Electroweak Physics and Searches at HERA

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on behalf of the H1 and ZEUS Collaborations

May 23rd 2011

Outline:

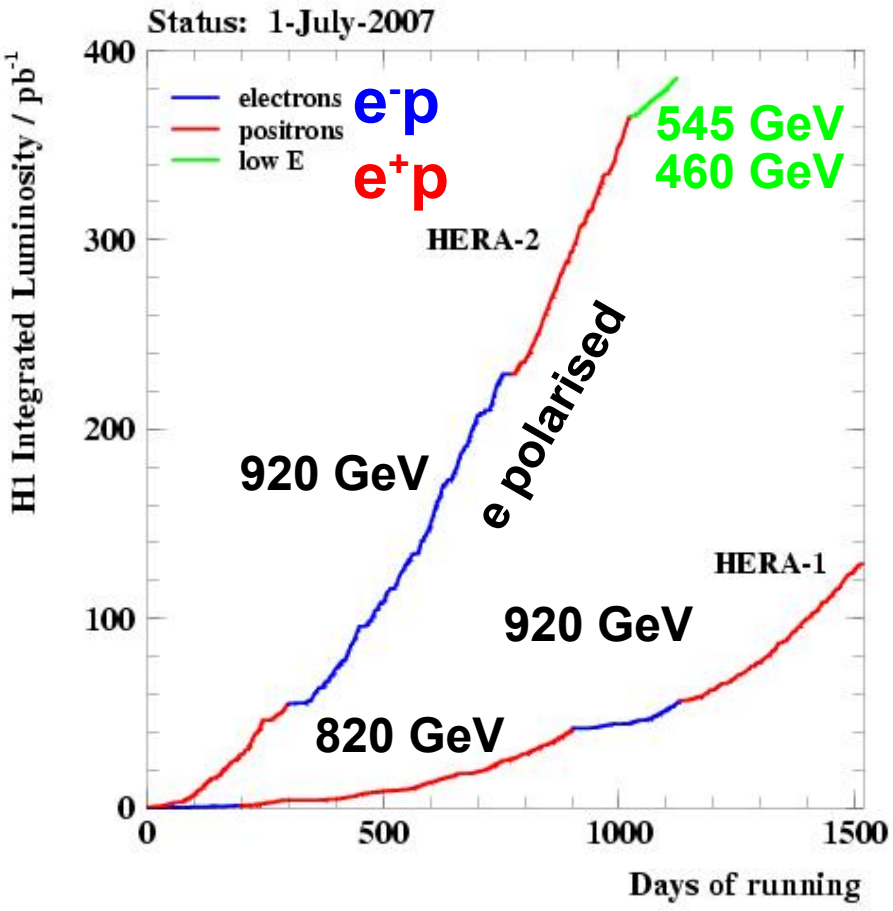
- **H1 and ZEUS at HERA**
- **Electroweak Physics**
- **Model based searches**
- **Model independent searches**

Universität Hamburg

BMBF - Förderschwerpunkt
Elementarteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

The HERA Collider

E_{cms}:
301 GeV
318 GeV



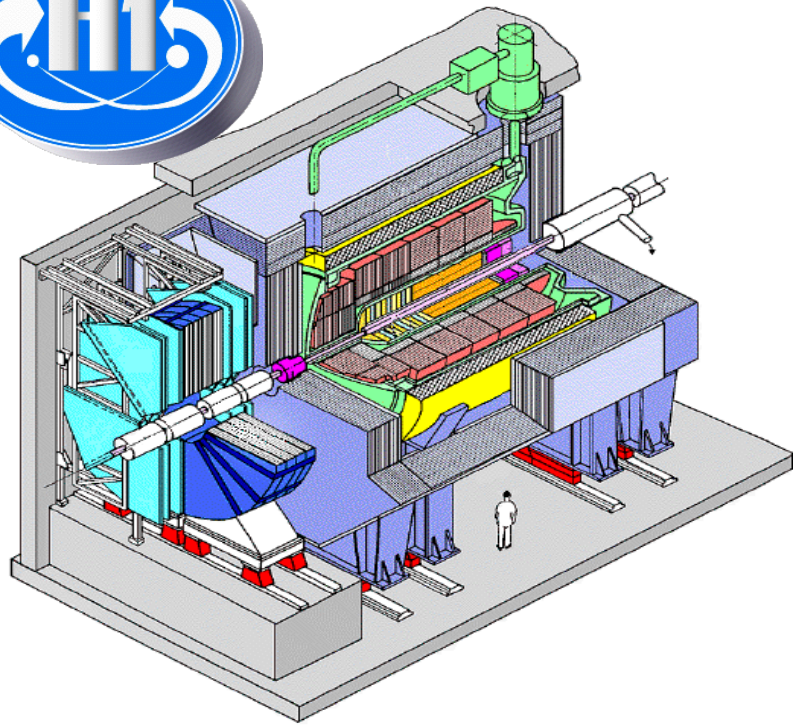
HERA-I: 1992-2000 L~120 pb^{-1}/exp.

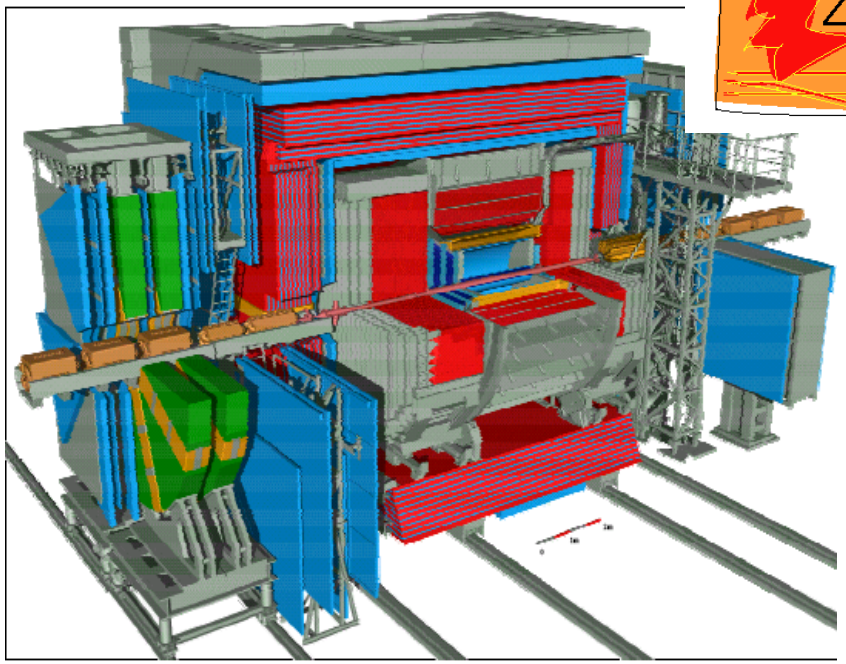
HERA-II: 2002-2007 L~350 pb^{-1}/exp.

- -Luminosity upgrade
- -Longitudinally polarised lepton beam

H1+ZEUS: Total luminosity ~ 1fb^{-1}

H1 and ZEUS: Hermetic Multi-purpose Detectors





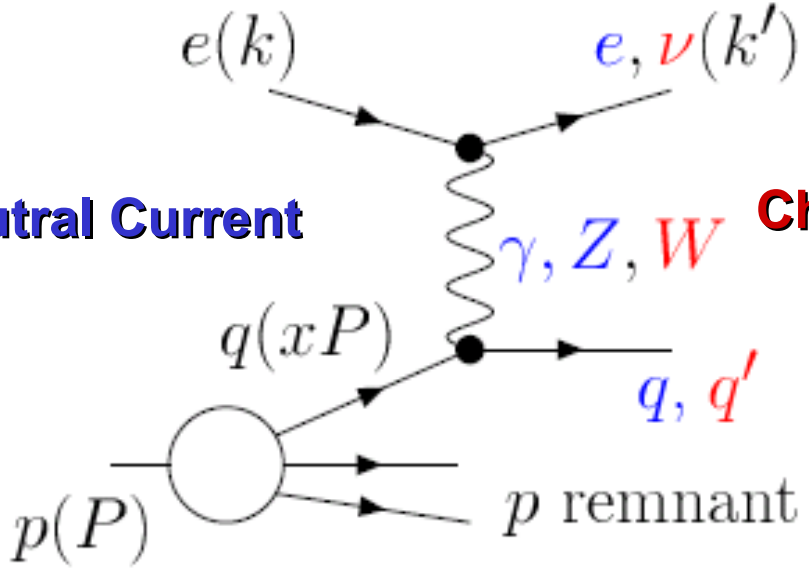
Liquid Argon Calorimeter

Optimised for precision measurement of the scattered lepton

Uranium-scintillator Calorimeter

Optimised for precision measurement of the hadronic final state

Main Process at H1 and ZEUS: Deep Inelastic $e^{\pm}p$ Scattering



$$Q^2 = -(k - k')^2$$

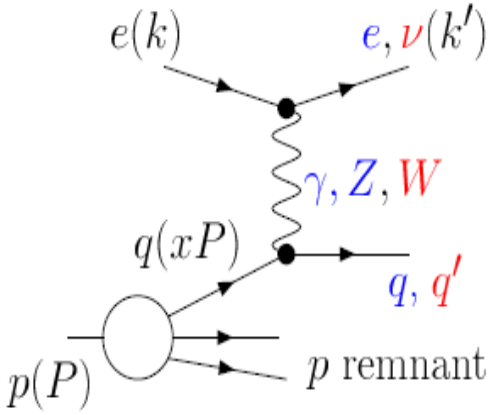
$$x = \frac{Q^2}{2P \cdot (k - k')}$$

$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

Q^2 – virtuality of the exchanged boson, resolution ~1/Q

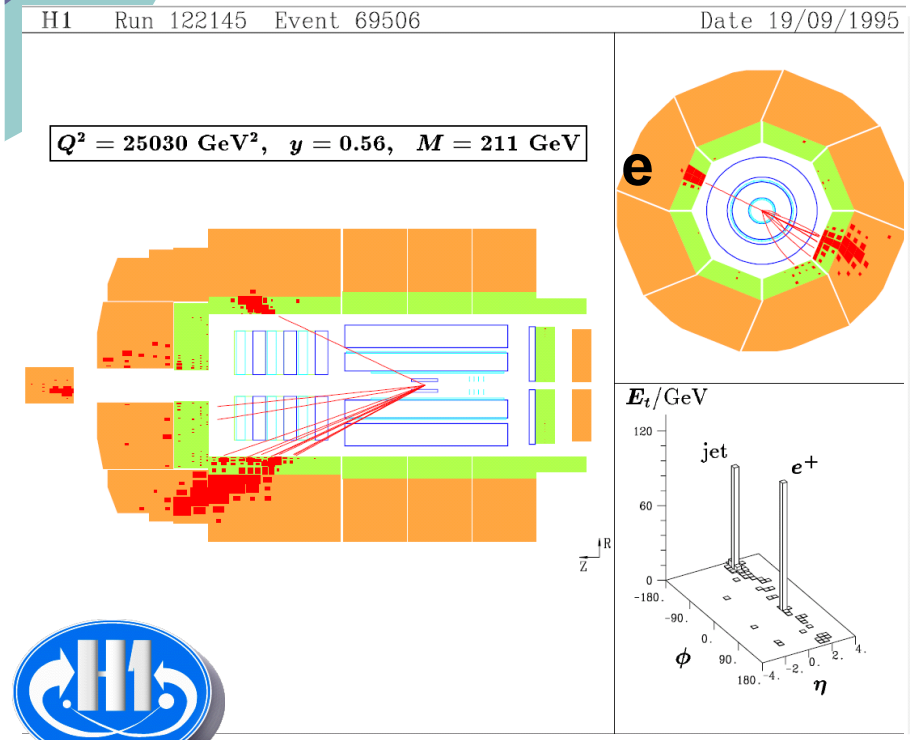
x – fraction of proton momentum carried by struck quark

y – inelasticity, fractional energy of the incoming lepton transferred to proton in proton rest frame

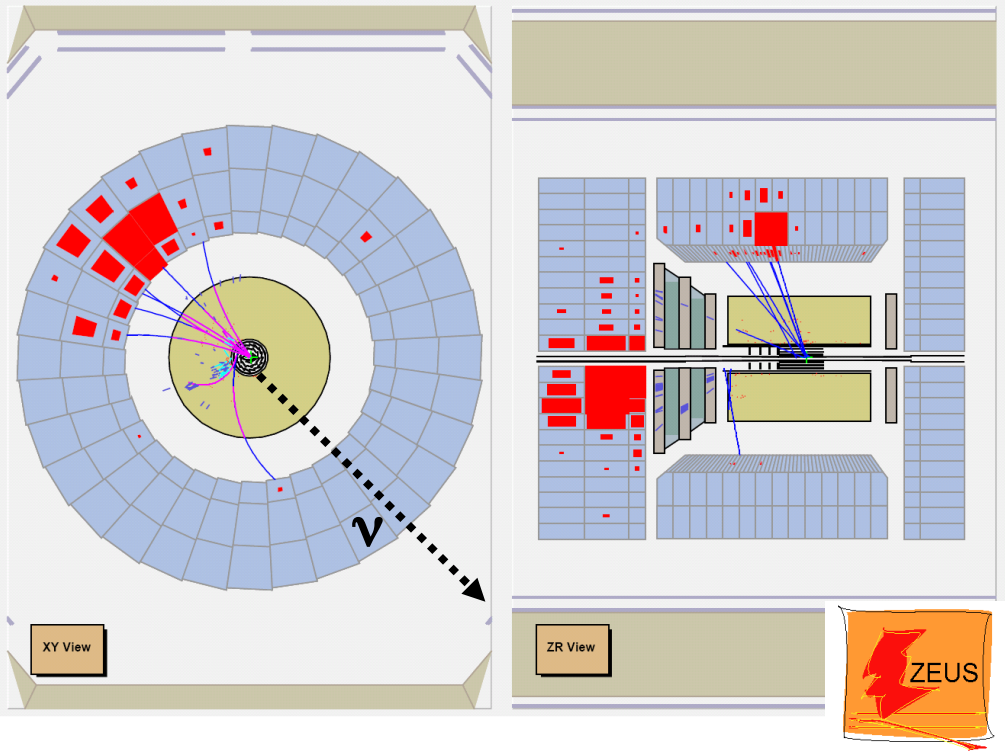


Main Process at H1 and ZEUS: Deep Inelastic $e^{\pm}p$ Scattering

Neutral Current

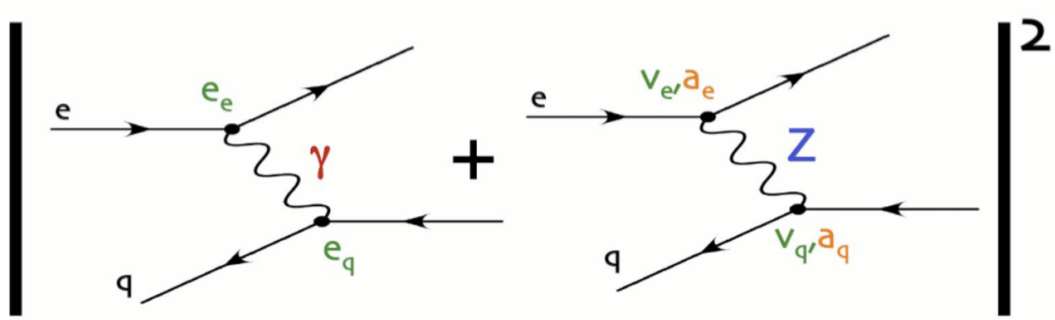


Charged Current



Cross Sections and Structure Functions: Neutral Current DIS

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\underbrace{Y_+ F_2(x,Q^2)}_{\text{dominant}} \mp \underbrace{Y_- x F_3(x,Q^2)}_{\text{important at high } Q^2} - \underbrace{y^2 F_L(x,Q^2)}_{\text{relevant at high y}}\right]$$



dominant relevant at high Q^2 polarisation of e

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

$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

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

$$F_2^\pm = F_2^\gamma - (v_e \mp P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \mp 2 P_e v_e a_e)\chi_Z^2 F_2^Z$$

$$xF_3^\pm = -(a_e \mp P_e v_e)\chi_Z xF_3^{\gamma Z} + (\mp P_e(v_e^2 + a_e^2) + 2 v_e a_e)\chi_Z^2 xF_3^Z$$

axial vector coupling of e to Z^0 relevant at high Q^2 vector coupling of e to Z^0

