Update of HKN nuclear PDFs

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nPDFs [HKN07: Nucl. Phys. C76,065207 (2007)]

http://research.kek.jp/people/kumanos/nuclp.html

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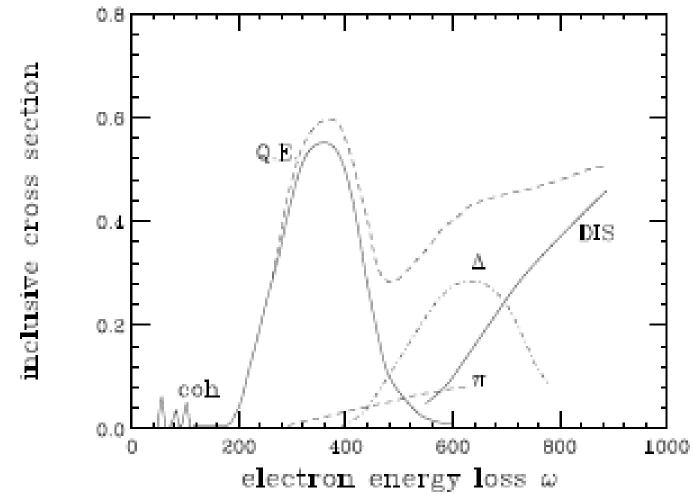
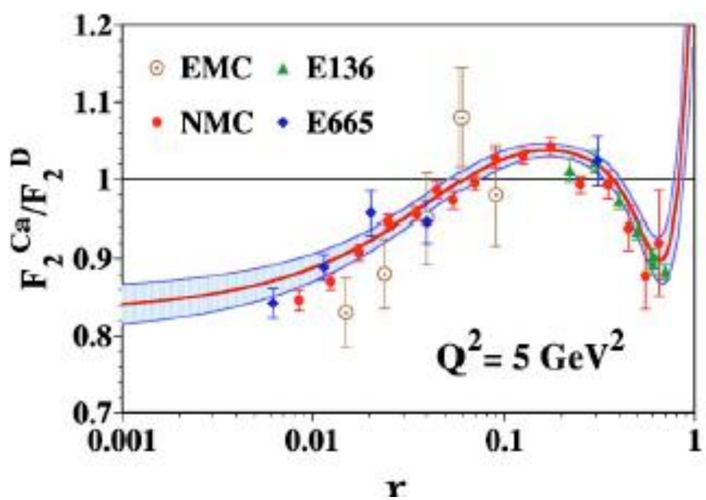
Introduction

- **Ambiguity of energy neutrino flux**
  - Measurement of energy dependence on final lepton $\nu(\bar{\nu}) + A \rightarrow l\,(\bar{l}\,) + X$
    - $$\frac{dN}{dE_l} = T \times N_{eff} \int \frac{d\sigma(E_\nu)}{dE_l} \Phi(E_\nu)\, dE_\nu$$
      - T:time of exposure
      - N_{eff} : effective # of target nucleons (nuclear)
      - $\sigma(E_\nu)$: x-section of induced neutrino energy
      - $\Phi(E_\nu)$: neutrino energy flux
    - Nuclear target needs for the neutrino reaction caused by the week interaction
  - Getting better understanding in wide energy range where exists several phenomena
    - QE, resonance, DIS
    - DIS process is well defined by the pQCD, and confirmed it by many experiments of the lepton DIS process
    - Nuclear effects on PDFs and neutrino physics ?

