EW and BSM Results from HERA

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On behalf of

Overview

Most of the results shown are

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

	HERA-1	HERA-2
e-	~20pb^{-1}	~200pb^{-1}
e+	~100pb^{-1}	~200pb^{-1}

➔ H1/ZEUS: 0.5fb^{-1}/exp

➔ H1+ZEUS: ~1fb^{-1}

Both EW and BSM results rely on

- either dominant inclusive DIS processes (neutral & charged current)

  advantage: high statistics

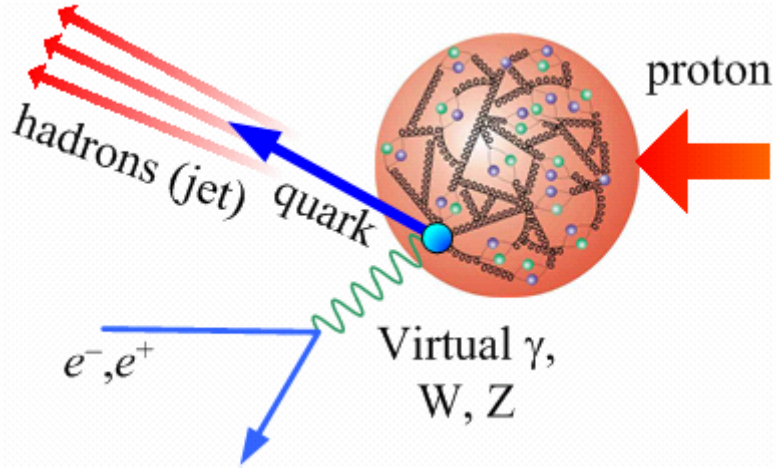
- or rare exclusive processes (single real W and lepton pair productions)

  advantage: well defined final states

Dominant SM Inclusive DIS Processes at HERA

Neutral Current (NC) Process:

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



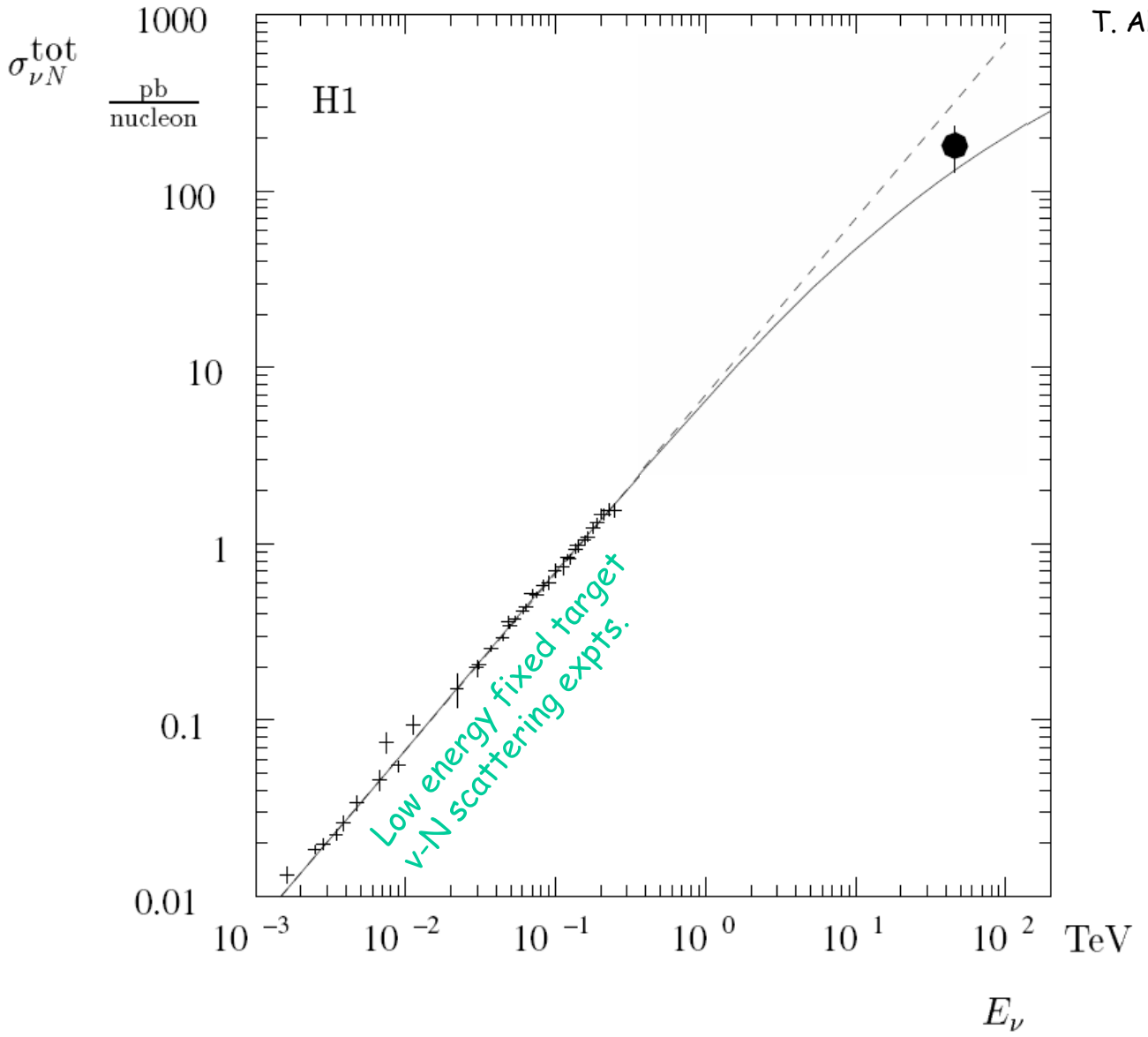
Charged Current (CC) Process:

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

- ➔ 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 pb^{-1}

ep collider of
26.7 GeV • 820 GeV

a fixed target exp. of
~50TeV

Early W (Propagator) Mass Determinations

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

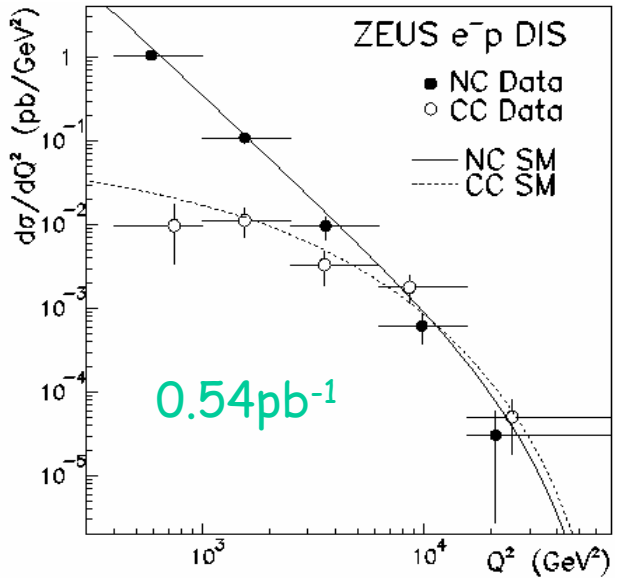
Fit to CC cross sections

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

First plot showing the EW unification in DIS

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

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



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

Fit to CC cross sections

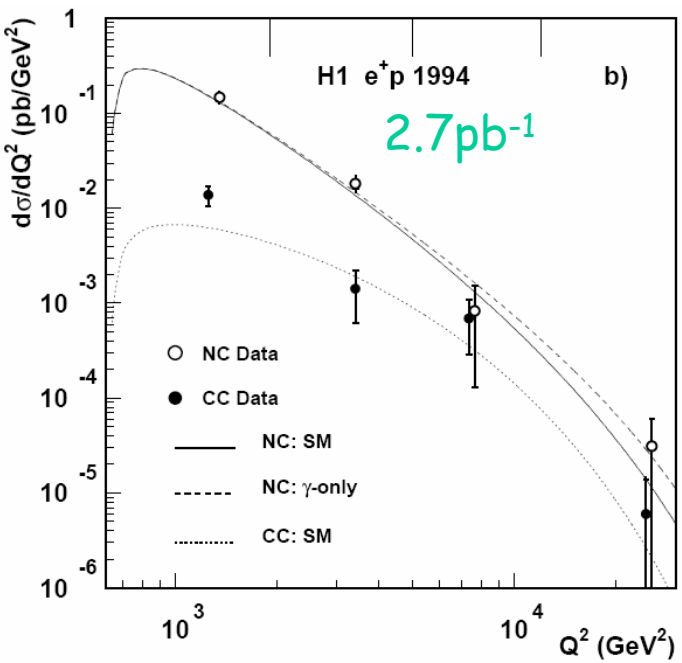
$m_W(e^-p) = 78\,^{+11}_{-9}\,^{+4}_{-3}$ GeV L(e-): 0.29pb^{-1}

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

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

e^-p and e^+p combined:

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



M_W: Improvement No.1

ZEUS (Eur. Phys. J. *C*3(00)411, Erratum, *C*27(03)):

A simultaneous G_F-M_W fit:

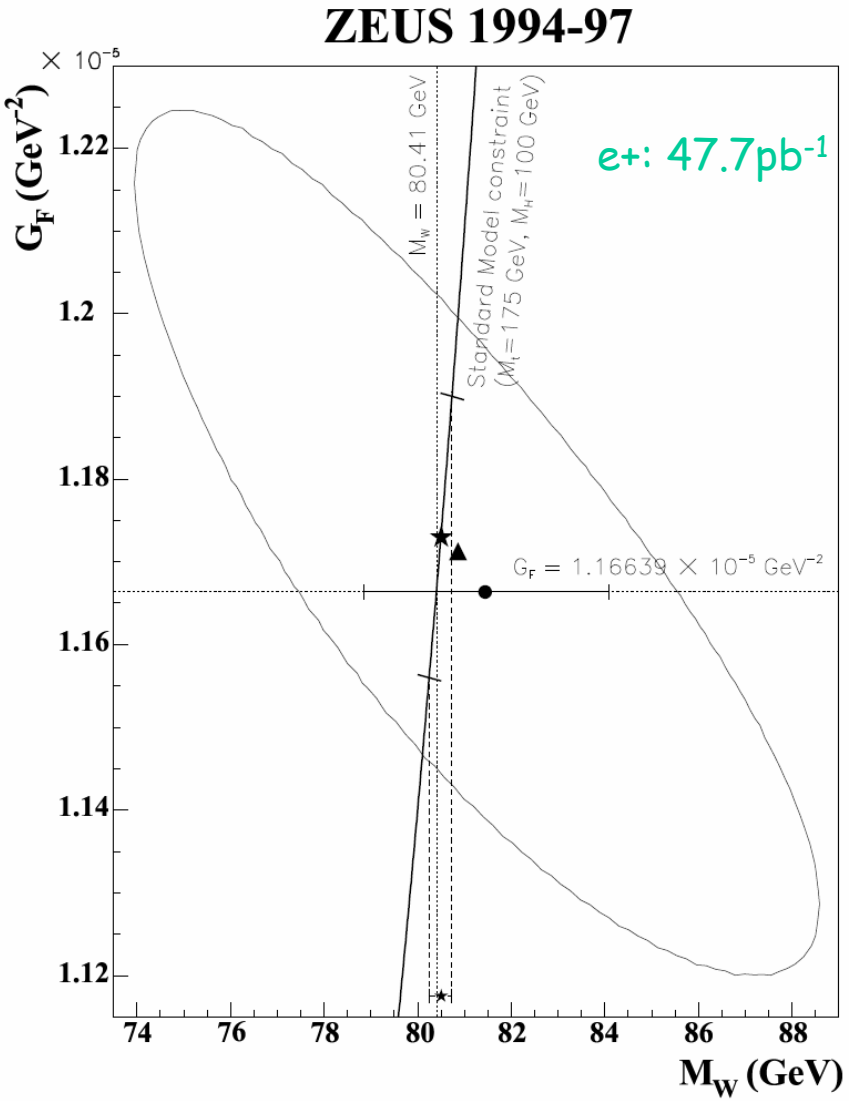
$$M_W = 80.8^{+4.9}_{-4.5}\,(\text{stat.})^{+5.0}_{-4.3}\,(\text{syst.})^{+1.4}_{-1.3}\,(\text{PDF})\ \text{GeV}$$

