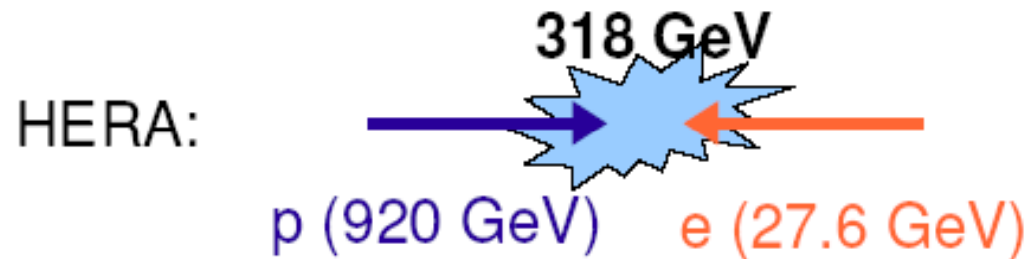


Searches for new Physics at HERA



- 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

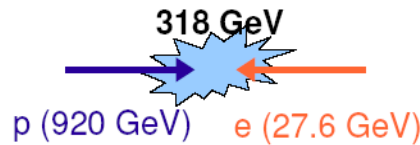


GEFÖRDERT VOM



Bundesministerium
für Bildung
und Forschung

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^+

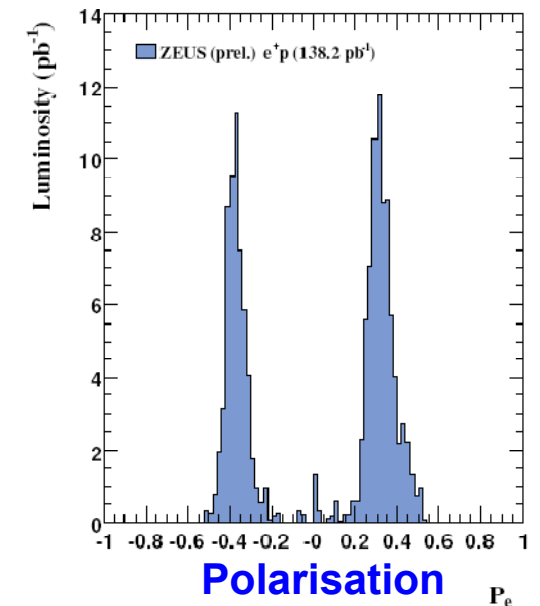
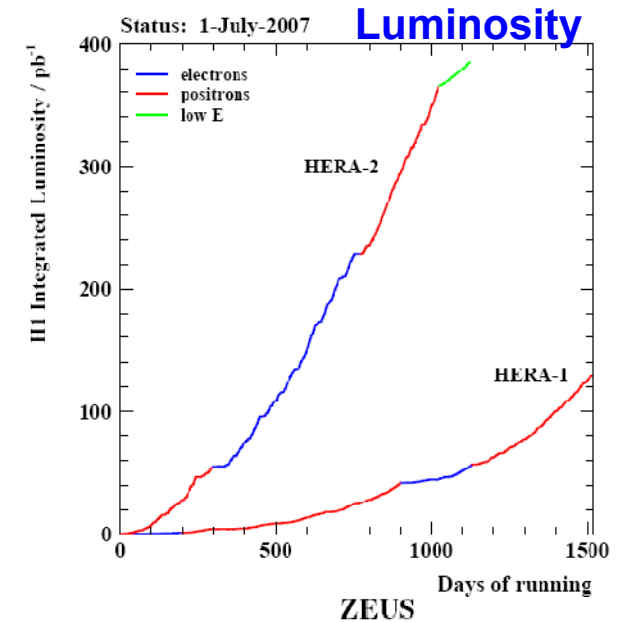
Recently: very good conditions

→ low background, stable beam conditions

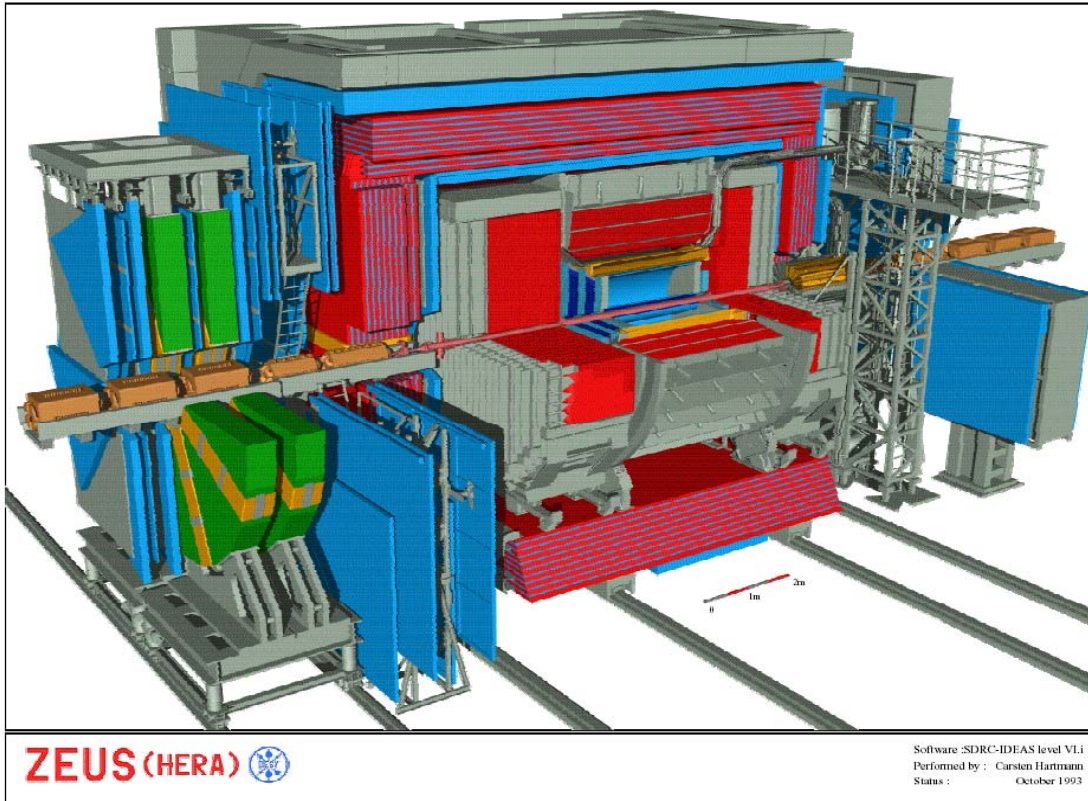
→ high data taking efficiencies, low thresholds

→ 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

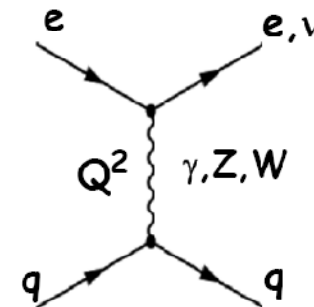
- electrons: 11%/sqrt(E)
- hadrons: 50%/sqrt(E)

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

Muon chambers in return yoke

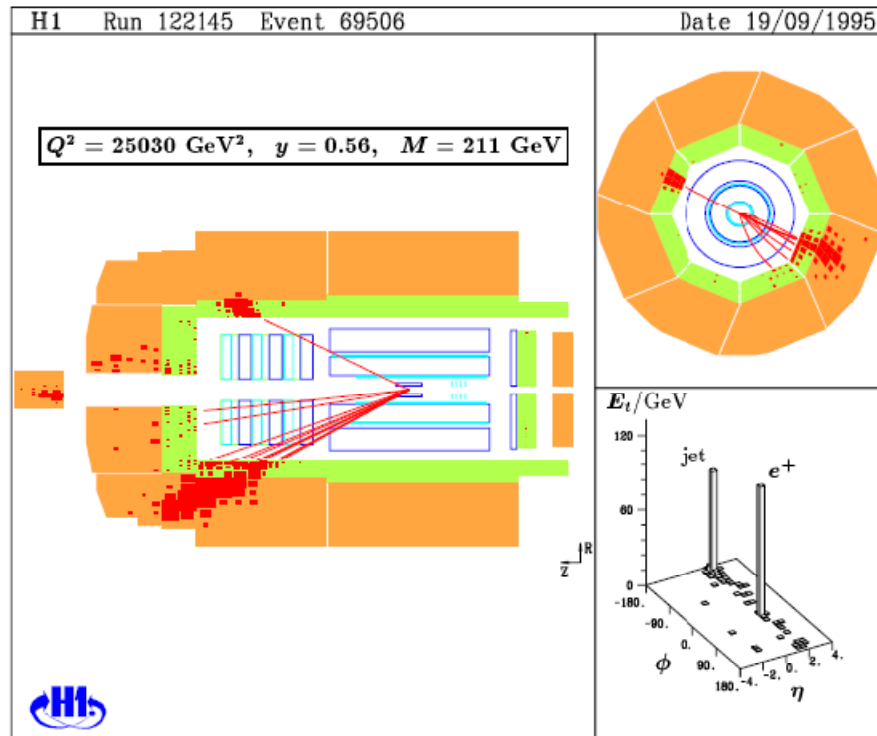
~ 10^8 ep collisions triggered by H1 & ZEUS

