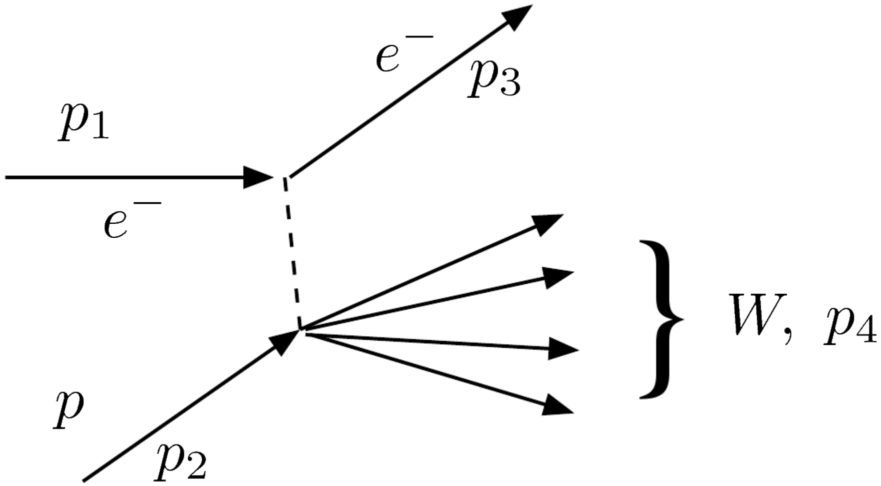


Inelastic e-p scattering

W=M → elastic scattering

2 < W < 1 GeV → inelastic scattering
(exitation of resonances)

W > 2 GeV → deep inelastic scattering

	lab frame - proton at rest before collision: $p_2 = (M, 0, 0, 0)$		lorentz invariant form
energy loss of incoming particle	$\nu = E_3 - E_1$		$\nu = \frac{p_2 q}{M}$
Bjorken x	$x = \frac{Q^2}{2M\nu}$	x in [0,1]	$x = \frac{Q^2}{2p_2 q}$
fractional energy loss of incoming particle	$y = 1 - \frac{E_3}{E_1}$	y in [0,1]	$y = \frac{p_2 q}{p_2 p_1}$
4-momentum transver	$q^2 = (p_1 - p_3)^2$		$q^2 = (p_1 - p_3)^2$

$$(Q^2 = -q^2)$$

Elastic Scattering:

cross-section in lab frame: proton at rest before collision

electron helicity spin flip

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4\frac{\theta}{2}} \frac{E_3}{E_1} \Big(\underbrace{\tfrac{G_E^2 + \tau G_M^2}{1+\tau}}_{f_2(Q^2)} \cos^2\frac{\theta}{2} + \underbrace{2\tau G_M^2}_{f_1(Q^2)} \sin^2\frac{\theta}{2} \Big)$$

$$\tau = \frac{Q^2}{4M}$$

LI cross-section

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} \Big(f_2(Q^2)(1 - y - \cancel{\tfrac{M^2 y^2}{Q^2}}) + \tfrac{1}{2} y^2 f_1(Q^2) \Big)$$

for large Q^2

Inelastic Scattering:

cross-section in lab frame: proton at rest before collision

el. structure function magn. structure function

$$\frac{d\sigma^2}{dE_3 d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4\frac{\theta}{2}} \frac{1}{\nu} \Big(\boxed{F_2(x, Q^2)} \cos^2\frac{\theta}{2} + \tfrac{2\nu}{M} \boxed{F_1(x, Q^2)} \sin^2\frac{\theta}{2} \Big)$$

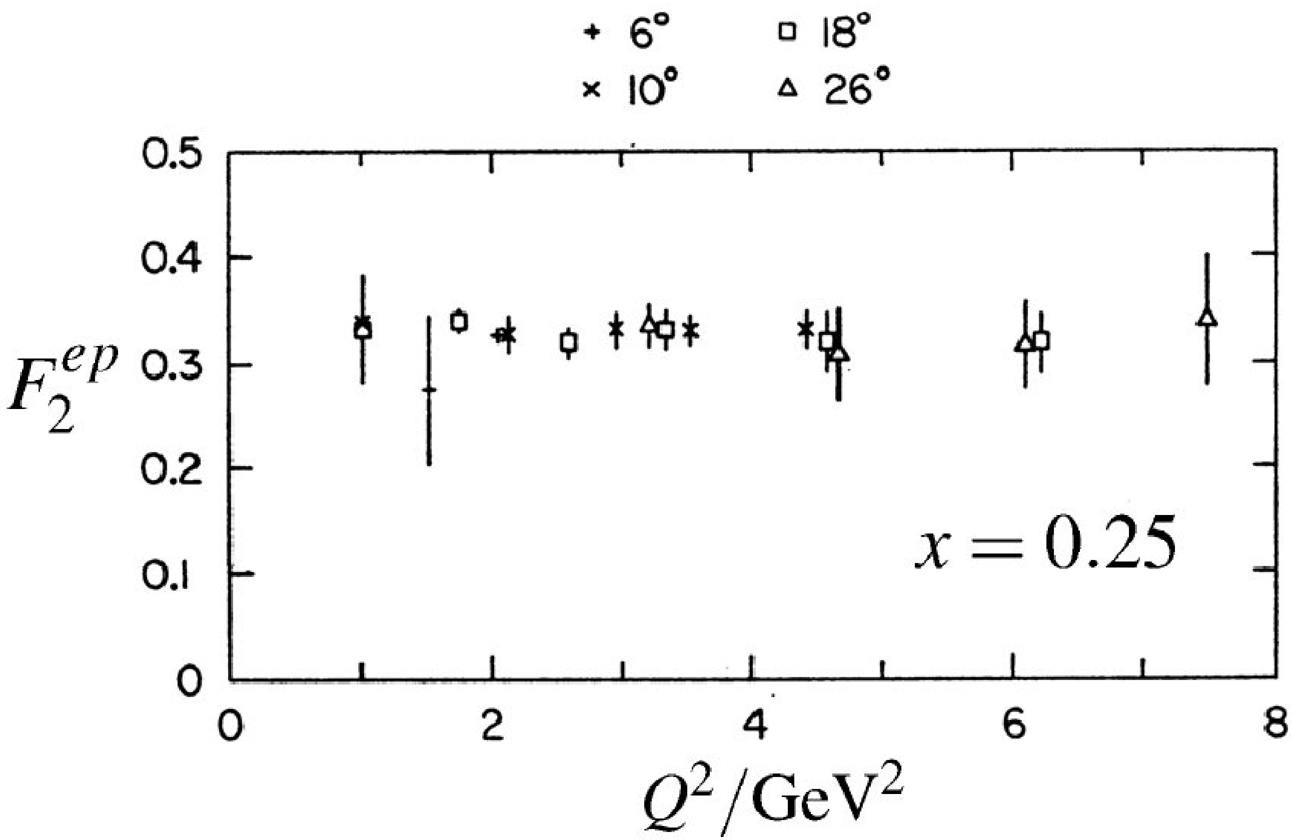
LI cross section

$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4} \Big((1 - y - \cancel{\tfrac{M^2 y^2}{Q^2}}) \frac{F_2(x, Q^2)}{x} + y^2 F_1(x, Q^2) \Big)$$

for large Q^2

Bjorken Scaling Hypothesis (1967)

"If scattering is caused by point-like constituents (partons), the structure functions for fixed x must be independent of Q^2."



J.T.Friedman + H.W.Kendall, Ann. Rev. Nucl. Sci. 22 (1972) 203

experimental observation: structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$ do not depend on Q^2

First evidence for point-like substructure of proton!

What is the spin of the partons?

Reminder elastic scattering: angluar dependence in Mott cross-section comes from "electron helicity conservation", thus is related to spin of incoming electron. Additional angular dependence of Dirac cross-section due to spin-spin IA of electron and proton. This term vanish in case of 0 spin of the target!

$$\left(\frac{d\sigma}{d\Omega}\right)_{Dirac} / \left(\frac{d\sigma}{d\Omega}\right)_{Mott} = 1 + \frac{Q^2}{2M^2}\tan^2\frac{\theta}{2}$$

Inelastic scattering:

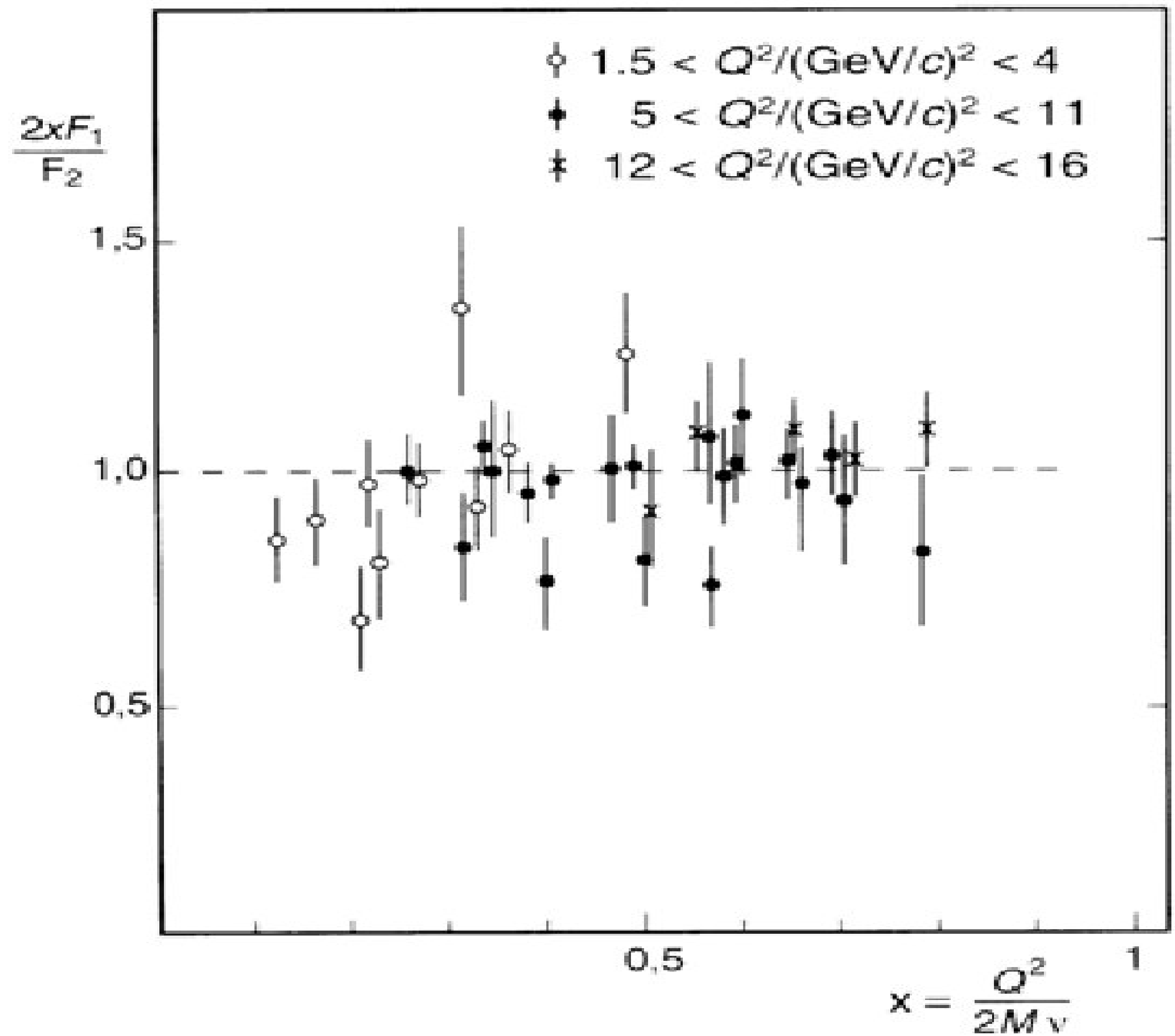
$$\left(\frac{d^2\sigma}{d\Omega dE_3}\right) / \left(\frac{d\sigma}{d\Omega}_{Mott}\right) = \frac{1}{\nu}\left(F_2(x) + \frac{2\nu}{M}F_1(x)\tan^2\frac{\theta}{2}\right)$$

$$\mu = Mx$$

$$= \frac{F_2(x)}{\nu}\left(1 + \frac{Q^2}{\mu^2}\frac{xF_1(x)}{F_2(x)}\tan^2\frac{\theta}{2}\right)$$

