PacificSpin2019, Miyazaki, Japan
August 27-30, 2019

Flaver Asymmetry of Quarks and Anti-Quarks in the Nucleon Sea

Toshi-Aki Shibata
Tokyo Tech/Nihon University

List of Contents

1. Introduction

'Flavor asymmetry of quarks and anti-quarks in the nucleon sea'

Two ways to look at the flavor asymmetry

The difference between the first moments

$$\int_0^1 d_s(x)dx + \int_0^1 \bar{d}(x)dx - \int_0^1 u_s(x)dx - \int_0^1 \bar{u}(x)dx = 2\left(\int_0^1 \bar{d}(x)dx - \int_0^1 \bar{u}(x)dx\right)$$

The difference at each Bjorken x

$$d_s(x) + \bar{d}(x) - u_s(x) - \bar{u}(x)$$

Experimental methods:

1) Reaction Types

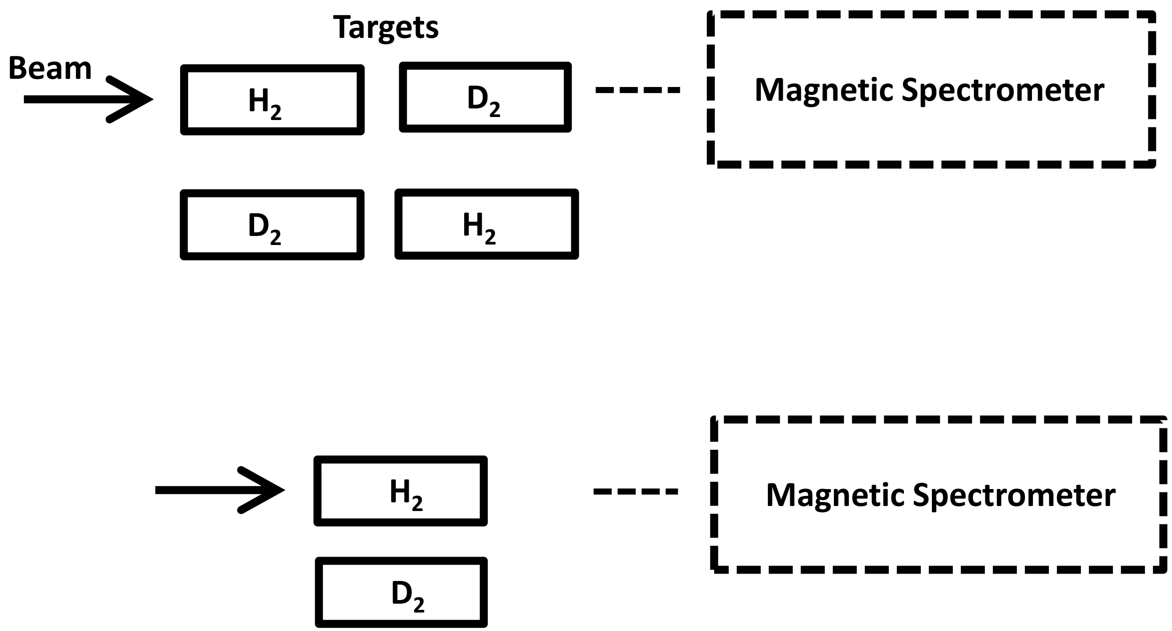
- **μ+p, μ+d, Deep Inelastic Scattering - inclusive measurement, NMC**
- **e+p, e+d, Deep Inelastic Scattering - semi-inclusive measurement, HERMES**
- **p+p, p+d, Drell-Yan process - NA51, E866/NuSea, E906/SeaQuest**
- **p+p, $W^{\pm}$ production,... RHIC, LHC**

2) Targets

Comparison of cross sections with a proton target and a deuterium target

Configuration of the beam, targets and a spectrometer

Comparison between the cross sections
with proton and deuterium targets



2. Deep Inelastic Scattering and Gottfried Sum

Gottfried sum: K. Gottfried, Phys. Rev. Lett. 18 (1967) 1174.

