Global analysis from DIS to the small-Q^2 region

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June 26, 2017

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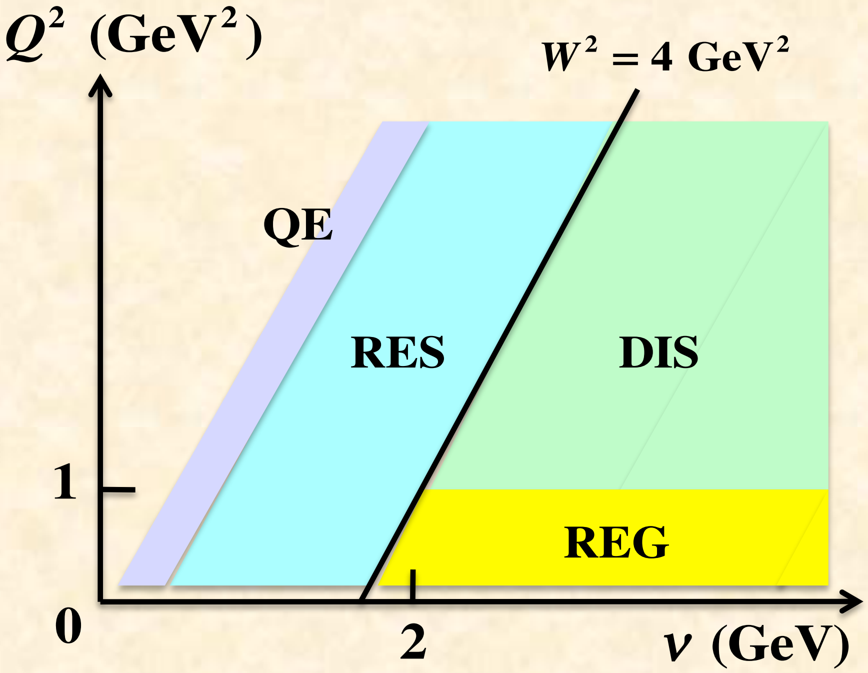
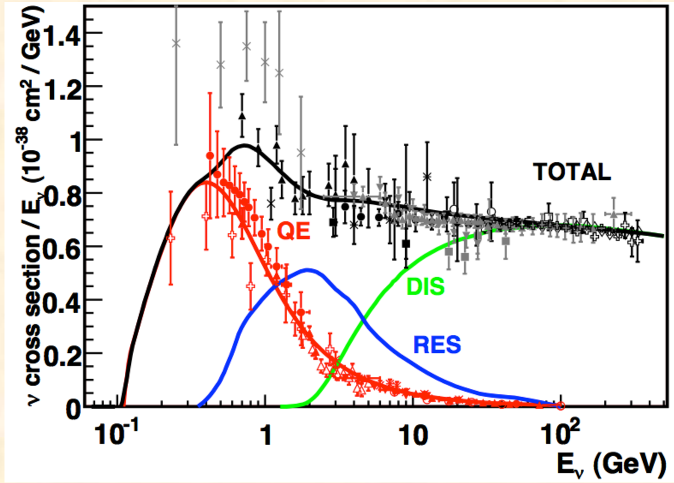
Motivation

Kinematical regions of neutrino-nucleus scattering





J.L. Hewett *et al.*, arXiv:1205.2671,
Proceedings of the 2011 workshop
on Fundamental Physics at the Intensity Frontier

Depending on the neutrino beam energy, different physics mechanisms contribute to the cross section.

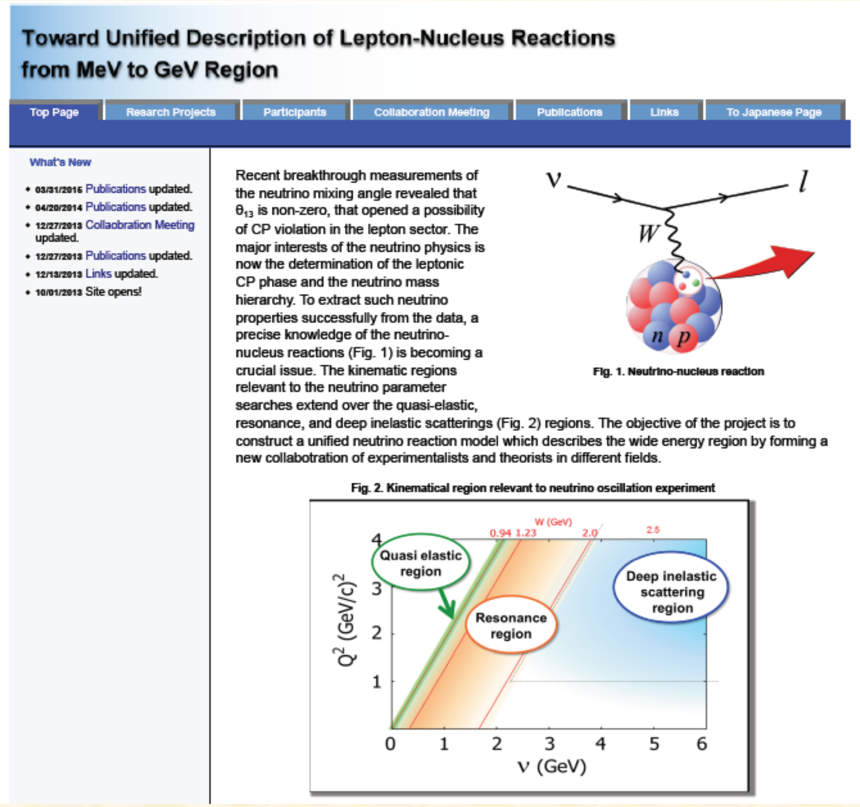
- QE (Quasi elastic)
- RES (Resonance)
- DIS (Deep inelastic scattering)
- REG (Regge)

ν flux		16%
ν flux and cross section	w/o ND measurement	21.8%
	w/ ND measurement	2.7%
ν cross section due to difference of nuclear target btw. near and far		5.0%
Final or Secondary Hadronic Interaction		3.0%
Super-K detector		4.0%
total	w/o ND measurement	23.5%
	w/ ND measurement	7.7%

ν interactions

A.K.Ichikawa@KEK workshop 2015

ν-interaction collaboration at J-PARC


Toward Unified Description of Lepton-Nucleus Reactions from MeV to GeV Region

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What's New

- 03/31/2016 Publications updated.
- 04/20/2014 Publications updated.
- 12/27/2013 Collaobration Meeting updated.
- 12/27/2013 Publications updated.
- 12/13/2013 Links updated.
- 10/01/2013 Site opens!

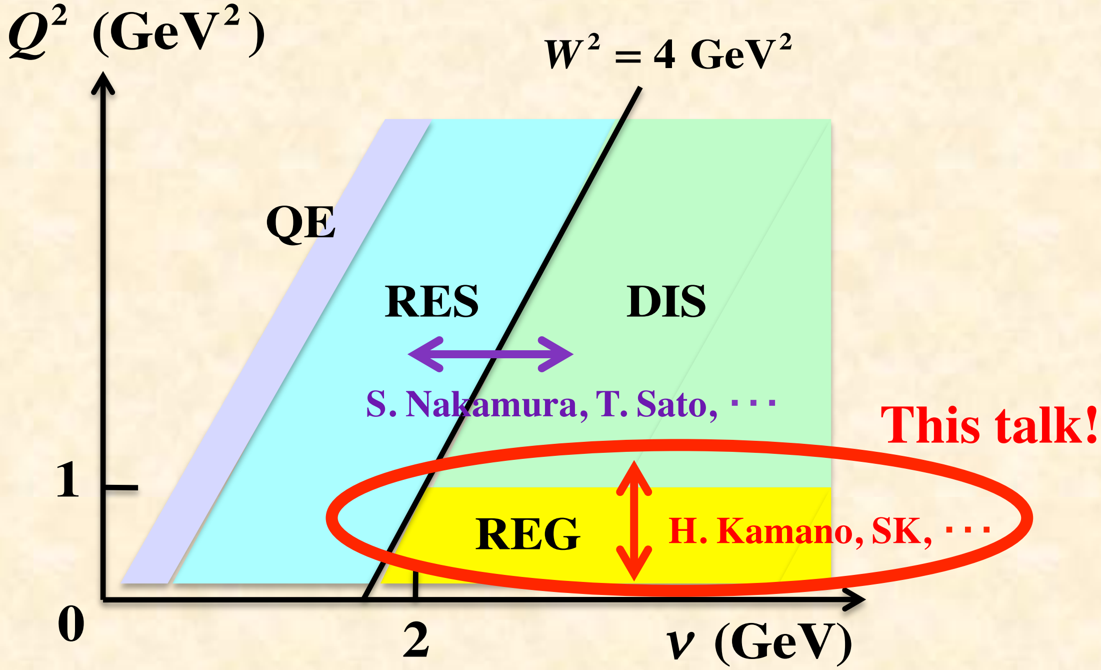
Recent breakthrough measurements of the neutrino mixing angle revealed that θ_{13} is non-zero, that opened a possibility of CP violation in the lepton sector. The major interests of the neutrino physics is now the determination of the leptonic CP phase and the neutrino mass hierarchy. To extract such neutrino properties successfully from the data, a precise knowledge of the neutrino-nucleus reactions (Fig. 1) is becoming a crucial issue. The kinematic regions relevant to the neutrino parameter searches extend over the quasi-elastic, resonance, and deep inelastic scatterings (Fig. 2) regions. The objective of the project is to construct a unified neutrino reaction model which describes the wide energy region by forming a new collabotration of experimentalists and theorists in different fields.

