Recent ZEUS Results

Uwe Schneekloth
DESY

QFTHEP 2003

MV ”Klement Gotwald”

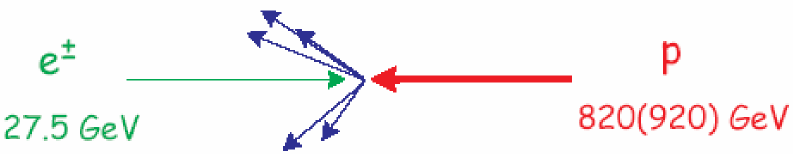
05.09.2003

Outline

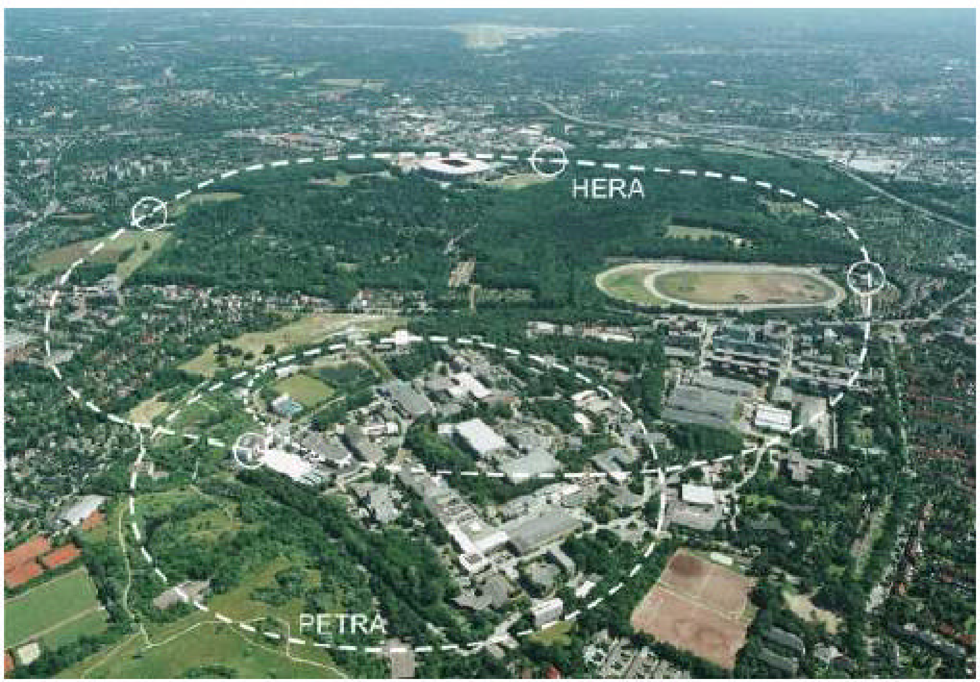
- Introduction
- Deep Inelastic Scattering
  - High Q^2 charged current cross section and structure function
- Search for New Physics
  - Lepton-flavor violation in tau production
  - Single-top production
- Deeply Virtual Compton Scattering
- Jets in Photoproduction
  - Scaling violation
  - Alpha s measurement
- Current Status and Prospects
- Summary

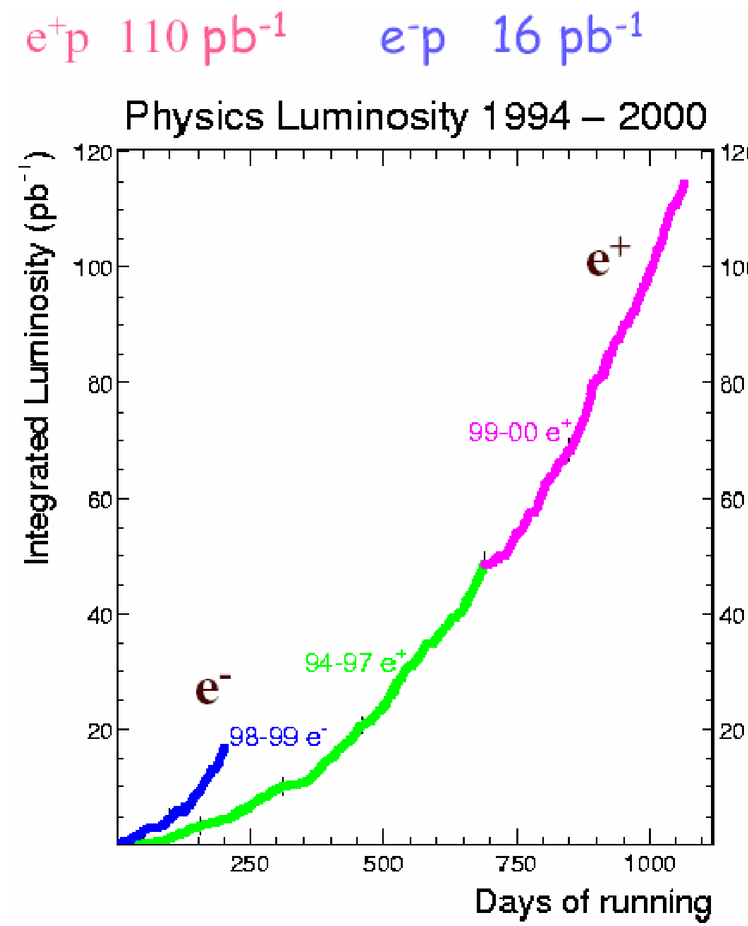
Introduction

HERA – the world's only ep collider

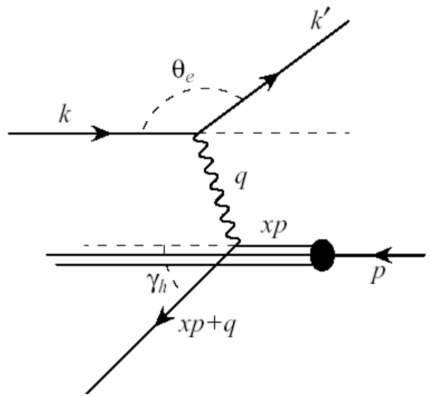


equivalent to 50 TeV fixed target

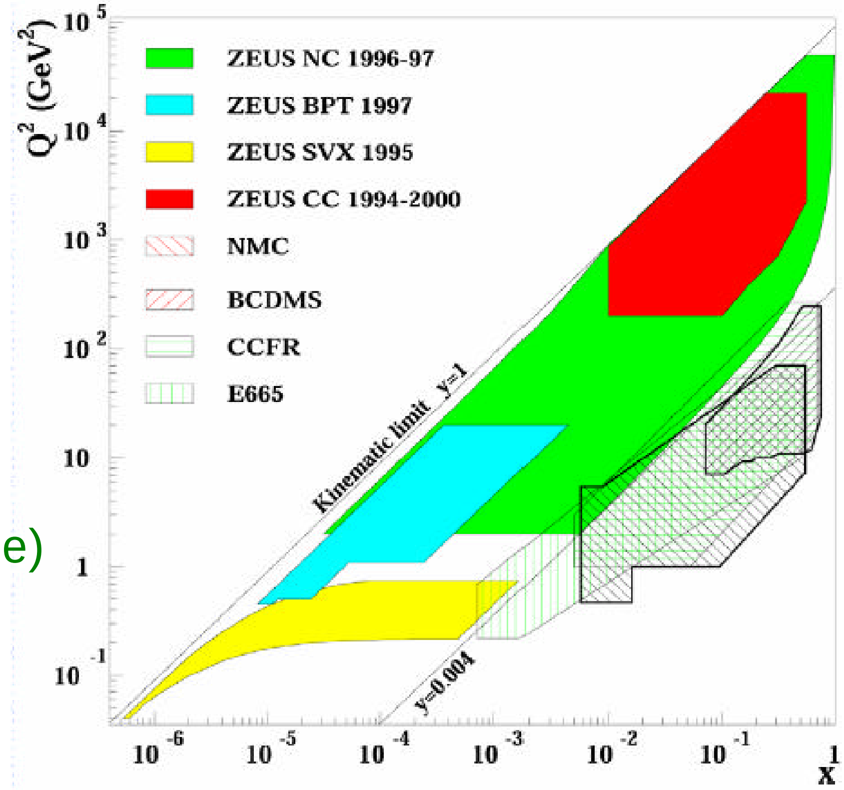




Introduction: HERA Kinematics



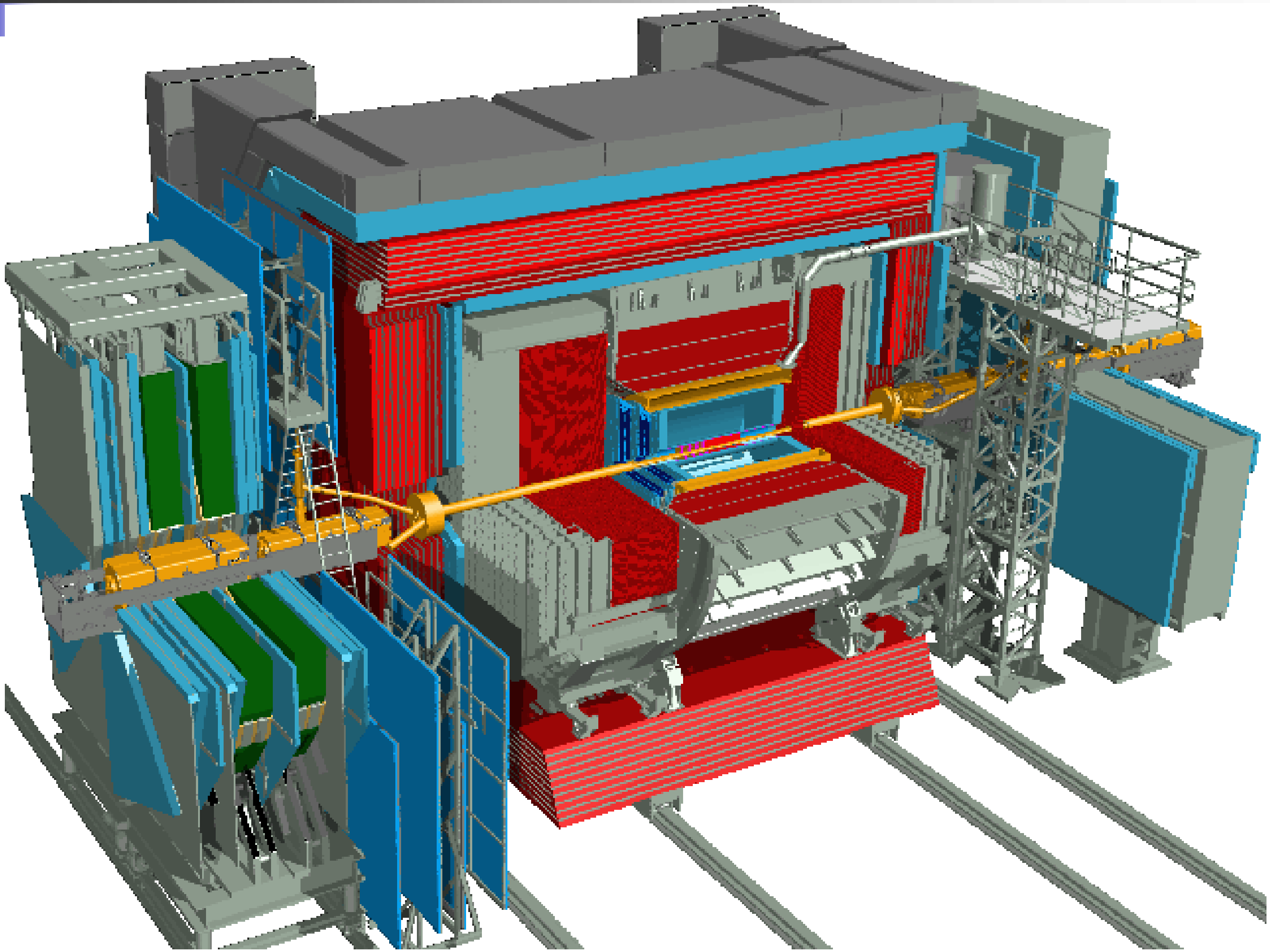
Kinematic range Q^2 vs. x



Kinematical variables:

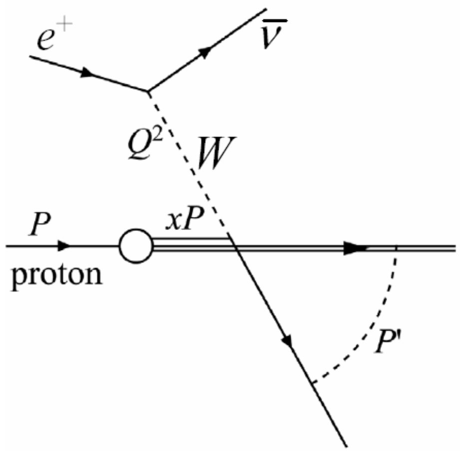
- (Negative) squared 4-moment transfer carried by exchange boson
  $$Q^2 = -q^2 = -(k-k')^2$$
- Fraction of proton momentum carried by struck quark (Bjorken scaling variable)
  $$x \equiv \frac{Q^2}{2\,p.q}$$
- Inelasticity
  $$y \equiv \frac{p.q}{p.k}$$
- Hadronic center-of-mass
  $$W^2 = (q+p)^2 = ys - Q^2$$

Introduction – ZEUS Detector



Charged Current DIS

$$e^+ p \rightarrow \overline{n}_e p$$



Motivation

- Exchange of W boson
- NC interactions: all (anti)quarks flavor
- CC interactions: only down-type quarks and up-type antiquarks in e⁺p
  => Study parton distribution functions (PDF) for different quark flavors.

$$\frac{ds^{CC}_{Born}(e^+p)}{dxdQ^2} = \frac{G_F^2}{4px}\frac{M_W^4}{(Q^2+M_W^2)^2}\left[Y_+F^{CC}_{2,e^+p}(x,Q^2) - y^2F^{CC}_{L,e^+p}(x,Q^2) - Y_-xF^{CC}_{3,e^+p}(x,Q^2)\right] \qquad Y_\pm = 1\pm(1-y)^2$$

Structure functions:

- Sums of quark and antiquark PDFs

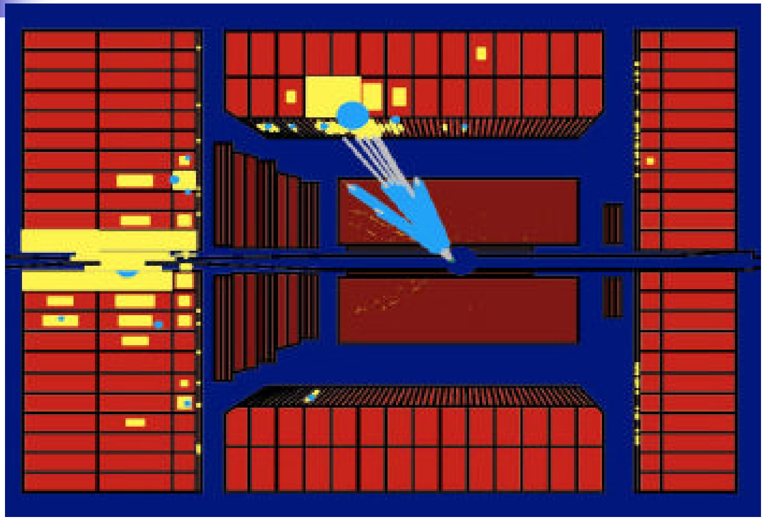
$$F^{CC}_{2,e^+p} = x\left[d(x,Q^2)+s(x,Q^2)+\bar{u}(x,Q^2)+\bar{c}(x,Q^2)\right]$$

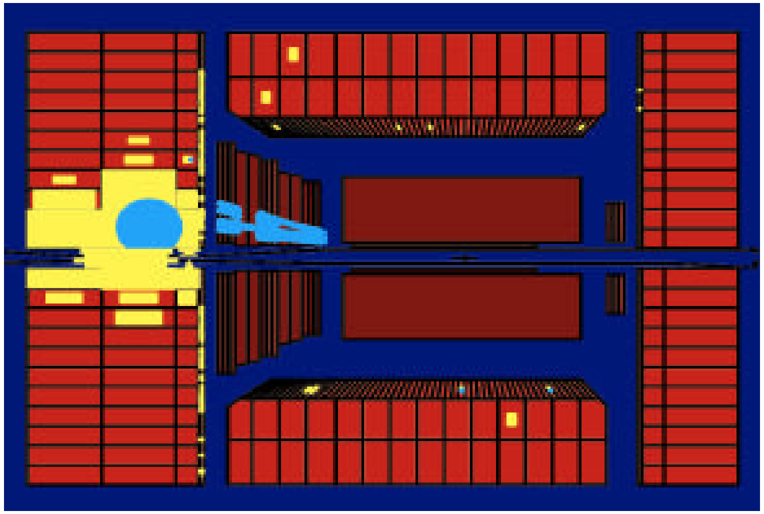
$$xF^{CC}_{3,e^+p} = x\left[d(x,Q^2)+s(x,Q^2)-\bar{u}(x,Q^2)+\bar{c}(x,Q^2)\right]$$

- Longitudinal structure function

F^{CC}_{L,e^+p} 0 at LO QCD, negligible at NLO QCD except at y close to 1

Charged Current DIS



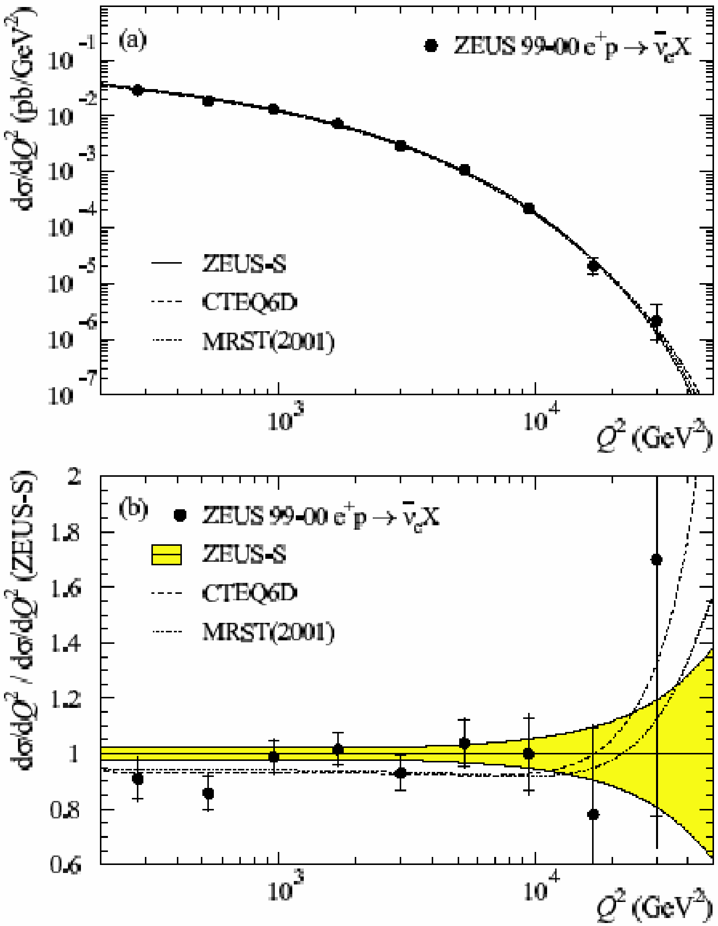


Data sample

- Q^2 > 200 GeV^2
- y < 0.9
- $P_{T,miss}$ > 20 GeV
  1164 events
- $P_{T,miss}$ > 14 GeV
  292 events

Charged Current DIS

Differential cross section vs Q^2



$$\frac{d^2s}{dxdQ^2} = \frac{N_{data} - N_{bg}}{N_{MC}} \cdot \frac{d^2s^{SM}_{Born}}{dxdQ^2}$$

Results:

- Diff.cross section decreases by 4 orders of magnitude due to W-boson propagator and decreasing quark density at large x
- Excellent agreement data and SM prediction.
- G_F fixed to PDG value, using ZEUS-S fit PDFs:

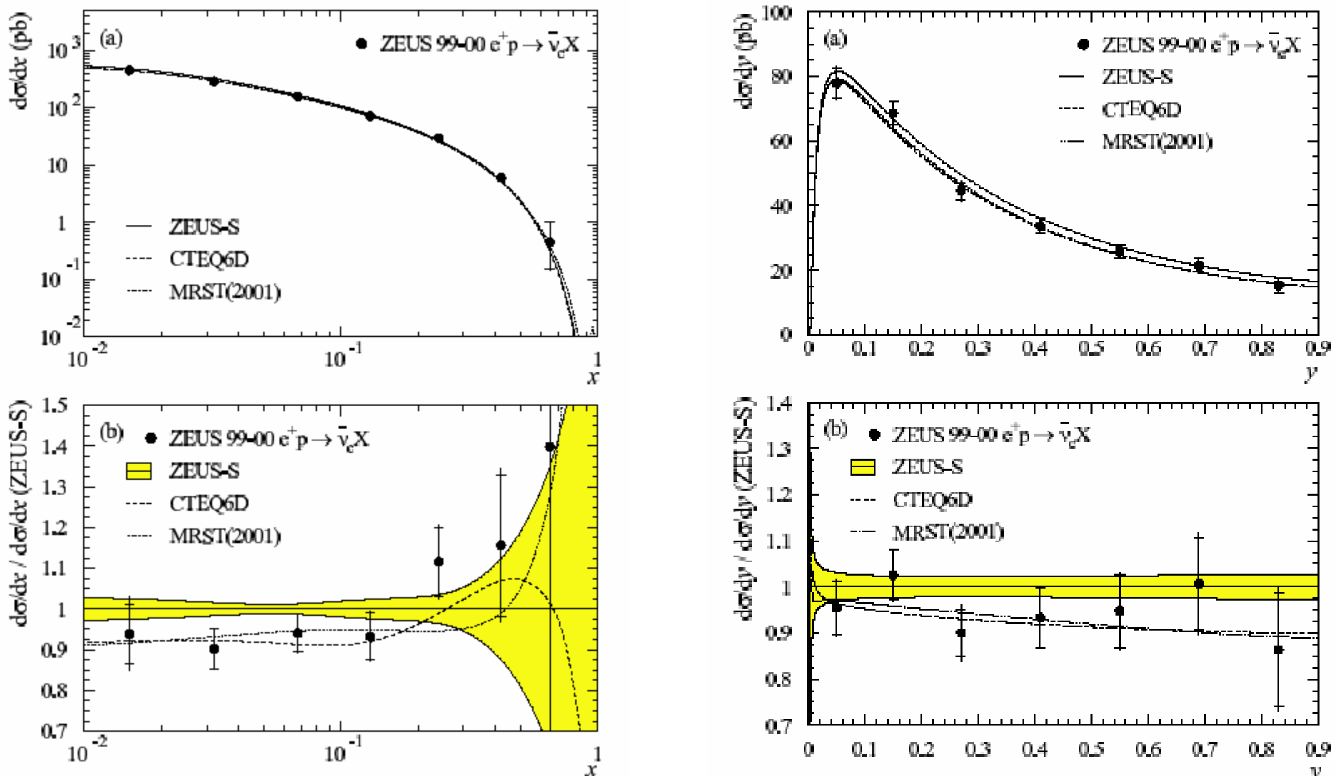
$$M_W = 78.9 \pm 2.0(stat.) \pm 1.8(syst.)^{+2.0}_{-1.8}(PDF)GeV$$

Main systematic uncertainties:

- calorimeter energy scale
- variation of selection thresholds
- parton-shower scheme
- luminosity measurement

