In-situ Determination of Relative Fluxes: the Low-ν Method

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with contributions from H. Duyang, M. Gonchar, S. R. Mishra, X. Tian

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RELATIVE FLUX WITH LOW-ν METHOD

- *Relative $\nu_\mu, \bar{\nu}_\mu$ flux vs. energy from low-ν_0 method:* (S. R. Mishra, Wold. Sci. 84 (1990), Ed. Geesman)

$$N(E_\nu,\ E_{\rm Had} < \nu_0) = k\Phi(E_\nu) f_c(\tfrac{\nu_0}{E_\nu})$$

the correction factor $f_c(\nu_0/E_\nu) \to 1$ *for* $\nu_0 \to 0$:

$$f_c(\tfrac{\nu_0}{E_\nu}) = 1 + \left(\frac{\nu_0}{E_\nu}\right) \frac{\mathcal{B}}{\mathcal{A}} - \left(\frac{\nu_0}{E_\nu}\right)^2 \frac{\mathcal{C}}{2\mathcal{A}} + ...$$

where $\mathcal{A} = G_F^2 M/\pi \int_0^1 \mathcal{F}_2(x)dx$, $\mathcal{B} = -G_F^2 M/\pi \int_0^1 (\mathcal{F}_2(x) \mp x\mathcal{F}_3(x))\, dx$ *and*
$\mathcal{C} = \mathcal{B} - G_F^2 M/\pi \int_0^1 \mathcal{F}_2(x) \left[(1 + 2Mx/\nu)/(1 + \mathcal{R}(x, Q^2)) - Mx/\nu - 1\right] dx$

- *In practice use MC to calculate the correction factor normalized at high E_ν:*

$$f_c(E_\nu) = \frac{\sigma(E_\nu,\ E_{\rm Had} < \nu_0)}{\sigma(E_\nu \to \infty,\ E_{\rm Had} < \nu_0)}$$

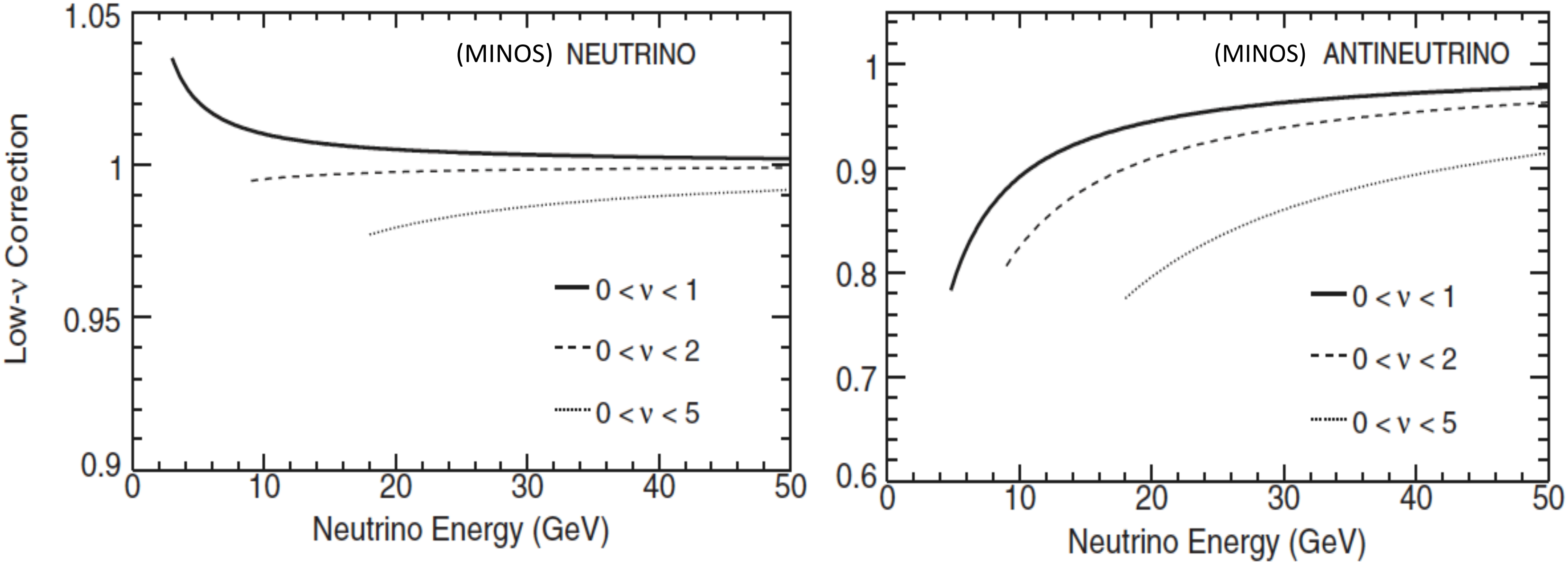
where the denominator is evaluated at the highest energy accessible in the spectrum.

$\Longrightarrow$ *Need precise muon energy scale and good resolution at low ν values*

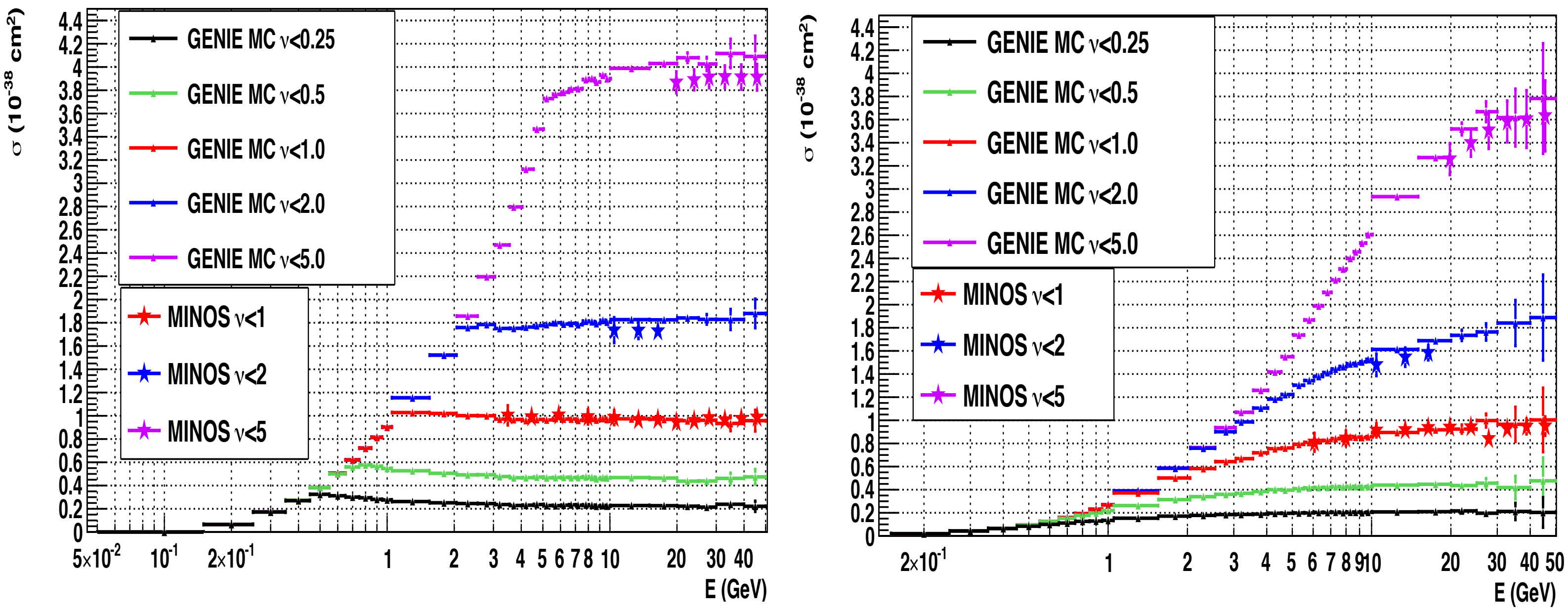
$\Longrightarrow$ *Reliable flux predictions for $E_\nu \gtrsim 2\nu_0$*

$\longrightarrow$ *DUNE spectra require* $\boxed{\nu_0 \simeq 0.25 \div 0.50 \textit{ GeV}}$

MINOS Coll., PRD 81 (2010) 072002



A. Bodek et al., EPJC 72 (2012) 1973



✦ Low-ν technique only provides RELATIVE BIN-TO-BIN flux as a function of E_ν, NOT ABSOLUTE flux

$\Longrightarrow$ Implicit constraint of fixed flux integral (introduces correlation among bins)

✦ Freedom to chose the energy range used to impose the normalization constraint

$\Longrightarrow$ E.g. E_ν bins with higher statistics / smaller systematic uncertainties

