HERA physics

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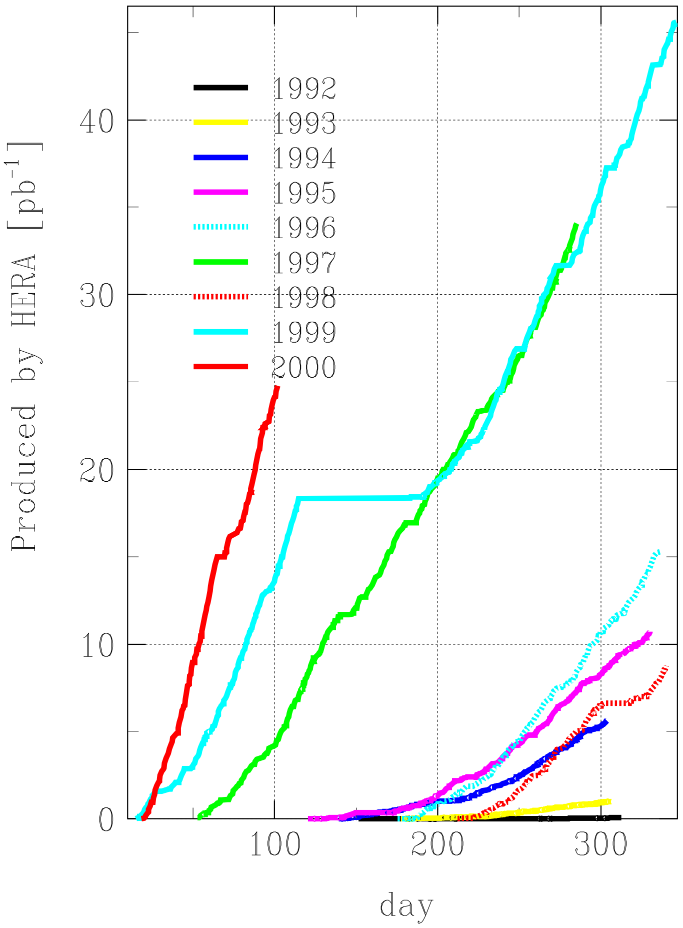
Pheno 2000
representing H1 and ZEUS

- Introduction
- DIS
  - Structure Functions
  - High Q^2 cross section
- QCD
  - jets, α_s
  - heavy flavor production
- Searches
  - contact interactions, ...
  - leptoquarks
  - excited fermions
- Summary and Outlook

HERA

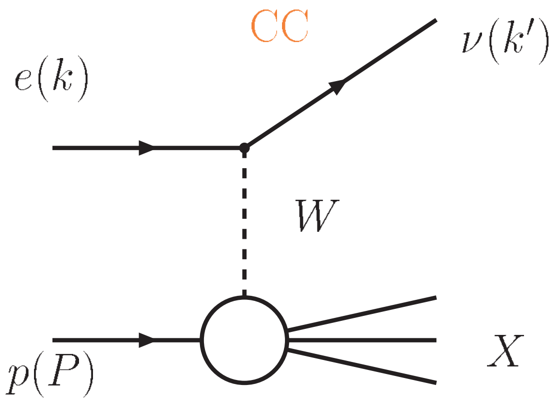
- collides 27.6GeV $e^{\pm}$ and 820 (920)GeV p
- four experiments: H1, ZEUS, Hermes, HERA-B
- main goals
  - proton structure ($\lambda \approx 10^{-18}$m)
  - QCD
  - new phenomena
- Machine performance improving steadily

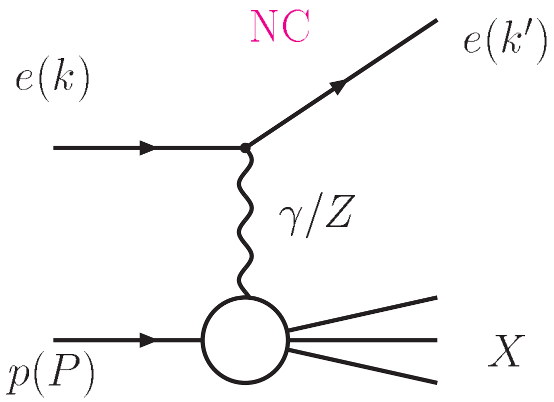


period	beams	$\sqrt{s}$
92 - 93	e^-p	300 GeV
94 - 97	e^+p	300 GeV
98 - 99	e^-p	320 GeV
99 - 00	e^+p	320 GeV

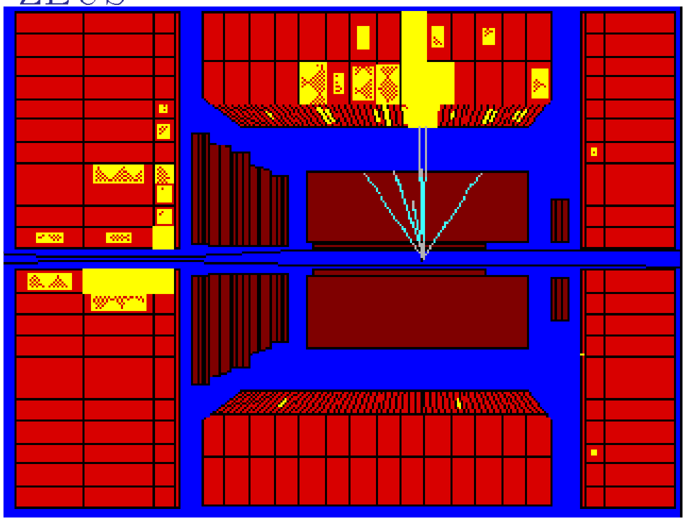
  - access to low cross section physics
  - increase Q^2 reach

inclusive DIS

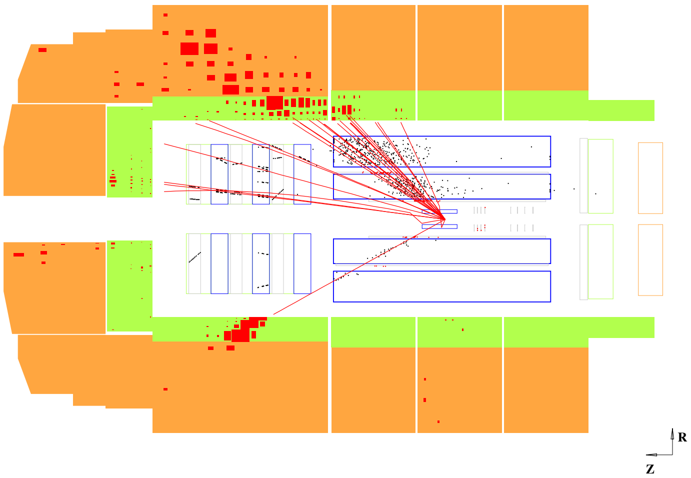




ZEUS



H1



kinematic variables

$Q^2 = -(k-k')^2$	momentum transfer	$0 < Q^2 < s = 10^5 \mathrm{GeV}^{\ 2}$
	virtuality of exchanged $\gamma/Z/W$	
$x = \frac{Q^2}{2P \cdot q}$	Bjorken x	$0 < x < 1$
	momentum fraction of struck parton	
$y = \frac{P \cdot q}{P \cdot k}$	inelasticity	$0 < y < 1$
	$\leftrightarrow \theta^*(eq)$	

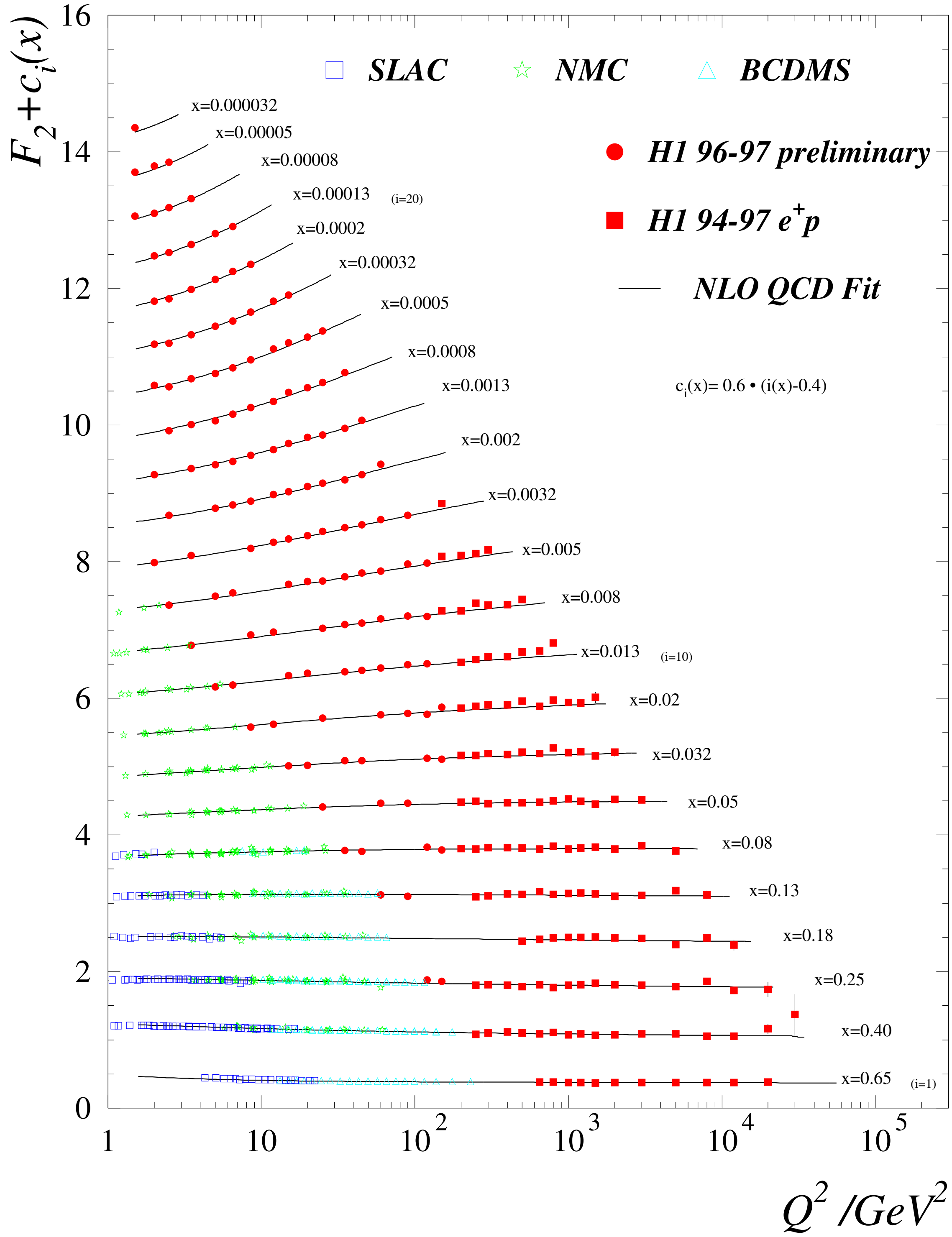
CC: hadronic measurements

NC: electron and hadronic measurements

proton structure Function, $F_2(x, Q^2)$

$$\frac{d^2\sigma^{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+F_2 - y^2F_L - Y_-xF_3)$$