- 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

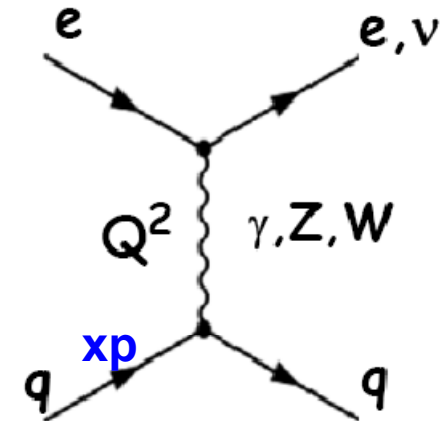


HERA data

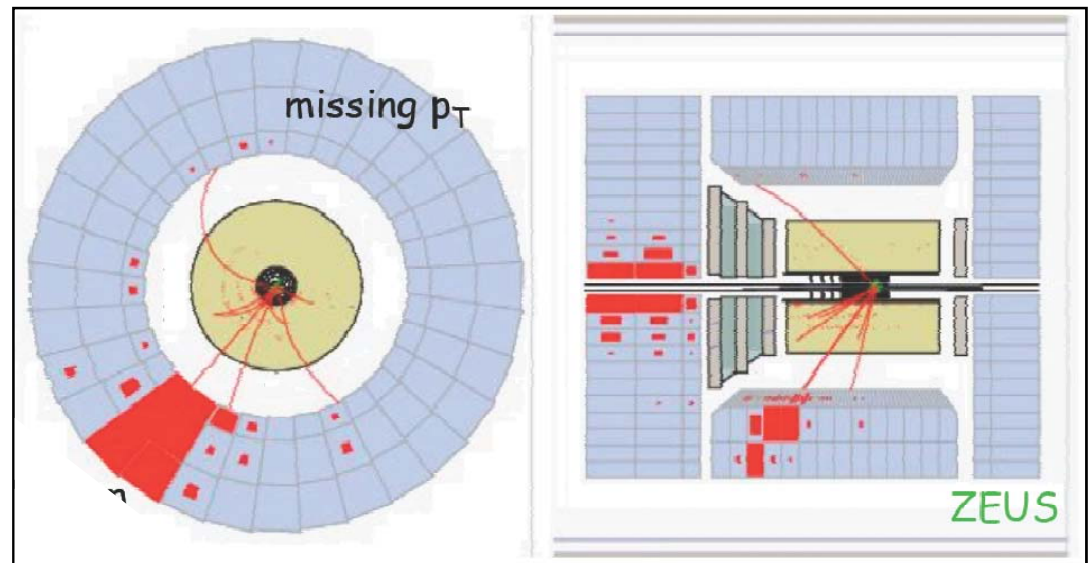
Neutral current: γ, Z



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

$\theta_e, \theta_{\text{hadrons}} \rightarrow E_e, P_{Te}, P_{T,\text{Hadronen}}$

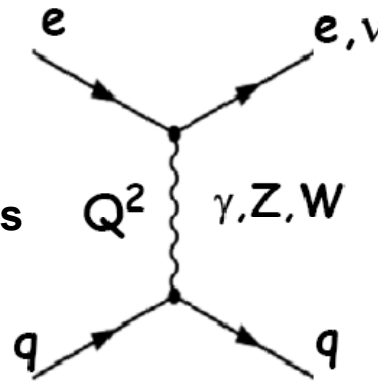
(c.f. γ +jet calibration at LHC)

\rightarrow 1% for electrons, 2...3 % for jets

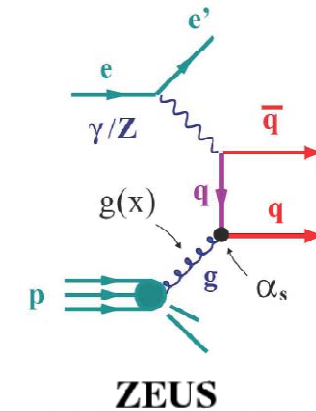
HERA data

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 $\sim 2\%$

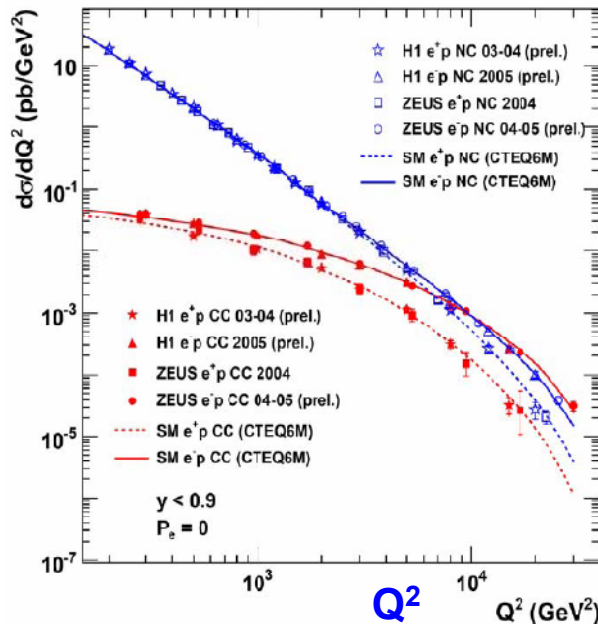


Inclusive Jet Production



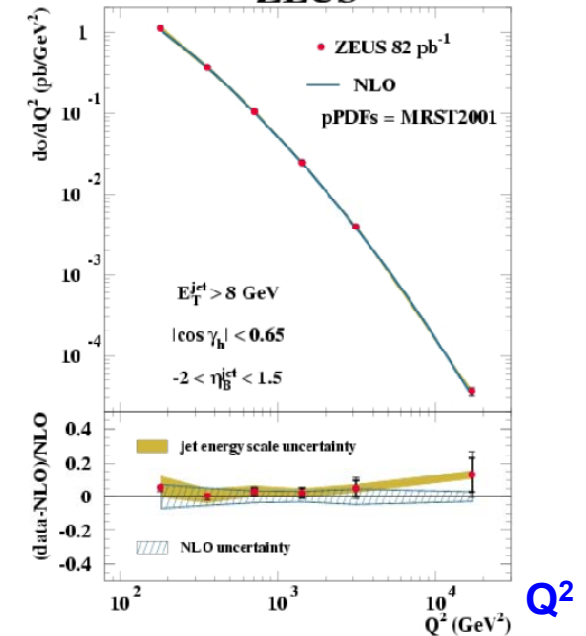
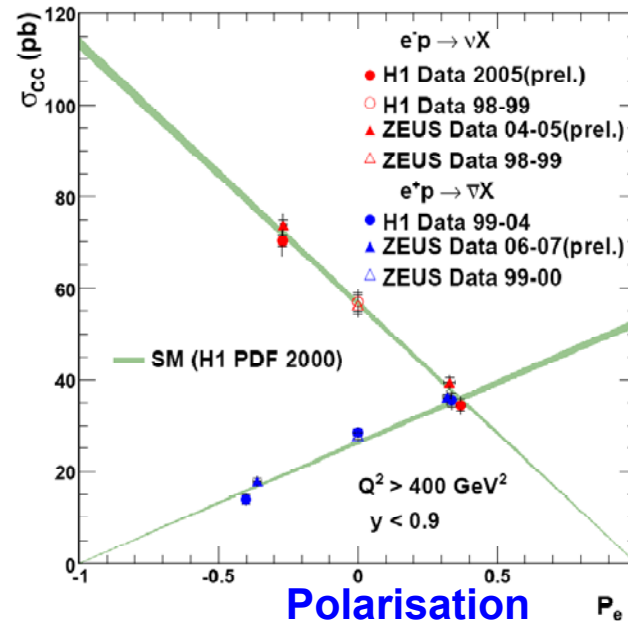
Neutral Current

