A Proposal for Precision Measurements of $\nu(\bar{\nu})$-H Interactions

R. Petti

University of South Carolina, Columbia SC, USA

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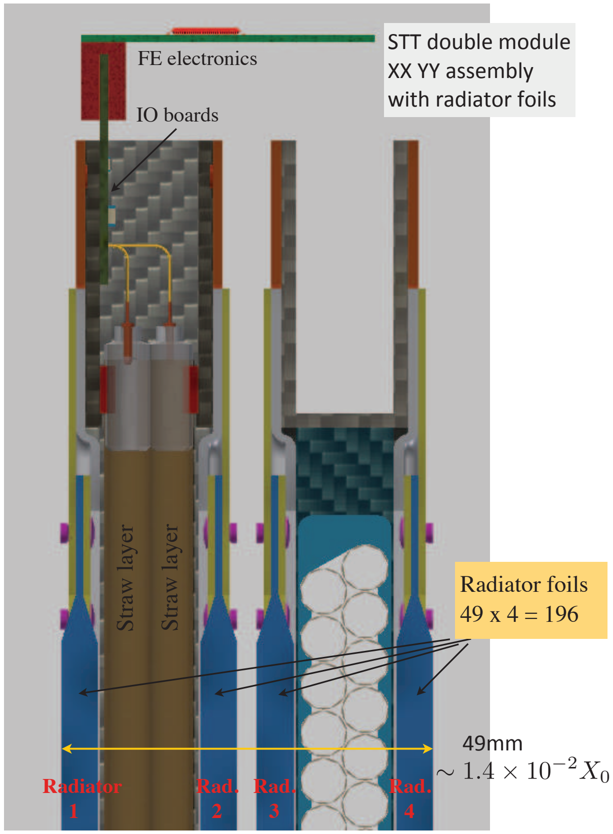
A DETECTOR TO CONTROL NEUTRINO TARGETS

✦ *Compact version of Straw Tube Tracker (STT) from DUNE CDR:*

- *Accurate control of various nuclear target(s) by separating target(s) from active tracker;*
- *Thin targets spread out uniformly within tracker by keeping low density* $\boxed{\rho \sim 0.16\ g/cm^3}$;
- *Total volume* $\sim 49\ m^3$, *fiducial mass 5 tons,* $X_0 \sim 3.5\ m$, *sampling 0.15 (0.36)%*$X_0 \perp (\parallel)$.

$\Longrightarrow$ *Need* $B \sim 0.6\,T$ *and to be surrounded by* 4π *electromagnetic calorimeter*



✦ *Radiator targets (100% purity) account for* $> 95\%$ *of STT mass and can be tuned to achieve desired statistics & resolutions.*

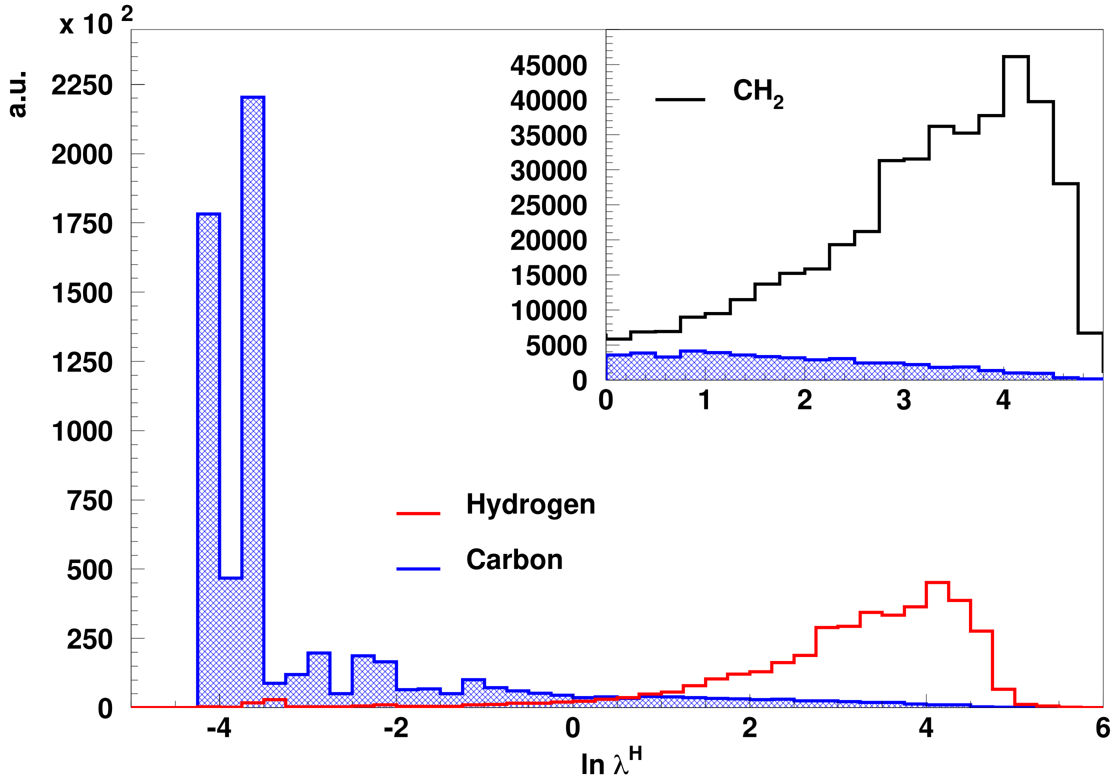
✦ *Separation from excellent vertex, angular & timing resolutions.*

