Overview of Nuclear Parton Distribution Functions

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Neutrino-Nucleus Interactions
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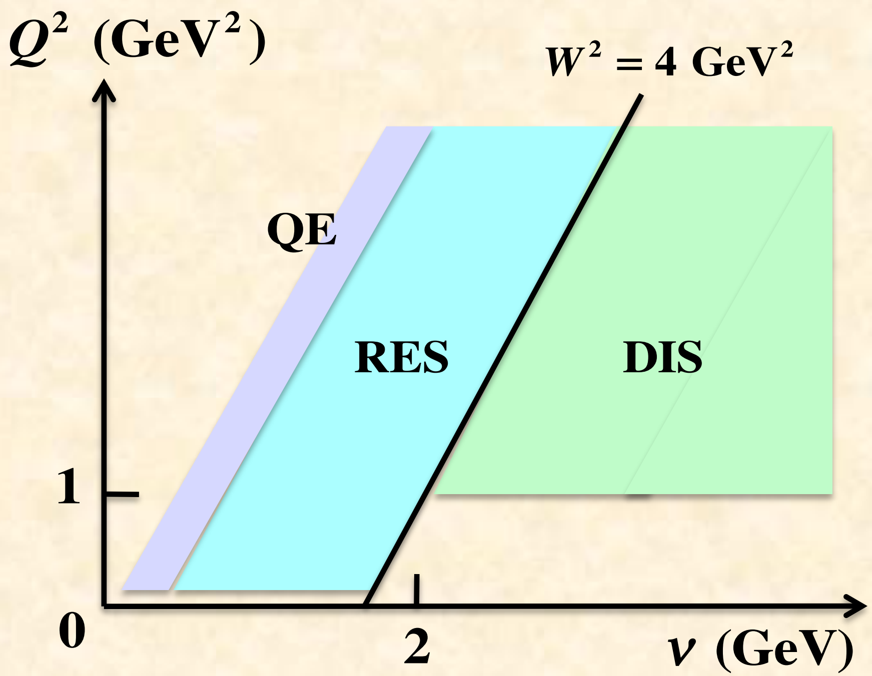
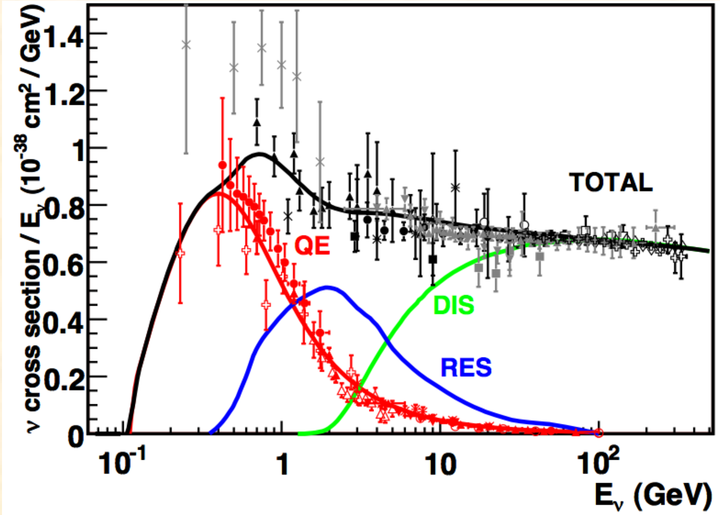
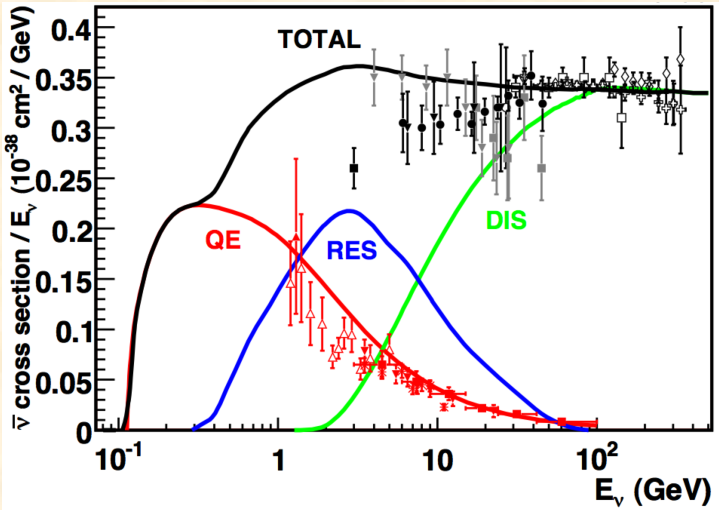
http://www.int.washington.edu/PROGRAMS/13-54w/

December 9, 2013

Kinematical regions of neutrino-nucleus scattering







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

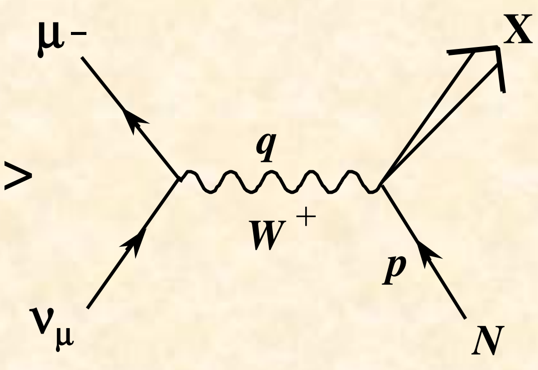
- QE (Quasi elastic)
- RES (Resonance)
- DIS (Deep inelastic)

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

Neutrino deep inelastic scattering (CC: Charged Current)

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



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

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

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

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

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

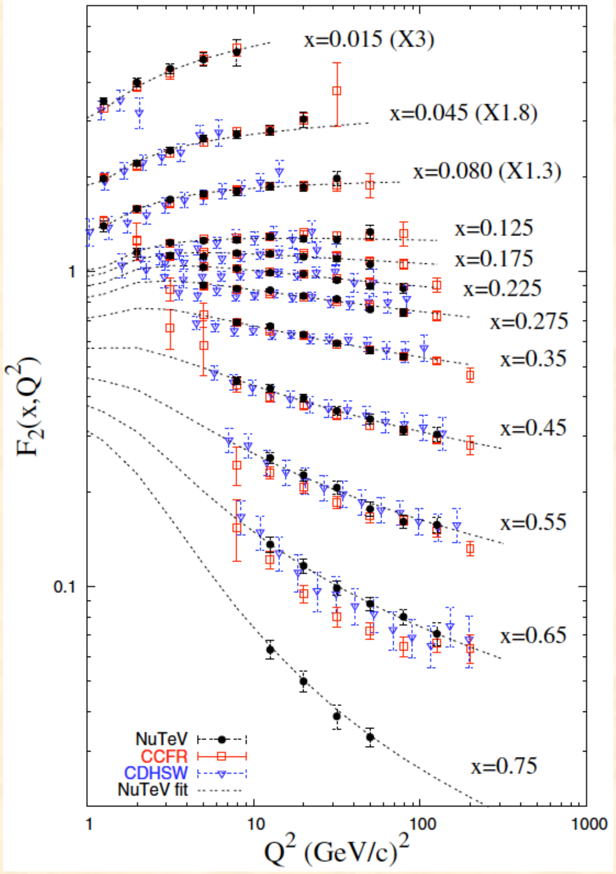
$$\frac{d\sigma_{\nu,\bar{\nu}}^{CC}}{dx\,dy} = \frac{G_F^2\,(s-M^2)}{2\pi\,(1+Q^2/M_W^2)^2}\left[x\,y^2F_1^{CC} + \left(1-y-\frac{M\,x\,y}{2E}\right)F_2^{CC} \underline{\pm x\,y\left(1-\frac{y}{2}\right)F_3^{CC}}\right]$$

