Searches for New Physics at HERA

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on behalf of
H1 and ZEUS Collaborations

Outline

- Inclusive measurements at high Q^2
- Quark radius
- Contact Interactions
- LED, Heavy Leptoquarks
- General Searches
- Multi-leptons
- Isolated leptons and missing p_T
- FCNC single-top production
- Excited Fermions
- Squark production in RPV SUSY

Weak Interactions and Neutrinos, WIN09
Perugia, Italy, 18 September 2009

HERA operation

World's only *ep* collider, located at DESY Hamburg.
Ended in June 2007, after 15 years of successful running.
Two colliding experiments: H1 and ZEUS.

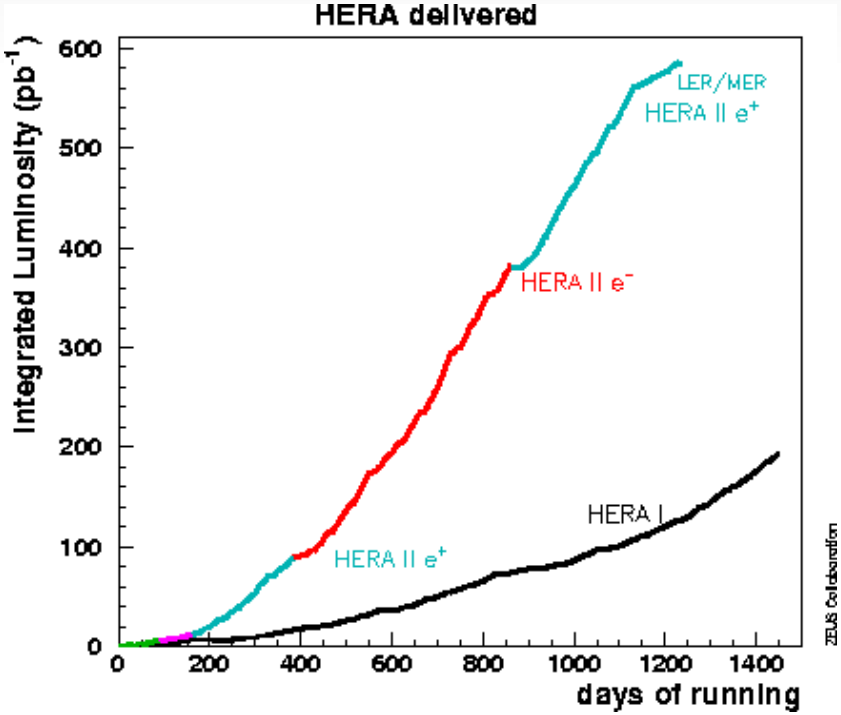
p (820/920 GeV) e (27.5 GeV)

$\sqrt{s}$ = 318 GeV

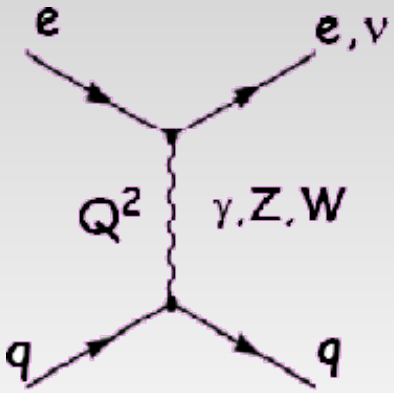
HERA I (1994-2000)
L=~120 pb^{-1} collected per experiment.
Mostly e$^+$p.

HERA II (2002-2007)
L=~360 pb^{-1} collected per experiment.
Similar amount of e$^+$p and e$^-$p.
Longitudinal polarisation of lepton beam (P=0.3-0.4).

Presented results are based on full datasets
~0.5 fb^{-1} per experiment



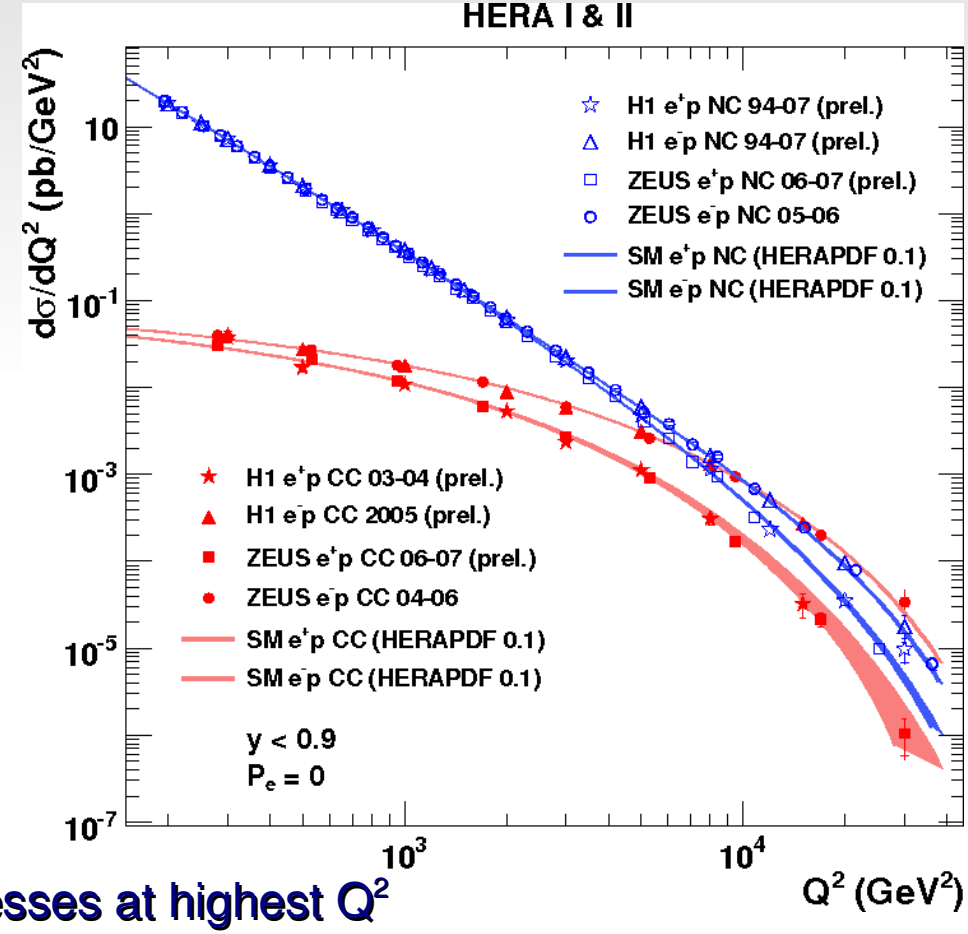
High-Q^2 NC and CC Cross Sections



Main processes studied at HERA:

Neutral Current (NC) DIS, ep→eX, mediated by γ or Z^0.

Charged Current (CC) DIS, ep→νX, mediated by $W^{\pm}$.



Excellent agreement between data and SM predictions over many orders of magnitude.

Q^2 (resolving power) up to 40000 GeV^2.
Spatial resolution ~ $1/Q \simeq 10^{-18}$ m = 10^{-3} fm.
1/1000 of proton radius.

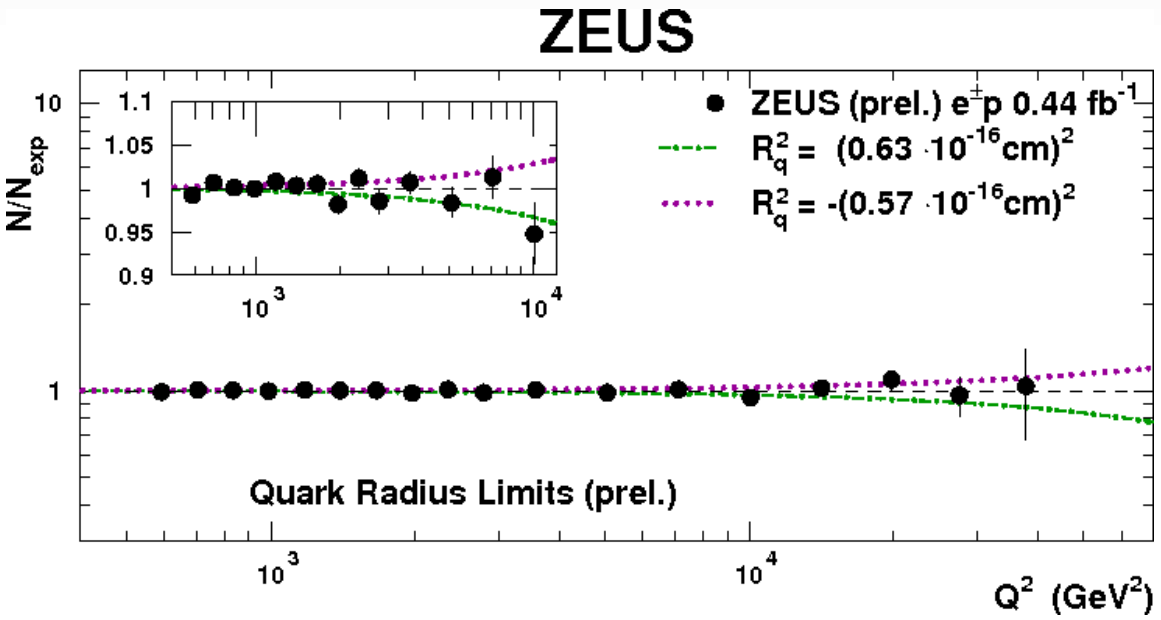
Search for Beyond SM physics by studying processes at highest Q^2 and/or processes with high p_T objects in the final state.

Quark Radius

If a quark has a finite size, the SM cross section is expected to decrease at higher Q^2.
Quark form-factor (electron assumed to be point-like):

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

R_q is a root-mean-square radius of the EW charge distribution in the quark.
The same dependence expected for e^-p and e^+p.

