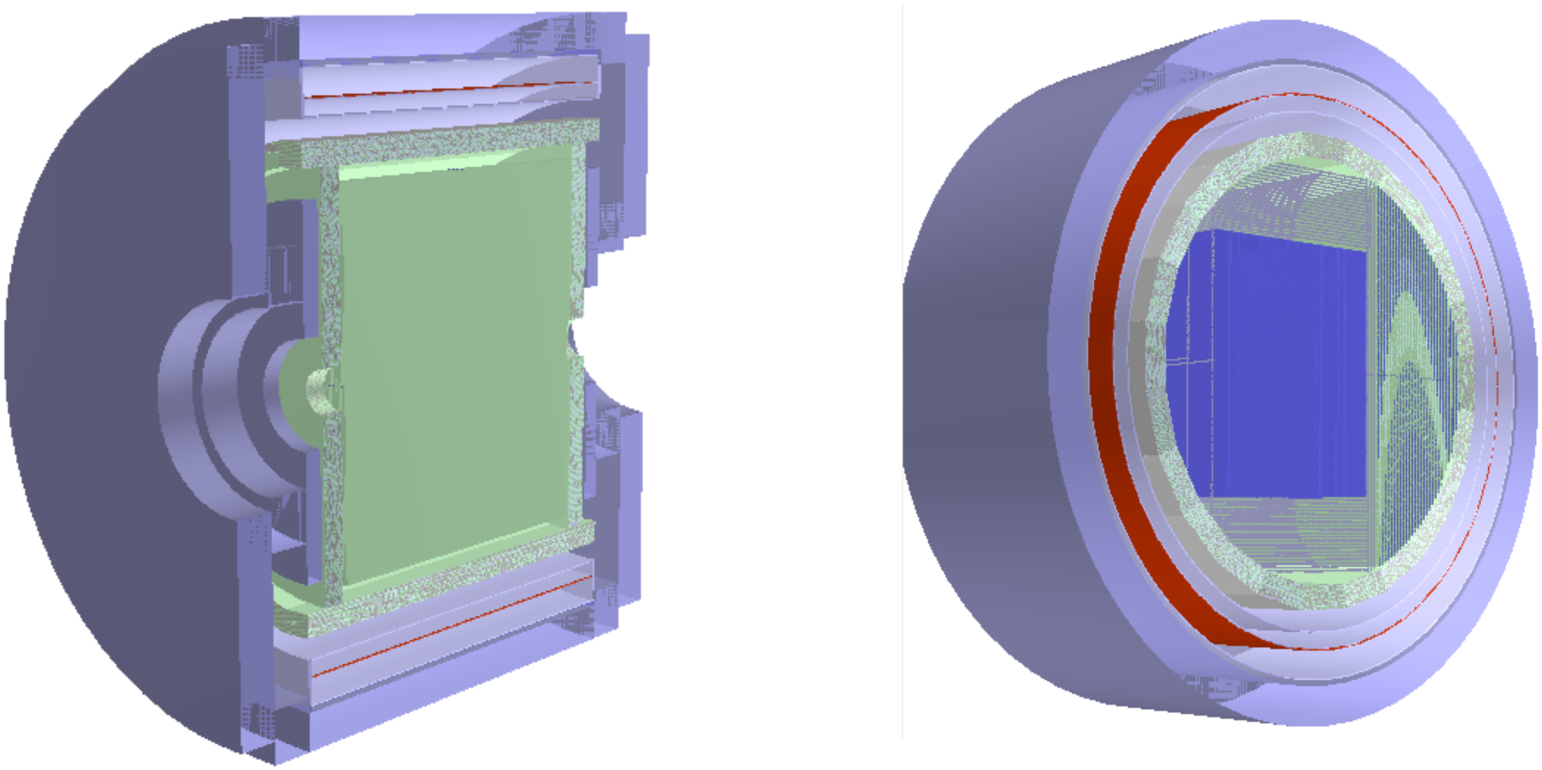
Physics Opportunities with the STT Configurations

R. Petti

University of South Carolina, USA

DUNE Near Detector discussion meeting
TIFR, Mumbai, India, February 29, 2020

STT CONFIGURATIONS CONSIDERED



(from talk by S. Bertolucci at LBNC, 6 December 2019)

STT mass: 7.4 tons
CH_2 FV mass: 4.7 tons
Graphite FV mass: 504 kg

STT mass: 2.0 tons
CH_2 FV mass: 1.44 tons
Graphite FV mass: 160 kg

- ✦ *Description of full STT option with the results of complete detector simulations, event reconstruction and physics performance is available in DUNE docdb # 13262:*

  `https://docs.dunescience.org/cgi-bin/private/ShowDocument?docid=13262`

  ⟹ *Benchmark for the STT performance in SAND and physics sensitivity studies*

- ✦ *Contribution (# 131) to the European Particle Physics Strategy Update 2018-2020:*

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

- ✦ *Ongoing sensitivity studies to evaluate the physics performance of 3DST+STT: rescale statistics by fiducial mass & study reconstruction/acceptance effects*

A Proposal to Enhance the DUNE Near-Detector Complex

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], 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. Diwan[412], H. Duyang[13], P. Evtoukhovitch[10], A. Falcone[14,15], O. Fedin[16], A. Ferrari[17], F. Ferraro[9,11], A. Gabrielli[5], A. Giri[31], M. Guerzoni[5], B. Guo[13], M.A. Iliescu[18,19], A. Jha[30], A.L. Kataev[20], R. Keloth[31], A. Khvedelidze[1,10], B. Kirby[12], U. Kose[5,19], S.A. Kulagin[20], C. Kullenberg[10], C. Kuruppu[13], R. Lalnuathunga[31], I. Lomidze[1], G. Laurenti[5], R. Majhi[30], V. Maleev[16], G .Mandrioli[5], N. Mauri[5,6], P. Mehta[21], S.R. Mishra[13], N. Moggi[5,6], R. Mohanta[30], A. Montanari[5], S. Movchan[10], S. Nagu[22], A. Nandi[7], 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], N. Talukdar[7], 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], S. Vasina[10], S. Zucchelli[5,6], and B. Wonsak[29]

