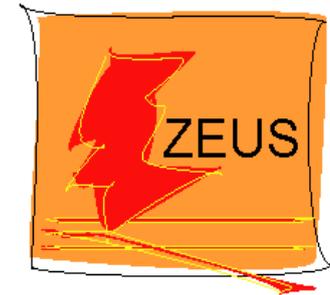


# Searches for Physics beyond the Standard Model at HERA



Antje Hüttmann (DESY)  
for the H1 and ZEUS collaborations



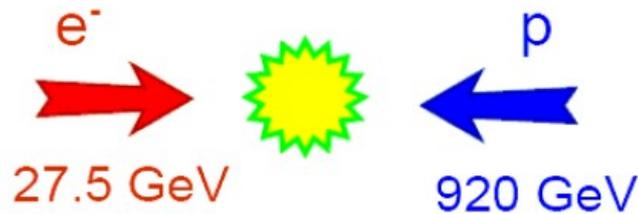
XL International Symposium on Multiparticle Dynamics  
September 25, 2010

# Outline

- The HERA collider
  - Deep Inelastic Scattering (DIS)
- **Model based searches**
    - ◆ Quark radius
    - ◆ Contact interactions
    - ◆ Leptoquarks
    - ◆ Squark production in RPV SUSY
    - ◆ Excited fermions
- **Model independent searches**
    - ◆ Isolated leptons and missing  $p_T$
    - ◆ Multi-leptons

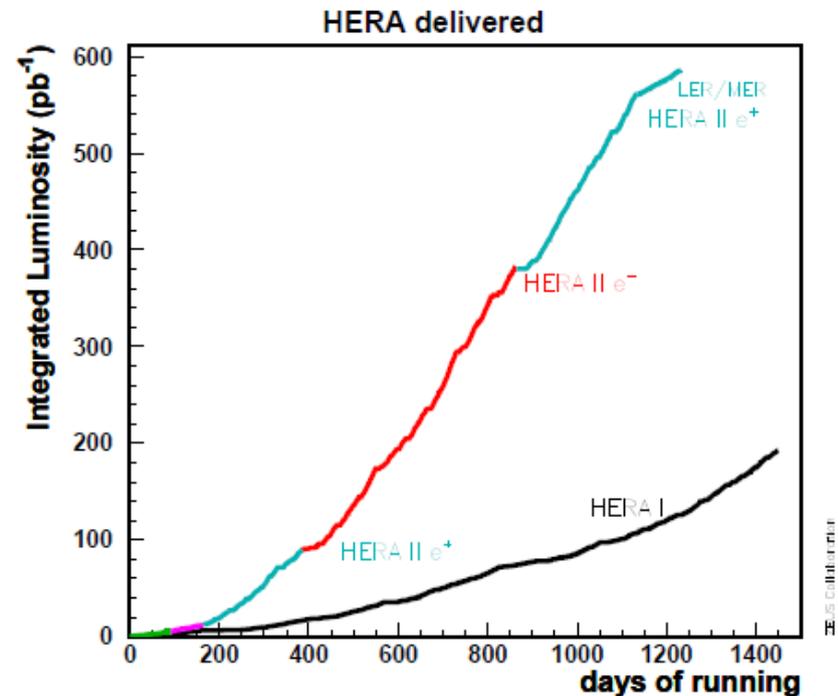
# The HERA Collider

- World's only *ep collider*, located at DESY in Hamburg
- In operation from 1992-2007

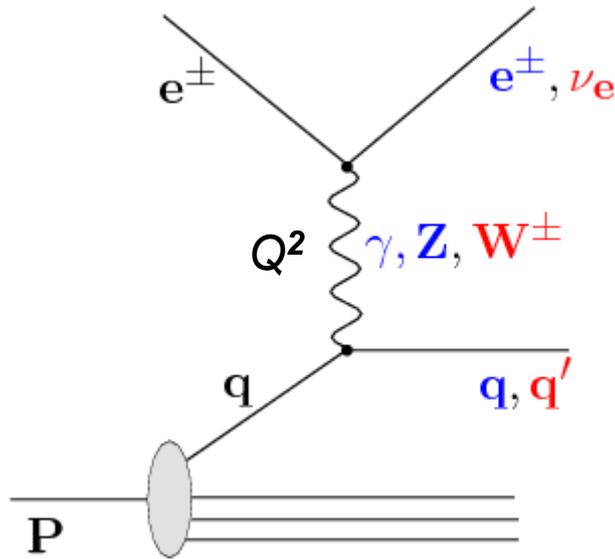


Center of mass energy:  
 $\sqrt{s} = 318 \text{ GeV}$

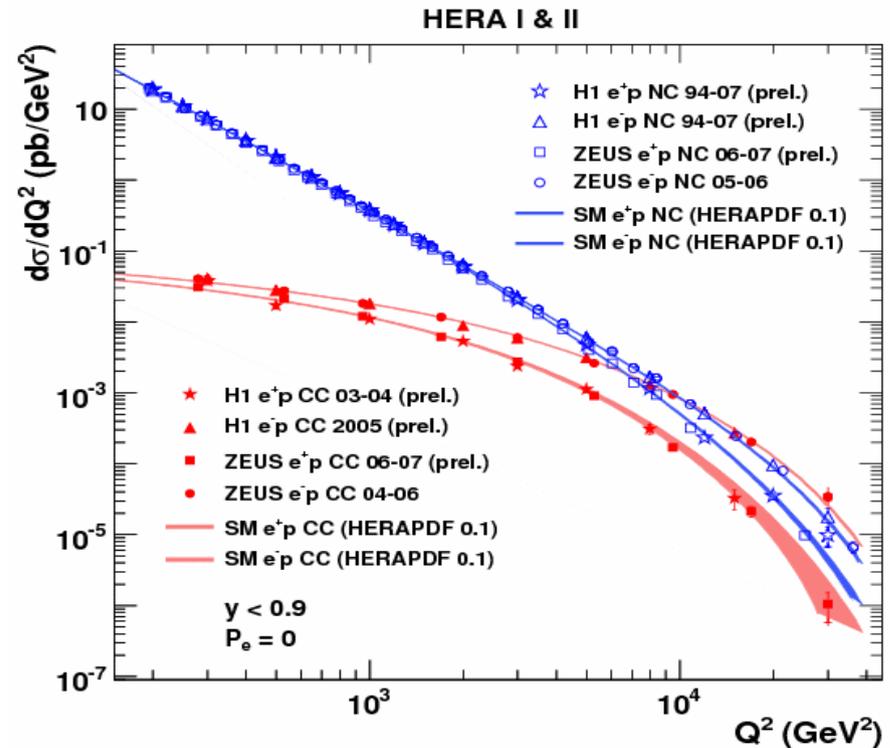
- Two collider experiments: H1 and ZEUS
- $0.5 \text{ fb}^{-1}$  of data collected by each experiment



# Deep Inelastic Scattering (DIS)



- **NC:**  $\gamma$  or  $Z$  exchanged,  $e^\pm$  in final state
- **CC:**  $W^\pm$  exchanged,  $\nu_e$  in final state
- $Q^2$  gives the resolving power
- New physics would appear at high  $Q^2$  (i.e. small scale)



- Excellent agreement between data and SM predictions (HERAPDF) over many orders of magnitude

# Quark Radius

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

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

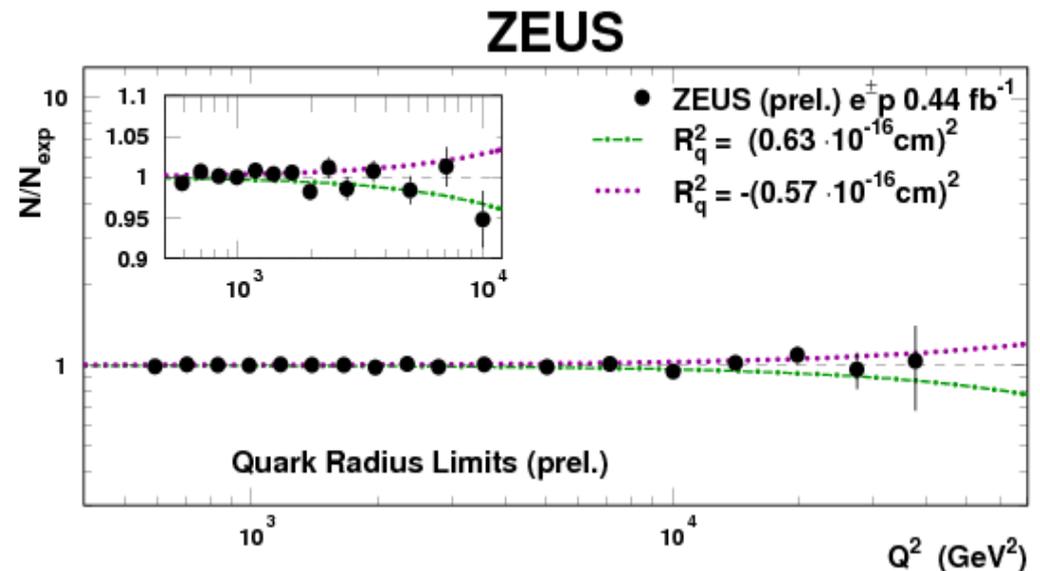
$R_q$ : root mean square radius of the electroweak charge distribution in the quark

- Excellent agreement with SM expectation  $\rightarrow$  limits set using full HERA data (95% CL)

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

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

Limit below 1/1000 of proton radius!