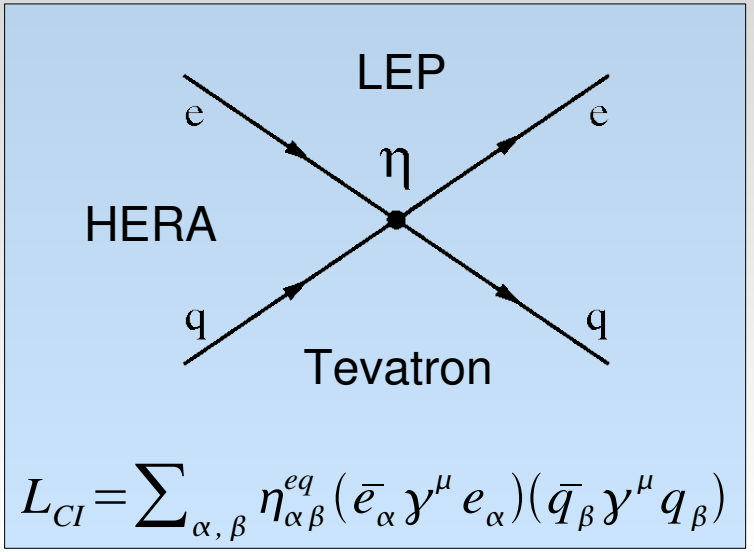


Excellent agreement with SM expectations up to highest Q^2.

ZEUS: $R_q < 0.63 \times 10^{-3}$ fm
H1: $R_q < 0.74 \times 10^{-3}$ fm
@ 95% C.L.

Contact Interactions (CI)

Reminder:
before W and Z^0 were discovered, weak interactions ($\Lambda \approx M_W$) were described as 4-fermion CI with Fermi constant $G_F = g^2/M^2_W$.

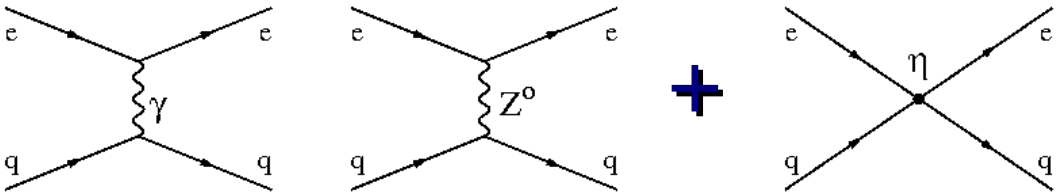


$$L_{CI} = \sum_{\alpha,\beta} \eta^{eq}_{\alpha\beta} (\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma^\mu q_\beta)$$

New interactions at higher scale ($\Lambda \gg \sqrt{s}$)
can be effectively described at lower energies
as 4-fermion *eeqq* Contact Interactions (CI).

α, β - electron, quark helicities (L,R).

CI modify the tree level eq→eq scattering amplitudes



$$M^{eq}_{\alpha\beta}(Q^2) = \frac{e^2 e_q}{Q^2} - \frac{e^2}{\sin^2\theta_W \cos^2\theta_W} \frac{g^e_\alpha g^q_\beta}{Q^2 + M^2_Z} + \eta^{eq}_{\alpha\beta}$$

Search for deviations from SM cross sections at highest Q^2.

CI, General Models

Also referred to as Compositeness Models.

Couplings $\eta^{eq}_{\alpha\beta}$ are related to the effective mass scale Λ of new interactions:

$$\eta^{eq}_{\alpha\beta} = \frac{\epsilon\, g^2_{CI}}{\Lambda^2}$$

g_{CI} is a coupling strength ($g^2_{CI} = 4\pi$), $\epsilon = \pm 1$.

Different models assume different helicity structure of new interactions (given by set of 4 couplings $\eta^{eq}_{\alpha\beta}$)

Parity conserving models fulfill the relation:

$$\eta^{eq}_{LL} + \eta^{eq}_{LR} - \eta^{eq}_{RL} - \eta^{eq}_{RR} = 0$$

Family universality assumed.

Models conserving parity:

Model	η^{ed}_{LL}	η^{ed}_{LR}	η^{ed}_{RL}	η^{ed}_{RR}	η^{eu}_{LL}	η^{eu}_{LR}	η^{eu}_{RL}	η^{eu}_{RR}
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$	$+\eta$	$-\eta$	$-\eta$	$+\eta$
VA	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$
X1	$+\eta$	$-\eta$			$+\eta$	$-\eta$		
X2	$+\eta$		$+\eta$		$+\eta$		$+\eta$	
X3	$+\eta$			$+\eta$	$+\eta$			$+\eta$
X4		$+\eta$	$+\eta$			$+\eta$	$+\eta$	
X5		$+\eta$		$+\eta$		$+\eta$		$+\eta$
X6			$+\eta$	$-\eta$			$+\eta$	$-\eta$
U1					$+\eta$	$-\eta$		
U2					$+\eta$		$+\eta$	
U3					$+\eta$			$+\eta$
U4						$+\eta$	$+\eta$	
U5						$+\eta$		$+\eta$
U6							$+\eta$	$-\eta$

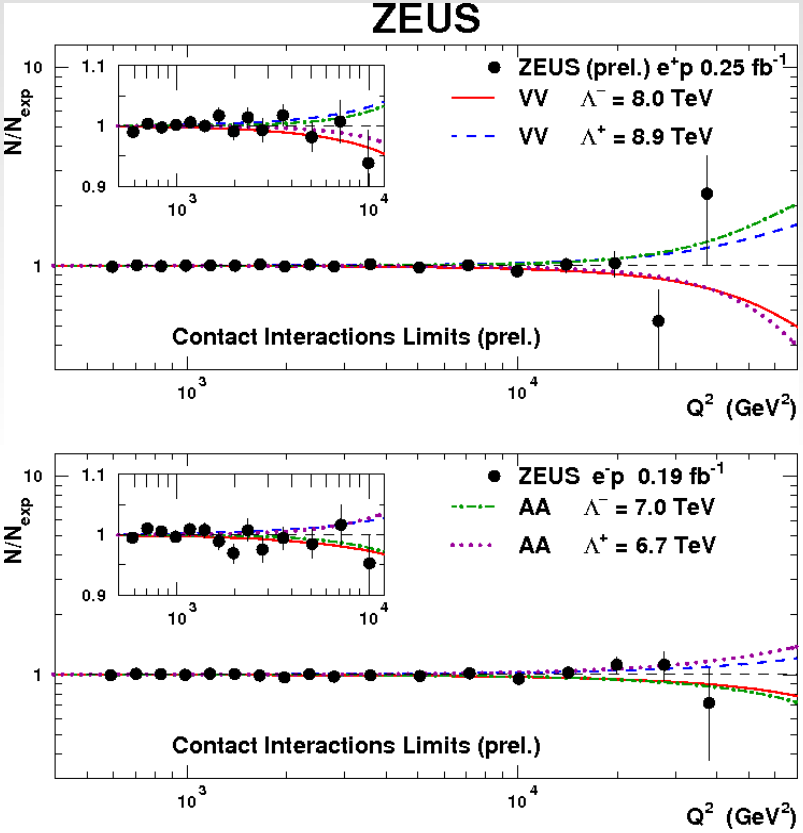
Models violating parity:

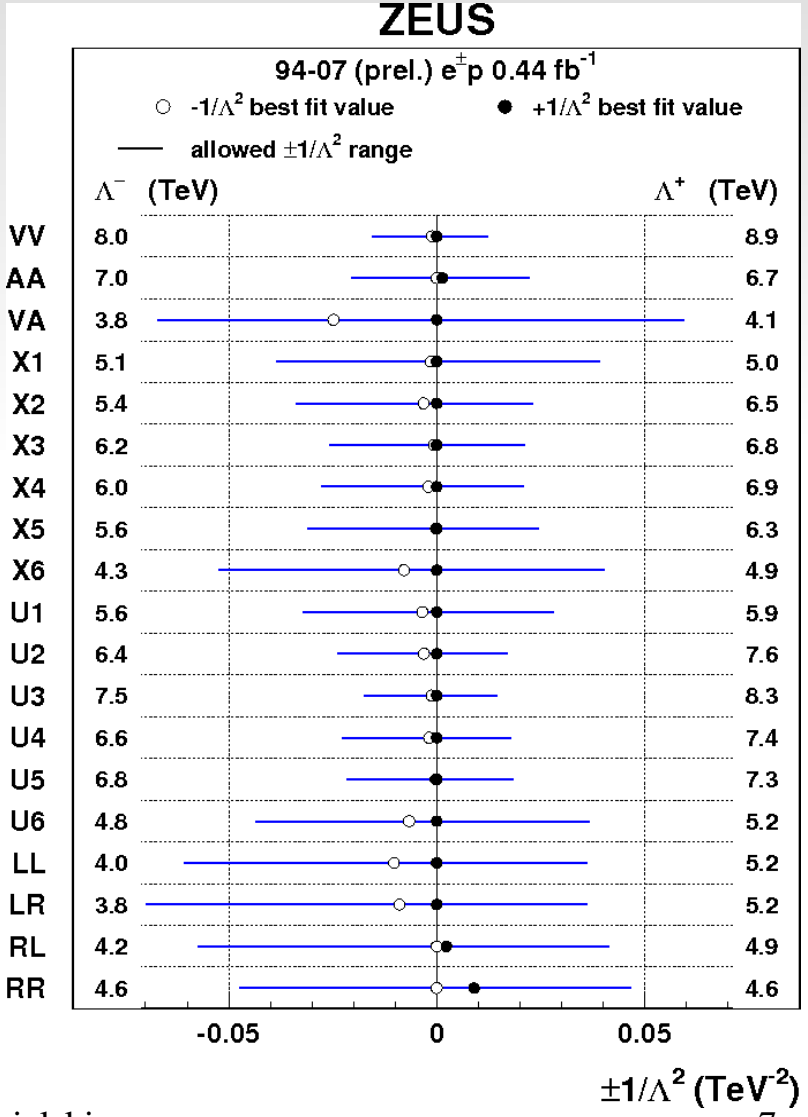
LL	$+\eta$				$+\eta$			
LR		$+\eta$				$+\eta$		
RL			$+\eta$				$+\eta$	
RR				$+\eta$				$+\eta$

CI, General Models

$$\eta^{eq}_{\alpha\beta} = \frac{\epsilon\, g^2_{CI}}{\Lambda^2}$$

ZEUS CI analysis based on full NC sample of L=0.44 fb^{-1}.
Models with 19 different helicity structure tested.





ZEUS: Λ > 3.8 - 8.9 TeV @95% C.L.

