Neutrino-nucleus interactions in the DIS region

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Workshop on "Neutrino frontier in 2014"
MEXT Kakenhi (#2504), Unification and Development of the Neutrino Science Frontier
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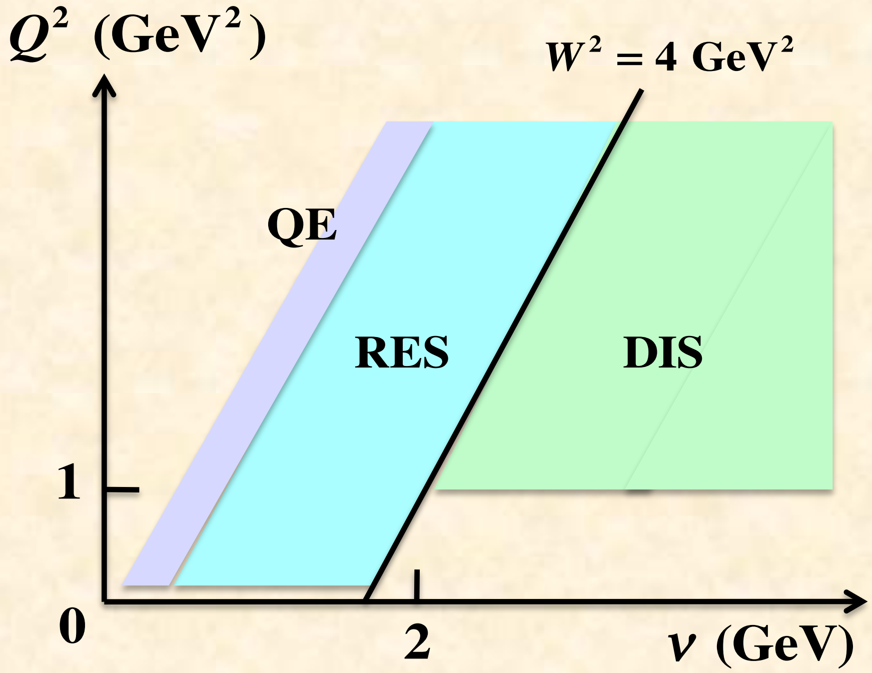
http://hep-www.px.tsukuba.ac.jp/cgi-bin/nfws2014/nfws2014.pl

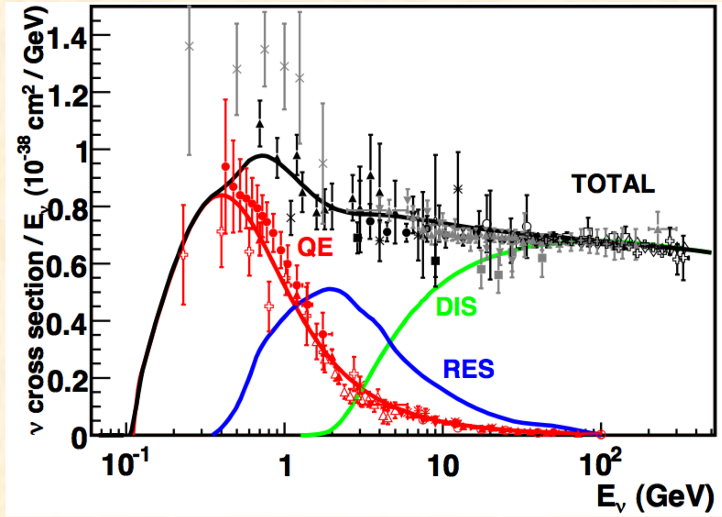
December 22, 2014

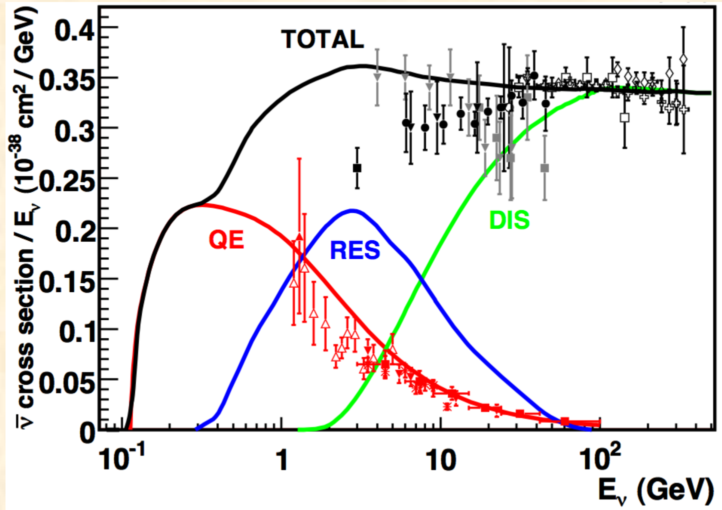
Contents

Introduction to neutrino deep inelastic scattering (DIS)

Kinematical regions of neutrino-nucleus scattering







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

- QE (Quasi elastic)
- RES (Resonance)
- DIS (Deep inelastic)

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

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

Durham HEP server: http://durpdg.dur.ac.uk/pdfs

Unpolarized Parton Distributions

Access the parton distribution code, on-line calculation and graphical display of the distributions, from CTEQ, GRV, MRST/MSTW, Alekhin, ZEUS, H1, HERAPDF, BBG and NNPDF.

CTEQ fortran code and grids
GRV/GJR fortran code and grids
MRST fortran code and grids, C++ code
MSTW fortran, C++ and Mathematica codes + grids etc.
ALEKHIN fortran,C++,Mathematica code, and grids
ZEUS ZEUS 2002 PDFs, ZEUS 2005 jet fit PDFs
HERAPDF Combined H1/ZEUS page, HERAPDF1.0 paper
H1 H1 2000
BBG BBG06_NS
NNPDF Non Singlet PDF code - hep-ph/0701127

Polarized Parton Distributions

Currently available parametrizations

LSS2001 E.Leader, A.V.Sidorov and D.B.Stamenov, Eur.Phys.J.C23 (2002) 479
LSS2005 E.Leader, A.V.Sidorov and D.B.Stamenov, Phys.Rev.D73 (2006) 034023
LSS2006 E.Leader, A.V.Sidorov and D.B.Stamenov, Phys.Rev.D75 (2007) 074027
LSS2010 E.Leader, A.V.Sidorov and D.B.Stamenov, Phys.Rev.D82 (2010) 114018
GRSV M. Glueck, E. Reya, M. Stratmann and W. Vogelsang, Phys. Rev. D53 (1996) 4775
GRSV2000 M. Glueck, E. Reya, M. Stratmann and W. Vogelsang, Phys. Rev. D63 (2001) 094005
GS T. Gehrmann and W.J. Stirling, Phys. Rev. D53 (1996) 6100
BB J. Bluemlein and H. Boettcher - Nucl.Phys.B636(2002)225
AAC Asymmetry Analysis Collaboration - M. Hirai et al- Phys. Rev. D69 (2004) 054021
DS2000 D. de Florian and R. Sassot, Phys. Rev. D62 (2000) 094025
DNS2005 D. de Florian, G.A. Navarro and R. Sassot, Phys. Rev. D71 (2005) 094018

Diffractive Parton Distributions

MRW2006 A.D.Martin, M.G.Ryskin and G.Watt

Pion Parton Distributions

MRS fortran code and grids

PDFs from nuclei

HKM M. Hirai, S. Kumano and M. Miyama - Phys. Rev. D64 (2001) 034003
EKS98 K.J.Eskola, V.J.Kolhinen and C.A. Salgado - Eur.Phys.J C9(1999)61 and K.J.Eskola, V.J.Kolhinen and P.V.Ruuskanen - Nucl.Phys.B535(1998)351
nDS D. de Florian and R. Sassot, Phys.Rev.D69(2004)074028
FGS10 L. Frankfurt, V. Guzey, M. Strikman, arXiv:1106.2091 [hep-ph]

Generalized Parton Distributions

GPD GPD code of Vinnikov

Deeply Virtual Compton Scattering

DVCS DVCS code of Freund and McDermott

Fragmentation Functions

FF Fragmentation Distribution database site compiled by Marco Radici and Rainer Jakob

Our contributions on nuclear PDFs

Our home page: http://research.kek.jp/people/kumanos/nuclp.html

Hepforge (LHAPDF): http://www.hepforge.org/

LHAPDF the Les Houches Accord PDF Interface

LHAPDF provides a unified and easy to use interface to modern PDF sets. It is designed to work not only with individual PDF sets but also with the more recent multiple "error" sets. It can be viewed as the successor to PDFLIB, incorporating many of the older sets found in the latter, including pion and photon PDFs. In LHAPDF the computer code and input parameters/grids are separated thus allowing more easy updating and no limit to the expansion possibilities. The code and data sets can be downloaded together or inidivually as desired. From version 4.1 onwards a configuration script facilitates the installation of LHAPDF.

2013-10-09: C++ LHAPDF6 6.0.4 patch version is now available
See the LHAPDF6 announcement talk from PDF4LHC (some small details have changed since).
Code tarball for download from here.
New PDF data files for download from here.

Note: from version 5.7.1 onwards the PDF grid files are not bundled with the tarball.
Note: Problems compiling on MacOS (particularily v10.6)
Latest: new version of **bin/lhapdf-getdata** script needed for all versions

← **Our nuclear PDFs are included.**

Contents:

- Installing LHAPDF.
- Configuration options.
- List (and download) of PDF sets.
- On-line user manual.
- PDF set numbers
- A wrapper for C++.
- A wrapper for C++. (old version)
- A little bit of theory.

Downloads:

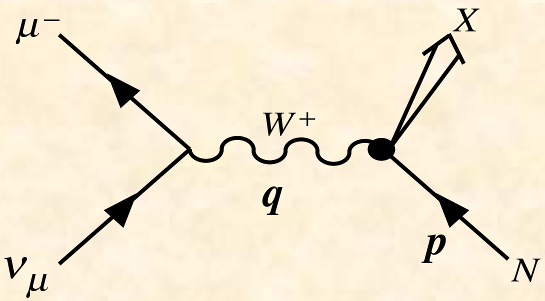
Latest version 6 release (09/10/2013):
- 6.0.4: LHAPDF-6.0.4.tar.gz (PDF sets)
- 6.0.3: LHAPDF-6.0.3.tar.gz (PDF sets)
- 6.0.2: LHAPDF-6.0.2.tar.gz (PDF sets)
- 6.0.1: LHAPDF-6.0.1.tar.gz (PDF sets)
- 6.0.0: LHAPDF-6.0.0.tar.gz (PDF sets)

Latest (& final) version 5 release (24/09/2013):

