Studies of parton distributions at a neutrino factory

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parton distributions in the nucleon

in nuclei

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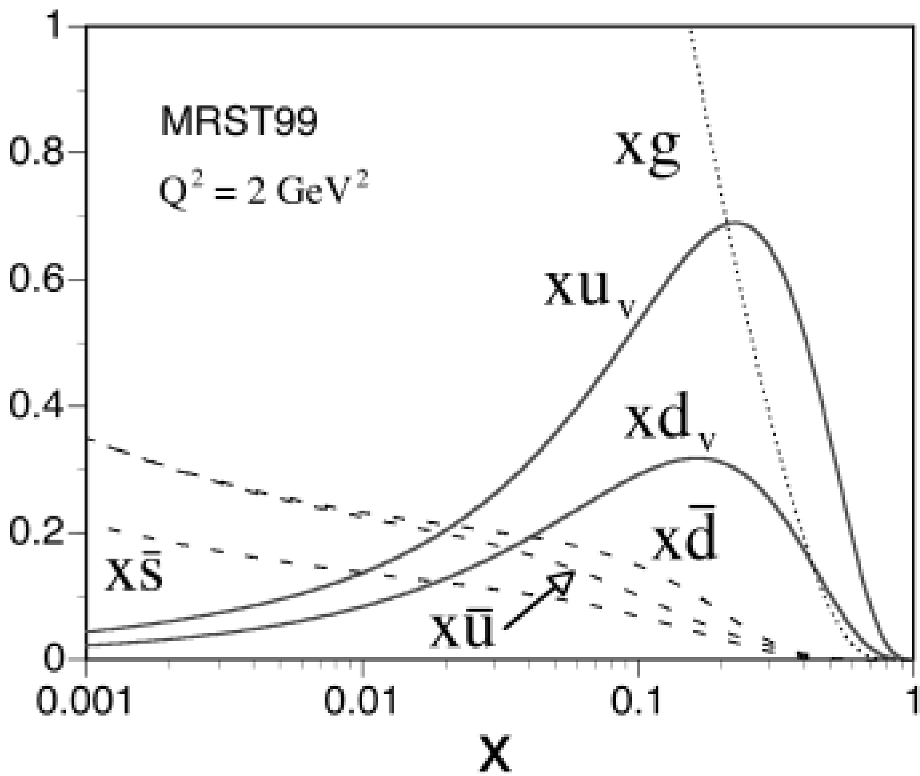
- isospin-symmetry violation

(4) Summary

Recent unpolarized distributions

- CTEQ5, Eur. Phys. J. C12 (2000) 375
- GRV98, Eur. Phys. J. C5 (1998) 461
- MRST99, Eur. Phys. J. C14 (2000) 133



Neutrino data are important for determining valence-quark distributions in the "*nucleon*".

However, the used CCFR target is iron!?

What can be done at a ν factory?

• unpolarized distributions in the ***nucleon***

$$\frac{d\sigma^{\nu,\bar\nu}}{dE' \, d\Omega} = \frac{G_F^2 \, E'^2}{2\,\pi^2\,(1+Q^2/M_W^2)^2}$$
$$\times \left[\frac{F_2}{\nu}\cos^2\frac{\theta}{2} + \frac{2F_1}{\nu}\sin^2\frac{\theta}{2} \mp \frac{E+E'}{M^2} F_3 \sin^2\frac{\theta}{2} \right]$$

in parton model

$$F_2 = 2\,x\,F_1$$
$$F_2^{\nu p} = 2\,x\,(d + s + \bar u + \bar c)$$
$$F_2^{\bar\nu p} = 2\,x\,(u + c + \bar d + \bar s)$$
$$F_2^{\nu n} = 2\,x\,(u + s + \bar d + \bar c)$$
$$F_2^{\bar\nu n} = 2\,x\,(d + c + \bar u + \bar s)$$
$$xF_3^{\nu p} = 2\,x\,(d + s - \bar u - \bar c)$$
$$xF_3^{\bar\nu p} = 2\,x\,(u + c - \bar d - \bar s)$$
$$xF_3^{\nu n} = 2\,x\,(u + s - \bar d - \bar c)$$
$$xF_3^{\bar\nu n} = 2\,x\,(d + c - \bar u - \bar s)$$

parity-violation terms

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

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

valence-quark distributions

kinematical range

suppose $E_\nu = 30$ GeV

$$x = \frac{Q^2}{2\,M\,q_0}$$

$$x_{min} = \frac{\min(Q^2)}{2\,M\,\max(q_0)} = \frac{1}{2\cdot 1\cdot 30} = 0.017$$

where $\min(Q^2) \sim 1\ \mathrm{GeV}^2$, $\max(q_0) = E_\nu$

Fe target → p, d, ^{3}He targets
with intense ν beam

↓

accurate determination of u_v and d_v
in the "*nucleon*"

↓

accurate determination of $\bar{q}$ and g

↓

important for finding any exotic signature beyond current theoretical framework

Parton Distributions in Nuclei

References

Nuclear parametrization, F_3

- M. Hirai, SK, and M. Miyama,
  hep-ph/0103208, to be published in Phys. Rev. D.
- R. Kobayashi, SK, and M. Miyama,
  Phys. Lett. B354, 465 (1995).

Purposes

Determination of parton distributions

- unpolarized distributions in the nucleon

  3 major groups (CTEQ, GRV, MRS)

- polarized distributions in the nucleon

  several groups (GS, GRSV, ..., AAC)

- distributions in nuclei

  no χ^2 analysis! (see Eskola, Kolhinen, Ruuskanen)

  → **for understanding nuclear mechanisms in the high-enegy region**

  → **for heavy-ion physics**

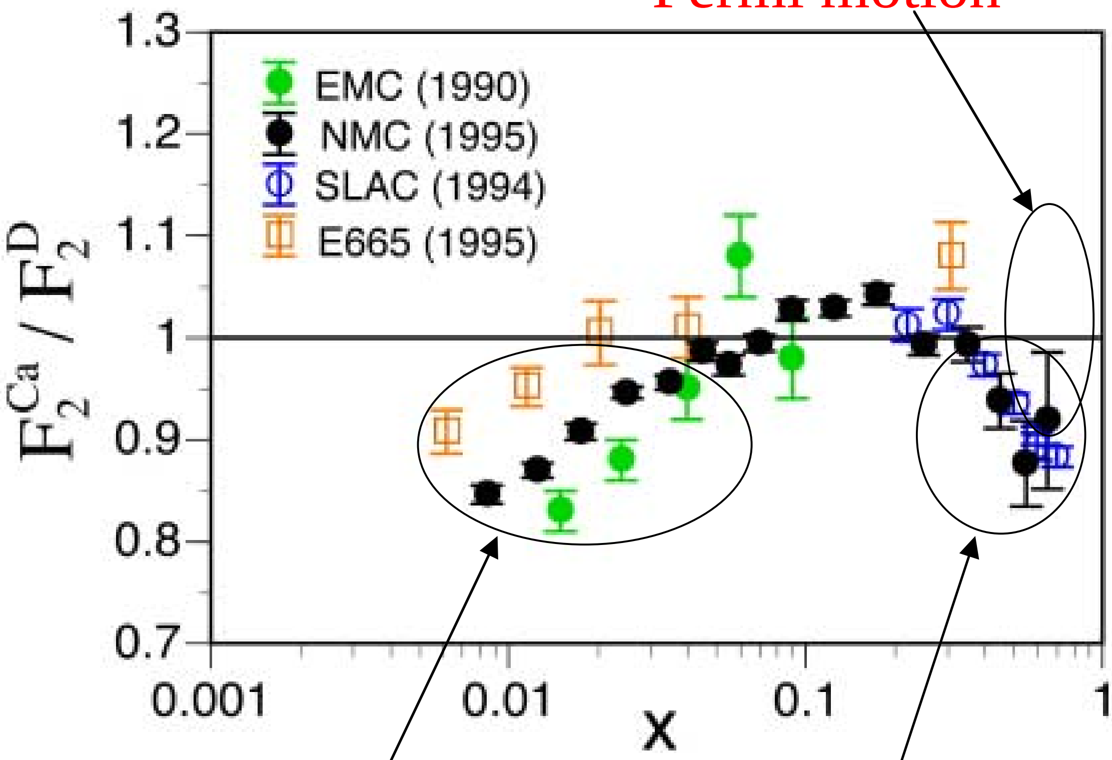
  → **re-examination of $q_V(x)$ in the nucleon**

• parton distributions in nuclei

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

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

Fermi motion



shadowing

original EMC finding
(binding, subnucleon?)

However, little is known about F_3 (namely valence-quark) modification at small x due to lack of accurate deuteron data.

