

EW and BSM Results from HERA



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On behalf of



Ringberg workshop
New Trends in HERA Physics 2008



Overview

Most of the results shown are

- based on full HERA data
- including polarized e beam at HERA-2

	HERA-1	HERA-2
e-	$\sim 20\text{pb}^{-1}$	$\sim 200\text{pb}^{-1}$
e+	$\sim 100\text{pb}^{-1}$	$\sim 200\text{pb}^{-1}$
→	H1/ZEUS: $0.5\text{fb}^{-1}/\text{exp}$	
→	H1+ZEUS: $\sim 1\text{fb}^{-1}$	

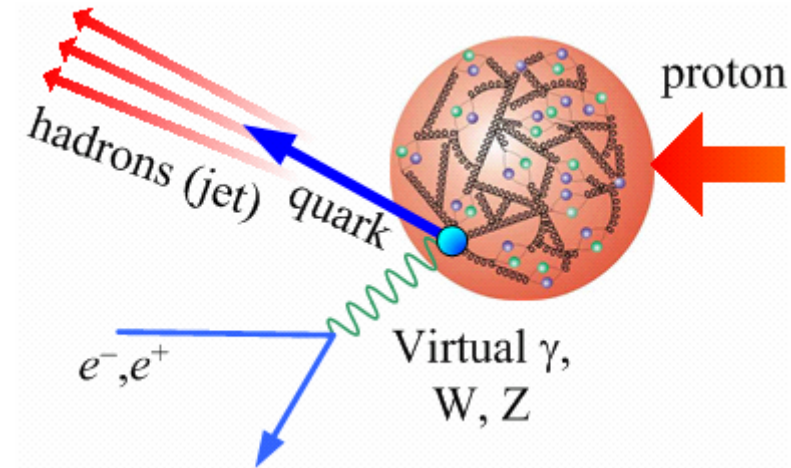
Both EW and BSM results rely on

- either **dominant inclusive DIS processes** (neutral & charged current)
advantage: high statistics
- or **rare exclusive processes** (single real W and lepton pair productions)
advantage: well defined final states

Dominant SM Inclusive DIS Processes at HERA

Neutral Current (NC) Process:

$$\sigma_{\text{NC}}(x, Q^2) \propto \frac{\alpha^2}{Q^4} \Phi_{\text{NC}}(\text{PDFs}, v_q, a_q, P_e)$$



Charged Current (CC) Process:

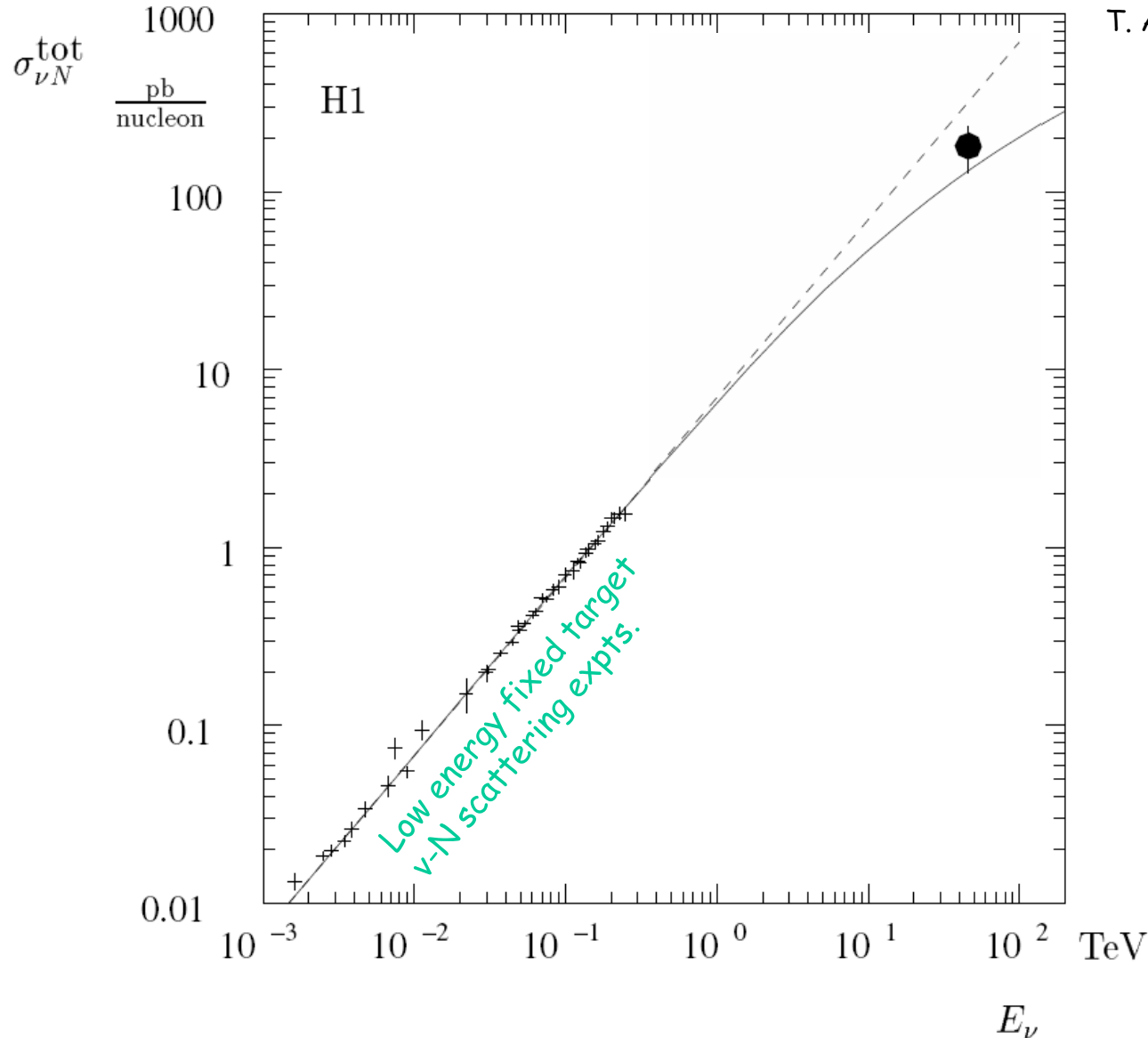
$$\sigma_{\text{CC}}^{\pm}(x, Q^2) \propto G_F^2 \frac{1 \pm P_e}{\left(1 + \frac{Q^2}{M_W^2}\right)^2} \Phi_{\text{CC}}(\text{PDFs})$$

- σ_{CC} damped by M_W (prop. mass)
- σ_{CC} normalization probes G_F
- σ_{NC} sensitive to light coupling v_q, a_q

HERA-1: $P_e = 0$

HERA-2: $P_e \sim \pm 40\%$

First Evidence of Massive W Mass at HERA



T. Ahmed et al., Phys. Lett. B324 (94) 241

H1 93 Data:
 $L=0.35 \text{ pb}^{-1}$

ep collider of
 $26.7 \text{ GeV} \cdot 820 \text{ GeV}$



a fixed target exp. of
 $\sim 50 \text{ TeV}$

Early W (Propagator) Mass Determinations

ZEUS (Phys. Rev. Lett. 75(1995)1006):

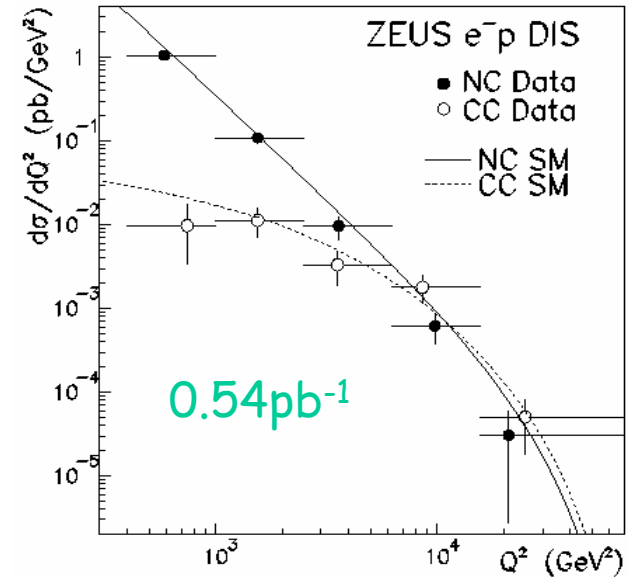
Fit to CC cross sections

$$M_W = 76 \pm 16 \pm 13 \text{ GeV} \quad L(e^-): 0.54 \text{ pb}^{-1}$$

First plot showing the EW unification in DIS

e-p and e+p combined (Z. Phys. C72(1996)1):

$$M_W = 79^{+8+4}_{-7-4} \text{ GeV} \quad L: 0.82 \text{ pb}^{-1}(e^-) + 2.93 \text{ pb}^{-1}(e^+)$$



H1 (Phys. Lett. B379(1996)319, hep-ex/9603009):

Fit to CC cross sections

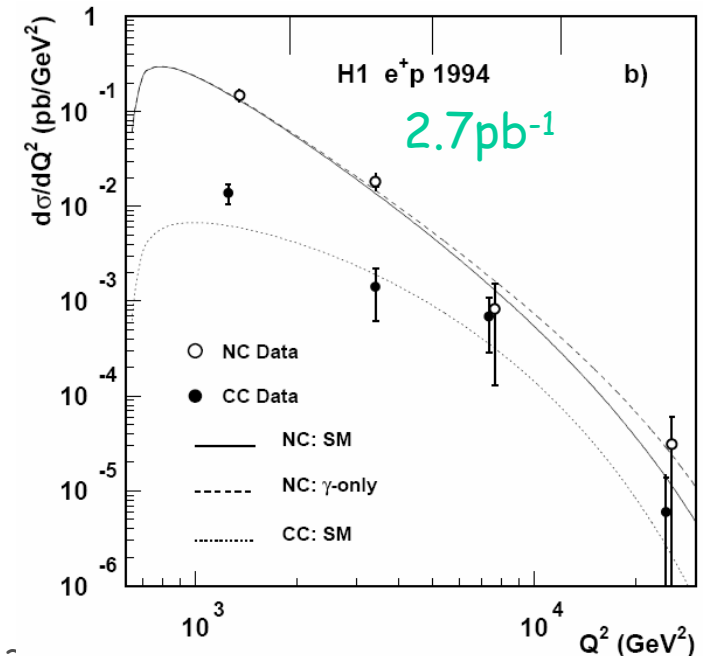
$$m_W(e^-p) = 78^{+11}_{-9} \text{ }^{+4}_{-3} \text{ GeV} \quad L(e^-): 0.29 \text{ pb}^{-1}$$

$$m_W(e^+p) = 97^{+18}_{-15} \text{ }^{+5}_{-10} \text{ GeV} \quad L(e^+): 2.7 \text{ pb}^{-1}$$

Better sensitivity from e-p data is mainly due to its larger cross section

e-p and e+p combined:

$$m_W = 84^{+9}_{-6} \text{ }^{+5}_{-4} \text{ GeV}$$



M_W : Improvement No.1

ZEUS (Eur. Phys. J. C3(00)411, Erratum, C27(03)):

A simultaneous G_F - M_W fit:

$$M_W = 80.8^{+4.9}_{-4.5} (\text{stat.})^{+5.0}_{-4.3} (\text{syst.})^{+1.4}_{-1.3} (\text{PDF}) \text{ GeV}$$

Fixing G_F :

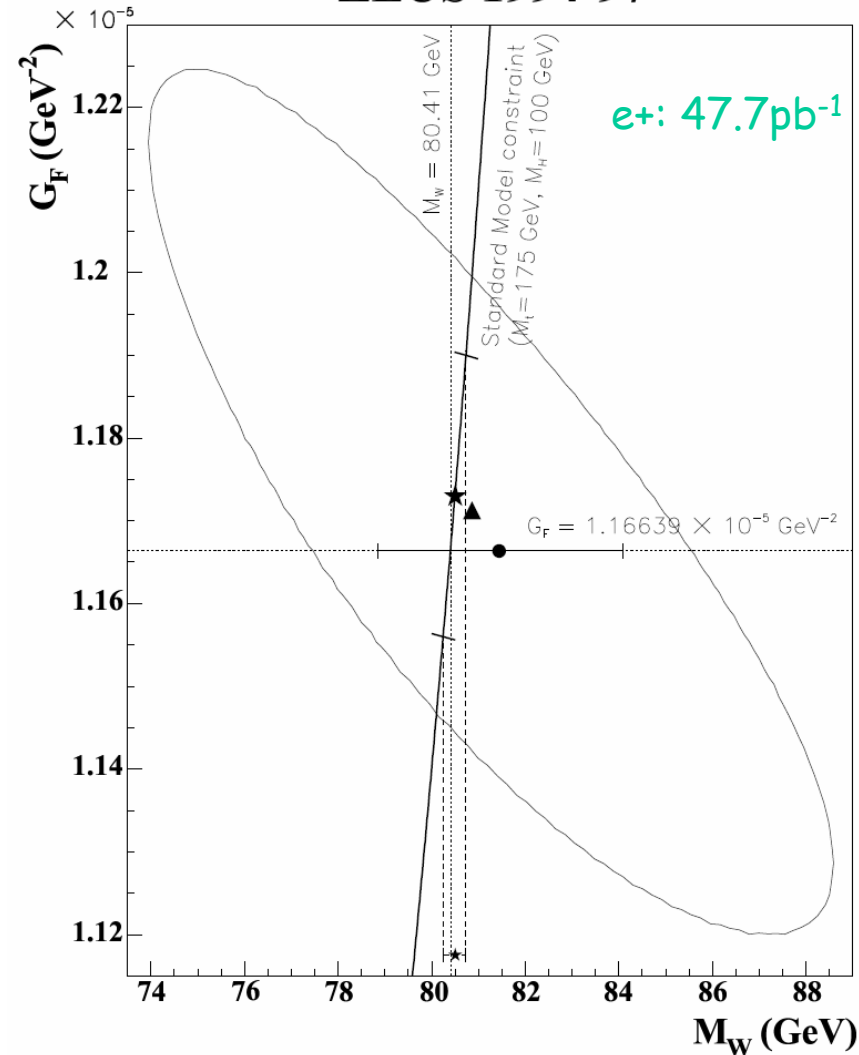
$$M_W = 81.4^{+2.7}_{-2.6} (\text{stat.}) \pm 2.0 (\text{syst.})^{+3.3}_{-3.0} (\text{PDF}) \text{ GeV}$$