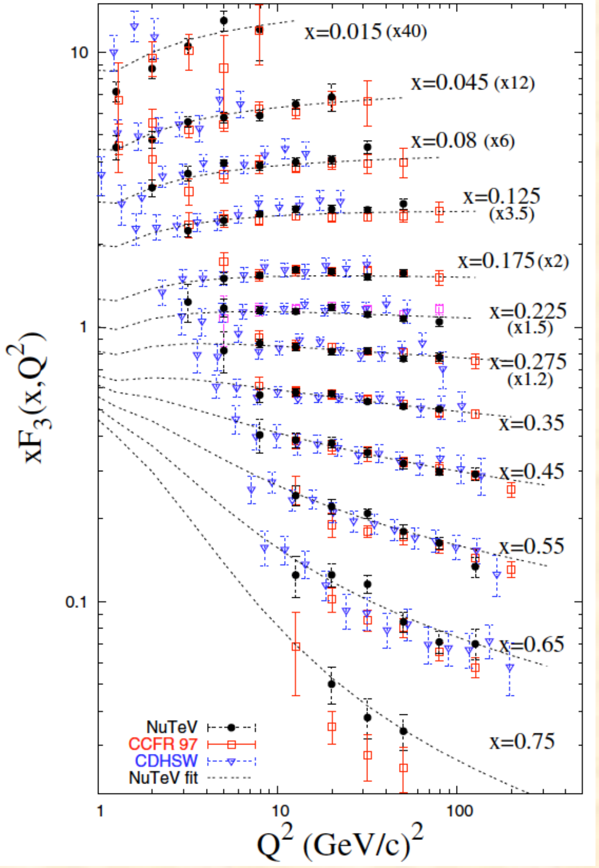
Neutrino DIS experiments

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

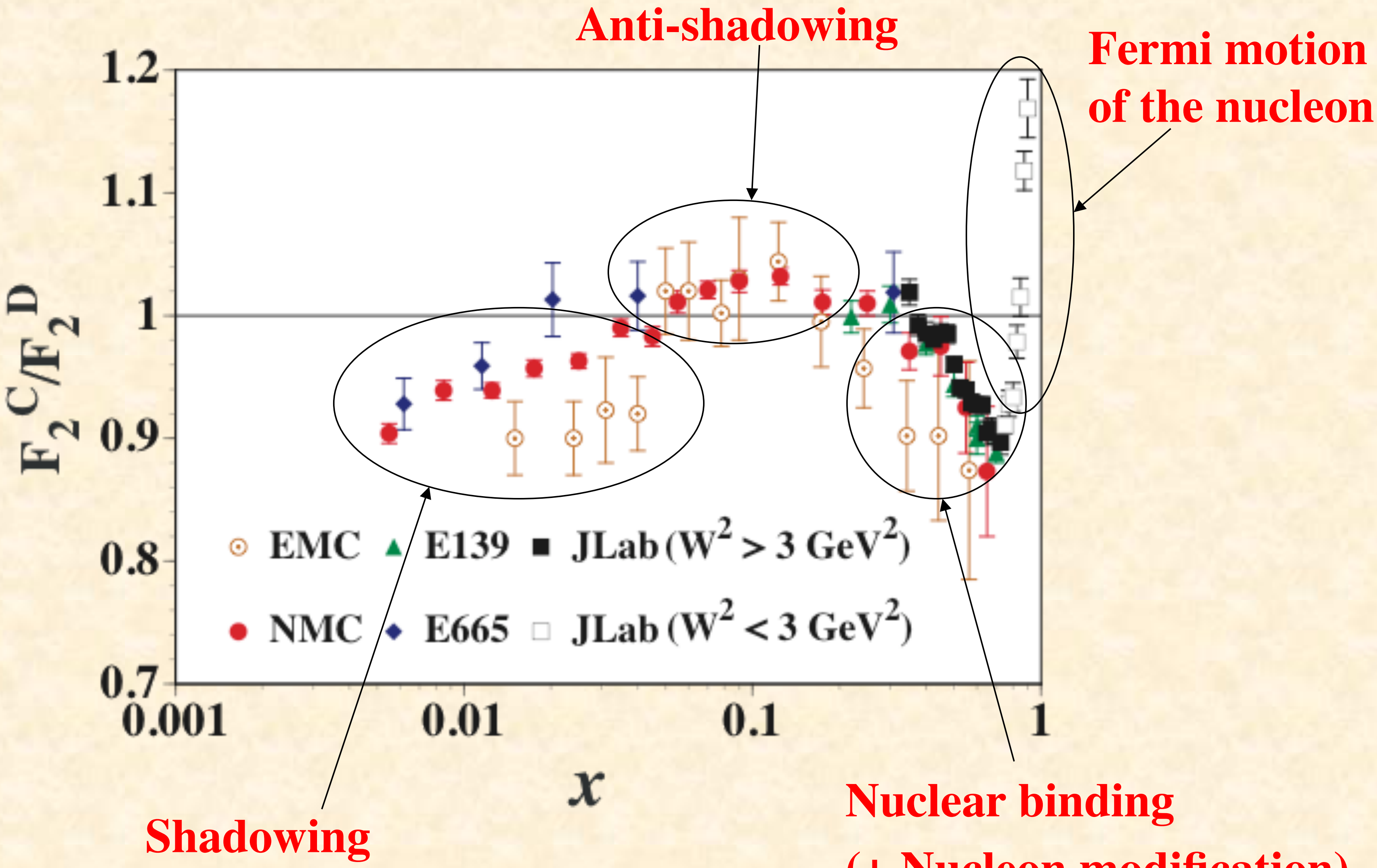
M. Tzanov *et al.* (NuTeV), PRD74 (2006) 012008.