# Contact Interactions

- **Effective theory** describing low energy effects from physics at much higher energy scales  $\Lambda \gg \sqrt{s}$
- Could **alter SM DIS distributions** at high  $Q^2$
- Vector-type **eeqq CI**:

$$\mathcal{L}_{CI} = \sum_{a,b=L,R}^{q=u,d} \eta_{ab}^q (\bar{e}_a \gamma_\mu e_a) (\bar{q}_b \gamma^\mu q_b)$$

- **General models:**

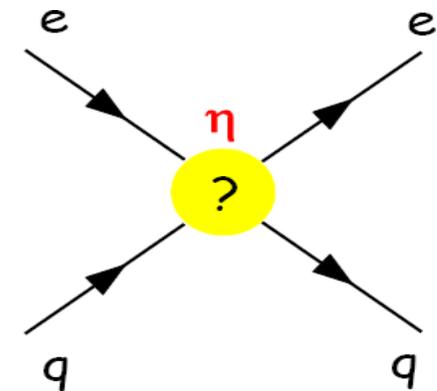
$$\eta_{ab}^q = \pm 4\pi / \Lambda^2$$

- No deviations from NC DIS seen by both H1 and ZEUS → **limits set on 19 models** with different helicity structure:

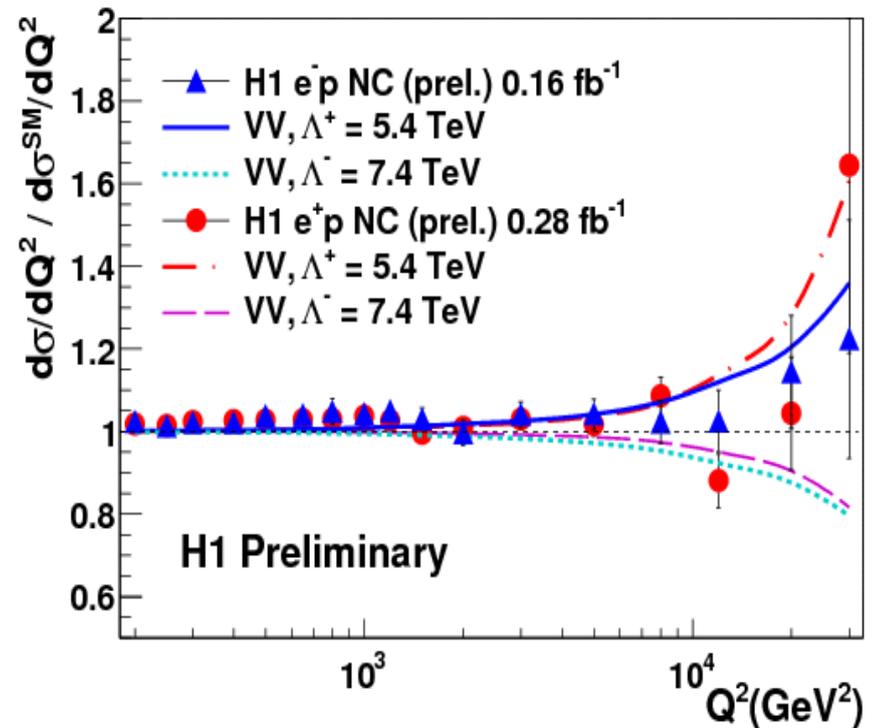
H1:  $\Lambda > 3.7 - 7.4$  TeV

ZEUS:  $\Lambda > 3.8 - 8.9$  TeV

95% CL



Search for General Compositeness



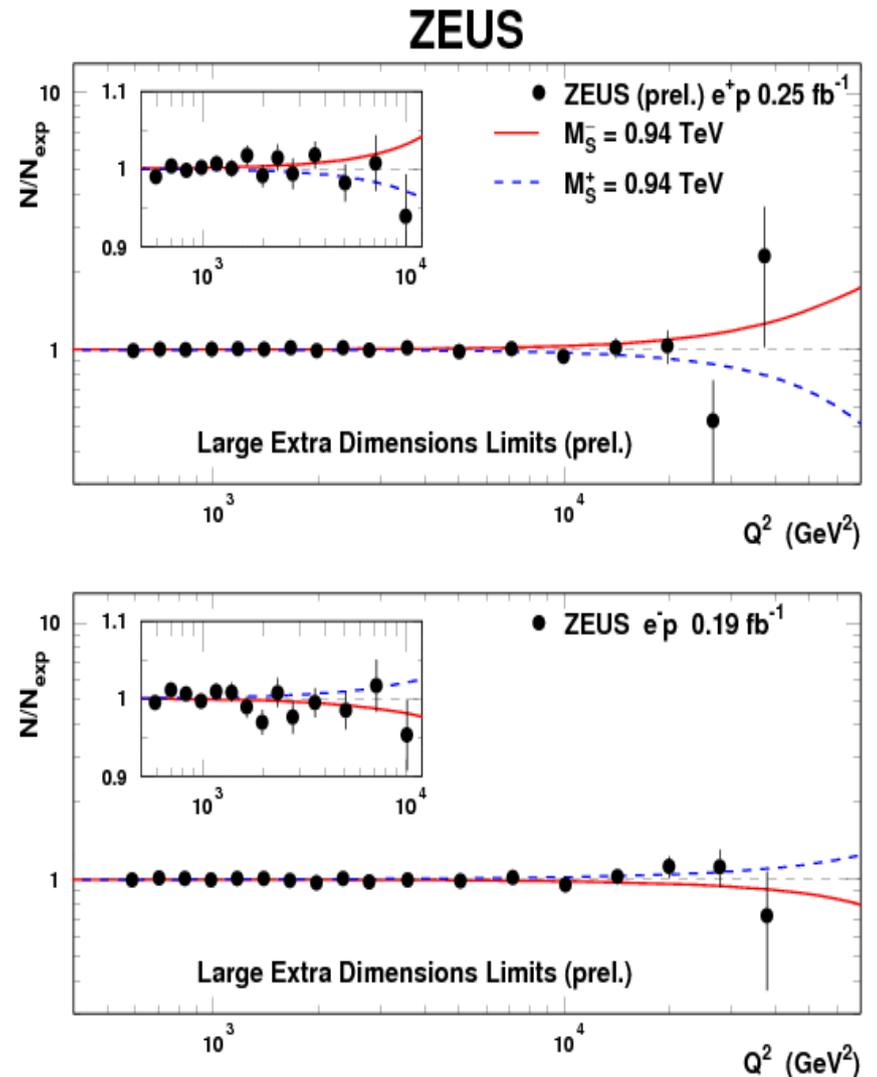
# Large Extra Dimensions

- ADD (Arkani-Hamed, Dimopoulos, Dvali) model: **space time is  $4+n$  dimensional**
- gravity can propagate into the extra dimensions
- Fundamental Planck scale  $M_S$  in  $4+n$  dimensions can be  $\sim 1\text{TeV}$
- ➡ **Strength of gravitational and electroweak interactions comparable** at high energies, hierarchy problem solved
- Virtual graviton exchange contribution to  $eq \rightarrow eq$  scattering described by **contact interaction with effective coupling**  
 $\eta_G \sim \pm 1/M_S$
- Limits set by both H1 and ZEUS (95% CL):

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

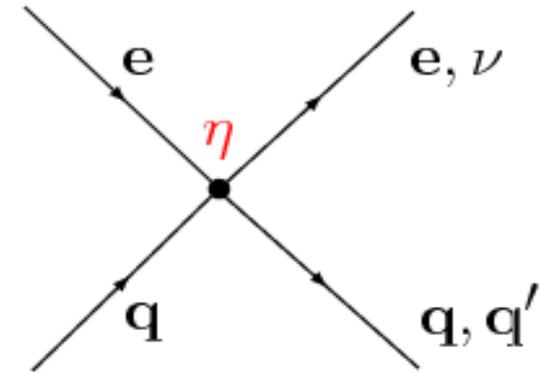
$$\text{ZEUS} : M_S^+, M_S^- > 0.94 \text{ TeV}$$

independent of  $n$ !



