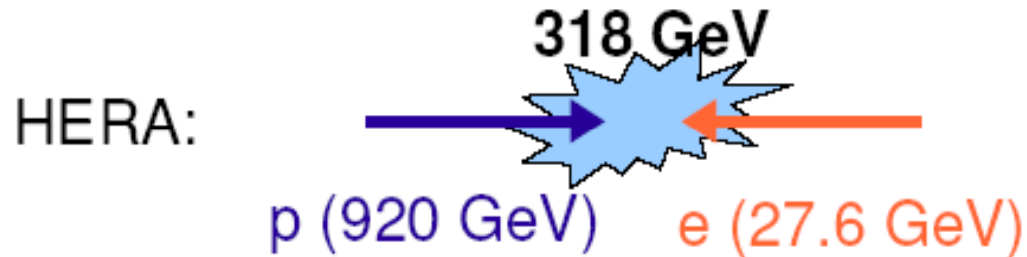
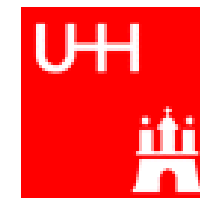


# Searches for new Physics at HERA

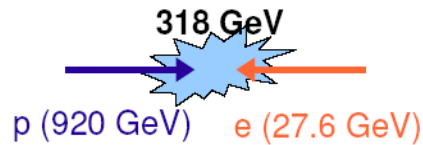


- HERA data & experiments
- Model – independent Search
- Single top & lepton +  $P_{T,miss}$
- Supersymmetry
- Contact Interactions
- Excited Fermions

Peter Schleper  
Hamburg University  
Physics at LHC  
Split, 30. Sept. 2008



# HERA Performance



## HERA-I : 1992 - 2000

- $\sim 120 \text{ pb}^{-1}$  per experiment, mostly  $e^+p$

## HERA-II: 2003 - 2007

Upgrade: luminosity & polarisation:  $e_L^-$ ,  $e_R^-$ ,  $e_L^+$ ,  $e_R^+$

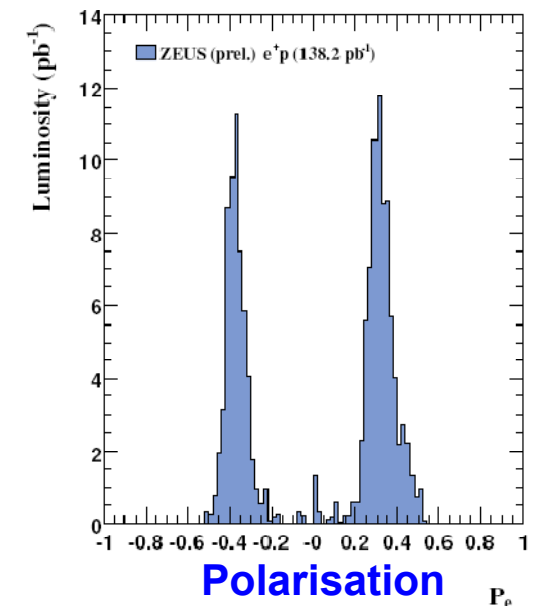
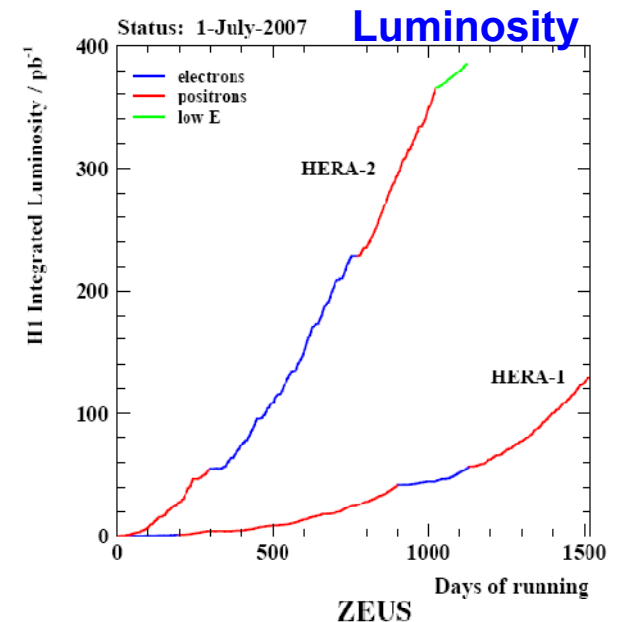
Recently: very good conditions

→ low background, stable beam conditions

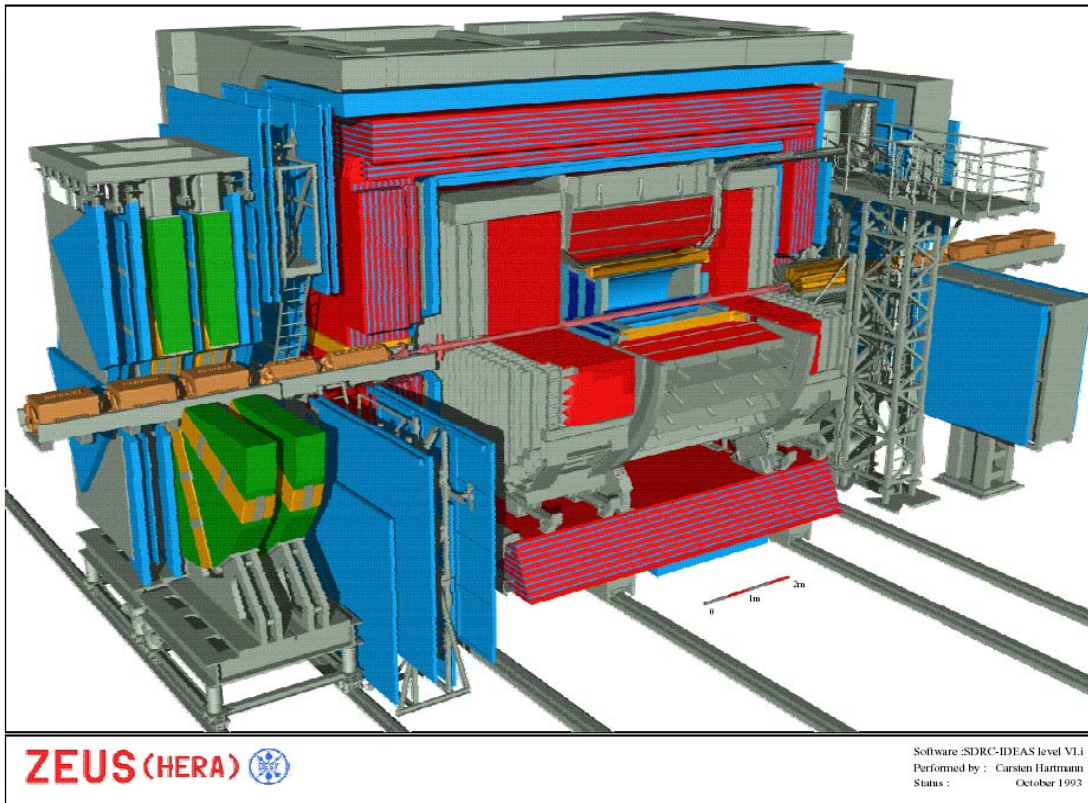
→ high data taking efficiencies, low thresholds

→ no major problems on central detectors

- **polarisation**
  - average  $\sim 40\%$
- **electron & positron running**
  - $\sim 184 \text{ pb}^{-1} e^-p$
  - $\sim 294 \text{ pb}^{-1} e^+p$
- **luminosity HERA I & II**
  - $\sim 478 \text{ pb}^{-1}$  per experiment,  $\sim 90\%$  at 320 GeV
- end of HERA running in June, 2007 → final data set



# HERA Experiments: H1 & ZEUS



multi-purpose detectors

Tracking (B-Feld: 1.15 ... 1.5 Tesla)

- 3 layers silicon vertex detectors
- central driftchambers (~60 hits)
- forward straw tubes or drift chambers

Calorimeters: hermetic up to  $\eta < 3.5..4$

**ZEUS: Uran-Szint.** → compensating

- electrons: 18%/sqrt(E)
- hadrons: 35%/sqrt(E),

**H1: Liquid Argon** → high granularity

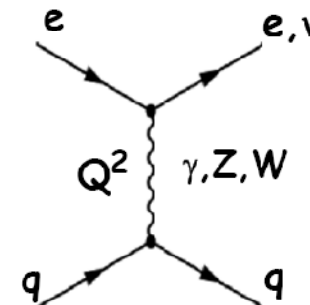
- electrons: 11%/sqrt(E)
- hadrons: 50%/sqrt(E)

Jets from tracks + calor. for  $\eta < 1.5$

Muon chambers in return yoke

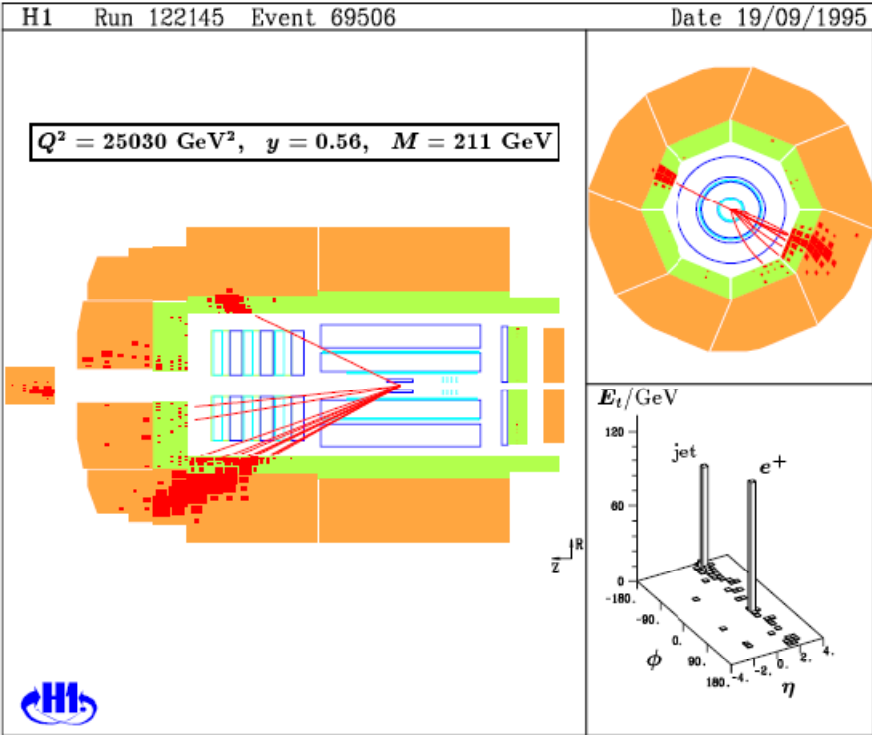
~  $10^8$  ep collisions triggered by H1 & ZEUS

