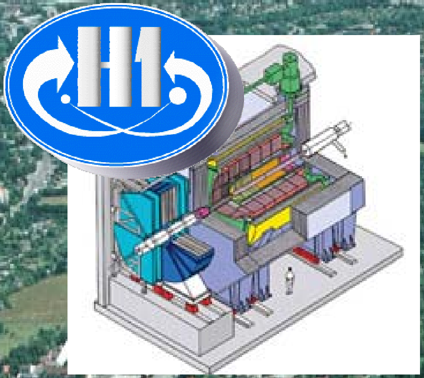
Review of the results of the electron-proton collider HERA

Vladimir Chekelian (MPI for Physics & ITEP)



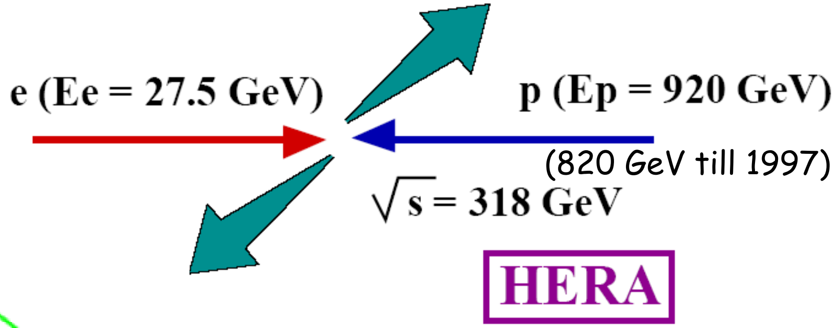
HERA

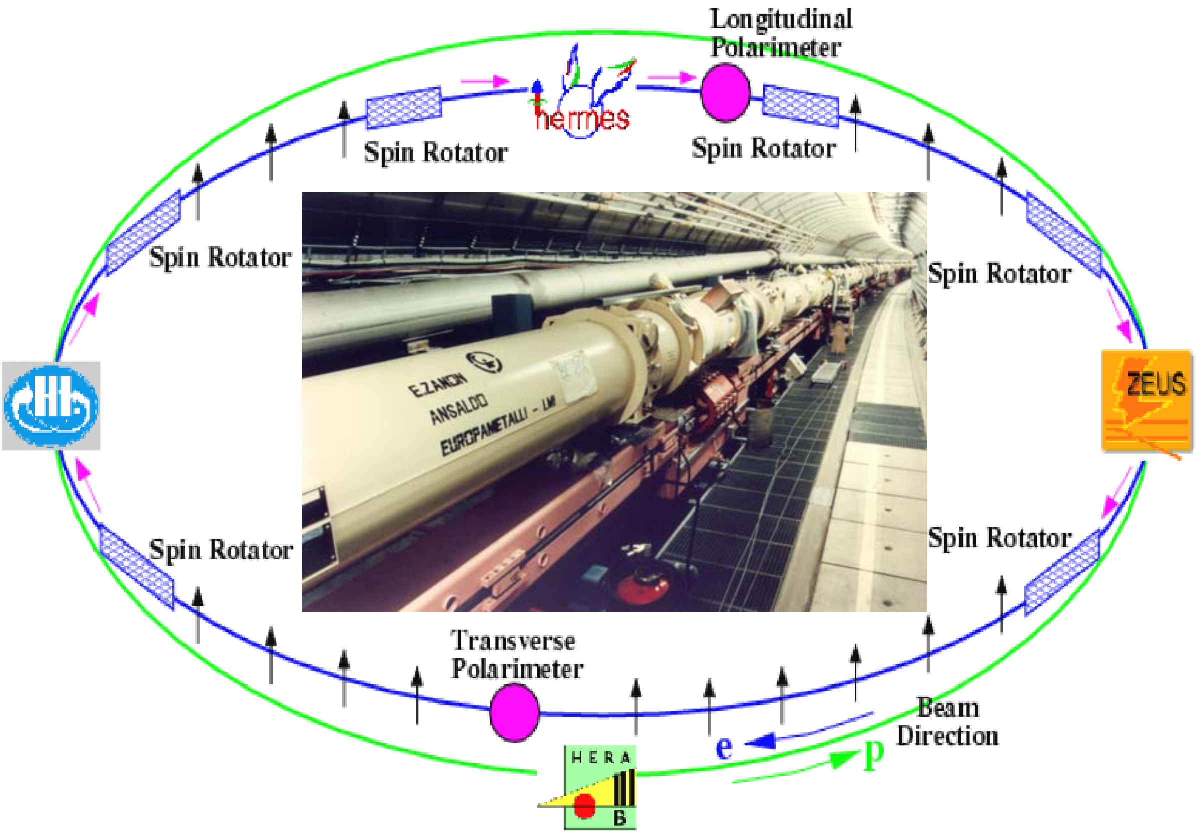
ep (27.5 x 920 GeV)

15 Years of data taking:
31 May 1992 – 30 June 2007

13th Lomonosov conf., Moscow 23-29.08.2007

HERA Fundamentals





Circumference 6.3 km

Peak luminosity

$5\ 10^{31}\ cm^{-2}\ sec^{-1}$

$Q^2_{max} = 10^5\ GeV^2$

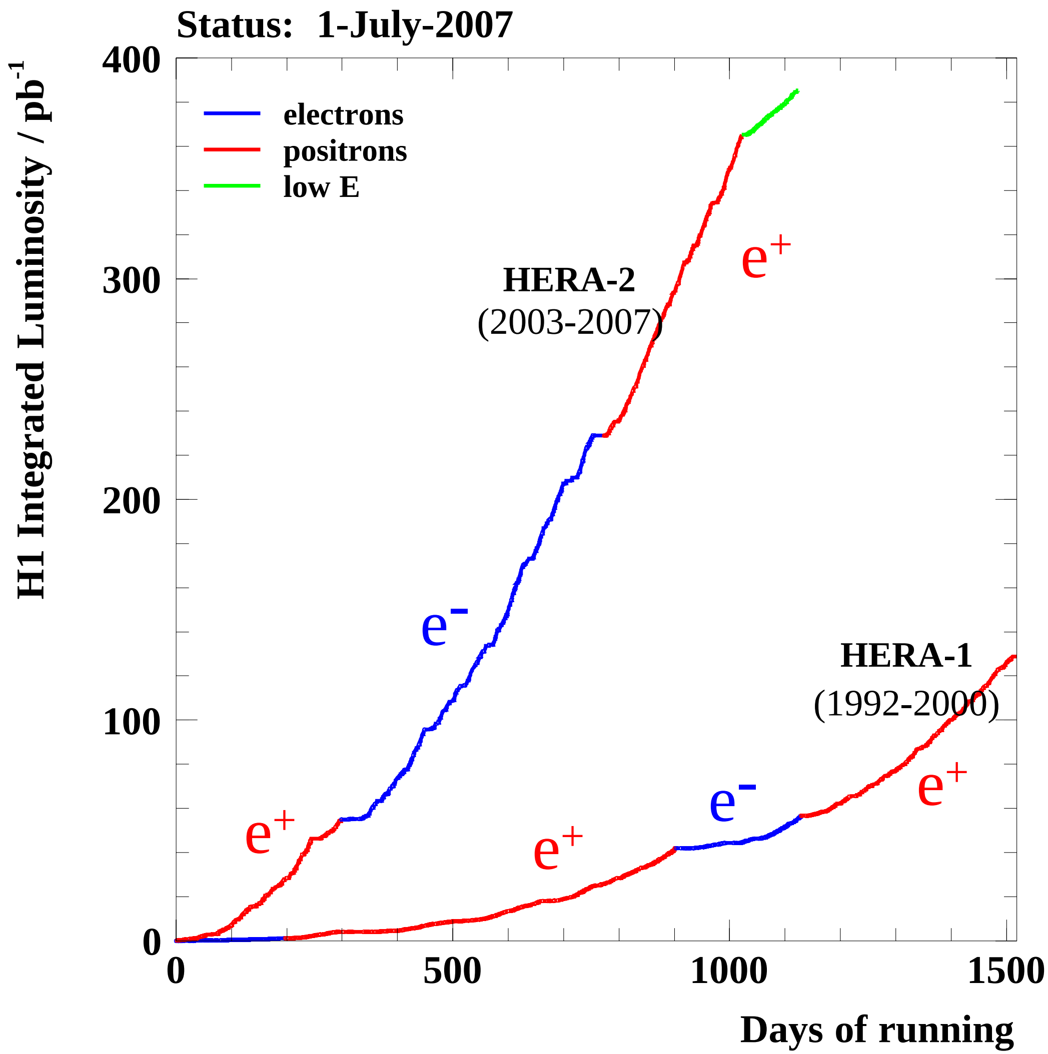
$\lambda_{max} \sim 1/1000\ r_{proton}$

Longitudinal e polarisation

$P_e = (N_R - N_L)/(N_R + N_L) \sim 40\%$

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

HERA I & II



per expt.	HERA I	HERA II
e^+p	~100 pb^{-1}	~200 pb^{-1}
e^-p	~20 pb^{-1}	~180 pb^{-1}

HERA II (2003-2007):

- lumi upgrade
- longitudinally polarised e beams

H1+ZEUS in total ~ 1 fb^{-1}

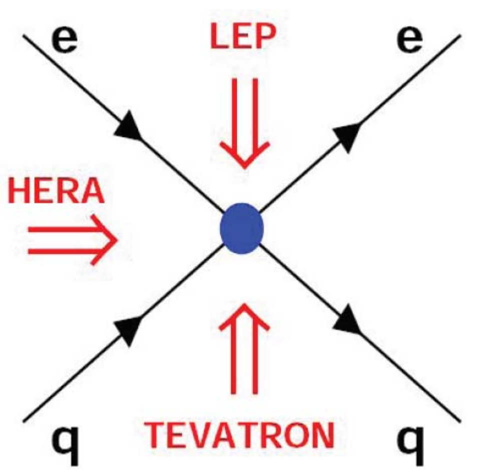
about equally shared between

- experiments (H1, ZEUS)
- e^+ and e^-,
- positive and negative P_e

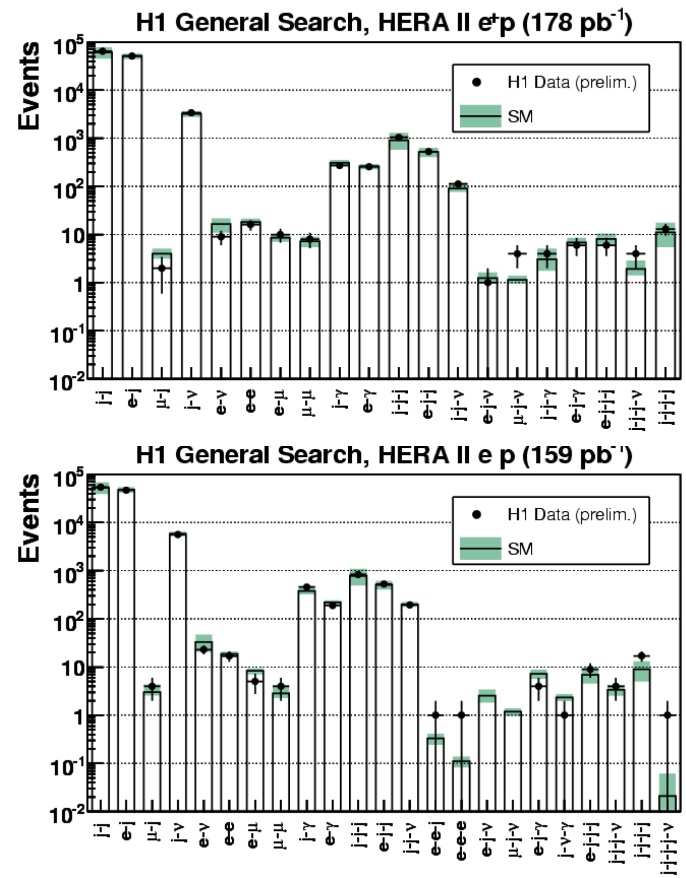
→ low proton energy run 20 pb^{-1} for direct F_L measurements

Energy Frontiers at HERA

complementary to LEP & TeVatron



Model-independent search

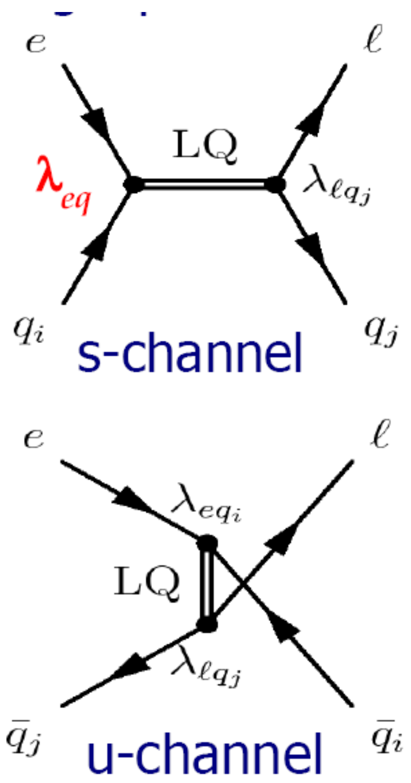


Searches for New Physics:

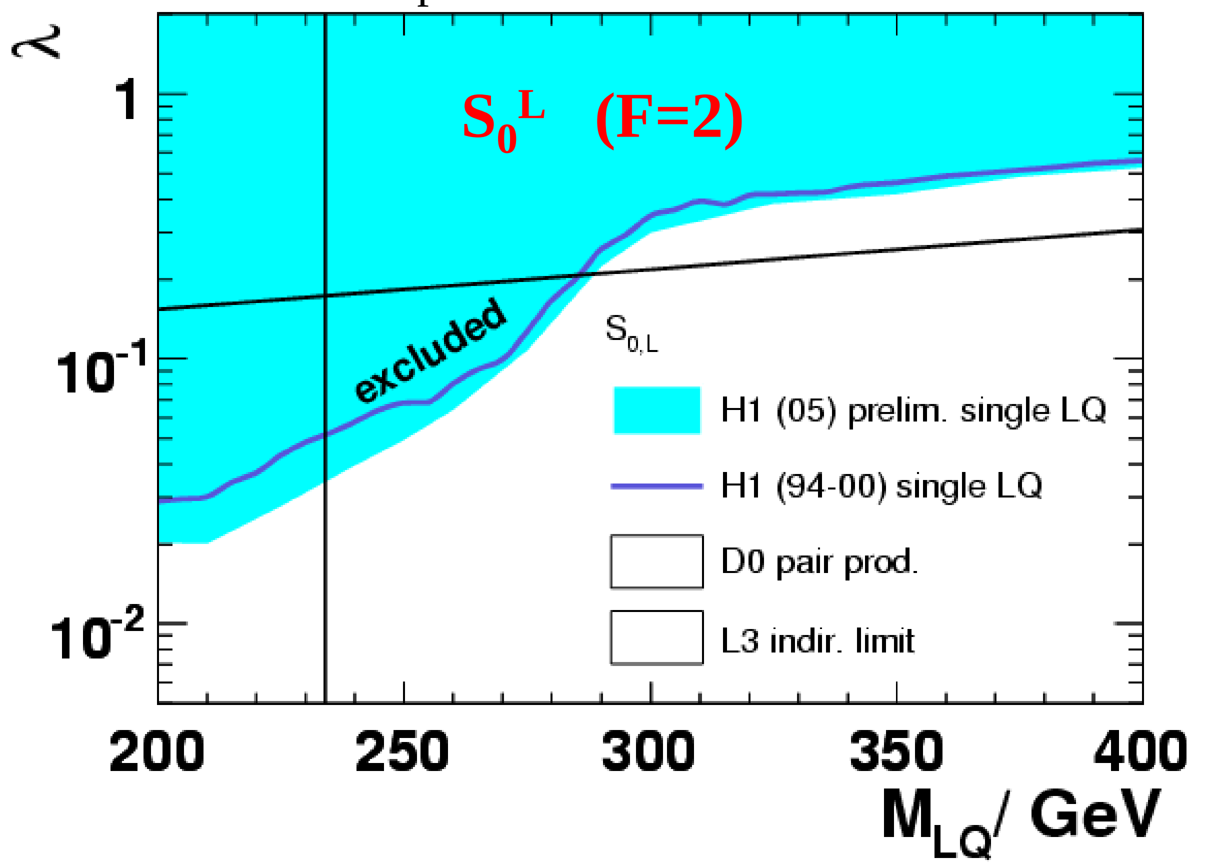
leptoquarks, exited fermions, contact interactions, SUSY, $H^{\pm\pm}$, LFV, extra dimentions, multi-leptons, …

Leptoquarks (LQ)

Leptoquark: colour triplet boson with leptonic and baryonic quantum number
Fermion number: F = L+3B = 0 (e^+p) / 2 (e^-p)
Buchmueller-Ruecl-Wyler classification: 7 scalars & 7 vectors (spin, isospin, chirality)

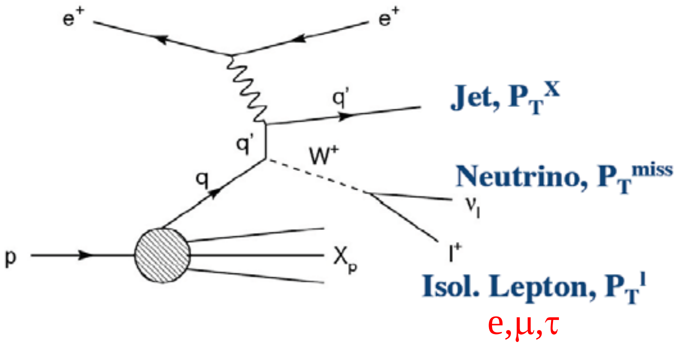


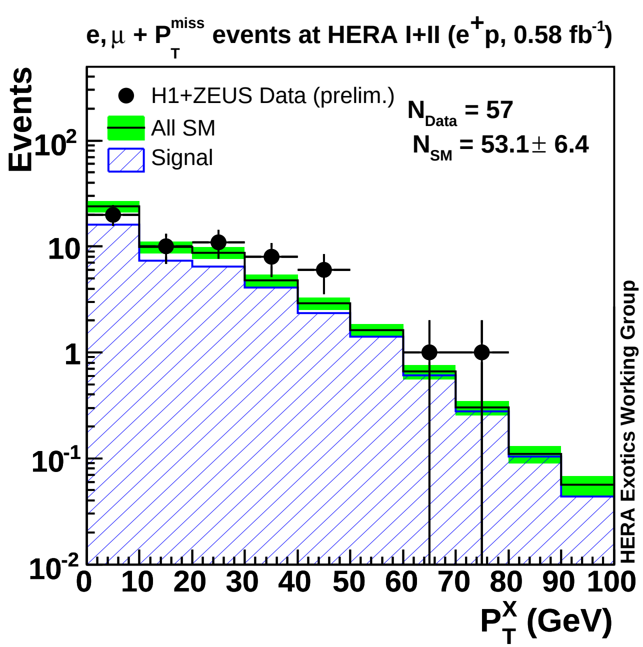
Comparison with LEP & TeVatron



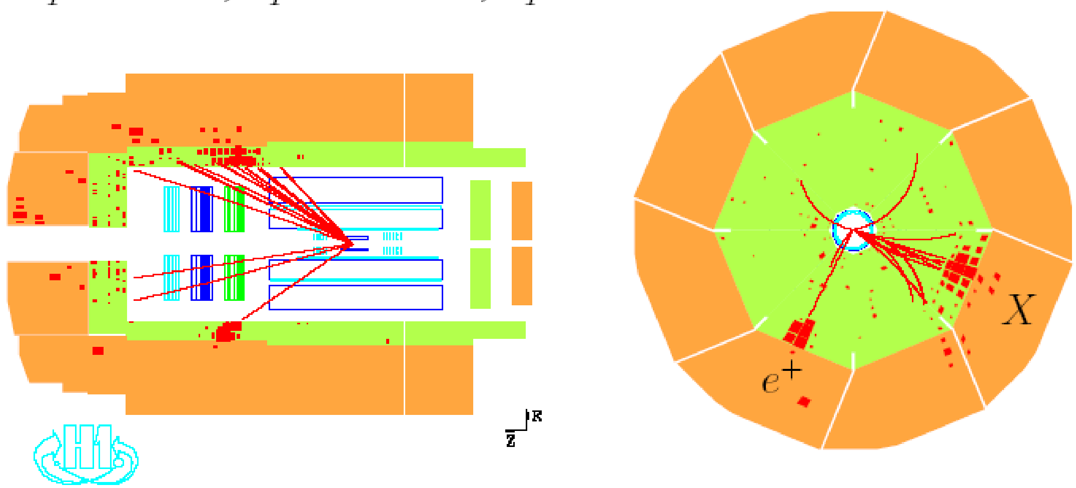
Isolated Leptons with P_T^{miss} at HERA

σ_W ~ 1.3 pb





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



H1 + ZEUS	e^+p (0.58 fb^{-1}) data/SM			ep (0.97 fb^{-1})
	e	μ	e,μ comb.	e,μ combined
All P_T^X	39/41.3	18/11.8	57/53.1	87/92.7
P_T^X > 25 GeV	12/7.4	11/7.2	23/14.6 (1.8σ)	29/25.3

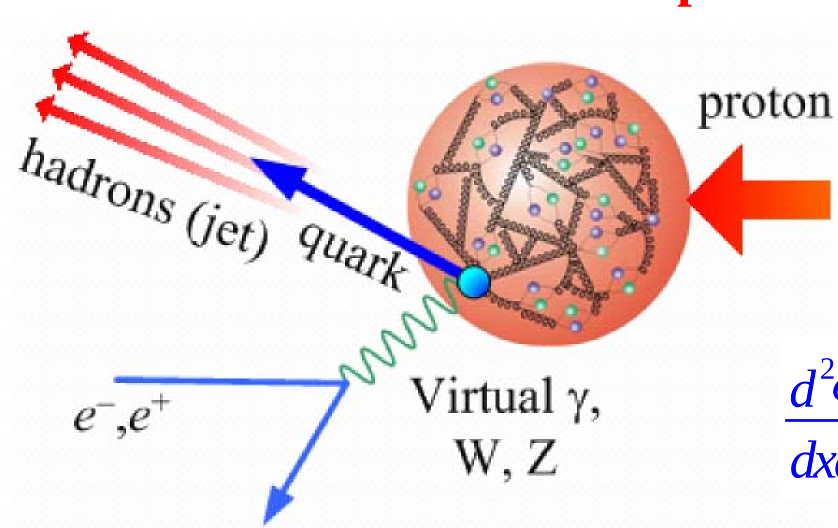
e^+p H1 ($5^o<\theta_l<140^o$): data/SM -> 21/8.9 (3.0σ)

~1 fb^{-1} (H1+ZEUS) for W production study

Deep Inelastic Scattering at HERA

Neutral (NC) and Charged (CC) Current DIS :

$$e^{\pm} p \rightarrow e^{\pm}(\nu)X$$



$Q^2 = -q^2 = -(k-k')^2$ virtuality of γ^*, Z^0, W

$x = Q^2/2(Pq)$ Bjorken x

$y = (Pq)/(Pk)$ inelasticity

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

$$\frac{d^2\sigma_{NC}^{e^{\pm}p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \left[F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3 \right], Y_{\pm} = 1 \pm (1-y)^2$$

Factorisation

$$\sigma_{DIS} \sim \hat{\sigma} \otimes pdf\,(x)$$

$\hat{\sigma}$ – perturbative QCD cross section

pdf – universal parton distribution functions

QPM: $F_2(x,Q^2) = x\sum A_i(q_i + \bar{q}_i)$ $xF_3(x,Q^2) = x\sum B_i(q_i - \bar{q}_i)$

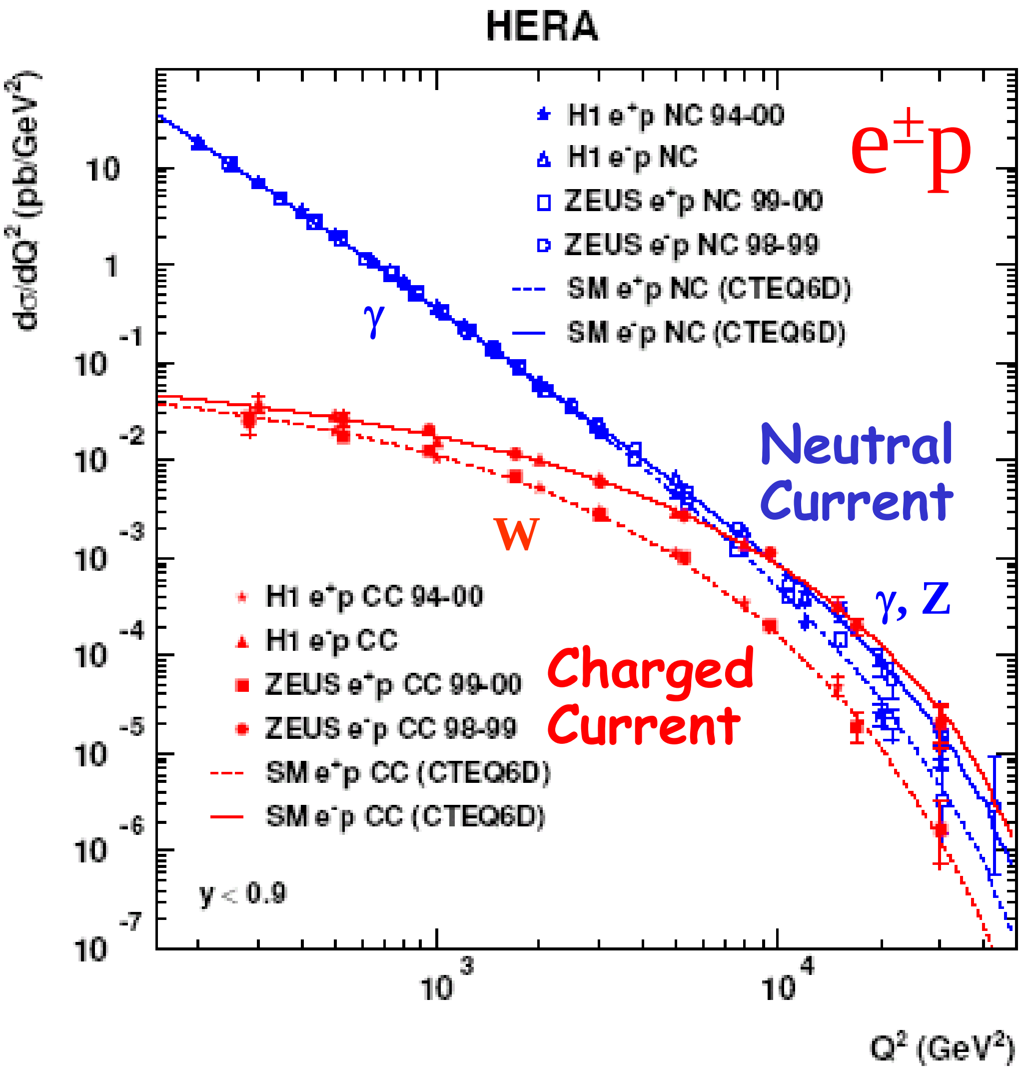
$F_L = F_2 - 2xF_1 = 0$

→ probe proton with the spatial resolution of $\lambda \sim 1/Q$

→ probe the EW sector of the Standard Model

→ probe new physics beyond the Standard Model

Electroweak Unification



EW component of SM:

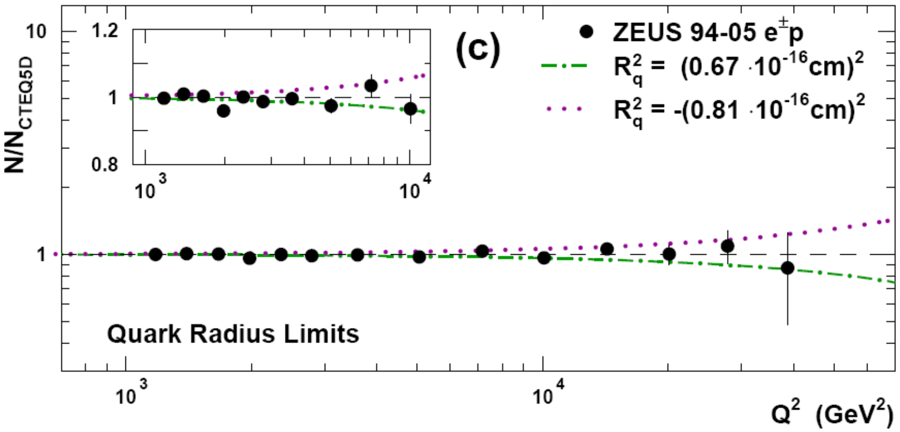
$\sigma_{NC} \approx \sigma_{CC}$ at $Q^2 \approx M_Z^2, M_W^2$

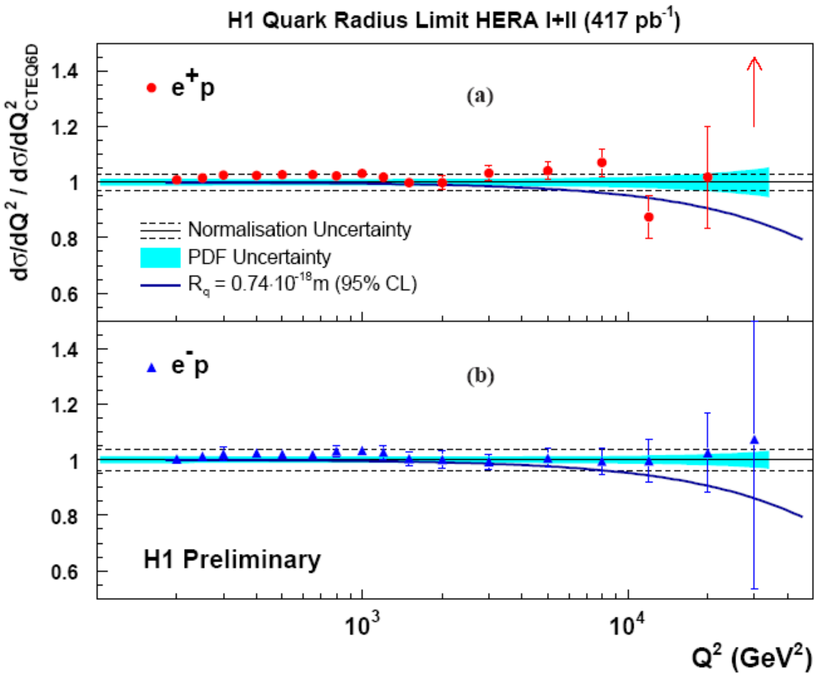
-> residual differences due to u/d flavour asymmetry and helicity factors

The highest Q^2:

search for deviations from SM

NC at High Q^2





Quark "form factor" with R_q

corresponding to the average radius

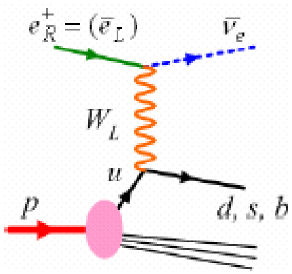
of the spacial distribution of the quark charge

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{1}{6}R_q^2 Q^2\right)^2$$

Quark is pointlike :

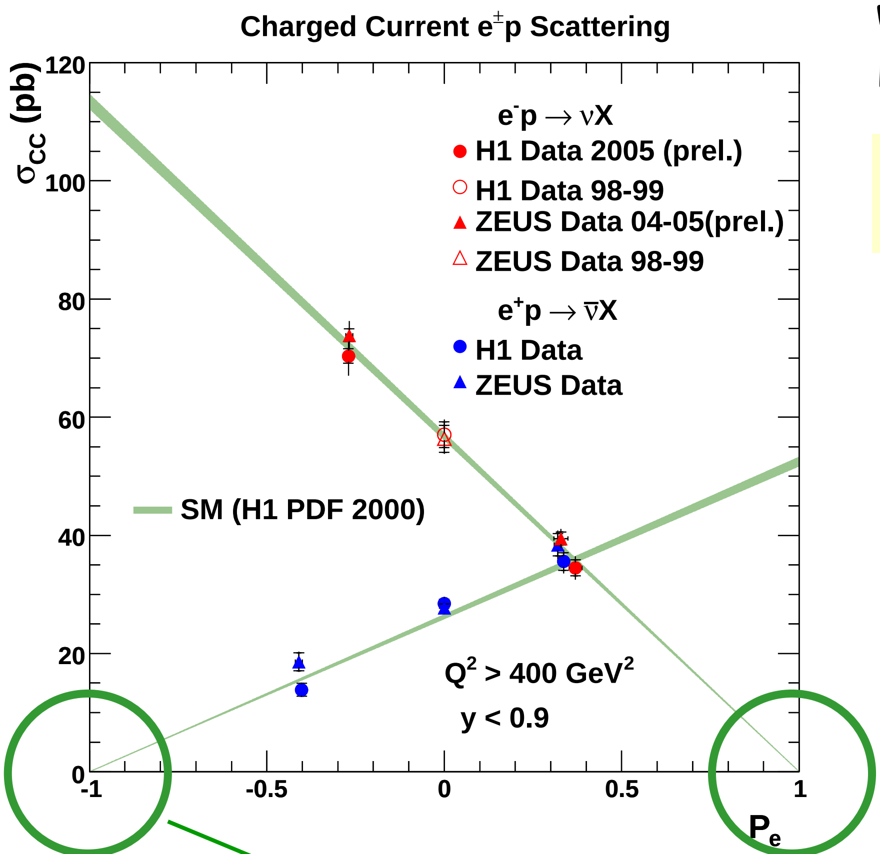
ZEUS $R_q < 0.67 \times 10^{-18}$ m (95% CL)

H1 $R_q < 0.74 \times 10^{-18}$ m (95% CL)

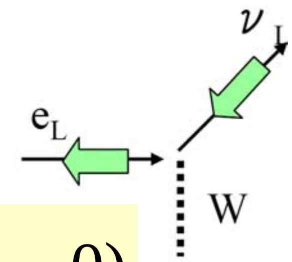


Total CC Cross Section

σ_{CC}^{tot} using longitudinally polarised e^+ and e^- beams



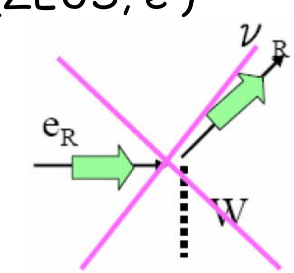
weak CC is pure left-handed (V-A):



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

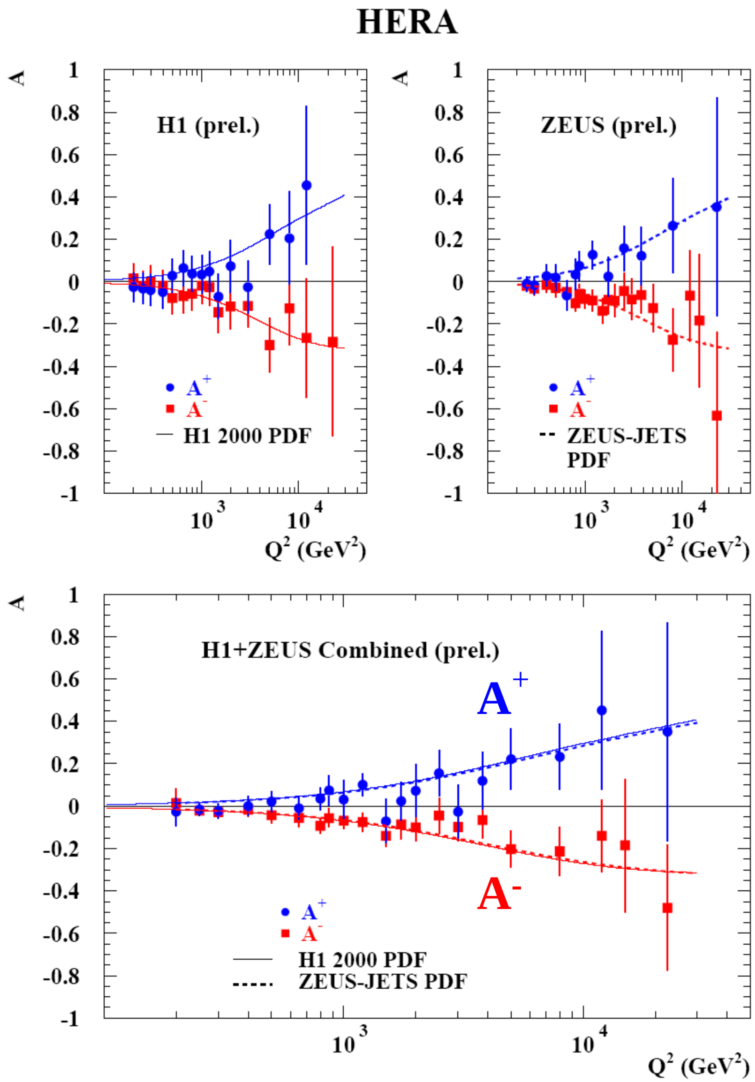
$P_e = (N_R - N_L)/(N_R + N_L)$

- linear dependence is firmly established both for e^+ and e^-
- W_R mass limits at 95% CL ($g_R = g_L$, light ν_R):
  - W_R > 208 GeV (H1, e^-)
  - W_R > 186 GeV (H1, e^+)
  - W_R > 180 GeV (ZEUS, e^-)



absence of right-handed weak current

NC: Polarisation Asymmetry



Polarisation asymmetry (**H1, ZEUS, H1 & ZEUS**):

$$A^{\pm} = \frac{2}{P_e^R - P_e^L} \cdot \frac{\sigma_{NC}^{\pm}(P_e^R) - \sigma_{NC}^{\pm}(P_e^L)}{\sigma_{NC}^{\pm}(P_e^R) + \sigma_{NC}^{\pm}(P_e^L)} \qquad P_e^R > 0 \quad P_e^L < 0$$

→ **a direct measure of parity violation in NC**

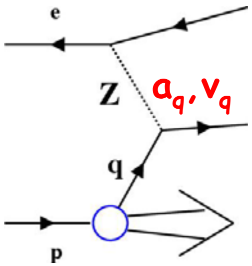
$$A^{\pm} \simeq \mp a_e \kappa \frac{F_2^{\gamma Z}}{F_2} = \pm a_e \kappa \frac{1 + d_v / u_v}{4 + d_v / u_v}$$

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

at low Q² : $A^+ \approx 0$, $A^- \approx 0$

at high Q² : A^+ and A^- are of opposite sign and $A^+ - A^-$ significantly above zero

Light Quark Couplings to Z



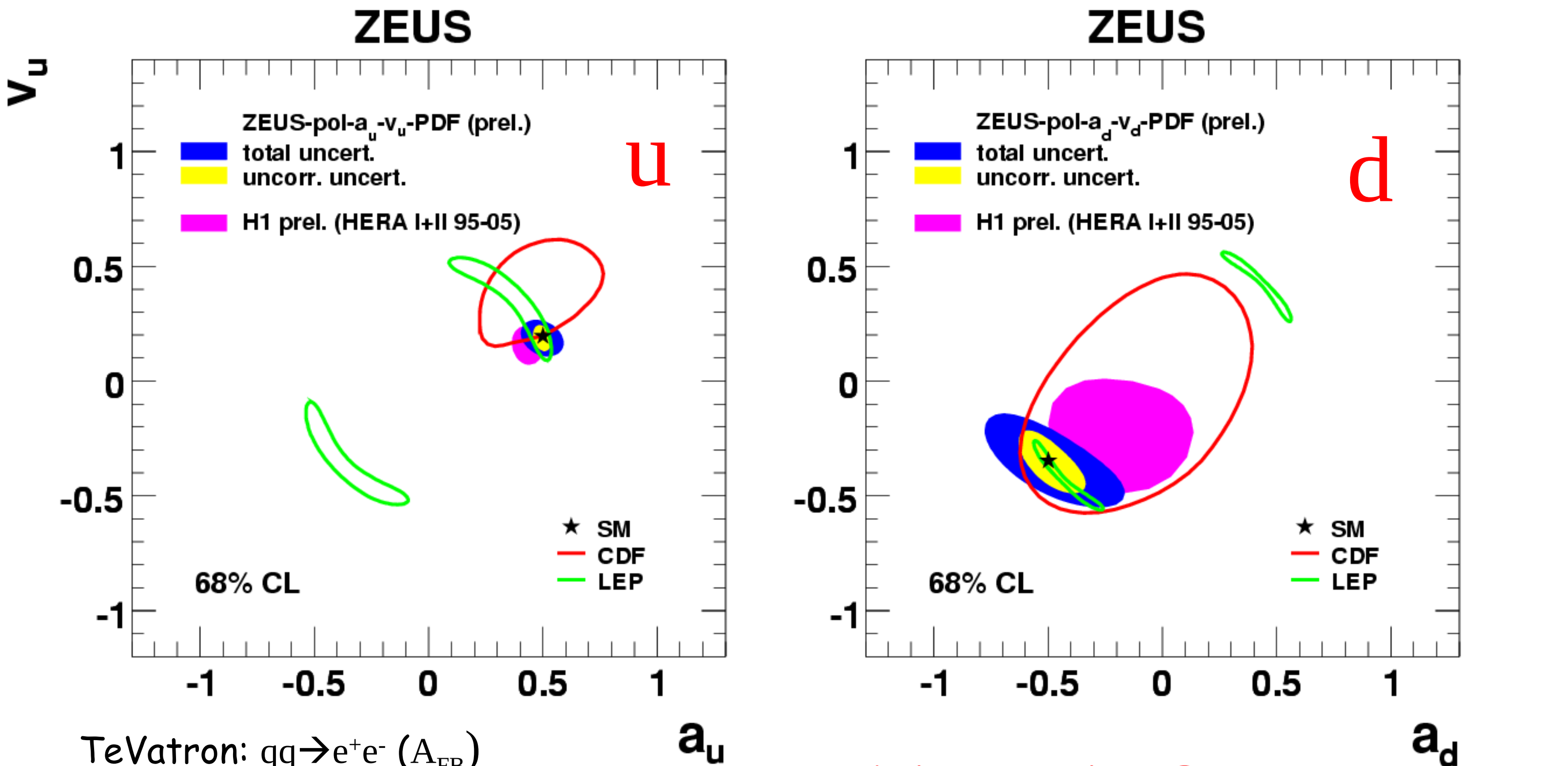
coherent EW+PDF analysis of NC and CC HERA data