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

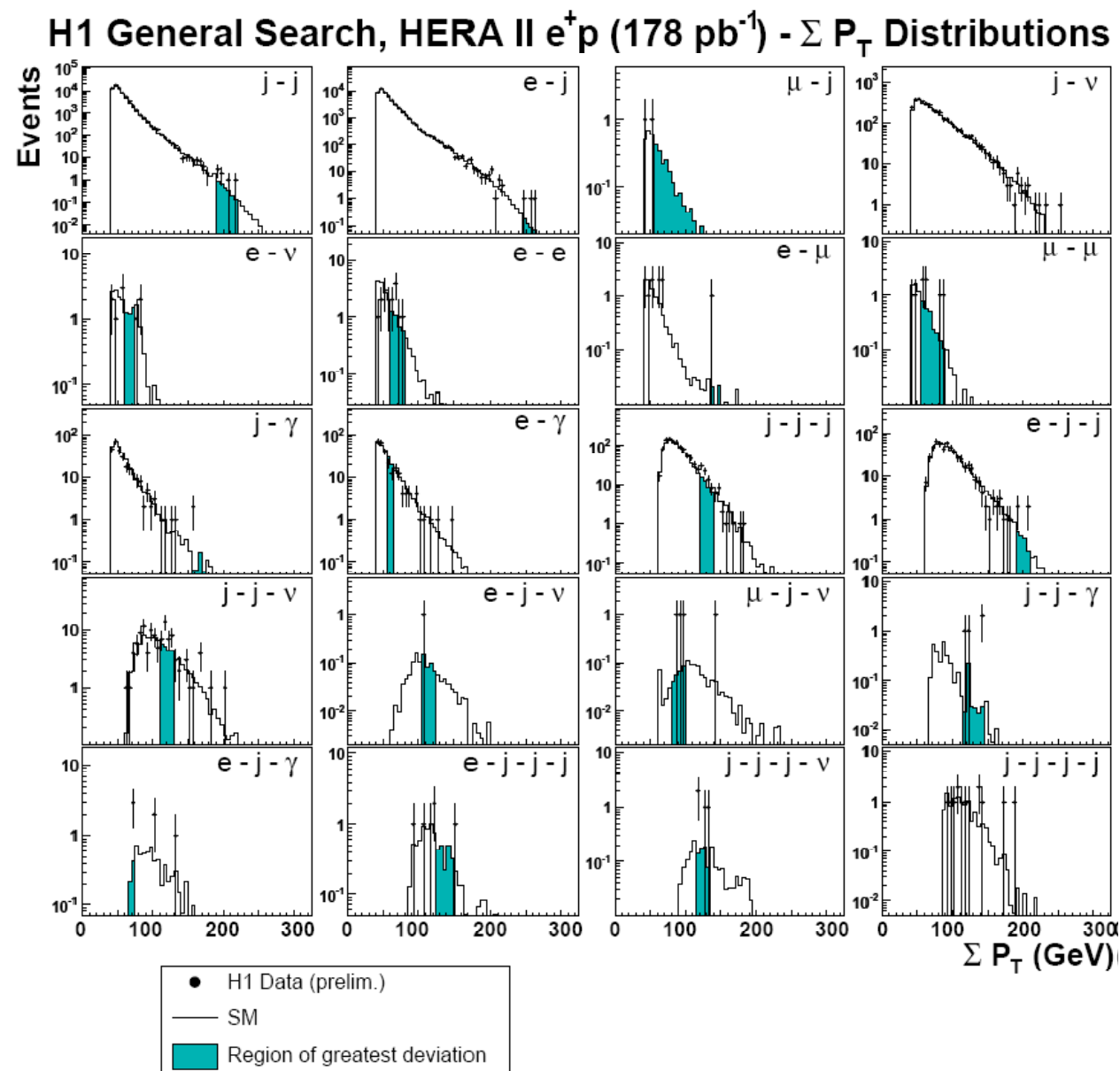
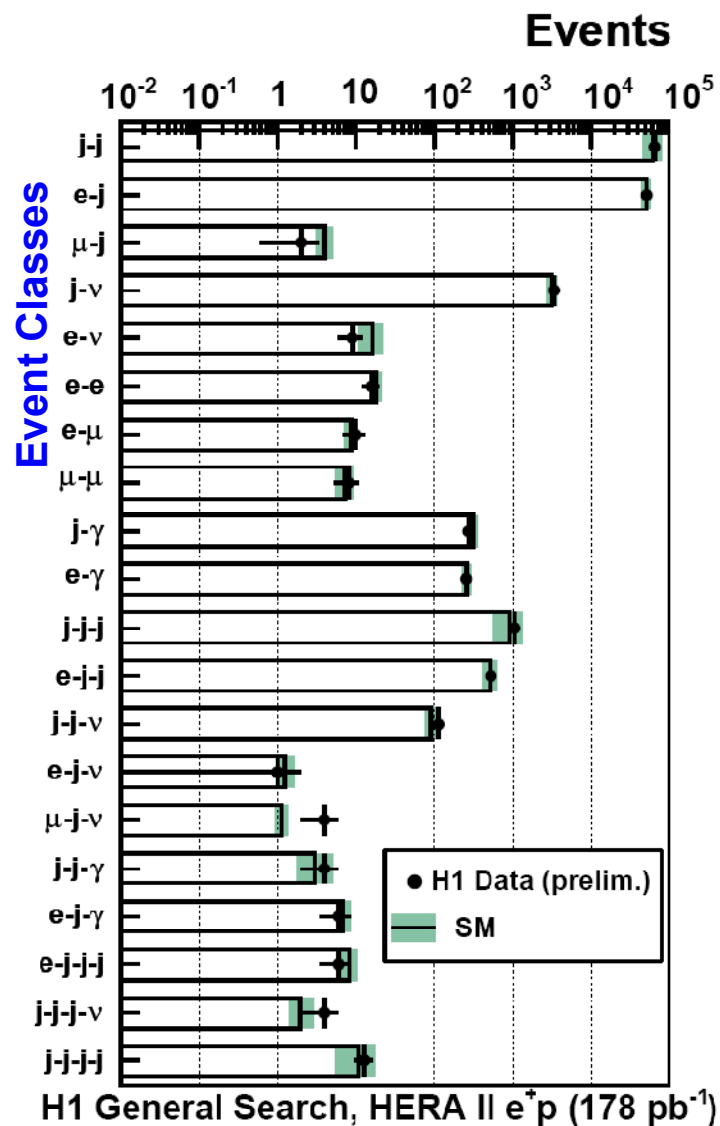
$e+q$: no pair production, but single production of new particles

high precision on SM processes

Model independent search

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

Model – independent Search



Model – independent Search

Precision :

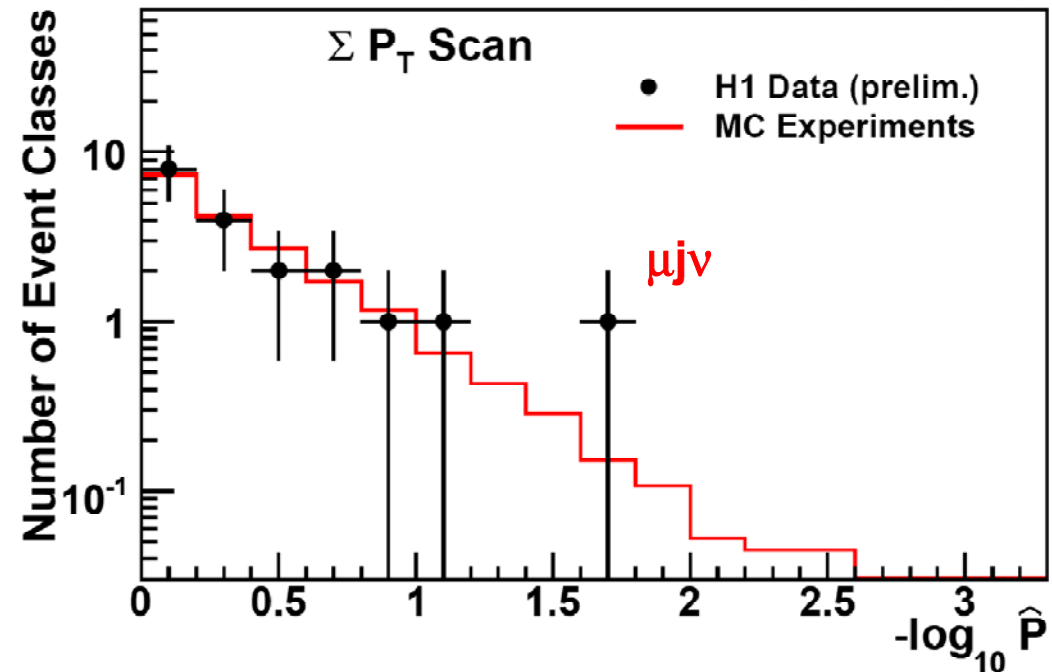
- Systematics: few %
- Statistics: limited at large M, PT and large multiplicity
- Theory: uncertainty large for multi-jet channels

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 pb $^{-1}$)



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

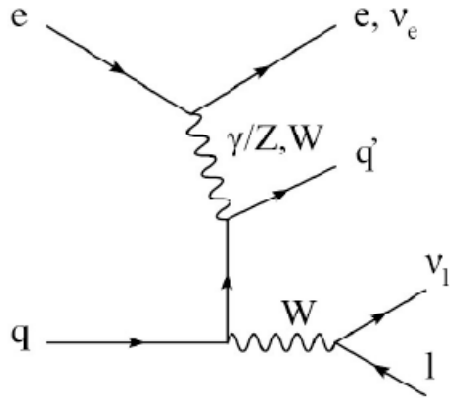
e^+p : H1 observation: 21 / 8.9 ± 1.5 events (3.0σ)