Within the SM framework:

$$G_F = \frac{\pi\alpha}{\sqrt{2}} \frac{M_Z^2}{(M_Z^2 - M_W^2) M_W^2} \frac{1}{1 - \Delta r}$$

$$M_W = 80.50^{+0.24}_{-0.25} (\text{stat.})^{+0.13}_{-0.16} (\text{syst.}) \pm 0.31 (\text{PDF})^{+0.03}_{-0.06} (\Delta M_t, \Delta M_H, \Delta M_Z) \text{ GeV}$$

ZEUS 1994-97



M_W : Improvement No.2

H1 (Phys. Lett. B632(06)35, hep-ex/0507080):

Fit	Fixed parameters	
	CC	NC
G - M_{prop} -PDF	—	α, G_F, M_Z
M_{prop} -PDF	G_F	α, G_F, M_Z
M_W -PDF	α, M_Z, m_t, M_H	
m_t -PDF	α, M_Z, M_W, M_H	

Correlation with PDFs is further taken into account for the 1st time

Propagator W mass:

$$M_{\text{prop}} = 82.87 \pm 1.82_{\text{exp}} \left. \begin{array}{l} +0.30 \\ -0.16 \end{array} \right|_{\text{model}} \text{ GeV}$$

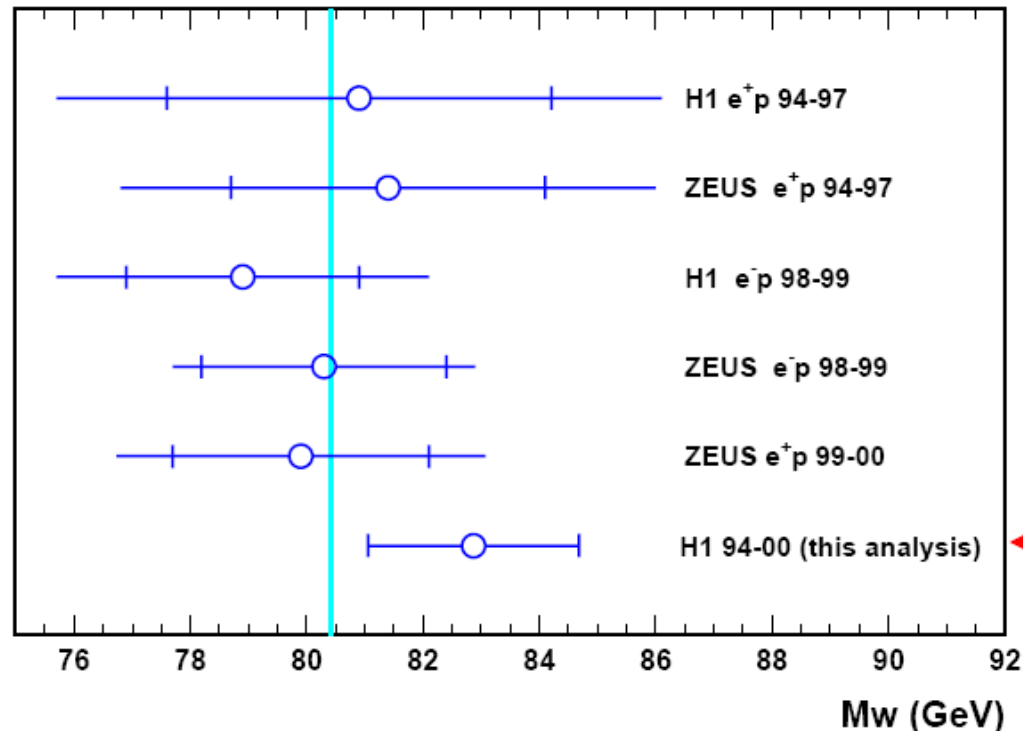
W mass within the SM:

$$M_W = 80.786 \pm 0.205_{\text{exp}} \left. \begin{array}{l} +0.063 \\ -0.098 \end{array} \right|_{\text{th}}$$

→ Indirect determination:

$$\sin^2 \theta_W = 0.2151 \pm 0.0040_{\text{exp}} \left. \begin{array}{l} +0.0019 \\ -0.0011 \end{array} \right|_{\text{th}}$$

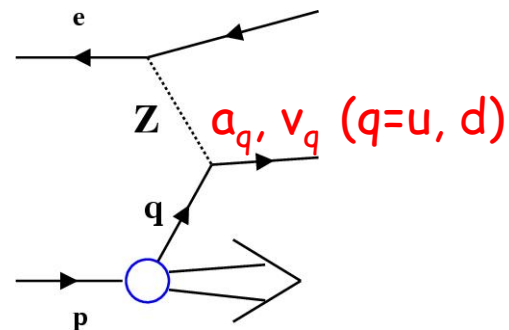
HERA measurement of W propagator mass



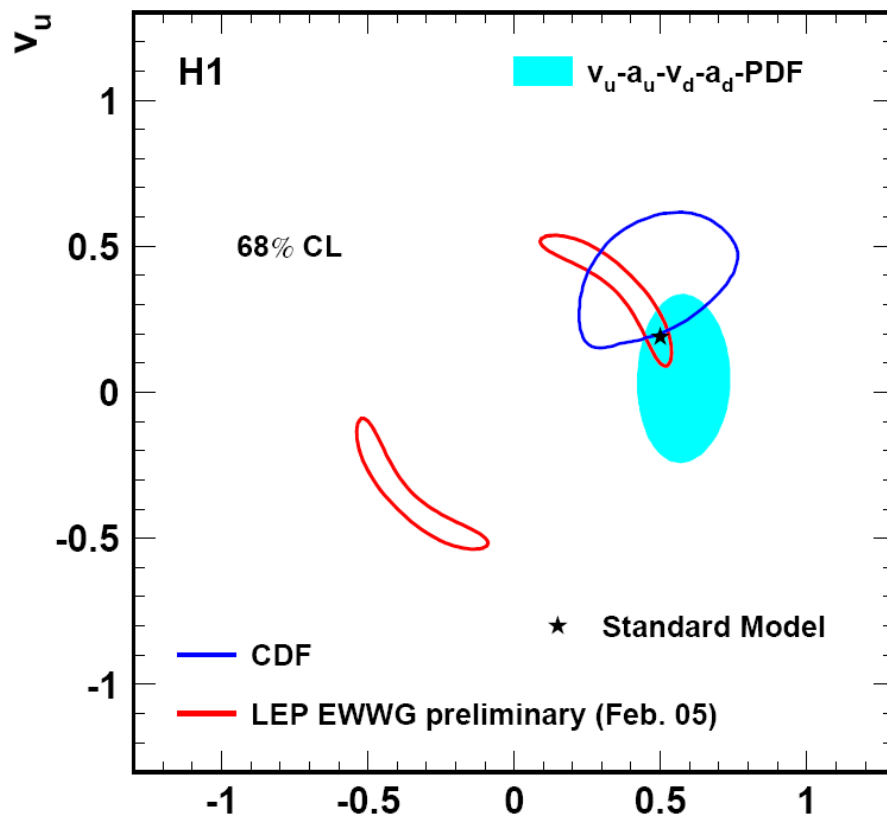
Light Quark Couplings to Z (HERA-1)

H1 (Phys. Lett. B632(06)35, hep-ex/0507080):

Fit	Fixed parameters	
	CC	NC
$v_u - a_u - v_d - a_d$ -PDF	G_F, M_W	α, M_Z, M_W
$v_u - a_u$ -PDF	G_F, M_W	$\alpha, M_Z, M_W, v_d, a_d$
$v_d - a_d$ -PDF	G_F, M_W	$\alpha, M_Z, M_W, v_u, a_u$
$I_{u,R}^3 - I_{d,R}^3$ -PDF	G_F, M_W	$\alpha, M_Z, M_W, v_{q,L}, a_{q,L}$

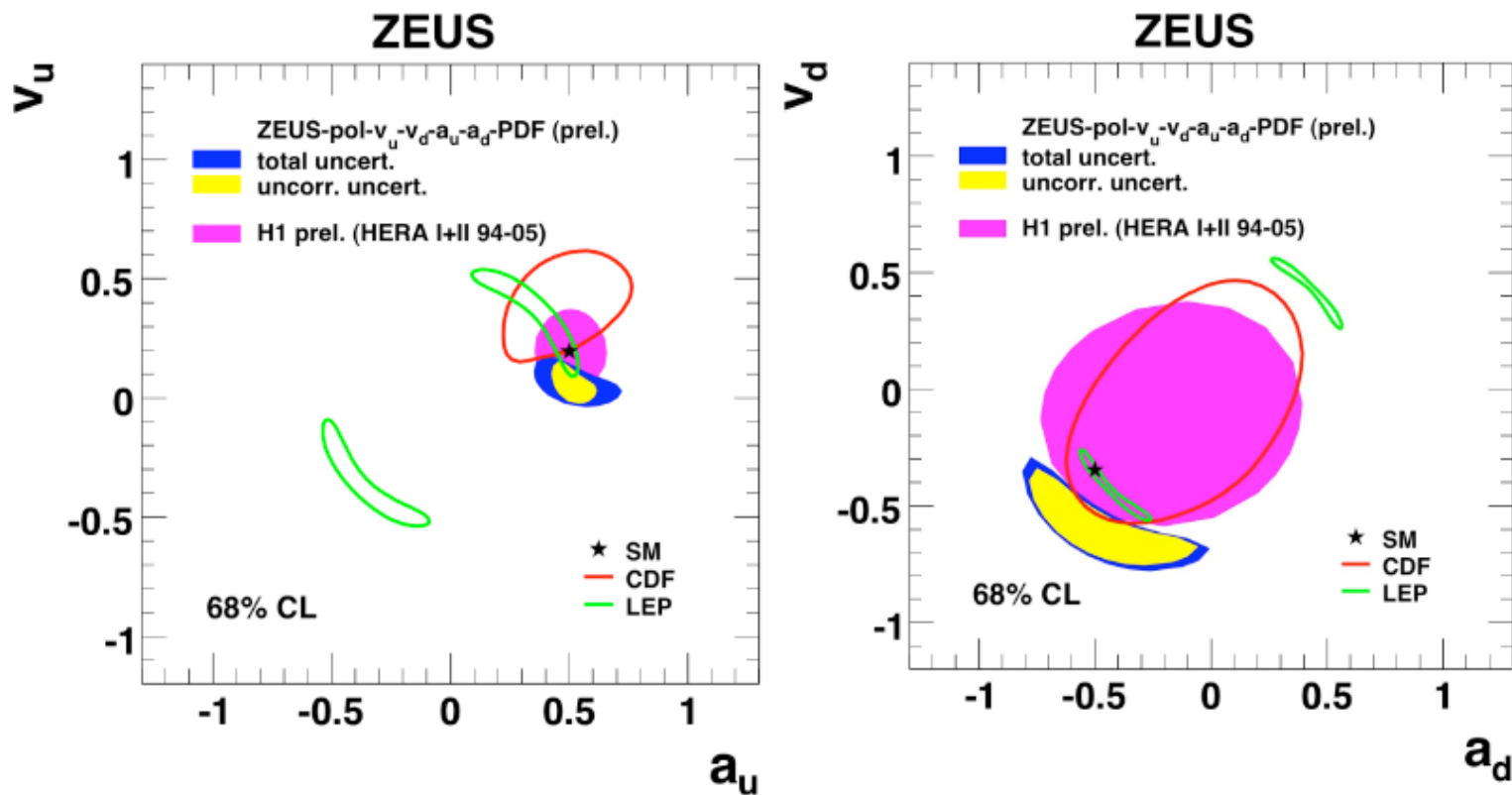


- Tevatron: $qq \rightarrow ee$ Drell-Yan, A_{FB}
- LEP: $ee \rightarrow qq(\gamma)$ ($a_q^2 + v_q^2$)
- Similar results on d couplings (unshown, less constrained)
- ➔ HERA-1 results competitive
- ➔ HERA data resolve sign ambiguity



