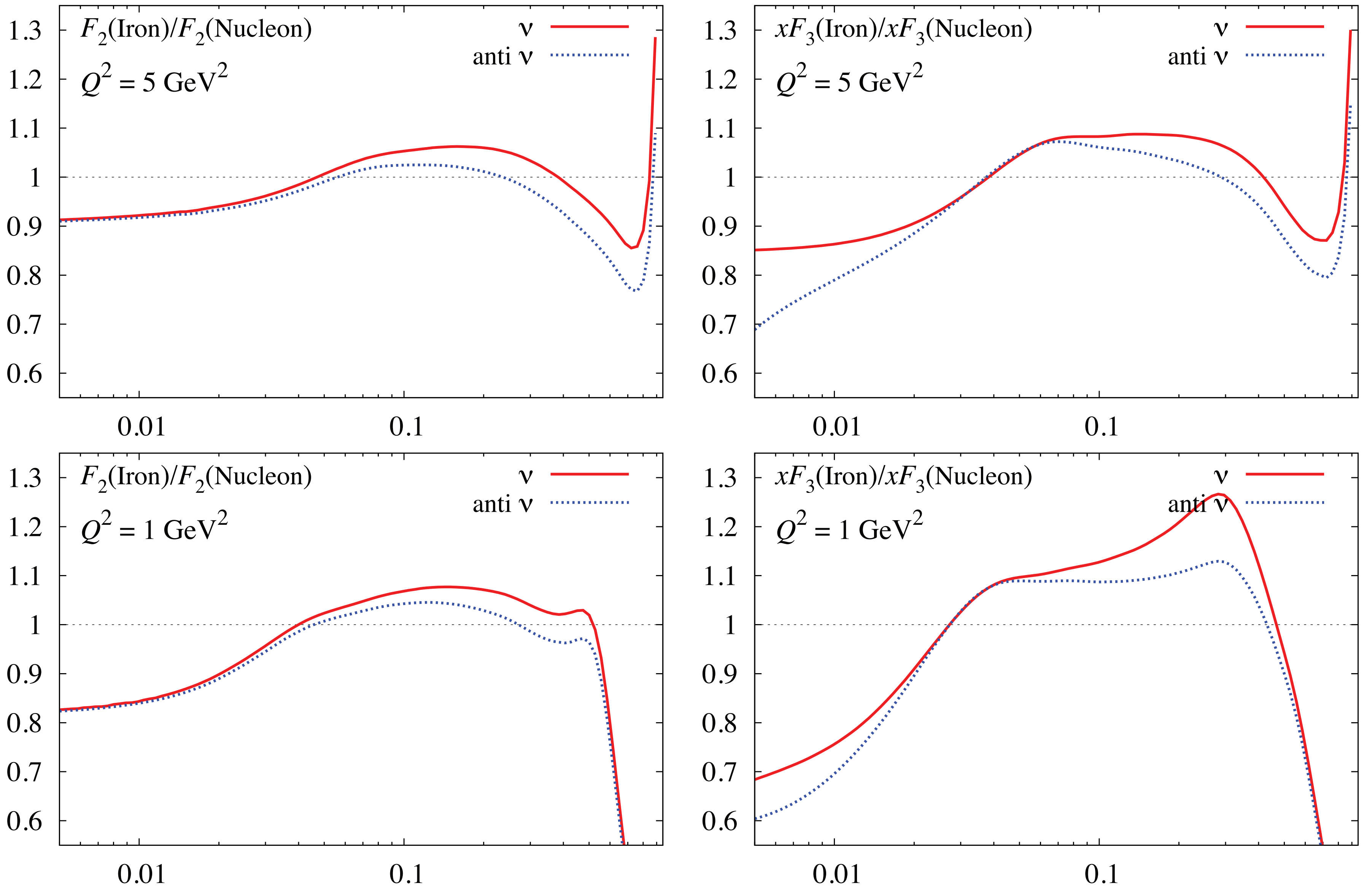
- *Comparison with e/μ DIS results and nuclear models;*
- *Study flavor dependence of nuclear modifications ($W^{\pm}/Z$ helicity, C-parity, Isospin);*
- *Effect of the axial-vector current.*