# First Generation Leptoquarks

- Scalar or vector **bosons carrying both lepton and baryon number**, color charge and fractional electric charge
- **Buchmüller-Rückl-Wyler model**: SM symmetry, lepton and baryon number conserved
- **Experimental constraints**: LQs couple either to LH or to RH fermions, LQ couplings flavor diagonal



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

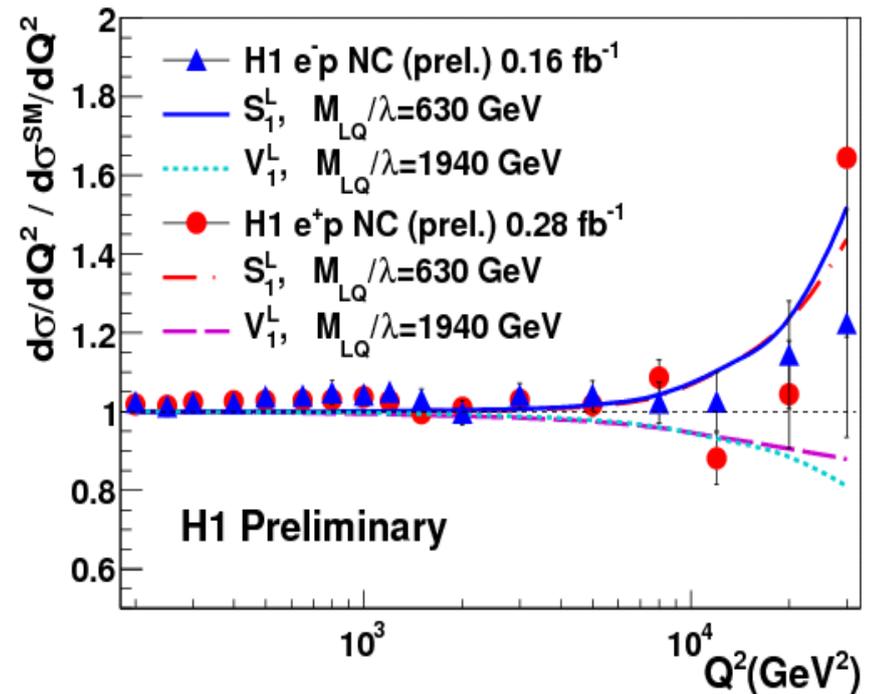
- **Heavy LQ exchange** can be described by a four fermion **contact interaction** with effective coupling  $\eta \sim \lambda^2/M_{LQ}^2$
- Limits set by H1 and ZEUS (95% CL):

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

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

depending on the LQ type

Search for Heavy Leptoquarks

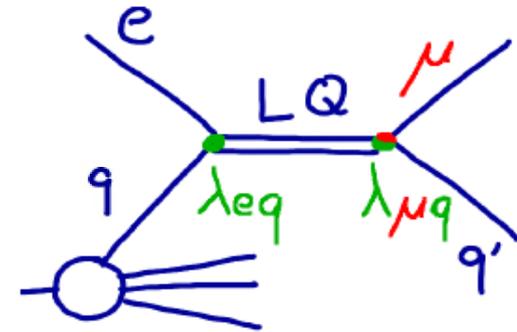


# Lepton Flavor Violation (I)

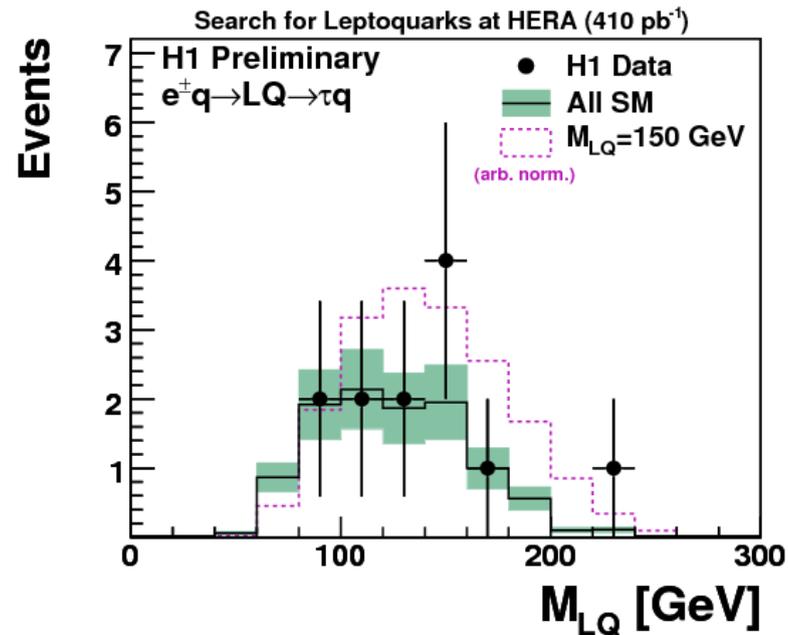
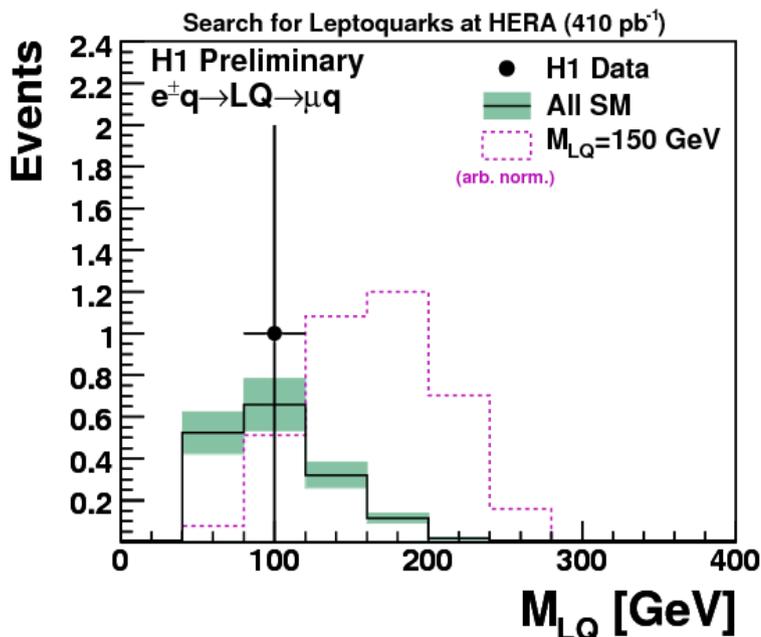
- If LQ couplings **not** assumed as **flavor diagonal**, LQs can **mediate LFV**:

$$ep \rightarrow LQ \rightarrow \mu X$$

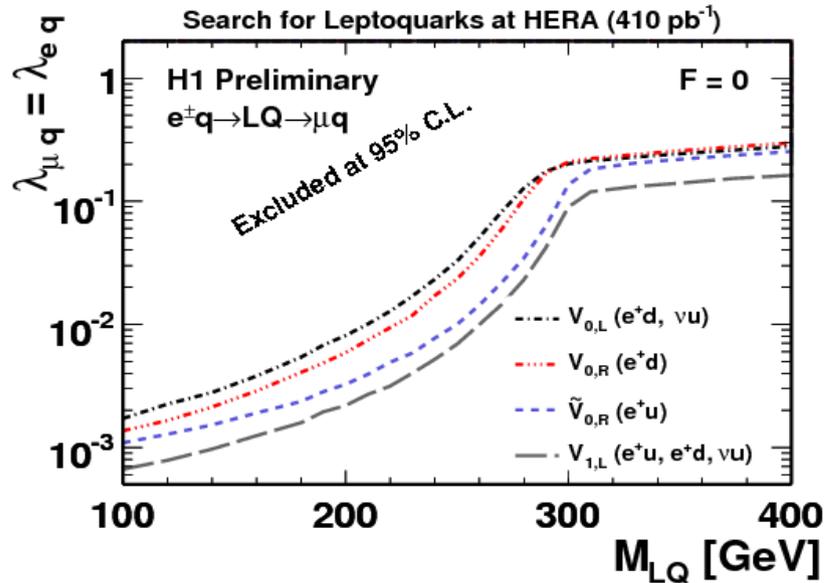
$$ep \rightarrow LQ \rightarrow \tau X$$