✦ *Radiators can be replaced by thin nuclear targets: C, Ca, Ar, Fe, etc.*

✦ *Novel technique to measure $\nu(\bar{\nu})$-Hydrogen by subtracting CH_2 and C targets*:

- $\boxed{\text{714 kg of H}}$ *fiducial mass provides* $3.4(2.5) \times 10^6$ $\nu_\mu(\bar{\nu}_\mu)$ *CC on H in 5 years;*
- *Kinematic selection results in clean H samples of inclusive & exclusive CC topologies with 80-92% purity and >90% efficiency before subtraction;*
- *Model-independent data subtraction of (small) residual C bkgnd with dedicated graphite target.*

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



H. Duyang, B. Guo,
S.R. Mishra, RP,
arXiv:1809.08752 [hep-ph]

ADDITION TO DUNE ND COMPLEX

✦ *Compact STT flexible and can be adapted to different detector geometries.*

✦ *Large statistics $\nu(\bar{\nu})$-H samples are necessary to reduce Ar systematics in DUNE*

$\Longrightarrow$ *Proposal to enhance DUNE ND complex by integrating compact STT*

✦ Option I:
Additional self-contained detector including compact STT, magnet, & ECAL

- *Use extra space available in ND hall either off-axis or on-axis once DUNEprism off-axis;*
- *Low-cost solution being studied by re-using KLOE magnet & ECAL with compact STT.*

✦ Option II:
High pressure Ar gas TPC & compact STT within the same magnetic volume.

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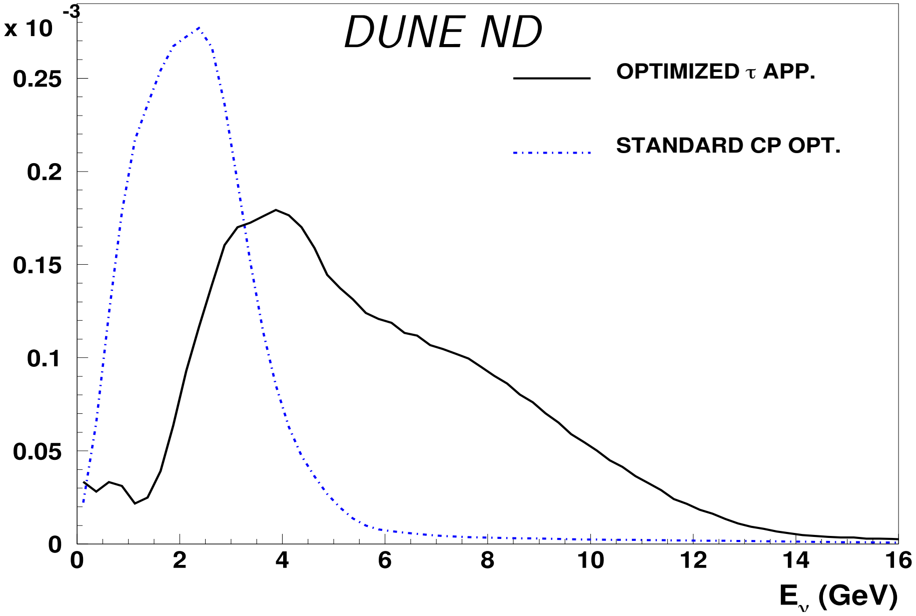
LBNF BEAMS & EXPECTED STATISTICS



Process	Events (5 t)
Standard CP optimized (1.2 MW):	
ν_μ-CH_2 CC (FHC, 5 y)	34×10^6
$\bar{\nu}_\mu$-CH_2 CC (RHC, 5 y)	13×10^6
ν_μ-H CC (FHC, 5 y)	3.4×10^6
$\bar{\nu}_\mu$-H CC (RHC, 5 y)	2.5×10^6
Optimized ν_τ appearance (2.4 MW):	
ν_μ-CH_2 CC (FHC, 2 y)	66×10^6
$\bar{\nu}_\mu$-CH_2 CC (RHC, 2 y)	24×10^6
ν_μ-H CC (FHC, 2 y)	6.5×10^6
$\bar{\nu}_\mu$-H CC (RHC, 2 y)	4.3×10^6

✦ *Available LBNF beam optimized for FD ν_τ appearance (120 GeV):*
Conceivable dedicated run after 5y FHC + 5y RHC with the "standard" beams optimized for CP

- *LBNF & DUNE (202x): 120 GeV p, 1.2 MW, 1.47×10^{21} pot/y, ND at 574m;*
- *LBNF upgrade: 120 GeV p,* $\boxed{\textbf{2.4 MW}}$, *$\sim3\times10^{21}$ pot/y.*