Parametrization of nuclear parton distributions

1. functional form of $f_i^A(x)$
2. constraints: A dependence, conservation laws
3. χ^2 fitting to experimental data
4. results: optimum nuclear parton distributions

Ref. hep-ph/0103208 (Phys. Rev. D)

- 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: $u^n = d^p \equiv d\,,\ \ d^n = u^p \equiv u$

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

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

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

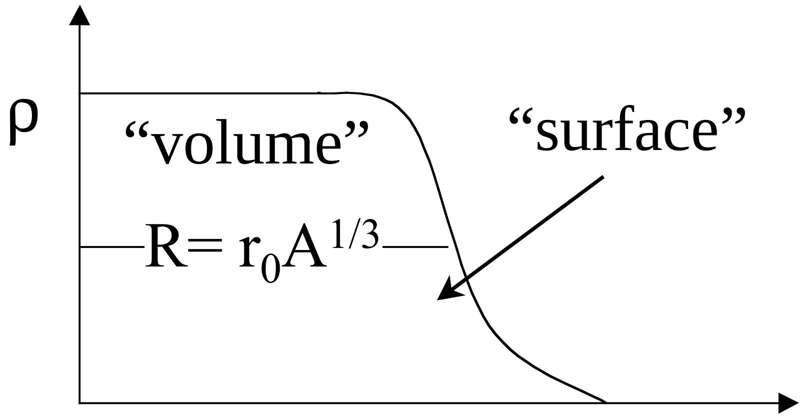
$$d_v^A(x) = w_{d_v}(x,A)\ \frac{Z\, d_v(x) + N\, u_v(x)}{A}$$

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

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

A dependence

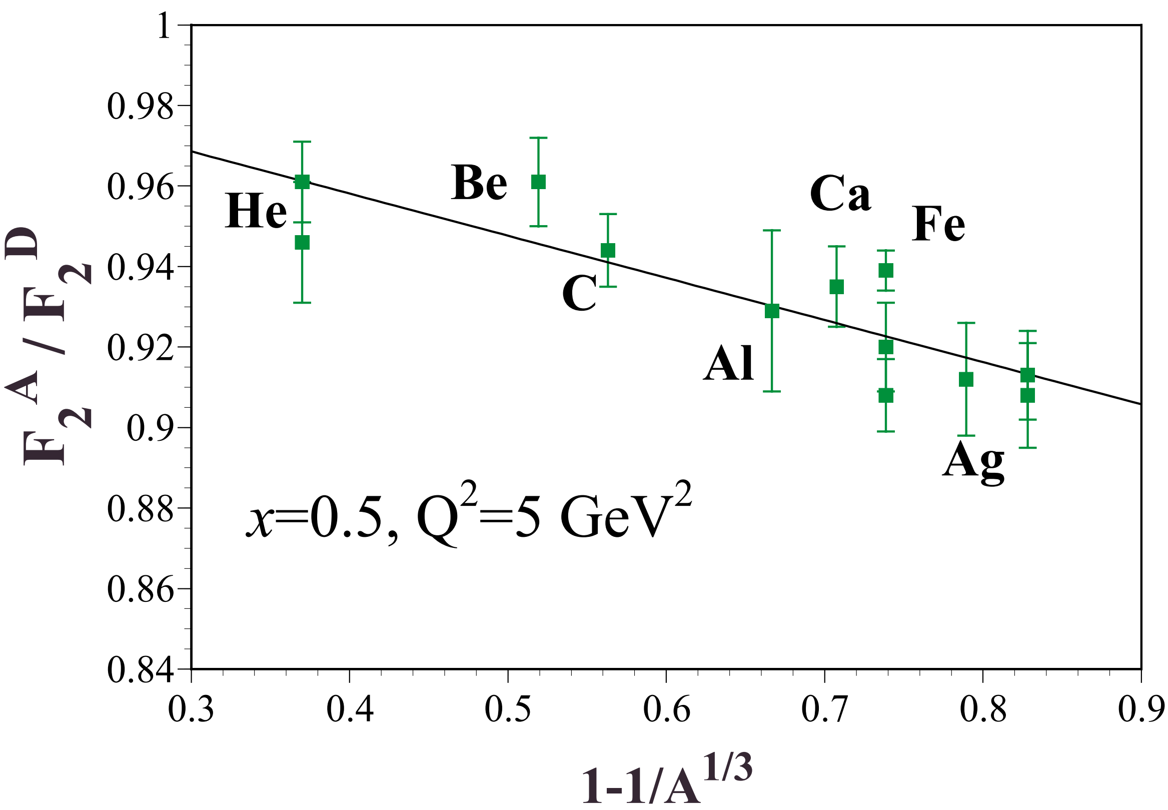
Ref. I. Sick and D. Day, Phys. Lett. B 274 (1992)



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, β_i: parameters to be determined by χ^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**

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

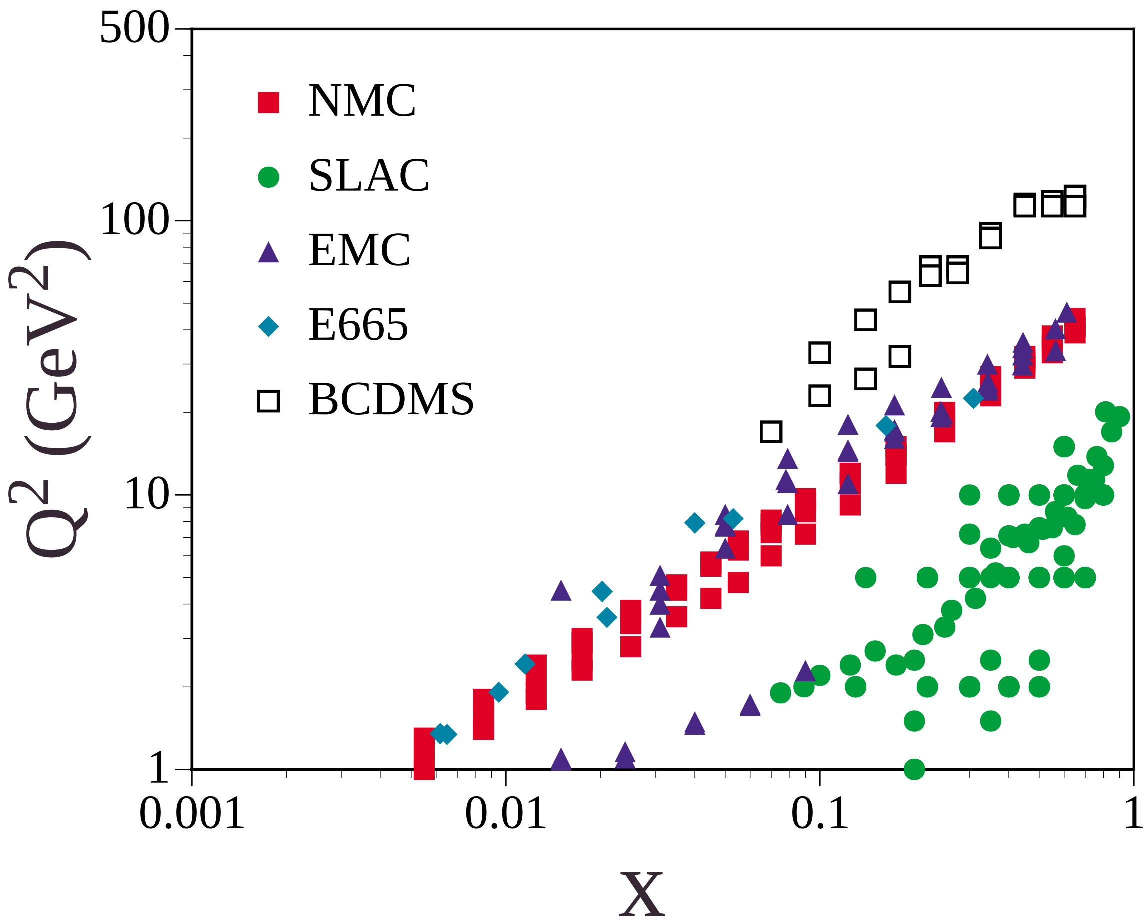
- **Momentum**

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

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 (Λ_{QCD}=174 MeV)