ZEUS: no events in excess of SM

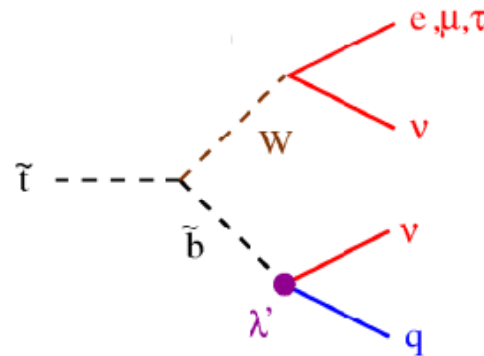
e^-p : H1 and ZEUS: Agreement with SM

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

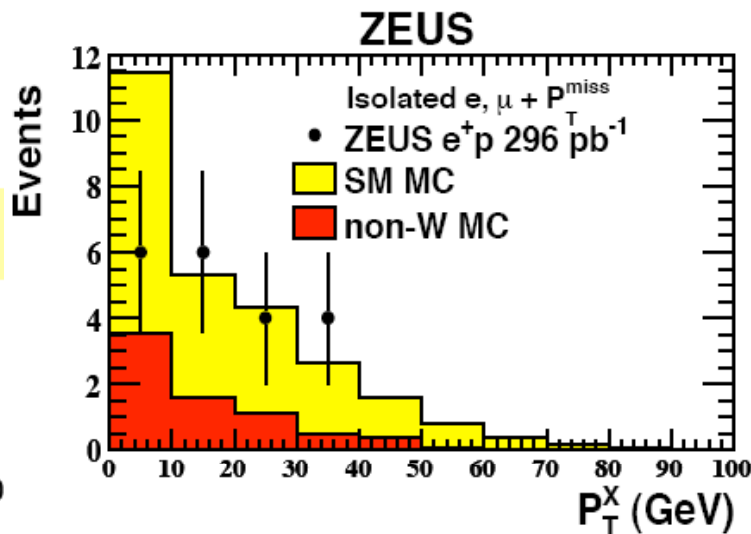
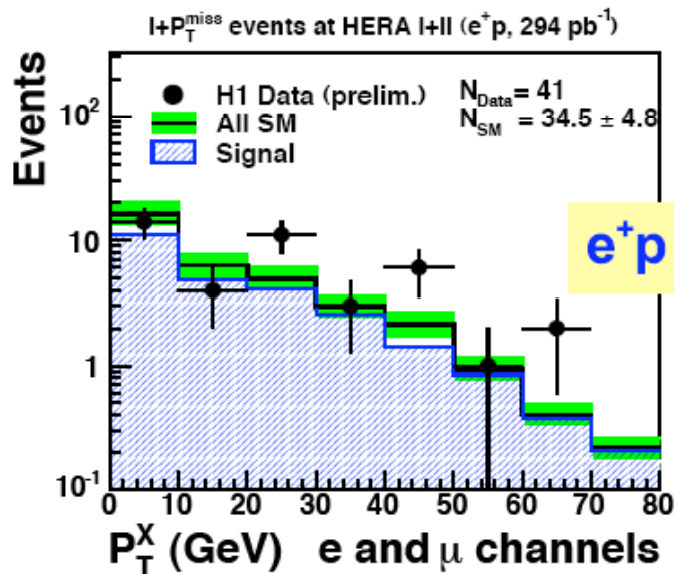
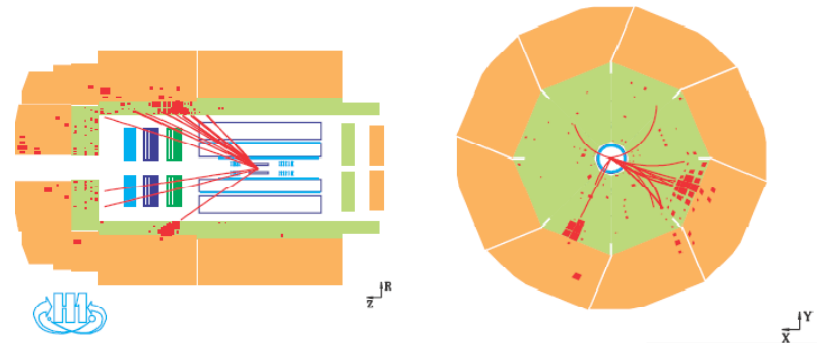
W production in SM:
small $P_{T,X}$ of hadrons



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

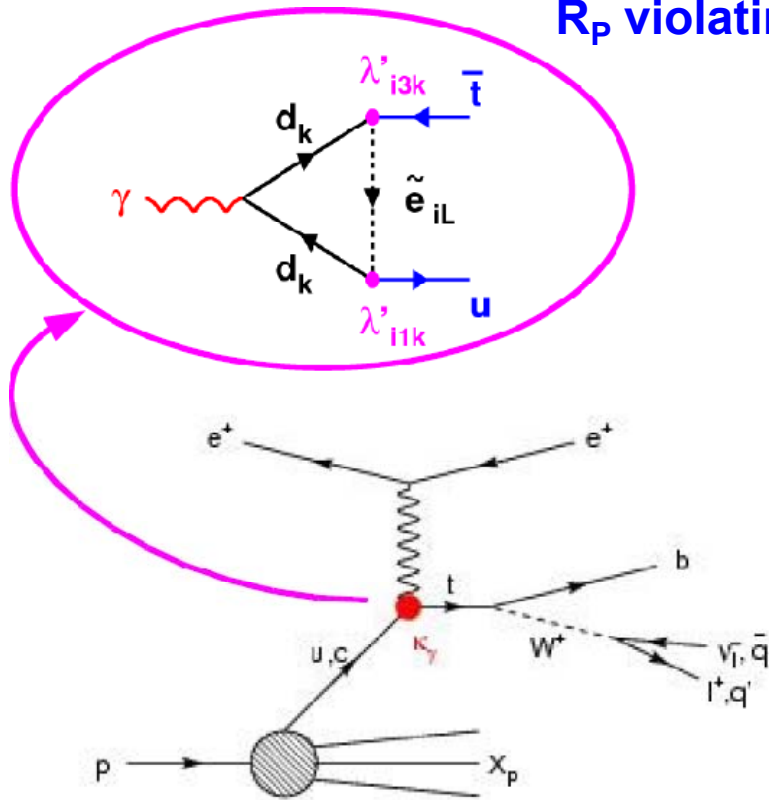
H1: 3σ

H1+ZEUS: 1.8σ

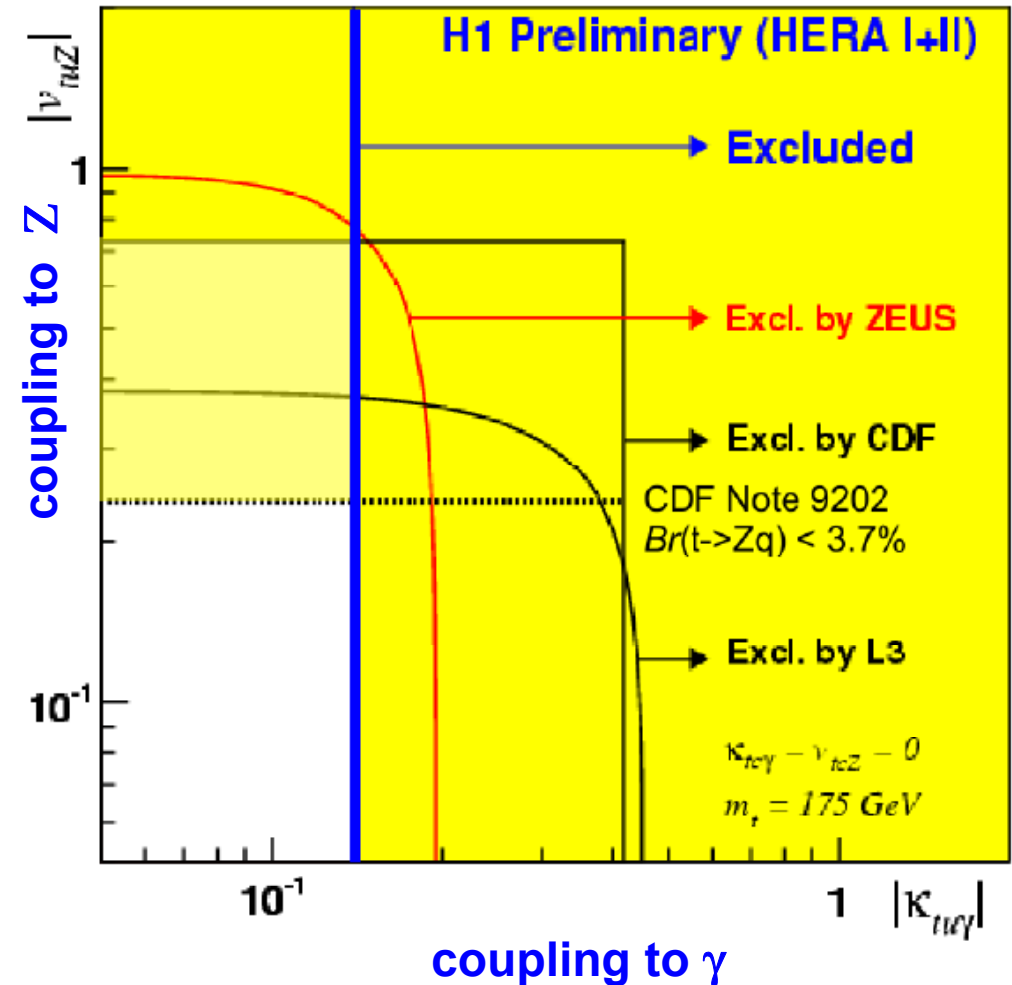
→ not confirmed by ZEUS

Single Top

R_p violating SUSY



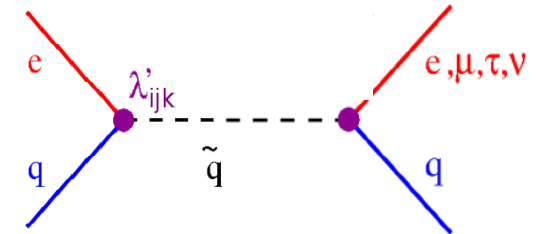
- parameterize $t\bar{u}$ -vertex by effective couplings $\kappa_{t\bar{u}\gamma}$ and $\nu_{t\bar{u}Z}$
- explicit reconstruction of top mass