MINERνA (He, C, Fe, Pb), …



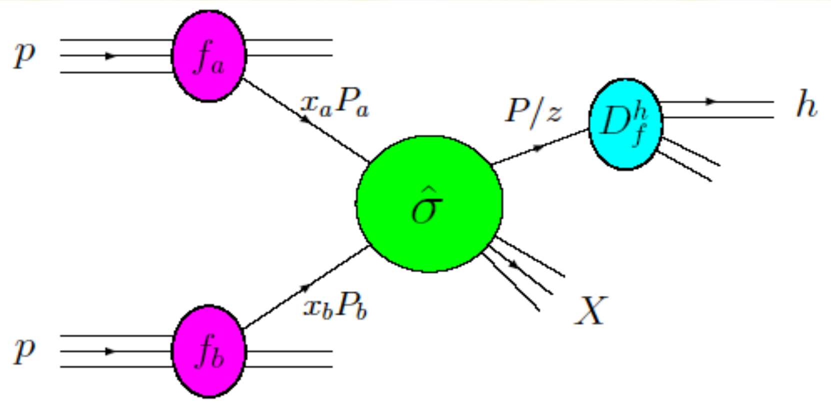


Nuclear modifications of structure function F_2



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**

Experimental data: total number = 1241

(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

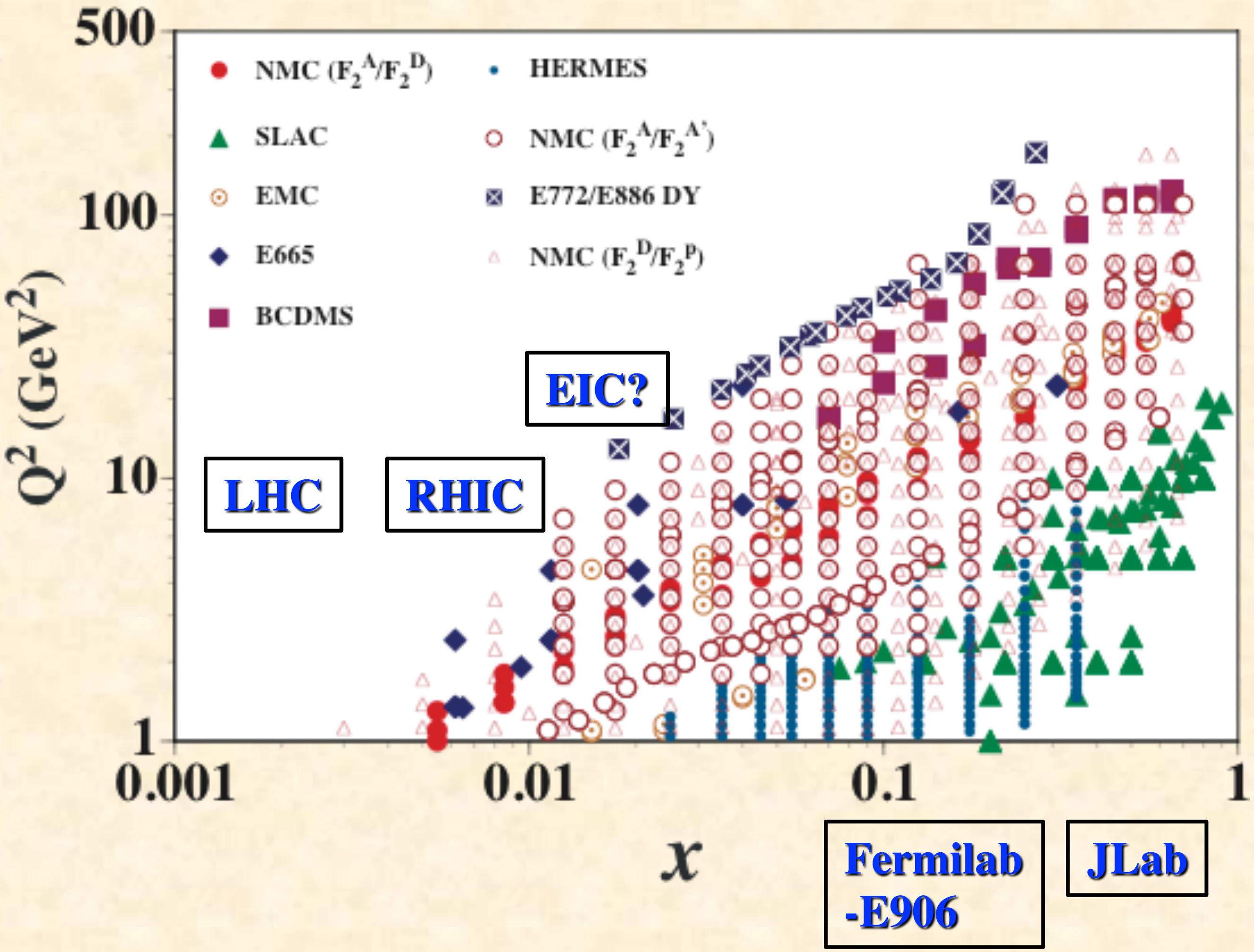
+ JLab data

(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



Situation of data for nuclear PDFs

Process/ Experiment	Leading order subprocess	Parton behaviour probed
DIS ($\mu N \to \mu X$) $F_2^{\mu p}, F_2^{\mu d}, F_2^{\mu n}/F_2^{\mu p}$ (SLAC, BCDMS, NMC, E665)*	$\gamma^* q \to q$	Four structure functions → $u + \bar{u}$, $d + \bar{d}$, $\bar{u} + \bar{d}$, s (assumed $= \bar{s}$), but only $\int xg(x, Q_0^2)dx \simeq 0.35$ and $\int(\bar{d} - \bar{u})dx \simeq 0.1$
DIS ($\nu N \to \mu X$) $F_2^{\nu N}, xF_3^{\nu N}$ (CCFR)*	$W^* q \to q'$	
DIS (small x) F_2^{ep} (H1, ZEUS)*	$\gamma^*(Z^*)q \to q$	λ ($x\bar{q} \sim x^{-\lambda_S}$, $xg \sim x^{-\lambda_g}$)
DIS (F_L) NMC, HERA	$\gamma^* g \to q\bar{q}$	g
$\ell N \to c\bar{c}X$ F_2^c (EMC; H1, ZEUS)*	$\gamma^* c \to c$	c ($x \gtrsim 0.01$; $x \lesssim 0.01$)
$\nu N \to \mu^+\mu^- X$ (CCFR)*	$W^* s \to c$ $\hookrightarrow \mu^+$	$s \approx \frac{1}{4}(\bar{u} + \bar{d})$
$pN \to \gamma X$ (WA70*, UA6, E706, ...)	$qg \to \gamma q$	g at $x \simeq 2p_T^\gamma/\sqrt{s}$ → $x \approx 0.2 - 0.6$
$pN \to \mu^+\mu^- X$ (E605, E772)*	$q\bar{q} \to \gamma^*$	$\bar{q} = ...(1-x)^{\eta_S}$
$pp, pn \to \mu^+\mu^- X$ (E866, NA51)*	$u\bar{u}, d\bar{d} \to \gamma^*$ $u\bar{d}, d\bar{u} \to \gamma^*$	$\bar{u} - \bar{d}$ ($0.04 \lesssim x \lesssim 0.3$)
$ep, en \to e\pi X$ (HERMES)	$\gamma^* q \to q$ with $q = u, d, \bar{u}, \bar{d}$	$\bar{u} - \bar{d}$ ($0.04 \lesssim x \lesssim 0.2$)
$p\bar{p} \to WX(ZX)$ (UA1, UA2; CDF, D0)	$ud \to W$	u, d at $x \simeq M_W/\sqrt{s}$ → $x \approx 0.13$; 0.05
→ **$\ell^\pm$ asym** (CDF)*		slope of u/d at $x \approx 0.05 - 0.1$
$p\bar{p} \to t\bar{t}X$ (CDF, D0)	$q\bar{q}, gg \to t\bar{t}$	q, g at $x \gtrsim 2m_t/\sqrt{s} \simeq 0.2$
$p\bar{p} \to$ jet $+ X$ (CDF, D0)	$gg, qg, qq \to 2j$	q, g at $x \simeq 2E_T/\sqrt{s}$ → $x \approx 0.05 - 0.5$

Available data for nuclear PDFs

Jlab at large x

Nuclear target Fe (CCFR, NuTeV)
Not for p and d.

Small-*x*,
high-energy electron facility (EIC, LHeC)?

Fermilab

RHIC, LHC (J-PARC?, GSI?)

RHIC, LHC

hep/ph-9803445

Updated information
In A. D. Martin *et al.* (MSTW08), Eur.Phys.J. C63 (2009) 189.

Current nuclear data are kinematically limited.

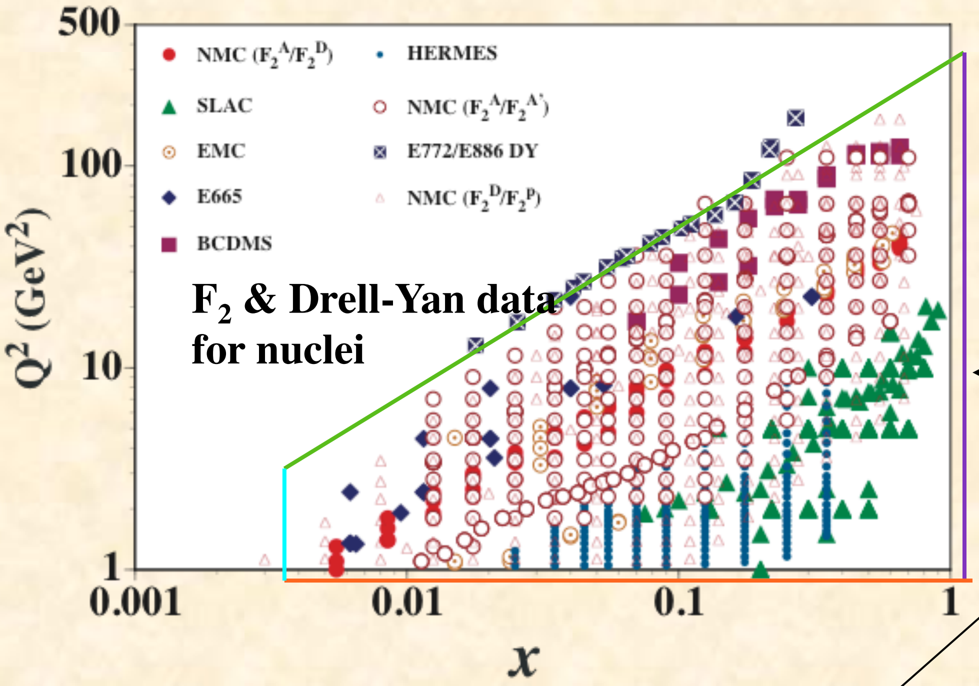
$$x = \frac{Q^2}{2p \cdot q} \simeq \frac{Q^2}{ys}$$

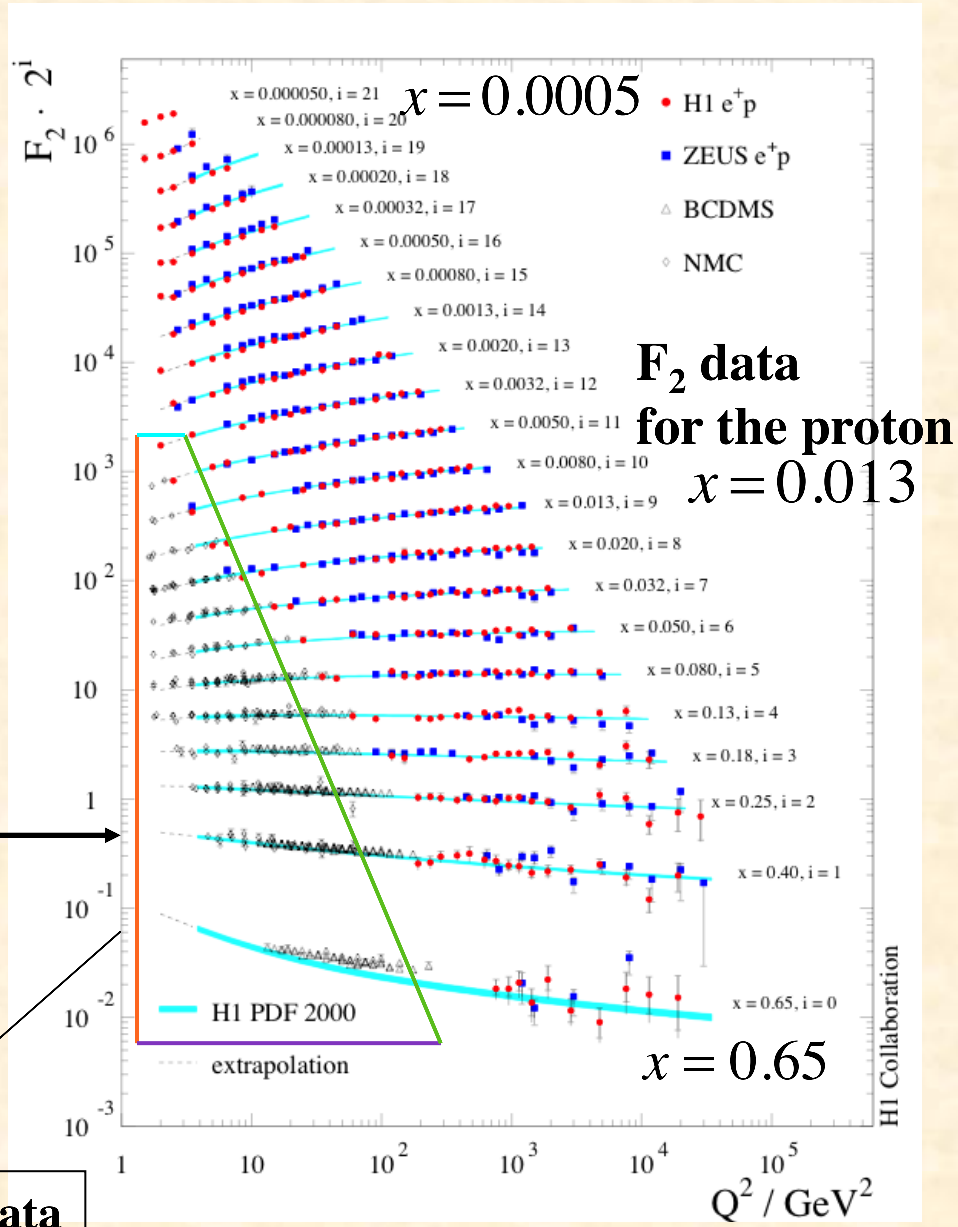
(from H1 and ZEUS, hep-ex/0502008)