Charged Current DIS

Differential cross sections ds/dx and ds/dy

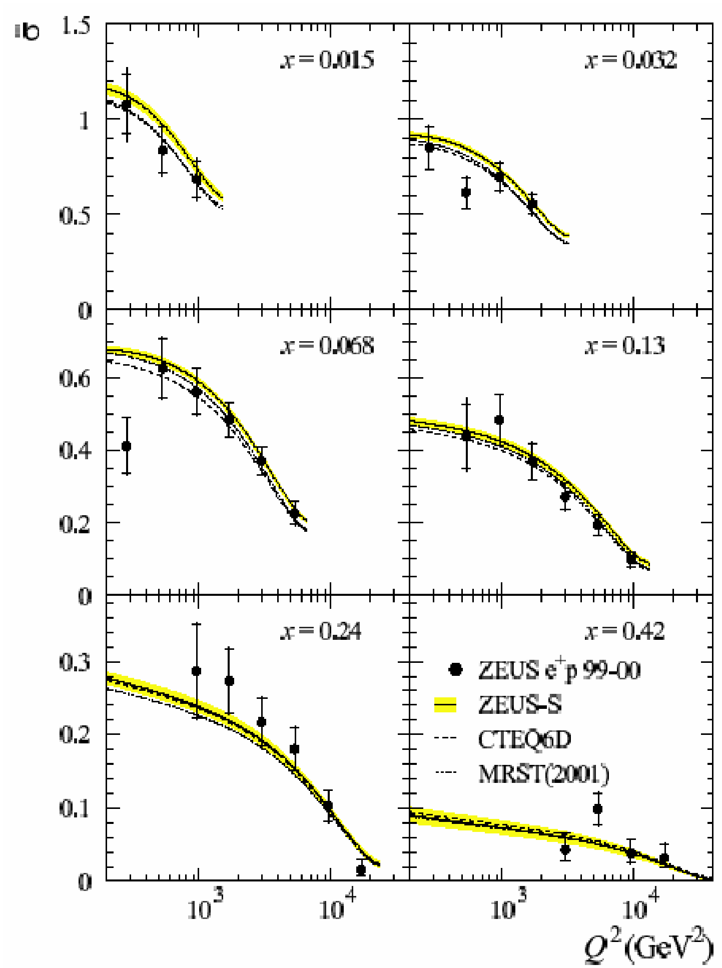


Data and SM prediction in good agreement:

- Confirms decomposition of p momentum into different quark flavors, evolution of parton distributions towards large scales.
- Uncertainty at large x,Q^2: lack of data constraining d-quark density.

Charged Current DIS

Reduced double-differential cross section as function of Q^2



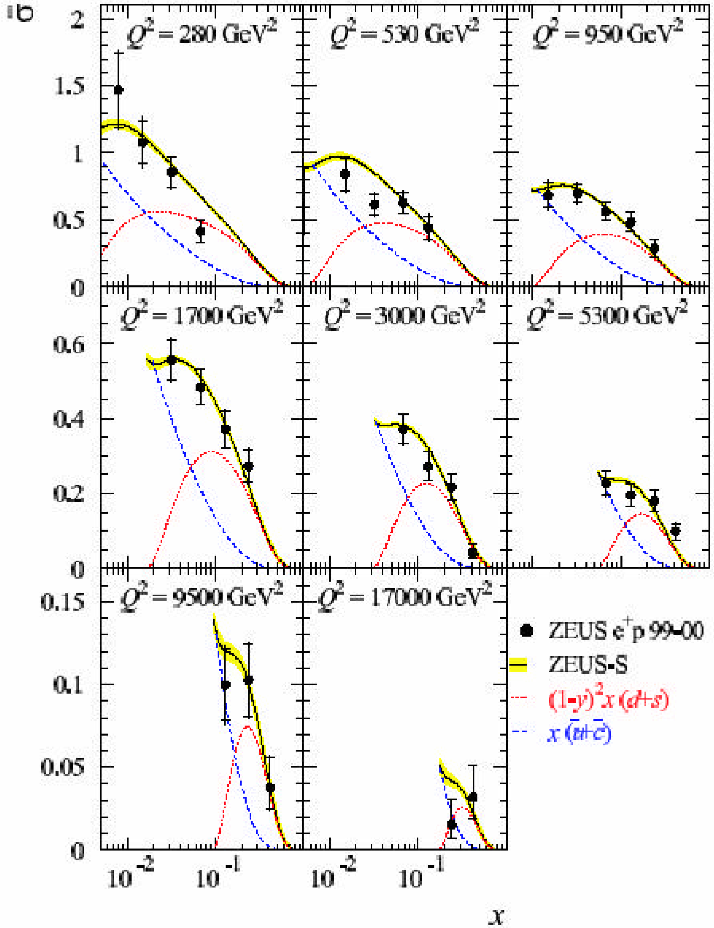
$$\tilde{s} = \left[\frac{G_F^2}{2px} \left(\frac{M_W^2}{M_W^2 + Q^2} \right) \right]^{-1} \frac{d^2 s}{dx dQ^2}$$

At leading order in QCD $\tilde{s}$ depends on quark momentum distributions:

$$\tilde{s}\,(e^+ p \rightarrow \bar{n}_e X) = x\left[\bar{u} + \bar{c} + (1-y)^2 (d+s) \right]$$

Charged Current DIS

Reduced double-differential cross section as function of x



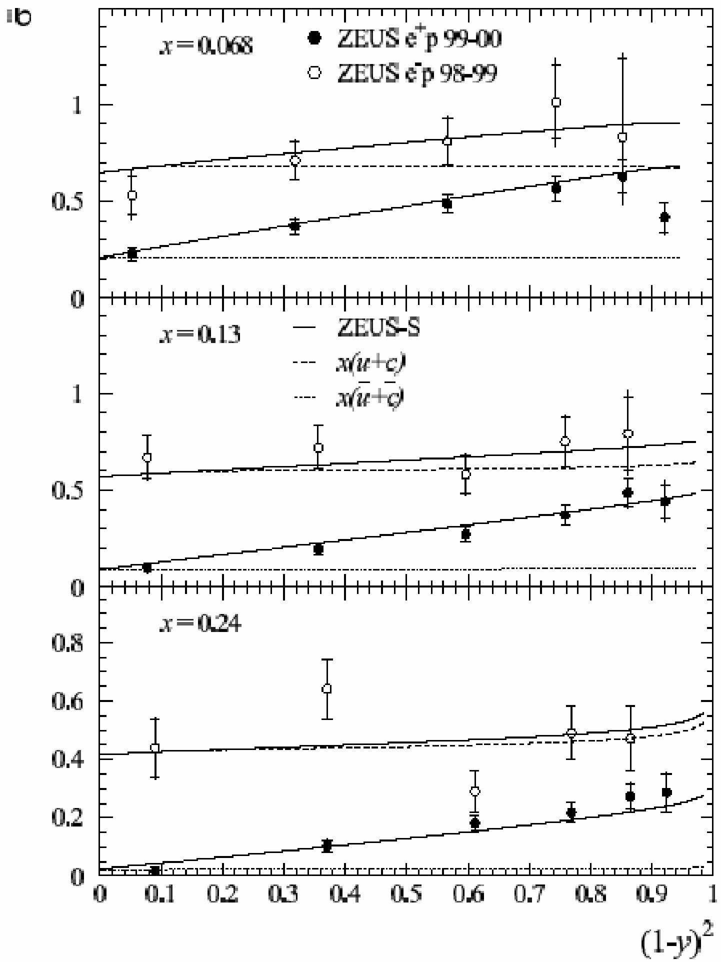
Separate contributions of parton density functions

$$(1-y)^2 x(d+s)$$

$$x(\bar{u}+\bar{c})$$

Charged Current DIS

Helicity structure: reduced cross section as function of $(1\text{-}y)^2$



W boson couples only to:

- left-handed fermions
- right-handed antifermions

Helicity plot:

- plot s vs $(1\text{-}y)^2$ for fixed x
- Region of approximate scaling: straight line.

$$\tilde{s}_{CC}(e^+p) = x\left[(\bar{u}_s+\bar{c}_s)+(1-y)^2(d_v+d_s+s_s)\right]$$

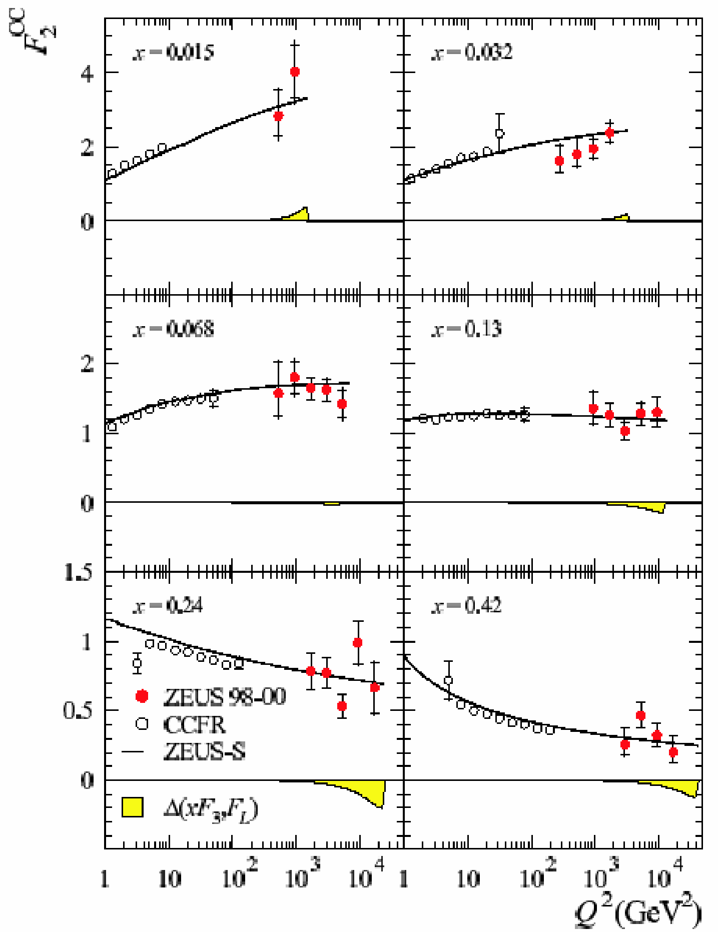
$$\tilde{s}_{CC}(e^-p) = x\left[(u_v+u_s+c_s)+(1-y)^2(\bar{d}_s+\bar{s}_s)\right]$$

Valence quarks:

- intercept: u_v
- slope: d_v

Charged Current DIS

Extraction of structure function F_2^{cc}



$$F_2^{CC} = \frac{2}{Y_+}\left(\tilde{s}^{e^+p}_{CC} + \tilde{s}^{e^-p}_{CC}\right) + \Delta(xF_3^{CC}, F_L^{CC})$$

$$Y_+ = 1 + (1-y)^2$$

Measured reduced cross sections

Correction term computed at NLO in QCD using ZEUS-S fit

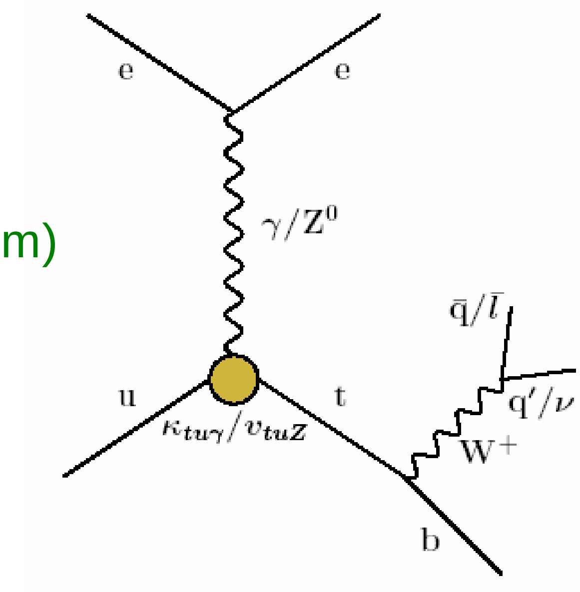
Data at much higher Q^2 than previous data, well described by SM prediction

