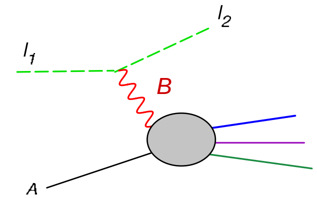
Deep Inelastic Scattering in Lepton-Hadron Collisions
—Probing the Parton Structure of the Nucleon with Leptons

- Basic Formalism
  (indep. of strong dynamics and parton picture)
- Experimental Development
  - Fixed target experiments
  - HERA experiments
- Parton Model and QCD
  - Parton Picture of Feynman-Bjorken
  - Asymptotic freedom, factorization and QCD
- Phenomenology
  - QCD parameters
  - Parton distribution functions
  - Other interesting topics

Basic Formalism
(leading order in EW coupling)

Lepton-hadron scattering process

$$\ell_1(\ell_1) + N(P) \longrightarrow \ell_2(\ell_2) + X(P_X)$$



(B = g, W, Z)

Effective fermion-boson electro-weak interaction Lagrangian:

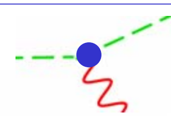
$$\mathcal{L}^{\mathrm{EW}}_{\mathrm{int}} = -g_B \left[j^{(\ell)}_\mu(x) + J^{(h)}_\mu(x) \right] \; V^\mu_B(x)$$

EW SU(2)xU(1) gauge coupling constants

B	γ	$W^\pm$	Z
g_B	$-e$	$\frac{g}{2\sqrt{2}}$	$\frac{g}{2\cos\theta_W}$

Basic Formalism: current operators and coupling

Fermion current operator:



$$\begin{aligned} J^{(f)}_\mu(x) &= \overline{\psi}_f(x)\gamma_\mu \left(g_V - g_A\gamma^5\right)\psi_f(x) \\ &= \overline{\psi}_f(x)\gamma_\mu \left[g_R(1+\gamma^5) + g_L(1-\gamma^5)\right]\psi_f(x) \end{aligned}$$

V-A couplings:

or,

Left-right (chiral) couplings:

Charge

Weak isospin

Weinberg angle

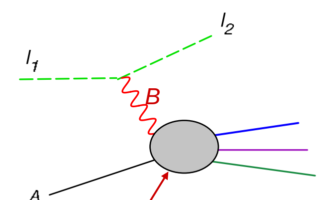
CKM mixing matrix

	γ	Z	$W^\pm$
g_V	Q_i	$T^i_{3L} - 2Q_i\sin^2\theta_W$	$1\cdot V_{ij}$
g_A	0	T^i_{3L}	$1\cdot V_{ij}$
g_R	$\frac{Q_i}{2}$	$-Q_i\sin^2\theta_W$	0
g_L	$\frac{Q_i}{2}$	$T^i_{3L} - Q_i\sin^2\theta_W$	$1\cdot V_{ij}$

Basic Formalism: Scattering Amplitudes

Scattering Amplitudes

$$\mathcal{M} = J^*_\mu(P,q)\frac{g_B^2 G^\mu{}_\nu}{Q^2+M_B^2} j^\nu(q,\ell)$$



Spin 1 projection tensor $\quad G^\mu{}_\nu = g^\mu{}_\nu - q^\mu q_\nu/M_B^2.$

Lepton current amplitude (known):

$$j^\mu(q,\ell) = \langle \ell_2 | j^\mu | \ell_1 \rangle = \overline{u}(\ell_2)\gamma^\mu[g_R(1+\gamma^5) + g_L(1-\gamma^5)]u(\ell_1)$$

Hadron current amplitude (unknown):

$$J^*_\mu(P,q) = \langle P_X | J^\dagger_\mu | P \rangle$$

Object of study:
- * Parton structure of the nucleon; (short distance)
- * QCD dynamics at the confinement scale (long dis.)

Basic Formalism: Cross section

Cross section

(amplitude)² phase space / flux

$$d\sigma = \frac{G_1 G_2}{2\Delta(s, m_{\ell_1}^2, M^2)}\, 4\pi Q^2\, L^\mu_\nu\, W^\nu_\mu\, d\Gamma$$

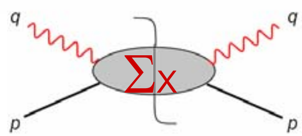
$$\boxed{G_i = g_{B_i}^2/(Q^2 + M_{B_i}^2)}$$

Lepton tensor (known):

$$L^\mu{}_\nu = \frac{1}{Q^2}\overline{\sum_{\text{spin}}}\langle \ell_1|j_\nu^\dagger|\ell_2\rangle\langle \ell_2|j^\mu|\ell_1\rangle$$

Hadron tensor (unknown):

$$W^\mu{}_\nu = \frac{1}{4\pi}\overline{\sum_{\text{spin}}}(2\pi)^4\delta^4(P+q-P_X)\langle P|J^\mu|P_X\rangle\langle P_X|J_\nu^\dagger|P\rangle$$



Object of study:

* Parton structure of the nucleon;
* QCD dynamics at the confinement scale

Basic Formalism: Structure Functions

Expansion of $W^\mu{}_\nu$ in terms of <u>*independent*</u> components

$$W^\mu{}_\nu = -g^\mu{}_\nu W_1 + \frac{P^\mu P_\nu}{M^2}W_2 - i\frac{\epsilon^{Pq\mu}{}_\nu}{2M^2}W_3 + \frac{q^\mu q_\nu}{M^2}W_4 + \frac{P^\mu q_\nu + q^\mu P_\nu}{2M^2}W_5 + \frac{P^\mu q_\nu - q^\mu P_\nu}{2M^2}W_6$$

Cross section in terms of the structure functions

$$\frac{d\sigma}{dE_2\, d\cos\theta} = \frac{2E_2^2}{\pi M}\frac{G_1 G_2}{n_\ell}\left\{g_{+\ell}^2\left[2W_1\sin^2\frac{\theta}{2} + W_2\cos^2\frac{\theta}{2}\right] \pm g_{-\ell}^2\left[\frac{E_1+E_2}{M}W_3\sin^2\frac{\theta}{2}\right]\right\}$$

Charged Current (CC) processes (neutrino beams):
W-exchange (diagonal); left-handed coupling only; ….

Neutral Current (NC) processes (e,μ scat.)---low energy:
(fixed tgt): γ-exchange (diagonal); vector coupling only; …

Neutral Current (NC) processes (e,μ scat.)---high energy
(hera): γ & Z exchanges: G_1^2, G_1G_2, G_2^2 terms; ….