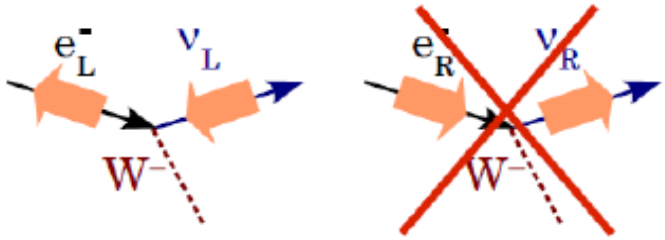
Cross Sections and Structure Functions: Charged Current DIS

$$\frac{\mathrm{d}^2\sigma^{\pm}_{\mathrm{CC}}}{\mathrm{d}x\mathrm{d}Q^2} = (1-P_e)\frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2 \left(Y_+ W_2^{\pm} - Y_{\mp} x W_3^{\pm} - y^2 W_L^{\pm}\right)\cdot\left(1+\delta^{\mathrm{CC}}_{\mathrm{weak}}\right)$$

$$\begin{aligned} W_2^- &= x(u+c+\overline{d}+\overline{s}) \\ xW_3^- &= x(u+c-\overline{d}-\overline{s}) \end{aligned}$$

$$\begin{aligned} W_2^+ &= x(\overline{u}+\overline{c}+d+s) \\ xW_3^+ &= x(d+s-\overline{u}-\overline{c}) \end{aligned}$$

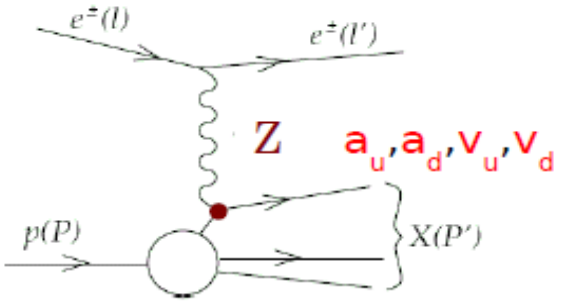
- e^- and e^+ sensitive to different quark densities
- Linear dependence on polarisation
- In the SM weak interactions only between left-handed particles and right-handed anti-particles



Electroweak Fits - Introduction

More on fits (and structure functions) in E.Rizvi's talk

- Combined fit of electroweak quark couplings a_u, v_u, a_d, v_d and PDFs ⇒QCD-EW fit using DIS cross sections
- γZ interference terms and Z exchange in NC cross sections depend on weak couplings



$$[F_2^\gamma, F_2^{\gamma Z}, F_2^Z] = \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2] x(q + \bar{q})$$

$$[xF_3^{\gamma Z}, xF_3^Z] = \sum_q [e_q a_q, v_q a_q] x(q - \bar{q})$$

dominant — relevant at high Q^2 — polarisation of e

$$F_2^\pm = F_2^\gamma - (v_e \mp P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \mp 2 P_e v_e a_e)\chi_Z^2 F_2^Z$$

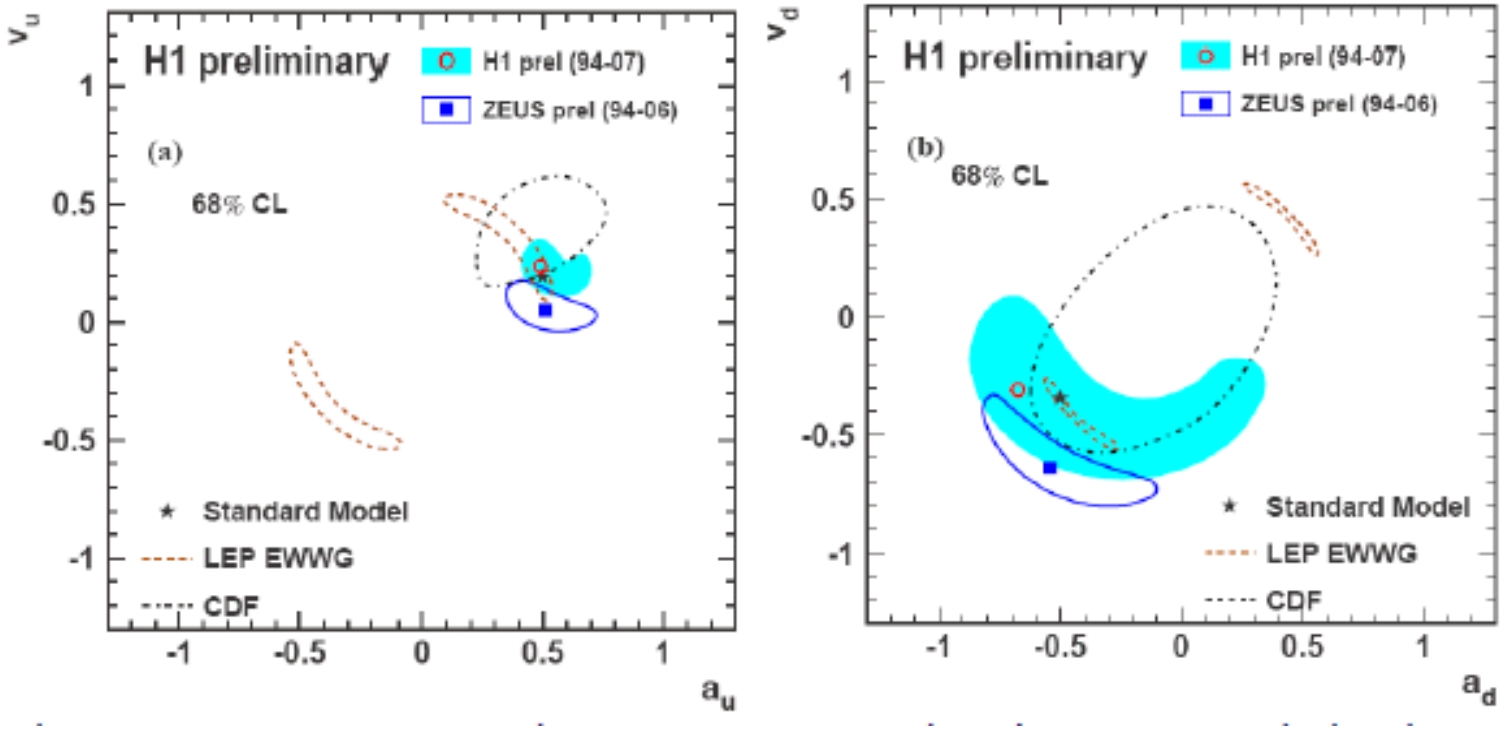
$$xF_3^\pm = -(a_e \mp P_e v_e)\chi_Z xF_3^{\gamma Z} + (\mp P_e(v_e^2 + a_e^2) + 2 v_e a_e)\chi_Z^2 xF_3^Z$$

axial vector coupling of e to Z^0 — relevant at high Q^2 — vector coupling of e to Z^0

v_e very small: terms can be neglected

Electroweak Fits - Results

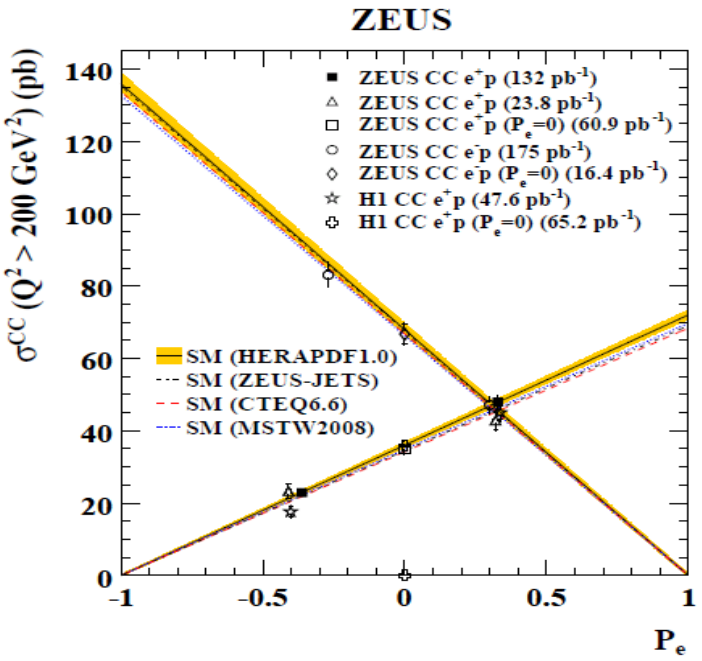
H1prelim-10-042

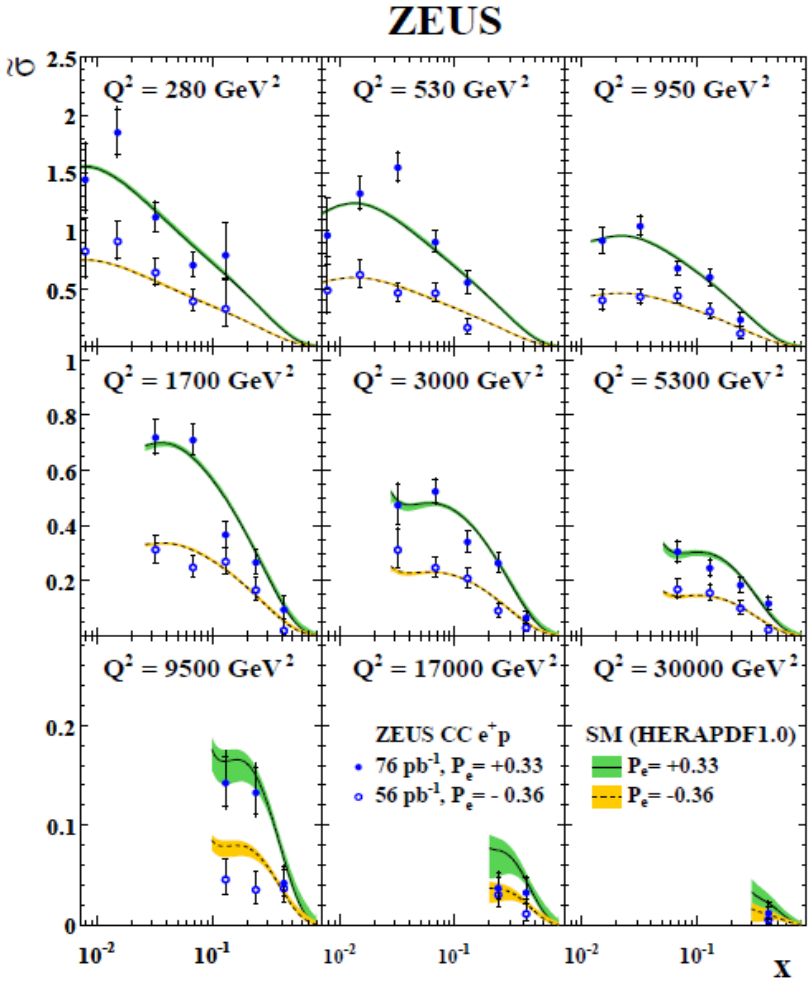


- Consistent with Standard Model, χ^2/dof=0.96
- Much improvement with HERA-II due to polarisation (and statistics)
- Able to resolve ambiguity of e^+e^-
- Results competitive with LEP and CDF results

New CC Results

More on high Q^2 results in T.H.Tran's talk





- ZEUS: Final results on polarised e^+p CC data (132 pb^{-1})
- Results in agreement with SM
- Able to constrain PDFs
- From cross section limit at P_e=-1:
  M_{WR}>198 GeV at 95% CL

