Neutrino deep inelastic scattering

Shunzo Kumano
High Energy Accelerator Research Organization (KEK)
J-PARC Center (J-PARC)
Graduate University for Advanced Studies (SOKENDAI)
http://research.kek.jp/people/kumanos/

30th Neutrino workshop “Neutrino Interaction Physics”
IPMU, Tokyo University, Kashiwa, Japan
https://www.icrr.u-tokyo.ac.jp/indico/event/91/

(with the project of Unification and Development of the Neutrino Science Frontier
http://www-he.scphys.kyoto-u.ac.jp/nufrontier/en/index.html

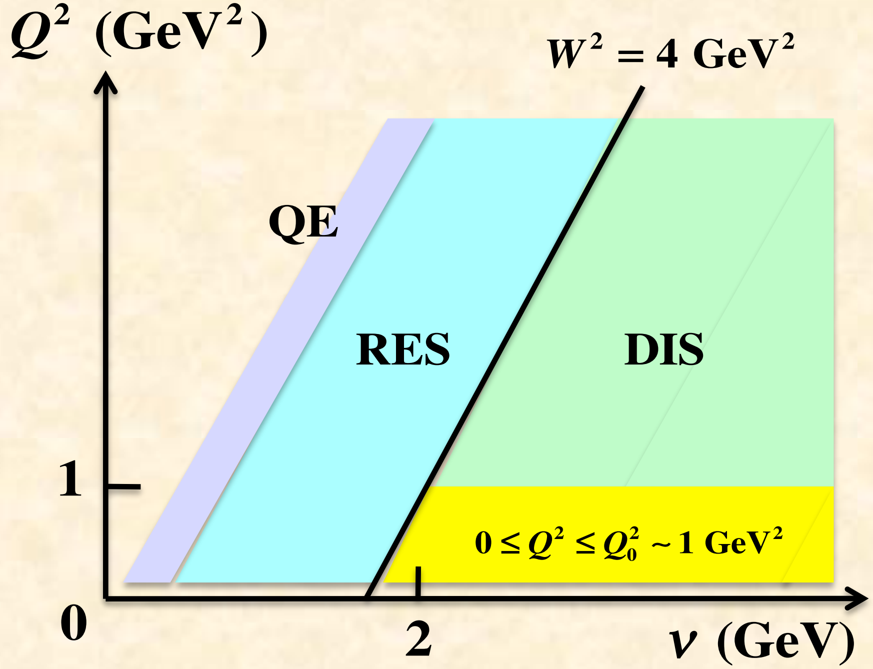
February 4, 2017

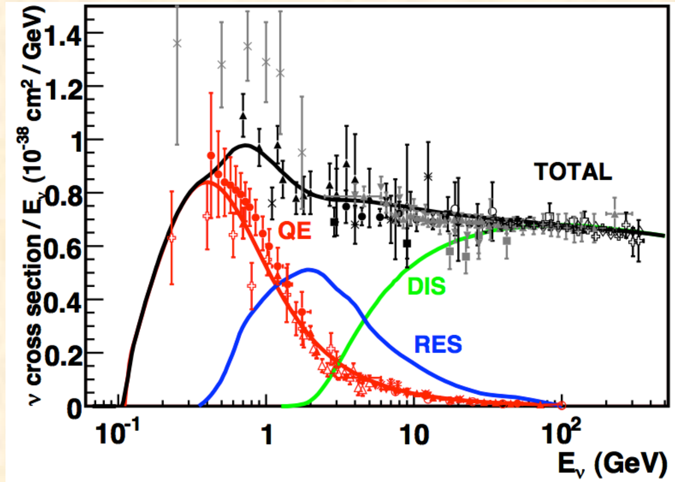
Contents

1. Motivation
2. Deep inelastic scattering (DIS)
3. Parton distributions functions (PDFs)
4. Nuclear modifications
5. Summary

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)**

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%

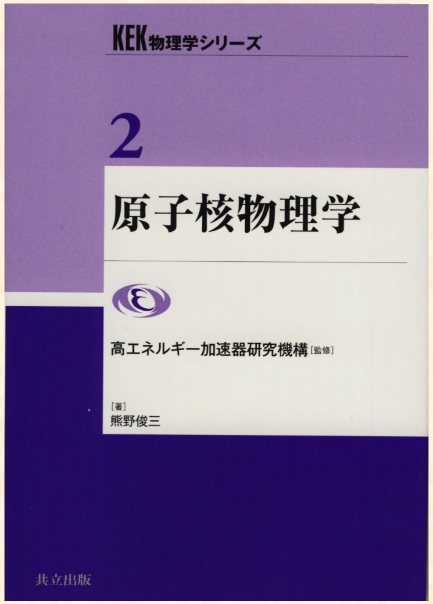
ν interactions

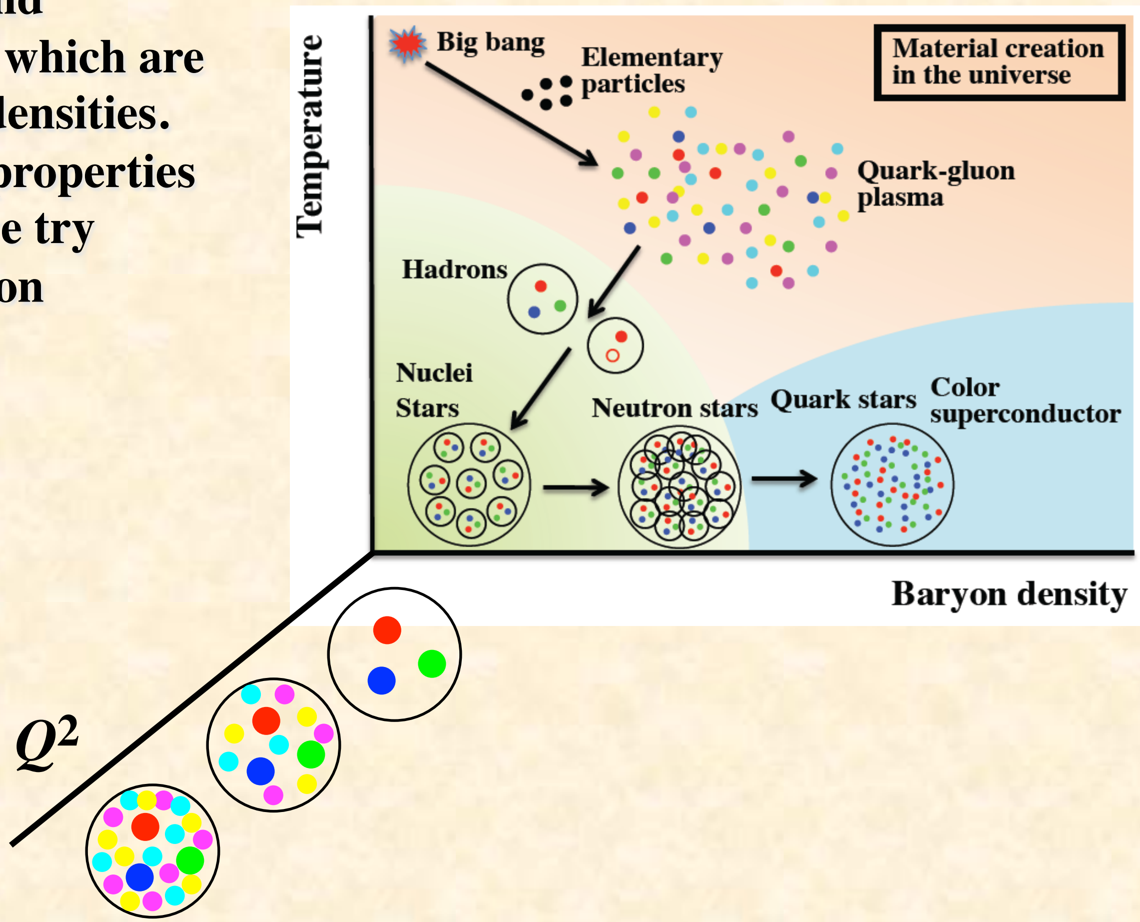
A.K.Ichikawa@KEK workshop 2015

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

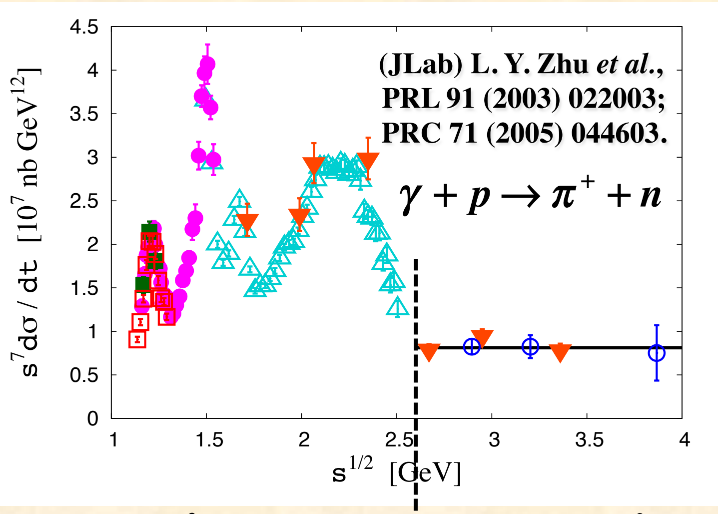
Nuclear physics: Hadron degrees of freedom (d.o.f.)
→ Quark-gluon d.o.f. (QCD)

Nuclear physics is the field of science to study
(1) material creation in the universe and
(2) quark-hadron many-body systems which are quantum materials with ultimate densities.
Clarifying the origin of elements and properties of quark-gluon many-body systems, we try to understand our universe and creation of materials.



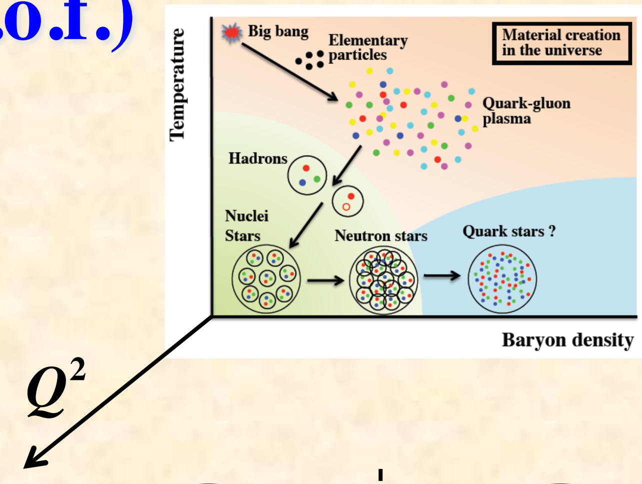


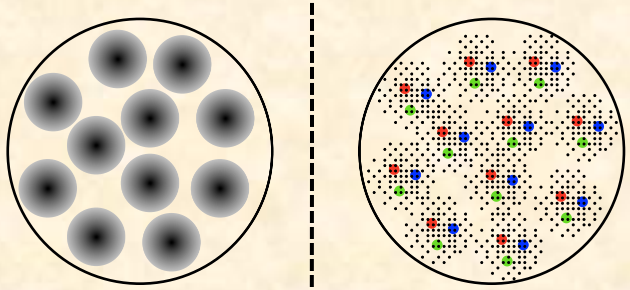
Hadron degrees of freedom (d.o.f.) ⇔ Quark d.o.f.



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.

New discovery or not?

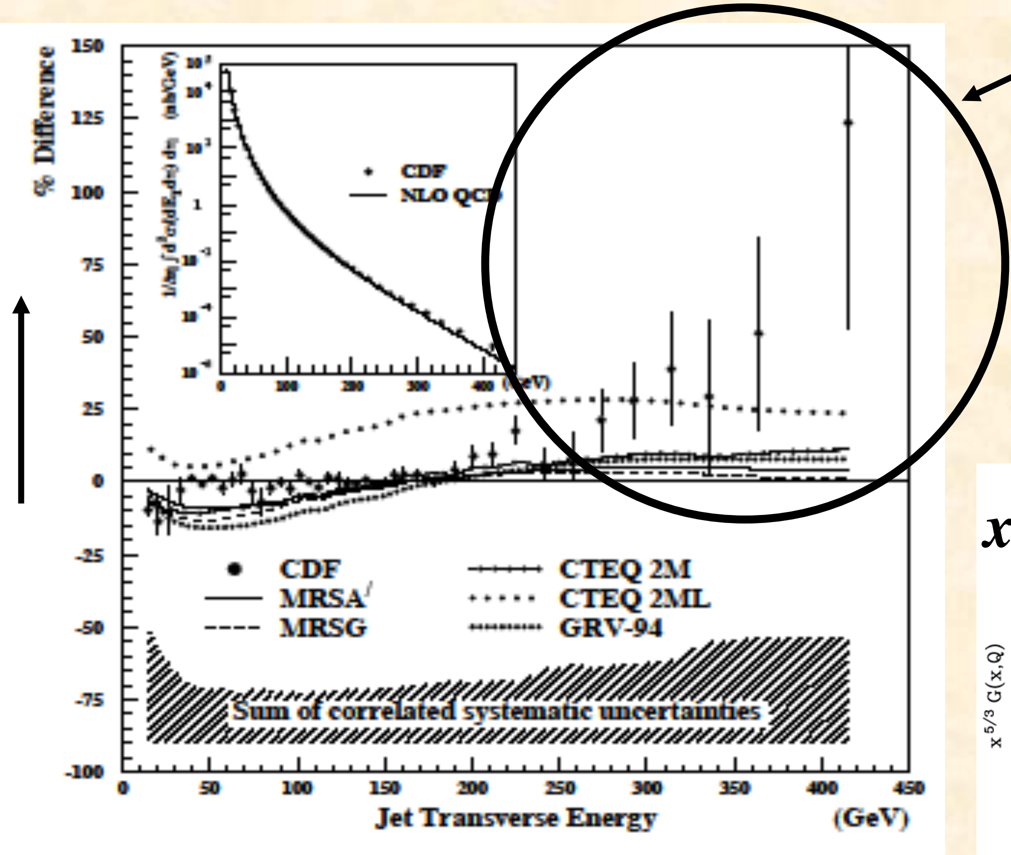
CDF experiment: PRL, 77 (1996) 438.

$p + \bar{p} \to \text{jet} + X$

$\sqrt{s} = 1.8$ TeV, $E_T^{jet} = 15 - 400$ GeV

Comparison of theoretical calculations with CDF experimental data.

Difference between theory and experiment



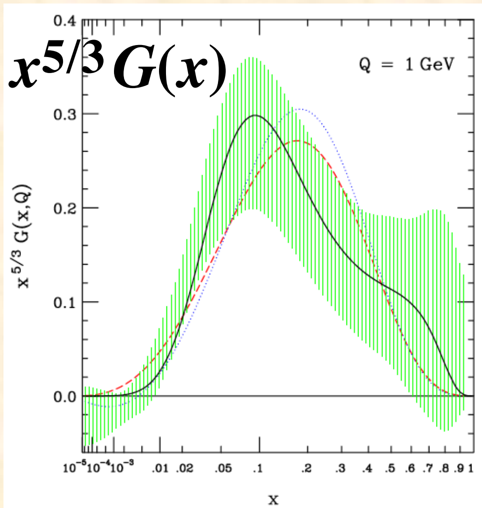
Jet transverse energy

New physics ???

Could be explained without new physics

(importance of accurate PDFs)

JET cross sections are "explained" by the CTEQ6 PDFs.

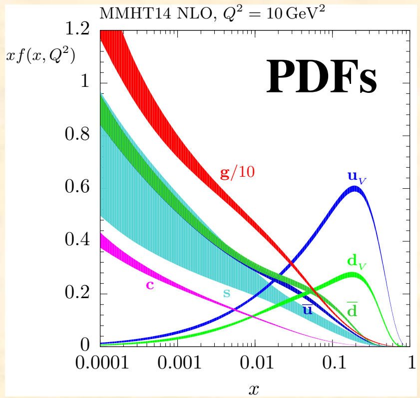


x

CTEQ6

CTEQ5

MRST2001



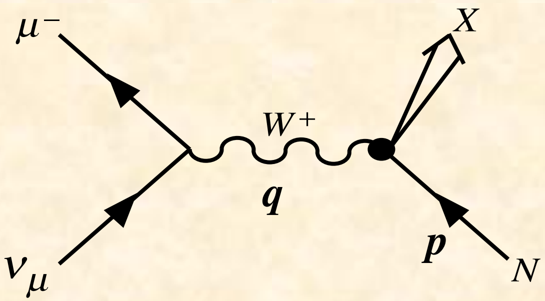
Structure functions of nucleon

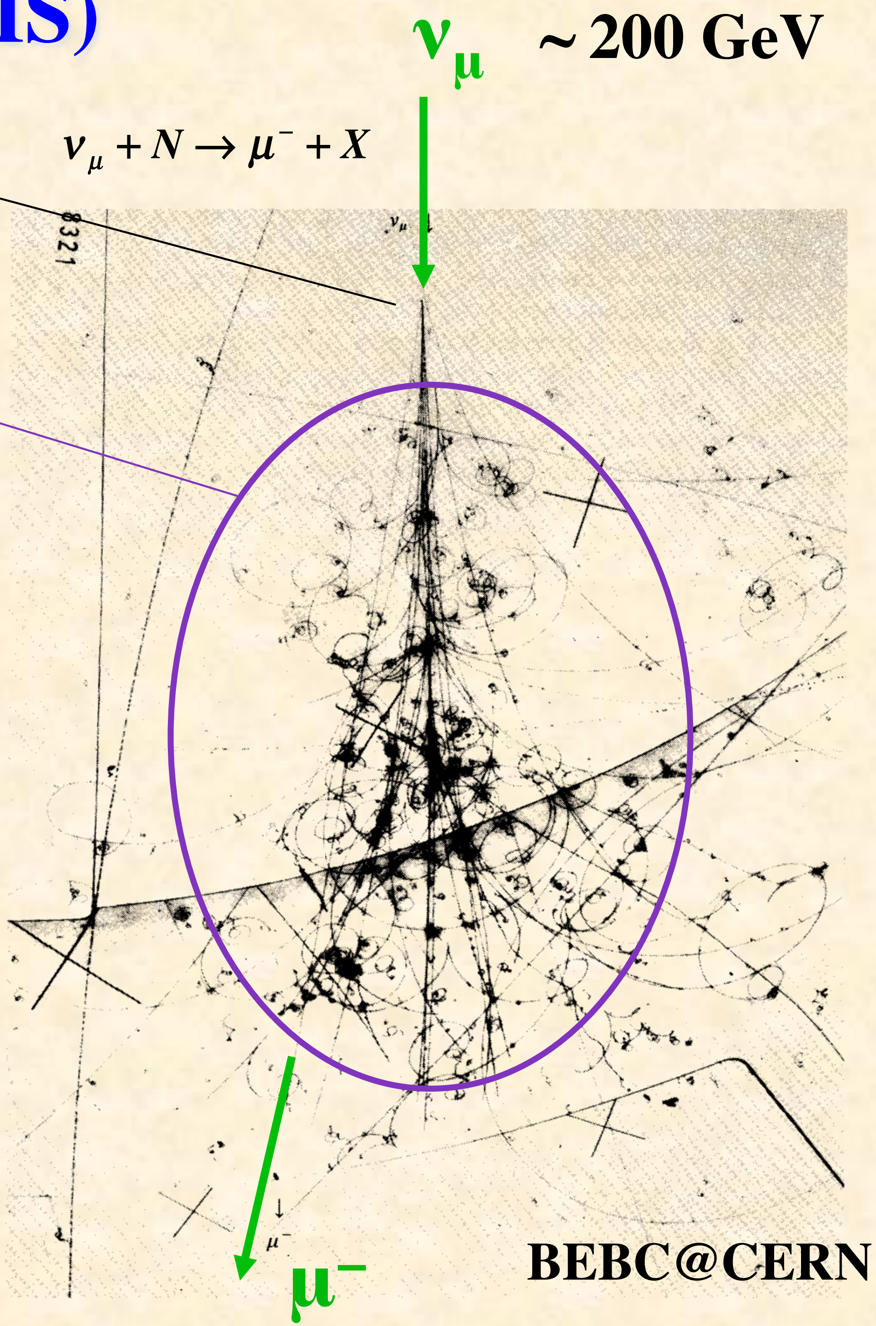
Introduction to neutrino deep inelastic scattering (DIS)

Deep inelastic scattering (DIS)

