IGGS AND SUPERSYMMETRY

Orsay , March 19-22, 2001

Searches for $\not{R}_p$ SUSY

and other exciting Phenomena

at HERA

Jochen Dingfelder

Physikalisches Institut, Heidelberg

On behalf of

H1 and ZEUS Collaborations

Outline:

- ⋆ Introduction
- ⋆ Searches for squark production at HERA
- ⋆ Events with a high P_T lepton and missing P_T
- ⋆ Search for single top production
- ⋆ Conclusions and future prospects

Introduction to HERA (1)

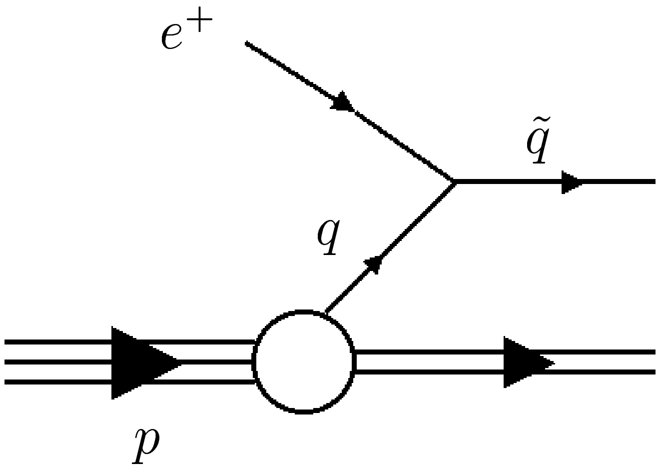
HERA: $e \longrightarrow \Longleftarrow p$

27.5 GeV 920 GeV $\Rightarrow \sqrt{s} \approx$ 320 GeV

- Initial state with leptonic and baryonic quantum numbers

  $\Rightarrow$ ideally suited to look for particles with coupling to eq-pairs

  $\Rightarrow$ look for singly produced squarks ($\tilde{q}$) in s-channel



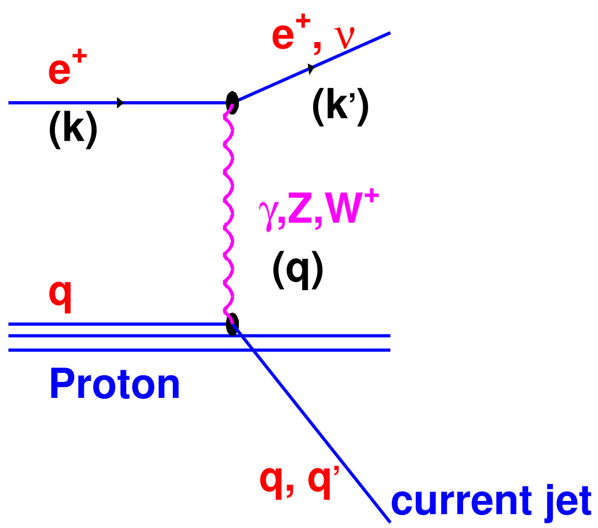
Main SM processes at high $\mathrm{E_T}$:

Neutral Current DIS (γ, Z exchange)

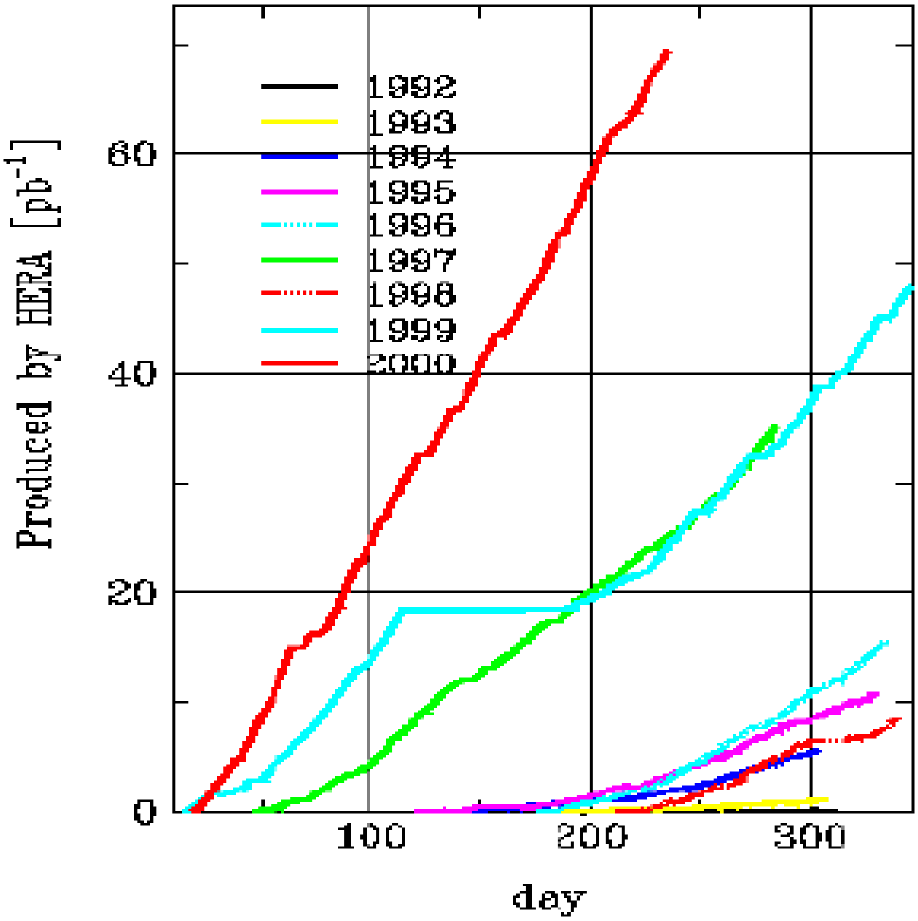
Charged Current DIS ($W^{\pm}$ exchange)

Photoproduction ($Q^2 \approx 0, \gamma$ quasi-real)

$\Rightarrow e$ lost in beam pipe



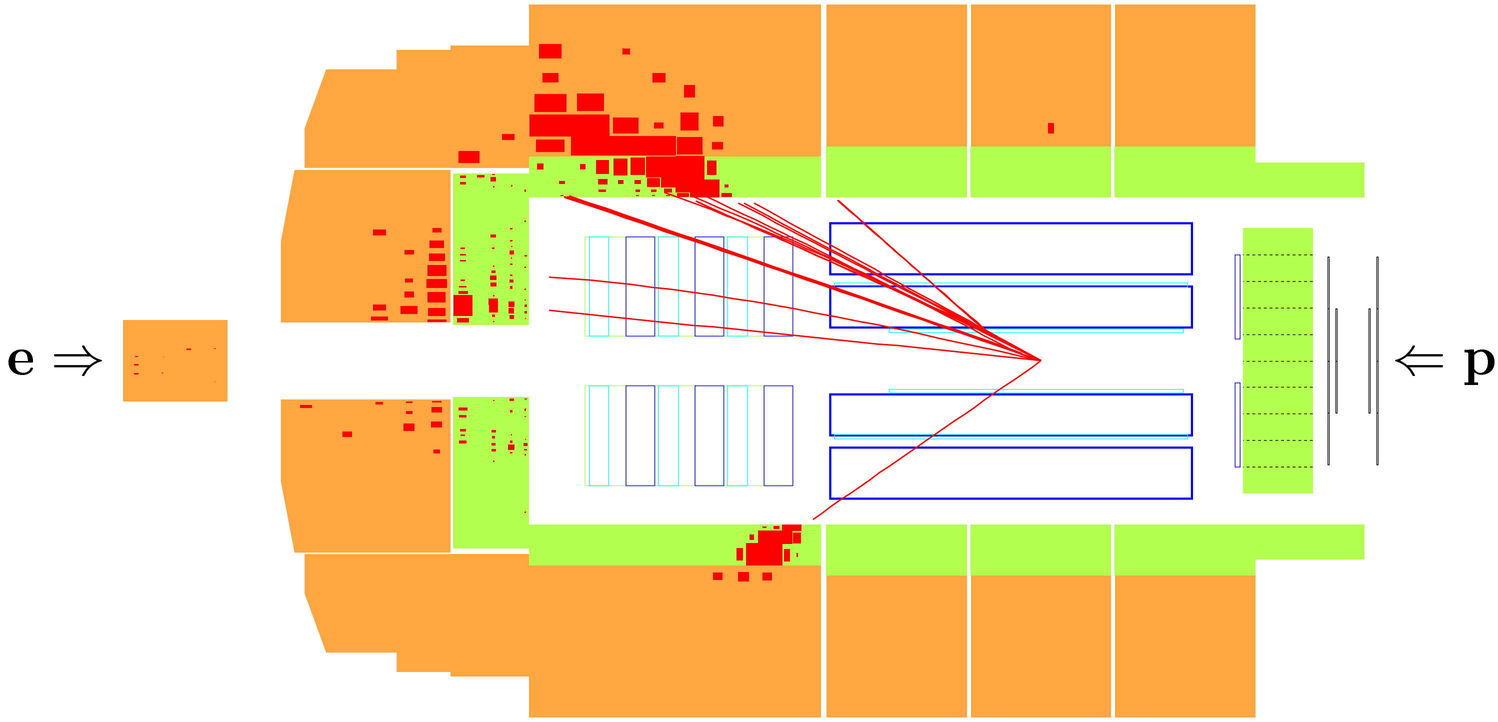
Introduction to HERA (2)



HERA did an excellent job !

