# Parton distributions in the nucleon and nuclei

Shunzo Kumano
Saga University

kumanos@cc.saga-u.ac.jp
http://hs.phys.saga-u.ac.jp

Workshop on Physics in ep Collision VI
Nov. 9-10, 2001, KEK, Japan

Nov. 9, 2001

# Contents

- Unpolarized distributions in the nucleon
- Polarized distributions in the nucleon
- Distributions in nuclei
- Selected topics
- Summary

# Introduction: current status

Parton distributions are determined
by fitting various experimental data.

- electron/muon $\mu + p \to \mu + X$
- neutrino $\nu_\mu + p \to \mu + X$
- Drell-Yan $p + p \to \mu^+\mu^- + X$
- direct photon $\mu/p + p \to \gamma + X$
- ...

(1) assume parton distributions at $Q_0^2$ ($\sim$1 GeV$^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 structure functions
at experimental $Q^2$ points

(3) then, $A_i$ , $\alpha_i$ , $\beta_i$ , $\gamma_i$ are determined
in comparison with data

# Available data for determining parton distributions

(Ref. MRST, hep/ph-9803445)

HERA

| 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 $\to$ $u+\bar{u}$, $d+\bar{d}$, $\bar{u}+\bar{d}$, $s$ (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)* | $\gamma^*(Z^*)q \to q$ | $\lambda$ $(x\bar{q} \sim x^{-\lambda_S},\ xg \sim x^{-\lambda_g})$ |
| **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 $x \simeq 2p_T^\gamma/\sqrt{s} \to$ $x \approx 0.2-0.6$ |
| $pN \to \mu^+\mu^- X$ (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 $x \simeq M_W/\sqrt{s} \to$ $x \approx 0.13;\ 0.05$ |
| $\to \ell^\pm$ **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 $x \simeq 2E_T/\sqrt{s} \to$ $x \approx 0.05-0.5$ |

# Used data for MRST01

(Ref. MRST, hep/ph-0110215)

**HERA**

| Data set | No. of data pts | MRST | MRST 0.117 | MRST 0.121 | MRST J |
|---|---|---|---|---|---|
| H1 $ep$ | 400 | 382 | 386 | 378 | 377 |
| ZEUS $ep$ | 272 | 254 | 255 | 258 | 253 |
| BCDMS $\theta p$ | 167 | 193 | 182 | 208 | 183 |
| BCDMS $\theta d$ | 155 | 218 | 211 | 226 | 219 |
| NMC $\theta p$ | 126 | 134 | 143 | 127 | 135 |
| NMC $\theta d$ | 126 | 100 | 108 | 95 | 100 |
| SLAC $ep$ | 53 | 66 | 71 | 63 | 67 |
| SLAC $ed$ | 54 | 56 | 67 | 47 | 58 |
| E665 $\theta p$ | 53 | 51 | 50 | 52 | 51 |
| E665 $\theta d$ | 53 | 61 | 61 | 61 | 61 |
| CCFR $F_2{}^N$ | 74 | 85 | 88 | 82 | 89 |
| CCFR $F_3{}^N$ | 105 | 107 | 103 | 112 | 110 |
| NMC $n/p$ | 156 | 155 | 155 | 153 | 161 |
| E605 DY | 136 | 232 | 229 | 247 | 273 |
| Tevatron Jets | 113 | 170 | 168 | 167 | 118 |
| Total | 2097 | 2328 | 2346 | 2345 | 2337 |

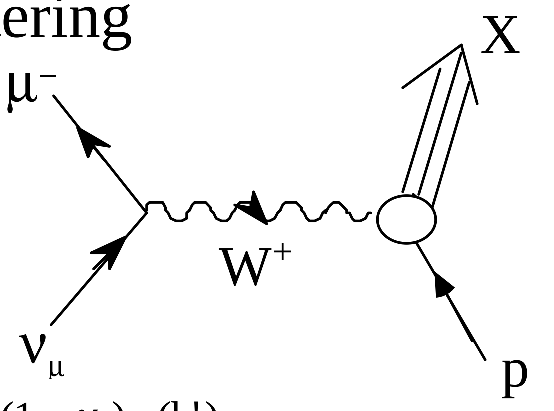
# Determination of each distribution

## Valence quark

note: $q_v \equiv q - \bar{q}$

neutrino deep inelastic scattering

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




$$L^{\mu\nu} = \overline{\sum_{\text{spins}}} \bar{u}(k)\,\gamma^\mu (1-\gamma_5)\,u(k) \cdot \bar{u}(k')\,\gamma^\nu (1-\gamma_5)\,u(k')$$

$$= 2\left[\, k^\mu k'^\nu + k^\nu k'^\mu - g^{\mu\nu} k\cdot k' \;\underline{+\, i\varepsilon^{\mu\nu\rho\sigma} k_\rho k'_\sigma}\,\right]$$

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

$$\boxed{-\frac{i}{M} W_3\, \varepsilon_{\mu\nu\rho\sigma}\, p^\rho q^\sigma}$$

$$\frac{d\sigma^{W^\pm}}{dE'\, d\Omega} = \frac{G_F^2 E'^2}{2\pi^2 (1+Q^2/M_W^2)^2}$$

$$\times\left[ W_2 \cos^2\frac{\theta}{2} + 2W_1 \sin^2\frac{\theta}{2} \;\underline{\mp \frac{E+E'}{M} W_3 \sin^2\frac{\theta}{2}}\, \right]$$

parity violation: $\underline{W_3 \propto \sigma_L - \sigma_R}$ , $F_3 = \nu W_3$

in parton model

$$F_3^{\nu p} = 2\,(d + s - \bar{u} - \bar{c})\;, \quad F_3^{\bar{\nu} p} = 2\,(u + c - \bar{d} - \bar{s})$$

$$\underline{F_3^p = \frac{F_3^{\nu p} + F_3^{\bar{\nu} p}}{2} = u_v + d_v} \quad \text{if } s=\bar{s},\ c=\bar{c}$$

# Sea quark

## e/μ scattering

$$F_2^p = \frac{4}{9}\, x\, (u+\bar{u}) + \frac{1}{9}\, x\, (d+\bar{d}+s+\bar{s})$$

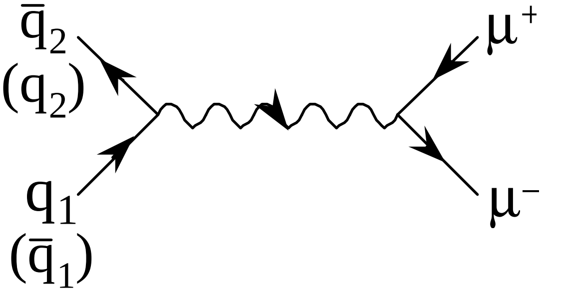
$$F_2^n = \frac{4}{9}\, x\, (d+\bar{d}) + \frac{1}{9}\, x\, (u+\bar{u}+s+\bar{s})$$

$$F_2^N = \frac{F_2^p+F_2^n}{2} = \frac{5}{18}\, x\, (u+\bar{u}+d+\bar{d}) + \frac{2}{18}\, x\, (s+\bar{s})$$

$$= \underline{\frac{5}{18}\, x\, V} + \underline{\frac{4}{18}\, x\, S} \quad \text{if SU(3) symmetric sea}$$

## 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 $F_2$

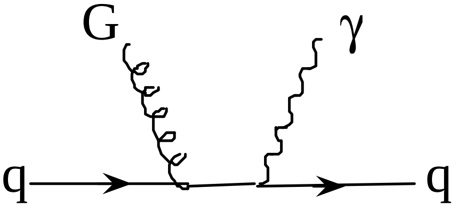
$$\frac{\partial}{\partial(\ln Q^2)} q_i(x,Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right) q_i(y,Q^2) + P_{qG}\left(\frac{x}{y}\right) G(y,Q^2)\right]$$

$$\frac{\partial}{\partial(\ln Q^2)} G(x,Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{Gq}\left(\frac{x}{y}\right) q_i(y,Q^2) + P_{GG}\left(\frac{x}{y}\right) G(y,Q^2)\right]$$

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

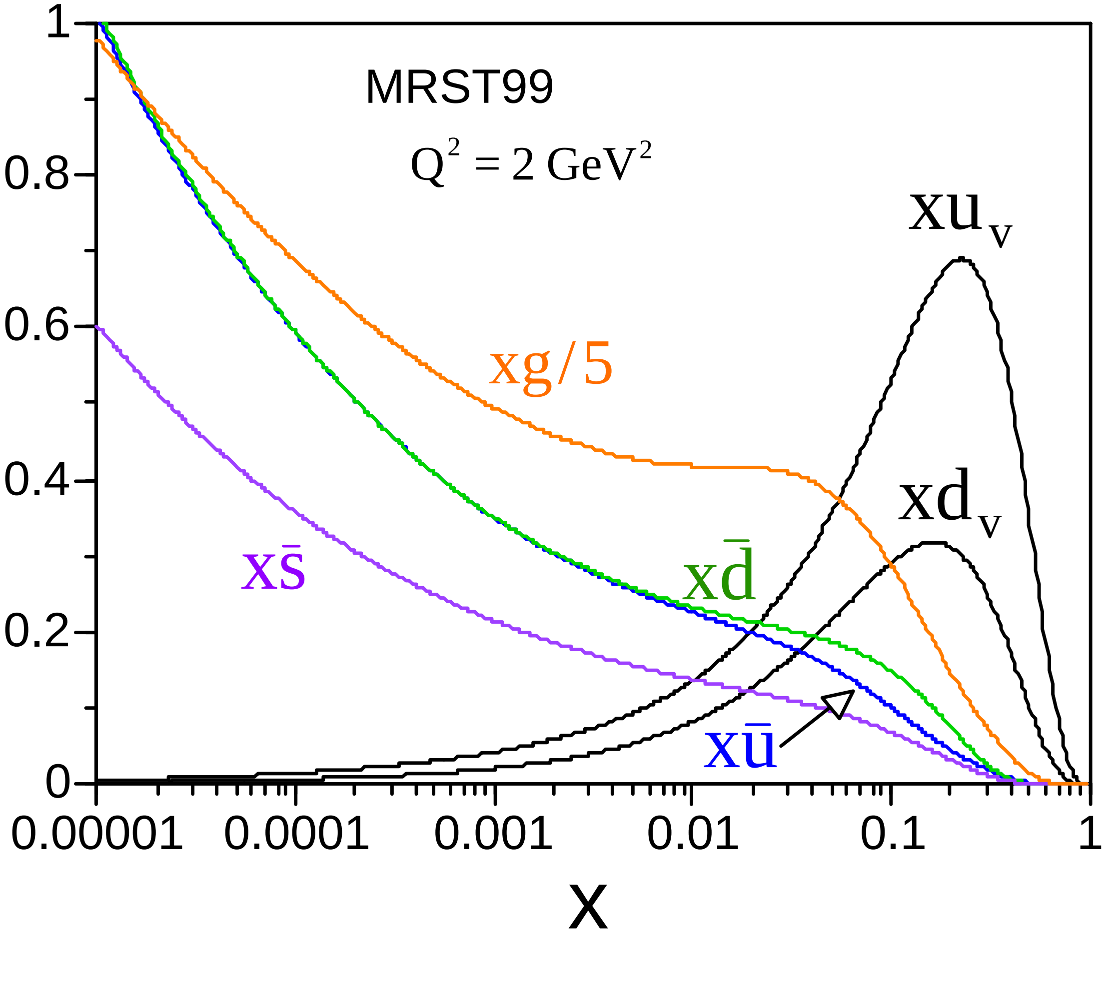
## direct photon

$$p + p \rightarrow \gamma + X$$



# Recent unpolarized distributions

- CTEQ5, Eur. Phys. J. C12 (2000) 375
- GRV98, Eur. Phys. J. C5 (1998) 461
- MRST99, Eur. Phys. J. C14 (2000) 133
  (MRST01, hep-ph/0110215)




HERA data are important for determining small-x distributions in the nucleon.

# Polarized parton distributions

Refs. (1) Y. Goto, N. Hayashi, M. Hirai, H. Horikawa, S. Kumano, M. Miyama, T. Morii, N. Saito, T.-A. Shibata, E. Taniguchi, T. Yamanishi
Asymmetry Analysis Collaboration (AAC)
Phys. Rev. D62 (2000) 034017.

(2) AAC, research in progress.

A library for polarized parton distributions can be obtained from

http://spin.riken.bnl.gov/aac.

## • polarized parton distributions

status of proton-spin issue

polarized e/μ-proton scattering

$\rightarrow$ measurement of $g_1$

$$g_1^{LO} = \frac{1}{2}\sum_i e_i^2 (\Delta q_i + \Delta \bar{q}_i)$$

proton, deuteron, $^3$He $g_1$ data

with isospin symmetry

$\rightarrow$ valence and sea polarization

$$\Delta u_v, \Delta d_v, \Delta \bar{q}$$

quark spin content

$$\Delta\Sigma = \Delta u_v + \Delta d_v + 6 \cdot \Delta \bar{q}$$

experimentally $\int_0^1 dx\, \Delta\Sigma(x) \approx 0.1 - 0.3$

rest of the spin ???