✦ The correction factor $f_c(E_\nu)$ can be affected by model uncertainties on (anti)neutrino-nucleus cross-sections (QE, RES, DIS)

- Typically keep $f_c(E_\nu)$ at the level of few percent or below (small ν_0/E_ν) to minimize model uncertainties (correction to correction);
- For $\nu_0 = 0.25 \div 0.50$ GeV samples almost entirely QE $(99 \div 75\%)$ and RES;
- Low-ν sensitive only to model uncertainties modifying the total cross-section vs. E_ν (integrated over Q^2 and other kinematic variebles)

  $\Longrightarrow$ Shape of $\sigma(E_\nu)$ intrinsically more stable

EMPIRICAL PARAMETERIZATION (EP) OF FLUXES

Talk by Sanjib Mishra

- *Measurement of CC spectra of $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ constrains flux predictions:*

$$\begin{aligned} \nu_\mu &\equiv \pi^+ \oplus K^+ \\ \bar{\nu}_\mu &\equiv \pi^- \oplus K^- \\ \nu_e &\equiv \mu^+(\pi^+ \to \nu_\mu) \oplus K^+(\to \nu_\mu) \oplus K^0_L \\ \bar{\nu}_e &\equiv \mu^-(\pi^- \to \bar{\nu}_\mu) \oplus K^-(\to \bar{\nu}_\mu) \oplus K^0_L \end{aligned}$$

	1<Enu<5	5<Enu<15
Mu+	87%	54%
K+	10%	33%
KL	3%	15%

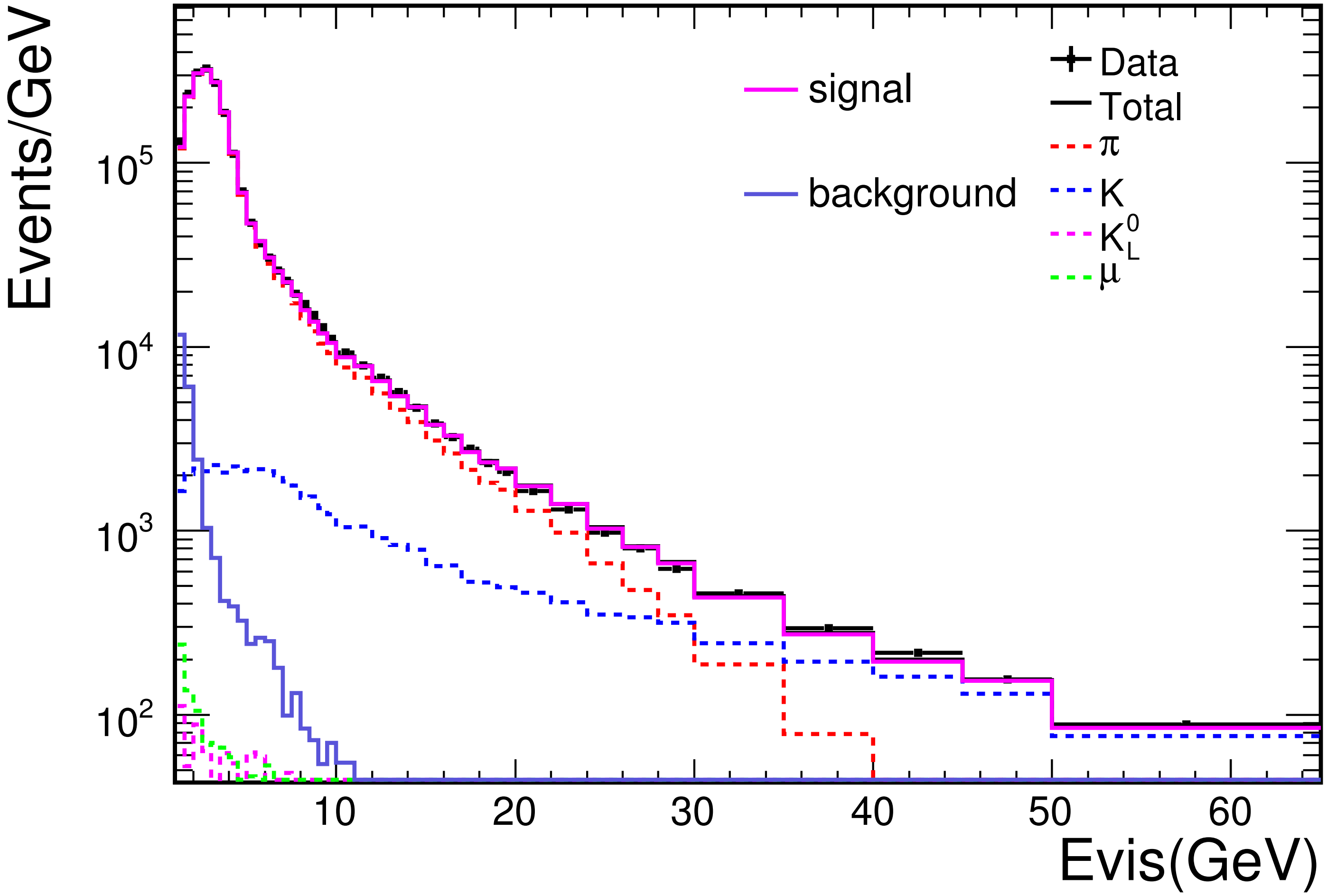
$\Longrightarrow$ *Need good reconstruction & identification of all 4 neutrino species.*

- *Fit Near Detector $\nu_\mu, \bar{\nu}_\mu$ $(\nu_e, \bar{\nu}_e)$ spectra in 4-5 (x,y) radial bins:*
  - *Trace secondaries through beam-elements, decay;*
  - *Predict (anti)neutrino fluxes by folding experiental acceptance;*
  - *Compare predicted to measured spectra $\Longrightarrow \chi^2$ minimization:*

$$\frac{d^2\sigma}{dx_F dP_T^2} = f(x_F)g(P_T)h(x_F, P_T)$$

  - *Functional form constraint allows flux prediction close to $E_\nu \sim \nu^0$.*

- *Add measurements of π^+/K^+ and π^-/K^- ratios from hadro-production experiments to the empirical fit of the neutrino spectra in the Near Detector*



Example of Low-ν EP fit to the MINOS low energy (LE) data
(J. Ling and S.R. Mishra)

STUDIES ADDRESSING SYSTEMATICS

✦ *MINOS ν_μ & $\bar{\nu}_\mu$ flux extraction for total cross-section [PRD 81 (2010) 072002]:*

- *To increase statistics use variable ν_0 cut:*
  $\nu < 1$ GeV for $E_\nu < 9$ GeV; $\nu < 2$ GeV for $9 < E_\nu < 18$ GeV; $\nu < 5$ GeV for $E_\nu > 18$ GeV;
- *Overlap between flux & cross-section samples:*
  60% (90%) for ν_μ ($\bar{\nu}_\mu$) at $E_\nu \sim 3$ GeV and 30% (60%) for $E_\nu > 6$ GeV.

✦ *Phenomenological study by Bodek at al. [EPJC 72 (2012) 1973] to understand systematics related to the cross-section modeling and the possibility to extend the low-ν method to values of $\nu_0 \sim 0.25 \div 0.5$ GeV*

✦ *DUNE (LBNE) study of $\nu_\mu, \bar{\nu}_\mu$ fluxes (H. Duyang, S.R. Mishra, docdb #7285):*

- *Use standalone simulation with DUNE spectra and parameterized detector smearing;*
- *Fit modified ν_μ and $\bar{\nu}_\mu$ CC spectra in the ND (fake data) with $E_{\rm Had} < \nu_0 = 0.5$ GeV;*
- *Extract fluxes from EP fits and extrapolate to the FD (focus on FD/ND ratio).*

✦ *NOMAD ν_μ flux extraction to validate DUNE ND sensitivity with real data & full reconstruction/simulation (M. Gonchar, R. Petti, docdb #9275):*

- *Default flux sample $\nu < 3$ GeV including 1-track events;*
- *Complementary cross-section sample with $\nu > 3$ GeV (0% overlap);*
- *DUNE FGT similar to NOMAD with higher granularity (× 12) and statistics (× 100)*