	Year	Beam	$\sqrt{s}$ (GeV)	$\int$ Luminosity (pb^{-1})
$\Rightarrow$	94-97	e^+p	300	$\sim$ 40
	98-99	e^-p	320	$\sim$ 15
	99-00	e^+p	320	$\sim$ 80

H1 Detector: high Q^2 NC event



Liquid Argon Calorimeter (44000 Cells):

$$\sigma(E)/E(em) \approx 12\%/\sqrt{E/\text{ GeV}} \oplus 1\%$$

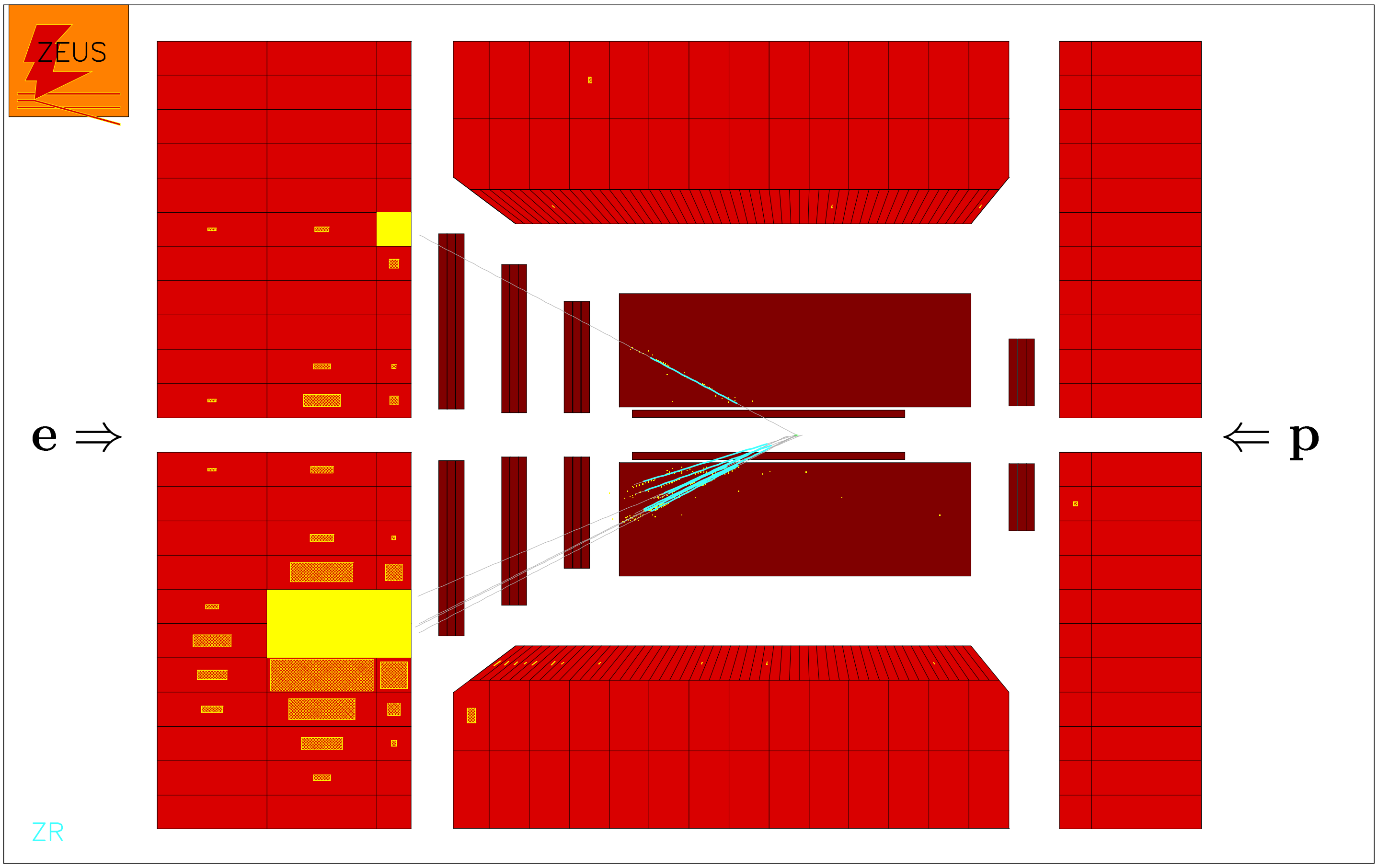
$$\sigma(E)/E(had) \approx 50\%/\sqrt{E/\text{ GeV}} \oplus 2\%$$

$$\Delta E/E_{em} = 1 - 3\%$$

$$\Delta E/E_{had} = 4\%$$

$$\Delta\theta_e = 2 - 5 \text{ mrad}$$

ZEUS Detector: high Q^2 NC event



Uranium-Scintillator Calorimeter (6000 Cells):

$$\sigma(E)/E(em) \approx 18\%/\sqrt{E/\text{ GeV}}$$

$$\sigma(E)/E(had) \approx 35\%/\sqrt{E/\text{ GeV}}$$

$$\Delta E/E_{em} = 1 - 2\%$$

$$\Delta E/E_{had} = 2\%$$

$$\Delta\theta_e \approx 3 \text{ mrad}$$

Production of Squarks

Minimal Supersymmetric Standard Model (MSSM):

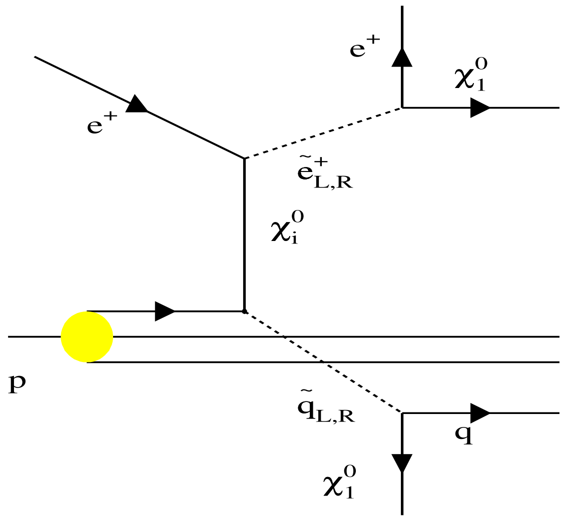
- **R-parity:** $R_p = (-1)^{3B+L+2S}$ **(= 1,-1 for particles , sparticles)**
- R_p**-conservation** $\Rightarrow$ **associated $\tilde{e}\tilde{q}$-production**

Consider : $\tilde{e}(\tilde{q}) \to e(q) + \chi_1^0$

LSP=χ_1^0 stable $\Rightarrow$ undetected

Signature: e **+ jet +** P_T^{miss}

ZEUS: PLB 434,214
H1: PLB 380,461



R-parity violating $(\not{\mathrm{R}}_{\mathrm{p}})$ SUSY:

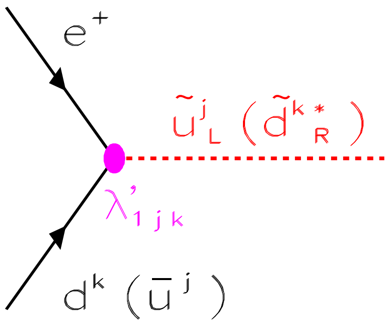
$\not{R}_p$ part of SUSY superpotential

$$\boxed{W_{\not{R}_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D} k}$$

$$\hookrightarrow \not{L}$$

- **Resonant production of single squarks possible**
- **SUSY particles can decay into standard particles**

($\Rightarrow$ LSP no more stable)



e^+ **beam $\Rightarrow$ mainly probing λ'_{1j1} couplings :**

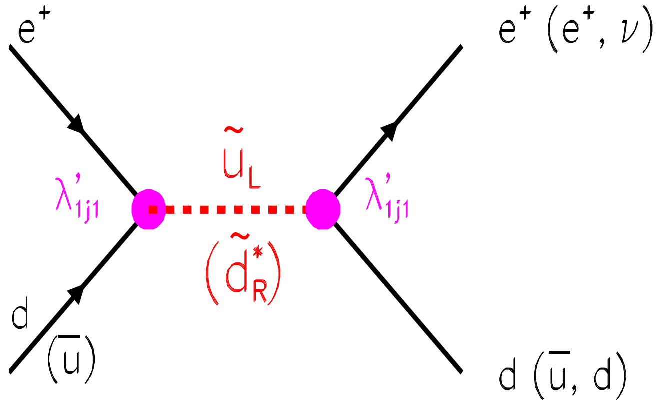
$$e^+ d \to \tilde{u}_L, \tilde{c}_L, \tilde{t}_L$$

Cross section :

$$\sigma(ep \to \tilde{u}_L^j) \propto \lambda'^2_{1j1} \cdot d^k \left(x = M_{\tilde{q}}^2/s\right)$$

Squark Decays

$R_p\!\!\!/$ Decays (Leptoquark-like):

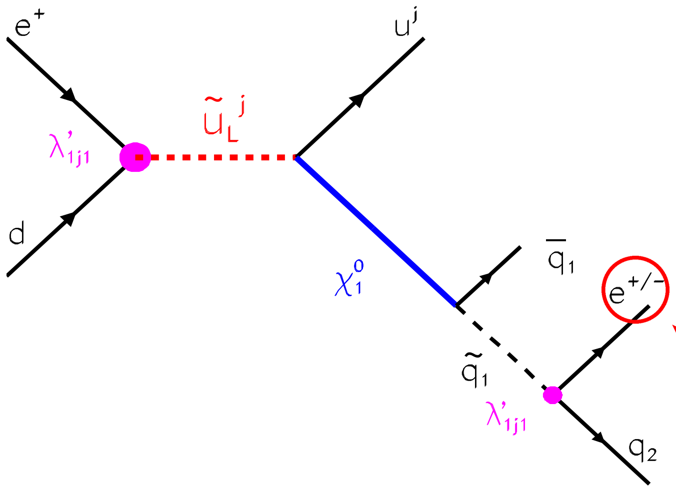


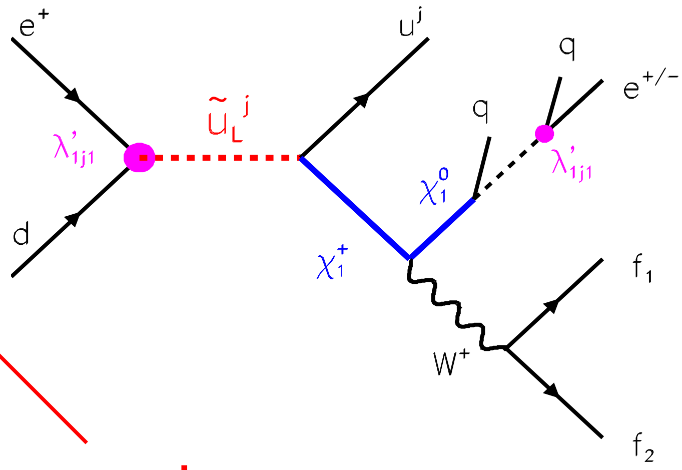
Signature :

High P_T e (ν) + jet

$\Rightarrow$ **Look for NC (CC) events at high E_T**

Gauge Decays: $\tilde{q} \rightarrow \chi_i^0 + q$, $\tilde{q} \rightarrow \chi_i^+ + q'$, $\tilde{q} \rightarrow \tilde{g} + q$





wrong charge e
lepton number violation !

