High Q^2 and High P_T Processes at HERA

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on behalf of the

H1 and ZEUS

Collaborations

Overview

HERA: **unique $e^{\pm}p$ collider**

$\rightarrow$ study of Deep Inelastic Scattering (DIS)

820/920 GeV (p) $\Rightarrow \sqrt{s} \approx$ 300/320 GeV $\Leftarrow$ 27.5 GeV ($e^{\pm}$)

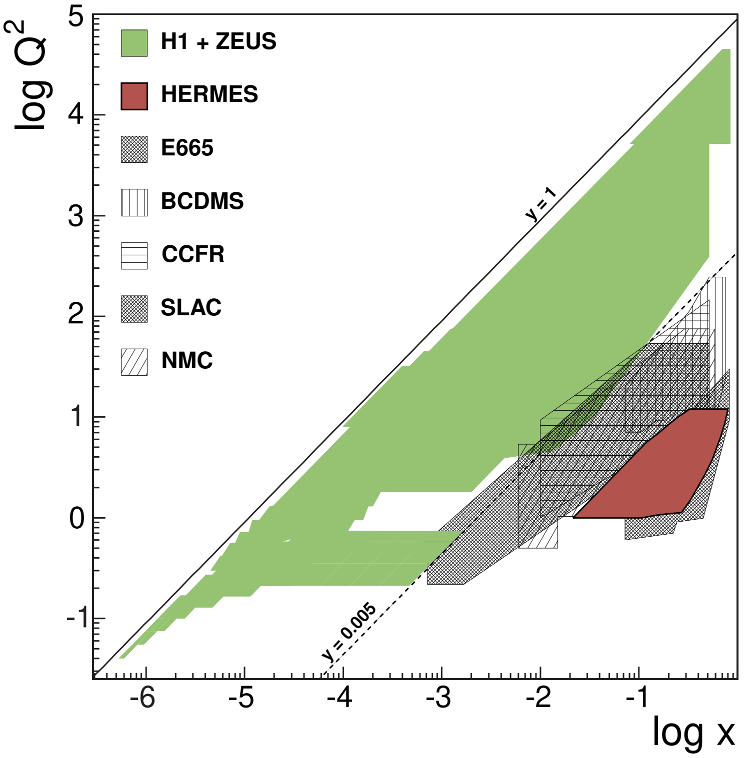
$\rightarrow \sqrt{s}$ increased from 300 GeV to 320 GeV (1998)

this talk: high $\boldsymbol{Q^2}$ domain ($>$ $\mathbf{200}$ GeV^2)

- **inclusive cross section measurement**
  - neutral currents (NC) and charged currents (CC)
  - test of the standard model at high Q^2:

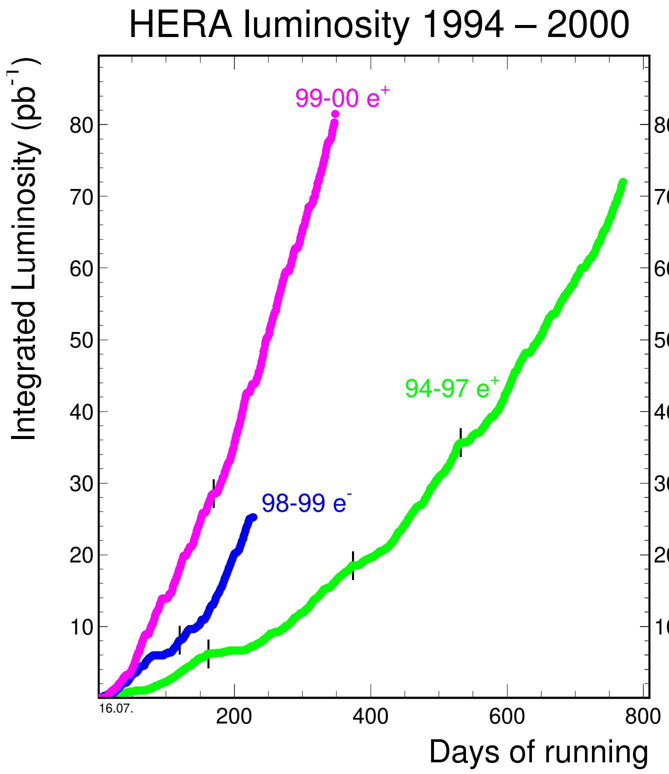
    contact interactions (CI), large extra dimensions (LED) and Leptoquarks (LQ)
- **isolated Leptons**
  - W production at high P_T
  - search for single top production

Physics Motivation



- high Q^2: test of standard model
  - probe the proton down to $d \approx 1/\sqrt{s} \approx 10^{-18}$ m
  - probe physics in the region where em (γ) and weak(W, Z_0) interaction are of comparable strength
  - search for new phenomena and SM extension
- medium Q^2: precise measurement of structure functions
  - overlap to fixed target at low y
  - measurement of F_L at high y
  - sea quarks and gluon densities at low x

The HERA data – Luminosity



data taken since 1994 (up to 06/2000)

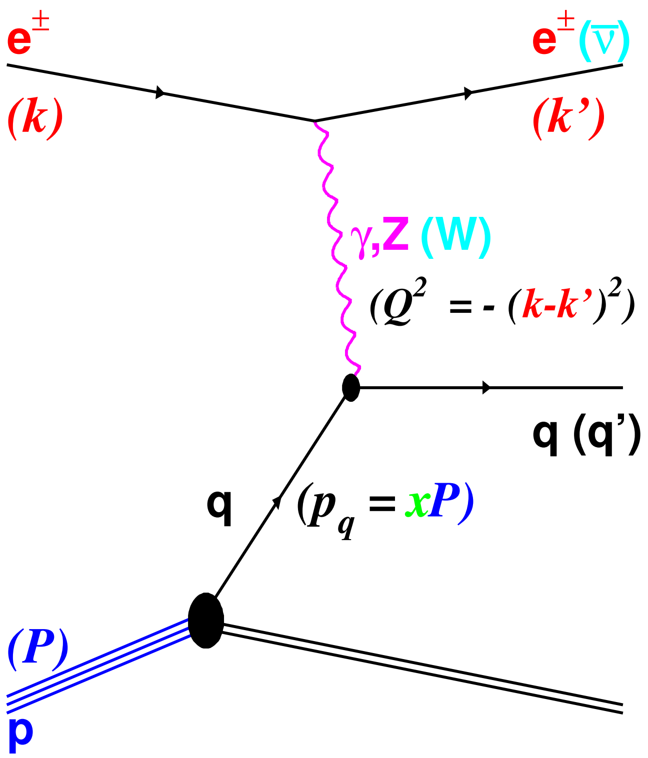
$\approx$ 100 pb^{-1} physics data for **each** experiment

- 1994 - 1997: e^+ 37 pb^{-1} (H1) / 48 pb^{-1} (ZEUS)
- 1998 - 1999: e^- 18 pb^{-1} (H1) / 16 pb^{-1} (ZEUS)
- 1999 - 2000: e^+ 46 pb^{-1} (H1) / 48 pb^{-1} (ZEUS)

high int. luminosities $\Rightarrow$ statistics for high Q^2 region

Study NC and CC interactions with e^+p and e^-p beams with the same apparatus

HERA DIS Kinematics

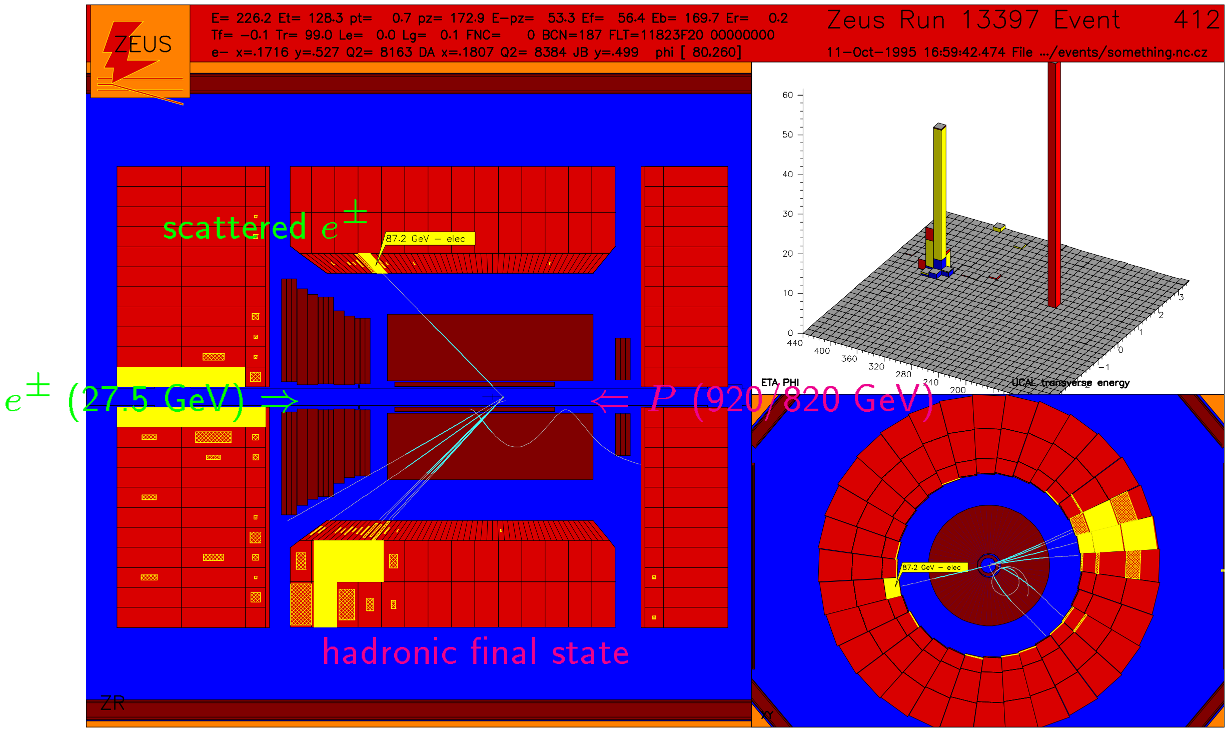


- Q^2: squared four momentum transfer
- x: fractional quark momentum
- y: inelasticity
- s: squared C.M. energy
- M^2: squared lepton–quark invariant mass

$$Q^2 = x \cdot y \cdot s$$

NC Event signature

- hadronic energy (jet)
- charged track with associated em energy cluster



main selection criterion:

electromagnetic energy in uranium-scintillator calorimeter (6000 cells)

UCAL: $\sigma(E)/E$: $18\%/\sqrt(E)$ em, $35\%/\sqrt(E)$ had

good determination of e and jet parameters due to

overconstrained kinematics in NC events

Neutral Current cross section

Born cross section for $e^{\pm}p \rightarrow e^{\pm}X$

$$\left(\frac{d^2\sigma_{NC(e^{\pm})}}{dxdQ^2}\right)_{\text{Born}} = \frac{2\pi\alpha^2}{xQ^4}(Y_+\tilde{F}_2^{NC} \mp Y_- x\tilde{F}_3^{NC} - y^2 F_L^{NC})$$

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

In leading order QCD:

- $\tilde{F}_2(x,Q^2) = x\sum_{Quarks} A_f[q(x,Q^2) + \bar{q}(x,Q^2)]$

  γ, Z couple to all quark flavours

- $x\tilde{F}_3(x,Q^2) = x\sum_{Quarks} B_f[q(x,Q^2) - \bar{q}(x,Q^2)]$

  γ/Z interference term, sensitive to valence quarks

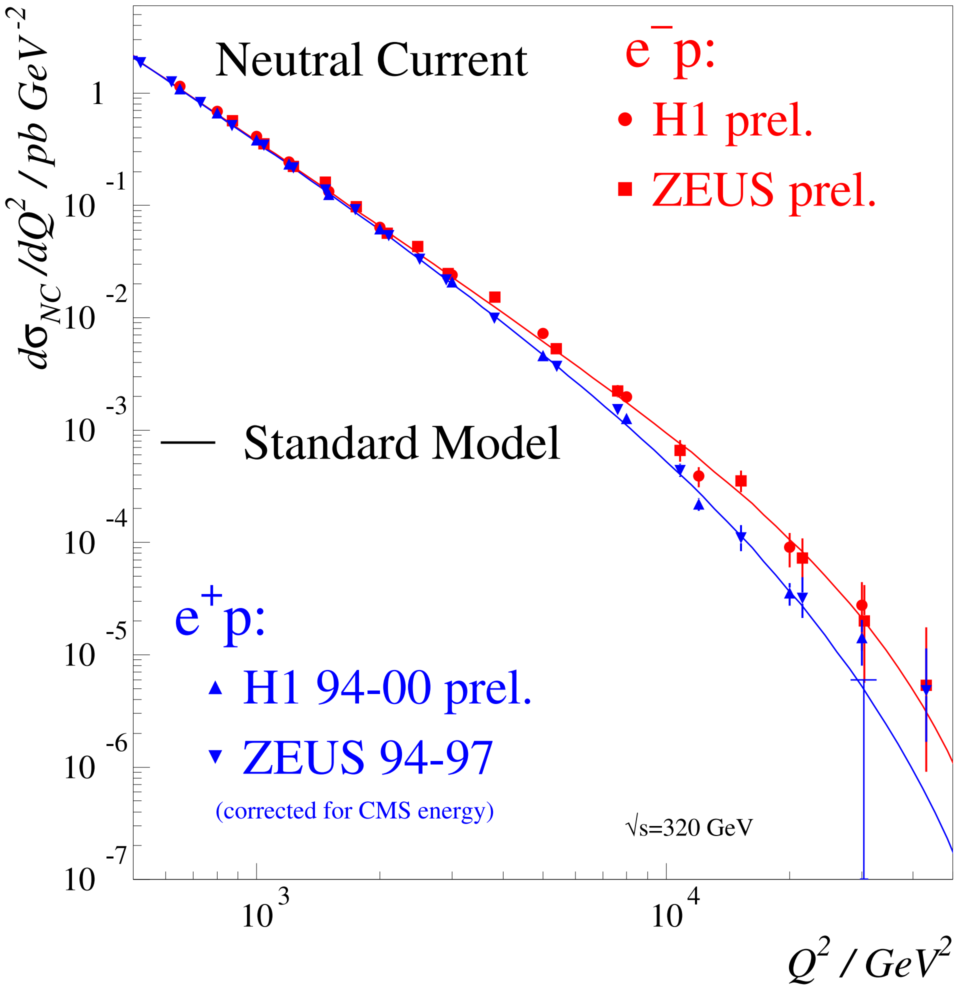
- $F_L(x,Q^2)$

  longitudinal structure function, sensitive to gluon

reduced cross section:

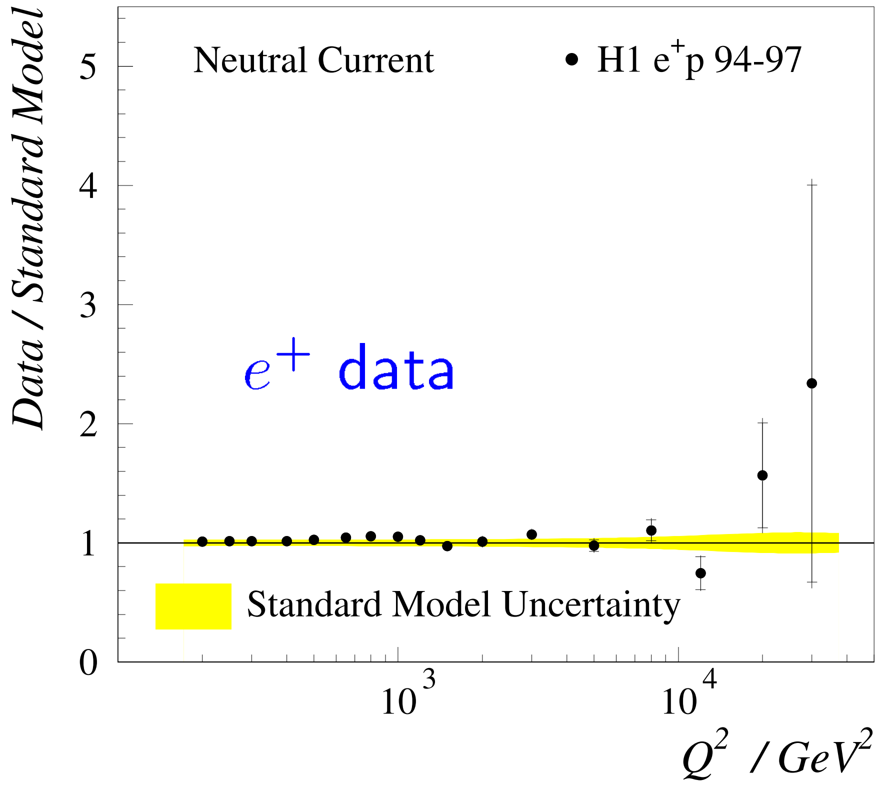
$$\tilde{\sigma} = \frac{xQ^4}{2\pi\alpha^2} \cdot \frac{1}{Y_+} \cdot \frac{d^2\sigma_{Born}^{NC}}{dxdQ^2} = \tilde{F}_2^{NC} \pm \frac{Y_-}{Y_+} x\tilde{F}_3^{NC} - \frac{y^2}{Y_+} F_L^{NC}$$

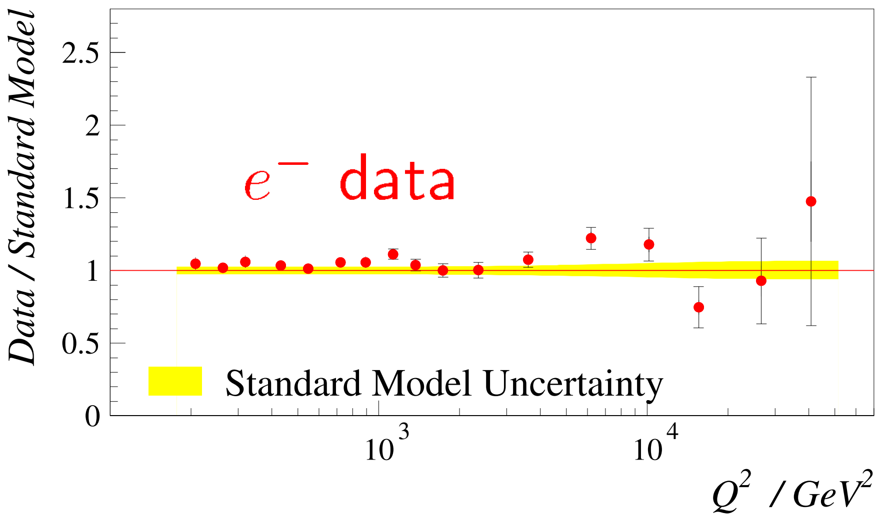
NC cross section $d\sigma/dQ^2$



- SM describes the HERA data well in wide Q^2 range
- $\sigma(e^-p) > \sigma(e^+p)$ at $Q^2 \geq 5000$ GeV^2 due to constructive γ/Z interference in e^- (destructive in e^+)
- first time to probe the high Q^2 region with preccision

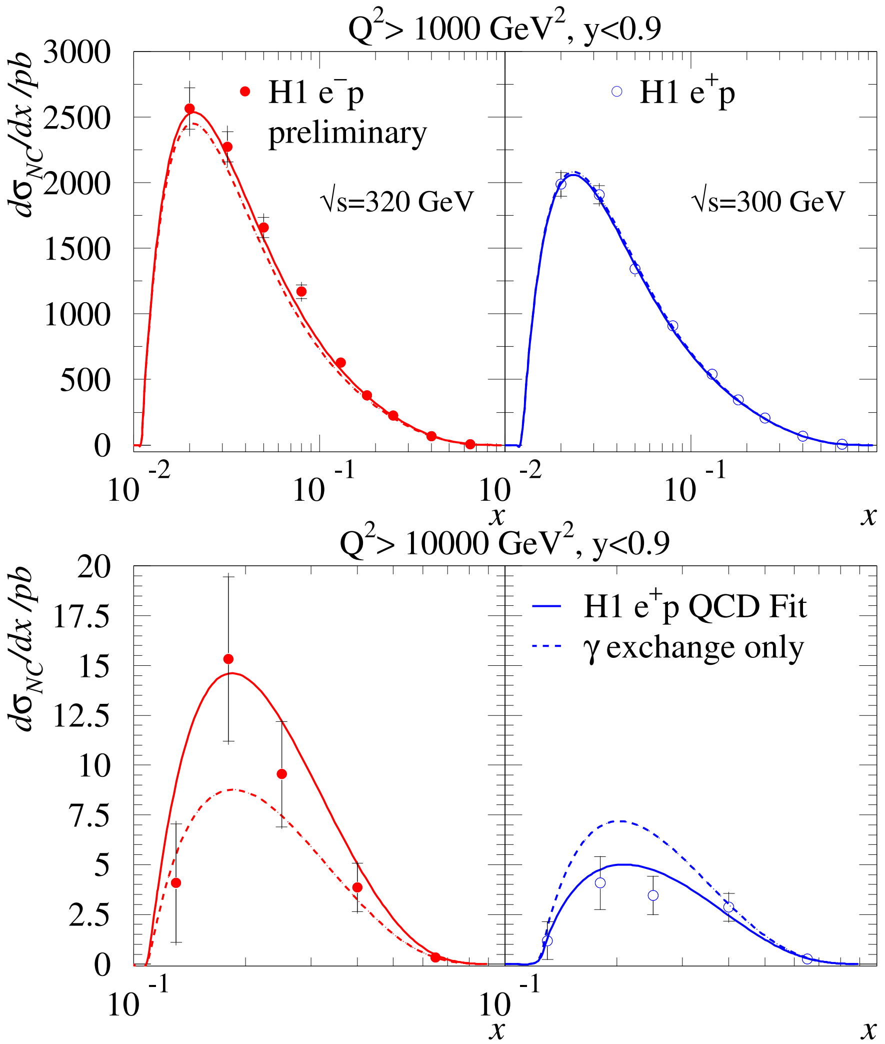
NC $d\sigma/dQ^2$ compared to Standard Model





$\Rightarrow$ test of SM at high Q^2: room for new contriburions / extensions of the Standard Model

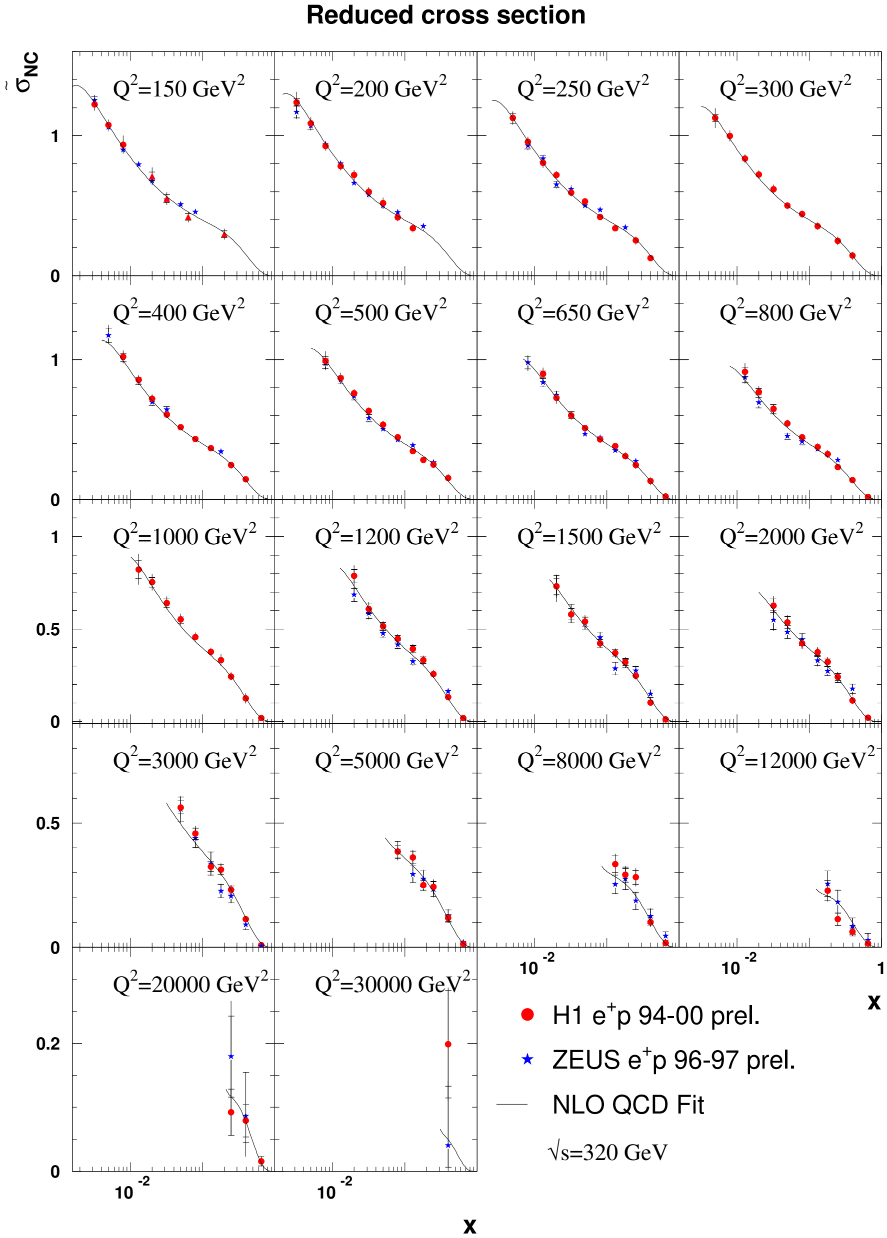
NC cross section $d\sigma/dx$



- $\gamma - Z$ interference at $Q^2 \approx M_Z^2$ clearly visible
- good agreement between data and SM
- e^-: constructive γ/Z interference
- e^+: destructive γ/Z interference

Reduced NC cross section $\tilde{\sigma}_{NC}$

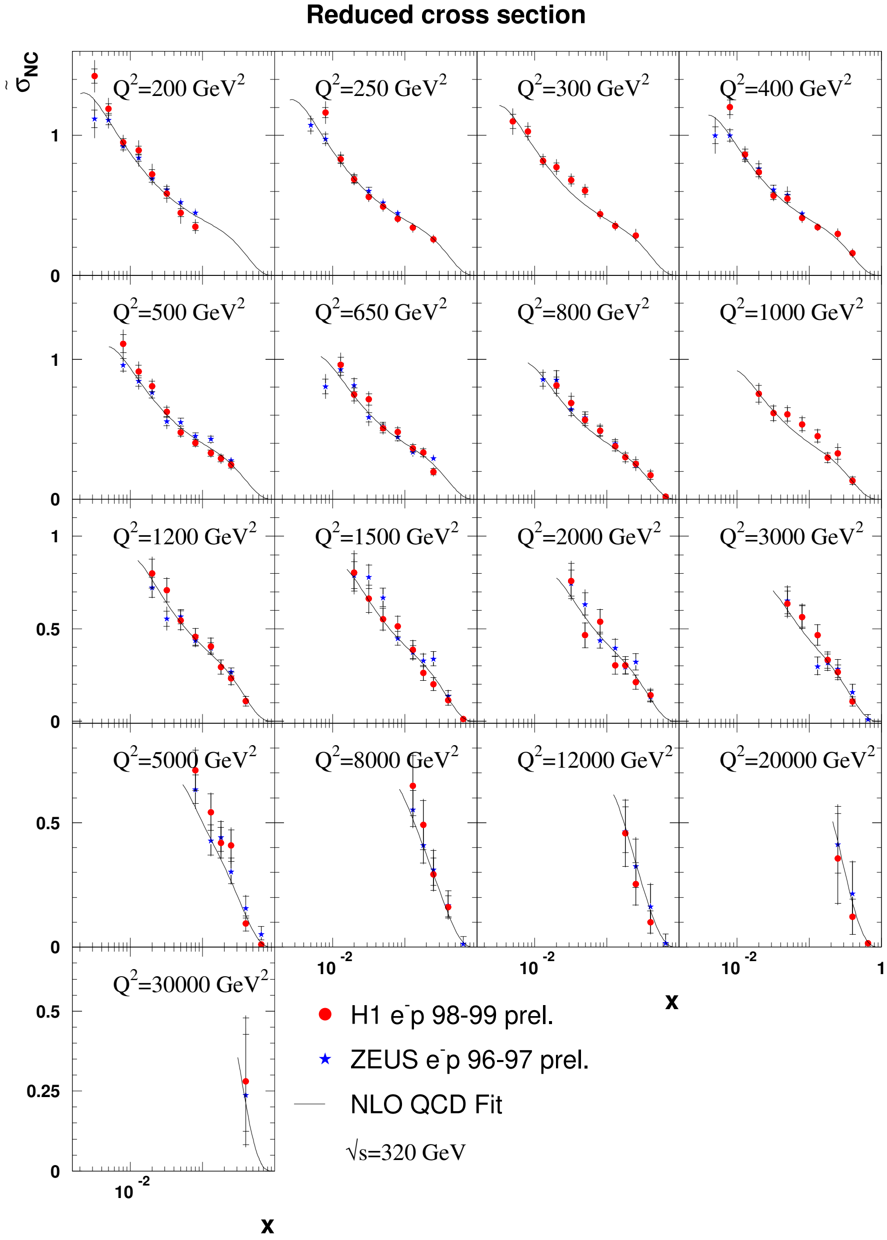
e^+ data



- HERA data agrees with QCD in wide Q^2 range up to $Q^2 = 30000$ GeV^2
- NLO QCD fit: including fixed target data and scaling violation