CCFR n Fe data not included in ZEUS fit

Search for Single-top Production

Motivation

- Single-top production through flavor-changing neutral current (FCNC)
- Standard Model contribution < 1fb (GIM mechanism)
- Several theories beyond the SM predict FCNC
- FCNC coupling at tuV,tcV
  Most sensitive to tuV (charm PDF of proton small at high x)
- Effective anomalous coupling at
  t-u-? or t-u-Z vertex

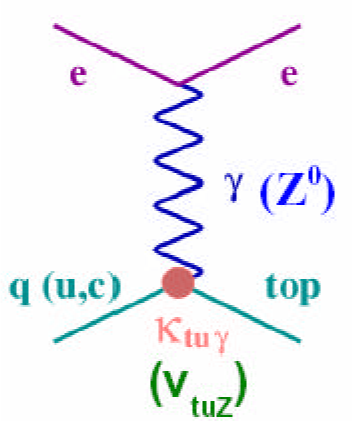


$$\Delta L_{eff} = e e_t \bar{t} \frac{i\sigma_{\mu\nu} q^{\nu}}{\Lambda} \kappa_{tu\gamma} u A^{\mu} + \frac{g}{2\cos\theta_W} \bar{t} \gamma_{\mu} v_{tuZ} u Z^{\mu} + h.c.$$

magnetic

vector coupling

Single-top: Experimental Signature



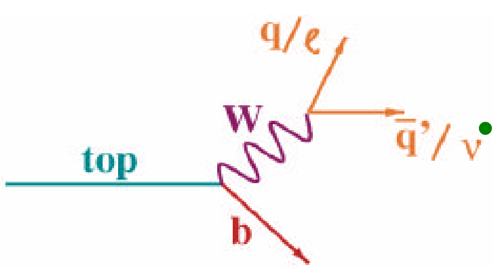
Production modes:

Final states for gamma and Z exchange quite different

- ?-exchange: $e^{\pm}$ forward peaked (escapes through rear beam pipe hole 65%)
- Z-exchange: $e^{\pm}$ in central part

Decay modes:

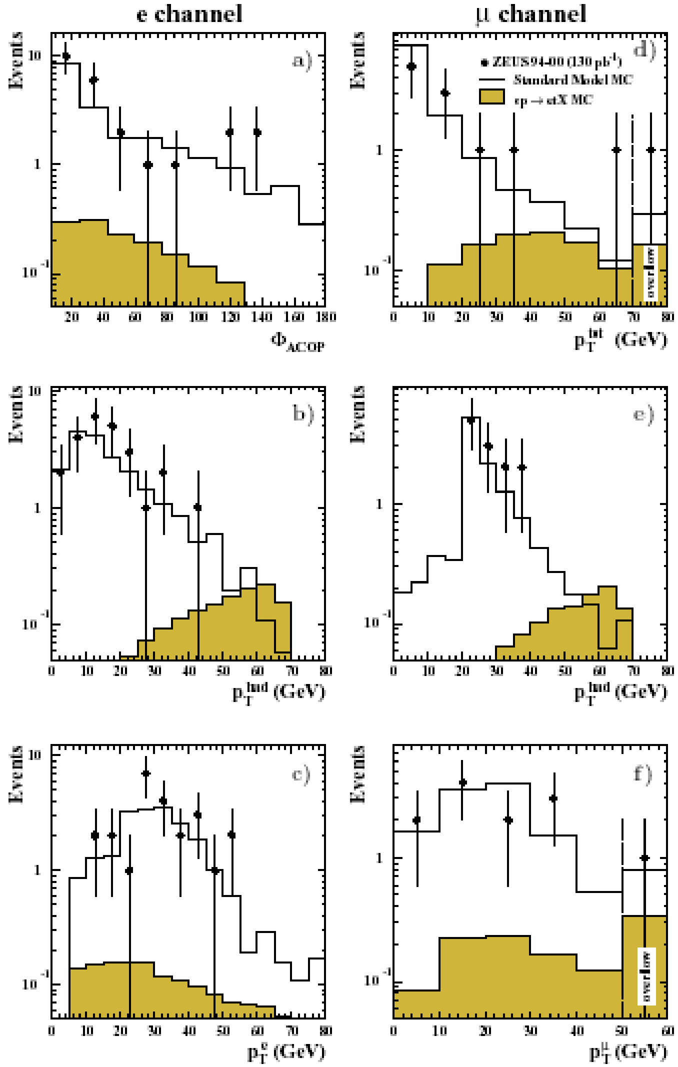
- Standard Model
  - leptonic (BR 32%): t→bW, W→l? isol.lepton, jet, p_{Tmiss}
  - hadronic (BR 68%): t→bW, W→q¯q 3 jets, m_W, m_{top}
- Flavor Changing Neutral Currents
  - k_{t-u-g} t→u? n-jets (+lepton pairs)
  - v_{t-u-Z} t→uZ^0



Data sample:

integrated luminosity: 130.1 pb^{-1} v s 300 and 318 GeV

Single-top: Lepton Decay Modes



Data selection

- Isolated high energy lepton ($e^\pm$ or $\mu^\pm$),
- missing momentum and jet
- $p_{had\ T}$ > 40 GeV also looked at >25 GeV

Number of events after final selection

channel	e	mu
obs/exp events	0 / 0.94±.1	0 / 0.95 ±.1

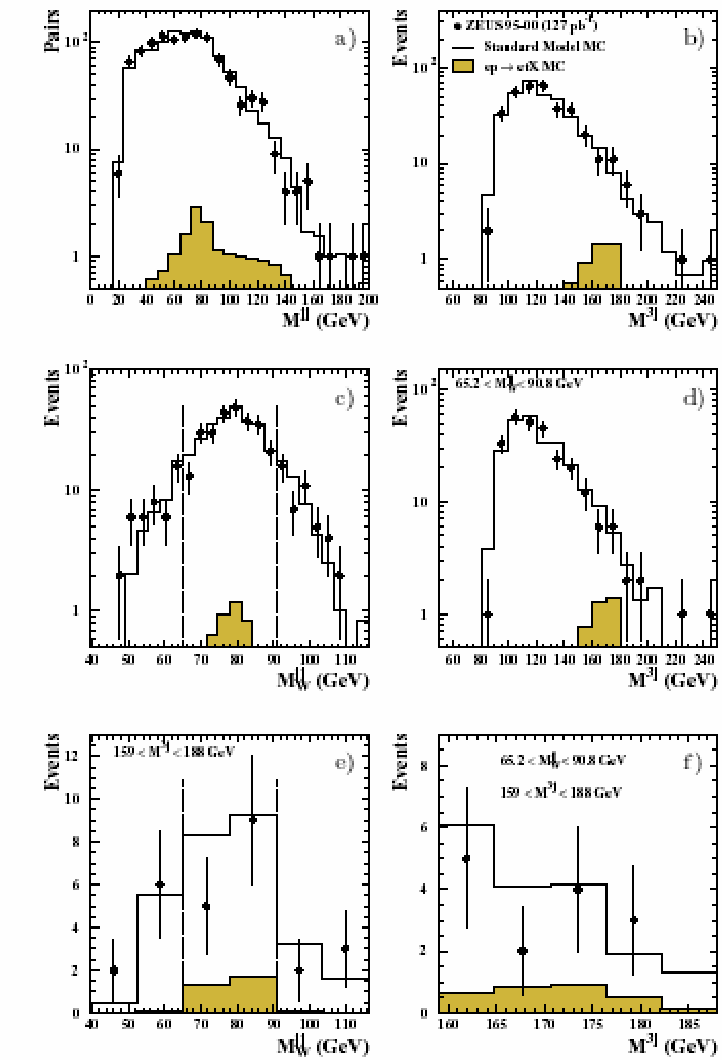
Single-top MC

- eu→ et simulated using CompHEP, input to PYTHIA6 (proton remnant,QED rad correction and hadronization)
- ? exchange checked with HEXF (same result)
- Contribution of interference term < 1%

Standard Model background

- NC DIS LEPTO 6.5, HERACLES for rad. corr.
- 2 photon processes: GRAPE generator
- single-W production: EPVEC, include higher order QCD corrections

Search for Single-top Production



Data selection

- 3 jets with large $E_{jet,T}$
- no missing transverse momentum
- invariant mass $M_{jj} \cong M_W$, $M_{3j} \cong M_{top}$

jet mass cuts $65.2 < M_{jj} < 90.8$ GeV

$159 < M_{3j} < 188$ GeV

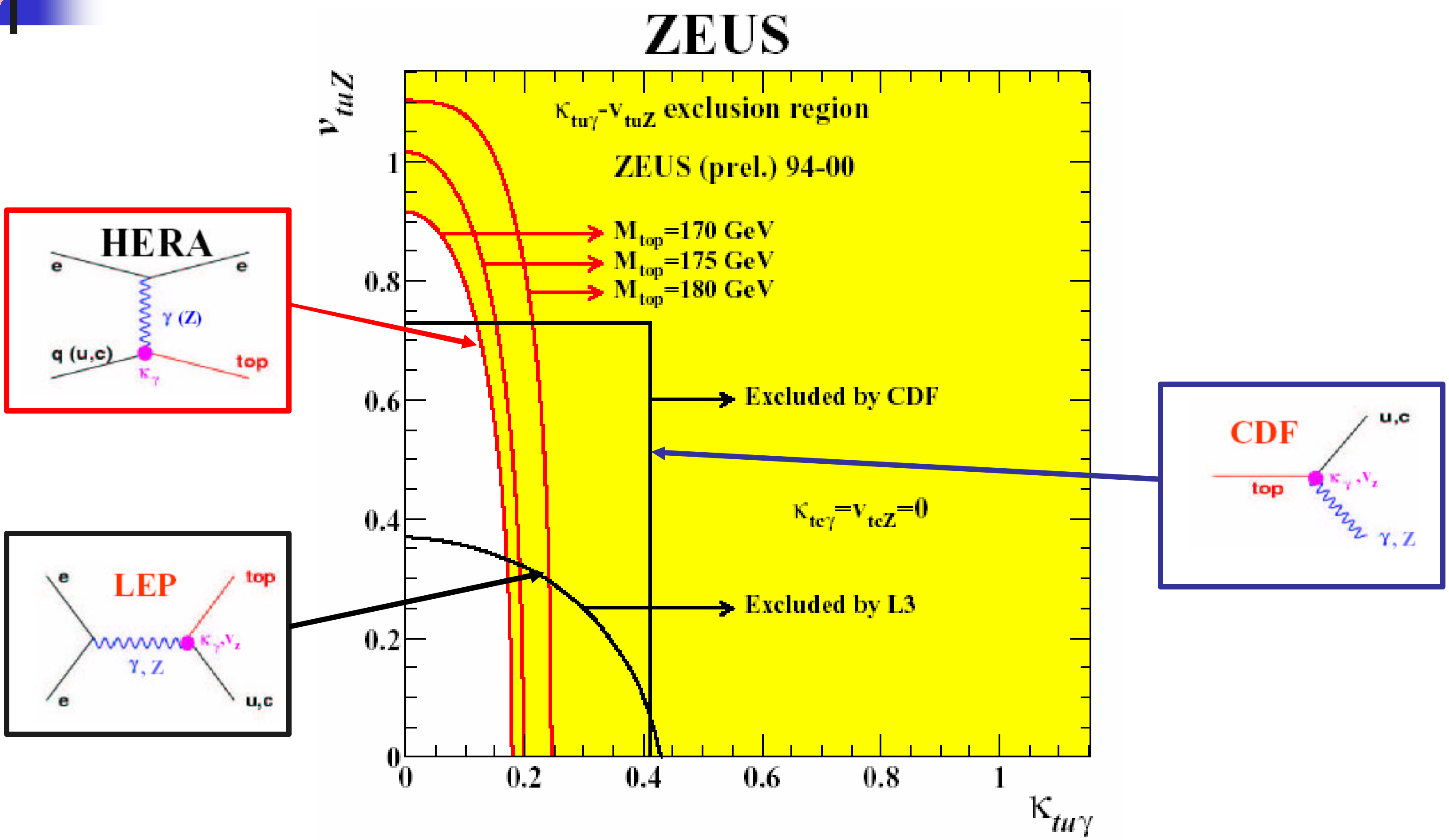
Number of events after final selection

channel	hadronic
obs/exp events	14 / 17.6

No excess observed

Set limits using two-dimensional probability density

Single-top Production: Results

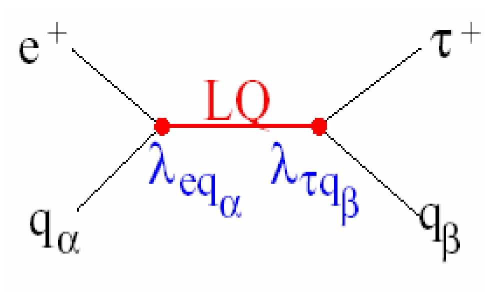


Limits on anomalous couplings significantly improved

Lepton Flavor Violation in t Production

Motivation for search $e^+p \rightarrow t\ X$

- Many extensions of Standard Model allow Lepton Flavor Violation



  - Leptoquark (LQ): both lepton and baryon numbers and lepton-quark Yukawa couplings
  - LFV if LQ couples to two different generations
  - Mediated by squarks in R-parity-violation SUSY models