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

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



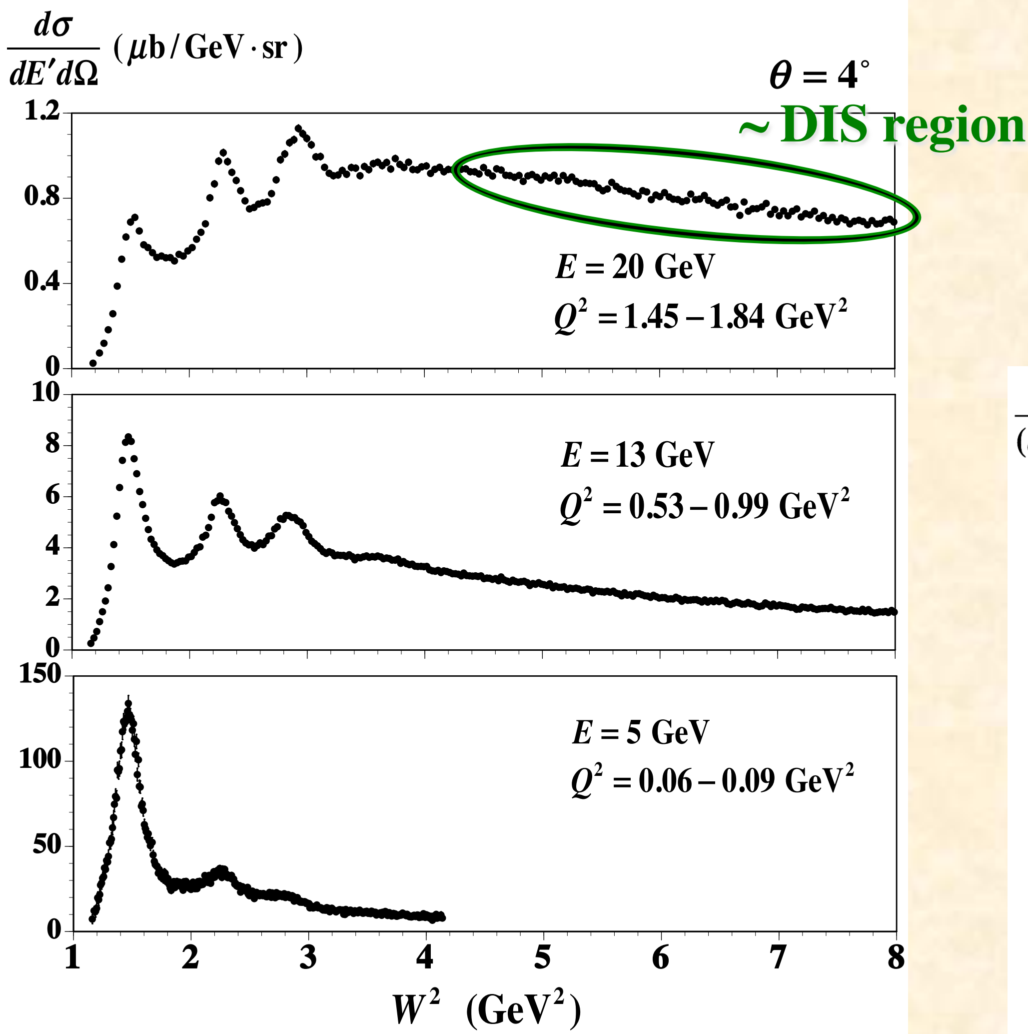


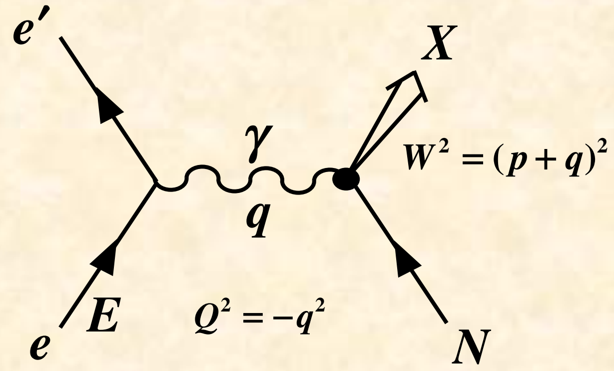
Momentum transfer: $q^2 = (k - k')^2 = -Q^2$

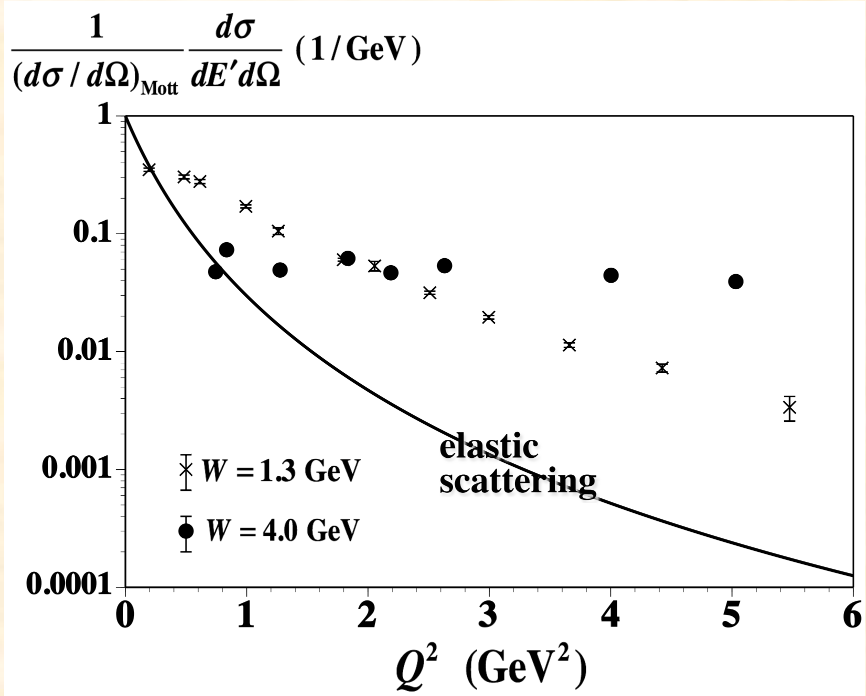
Bjorken scaling variable: $x = \dfrac{Q^2}{2p \cdot q}$

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

Lepton scattering



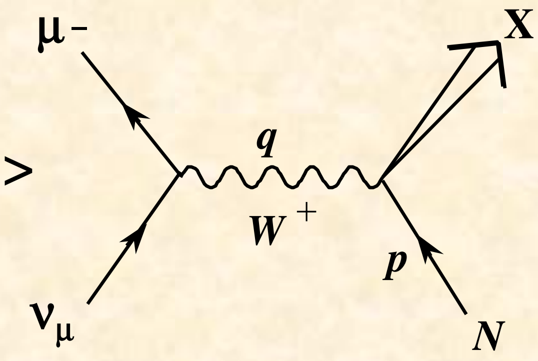




Neutrino deep inelastic scattering (CC: Charged Current)

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

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



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

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

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

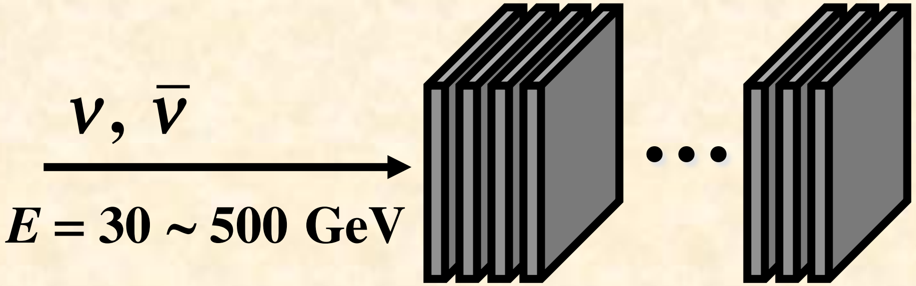
$$MW_1=F_1\,,\quad \nu W_2=F_2\,,\quad \nu W_3=F_3\,,\quad x=\frac{Q^2}{2p\cdot q}\,,\quad y=\frac{p\cdot q}{p\cdot k}$$

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

Neutrino DIS experiments

• CDHS,	H. Abramowics *et al*.,	Z. Phys. C 25 (1984) 29
• WA25,	D. Allasia *et al*.,	Z. Phys. C 28 (1985) 321
• WA59,	K. Varvell *et al*.,	Z. Phys. C 36 (1987) 1
• CDHSW,	P. Berge *et al*.,	Z. Phys. C 49 (1991) 187
• Serpukhov,	A. V. Sidorov *et al*.,	Eur. Phys. J. C 10 (1999) 405
• CCFR,	U.-K. Yang *et al*.,	PRL 86 (2001) 2742
• NuTeV/CCFR $\mu^+\mu^-$,	M. Goncharov *et al*.,	PRD 64 (2001) 112006
• CHORUS,	G. Onengut *et al*.,	PLB 632 (2006) 65
• NuTeV,	M. Tzanov *et al*.,	PRD 74 (2006) 012008
• Minverva,	J. Mousseau *et al*.,	PRD 93 (2016) 071101, in progress

Neutrino DIS experiments

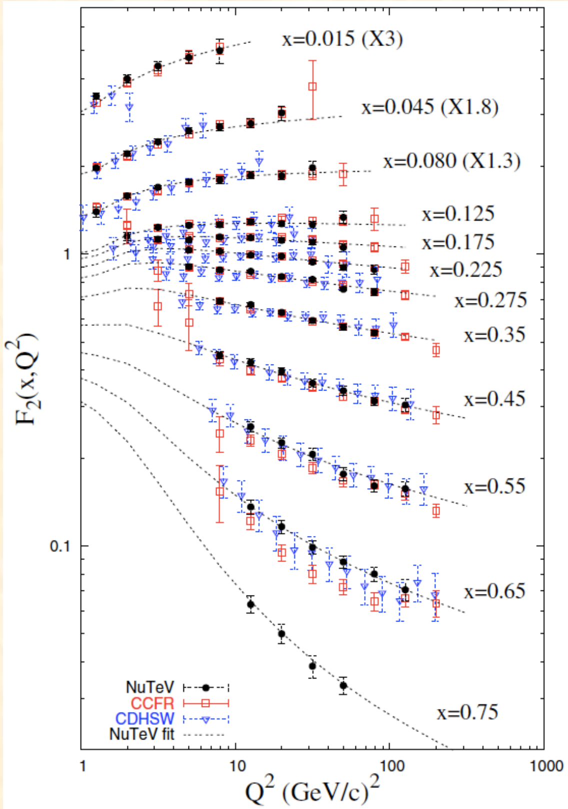


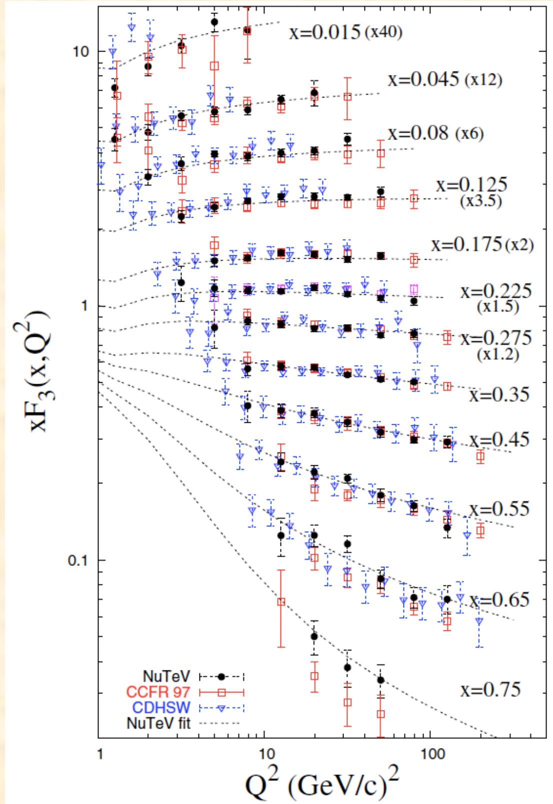
Huge Fe target (690 ton)

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), …

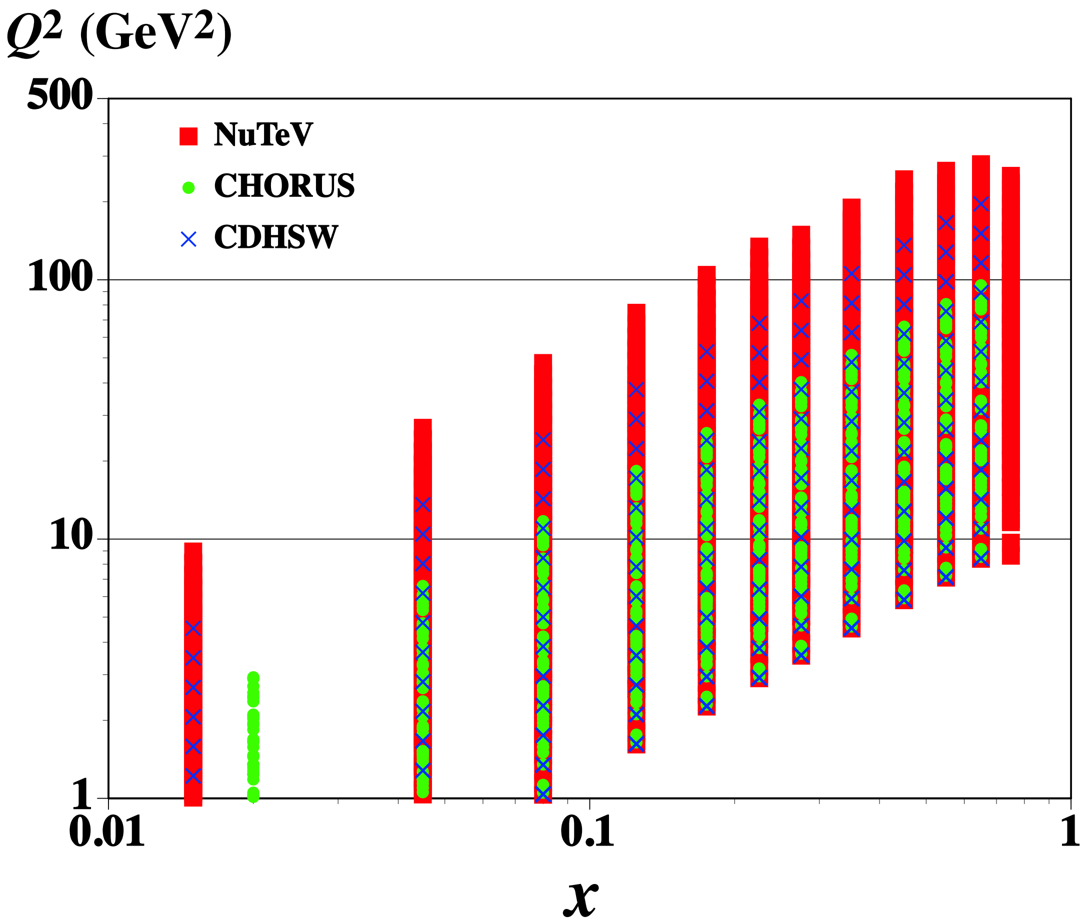
M. Tzanov *et al.* (NuTeV), PRD74 (2006) 012008.



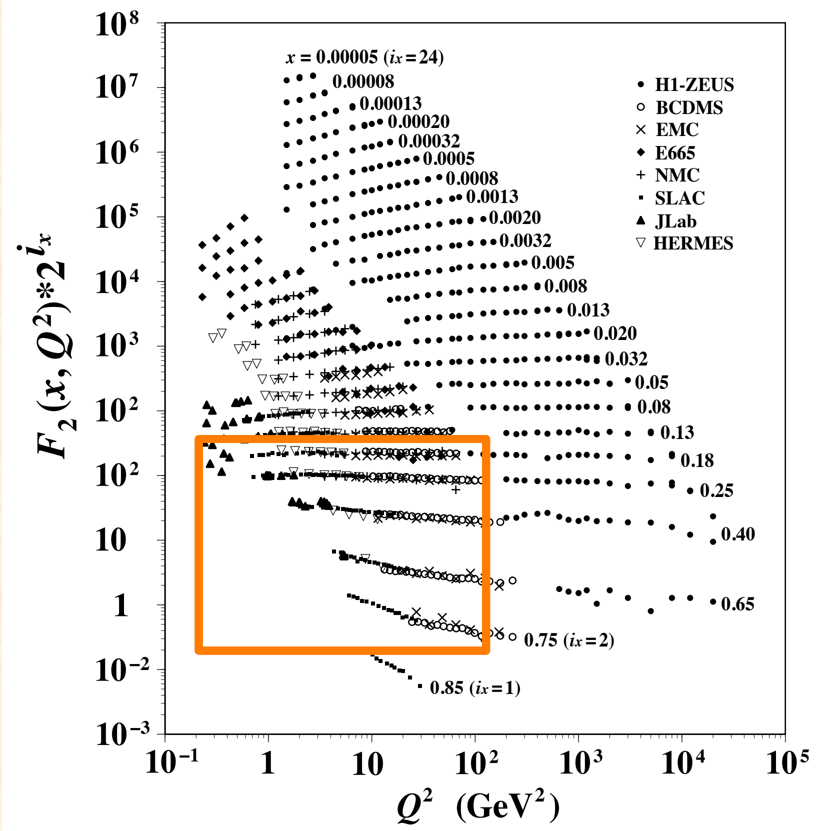


Neutrino DIS experiments: kinematical range

Neutrino DIS



Charged-lepton DIS

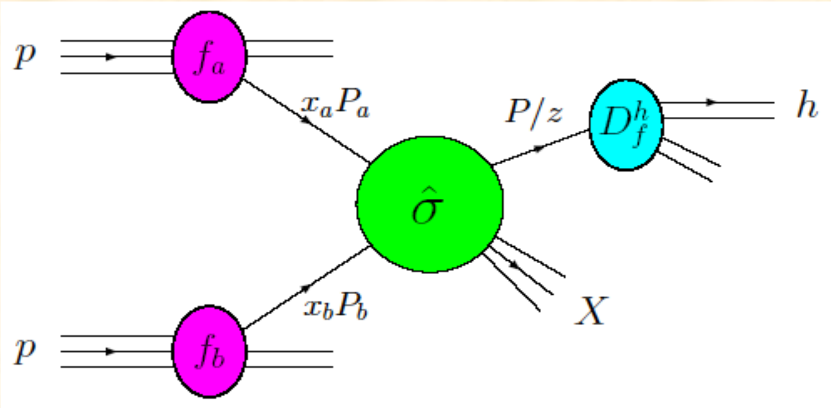


S. Kumano, Nuclear Physics (in Japanese), KEK Physics Series, Volume 2, Kyoritsu Shuppan (2015)

Parton distribution functions in the nucleon

High-energy hadron reactions

PDFs are needed for describing high-energy hadron reactions in order to find any new phenomena.



$$\sigma = \sum_{a,b,c} f_a(x_a, Q^2) \otimes f_b(x_b, Q^2) \otimes \hat{\sigma}(ab \to cX) \otimes D_c^h(z, Q^2)$$

$f_a(x_a, Q^2)$: **parton distribution functions**

$\hat{\sigma}(ab \to cX)$: **partonic cross sections**

$D_c^h(z, Q^2)$: **fragmentation functions**

Recent works on unpolarized PDFs

ABKM (Alekhin, Blümlein, Klein, Moch)

ABKM-2010, 2011, S. Alekhin *et al*., Phys. Rev. D 81 (2010) 014032; Phys. Rev. D86（2012）054009;

ABM-2014, S. Alekhin *et al*., Phys. Rev. D89（2014）054028 [D91 (2015) 094002, D94 (2016) 114038]

ABMP-2016: S. Alekhin *et al*., arXiv:1609.03327.

CTEQ (Coordinated Theoretical-Experimental Project on QCD)

CTEQ6.6, P. M. Nadolsky *et al*., Phys. Rev. D 78 (2008) 013004.

CT10, H.-L. Lau *et al*., Phys. Rev. D 82 (2010) 074024.

CT12, J. F. Owens *et al*., Phys. Rev. D 87 (2013) 094012. CT14, S. Dulat *et al*., Phys. Rev. D 93 (2016) 033006.

GJR (Glück, Jimenez-Delgado, Reya)

GJR-2008, M. Gluck *et al*., Eur. Phys. J. C 53 (2008) 355; PRD79 (2009) 074023;

JR-2014, Phys. Rev. D89 (2014) 074049.

HERA (H1 and ZEUS collaborations)

HERAPDF, F. D. Aaron *et al*., JHEP 01 (2010) 109: Eur. Phys. J. C73（2013）2311;

H Abramowicz *et al*., Phys. Rev. D 93 (2016) 092002; I. Abt *et al*., Phys. Rev. D 94 (2016) 052007.

MSTW (Martin, Stirling, Thorne, Watt, L. A. Harland-Lang, P. Motylinski)

MSTW2008, A. D. Martin *et al*., Eur. Phys. J. C 63 (2009) 189;

MMHT2014, A. Harland-Lang *et al*., Eur. Phys. J. C (2015) 75.

Neural Network (Ball, Bertone, Carrazza, Del Debbio, Forte, Guffanti, Hartland, Latorre, Rojo, Ubiali, ...)

NNPDF, R. D. Ball *et al*., Nucl. Phys. B 838 (2010) 136; B855（2012）153;

B867（2013）244; B874（2013）36; B877（2013）290;

JHEP 04 (2015) 040; JHEP 1509 (2015) 191; arXiv:1605.06515.