- 96 ns BC → 100 Hz trigger rate
- Thresholds:  $P_T > 5 \dots 10$  GeV for electrons and jets
- Luminosity: ~ 1.6 ... 3.5 % precision
- Polarisation: ~ 3 ... 5 % precision

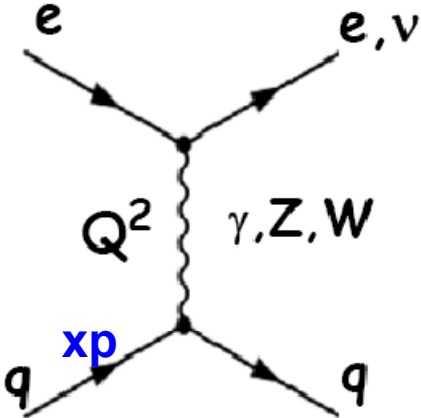


# HERA data

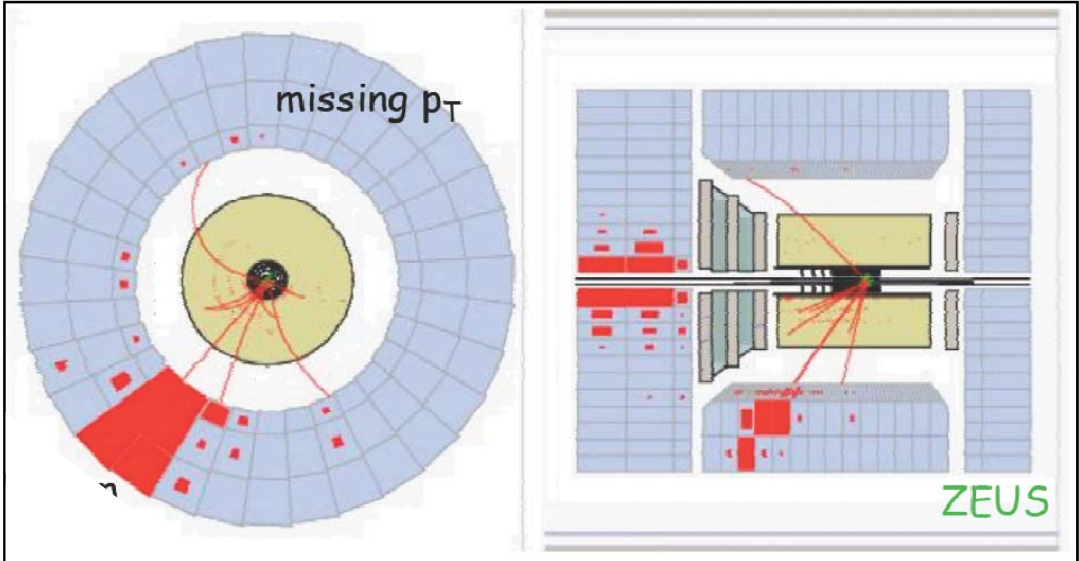
## Neutral current: $\gamma, Z$



$Q^2$  up to  $\sim 40000 \text{ GeV}^2$   
 $\rightarrow$  resolution  $\sim 0.001 \text{ fm}$



## Charged current: W



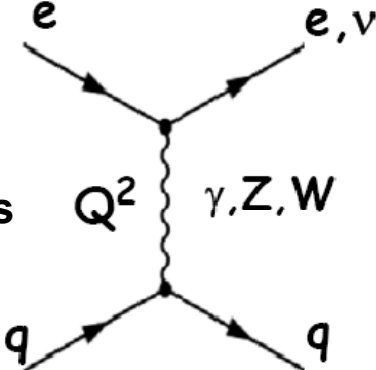
### Calorimeter E-scales:

- kinematic constraints on  $P_T$  and long. momentum
- $\theta_e, \theta_{\text{hadrons}} \rightarrow E_e, P_{Te}, P_{T,\text{Hadronen}}$  (c.f.  $\gamma$ +jet calibration at LHC)
- $\rightarrow$  1% for electrons, 2...3 % for jets

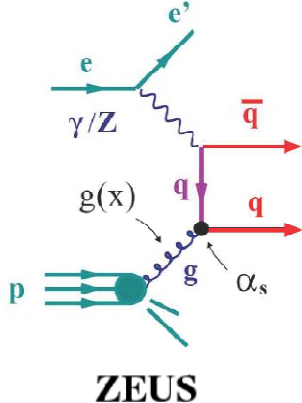
# HERA data

## Inclusive measurements

- used for PDF determinations (low  $Q^2$ )
- Contact interaction analysis (high  $Q^2$ )
- Squarks in RP violating SUSY, leptoquarks
- dominant sources of background for many searches, systematics  $\sim 2\%$

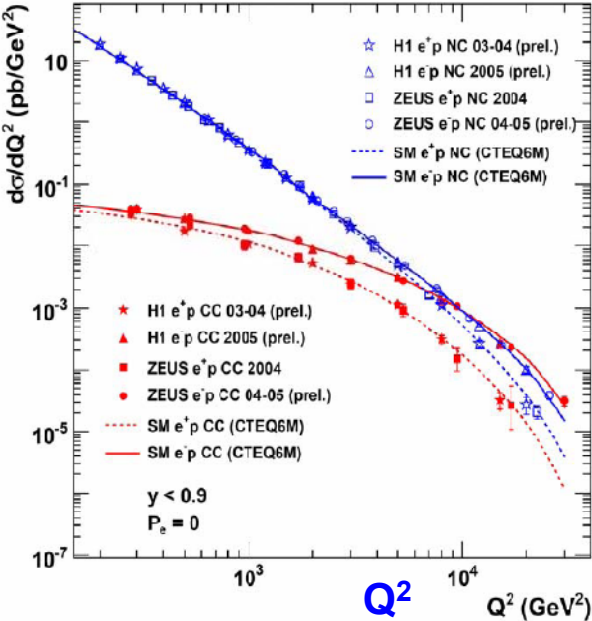


## Inclusive Jet Production



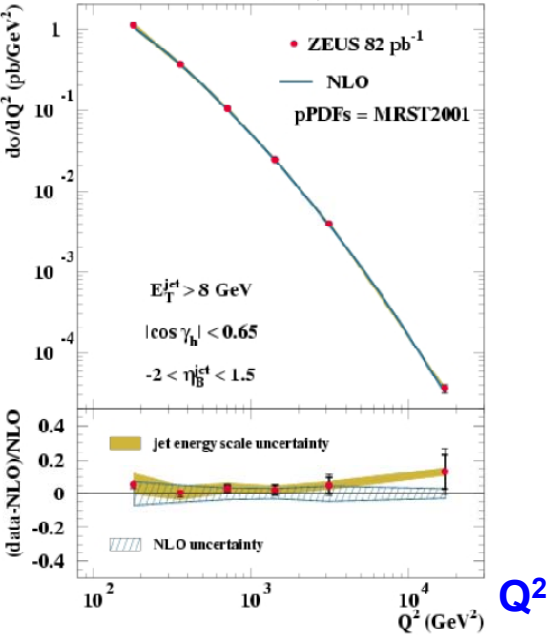
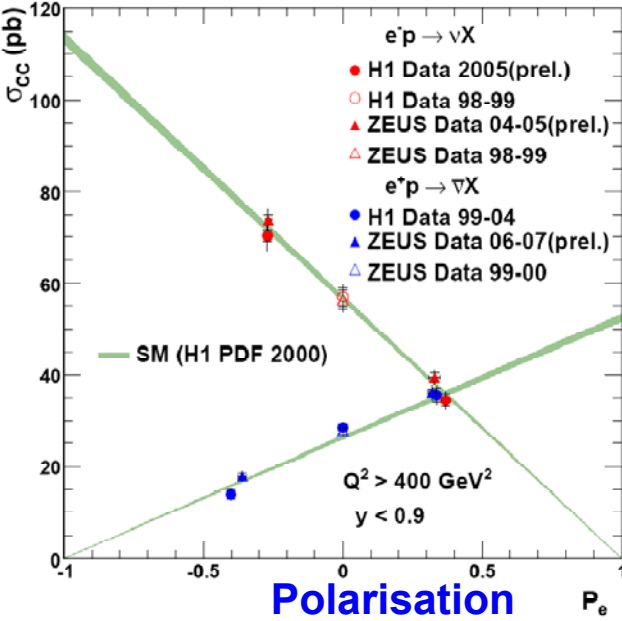
## Neutral Current

