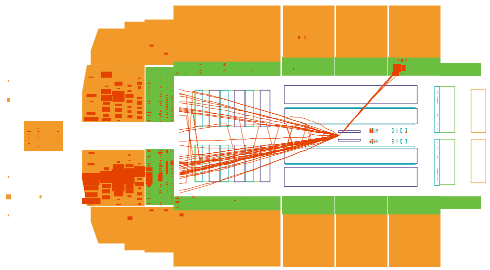
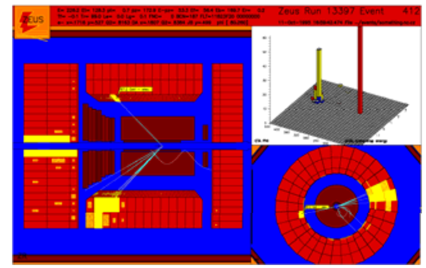
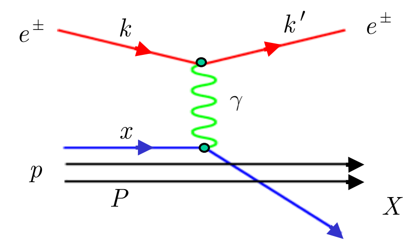
Physics with the HERA Collider



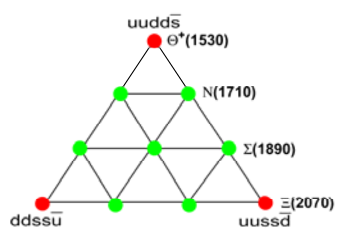


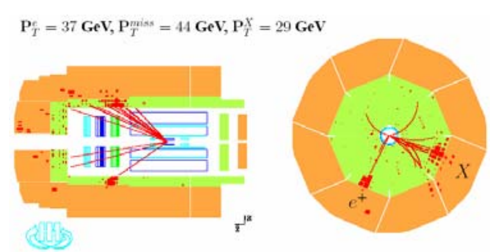
- Introduction to Electron-Proton Deep Inelastic Scattering

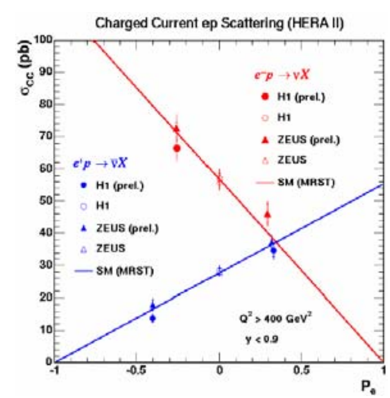
  Quark-Parton-Model, Structure Functions, Quantum Chromodynamics



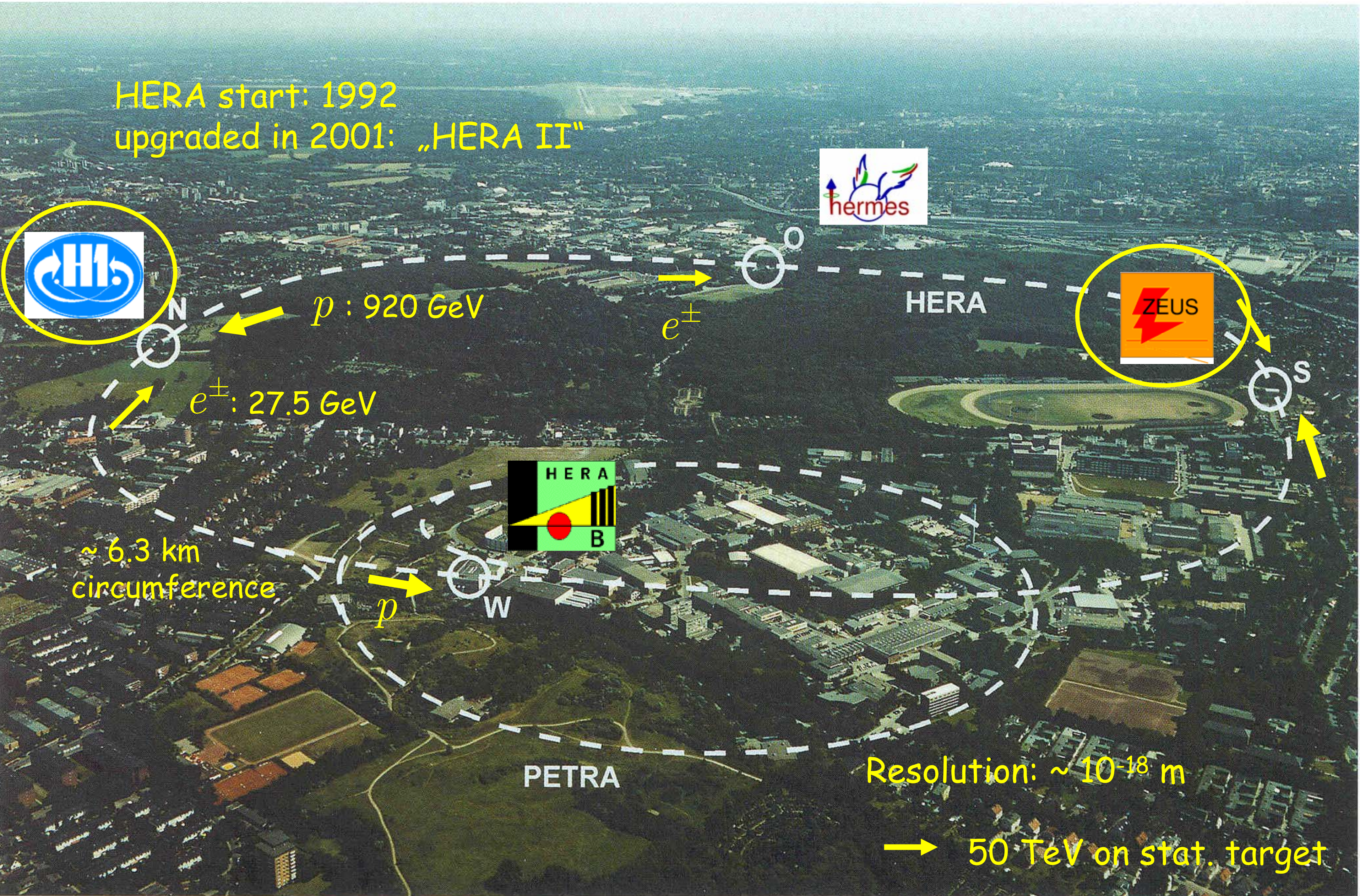
- Measurements of the Structure Functions
- Gluon density and the Strong Coupling Constant
- Testing the Electroweak Model in the Space-like Region
- Open questions
- Conclusions



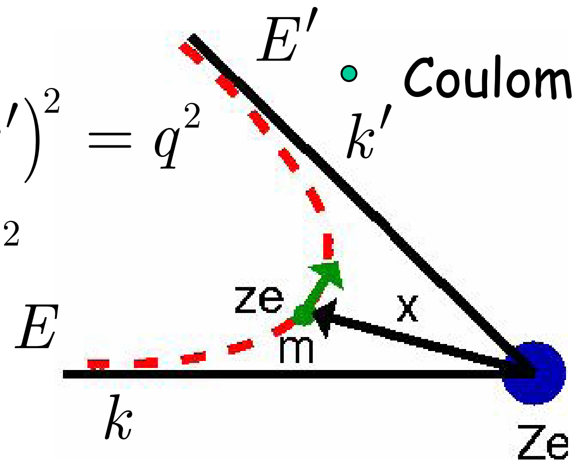




HERA – the world's largest electron microscope
(Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany)



From Rutherford to Deep Inelastic Scattering (DIS)



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

- Coulomb force: $F = \dfrac{1}{4\pi\varepsilon_0}\dfrac{eZe}{r^2}$ scattering of spinless objects

$$\left(\frac{d\sigma}{d\Omega}\right)_{Ruth} = \frac{\alpha^2 Z^2}{4E^2\sin^4(\theta/2)} \qquad \alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c}$$

- include spin of beam electron: $\dfrac{d\sigma}{d\Omega} = \left(\dfrac{d\sigma}{d\Omega}\right)_{Ruth}\left(1-\sin^2(\theta/2)\right)$

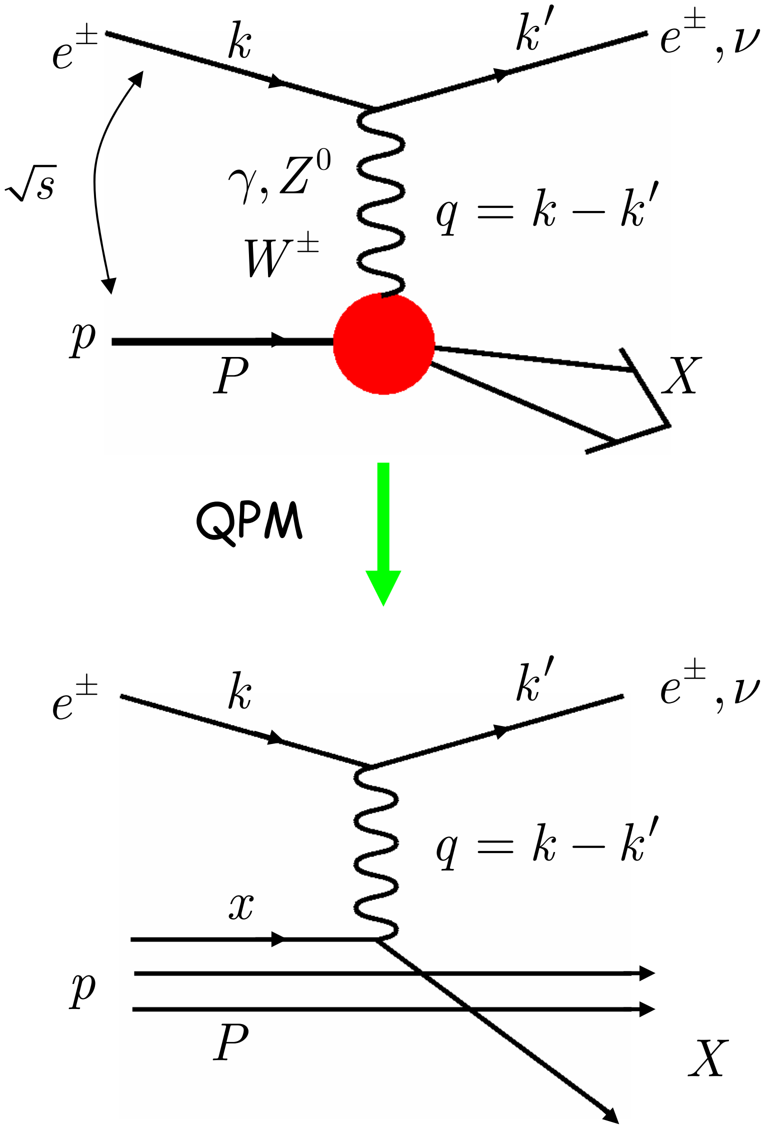
(no backscattering)

- proton spin + target mass correction (Z=1):

$$\frac{d\sigma}{dQ^2} = \frac{\pi\alpha^2}{4E^2\sin^4(\theta/2)}\frac{1}{EE'}\left(\cos^2(\theta/2) + 2\tau\sin^2(\theta/2)\right)$$

$$d\Omega = \left(\pi/E'^2\right)dQ^2 \qquad \tau = Q^2/(4M^2)$$

Deep Inelastic Scattering (DIS)



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

(momentum transfer)^2

virtuality of $\gamma^*, Z^0, W^\pm$ → („size" of the probe)$^{-1}$

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

fraction of the proton momentum carried by the charged parton

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

fraction of the electron energy carried by the virtual photon („inelasticity")

$$s = (k + P)^2$$

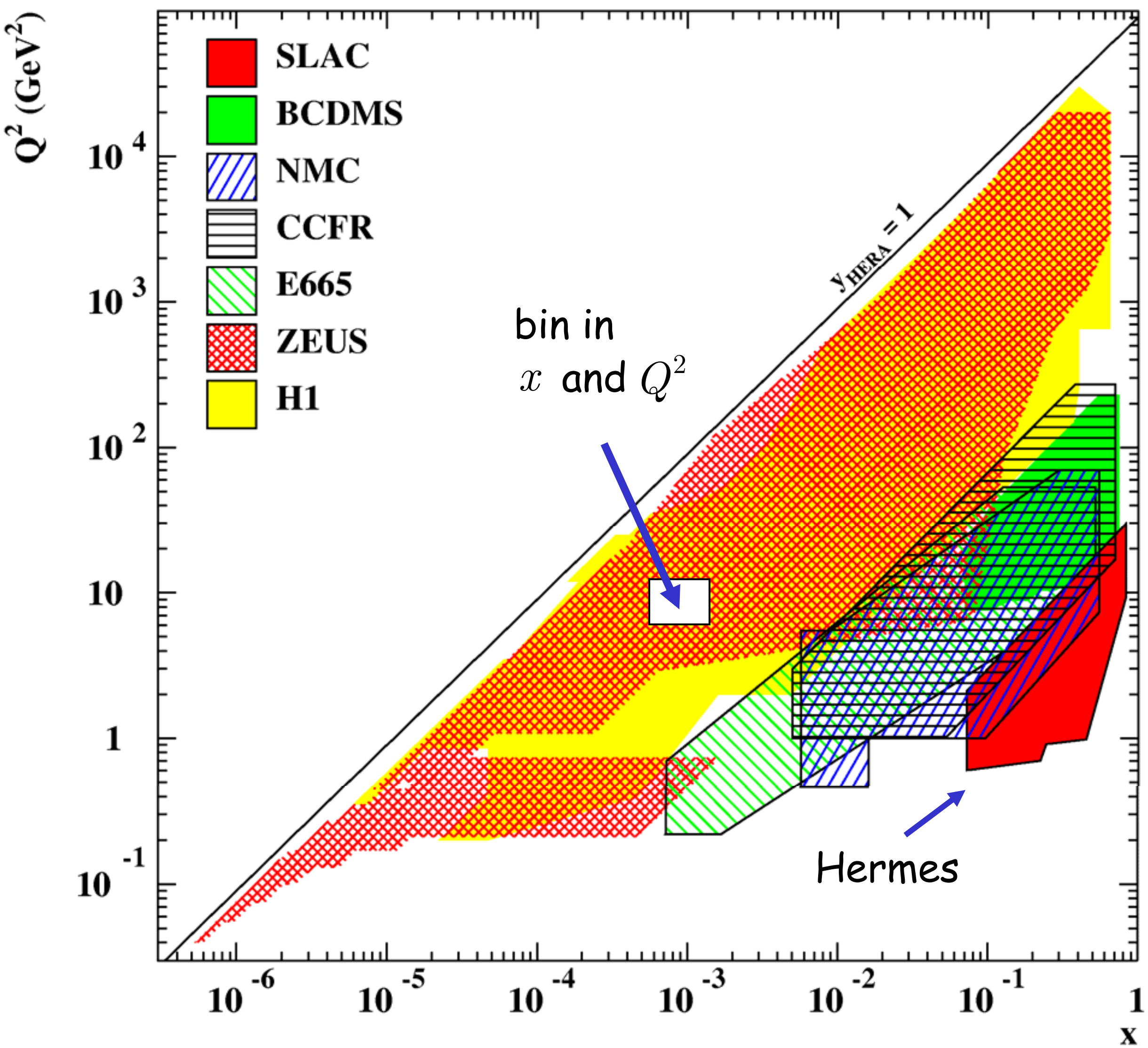
center of mass energy of ep system

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

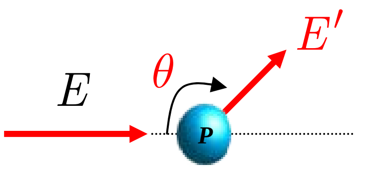
(mass)^2 of $\gamma^* p$ system

$$Q^2 = sxy$$

The Kinematic Reach of HERA



Determination of kinematics („e"-method) :



$$Q^2 = 4EE' \cos^2\left(\frac{\theta}{2}\right)$$

$$y = 1 - \frac{E'}{E} \sin^2\left(\frac{\theta}{2}\right)$$

$$x = \frac{Q^2}{sy}$$

Determination of cross sections :

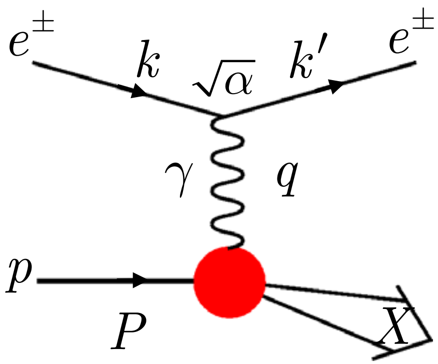
$$\frac{d^2\sigma}{dx dQ^2} \sim \frac{N - B}{\mathcal{L}\,\varepsilon}$$

backgr.

luminosity

efficiency

Cross Section and Structure Functions



(unpolarized particles)

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2MQ^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$

$L_{\mu\nu}$ lepton tensor

$W_{\mu\nu}$ hadronic tensor

$$L_{\mu\nu} = 2\left[k_\mu k'_\nu + k'_\mu k_\nu + \frac{q^2}{2}g_{\mu\nu}\right]$$

← minimal electromagnetic coupling

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right)2F_1 + \left(P_\mu - \frac{P\cdot q}{q^2}q_\mu\right)\left(P_\nu - \frac{P\cdot q}{q^2}q_\nu\right)\frac{2}{P\cdot q}F_2$$

most general tensor satisfying charge conservation

NC cross section :

$$\left(\frac{d^2\sigma}{dxdQ^2} = \frac{\pi\alpha^2}{4E^2\sin^4(\theta/2)}\frac{1}{EE'}\left(F_2\cos^2(\theta/2) + F_1 2\tau\sin^2(\theta/2)\right)\right)$$

$$\frac{d^2\sigma(e^\pm p)}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[xy^2F_1 + (1-y)F_2\right]$$

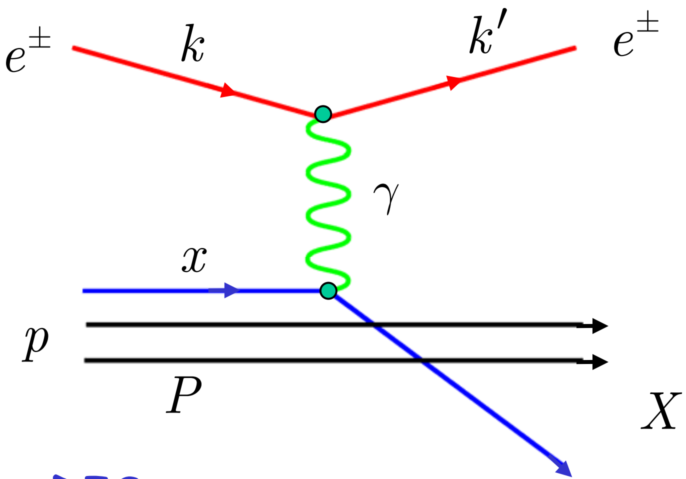
$$= \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 - y^2F_L\right]$$

$$F_L \equiv F_2 - 2xF_1$$

longitudinal structure function

$$Y_\pm = 1 \pm (1-y)^2$$

Structure Functions within the Quark-Parton-Model



$$\frac{d^2\sigma(e^{\pm}p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2 - y^2 F_L\right]$$

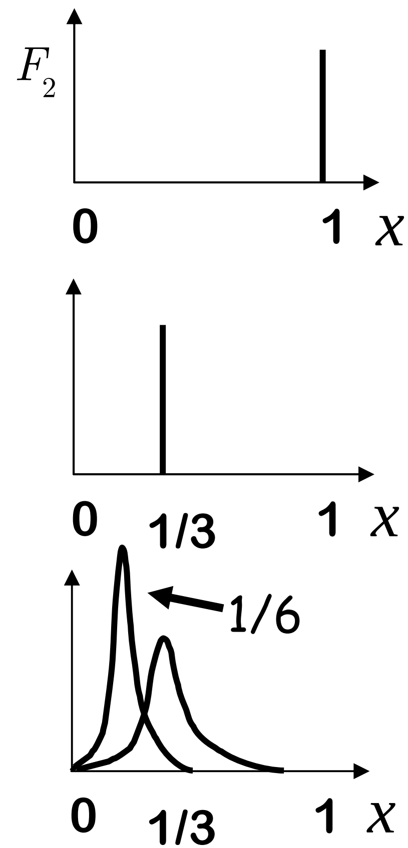
QPM: $F_2(x) = \sum_{i=u,d} e_i^2 x q_i(x)$

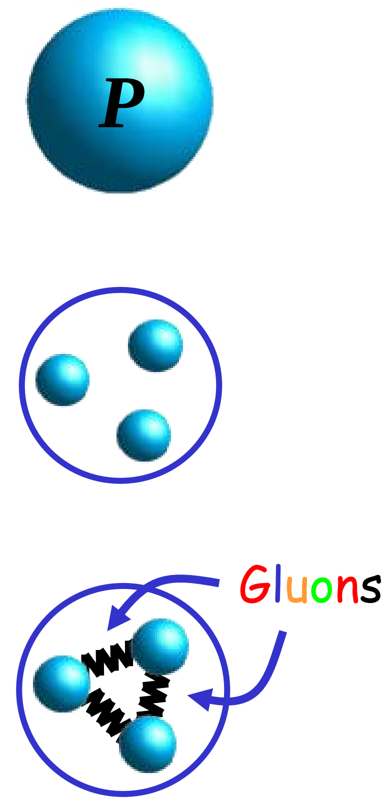
parton densities $xq_i(x)$ (pdf)

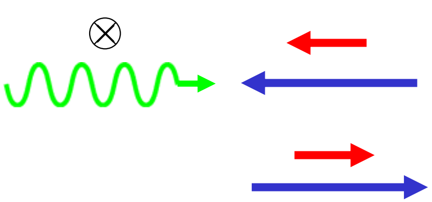
DIS =

- electron scatters off a charged constituent (parton) of the proton (= elastic scattering)
- identify the charged partons with QUARKS (= spin 1/2 fermions)