CI, Large Extra Dimensions

Arkani-Hamed-Dimopolous-Dvali Model

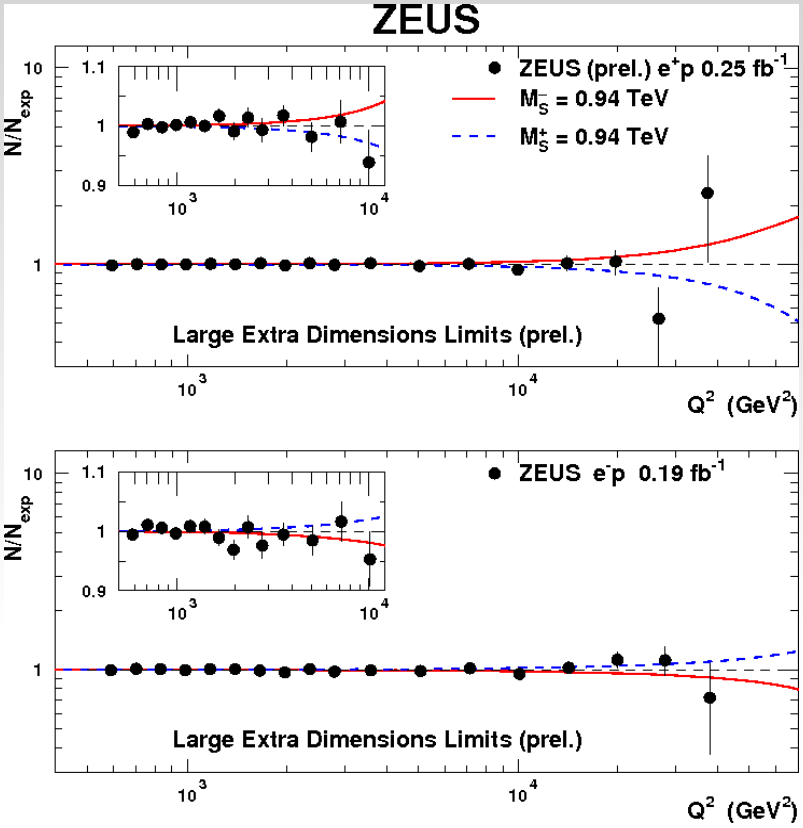
If gravity propagates in 4+δ dimensions,
effective Plank scale M_S can be as low as 1 TeV.

Contribution of graviton exchange
(Kaluza-Klein tower) to $e^{\pm}p$ NC DIS:

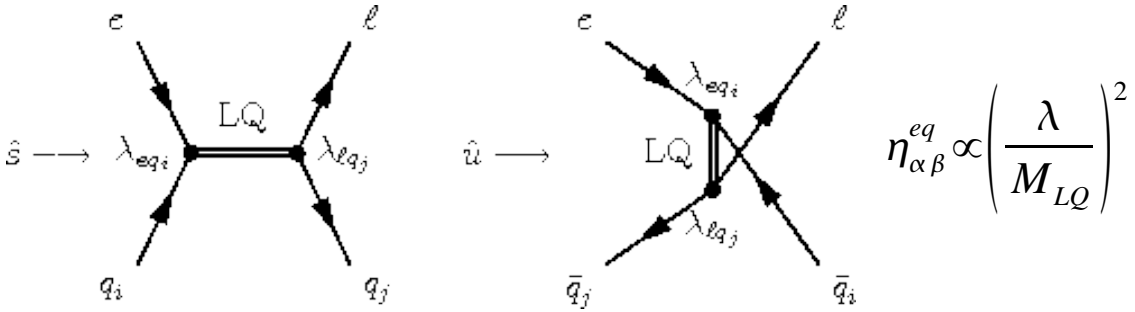
$$\eta_G = \frac{\lambda}{M_S^4}$$

$\lambda = \pm 1$ - coupling strengh.

ZEUS: $M_S^+ > 0.94$ TeV, $M_S^- > 0.94$ TeV @ 95% C.L.



CI, heavy Leptoquarks



$$\eta^{eq}_{\alpha\beta} \propto \left(\frac{\lambda}{M_{LQ}}\right)^2$$

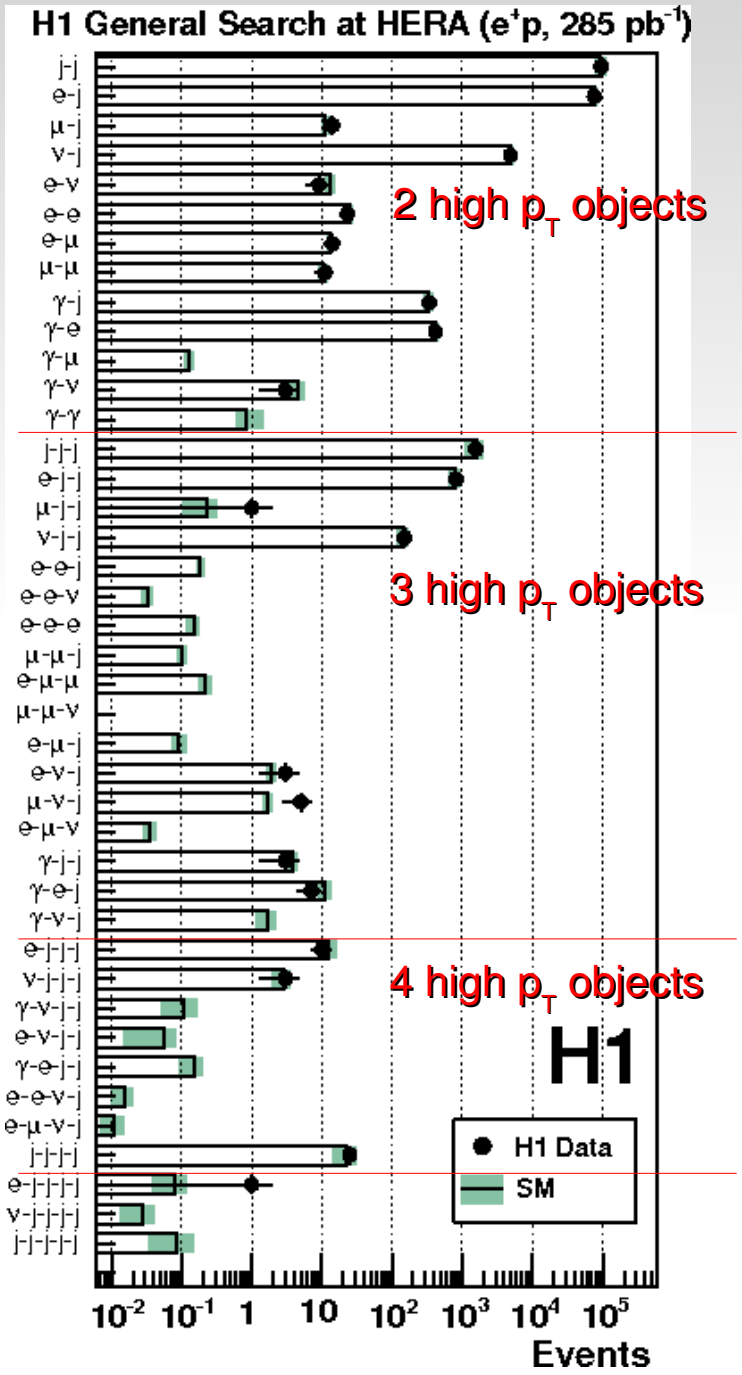
Buchmueller-Rueckl-Wyler Model

7 scalar, 7 vector Leptoquarks at HERA.

λ - Yukawa LQ-*e*-*q* couplling.

$M_{LQ}/\lambda > 0.41$-1.88 TeV @95% C.L.

General Searches



Analysis based on complete set of H1 $e^{\pm}p$ data, $L=0.46\ fb^{-1}$.

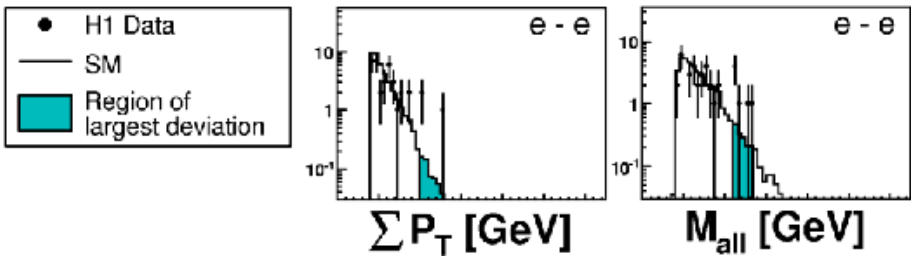
Model independent, generic search for final states with ≥ 2 high-p_T objects:

- γ, e, μ, ν, jet
- $p_T > 20$ GeV
- $10^\circ < \theta < 140^\circ$
- $D(\eta,\varphi) > 1$

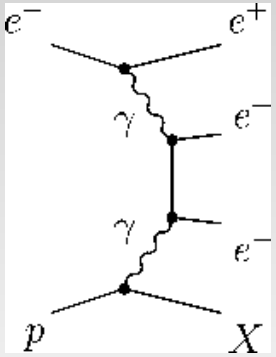
Events counted in distinct channels, separately for e^+p and e^-p data.

Good agreement of event yields with SM expectations (NC, CC, photoproduction, lepton pair production, W production, QEDC).
Good understanding of detector and physics processes at HERA.

No indication for BSM physics.
All deviations compatible with statistical fluctuations (largest for e-e channel in e^+p data).



Multileptons

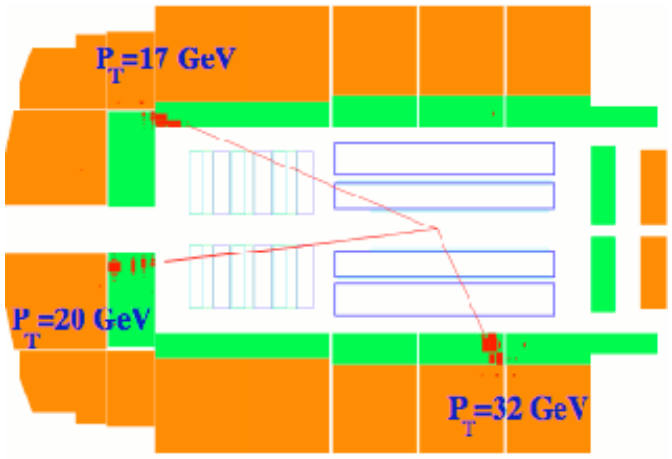


- The main multi-lepton process at HERA is $\gamma\gamma$ process.
- Precise SM QED predictions, modelled with GRAPE.
- Cross section steeply falling with p_T , low at high masses
  - → any deviation is an indication of new phenomena, eg. exotic resonances ($H^{\pm\pm}$) .

