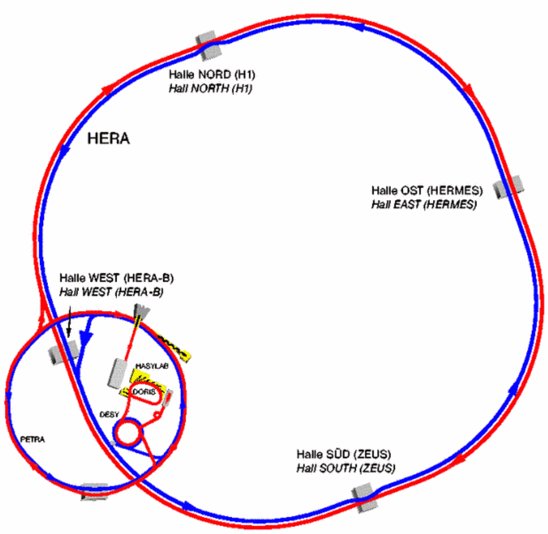
Physics at HERA

UCSB: January 12 - 16, 2004
Conference on Collider Physics
Günter Wolf (DESY)

- Recent results from the HERA collider experiments
  - Large Q^2 scattering
  - Structure functions
  - Search for new physics
  - Diffractive scattering
  - HERAII and physics prospects

HERA electron-proton collider at DESY

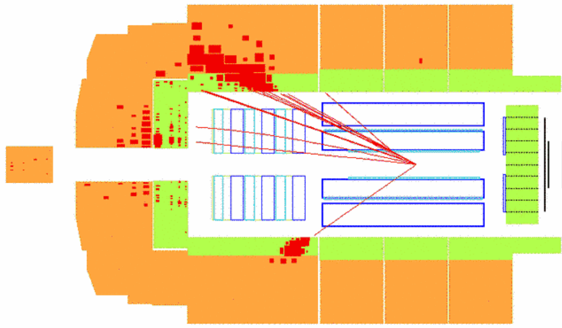


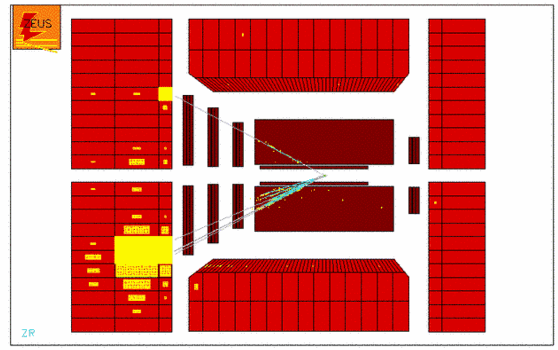
27.5 GeV e → ← 920 GeV p

e p c.m. energy $s^{1/2}$ = 318 GeV

run period	e beam	lumi (pb^{-1}) H1	ZEUS
1994 - 1997	e^+	37	48
1999 - 2000	e^+	65	66
sum	e^+	102	114
1998 - 1999	e^-	14	17

H1 and ZEUS collider experiments





Liquid Argon Calorimeter

44 000 cells

$\sigma_{\theta_e} = 2 - 5$ mrad

$\sigma/\sqrt{E} = 12\%$ electron

$\sigma/\sqrt{E} = 50\%$ hadron

Uranium-Scintillator Calorimeter

6 000 cells read out by 12000 PMT's

$\sigma_{\theta_e} = 5$ mrad

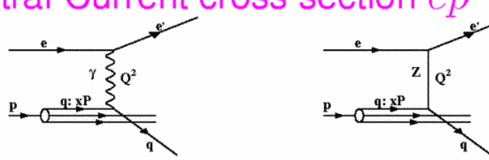
$\sigma/\sqrt{E} = 18\%$ electron in test beam

$\sigma/\sqrt{E} = 35\%$ hadron in test beam

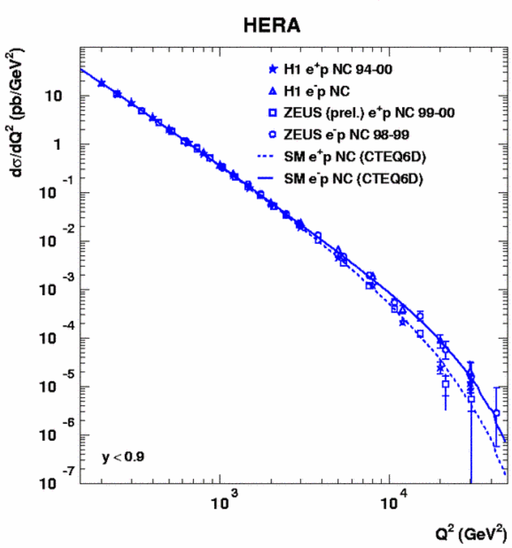
99% solid angle coverage with calorimetry

plus tracking, vertex, μ and leading e, p, n detection

Neutral-Current cross section $ep \to eX$



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



$$F_2^{NC} = \frac{1}{2}\sum_f xq_f^+ \left[(V_f^L)^2 + (V_f^R)^2 + (A_f^L)^2 + (A_f^R)^2\right]$$

$$xF_3^{NC} = \sum_f xq_f^- [V_f^L A_f^L - V_f^R A_f^R]$$

$$xq_f^{\pm} = xq_f(x,Q^2) \pm x\bar{q}_f(x,Q^2)$$

$$V_f^{L,R} = e_f - (v_e \pm a_e)\, v_f$$

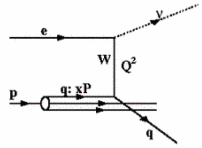
$$A_f^{L,R} = -(v_e \pm a_e)\, a_f \chi_Z(Q^2)$$

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

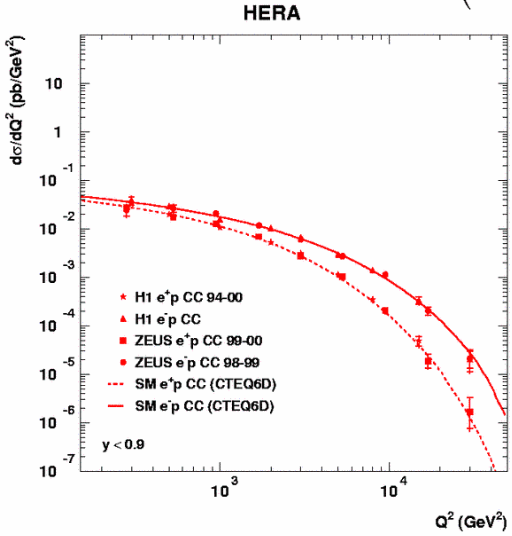
interference γ/Z opposite sign for e^-p, e^+p

$\Longrightarrow$ direct detection of weak contribution

Charged-Current cross section $ep \to \nu X$



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



$$e^-p: F_2^{CC} = x[u(x,Q^2) + c(x,Q^2) + \bar{d}(x,Q^2) + \bar{s}(x,Q^2)]$$
$$xF_3^{CC} = x[u(x,Q^2) + c(x,Q^2) - \bar{d}(x,Q^2) - \bar{s}(x,Q^2)]$$
$$e^+p: F_2^{CC} = x[d(x,Q^2) + s(x,Q^2) + \bar{u}(x,Q^2) + \bar{c}(x,Q^2)]$$
$$xF_3^{CC} = x[d(x,Q^2) + s(x,Q^2) - \bar{u}(x,Q^2) - \bar{c}(x,Q^2)]$$

$Q^2 < 2000$ GeV^2: slow fall-off with Q^2

$\to$ due to large M_W in propagator

$Q^2 < 500$ GeV^2: sea quarks dominate

$\to$ same cross section for e^-p and e^+p

$Q^2 > 1000$ GeV^2: valence q dominate

$\to \sigma^{CC}_{e^-p} > \sigma^{CC}_{e^+p}$

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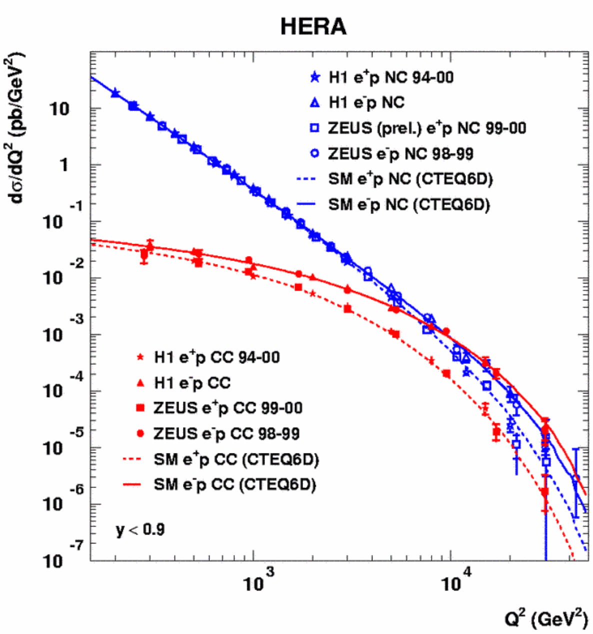
Electroweak unification



$Q^2 < 1000$ GeV^2:

$\sigma^{NC} \gg \sigma^{CC}$ due to γ vs W propagator

$Q^2 \geq 10000$ GeV^2:

unification of weak and electromag forces

Standard Model (curves)

gives an excellent description of the four cross sections

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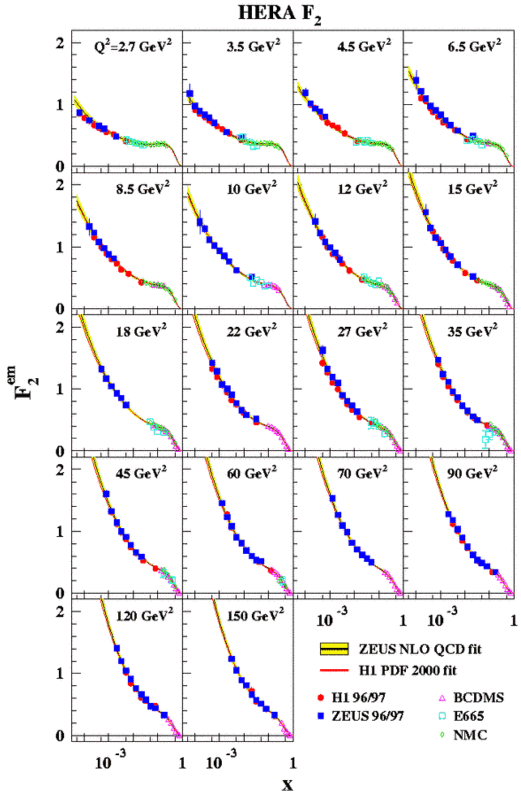
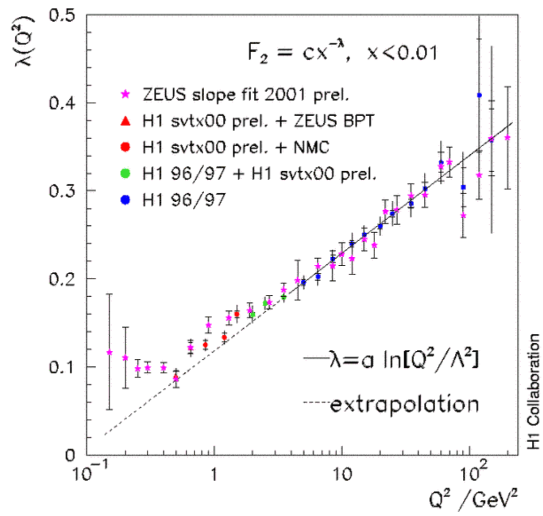
Structure function F_2 vs x



$F_2(x, Q^2) = \sum_q eq^2 x \cdot q(x, Q^2)$

$\Longrightarrow$ rapid rise of F_2 as $x \to 0$

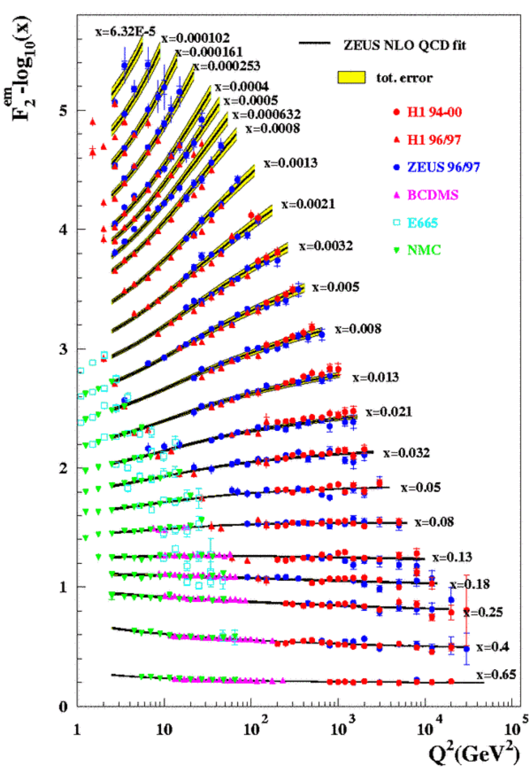
parametrize $F_2 = c \cdot x^{-\lambda}$



for $Q^2 < 70$ GeV^2: $\lambda \propto \ln Q^2$

NO SLOW DOWN of F_2 rise observed yet

Structure function F_2 vs Q^2



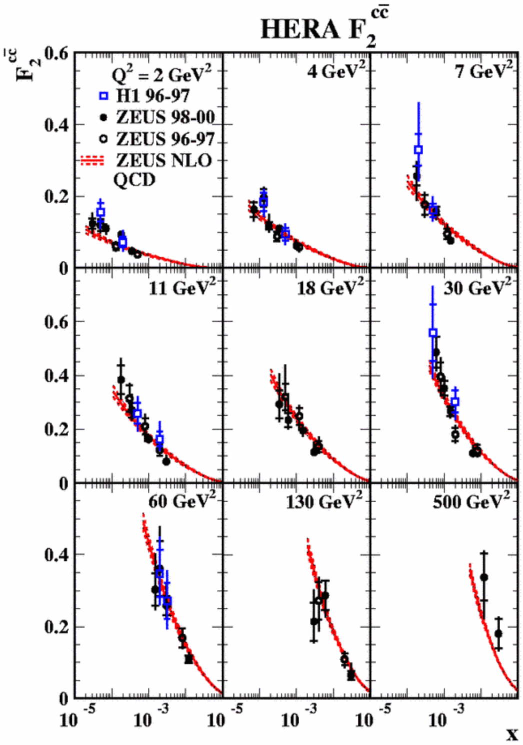
$x > 0.1$: data span four decades of Q^2

$x > 0.13$: negative log scaling violations

$x < 0.08$: positive log scaling violations

Standard Model gives an excellent description of the Q^2 dependence of F_2

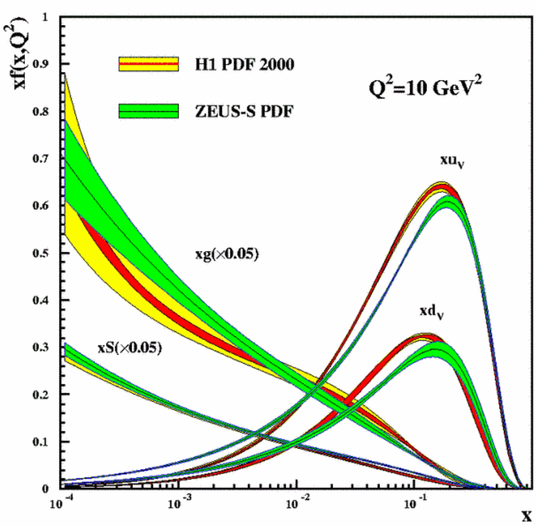
F_2: heavy quark contribution

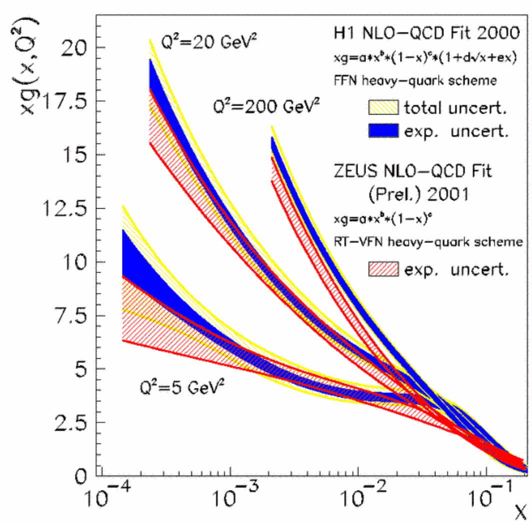


x, Q^2 dependence of F_2^{cc} similar to F_2

very roughly: $F_2^{cc}/F_2 = \frac{4/3}{13/3}$

Parton densities



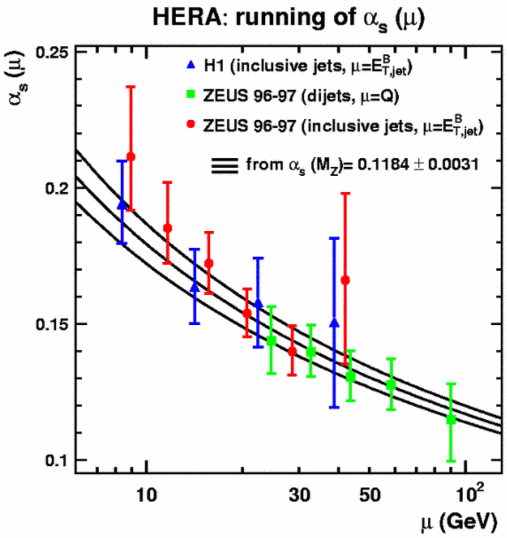


good agreement between quark densities from H1 and ZEUS

some differences betwee gluon densities from H1 and ZEUS

prominent feature: rapid rise of $xg(x, Q^2)$ as $x \to 0$

α_s strong coupling parameter



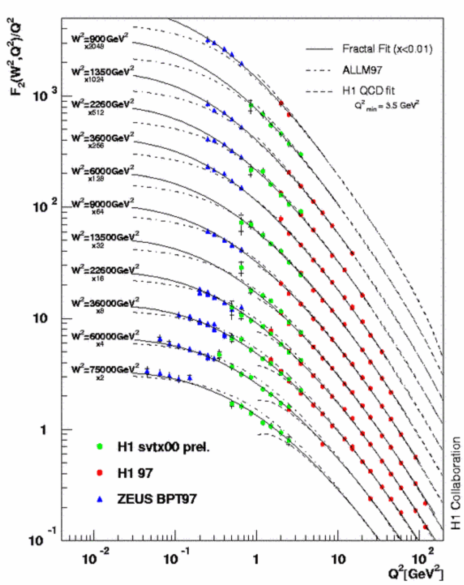
HERA data show clearly the running of α_s