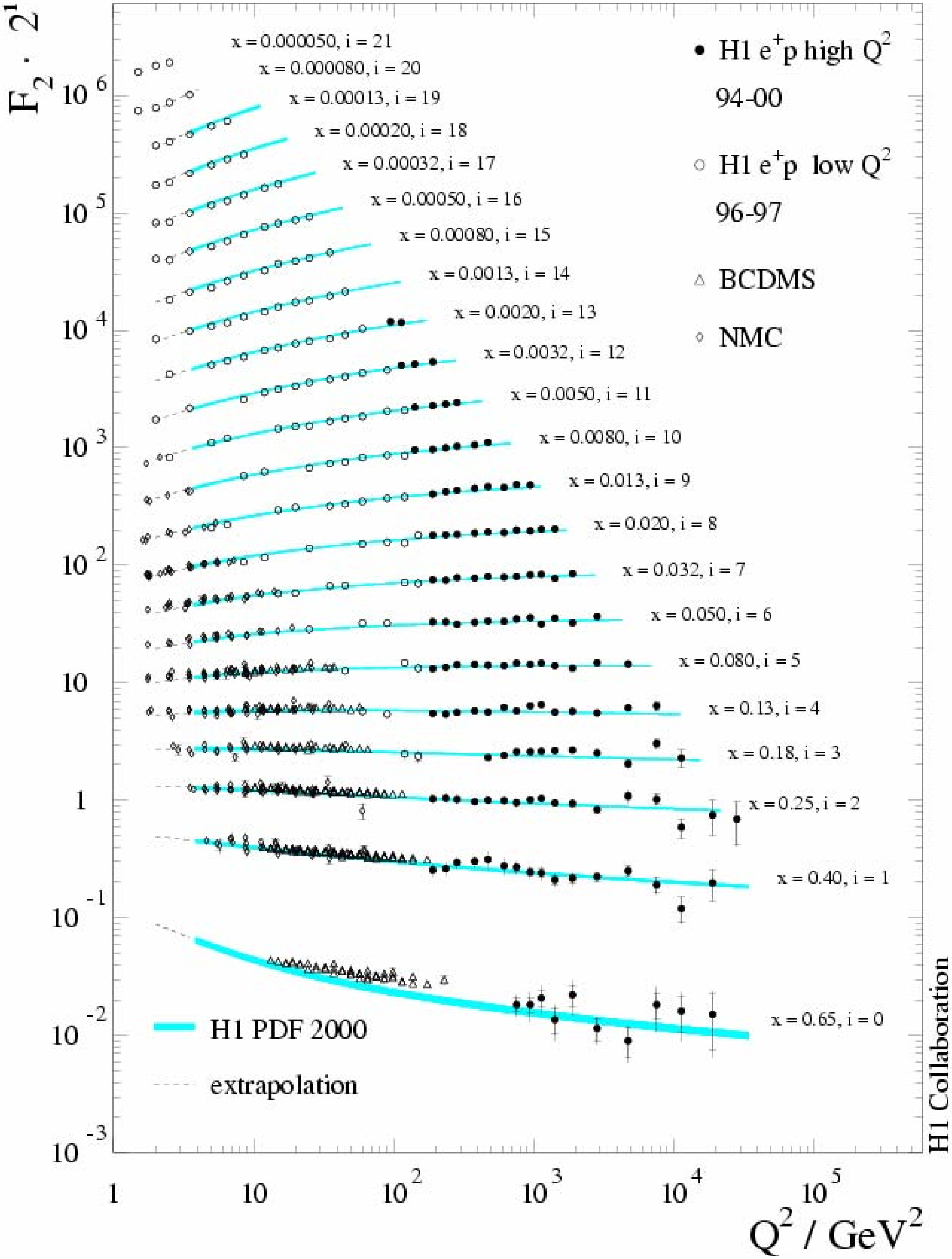
→ Quark-Parton-Model (QPM)

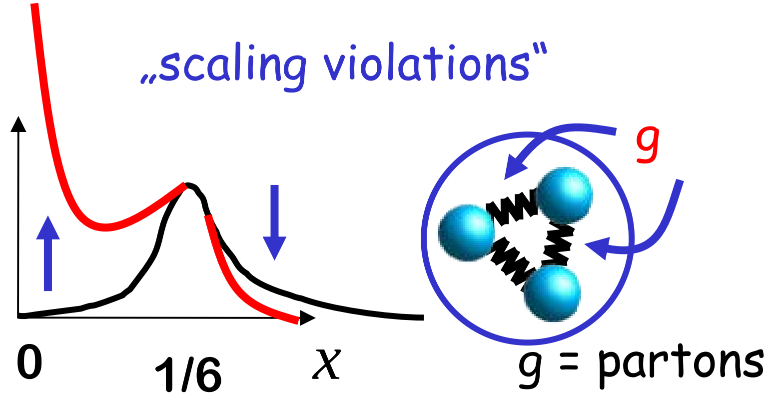






$$F_L = 0$$

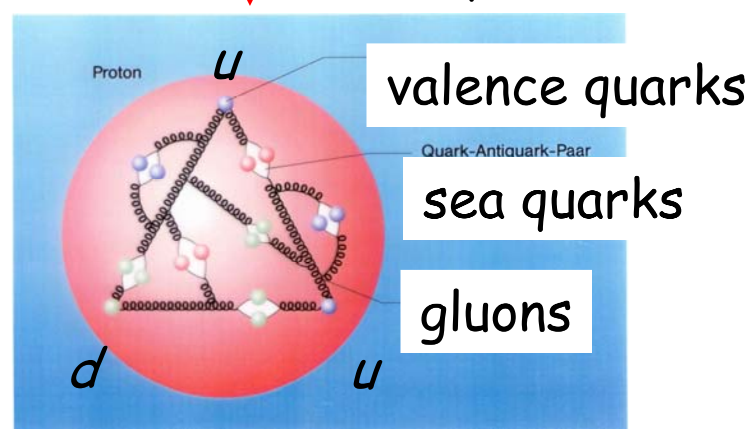




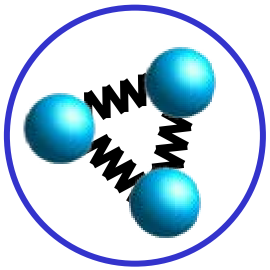
HERA's discovery:

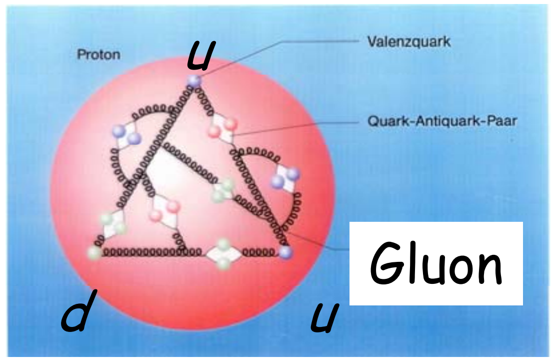
strong rise of the parton densities at low momentum fraction

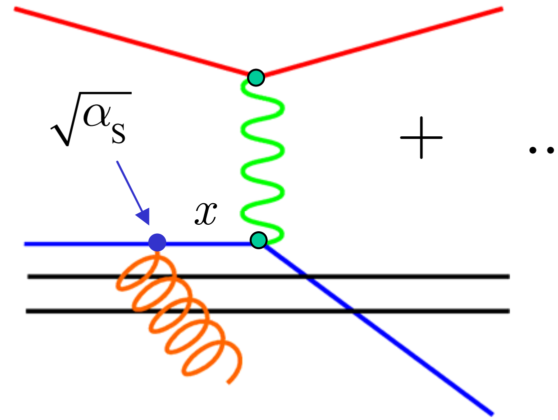
The new picture of the proton



Quantum Chromodynamics (QCD)







Basic ingredients of QCD:

1. Asymptotic freedom (Nobel Prize 2004) :

$\alpha_s \rightarrow 0$ at short distances

→ perturbative QCD (pQCD)

2. Factorization :

„hard" scale Q^2

$$\sigma = \sum_i \sigma_{\gamma^* i}(Q^2) \otimes pdf_i$$

non-perturbative part

3. Evolution :

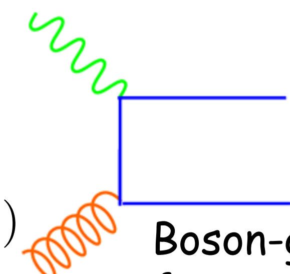
Parton densities become functions of Q^2

$xq_i(x) \rightarrow xq_i(x, Q^2)$ quarks

$x\bar{q}_i(x, Q^2)$ antiquarks

+ gluons

$g(x, Q^2)$



Boson-gluon fusion (BGF)

Quantum Chromodynamics (cont.)

Parton evolution according to Altarelli-Parisi (DGLAP) integro-differential equations:

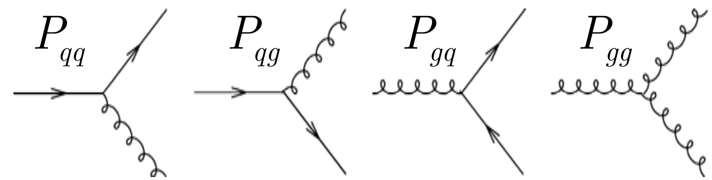
$$\frac{d}{d\ln Q^2}\begin{pmatrix} g \\ q_S \end{pmatrix} = \frac{\alpha_S(Q^2)}{2\pi}\begin{bmatrix} P_{gg} & P_{gq} \\ P_{qg} & P_{qq} \end{bmatrix} \otimes \begin{pmatrix} g \\ q_S \end{pmatrix}$$

$$\frac{d}{d\ln Q^2} q_{NS} = \frac{\alpha_S(Q^2)}{2\pi} P_{qq}^{NS} \otimes q_{NS}$$

$$q_S(x,Q^2) = \sum_i (q_i + \overline{q}_i)$$

$$q_{NS}(x,Q^2) = \sum_i (q_i - \overline{q}_i)$$

P_{ij} : splitting functions



$$\frac{1}{x} F_2(x,Q^2) = \sum_{i=1}^{n_f} e_i^2 C_i(x,Q^2) \otimes (q+\overline{q})(x,Q^2) + C_g(x,Q^2) \otimes g(x,Q^2)$$

$C_i(x,Q^2), C_g(x,Q^2), P_{ij}$ calculable in QCD ~ $O\left(\alpha_s\left(Q^2\right)\right) + \ldots$

Theoretical approach:

Test of the QCD evolution

QCD fits to F_2 using gluon and quark densities

→ input: parton densities at some (low) ${Q_0}^2$

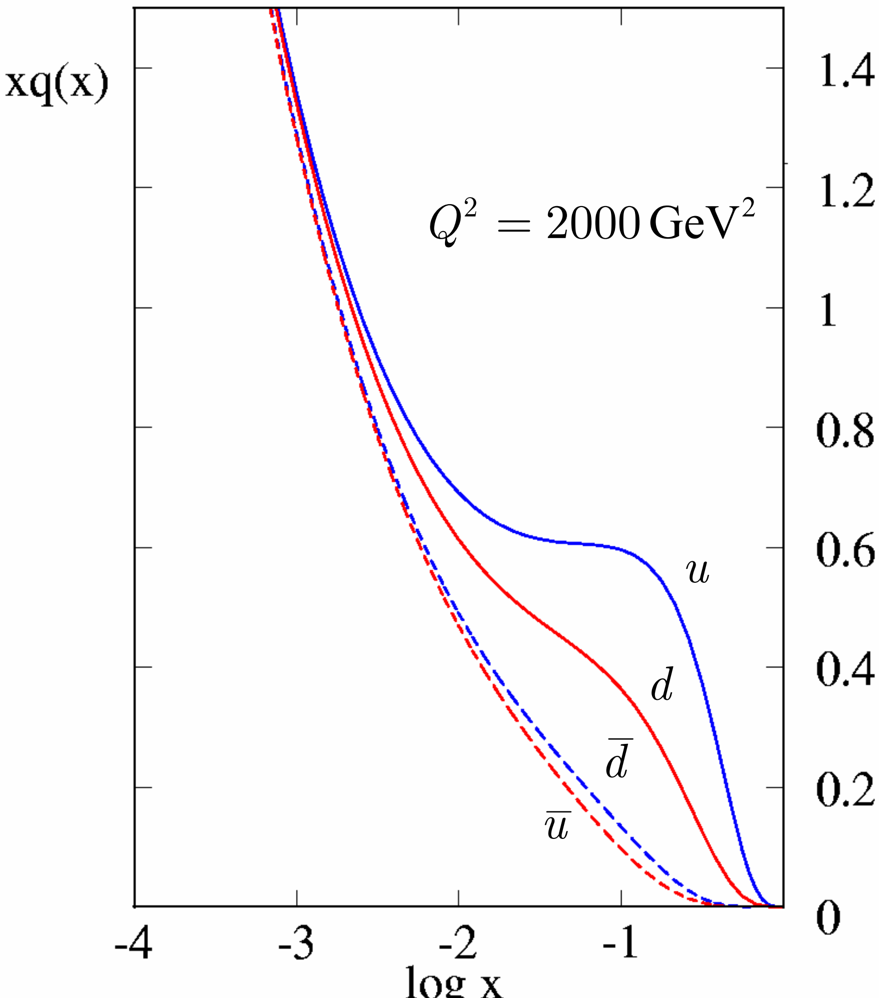
→ fit F_2 for $Q^2 > {Q_0}^2$

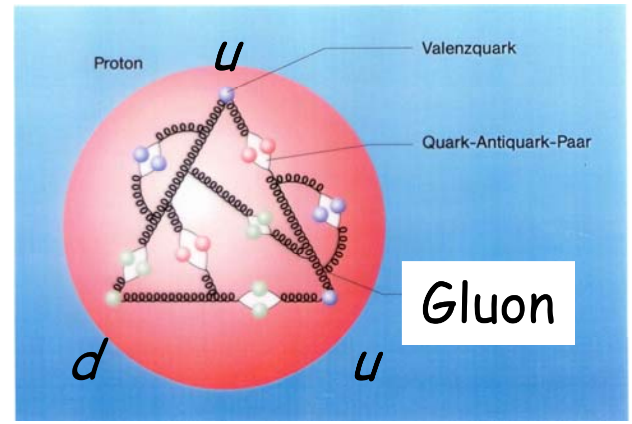
Quantitative Picture of the DGLAP Evolution

Ansatz for parton densities (non-pertubative):

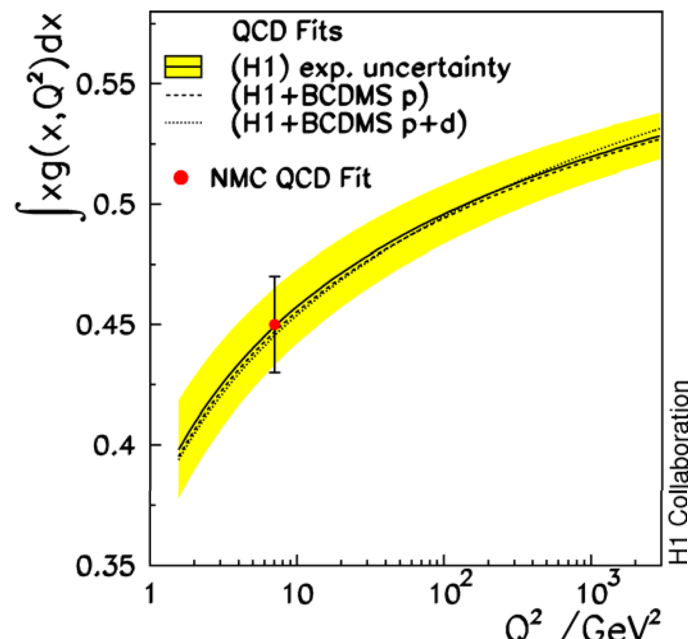
$$xq(x,Q_0) = Ax^B(1-x)^C\left[1 + D\sqrt{x} + Ex + ...\right]$$

QCD evolution (perturbative):

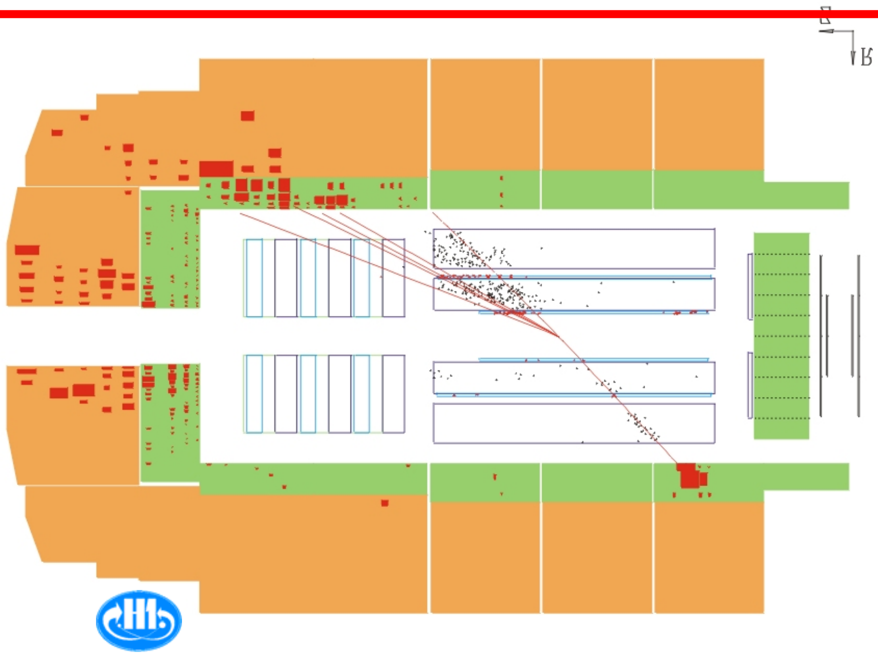


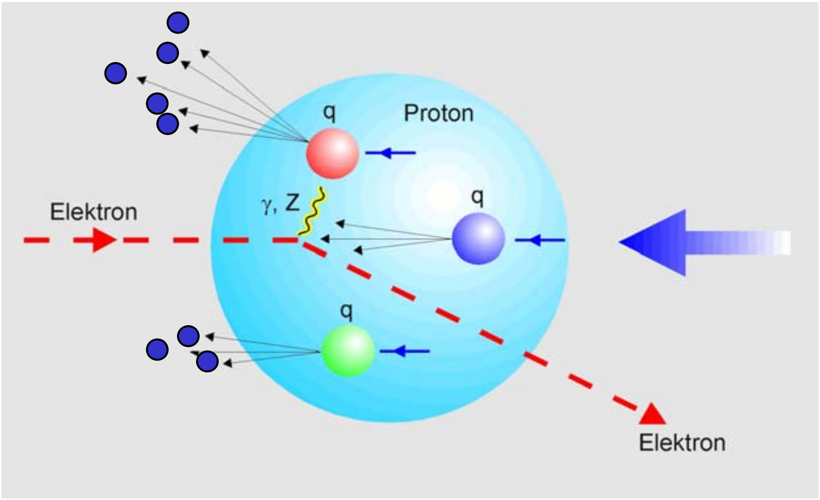


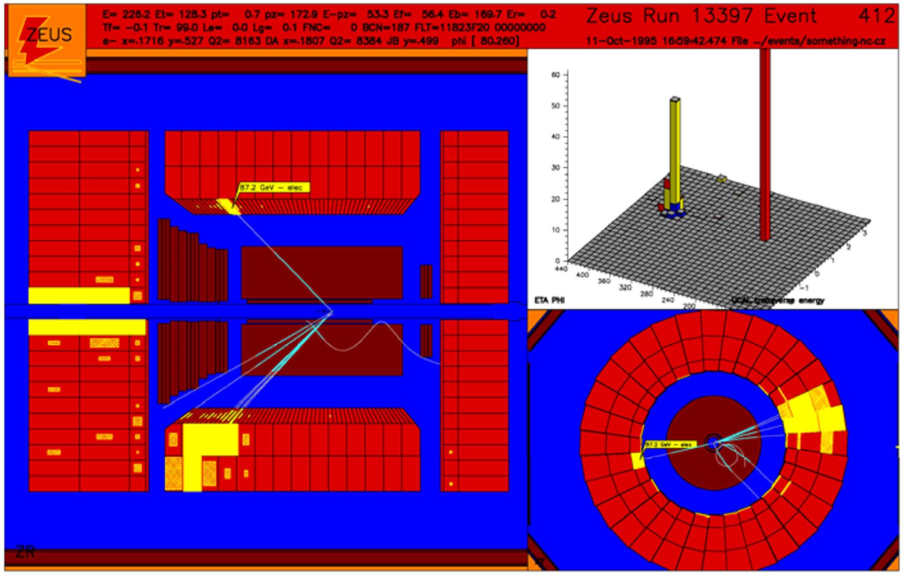
Quarks carry only about 1/2 of the nucleon momentum:



Electron Proton Scattering in Real Detectors ....







Netral current events in

H1 (medium Q^2)

ZEUS (large Q^2)

Precision Measurements of F_2

$$\frac{d^2\sigma(e^\pm p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2 - y^2 F_L\right]$$

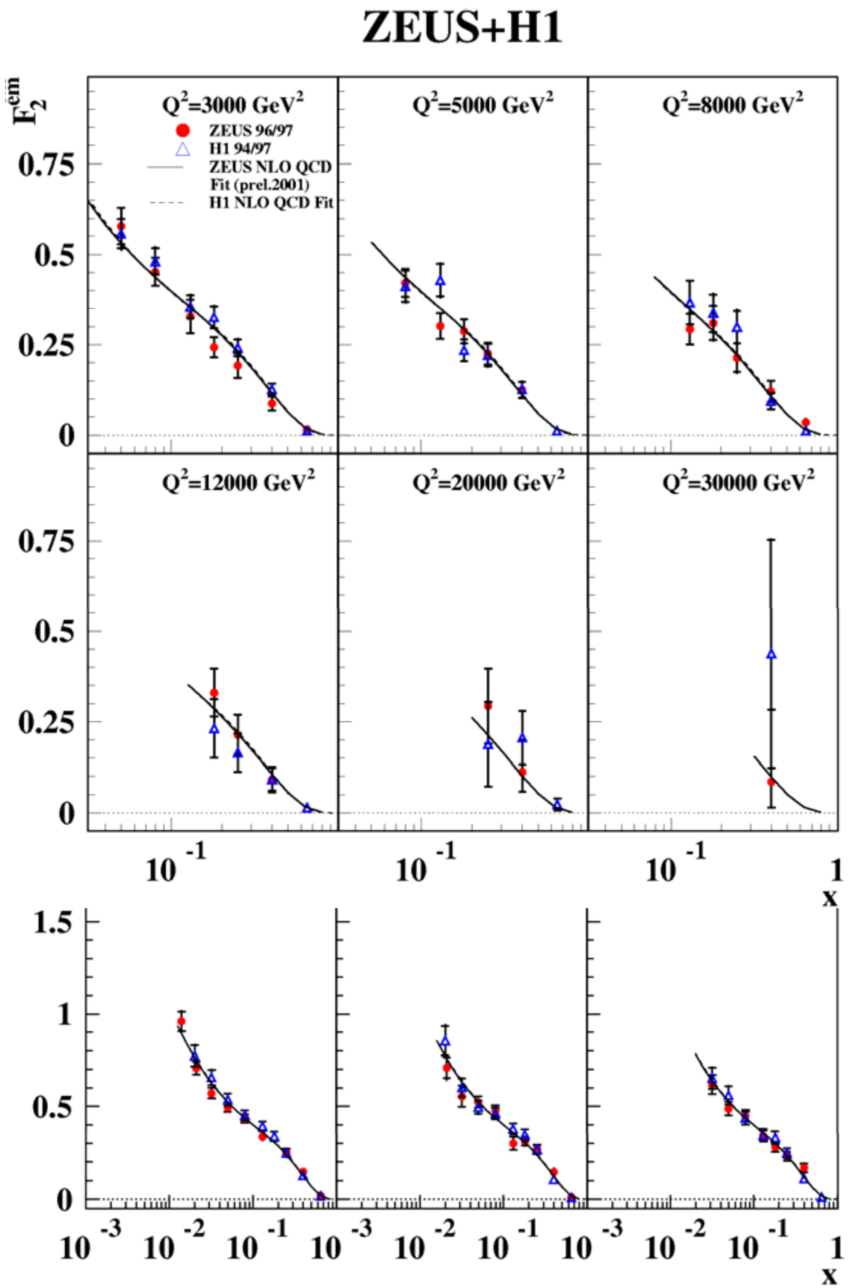
measured cross section in bins of x and Q^2

→ to measure F_2 need to get rid of F_L !