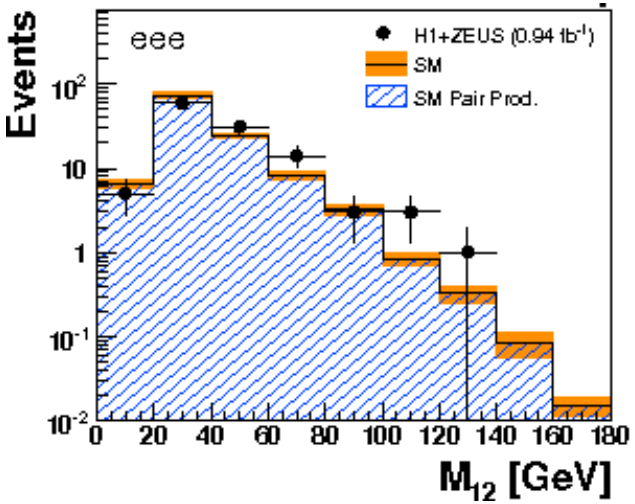
Combined H1 and ZEUS analysis in the common phase-space, L= ~ 1 fb^{-1} .

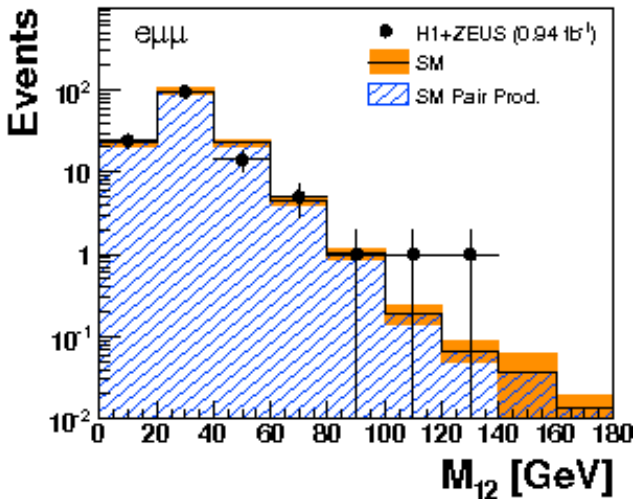
- Events selected by requiring at least 2 isolated, high-p_T e or μ.
- Two leptons must satisfy: $20^\circ < \theta < 150^\circ$, p_T > 15, 10 GeV
- Events classified into independent exclusive samples: ee, $\mu\mu$, eμ, eee, e$\mu\mu$, ...

eee event in H1 detector:



Inv. mass of highest p_T leptons for *eee*, *e$\mu\mu$* channel (examples):





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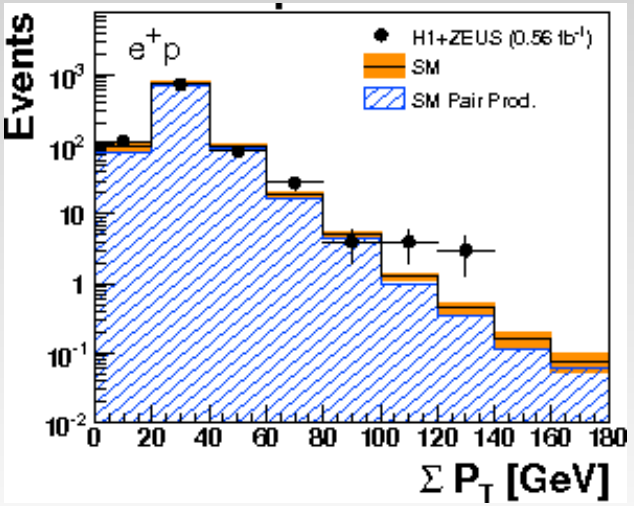
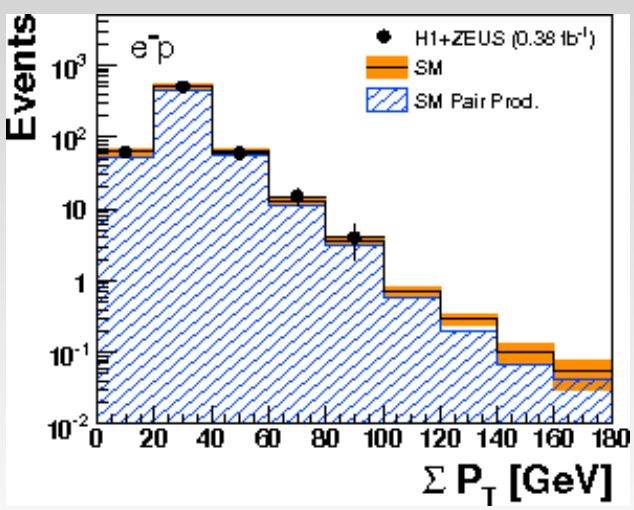




Overall good agreement with the SM.

For $\Sigma p_T > 100$ GeV:

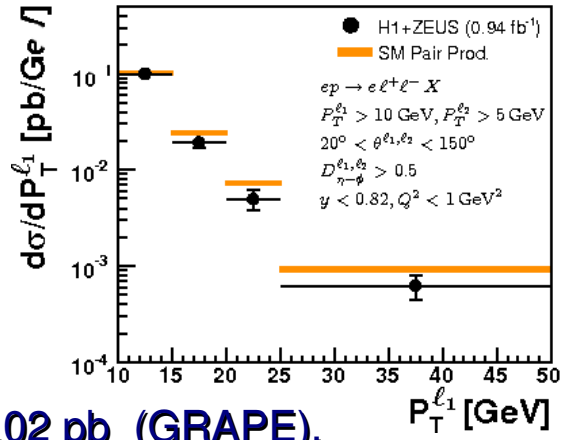
7 events observed in e^+p data, while 1.94 $\pm$0.17 expected (2.6 σ significance).

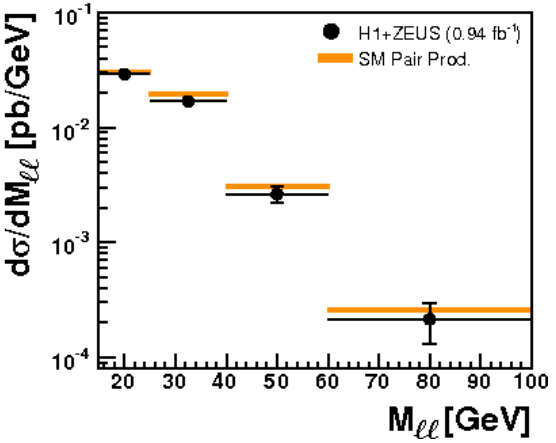
Multi-Leptons at HERA (0.94 fb^{-1})

$\sum P_T > 100$ GeV

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

Differential cross section for the $\gamma\gamma \to \ell\ell$ process measured as a function of p_T of leading lepton and lepton-pair mass.



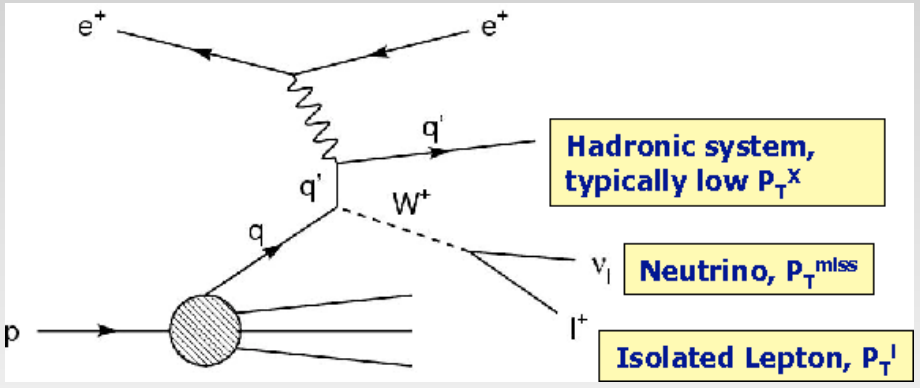


Measured total visible cross section:

0.66 $\pm$ 0.03 (stat.) $\pm$ 0.03 (sys.) pb

in agreement with the SM prediction of 0.69$\pm$0.02 pb (GRAPE).

Isolated Leptons & missing p_T



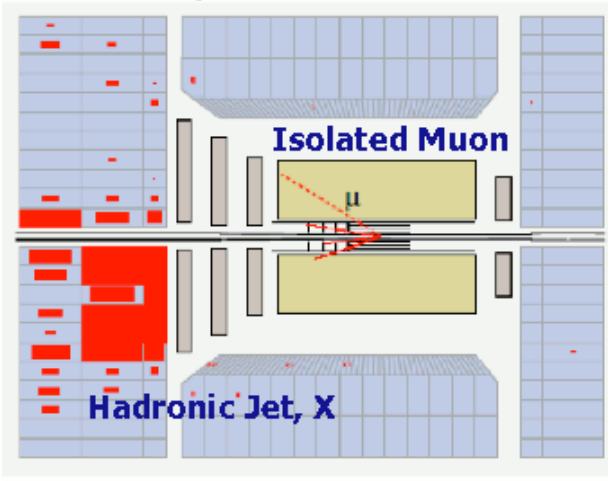
The main corresponding SM process is single W production. Modelled with EPVEC (NLO corr., ~15% unc.).

- Rare process, $\sigma \sim 1.3$ pb.
- Search for new phenomena (eg. anomalous single-top production, bosonic stop decay).

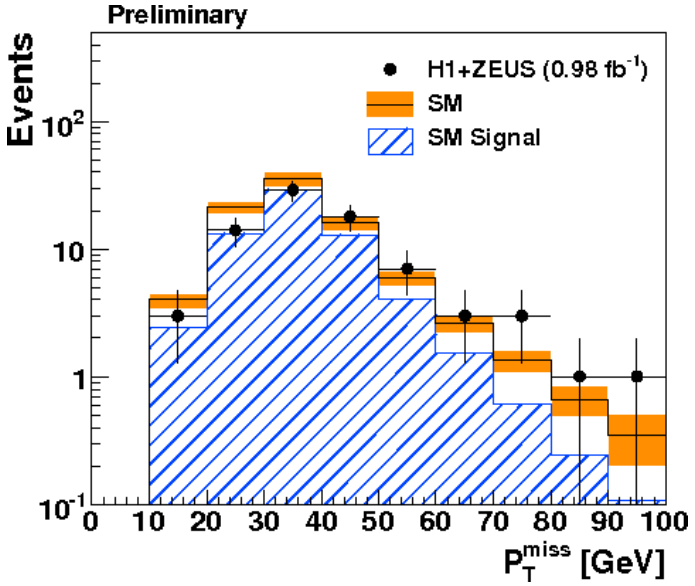
Combined H1 and ZEUS analysis in the common phase-space, L= ~ 1 fb^{-1} .