HERA II



## Charged Current

Charged Current  $e^+p$  Scattering



**HERA combined (new analysis):**

$$\alpha_s(M_Z) = 0.1198 \pm 0.0019 \text{ (exp.)} \pm 0.0026 \text{ (th.)}$$

# Model – independent Search (H1)

**HERA: highest energy with lepton in the initial state**

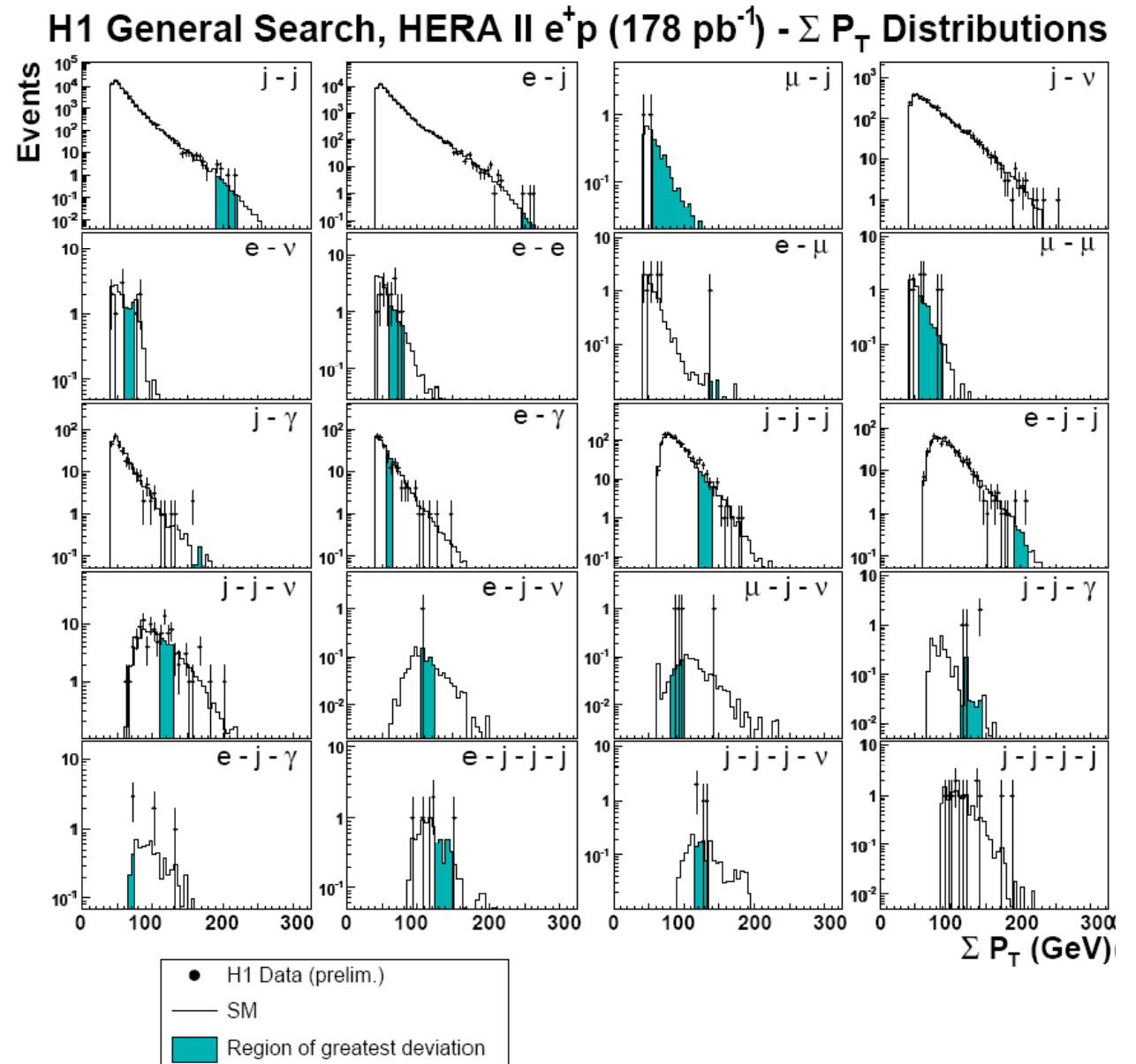
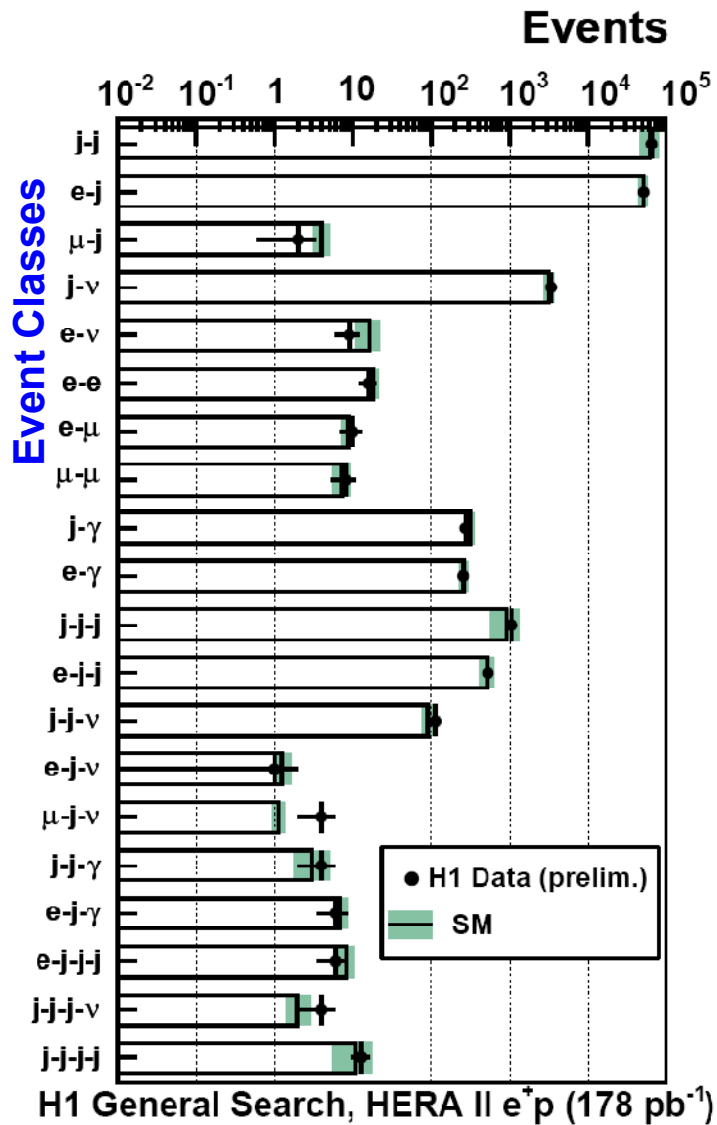
**e+q: no pair production, but single production of new particles**

**high precision on SM processes**

## Model independent search

- Inclusive search for particles at high  $P_T$
- **Electrons ,Photons, Muons, Hadronic Jets, Neutrinos (PTmiss)**
- phase space for all:
  - **$P_T > 20 \text{ GeV}$**
  - **$10^\circ < \theta < 140^\circ$**
- All combinations: ee, e $\gamma$ ,e $\mu$ ,ej,....jj, ejj, ejv  $\rightarrow$  event classes
- **Mass** and  $\sum P_T$  (Jacobi-peak)
- Comparison to SM (LO+PS + K-factors from NLO)  
 $\rightarrow$  look for deviations (max. deviations)
- Statistical interpretation via monte carlo experiments  $\rightarrow$  probability

# Model – independent Search



# Model – independent Search

Precision :

→ Systematics: few %

→ Statistics: limited at large M, PT  
and large multiplicity

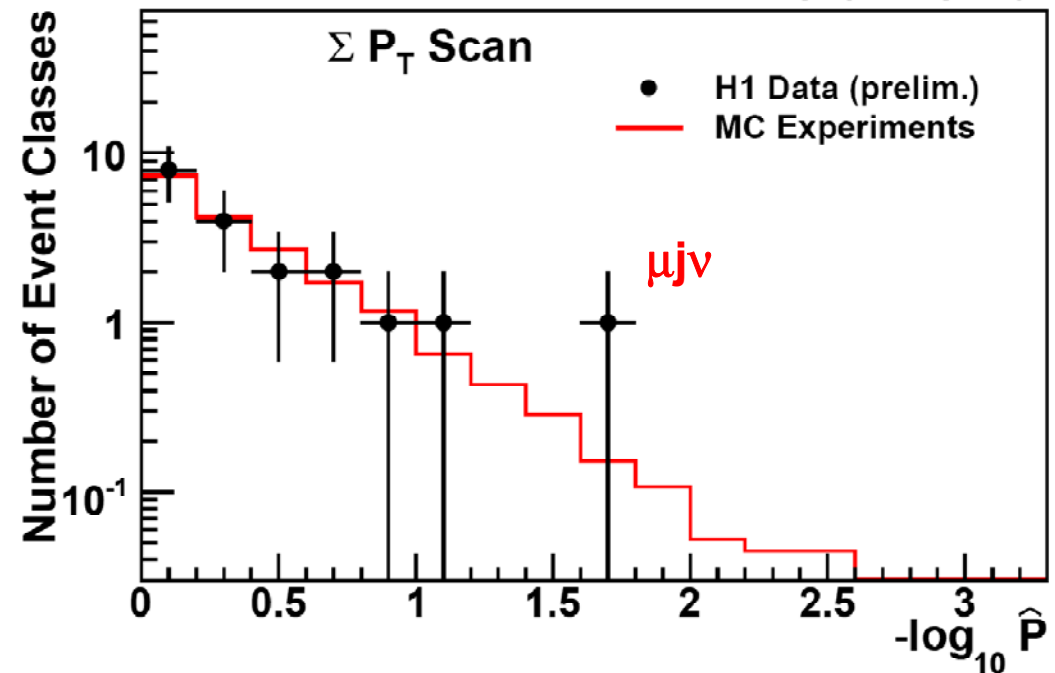
→ Theory: uncertainty large for  
multi-jet channels

Distribution for data follows  
expectation

→ Excellent understanding  
of most final states at HERA

Probability of max. deviation for event classes

H1 General Search, HERA II  $e^+p$  (178  $\text{pb}^{-1}$ )



**Exception:** Largest deviation for  $\mu j\nu$  channel

$e^+p$ : H1 observation: 21 /  $8.9 \pm 1.5$  events ( $3.0\sigma$ )