- $Y_\pm = 1 \pm (1-y)^2$
- F_2 dominates $(Q^2 \ll M_Z^2)$



scaling-violation

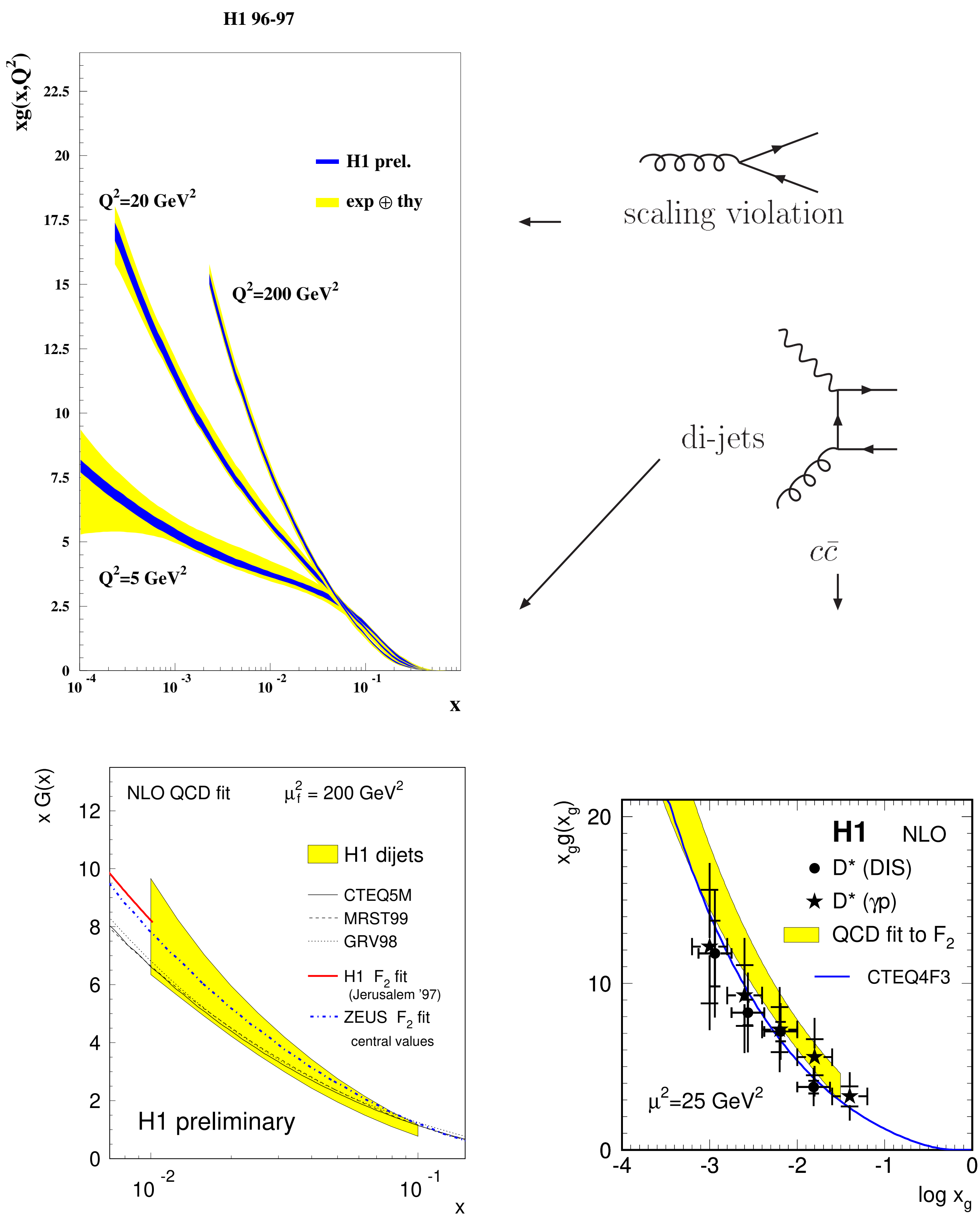
small x

large x

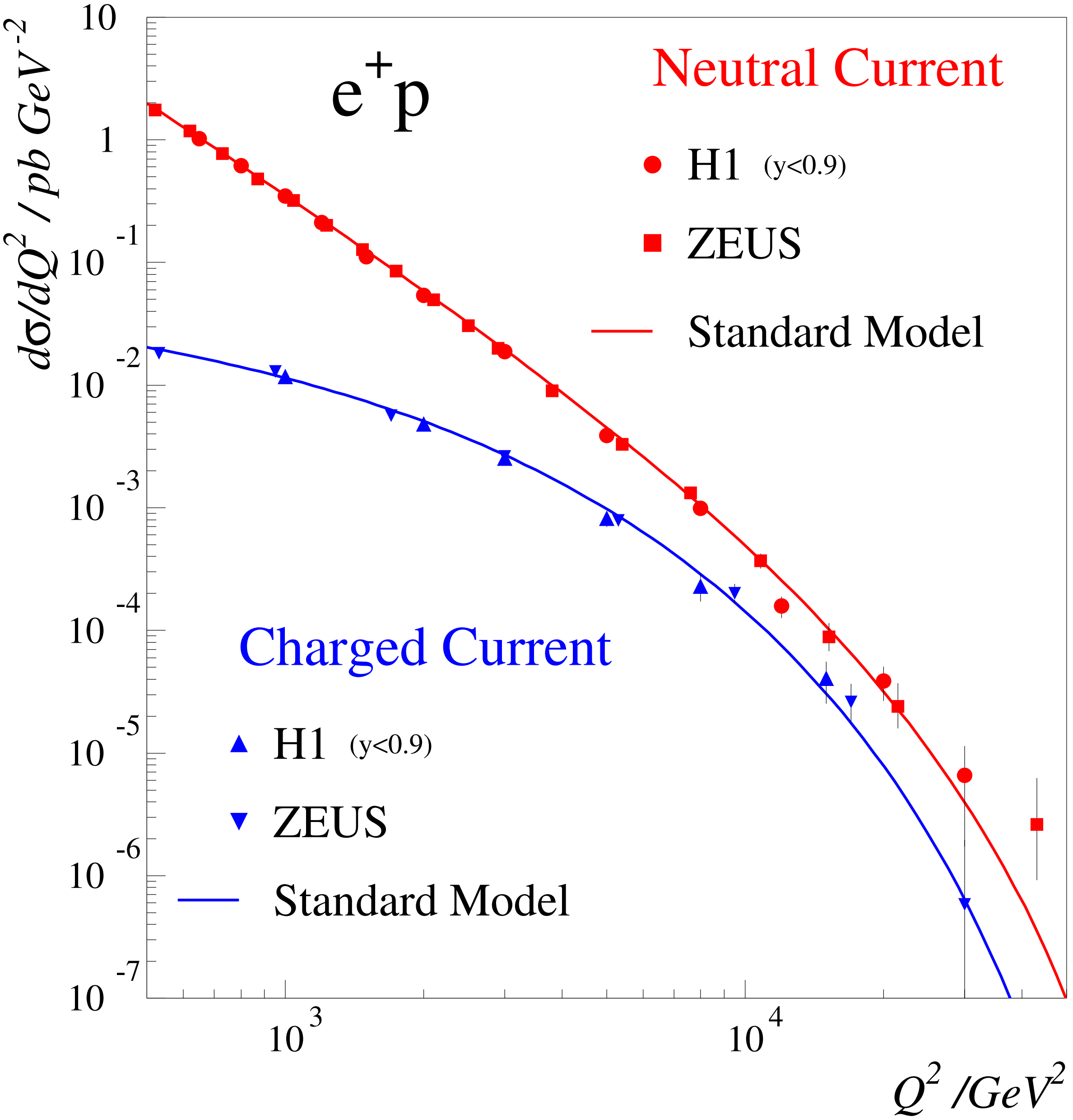
well described by QCD over more than four orders of magnitude