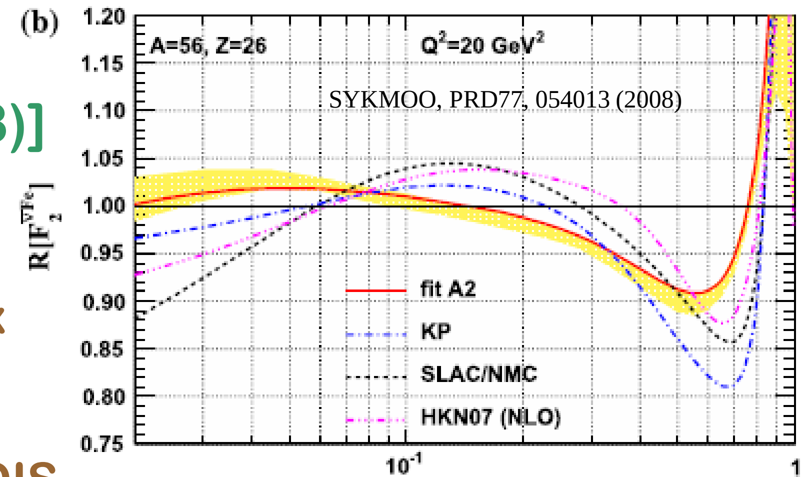


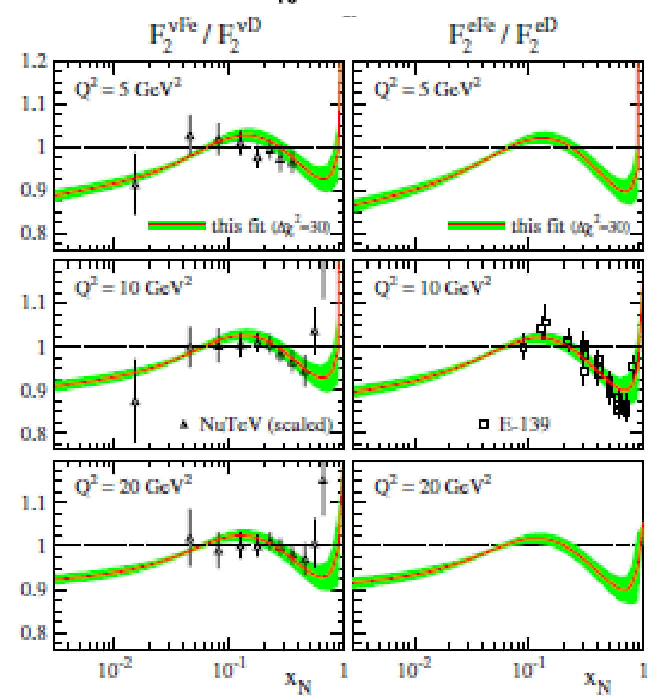
ω(MeV) = ν (= E_ν-E_l)
arXic:1310.3869
O. Benhar and N. Rocco

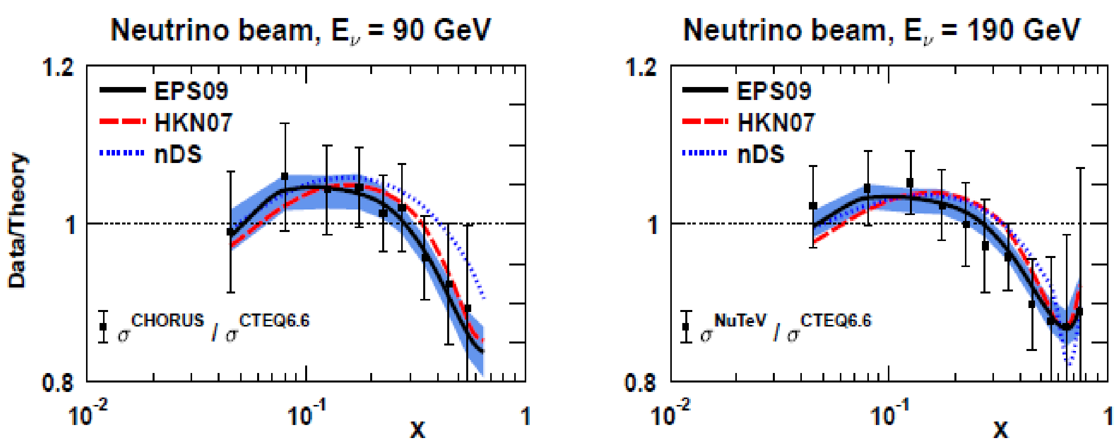


nPDFs from neutrino DIS

- **Discrepancy of nuclear effect ?**
  - K. Schienbein, et. al [PRD77,054013(2008)]
    - Using (anti-)neutrino DIS data
    - Shallow EMC effect
    - Moving the anti-shadowing peak for small-x
  - DSSZ12 [PRD85,0704028 (2012)]
    - Combined data set with lepton & neutrino DIS
      - Using F_2 & xF_3 data, not x-sect !
    - Showing same effect … ?
  - Paukkunen, Salgado [JHEP07,032,(2010)]