# Initial parton distributions

$$\Delta f_i(x,Q_0^2) = A_i\, x^{\alpha_i}\,(1+\gamma_i x^{\lambda_i})\, f_i(x,Q_0^2)$$

$$(i = u_v,\, d_v,\, \bar{q},\, g) \quad A_i,\ \alpha_i,\ \gamma_i,\ \lambda_i : \text{free}$$

positivity $\left|\Delta f_i(x,Q_0^2)\right| \le f_i(x,Q_0^2)$, $\left|A_1\right| \le 1$

**flavor-symmetric distributions at initial $Q_0^2$**

$$\Delta\bar{u}(x) = \Delta\bar{d}(x) = \Delta\bar{s}(x)$$

**first moments $\eta_{uv}$ , $\eta_{dv}$ are fixed**

$$\boldsymbol{F = 0.463 \pm 0.008,\quad D = 0.804 \pm 0.008}$$

$$\boldsymbol{\eta_{uv} = 0.986,\quad \eta_{dv} = -0.341}$$

**$\gamma_{uv}$ and $\gamma_{dv}$ are determined so as to satisfy these conditions.**

$$\eta_i = \int_{x_{\min}}^{1} \Delta f(x,\gamma)\,dx\,,$$

*We determine* **14** *parameters by the $\chi^2$-fitting !*

$$A_{uv},\ \alpha_{uv},\ \lambda_{uv},\ A_{dv},\ \alpha_{dv},\ \lambda_{dv},$$

$$A_{\bar{q}},\ \alpha_{\bar{q}},\ \gamma_{\bar{q}},\ \lambda_{\bar{q}},\ A_g,\ \alpha_g,\ \gamma_g,\ \lambda_g$$

## $\chi^2$-fitting to the data
## [proton, neutron ($^3$He), deuteron]

$$A_1 = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} \approx \frac{g_1}{F_1} = g_1 \frac{2x(1+R)}{F_2}$$

$$\left( R(x, Q^2) = \frac{F_L}{2xF_1} = \frac{F_2 - 2xF_1}{2xF_1} \right)$$

$$\chi^2 = \sum_i \frac{\left(A^{data}_{1,i} - A^{cal}_{1,i}\right)^2}{\left(\sigma^{data}_i\right)^2}$$

**which is minimized by the subroutine MINUIT**

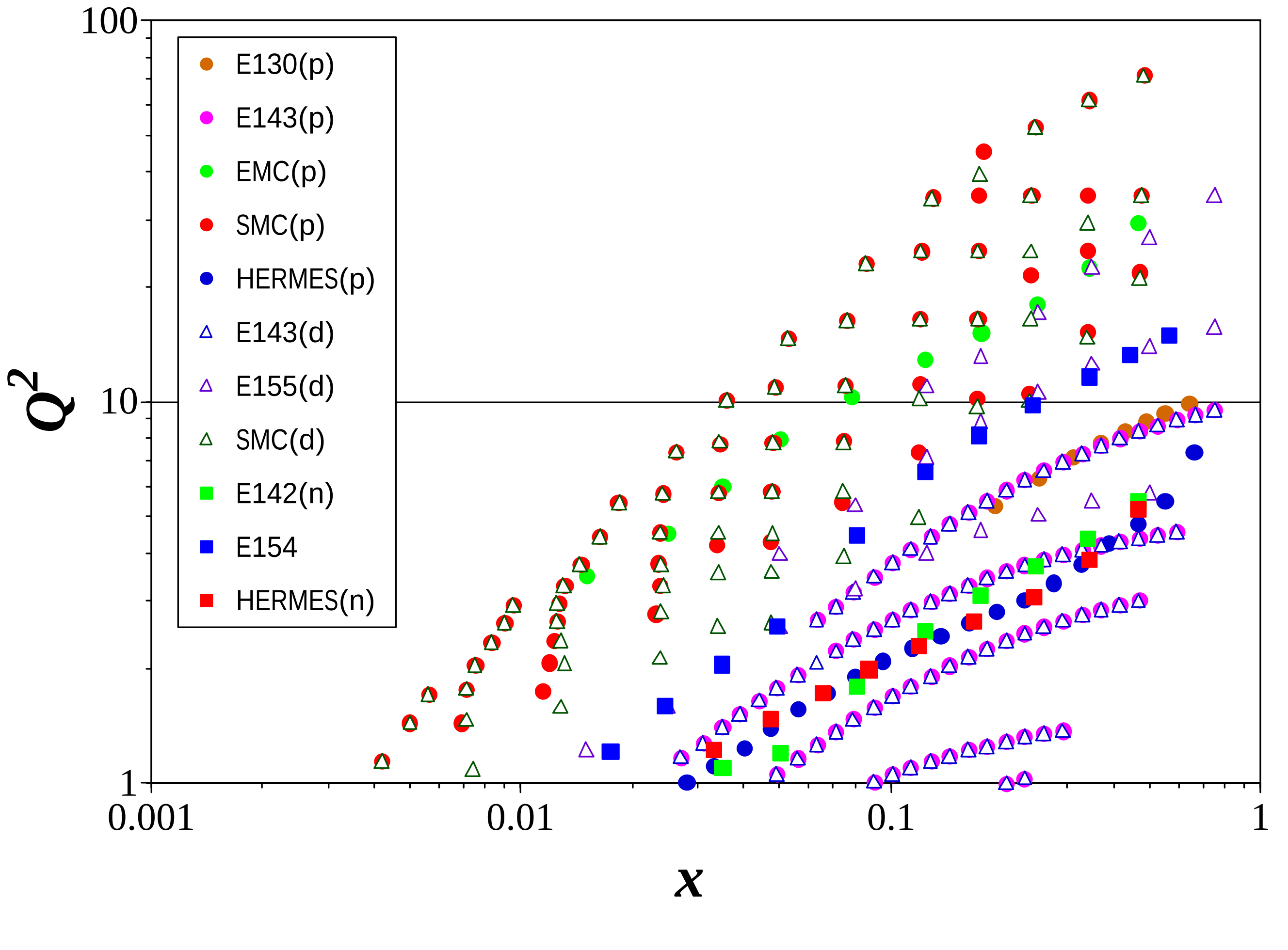
**We analyzed with the following conditions.**

- **Unpolarized PDF** **GRV98**
- **Initial $Q^2$** $\mathbf{Q_0^2 = 1\ GeV^2}$
- **Number of flavor** $\mathbf{N_f = 3}$
- $\mathbf{\Lambda_{QCD}}$ $\mathbf{\Lambda_{LO} = 204\ MeV}$

  $\mathbf{\Lambda_{NLO} = 299\ MeV}$

# Experimental data

| Target | Exp. | *x* | $Q^2$ $GeV^2$ | Data # |
|---|---|---|---|---|
| Proton | EMC | 0.015-0.466 | 3.5~29.5 | 10 |
| | SMC | 0.005-0.480 | 0.25~72.07 | 59 |
| | E130 | 0.18-0.70 | 3.5~10.0 | 8 |
| | E143 | 0.022-0.847 | 0.28~9.53 | 81 |
| | HERMES | 0.028-0.66 | 1.01~7.36 | 19 |
| Deuteron | SMC | 0.005-0.480 | 1.3~54.4 | 65 |
| | E143 | 0.022-0.847 | 0.28~9.53 | 81 |
| | E155 | 0.015-0.75 | 1.22-34.79 | 24 |
| Neutron | E142 | 0.035-0.466 | 1.1~5.5 | 8 |
| | E154 | 0.0174-0.5643 | 1.21~15.0 | 11 |
| | HERMES | 0.033-0.464 | 1.22~5.25 | 9 |
| Total | | | | 375 |