EPJ C70, (2010) 965-982

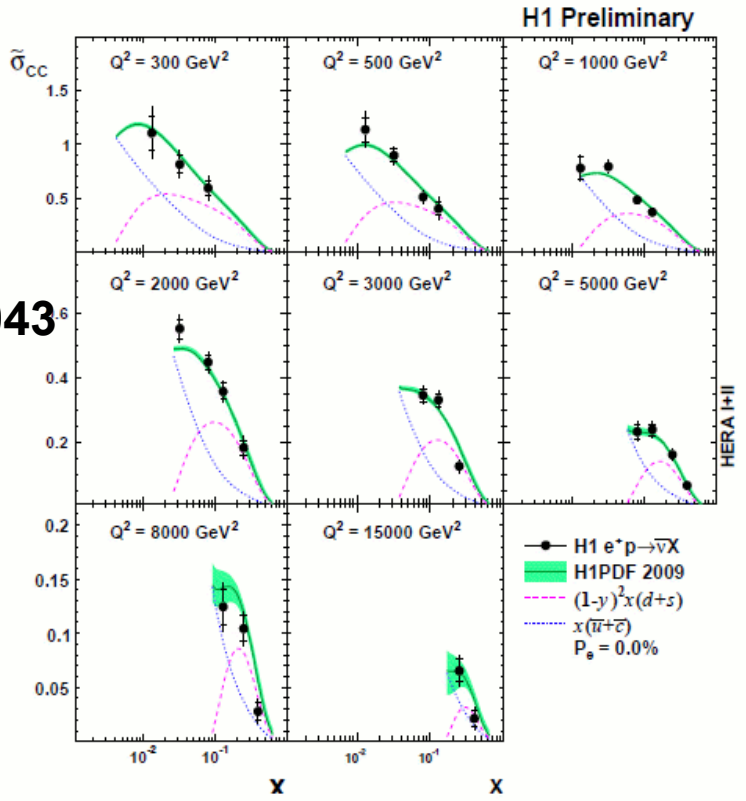
New CC Results

e^+p

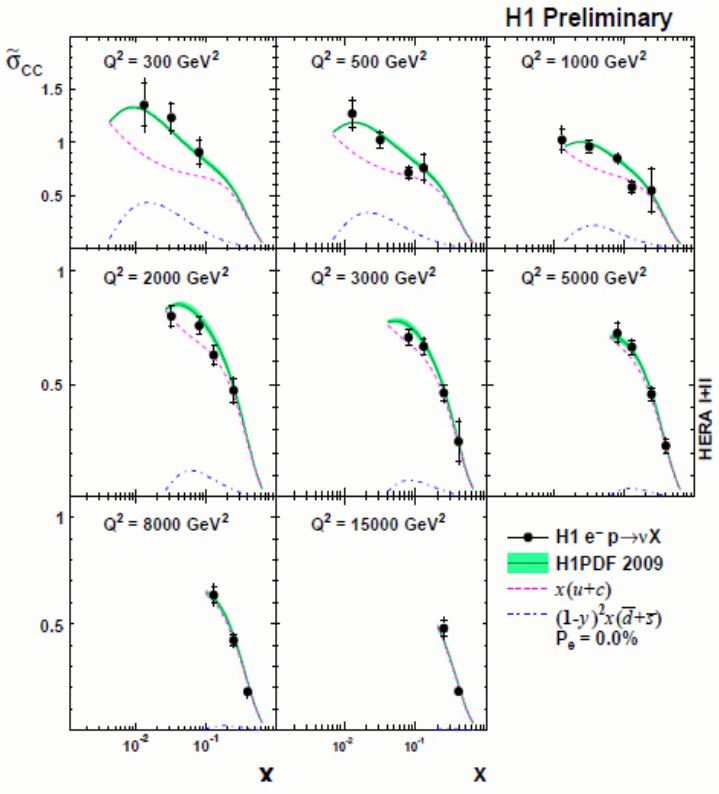
e^-p

H1prelim-09-043

$$\tilde{\sigma}_{cc}^{e^+p} \sim \bar{u} + \bar{c} + (1-y)^2(d+s)$$



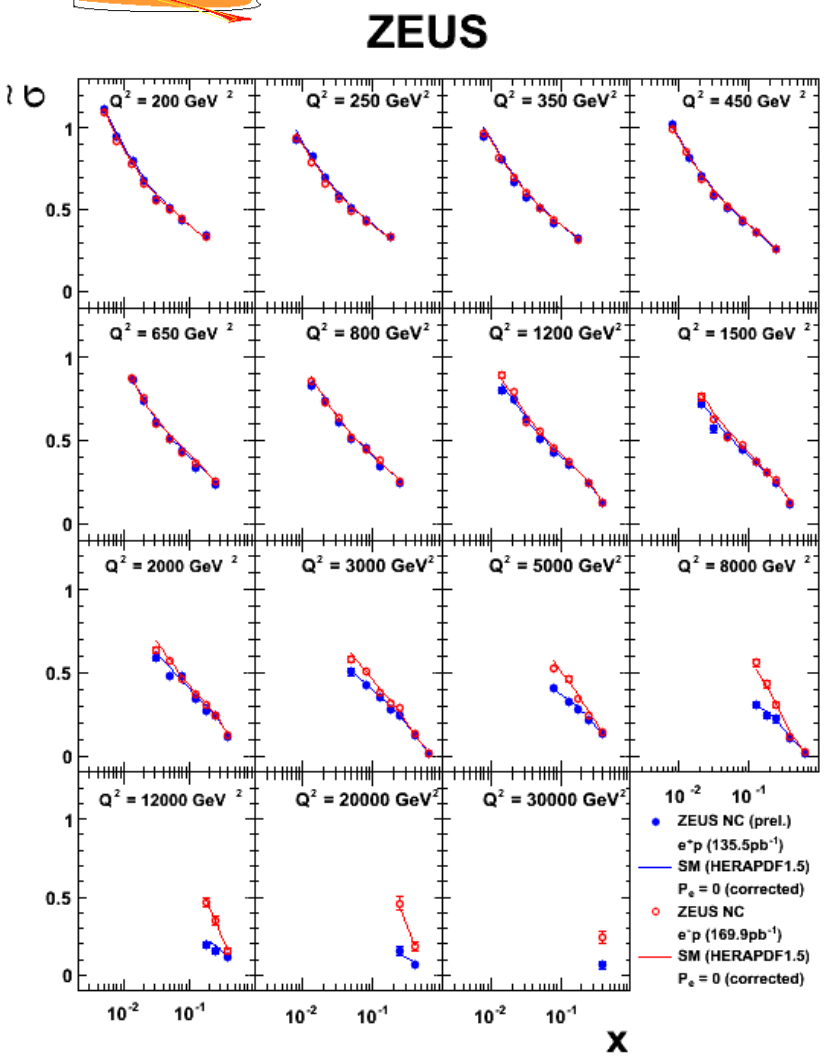
$$\tilde{\sigma}_{cc}^{e^-p} \sim u + c + (1-y)^2(\bar{d}+\bar{s})$$



- H1: New preliminary of whole HERA data set – about 450 pb^{-1}
- Shown here: flavour dependence
- Good agreement with SM

New NC Results – High Q^2

Comparison of e^+p and e^-p

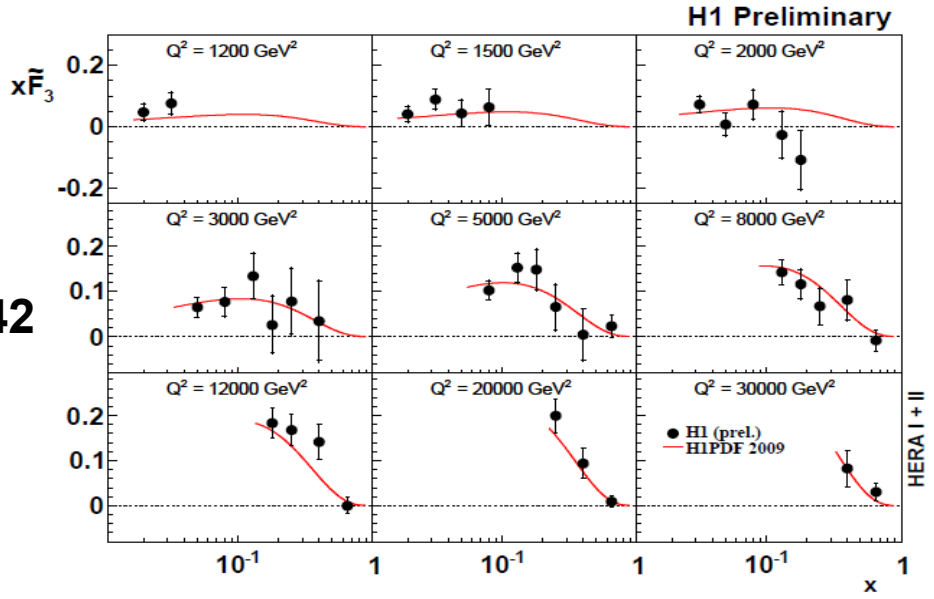


- New preliminary results from H1 and ZEUS:
  - H1: complete HERA data (about 450 pb^{-1})
  - ZEUS: 06/07 e^+p data (about 135 pb^{-1}), last unpublished data set
- Results in good agreement with Standard Model, important input to PDF fits

ZEUS-prel-11-003

New NC Results – High Q^2
F_3 Extraction

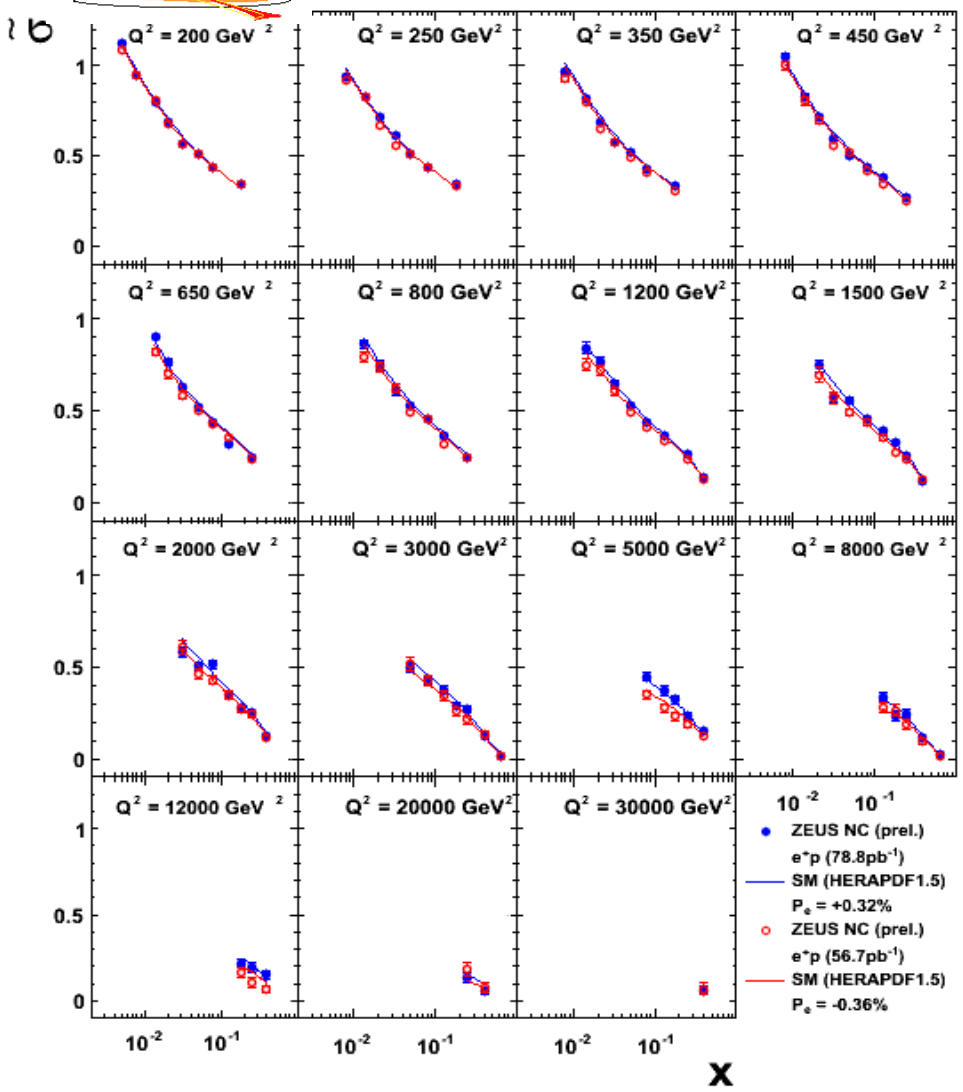
H1prelim-09-042



- The difference of the e^-p and the e^+p cross section gives F_3
- Very precise measurement in agreement with SM

$$\tilde{\sigma}^{e^\pm p} = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma_{NC}^{e^\pm p}}{dxdQ^2} = \tilde{F}_2(x,Q^2) \mp \frac{Y_-}{Y_+} x\tilde{F}_3(x,Q^2) - \frac{y^2}{Y_+}\tilde{F}_L(x,Q^2)$$

New NC Results – High Q^2
Polarisation Dependence



- 78.8 pb^{-1} RH data (P_e=+0.32), 56.7 pb^{-1} LH data (P_e=-0.36)
- At high Q^2 polarisation dependence clearly visible and in agreement with Standard Model

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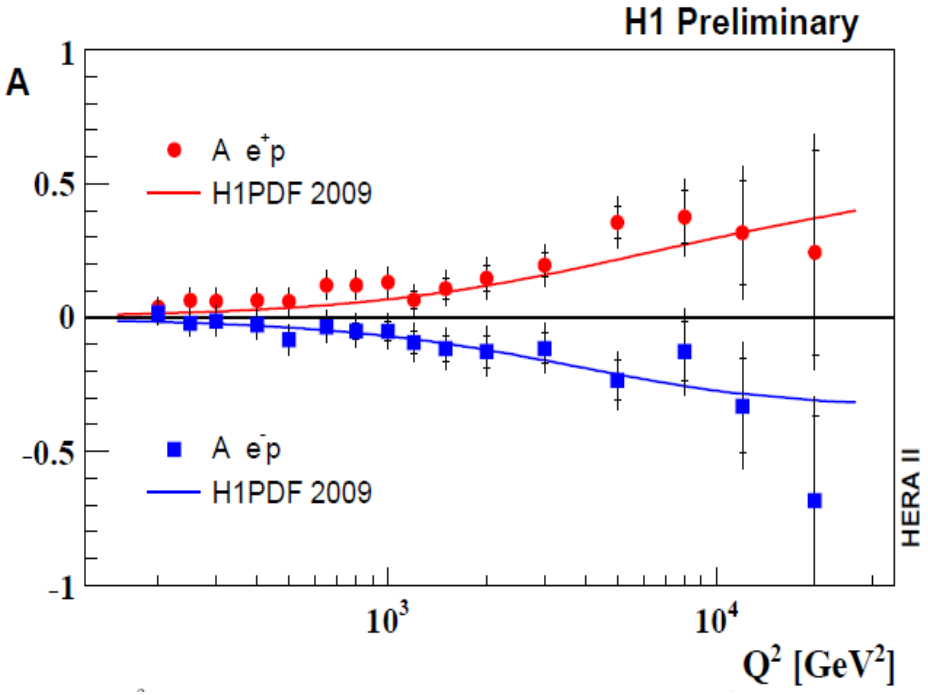
New NC Results – High Q^2
Asymmetry



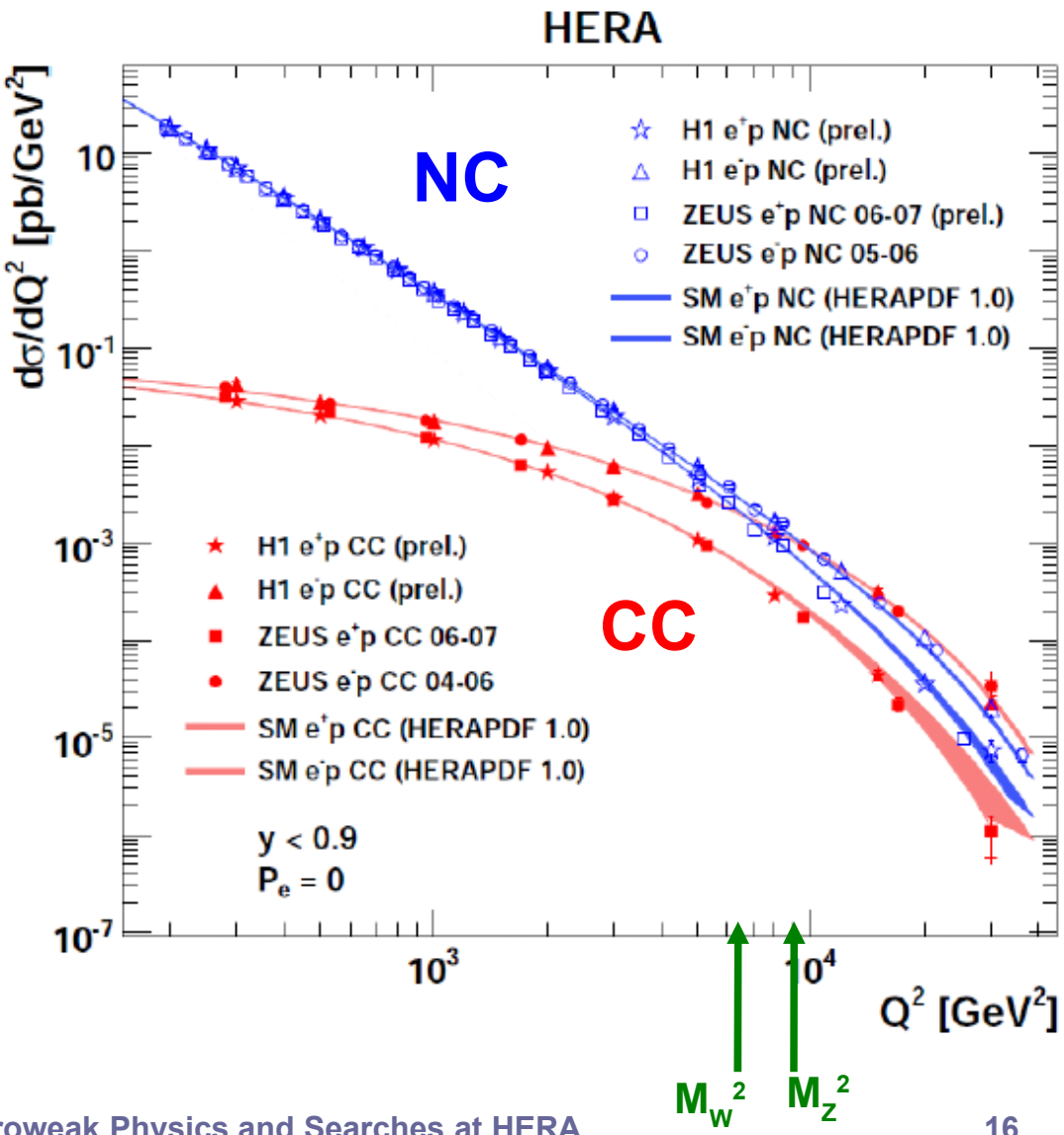
H1prelim-09-042

- Through the polarisation asymmetry parity violation was directly measured
- Behaviour in agreement with Standard Model

$$A^{\pm} = \frac{2}{P_e^+ - P_e^-} \frac{\sigma^{\pm}(P_e^+) - \sigma^{\pm}(P_e^-)}{\sigma^{\pm}(P_e^+) + \sigma^{\pm}(P_e^-)} \approx \mp \chi_Z a_e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \sim \mp a_e v_q$$

