Lectures on Deep Inelastic Scattering

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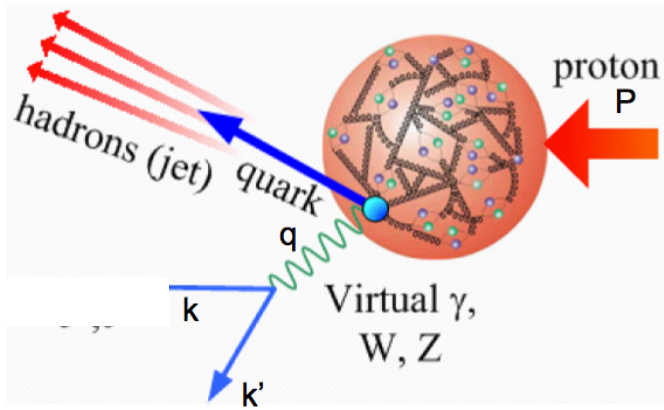
(DESY)



- **Part I:**
  - **Introduction to DIS formalism**
  - **Physics Results from DIS experiments**

- **Part II:**
  - **impact of DIS measurements**
  - **Relevance of DIS to LHC physics**
  - **Oulook**

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Today's Lecture

Lectures will present state of the art in the field blended in with new experimental results*

- Motivation
- A leap into history
- Quark Parton Model
- Parton Distribution Functions (PDFs)
- QCD add on features
- Selected Experimental measurements

* Disclaimer: more coverage of H1, NuTeV and ATLAS is given due to my biases...

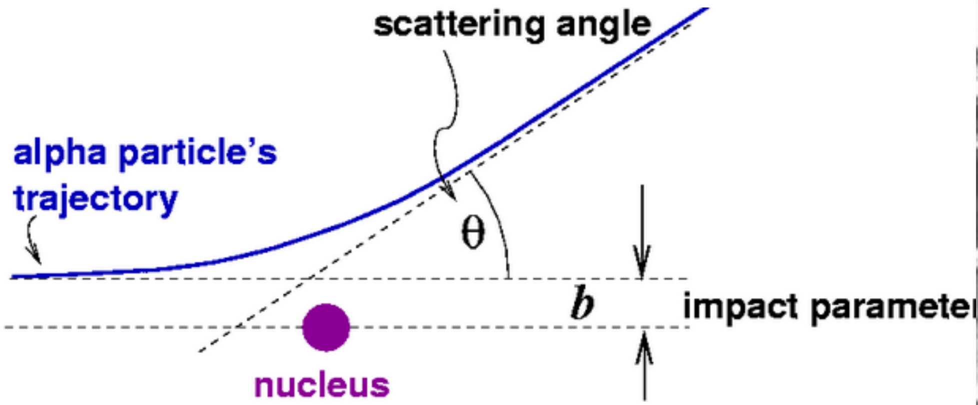
Motivation

- Deep inelastic scattering is the ideal process for the determination of the quark and gluon distributions in the proton.
  - Studies of the proton substructure of the nucleon are of great interest for the development of strong interaction theory

- With high energy and luminosity, the LHC search range will be extended to high masses, up to 5 TeV in pair production. At correspondingly large momentum the constituents of proton are unknown to a considerable extent.
  - Accurate knowledge of constituents of protons also a necessary input for new physics searches and studies at the Large Hadron Collider

Introduction to Deep Inelastic Scattering (DIS)

- Rutherford's gold foil experiment 1909 (performed by Geiger and Marsden)



Geiger and Rutherford

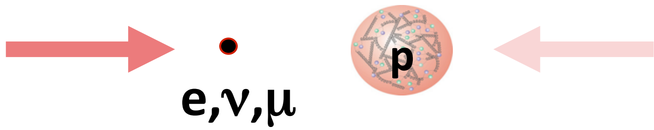
Rutherford's gold foil experiment set the scene for a century of ever-deeper and more precise resolution of the constituents of the atom, the nucleus and the nucleon.

➔ **Ideas for detecting quarks were formulated:**

To probe the interiors of target, pointlike and easily produced particle needed to be used.

Probing the Proton Structure

- **Proton can be probed via elementary particles as:**
  - neutrinos (fixed target experiments) - interact only weakly
  - electrons (fixed target and collider experiments) - interact electroweakly



- **Deep Inelastic Scattering (DIS) is the cleanest probe to study the substructure of nucleon**
  - scattering of a lepton off the nucleon involving a large momentum transfer and resulting into a hadronic shower and a lepton

- **Kinematic Lorentz Invariant Variables:**
  - virtuality of exchanged boson

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

  - proton momentum fraction of the scattered quark (Bjorken scaling variable)

$$x = \frac{Q^2}{2p \cdot q}$$

  - inelasticity parameter:

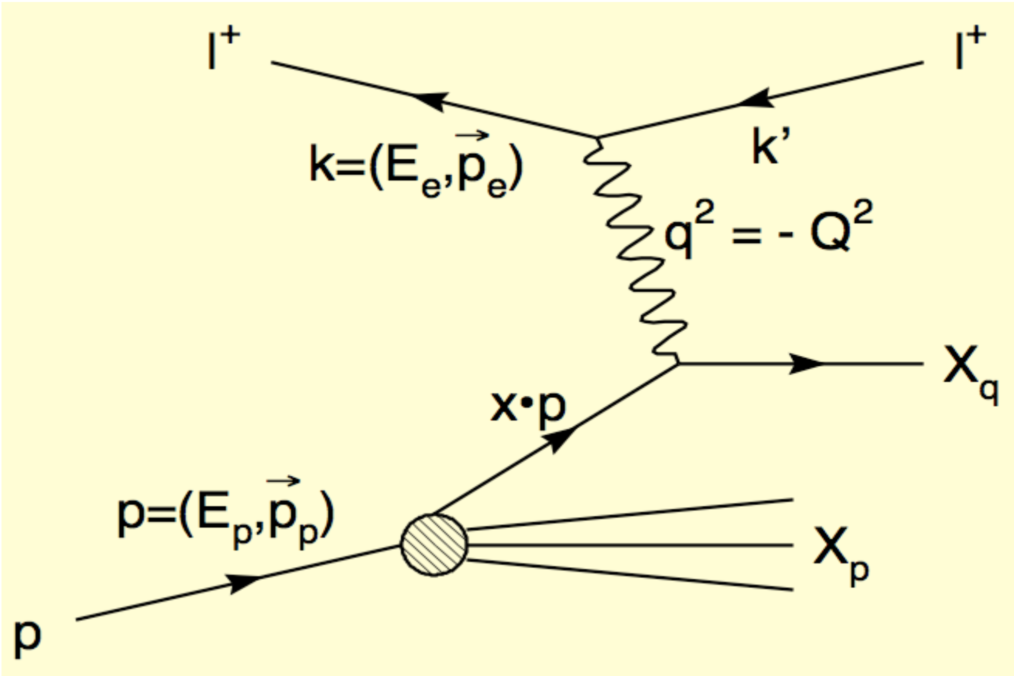
$$y = \frac{p \cdot q}{p \cdot k}$$

  - invariant centre of mass energy:

$$s = (k + p)^2 = \frac{Q^2}{xy}$$

  - Invariant centre of mass energy of the virtual boson-proton system)

$$W^2 = (P + q)^2 = m_p^2 - Q^2 + 2P \cdot q = ys - Q^2 + m_p^2(1 - y).$$



DIS Cross Sections

- Factorisable nature of interaction: Inclusive scattering cross section is a product of leptonic and hadronic tensors times propagator characteristic of the exchanged particle:

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4 x} \sum_j \eta_j L_j^{\mu\nu} W_j^{\mu\nu}$$

$$\eta_\gamma = 1; \qquad \eta_{\gamma Z} = \left(\frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\right)\left(\frac{Q^2}{Q^2 + M_Z^2}\right); \qquad \eta_Z = \eta_{\gamma Z}^2;$$

$$\eta_W = \frac{1}{2}\left(\frac{G_F M_W^2}{4\pi\alpha}\frac{Q^2}{Q^2 + M_W^2}\right)^2,$$

For NC: j=γ, Z, γZ
For CC: j=W+, W-

Leptonic tensor: related to the coupling of the lepton with the exchanged boson

- contains the electromagnetic or the weak couplings
- can be calculated exactly in the standard electroweak U(1) × SU(2) theory.

Hadronic tensor: related to the interaction of the exchanged boson with proton

- can't be calculated, but only be reduced to a sum of structure functions:

~m_{lepton}

$$W^{\alpha\beta} = -g^{\alpha\beta} W_1 + \frac{p^\alpha p^\beta}{M^2} W_2 - \frac{i\epsilon^{\alpha\beta\gamma\delta} p_\gamma q_\delta}{2M^2} W_3 + \frac{q^\alpha q^\beta}{M^2} W_4 + \frac{p^\alpha q^\beta + p^\beta q^\alpha}{M^2} W_5 + \frac{i(p^\alpha q^\beta - p^\beta q^\alpha)}{2M^2} W_6$$

$$\frac{d^2\sigma}{dx dQ^2} = A^i \left\{ \left(1 - y - \frac{x^2 y^2 M^2}{Q^2}\right) F_2^i + y^2 x F_1^i \mp \left(y - \frac{y^2}{2}\right) x F_3^i \right\}$$

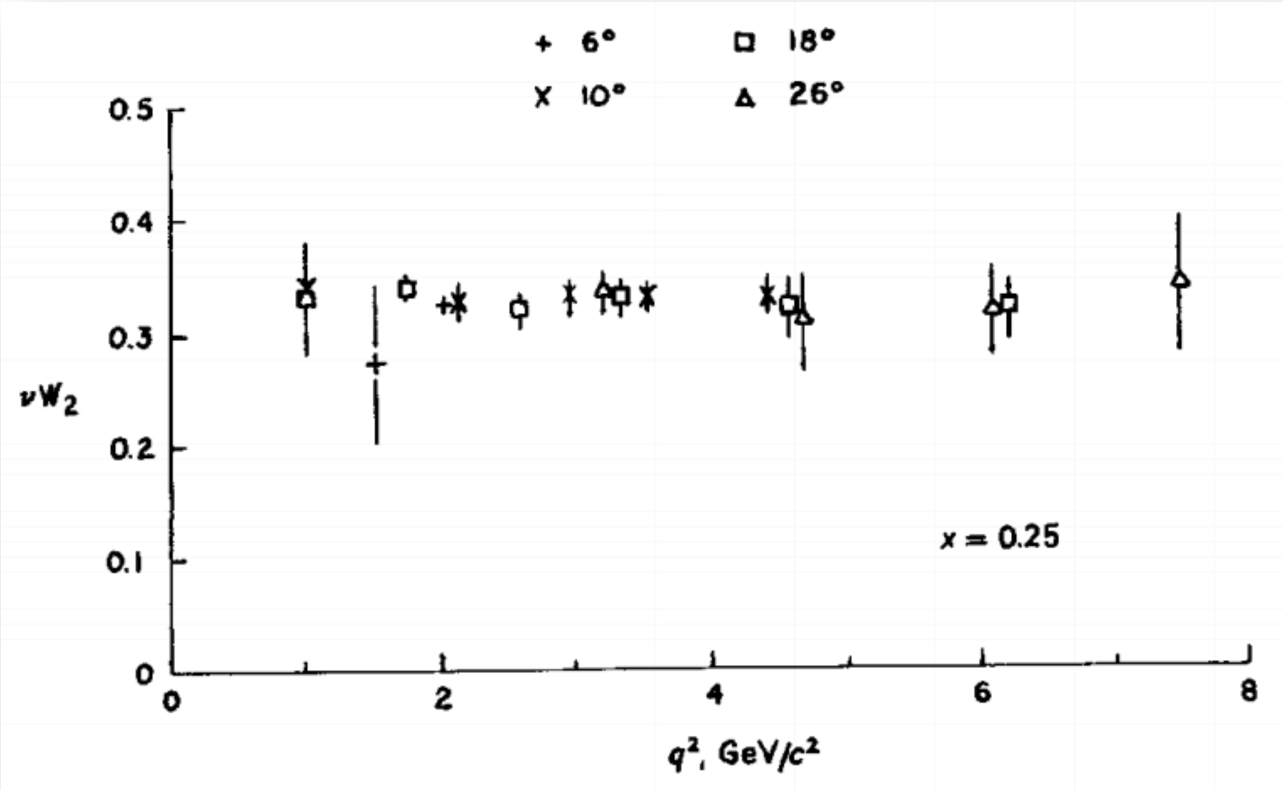
e+ (upper sign), e- (lower sign)

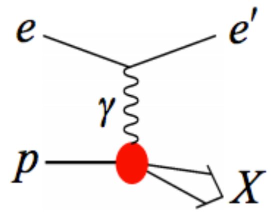
A^i: process dependent

Scaling of the structure functions

Structure functions can be extracted experimentally by looking at x,y,Q^2 dependence of the cross-section

- Experimental observation of scaling behaviour of F_2 is first evidence for a partonic sub-structure in the nucleon:





$E_e = 1.5 \ldots 20\,\text{GeV}$

$\theta = 6^\circ \ldots 26^\circ$

$Q^2 = 1 \ldots 7\,\text{GeV}^2$

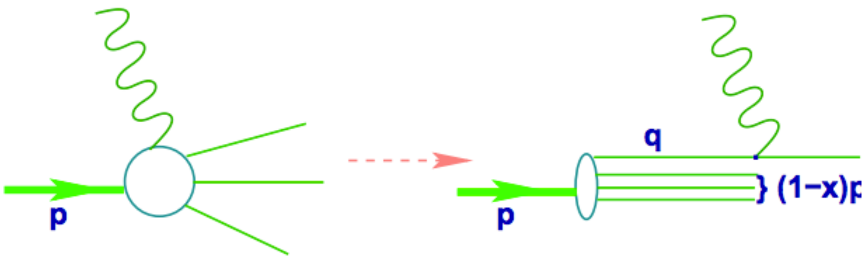
[MIT-SLAC Collab. 1970]

Scaling refers to the dependence of the structure functions on a single dimensionless variable x: Bjorken scaling

Once able to look into nucleon, can look into the properties of those partons…

Quark Parton Model (QPM)

- In Quark Parton Model:
  - inelastic scattering with nucleon is viewed as elastic scattering between lepton and a pointlike constituent of the target – **partons** (non-interacting) – explicitly assumed to be spin-1/2 particles



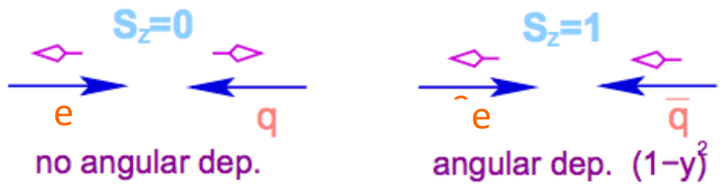
Each parton carries the fraction x with a probability q(x)

$$\left(\frac{d\sigma}{dxdQ^2}\right)_{ep\to eX} = \sum_i \int dx e_i^2 q_i(x) \left(\frac{d\sigma}{dxdQ^2}\right)_{eq_i\to eq_i}.$$