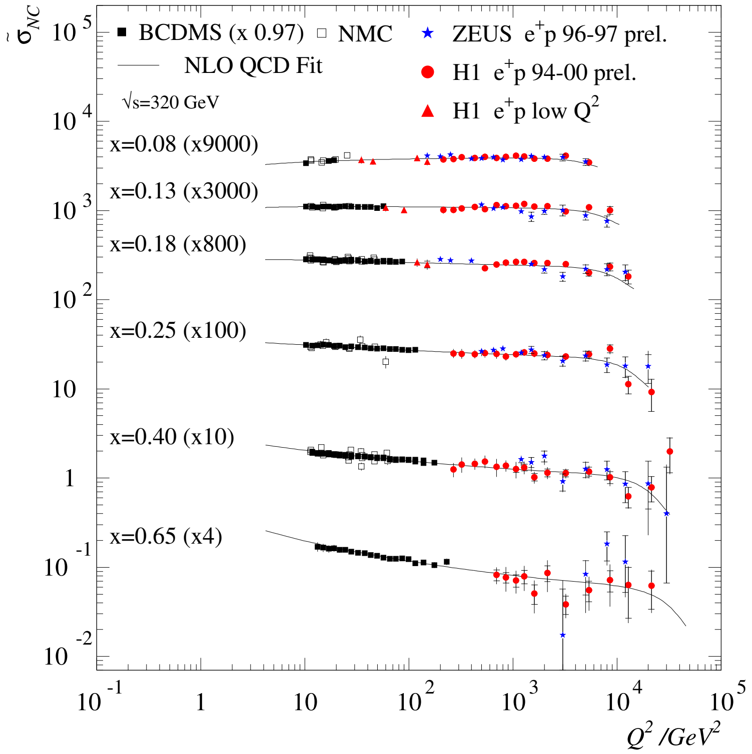
Reduced NC cross section $\tilde{\sigma}_{NC}$

e^-data

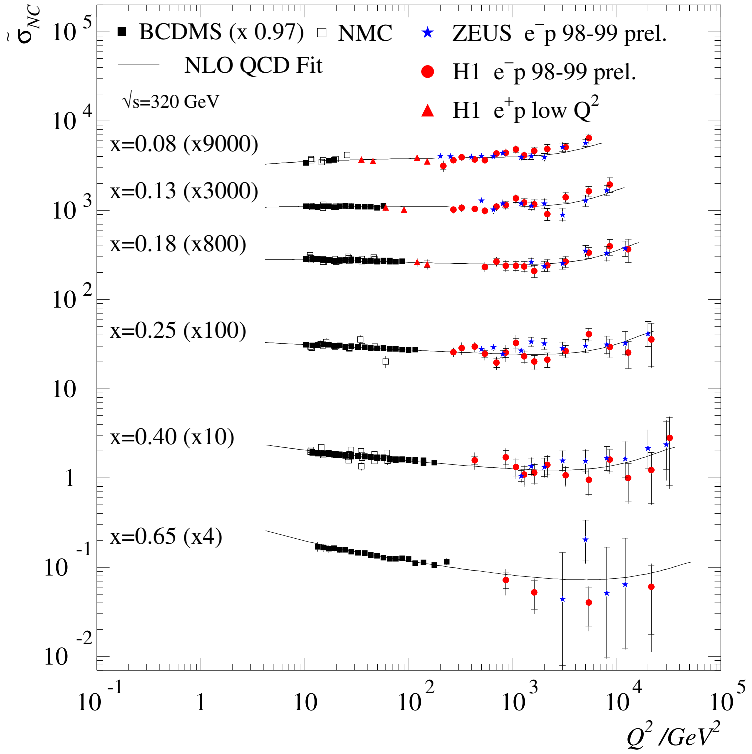


- NLQ QCD gives good description of e^+ and e^- data

NC reduced cross section $\tilde{\sigma}_{NC}$ at high x, Q^2



test of SM over 4 orders of magnitude in Q^2



positive (negative) interference between γ/Z was observed at high Q^2 in e^- (e^+)

$\Rightarrow$ use difference to extract xF_3

Extraction of xF_3

reminder:

$$\left(\frac{d^2\sigma_{NC(e^\pm)}}{dx\,dQ^2}\right)_{\text{Born}} = \frac{2\pi\alpha^2}{xQ^4}\left(Y_+F_2^{NC} \mp Y_- xF_3^{NC} - y^2F_L^{NC}\right)$$

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

- sign of xF_3 contribution depends on lepton charge
- y^2F_L contribution negligible at high Q^2
- F_L only relevant at lowest Q^2 and lowest x ($=$ high y)

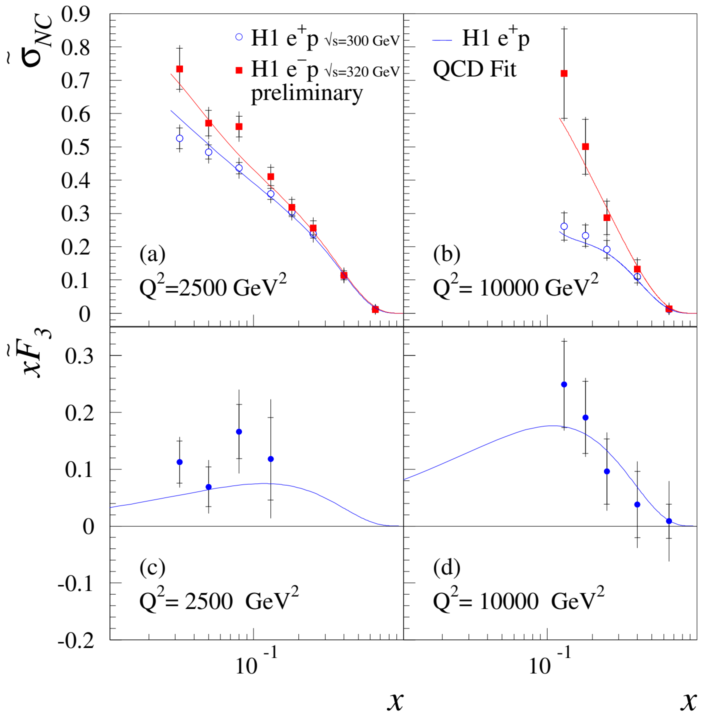
$\Rightarrow$ different proton beam energies (E_P) need $Y_\pm^{E_P}$

$$\sigma^+ = \frac{2\pi\alpha^2}{xQ^4}\cdot\left(Y_+^{820}\cdot F_2 - y_{820}^2F_L - Y_-^{820}\cdot xF_3\right)$$
$$\sigma^- = \frac{2\pi\alpha^2}{xQ^4}\cdot\left(Y_+^{920}\cdot F_2 - y_{920}^2F_L + Y_-^{920}\cdot xF_3\right)$$

using reduced cross sections $\tilde{\sigma}$ to extract xF_3

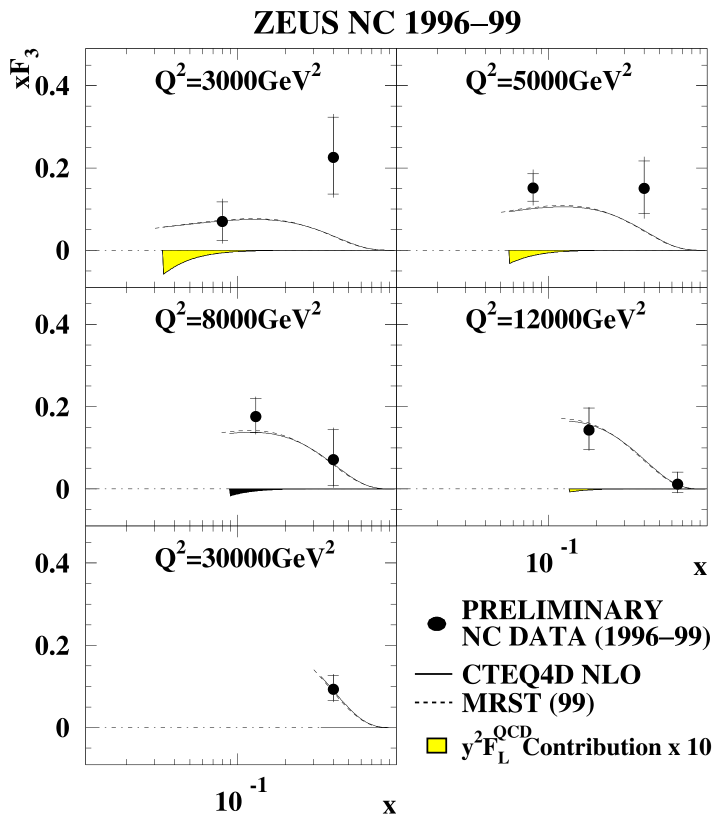
$$xF_3 = \left(\frac{Y_-^{920}}{Y_+^{920}} + \frac{Y_-^{820}}{Y_+^{820}}\right)^{-1}\cdot\left(\frac{1}{Y_+^{920}}\cdot\tilde{\sigma}^- - \frac{1}{Y_+^{820}}\cdot\tilde{\sigma}^+\right) - \Delta F_L$$

Measurement of xF_3 at fixed Q^2



first measurement of $x\tilde{F}_3^{NC}$ at high Q^2

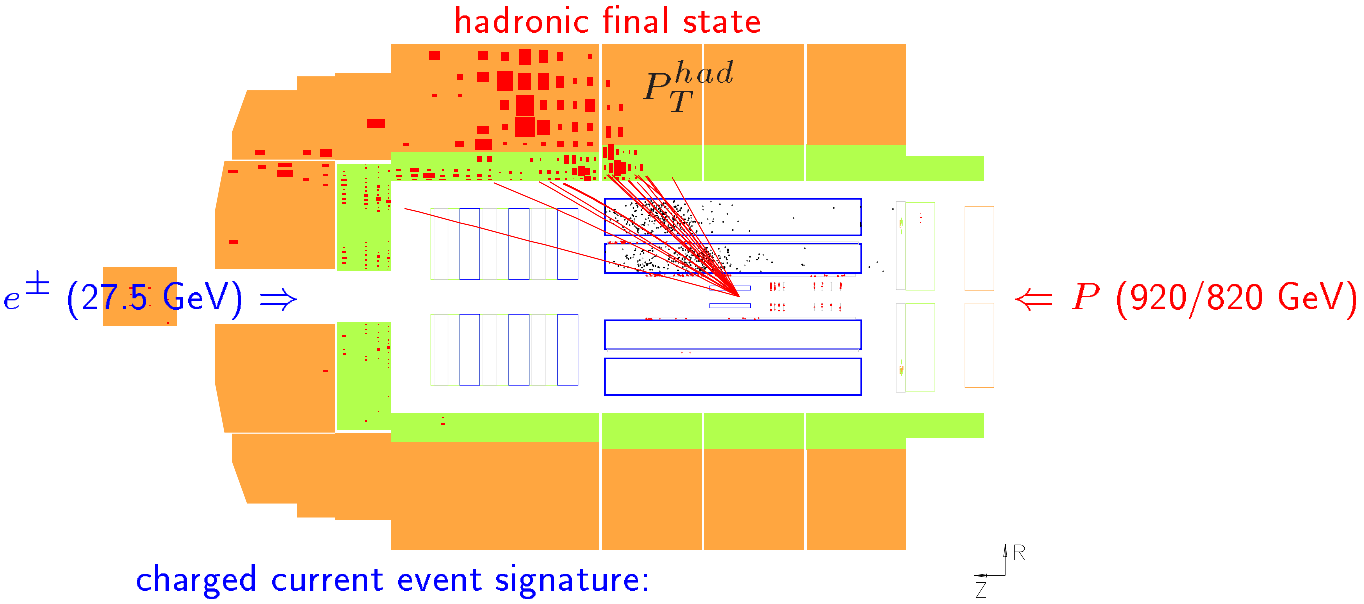
sensitive to valence quark structure



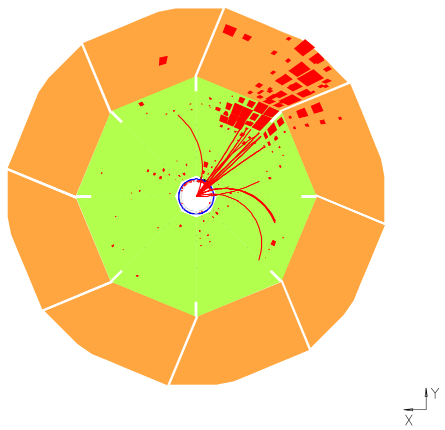
errors limited by e^- statistics

F_L correction taken from QCD fit, only 1 % at lowest Q^2 and lowest x (corresponding to highest y)

CC Event signature



charged current event signature:
missing P_T (ν) and hadronic energy (jet)



liquid argon calorimeter (LAr):

high granularity: 45000 cells
$\sigma(E)/E$:
EM: $\sigma(E)/E = 12\%/\sqrt{E} \oplus 1\%$
HAD: $\sigma(E)/E = 50\%/\sqrt{E} \oplus 1\%$

good understanding of had. energy scale needed

reconstruction based on hadronic calorimeter data:

$$(E - p_Z)_{\text{had}} \text{ and } p_{\text{T,had}} \Rightarrow Q^2, x, y$$

Charged Current cross section

charged current cross section suppressed due to high $W^{\pm}$–mass

$$\frac{d^2\sigma^{CC}}{dxdQ^2} = \frac{G_F}{2\pi x}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \times \Phi^{\pm}_{CC}(x,Q^2)$$

leading order cross section $e^{\pm}p \rightarrow \nu X$:

$$e^+p\ :\ \frac{d^2\sigma^{CC}}{dxdQ^2} \propto x \cdot [(\bar{u}+\bar{c}) + (1-y)^2(d+s)]$$