- H1 used full HERA data to look for **final states with  $\mu$  or  $\tau$**  and at least one jet
- No deviations from SM** → limits set on the Yukawa coupling  $\lambda$  as a function of the LQ mass



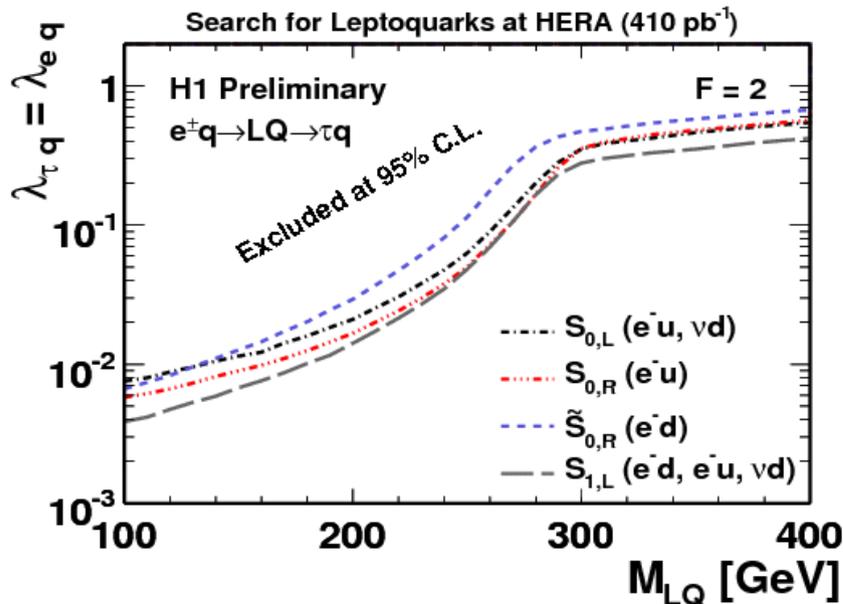
# Lepton Flavor Violation (II)



Assuming

$$\lambda_{e q} = \lambda_{\mu q} = \sqrt{4\pi\alpha} = 0.3 \quad \text{and} \quad \lambda_{\tau q} = 0 :$$

$M_{LQ} < 304\text{-}530$  GeV excluded,  
depending on LQ type (95% CL)



Assuming

$$\lambda_{e q} = \lambda_{\tau q} = \sqrt{4\pi\alpha} = 0.3 \quad \text{and} \quad \lambda_{\mu q} = 0 :$$

$M_{LQ} < 272\text{-}450$  GeV excluded,  
depending on LQ type (95% CL)

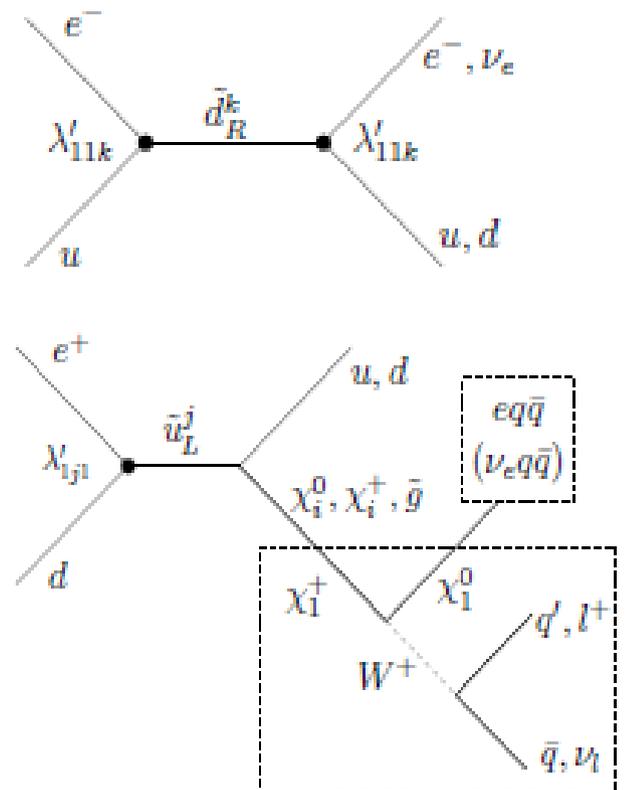
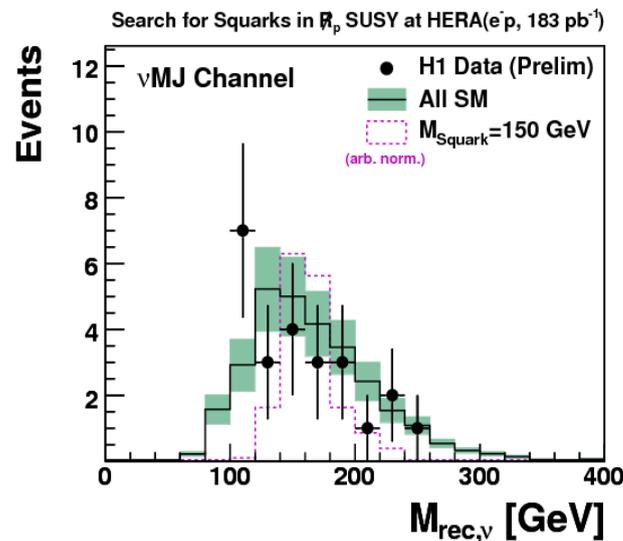
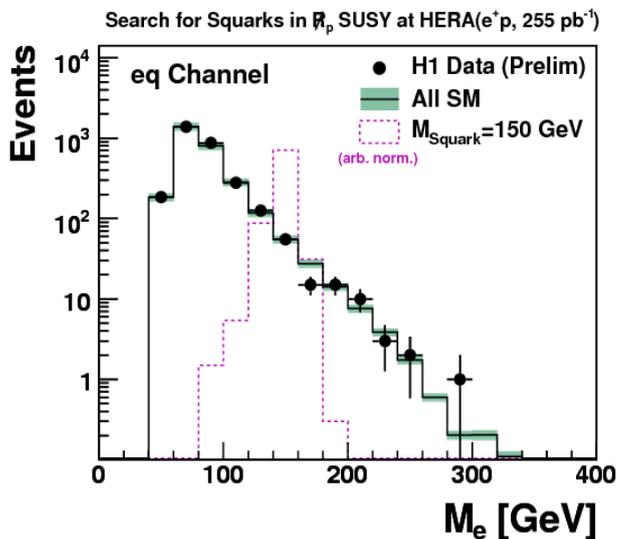
# Squark Production in RPV SUSY (I)

- 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 ( $\rightarrow$  cascade decays)
- **No deviations from SM** in any of the 17 relevant final states seen  $\rightarrow$  limits set

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

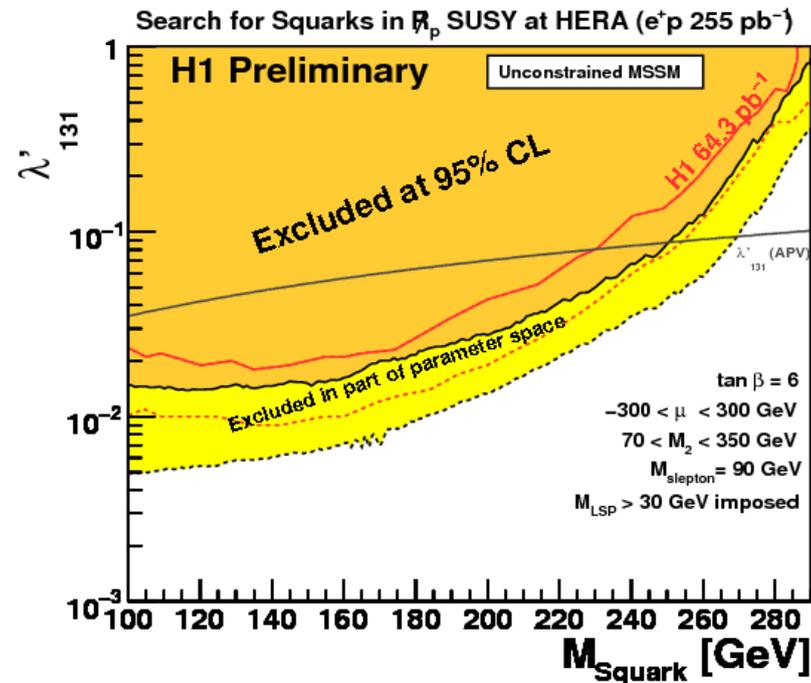
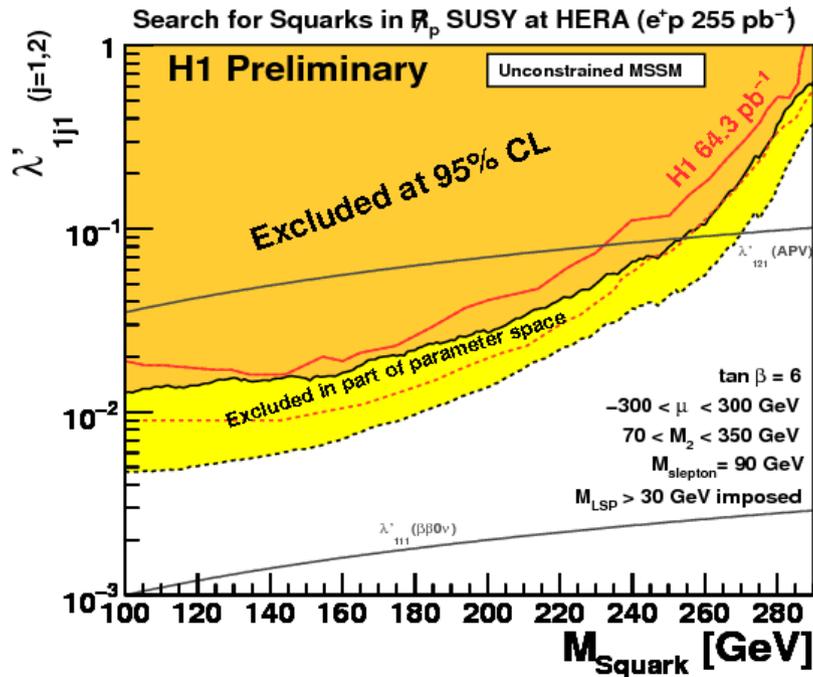
SM particles: +1