  - Bjorken-x has a meaning of momentum fraction carried by the struck quark:

$$\begin{aligned}(\epsilon p + q)^2 &= m_{lepton} \approx 0 \\ q^2 + 2\epsilon pq^2 &\approx 0 \\ \epsilon &= \frac{Q^2}{2pq} = x\end{aligned}$$

The elastic scattering cross section for spin ½:



$$\frac{d^2\sigma^\nu}{dxdy} \sim [\underbrace{q(x)}_{J=0} + \underbrace{\bar{q}(x)(1-y)^2}_{J=1}]$$

  - Considering probability distribution for the quark to have momentum fraction *x, xq(x),*

Callan-Gross relation

$$F_2(x) = 2xF_1(x)$$

$$F_2(x) = \sum_q e_q^2 xq(x), \qquad F_L(x) = 0.$$

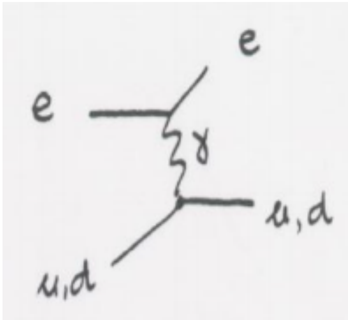
Verification of QPM: fractional electric charge

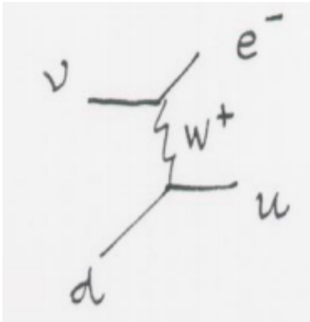
- Using different probes (e, nu) in DIS processes: can probe electric charge of the partons

proton: uud

neutron: ddu

$$F_2(x) = \sum_i e_i^2 x[q_i(x) + \bar{q}_i(x)]$$





Neutrinos:

- interact only weakly
- left handed particles

$$\begin{aligned} F_2^{ep}(x) &= x[e_u^2(u+\bar{u}) + e_d^2(d+\bar{d})] \\ F_2^{en}(x) &= x[e_u^2(d+\bar{d}) + e_d^2(u+\bar{u})] \\ F_2^{eN}(x) &= \frac{1}{2}(F_2^{ep} + F_2^{en}) \\ &= x\frac{e_u^2 + e_d^2}{2}[u+\bar{u}+d+\bar{d}] \end{aligned}$$

$$\begin{aligned} F_2^{\nu p}(x) &= 2x[d+\bar{u}] \\ F_2^{\nu n}(x) &= 2x[u+\bar{d}] \\ F_2^{\nu N}(x) &= \frac{1}{2}(F_2^{\nu p} + F_2^{\nu n}) \\ &= x[u+\bar{u}+d+\bar{d}] \end{aligned}$$

Confirmed by experimental measurements

$$\frac{F_2^{eN}}{F_2^{\nu N}} = \frac{1}{2}(e_u^2 + e_d^2) = \frac{5}{18} = 0.28 \quad \longleftrightarrow \quad \frac{\mathrm{SLAC}eN}{\mathrm{GGM}\nu N} = 0.29 \pm 0.05$$

Verification of QPM: fractional electric charge

- Using different probes (e, n … s

  proton: uud

  neutron: ddu

$$F_2^{ep}(x) = x[e_u^2(u+\bar{u} \ldots$$

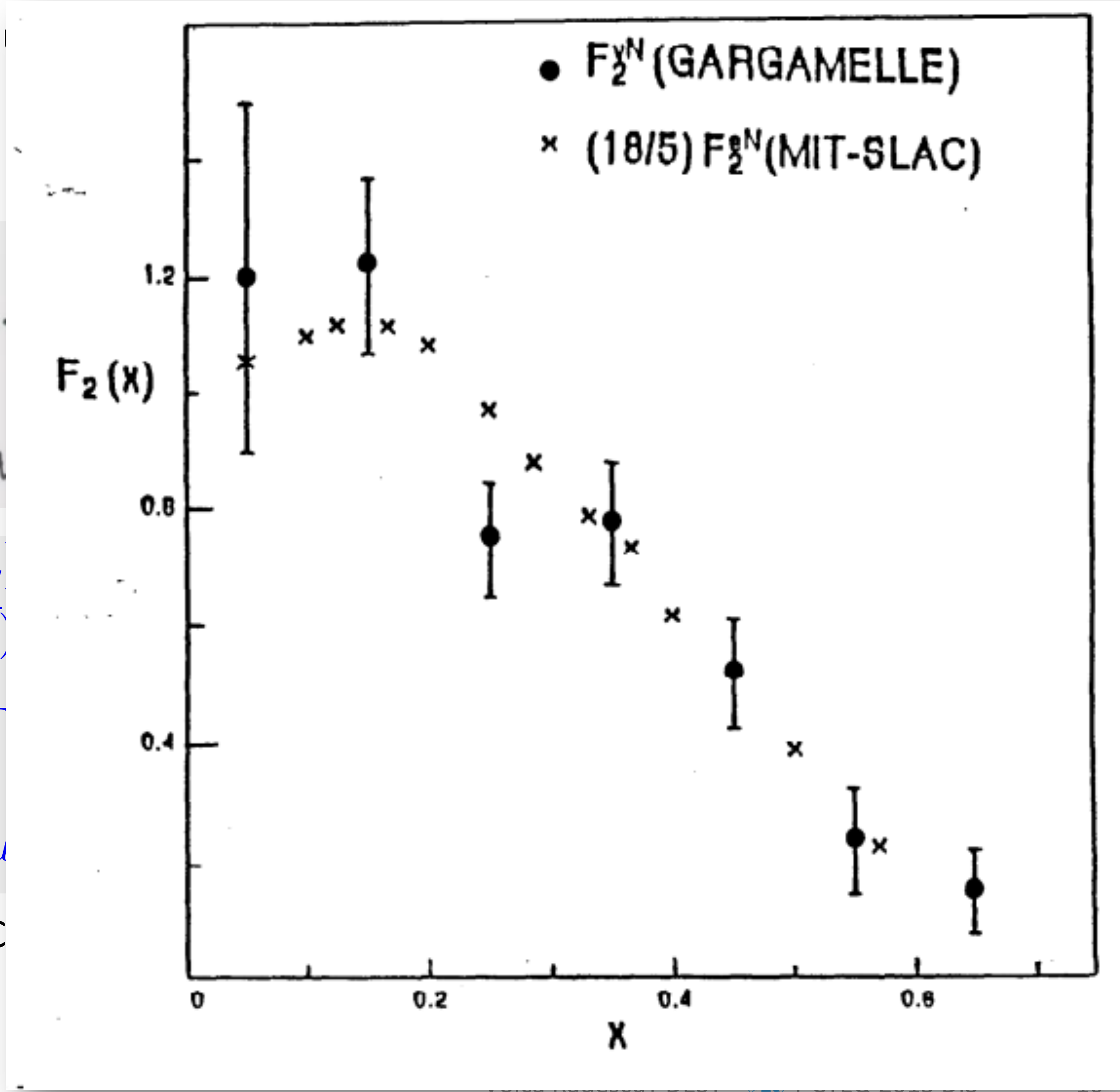
$$F_2^{en}(x) = x[e_u^2(d+\bar{d}) \ldots$$

$$F_2^{eN}(x) = \frac{1}{2}(F_2^{ep} + F \ldots$$

$$= x\frac{e_u^2+e_d^2}{2}[u \ldots$$

C

$$\frac{F_2^{eN}}{F_2^{\nu N}} = \frac{1}{2}(e_u^2+e_d^2) = \frac{5}{18}$$



Verification of QPM: valence, sea quarks

- Partons: valence and sea $u = u_{val} + u_{sea}; \quad u_{sea} = \bar{u}$

  $d = d_{val} + d_{sea}; \quad d_{sea} = \bar{d} = \bar{u}$

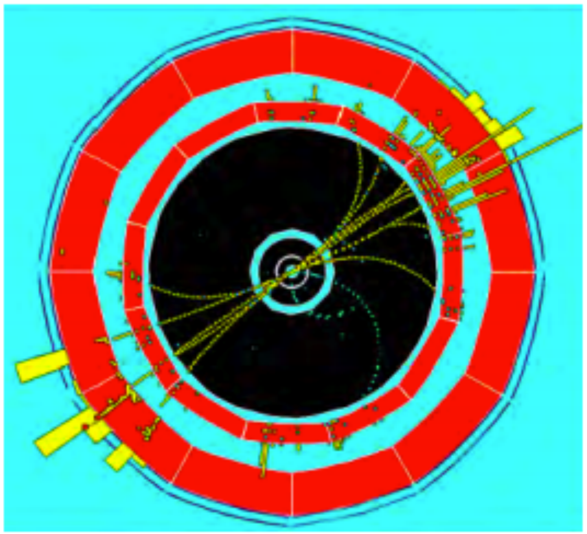
  - Gross-LLewellyn-Smith sum rule: counting the net number of quarks in the nucleons

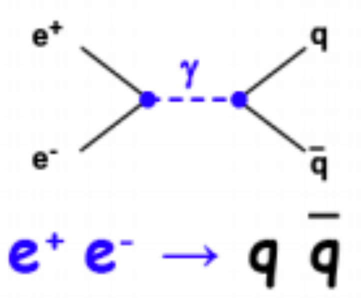
$$xF_3^{\nu p} = 2x(d - \bar{d}) = 2xd_v$$
$$xF_3^{\nu n} = 2x(u - \bar{u}) = 2xu_v$$

$$\int_0^1 xF_3^{\nu N} \frac{dx}{x} = \int_0^1 (u_v + d_v)dx$$

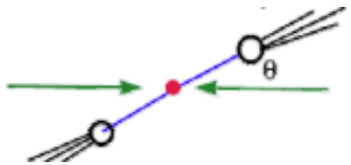
QPM predicts that GLS=3; experimental findings agree within errors (Gargamelle).

- The observation of jet production was a major success of the Quark Parton Model approach:





The lowest order reaction leads to two jets of particles which are back-to-back in azimuth as predicted for spin-½ quarks



Some of the puzzles of the QPM:

- If the proton would be solely constituted of charged quarks, it was expected that

$$\int_0^1 dx\, x \sum_i q_i(x) = 1$$

  - Experimentally was found that half of momentum of proton is NOT carried by quarks
    - Gargamelle: 0.49±0.07

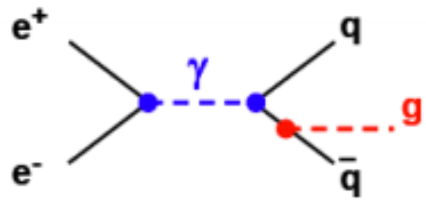
- Initial phase of multi-hadron production is similar to muon pair production through e^+e^- annhilation:
  - Measures directly the sum of the squares of the quarks charges (number of quark flavours)

$$R_\gamma = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \sum_q e_q^2 = \frac{11}{9}$$

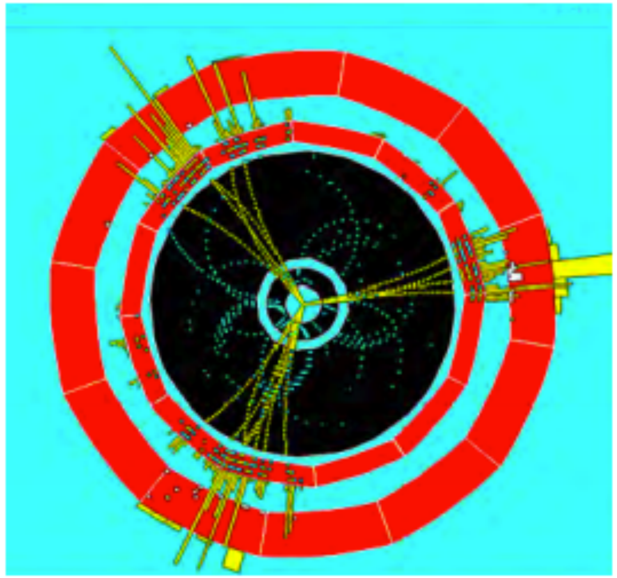
    - But actual experimental result is ~ 11/3

➔ **Indication that colour is more than just a quantum number:**
  - discovery of the gluons at PETRA: 3 jet events

3 jets discovered at DESY in 1979

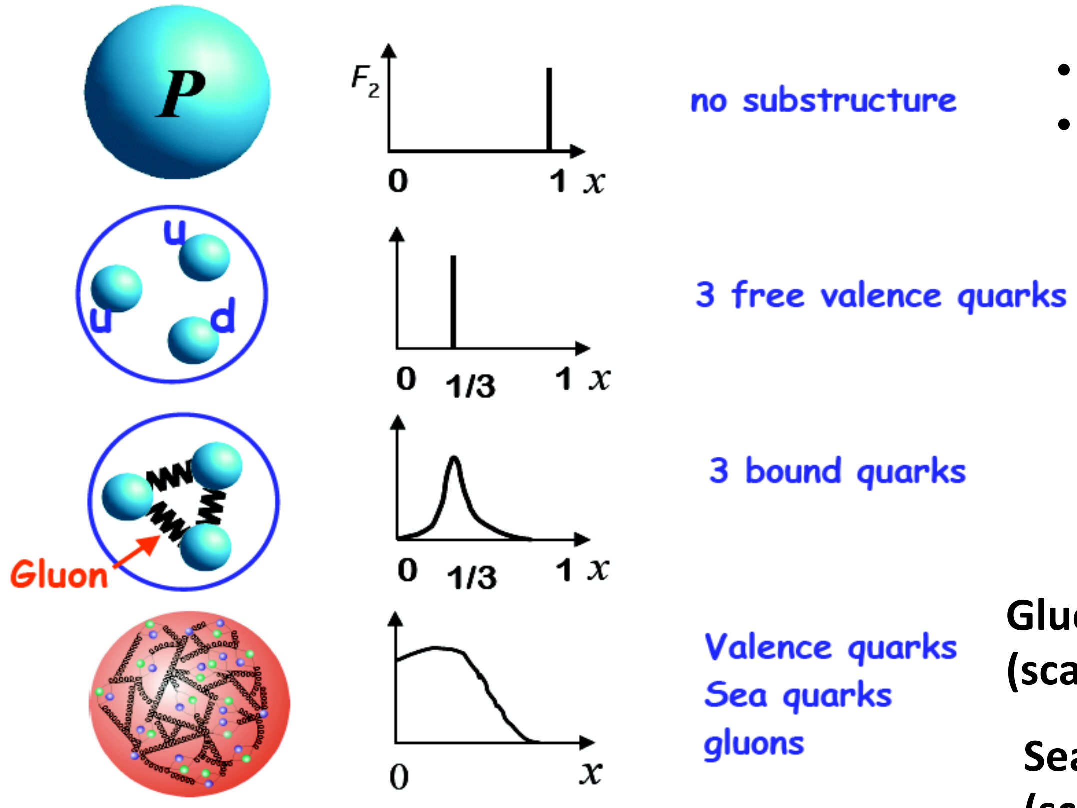


$$e^+ e^- \to q\,\bar{q}\,\,g$$

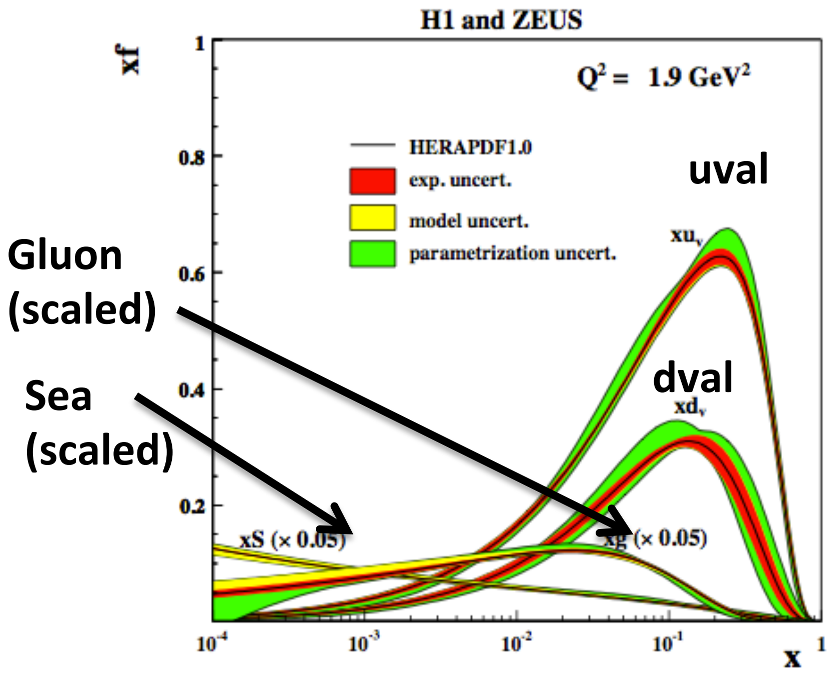


Parton Distribution Functions (PDFs)

The proton has a dynamic structure determined by the resolving power of the process



- In QPM: there is no Q^2 dependence
- In QCD: the Q^2 dependence is determined by the QCD evolution.