IMPACT OF CROSS-SECTION UNCERTAINTIES

✦ *Example: discrepancy between MiniBooNE and NOMAD on QE total cross-section*

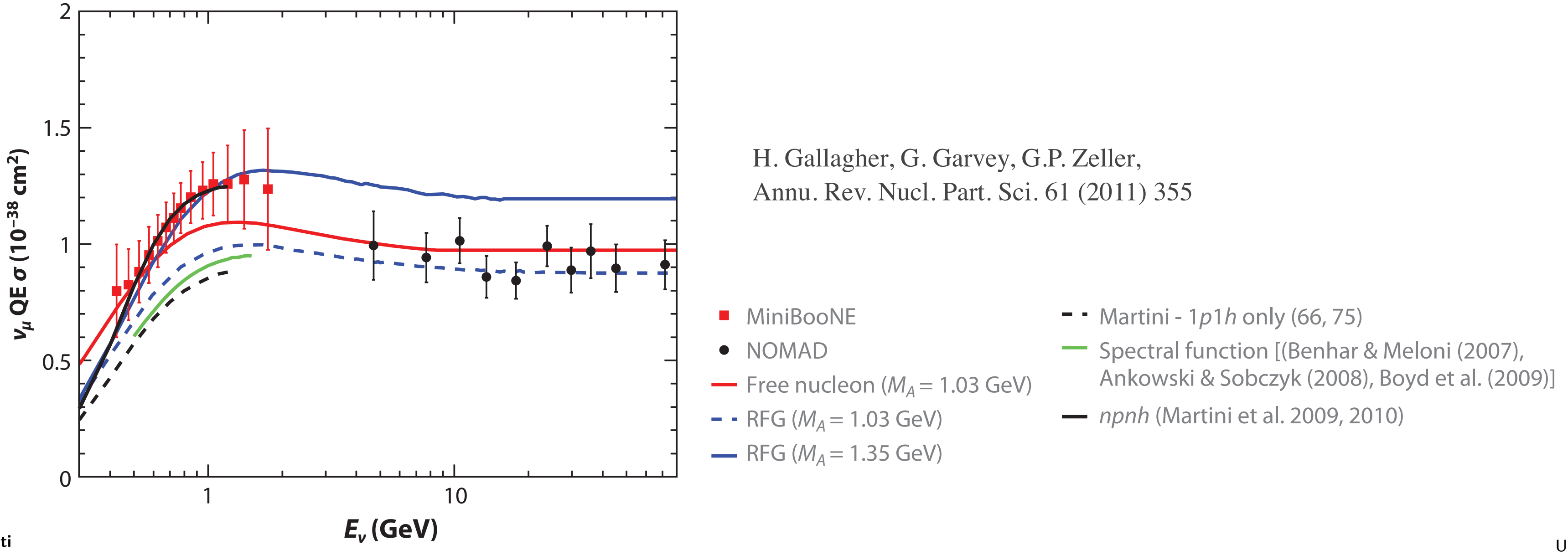
$\Longrightarrow$ *Overall normalization factor or $\sigma(E_\nu)$ shape difference?*

✦ *A variety of theoretical issues on QE:*

- *Impulse approximation + Fermi gas vs. realistic nuclear modeling;*
- *Impact of many particle - many hole processes (e.g. MiniBooNE);*
- *Transverse vs. longitudinal response;*
- *Role of Final State Interactions (FSI), etc.*

$\Longrightarrow$ *Main question: what level of $\sigma(E_\nu)$ shape distortion can result in sizeable ($\sim 1 \div 2$ %) effects on low-ν technique (primarily f_c)?*

$\Longrightarrow$ *Can be tested empirically introducing arbitrary fudge factors in MC.*

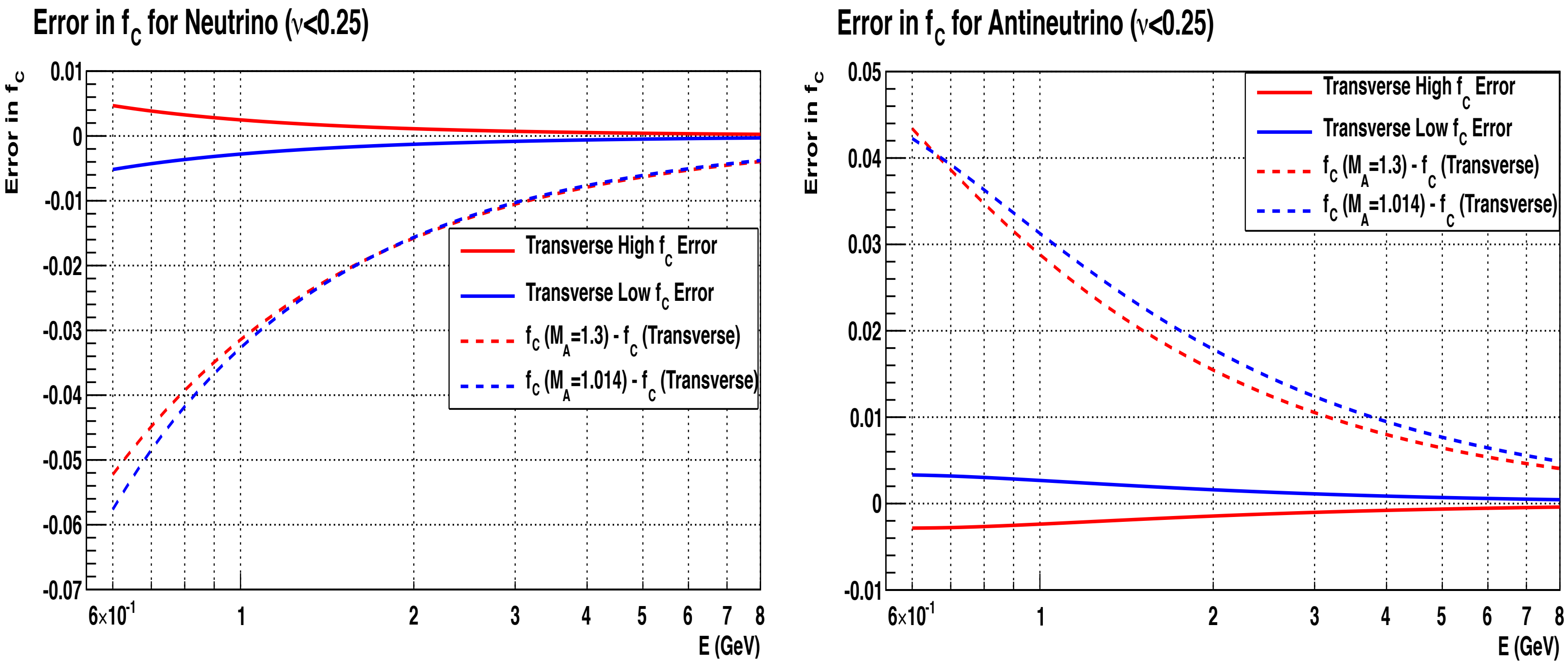


H. Gallagher, G. Garvey, G.P. Zeller,
Annu. Rev. Nucl. Part. Sci. 61 (2011) 355

- ✦ *Bodek at al. [EPJC 72 (2012) 1973] showed low-ν works well down to very low values $\nu_0 = 0.25$ GeV and $\nu_0 = 0.5$ GeV and estimated model uncertainties:*
  - *Averaging different models gives uncertainty $< 1.9\%$ for ν_μ at $E_\nu > 0.7$ GeV;*
  - *Averaging different models gives uncertainty $< 2.5\%$ for $\bar{\nu}_\mu$ at $E_\nu > 1.0$ GeV.*