Parton distribution functions are determined by fitting various experimental data.

- electron/muon: $\mu + p \rightarrow \mu + X$
- neutrino: $\nu_\mu + p \rightarrow \mu + X$
- Drell-Yan: $p + p \rightarrow \mu^+\mu^- + X$
- $\cdots$

(1) assume functional form of PDFs at fixed $Q^2 (\equiv Q_0^2)$:

e.g. $f_i(x, Q_0^2) = A_i x^{\alpha_i} (1-x)^{\beta_i} (1+\gamma_i x)$,

where $i = u_v,\ d_v,\ \bar{u},\ \bar{d},\ \bar{s},\ g$

(2) calculate observables at their experimental Q^2 points.

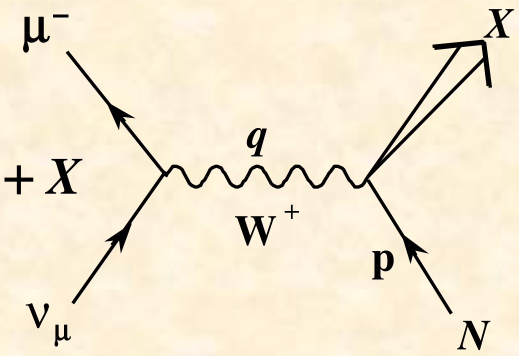
(3) then, the parameters $A_i,\ \alpha_i,\ \beta_i,\ \gamma_i$ are determined so as to minimize χ^2 in comparison with data.

Determination of each distribution

Valence quark

$q_v(x) \equiv q(x) - \bar{q}(x)$

$\nu_\mu + p \to \mu^- + X$



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

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

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

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

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

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

$$\frac{1}{2} [F_3^{\nu p} + F_3^{\bar{\nu} p}]_{CC} = u_v + d_v + s - \bar{s} + c - \bar{c}$$

Note: Nuclear corrections in CCFR/NuTeV (ν+Fe).

Valence: also F_2 at large x

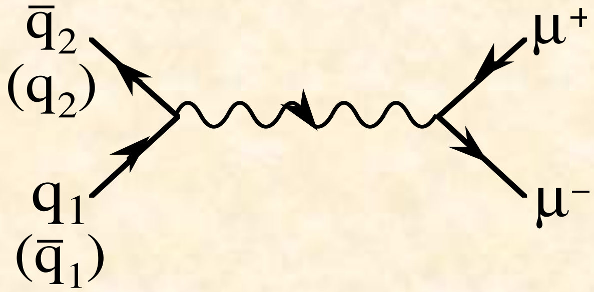
Sea quark

e/μ scattering

$$F_2^N = \frac{F_2^p + F_2^n}{2} = \frac{x}{2}\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}+s+\bar{s}) + \frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}+s+\bar{s})\right] = \frac{x}{2}\left[\frac{5}{9}(u+\bar{u}+d+\bar{d}) + \frac{2}{9}(s+\bar{s})\right]$$

$$= \frac{x}{2}\left[\frac{5}{9}(u_v+d_v) + \frac{10}{9}(\bar{u}+\bar{d}) + \frac{2}{9}(s+\bar{s})\right] = \frac{5}{18}x(u_v+d_v) + \frac{2}{18}x\left[5(\bar{u}+\bar{d}) + (s+\bar{s})\right]$$

Drell-Yan (lepton-pair production)



$$p_1 + p_2 \rightarrow \mu^+\mu^- + X$$

$$d\sigma \propto q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)$$

at large $x_F = x_1 - x_2$

projectile target

$$d\sigma \propto q_V(x_1)\bar{q}(x_2)$$

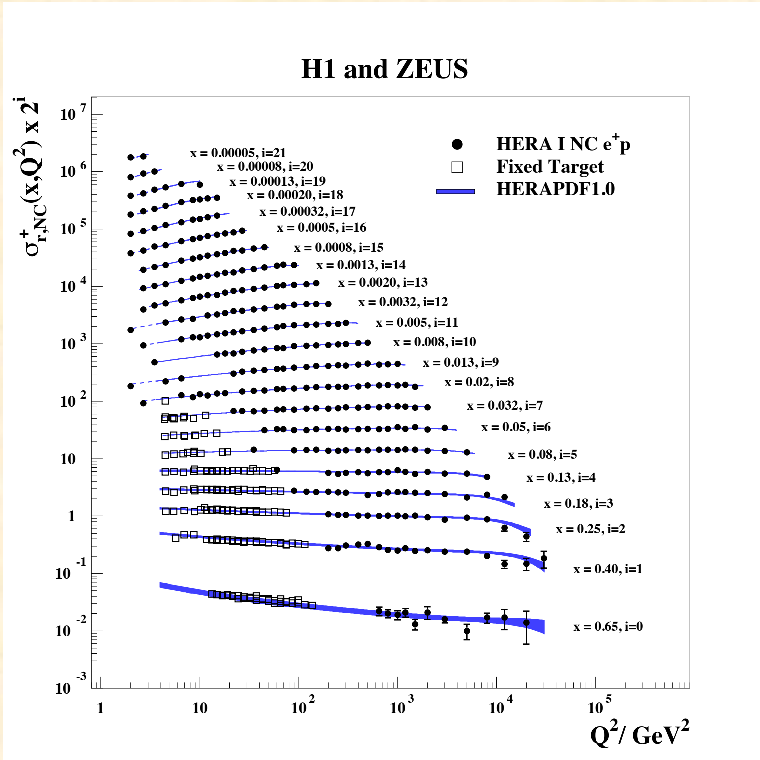
$\bar{q}(x_2)$ can be obtained if $q_V(x_1)$ is known.

Gluon

scaling violation of F_2

$$\frac{\partial}{\partial(\ln Q^2)}\begin{pmatrix} q_s(x,t) \\ g(x,t) \end{pmatrix} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\begin{pmatrix} P_{qq}(x/y) & P_{qg}(x/y) \\ P_{gq}(x/y) & P_{gg}(x/y) \end{pmatrix}\begin{pmatrix} q_s(y,t) \\ g(y,t) \end{pmatrix}$$

H1 and ZEUS
JHEP01(2010)109

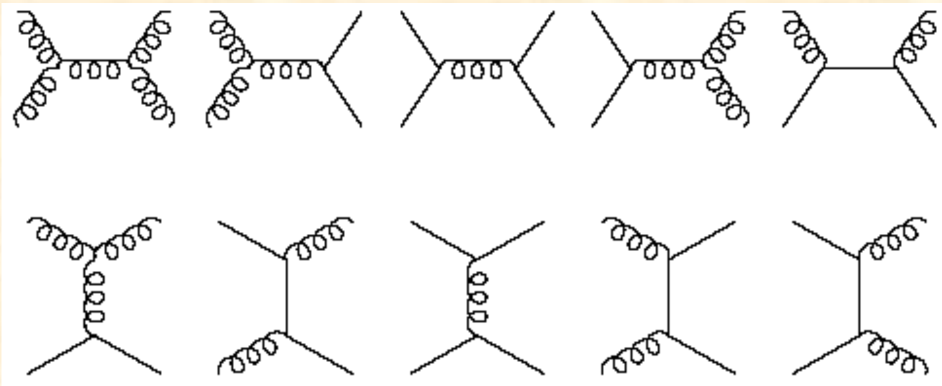


at small x

$$\frac{\partial F_2}{\partial(\ln Q^2)} \approx \frac{10\,\alpha_s}{27\pi} g$$

K. Prytz, Phys. Lett. B311 (1993) 286.

jet production



Structure functions in parton model for neutrino-nucleon scattering

$F_2 = 2\,x\,F_1$

$$F_2^{\nu p} = 2\,x\,(d + s + \bar{u} + \bar{c})$$
$$F_2^{\bar{\nu} p} = 2\,x\,(u + c + \bar{d} + \bar{s})$$

$$F_2^{\nu n} = 2\,x\,(u + s + \bar{d} + \bar{c})$$
$$F_2^{\bar{\nu} n} = 2\,x\,(d + c + \bar{u} + \bar{s})$$

$$xF_3^{\nu p} = 2\,x\,(d + s - \bar{u} - \bar{c})$$
$$xF_3^{\bar{\nu} p} = 2\,x\,(u + c - \bar{d} - \bar{s})$$

$$xF_3^{\nu n} = 2\,x\,(u + s - \bar{d} - \bar{c})$$
$$xF_3^{\bar{\nu} n} = 2\,x\,(d + c - \bar{u} - \bar{s})$$

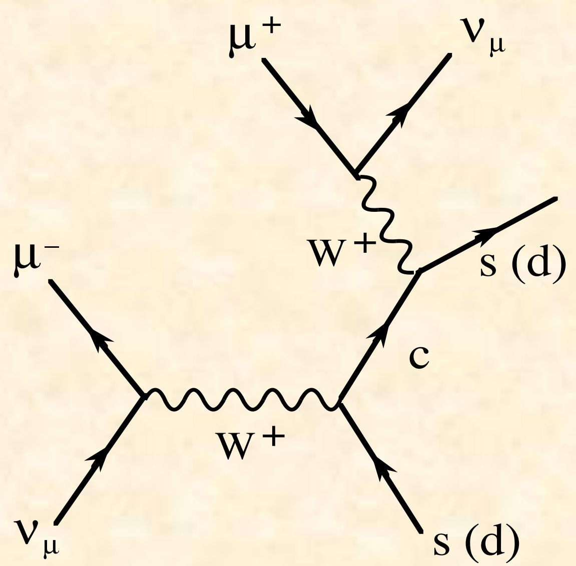
$\longrightarrow$

$$F_3^{\nu p} + F_3^{\bar{\nu} p} = 2\,\underline{(u_v + d_v)} + 2\,(s - \bar{s}) + 2\,(c - \bar{c})$$

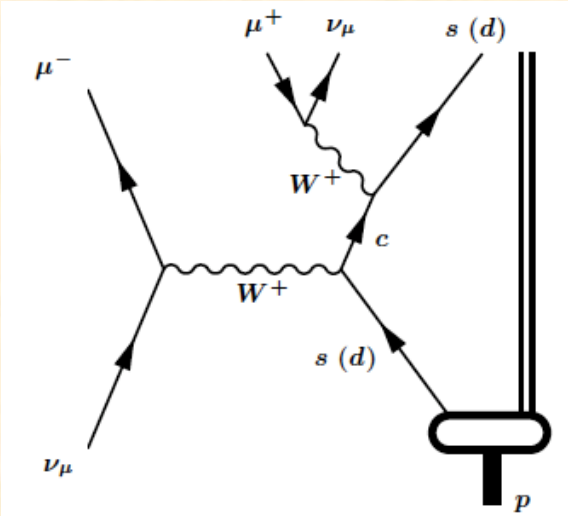
valence-quark distributions

$$F_3^{\nu(p+n)/2} - F_3^{\bar{\nu}(p+n)/2} = 2\,(s + \bar{s}) - 2\,(c + \bar{c})$$

also $\nu p \rightarrow \mu^- \mu^+ X$ for finding $2\,\bar{s} / (\bar{u} + \bar{d})$



$s(x)$ from neutrino-induced opposite-sign dimuon events



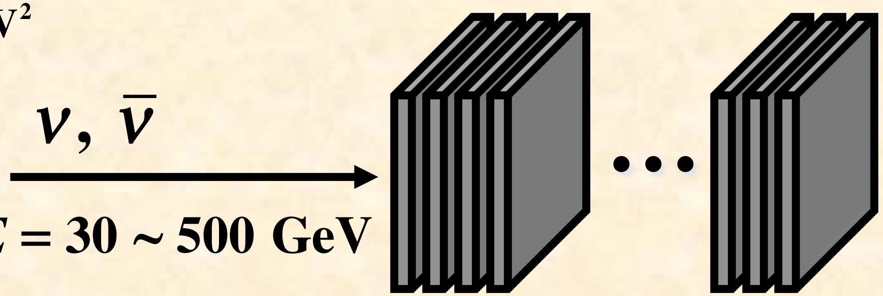
A. Kayis-Topaksu *et al.*, NPB7 98 (2008) 1.
U. Dore, arXiv: 1103.4572 [hep-ex].

$$\kappa = \frac{\int dx\, x\,[s(x,Q^2)+\bar{s}(x,Q^2)]}{\int dx\, x\,[\bar{u}(x,Q^2)+\bar{d}(x,Q^2)]}$$

$Q^2 = 20\ \mathrm{GeV}^2$

CCFR, NuTeV

Experiment	κ
This analysis	0.33 ± 0.07
CDHS [1]	0.47 ± 0.09
CCFR [2]	0.44 ± 0.09
CHARM II [3]	0.39 ± 0.09
NOMAD [4]	0.48 ± 0.17
NuTeV [5]	0.38 ± 0.08

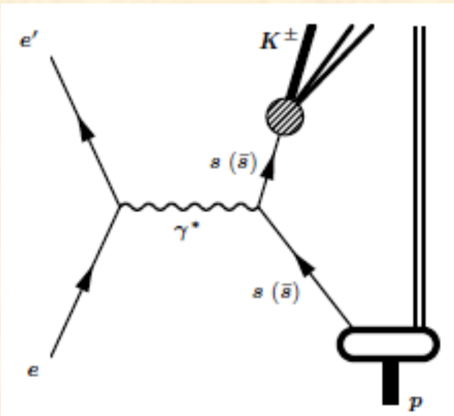


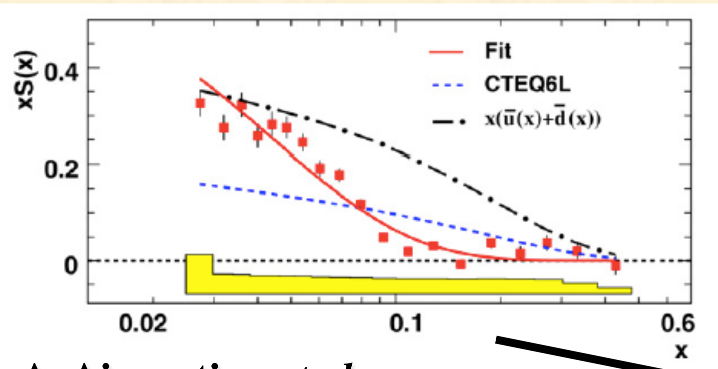
$E = 30 \sim 500$ GeV

Huge Fe target (690 ton)

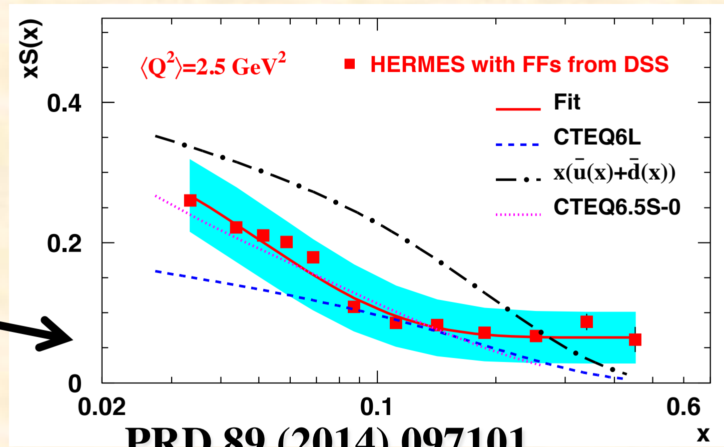
Issue: nuclear corrections

HERMES semi-inclusive measurement





A. Airapetian *et al.*,
PLB 666 (2008) 446.



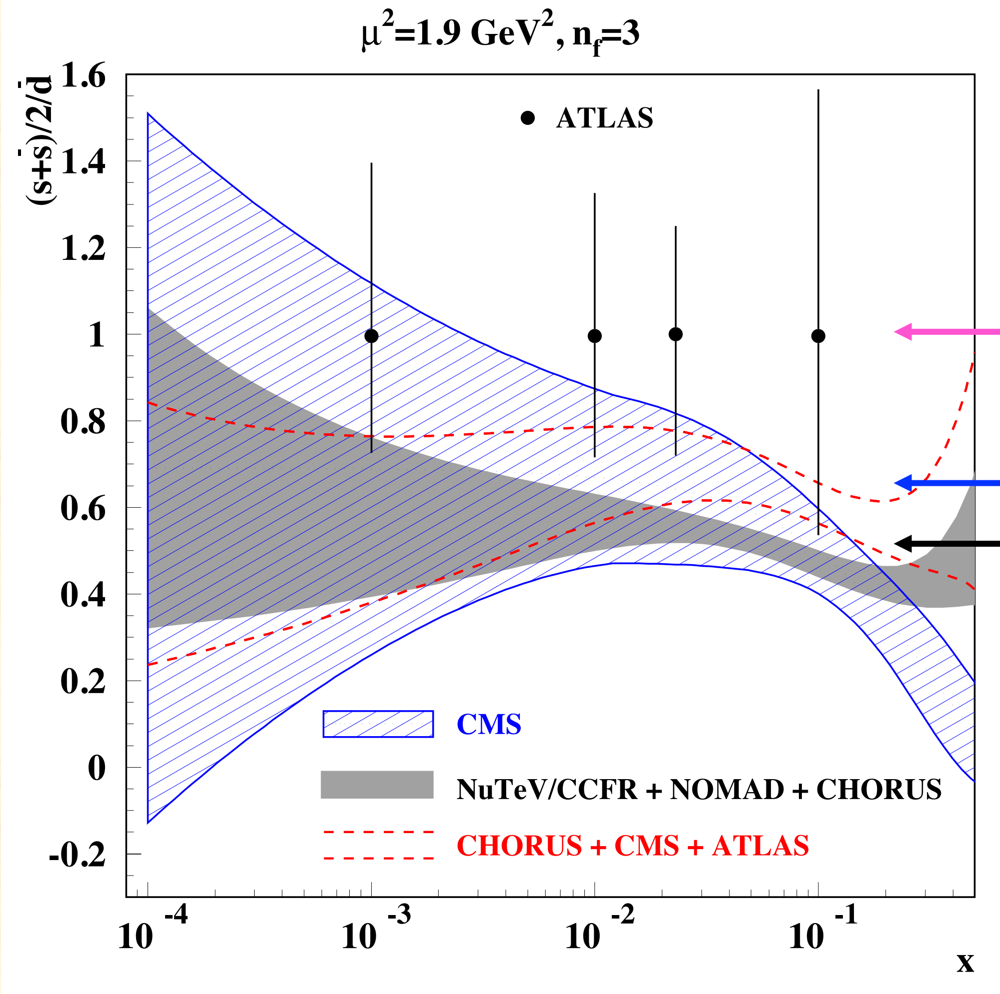
PRD 89 (2014) 097101.

Strange-quark distribution with LHC measurements

S. Alekhin *et al.*,
PRD 91 (2015) 094002.

Neutrino: $s + W \to c$

LHC: $g + s \to W + c$



ATLAS

CMS

Neutrino

ATLAS and CMS/neutrino results are different.

