Flavor-dependent antiquark distributions in the nucleons and nuclei

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Workshop INT-17-68W, The Flavor Structure of Nucleon Sea
October 2 - 13, 2017, University of Washington, Seattle, USA
http://www.int.washington.edu/PROGRAMS/17-68W/

October 2, 2017

Contents

Introduction

- ubar/dbar asymmetry

Flavor dependence of nucleonic and nuclear PDFs

- Unpolarized antiquark distributions in the nucleon
- Unpolarized antiquark distributions in nuclei Skip some pages
- Longitudinally-polarized antiquark distributions
- Transversity distributions in pd Drell-Yan
- Tensor-polarized PDFs of spin-1 deuteron
- Strange-quark distribution Skip some pages

Summary

Introduction

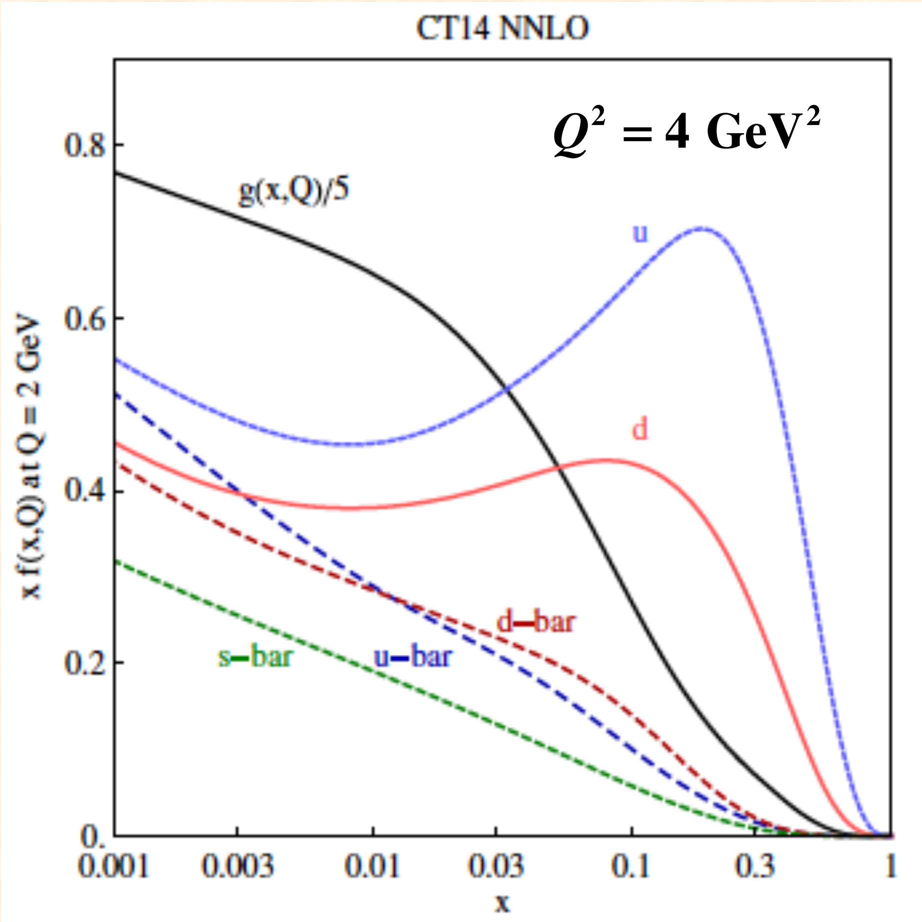
Summary articles

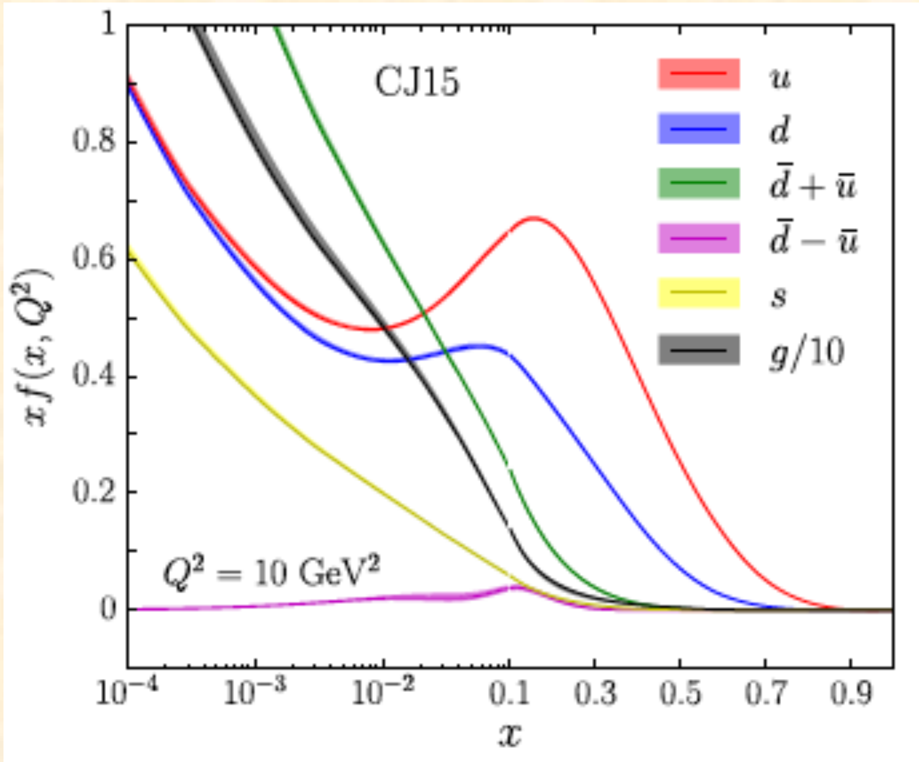
J. Speth and A. W. Thomas, Adv. Nucl. Phys. 24 (1997) 83;
P. L. McGaughey, J. M. Moss, J. C. Peng, Annu. Rev. Nucl. Part. Sci. 49 (1999) 217;
G. T. Garvey and J.-C. Peng, Prog. Part. Nucl. Phys. 47, 203 (2001);
J.-C. Peng and J.-W. Qiu, Prog. Part. Nucl. Phys. 76, 43 (2014).

S. Kumano, Phys. Rept. 303 (1998) 183.

Contents

Recent Parton Distribution Functions (PDFs)





$Q^2 = 10$ GeV^2

Gottfried sum rule and NMC measurement

$$S_G = \int_0^1 \frac{dx}{x}\left[F_2^{\mu p}(x) - F_2^{\mu n}(x)\right]$$
$$= \frac{1}{3} + \frac{2}{3}\int_0^1 dx\left[\bar{u}(x) - \bar{d}(x)\right]$$
$$= \frac{1}{3} \quad \text{if } \bar{u} = \bar{d}$$

(Gottfried sum rule)

$$F_2^{\mu p}(x)_{\text{LO}} = x\left[\frac{4}{9}\{u(x)+\bar{u}(x)\} + \frac{1}{9}\{d(x)+\bar{d}(x)\} + \frac{1}{9}\{s(x)+\bar{s}(x)\}\right]$$

$$F_2^{\mu n}(x)_{\text{LO}} = x\left[\frac{4}{9}\{u(x)+\bar{u}(x)\} + \frac{1}{9}\{d(x)+\bar{d}(x)\} + \frac{1}{9}\{s(x)+\bar{s}(x)\}\right]_n$$
$$= x\left[\frac{4}{9}\{d(x)+\bar{d}(x)\} + \frac{1}{9}\{u(x)+\bar{u}(x)\} + \frac{1}{9}\{s(x)+\bar{s}(x)\}\right]$$

$$\frac{1}{x}\left[F_2^{\mu p}(x)_{\text{LO}} - F_2^{\mu n}(x)_{\text{LO}}\right] = \frac{3}{9}\{u(x)+\bar{u}(x)\} - \frac{3}{9}\{d(x)+\bar{d}(x)\}$$

$$\int_0^1 \frac{dx}{x}\left[F_2^{\mu p}(x)_{\text{LO}} - F_2^{\mu n}(x)_{\text{LO}}\right] = \int_0^1 dx\left[\frac{1}{3}\{u_v(x)+2\bar{u}(x)\} - \frac{1}{3}\{d_v(x)+2\bar{d}(x)\}\right]$$
$$= \frac{2}{3} - \frac{1}{3} + \frac{2}{3}\int_0^1 dx\left[\bar{u}(x) - \bar{d}(x)\right]$$

NMC measurement

PRL 66 (1991) 2712; PRD 50 (1994) R1

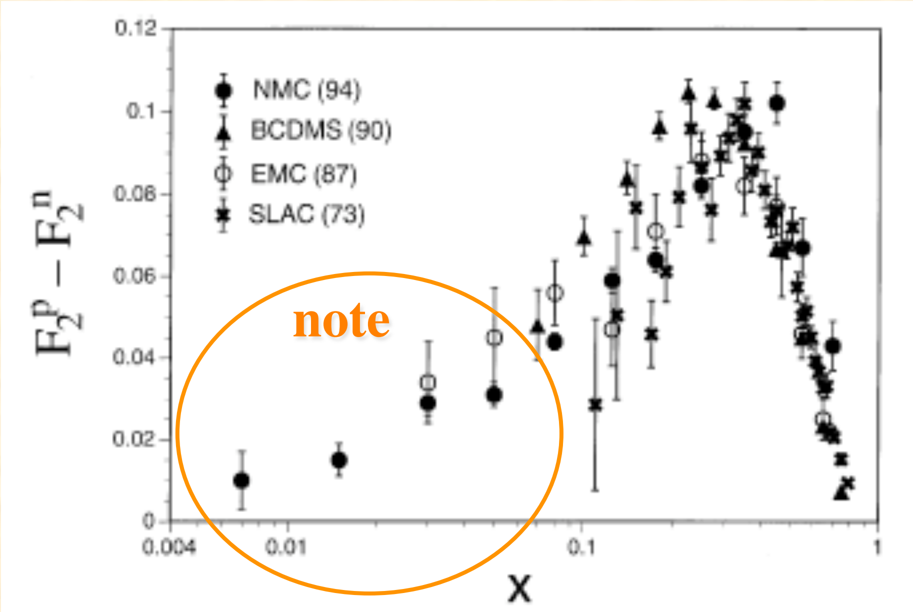
$$\int_{0.004}^{0.8} \frac{dx}{x}\left[F_2^{\mu p}(x) - F_2^{\mu n}(x)\right] = 0.221 \pm 0.008 \pm 0.019$$

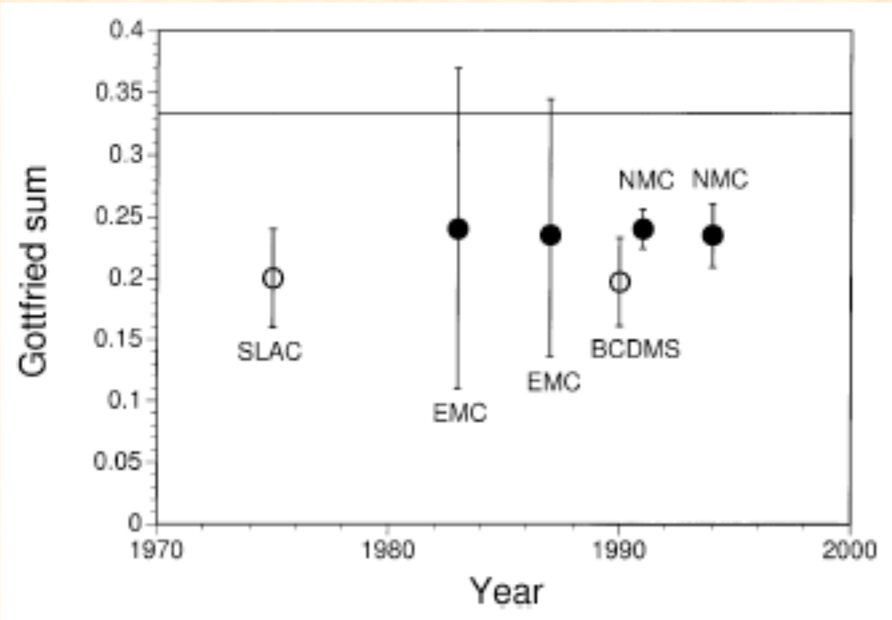
Extrapolating the NMC data, they obtained

$$S_G = 0.235 \pm 0.026$$

30% is missing! $\Rightarrow$ $\bar{u} < \bar{d}$?

Experimental measurements before Fermilab Drell-Yan





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

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

$$\int_{0.004}^{0.8} \frac{dx}{x}\left[F_2^{\mu p}(x) - F_2^{\mu n}(x)\right] = 0.221 \pm 0.008 \pm 0.019$$

$$S_G = 0.235 \pm 0.026$$

NMC: small-x measurements

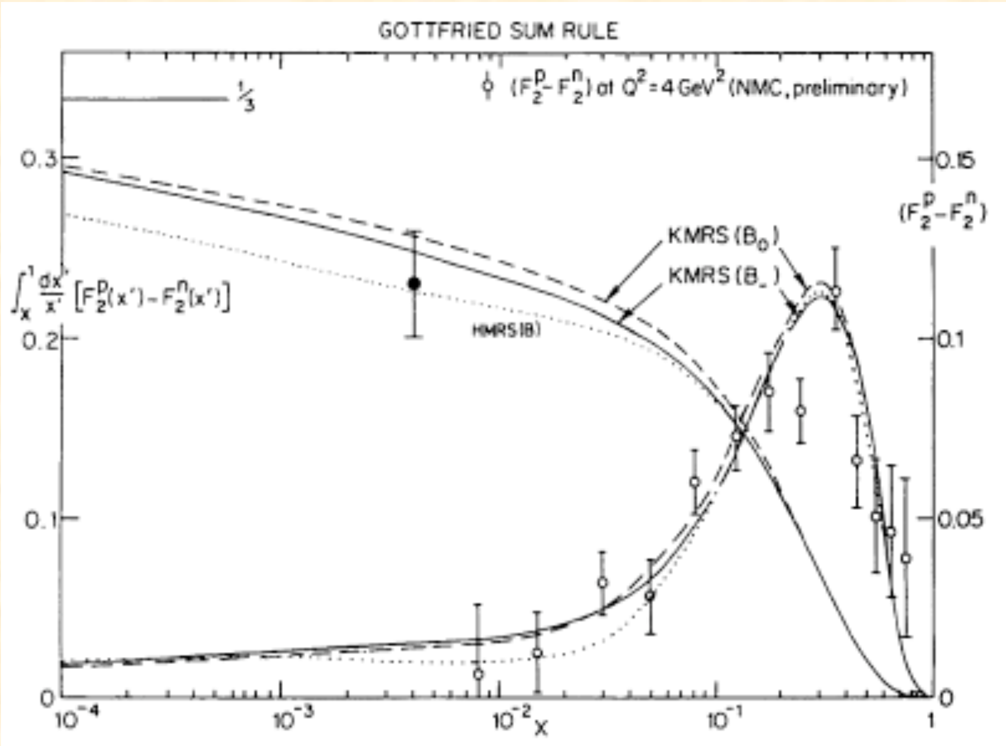
Integral in a measured x-region without x-extrapolation

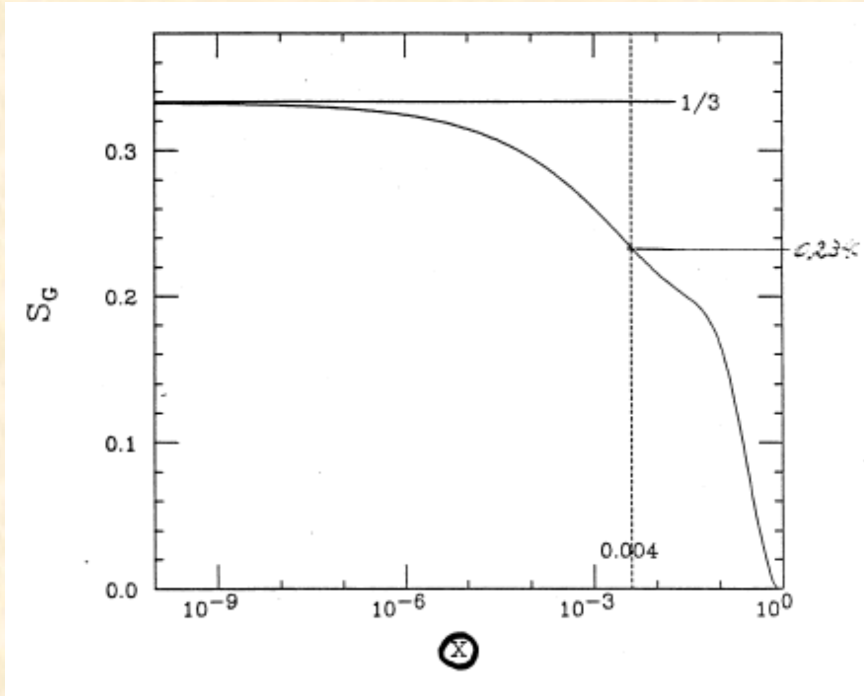
Integral with x-extrapolation

Could the NMC result be explained by $\bar{u} = \bar{d}$?

$$S_G(x) = \frac{1}{3}\int_x^1 dx'\left[u_v(x') - d_v(x')\right]$$

A significant contribution from the small-*x* region???



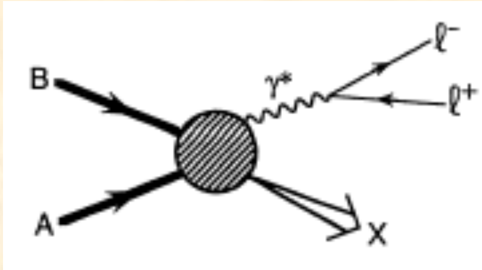


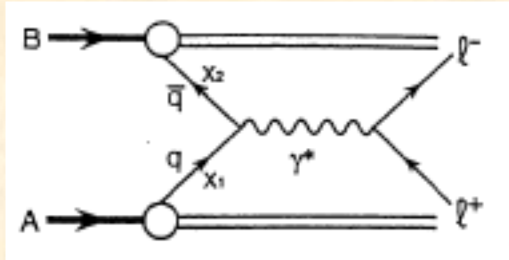
This idea ($\bar{u} = \bar{d}$) was ruled out by
Fermilab E772/E866, NA51, and HERMES.

CERN-NA51 Drell-Yan, PL B332 (1994) 244

$$\frac{\bar{u}}{\bar{d}} = 0.51 \pm 0.04(\text{stat.}) \pm 0.05(\text{syst.}) \quad x = 0.18$$

Drell-Yan process





$$d\sigma^{AB} \propto \sum_i e_i^2 \left[q_i^A(x_1,q^2)\bar{q}_i^B(x_2,q^2) + \bar{q}_i^A(x_1,q^2) q_i^B(x_2,q^2) \right] \qquad q^2 = m_{\mu\mu}^2$$

$$d\sigma^{pp} \propto \frac{4}{9}\left[u(x_1)\bar{u}(x_2)+\bar{u}(x_1)u(x_2)\right]+\frac{1}{9}\left[d(x_1)\bar{d}(x_2)+\bar{d}(x_1)d(x_2)\right]+\frac{1}{9}\left[s(x_1)\bar{s}(x_2)+\bar{s}(x_1)s(x_2)\right]$$

$$d\sigma^{pn} \propto \frac{4}{9}\left[u(x_1)\bar{d}(x_2)+\bar{u}(x_1)d(x_2)\right]+\frac{1}{9}\left[d(x_1)\bar{u}(x_2)+\bar{d}(x_1)u(x_2)\right]+\frac{1}{9}\left[s(x_1)\bar{s}(x_2)+\bar{s}(x_1)s(x_2)\right]$$

At large $x_F = x_1 - x_2 \ (x_1 \to 1,\ x_2 \to 0)$

$$\bar{u}(x_1),\ \bar{d}(x_1),\ \bar{s}(x_1) \ll u(x_1),\ d(x_1) \to u_v(x_1),\ d_v(x_1)$$

$$d\sigma^{pp} - d\sigma^{pn} \propto \frac{4}{9}\left[u_v(x_1)\left\{\bar{u}(x_2)-\bar{d}(x_2)\right\}\right]-\frac{1}{9}\left[d_v(x_1)\left\{\bar{u}(x_2)-\bar{d}(x_2)\right\}\right]$$

$$d\sigma^{pp} + d\sigma^{pn} \propto \frac{4}{9}\left[u_v(x_1)\left\{\bar{u}(x_2)+\bar{d}(x_2)\right\}\right]+\frac{1}{9}\left[d_v(x_1)\left\{\bar{u}(x_2)+\bar{d}(x_2)\right\}\right]+\cancel{\frac{2}{9}\left[s(x_1)\bar{s}(x_2)\right]}$$

$$A_{DY} = \frac{d\sigma^{pp} - d\sigma^{pn}}{d\sigma^{pp} + d\sigma^{pn}} \to \frac{\left\{4u_v(x_1) - d_v(x_1)\right\}\left\{\bar{u}(x_2)-\bar{d}(x_2)\right\}}{\left\{4u_v(x_1) + d_v(x_1)\right\}\left\{\bar{u}(x_2)+\bar{d}(x_2)\right\}} \quad \text{at large } x_F$$

$\boxed{\bar{u} - \bar{d} \text{ determination}}$

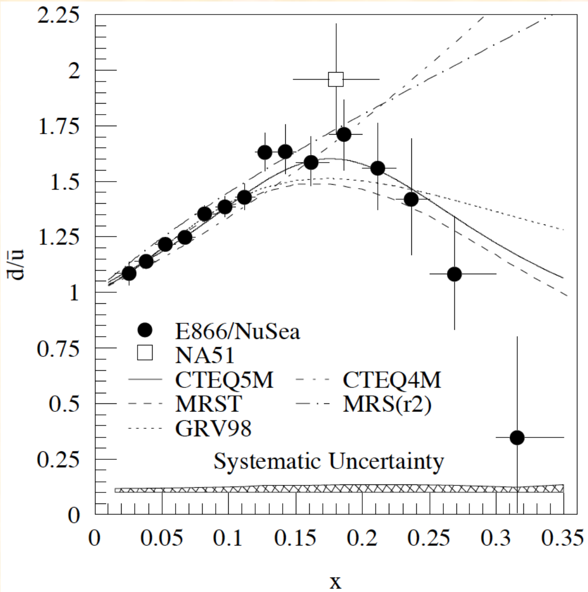
Roughly, $\dfrac{2\sigma^{pd}}{\sigma^{pp}} \sim 1 + \dfrac{1}{2}\left[\dfrac{\bar{d}(x_2)}{\bar{u}(x_2)} - 1\right]$ at large x_F

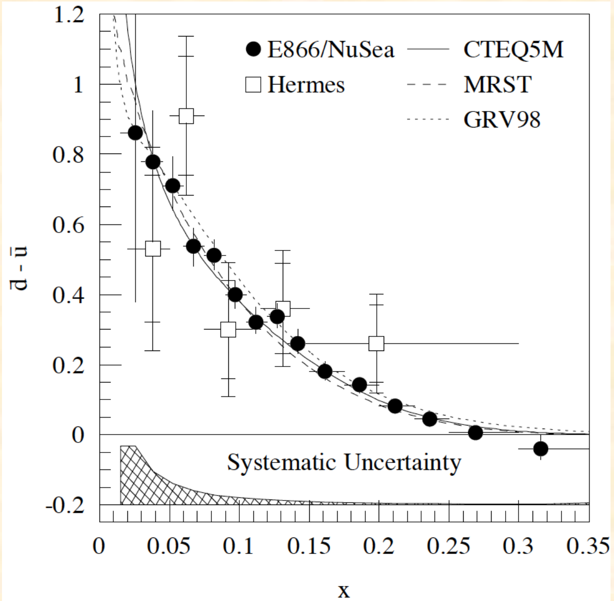
Drell-Yan and semi-inclusive DIS

(E866) E. A. Hawker et al., PRL 80 (1998) 3715 ;
R. S. Towell et al., PR D 64 (2001) 052002.
(HERMES) K. Ackerstaff et al., PRL 81, (1998) 5519.