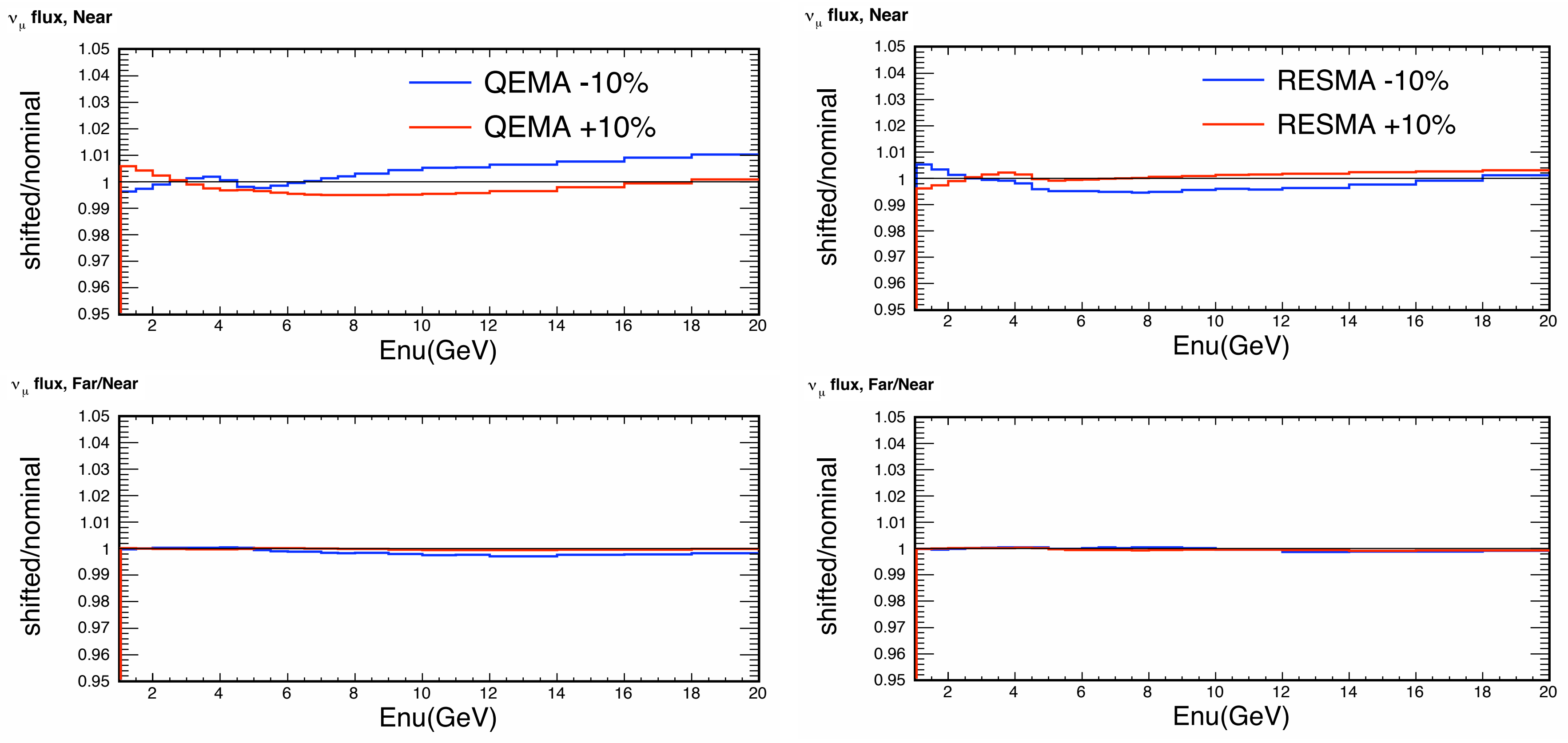
- ✦ *Stringent constraints on QE models will be available in DUNE ND from in-situ precision measurements of double differential cross-section*

  $\Longrightarrow$ *Substantial reduction of model dependence expected*



✦ *Duyang and Mishra (docdb #7285) showed that variations of the axial mass M_A in both QE and RES events have small impact on the low-ν extraction of fluxes at DUNE*

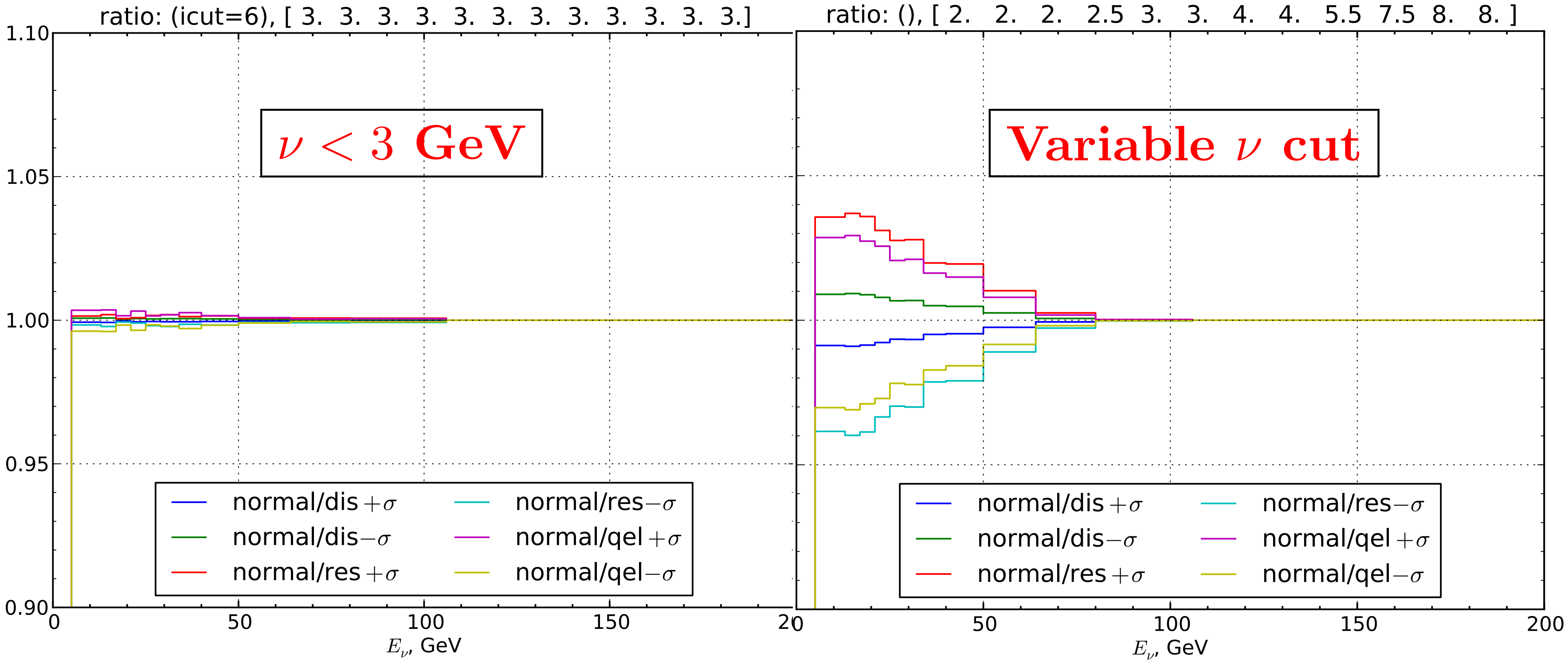
$\Longrightarrow$ *Ratio FD/ND stable against cross-section uncertainties*
$\Longrightarrow$ *Overall uncertainty of the FD/ND flux ratio $\sim 2\%$ including all systematics*



✦ *Gonchar and Petti (docdb #9275) showed with NOMAD analysis that a variable ν_0 cut as a function of E_ν dramatically enhances effect of cross-section uncertainties*

- *Fixed ν_0 cut provides reduced dependence upon cross-section models;*
- *Variable ν_0 cut alters event composition (QE/RES/DIS) and corresponding E_ν dependence.*

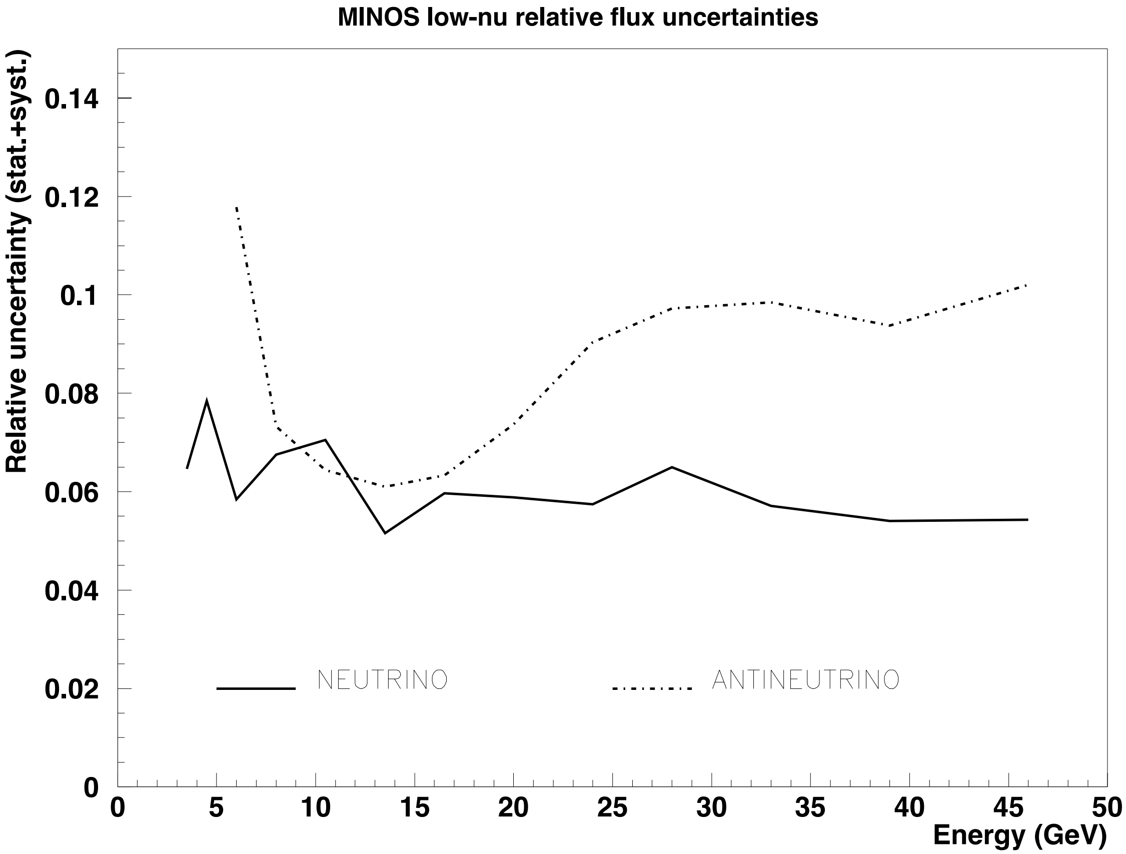
$\Longrightarrow$ *Must keep the lowest fixed ν_0 cut allowed by experimental resolution / statistics*