The gluon density

- Not directly measurable in DIS



high Q^2 cross section, e^+p



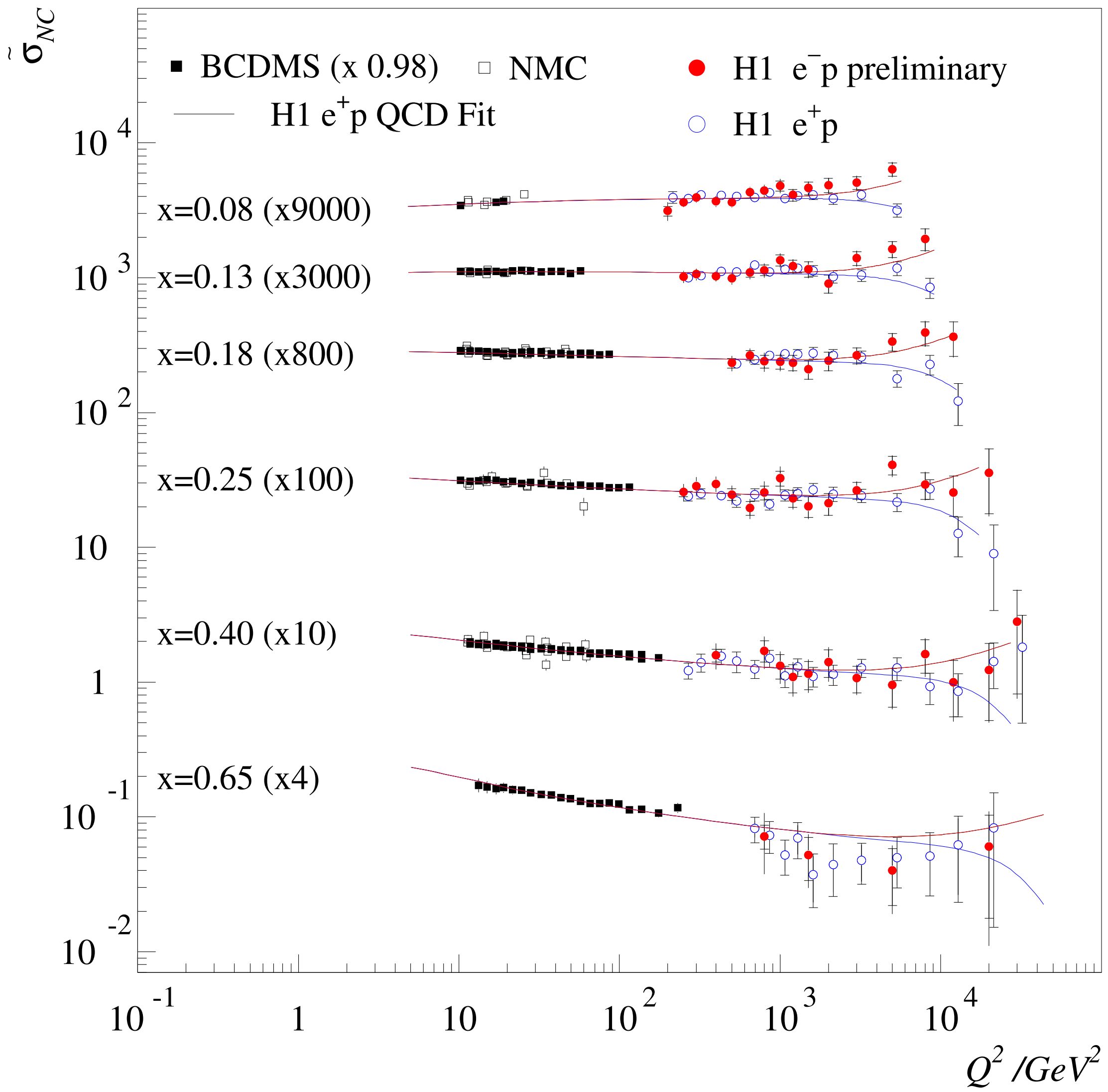
- CC and NC cross sections similar at highest Q^2
- manifest electroweak unification
- CC: $\rightarrow$ W-propagator mass

$$\frac{d\sigma}{dQ^2} \propto G_F^2 \left(\frac{M_W^2}{Q^2 + M_W^2} \right)$$

$$M_W = 81.4^{+2.7}_{-2.6}(\text{stat.}) \pm 2.0(\text{syst.})^{+3.3}_{-3.0}(\text{PDF})\text{GeV}$$

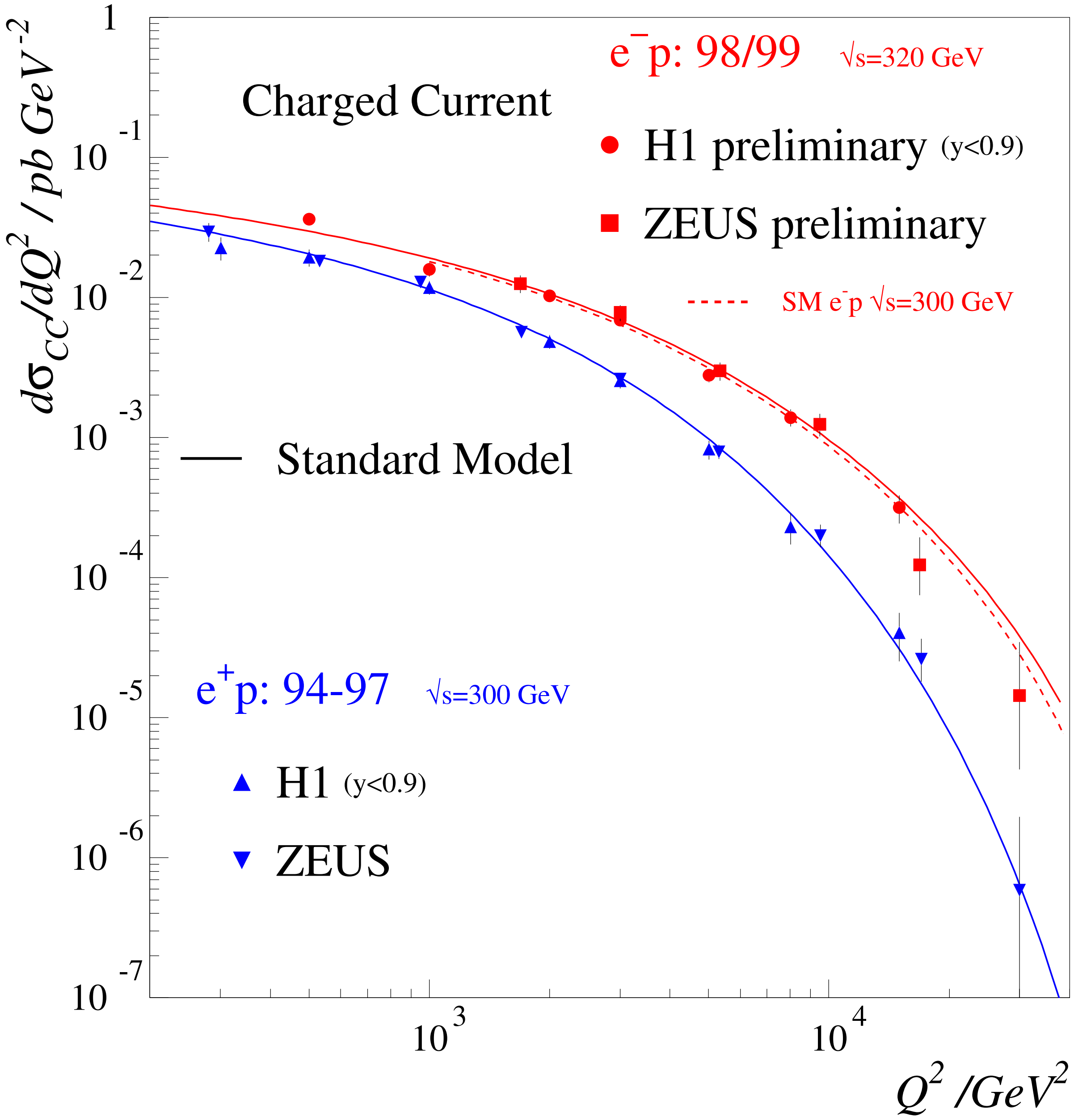
NC $e^{\pm}p$ cross section, $\gamma - Z$ interference

$$\tilde{\sigma}_{\rm NC} = \left[\frac{2\pi\alpha^2}{xQ^4}Y_+\right]^{-1}\frac{d^2\sigma^{\pm}_{\rm NC}}{dxdQ^2} \sim F_2 \mp \frac{Y_-}{Y_+}xF_3$$



- $\gamma - Z$ interference at high Q^2, sign as expected
- slight excess in e^+p at $x \sim 0.4$
- better statistical precision needed

CC cross sections



- $\sigma_{CC}(e^-p) \gg \sigma_{CC}(e^+p)$
- small difference due to beam energy 820GeV $\longrightarrow$ 920GeV
- valence quarks in the proton + helicity suppression
  $e^-p \ \sim xu$ $\qquad$ $e^+p :\sim (1-y)^2 xd$

High Q^2 data agree well with SM expectations

$\hookrightarrow$ constrain non-standard interactions

exclusive processes, QCD

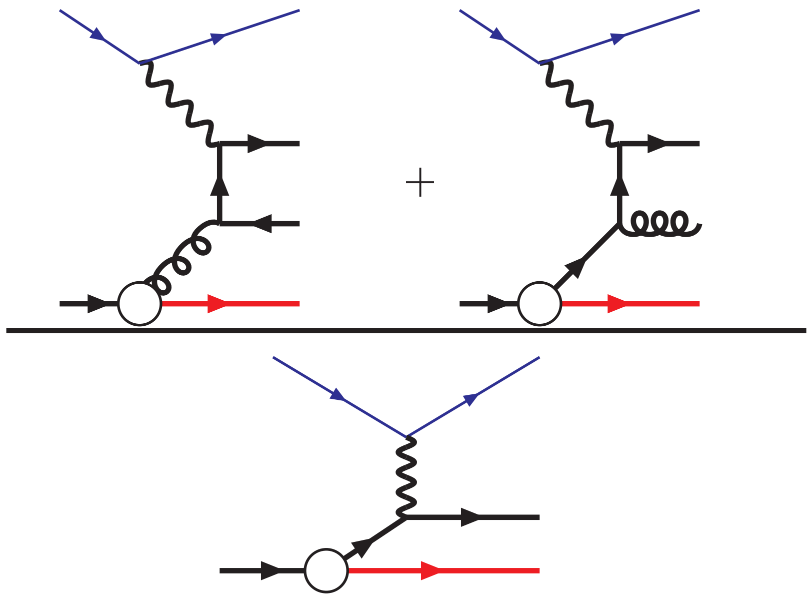
presence of a hard scale $\leftarrow$ perturbative QCD

- jets with large E_T
- heavy quark production, ($Q^2 \rightarrow 0$, photoproduction)

Multi-jet production

- sensitive to α_s:

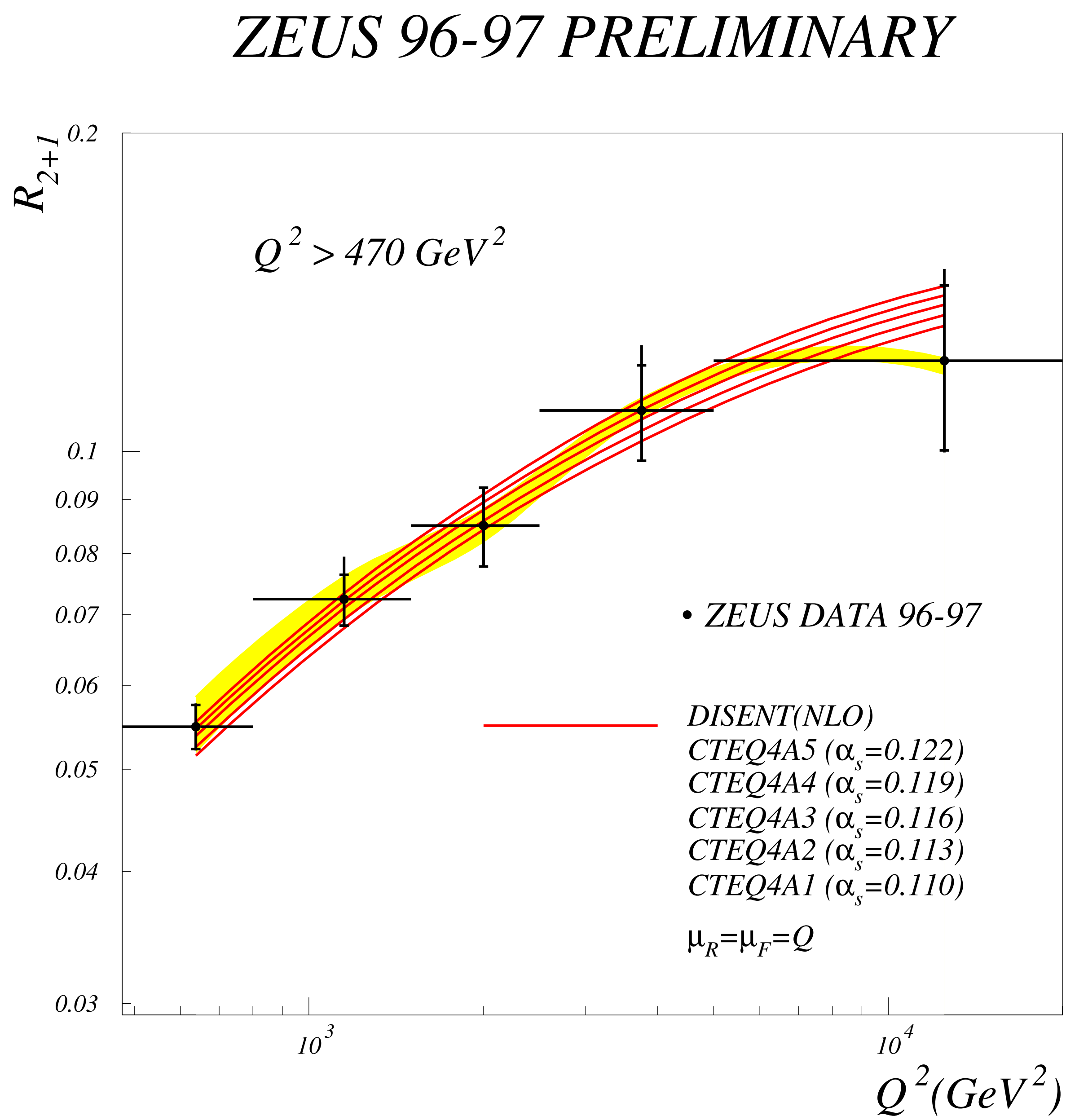
$R_{2+1} =$



'2+1'

'1+1'

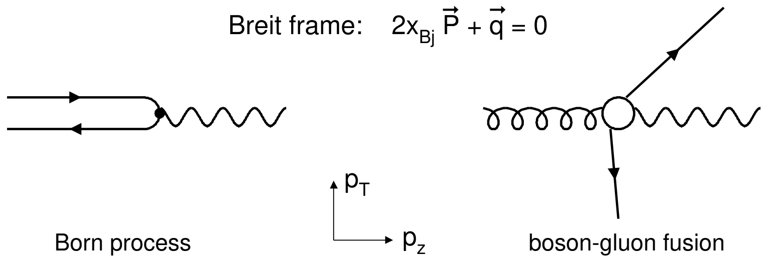
- two scales: Q^2 and E_T^2

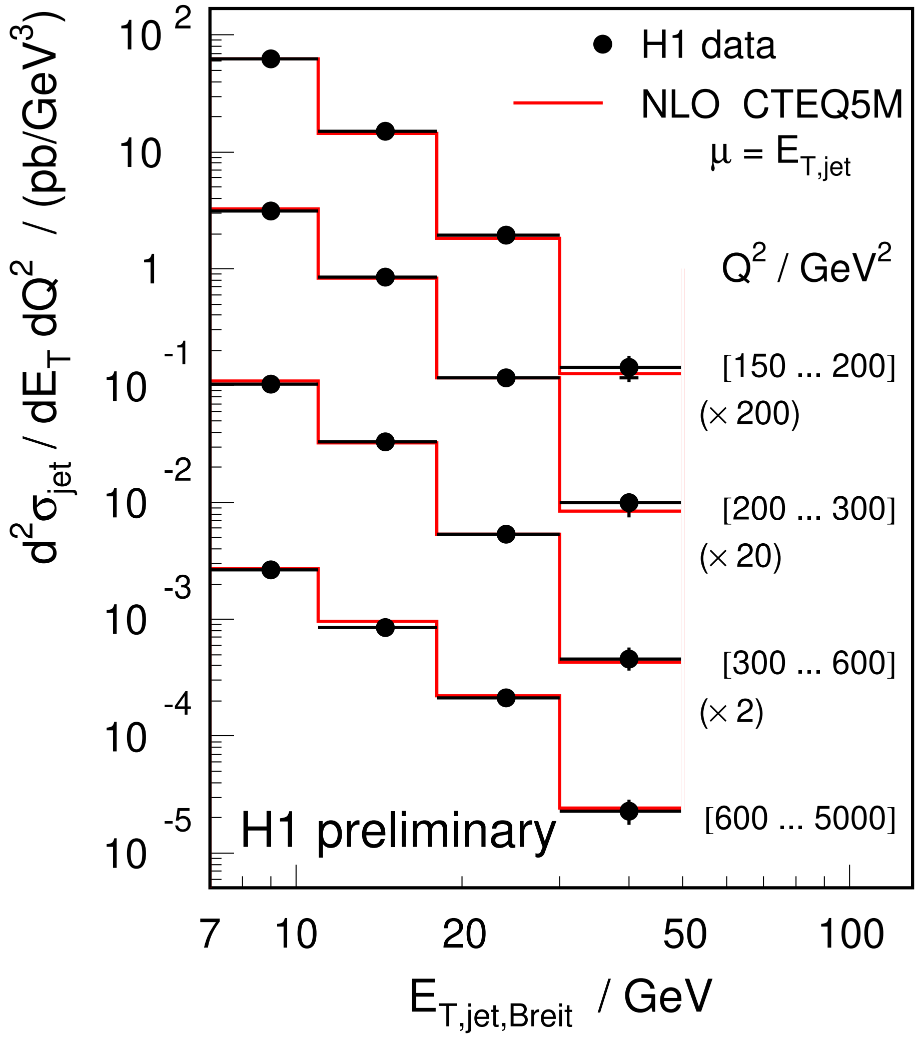


$$\alpha_s(M_Z) = 0.120 \pm 0.003(stat) \pm^{0.005}_{0.006}(exp) \pm^{0.003}_{0.002}(th)$$

jet cross section in the Breit frame

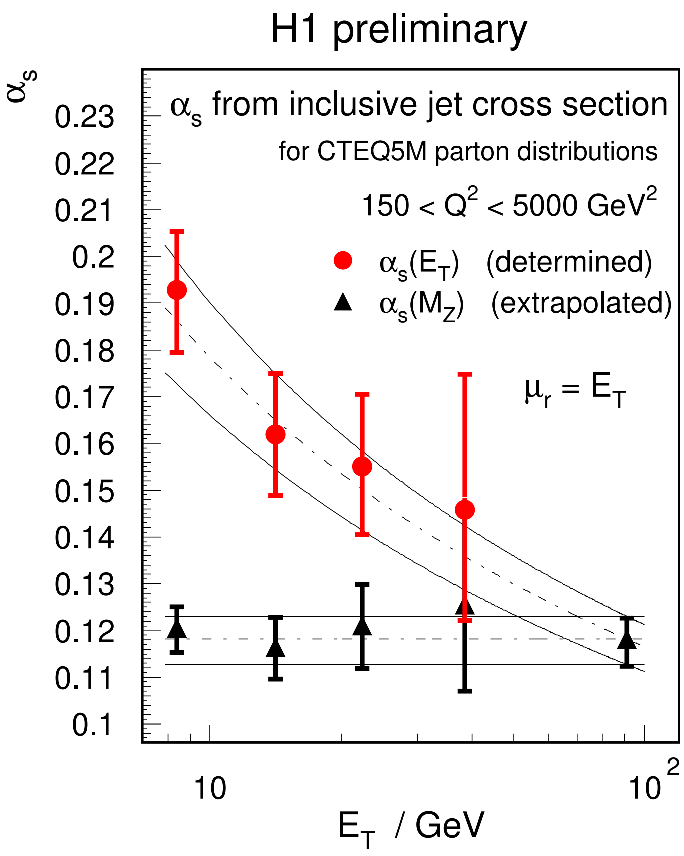
- inclusive jet-cross section in the Breit frame
  photon and proton collide head-on





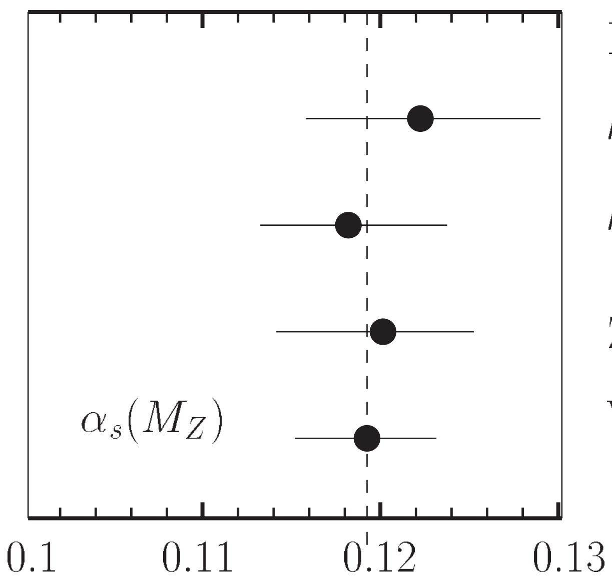
- well described by NLO-QCD $\Rightarrow$ extract α_s