Electroweak Unification

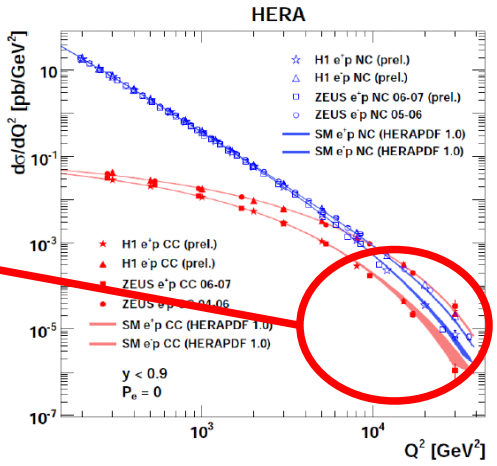
- Electroweak unification at the $M_{W/Z}$ scale
- SM provides good description of data over many orders of magnitude
- High Q^2 region especially interesting for BSM scenarios



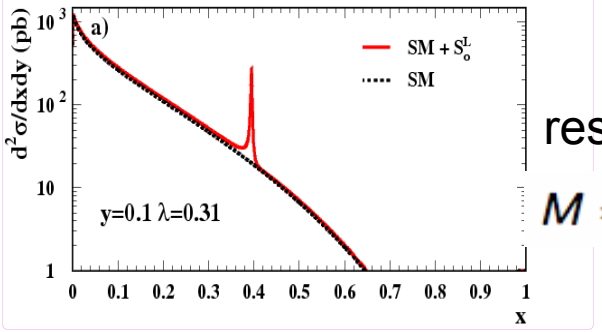
More details on searches in J.Maeda's talk

Searches at HERA

- Searches in inclusive DIS
  - NC: Contact Interactions, quark radius, Extra Dimensions
  - CC: Polarisation dependence

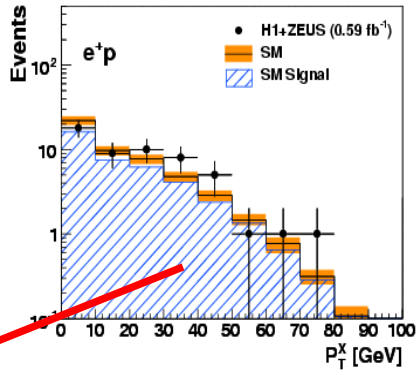


- Model based searches
  - Quark radius
  - Contact Interactions
  - Leptoquarks and LFV
  - Squark production in RPV SUSY



resonance:

$$M = \sqrt{xs}$$



- Model independent searches
  - Isolated leptons and missing p_T
  - Multi-leptons

Quark Radius

- Spatial distribution of the quark charge would reduce the SM cross section at high momentum transfer Q^2

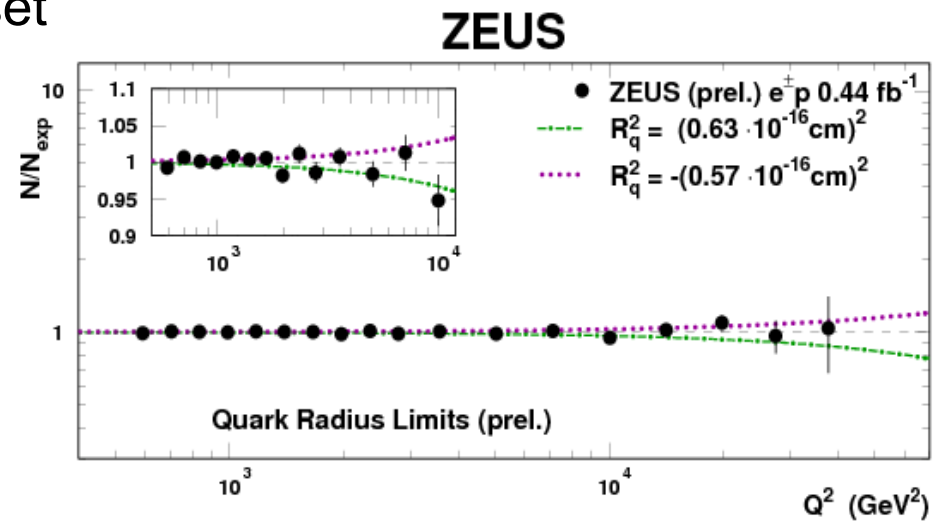
$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot \left[1 - \frac{R_q^2}{6} Q^2\right]^2$$

R_q: root-mean-square radius of the electroweak charge distribution in the quark

- Good agreement with SM expectation → limits (95% CL) set using full HERA data (H1 and ZEUS 440 pb^{-1} each) assuming electron as point-like

H1: $R_q < 0.65 \cdot 10^{-18}$ m

ZEUS: $R_q < 0.63 \cdot 10^{-18}$ m

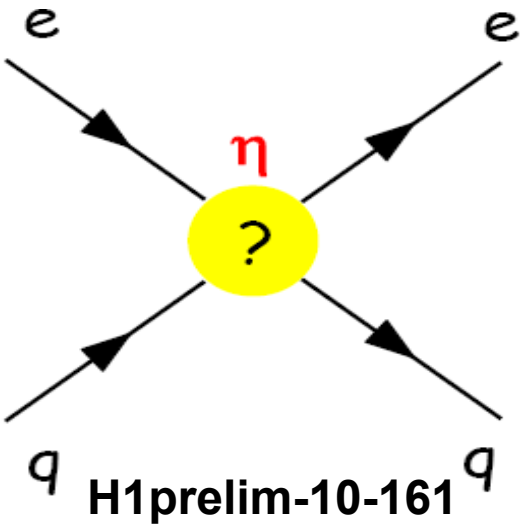


Limit below 1/1000 of proton radius

ZEUS-prel-09-013

Contact Interactions

HERA



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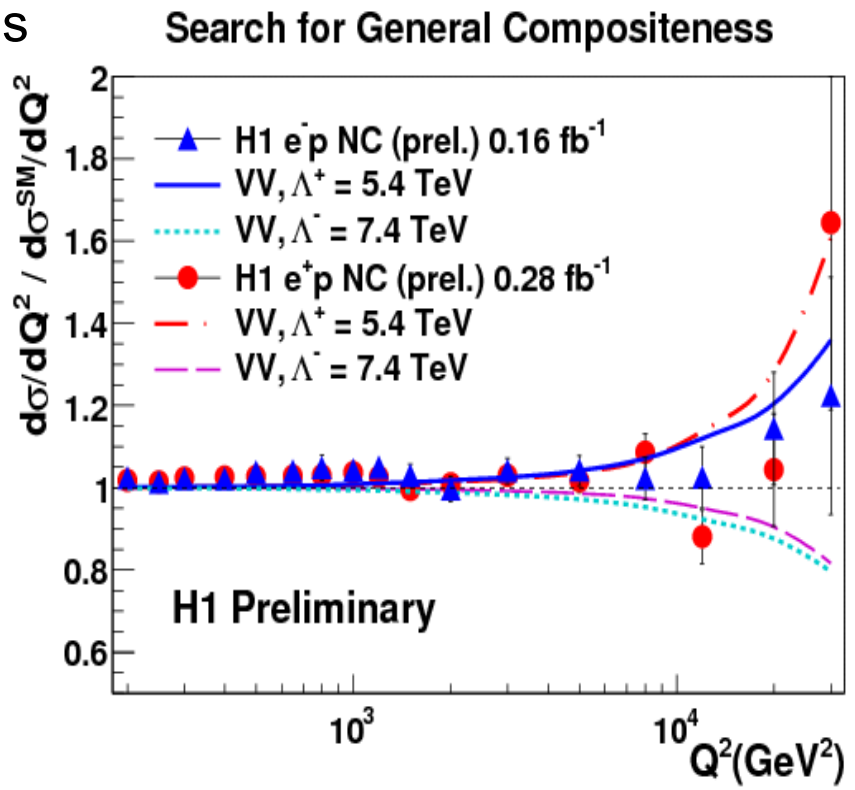
- Model describing low energy effects from physics at much higher energy scales

$$\Lambda \gg \sqrt{s}$$

- Modifications of high Q^2 cross sections via virtual effects
  - General models: $\eta_{ab}^{q} = \pm \frac{4\pi}{\Lambda^2}$
- No deviations from SM seen by H1 and ZEUS → limits set on 19 models with different helicity structure:

H1: Λ > 3.7 – 7.4 TeV

ZEUS: Λ > 3.8 – 8.9 TeV



Large Extra Dimensions

- ADD (Arkani-Hamed, Dimopoulos, Dvali) model: space time is *4+n* dimensional
- Gravity can propagate into the extra dimensions
- Effective mass scale M_S can be ~ 1TeV
- Virtual graviton exchange contribution to $eq \rightarrow eq$ scattering described by contact interaction with effective coupling

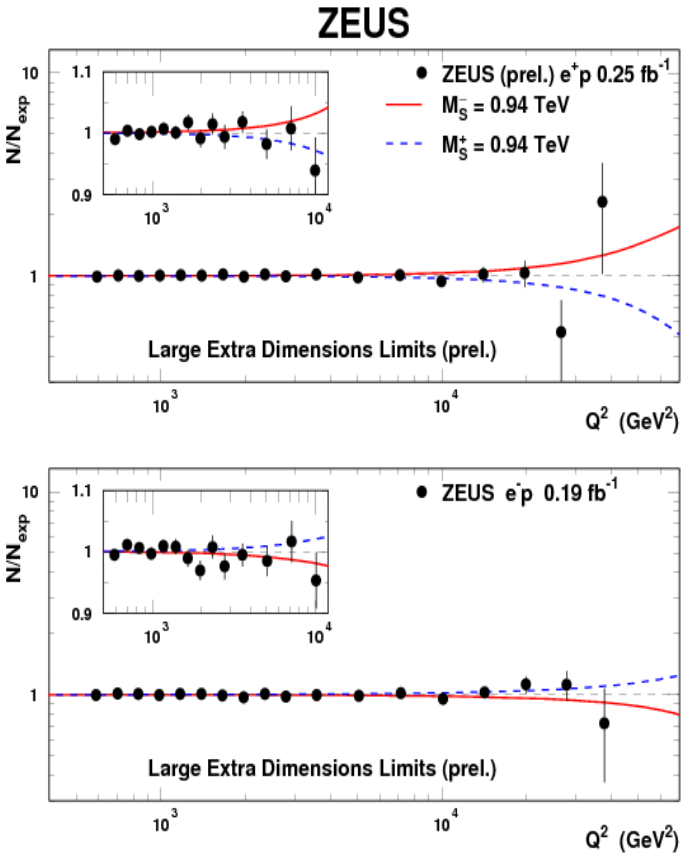
$$\eta_G = \frac{\lambda}{M_S^4}$$

- Limits set by H1 and ZEUS (95% CL):

$$\text{H1}: M_S^+ > 0.90\,\text{TeV},\ M_S^- > 0.91\,\text{TeV}$$

$$\text{ZEUS}: M_S^+,\ M_S^- > 0.94\,\text{TeV}$$

ZEUS-prel-09-013



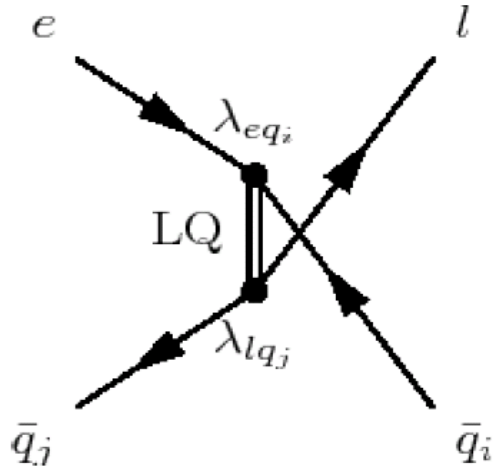
independent of *n*

$\lambda = \pm 1$

Heavy Leptoquarks

- Scalar or vector bosons carrying both lepton and baryon number
- Buchmüller-Rückl-Wyler model: SM symmetry, lepton and baryon number conserved

→ 7 scalar and 7 vector 1st generation LQs, same final states as NC/CC DIS



- Heavy LQ exchange can be described by a contact interaction with effective coupling