α_s values are in good agreement with other measurements

F_2 transition $Q^2 \rightarrow 0$

For fixed x: $F_2(x, Q^2) \propto Q^2$ as $Q^2 \rightarrow 0$ plot $F_2(x, Q^2)/Q^2$

remember: $\sigma^{tot}_{\gamma^* p}(W, Q^2) = \frac{4\pi^2\alpha}{Q^2} \cdot F_2(x, Q^2)$, $W^2 \approx Q^2/x$

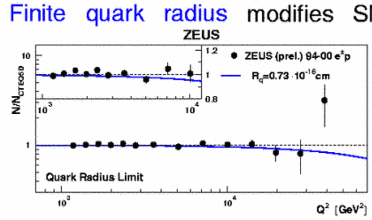


somewhere around $Q^2 \approx 3 \rightarrow 0.5$ GeV^2

transition from partonic $\rightarrow$ hadronic behaviour

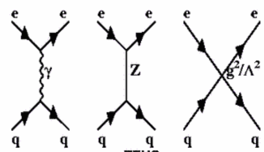
Search for new physics

Finite quark radius modifies SM cross section: $\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot (1 - \frac{R_q^2}{6} \cdot Q^2)^2$



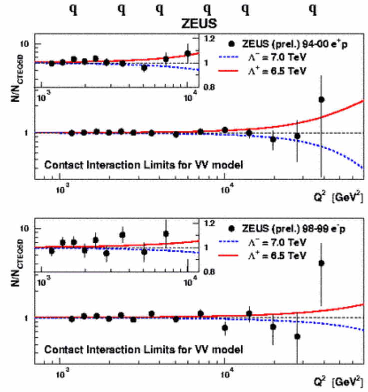
$\Longrightarrow R_q < 0.73 \cdot 10^{-16}$ cm

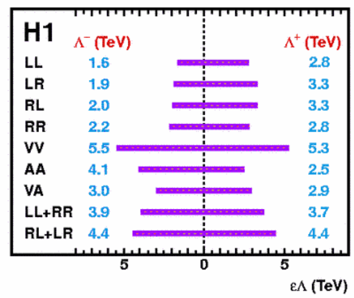
Contact interactions



$$\mathcal{L} = \frac{g^2}{\Lambda^2} \sum_{q=u,d} \sum_{\alpha=L,R} \sum_{\beta=L,R} \eta_{\alpha\beta}^{eq} (\overline{e}_\alpha \gamma^\mu e_\alpha)(\overline{q}_\beta \gamma_\mu q_\beta)$$

$g^2 = 4\pi$, $|\eta_{\alpha\beta}^{eq}| = 0$ or 1





95 % exclusion limits for Λ

Search for new physics

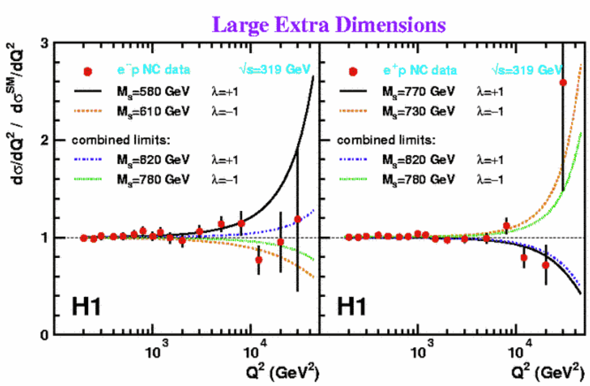
Large extra dimensions

$M_P^2 \propto R^2 M_S^{2+n}$

$M_P = 1.2 10^{19}$ GeV Planck scale

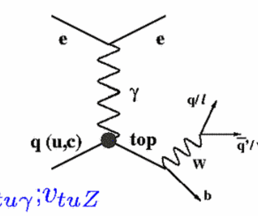
R size, n num. of compact. dimen. e.g. $R \approx 1$ mm = 5.10^{12} GeV^{-1}

M_S scale of gravt. int. $M_S^{1+\delta/2} \approx R^{-\delta/2} M_P$

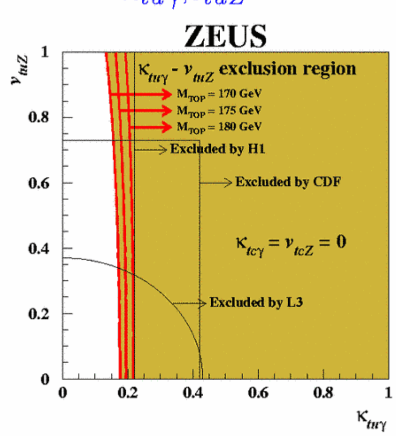


$M_S > 0.82$ TeV for $\lambda = +1$, $M_S > 0.78$ TeV for $\lambda = -1$

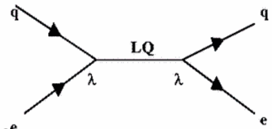
Single top production



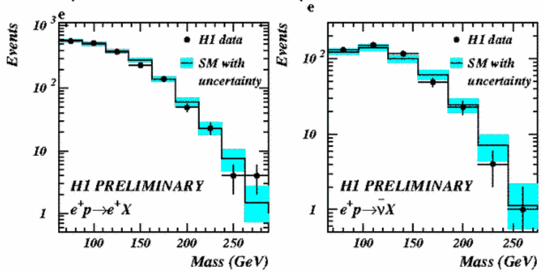
$\kappa_{tu\gamma}; v_{tuZ}$

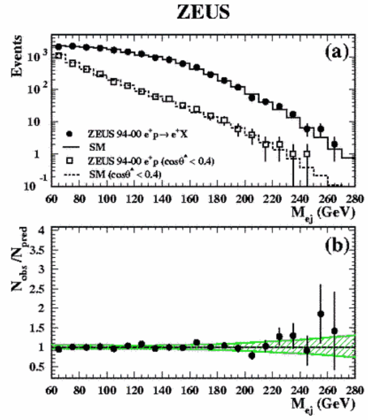


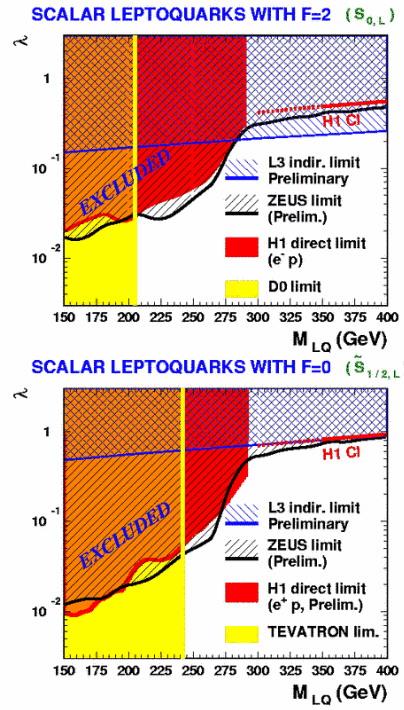
Search for new physics: leptoquarks



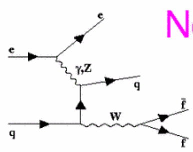
$\sigma(ep \rightarrow LQ) = (\pi/4s)\lambda^2 q(M_{LQ}^2/s)$ (spin = 0)



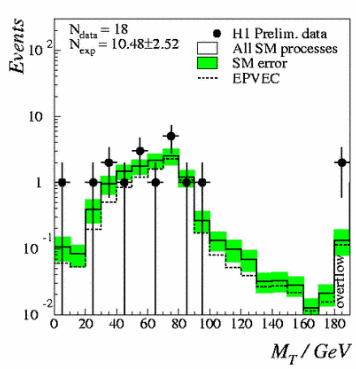


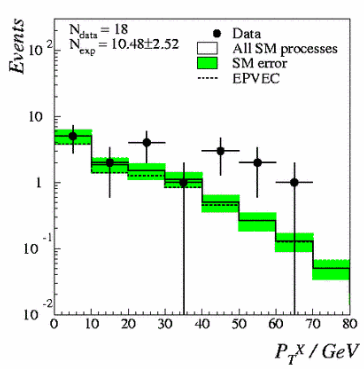


New Physics? events with lepton + missing p_T



	H1 (115 pb^{-1})			ZEUS (130 pb^{-1})		
	observed $(e+\mu)$	expected	W	observed	expected	W
$p_t^{miss} > 12$ GeV	5+8 = 13	5$\pm$ 1.3	4.2			
$p_t^{miss} > 25$ GeV	4+6 = 10	2.8$\pm$ 0.7	2.3	2+5 = 7	2.8	
$p_t^{miss} > 40$ GeV	2+4 = 6	1.0$\pm$ 0.3	0.9	0	2.0$\pm$0.2	1.3