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

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

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





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 $w_i(x, A)$

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

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

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

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

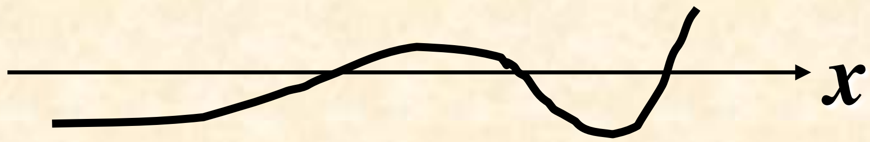
at Q^2=1 GeV^2 ($\equiv Q_0^2$)

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

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

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

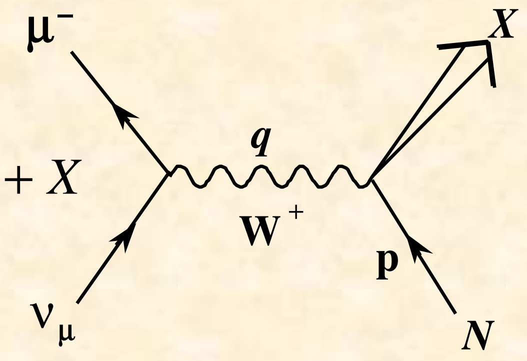
(2) calculate observables at their experimental Q^2 **points.**

(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

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



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

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

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

where $\varepsilon_{0123} = +1$

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

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

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

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

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

Valence: also F_2 at large x

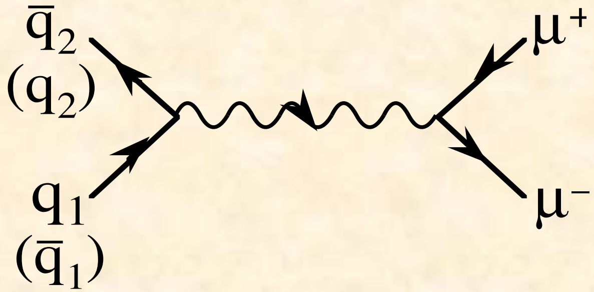
Sea quark

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)



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

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

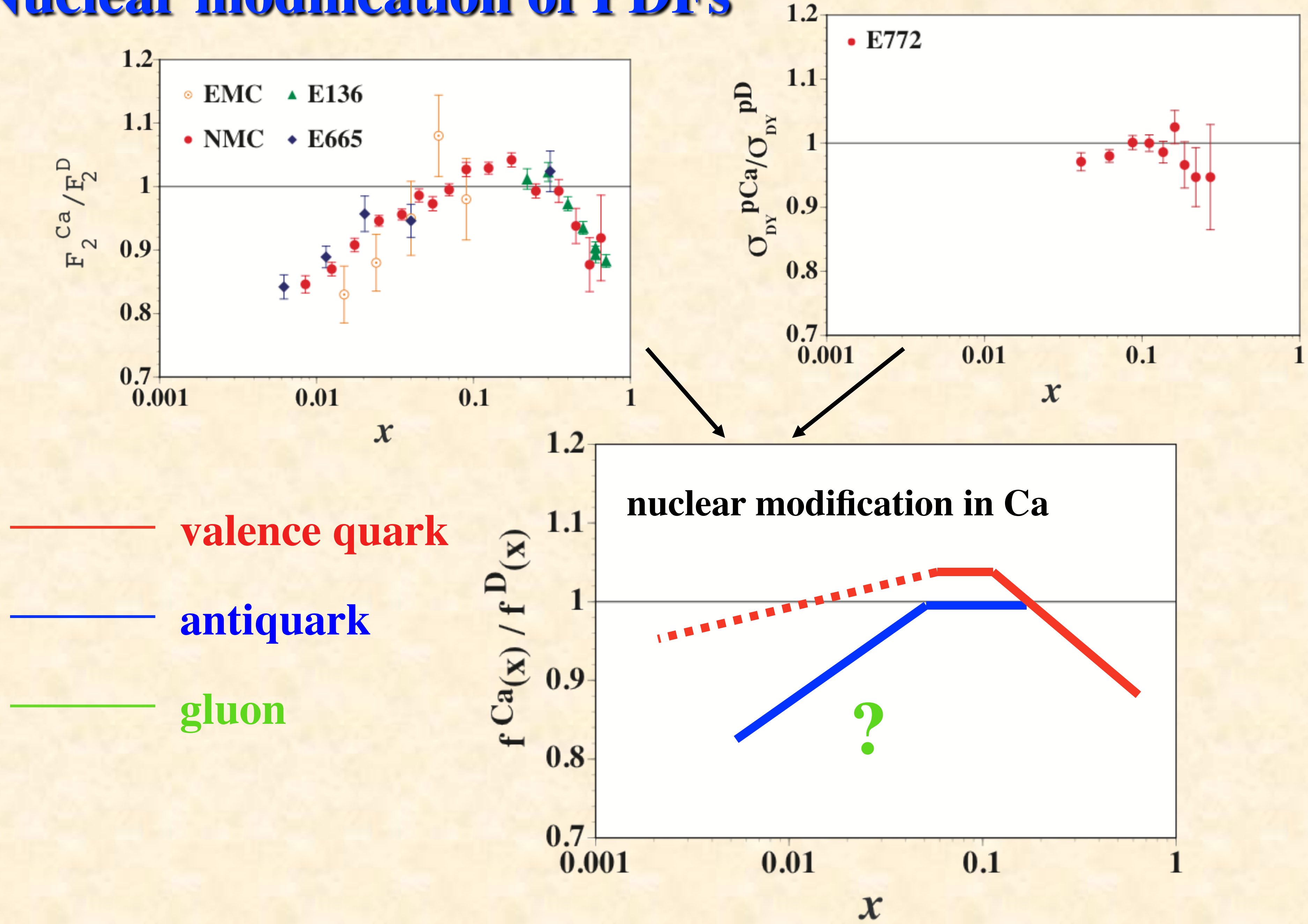
at large $x_F = x_1 - x_2$

projectile **target**

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

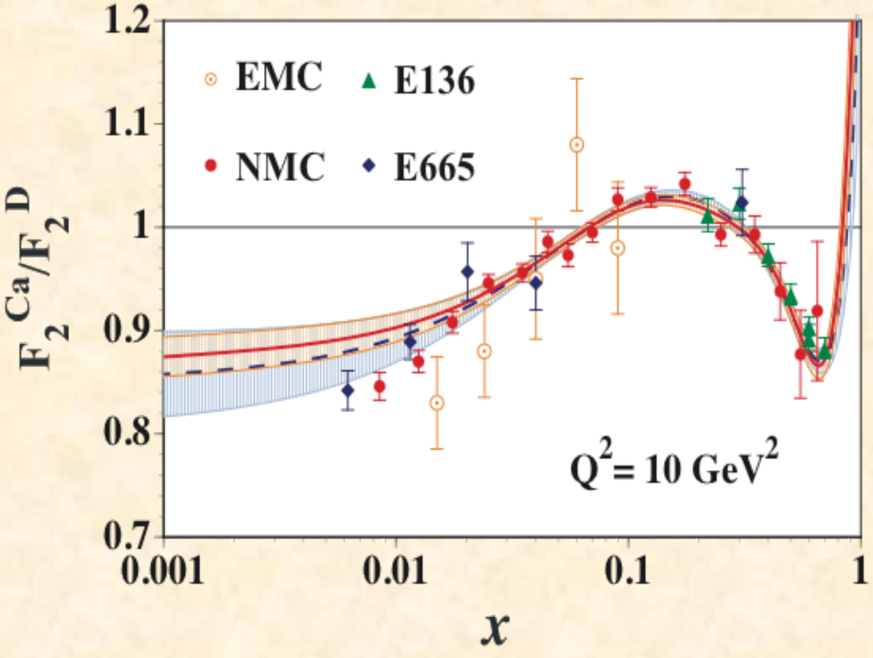
$\bar{q}(x_2)$ can be obtained if $q_V(x_1)$ is known.