α_s from jet cross sections



- single experiment, α_s running
- consistent results for $\mu_r^2 = Q^2$ and $\mu_r^2 = E_T^2$

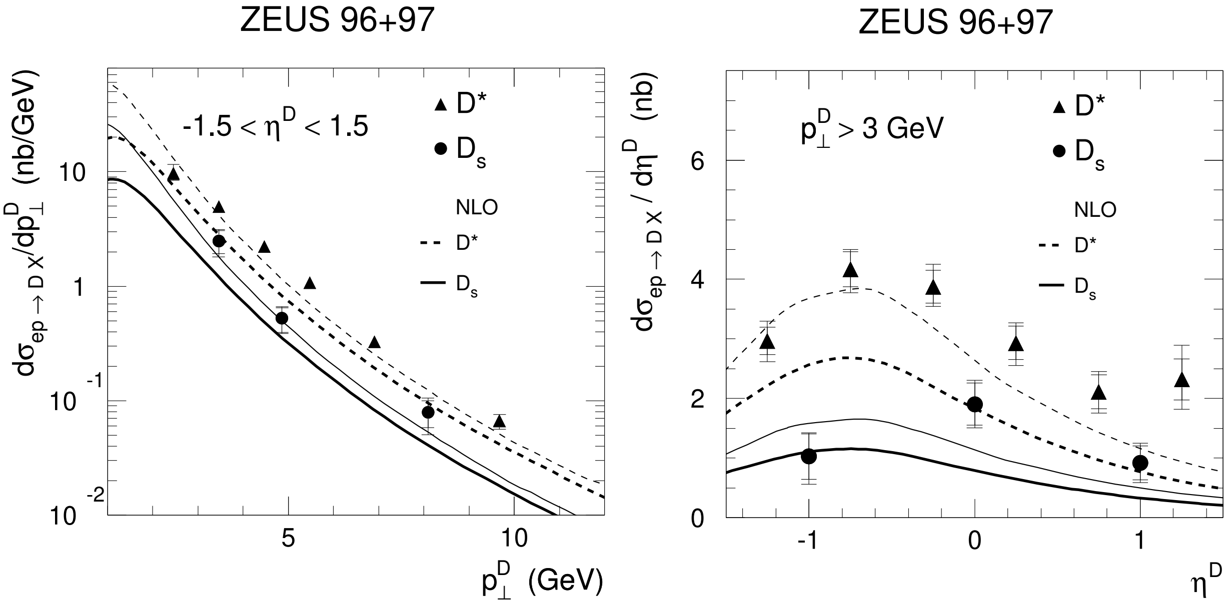
$$\alpha_s(M_Z) = 0.1181 \pm 0.0030(exp) \pm^{0.0039}_{0.0046} (theo) \pm^{0.0033}_{0.0015} (pdf)$$



- good agreement with world average

Heavy Quark Production

- quark mass $\longrightarrow$ perturbative QCD
- D^* and D_s in photoproduction



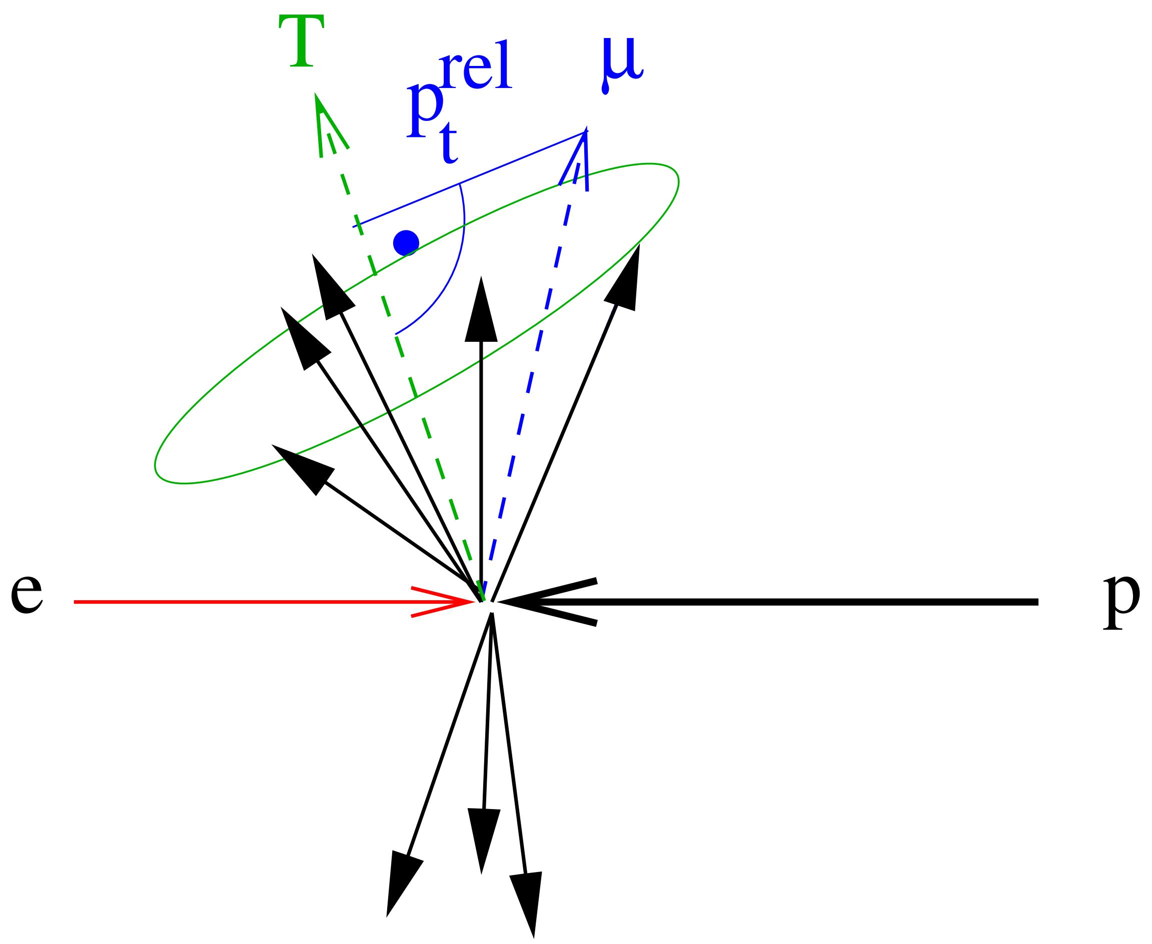
- Reasonable description of p_T spectrum by NLO QCD, curves for $\mu_r = \sqrt{m_c + p_T^2}, m_c = 1.5\text{GeV}$ and $\mu_r = 0.5\sqrt{m_c + p_T^2}, m_c = 1.1\text{GeV}$
- prediction too low in forward region, something missing?
- New D_s result, cross-check fragmentation

		$\sigma(D^*)/\sigma(D_s)$
HERA	ep	$0.41 \pm 0.07^{+0.03}_{-0.05}$
LEP	ee	0.43 ± 0.04

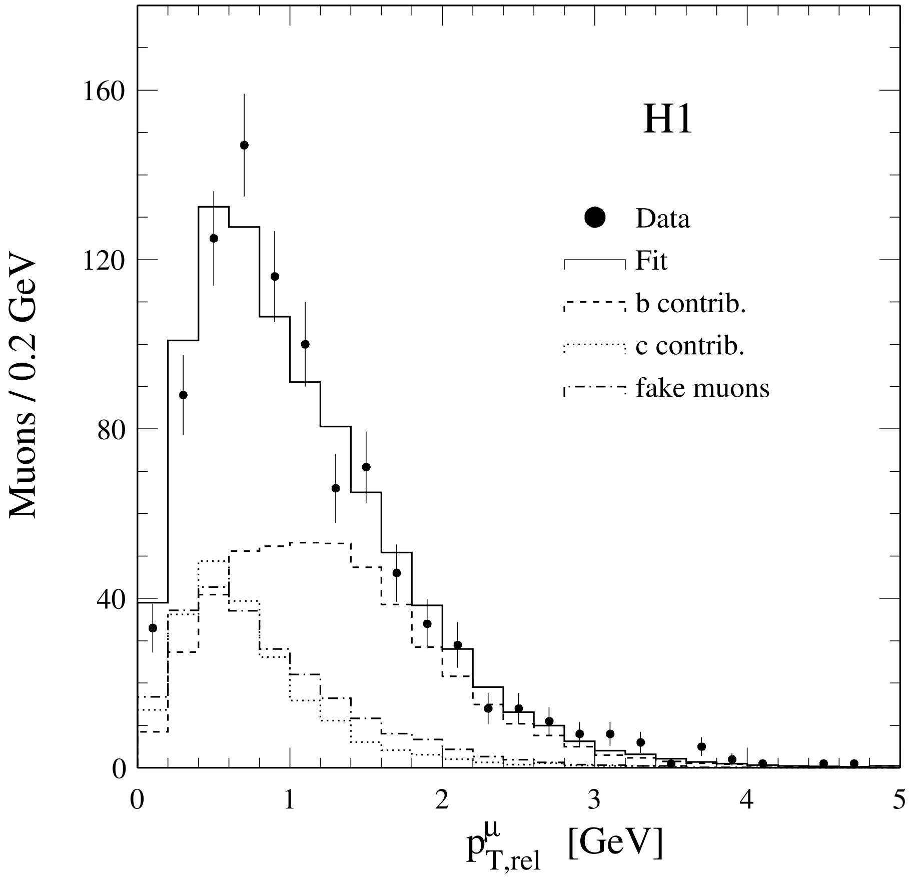
independent of production

b-production

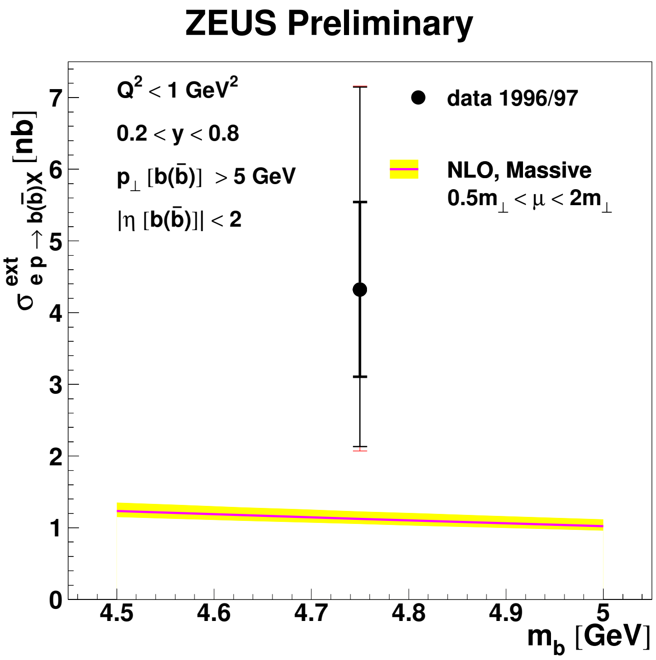
- small cross section, suppressed by mass and charge
- first observation in electroproduction:
  - semileptonic b-decays $\Rightarrow$ select leptons+jets
    $\hookrightarrow$ b-enriched sample
  - leptons from b-decays have higher transverse momentum relative to the jet $\rightarrow$ $p_{T,rel}$