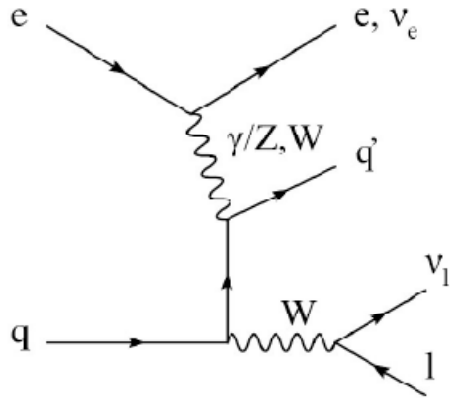
ZEUS: no events in excess of SM

$e^-p$ : H1 and ZEUS: Agreement with SM

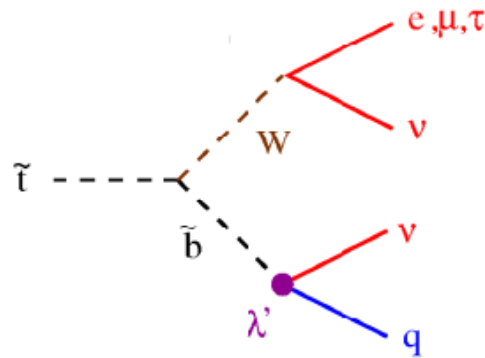


# Lepton + $P_{T,miss}$ + X

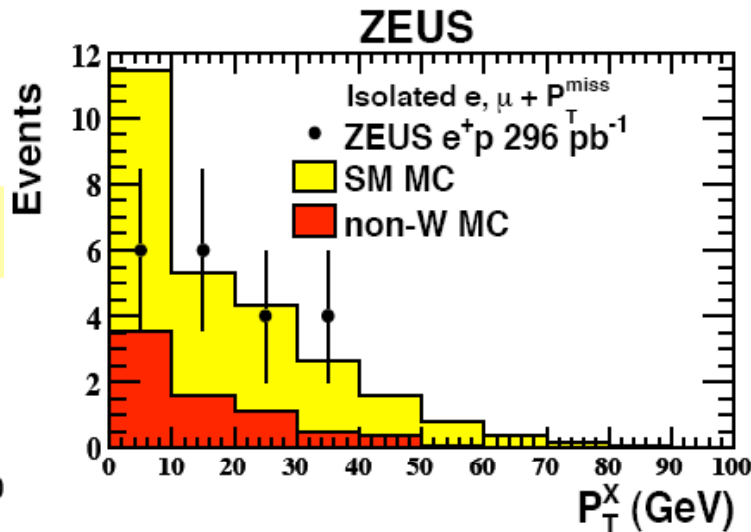
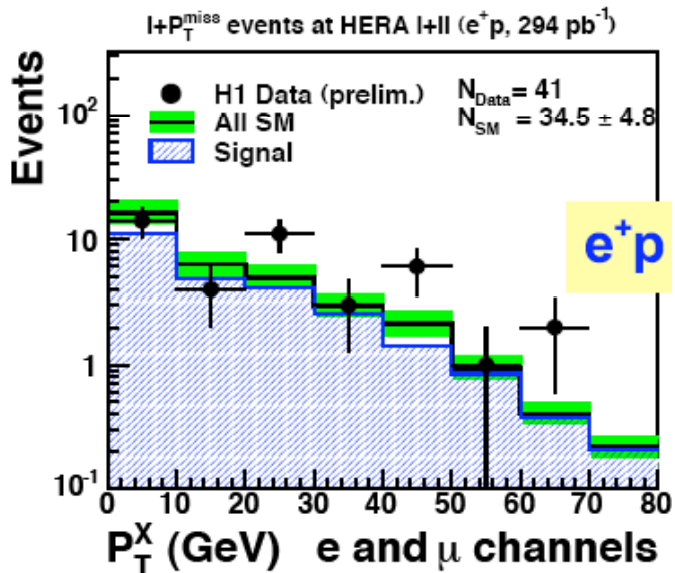
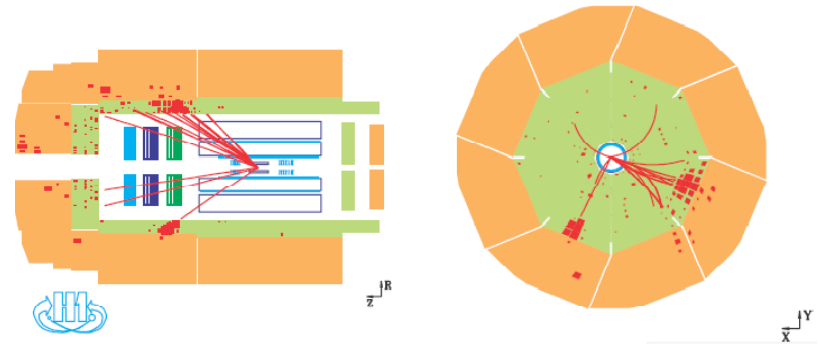
**W production in SM:**  
small  $P_{T,X}$  of hadrons



**SUSY with  $R_p$  violation**  
Single stop production



**H1: events with unexpected large  $P_{T,X} > 25$  GeV**



$e, \mu + P_{T,miss}$ ,  $e^+p$  data

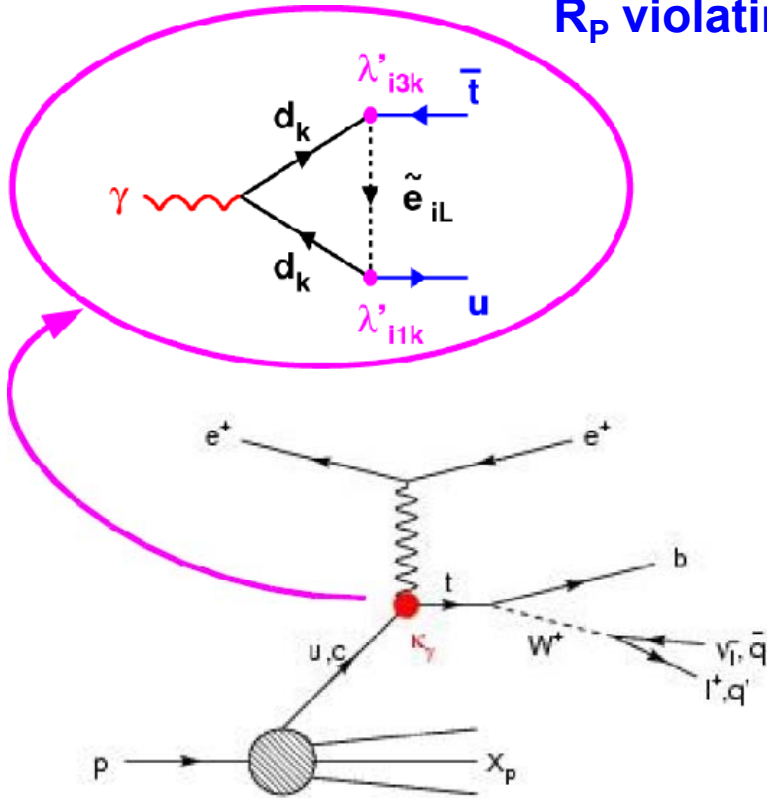
H1:  $3 \sigma$

H1+ZEUS:  $1.8 \sigma$

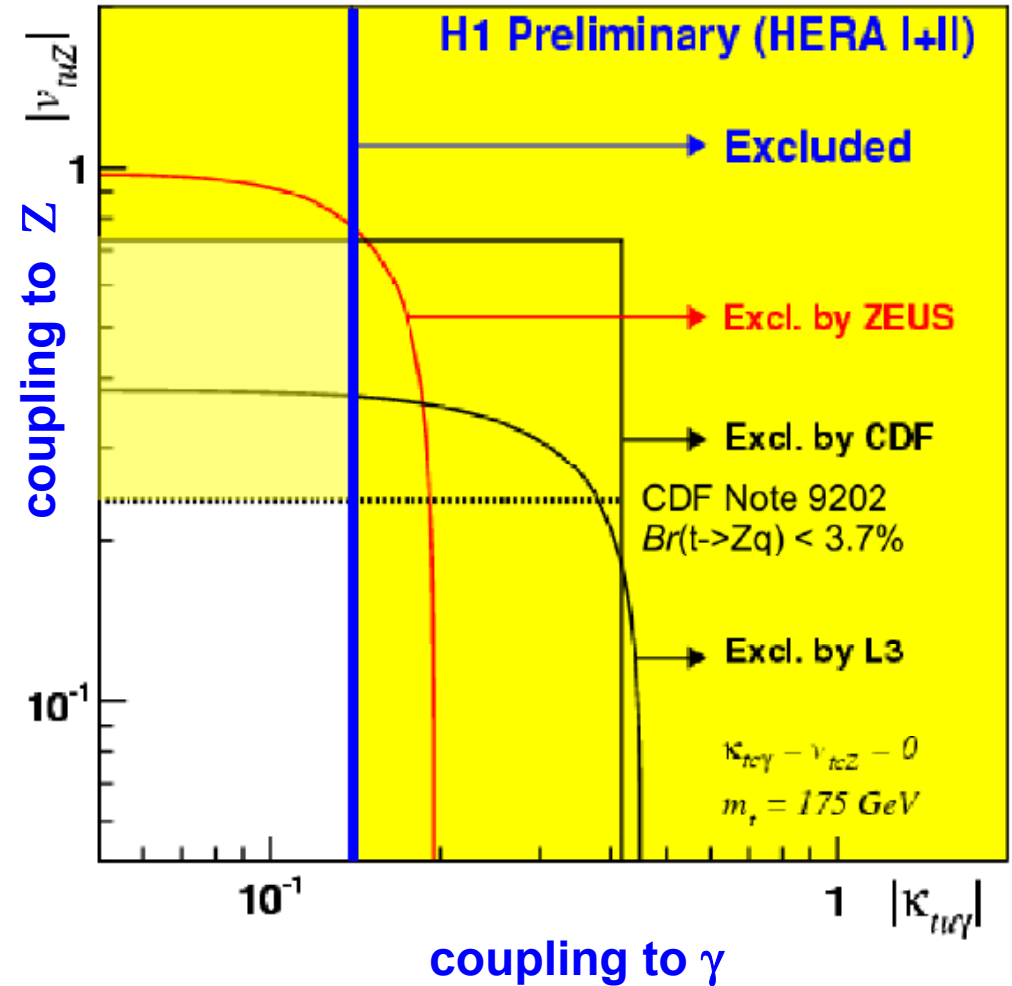
→ not confirmed by ZEUS

# Single Top

$R_p$  violating SUSY



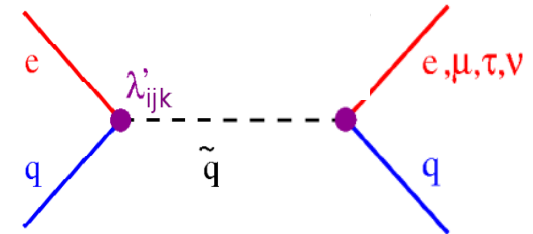
- parameterize  $t\bar{u}$ -vertex by effective couplings  $\kappa_{t\bar{u}\gamma}$  and  $\nu_{t\bar{u}Z}$
- explicit reconstruction of top mass