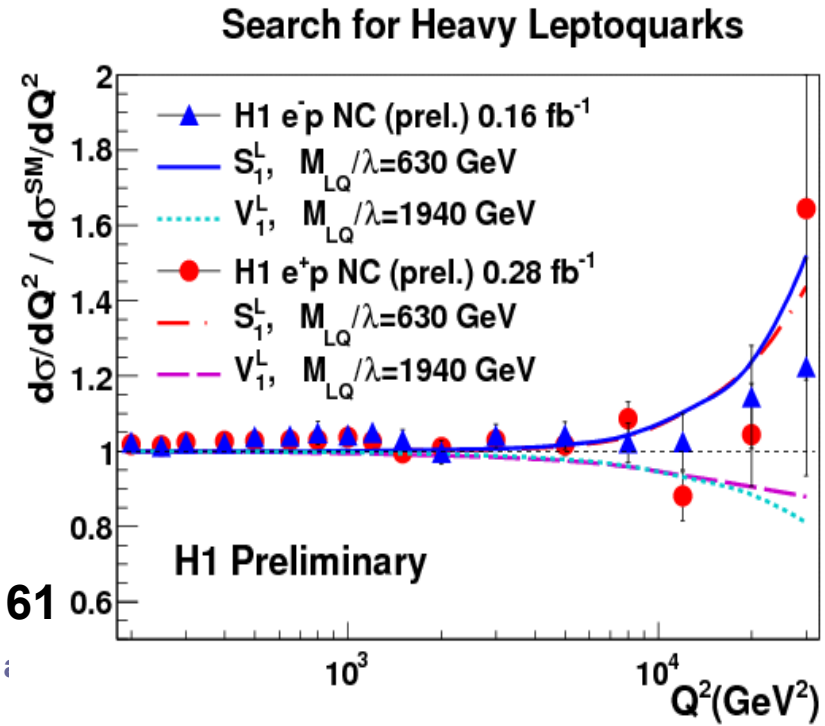
$$\eta \sim \frac{\lambda^2}{M_{LQ}^2}$$

- Limits set by H1 and ZEUS (95% CL):

H1: $M_{LQ}/\lambda > 0.4$ - 1.94 TeV

ZEUS: $M_{LQ}/\lambda > 0.41$ - 1.88 TeV

depending on the LQ type



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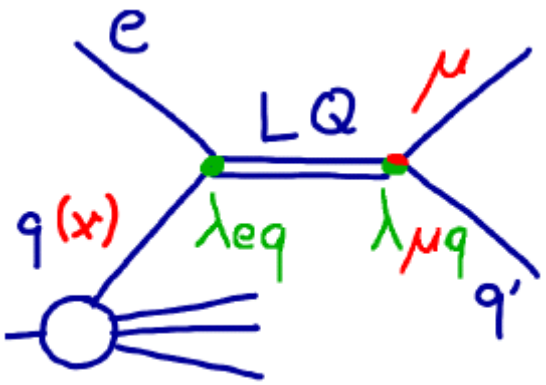
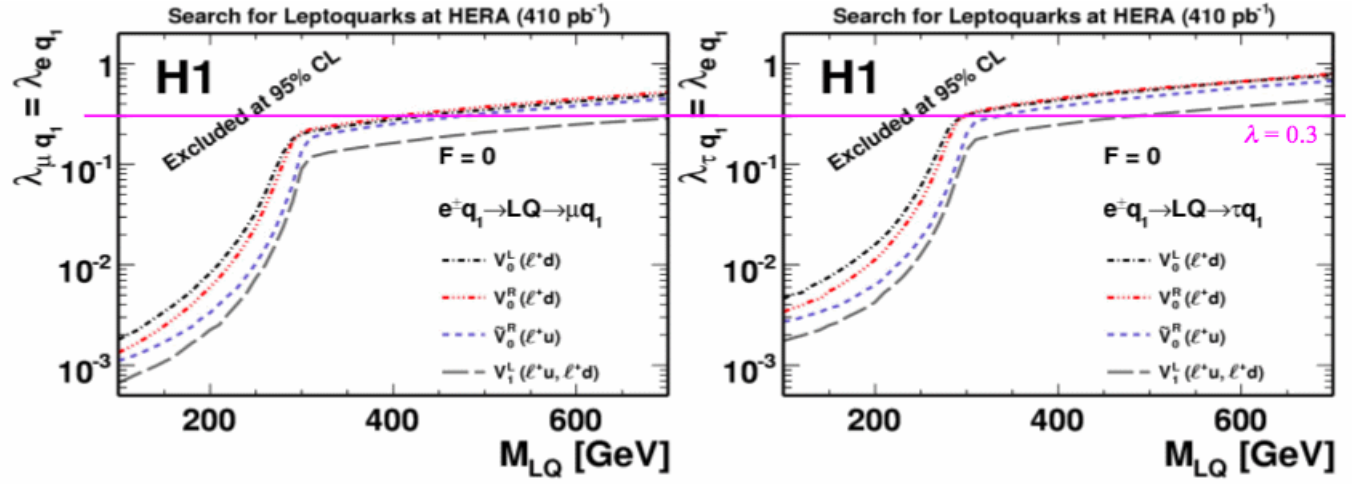
Lepton Flavour Violation

- If LQ couplings not assumed as flavour diagonal, LQs can mediate LFV:

$$ep \to LQ \to \mu X \quad ep \to LQ \to \tau X$$



- H1 used full HERA data to look for final states with μ or τ and at least one jet
- No deviations from SM → limits set on λ as a function of the LQ mass



DESY 11-044
(submitted to Phys.Lett.B 03/11)

$\lambda_{eq} = \lambda_{\mu q} = \sqrt{4\pi\alpha} = 0.3$ and $\lambda_{\tau q} = 0$:
up to M_{LQ} < 712 GeV excluded, for V_1^L

$\lambda_{eq} = \lambda_{\tau q} = \sqrt{4\pi\alpha} = 0.3$ and $\lambda_{\mu q} = 0$:
up to M_{LQ} < 479 GeV excluded, for V_1^L

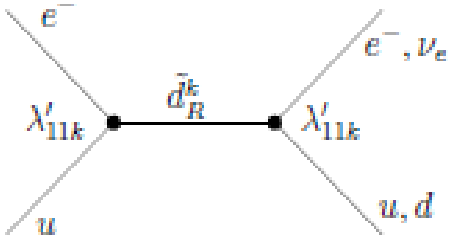
Squark Production in RPV SUSY

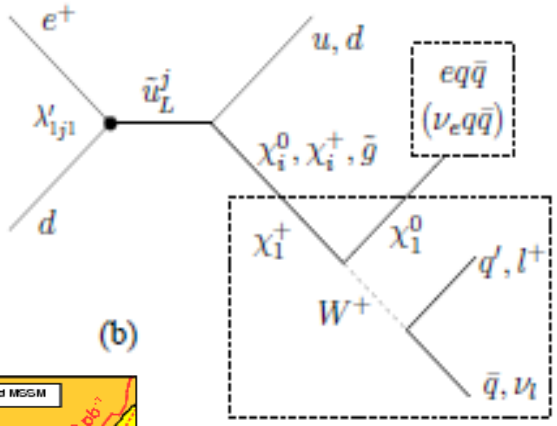
- *R*-parity: $R_p = (-1)^{L+3B+2S}$
- SM particles: +1
- SUSY particles: -1

- In RPV SUSY single resonant squark production possible in *ep* collisions
- Squarks decay to l+q (DIS-like final states) or to quark and gaugino (→ cascade decays)
- No deviations from SM in any of the 17 relevant final states seen → limits set
- Limits set using full H1 data (parameter scan):
- MSSM

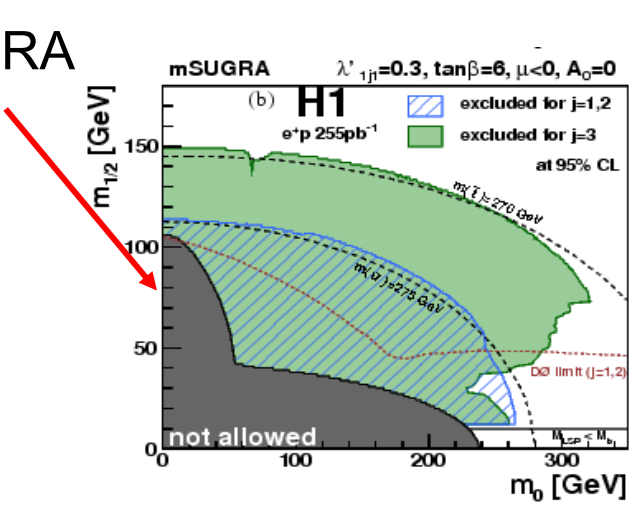
$$M(\tilde{u_L}, \tilde{c_L}, \tilde{t_L}) > 275 \text{ GeV for } \lambda'_{1j1} = \sqrt{4\pi\alpha} = 0.3$$

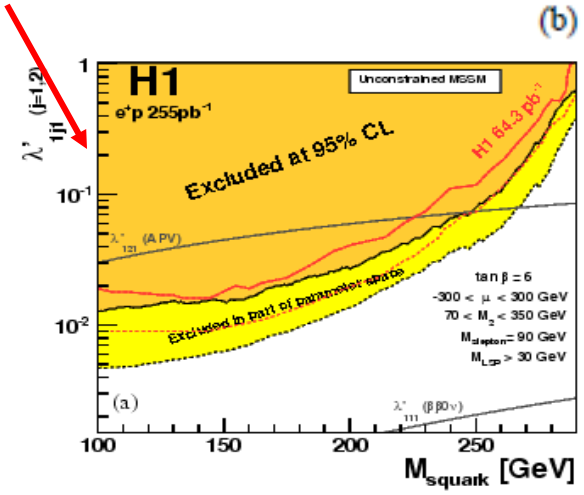
$$M(\tilde{d_R}, \tilde{s_R}, \tilde{b_R}) > 290 \text{ GeV for } \lambda'_{11k} = 0.3$$





- MSUGRA





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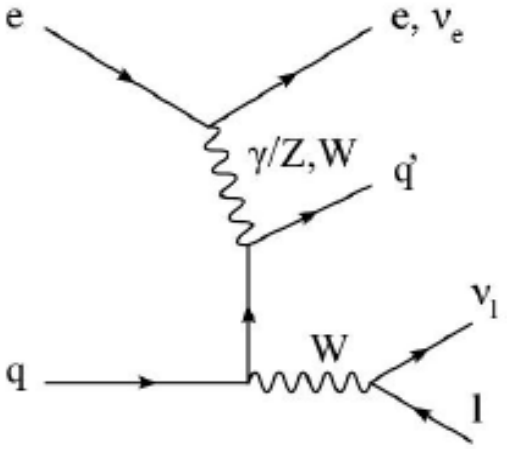
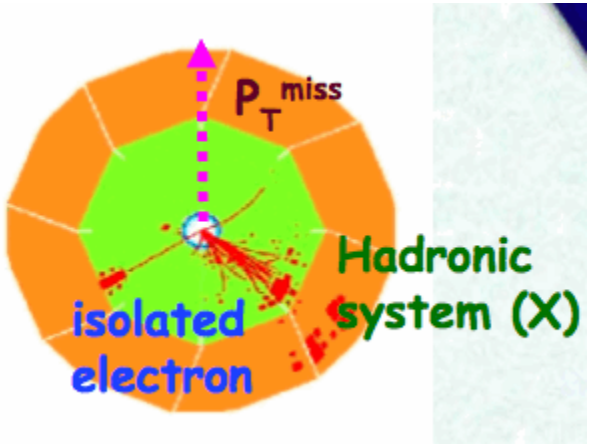
Isolated Leptons and Missing p_T

- Small SM cross section: main SM process producing isolated leptons and missing p_T is single W production (σ~1 pb) with the W decaying in lepton + neutrino
- Possible new physics scenarios are e.g. single top production, stop decay
- Now final results from HERA: combination of all H1 and ZEUS data, i.e. 1 fb^{-1}





Isolated Leptons and Missing p_T

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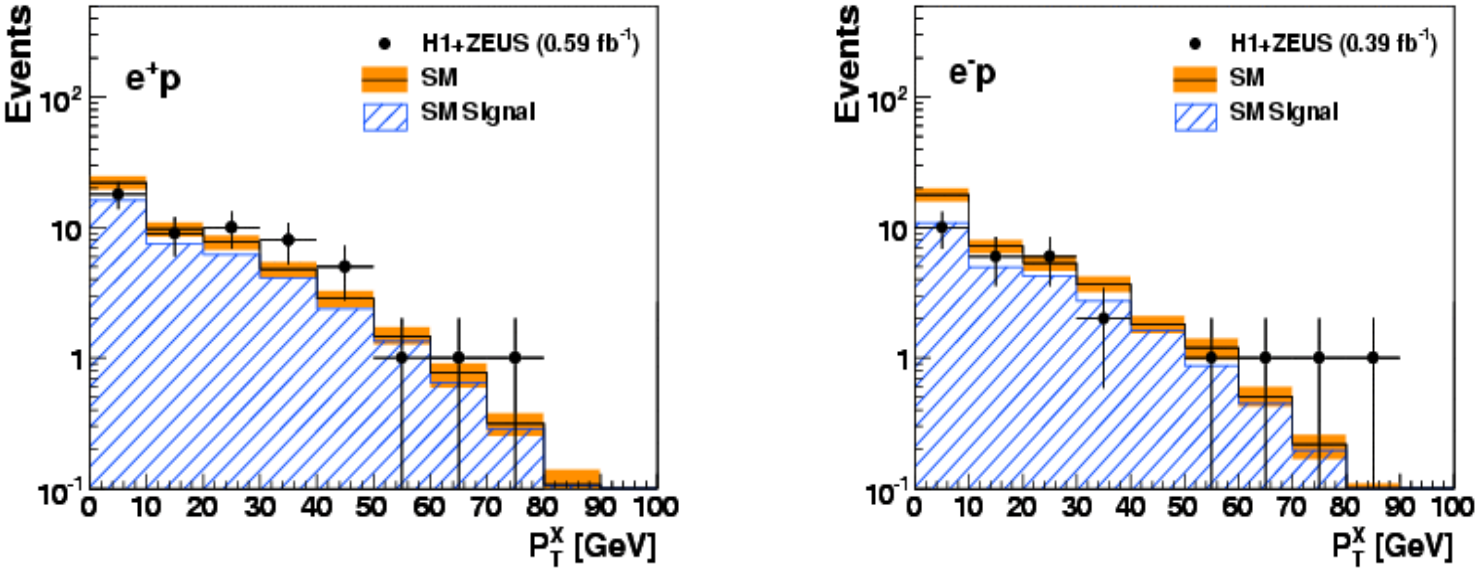
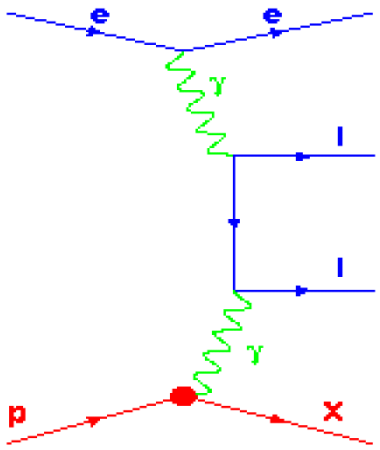


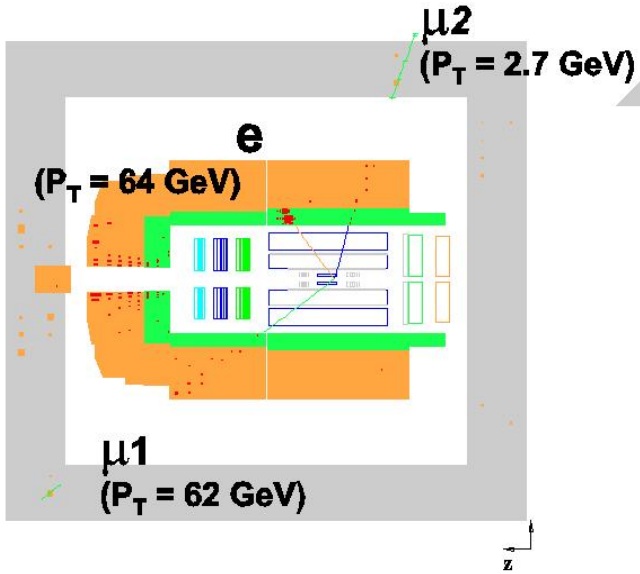
- Overall good agreement with SM
- e^+p data, $p_T^X > 25$ GeV: 23 events observed, 14.0±1.9 expected
- No excess in e^-p data
- Single W boson production cross section measured:

1.06±0.16(stat.)±0.07(syst.) pb (SM expectation: 1.26±0.19 pb)

Multi-Leptons with High p_T

- The main SM process producing multi-leptons is γ-γ interactions
- SM expectation is very small at high lepton p_T, but very precisely calculable⇒perfect to look for BSM deviations (e.g. $H^{\pm\pm}$)
- Here as well final results from HERA: combination of all H1 and ZEUS data, i.e. 1 fb^{-1}
- Topologies: **ee, eee, eμ, μμ, eμμ**





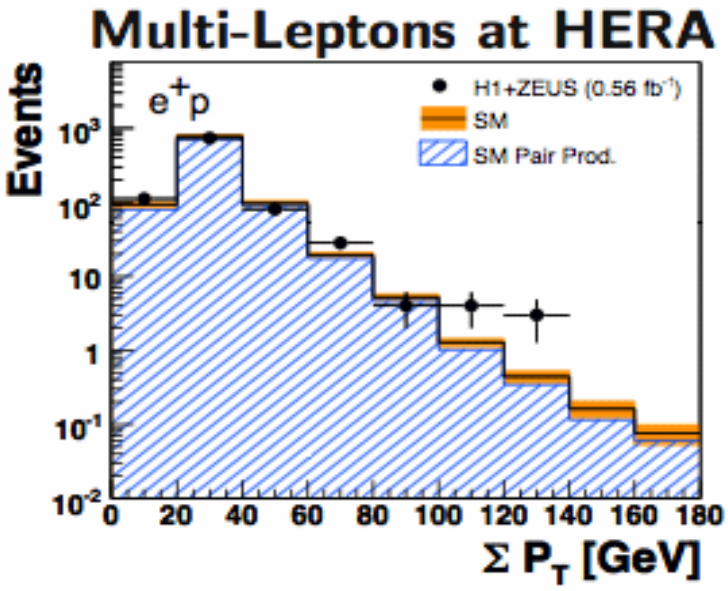
Multi-Leptons with High p_T

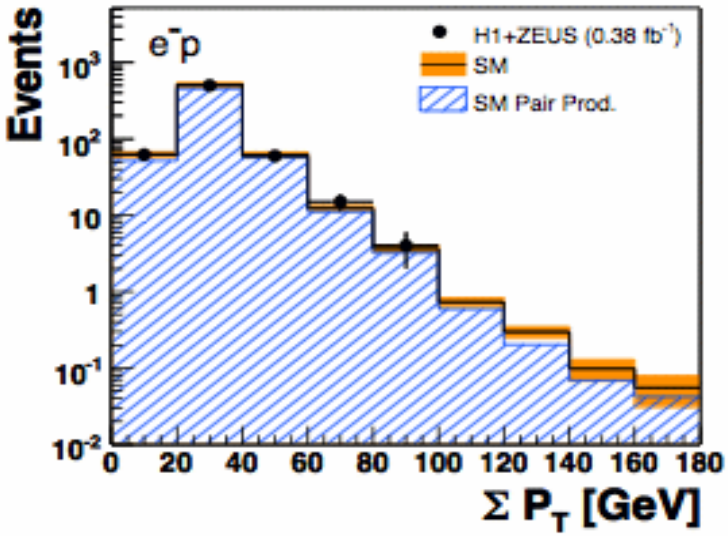
- Overall good agreement with SM
- e^+p data, $\Sigma p_T > 100$ GeV:

7 events observed,
1.94±0.17 expected

- No excess in e^-p data
- Lepton pair production cross section measured in photoproduction regime:

0.66±0.03(stat.)±0.03(syst.) pb
(SM expectation: 0.69±0.02 pb)





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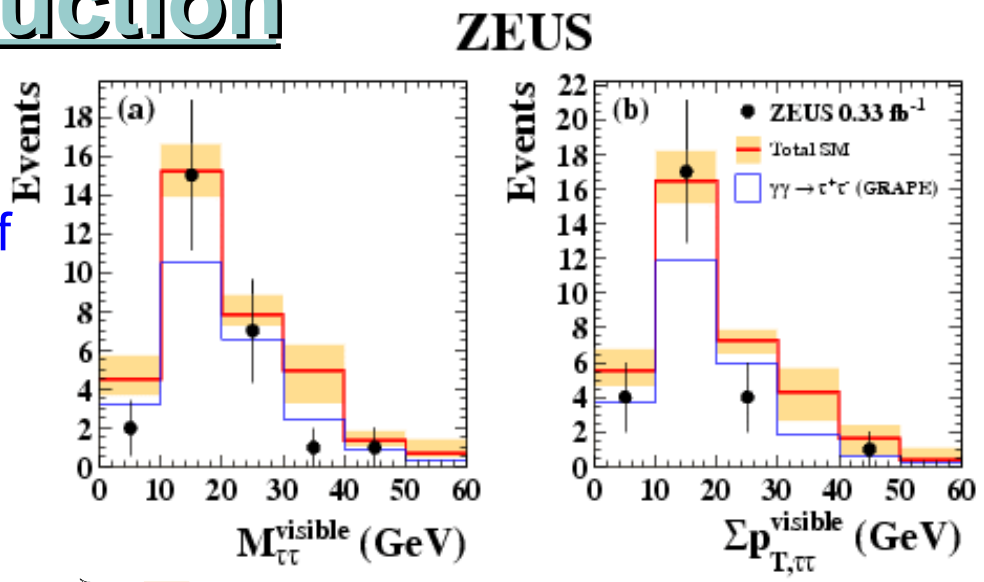
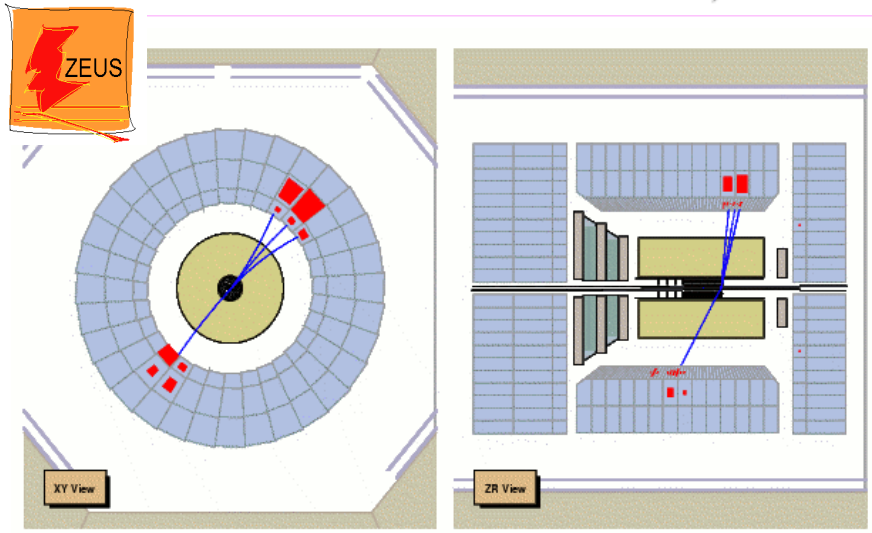
Tau-pair Production

- ZEUS measured production of two τ-leptons with high transverse momentum in HERA-II data (0.33 fb^{-1})
- Identification from decays in electrons, muons and hadronic jets (discriminant method)
- No deviations from SM found
- Cross section measured:
  $3.3 \pm 1.3(\text{stat.})^{+1.0}_{-0.7}(\text{syst.})$ pb
  (SM expectation: 5.67±0.16 pb)





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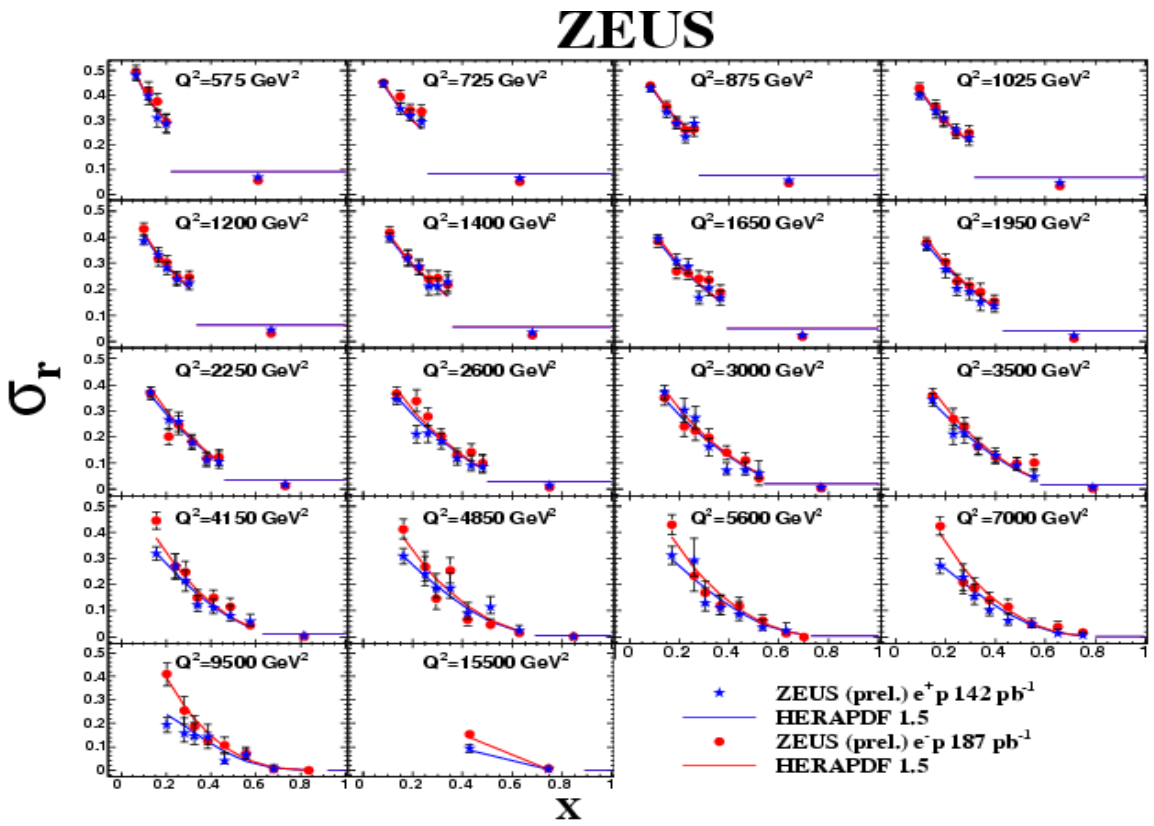
Summary

- Many HERA results now with the full statistics (0.5 fb^{-1} per experiment) ⇒ very precise measurements also at high Q^2
- New results on
  - **NC at high Q^2**
  - **CC at high Q^2**
  - **Fits of electroweak couplings and PDFs**
- Several possible BSM scenarios were investigated
- No evidence for new physics found ⇒ competitive limits set on
  - **Contact Interactions**
  - **Leptoquarks and Lepton Flavour Violation**
  - **Squarks in R-parity violating SUSY**
  - **Isolated leptons (combined H1 and ZEUS)**
  - **Multi-leptons (combined + tau-pairs)**

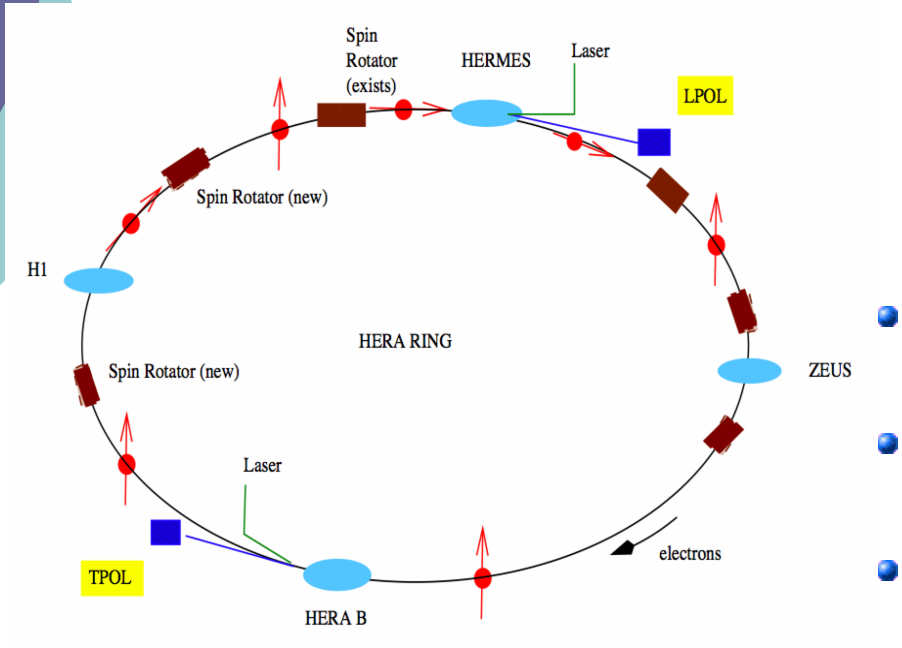
Backup

New NC results – High x



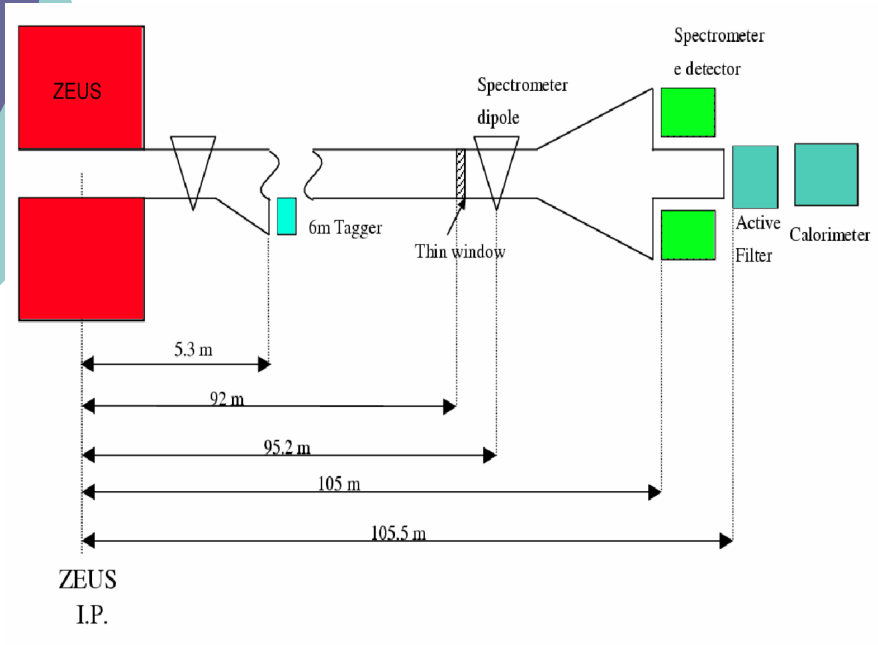
- Motivation: not so many precise constraints on PDFs at high x
- New x determination method using hadronic system information
- When no jet is found, cross section is integrated
- Results for HERA-II e^-p and e^+p data