✦ *Assume a modest 2y run with ν_τ optimized beam and upgraded intensity.*

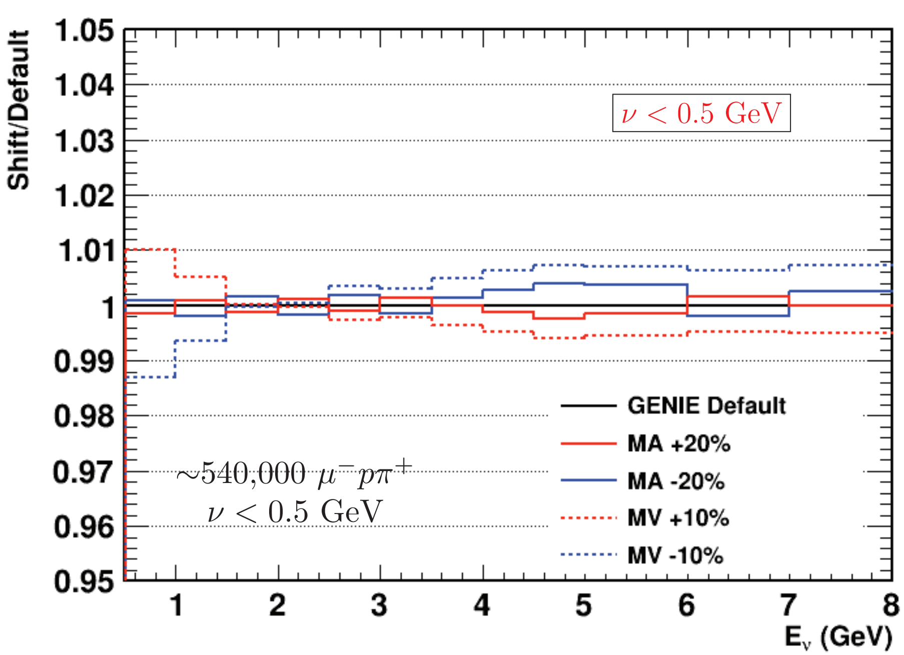
$\Longrightarrow$ *Compact STT provides desired statistics $\sim 10^8$ & high resolution $\Delta E_\mu < 0.2\%$*

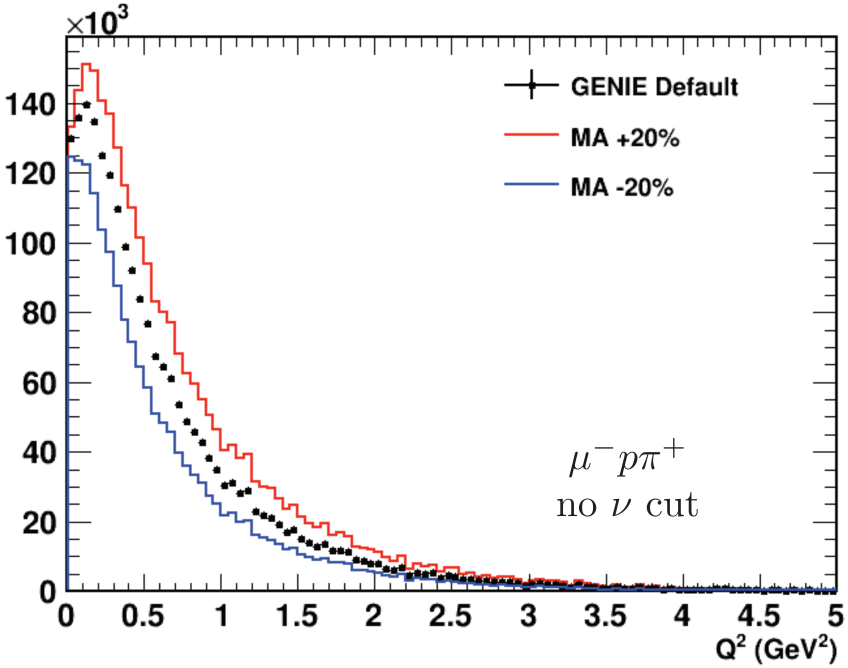
PRECISION FLUX MEASUREMENTS

✦ *Relative* ν_μ *&* $\bar{\nu}_\mu$ *fluxes vs.* E_ν *with exclusive topology on Hydrogen* $\nu(\bar{\nu})p \to \mu^\mp p \pi^\pm$*:*

- *Cut* $\boxed{\nu < 0.5 \text{ GeV}}$ *flattens cross-sections reducing uncertainties on* E_ν *dependence;*
- *Flux uncertainties dominated by muon energy scale (*$\Delta E_\mu \sim 0.2\%$ *in low density tracker);*
- *Direct determination of H form factors from measured* Q^2 *distribution without* ν *cut (25% overlap).*

$\Longrightarrow$ *Potentially achieve unprecedented precision on fluxes* $\sim 1\%$