If parton spin = 0 $\rightarrow$ $F_1(x) = 0$

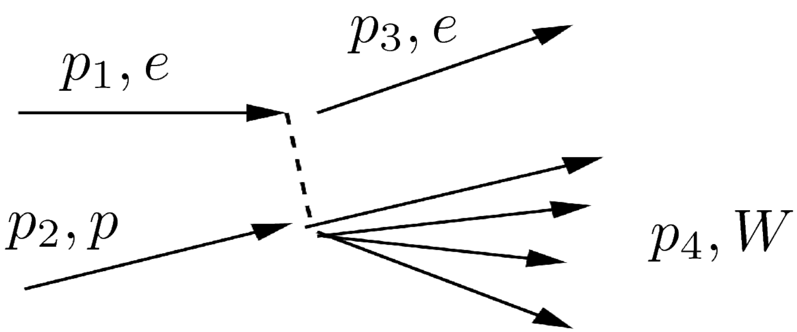
If parton spin = ½ $\rightarrow$ $\boxed{F_2(x) = 2xF_1(x)}$ Callan-Gross relation



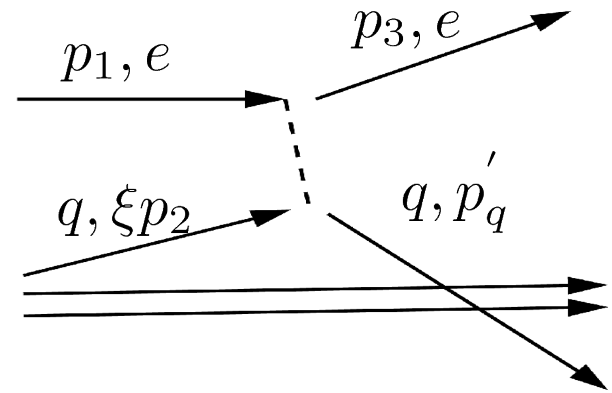
partons have spin ½ !

Quark-Parton Model

Inelastic scattering from proton



Quark-Parton-Model:
elastic scattering from point-like quark within proton



quark in quark-parton model as free-particle which is only true in "infinite momentum frame", Thus assuming all masses and transverse momentum components are negligible.

$$p_{quark} = \xi p_2$$

$$p^{'}_{quark} = \xi p_2 + q$$

$$p^{'2}_{quark} = \xi^2 p_2^2 + q^2 + 2\xi p_2 q = m_q^2 \quad \Longrightarrow \quad \xi = -\frac{q^2}{2p_2 q} = x$$

masses are negligible in IMF

Bjorken variable x can (in IMF) be identified as fraction of four momentum carried by quark involved in scatter process.

Cross section of electron with one quark which carries the momentum fraction x of the proton:

$$\left(\frac{d\sigma}{d\Omega}\right)_{quark,x} = \frac{\alpha^2 e_i^2}{4E_1^2 \sin^4\frac{\theta}{2}} \frac{E_3}{E_1} (\cos^2\frac{\theta}{2} + \frac{Q^2}{2M_Q^2}\sin^2\frac{\theta}{2})$$

e_i : charge of quark in units of e

$M_Q^2 = x^2 p_2^2$ (not the "real" quark mass)

Lorentz invariant form:

$$\left(\frac{d\sigma}{dQ^2}\right)_{quark,x} = \frac{4\pi\alpha^2 e_i^2}{Q^4}[(1-y) + \frac{y^2}{2}]$$

To get the complete cross-section, need to sum over all quarks in the proton and
To integrate about their x-distributions.

Quark momentum distribution: $q^p(x)$

$$\left(\frac{d\sigma}{dQ^2}\right)_{quark} = \left(\frac{d\sigma}{dQ^2}\right)_{quark,x} q^p(x)dx$$

$$\left(\frac{d^2\sigma}{dxdQ^2}\right)_{quark} = \left(\frac{d\sigma}{dQ^2}\right)_{quark,x} q^p(x)$$

$$\left(\frac{d^2\sigma}{dxdQ^2}\right)_{proton} = \frac{4\pi\alpha^2}{Q^4}[(1-y)+\frac{y^2}{2}] \times \sum_i e_i^2 q^p(x)$$

sum over all quarks in proton

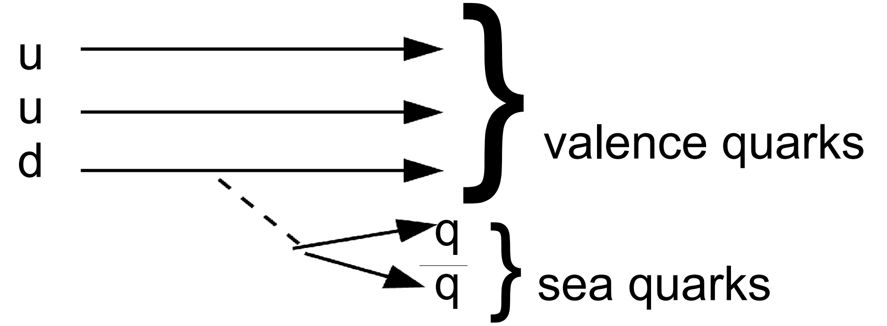
compare with electron proton cross-section in terms of structure functions

$$\left(\frac{d^2\sigma}{dxdQ^2}\right)_{proton} = \frac{4\pi\alpha^2}{Q^4}[(1-y)\frac{F_2(x)}{x} + y^2 F_1(x)]$$

$$\Longrightarrow \qquad F_2(x) = 2xF_1(x) = x\sum_i e_i^2 q^p(x)$$

Can related structure functions (in IMF) to quark momentum distribution!

Sum rules for quark parton distributions



$$u(x) = u_v(x) + u_s(x)$$

$$d(x) = d_v(x) + d_s(x)$$

$$\int_0^1 u_v^p(x) = 2$$ number of u valence quarks in proton

$$\int_0^1 d_v^p(x) = 1$$ number of d valence quarks in proton

$$\int_0^1 u_v^n(x) = 1$$ number of u valence quarks in neutron

$$\int_0^1 d_v^n(x) = 2$$ number of d valence quarks in neutron

$$\int_0^1 x(u(x) + d(x) + \overline{u(x)} + \overline{d(x)})dx \overset{?}{=} 1$$

momentum conservation
(if all momentum is distributed among quarks)

$$d_s(x) = \overline{d_s(x)} \qquad u_s(x) = \overline{u_s(x)}$$

(heavier sea quarks strongly suppressed)

Structure function for electron proton scattering:

$$\frac{F_2^{ep}(x)}{x} = \sum_i e_i^2 q_i(x)$$
$$= \frac{4}{9}(u^p(x) + \overline{u^p(x)}) + \frac{1}{9}(d^p(x) + \overline{d^p(x)})$$

heavier sea quarks are strongly suppressed!

Structure function for electron neutron scattering:

$$\frac{F_2^{en}(x)}{x} = \sum_i e_i^2 q_i(x)$$
$$= \frac{4}{9}(u^n(x) + \overline{u^n(x)}) + \frac{1}{9}(d^n(x) + \overline{d^n(x)})$$
$$= \frac{4}{9}(d(x) + \overline{d(x)}) + \frac{1}{9}(u(x) + \overline{u(x)})$$

Isospin symmetrie: $u \Leftrightarrow d \qquad p \Leftrightarrow n$

$$u(x) \equiv u^p(x) = d^n(x) \qquad d(x) \equiv d^p(x) = u^n(x)$$
$$\overline{u(x)} \equiv \overline{u^p(x)} = \overline{d^n(x)} \qquad \overline{d(x)} \equiv \overline{d^p(x)} = \overline{u^n(x)}$$

$$\int_0^1 F_2^{ep}(x)dx = \int x\frac{4}{9}(u(x) + \overline{u(x)}) + \frac{1}{9}(d(x) + \overline{d(x)})dx = \frac{4}{9}f_u + \frac{1}{9}f_d$$

$$\int_0^1 F_2^{en}(x)dx = \int x\frac{4}{9}(d(x) + \overline{d(x)}) + \frac{1}{9}(u(x) + \overline{u(x)})dx = \frac{4}{9}f_d + \frac{1}{9}f_u$$

$$f_u = \int_0^1 x(u(x) + \overline{u(x)})dx$$

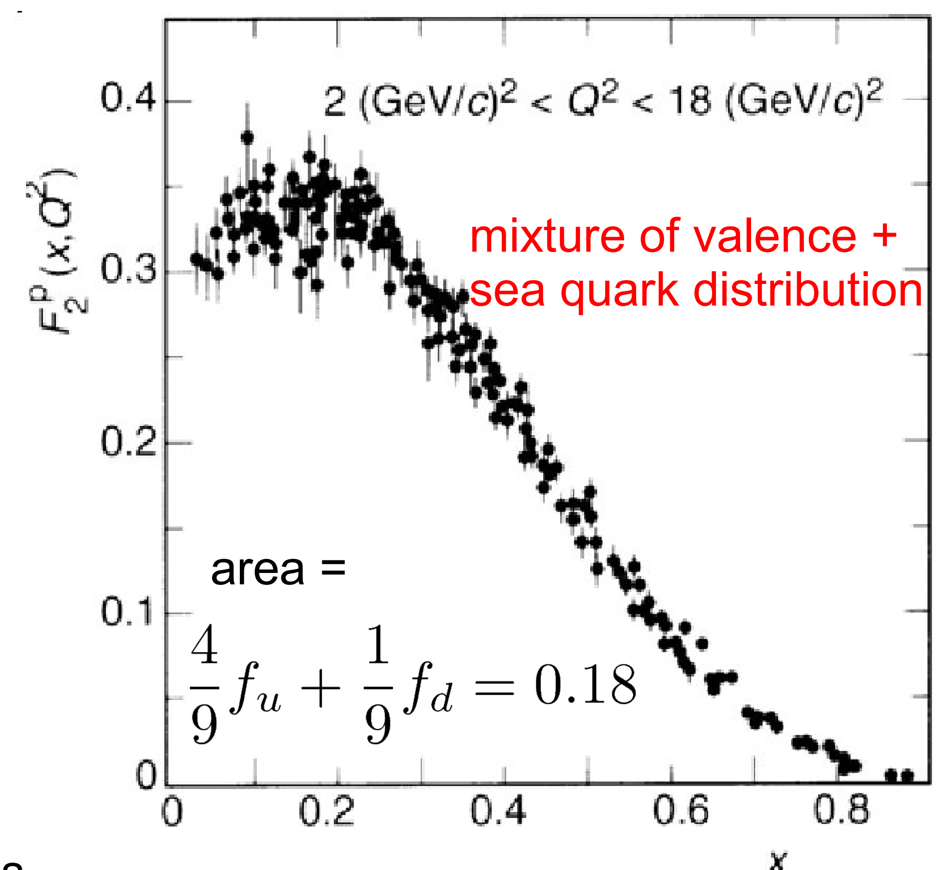
$$f_d = \int_0^1 x(d(x) + \overline{d(x)})dx$$