Deep inelastic scattering

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

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

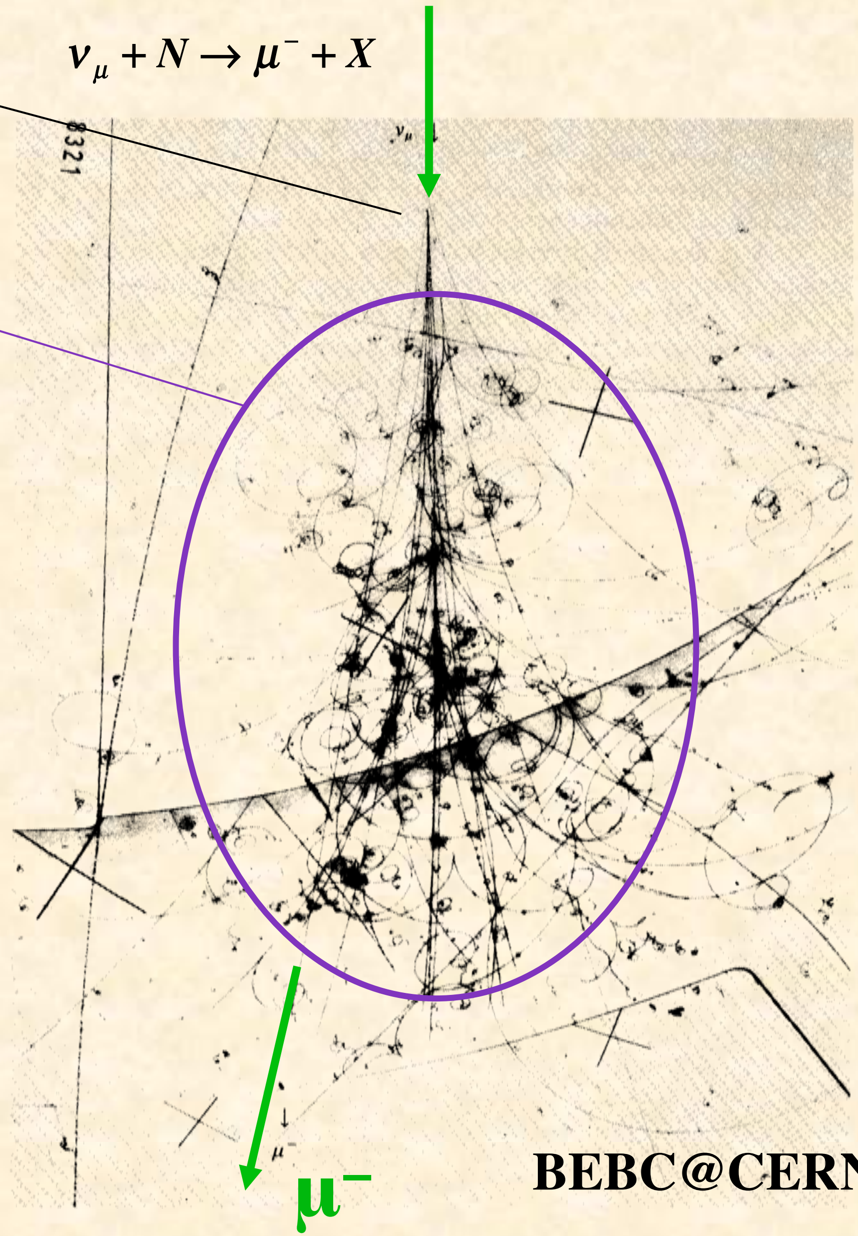


Momentum transfer: $q^2 = (k - k')^2 = -Q^2$

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

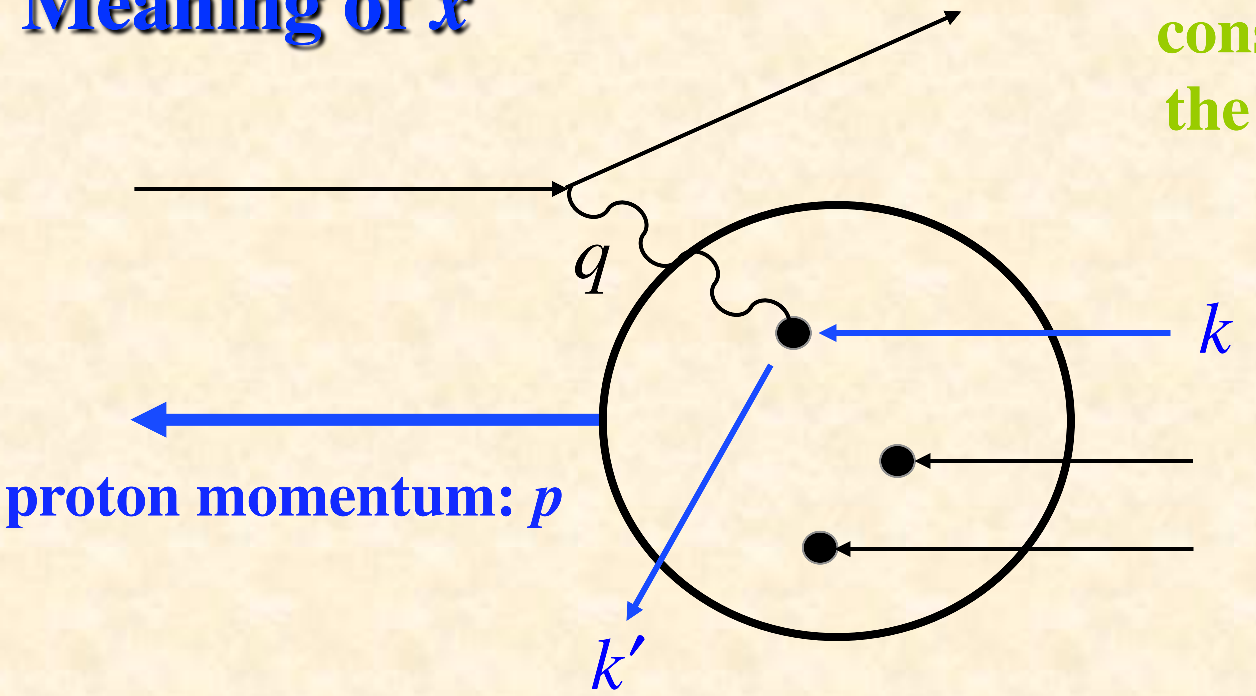
Invariant mass: $W^2 = p_X^2 = (p+q)^2$

ν_μ ~200 GeV



BEBC@CERN

Meaning of *x*



consider the frame where the proton is moving fast

$$(k+q)^2 = k'^2$$

$$(k+q)^2 = m_q^2 + 2k\cdot q - Q^2$$

$$k'^2 = m_q^2$$

$$\longrightarrow 2k\cdot q = Q^2$$

if $k = \xi p,\ \ 2\xi p\cdot q = Q^2$

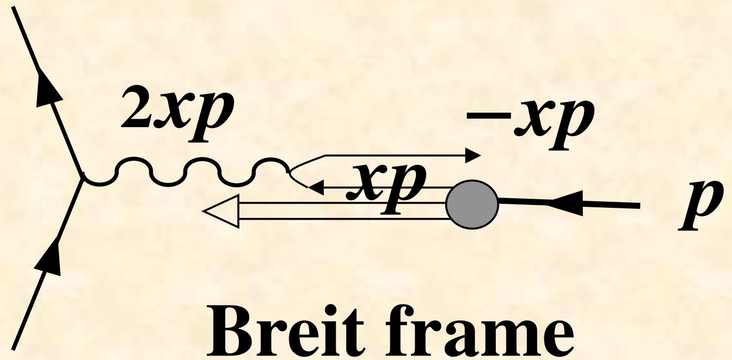
$$\xi = \frac{Q^2}{2p\cdot q} = x$$

***x* = momentum fraction carried by the struck parton**

For example, *x*=0.5 means that the struck parton carries 50% momentum of the proton.

Meaning of Q^2

Breit frame is defined as the frame in which exchanged boson is completely spacelike: $q = (0, 0, 0, q)$.



Breit frame

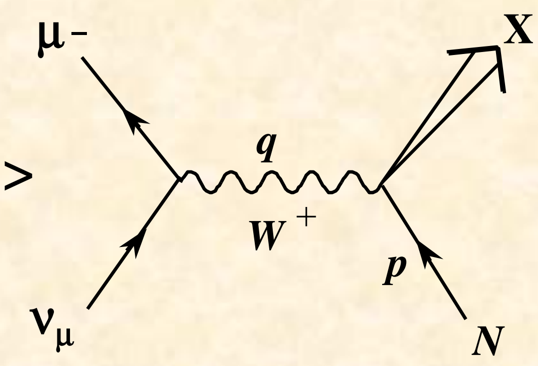
q^0=0: photon does not transfer any energy

Spatial resolution = reduced wavelength $\lambda\!\!\!^{-} = \frac{1}{|\vec{q}|} = \frac{1}{\sqrt{Q^2}}$

Q^2 corresponds to the "spatial resolution".

Neutrino deep inelastic scattering (CC: Charged Current)

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



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

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

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

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

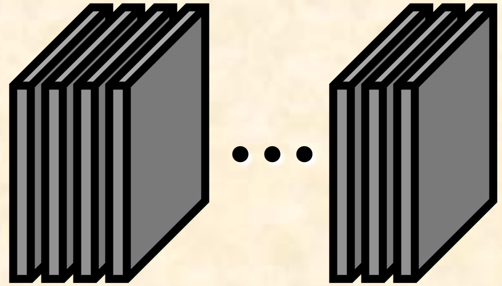
$$MW_1 = F_1\,,\quad \nu W_2 = F_2\,,\quad \nu W_3 = F_3\,,\quad x = \frac{Q^2}{2p\cdot q}\,,\quad y = \frac{p\cdot q}{p\cdot k}$$

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

Neutrino DIS experiments

$\nu, \bar{\nu}$

E = 30 ~ 500 GeV

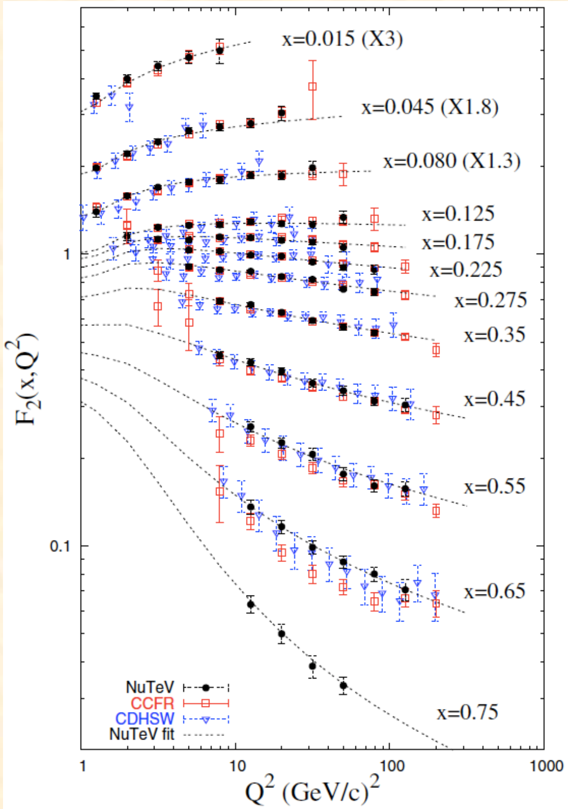


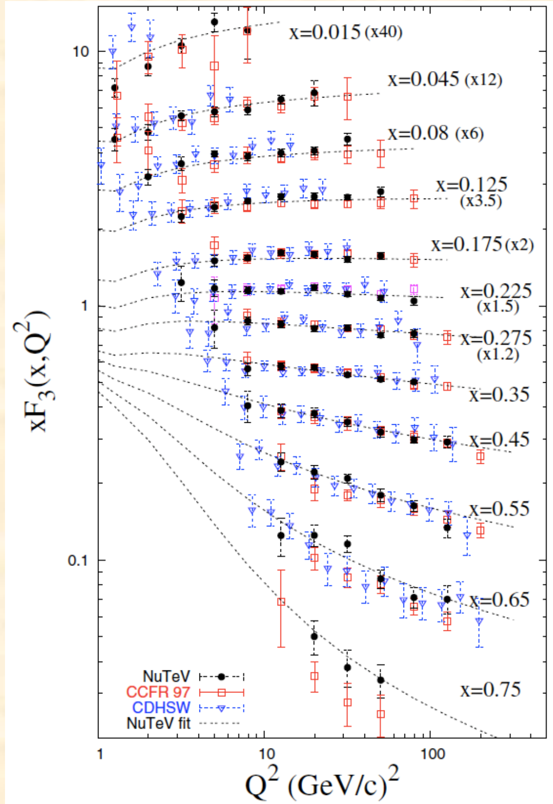
Huge Fe target (690 ton)

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.

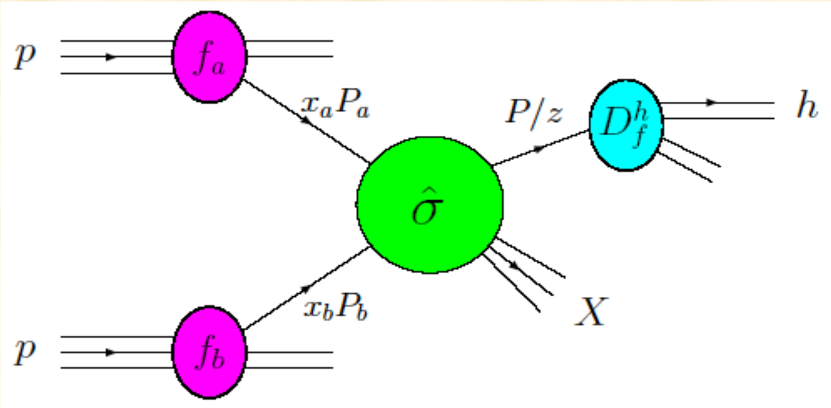




Parton Distribution Functions in the Nucleon

High-energy nuclear reactions

Nuclear PDFs are needed for describing high-energy nuclear 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.

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.

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.

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*., arXiv:1412.3989.

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

NNPDF2.0, R. D. Ball *et al*., Nucl. Phys. B 838 (2010) 136; B855（2012）153;

B867（2013）244; B874（2013）36; B877（2013）290; arXiv:1410.8849.

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 $Q^2 (\equiv Q_0^2)$ **:**

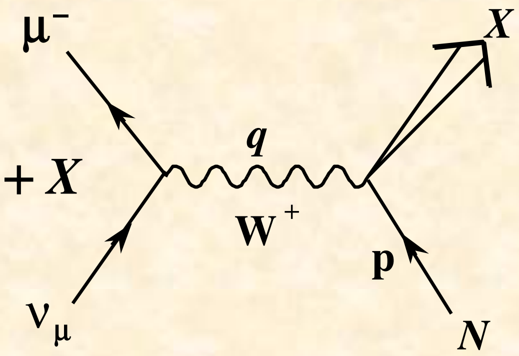
e.g. $f_i(x, Q_0^2) = A_i x^{\alpha_i} (1-x)^{\beta_i} (1+\gamma_i x),$

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

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

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

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

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

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

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

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

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

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

Valence: also F_2 at large x

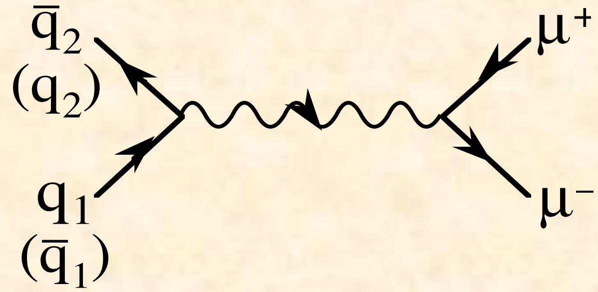
Sea quark

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 (↑ x_1) target (↑ x_2)

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

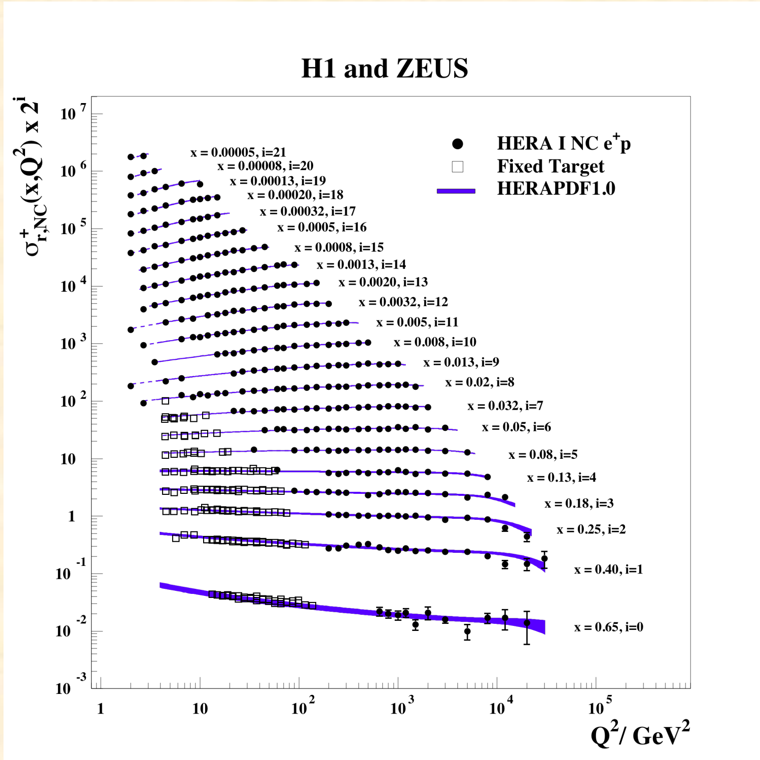
$\bar{q}(x_2)$ can be obtained if $q_V(x_1)$ is known.

Gluon

scaling violation of F_2

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

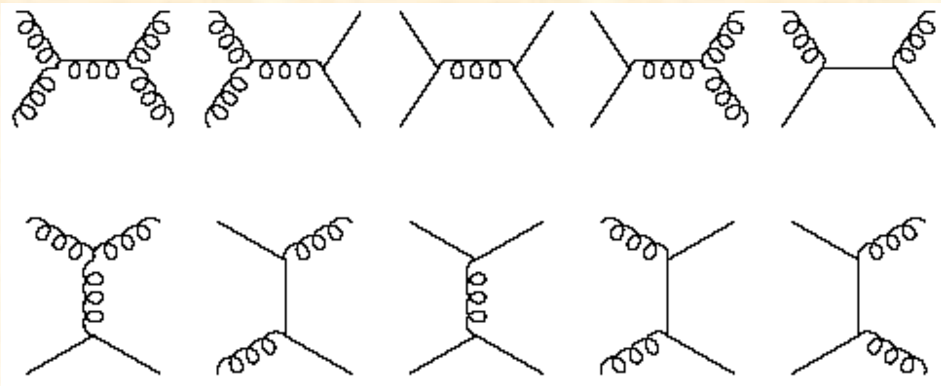
H1 and ZEUS
JHEP01(2010)109



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

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

jet production



Situation of data for PDFs of the nucleon (MMLT-2014)

