YAMAGATA UNIVERSITY

July 25th, 2013, Spin Fest @ RIKEN

Not only "polarized", let's talk "unpolarized" as well.

Polarized DIS/SIDIS experiments

To study **"flavor"** and **"spin"** structure of the **proton**.

1. DIS & Flavor structure of the proton
2. Spin structure of the proton in DIS
3. Transverse Momentum Dependent PDF in DIS
4. Generalized Parton Distribution functions

Yoshiyuki Miyachi, Yamagata University

From “text books”:

YAMAGATA UNIVERSITY

Quark & Leptons, F. Halzen and A. D. Martin (**1984**)

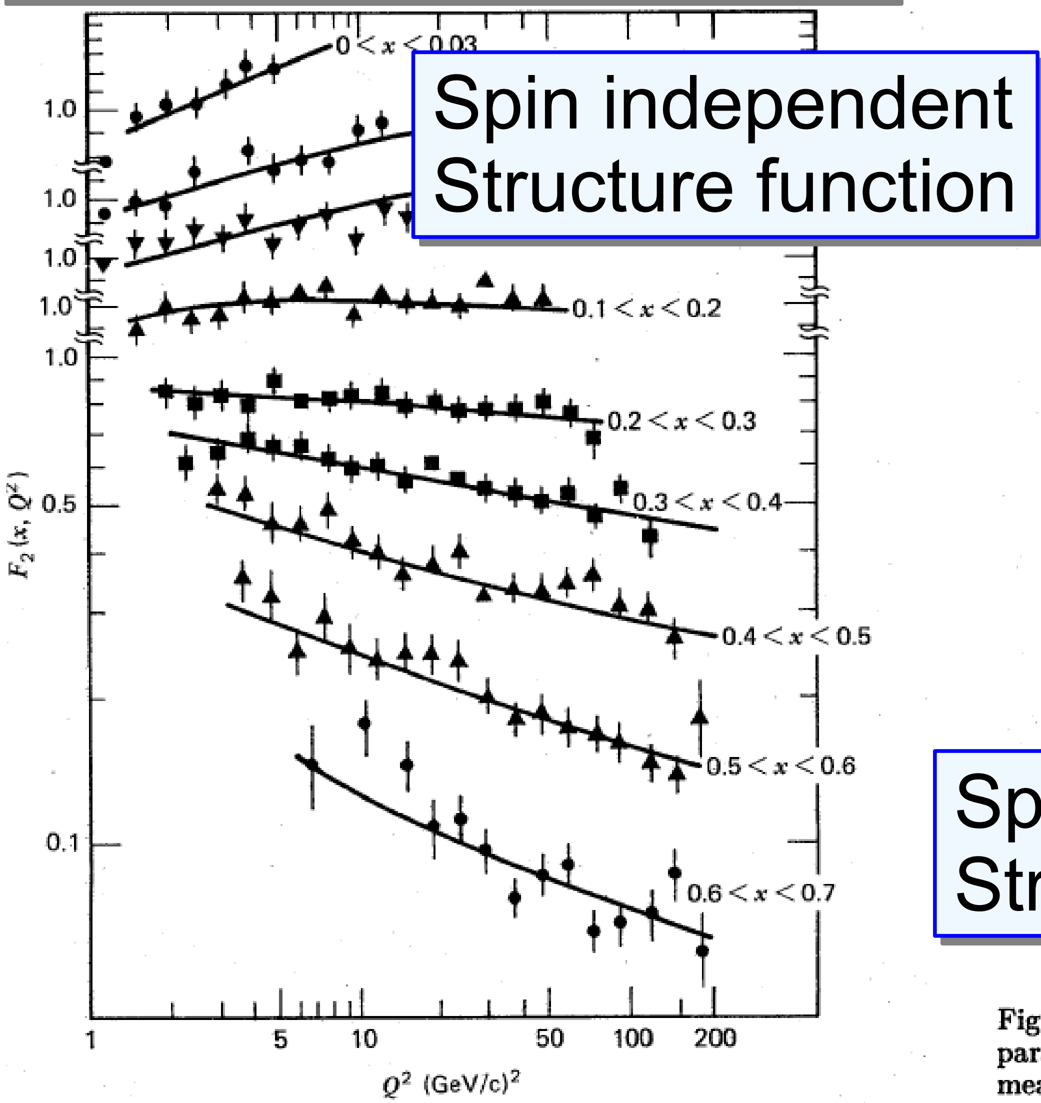


Fig. 10.10 Deviations from scaling. With increasing Q^2, the structure function $F_2(x, Q^2)$ increases at small x and decreases at large x. The data are from the CDHS counter experiment at CERN.

The structure of the proton, R. G. Roberts (**1990**)

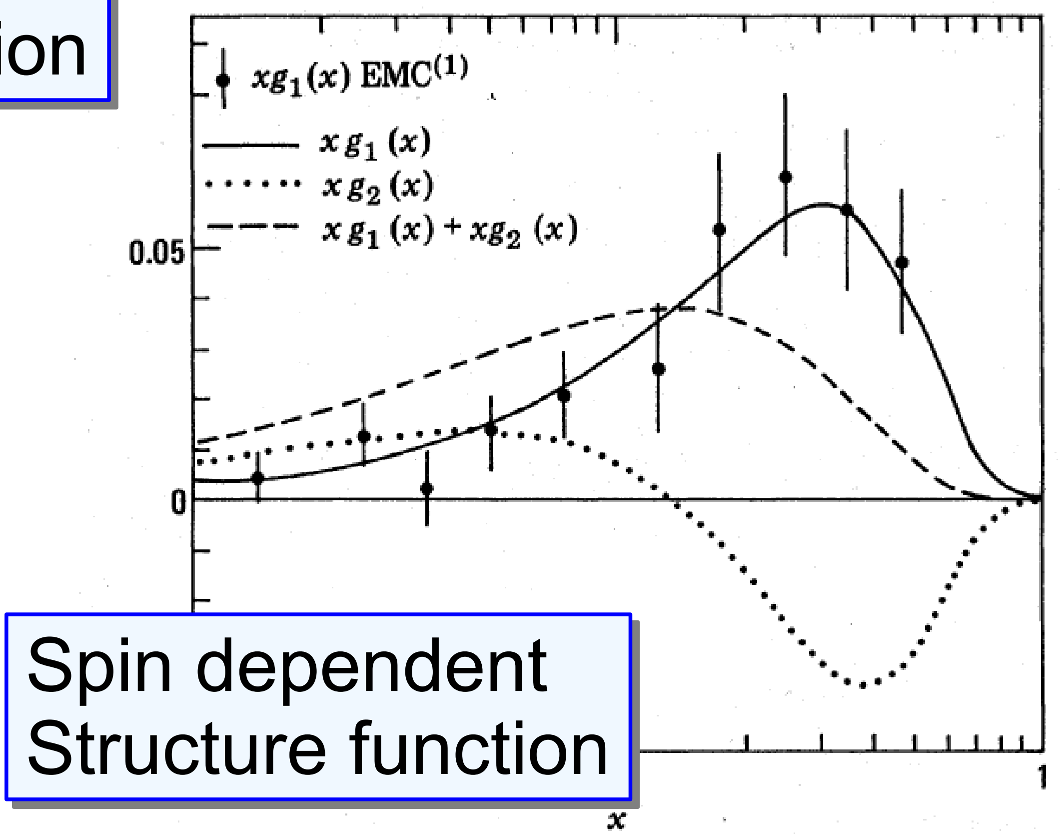


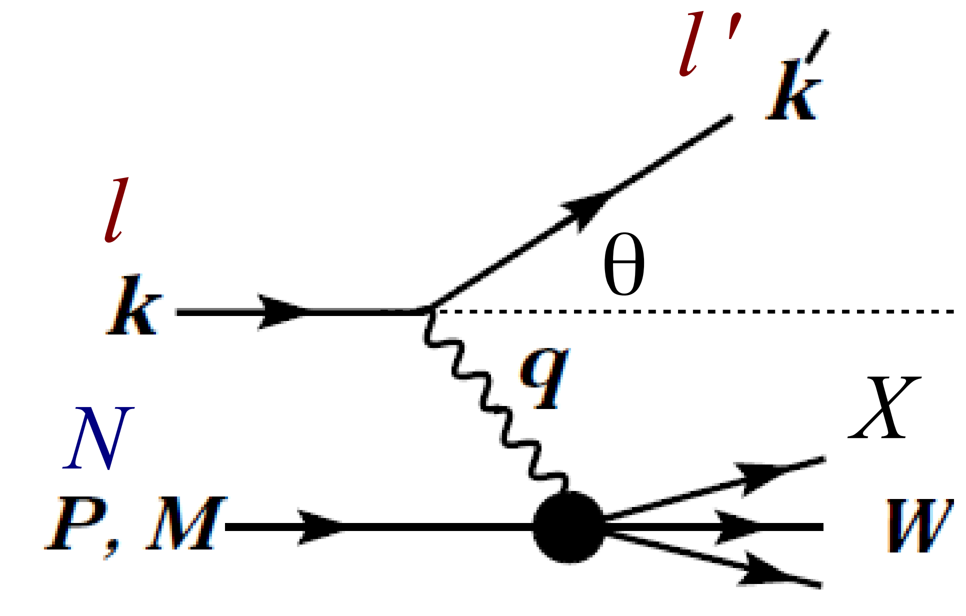
Fig. 3.9 Expectations for $xg_2(x)$, $xg_1(x) + xg_2(x)$ based on taking a parametrisation of the asymmetry $A(x) = g_1(x)/F_1(x)$ together with the measured values of $g_1(x)$.