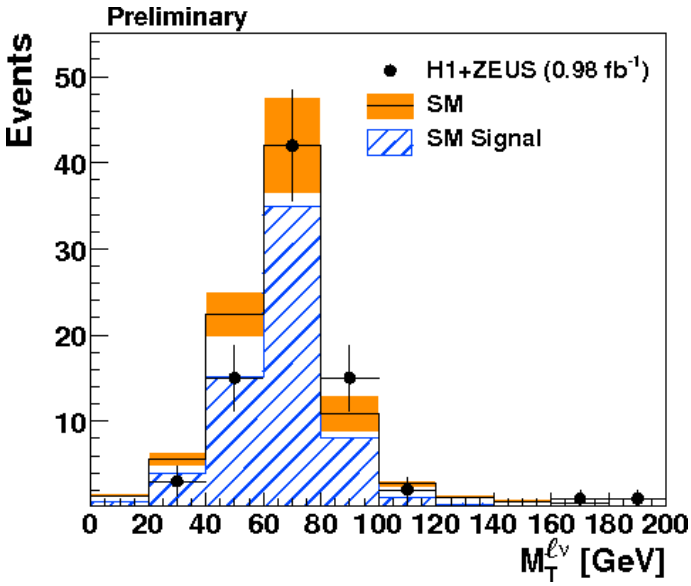
- isolated high-p_T e or μ (p_T > 10 GeV, 15° < θ < 120°)
- missing p_T (p_T^{miss} > 12 GeV)
- hadronic system p_T^X.

High purity (75 %) of W production, clear jacobian peak

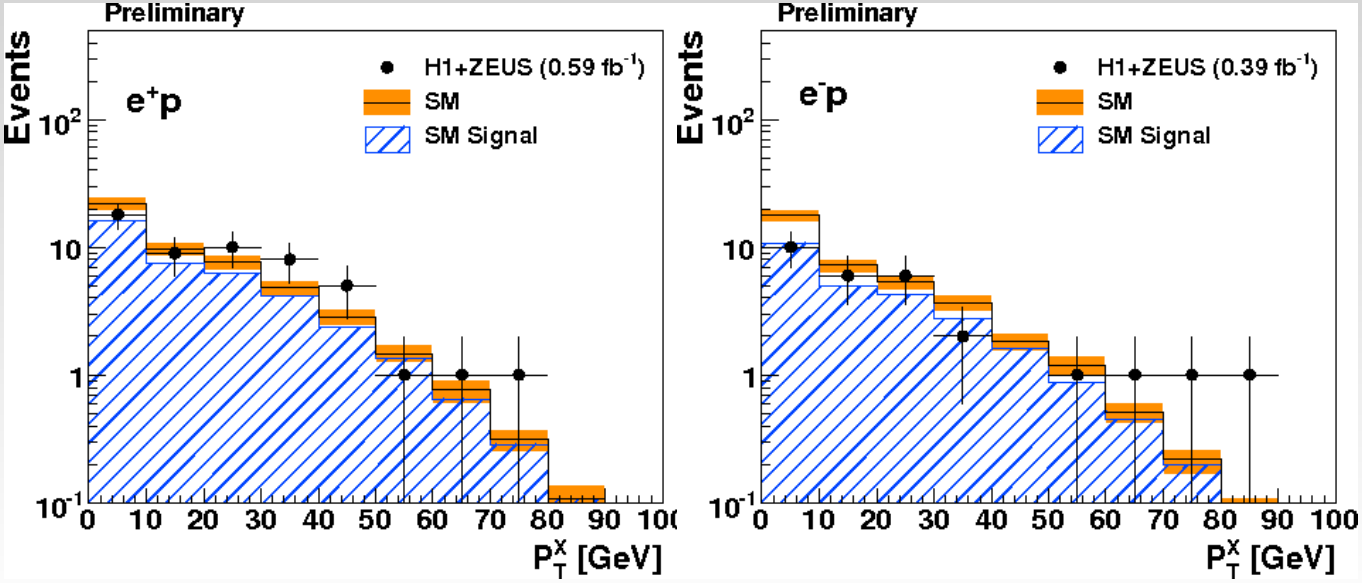


μ + P_T^{Miss} event in ZEUS





Isolated Leptons & missing p_T



Overall good agreement with the SM.

For $p_T^X > 25$ GeV:

23 events observed in e^+p data, while 14.02 $\pm$1.94 expected (1.9 σ significance).

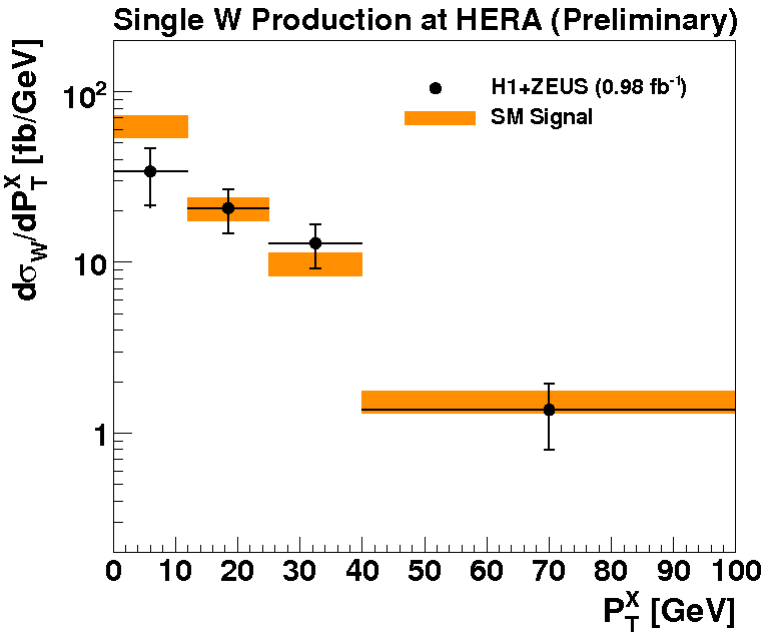
Differential cross section for W production extracted as a function of hadronic transverse momentum p_T^X.

Branching ratio of W leptonic decays (~10 %) used to measure full W production cross section.

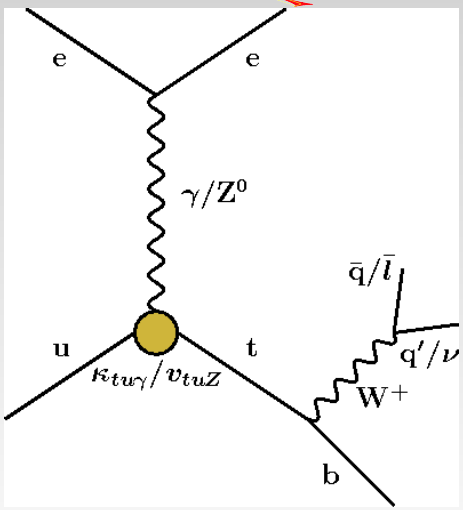
Measured total single W production cross section:

1.07 $\pm$0.16 (stat.) $\pm$ 0.08 (sys.) pb

in agreement with the SM prediction of 1.26$\pm$0.19 pb (EPVEC).



Anomalous single-top production

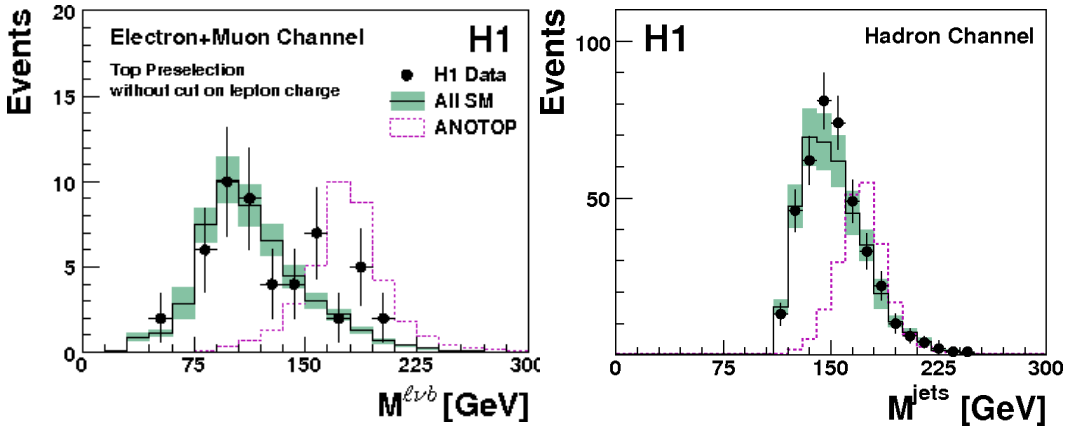


- The SM single-top production negligible at HERA (σ <1 fb).
- FCNC single-top production predicted by several BSM theories.
- At HERA sensitivity to anomalous t-u-γ and t-u-Z couplings.

Search for t → bW, with W → $\ell\nu$: topology as for isolated lepton and missing p_T but higher p_T^X (b jet)

W → qq : 3 jets

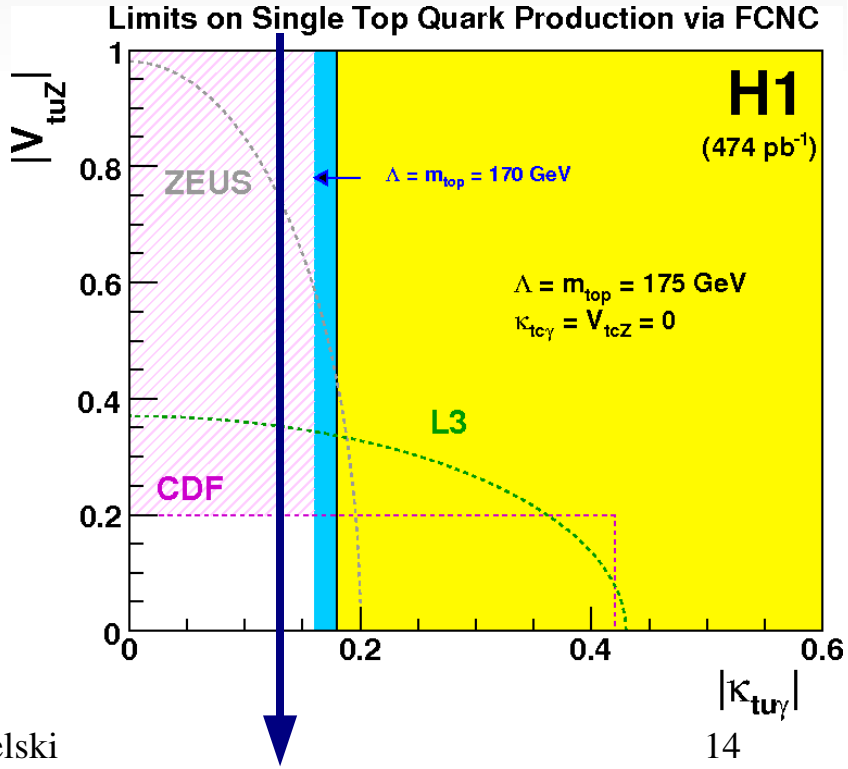
H1 analysis based on full dataset (L=0.47 fb^{-1})



No significant excess in the signal region.