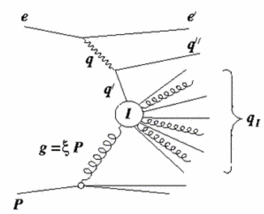
H1 sees excess

ZEUS does not

need more data

$\Longrightarrow$ HERAII running

Search for new physics: instantons

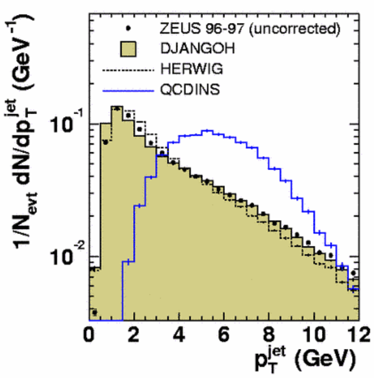


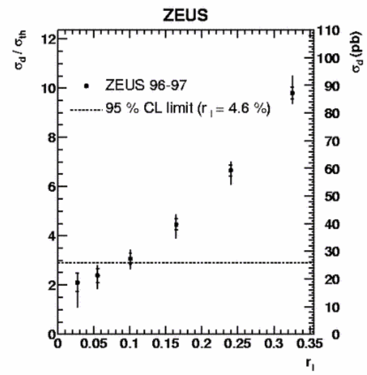
$q'g$ - fusion in the presence of an instanton produces

(see e.g. Ringwald and Schrempp):

- high particle multiplicity
- isotropic particle distribution in $q'g$ - system
- cross section expected to be comparable to standard DIS for large Q^2 in a certain region of phase space

new study by ZEUS (2003), previous studies by H1 (1996,2002)





fract. of I induced events

after cut in Fisher discr t

data: $\sigma_{inst} < 26$ pb

(95% C.L. upper limit)

theory: $\sigma_{inst} = 8.9$ pb

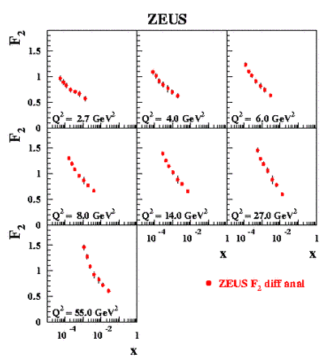
(Ringwald and Schrempp)

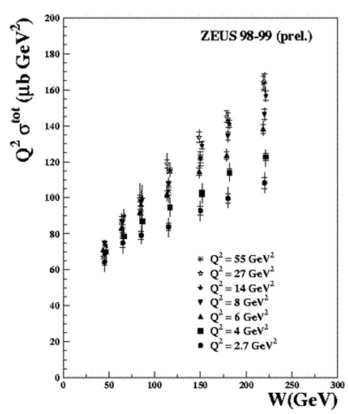
$\Longrightarrow$ maybe we are close,

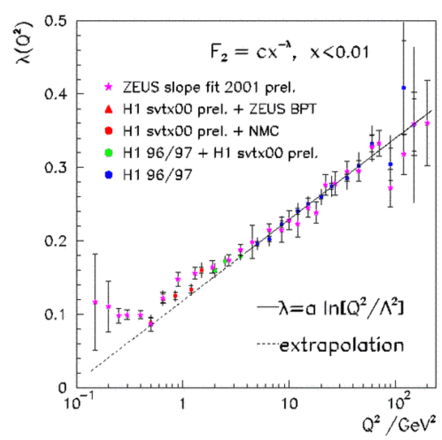
need more data

$F_2(x, Q^2)$ and $\sigma^{tot}_{\gamma^* p}$

$$\sigma^{tot}_{\gamma^* p}(W, Q^2) = \frac{4\pi^2\alpha}{Q^2} \cdot F_2(x, Q^2)\,,\, W^2 \approx Q^2/x \qquad \sigma^{tot}_{\gamma^* p} \propto (W^2)^{\lambda}$$







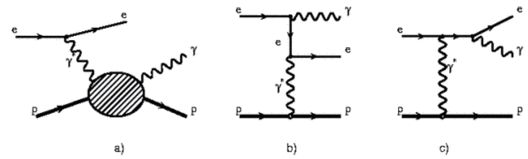
Write $\sigma^{tot}_{\gamma^* p} \propto (W^2)^{(\alpha_{IP}(0)-1)}$

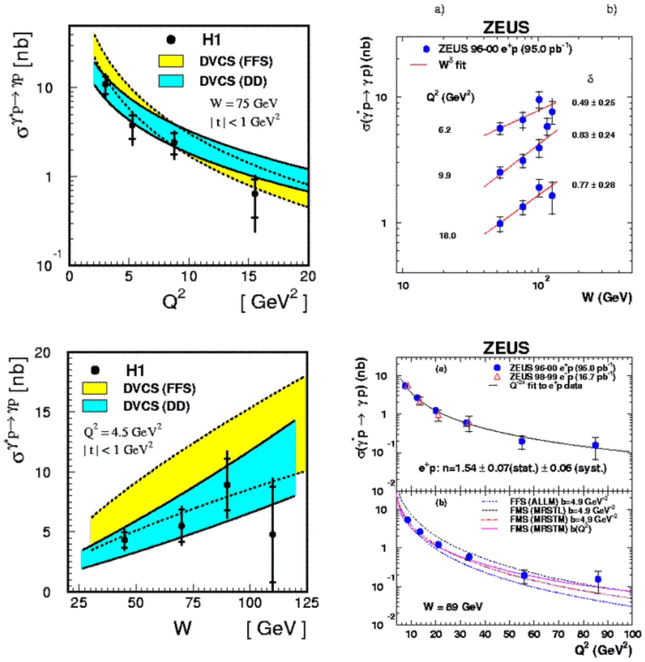
$\Longrightarrow$ $\alpha_{IP}(0)$ increases with Q^2 $\Longrightarrow$ violates Regge factorisation

at $Q^2 \approx 100$ GeV^2: $\lambda = 0.35 \Longrightarrow \alpha_{IP}(0) = 1.35$

$\alpha_{IP}(0) = 1.35$ much larger than in hadronic interact.: $\alpha_{IP}(0) = 1.09$ (Donnachie, Landshoff + others)

Diffraction: deep inelastic virtual compton scattering





$ep \to e + \gamma + p$

dominated by Bethe-Heitler (BH) (diag. b,c)

except when γ is produced forward

determine DVCS by subtracting BH

W-dependence (ZEUS e^+p):

$\sigma(\gamma^* p \to \gamma + p) \propto (W^2)^\lambda$

$\lambda \; = \; 0.37 \pm 0.07(stat) \pm^{0.04}_{0.03} \, (syst)$

$\to \overline{\alpha_{IP}} = 1 + \lambda/2 = 1.18 \pm 0.04$

Q^2-dependence (ZEUS e^+p):

$\sigma(\gamma^* p \to \gamma + p) \propto Q^{-2n}$

$n = 1.54 \pm 0.07(stat) \pm 0.06(syst)$

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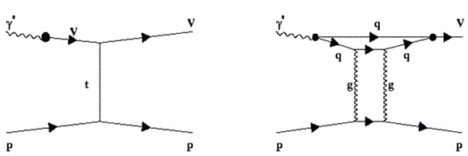
DIS vectormeson production



write:

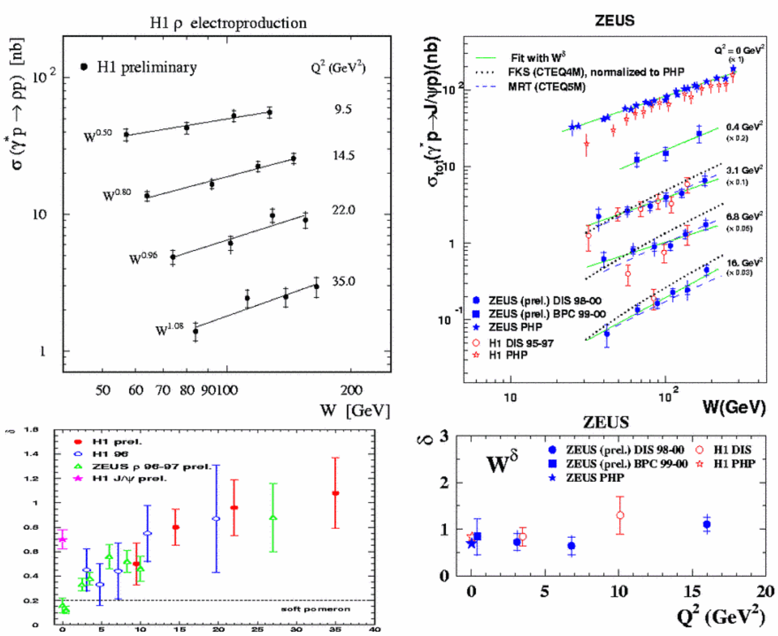
$\sigma_{\gamma^* p \to Vp} \propto W^\delta$