- d valence quark probed
- d suppressed by the $(1-y)^2$ factor

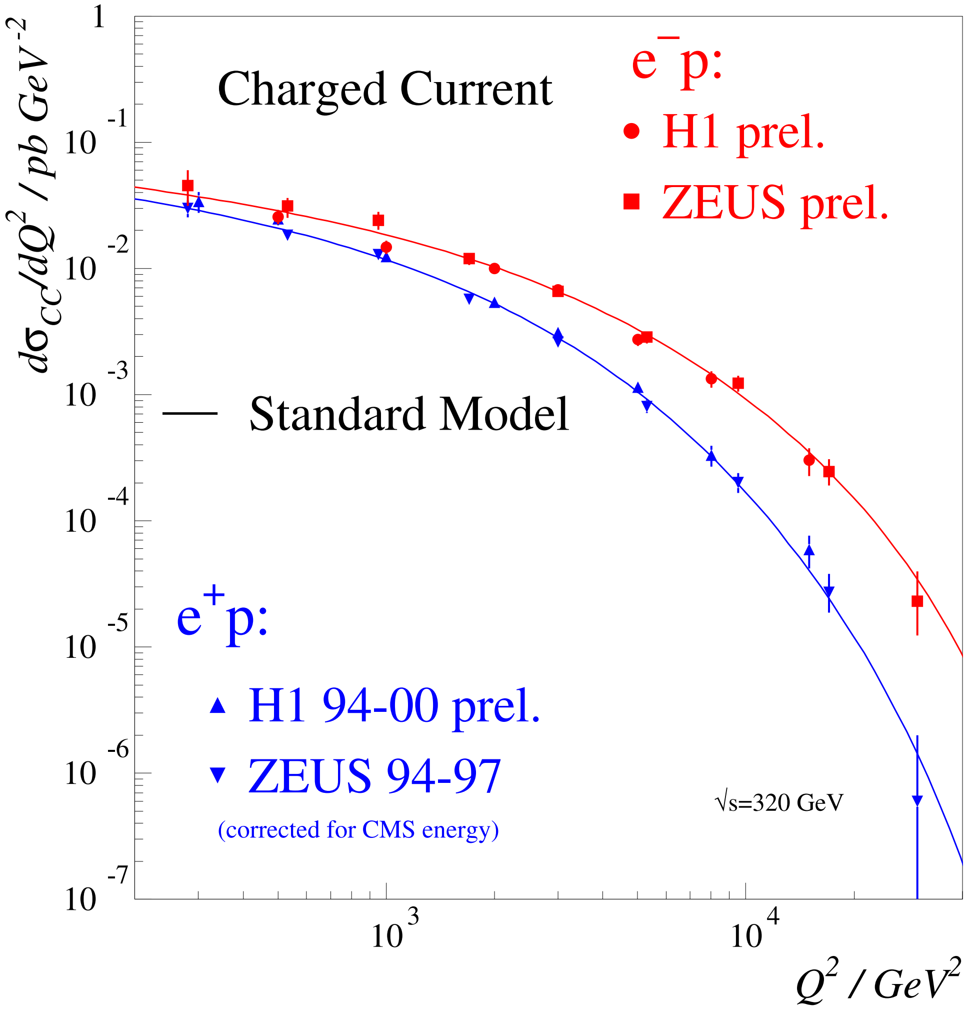
$$e^-p\ :\ \frac{d^2\sigma^{CC}}{dxdQ^2} \propto x \cdot [(u+c) + (1-y)^2(\bar{d}+\bar{s})]$$

- u valence quark probed
- u unsuppressed

reduced cross section

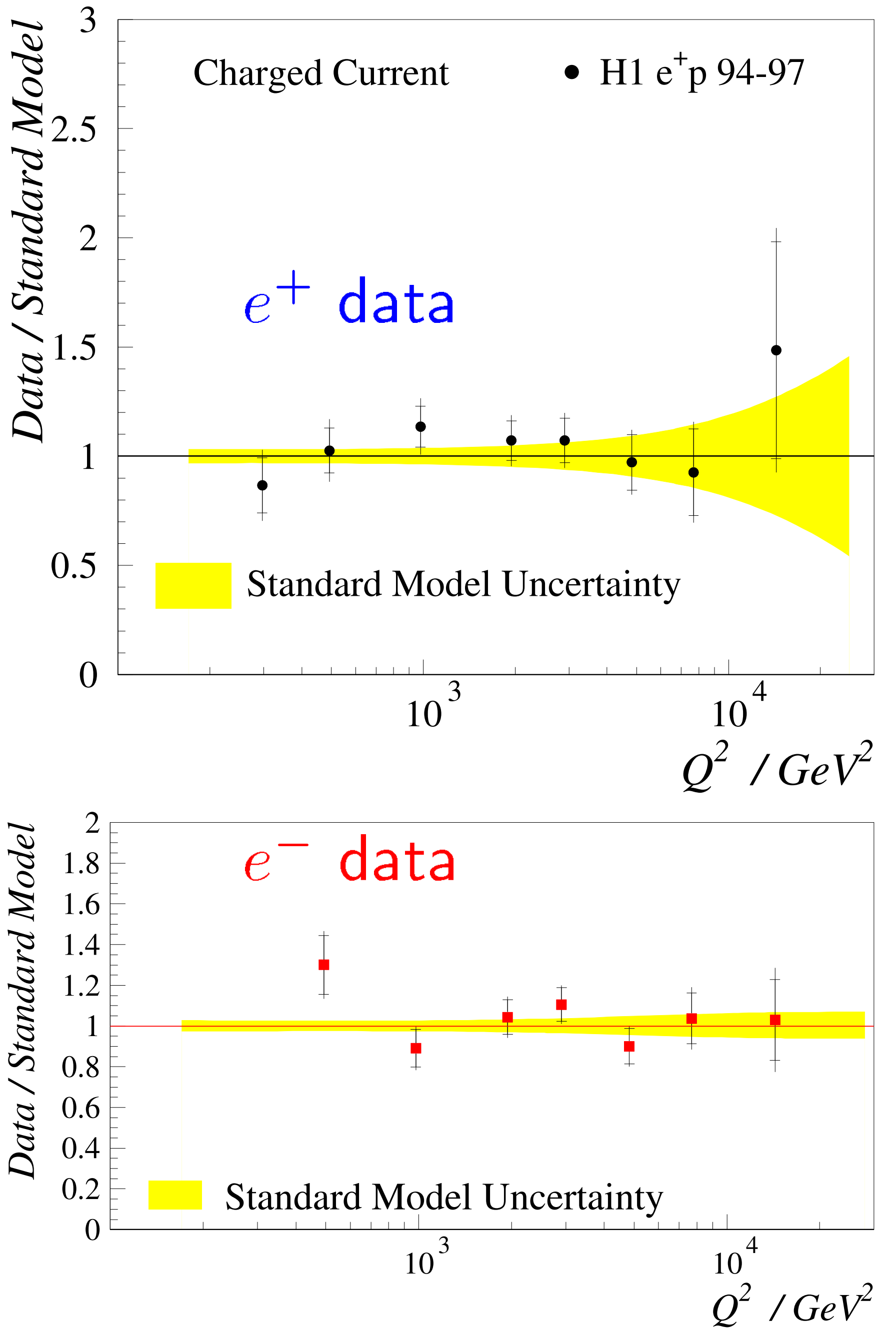
$$\tilde{\sigma}_{CC} = \frac{2\pi x}{G_F^2}\left(\frac{M_W^2+Q^2}{M_W^2}\right)^2 \times \frac{d^2\sigma^{CC}}{dxdQ^2}$$

CC cross section $d\sigma/dQ^2$



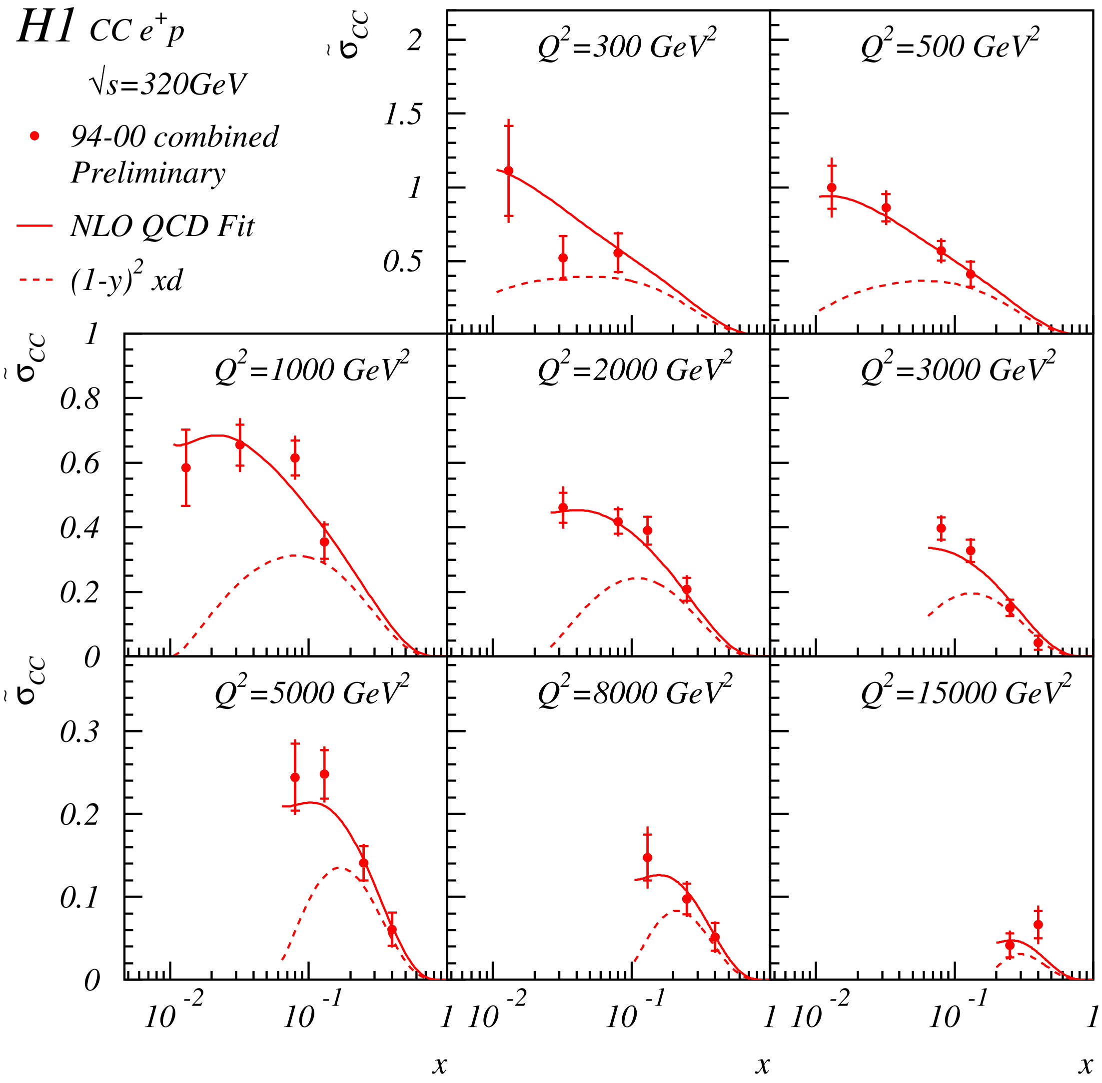
- HERA data agrees with SM on wide Q^2 range
- $\sigma(e^-p) > \sigma(e^+p)$ due to:
  $\sigma(e^-p) \propto (u + c)$ while
  $\sigma(e^+p) \propto (1 - y)^2(d + s)$

CC $d\sigma/dQ^2$ compared to Standard Model



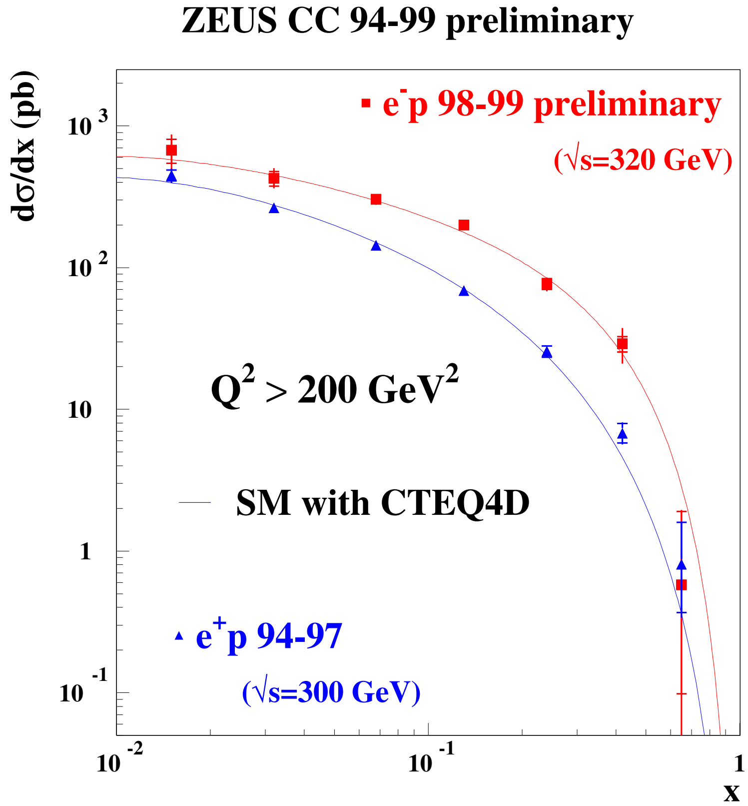
CC reduced cross section $\tilde{\sigma}_{CC}$ for x, Q^2

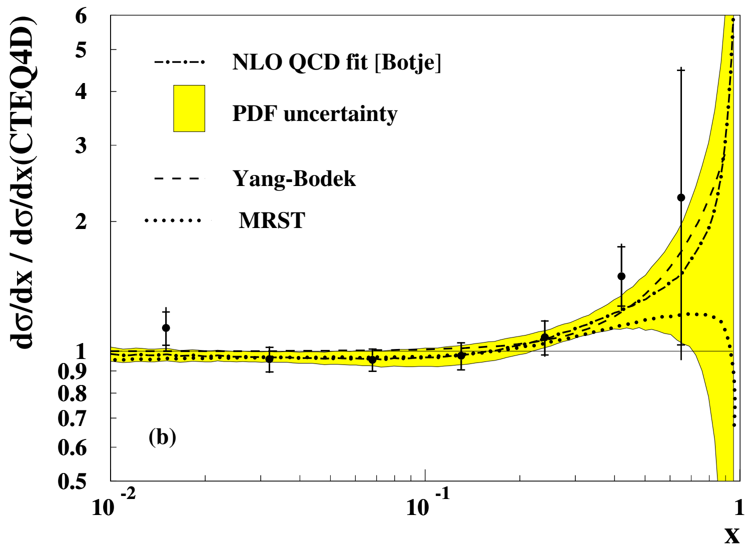
e^+ data



- e^+:
  $\tilde{\sigma}_{CC} = x \sum_{i=1,2} [\bar{u}_i + (1-y)^2 d_i]$
- sensitivity to d quark at high x