Fig. 1. Neutrino-nucleus reaction

Fig. 2. Kinematical region relevant to neutrino oscillation experiment

Activities at the J-PARC branch, KEK theory center
http://j-parc-th.kek.jp/html/English/e-index.html

Y. Hayato, M. Hirai, W. Horiuchi, H. Kamano, S. Kumano, T. Murata, S. Nakamura, K. Saito, M. Sakuda, T. Sato
http://nuint.kek.jp/index_e.html

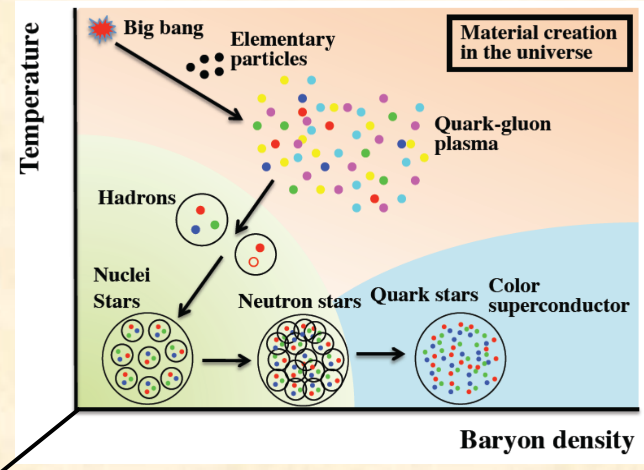


For the details, see

Towards a unified model of neutrino-nucleus reactions for neutrino oscillation experiments, S. X. Nakamura, H. Kamano, Y. Hayato, M. Hirai, W. Horiuchi, S. Kumano, T. Murata, K. Saito, M. Sakuda, T. Sato, and Y. Suzuki, Rep. Prog. Phys. 80 (2017) 056301.

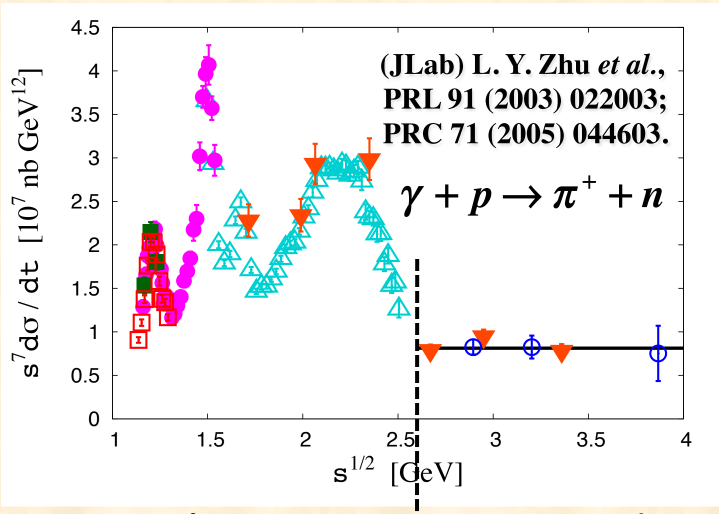
General motivation

Ultimate purpose of Theoretical nuclear physics
= Describe hadronic many-body systems
in the whole phase diagram
from low to high energies.



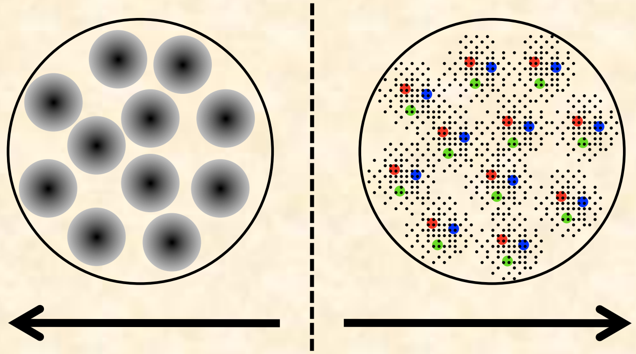
Q^2

Transition from hadron to quark-gluon d.o.f.:
H. Kawamura, S. Kumano, T. Sekihara,
Phys. Rev. D 88 (2013) 034010.



Low energies:
Hadron degrees of freedom (Resonances)

High energies:
Quark-gluon degrees of freedom (Perturbative QCD: Constituent-counting rule)



Low energies:
Hadron degrees of freedom

High energies:
Quark-gluon degrees of freedom

Nuclei should be described by quark and gluon degrees of freedom at high energies.

Structure functions of nucleon and nuclei

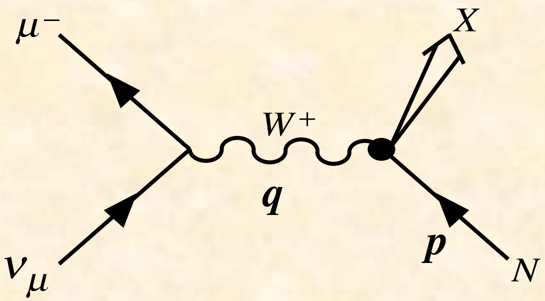
Deep inelastic scattering (DIS)

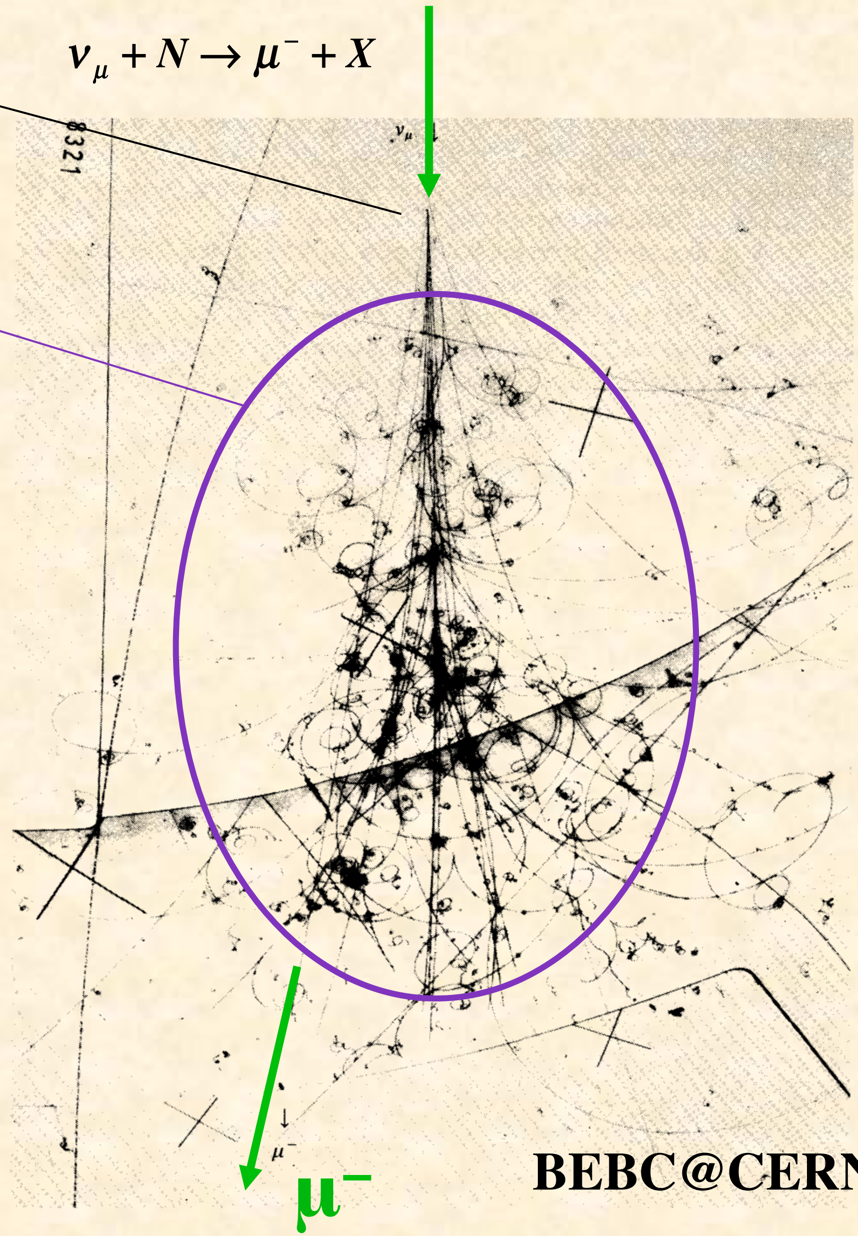
ν_μ ~ 200 GeV

$\nu_\mu + N \rightarrow \mu^- + X$

A nucleon is broken up by a high-energy neutrino.