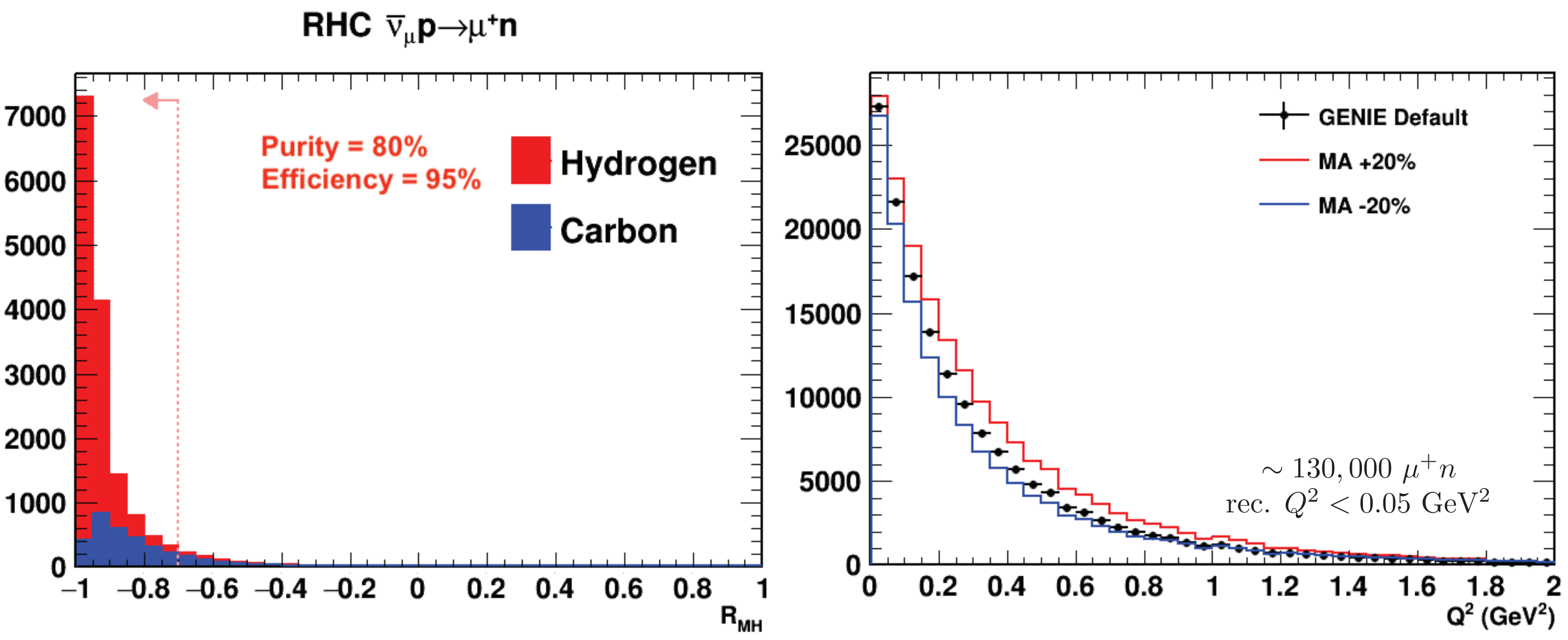


- ✦ *Relative $\bar{\nu}_\mu$ fluxes using QE on Hydrogen $\bar{\nu}p \to \mu^+ n$ with $\nu < 0.5$ GeV (or lower).*

- ✦ *Absolute & relative $\bar{\nu}_\mu$ fluxes from QE on Hydrogen $\bar{\nu}p \to \mu^+ n$ with $Q^2 \sim 0$:*

$$\frac{d\sigma}{dQ^2}\Big|_{Q^2=0} \;=\; \frac{G_F^2 \cos^2\theta_c}{2\pi}\left[F_1^2(0) + G_A^2(0)\right]$$

  - *Cross-section independent of neutrino energy for $\sqrt{2E_\nu M} > m_l$;*
  - *At $Q^2 = 0$ QE cross-section determined by neutron β-decay to a precision $\ll 1\%$;*
  - *Neutron interactions in STT & ECAL allow reconstruction of lower Q^2 than protons.*

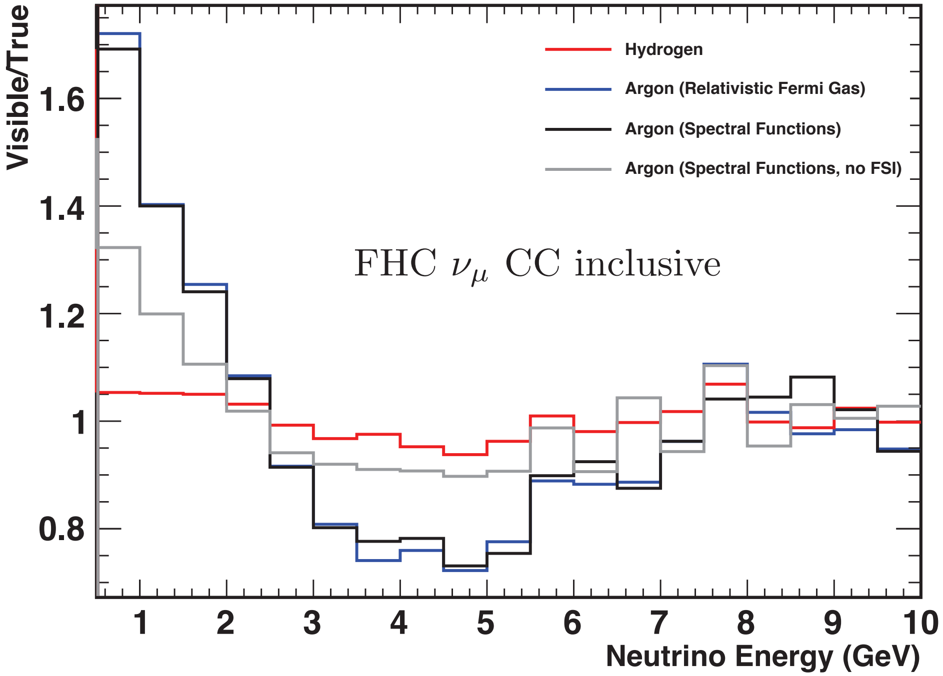


NUCLEAR SMEARING & ENERGY SCALE

✦ *For most $\nu(\bar{\nu})$-H topologies (e.g. $\mu p \pi$) response function defined by $\delta p/p$ resolution*
$\Longrightarrow$ *Unfolding of detector response can be calibrated accurately in low-density STT*