Significant contributions from Indian colleagues

(docdb will be updated soon)

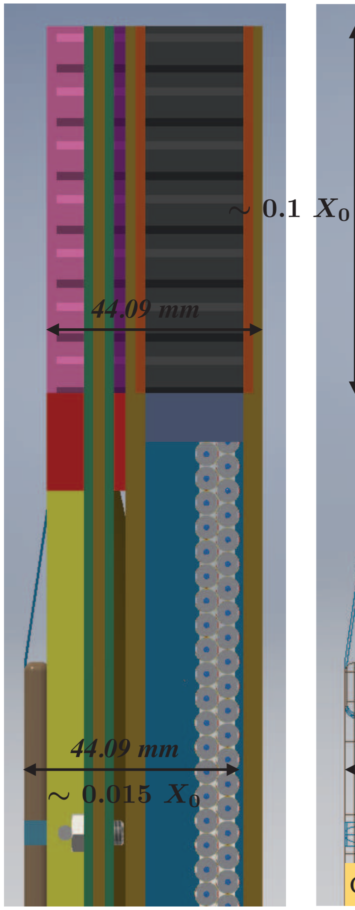
DUNE docdb # 13262

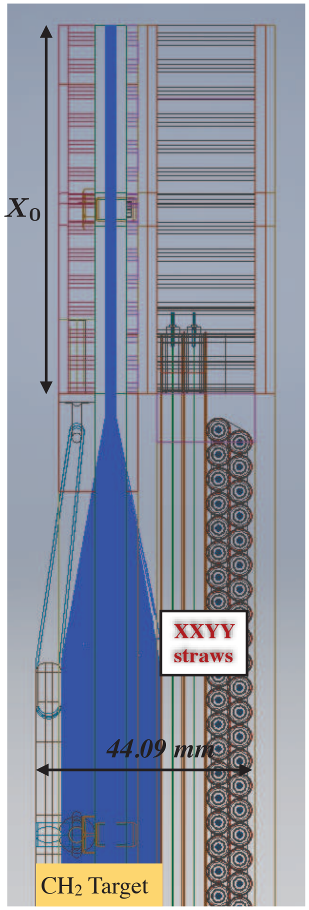
A TOOL TO REDUCE SYSTEMATICS

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

- *Typical ν-detectors: systematics from target composition & materials, limited target options;*
- *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}.

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





✦ *Targets (100% purity) account for $\sim 97\%$ of STT mass (straws 3%) and can be tuned to achieve desired statistics & resolutions.*

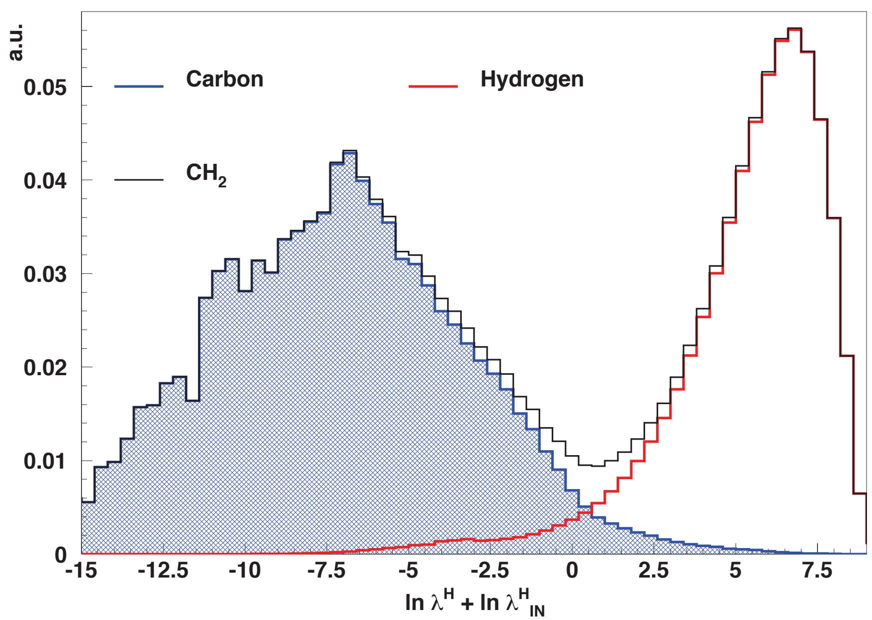
✦ *Separation from excellent vertex, angular & timing resolutions.*

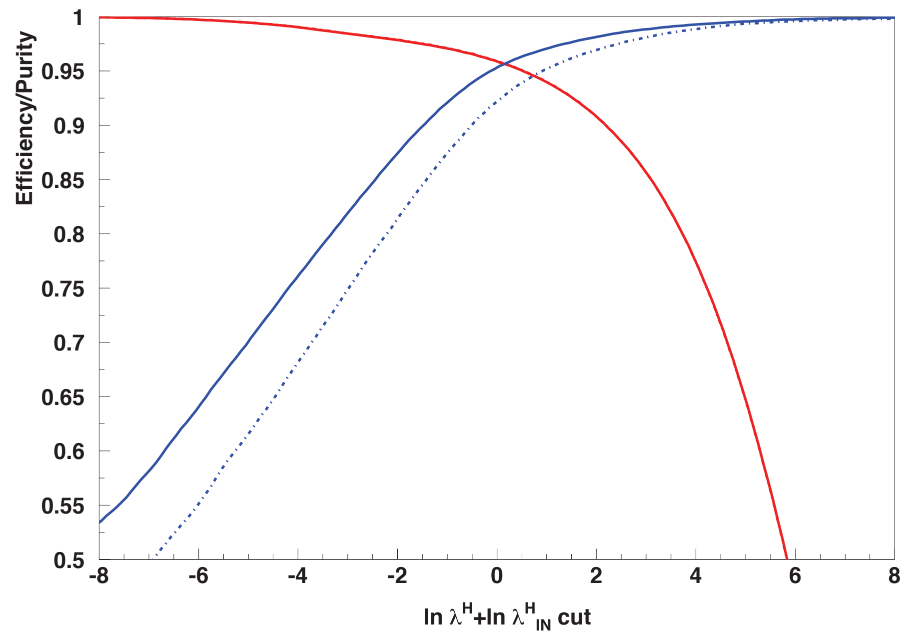
✦ *Thin targets can be replaced during data taking: C, Ca, Ar, Fe, Pb, etc.*