Hadrons are produced; however, these are not usually measured. (inclusive reaction)





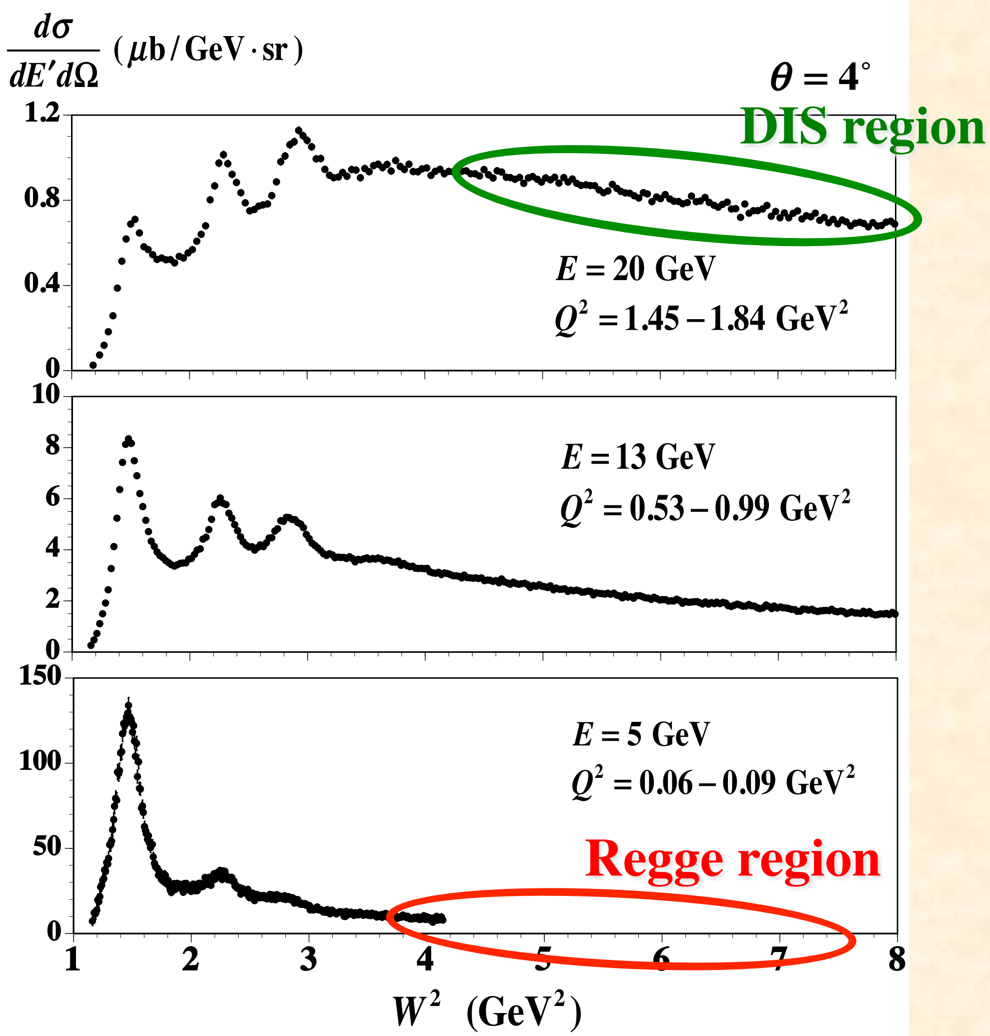
Momentum transfer: $q^2 = (k - k')^2 = -Q^2$

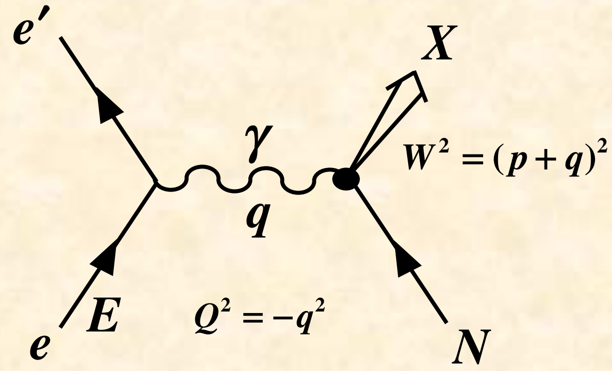
Bjorken scaling variable: $x = \dfrac{Q^2}{2p \cdot q}$

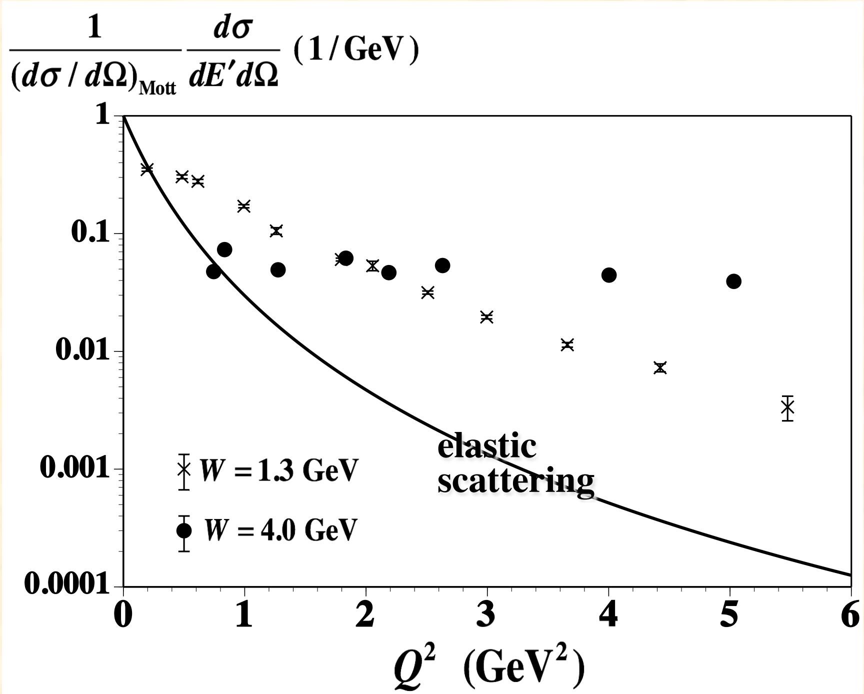
Invariant mass: $W^2 = p_X^2 = (p + q)^2$

BEBC@CERN

Lepton scattering

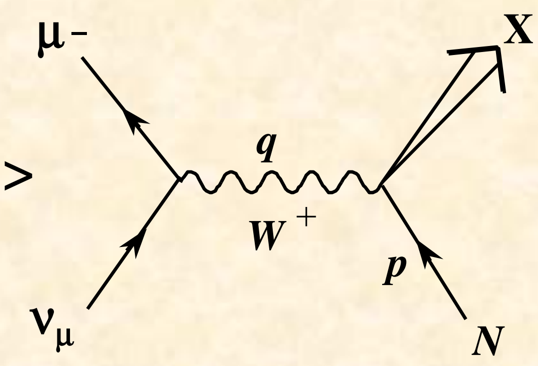






Neutrino deep inelastic scattering (CC: Charged Current)

$$d\sigma = \frac{1}{4k\cdot p}\,\frac{1}{2}\sum_{spins}\sum_{X}(2\pi)^4\,\delta^4(k+p-k'-p_X)\,|M|^2\,\frac{d^3k'}{(2\pi)^3\,2E'}$$



$$M = \frac{1}{1+Q^2/M_W^2}\,\frac{G_F}{\sqrt{2}}\,\bar{u}(k',\lambda')\,\gamma^\mu\,(1-\gamma_5)\,u(k,\lambda)\,<X|J_\mu^{CC}|p,\lambda_p>$$

$$\frac{d\sigma}{dE'd\Omega} = \frac{G_F^2}{(1+Q^2/M_W^2)^2}\,\frac{k'}{32\pi^2 E}\,L^{\mu\nu}\,W_{\mu\nu}$$

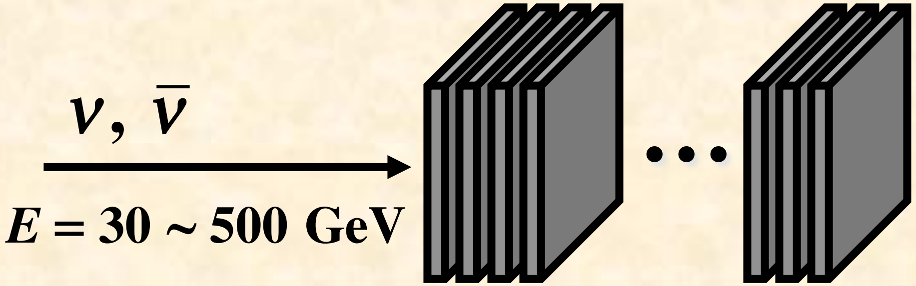
$$L^{\mu\nu} = 8\left[k^\mu k'^\nu + k'^\mu k^\nu - k\cdot k' g^{\mu\nu} + i\varepsilon^{\mu\nu\rho\sigma}k_\rho k'_\sigma\right], \quad \varepsilon_{0123} = +1$$

$$W_{\mu\nu} = -W_1\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) + W_2\frac{1}{M^2}\left(p_\mu - \frac{p\cdot q}{q^2}q_\mu\right)\left(p_\nu - \frac{p\cdot q}{q^2}q_\nu\right) + \frac{i}{2M^2}W_3\varepsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma$$

$$MW_1 = F_1\,,\quad \nu W_2 = F_2\,,\quad \nu W_3 = F_3\,,\quad x = \frac{Q^2}{2p\cdot q}\,,\quad y = \frac{p\cdot q}{p\cdot k}$$

$$\frac{d\sigma_{\nu,\bar{\nu}}^{CC}}{dx\,dy} = \frac{G_F^2\,(s-M^2)}{2\pi\,(1+Q^2/M_W^2)^2}\left[x\,y^2 F_1^{CC} + \left(1-y-\frac{M\,x\,y}{2E}\right)F_2^{CC} \pm x\,y\left(1-\frac{y}{2}\right)F_3^{CC}\right]$$