ρ^0: find at Q^2 near 0: $\delta_\rho \approx 0.2$

rising to $\delta_\rho \; = \; 0.8$ at high Q^2

J/Psi: $\delta_\rho \approx 0.8$ all Q^2

charm mass provides hard scale



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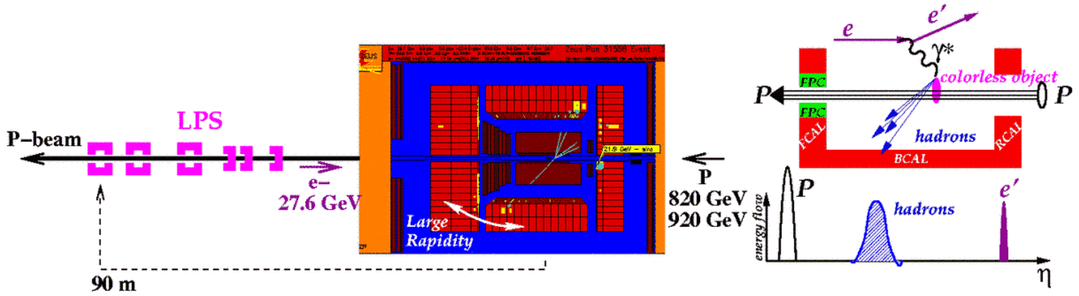
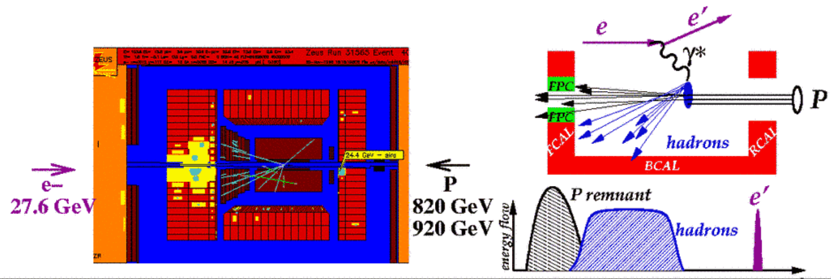
Deep inelastic inclusive diffractive scattering: event topologies

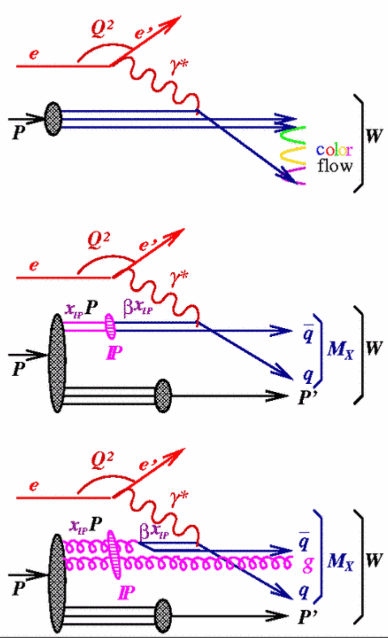
1. Diffractive scattering ($\mathrm{M_X = 5\,GeV,\ Q^2 = 19\,GeV^2,\ W = 123\,GeV}$)



2. Non-diffractive scattering ($\mathrm{M_X = 45\,GeV,\ Q^2 = 13\,GeV^2,\ W = 93\,GeV}$)

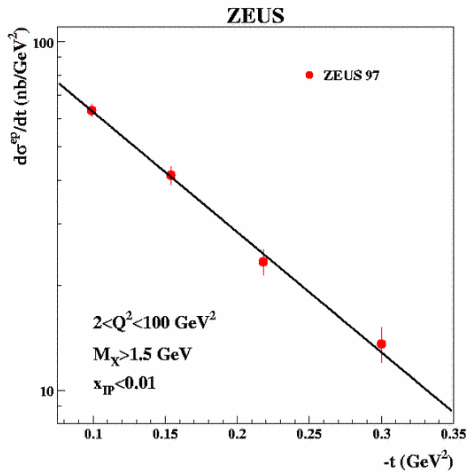


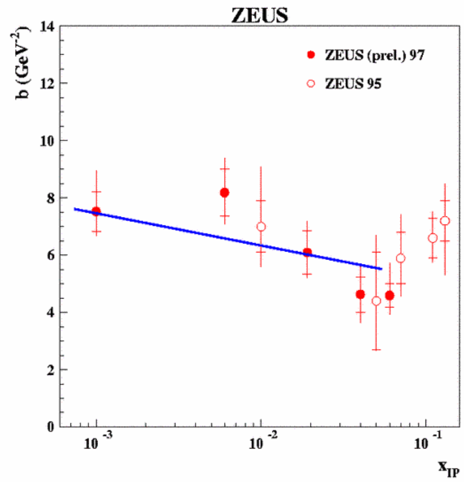
○ Kinematics of $e + p \to e' + X + N$



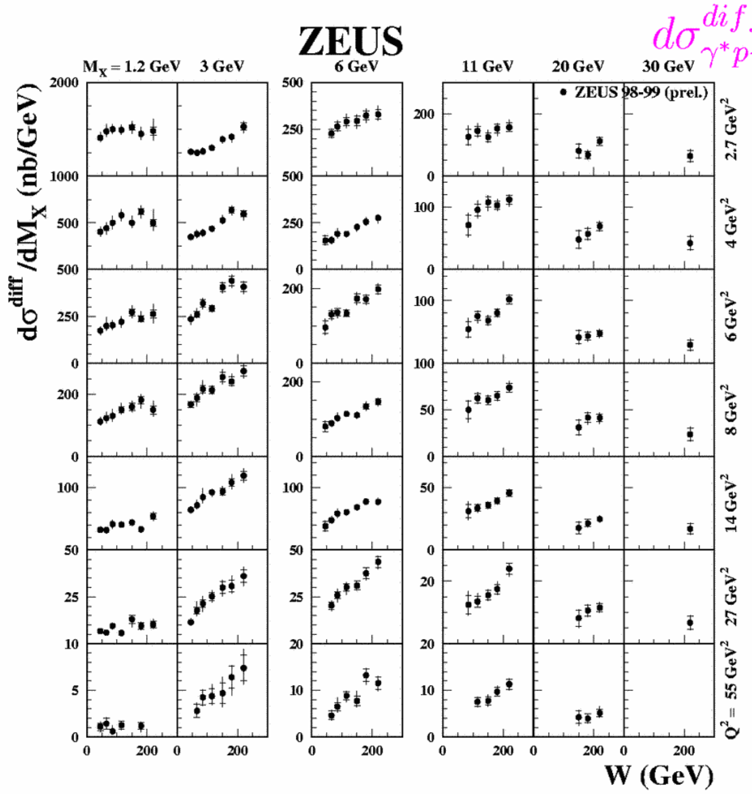
- $Q^2 = -q^2 = -(k-k')^2$
- $x = \dfrac{Q^2}{2q \cdot p}$
- $W = \sqrt{(p+q)^2} \approx \sqrt{\dfrac{Q^2}{x}}$
- $M_X^2 = (k - k' + p - p')^2$
- $x_{I\!P} = \dfrac{(p-p') \cdot q}{p \cdot q} \approx \dfrac{M_X^2 + Q^2}{W^2 + Q^2}$
- $\beta = \dfrac{Q^2}{2(p-p') \cdot q} = \dfrac{x}{x_{I\!P}} \approx \dfrac{Q^2}{M_X^2 + Q^2}$

Measurement of the t-dependence and $d\sigma/dM_X$ with the LPS

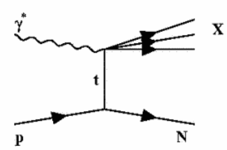




- Fit $d\sigma/d|t| \propto exp(-b|t|)$
  $->b \approx 6-8$ GeV^{-2} $\Longrightarrow$ similar to slopes measured for elastic had-had scattering
- expect shrinkage of diff. peak: $b = b_0 + 2\alpha' \ln(1/x_{IP}) \rightarrow b$ should rise as $x_{IP} \rightarrow 0$
  dashed line expected for $b_0 = 5$GeV^{-2}, $\alpha' = 0.25$ GeV^{-2}
  $\Longrightarrow$ data cannot yet decide between constant or rising b

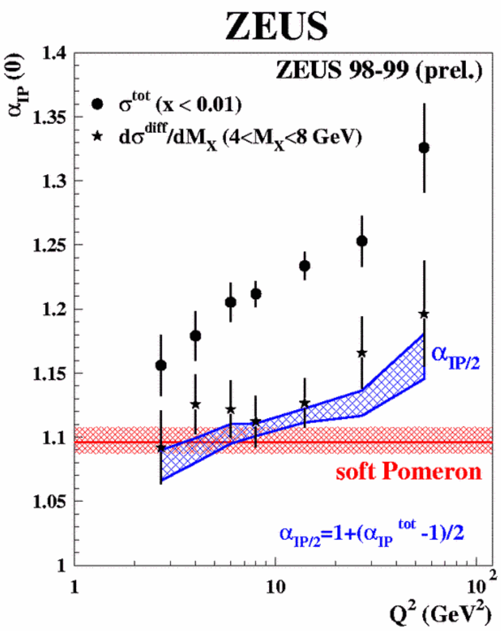


$d\sigma^{diff}_{\gamma^* p \rightarrow XN}(M_X, W, Q^2)/dM_X$,
$M_N < 2.3$ GeV



- For $M_X < 2$ GeV, $d\sigma/dM_X$ depends weakly on W.
- For $M_X > 2$ GeV, $d\sigma/dM_X$ rises rapidly with W.