Experimentally found:

$$\int_0^1 F_2^{ep}(x)dx \sim 0.18$$

$$\int_0^1 F_2^{en}(x)dx \sim 0.12$$

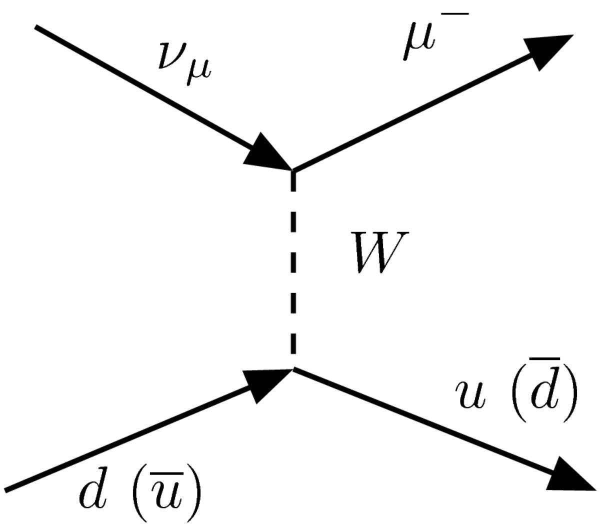
$$\Rightarrow \quad f_u = 0.36 \qquad f_d = 0.18$$

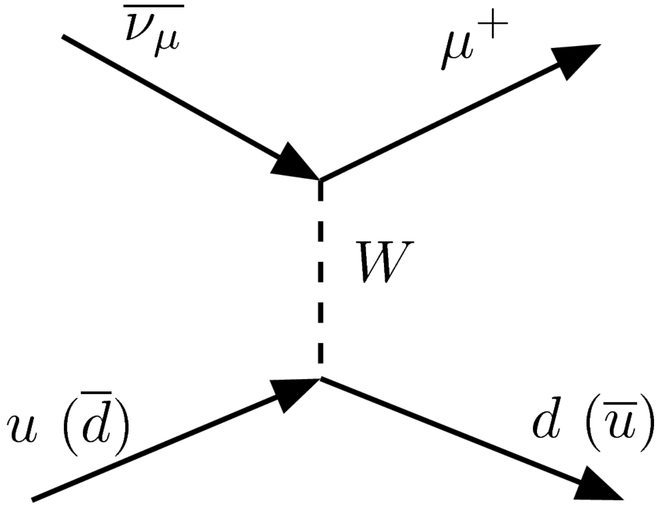


~ 50% of proton momentum is carried by quarks

How does valence & sea quark momentum distributions look like?

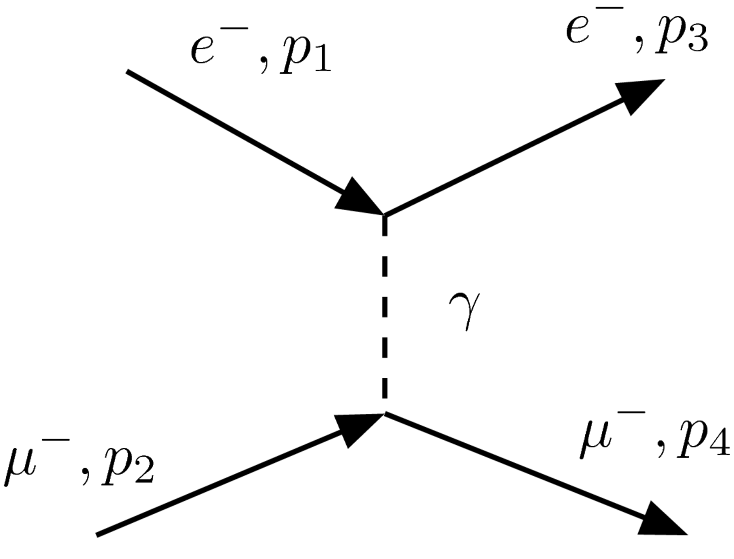
Neutrino-Nucleon scattering

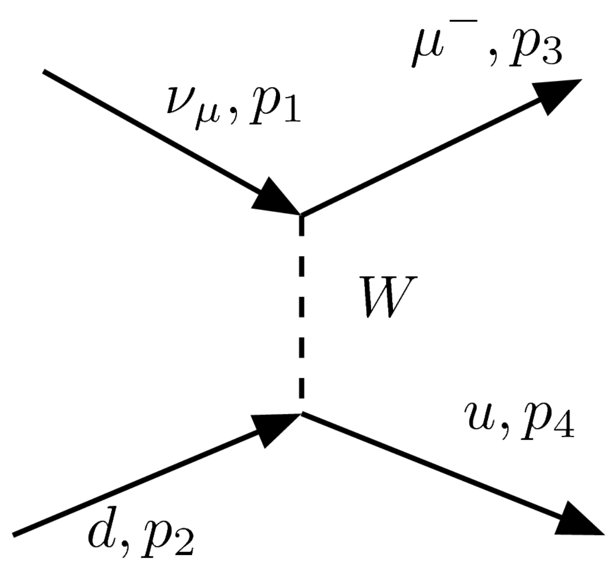




Property of weak IA: W boson couples only to LH particles
(will be discussed in detail later)

$$M_{fi}^{QED} = -\frac{e^2}{q^2}[\overline{u_e}(p_2)\gamma^\mu u_e(p_1)]g_{\mu\nu}[\overline{u_\mu}(p_2)\gamma^\nu u_\mu(p_4)]$$





weak
coupling
constant

$$M_{fi}^{weak} = -\frac{\boxed{g_W^2}}{\boxed{2(q^2 + m_W^2)}}[\overline{u_\mu}(p_3)\gamma^\mu \boxed{\frac{1}{2}(1-\gamma^5)} u_\nu(p_1)]g_{\mu\nu}[\overline{u_u}(p_4)\gamma^\nu \boxed{\frac{1}{2}(1-\gamma^5)} u_d(p_3)]$$

propagator of
massive W boson

LH component only

$$q^2 + m_W^2 \sim m_W^2$$

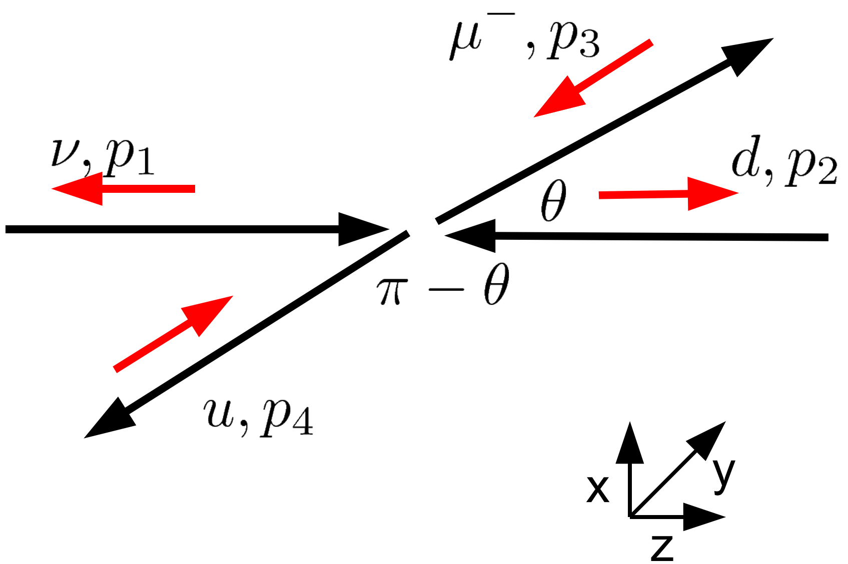
Cross-section for: $\nu + d \rightarrow \mu^- + u$

In CMS : $$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\frac{|\vec{p_i}|}{|\vec{p_f}|}|M^{fi}|^2$$

$\vec{p_i}$ momentum of one incoming particle
$\vec{p_f}$ momentum of one outgoing particle

in the following assume E >> m!

θ in CMS



$$\begin{array}{ll} [0,0] & p_1 = (E, 0, 0, E) \\ [\pi, 0] & p_2 = (E, 0, 0, -E) \\ [\theta, 0] & p_3 = (E, E\sin\theta, 0, E\cos\theta) \\ [\pi - \theta, \pi] & p_4 = (E, -E\sin\theta, 0, -E\cos\theta) \end{array}$$

$$\vec{p} = |\vec{p}|\begin{pmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{pmatrix}$$

4 common eigenstates for energy, momentum and helicity:

$$p = |p| \begin{pmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{pmatrix}$$

particles:

$$u_{h=+1} = \sqrt{E+m} \begin{pmatrix} \cos(\theta/2) \\ e^{i\phi}\sin(\theta/2) \\ \frac{|\vec{p}|}{E+m}\cos(\theta/s) \\ \frac{|\vec{p}|}{E+m}e^{i\phi}\sin(\theta/2) \end{pmatrix} \quad u_{h=-1} = \sqrt{E+m} \begin{pmatrix} -\sin(\theta/2) \\ e^{i\phi}\cos(\theta/2) \\ \frac{|\vec{p}|}{E+m}\sin(\theta/s) \\ \frac{-|\vec{p}|}{E+m}e^{i\phi}\cos(\theta/2) \end{pmatrix}$$

antiparticles:

$$v_{h=1} = \sqrt{E+m} \begin{pmatrix} \frac{|\vec{p}|}{E+m}\sin(\theta/2) \\ -\frac{|\vec{p}|}{E+m}e^{i\phi}\cos(\theta/2) \\ -\sin(\theta/2) \\ e^{i\phi}\cos(\theta/2) \end{pmatrix}, v_{h=-1} = \sqrt{E+m} \begin{pmatrix} \frac{|\vec{p}|}{E+m}\cos(\theta/2) \\ -\frac{|\vec{p}|}{E+m}e^{i\phi}\sin(\theta/2) \\ -\cos(\theta/2) \\ e^{i\phi}\sin(\theta/2) \end{pmatrix}$$

neutrino

$$u_{h=-1}(p_1) = \sqrt{E} \begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix}$$

d quark

$$u_{h=-1}(p_2) = \sqrt{E} \begin{pmatrix} -1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

muon

$$u_{h=-1}(p_3) = \sqrt{E} \begin{pmatrix} -\sin\frac{\theta}{2} \\ \cos\frac{\theta}{2} \\ \sin\frac{\theta}{2} \\ -\cos\frac{\theta}{2} \end{pmatrix}$$

u quark

$$u_{h=-1}(p_4) = \sqrt{E} \begin{pmatrix} -\cos\frac{\theta}{2} \\ -\sin\frac{\theta}{2} \\ \cos\frac{\theta}{2} \\ \sin\frac{\theta}{2} \end{pmatrix}$$