$$S_G = \int_0^1 \frac{1}{x}\{F_2^{\rm p}(x) - F_2^{\rm n}(x)\}dx$$

$$F_2^{\rm p}(x) = x\sum_f e_f^2 \left(q_f^{\rm p}(x) + \bar{q}_f^{\rm p}(x)\right) = x\ \left[\tfrac{4}{9}\left(u^{\rm p}(x) + \bar{u}^{\rm p}(x)\right) + \tfrac{1}{9}\left(d^{\rm p}(x) + \bar{d}^{\rm p}(x)\right) + \tfrac{1}{9}\left(s^{\rm p}(x) + \bar{s}^{\rm p}(x)\right)\right],$$

$$F_2^{\rm n}(x) = x\sum_f e_f^2 \left(q_f^{\rm n}(x) + \bar{q}_f^{\rm n}(x)\right) = x\ \left[\tfrac{4}{9}\left(u^{\rm n}(x) + \bar{u}^{\rm n}(x)\right) + \tfrac{1}{9}\left(d^{\rm n}(x) + \bar{d}^{\rm n}(x)\right) + \tfrac{1}{9}\left(s^{\rm n}(x) + \bar{s}^{\rm n}(x)\right)\right].$$

quark $\rightarrow$ valence quark + sea quark

$$\int_0^1 u^{\rm p}(x)dx = \int_0^1 u_{\rm v}^{\rm p}(x)dx + \int_0^1 u_{\rm s}^{\rm p}(x)dx = 2 + \int_0^1 u_{\rm s}^{\rm p}(x)dx, ...$$

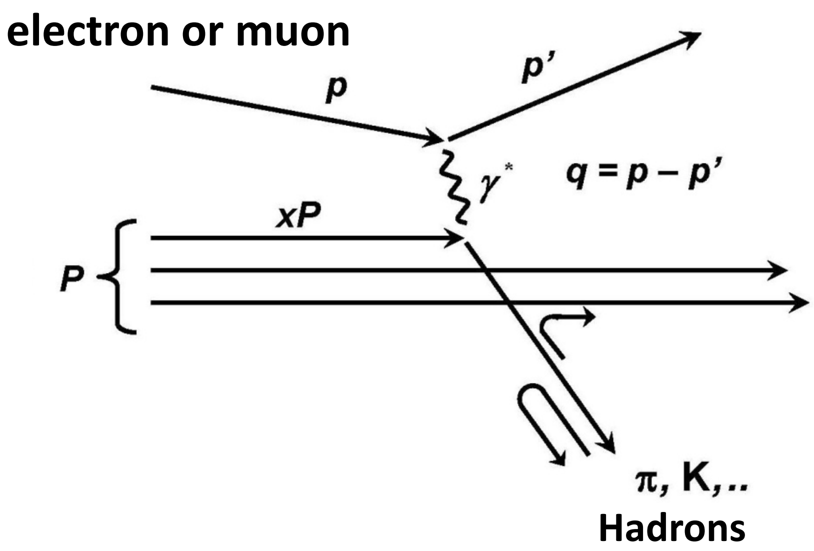
Here, $\int_0^1 u_{\rm s}^{\rm p}(x)dx = \int_0^1 \bar{u}_{\rm s}^{\rm p}(x)dx$, **... flavor number conservation**

Assumption: $\int_0^1 \left(s^{\rm p}(x) + \bar{s}^{\rm p}(x)\right)dx = \int_0^1 \left(s^{\rm n}(x) + \bar{s}^{\rm n}(x)\right)dx$

Then, $S_G = \frac{1}{3} + \frac{8}{9}\int_0^1 \bar{u}^{\rm p}(x)dx + \frac{2}{9}\int_0^1 \bar{d}^{\rm p}(x)dx - \frac{8}{9}\int_0^1 \bar{u}^{\rm n}(x)dx - \frac{2}{9}\int_0^1 \bar{d}^{\rm n}(x)dx$

valence quarks + sea quarks

Deep inelastic scattering



Space-like virtual photon

Proton	**Neutron**
$\frac{8}{9}\int_0^1 \bar{u}^{\,\mathrm{p}}(x)dx$	$\frac{8}{9}\int_0^1 \bar{u}^{\,\mathrm{n}}(x)dx$
$\frac{2}{9}\int_0^1 \bar{d}^{\mathrm{p}}(x)dx$	$\frac{2}{9}\int_0^1 \bar{d}^{\mathrm{n}}(x)dx$