✦ "Solid" Hydrogen target: $\nu(\bar{\nu})$-H from subtraction of CH_2 and 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.*

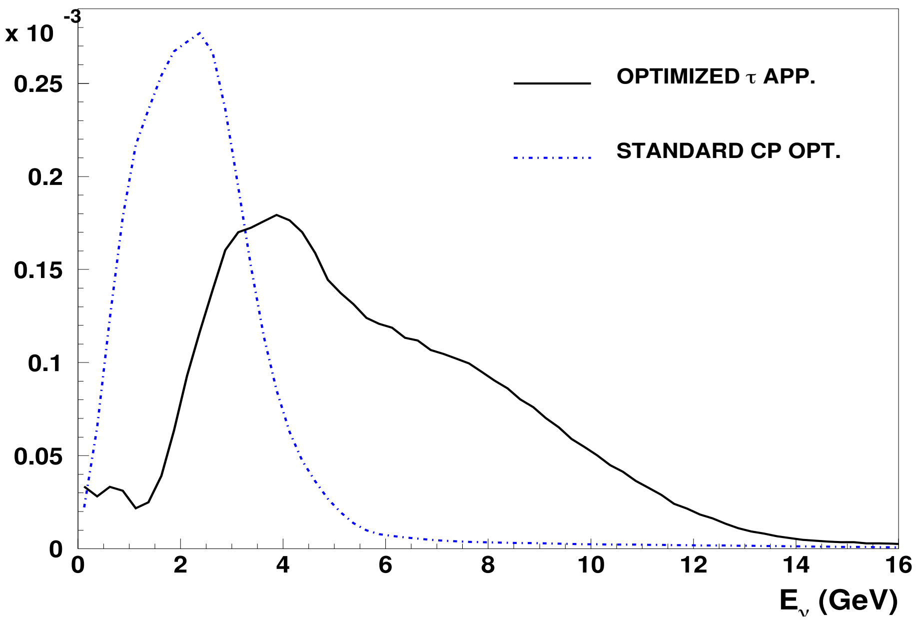
$\Longrightarrow$ *Viable and realistic alternative to liquid H_2 detectors*





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

BEAM SPECTRA & STATISTICS



Interactions	CH_2	H
Standard CP optimized (1.2 MW):		
ν_μ CC (FHC, 5 y)	33×10^6	3.1×10^6
$\bar{\nu}_\mu$ CC (RHC, 5 y)	12×10^6	2.3×10^6
Optimized ν_τ appearance (2.4 MW):		
ν_μ CC (FHC, 2 y)	62×10^6	6.0×10^6
$\bar{\nu}_\mu$ CC (RHC, 2 y)	22×10^6	4.0×10^6

- ✦ *Two LBNF beam options: low-energy CP optimized & high-energy 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 (x 2)**, *$\sim3\times10^{21}$ pot/y.*
- ✦ *Conceivable high-energy run after 5y FHC + 5y RHC with the "standard" beams optimized for CP*

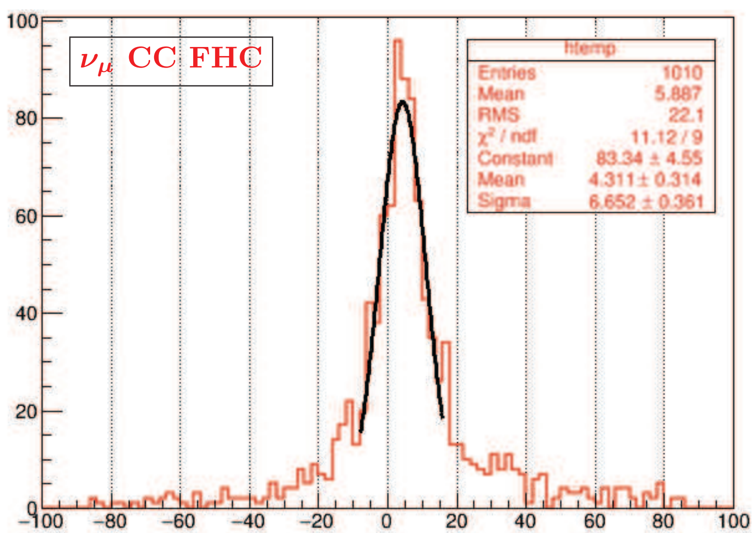
$\Longrightarrow$ *STT could collect a CC statistics $\sim 10^8$ with a high resolution event reconstruction*

RECONSTRUCTION & ENERGY SCALES

- *Detector simulations with GENIE+GEANT4+edep-sim and FLUKA, preliminary single particle reconstruction (tracks, vertex, clusters) & neutrino energy reconstruction*

- *Low-density design allows accurate in-situ calibrations:*
  - *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).*