Compute particle current:

$$\overline{\psi}\gamma^\mu\phi = \begin{pmatrix} \psi^{T*}\gamma^0\gamma^0\phi \\ \psi^{T*}\gamma^0\gamma^1\phi \\ \psi^{T*}\gamma^0\gamma^2\phi \\ \psi^{T*}\gamma^0\gamma^3\phi \end{pmatrix}$$

$$\gamma^0\gamma^0 = \begin{pmatrix} I & 0 \\ 0 & I \end{pmatrix} \qquad \gamma^0\gamma^1 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$

$$\gamma^0\gamma^2 = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & -i & 0 & 0 \\ i & 0 & 0 & 0 \end{pmatrix} \qquad \gamma^0\gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

$$\overline{u_{h=-1}(p_3)}\gamma^\mu u_{h=-1}(p_1) = 2E(\cos\tfrac{\theta}{2}, \sin\tfrac{\theta}{2}, -i\sin\tfrac{\theta}{2}, \cos\tfrac{\theta}{2})$$

$$\overline{u_{h=-1}(p_4)}\gamma^\mu u_{h=-1}(p_2) = 2E(\cos\tfrac{\theta}{2}, -\sin\tfrac{\theta}{2}, -i\sin\tfrac{\theta}{2}, -\cos\tfrac{\theta}{2})$$

$$M_{fi} = \frac{g_W^2 E^2}{2m_W^2}(\cos^2\tfrac{\theta}{2} + \sin^2\tfrac{\theta}{2} + \sin^2\tfrac{\theta}{2} + \cos^2\tfrac{\theta}{2}) = \frac{4g_W^2 E^2}{m_W^2}$$

$$\overline{|M_{fi}|^2} = \frac{1}{2}\left|\frac{g_W^2 4E^2}{m_W^2}\right| = \frac{1}{2}\left|\frac{g_W^2 s}{m_W^2}\right|$$

neutrinos are always LH;
Incoming d quarks are in 50% of the case LH, 50% RH

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\frac{1}{2}\left(\frac{g_W^2 s}{m_W^2}\right)^2 = \left(\frac{g_W^2}{8\sqrt{2}\pi m_W^2}\right)^2 s$$

no angular dependence

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2} \qquad \rightarrow \frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2}s$$

$$\boxed{\sigma_{\nu q} = \int \frac{G_F^2}{4\pi^2}d\Omega = \frac{G_F^2 s}{\pi}}$$

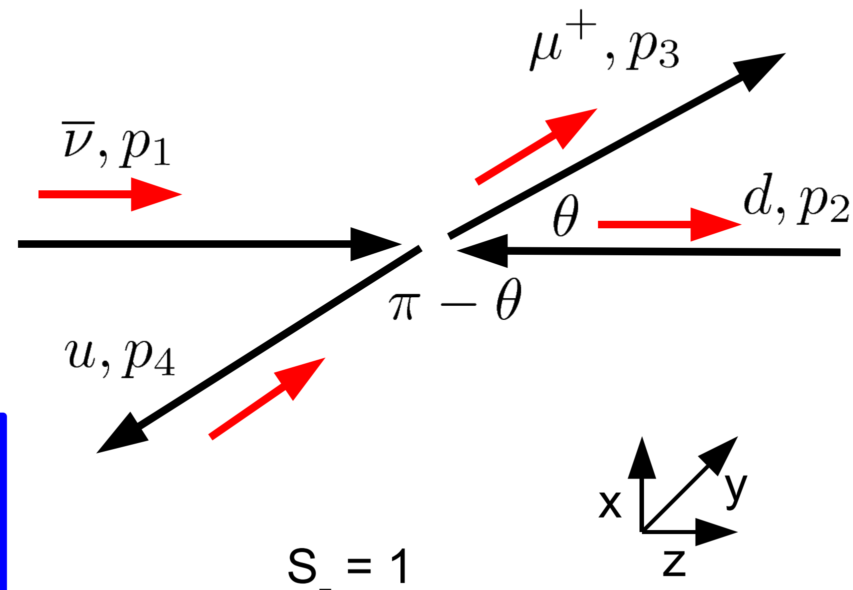
now consider $\overline{\nu}q$ scattering,

same computation, but this time one LH particle current and one RH antiparticle current

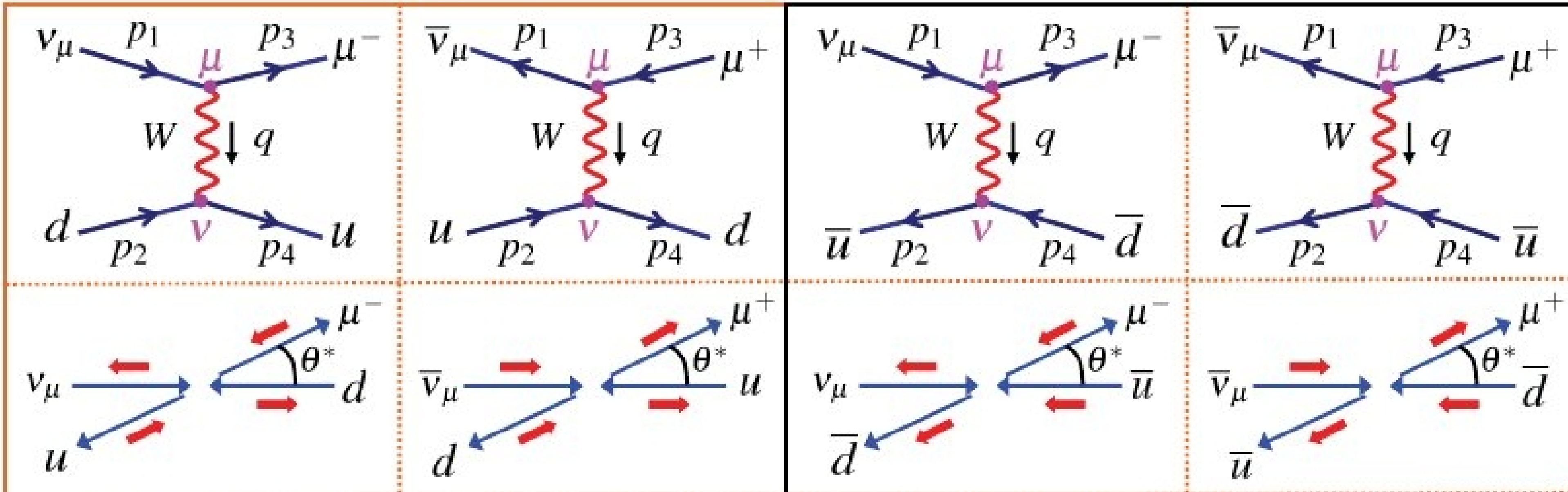
$$\frac{d\sigma_{\overline{\nu}q}}{d\Omega} = \frac{G_F^2}{16\pi^2}(1+\cos\theta)^2 s$$

$$\int (1+\cos\frac{\theta}{2})^2 d\Omega = \frac{16\pi}{3}$$

$$\boxed{\rightarrow \sigma_{\overline{\nu}q} = \frac{G_F^2 s}{3\pi}}$$



Summary of (anti-)neutrino IA with valence and sea quarks



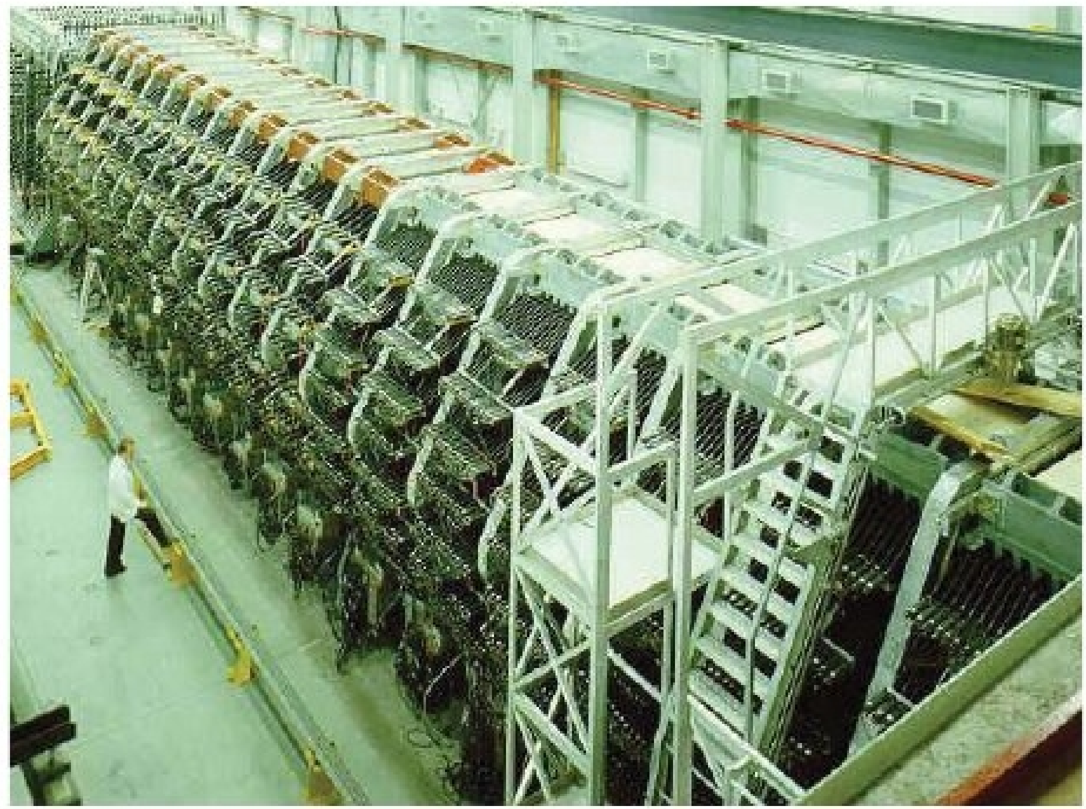
$S_z = 0$	$S_z = +1$	$S_z = -1$	$S_z = 0$
$\frac{d\sigma_{\nu q}}{d\Omega^*} = \frac{G_F^2}{4\pi^2}\hat{s}$	$\frac{d\sigma_{\overline{\nu} q}}{d\Omega^*} = \frac{G_F^2}{16\pi^2}(1+\cos\theta^*)^2\hat{s}$	$\frac{d\sigma_{\nu \overline{q}}}{d\Omega^*} = \frac{G_F^2}{16\pi^2}(1+\cos\theta^*)^2\hat{s}$	$\frac{d\sigma_{\overline{\nu}\overline{q}}}{d\Omega^*} = \frac{G_F^2}{4\pi^2}\hat{s}$
$\sigma_{\nu q} = \frac{G_F^2 \hat{s}}{\pi}$	$\sigma_{\overline{\nu} q} = \frac{G_F^2 \hat{s}}{3\pi}$	$\sigma_{\nu \overline{q}} = \frac{G_F^2 \hat{s}}{3\pi}$	$\sigma_{\overline{\nu}\overline{q}} = \frac{G_F^2 \hat{s}}{\pi}$

Differential cross sections still given in CMS system, transform in LI notation ....