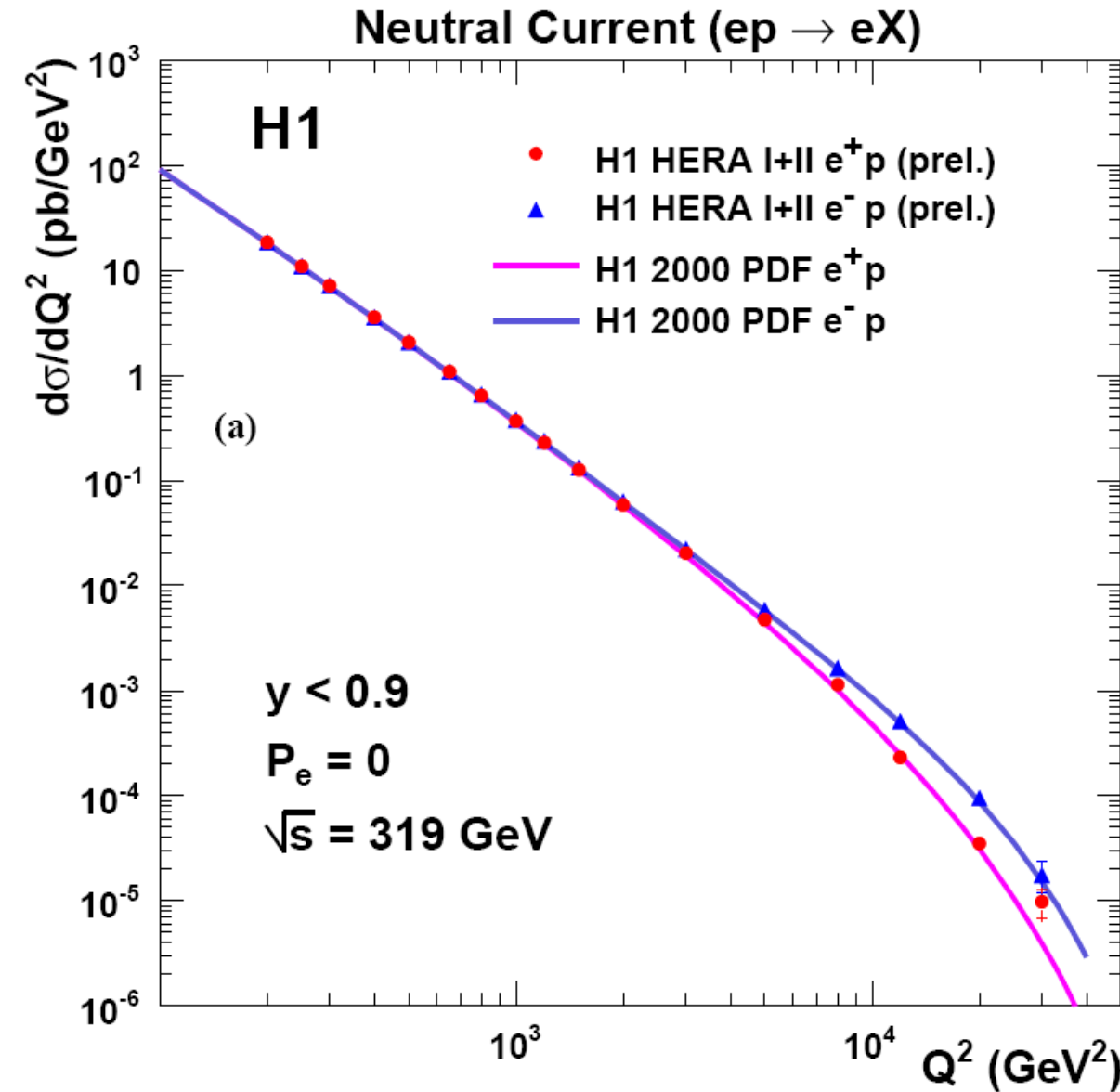
Preliminary Results Including HERA-2 Data

- The polarized e beam brings additional sensitivity in particular on v_q
- Larger data sample from HERA-2 also helps



H1 still has more HERA-2 data to be included

NC Q^2 Spectra and Finite Quark Size



$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{\text{SM}}}{dQ^2} f_e^2(Q^2) f_q^2(Q^2)$$

$$f(Q^2) = 1 - \frac{\langle r^2 \rangle}{6} Q^2$$

Assume e point-like ($f_e=1$)

H1:

$$\langle r_q \rangle < 0.74 \times 10^{-3} \text{ fm (95\%CL)}$$

ZEUS:

$$\langle r_q \rangle < 0.62 \times 10^{-3} \text{ fm (95\%CL)}$$

For this study, the small residual P_e effect in the combined L+R HERA-2 data is corrected for

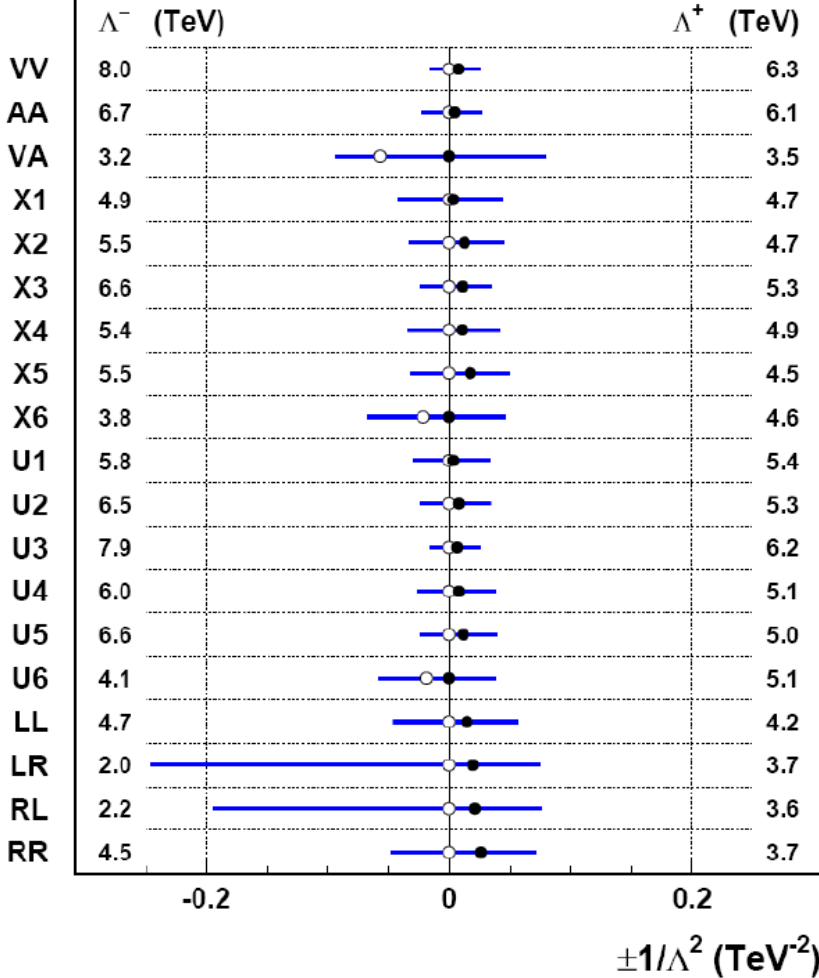
High Q^2 Spectra vs. Contact Interactions

ZEUS

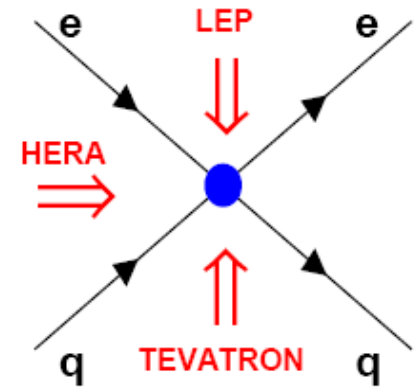
94-06 (prel.) e^+p 330 pb^{-1}

○ $-1/\Lambda^2$ best fit value ● $+1/\Lambda^2$ best fit value

— allowed $\pm 1/\Lambda^2$ range



High Q^2 spectra may be modified by new physics at large scale Λ as a four-fermion contact interaction



$$L = \sum_{i,j=L,R} \mathcal{E}_{i,j}^{e,q} \frac{4\pi}{\Lambda^2} \eta_{ij}^{eq} (\bar{e}_i \gamma^\mu e_i) (\bar{q}_j \gamma_\mu q_j)$$

Typical excluded scale
> 5TeV

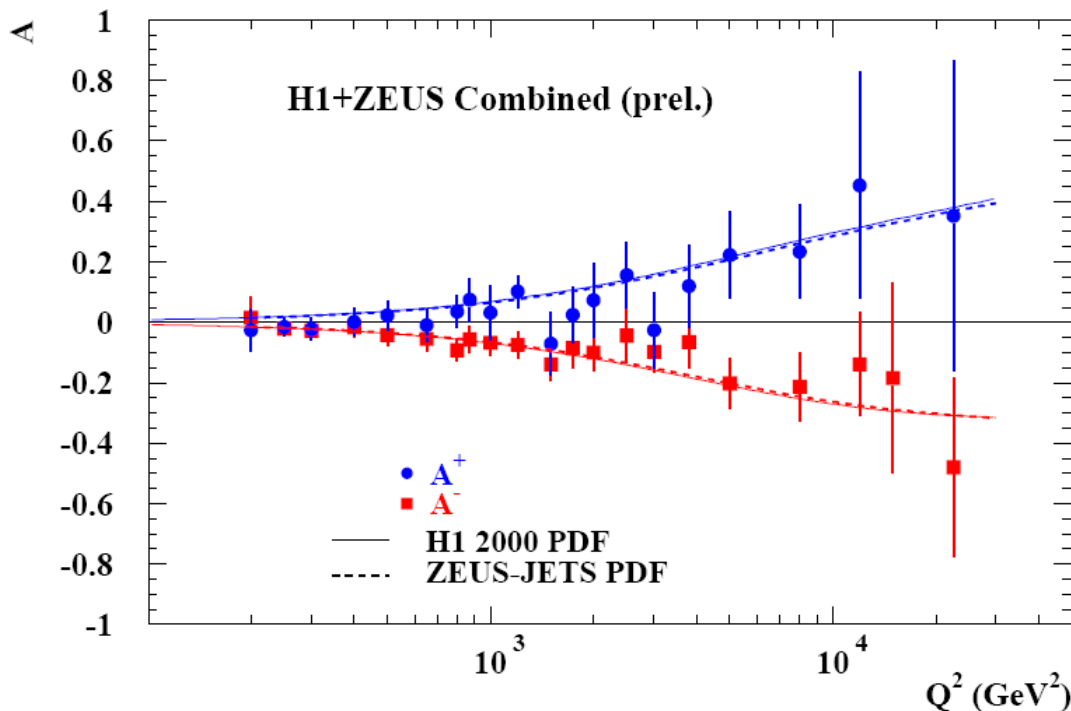
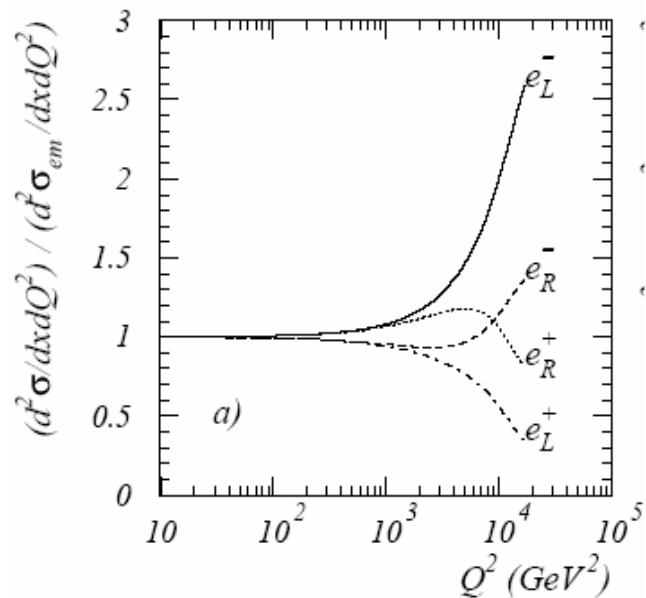
Similar sensitivity
from Tevatron in
Drell-Yan