✦ *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.*



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

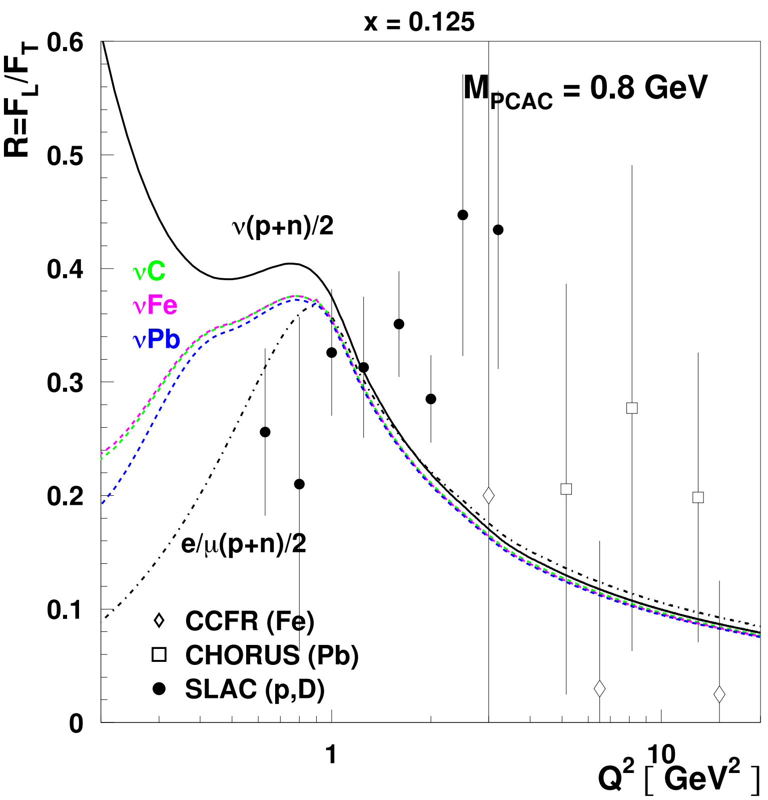
- *Neutrino scattering is characterized by an* $\boxed{\text{AXIAL-VECTOR CURRENT}}$ *in addition to the the Vector current.*

- *Axial Current is only Partially Conserved (PCAC) and dominates SFs at low Q^2:*

$$F_2 \to F_L = \frac{f_\pi^2 \sigma_\pi}{\pi} \qquad Q^2 \to 0$$

- *The finite PCAC contribution to F_L strongly affects the asymptotic behaviour of $\boxed{R = \sigma_L/\sigma_T}$ for $Q^2 \to 0$:*

$$F_T \sim Q^2 \qquad F_L \sim \frac{f_\pi^2 \sigma_\pi}{\pi} > 0$$



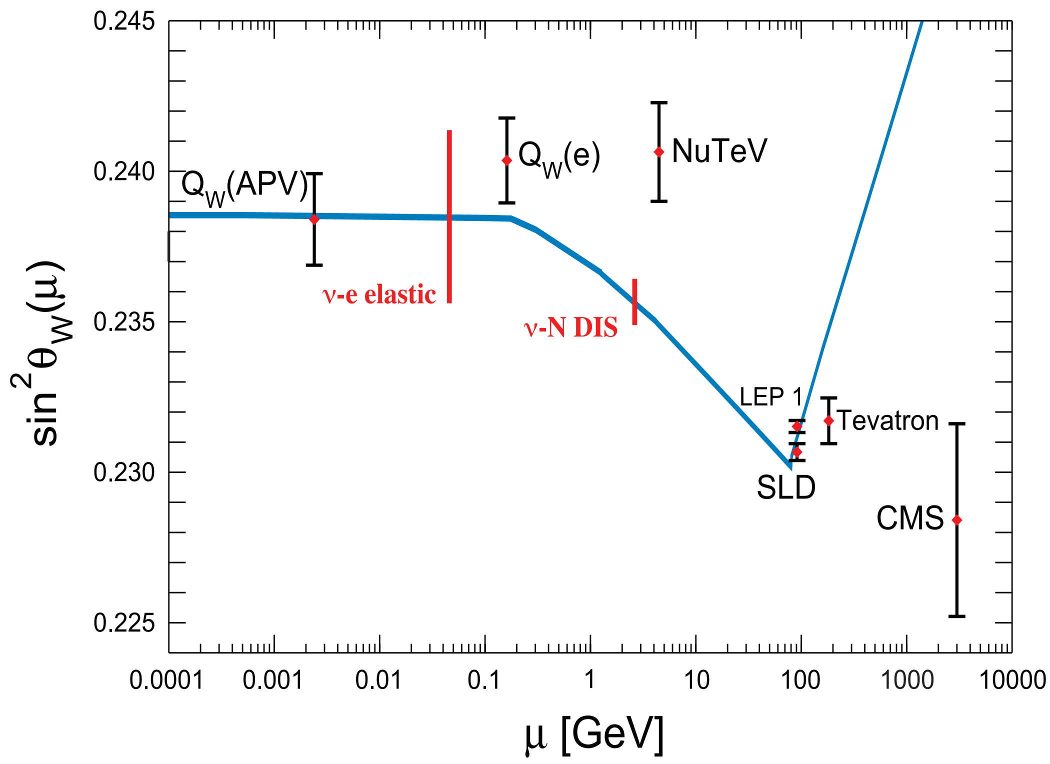
$\Longrightarrow$ *Substantial difference with respect to charged lepton scattering.*