CC cross section $d\sigma/dx$





presently parton densities
not well constrained
at very high x ($x \geq 0.5$):

large uncertainty at high x where
where the d quark
dominantly contributes

with e^+ and e^- data:
$\Rightarrow$ get u,d PDF's at high x

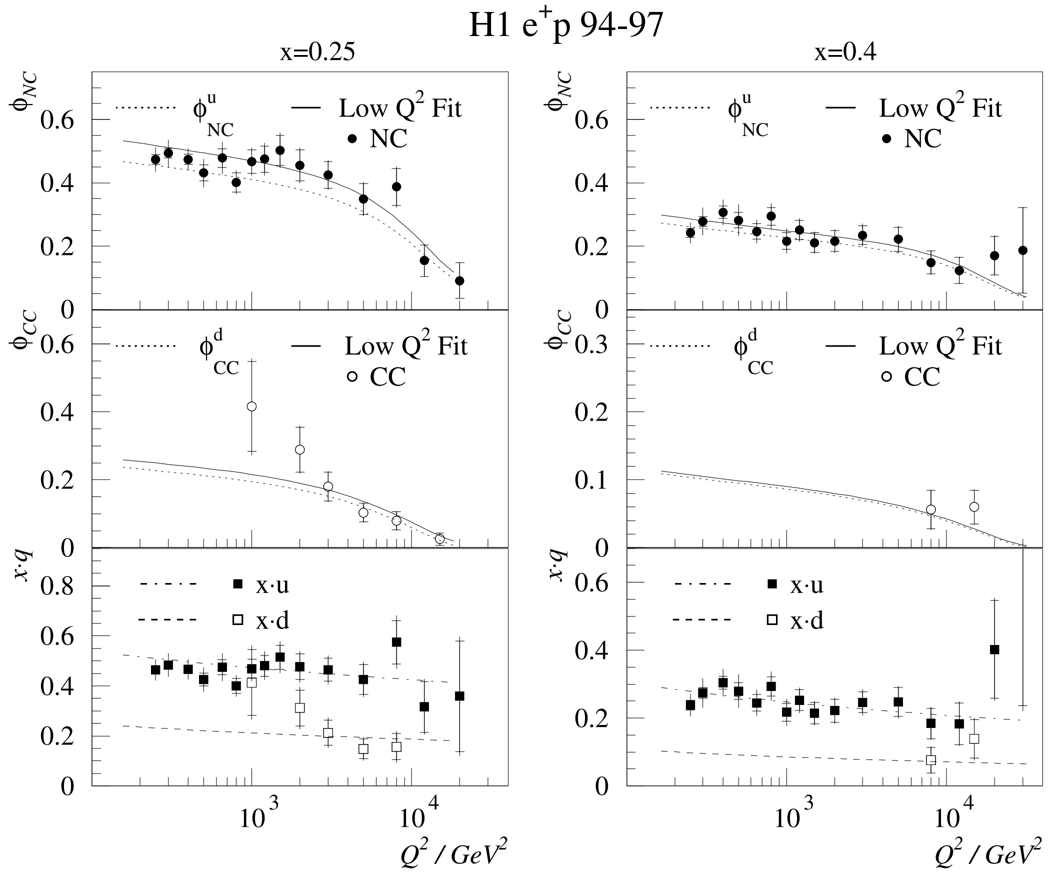
Parton Densities from high Q^2 / high x CC/NC

$\Rightarrow$ extract u quark and d quark densities in high x region from e^+ data

$\Rightarrow$ use the reduced cross sections $\tilde{\sigma}$:

$$\tilde{\sigma}_{NC}(e^+) \propto \Phi_{NC} \propto (1+(1-y)^2) \sum e_i^2 x q_i$$

$$\tilde{\sigma}_{CC}(e^+) \propto \Phi_{CC} \propto x\bar{u} + (1-y)^2 xd$$



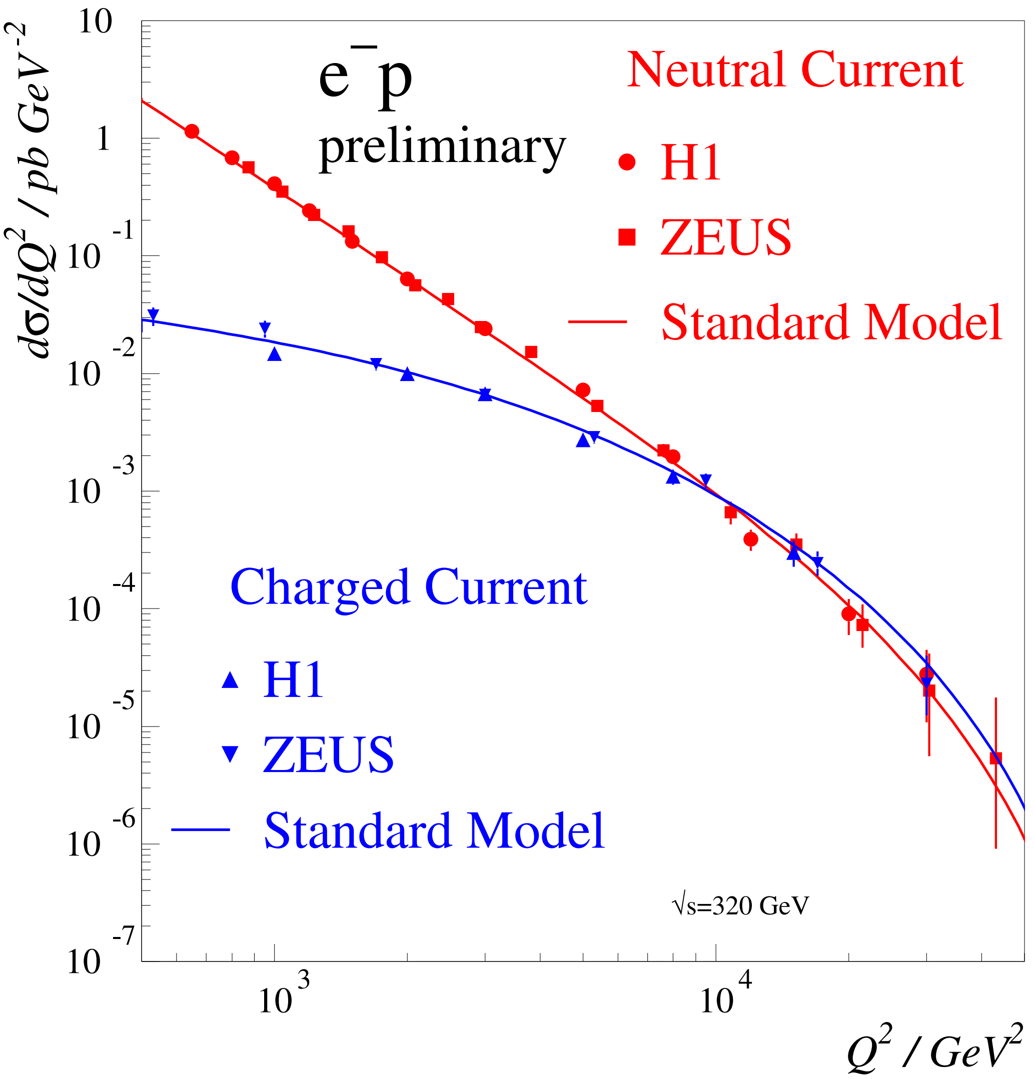
NC

CC

$x \cdot u$

$x \cdot d$

High Q^2 at HERA: electroweak unification



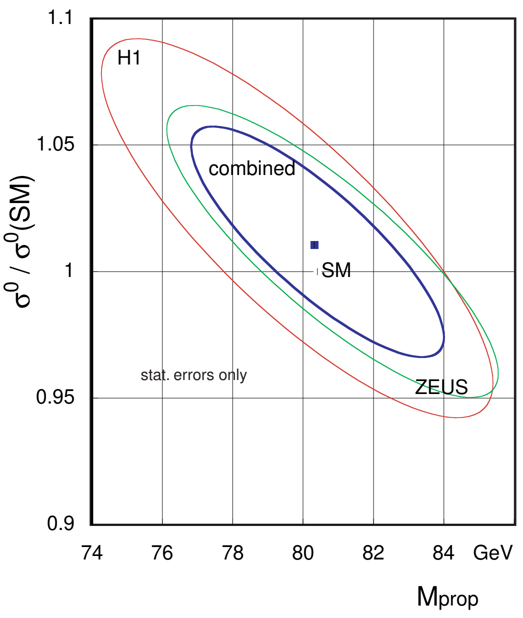
- compare NC and CC cross sections for e^-p data
- for large $Q^2 \approx M_Z^2$ NC and CC cross section are of similar size

Test of EW theory form CC $d\sigma/dQ^2$

CC $d\sigma/dQ^2$ cross section contains propagator term

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

$\rightarrow$ fit to Q^2 dependance of CC $d\sigma/dQ^2$ gives M_W



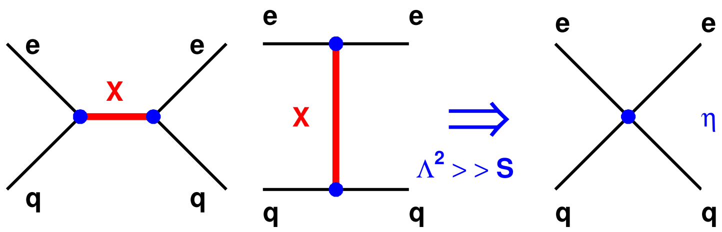
$M_{prop} = 80.9 \pm 3.3(\text{stat.}) \pm 1.7(\text{syst.}) \pm 3.7(\text{pdf})$ GeV (H1)

$M_{prop} = 81.4^{+2.7}_{-2.6}(\text{stat.}) \pm 2.0(\text{syst.})^{+3.3}_{-3.0}(\text{pdf})$ GeV (ZEUS)

- consistency check of indirect determination (W space–like) with world average from direct measurement (W time–like)
- important test of the universality of the SM

Beyond the Standart Model: Contact Interactions

- high Q^2 domain: region to look for New Physics beyond the Standard Model
- Processes with large characteristic energy scale ($\Lambda \gg \sqrt{s}$): parameterize as an effective 4 fermion contact interactions **CI**



4 Fermion ($eeqq$) CI with effective coupling $\eta^q_{ij} = \epsilon^q_{ij} (\frac{g}{\Lambda^q_{ij}})^2$

where g^2: coupling strength ($= \ 4\pi$), Λ^q_{ij}: effective mass scale
$\rightarrow$ only vector coupling assumed for HERA, scalar and tensor coupling terms beyond the sensitivity of HERA

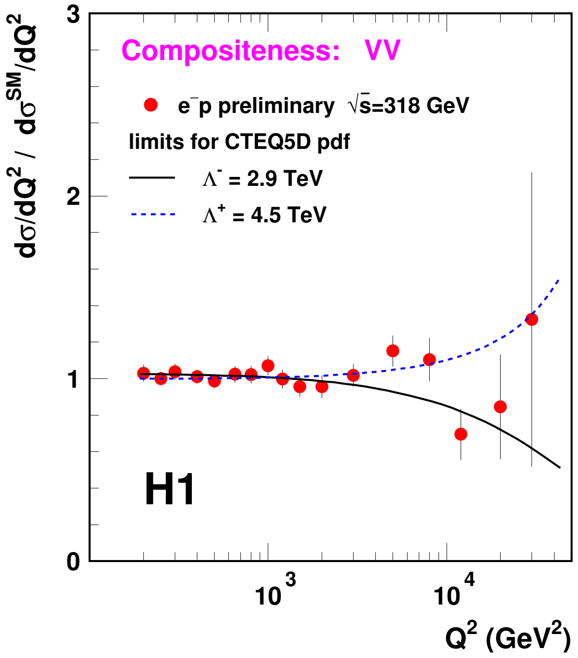
$$\mathcal{L}_{CI} = \sum \eta^q_{ij} (\bar{e}_i \gamma^\mu e_i)(\bar{q}_j \gamma_\mu q_j)$$
$$\Rightarrow \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{CI}$$

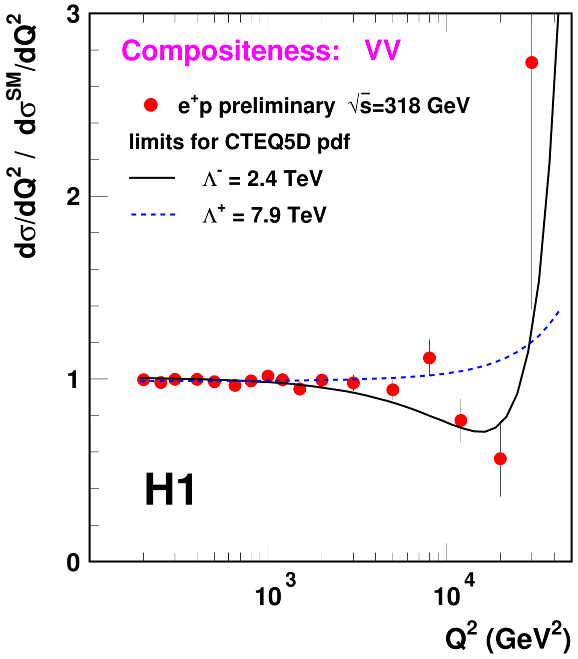
$\epsilon^q_{ij} = \pm 1$: positive or negative interference with SM;
$i, j = L, R$: left/right - handed particles (helicities);
$q = u, d$: quark flavours

$|CI|^2 +$ interference $\Rightarrow$ CI affect $d\sigma / dQ^2$

Fits on contact interaction models

look for distortions of Q^2 spectrum





Compositeness

example VV

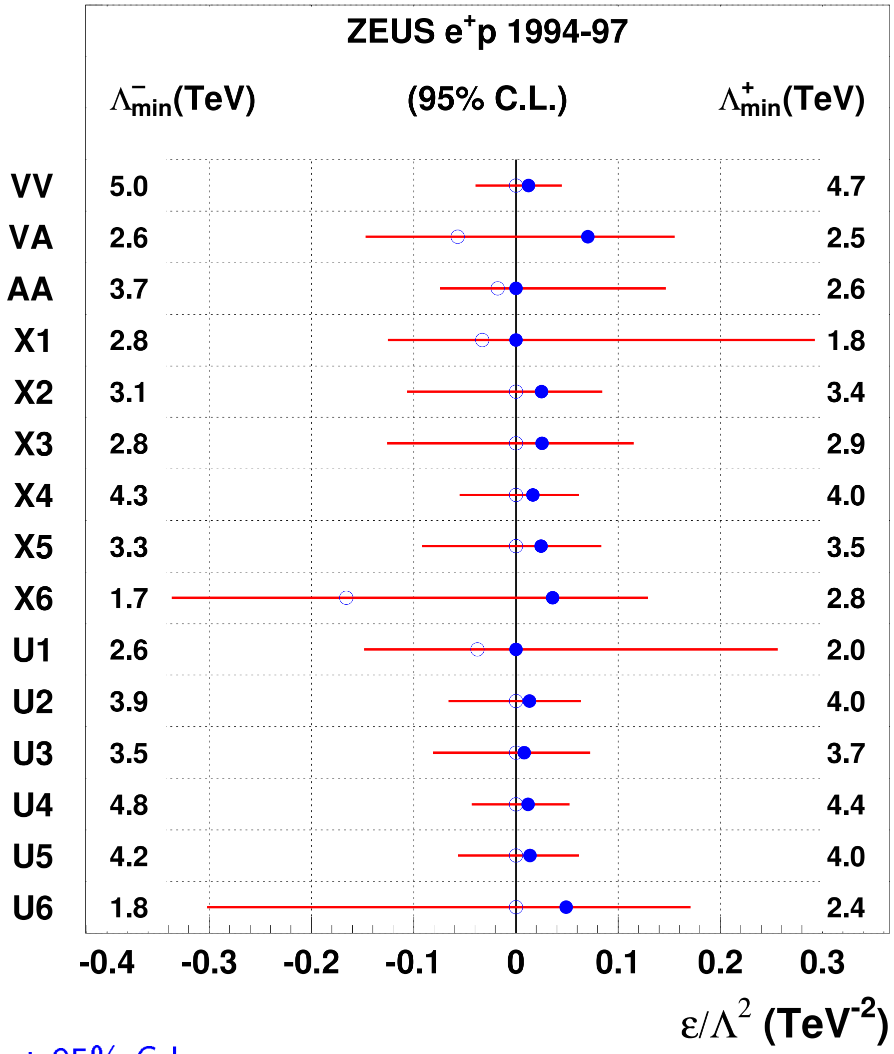
fit to various models:
LL, LR, RL, RR
VV, AA, VA
LL+RR, LR+RL

fit to $d\sigma/dQ^2$ yields limits on Λ

Λ^-: neg. interference
Λ^+: pos. interference

Limits for Compositeness Models

for compositness models $\eta_{ij}^{q} = \epsilon\frac{g^2}{\Lambda^2} = \pm\frac{4\pi}{\Lambda^2}$