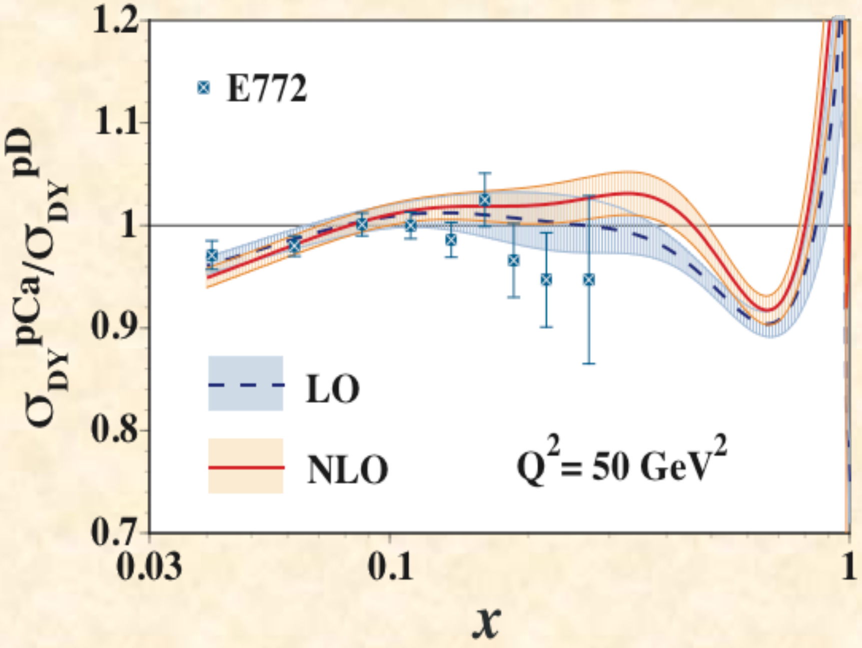
Nuclear modification of PDFs



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

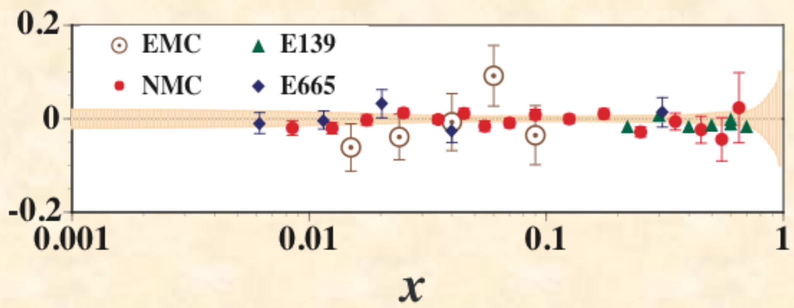
LO analysis **NLO analysis**

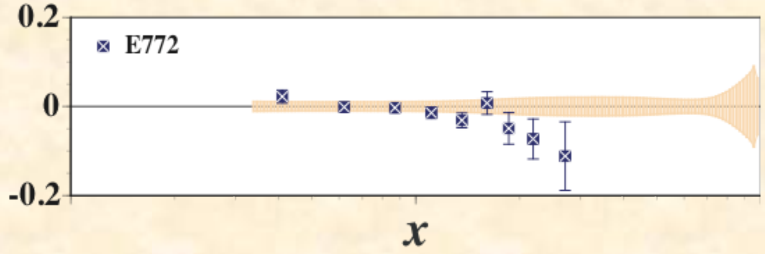




$(R^{exp}-R^{theo})/R^{theo}$ at the same Q^2 points

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



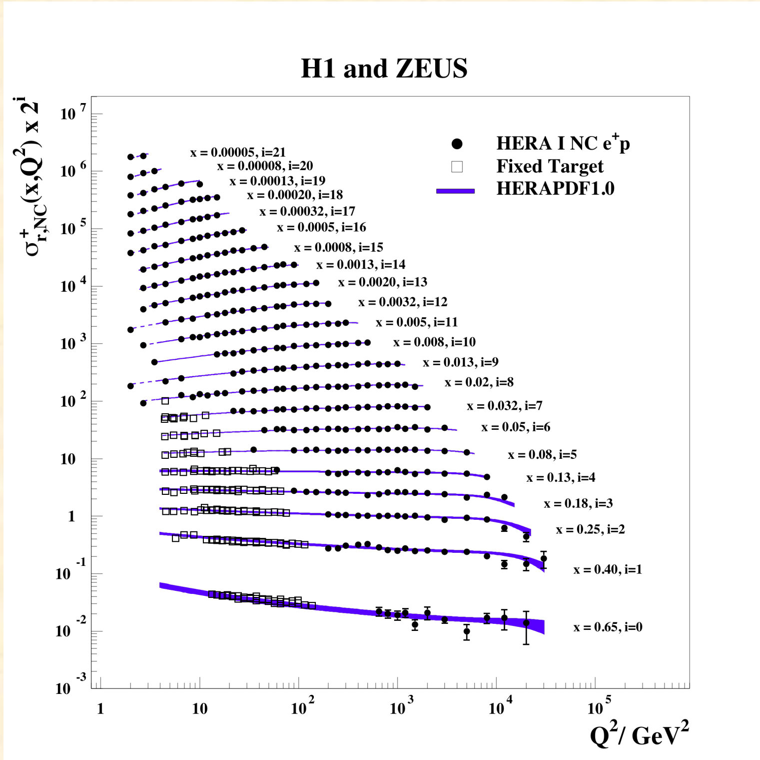


Gluon

scaling violation of F_2

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

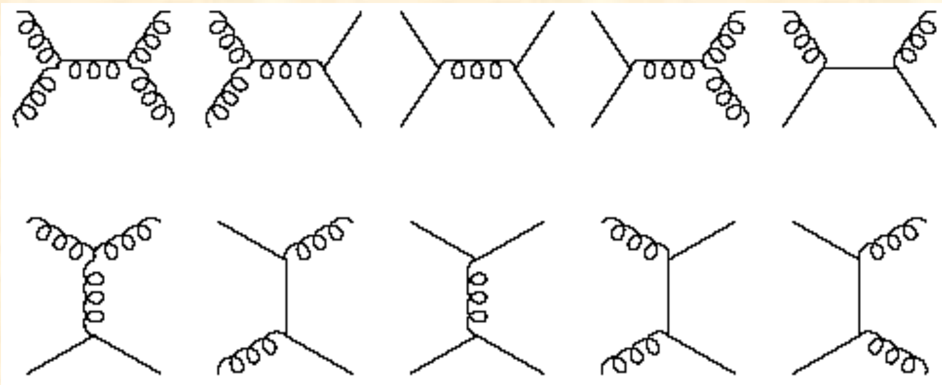
H1 and ZEUS
JHEP01(2010)109



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



Scaling Violation and Gluon Distributions

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

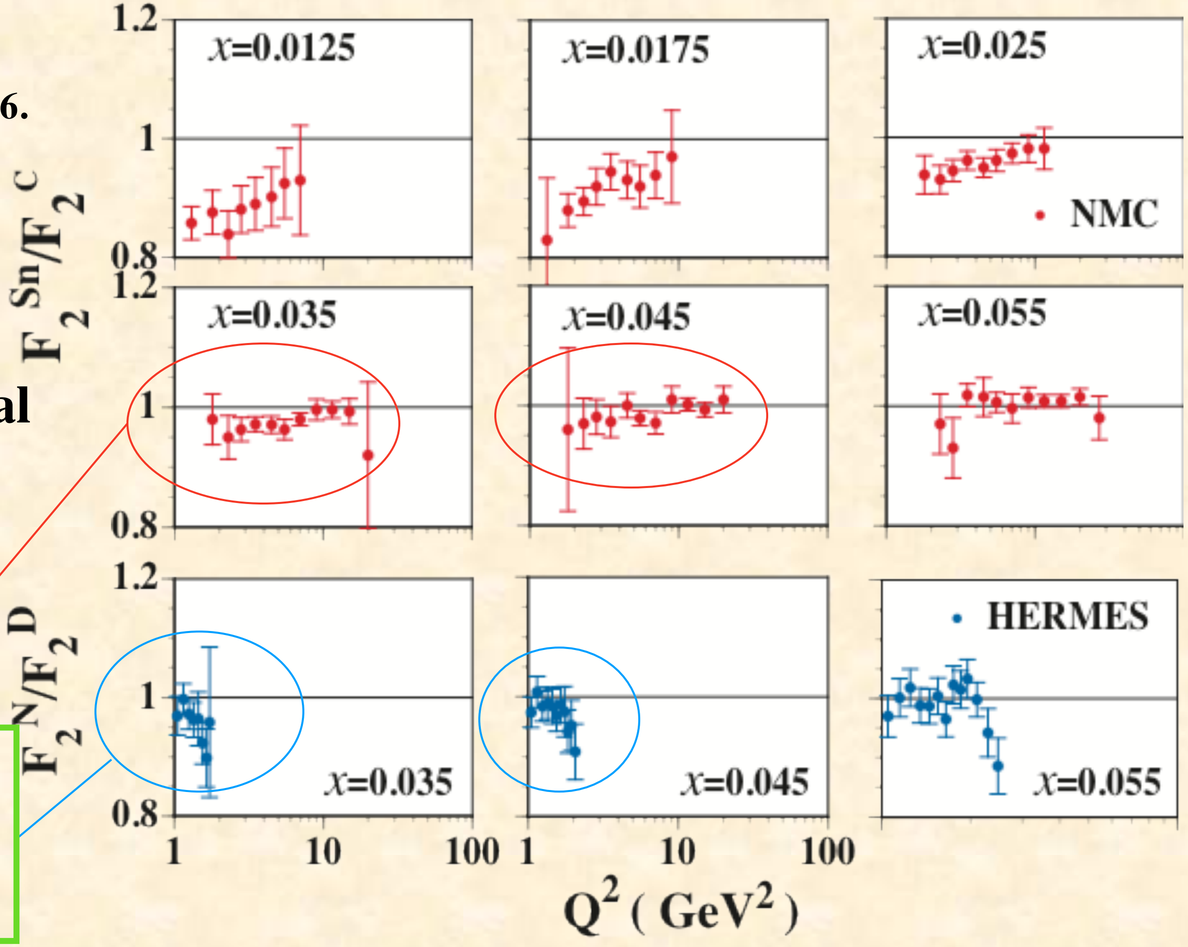
dominant term at small x

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

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

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

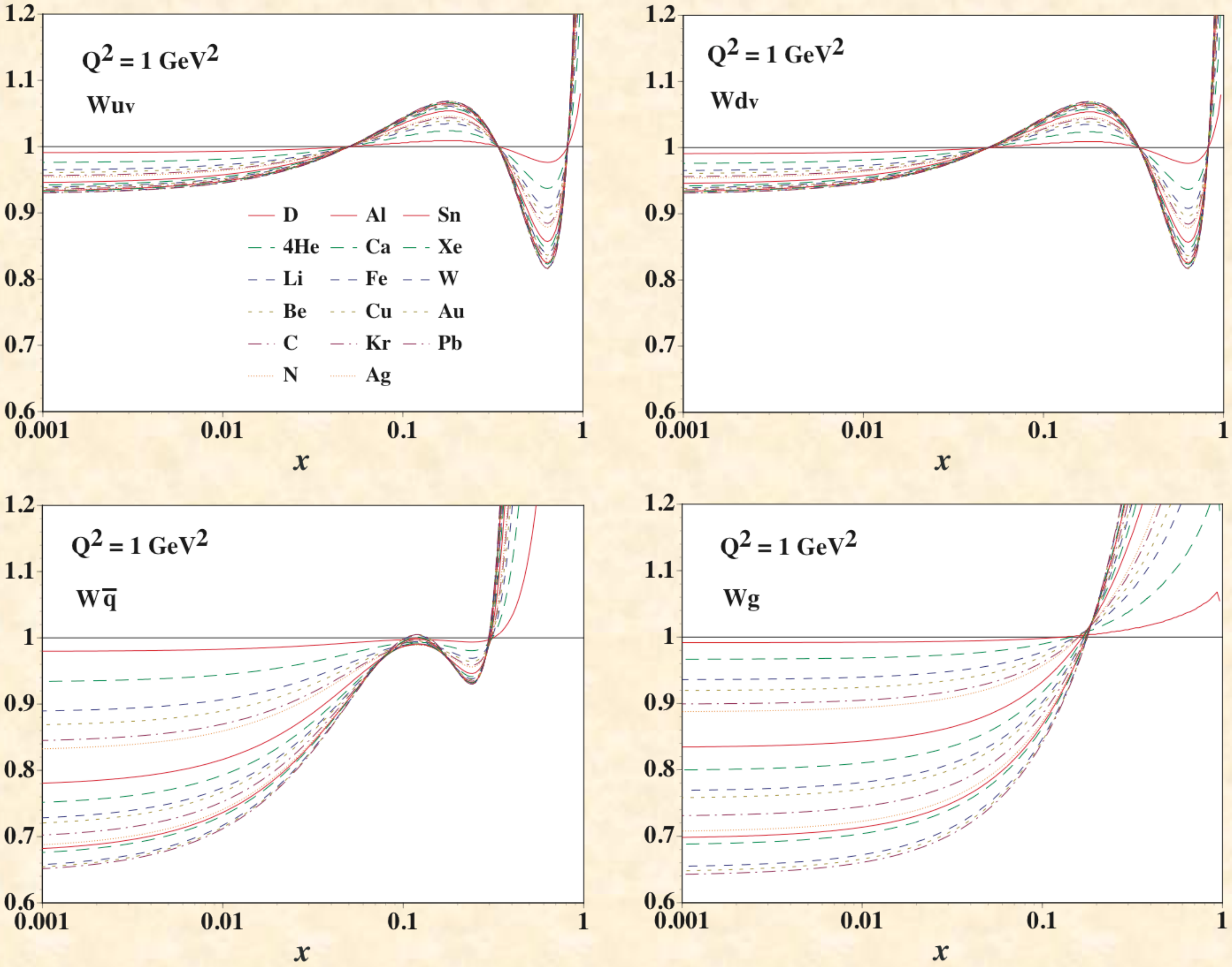
Q^2 dependence of F_2 is proportional to the gluon distribution.



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

Nuclear 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; arXiv:1307.3454.
  - 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

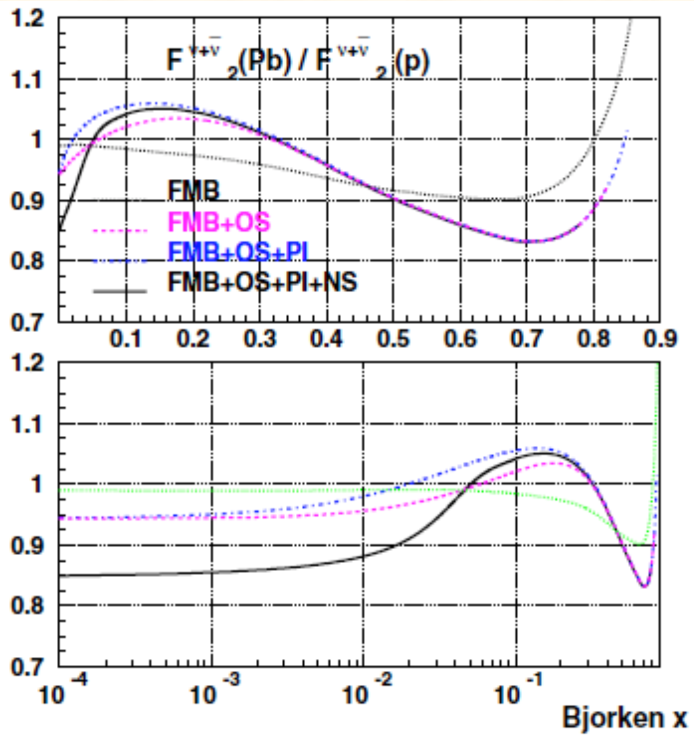
See also L. Frankfurt, V. Guzey, and M. Strikman, Phys. Rev. D 71 (2005) 054001;
Phys. Lett. B687 (2010) 167; Phys. Rept. 512 (2012) 255; arXiv:1310.5879.