# Supersymmetry: R-parity violating

## $R_p$ conserved:

- $e+q \rightarrow$  selectron-squark
- $E_{CMS}$  too small (Tevatron constrains)



## $R_p$ violation:

$$W_{RPV} = \lambda'_{ijk} L_i Q_j \bar{D}_k$$

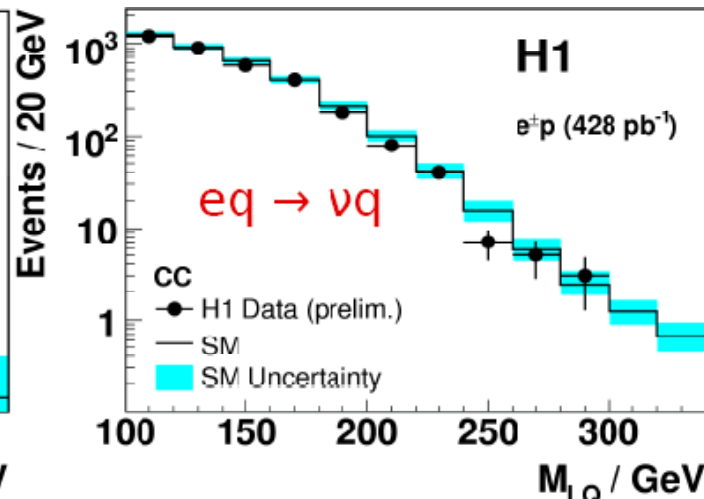
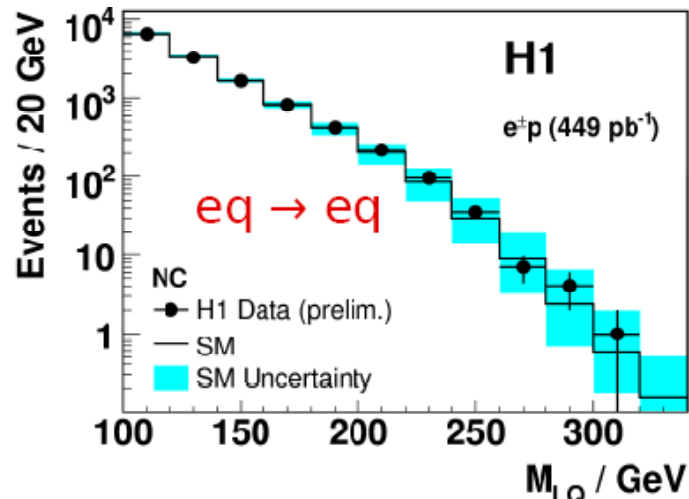
- $e+q \rightarrow$  squark (s-channel resonance + u-channel)
- irreducible background / interference with deep inelastic  $e+q \rightarrow e+q$

$$e^+ d \xrightarrow{\lambda'_{ijl}} \tilde{u}_{j,L} \rightarrow e^+ d$$

$$e^- u \xrightarrow{\lambda'_{ik}} \tilde{d}_{k,R} \rightarrow e^- u$$

$$e^- u \xrightarrow{\lambda'_{ik}} \tilde{d}_{k,R} \rightarrow \nu d$$

No significant deviation from standard model expectation observed



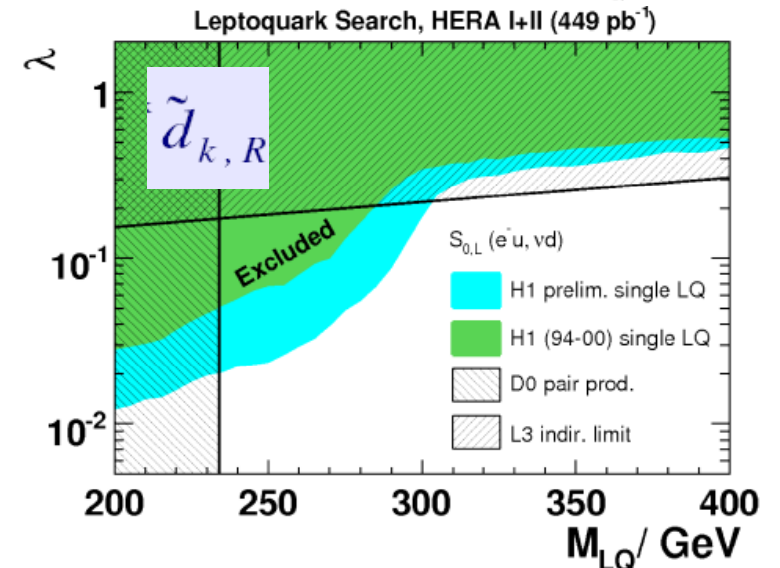
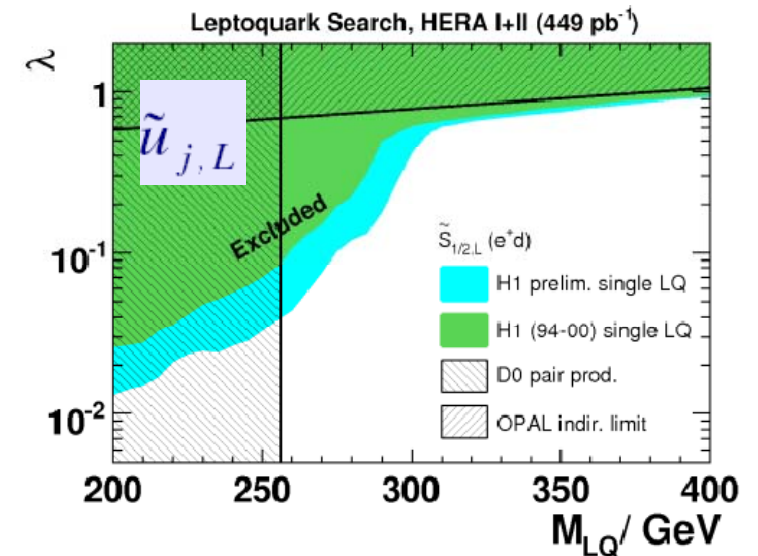
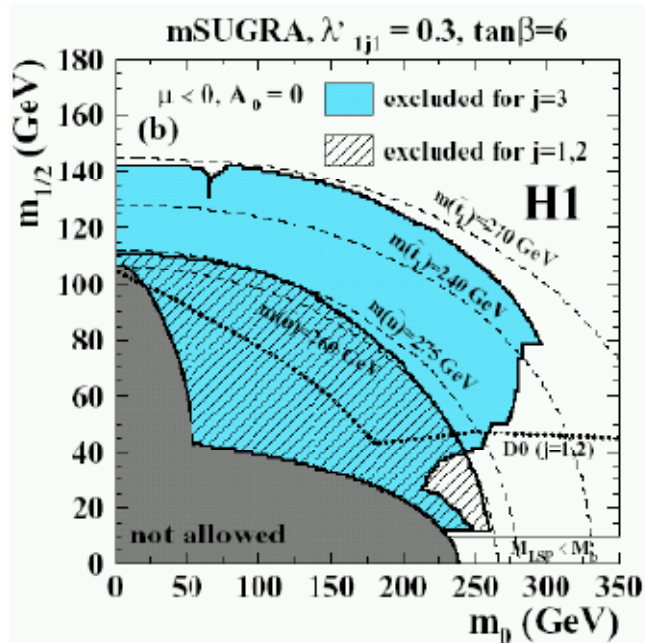
# Squarks in $R_p$ viol. SUSY

if decays via  $\lambda'$  dominate,  $BR(R_p\text{-viol.})=1$

- mass range up to & beyond  $E_{\text{CMS}}$  due to interference
- signature same as for some leptoquarks

If squark decays into gauginos are possible

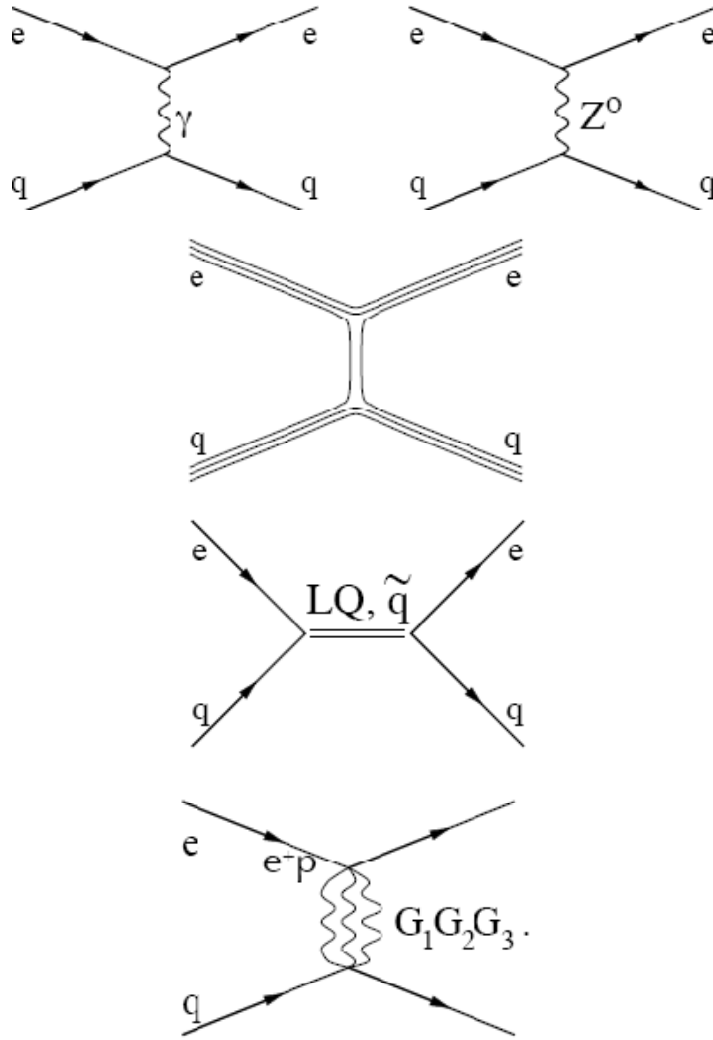
- 3-body decays of gauginos into e+jets
- scan of mSUGRA parameter space



