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H1 Collaboration

June 17, 2001

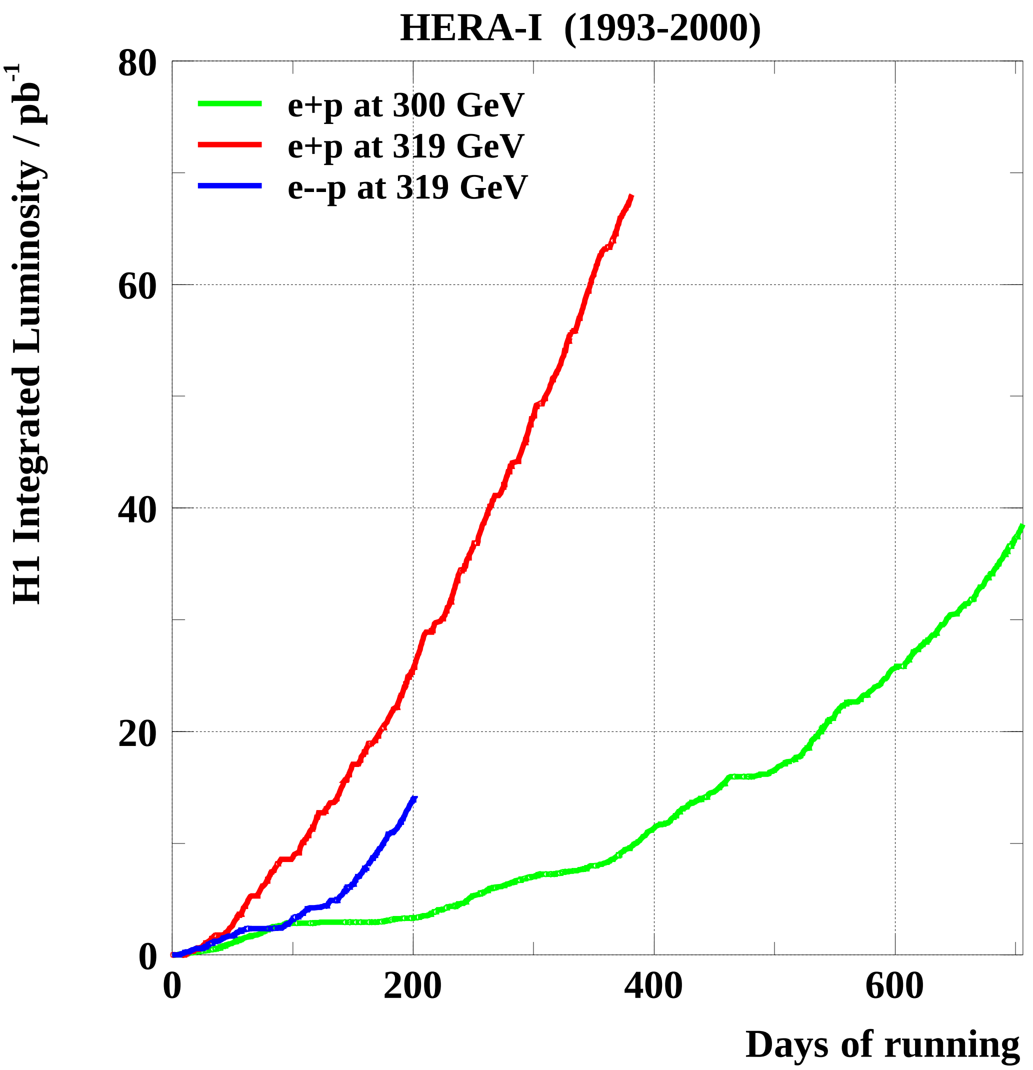
SUSY Searches at HERA

Introduction

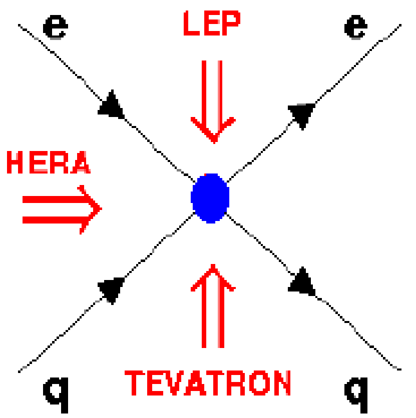
HERA - electron(positron)-proton collider at DESY