1. DIS & Flavor structure of the proton

- Deep inelastic scattering
  - Structure function of the proton
  - Parton distribution function of the proton
  - Sum rules
- Gottfried sum rule
  - Gottfried sum rule in DIS
  - Flavor asymmetry in the proton sea
  - DIS and Drell-Yan
  - Drell-Yan experiments

Deep Inelastic Scattering: kinematics

$$l + N \rightarrow l' + X$$



Lab. Flame

$$q = k - k' \qquad \nu = E - E'$$

Virtuality

$$Q^2 = -q^2 = 2EE'\sin^2\frac{\theta}{2}$$

$$x = \frac{Q^2}{2P\cdot q} = \frac{Q^2}{2M\cdot\nu}$$

Bjorken x

$$y = \frac{P\cdot q}{P\cdot k} = \frac{\nu}{E}$$

$$W^2 = (P+q)^2$$

Inv. mass of X > Resonance

Experiment:

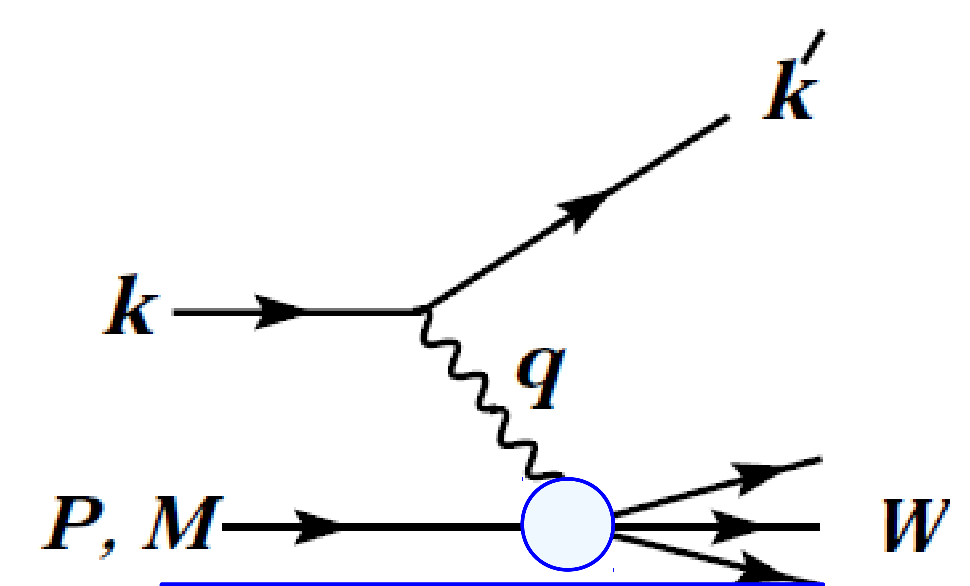
$E, E', \theta \Rightarrow x, y, Q^2, W$

Event by event

DIS cross section and structure functions

Unpolarized DIS

$$\frac{d^2\sigma^i}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\eta^i\left\{\left(1 - y - \frac{x^2y^2M^2}{Q^2}\right)F_2^i + y^2 xF_1^i \mp \left(y - \frac{y^2}{2}\right)xF_3^i\right\},$$



Structure functions

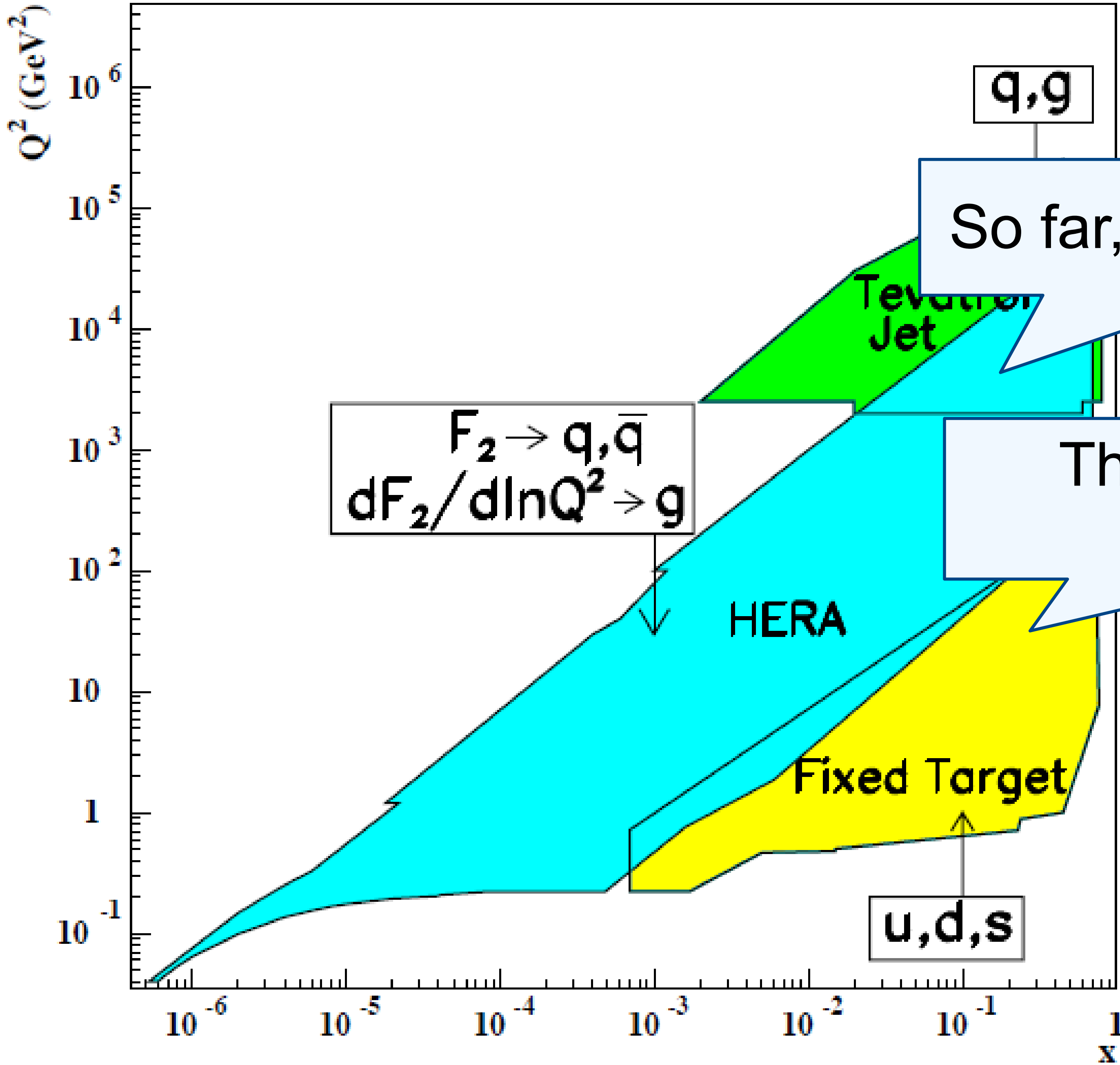
Polarized DIS

λ_l: Lepton helicity

$$\frac{d^2\Delta\sigma^i}{dxdy} = \frac{8\pi\alpha^2}{xyQ^2}\eta^i\left\{-\lambda_\ell y\left(2 - y - 2x^2y^2\frac{M^2}{Q^2}\right)xg_1^i + \lambda_\ell 4x^3y^2\frac{M^2}{Q^2}g_2^i\right.$$
$$+ 2x^2y\frac{M^2}{Q^2}\left(1 - y - x^2y^2\frac{M^2}{Q^2}\right)g_3^i$$
$$\left. - \left(1 + 2x^2y\frac{M^2}{Q^2}\right)\left[\left(1 - y - x^2y^2\frac{M^2}{Q^2}\right)g_4^i + xy^2g_5^i\right]\right\}$$