- $2xF_1^{\nu(\overline{\nu})} = 2\left[xq^{\nu(\overline{\nu})} + \overline{x}q^{\nu(\overline{\nu})}\right] \propto \sigma_T$
- $F_2^{\nu(\overline{\nu})} = 2\left[xq^{\nu(\overline{\nu})} + x\overline{q}^{\nu(\overline{\nu})} + 2xk^{\nu(\overline{\nu})}\right] \propto \sigma_T + \sigma_L$
- $xF_3^{\nu(\overline{\nu})} = 2\left[xq^{\nu(\overline{\nu})} - x\overline{q}^{\nu(\overline{\nu})}\right]$

QCD features

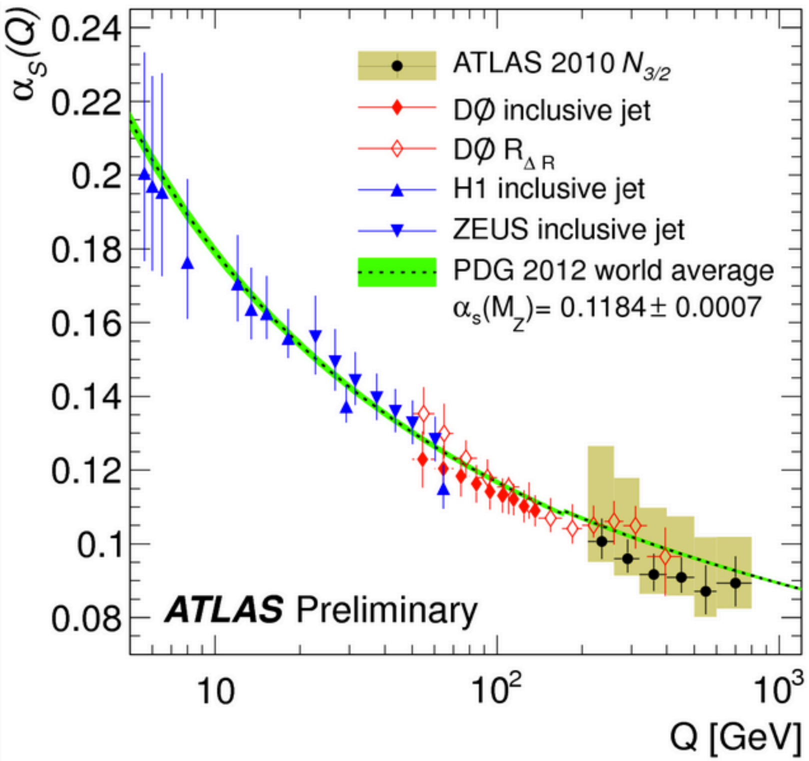
- Quantum Chromo Dynamics is theory of strong interactions among quarks and gluons
  - The charge of the strong interaction is a new quantum number called colour with 3 d.o.f (RGB)
  - The gauge bosons of the strong interactions are 8 massless gluons with no electric nor weak charge, gluons carry colour charges and are therefore able to self-interact
  - **The strong interaction is characterised by a strong coupling parameter:**

Characteristics:

Quarks are bound inside protons, strongly coupled, cannot measure directly their distributions: confinement (strength at large distance → at low Q)

At large scattering scales the coupling of strong force decreases and quarks become quasi-free partons: asymptotic freedom (weakness at short distance → at large Q)

- interactions of quarks and gluons at large scales can be calculated perturbatively in running strong coupling.



Renormalisation and running coupling

- Calculation of a scattering cross section in pQCD reduces to summing over the amplitudes of all possible intermediate states:
  - 4-momentum conserved at each vertex, however inclusion of loop diagram leads to divergences
  - ➔ **Renormalisation method: introducing a scale for which UV divergence is removed**

However any observable (R) should be free of such scale:

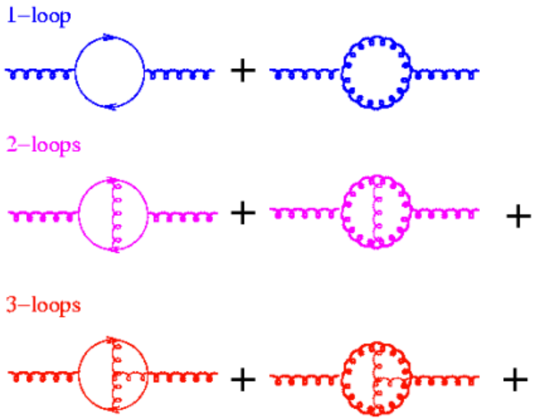
$$\mu \frac{d}{d\mu^2} R(\frac{Q^2}{\mu^2}, \alpha) = \left(\mu^2 \frac{\partial}{\partial \mu^2} + \mu^2 \frac{\partial \alpha}{\partial \mu^2} \frac{\partial}{\partial \alpha} \right) R = 0$$

This way we obtain the equation for running alpha:

$$t = \log \left(\frac{Q^2}{\mu^2} \right) \text{ and } \beta(\alpha) = \mu^2 \frac{\partial \alpha}{\partial \mu^2}$$

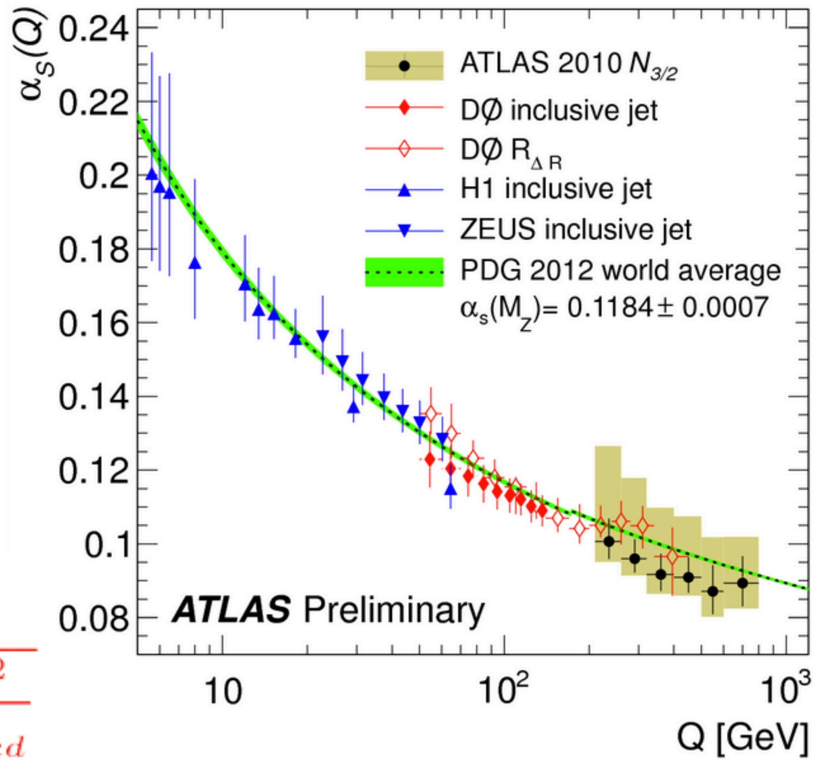
- Perturbation expansion of beta function:

$$\beta(\alpha_s) = -b\alpha_s^2 \left(1 + b'\alpha_s + b''\alpha_s^2 + \ldots\right)$$



Running coupling in one loop:

$$\alpha_s = \frac{12\pi}{(33 - 2n_f) \log \frac{Q^2}{\Lambda_{qcd}^2}}$$



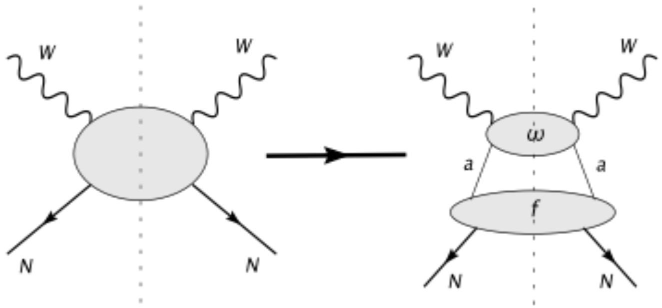
Factorisation theorem

Perturbative calculations are performed in context of the factorisation theorem:

- extended to the case of heavy quarks [Collins 1998]

Factorisation Theorem: short and long distances processes are separable → introduce μ_F

- soft part: PDFs – parametrised and determined from data
- hard part: process dependent - calculable



$$F_2(x,Q^2) \sim \sum_a f_a(x,\mu_f) \otimes \hat{F}_2^a(x,\frac{Q}{\mu_f})$$

physical PDF partonic

⇨ Structure Functions (F_i) are a convolution of PDFs (f_a) with hard scattering coefficient function

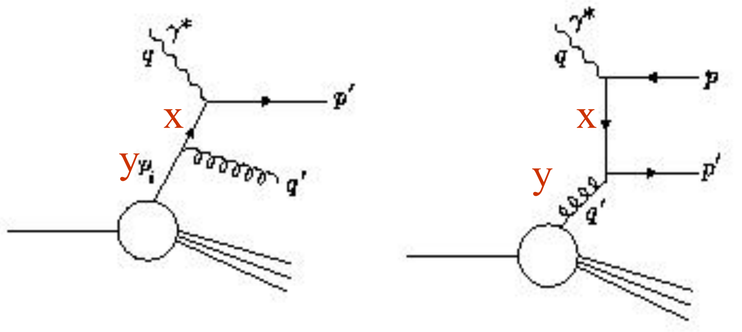
- Physical Structure Function is INDEPENDENT of choice of the scale:
  - both, pdf's and the short-dist. coefficient depend on **μf** (long distance physics)
  - There is also short distance physics: we can insert perturbative corrections to loops μr

a *measurable* cross section dσ has to be *independent* of μ_r and μ_f

$$\mu_{r,f}\frac{d\sigma}{d\mu_{r,f}} = \frac{d\sigma}{d\ln\mu_{r,f}} = 0$$ → renormalization group equations

Determination of QCD Evolution equations

- Ilustration of what could happen before the quark is struck



$y > x, \; z = x/y$

We already stated that physical quantity should
Be independent of choice of the factorisation scale:

now we can compute $\frac{dF_2(x,Q^2)}{d\ln\mu_f} = 0$:

$$\frac{dq(n,\mu_f)}{d\ln\mu_f}\hat{F}_2(n,\frac{\mu_f}{Q}) + q(n,\mu_f)\frac{d\hat{F}_2(n,\frac{\mu_f}{Q})}{d\ln\mu_f} = 0$$

calculable in pQCD

$$\frac{d}{d\ln\mu}\begin{pmatrix} q(x,\mu) \\ g(x,\mu) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \mathcal{P}_{qq} & \mathcal{P}_{qg} \\ \mathcal{P}_{gq} & \mathcal{P}_{gg} \end{pmatrix}_{(z,\alpha_s)} \cdot \begin{pmatrix} q(x/z,\mu) \\ g(x/z),\mu) \end{pmatrix}$$

Dokshitzer Gribov Lipatov Altarelli evolution eq.

