Toward construction of the unified lepton-nucleus interaction model from a few hundred of MeV to GeV region

S. Nakamura (YITP, Kyoto U.)

Y. Hayato (ICRR, U. of Tokyo), M. Hirai (Tokyo U. of Science), H. Kamano (RCNP, Osaka U.), S. Kumano (KEK), K. Saito (Tokyo U. of Science), M. Sakuda (Okayama U.), T. Sato (Osaka U./KEK)

[Collaboration@J-PARC Branch of KEK Theory Center]

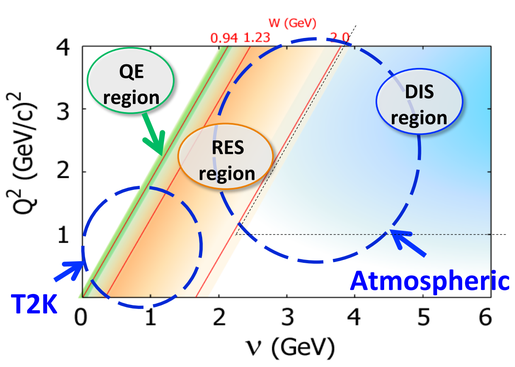
Motivation & Goals: Lepton-nucleus interactions in the new era of large θ_{13}

✓ Need for precise knowledge of lepton-nucleus interactions:

- A few % accuracy of the neutrino cross sections is required for the determination of precise value of θ_{13} and CP-phase δ.
- Neutrino experiments probe *overlapping region* among Quasi-elastic(QE), Resonance(RES), and Deep-inelastic scattering (DIS).

Long-baseline (LBL) experiments ➔ QE and 1π production from Δ(1232)

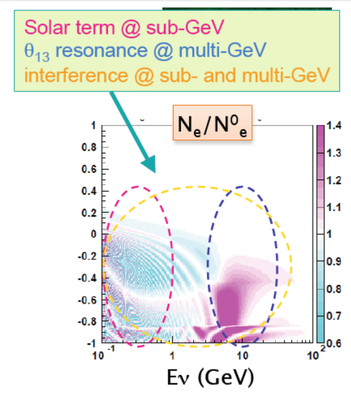
Atmospheric experiments ➔ N* resonances and DIS



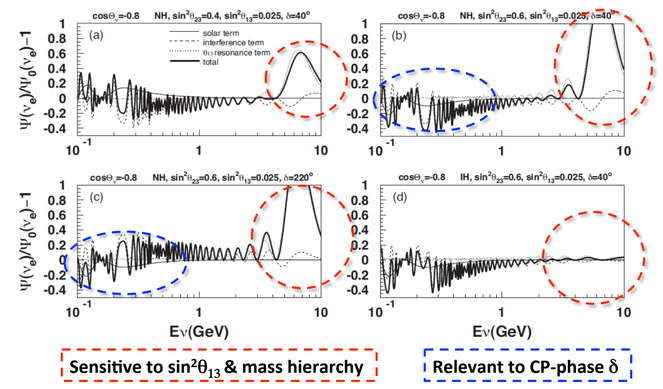
Combining *baseline models*, we develop an approach to tackle overlapping regions !!

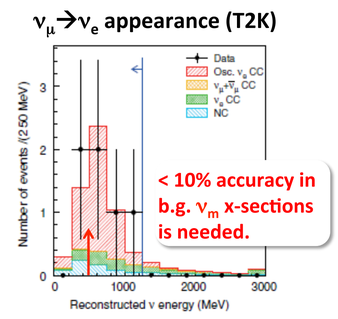
➔ A new collaboration at J-PARC Branch of KEK Theory Center

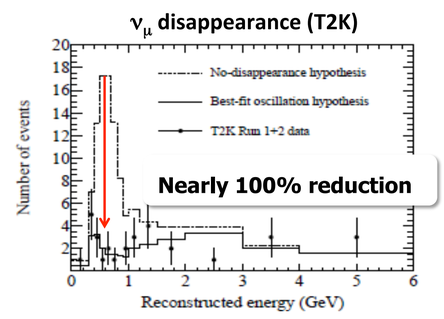
http://j-parc-th.kek.jp/html/English/e-index.html



LOI for experiments at Hyper-Kamiokande, arXiv:1109.3236





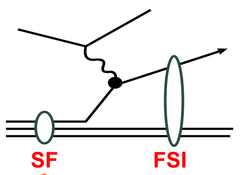


Current status of baseline models

QE

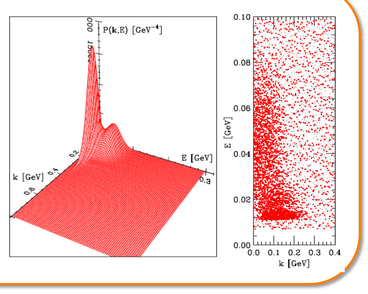
✓ Impulse approx. with spectral function + FSI