$\Rightarrow$ **large variety of decay modes**

Signatures: lepton(s) + multijets

Classification of Squark Final States

Signature	Main Background
$R\!\!\!/_p$ Decays	
e + jet	NC DIS
ν + jet	CC DIS
Gauge Decays	
e^+ + multi-jets	NC DIS
e^- + multi-jets	$\sim$ background free (e^+ beam !)
ν + multi-jets	CC DIS
e + ℓ + multi-jets	small SM background

Branching ratios for these channels depend on:

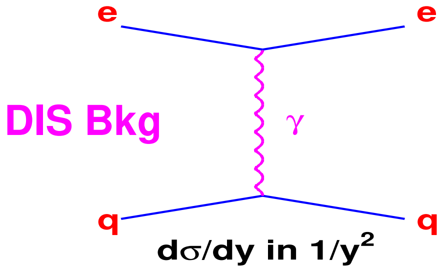
- $M_{\tilde{q}}$, λ'
- M_2 $=$ soft SUSY breaking mass term
- μ $=$ mixing massterm for 2 Higgs doublets
- tanβ $=$ ratio of the vev's of the 2 neutral Higgses

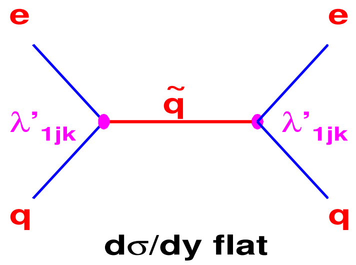
The analyses cover $\sim$ 100 % of the $\tilde{q}$ decay modes

Leptoquark-like Decays of Squarks

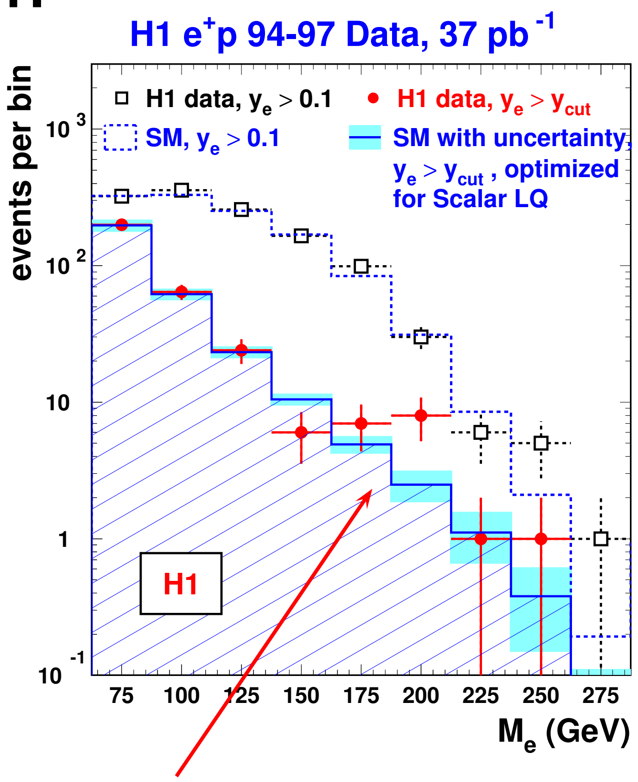
Main Analysis Cuts:

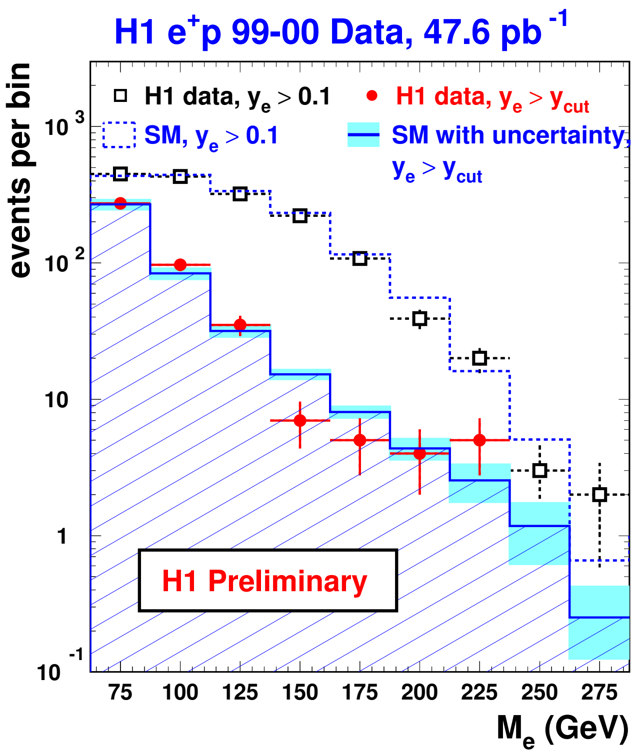
- high Q^2 NC-selection , high p_T electron
- Optimized angular (y) cut: $y > y(M_{\tilde{q}})$





H1:





Excess at $M \approx$ 200 GeV $\Longrightarrow$ No Excess

ZEUS: ($M > 220$ **GeV,** $y > 0.25$)

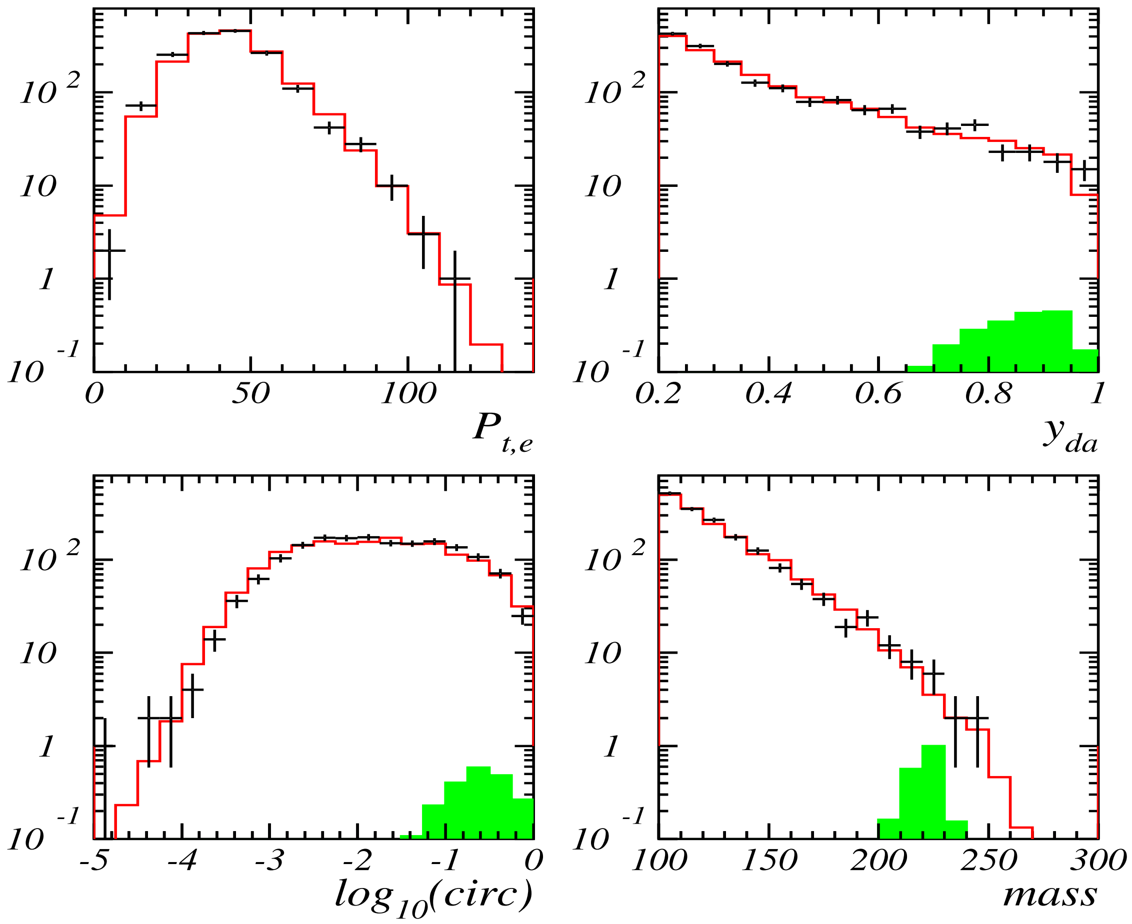
$$N_{obs} = 4 \quad \Longrightarrow \quad N_{obs} = 0$$
$$N_{exp} = 1.9 \qquad\qquad N_{exp} = 1.6$$

ZEUS: Gauge Decays into $\mathrm{e} + \mathrm{jets} + \mathrm{X}$

Main preselection cuts:

- **Isolated electron with $P_T^e > 8$ GeV**
- $Q^2_{DA} > 1000$ **GeV^2**
- $0.2 < y_{DA} < 0.98$