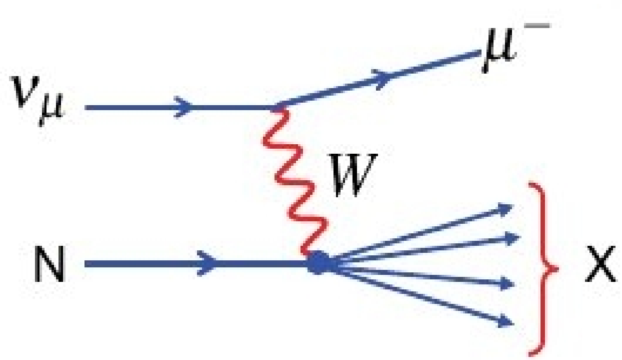
$$\frac{d\sigma_{\nu q}}{dy} = \frac{G_F^2}{4\pi^2}s \qquad \frac{d\sigma_{\overline{\nu} q}}{dy} = \frac{d\sigma_{\nu \overline{q}}}{dy} = \frac{G_F^2}{4\pi^2}(1-y)^2 s \qquad \frac{d\sigma_{\overline{\nu q}}}{dy} = \frac{G_F^2}{4\pi^2}s$$

CDHS Experiment at CERN (1976 – 84)
(CERN-Dortmund-Heidelberg-Saclay - Experiment)

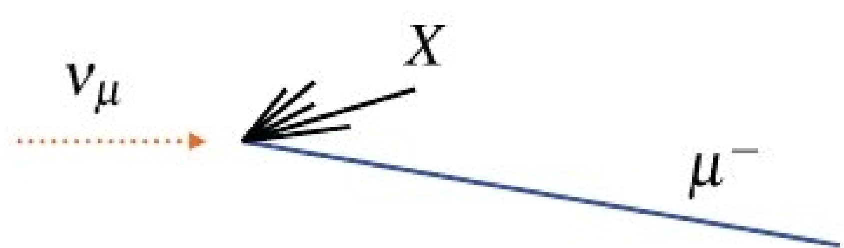
- 1250 tons
- Magnetized iron modules
- Separated by drift chambers

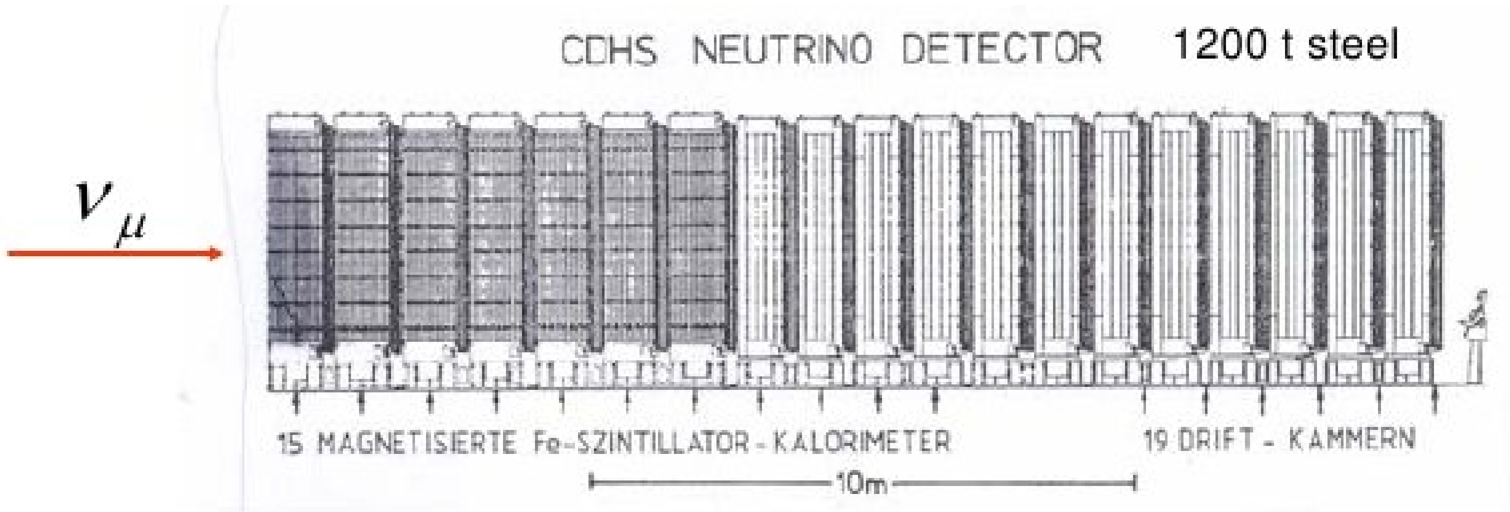


Study Neutrino Deep Inelastic Scattering

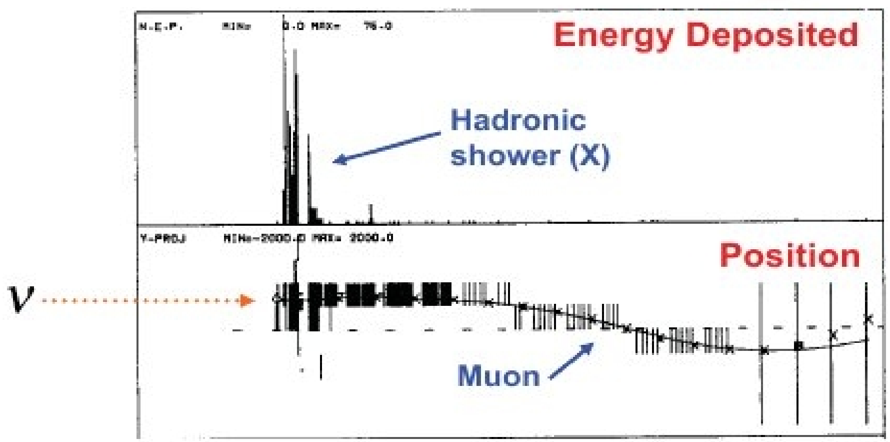


Experimental Signature:





Example Event:



- **Measure energy of X**

  E_X

- **Measure muon momentum from curvature in B-field**

  E_μ

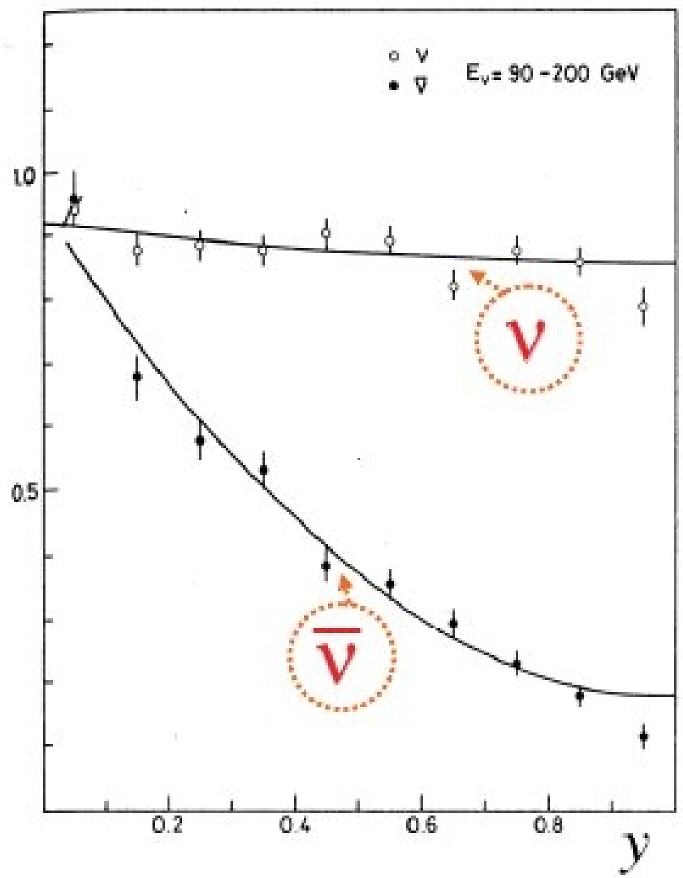
★ **For each event can determine neutrino energy and y !**

$$E_\nu = E_X + E_\mu$$

$$E_\mu = (1-y)E_\nu \quad \longrightarrow \quad y = \left(1 - \frac{E_\mu}{E_\nu}\right)$$