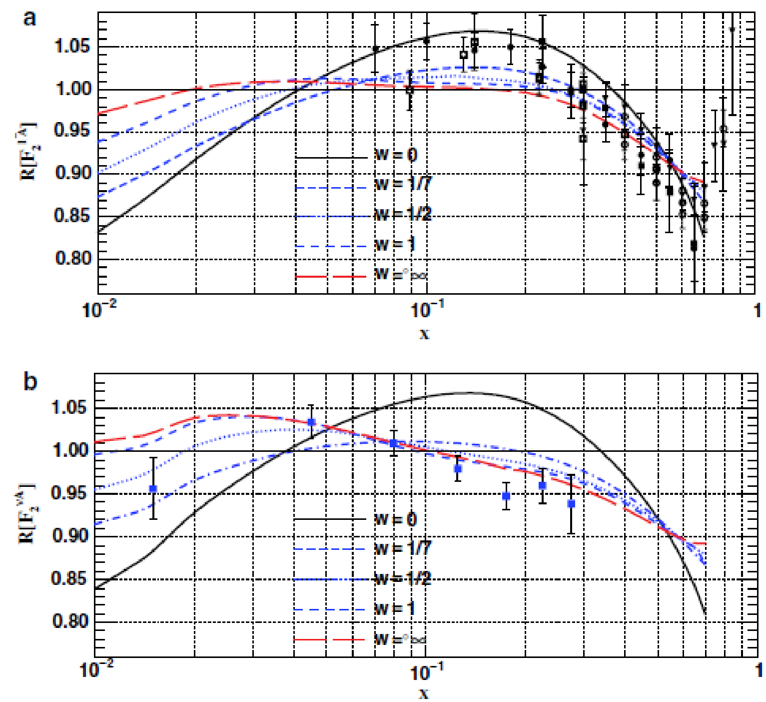






An issue of global analysis (χ^2 analysis)

- Assuming the same model when using data sets simultaneously
- Information fall ?
  - larger # of ν-DIS data of Fe, Pb targets
    - 100 (NC-DIS,DY) v.s. 5000 (CC-DIS)
    - Large error data become numerical noise in total χ^2
  - Weight dependence ?
    - Obtained intermediate model which has possibility to reproduce these data sets
- Are nuclear effects different ?
  - Attributing to structure and dynamics in a nucleus, base on strong interaction
  - EW probe dependent ?
  - To answer the equation, test of significance for data set needs



K. Kovarik, et. al, PRL106,122301(2011)

$\chi^2=\chi^2_{lA\text{-}DIS}+w^*\chi^2_{\nu A-DIS}$

Neutrino-nuclear DIS

- **Cross section**

$$d\sigma^{\overset{(-)}{\nu} A} \propto y^2 x F_1^{\overset{(-)}{\nu} A} + \left(1 - y + \frac{(xyM)^2}{Q^2}\right) F_2^{\overset{(-)}{\nu} A} \pm y\left(1 - \frac{y}{2}\right) x F_3^{\overset{(-)}{\nu} A},$$

  – Assuming the Callan-Gross eq. at LO

    • $F_2(x)=2xF_1(x)$

$$d\sigma^{\overset{(-)}{\nu} A} \to \begin{cases} \frac{1}{2}\left(F_2^{\overset{(-)}{\nu} A} \pm x F_3^{\overset{(-)}{\nu} A}\right) & (\text{for } y \to 1) \\ F_2^{\overset{(-)}{\nu} A} & (\text{for } y \to 0) \end{cases}$$

$$\begin{cases} Q^2 = 4E_\nu E_l \sin^2\left(\frac{\theta_{Lab}}{2}\right) = 2ME_\nu xy \\ x = \frac{2E_\nu E_l}{M(E_\nu - E_l)} \sin^2\left(\frac{\theta_{Lab}}{2}\right) = \frac{2E_l}{My} \sin^2\left(\frac{\theta_{Lab}}{2}\right) \\ y = 1 - \frac{E_l}{E_\nu} \end{cases}$$