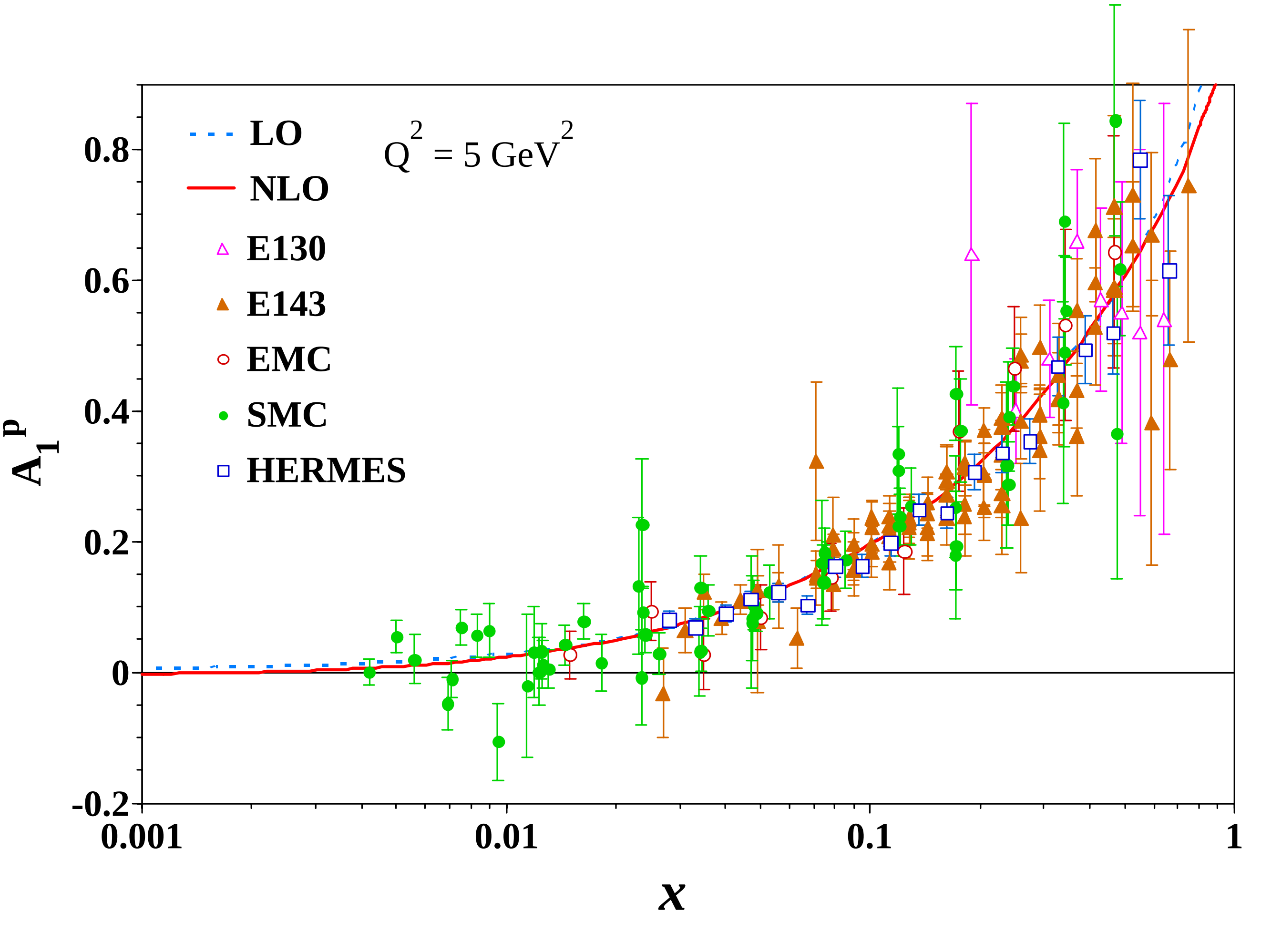


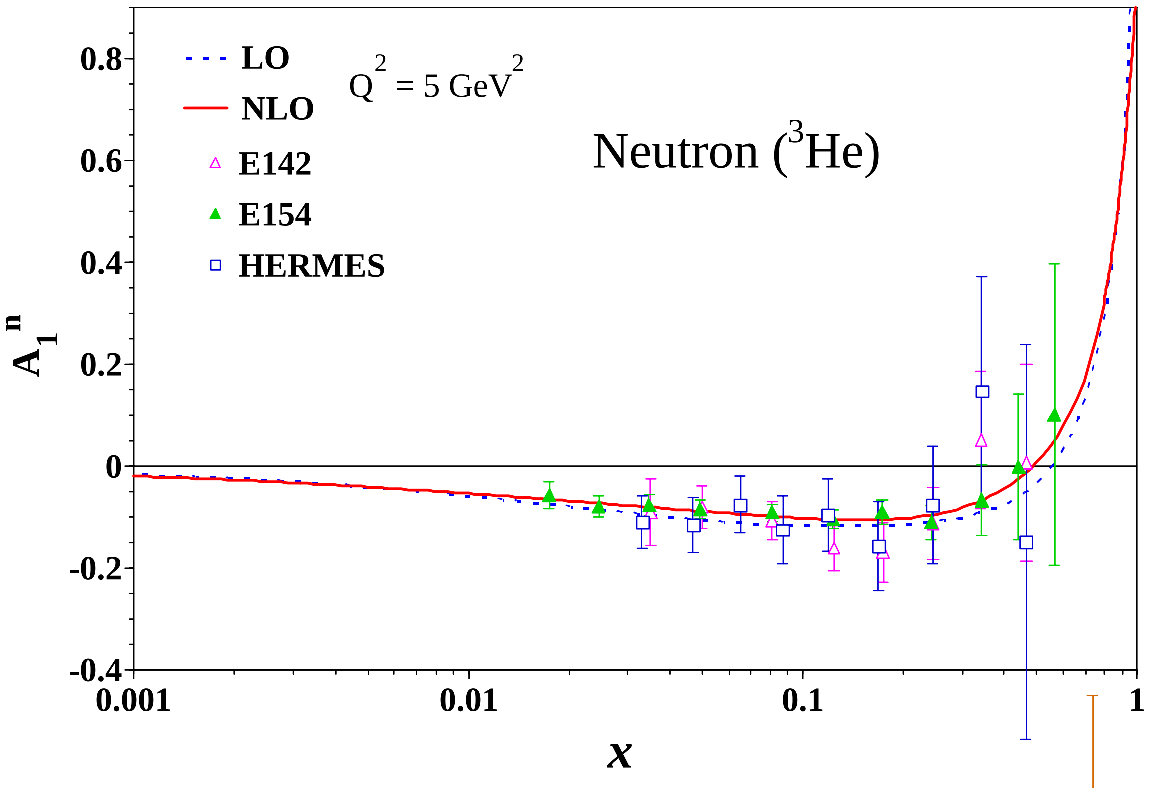
# Results

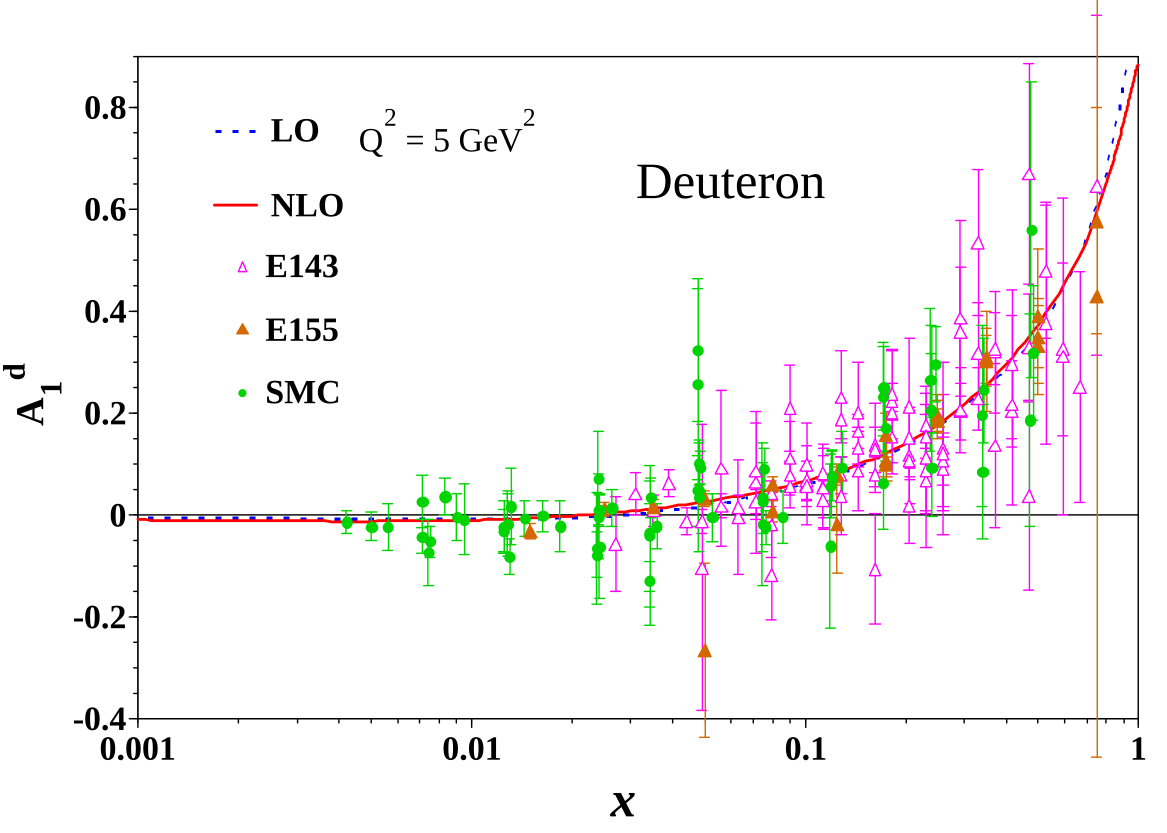
**Total $\chi^2$** LO $\chi^2$/d.o.f = 0.896
NLO $\chi^2$/d.o.f = 0.834

**Total data 375**

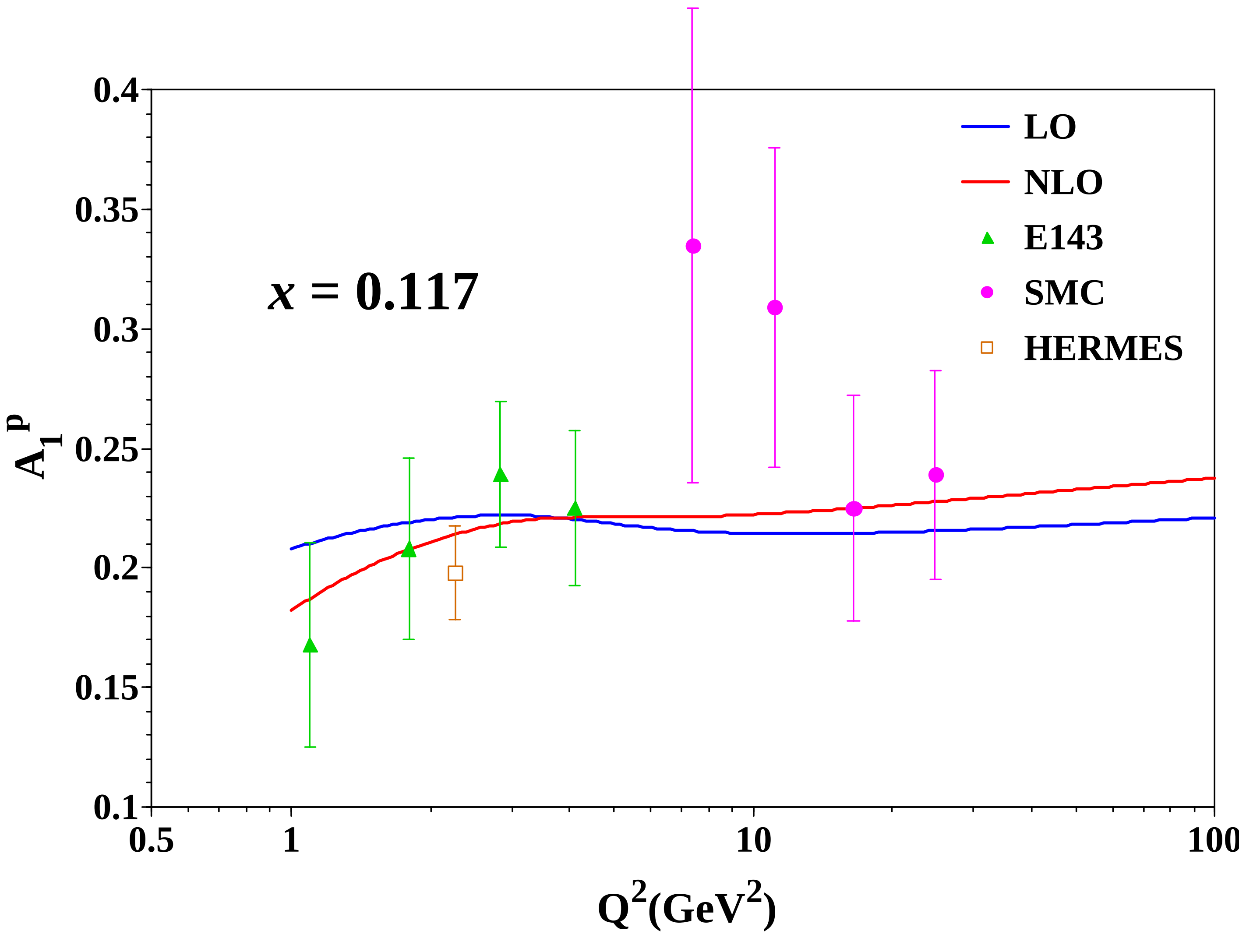
## Spin asymmetry $A_1^p$



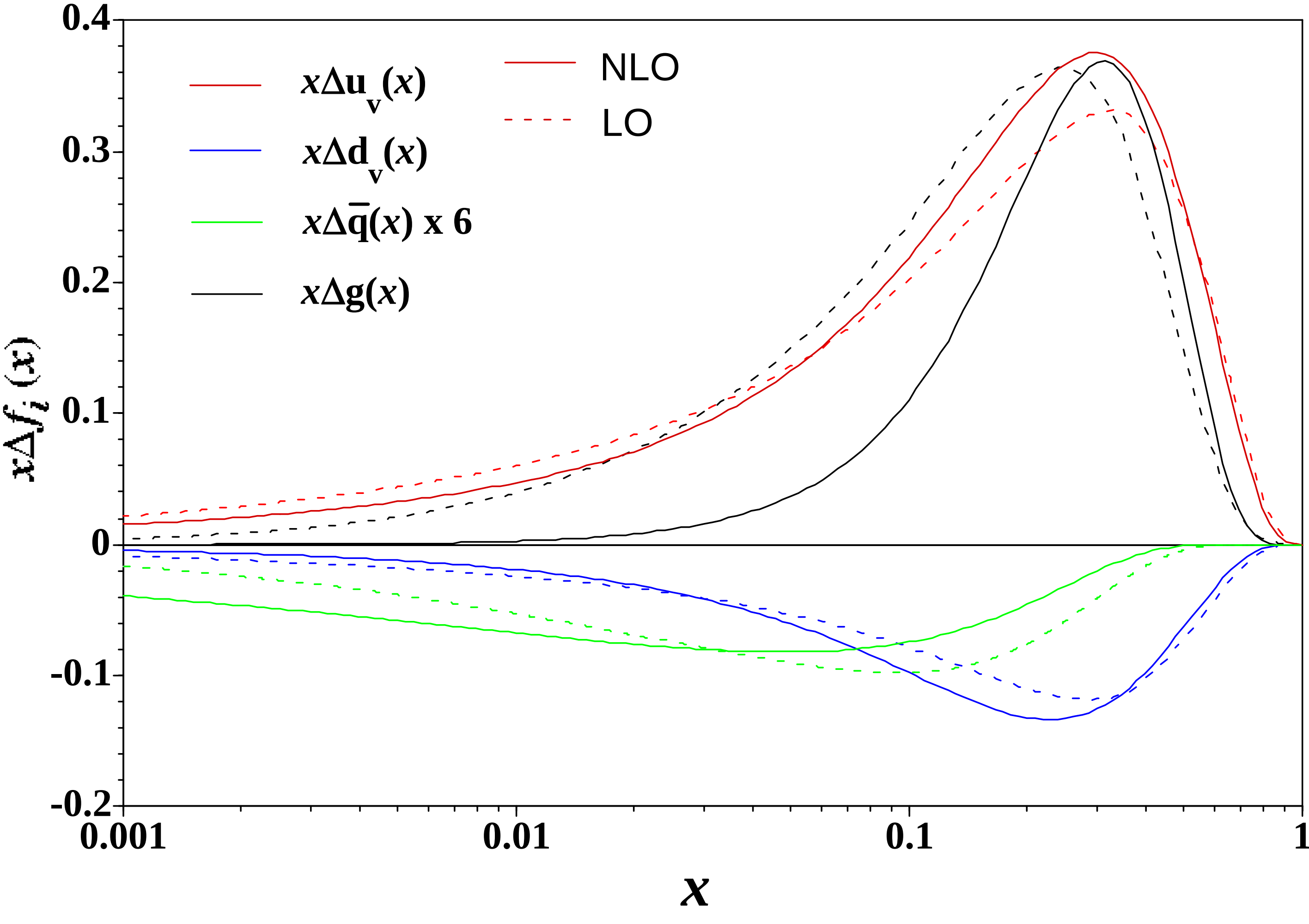

LO
NLO
E142
E154
HERMES
Q^2 = 5 GeV^2
Neutron (^3He)
A_1^n
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0.001
0.01
0.1
1
x


LO
NLO
E143
E155
SMC
Q^2 = 5 GeV^2
Deuteron
A_1^d
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0.001
0.01
0.1
1
x

# $Q^2$ dependence of $A_1^p$



# Parton distributions ($Q^2$=1 GeV$^2$ )



- **First moments** **($Q^2$ =1 GeV$^2$)**

| | $\Delta u_v$ | $\Delta d_v$ | $\Delta\bar{q}$ | $\Delta g$ |
|---|---|---|---|---|
| LO | 0.926 | -0.341 | -0.064 | 0.831 |
| NLO | 0.926 | -0.341 | -0.089 | 0.532 |

- **Spin content $\Delta\Sigma$**

**LO : 0.201**

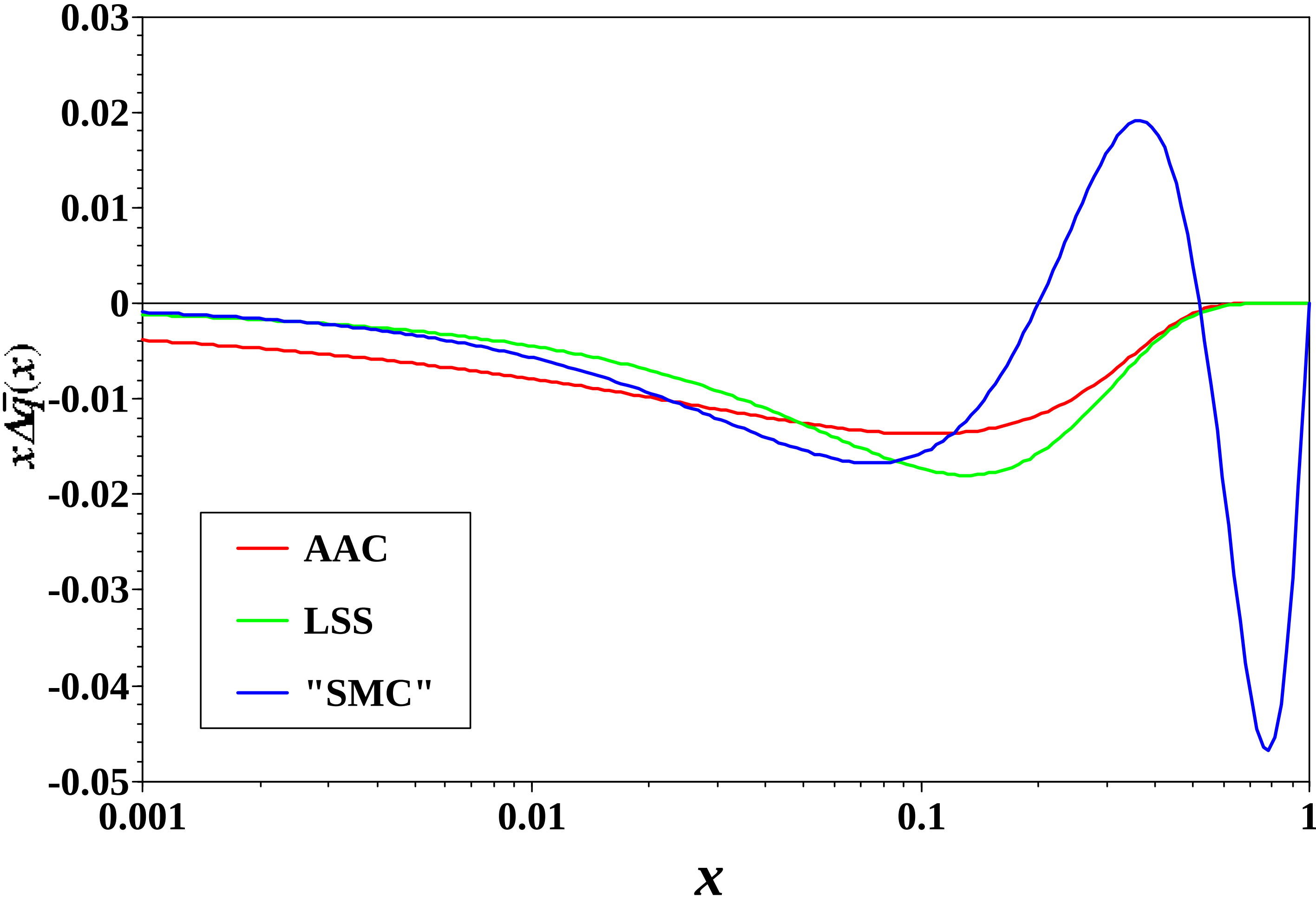
**NLO : 0.051**

rather small spin content in the NLO

$\Delta\Sigma$=0.1~0.3 ?