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:

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



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

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:

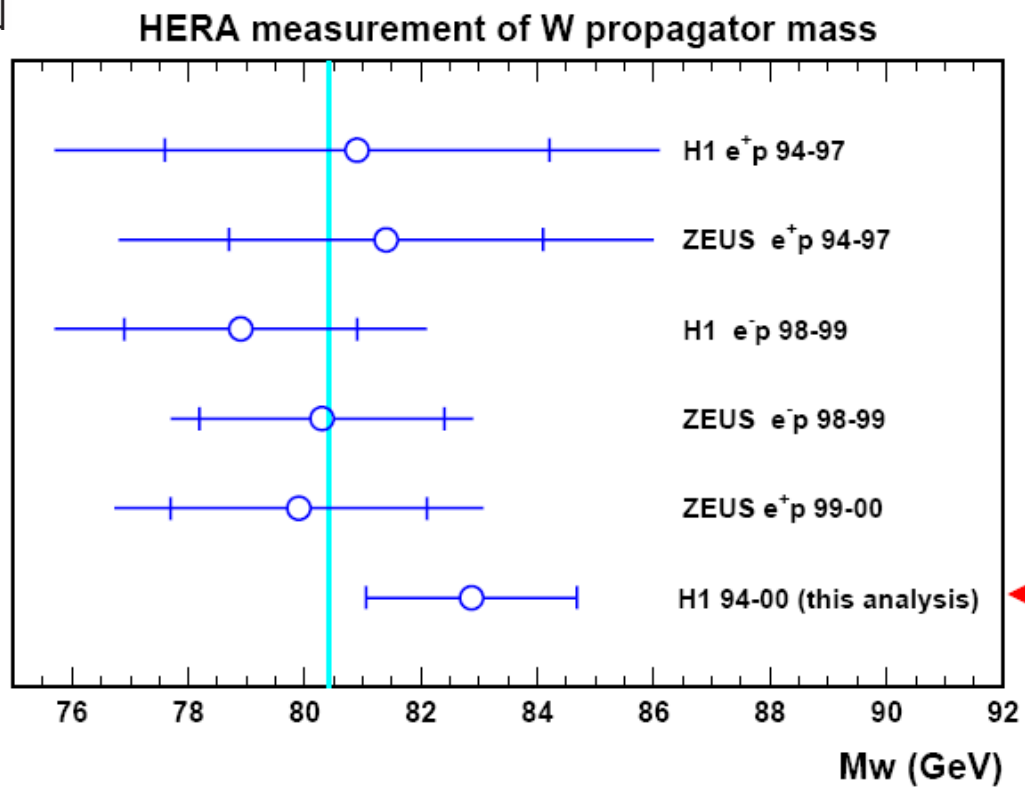
$$M_{\text{prop}} = 82.87 \pm 1.82_{\text{exp}}\ ^{+0.30}_{-0.16}\big|_{\text{model}}\ \text{GeV}$$

W mass within the SM:

$$M_W = 80.786 \pm 0.205_{\text{exp}}\ ^{+0.063}_{-0.098}\big|_{\text{th}}$$

➔ Indirect determination:

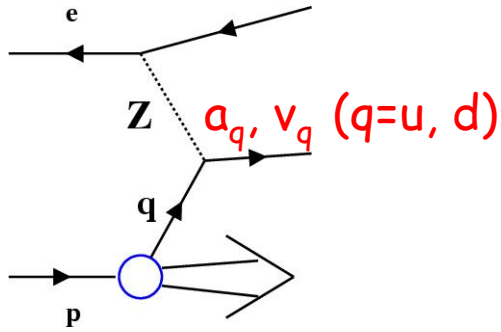
$$\sin^2\theta_W = 0.2151 \pm 0.0040_{\text{exp}}\ ^{+0.0019}_{-0.0011}\big|_{\text{th}}$$



Light Quark Couplings to Z (HERA-1)

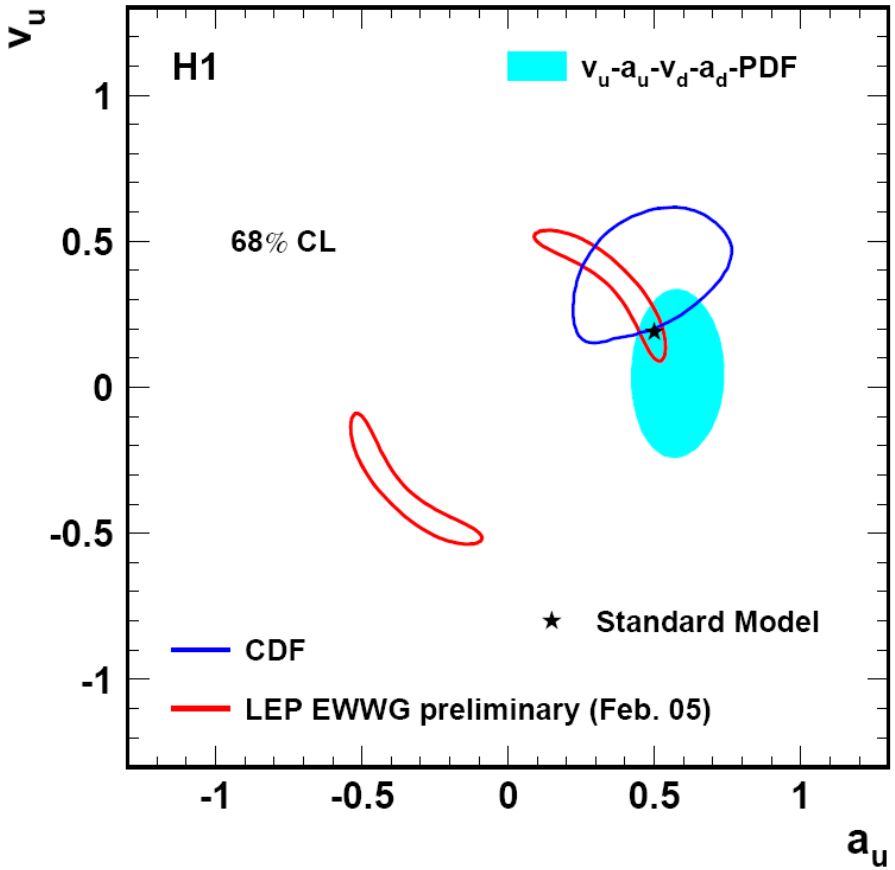
H1 (Phys. Lett. B632(06)35, hep-ex/0507080):

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	$\alpha, M_Z, M_W, v_u, a_u$
$I^3_{u,R}$-$I^3_{d,R}$-PDF	G_F, M_W	$\alpha, M_Z, M_W, v_{q,L}, a_{q,L}$



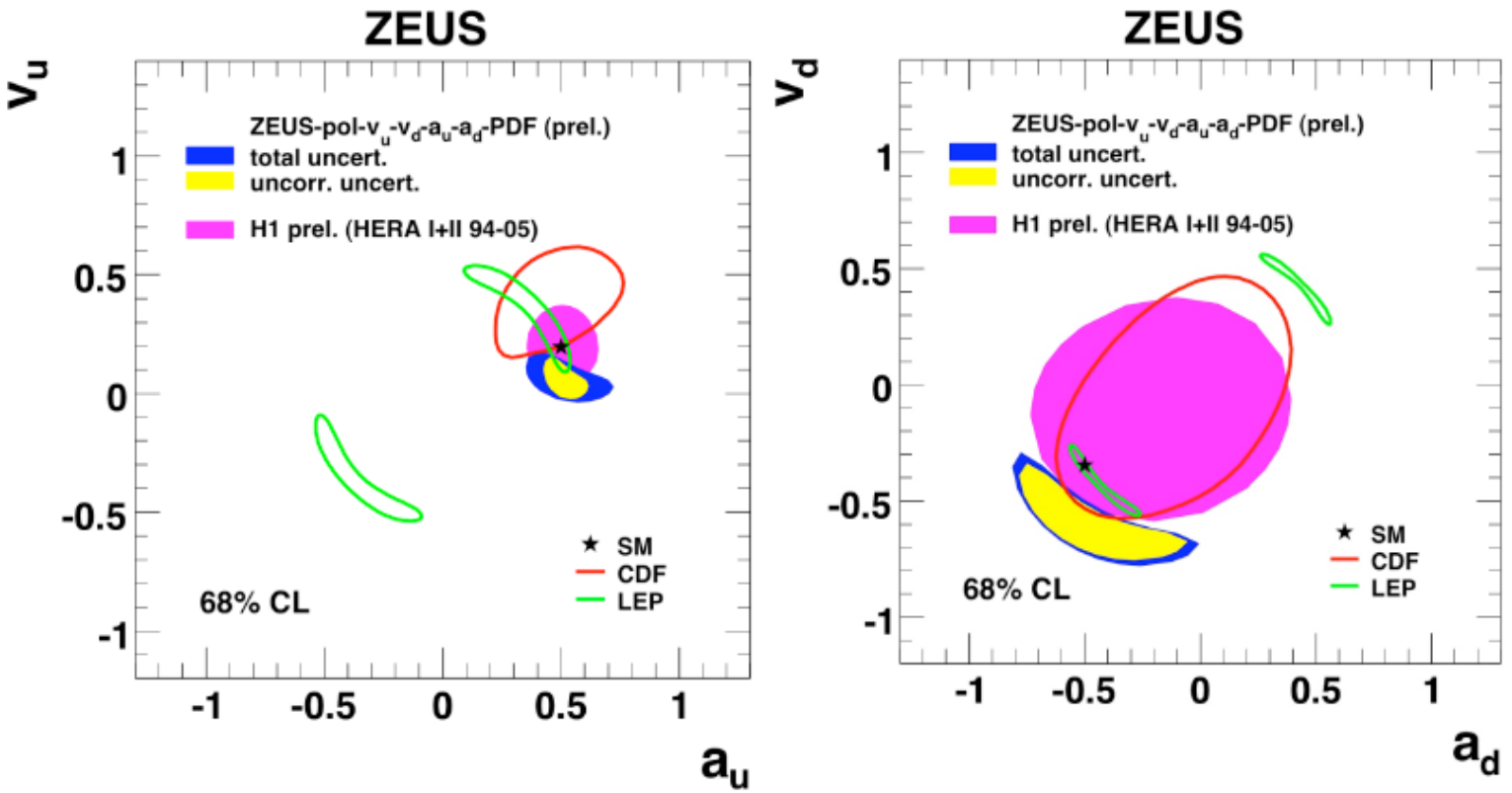
- Tevatron: qq→ee Drell-Yan, A_{FB}
- LEP: ee→qq(γ) ($a^2_q+v^2_q$)
- Similar results on d couplings (unshown, less constrained)