- cut: use only events with $y < y_{\text{cut}}$ (typically $y_{\text{cut}} = 0.6$)
- Correct for remaining contribution using QCD

Big surprise in the early HERA running:

→ F_2 rising much faster with falling x than expected in Regge picture



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Big surprise in the early HERA running:

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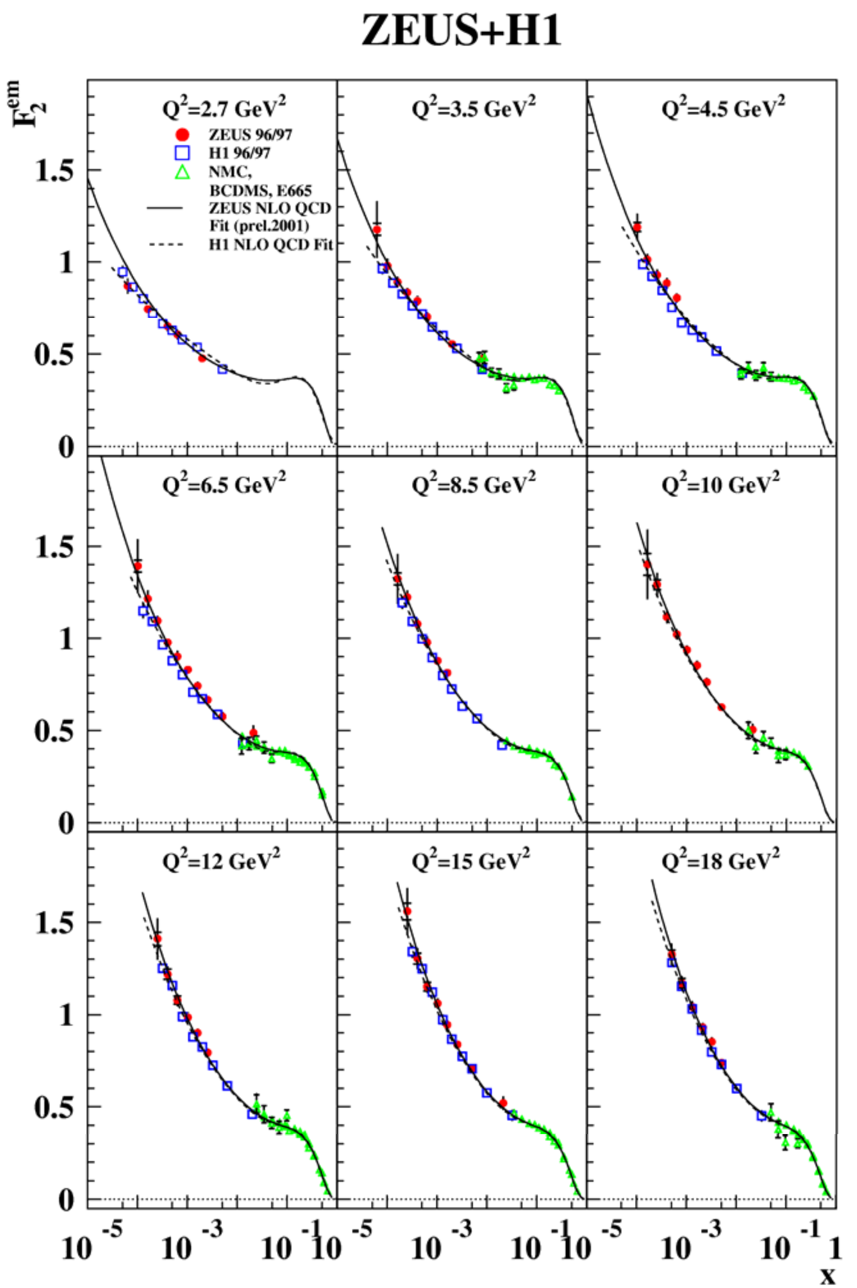
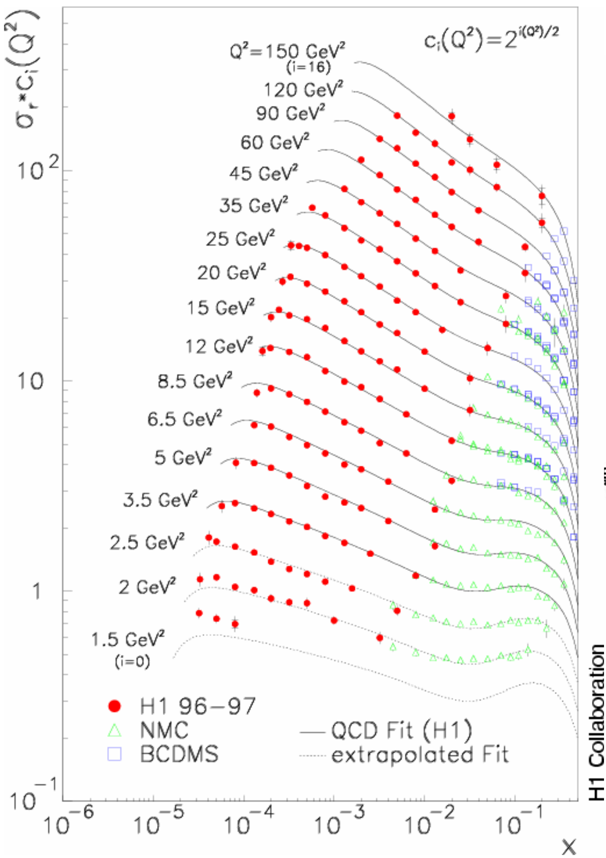
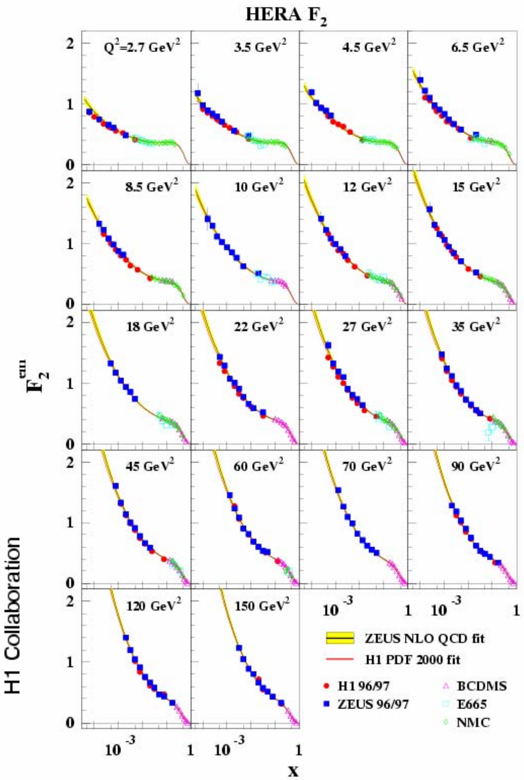
HERA data overlap and agree with fixed target data, similar in precision

Data well described by QCD evolution

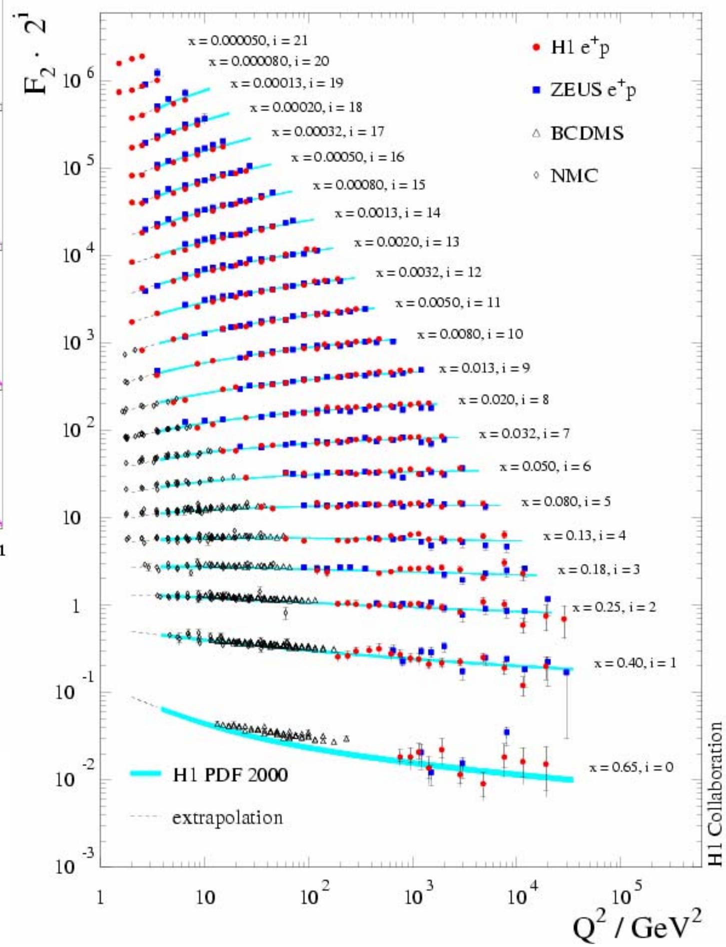


Precise SF data from HERA





precision data ±2-3%
5 decades in x
5 decades in Q^2

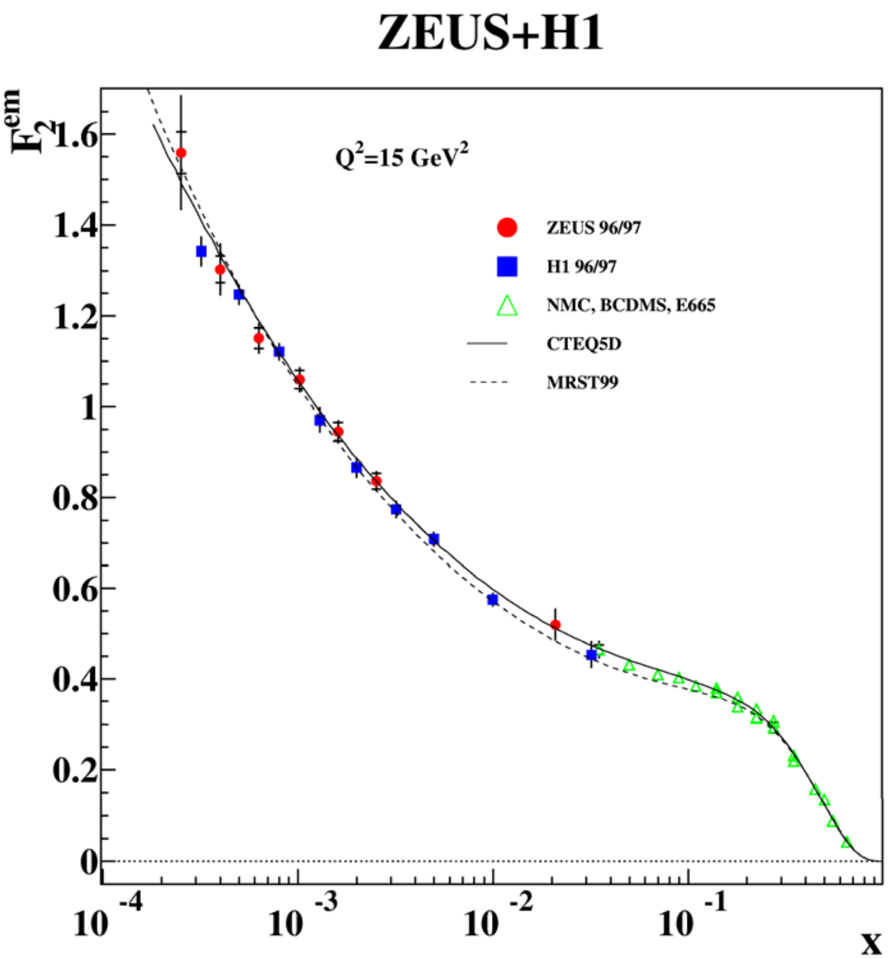


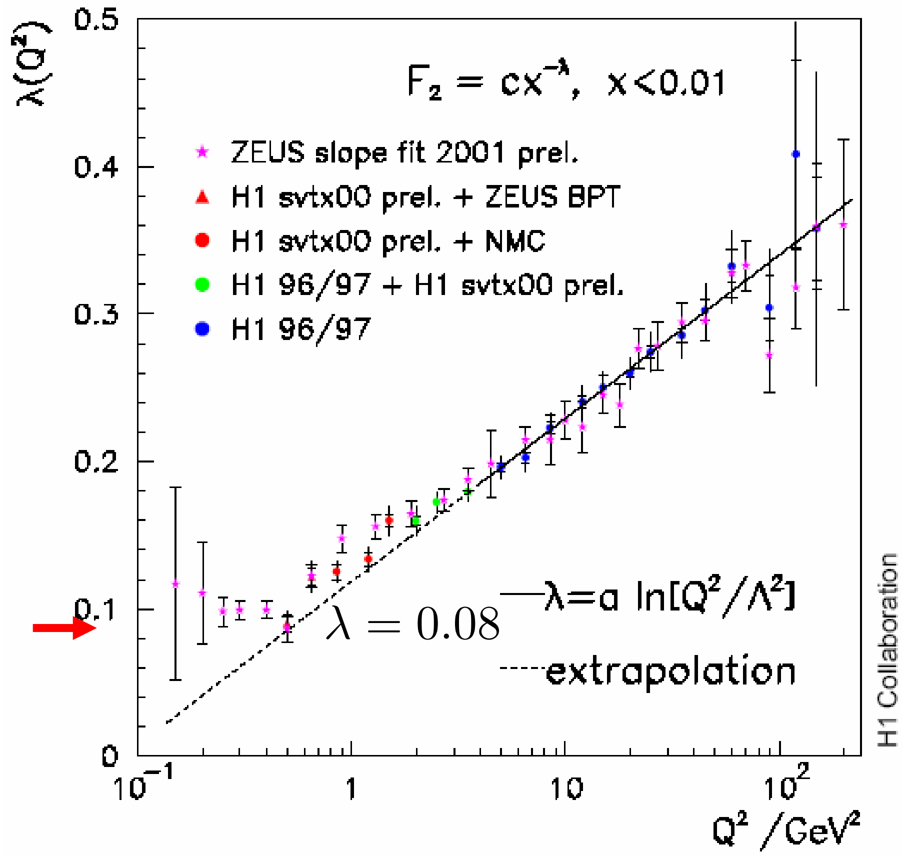
rich possibilities to determine pdfs,
test QCD (DGLAP, BFKL, …),
transition from DIS to γp, …

Strong Rise of F_2 Towards low x

QCD fits: rise is driven by the gluons

Parameterize low x part of $F_2 \sim x^{-\lambda}$

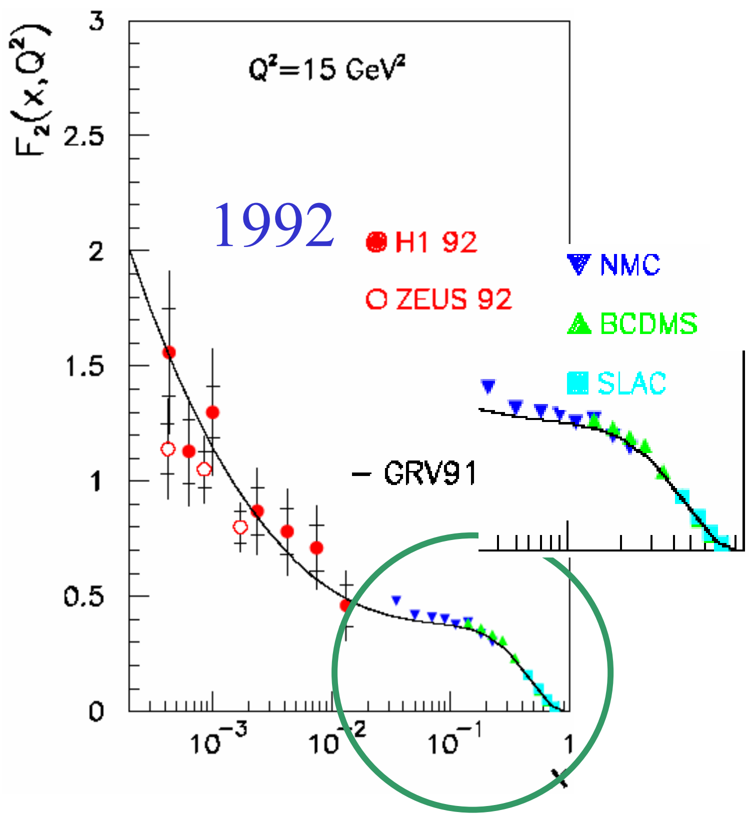


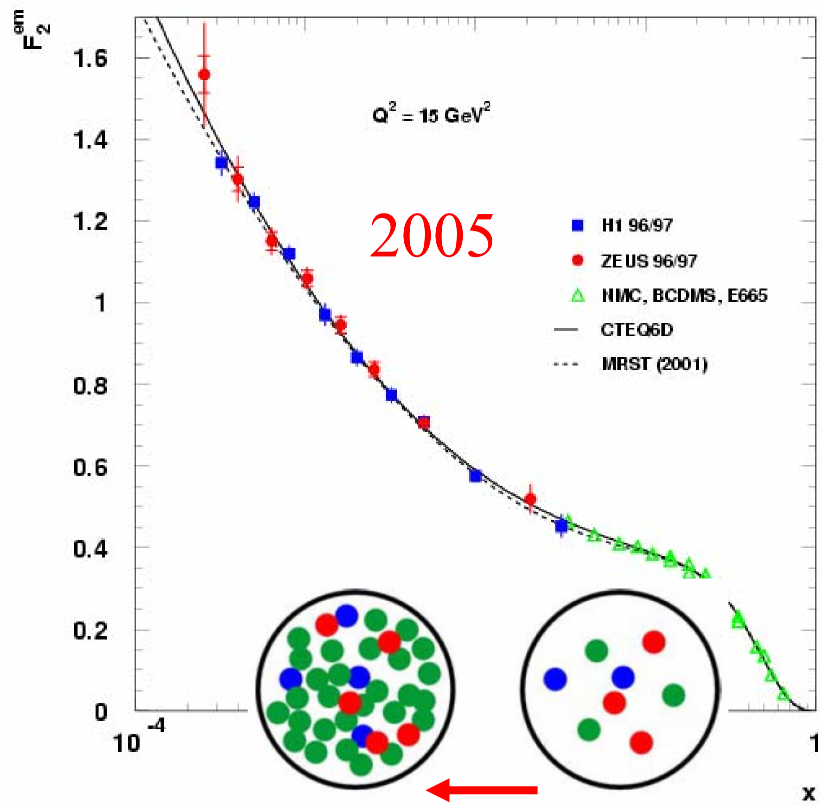


At low Q^2 the slope λ is approaching the „soft" Regge limit

2004 Nobel Prize in Physics for the Discovery of Asymptotic Freedom
David Gross, David Politzer, Frank Wilczek

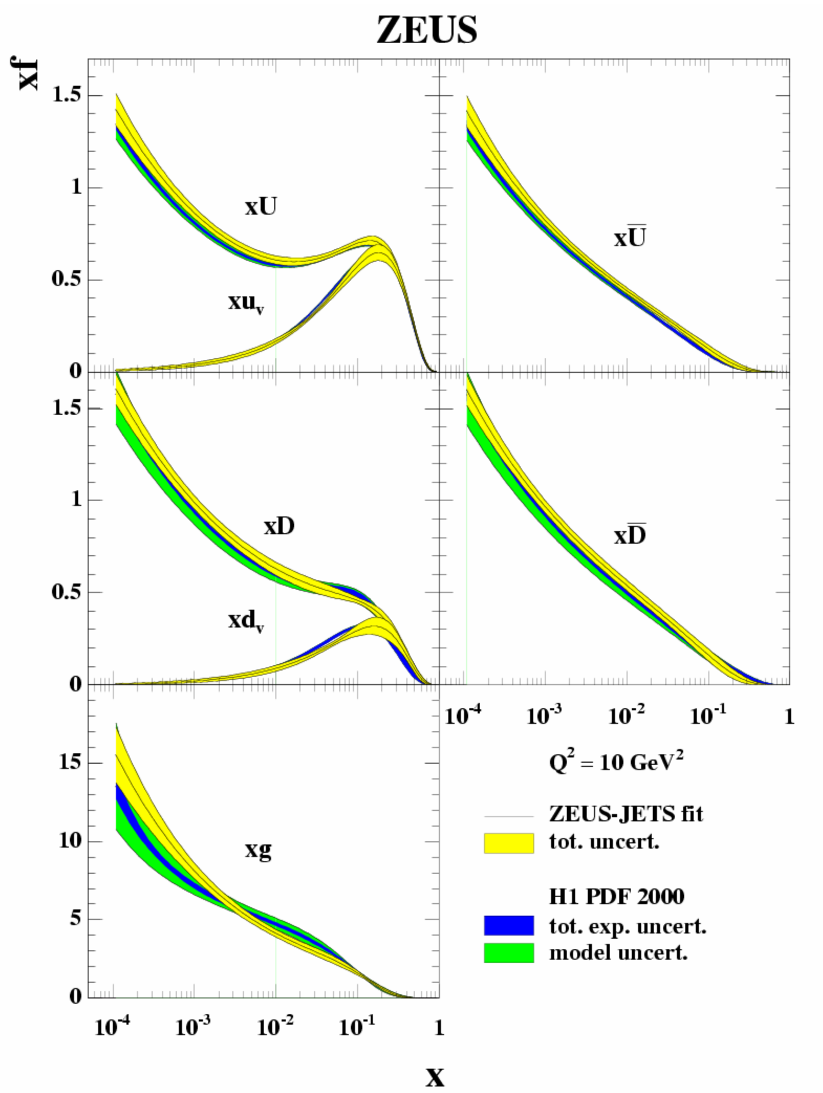
Frank Wilczek: … The most dramatic of these (experimental consequences), that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later. …





PDFs from HERA

Parton distributions (NLO): unfolded using the HERA $e^{\pm}$ p data only



H1: NC+CC $U, \bar{U}, D, \bar{D}, xg \leftrightarrow V, A, xg, \alpha_s$

ZEUS: NC+CC & jets $u_v, d_v, \bar{u} \pm \bar{d}, xg, \alpha_s$

treatment of systematics, parameterisation forms and other details are subject to conventions