NC Q^2 Spectra from HERA-2 & P Violation

Remember at high Q^2 ,

- Z (γ Z interference) important
- e beam polarized at HERA-2

→ Expect to see different e^+/e^- NC cross sections at high Q^2



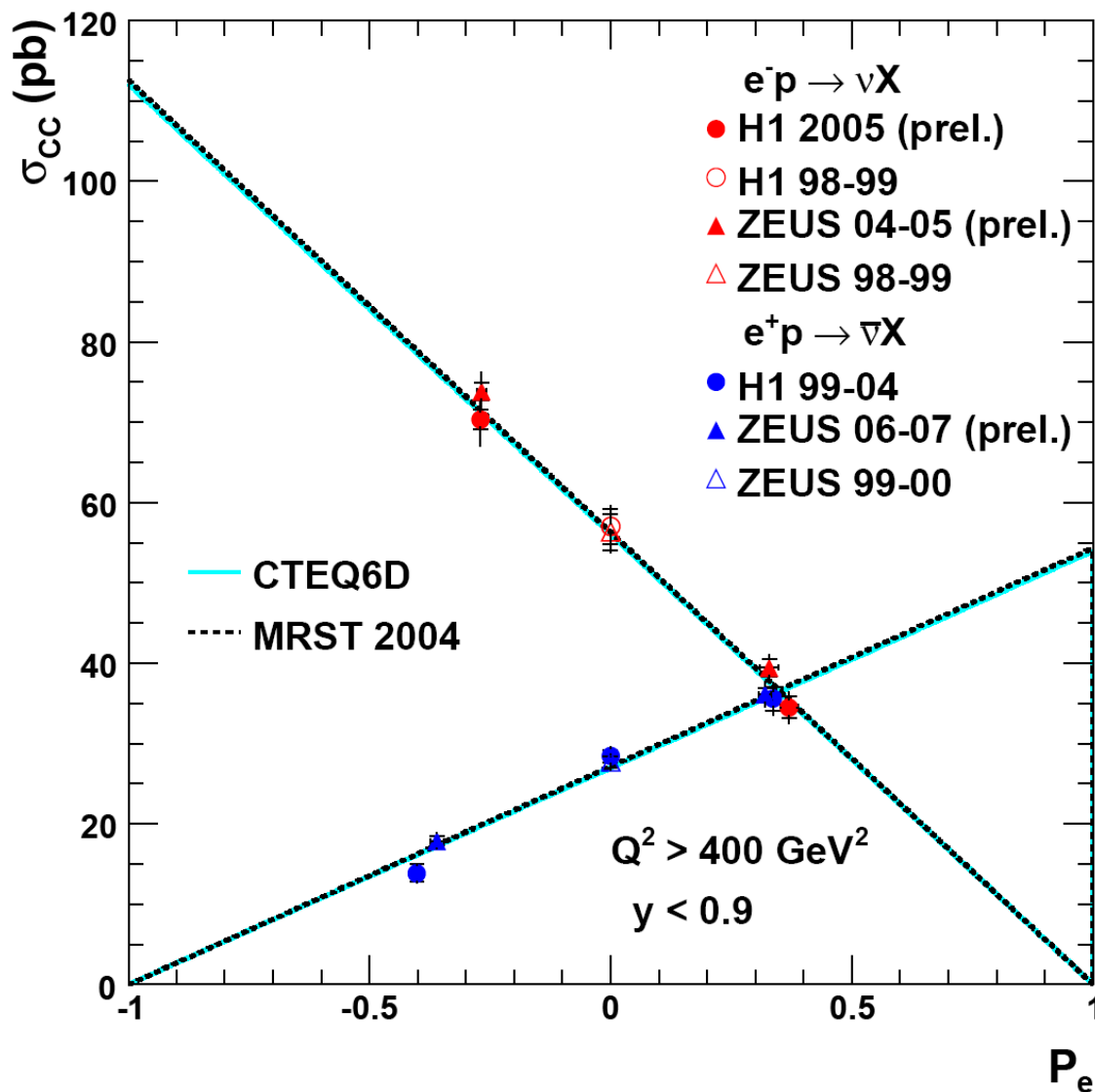
Define an asymmetry:

$$A^\pm = \frac{2}{P_R - P_L} \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)}$$

→ 1st observation of parity violation in NC DIS at distance down to 10^{-3} fm

CC Cross Section & Right-Handed W Boson

Charged Current $e^\pm p$ Scattering



Extrapolated cross sections ~ 0

- at $P_e = +1$ for e^-
- at $P_e = -1$ for e^+

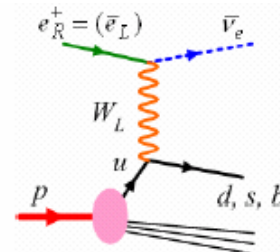
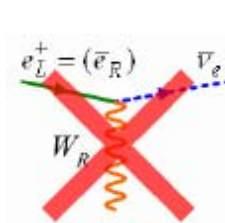
→ Only left-hand W in SM

If $g_L = g_R$ & ν_R light

→ H1: $M_{WR} > 208 \text{ GeV}$ (95%CL)

Improvement expected with full HERA-2 data

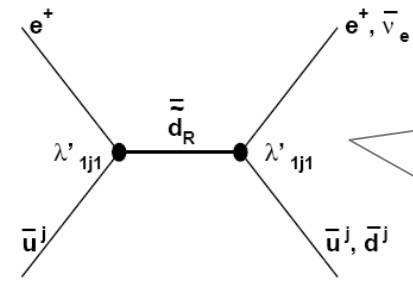
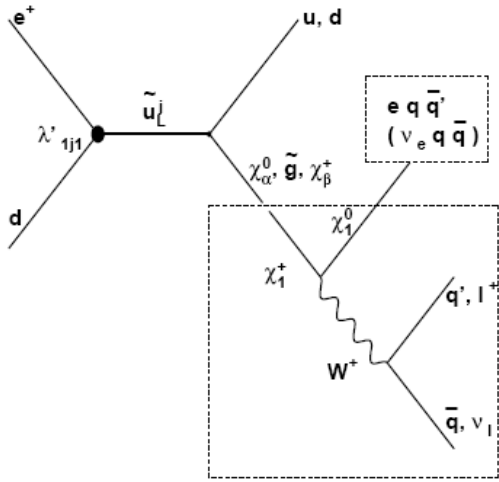
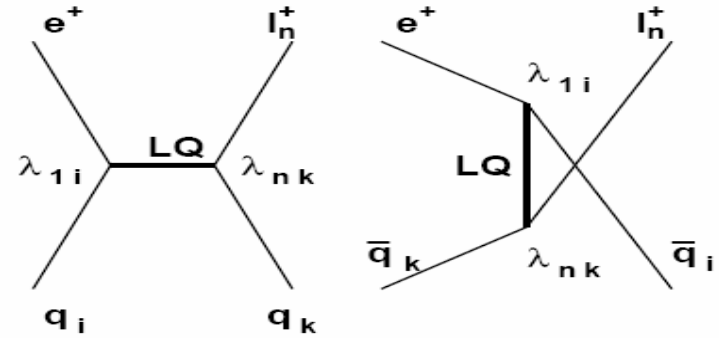
Although Tevatron limit is more stringent



Other Searches in Inclusive DIS

Leptoquarks (LQs):

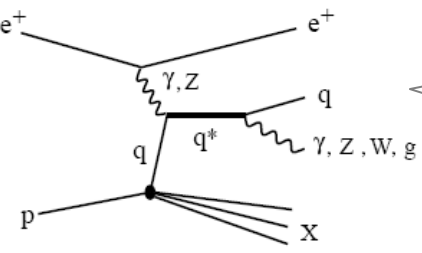
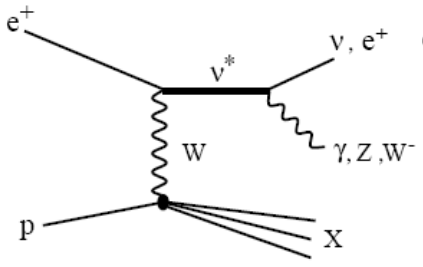
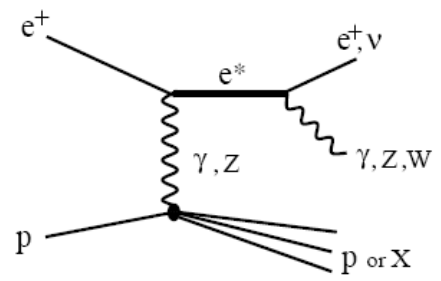
- resonances in s-channel
- final state identical to DIS events



Squarks in R-parity* violating SUSY:

- similar to LQs
- but it can have gauge decay modes

* R-parity = $(-1)^{3B+L+2S}$



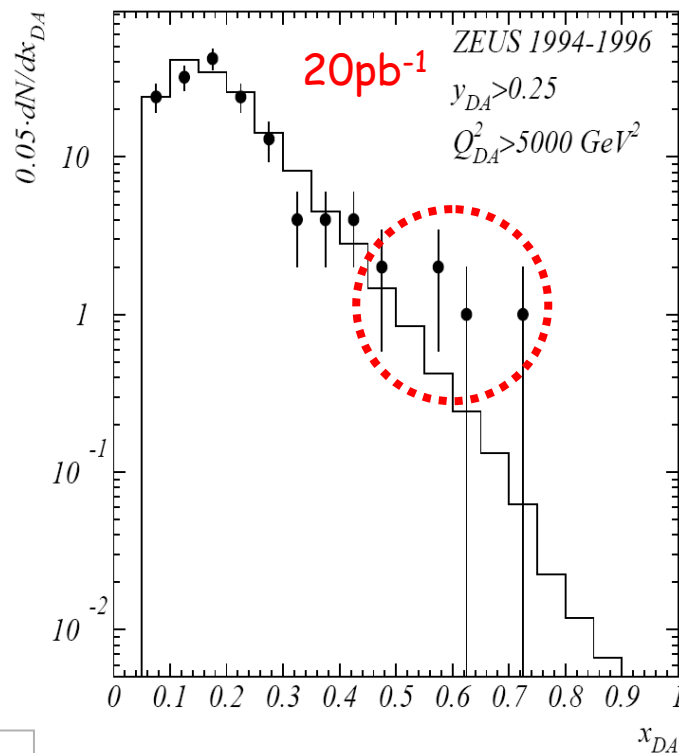
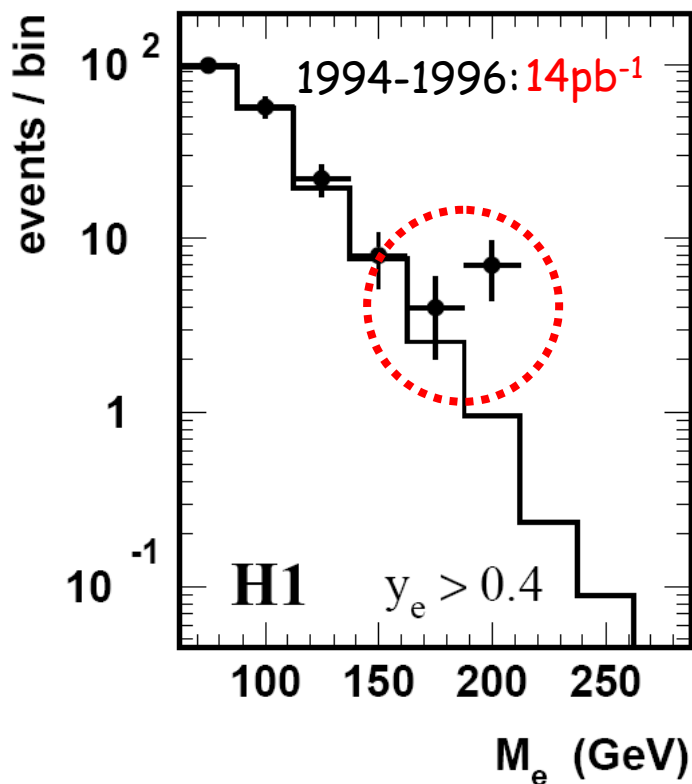
Excited fermions:

- have gauge boson (decay) in final state

Remember an Old Exciting Moment in 1997

H1, Z. Phys. C74 (97) 191, >300 citations

ZEUS, Z. Phys. C74 (97) 207, >300 citations

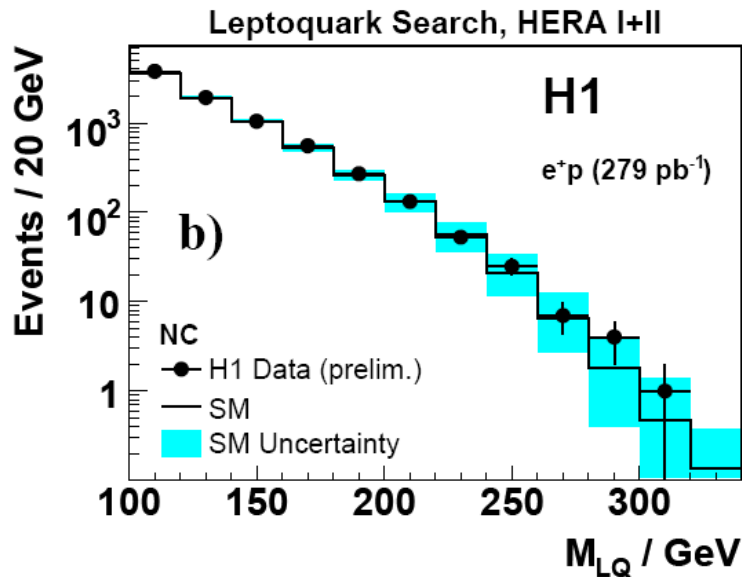


$$M^2 = x_s$$

→ A huge number of speculations including resonant production of LQs or squarks

The "Final" Word of HERA on LQs

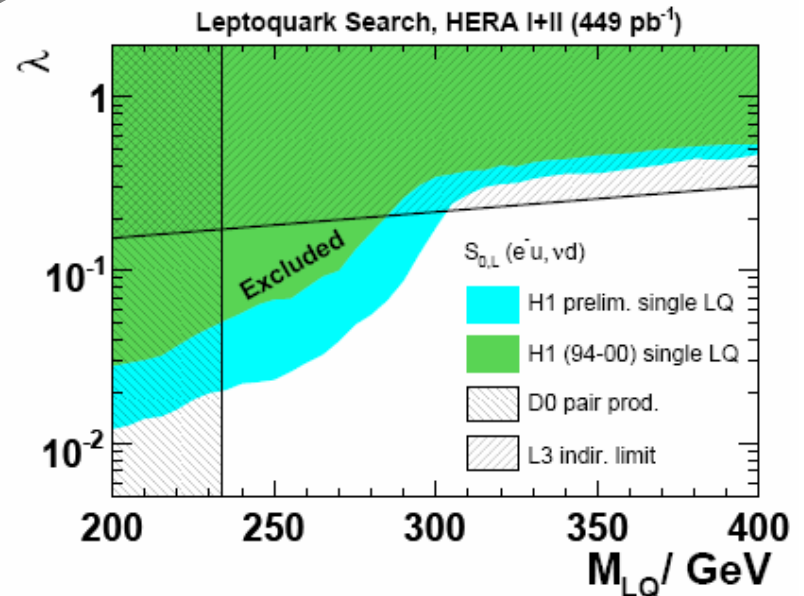
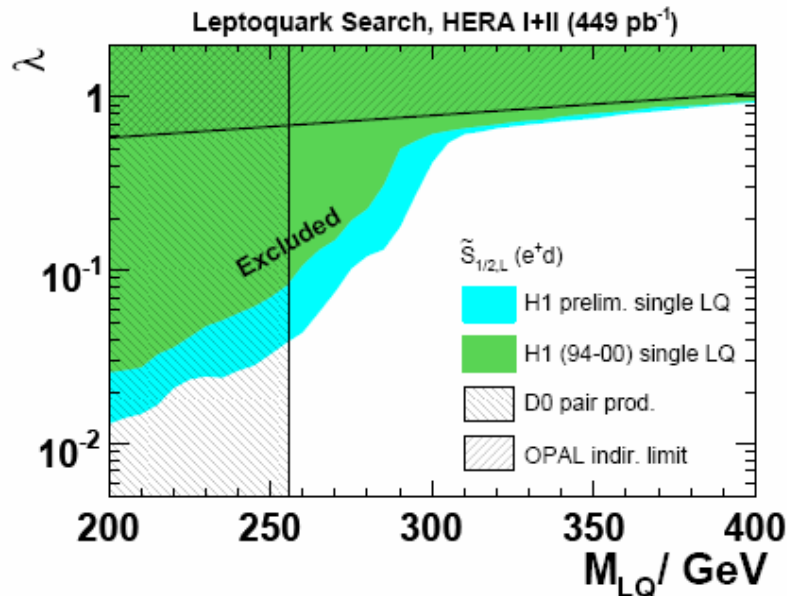
H1 HERA-1+2: H1prelim-07-164
 ZEUS HERA-1: Phys. Rev. D68 (2003) 052004



Unfortunately no more excess/deviation in the whole spectrum

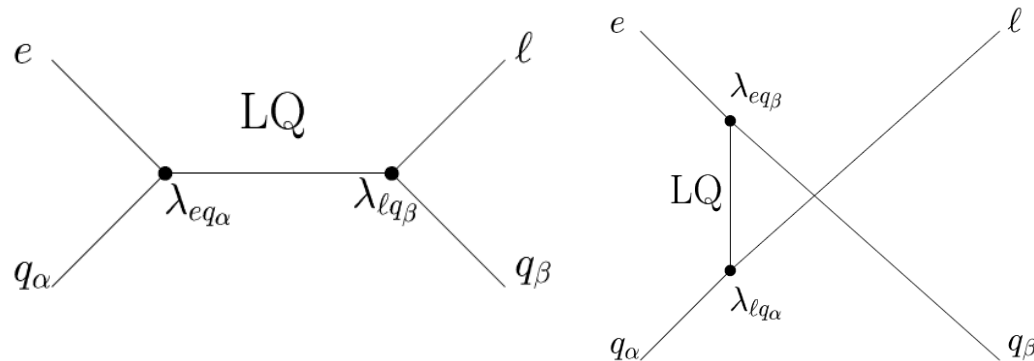
HERA may have the most stringent constraints on LQs until LHC

ZEUS has similar mass dis. and limits



Lepton Flavor Violating LQs

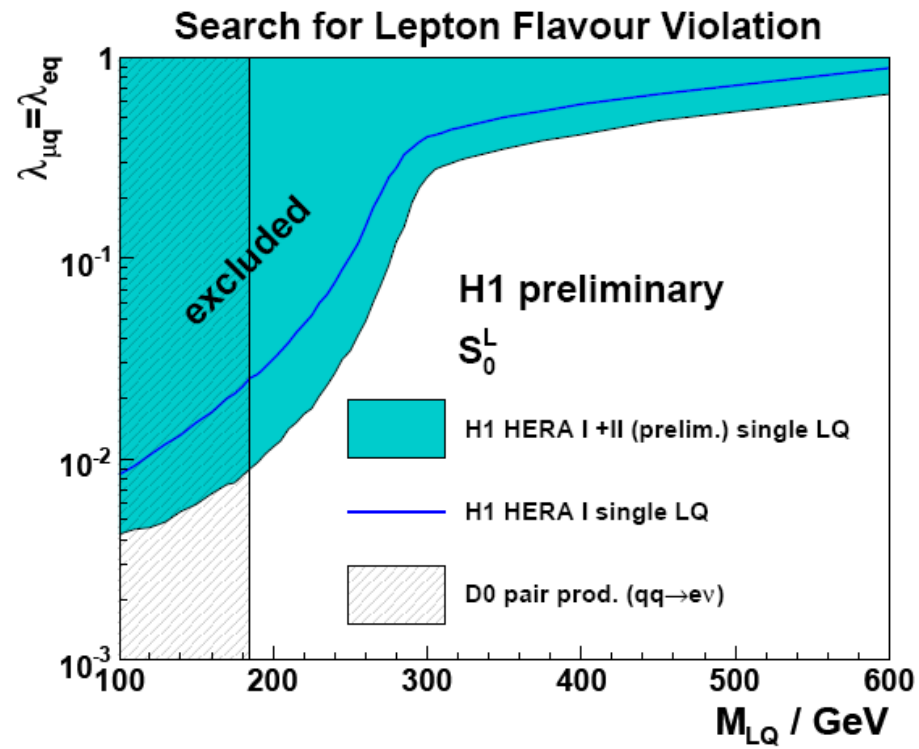
H1 HERA1+2: H1prelim-07-167
 ZEUS HERA-1: Eur. Phys. J. C44 (2005) 463



Final state lepton $l \neq e$ beam
 → Essentially background free

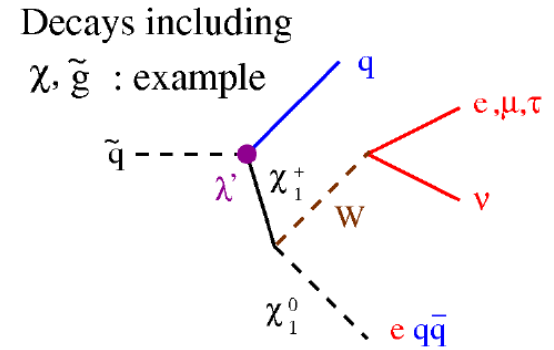
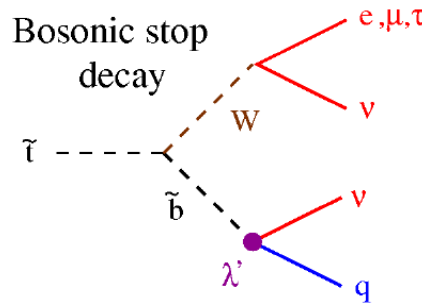
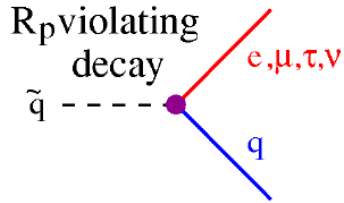
H1 has preliminary limits for full e-p data sample (HERA-2 has a 10-fold increase)

HERA limits in general more stringent than others (e.g. rare lepton and meson decays, muon-electron conversion on nuclei)

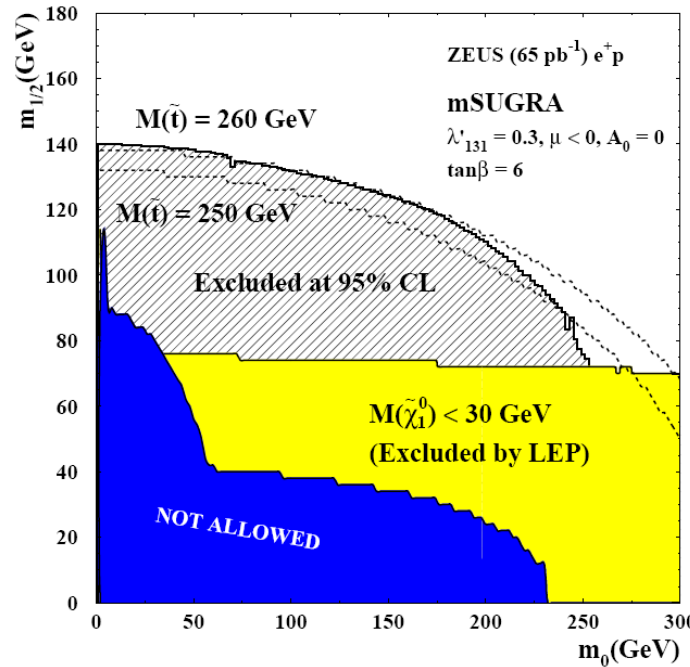
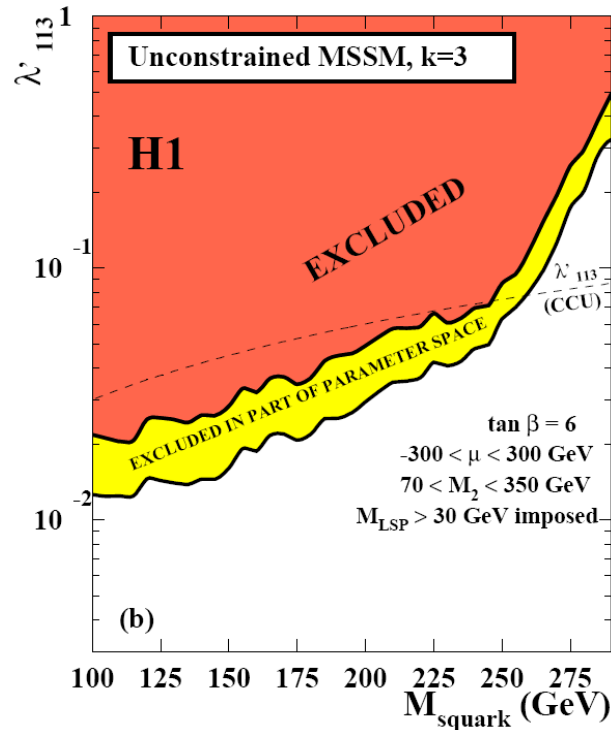


Searches for R-Parity Violating SUSY

Limits on LQs also apply to squarks if R-parity violating decay dominates



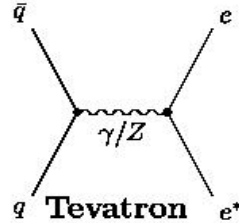
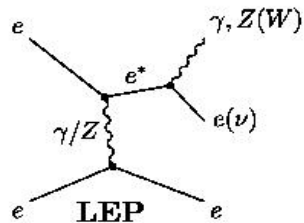
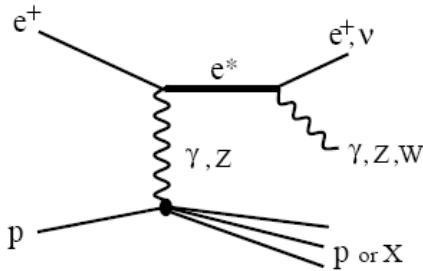
ZEUS



Dedicated scan in both MSSM and mSUGRA parameter space performed by **H1** with HERA-1 data (Eur. Phys. J. C36 (2004) 425) and by **ZEUS** for stop (Eur. Phys. J. C50 (2007) 261)