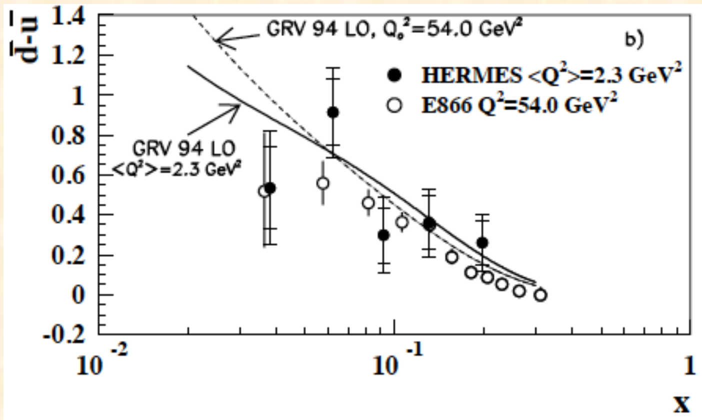
Fermilab E866, NA51, HERMES data

[From PRD 64 (2001) 052002]





[From PRL 81 (1998) 5519]



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

- unpolarized: established
- polarized: not well unknown

semi-inclusive (HERMES) + RHIC W production + …

theory

(1) perturbative QCD

(2) nonperturbative

meson clouds, chiral soliton, Pauli exclusion, …

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

Perturbative QCD contribution to $\bar{u} / \bar{d}$

$$\frac{\partial}{\partial(\ln Q^2)} q^{\pm}(x,Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y} P_{q^{\pm}}\left(\frac{x}{y}\right) q^{\pm}(y,Q^2) \quad \text{(+ gluon term)}$$

$$q^{\pm} = q \pm \bar{q}, \quad P_{q^{\pm}} = P_{qq} \pm P_{q\bar{q}} \qquad \bar{q} = (q^+ - q^-)/2$$

$$\frac{\partial}{\partial(\ln Q^2)}\left[\bar{u}(x,Q^2) - \bar{d}(x,Q^2)\right] = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right)\left\{\bar{u}(y,Q^2) - \bar{d}(y,Q^2)\right\} + P_{\bar{q}q}\left(\frac{x}{y}\right)\left\{u(y,Q^2) - d(y,Q^2)\right\}\right]$$

$$P_{\bar{q}q} = 0 \ \text{ in LO}$$
$$\neq 0 \ \text{ in NLO}$$

Therefore, $\left(\bar{u} - \bar{d}\right)_{pQCD} = 0$ in LO

$\neq 0$ in NLO

$$\left(\bar{u} - \bar{d}\right)_{pQCD} \ll \left(\bar{u} - \bar{d}\right)_{nonperturbative}$$

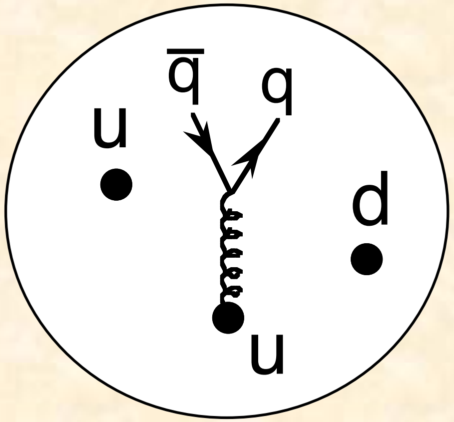
Of course, it depends on the initial scale for the evolution.

$\bar{u}/\bar{d}$ could be an appropriate quantity for testing nonperturbative aspects.

Nonperturbative mechanisms for the $\Delta\bar{u}_T / \Delta\bar{d}_T$ asymmetry

- Virtual meson clouds
- Pauli exclusion principle
- ...

Pauli exclusion principle (unpolarized)



2 (spin) × 3 (color) = 6 states

- 2 of 6 states are occupied for u-quark
- 1 of 6 for d-quark

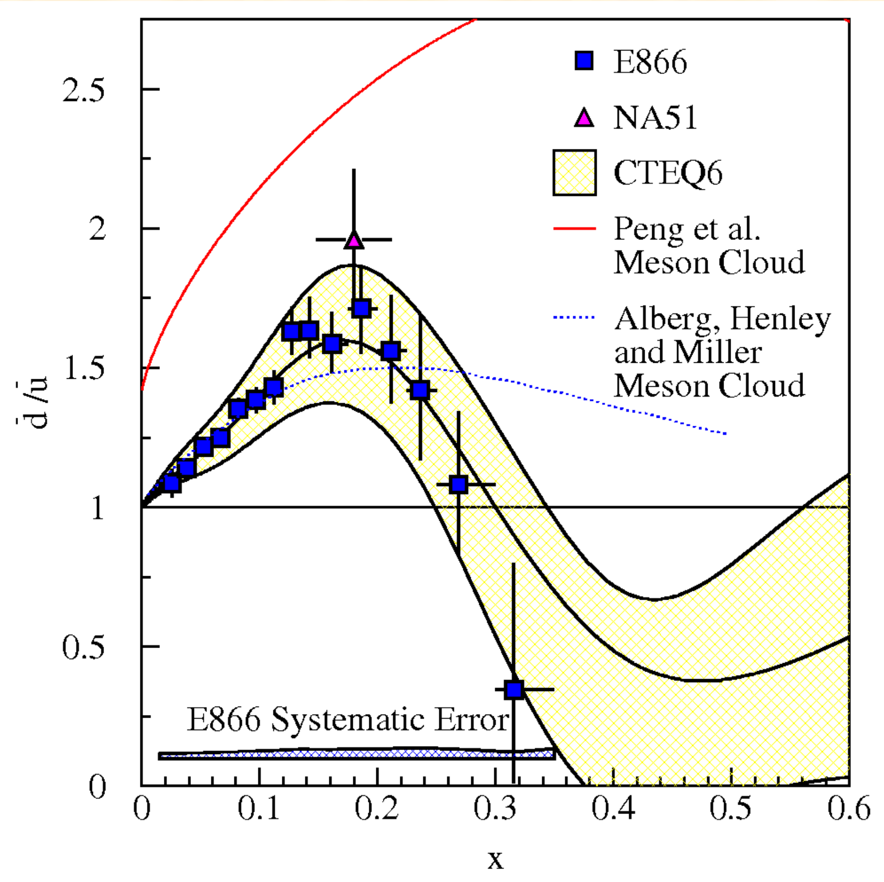
4 u-quarks and 5 d-quarks can be accommodated.

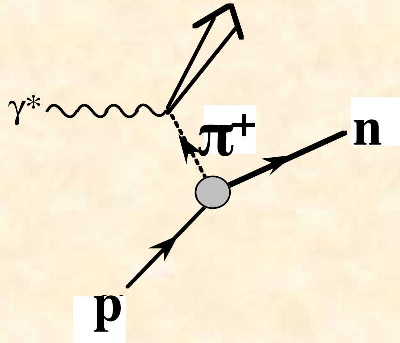
↓

naive counting estimate: $\bar{u} / \bar{d} = 4/5$

Meson clouds ⇔ Drell-Yan data

P. E. Reimer, talks at J-PARC and Riken workshops (2008)





+ other terms

It is difficult to explain

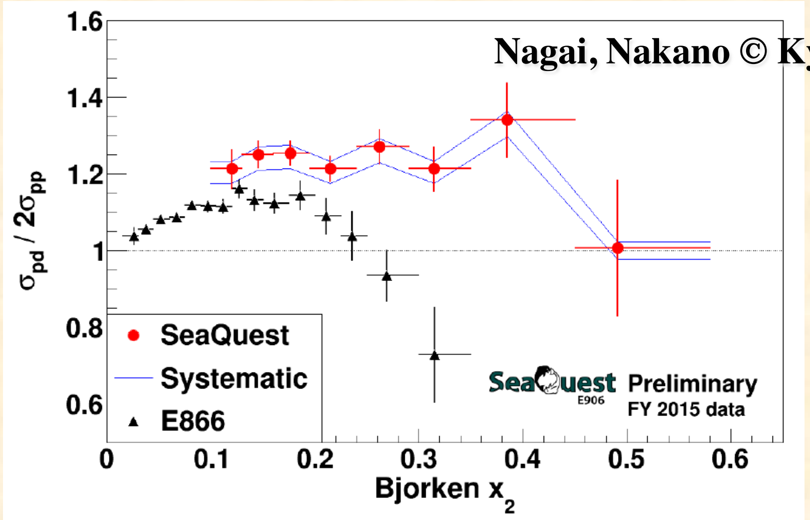
$$\frac{\bar{d}}{\bar{u}} \rightarrow 1 \text{ or } < 1 \text{ at } x > 0.26.$$

Flavor dependence of antiquark distributions

Gottfried sum: $S_G = \int_0^1 \frac{dx}{x}\left[F_2^{\mu p}(x) - F_2^{\mu n}(x)\right] = \frac{1}{3} + \frac{2}{3}\int_0^1 dx\left[\bar{u}(x) - \bar{d}(x)\right]$

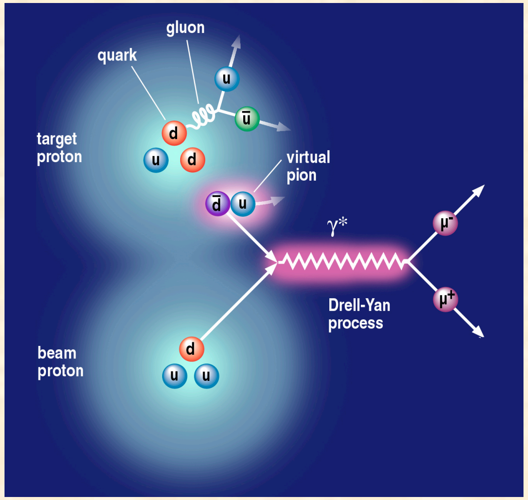
$S_G(\text{experiment}) = 0.235 \pm 0.026$

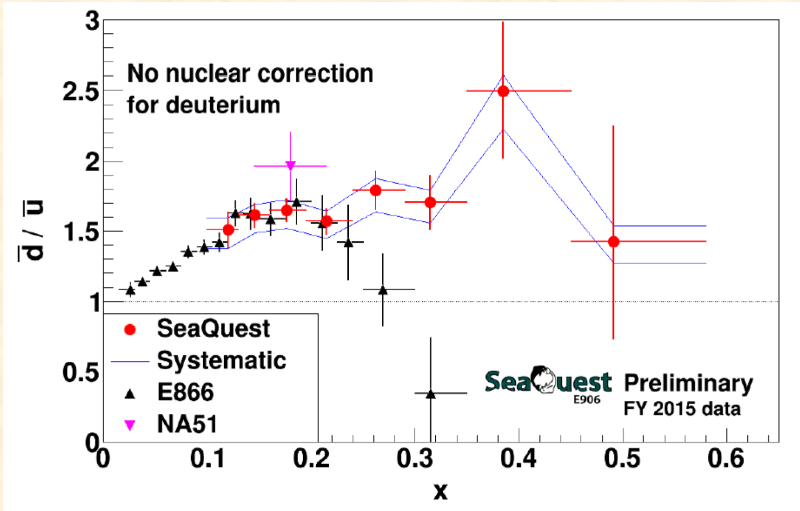
Nagai, Nakano © Kyoto, 2016



Fermilab-MI-E906

$$\frac{2\sigma^{pd}}{\sigma^{pp}} \sim 1 + \frac{1}{2}\left[\frac{\bar{d}(x_2)}{\bar{u}(x_2)} - 1\right] \text{ at large } x_F$$





Our theoretical studies

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

References:

SK, PRD 43 (1991) 59 & 3067

SK and J. T. Londergan, PRD 44 (1991) 717; 46 (1992) 457

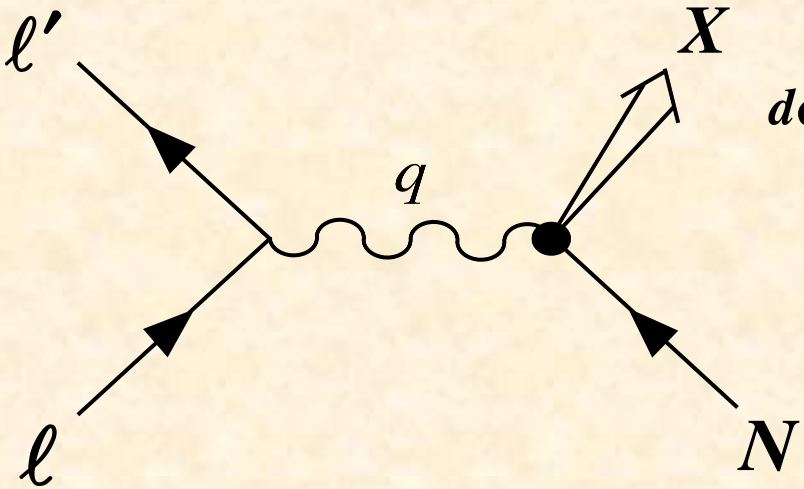
SK, Phys. Rep. 303 (1998) 183.

See also similar works by

Alberg, Miller, Peng, and workshop participants, …

Skip most pages

Cross section for $e + p \to e' + X$



$$d\sigma = \frac{1}{4\sqrt{(k\cdot p)^2 - m^2 M_N^2}} \times \overline{\sum_{pol}} \sum_X (2\pi)^4 \delta^4(k + p - k' - p_X)\, |M|^2 \frac{d^3k'}{(2\pi)^3 2E'}$$

$$M = e\,\bar{u}(k',\lambda')\,\gamma_\mu\, u(k,\lambda)\, \frac{g^{\mu\nu}}{q^2}\, \langle X | e J_\nu^{em}(0) | p, \lambda_N \rangle$$

$$\frac{d\sigma}{dE'_\ell d\Omega'_\ell} = \frac{E'_e}{E_e} \frac{\alpha^2}{(Q^2)^2} L^{\mu\nu} W_{\mu\nu}$$

Lepton tensor: $L^{\mu\nu} = \overline{\sum_{\lambda,\lambda'}} \left[\bar{u}(k',\lambda')\,\gamma^\mu\, u(k,\lambda)\right]^* \left[\bar{u}(k',\lambda')\,\gamma^\nu\, u(k,\lambda)\right]$

$$= 2\left[k^\mu k'^\nu + k'^\mu k^\nu - (k\cdot k' - m^2) g^{\mu\nu}\right]$$

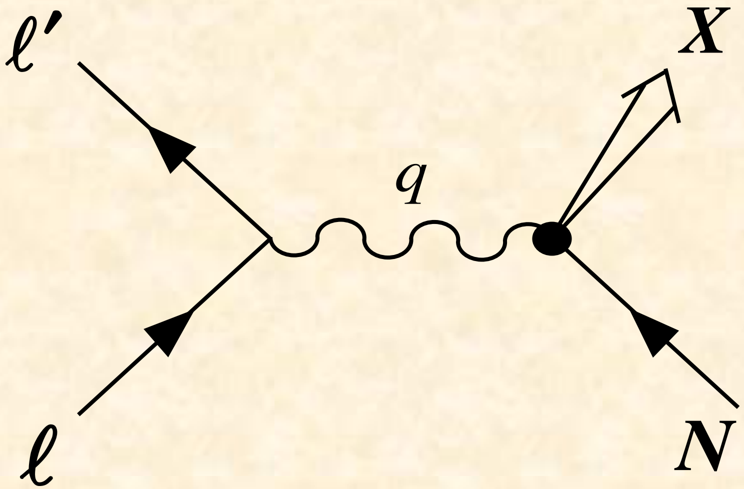
Hadron tensor: $W_{\mu\nu} = \frac{1}{4\pi M_N} \overline{\sum_{\lambda_N}} \sum_X (2\pi)^4 \delta^4(p + q - p_X)\, \langle p,\lambda_N | J_\mu^{em}(0) | X \rangle \langle X | J_\nu^{em}(0) | p, \lambda_N \rangle$

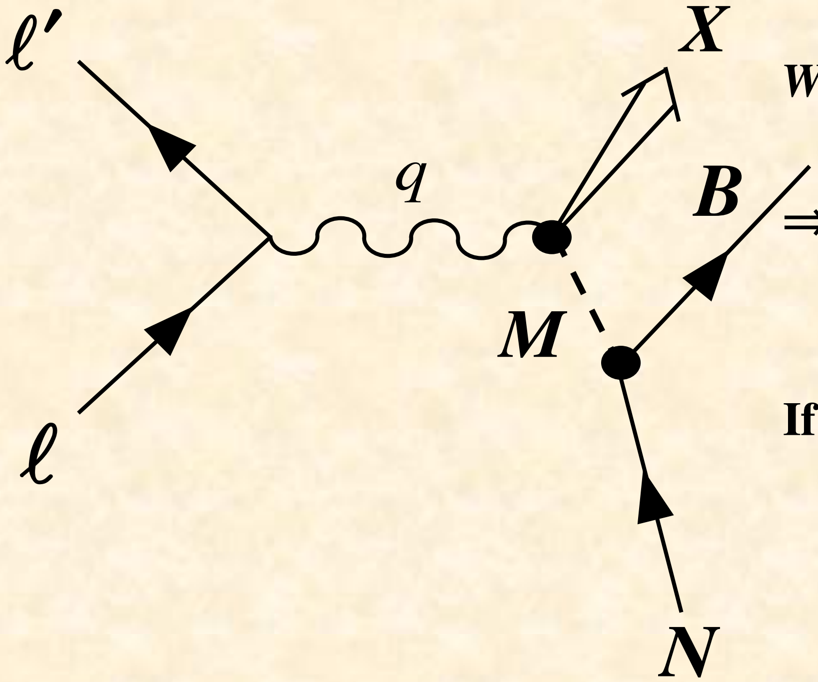
$$= \frac{1}{4\pi M_N} \overline{\sum_{\lambda_N}} \int d^4\xi\, e^{iq\cdot\xi} \langle p,\lambda_N | \left[J_\mu^{em}(\xi), J_\nu^{em}(0)\right] | p, \lambda_N \rangle$$

Mesonic contributions to $\bar{u}-\bar{d}$

$$\frac{d\sigma}{dE'_\ell d\Omega'_\ell}=\frac{E'_e}{E_e}\frac{\alpha^2}{(Q^2)^2}L^{\mu\nu}W_{\mu\nu}$$

$$L^{\mu\nu}=2\left[k^\mu k'^\nu+k'^\mu k^\nu-(k\cdot k'-m^2)g^{\mu\nu}\right]$$





For example, $B=N,\ M=\pi$

$$M=e\,\bar{u}(k',\lambda')\gamma_\mu u(k,\lambda)\frac{g^{\mu\nu}}{q^2}\left\langle X\right|eJ_\nu^{em}(0)\left|p_\pi\right\rangle$$

$$\times\frac{1}{t-m_\pi^2}ig_{\pi NN}F_{\pi NN}(t)\bar{u}(p_{N'})\gamma_5 u(p_N)$$

$$W_{\mu\nu}^{(N)}(p_N,q)=\int\frac{d^3p_{N'}}{(2\pi)^3}\frac{m_N}{E'_N}\frac{g_{\pi NN}^2}{4m_N^2}\frac{-t}{(t-m_\pi^2)^2}\left[F_{\pi NN}(t)\right]^2W_{\mu\nu}^{(\pi)}(p_\pi,q)$$

$$\Rightarrow x\bar{q}_N(x,Q^2)=\int_x^1 dy\, f_\pi^{\pi NN}(y)\frac{x}{y}\bar{q}_\pi(x/y,Q^2)$$

$$f_\pi^{\pi NN}(y)=\left|\phi_\pi\cdot\tau\right|^2\frac{g_{\pi NN}^2}{16\pi^2}y\int dt\frac{-t}{(-t+m_\pi^2)^2}\left[F_{\pi NN}(t)\right]^2$$

If $B=\Delta,\ M=\pi$

$$f_\pi^{\pi N\Delta}(y)=\left|\phi_\pi\cdot T\right|^2\frac{g_{\pi N\Delta}^2}{24\pi^2(2m_N)^2}y\int dt\frac{1}{(-t+m_\pi^2)^2}\left[F_{\pi N\Delta}(t)\right]^2$$

$$\times\left[(m_N+m_\Delta)^2-t\right]\left[\frac{(m_N^2-m_\Delta^2-t)^2}{4m_\Delta^2}-t\right]$$

Flavor asymmetric antiquark distributions

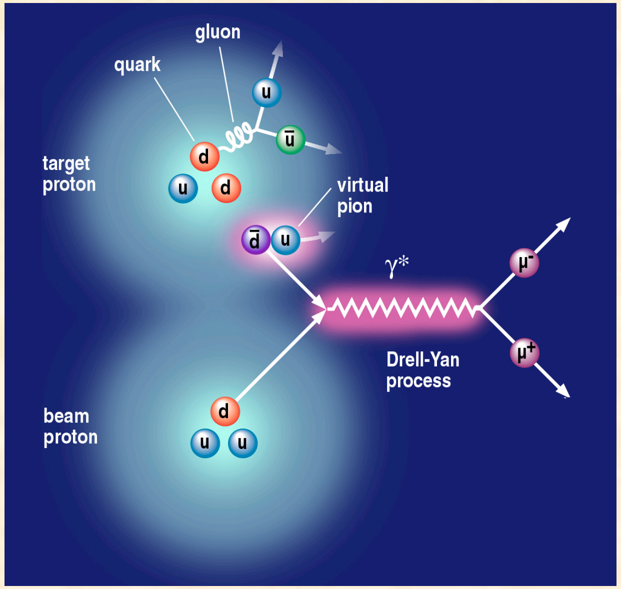
$\Rightarrow$ Nonperturbative QCD mechanisms (mesonic effects, . . .)

Consider the distributions $\bar{u}-\bar{d},\ \dfrac{\bar{u}+\bar{d}}{2}-\bar{s}$.

Perturbative QCD effects should be flavor symmetric for $\bar{u},\ \bar{d},\ \bar{s}$.

Then, $\bar{u}-\bar{d},\ \dfrac{\bar{u}+\bar{d}}{2}-\bar{s}$ **= created by non-perturbative mechanism(s)**

$\Rightarrow$ **One of candidates is the contribution from mesons.**



(from E866 web page)

theory experiment

$$x\bar{q}_N(x) = \int_x^1 dy\, f_\pi(y)\frac{x}{y}\bar{q}_\pi(x/y)$$

We may study $\bar{q}_N$ **at** $x \sim 0.15$.

$f_\pi(y)$ **is peaked at** $y \sim 0.25$.