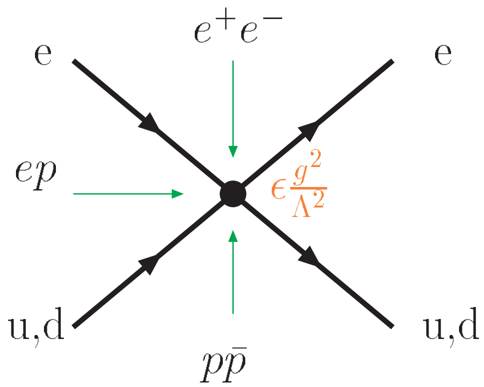
b-production



- ZEUS: $\ell = e, \mu$
- data factor ~ 4 above LO MC (Zeus and H1)
- NLO calculations closer, but low too



contact interactions



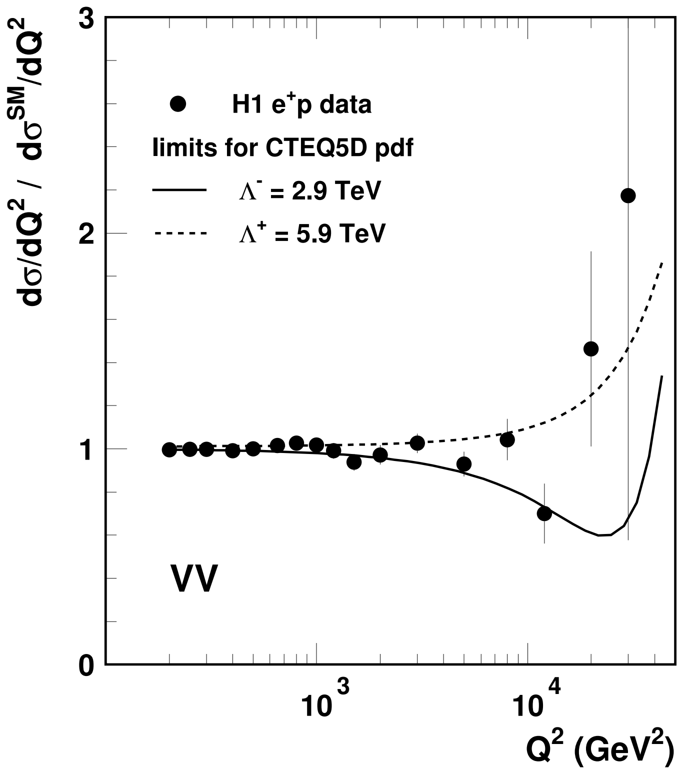
Low energy limit of

- heavy bosons, $\Lambda^2 \gg s$
- common constituents

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \epsilon \frac{g^2}{\Lambda^2} \sum_{q=u,d} \{ \eta^q_{LL} (\bar{e}_L \gamma^\mu e_L)(\bar{q}_L \gamma_\mu q_L) + \eta^q_{LR} (\bar{e}_L \gamma^\mu e_L)(\bar{q}_R \gamma_\mu q_R) + \eta^q_{RL} (\bar{e}_R \gamma^\mu e_R)(\bar{q}_L \gamma_\mu q_L) + \eta^q_{RR} (\bar{e}_R \gamma^\mu e_R)(\bar{q}_R \gamma_\mu q_R) \}$$

$\epsilon = \pm 1$, $g^2 = 4\pi$ by convention



example

VV :

$\eta_{LL} = \eta_{LR} = \eta_{RL} = \eta_{RR} = +1$

95 % C.L. Exclusion limits

$\epsilon = +1 \quad \Lambda > 5.9$ TeV

$\epsilon = -1 \quad \Lambda > 2.9$ TeV

Limits for individual couplings and other combinations:

$$\Lambda > 1.7 \text{ TeV} \ \ldots 5 \text{ TeV}$$

Large extra dimensions

- scenario with n extra dimensions, Radius R (sub-millimeter)
  gravitation strong at small distances
- 4+n dimensions $M_P \longrightarrow M_S$:
  $M_p^2 \sim R^n M_S^{2+n}$, M_S could be $\mathcal{O}(\text{TeV})$
- graviton exchange contributes to $eq \longrightarrow eq$ (Giudice *et al.*),
  but also $eg \longrightarrow eg$

$$\begin{array}{ll} M_S > 0.48 \text{ TeV} & \text{for} \lambda = +1 \\ M_S > 0.72 \text{ TeV} & \text{for} \lambda = -1 \end{array}$$

Quark substructure

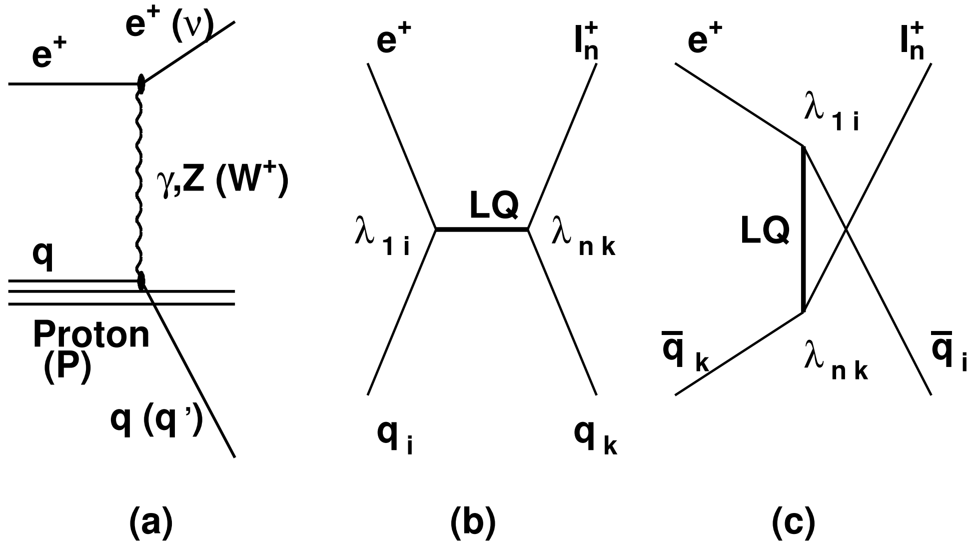
quark formfactor

$$f(Q^2) = 1 - \frac{1}{6} \underbrace{< r^2 >}_{R_q^2} Q^2$$

$$\hookrightarrow R_q < 1.7 \times 10^{-16} cm$$

Leptoquarks

Scalar or Vector-bosons with both, $L \neq 0$ and $B \neq 0$



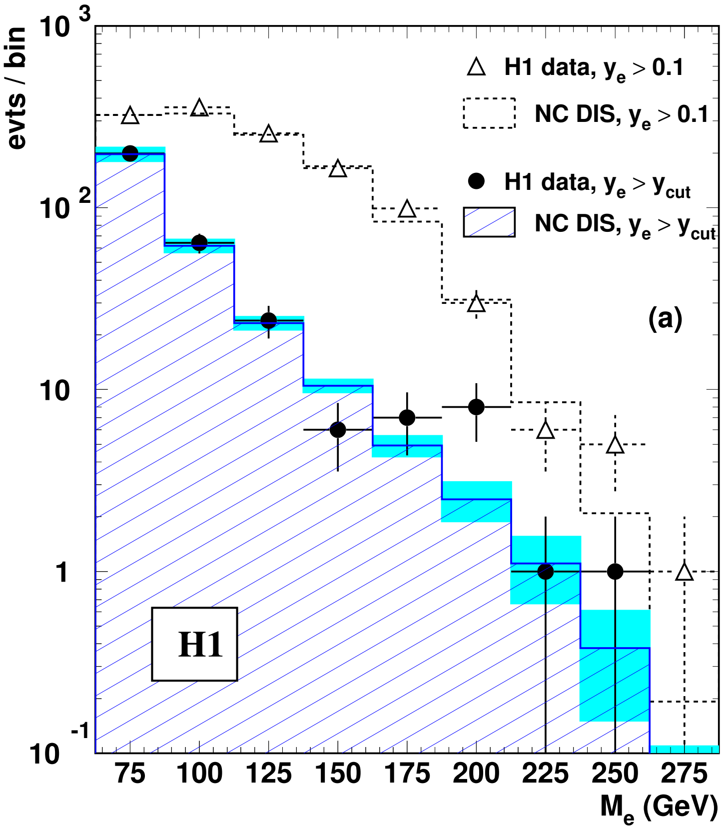
first generation LQ: final states like NC,CC DIS