➔ HERA-1 results competitive
➔ HERA data resolve sign ambiguity



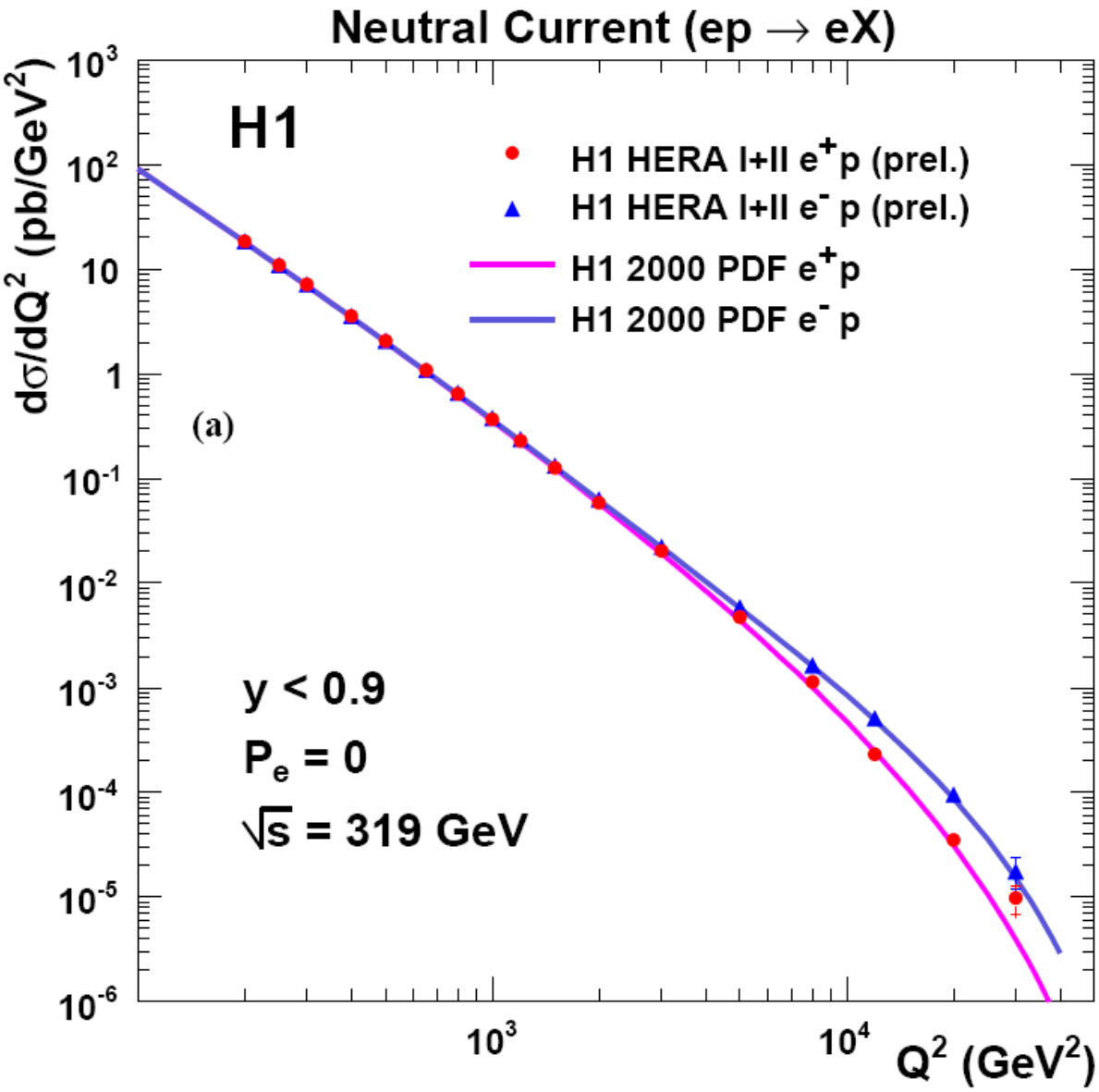
Preliminary Results Including HERA-2 Data

- 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



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

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

Assume e point-like (f_e=1)

H1:

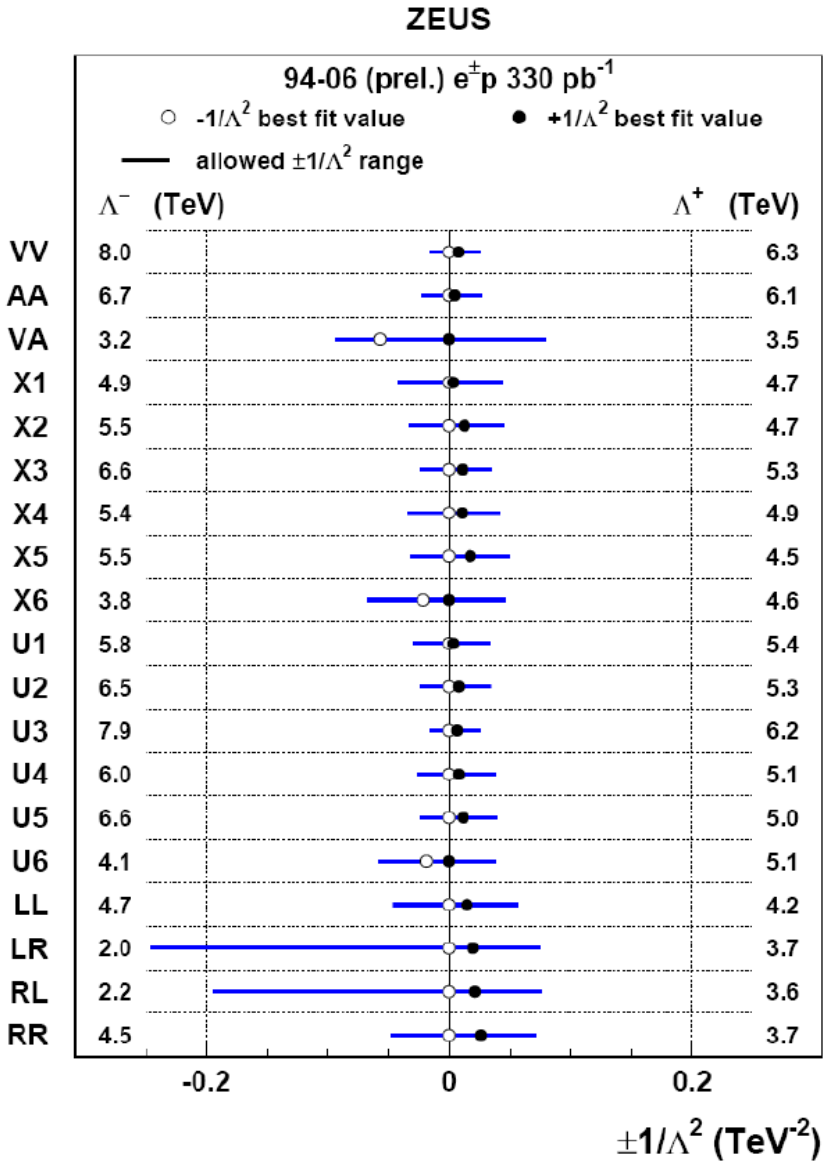
$\langle r_q \rangle < 0.74 \times 10^{-3}$ fm (95%CL)

ZEUS:

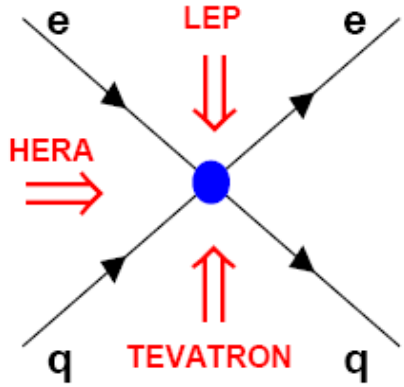
$\langle r_q \rangle < 0.62 \times 10^{-3}$ fm (95%CL)

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



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



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

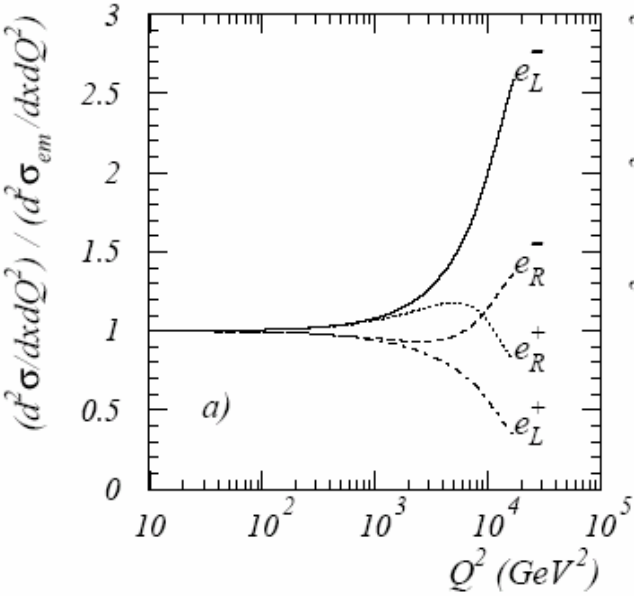
Typical excluded scale > 5TeV

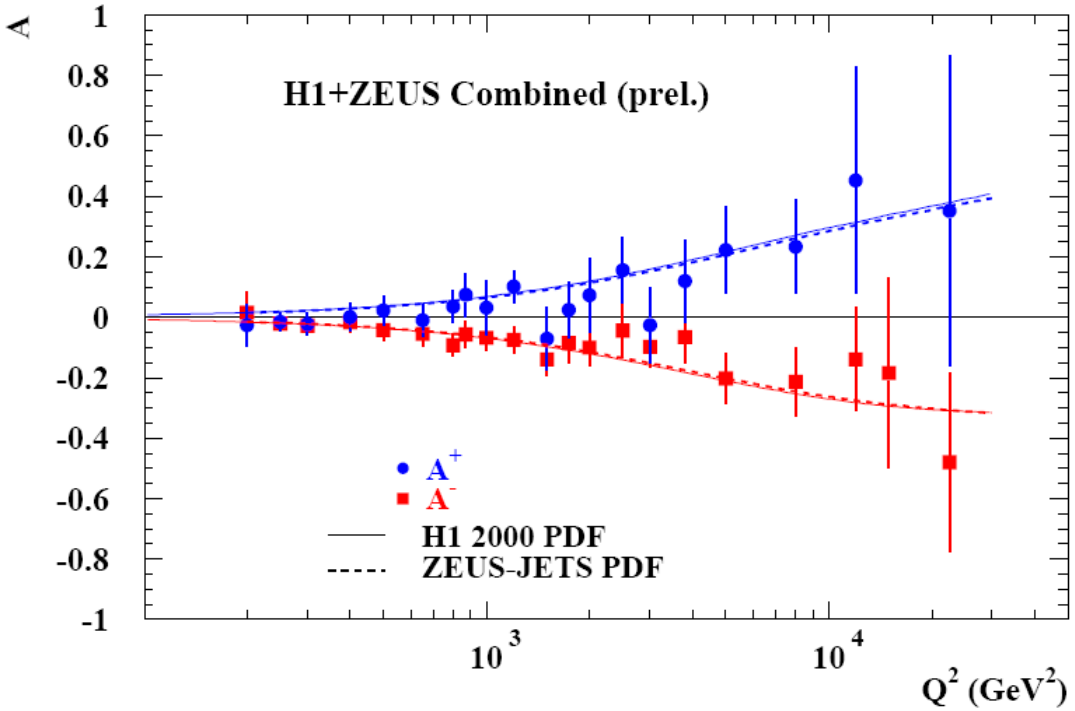
Similar sensitivity from Tevatron in Drell-Yan

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

Remember at high Q^2,
- Z (γZ interference) important
- e beam polarized at HERA-2