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

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

- total number of data: 309

- number of flavor: $n_f = 3$

- subroutine for the χ^2 analysis: CERN - Minuit

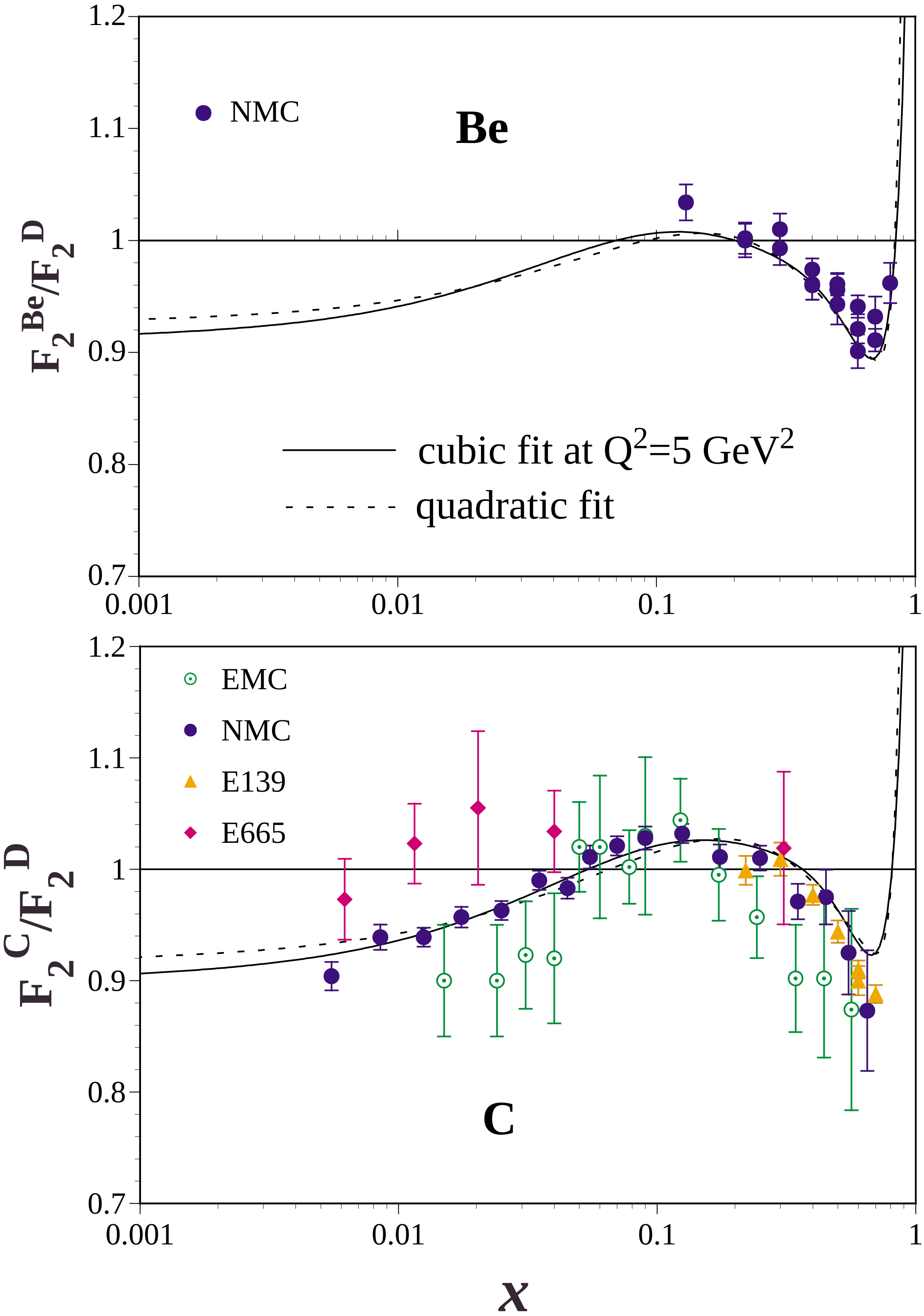
$$\chi^2 = \sum_i \frac{(R_i^{data} - R_i^{calc})^2}{(\sigma_i^{data})^2}$$

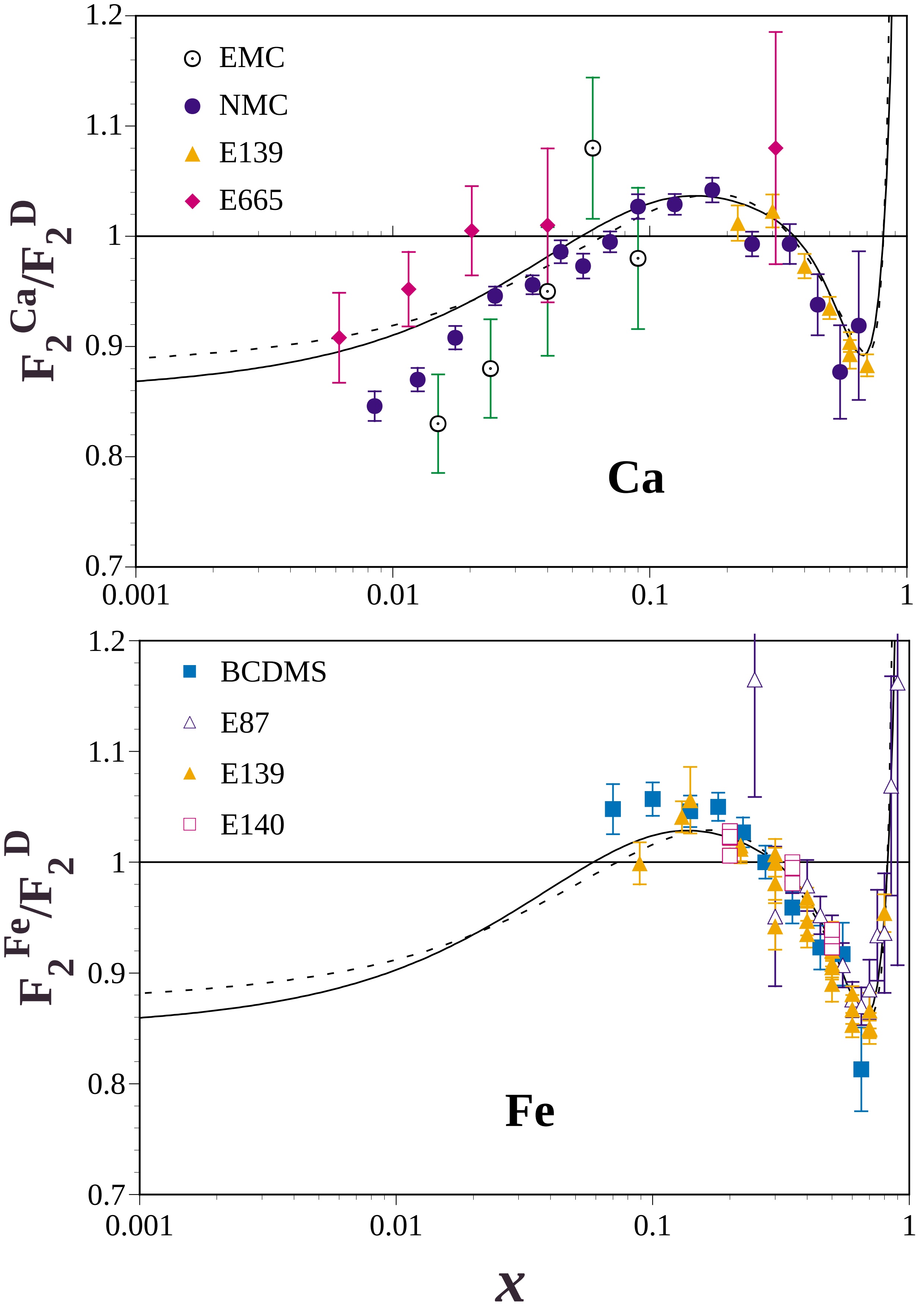
$$R = \frac{F_2^A}{F_2^D}, \qquad \sigma_i^{data} = \sqrt{(\sigma_i^{sys})^2 + (\sigma_i^{stat})^2}$$