$\rightarrow$ check the antiquark distributon

# Antiquark distribution $\Delta\bar{q}$



# Error estimation

## Hessian method

**$\chi^2(a)$ is expanded around its minimum $a_0$**

$$\chi^2(a_0+\delta a)=\chi^2(a_0)+\sum_i \frac{\partial\chi^2(a_0)}{\partial a_i}\delta a_i+\frac{1}{2}\sum_{i,j}\frac{\partial^2\chi^2(a_0)}{\partial a_i\partial a_j}\delta a_i\delta a_j+\cdots$$

**where Hessian matrix is defined by**

$$H_{ij}=\frac{1}{2}\frac{\partial^2\chi^2(a_0)}{\partial a_i\partial a_j}=\varepsilon_{ij}^{-1}$$

**$\varepsilon_{ij}$ is error matrix**

**diagonal elements**

**square root of parameter errors**

**non-diagonal elements**

**correlation effects with other parameters**

**In the $\chi^2$ analysis, 1σ standard error is given by**

$$\chi^2(a_0+\delta a)-\chi^2(a_0)=\sum_{i,j}\delta a_i H_{ij}\delta a_j\approx N$$

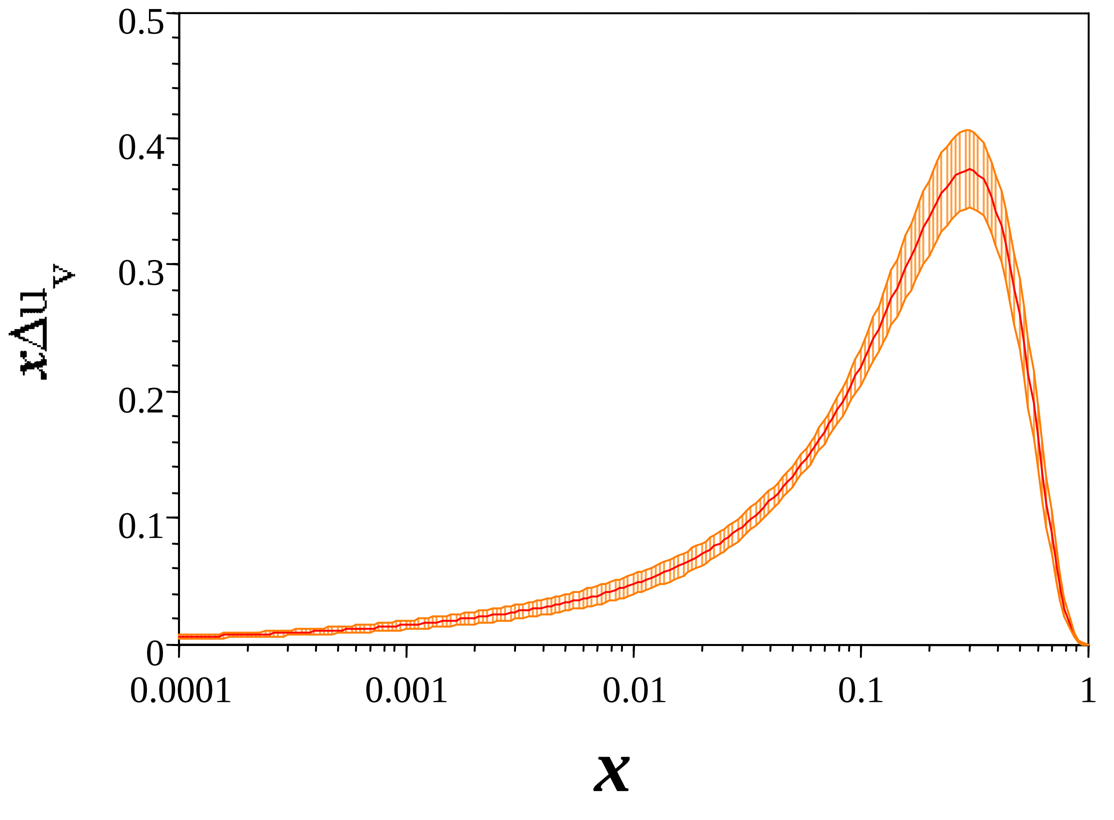
**where N is the number of parameters.**

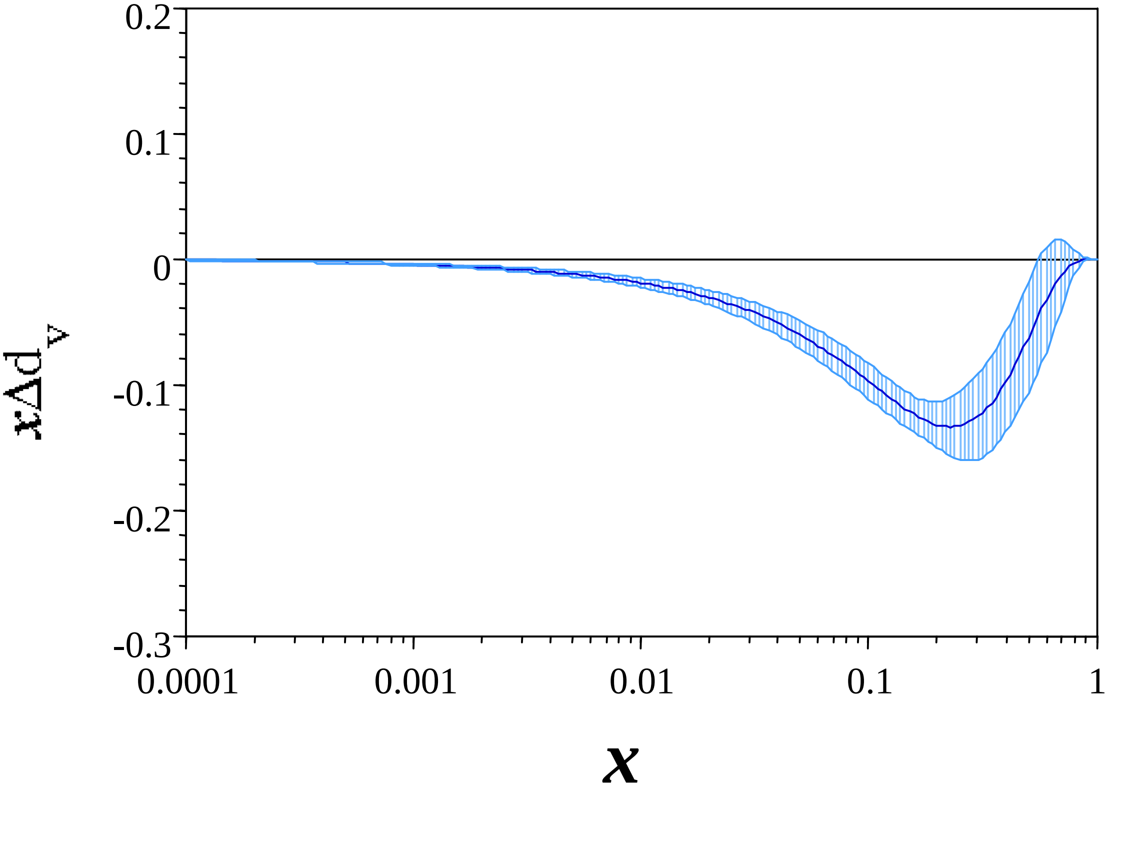
**Uncertainty of a distribution $F(x)$ is given by**

$$\boxed{[\delta F(x)]^2=\sum_{i,j}\frac{\partial F(x)}{\partial a_i}\varepsilon_{ij}\frac{\partial F(x)}{\partial a_j}}$$

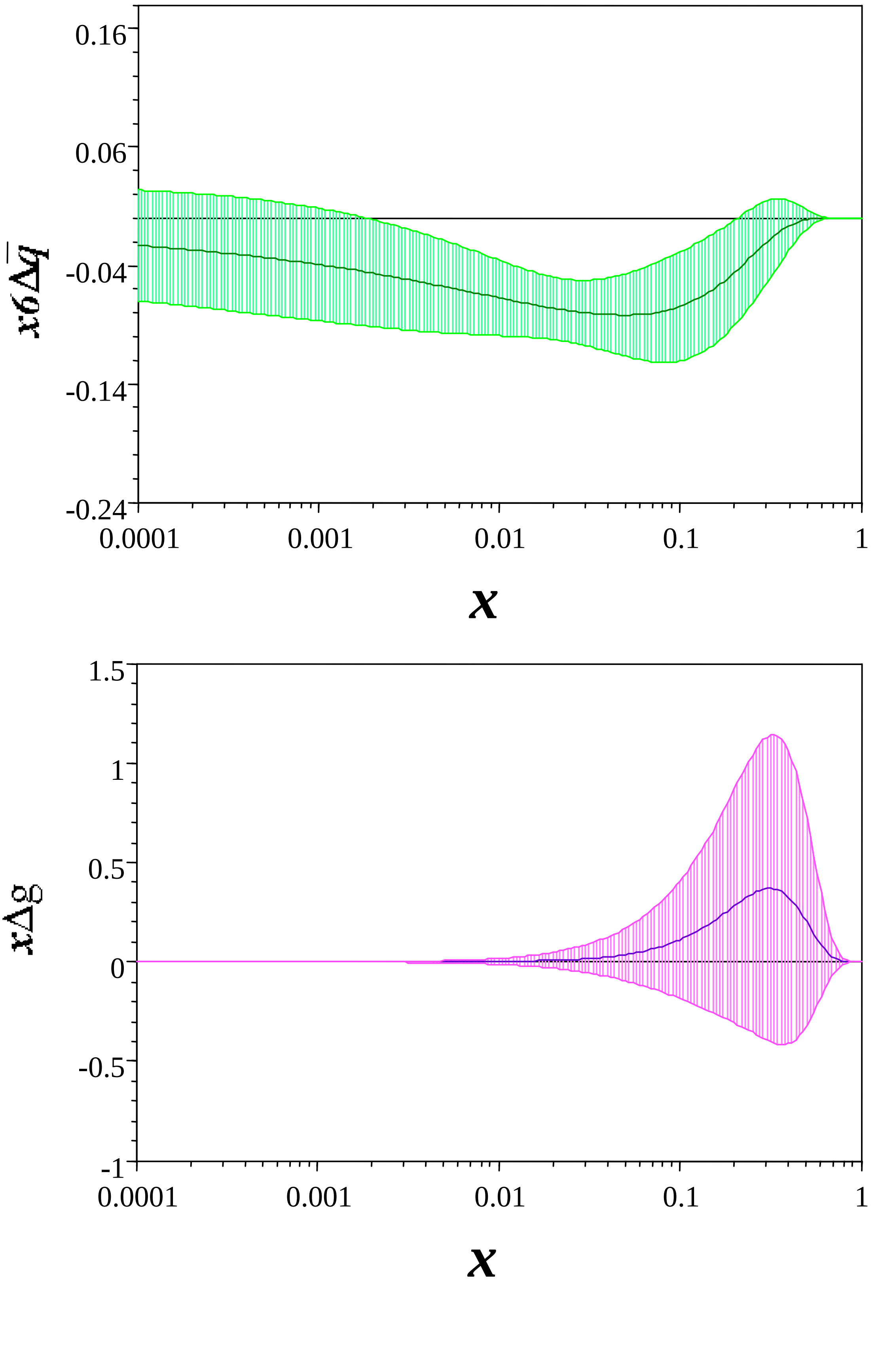
# Results

preliminary



preliminary



# - Summary -

- $\chi^2$ analysis of available DIS data
  - NLO $\chi^2$ is significantly smaller than LO $\chi^2$.
    $\rightarrow$ NLO analysis is necessary.
  - $\Delta g(x)$ determination is rather difficult.

- $\mathbf{\Delta\Sigma_{LO}=20\%,\ \Delta\Sigma_{NLO}=5\sim28\%}$
  - small-x behavior of $\Delta\bar{q}(x)$ is not uniquely determined.

    $\rightarrow$ need small-x measurements

    **polarized-HERA, eRHIC ?**

- **propose three AAC distributions:**

  **LO, NLO-1 ($\alpha_q$=free),**

  **NLO-2 ($\alpha_q$=1.0 fixed)**
  - see **Phys. Rev. D62 (2000) 034017,**
    http://spin.riken.bnl.gov/aac for the details.