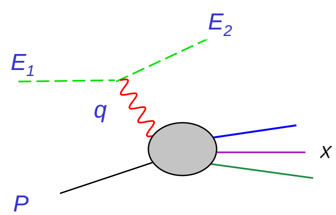
Basic Formalism: Scaling structure functions

Kinematic variables

$$\nu = \frac{P\cdot q}{\sqrt{P\cdot P}} = E_1 - E_2$$

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

$$y = \frac{P\cdot q}{P\cdot \ell_1} = \frac{\nu}{E_1}$$



Scaling (dimensionless) structure functions

$$\boxed{\begin{aligned} F_1(x,Q) &= W_1 \\ F_2(x,Q) &= \frac{\nu}{M}W_2 \\ F_3(x,Q) &= \frac{\nu}{M}W_3 \end{aligned}}$$

Scaling form of cross section formula:

$$(\ g_{\pm\ell}^2 = g_{L\ell}^2 \pm g_{R\ell}^2\ )$$

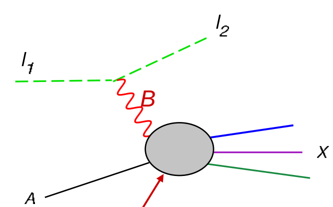
$$\boxed{\frac{d\sigma}{dx\,dy} = \frac{2ME_1}{\pi}\frac{G_1G_2}{n_\ell}\left\{g_{+\ell}^2\left[xF_1\,y^2 + F_2\left[(1-y) - \left(\frac{Mxy}{2E_1}\right)\right]\right] \pm g_{-\ell}^2\left[xF_3\,y(1-\frac{y}{2})\right]\right\}}$$

n_ℓ is the number of polarization states of the incoming lepton

Basic Formalism: Helicity Amplitudes

Scattering Amplitudes

$$\mathcal{M}^{\lambda_2\sigma_2}_{\lambda_1\sigma_1} = J^{*\sigma_2}_{\sigma_1 m}(Q^2, q\cdot P)\,\frac{g_B^2\, d^1(\psi)^m{}_n}{Q^2 + M_B^2}\, j^{\lambda_2 n}_{\lambda_1}(Q^2)$$



Spin 1 rotation matrix $\quad d^1(\psi)^m{}_n$

Lepton current amplitude (known):

$$j^{\lambda_2 n}_{\lambda_1}(Q) = \epsilon^{n*}_\mu\langle \ell_2,\lambda_2|j^\mu|\ell_1,\lambda_1\rangle = \bar{u}_{\lambda_2}(\ell_2)\,\epsilon^{n*}\cdot\Gamma\, u_{\lambda_1}(\ell_1)$$

Hadron current amplitude (unknown):

$$J^{*\sigma_2}_{\sigma_1 m}(Q^2, q\cdot P) = \langle P_X,\sigma_2|J^\dagger_\mu|P,\sigma_1\rangle\,\epsilon^\mu_m$$

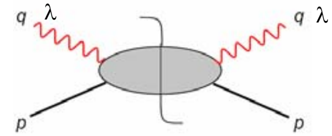
Object of study:

* Parton structure of the nucleon;
* QCD dynamics at the confinement scale

Basic Formalism: Helicity structure functions

Forward Compton scattering amplitude for vector boson polarization λ

$$F_\lambda = \epsilon_\mu^{\lambda *}(P,q)\, W^\mu{}_\nu(P,q)\, \epsilon_\lambda^\nu(P,q)$$



Relations between invariant and helicity S.F.s

$$\begin{aligned} F_{right} = \quad F_+(x,Q) &= \quad F_1 - \tfrac{1}{2}\kappa\, F_3 \\ F_{left} = \quad F_-(x,Q) &= \quad F_1 + \tfrac{1}{2}\kappa\, F_3 \\ F_{long} = \quad F_0(x,Q) &= -F_1 + \tfrac{1}{2x}\kappa^2\, F_2 \end{aligned}$$

Where at high energies $\kappa = \sqrt{1 - \frac{Q^2}{\nu^2}} \approx 1$

Should have been absorbed into the definition of the scaling S.F.'s $F_{2,3}$!

Conversely,

$$\begin{aligned} F_1 &= \tfrac{1}{2}(F_1 + F_2) = \tfrac{1}{2}(F_{right} + F_{left}) = F_T \\ F_2 &= 2x(F_T + F_L)\,\tfrac{1}{\kappa^2} \\ F_3 &= (F_{right} - F_{left})\,\tfrac{1}{\kappa} \end{aligned}$$

Cross section formula:

$$\frac{d\sigma}{dx dy} = \frac{yQ^2}{2\pi}\frac{G_1 G_2}{n_\ell}\left\{g_{+\ell}^2\left[F_T(1+\cosh^2\psi) + F_L\sinh^2\psi\right] \mp g_{-\ell}^2\left[\kappa F_3\cosh\psi\right]\right\}$$

where $\cosh\psi = \dfrac{E_1 + E_2}{\sqrt{Q^2+\nu^2}} \underset{M \to 0}{\longrightarrow} \dfrac{(2-y)}{y}$

Experimental Development

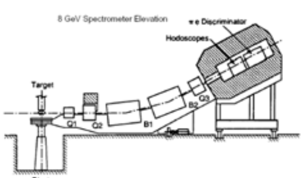
Interesting and comprehensive description of the entire history of probing the structure of nuclei—from (pre-) Rutherford scattering … 1930's …50's (Hofstadter) …60's, 70's (SLAC), …SPS, Fermilab, HERA Highly recommended!

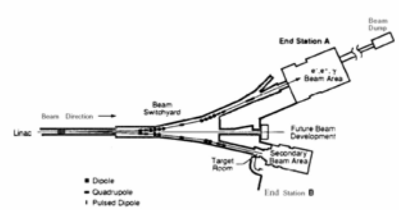
2-lecture series by E. Tassi at CTEQ2003

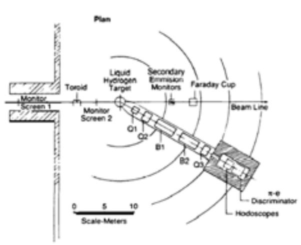
http://www-zeus.desy.de/~tassi/cteq2003.html

The SLAC-MIT Experiment

Under the leadership of Taylor, Friedman, Kendall (Nobel prize, 1990)