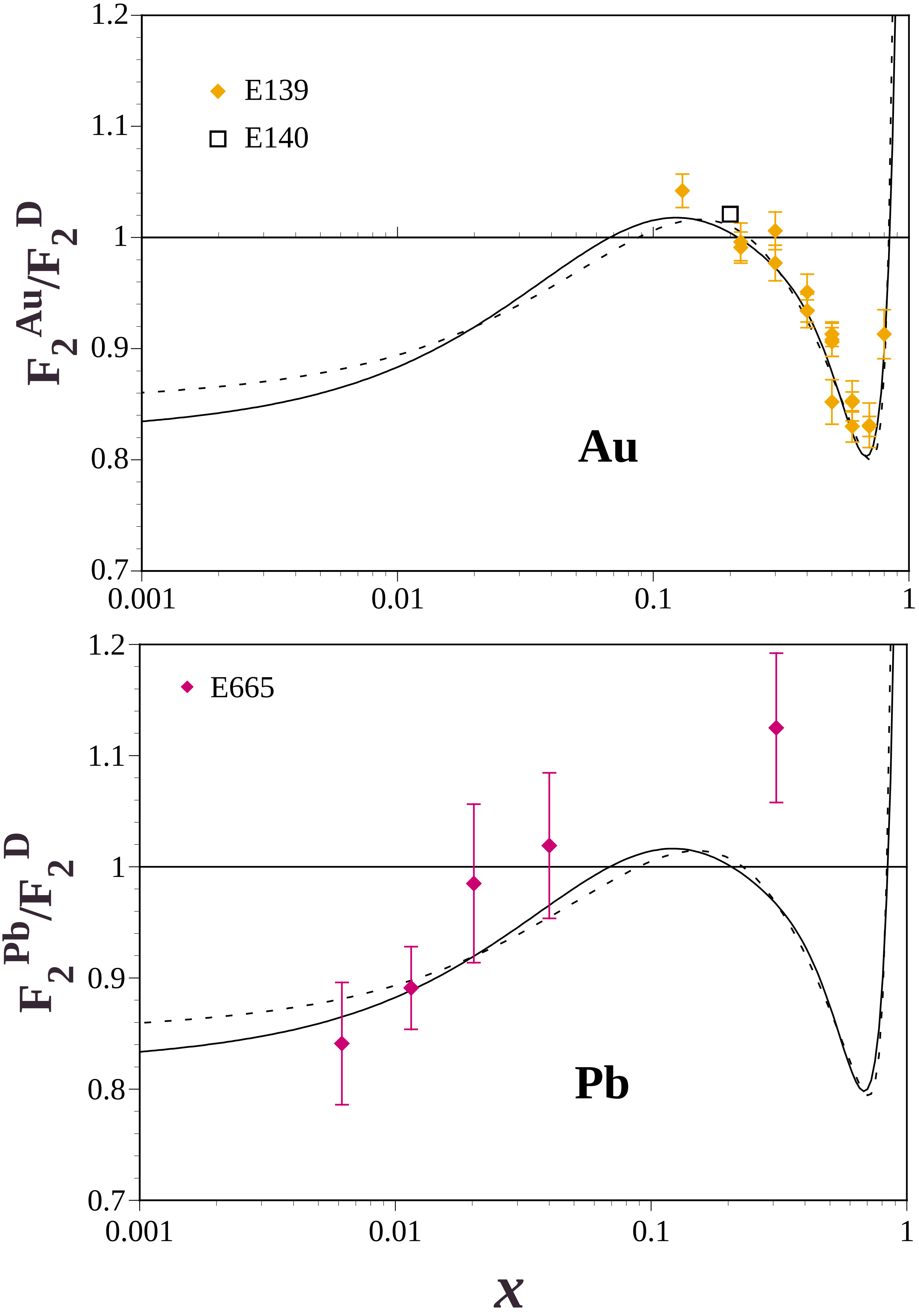
→ obtained χ^2_{min}/d.o.f. = 583.7 / 302 (quadratic)

= 546.6 / 300 (cubic)

Analysis results



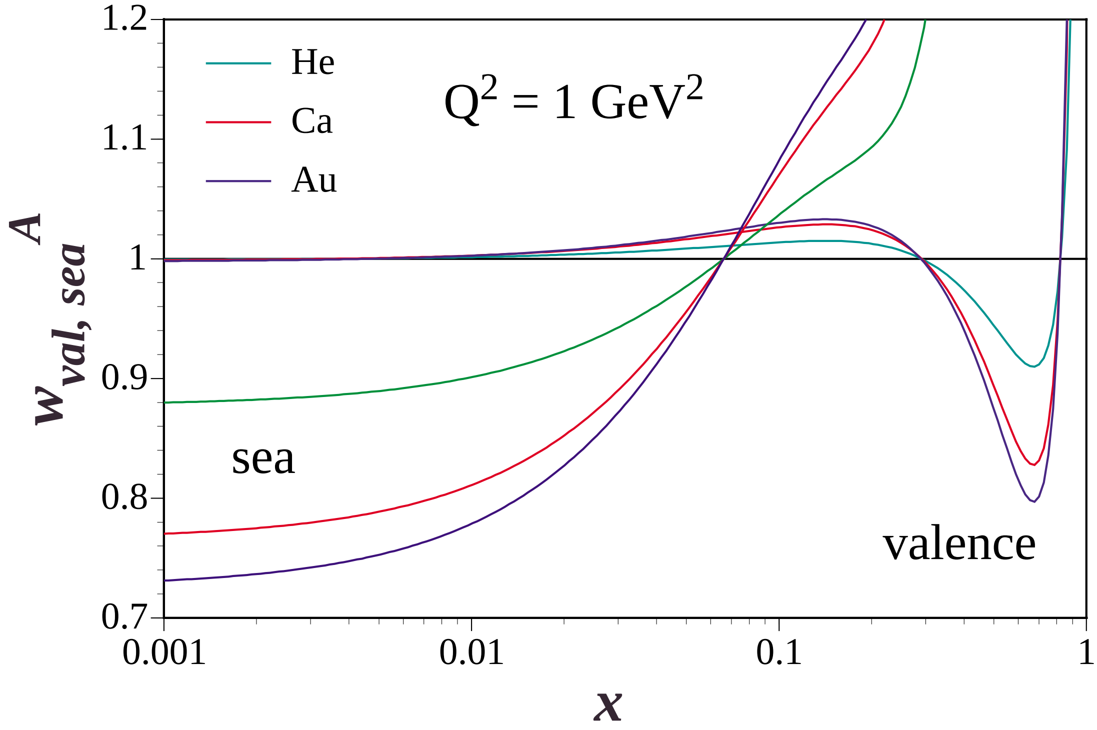

EMC
NMC
E139
E665
Ca
F_2^{Ca}/F_2^D
BCDMS
E87
E139
E140
Fe
F_2^{Fe}/F_2^D
x
1.2
1.1
1
0.9
0.8
0.7
0.001
0.01
0.1
1

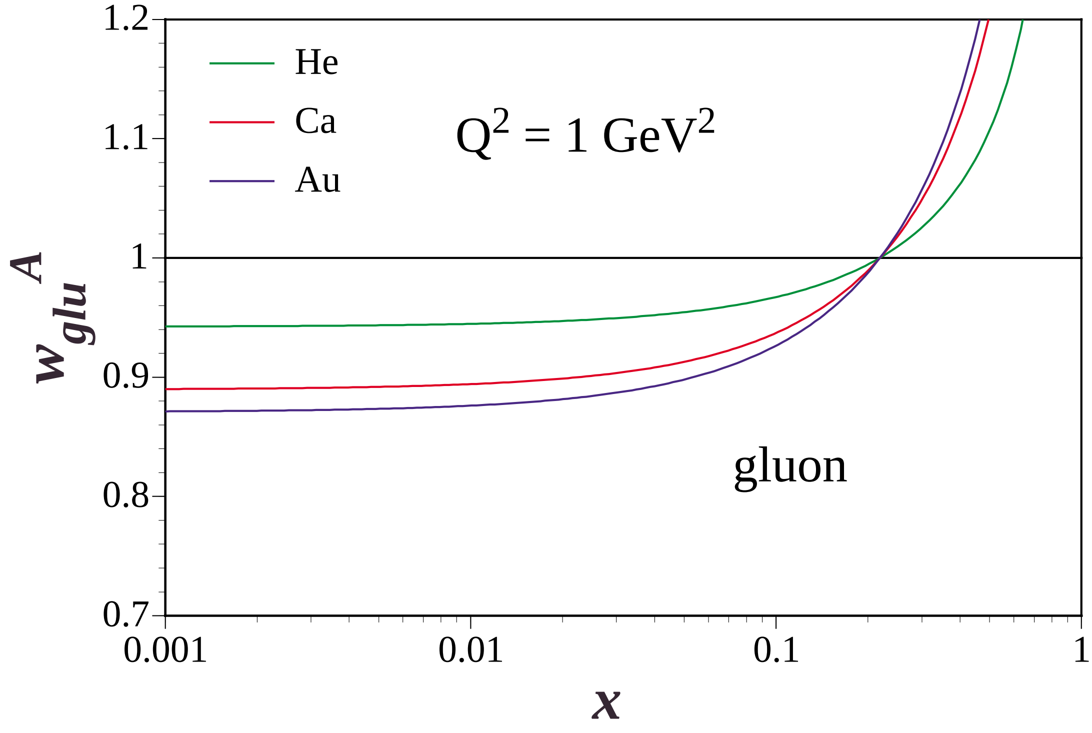


E139
E140
Au
F_2^{Au}/F_2^D
1.2
1.1
1
0.9
0.8
0.7
0.001
0.01
0.1
1
E665
Pb
F_2^{Pb}/F_2^D
1.2
1.1
1
0.9
0.8
0.7
0.001
0.01
0.1
1
x