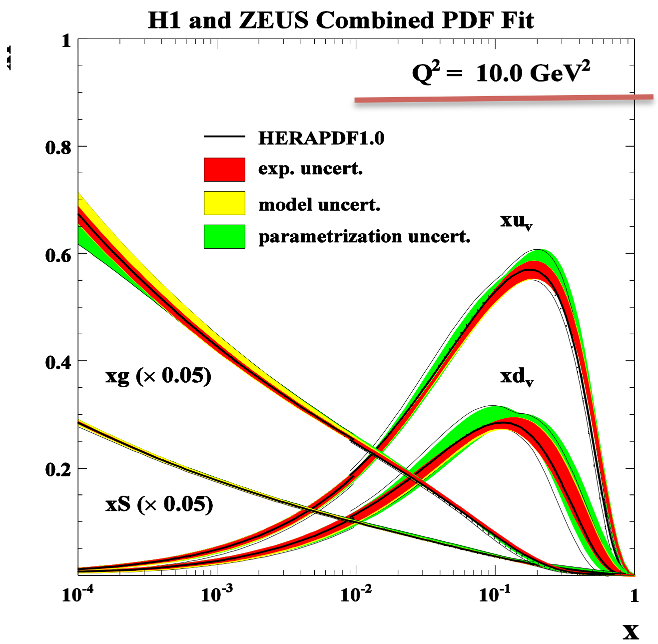
- Theory can predict the rate at which the parton distributions (both quarks and gluons) evolve with Q^2 -BUT it does not predict their shape at Q^2_0

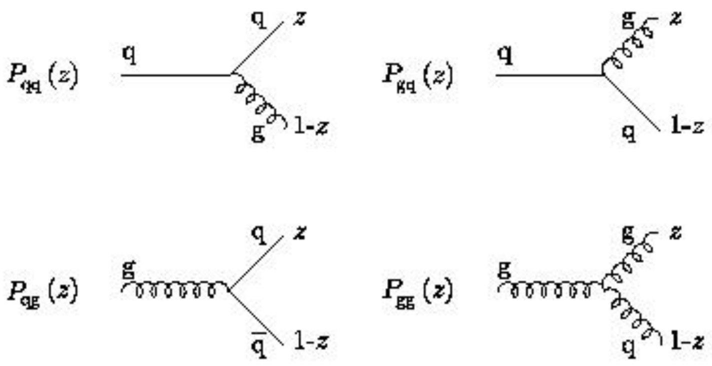
think of evolution as the effect of increasing the resolution scale

QCD Evolution equations

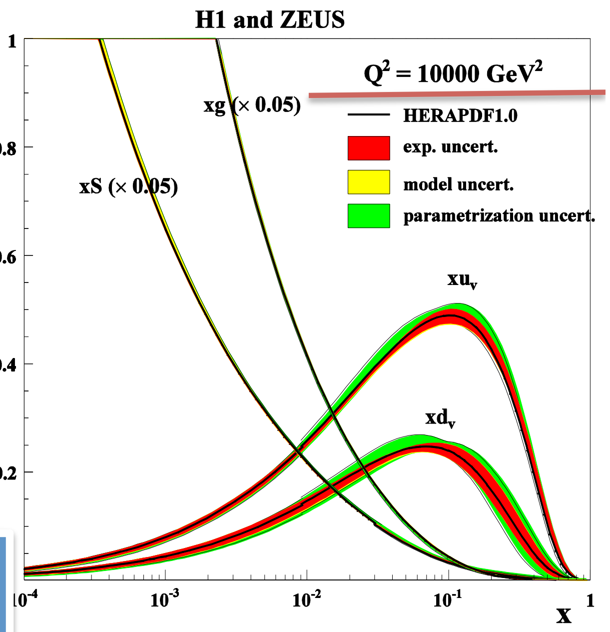
- Parton momentum distributions change with the scale of the probe:
  - $Q^2=p^2-E^2 \sim 10\ GeV^2$ is typical scale for low energy experiments
  - $Q^2=p^2-E^2 \sim 10000\ GeV^2$ is the scale that we are now starting to probe at the LHC

Q2 evolution





$y > x,\ \ z = x/y$



- Valence quarks are radiating gluons
- Gluons are splitting into quark antiquark pairs

Total momentum carried by the valence quarks is ~ 0.5 => the rest is the gluon and sea quarks.

PDF parametrisation

PDFs are parametrised at a starting scake and QCD evolution evolve them to any scale!

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}(1+D_g x+E_g x^2+F_g\sqrt{x}+\ldots) \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v} x+E_{u_v} x^2+F_{u_v}\sqrt{x}+\ldots) \\
xd_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v} x+E_{u_v} x^2+F_{u_v}\sqrt{x}+\ldots) \\
x\bar{u}(x) &= A_{\bar{u}} x^{B_{\bar{u}}}(1-x)^{C_{\bar{u}}}(1+D_{\bar{u}} x+E_{\bar{u}} x^2+F_{\bar{u}}\sqrt{x}+\ldots) \\
x\bar{d}(x) &= A_{\bar{d}} x^{B_{\bar{d}}}(1-x)^{C_{\bar{d}}}(1+D_{\bar{d}} x+E_{\bar{d}} x^2+F_{\bar{d}}\sqrt{x}+\ldots)
\end{aligned}
$$

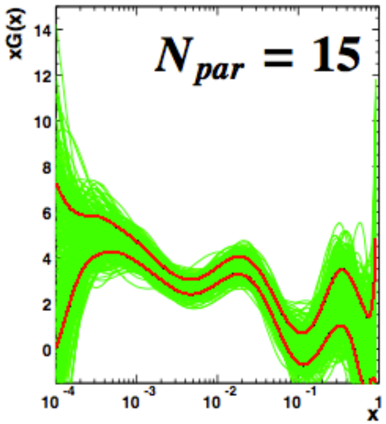
B → low x behaviour
- B>0 for valence like shape
- B<0 for sea

C → high x behaviour

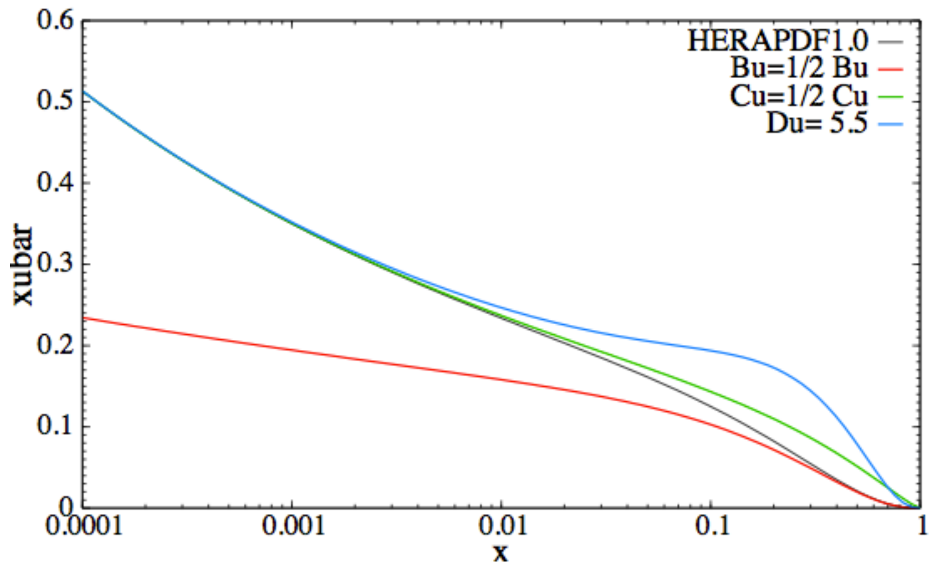
D, E, F → interpolate between low and high x

There are many studies done to assess biases due to parametrisation ansatz:

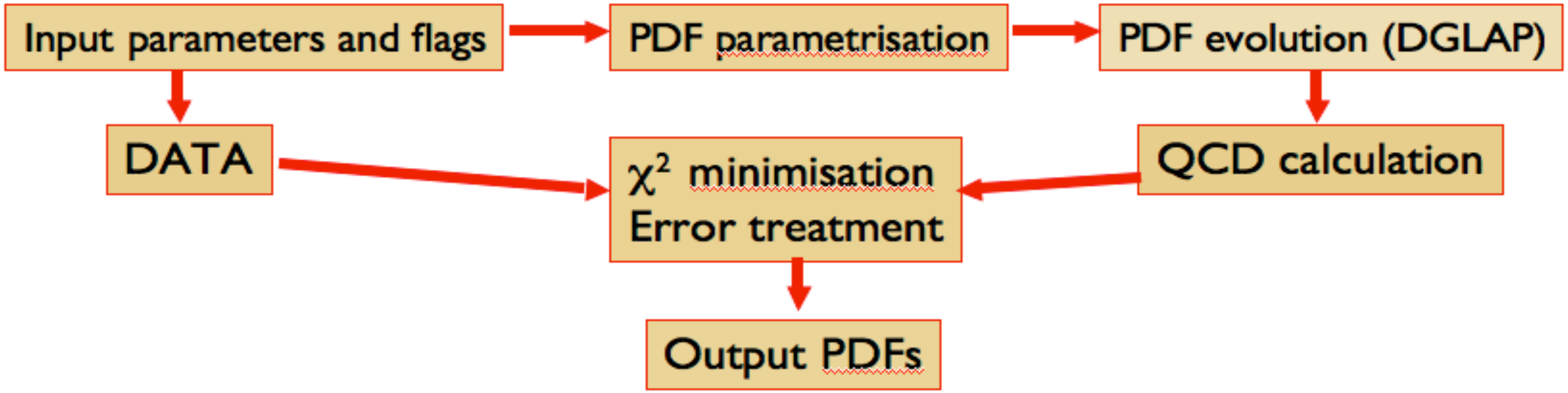
- Neural network PDF: very flexible parametrisation
- Use of Chebyshev Polynomial
  - These flexible parametrisation require though Regularisation Methods to smooth the PDFs



xubar from HERAPDF at starting scale:



Schematics of PDF extraction



PDFs are extracted from QCD fits to double differential cross section data:

- Parametrise PDFs at a starting scale by smooth functions with sufficient parameters;
- Evolve PDFs to other scales by the evolution equations (DGLAP)
- Compute cross sections for DIS (or other processes) at NLO (NNLO)
- Calculate χ^2 measure of agreement between data and theory model
- Obtain the best estimate of the PDFs by varying the free parameters to minimize χ^2

- For tomorrow..

HERAFitter Framework provides means to the experimentalist to assess the impact of measurements

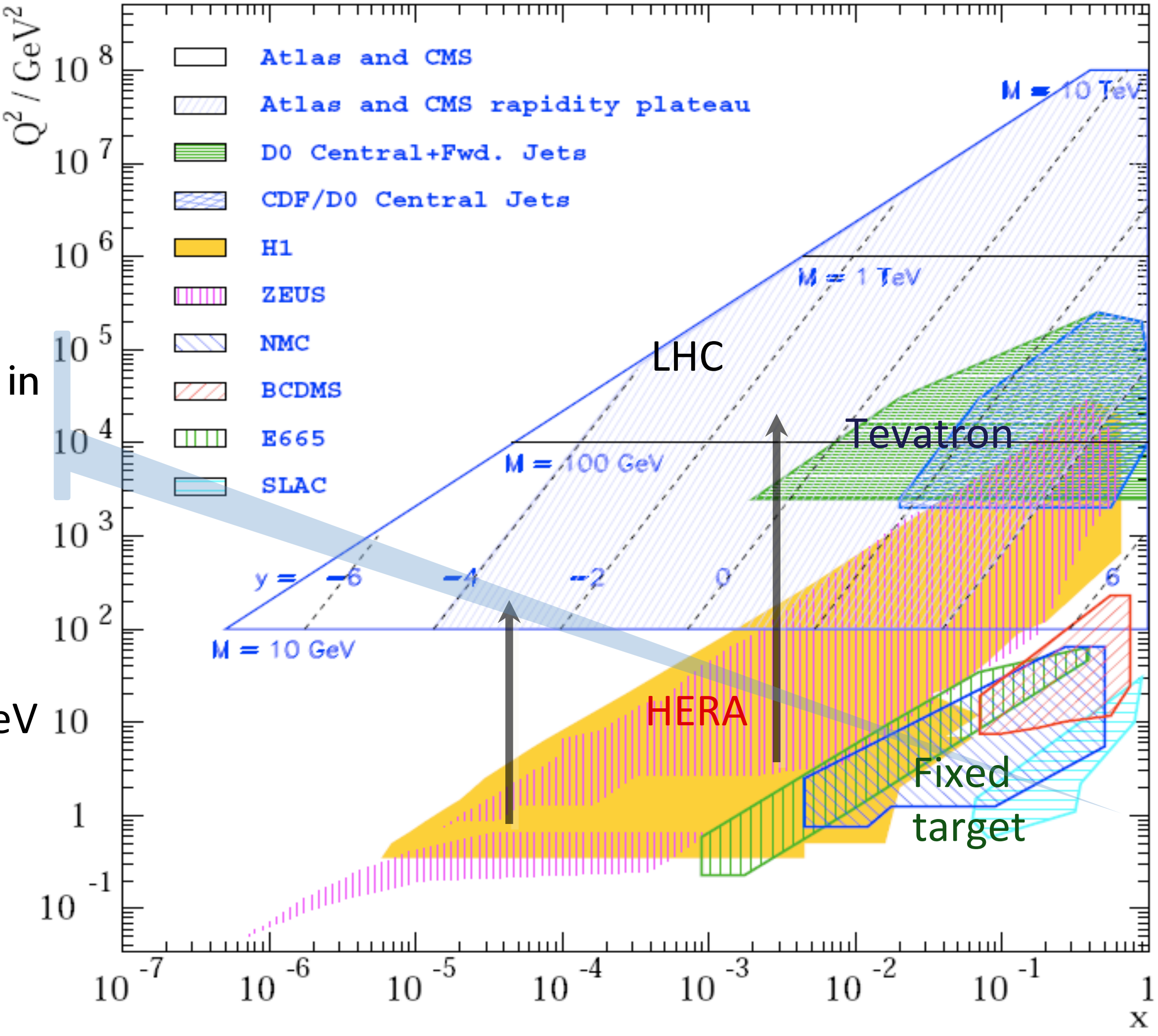
www.herafitter.org

Experimental Data on the Proton Structure

- Persistent experimental effort over the last 40 years both by fixed-target and collider experiments around the world supported by the theoretical developments

  - Large extension in kinematic space in x and Q^2 from the original SLAC measurements

- **DIS experiments may be classified as:**
  - low energy: SLAC, now JLAB
  - medium: BCDMS, NMC, CCFR/NuTeV
  - high energy: HERA