→ PDFs from the H1, ZEUS and global fits are in agreement

Gluon:

- dominant at low x
- Note: the scale for xg distr. is 10 times larger

→ scaling violations

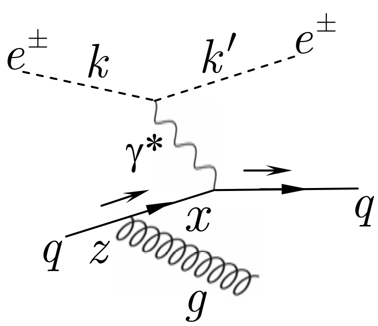
- xg is not an observable
- at Q^2 of a few GeV^2 gluons become valence-like

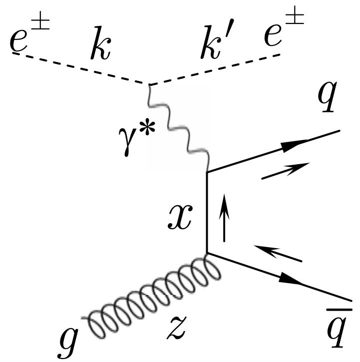
→ jets, heavy flavours, $F_L(x,Q^2)$

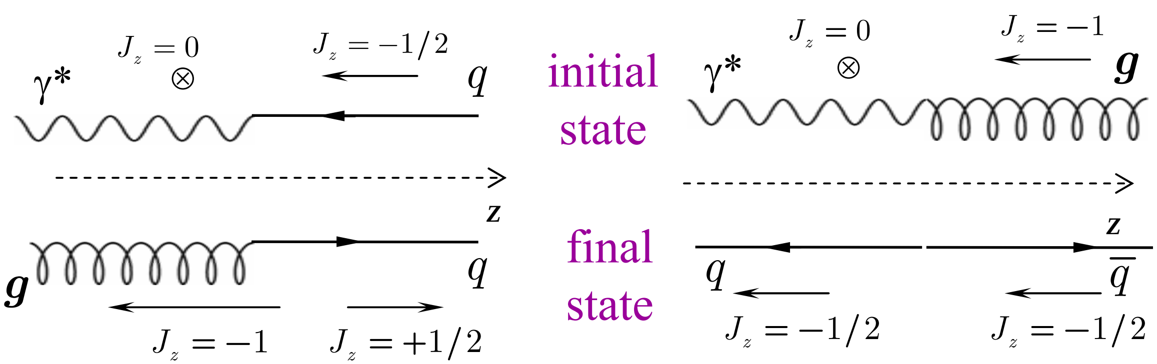
- directly sensitive to xg
- jets constrain xg at x ~ 0.1
- F_L can pin down xg at low x

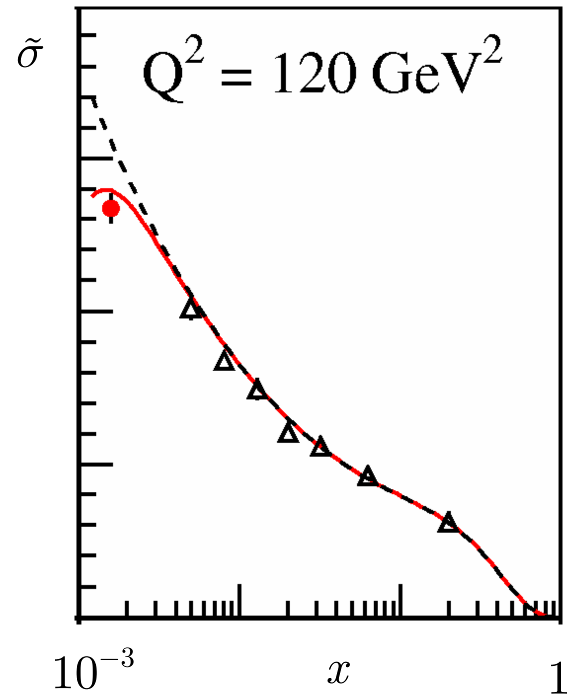
The Longitudinal Structure Function F_L

LO QCD :









$$F_L = \frac{Y_+}{y^2}\left(F_2^{\mathrm{QCD}} - \tilde{\sigma}\right)$$

extrapolated in Q^2 using DGLAP

$$\frac{d^2\sigma(e^\pm p)}{dx\, dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2 - y^2 F_L\right]$$

in principle need 2 measurements at different $\sqrt{s}$

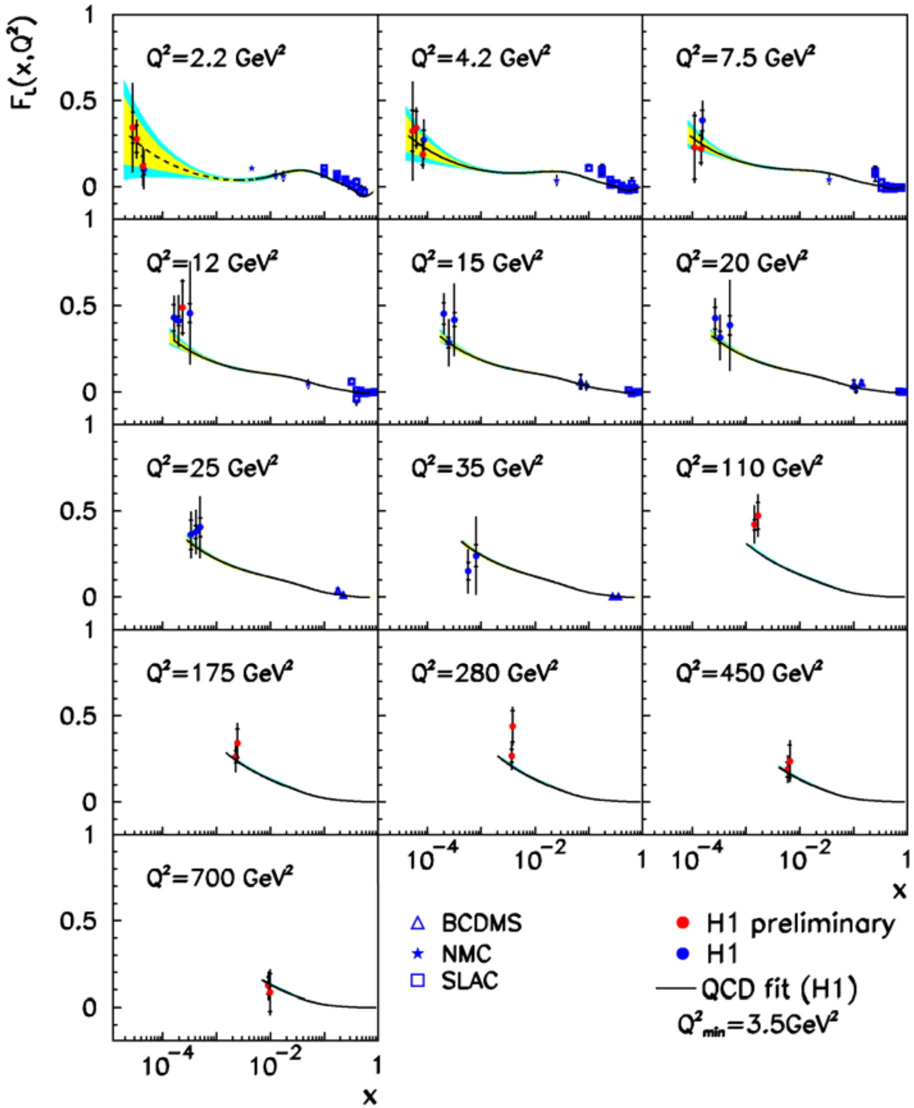
F_L important at high $y\,(=\mathrm{low}\ x)$

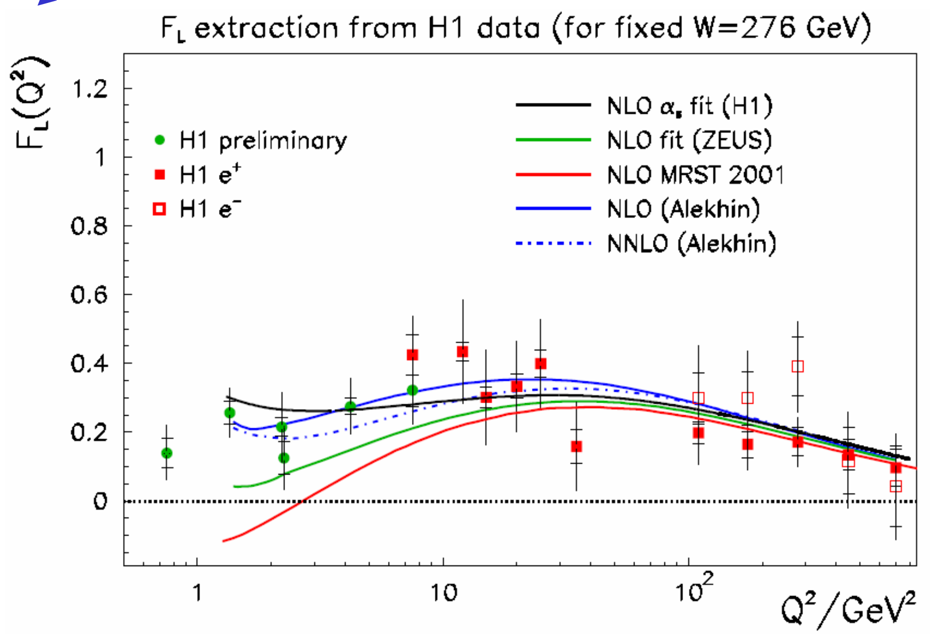
„Subtraction method"

Longitudinal Structure Function (cont.)

„derivative method“ $\left(\frac{\partial \tilde{\sigma}}{\partial \ln y}\right)_{Q^2}$

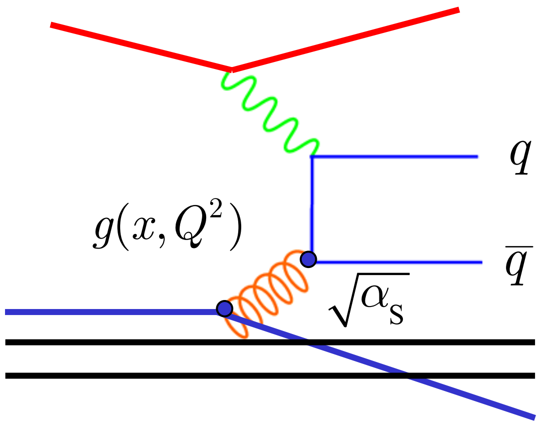
„subtraction method“





- extension of F_L to much lower x
- consistent with QCD

QCD: Strong Coupling Constant

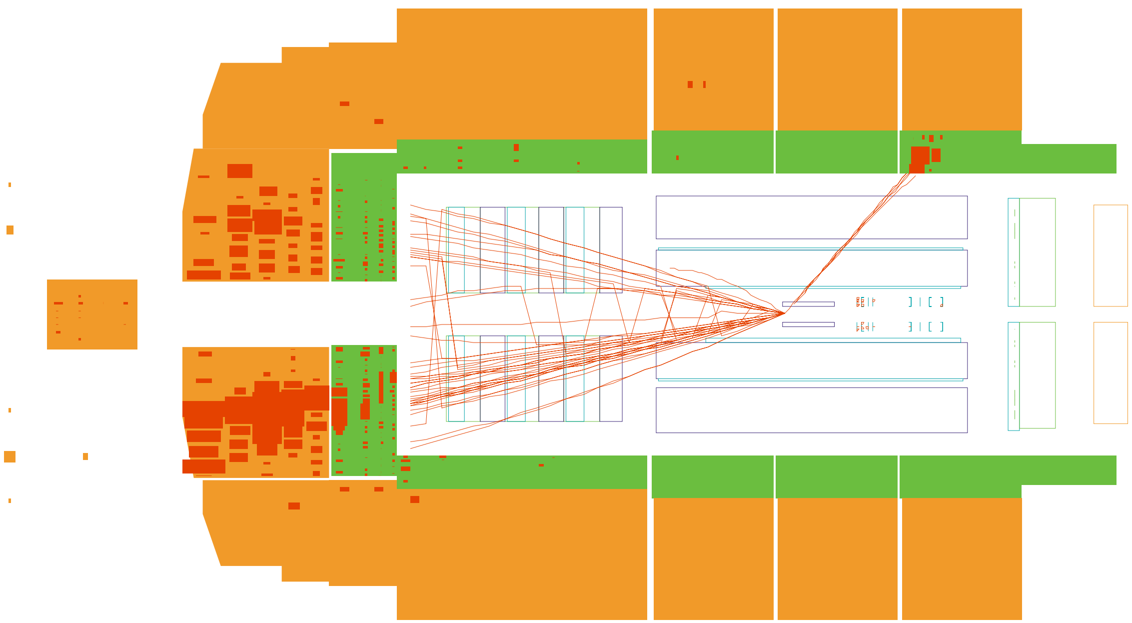


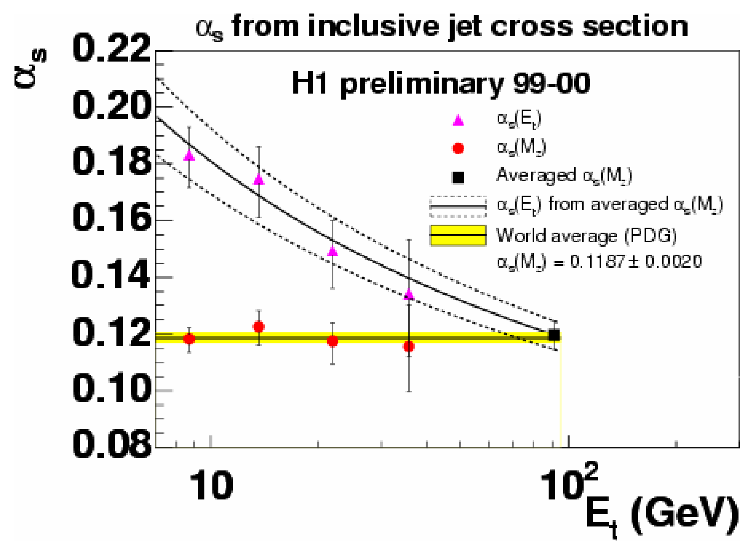
Spectacular multi-jet events (here: di-jet event)

→ hadronic final state

(multi) jet events:

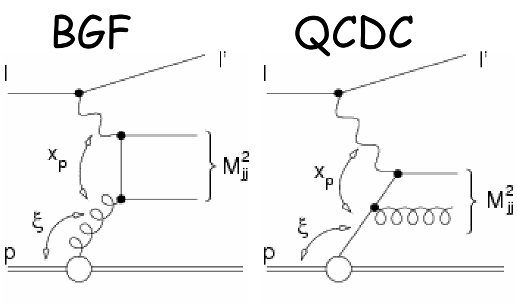
→ α_S





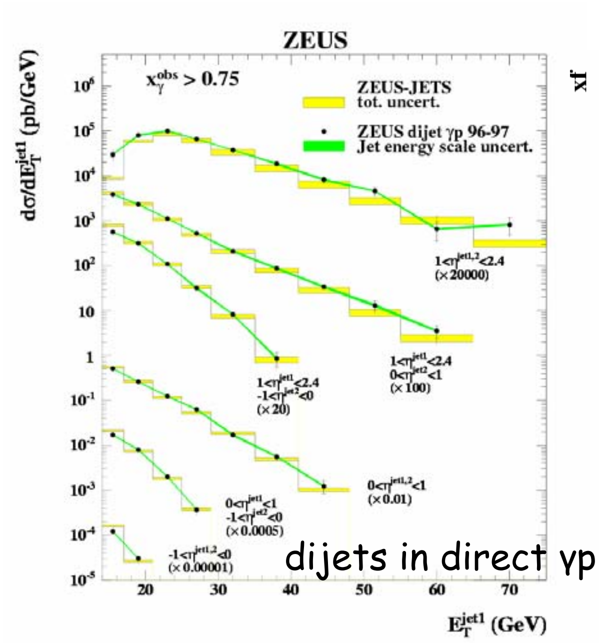
ZEUS NLO QCD fit (inclusive & jets)

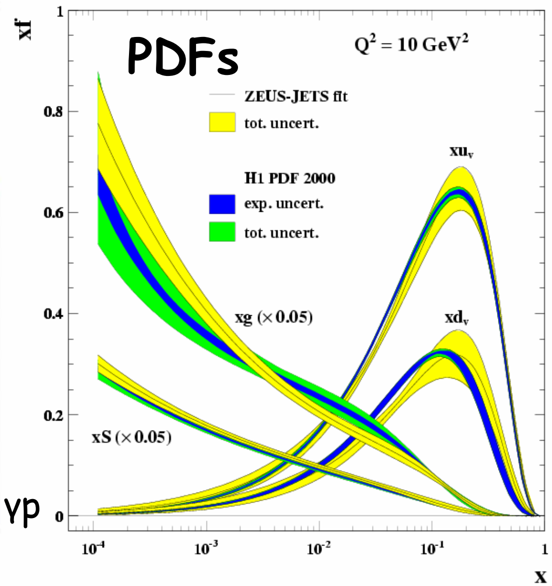
Include jets in direct γp and DIS into a QCD fit



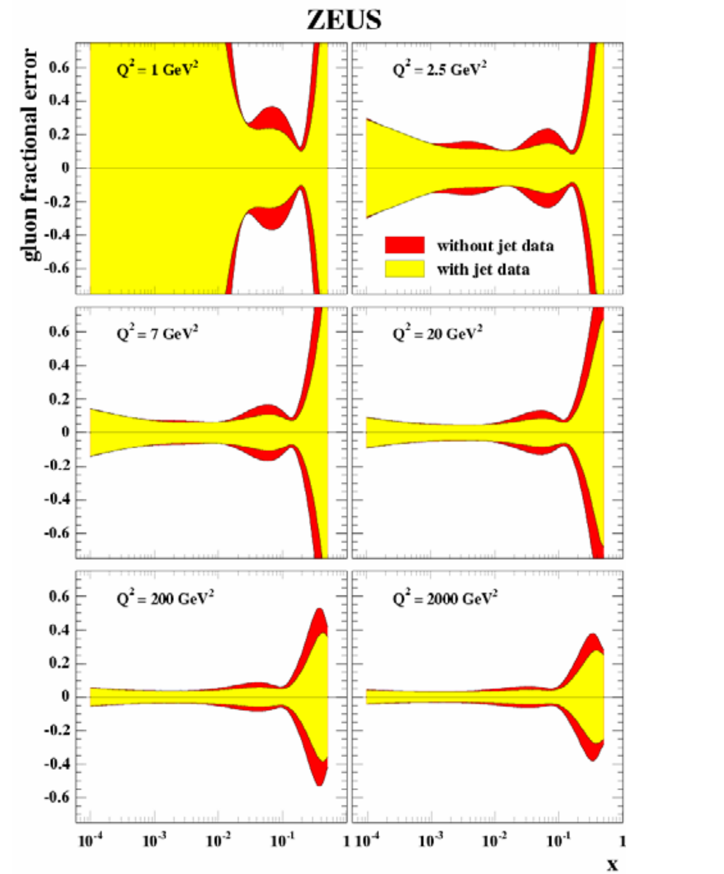
Boson Gluon Fusion :
depends on xg(x)
→ constrains gluon at medium & high x (0.01-0.4)

QCD-Compton :
depends on q(x) and α_s





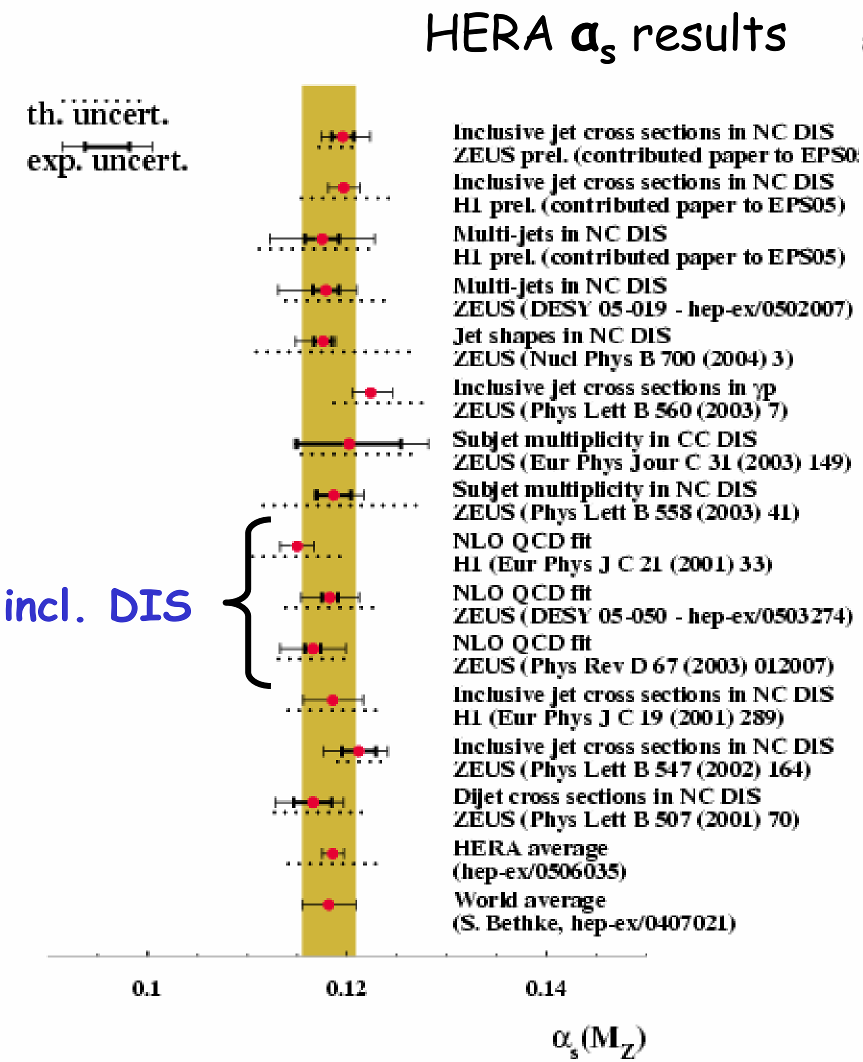
Gluon uncertainty (with/wo jets)