✦ *Compare inclusive CC distributions of variable X from $\nu(\bar{\nu})$-H and Ar*
$\Longrightarrow$ *Determine product of nuclear smearing times σ for the particular ND spectrum*

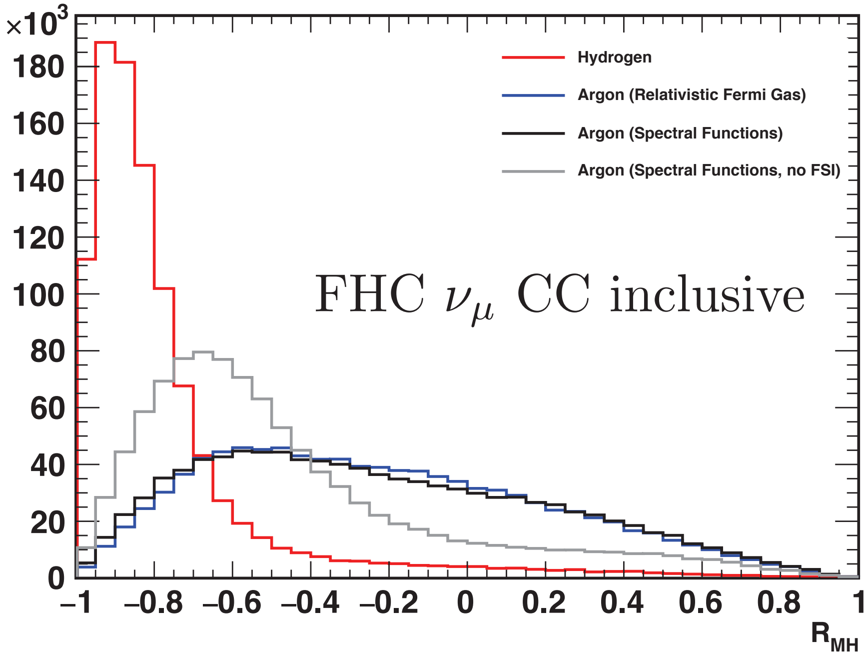
✦ *H allows model-independent measurement of initial and final state nuclear effects*

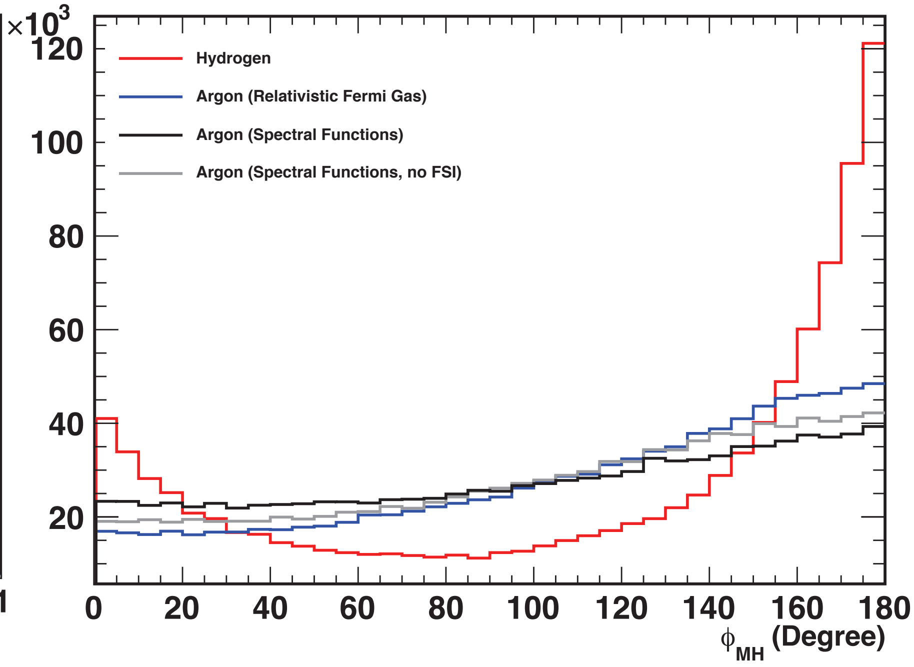


Substantial nuclear smearing
rapidly varying in oscillation range!