Neutrino DIS experiments

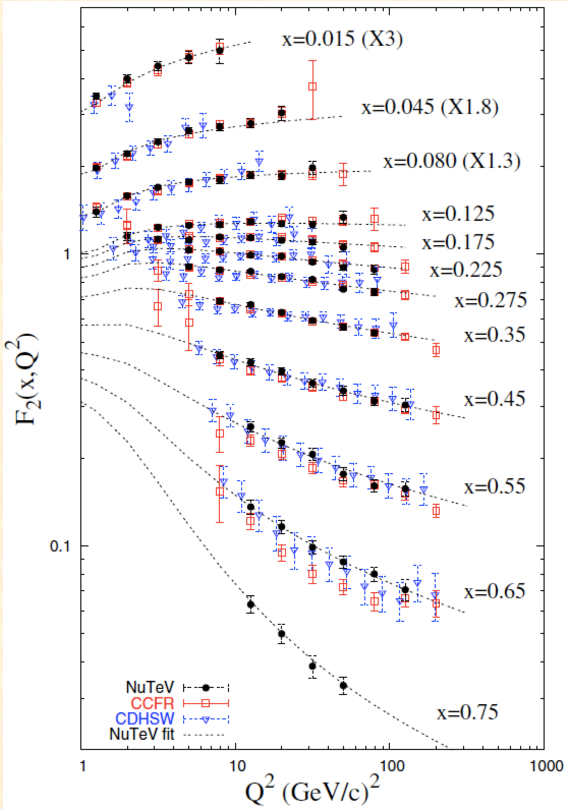


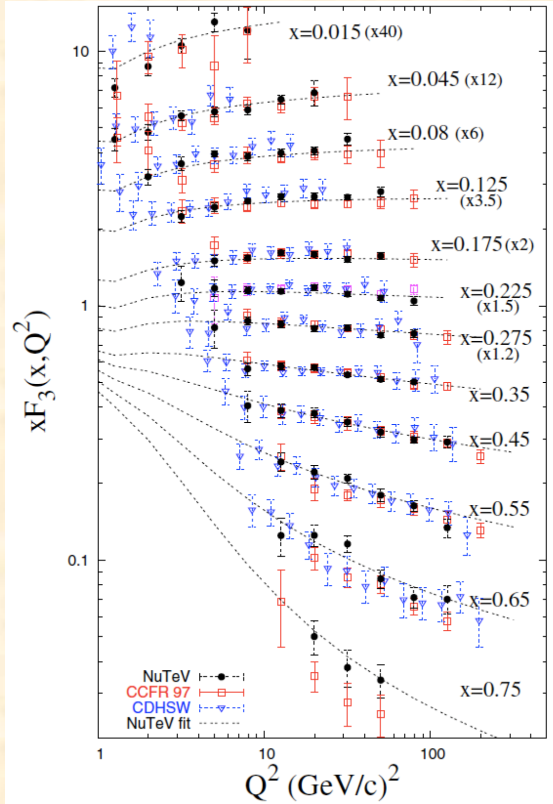
Huge Fe target (690 ton)

Experiment	Target	ν energy (GeV)
CCFR	Fe	30-360
CDHSW	Fe	20-212
CHORUS	Pb	10-200
NuTeV	Fe	30-500

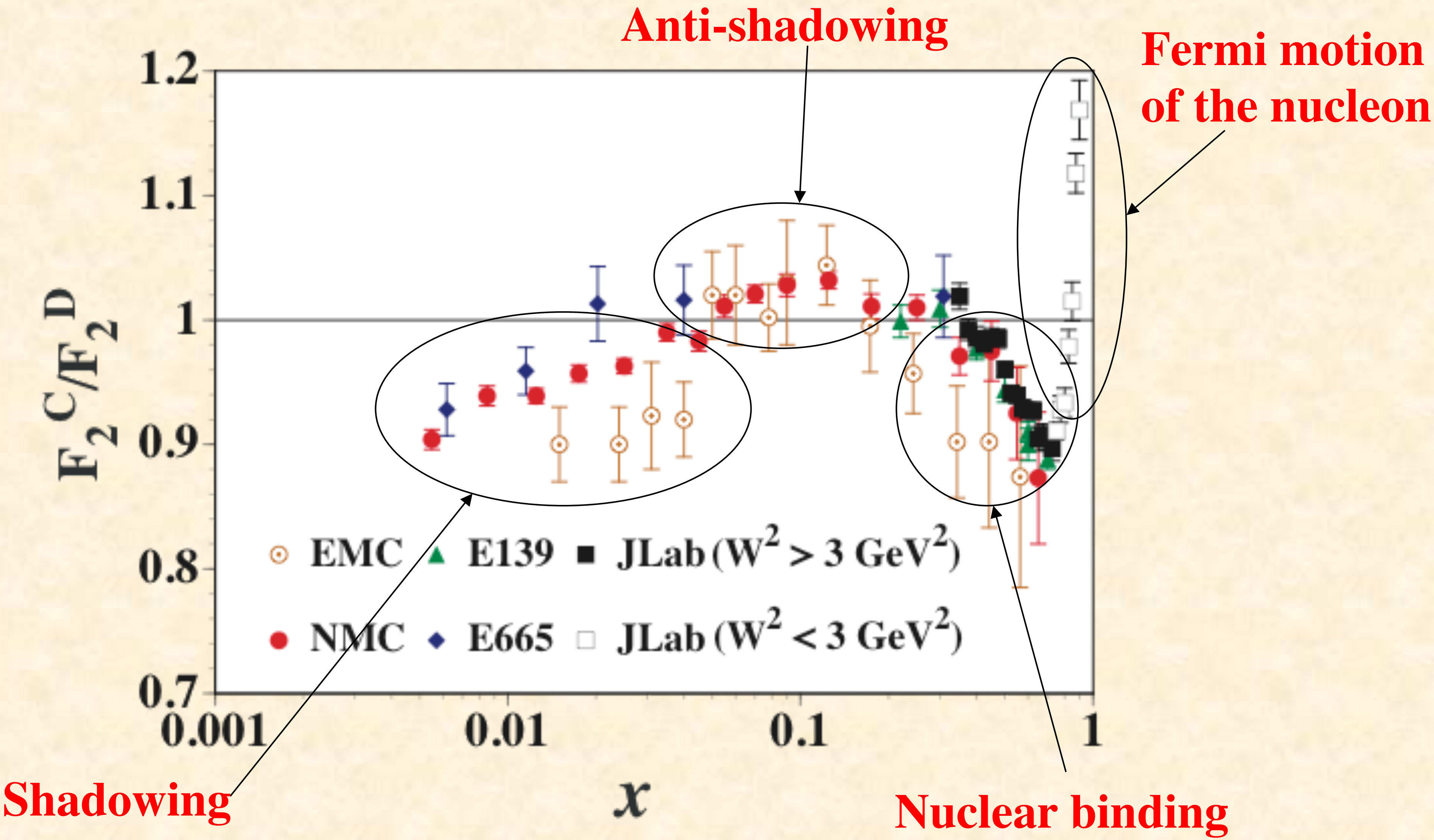
MINERνA (He, C, Fe, Pb), …

M. Tzanov *et al.* (NuTeV), PRD74 (2006) 012008.





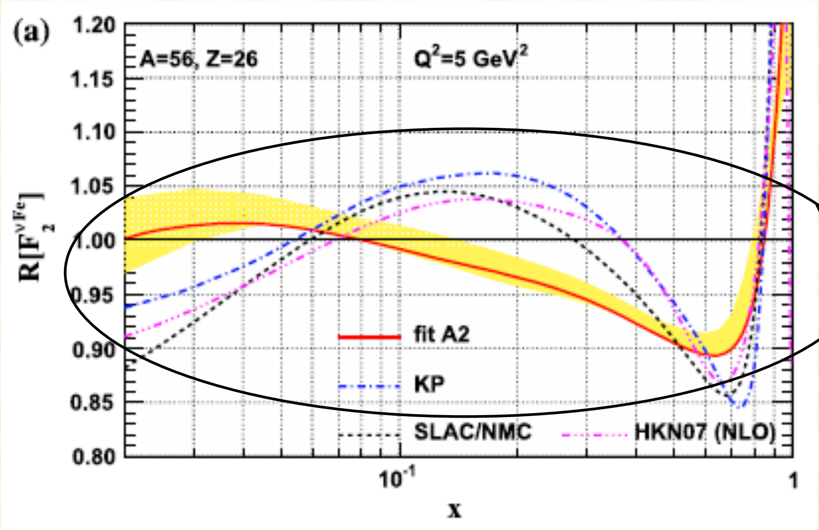
Nuclear modifications of structure function F_2



D. F. Geesaman, K. Saito, A. W. Thomas,
Ann. Rev. Nucl. Part. Sci. 45 (1995) 337

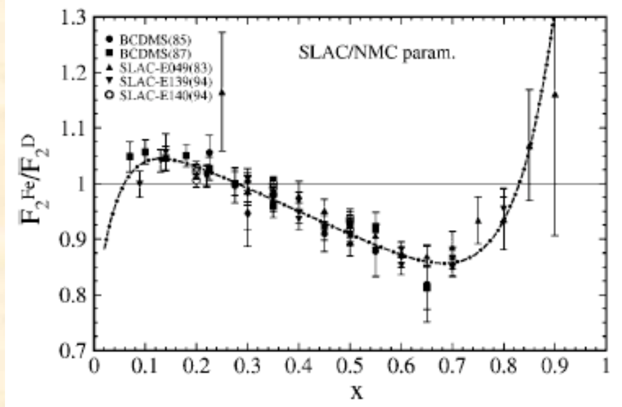
Analysis of CTEQ-2008 (Schienbein *et al.*)

I. Schienbein *et al.*,
PRD 77 (2008) 054013

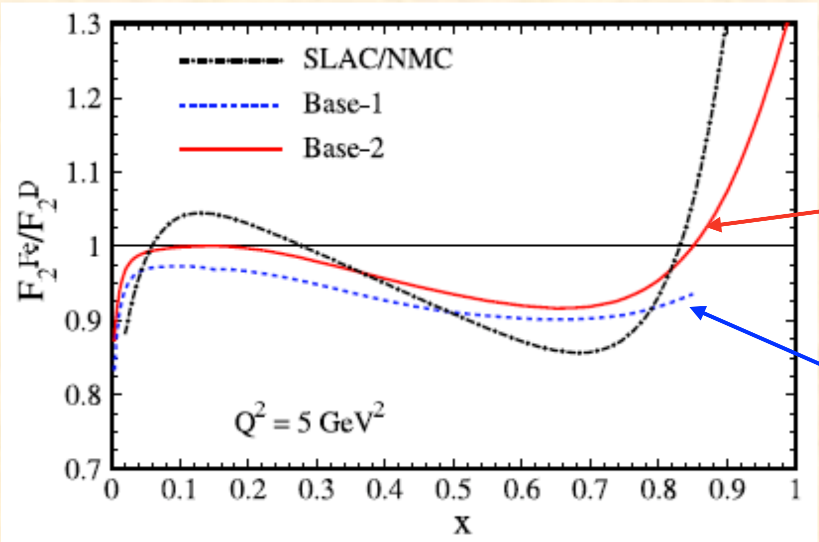


Differences
from typical NPDFs.