Supersymmetry: R-parity violating

R_p conserved:

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



R_p violation:

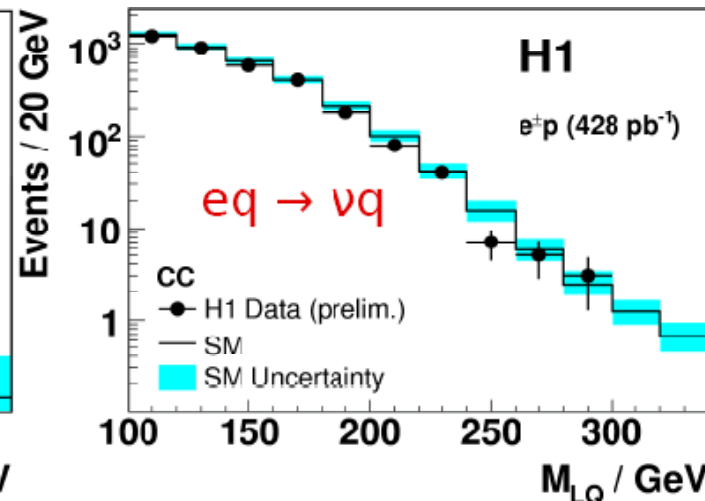
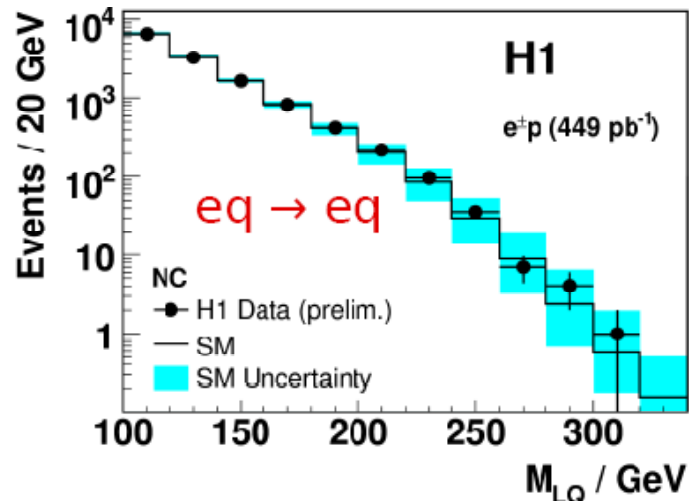
$$W_{RPV} = \lambda'_{ijk} L_i Q_j \bar{D}_k$$

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

$$e^+ d \xrightarrow{\lambda'_{1j1}} \tilde{u}_{j,L} \rightarrow e^+ d$$

$$e^- u \xrightarrow{\lambda'_{11k}} \tilde{d}_{k,R} \rightarrow e^- u$$

$$e^- u \xrightarrow{\lambda'_{11k}} \tilde{d}_{k,R} \rightarrow \nu d$$



No significant deviation from standard model expectation observed

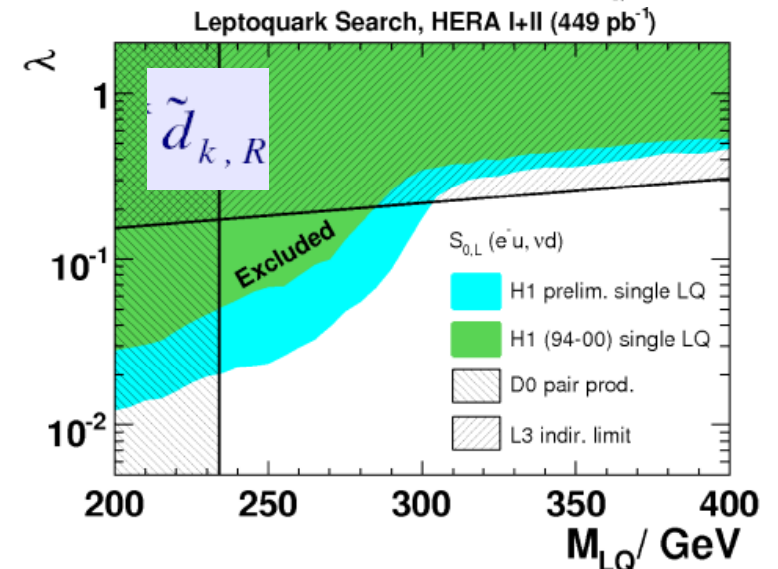
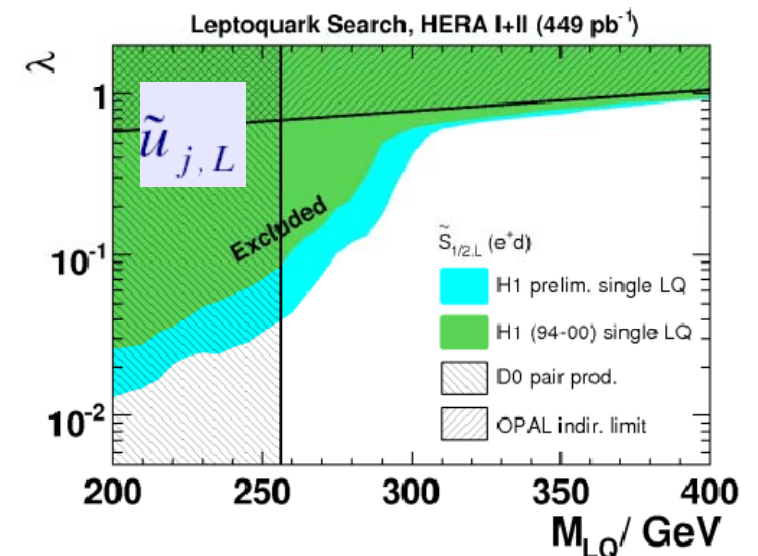
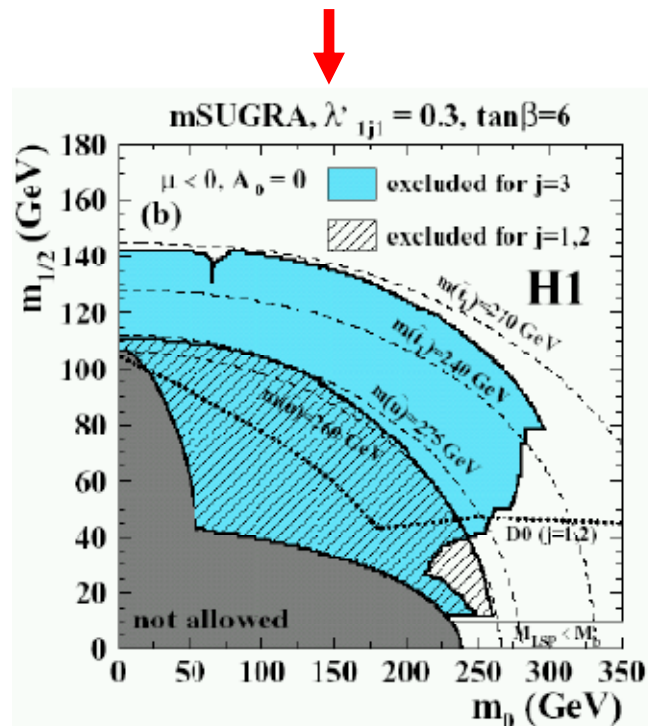
Squarks in R_p viol. SUSY

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

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

If squark decays into gauginos are possible

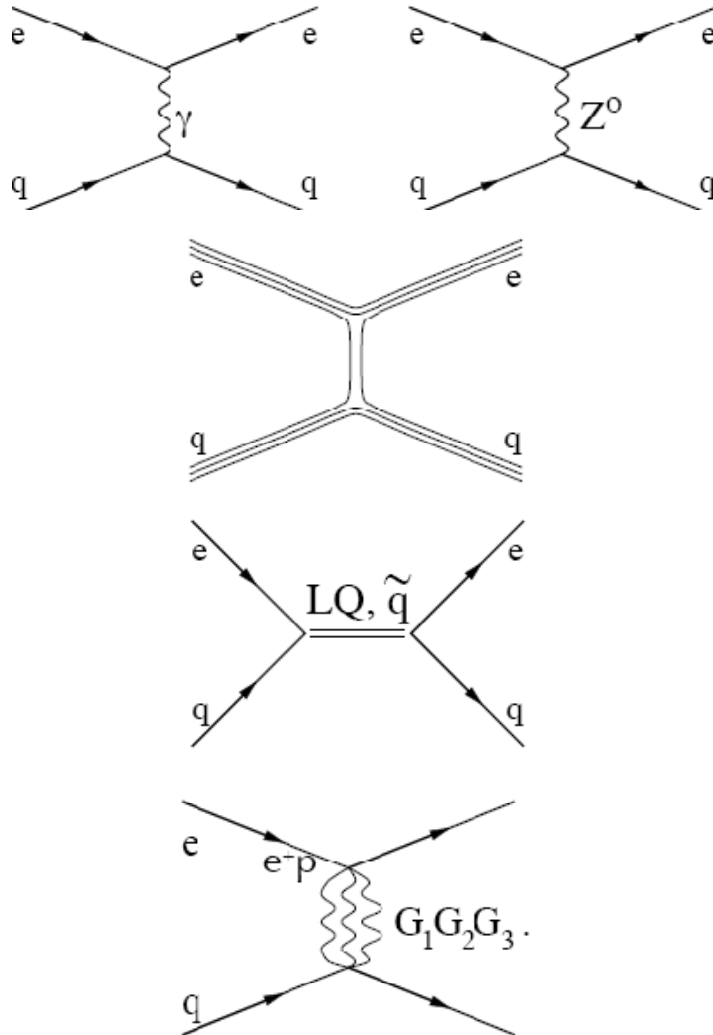
- 3-body decays of gauginos into e +jets
- scan of mSUGRA parameter space