Set limits on anomalous $\kappa_{tu\gamma}$ coupling (V_{tuZ}=0).

HERA limits on $\kappa_{tu\gamma}$ most stringent.



$\kappa_{tu\gamma}$ <0.13 , ZEUS prel. (L=~0.4 fb^{-1})

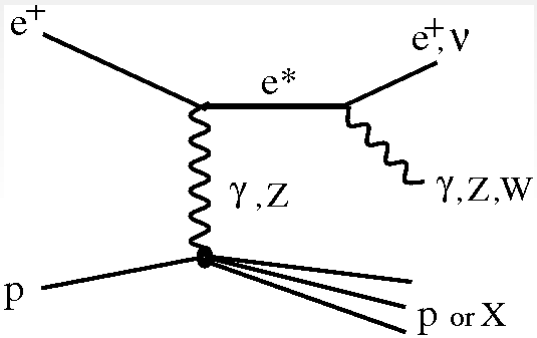
Excited Fermions

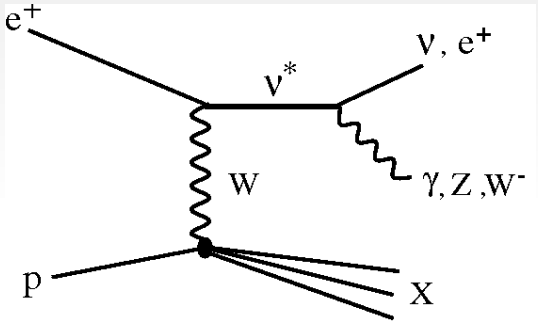
Excited fermions would be a signature for compositeness. Explanation of 3 lepton families and mass hierarchy.
Effective lagrangian (Hagiwara et. al.):

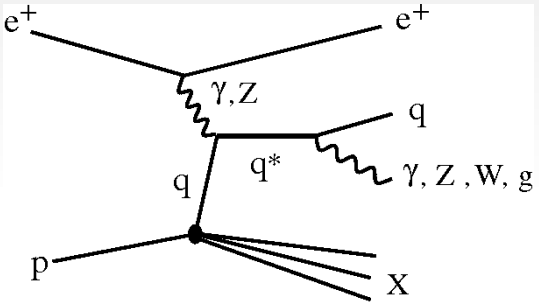
$$\mathcal{L}_{GM} = \frac{1}{2\Lambda}\bar{F}^*_R\sigma^{\mu\nu}\left[gf\frac{\tau^a}{2}W^a_{\mu\nu} + g'f'\frac{Y}{2}B_{\mu\nu} + g_s f_s\frac{\lambda^a}{2}G^a_{\mu\nu}\right]F_L$$

SU(2) U(1) SU(3)

Parameters:
Λ - compositeness scale
f, f', f_s - relative strengh to Z/W, γ, g



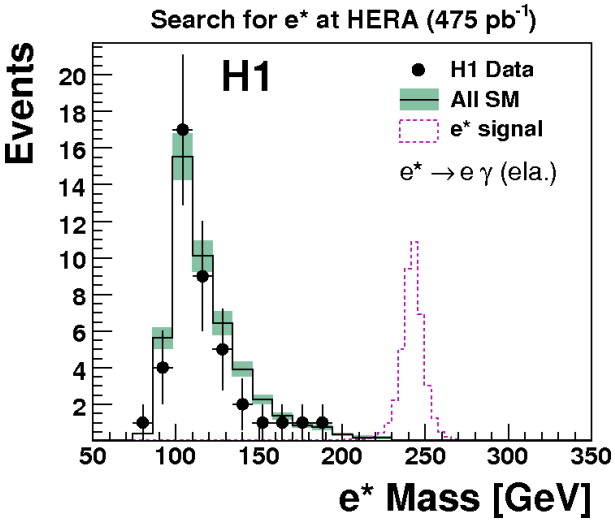




Decay to standard fermions and gauge bosons: $f^* \to f + \gamma, Z, W$ with $Z \to ee, \tau\tau, qq$ and $W \to e\nu, \mu\nu, qq'$.

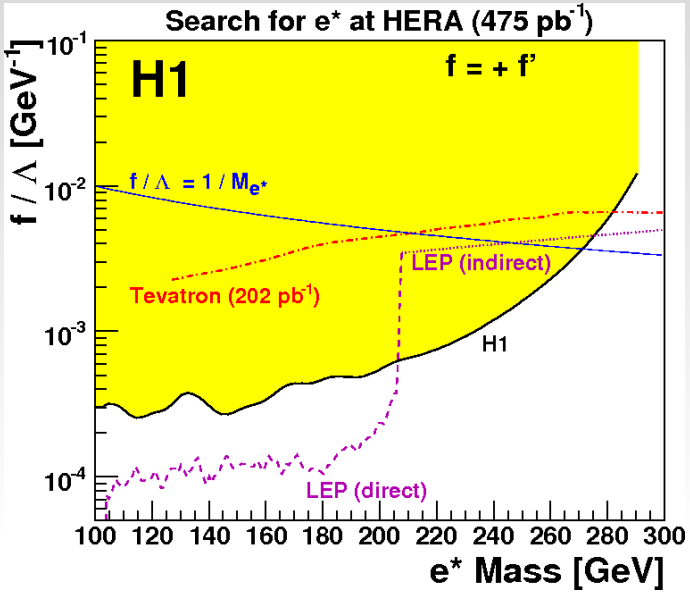
Variety of experimental signatures: isolated leptons, missing p_T, γ, jets.

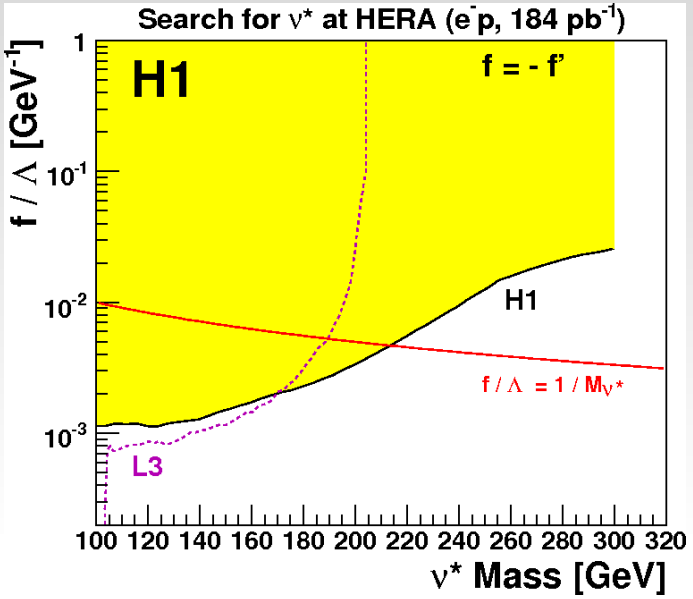
H1 analysis based on full dataset (L=0.47 fb^{-1}).
80%-90% of decay channels looked at.

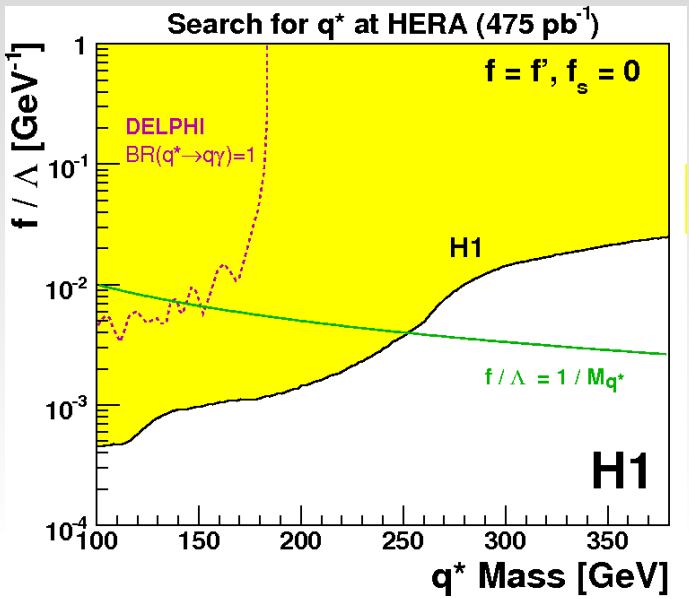


Excited Fermions

No deviation from SM observed. Limits set on f/Λ ratio (95% C.L.).