✦ *Additional handles to resolve potential degeneracies in the nuclear smearing:*

- *Comparisons of H and Ar interactions in bins of muon variables* (p_μ, θ_μ)*;*
- *Comparisons of H and Ar interactions in bins of the radial distance from the beam axis & different ND locations provide a variation of the input spectra;*
- *Exclusive topologies* ($\mu p \pi$, μn, *etc.) in both H and Ar & complete set of kinematic variables;*
- *Simultaneous analysis of* ν *AND* $\bar{\nu}$ *to gather information about* ν*-n (isospin symmetry);*
- *Selection of Ar events with a total charge at the primary vertex* $C_{\rm vtx} = 0$ *for neutrinos and* $C_{\rm vtx} = +1$ *for antineutrinos to check the impact of* n *and* p *interactions.*





GENERAL PURPOSE PHYSICS FACILITY

✦ *Addition of "compact STT" can address the main issues of neutrino experiments (statistics, control of targets & fluxes) filling 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 DUNE 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, Gross-Llewellyn Smith);*
- *Measurements of strangeness content of the nucleon ($s(x), \bar{s}(x), \Delta s$, etc.);*
- *Studies of perturbative and non-perturbative 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 (Fe, Ar, Ca, C, etc.);*
- *Precision measurements of cross-sections and particle production; etc. .....*
- *Searches for New Physics (BSM): sterile ν, MiniBooNE anomaly, ν_τ search, axion-like particles, dark photons, sub-GeV dark matter, etc. .....*

$\Longrightarrow$ *Significant discovery potential & hundreds of diverse physics topics!*

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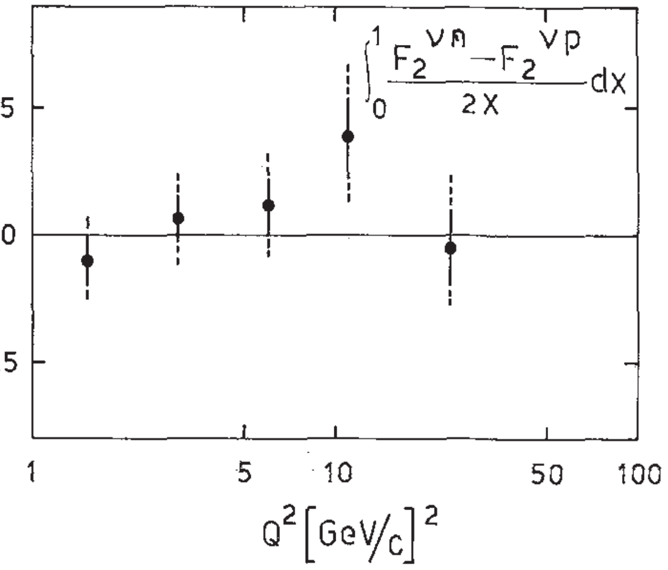
ADLER SUM RULE & ISOSPIN PHYSICS

- ✦ *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*
  - *Generalize the integral 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*



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- ✦ *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 $F_2^{\nu n}/F_2^{\nu p}$ 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**$\times$**10**^{6}
$\bar\nu_\mu$ **CC (5 y)**	**2.5**$\times$**10**^{6}
Optimized ν_τ appearance:	
ν_μ **CC (2 y)**	**6.5**$\times$**10**^{6}
ν_μ **CC (2 y)**	**4.3**$\times$**10**^{6}

NUCLEAR MODIFICATIONS OF NUCLEON PROPERTIES

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

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

  - *Comparison with e/μ DIS results and nuclear models;*
  - *Study flavor dependence of nuclear modifications using ν & $\bar{\nu}$;*
  - *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.*

SUMMARY

- ✦ *To overcome limitations from Ar target in DUNE necessary to have a hydrogen target, which offers unique handle on 3 important systematics for LBL analyses:*
  - *Determination of the neutrino and antineutrino fluxes as a function of E_ν;*
  - *Constraint of the response function associated to the nuclear smearing (unfolding);*
  - *Calibration of the reconstructed neutrino energy scale.*