Benhar, Farina, Nakamura, Sakuda, Seki, PRD72 053005 (2005)

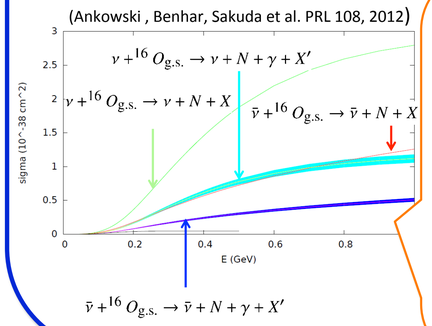


Spectral function:
Energy-momentum distribution of nucleons in a nucleus

$$P_{MF}(\mathbf{p},E) = \sum_n Z_n \, |\phi_n(\mathbf{p})|^2 F_n(E-E_n)$$



NC ν-^{16}O reaction
(Ankowski , Benhar, Sakuda et al. PRL 108, 2012)



In the QE and 1π regions, the ratio

$$\frac{\sigma[\nu(\bar\nu) + {}^{16}O_{g.s.} \to \nu(\bar\nu) + N + \gamma + X']}{\sigma[\nu(\bar\nu) + {}^{16}O_{g.s.} \to \nu(\bar\nu) + N + X]}$$

is about 40 % !!
(This is true also for CC reactions.)

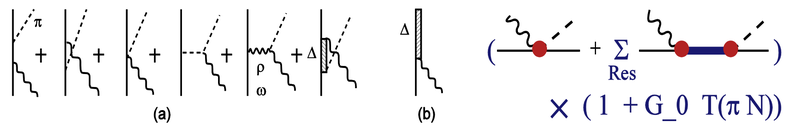
Detailed information on the photo-deexcitation processes of nucleus will be necessary for understanding neutrino-induced QE and 1π reactions.

RES

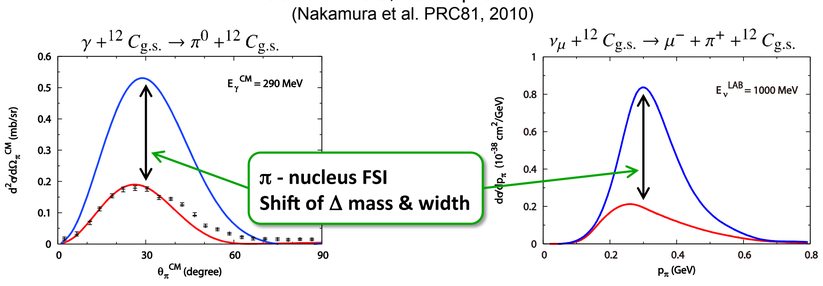
✓ Dynamical model of 1π (Δ) with spectral function

Sato, Lee, PRC54 2660 (1996)
Sato, Uno, Lee, PRC67 065201 (2003)
Szczerbinska, Sato, Kubodera, Lee, PLB649 132 (2007)

$$T = V + VGT$$



Coherent CC,NC 1π production
(Nakamura et al. PRC81, 2010)



✓ Nucleon resonance model beyond Δ(1232)

➔ Unitary Dynamical Coupled-Channels (DCC) model for πN, ππN, ηN, KΛ, KΣ, ωN production reactions

Comprehensive description of meson production reactions with π, γ, e beams up to $s^{1/2}$ = 2.1 GeV and Q^2 = 1.5 $(GeV/c)^2$ has been achieved.

Matsuyama, Sato, Lee, Phys. Rep. 439, 193 (2007)
Kamano, AIP Conf. Proc. 1374, 501 (2011)
Kamano, Lee, AIP Conf. Proc. 1432, 74 (2011)

DIS

Hirai, Kumano, Miyama, Phys. Rev. D64 034003 (2001)
Hirai, Kumano, Nagai, Phys. Rev. C70 044905 (2004)
Hirai, Kumano, Nagai, Phys. Rev. C76 065207 (2007)

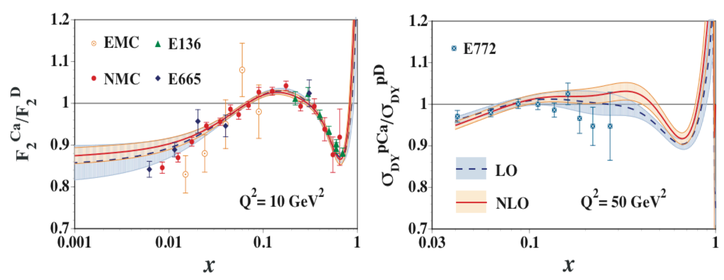
Global analysis of DIS data ➔ NPDFs (Nuclear Parton Distribution Functions)