# Nuclear parton distributions

Ref. M. Hirai, S. Kumano, M. Miyama,

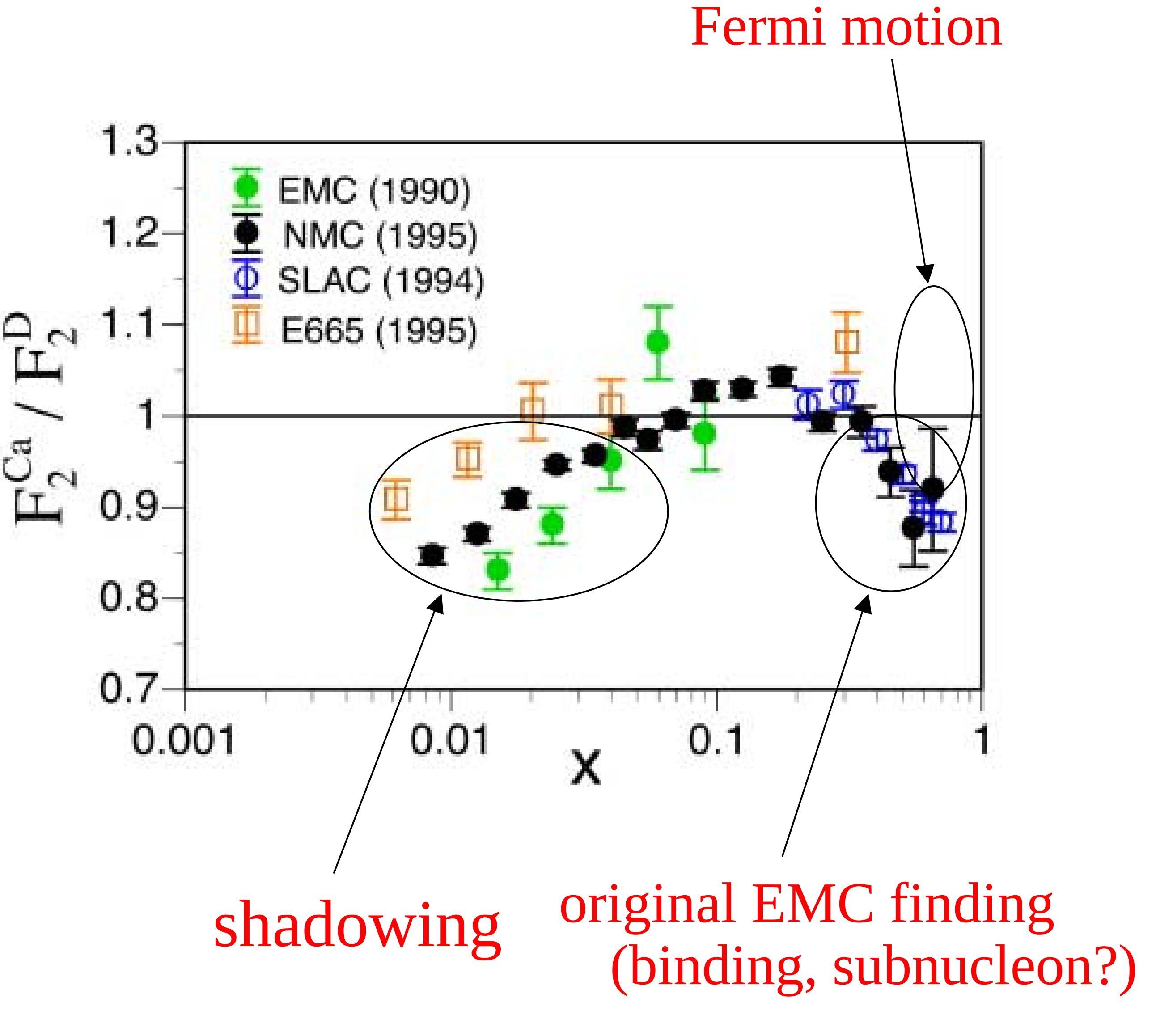
Phys. Rev. D64 (2001) 034003.

A library for nuclear parton distributions
can be obtained from
http://hs.phys.saga-u.ac.jp/nuclp.html.

# • parton distributions in nuclei

Nuclear modification of $F_2^A / F_2^D$ is well known in electron/muon scattering.

$$F_2^A = \frac{1}{9}\, x \left[4\, u_v(x) + d_v(x)\right]_A + \frac{2}{9}\, x\, S_A(x)$$



Nuclear parton distributions (per nucleon)

if there *were* no modification

$$A\, u^A = Z\, u^p + N\, u^n, \quad A\, d^A = Z\, d^p + N\, d^n$$

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

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

Take into accont the nuclear modification by the factors $w_i(x,A)$

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

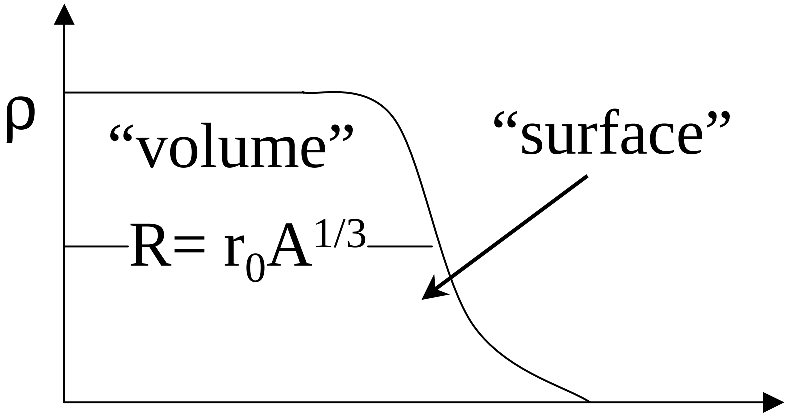
$$d_v^A(x) = w_{d_v}(x,A)\, \frac{Z\, d_v(x) + N\, u_v(x)}{A}$$

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

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

## A dependence

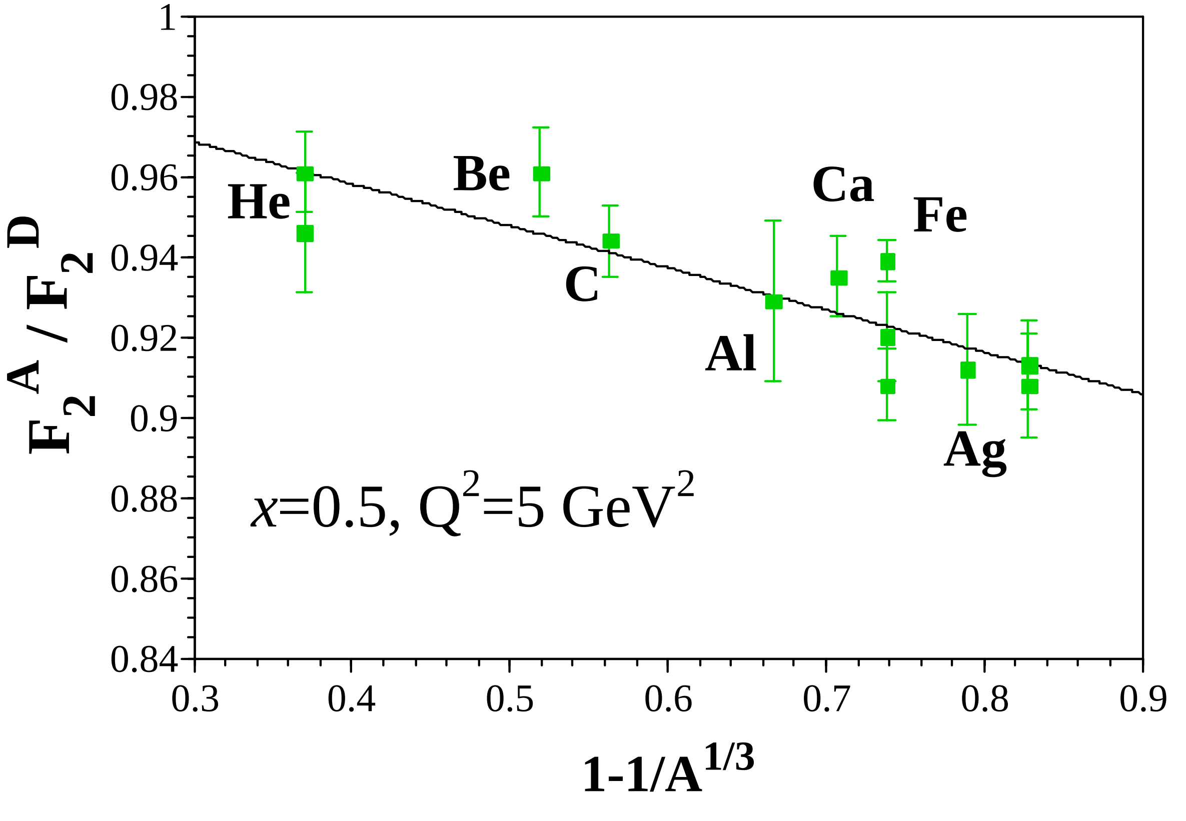
Ref. I. Sick and D. Day, Phys. Lett. B 274 (1992)




roughly speaking $\sigma_A = A\,\sigma_V + A^{2/3}\,\sigma_S$

$$\rightarrow \frac{\sigma_A}{A} = \sigma_V + \frac{1}{A^{1/3}}\,\sigma_S$$

$\sim \frac{1}{A^{1/3}}$ dependence



# Functional form of $w_i(x,A)$

$$f_i^A(x) = w_i(x,A)\, f_i(x), \quad i = u_v, d_v, \bar{q}, g$$

first, assume the A dependence as $1/A^{1/3}$

then, use

$$w_i(x,A) = 1 + (1-1/A^{1/3})\,\frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$

$a_i$, $b_i$, $c_i$, $d_i$, $\beta_i$: parameters to be determined by $\chi^2$ analysis

Fermi motion: $\dfrac{1}{(1-x)^{\beta_i}} \to \infty$ as $x \to 1$ if $\beta_i > 0$

Shadowing: $w_i(x \to 0, A) = 1 + (1-1/A^{1/3})\, a_i < 1$

Fine tuning: $b_i$, $c_i$, $d_i$

# Constraints

- **Nuclear charge**

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

$$= A \int dx \left( \frac{2}{3} u_V^A - \frac{1}{3} d_V^A \right)$$

- **Baryon number**

$$A = A \int dx \, \frac{1}{3} (u_V^A + d_V^A)$$

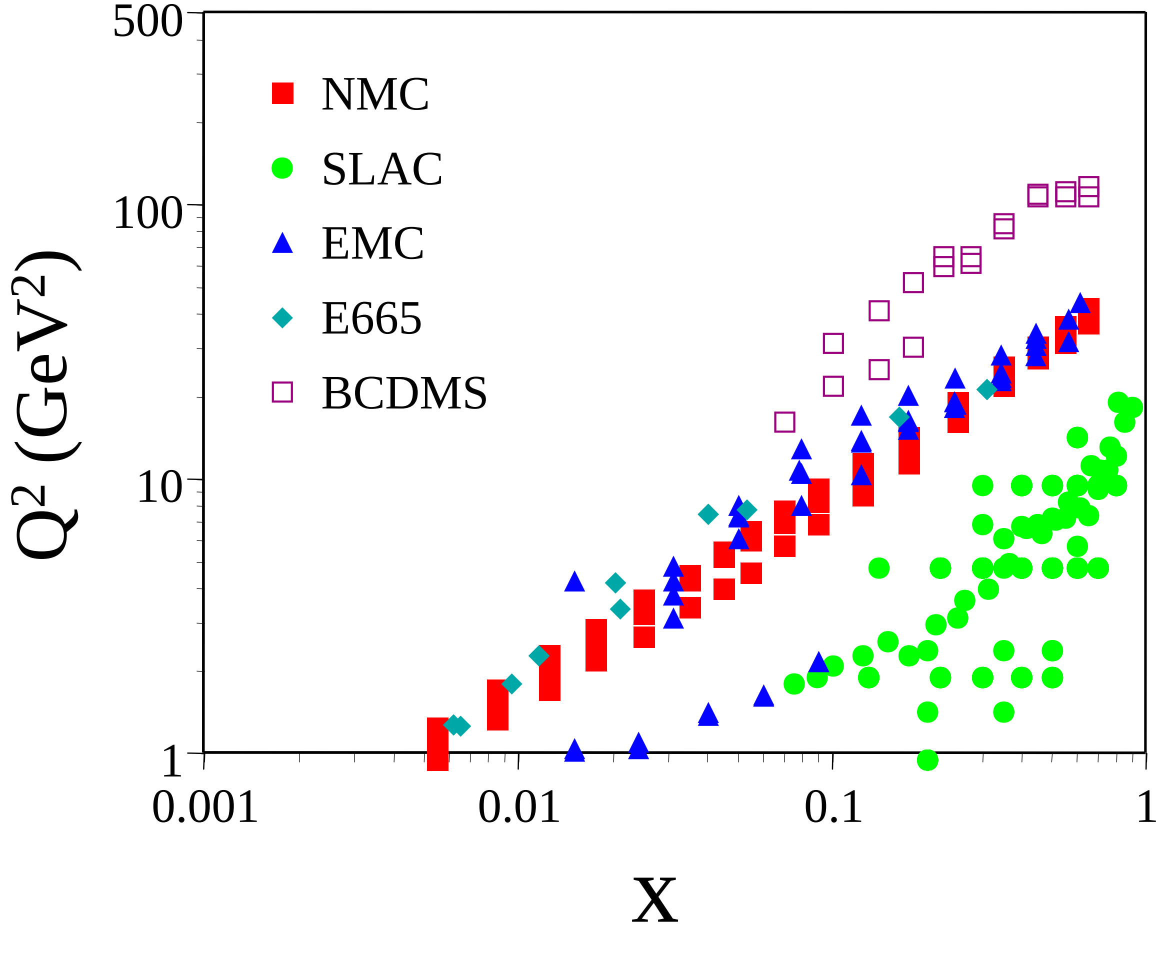
- **Momentum**

$$A = A \int dx \, x (u_V^A + d_V^A + 6 \, \bar{q}^A + g^A)$$

Three parameters can be determined by these conditions.