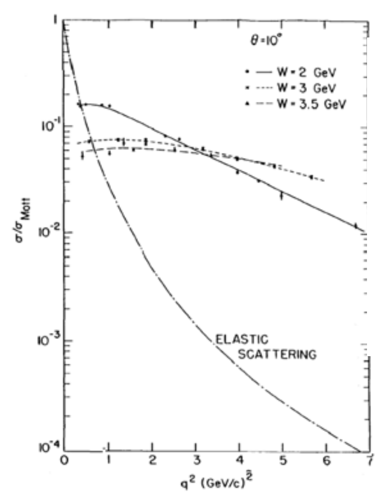


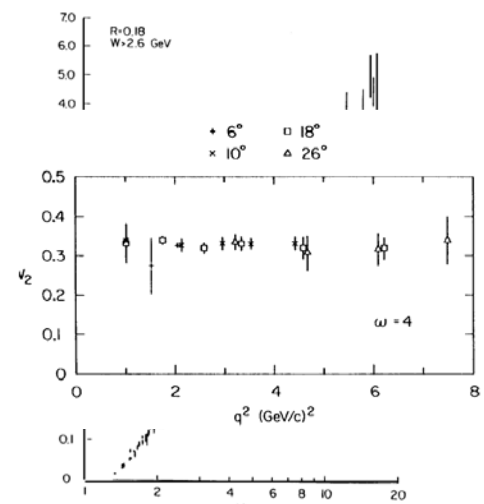




First SLAC-MIT results ~ 1969

Two unexpected results…



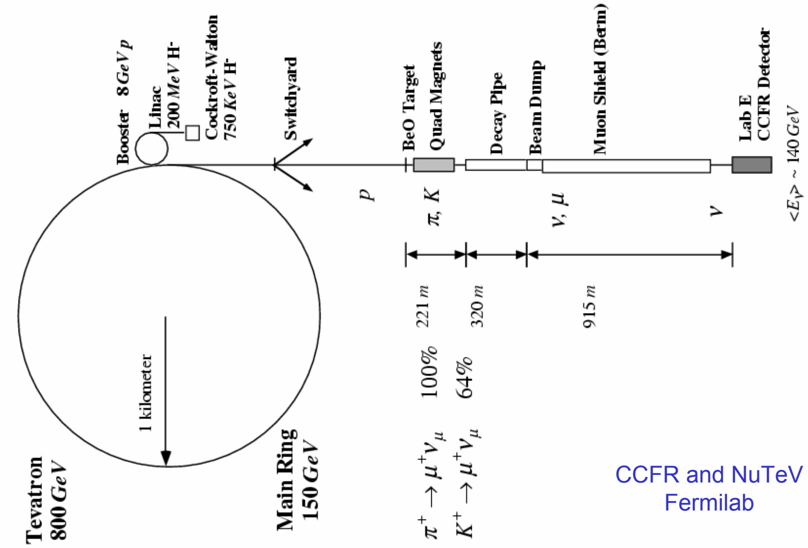


Experimental Development
— modern experiments (high Q)

DIS

e N	*SLAC*
μ N	*BCDMS*
	NMC, E665
	H1, ZEUS
ν N	*CDHS, CHARM*
ν̄ N	*CCFR*
	CHORUS
	NuTeV

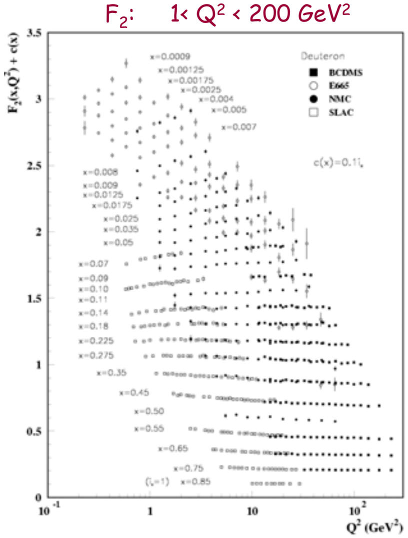
The highest energy (anti-) neutrino DIS experiments



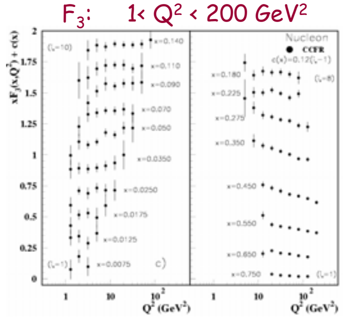
CCFR and NuTeV
Fermilab

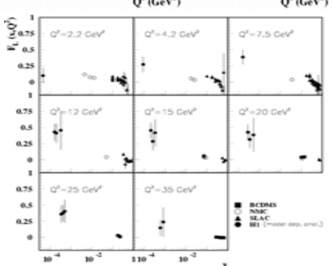
Fixed targets results: An overview (PDG)
(Neutral Current "old" results)

F_2: $1 < Q^2 < 200$ GeV^2



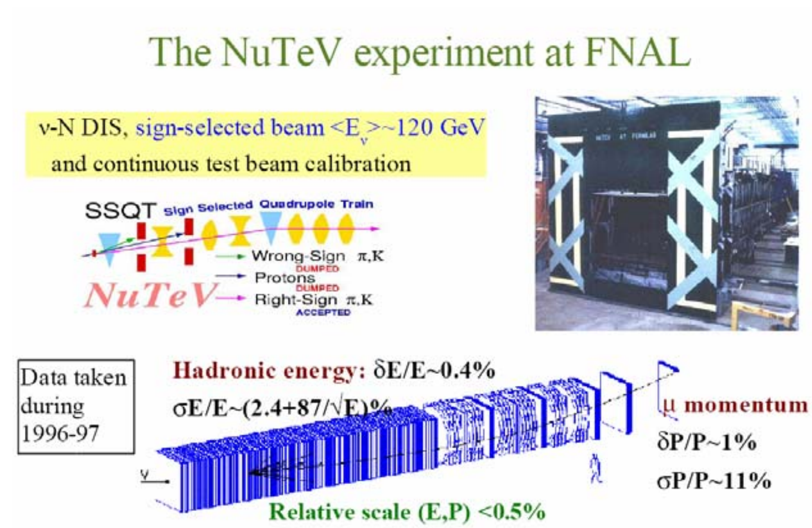
F_3: $1 < Q^2 < 200$ GeV^2



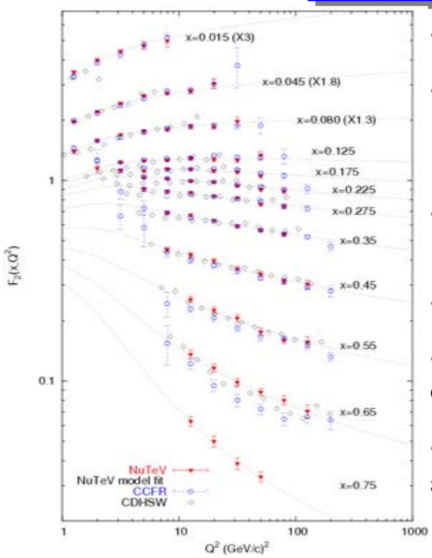


F_L

The highest energy (anti-) neutrino DIS experiment

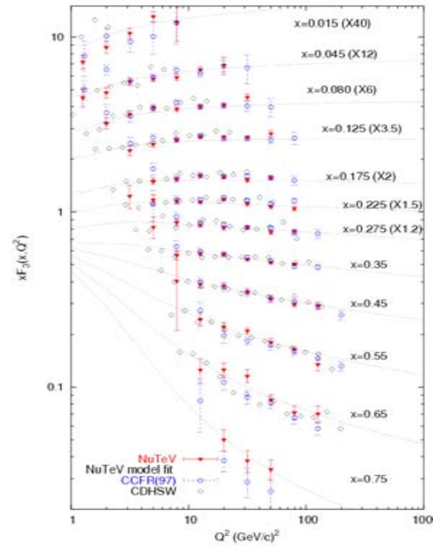


F_2 Measurement



- Isoscalar ν-Fe F_2
- NuTeV F_2 is compared with CCFR and CDHSW results
  - the line is a fit to NuTeV data
- All systematic uncertainties are included
- All data sets agree for $x<0.4$.
- At $x>0.4$ NuTeV agrees with CDHSW
- At $x>0.4$ NuTeV is systematically above CCFR