Polarisation



- Transverse polarisation through Sokolov-Ternov effect (self-polarisation of relativistic electrons in a magnetic field, spin flip by synchrotron radiation emission)
- Spin is rotated to provide longitudinal polarisation
- Polarisation at HERA was typically 30-40%
- Monitored by Compton backscattering of laser beams

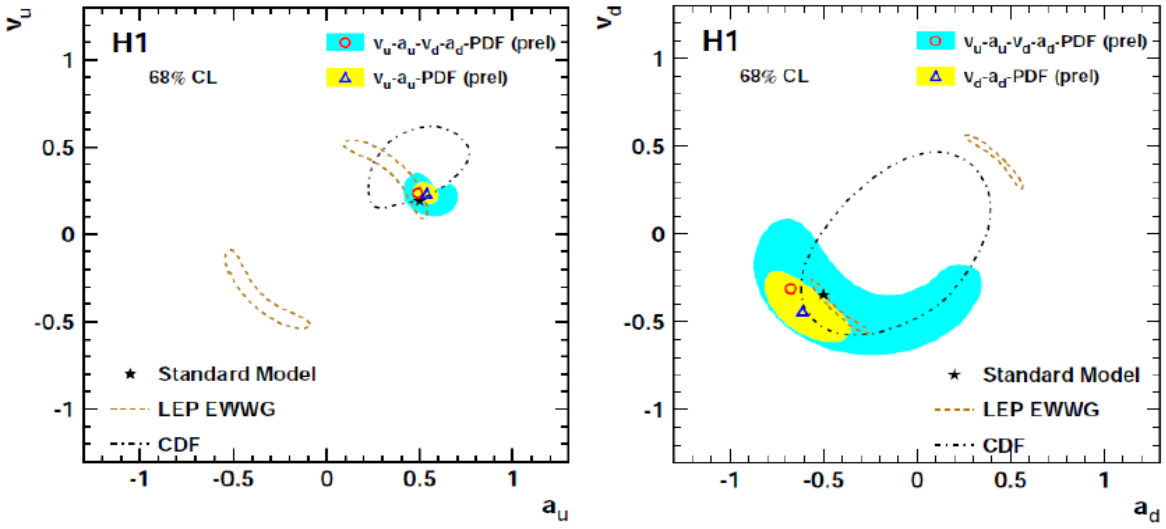
Luminosity



ZEUS HERA-II Luminosity System

- Lumi determination based on Bethe-Heitler process ep->epγ
- Bethe-Heitler cross section known very precisely (0.5% uncertainty)
- Signature: small angle electron and photon outside main detector acceptance region
- Precision of about 2% reached

Electroweak Fits – More results

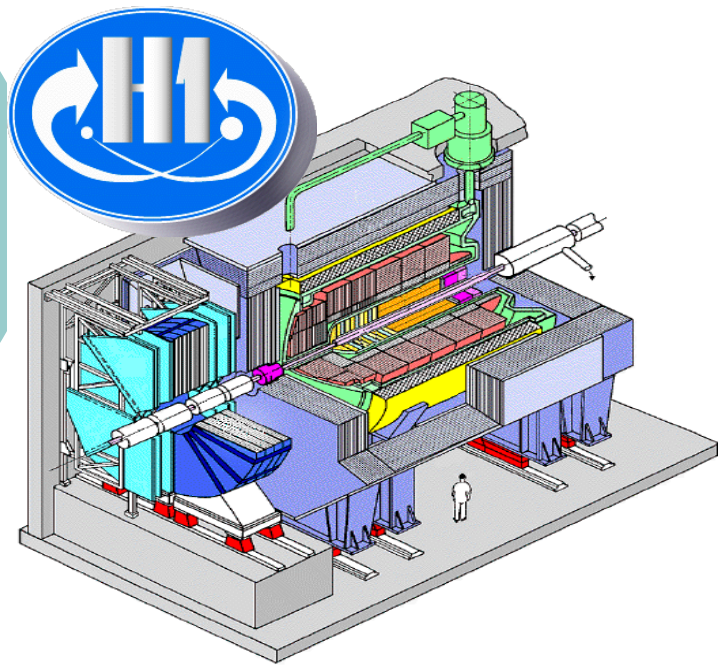


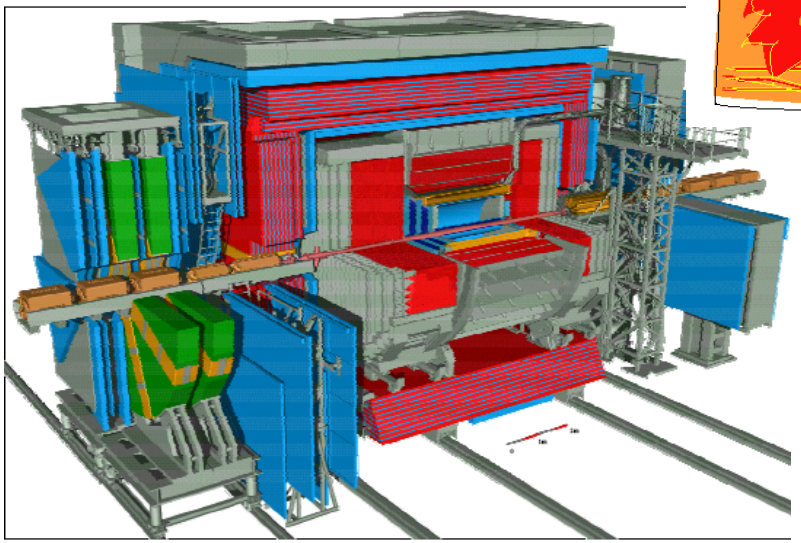
Fits also done with fixing couplings of one quark flavor

⇒ Even better and very competitive precision

Fit	v_u-a_u-v_d-a_d-PDF	v_u-a_u-PDF	v_d-a_d-PDF	SM
a_u	$0.49 \pm 0.06 \pm 0.04$	0.53 ± 0.04	–	0.5
v_u	$0.23 \pm 0.08 \pm 0.02$	0.23 ± 0.04	–	0.191
a_d	$-0.67 \pm 0.19 \pm 0.07$	–	-0.61 ± 0.15	-0.5
v_d	$-0.31 \pm 0.27 \pm 0.06$	–	-0.44 ± 0.13	-0.346
χ^2/dof	1183.8/1230	1184.5/1232	1184.2/1232	–

H1 and ZEUS: Hermetic multi-purpose detectors





Liquid Argon Calorimeter

optimized for precision measurement of the scattered lepton

$\sigma_E/E = 12\%/\sqrt{E}$ (electron)

$\sigma_E/E = 50\%/\sqrt{E}$ (hadron)

Uranium-scintillator Calorimeter

optimized for precision measurement of the hadronic final state

$\sigma_E/E = 18\%/\sqrt{E}$ (electron)

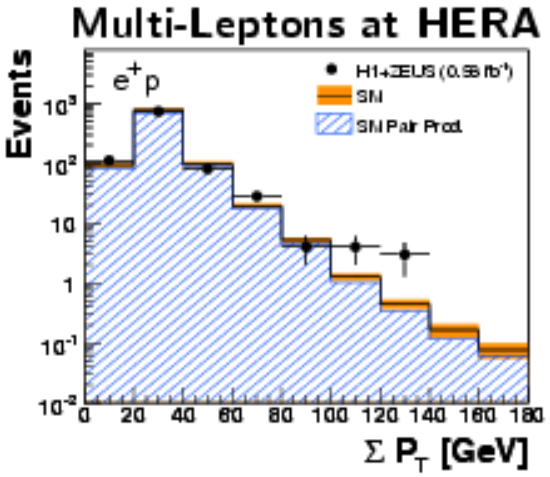
$\sigma_E/E = 35\%/\sqrt{E}$ (hadron)

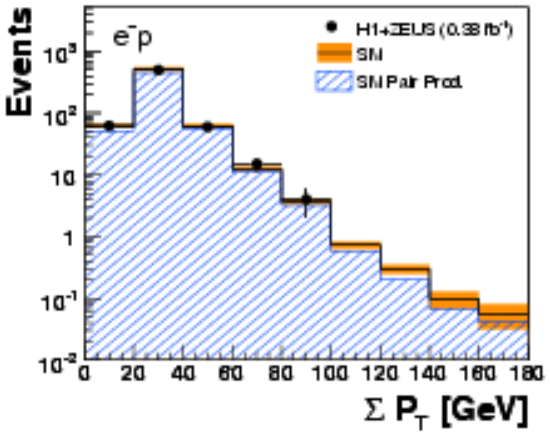
Isolated Leptons and Missing p_T

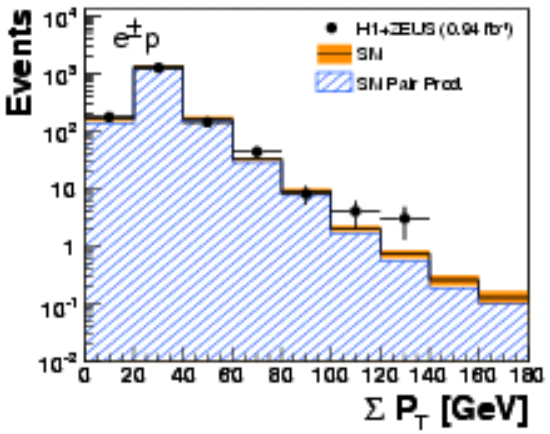
H1+ZEUS 1994–2007 $e^{\pm}p$ 0.98 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	61	69.2 ± 8.2	48.3 ± 7.4	20.9 ± 3.2
	$P_T^X > 25$ GeV	16	13.0 ± 1.7	10.0 ± 1.6	3.1 ± 0.7
Muon	Total	20	18.6 ± 2.7	16.4 ± 2.6	2.2 ± 0.5
	$P_T^X > 25$ GeV	13	11.0 ± 1.6	9.8 ± 1.6	1.2 ± 0.3
Combined	Total	81	87.8 ± 11.0	64.7 ± 9.9	23.1 ± 3.3
	$P_T^X > 25$ GeV	29	24.0 ± 3.2	19.7 ± 3.1	4.3 ± 0.8

Multi-Leptons with High p_T

Multi-Leptons at HERA (0.94 fb^{-1}) $\sum P_T > 100$ GeV				
Data sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
e^+p (0.56 fb^{-1})	7	1.94 ± 0.17	1.52 ± 0.14	0.42 ± 0.07
e^-p (0.38 fb^{-1})	0	1.19 ± 0.12	0.90 ± 0.10	0.29 ± 0.05
All (0.94 fb^{-1})	7	3.13 ± 0.26	2.42 ± 0.21	0.71 ± 0.10



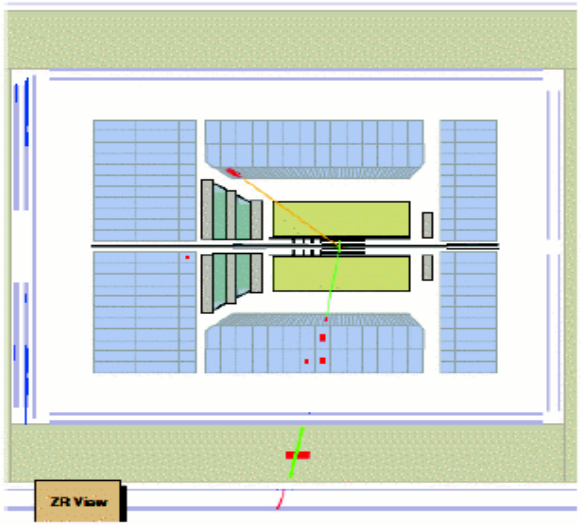


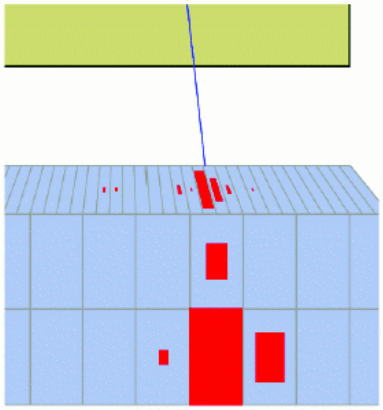


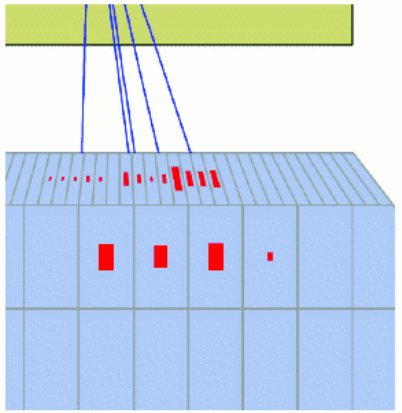
Ditau production

ZEUS ditau events HERA II data (L=0.33 fb^{-1})

Topology	$(e\text{-})e\text{-}\mu$	$(e\text{-})e$-jet	$(e\text{-})\mu$-jet	$(e\text{-})$jet-jet	Total
Data	4	7	4	10	25
Total MC	$3.6^{+1.3}_{-0.3}$	$8.8^{+1.8}_{-0.8}$	$8.0^{+2.2}_{-1.2}$	$14.4^{+2.2}_{-3.5}$	$34.8^{+3.9}_{-3.8}$
$\tau^+\tau^-$ MC	$3.0^{+0.3}_{-0.2}$	$5.3^{+0.3}_{-0.2}$	$5.9^{+0.5}_{-0.5}$	$9.0^{+0.4}_{-0.3}$	$23.2^{+0.7}_{-0.7}$
purity	82 %	60 %	73 %	63 %	67 %