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



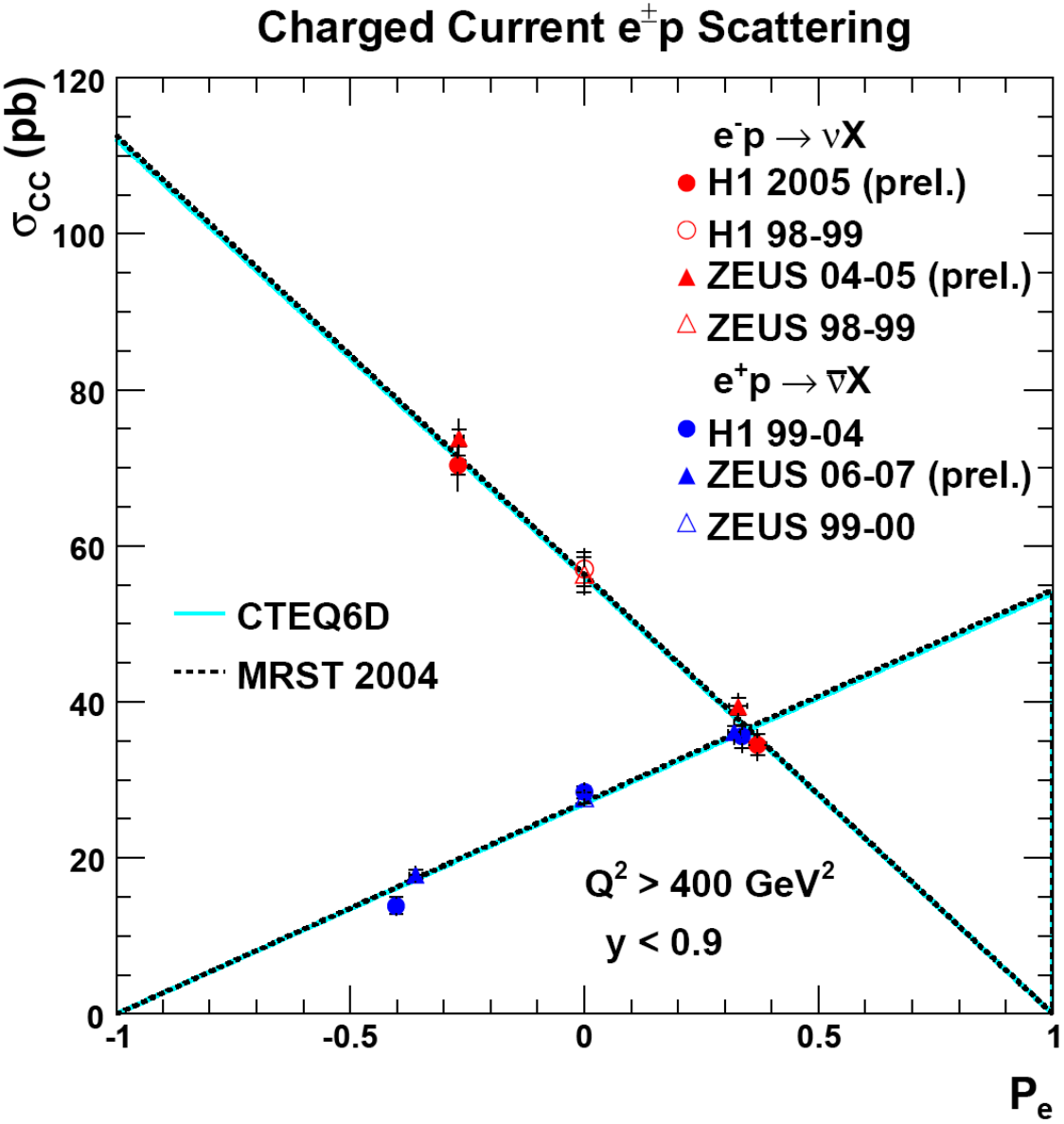


Define an asymmetry:

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

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

CC Cross Section & Right-Handed W Boson



Extrapolated cross sections~0
- at P_e=+1 for e-
- at P_e=-1 for e+

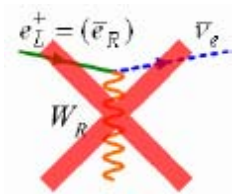
➔ Only left-hand W in SM

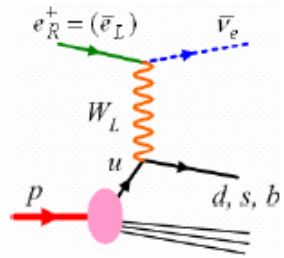
If g_L=g_R & ν_R light

➔ H1: M_{WR}>208 GeV (95%CL)

Improvement expected with full HERA-2 data

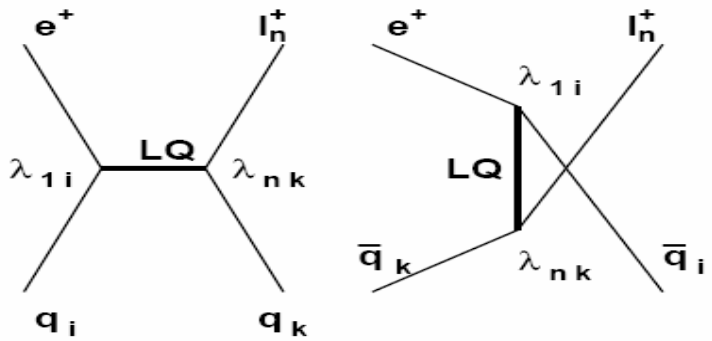
Although Tevatron limit is more stringent

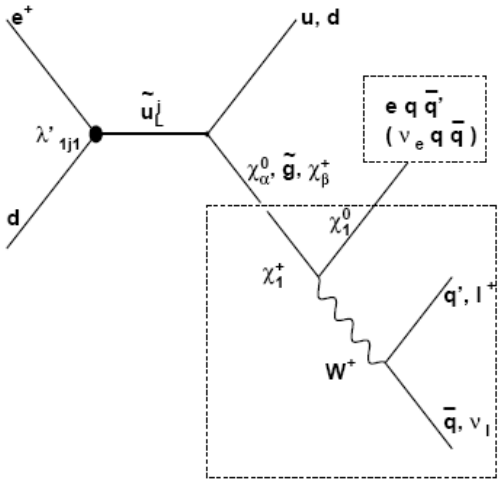


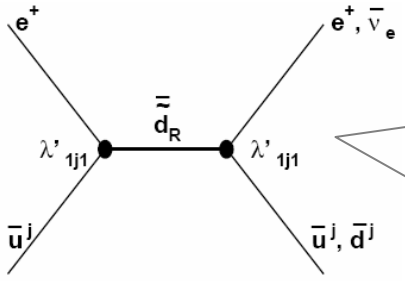


Other Searches in Inclusive DIS

Leptoquarks (LQs):
- resonances in s-channel
- final state identical to DIS events

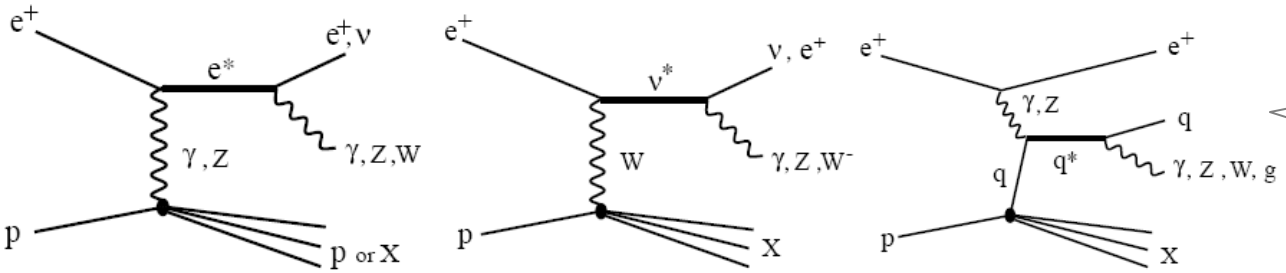






Squarks in R-parity* violating SUSY:
- similar to LQs
- but it can have gauge decay modes

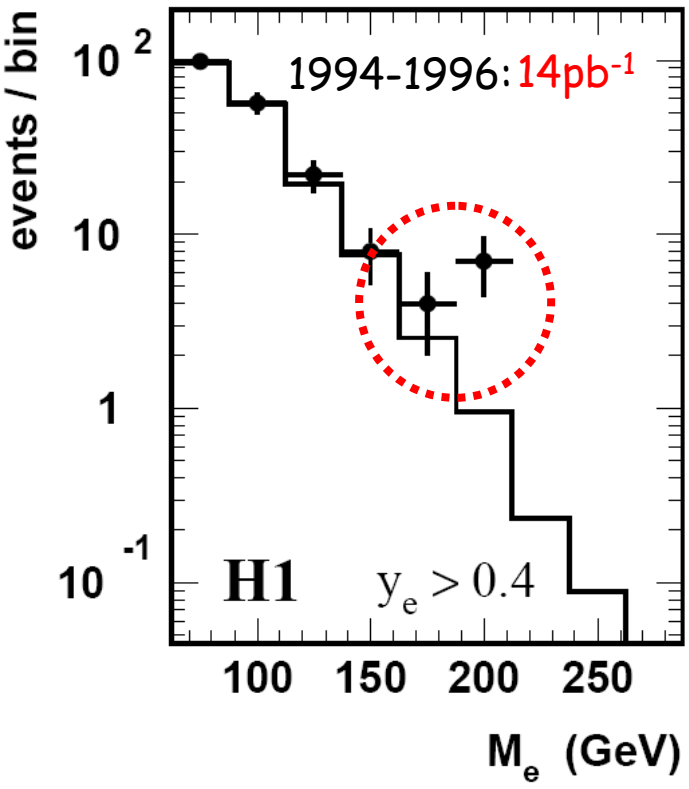
* R-parity=$(-1)^{3B+L+2S}$



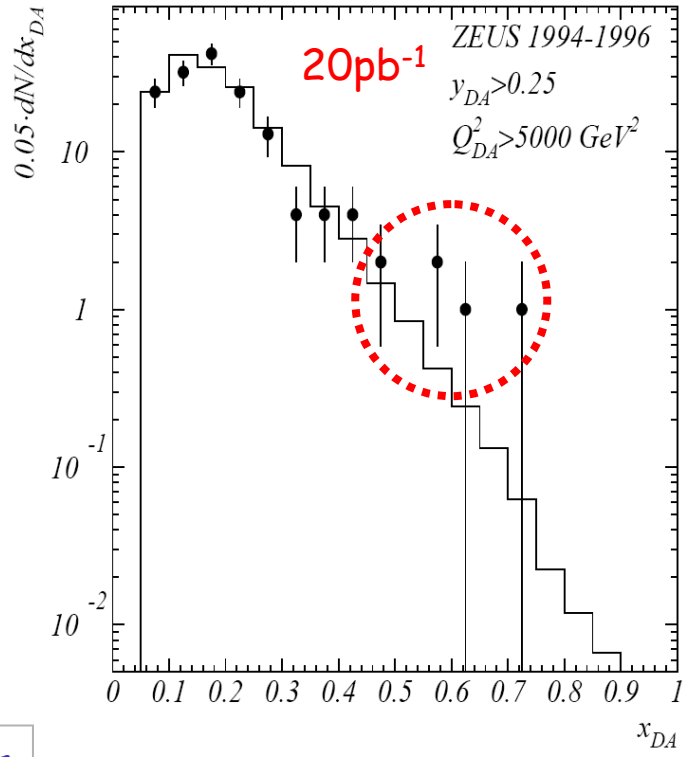
Excited fermions:
- have gauge boson (decay) in final state