$\mathrm{M} > 100$ GeV



Observed data events: 1683

Total SM expectation: 1661

Hypothetical signal of a 220 GeV squark

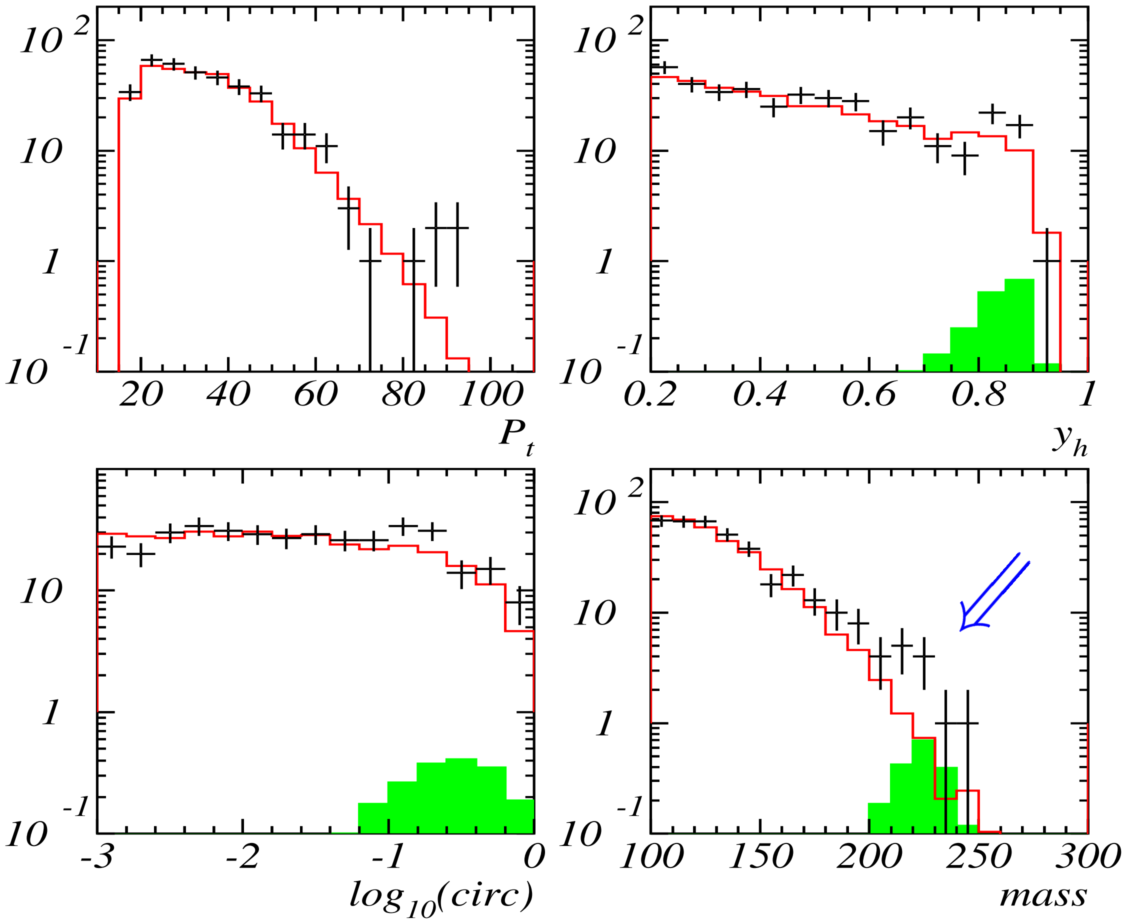
- **Good agreement with SM expectation**
- **No wrong-charge electron event found by ZEUS and H1 !**

ZEUS: Gauge Decays into $\nu + \mathrm{jets} + \mathrm{X}$ (1)

Main preselection cuts:

- $P_T^{miss} > 18$ GeV , no electron found with $E_e > 8$ GeV
- $y_h > 0.2$
- circularity $> 10^{-3}$

$\mathrm{M} > 100$ **GeV**



Observed data events: 488

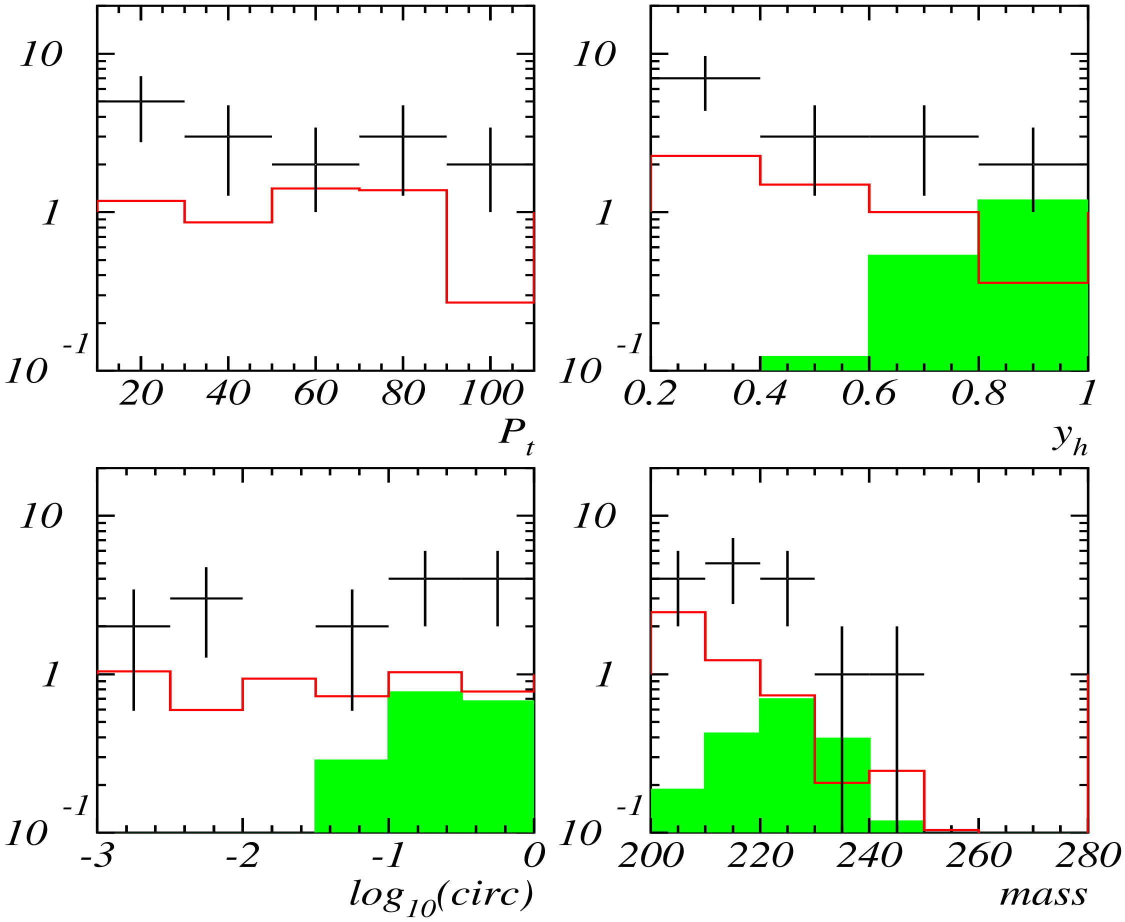
Total SM expectation: 480

Hypothetical signal of a 220 GeV squark

Slight excess at $\mathrm{M} > 200$ GeV $\Rightarrow$ closer look at high masses

ZEUS: Gauge Decays into $\nu + \mathrm{jets} + \mathrm{X}$ (2)

$\mathrm{M} > 200$ GeV



Observed data events: 15

Total SM expectation: 5.1

Hypothetical signal of a 220 GeV squark

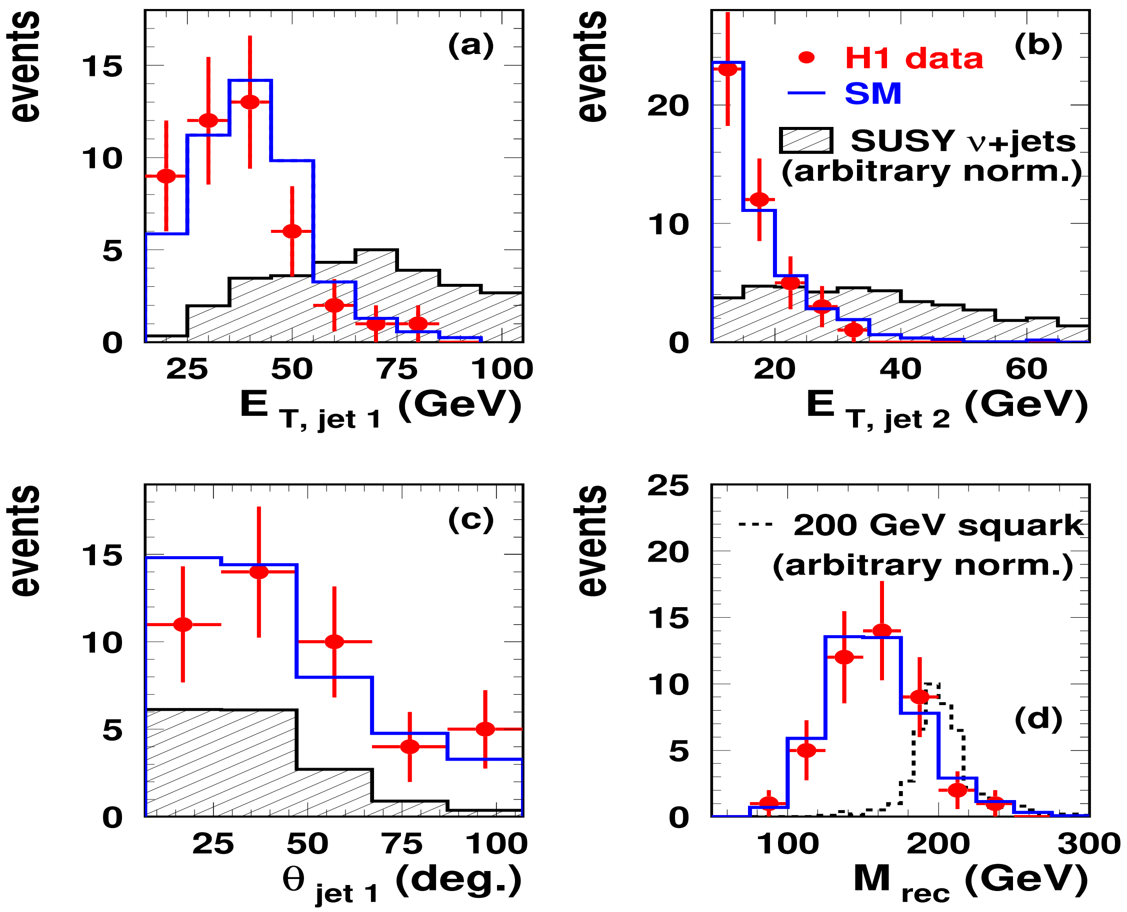
- **Excess not confined to signal region in y_h and circularity**
- **Reasons for this excess under investigation**

H1: Gauge Decays into $\nu + \mathrm{jets} + \mathrm{X}$

Main preselection cuts:

- $P_T^{miss} > 25$ **GeV**
- ≥ 2 **high** P_T **jets ,** $E_T^{jet1} > 15$ **GeV ,** $\theta_{jet1} > 10^\circ$

- **Reconstruct ν kinematics using energy-momentum conservation (in channels with one ν) $\Rightarrow$ compute squark mass M_{rec}**



typical efficiencies: $\epsilon = 30 - 50\%$

H1 sees no deviation from SM in channels $e(\nu)$ + jets + X

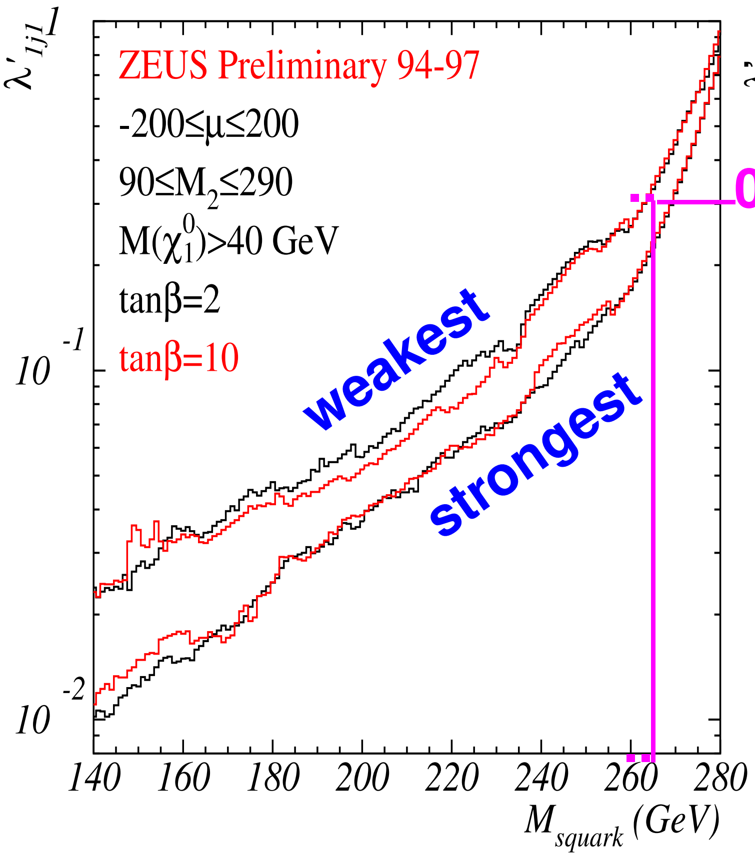
Results in the Unconstrained MSSM

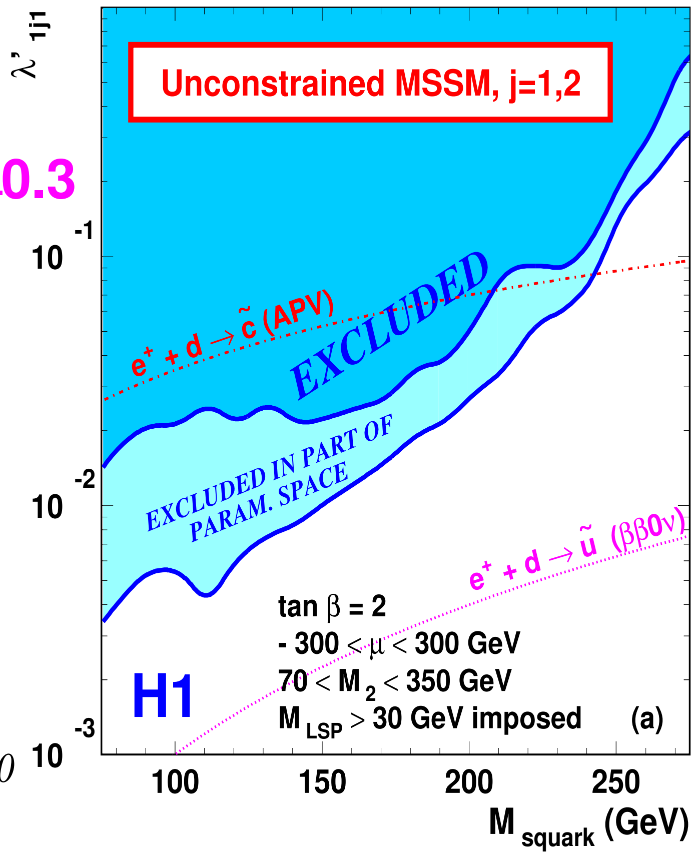
Unconstrained (phenomenological) MSSM:

Assume that sfermion and gaugino sector not related

$\Rightarrow$ sfermion masses $M_{\tilde{q}}, M_{\tilde{l}}$ free parameters

$\Rightarrow$ **Scan in SUSY parameter space: (M_2, μ) , tanβ**





- **Limits are widely model independent**
- $\lambda'_{1j1} = 0.3$ **(em. strength)** $\rightarrow$ **masses** $M_{\tilde{q}}$ **up to 260 GeV can be ruled out**
- **For $\tilde{c}$ (and $\tilde{t}$) production HERA limits better than indirect bounds from low energy experiments**

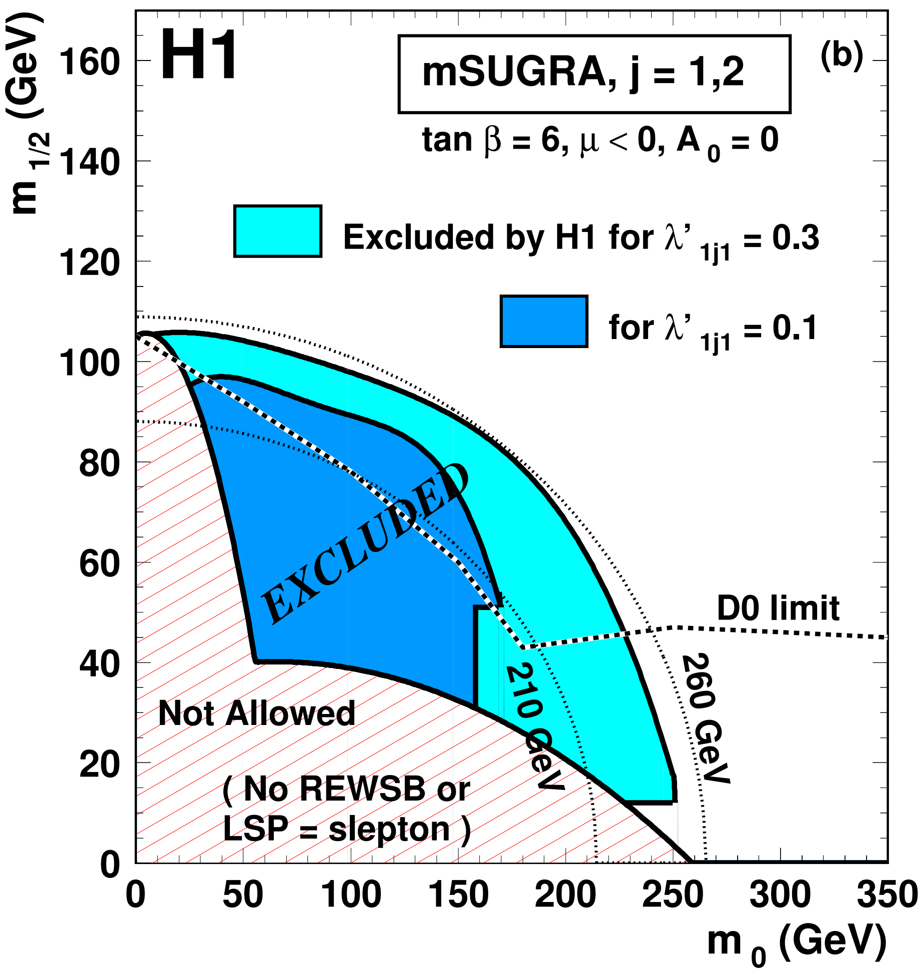
Results in Constrained MSSM Models (1)

- H1 also set limits in **constrained models**:
  - Sfermion and gaugino sector related by RGE
  - m_0 $=$ common sfermion mass at GUT scale
  - $m_{1/2}$ $=$ common gaugino mass at GUT scale
- particular case of **mSUGRA**:

  Assume in addition that electroweak symmetry breaking driven

  by radiative corrections

  $\Rightarrow$ only 5 parameters: $m_0, m_{1/2},$ sign of μ, tanβ,A_0



- For $\lambda'_{1j1} = 0.3$

  H1 limit $\sim$ follows

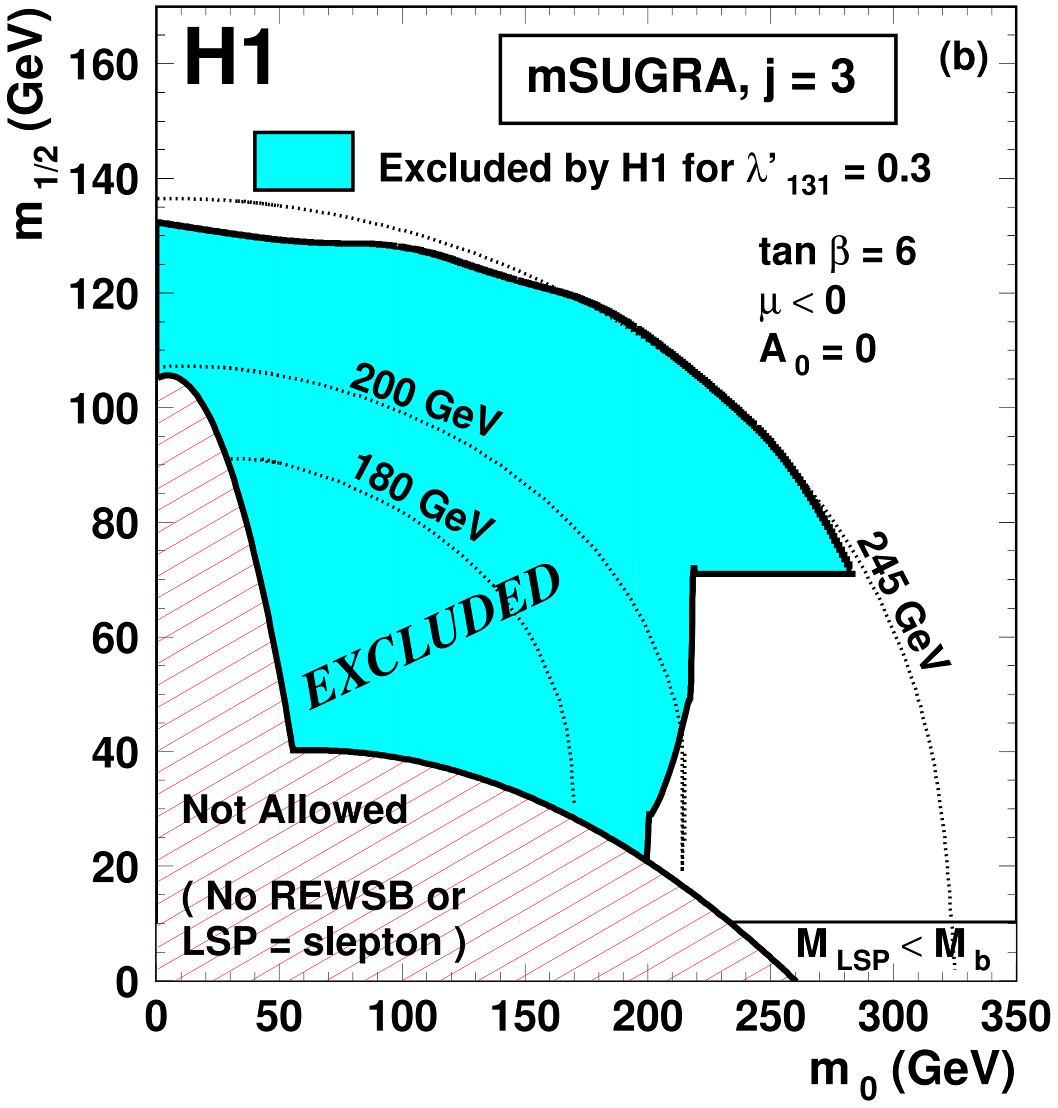
  $M_{\tilde{q}} = 260$ GeV isocurve

  $\Rightarrow$ H1 probes domain

  not ruled out by D0

- In such constrained models LEP has highest sensitivity

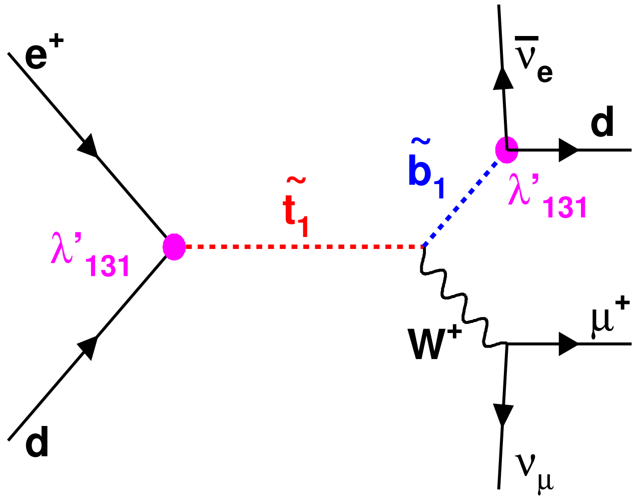
Results in Constrained MSSM Models (2)



- **Larger part of $m_0, m_{1/2}$ parameter space covered (compared to λ'_{1j1} , $j \neq 3$)**
- $\tilde{t}_1$ **masses up to $\sim$ 245 GeV can be excluded for** $\lambda'_{131} = 0.3$
- **For intermediate masses H1 probes part of parameter space not covered by LEP (increased sensitivity with larger $\sqrt{s} \Rightarrow$ discovery potential)**

Other Decay Modes of the Stop

- Special interest in $\tilde{t}$: Could be the lightest squark ?
  $\rightarrow$ Search for $\tilde{t}$ in different decay modes
- So far only $\tilde{t} \rightarrow$ fermions considered
  But: Bosonic $\tilde{t}$ decays can contribute



Possible $R\!\!\!/_p$ $\tilde{b}$ decay:

$\tilde{b} \rightarrow \nu d$

[T.Kon, Mod.Phys.Lett.A12(1997)]

Limit on coupling:

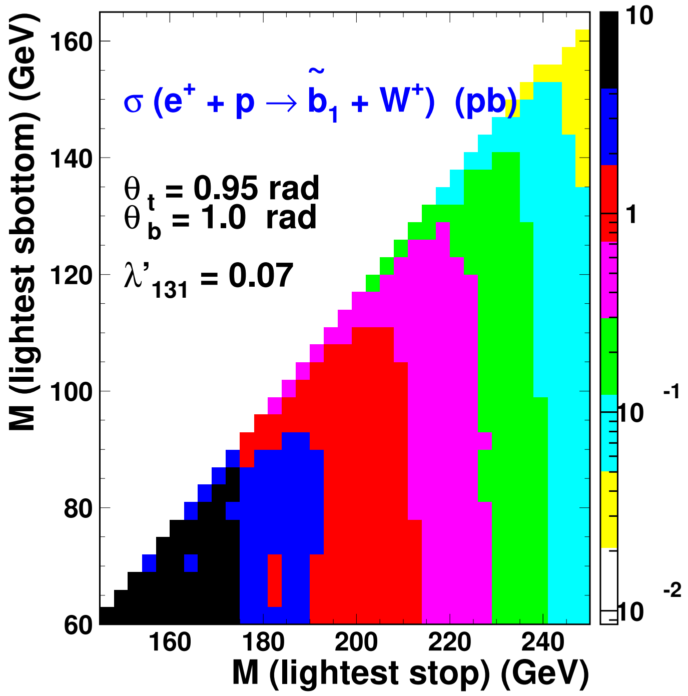
$\lambda'_{131} < 0.07$ (APV)

at $M_{\tilde{t}_1} = 200$ GeV

$\Rightarrow$ expect $\sim$ 100 events $\tilde{t} \rightarrow \tilde{b}W$

$\Rightarrow$ a few events in leptonic channel

ℓ + jet + p_T^{miss}

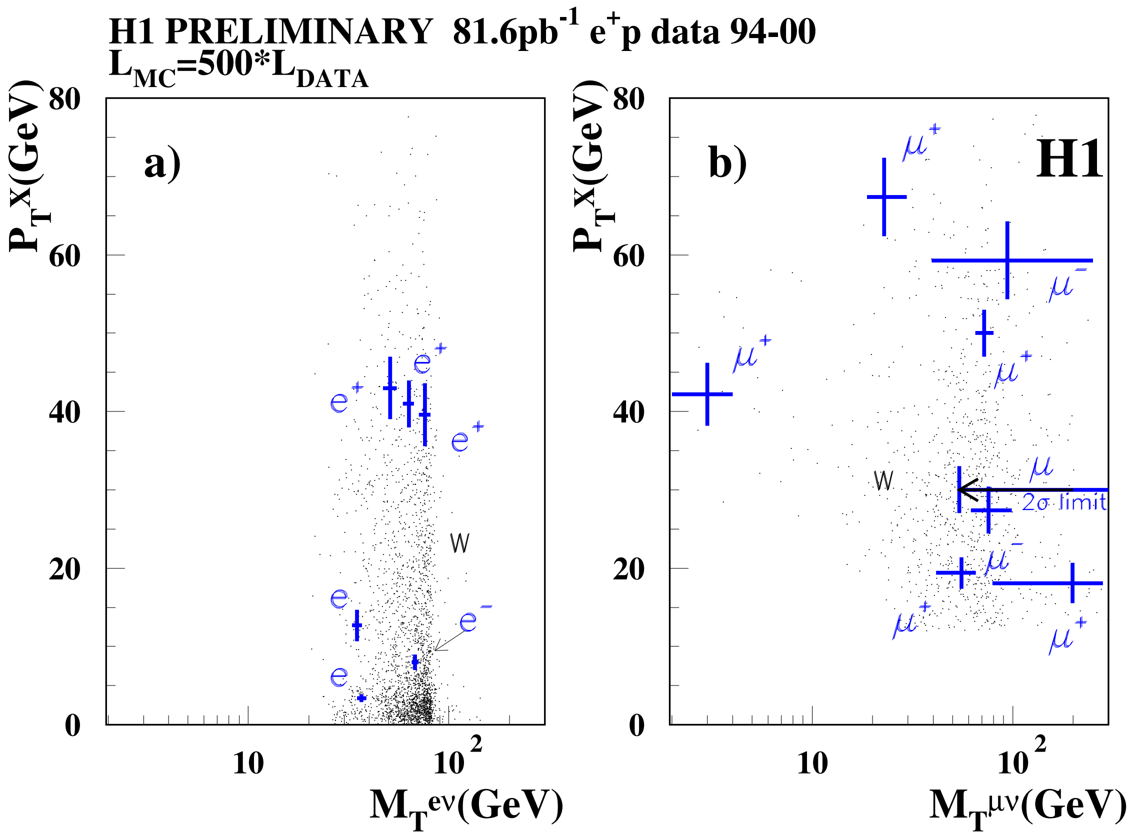


$\Rightarrow$ Dedicated stop analysis in under way !