Effect of cross-section variation:
QE, RES +- 15%
DIS +- 2.1%

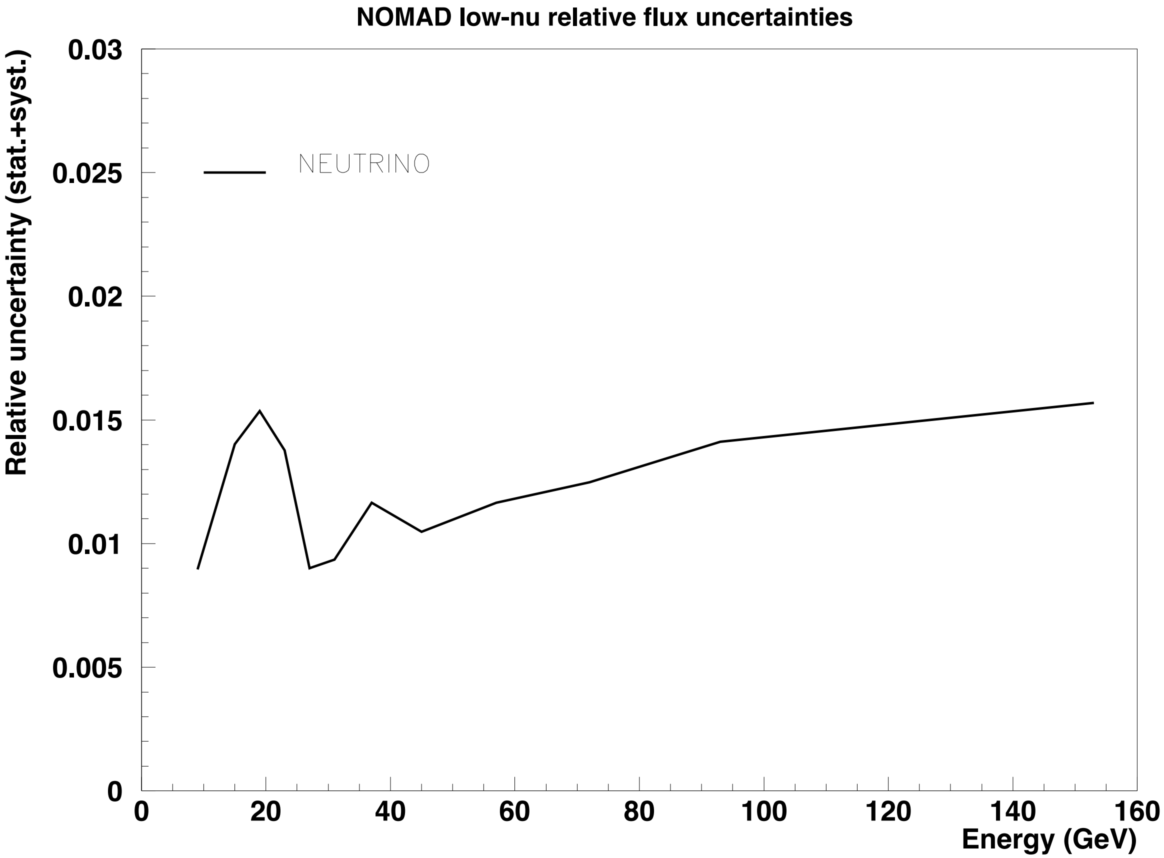
IMPACT OF ENERGY SCALE UNCERTAINTIES

- *Effect of energy scale uncertainties largely dominated by muon δE_μ (small $y_{\rm Bj}$)*
- *MINOS low-ν flux determination [PRD 81 (2010) 072002] used variable ν_0 cut and was intrinsically limited by the large energy scale uncertainties:*
  $\delta E_\mu = 2\%$ (stopping) or 4% (exiting); hadronic scale uncertainty $\delta E_{\rm Had} = 5.6\%$



- ✦ *NOMAD low-ν flux extraction (Gonchar and Petti, docdb #9275) used a fixed ν_0 cut and exploited the high detector resolution / low energy scale uncertainties:* $\delta E_\mu = 0.2\%$; *hadronic scale uncertainty* $\delta E_{\rm Had} = 0.5\%$

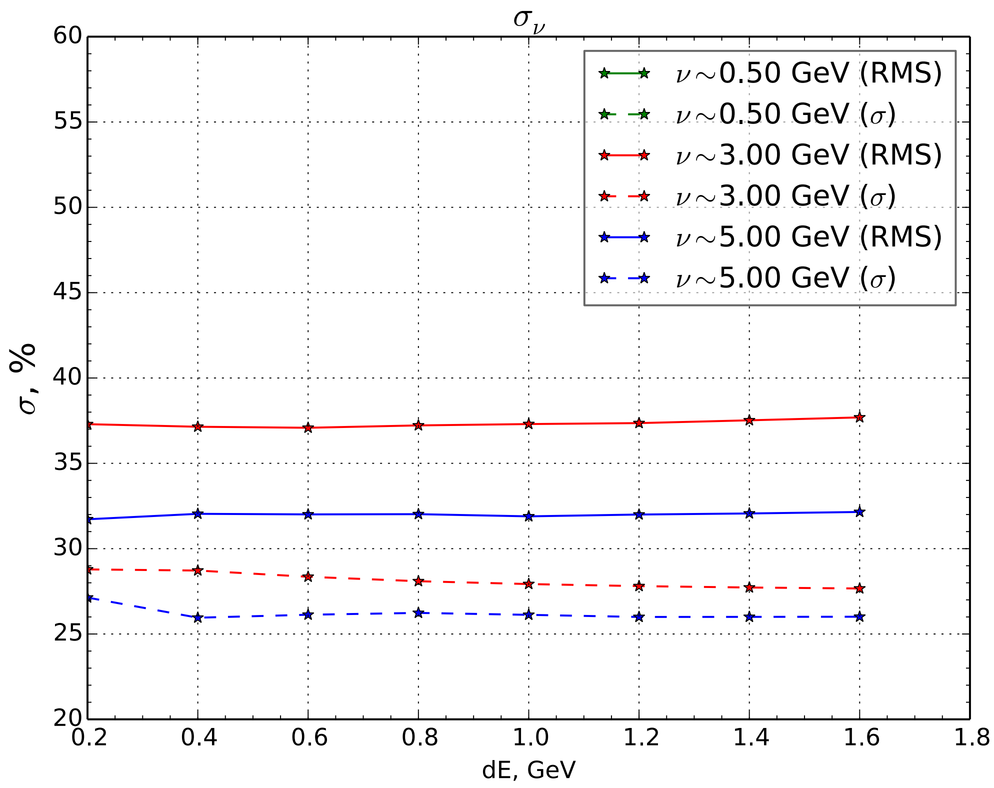
$\Longrightarrow$ *Crucial to achieve a muon energy scale uncertainty* $\delta E_\mu \leq 0.2\%$ *in DUNE ND to keep uncertainty on FD/ND* $\sim 1\%$



IMPACT OF ν_0 SMEARING

- ✦ *Even a high resolution detector (NOMAD, DUNE ND) can still be subject to* *significant smearing on the reconstructed ν:*
  - *Reconstruction of low momentum / large angle tracks (protons);*
  - *Fermi motion and nuclear effects;*
  - *Final state interactions, etc.*

$\Longrightarrow$ *Dominant systematic uncertainty from variation of ν_0 cut once small energy scale uncertainties*



- ✦ *Study of variation of ν_0 cut requires full reconstruction and detector simulation*