$\Rightarrow \bar{q}_\pi(x/y \sim 0.6) \simeq V_\pi$ **(valence in** π**)**

First, we investigate $\dfrac{\bar{u}+\bar{d}}{2}-\bar{s}$ for testing our model and fixing a parameter

- **Pion structure function**

  Measurements of pion Drell-Yan (NA3, NA10, E615): $\dfrac{x(\bar{u}+\bar{d})}{2}-x\bar{s}=\dfrac{1}{2}xV_\pi$

- **πNN form factor**

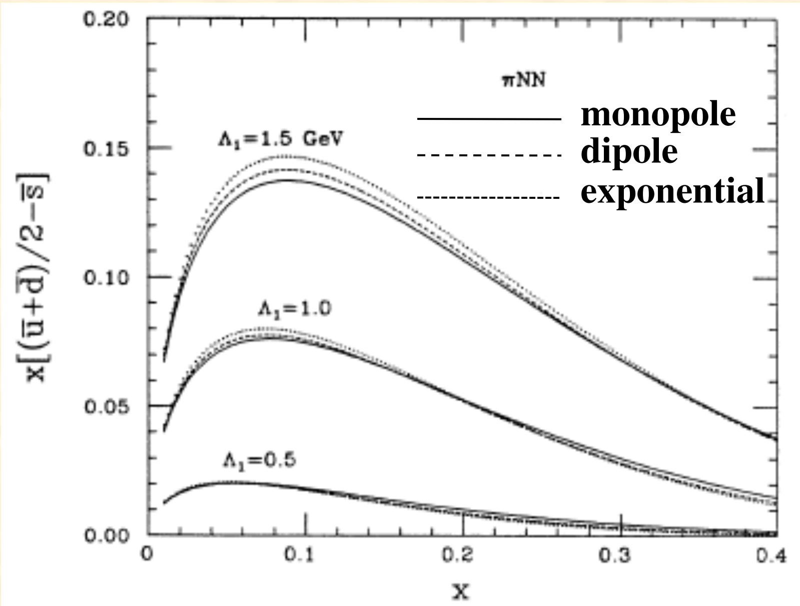
  $$F^{(1)}_{\pi NN}(t)=\frac{1}{1-t/(\Lambda_1)^2},\quad F^{(2)}_{\pi NN}(t)=\frac{1}{\left[1-t/(\Lambda_1)^2\right]^2},\quad F^{(0)}_{\pi NN}(t)=e^{-(-t)/(\Lambda_0)^2}$$

  Relation among the cutoff parameters

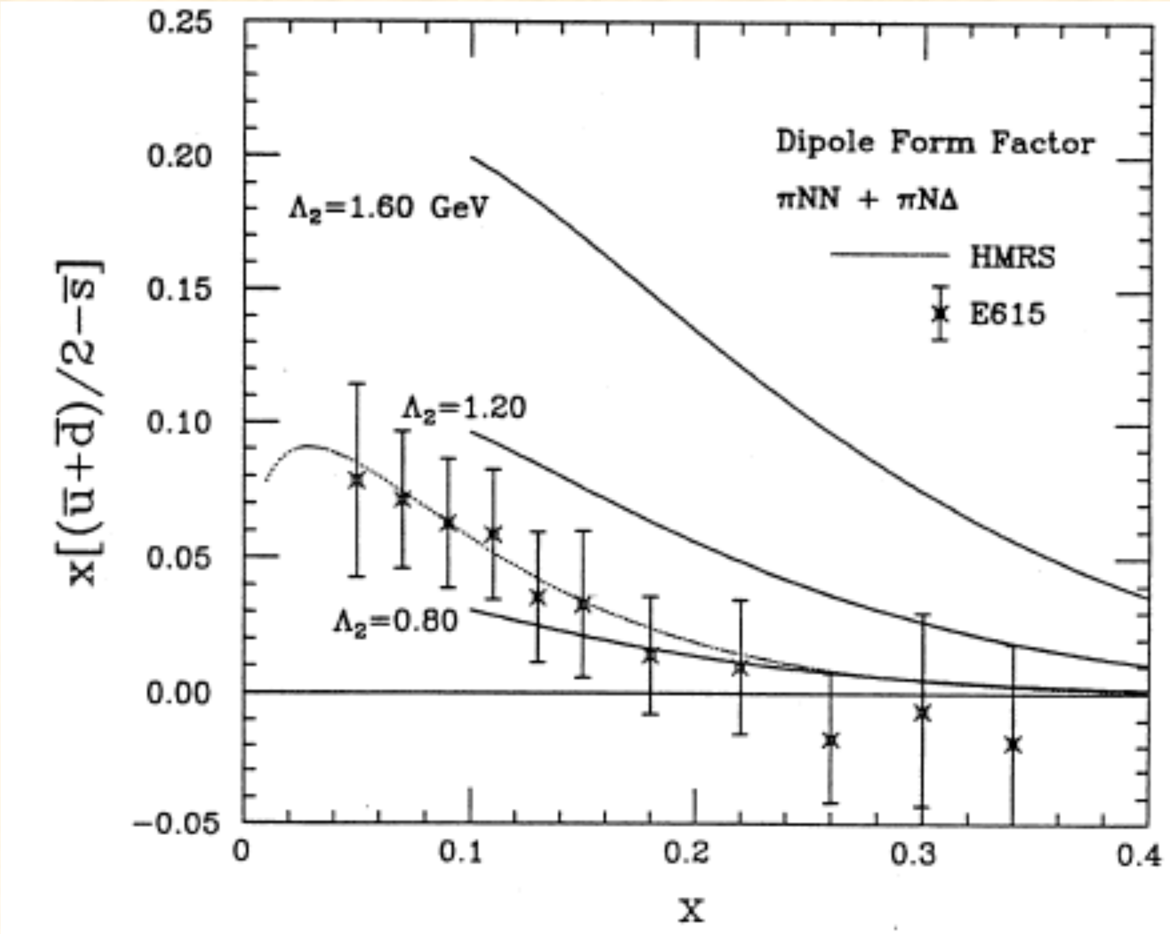
  $e.g.$ **if related by**

  $$F^{(1)}_{\pi NN}(t_0)=F^{(2)}_{\pi NN}(t_0)=F^{(0)}_{\pi NN}(t_0)=0.4$$

  $$\Rightarrow\ \Lambda_1=0.62\Lambda_2=0.78\Lambda_0$$



Fix πNN/πNΔ cutoff parameter Λ_2 by $\dfrac{\bar{u}+\bar{d}}{2}-\bar{s}$ (then predict $\bar{u}-\bar{d}$)



$\dfrac{x(\bar{u}+\bar{d})}{2}-x\bar{s} \;\Rightarrow\; \Lambda_2 \simeq 1$ GeV ($\Lambda_1 \simeq 0.6 \sim 0.7$ GeV: soft form factor)

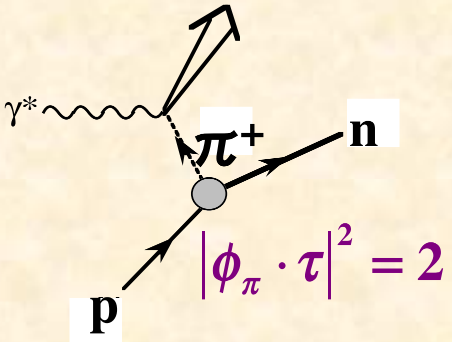
$\overline{\mathrm{u}}/\overline{\mathrm{d}}$ asymmetry

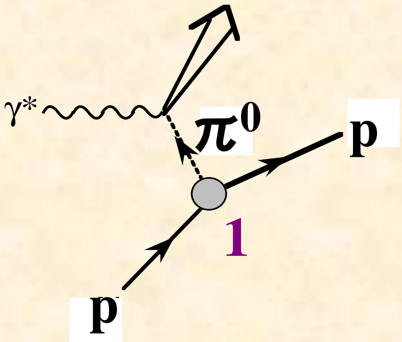
$$S_G = \int_0^1 \frac{dx}{x}\left[F_2^{\mu p}(x) - F_2^{\mu n}(x)\right] = \frac{1}{3} + \frac{2}{3}\int_0^1 dx\left[\bar{u}(x) - \bar{d}(x)\right]$$

$$(\text{NMC:}\;\; S_G = 0.235 \pm 0.026)$$

- **Gottfried sum**

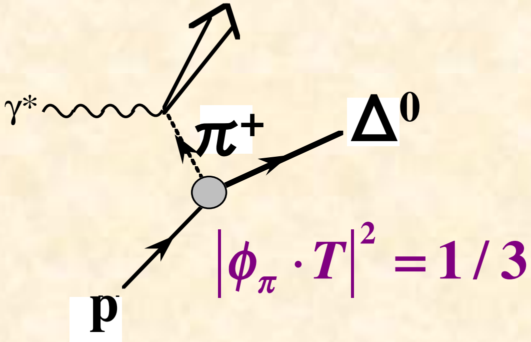
Effects of “meson-clouds”

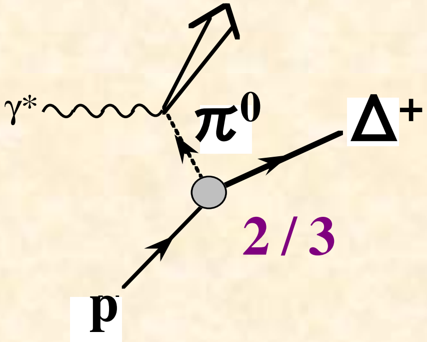


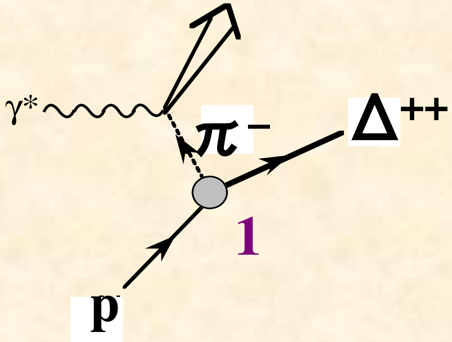


$$\left[\sum_\pi |\phi_\pi \cdot \tau|^2 (\bar{u} - \bar{d})_\pi\right]_{\pi NN} = -2V_\pi$$

$$\left[\sum_\pi |\phi_\pi \cdot T|^2 (\bar{u} - \bar{d})_\pi\right]_{\pi N\Delta} = +\frac{2}{3}V_\pi$$





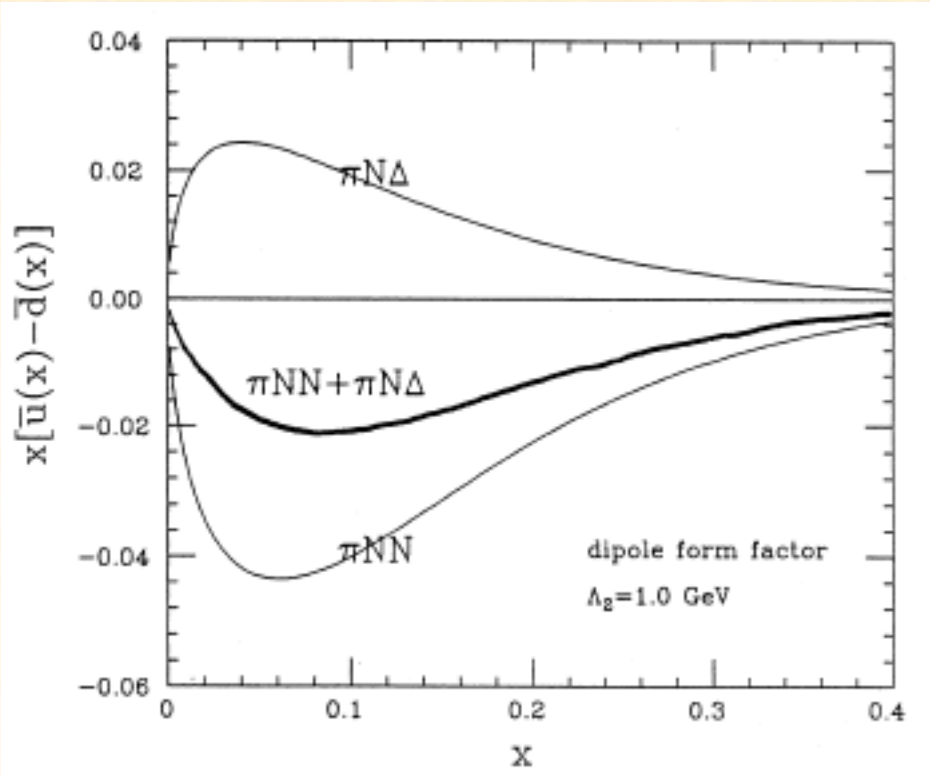


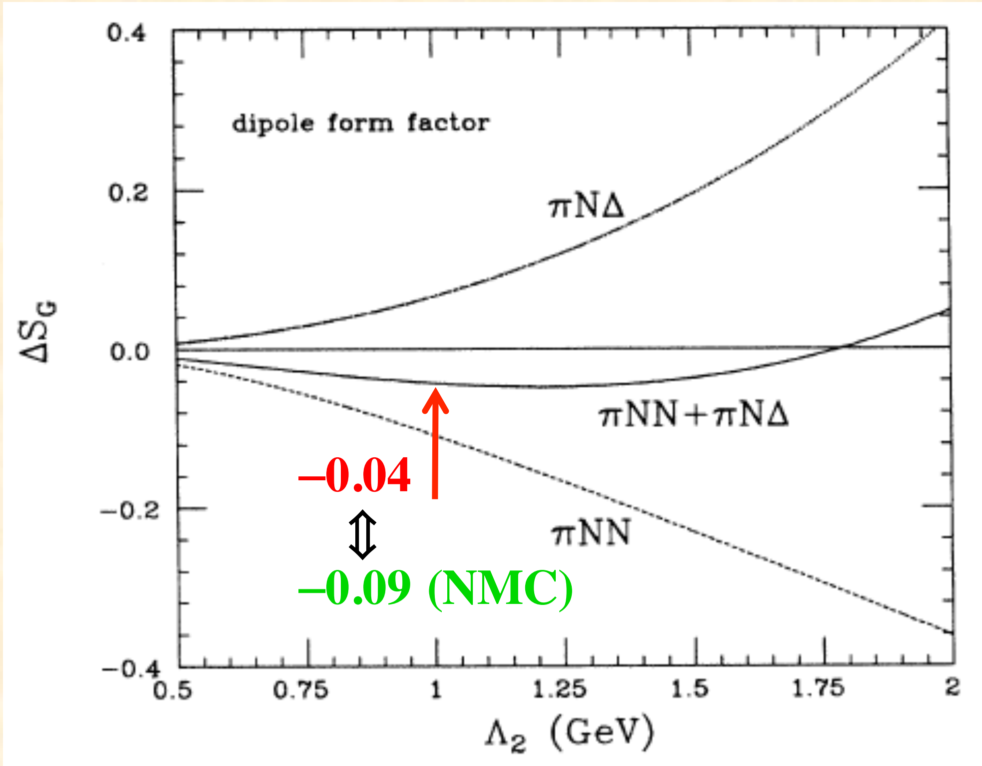
$\left(\bar{u} - \bar{d}\right)_{\pi^+} = -V_\pi$ $\quad\left(\bar{u} - \bar{d}\right)_{\pi^0} = 0$ $\quad\left(\bar{u} - \bar{d}\right)_{\pi^-} = +V_\pi$

Pionic contributions to $\bar{u} - \bar{d}$

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

as a function of Λ_2





Summary on the unpolarized $\bar{u}-\bar{d}$

Meson-cloud model

It can explain the order of magnitude of the Gottfried-sum-rule violation by NMC.

In addition to $p \to \pi N$, $p \to \pi\Delta$ should be included in the calculation.

In addition to π, other mesons should be considered.

It becomes a successful model in explaining $\bar{u}-\bar{d}$, $\dfrac{\bar{u}+\bar{d}}{2}-\bar{s}$.

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

Reference:

SK, PL B 342 (1995) 339.

Introduction to nuclear $\bar{u}-\bar{d}$

Nuclear PDFs

$$f_i^A(x) = w_i(x,A,Z)\frac{1}{A}\left[Z f_i^p(x) + (A-Z) f_i^n(x)\right], \quad A-Z=N$$

p = proton, n = neutron, $w_i(x,A,Z)$ = nuclear modification

$$\bar{u}^A(x) = w_{\bar{u}}(x,A,Z)\frac{1}{A}\left[Z\bar{u}^p(x) + (A-Z)\bar{u}^n(x)\right] = w_{\bar{u}}(x,A,Z)\frac{1}{A}\left[Z\bar{u}(x) + (A-Z)\bar{d}(x)\right]$$

$$\bar{d}^A(x) = w_{\bar{d}}(x,A,Z)\frac{1}{A}\left[Z\bar{d}^p(x) + (A-Z)\bar{d}^n(x)\right] = w_{\bar{d}}(x,A,Z)\frac{1}{A}\left[Z\bar{d}(x) + (A-Z)\bar{u}(x)\right]$$

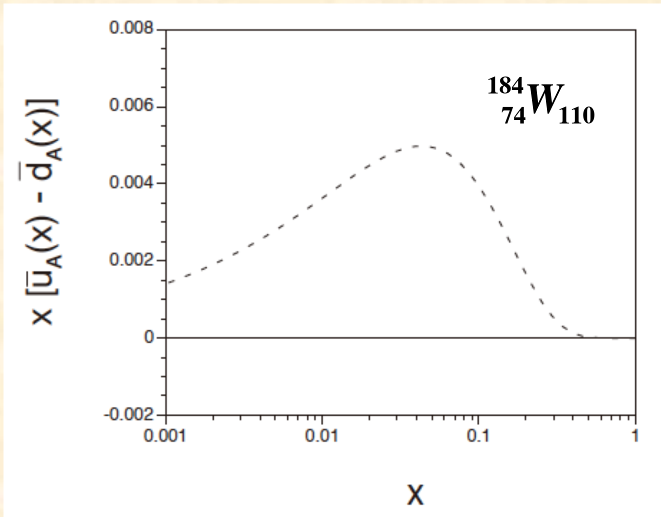
If $w_{\bar{u}} = w_{\bar{d}} \equiv w_{\bar{q}}$,

$$\bar{u}^A(x) - \bar{d}^A(x) = -\varepsilon\, w_{\bar{q}}(x,A,Z)\left[\bar{u}(x) - \bar{d}(x)\right]$$

Neutron excess $\varepsilon \equiv \dfrac{N-Z}{N+Z}$

$\varepsilon = 0$ (isoscalar), $= 1$ (neutron matter)
$= 0.071$ ($^{56}_{26}Fe_{30}$), 0.196 ($^{184}_{74}W_{110}$)

Expected $\bar{u}-\bar{d}$ in the tungsten
if there is no nulcear modification $w_{\bar{q}} = 1$.



$\bar{u}$ excess over $\bar{d}$ ($\bar{u} > \bar{d}$) because of the neutron excess
even if there is no nuclear modificaiton.

Possible nuclear modification of $\bar{u} - \bar{d}$ (namely $w_{\bar{q}} \neq 1$)

Average nucleon separation in a nucleus ~2 fm

Average longitudinal nucleon separation in a Lorentz contracted nucleus:

$$L = (2\text{ fm})\frac{M_A}{P_A} = (2\text{ fm})\frac{m_N}{p_N}$$

F. E. Close, J.-W. Qiu, R.G. Roberts, Phys. Rev. D40 (1989) 2820.

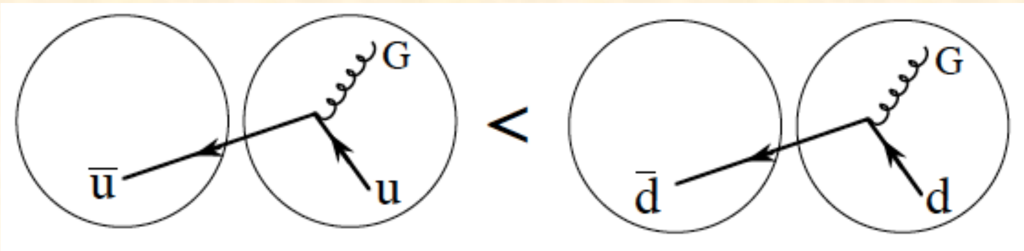
Longitudinal locarization size of a parton with momentum xp_N : $\Delta L = \frac{1}{xp_N}$

At small x, the parton localization size exceeds the average nucleon separation:

$$\Delta L > L \quad \Rightarrow \frac{1}{xp_N} > (2\text{ fm})\frac{m_N}{p_N} \quad \Rightarrow x < \frac{1}{(2\text{ fm})m_N} = \frac{200\text{ fm}\cdot\text{MeV}}{(2\text{ fm})(1000\text{ MeV})} = 0.1$$

Then, partons from different nucleons could interact with each other (parton recombination).

Due to d excess over u in a neutron-excess nucleus,
more $\bar{d}$ quarks are lost than $\bar{u}$ in the recombination process.