S. A. Kulagin and R. Petti, Phys. Rev. D 76 (2007) 094023; C 82 (2010) 054614.
A. Bodek and U.-K. Yang, arXiv:1011.6592.

Kulagin and Petti's analysis

S. A. Kulagin and R. Petti, Phys. Rev. D76 (2007) 094023.

- Although most global analyses assume rather a model-independent functional form with a number of parameters, their approach is different in the sense that only the "off-shell" effects in the nucleon are parametrized.
- They tried to obtain structure functions rather than the PDFs.

Nuclear structure functions
= Conventional nuclear physics + Nucleon modifications in nuclear medium
= Binding, Fermi motion + Pion excess + Shadowing (Multiple scattering)
+ Off-shell effects (with parameters to be determined from data)



Off-shell effects: $F_2(x,Q^2,p^2) = F_2(x,Q^2)\left[1+\delta f_2(x)\frac{p^2-M_N^2}{M_N^2}\right]$

Parametrization: $\delta f_2(x) = C_N(x-x_1)(x-x_0)(1+x_0-x)$

FMB: Fermi Motion + Binding
OS: +Off-Sell
PI: +Pion
NS: +Nuclear Shadowing

Functional form of initial distributions at Q_0^2

Initial nuclear PDFs at

$$f_i^A(x) = \frac{1}{A}\left[Z f_i^{p/A}(x) + (A-Z) f_i^{n/A}(x)\right] \qquad f_i^{N/A}(x): \text{ PDF of bound nucleon in the nucleus}$$

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)

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

- 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.

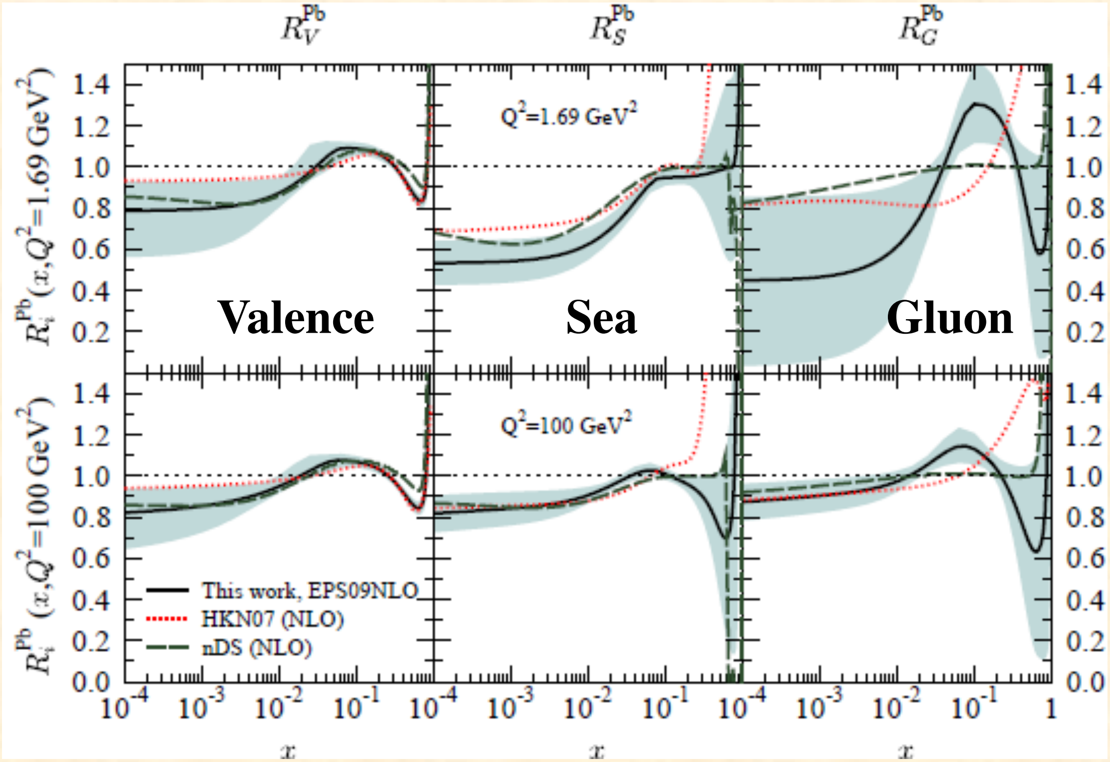
Valence quark: Well determined except at small *x*.