Similar results for couplings with lepton flavour violation

# Contact Interactions

## Standard Model



## + 4-Fermion interaction

$$\mathcal{L}_{CI} = \sum_{i,j=L,R; q=u\dots b} \eta_{ij}^{eq} (\bar{e}_i \gamma^\mu e_i) (\bar{q}_j \gamma_\mu q_j)$$

$$\eta_{ij} = \epsilon_{i,j} \frac{4\pi}{\Lambda^2} \quad \text{Compositeness}$$

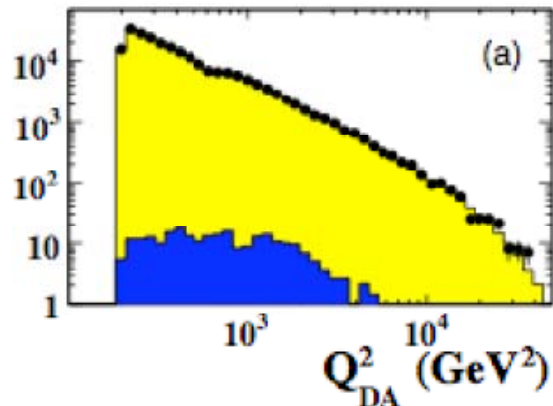
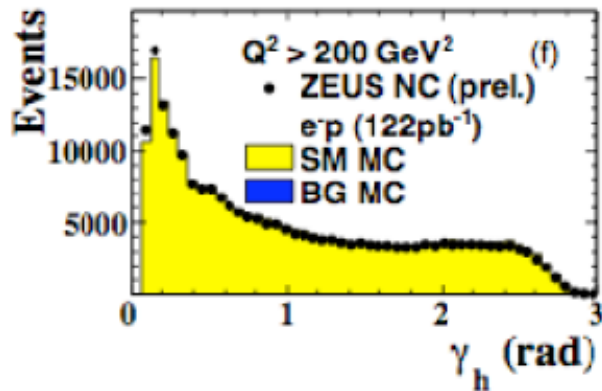
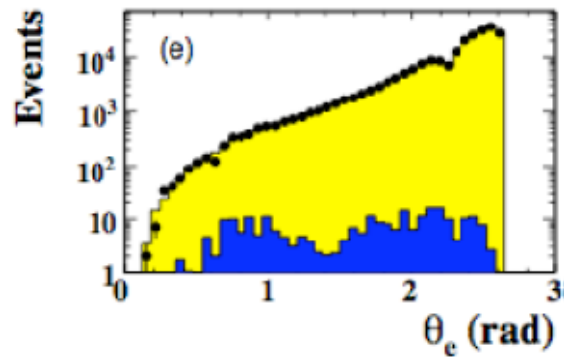
$$\left(1 - \frac{R_q^2}{6} Q^2\right) \quad \text{Quark radius}$$

$$\eta \sim (\lambda/M_{LQ})^2 \quad \text{Leptoquark (M > E}_{\text{CMS}}\text{)}$$

$$\text{Squarks in R}_p\text{-viol.}$$

$$\eta_G \sim 1/M_S^4 \quad \text{Large Extra Dimensions}$$

# Contact Interactions

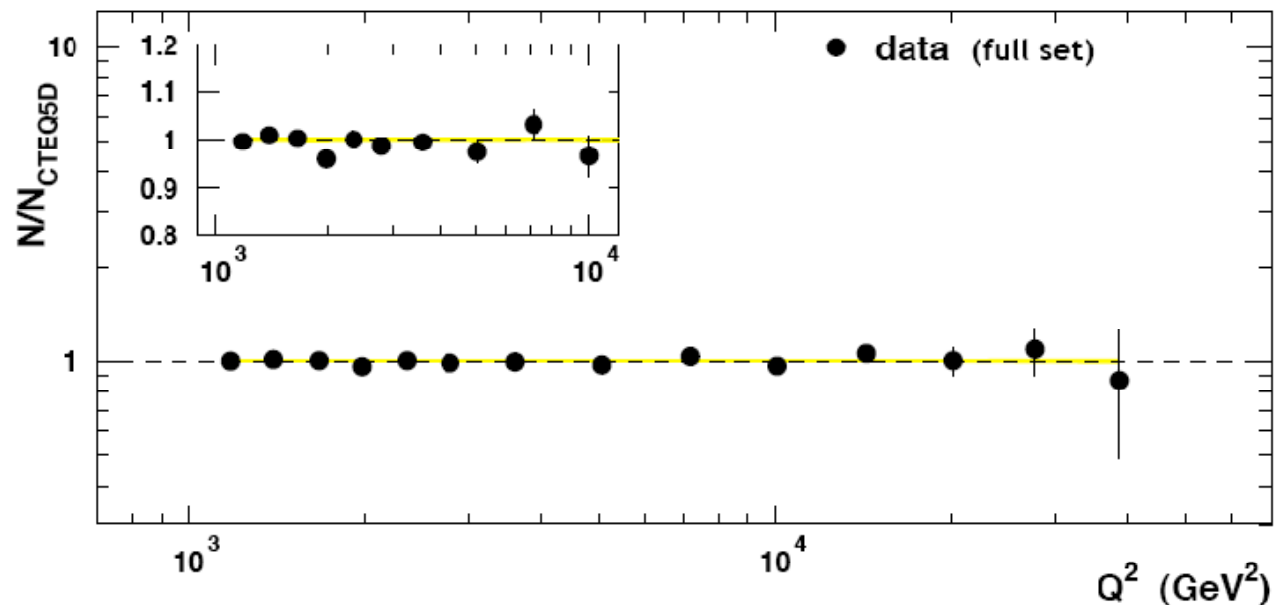


## ZEUS ep data

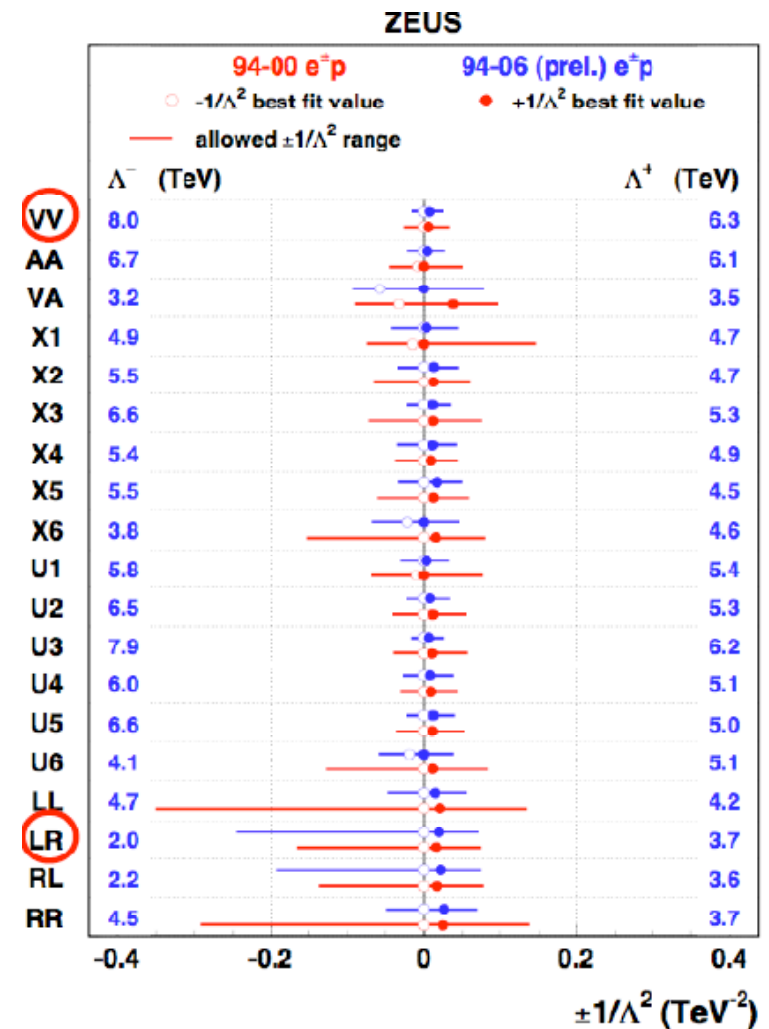
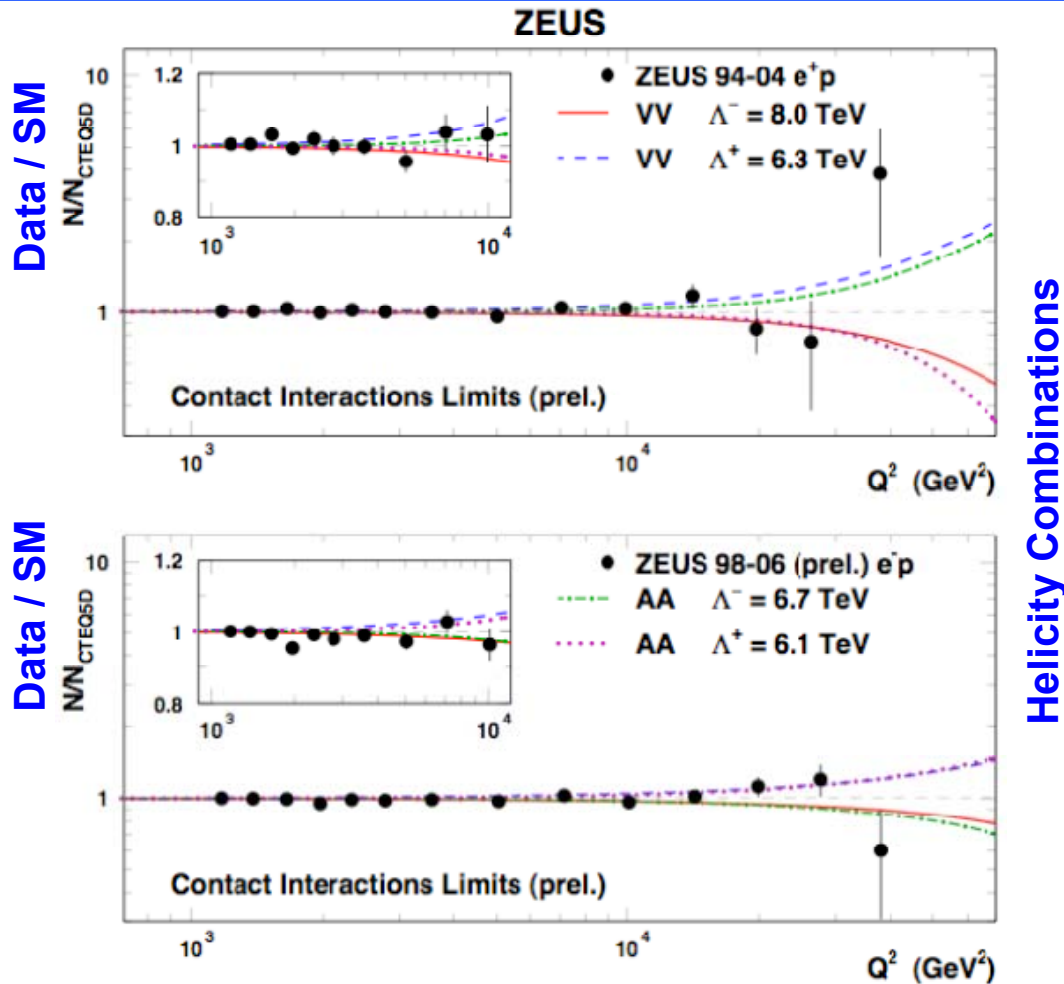
- HERA I  $\sqrt{s} = 300$  GeV 1994-2000 128 pb<sup>-1</sup>
  - unpolarized e<sup>+</sup> (112 pb<sup>-1</sup>) and e<sup>-</sup> data sets
- HERA II  $\sqrt{s} = 318$  GeV 2003-2005 146 pb<sup>-1</sup>
  - polarization e<sup>-</sup> -0.27, +0.33, e<sup>+</sup> -0.41, +0.32