Compare $\alpha_{I\!P}$ for diffractive and total $\gamma^* p$ scattering



- $\sigma^{tot}_{\gamma^* p} = \frac{4\pi^2\alpha}{Q^2} \cdot F_2(x,Q^2)$
  $\sim \frac{1}{W^2} Im T_{\gamma^* p \to \gamma^* p}(W^2, t=0) \sim (W^2)^{\alpha^{tot}_{I\!P}(0)-1}$
  (Optical theorem)
- $\frac{d^2\sigma^{diff}}{dM_X dt} \sim \quad |T_{\gamma^* p \to \gamma^* p}|^2 \quad \sim (W^2)^{2(\alpha^{diff}_{I\!P}(0)-1)}$
  at $t = 0$
- Data ($4 < M_X < 8$ GeV) show
  $\Longrightarrow \alpha^{diff}_{I\!P} \approx 1 + (\alpha^{tot}_{I\!P} - 1)/2$

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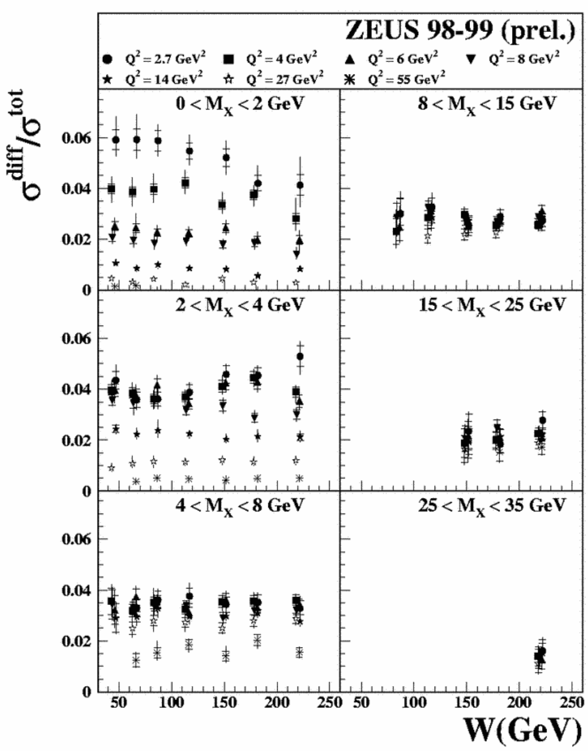

$$r^{diff}_{tot} = \frac{\int_{M_a}^{M_b} dM_X d\sigma^{diff}_{\gamma^* p \to XN, M_N < 2.3 GeV}/dM_X}{\sigma^{tot}_{\gamma^* p}}$$

- The diffractive cross section has about the same W-dependence as σ^{tot} .
- The low M_X bins exhibit a strong decrease of r^{diff}_{tot} with increasing Q^2 .
- For $M_X > 8$ GeV: no Q^2 dependence.
- $\sigma^{diff}_{(M_X < 35 \text{ GeV})}/\sigma^{tot}$ at $W = 220$ GeV:
  $= 19.8^{+1.5}_{-1.4}\%$ ($Q^2 = 2.7$ GeV^2)
  $= 10.1^{+0.6}_{-0.7}\%$ ($Q^2 = 27$ GeV^2)
  $\Longrightarrow$ Slowly decreasing with Q^2
- Diffraction is a substantial part of deep inelastic scattering

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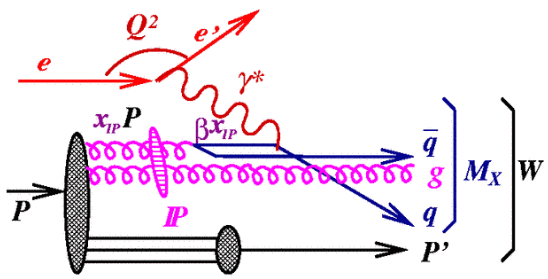
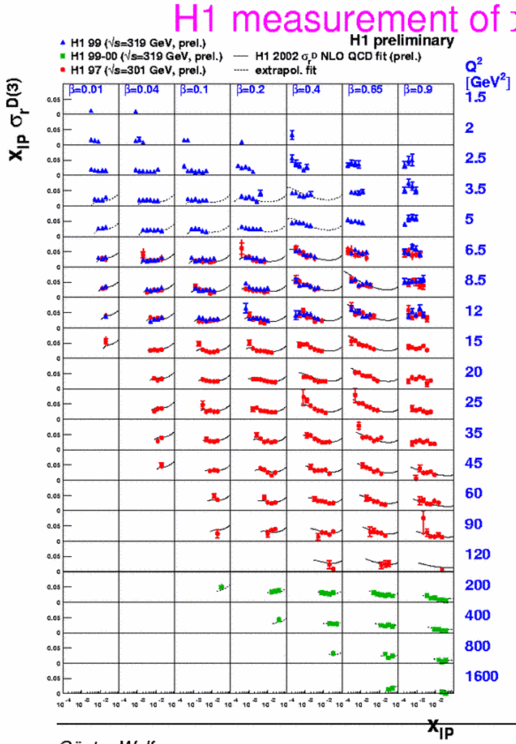
Diffractive structure function of the proton



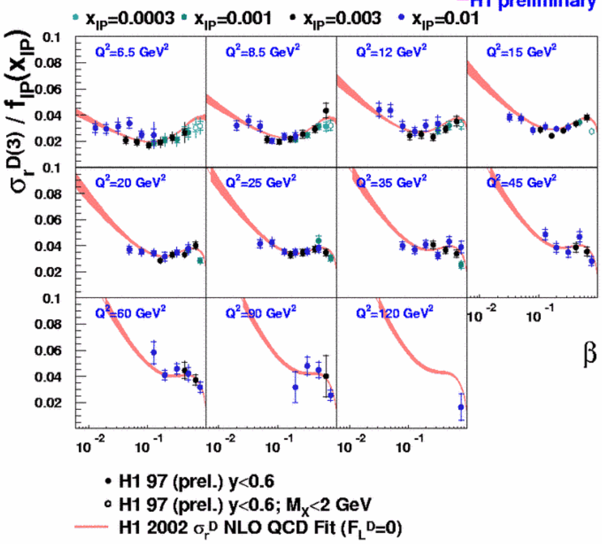
$$x_{IP} F_2^{D(3)}(\beta, x_{IP}, Q^2) = \frac{1}{4\pi^2\alpha} \cdot \frac{Q^2(Q^2+M_X^2)}{2M_X} \cdot \frac{d\sigma^{diff}_{\gamma^* p \to XN}}{dM_X}$$

H1 measurement of $x_{\mathbb{P}} F_2^{D(3)}(x_{\mathbb{P}}, \beta, Q^2)$ and QCD fit



- $\sigma_r^{D(3)} = F_2^{D(3)}(x_{IP}, \beta, Q^2)$
  diffractive structure function of the proton
- new data for $1.5 < Q^2 < 12$ GeV^2
  and $130 < Q^2 < 1600$ GeV^2
- New QCD fit to $F_2^{D(3)}(x_{IP}, \beta, Q^2)$
  use data with $6 < Q^2 < 120$ GeV^2
  assume PDF's independent of x_{IP}
  Pomeron modelled in terms of
  light quark flavour singlet:
  $\sum(z) = u(z) + d(z) + s(z) + \overline{u(z)} + ..$
  plus gluon distribution:
  $g(z)$