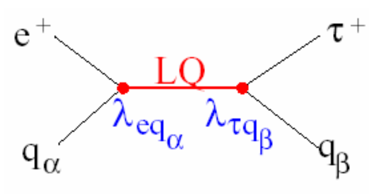
Lepton Flavor Violation in*t* Production

Buchmüller-Rückl-Wyler model: 14 LQ types, fermion number 0, 2

Narrow width approximation

$$(M_{LQ} < \sqrt{s})$$

$$s^{NWA}(l, M_{LQ}) \propto l^2_{lq_i} B_{lq_j}$$



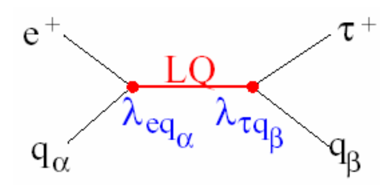
l_{eq_i} LQ coupling to electron and quark (generation i)

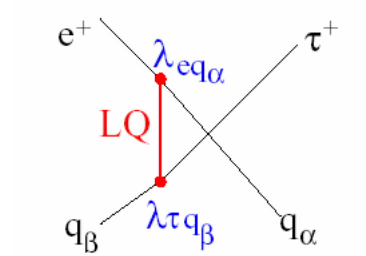
B_{lq_i} Branching ratio to lepton and quark

High mass approximation

$$(M_{LQ} >> \sqrt{s})$$

$$s^{HMA}(l, M_{LQ}) \propto \left[\frac{l_{eq_i} l_{eq_j}}{M^2_{LQ}} \right]^2$$





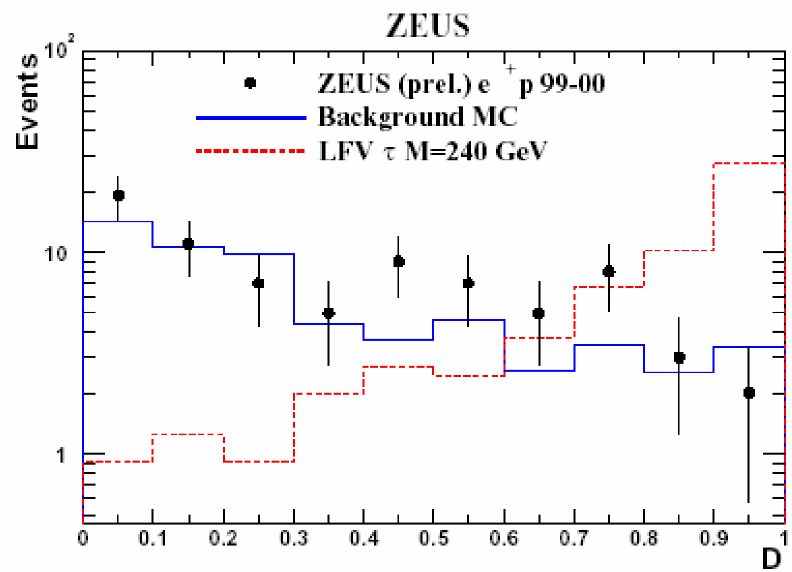
Lepton Flavor Violation in t Production

- Event Signature
  - High transverse momentum isolated t balanced by a jet
  - Only tau decay products visible in detector
    → large transverse momentum imbalance $P_{t,mis}$
- Look at leptonic (35%) and hadronic (65%) decays
- Leptonic decays:
  - $P_{t,mis}$ > 15 GeV (20 GeV)
  - 20 < E-P_z < 52 GeV
  - $P_{t,mis}$ / v E_t > 2.5 v GeV
  - Isolated e: E > 20 GeV µ: p_t > 5 GeV

Lepton Flavor Violation in *t* Production

Hadronic *t* decays:

- No electron with E > 10 GeV
- E_t > 50 GeV
- 15 < E-P_z < 60 GeV
- *t* jet candidate:
  - p_t > 15 GeV
  - 1 to 3 tracks
- *t* discriminant:
  - jet shape: 6 observables
  (radial extension of jet energy)

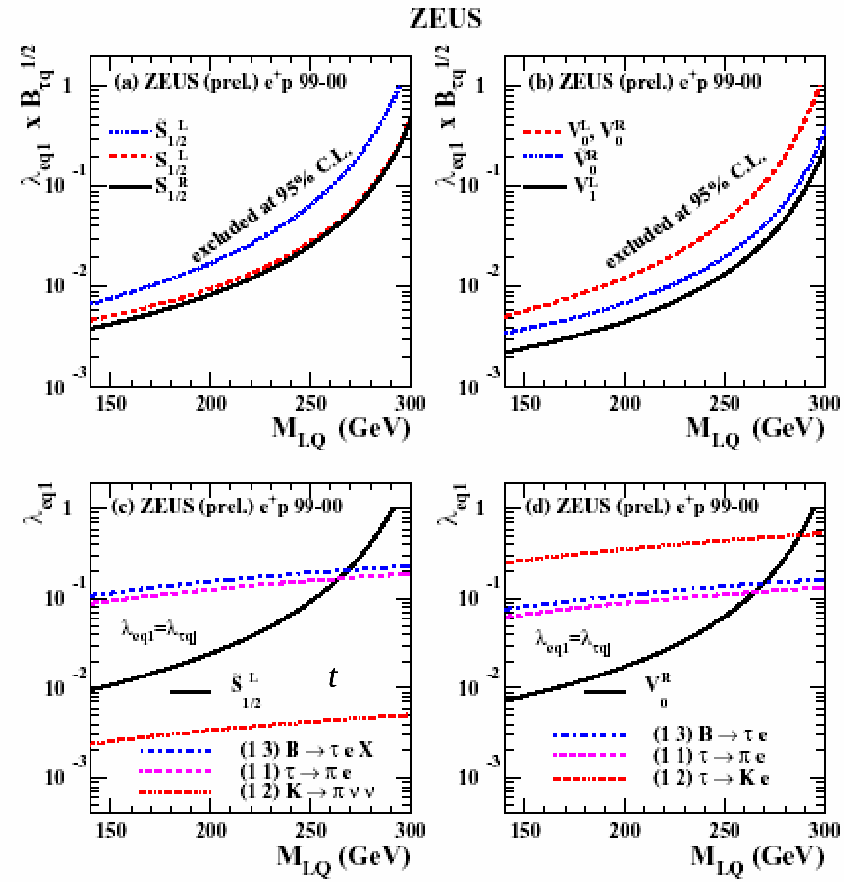


No candidate event in any channel

Standard Model processes expect 0.8±0.3 events (CC DIS, di-μ and di-*t* production in photon-photon interactions or photoproduction)

Lepton Flavor Violation in *t* Production

Results: Limits on $l_{eq_1}\sqrt{B_{tq}}$ as function of M_{LQ} for lower mass scalar and vector Leptoquarks



95% C.L. lower limits on LQ assuming $?_{eq_1} = ?_{tq}$=0.3 (electromagnetic strength)

$\tilde{S}^L_{1/2}$	$S^L_{1/2}$	$S^R_{1/2}$	V^L_0	V^R_0	$\tilde{V}^R_0$	V^L_1
276	293	293	276	281	296	299

Limits on $l_{eq_1}\sqrt{B_{tq}}$ equivalent to limits on $l'_{ej1}\sqrt{B_{\tilde{u}^j \to tq}}$ for $\tilde{u}^j$ squarks

Lepton Flavor Violation in *t* Production

Upper 95%C.L. limits on $?_{eq_a}\ ?_{t\,q_ß}/M^2_{LQ}$ (TeV^{-2}) for F=0 high mass LQs

$e \to \tau$			ZEUS			$F=0$	
$\alpha\beta$	$S^L_{1/2}$ e^+u_α	$S^R_{1/2}$ $e^+(u+d)_\alpha$	$\tilde{S}^L_{1/2}$ e^+d_α	V^L_0 e^+d_α	V^R_0 e^+d_α	$\tilde{V}^R_0$ e^+u_α	V^L_1 $e^+(\sqrt{2}u+d)_\alpha$
1 1	$\tau \to \pi e$ 0.4 **2.2**	$\tau \to \pi e$ 0.2 **1.8**	$\tau \to \pi e$ 0.4 **3.2**	$\tau \to \pi e$ 0.2 **2.3**	$\tau \to \pi e$ 0.2 **2.3**	$\tau \to \pi e$ 0.2 **1.7**	$\tau \to \pi e$ 0.06 **0.8**
1 2	$\boxed{2.2}$	$\tau \to Ke$ 6.3 $\boxed{1.9}$	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **3.4**	$\tau \to Ke$ 3.2 $\boxed{2.6}$	$\tau \to Ke$ 3.2 $\boxed{2.6}$	$\boxed{1.9}$	$K \to \pi\nu\bar{\nu}$ 1.5×10^{-4} **0.9**
1 3	*	$B \to \tau\bar{e}$ 0.6 **3.8**	$B \to \tau\bar{e}$ 0.6 **3.8**	$B \to \tau\bar{e}$ 0.3 **3.2**	$B \to \tau\bar{e}$ 0.3 **3.2**	*	$B \to \tau\bar{e}$ 0.3 **3.2**
2 1	$\boxed{11}$	$\tau \to Ke$ 6.3 **6.4**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **7.8**	$\tau \to Ke$ 3.2 **3.5**	$\tau \to Ke$ 3.2 **3.5**	$\boxed{4.6}$	$K \to \pi\nu\bar{\nu}$ 1.5×10^{-4} **1.9**
2 2	$\tau \to ee\bar{e}$ 20 $\boxed{13}$	$\tau \to ee\bar{e}$ 30 $\boxed{7.3}$	$\tau \to ee\bar{e}$ 66 $\boxed{8.9}$	$\tau \to ee\bar{e}$ 33 $\boxed{4.4}$	$\tau \to ee\bar{e}$ 33 $\boxed{4.4}$	$\tau \to ee\bar{e}$ 10 $\boxed{7.1}$	$\tau \to ee\bar{e}$ 6.1 $\boxed{2.7}$
2 3	*	$B \to \tau\bar{e}X$ 14 $\boxed{11}$	$B \to \tau\bar{e}X$ 14 $\boxed{11}$	$B \to \tau\bar{e}X$ 7.2 $\boxed{6.8}$	$B \to \tau\bar{e}X$ 7.2 $\boxed{6.8}$	*	$B \to \tau\bar{e}X$ 7.2 $\boxed{6.8}$
3 1	*	$B \to \tau\bar{e}$ 0.6 **11**	$B \to \tau\bar{e}$ 0.6 **11**	V_{ub} 0.12 **4.0**	$B \to \tau\bar{e}$ 0.3 **4.0**	*	V_{ub} 0.12 **4.0**
3 2	*	$B \to \tau\bar{e}X$ 14 **14**	$B \to \tau\bar{e}X$ 14 **14**	$B \to \tau\bar{e}X$ 7.2 $\boxed{5.2}$	$B \to \tau\bar{e}X$ 7.2 $\boxed{5.2}$	*	$B \to \tau\bar{e}X$ 7.2 $\boxed{5.2}$
3 3	*	$\tau \to ee\bar{e}$ 30 $\boxed{19}$	$\tau \to ee\bar{e}$ 66 $\boxed{19}$	$\tau \to ee\bar{e}$ 33 $\boxed{10}$	$\tau \to ee\bar{e}$ 33 $\boxed{10}$	*	$\tau \to ee\bar{e}$ 6.1 **10**