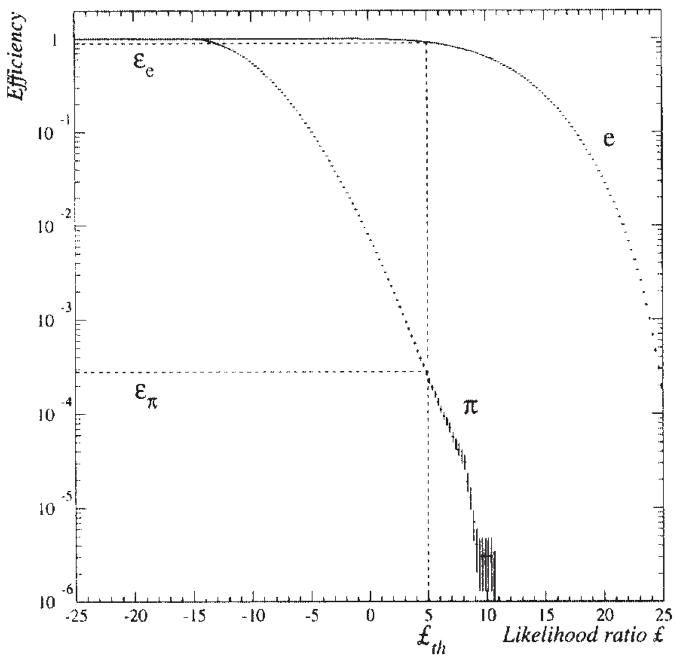
  $\Longrightarrow$ *Momentum scale uncertainty $< 0.2\%$ (NOMAD)*

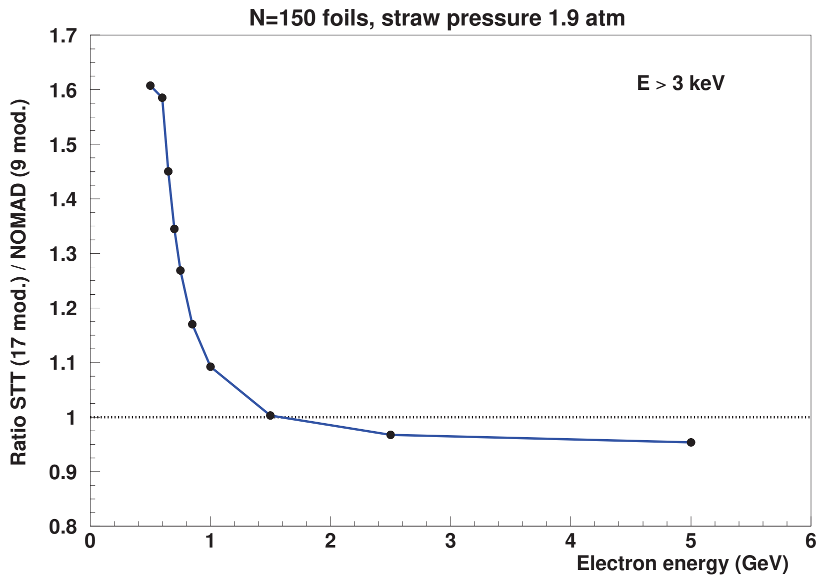


Preliminary event reconstruction with minimal use of MC truth

$e^{\pm}$ AND γ IDENTIFICATION

- *Design of CH_2 radiators optimized for $e^{\pm}$ ID with Transition Radiation:*
  - *π rejection $\sim 10^3$ with electron efficiency $> 90\%$ at $E > 0.5$ GeV;*
  - *STT performance substantially better than NOMAD for $E < 1.5$ GeV.*
- *Average conversion probability $\gamma \to e^+e^-$ 29.2% within STT tracking volume*
- *About 49% of π^0 with at least one converted γ in STT (more accurate reconstruction)*

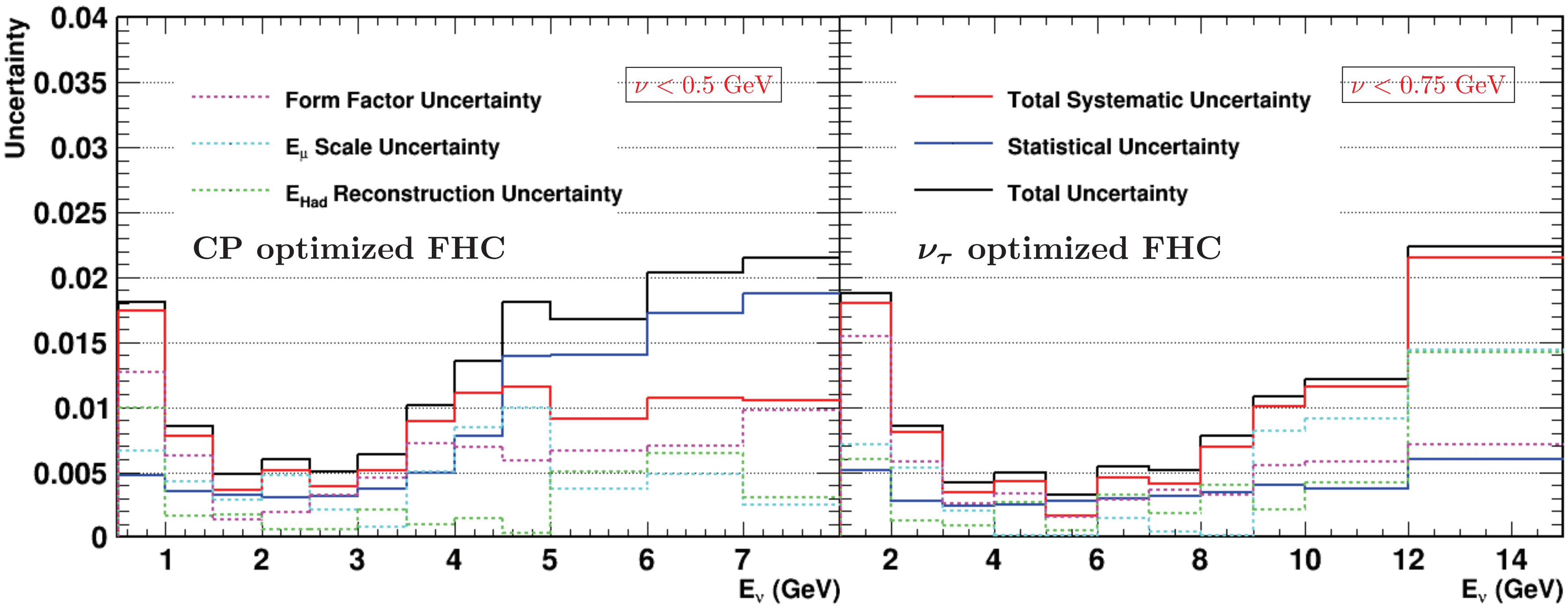




✦ Relative ν_μ flux vs. E_ν from exclusive $\nu_\mu p \to \mu^- p \pi^+$ on Hydrogen:

- Select well reconstructed $\mu^- p \pi^+$ topology on H ($\delta p/p \sim 3.5\%$);
- Cut $\nu < 0.5(0.75)$ 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).

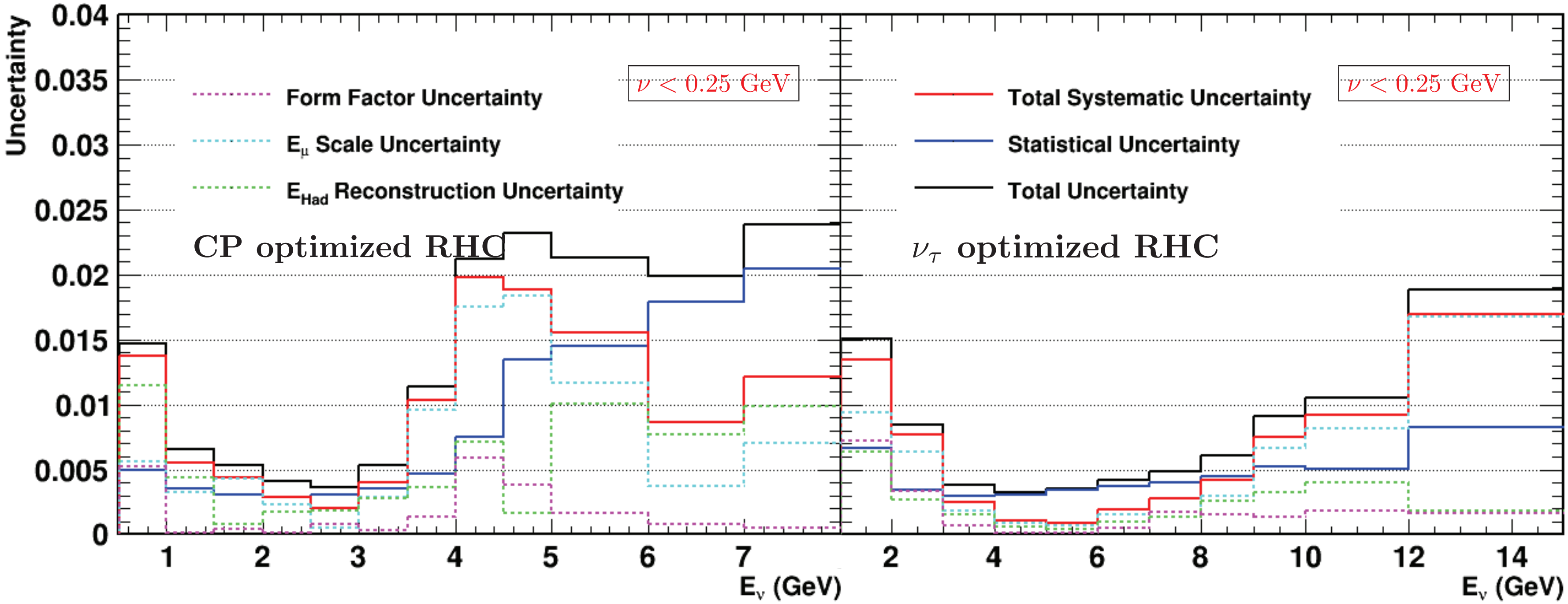
$\Longrightarrow$ Dramatic reduction of systematics vs. techniques using nuclear targets



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 (~80%);
- Cut $\nu < 0.1(0.25)$ 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]

PRECISION FLUX MEASUREMENTS

- ✦ *Relative ν_μ flux vs. E_ν from exclusive $\nu_\mu p \to \mu^- p \pi^+$ on Hydrogen*: $< 1\%$
  $\nu < 0.5$ GeV *flattens cross-sections reducing uncertainties on E_ν dependence.*

- ✦ *Relative $\bar{\nu}_\mu$ flux vs. E_ν from exclusive $\bar{\nu}_\mu p \to \mu^+ n$ QE on Hydrogen*: $< 1\%$
  $\nu < 0.25$ GeV*: uncertainties comparable to relative ν_μ flux from $\nu_\mu p \to \mu^- p \pi^+$ on H.*

- ✦ *Absolute $\bar{\nu}_\mu$ flux from QE $\bar{\nu}_\mu p \to \mu^+ n$ on H with $Q^2 < 0.05$ GeV^2 (neutron β decay)*

- ✦ *Absolute ν_μ flux from $\nu e^- \to \nu e^-$ elastic scattering*: $\sim 2\%$
  $\Longrightarrow$ *Complementary to measurement in LAr TPC with small systematics*

- ✦ *Ratio of $\bar{\nu}_\mu/\nu_\mu$ vs. E_ν from coherent π^-/π^+ on C (both CH_2 and graphite)*
  $\Longrightarrow$ *Excellent angular resolution (t variable) and light isoscalar target*

- ✦ *Ratio of ν_e/ν_μ AND $\bar{\nu}_e/\bar{\nu}_\mu$ vs. E_ν from CH_2 (& H) targets*
  $\Longrightarrow$ *Excellent $e^\pm$ charge measurement and $e^\pm$ identification ($\sim$ 80k $\bar{\nu}_e$ CC in FHC)*