Search for a narrow resonance in $M_{eq} = \sqrt{xs}$

angular distribution

- $y = 1/2(1 + \cos\theta^*)$
- flat for scalar
- $(1-y)^2$ for vector
- peaked at 0, steeply falling, for DIS

select $y > y_{\mathrm{cut}}$

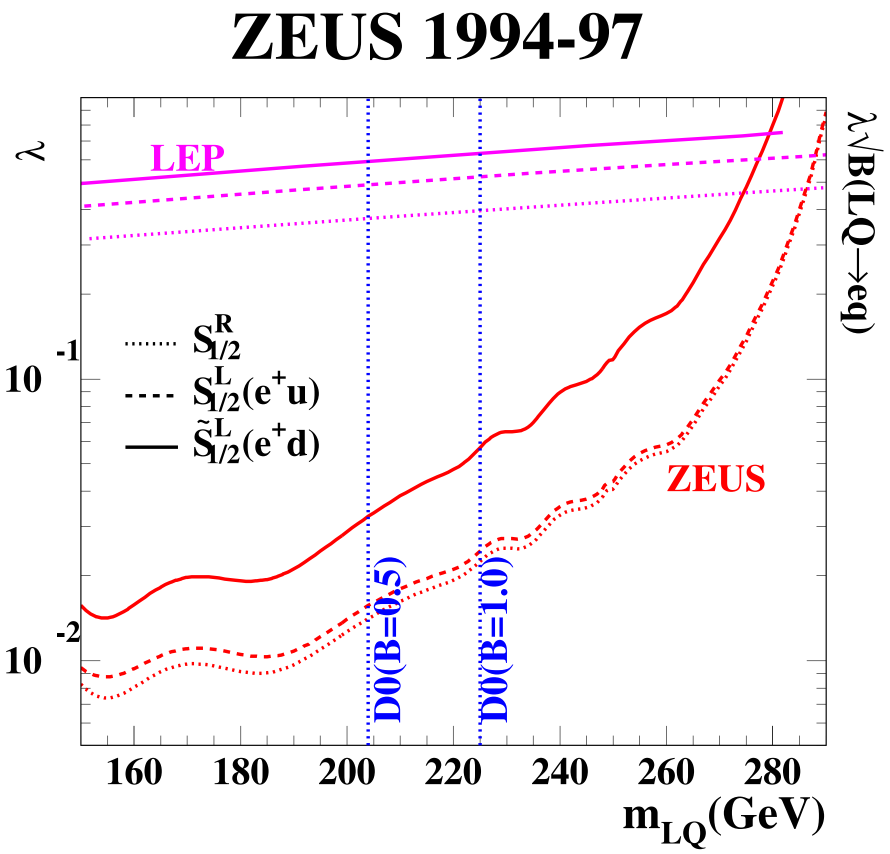


Exclusion limits, BRW model

- BRW:

$$\beta_e = BR(LQ \to eq) = 0,\ \frac{1}{2},\ 1$$

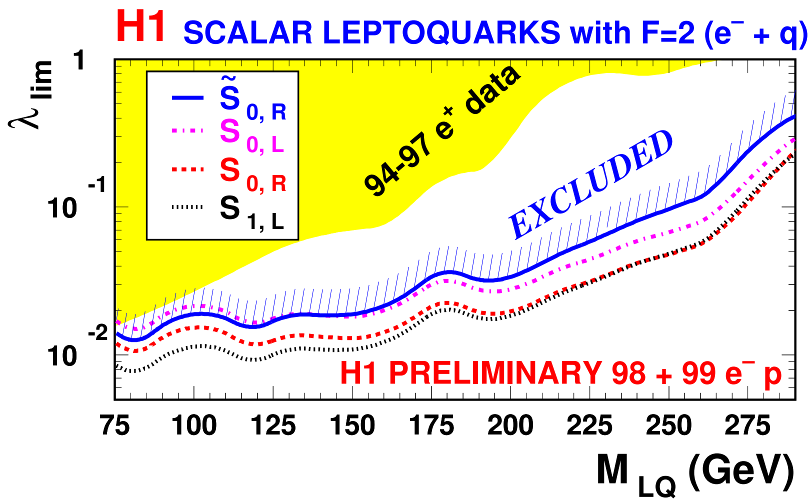
- e^+p, most sensitive to LQ coupling to $e^+ + q$ ($F = 0$).



BRW model
$\lambda = 0.3$
$(\lambda/4\pi = \alpha)$:

Scalar (Vector) LQ's excluded up to 275 (285) GeV

- e^-p data, sensitive to $e^- + q$ ($|F| = 2$).



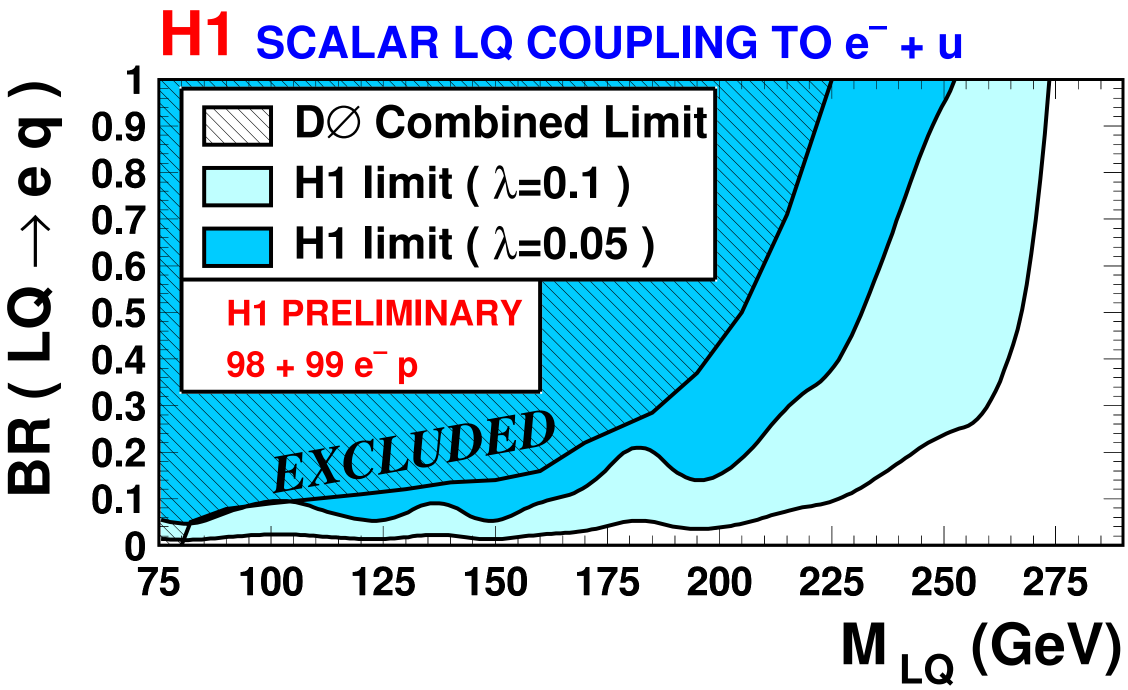
$\lambda = 0.3$ F=2 LQ's excluded up to 290 GeV

generic Leptoquarks

- LQ decay branching fractions

$$\beta_e = BR(LQ \to eq), \ \beta_\nu = BR(LQ \to \nu q)$$

  free parameters
- use NC and CC data
- exclusion limits on β_e for fixed λ
- example



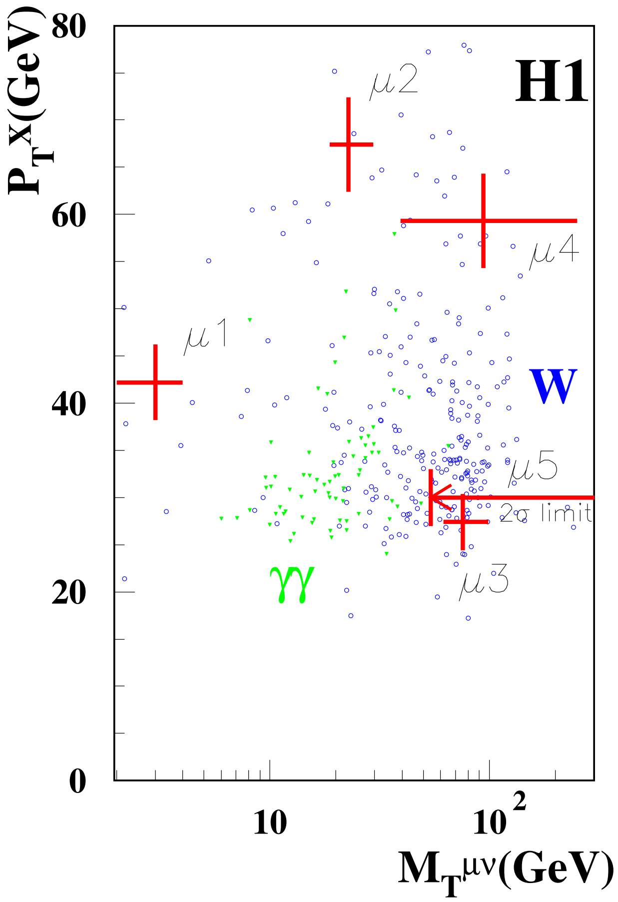
- sensitivity at low branching fractions

Lepton Flavor Violation

- τq: τ-jet + jet, $\Rightarrow$ no candidates
- μq: isolated μ+ jet, $\Rightarrow$ H1+Zeus: no candidates compatible with Leptoquarks