Similar results for couplings
with lepton flavour violation

Contact Interactions

Standard Model



+ 4-Fermion interaction

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

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

Compositeness

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

Quark radius

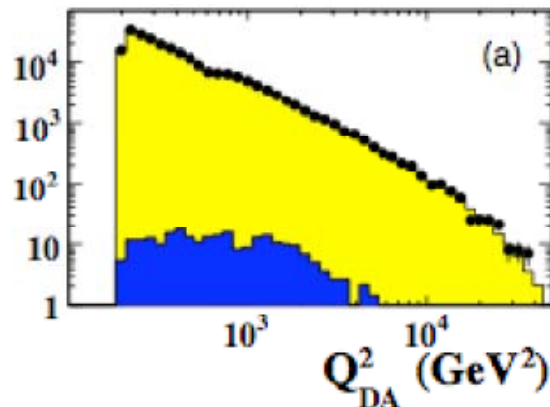
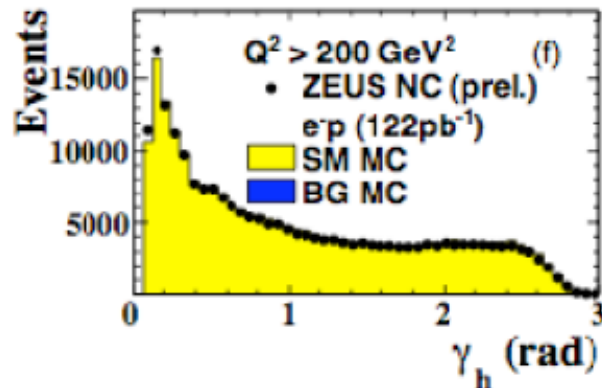
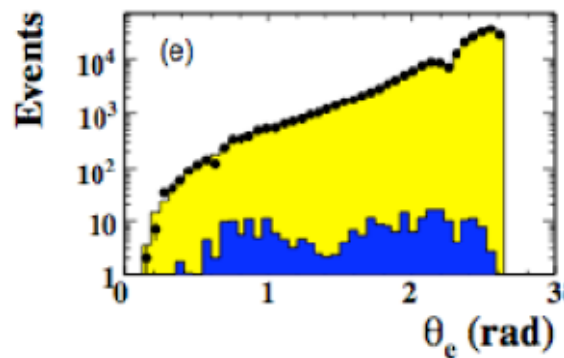
$$\eta \sim (\lambda/M_{LQ})^2$$