- ✦ *Determination of parent $\mu/\pi/K$ distributions from $\nu(\bar{\nu})$-H (& CH_2) at low-ν*
  $\Longrightarrow$ *Direct in-situ measurement for flux extrapolation to FD*

CONSTRAINING NUCLEAR SMEARING

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

$\Phi(E_\nu)$ ↓ **~1% in H**

$\sigma_{\rm X}(E_\nu)$ ↓ $F_i(Q^2)$

$R_{\rm phys}(E_\nu, E_{\rm vis})$ ↓ $R_{\rm phys} \equiv I$

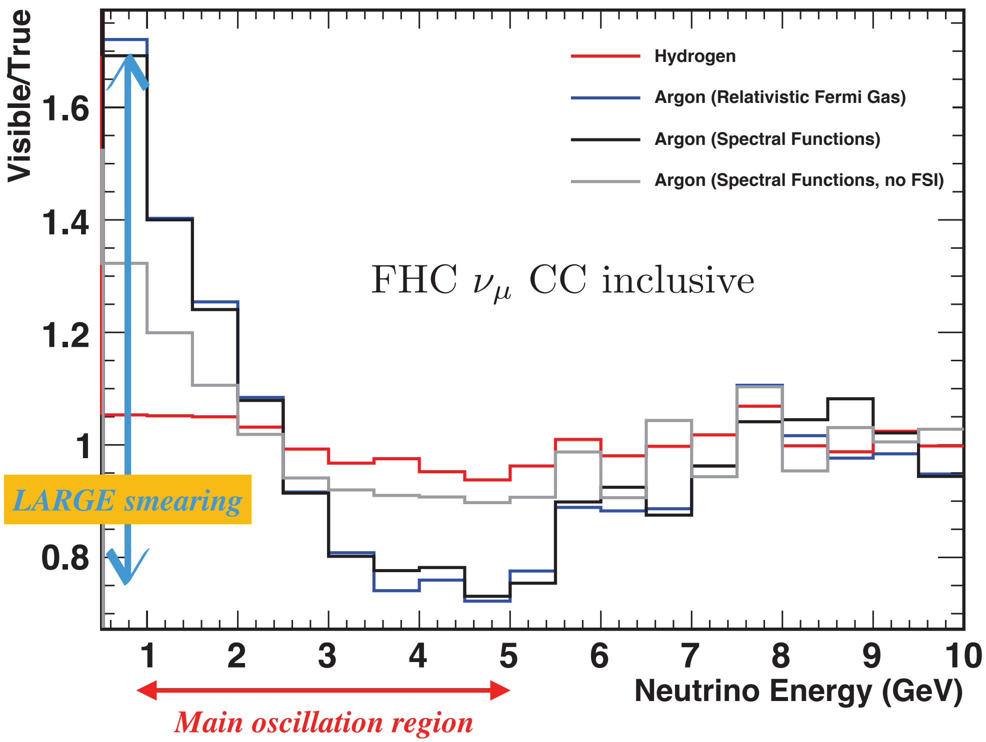
✦ *Hydrogen offers valuable information to reduce systematics:*

- *Constraining the nuclear smearing from comparison of Ar and H targets within SAME detector;*
- *Calibration of the (anti)neutrino energy scale.*

✦ *Providing necessary redundancy against MC/model & unexpected discrepancies:*

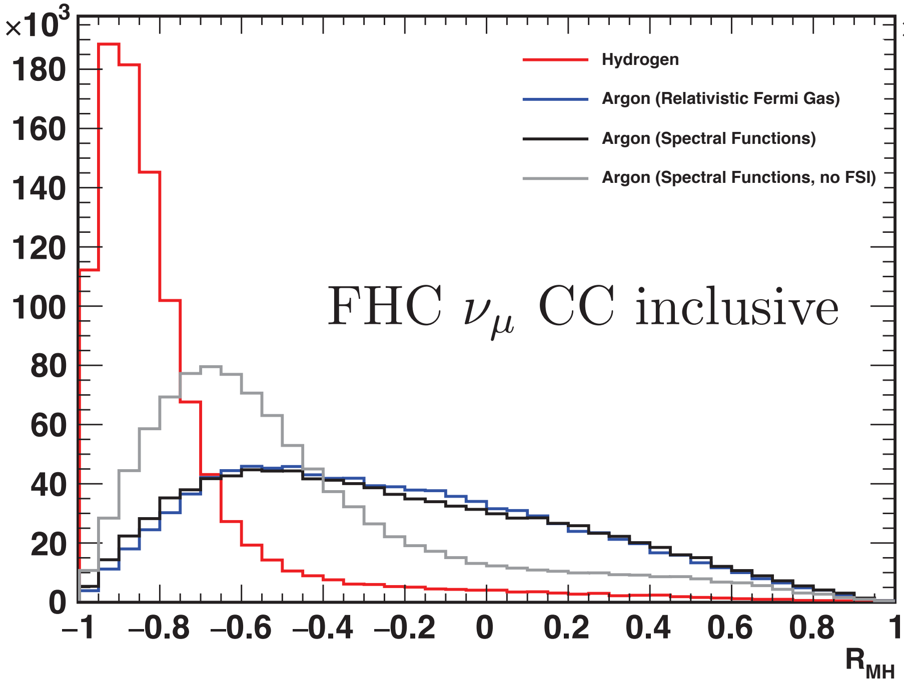
- *Ar detectors alone (even ideal) cannot resolve nuclear smearing & related systematics;*
- *DUNE-Prism alone sensitive to (beam) model & tuning to resolve off-axis discrepancies.*