Charged-lepton scattering



Neutrino scattering



Base-1 • remove CCFR data
• incorporate deuteron corrections

Base-2 corresponds to CTEQ6.1M with s≠sbar
• include CCFR data

Charged-lepton correction factors are applied.
• s≠sbar

Base-2: Using current nucleonic PDFs, they (and MRST) obtained very different corrections from charged-lepton data.

Base-1: However, it depends on the analysis method for determining "nucleonic" PDFs.

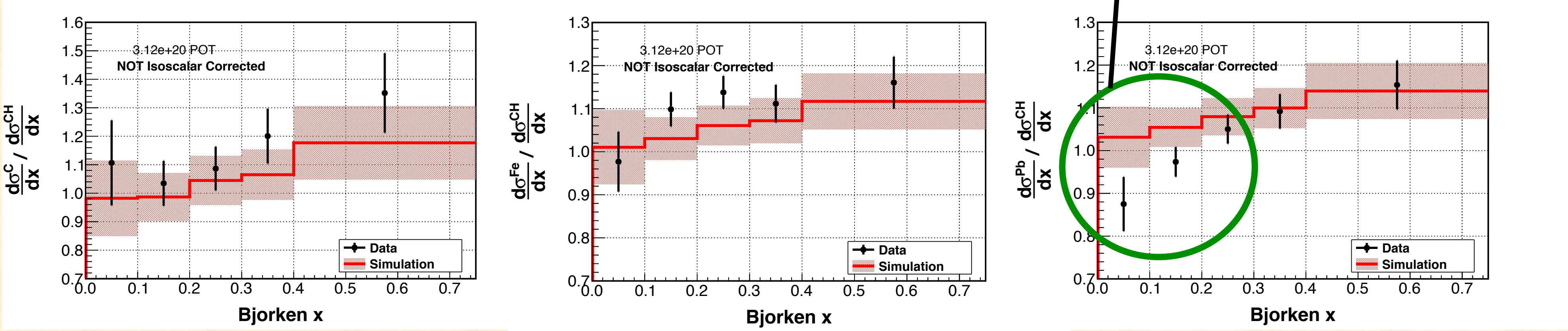
Recent progress on neutrino DIS ⇔ Charged DIS

Measurements by Minerνa

B. G. Tice *et al.*, PRL 112 (2014) 231801;
J. Mousseau *et al.*, PRD 93 (2016) 071101(R).

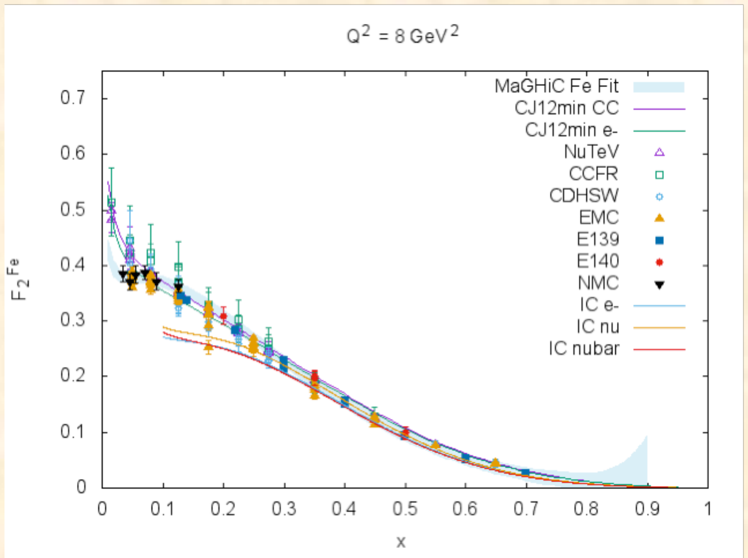
Different shadowing from charged-lepton case?!

C/CH **Fe/CH** **Pb/CH**



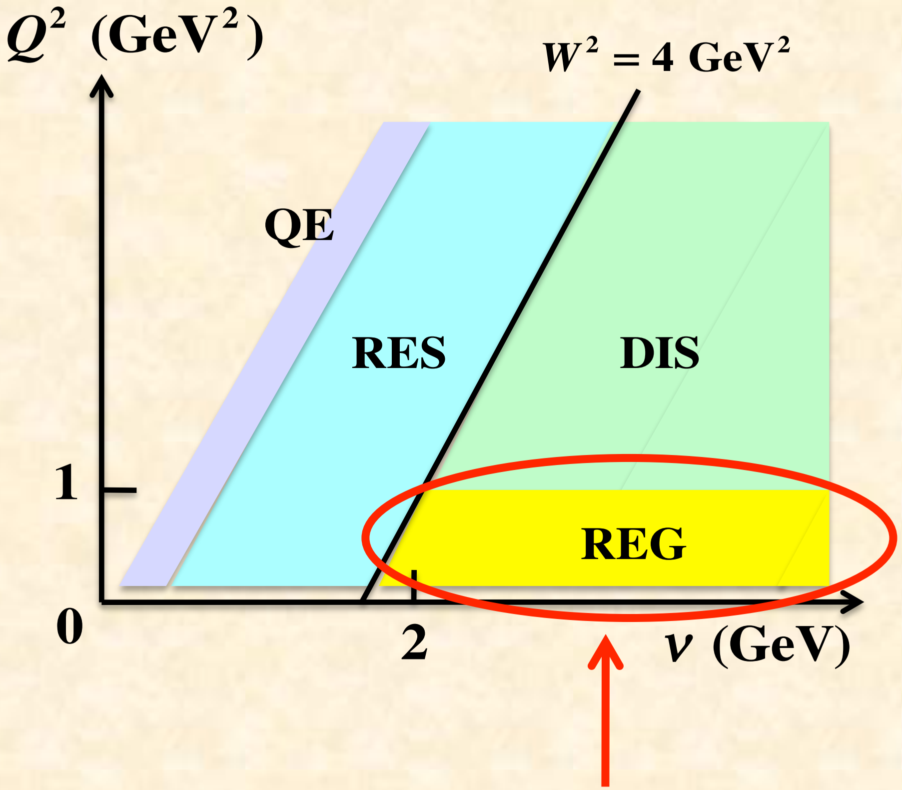
N. Kalantarians, E. Christy, and C. Keppel, arXiv:1706.02002

According to this analysis, both structure functions are same except for the small-x region (x<0.05) .



Small Q^2 region

$Q^2 \to 0$ region: Theoretical background



$$F_{T,L} = \frac{\gamma}{\pi} Q^2 \sigma_{T,L}, \quad \gamma = \frac{|\vec{q}\,|}{q_0} = \sqrt{1 + \frac{Q^2}{\nu^2}}$$

$\sigma_{T,L}$ = Total ν cross section

$$\sim \sum_f (2\pi)^4 \delta(p + q - p_f) \left| \langle f | \varepsilon_{T,L} \cdot J(0) | p \rangle \right|^2$$

$F_{T,L}$ = transverse, longitudinal cross section

Vector current conservation: $q_\mu W^{\mu\nu} = 0$

$\Rightarrow F_L^V \sim Q^2 F_T^V$ as $Q^2 \to 0$

PCAC (Partially Conserved Axial-vector Current):

$\partial_\mu A^\mu(x) = f_\pi m_\pi^2 \pi(x)$, A^μ = Axial-vector current,

f_π = Pion-decay constant, π = Pion field

$\Rightarrow F_L^A \sim \dfrac{f_\pi^2}{\pi} \sigma_\pi$ as $Q^2 \to 0$,

Pion-scattering cross section: σ_π

References:
A. Donnachie and P. V. Landshoff, Z. Phys. C 61 (1994) 139
B. Z. Kopeliovich, Nucl. Phys. B 139 (2005) 219;
S. A. Kulagin and R. Petti, Phys. Rev. D 76 (2007) 094023.