SUSY particles: -1



# Squarks in RPV SUSY (II)

- Limits set using full H1 data
- Scan on accessible SUSY parameter space done



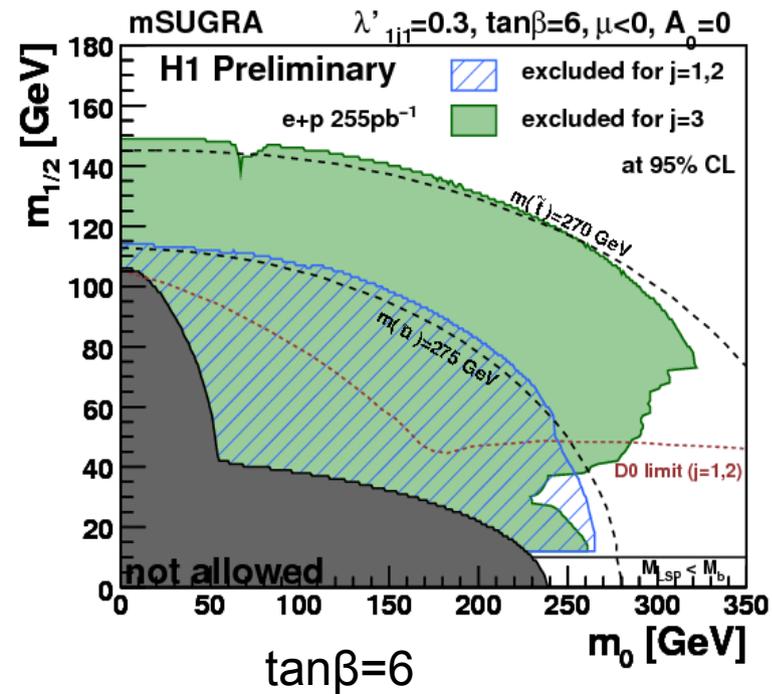
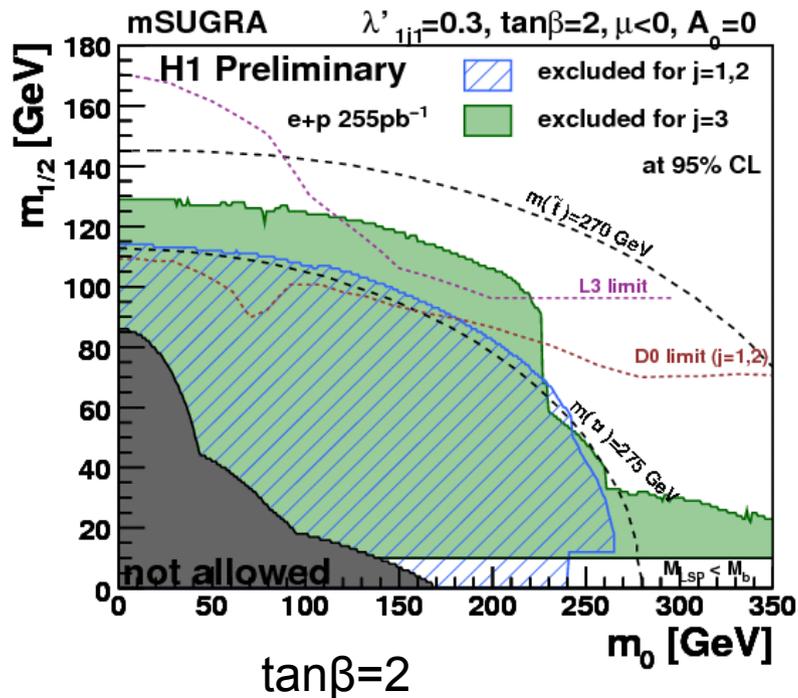
- Limits assuming a Yukawa coupling of electromagnetic strength:

$$M(\tilde{u}_L, \tilde{c}_L, \tilde{t}_L) > 275 \text{ GeV for } \lambda'_{1j1} = \sqrt{4\pi\alpha} = 0.3$$

$$M(\tilde{d}_R, \tilde{s}_R, \tilde{b}_R) > 290 \text{ GeV for } \lambda'_{11k} = 0.3$$

# Squarks in RPV SUSY (III)

- **Minimal Supergravity (mSUGRA) model:** only four free parameters and one sign
- $m_0$  ( $m_{1/2}$ ): universal scalar (gaugino) mass at the GUT scale
- Limits set in the  $m_0 - m_{1/2}$  plane assuming  $\lambda'_{1j1} = \sqrt{4\pi\alpha} = 0.3$
- Dashed black lines indicate curves of constant squark ( $\tilde{u}_L, \tilde{t}_1$ ) mass
- HERA limits extend beyond D0 limits



# Excited Fermions (I)

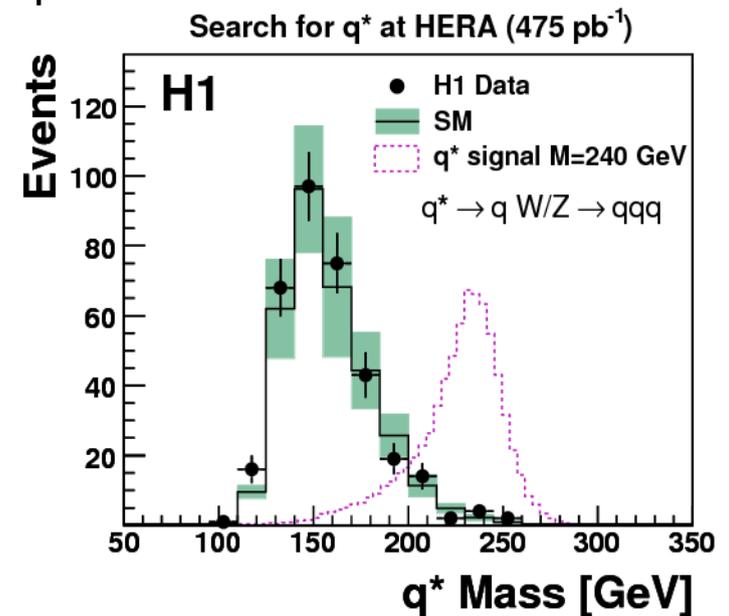
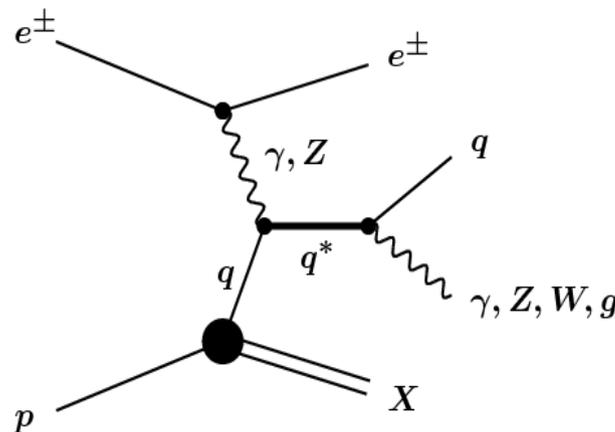
- Observation would be direct **evidence for compositeness** (fermion substructure)
- Compositeness could explain the three lepton/quark families and their mass hierarchy
- Excitation/de-excitation described by **effective Lagrangian**:

$$\mathcal{L}_{int} = \frac{1}{2\Lambda} \bar{F}_R^* \sigma^{\mu\nu} \left[ g f \frac{\tau^a}{2} W_{\mu\nu}^a + g' f' \frac{Y}{2} B_{\mu\nu} + g_s f_s \frac{\lambda^a}{2} G_{\mu\nu}^a \right] F_L + h.c.$$