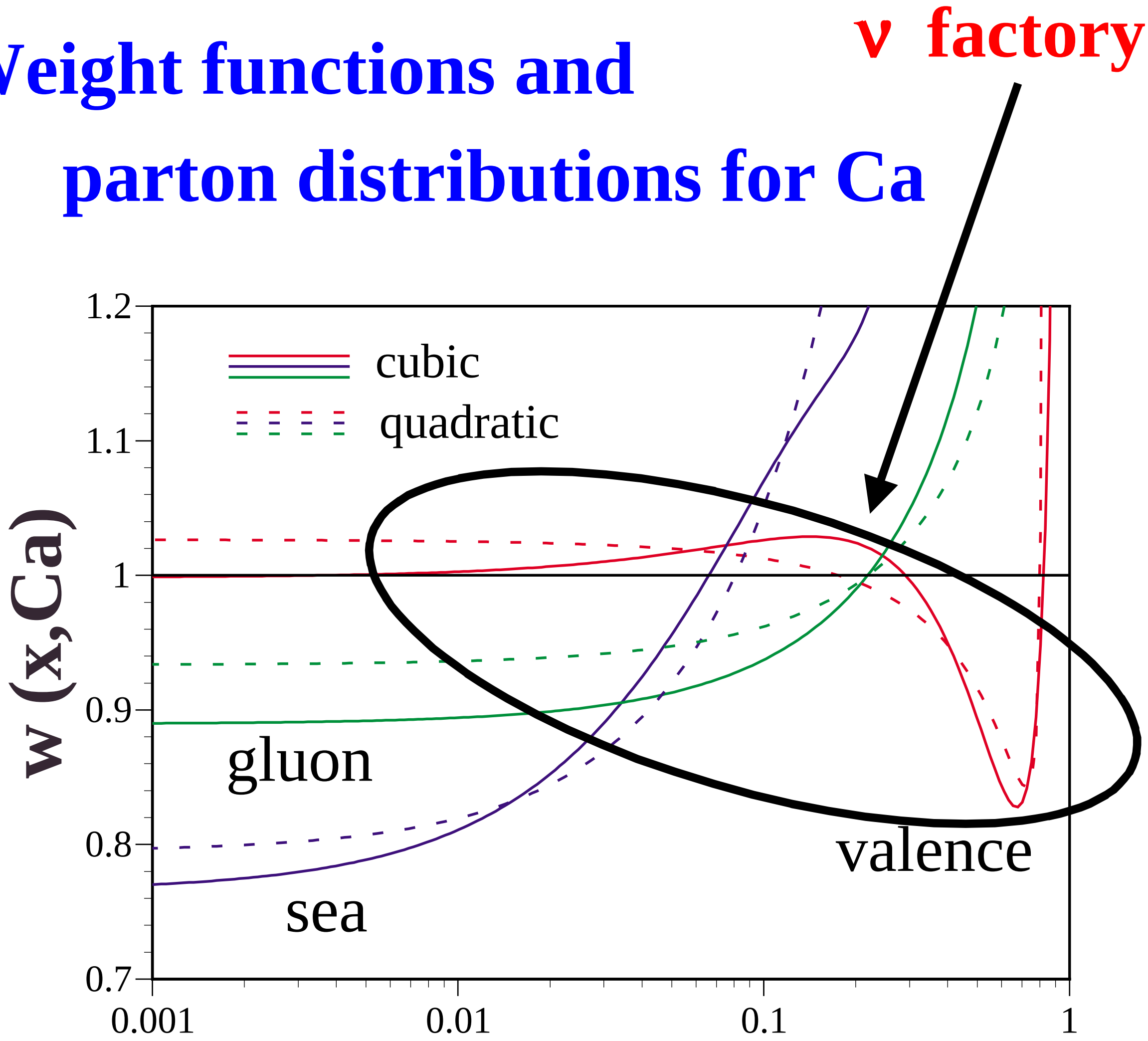
Weight functions $w_i(x,A)$ for He, Ca, Au

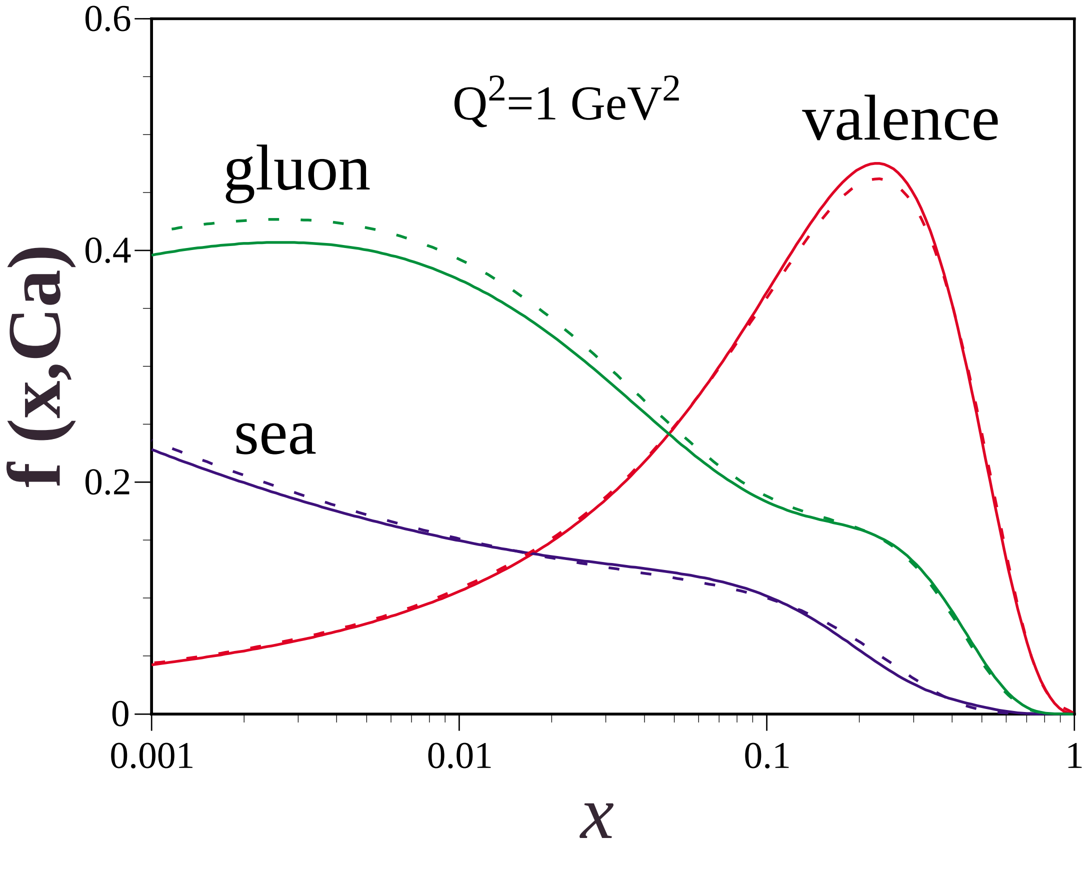
"cubic fit"