Data set	LO	NLO	NNLO
BCDMS μp F_2 [117]	162 / 153	176 / 163	178 / 163
BCDMS μd F_2 [118]	140 / 142	143 / 151	144 / 151
NMC μp F_2 [119]	141 / 115	132 / 123	122 / 123
NMC μd F_2 [119]	134 / 115	115 / 123	107 / 123
NMC $\mu n/\mu p$ [120]	122 / 137	131 / 148	127 / 148
E665 μp F_2 [121]	59 / 53	60 / 53	65 / 53
E665 μd F_2 [121]	52 / 53	52 / 53	61 / 53
SLAC ep F_2 [122, 39]	21 / 18	31 / 37	31 / 37
SLAC ed F_2 [122, 39]	13 / 18	30 / 38	25 / 38
NMC/BCDMS/SLAC/HERA F_L [119, 117, 123, 55, 56, 57]	113 / 53	68 / 57	62 / 67
E866/NuSea pp DY [80]	229 / 184	221 / 184	227 / 184
E866/NuSea pd/pp DY [81]	29 / 15	11 / 15	12 / 15
NuTeV νN F_2 [124]	35 / 49	39 / 53	38 / 53
CHORUS νN F_2 [125]	25 / 37	26 / 42	29 / 42
NuTeV νN xF_3 [124]	49 / 42	37 / 42	31 / 42
CHORUS νN xF_3 [125]	35 / 28	29 / 28	19 / 28
CCFR $\nu N \to \mu\mu X$ [22]	65 / 86	71 / 86	76 / 86
NuTeV $\nu N \to \mu\mu X$ [22]	53 / 40	38 / 40	43 / 40
HERA e^+p NC 820 GeV[53]	125 / 78	93 / 78	89 / 78
HERA e^+p NC 920 GeV[53]	479 /330	402 /330	371/ 330
HERA e^-p NC 920 GeV [53]	158/ 145	129/ 145	124 /145
HERA e^+p CC [53]	41 / 34	34 / 34	32 / 34
HERA e^-p CC [53]	29 / 34	23 / 34	21 / 34
HERA ep F_2^{charm} [54]	105 /52	72 / 52	83 / 52
H1 99–00 e^+p incl. jets [126]	77 / 24	14 / 24	—
ZEUS incl. jets [127, 128]	140/60	45 / 60	—
DØ II $p\bar{p}$ incl. jets [111]	125 / 110	116 / 110	118 / 110
CDF II $p\bar{p}$ incl. jets [110]	78 / 76	63 / 76	58 / 76
CDF II W asym. [58]	55 / 13	32 / 13	30 / 13
DØ II $W \to \nu e$ asym. [59]	47 / 12	28 / 12	26 / 12
DØ II $W \to \nu\mu$ asym. [60]	16 / 10	19 / 10	20 / 10
DØ II Z rap. [82]	34 / 28	16 / 28	18 / 28
CDF II Z rap. [61]	95 / 28	36 / 28	39 / 28
ATLAS W^+, W^-, Z [10]	94/30	38/30	39/30
CMS W asymm $p_T > 35$ GeV [9]	10/11	7/10	8/10
CMS asymm $p_T > 25$ GeV, 30 GeV[69]	7/24	8/24	9/24
LHCb $Z \to e^+e^-$[71]	76/9	13/9	21/9
LHCb W asymm $p_T > 20$ GeV[70]	27/10	12/10	18/10
CMS $Z \to e^+e^-$ [74]	46/35	19/35	22/35
ATLAS high-mass Drell-Yan [73]	42/13	21/13	17/13
CMS double diff. Drell-Yan [78]	—	372/132	150/132
Tevatron, ATLAS, CMS $\sigma_{t\bar{t}}$ [83]–[89]	53/13	7/13	10/13
ATLAS jets (2.76 TeV+7 TeV)[100, 99]	162/116	106/116	—
CMS jets (7 TeV) [98]	150/133	138/133	—
All data sets	**3706 / 2763**	**3267 / 2996**	**2717 / 2663**

CERN-BCDMS, NMC, Fermilab-E665, SLAC, HERA (e, μ deep inelastic)

Fermilab-E866 (Drell-Yan)

CHORUS, CCFR, NuTeV (ν deep inelastic)

HERA (NC, CC, charm, jets)

Tevatron (jets, W, Z)

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

Structure functions in parton model for neutrino-nucleon scattering

$F_2 = 2 x F_1$

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

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

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

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

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

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

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

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

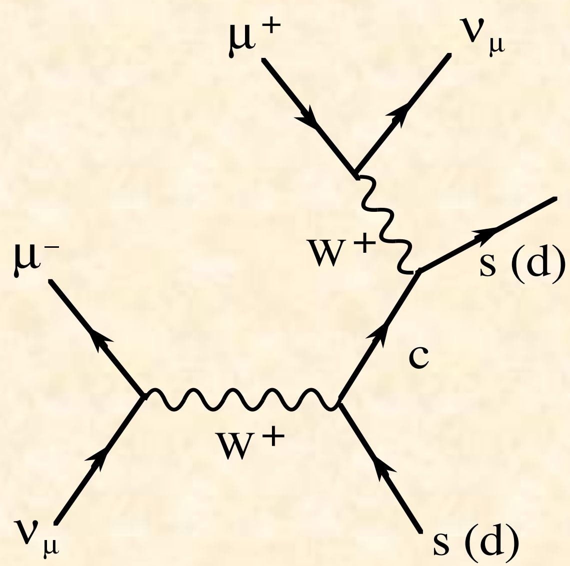
→

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

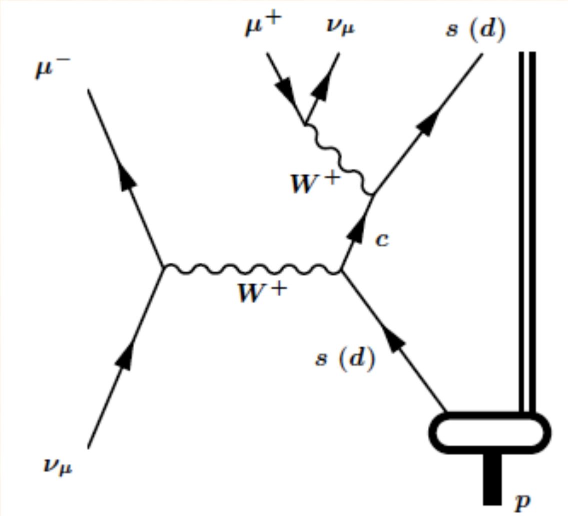
valence-quark distributions

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

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



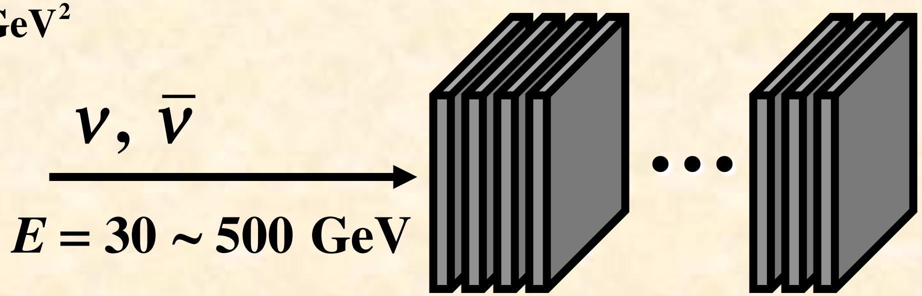
A. Kayis-Topaksu *et al.*, NPB7 98 (2008) 1.
U. Dore, arXiv: 1103.4572 [hep-ex].

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

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

CCFR, NuTeV

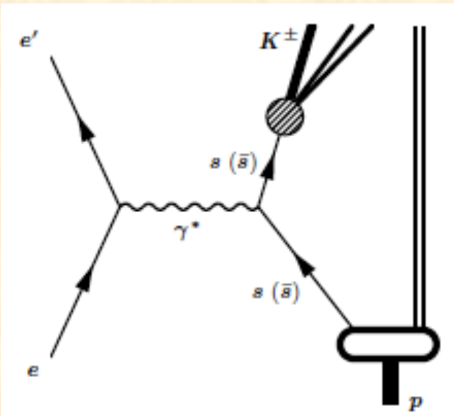
Experiment	κ
This analysis	0.33 ± 0.07
CDHS [1]	0.47 ± 0.09
CCFR [2]	0.44 ± 0.09
CHARM II [3]	0.39 ± 0.09
NOMAD [4]	0.48 ± 0.17
NuTeV [5]	0.38 ± 0.08

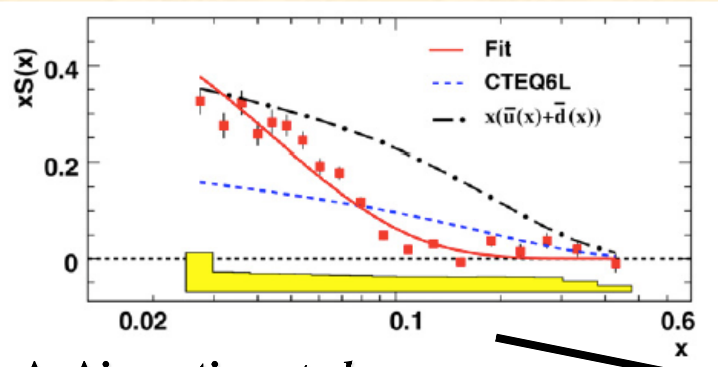


Huge Fe target (690 ton)

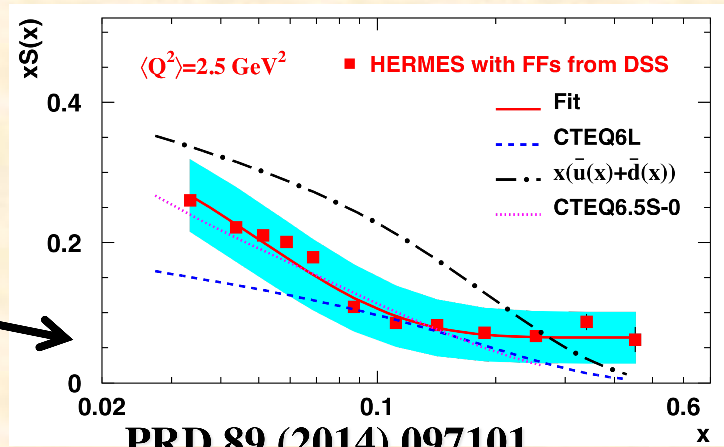
Issue: nuclear corrections

HERMES semi-inclusive measurement





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



PRD 89 (2014) 097101.

MMLT-2014

L. A. Harland-Lang, A. D. Martin, P. Motylinkski, and R. S. Thorne, arXiv:1412.3989.

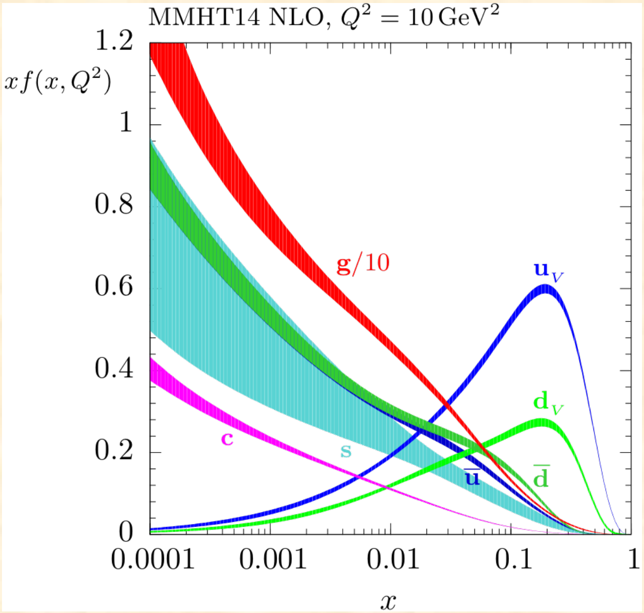
Functional form: $Q_0^2 = 1\ \mathrm{GeV}^2$

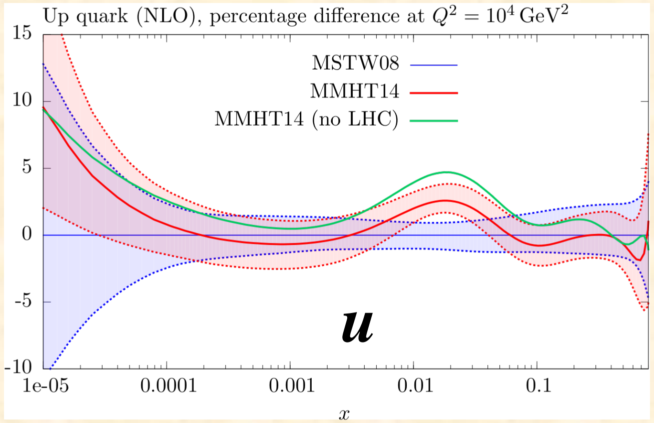
$$xf(x,Q_0^2) = Ax^{\delta}(1-x)^{\eta}\left[1+\sum_{i=1}^{n} a_i T_i(y(x))\right], \quad y = 1-2\sqrt{x},\ n=4,\ f = u_v,\ d_v,\ S,\ s_+ = s+\bar{s},\ \delta_S = \delta_{s_+}$$

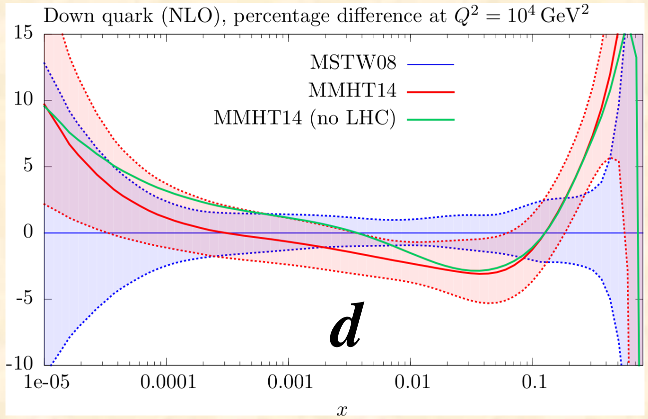
$$xg(x) = A_g x^{\delta_g}(1-x)^{\eta_g}\left[1+\sum_{i=1}^{2} a_{gi} T_i(y(x))\right] + A'_g x^{\delta'_g}(1-x)^{\eta'_g}$$

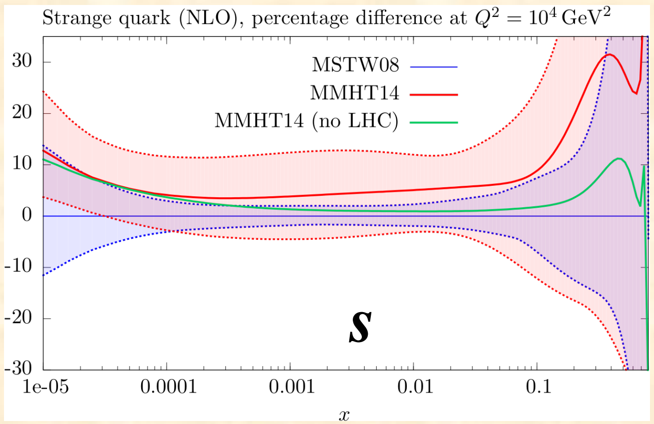
$$x\Delta(x) \equiv x(\bar{d}-\bar{u}) = Ax^{\delta}(1-x)^{\eta}(1+\gamma x+\varepsilon x^2), \qquad xs_- = x[s(x)-\bar{s}(x)] = A_- x^{\delta_-}(1-x)^{\eta_-}(1-x/x_0)$$