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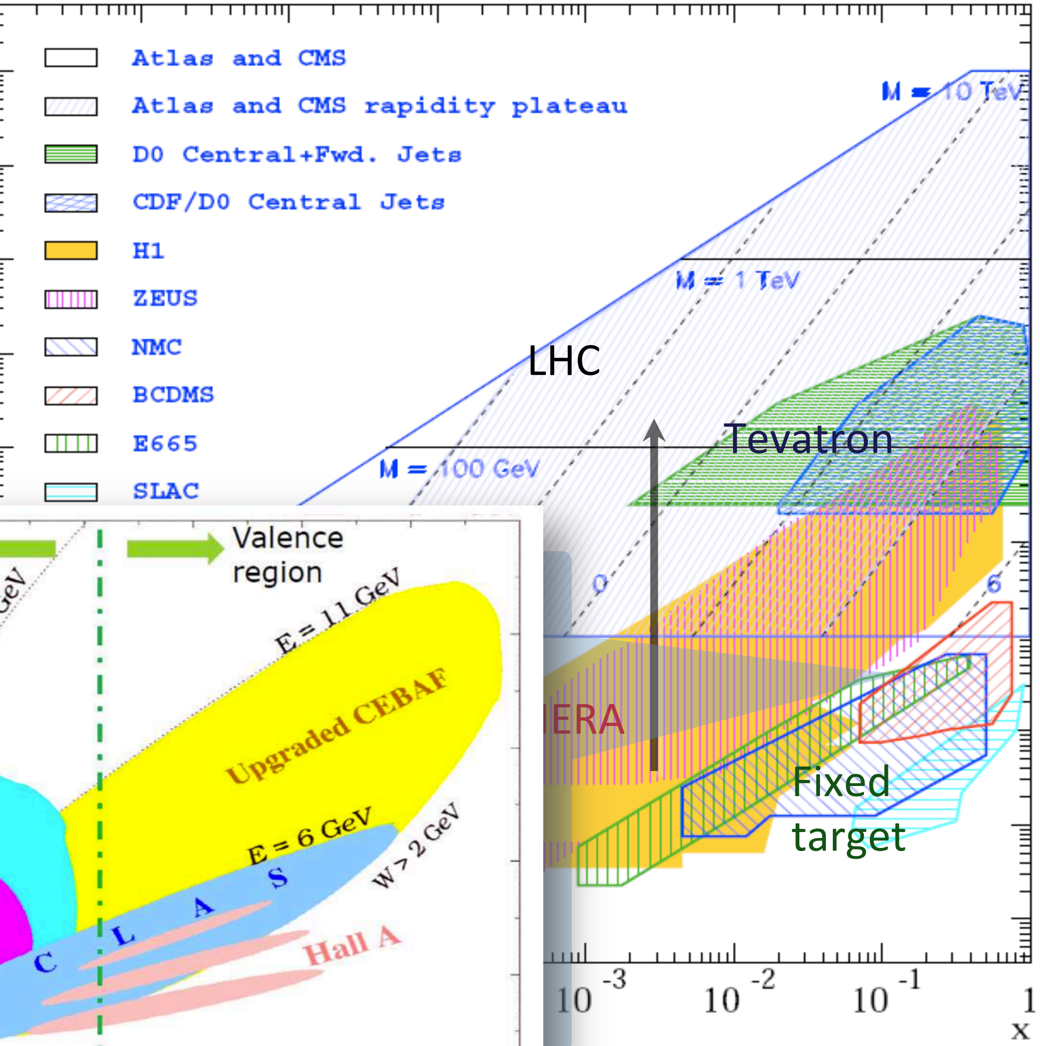
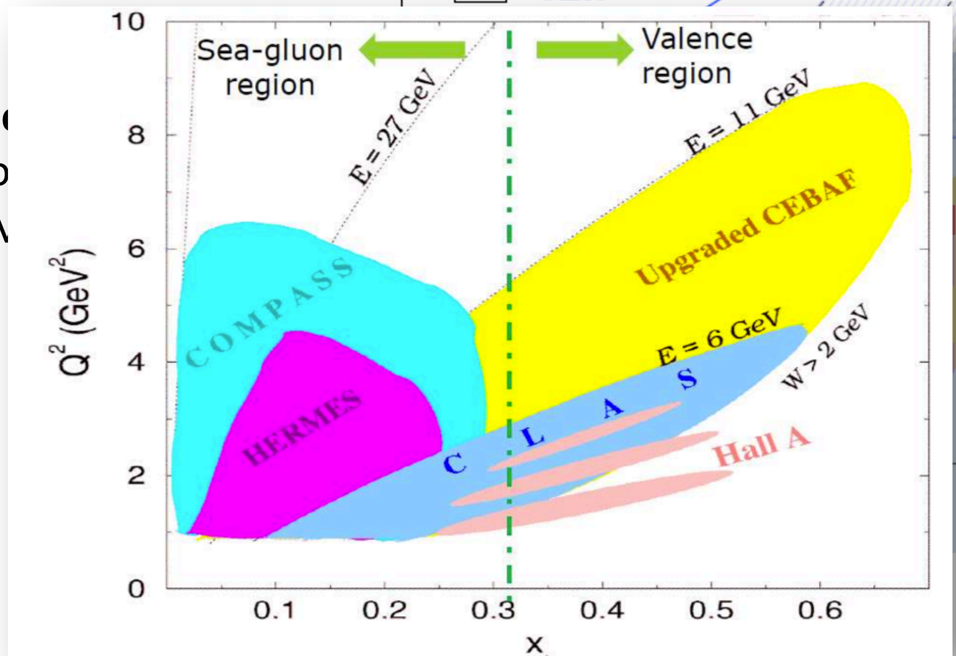


- **DIS experiments may be**
  - low energy: SLAC, no
  - medium: BCDMS, NM
  - high energy: HERA

And High X kinematics:
(tomorrow)

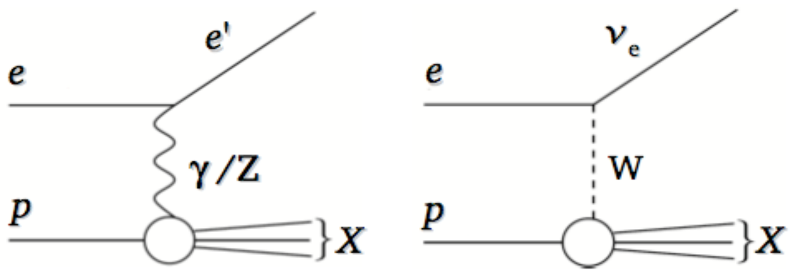


HERA Kinematic plane

HERA provides a rich physics program to study DIS

HERA-I	1992-2000	Ep=820,920 GeV	L~110/pb per exp.
HERA-II	2003-2007	Ep=920, 460,575 GeV	L~500/pb per exp.

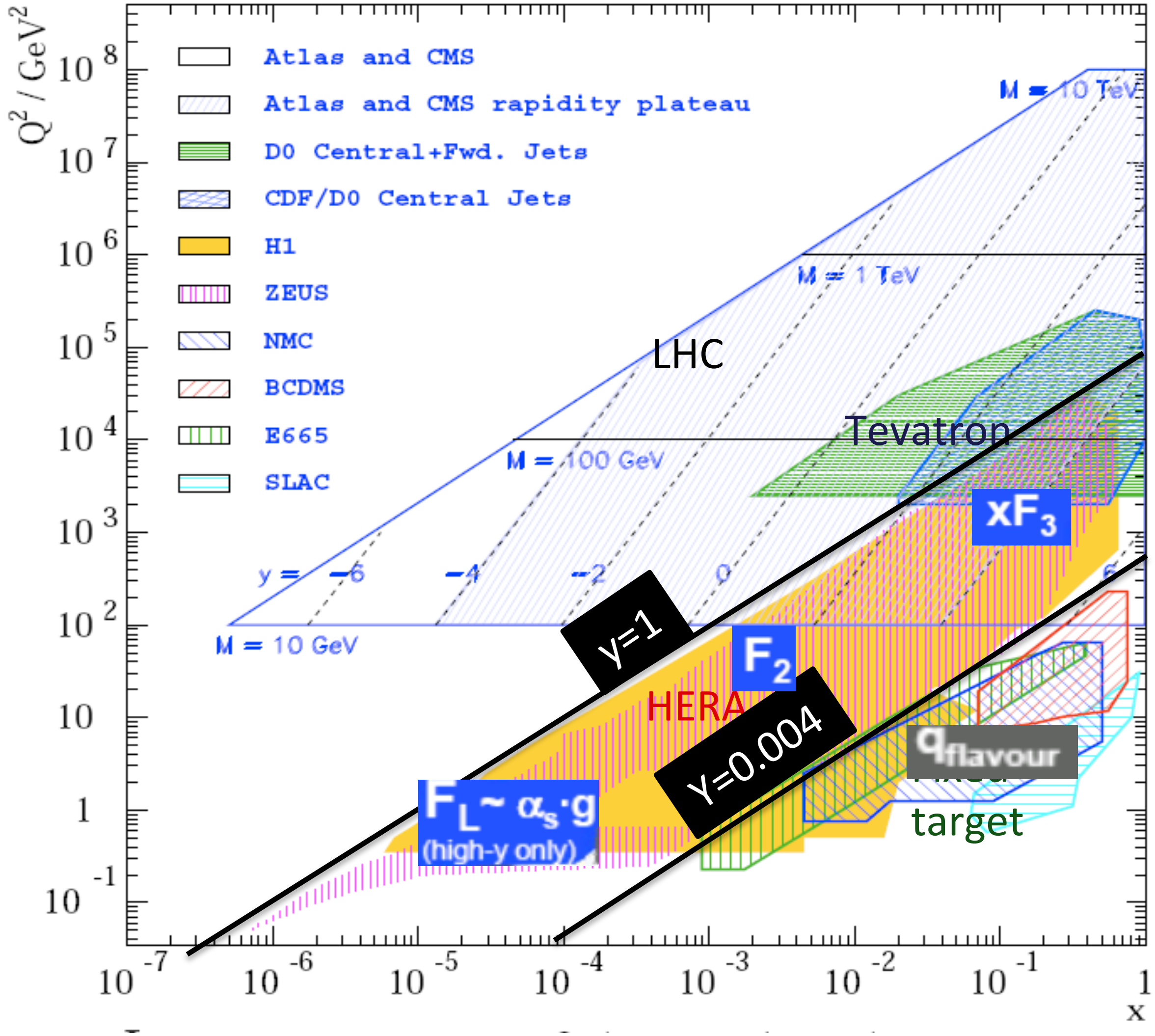
NC : $e\,p \rightarrow e'\,X$ CC : $e\,p \rightarrow \nu_e\ X$



Kinematic limits for HERA

$$E_e = 27.6GeV, E_p = 920GeV$$
$$\sqrt{s} = 2\sqrt{E_e E_p} = 319GeV$$

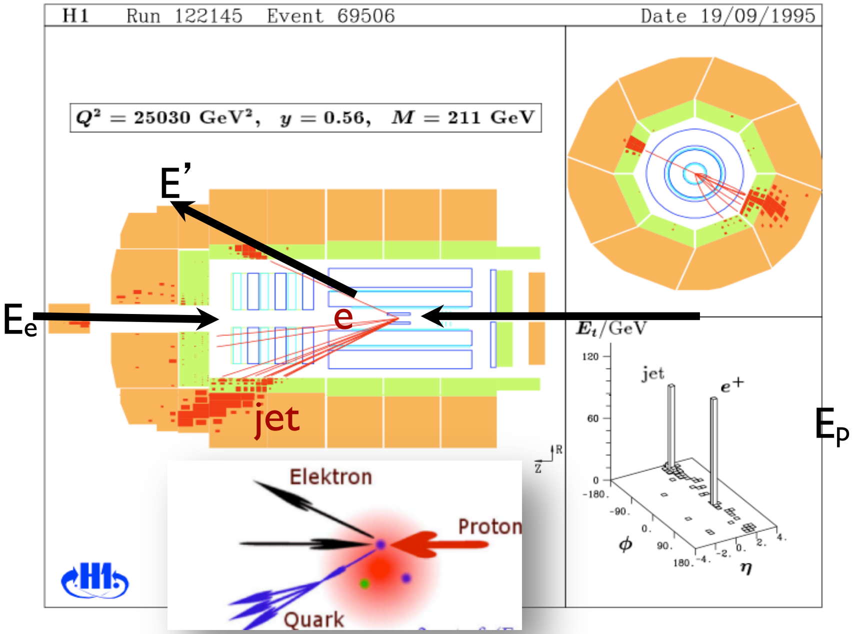
$$Q^2 = sxy - high$$
$$x = Q^2 / sy - low$$

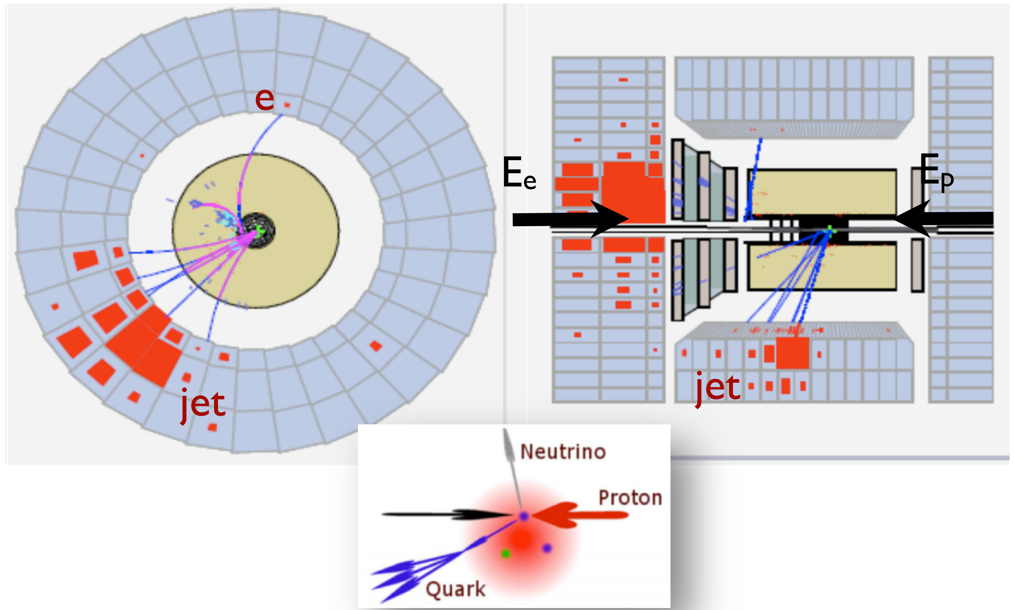


Detector and Kinematics at HERA: NC and CC DIS

- Neutral Current event sample in H1 detector

Charged Current event sample in ZEUS detector





$$s = 4E_eE_p$$
$$Q^2 = E_eE'(1+\cos\theta_e)$$
$$y = 1 - \frac{E'}{E_e}\frac{1}{2}(1-\cos\theta_e)$$
$$x = \frac{Q^2}{su}$$

- Determination of the Event Kinematics:
  - using lepton information (E_e', θ_e) — E_e', θ_e :
  - **using hadronic final state particles** — E_h, γ_h :
  - using both lepton and hadronic final state variables — θ_e, γ_h :

$$\sum_h E_h - p_{z,h} + E_e'(1-\cos\theta_e) \approx 2E_e$$

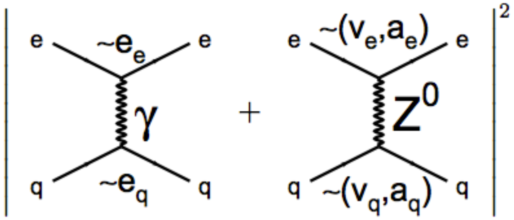
$$y_h = \frac{E_e'(1-\cos\theta_e)}{2E_e}$$

Redundant reconstruction of the kinematics allows extension of kinematic coverage, extra checks of systematic uncertainties.