$Q^2 \to 0$ region: Practical descriptions in ν reactions

$F_{1,2,3}^{\nu A}(x,Q^2 \to 0)$

(1) FLUKA, G. Battistoni *et al.*,
Acta Phys. Pol. B 40 (2009) 2431

$$F_{2,3}(x,Q^2) = \frac{2Q^2}{Q_0^2 + Q^2} F_{2,3}(x,Q_0^2)$$

(2) A. Bodek and U.-K. Yang, arXiv:1011.6592

charged-lepton:

$$F_2^{e/\mu}(x,Q^2 < 0.8\ \text{GeV}^2) = K_{valence}^{vector}(Q^2) F_{2,LO}^{valance}(\xi_w, Q^2 = 0.8\ \text{GeV}^2) + K_{sea}^{vector}(Q^2) F_{2,LO}^{sea}(\xi_w, Q^2 = 0.8\ \text{GeV}^2)$$

$$K_{valence}^{vector}(Q^2) = \frac{Q^2}{Q^2 + C_s}, \quad K_{sea}^{vector}(Q^2) = \left[1 - G_D^2(Q^2)\right] \frac{Q^2 + C_{v2}}{Q^2 + C_{v1}}$$

$$G_D(Q^2) = \frac{1}{(1 + Q^2/0.71)^2}, \quad \xi_w = \frac{2x(Q^2 + M_f^2 + B)}{Q^2\left[1 + \sqrt{1 + 4M^2x^2/Q^2}\right] + 2Ax}$$

neutrino:

Separate $F_i^\nu(x,Q^2)$ into vector and axial-vector parts.

$F_i^\nu(x,Q^2)_{\text{vector}} \to Q^2 \to 0 \quad (Q^2 \to 0)$ as the charged-lepton case.

$F_i^\nu(x,Q^2)_{\text{axial-vector}} \neq 0 \quad (Q^2 \to 0)$ due to PCAC.

Actual expressions are slightly complicated (see the original paper).

Summary on duality:
W. Melnitchouk, R. Ent, C. E. Keppel,
Phys. Rept. 406 (2005) 127.

Introduction to the Regge theory

Scattering amplitude for $a+b \to c+d$ expanded by t-channel partial wave amplitudes $a_l(t)$

$$A_{ab\to cd}(s,t) = \sum_{l=0}^{\infty}(2l+1)\,a_l(t)P_l(1+2s/t), \quad \cos\theta_t = 1+2s/t, \ P_l: \text{Legendre polynomials}$$

If it is dominated by a single resonace with mass m_J and spin J [note $P_l(z) \sim z^l$]

$$A_{ab\to cd}(s,t) \sim \frac{1}{t-m_J^2}\left(\frac{2s}{t}\right)^J$$

Let us assme that the angular momentum l is mathematically a complex variable.

Then, it is expressed by a complex integral s

$$A_{ab\to cd}(s,t) = \frac{1}{2i}\oint_C dl\,(2l+1)\frac{a(l,t)}{\sin(\pi l)}P(l,1+2s/t).$$

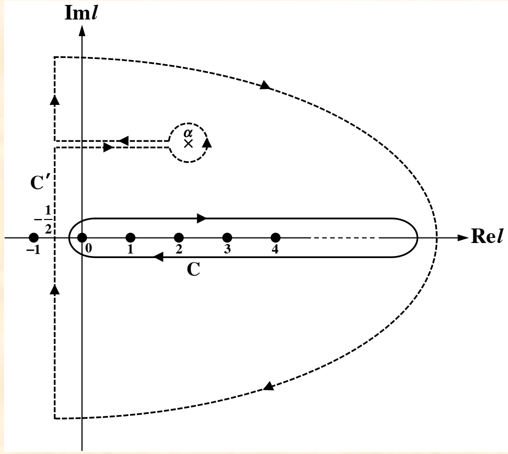
If there were one pole at $l=\alpha$ with $a(l,t)=\dfrac{\tilde\beta(t)}{1-\alpha(t)}$, we have

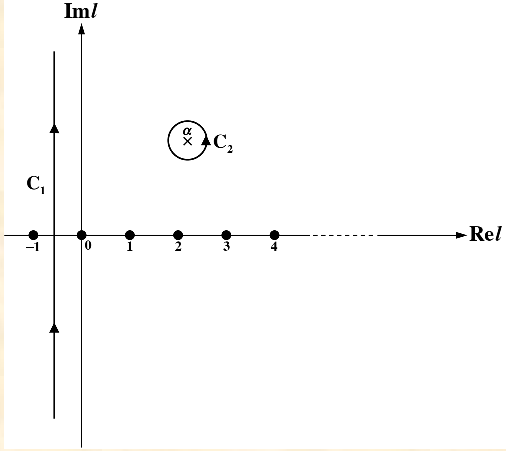
$$A_{ab\to cd}(s,t) = \{2\alpha(t)+1\}\frac{\pi\tilde\beta(t)}{\sin\{\pi\alpha(t)\}}P(\alpha(t),1+2s/t).$$

In the high-energy limit $s \gg |t|$, $P(l,z)\sim z^l$ and the amplitude becomes

$$A_{ab\to cd}(s,t) \sim \beta(t)\left(\frac{s}{s_0}\right)^{\alpha(t)} \Leftrightarrow A_{ab\to cd}(s,t) \sim \frac{1}{t-m_J^2}\left(\frac{2s}{t}\right)^J.$$

The scattering amplitude is expressed by the pole, which is called the Regge pole.





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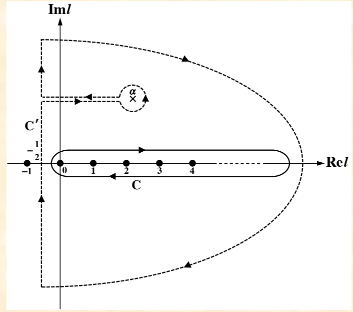
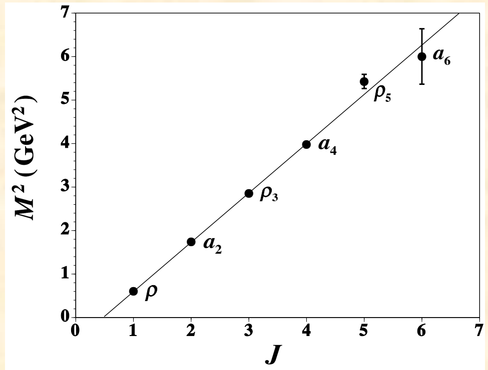


The scattering amplitude is expressed by the pole, which is called the Regge pole, with the mass $t = m_J^2$ and $J = \alpha(t = m_J^2)$.



Experimental data indicate

$$\alpha(t) = \alpha(0) + \alpha' t.$$

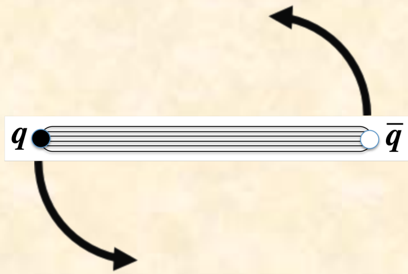
The total cross section is expressed by the forward elestic scattering (optical theorem),

$$\sigma_{tot} \propto s^{\alpha(0)-1}.$$

For the ρ-a_2 (ω-f_2) trajectory with $I = 1$ ($I = 0$), C = odd, and natural parity [$J = (-1)^J$],

$$\alpha(0) = 0.55.$$

Other tranjectories have smaller $\alpha(0)$.



Experimental measuremenets of pp and $p\bar{p}$ did not agree with

$$\sigma_{tot} \propto s^{0.55-1}.$$

$\Rightarrow$ We need to introduce the Pomeron ($I = 0, C$ = even: vacuum quantum number) with $\alpha(0) - 1 \simeq 0$:

$$\alpha_{tot} = C_P s^{\alpha_P(0)-1} + C_R s^{\alpha_R(0)-1}.$$

$\Rightarrow$ $F_2 \sim C_P x^{1-\alpha_P(0)} + C_R x^{1-\alpha_R(0)}$

$\Rightarrow$ Typical functional form: $F_2 = c_P x^{a_P}(1-x)^{b_P} + c_R x^{a_R}(1-x)^{b_R}$

$H = p + \sigma r^n = J/r + \sigma r^n$, $\quad J = pr$

$\frac{dH}{dr} = -\frac{J}{r^2} + n\sigma r^{n-1} = 0 \quad \Rightarrow J = n\sigma r^{n+1}$

$M = n\sigma r^n + \sigma r^n = (n+1)\sigma r^n = (n+1)\sigma\left(\frac{J}{n\sigma}\right)^{n/(n+1)}$

$M^2(n=1) = 4\sigma J$, consistent with linear confining potential

Our analysis method

- There are accurate structure-function (or PDF) code in the DIS region for both nucleon and nuclei: $F_2(x,Q^2)$ at $Q^2 \ge Q_0^2 = 1 \sim 2$ GeV^2, $W^2 \ge W_0^2 \sim 4$ GeV^2.

- We use a DIS code and extrapolate it to the Regge region. So far, our analysis is on charged-lepton F_2.

$$F_2(x,Q^2) = w(x,Q^2;x_0,Q_0^2)F_2(x_0,Q_0^2), \quad w(x,Q^2;x_0,Q_0^2) = \frac{F_2^{\rm REG}(x,Q^2)}{F_2^{\rm REG}(x_0,Q_0^2)}$$

$F_2^{\rm REG}(x,Q^2)$ = structure function valid in the Regge region.

- We parametrize $F_2^{\rm REG}(x,Q^2)$ based on the Regge + Pomeron picture.