- **Structure function F_2, xF_3**

  – Flavor deference by charged current $W^\pm$

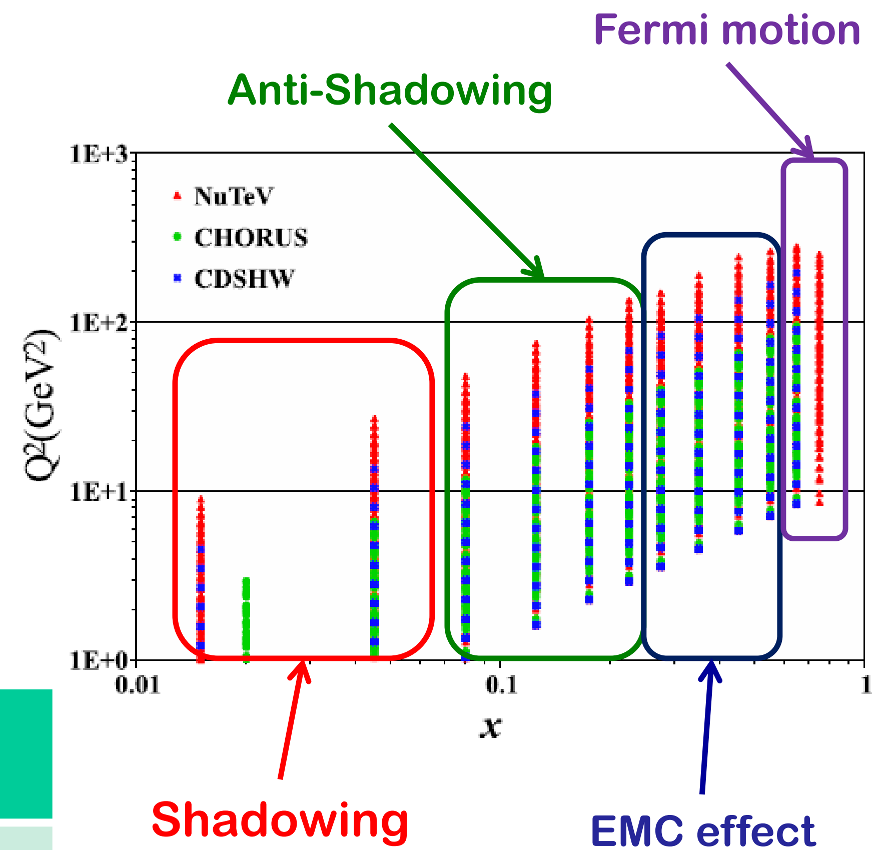
$$\begin{cases} F_2^{\nu A} = 2x\left(d^A + s^A + \bar{u}^A + \bar{c}^A + \ldots\right) \\ F_2^{\bar{\nu} A} = 2x\left(u^A + c^A + \bar{d}^A + \bar{s}^A + \ldots\right) \end{cases}, \quad \begin{cases} xF_3^{\nu A} = 2x\left[d^A + s^A - \bar{u}^A - \bar{c}^A + \ldots\right] \\ xF_3^{\bar{\nu} A} = 2x\left[u^A + c^A - \bar{d}^A - \bar{s}^A + \ldots\right] \end{cases}$$

  – $y \to 1$

$$\begin{cases} d\sigma^{(\nu+\bar{\nu})A} \propto \frac{1}{2}\left(F_2^{(\nu+\bar{\nu})A} + xF_3^{(\nu-\bar{\nu})A}\right) = 2x\left(d^A + \bar{d}^A + s^A + \bar{s}^A\right) \\ d\sigma^{(\nu-\bar{\nu})A} \propto \frac{1}{2}\left(F_2^{(\nu-\bar{\nu})A} + xF_3^{(\nu+\bar{\nu})A}\right) = 2x\left(d_v^A + s_v^A\right) \end{cases}$$

Kinematics of the neutrino DIS experiment

- **Kinematic in Lab frame**
  - $X = Q^2/2\langle M_N \rangle \nu$
  - $\nu = E_{had}$: energy of outgoing hadron
  - $y = E_{had}/(E_{had}+E_l)$
  - $Q^2 = 2\langle M_N \rangle x y E_\nu$, $(E_\nu = E_{had}+E_l)$
  - $W = \langle M_N \rangle^2 + Q^2(1-x)/x$
- $Q^2 > 4\ \mathrm{GeV}^2$, $W > 3.5\ \mathrm{GeV}$



Experiment	Target	Beam energy (GeV)	# of data ν & $\bar{\nu}$
NuTeV	Fe	35-340	2604
CHORUS	Pb	25-130	1204
CDHSW	Fe	23-187	1602

Global analyses of the Nuclear PDFs

- Q^2 dependence given by the DGLAP equation
  - Need the initial distributions at Q_0^2
  - Functional form is arbitrary
- Satisfying the conservation lows
  - Baryon number & charge: $\int \left[u_v^A(x) + d_v^A(x) \right] dx = 3, \quad \int \left[\frac{2}{3} u_v^A(x) - \frac{1}{3} d_v^A(x) \right] dx = \frac{Z}{A}$
  - Momentum: $\sum_{i=q,\bar{q},g} \int x f_i^A(x)\, dx = 1$
  - Fixed some free parameters by using these conditions
- Neglecting the effect in the region $1<x_{Bj}<A$
  - Not enough data to constrain on the behavior of the NPDFs
    - EPS09, SYKMOO08, HKN07
  - Small contribution in the region
  - ➢ DSSZ12: convolution type covering whole x_{Bj} region
- Uncertainty estimation by the Hessian method