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

Gluon: Large uncertainties in the whole-*x* region.

$Q^2 = 1.69\ \mathrm{GeV}^2$

$Q^2 = 100\ \mathrm{GeV}^2$



EPS09

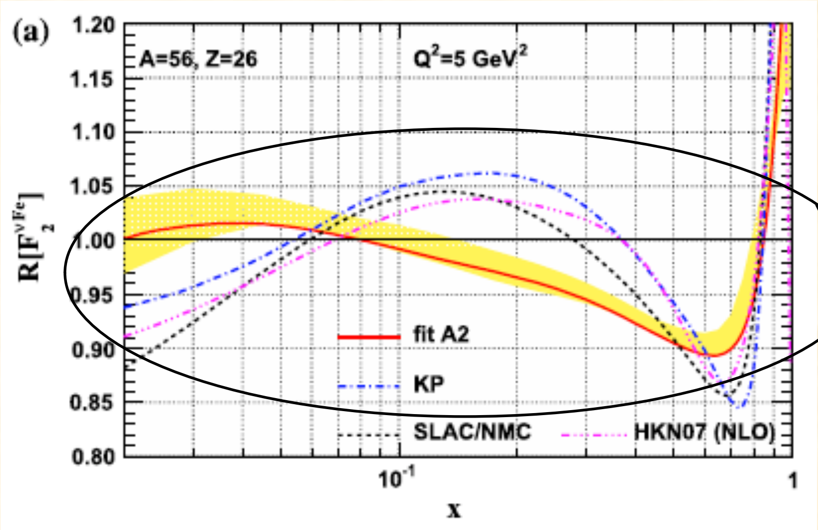
HKN07

DS04

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

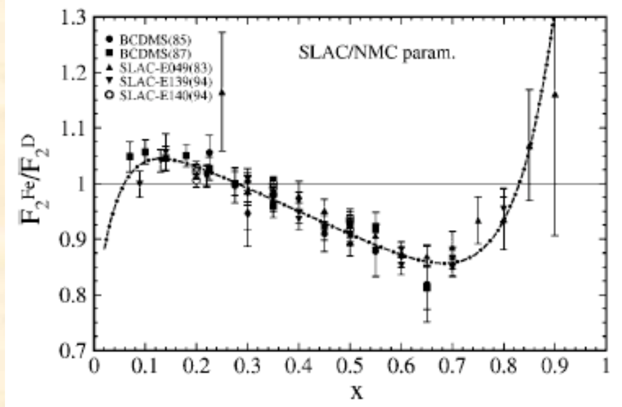
Analysis of CTEQ-2008 (Schienbein *et al.*)

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

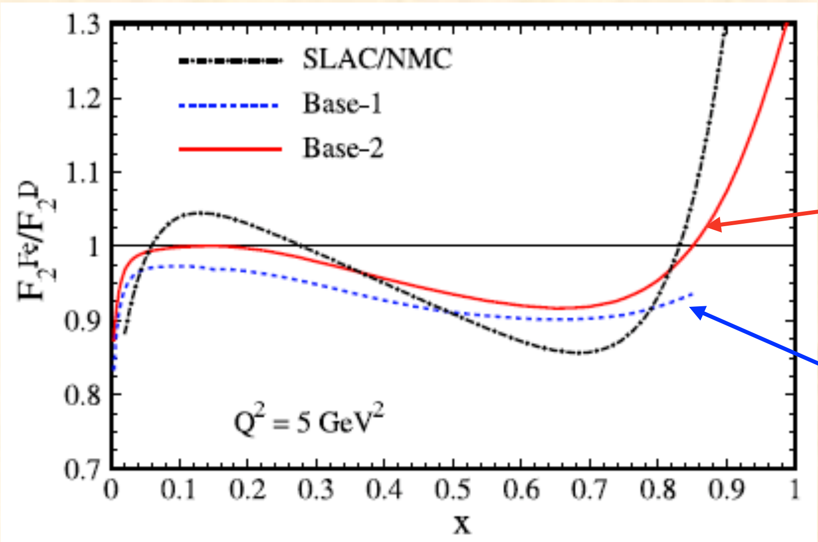


Differences from typical NPDFs.

Charged-lepton scattering



Neutrino scattering



Base-1
- remove CCFR data
- incorporate deuteron corrections

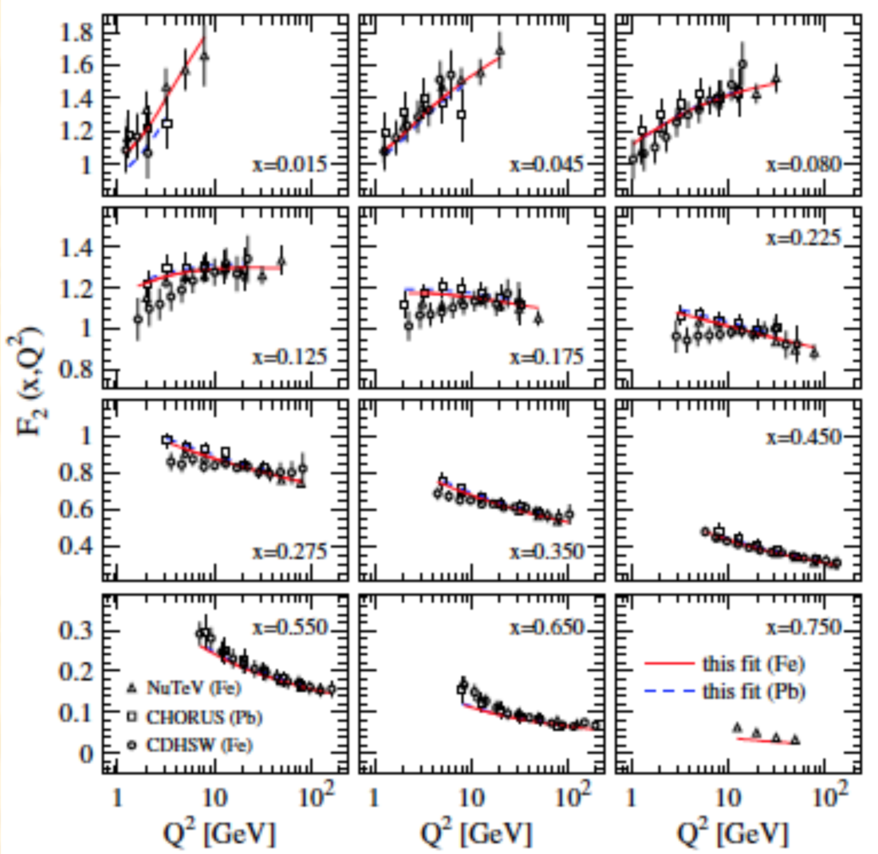
Base-2 corresponds to CTEQ6.1M with s≠sbar
- include CCFR data
  Charged-lepton correction factors are applied.
- s≠sbar

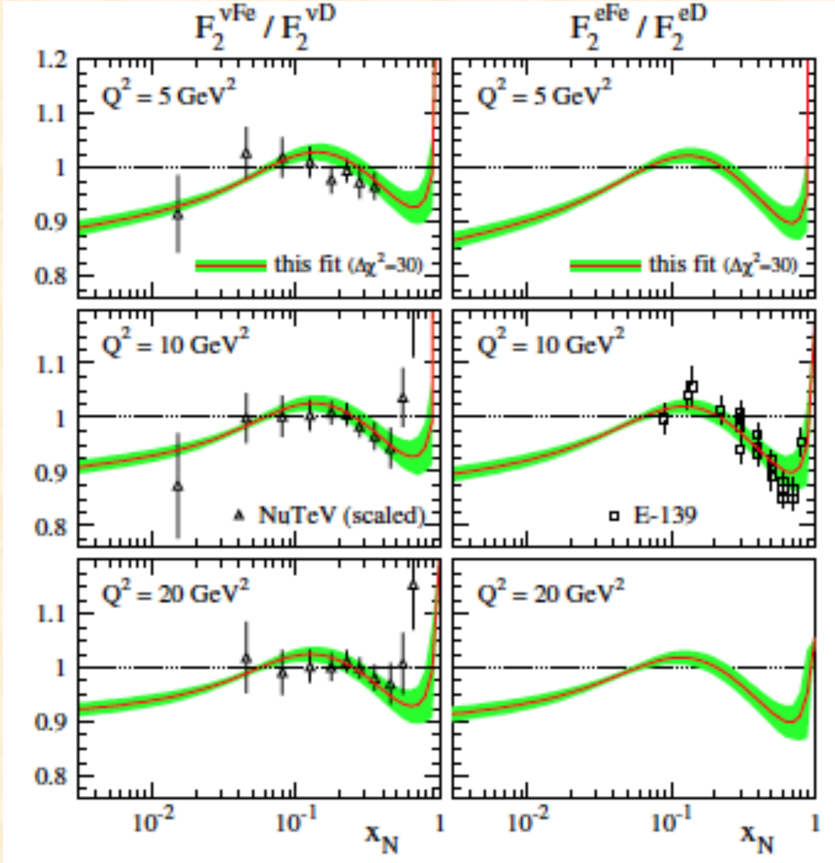
Base-2: Using current nucleonic PDFs, they (and MRST) obtained very different corrections from charged-lepton data.