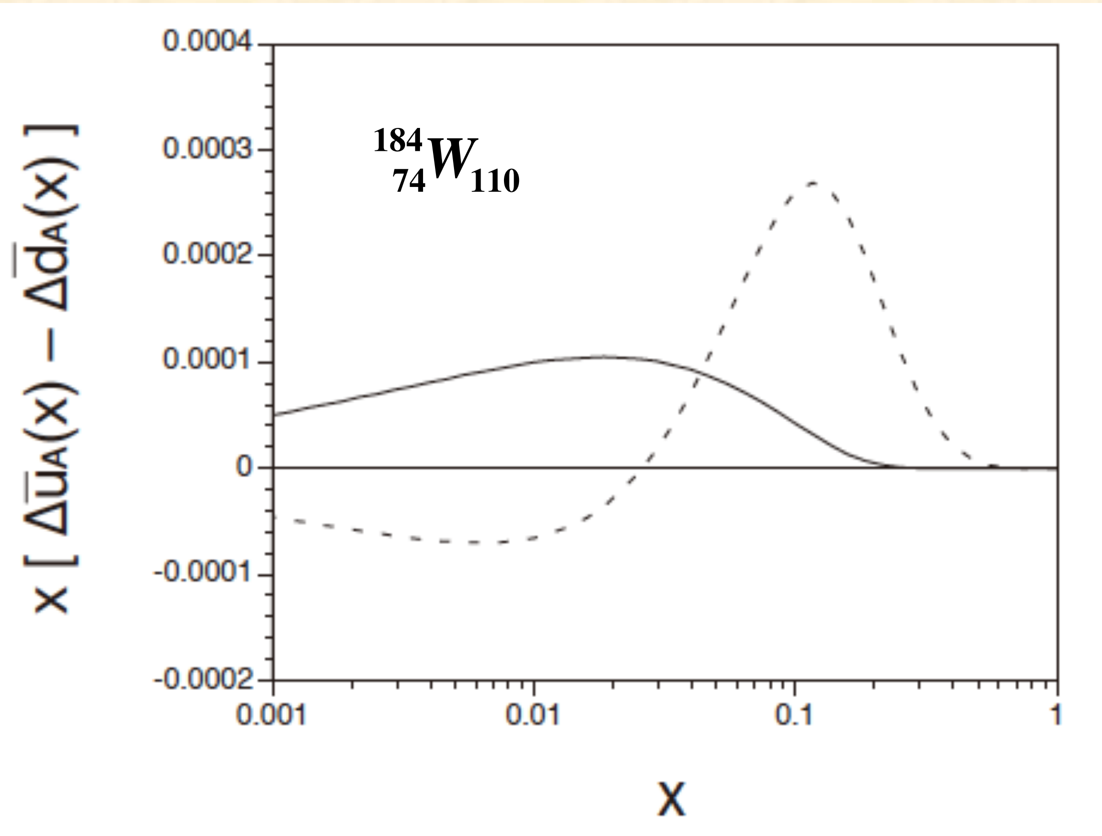
Nuclear modification of $\bar{u}-\bar{d}$ in the recombination model

———— $\bar{u}(x)=\bar{d}(x)$ in the nucleon

- - - - - - - - $\bar{u}(x)\neq\bar{d}(x)$

Finite $\bar{u}^A(x)-\bar{d}^A(x)$ even if $\bar{u}(x)-\bar{d}(x)=0.$

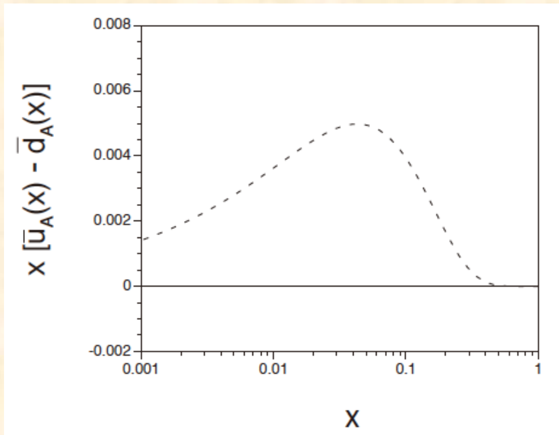
We discussed only the recombincation,
but there could be other interesting mechanism(s)
for creating $\bar{u}^A(x)-\bar{d}^A(x)\neq 0.$



Without nuclear modification

$$\bar{u}^A(x)-\bar{d}^A(x)=-\varepsilon\left[\bar{u}(x)-\bar{d}(x)\right]$$

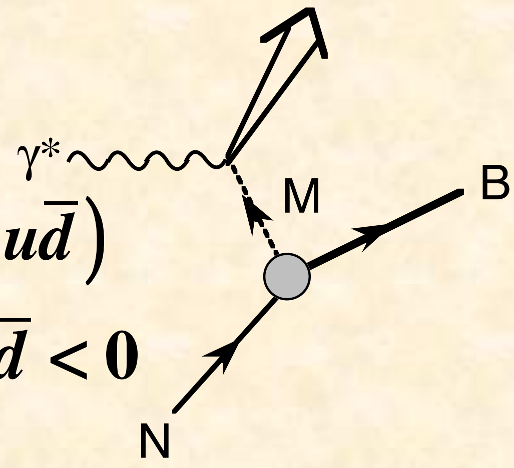
$$\varepsilon\equiv\frac{N-Z}{N+Z}$$



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

Reference: SK and M. Miyama, Phys. Rev. D65 (2002) 034012

Meson-cloud model



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

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

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

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

polarized: e.g. $\rho^{+}\left(u\bar{d}\right)\ \Rightarrow\ \Delta\bar{d}$ **excess:** $\Delta\bar{u}-\Delta\bar{d}<0$

$\Delta\bar{u} - \Delta\bar{d}$ distribution

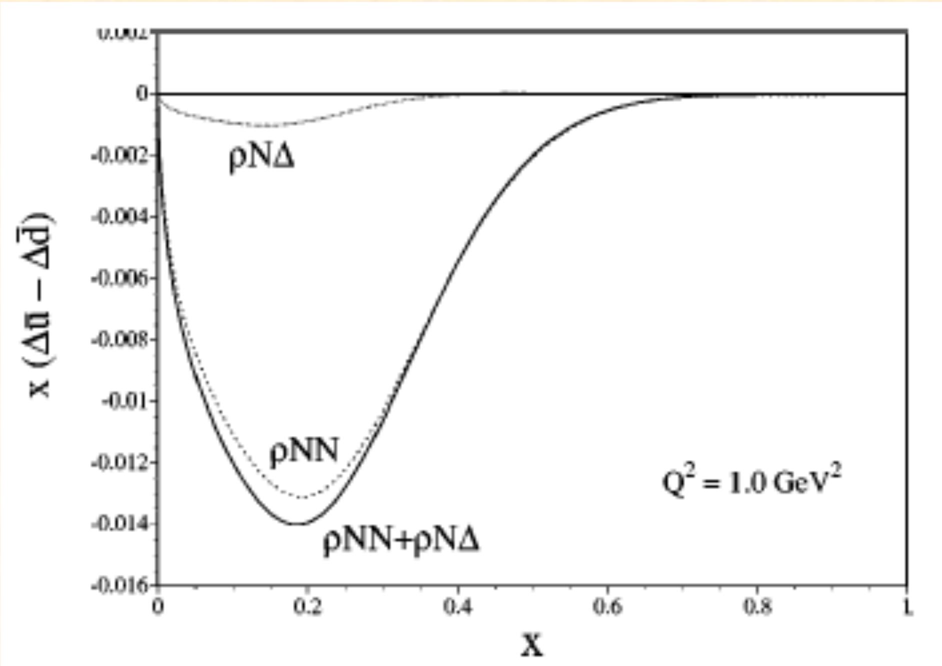
naive quark model: $\rho^{+}\left(u\bar{d}\right),\quad \rho^{0}\left(\left(u\bar{u}-d\bar{d}\right)/\sqrt{2}\right),\quad \rho^{-}\left(\bar{u}d\right)$

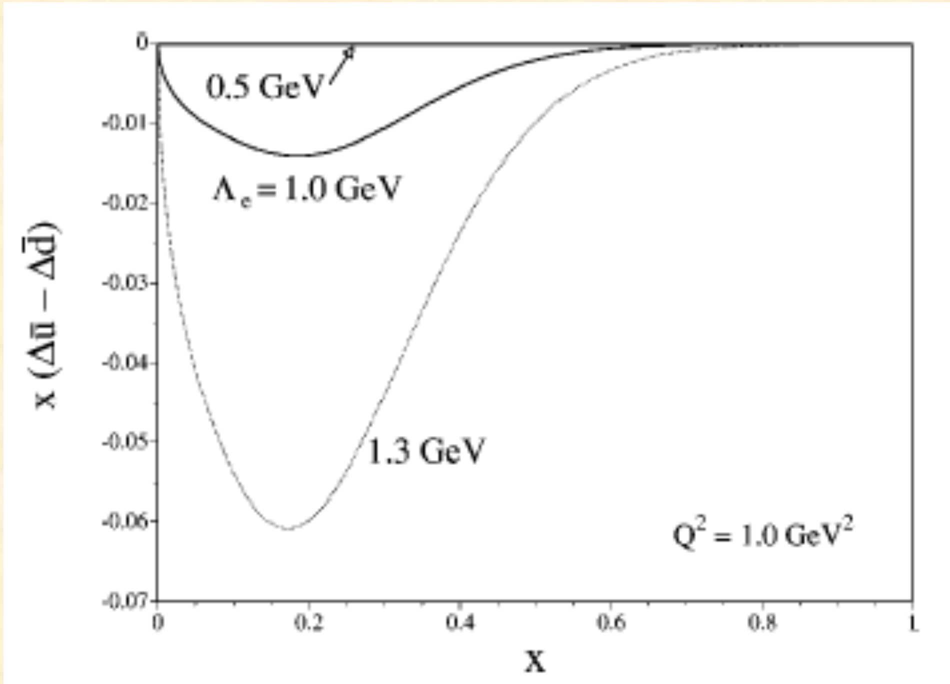
$$\left[\Delta\bar{u}-\Delta\bar{d}\right]_{\rho NB} = \Delta f_{\rho^{+}pn}\otimes\left[\Delta\bar{u}-\Delta\bar{d}\right]_{\rho^{+}} + \Delta f_{\rho^{0}pp}\otimes\left[\Delta\bar{u}-\Delta\bar{d}\right]_{\rho^{0}}$$
$$+\Delta f_{\rho^{+}p\Delta^{0}}\otimes\left[\Delta\bar{u}-\Delta\bar{d}\right]_{\rho^{+}} + \Delta f_{\rho^{0}p\Delta^{+}}\otimes\left[\Delta\bar{u}-\Delta\bar{d}\right]_{\rho^{0}}$$
$$+\Delta f_{\rho^{-}p\Delta^{++}}\otimes\left[\Delta\bar{u}-\Delta\bar{d}\right]_{\rho^{-}}$$

charge symmetry in ρ: $\Delta\bar{u}^{val}_{\rho^{-}} = \Delta\bar{d}^{val}_{\rho^{+}} = 2\Delta\bar{u}^{val}_{\rho^{0}} = 2\Delta\bar{d}^{val}_{\rho^{0}} = \Delta v_{\rho}$

$$\left[\Delta\bar{u}-\Delta\bar{d}\right]_{\rho NB} = \left(-2\Delta f_{\rho NN} + \frac{2}{3}\Delta f_{\rho N\Delta}\right)\otimes\Delta v_{\rho}$$

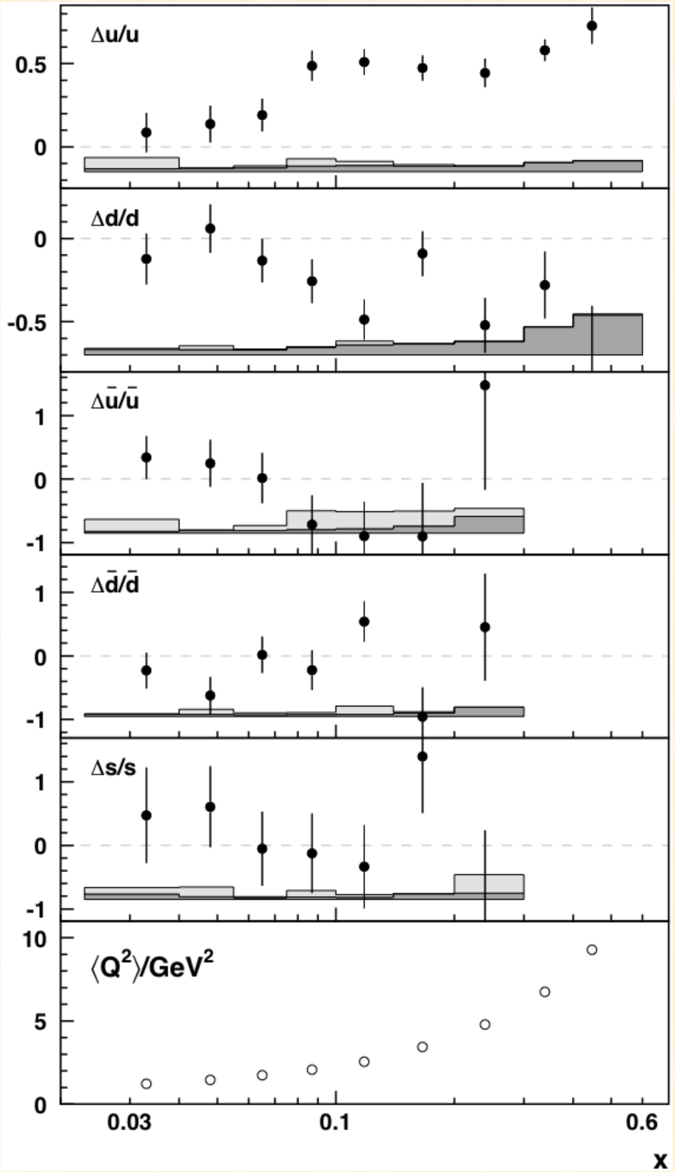
$\Delta\bar{u} - \Delta\bar{d}$ distributions



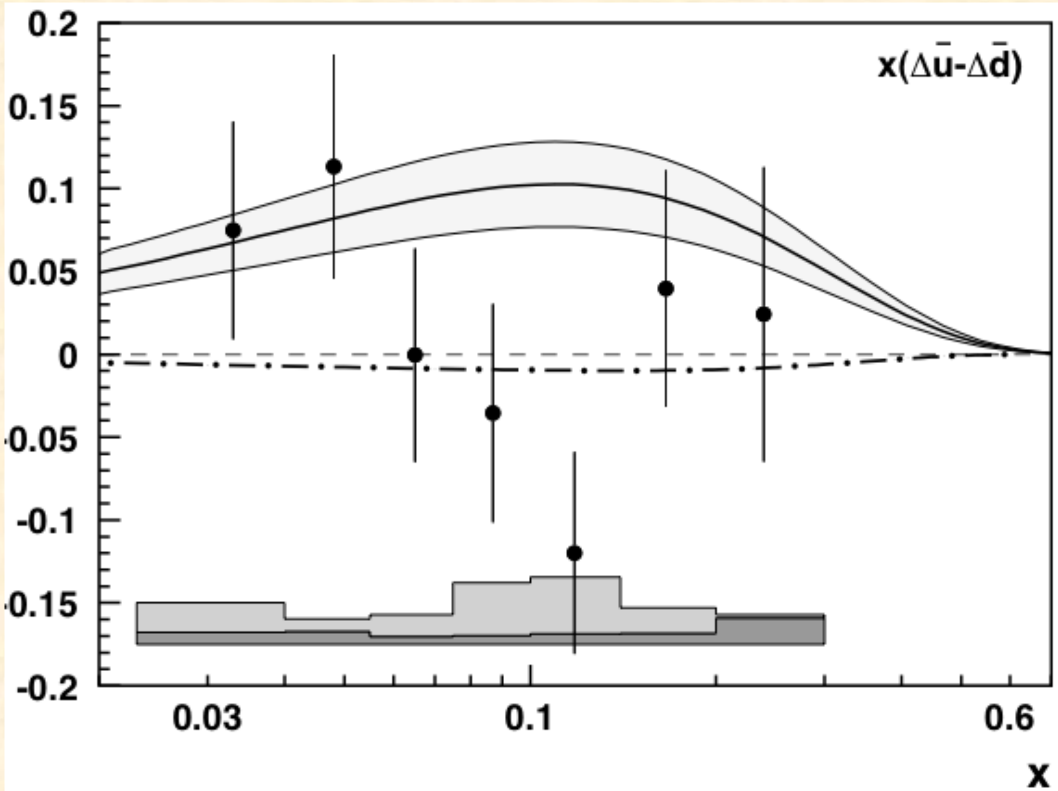


Flavor symmetric antiquark distributions

A. Airapetian et al. (HERMES),
PRL. 92 (2004) 012005;
PRD 71 (2005) 012003.



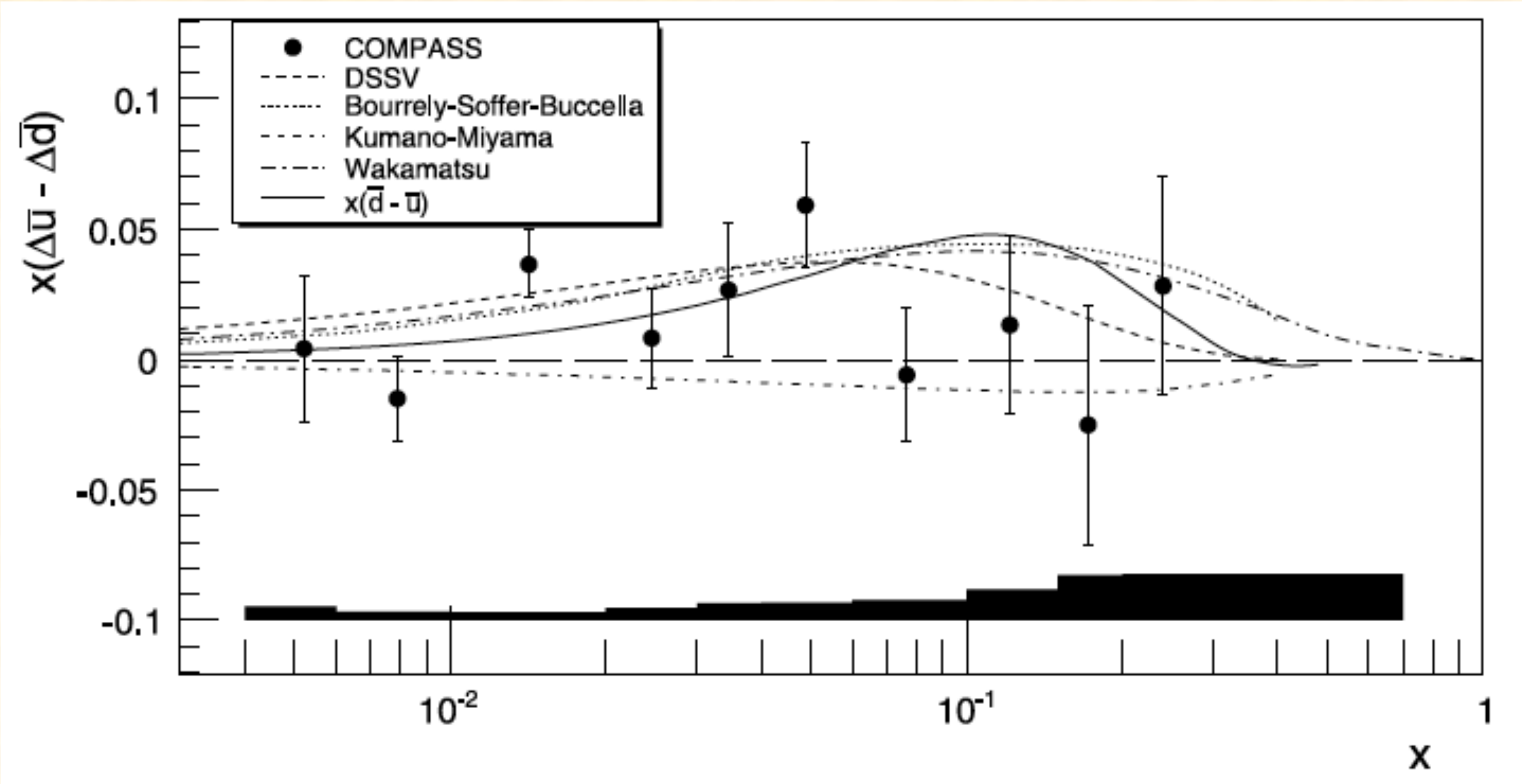
At this stage, the data are consistent with $\Delta\bar{u} = \Delta\bar{d}$.



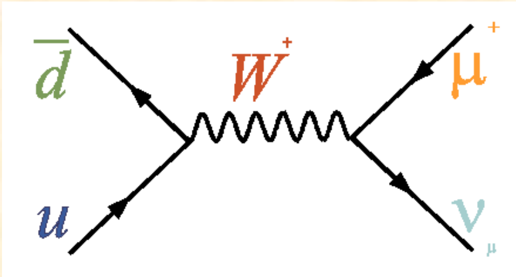
Our studies in S. Kumano and M. Miyama,
Phys. Rev. D65 (2002) 034012

Flavor symmetric antiquark distributions, COMPASS 2010

M. G. Alekseev *et al.* (COMPASS),
Phys. Lett. B693 (2010) 227.

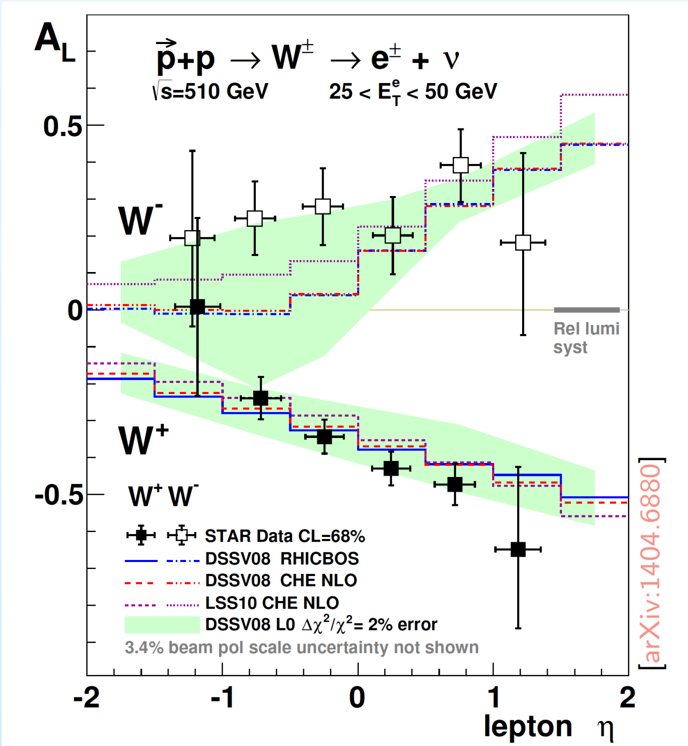


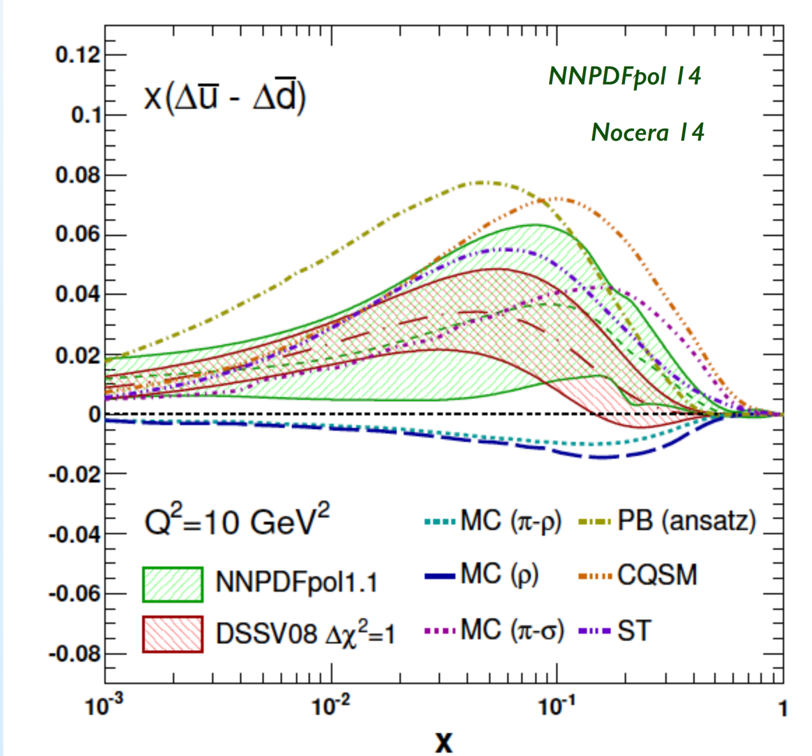
W Production



$$A_L^{W^+} = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

W production data are useful for determining $\Delta q / q$ and $\Delta\bar{q} / q$, especially the polarized antiquark distributions.





J. Rojo (NNPDF), QCD-N'16

Antiquark flavor asymmetries in Drell-Yan processes (especially in transversity)

Polarized proton-deuteron Drell-Yan

SK and M. Miyama, Phys. Lett. B479 (2000) 149.