Remember an Old Exciting Moment in 1997

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



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

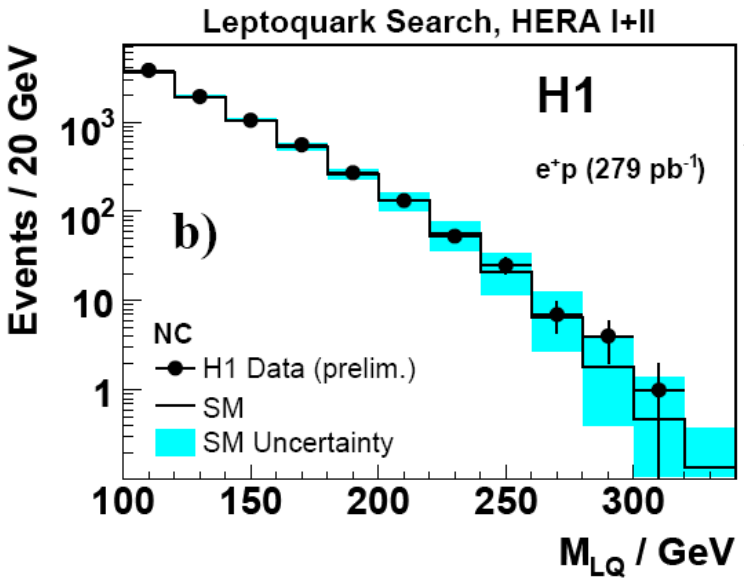


$M^2=xs$

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

The "Final" Word of HERA on LQs

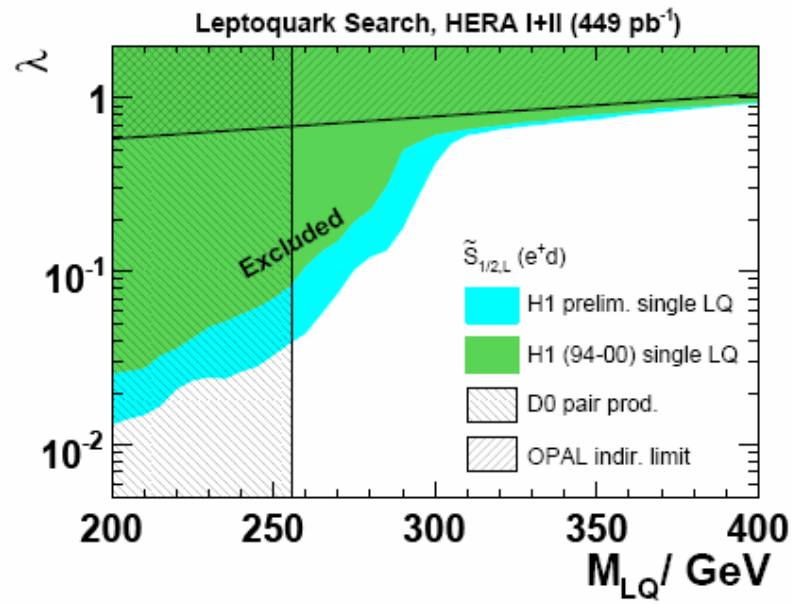
H1 HERA-1+2: H1prelim-07-164
ZEUS HERA-1: Phys. Rev. D68 (2003) 052004

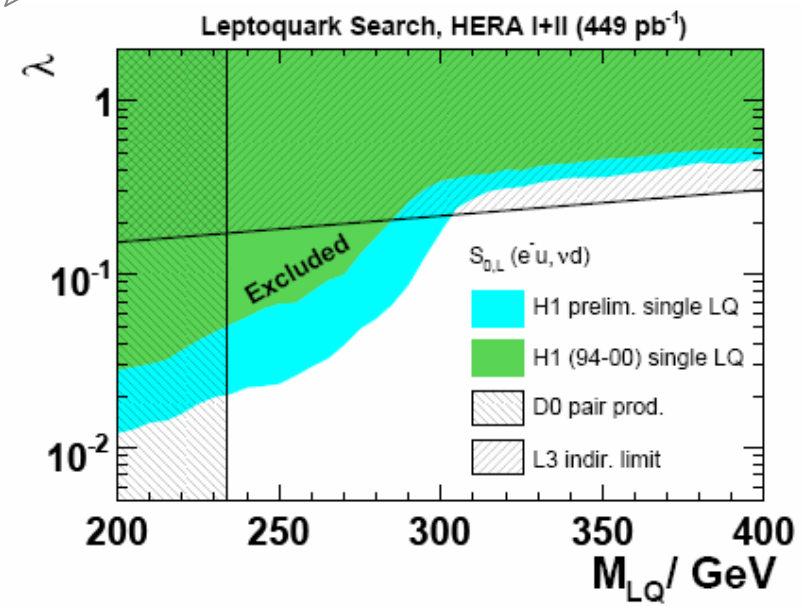


Unfortunately no more excess/deviation in the whole spectrum

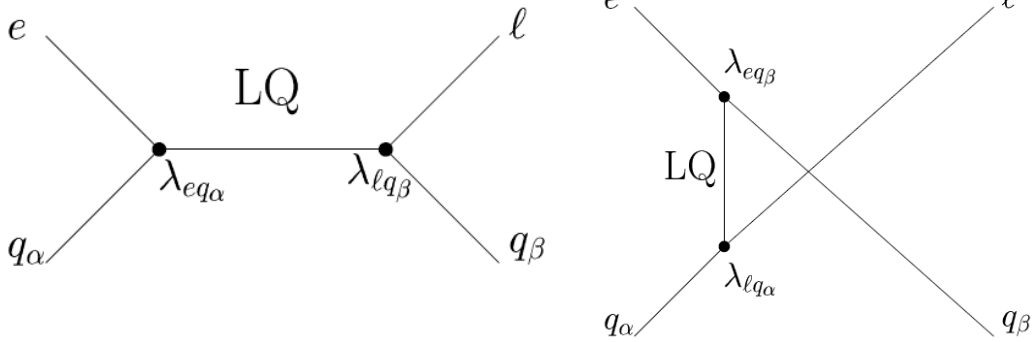
HERA may have the most stringent constraints on LQs until LHC

ZEUS has similar mass dis. and limits





Lepton Flavor Violating LQs

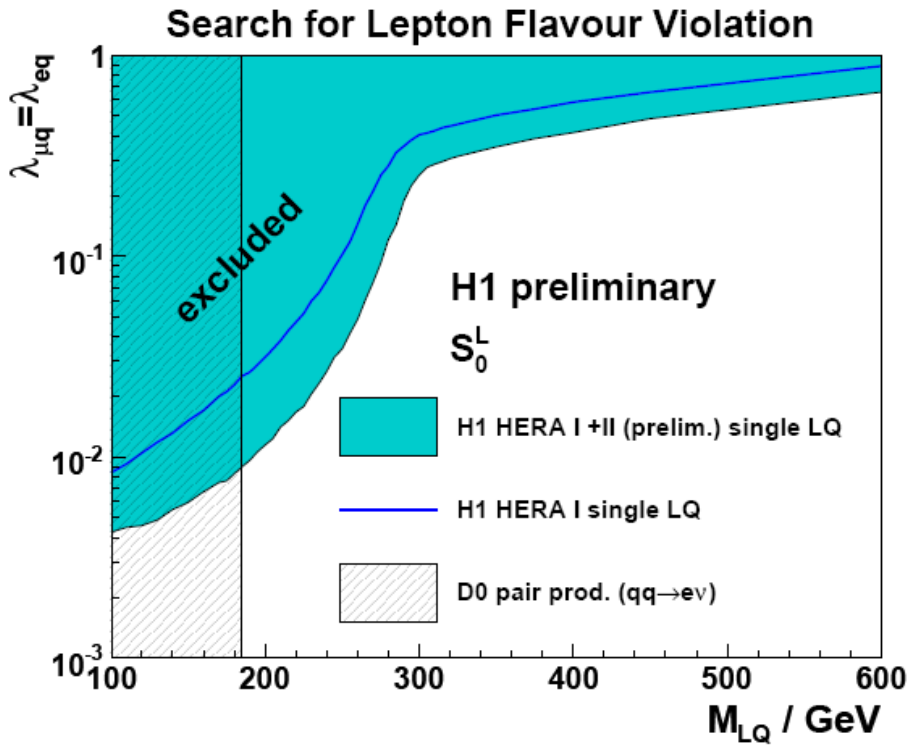


H1 HERA1+2: H1prelim-07-167
ZEUS HERA-1: Eur. Phys. J. C44 (2005) 463

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

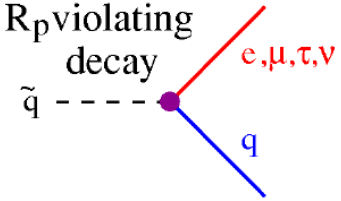
H1 has preliminary limits for full e-p data sample (HERA-2 has a 10-fold increase)

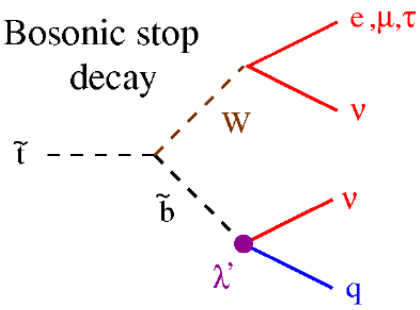
HERA limits in general more stringent than others (e.g. rare lepton and meson decays, muon-electron conversion on nuclei)

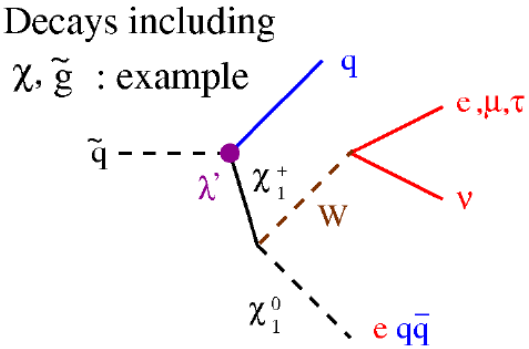


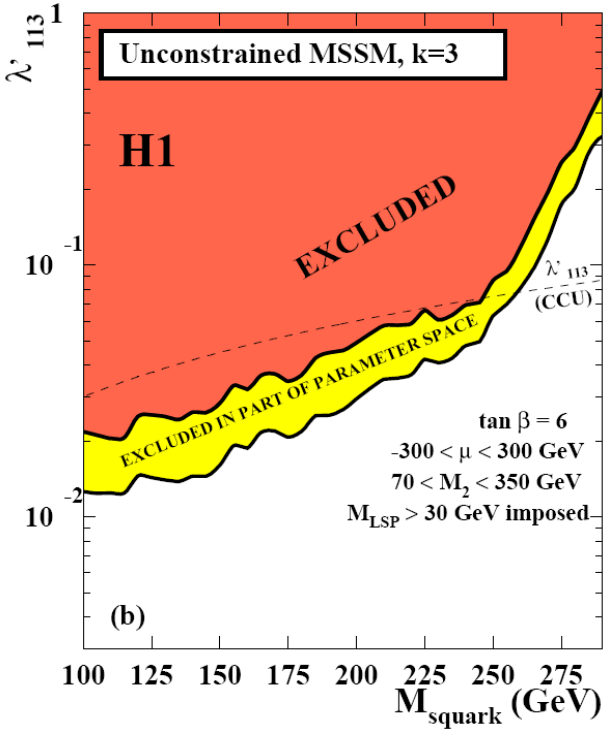
Searches for R-Parity Violating SUSY

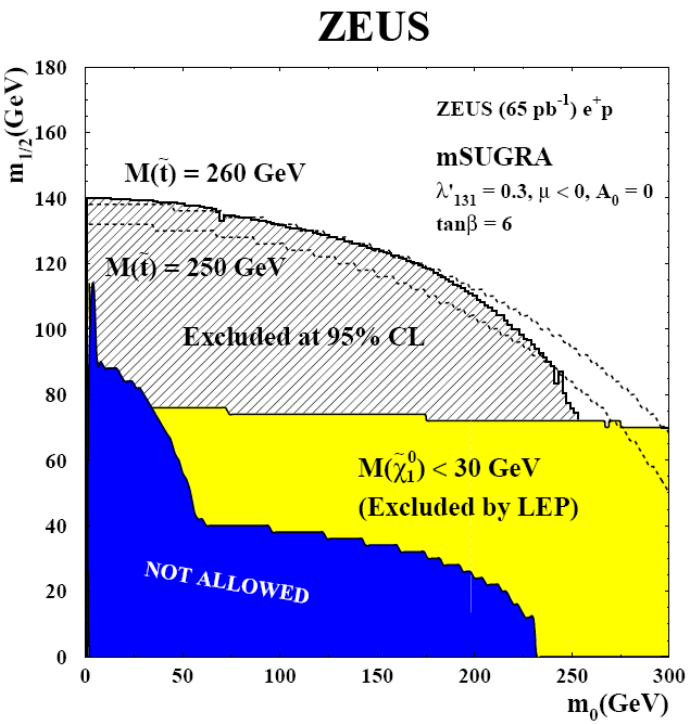
Limits on LQs also apply to squarks if R-parity violating decay dominates