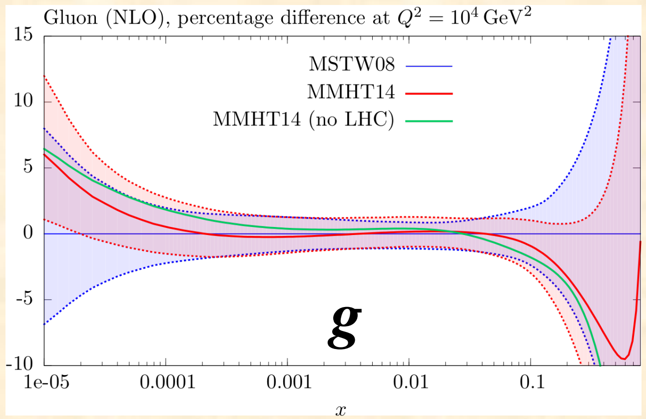
- **NLO, NNLO**



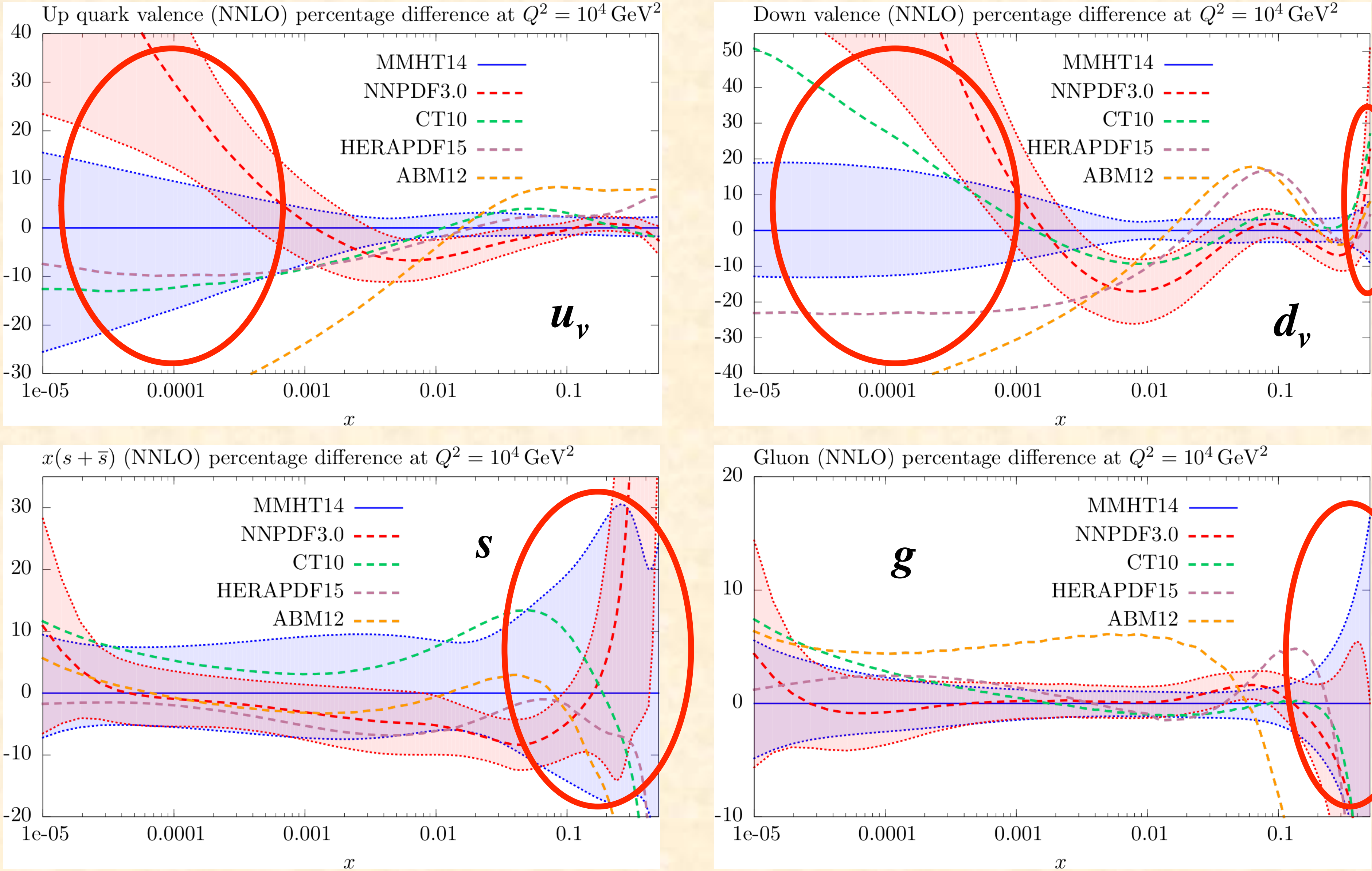








Comparisons with various PDFs



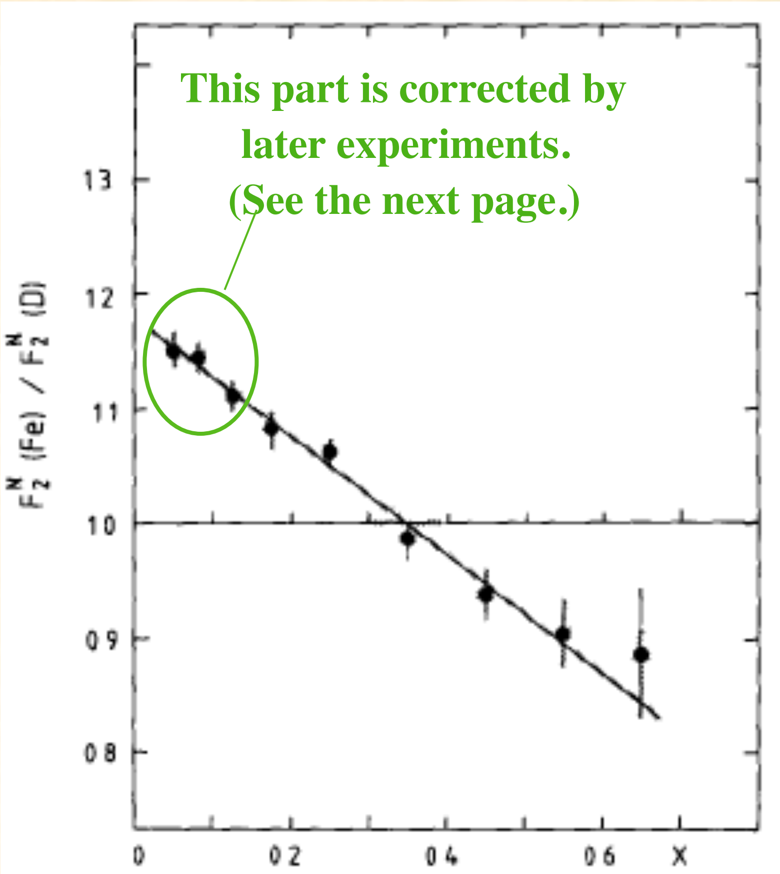
Nuclear modifications of parton distribution functions: Physics mechanisms

EMC (European Muon Collaboration) effect

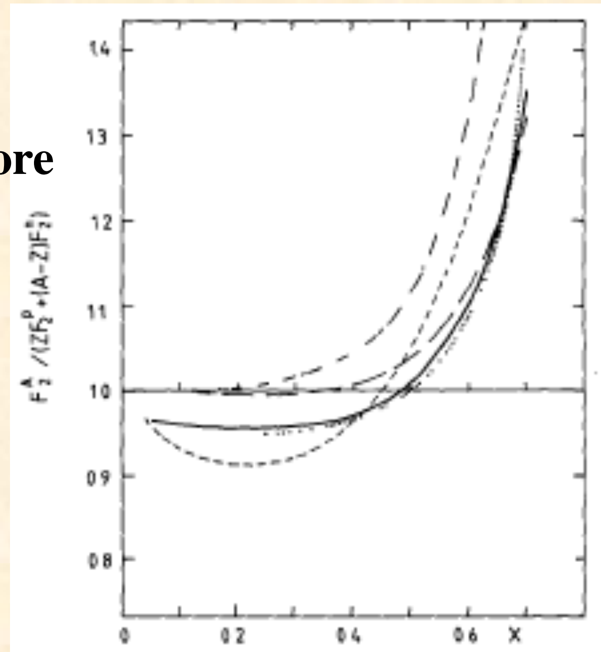
J. J. Aubert et al. (EMC),
Phys. Lett. B123 (1983) 275.

In the EMC paper of 1983, they to pointed out that nuclear modifications exist in a deep Inelastic structure function F_2.

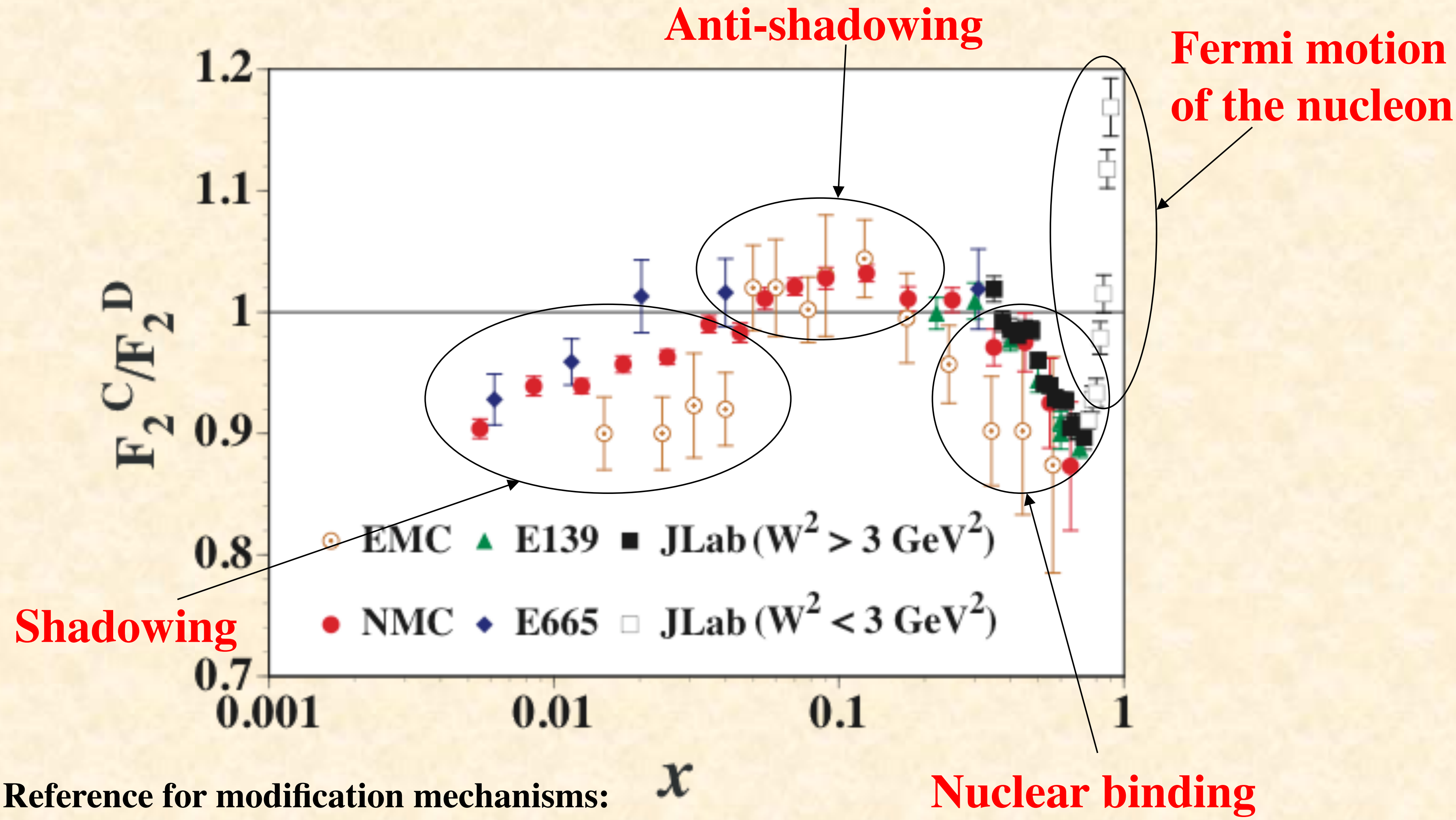
In general, nuclear binding energies are negligible in comparison with typical DIS energies (Q, ν), so that such modifications were expected to be small.



Fermi motion effects were theoretically calculated before the EMC publication. →

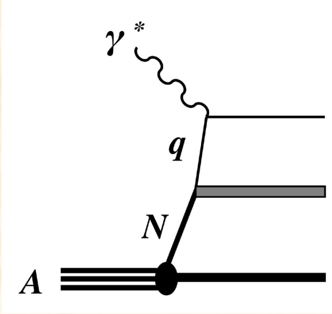


Nuclear modifications of structure function F_2



Reference for modification mechanisms:
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: $S(p) = \sum_i |\phi_i(\vec{p})|^2 \delta(p_0 - M_N - \varepsilon_i)$

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**

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

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

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

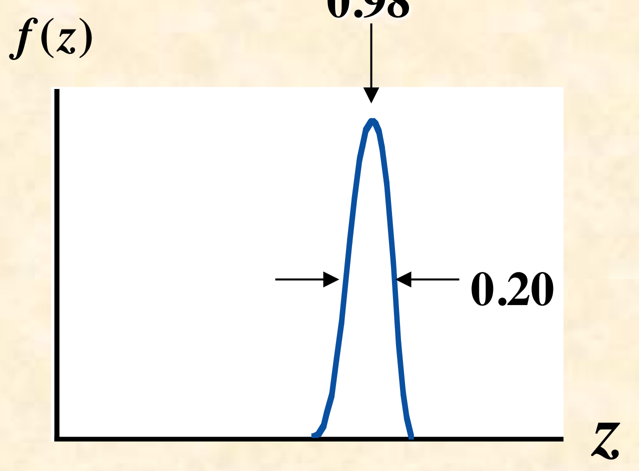
$$p\cdot q = p^+ q^- + p^- q^+ - \vec{p}_T \cdot \vec{q}_T \simeq p^+ q^-$$

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

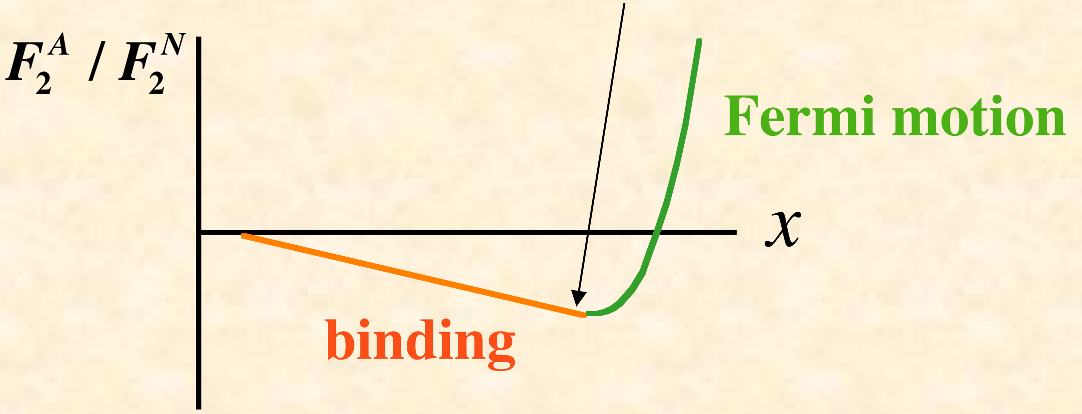


Because the peak shifts slightly (1→ 0.98), nuclear modification of F_2 is created.

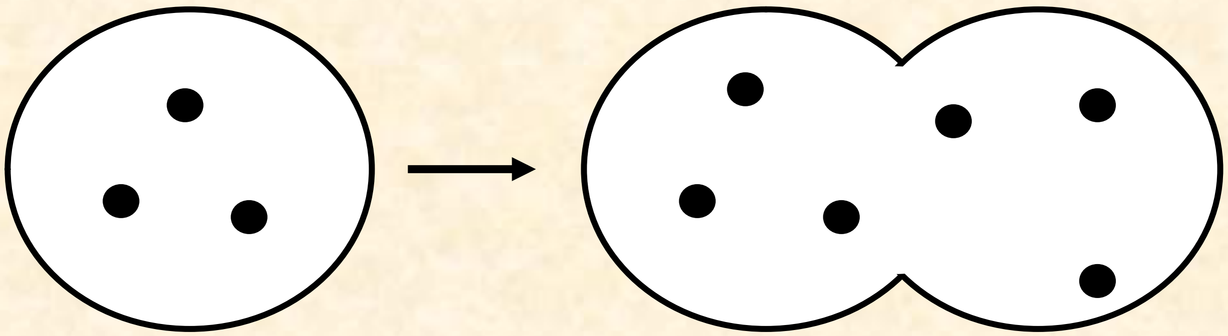
$$F_2^A(x,Q^2) \simeq F_2^N(x/0.98,Q^2)$$

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

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



Theoretical Ideas at Medium x: Q^2 Rescaling Model



Average nucleon separation (2 fm) ≈ Nucleon diameter

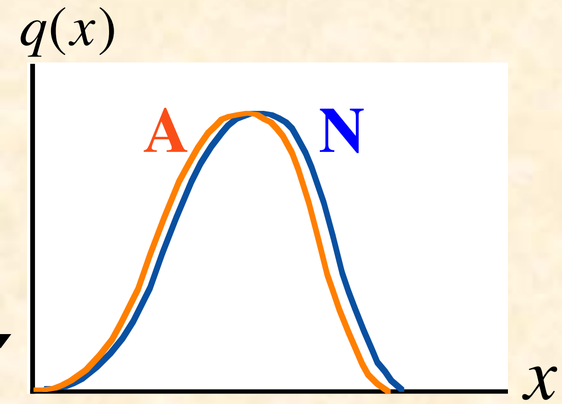
Free nucleon **Nucleon may overlap in a nucleus.**

↓

Confinement radius changes: $\lambda_A > \lambda_N$

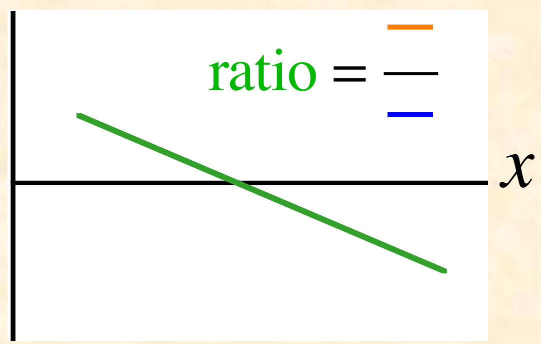
↓

Quark momentum distribution changes.