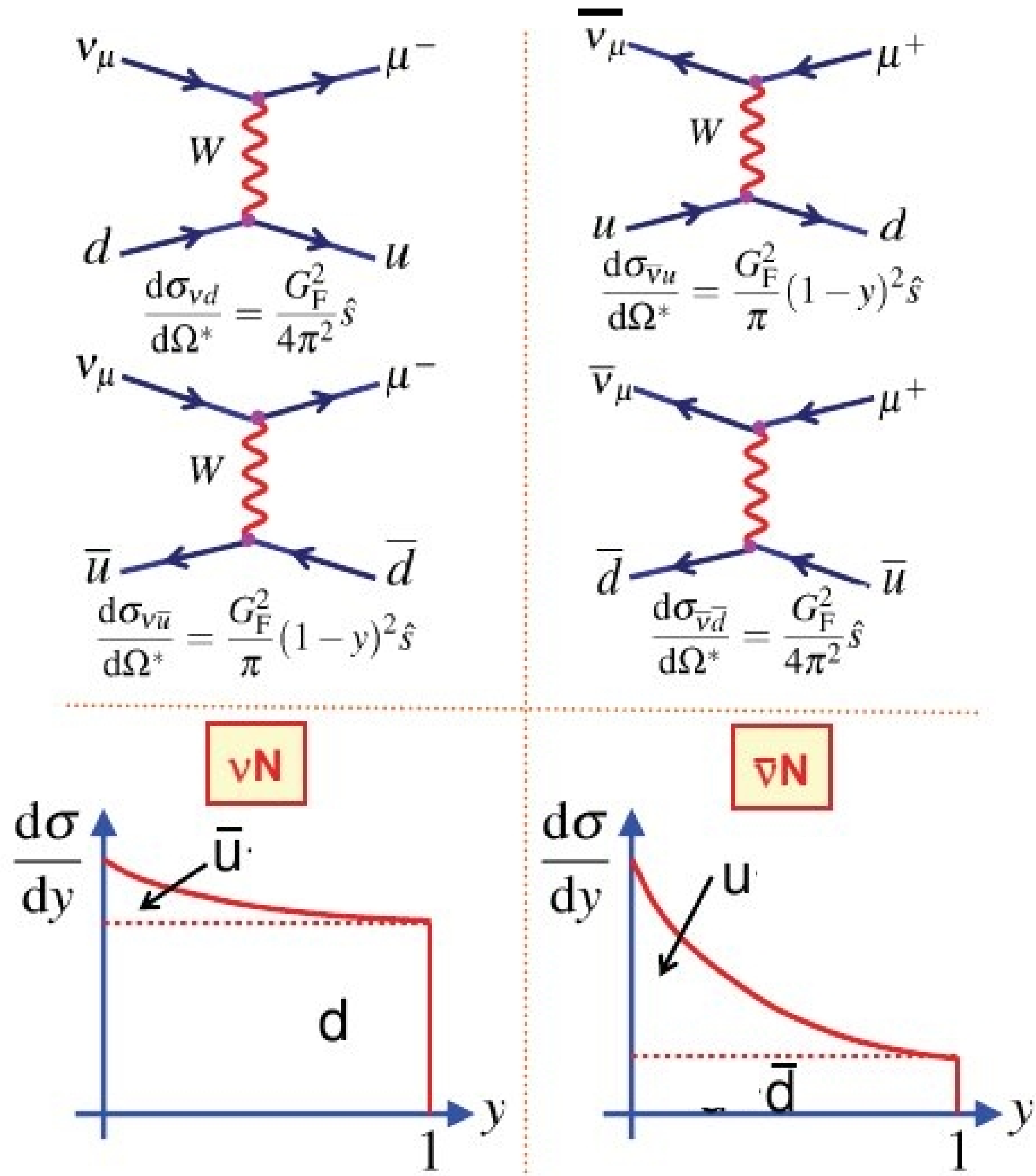
Measured y distribution

- CDHS measured y distribution



J. de Groot et al., Z.Phys. C1 (1979) 143

- Shapes can be understood in terms of (anti)neutrino – (anti)quark scattering



$$\frac{d\sigma_{\nu d}}{d\Omega^*} = \frac{G_F^2}{4\pi^2}\hat{s}$$

$$\frac{d\sigma_{\bar{\nu} u}}{d\Omega^*} = \frac{G_F^2}{\pi}(1-y)^2\hat{s}$$

$$\frac{d\sigma_{\nu \bar{u}}}{d\Omega^*} = \frac{G_F^2}{\pi}(1-y)^2\hat{s}$$

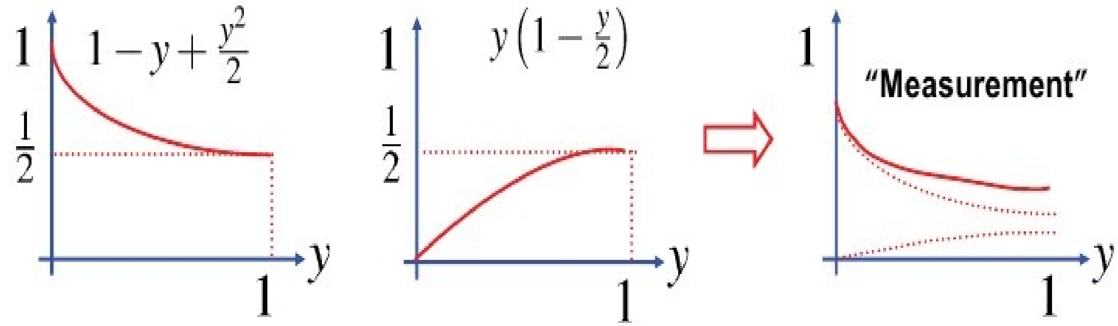
$$\frac{d\sigma_{\bar{\nu} \bar{d}}}{d\Omega^*} = \frac{G_F^2}{4\pi^2}\hat{s}$$

$$\frac{d\sigma^{\nu p}}{dy} = \frac{d\sigma^{\nu q}}{dy} + \frac{d\sigma^{\nu \bar{q}}}{dy} = \frac{G_F^2 s x}{\pi} \left(d(x) + (1-y)^2 \overline{u(x)} \right) dx$$

use notation with structure functions

$$\frac{d^2\sigma^{\nu p}}{dx dy} = \frac{G_F^2 s}{2\pi} \left((1-y) F_2^{\nu p}(x) + y^2 x F_1^{\nu p}(x) + y(1-\tfrac{y}{2}) x F_3^{\nu p}(x) \right)$$

Exploit y dependence to fit for structure functions



compare expressions in orders of y

$$F_2^{\nu p} = 2xd(x) + 2x\overline{u(x)}$$

$$-4x\overline{u(x)} = -F_2 + xF_3$$

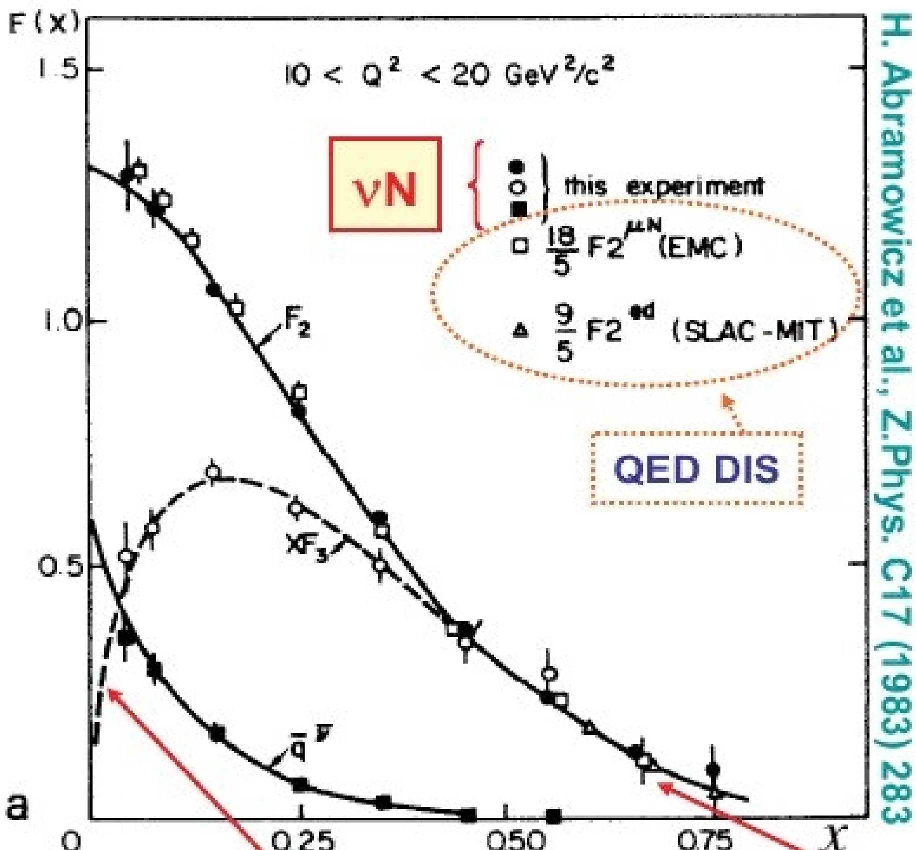
$$2\overline{u(x)} = xF_1 - xF_3/2$$

$\Rightarrow F_2(x)^{\nu p} = 2xF_1^{\nu p}(x) = 2x(d(x) + \overline{u(x)})$ / $F_2(x)^{\nu n} = 2xF_1^{\nu n}(x) = 2x(u(x) + \overline{d(x)})$

$\Rightarrow xF_3(x)^{\nu p} = 2x(d(x) - \overline{u(x)})$ / $xF_3(x)^{\nu n} = 2x(u(x) - \overline{d(x)})$

Measurement of neutrino structure functions

- **CDHS Experiment** $\nu_\mu + \mathrm{Fe} \to \mu^- + X$



$$F_2^{\nu N} = x[u(x) + d(x) + \overline{u}(x) + \overline{d}(x)]$$
$$xF_3^{\nu N} = x[u(x) + d(x) - \overline{u}(x) - \overline{d}(x)]$$

$$\Rightarrow F_2^{\nu N} - xF_3^{\nu N} = 2x[\overline{u} + \overline{d}]$$

- **Difference in neutrino structure functions measures anti-quark (sea) parton distribution functions**

Sea dominates so expect xF_3 to go to zero as $q(x) = \overline{q}(x)$

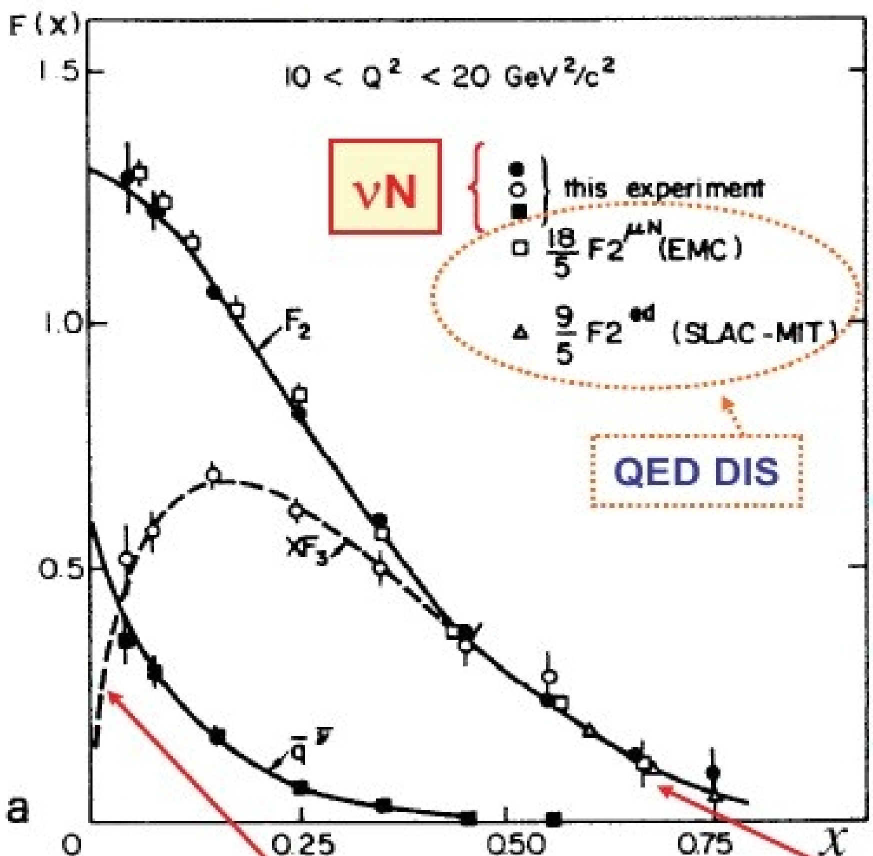
Sea contribution goes to zero

$$\int F_3(x)^{\nu N} dx = \int u_V(x) + d_V(x)$$

experimental result: 3.0 ± 0.2

Measurement of neutrino structure functions

- **CDHS Experiment** $\nu_\mu + \mathrm{Fe} \rightarrow \mu^- + X$



H. Abramowicz et al., Z.Phys. C17 (1983) 283

$$F_2^{ep} = 2xF_1^{ep} = x[\tfrac{4}{9}u(x) + \tfrac{1}{9}d(x) + \tfrac{4}{9}\overline{u}(x) + \tfrac{1}{9}\overline{d}(x)]$$

$$F_2^{en} = 2xF_1^{en} = x[\tfrac{4}{9}d(x) + \tfrac{1}{9}u(x) + \tfrac{4}{9}\overline{d}(x) + \tfrac{1}{9}\overline{u}(x)]$$

$$\boxed{F_2^{eN} = \tfrac{1}{2}\left(F_2^{ep} + F_2^{en}\right) = \tfrac{5}{18}x[u(x) + d(x) + \overline{u}(x) + \overline{d}(x)]}$$