xF_3 Measurement



- Isoscalar ν-Fe xF_3
- NuTeV xF_3 is compared with CCFR and CDHSW results
  - the line is a fit to NuTeV data
- All systematic uncertainties are included
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- At $x>0.4$ NuTeV is systematically above CCFR

The HERA Collider

The first and only ep collider in the world

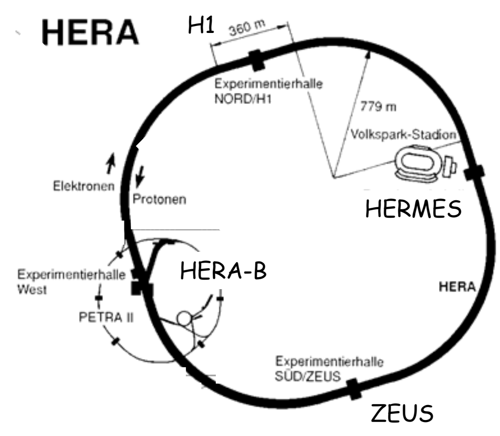
Located in Hamburg

$e^{\pm}$	p
27.5 GeV	920 GeV

$\sqrt{s}$ = 318 GeV

Equivalent to fixed target experiment with 50 TeV $e^{\pm}$

Two independent storage rings



H1 - ZEUS

Colliding beam experiments

HERA-B

Uses p beam on wire target
Goal: B - physics

HERMES

Uses $e^{\pm}$ beam on gas jet target
Both lepton and target polarized
Measurement of polarized structure functions

The Collider Experiments

H1 Detector

Complete 4π detector with

Tracking
- **Si-μVTX**
- **Central drift chamber**

Liquid Ar calorimeter

$\sigma_E/E = 12\%/\sqrt{E[GeV]}$ (e.m.)

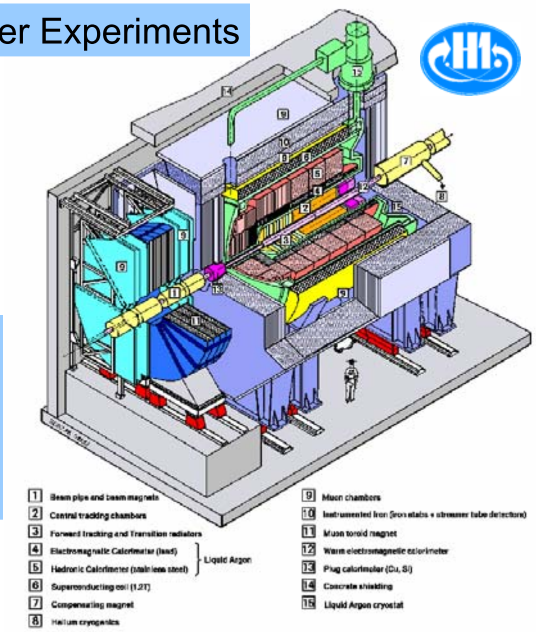
$\sigma_E/E = 50\%/\sqrt{E[GeV]}$ (had)

Rear Pb-scintillator calorimeter

$\sigma_E/E = 7.5\%/\sqrt{E[GeV]}$ (e.m.)

μ chambers

and much more…



ZEUS Detector

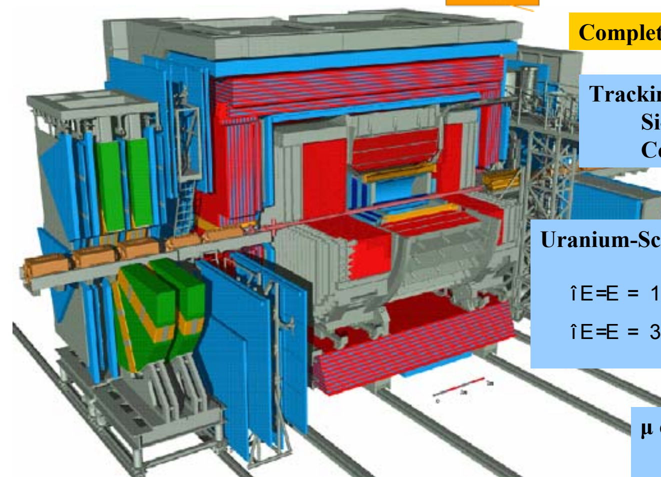
Complete 4π detector with

Tracking
- **Si-μVTX**
- **Central drift chamber**

Uranium-Scintillator calorimeter

$\sigma_E/E = 18\%/\sqrt{E[GeV]}$ (e.m.)

$\sigma_E/E = 35\%/\sqrt{E[GeV]}$ (had)