Proton-deuteron Drell-Yan for $\Delta_T\bar{u}-\Delta_T\bar{d}$

$$\Delta_{(T)} = \Delta \text{ or } \Delta_T$$

$$R_{pd} \equiv \frac{\Delta_{(T)}\sigma^{pd}}{2\Delta_{(T)}\sigma^{pp}} = \frac{\sum_a e_a^2\left[\Delta_{(T)}q_a(x_1)\Delta_{(T)}\bar{q}_a^d(x_2)+\Delta_{(T)}\bar{q}_a(x_1)\Delta_{(T)}q_a^d(x_2)\right]}{2\sum_a e_a^2\left[\Delta_{(T)}q_a(x_1)\Delta_{(T)}\bar{q}_a(x_2)+\Delta_{(T)}\bar{q}_a(x_1)\Delta_{(T)}q_a(x_2)\right]}$$

- neglect nuclear effects in the deuteron
- assume isospin symmetry

$$x_F = x_1 - x_2$$

- $x_F \to +1$ region

$$R_{pd}(x_F\to 1) = \frac{\sum_a e_a^2\left[\Delta_{(T)}q_{v,a}(x_1)\Delta_{(T)}\bar{q}_a^d(x_2)\right]}{2\sum_a e_a^2\left[\Delta_{(T)}q_{v,a}(x_1)\Delta_{(T)}\bar{q}_a(x_2)\right]}$$

$$= 1 - \frac{\left[4\Delta_{(T)}u_v(x_1)-\Delta_{(T)}d_v(x_1)\right]\left[\Delta_{(T)}\bar{u}(x_2)-\Delta_{(T)}\bar{d}(x_2)\right]}{8\Delta_{(T)}u_v(x_1)\Delta_{(T)}\bar{u}(x_2)+2\Delta_{(T)}d_v(x_1)\Delta_{(T)}\bar{d}(x_2)}$$

suppose $\Delta_{(T)}u_v(x\to 1)\gg\Delta_{(T)}d_v(x\to 1)$

$$R_{pd}(x_F\to 1)=1-\left[\frac{\Delta_{(T)}\bar{u}(x_2)-\Delta_{(T)}\bar{d}(x_2)}{2\Delta_{(T)}\bar{u}(x_2)}\right]_{x_2\to 0}$$

$$=\frac{1}{2}\left[1+\frac{\Delta_{(T)}\bar{d}(x_2)}{\Delta_{(T)}\bar{u}(x_2)}\right]_{x_2\to 0}$$

$$\Delta_{(T)}\bar{u}=\Delta_{(T)}\bar{d}\quad\Rightarrow\quad R_{pd}(x_F\to 1)=1$$

$$\text{if }\Delta_{(T)}\bar{u},\Delta_{(T)}\bar{d}<0,\quad\left|\Delta_{(T)}\bar{u}\right|<\left|\Delta_{(T)}\bar{d}\right|\quad\Rightarrow\quad R_{pd}(x_F\to 1)>1$$

$$\left|\Delta_{(T)}\bar{u}\right|>\left|\Delta_{(T)}\bar{d}\right|\quad\Rightarrow\quad R_{pd}(x_F\to 1)<1$$

• $x_F\to -1$ region

$$R_{pd}(x_F\to 1)=\frac{\left[4\Delta_{(T)}\bar{u}(x_1)+\Delta_{(T)}\bar{d}(x_1)\right]\left[\Delta_{(T)}u_v(x_2)+\Delta_{(T)}d_v(x_2)\right]}{8\Delta_{(T)}\bar{u}(x_1)\Delta_{(T)}u_v(x_2)+2\Delta_{(T)}\bar{d}(x_1)\Delta_{(T)}d_v(x_2)}$$

suppose $\Delta_{(T)}u_v(x\to 1)\gg\Delta_{(T)}d_v(x\to 1)$

$$R_{pd}(x_F\to -1)=\frac{1}{2}\left[1+\frac{\Delta_{(T)}\bar{d}(x_1)}{4\Delta_{(T)}\bar{u}(x_1)}\right]_{x_1\to 0}$$

$$\Delta_{(T)}\bar{u}=\Delta_{(T)}\bar{d}\quad\Rightarrow\quad R_{pd}(x_F\to -1)=\frac{5}{8}=0.625$$

$$\text{if }\Delta_{(T)}\bar{u},\Delta_{(T)}\bar{d}<0,\quad\left|\Delta_{(T)}\bar{u}\right|<\left|\Delta_{(T)}\bar{d}\right|\quad\Rightarrow\quad R_{pd}(x_F\to -1)>0.625$$

$$\left|\Delta_{(T)}\bar{u}\right|>\left|\Delta_{(T)}\bar{d}\right|\quad\Rightarrow\quad R_{pd}(x_F\to -1)<0.625$$

Numerical analysis

$$r_{\bar{q}} \equiv \frac{\Delta_{(T)}\bar{u}}{\Delta_{(T)}\bar{d}} = 0.7, 1.0, \text{or } 1.3 \quad \text{at } Q^2 = 1\,\text{GeV}^2$$

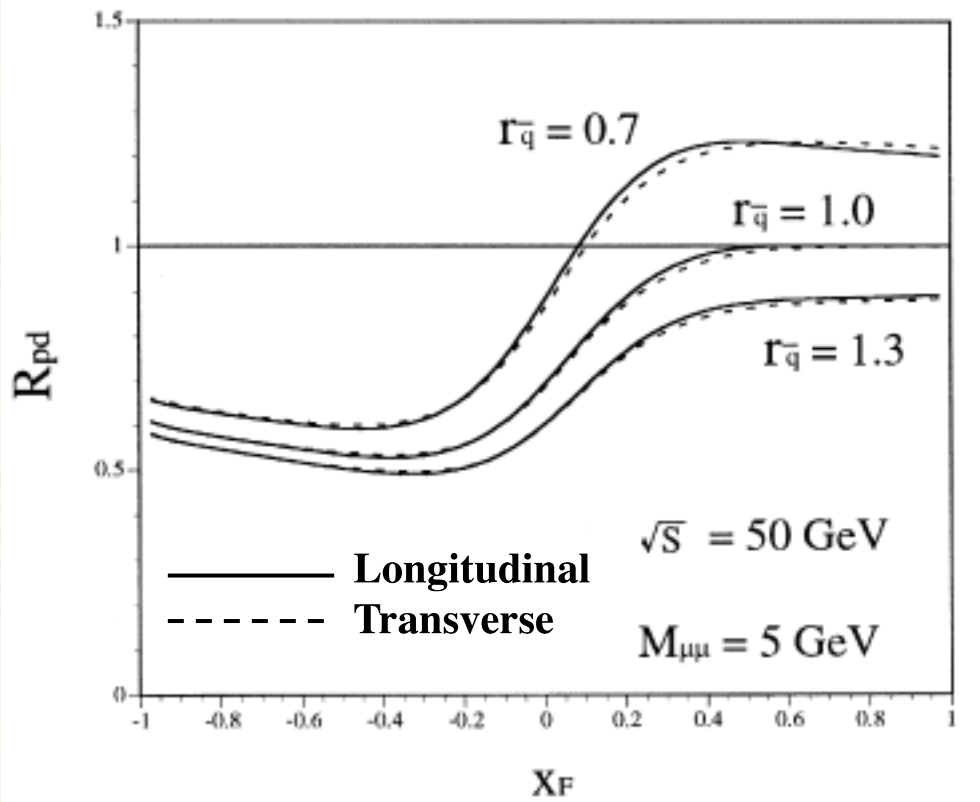
polarized PDFs: LSS-99 at $Q^2 = 1\,\text{GeV}^2$

$M_{\mu\mu} = 5\,\text{GeV}, \quad \sqrt{s} = 50\,\text{GeV}$

$Q^2 = 1\,\text{GeV}^2$ evolution $\Rightarrow Q^2 = M_{\mu\mu}^2$

$\Rightarrow$ calculate $R_{pd} \equiv \dfrac{\Delta_{(T)}\sigma^{pd}}{2\Delta_{(T)}\sigma^{pd}}$

assume $\Delta_T q(x) = \Delta q(x)$
at $Q^2 = 1\,\text{GeV}^2$



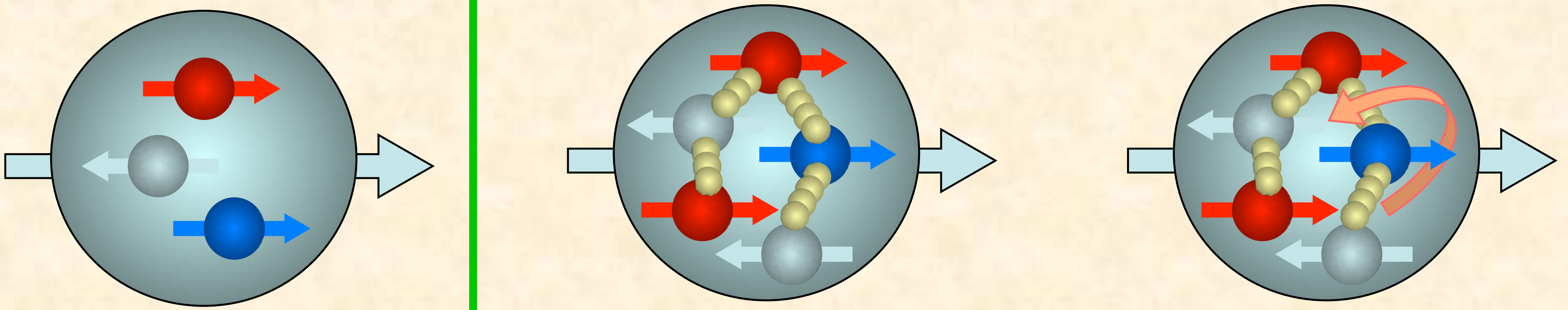
Tensor-polarized structure functions for spin-1 deuteron

S. Kumano and Qin-Tao Song,
Phys. Rev. D 94 (2016) 054022. → Song's talk on Oct.12

W. Cosyn, Yu-Bing Dong, S. Kumano, and M. Sargsian,
Phys. Rev. D 95 (2017) 074036.

Nucleon spin

Almost none of nucleon spin is carried by quarks! → **Nucleon spin crisis!?**

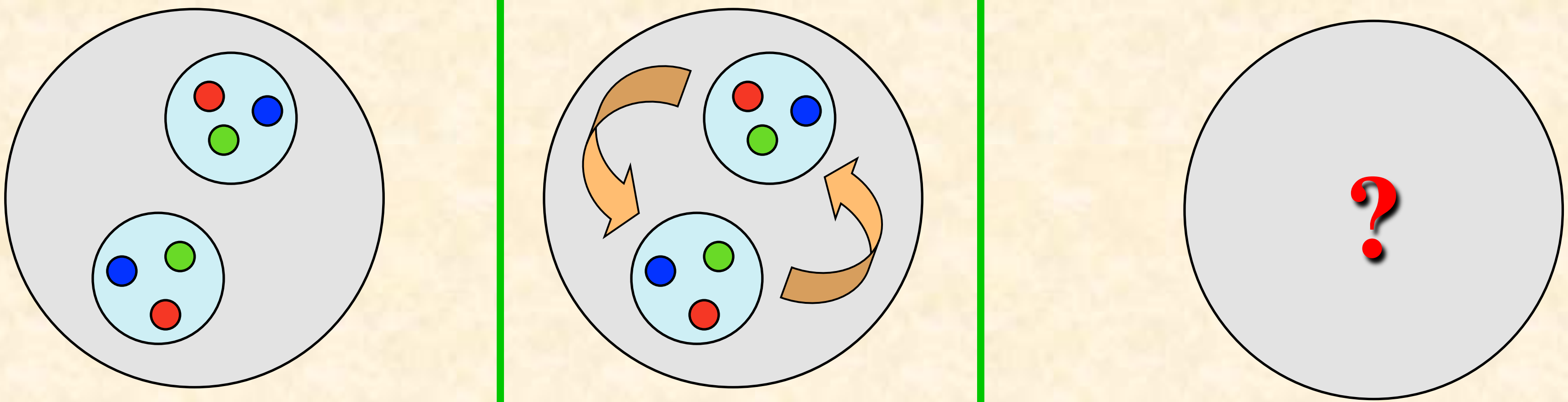


Naïve Quark Model | Sea-quarks and gluons? | Orbital angular momenta ?

"old" standard model

Tensor structure b_1 (*e.g.* deuteron)

Tensor-structure crisis!?



only S wave | S + D waves

$b_1 = 0$

standard model $b_1 \neq 0$

$b_1^{\text{experiment}} \neq b_1^{\text{"standard model"}}$

Electron scattering from a spin-1 hadron

P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571.
[L. L. Frankfurt and M. I. Strikman, NP A405 (1983) 557.]

$$W_{\mu\nu} = \boxed{-F_1 g_{\mu\nu} + F_2 \frac{p_\mu p_\nu}{\nu} + g_1 \frac{i}{\nu}\varepsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + g_2 \frac{i}{\nu^2}\varepsilon_{\mu\nu\lambda\sigma} q^\lambda \left(p\cdot q s^\sigma - s\cdot q p^\sigma \right)}$$

spin-1/2, spin-1

$$\boxed{-b_1 r_{\mu\nu} + \frac{1}{6} b_2 \left(s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu} \right) + \frac{1}{2} b_3 \left(s_{\mu\nu} - u_{\mu\nu} \right) + \frac{1}{2} b_4 \left(s_{\mu\nu} - t_{\mu\nu} \right)}$$

spin-1 only

Note: Obvious factors from $q^\mu W_{\mu\nu} = q^\nu W_{\mu\nu} = 0$ are not explicitly written.

$E^\mu =$ polarization vector

$$\nu = p\cdot q,\ \ \kappa = 1 + M^2 Q^2/\nu^2\ ,\ \ E^2 = -M^2,\ \ s^\sigma = -\frac{i}{M^2}\varepsilon^{\sigma\alpha\beta\tau} E_\alpha^* E_\beta p_\tau$$

$$r_{\mu\nu} = \frac{1}{\nu^2}\left(q\cdot E^* q\cdot E - \frac{1}{3}\nu^2\kappa \right) g_{\mu\nu}\ ,\qquad s_{\mu\nu} = \frac{2}{\nu^2}\left(q\cdot E^* q\cdot E - \frac{1}{3}\nu^2\kappa \right)\frac{p_\mu p_\nu}{\nu}$$

$$t_{\mu\nu} = \frac{1}{2\nu^2}\left(q\cdot E^* p_\mu E_\nu + q\cdot E^* p_\nu E_\mu + q\cdot E p_\mu E_\nu^* + q\cdot E p_\nu E_\mu^* - \frac{4}{3}\nu p_\mu p_\nu \right)$$

$$u_{\mu\nu} = \frac{1}{\nu}\left(E_\mu^* E_\nu + E_\nu^* E_\mu + \frac{2}{3}M^2 g_{\mu\nu} - \frac{2}{3} p_\mu p_\nu \right)$$

$b_1, \cdots, b_4$ tems are defined so that they vanish by spin average.

b_1, b_2 tems are defined to satisfy $2xb_1 = b_2$ in the Bjorken scaling limit.

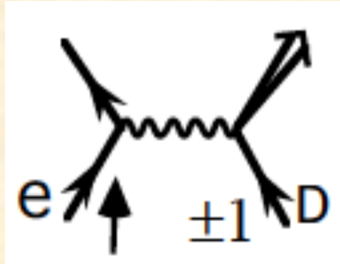
$2xb_1 = b_2$ in the scaling limit $\sim O(1)$

b_3, b_4 = twist-4 $\sim \dfrac{M^2}{Q^2}$

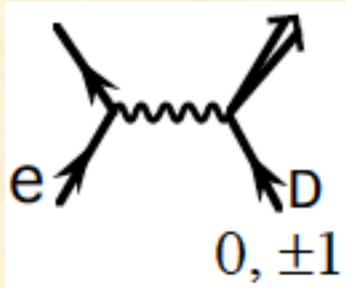
Structure Functions

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

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



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



note: $\sigma(0) - \frac{\sigma(+1)+\sigma(-1)}{2} = 3\langle\sigma\rangle - \frac{3}{2}\left[\sigma(+1)+\sigma(-1)\right]$

Parton Model

$$F_1 = \frac{1}{2}\sum_i e_i^2\left(q_i + \bar{q}_i\right) \qquad q_i = \frac{1}{3}\left(q_i^{+1} + q_i^{0} + q_i^{-1}\right)$$

$$g_1 = \frac{1}{2}\sum_i e_i^2\left(\Delta q_i + \Delta \bar{q}_i\right) \qquad \Delta q_i = q_{i\uparrow}^{+1} - q_{i\downarrow}^{+1}$$

$$\left[q_\uparrow^H\left(x,Q^2\right)\right] \qquad b_1 = \frac{1}{2}\sum_i e_i^2\left(\delta_T q_i + \delta_T \bar{q}_i\right) \qquad \delta_T q_i = q_i^0 - \frac{q_i^{+1} + q_i^{-1}}{2}$$

Standard convolution approach

Convolution model: $A_{hH,hH}(x)=\int\frac{dy}{y}\sum_s f_s^H(y)\hat{A}_{hs,hs}(x/y)\equiv\sum_s f_s^H(y)\otimes\hat{A}_{hs,hs}(y)$

$$A_{hH,h'H'}=\varepsilon_{h'}^{*\mu}W_{\mu\nu}^{H'H}\varepsilon_h^{\nu},\quad b_1=A_{+0,+0}-\frac{A_{++,++}+A_{+-,+-}}{2},$$

$$\hat{A}_{+\uparrow,+\uparrow}=F_1-g_1,\quad \hat{A}_{+\downarrow,+\downarrow}=F_1+g_1$$

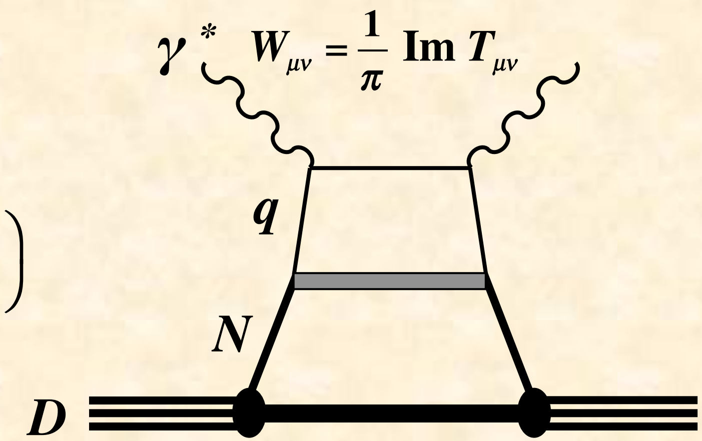
Momentum distribution: $f^H(y)=\int d^3p\left|\phi^H(\vec{p})\right|^2\delta\left(y-\frac{E+p_z}{M}\right)$

$$f^H(y)\equiv f_\uparrow^H(y)+f_\downarrow^H(y)$$

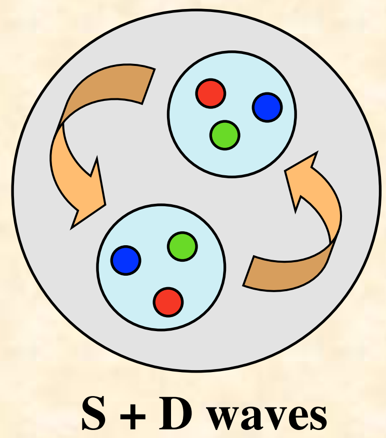
D-state admixture: $\phi^H(\vec{p})=\phi_{\ell=0}^H(\vec{p})+\phi_{\ell=2}^H(\vec{p})$

$$b_1(x)=\frac{1}{2}\int\frac{dy}{y}\sum_{i=p,n}\left[f^0(y)-\frac{f^+(y)+f^-(y)}{2}\right]F_1(x/y)=\int\frac{dy}{y}\delta f_T(y)F_1(x/y)$$

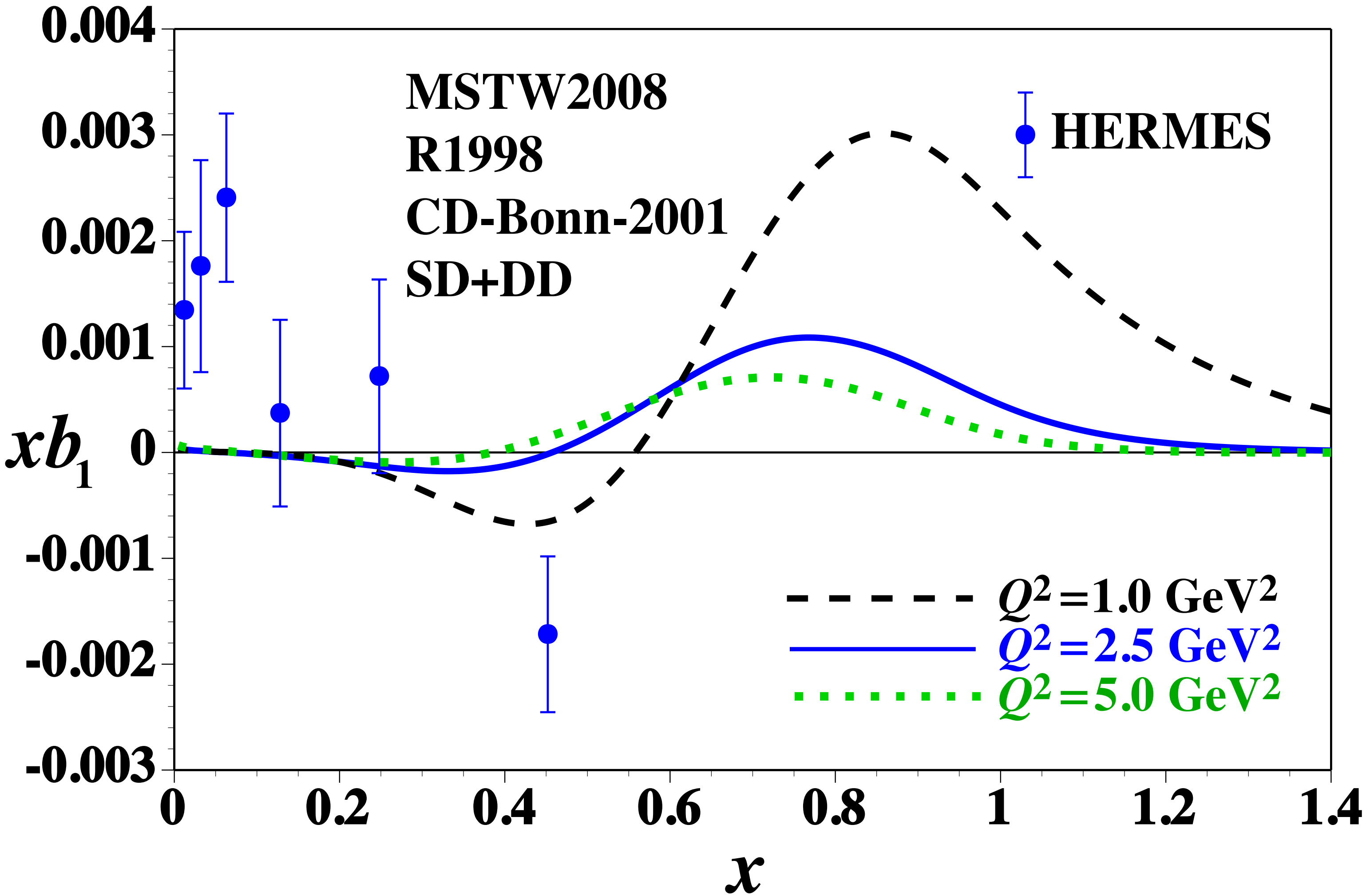
$$\delta_T f(y)=\int d^3py\left[-\frac{3}{4\sqrt{2}\pi}\phi_0(p)\phi_2(p)+\left|\phi_2(p)\right|^2\frac{3}{16\pi}\right](3\cos^2\theta-1)\delta\left(y-\frac{p\cdot q}{M\nu}\right)$$



Standard model of the deuteron



Comparison with HERMES measurements



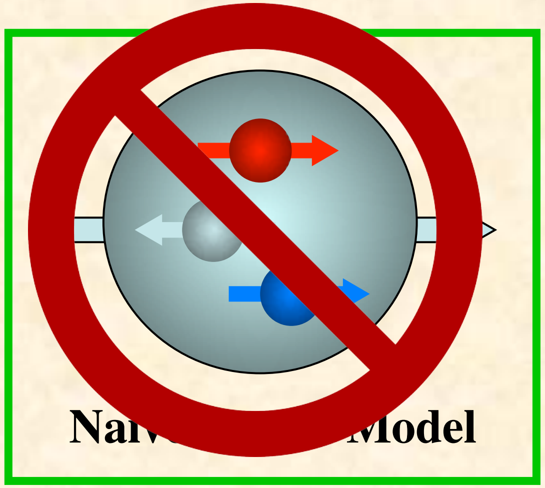
$|b_1(\text{theory})| \ll |b_1(\text{HERMES})|$
at $x < 0.5$

Standard convolution model does not work for the deuteron tensor structure!?