  References for the nucleon:

  A. Donnachie and P. V. Landshoff, ZP C61 (1994) 139; PLB 518 (2001) 63;
  H. Abramowicz, E. Levin, A. Levy, U. Maor (ALLM), PLB 269 (1991) 465; hep-ph/9712415;
  I. Abt, A. M. Cooper-Sarkar, B. Foster, V. Myronenko, K. Wichmann, M. Wing, PRD 94, 034032 (2016).

$$F_2^{\rm REG}(x,Q^2) = \frac{Q^2}{m_0^2+Q^2}\left[F_2^P(x,Q^2)+F_2^R(x,Q^2)\right], \quad F_2^V(x,Q^2) = c_V x_V^{a_V(t)}(1-x)^{b_V(t)}, \quad V = P, R$$

$$t = \ln\left[\frac{\ln\{(Q^2+\mu_0^2)/\Lambda^2\}}{\ln(\mu_0^2/\Lambda^2)}\right], \qquad \frac{1}{x_V} = 1 + \frac{W^2 - M_N^2}{Q^2+m_V^2}$$

ALLM: $d = d_1 + d_2 \dfrac{1}{1+t^{d_3}}$ $(d = a_P,\, c_P)$, $\quad e = e_1 + e_2 t^{e_3}$ $(d = b_P,\, a_R,\, b_R,\, c_R)$

Introduce m_0^2 so as to have $F_2^{\rm REG}(x,Q^2) \sim Q^2$ at $Q^2 \to 0$.

Note $x = \dfrac{Q^2}{2M_N\nu} \to 0$ as $Q^2 \to 0$, whereas there is $x_{\min}$ in practical structure-function (PDF) codes.

$F_2^{\rm DIS}(x \to 0, Q^2 \to 0)$ cannot be calculated.

$\Rightarrow$ We may modify $x \to x_V$.

$$F_2(x,Q^2) = w(x,Q^2;x_0,Q_0^2)F_2(x_0,Q_0^2), \quad w(x,Q^2;x_0,Q_0^2) = \frac{F_2^{\mathrm{REG}}(x,Q^2)}{F_2^{\mathrm{REG}}(x_0,Q_0^2)}$$

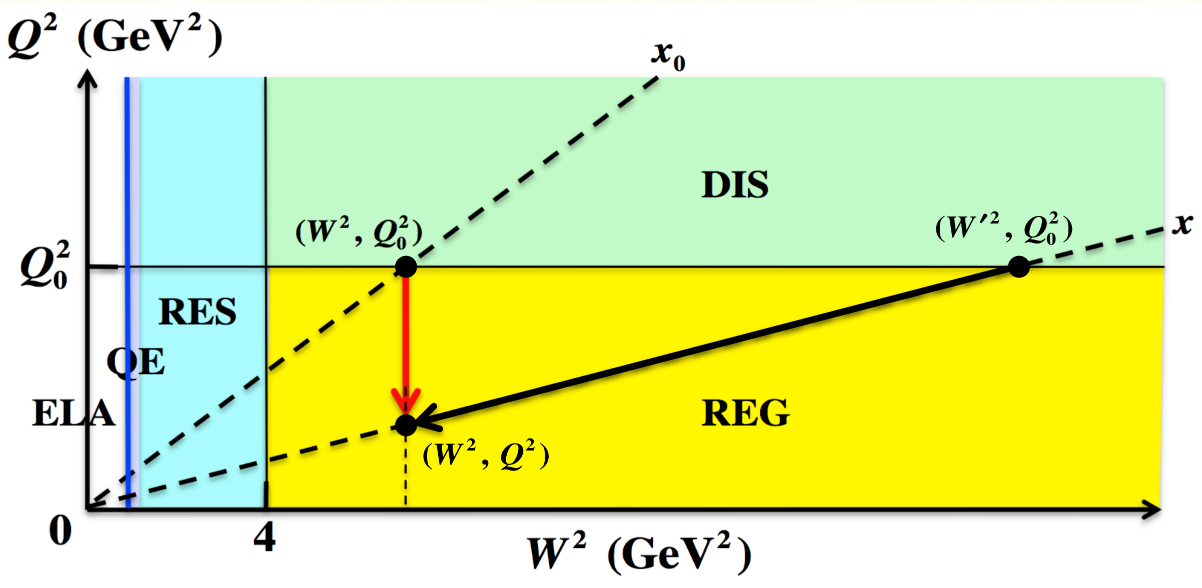
$$F_2^{\mathrm{REG}}(x,Q^2) = \frac{Q^2}{m_0^2+Q^2}\left[F_2^P(x,Q^2)+F_2^R(x,Q^2)\right], \quad F_2^V(x,Q^2) = c_V x_V^{a_V(t)}(1-x)^{b_V(t)}, \; V=P,R$$

If we use $F_2(x,Q^2) = w(Q^2;Q_0^2)F_2(x,Q_0^2)$, the exprapolation path is long and there is a limit $x_{\min}$.

The extrapolation function w depends on x according to exerimental measurements.

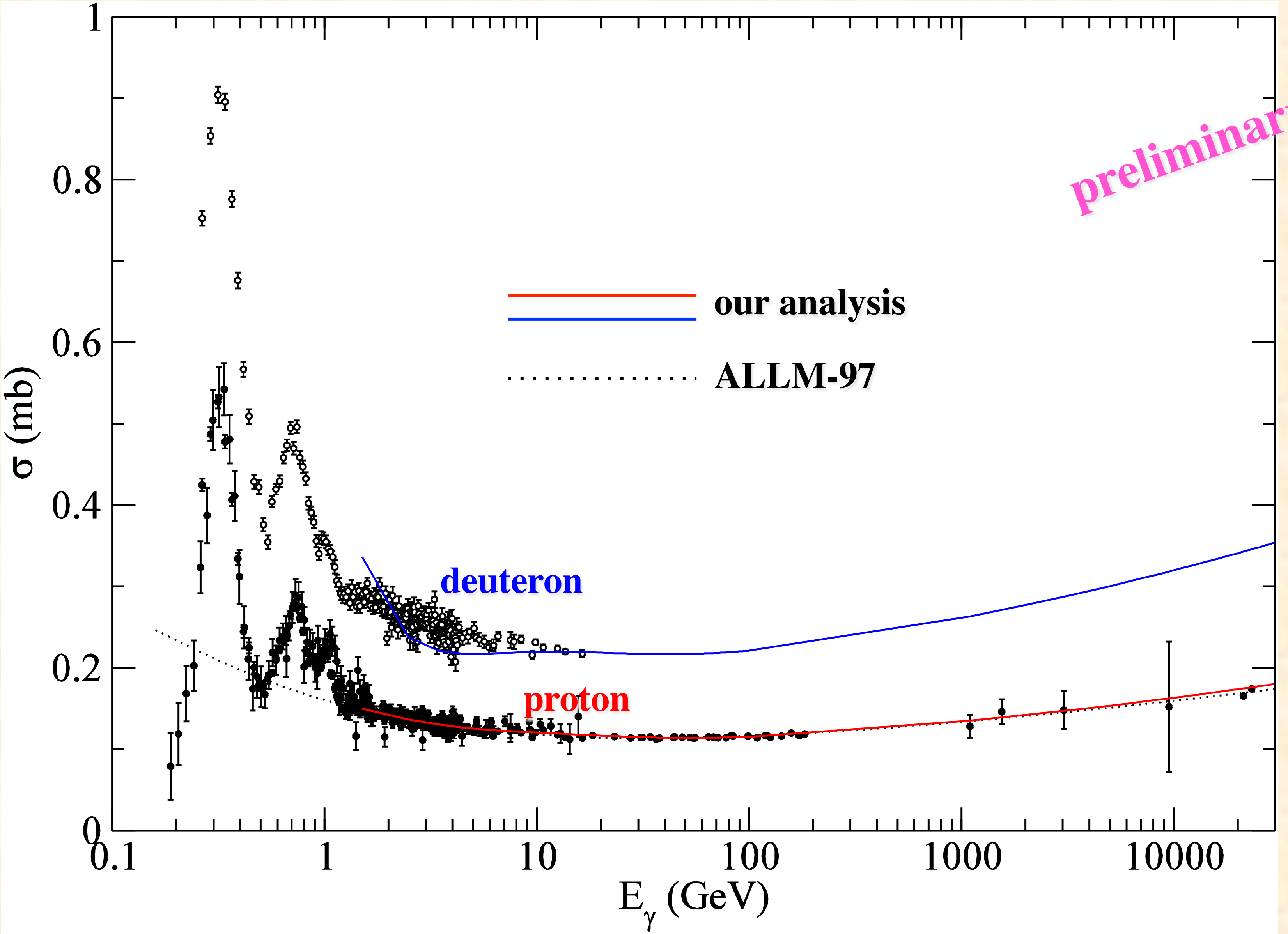
$$W^2 = (p+q)^2 = M_N^2 - Q^2 + 2p\cdot q = M_N^2 - Q^2 + \frac{Q^2}{x}$$

$$\Rightarrow \frac{1}{x} = 1 + \frac{W^2 - M_N^2}{Q^2} \qquad \Rightarrow \frac{1}{x_0} \equiv 1 + \frac{W^2 - M_N^2}{Q_0^2}$$



Experiment / Publication	Year
SLAC	1992
Fermilab-E665	1996
NMC	1997
H1-ZEUS	2010
HERMES	2011
JLab-C	2015
PDG2016-γp	2016