Neutrino scattering

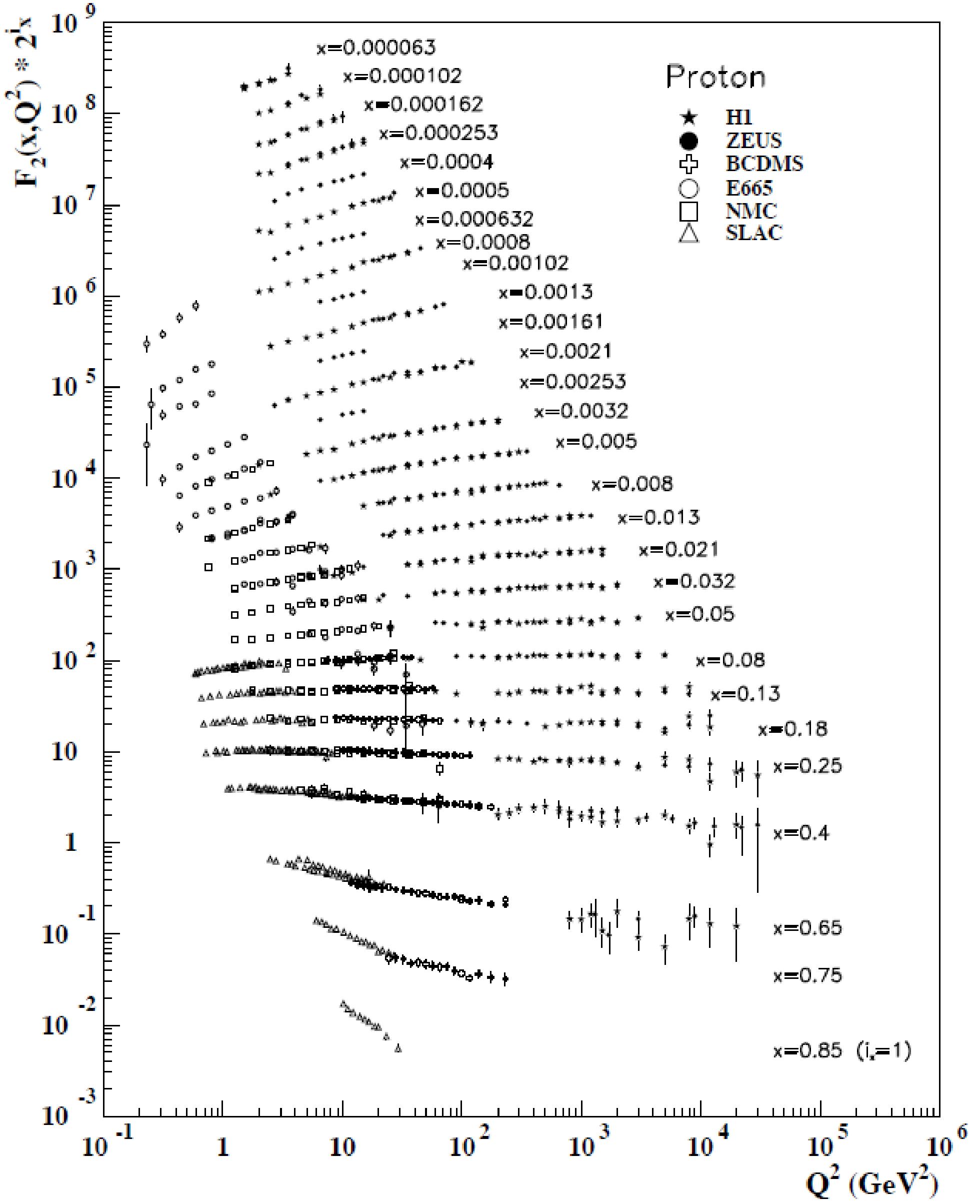
Kinematic coverage

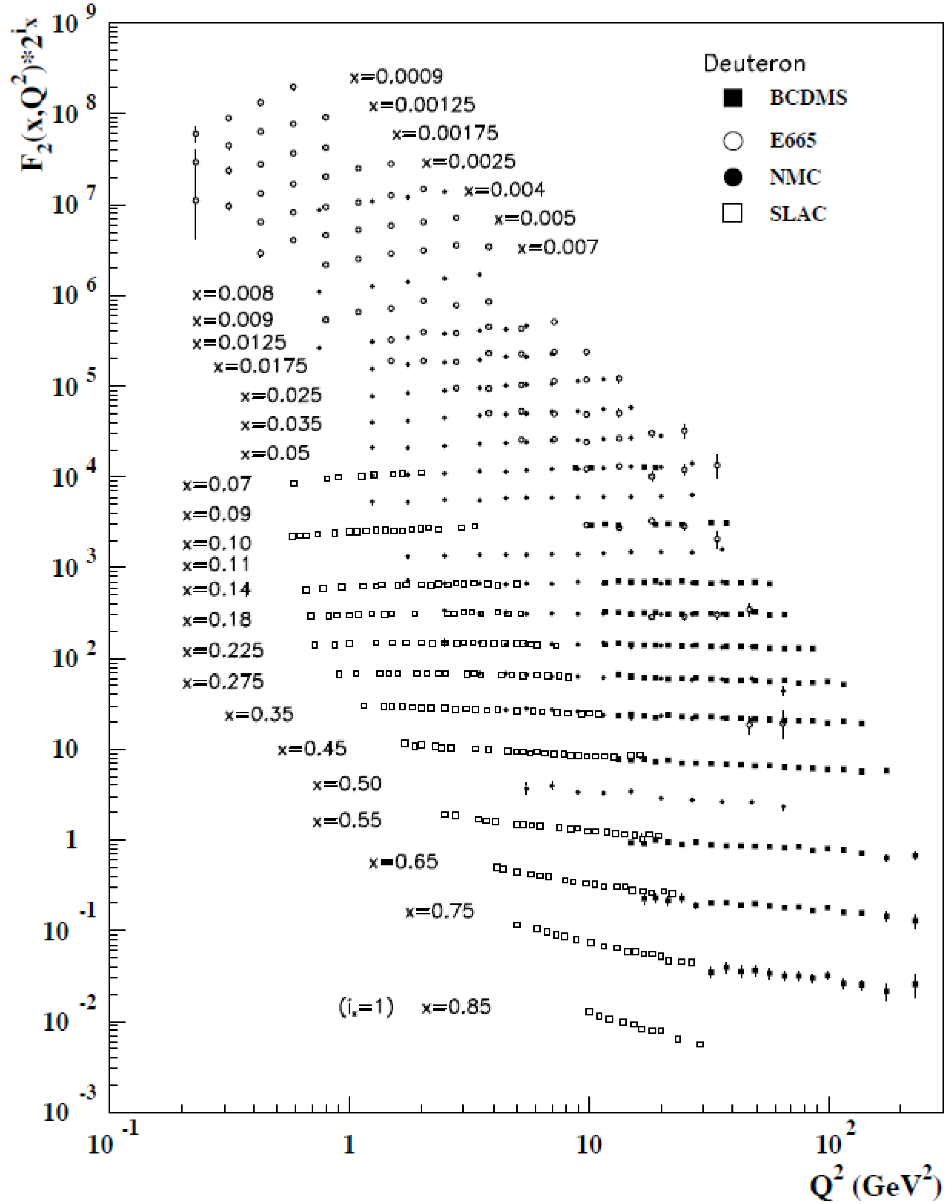


So far, no pol. l-N collider

This lecture covers "Fixed Target"

Structure function: F_2





Deep inelastic scattering and partons

YAMAGATA UNIVERSITY

$$l + N \rightarrow l' + X$$

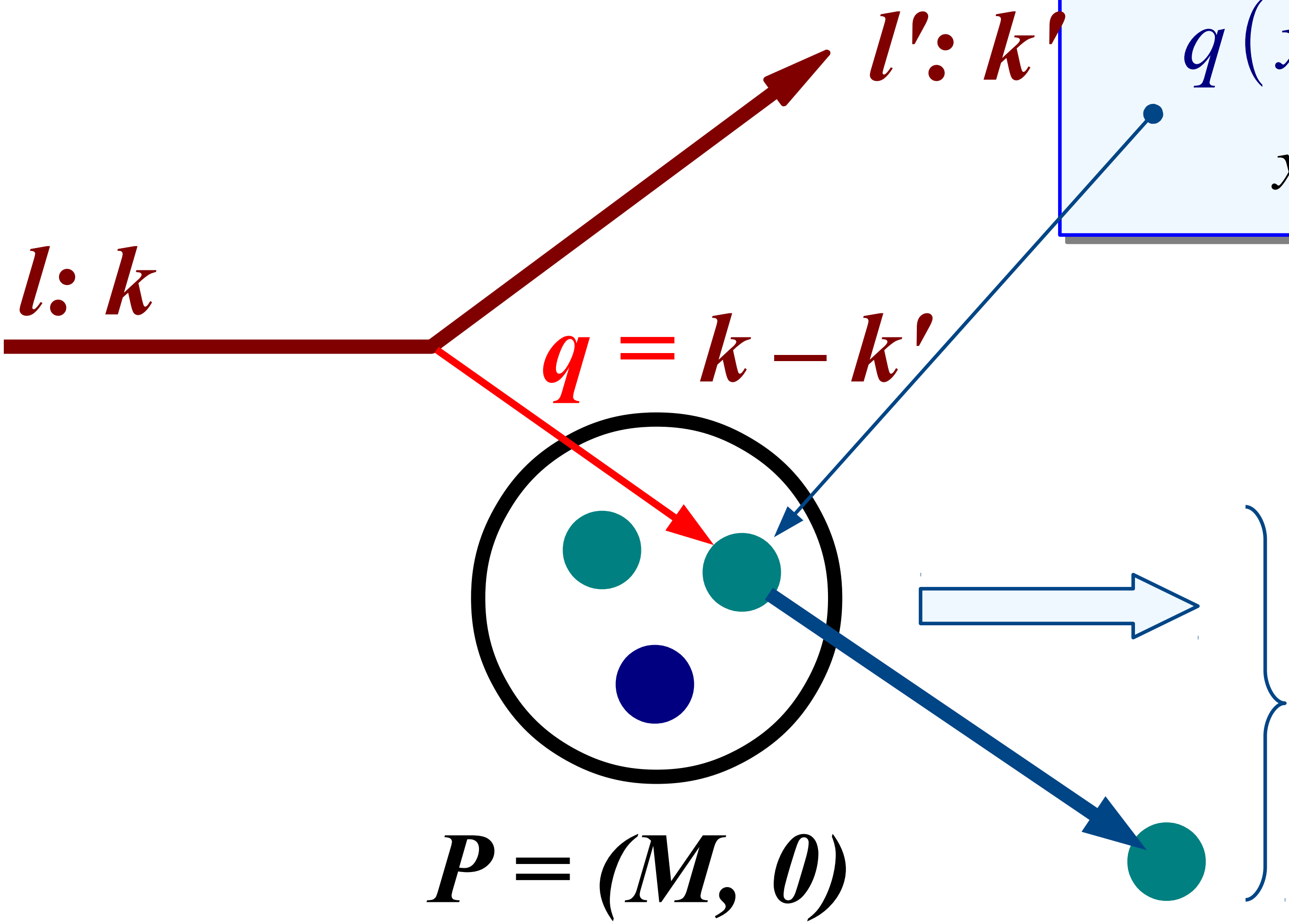
At Bjorken limit:

$$\frac{d\sigma}{dx} \propto F_1(x) = \frac{1}{2}\sum_q e_q^2 q(x)$$

$q(x)$ Parton number density

x Parton mometum fraction

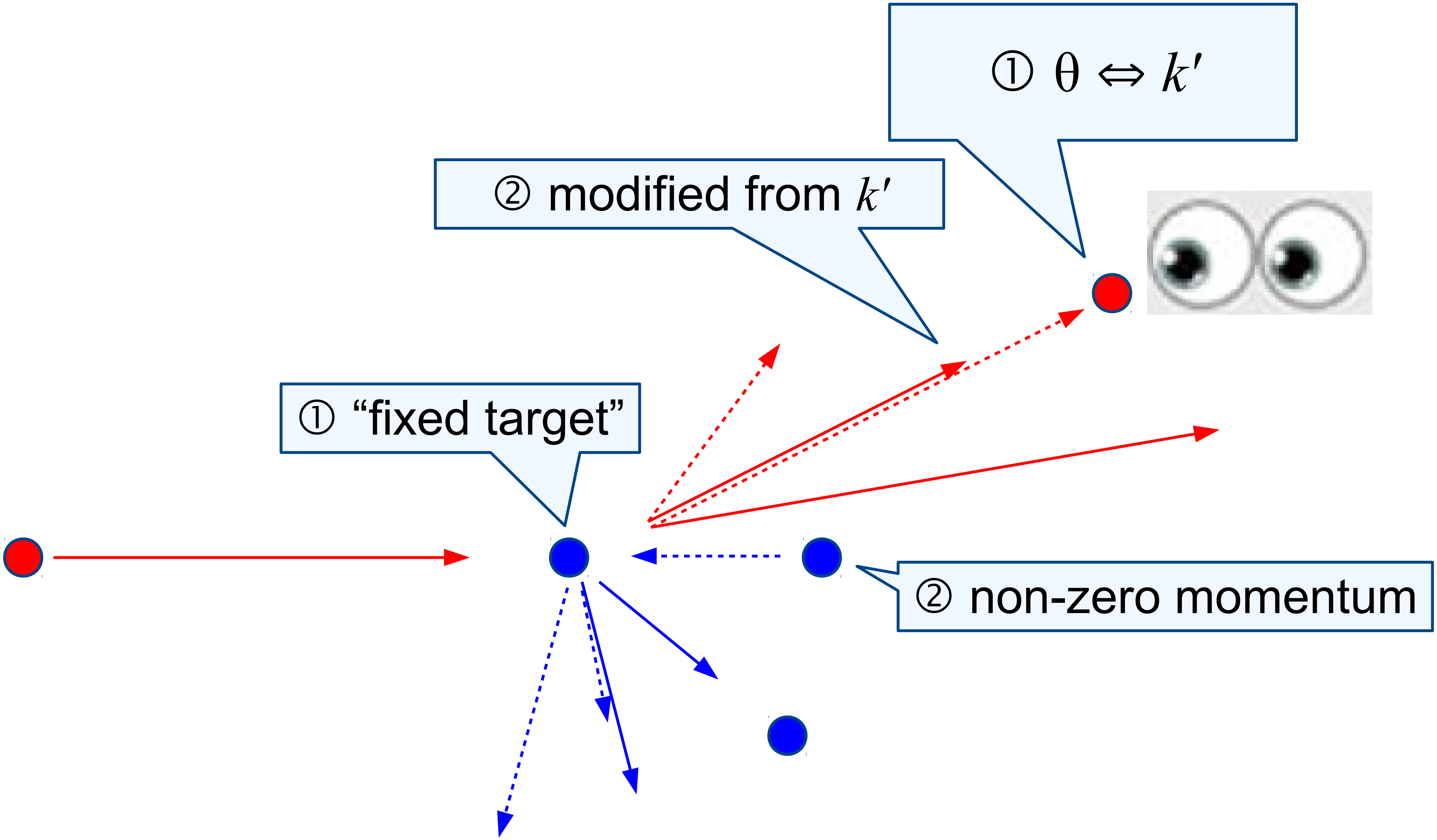
Bjorken $x = \frac{Q^2}{2M\nu}$



X

$$W^2 = (P+q)^2$$

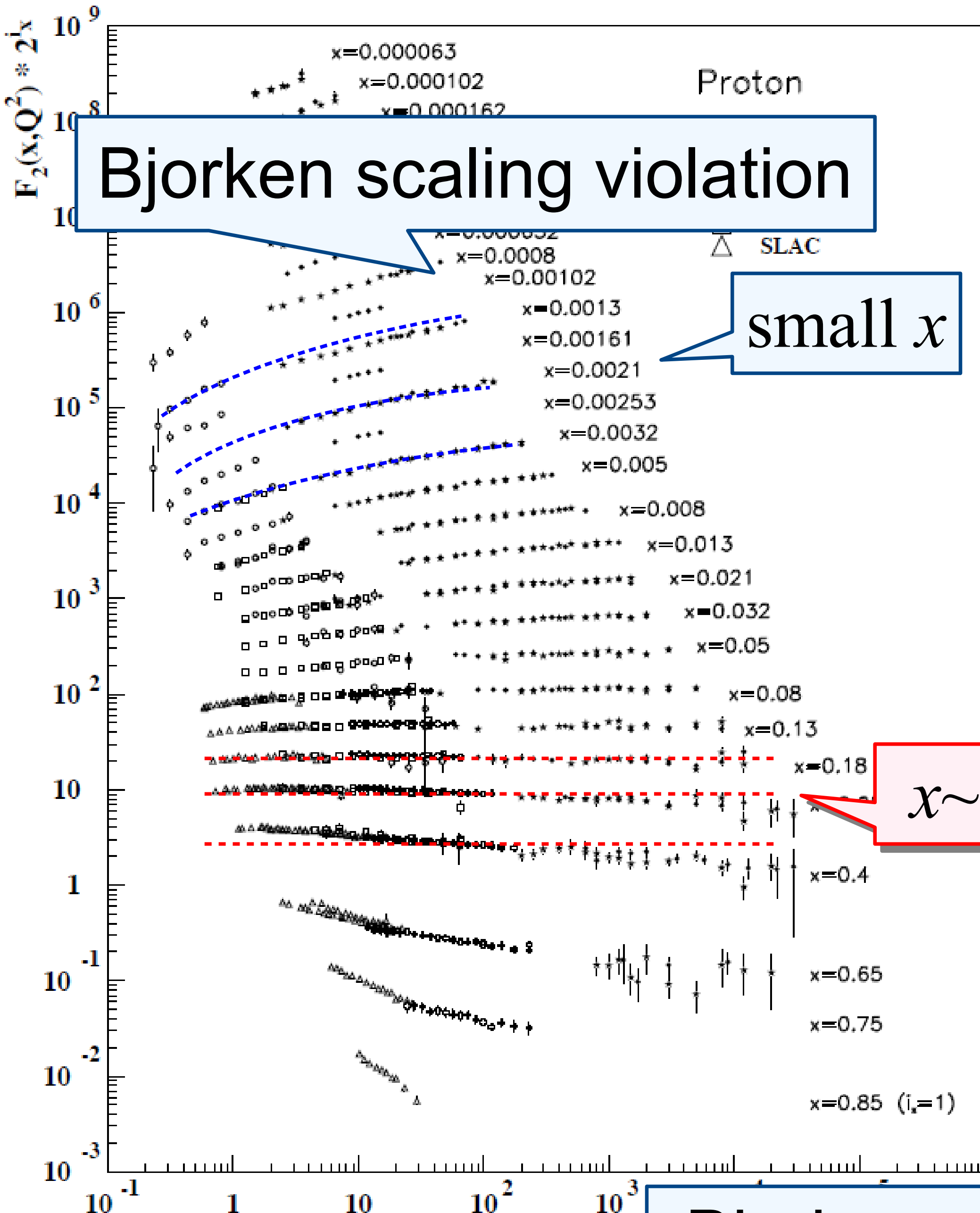
DIS: l-q elastic scattering



At θ, scattering lepton momentum → quark momentum

Structure function, quark and gluon

YAMAGATA UNIVERSITY



Bjorken scaling violation

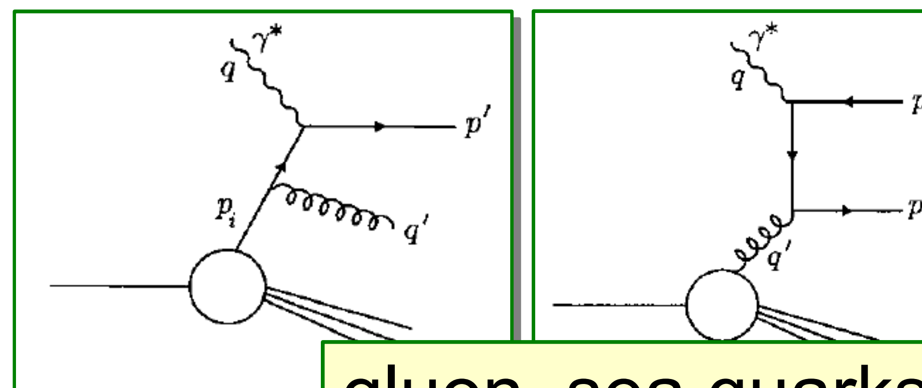
small x

x~0.3

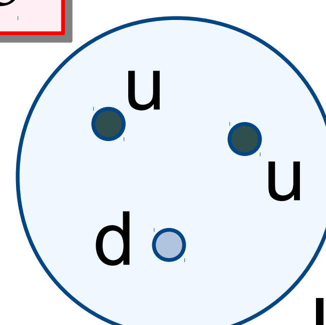
Bjorken scaling

$$F_2(x) = 2x\,F_1(x) = x\sum_q e_q^2 q(x)$$

Increasing vs Q^2



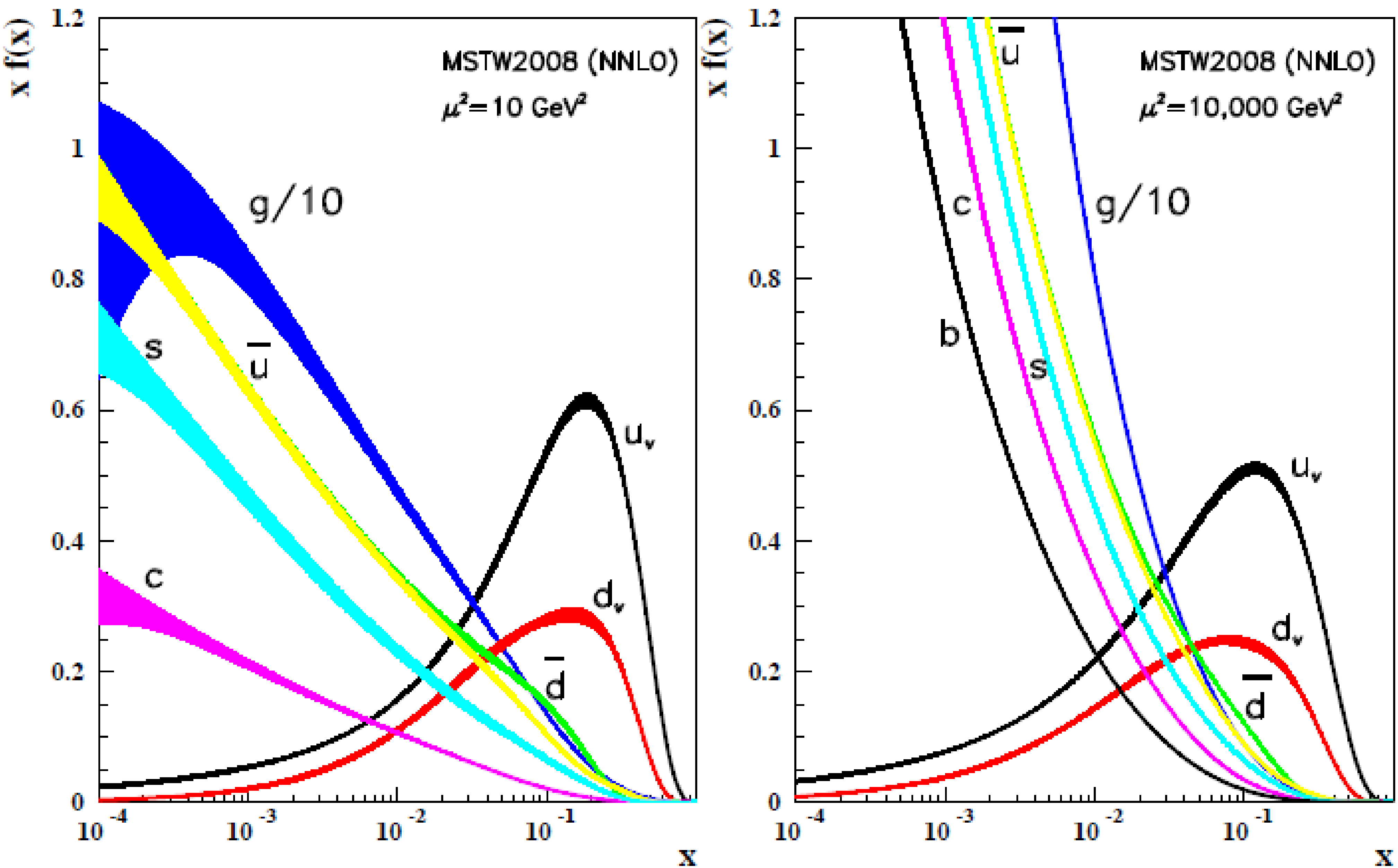
gluon, sea quarks



Valence quarks

Independent on Q^2

Parton distribution function: $q(x,Q^2)$



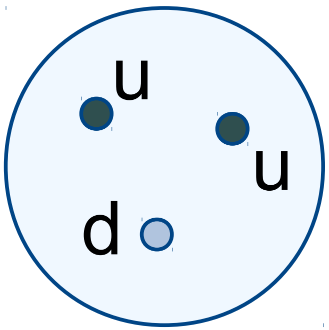
Sum rules

Valence quark: (uud)

$$u_v(x) = u(x) - \bar{u}(x) \qquad \int_0^1 dx\, u_v(x) = 2$$

$$d_v(x) = d(x) - \bar{d}(x) \qquad \int_0^1 dx\, d_v(x) = 1$$

$$d_s(x) = s(x) - \bar{s}(x) \qquad \int_0^1 dx\, s_v(x) = 0$$



Momentum sum rule:

$$\int dx\, x\left(\underline{u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + s(x) + \bar{s}(x) + \ldots}\right) = 1$$

$$= \sum(x)$$

YAMAGATA UNIVERSITY

Gottfried sum rule

$$F_2^p(x) = \sum_q e_q^2 \cdot x \cdot q(x)$$

Charge symmetry

$$u^p = d^n$$

$$\begin{cases} \dfrac{F_2^p(x)}{x} = \left(\dfrac{2}{3}\right)^2 \left(\mathrm{u}^p + \bar{\mathrm{u}}^p\right) + \left(\dfrac{1}{3}\right)^2 \left(\mathrm{d}^p + \bar{\mathrm{d}}^p\right) \cancel{+ \left(\dfrac{1}{3}\right)^2 \left(\mathrm{s}^p + \bar{\mathrm{s}}^p\right) + \ldots} \\[2ex] \dfrac{F_2^n(x)}{x} = \left(\dfrac{2}{3}\right)^2 \left(\mathrm{d}^p + \bar{\mathrm{d}}^p\right) + \left(\dfrac{1}{3}\right)^2 \left(\mathrm{u}^p + \bar{\mathrm{u}}^p\right) \cancel{+ \left(\dfrac{1}{3}\right)^2 \left(\mathrm{s}^p + \bar{\mathrm{s}}^p\right) + \ldots} \end{cases}$$

$$\frac{F_2^p(x) - F_2^n(x)}{x} = \frac{1}{3}\left(\left(\mathrm{u} - \bar{\mathrm{u}}\right) - \left(\mathrm{d} - \bar{\mathrm{d}}\right)\right) - \frac{2}{3}\left(\bar{\mathrm{d}} - \bar{\mathrm{u}}\right)$$