Two experiments: H1 and ZEUS

Very successful HERA operation in 1999-2000



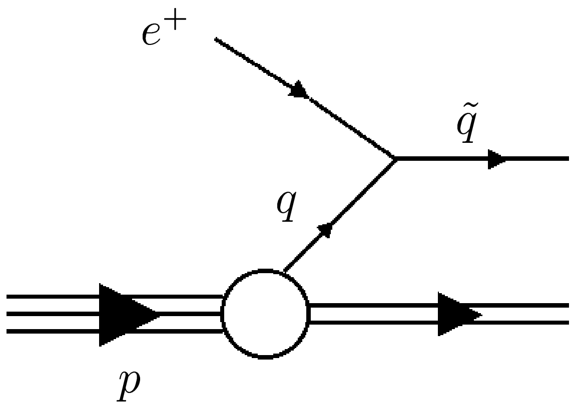
Total luminosity is about 130 pb^{-1} per experiment



- **Initial state** with **leptonic** and **baryonic** quantum numbers

  ⇒ **ideally suited to look for particles with coupling to eq-pairs**

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



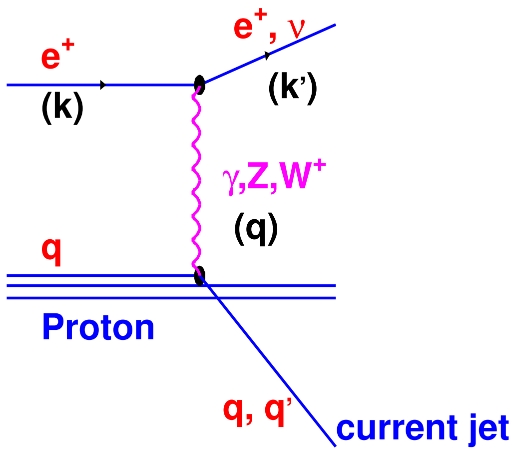
Main SM processes at high $\mathrm{E_T}$:

Neutral Current DIS (γ, Z exchange)

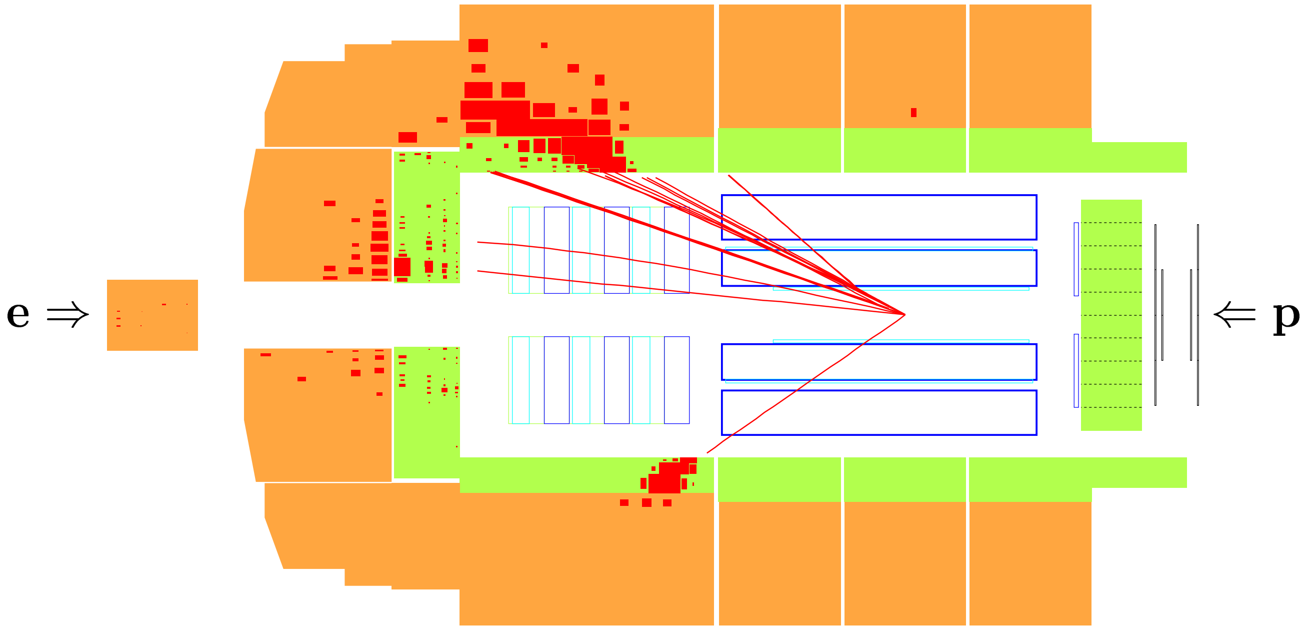
Charged Current DIS ($W^\pm$ exchange)