$$\Rightarrow \boxed{F_2^{\nu N} = \tfrac{18}{5}F_2^{eN}}$$

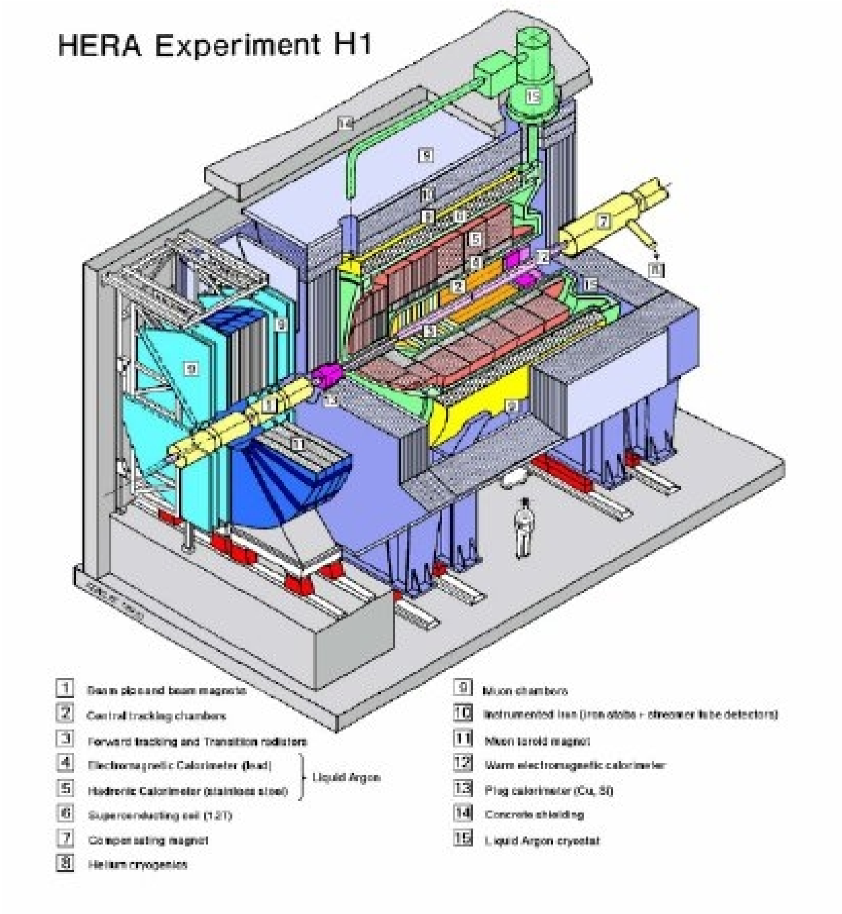
$$F_2^{eN} = \frac{5}{18}F_2^{\nu N}$$

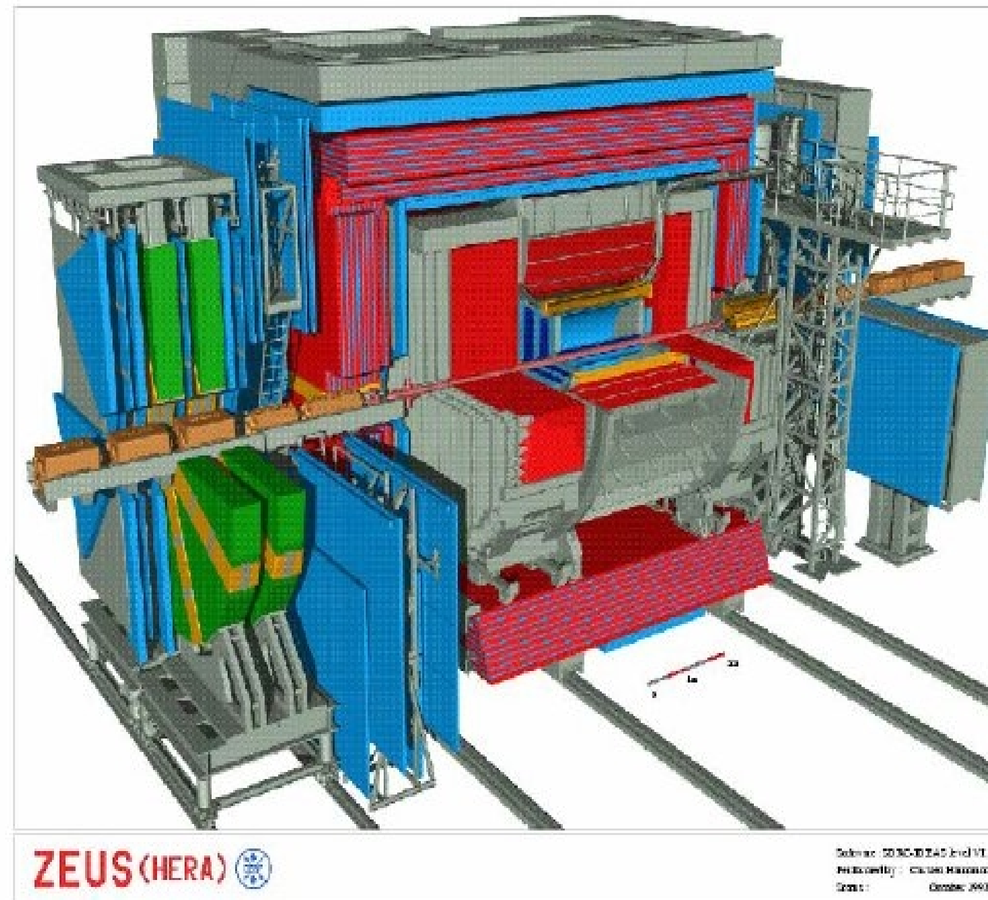
Experiment: 0.29 ± 0.02

Sea dominates so expect xF_3 to go to zero as q(x) = $\overline{q}$(x)

Sea contribution goes to zero

HERA Collider at DESY

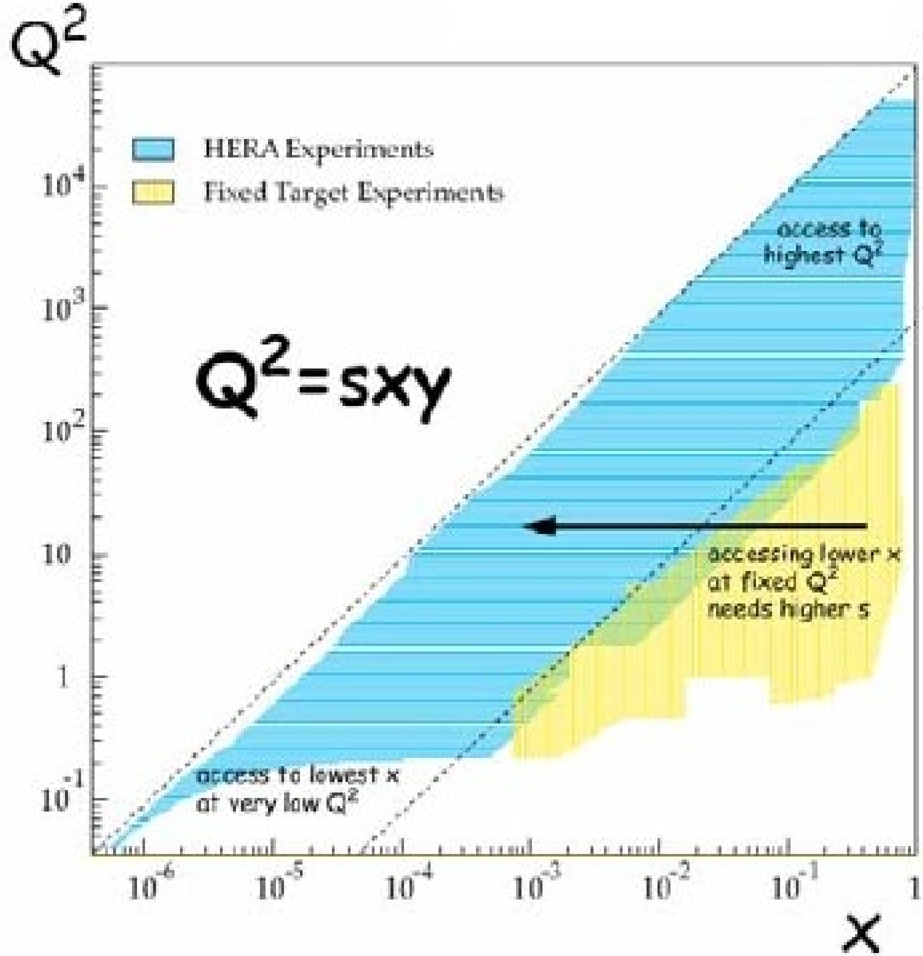




$e^{\pm}$ → ← p

30 GeV 900 GeV

Accessing the low x region:



HERA: y = 1

s~10^5 GeV^2

Fixed Target: y = 1

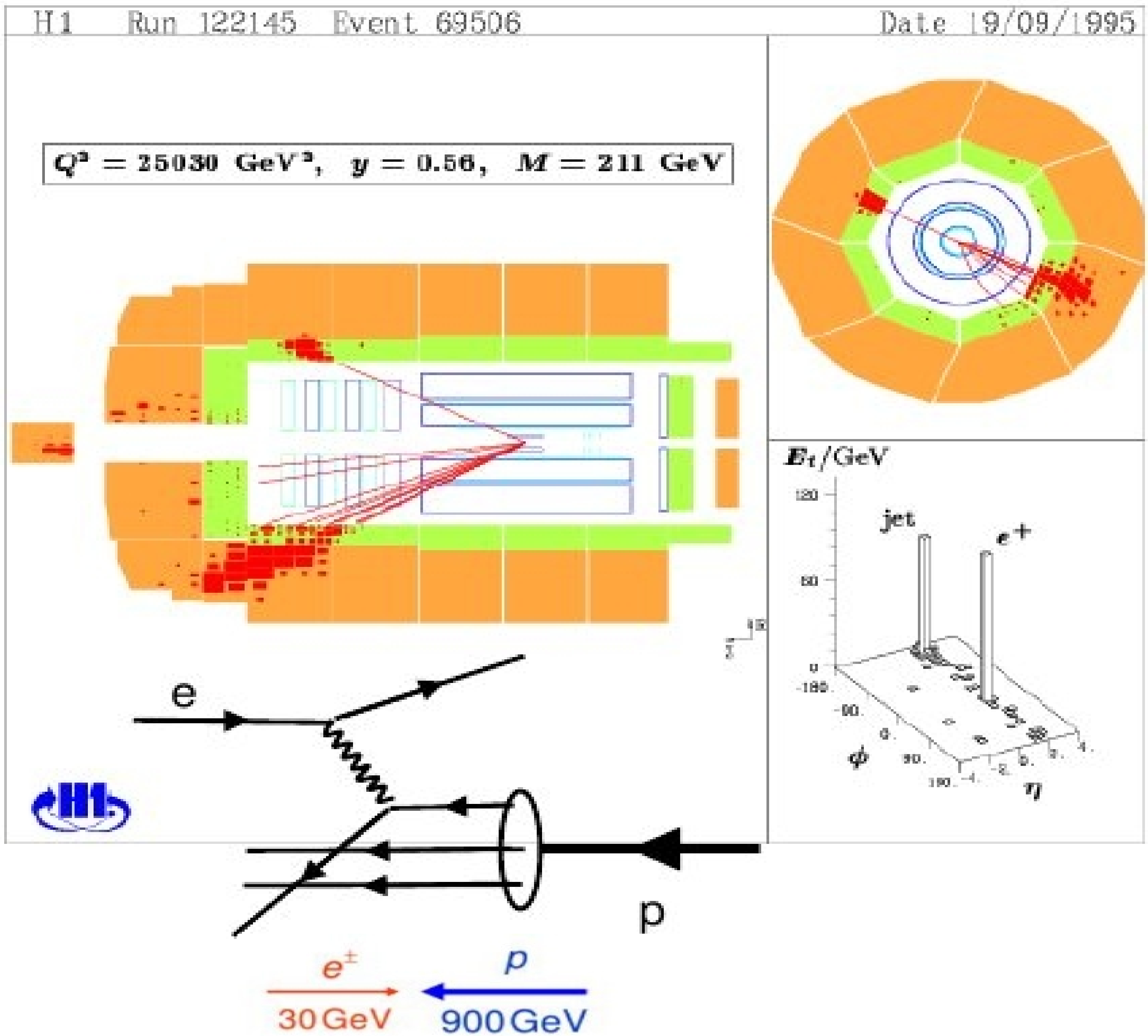
s<10^3 GeV^2

HERA

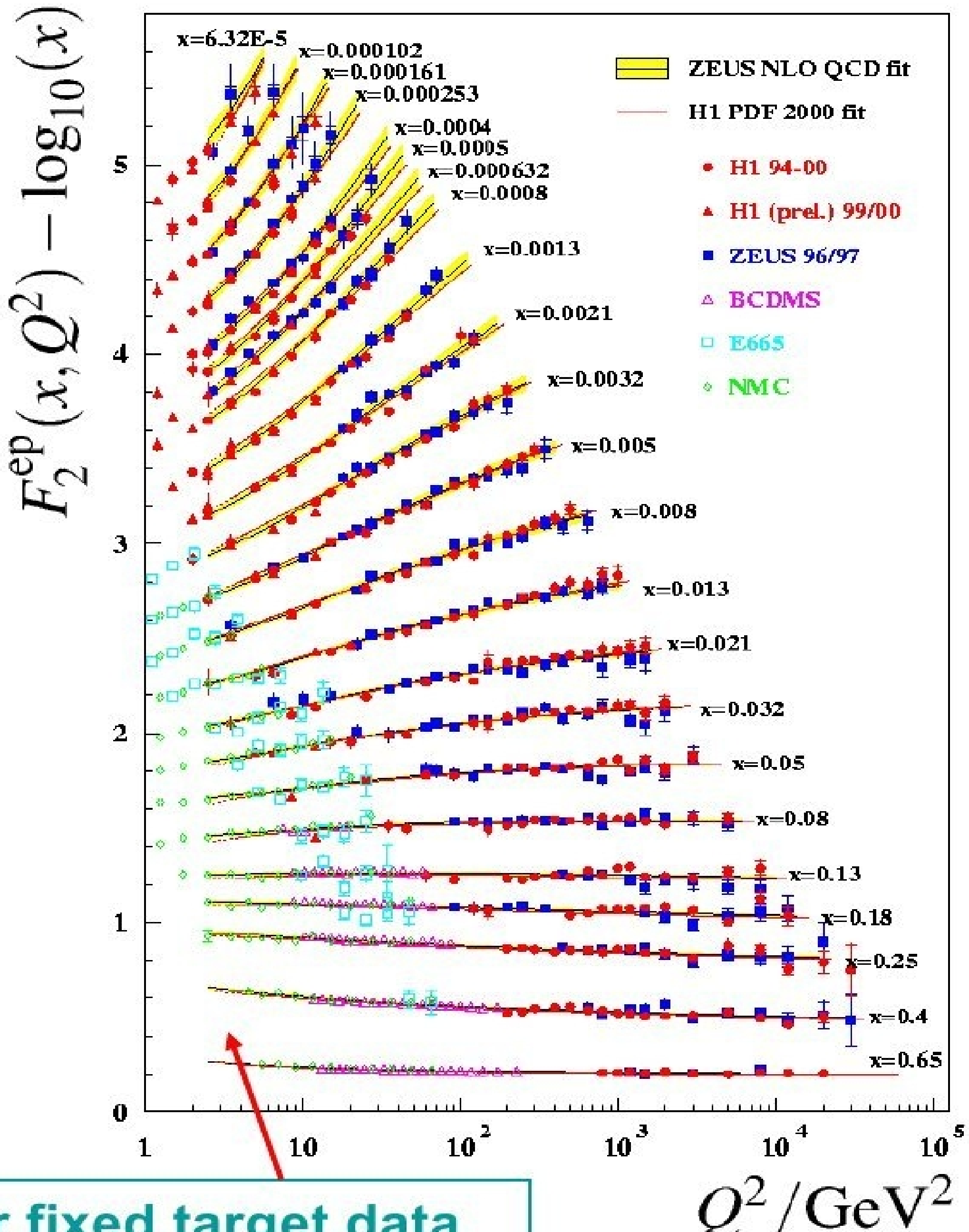
$e^{\pm}$ → 30 GeV

← p 900 GeV

$$s = 4E_eE_p \approx 10^5 \mathrm{GeV}^2$$


H1 Run 122145 Event 69506
Date 19/09/1995
$Q^2 = 25030$ GeV^2, $y = 0.56$, $M = 211$ GeV
E_t/GeV
jet
e^+
ϕ
η
e
p
$e^\pm$
30 GeV
p
900 GeV

Scaling violation

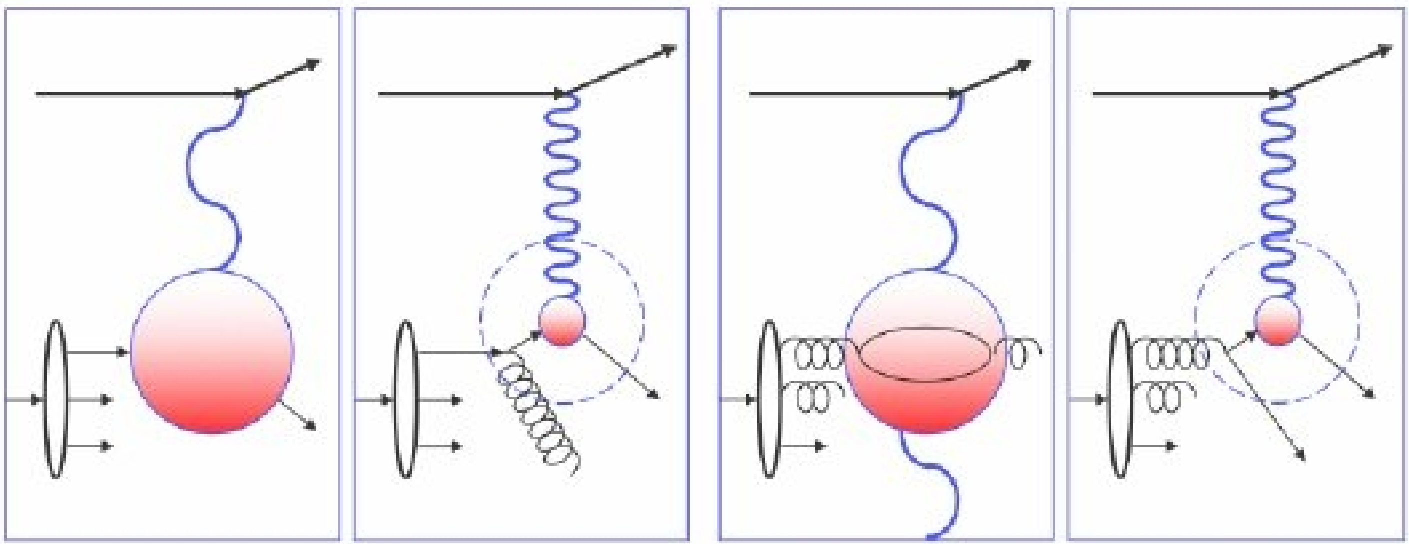


Earlier fixed target data

QCD explains observed scaling violation

Large x: valence quarks

Small x: Gluons, sea quarks

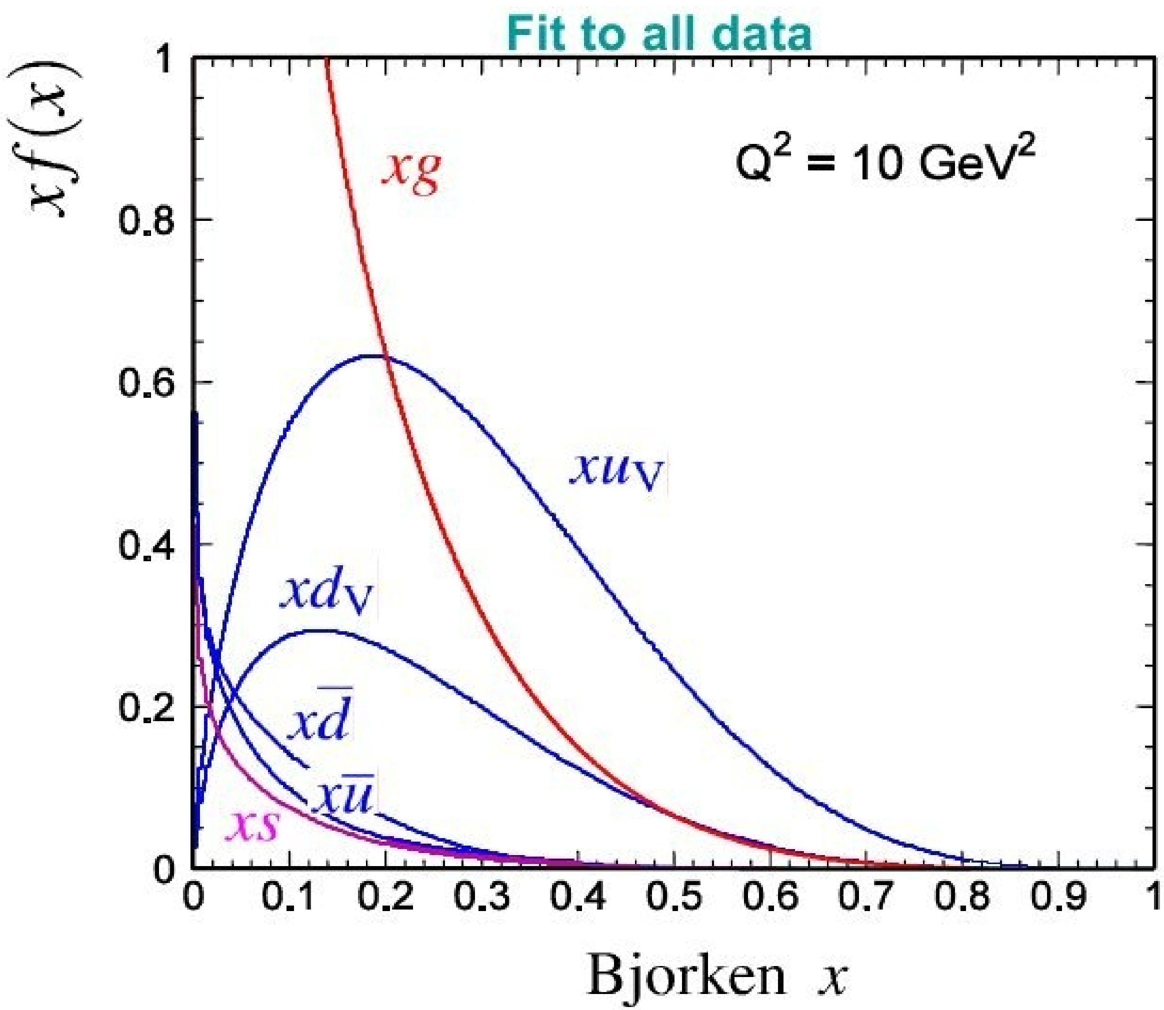


$Q^2 \uparrow \Rightarrow F_2 \downarrow$ for fixed x

$Q^2 \uparrow \Rightarrow F_2 \uparrow$ for fixed x

only understandable if gluon self IA are taken into account, however exactly predicted by QCD
low x range exploited to measure gluon momentum functions

Parton density distribution in protons



Note:

- Apart from at large x
  $u_V(x) \approx 2d_V(x)$
- For $x < 0.2$
  gluons dominate
- In fits to data assume
  $u_s(x) = \overline{u}(x)$
- $\overline{d}(x) > \overline{u}(x)$
  not understood –
  exclusion principle?
- Small strange quark component $s(x)$

Summary of structure of protons

- Protons consist of
  - point-like particles → structure functions depend only on x not on x and Q^2
  - with spin ½ → $F_2(x) = 2xF_1(x)$
  - number of valence quarks = 3 → neutrino scattering
- (valence + sea) quarks carry 50% of the proton momentum
- momentum distribution of valence and sea quarks and gluons are measured