Situation of data for PDFs of the nucleon (CTEQ14)

ID#	Experimental data set		N_{pt}	χ^2_e	χ^2_e/N_{pt}	S_n
101	BCDMS F_2^p	[24]	337	384	1.14	1.74
102	BCDMS F_2^d	[25]	250	294	1.18	1.89
104	NMC F_2^d/F_2^p	[26]	123	133	1.08	0.68
106	NMC σ_{red}^p	[26]	201	372	1.85	6.89
108	CDHSW F_2^p	[27]	85	72	0.85	-0.99
109	CDHSW F_3^p	[27]	96	80	0.83	-1.18
110	CCFR F_2^p	[28]	69	70	1.02	0.15
111	CCFR xF_3^p	[29]	86	31	0.36	-5.73
124	NuTeV $\nu\mu\mu$ SIDIS	[30]	38	24	0.62	-1.83
125	NuTeV $\bar{\nu}\mu\mu$ SIDIS	[30]	33	39	1.18	0.78
126	CCFR $\nu\mu\mu$ SIDIS	[31]	40	29	0.72	-1.32
127	CCFR $\bar{\nu}\mu\mu$ SIDIS	[31]	38	20	0.53	-2.46
145	H1 σ_r^b	[32]	10	6.8	0.68	-0.67
147	Combined HERA charm production	[33]	47	59	1.26	1.22
159	HERA1 Combined NC and CC DIS	[34]	579	591	1.02	0.37
169	H1 F_L	[35]	9	17	1.92	1.7

ID#	Experimental data set		N_{pt}	χ^2_e	χ^2_e/N_{pt}	S_n
201	E605 Drell-Yan process	[37]	119	116	0.98	-0.15
203	E866 Drell-Yan process, $\sigma_{pd}/(2\sigma_{pp})$	[38]	15	13	0.87	-0.25
204	E866 Drell-Yan process, $Q^3 d^2\sigma_{pp}/(dQdx_F)$	[39]	184	252	1.37	3.19
225	CDF Run-1 electron A_{ch}, $p_{T\ell} > 25$ GeV	[40]	11	8.9	0.81	-0.32
227	CDF Run-2 electron A_{ch}, $p_{T\ell} > 25$ GeV	[41]	11	14	1.24	0.67
234	DØ Run-2 muon A_{ch}, $p_{T\ell} > 20$ GeV	[42]	9	8.3	0.92	-0.02
240	LHCb 7 TeV 35 pb^{-1} W/Z $d\sigma/dy_\ell$	[43]	14	9.9	0.71	-0.73
241	LHCb 7 TeV 35 pb^{-1} A_{ch}, $p_{T\ell} > 20$ GeV	[43]	5	5.3	1.06	0.30
260	DØ Run-2 Z rapidity	[44]	28	17	0.59	-1.71
261	CDF Run-2 Z rapidity	[45]	29	48	1.64	2.13
266	CMS 7 TeV 4.7 fb^{-1}, muon A_{ch}, $p_{T\ell} > 35$ GeV	[46]	11	12.1	1.10	0.37
267	CMS 7 TeV 840 pb^{-1}, electron A_{ch}, $p_{T\ell} > 35$ GeV	[47]	11	10.1	0.92	-0.06
268	ATLAS 7 TeV 35 pb^{-1} W/Z cross sec., A_{ch}	[48]	41	51	1.25	1.11
281	DØ Run-2 9.7 fb^{-1} electron A_{ch}, $p_{T\ell} > 25$ GeV	[15]	13	35	2.67	3.11
504	CDF Run-2 inclusive jet production	[49]	72	105	1.45	2.45
514	DØ Run-2 inclusive jet production	[50]	110	120	1.09	0.67
535	ATLAS 7 TeV 35 pb^{-1} incl. jet production	[51]	90	50	0.55	-3.59
538	CMS 7 TeV 5 fb^{-1} incl. jet production	[52]	133	177	1.33	2.51

CERN-BCDMS, NMC

CDHSW, CCFR, NuTeV
(ν deep inelastic)

HERA (NC, CC, charm)

Fermilab-E866 (Drell-Yan)

Tevatron (jets, W, Z)

LHC (jets, W, Z, Drell-Yan)

Recent progress

CTEQ14

CT14, S. Dulat *et al*., PRD93 (2016) 033006

Functional form: $Q_0^2 = (1.3)^2 \text{ GeV}^2$

$$xf(x, Q_0^2) = x^{a_1}(1-x)^{a_2}P(x)$$

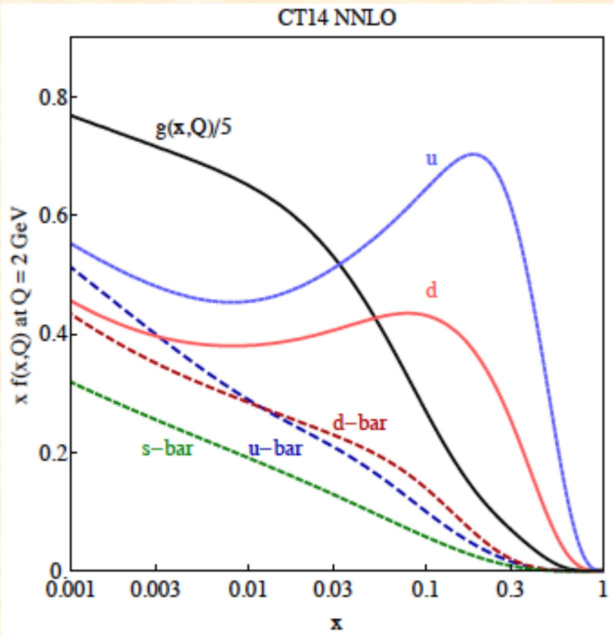
used to be $P(x) = \exp\left(a_0 + a_3\sqrt{x} + a_4 x + a_5 x^2\right)$

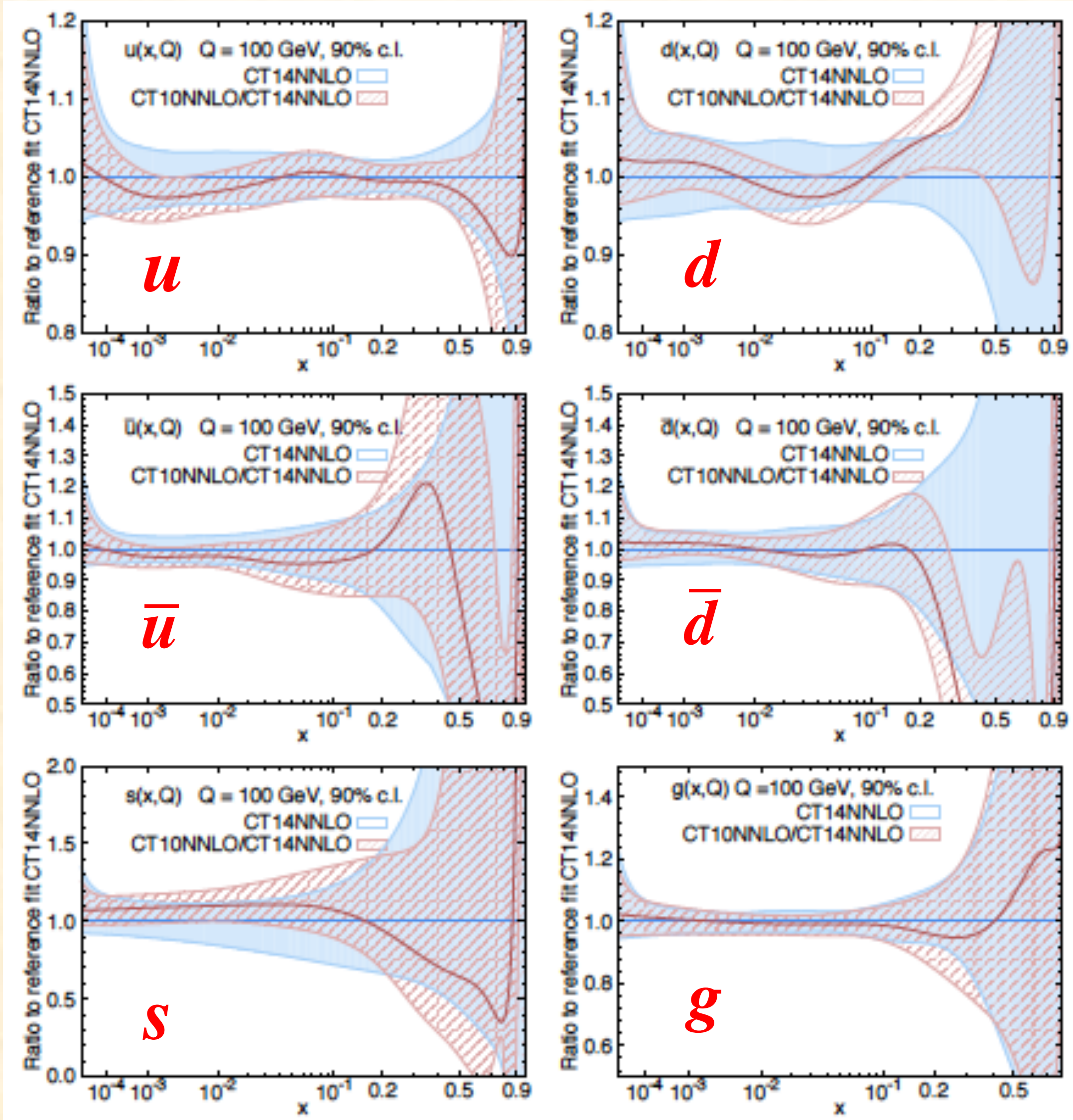
Expansion by Bernstein polynomials:

$$P(x) = \sum_{i=0}^{n} d_i p_i(y = \sqrt{x}),\ \ p_0(y) = (1-y)^4,$$

$$p_1(y) = 4y(1-y)^3,\ \ p_2(y) = 6y^2(1-y)^2,$$

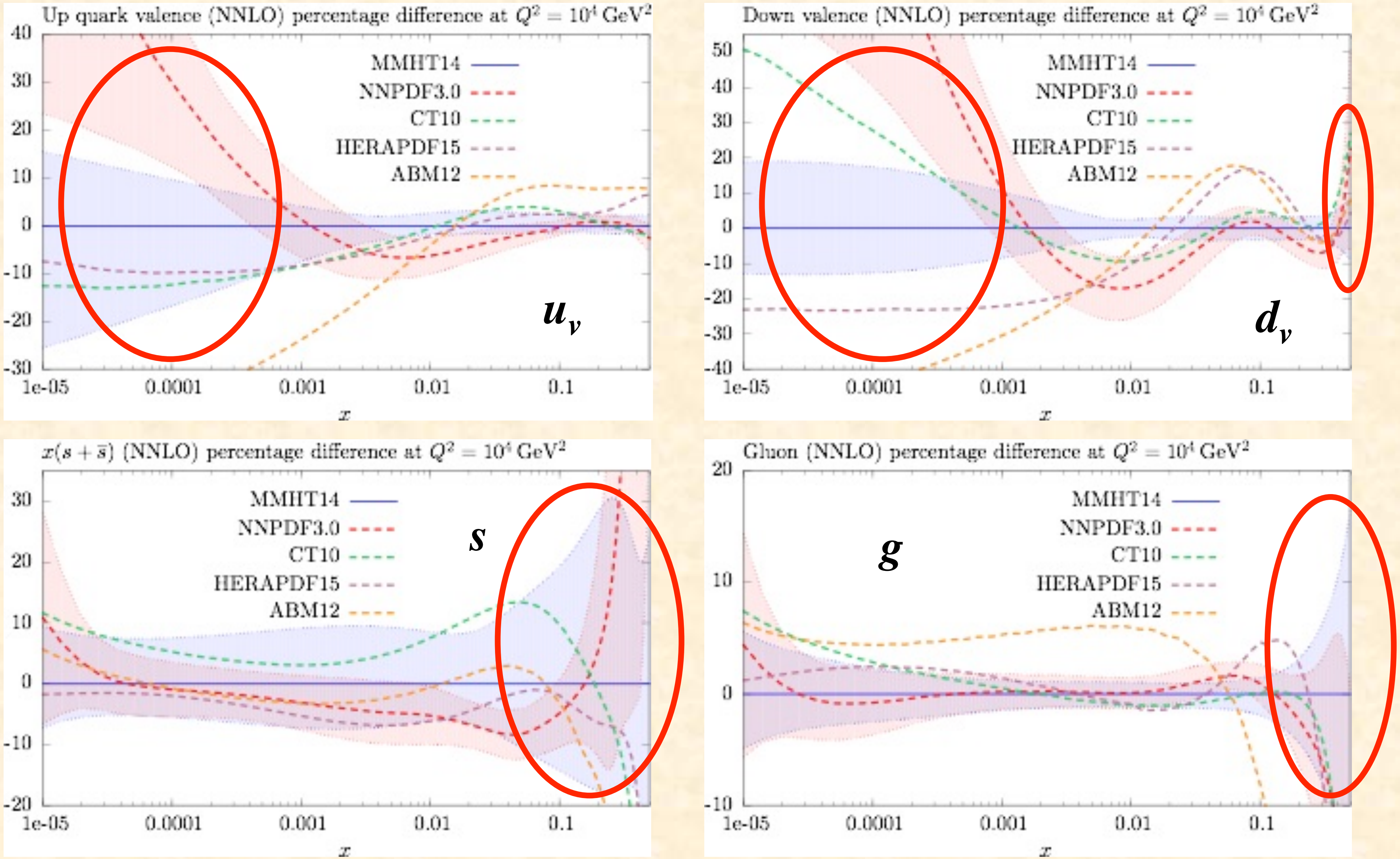
$$p_3(y) = 4y^3(1-y),\ \ p_4(y) = y^4$$





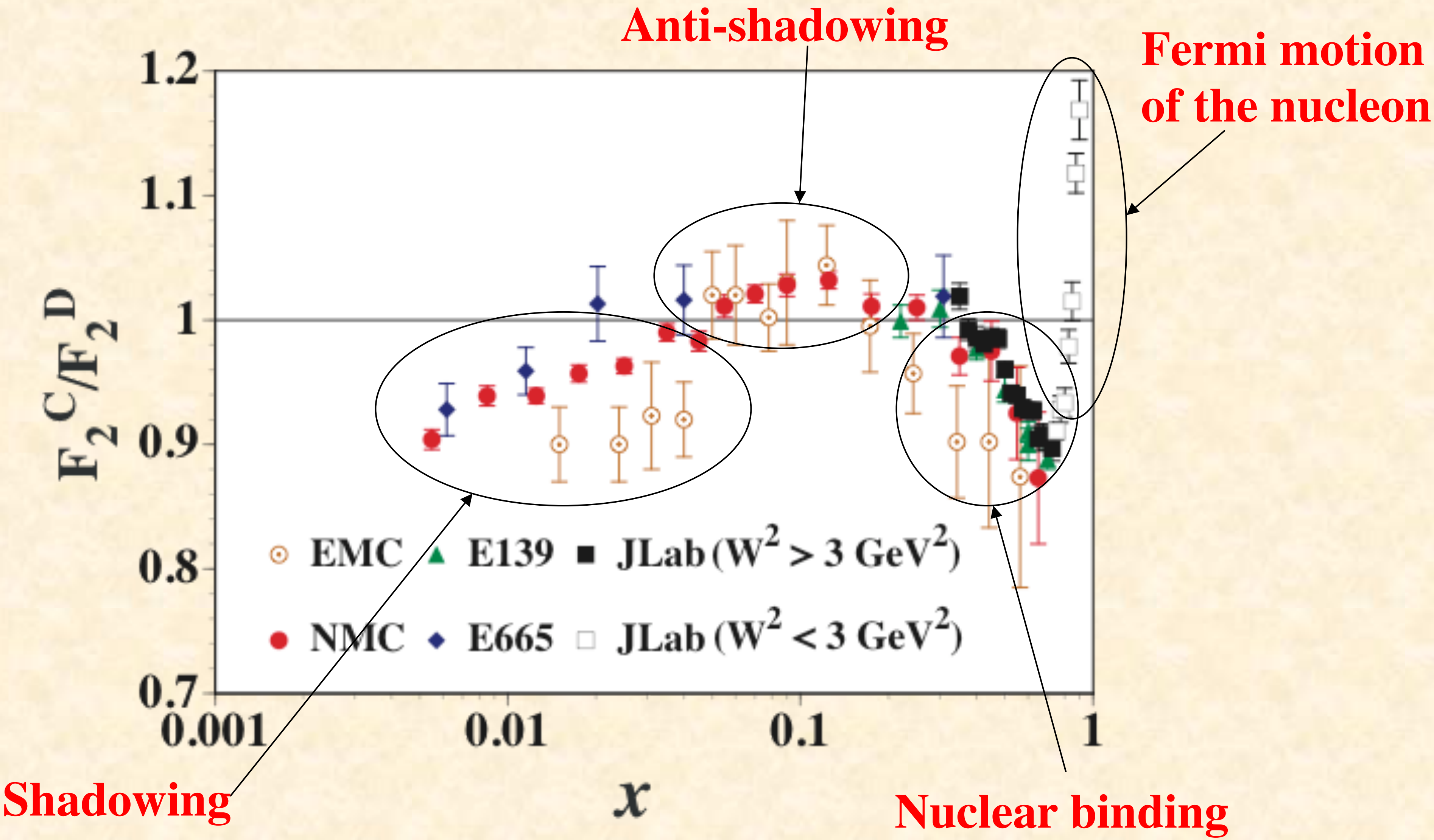
Comparisons with various PDFs

L. A. Harland-Lang, A. D. Martin,
P. Motylinkski, and R. S. Thorne,
Eur. Phys. J. C 75 (2015) 204.



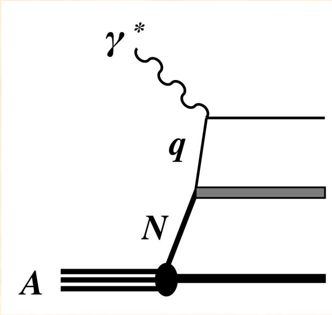
Structure functions of nuclei

Nuclear modifications of structure function F_2



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

Binding and Fermi motion



Convolution: $W^A_{\mu\nu}(p_A, q) = \int d^4p\, S(p)\, W^N_{\mu\nu}(p_N, q)$

$S(p)$ = **Spectral function = nucleon momentum distribution in a nucleus**

In a simple shell model: $S(p) = \sum_i \left|\phi_i(\vec{p})\right|^2 \delta(p_0 - M_N - \varepsilon_i)$

Separation energy: ε_i

$$\hat{P}_2^{\mu\nu} = -\frac{M_N^2 \nu}{2\tilde{p}^2}\left(g^{\mu\nu} - \frac{3\tilde{p}^\mu \tilde{p}^\nu}{\tilde{p}^2}\right)$$

$$\hat{P}_2^{\mu\nu} W_{\mu\nu} = F_2$$

Projecting out F_2**:** $F_2^A(x, Q^2) = \sum_i \int dz\, f_i(z)\, F_2^N(x/z, Q^2)$

$$z = \frac{p\cdot q}{M_N \nu} \simeq \frac{p\cdot q}{p_A \cdot q / A} \simeq \frac{p^+}{p_A^+ / A}$$ **lightcone momentum fraction**

$$a^\pm = \frac{a^0 \pm a^3}{\sqrt{2}}$$

$$q = (\nu,\ 0,\ 0,\ -\sqrt{\nu^2 + Q^2})$$

$$q^+ = -\frac{M x}{\sqrt{2}},\quad q^- = \frac{2\nu + M x}{\sqrt{2}} = \sqrt{2}\nu \gg M$$

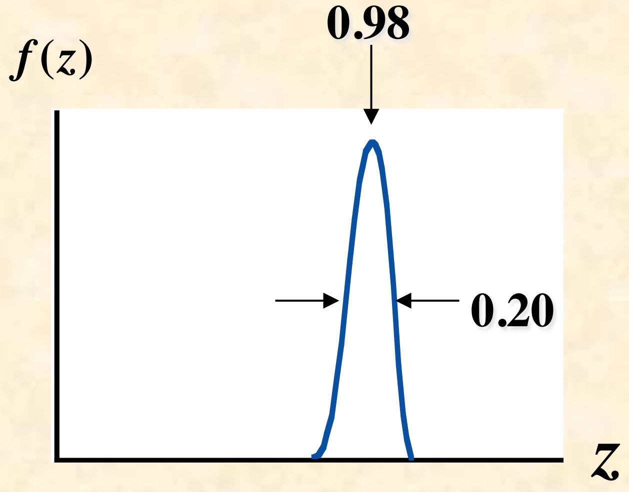
$$p\cdot q = p^+ q^- + p^- q^+ - \vec{p}_T \cdot \vec{q}_T \simeq p^+ q^-$$

$$f_i(z) = \int d^3p\, z\, \delta\left(z - \frac{p\cdot q}{M_N \nu}\right) \left|\phi_i(\vec{p})\right|^2$$ **lightcone momentum distribution for a nucleon** i

$$F_2^A(x,Q^2) = \sum_i \int dz\, f_i(z)\, F_2^N(x/z,Q^2) \qquad f_i(z) = \int d^3p\, z\, \delta\left(z - \frac{p\cdot q}{M_N \nu}\right) |\phi_i(\vec{p})|^2$$

$$z = \frac{p\cdot q}{M_N\nu} = \frac{p^0\nu - \vec{p}\cdot\vec{q}}{M_N\nu} = 1 - \frac{|\varepsilon_i|}{M_N} - \frac{\vec{p}\cdot\vec{q}}{M_N\nu} \approx 1.00 - 0.02 \pm 0.20 \text{ for a medium-size nucleus}$$

If $f_i(z)$ were $f_i(z) = \delta(z-1)$, there is no nuclear modification: $F_2^A(x,Q^2) = F_2^N(x,Q^2)$.