Limits at at 95% C.L.

show Λ values of best fit for $\epsilon = \pm 1$

- no evidence for CI signal $\Rightarrow$ set limits
- various models considered:
  - VV, AA, VA: vector/axial couplings
  - U_i: parity conserving combinations
  - X_i: same as U_i with $\eta_{ij}^{eu} = \eta_{ij}^{ed}$

CI: large extra dimensions

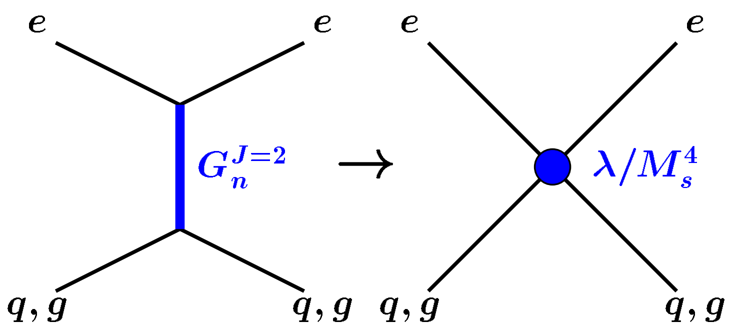
- gravity characterized by a scale $M_S \approx \mathcal{O}(\text{TeV})$ in $4+n$ dimensions
- extra spatial dim. n restricted to volume of size R
- scales related by $M_P \approx R^n M_S^{2+n}$
- $\rightarrow$ may lead to modification of Newton's law at $r < R$:
  $F \propto 1/r^{2+n}$,
  becomes strong at M_S
- SM:particles confined to 4 dim., only graviton propagates into n additional dimensions

graviton field $G_{\mu\nu}^{(j)}$ coupling to $\mathcal{L}_{SM}$:

$$\mathcal{L}_G = -\frac{\sqrt{8\pi}}{M_P} G_{\mu\nu}^{(j)} T^{\mu\nu}$$

$\Rightarrow$ effective CI coupling:

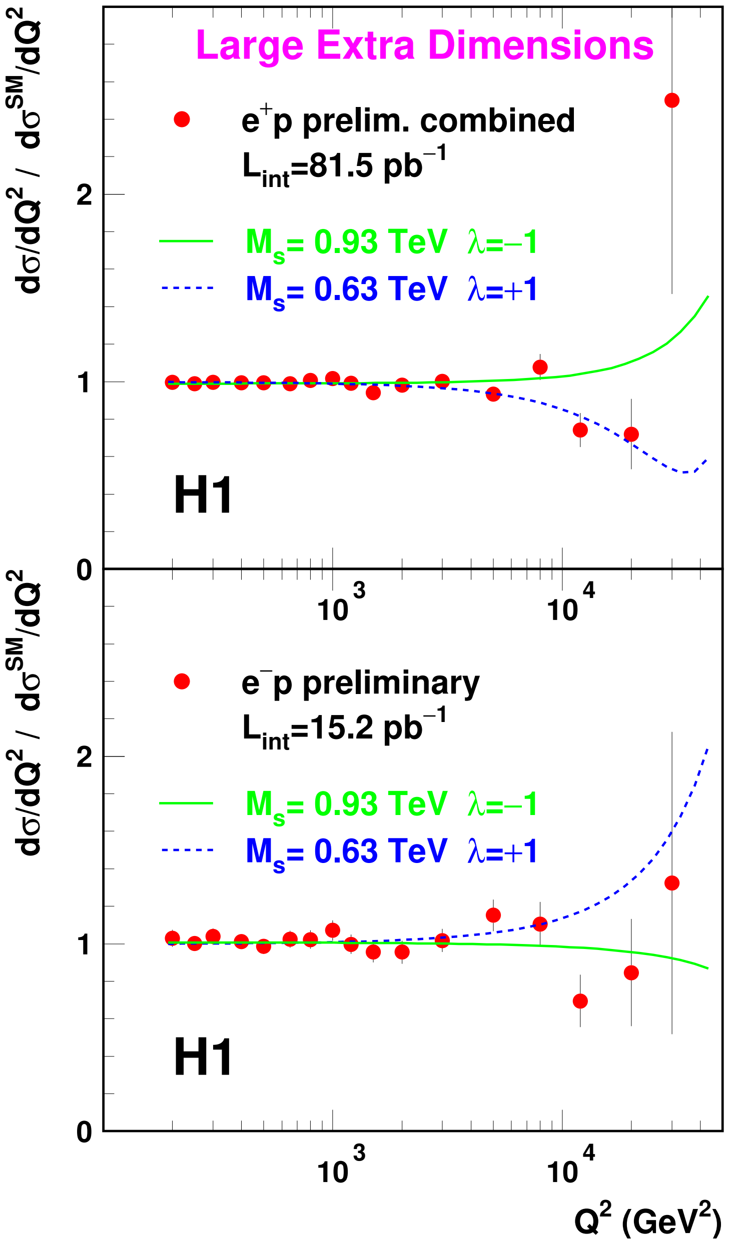
$$\eta_G \propto \frac{\lambda}{M_S^4}$$



$\rightarrow$ electron-gluon scattering also affected

Fits for large extra dimensions

Gravitational effects investigated by fitting $d\sigma/dQ^2$ with λ/M_S^4 as free parameter



result:

$\lambda/M_S^4 =$

$3.3^{+4.2}_{-3.3}(\text{stat})^{+0.4}_{-1.3}(\text{pdf})\ \text{TeV}^{-4}$

compatible with SM

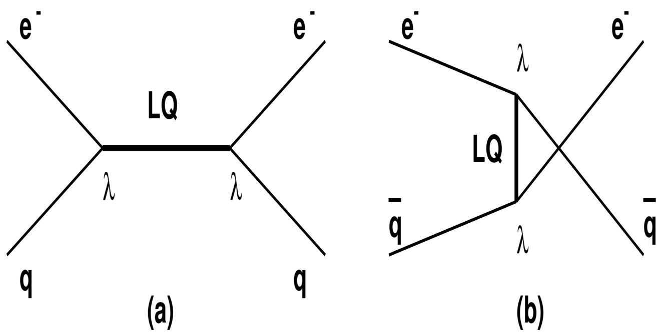
lower limits for M_S at 95% CL (for pos./neg. coupling):

$M_S > 0.93$ TeV for $\lambda = -1$

$M_S > 0.63$ TeV for $\lambda = +1$

Leptoquarks

- leptoquarks appear in many extensions to the SM
- scalar or vector colour triplet bosons
- carry $B,\ L \neq 0$ and couple to quarks and leptons



in ep collisions:
produced in s channel
exchanged in u channel

$F = 0\ (e^+ + q \to LQ)$
$|F| = 2\ (e^+ + \bar{q} \to LQ)$
$|F| = 2\ (e^- + q \to LQ)$

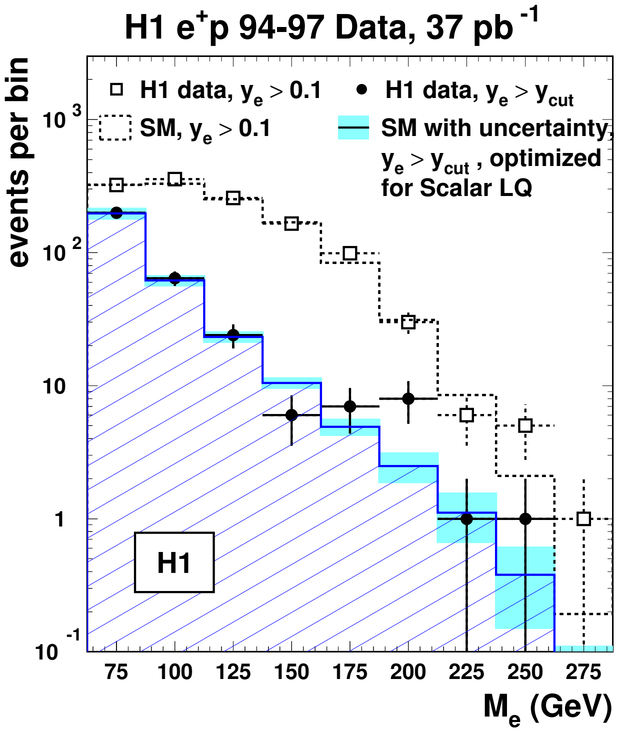
DIS high Q^2 like final state, different angular distribution (y):
$\sigma(e^- p \to LQ) = (\pi/4s)\lambda^2 q|_{x=M^2/s}$

- DIS: $d\sigma/dy \propto 1/y^2$
- LQ:
  - scalar LQ: decays isotropically in $y = (1 - \cos(\theta^\star))/2$
  - vector LQ: $\sigma \propto (1 + \cos(\theta^\star))^2 = (1 - y)^2$

$\Rightarrow$ search for resonance in e-jet mass $M = \sqrt{x \cdot s}$

Classifies LQ's depending of quantum numbers:
$S^J_{L,R}, V^J_{L,R}$
S, V: scalar/vector; L, R: left/right haded fermions; J: weak isospin

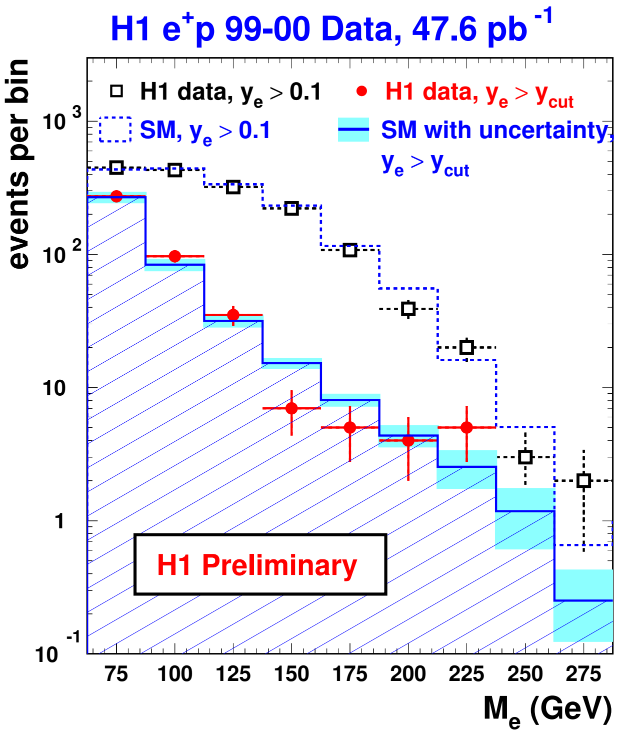
LQ: Direct searches for eq resonances



select high Q^2 DIS

increase signal/bg ratio by optizising y or $\cos(\theta^\star) = 1 - 2y$ cut

slight excess around 200 GeV at high y, mainly due to 1994-1996 events



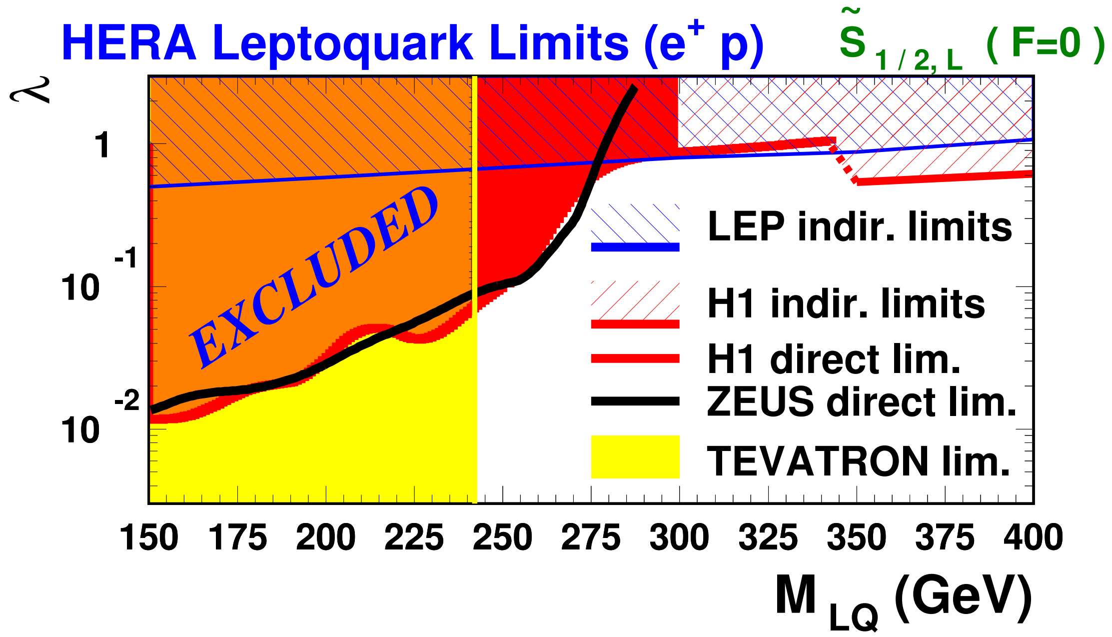
no evidence seen!