Inclusive differential cross sections at HERA

- **NC:**

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} \propto$$



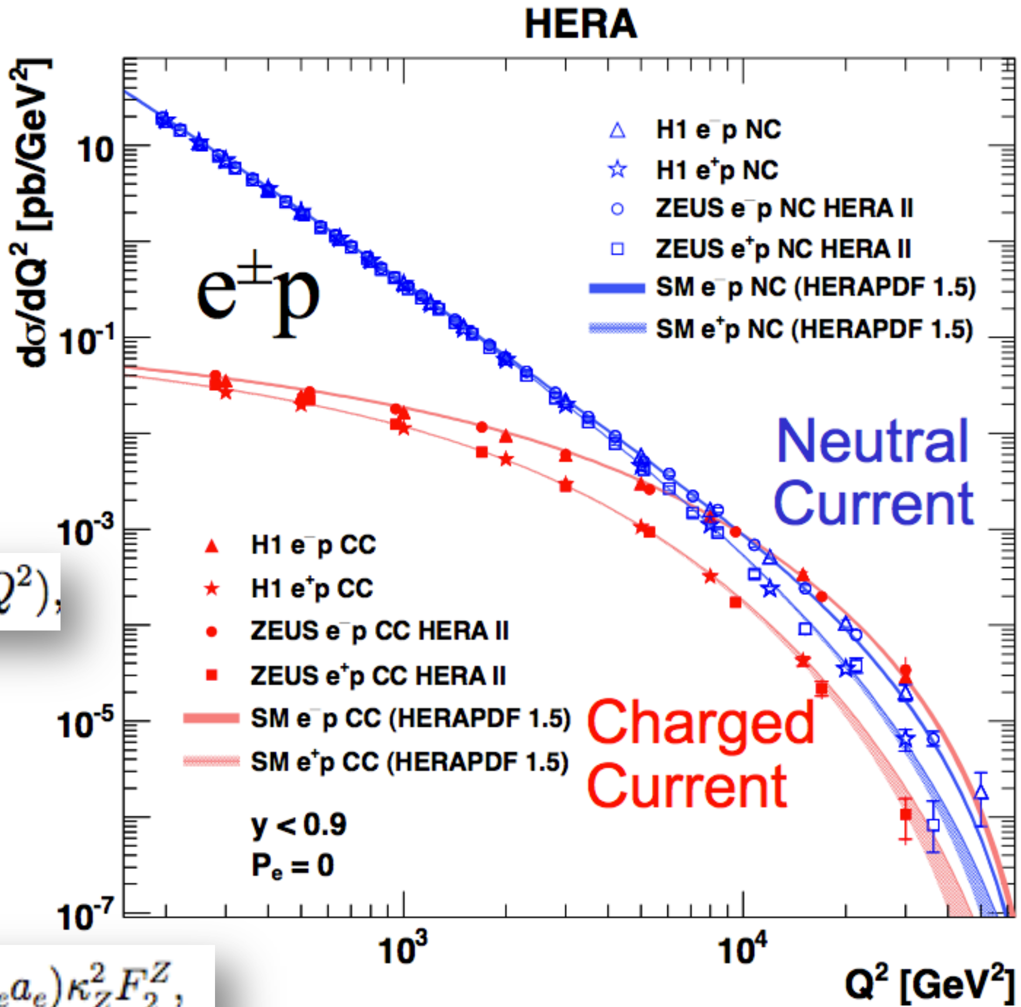
$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{x}\left[\frac{1}{Q^2}\right]^2 \phi^{\pm}_{NC}(x,Q^2)$$

$$\phi_{NC} = Y_+\tilde{F}_2^{\pm}(x,Q^2) - y^2\tilde{F}_L^{\pm}(x,Q^2) \mp Y_- x\tilde{F}_3^{\pm}(x,Q^2),$$

xF_3 only sensitive at large Q^2 ($\sim M_Z^2$)

F_L only sensitive at low Q^2 and high y

F_2 dominates



$$\tilde{F}_2^{\pm} = F_2 - (v_e \pm P_e a_e)\kappa_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\kappa_Z^2 F_2^Z,$$

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\kappa_Z xF_3^{\gamma Z} + (2v_e a_e \pm P_e(v_e^2 + a_e^2))\kappa_Z^2 xF_3^Z,$$

$$\kappa_Z(Q^2) = \frac{1}{4sin^2(\theta_W)cos^2(\theta_W)}\frac{Q^2}{Q^2+M_Z^2}$$

$$xF_3 \sim \sum(xq_i - x\bar{q}_i)$$

$$F_L \sim \alpha_S g$$

$$F_2 \sim \sum e_i^2(xq_i + x\bar{q}_i)$$

Electro-Weak Unification

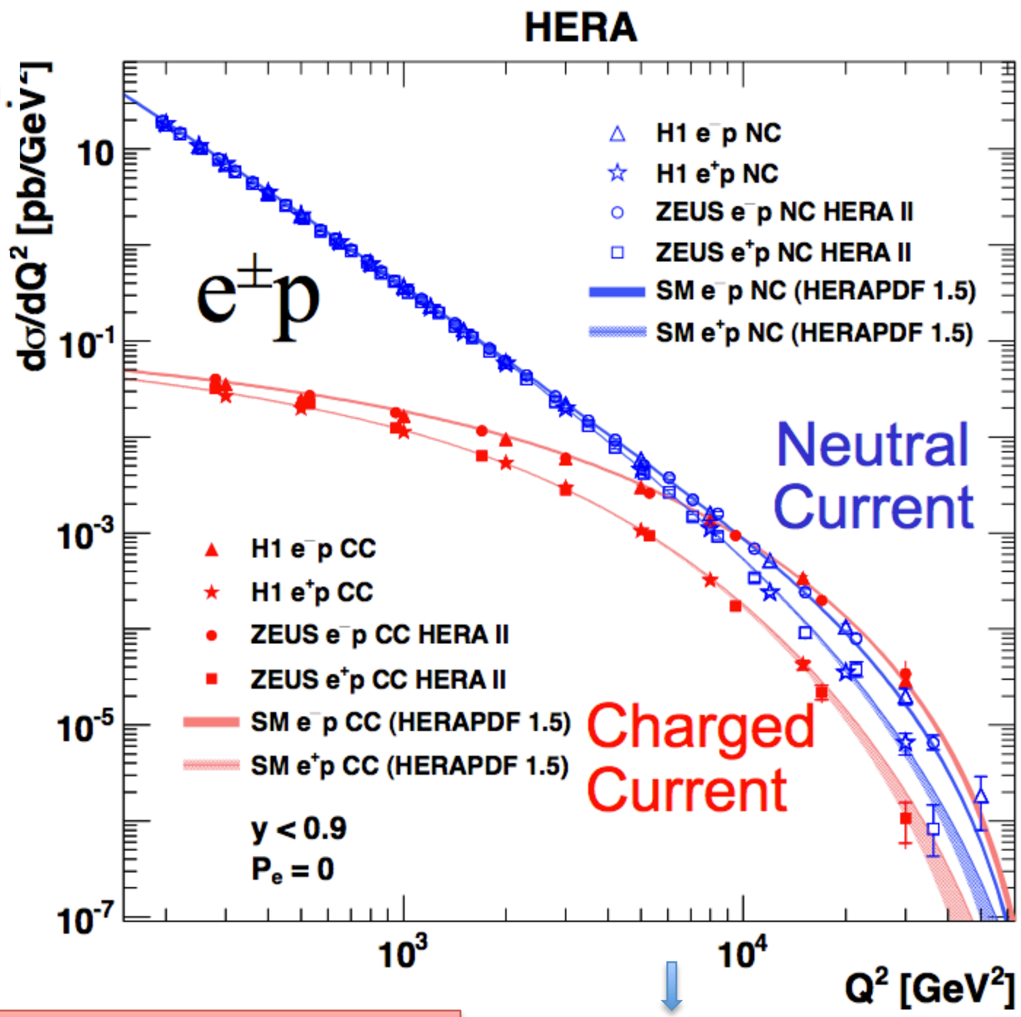
- **CC:**

$$\frac{d^2\sigma^{\pm}_{CC}}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{2\pi x}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2 \phi^{\pm}_{CC}(x,Q^2).$$

$$e^+: \quad \phi^+_{CC} = x[(\bar{u}(x)+\bar{c}(x)) + (1-y)^2(d(x)+s(x))],$$

$$e^-: \quad \phi^-_{CC} = x[(u(x)+c(x)) + (1-y)^2(\bar{d}(x)+\bar{s}(x))].$$

CC e⁻p > CC e+p because W⁻ is exchanged for CCe⁻p which couples to u and is more abundant in the proton

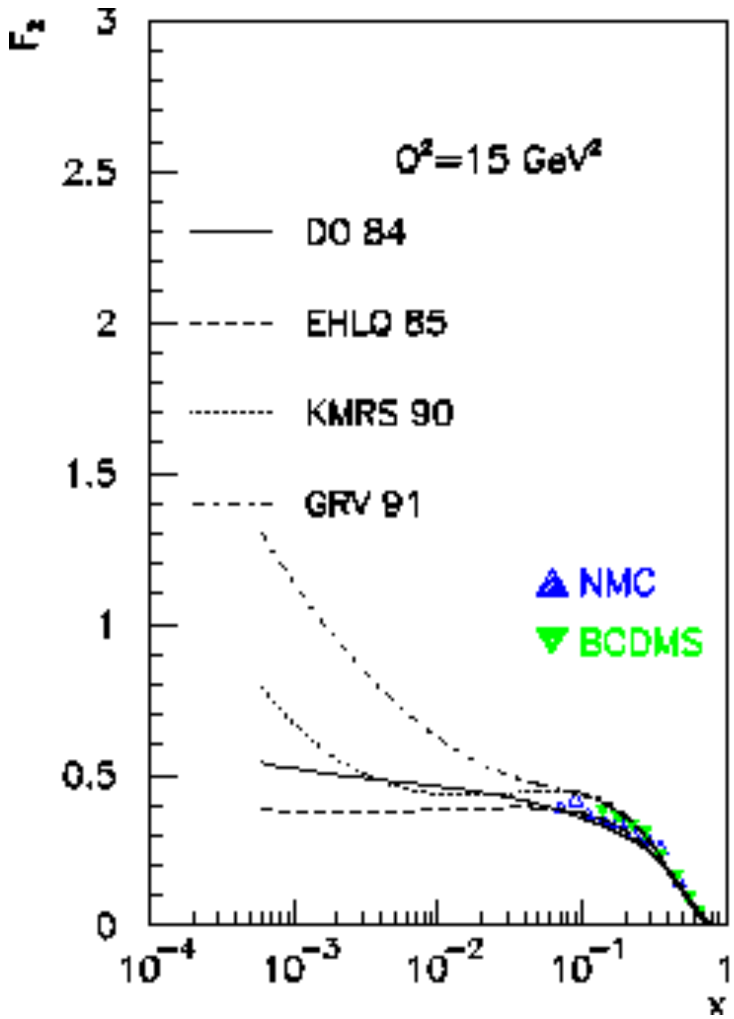


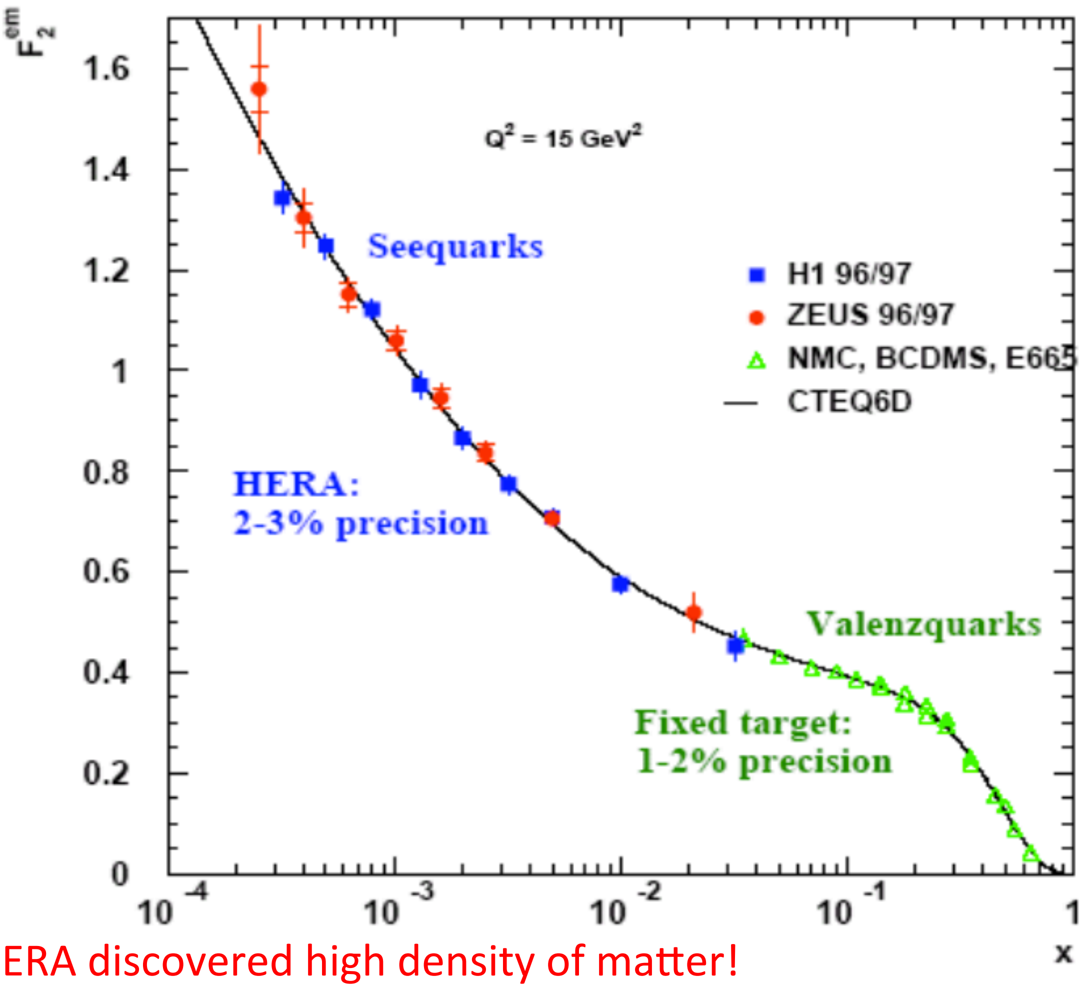
Electro-weak unification is clearly observed at $Q^2 \sim M_Z^2$ $\sigma_{NC}=\sigma_{CC}$

Rise of F_2 at low x seen at HERA

- Expectations on the density of partons before HERA…. And after HERA (high energy ep)
  - **Before the HERA measurements most of the predictions for low-x were not rising!**

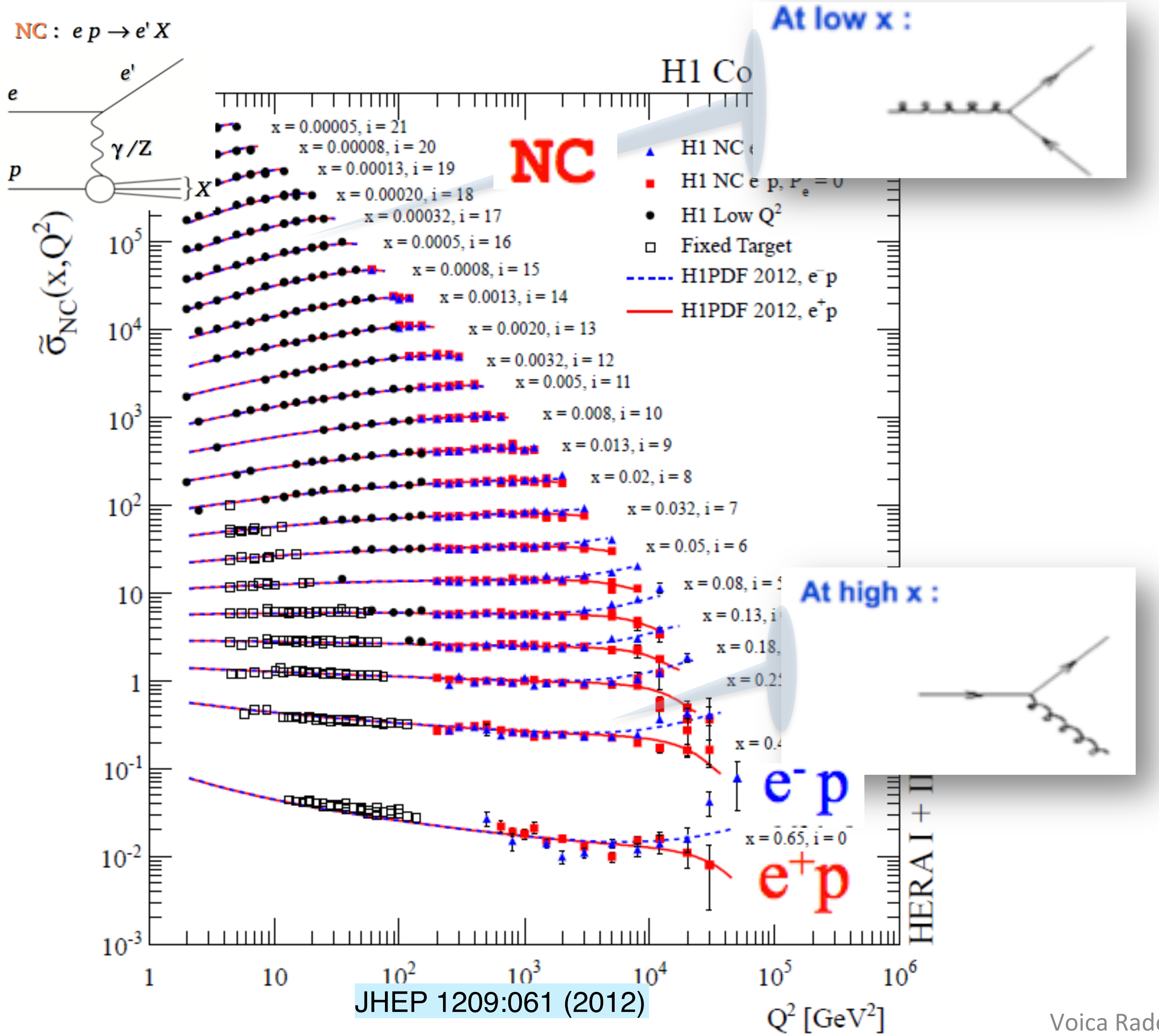
1997 data ~30pb-1





HERA discovered high density of matter!