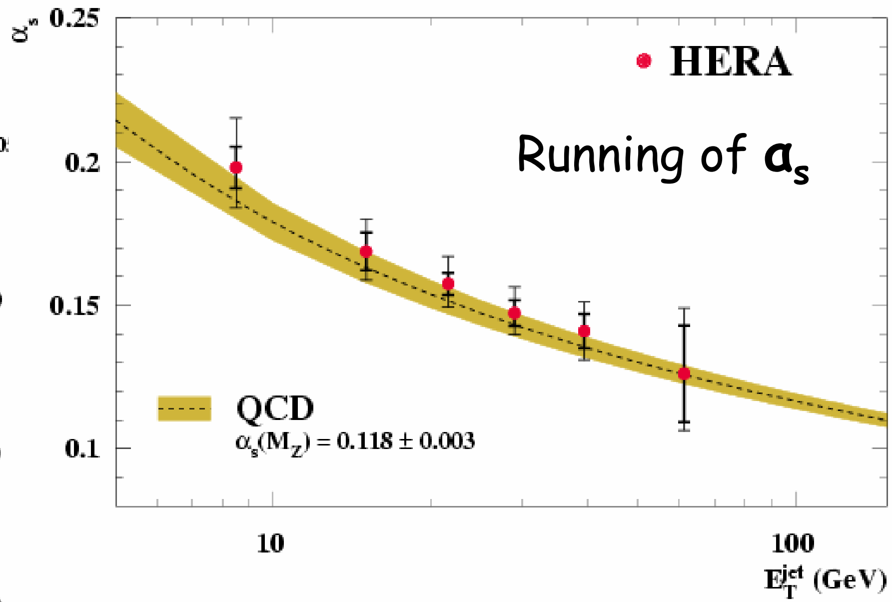


Strong coupling:

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0028(\text{exp}) \pm 0.0008(\text{model}) \pm 0.0050(\text{scales})$$

Summary for Strong Coupling at HERA





HERA-average:

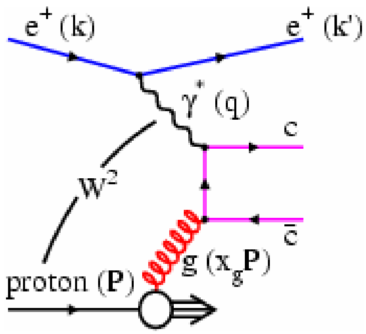
$$\alpha_s(M_Z^2) = 0.1186 \pm 0.0011(\text{exp.}) \pm 0.0050(\text{th.})$$

- small experimental error ~1%
- theory error dominates (NLO)
- call for NNLO

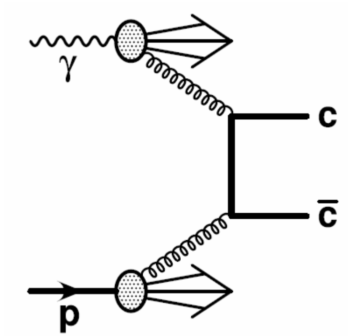
Charm Production

-> dominated by Boson Gluon Fusion (BGF)
-> resolved photon plays important role in γp

$$p\,/\,g \text{ pdf's } \otimes \text{ pQCD } \otimes \text{ fragmentation}$$



direct

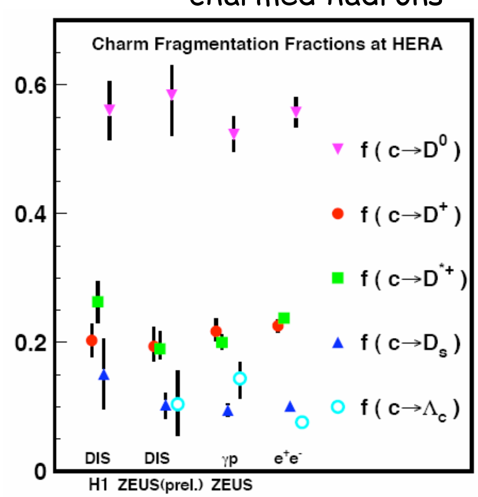


resolved

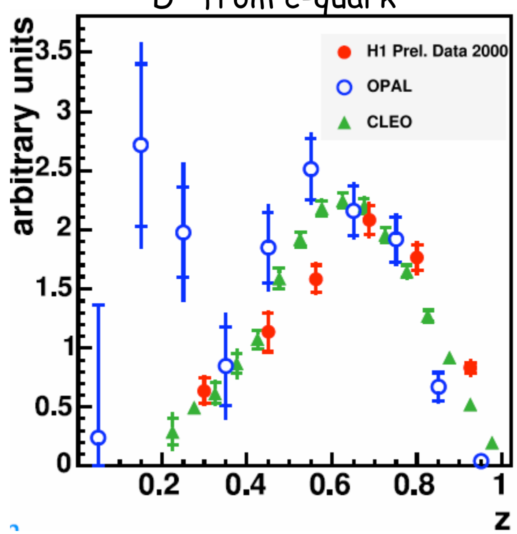
Perturbative QCD:
- hard scale m_c^2.
- multi-scale problem m_c^2, Q^2, p_t^2

PDFs:
- directly sensitive to xg
- photon structure

Fractional rates of charmed hadrons



Fractional momentum of D* from c-quark



Fragmentation:

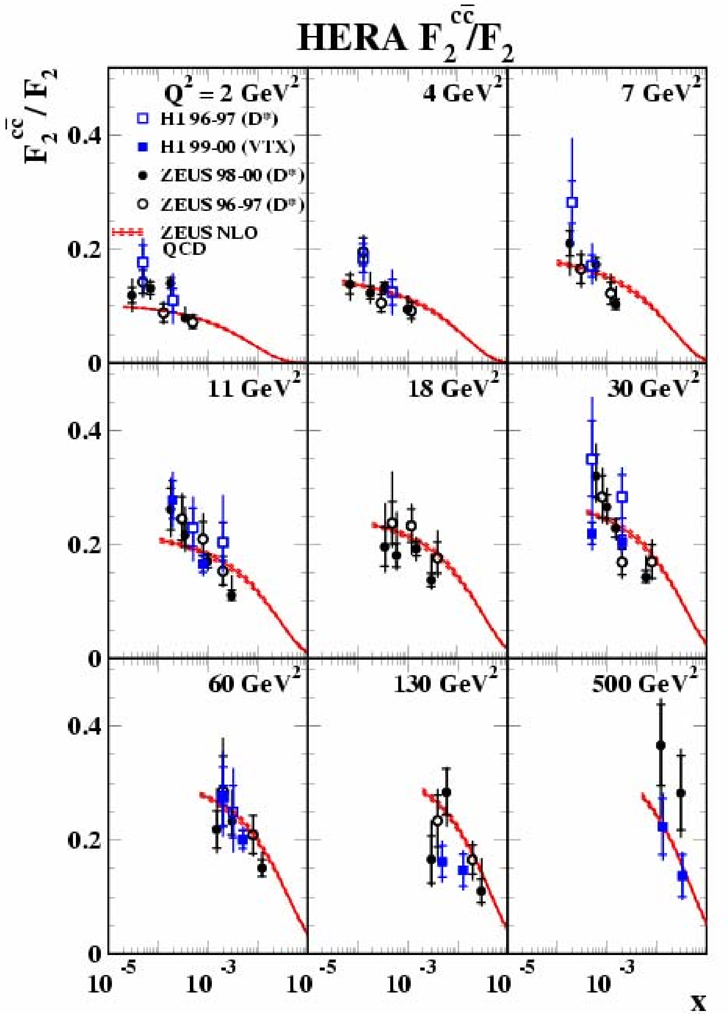
H1 hemisphere method
$\langle\sqrt{\hat{s}}\rangle \approx 10$ GeV,
$z = \frac{(E+p_L)_{D^*}}{\sum_{hem}(E+p)}$

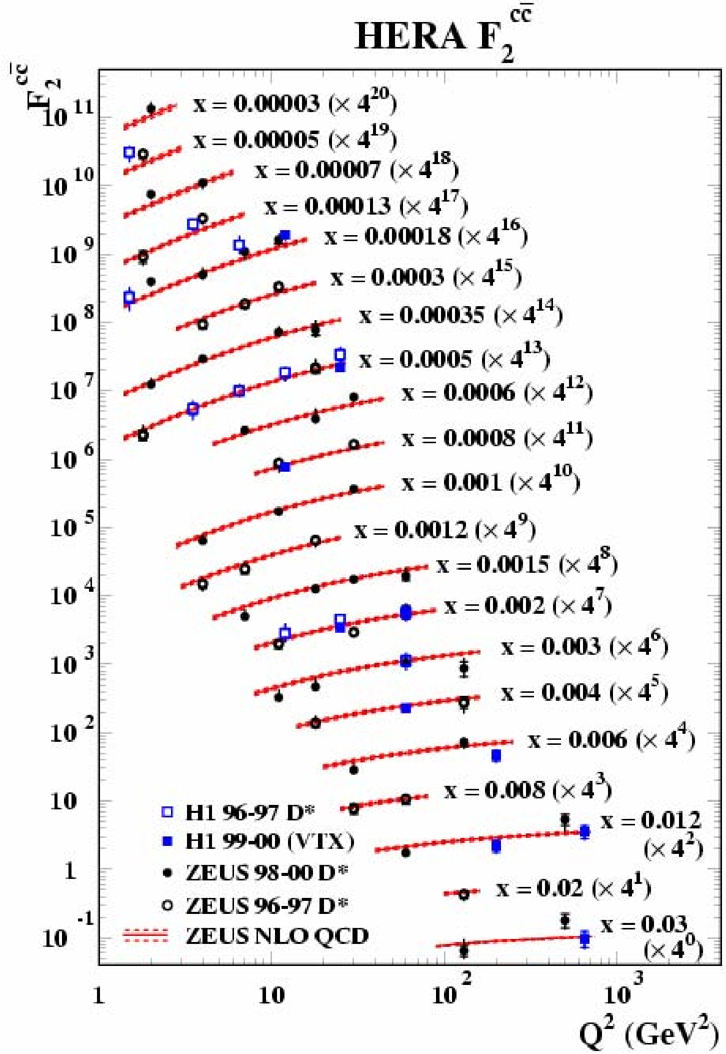
CLEO $\sqrt{s} \approx 10$ GeV,
$z = p_{D^*}/p_{max}$

OPAL $\sqrt{s} = 91.2$ GeV,
$z = 2E_{D^*}/\sqrt{s}$

HERA ep results are consistent with e^+e^- measurements, supporting universality of fragmentation

Charm Structure Function $F_2^{cc}(x,Q2)$

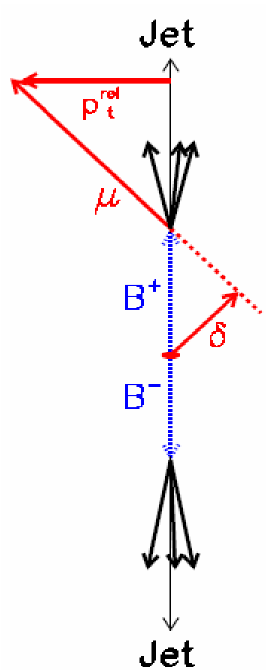




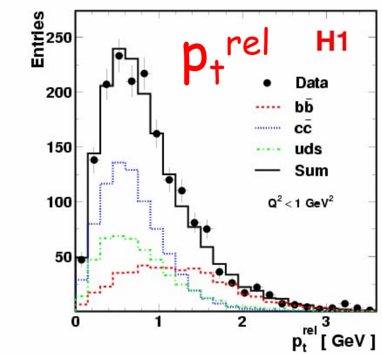
- charm contribution up to 25-30%
- consistent with gluon from scaling violations

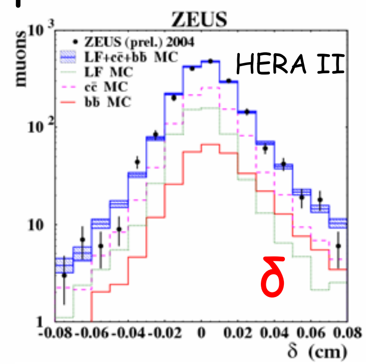
- scaling violations of F_2^{cc} are increasing with decreasing of x (similar to F_2)

Beauty identification techniques



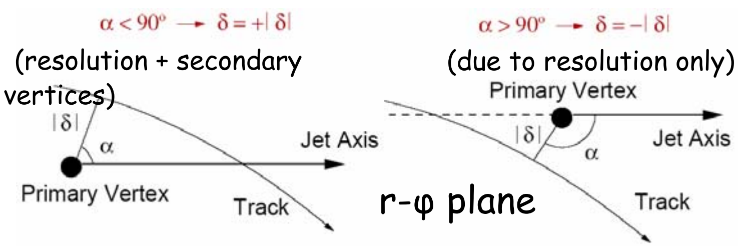
μ - transverse momentum and impact parameter

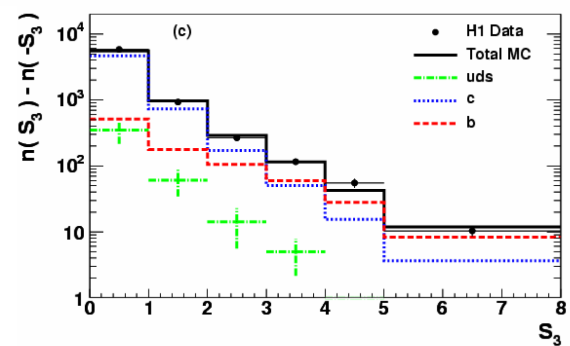




- heavy mass
- long lifetime
- decay channels (μ,D)
- production (correlations)

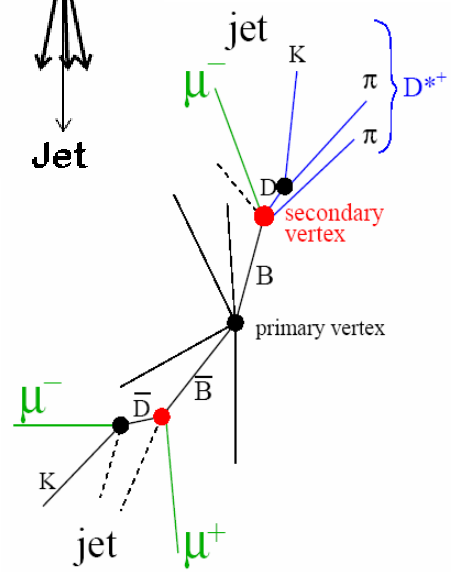
Inclusive lifetime tag

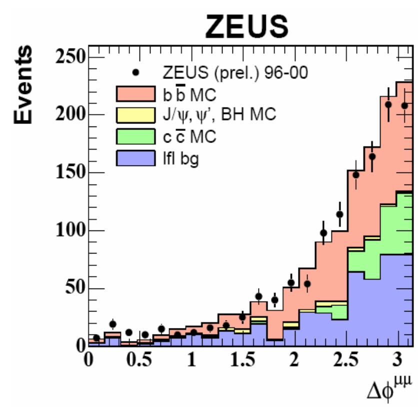




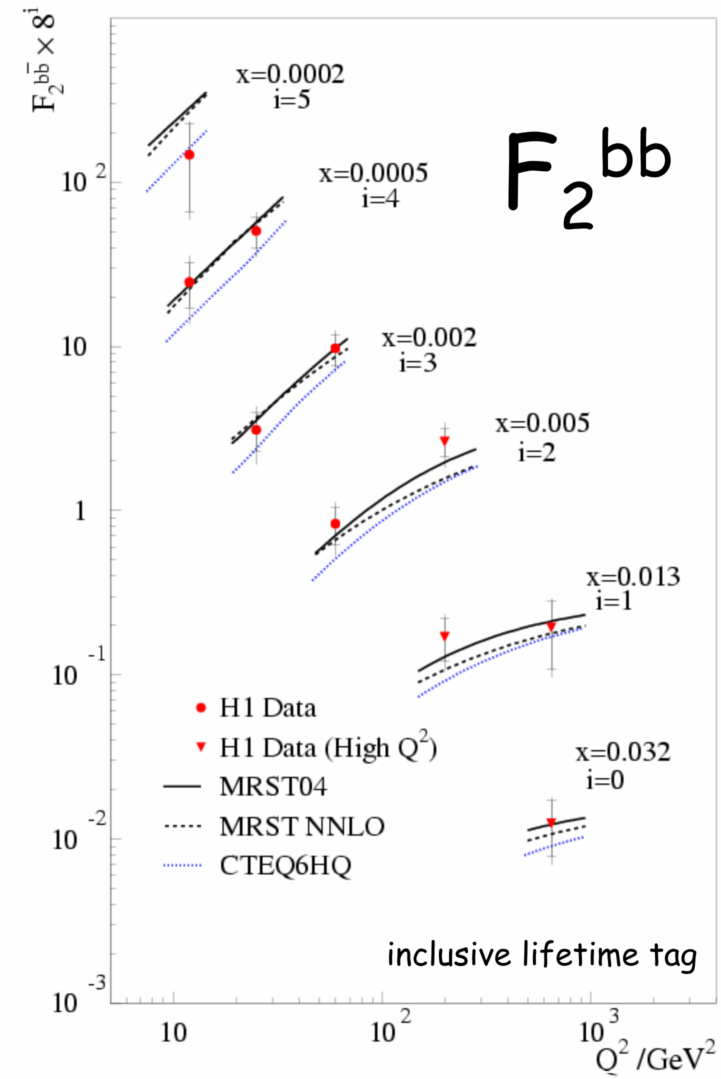
- all tracks with p_t> 500 MeV
- subtract the contents of negative bins
- both c and b are defined from the fit
- small extrapolation to the full phase space

Two-quark correlations D*μ, μμ (Q, m, φ)

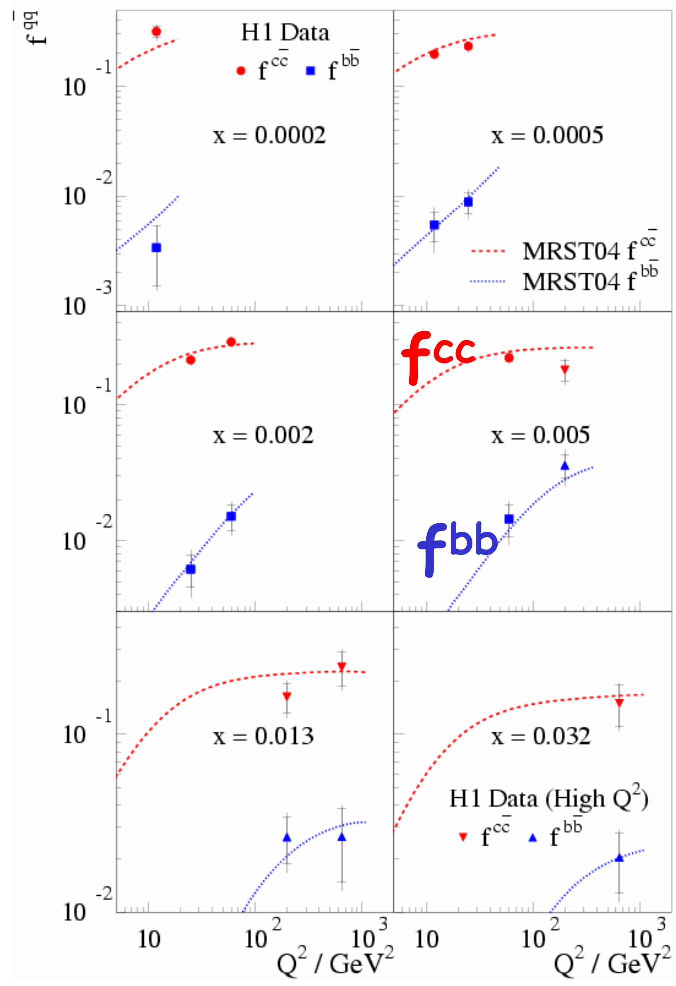




Beauty Structure Function F_2^{bb} (x,Q2)



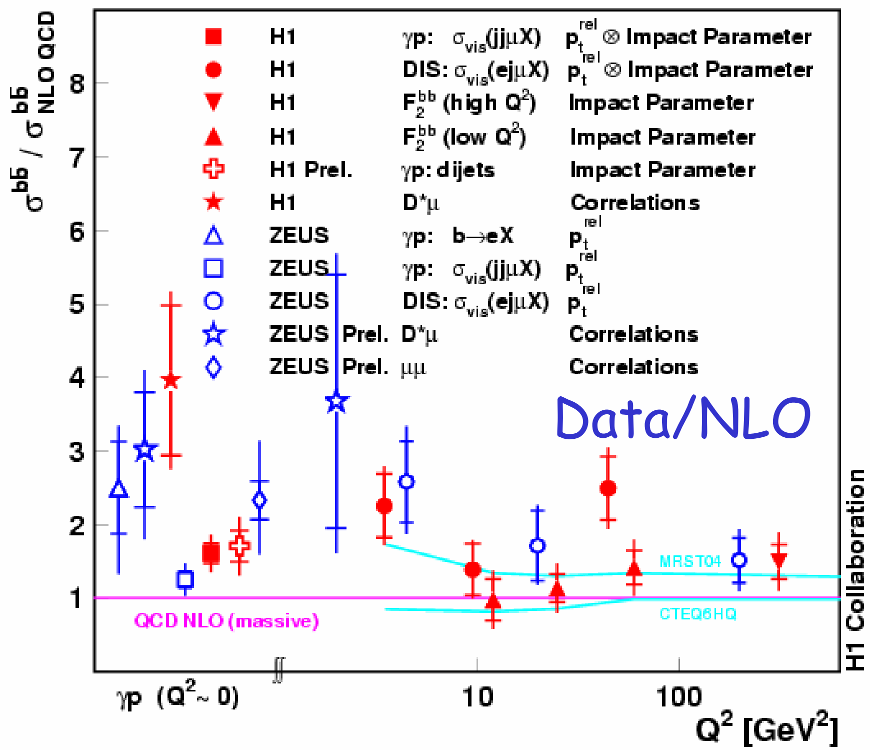
Cross section fractions

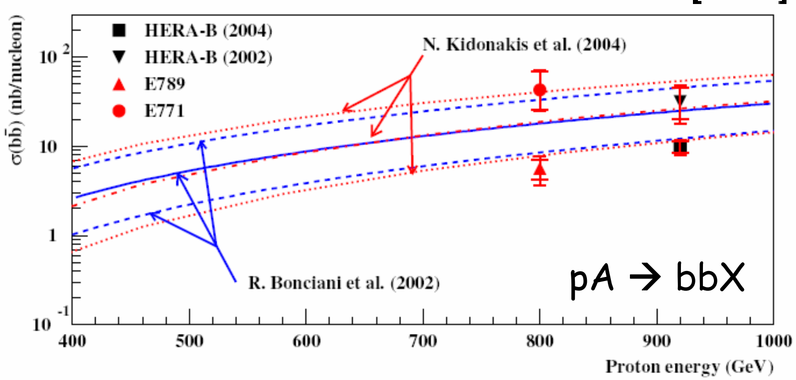


- measured for the first time
- compared with NLO and NNLO

- charm roughly constant ~ 24%
- beauty changes from ~ 0.3% to ~ 3%

Summary for beauty at HERA





HERA collider experiments

- NLO is consistent both with DIS and γp data

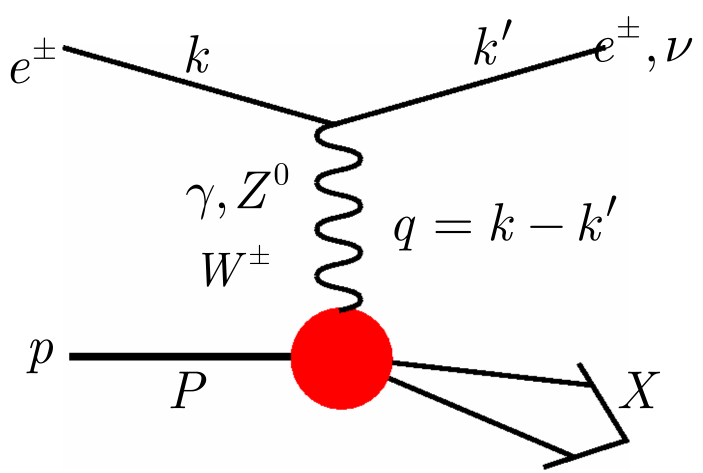
(although systematically higher)