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

⇒ e lost in beam pipe



H1 Detector: high Q^2 NC event



Liquid Argon Calorimeter (44000 Cells):

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

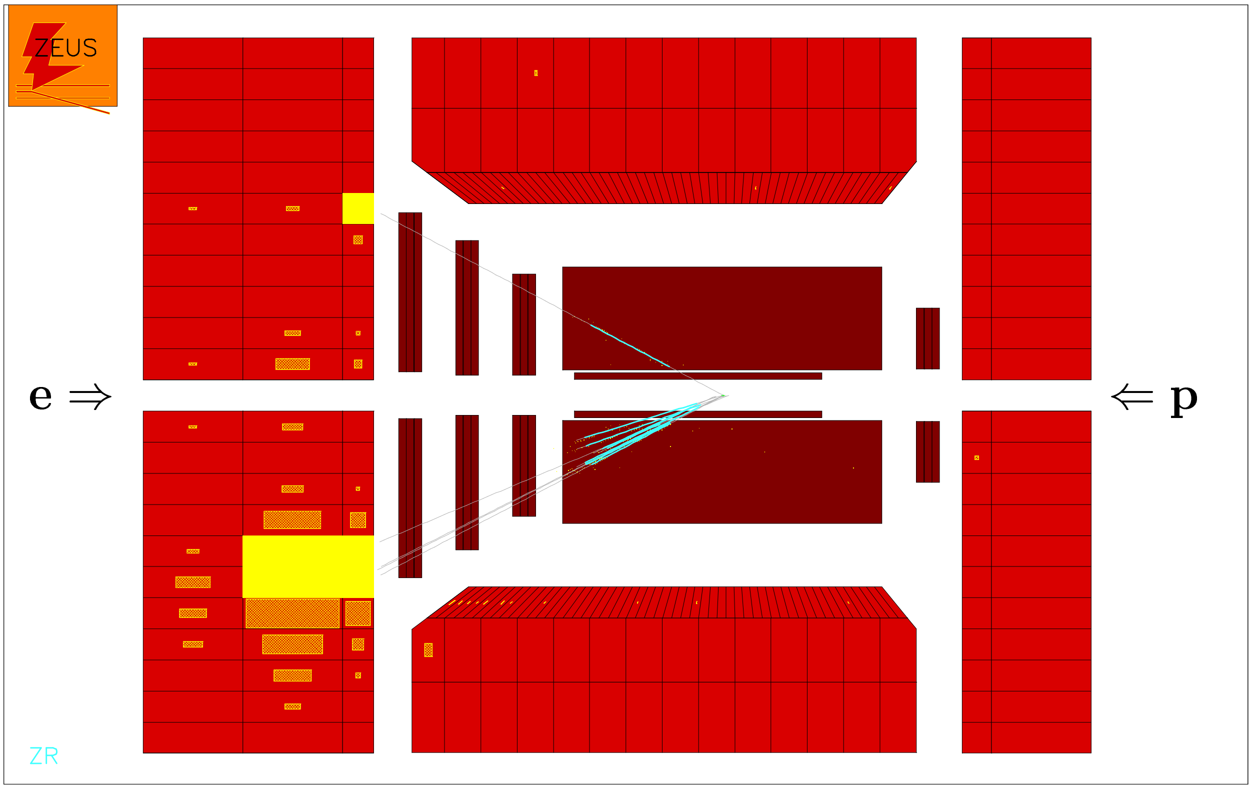
$$\sigma(E)/E(had) \approx 50\%/\sqrt{E/\text{ GeV}} \oplus 2\%$$