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

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

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

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



TeVatron: $q\bar{q} \rightarrow e^+e^-$ (A_{FB})

LEP EWWG: $ee \rightarrow q\bar{q}$ at Z (a^2v^2, a^2+v^2)

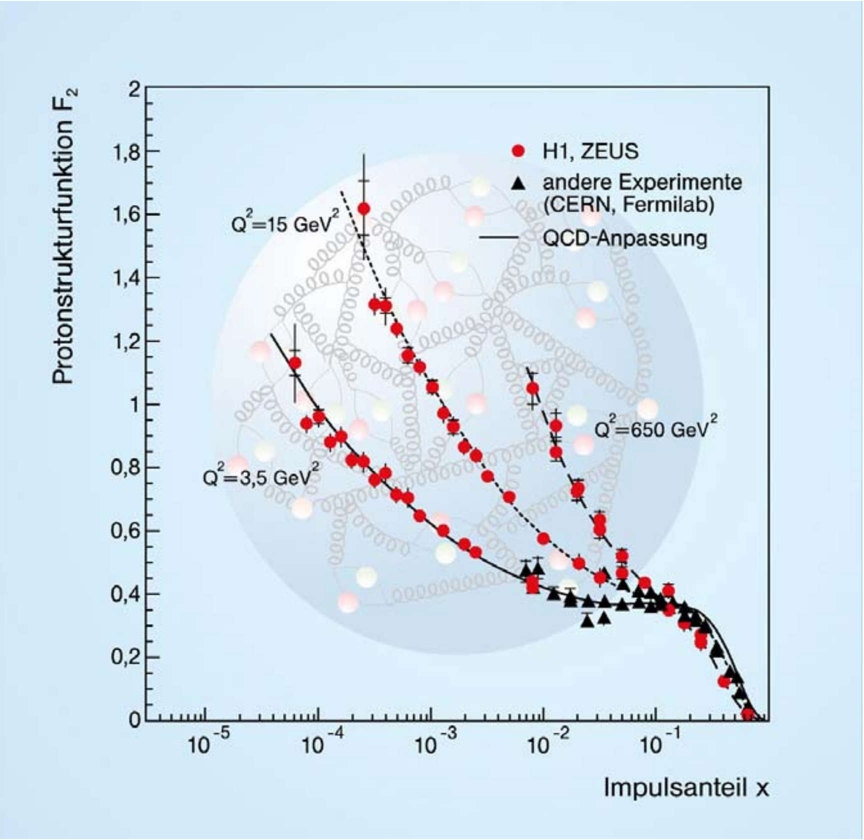
-> help to resolve LEP ambiguity

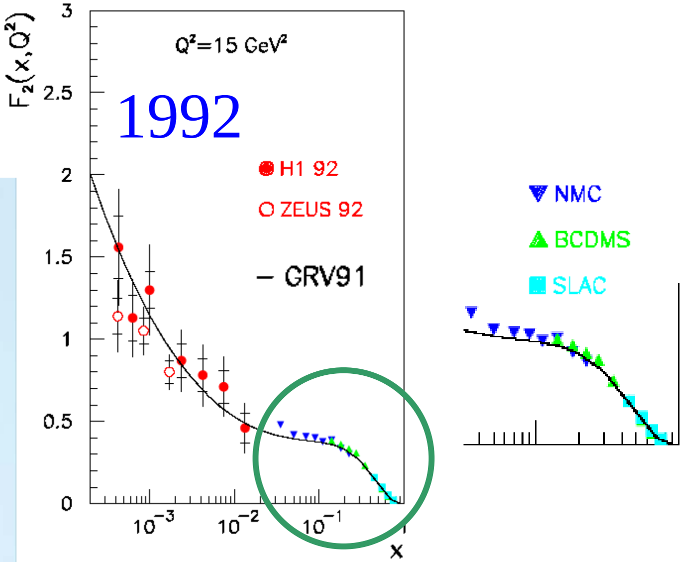
-> the best precision on u quark coupling to Z

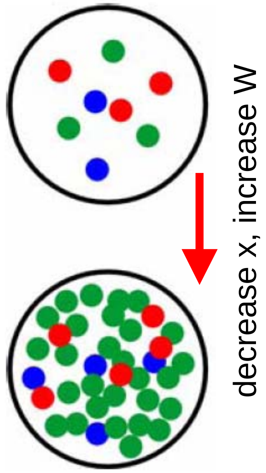
The Rise of F_2 to Low x at HERA

the first HERA data:

-> discovery of the F_2 rise at low x







Nobel Prize Laureate Frank Wilczek:

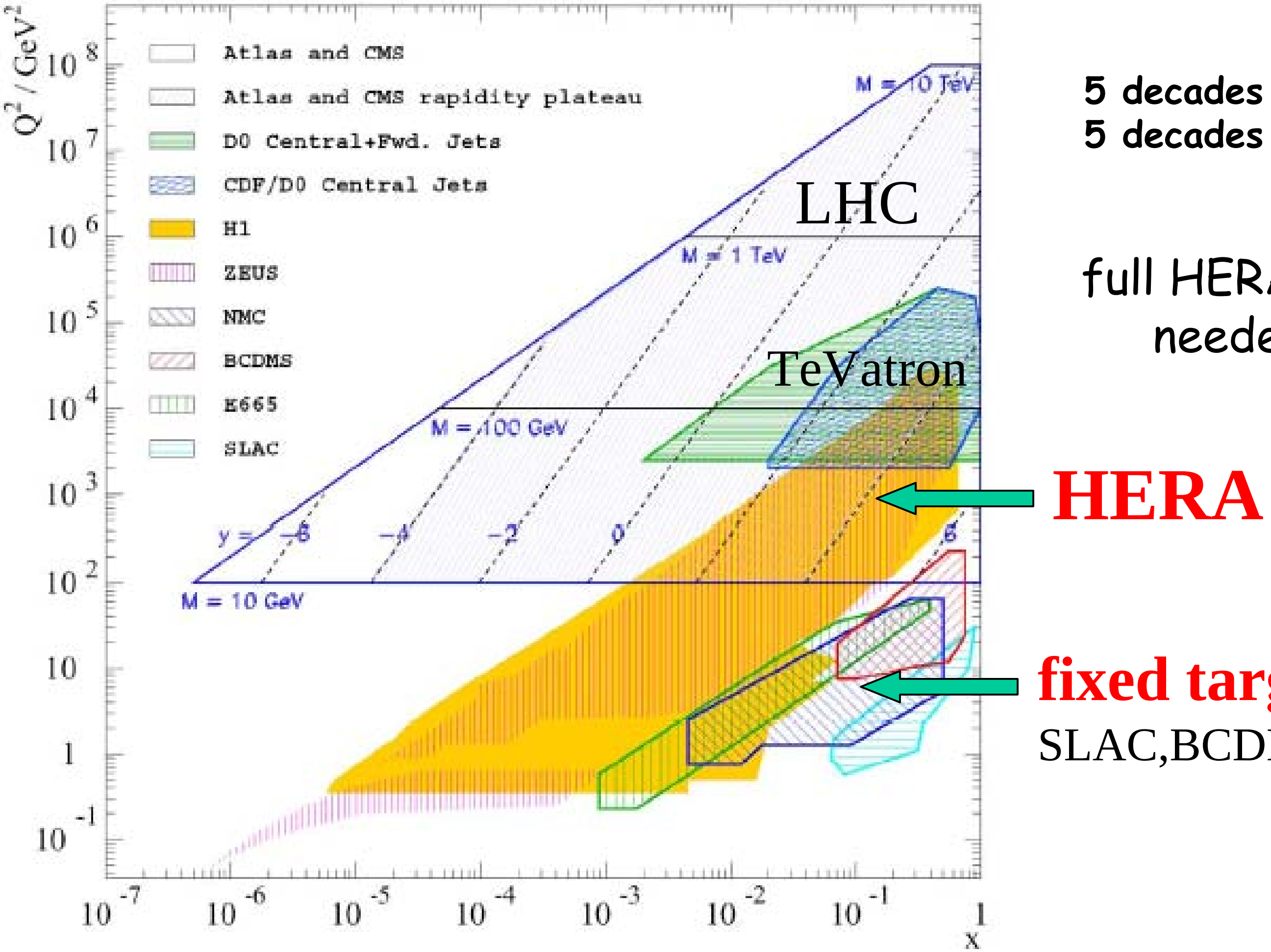
… The most dramatic of these (experimental consequences), that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later. …