$\Lambda$ : compositeness scale

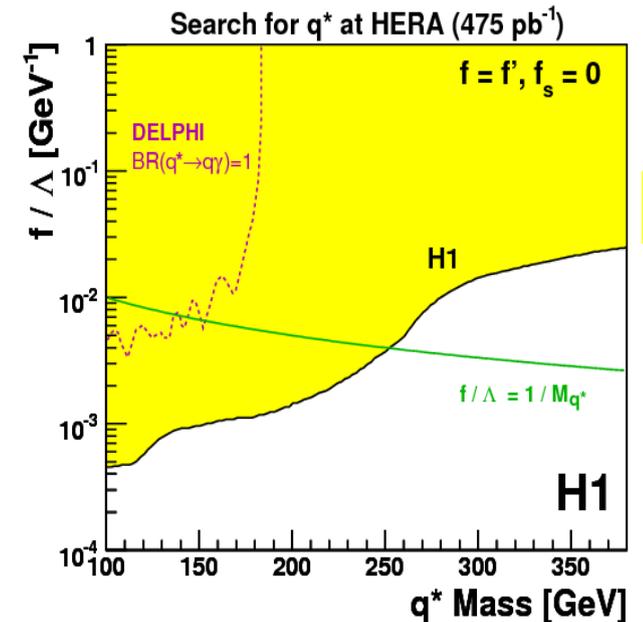
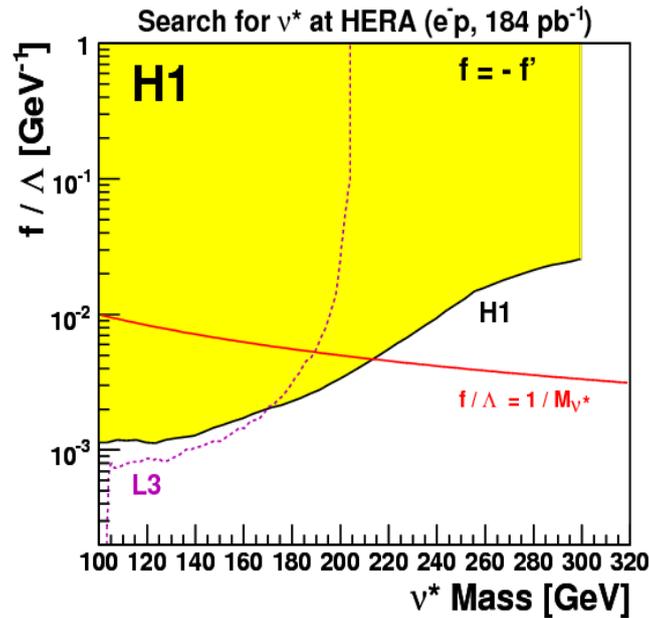
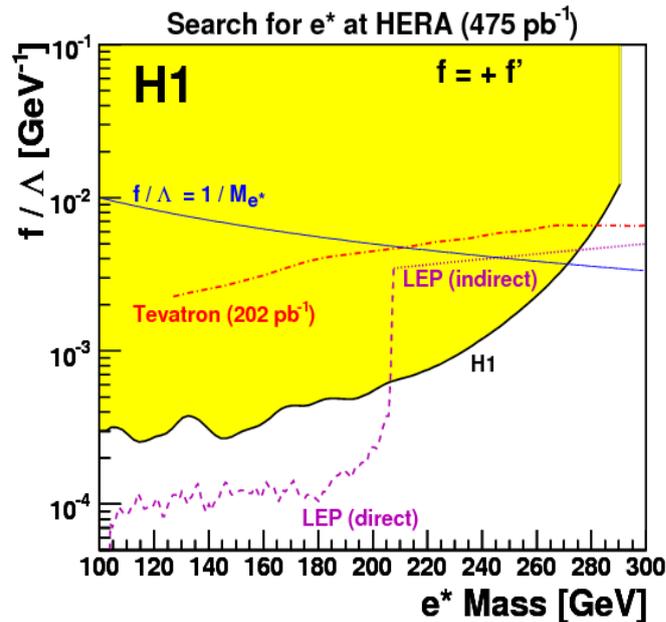
$f, f', f_s$ : coupling parameters associated to SM gauge groups

- Excited fermions decay to standard fermions and **gauge bosons**
- leptonic and hadronic decay channels of gauge bosons investigated



# Excited Fermions (II)

H1 analyzed the full HERA data, **no deviations from SM observed in any channel**  
 → **limits set on  $f/\Lambda$**  as a function of the excited fermion mass (95% CL)



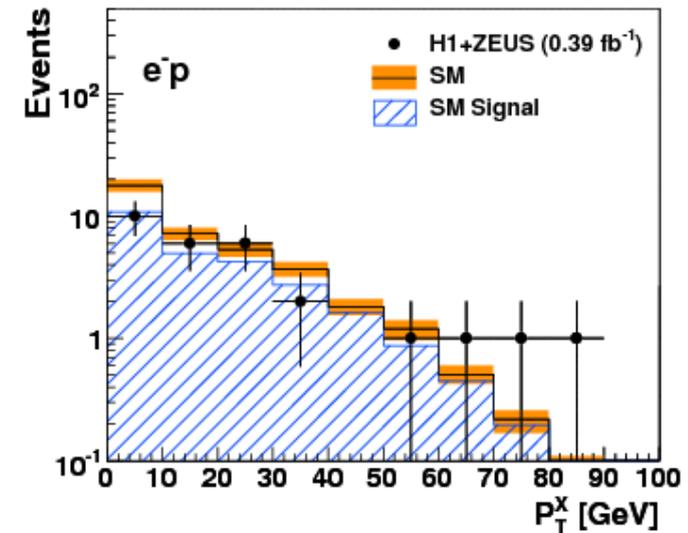
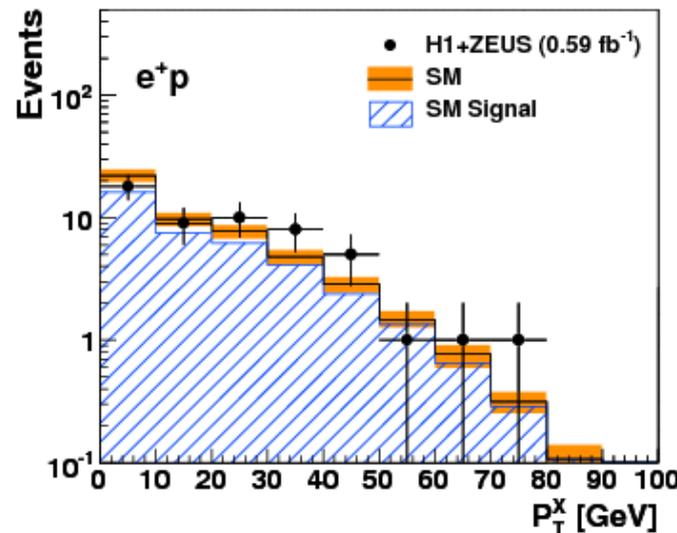
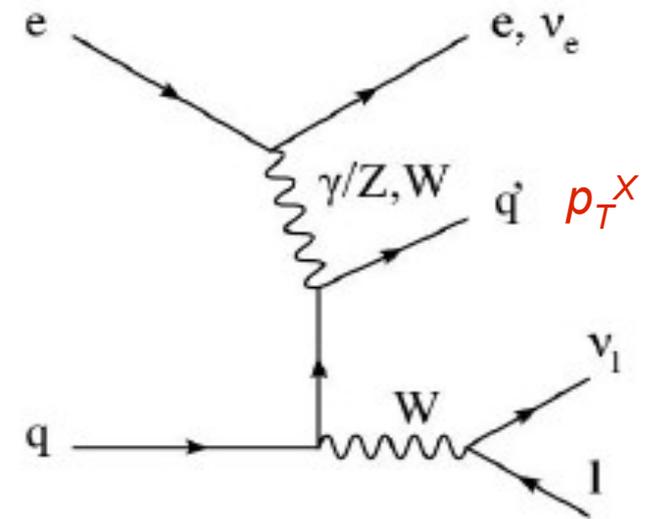
Mass limits **assuming  $f/\Lambda = 1/M_{f^*}$**