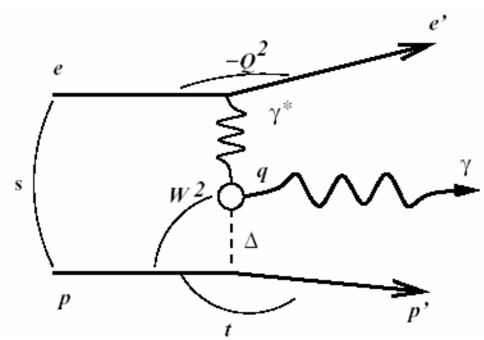
a and ß quark generations
Upper entry: most stringent low energy limits
Lower entry: ZEUS limits
Box: ZEUS best limit

Similar limits for |F|=2 LQs

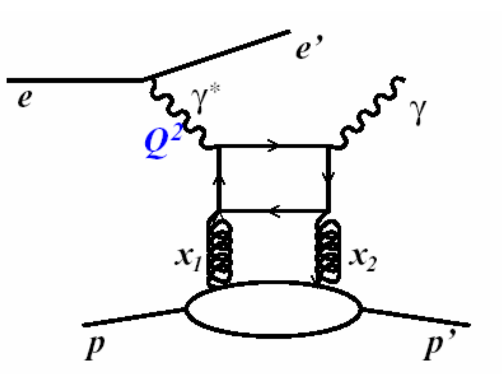
Some limits also apply to R_p-violating squarks.
If higher generation quarks involved ZEUS limits most stringent

Deeply Virtual Compton Scattering

DVCS: QCD process



Dominant at low x



Motivation

- Study proton structure by measuring correlations between pairs of gluons within the proton.
- Correlations are parametrized by generalized parton distribution functions (GPD)
- GPD information about the wave function of the proton

Advantages

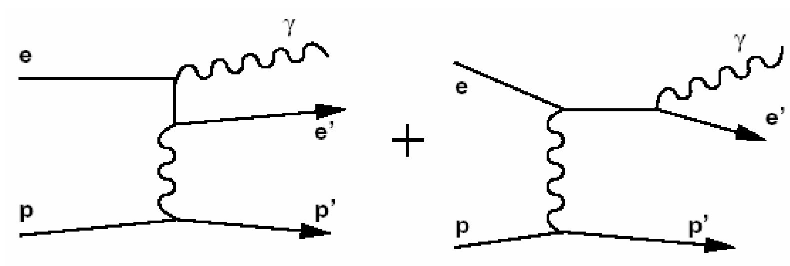
- Simple state and absence of hadronization, no form factors

  → QCD predictions more reliable than for many other exclusive final states.
- Process one of the best understood exclusive processes in ep.

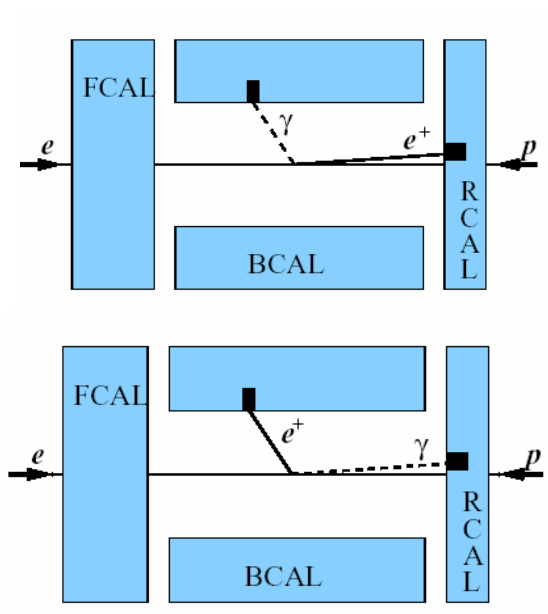
Deeply Virtual Compton Scattering

Background process

Bethe – Heitler process



DVCS event signature 2 isolated electromagnetic clusters



g_1: RCAL

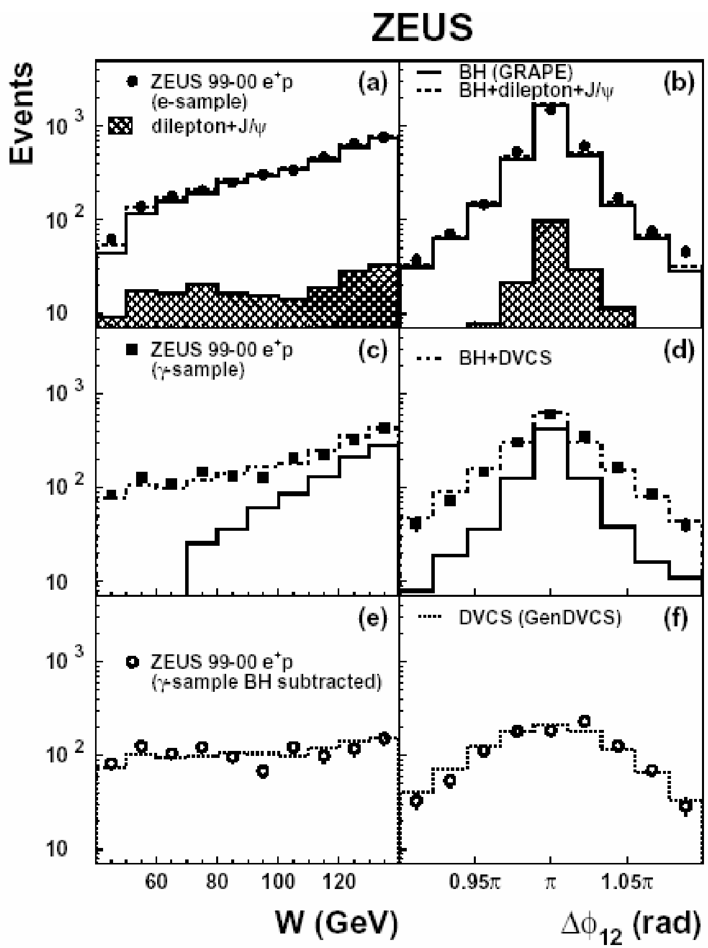
g_2: 1.2 > ? > -1.6

$E_1 > E_2$ $?_1 < ?_2$

3 classes of events:

- RCAL: e^+, central photon: DVCS and HB
- RCALg , central e: only BH
- RCALg , central e^- non-resonant e^+e^-, J/Psi production

Deeply Virtual Compton Scattering



Comparison with MC:

BH and QED di-lepton production:
Grape generator

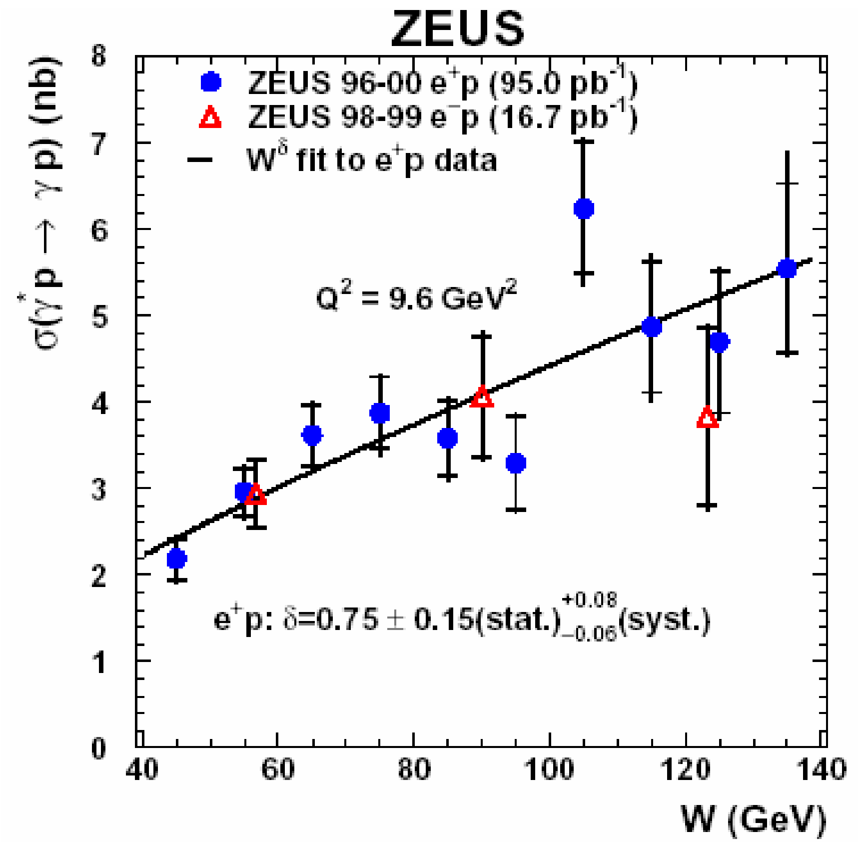
DVCS
GenDVCS based on Frankfurt, Freund and Strikman