Gottfried sum rule

YAMAGATA UNIVERSITY

$$F_2^p(x)=\sum_q e_q^2\cdot x\cdot q(x)$$

$$\frac{F_2^p(x)-F_2^n(x)}{x}=\frac{1}{3}\left(\boxed{(\mathrm{u}-\bar{\mathrm{u}})}-\boxed{(\mathrm{d}-\bar{\mathrm{d}})}\right)-\frac{2}{3}\boxed{(\bar{\mathrm{d}}-\bar{\mathrm{u}})}$$

$$\left\{\begin{array}{l}\boxed{\int(\mathrm{u}-\bar{\mathrm{u}})\,dx=2}\\ \boxed{\int(\mathrm{d}-\bar{\mathrm{d}})\,dx=1}\\ \boxed{\bar{\mathrm{u}}(x)=\bar{\mathrm{d}}(x)}\end{array}\right.$$

Flavor symmetric sea

$$\int F_2^p(x)-F_2^n(x)\frac{dx}{x}=\frac{1}{3}$$

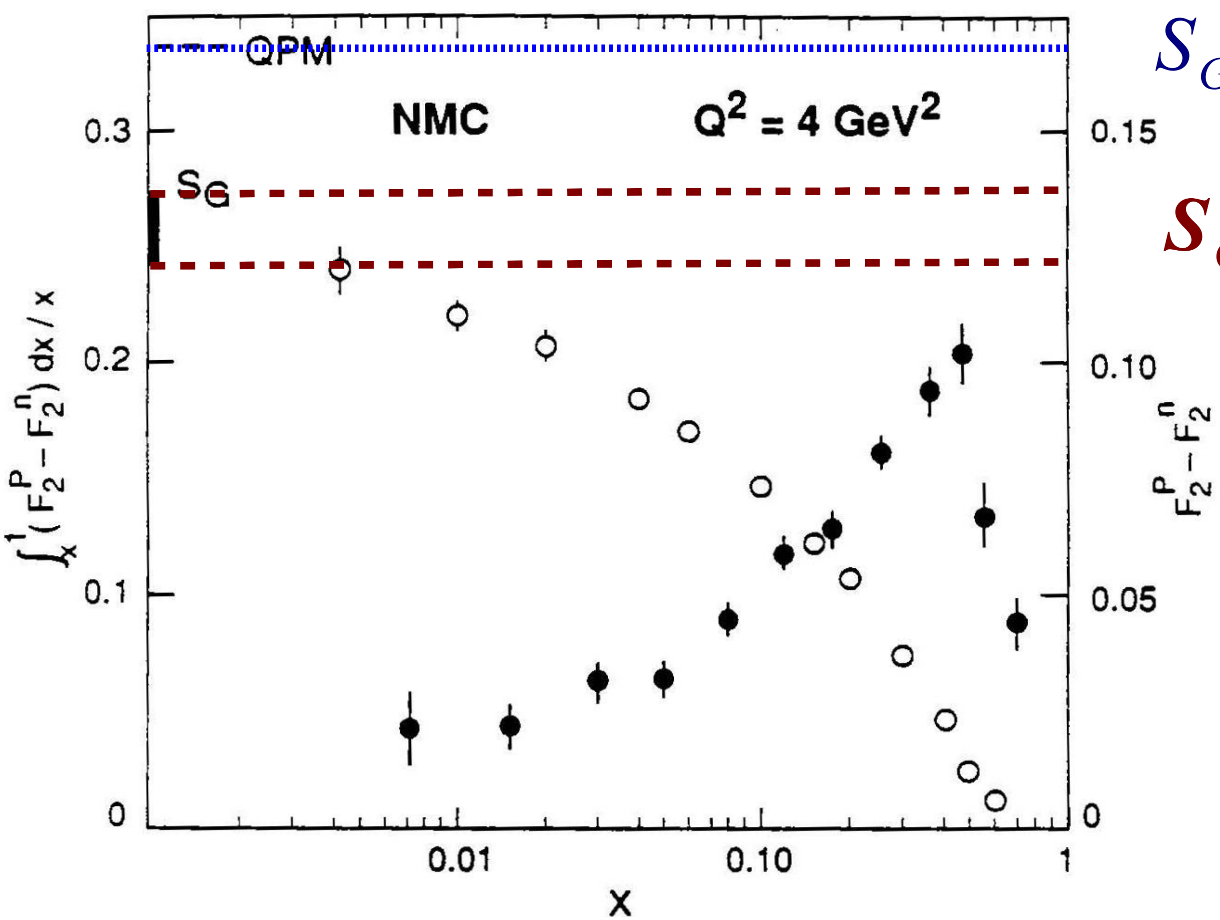
Gottfried Sum Rule

Gottfried sum rule

CERN-NMC（1990）

$$\left\{\begin{array}{l} \mu + p \rightarrow \mu + X \\ \mu + n \rightarrow \mu + X \end{array}\right. \Rightarrow F_2^p - F_2^n$$

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

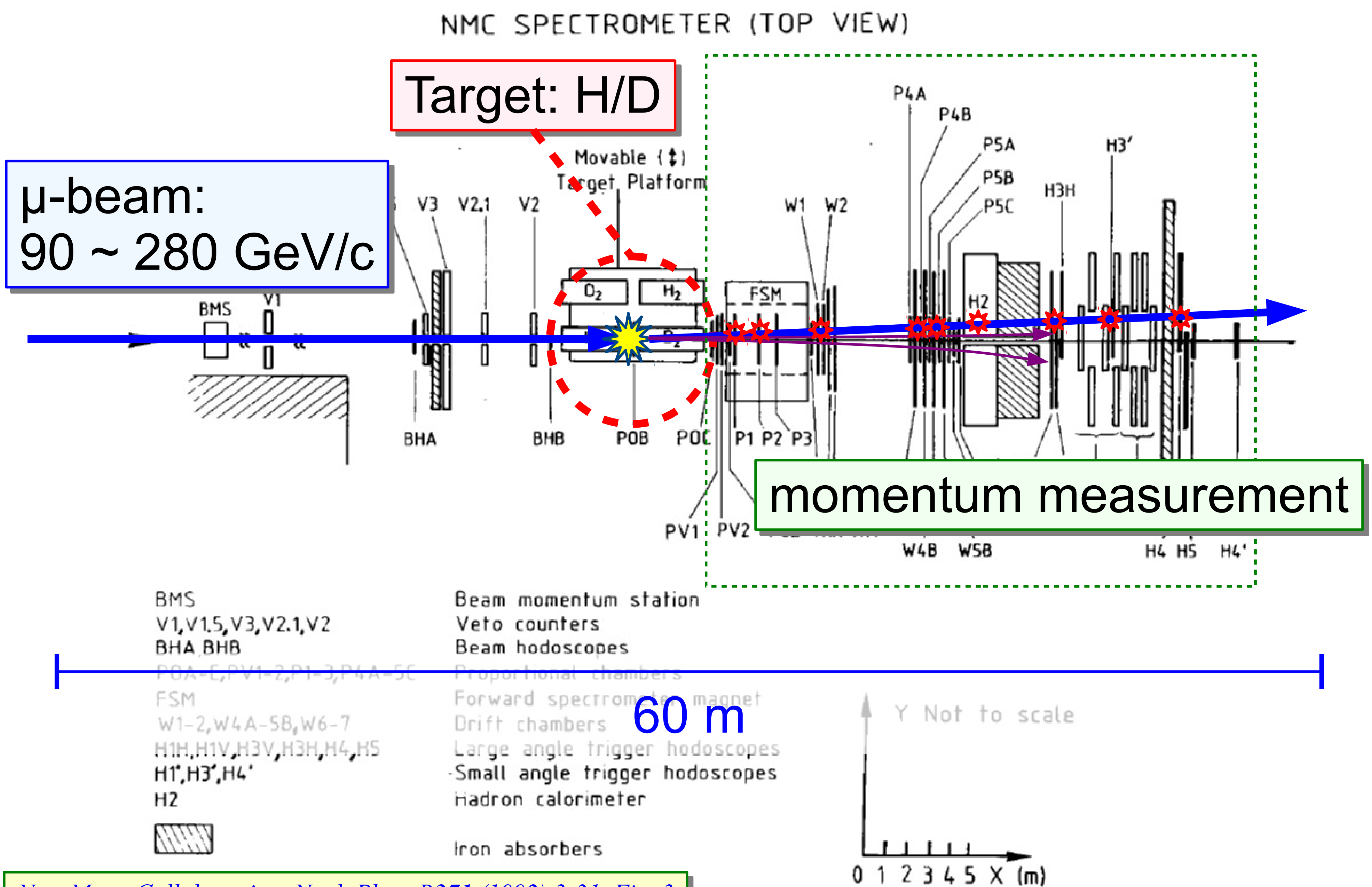


$S_G = \frac{1}{3}$ if $\bar{d} = \bar{u}$

$S_G = 0.2281 \pm 0.0065$

$\left(\bar{d} - \bar{u}\right) \sim 0.11$

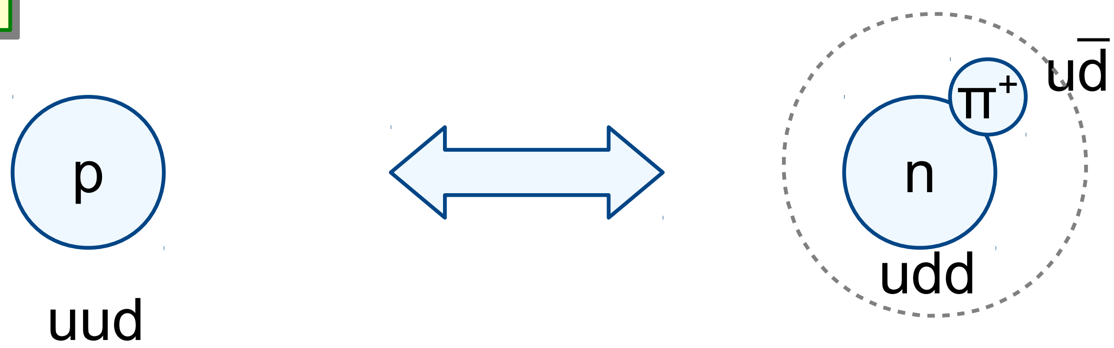
CERN-NMC:



New Muon Collaboration, Nucl. Phys. B371 (1992) 3-31, Fig. 3

What does $\bar{d} > \bar{u}$ mean?