If we assume $\int_0^1 \bar{u}^{\,\mathrm{p}}(x)dx = \int_0^1 \bar{d}^{\mathrm{n}}(x)dx$**, and** $\int_0^1 \bar{d}^{\mathrm{p}}(x)dx = \int_0^1 \bar{u}^{\,\mathrm{n}}(x)dx$**,**

$S_G = \frac{1}{3} + \frac{2}{3}\left(\int_0^1 \bar{u}^{\,\mathrm{p}}(x)dx - \int_0^1 \bar{d}^{\mathrm{p}}(x)dx\right)$**,** **flavor symmetry or asymmetry**

P. Amaudruz et al., NMC, Phys. Rev. Lett. 66 (1991) 2712,

M. Arneodo et al., NMC, Phys. Rev. D50 (1994) R1.

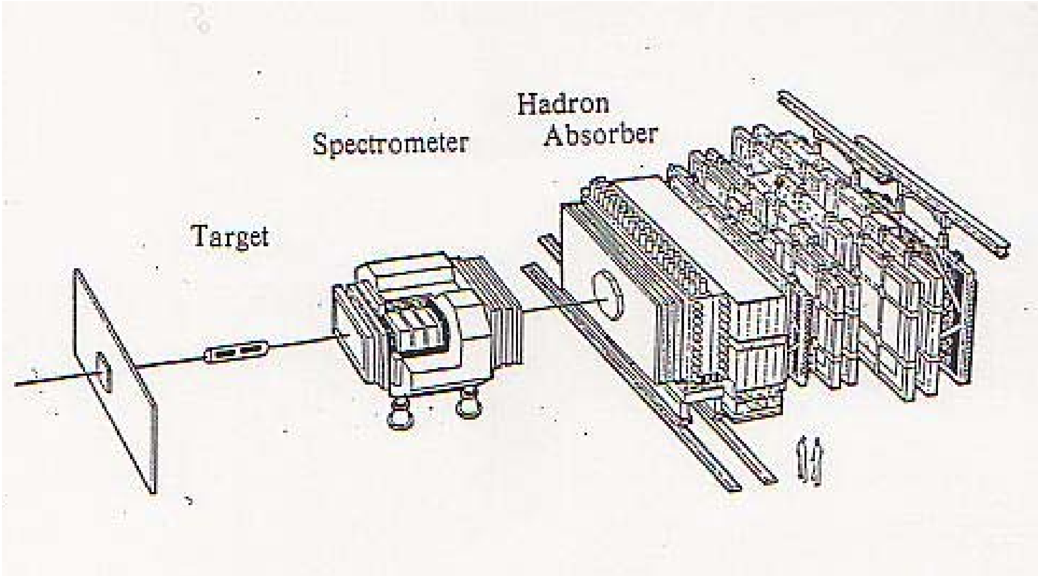
measured x range, 0.004 $< x <$ 0.8.

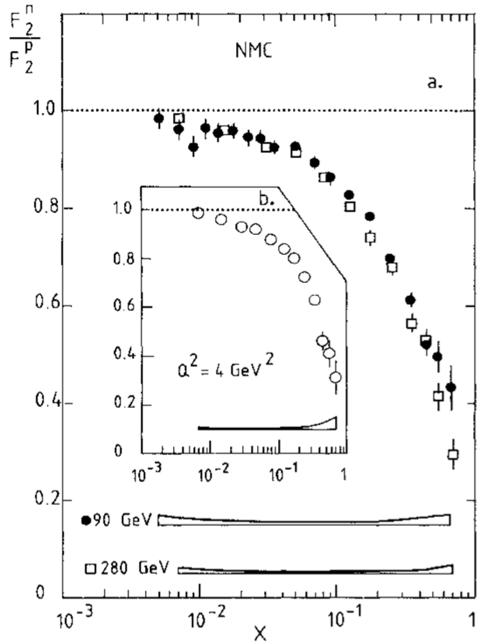
$$F_2^{\mathrm{p}}(x), \qquad F_2^{\mathrm{d}}(x) \approx F_2^{\mathrm{p}}(x) + F_2^{\mathrm{n}}(x).$$