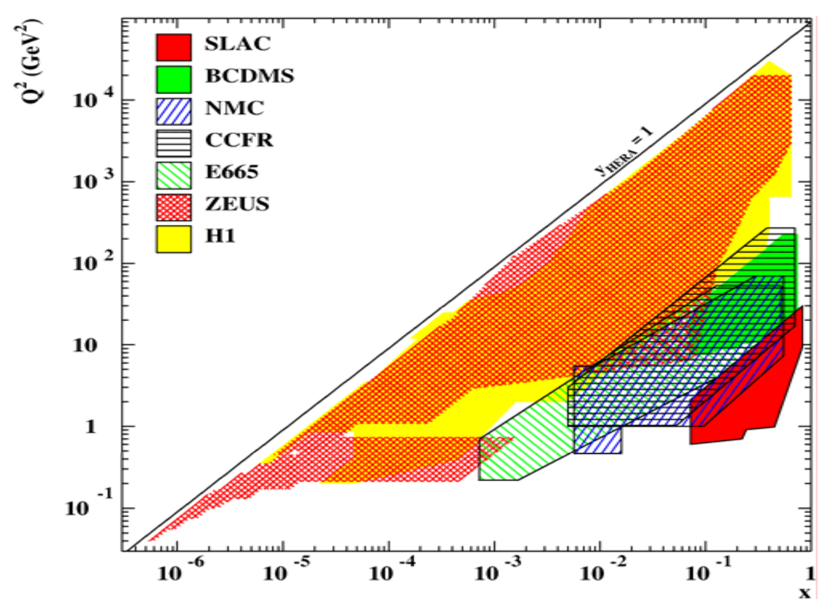


μ chambers

and much more…

Both detectors asymmetric

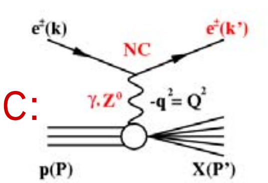
Kinematic Regions of DIS

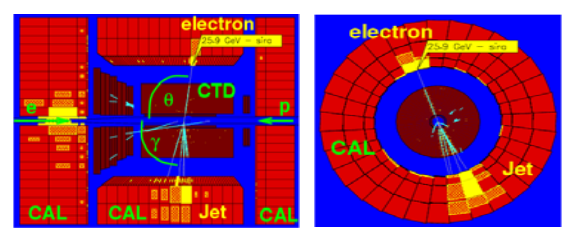


NC and CC incl. Processes measured at HERA

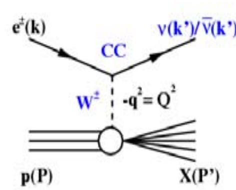
$$\text{NC}: \quad e^{\pm} + p \rightarrow e^{\pm} + X, \qquad \text{CC}: \quad e^{\pm} + p \rightarrow \bar{\nu}_e(\nu_e) + X$$

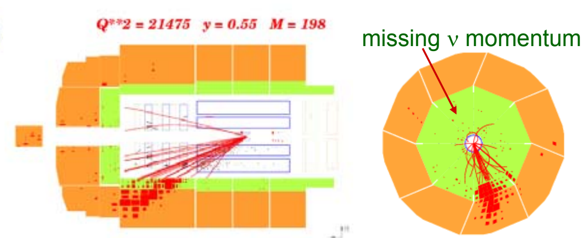
NC:





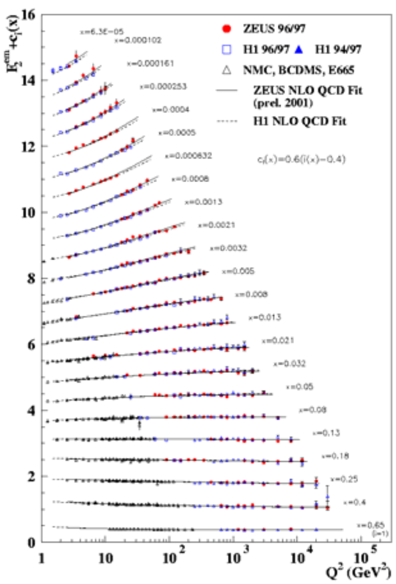
CC:





Measurement of $F^{\gamma}_2(x,Q^2)$

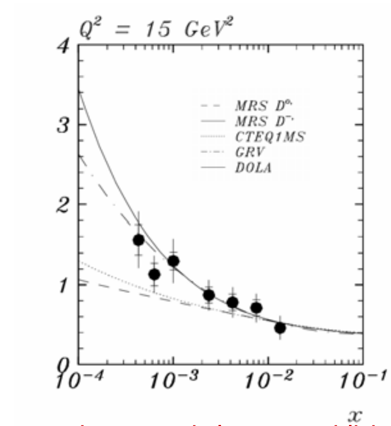
- For $Q^2 \ll M_Z^2 \rightarrow xF_3$ negligible;
- F_L only important at high y;
- Both F_L and xF_3 ~ calculable in QCD
- Correct for higher order QED radiation
- Extract $F_2(x,Q^2)$ from measurement of $\frac{d^2\hat{\sigma}^{ep}}{dxdQ^2}$

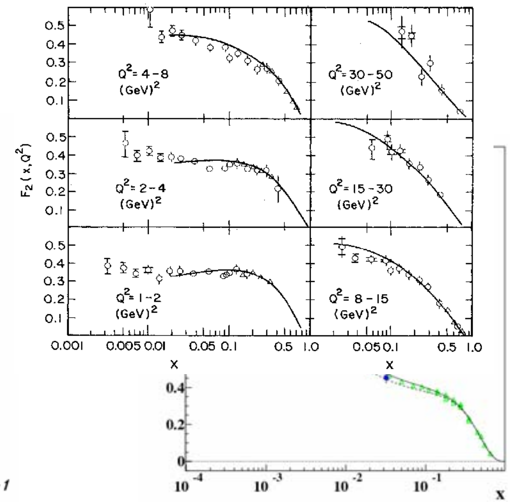


These are difficult measurements: nevertheless precision level has reached: errors of 2-3%

A major finding at Hera: rise of $F_2(x,Q)$ at small x

Early fixed-target results:

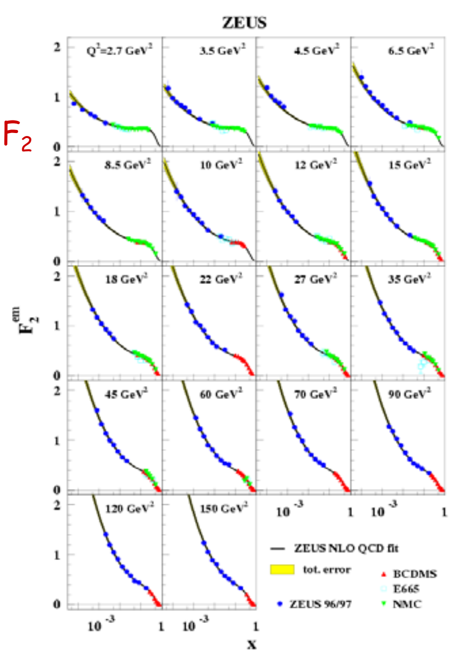


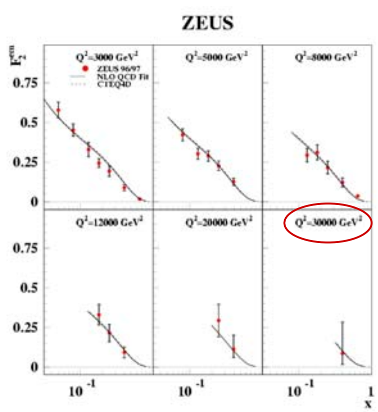


F_2 rise towards low-x established with ~20 nb^{-1} in early Hera run

Recent precise determination of F_2 (1996-97 data samples)