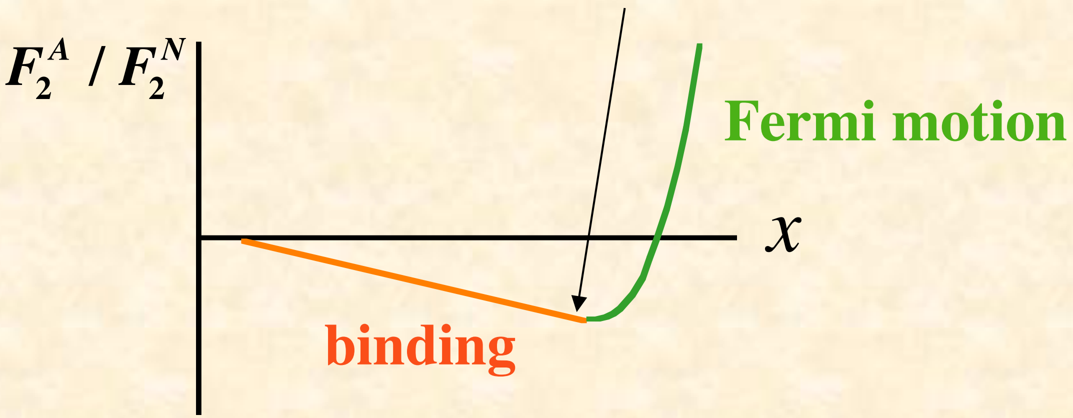


Because the peak shifts slightly (1→ 0.98), nuclear modification of F_2 is created.

$$F_2^A(x,Q^2) \simeq F_2^N(x/0.98,Q^2)$$

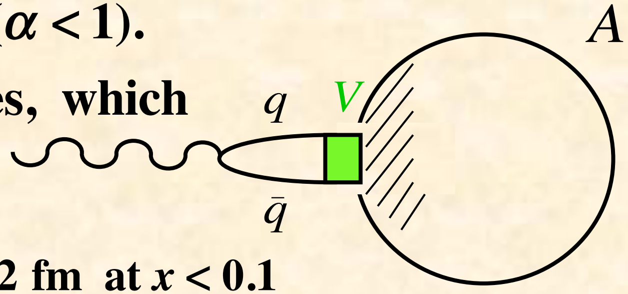
For $x = 0.60,\ x/0.98 = 0.61$

$$\frac{F_2^N(x=0.61)}{F_2^N(x=0.60)} = \frac{0.021}{0.024} = 0.88$$



Shadowing

- Shadowing means that internal constituents are shadowed due to the existence of nuclear surface ones, so that the cross section is smaller than the each nucleon contribution: $\sigma_A = A^{\alpha}\sigma_N$ $(\alpha < 1)$.
- A virtual photon transforms into vector meson (or $q\bar{q}$) states, which then interact with a target nucleus.

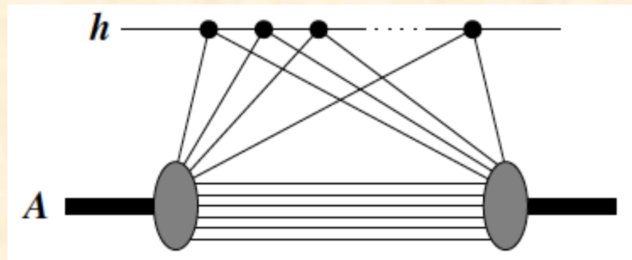


Propagation length of V ($q\bar{q}$): $\lambda = \frac{1}{|E_V - E_\gamma|} = \frac{2\nu}{M_V^2 + Q^2} = \frac{0.2\ \text{fm}}{x} > 2\ \text{fm}$ at $x < 0.1$

At small x, the virtual photon interacts with the target nucleus as if it were a vector meson (or $q\bar{q}$).

- Shadowing takes place due to multiple scattering.

For example, the vector meson interacts elastically with a surface nucleon and then interacts inelastically with a central nucleon.
Because this amplitude is opposite in phase to the one-step amplitude for an inelastic interaction with the central nucleon, the nucleon sees a reduced hadronic flux (namely the shadowing).



Nuclear
Parton Distribution Functions

Experimental data

(1) F_2^A / F_2^D

NMC: p, He, Li, C, Ca
SLAC: He, Be, C, Al, Ca, Fe, Ag, Au
EMC: C, Ca, Cu, Sn
E665: C, Ca, Xe, Pb
BCDMS: N, Fe
HERMES: N, Kr

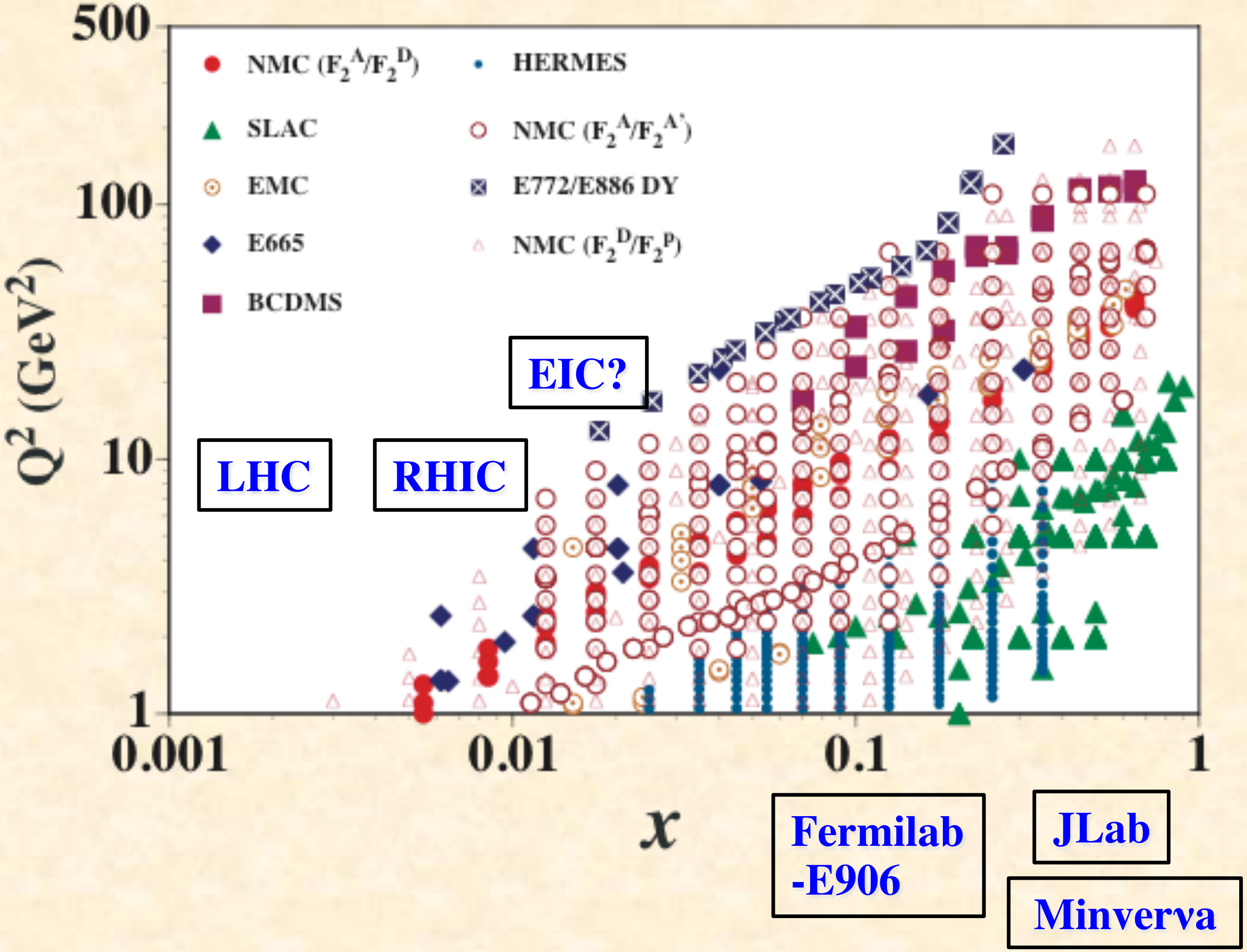
+ JLab data

(2) $F_2^A / F_2^{A'}$

NMC: Be / C, Al / C, Ca / C, Fe / C, Sn / C, Pb / C, C / Li, Ca / Li

(3) $\sigma_{DY}^A / \sigma_{DY}^{A'}$

E772: C / D, Ca / D, Fe / D, W / D
E866: Fe / Be, W / Be



Current nuclear data are kinematically limited.

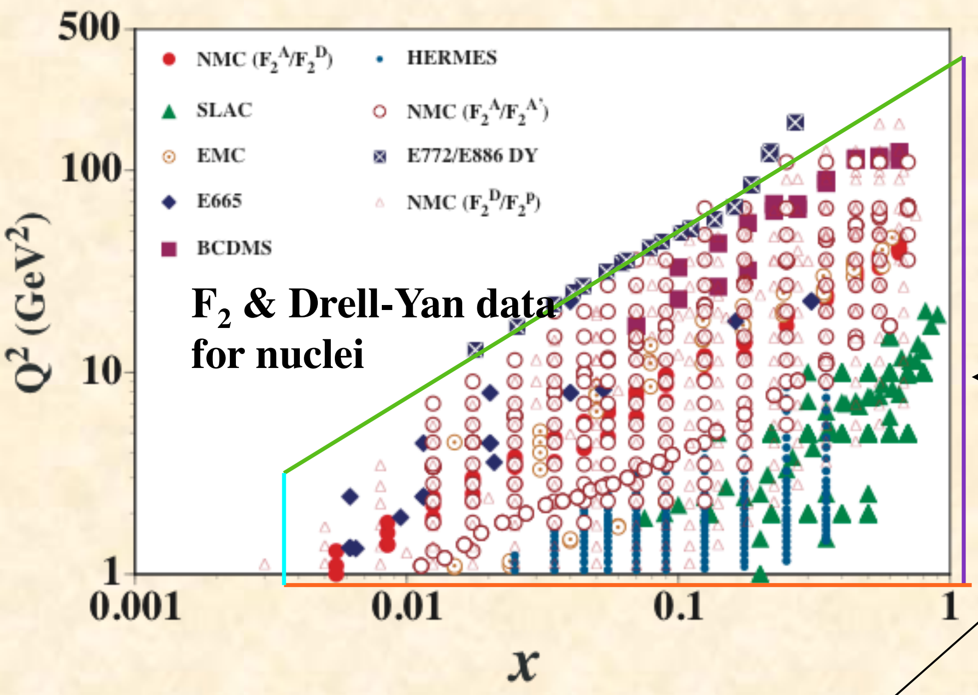
$$x = \frac{Q^2}{2p \cdot q} \simeq \frac{Q^2}{ys}$$

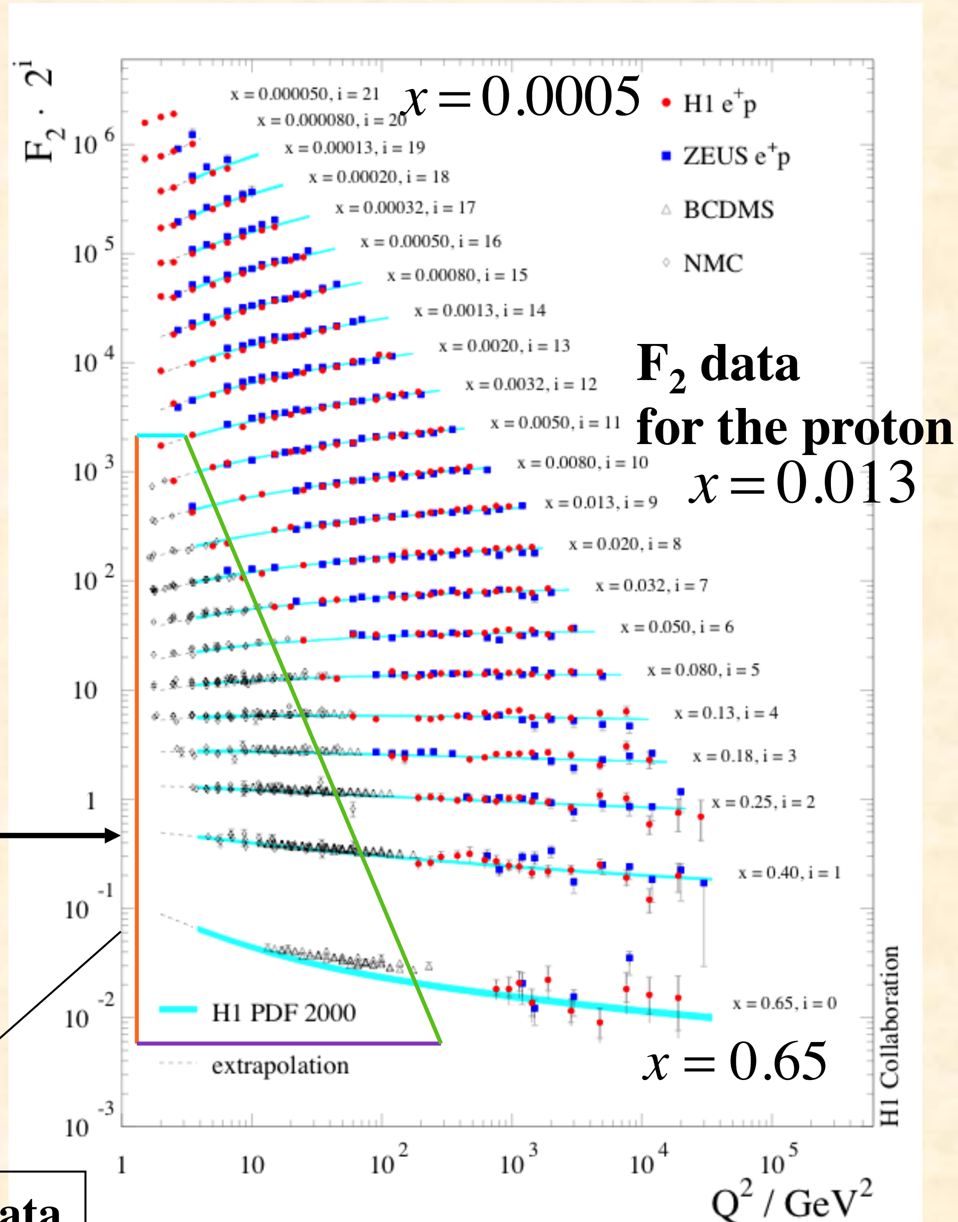
(from H1 and ZEUS, hep-ex/0502008)

$$\text{fixed target: } \min(x) = \frac{Q^2}{2M_N E_{lepton}} \le \frac{1}{2E_{lepton}(\text{GeV})}$$

$$\text{if } Q^2 \ge 1\ \text{GeV}^2$$

$$\text{for } E_{lepton}(\text{NMC}) = 200\ \text{GeV},\ \min(x) = \frac{1}{2 \cdot 200} = 0.003$$





region of nuclear data

Functional form

Nuclear PDFs "per nucleon"

If there were no nuclear modification

$$Au^A(x) = Zu^p(x) + Nu^n(x), \quad Ad^A(x) = Zd^p(x) + Nd^n(x) \qquad p = \text{proton}, \quad n = \text{neutron}$$

Isospin symmetry: $u^n = d^p \equiv d, \qquad d^n = u^p \equiv u$

$$\rightarrow \quad u^A(x) = \frac{Zu(x) + Nd(x)}{A}, \qquad d^A(x) = \frac{Zd(x) + Nu(x)}{A}$$

Take account of nuclear effects by $w_i(x, A)$

$$u_v^A(x) = w_{u_v}(x,A)\frac{Zu_v(x) + Nd_v(x)}{A}, \quad d_v^A(x) = w_{d_v}(x,A)\frac{Zd_v(x) + Nu_v(x)}{A}$$

$$\bar{u}^A(x) = w_{\bar{q}}(x,A)\frac{Z\bar{u}(x) + N\bar{d}(x)}{A}, \qquad \bar{d}^A(x) = w_{\bar{q}}(x,A)\frac{Z\bar{d}(x) + N\bar{u}(x)}{A}$$

$$\bar{s}^A(x) = w_{\bar{q}}(x,A)\bar{s}(x)$$

$$g^A(x) = w_g(x,A)g(x)$$

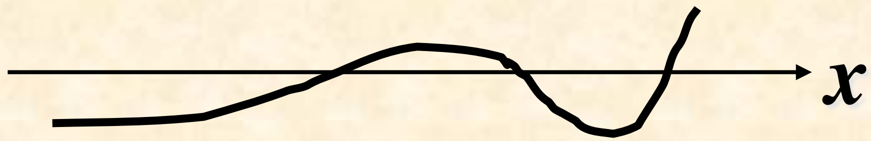
at Q^2=1 GeV^2 ($\equiv Q_0^2$)

Nuclear modifications and constraints

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

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

Note: The region $x > 1$ cannot be described by this parametrization.



A simple function = cubic polynomial

Three constraints

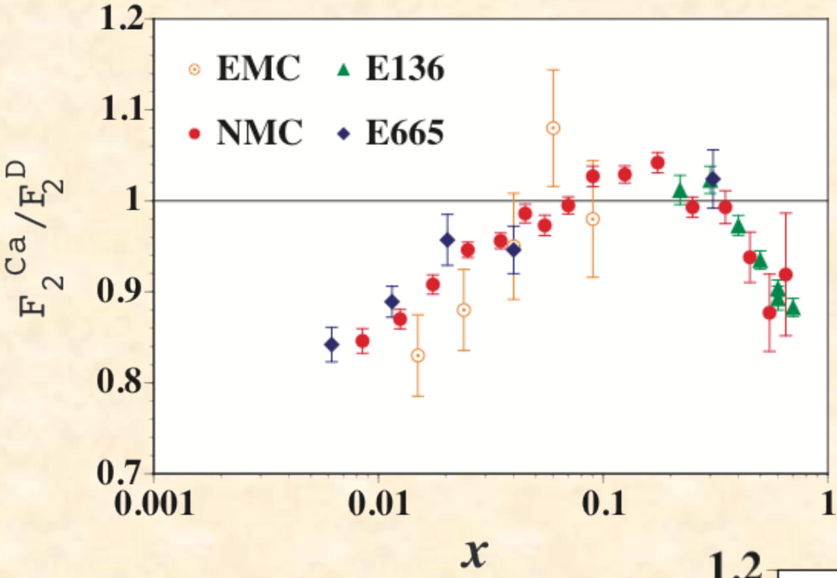
Nuclear charge: $Z = A\int dx\left[\frac{2}{3}\left(u^A - \bar{u}^A\right) - \frac{1}{3}\left(d^A - \bar{d}^A\right) - \frac{1}{3}\left(s^A - \bar{s}^A\right)\right] = A\int dx\left[\frac{2}{3}u_v^A - \frac{1}{3}d_v^A\right]$

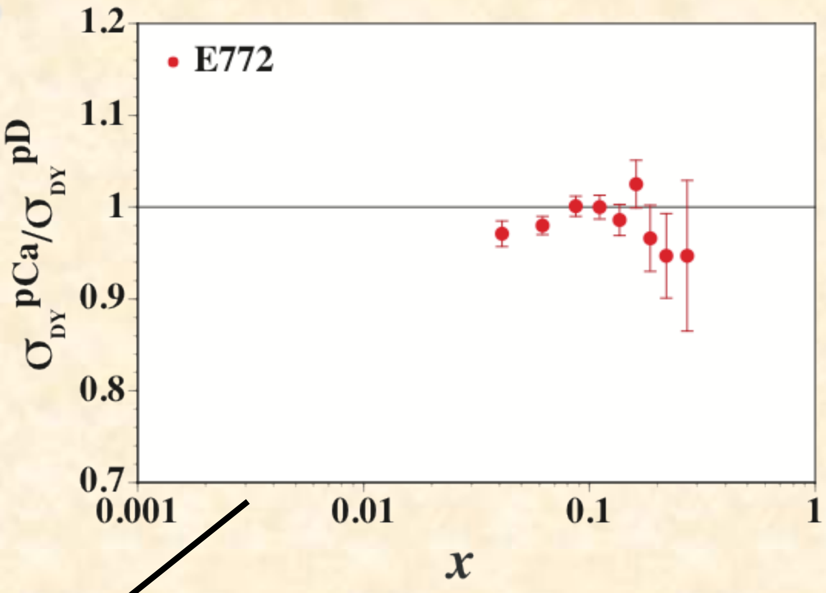
Baryon number: $A = A\int dx\left[\frac{1}{3}\left(u^A - \bar{u}^A\right) + \frac{1}{3}\left(d^A - \bar{d}^A\right) + \frac{1}{3}\left(s^A - \bar{s}^A\right)\right] = A\int dx\left[\frac{1}{3}u_v^A + \frac{1}{3}d_v^A\right]$

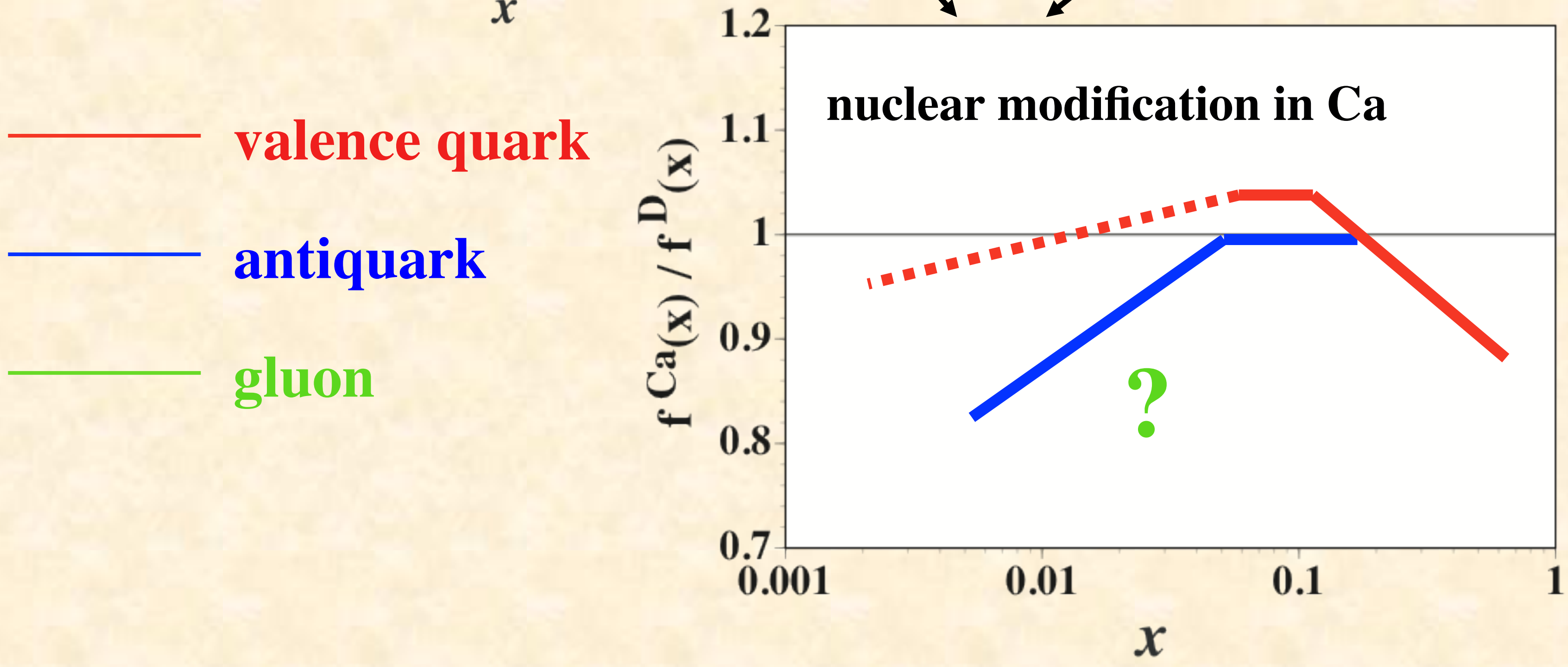
Momentum: $A = A\int dx\left[u^A + \bar{u}^A + d^A + \bar{d}^A + s^A + \bar{s}^A + g\right]$

$$= A\int dx\left[u_v^A + d_v^A + 2\left(\bar{u}^A + \bar{d}^A + \bar{s}^A\right) + g\right]$$

Nuclear modification of PDFs







Global analyses on nuclear PDFs

I may miss some papers.