Functional form of initial distributions at Q_0^2

- **Definition of NPDF (as initial condition of the DGLAP eq.)**
  - $f_i^A(x) = \frac{1}{A}\left(Z\ f_i^{p/A}(x) + (A-Z)\ f_i^{n/A}(x) \right), \left[\ f_i^{N/A}(x):\ \text{PDF of bound nucleon in the nucleus} \right]$
  - **Assuming isospin symmetry:** $u \equiv d^n = u^p,\ d \equiv u^n = d^p$

- **Functional forms**
  - **HKN07 (Q_0^2=1 GeV^2)**

$$f_i^A(x) = w_i(x,A,Z)\frac{1}{A}\left(Z\ f_a^p(x) + (A-Z)\ f_a^n(x) \right),\ w_i(x,A,Z) = 1 + \left(1 - \frac{1}{A^{1/3}}\right)\frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{0.1}}$$

  - **EPS09 (Q_0^2=1.69 GeV^2)**

$$f_i^{N/A}(x) = R_i^A(x)\, f_i^{\text{CTEQ6.1M}}(x,Q_0^2),\ R_i^A(x) = \begin{cases} a_0 + (a_1 + a_2 x)[\exp(-x) - \exp(-x_a)] & (x \le x_a : \text{shadowing}) \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & (x_a \le x \le x_e : \text{antishadowing}) \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & (x_e \le x \le 1 : \text{EMC\&Fermi}) \end{cases}$$