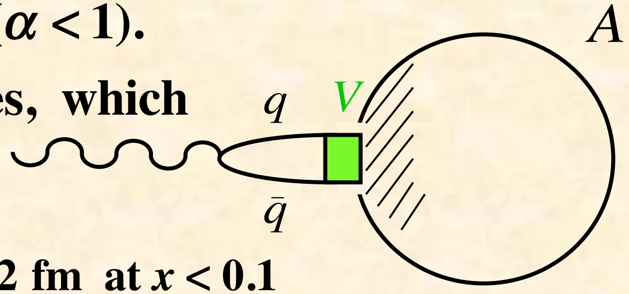
↓

Ratio $q_A(x)/q_N(x)$ is similar to the observed EMC data in 1983.



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.

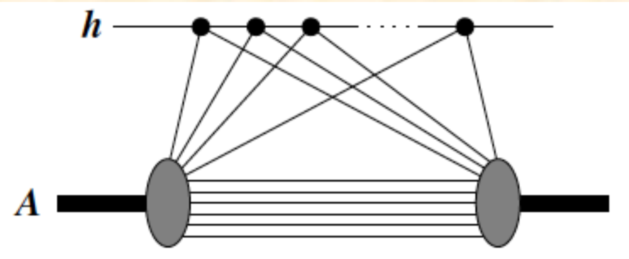


Propagation length of V ($q\bar{q}$): $\lambda = \dfrac{1}{\left|E_V - E_\gamma\right|} = \dfrac{2\nu}{M_V^2 + Q^2} = \dfrac{0.2\ \text{fm}}{x} > 2\ \text{fm}$ at $x < 0.1$

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

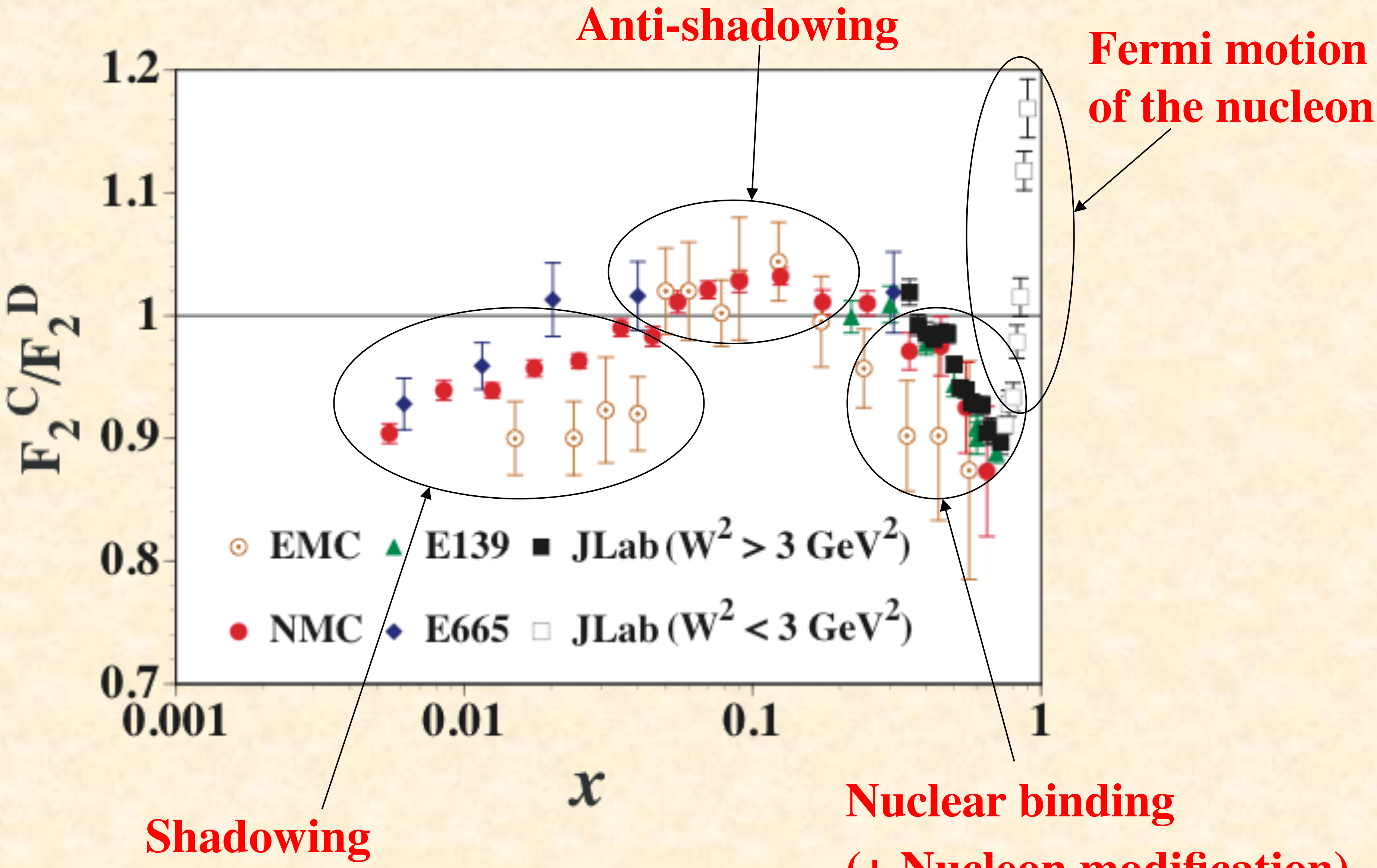
- Shadowing takes place due to multiple scattering.

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

Nuclear modifications of structure function F_2



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

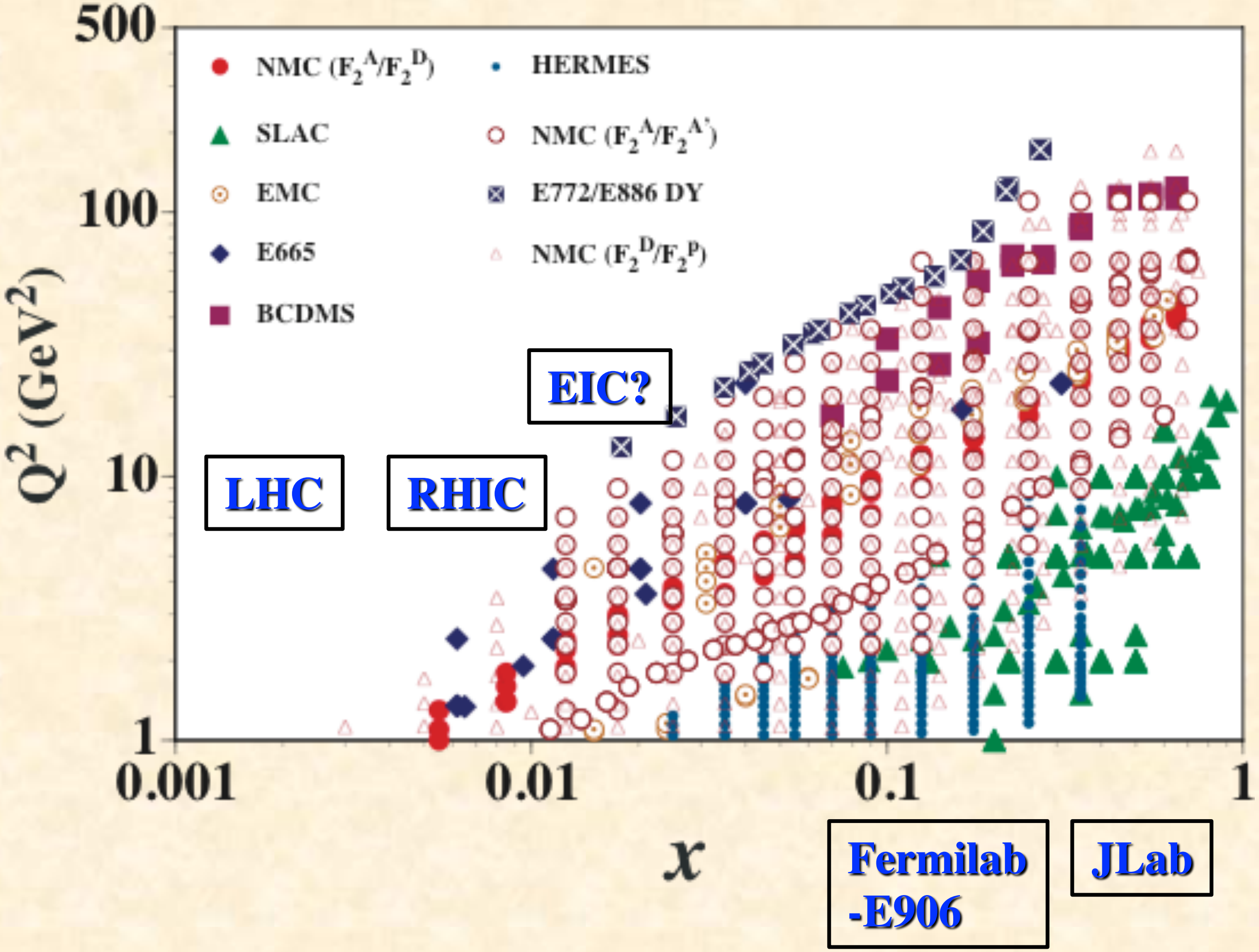
+ JLab data

(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.

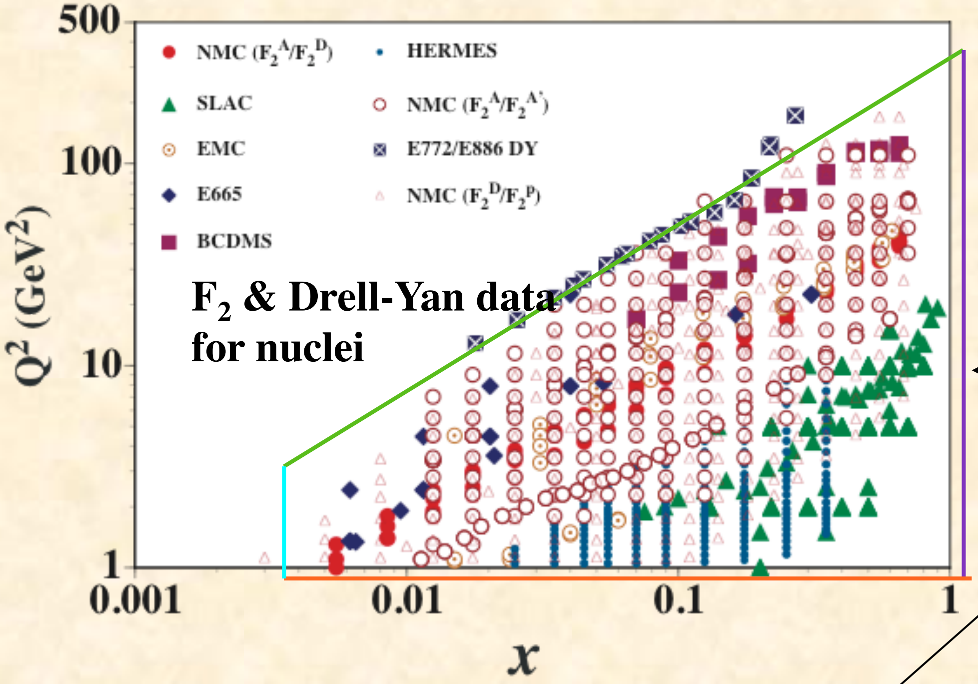
$$x = \frac{Q^2}{2p \cdot q} \simeq \frac{Q^2}{ys}$$

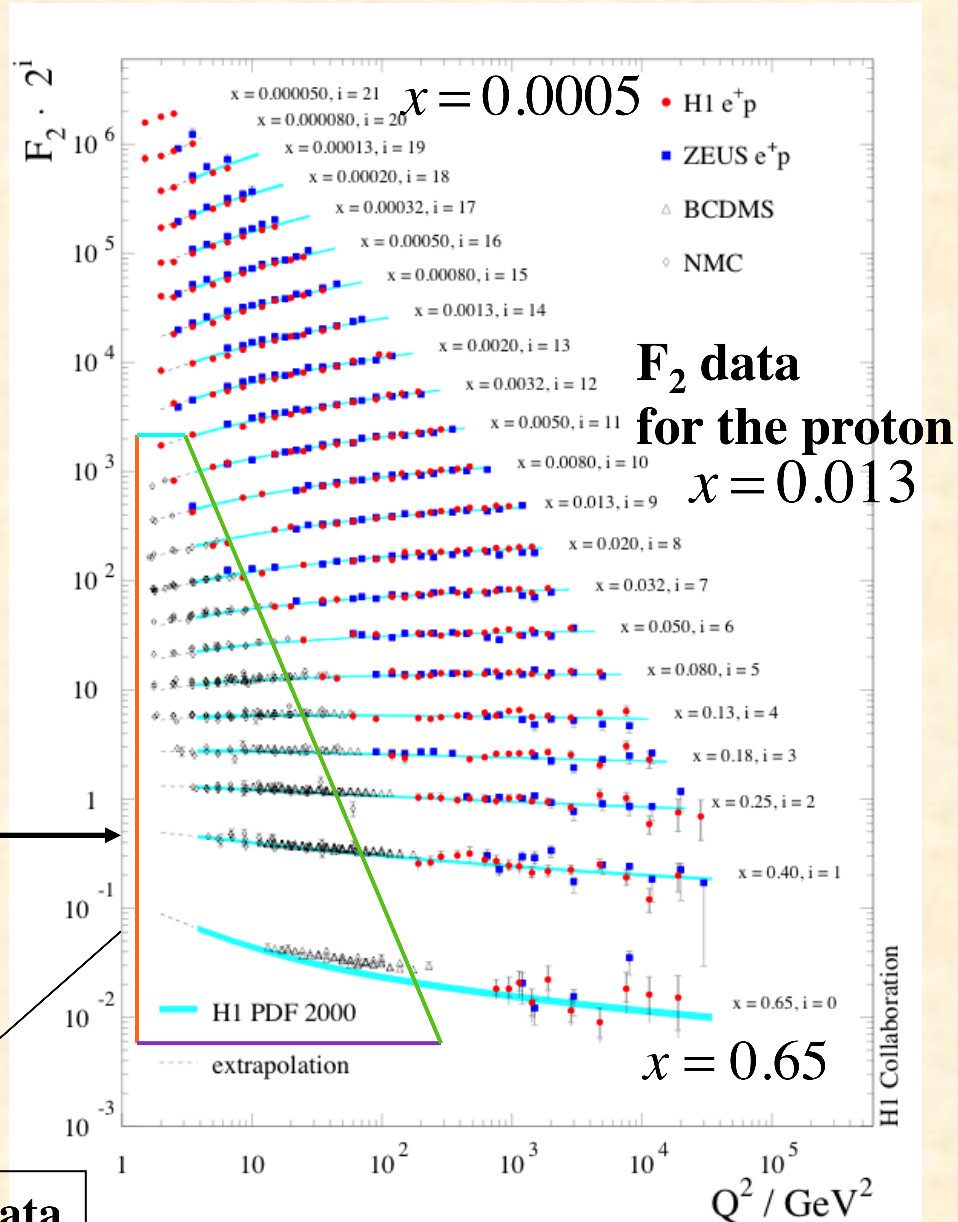
(from H1 and ZEUS, hep-ex/0502008)