HKN

- M. Hirai, S. Kumano, and T. -H. Nagai, Phys. Rev. C 76 (2007) 065207.
- Charged-lepton DIS, DY.

EPS

- K. J. Eskola, H. Paukkunen, and C. A. Salgado, JHEP 04 (2009) 065; arXiv:1612.05741.
- Charged-lepton DIS, DY, π^0 production in dAu, Neutrino

nCTEQ

- I. Schienbein, J. Y. Yu, C. Keppel, J. G. Morfin, F. I. Olness, J. F. Owens, Phys. Rev. D 77 (2008) 054013; D80 (2009) 094004;
  K. Kovarik *et al.*, PRL 106 (2011) 122301; PoS DIS2013 (2013) 274; PoS DIS2014 (2014) 047; Phys. Rev. D 93 (2016) 085037.
- Neutrino DIS, Charged-lepton DIS, DY.

DSZS

- D. de Florian, R. Sassot, P. Zurita, M. Stratmann, Phys. Rev. D85 (2012) 074028.
- Charged-lepton DIS, DY, RHIC-π

See also L. Frankfurt, V. Guzey, and M. Strikman, Phys. Rev. D 71 (2005) 054001; Phys. Lett. B687 (2010) 167; Phys. Rept. 512 (2012) 255.

S. A. Kulagin and R. Petti, Phys. Rev. D 76 (2007) 094023; C 82 (2010) 054614; C 90 (2014) 045204; D 94 (2016) 113013.

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

Functional form of initial distributions at Q_0^2

Initial nuclear PDFs at

$$f_i^A(x) = \frac{1}{A}\left[Z f_i^{p/A}(x) + (A-Z) f_i^{n/A}(x)\right]$$

$f_i^{N/A}(x)$: PDF of bound nucleon in the nucleus

Isospin symmetry is assumed: $u \equiv d^n = u^p,\, d \equiv u^n = d^p$

Functional forms

- HKN07 ($Q_0^2 = 1$ GeV^2)

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

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

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

- CTEQ-08 ($Q_0^2 = 1.69$ GeV^2)

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

- DSZS12 ($Q_0^2 = 1.0$ GeV^2)

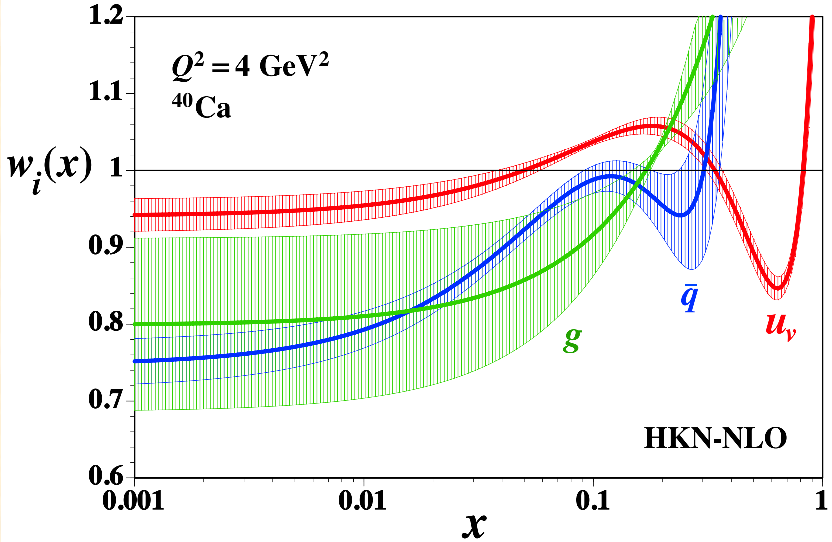
$$f_i^{N/A}(x) \equiv R_i^A(x) f_i^{MSTW\,2009}(x,Q_0^2),\; R_v^A(x) = \varepsilon_1 x^{\alpha_v}(1-x)^{\beta_1}[1 + \varepsilon_2(1-x)^{\beta_2}][1 + a_v(1-x)^{\beta_3}]$$

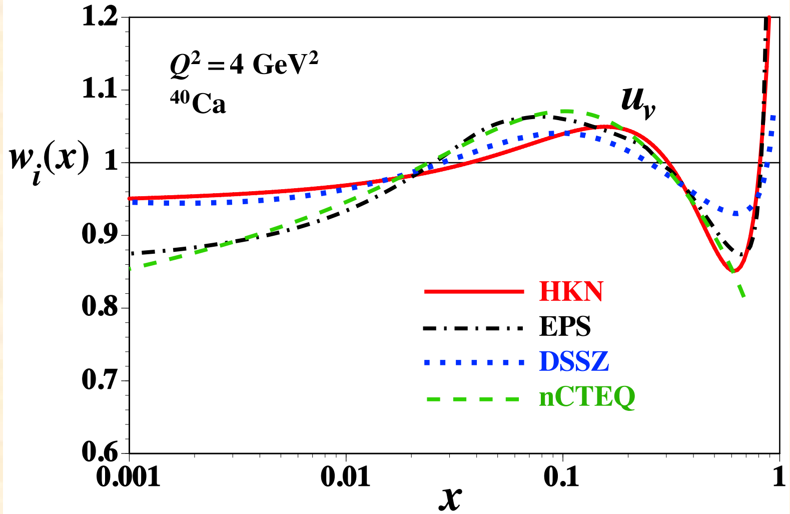
$$R_s^A(x) = R_v^A(x)\frac{\varepsilon_s}{\varepsilon_1}\frac{1 + a_s x^{\alpha_s}}{1 + a_s}, \quad R_g^A(x) = R_g^A(x)\frac{\varepsilon_g}{\varepsilon_1}\frac{1 + a_g x^{\alpha_g}}{1 + a_g}$$

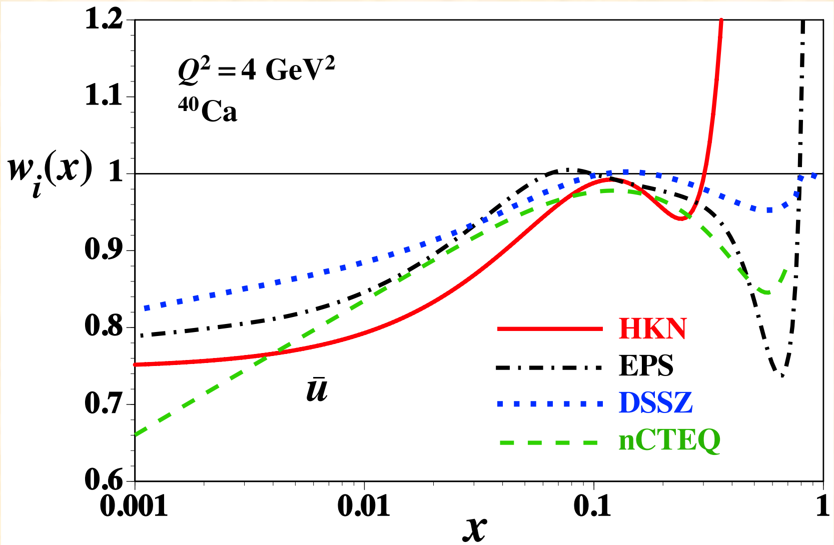
Review on neutrino interactions (arXiv: 1610.01464)

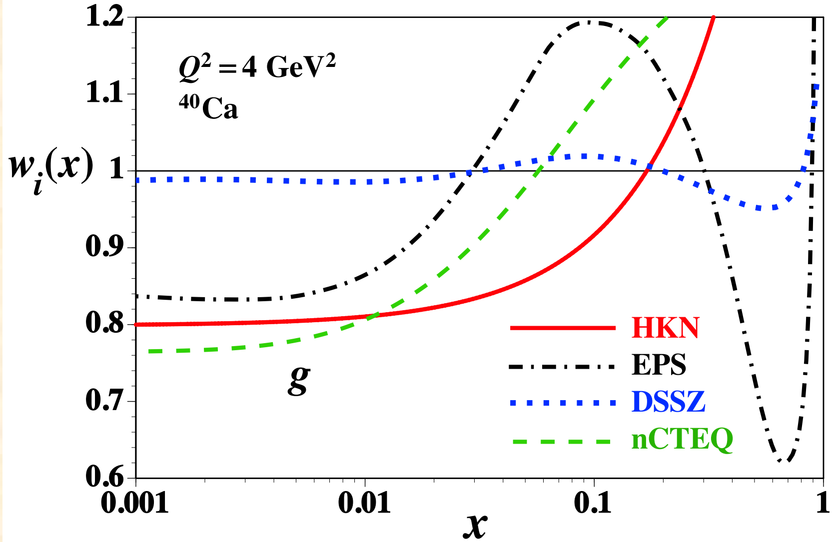
Towards a Unified Model of Neutrino-Nucleus Reactions for Neutrino Oscillation Experiments

S.X. Nakamura[1], H. Kamano[2,3], Y. Hayato[4], M. Hirai[5], W. Horiuchi[6], S. Kumano[2,3], T. Murata[1], K. Saito[7,3], M. Sakuda[8], T. Sato[1,3], Y. Suzuki[9,10]



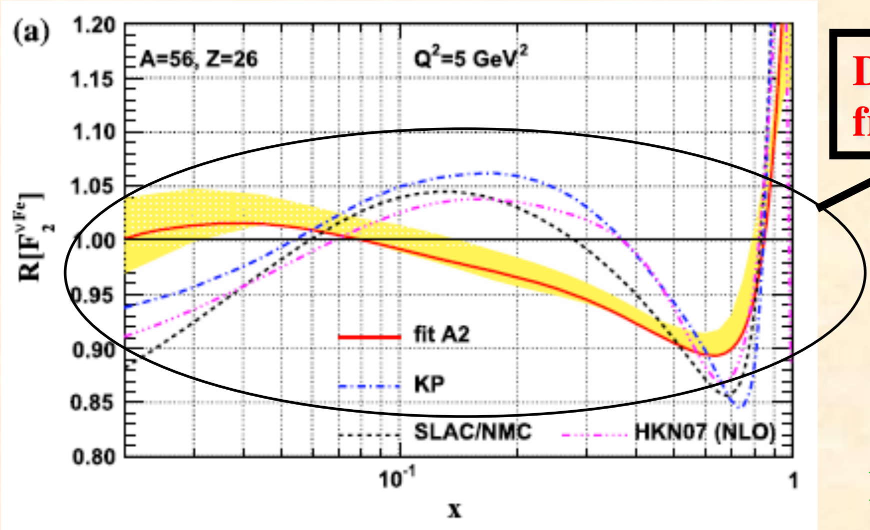






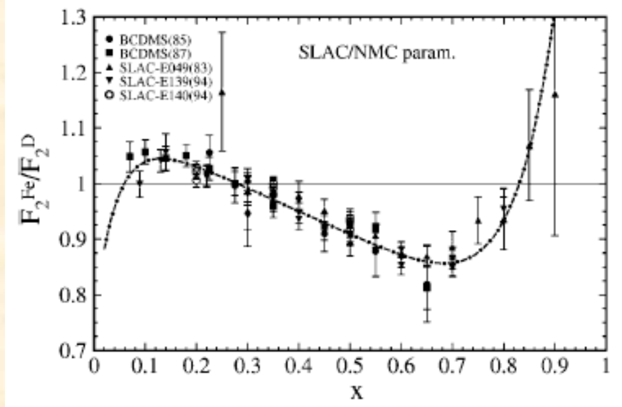
Analysis of CTEQ-2008 (Schienbein *et al.*)

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



Differences from typical NPDFs.

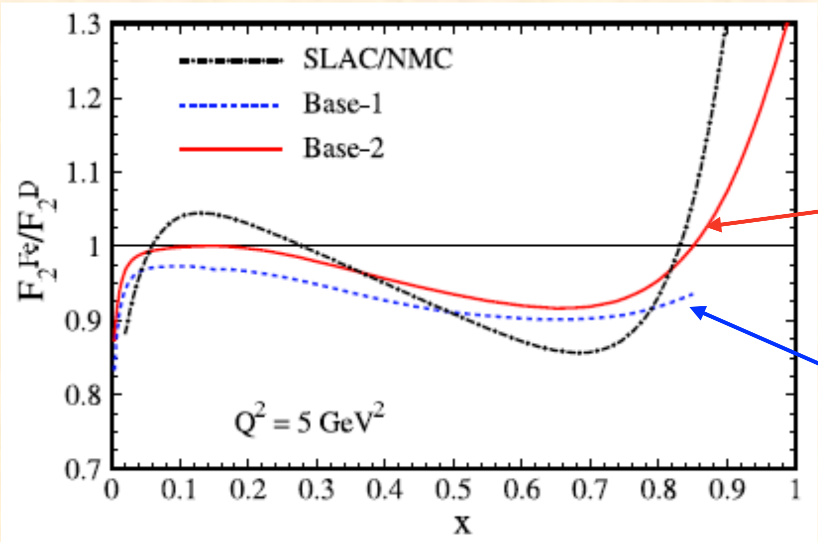
Charged-lepton scattering



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

Neutrino scattering

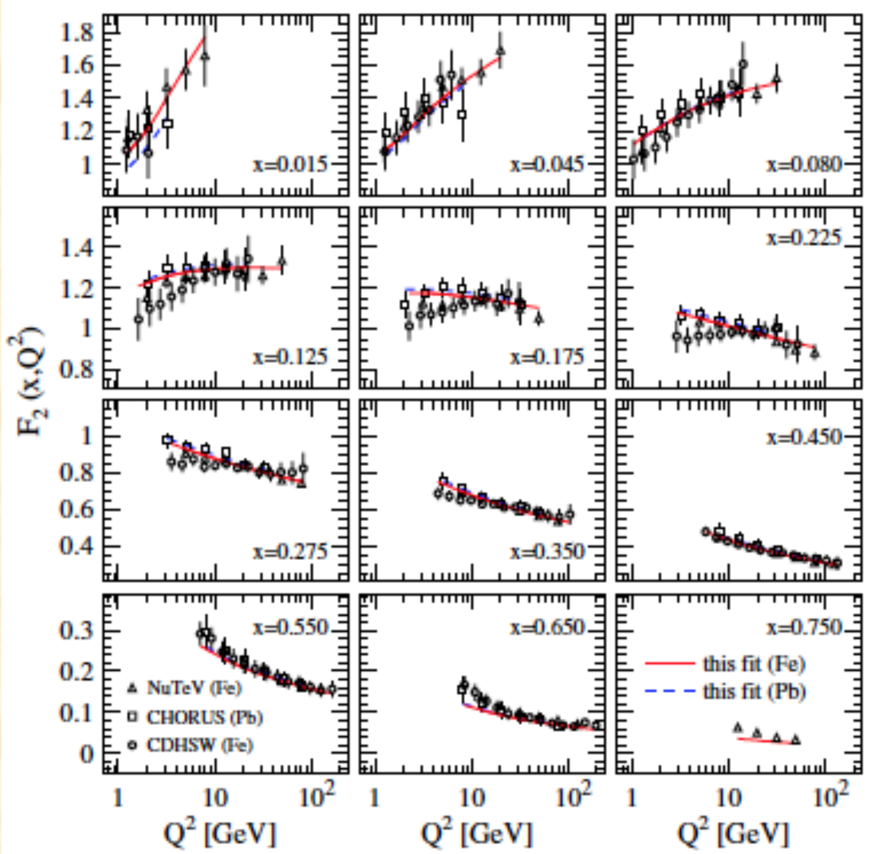


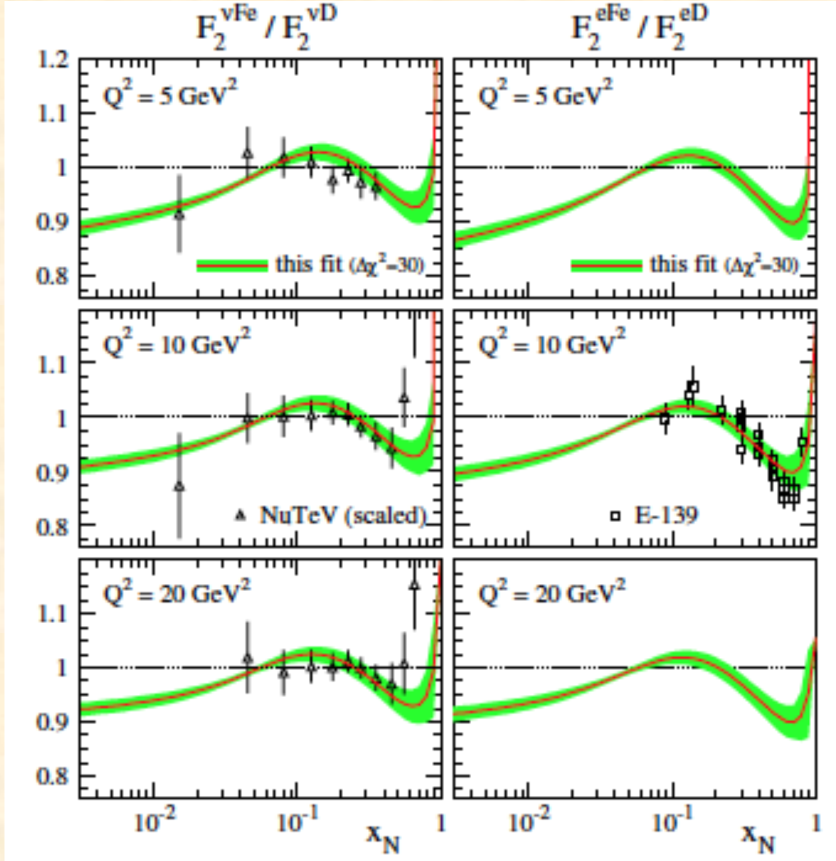
Base-2: Using current nucleonic PDFs, they (and MRST) obtained very different corrections from charged-lepton data.