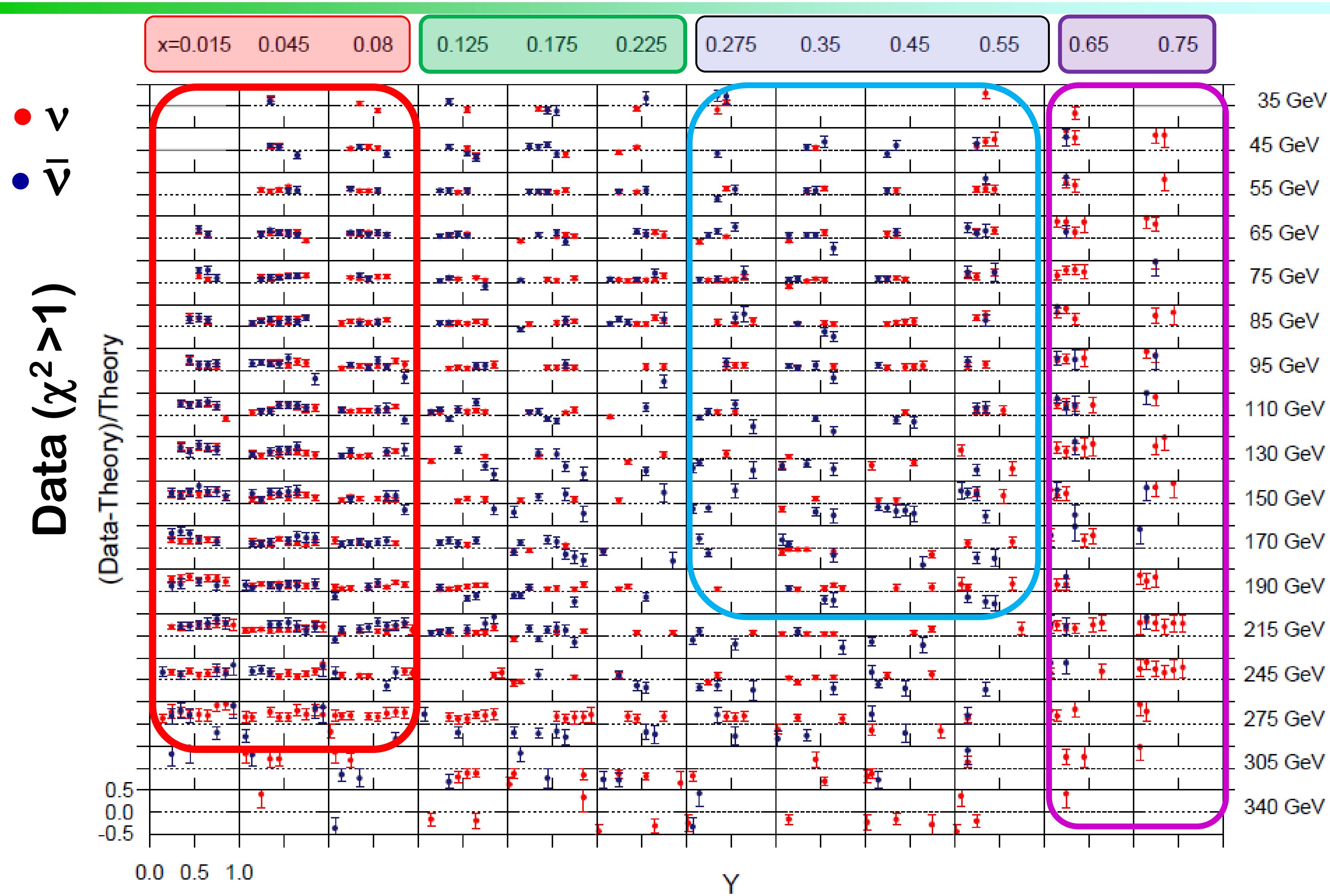
  - **nCTEQ15 (Q_0^2=1.69 GeV^2)**

$$x f_i^{N/A}(x) = \begin{cases} A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1 + e^{A_4} x)^{A_5} & : i = u_v, d_v, g, \bar{u} + \bar{d}, s, \bar{s} \\ A_0 x^{A_1}(1-x)^{A_2} + (1 + A_3 x)(1-x)^{A_4} & : i = \bar{d} / \bar{u} \end{cases}$$