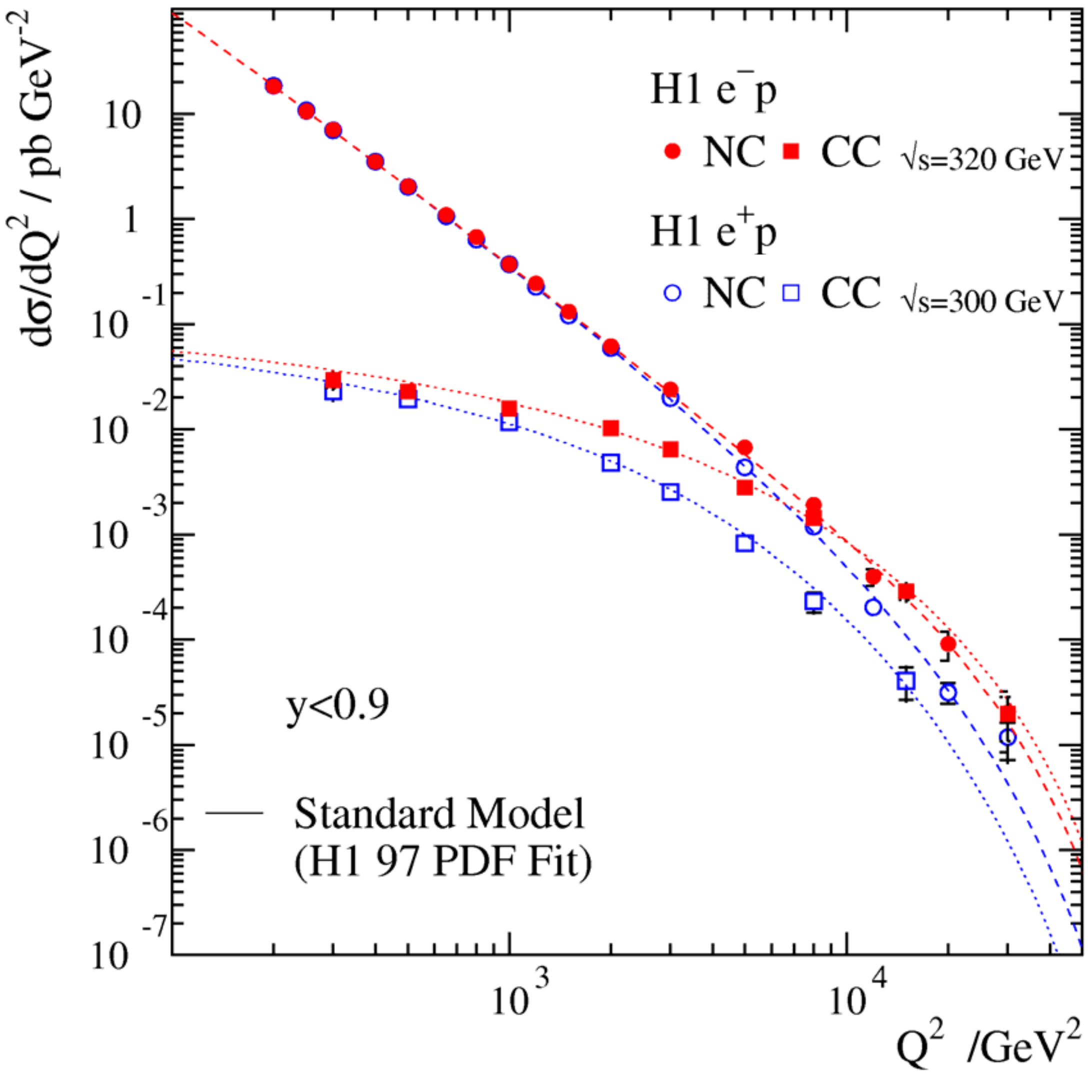
HERA-B

- close to kinematic threshold
- old and new results are compatible within 1.5 σ

Electroweak Sector: Scattering at high Q^2

High $Q^2 \approx M_Z^2, M_W^2$

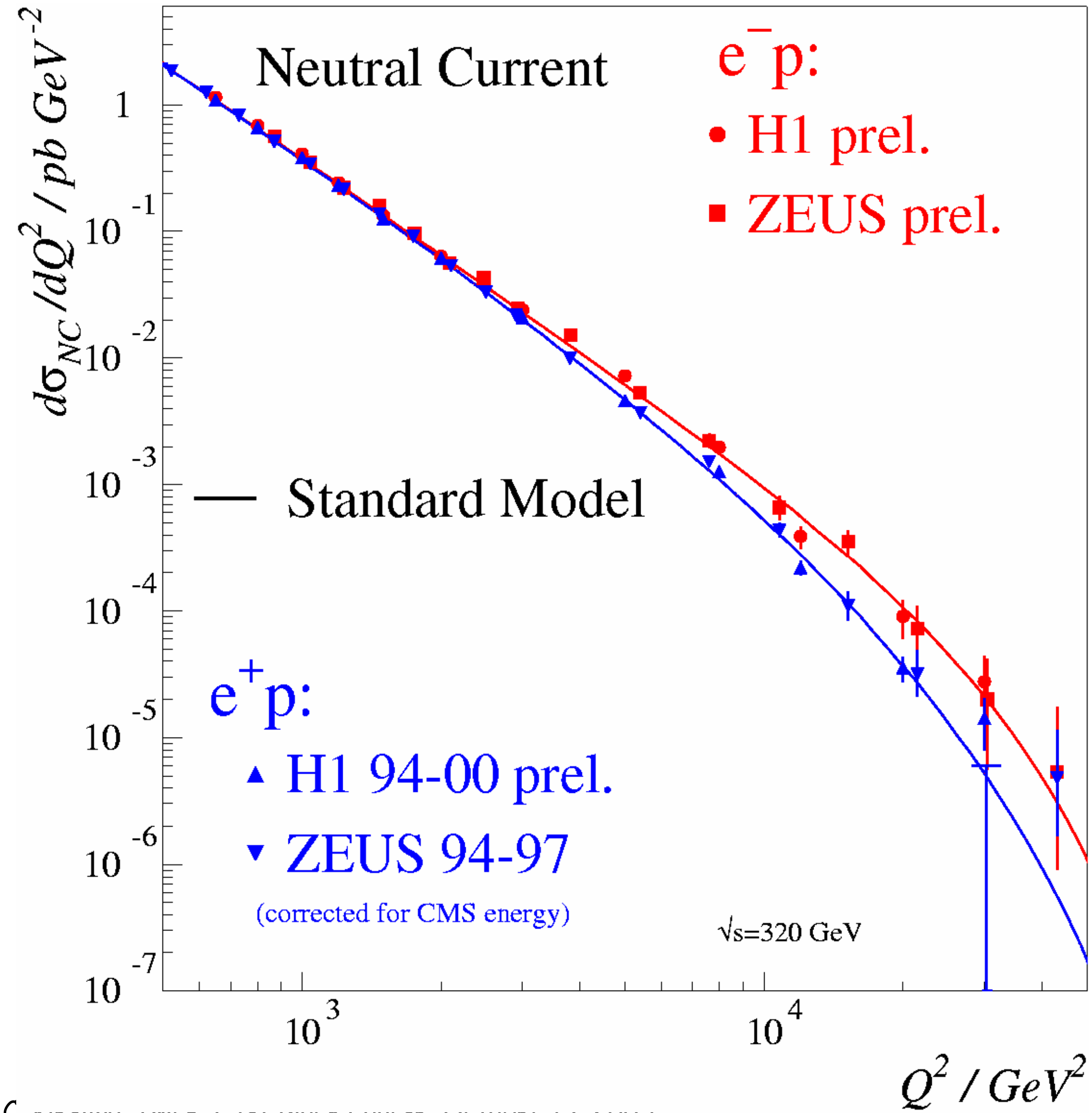




e^+ and e^- cross sections are different !

Unification of weak and electromagnetic forces

NC Cross Section at high Q^2 and xF_3



$$\tilde{\sigma}_{NC}(e^{\pm}p) \sim \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

$$Y_{\pm} = 1 \pm (1-y)^2$$

New structure function xF_3

$$xF_3(x,Q^2) =$$

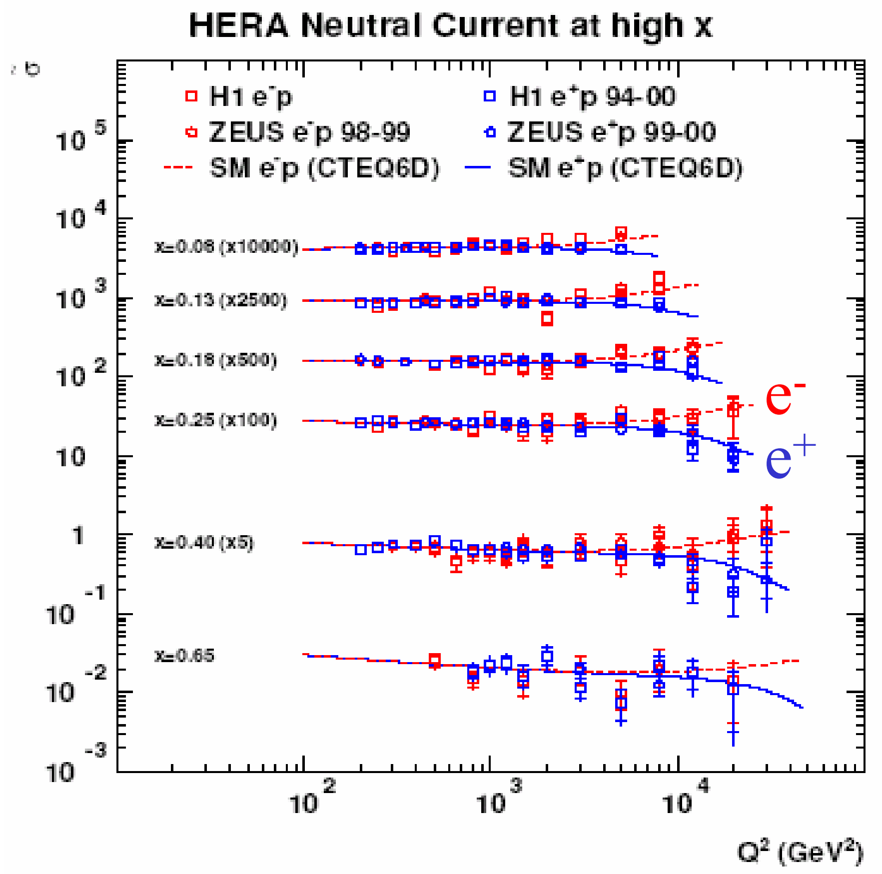
$$\sum_i e_i^2 \left(xq(x,Q^2) - x\overline{q}(x,Q^2) \right)$$

F_L can be safely neglected at high Q^2

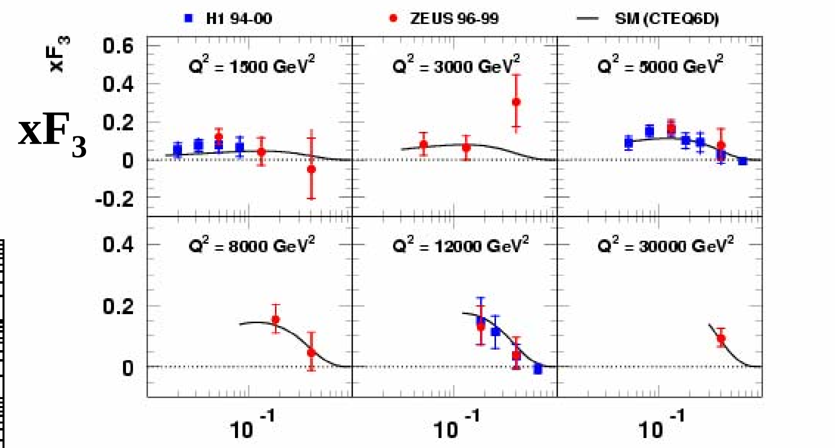
Difference between $e^{\pm}p$ is due to γZ interference

NC Cross Section at high x and xF_3

$$\tilde{\sigma}^{\pm}_{NC} = F_2 \mp \frac{Y_-}{Y_+} xF_3$$

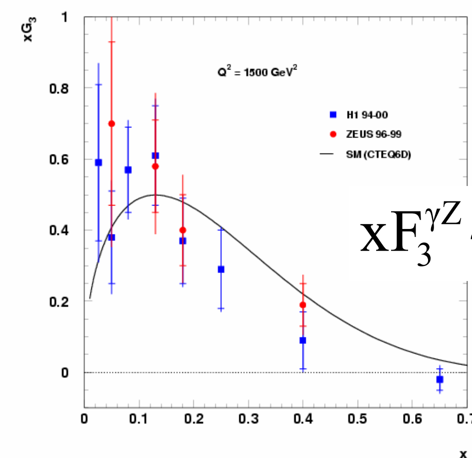


sensitive to EW param. & polarisation



mostly due to γZ interference :

$$xF_3^{\gamma Z} = xF_3 / [-a_e k_w / (Q^2 + M_Z^2)]$$

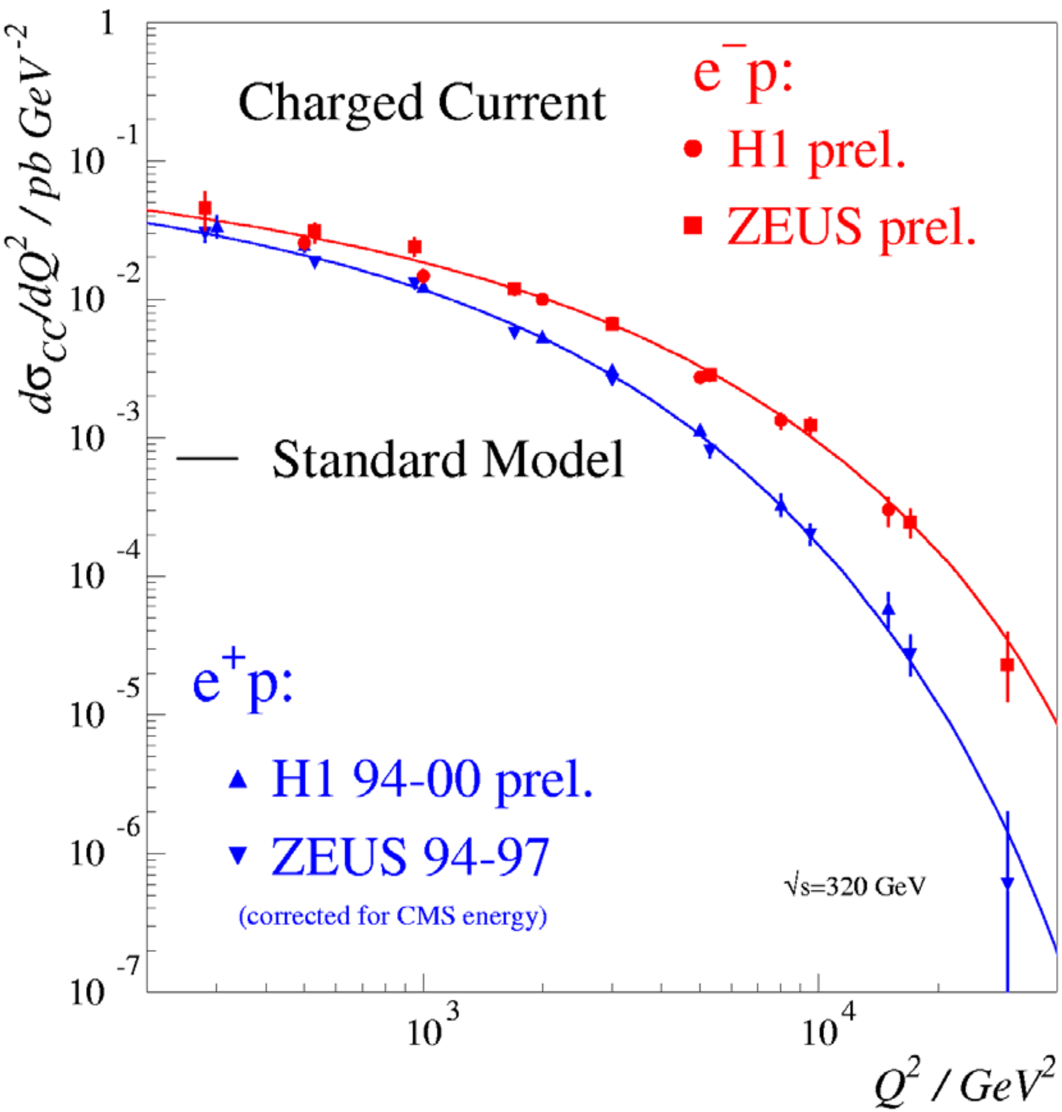


$$xF_3^{\gamma Z} \sim 2u_v + d_v$$

xF_3 constrains u_v,d_v at high x

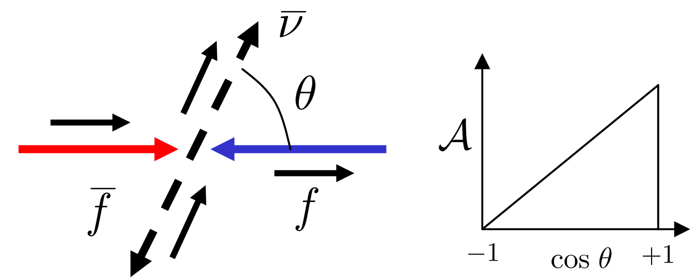
CC Cross Section at high Q^2 and the valence quarks

$$ep \rightarrow \nu X$$



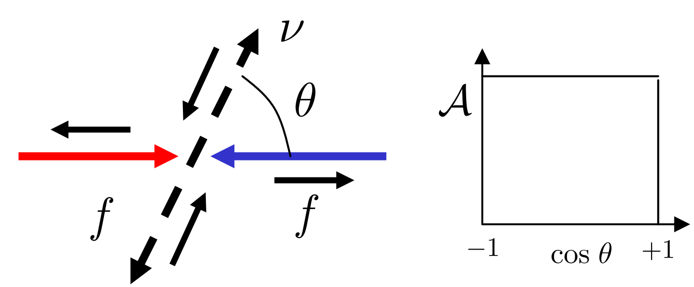
$$\sigma_{CC}(e^+p) \sim \left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2$$

$$\left[(1-y)^2 (d+s) + (\overline{u} + \overline{c})\right]$$

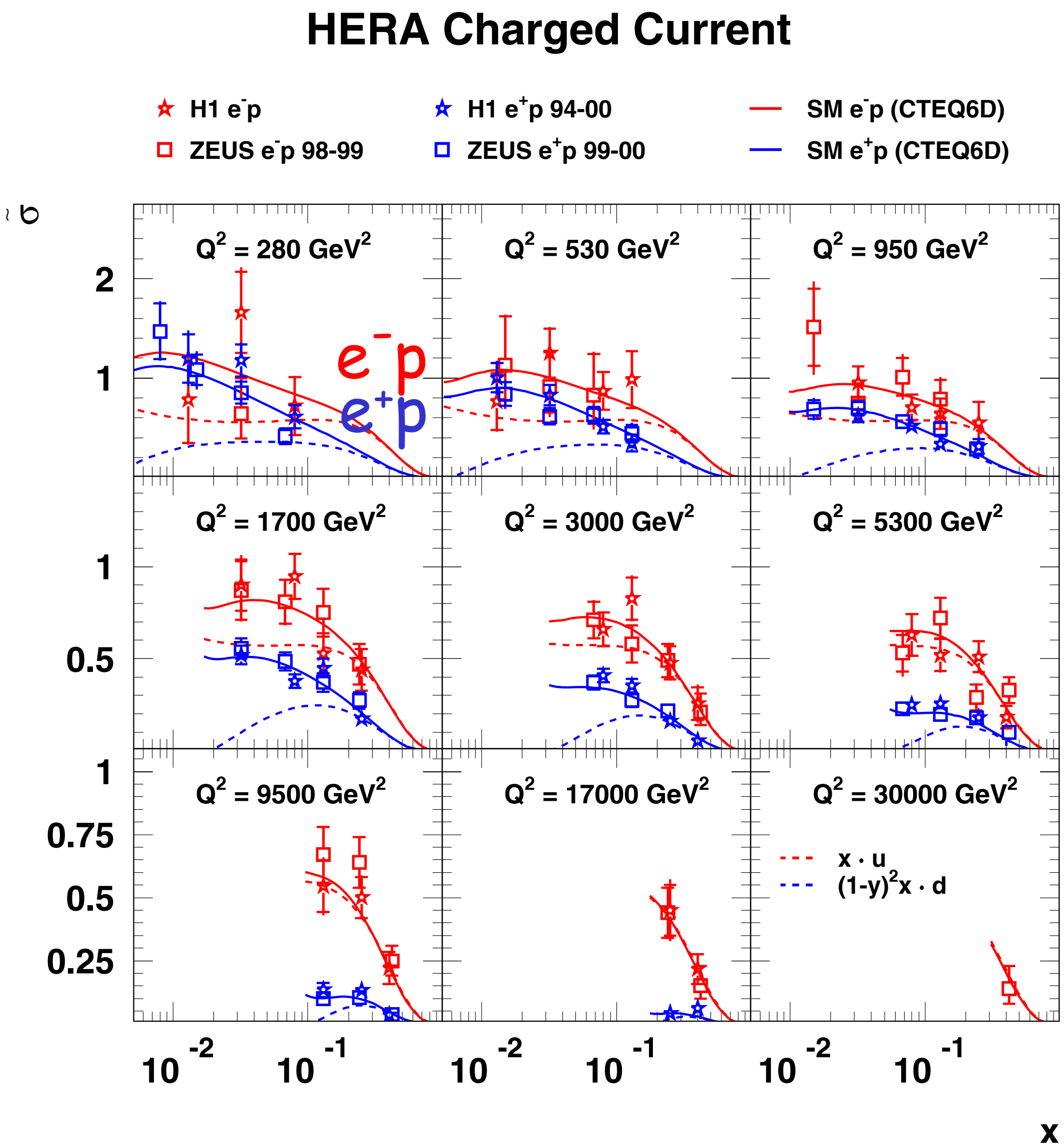


$$\sigma_{CC}(e^-p) \sim \left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2$$

$$\left[(1-y)^2 (\overline{d} + \overline{s}) + (u + c)\right]$$



Charged Currents & flavour separation



The CC e^+p cross section

- dominated by d quark

$$\tilde{\sigma}_{CC}^{e^+p}(x,Q^2) \sim (\bar{u}+\bar{c}) + (1-y)^2(d+s)$$

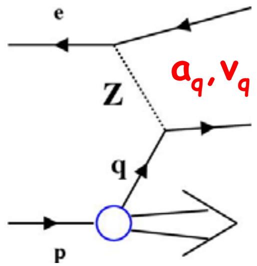
The CC e^-p cross section

- dominated by u quark

$$\tilde{\sigma}_{CC}^{e^-p}(x,Q^2) \sim (u+c) + (1-y)^2(\bar{d}+\bar{s})$$

- constrain d (u) quark density
- free of nuclear corrections and isospin assumptions