Radiative corrections: HERACLES

Good agreement

Deeply Virtual Compton Scattering

Total cross section: W dependence



No significant differences between e^+ p and e^- p

Fit W^d

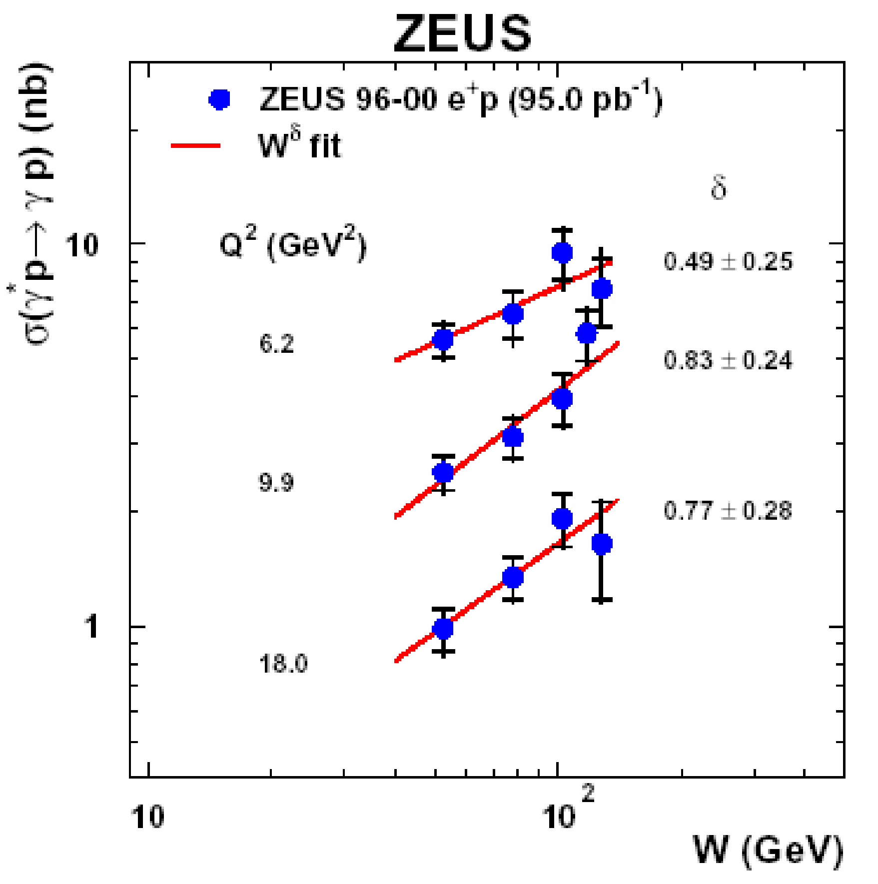
d = .75±.15 $_{-0.06}^{+0.08}$

comparable to J/Psi production

Steep rise → presence of hard underlying process

Deeply Virtual Compton Scattering

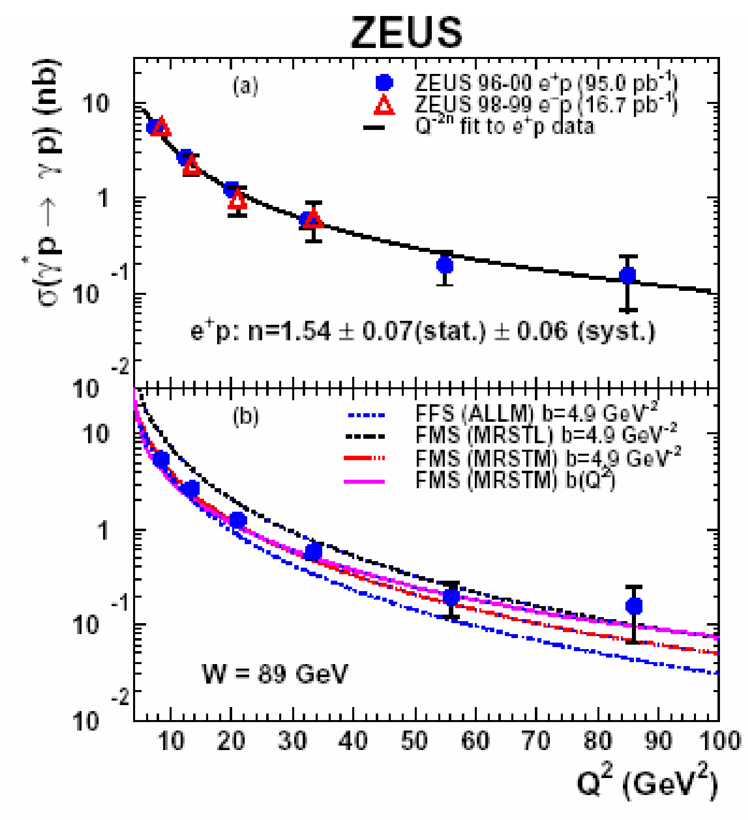
Total cross section: W dependence as function of Q^2



Compatible with
- no dependence on Q^2,
- increase with Q^2 as in exclusive production of light vector mesons.

Deeply Virtual Compton Scattering

Total cross section: Q^2 dependence for W = 89 GeV



e^-p, e^+p no difference

→insensitive to interference term

Fit Q^{-2n}

- e^+p n=1.54 +- 0.07 +- 0.06 lower than for exclusive vector meson production
- e^-p n=1.69 +- 0.21 +0.09 -.06

GPD based model:

Freund, McDermot, Strikman

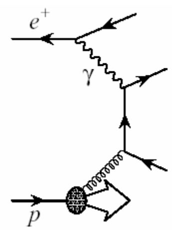
Exponential slope of t dependence

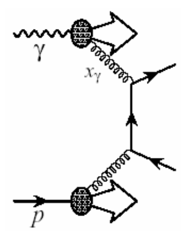
$$b = 8(1 - 0.15\ln(Q^2/2))GeV^{-2}$$

Jet-Production in Photoproduction

Jet-production provides test of QCD

- Comparison of jet cross sections for same reaction at different energies
- Parton model predicts scaled invariant cross section independent of center of mass energy
- QCD predicts non-scaling behavior due to evolution of structure functions of colliding hadrons and running of a_s.
- 2 QCD processes:
  - photon interacts directly with parton in proton
  - photon source of partons, interacts with parton in proton





- Should observed scaling violation in both processes
- Measurement of high $E_{T,jet}$ cross section over wide range of allows determination of a_s

Jet-Production in Photoproduction

Data

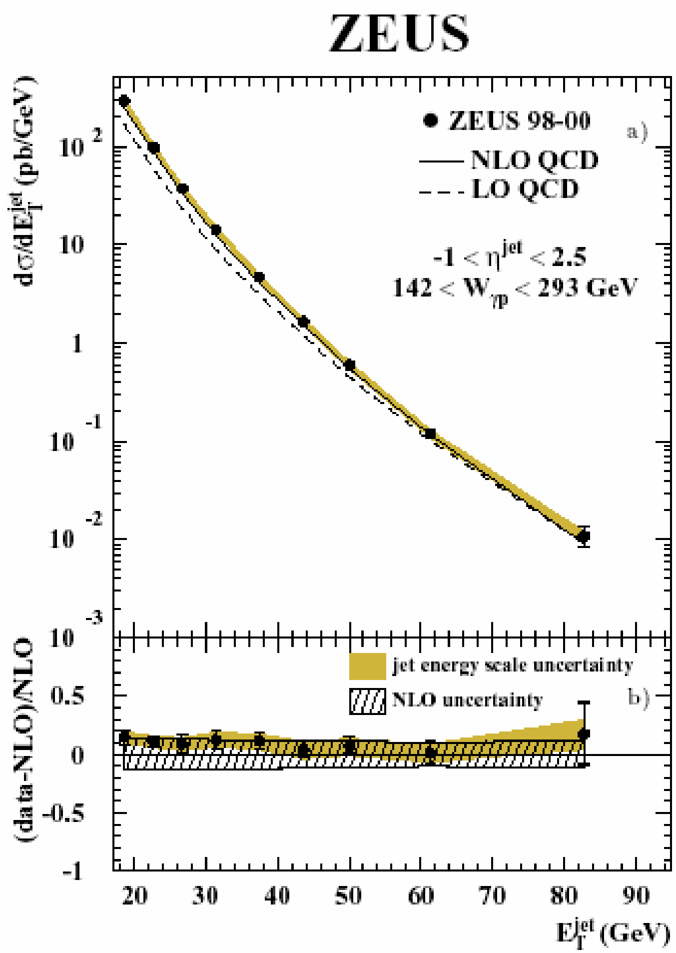
- At least one jet E_T > 10 GeV and ? < 2.5
- $Q^2 <= 1$ GeV , median 10^{-3} GeV^2
- 142 < W < 293 GeV

Fixed-order QCD calculations

- Leading and next-to-leading order QCD calculations: Klasen, Kleinwort, Kramer
- Used MRST99 parametrizations of parton distribution functions (PDF)
- GRV for photon
- QCD calculations refer to partons
  → predictions were corrected to hadron level

Jet-Production in Photoproduction

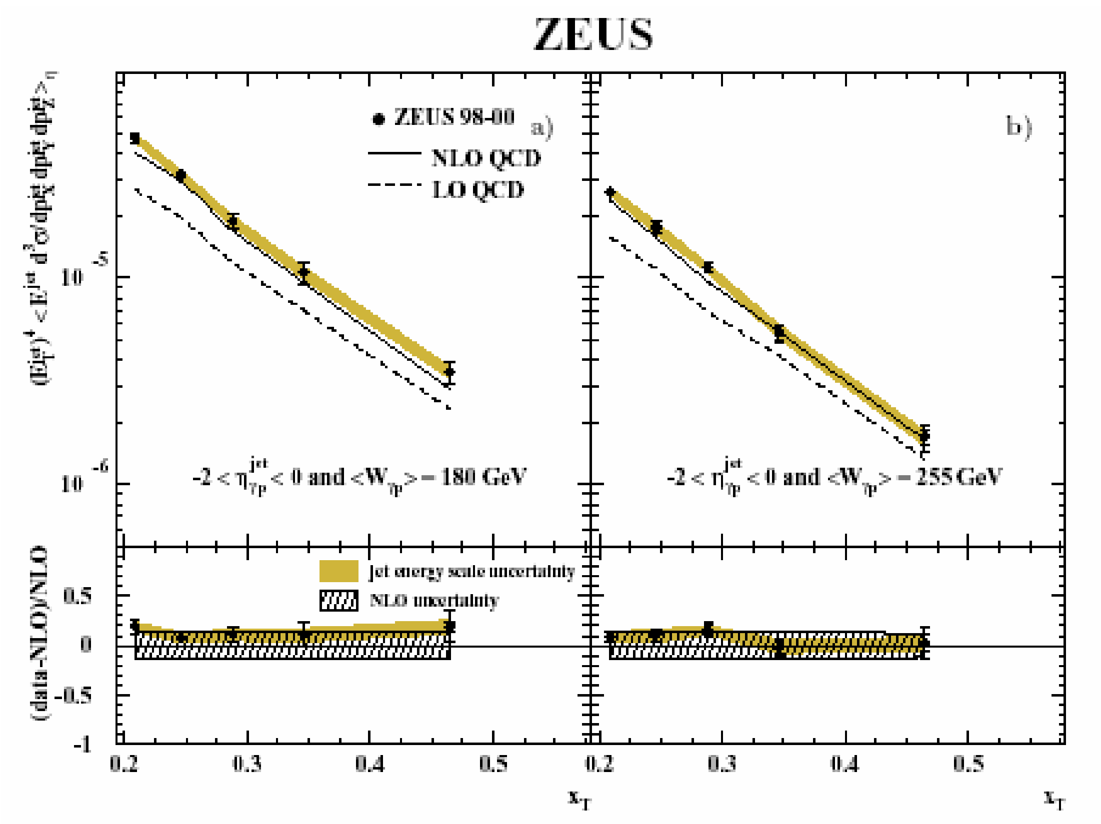
Inclusive jet differential cross section



- LO QCD calculations under-estimates cross section by 50% for $E_{T,jet}$ < 45 GeV
- NLO calculations in good agreement over whole $E_{T,jet}$ range

Jet-Production in Photoproduction

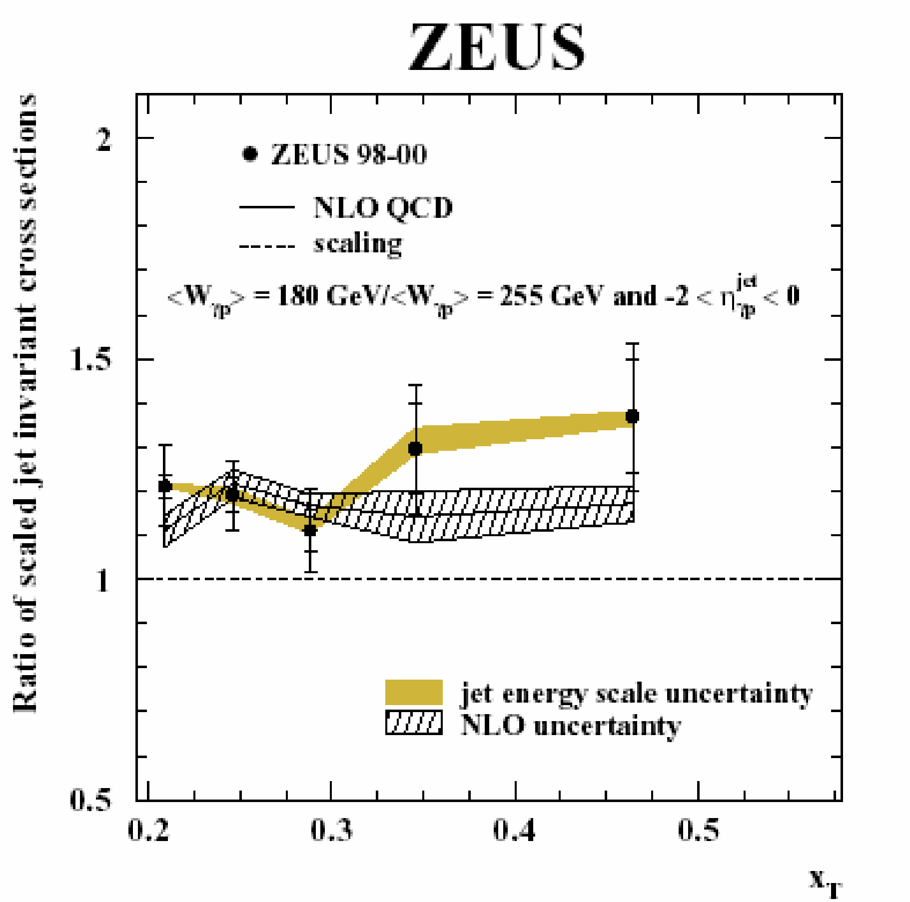
Scaled invariant cross section $(E_T^{jet})^4\left[\frac{E^{jet}d^3s}{dp_X^{jet}dp_Y^{jet}dp_Z^{jet}}\right]_h$ vs x_T