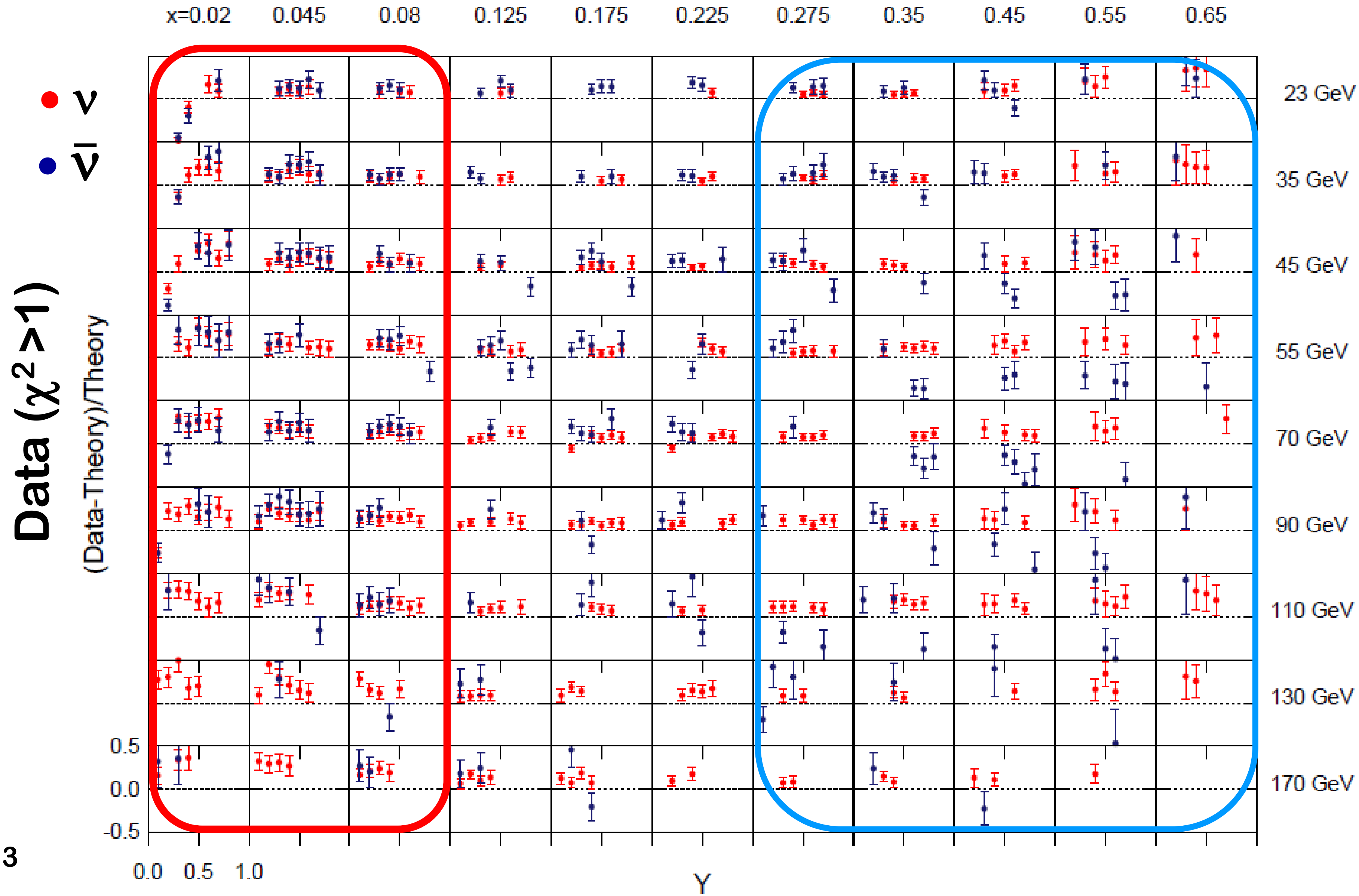
  - **DSSZ (Q_0^2=0.4 GeV^2)**

$$f_i^{N/A}(x_N) = \int_x^A \frac{dy}{y} W_i(y,A,Z)\ f_i^N\left(\frac{x_N}{y}, Q_0^2\right),\ \begin{cases} W_v(y,A,Z) = [\ a_v\,\delta(1 - \bullet_v - y) + (1 - a_v)\,\delta(1 - \ _{v'} - y)] + n_v\left(\frac{y}{A}\right)^{\alpha_v}\left(1 - \frac{y}{A}\right)^{\beta_v} + n_s\left(\frac{y}{A}\right)^{\alpha_s}\left(1 - \frac{y}{A}\right)^{\beta_s}, \\ W_{s,g}(y,A,Z) = A\delta(1-y) + \frac{a_{s,g}}{N_{s,g}}\left(\frac{y}{A}\right)^{\alpha_{s,g}}\left(1 - \frac{y}{A}\right)^{\beta_{s,g}} \end{cases}$$

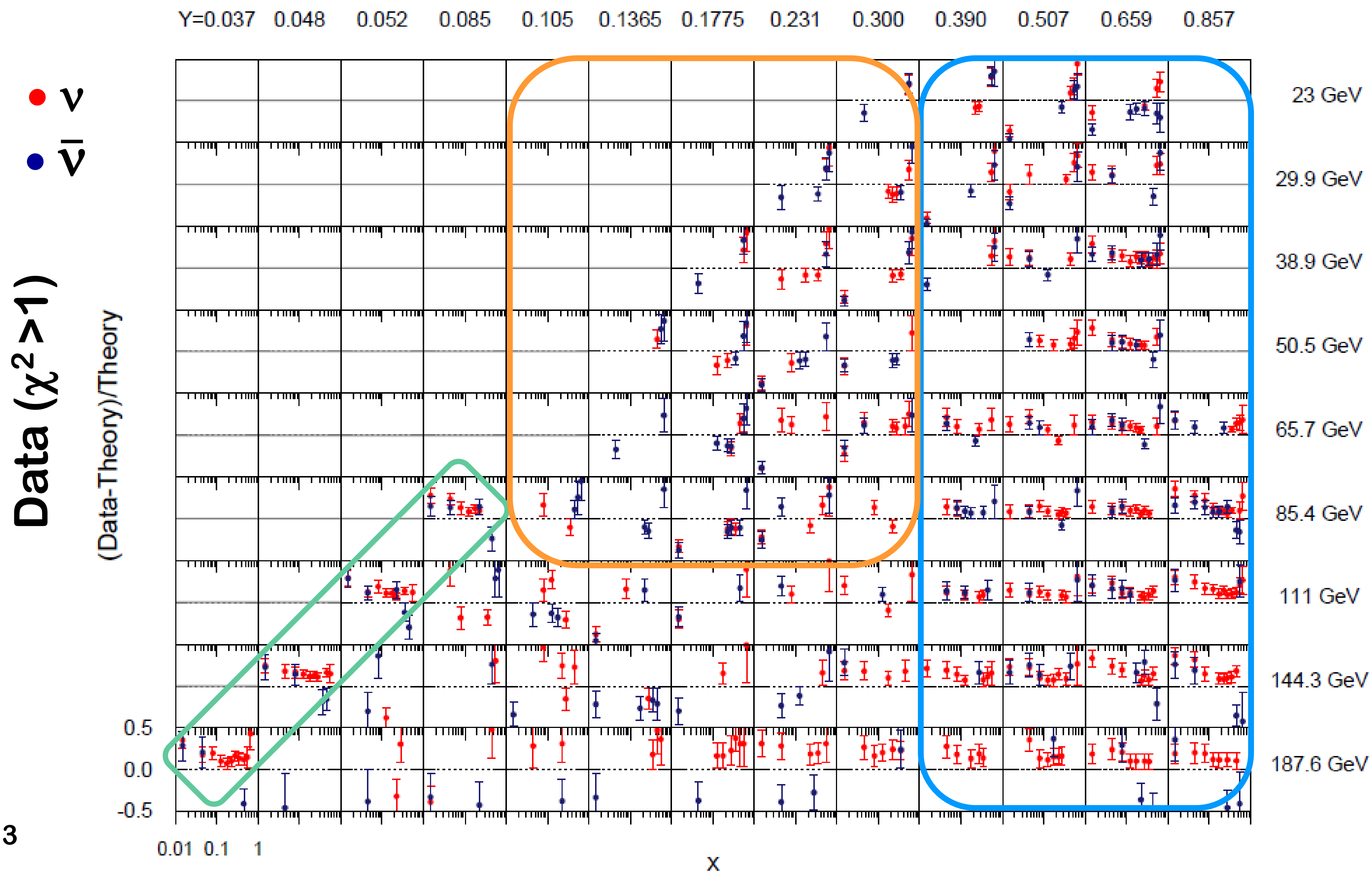
Comparison with HKN07 (NuTeV)