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

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

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





region of nuclear data

Functional form

Nuclear PDFs "per nucleon"

If there were no nuclear modification

$$A u^A(x) = Z u^p(x) + N u^n(x), \quad A d^A(x) = Z d^p(x) + N d^n(x) \qquad p = \text{proton}, \quad n = \text{neutron}$$

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

$$\rightarrow \quad u^A(x) = \frac{Z u(x) + N d(x)}{A}, \qquad d^A(x) = \frac{Z d(x) + N u(x)}{A}$$

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

$$u_v^A(x) = w_{u_v}(x,A) \frac{Z u_v(x) + N d_v(x)}{A}, \quad d_v^A(x) = w_{d_v}(x,A) \frac{Z d_v(x) + N u_v(x)}{A}$$

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

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

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

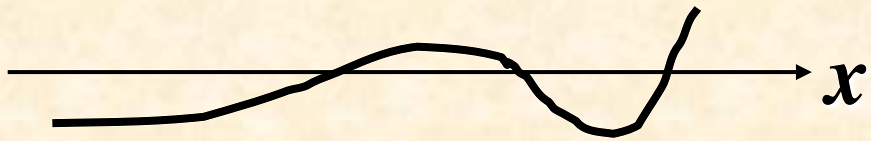
at Q^2=1 GeV^2 ($\equiv Q_0^2$)

Functional form of $w_i(x, A)$

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

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

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



A simple function = cubic polynomial

Three constraints

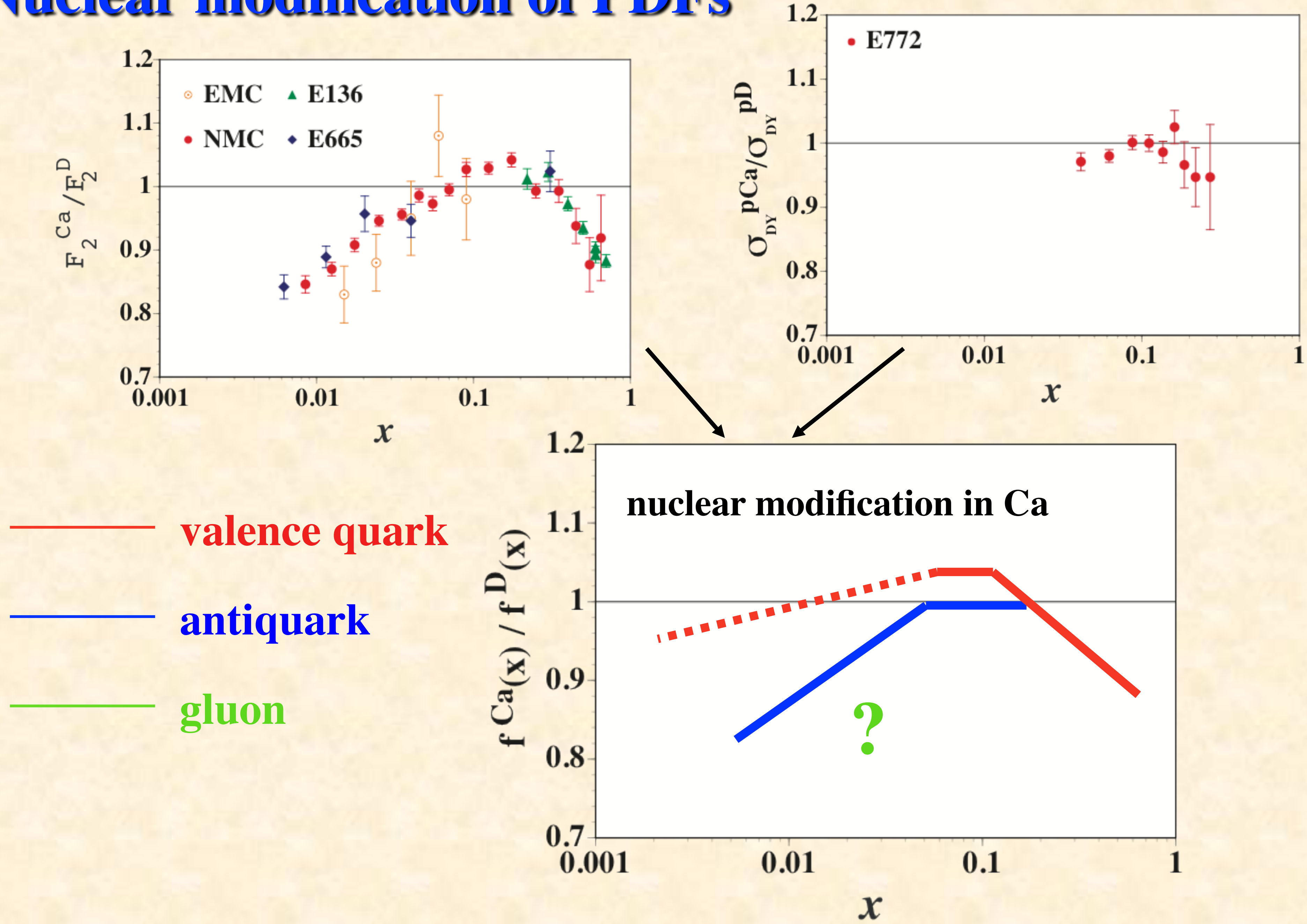
Nuclear charge: $Z = A \int dx \left[\frac{2}{3}\left(u^A - \bar{u}^A\right) - \frac{1}{3}\left(d^A - \bar{d}^A\right) - \frac{1}{3}\left(s^A - \bar{s}^A\right) \right] = A \int dx \left[\frac{2}{3} u_v^A - \frac{1}{3} d_v^A \right]$

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

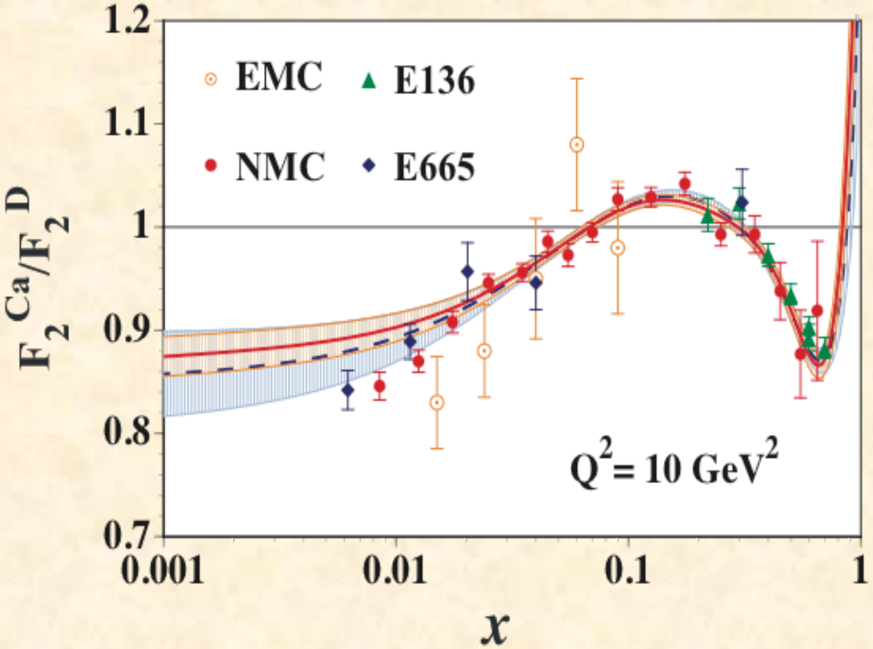
$$= A \int dx \left[u_v^A + d_v^A + 2\left(\bar{u}^A + \bar{d}^A + \bar{s}^A\right) + g \right]$$

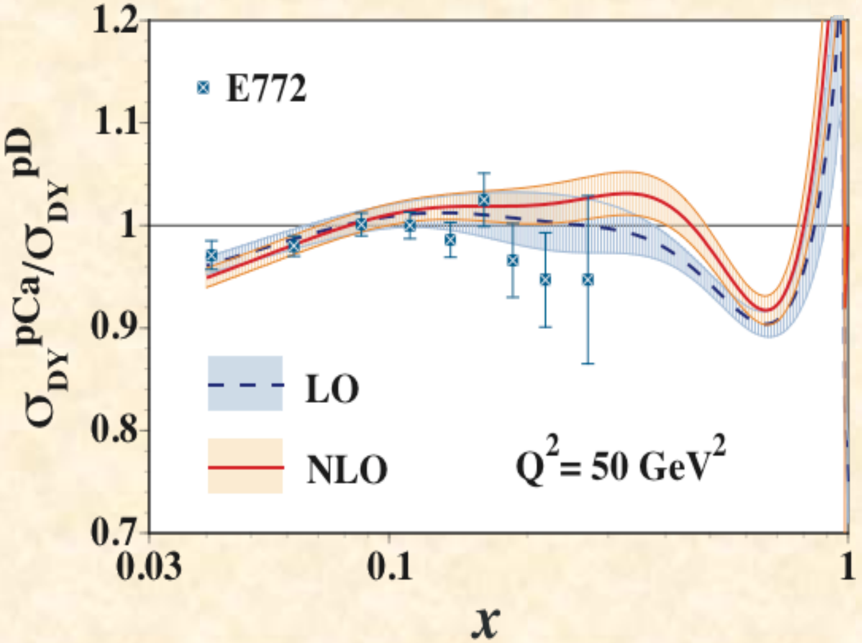
Nuclear modification of PDFs



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

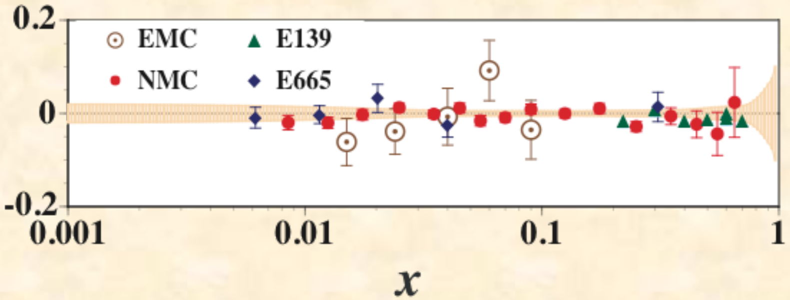
LO analysis **NLO analysis**

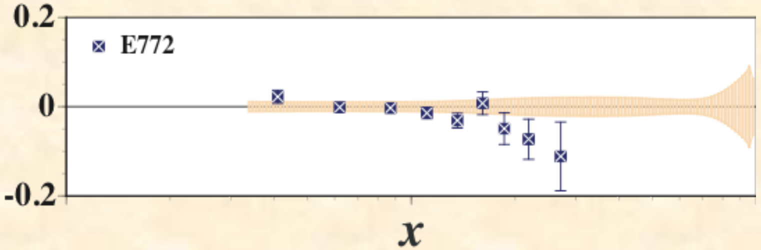




$(R^{exp}-R^{theo})/R^{theo}$ at the same Q^2 points

$R= F_2^{Ca}/F_2^D,\ \sigma_{DY}^{pCa}/\sigma_{DY}^{pD}$





Scaling Violation and Gluon Distributions

$$\frac{\partial}{\partial \log Q^2} q_i^+(x,Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j P_{q_i q_j}(x/y) q_j^+(y,Q^2) + P_{qg}(x/y) g(y,Q^2)\right]$$