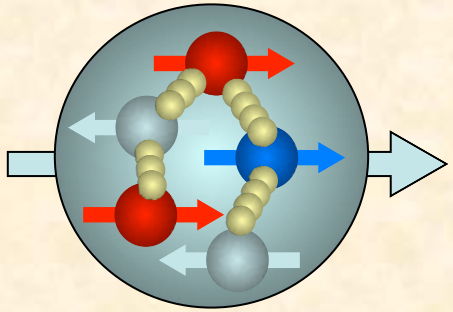
Summary I

Nucleon spin

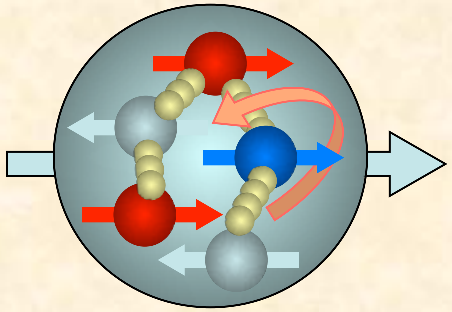
Nucleon spin crisis!?



"old" standard model



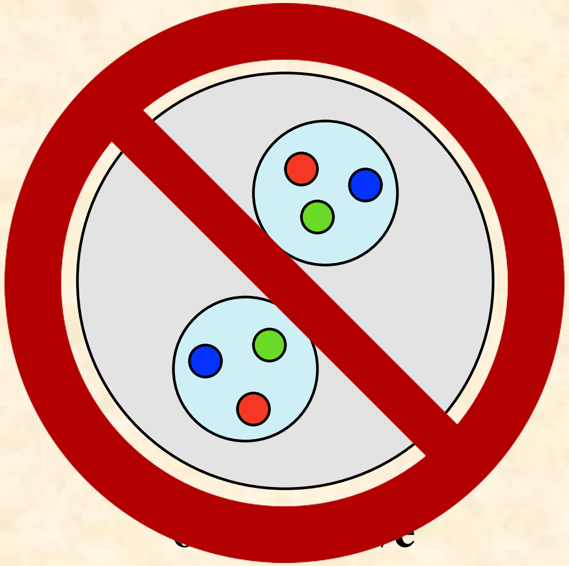
Sea-quarks and gluons?



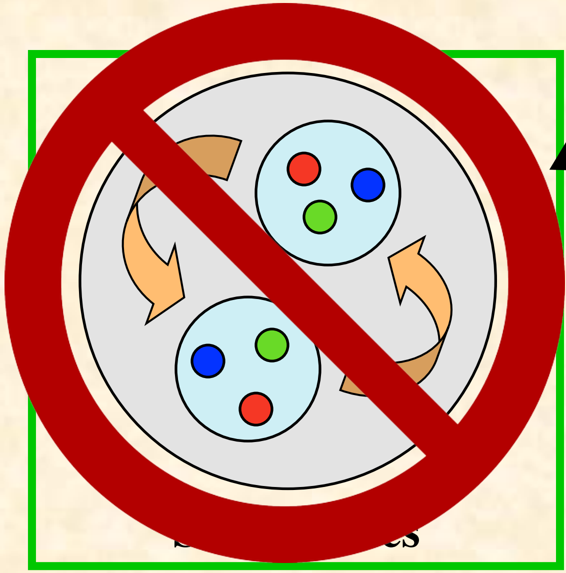
Orbital angular momenta ?

We have shown in this work
that the standard deuteron model
does not work!?
→ new hadron physics?!

Tensor structure

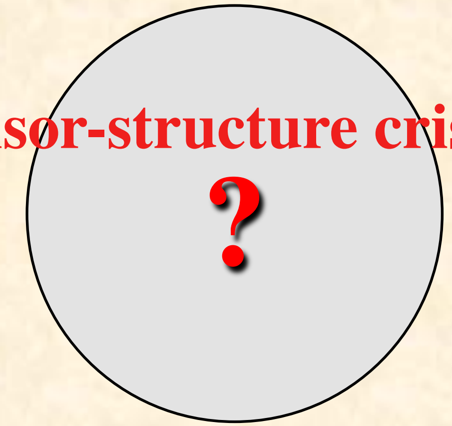


$b_1 = 0$



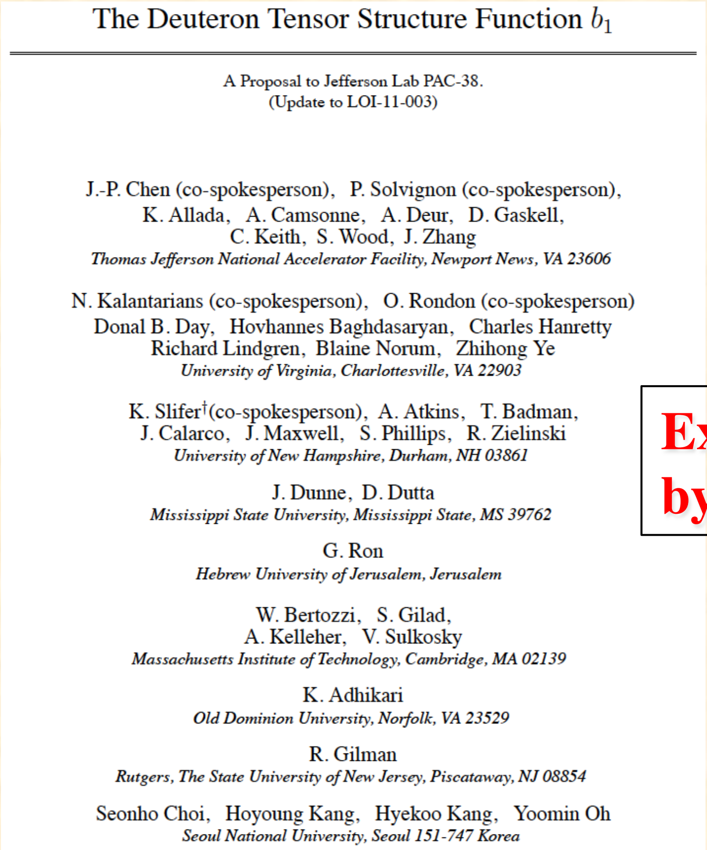
standard model $b_1 \neq 0$

Tensor-structure crisis!?



$b_1^{\text{experiment}} \neq b_1^{\text{“standard model”}}$

JLab PAC-38 (Aug. 22-26, 2011) proposal, PR12-11-110



The Deuteron Tensor Structure Function b_1

A Proposal to Jefferson Lab PAC-38.
(Update to LOI-11-003)

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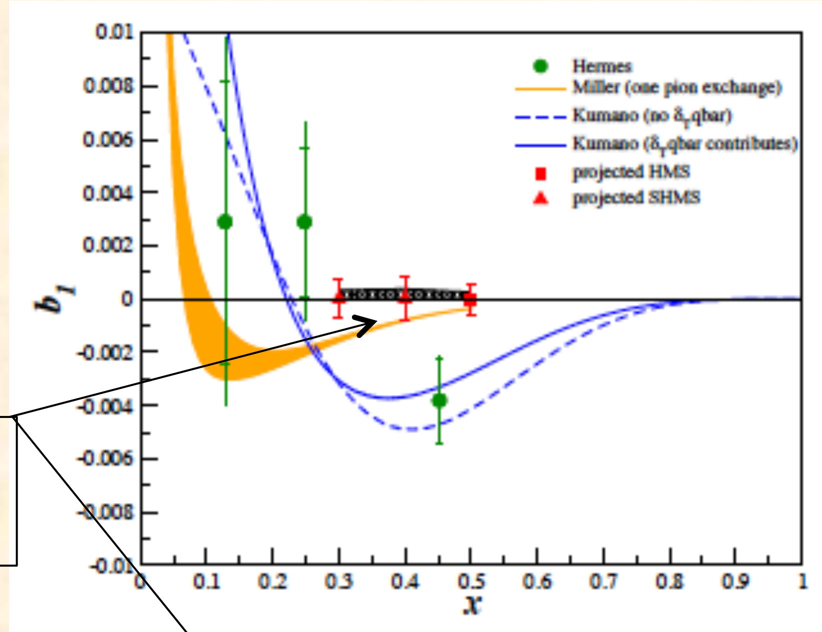
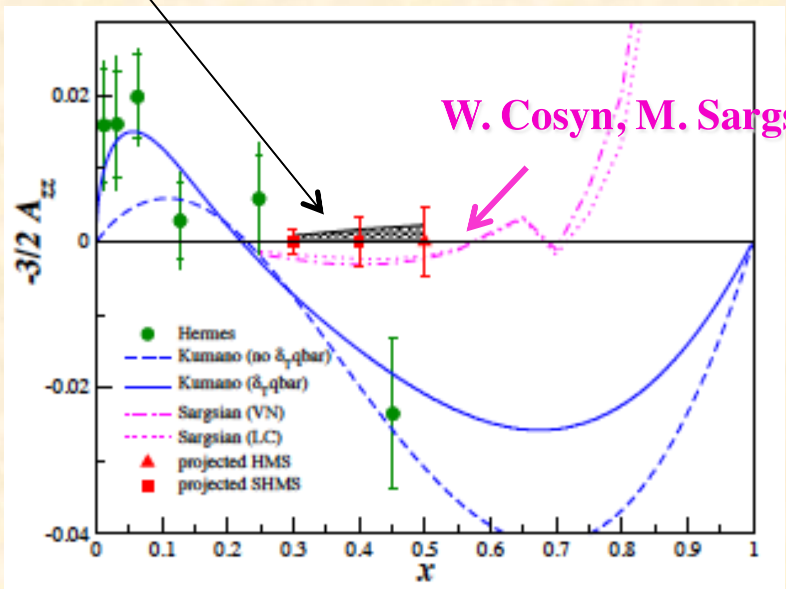
Seonho Choi, Hoyoung Kang, Hyekoo Kang, Yoomin Oh
Seoul National University, Seoul 151-747 Korea

Approved!

Expected errors by JLab





W. Cosyn, M. Sargsian

$$-\frac{3}{2}A_{zz} \sim \frac{b_1}{F_1}$$

Experimental possibility at Fermilab

E1039

Polarized fixed-target experiments at the Main Injector

© Fermilab

Drell-Yan experiment with a polarized proton target

Co-Spokespersons: A. Klein, X. Jiang, Los Alamos National Laboratory

List of Collaborators:

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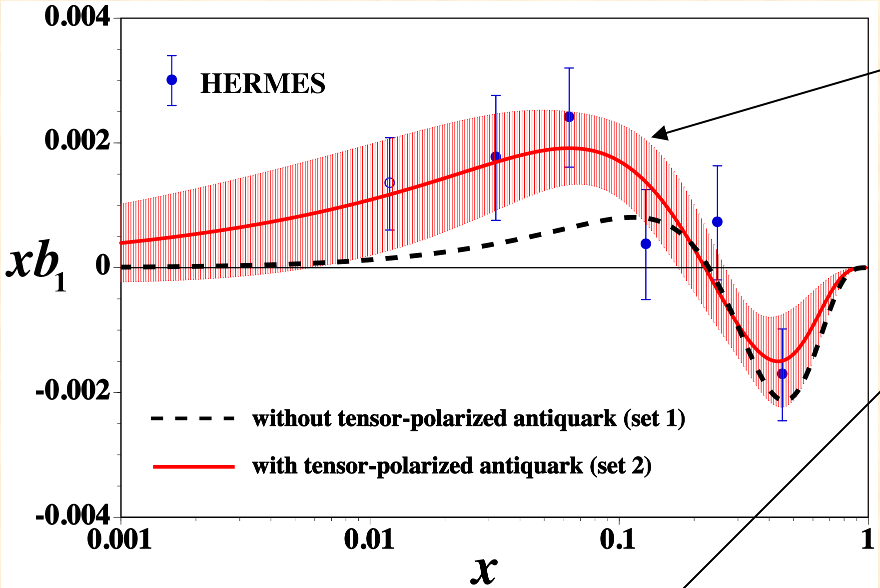
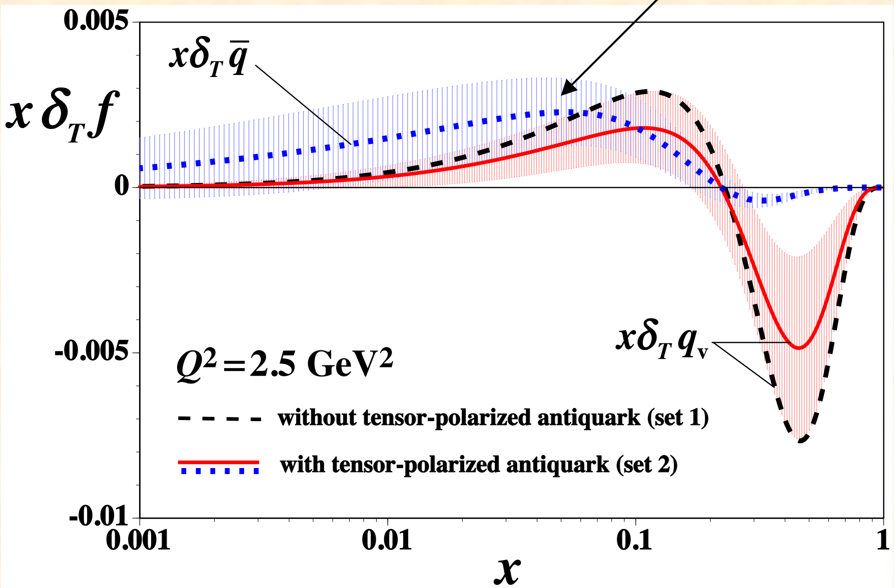
Tensor-polarized PDFs with errors



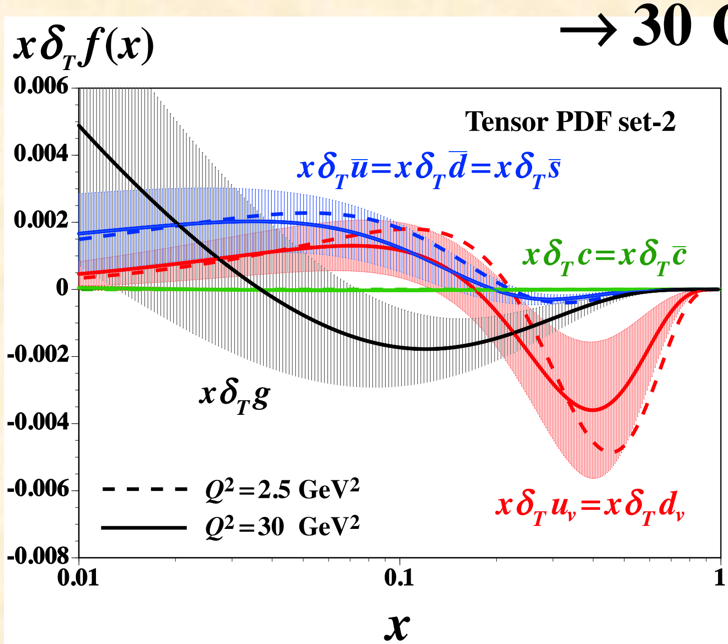
still large errors,
need experimental improvement
→ JLab, EIC, ...

experimental measurement
for antiquark distributions
→ Fermilab, ...



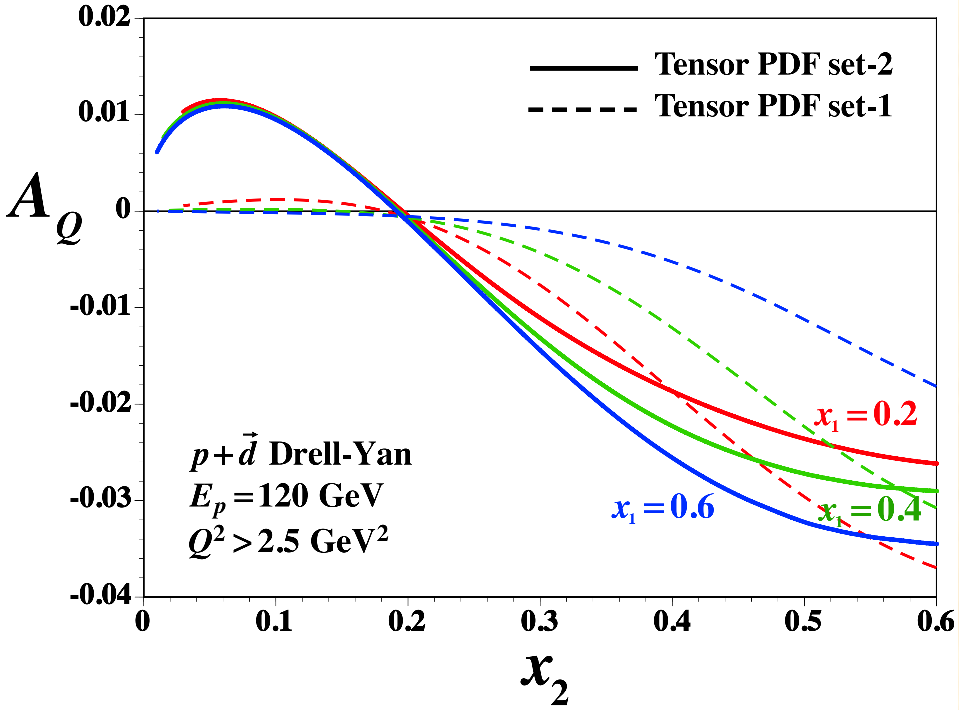
Q^2 evolution

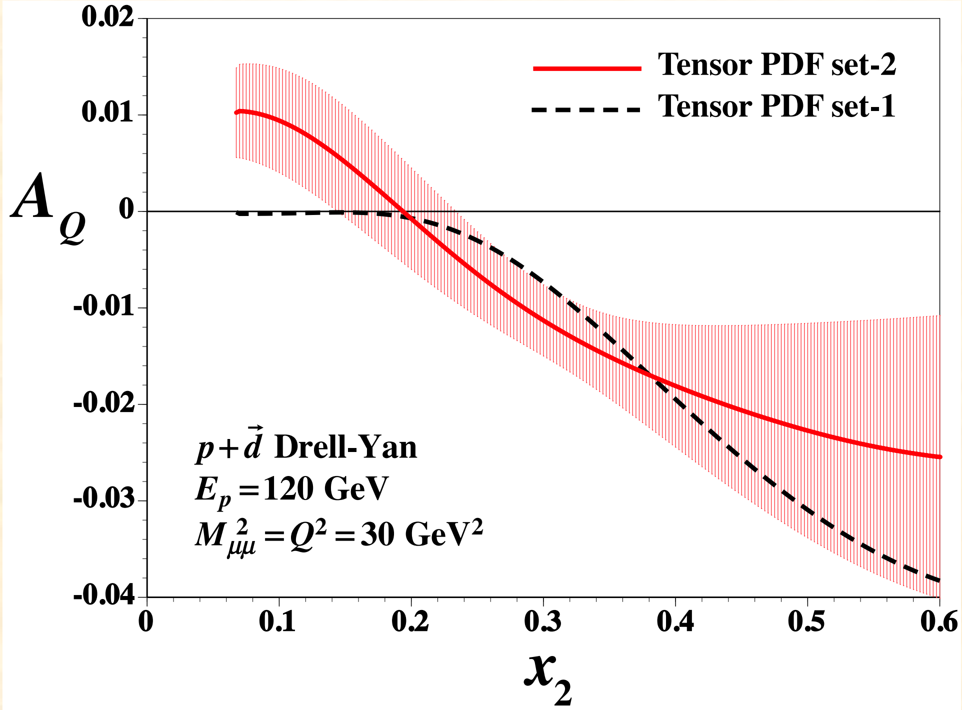
$Q^2 = 2.5$ GeV^2
$\to 30$ GeV^2



Tensor-polarized spin asymmetry

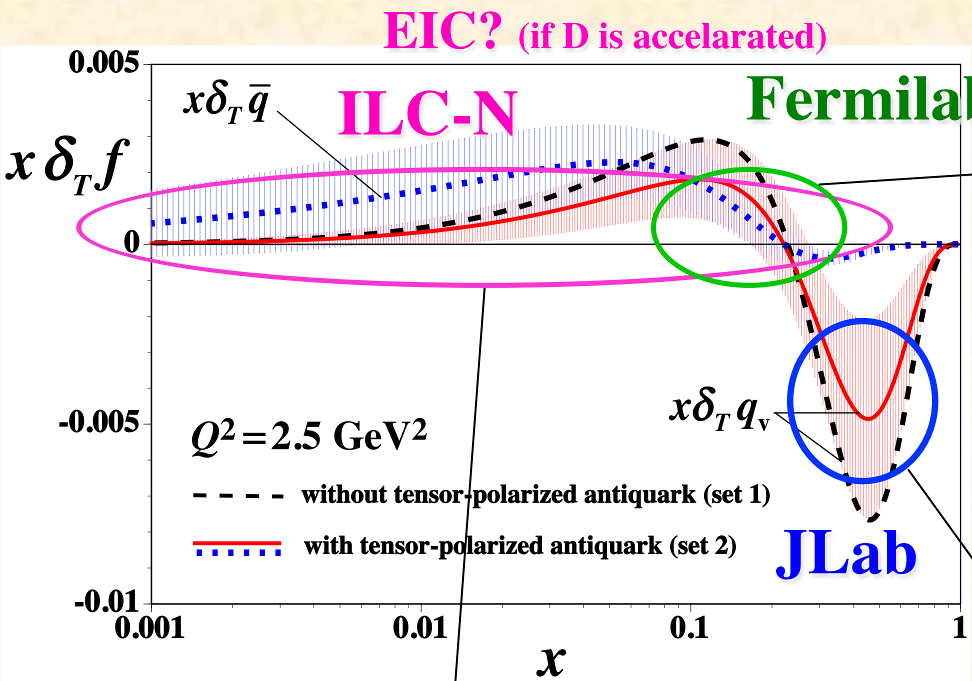
$$A_Q = \frac{\sum_a e_a^2 \left[q_a(x_A)\, \delta_T \bar{q}_a(x_B) + \bar{q}_a(x_A)\, \delta_T q_a(x_B) \right]}{\sum_a e_a^2 \left[q_a(x_A)\, \bar{q}_a(x_B) + \bar{q}_a(x_A)\, q_a(x_B) \right]}$$