F_2



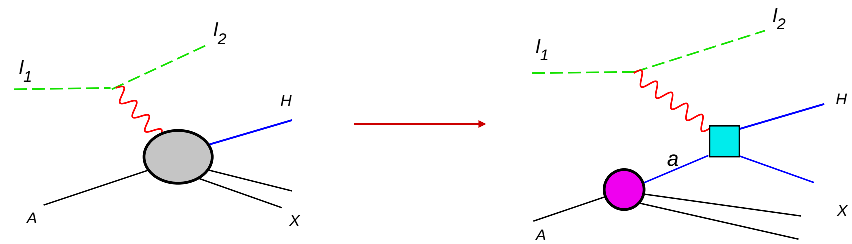


At high-Q^2 still statistics limited... $\rightarrow$ priority to the measurements at high-Q^2

Physical Interpretations of DIS Structure Function measurements

- The Parton Model (Feynman-Bjorken)
- Theoretical basis of the parton picture and the QCD improved parton model

high energy (Bjorken) limit

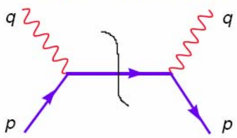


Parton Model results on Structure Functions

$$F_\lambda(x,Q^2) \sim \int_0^1 \frac{d\xi}{\xi} \sum_a f_A^a(\xi)\ \hat{F}_\lambda^a(x/\xi,Q^2) + \mathcal{O}(\frac{m}{Q}).$$

where $\hat{F}_\lambda^a(z,Q^2)$ is the "partonic structure function" for DIS on the parton target a.

The Feynman diagram contributing to this elementary quantity and the result of a straightforward calculation are (for electro-magnetic coupling case):



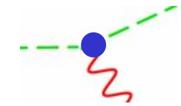
$$\begin{aligned} \hat{F}_T^a(x/\xi,Q^2) &= Q_a^2\ \delta(x/\xi \Leftrightarrow 1) \\ \hat{F}_L^a(x/\xi,Q^2) &= 0 \\ \hat{F}_{PV}^a(x/\xi,Q^2) &= 0 \end{aligned}$$

$\Longrightarrow$ the simple scaling parton model results:

$$\begin{aligned} F_T(x,Q^2) &= \textstyle\sum_a Q_a^2\ f_A^a(x) \quad &\text{(Bj. }\Leftrightarrow\text{Feynman)} \\ F_L(x,Q^2) &= 0 \quad &\text{(Callan }\Leftrightarrow\text{Gross)} \end{aligned}$$

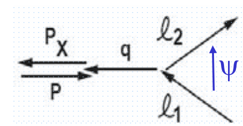
Features of the DIS structure functions due to SM couplings

For CC processes, only one helicity vertex (out of 2x2x3=12) is non-zero:



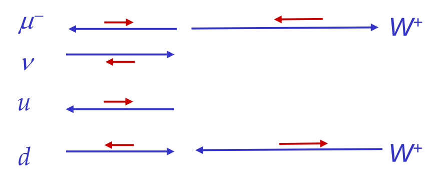
$$j_L^{L\,L}(Q) = j_{-1/2}^{-1/2\,-1}(Q) = \sqrt{8Q^2}$$

In Brick-Wall (Breit) frame:



Lorentz boost with v = *tanh* ψ

Allowed spin configurations:



Vector γ coupling:

Left-handed W coupling:

	γ	Z	$W^\pm$
g_V	Q_i	$T_{3L}^i - 2Q_i\sin^2\theta_W$	$1\cdot V_{ij}$
g_A	0	T_{3L}^i	$1\cdot V_{ij}$
g_R	$\frac{Q_i}{2}$	$-Q_i\sin^2\theta_W$	0
g_L	$\frac{Q_i}{2}$	$T_{3L}^i - Q_i\sin^2\theta_W$	$1\cdot V_{ij}$

continued

Consequences on CC Cross sections (parton model level):

$$\frac{d\sigma^{\nu/\bar\nu}}{dxdy} \propto W\cdot L \propto F_{\nu/\bar\nu}\left(\frac{1\pm\cosh\psi}{2}\right)^2$$

$$\cosh\psi = \frac{2-y}{y} \quad \longrightarrow \quad \frac{1\pm\cosh\psi}{2} \propto \begin{cases} 1 \\ 1-y \end{cases}$$

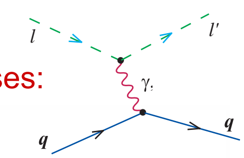
$$\longrightarrow \quad \frac{\sigma^{\bar\nu}}{\sigma^\nu} = \int dy \frac{d\sigma^{\bar\nu}}{dy} \Big/ \int dy \frac{d\sigma^\nu}{dy} \approx \frac{1}{3}$$

These qualitative features were verified in early (bubble chamber) high energy neutrino scattering experiments.

Gargamelle (CERN)

Refined measurements reveal QCD corrections to the approximate naïve parton model results. These are embodies in all modern "QCD fits" and "global analyses".

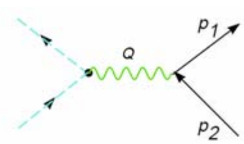
Leading (diagonal) EM NC scattering processes:



$$\frac{d\sigma}{dxdy} \quad \propto \quad F_T(1+\cosh^2\psi)$$

(y is the hyperbolic "angle" connecting the lepton and hadron vertices.)

Analogous to the familiar angular distribution of scattering of spin ½ elementary particles in the CM frame:



$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta)$$

At HERA, the γ-Z interference term also contribute, giving rise to more complicated patterns for the "angular" (y) distribution.

Features of the partonic interactions revealed by DIS experiments have firmly established that the lepton probes interact primarily with spin ½ quark partons inside the nucleons with couplings of the SM.

Structure functions: Quark Parton Model

Quark parton model (QPM) NC SFs for proton target:

$$[F_2^\gamma, F_2^{\gamma Z}, F_2^Z] = x\sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2]\{q + \bar{q}\}$$

$$[xF_3^{\gamma Z}, xF_3^Z] = 2x\sum_q [e_q a_q, v_q a_q]\{q - \bar{q}\} = 2x\sum_{q=u,d} [e_q a_q, v_q a_q] q_v$$

QPM CC SFs for proton targets:

$$xF_{2,W+}^{CC} = x\{\bar{u} + \bar{c} + d + s\}, \qquad xF_{3,W+}^{CC} = x\{d + s - (\bar{u} + \bar{c})\}$$

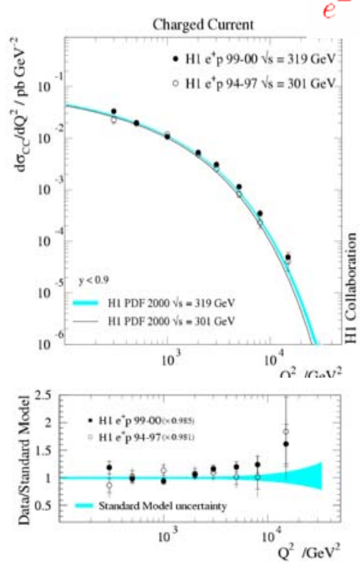
$$xF_{2,W-}^{CC} = x\{u + c + (\bar{d} + \bar{s})\}, \qquad xF_{3,W-}^{CC} = x\{u + c - (\bar{d} + \bar{s})\}$$