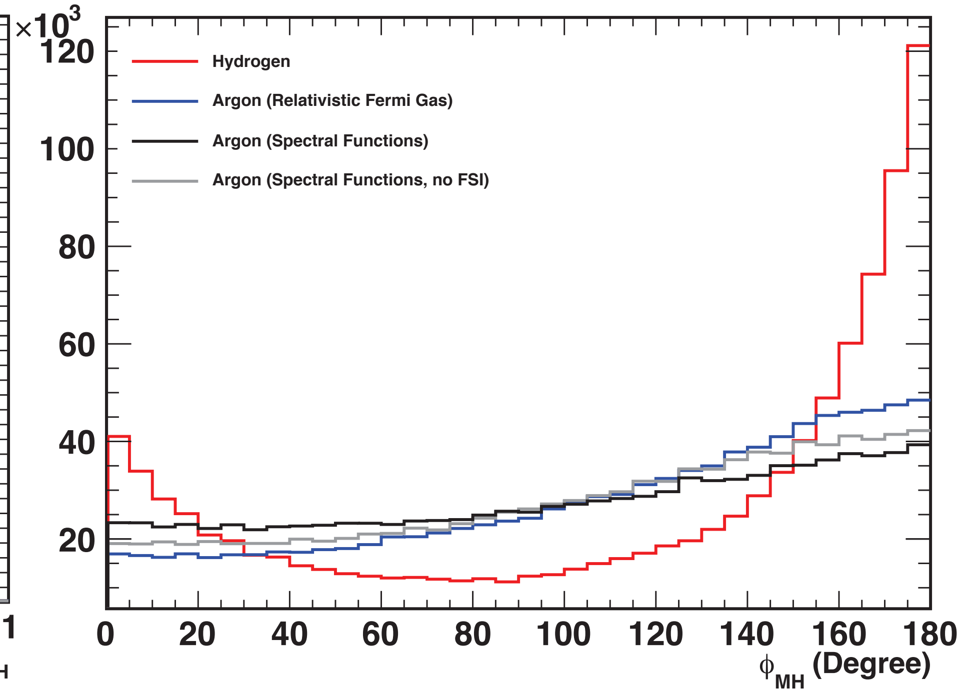
$\Longrightarrow$ *Synergy between DUNE-Prism and Hydrogen measurements in STT to resolve systematics from beam modeling & nuclear smearing*



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





- ✦ *Study a complete set of kinematic variables sensitive to nuclear smearing;*
- ✦ *Exclusive topologies ($\mu p \pi$, μn, etc.) in both H and Ar;*
- ✦ *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.*

$\Longrightarrow$ *Additional handles to resolve potential degeneracies in the nuclear smearing*

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.....*

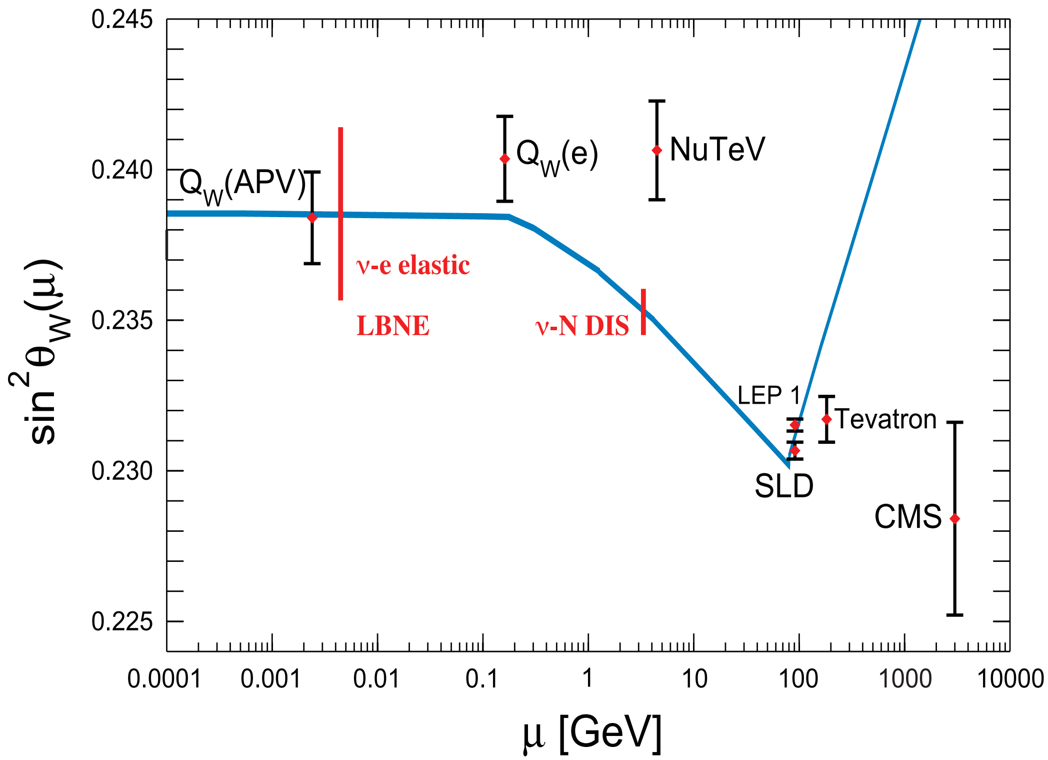
$\Longrightarrow$ *Discovery potential & hundreds of diverse physics topics*

✦ *No additional requirements: same control of targets & fluxes reducing LBL systematics*

ELECTROWEAK MEASUREMENTS

✦ *Complementarity with colliders & low-energy measurements* with comparable sensitivity:

- *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 like LEP*

✦ *Further reduction of uncertainties depending upon beam exposure*

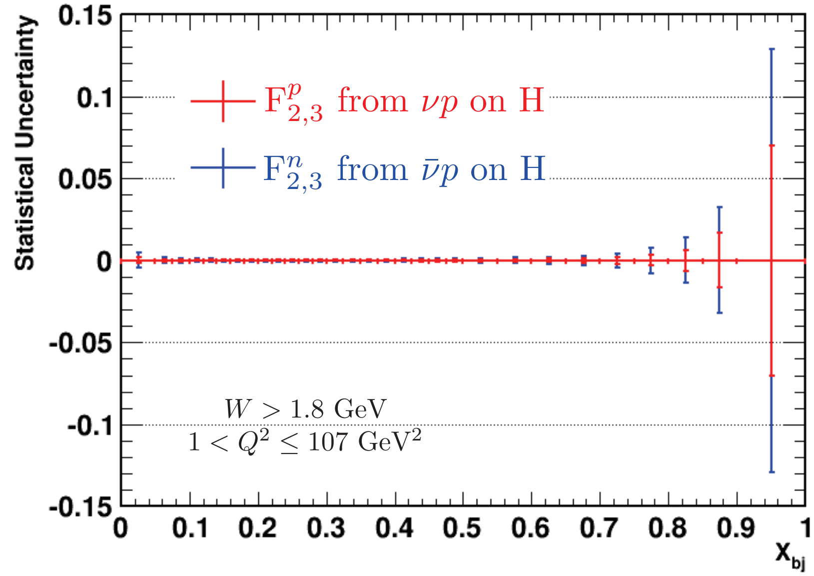
ADLER SUM RULE & ISOSPIN PHYSICS

✦ *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 $x \to 1$*

(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.*

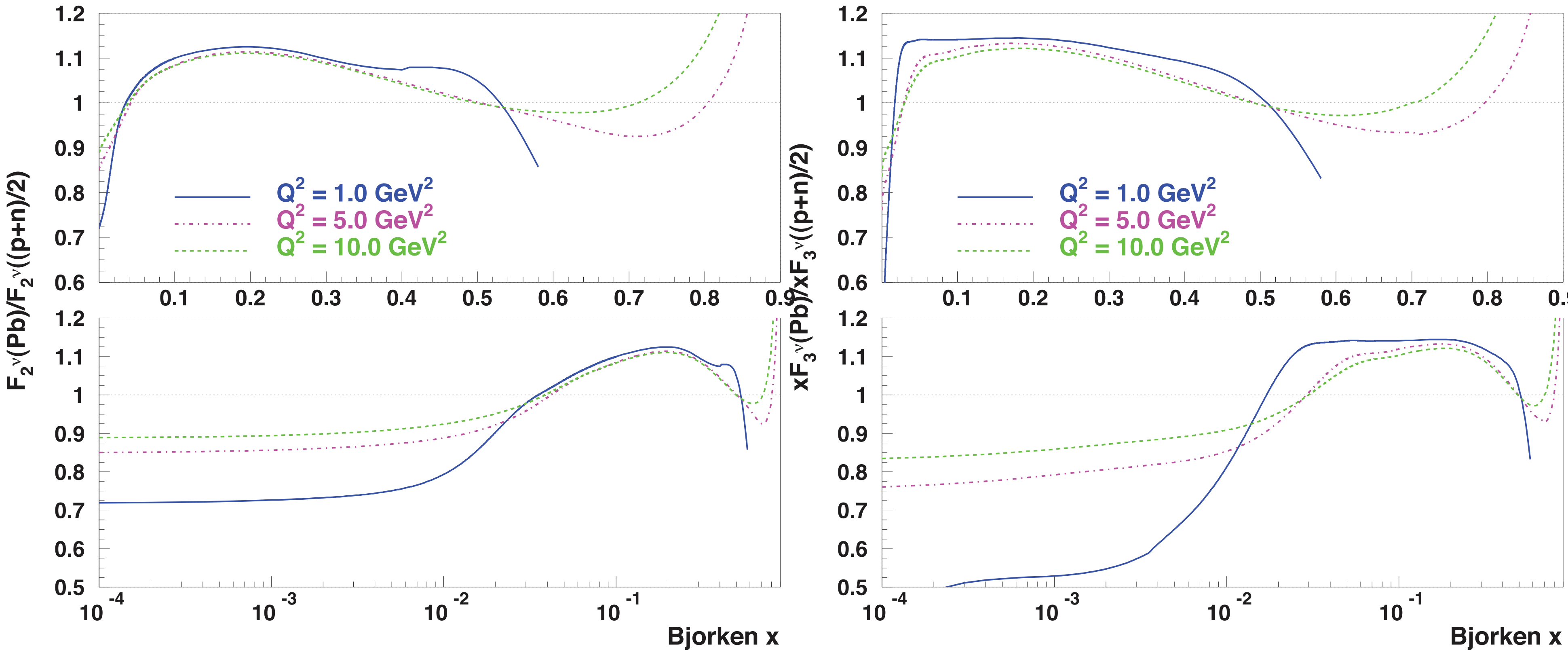
✦ *Study nuclear modifications to parton distributions in a wide range of Q^2 and x.*

✦ *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 $(p+n)/2$

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

SUMMARY

- ✦ *STT options offer a control of configuration, material & mass of neutrino targets similar to electron experiments & fully tunable suite of various target materials.*

  $\Longrightarrow$ *High resolution detector with momentum scale uncertainty <0.2%*

- ✦ *Concept of "solid" hydrogen target: high statistics $\mathcal{O}(10^6)$ samples of $\nu(\bar{\nu})$-hydrogen interactions, allowing precisions in the measurement of ν & $\bar{\nu}$ fluxes $< 1\%$.*

- ✦ *STT combined with the intensity and $\nu(\bar{\nu})$ spectra at LBNF enable a unique combination of physics measurements within the ND complex:*
  - *Reduction of systematic uncertainties for long-baseline oscillation analyses;*
  - *Hundreds of diverse physics topics from precision measurements and searches for new physics, complementary to ongoing fixed-target, collider and nuclear physics efforts.*

  $\Longrightarrow$ *Many opportunities for valuable contributions:*
  hardware, simulations, reconstruction, physics sensitivity studies, etc.

New ideas or suggestions to further broaden physics scope welcomed

Backup slides