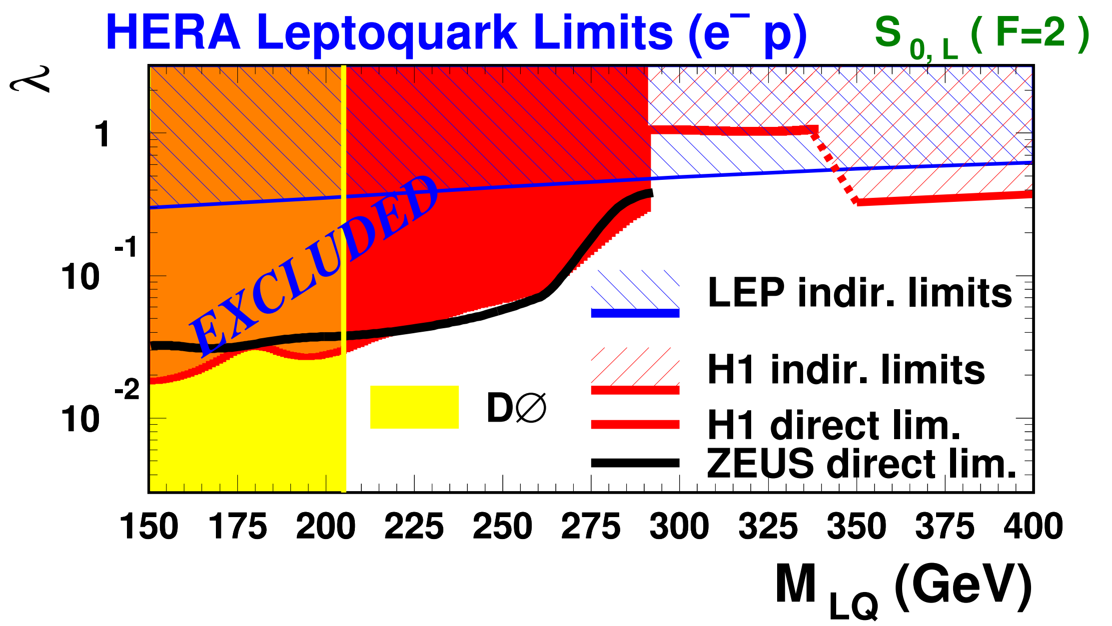
excess from 94 - 97 not confirmed by the new data!

mass spectrum before and after optimized cuts on $y = (1 - \cos\theta^*)/2$

LQ current Limits

complementarity of HERA data with LEP and TEVATRON

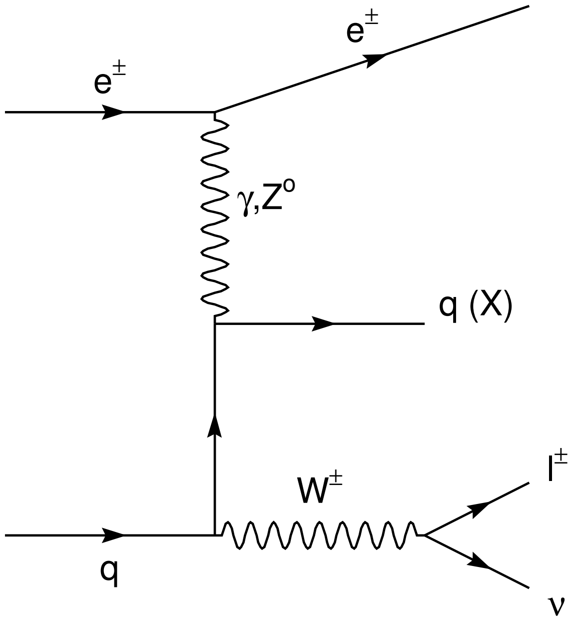




→ Buchmüller, Rückel and Wyler (BRW) model

W Production - Isolated Leptons

H1 and ZEUS each have collected $\approx \mathbf{100}$ pb^{-1} of data:
$\Rightarrow$ sensitivity to rare SM processes, i.e. direct W–Production



Jet: P_T^X

Isolated Lepton

missing P_T

P_T^X: transverse momentum of the hadronic system
SM prediction (QCD LO): $\sigma(ep \to eW^{\pm}X) \simeq 1$ pb

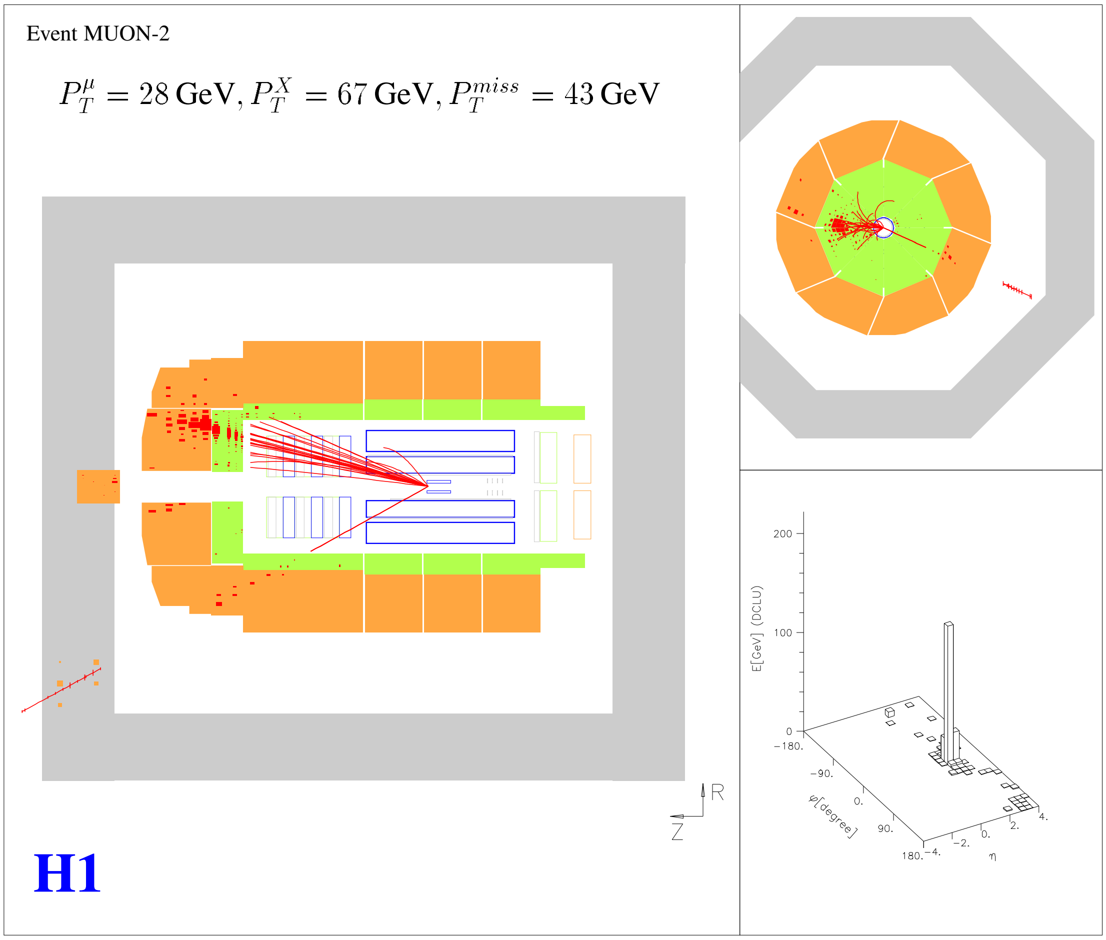
$\longrightarrow$ with current luminosity only few events in semileptonic decay expected

look for events with high P_T isolated lepton and missing P_T

Isolated Lepton event shape

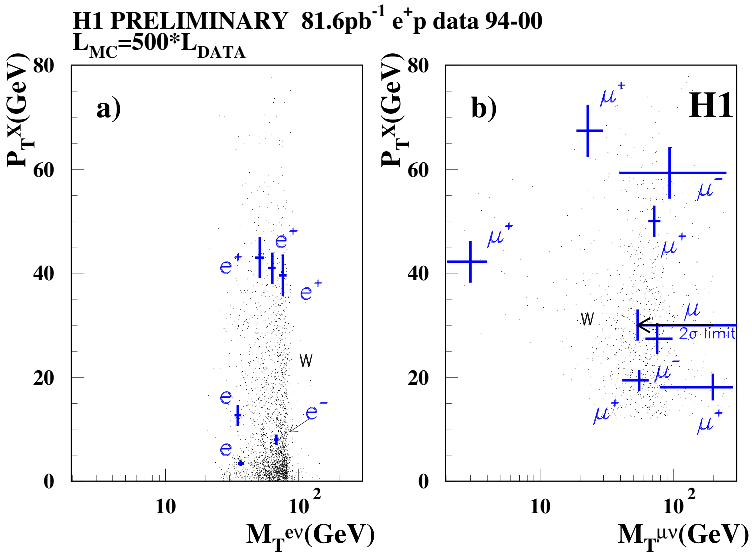
searches for W events with isolated leptons with missing transverse momentum $P_T^{\text{miss}} > 12$ GeV,
large P_T^X (> 12 GeV) and
large P_T^μ (> 10 GeV)

$$e^+p \to \mu^+X$$



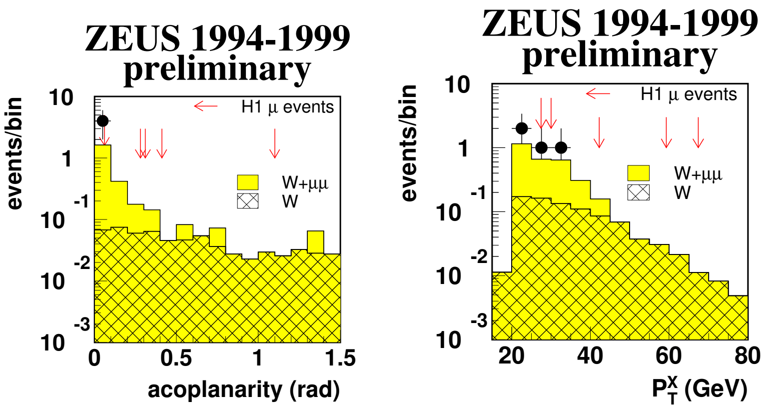
Results: 1994 - 2000 data

H1: 4 new events in 99-00 data (5 in 94-97, published), for $P_T^X > 25$ GeV



H1 total ($e^{\pm}$, $P_T^X > 25$ GeV): 9 (SM: 2.3 ± 0.6)

ZEUS: 6 new events, kinematics compatible with SM

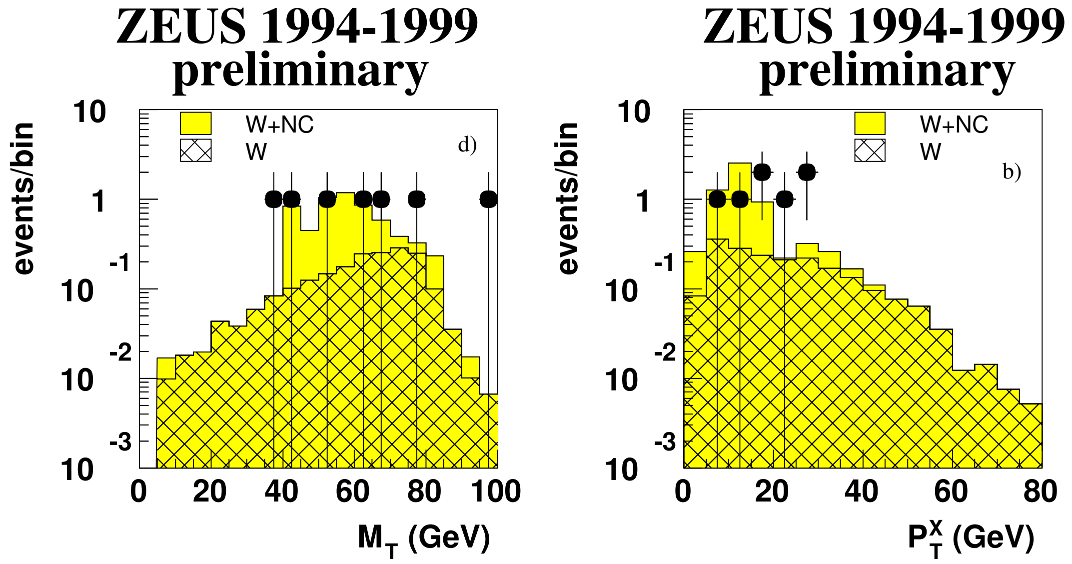


ZEUS total ($e^{\pm}$): no P_T^X cut applied !

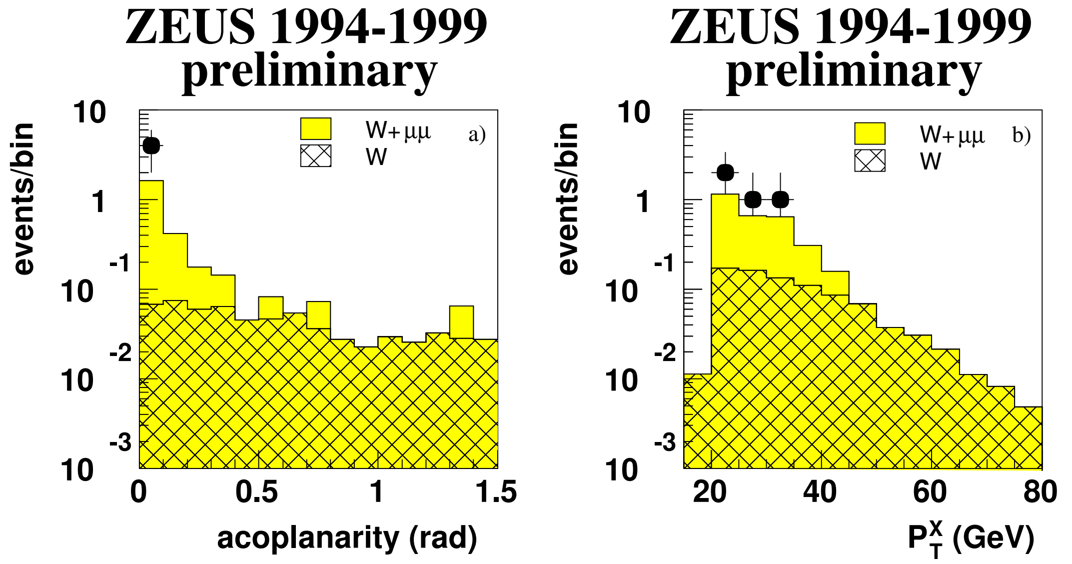
e–channel: 7 (SM: 6.1 ± 0.9);
μ–channel: 4 (SM: 3.7 ± 0.4)