Weight functions and parton distributions for Ca



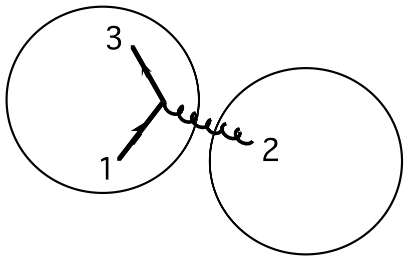


Theoretical predictions of F_3^A/F_3^D

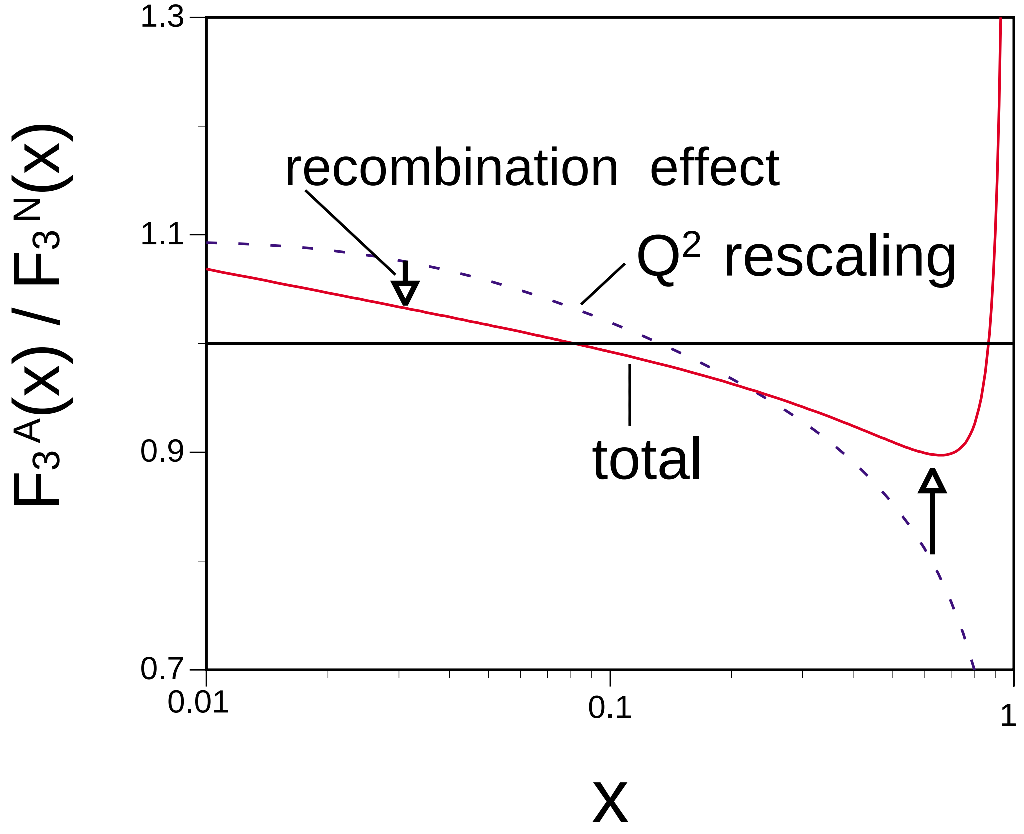
(1) Q^2 rescaling & recombination

Q^2 rescaling: $V_A(Q^2) = V_N(\xi_A Q^2)$

Recombination:

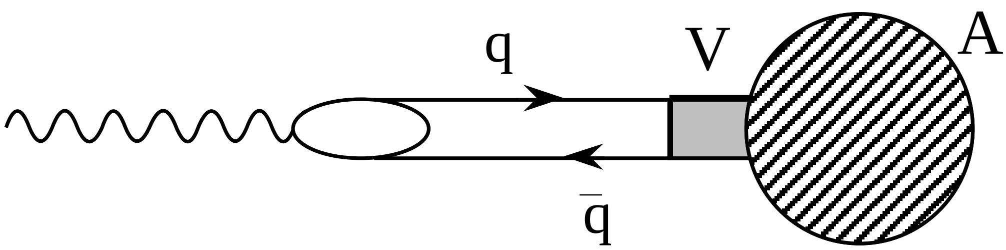


$\Delta q_3(x_3) \propto p_1(x)\, p_2(x)\, \Gamma(x_1,x_2,x_3)$

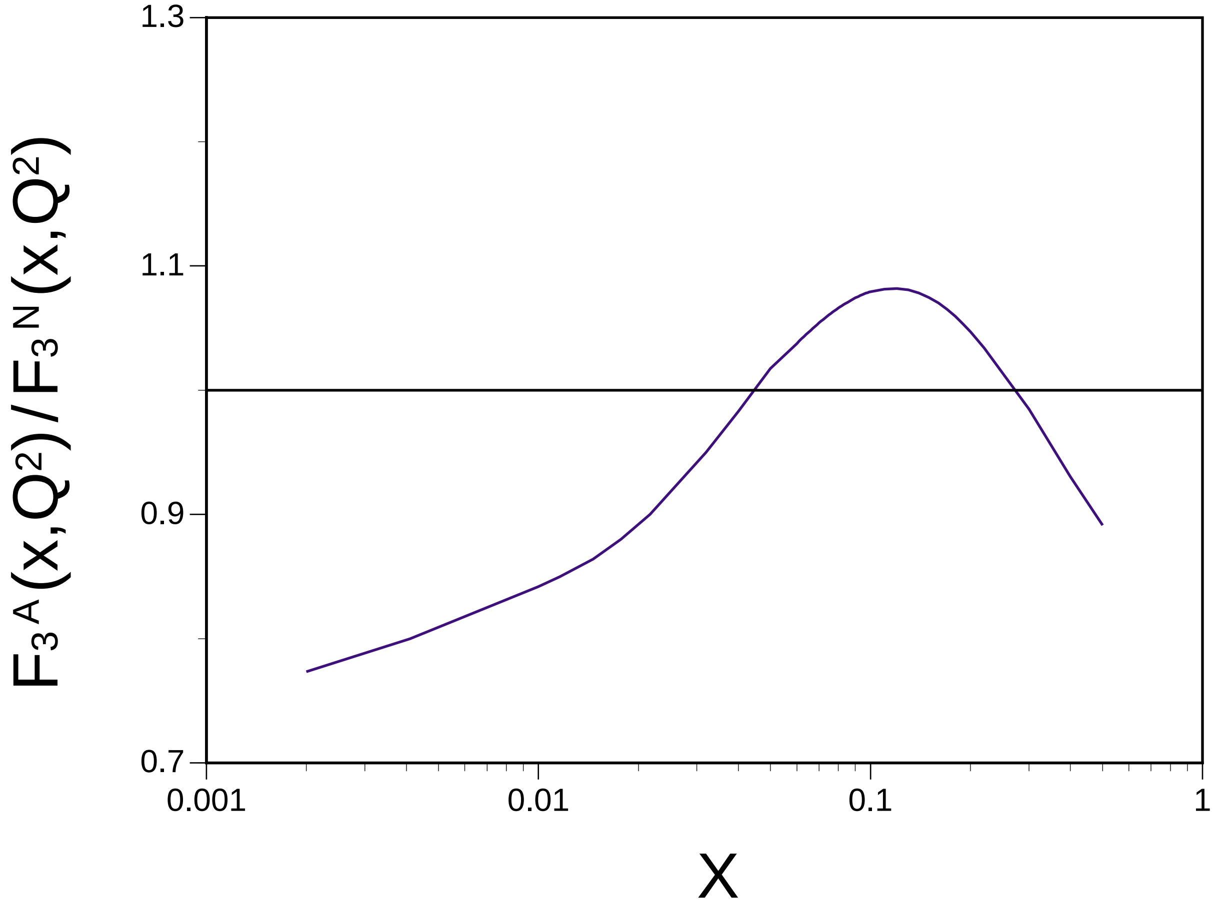


anti-shadowing ?

(2) vector-meson type



e.g. Frankfurt-Liuti-Strikman, PRL, 65, 1725 (1990)



shadowing ?

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 $\rightarrow$ application to heavy-ion physics

Summary of nuclear parametrization

- first χ^2 analysis

  for the nuclear parton distributions

  Computer codes could be obtained from

  http://www-hs.phys.saga-u.ac.jp.

- reasonably good fit with

  χ^2_{min} / d.o.f. = 1.93 (quad.), 1.82 (cubic)

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

- need analysis refinement

- $q_V(x)$ in the nucleon is determined

  by ν-Fe scattering at this stage

  $\rightarrow$ reinvestigate with nuclear modification

  $\rightarrow$ ν-N scattering (ν factory)

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

Selected Topics on
Parton Distributions
in the Nucleon

References

Polarized distributions

- Y. Goto et al. (AAC), Phys. Rev. D62 (2000) 034017.
- B. Lampe and E. Reya, Phys. Rep. 332 (2000) 1.

Light-antiquark flavor asymmetry, Isospin

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

$\boxed{\text{• polarized parton distributions}}$

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

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

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

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

flavor-symmetric distributions at initial Q_0^2

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

first moments η_{uv} , η_{dv} are fixed

$$F = 0.463 \pm 0.008,\quad D = 0.804 \pm 0.008$$

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

γ_{uv} and γ_{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 χ^2 fitting !

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

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

χ^2 fitting to the data

[proton, neutron (^{3}He), deuteron]

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

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

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

which is minimized by the subroutine MINUIT

We analyzed with the following conditions.