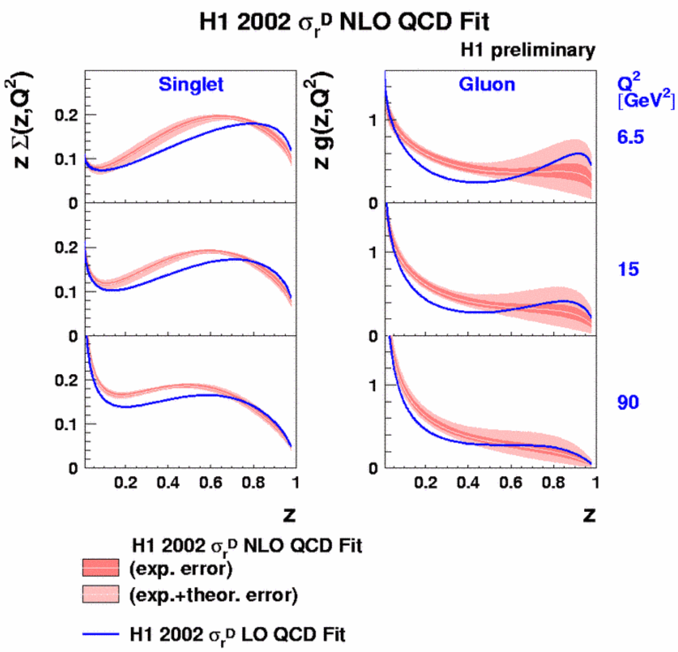
H1 $F_2^{D(2)}(\beta, Q^2)$ and QCD fit



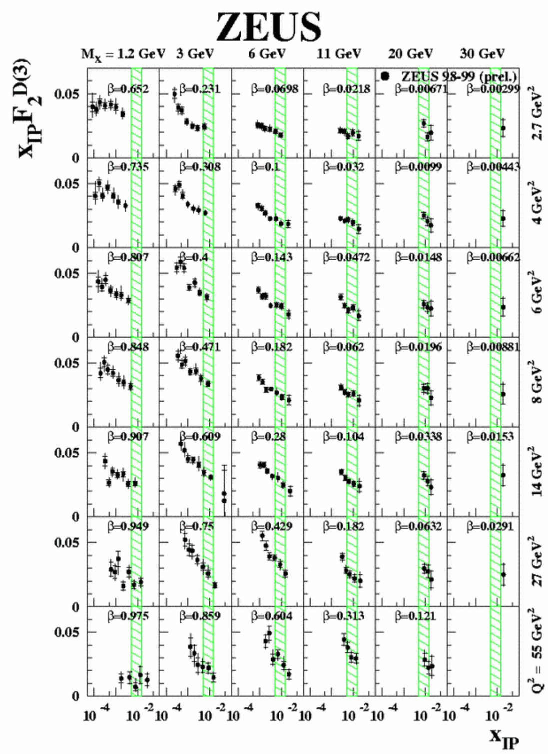
- factorize diff. structure funct. of proton into probability finding Pomeron with fract x_{IP} of proton momentum
  and structure function of the Pomeron:
  $F_2^{D(3)}(x_{IP}, \beta, Q^2) =$
  $f_{IP}(x_{pom}) \cdot F_2^{D(2)}(\beta, Q^2)$

  note
  $\sigma_r^{D(3)} / f_{IP}(x_{IP}) = F_2^{D(2)}(x_{IP}, Q^2)$
- red band shows result of QCD fit to $F_2^{D(3)}(x_{IP}, \beta, Q^2)$

H1 Diffractive PDF's from QCD fit



- inner error bands:
  experimental stat + syst errors
  outer error bands:
  include uncertainties from theoretical assumptions
- $75 \pm 15\%$ of Pomeron momentum with $0.01 < z < 1$ is carried by gluons, the rest by quarks
- large uncertainty on $g(z, Q^2)$ at large z



Determine structure function of Pomeron $F_2^{D(2)}$ (FPC)

- Following Ingelman + Schlein,

  diff. struct. function of proton

  = (flux of Pomerons) × (struct. funct. of Pomeron)

  $F_2^{D(3)}(Q^2,\beta,x_{IP}) =$

  $f_{IP/p}(x_{IP},Q^2)\cdot F_2^{D(2)}(\beta,Q^2)$

  For Pomeron flux factor use ansatz

  $f_{IP/p}(x_{IP},Q^2) = \frac{C}{x_{IP}}\cdot(\frac{x_0}{x_{IP}})^{n(Q^2)}$

- Set $x_0 = 0.01$, $C = 1$

  $\Longrightarrow$ determine $F_2^{D(2)}$ at $x_{IP} = 0.01$

  $\Longrightarrow F_2^{D(2)}(\beta,Q^2) = x_0 F_2^{D(3)}(x_0,\beta,Q^2)$

- use all $x_{IP}F_2^{D(3)}$ data with

  $0.005 < x_{IP} < 0.015$

  and transport them to $x_{IP} = 0.01$

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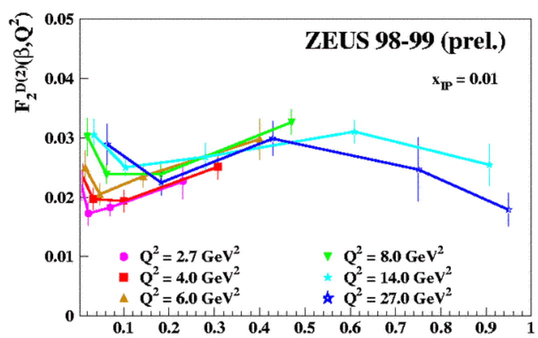
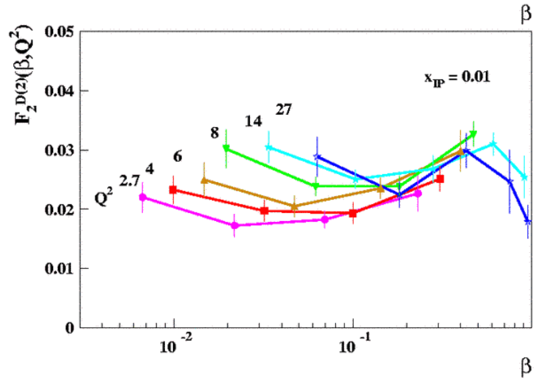
Pomeron structure function $F_2^{D(2)}(\beta,Q^2)$





- Structure Function, Proton $x,Q^2 \to F_2(x,Q^2)$

  Pomeron $\beta,Q^2 \to F_2^{D(2)}(\beta,Q^2)$

  $\Longrightarrow$ Probability for finding a quark

  with momentum fraction β in Pomeron

- In the "valence" region, $\beta > 0.1$,

  $F_2^{D(2)}$ has a maximum around $\beta = 0.5$

  is main contribution due to a Pomeron in a $q\bar{q}$ state ?

- For high β , $F_2^{D(2)}$ seems to decerase with rising Q^2

- In the "sea" region, $\beta < 0.1$,

  $F_2^{D(2)}$ rises as $\beta \to 0$ and as Q^2 increases

- $\Longrightarrow$ Evidence for pQCD evolution of the Pomeron structure function with β and Q^2

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HERA upgrade

Goals for HERAII

- increase luminosity from $1.5 \cdot 10^{31}$cm^{-2} s^{-1} by factor 3 - 5
- deliver within 2004-2007 1 fb^{-1} equivalent to 5-10 times luminosity collected with HERAI
- provide polarized e$^+$ and e$^-$ beams with $\geq$ 50% polarisation

Required from HERA

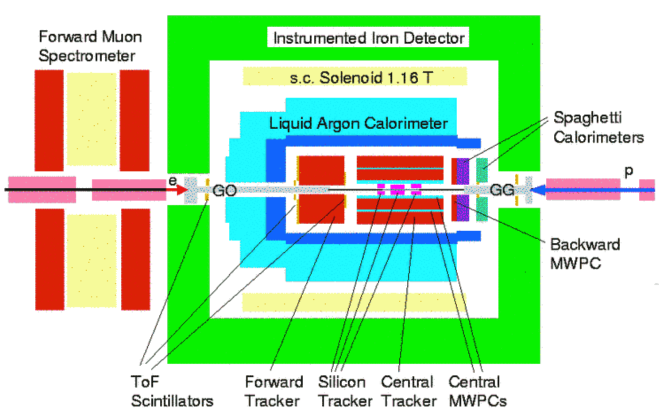
- insertion of extra focussing/separtion quads
- rearrangement of beam lines in interactions regions
- insertion of spin rotators

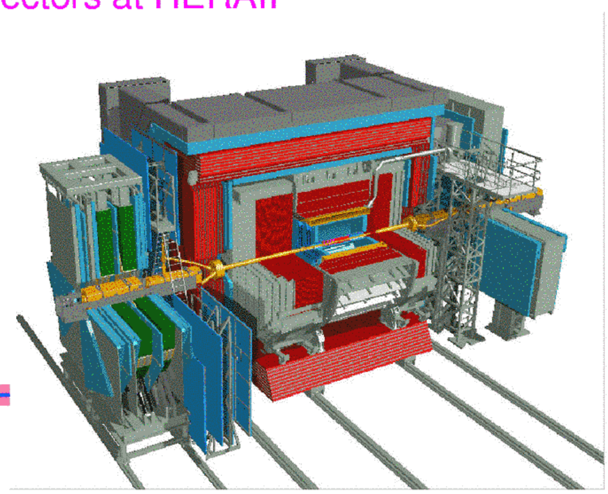
Upgrade of H1 and ZEUS detectors

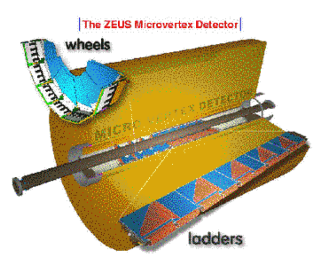
- addition of vertex, tracking and forward proton(H1) detectors, substantial reduction of size of beam pipe
- upgrade of luminosity detectors
- carefull shielding of H1 and ZEUS detectors against stray radiation

Running in 2001/2 after upgrade showed for both experiments untolerable high backgrounds
$\Longrightarrow$ required modification of masking in the IR's (2002/3) and improvement of vacuum system