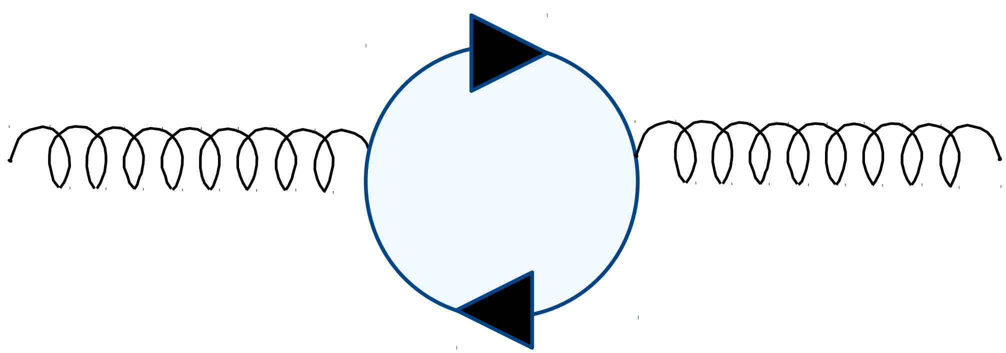
Pion cloud model



$$\bar{d} > \bar{u}$$

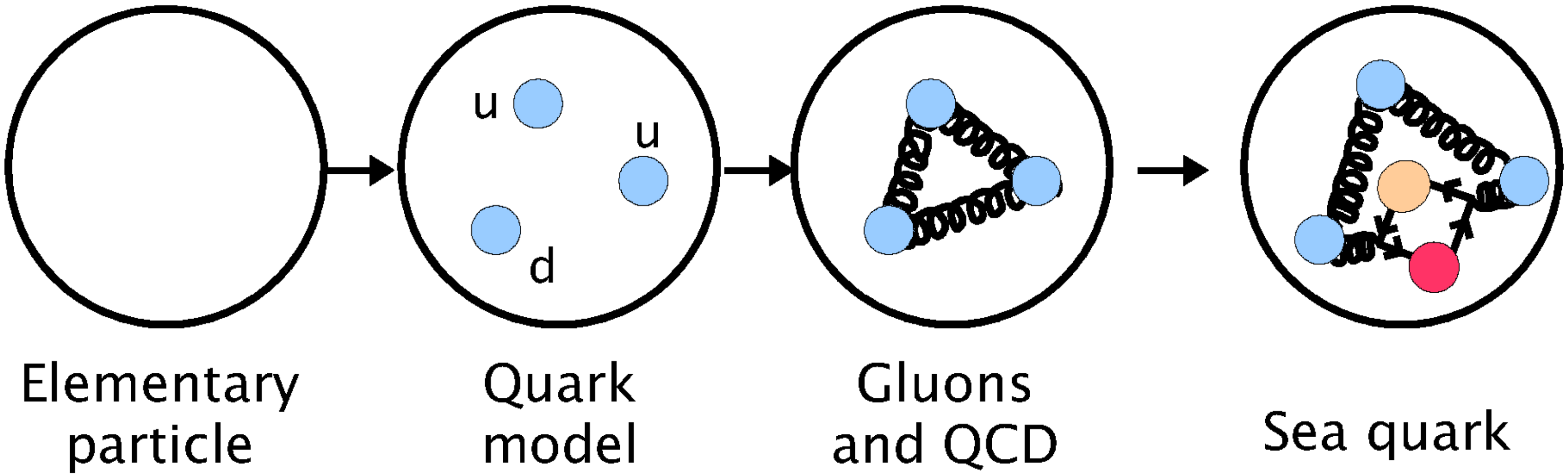
Chiral quark, instanton, ...

Perturbative QCD



$$\bar{d} = \bar{u}$$

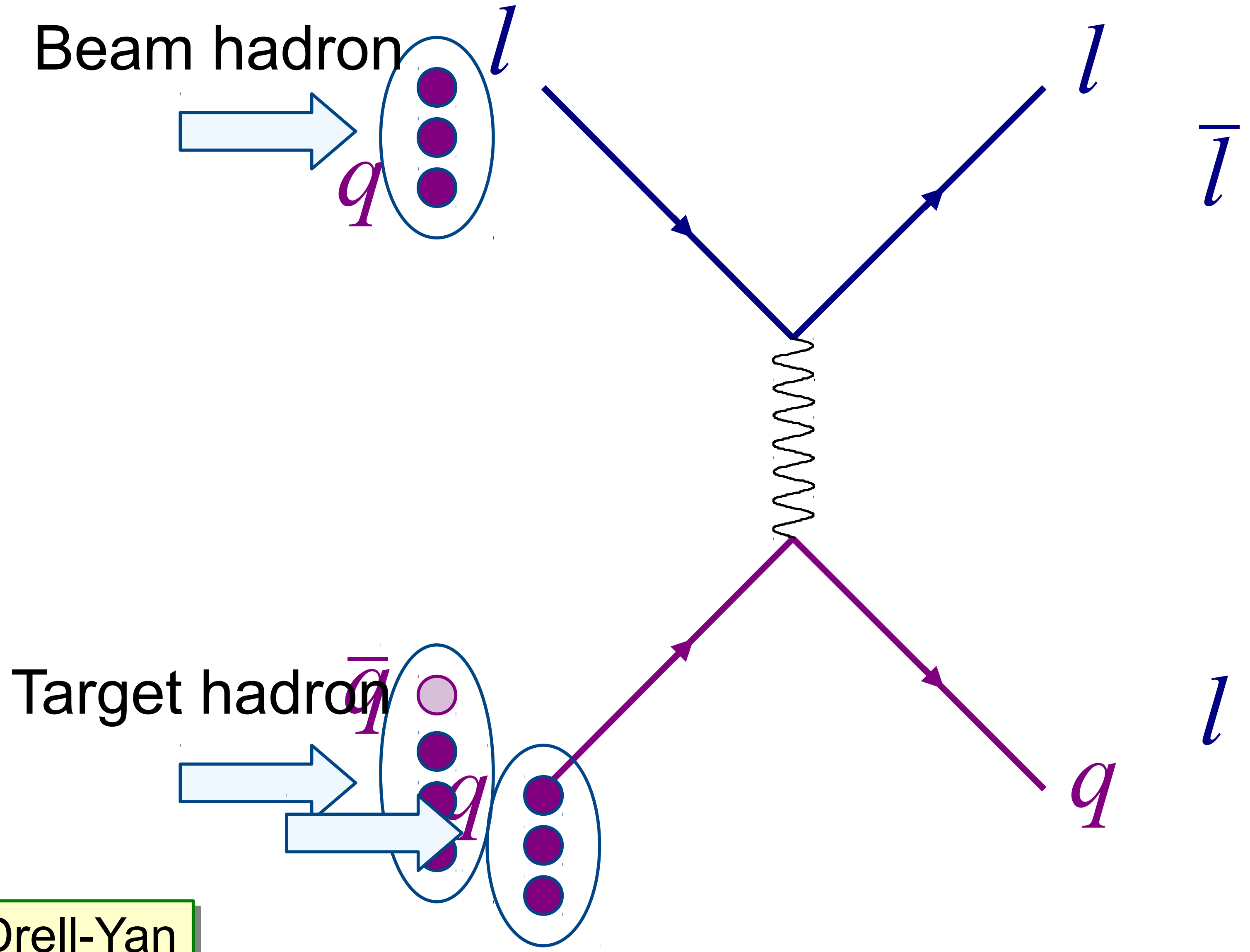
Development of “The proton structure”



Drell-Yan as a sea-quark -probe

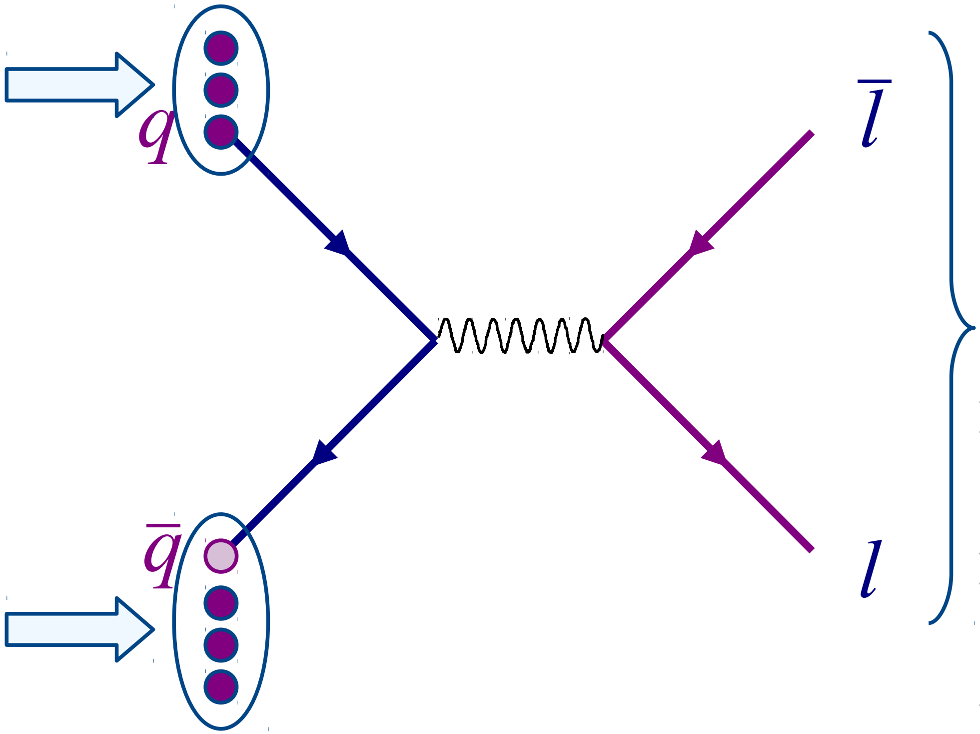
Deep Inelastic Scattering

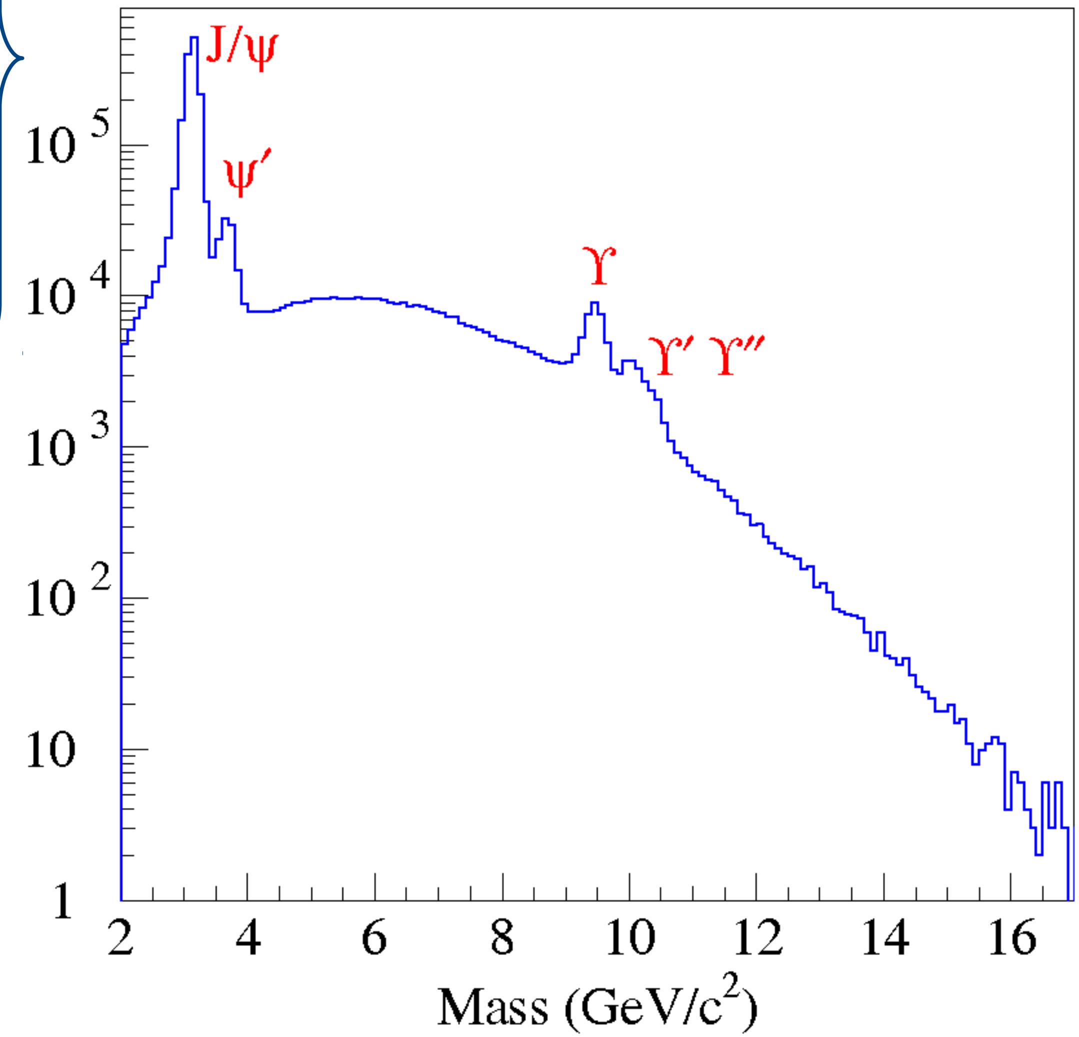
Probing quark and q-bar, equally.