- **Unpolarized PDF** **GRV98**
- **Initial Q^2** **$Q_0^2 = 1$ GeV ^{2}**
- **Number of flavor** **$N_f = 3$**
- **Λ_{QCD}** **$\Lambda_{LO} = 204$ MeV**
  $\Lambda_{NLO} = 299$ MeV

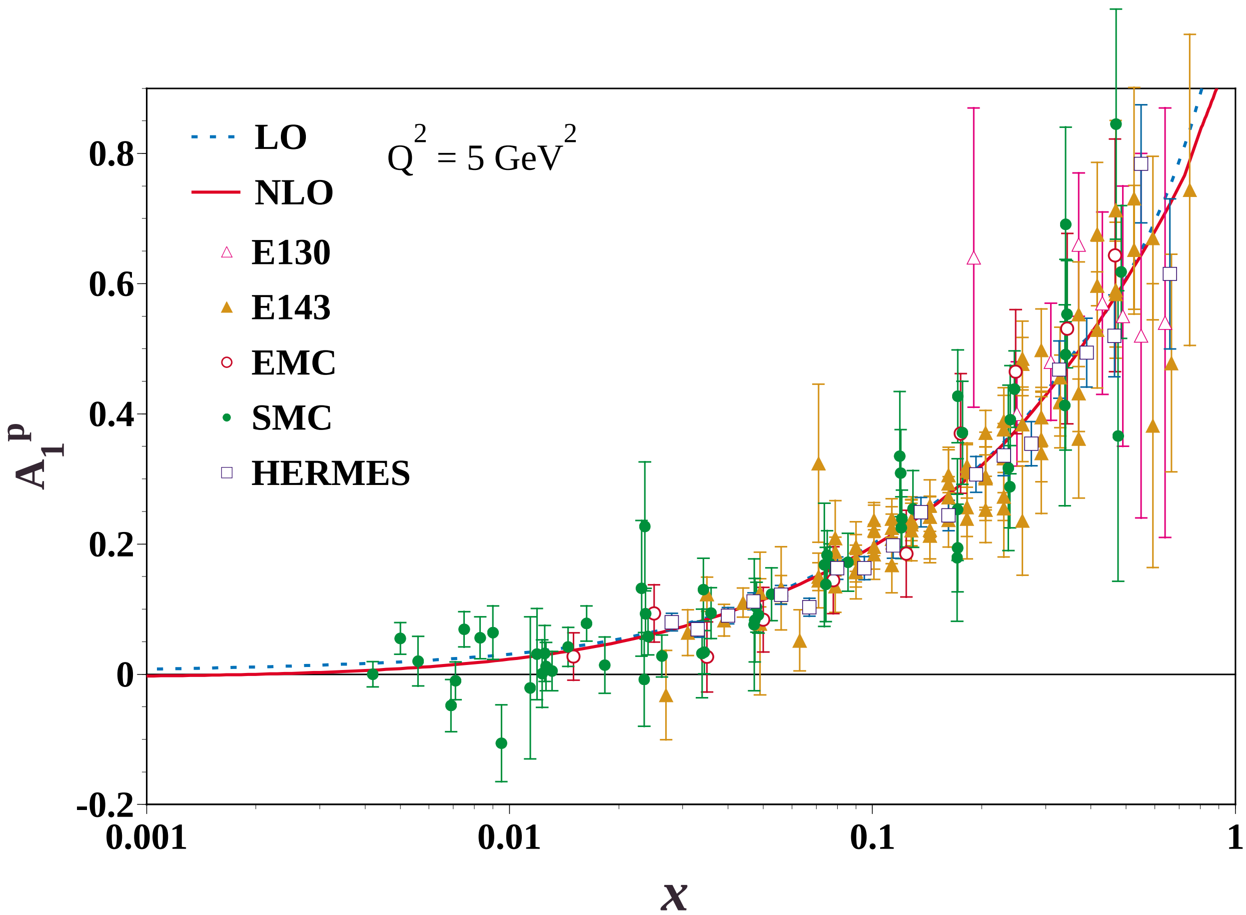
- Results -

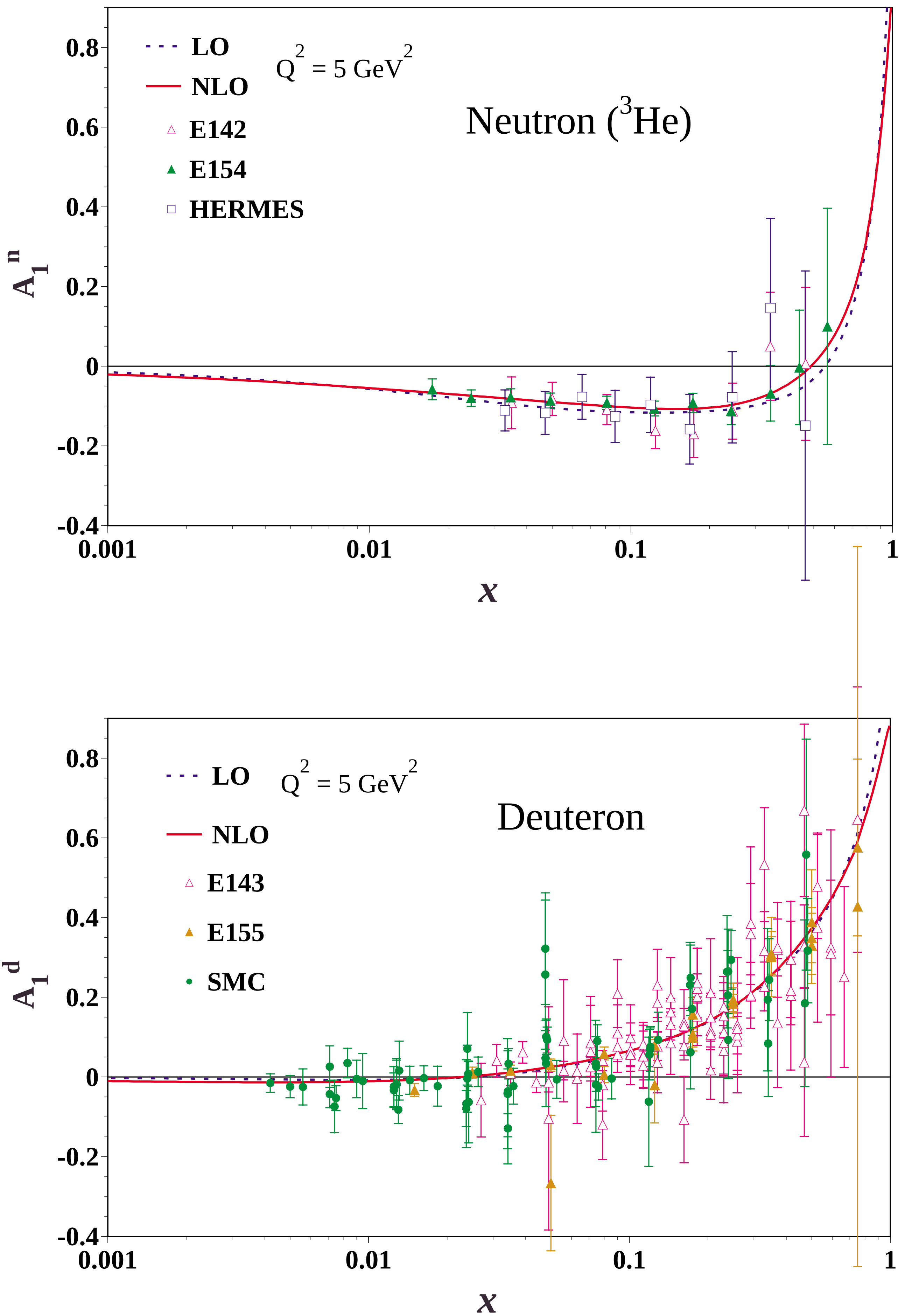
Total χ^2 LO χ^2/d.o.f. = 322.6 / 360

NLO χ^2 /d.o.f. = 300.4 / 360

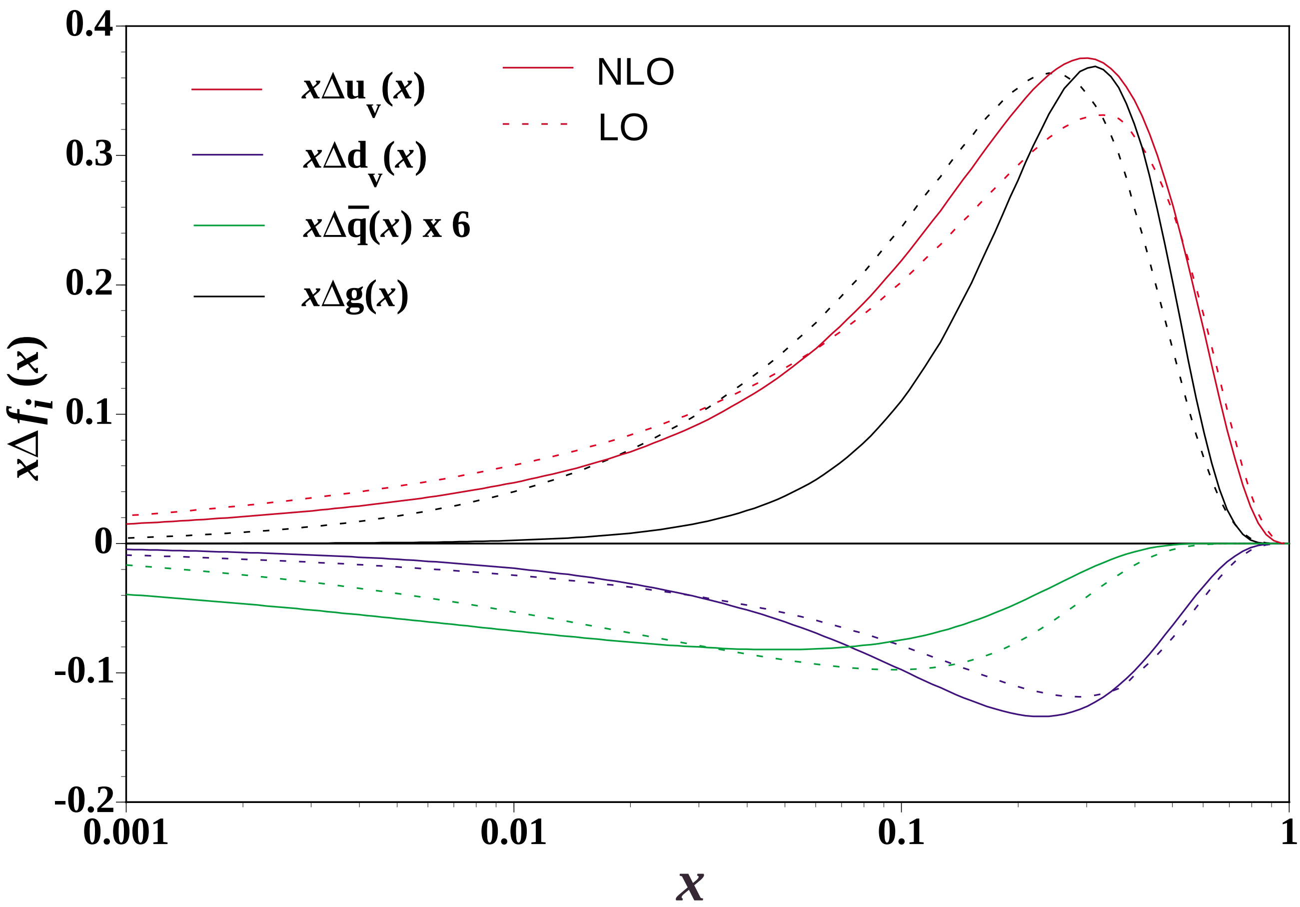
Total data 375

Spin asymmetry A_1^p




LO
NLO
$Q^2 = 5$ GeV^2
Neutron (^{3}He)
E142
E154
HERMES
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
$Q^2 = 5$ GeV^2
Deuteron
E143
E155
SMC
A_1^d
x

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



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

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

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

$$\downarrow$$

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

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

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 ν factory

e/μ scattering $\rightarrow \Delta\Sigma = 0 \sim 30\%$

- not uniquely determined
- issue of using low-energy data

for fixing $\int dx \Delta u_v$, $\int dx \Delta d_v$

ν scattering

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

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

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

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

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

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

$\bar{u}/\bar{d}$, $\Delta\bar{u}/\Delta\bar{d}$ asymmetries at a ν factory

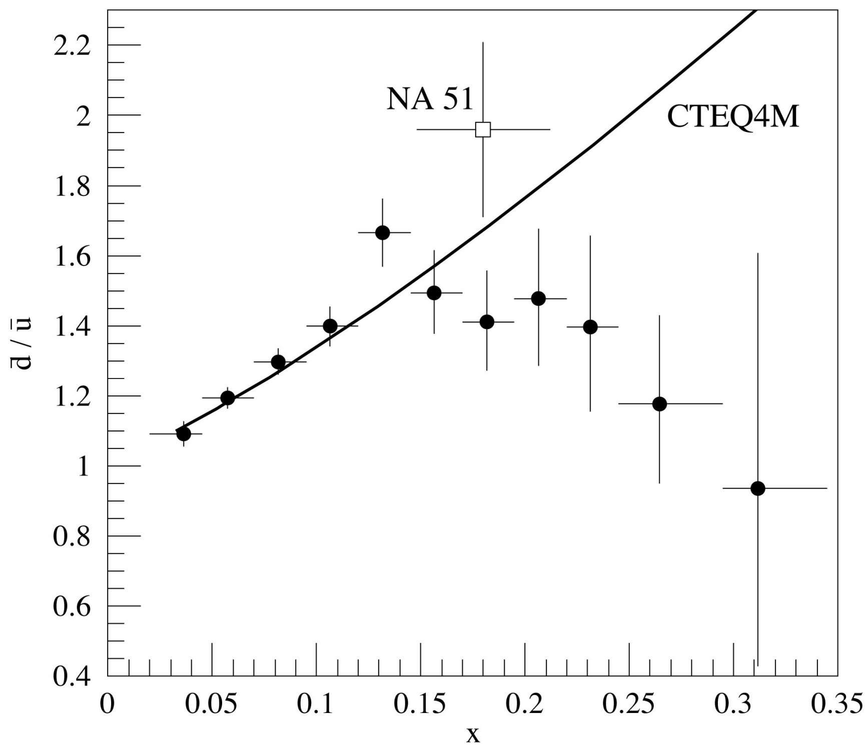
introduction

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

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

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

- Drell-Yan p-n asymmetry (NA51, E866)



(from hep-ex/9803011)

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

$$\bar{u} - \bar{d} = \frac{1}{4}(F_2^{\nu p}/x - F_3^{\nu p}) - \frac{1}{4}(F_2^{\nu n}/x - F_3^{\nu n})$$

see SK, Phys. Rep. 303 (1998) 183 -- Sec 5.5

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