PRD 76 (2007) 094023

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 (∼0.35%)*
- $\mathcal{R}_{\nu e} = \frac{\sigma^{\bar\nu}_{\rm NC}}{\sigma^\nu_{\rm NC}}$ *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*

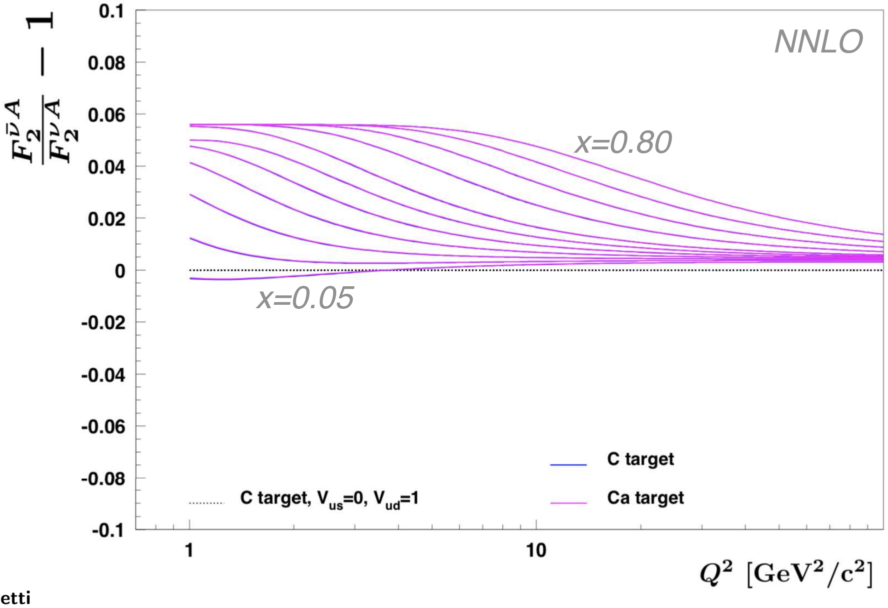
TESTS OF ISOSPIN SYMMETRY

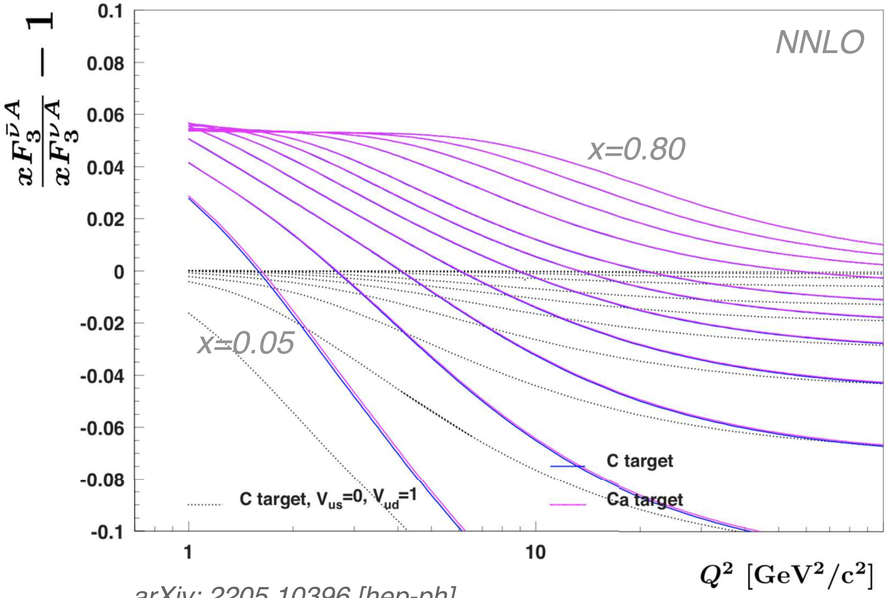
✦ *Isospin symmetry can be verified with* ISOSCALAR TARGET :