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

Neutrino DIS ⇔ Charged DIS issue

D. de Florian, R. Sassot, P. Zurita, and M. Stratmann,
Phys. Rev. D 85 (2012) 074028.

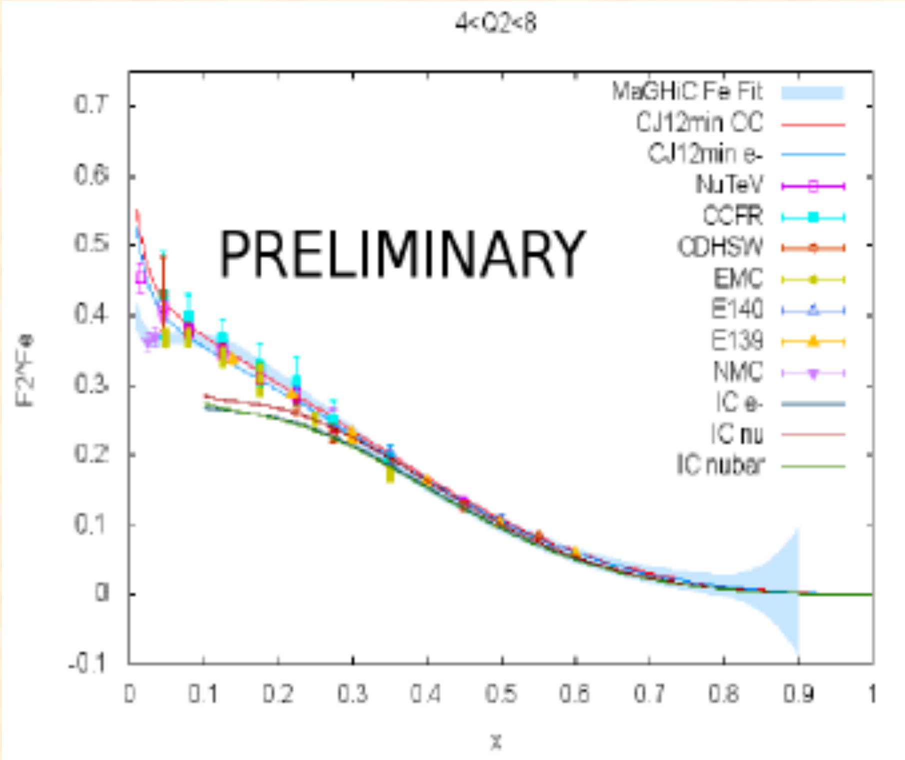




According to their analysis, the issue does not exist!?

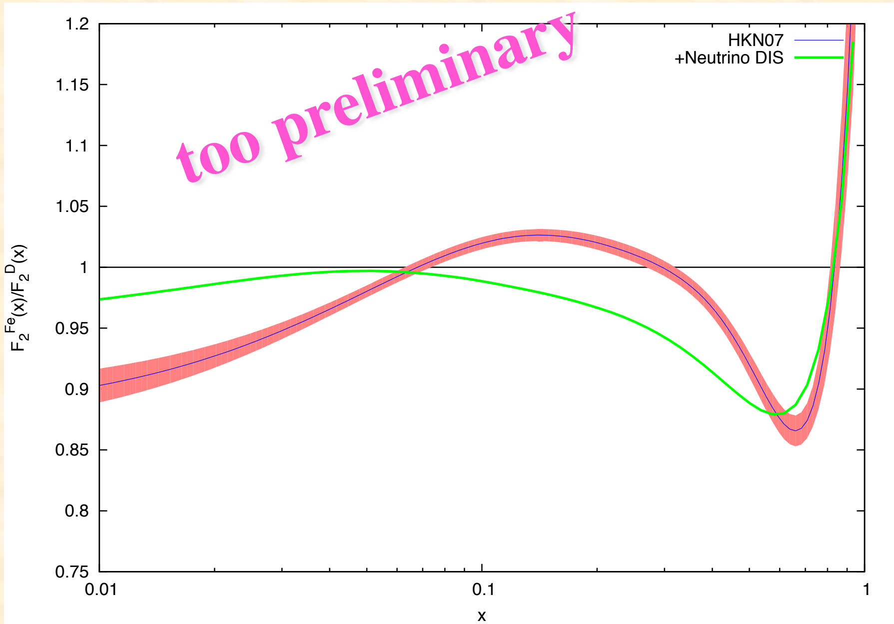
N. Kalantarians: Neutrino DIS ⇔ Charged DIS

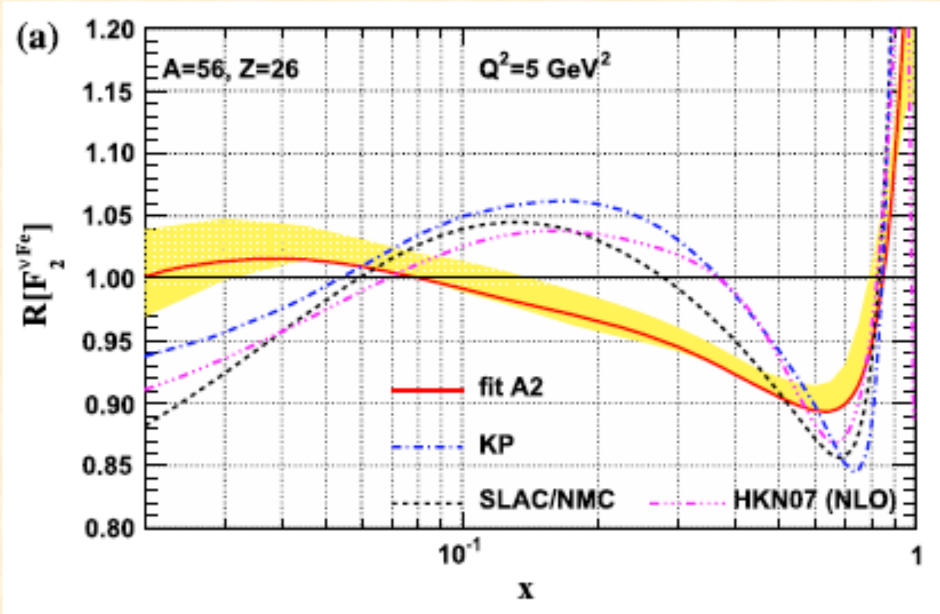
N. Kalantarians at NuInt15
JPS Conf. Proc. 12 (2016) 010028.



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

Our research in progress (M. Hirai, SK, K. Saito)



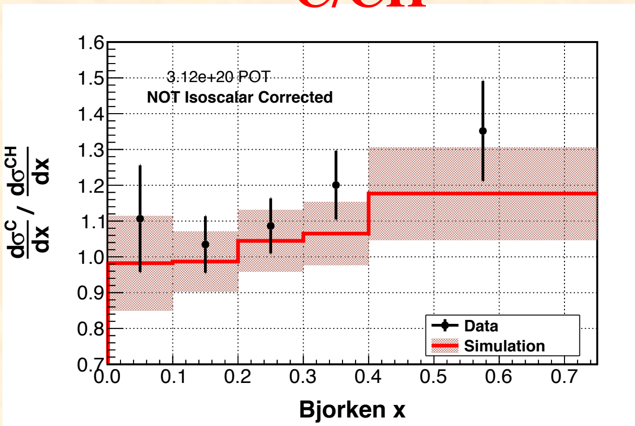


We are getting a similar modification to the nCTEQ one.

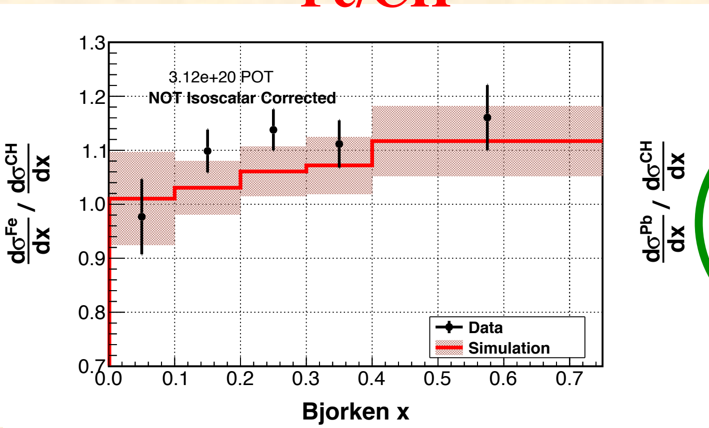
Measurements by Minerνa

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

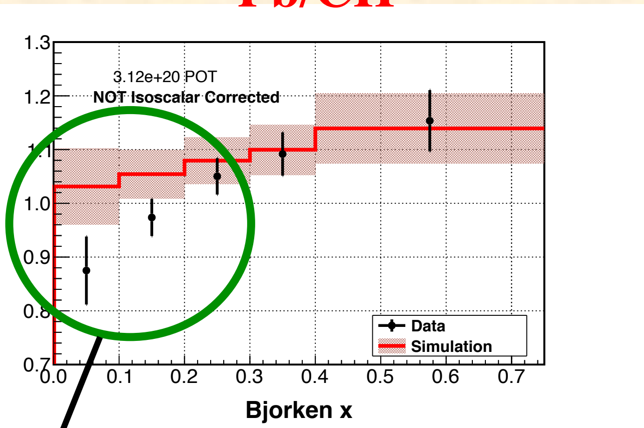
C/CH



Fe/CH



Pb/CH



Different shadowing from charged-lepton case?!

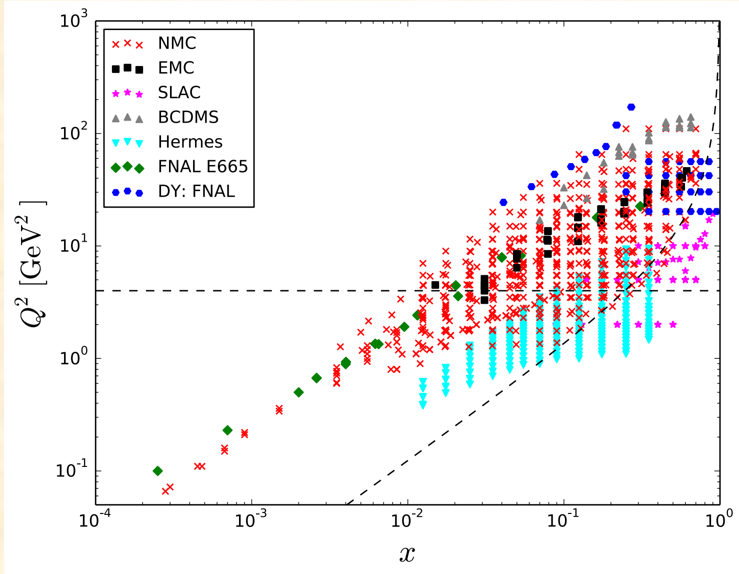
Recent analysis by nCTEQ15: data set

K. Kovarik *et al.*, PRD 93 (2016) 085037

Charged-lepton DIS

F_2^A/F_2^D Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
D	NMC-97	5160	[48]	292	201	247.73
He/D	Hermes	5156	[49]	182	17	13.45
	NMC-95,re	5124	[50]	18	12	9.78
	SLAC-E139	5141	[51]	18	3	1.42
Li/D	NMC-95	5115	[52]	24	11	6.10
Be/D	SLAC-E139	5138	[51]	17	3	1.37
C/D	FNAL-E665-95	5125	[53]	11	3	1.44
	SLAC-E139	5139	[51]	7	2	1.36
	EMC-88	5107	[54]	9	9	7.41
	EMC-90	5110	[55]	9	0	0.00
	NMC-95	5113	[52]	24	12	8.40
	NMC-95,re	5114	[50]	18	12	13.29
N/D	Hermes	5157	[49]	175	19	9.92
	BCDMS-85	5103	[56]	9	9	4.65
Al/D	SLAC-E049	5134	[57]	18	0	0.00
	SLAC-E139	5136	[51]	17	3	1.14
Ca/D	NMC-95,re	5121	[50]	18	12	11.54
	FNAL-E665-95	5126	[53]	11	3	0.94
	SLAC-E139	5140	[51]	7	2	1.63
	EMC-90	5109	[55]	9	0	0.00
Fe/D	SLAC-E049	5131	[58]	14	2	0.78
	SLAC-E139	5132	[51]	23	6	7.76
	SLAC-E140	5133	[59]	10	0	0.00
	BCDMS-87	5101	[60]	10	10	5.77
	BCDMS-85	5102	[56]	6	6	2.56
Cu/D	EMC-93	5104	[61]	10	9	4.71
	EMC-93(chariot)	5105	[61]	9	9	4.88
	EMC-88	5106	[54]	9	9	3.39
Kr/D	Hermes	5158	[49]	167	12	9.79
Ag/D	SLAC-E139	5135	[51]	7	2	1.60
Sn/D	EMC-88	5108	[54]	8	8	17.20
Xe/D	FNAL-E665-92	5127	[62]	10	2	0.72
Au/D	SLAC-E139	5137	[51]	18	3	1.74
Pb/D	FNAL-E665-95	5129	[53]	11	3	1.20
Total:				1205	414	403.70

$F_2^A/F_2^{A'}$ Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
C/Li	NMC-95,re	5123	[50]	25	7	5.56
Ca/Li	NMC-95,re	5122	[50]	25	7	1.11
Be/C	NMC-96	5112	[63]	15	14	4.08
Al/C	NMC-96	5111	[63]	15	14	5.39
Ca/C	NMC-95,re	5120	[50]	25	7	4.32
	NMC-96	5119	[63]	15	14	5.43
Fe/C	NMC-96	5143	[63]	15	14	9.78
Sn/C	NMC-96	5159	[64]	146	111	64.44
Pb/C	NMC-96	5116	[63]	15	14	7.74
Total:				296	202	107.85

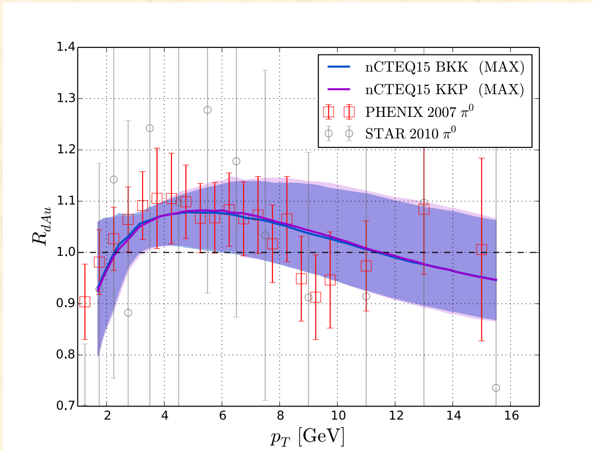


Drell-Yan

$\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
C/H2	FNAL-E772-90	5203	[65]	9	9	7.92
Ca/H2	FNAL-E772-90	5204	[65]	9	9	2.73
Fe/H2	FNAL-E772-90	5205	[65]	9	9	3.17
W/H2	FNAL-E772-90	5206	[65]	9	9	7.28
Fe/Be	FNAL-E886-99	5201	[66]	28	28	23.09
W/Be	FNAL-E886-99	5202	[66]	28	28	23.62
Total:				92	92	67.81

Pion-production in dA

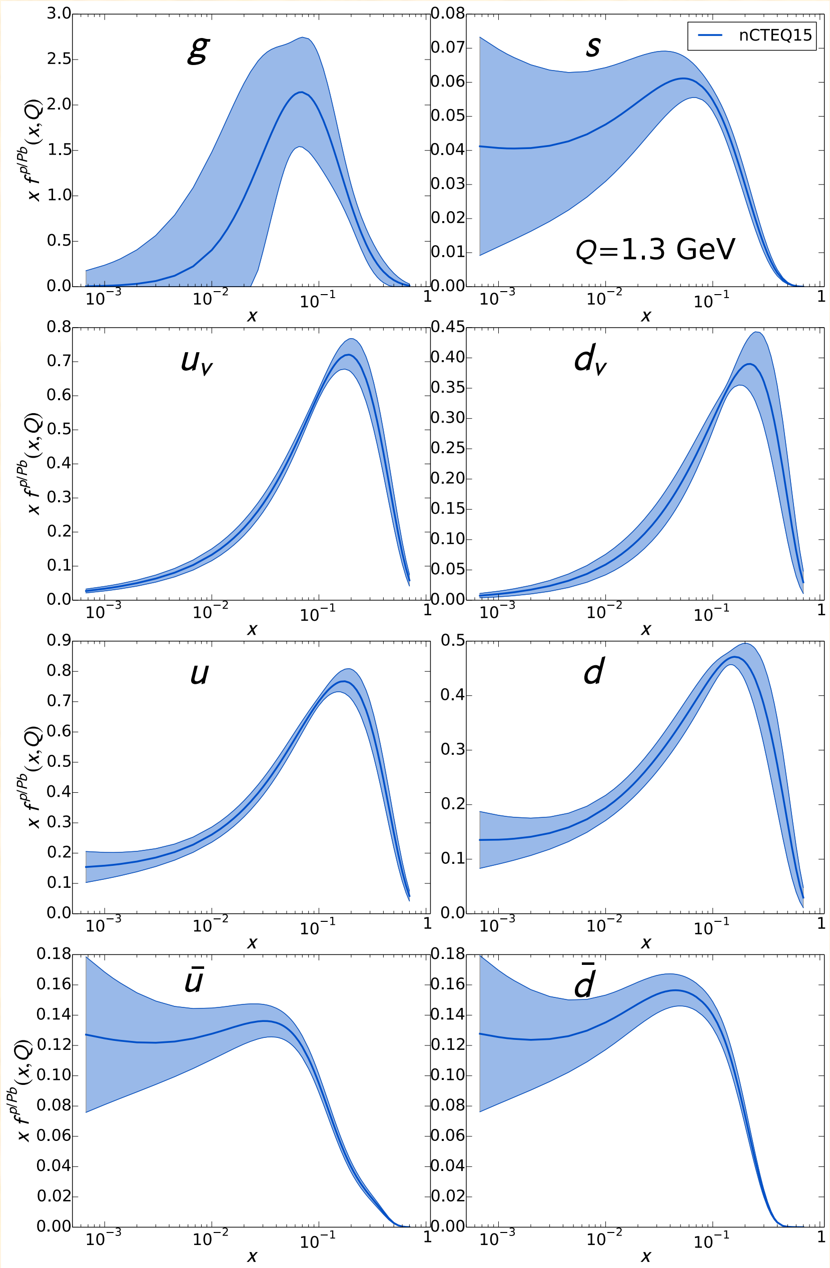
$R_{dAu}^{\pi}/R_{pp}^{\pi}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
dAu/pp	PHENIX	PHENIX	[67]	21	20	6.63
	STAR-2010	STAR	[68]	13	12	1.41
Total:				34	32	8.04