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

Neutrino DIS ⇔ 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!?

Activities in 2013

1. K. Kovarik *et al*. (CTEQ), arXiv:1307.3454 (DIS-2013).

2. 2. H. Honkanen, M. Strikman, and V. Guzey, arXiv:1310.5879.

H. Honkanen, M. Strikman, and V. Guzey, arXiv:1310.5879.

$$0 \le x_A = \frac{Q^2}{2M_A\nu} \le 1, \quad x_A = \frac{Q^2}{2M_A\nu} = \frac{M_N}{M_A}\frac{Q^2}{2M_N\nu} \simeq \frac{1}{A}x \le 1 \quad \Rightarrow 0 \le x \lesssim A \text{ for a nucleus}$$

$$x_A = \frac{Q^2}{2M_A\nu} = \frac{Q^2}{2(Zm_p + Nm_n - A\varepsilon_A)\nu} = \frac{Q^2}{2[(A-N)m_p + Nm_n - A\varepsilon_A]\nu} = \frac{Q^2}{2[Am_p + N(m_n - m_p) - A\varepsilon_A]\nu}$$

$$= \frac{Q^2}{2m_p\nu A\left[1 + \frac{N}{A}\frac{m_n - m_p}{m_p} - \frac{\varepsilon_A}{m_p}\right]} = \frac{1}{A}\frac{x_p}{1+r_A}, \quad x_p = \frac{Q^2}{2m_p\nu}, \quad r_A = \frac{1}{m_p}\left[(m_n - m_p)\frac{N}{A} - \varepsilon_A\right]$$

$$x_{HSG} \equiv \frac{1}{A}x_A = \frac{x_p}{1+r_A} \quad x_p = x_{HSG}(1+r_A)$$

Two effects are included:

- Binding effect on the scaling variable:

$$x_p = x\,(1+r_A), \quad x_p = \frac{Q^2}{2m_p\nu}$$

$$r_A = \frac{1}{m_p}\left[(m_n - m_p)\frac{N}{A} - \varepsilon_A\right], \quad \varepsilon_A = \text{binding energy}$$

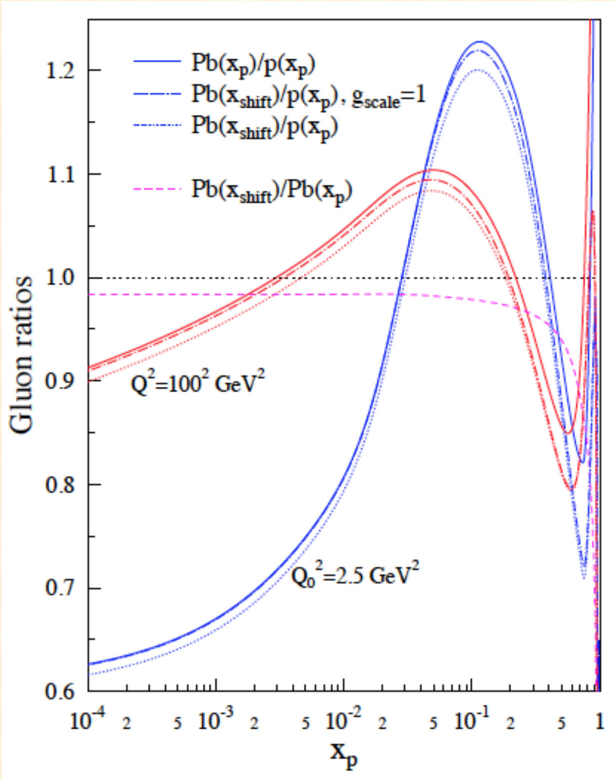
- QED effect on the nuclear PDFs:

Momentum conservation, $\sum_i \int_0^1 dx\, f_i^A(x,Q^2) = 1 - \eta_\gamma$

η_γ = photon momentum

$\Rightarrow$ attribute the effect to the gluon modification: $g_{scale} \equiv \frac{\eta_g - \eta_\gamma}{\eta_g}$

$$xf_i^A(x,Q^2) = \begin{cases} \frac{x_p}{1+r_A} f_i^A\left(\frac{x_p}{1+r_A}, Q^2\right) & \text{for } i = q, \bar{q} \\ g_{scale}\frac{x_p}{1+r_A} f_i^A\left(\frac{x_p}{1+r_A}, Q^2\right) & \text{for } i = g \end{cases}$$

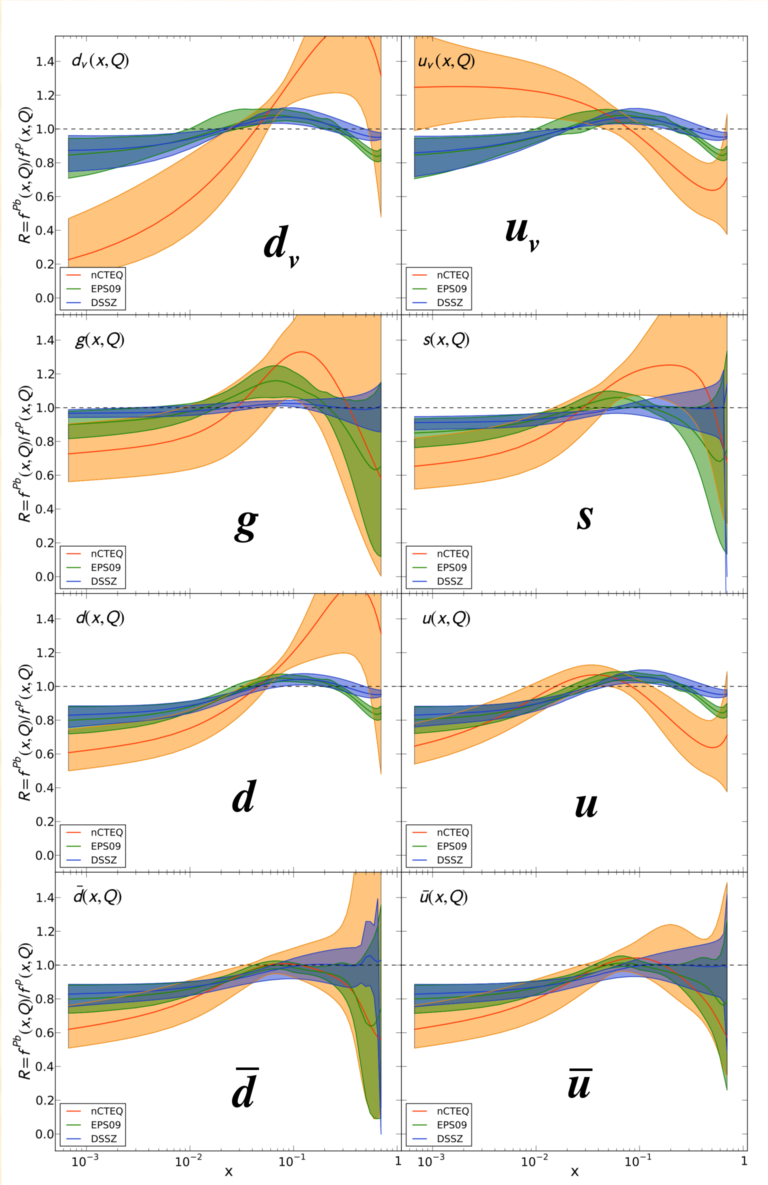


K. Kovarik *et al.* (CTEQ), arXiv:1307.3454 (DIS-2013)

K. Kovarik, T. Jezo, A. Kusina, F. I. Olness, I. Schienbein, T. Stavreva, J. Y. Yu, Charged lepton DIS + Drell-Yan

$$x f_k(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5} ,$$
$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4} ,$$

^{208}Pb, $Q^2 = 100$ GeV^2



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 data

- JLab, Fermilab-DY, Minerνa, LHC, … (J-PARC high-momentum?)

Large grant was approved for neutrino-research activities
in Japan from 2013.
We hope that we answer some of these issues in the near future.

The End

The End