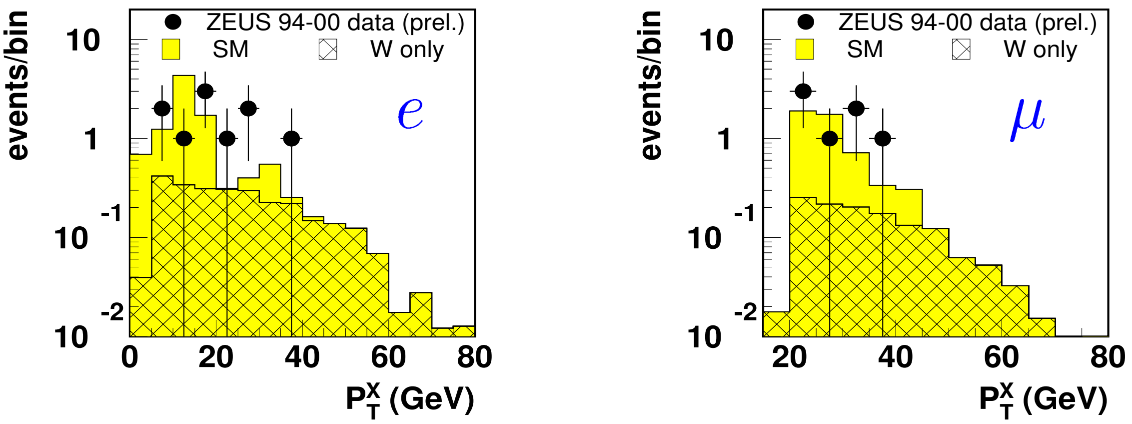
H1 and ZEUS isolated Lepton Events - A Mystery (1)

- **H1 observed an excess of isolated high P_T lepton events with large missing transverse momentum p_T^{miss}**
- **dominating background : SM W production (mainly low had. P_T)**

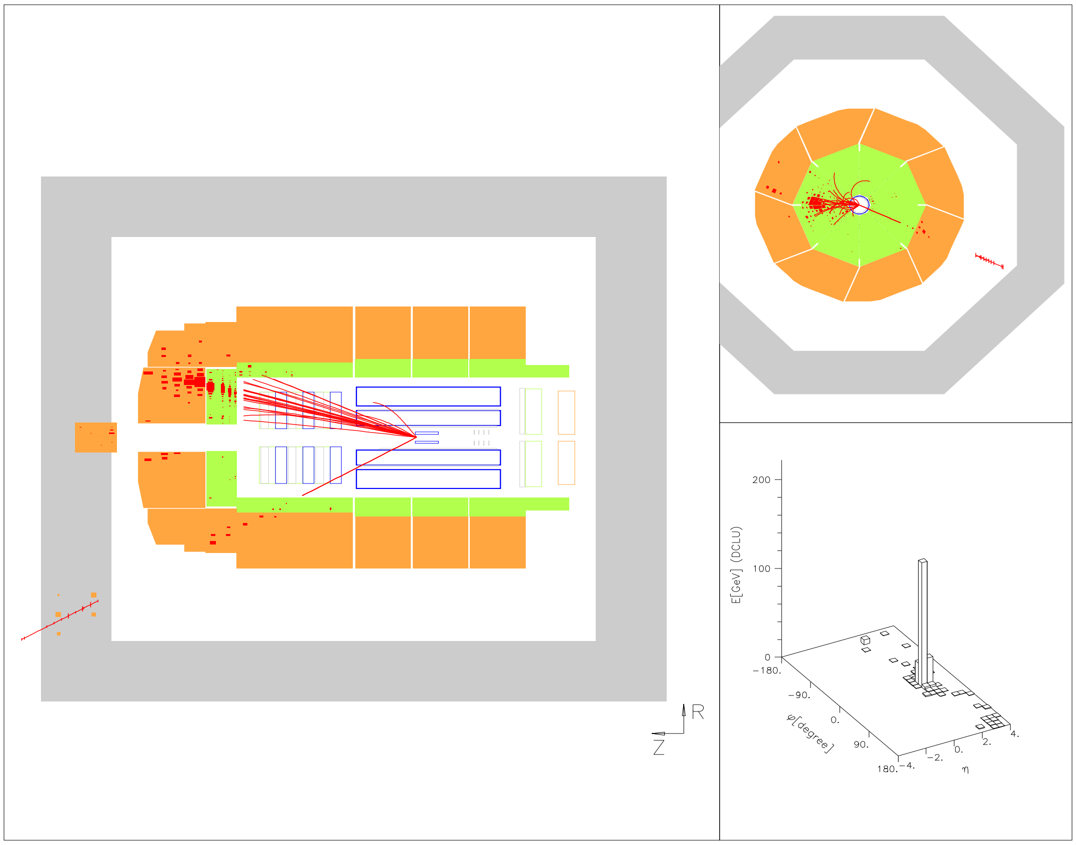
H1 events ℓ + jet + p_T^{miss} :



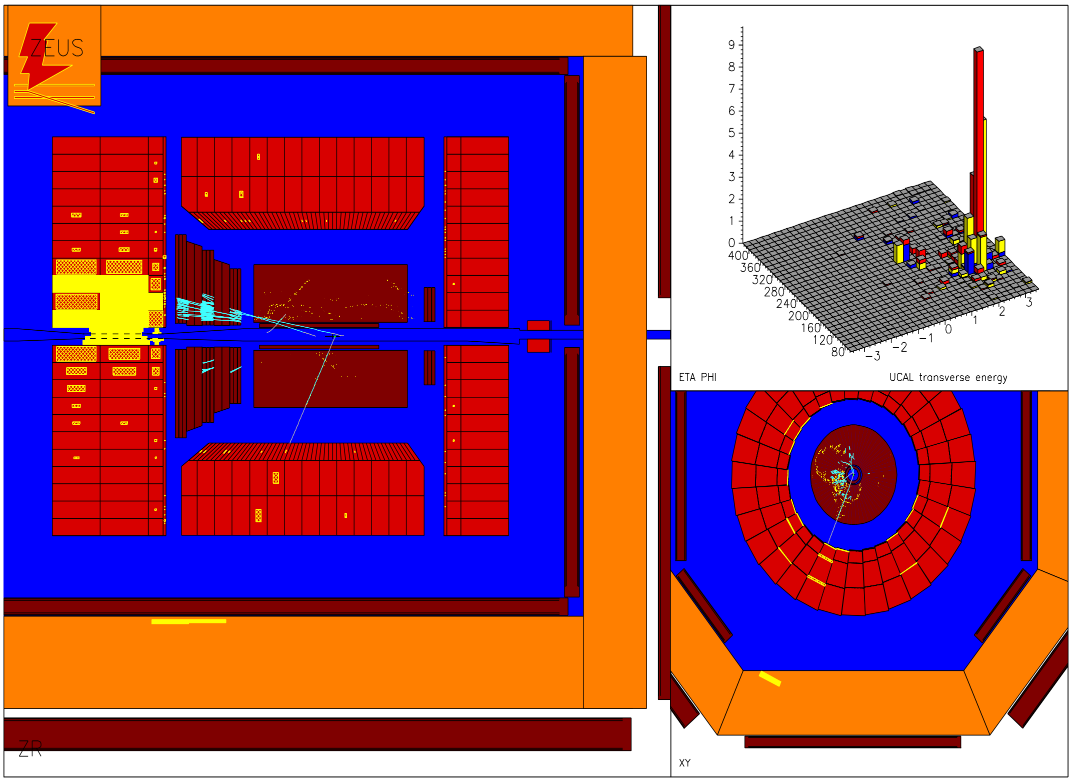
ZEUS events ℓ + jet + p_T^{miss} : (looser cuts than H1)



H1 and ZEUS isolated Lepton Events - A Mystery (2)



$P_T(\mu^+)=38^{+20}_{-10}$ GeV, $P_T^X=36$ GeV, $Acoplanarity=1.9$, $\not{P}_T=61^{+17}_{-8}$ GeV, $M_T=91^{+39}_{-19}$ GeV



H1 and ZEUS isolated Lepton Events - A Mystery (3)

- **ZEUS** analysis after cuts to suppress non-W background

ZEUS preliminary 1994-2000 $e^{\pm}$p (130 pb^{-1})	Electrons obs./expected	Muons obs./expected
$P_T^X > 25$ GeV	1 / 1.14 $\pm$ 0.06	1 / 1.29 $\pm$ 0.16
$P_T^X > 40$ GeV	0 / 0.46 $\pm$ 0.03	0 / 0.50 $\pm$ 0.08

$\Rightarrow$ Event rates consistent with SM expectation

- **H1** analysis (W-selection, status Osaka)

H1 preliminary 1994-2000 e^{+}p (82 pb^{-1})	Electrons obs./expected	Muons obs./expected
$P_T^X > 25$ GeV	3 / 1.05 $\pm$ 0.27	6 / 1.21 $\pm$ 0.32
$P_T^X > 40$ GeV	2 / 0.33 $\pm$ 0.10	4 / 0.46 $\pm$ 0.13

$\Rightarrow$ Excess at high P_T^X in both 94-97 e^+p and 99-00 e^+p data

H1 and ZEUS background rates consistent,

but discrepancy in observed event rates!

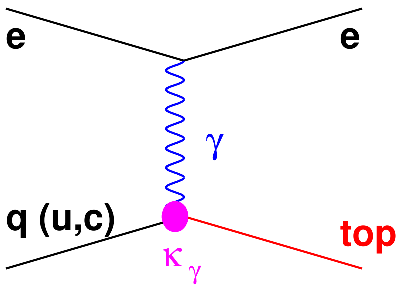
Anomalous Single Top Production

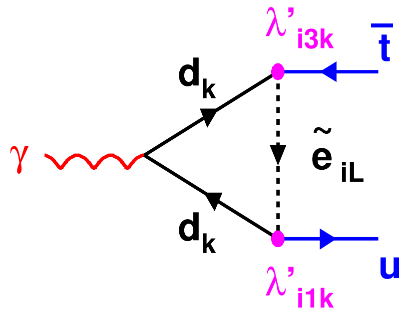
Could the H1 isolated leptons come from a top decay ?