Light Quark Couplings to the Z^0



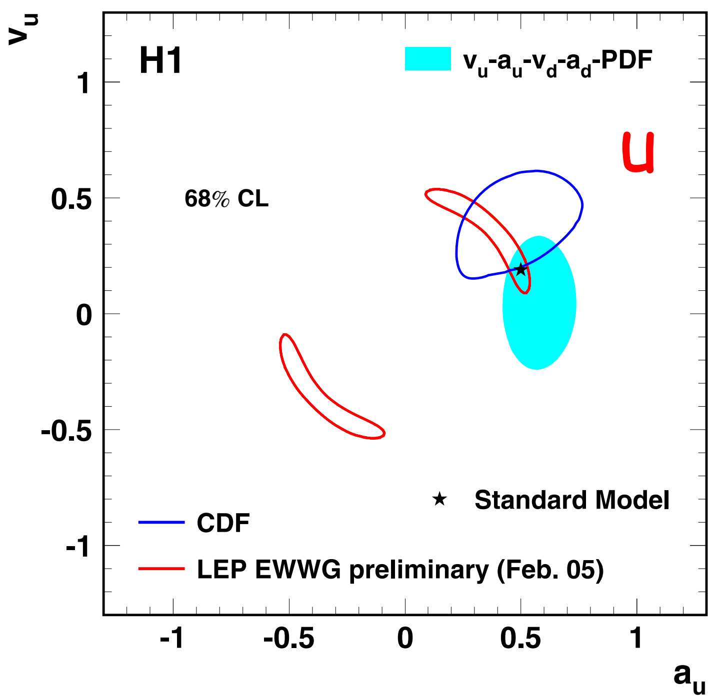
first coherent EW+PDF analysis at HERA (NC+CC data)

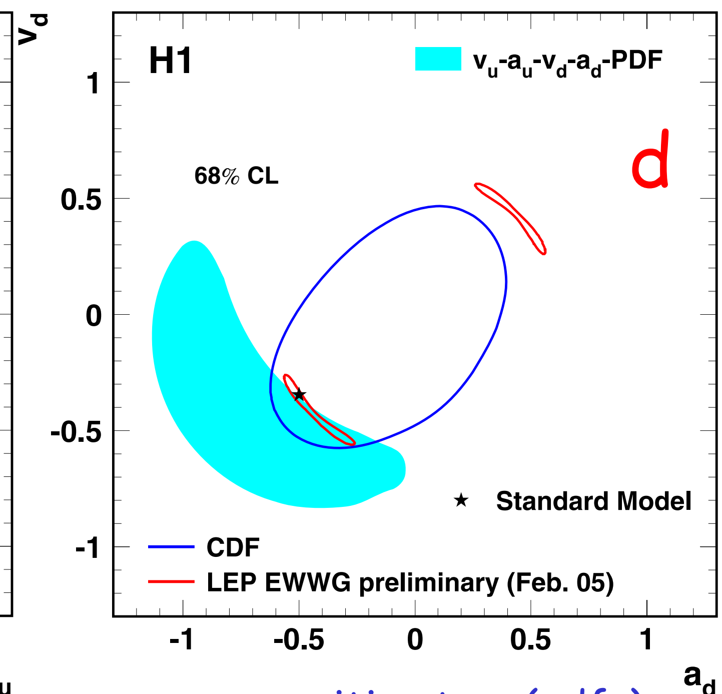
$$a_q = I_q^3 \rightarrow (a_u = +1/2; a_d = -1/2)$$

$$v_q = I_q^3 - 2e_q \sin^2\theta_W$$

$$F_2 \approx F_2^{em} + (v_e^2 + a_e^2) K_Z^2 \bullet x \sum (v_q^2 + a_q^2)(q + \bar{q})$$

$$xF_3^{NC} \approx -a_e K_Z \bullet 2x \sum e_q a_q (q - \bar{q})$$





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

TeVatron: qq→ee Drell-Yan, A_{FB}

LEP: ee→qq(g) (a^2_q+v^2_q)

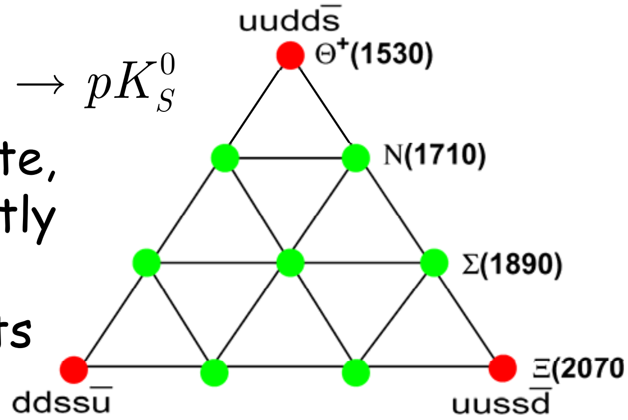
- more sensitive to u (pdfs)
- compatible precision with the TeVatron
- helps to resolve LEP ambiguities

New Hadronic States: Pentaquarks

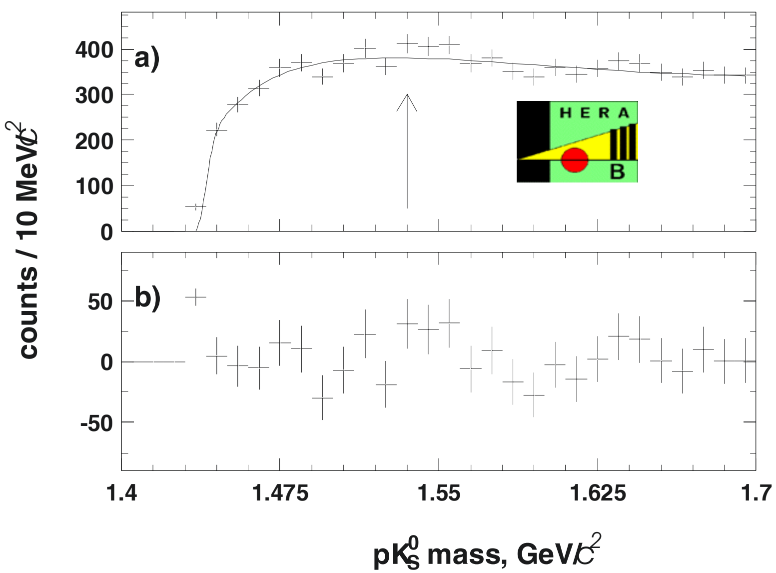
„The nucleon is made from 3 quarks"

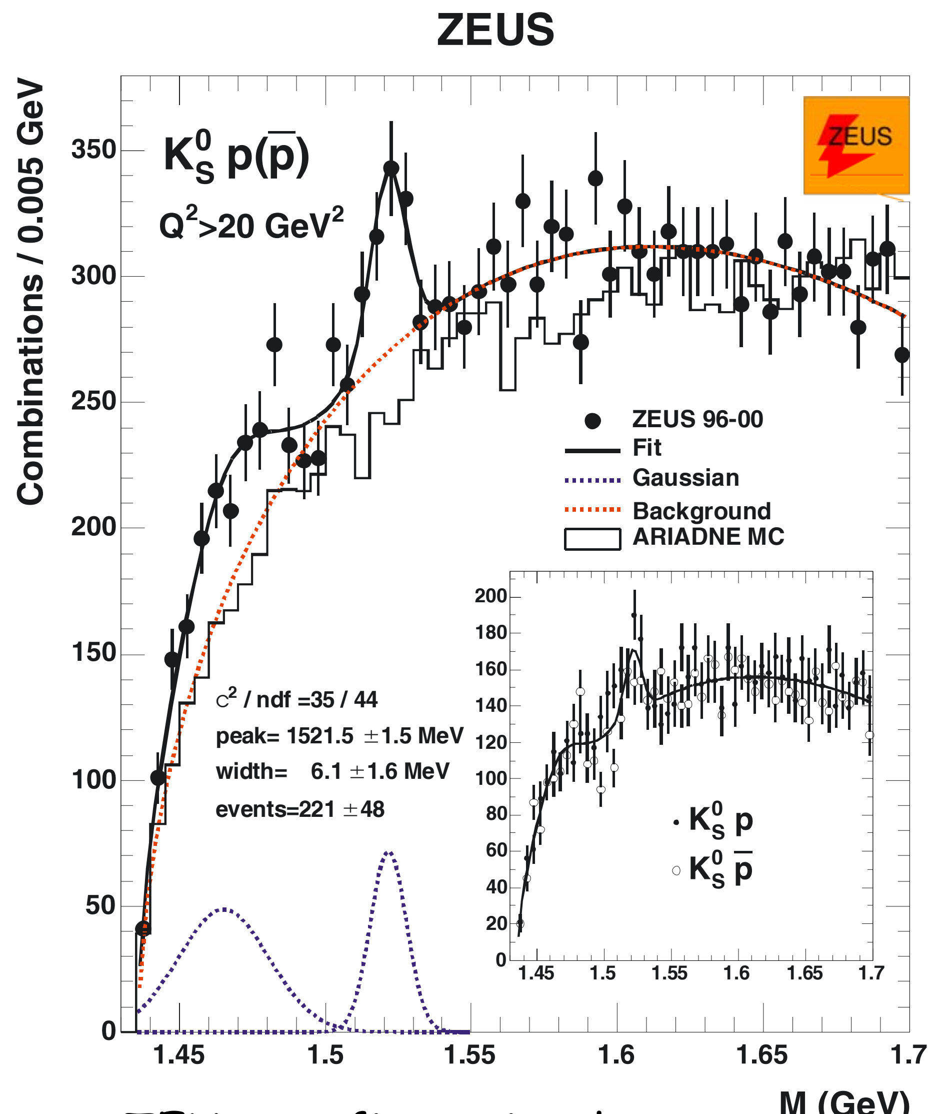
$$\theta^+(1530) \rightarrow nK^+$$

$$\rightarrow pK_S^0$$



narrow state, seen recently in several experiments

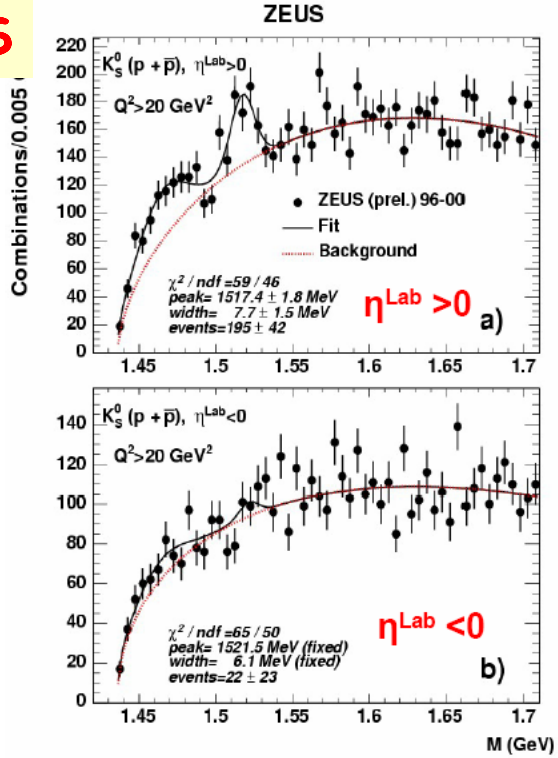




ZEUS confirms signal,
HERA-B does not see it ....

θ^+ search at HERA

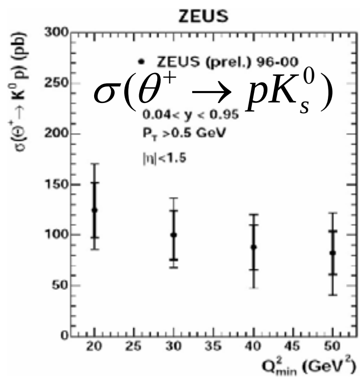
YES

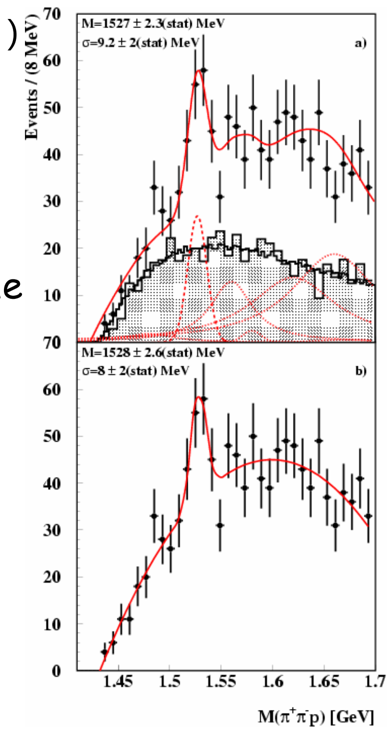


ZEUS $(pK^0_S, \bar{p}K^0_S)$

M=1521±1.5±3 MeV
4.6 σ effect

- Q^2 > 20 GeV^2
- both in pK^0_s, $\bar{p}K^0_s$
- predominantly in the forward direction

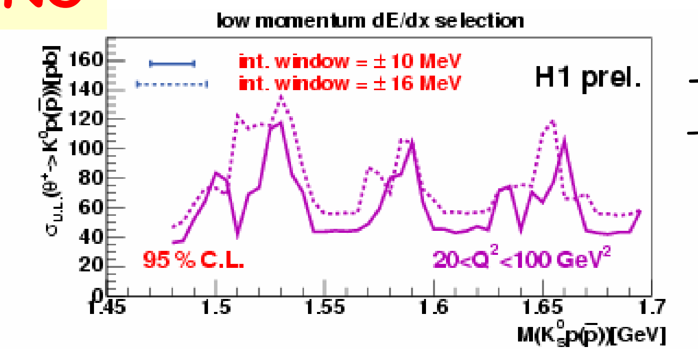




HERMES (pK_s^0)

M=1527 ± 2.3(sta) MeV
~4σ effect
no signal in $\bar{p}K^0_s$

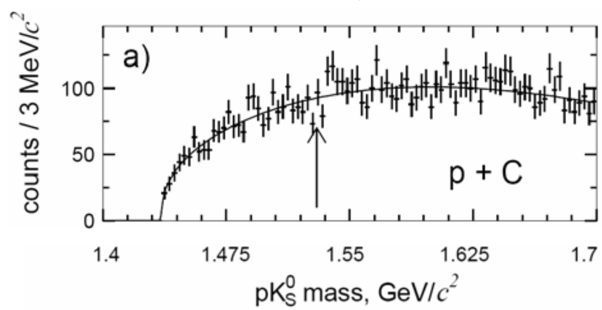
NO



H1 $(pK^0_S, \bar{p}K^0_S)$

- limits at 95% CL
- for Q^2>20 GeV^2:
  σ < 100-120 pb
  (ZEUS σ~120 pb)

HERA-B (pK_s^0) limits at 95% CL:

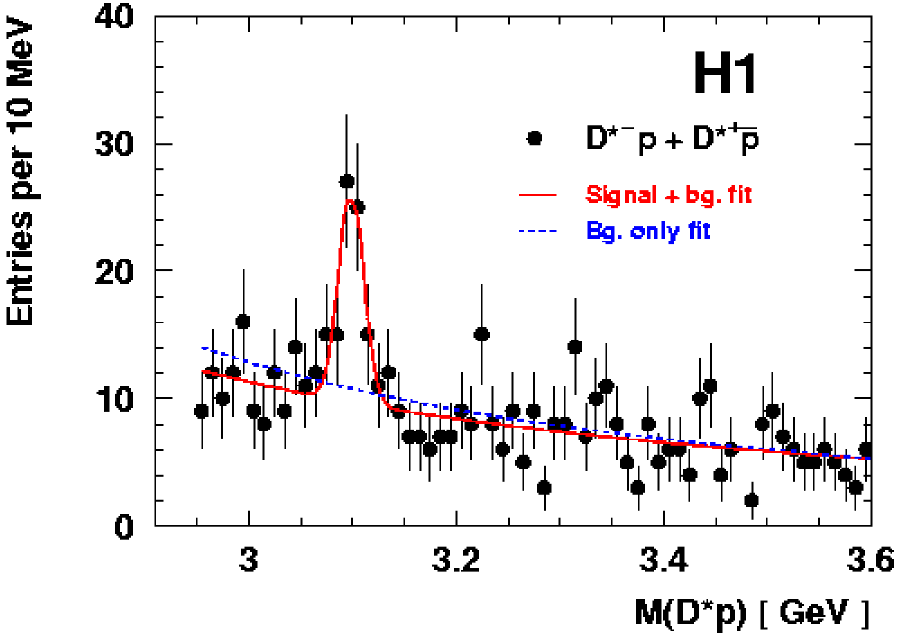


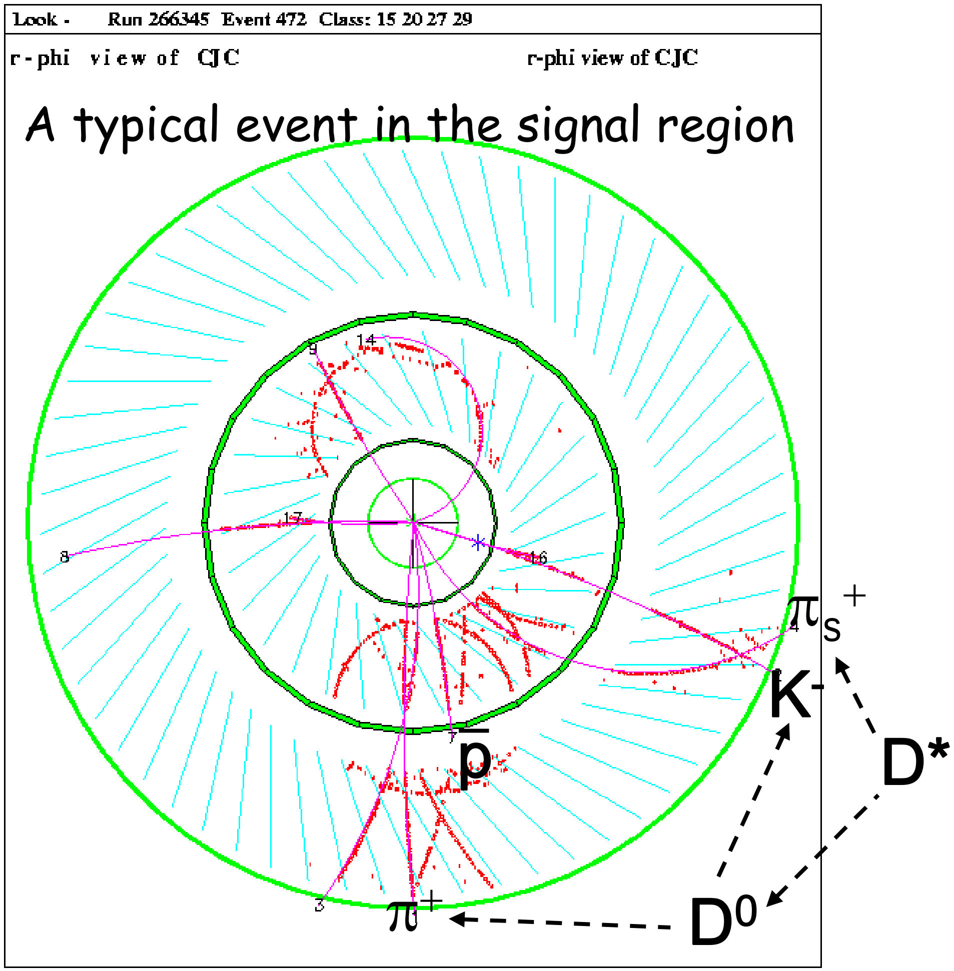
Br×dσ/dy <3.7μb/N

$\frac{\theta^+}{\Lambda(1520)}$<2.7%

Observation of an Anti-charm Pentaquark

New state seen in H1: a charmed pentaquark $\theta_C \rightarrow D^{*-}p(D^{*+}\overline{p}) \quad uudd\bar{c}$





Mass: $3099 \pm 3(\text{stat.}) \pm 5(\text{syst.})\ \text{MeV}$

Width: $12 \pm 3(\text{stat.})\ \text{MeV}$

Background fluctuation prob. 4×10^{-8}

$$= 5.4\sigma$$

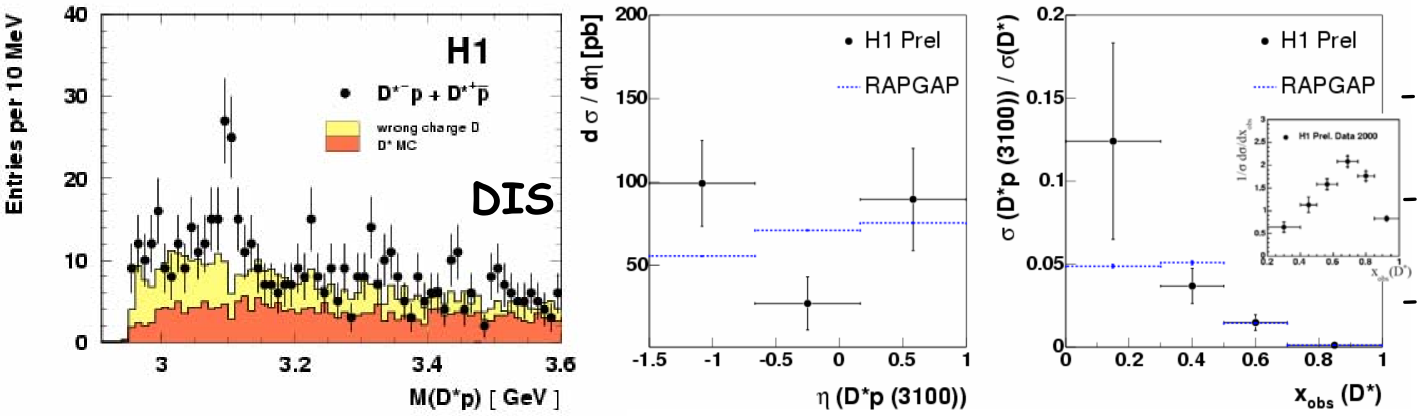
ZEUS/CDF do not confirm the signal ...