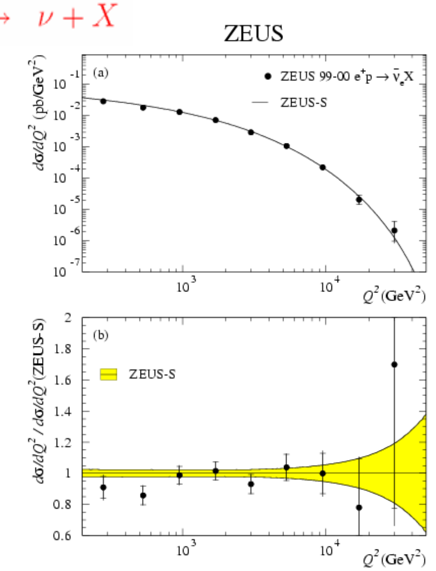
For neutron targets, invoke (flavor) isospin symmetry:

$u \Leftrightarrow d$ and $\bar{u} \Leftrightarrow \bar{d}$

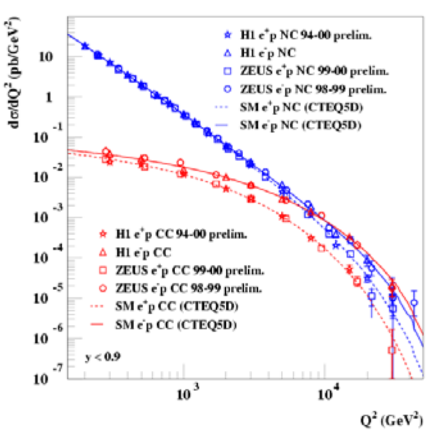
High-Q2 CC cross section from HERA

$$e^+ + p \rightarrow \bar{\nu} + X$$
$$e^- + p \rightarrow \nu + X$$





Comparing NC and CC Xsec's at HERA: EW Unification

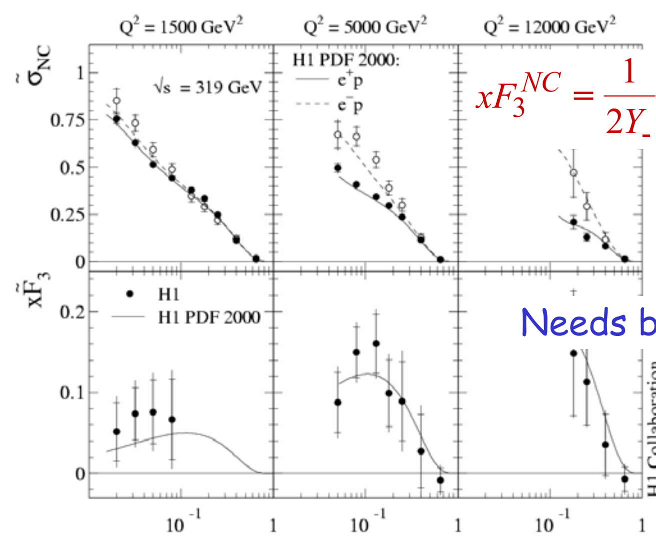


NC cross section sharply decreases with decreasing Q^2 (dominant γ exchange): $\sim 1/Q^4$

CC cross section approaches a constant at low Q^2 $\sim[M^2_W/(Q^2+M^2_W)]^2$

Dramatic confirmation of the unification of the electromagnetic and weak interactions of the SM in Deep Inelastic Scattering.

Manifestation of γZ interference: xF_3 (NC) at Hera

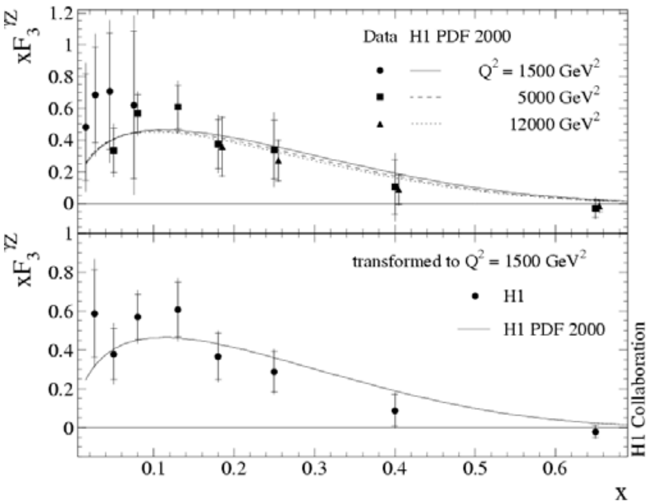


$$xF_3^{NC} = \frac{1}{2Y_-}[\tilde{\sigma}(e^- p) - \tilde{\sigma}(e^+ p)]$$

Needs better e- data!

$$\frac{d^2\sigma^{NC}_{Born}(e^\pm p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+ F_2^{NC}(x,Q^2) - y^2 F_L^{NC}(x,Q^2) \mp Y_- xF_3^{NC}(x,Q^2)]$$

$xF_3^{\gamma Z}$ (NC)



$$xF_3^{NC} = -a_e \frac{\kappa Q^2}{(Q^2+M_Z^2)} xF_3^{\gamma Z} + (2v_e a_e)\left(\frac{\kappa Q^2}{Q^2+M_Z^2}\right)^2 xF_3^Z$$

$$xF_3^{\gamma Z} \approx -F_3^{NC}(Q^2+M_Z^2)/(a_e \kappa Q^2)$$

Helicity structure

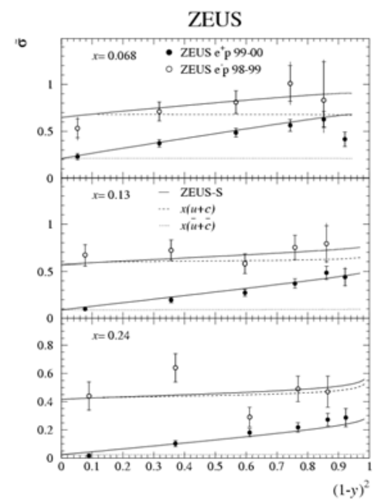
$e^- q$	$e^+ q$
⇒ L.H.+L.H.	R.H.+L.H.
⇒ in CMS $\sum_{e^-,q} S_i = 0$	$= 1$
⇒ isotropic in θ_{CMS}	peaked forward

Down-type (anti-)quarks contribution suppressed by helicity:

$$\tilde{\sigma}^{e^-p} = x\left[u+c+(1-y)^2(\bar{d}+\bar{s})\right]$$
$$\tilde{\sigma}^{e^+p} = x\left[\bar{u}+\bar{c}+(1-y)^2(d+s)\right]$$