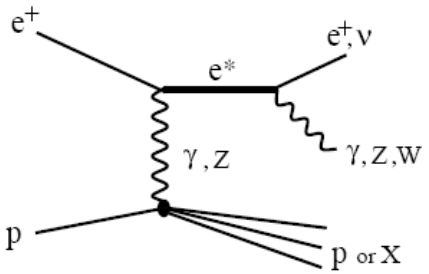


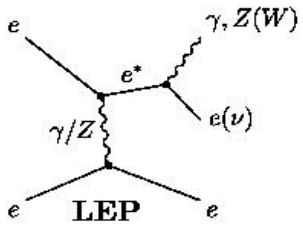


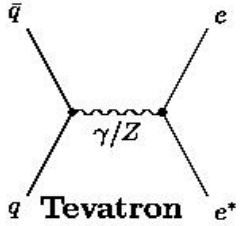


Dedicated scan in both MSSM and mSUGRA parameter space performed by **H1** with HERA-1 data (Eur. Phys. J. C36 (2004) 425) and by **ZEUS** for stop (Eur. Phys. J. C50 (2007) 261)

Excited State of Electrons







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

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

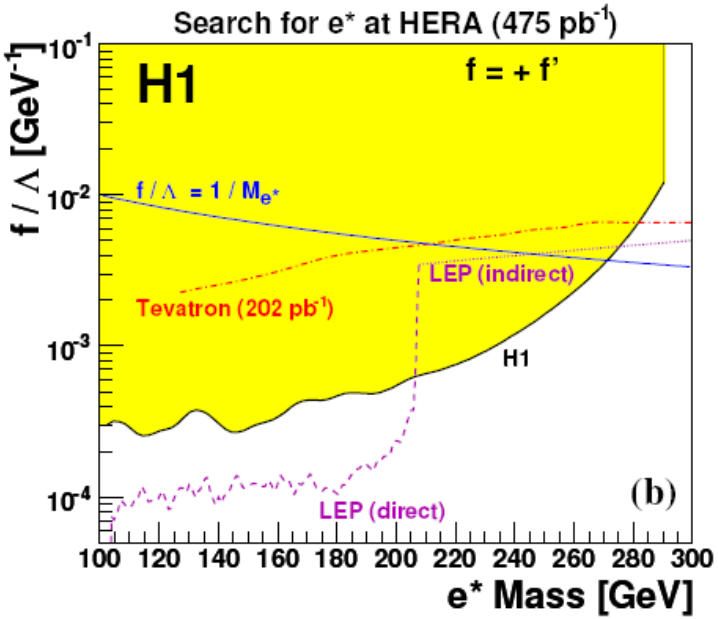
Channel	Data	SM	Signal Efficiency [%]
$e^* \to e\gamma$ (ela.)	42	48 ± 4	60–70
$e^* \to e\gamma$ (inel.)	65	65 ± 8	60–70
$e^* \to \nu W \to \nu q\bar{q}$	129	133 ± 32	20–55
$e^* \to \nu W \to \nu e\nu$	4	4.5 ± 0.7	60
$e^* \to eZ \to e\nu\nu$			35
$e^* \to eZ \to eq\bar{q}$	286	277 ± 62	20–55
$e^* \to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

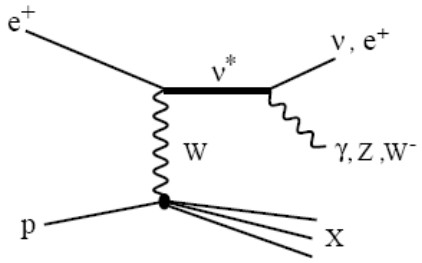
Relative coupling strength for SU(2)

Relative coupling strength for U(1)



Excited State of Neutrinos

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

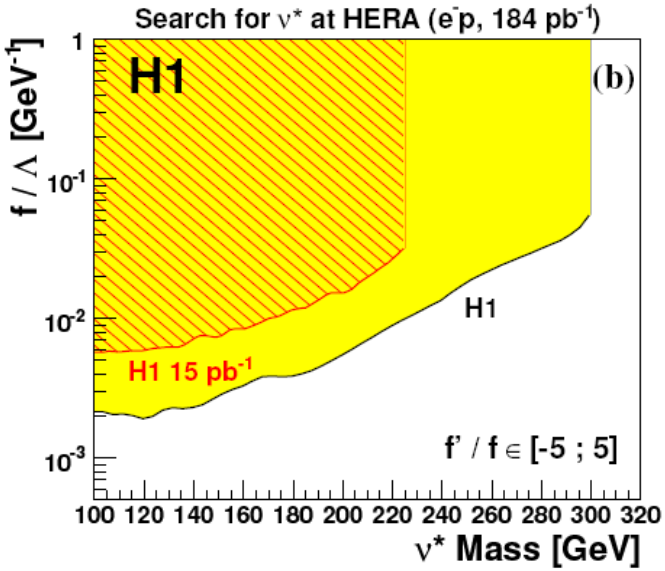


Search for ν^* at HERA (e^-p, 184 pb^{-1})

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

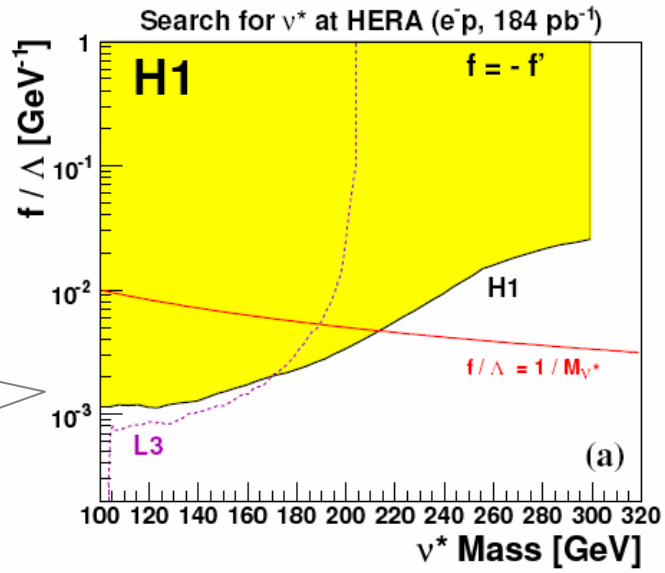
ν* cross section in e⁻p is much larger than that in e⁺p

➔ Search sensitivity best in e⁻p



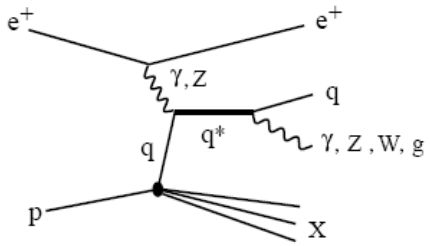
Significant improvement over HERA-1 data due to 10-fold increase in L

HERA (H1) limit more stringent for M_{ν^*}>~170GeV



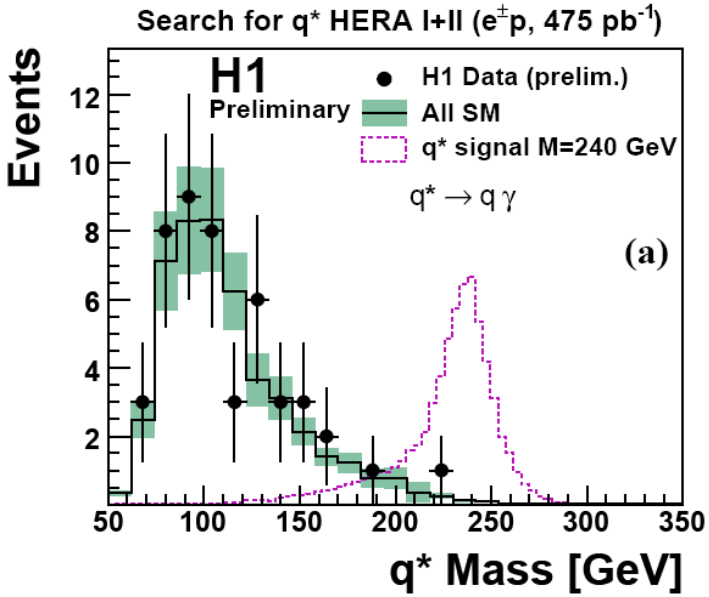
Excited State of Quarks

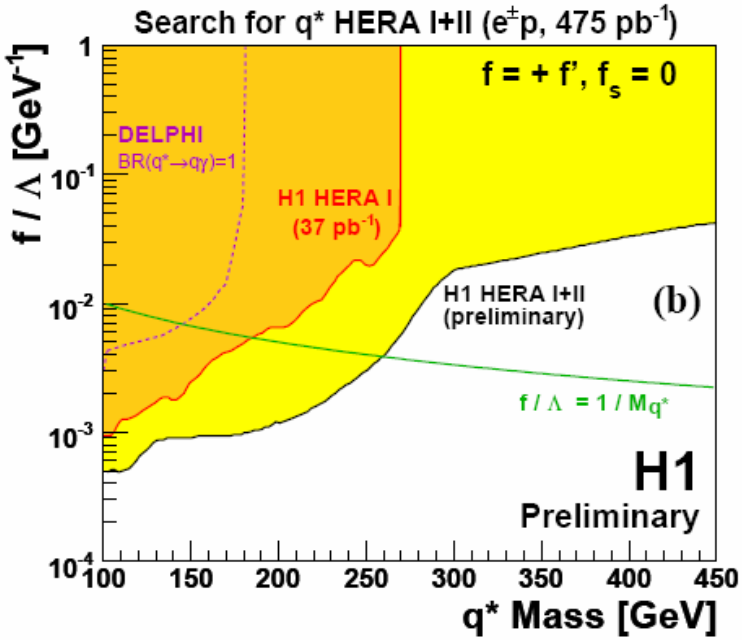
H1prelim-08-161



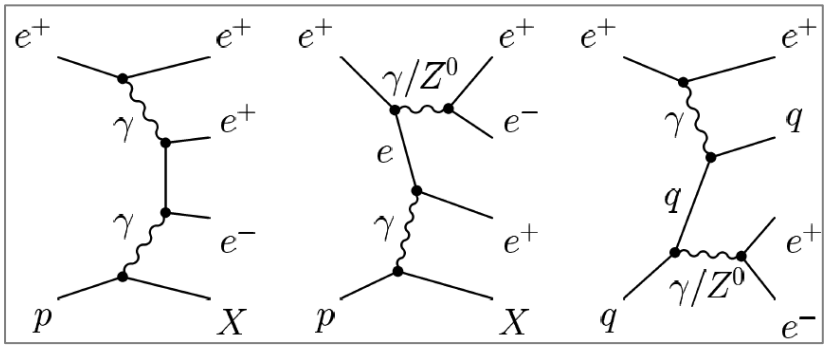
Search for q^*, HERA I+II (475 pb^{-1}, preliminary)