Scaling violations from F_2 at HERA (ep)



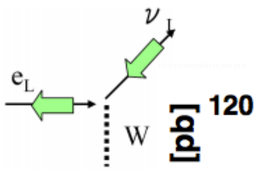
JHEP 1209:061 (2012)

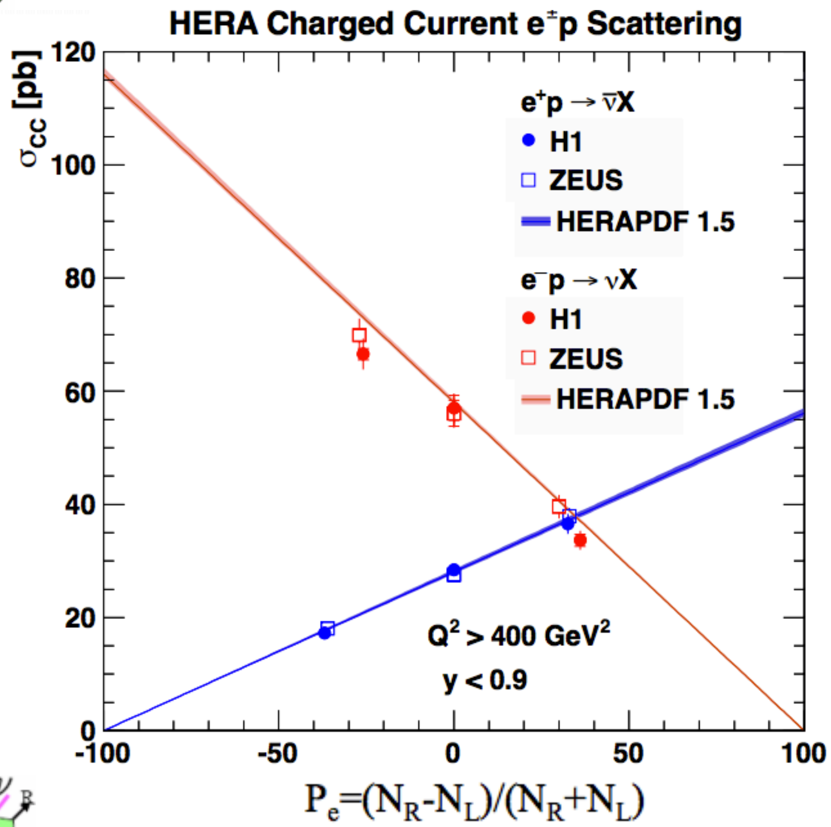
$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2)xg(x,Q^2)$$

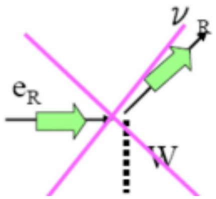
$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2)q(x,Q^2)$$

Polarisation effects in CC and NC

- SM predicts that CC cross section vanishes for right-handed electrons and left-handed positrons.



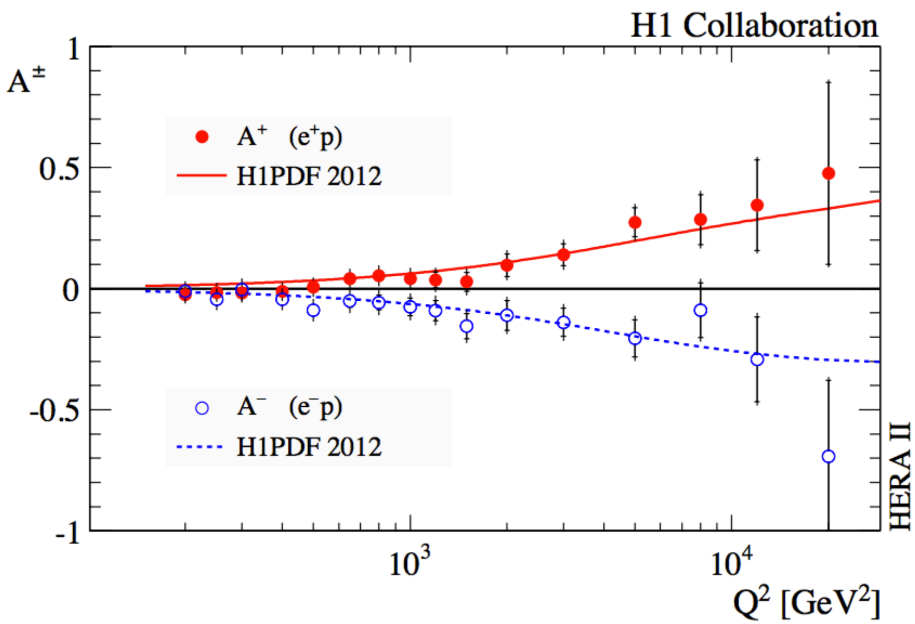




→ absence of right-handed weak current

- SM predicts a difference in the NC cross section for leptons with different helicity states arising from the chiral structure of the neutral electroweak exchange

$$A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$$



→ a direct measure of parity violation in NC

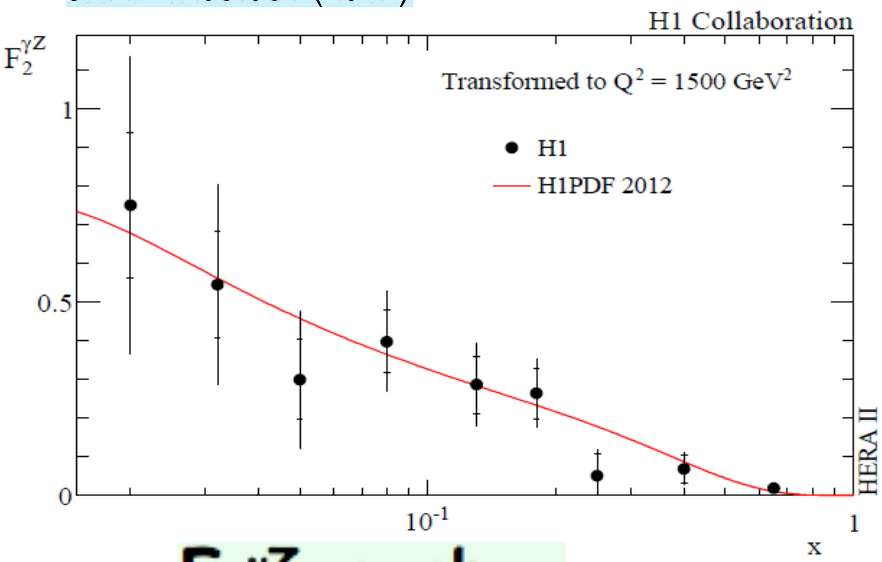
Measurements of Asymmetries from HERA

- Explore polarisation asymmetry to extract $F_2^{\gamma Z}$
- Explore charge asymmetry to extract $xF_3^{\gamma Z}$ (improved measurement from HERA I+II)

$$\tilde{F}_2^{\pm} \approx F_2 - (v_e \pm P_e a_e)\kappa \frac{Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z}$$

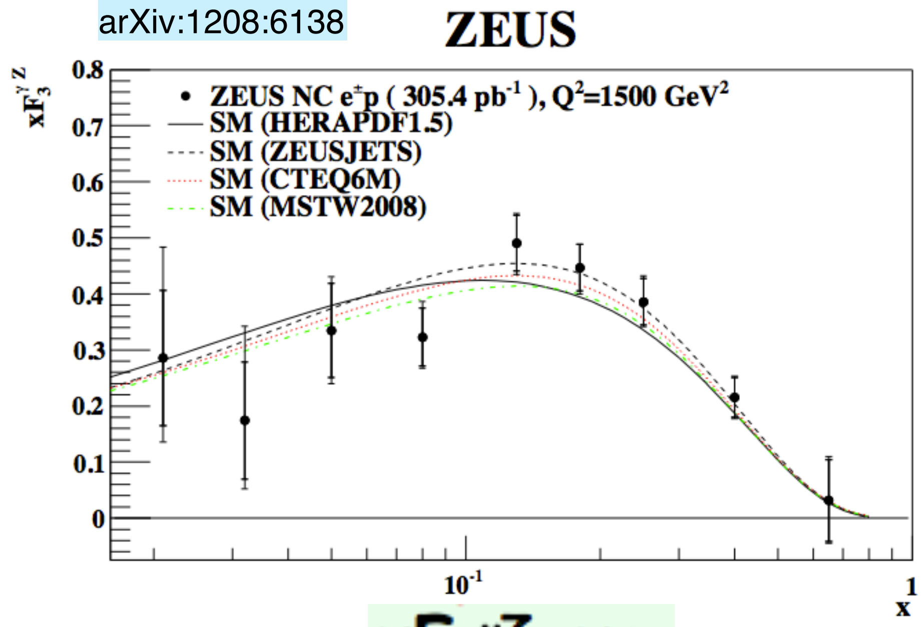
$$\sigma_r^{\pm} = \tilde{F}_2^{\pm} \mp \frac{1-(1-y)^2}{1+(1+y)^2} x\tilde{F}_3 - \frac{y^2}{1+(1-y)^2}\tilde{F}_L$$

JHEP 1209:061 (2012)



$F_2^{\gamma Z}$~q+qbar

arXiv:1208:6138



$xF_3^{\gamma Z}$~xq_v

The shape of the distribution reflects their parton sensitivity

Summary Lecture I

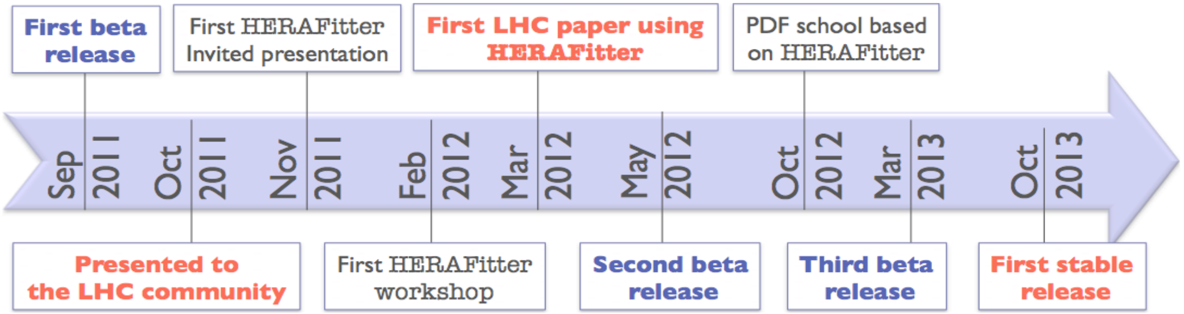
- **Today have presented the basis of DIS formalism:**
  - **Kinematic variables to describe the process**
  - **Differential Cross Section in terms of Structure Functions for different processes**
  - **Relation of Structure Functions to PDFs (factorisation theorem)**
- **Some Milestones of Experimental Results:**
  - **Discovery of gluon**
  - **Electroweak Unification**

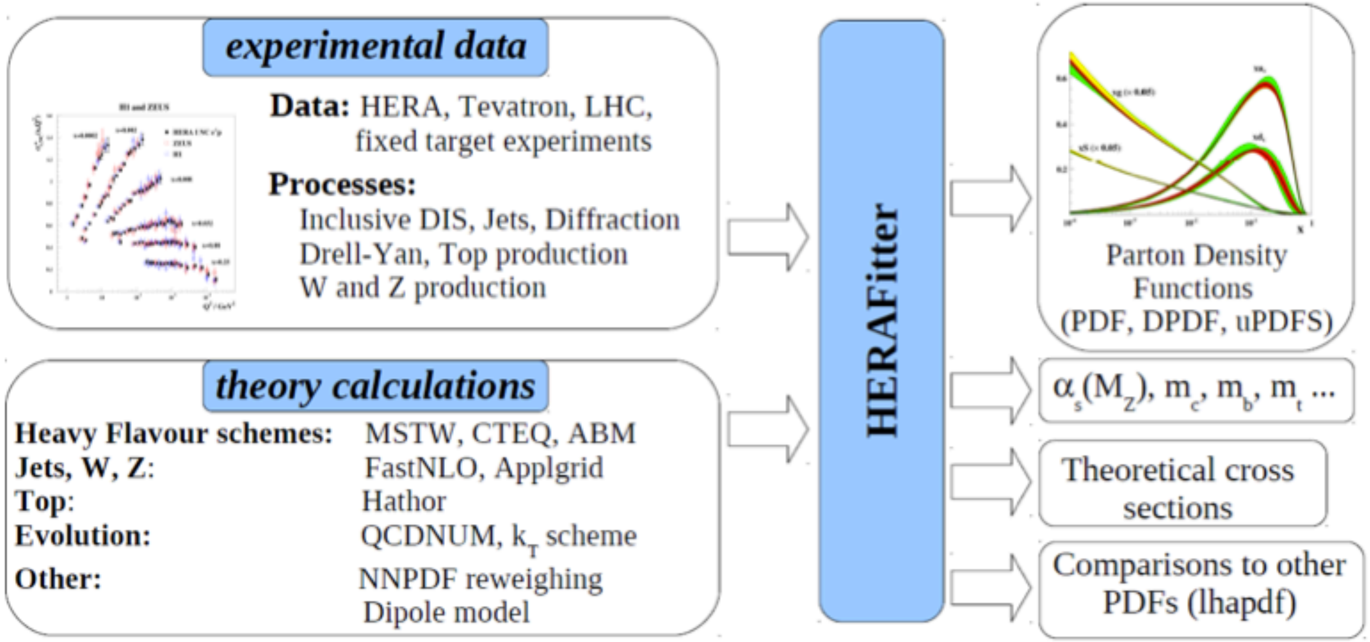
- Tomorrow:
  - Will continue with more Experimental results
  - Applicability of DIS measurements: determination of PDFs
    - importance of precision measurements and what does it involves
  - From Low x to High x
  - Relating DIS to LHC
    - Most recent data sensitive to PDFs
  - Outlook

HERAFitter QCD platform

Heritage of HERA transferred to LHC:

Open Source QCD Framework freely available at https://www.herafitter.org

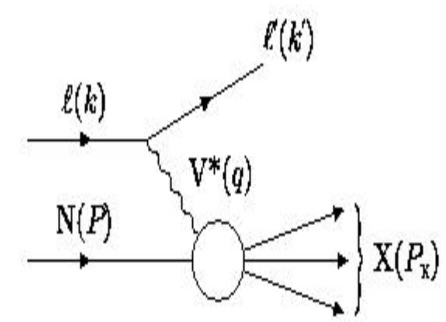




DIS Cross Sections

- Factorisable nature of interaction: Inclusive scattering cross section is a product of leptonic and hadronic tensors times propagator characteristic of the exchanged particle:

$$\frac{d^2\sigma}{dx dQ^2} \sim \Big|$$



$$\Big|^2 \quad L^{\mu\nu} W_{\mu\nu}$$

For NC: V=γ, Z, γZ
For CC: V=W+, W-

Leptonic tensor: related to the coupling of the lepton with the exchanged boson

- contains the electromagnetic or the weak couplings
- can be calculated exactly in the standard electroweak U(1) × SU(2) theory.