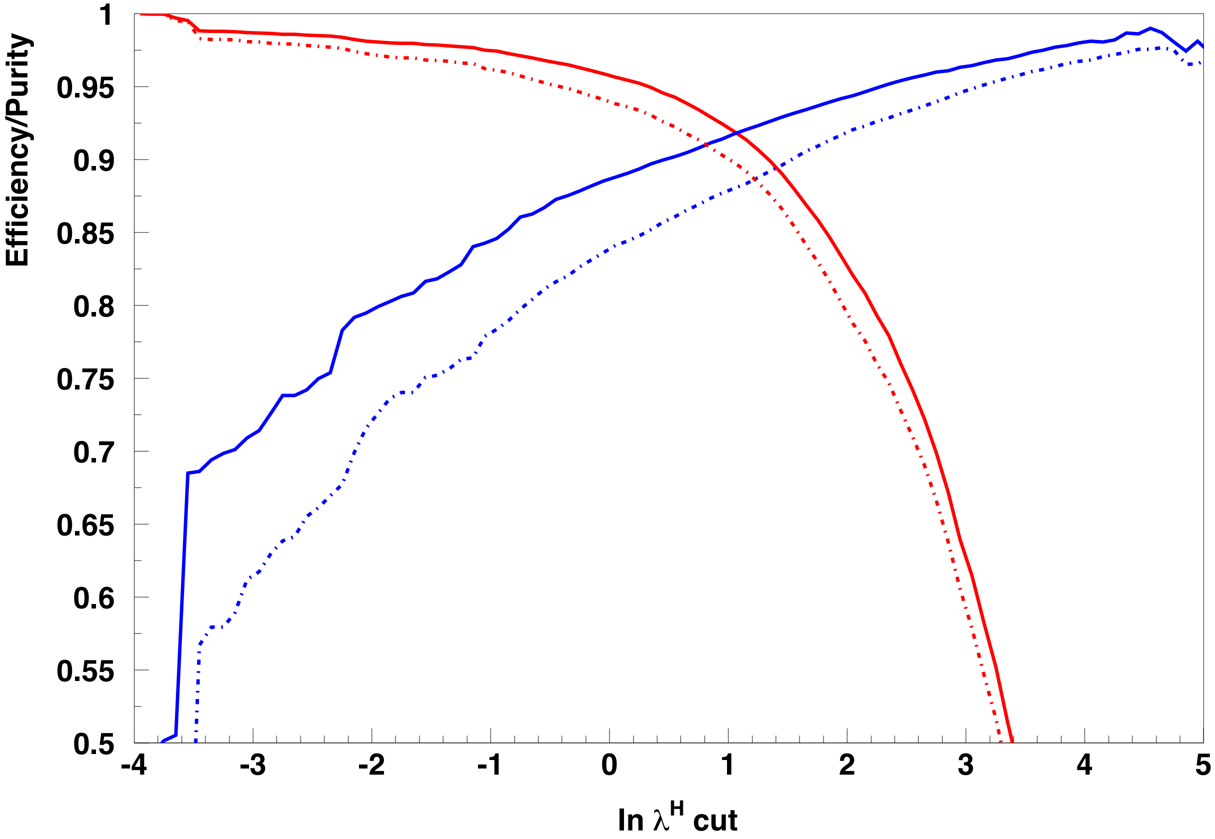
- ✦ *All $\nu(\bar{\nu})$-H CC topologies can be selected in a compact STT with high efficiency & purity via a data-driven background subtraction with high statistics*
  $\Longrightarrow$ *Various options to implement within ND complex with minimal design changes*

- ✦ *Addition of compact STT addresses the limitations of current ND design, providing the required redundancy and direct in-situ constraints of relevant systematics*

- ✦ *Compact STT additionally offers a rich physics program, with hundreds of diverse topics, complementary to ongoing fixed-target, collider and nuclear physics efforts.*

We welcome, and need, your support to help build the DUNE ND to precisely measure processes that would ultimately allow DISCOVERIES at Fermilab