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

- *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*

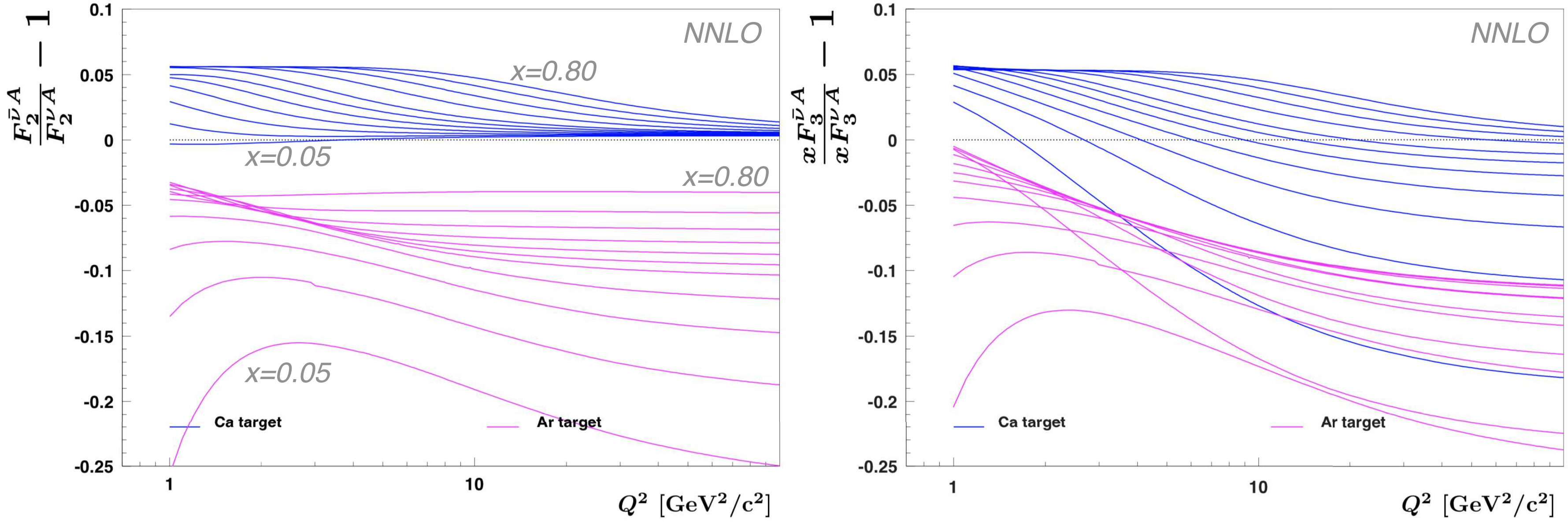




arXiv: 2205.10396 [hep-ph]

- ✦ *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*



SUMMARY

- *"Solid" hydrogen concept gives access to the flavor content of free protons and neutrons, as well as a tool to constrain main systematics in measurements.*

- *SAND can provide in-situ constraints of systematics for LBL analyses:*
  - *Precision measurement of the ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$ on-axis fluxes as a function of energy;*
  - *Inclusive and exclusive ν-H and $\bar{\nu}$-H CC event samples free from nuclear effects to calibrate the (anti)neutrino energy scale in ν-A CC interactions.*
  - *Inclusive and exclusive ν-A and $\bar{\nu}$-A CC event samples on Ar and other nuclear targets.*

- *Rich short-baseline physics potential including hundreds of diverse physics topics from precision measurements and searches for new physics, complementary to ongoing fixed-target, collider and nuclear physics efforts.*

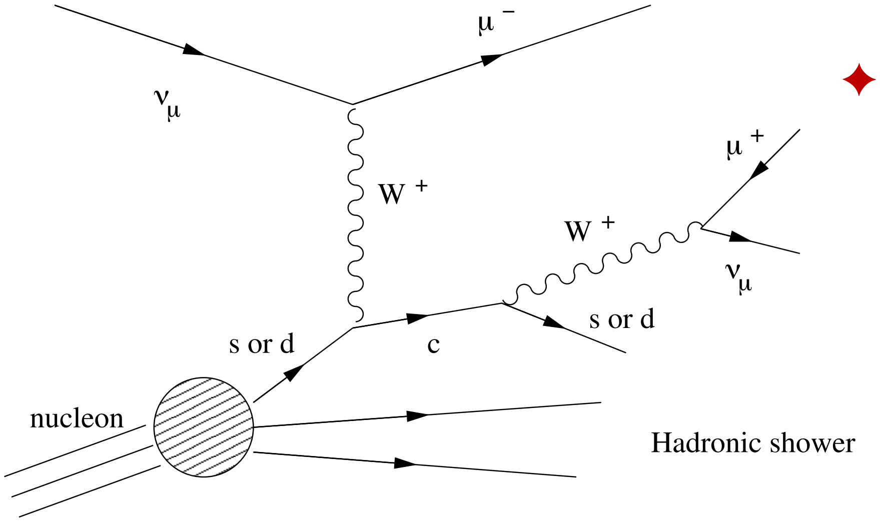
  $\Longrightarrow$ *Synergy with LBL program sharing common requirements/measurements*