- $t \to b + W \to b + \ell + \nu \Rightarrow$ **high hadronic P_T expected (b-quark)**
- **Single top production in SM negligible**

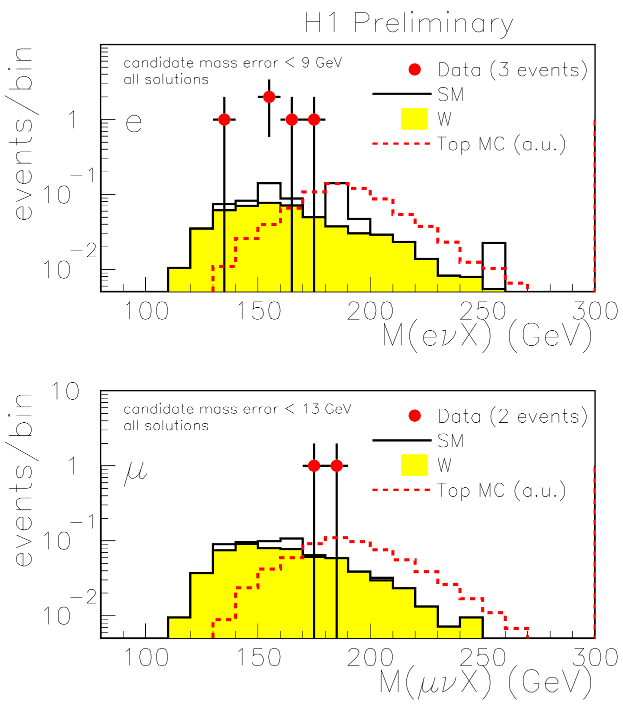
  $\Rightarrow$ **production in a FCNC process with anomalous $tu\gamma$-coupling**

  (e.g. in $R\!\!\!/_p$ SUSY models)





H1 Top Selection $W \to \ell\nu$: $N_{obs} = 5$ **(3e,2μ)** , $N_{exp} = 1.4 \pm 0.48$



$W \to e\nu$

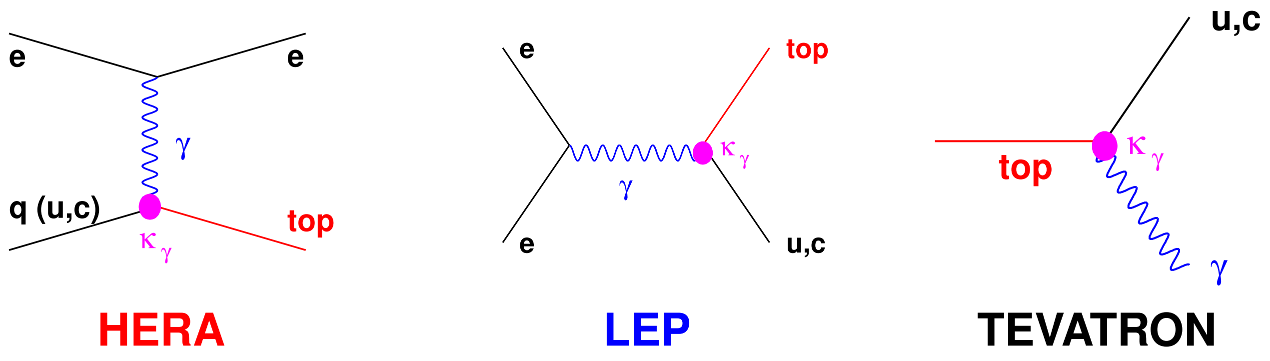
$W \to \mu\nu$

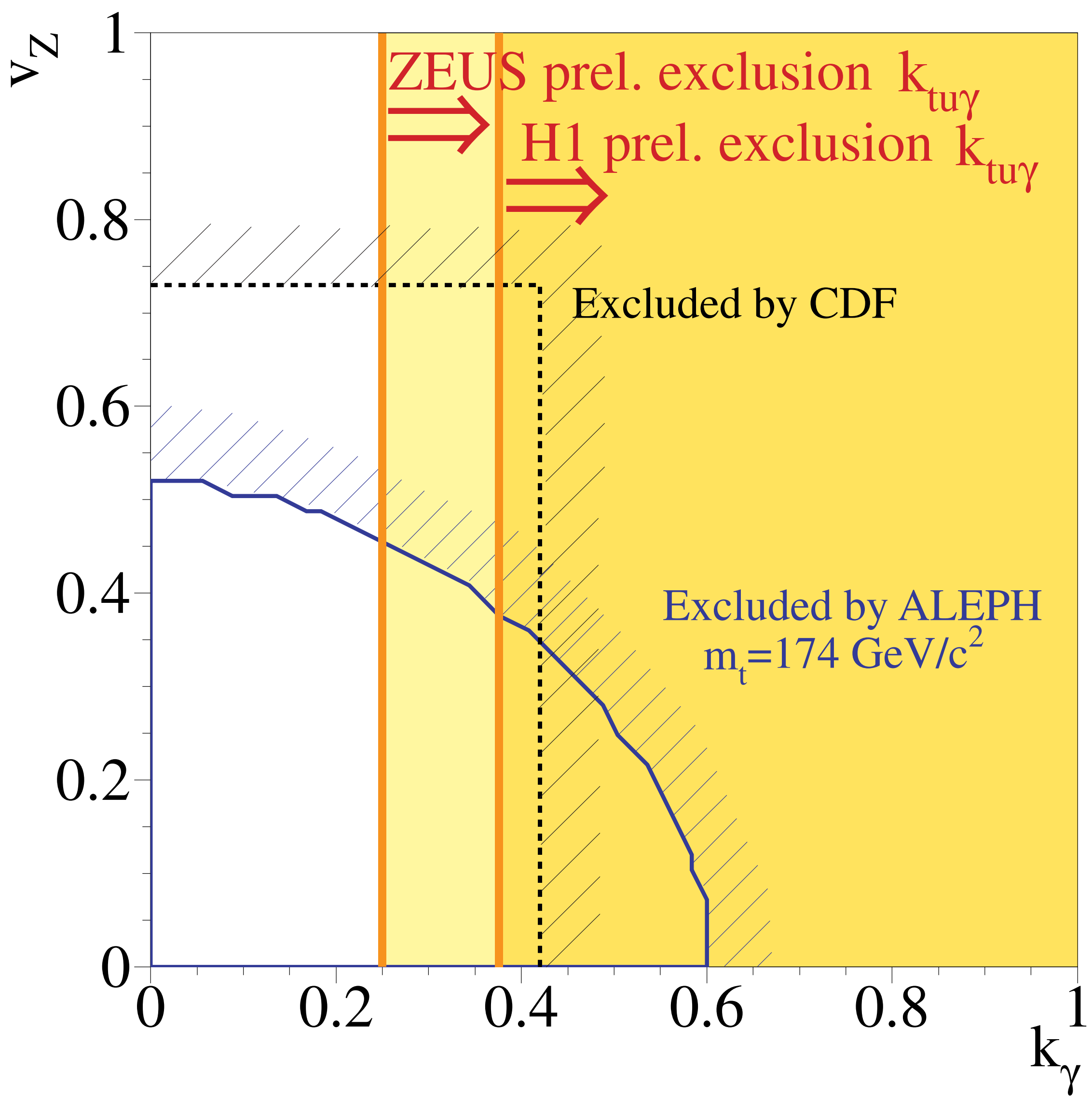
W mass constraint imposed

$\Rightarrow$ **2 possible solutions per event**

H1 Top Selection $W \to q\bar{q}'$: $N_{obs} = 10$, $N_{exp} = 8.3^{+5.9}_{-4.6}$

Exclusion Limits for FCNC-Coupling





- **HERA has large sensitivity to FCNC top production beyond the reach of other experiments ⇒ most stringent limits on κ_γ**

Conclusions

- ⋆ No evidence for squark production found in various analysed channels in 1994-97 e^+p data ($\sim$ 100 % of squark decay modes)
- ⋆ Full scan of SUSY parameter space performed
  $\Rightarrow$ mass dependent limits on λ' found to be rather model independent
  For $\lambda' = 0.3 \Rightarrow M_{\tilde{q}} < 260$ GeV excluded
  Improvement of indirect limits for $\tilde{c}$ and $\tilde{t}$
- ⋆ Constraints set on mSUGRA parameters
  $\Rightarrow$ competitiveness/complementarity with other experiments

- ⋆ Isolated lepton events still puzzling
- ⋆ Some events compatible with single top production $\Rightarrow$ improved limits on anomalous top coupling

$\longrightarrow$ future prospects for HERA

Future Prospects

★ **Shutdown since fall 2000: lumi & detector upgrade**

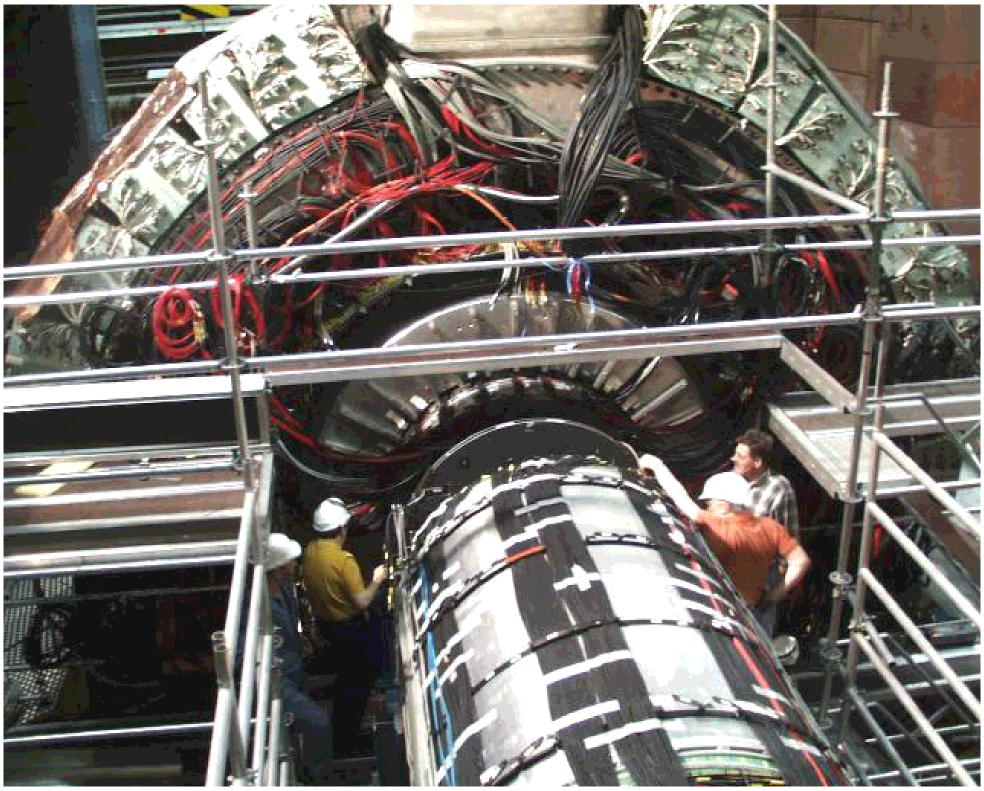
★ **Restart in September 2001**

New focussing magnets $\Rightarrow$ 5x higher luminosity

HERA II will bring $\sim$ 1fb^{-1}/experiment in $\sim$ 5 years

★ **Polarized $e^{\pm}$ beams**

(increased squark production cross section and sensitivity)



★ **... more exciting HERA results to come ...**