ZEUS distributions

electron channel



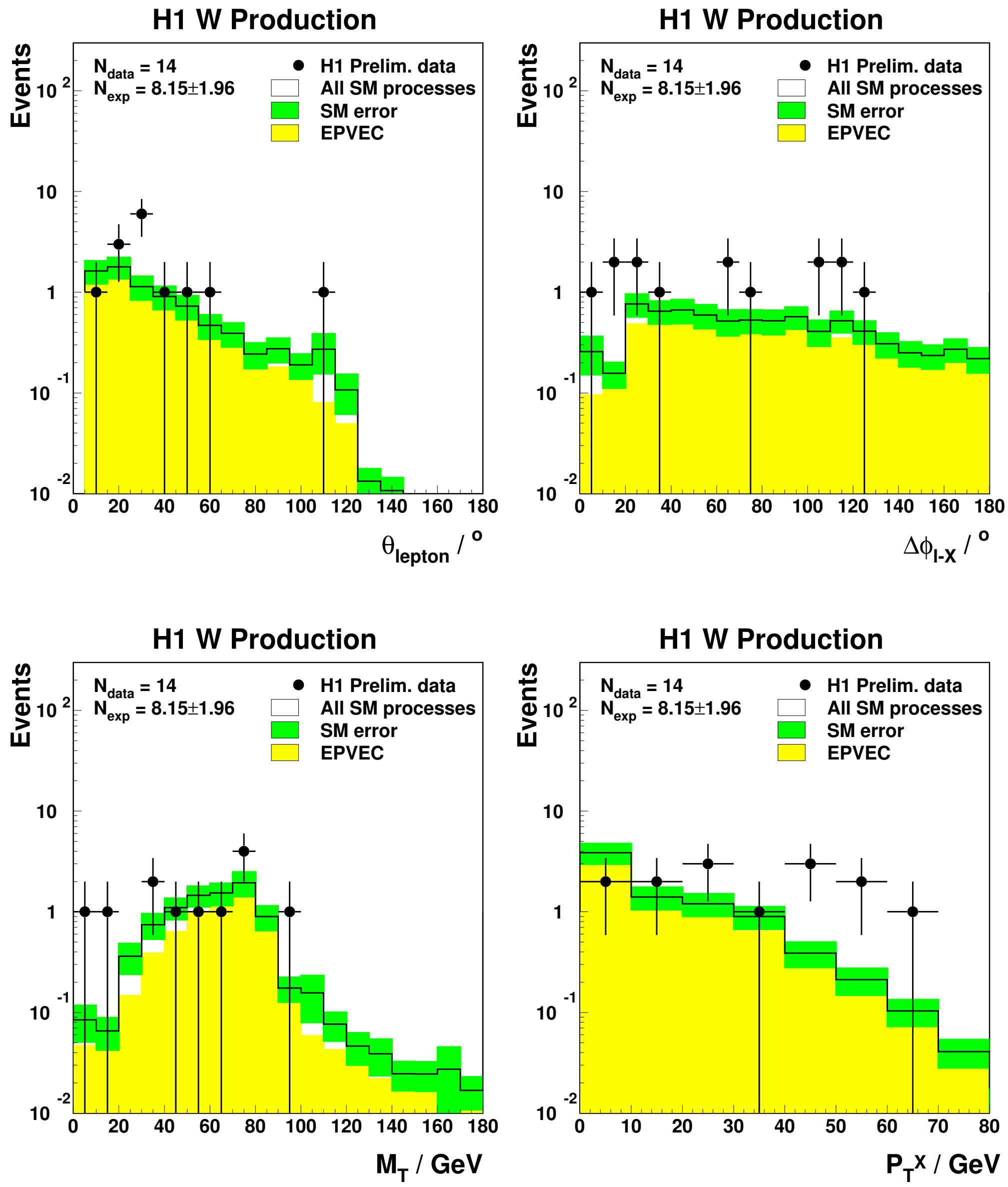
muon channel



data agree well with SM in shape and normalisation, all at small P_T^X

H1 distributions

electron and muon channel combined



excess over expectation at large P_T^X

shape of other distributions compatible with expectations for W production

W analysis: H1 ZEUS comparison

standard cuts are different for H1/ZEUS
$\Rightarrow$ different SM expectation

comparision with similar cuts:

- ZEUS apply extra H1 cuts (P_T^{miss}, $E - p_z$)
- H1 restrict measurement to ZEUS Θ_l range

$\Rightarrow$ SM expectations similar for H1 / ZEUS

Tables: observed events in 82 pb^{-1} / SM predictions

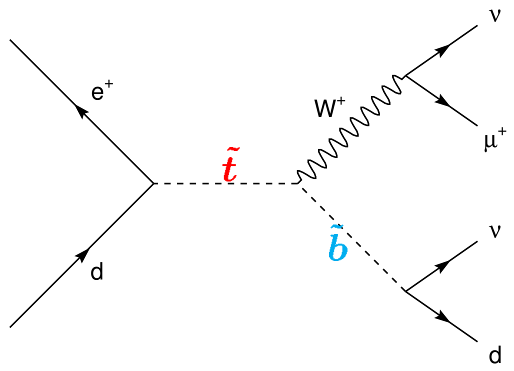
$P_T^X > 25$ GeV	Electrons	Muons
ZEUS 94-99	1 / 0.78	0 / 0.32
H1 94-00	3 / 0.84 ± 0.22	6 / 0.94 ± 0.26

- H1 sees excess for $P_T^X > 25$ GeV
- ZEUS in agreement with SM expectation

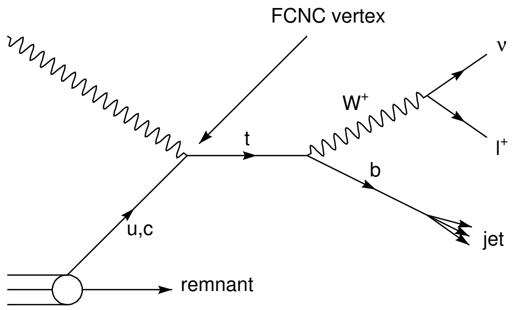
W production in BSM

Beyond the Standard Model W production may be background to other processes with the same signature: jet, isolated lepton, missing P_T:

- anomalous $WW\gamma$ couplings
- compositness
- R_p violating SUSY
- anomalous single top production



SUSY process



single top production

not SM expected process

SM expectaion verry small

Search for single top $t \to Wb$

Lepton channel:

H1 apply W selection with additional cuts:
$P_T^{\text{jet}} > 25$ GeV for $\Theta^{\text{jet}} > 35^\circ$
$P_T^{\text{jet}} > 35$ GeV for $\Theta^{\text{jet}} < 35^\circ$
$M_T^{l\nu} > 10$ GeV
Reject events with negatively charged leptons

ZEUS apply W selection with $P_T^{\text{X}} > 40$ GeV

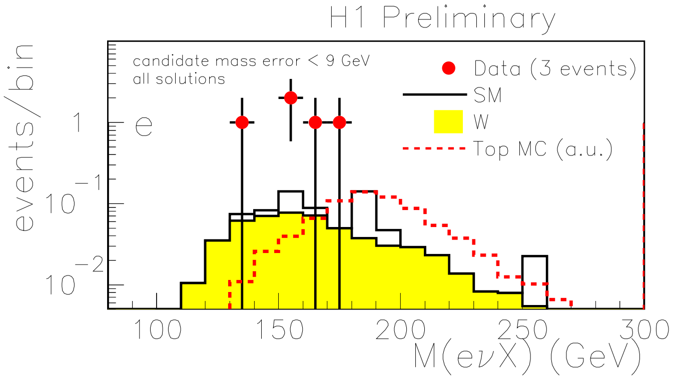
H1 see 5 events $(1.44 \pm 0.48$ SM expected)
ZEUS see 0 events (0.65 SM expected)

Hadron channel (H1):

3 jets
$P_T^{\text{jet1}} > 25$ GeV, $P_T^{\text{jet2}} > 15$ GeV, $P_T^{\text{jet3}} > 10$ GeV
$E_T^{\text{tot}} > 120$ GeV
$70 < M_{ij} < 90$ GeV (any combinations)
$150 < M_{\text{tot}} < 190$ GeV

H1 see 10 events $(8.3^{+5.9}_{-4.6}$ SM expected)

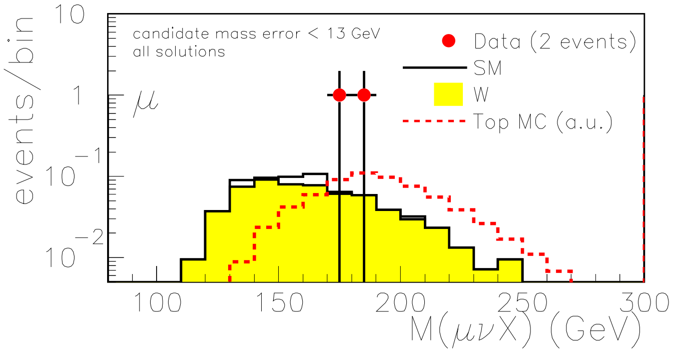
H1 search for single top $t \rightarrow Wb$



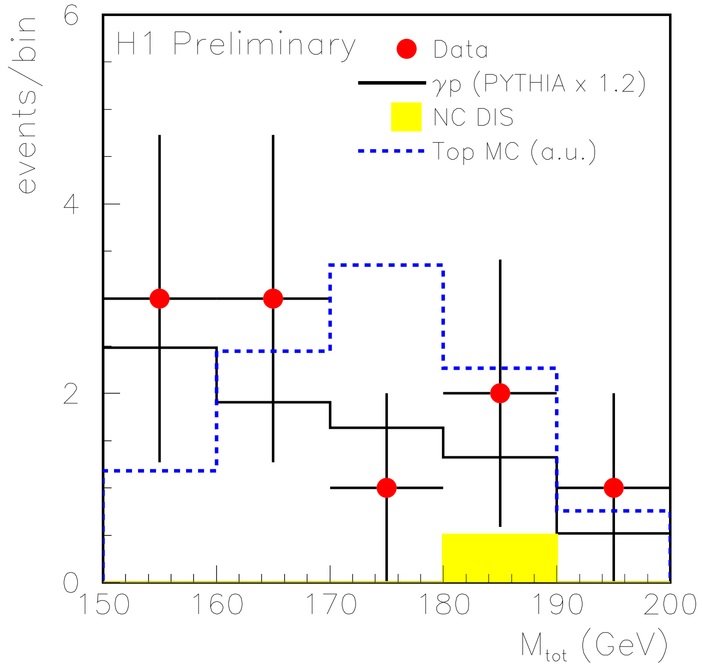
$W \rightarrow e\nu$

impose W mass constraint

$\Rightarrow$ 2 possible solutions per event

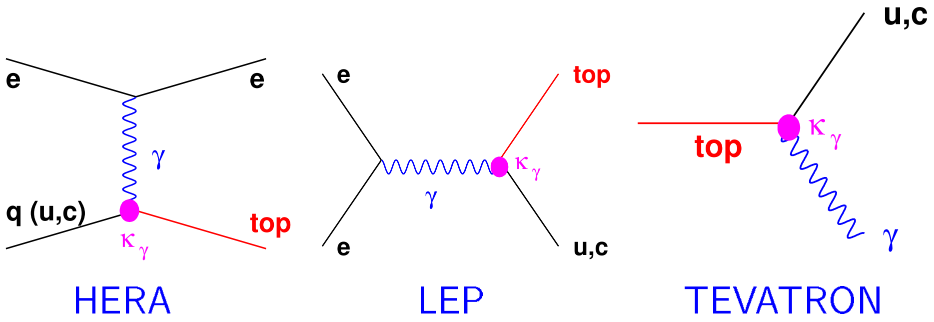


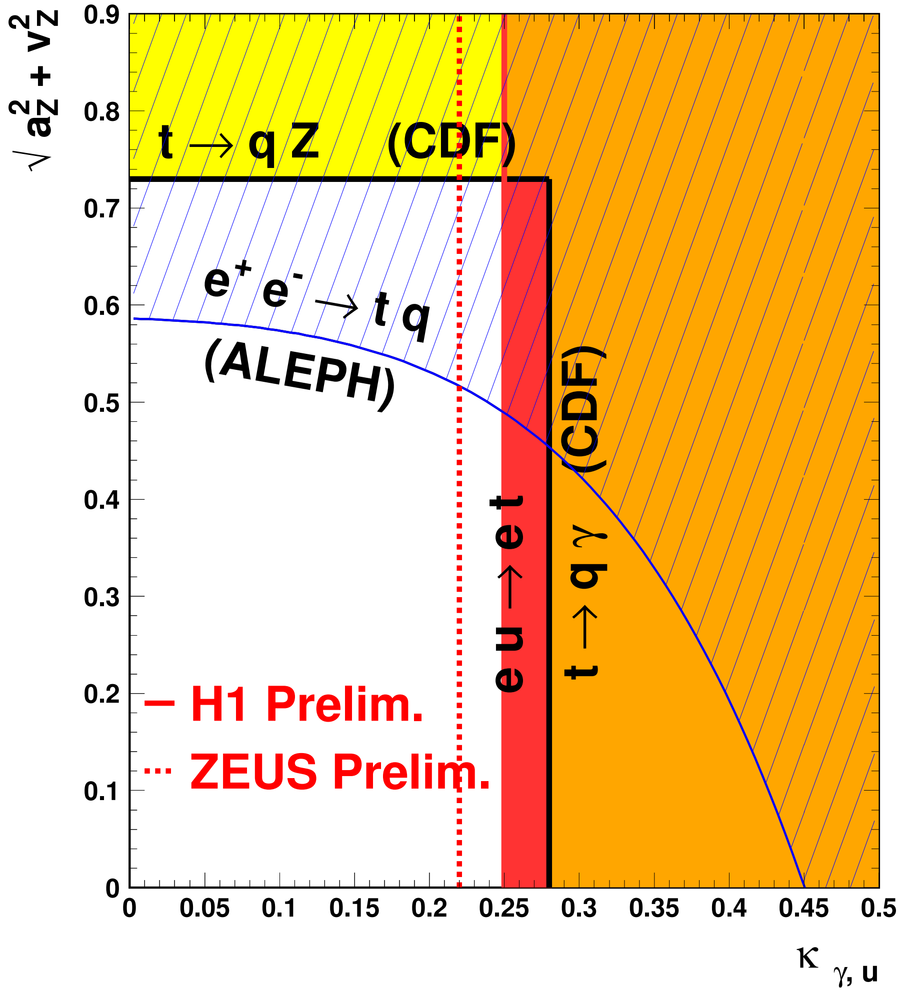
$W \rightarrow \mu\nu$



$W \rightarrow q\bar{q}'$

Limits for FCNC couplings





unique FCNC reach at HERA

HERA upgrade 2000

luminosity upgrade

- factor **5** increase in luminosity:
  $\mathbf{150}$ pb^{-1} / year

electron polarisation

- NC: study connection between helicity structure of SM and parity violation in NC
- CC: test for right handed contriburion to charged current processes ($\sigma_{CC}^{pol.} = (1 + P) \cdot \sigma_{CC}$)
- complete study of proton structure at high Q^2

test of standard model

- probe short distances with high precision

Summary

Inclusive NC/CC cross section measurements

- all 4 cross sections measured at HERA (NC,CC for $e^{\pm}$)
- good description of data by SM/pQCD over a large Q^2 range
- first extraction of xF_3 at large Q^2 (NC)
- sensitvity to d and u valence quarks
- electroweak unification observed, M_W consistency check

Contact Interactions

- searches for new physics performed for contact interactions and large extra dimensions
- no signs for new physics
- no evidence for direct leptoquark production with 100 pb^{-1} per experiment

Isolated Leptons

- isolated leptons with P_T^{miss} observed at HERA
- H1 sees an excess in the high P_T^X region, ZEUS measurement compatible to SM
- search for single top production sets limits for FCNC $tu\gamma$ coupling