- $M_{e^*} > 272 \text{ GeV}$
- $M_{\nu^*} > 213 \text{ GeV}$
- $M_{q^*} > 252 \text{ GeV}$

Tevatron:  
 $q^*$  analyzed  
 assuming  $f_s = 1$   
 (not shown here)

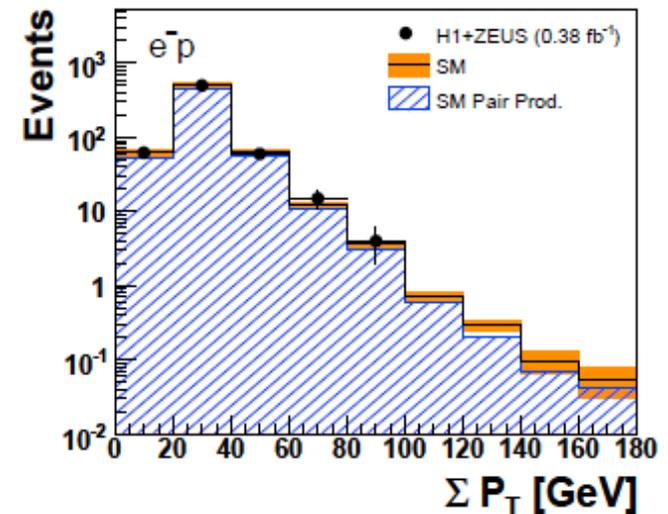
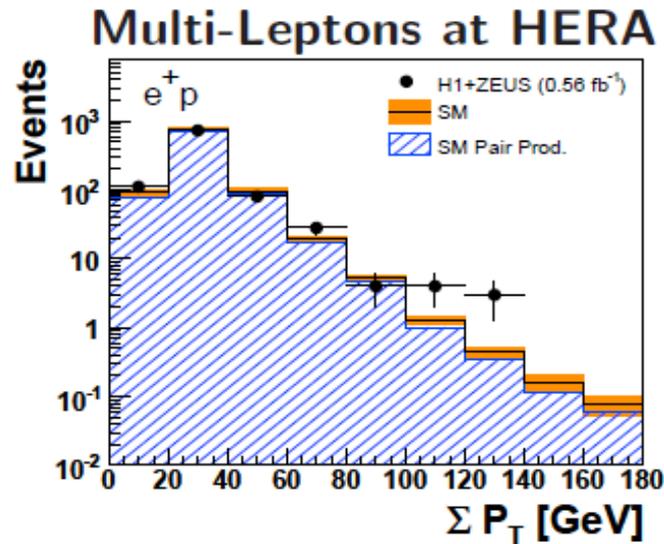
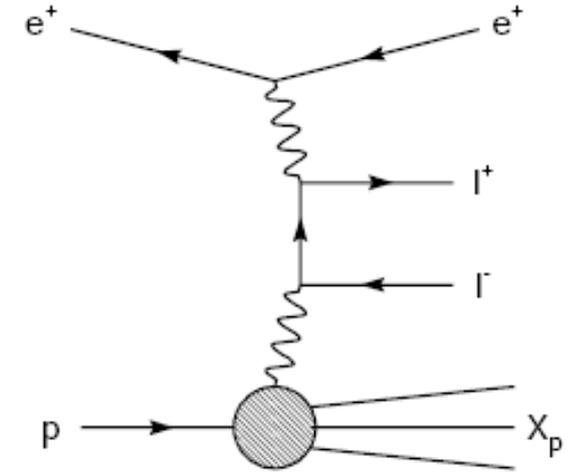
# Isolated Leptons and Missing $p_T$

- Look for events with isolated leptons and missing  $p_T$
- Main corresponding **SM process: single  $W$  production**
- **Search for new phenomena:** anomalous single top production, stop decay,...
- H1 and ZEUS results combined,  $L = 0.98 \text{ fb}^{-1}$
- **$e^+p$  data,  $p_T^X > 25 \text{ GeV}$ :**  
23 events observed,  
 $14.0 \pm 1.9$  expected
- No excess in  $e^-p$  data



# Multi-Leptons

- Look for events with **at least 2 isolated high- $p_T$  electrons or muons** (topologies:  $ee$ ,  $\mu\mu$ ,  $e\mu$ ,  $eee$ ,  $e\mu\mu$ )
- Main production process in **SM:  $\gamma\text{-}\gamma$  interactions**
- SM expectation **small at high invariant mass, high  $p_T$  of the leptons**  $\rightarrow$  look for deviations from SM, would be indication of new phenomena (e.g. exotic resonances such as  $H^{\pm\pm}$ )
- H1 and ZEUS combined their results ( $L=0.94 \text{ fb}^{-1}$ )
- **$e^+p$  data,  $\Sigma p_T > 100 \text{ GeV}$ :**  
7 events observed,  
 $1.94 \pm 0.17$  expected
- No excess in  $e^-p$  data



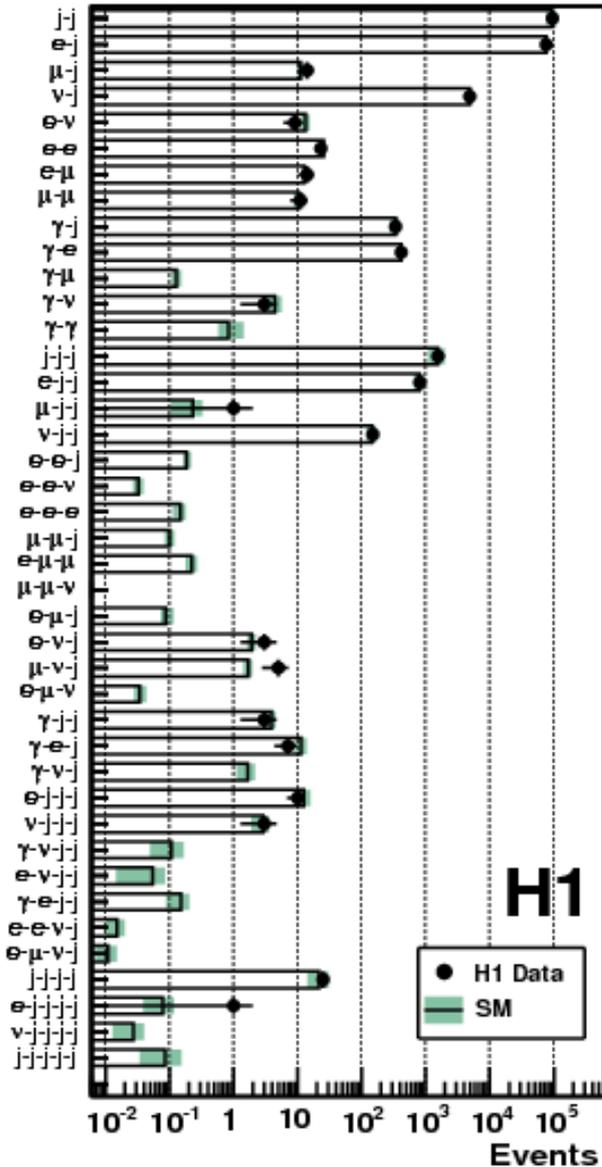
# Summary

- Searches for new physics have been performed by H1 and ZEUS with the full data sets of  $0.5 \text{ fb}^{-1}$  per experiment
- Standard Model very healthy – no signs of new physics at HERA observed
- Limits set on various BSM scenarios