Drell-Yan

Drell-Yan cross section





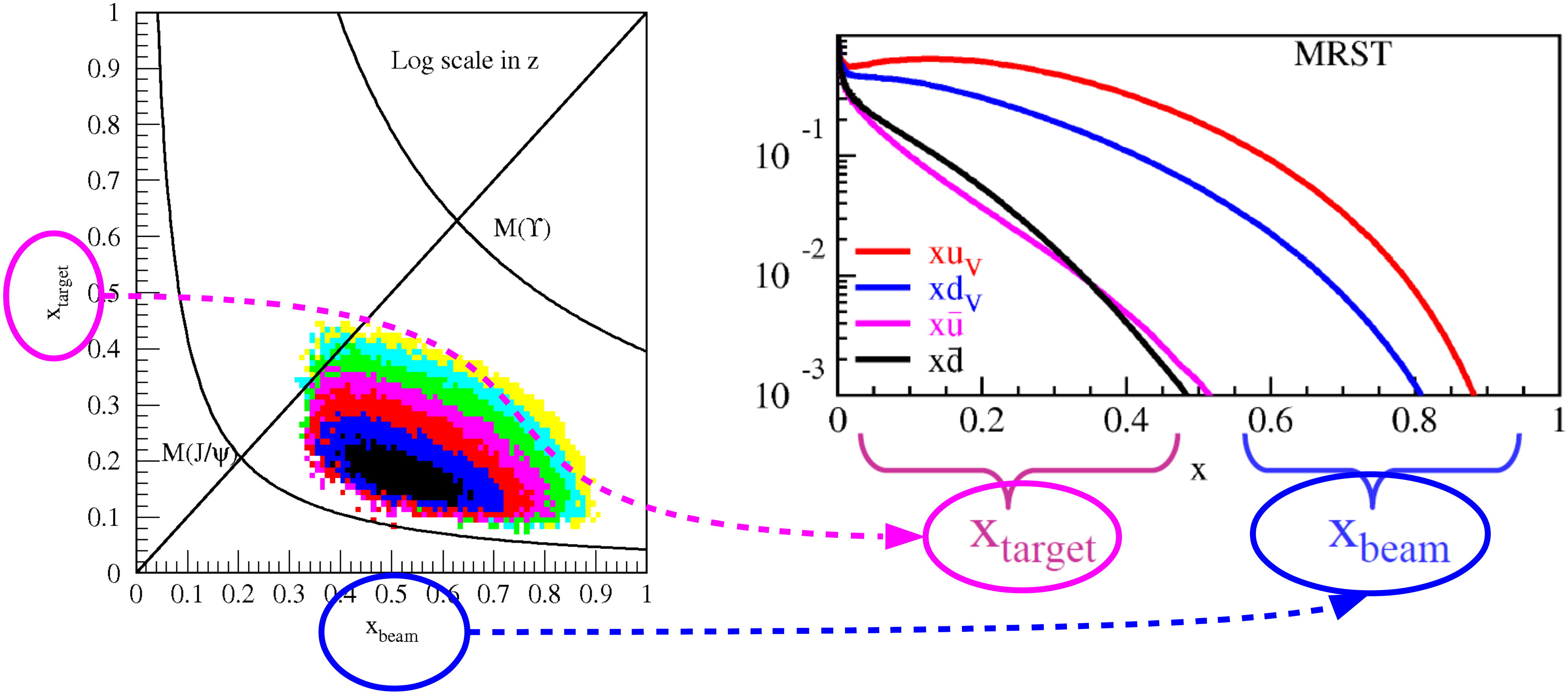
Drell-Yan cross section (fixed target)

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum_i e_i{}^2\left\{\cancel{q_i^{\mathrm{T}}(x^{\mathrm{T}})\bar{q}_i^{\mathrm{B}}(x^{\mathrm{B}})} + \bar{q}_i^{\mathrm{T}}(x^{\mathrm{T}})q_i^{\mathrm{B}}(x^{\mathrm{B}})\right\}$$

Anti-quarks in the target

Quaks in the beam

$$x_F = x_{beam} - x_{target} > 0$$



Drell-Yan Cross section ratio

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum_i e_i{}^2\left\{\cancel{q_i^{\mathrm{T}}(x^{\mathrm{T}})\bar{q}_i^{\mathrm{B}}(x^{\mathrm{B}})} + \bar{q}_i^{\mathrm{T}}(x^{\mathrm{T}})q_i^{\mathrm{B}}(x^{\mathrm{B}})\right\}$$

u-quark dominance

$$p + p \to \mu^+ + \mu^- + X \qquad \frac{d^2\sigma^{pp}}{d\,x_1\,d\,x_2} \propto \left(\frac{2}{3}\right)^2 \mathrm{u}^p(x_{beam})\,\bar{\mathrm{u}}^p(x_{target})$$

$$p + d \to \mu^+ + \mu^- + X \qquad \frac{d^2\sigma^{pd}}{d\,x_1\,d\,x_2} \propto \left(\frac{2}{3}\right)^2 \mathrm{u}^p(x_{beam})\,\bar{\mathrm{u}}^d(x_{target})$$

$$\bar{\mathrm{u}}^d(x_{target}) = \frac{\bar{\mathrm{u}}^p + \bar{\mathrm{u}}^n}{2} = \frac{\bar{\mathrm{u}}^p(x_{target}) + \bar{\mathrm{d}}^p(x_{target})}{2}$$

$$\bar{\mathrm{u}}^{\mathrm{n}} = \bar{\mathrm{d}}^{\mathrm{p}}$$

$$\propto \left(\frac{2}{3}\right)^2 \mathrm{u}^p(x_{beam})\left(\frac{\bar{\mathrm{u}}^p(x_{target}) + \bar{\mathrm{d}}^p(x_{target})}{2}\right)$$

$$\frac{d^2\sigma^{pd}}{d\,x_1\,d\,x_2} \Big/ \frac{d^2\sigma^{pp}}{d\,x_1\,d\,x_2} \propto \frac{1}{2}\left(1 + \frac{\bar{\mathrm{d}}}{\bar{\mathrm{u}}}\right)$$

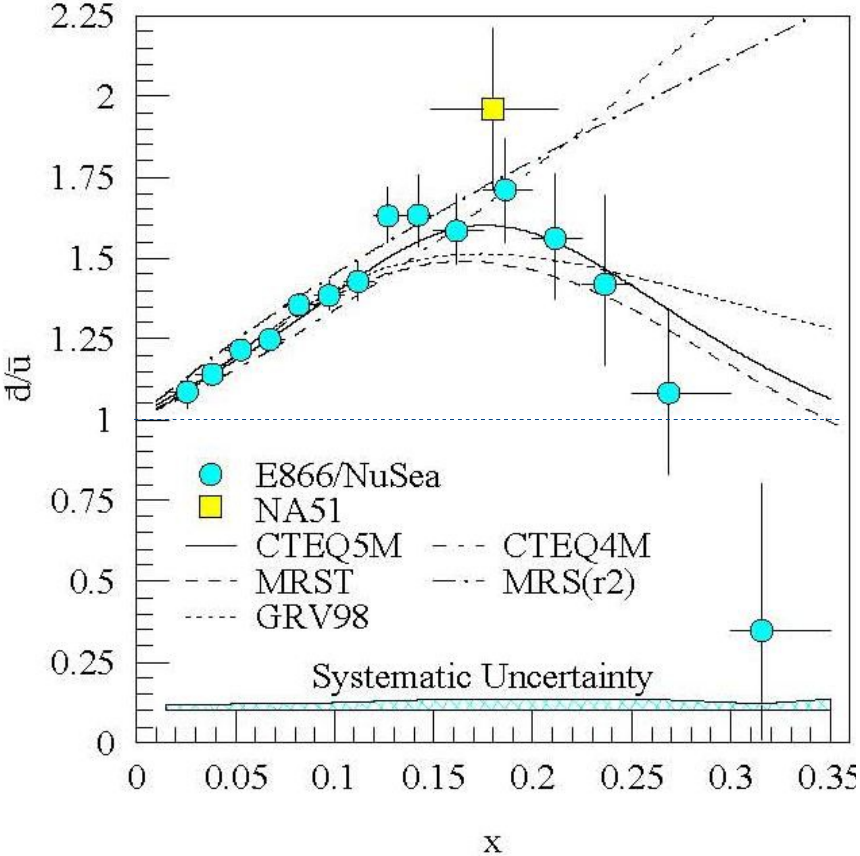
Drell-Yan cross section ratio

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum_i e_i^{\,2}\left\{\cancel{q_i^{\mathrm{T}}(x^{\mathrm{T}})\bar{q}_i^{\mathrm{B}}(x^{\mathrm{B}})} + \bar{q}_i^{\mathrm{T}}(x^{\mathrm{T}})q_i^{\mathrm{B}}(x^{\mathrm{B}})\right\}$$

$$\left\{\begin{array}{l} p + p \rightarrow \mu^+ + \mu^- + X \\ p + d \rightarrow \mu^+ + \mu^- + X \end{array}\right.$$