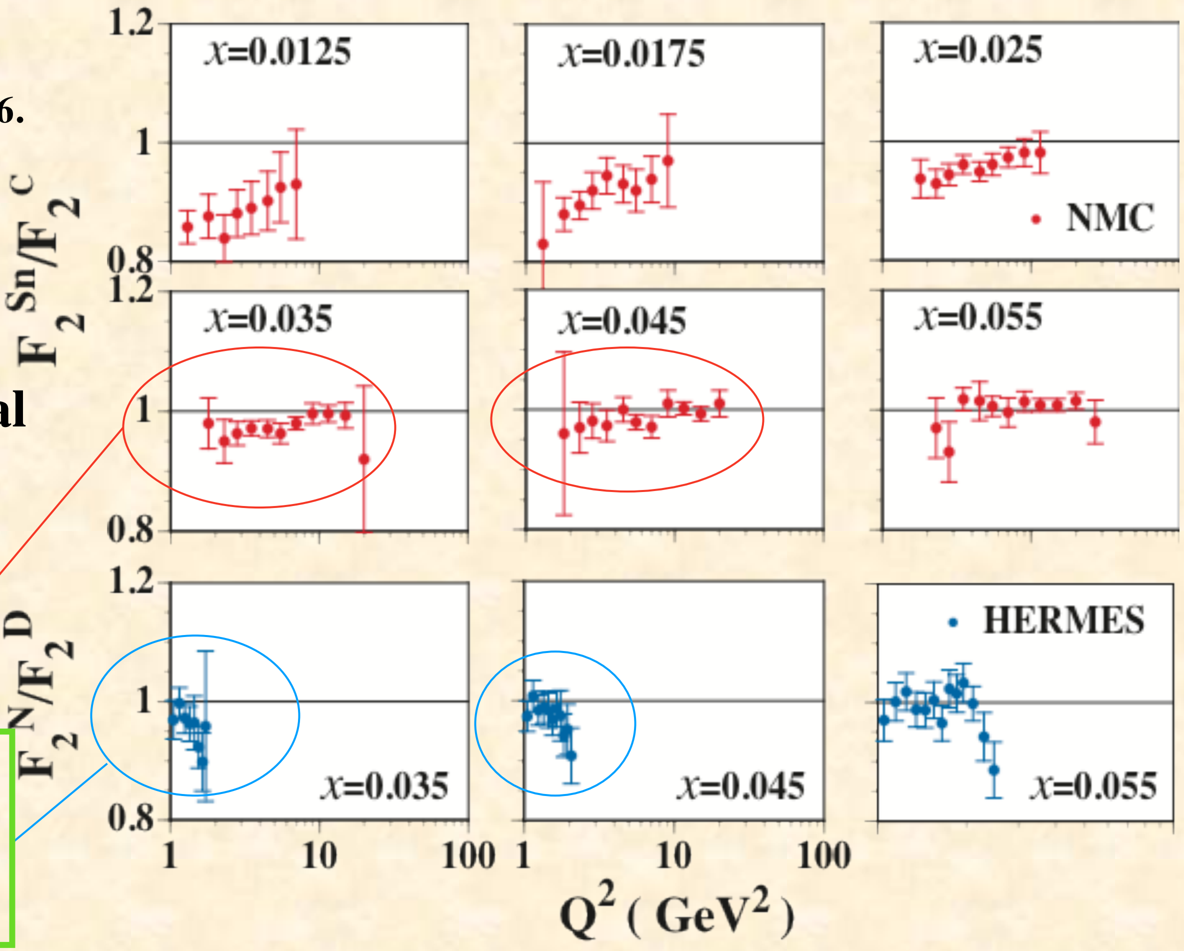
dominant term at small x

$$q_i^+ = q_i + \bar{q}_i$$

at small x **K. Prytz, PLB 311 (1993) 286.**

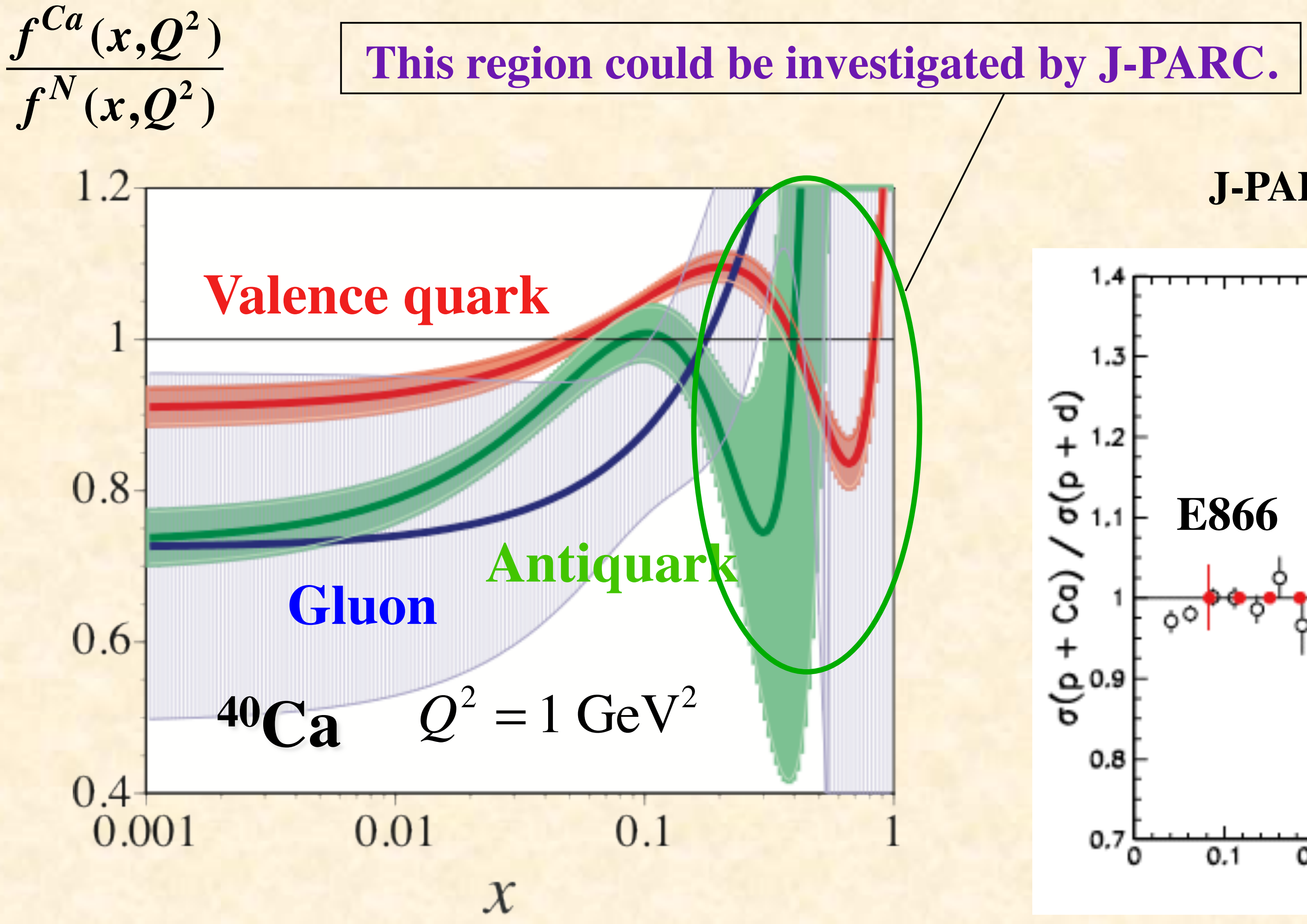
$$\frac{\partial F_2}{\partial(\ln Q^2)} \approx \frac{20\,\alpha_s}{27\pi} xg$$

Q^2 dependence of F_2 is proportional to the gluon distribution.



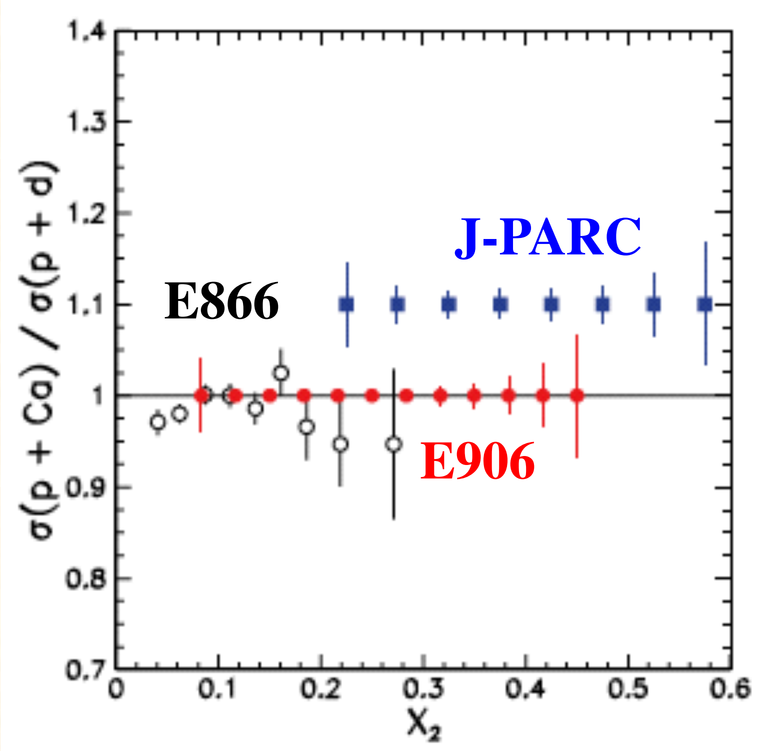
No experimental consensus of Q^2 dependence!
→ $G^A(x)$ determination is difficult.

Nuclear corrections on parton distribution functions



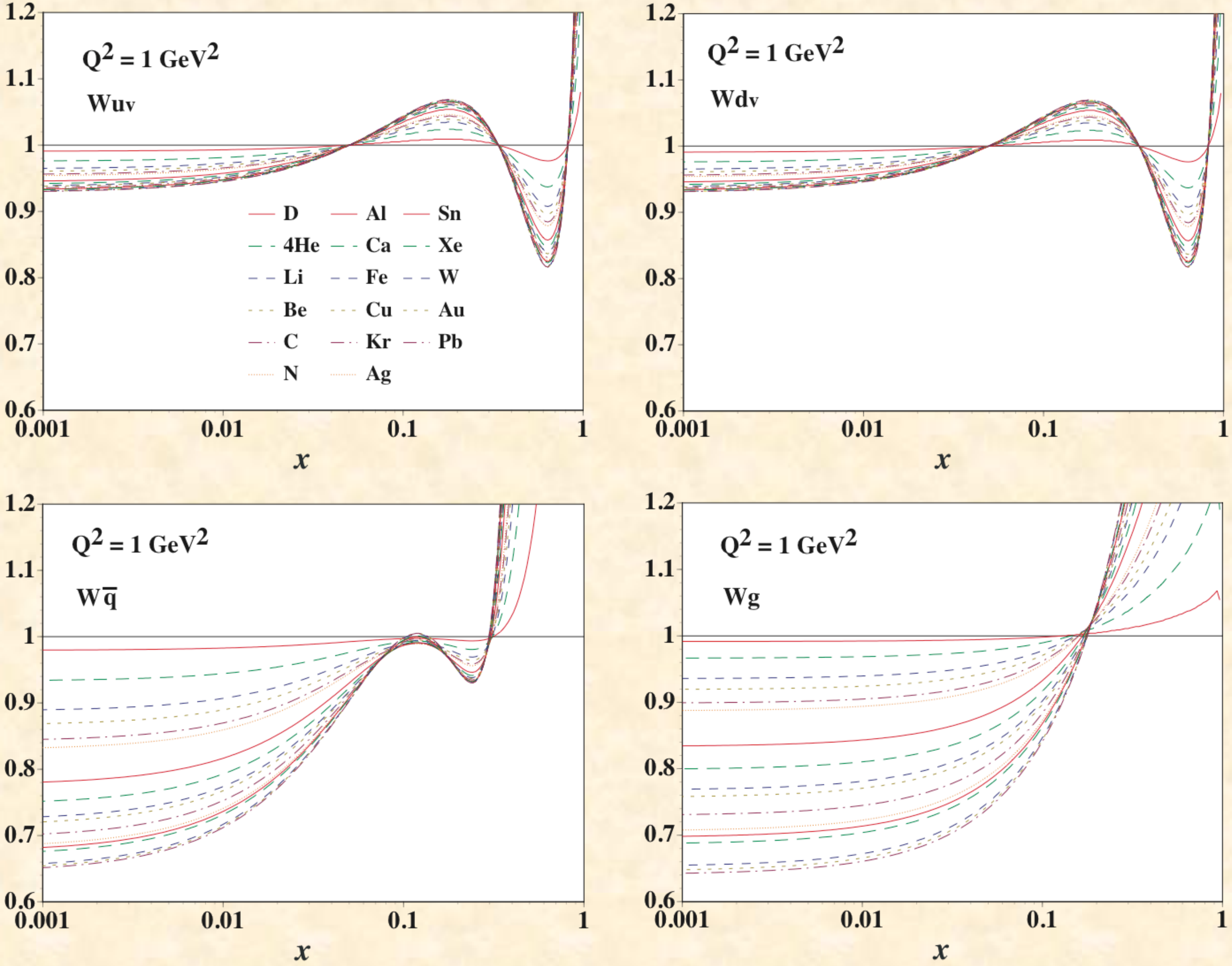
Global NPDF analysis result

J-PARC proposal P04



Nuclear PDFs

M. Hirai, S. Kumano, T.-H. Nagai, PRC 76 (2007) 065207.
http://research.kek.jp/people/kumanos/nuclp.html



Recent global analyses on nuclear PDFs

I may miss some papers.

HKN07

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

EPS09

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

CTEQ

- 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.
- Neutrino DIS, Charged-lepton DIS, DY.

DSZS12

- 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; arXiv:1310.5879.
S. A. Kulagin and R. Petti, Phys. Rev. D 76 (2007) 094023; C 82 (2010) 054614; arXiv:1405.2529.
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)

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

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

Comparison of nuclear PDFs

Different analysis results are consistent with each other because they are roughly within uncertainty bands.

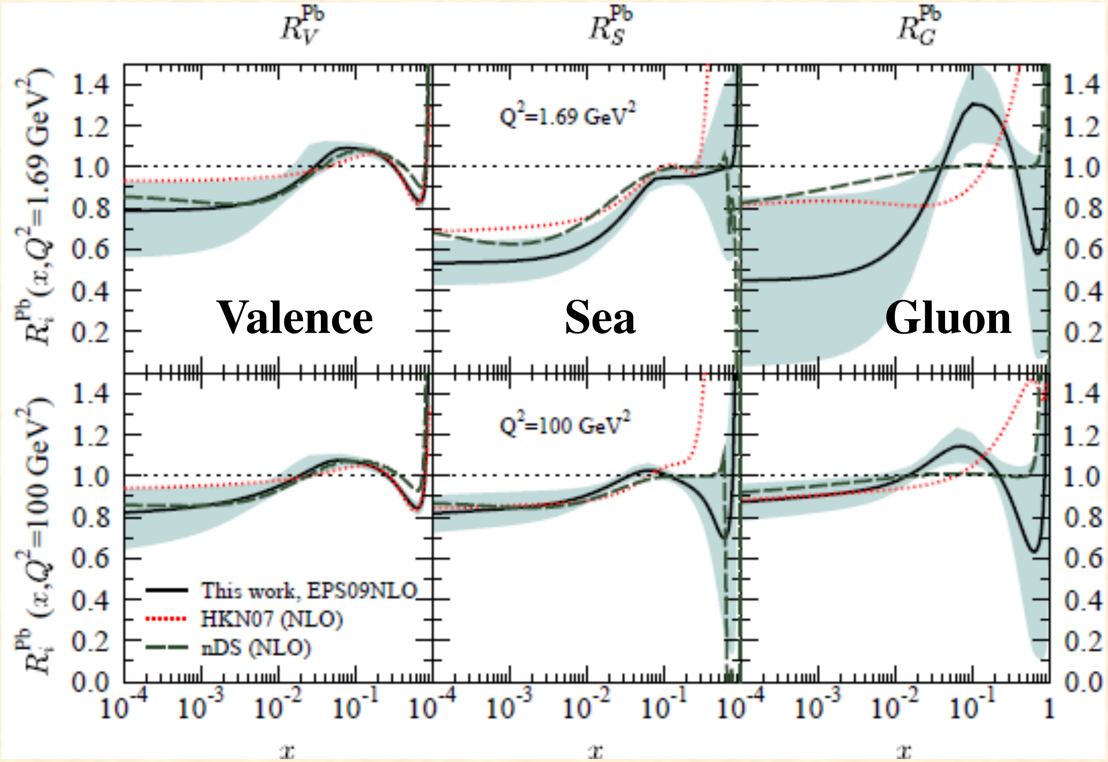
Valence quark: Well determined except at small x.

Antiquark: Determined at small x, Large uncertainties at medium and large x.

Gluon: Large uncertainties in the whole-x region.

$Q^2 = 1.69$ GeV^2

$Q^2 = 100$ GeV^2



EPS09

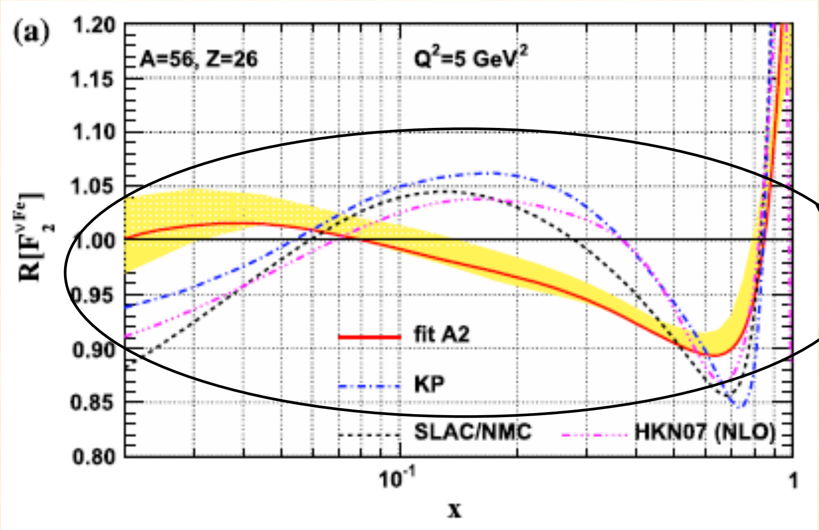
HKN07

DS04

EPS09 (K. J. Eskola *et al.*), JHEP 04 (2009) 065

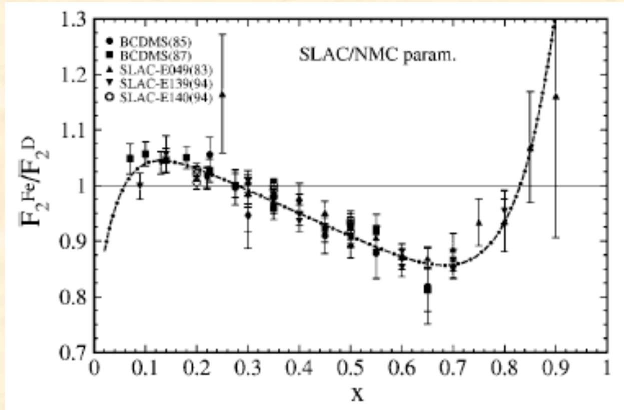
Analysis of CTEQ-2008 (Schienbein *et al.*)

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

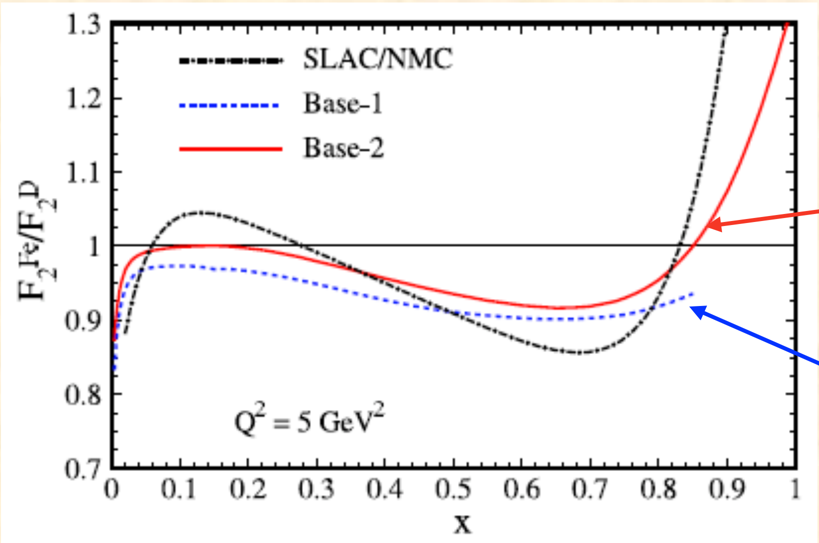


Differences from typical NPDFs.