## Measurement via 2-angle method:

- Resolution  $\ll$  Binning
- Results limited by statistics

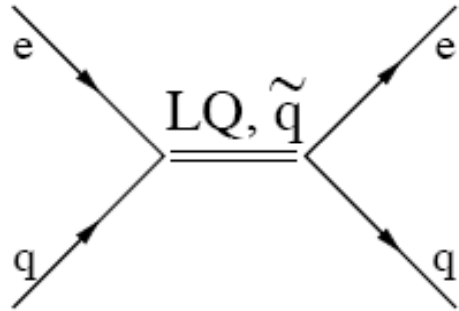


# Contact Interactions



Typical Range of Contact Interaction scales:  
**2 ... 8 TeV**

# Leptoquarks (indirect)



scalar

Leptoquark masses excluded for:

- Indirect search

$$M / \lambda' > 0.3 \dots 2 \text{ TeV}$$

- Direct searches for peak in  $M_{eq}$

$$M < 300 \text{ GeV} \rightarrow \lambda < 0.01$$

Squarks in R-parity viol. SUSY:

$\lambda'_{ijk} L_i Q_j D_k$  coupling

$\tilde{u}$  has same coupling as  $\tilde{S}_{1/2}$

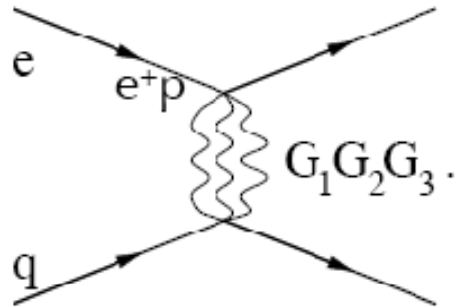
same limit applies

vector

ZEUS 1994-2005 (prel.) $e^\pm p$		
Model	Coupling Structure	95% C.L. (TeV) $M_{LQ}/\lambda_{LQ}$
$S_\circ^L$	$a_{LL}^{eu} = +\frac{1}{2}$	0.96
$S_\circ^R$	$a_{RR}^{eu} = +\frac{1}{2}$	0.82
$\tilde{S}_\circ^R$	$a_{RR}^{ed} = +\frac{1}{2}$	0.32
$S_{1/2}^L$	$a_{LR}^{eu} = -\frac{1}{2}$	0.88
$S_{1/2}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = -\frac{1}{2}$	0.46
$\tilde{S}_{1/2}^L$	$a_{LR}^{ed} = -\frac{1}{2}$	0.44
$S_1^L$	$a_{LL}^{ed} = +1, a_{LL}^{eu} = +\frac{1}{2}$	0.74
$V_\circ^L$	$a_{LL}^{ed} = -1$	0.80
$V_\circ^R$	$a_{RR}^{ed} = -1$	0.62
$\tilde{V}_\circ^R$	$a_{RR}^{eu} = -1$	1.33
$V_{1/2}^L$	$a_{LR}^{ed} = +1$	0.46
$V_{1/2}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = +1$	1.00
$\tilde{V}_{1/2}^L$	$a_{LR}^{eu} = +1$	1.10
$V_1^L$	$a_{LL}^{ed} = -1, a_{LL}^{eu} = -2$	1.91



# Large Extra Dimension

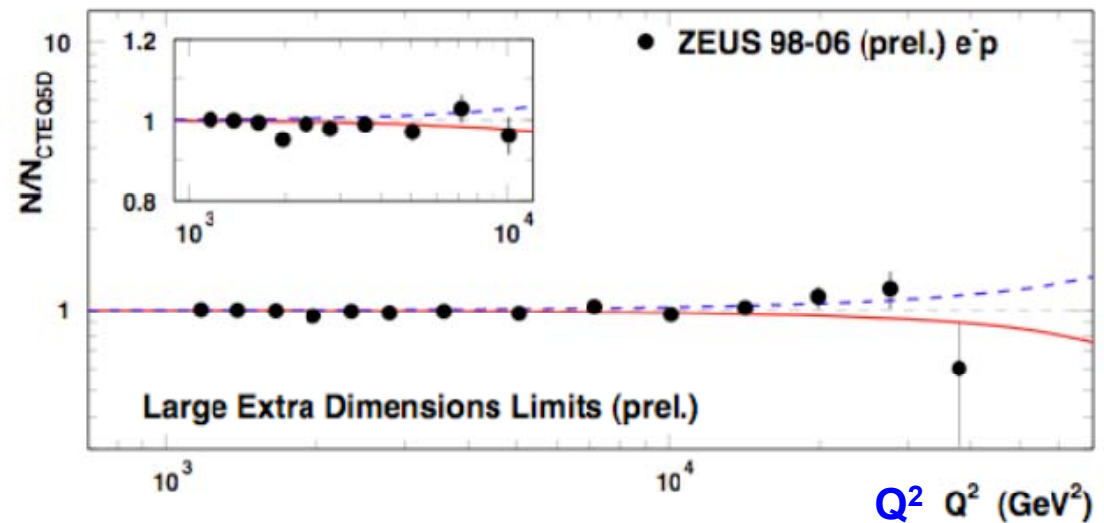
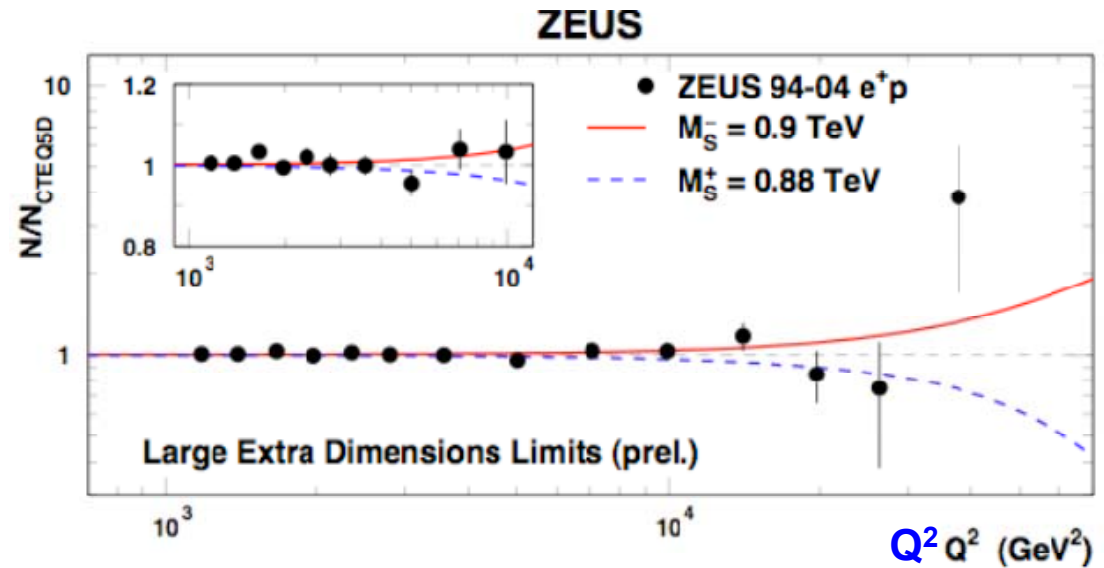


## LED's limited to

- $M_{S(-)} > 0.9 \text{ TeV}$
- $M_{S(+)} > 0.9 \text{ TeV}$

## Quark Radius limited to

- $RQ < 0.62 \times 10^{-18} \text{ m}$

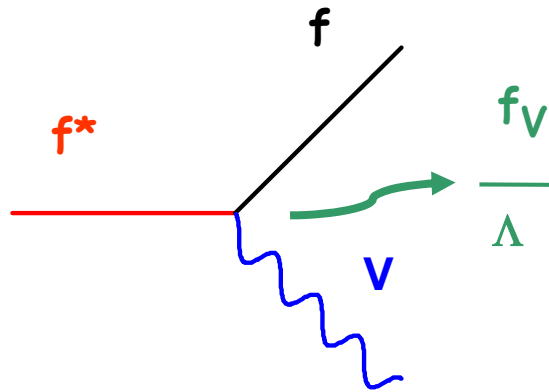


# Excited Leptons (H1)

## Effective lagrangian to parameterize compositeness:

- Spin  $\frac{1}{2}$ , isospin  $\frac{1}{2}$ , vector currents as SM leptons

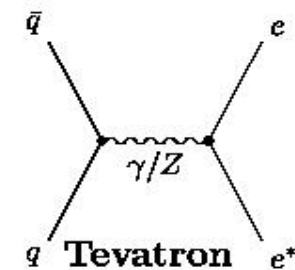
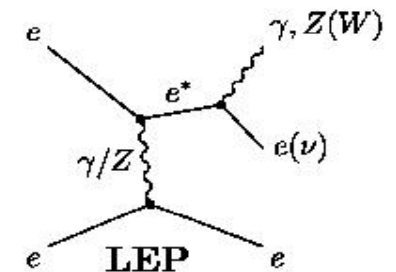
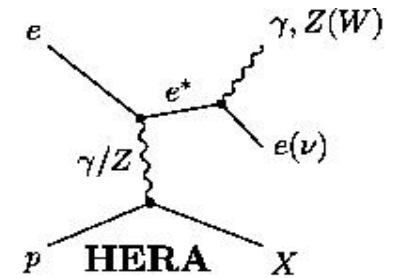
$$L_{F^*F} = \frac{1}{2\Lambda} \bar{F}_R^* \sigma^{\mu\nu} \left[ g f \frac{\vec{\tau}}{2} \partial_\mu \vec{W}_\nu + g' f' \frac{Y}{2} \partial_\mu B_\nu \right] F_L + h.c.$$