-> The rise is driven by gluon

can not rise forever: search for new gluon dynamics

precise data allowi to look for smallest deviations

Kinematic Reach in x and Q^2



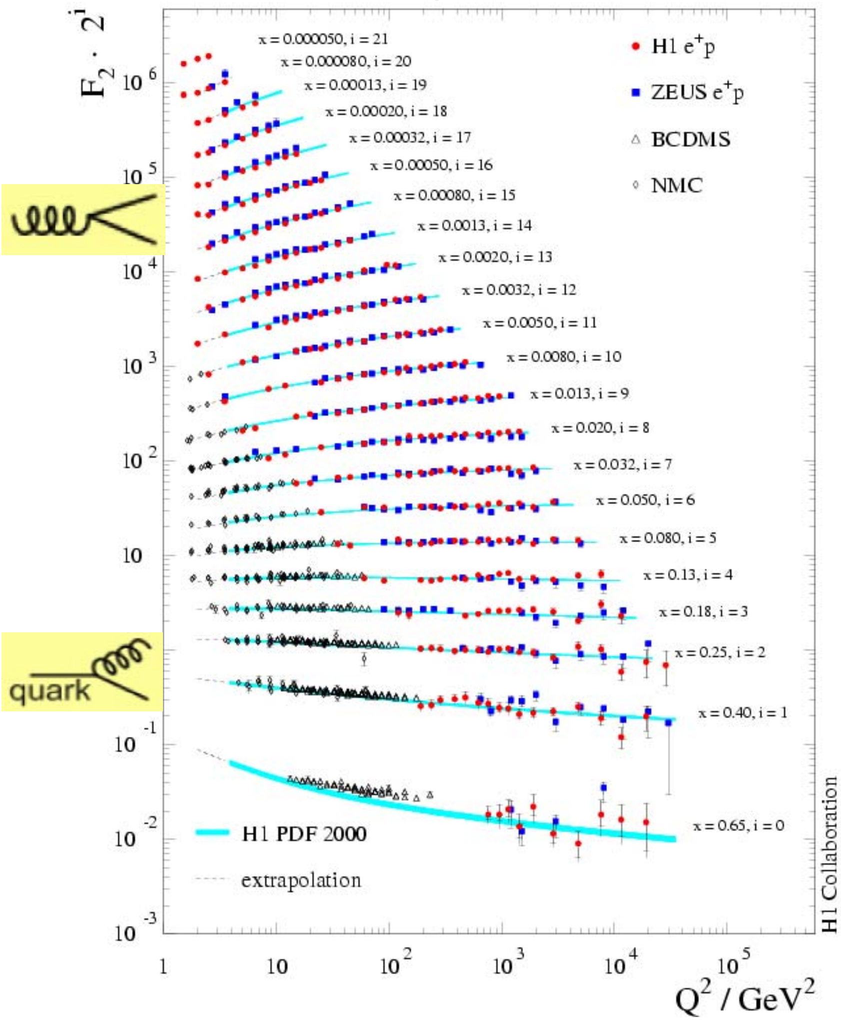
5 decades in x
5 decades in Q^2

full HERA x range is needed for LHC

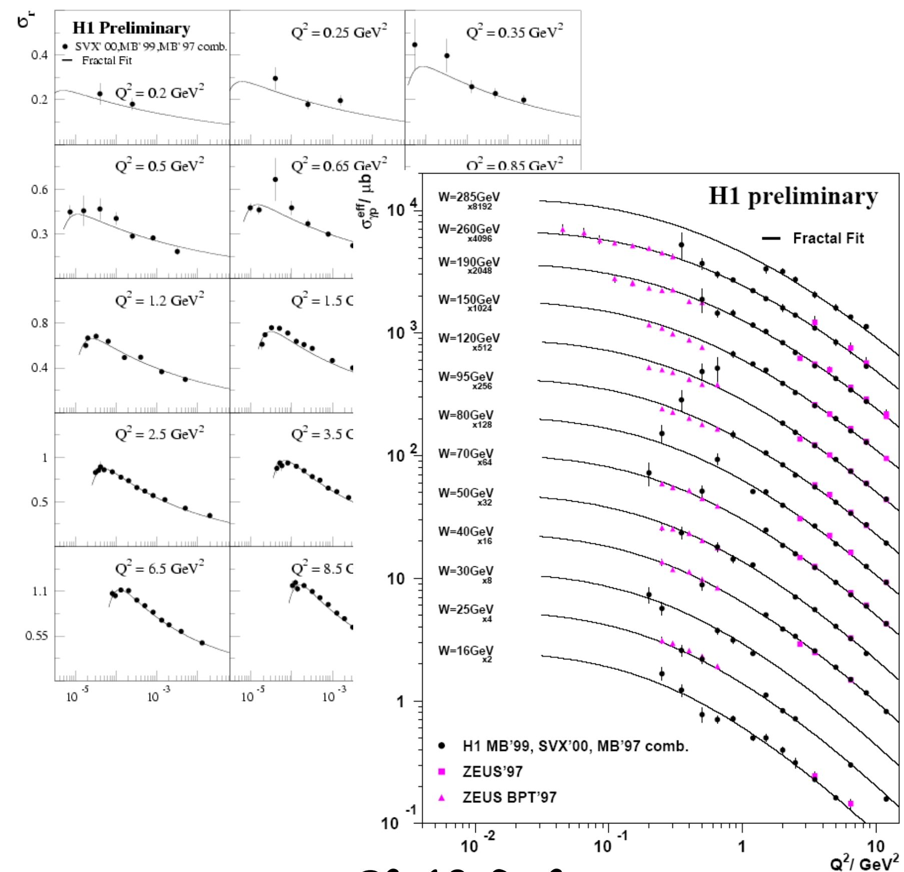
SLAC,BCDMS,NMC,E665, …

Precise SF Data from HERA

Scaling violations



Final word on NC SF at Q^2 < 10 Gev^2



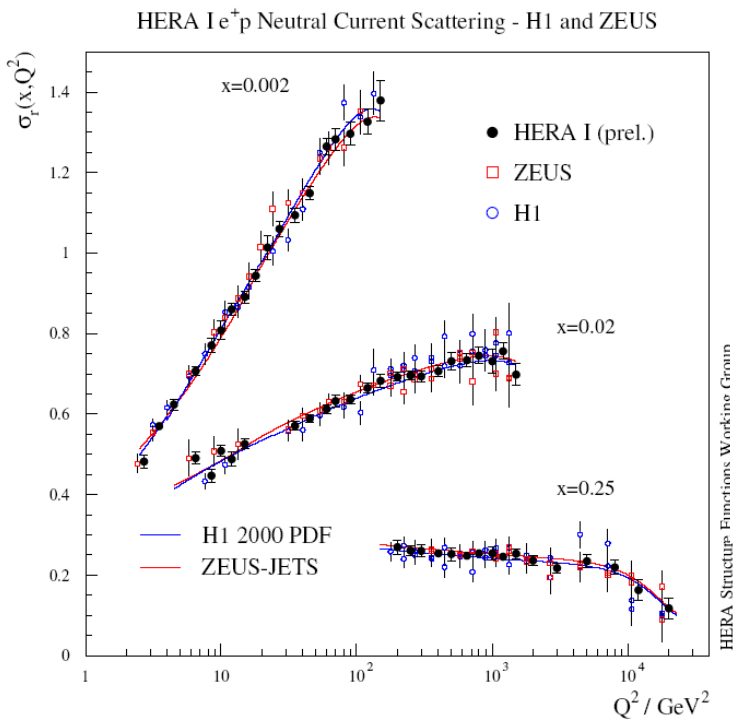
- all H1 data with Q^2<10 Gev^2 are "averaged"
- final precision ±1-2%

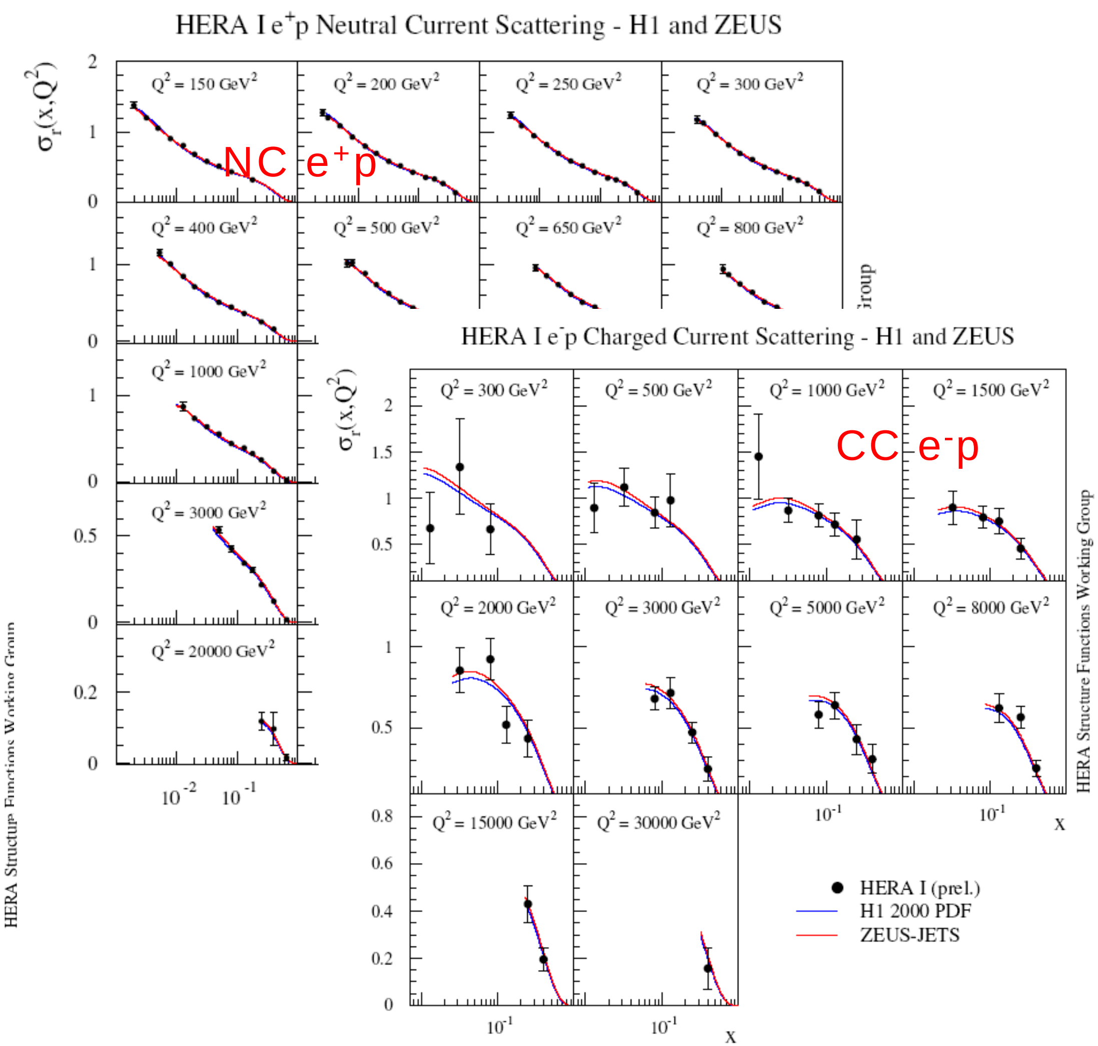
-> rich possibilities to determine pdfs, test QCD, transition from DIS to γp, …

Combined H1+ZEUS Inclusive Cross Sections

Aim: to have "the HERA data set"

expert knowledge in the treatment of correlations between individual data sets



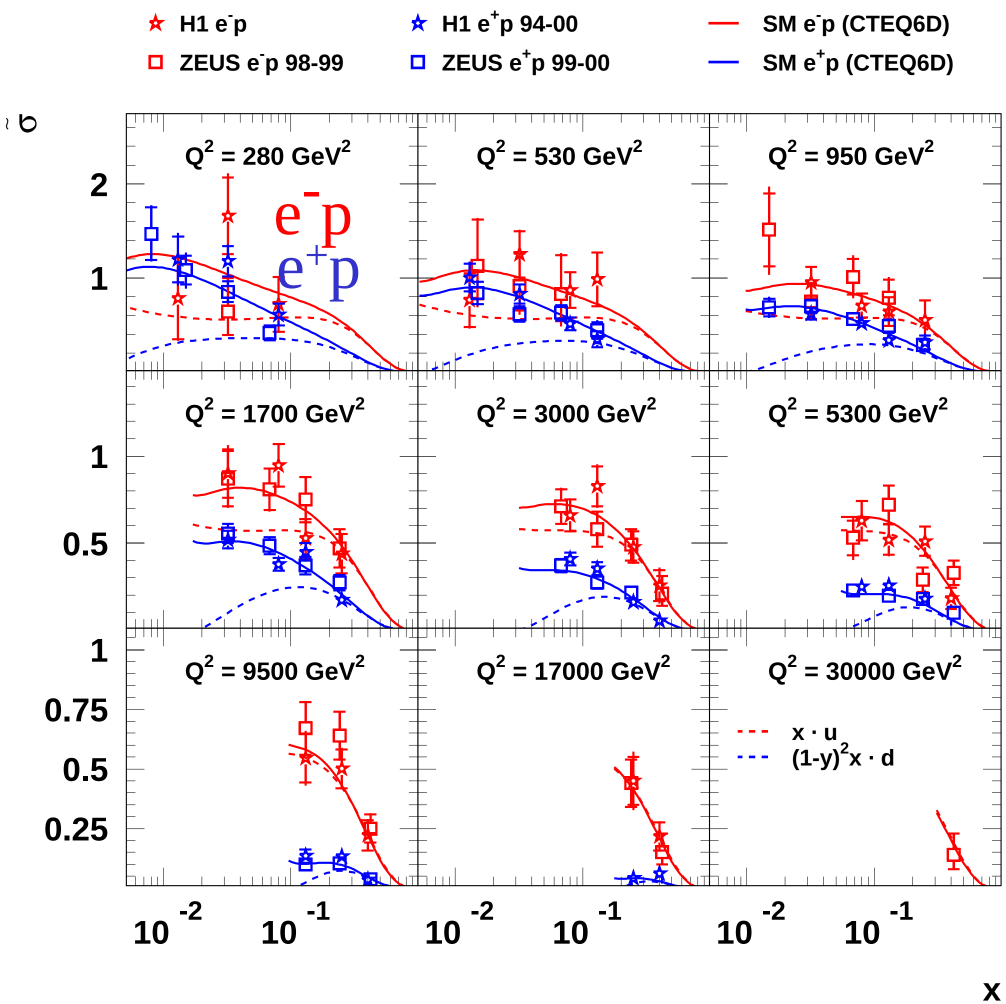


The 1st step: combine all published NC,CC HERA I results (H1 & ZEUS) $1.5 < Q^2 < 30000$ GeV^2

Flavour Separation: Charged Current

$$\frac{d^2\sigma_{CC}(e^{\pm}p)}{dxdQ^2} = \frac{G_F^2 M_W^4}{2\pi x}\frac{1}{(Q^2+M_W^2)^2}\frac{1}{2}\left[Y_+W_2 - y^2W_L \mp Y_-xW_3\right]$$

$\tilde{\sigma}_{CC}(x,Q^2)$ - reduced CC cross section



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

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

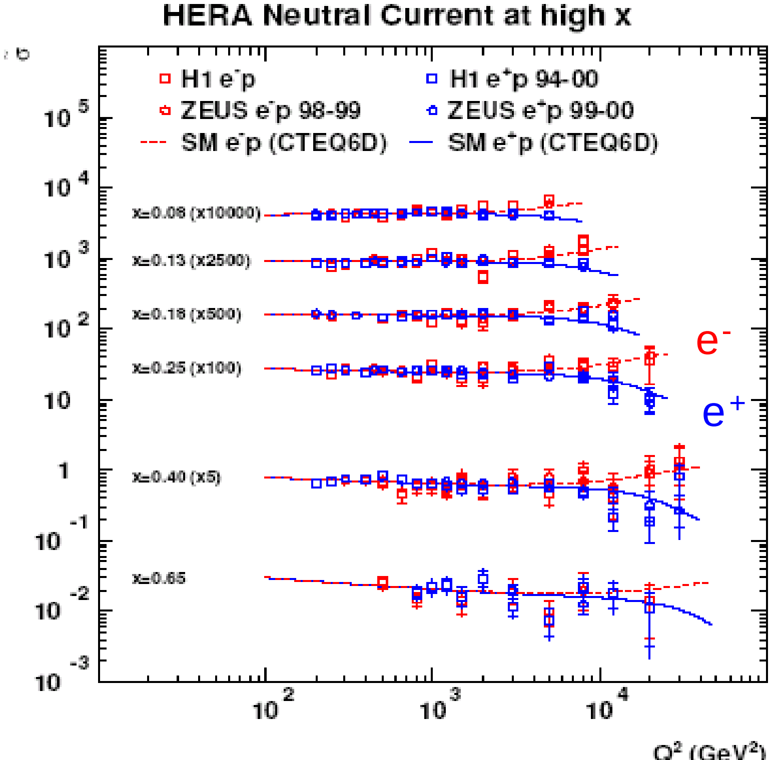
reduced NC cross section:

$$\tilde{\sigma}^{\pm}_{NC} = \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

mostly due to γZ interference →

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

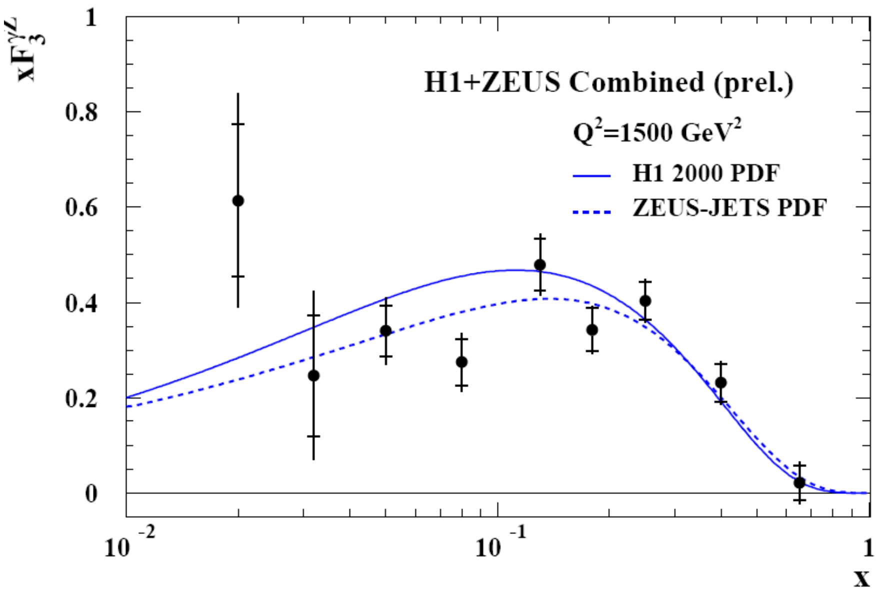
$$xF_3^{\gamma Z} = -x\frac{Y_+}{2Y_-}\left(\tilde{\sigma}^-_{NC} - \tilde{\sigma}^+_{NC}\right)/\,a_e\kappa \sim 2u_v + d_v$$