# Experimental data on $F_2^A/F_2^D$

| | |
|---|---|
| NMC: | 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 |



# Analysis conditions

- parton distributions in the nucleon

  MRST98 - LO ($\Lambda_{QCD}$=174 MeV)

- $Q^2$ point at which the parametrized distributions are defined: $Q^2 = 1$ GeV$^2$

- used experimental data: $Q^2 \geq 1$ GeV$^2$

- total number of data: 309

- number of flavor: $n_f = 3$

- subroutine for the $\chi^2$ analysis: CERN - Minuit

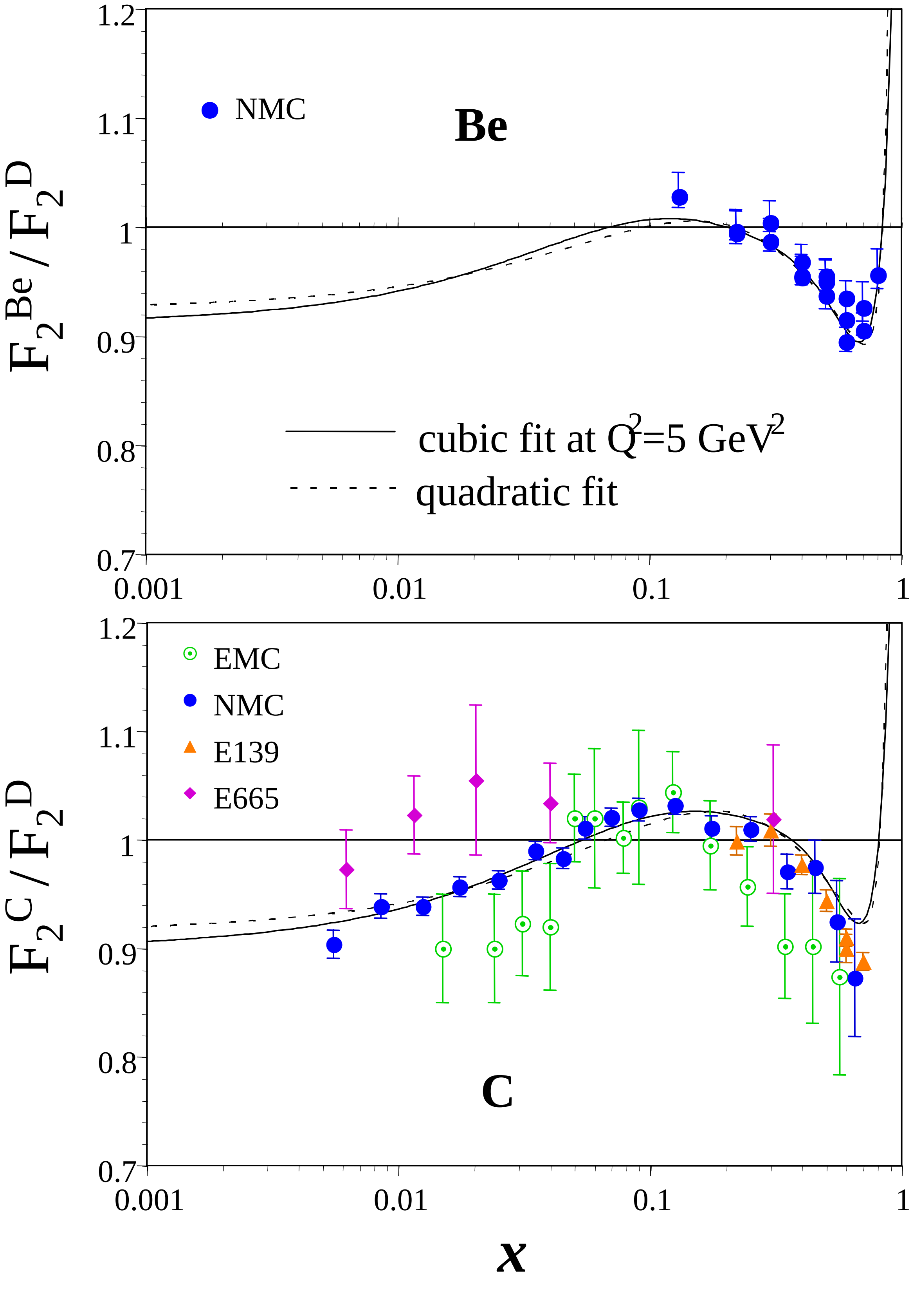
$$\chi^2 = \sum_i \frac{(R_i^{data} - R_i^{calc})^2}{(\sigma_i^{data})^2}$$

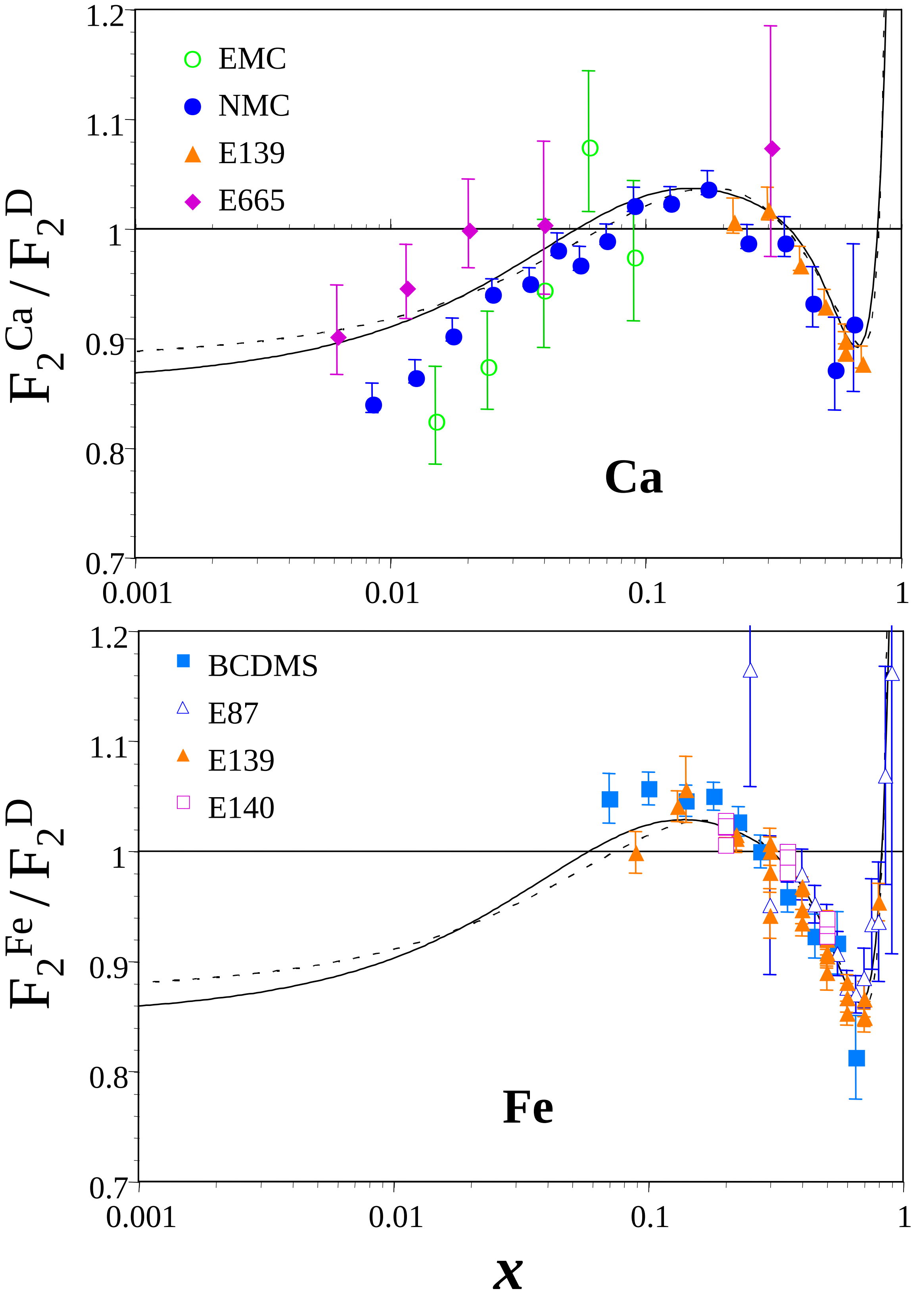
$$R = \frac{F_2^A}{F_2^D}, \qquad \sigma_i^{data} = \sqrt{(\sigma_i^{sys})^2 + (\sigma_i^{stat})^2}$$

$\rightarrow$ obtained $\chi^2_{min}$/d.o.f. = 583.7 / 302 (quadratic)

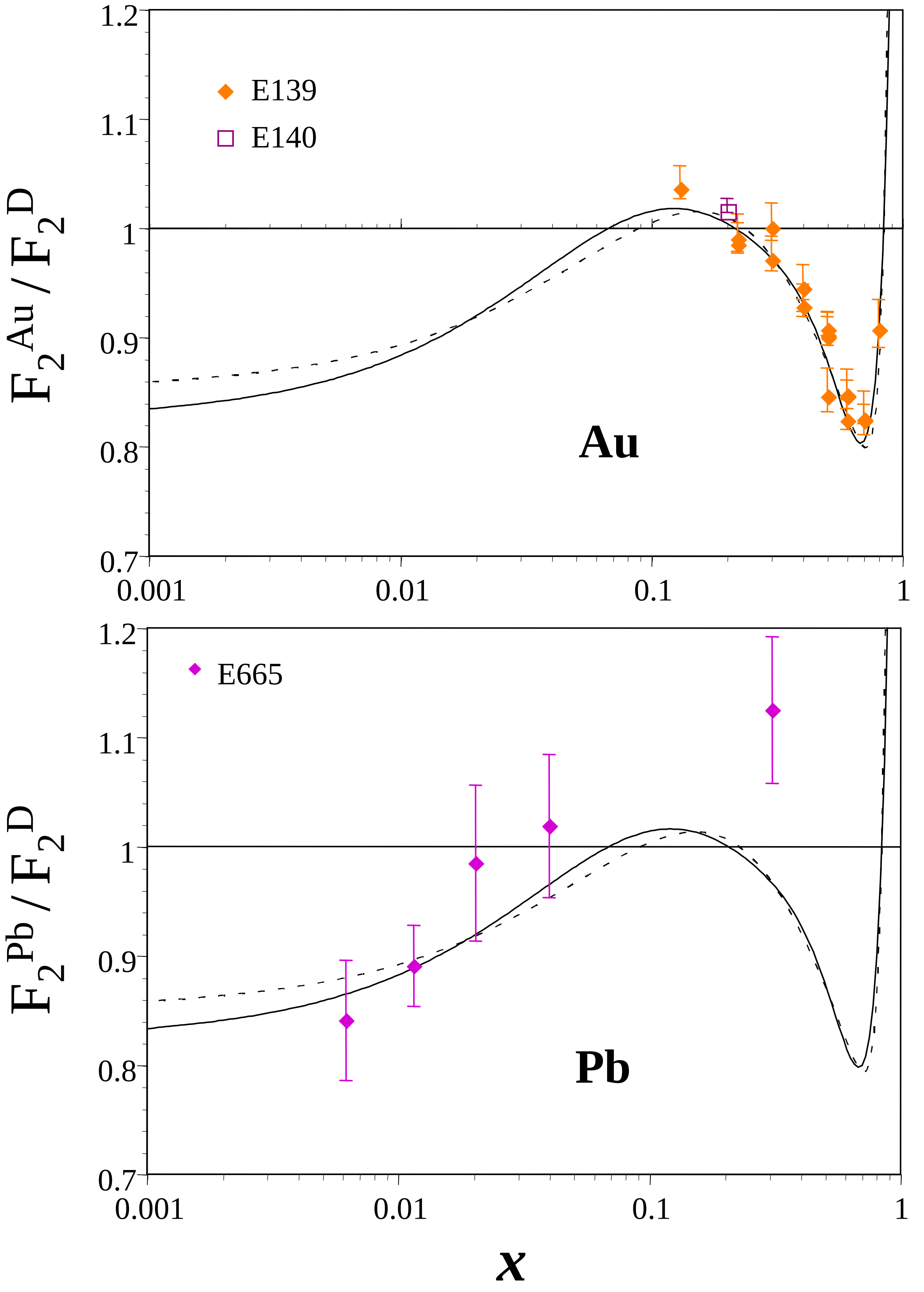
= 546.6 / 300 (cubic)