# *Backup*

# General Searches

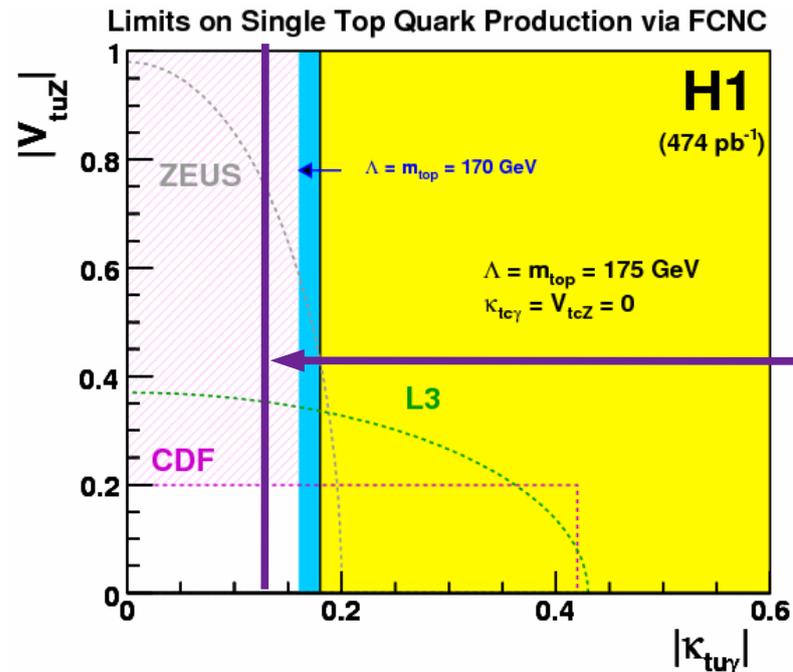
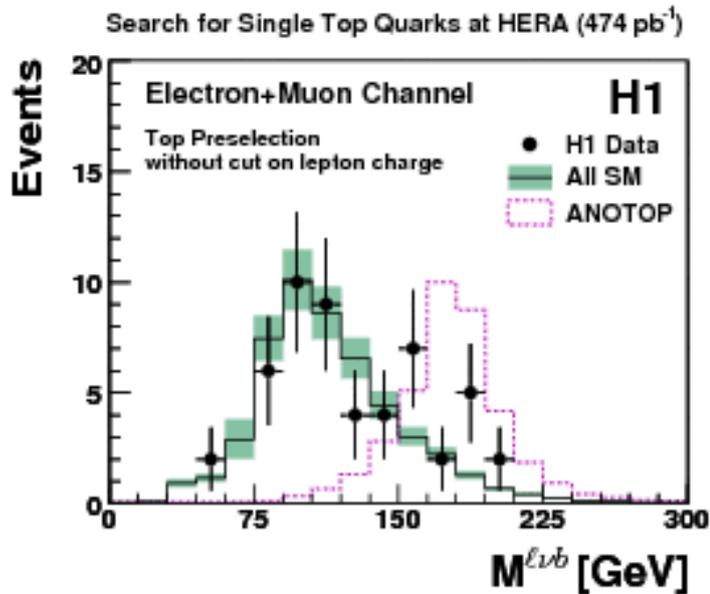
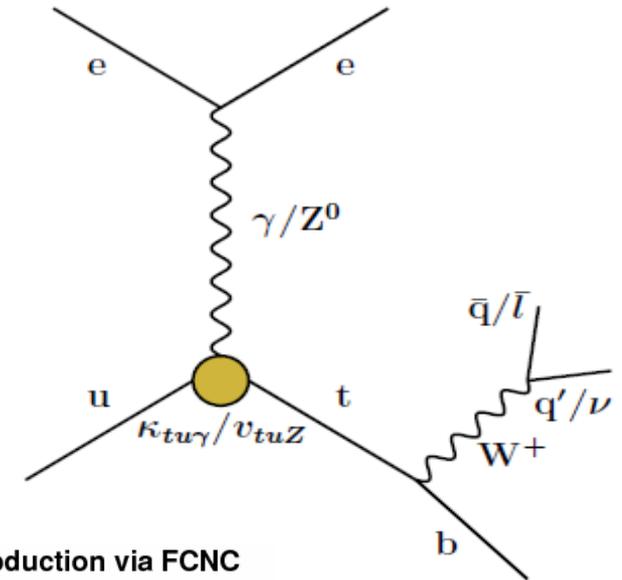
H1 General Search at HERA ( $e^+p$ ,  $285 \text{ pb}^{-1}$ )



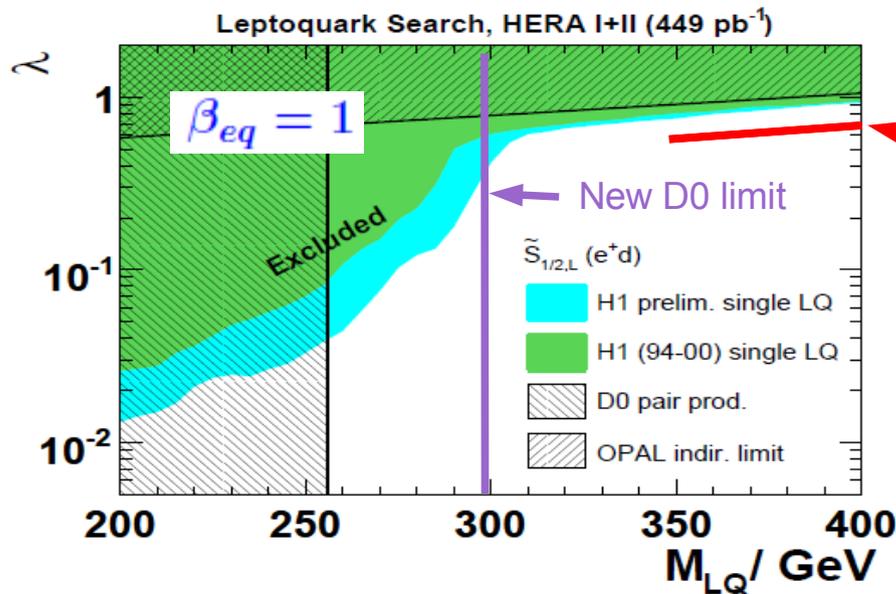
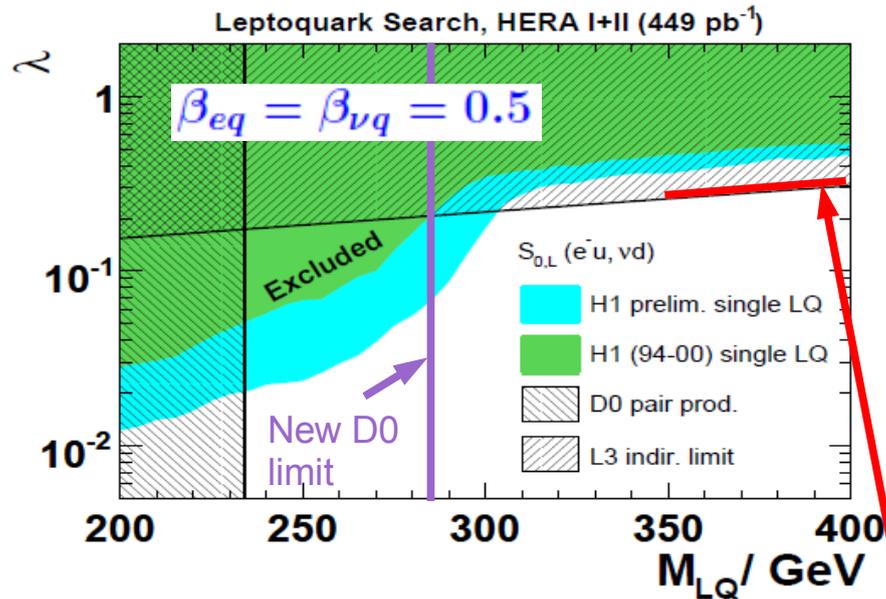
- **Model independent** generic search for final states with  $\geq 2$  **high- $p_T$  objects** (e,  $\mu$ , jet,  $\gamma$ ,  $\nu$ ), separately for  $e^+p$  and  $e^-p$  collisions
- Complete H1 data analyzed ( $L=0.46 \text{ fb}^{-1}$ )
- At least one event in 27 topologies
- Events found e.g. in multi-lepton analysis are found again
- **Look for possible deviations from SM** in total event number and in  $\Sigma p_T$  and  $M_{all}$  distributions
- **Statistical analysis** used to quantify the significance of the deviations
- **Good agreement with SM**, all deviations consistent with statistical fluctuations
- Number of fluctuations given the large number of search channels is consistent

# Anomalous Single Top Production

- Top quarks at HERA can only be singly produced
- SM cross section negligible ( $\sigma < 1\text{fb}^{-1}$ ), but production predicted by several BSM theories → **observation would be clear indication of new physics**
- 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)



# First Generation Leptoquark Limits



- Full H1 data analyzed for NC/CC-like final states
- No deviations from SM seen
- Limits set on Yukawa coupling  $\lambda$  as a function of the LQ mass (95% CL)
- For  $\lambda = \sqrt{4\pi\alpha} = 0.3$ :  
 $M_{LQ} < 291\text{-}330$  GeV excluded, depending on LQ type
- ZEUS CI limit (94-07 prel.):  
 $M_{LQ}/\lambda > 0.41\text{-}1.88$  TeV, depending on LQ type (95% CL)