Helicity-structure of EW confirmed

Assuming $q_s = \bar{q}_s$ ⇒
$$\tilde{\sigma}^{e^-p} - \tilde{\sigma}^{e^+p} = xu_v - (1-y)^2 x d_v$$
⇒ access to valence PDFs



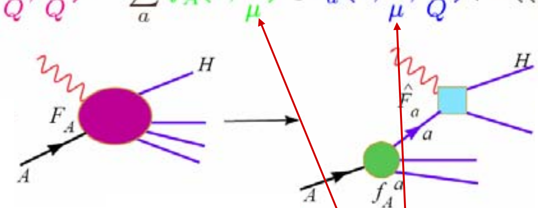
Needs e$^-$ data

QCD and DIS

Cf. Introductory course

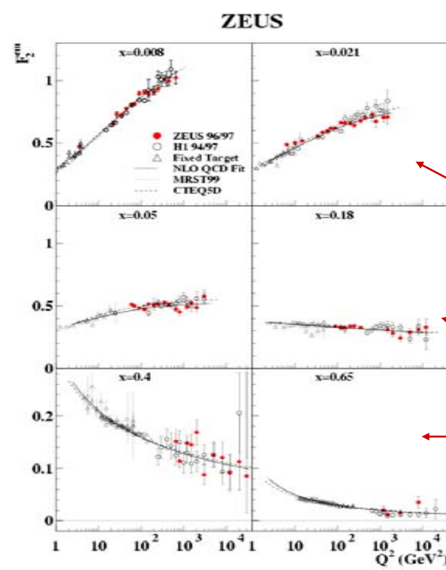
Master Equation for QCD Parton Model
– the Factorization Theorem

$$F_A^\lambda(x, \frac{m}{Q}, \frac{M}{Q}) = \sum_a f_A^a(x, \frac{m}{\mu}) \otimes \hat{F}_a^\lambda(x, \frac{Q}{\mu}, \frac{M}{Q}) + \mathcal{O}((\frac{\Lambda}{Q})^2)$$



μ is the factorization scale.
Usually choose $\mu = Q$: that is how $f(x,Q)$ acquires Q-dep.

F_2 : "Scaling violation" — Q-dependence inherent in QCD



Renormalization group equation governs the scale dependence of parton distributions and hard cross sections. (DGLAP)

Rise with increasing Q at small-x

Flat behavior at medium x

decrease with increasing Q at high x

QCD evolution

Cf. Introductory course

Evolution performed in terms of (1/2/3) non-singlet, singlet and gluon densities:

$$\frac{\partial}{\partial \ln \mu_F^2} q_{NS}^{\pm} = P_{NS}^{\pm} \otimes q_{NS}^{\pm}$$

$$\frac{\partial}{\partial \ln \mu_F^2} \begin{Bmatrix} \Sigma \\ g \end{Bmatrix} = \begin{Bmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{Bmatrix} \otimes \begin{Bmatrix} \Sigma \\ g \end{Bmatrix} = \mathrm{P} \otimes \mathrm{q}$$

Where

$$P(x) = a_s P^{(0)}(x) + a_s^2 \left[P^{(1)}(x) - \beta_0 \ln \frac{\mu_F^2}{\mu_R^2} P^{(0)}(x) \right] \qquad \text{with} \quad a_s = \frac{\alpha_s(\mu_R^2)}{4\pi}$$

$$\frac{da_s}{d \ln \mu_R^2} = \beta(a_s) = \sum_{l=0}^{\infty} a_s^{l+2} \beta_l \cong a_s^2 \beta_0 + a_s^3 \beta_1 \qquad \text{where} \quad \beta_0 = 11 - \frac{2}{3} N_F$$

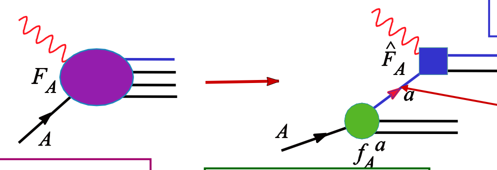
$$\text{and} \quad \beta_1 = 102 - \frac{38}{3} N_F$$

Parton Distribution Functions (PDF): most significant physical results derived from DIS (with help from other hard scattering processes)

A common misconception:

Parton distribution functions ≠ "Structure functions"

These are the hard Xsecs.



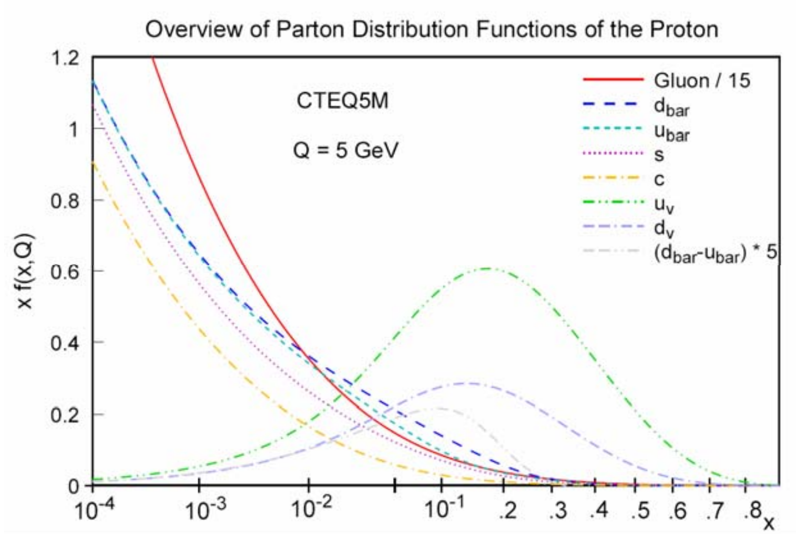
These are the (process-dep) S.F.s

These are the (universal) PDFs

There is a convo-lution integral and a summation over partons here!

Parton Distributions: one example

Cf. course on global analysis and PDFs



Summary and Conclusion

Outline of the course:

- Basic Formalism (indep. of strong dynamics and
- Experimental Development
  - Fixed target experiments
  - HERA experiments
- Parton Model and QCD
  - Parton Picture of Feynman-E
  - Asymptotic freedom, factoriz
- Phenomenology
  - QCD parameters
  - Parton distribution functions
  - Other interesting topics

Important to know the model indep. foundation of the measured structure functions and their basic properties.

There is a long and distinguished history, dating back to Rutherford

These highest energy and highest statistics expts. provide the basis for modern precision phenomenology

DIS experiments provided direct evidence for the parton structure of the nucleon, and confirmed every aspect of the SU(3)xSU(2)xU(1) SM.

Cf. the rest of the Summer School courses for exciting consequences of PQCD as well as other modern theories to follow.