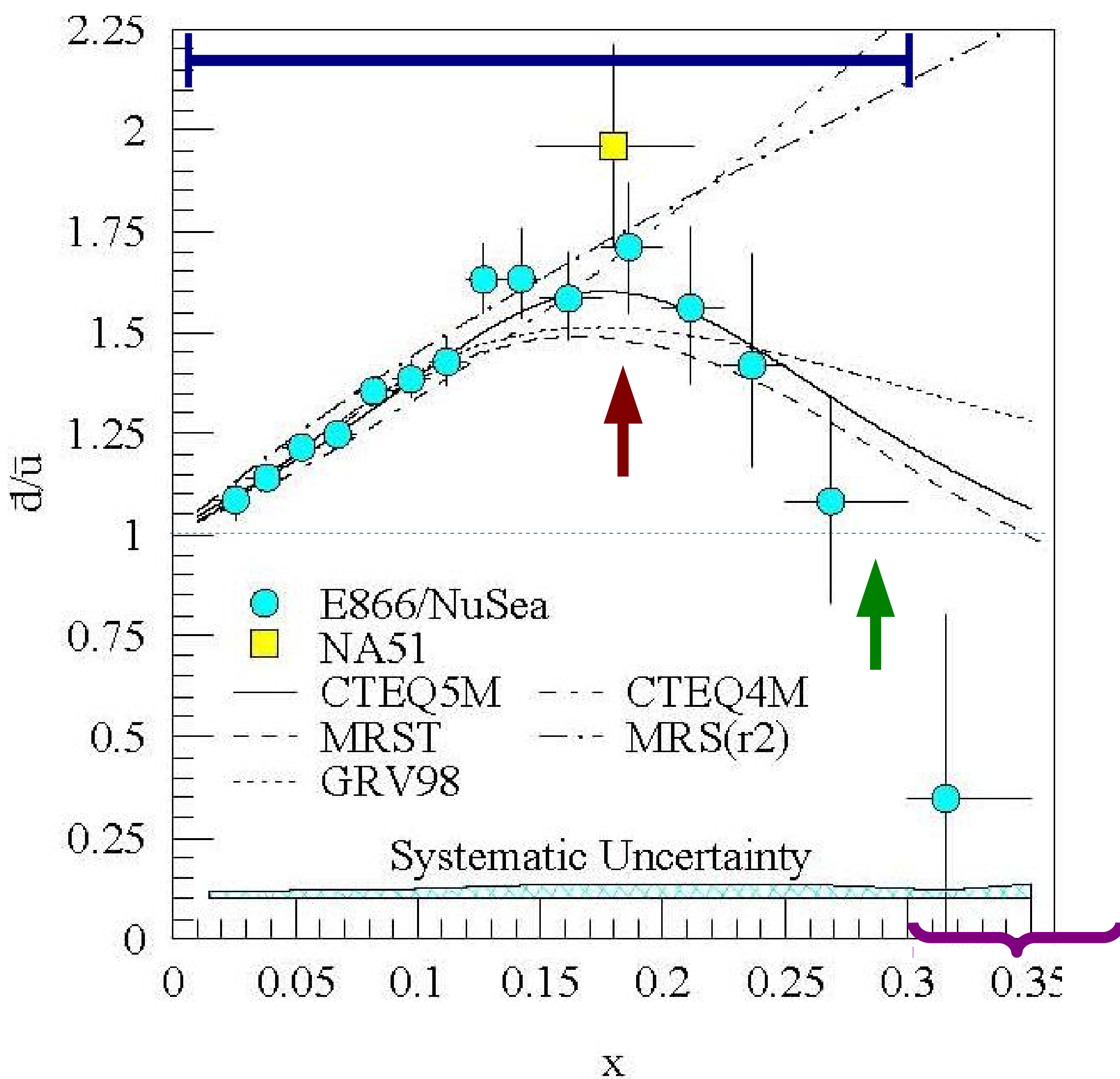
$$\Rightarrow \frac{d^2\sigma^{pd}}{d^2\sigma^{pp}} \propto \left(1 + \boxed{\frac{\bar{d}}{\bar{u}}}\right)$$

Using **800 GeV proton beam**, FNAL-E866/NeuSea measured



Improved Measurement of the anti-d/anti-u Asymmetry in the Nucleon Sea,	*PRD 64, 052002 (2001)*
Anti-d/anti-u Asymmetry and the Origin of the Nucleon Sea,	*PRD 58, 092004 (1998)*
Measurement of the Flavor Asymmetry in the Nucleon Sea,	*PRL 80 3715 (1998)*

E866/NeuSea@FNAL



$\bar{d} > \bar{u} \quad (0.015 < x < 0.3)$

$\bar{d}/\bar{u} = 1.6 \quad (x \sim 0.2)$

$\bar{d} = \bar{u} \quad (x \sim 0.3)$

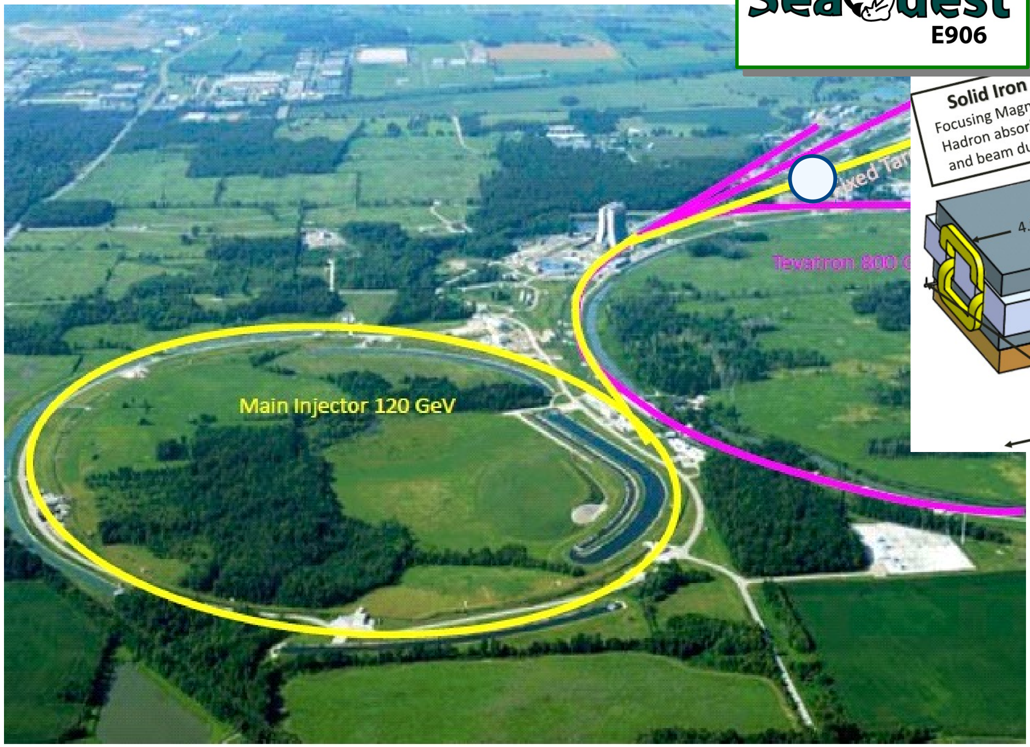
$\bar{d} < \bar{u} \quad (x > 0.3)$

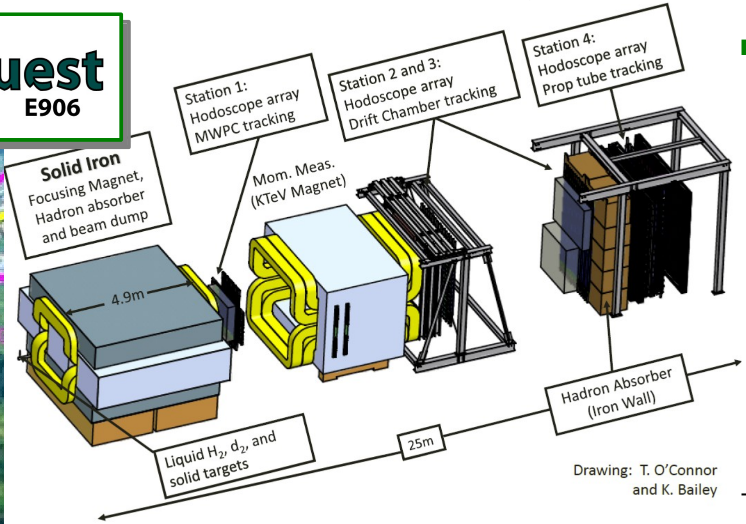
No low-energy effective model can explain this result.

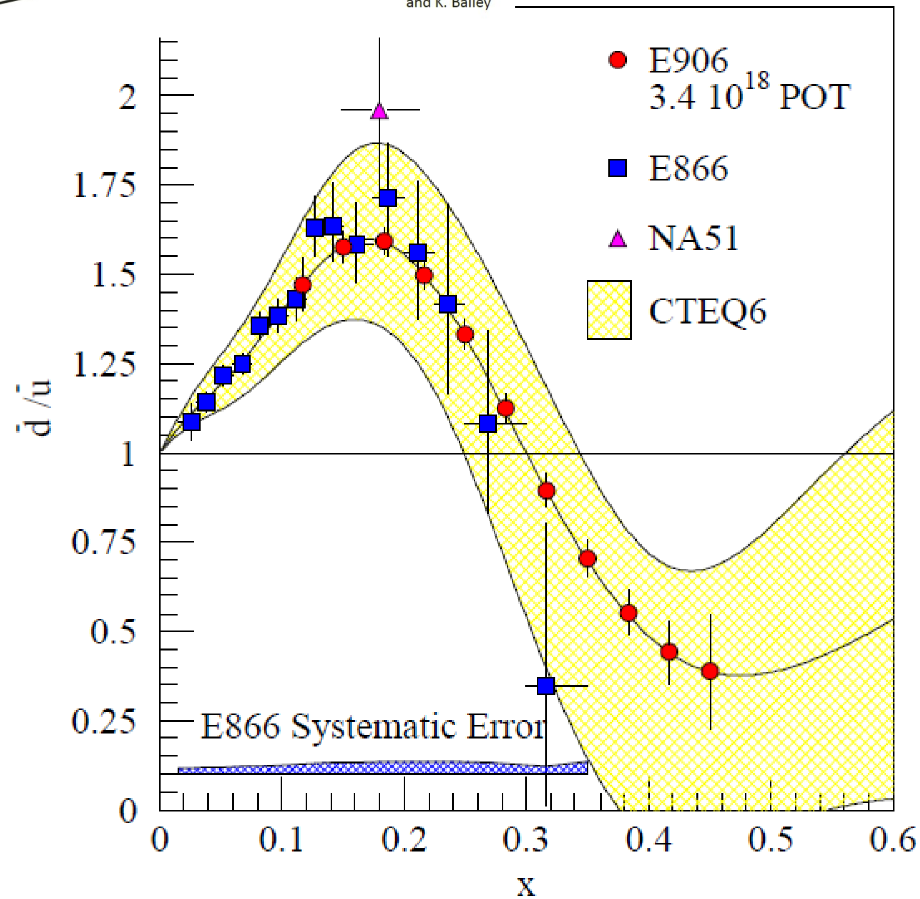
Are the light sea quarks flavor asymmetric?

YAMAGATA UNIVERSITY

SeaQuest E906







- Commissioning: 03-04, 2012
- Beam time: 2013-2015
- 120 GeV proton beam
  from the main injector
  2E+12 /s for 5 s spills each minutes
- Determine Flavor (a)symmetry
  in the large x region