f_i^A = Nuclear PDF, f_i^N = Nucleonic PDF, w_i = Nuclear modification

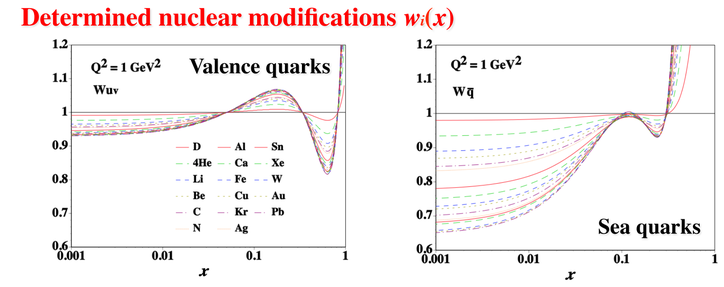
$$f_i^A(x,Q_0^2) = w_i(x,A) f_i^N(x,Q_0^2) \quad i = u_v, d_v, \bar u, \bar d, \bar s, g$$

$$w_i(x,A) = 1 + \left(1 - \frac{1}{A^\alpha}\right)\frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^\beta}$$

Comparison with typical data, F_2^{Ca}/F_2^D & $\sigma_{DY}^{pCa}/\sigma_{DY}^{pD}$



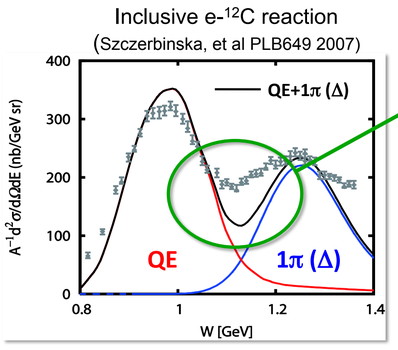
Determined nuclear modifications $w_i(x)$



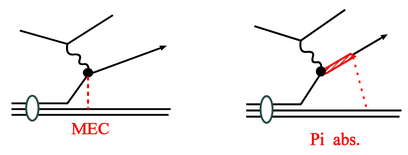
What to do

✓ Improve overlapping region between QE and RES (Δ):

Inclusive e-^{12}C reaction
(Szczerbinska, et al PLB649 2007)



Missing strength is considered due to nuclear many-body effects (meson exchange current, 2p-2h mechanisms, RPA correlations, ...)



Would play significant role in understanding "QE" ν-reactions !!

✓ Extend the DCC-model for N*s to neutrino reactions.

- Currently applicable to π, γ, e induced reactions up to $s^{1/2}$ = 2.1 GeV, Q2 = 1.5 $(GeV/c)^2$.

✓ Combine nuclear effects into the neutrino DIS model.

✓ Improve overlapping region between N* and DIS.

- Achieved by matching of physical quantities such as structure functions.

Recent work

arXiv:1207.5724; to appear in PRD

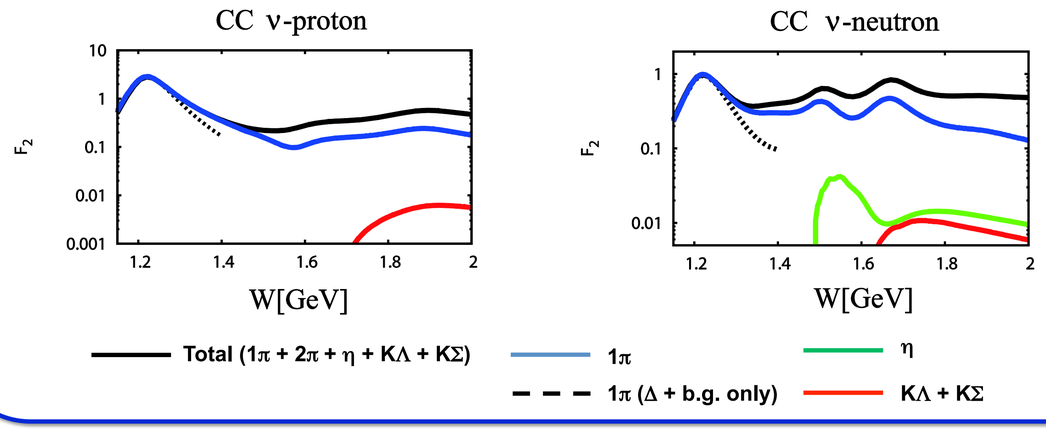
✓ Forward neutrino-induced meson-production reactions in the nucleon resonance region up to $s^{1/2}$ = 2 GeV: The first trial

- Benchmark for the future full meson production model.
- η and kaon production rates needed for back ground estimation of proton decay analysis

For $Q^2 = 0$ and $m_l = 0$,

$$\frac{d\sigma_\nu}{dE'd\Omega} = \frac{G_F^2 V_{ud}^2}{2\pi^2}\frac{E'^2}{E-E'}F_2$$

Using PCAC,

$$F_2 = \frac{2f_\pi^2}{\pi}\sigma(\text{virtual}\,\pi + \text{N})$$

Use prediction from the DCC-model