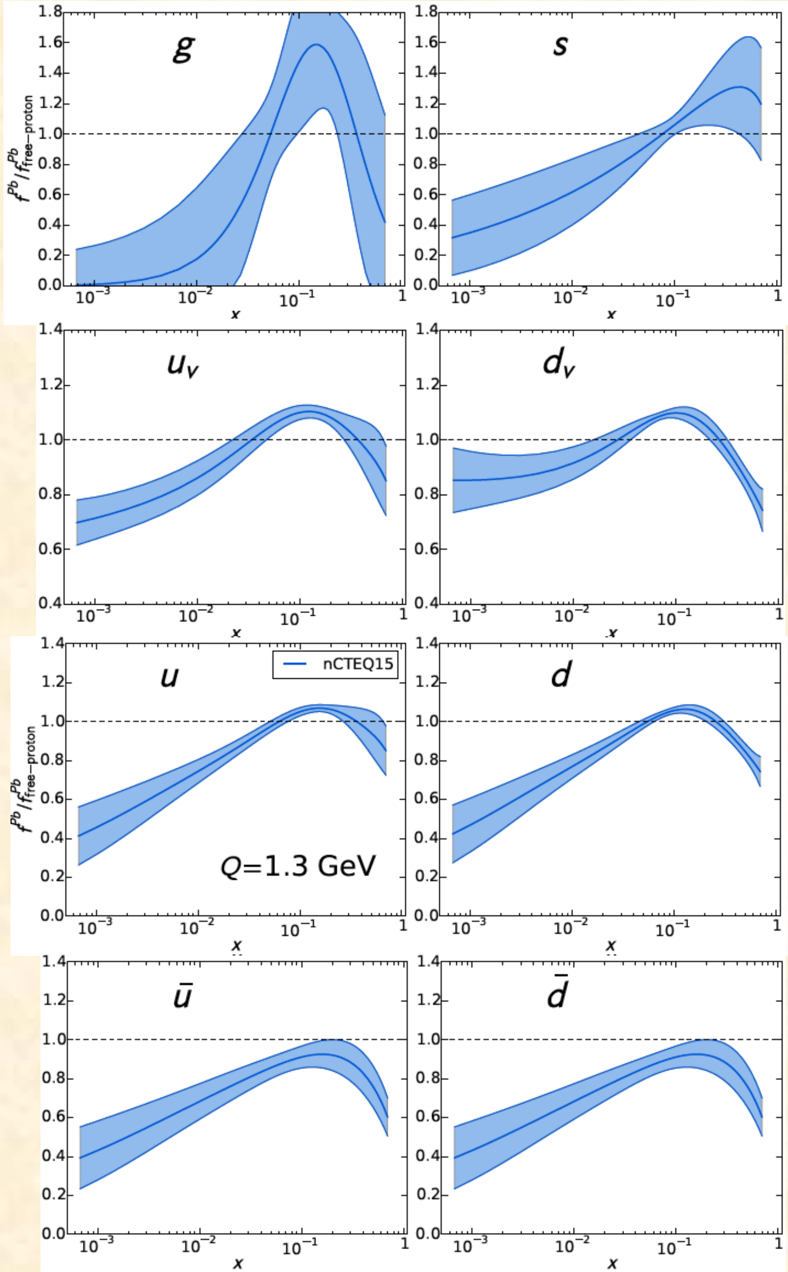


- DIS: $Q > 2$ GeV and $W > 3.5$ GeV
- DY: $2 < M < 300$ GeV
- π^0 production: $p_T > 1.7$ GeV

nCTEQ15

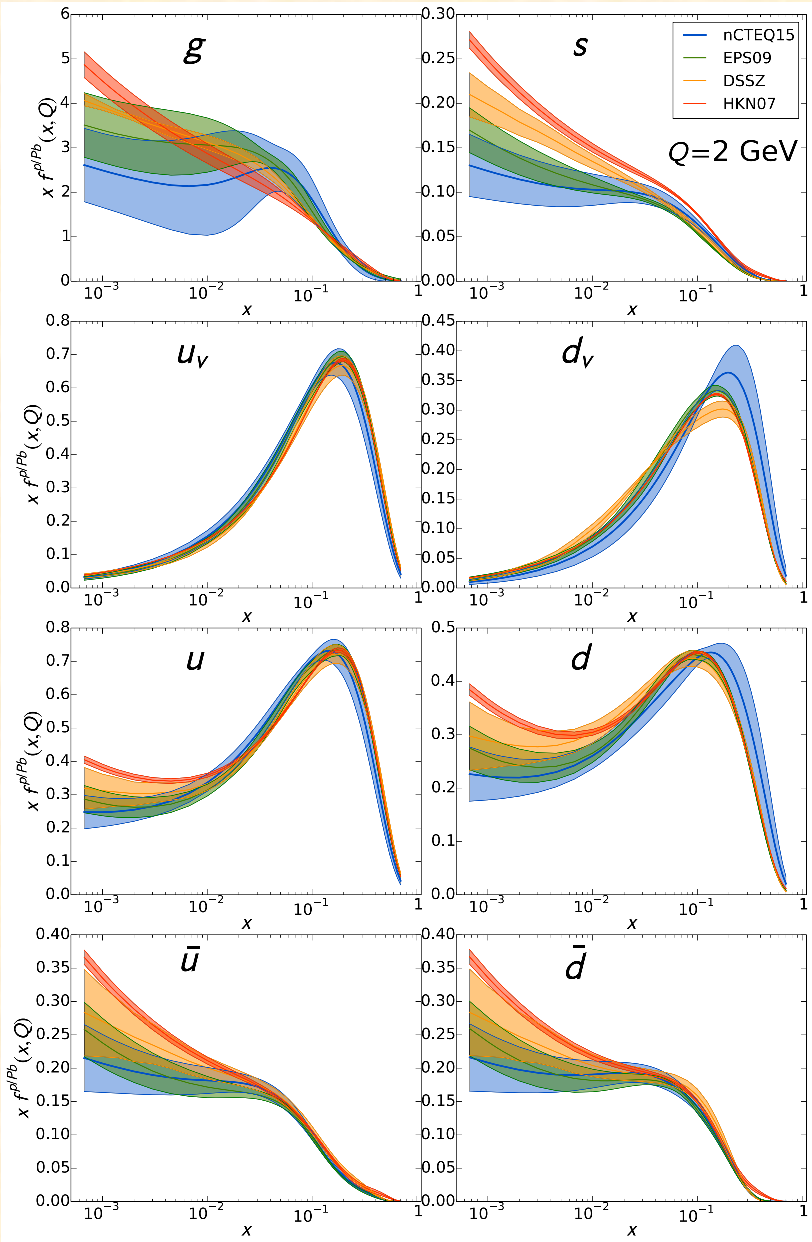
$Q^2 = (1.3)^2\ \mathrm{GeV}^2$

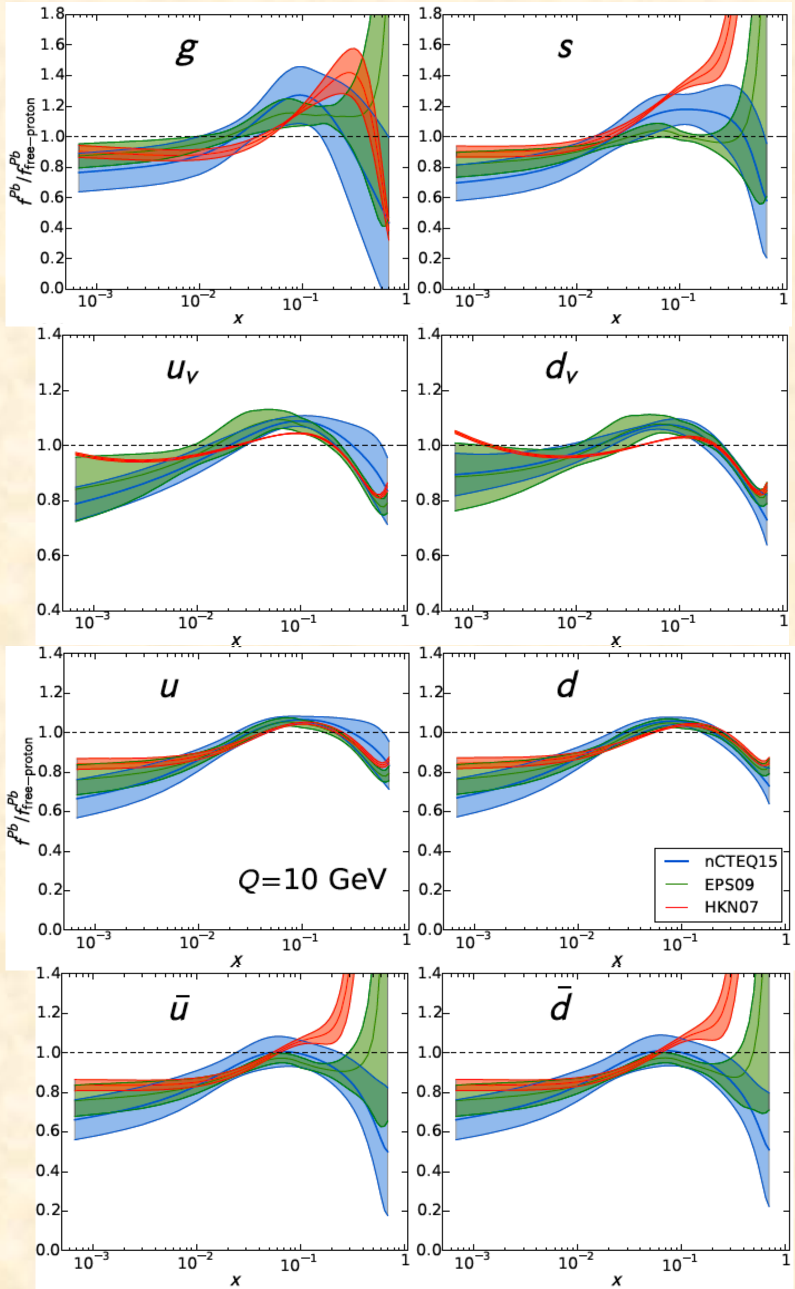




nCTEQ15: Comparison with others

$Q^2 = (2)^2\ \mathrm{GeV}^2$





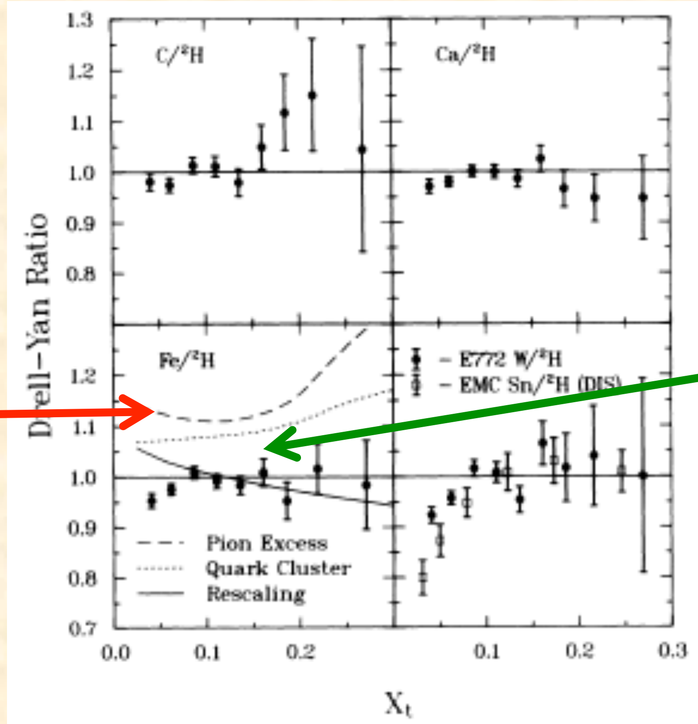
Nuclear antiquark distributions and Drell-Yan

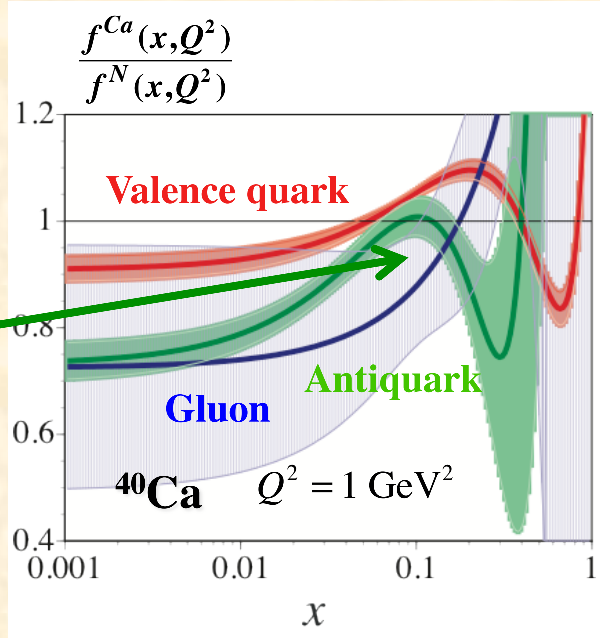
D. M. Alde *et al.*,
PRL. 64, 2479 (1990).

$$\frac{\sigma_{pA}}{\sigma_{pD}} \approx \frac{\bar{q}_A}{\bar{q}_D}$$

No nuclear effects
from pion contributions

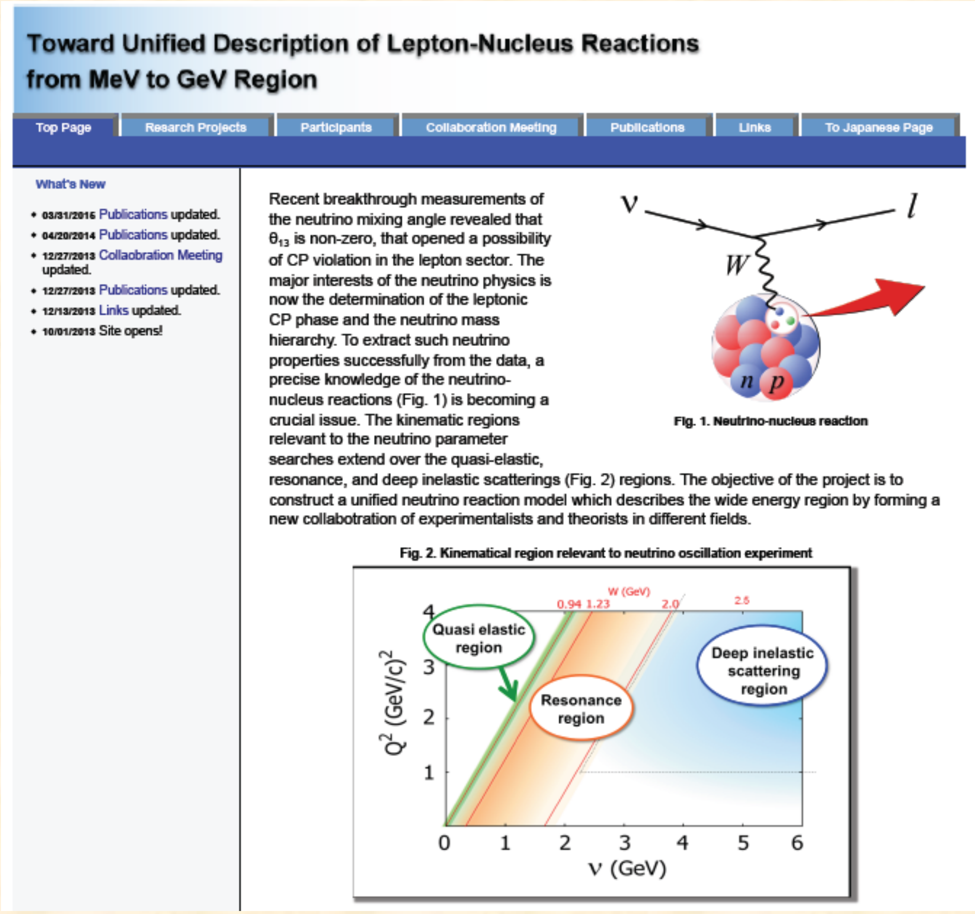
E. L. Berger, F. Coester, R. B. Wiringa,
PRD 29, 398 (1984)





Fermilab-E906 in progress!

ν-interaction collaboration at J-PARC


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

Top Page | Resarch Projects | Participants | Collaboration Meeting | Publications | Links | To Japanese Page

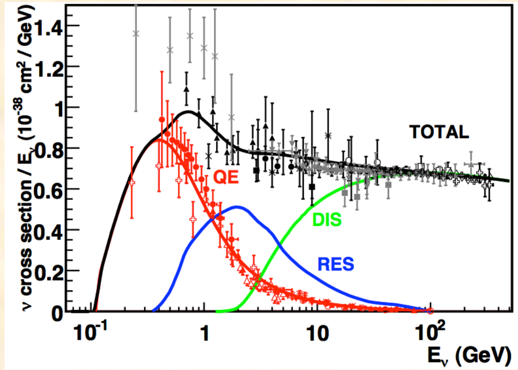
What's New

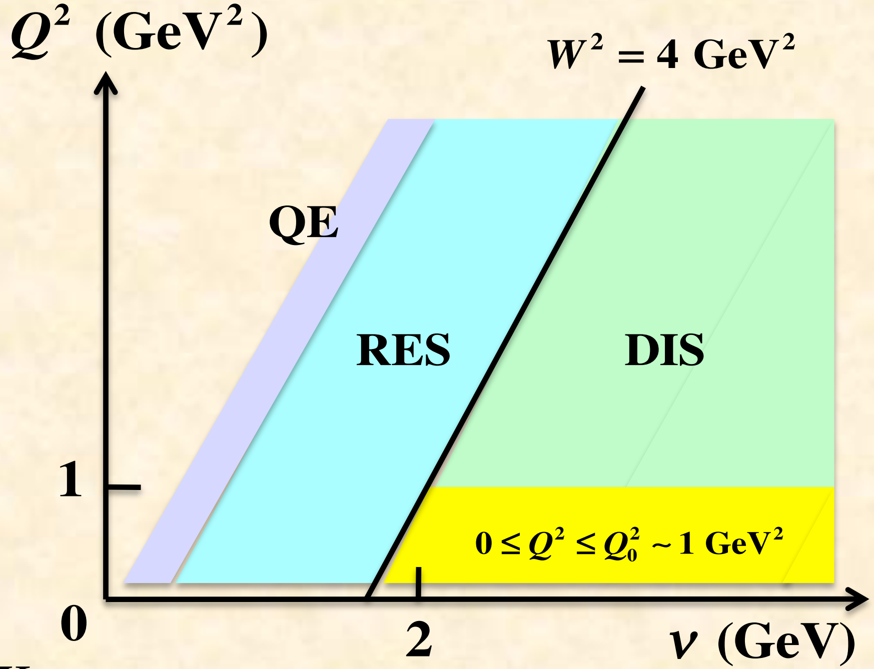
- 03/31/2016 Publications updated.
- 04/20/2014 Publications updated.
- 12/27/2013 Collaobration Meeting updated.
- 12/27/2013 Publications updated.
- 12/13/2013 Links updated.
- 10/01/2013 Site opens!

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



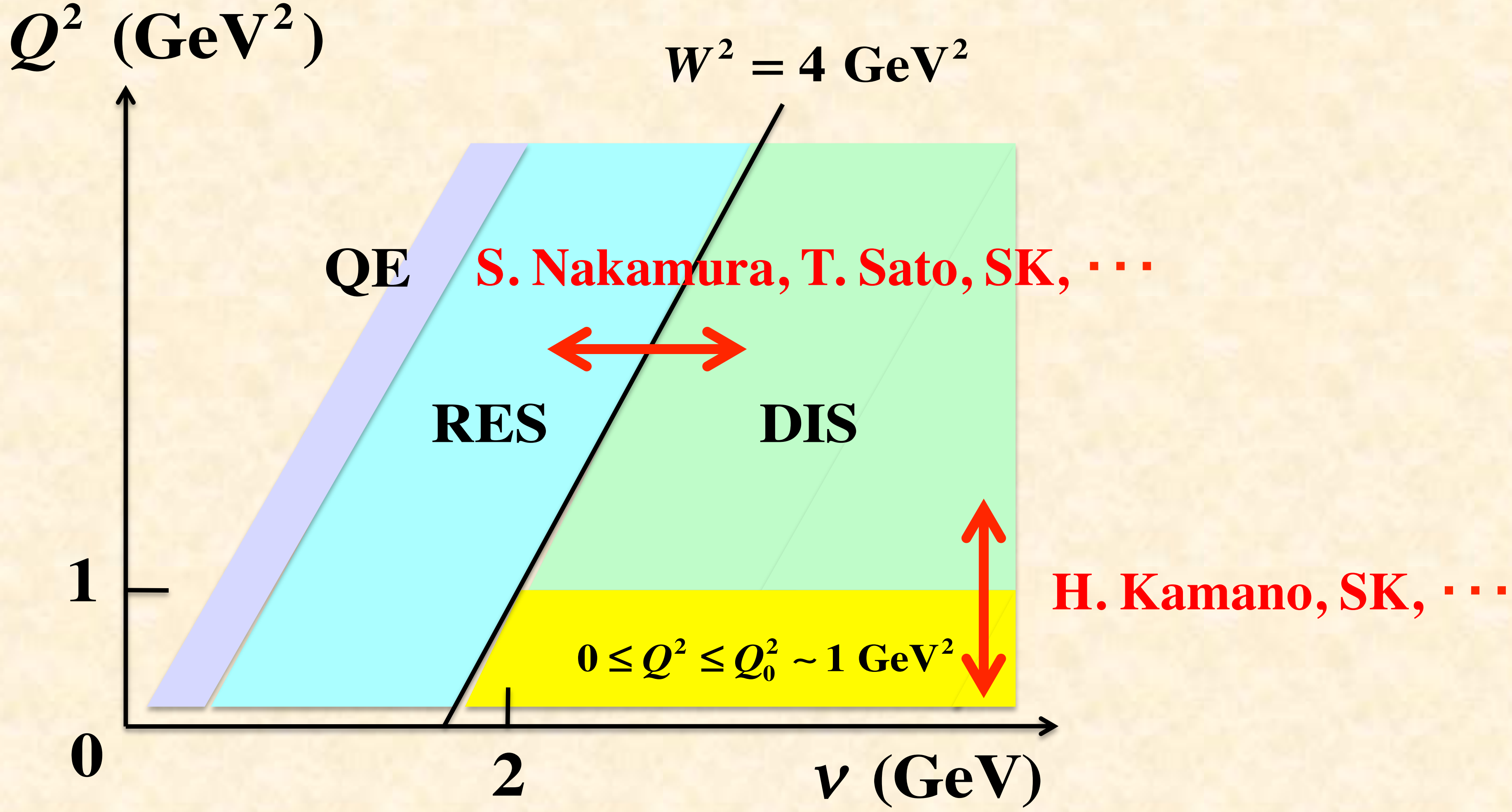


Y. Hayato, M. Hirai, W. Horiuchi, H. Kamano, S. Kumano,
T. Murata, S. Nakamura, K. Saito, M. Sakuda, T. Sato

http://nuint.kek.jp/index_e.html, ν interactions

http://j-parc-th.kek.jp/ J-PARC branch, KEK Theory

Research in progress at J-PARC theory



Summary

Global analyses for the nuclear PDFs
by using data of charged-lepton, neutrino DIS, pA, AA collisions

Valence quark: reasonably good, in progress at JLab, Minerva for large x

Antiquark: good only at $x = 0.1$, in progress at Fermilab (E906) $x = 0.1 \sim 0.4$.

Gluon: large uncertainties in the whole-x region, LHC, RHIC

Issues

- Charged-lepton DIS ⇔ Neutrino DIS
- Matching with resonance model and $Q^2 \to 0$ region
- Gluon distributions

New experimental information

- JLab, Fermilab-DY, Minerva, LHC, …

The End

The End