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

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

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

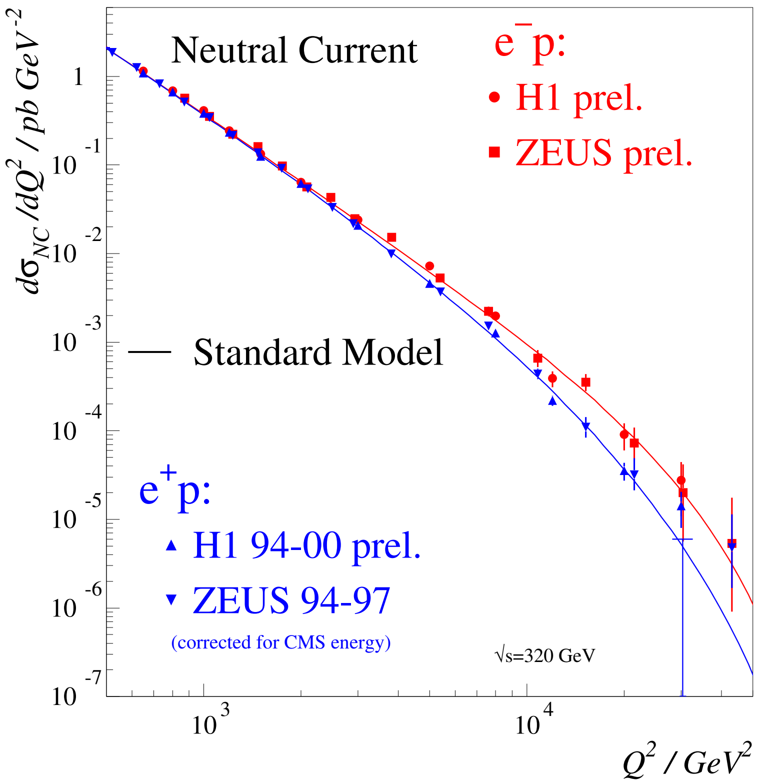
ZEUS Detector: high Q^2 NC event

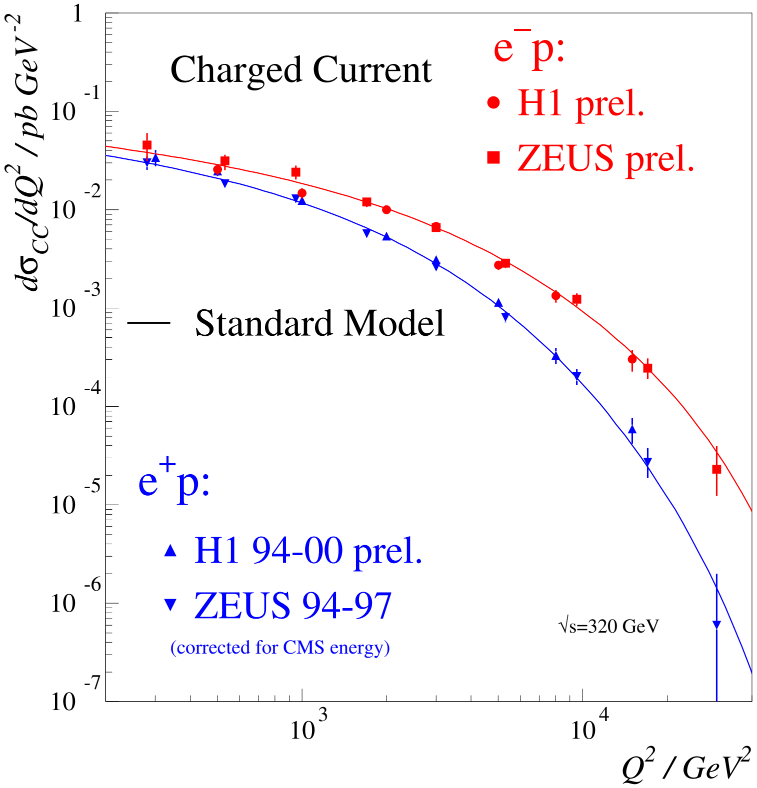


Uranium-Scintillator Calorimeter (6000 Cells):

$$\sigma(E)/E(em) \approx 18\%/\sqrt{E/\text{ GeV}}$$
$$\sigma(E)/E(had) \approx 35\%/\sqrt{E/\text{ GeV}}$$
$$\Delta E/E_{em} = 1-2\%$$
$$\Delta E/E_{had} = 2\%$$
$$\Delta\theta_e \approx 3 \text{ mrad}$$