Hadronic tensor: related to the interaction of the exchanged boson with proton

- can't be calculated, but only be reduced to a sum of structure functions:

~m_{lepton}

$$W^{\alpha\beta} = -g^{\alpha\beta} W_1 + \frac{p^\alpha p^\beta}{M^2} W_2 - \frac{i\epsilon^{\alpha\beta\gamma\delta} p_\gamma q_\delta}{2M^2} W_3 + \frac{q^\alpha q^\beta}{M^2} W_4 + \frac{p^\alpha q^\beta + p^\beta q^\alpha}{M^2} W_5 + \frac{i(p^\alpha q^\beta - p^\beta q^\alpha)}{2M^2} W_6$$

$$\frac{d^2\sigma}{dx dQ^2} = A^i \left\{ (1 - y - \frac{x^2 y^2 M^2}{Q^2}) F_2^i + y^2 x F_1^i \mp (y - \frac{y^2}{2}) x F_3^i \right\}$$

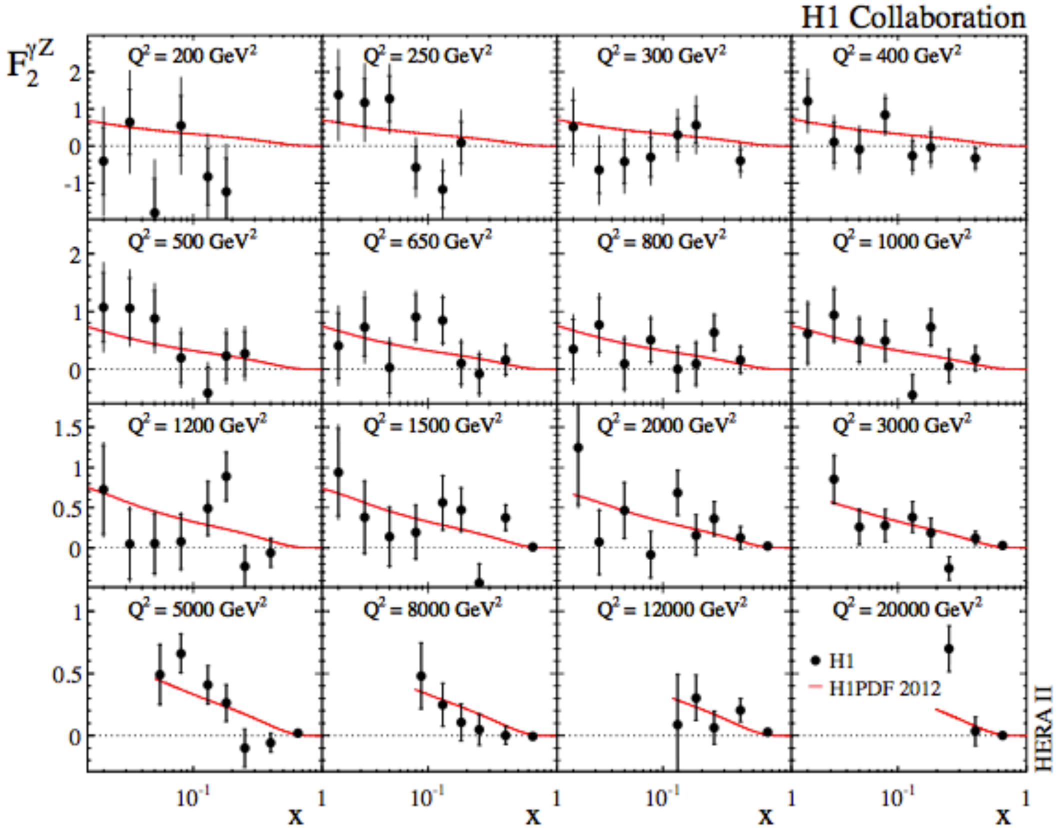
A^i: process dependent

The First Measurement of Parity Violating SF $F_2^{\gamma Z}(x,Q^2)$

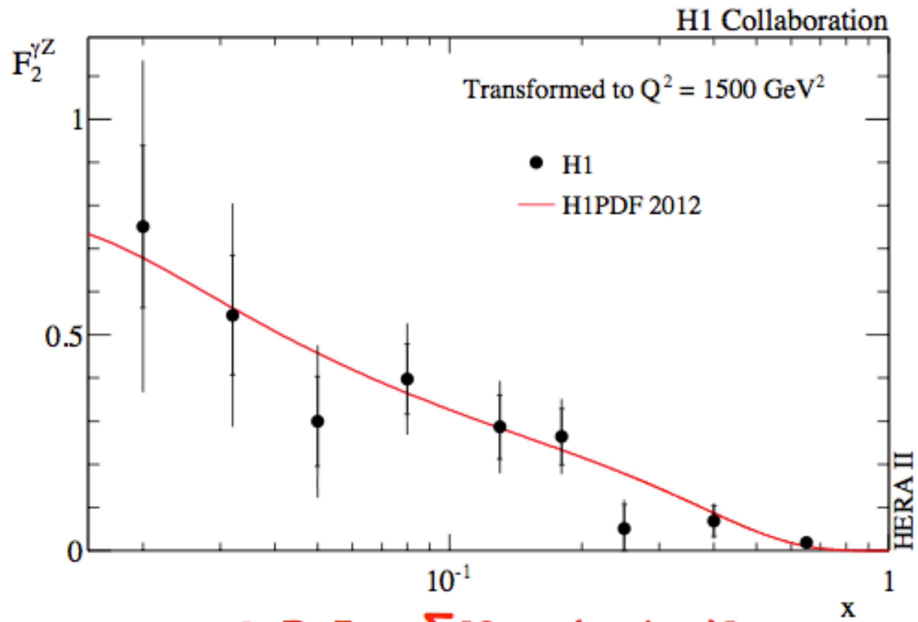
$$\frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{P_L^{\pm} - P_R^{\pm}} = \frac{\kappa Q^2}{Q^2 + M_Z^2}\left[\mp a_e F_2^{\gamma Z} + \frac{Y_-}{Y_+} v_e x F_3^{\gamma Z} - \frac{Y_-}{Y_+}\frac{\kappa Q^2}{Q^2+M_Z^2}(v_e^2 + a_e^2) x F_3^Z\right]$$

taking the difference for e^+p and e^-p, the terms with $xF_3^{\gamma Z}$ and xF_3^Z cancel and $F_2^{\gamma Z}$ can be directly extracted from measured polarised cross sections

$$\kappa^{-1} = 4\frac{M_W^2}{M_Z^2}\left(1 - \frac{M_W^2}{M_Z^2}\right)$$



transform the $F_2^{\gamma Z}(x,Q^2)$ measurements to Q^2 = 1500 GeV^2 and average them to get $F_2^{\gamma Z}(x)$ at Q^2 = 1500 GeV^2



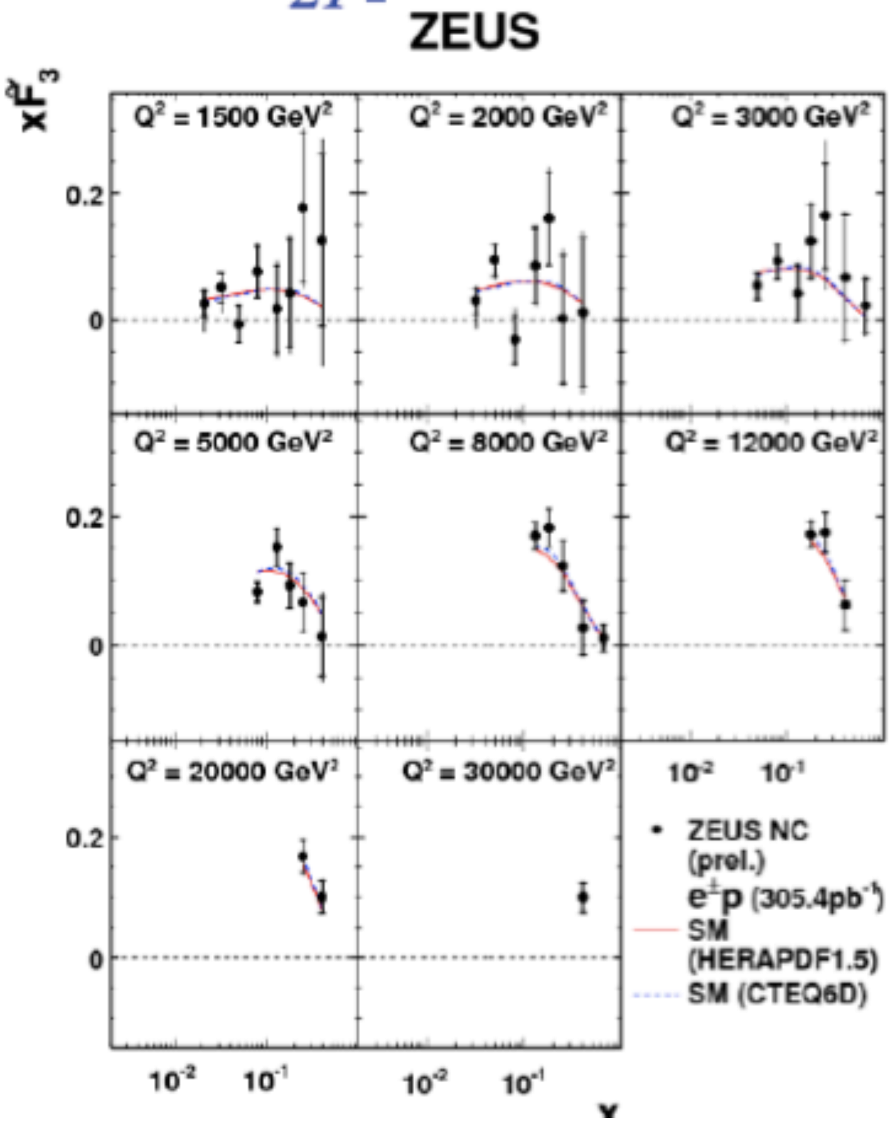
→ $F_2^{\gamma Z} = x\Sigma[2e_q v_q(q+\bar{q})]$

Structure Function $xF_3(x,Q^2)$

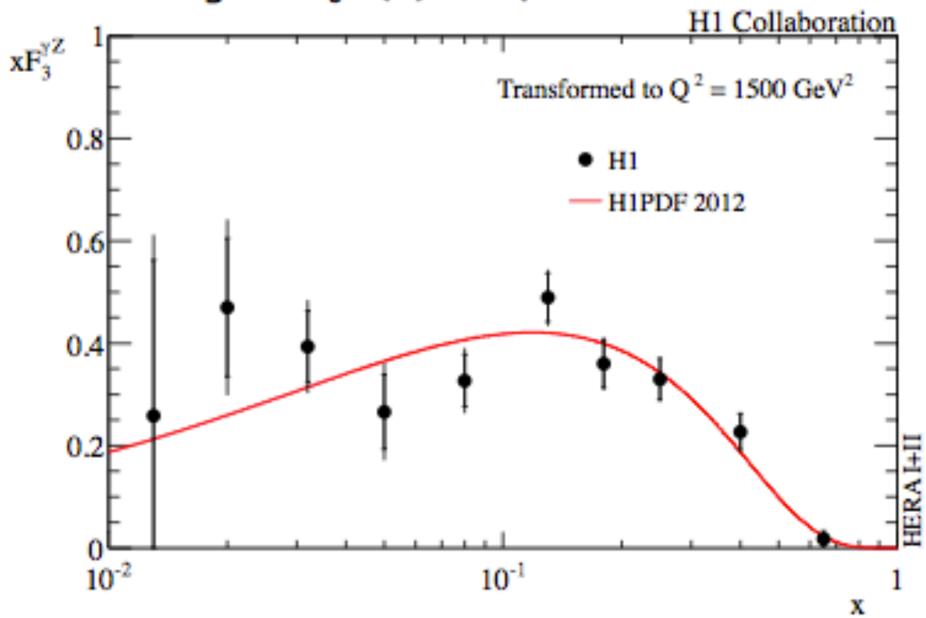
$x\tilde{F}_3 = \frac{Y_+}{2Y_-}\left(\tilde{\sigma}^-_{NC} - \tilde{\sigma}^+_{NC}\right)$ - charge asymmetry of unpolarised $e^{\pm}p$ NC cross sections

→ *mostly due to γZ interference*

$xF_3^{\gamma Z} = -x\tilde{F}_3 \cdot (Q^2 + M_Z^2)/(a_e \kappa Q^2)$



transform the $xF_3^{\gamma Z}(x,Q^2)$ measurements to Q^2 = 1500 GeV² and average them to get $xF_3^{\gamma Z}(x)$ at Q^2 = 1500 GeV²



→ sensitive to valence quark: $F_3^{\gamma Z} \approx (2u_v + d_v)/3$

$$\int_{0.016}^{0.725} dx\, F_3^{\gamma Z}(x, Q^2 = 1500\,\mathrm{GeV}^2) = 1.22 \pm 0.09(\mathrm{stat}) \pm 0.07(\mathrm{syst})$$

(H1PDF2012: 1.16+0.02-0.03)