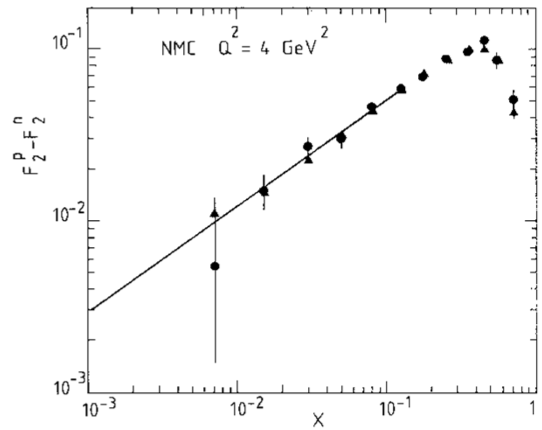
$$S_G = 0.235 \pm\ 0.026, \quad S_G < \frac{1}{3}, \quad \longrightarrow \quad \int_0^1 \bar{d}^{\,\mathrm{p}}(x)dx - \int_0^1 \bar{u}^{\,\mathrm{p}}(x)dx = 0.147 \pm 0.039,$$

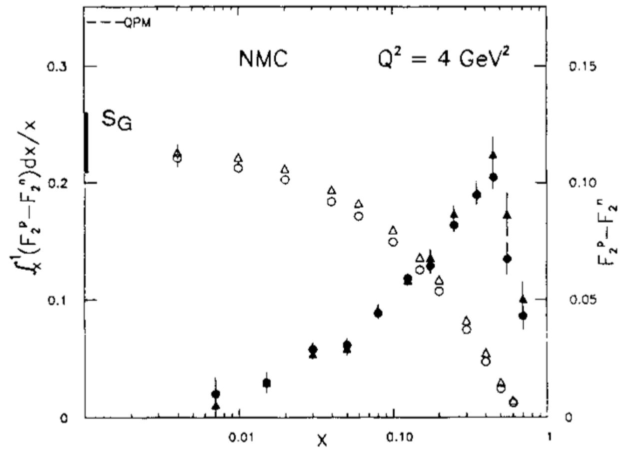
3.7σ **away from 0.**

flavor asymmety of sea quarks in the proton


Target
Spectrometer
Hadron
Absorber


F_2^n / F_2^p
NMC
a.
b.
$Q^2 = 4\ GeV^2$
●90 GeV
□ 280 GeV
X


NMC $Q^2 = 4\ GeV^2$
$F_2^p - F_2^n$
X


QPM
NMC
$Q^2 = 4\ GeV^2$
S_G
$\int_x^1 (F_2^p - F_2^n) dx/x$
$F_2^p - F_2^n$
X

3. Drell-Yan process

Drell-Yan process:

Feynman diagram is rotated by 90°, compared to the deep inelastic scattering.

An anti-quark is involved in each reaction event.

QCD higher order corrections in initial state

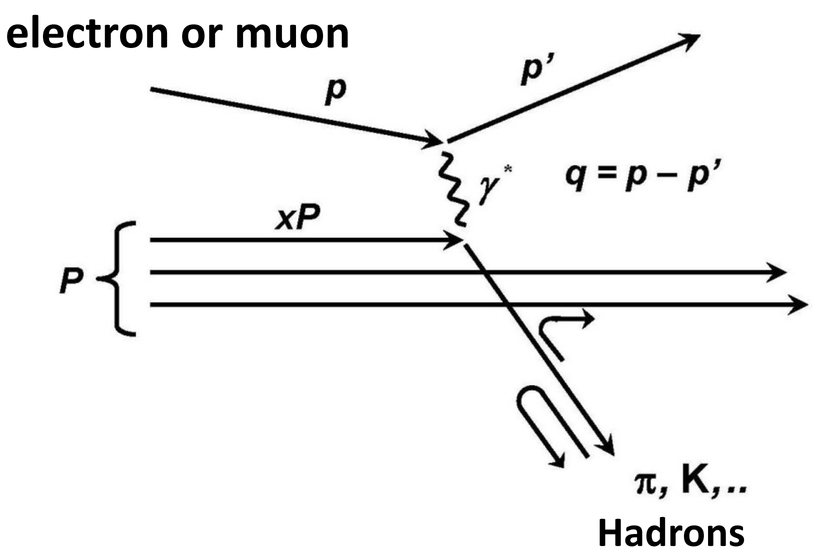
S.D. Ellis and W.J. Stirling, Phys. Lett. 256 (1991) 258.