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.

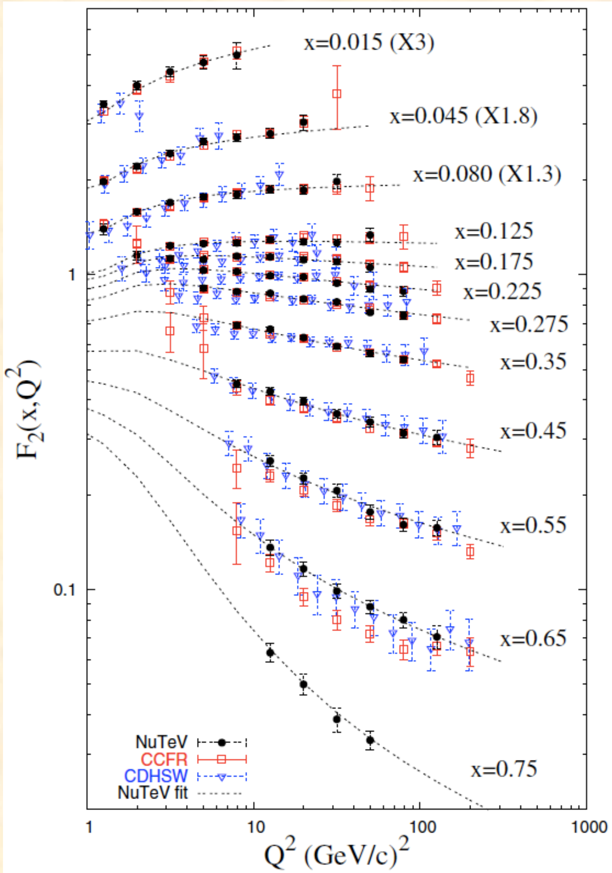
Base-1: However, it depends on the analysis method for determining "nucleonic" PDFs.

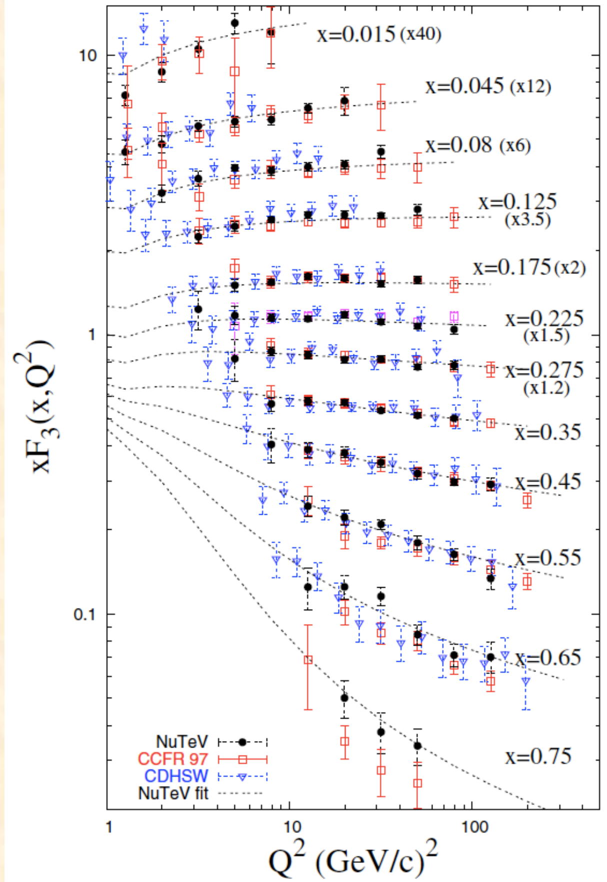
Neutrino DIS experiments

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

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

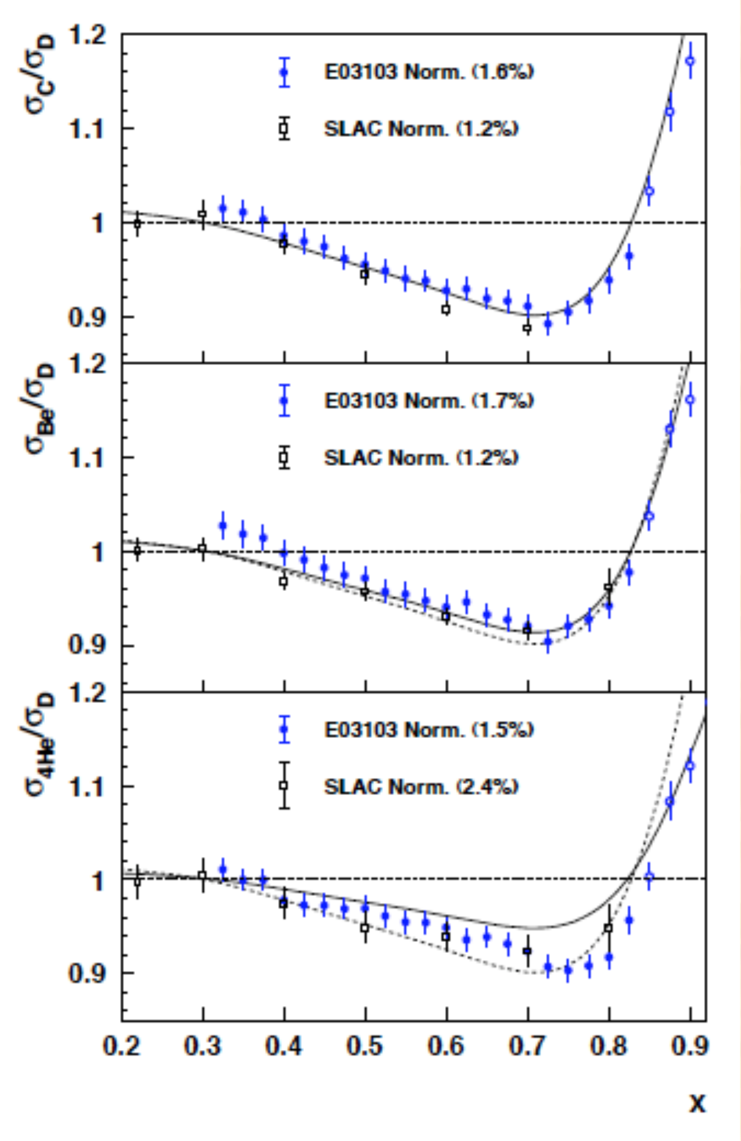
Future: MINERνA (He, C, Fe, Pb), …





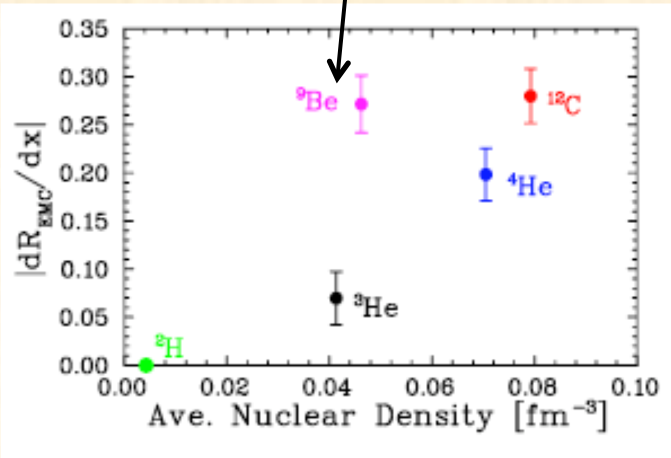
Measurements at JLab

J. Seely *et al.*,
Phys. Rev. Lett. 103 (2009) 202301.



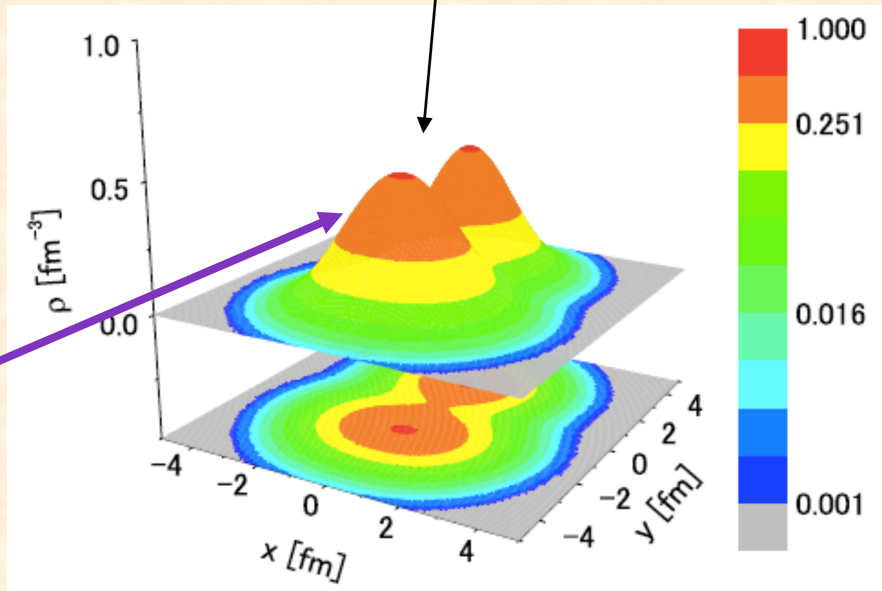
Results indicate that nuclear modifications may not be described by usual *A* (and density) dependence for light nuclei.

Anomalous (!?) for ^{9}Be



Nuclear effects of ^{9}Be

Typical nuclear clustering



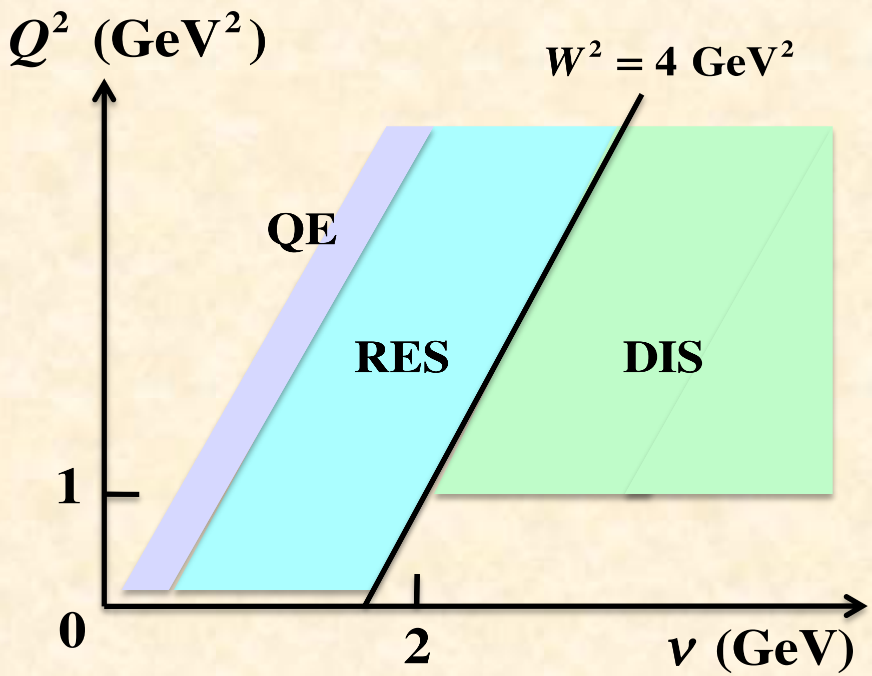
High-density regions
= Something new?
(Nucleon modifications,
Short-range correlations, …)

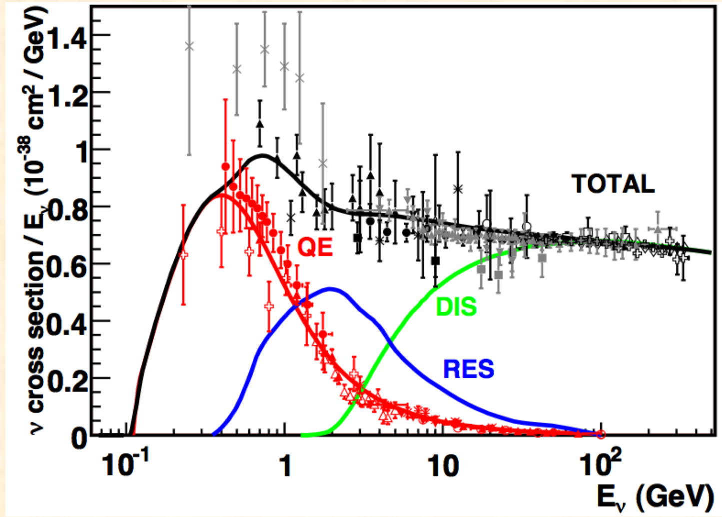
A theoretical-model density with cluster structure for ^{9}Be

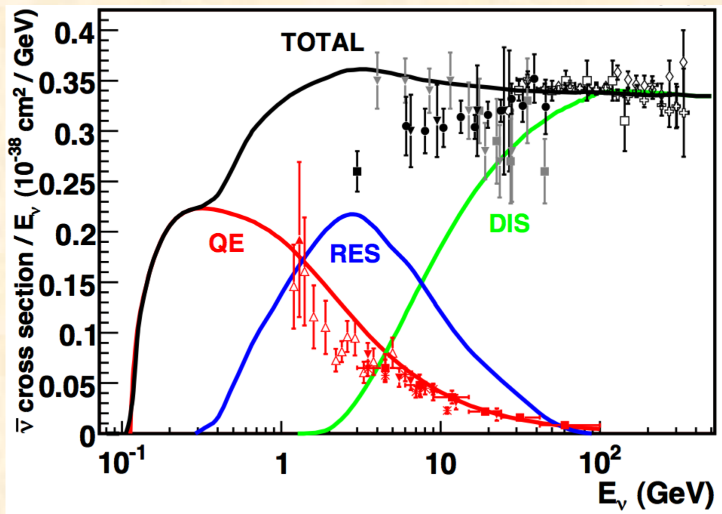
A signature of nuclear clustering in high-energy processes, particularly in structure functions of deep inelastic scattering.

→ Internal nucleon modifications, Short-range correlations, …

Kinematical regions of neutrino-nucleus scattering







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

- QE (Quasi elastic)
- RES (Resonance)
- DIS (Deep inelastic)

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

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

Summary on nuclear-PDF determination

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 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

Issues

- Charged-lepton DIS ⇔ Neutrino DIS
- Matching with resonance model
- Gluon distributions

New experimental informaiton

- JLab, Fermilab-DY, Minerva, LHC, …

The End

The End