$xF_3^{\gamma Z}$: little dependence on Q^2

→ **transform to one Q^2 value of 1500 GeV²**

→ **and average (all Q^2 & H1 & ZEUS)**



constrain u_v,d_v at high x :

$$\int_0^1 F_3^{\gamma Z} dx = \frac{1}{3}\int_0^1 (2u_v + d_v)dx = \frac{5}{3}$$

combined H1 & ZEUS results:

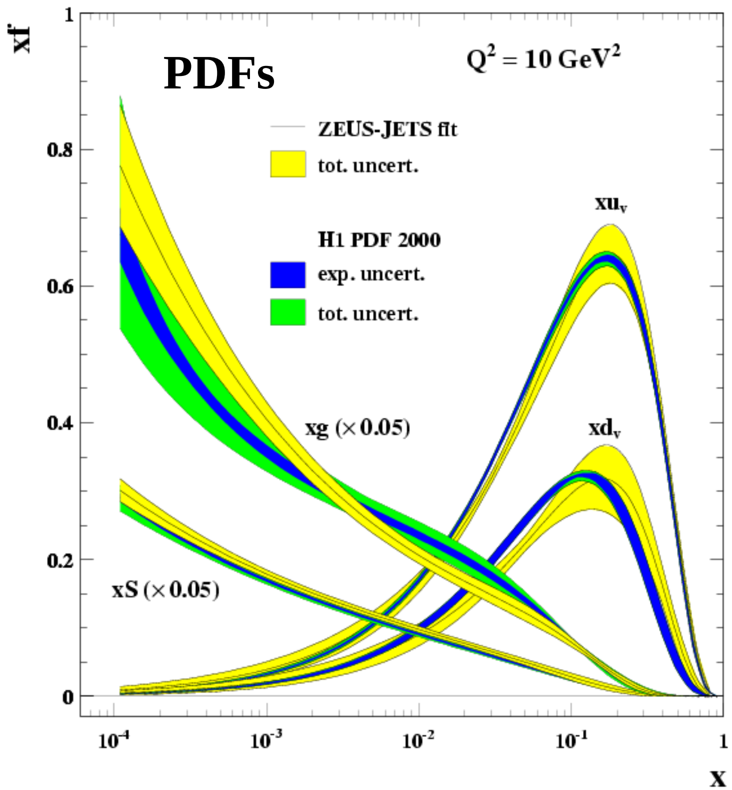
$$\int_{0.02}^{0.65} F_3^{\gamma Z}\, dx = 1.21 \pm 0.09(sta) \pm 0.08(sys)$$

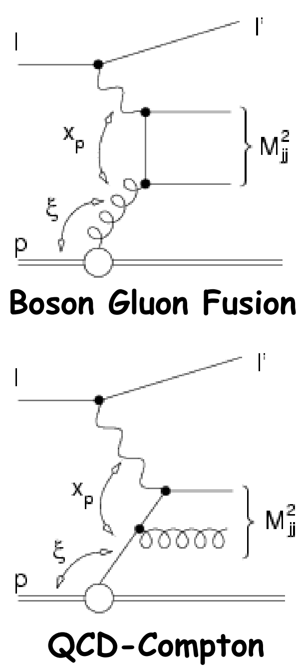
NLO QCD fits: 1.12±0.02 (H1), 1.06±0.02 (ZEUS)

PDFs from HERA

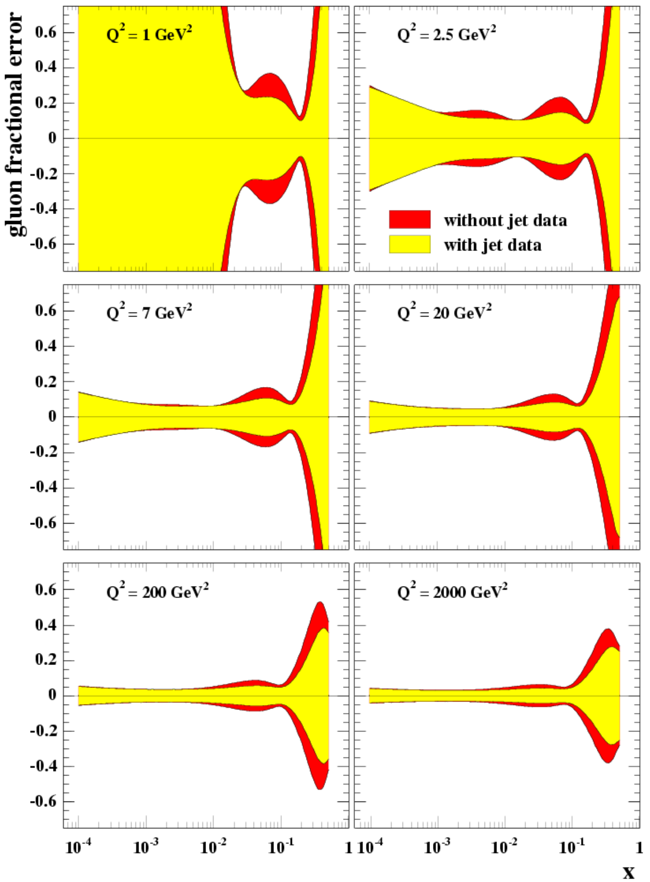
Parton distributions unfolded in NLO QCD fit using the HERA $e^{\pm}$ p data only

Inclusive NC,CC cross sections **(+ jets)**





Gluon uncertainty (with/wo jets)



Gluon and sea are devided by a factor of 20

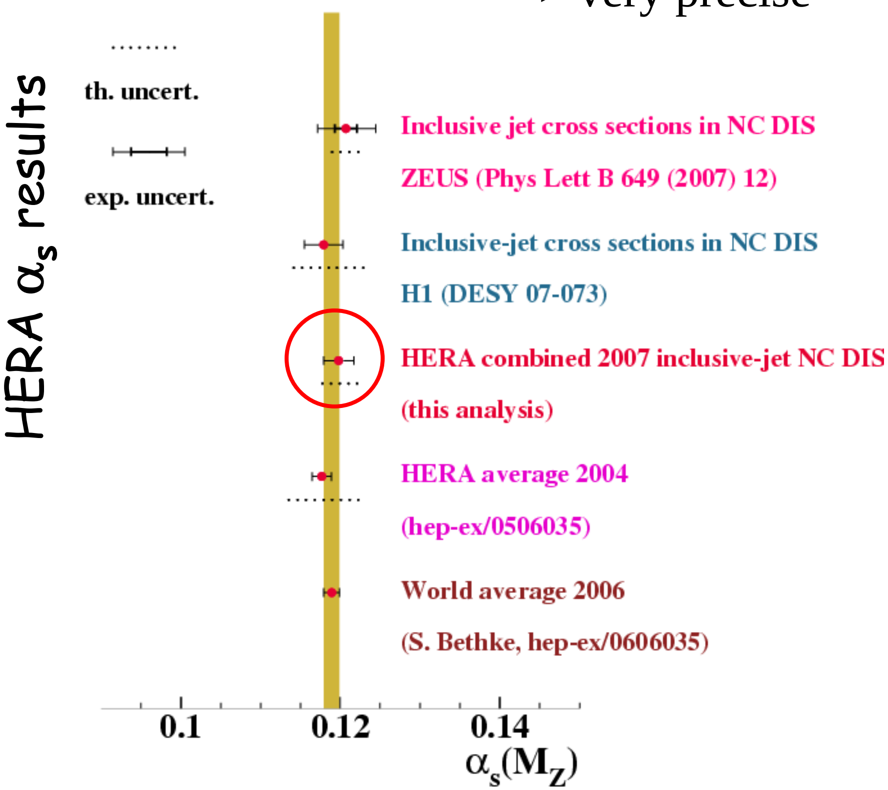
→ jets help to constrain gluon at medium & high x (0.01-0.4)

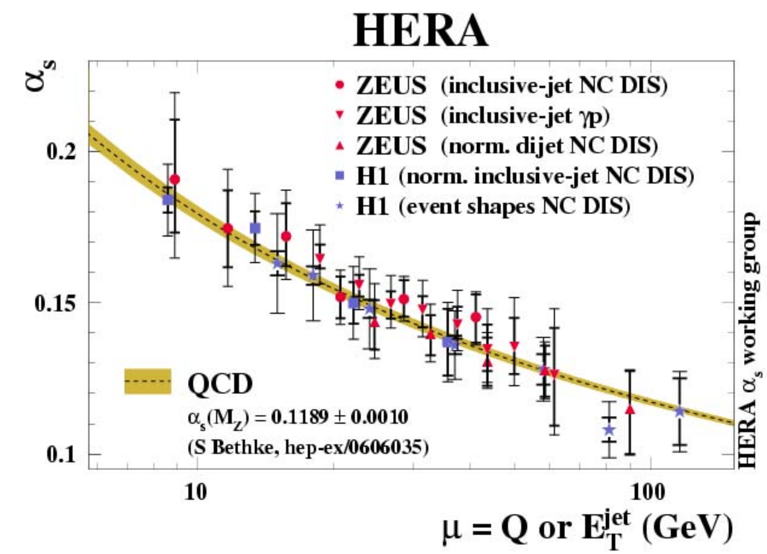
The Strong Coupling α_s at HERA

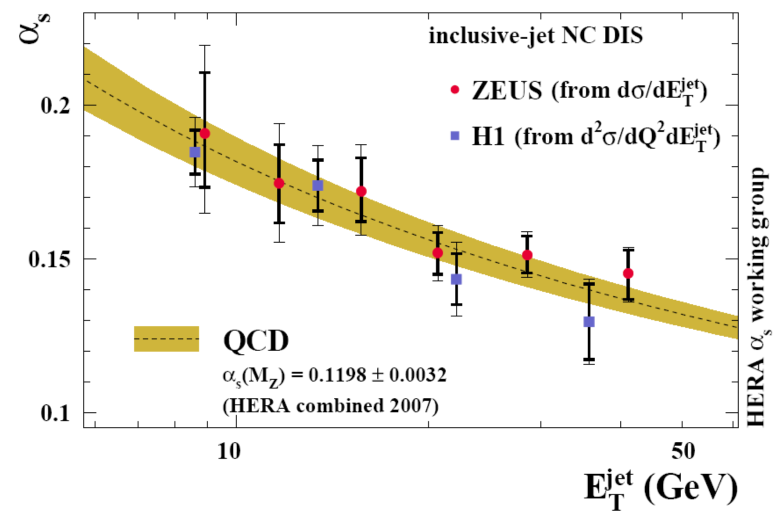
HERA combined 2007:

$$\alpha_s(M_Z^2) = 0.1198 \pm 0.0019(\text{exp.}) \pm 0.0026(\text{th.})$$

-> very precise



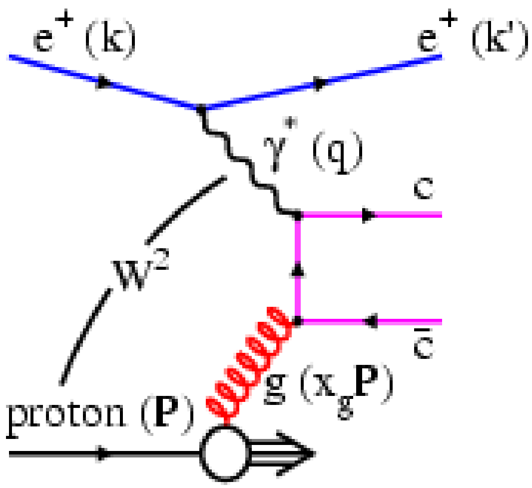


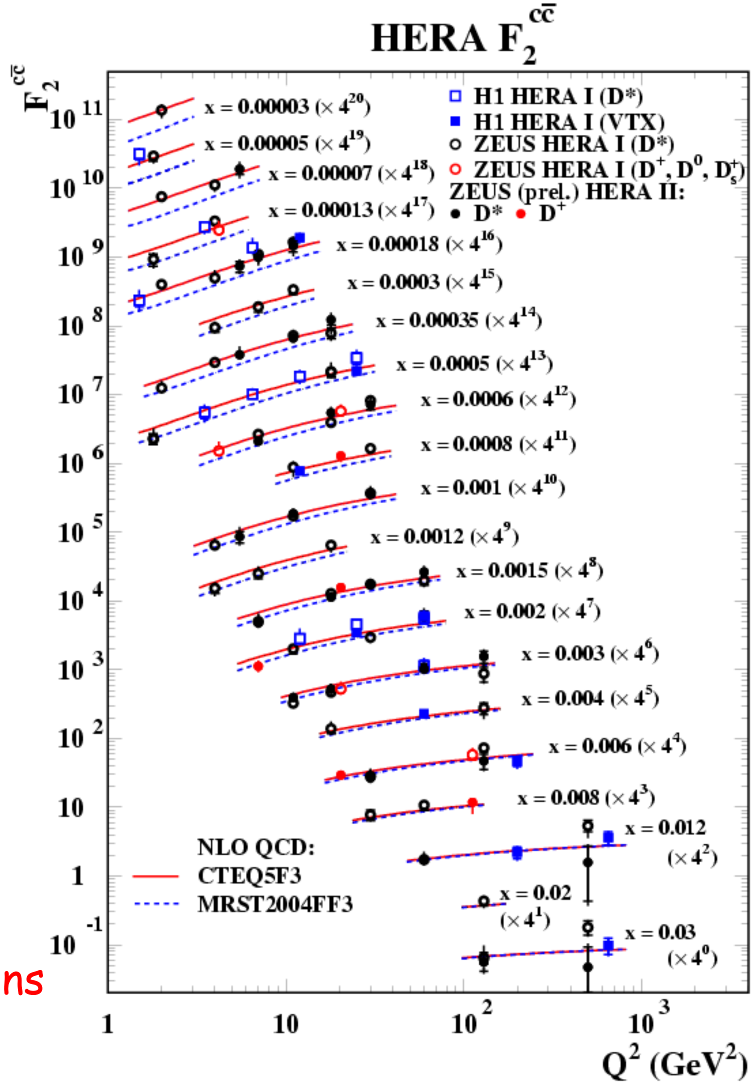


Running of α_s from HERA data alone

Charm Structure Function $F_2^{cc}(x,Q^2)$

Boson Gluon Fusion (BGF)