$$\frac{d\sigma}{dx_b dx_t} = \frac{8\pi\alpha^2}{9\, s\, x_b\, x_t} \sum_f e_f^2 \left[q_f(x_b)\bar{q}_f(x_t) + \bar{q}_f(x_b)q_f(x_t)\right]$$

$$\frac{\sigma_{\rm pd}}{\sigma_{\rm pp}} \approx \frac{\sigma_{\rm pp}+\sigma_{\rm pn}}{\sigma_{\rm pp}} = 1 + \frac{\sigma_{\rm pn}}{\sigma_{\rm pp}} = 1 + \frac{\frac{4}{9}u^{\rm p}(x_b)\bar{u}^{\rm n}(x_t) + \frac{1}{9}d^{\rm p}(x_b)\bar{d}^{\rm n}(x_t) + \frac{1}{9}s^{\rm p}(x_b)\bar{s}^{\rm n}(x_t)}{\frac{4}{9}u^{\rm p}(x_b)\bar{u}^{\rm p}(x_t) + \frac{1}{9}d^{\rm p}(x_b)\bar{d}^{\rm p}(x_t) + \frac{1}{9}s^{\rm p}(x_b)\bar{s}^{\rm p}(x_t)} \approx 1 + \frac{\bar{u}^{\rm n}(x_t)}{\bar{u}^{\rm p}(x_t)} = 1 + \frac{\bar{d}^{\rm p}(x_t)}{\bar{u}^{\rm p}(x_t)}$$

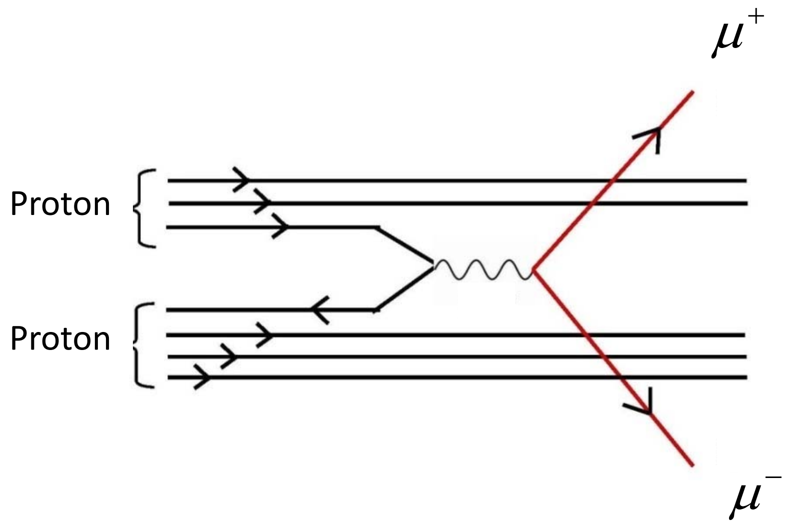
Proton beam is almost u quark beam for Drell-Yan process.

Deep inelastic scattering



Space-like virtual photon

Drell-Yan process



Time-like virtual photon

Proton beam:

450 GeV - NA51,

800 GeV - E866/NuSea,

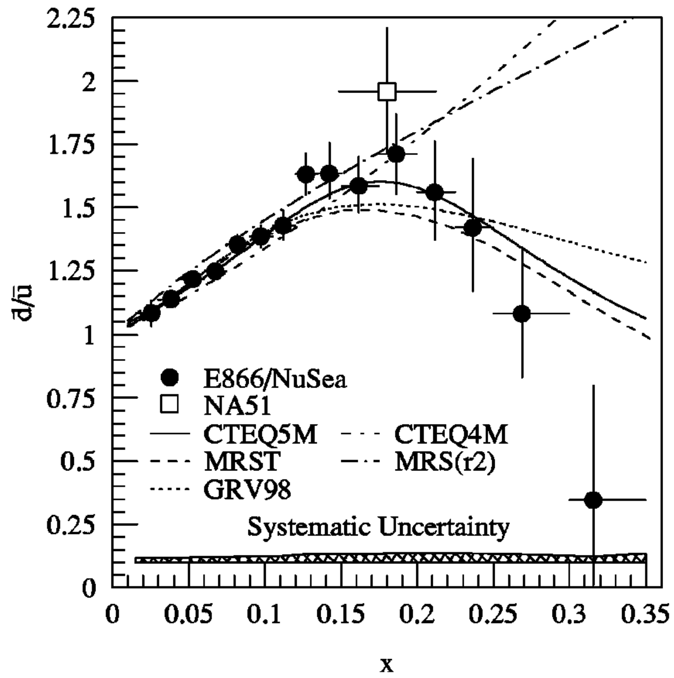
120 GeV - E906/SeaQuest

E866/NuSea, R.S. Towell et al., Phys. Rev. D64 (2001) 052002

measured x range, $0.015 < x < 0.35$,

$$\int_0^1 \bar{d}(x)dx - \int_0^1 \bar{u}(x)dx = 0.118 \pm 0.012$$ **at an average scale of 54 GeV^2.**

E866/NuSea



2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
d̄/ū
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
x
E866/NuSea
NA51
CTEQ5M
CTEQ4M
MRST
MRS(r2)
GRV98
Systematic Uncertainty

$F_2^{\mathrm{p}}(x)$ **can be extended to small** x **with HERA e+p data.**

$F_2^{\mathrm{d}}(x)$ **will be extended to small** x **with EIC.**

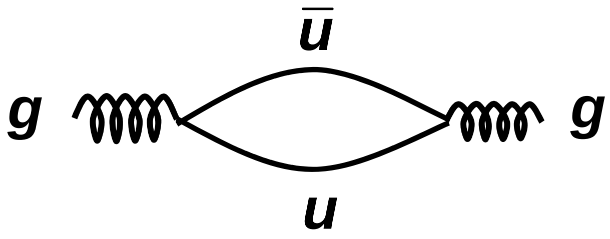
The moments of PDFs are important for

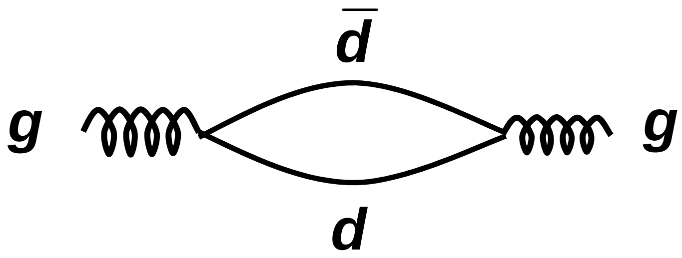
number of sea quarks,

momentum fractions carried by quarks, etc.

Origin of sea quarks

Gluon splitting





Hadronic effects

$|\mathbf{P}\rangle = \alpha\ |p\rangle + \beta\ |n\pi^{+}\rangle + \gamma\ |p\pi^{0}\rangle$

$u\bar{d}$ $\quad u\bar{u} - d\bar{d}$

Valence quarks and sea quarks in the proton:

In atomic physics, an atom consists of electrons in closed shells (0^+) + valence electrons.

In nuclear physics, a nucleus consists of nucleons in closed shells (0^+) + valence nucleons.

In hadron physics, closed shells of sea quarks do not exist. There is no symmetry which requires that sea quarks should form 0^+ closed shells.

$\longrightarrow$ **sea quarks can carry a part of quantum numbers such as spin, though the flavor numbers are carried by valence quarks.**

The meaning of 'valence' is differenct in hadron physics, compared to atomic and nuclear physics.

4. Summary

• Flavor asymmetry of sea quarks in the proton was presented with focus on the first moments.

• The Gottfried sum was evaluated from $F_2(x)$ of proton and deuteron measured by deep inelastic scattering

• The value is significantly smaller than the expected value of $\frac{1}{3}$, indicating flavor asymmety of sea quarks in the proton

• The first moment is expected to become further precise with deuteron data at small x in future.

• From Drell-Yan experiments, $\frac{\bar{d}(x)}{\bar{u}(x)}$ was extracted as a function of x. These data show the flavor asymmetry.

• p+p collisions with $W^{\pm}$ production etc. are being used to extract $\bar{d}(x) - \bar{u}(x)$.

• Origin of flavor asymmetry of sea quarks, and origin of sea quarks are important subjects of QCD.