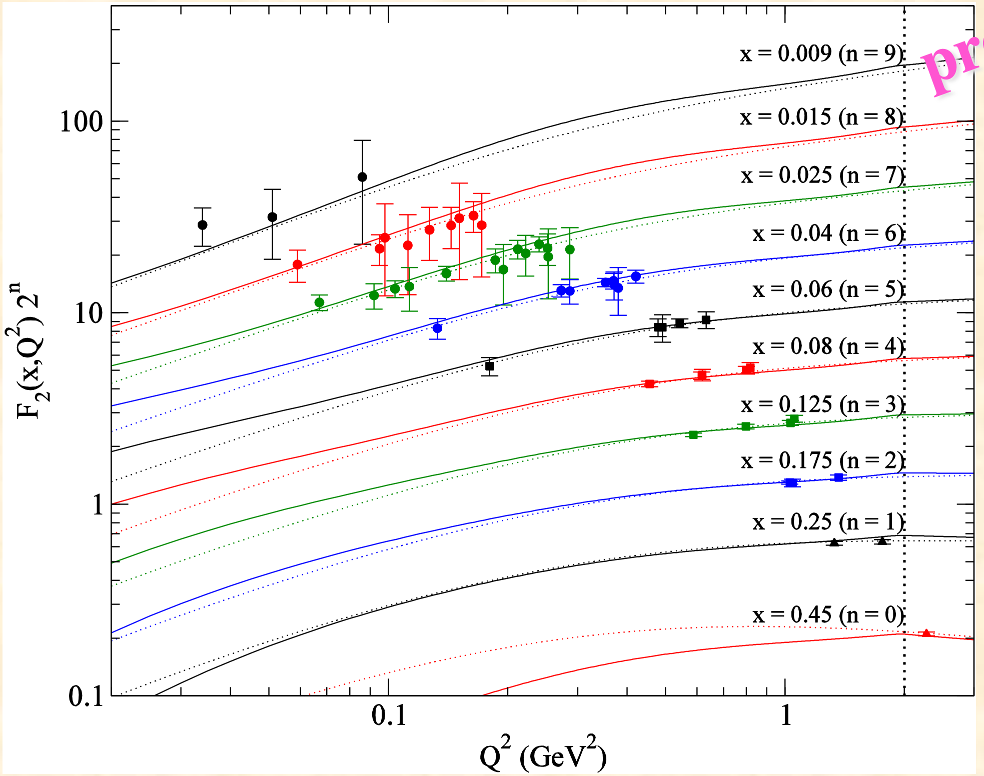
Photoproduction ($\gamma + p,d \to X$) cross sections



Comparison with JLab/SLAC data

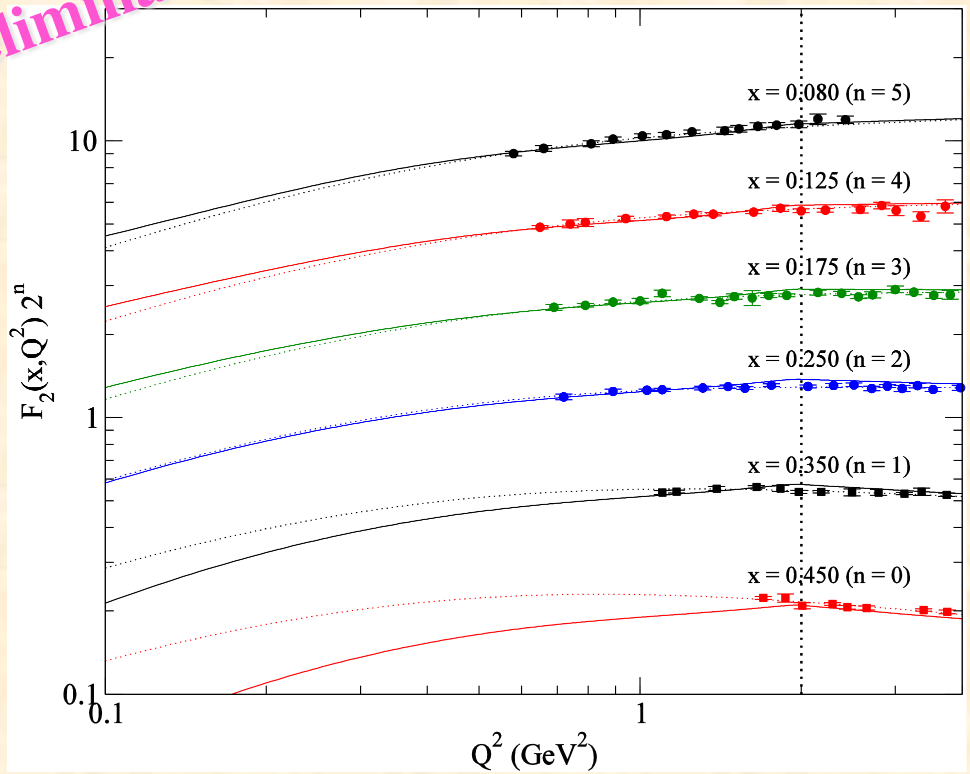
our analysis
ALLM-97

JLab



preliminary

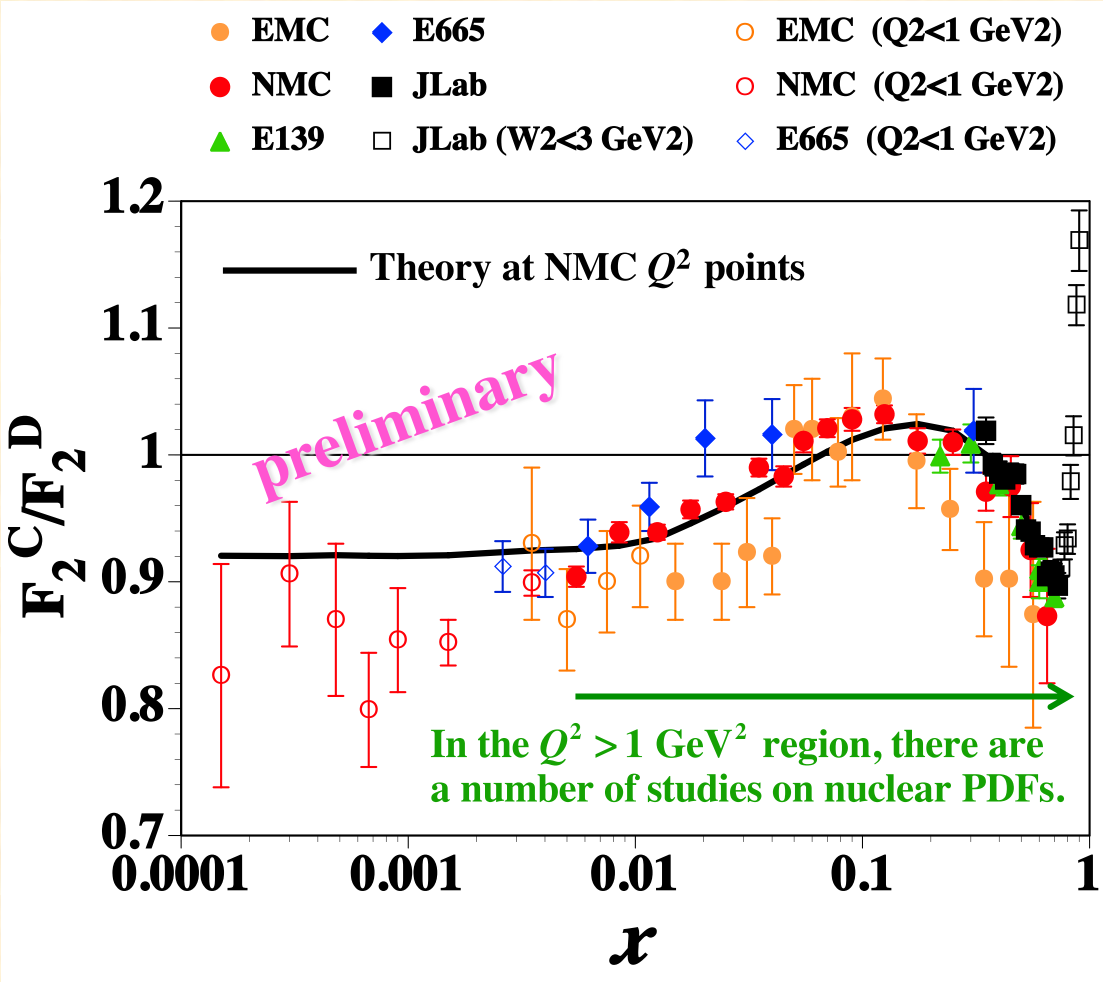
SLAC



Comparison with nuclear data on F_2^A / F_2^D

$F_2^A(x,Q^2) = w(x,Q^2;x_0,Q_0^2) F_2^A(x_0,Q_0^2)$

At this stage, we use $w(x,Q^2;x_0,Q_0^2)$ obtained for the nucleon, so that nuclear modifications are constained only in $F_2^A(x_0,Q_0^2)$.



Nuclear $F_2^A(x_0,Q_0^2)$ from M. Hirai, S. Kumano, T.-H. Nagai, Phys. Rev. C 76 (2007) 065207.

Summary

- **Lepton-nucleus cross sections should be understood in the wide kinematical regions for neutrino experiments.**
  Especially, the order of 5% accuracy is needed for future oscillation measurements.

- **There are significant studies in the quasi-elastic, resonace, and DIS regions *separatedly*.**
  $\rightarrow$ It is desirable to have a unified code for calculating the cross sections.

- **The Regge region ($W^2 \geq 4$ GeV^2, $Q^2 < 1$ GeV^2) is not well investigated.**
  We tried to extrapolate the charged-lepton DIS structure functions to the Regge region by a global analysis of existing experimental data with $W^2 \geq 4$ GeV^2 and $Q^2 < 1$ GeV^2.

  $\rightarrow$ Need further efforts on elaboration.
  $\rightarrow$ Nuclear modifications.
  $\rightarrow$ Neutrino-nucleus structure functions.

  Our studies will be submitted for publication in the near future.

The End

The End