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



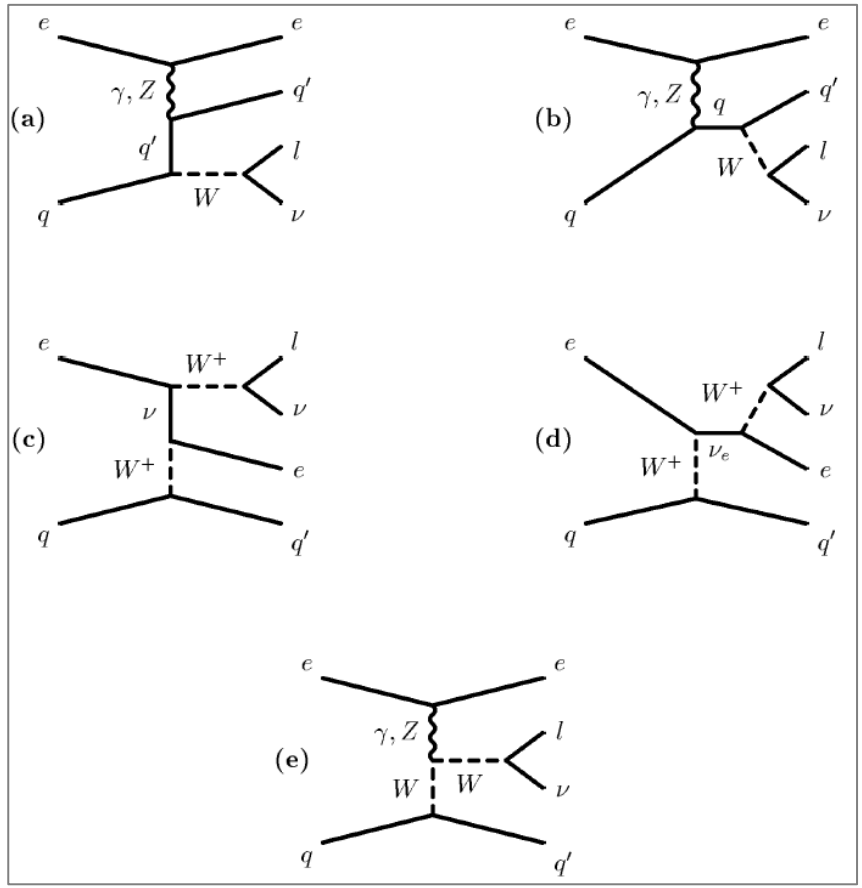


Search for New Physics in Rare Excl. Processes



Pair production

➔ Multi-leptons + high P_T



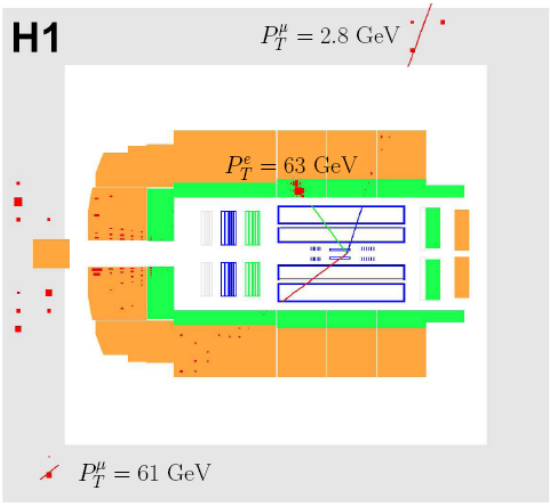
Single real W production

➔ Isolated lepton + missing E_T

Multi-Lepton Events @ High P_T

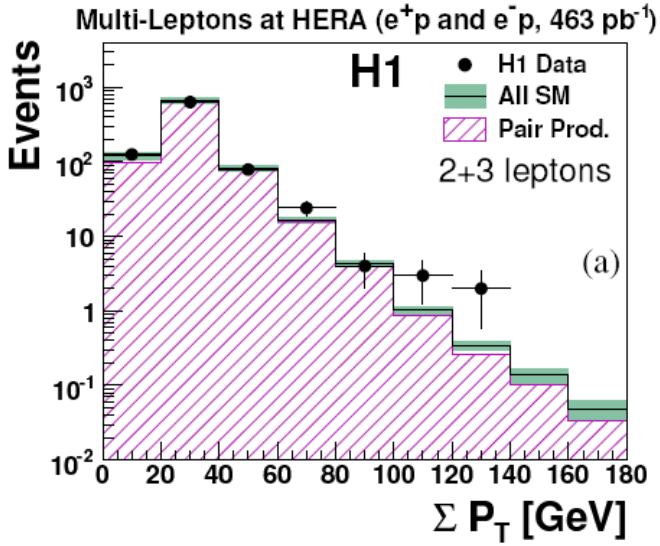
1st excess reported in 2003 by H1 in 2e, 3e modes
(H1, Eur. Phys. J. C31 (2003) 17)

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



- At high mass (M_{ll} > 100 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 GeV):

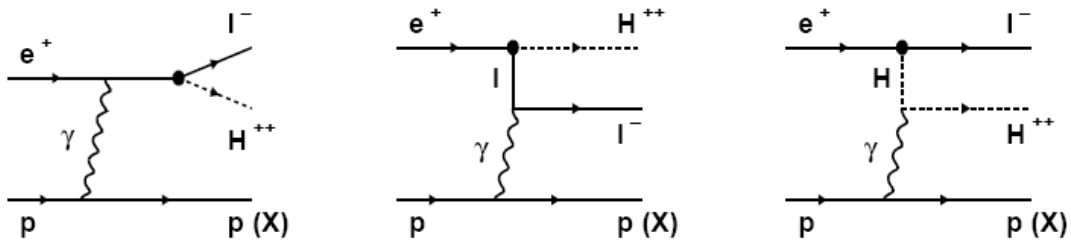
Data set	H1 publication	
	Data	SM (pair)
e^+p	5	0.96±0.12 (0.78)
e^-p	0	0.64±0.09 (0.51)
All	5	1.60±0.20 (1.29)

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, eμ or eτ pair of high P_T leptons with like charge

For m_{el}>65GeV, obs/exp are

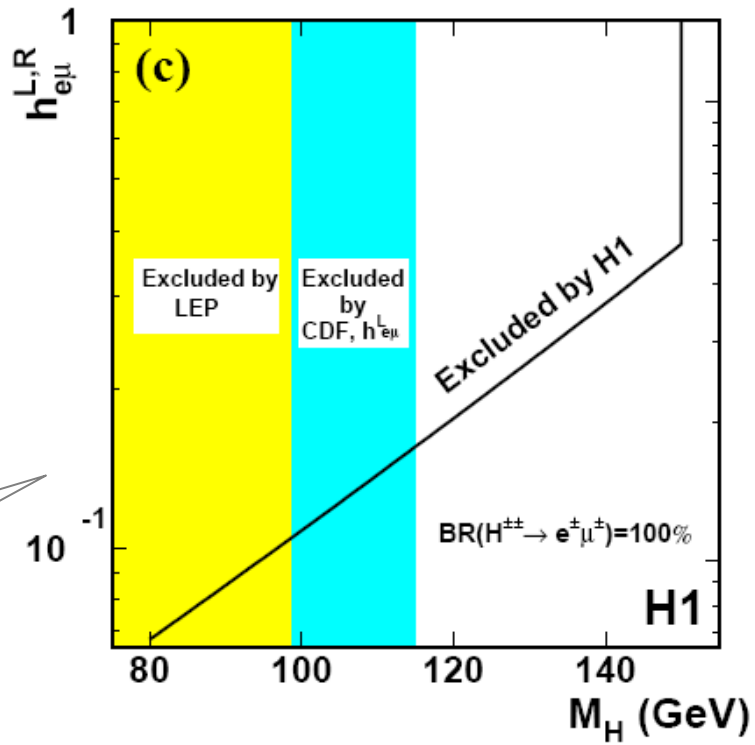
3 / 2.45±0.11 (ee)

1 / 4.17±0.44 (eμ)

1 / 2.07±0.54 (eτ)

➔ Limits on $\sigma(H^{++})\cdot Br(el)$ vs. M_H

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

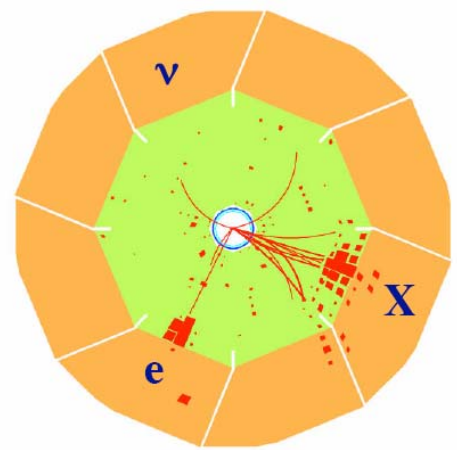


Isolated Lepton Events with Large Missing P_T

1st excess seen by H1 & published in 1998

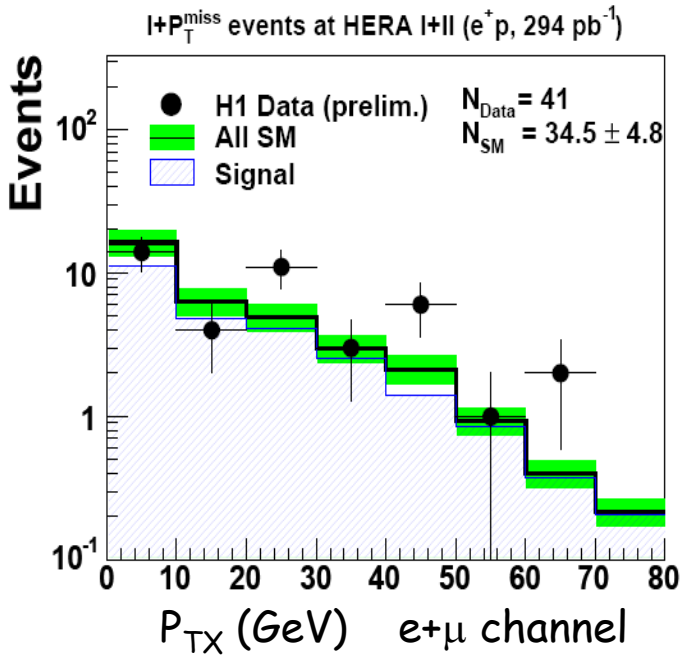
(H1 Collab., Eur. Phys. J. C5 (98) 575)

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:

$\sigma_{ep\to lWX} = 0.89^{+0.25}_{-0.22}$ (stat) ± 0.10 (syst) [pb] @ $\sqrt{s}$=316 GeV

H1 (preliminary):

$\sigma_{ep\to lWX}$ = 1.23 ± 0.25 (stat) ± 0.22 (syst) [pb] @ $\sqrt{s}$=320 GeV

In agreement with the SM expectation:

$\sigma_{ep\to lWx}$ = 1.2 pb @ $\sqrt{s}$=316 GeV
= 1.3 pb @ $\sqrt{s}$=320 GeV

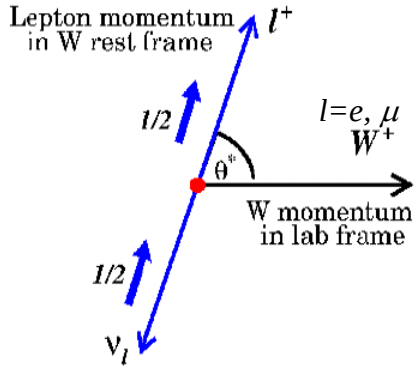
NLO calculation has an uncertainty of ±15%!