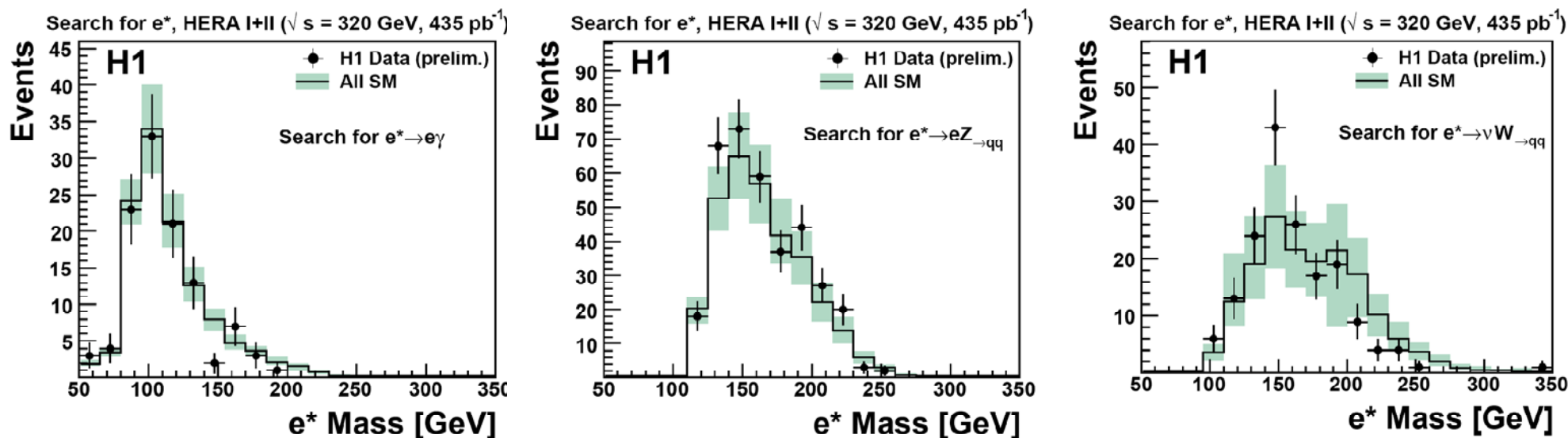
$\Lambda$  compositeness scale

$f, f'$  relative strength  
for  $W_\mu, B_\mu \rightarrow \gamma, Z$

Resonance production for masses  $< E_{\text{CMS}}$



# Excited electrons

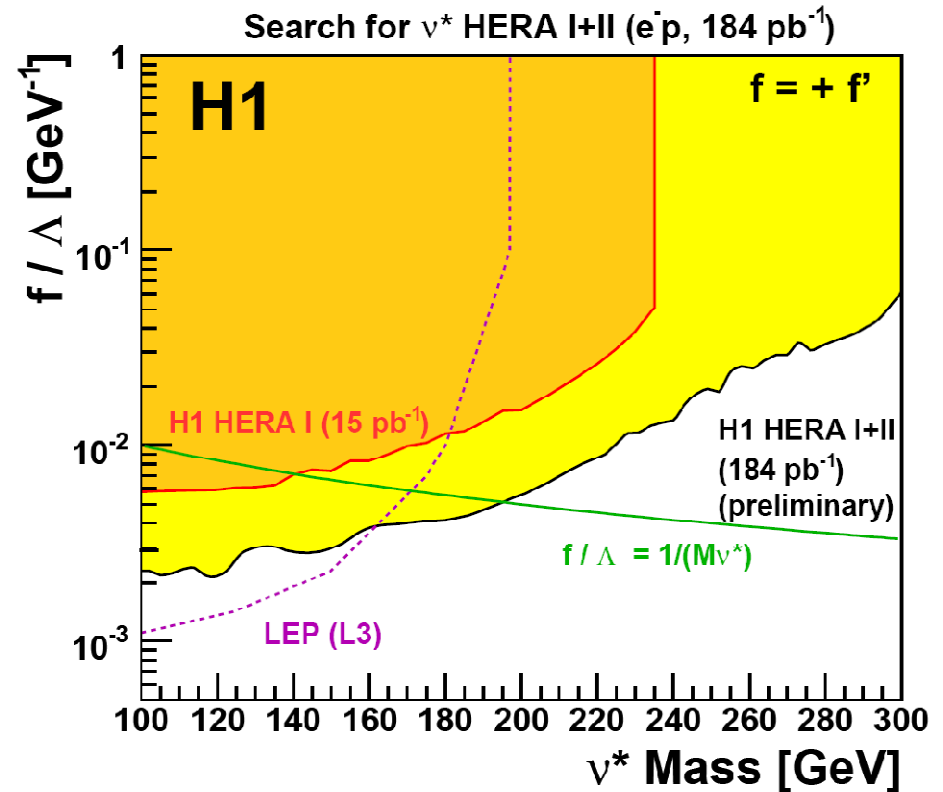
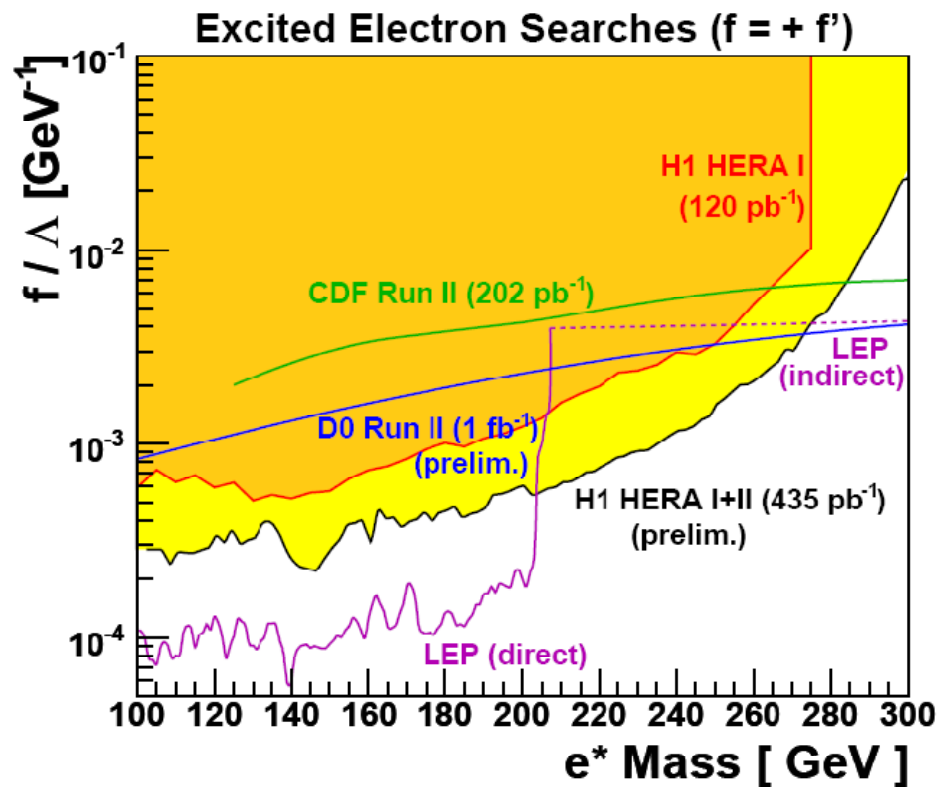


Search for  $e^*$  HERA I+II ( $\sqrt{s} = 320 \text{ GeV}$ ,  $435 \text{ pb}^{-1}$ , preliminary)

Selection	Data	SM	Efficiency $\times$ BR
$e^* \rightarrow \nu W \rightarrow qq$	172	$175 \pm 39$	$\sim 40 \%$
$e^* \rightarrow eZ \rightarrow qq$	351	$318 \pm 64$	$\sim 45 \%$
$e^* \rightarrow e\gamma$	112	$125 \pm 19$	60 70 %

**Full statistics: No excess seen**

# Excited Electrons and Neutrinos



**HERA: Limits typically 220 ... 280 GeV for  $M \sim \Lambda / f$**

**LEP:  $M > 208$  GeV direct search**

**LEP/Tevatron: indirect limits for  $M > 280$  GeV**

# Conclusion

**HERA: final statistics available:  $0.5 \text{ fb}^{-1}$  per experiment**

**Precision dictated by**

- luminosity for indirect searches: Contact interactions
- beam energies for direct searches
- experimental errors small in most cases

**Model – independent search (H1 full statistics):**

- **few % level of understanding of ~ ALL final states at HERA**
- exception: H1:  $\mu\nu$  channel for  $e^+$  scattering  
ZEUS: not confirmed

**Resonance searches on squarks, leptoquarks**

- mass limit for small couplings  **$\sim 300 \text{ GeV}$ , and beyond via interference**

**Contact interactions (ZEUS  $285 \text{ pb}^{-1}$ ):**

- limits on scale  $\sim 10 \times E_{\text{CMS}}$  ... **up to  $7.5 \text{ TeV}$**
- improvements from luminosity and polarisation still to come

**Excited Leptons (H1 full statistics):**

- mass limit  **$\sim 220 \dots 280 \text{ GeV}$**