H1 and ZEUS detectors at HERAII

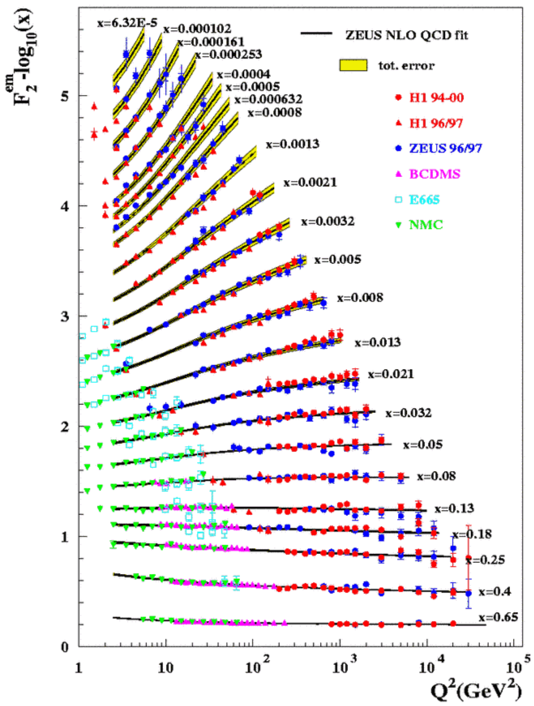


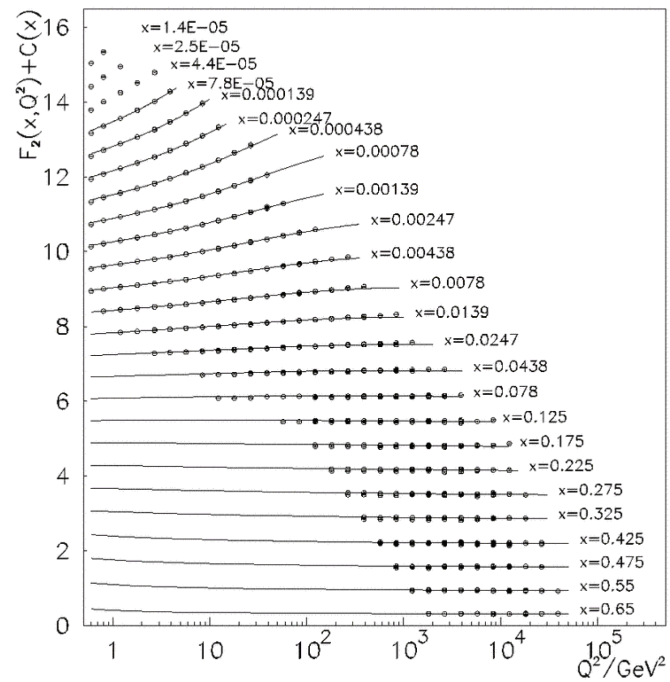




beampipe H×W = 11.5×4.2 cm^2 - closest distance to beam 2.0 cm

F_2 from HERA1 and HERA2

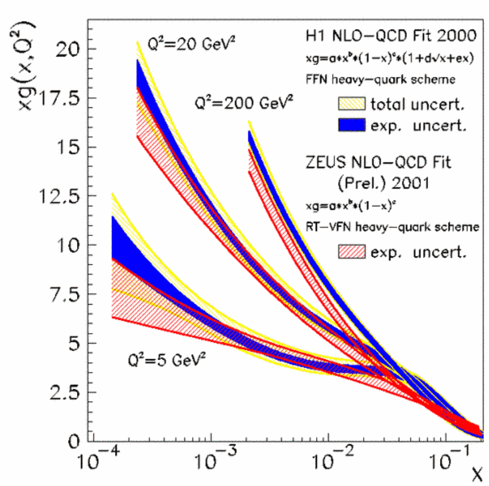


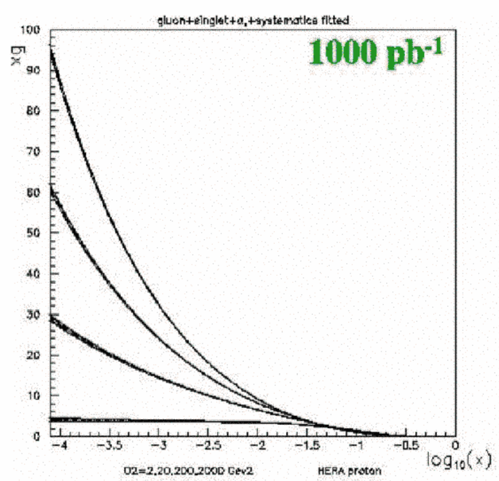


HERAI vs HERAII for gluon density

HERAI: $O(50\ \mathrm{pb}^{-1})$

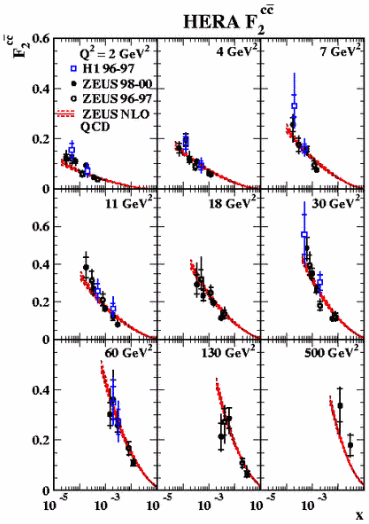
HERAI: $O(1000\ \mathrm{pb}^{-1})$



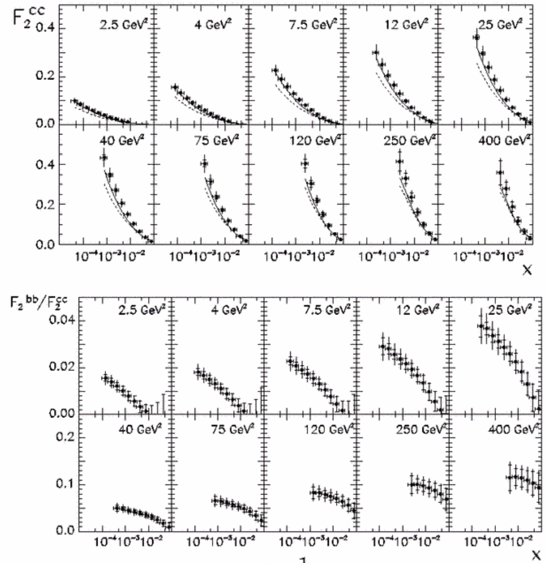


Physics with HERAII: $F_2^{\text{charm}}, F_2^{\text{beauty}}$:

HERAI: $O(50\ \text{pb}^{-1})$



HERAI: $O(1000\ \text{pb}^{-1})$



500pb^{-1}

HERAII sensitive to intrinsic c,b in proton

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Physics with HERAII: σ_{CC} with polarized e^-, e^+

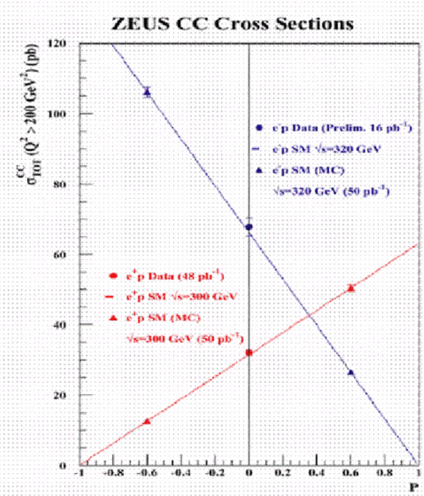
Standard Model:

$\sigma(e^-_{righthanded}\, p \rightarrow \nu p)$ = 0

as well as

$\sigma(e^+_{lefthanded}\, p \rightarrow \nu p)$ = 0

sensitive probe for new physics



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HERA upgrade: current status

recent running showed background conditions now to be acceptable

- background under control - scaled to maximum currents
- L_{spec} close to design
- 50 $\%$ polarisation for e beam observed
- over the coming months gardually increase the beam currents:
  from $I_{proton} = 60$ mA to 100 mA
  from $I_{electron} = 30$ mA to 50 mA

HERA + experiments have started to climb the 1 fb^{-1} peak

HERA questions to workshop

- HERA data show $F_2(x, Q^2) \propto x^{-\lambda}$, $\lambda \propto \ln(Q^2/Q_0^2)$ up to $Q^2 = 100$ GeV^2
  Q: what if growth of $F_2(x, Q^2)$ continues up to $Q^2 = 1000$ GeV^2 ?
  does theory expect saturation and at which Q^2 ?
- The parton densities $x \cdot q_i(x, Q^2)$, $x \cdot g(x, Q^2)$ are extracted via DGLAP evolution from the measured structure functions $F_i(x, Q^2)$
  Q: since data show large diffractive contribution, which has a large rapidity gap for parton/particle emission: must this fact be taken into account when extracting the parton densities ?
- HERAII will provide high precision measurements for $F^{c\bar{c}}$, $F^{b\bar{b}}$
  Q: at what level shoul one observe intrinsic $c\bar{c}$, $b\bar{b}$ in the proton?
- Instanton (I) interactions are an essential feature of QCD which has not yet been seen experimentally
  Q: at what level should one see them - are the Ringwald-Schrempp predict. the last word?
  are there extra features which allow further discriminat. of (I) against standard interact.?