➔ Both measurements have a significance of ~5 standard deviations

W Polarization Fractions @ HERA

H1prelim-07-161

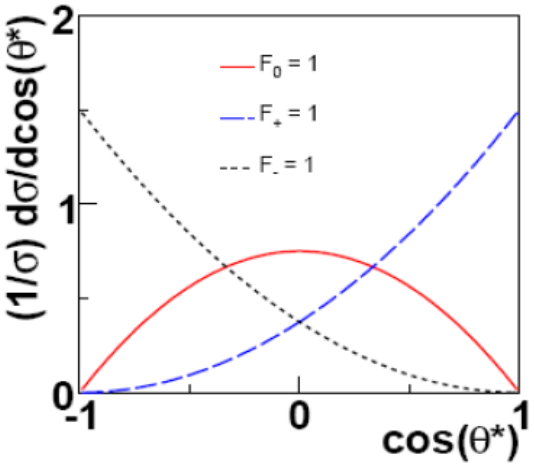
Restricted to the isolated lepton sample in which a W is reconstructed

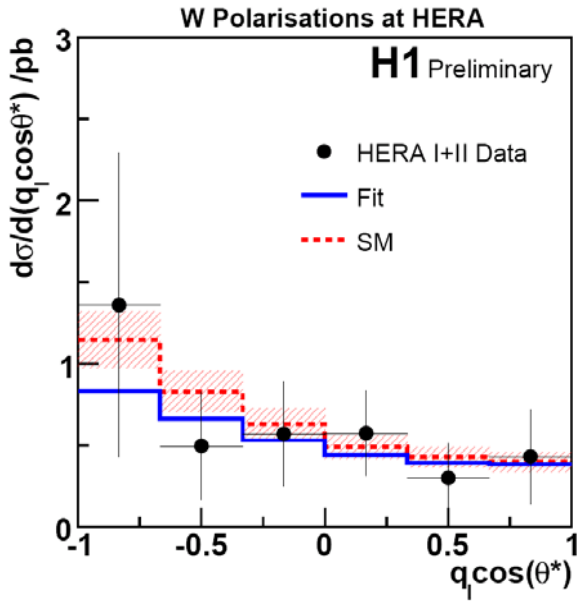


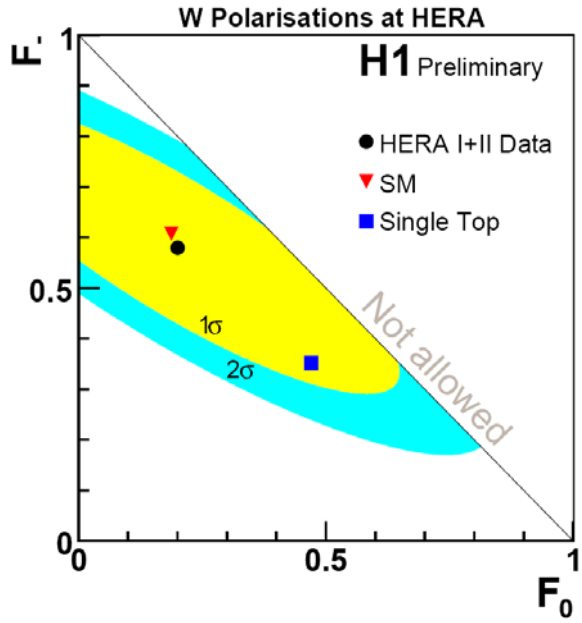
Angular distribution and polarization fractions:

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

left longitudinal right $F_+ = 1 - F_- - F_0$







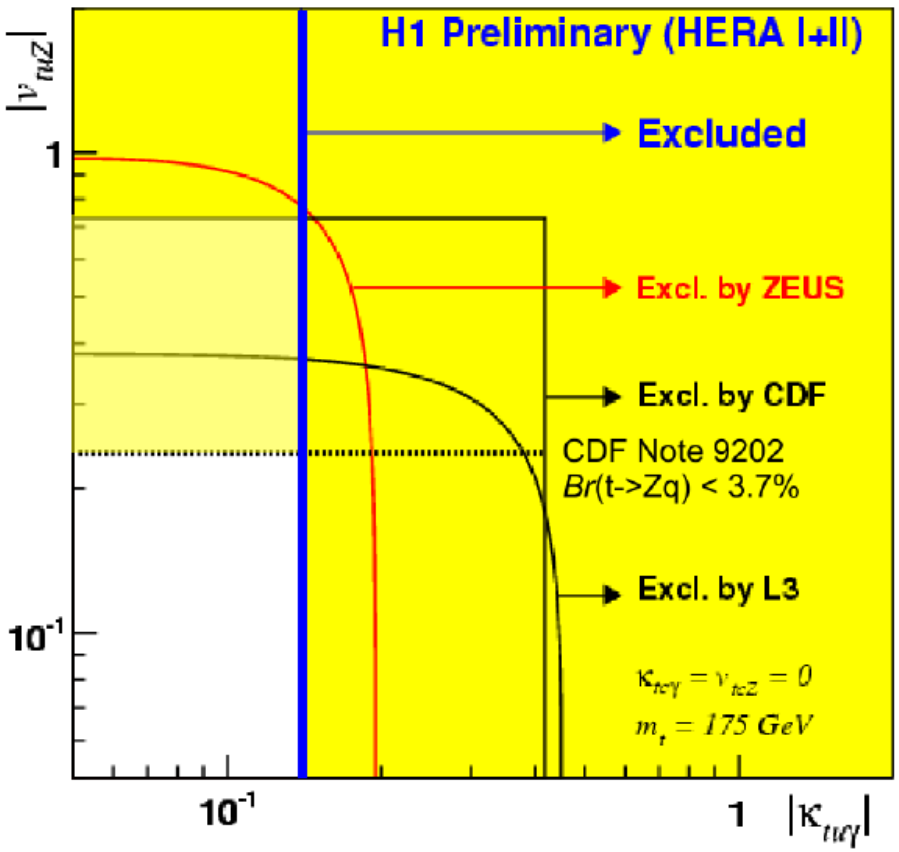
Isolated Lepton Events & Single Top Production

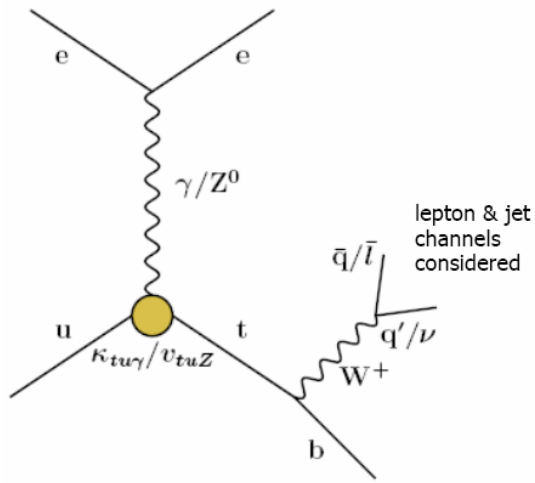
H1prelim-07-163; ZEUS, Phys. Lett. B559 (2003) 153, addendum: DESY-03-188

Negligible SM production cross section (~1fb)

➔ 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

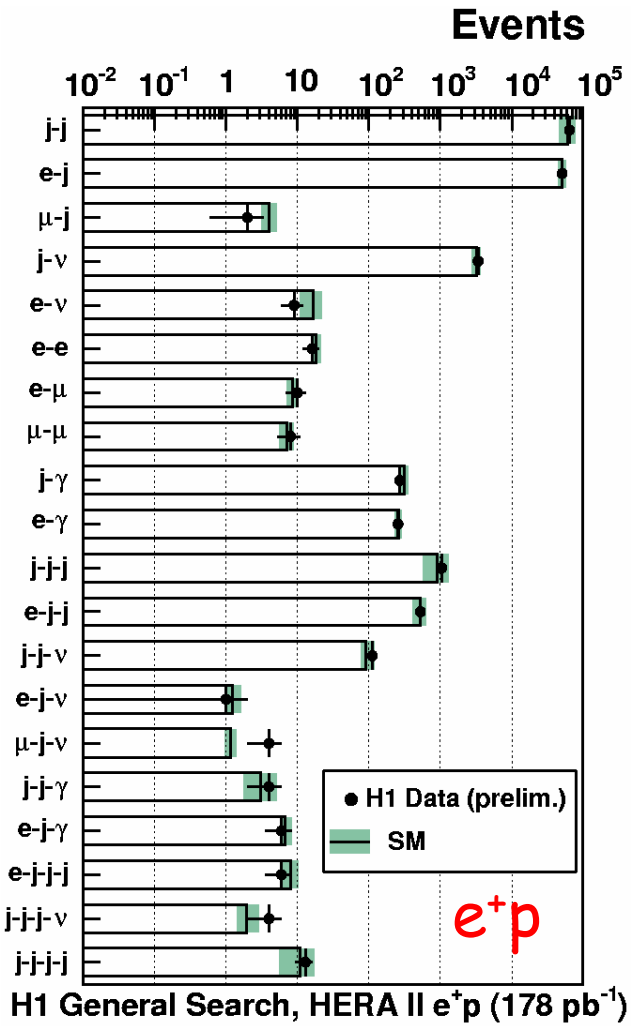
H1prelim-07-061

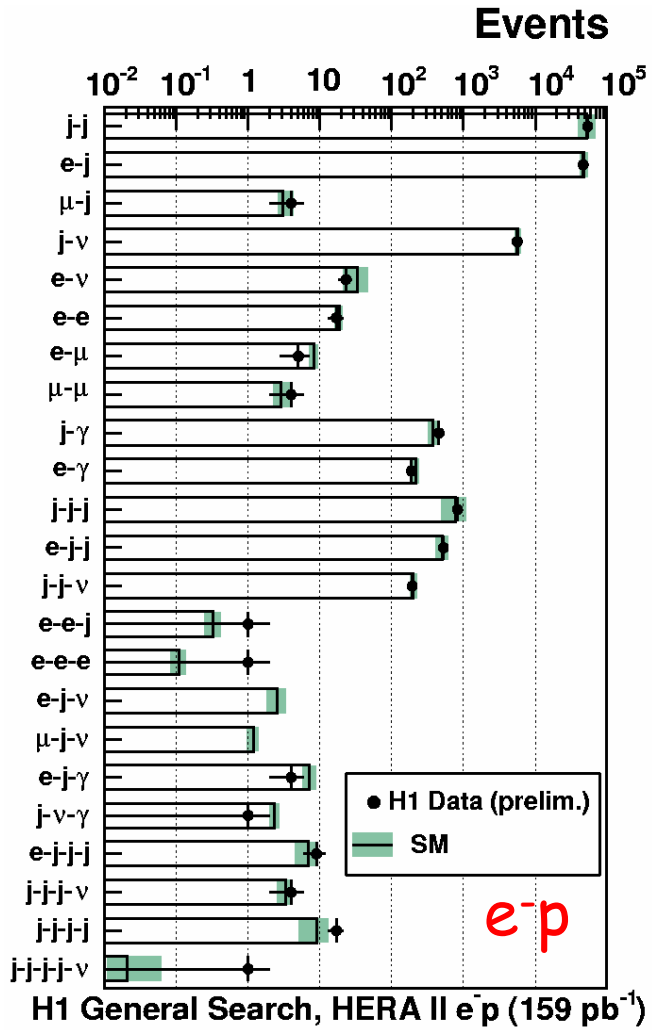
Analyze 2 to 4 body topologies at high P_T (>20 GeV) in common angular region (θ: 10°-140°)

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 momenta

    have 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