Backup slides

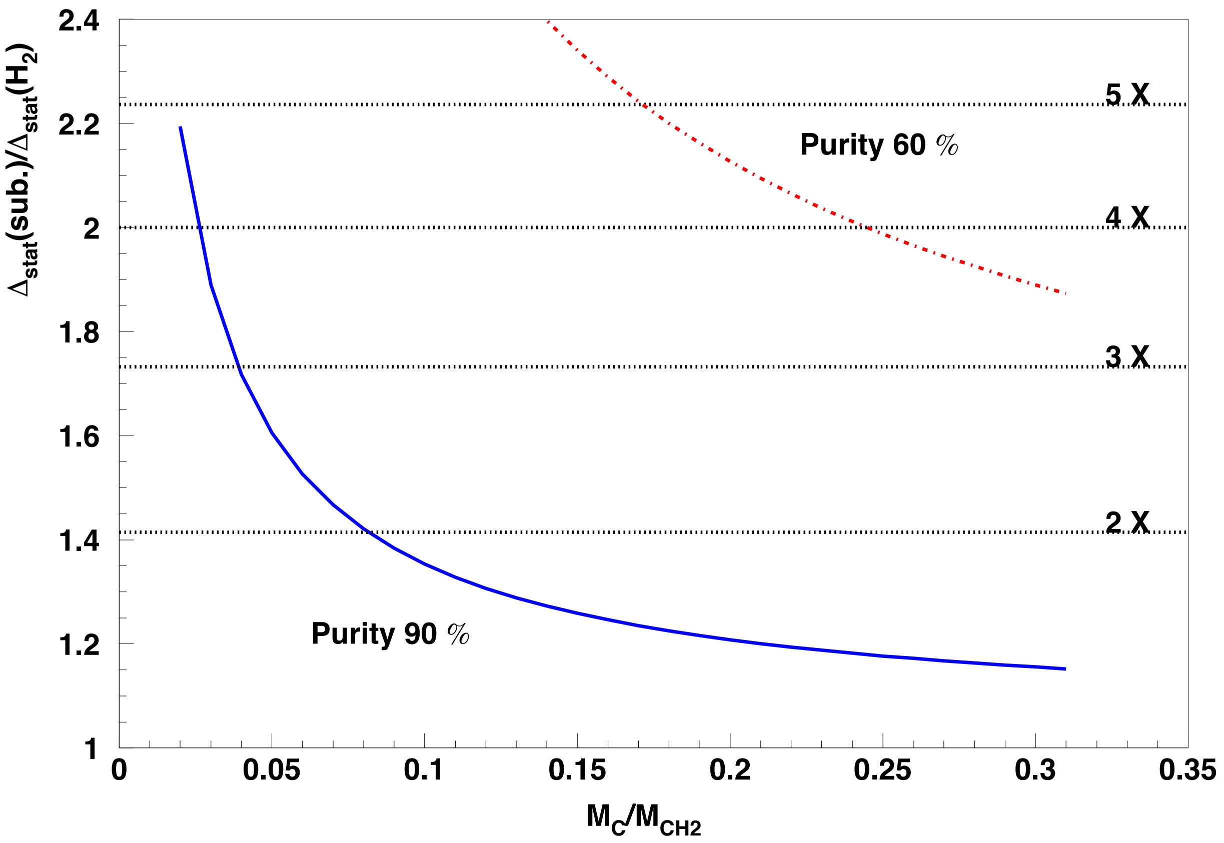


Event-by-event probability of H or C interaction

Vary efficiency/purity and define control samples to validate selection

	R_{mH} and $p_{T\perp}^{H}$ cuts		$\ln\lambda^{H}$ cut	
Process	Efficiency	Purity	Efficiency	Purity
$\nu_\mu p \to \mu^- p \pi^+$	93%	86%	90%	92%
$\bar{\nu}_\mu p \to \mu^+ p \pi^-$	89%	84%	90%	88%
$\bar{\nu}_\mu p \to \mu^+ n$	95%	80%		
$\nu_\mu p$ CC inclusive	83%	73%		

TABLE I. Efficiency and purity for the kinematic selection of H interactions from the CH_2 plastic target using simple cuts on R_{mH} and $p_{T\perp}^{H}$ (described in the text), as well as on the multi-variate likelihood ratio $\ln\lambda^{H}$. The cuts on $\ln\lambda^{H}$ are chosen to retain a fixed 90% signal efficiency.



$$N_H(\vec{x}) \equiv N_{CH_2}(\vec{x}) - N_C(\vec{x}) \times \frac{M_{C/CH_2}}{M_C}$$

Data-driven subtraction of small backgrounds (model-independent)

Process	CH_2 target	H target	CH_2 selected	C bkgnd
ν_μ CC $\mu^- p \pi^+$	3,924,000	2,484,000	2,430,000	194,000
ν_μ CC inclusive	34,900,000	3,591,000	4,140,000	1,160,000
$\bar{\nu}_\mu$ CC $\mu^+ p \pi^-$	836,000	373,000	365,000	29,100
$\bar{\nu}_\mu$ CC $\mu^+ n$	4,960.000	1,240,000	360,000	70,000
			648,000	126,000
$\bar{\nu}_\mu$ CC inclusive	13,000,000	2,882,000		

TABLE II. Number of events expected in the selection of various processes on H with (anti)neutrino beams similar to the ones available in DUNE [1, 2], assuming 5+5 years of data taking with the neutrino and antineutrino beam polarities. The first two columns (CH_2 and H targets) refer to the initial statistics, while the last two include all selection cuts described in this paper. For the CH_2 and C targets the numbers refer to the given final state topologies originated from either p or n interactions. For the $\mu^+ n$ topologies the first line refers to the events with n identified in the tracker (25%) and the second to the ones with n identified in ECAL (45%). See the text for details.

	NuWro		GiBUU		GENIE	
Process	Efficiency	Purity	Efficiency	Purity	Efficiency	Purity
$\nu_\mu p \to \mu^- p \pi^+$	93%	86%	93%	84%	93%	91%
$\bar{\nu}_\mu p \to \mu^+ p \pi^-$	89%	84%	89%	87%	89%	89%

TABLE III. Comparison of the efficiency and purity for the kinematic selection of H interactions from the CH_2 plastic target using simple cuts on R_{mH} and $p_{T\perp}^{H}$ with the NuWro [21], GiBUU [22], and GENIE [23] event generators. The same selection cuts as in Tab. I are used in all cases.

Check of model dependence in the H selection

OPTION II: H_2 GAS TARGET

- *Assume liquid H_2 bubble chamber with volume > 10 m^3 not feasible (safety).*
- *Default high pressure TPC with $\sim$ 106 m^3 total volume at 10 atm*
- *Using nominal HPgTPC event rates with Ar gas estimate achievable $\nu(\bar{\nu})$-H rates:*

  Statistics reduction for Ar: $t_{Ar}/t_{Ar+H_2} =$ **factor 2**

  Statistics reduction for H: $\rho_{H_2}/\rho_{Ar} \times \sigma_p/\sigma_{p+n} \times t_{H_2}/t_{Ar+H_2} =$ **factor 60**

HPgTPC:

Process	*FHC (5y)*	*RHC (5y)*
ν_μ **CC on H**	**136,000**	**9,680**
$\bar{\nu}_\mu$ **CC on H**	**5,642**	**98,750**

OPTION III: SCINTILLATOR

✦ *Consider interactions on the H content in plastic CH scintillator ($\sim 7\%$ by weight)*

$\Longrightarrow$ *Factor of 2 lower H content than pure polypropylene CH_2*

✦ *Angular, vertex, and momentum resolutions cannot provide accurate C subtraction:*

- *Lower purities achievable from larger reconstruction smearing of transverse plane kinematics;*
- *Vertex location and lower efficiency in associating interactions to each material.*

$\Longrightarrow$ *Larger systematic uncertainties from the subtraction procedure*

✦ *Small impurities from glue, fibers, coatings, etc. make subtraction of nuclear components difficult in relation to small H content of about 7%.*