Comparison with HKN07 (CHORUS)

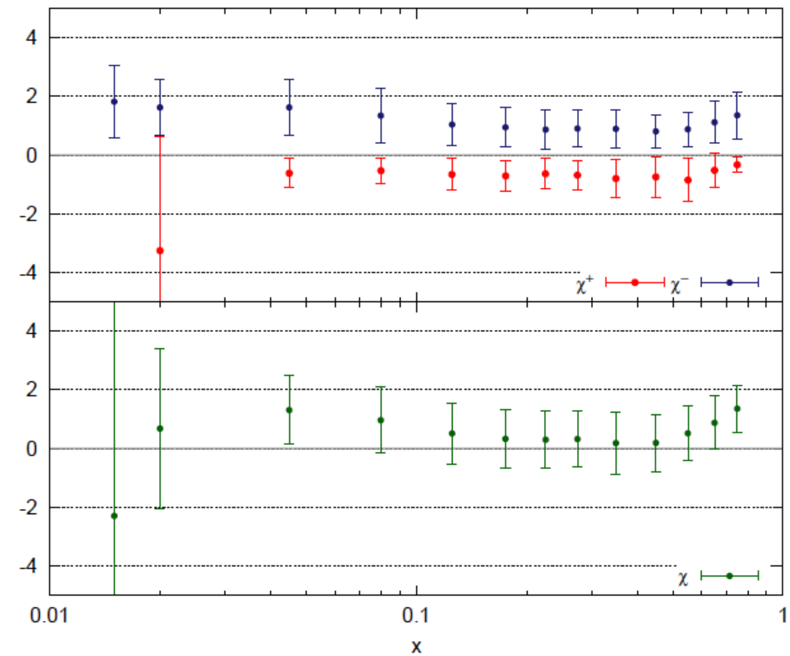


Comparison with HKN07 (CDSHW)



Significance test of the neutrino data set

- $\chi=(D-T)/\sigma_D$, not χ^2
  - T is calculated by HKN07
  - χ means difference from NC DIS & corrective direction for HKN07
    - χ_+ (>0) : upper correction
    - Error bar is standard deviation for each χ
- No significance for anti-shadowing & EMC effect
- Possibility of improving the fermi motion effect
  - Not determining well with now lepton DIS data only



	Shadowing				Anit-shadowing			EMC				Fermi M	
x^{Bj}	0.015	0.02	0.045	0.08	0.125	0.175	0.225	0.275	0.35	0.45	0.55	0.65	0.75
+	244	92	450	427	355	315	308	306	285	281	345	329	111
-	94	22	72	110	161	188	188	173	205	186	90	60	14

Summary

- Refine neutrino energy flux Φ (E_ν)
  - Event generator dependence on estimation of the flux
  - Overall understanding for wide energy region (QE, resonance & DIS)
  - Taking into account of nuclear effect is important as long as using nuclear target
- Only χ^2 analysis cannot estimate models if these are different
  - Need to check significance or consistency of the data sets
  - As another test, Bayesian estimation is effective

$$P\left(\sigma \mid D_{CC}\right) = \frac{P(D_{CC} \mid \chi^2, \sigma_{nPDF})P(\sigma_{nPDF})}{P(D_{CC})}$$

  - Is nuclear effect prove dependent ?
  - We are performing analysis with only neutrino data