Excited State of Electrons

H1, to appear in Phys. Lett. B, arXiv.0805.4530



Search for e^* at HERA (475 pb^{-1})

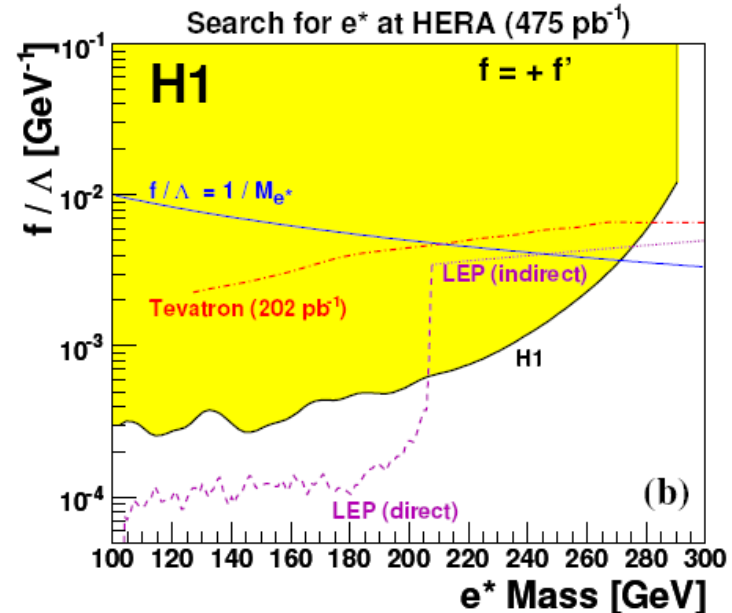
Channel	Data	SM	Signal Efficiency [%]
$e^* \rightarrow e\gamma$ (ela.)	42	48 ± 4	60–70
$e^* \rightarrow e\gamma$ (inel.)	65	65 ± 8	60–70
$e^* \rightarrow \nu W \rightarrow \nu q\bar{q}$	129	133 ± 32	20–55
$e^* \rightarrow \nu W \rightarrow \nu e\nu$	4	4.5 ± 0.7	60
$e^* \rightarrow eZ \rightarrow e\nu\nu$			35
$e^* \rightarrow eZ \rightarrow eq\bar{q}$	286	277 ± 62	20–55
$e^* \rightarrow eZ \rightarrow eee$	0	0.72 ± 0.06	60
$e^* \rightarrow eZ \rightarrow e\mu\mu$	0	0.52 ± 0.05	40–15

$$L_{F^*F} = \frac{1}{2\Lambda} \bar{F}_R^* \sigma^{\mu\nu} [gf \frac{\vec{\tau}}{2} \partial_\mu \vec{W}_\nu + g' f' \frac{Y}{2} \partial_\mu B_\nu] F_L + h.c.$$

Composite scale

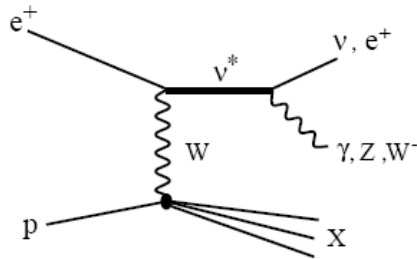
Relative coupling strength for SU(2)

Relative coupling strength for U(1)



Excited State of Neutrinos

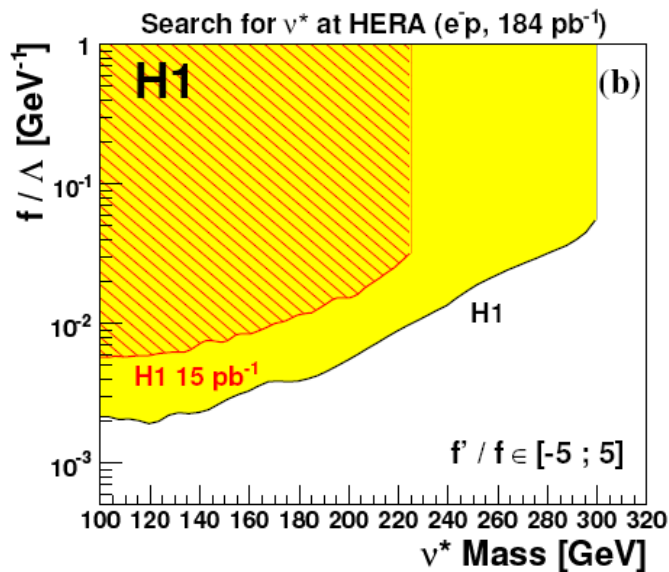
H1, Phys. Lett. B663 (2008) 382, arXiv.0802.1858



ν^* cross section in e^-p is much larger than that in e^+p
 → Search sensitivity best in e^-p

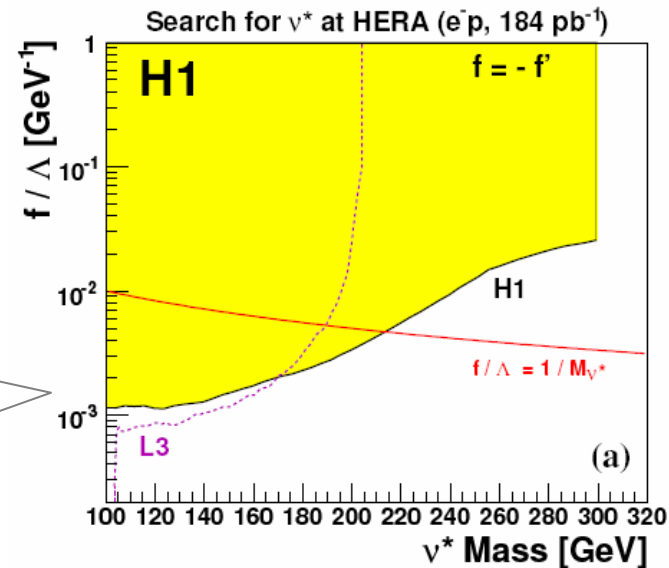
Search for ν^* at HERA (e^-p , 184 pb^{-1})

Channel	Data	SM	Signal Efficiency [%]
$\nu^* \rightarrow \nu \gamma$	7	12.3 ± 3.0	50–55
$\nu^* \rightarrow eW \rightarrow eq\bar{q}$	220	223 ± 47	40–65
$\nu^* \rightarrow eW \rightarrow e\nu\mu$	0	0.40 ± 0.05	35
$\nu^* \rightarrow eW \rightarrow e\nu e$	0	0.7 ± 0.1	45
$\nu^* \rightarrow \nu Z \rightarrow \nu q\bar{q}$	89	95 ± 21	25–55
$\nu^* \rightarrow \nu Z \rightarrow \nu ee$	0	0.19 ± 0.05	45



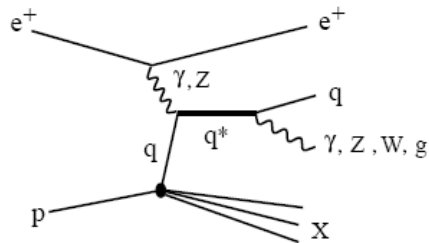
Significant improvement over HERA-1 data due to 10-fold increase in L

HERA (H1) limit more stringent for $M_{\nu^*} > \sim 170 \text{ GeV}$



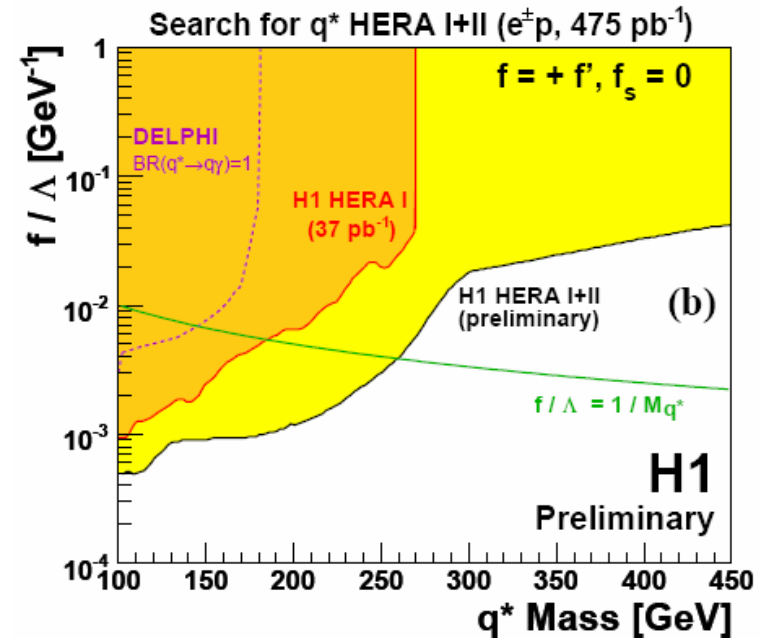
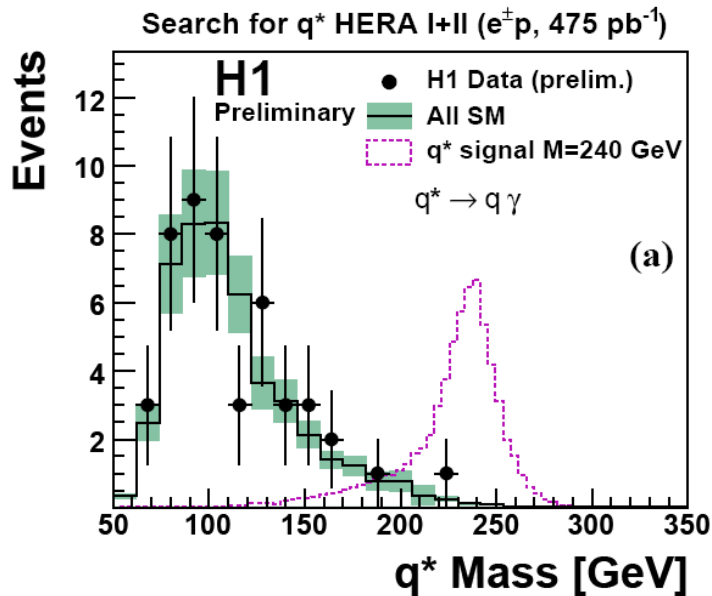
Excited State of Quarks

H1prelim-08-161

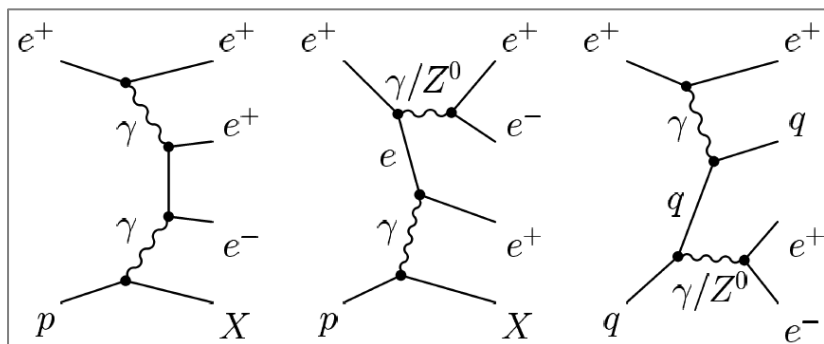


Search for q^* , HERA I+II (475 pb⁻¹, preliminary)

Channel	Data	SM	Signal Efficiency [%]
$q^* \rightarrow q\gamma$	47	47 ± 7	35–45
$q^* \rightarrow qW/Z \rightarrow qq\bar{q}$	346	338 ± 137	5–60
$q^* \rightarrow qW \rightarrow qe\nu$	6	6.0 ± 0.8	25–40
$q^* \rightarrow qW \rightarrow q\mu\nu$	5	4.4 ± 0.7	25–50
$q^* \rightarrow qZ \rightarrow qee$	0	0.44 ± 0.08	35
$q^* \rightarrow qZ \rightarrow q\mu\mu$	0	0.87 ± 0.08	35