**Leptoquark ($M > E_{\text{CMS}}$)
Squarks in R_P -viol.**

$$\eta_G \sim 1/M_S^4$$

Large Extra Dimensions

Contact Interactions

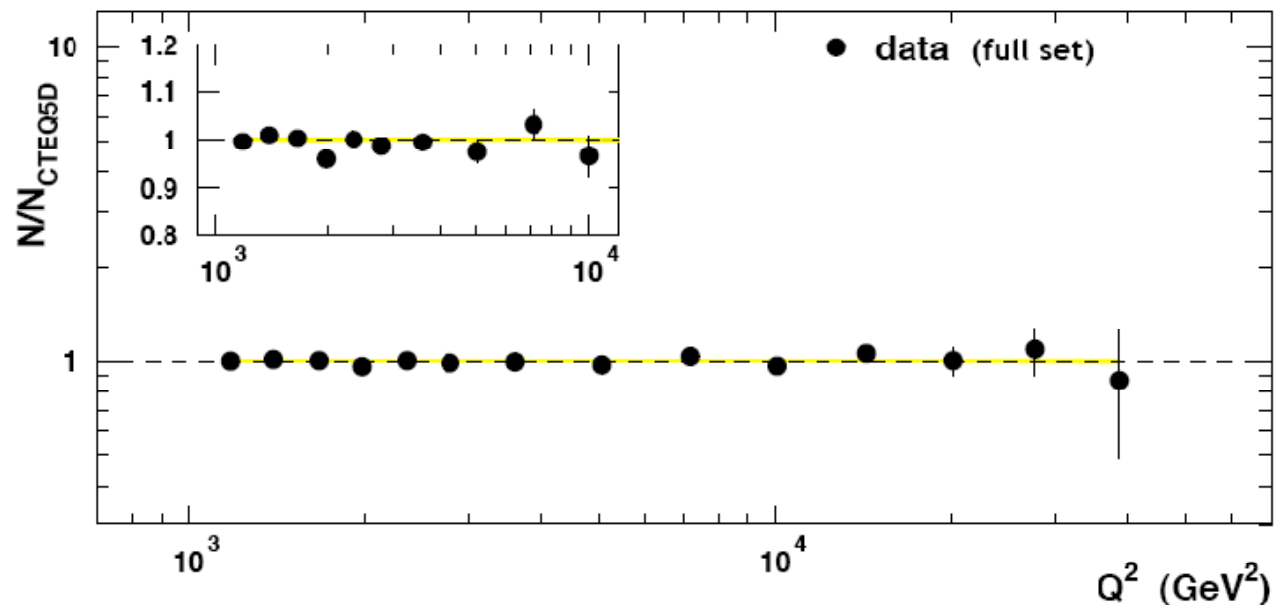


ZEUS ep data

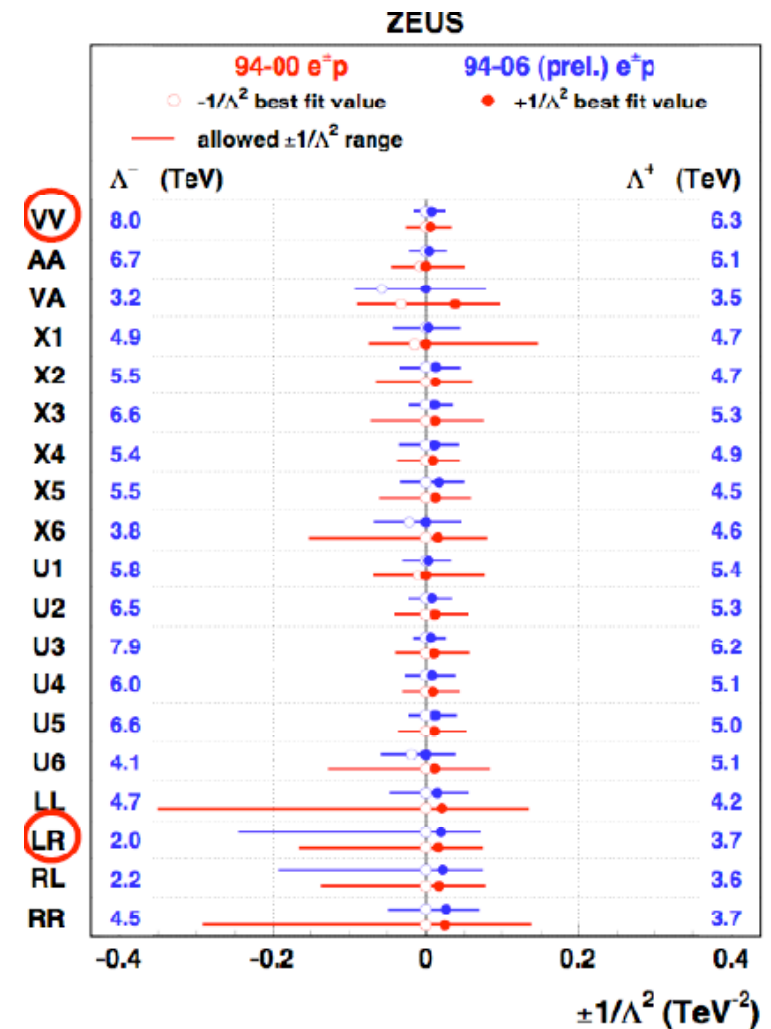
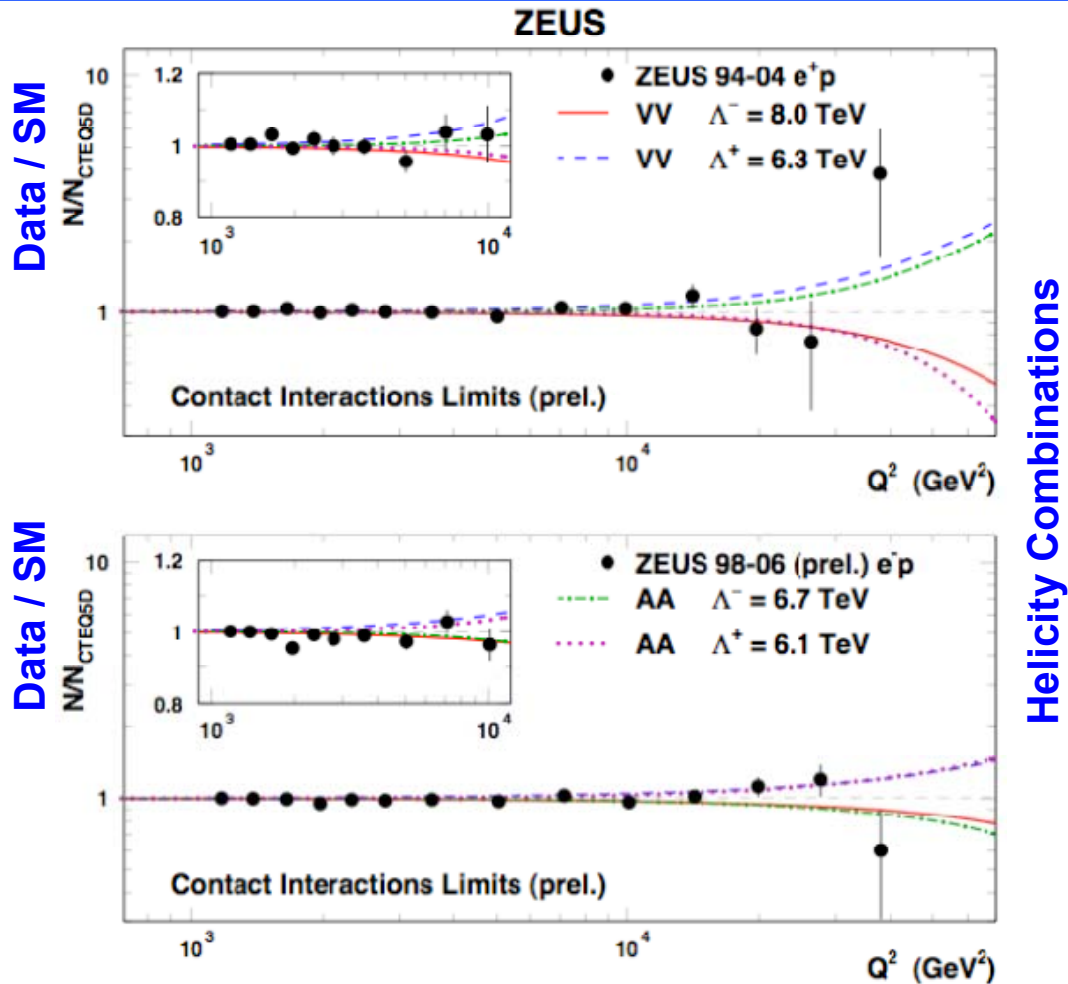
- HERA I $\sqrt{s} = 300 \text{ GeV}$ 1994-2000 128 pb^{-1}
 - unpolarized e^+ (112 pb^{-1}) and e^- data sets
- HERA II $\sqrt{s} = 318 \text{ GeV}$ 2003-2005 146 pb^{-1}
 - polarization $e^- -0.27, +0.33, e^+ -0.41, +0.32$

Measurement via 2-angle method:

- Resolution \ll Binning
- Results limited by statistics

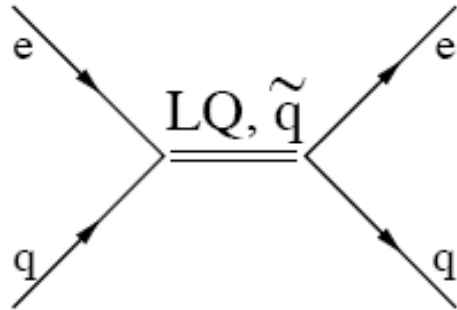


Contact Interactions



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

Leptoquarks (indirect)



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 $\tilde{S}_{1/2}$

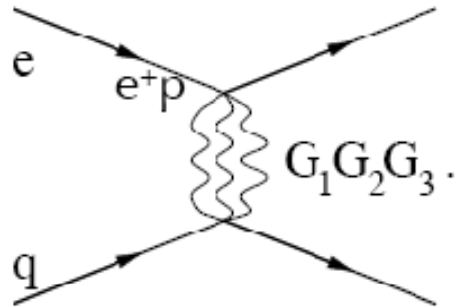
same limit applies

scalar

vector

ZEUS 1994-2005 (prel.) $e^\pm p$		
Model	Coupling Structure	95% C.L. (TeV) M_{LQ}/λ_{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

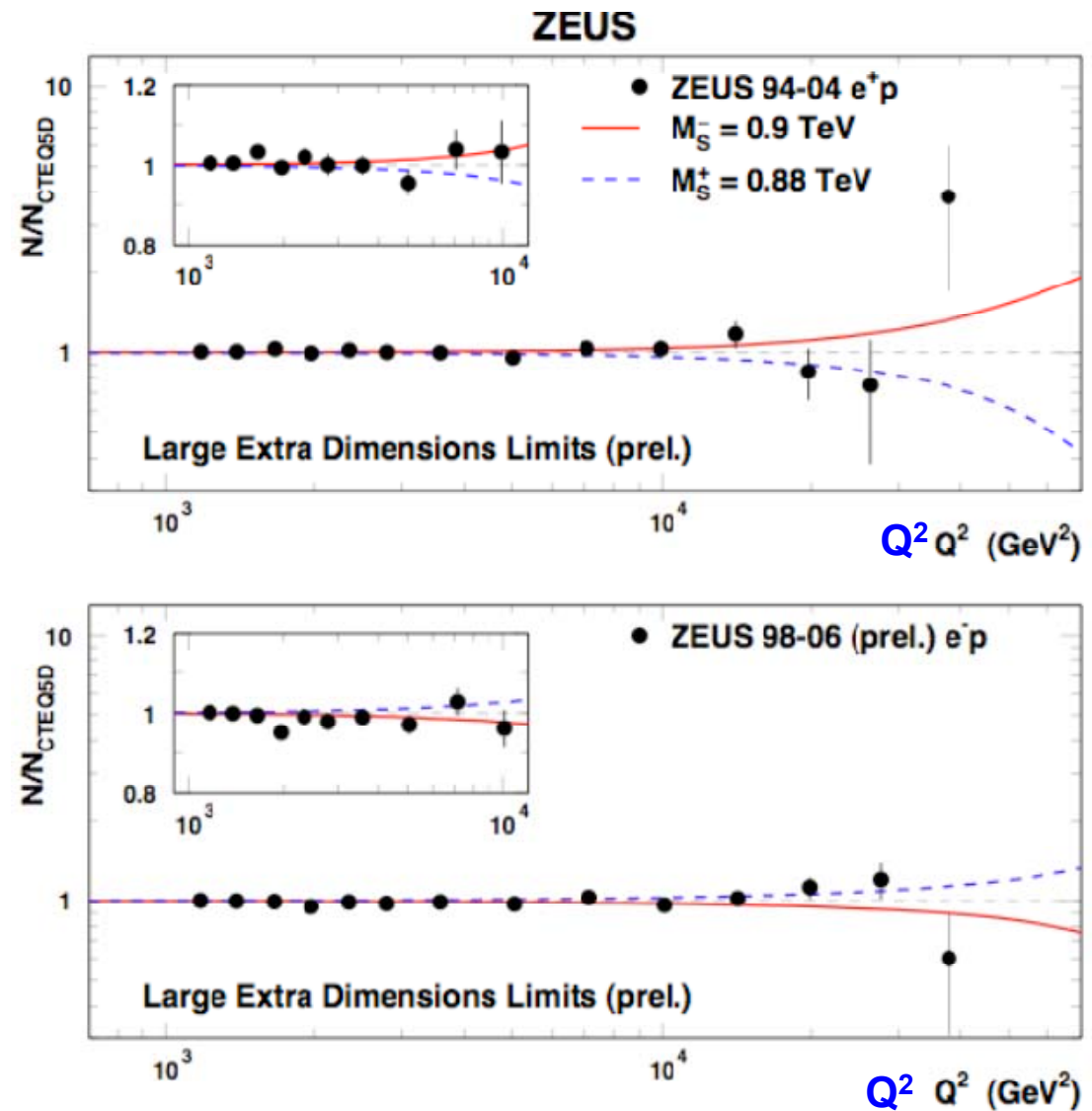


LED's limited to

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

Quark Radius limited to

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

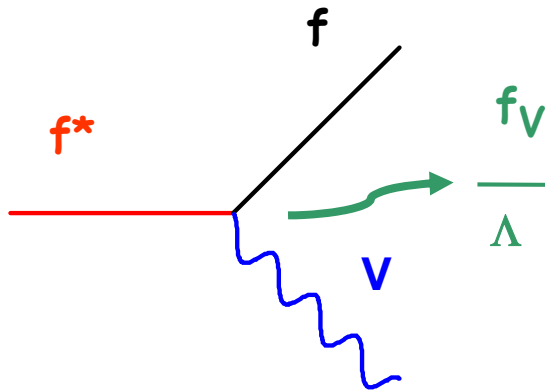


Excited Leptons (H1)