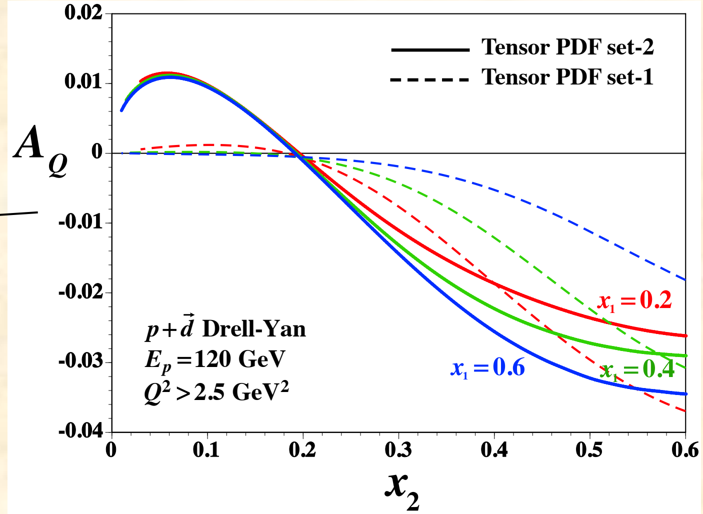


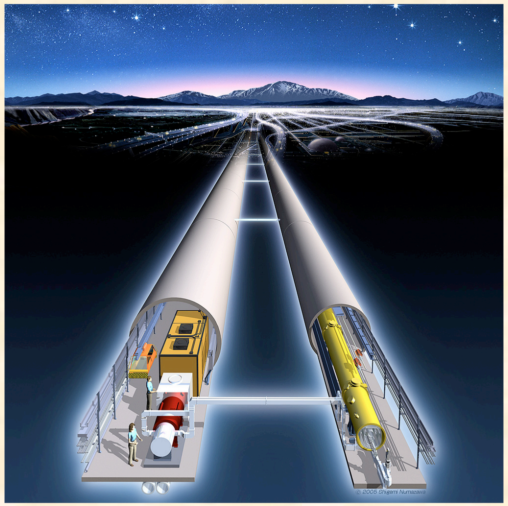


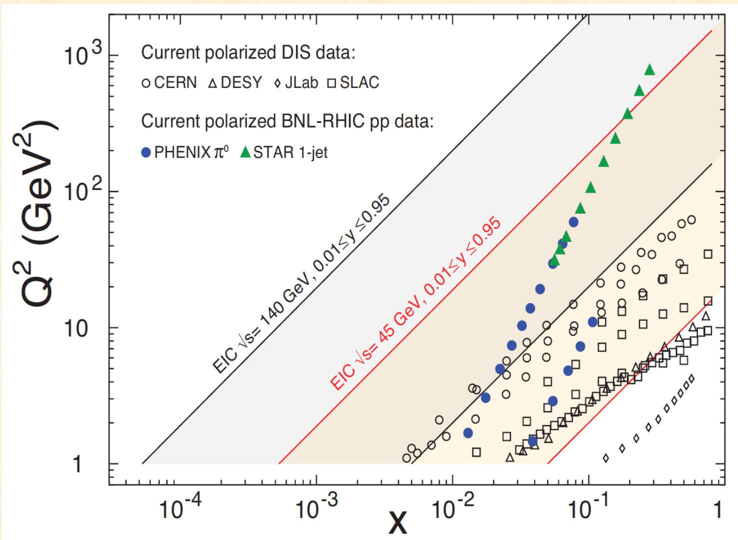
S. Kumano and Qin-Tao Song,
Phys. Rev. D94 (2016) 054022.

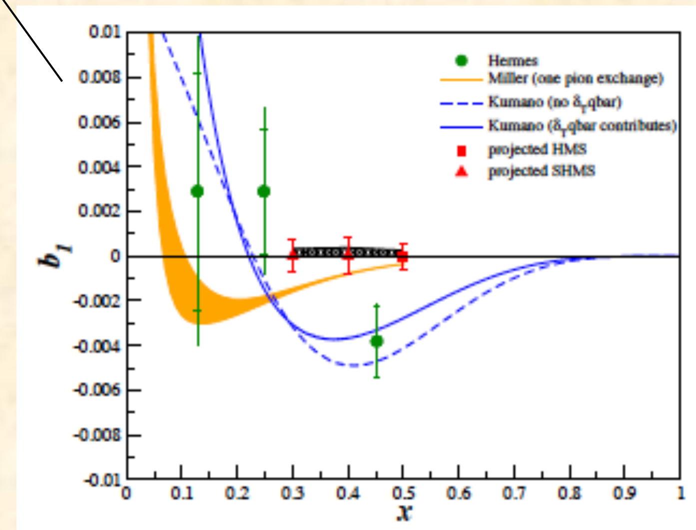
Small-x physics of b_1 at EIC





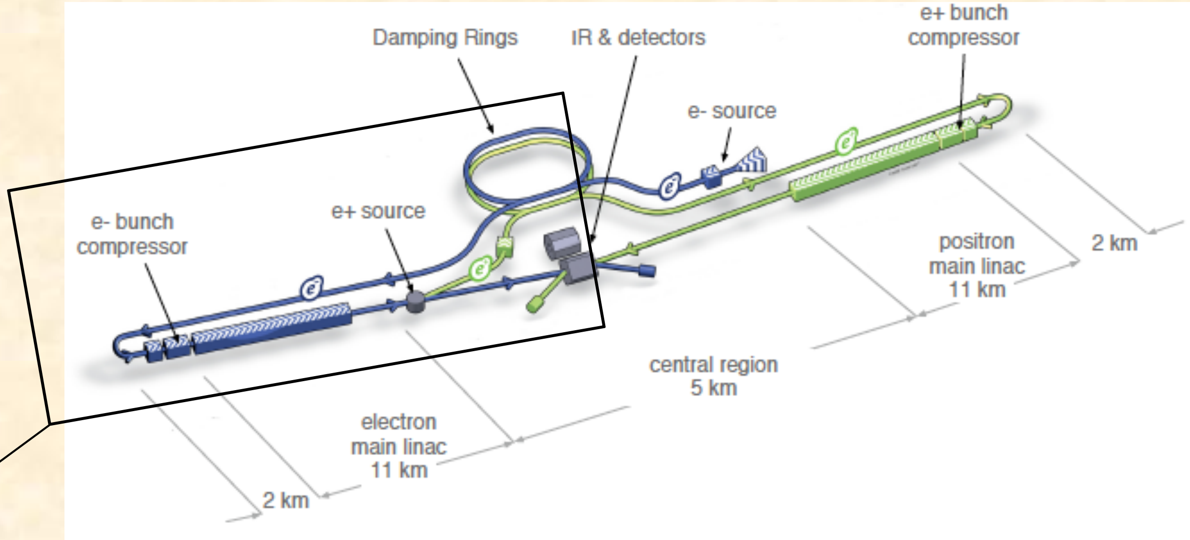


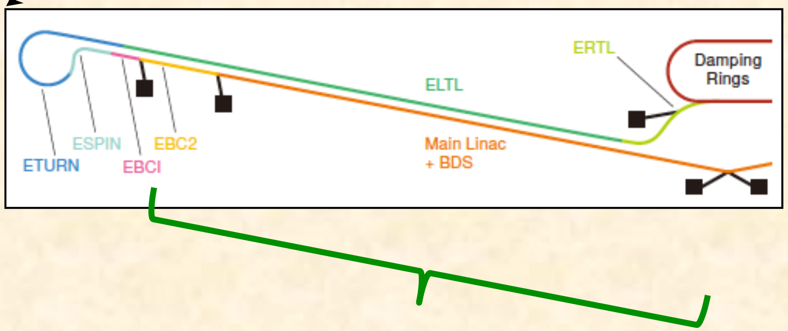




ILC-N (Fixed target option) for hadron physics?

ILC TDR (Technical Design Report)
https://www.linearcollider.org/ILC/Publications/Technical-Design-Report





5 – 250 GeV electron beams
for fixed target experiments

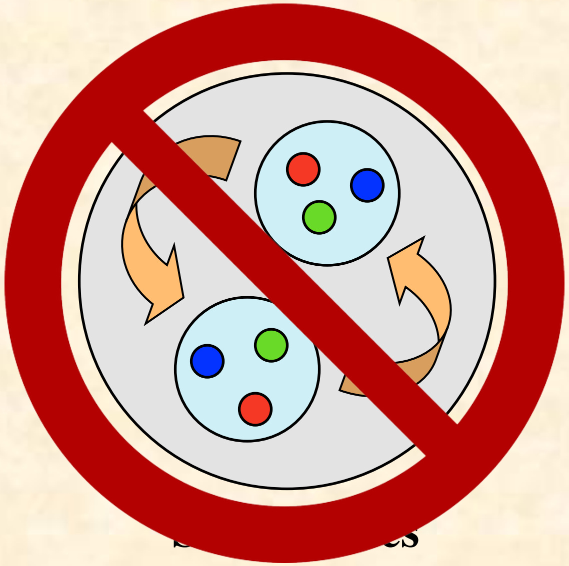
Possibilities for hadron and nuclear physics
- e^+e^- annihilation processes
- fixed target experiments
  with 5 – 250 GeV electron beams (ILC-N)

→ No serious studies about these feasibilities.

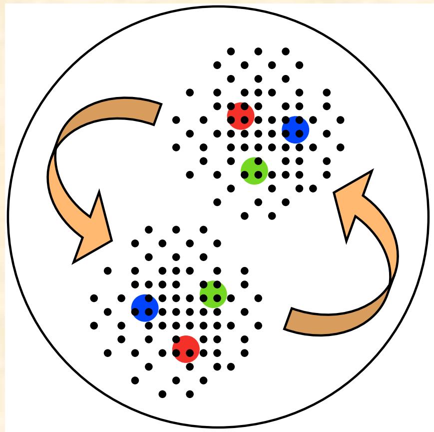
Summary on tensor structure

Spin-1 structure functions of the deuteron

- new spin structure
- tensor structure in quark-gluon degrees of freedom
- new exotic signature in hadron-nuclear physics?
- experiments: Jlab (approved), Fermilab, ... , EIC, ILC, ...
- ILC/EIC → appropriate to study tensor-polarized antiquark distributions at small-x, Q^2 evolution of b_1



standard model



? new exotic mechanism?

Strange-quark distribution

Skip some pages

Structure functions in parton model for neutrino-nucleon scattering

$F_2 = 2\,x\,F_1$

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

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

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

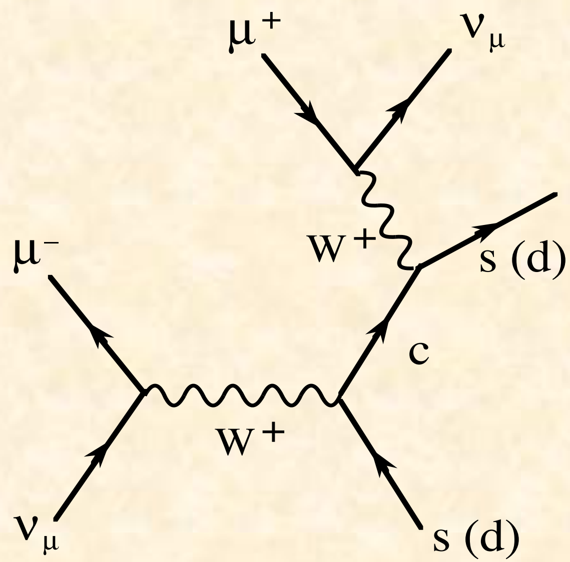
$$xF_3^{\nu n} = 2\,x\,(u + s - \bar{d} - \bar{c})$$
$$xF_3^{\bar{\nu} n} = 2\,x\,(d + c - \bar{u} - \bar{s})$$

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

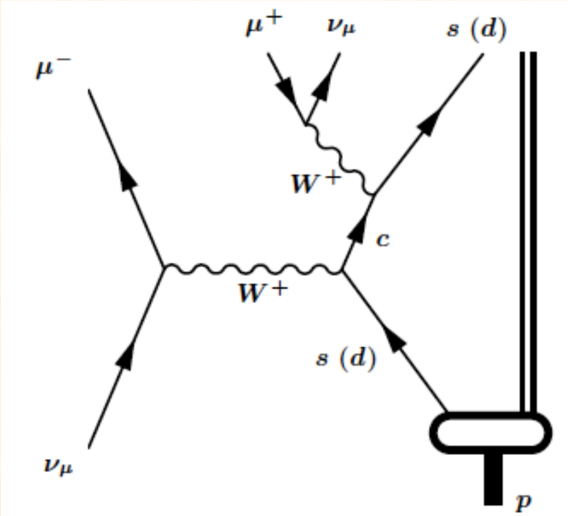
valence-quark distributions

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

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].

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

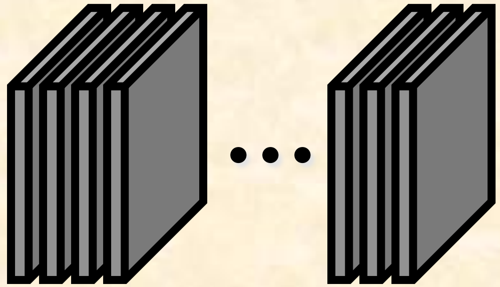
$Q^2 = 20\ \mathrm{GeV}^2$

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

$\nu,\ \bar{\nu}$

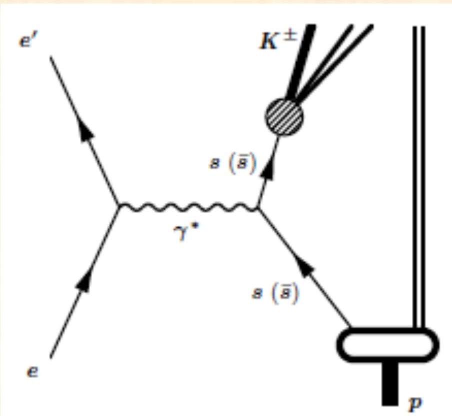
$E = 30 \sim 500$ GeV

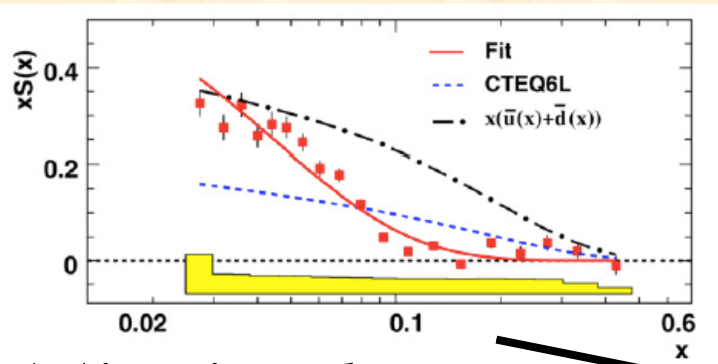


Huge Fe target (690 ton)

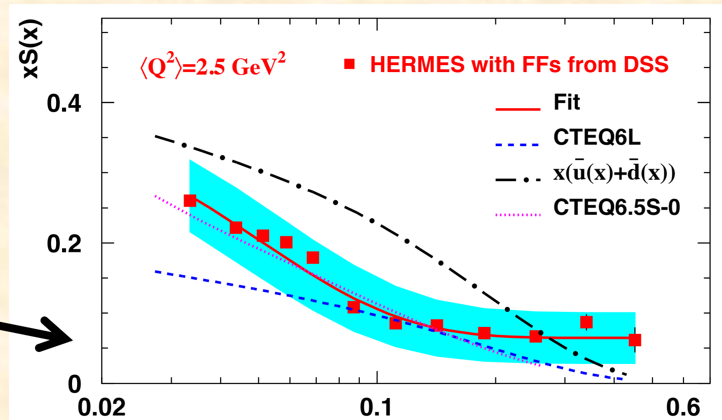
Issue: nuclear corrections

HERMES semi-inclusive measurement





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



PRD 89 (2014) 097101.

Neutral network

NNPDF (R. D. Ball *et al.*), JHEP 04 (2015) 040

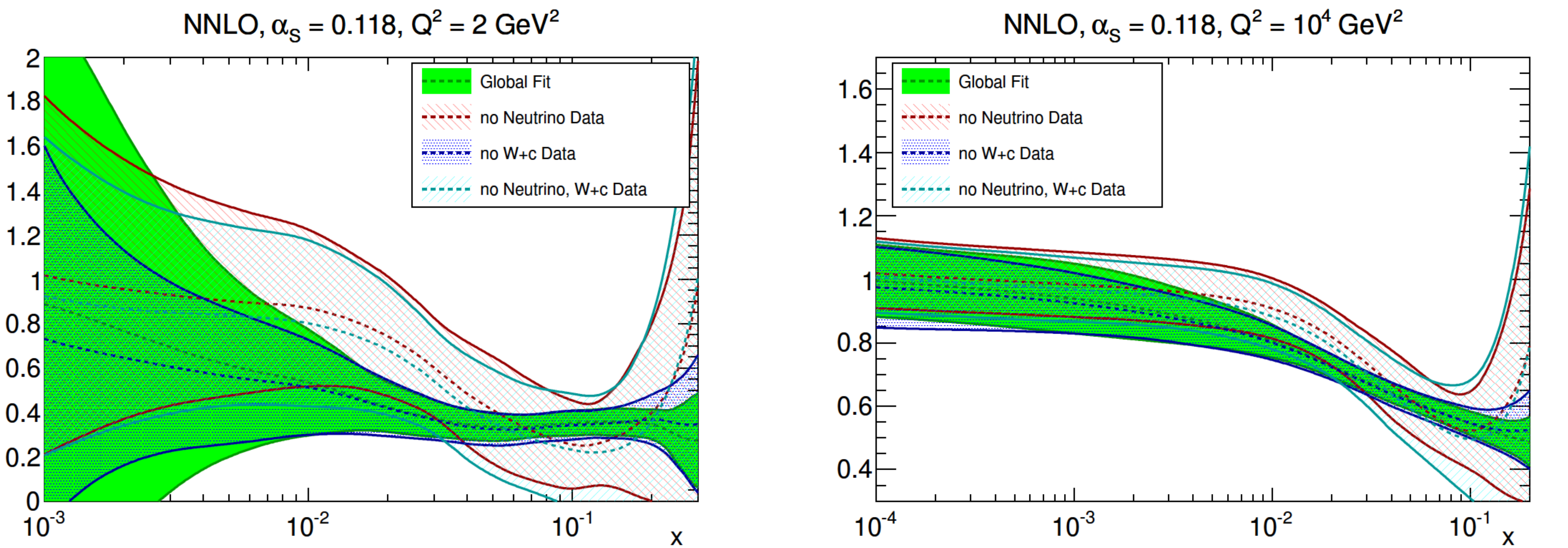


Figure 54. The strangeness ratio r_s eq. (5.2), at NNLO sets with $\alpha_s(M_Z) = 0.118$ plotted vs. x at $Q^2 = 2\,\mathrm{GeV}^2$ (left) and $Q^2 = 10^4\,\mathrm{GeV}^2$ (right) for the default NNPDF3.0 PDF set compared to set obtained excluding from the fitted dataset either neutrino data, or W+c, or both neutrino and W+c data. and a fit with neither of the two datasets.

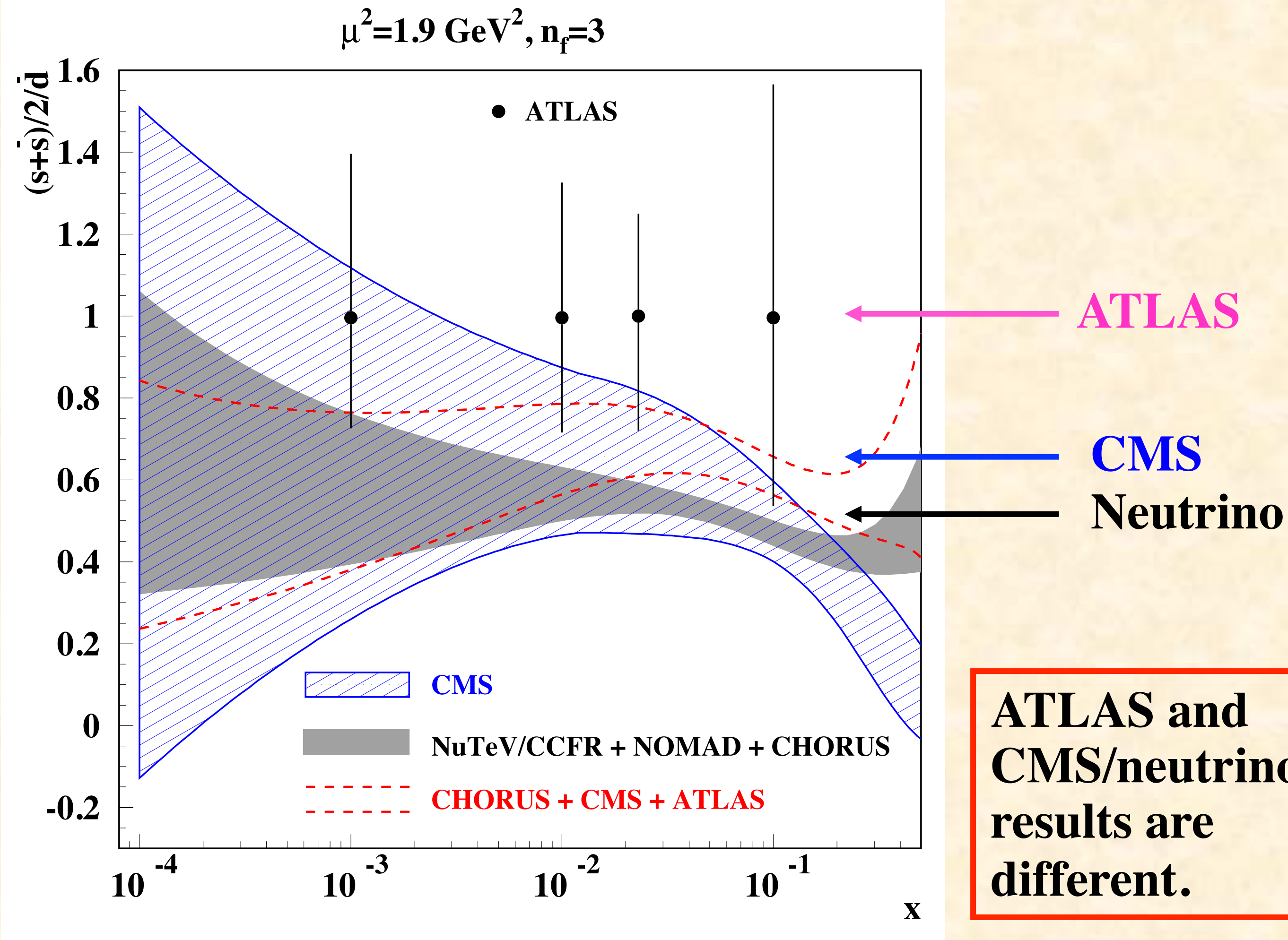
$$r_s(x, Q^2) = \frac{s(x, Q^2) + \bar{s}(x, Q^2)}{\bar{d}(x, Q^2) + \bar{u}(x, Q^2)}$$

Strange-quark distribution with LHC measurements

S. Alekhin *et al.*,
PRD 91 (2015) 094002.

Neutrino: $s + W \to c$

LHC: $g + s \to W + c$



ATLAS and CMS/neutrino results are different.