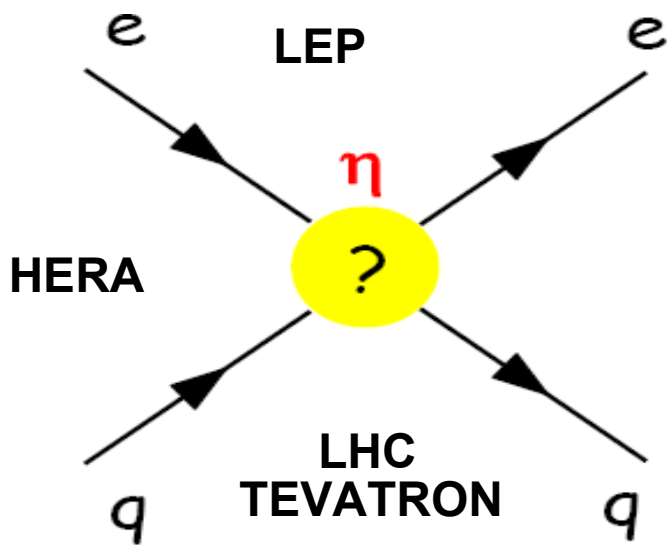


Contact Interactions

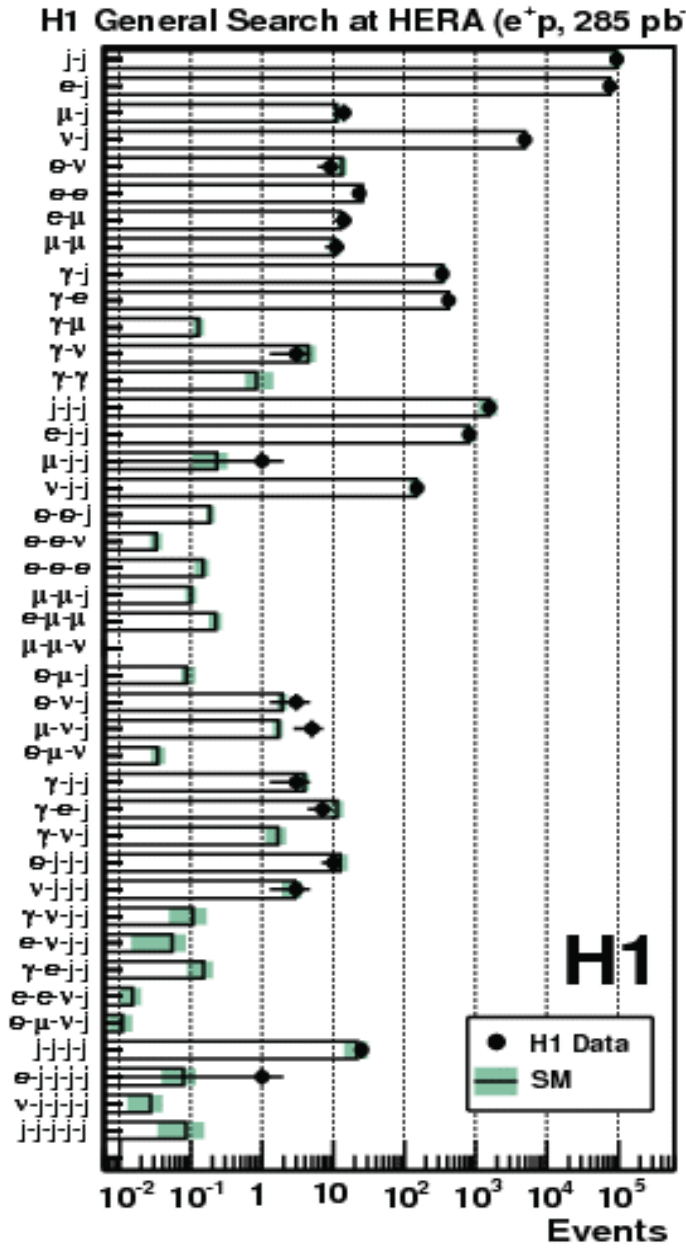
- Vector-type *eeqq* CI: $\mathcal{L}_{CI} = \sum_{a,b=L,R}^{q=u,d} \eta^q_{ab} (\bar{e}_a \gamma_\mu e_a)(\bar{q}_b \gamma^\mu q_b)$

$$\eta^q_{ab} = \pm 4\pi / \Lambda^2$$

$$\Lambda \gg \sqrt{s}$$



General Searches

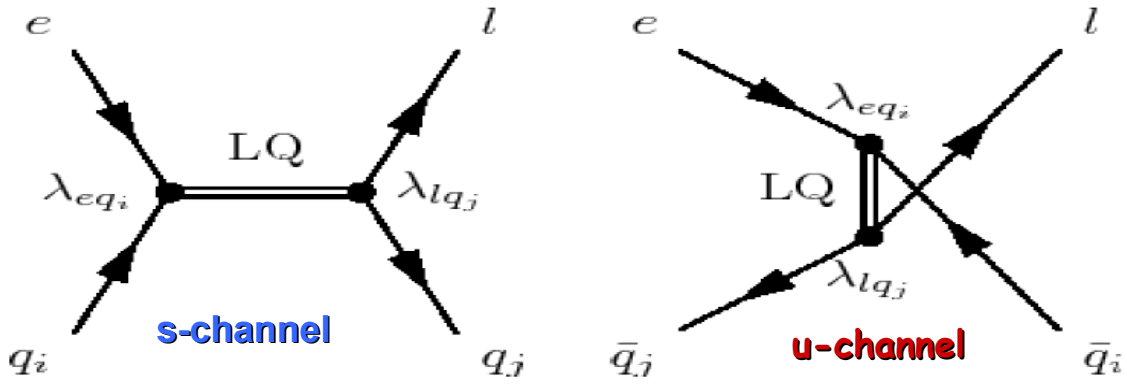


- H1 analysed full data, separately for e^+p and e^-p
- Model-independent generic search for final states with ≥ 2 high-p_T objects (e, μ, jet, γ, ν),
- In 27 topologies there was at least one event
- Possible deviations from SM in total event number and in Σp_T and M_{all} distributions were investigated and statistically analysed
- Good agreement with SM, all deviations consistent with statistical fluctuations

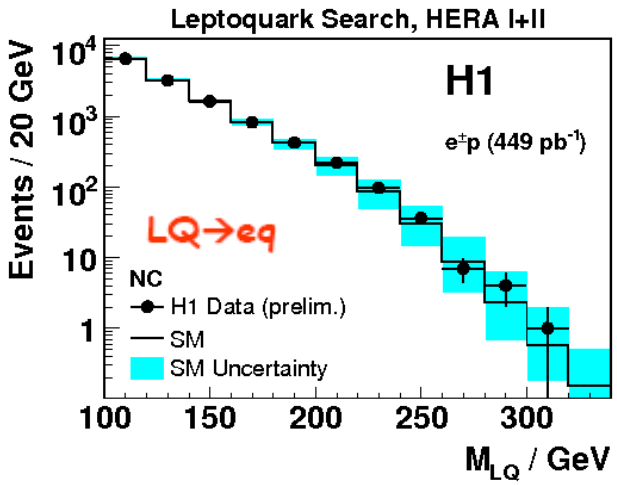
Leptoquarks

s channel ->resonant production $M_{LQ} < \sqrt{(xs)}$

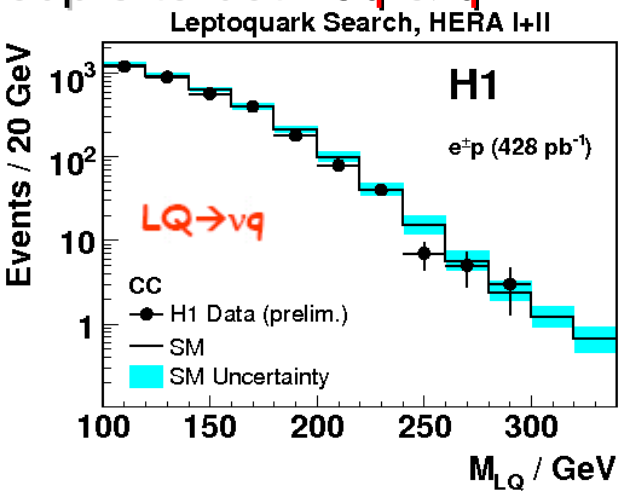
u channel ->contact interaction $M_{LQ} >> \sqrt{(xs)}$



✓ All 14 LQs => LQ->eq'



✓ 2 scalar & 2 vector LQ couple to both eq & q



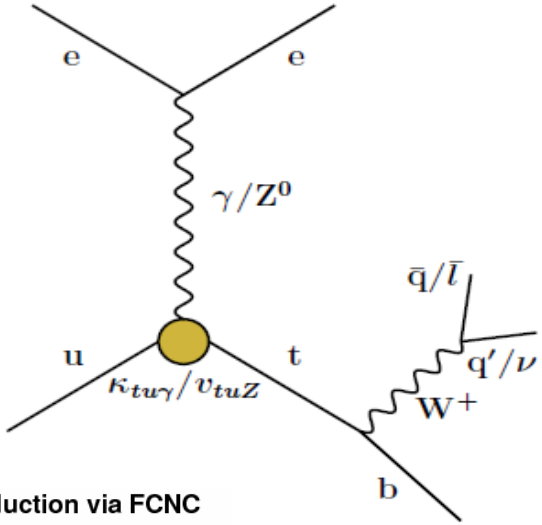
Leptoquarks – Aachen Notation

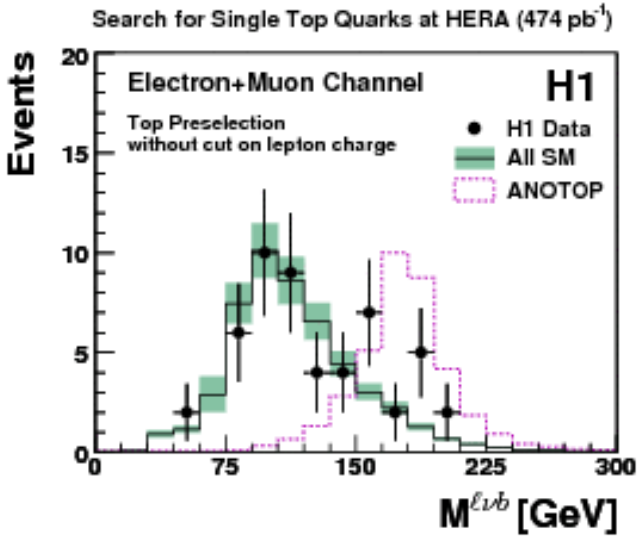
Fermion number F = 3B + L = 0,2

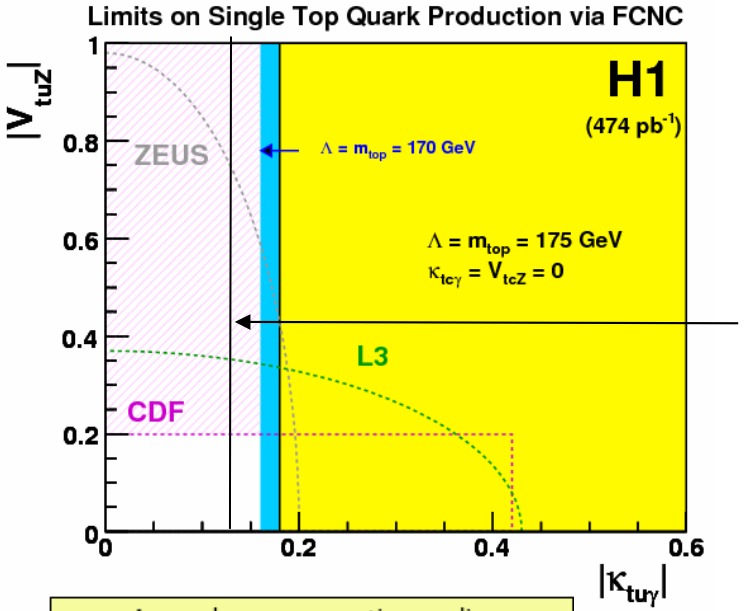
Model	Fermion number F	Charge Q	$B\Pi(LQ \to e^{\pm}q)$ β	Coupling		Squark type
S_0^L	2	−1/3	1/2	$e_L u$	νd	$\tilde{d}_R$
S_0^R	2	−1/3	1	$e_R u$		
$\tilde{S}_0$	2	4/3	1	$e_R d$		
$S_{1/2}^L$	0	−5/3	1	$e_L u$		
		−2/3	0		νu	
$S_{1/2}^R$	0	−5/3	1	$e_R \bar{u}$		
		−2/3	1	$e_R \bar{d}$		
$\tilde{S}_{1/2}$	0	2/3	1	$e_L \bar{d}$		$\overline{\tilde{u}_L}$
		+1/3	0		$\nu \bar{d}$	$\overline{\tilde{d}_L}$
S_1	2	−4/3	1	$e_L d$		
		−1/3	1/2	$e_L u$	νd	
		+2/3	0		νu	
V_0^L	0	2/3	1/2	$e_L \bar{d}$	$\nu \bar{u}$	
V_0^R	0	−2/3	1	$e_R \bar{d}$		
$\tilde{V}_0$	0	−5/3	1	$e_R \bar{u}$		
$V_{1/2}^L$	2	−4/3	1	$e_L d$		
		−1/3	0		νd	
$V_{1/2}^R$	2	−4/3	1	$e_R d$		
		−1/3	1	$e_R u$		
$\tilde{V}_{1/2}$	2	1/3	1	$e_L u$		
		+2/3	0		νu	
V_1	0	−5/3	1	$e_L u$		
		−2/3	1/2	$e_L d$	$\nu \bar{u}$	
		+1/3	0		$\nu \bar{d}$	

Anomalous Single Top Production

- Top quarks at HERA can only be singly produced via FC NC
- SM cross section negligible ($\sigma < 1 fb^{-1}$), but production predicted by several BSM theories
- Full HERA data analyzed by both H1 and ZEUS
- No deviations from SM seen → limits set on couplings $\kappa_{tu\gamma}$, v_{tuZ} (95% CL)





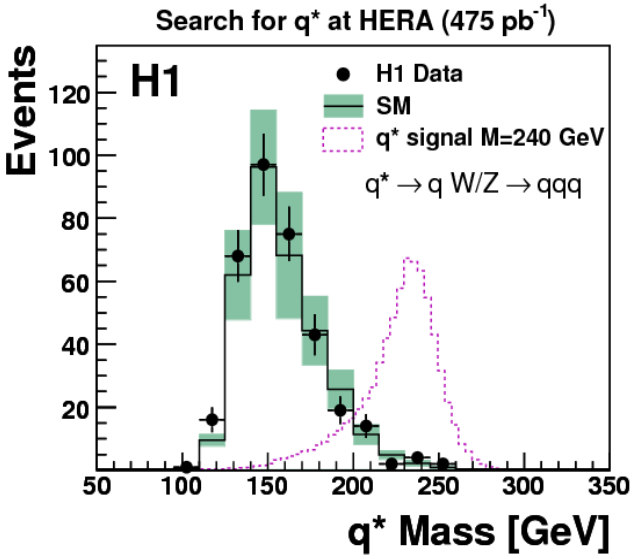


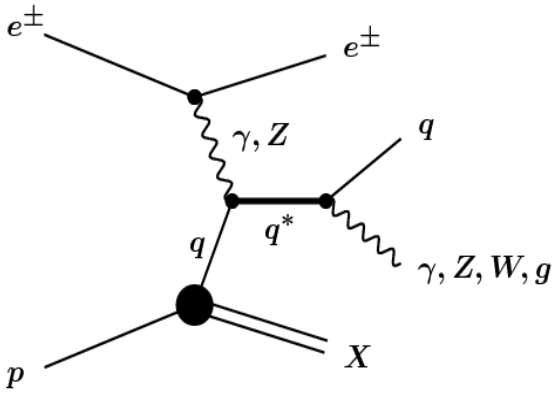
ZEUS preliminary, $L \approx 0.36$ fb^{-1}

$\kappa_{tu\gamma}$: Anomalous γ magnetic coupling
V_{tuZ} : Anomalous Z vector coupling

Excited Quarks

- Observation would be direct evidence for compositeness (fermion substructure), explaining possibly the three lepton/quark families and their mass hierarchy
- Excited fermions would decay to standard fermions + gauge bosons
  - leptonic and hadronic decay channels of gauge bosons investigated by H1





Λ: compositeness scale
f, f', f_S: coupling parameters associated to SM gauge groups