Best sensitivity achieved for masses beyond LEP reach.

f/Λ limits can be can be translated into mass limits assuming $f/\Lambda = 1/M_f^*$

- $M_{e^*} > 272$ GeV
- $M_{\nu^*} > 213$ GeV
- $M_{q^*} > 252$ GeV (for $f_s=0$, HERA unique)

Squark Production in RPV SUSY

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

(+1 for SM, -1 for SUSY particles)

R_P conserved – pair production of SUSY particles,

R_P violated – single production

If RPV → single resonant squark production possible at HERA.

$$W_R = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

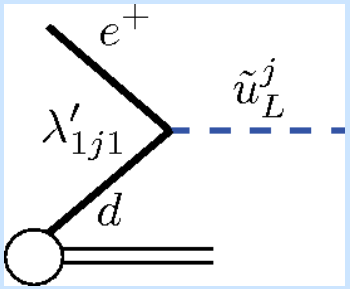
L: left-handed (s)leptons, **Q**: left-handed (s)quarks, **D**: right-handed down-type (s)quarks

i,*j*,*k* generation indices (27 couplings)

Production: RPV

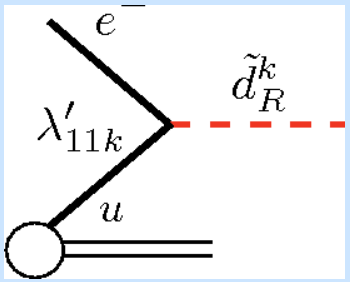
$e^+p : \lambda'_{1j1}$

$\tilde{u}_L, \tilde{c}_L$

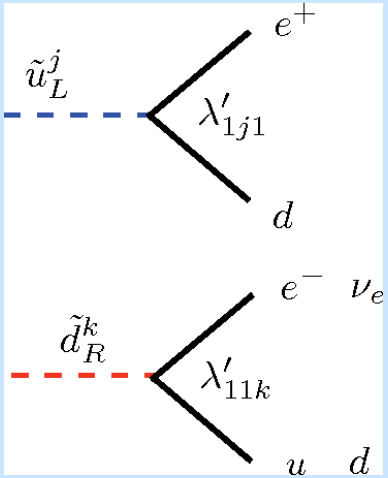


$e^-p : \lambda'_{11k}$

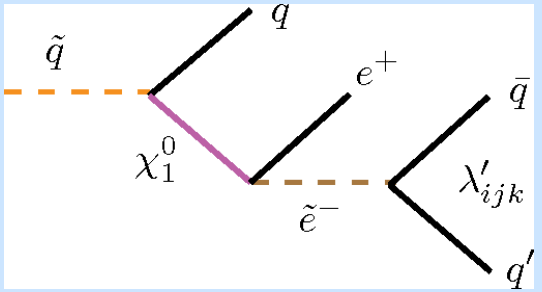
$\tilde{d}_R, \tilde{s}_R$



Decays: RPV



Gauge coupling (neutralinos or charginos)

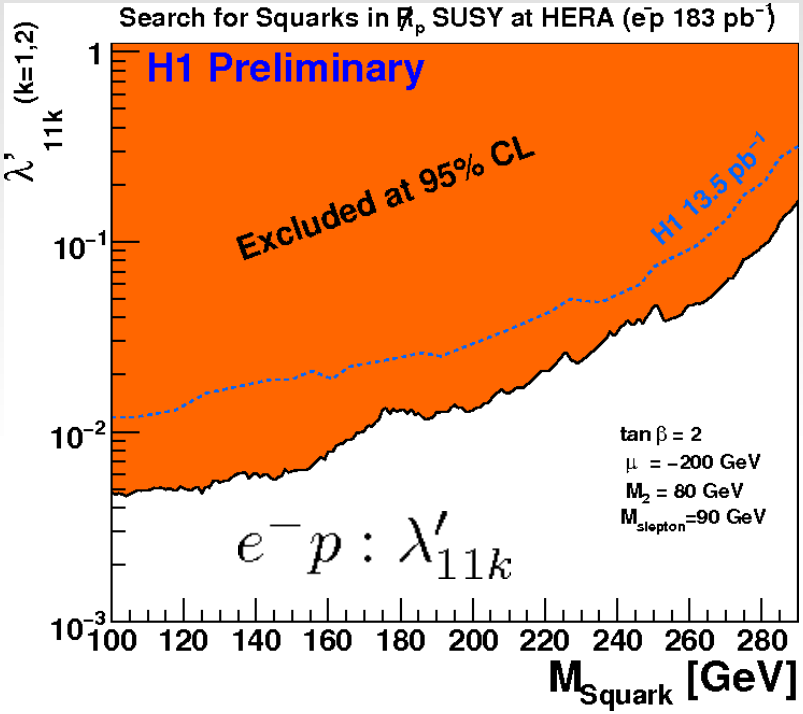


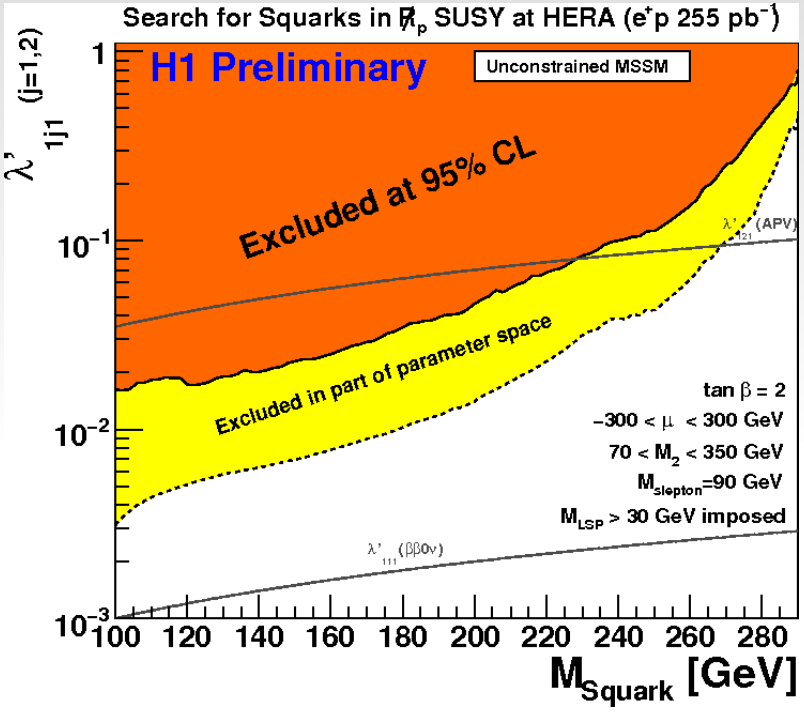
Many final states:

DIS-like or multi-jets with isolated lepton(s) , missing p_T

Squark Production in RPV SUSY

No deviations from SM observed. Limits set (SUSYGEN3).





Photino-like neutralino

$$\tan\beta = 2$$
$$\mu = -200\ \text{GeV}$$
$$M_2 = 80\ \text{GeV}$$

Parameter scan

$$\tan\beta = 2$$
$$-300 < \mu < 300\ \text{GeV}$$
$$70 < M_2 < 350\ \text{GeV}$$

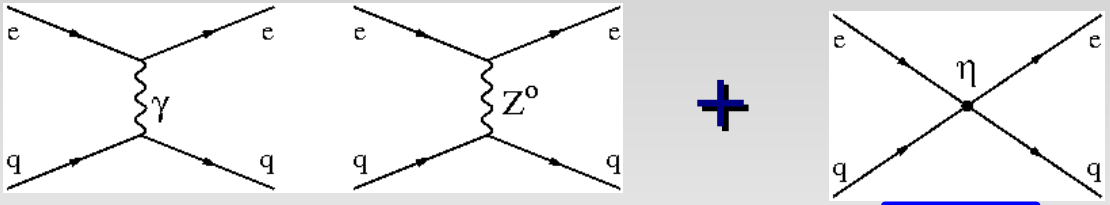
For $\lambda = \sqrt{4\pi\alpha} = 0.3$:
$M_{\text{d-squark}} < 290$ GeV
$M_{\text{u-squark}} < 275$ GeV
excluded @95%C.L.

Summary

- Searches for BSM phenomena have been performed by ZEUS and H1 with full datasets of ~0.45 fb^{-1}/exp. and variety of processes under study.
- H1+ZEUS combined analyses (~1 fb^{-1}) of multi- and isolated lepton production to measure rare processes with higher statistical precision.
- No deviations from SM have been found.
- Limits have been set on many BSM scenarios.
  HERA complementary to Tevatron and LEP,
  stringent limits on anomalous single-top production and excited fermions.

Contact Interactions

4-fermion CI at HERA:



$$M^{eq}_{\alpha\beta}(Q^2) = \frac{e^2 e_q}{Q^2} - \frac{e^2}{\sin^2\theta_W \cos^2\theta_W} \frac{g^e_\alpha g^q_\beta}{Q^2 + M_Z^2} + \eta^{eq}_{\alpha\beta}$$

α, β - electron, quark helicities (L,R).

NC e^-p scattering:

$$\frac{d^2\sigma(e^- p)}{dxdy} = \frac{sx}{16\pi}\sum q(x)\left\{P_- M^2_{LL} + P_+ M^2_{RR} + (1-y)^2\left(P_- M^2_{LR} + P_+ M^2_{RL}\right)\right\}$$
$$+\bar{q}(x)\left\{P_- M^2_{LR} + P_+ M^2_{RL} + (1-y)^2\left(P_- M^2_{RR} + P_+ M^2_{LL}\right)\right\}$$

NC e^+p scattering:

$$\frac{d^2\sigma(e^+ p)}{dxdy} = \frac{sx}{16\pi}\sum q(x)\left\{P_+ M^2_{LR} + P_- M^2_{RL} + (1-y)^2\left(P_+ M^2_{LL} + P_- M^2_{RR}\right)\right\}$$
$$+\bar{q}(x)\left\{P_+ M^2_{LL} + P_- M^2_{RR} + (1-y)^2\left(P_+ M^2_{LR} + P_- M^2_{RL}\right)\right\}$$

At high Q^2 and high x quark distribution dominate (valence quarks).
Some contributions are suppresed by helicity factor $(1-y)^2$.
NC e^-p sensitive to LL and RR, NC e^+p sensitive to LR and RL configurations.

$$P_\pm = 1 \pm P$$

SM MEs modyfied by quark form-factor: $M^{eq}_{\alpha\beta}(Q^2) = M^{eq}_{\alpha\beta}(Q^2)^{SM}(1 - R_q^2 Q^2/6)$

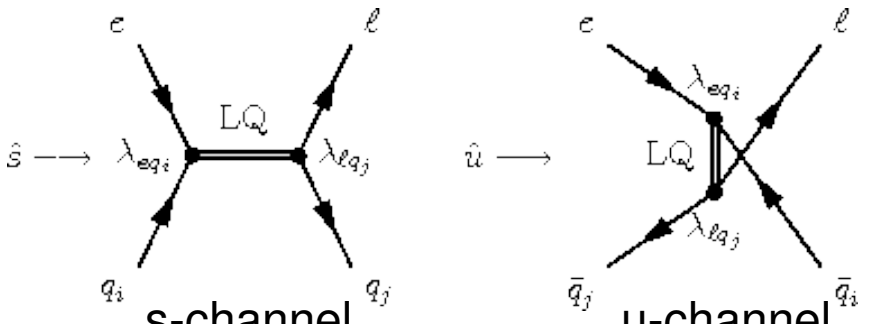
Leptoquarks Production

The Buchmueller-Rueckl-Wyler Model

- Leptoquarks (LQ) - hypothetical bosons connecting lepton and quark sectors.
- Carry SU(3) colour, fractional charge, lepton (L),barion (B) and fermion number F=3B+L=0,2.
- Chiral objects ie. either left- or right-handed coupling to lepton, but not both.

At HERA:
7 scalar and 7 vector LQs coupling to *eq*.
4 LQs couple also to *νq*.