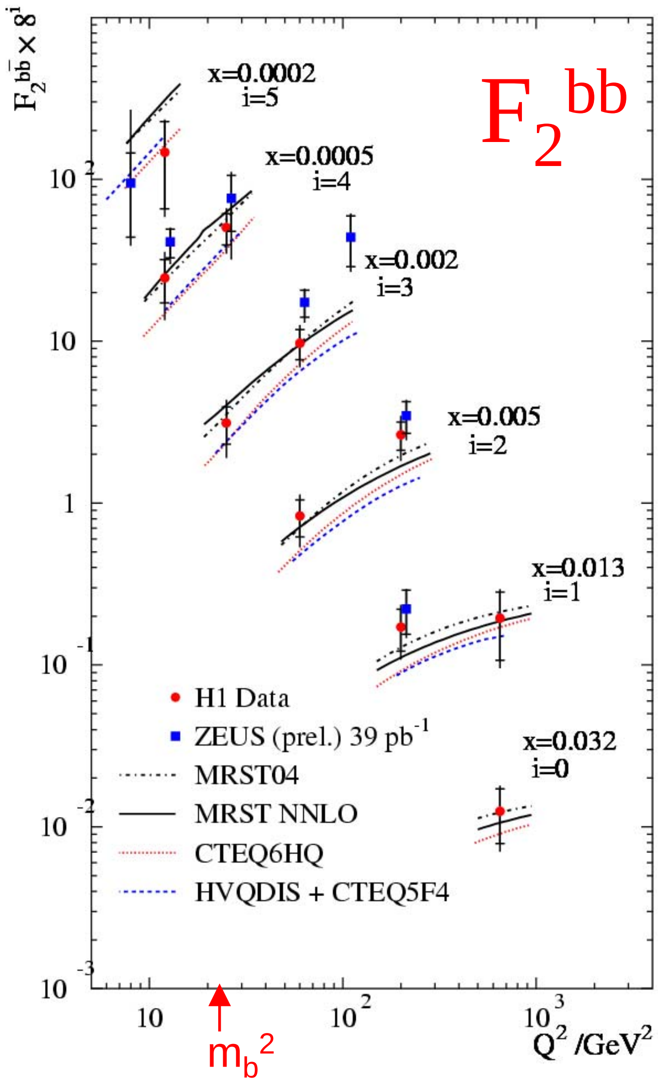
scaling violations of F_2^{cc} are increasing with decreasing of x (similarly to F_2)

→ charm contribution up to 25-30%

→ consistent with gluon from scaling violations

→ heavy quark treatment in QCD fit is very important

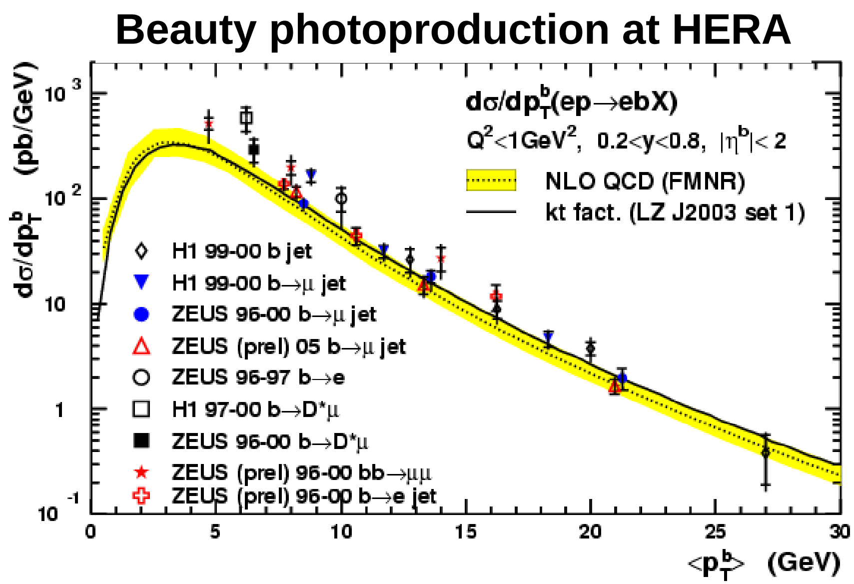
Beauty Structure Function $F_2^{bb}(x,Q^2)$



first F_2^{bb} measurements (inclusive lifetime tag method)

- consistent with pQCD predictions
- beauty fraction increases rapidly with Q^2 from ~0.3% ($Q^2 < m_b^2$) to ~3%

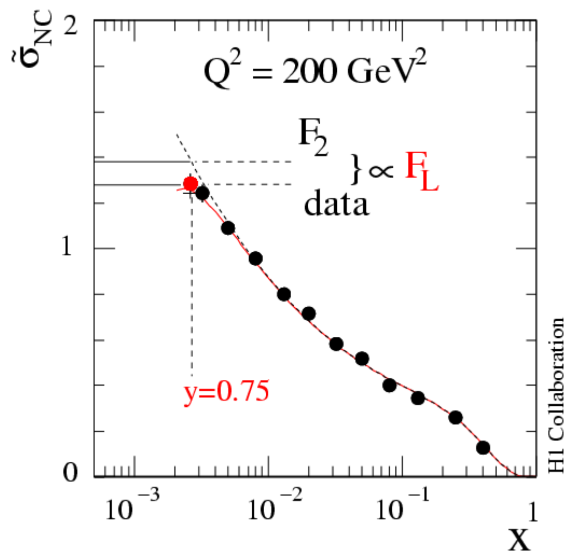
-> important for LHC (e.g. bb->H)



-> beauty photoproduction is in agreement with NLO QCD showing a tendency to be slightly above theory at low p_T^b

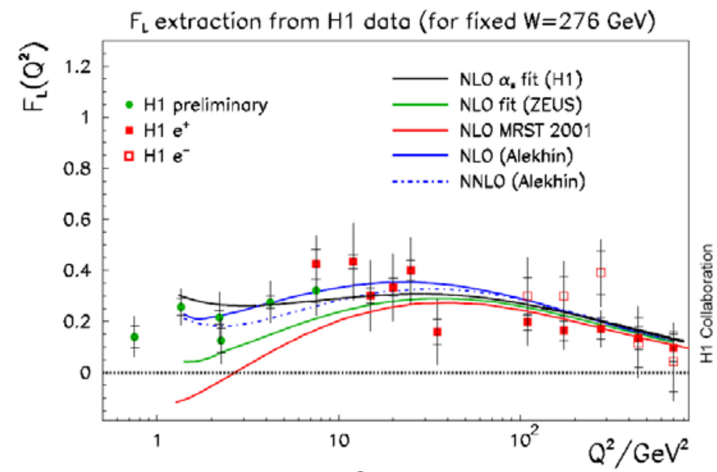
High y Measurements and Determination of F_L

$$\tilde{\sigma}_{NC} = F_2 - \frac{y^2}{Y_+} F_L$$



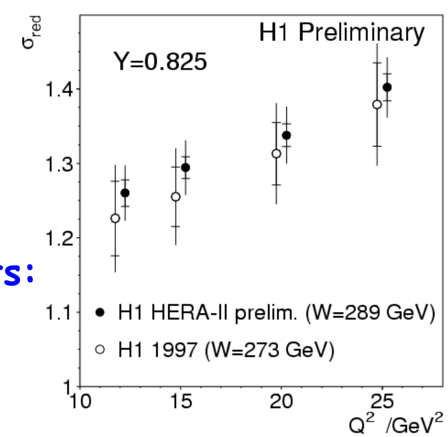
"Determination" of F_L by H1

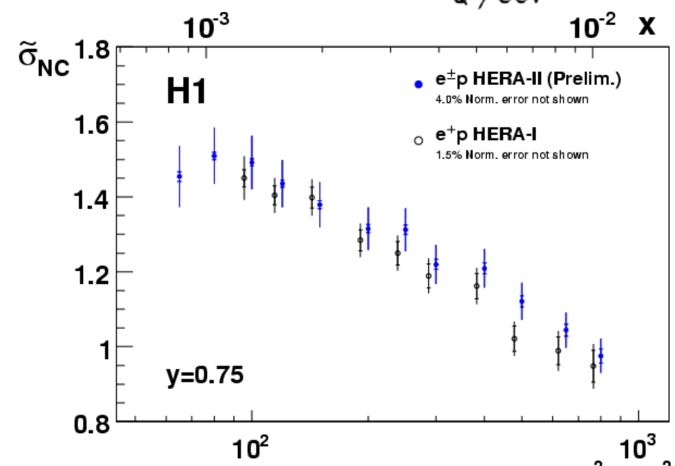
-> by making an assumption about F_2 from the QCD fit, fit $F_2(x)=ce^{-x}$, …



HERA II vs HERA I

recent improvements of the high y measurements:





13th Lomonosov conf.
Moscow 23.08.2007

low proton beam energy running for direct F_L measurements →

Low E_p Data - Direct F_L Measurement

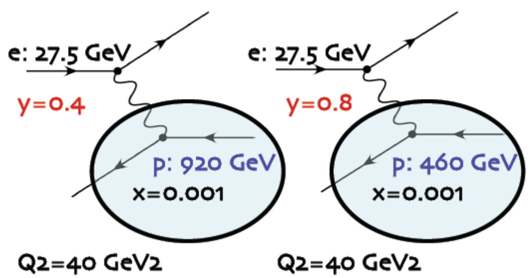
$$\tilde{\sigma}_{NC} = F_2 - f(y) F_L$$

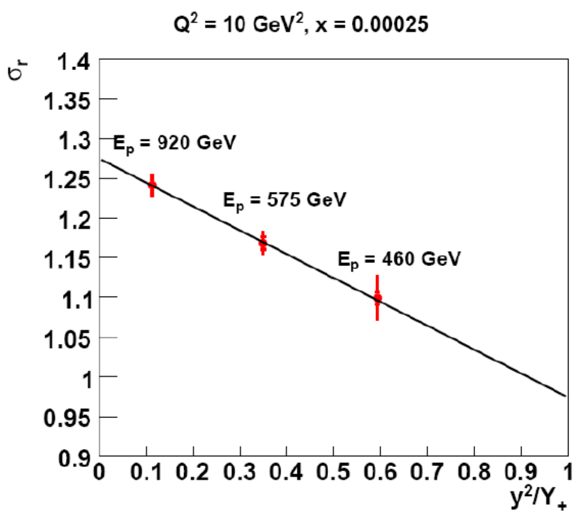
$$f(y) = y^2 / [1 + (1-y)^2]$$

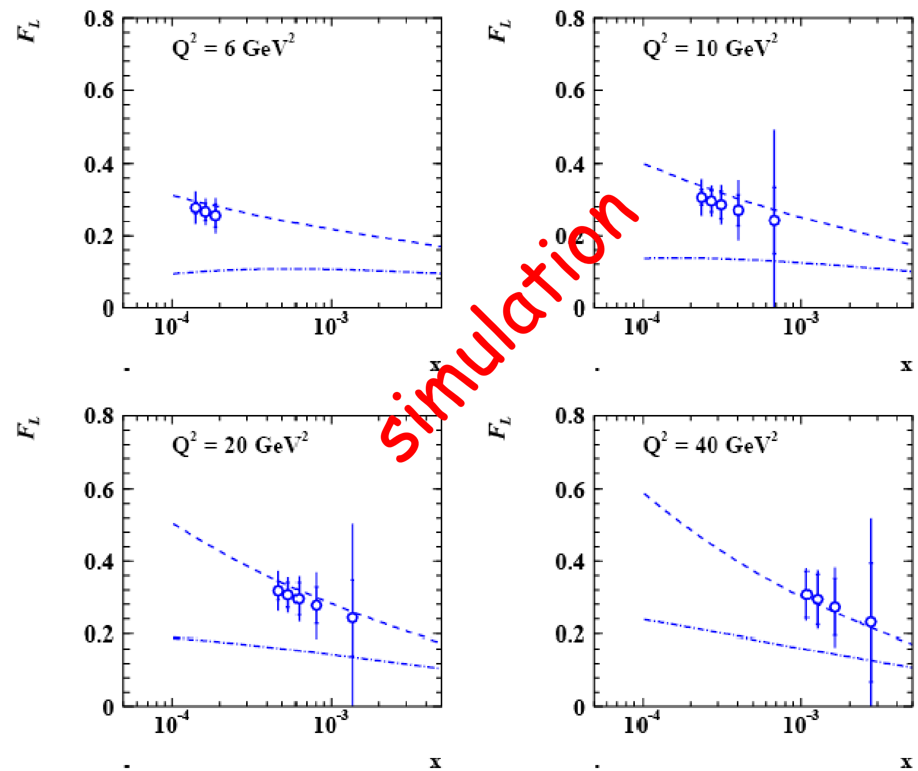
Collected data:

E_p = 460 GeV 13 pb^{-1}

E_p = 575 GeV 7 pb^{-1}

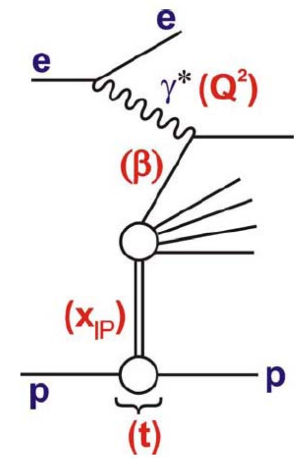






FL measurements should allow to distinguish between different PDFs (MRST, CTEQ)

Hard Diffraction & DPDFs



QCD factorisation in diffraction:

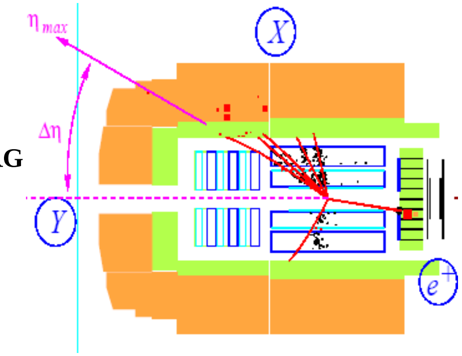
$$\sigma(\gamma^* p \rightarrow Xp) \approx p_{q/p}(x_{IP}, t; x, Q^2) \otimes \hat{\sigma}_{\gamma^* p}(x, Q^2)$$

$$f_{IP/p}(x_{IP}, t) \otimes p_{q/p}(\beta, Q^2)$$

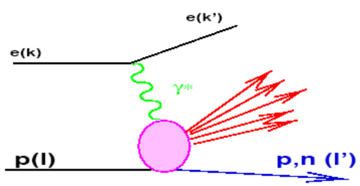
(Regge factorisation)

Typically ~10% at HERA
~1% at TeVatron

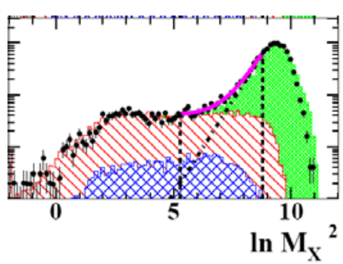
LRG

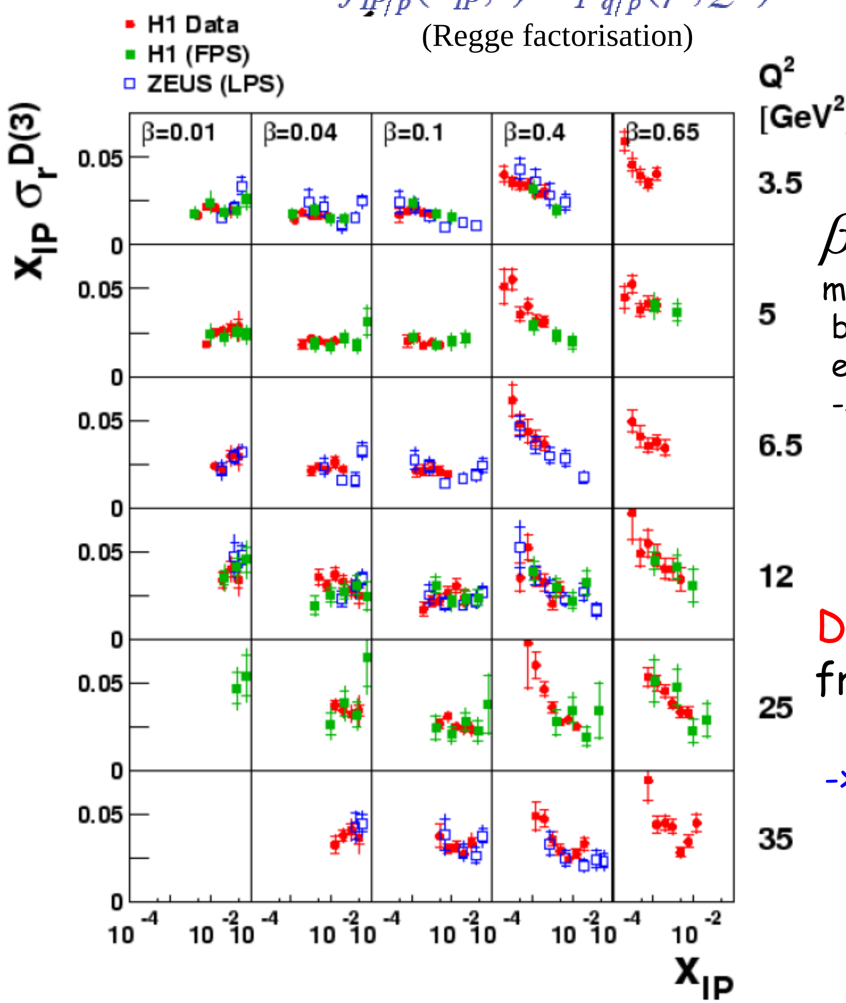


LPS



Mx





$$\beta = x / x_{IP}$$

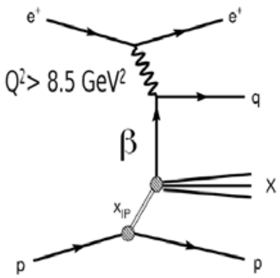
momentum fraction carried by a parton of the colorless exchange (pomeron)
-> two gluons exchange ?

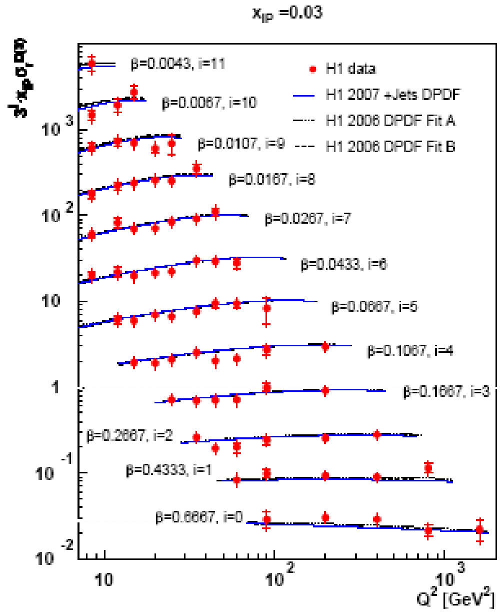
Diffractive PDFs
from the fit to $\sigma_r^{D(3)}$

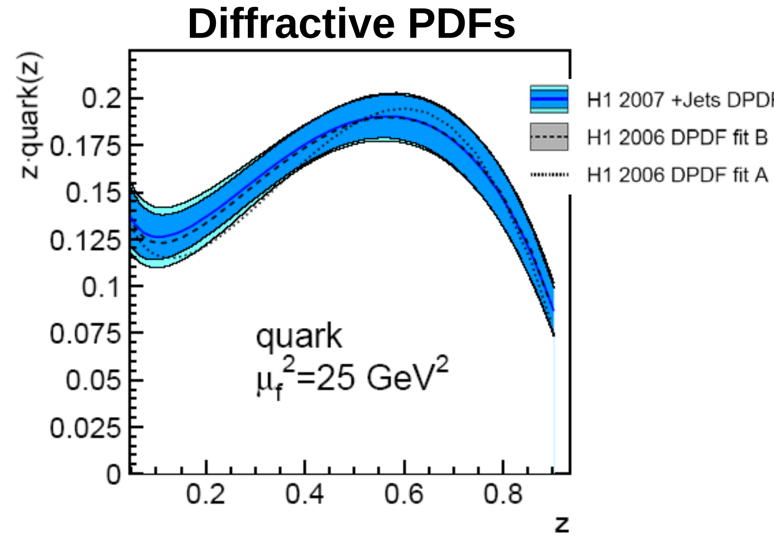
-> predictions for diffr. final states jets, D*, ...

Diffractive PDFs from “Inclusive + Jets”

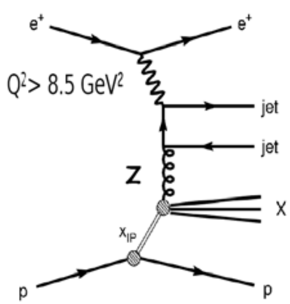
inclusive diffraction

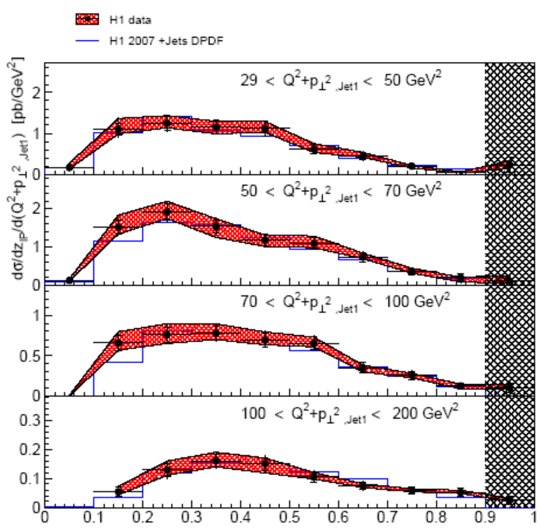


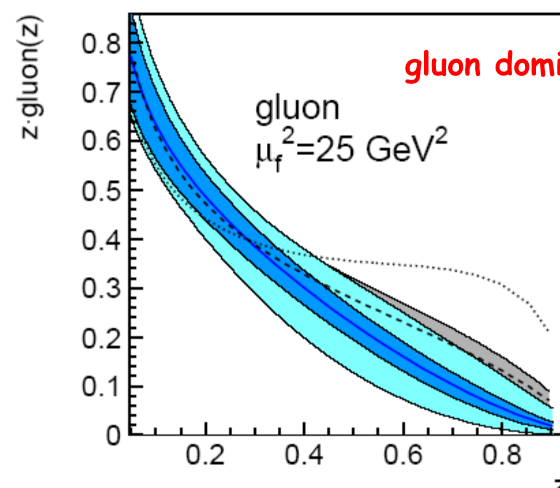




add diffractive dijets into NLO fit







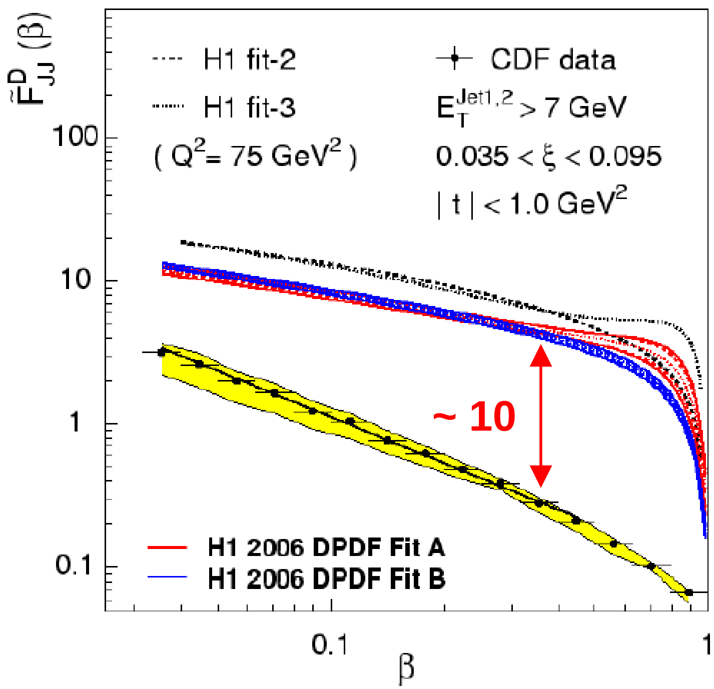
gluon dominates (~70%)

-> consistent picture
-> dijets help to improve gluon density at high β

Factorisation Breaking in Diffraction

Fact. breaking in ppbar

diffr. dijets at CDF



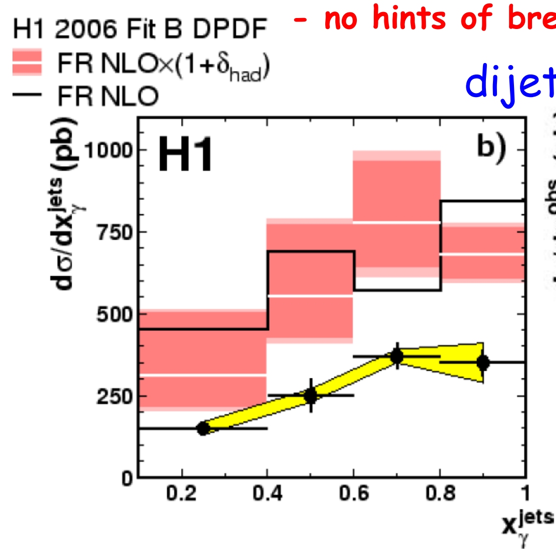
Calculations using DPDFs from HERA are 10 times higher than measured dijet cross sections at CDF

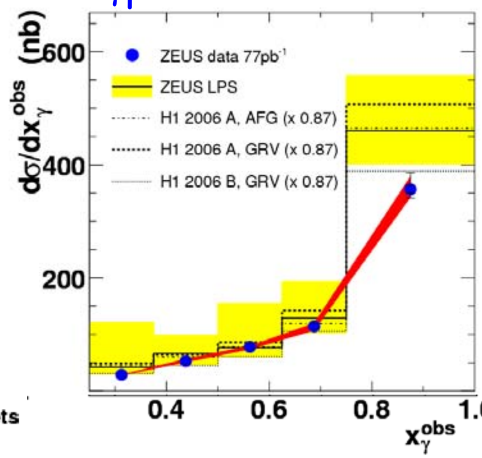
-> gap survival probability

Tests of QCD fact. at HERA

- **factorisation works nicely in DIS dijets and D* (as expected)**
- **no hints of breaking in D* in γp**

dijets in γp





H1 sees a global suppression ~ 0.5

ZEUS does not see suppr. (due to harder jets ?)

-> needs clarification

-> important for LHC

Conclusions

After 15 years of data taking HERA finished its operation in June 2007

- in total H1+ZEUS collected ~ 1 fb^{-1} about equally shared between different polarity and polarization of the e beam

Rich physics output from HERA

- search for new physics ongoing -> no signs for new physics found 1.8-3.0 σ effect on isolated leptons remains
- high $Q^2 > \sim m_Z^2, m_W^2$: EW physics -> text book plots
- physics program centered around QCD : -> SF, PDFs, jets, HQ, α_s, diffraction, VM, …

New step in the HERA program

- make full use of statistics, reach ultimate precision in systematics
- the "HERA final results" : H1+ZEUS (combined working groups)

-> provide information essential for LHC collider and beyond