$\Longrightarrow$ *Use NOMAD data as benchmark for DUNE FGT*

NOMAD results on low-ν extraction of relative ν_μ flux

E_ν GeV	Φ	$\delta_{\rm stat}$ %	$\delta_{\rm sys}$ %	$\delta_{\rm tot}$ %	$\delta_{\rm cut1}$ %	$\delta_{\rm cut2}$ %	$\delta_{\rm ehad}$ %	$\delta_{\rm elep}$ %	$\delta_{\rm csc}$ %	$\Phi_5 - \Phi_3$	$\Phi_5 - \Phi_3/\Phi$ %	overlap %
9.000	5.505	0.453	0.773	**0.896**	0.439	0.003	0.051	0.607	0.185	–0.0151	–0.2738	68.16
15.00	3.008	0.578	1.277	**1.402**	1.230	0.000	0.039	0.301	0.165	0.0290	0.9658	66.56
19.00	2.274	0.645	1.394	**1.536**	1.366	0.001	0.033	0.256	0.103	0.0400	1.7571	66.49
23.00	1.729	0.734	1.165	**1.377**	1.136	0.001	0.024	0.184	0.183	0.0277	1.6008	66.67
27.00	1.258	0.849	0.302	**0.901**	0.292	0.001	0.004	0.068	0.034	0.0115	0.9169	66.66
31.50	1.072	0.916	0.192	**0.936**	0.175	0.000	0.004	0.074	0.026	–0.0046	–0.4317	67.01
37.00	0.846	1.023	0.558	**1.165**	0.531	0.000	0.006	0.043	0.166	0.0095	1.1215	66.73
45.00	0.839	1.028	0.204	**1.048**	0.011	0.200	0.006	0.038	0.000	–0.0043	–0.5136	67.23
57.00	0.640	0.957	0.666	**1.166**	0.011	0.664	0.015	0.031	0.039	–0.0055	–0.8558	67.44
72.00	0.447	1.138	0.513	**1.248**	0.011	0.504	0.005	0.079	0.058	–0.0026	–0.5760	67.61
93.00	0.420	1.171	0.786	**1.411**	0.010	0.783	0.004	0.019	0.056	–0.0041	–0.9875	67.67
153.00	0.355	1.269	0.922	**1.569**	0.009	0.869	0.018	0.299	0.077	–0.0065	–1.8465	68.21

- *Muon energy scale* $\delta E_\mu = 0.2\%$;
- *Hadronic energy scale* $\delta E_{\rm Had} = 0.5\%$;
- *Cross-section variations* $\pm 15\%$ *QE & RES,* $\pm 2.1\%$ *DIS;*
- *Cut 1 (*$\nu < 3$ *GeV) variation* ± 1 *GeV (33%);*
- *Cut 2 (*$\nu < 5$ *GeV) variation* ± 1.5 *GeV (30%).*

REQUIREMENTS FOR DUNE ND (LOW-ν)

$\boxed{\text{Glo-Sci-51,23}}$ *measure absolute and relative* ν_μ, ν_e *and* $\bar{\nu}_\mu, \bar{\nu}_e$ *spectra separately.*

$\Longrightarrow$ *Absolute* $\nu_\mu (\bar{\nu}_\mu)$ *fluxes to* $\sim$ *2-3%, relative* $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ *fluxes FD/ND to* $\lesssim 2\%$

$\boxed{\text{Glo-Sci-41}}$ $\Delta_{\mathrm{Syst.}}$ *on FD/ND must be significantly less than* $\Delta_{\mathrm{Stat.}}$ *in FD.*

$\Longrightarrow$ $\Delta_{\mathrm{Stat.}}$ *on relative fluxes in ND* $\ll 1\%$ *for not to limit FD/ND predictions*

✦ *Identify and measure ALL 4 species in LBNF beams:* $\boxed{\nu_\mu}$, $\boxed{\bar{\nu}_\mu}$, $\boxed{\nu_e}$, *and* $\boxed{\bar{\nu}_e}$ *CC with particular emphasis on the low-*ν *topologies at* $\nu < 1$ *GeV (flux samples)*

- *Measure the relative* E_ν *distribution vs. the radial distance from beam axis (e.g. radial bins);*
- *Extract the parent meson distributions from EP fits to low-*ν *flux samples for FD/ND extrapolation.*

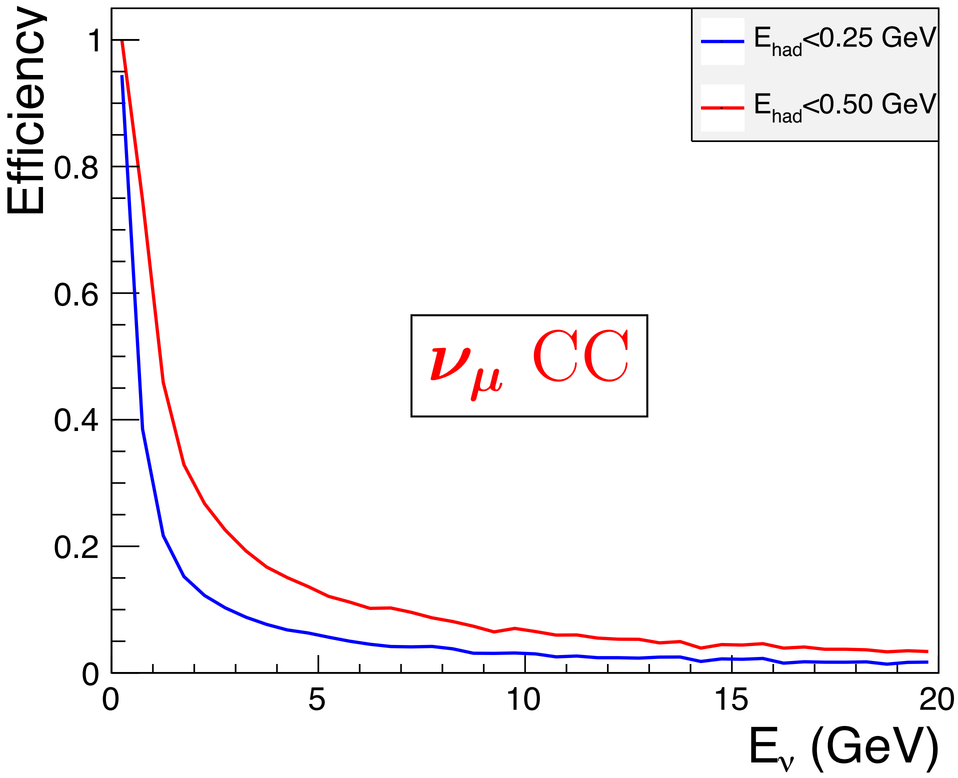
✦ *Minimal ND statistics required defined by target statistical precision* $\Delta_{\mathrm{Stat.}} \ll 1\%$ *and lowest FIXED cut* $\boxed{\nu < 0.25 \text{ GeV}}$ *to constrain LBNF fluxes down to* $E_\nu \sim 0.5$ *GeV*

- *Need samples equivalent to* $\gtrsim 3 \times 10^6$ ν_μ *CC interactions after reconstruction and all analysis cuts to fully exploit the* E_ν *vs. radial distributions*
- ε *for* $\nu < 0.25$ *GeV cut 9% for* ν_μ *CC and 11% for* $\bar{\nu}_\mu$ *CC,* ε *for reconstruction/selection* $\sim 90\%$
- *Important to constrain the high energy tail of the spectrum (normalization in FD, non-standard oscillations, etc.) requiring even higher statistics*

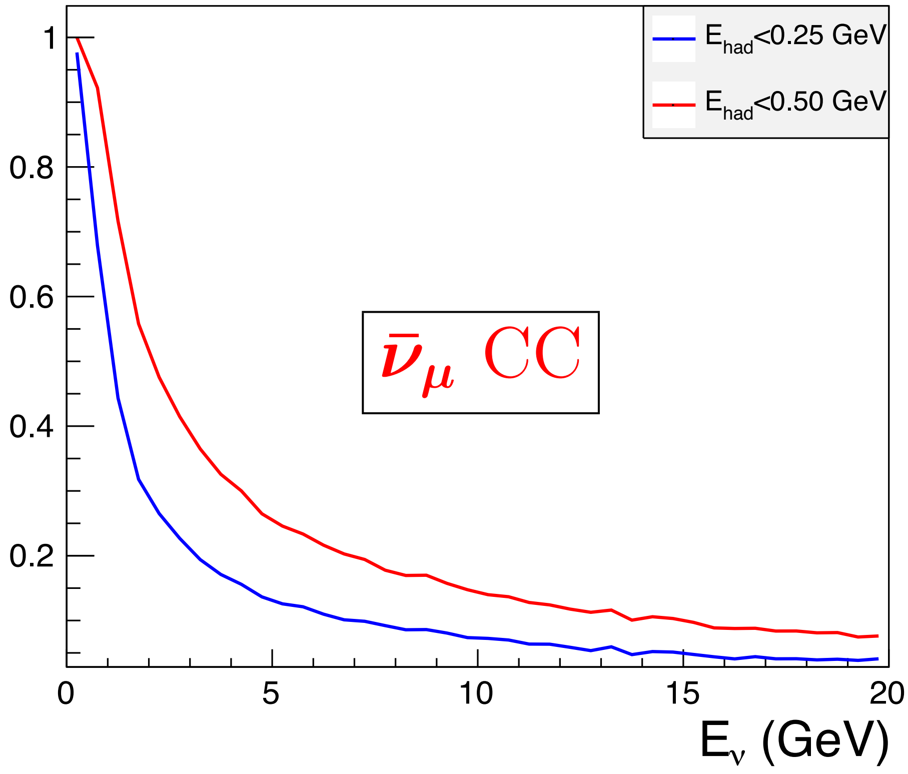
$\Longrightarrow$ *Need to collect at least* $\sim 37 \times 10^7$ ν_μ *CC,*
corresponding to a minimum FV of 3 tons with default 1.2 MW beam in 5y