Data well described by NLO calculations

Jet-Production in Photoproduction

Ratio of scaled jet invariant cross sections for $\langle W_{gp} \rangle$ 180 and 255 GeV

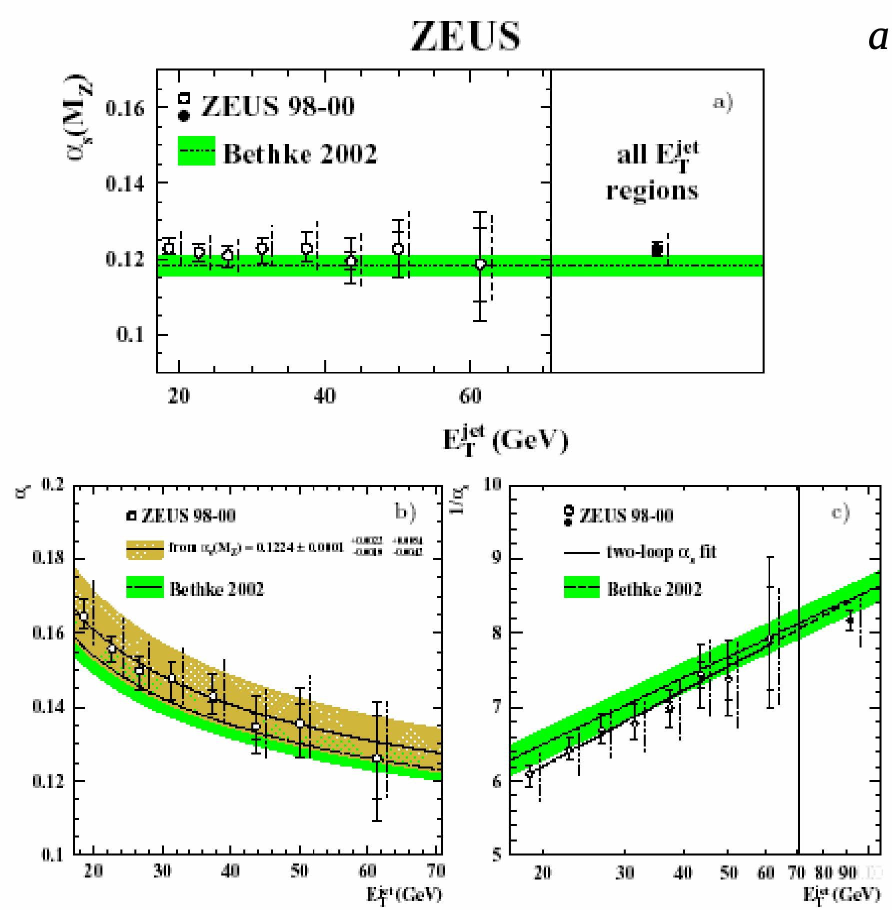


- Clear deviation from 1
- In good agreement with NLO QCD, including running of a_s and evolution of PDFs

First observation of scaling violations in ?p interactions

Jet-Production in Photoproduction

a_s determination: QCD fit of measured $ds \,/\, dE_T^{jet}$



$$a_s(M_Z) = 0.1224 \pm 0.0001(\text{stat.})^{+0.0022}_{-0.0019}(\text{exp.})^{+0.0054}_{-0.0042}(\text{th.})$$

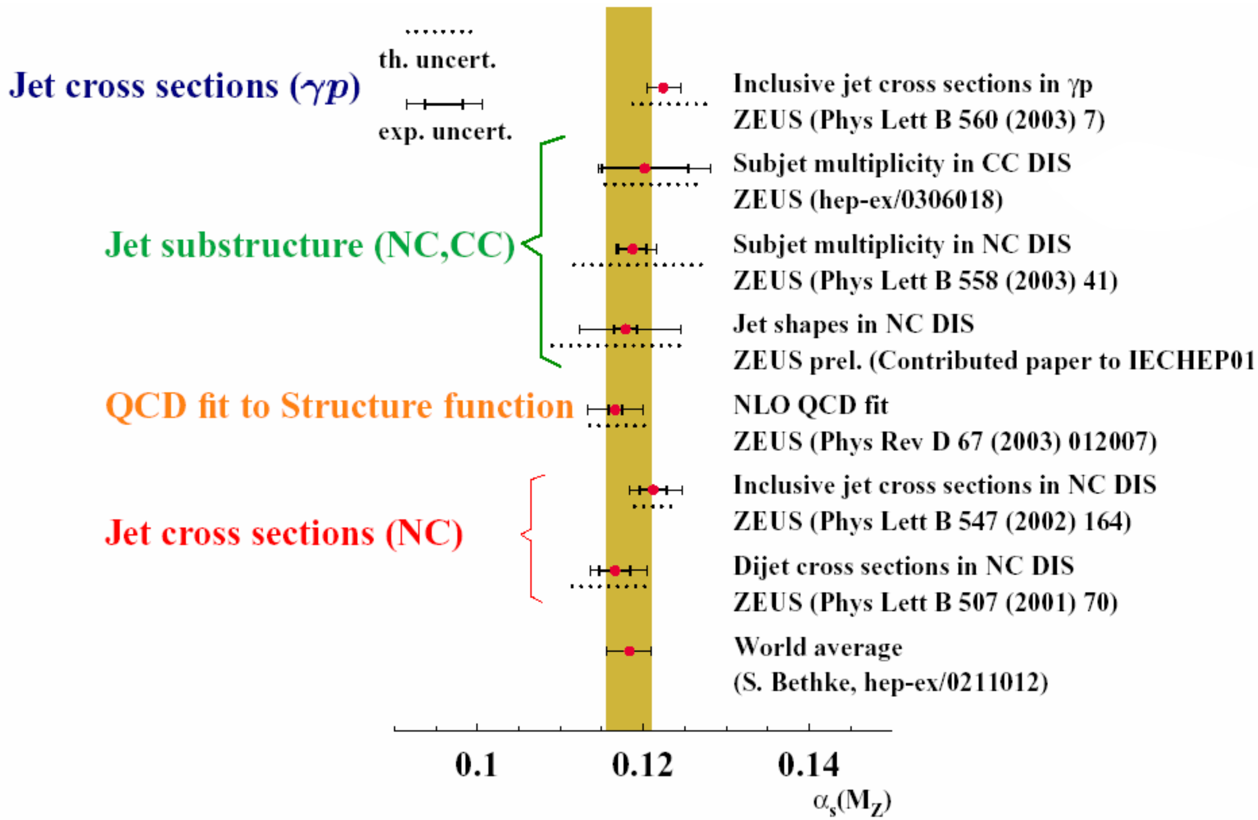
Main uncertainties:

- experimental:
  - jet energy scale ±1.5%
- theoretical
  - terms beyond NLO +4.2% -3.3%
  - uncertainties of photon PDF and hadronization correction +0.7% and 0.8%
  - Uncertainty of proton PDF ±0.9%

Energy-scale dependence of a_s

- Good agreement with running of a_s
- Extrapolation to $E_T^{jet} = M_Z$

ZEUS Determinations of a_s



First measurement of a_s in photoproduction:
- small error,
- comparable with world average.

All measurements consistent.

Looking forward to improved theoretical predictions to match experimental errors.

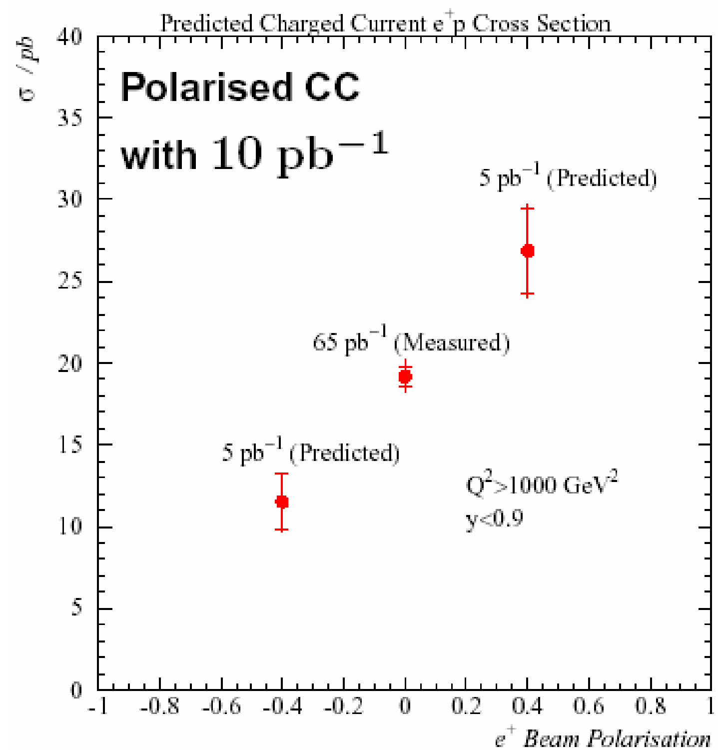
HERA II: increased precision data, at higher transverse energy.

Status and Prospects

- 2000-2001 Shutdown for HERA Luminosity Upgrade
  - Increase HERA luminosity by factor 4-5
  - Install spin rotators (longitudinal polarization) for H1 and ZEUS
  - Detector Upgrades:
    - Silicon-Micro-Vertex detector,
    - improved forward tracking,
    - new luminosity measuring system
- 2001-2002
  - Re-commissioning of HERA (achieved design specific luminosity)
  - Beam currents limited by poor background conditions
  - Understanding and improving background conditions
  - Achieved 60% longitudinal polarization within a few days

Status and Prospects

- March-July 2003
  - Shutdown for background improvements
  - Presently startup of HERA
- End September
  - Start luminosity operation
  - Few $10pb^{-1}$ expected this year
  - Sufficient to establish polarization dependence
- HERA operation until 2007
  - Goal $1fb^{-1}$ with polarization
  - Precision data at high x,Q^2
  - Chiral structure
  - Precision heavy flavor physics



Conclusions

- Deep Inelastic Scattering
  - Charged Current cross section measured up to Q^2=60,000 GeV^2
  - M_W measured in space-like region
  - Extracted structure function F_2^{cc}
- Search for New Physics
  - New limits: Lepton-flavor violation in tau production
  - New limits: Single-top production
- Deeply Virtual Compton Scattering
  - $s(g^* p \to gp)$ measured for 2 < Q^2< 100GeV^2, 30 < W < 140 GeV
  - $s(g^* p \to gp)$ rises steeply with W → hard process
- Jets in Photoproduction
  - Scaling violations observed in jet photoproduction for first time.
  - a_s extracted from photoproduction for first time:
    - very precise error, comparable with world average
- Looking forward to high luminosity data with polarization