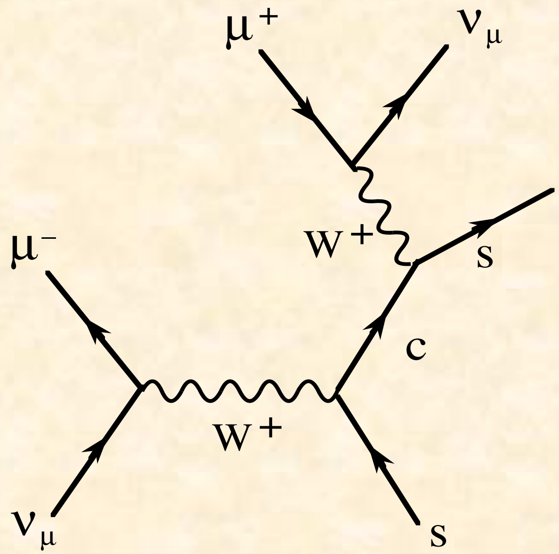
$s - \bar{s}$ asymmetry

Neutrino-Nucleon Scattering: charged current (CC)

Neutrino-induced opposite-sign dimuon events have been used for determining the strange-quark distribution.

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

for finding $\dfrac{2\bar{s}}{(\bar{u}+\bar{d})}$



Inconsistent with the strange distribution by HERMES?

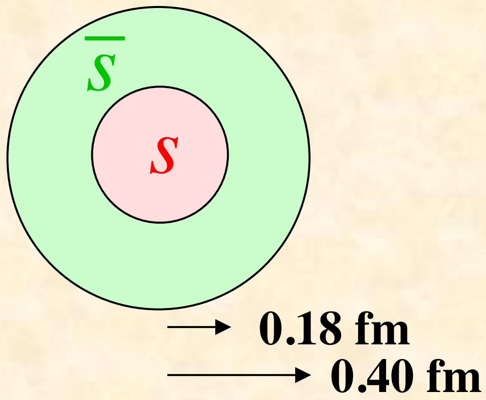
Motivations for $s(x) - \bar{s}(x)$

- Nucleon does not have net strangeness: $\int_0^1 dx\left[s(x) - \bar{s}(x)\right] = 0.$
  However, it does not mean $s(x) = \bar{s}(x)$. $\rightarrow$ could be $s(x) \neq \bar{s}(x)$
- If s and $\bar{s}$ are created perturbatively, they should be equal $s(x) = \bar{s}(x)$.
- Hadron models predict the asymmetry: $s(x) \neq \bar{s}(x)$.

$$p(uud) \rightarrow KY \quad [K^+(u\bar{s})\Lambda(uds),\ K^+(u\bar{s})\Sigma^0(uds),\ K^0(d\bar{s})\Sigma^+(uus), \cdots]$$

$$1/m_{K^+} = 1/494 \text{ MeV} = 0.40 \text{ fm}$$

$$1/m_\Lambda = 1/1116 \text{ MeV} = 0.18 \text{ fm}$$

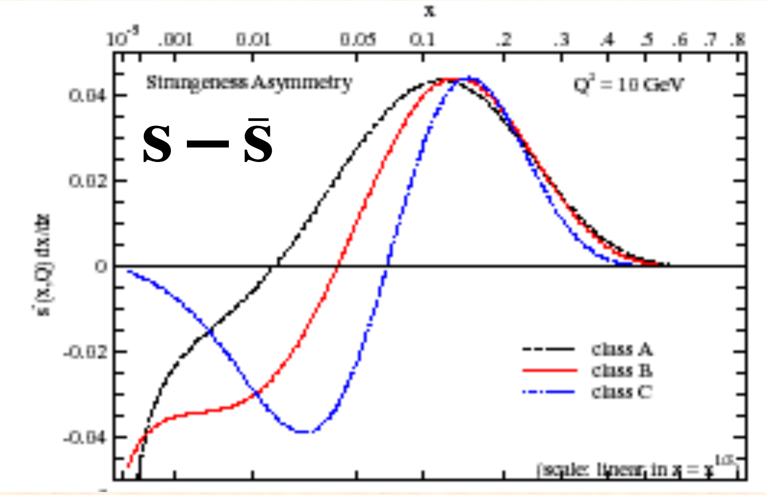


- The asymmetry could be important for NuTeV anomaly.

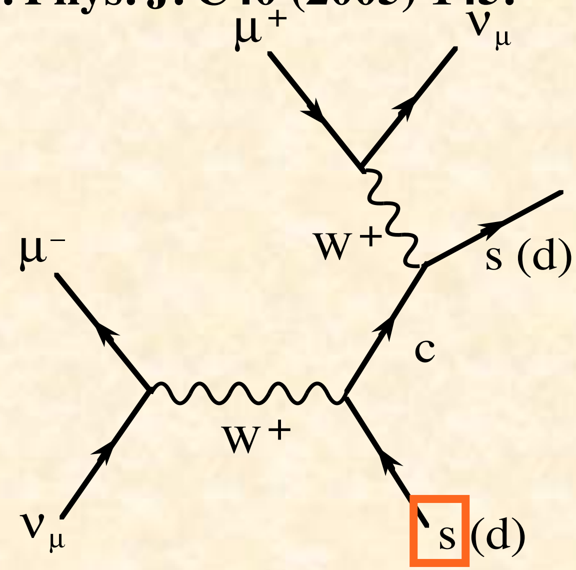
$s-\bar{s}$ effects on $\sin^2\theta_W$

CTEQ, Phys. Rev. Lett. 93 (2004) 041802;
Eur. Phys. J. C40 (2005) 145.

Global fit to the data including
CCFR-NuTeV dimuon data with $s\text{-}\bar{s} \neq 0$



x



(note: $-\ 0.001 < \langle x \rangle_{s\_} < 0.005$ in the 2007 version)

$$-0.001 < \int dx\, x(s-\bar{s}) < +0.004$$

$$\boxed{-0.005 < \delta(\sin^2\theta_W) < +0.001}$$

of the order of the NuTeV deviation

→ could not be "anomalous"

$s - \bar{s}$

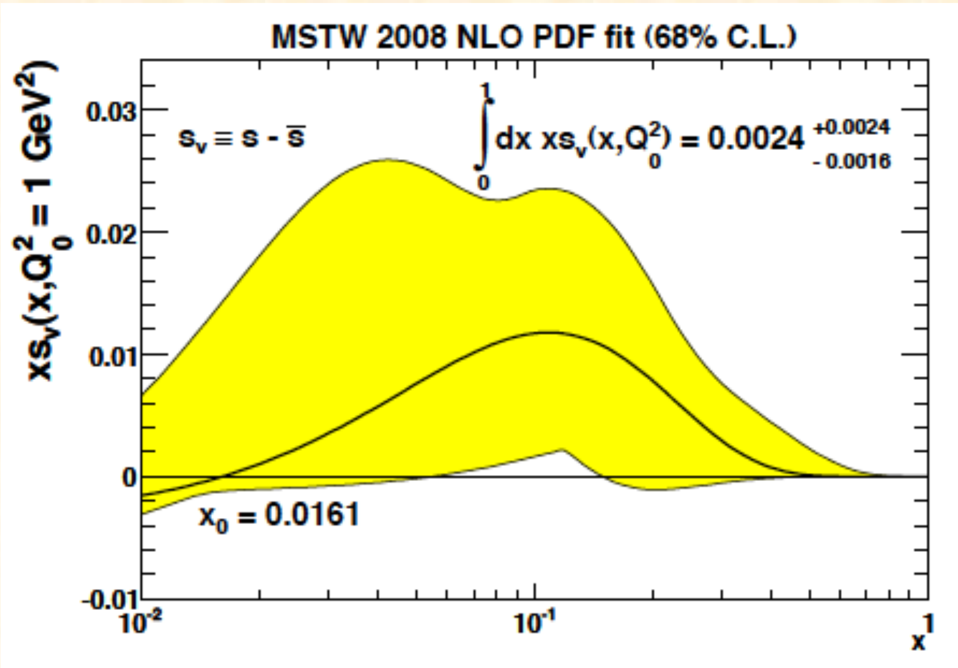
CTEQ (2007)

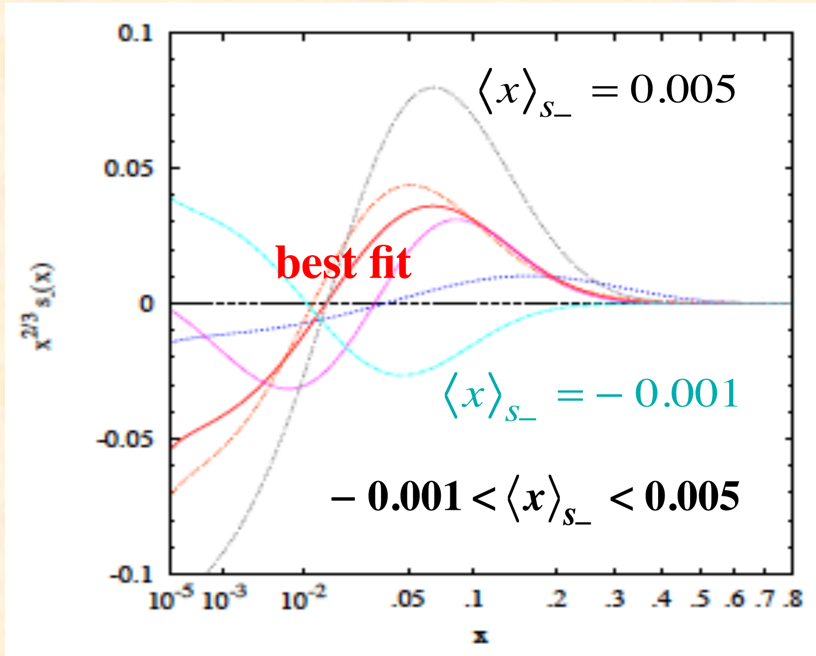
H.-L. Lai *et al.*, JHEP 04 (2007) 089.

MSTW (2009)

$$Q_0^2 = 1\ \mathrm{GeV}$$
$$x\left[s(x) - \bar{s}(x)\right] = A_- x^{\delta_-}(1-x)^{\eta_-}(1 - x/x_0)$$

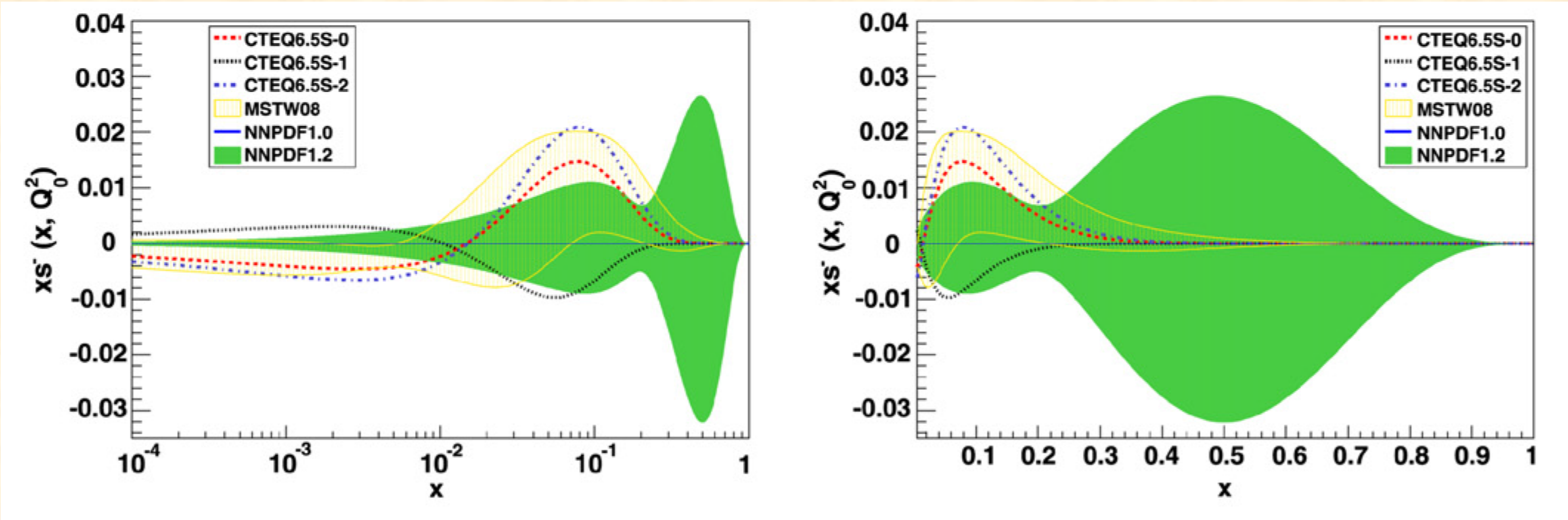
$$Q_0^2 = (1.3)^2\ \mathrm{GeV}^2$$
$$s_-(x,Q_0^2) = s_+(x,Q_0^2)\frac{2}{\pi}\tan^{-1}\left[cx^a\left(1-\frac{x}{b}\right)e^{dx+ex^2}\right]$$
$$s_+(x,Q_0^2) = A_0 x^{A_1}(1-x)^{A_2}P_+(x),\quad P_+(x) = e^{A_3\sqrt{x}+A_4x+A_5x^2}$$





Neural network

NNPDF (R. D. Ball *et al.*), NPB 823 (2009) 195



NuTeV $\sin^2\theta_W$ anomaly

Nuclear modification difference between u_v and d_v:

S. Kumano, PR D66 (2002) 111301;

M. Hirai, SK, T.-H. Nagai, PR D71 (2005) 113007.

$\sin^2\theta_W$ anomaly

Others: $\sin^2\theta_W = 1 - m_W^2/m_Z^2 = 0.2227 \pm 0.0004$

NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0013\ \text{(stat)} \pm 0.0009\ \text{(syst)}$

G. P. Zeller et al., PRL 88 (2002) 091802; 90 (2003) 239902(E)

Paschos-Wolfenstein (PW) relation

$$R^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\bar{\nu} N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\bar{\nu} N}} = \frac{1}{2} - \sin^2\theta_W$$

N = isoscalar nucleon

NuTeV target: ^{56}Fe (Z = 26, N = 30)

not isoscalar nucleus

$\longrightarrow$ nuclear effects should be carefully taken into account

Charged current (CC) cross sections for νA and $\bar{\nu} A$:

$$\frac{d\sigma_{CC}^{\nu A}}{dx\,dy} = \sigma_0\, x\, [\, d^A(x) + s^A(x) + \{\bar{u}^A(x) + \bar{c}^A(x)\}\,(1-y)^2]$$

$$\frac{d\sigma_{CC}^{\bar{\nu} A}}{dx\,dy} = \sigma_0\, x\, [\, \bar{d}^A(x) + \bar{s}^A(x) + \{u^A(x) + c^A(x)\}\,(1-y)^2]$$

where $\sigma_0 = G_F^2\, s / \pi$

Neutral current (NC):

$$\frac{d\sigma_{NC}^{\nu A}}{dx\,dy} = \sigma_0\, x\, [\, \{u_L^2 + u_R^2\,(1-y)^2\}\{u^A(x) + c^A(x)\}$$
$$+ \{u_R^2 + u_L^2\,(1-y)^2\}\{\bar{u}^A(x) + \bar{c}^A(x)\}$$
$$+ \{d_L^2 + d_R^2\,(1-y)^2\}\{d^A(x) + s^A(x)\}$$
$$+ \{d_R^2 + d_L^2\,(1-y)^2\}\{\bar{d}^A(x) + \bar{s}^A(x)\}$$

$$\frac{d\sigma_{NC}^{\bar{\nu} A}}{dx\,dy} = \frac{d\sigma_{NC}^{\nu A}}{dx\,dy}\ (L \leftrightarrow R)$$

$$u_L = +\frac{1}{2} - \frac{2}{3}\sin\theta_W^2\,,\quad u_R = -\frac{2}{3}\sin\theta_W^2$$

$$d_L = -\frac{1}{2} + \frac{1}{3}\sin\theta_W^2\,,\quad u_R = +\frac{1}{3}\sin\theta_W^2$$

$$R_A^- = \frac{\sigma_{NC}^{\nu A}/dxdy - \sigma_{NC}^{\bar{\nu} A}/dxdy}{\sigma_{CC}^{\nu A}/dxdy - \sigma_{CC}^{\bar{\nu} A}/dxdy} = \frac{\{1-(1-y)^2\}\left[(u_L^2 - u_R^2)\{u_v^A(x)+c_v^A(x)\}+(d_L^2-d_R^2)\{d_v^A(x)+s_v^A(x)\}\right]}{d_v^A(x)+s_v^A(x)-(1-y)^2\{u_v^A(x)+c_v^A(x)\}}$$

$$q_v^A \equiv q^A - \bar{q}^A$$

(1) Difference between nuclear modifications of u_V and d_V: $\varepsilon_v(x) = \dfrac{w_{d_v}(x) - w_{u_v}(x)}{w_{d_v}(x) + w_{u_v}(x)}$

Nuclear effects are in the weight functions: w_{u_v} and w_{d_v}

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

(2) Neutron excess: $\varepsilon_n(x) = \dfrac{N-Z}{A}\,\dfrac{u_V(x) - d_V(x)}{u_V(x) + d_V(x)}$

(3) Strange, Charm: $\varepsilon_s(x)$, $\varepsilon_c(x) = \dfrac{2\,s_v^A(x) \quad \text{or} \quad 2\,c_v^A(x)}{[w_{uv}(x) + w_{dv}(x)][u_V(x) + d_V(x)]}$

$$R_A^- = \frac{(\frac{1}{2} - \sin^2\theta_W)\,\{1 + \varepsilon_v(x)\,\varepsilon_n(x)\} + \frac{1}{3}\sin^2\theta_W\,\{\varepsilon_v(x) + \varepsilon_n(x)\} + (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)\,\varepsilon_s(x) + (\frac{1}{2} - \frac{4}{3}\sin^2\theta_W)\,\varepsilon_c(x)}{1 + \varepsilon_v(x)\,\varepsilon_n(x) + \dfrac{1+(1-y)^2}{1-(1-y)^2}\,\{\varepsilon_v(x) + \varepsilon_n(x)\} + \dfrac{2\{\varepsilon_s(x) - (1-y)^2\,\varepsilon_c(x)\}}{1-(1-y)^2}}$$

Expand in ε_v, ε_n, ε_s, ε_c << 1

S. Kumano, PRD 66 (2002) 111301.

$$\mathbf{R_A^- = \frac{1}{2} - \sin^2\theta_W + O(\varepsilon_v) + O(\varepsilon_n) + O(\varepsilon_s) + O(\varepsilon_c)}$$

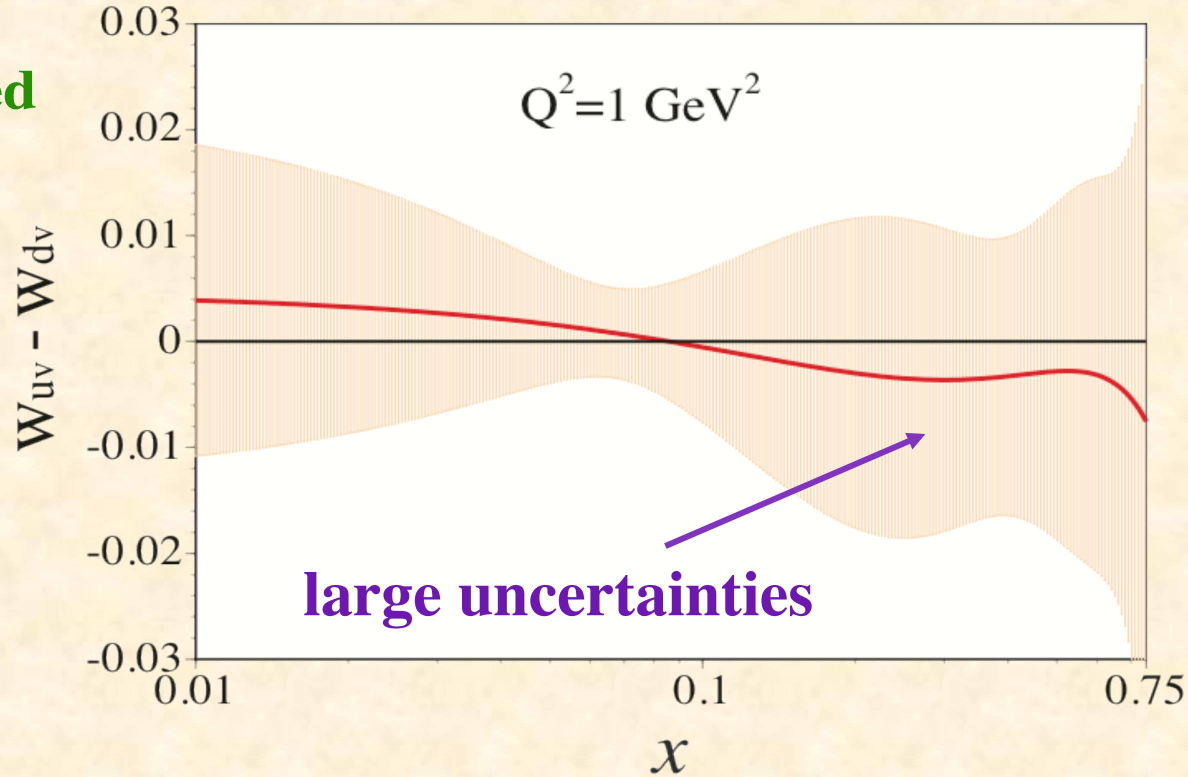
Analysis result for $\varepsilon_v(x)$

$$\varepsilon_v(x) = \frac{w_{d_v}(x) - w_{u_v}(x)}{w_{d_v}(x) + w_{u_v}(x)}$$

$$R_{\bar{A}} = \frac{1}{2} - \sin^2\theta_W - \varepsilon_v(x) \left\{ \left(\frac{1}{2} - \sin^2\theta_W\right) \frac{1+(1-y)^2}{1-(1-y)^2} - \frac{1}{3}\sin^2\theta_W \right\} + O(\varepsilon_v^2)$$

$$w_{uv} - w_{dv} = 1 + (1 - 1/A^{1/3}) \frac{a'_v + b'_v x + c'_v x^2 + d'_v x^3}{(1-x)^{\beta_v}}$$

a'_v, b'_v, c'_v, d'_v are determined by the analysis



M. Hirai, SK, T.-H. Nagai, PR D71 (2005) 113007.

Summary

Flavor dependence of the antiquark distributions is a good quantity to test nonperturbative aspects of the nucleons and nuclei.

E906 Drell-Yan

x dependence of ubar/dbar at x=0.3-0.4 seems to agree with theories.
However, the results are different from E866.

Polarized PDFs: Δubar/Δdbar

Now, experimental measurements are becoming clear.

Nuclear PDFs: ubar/bar

Fermilab Drell-Yan in progress, new developments are expected!
There is only one (or a few?) theoretical work.

Tensor-polarized PDFs

JLab experiment starts soon in 2019, Fermilab under consideration
May be exciting new hadron physics!?

The End

The End