Relative efficiency of the cut $\boxed{\nu < \nu_0}$ *in DUNE ND*

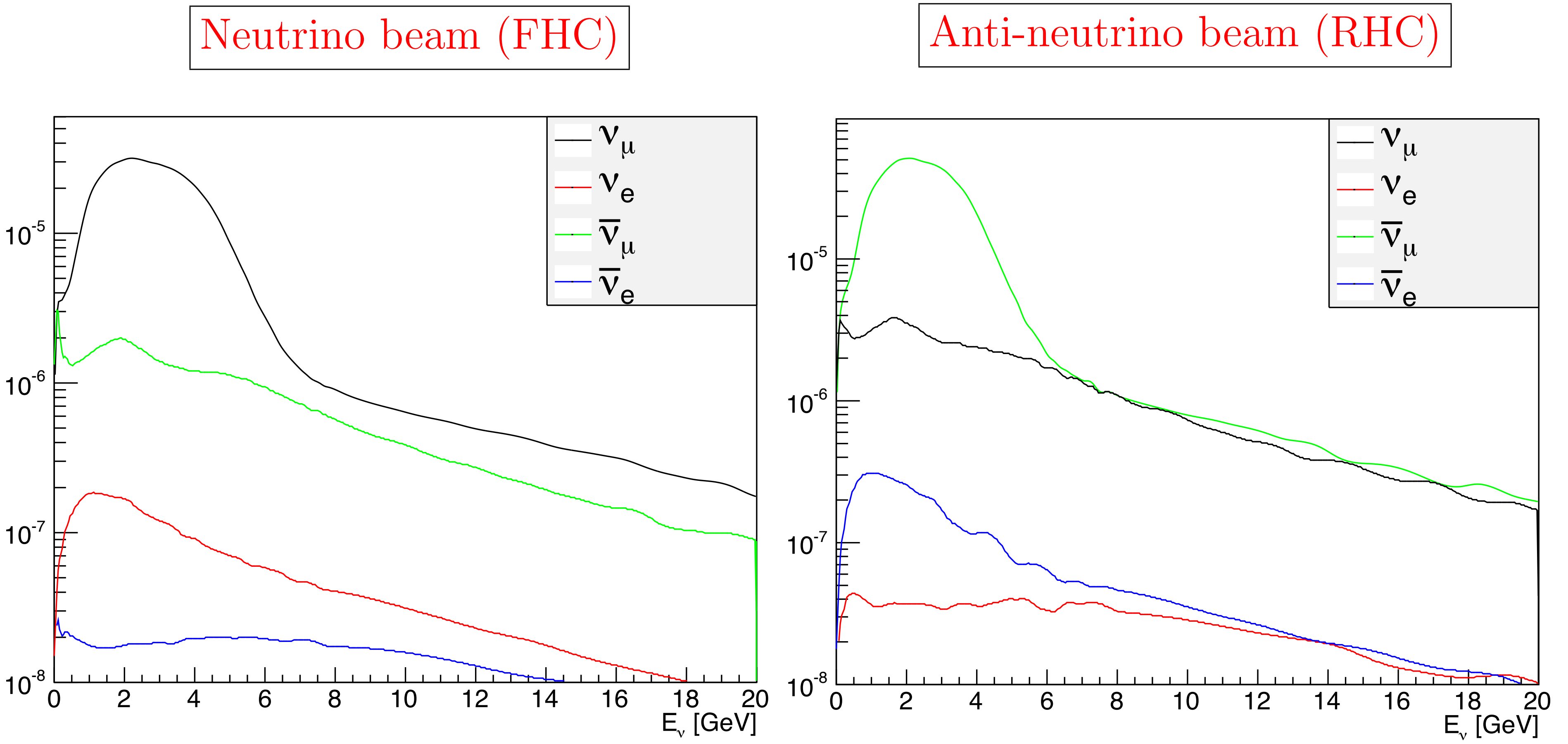
reconstruction efficiencies not included (typically $> 90\%$*)*



Cut	$\nu < 0.25$ *GeV*	$\nu < 0.50$ *GeV*
$\langle\varepsilon\rangle$	*9%*	*19%*



Cut	$\nu < 0.25$ *GeV*	$\nu < 0.50$ *GeV*
$\langle\varepsilon\rangle$	*11%*	*22%*


Neutrino beam (FHC)

Anti-neutrino beam (RHC)

Fluxes from G4DUNE v3r3p8 (neutrino) and v3r2p4b (anti-neutrino)

- *Energy scale uncertainties must be better than 0.5% to achieve target systematics on the relative fluxes FD/ND $\lesssim 2\%$ from low-ν technique:*
  - *Muon energy scale uncertainty* $\boxed{\delta E_\mu \ll 0.5\%}$;
  - *Hadron energy scale uncertainty* $\delta E_{\text{Had}} \lesssim 0.5\%$.

- *Need redundancy & accurate reconstruction of single-particle kinematics to constrain acceptances and low-ν smearing*

- *Need in-situ ancillary measurements:*
  - *Measurements of differential exclusive cross-sections (QE, RES, DIS);*
  - *Measurements to constrain nuclear effects, final state interactions (FSI) etc;*
  - *Control samples to validate efficiencies, energy scales, fitting procedure, parameterizations, etc.;*

Backup slides

EXTRAPOLATION FD/ND

- ✦ *Divide transverse fiducial volume (x, y) in 4-5 radial bins and perform EP fit to measured spectra in each radial bin*

  $\Longrightarrow$ *Enhanced sensitivity to $\nu(\bar{\nu})$ beam divergence*

- ✦ *Stringent constraints on $\pi^{\pm}, K^{\pm}, K_L^0$ components from $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ spectra in ND (EP fit) $\longrightarrow$ extrapolation to FD defined only by decay kinematics & beam geometry*

  $\Longrightarrow$ *High resolution ND as a precision "$\nu(\bar{\nu})$-source measurement device"*
  $\Longrightarrow$ *Large cancellation of systematic uncertainties in FD/ND ratio*

- ✦ *Main systematic uncertainties on the FD/ND extrapolation from simulation/modeling of beam transport elements:*
  - *Material profile along beam line;*
  - *Misalignments & B field in focusing system;*
  - *Effect of secondary/tertiary interactions.*

  $\Longrightarrow$ *Only differences which cannot be resolved by the ND resolution (EP) result in FD/ND systematics*

SYSTEMATIC UNCERTAINTIES

Correction factor $f_c(E_\nu)$:

- *Modeling $\sigma(E_\nu)$ shape: QE, RES, DIS*

Low-ν extraction in ND:

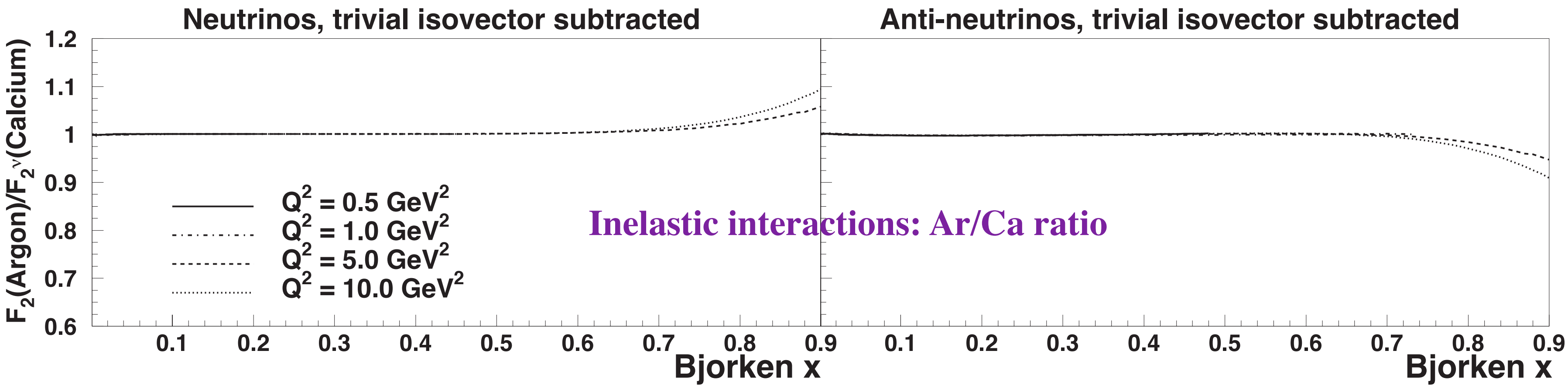
- *Muon energy scale δE_μ*
- *Hadron energy scale δE_{Had}*
- *Detector smearing and effect of ν_0 cut (including effect of FSI and nuclear smearing on resolution)*
- *Background calibration (control samples) & selection cuts*

EP fit of parent meson distributions:

- *Functional form for $d\sigma/dx_F dP_T^2$*
- *Fit procedure ($\Delta\chi^2$)*
- *Input(s) from external hadro-production measurements of $\pi^\pm/K^\pm$*

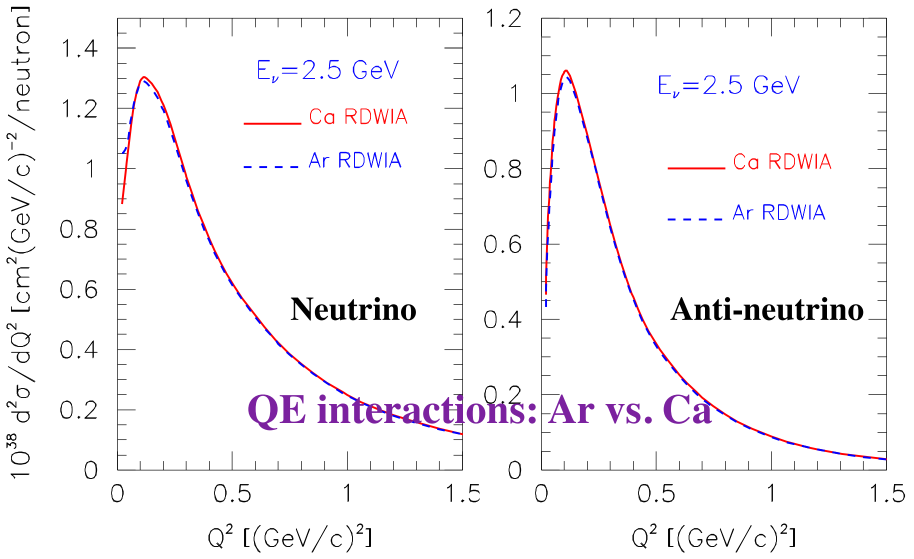
Extrapolation FD/ND:

- *Material profile along beam line*
- *Misalignments & B field in focusing system*
- *Effect of secondary/tertiary interactions*



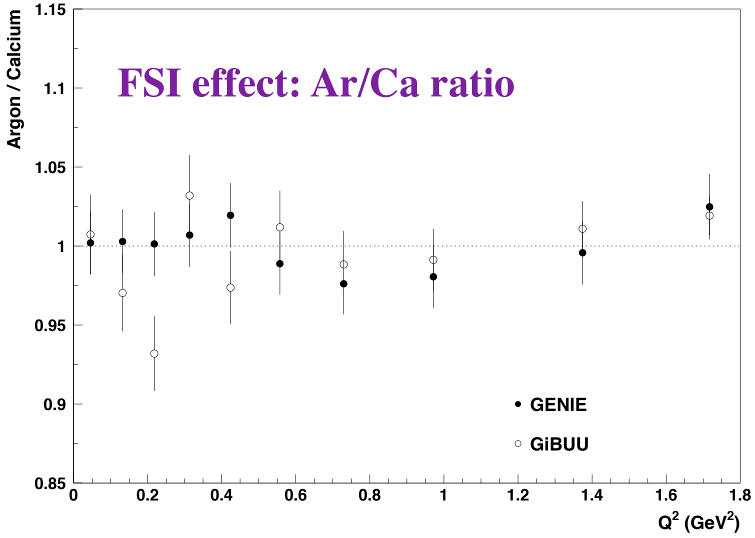
Inelastic interactions: Ar/Ca ratio

S. Kulagin and R.P, NPA 765 (2006) 126-187; PRD 76 (2007) 094023
PRC 82 (2010) 054614; arXiv:1405.2529 [hep-ph]



QE interactions: Ar vs. Ca

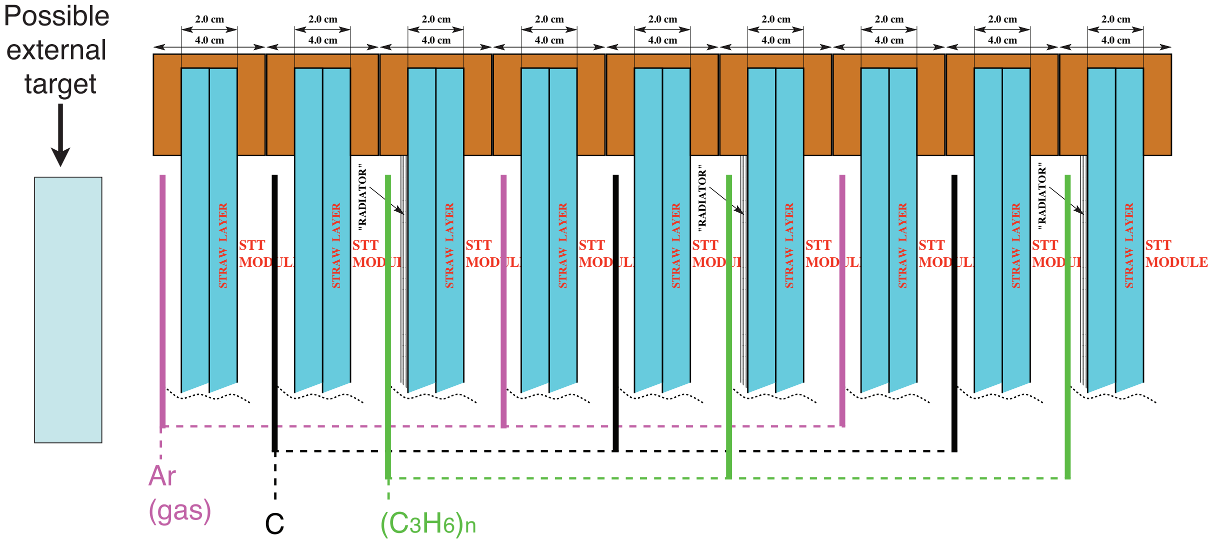
A.V. Butkevich, PRC 85 (2012) 065501; A.V. Butkevich and S. Kulagin, PRC 76 (2007) 045502



FSI effect: Ar/Ca ratio

HRI Group, GENIE and GiBUU simulations

NUCLEAR TARGETS



MAIN target
$(C_3H_6)_n$ radiators:
mass $\sim 5t$

- ✦ *Multiple nuclear targets in STT: $(C_3H_6)_n$ radiators, C, Ar gas, Ca, Fe, H_2O, D_2O, etc.*
  $\Longrightarrow$ *Separation from excellent vertex ($\sim 100\mu m$) and angular (< 2 mrad) resolutions*

- ✦ *Subtraction of* $\boxed{\text{C TARGET}}$ *(0.5 tons) from polypropylene* $\boxed{(\text{C}_3\text{H}_6)_n \text{ RADIATORS}}$
  provides $5.0(1.5) \times 10^6 \pm 13(6.6) \times 10^3 (sub.)$ $\nu(\bar{\nu})$ *CC interactions on free proton*
  $\Longrightarrow$ *Absolute $\bar{\nu}_\mu$ flux from QE*
  $\Longrightarrow$ *Model-independent measurement of nuclear effects and FSI from RATIOS A/H*

- ✦ *Pressurized* $\boxed{\text{Ar GAS}}$ *target ($\sim$ 140 atm) inside SS/C tubes and solid* $\boxed{\text{Ca TARGET}}$
  (more compact & effective) provide detailed understanding of the FD $A = 40$ target
  $\Longrightarrow$ *Collect $\times 10$ unoscillated FD statistics on Ar target*
  $\Longrightarrow$ *Study of flavor dependence & isospin physics*