- *Ongoing activities to finalize the design in preparation for the construction of the STT and LAr target to be ready for data taking around 2030.*

New suggestions and/or additional interest/contributions welcomed

Backup slides

STRANGENESS CONTENT OF NUCLEON



- *Charm dimuon production in $\nu(\bar{\nu})$ DIS*

$$\frac{d^2\sigma_{\mu\mu}}{dxdydz} = \frac{d^2\sigma_c}{dxdy} D_c(z) B_\mu; \qquad z = \frac{P_L(h_c)}{P_L^{\max}}$$

$$B_\mu = \sum_h f_h Br(h \to \mu^+ X); \; h = D^0, D^+, D_s^+, \Lambda_c^+$$

$D_c(z)$ *average fragmentation function*

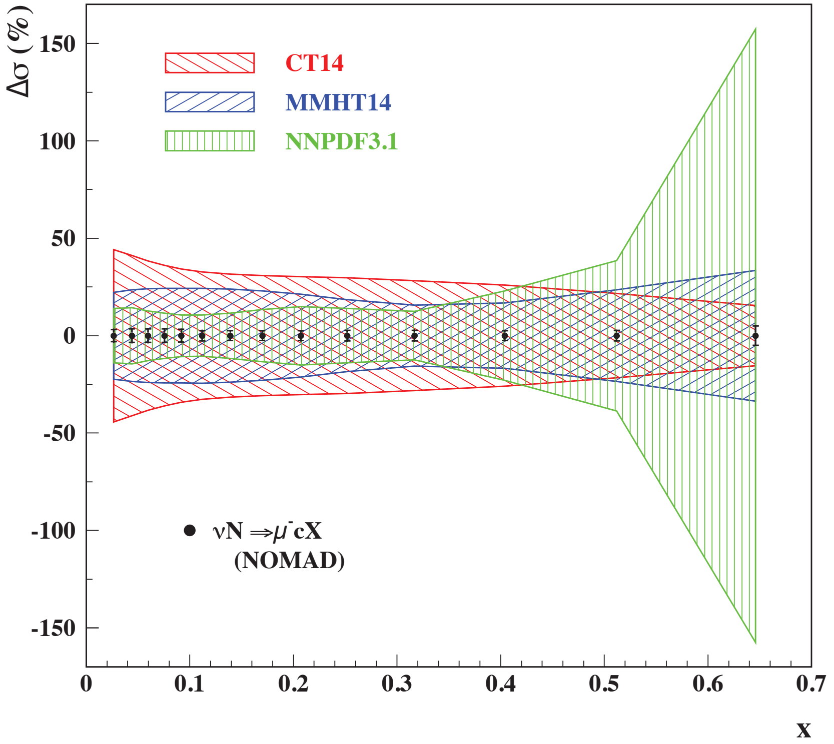
- *Charm production in ν and $\bar{\nu}$ DIS provides a clean and direct access to $s(x)$ and $\bar{s}(x)$*

$$F_{2,c}(x,Q) = 2\xi \left[|V_{cs}|^2 s(\xi,\mu) + |V_{cd}|^2 \frac{u(\xi,\mu) + d(\xi,\mu)}{2} \right]$$

$$\xi = x\left(1 + m_c^2/Q^2\right), \;\; \mu = \sqrt{Q^2 + m_c^2}$$

where simple LO approximations are given for illustration purpose

$$\begin{cases} \nu: & s/(d_v + d_s) \to c & \simeq 50\% \\ \bar{\nu}: & \bar{s}/\bar{d}_s \to \bar{c} & \simeq 90\% \end{cases}$$



- *NOMAD measurement allows reduction of $s(x)$ uncertainty down to $\sim 3\%$:*
  $\kappa_s = \int_0^1 x(s+\bar{s})dx / \int_0^1 x(\bar{u}+\bar{d})dx = 0.591 \pm 0.019$ *(NPB 876 (2013) 339)*

- *Recent ATLAS claims of enhanced $s(x)$ seems related to overconstrained PDF parameterization (S. Alekhin et al., PLB 777 (2018) 134, PRD 91 (2015) 094002)*

- *Precision measurement of charm dilepton production (both $\mu\mu$ and μe) and kinematic reconstruction of exclusive charmed hadrons (e.g., D^{*+}, D_s, Λ_c).*