Charmed pentaquarks ?

YES

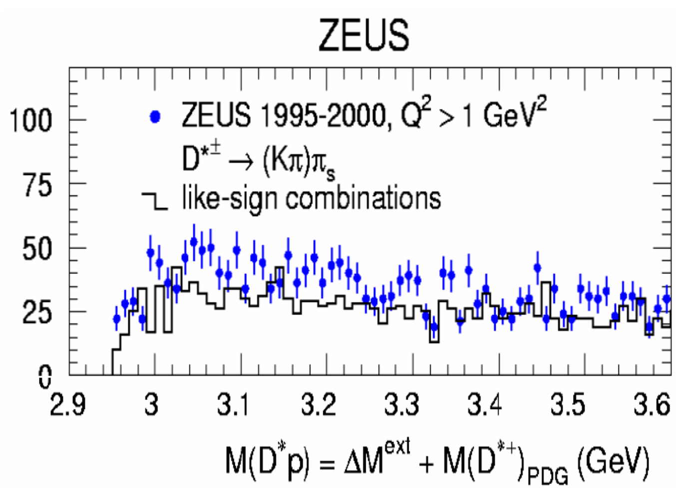
H1 observed D*p(3100) M=3099±3±5 MeV 5.4σ

not confirmed (so far) by other experiments



- suppression at central rapidity
- D*p fragm. is hard (similar to incl. D*)
- D* from D*p softer than incl. D*

NO



ZEUS

- no evidence for a signal at 3100 MeV
- in the phase space similar to H1:

$R_{corr}(D^*p/D^*) < 0.59\%$ at 95% CL

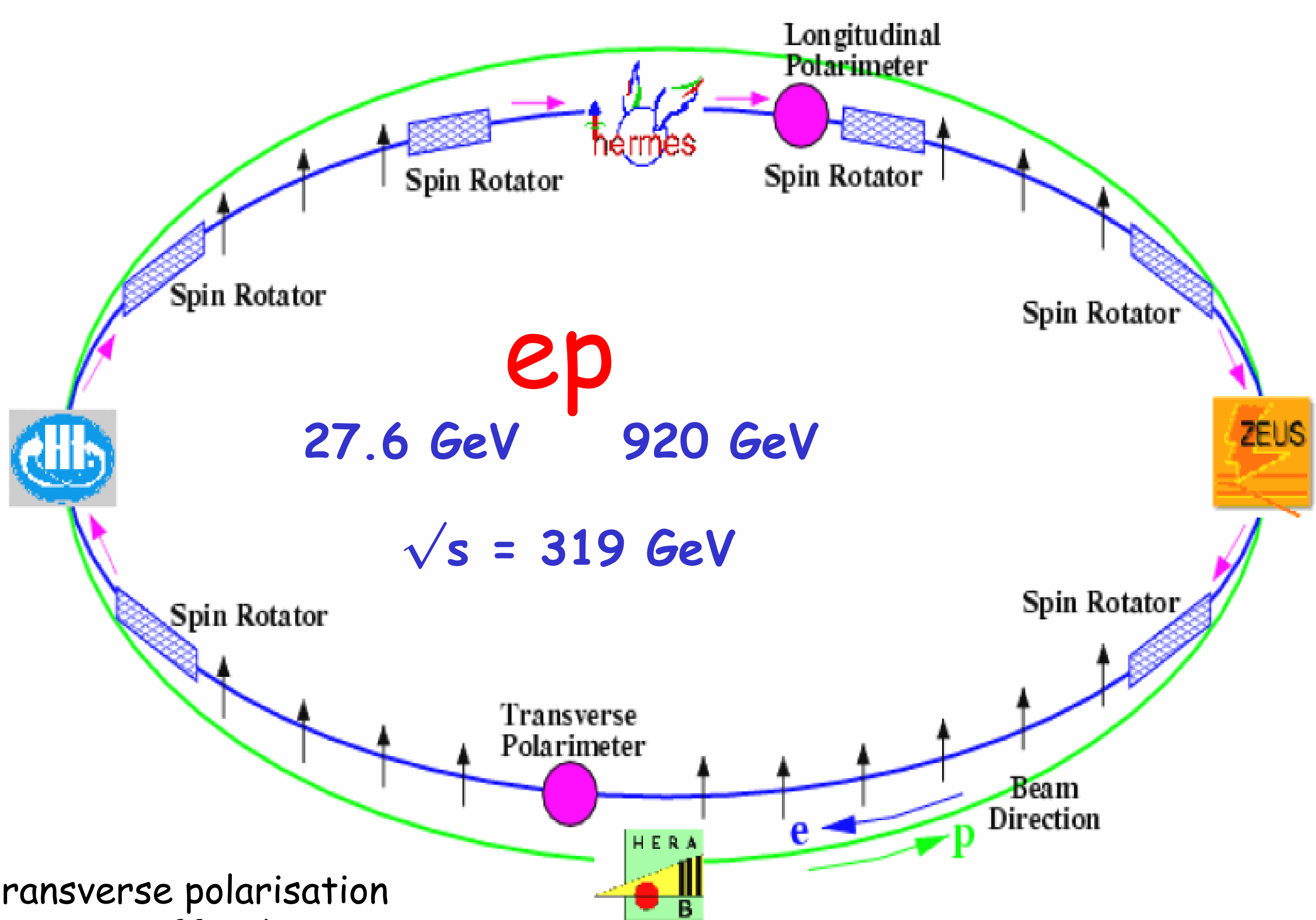
$< 0.51\%$ when including $D^* \to (K\pi\pi\pi)\pi_s$

compared to H1:

$R_{corr}(D^*p/D^*) = (1.59 \pm 0.33 + 0.33 - 0.45)\%$

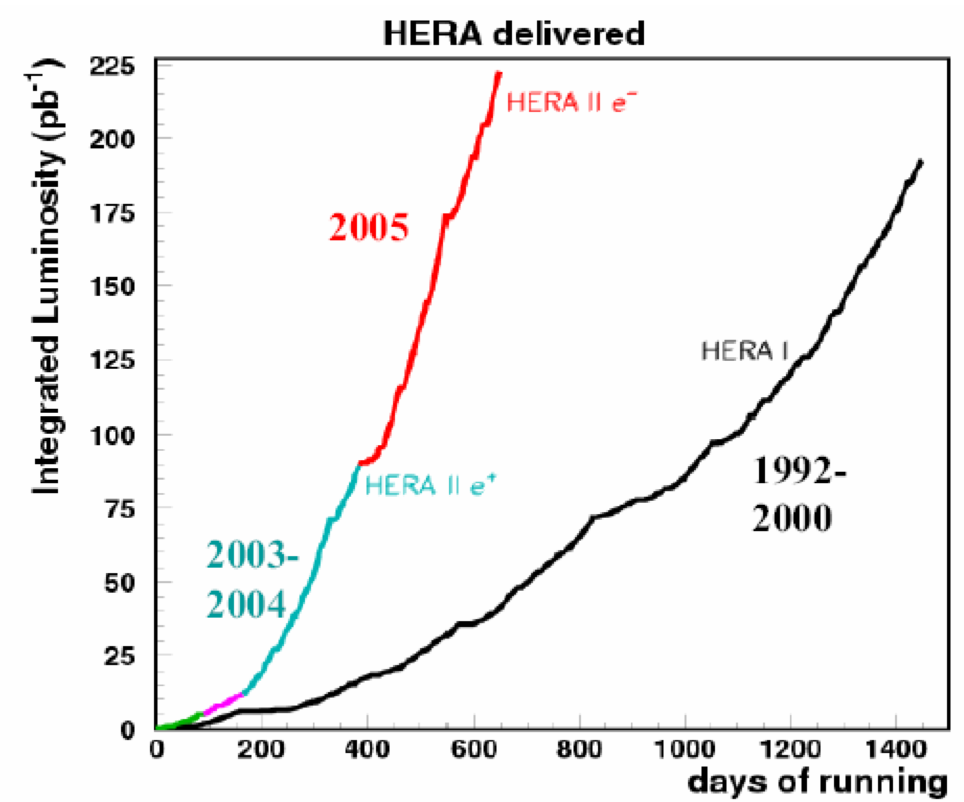
-> still incompatible

HERA II: High Lumi & Polarization of Leptons



natural transverse polarisation
(Sokolov-Ternov effect)
+ spin rotators

HERA II performance

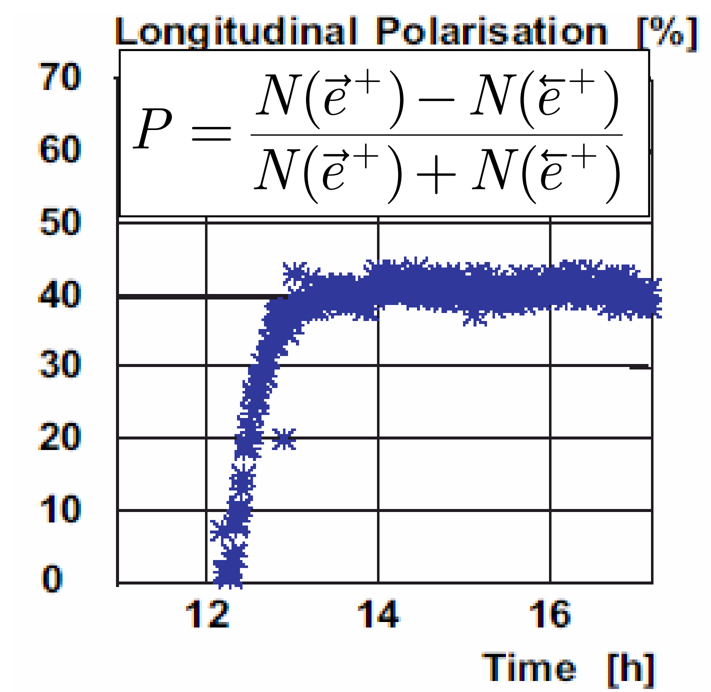


HERA II:

- detectors and luminosity upgrade

	e^+p	e^-p
HERA I:	100 pb^{-1}	20 pb^{-1}
HERA II:	50 pb^{-1}	100 pb^{-1}

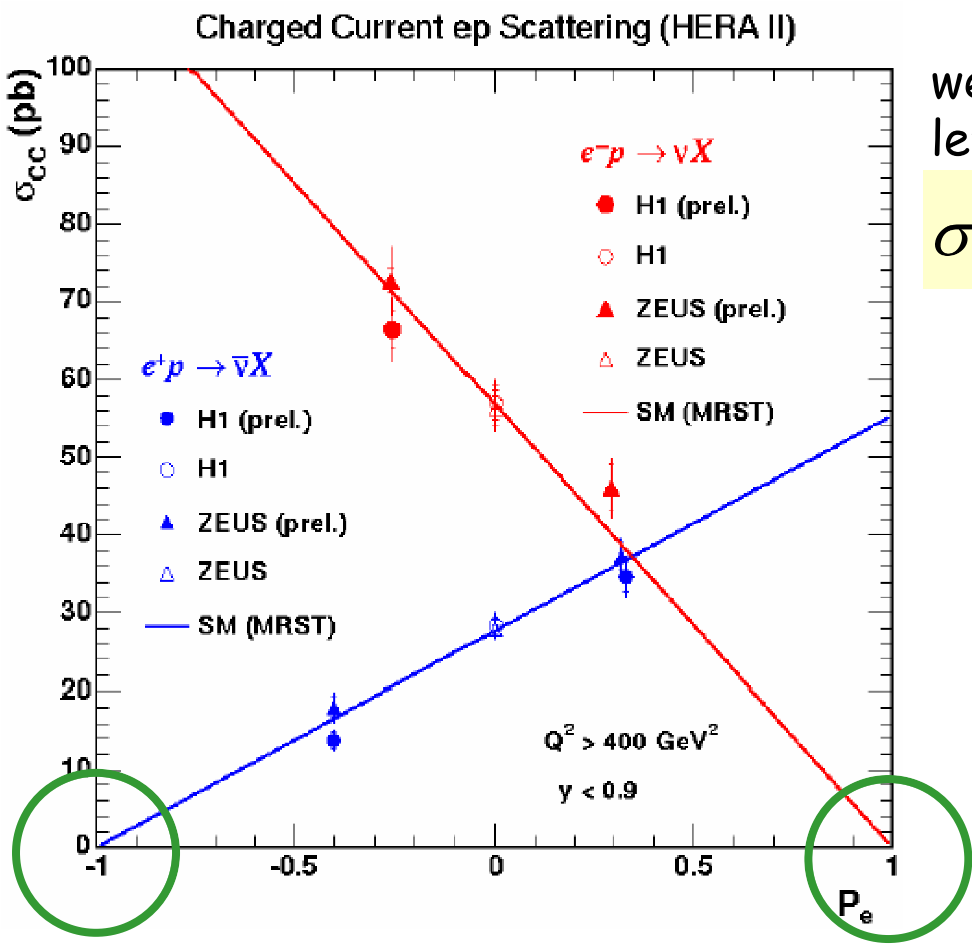
- longitudinally polarized e beam in the colliding experiments

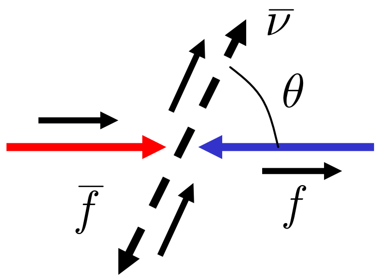


data taking until mid 2007:
~O(0.7) fb^{-1} per experiment in total

First results from HERA II

σ_{CC} total cross section using longitudinally polarized e^+ and e^-





weak CC is pure left-handed (V-A):

$$\sigma_{CC}^{e^\pm p}(P_e) = (1 \pm P_e)\sigma_{CC}^{e^\pm p}(P_e = 0)$$

$P_e = (N_R - N_L)/(N_R + N_L)$

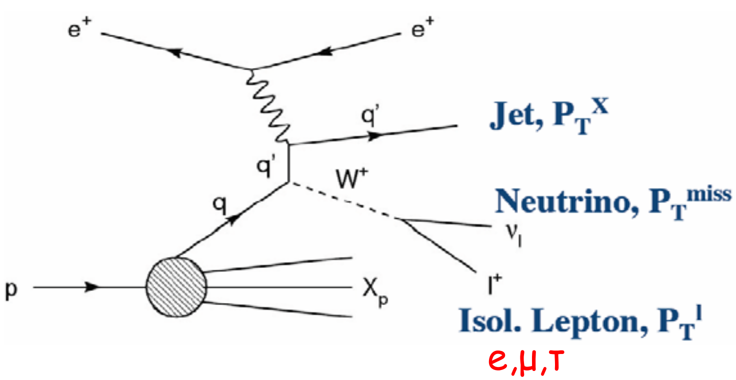
- linear dependence is firmly established both for e^+ and e^-
- in agreement with SM
- extrapolation to $P_e = -1$ (e^+p):

extrapolations to $P_e = -1, +1$ test the absence of right-handed weak current

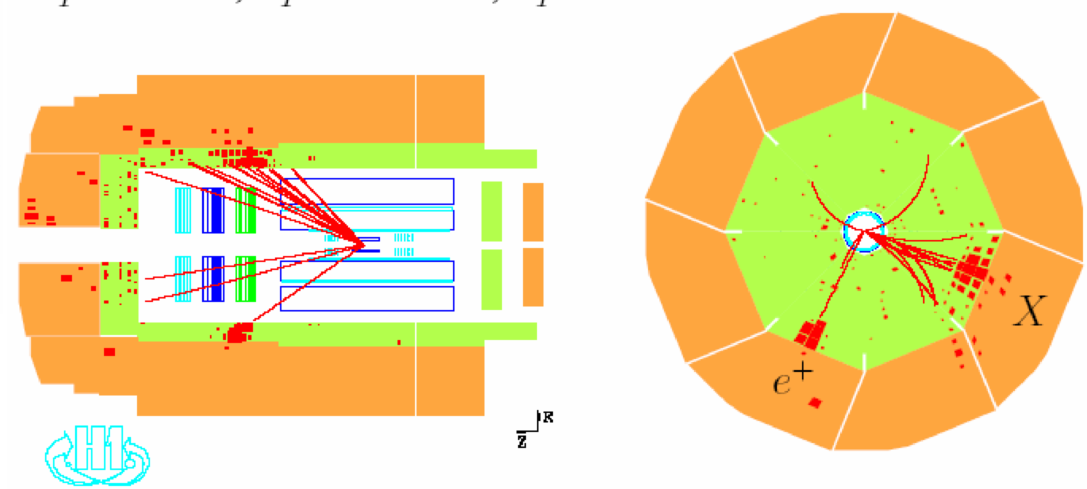
$$\sigma_{CC}^{e^+p}(P_e = -1) = -0.2 \pm 1.8(\text{sta}) \pm 1.6(\text{sys})\,\text{pb}$$

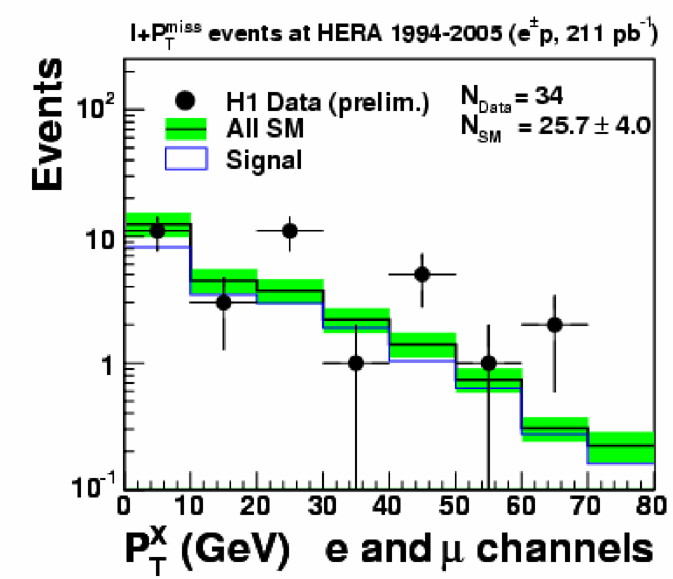
-> consistent with zero

Isolated leptons with PTmiss at HERA



$P_T^e = 37$ GeV, $P_T^{miss} = 44$ GeV, $P_T^X = 29$ GeV





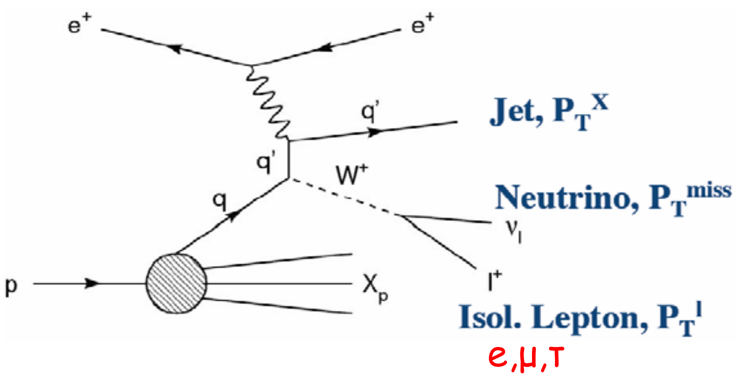
H1 e^+p, e^-p	HERA I (118 pb^{-1})		HERA I+II (211 pb^{-1})	
	e	μ	e (prel)	μ (prel)
All P_T^X	11/11.54	8/2.94	25/20.4	9/5.4
P_T^X > 25 GeV	5/1.76	6/1.68	11/3.2	6/3.2

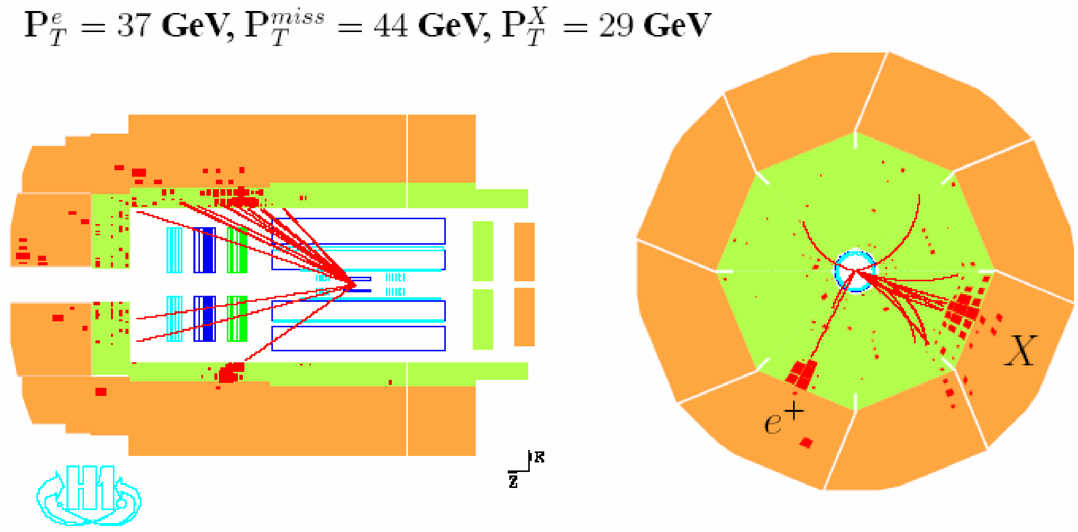
Double luminosity:

e - excess persists at HERA II

μ - excess comes only from HERA I

Isolated leptons with PTmiss at HERA (cont.)





H1 e⁺p: excess over SM both in e and μ channels
no excess in e⁻p data

ZEUS in agreement with SM

H1 1994-2005	e^+p (158 pb^{-1})		e^-p (53 pb^{-1})	
	e (prel)	μ (prel)	e (prel)	μ (prel)
All P_T^X	19/14.6	9/3.9	6/5.8	0/1.5
P_T^X > 25 GeV	9/2.3	6/2.3	2/0.9	0/0.9

τ-lepton channel (P_T^X > 25 GeV)
ZEUS (130 pb^{-1}) 2 / 0.20
H1 (108 pb^{-1}) 0 / 0.53

Summary & Outlook

Rich physics output from HERA:

- centered around QCD, but also EW, searches, …
- key word: precision

- investigate implications of QCD (evolution, scales, …)
- provide information essential for the LHC collider,
  see HERA-LHC workshop: http://www.desy.de/~heralhc/

- very often data are more precise than theory
- theory should catch up (… and it happens, e.g. NNLO in DIS)

HERA II:

- **lumi** is a main issue !!! ~ O(0.7fb-1) per experiment in total,
  exploit new detectors/triggers

- clarify isolated leptons, pdfs, HF, penta quarks, FL, …

- less than 2 years of running time left (until mid of 2007) …