$$\Delta\bar{u} - \Delta\bar{d} = \frac{1}{2}(g_1^{\nu p} + g_3^{\nu p}) - \frac{1}{2}(g_1^{\nu n} + g_3^{\nu n})$$

If the neutrino data are accurate enough,
the $\bar{u} - \bar{d}$ and $\Delta\bar{u} - \Delta\bar{d}$ distributions
can be extracted in principle.

Isospin symmetry violation at a ν factory

see SK, Phys.Rep. -- Sec 4.5 & 5.6

The isospin symmetry is usually taken for granted in parton distributions.

$$u_n = d_p \equiv d, \quad \bar{u}_n = \bar{d}_p \equiv \bar{d}$$
$$d_n = u_p \equiv u, \quad \bar{d}_n = \bar{u}_p \equiv \bar{u}$$
$$s_n = s_p \equiv s, \quad \bar{s}_n = \bar{s}_p \equiv \bar{s}$$
$$\cdots$$

Although we expect

isospin violation ~ $O(\alpha)$ = a few %,

this "common sense" has to be tested.

$$\int \frac{dx}{x} \left(F_2^{\nu p} + F_2^{\bar{\nu} p} - F_2^{\nu n} - F_2^{\bar{\nu} n}\right)$$
$$= 4 \int dx \left[(\bar{u} + \bar{d} + \bar{s} + \bar{c})_p - (\bar{u} + \bar{d} + \bar{s} + \bar{c})_n \right]$$

$= 0$ if isospin symmetry can be applied

$\neq 0$ could be a signature of violation

Polarized distributions & other topics

At this stage, $\int dx\, \Delta u_v(x), \int dx\, \Delta d_v(x)$ are fixed by semi-leptonic decays.

- not undoubtedly obvious whether such small-Q^2 data can be used in connection with DIS data

$\downarrow$ independent determination at a ν factory

understand accurate polarized valence-quark distributions

$\rightarrow$ accurate determination of antiquark distributions

- determination of quark spin content
- $\bar{u}/\bar{d}$ & $\Delta\bar{u}/\Delta\bar{d}$ asymmetries
- test of isospin symmetry

Summary

In general, ν measurements are important for finding the non-singlet part of structure functions and s(x). However, if the data are accurate enough, there are other interesting topics.

- accurate p, d, ^{3}He data
  - valence-quark distributions in the *nucleon*
  - nuclear modification of V(x)

    $\rightarrow$ determination of shadowing model
- polarizated distributions and other topics
  - valence-quark contributions to nucleon spin
  - new polarized structure functions
  - determination of quark spin content
  - (polarized) light-antiquark flavor asymmetry
  - (polarized) strange and charm distributions
  - isospin symmetry