However,

- H1 found 5 isolated μ events in 40pb^{-1} e^+p data, with 0.8 expected
- no candidates in 13.6pb^{-1} e^-p data
- Zeus: no candidates in 47.5pb^{-1} e^+p+16pb^{-1} e^-p data



striking kinematics

- isolated, high p_t μ
- large missing p_t
- high p_t hadronic jet

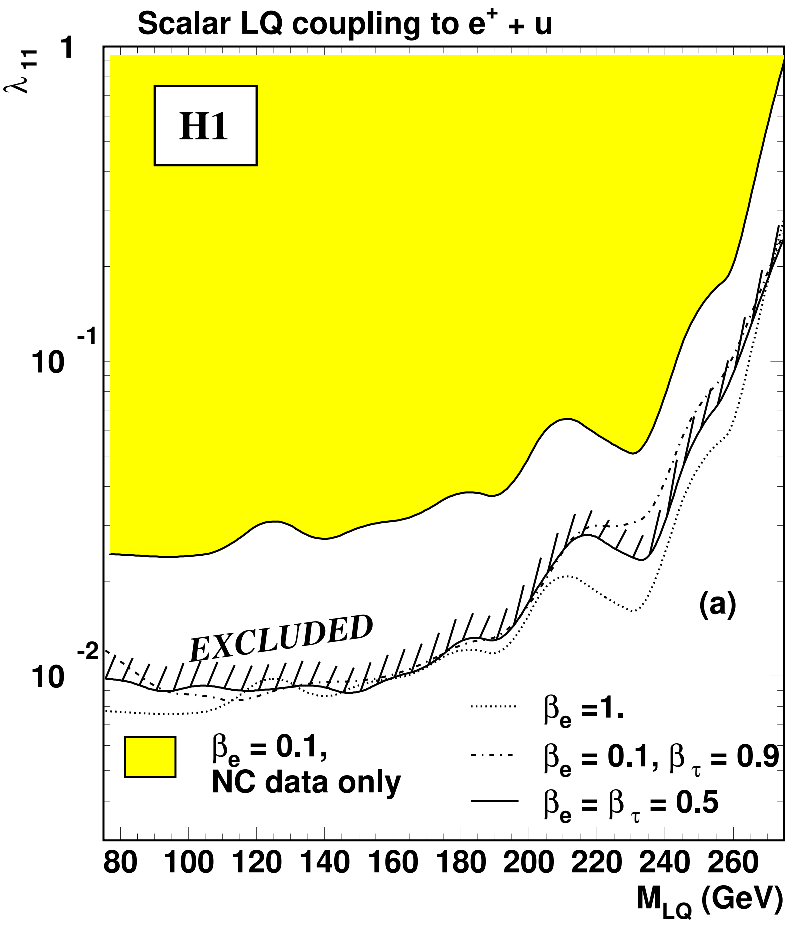
$\leftarrow$ SM-MC, 500 $\times$ $\mathcal{L}(data)$

- W
- inelastic $\gamma\gamma$

$p_T^X = \sum p_T$,
everything except μ

Limits on Lepton Flavor Violating Leptoquarks

- $M_{LQ} < \sqrt{s}$, direct search for real LQs
  - e.g. LQ coupling to $e^+u(\lambda_{11})$ and τq (λ_{3i}) production in e^+p, decay to e-jet or τ-jet ($e \to \mu$ small)
  - $\beta(LQ \to e^+q) + \beta(LQ \to \tau q) = 1$



fix β_e, limit on λ_{11}

- improved sensitivity for LQ's with small β_e

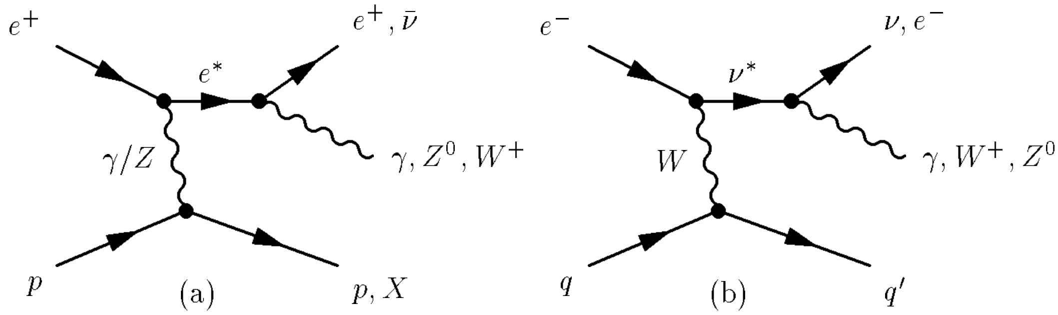
- $M_{LQ} \gg \sqrt{s}$, LFV through virtual LQs

$\Rightarrow$ $\sigma \propto (\lambda_{1i}\lambda_{2i}/M_{LQ}^2)^2$

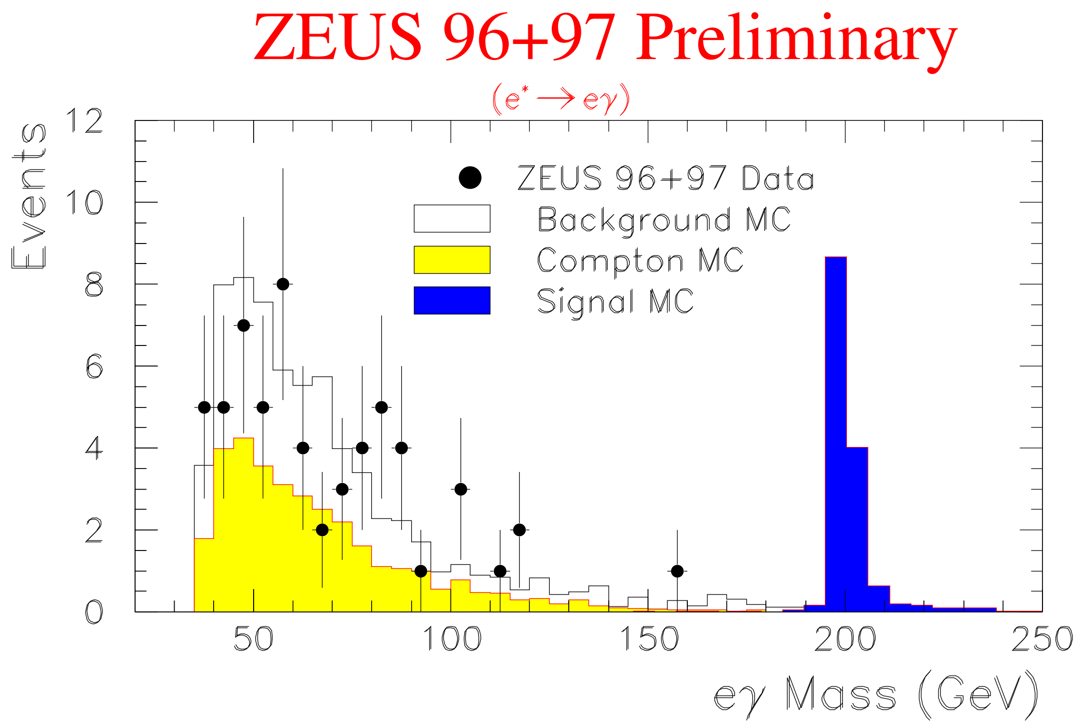
many limits comparable to or better than indirect constraints

excited fermions

- expected if fermions are not pointlike



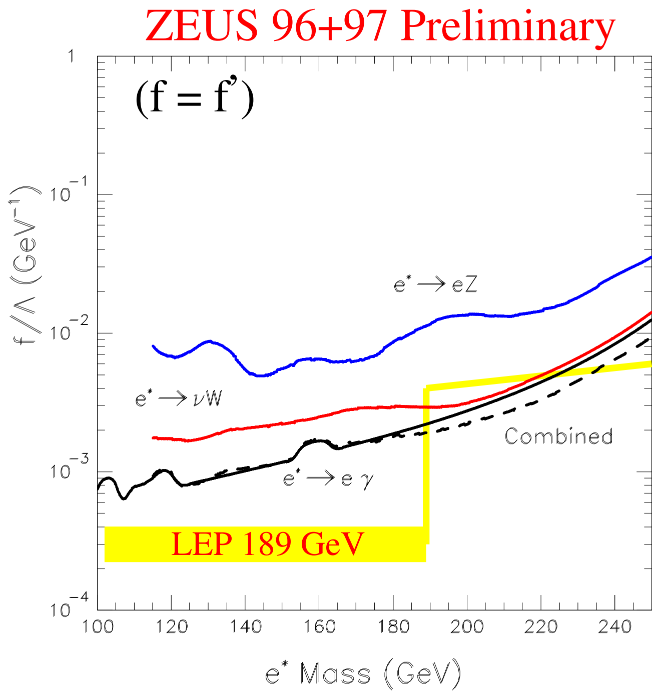
- Search for Fermion-Boson resonances
- e.g. $e^* \to e - \gamma, \to$ high energy electron and photon + empty detector



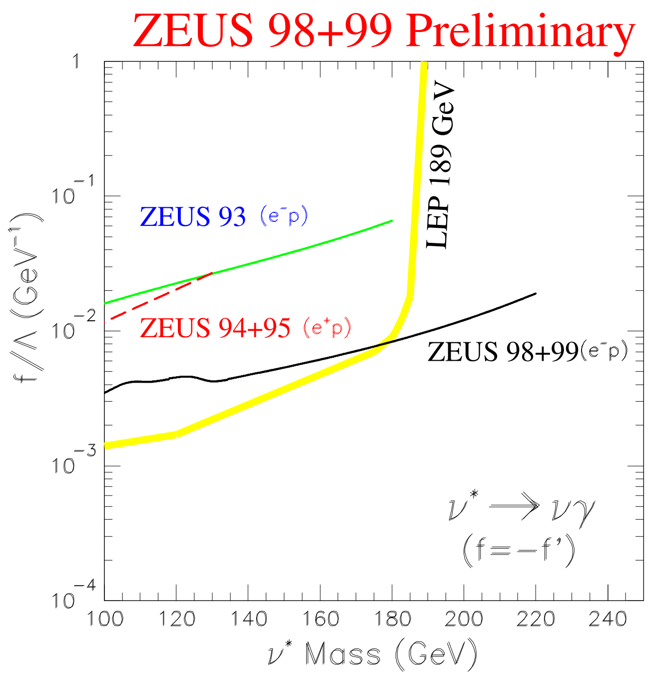
- No evidence or a resonance peak.

Excited fermions

phenomenological model Hagiwara, Komamiya & Zeppenfeld
couplings $f(SU(2)_L)$, $f'(U(1)_Y)$, $f_s(SU(3)_c)$



- e^+p data
- 95 % C.L. limits vs $m(e^*)$
- assuming $f = f'$, $f_s = 0$



- 95 % C.L. limits vs $m(\nu^*)$
- assuming $f = -f'$, $f_s = 0$
- much higher cross section in e^-p than in e^+p

HERA reach beyond LEP II kinematical limit

Summary and outlook

- measurement of the proton structure in a new kinematical domain
- probes QCD from highest Q^2 to soft
- DIS in a region where electromagnetic and weak force have equal strength
- No evidence for new physics in $\sim 40pb^{-}1$,
  - stringent limits for many non-standard scenarios
  - some tantalizing observations at highest Q^2
- Hera continues running until September 2000, double published statistics
- Restart in 2001, 5-fold Luminosity increase
- $\approx 1\ \mathrm{fb}^{-1}$ per experiment after 5 years