# Analysis results



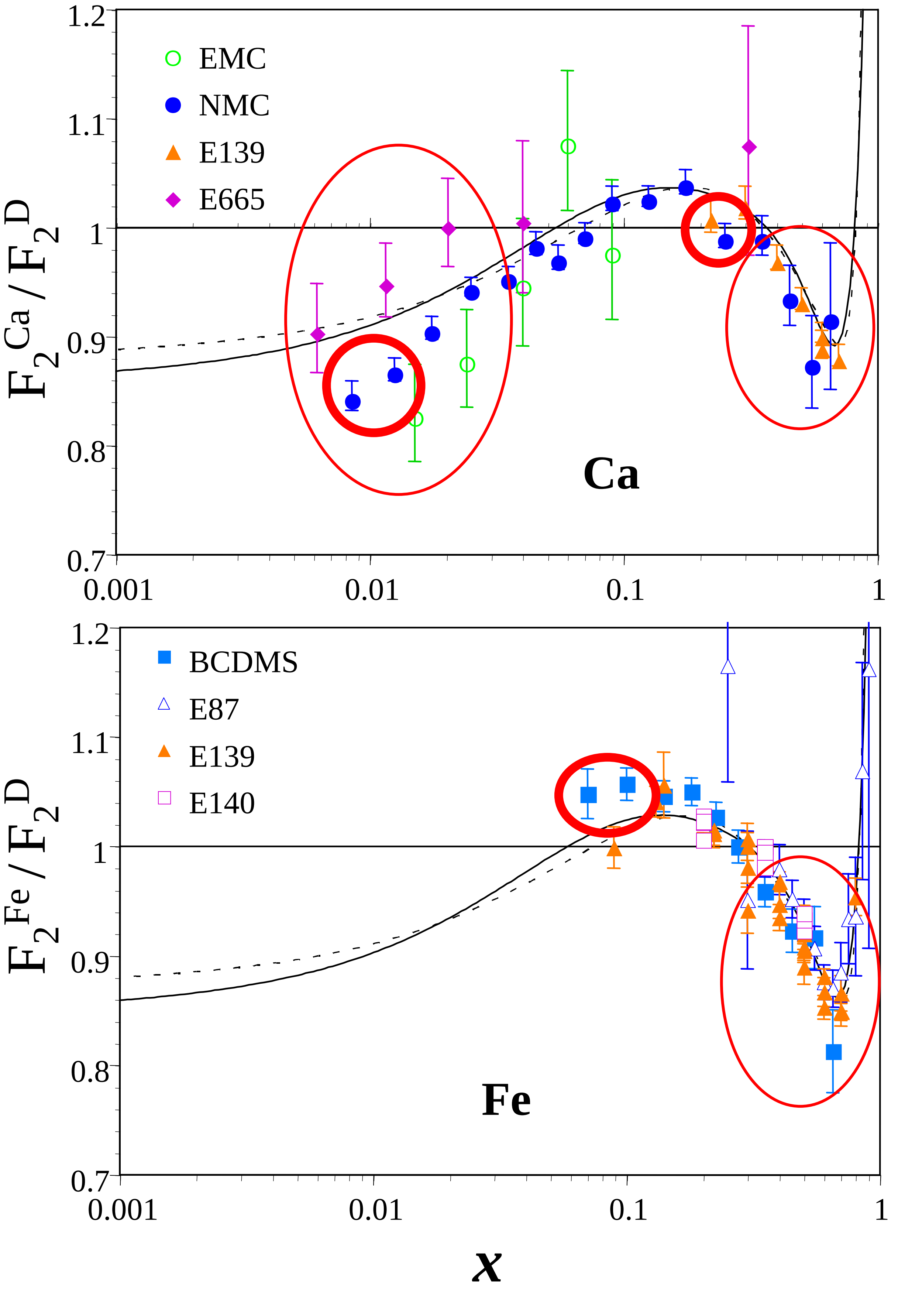


EMC
NMC
E139
E665
Ca
BCDMS
E87
E139
E140
Fe
$F_2^{Ca} / F_2^D$
$F_2^{Fe} / F_2^D$
$x$
1.2
1.1
1
0.9
0.8
0.7
0.001
0.01
0.1
1

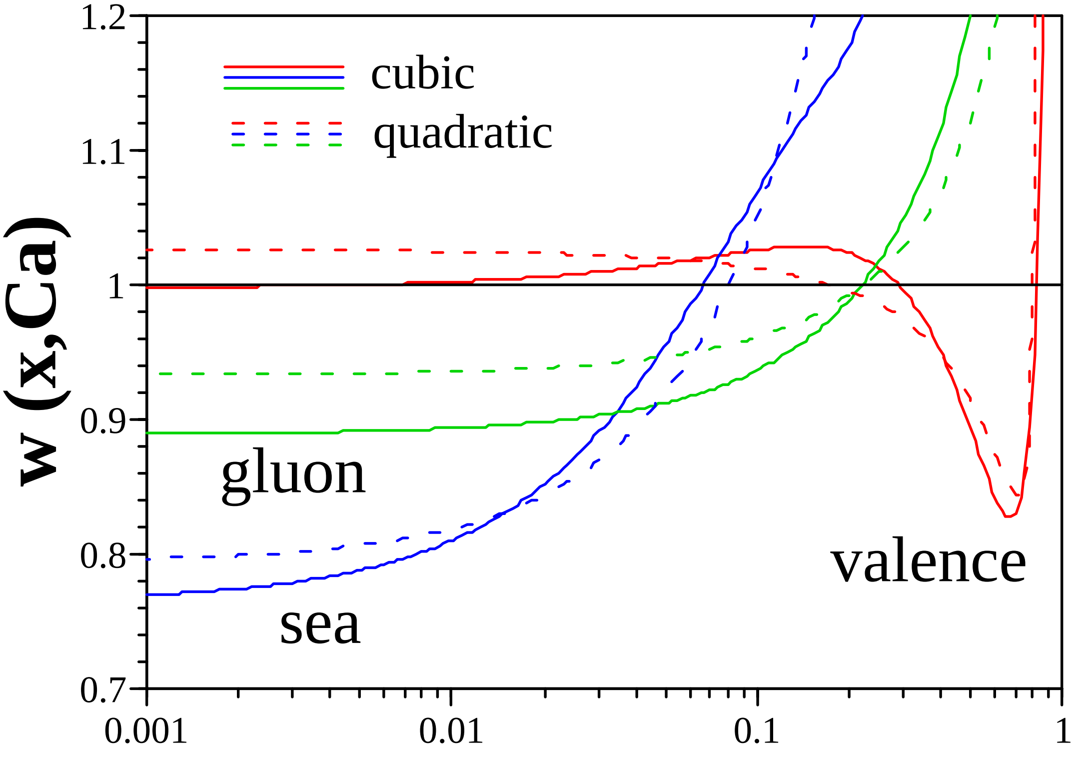


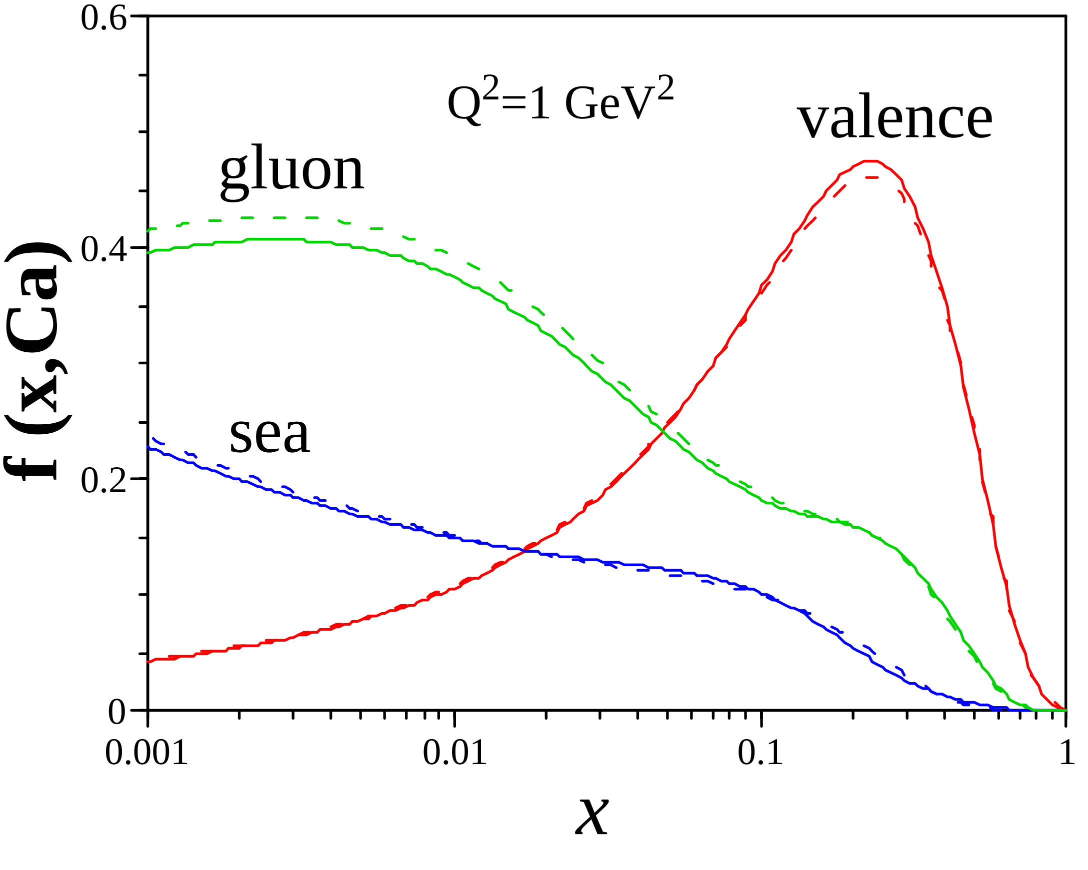
E139
E140
Au
E665
Pb
$F_2^{Au} / F_2^D$
$F_2^{Pb} / F_2^D$
x
0.7
0.8
0.9
1
1.1
1.2
0.001
0.01
0.1
1

# Example of $\chi^2$ contributions



# Weight functions and parton distributions for Ca



# Future possibilities

- Valence: $F_3$ at $\nu$ factories
  $F_2$ at eRHIC, HERA-eA

- Antiquark: Drell-Yan at RHIC, LHC,
  Fermilab
  $F_2$ at eRHIC, HERA-eA

- Gluon: direct $\gamma$ etc. at RHIC, LHC
  $dF_2/\ln(Q^2)$ at HERA-eA

# Summary

- first $\chi^2$ analysis
  for the nuclear parton distributions
  Computer codes could be obtained from
  http://www-hs.phys.saga-u.ac. jp

- nuclear PDFs are still premature
  $\rightarrow$ need analysis refinement

- reasonably good fit with
  $\chi^2_{min}$ / d.o.f. = 1.93 (quad.), 1.82 (cubic)

- $g^A(x)$ ? $\bar{q}^A(x)$ at medium x ?

- $q_V(x)$ in the nucleon is determined
  by $\nu$-Fe scattering at this stage
  $\rightarrow$ reinvestigate with nuclear modification

- relation to heavy-ion physics ?
- future experiments ?

# Comments

# on selected topics

- flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$
- spin-1 structure, e.g. $b_1$
- neutrino factory

# $\bar{u}/\bar{d}$ asymmetry

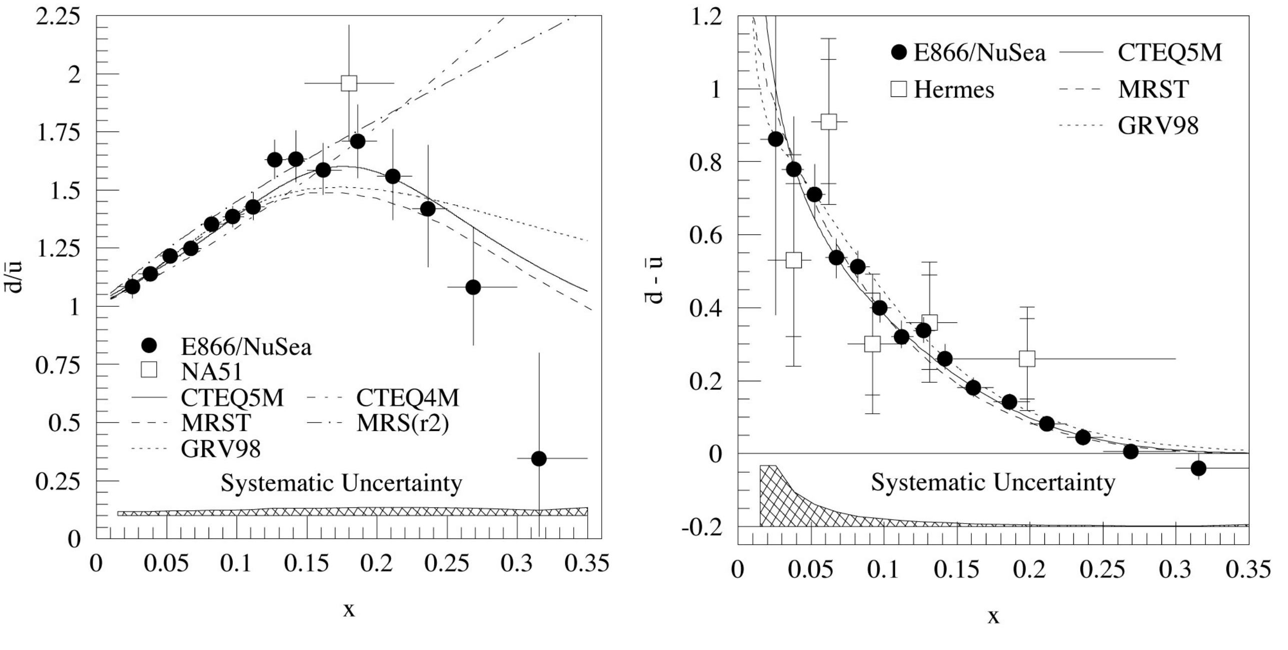
- Gottfried sum (NMC $S_G = 0.235 \pm 0.026$)

$$S_G = \int_0^1 \frac{dx}{x}\,[F_2^{\mu p}(x) - F_2^{\mu n}(x)]$$

$$= \frac{1}{3} + \frac{2}{3}\int_0^1 dx\,[\bar{u}(x) - \bar{d}(x)]$$

- Drell-Yan, semi-inclusive DIS

Fermilab E772/E866, NA51, HERMES




(from hep-ex/0103030)

see SK, Phys. Rep. 303 (1998) 183

# $\bar{u}/\bar{d}$ asymmetry

- unpolarized: well established
- polarized ?

  measured in the near future

  $W^{\pm}$, semi-inclusive DIS, ...

  theory $\rightarrow$ unclear

  (1) pQCD

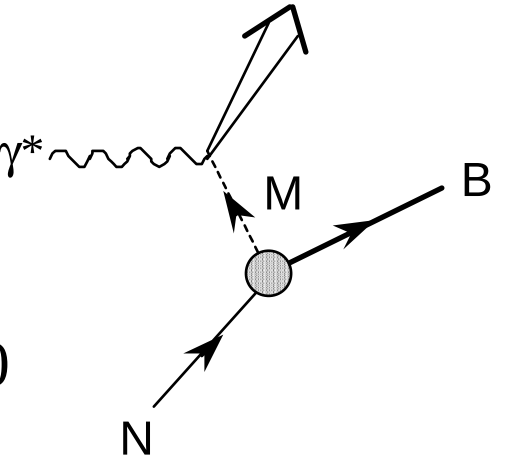
  (2) nonperturbative models

  meson clouds, soliton,

  Pauli exclusion, ...