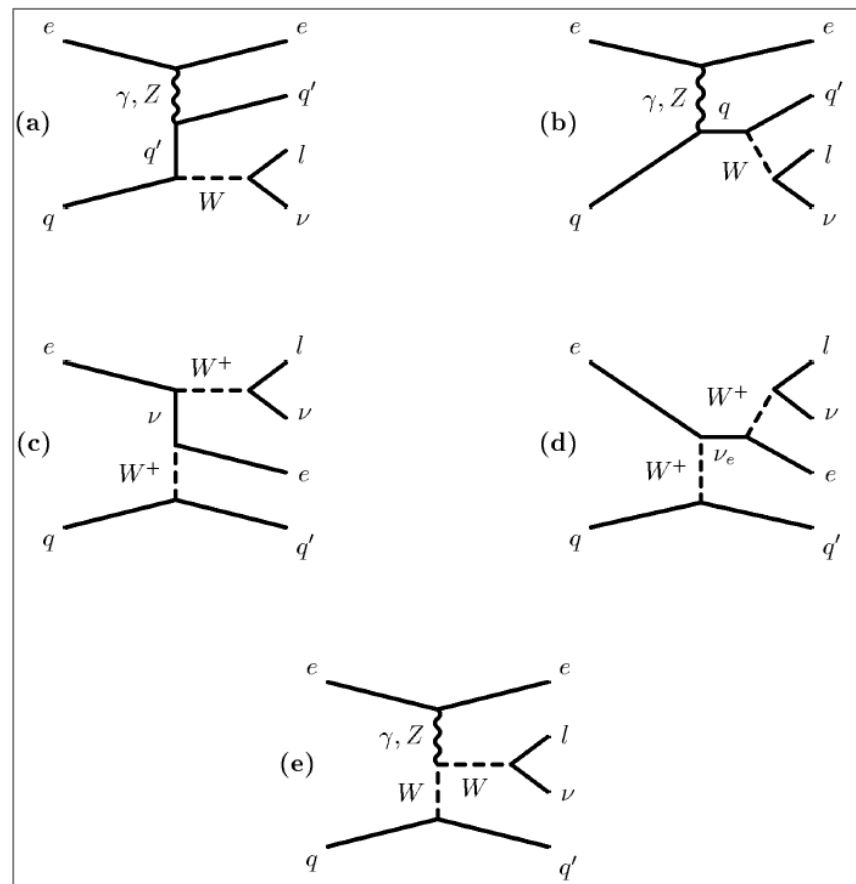


Search for New Physics in Rare Excl. Processes



Pair production
 → Multi-leptons + high P_T

Single real W production
 → Isolated lepton + missing E_T



Multi-Lepton Events @ High P_T

1st excess reported in 2003 by H1 in 2e, 3e modes
(H1, Eur. Phys. J. C31 (2003) 17)

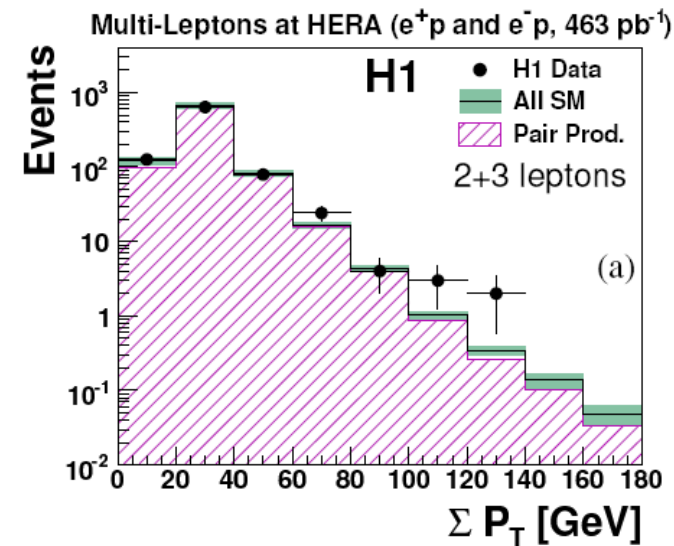
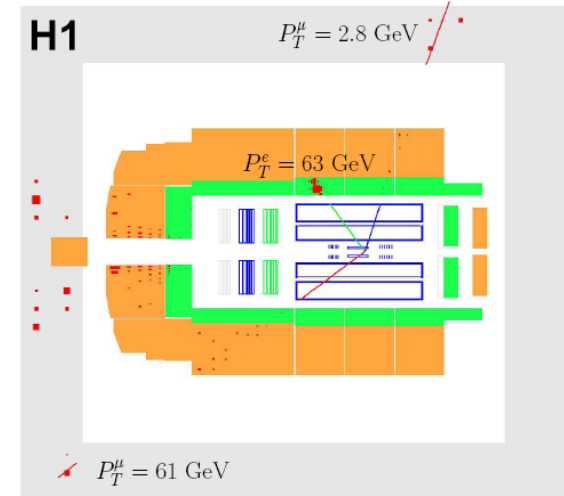
Latest results: (H1, arXiv.0806.3987[hep-ex], submitted to PLB)
(ZEUS-prel-07-022, 08-006)

➤ At high mass ($M_{ll} > 100 \text{ GeV}$):

Topology	H1 publication		ZEUS preliminary	
	Data	SM (pair)	Data	SM (pair)
ee	3	1.34±0.20 (0.83)	2	1.7±0.2 (0.9)
eμ	1	0.59±0.06 (0.59)		
eee	3	0.66±0.09 (0.66)	2	1.0±0.1 (1.0)
μμ	1	0.17±0.07 (0.17)		
eμμ	2	0.16±0.05 (0.16)		

➤ At high P_T (scalar sum $> 100 \text{ GeV}$):

Data set	H1 publication	
	Data	SM (pair)
e ⁺ p	5	0.96±0.12 (0.78)
e ⁻ p	0	0.64±0.09 (0.51)
All	5	1.60±0.20 (1.29)

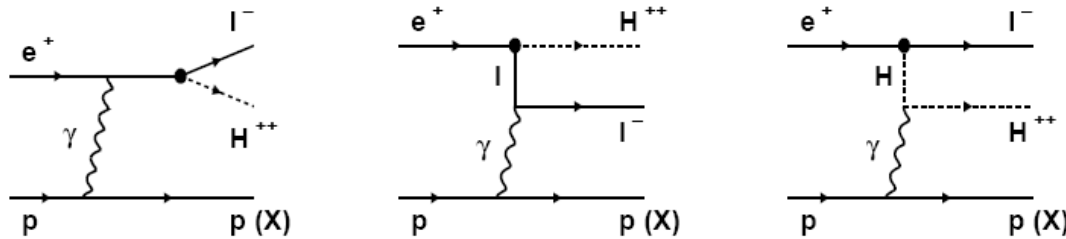


Excess up to 3σ observed in H1 e⁺ data
but not confirmed by ZEUS

Multi-Lepton Events & Double Charged H Boson

H1, Phys. Lett. B638 (2006) 432, hep-ex/0604027

H1 HERA-1 data: 118pb^{-1}



Look for ee , $e\mu$ or $e\tau$ pair of high P_T leptons with like charge

For $m_{e\ell} > 65\text{GeV}$, obs/exp are

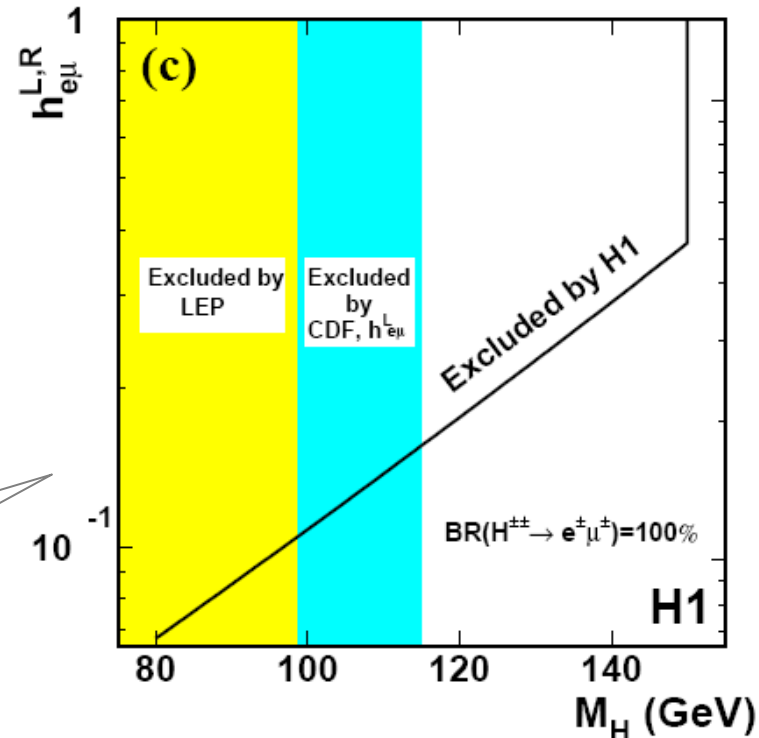
3 / 2.45 ± 0.11 (ee)

1 / 4.17 ± 0.44 ($e\mu$)

1 / 2.07 ± 0.54 ($e\tau$)

→ Limits on $\sigma(H^{++}) \cdot \text{Br}(e\ell)$ vs. M_H

Example on 95%CL limits of $h_{e\mu}^{L,R}$ vs. M_H
(for $h_{e\mu} = 0.3$, $M_H > 141\text{GeV}$)



Isolated Lepton Events with Large Missing P_T

1st excess seen by H1 & published in 1998

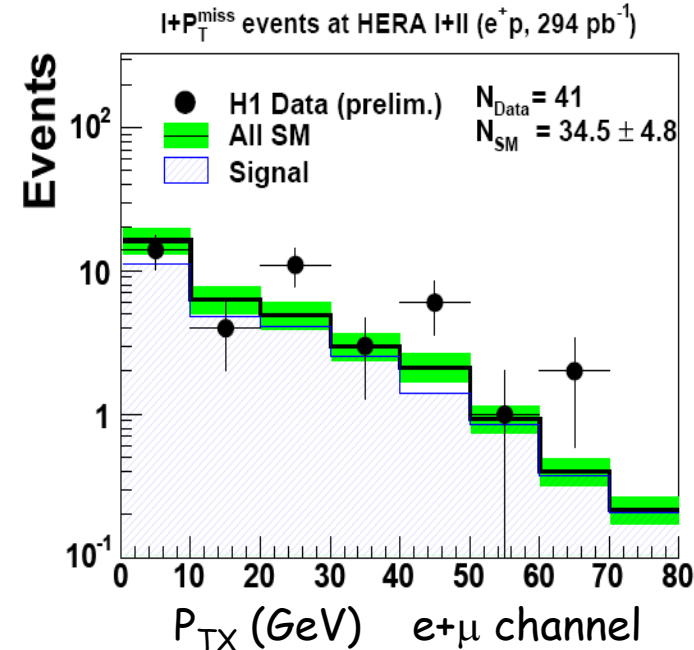
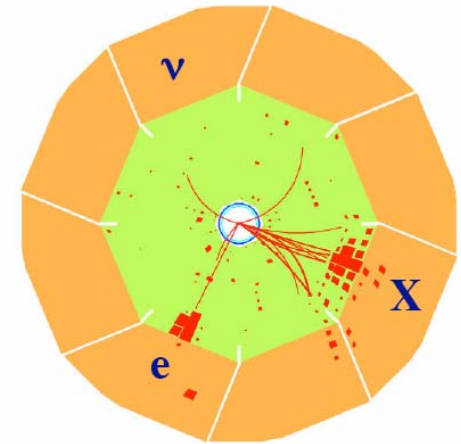
(H1 Collab., Eur. Phys. J. C5 (98) 575)

Latest results: (ZEUS, arXiv.0807.0589[hep-ex], submitted to PRL)
(H1prelim-07-063, 07-064)

Event yields at high P_{TX} (> 25 GeV):

Data set	Final state	H1 preliminary		ZEUS publication	
		Data	Exp (signal)	Data	Exp (signal)
e^+p	e	11	4.7 ± 0.9 (75%)	3	4.0 ± 0.6 (77%)
	μ	10	4.2 ± 0.7 (85%)	3	3.4 ± 0.5 (81%)
	τ	0	0.5 ± 0.1 (72%)		
e^-p	e	3	3.8 ± 0.6 (61%)	3	3.2 ± 0.5 (69%)
	μ	0	3.1 ± 0.5 (74%)	2	2.3 ± 0.4 (85%)
	τ	1	1.0 ± 0.1 (63%)		

Some interesting excess in H1 e^+p data remains
But not confirmed by ZEUS



Single W Production Cross Section

ZEUS, arXiv.0807.0589[hep-ex], submitted to PRL; H1prelim-07-161

The isolated lepton with large missing P_T is dominated by SM W production

→ This same sample is used to measure the W production cross section

ZEUS:

$$\sigma_{ep \rightarrow lWx} = 0.89^{+0.25}_{-0.22} \text{ (stat)} \pm 0.10 \text{ (syst)} \text{ [pb]} @ \sqrt{s}=316 \text{ GeV}$$

H1 (preliminary):

$$\sigma_{ep \rightarrow lWx} = 1.23 \pm 0.25 \text{ (stat)} \pm 0.22 \text{ (syst)} \text{ [pb]} @ \sqrt{s}=320 \text{ GeV}$$

In agreement with the SM expectation:

$$\begin{aligned} \sigma_{ep \rightarrow lWx} &= 1.2 \text{ pb} @ \sqrt{s}=316 \text{ GeV} \\ &= 1.3 \text{ pb} @ \sqrt{s}=320 \text{ GeV} \end{aligned}$$

NLO calculation has an uncertainty of $\pm 15\%$!