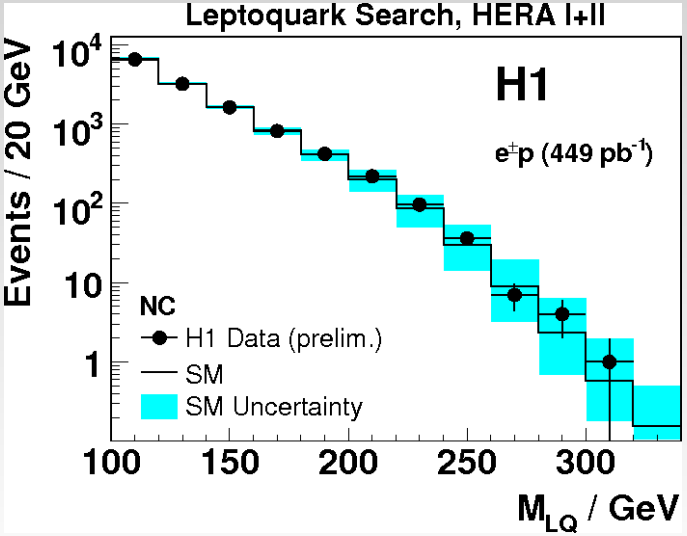
LQs can be resonantly produced in s-channel ($M_{LQ} < \sqrt{s}$) or exchanged in u-channel.



λ is the Yukawa LQ-*e*-*q* couplling.
Limit setting on M_{LQ}/λ.

$F=2$	Prod./Decay	β_e	$F=0$	Prod./Decay	β_e
	e^-p Scalar Leptoquarks **e^+p**				
$S_{0,L}$	$e_L^- u_L \to e^- u$	1/2	$S_{1/2,L}$	$e_R^+ u_R \to e^+ u$	1
	$\to \nu d$	1/2			
$S_{0,R}$	$e_R^- u_R \to e^- u$	1	$S_{1/2,R}$	$e_L^+ u_L \to e^+ u$	1
$\tilde{S}_{0,R}$	$e_R^- d_R \to e^- d$	1		$e_L^+ d_L \to e^+ d$	1
$S_{1,L}$	$e_L^- d_L \to e^- d$	1	$\tilde{S}_{1/2,L}$	$e_R^+ d_R \to e^+ d$	1
	$e_L^- u_L \to e^- u$	1/2			
	$\to \nu d$	1/2			
	Vector Leptoquarks				
$V_{1/2,R}$	$e_R^- d_L \to e^- d$	1	$V_{0,R}$	$e_L^+ d_R \to e^+ d$	1
	$e_R^- u_L \to e^- u$	1	$V_{0,L}$	$e_R^+ d_L \to e^+ d$	1/2
				$\to \bar{\nu} u$	1/2
$V_{1/2,L}$	$e_L^- d_R \to e^- d$	1	$\tilde{V}_{0,R}$	$e_L^+ u_R \to e^+ u$	1
$\tilde{V}_{1/2,L}$	$e_L^- u_R \to e^- u$	1	$V_{1,L}$	$e_R^+ u_L \to e^+ u$	1
				$e_R^+ d_L \to e^+ d$	1/2
				$\to \bar{\nu} u$	1/2

1st Generation Leptoquarks



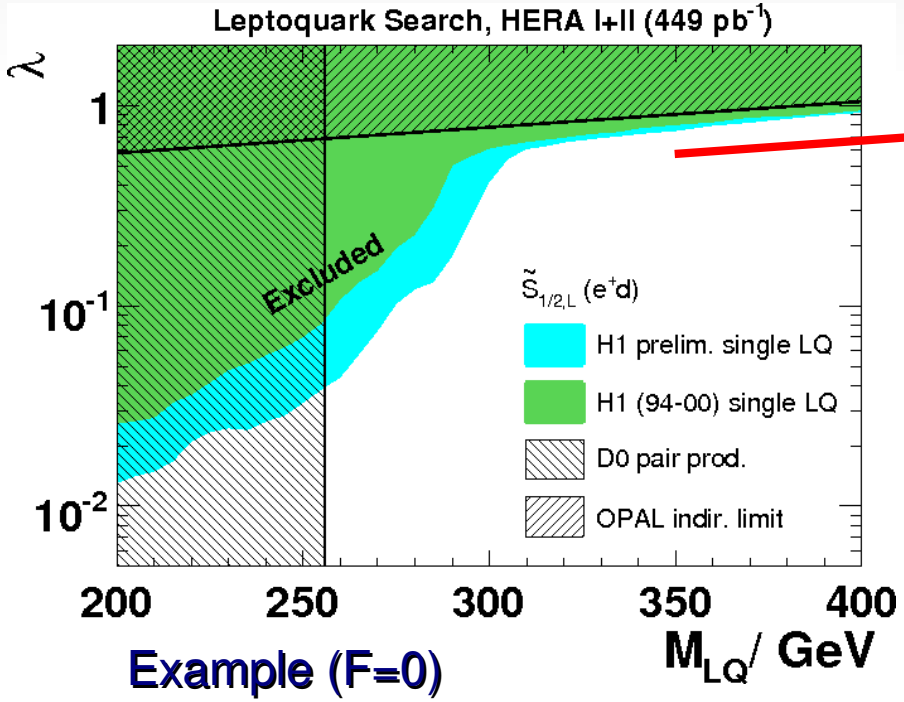
H1 analysis based on full NC and CC samples of L=0.45 fb^{-1}

LQ → eq

Large SM background from NC and CC processes.
Good description of data by SM prediction.
No LQ signal observed.

Limits set for all 14 LQs.

H1: For $\lambda=\sqrt{4\pi\alpha}=0.3$
M_{LQ}<291-330 GeV are excluded at 95%C.L.



Example (F=0)

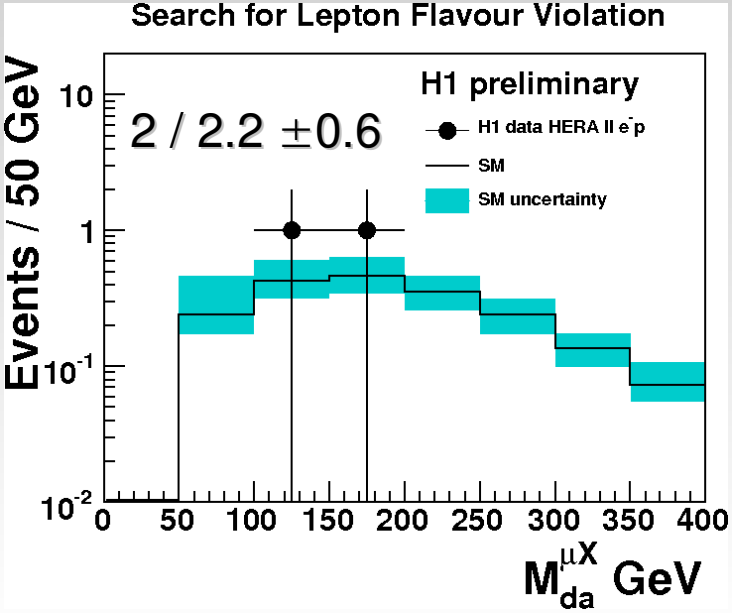
ZEUS CI (94-07 data):

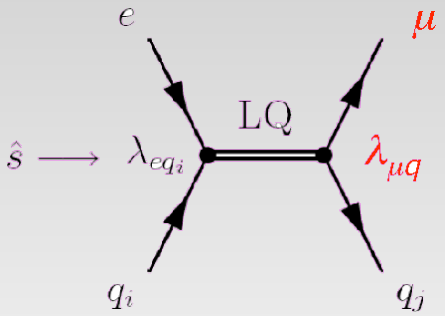
$$\eta^{eq}_{\alpha\beta} \propto \left(\frac{\lambda}{M_{LQ}}\right)^2$$

M_{LQ}/λ > 0.41-1.88 TeV @95% C.L.

LEP (OPAL, L3): indirect constraints from ee→qq.
Tevatron (D0): LQ+LQ pair production from qq anihilation or gg fusion (λ independent).

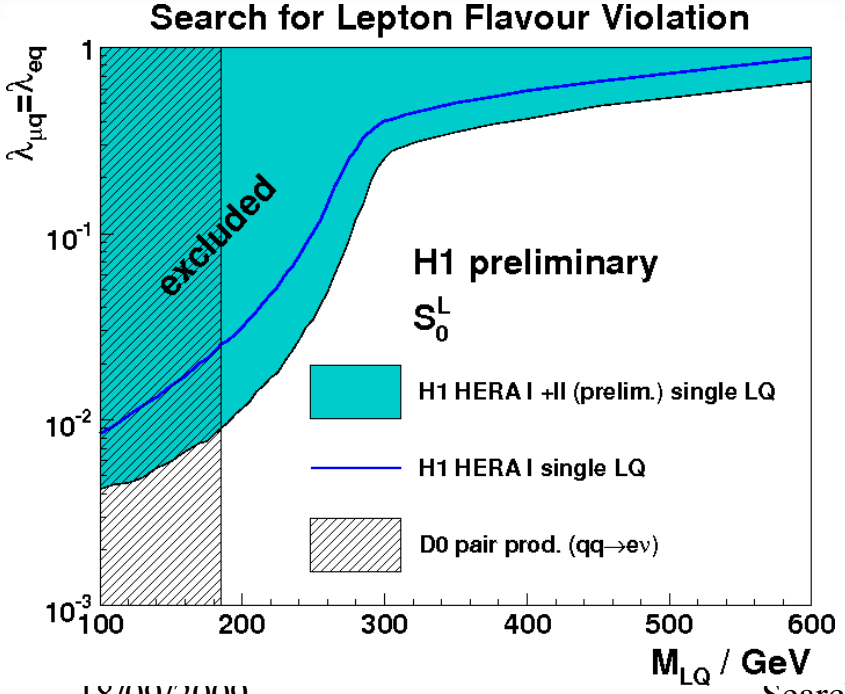
2nd Generation Leptoquarks





$e^-p \to LQ \to \mu X$ with e^-p data.

Search for Lepton Flavour Violation mediated by LQ.
Experimentaly clear process. Background dominated by lepton pair production.
No evidence for signal.



Limits set for 7 LQs (F=2), under assumption:
$\lambda_{\mu q}=\lambda_{eq}$, $\lambda_{\tau q}=0$.

For $\lambda=\sqrt{4\pi\alpha}=0.3$
M_{LQ}<291-433 GeV are excluded at 95%C.L.