$\Delta\bar{u}/\Delta\bar{d}$ and $\Delta_T\bar{u}/\Delta_T\bar{d}$ could be appropriate quantities for testing nonperturbative models.

# Meson-cloud model




unpolarized : e.g. $\pi^+(u\bar{d})$

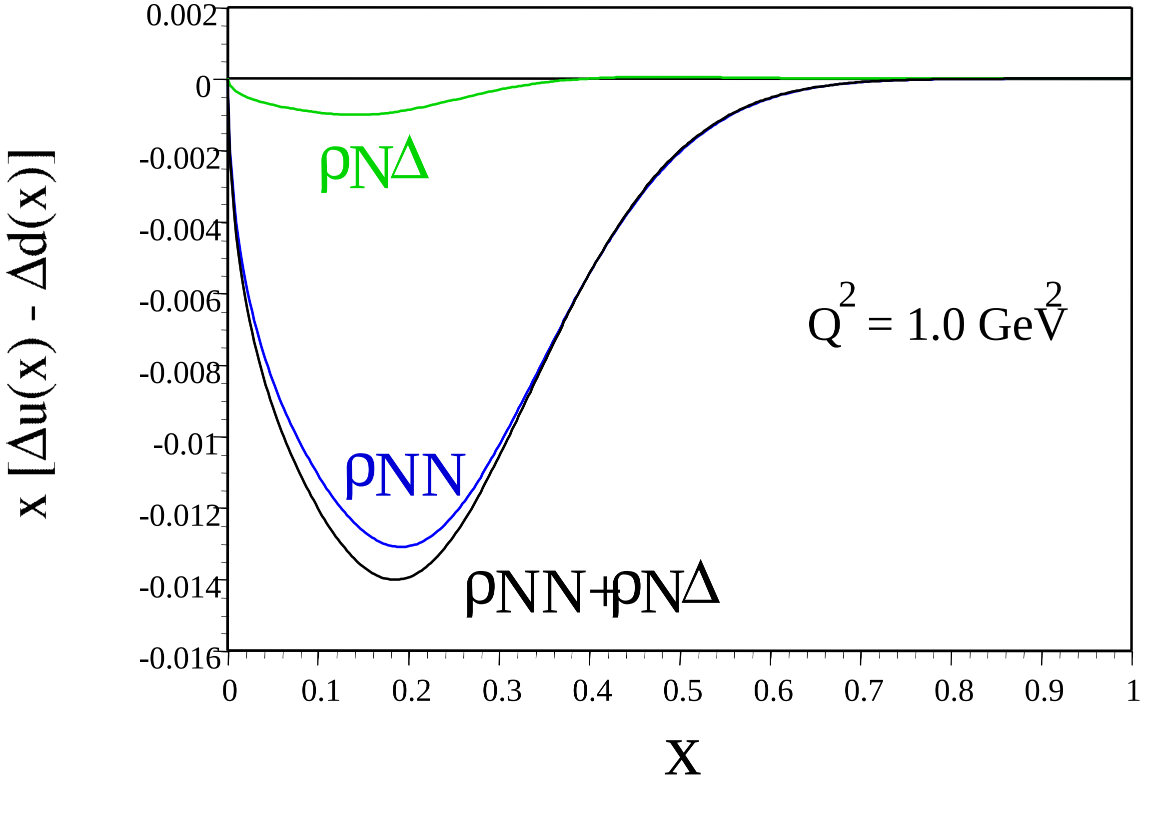
$\Rightarrow$ $\bar{d}$ excess : $\bar{u} - \bar{d} < 0$

## ρ contribution to $\Delta\bar{u} - \Delta\bar{d}$

$$\left[\Delta\bar{q}(x,Q^2)\right]_{MNB} = \int_x^1 \frac{dy}{y}\, \Delta f_{MNB}(y)\, \Delta\bar{q}_M(x/y,Q^2)$$

polarized : e.g. $\rho^+(u\bar{d})$

$\Rightarrow$ $\Delta\bar{d}$ excess : $\Delta\bar{u} - \Delta\bar{d} < 0$




Ref. SK and M. Miyama
hep-ph/0110097, Phys. Rev. D in press.

# Status: spin-1 physics

- $\vec{e} + \vec{d} \to e' + X$

  theoretical studies: some

  experimental: near future (HERMES)

- $\vec{p} + \vec{d}$ (e.g. $\vec{p} + \vec{d} \to \mu^+\mu^- + X$)

  theoretical studies: a few ...

  experimental: no (fixed target ?,
  RHIC ??)

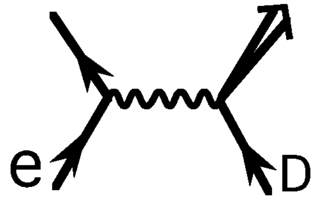
References

F.E.Close and SK, Phys. Rev. D42, 2377 (1990).

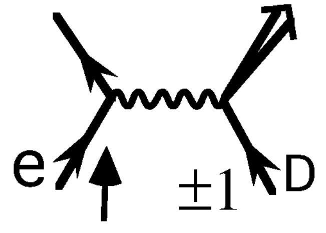
S. Hino and SK, Phys. Rev. D59 (1999) 094026:
D60 (1999) 054018.

## Structure functions for spin-one hadrons

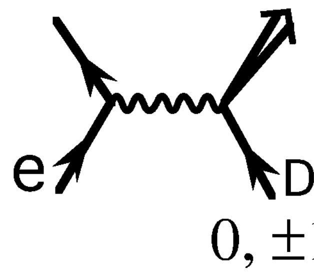
$$F_1 \propto \langle d\sigma \rangle$$




$$g_1 \propto d\sigma(\uparrow,+1) - d\sigma(\uparrow,-1)$$




$$b_1 \propto d\sigma(0) - \frac{d\sigma(+1)+d\sigma(-1)}{2}$$




in parton model $\left[\, q_{\uparrow}^{H}(x,Q^2) \,\right]$

$$F_1 = \frac{1}{2}\sum_i e_i^2 \left(q_i + \bar{q}_i\right)$$

$$q_i = \frac{1}{3}\left(q_{i\,\uparrow+\downarrow}^{+1} + q_{i\,\uparrow+\downarrow}^{0} + q_{i\,\uparrow+\downarrow}^{-1}\right)$$

$$g_1 = \frac{1}{2}\sum_i e_i^2 \left(\Delta q_i + \Delta\bar{q}_i\right)$$

$$\Delta q_i = q_{i\uparrow}^{+1} - q_{i\downarrow}^{+1}$$

$$b_1 = \frac{1}{2}\sum_i e_i^2 \left(\delta q_i + \delta\bar{q}_i\right)$$

$$\delta q_i = q_{i\,\uparrow+\downarrow}^{0} - \frac{q_{i\,\uparrow+\downarrow}^{+1} + q_{i\,\uparrow+\downarrow}^{-1}}{2}$$

tensor polarization

$\leftrightarrow$ longitudinal/transverse polarization

**tensor polarization**

$$\sigma\,(0) - \frac{\sigma\,(+1) + \sigma\,(-1)}{2}$$

$$= 3 < \sigma > - \frac{3}{2}\,[\,\sigma\,(+1) + \sigma\,(-1)\,]$$

**unpolarized** **longitudinally or transversely polarized**

proton-deuteron Drell-Yan

$$\sigma(\bullet,0) - \frac{1}{2}\,[\sigma(\bullet,+1) + \sigma(\bullet,-1)]$$

$$\propto \sum_q e_q^2\,[\, f_1^q(x_1)\, b_1^{\bar{q}}(x_2) + f_1^{\bar{q}}(x_1)\, b_1^q(x_2)\,]$$

Tensor polarized distributions could be measured.

# Role of ν measurements

$$\frac{d^2(\sigma^{\uparrow\downarrow}-\sigma^{\uparrow\uparrow})_{\nu(\bar\nu)}}{dxdy}=\frac{G_F^2 M E_\nu}{\pi}\Big\{\pm y(1-\frac{y}{2}-\frac{xyM}{2E})xg_1\mp\frac{x^2yM}{E}g_2$$
$$+y^2x(1+\frac{xM}{E})\underline{g_3}+(1-y-\frac{xyM}{2E})[(1+\frac{xM}{E})\underline{g_4}+\underline{g_5}]\Big\}$$

new parity-violating
polarized structure functions

in parton model

$g_{4+5}^{\nu p}/2x = g_3^{\nu p} = -(\Delta d + \Delta s - \Delta\bar u - \Delta\bar c)$

$g_{4+5}^{\bar\nu p}/2x = g_3^{\bar\nu p} = -(\Delta u + \Delta c - \Delta\bar d - \Delta\bar s)$

$\downarrow$

$g_3^{\nu p} + g_3^{\bar\nu p} = -(\Delta u_v + \Delta d_v)$
$\quad - (\Delta s - \Delta\bar s) - (\Delta c - \Delta\bar c)$

$g_3^{\nu(p+n)} - g_3^{\bar\nu(p+n)} = -2(\Delta s + \Delta\bar s) + 2(\Delta c + \Delta\bar c)$

Polarized <u>valence-quark</u> and sea-quark (strange, charm) distributions can be investigated in detail.

also $\nu p \to \mu^-\mu^+ X$ ($\mu^- c X$, $c \to \mu^+ X'$)

for finding $s/(\bar u + \bar d)$

# Quark spin content at a $\nu$ factory

e/$\mu$ scattering $\longrightarrow \Delta\Sigma = 0 \sim 30\%$

- not uniquely determined
- issue of using low-energy data for fixing $\int dx \Delta u_v, \int dx \Delta d_v$

## $\nu$ scattering

$$g_1^{\nu p} = \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{c}$$

$$g_1^{\bar{\nu} p} = \Delta u + \Delta c + \Delta\bar{d} + \Delta\bar{s}$$ in parton model

$$g_1^{\nu p} + g_1^{\bar{\nu} p} = (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s}) + (\Delta c + \Delta\bar{c})$$

in LO $\int dx\, (g_1^{\nu p} + g_1^{\bar{\nu} p}) = \Delta\Sigma$

in NLO $= \Delta\Sigma - n_f \frac{\alpha_s}{2\pi} \Delta G$

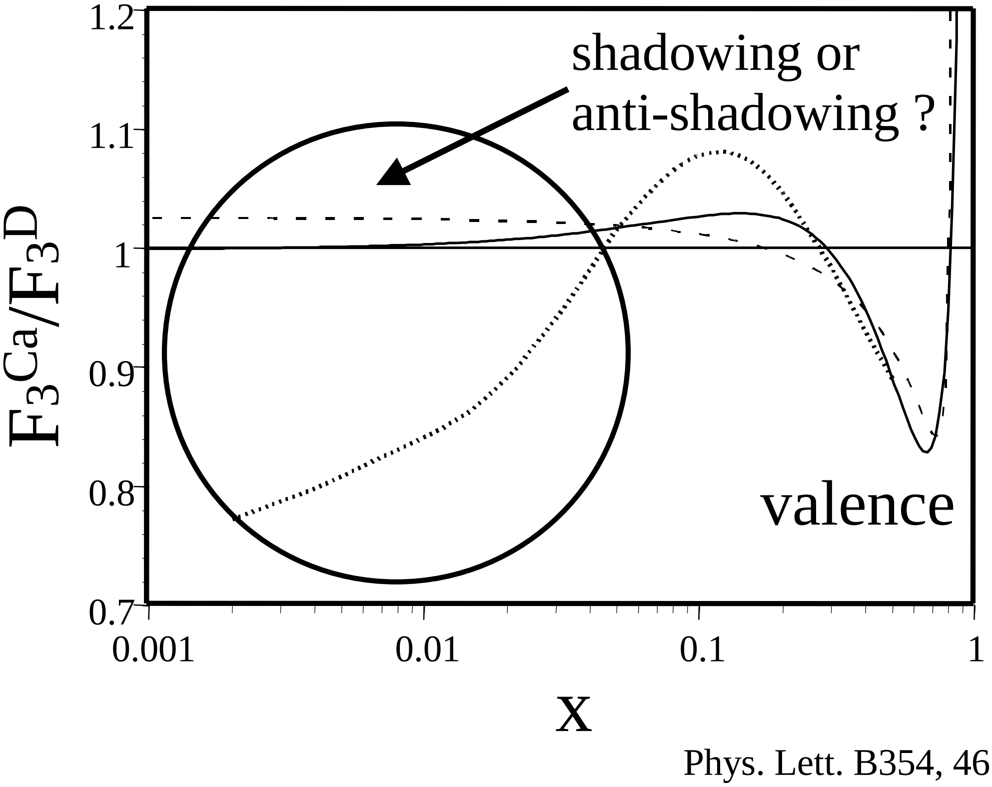
independent determination of quark spin content $\Delta\Sigma$ !

# Valence-quark distributions in nuclei

Nuclear modification of $F_3$ cannot be investigated at this stage due to lack of accurate deuteron data.

accurate $F_3^A/F_3^D$ data are valuable

- for determining the shadowing model
- for determining accurate nuclear parton distributions → application to heavy-ion physics




Phys. Lett. B354, 465 (1995)

# Summary

- unpolarized PDFs (parton distribution functions) are now relatively well understood.

- polarized PDFs : $\bar{q}$ is not known at small x

  $\rightarrow$ quark spin content ?

  HERA-like facility is needed.

- nuclear PDFs : only a few papers!

  nuclear G(x) ? $\rightarrow$ J/$\psi$ suppression

  should be determined by $\partial F_2^A / \partial(\ln Q^2)$

  at a HERA-like facility.

- other topics

  spin-1 physics

  flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$

  neutrino factory, ...