Effective lagrangian to parameterize compositeness:

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

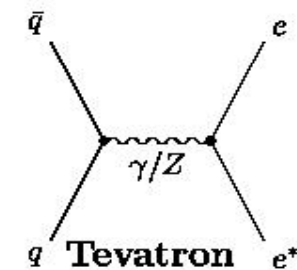
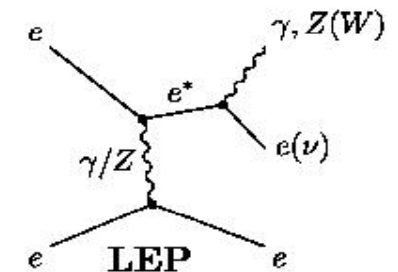
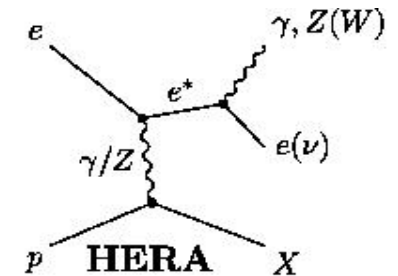
$$L_{F^*F} = \frac{1}{2\Lambda} \bar{F}_R^* \sigma^{\mu\nu} \left[g f \frac{\vec{\tau}}{2} \partial_\mu \vec{W}_\nu + g' f' \frac{Y}{2} \partial_\mu B_\nu \right] F_L + h.c.$$



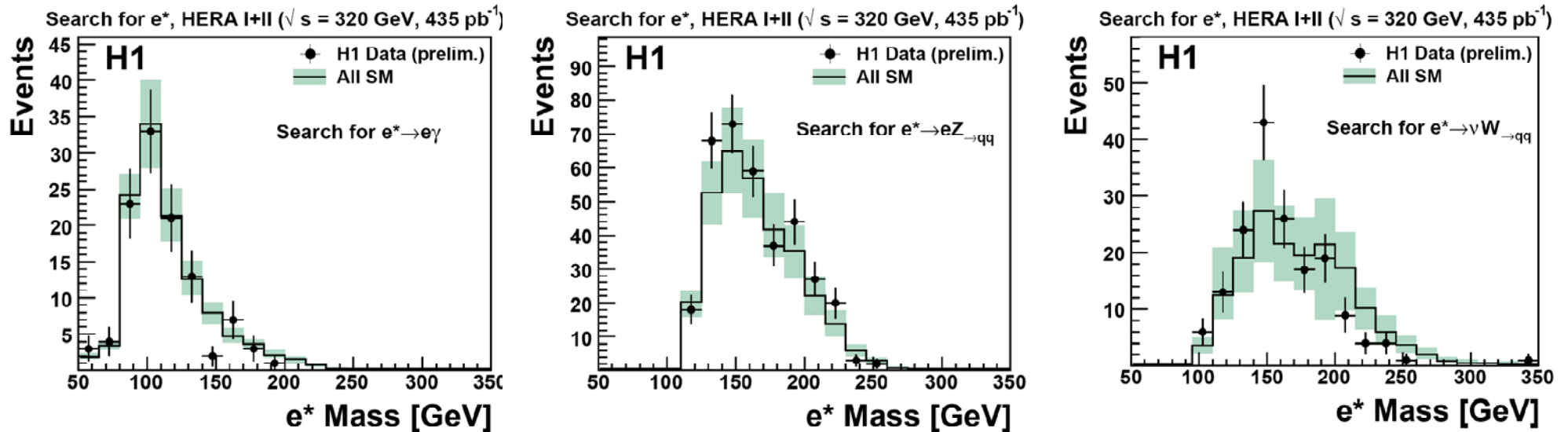
Λ compositeness scale

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

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



Excited electrons

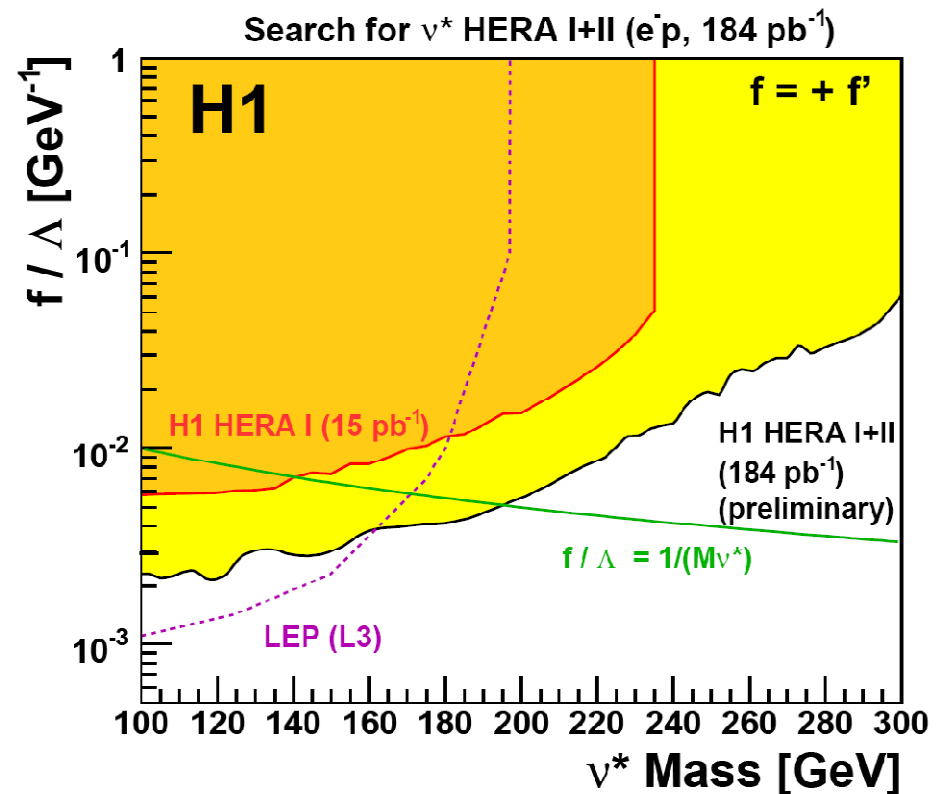
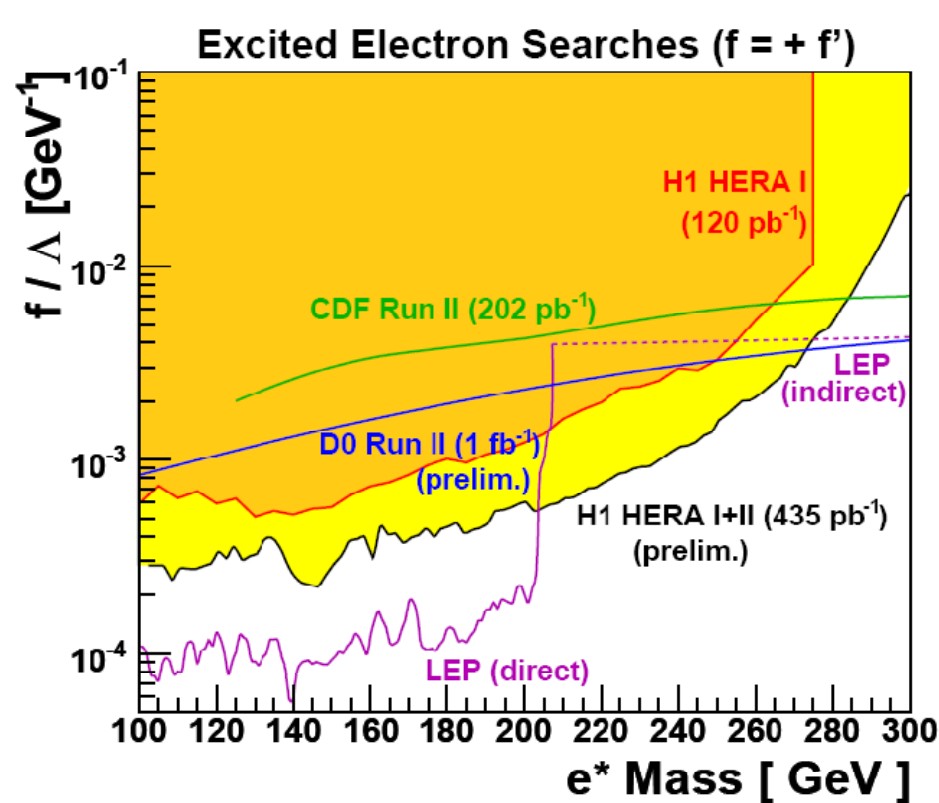


Search for e^* HERA I+II ($\sqrt{s} = 320$ GeV, 435 pb^{-1} , preliminary)

Selection	Data	SM	Efficiency \times BR
$e^* \rightarrow \nu W \rightarrow qq$	172	175 ± 39	$\sim 40 \%$
$e^* \rightarrow eZ \rightarrow qq$	351	318 ± 64	$\sim 45 \%$
$e^* \rightarrow e\gamma$	112	125 ± 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 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 pb^{-1}):

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

Excited Leptons (H1 full statistics):

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