→ Both measurements have a significance of ~ 5 standard deviations

W Polarization Fractions @ HERA

H1prelim-07-161

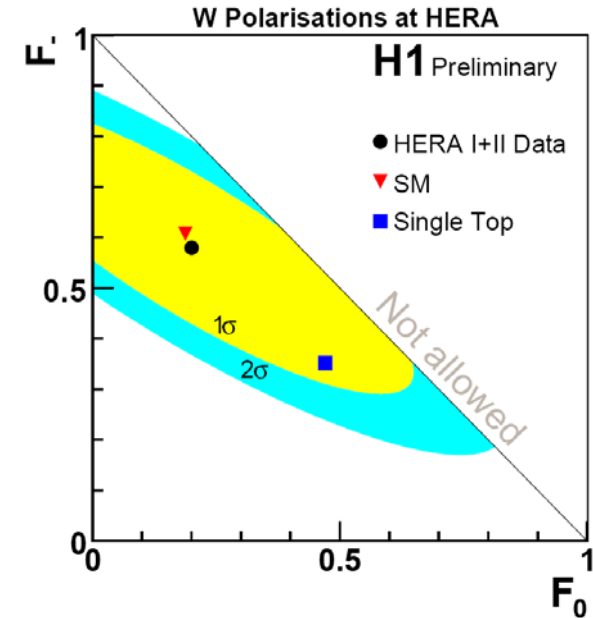
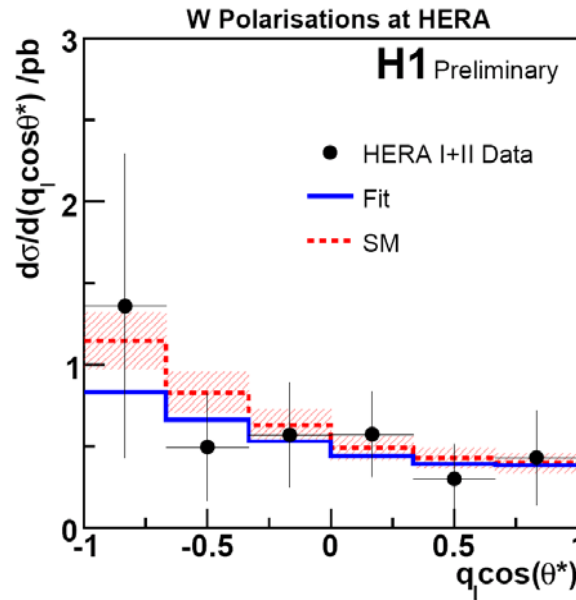
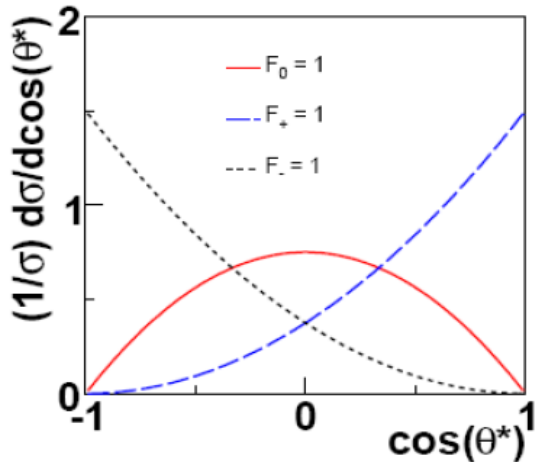
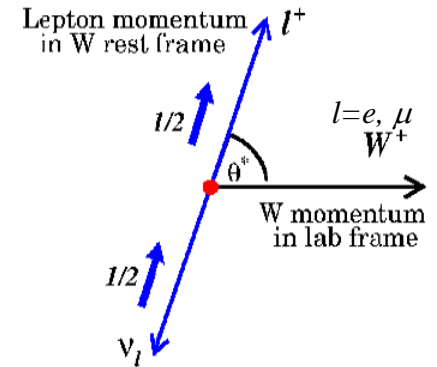
Restricted to the isolated lepton sample in which a W is reconstructed

Angular distribution and polarization fractions:

$$\frac{dN}{d \cos \theta^*} = F_- \frac{3}{8} (1 - \cos \theta^*)^2 + F_0 \frac{3}{4} \sin^2 \theta^* + F_+ (1 + \cos \theta^*)^2$$

left
longitudinal
right

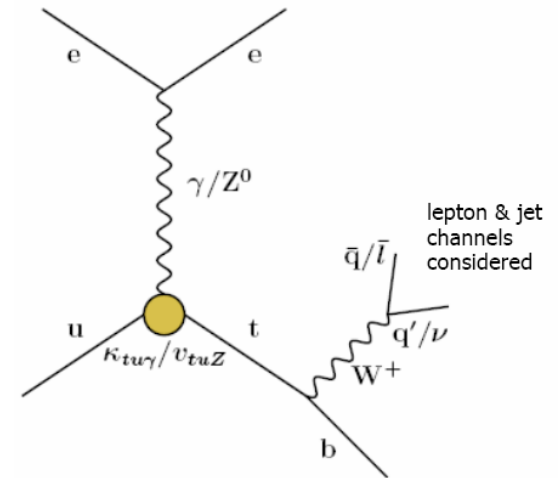
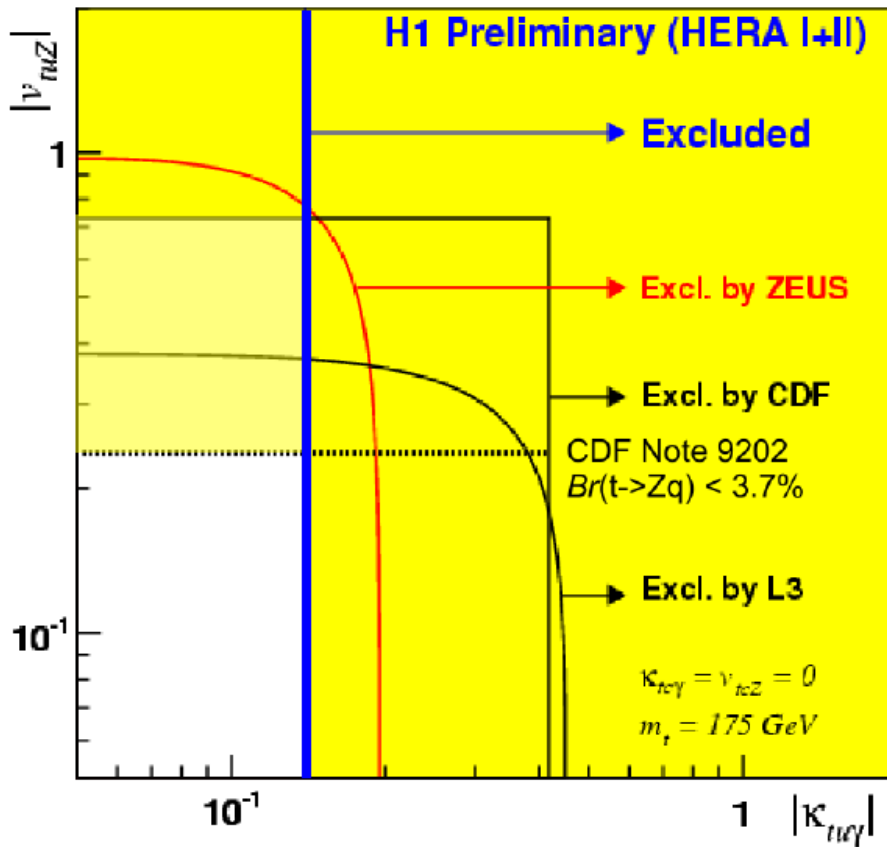
$F_+ = 1 - F_- - F_0$



Isolated Lepton Events & Single Top Production

H1prelim-07-163; ZEUS, Phys. Lett. B559 (2003) 153, addendum: DESY-03-188

Negligible **SM** production cross section ($\sim 1\text{fb}$)
 → Search for **anomalous** single top production
 (SM W production is background)



FCNC (Flavor changing neutral current)

- ZEUS limits based on HERA-1 data
- Limits more stringent for lower top quark mass, e.g. for ZEUS:

m_t (GeV)	175	170
$k_{tu\gamma}$	< 0.199	< 0.175
v_{tuZ}	< 0.98	< 0.87

Generic Searches

HERA II

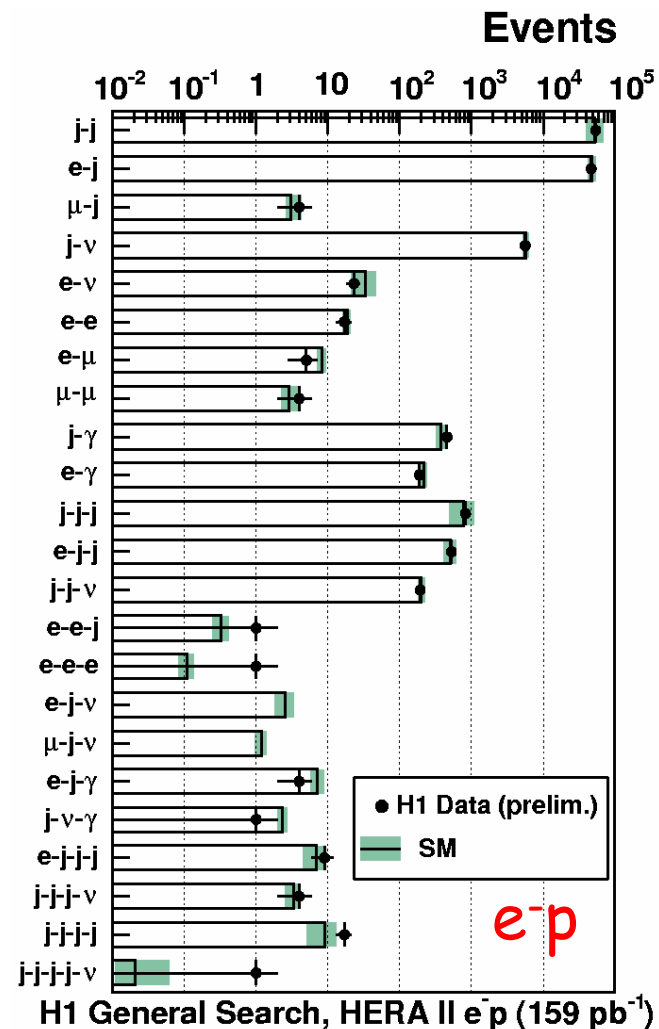
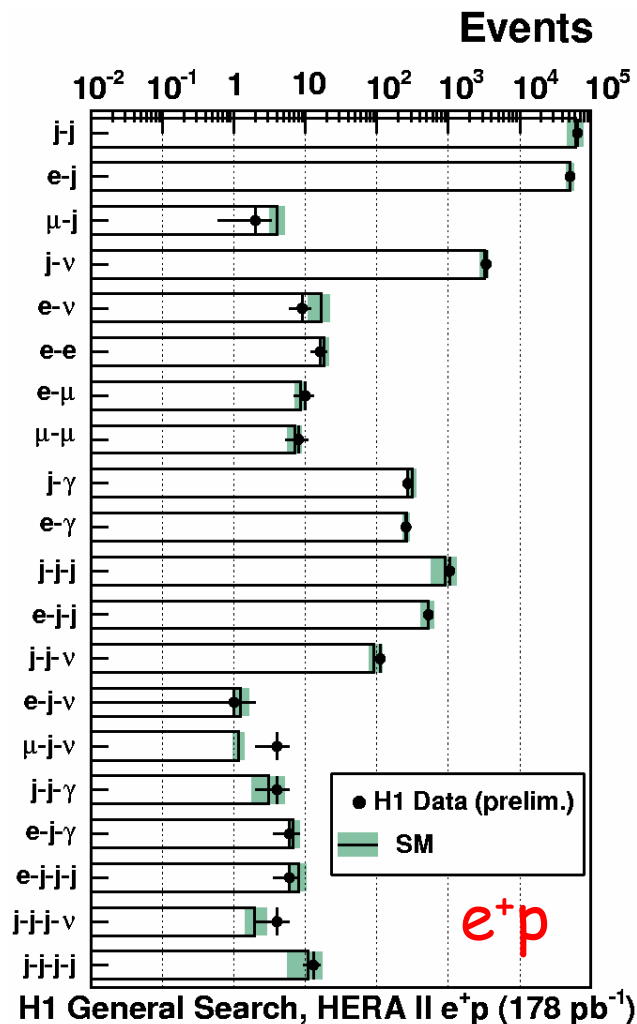
H1prelim-07-061

Analyze 2 to 4 body topologies at high P_T (>20 GeV) in common angular region ($\theta: 10^\circ-140^\circ$)

Results on HERA I (117 pb^{-1}) published (H1, PLB602 (2004) 14)

Excellent agreement data/expectation in most of the topologies

Good understanding of the detector and SM processes



Summary

- Rich EW and BSM search results (not all latter results have been shown)
 - Precision EW results with full HERA (H1+ZEUS combined) data yet to come
 - Search results, based mostly on the full HERA data,
 - found in general no significant deviation with the SM expectations
 - except in H1 e^+p sample where
 - * isolated lepton events with large transverse missing energy &
 - * multi-lepton events at high transverse momentahave excess up to 3σ but they are not confirmed by ZEUS
 - limits are often comparable to or more stringent than those from LEP and Tevatron which may remain true until LHC
- ➔ Publish the (ongoing) searches before LHC startup