High-Q^2 DIS





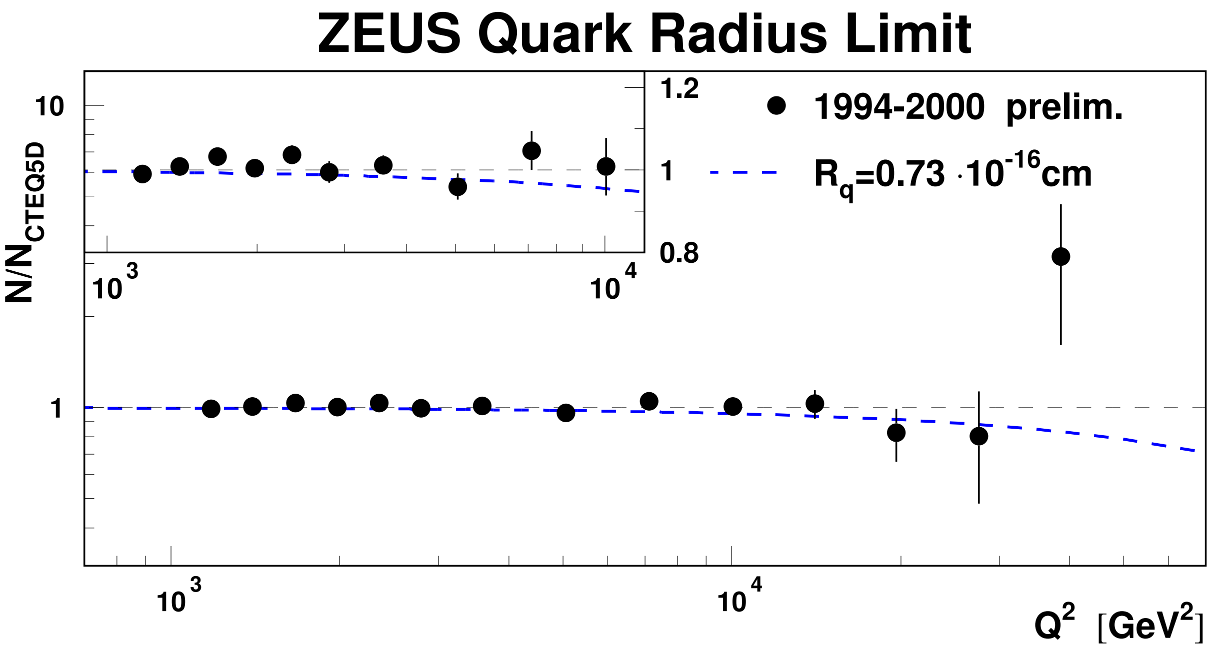
$\Rightarrow$ Good agreement with the Standard Model over ~6 orders of magnitude.

Sensitivity to a Compositeness

Assume a quark to be an extended object:

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

R_q– quark radius



Preliminary 95% CL limit from combined 1994-2000 $e^{\pm}p$ data

$$\boxed{R_q < 0.73 \cdot 10^{-16}\ \mathrm{cm}}$$

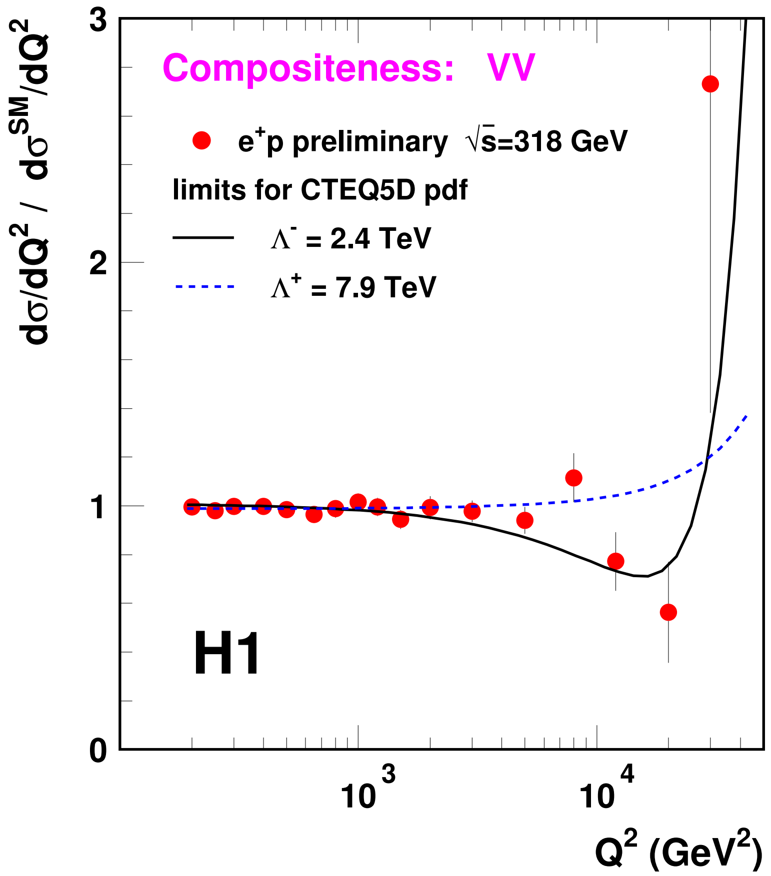
Comparable with $R_q < 1 \cdot 10^{-16} cm$ CDF bound.

Sensitivity to Contact Interaction Scale

Effective interaction coupling

$$\eta = \pm \frac{4\pi}{\Lambda^2}$$

$\Lambda-$ contact interaction scale



Depending on chiral structure assumed for the CI

$$\Lambda^{\pm} < 1.6 - 9.2TeV$$

Comparable with LEP and Tevatron limits.

Sensitivity to Large Extra Dimentions

Assume that gravity becomes strong at subatomic distances (Phys.Lett. B 429(1998) 263) resulting in effective CI coupling

$$\eta = \pm \frac{1}{M_S^4}$$

M_S- mass scale.

Prelim. combined fits:

ZEUS:

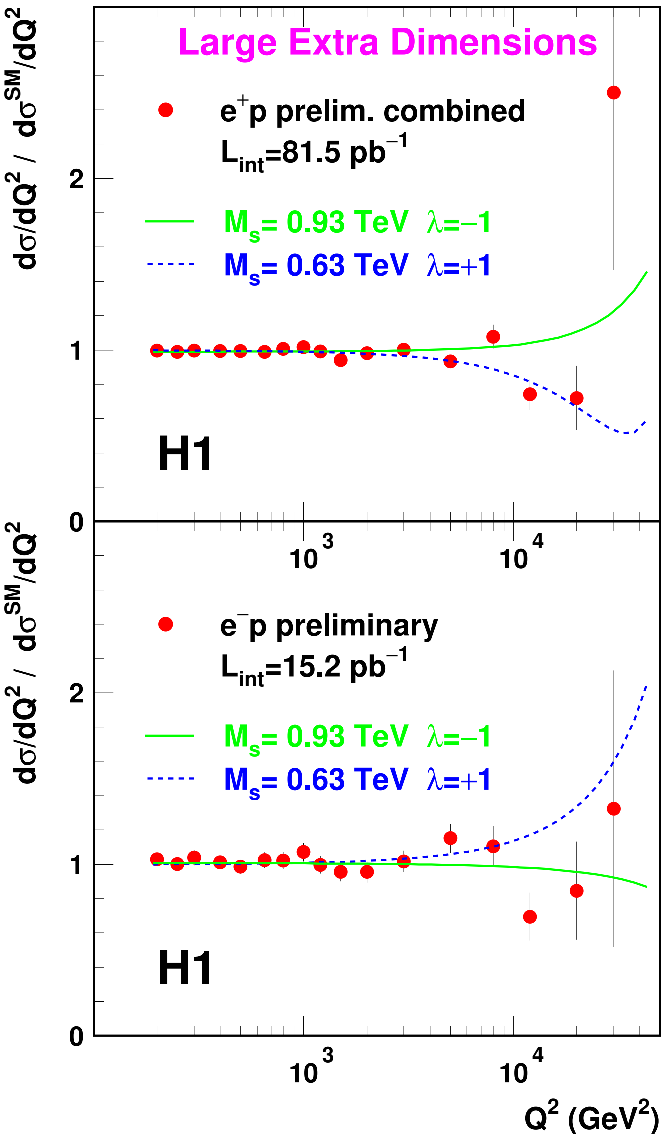
$M_S^+ > 0.81 \quad TeV$

$M_S^- > 0.82 \quad TeV$

H1:

$M_S^+ > 0.63 \quad TeV$

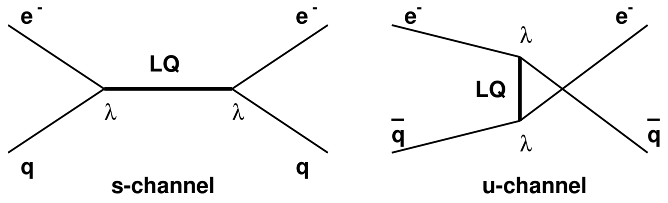
$M_S^- > 0.93 \quad TeV$

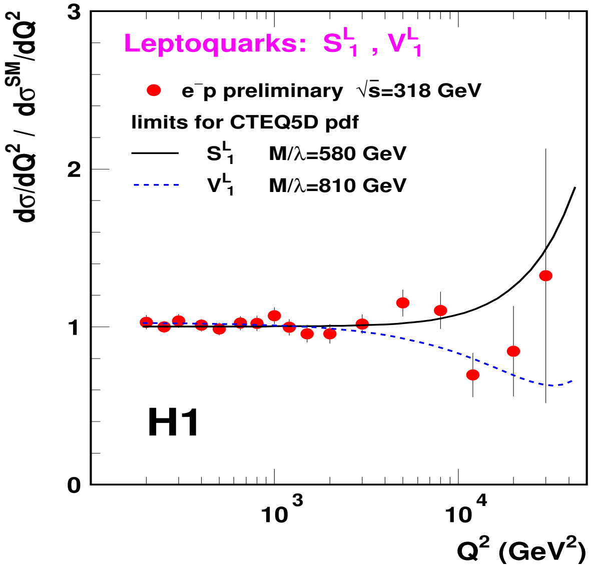


Contact Interactions / Leptoquarks

High mass leptoquarks $M_{LQ} \gg \sqrt{s}$

Both s- and u-channel important





H1 1994-00 preliminary, 95% CL limits

LQ	η^u $(\lambda/M_{LQ})^2$	η^d $(\lambda/M_{LQ})^2$	F	M_{LQ}/λ [GeV]
S^L_0	$+\frac{1}{2}$		2	1070
S^R_0	$+\frac{1}{2}$		2	960
$\tilde{S}^R_0$		$+\frac{1}{2}$	2	290
$S^L_{1/2}$	$-\frac{1}{2}$		0	380
$S^R_{1/2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	0	380
$\tilde{S}^L_{1/2}$		$-\frac{1}{2}$	0	650
S^L_1	$+\frac{1}{2}$	$+1$	2	690
V^L_0		-1	0	1030
V^R_0		-1	0	810
$\tilde{V}^R_0$	-1		0	530
$V^L_{1/2}$		$+1$	2	480
$V^R_{1/2}$	$+1$	$+1$	2	1510
$\tilde{V}^L_{1/2}$	$+1$		2	1690
V^L_1	-2	-1	0	680

Search for leptoquarks

Leptoquarks (LQs):

Scalar and vector
color triplet bosons
carry L and B numbers
$\Rightarrow$ Fermion number
$F = 3B + L = 0, 2$

Production cross section:

(e.g. for s-channel)

unknown Yukawa couplings

$$\sigma \propto (J+1)\frac{\pi}{4s}\lambda^2 q\left(\frac{M_{\mathrm{LQ}}{}^2}{s}\right)$$

known parton densities

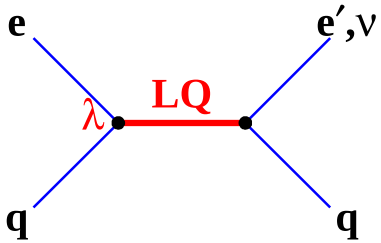
Decays (Final states: NC, CC-like):

Generic models

$BR(\mathrm{LQ} \to lq)$, $BR(\mathrm{LQ} \to \nu q)$
free parameters

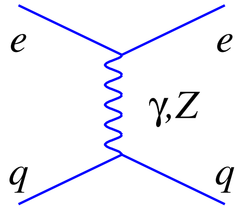
Buchmüller-Rückl-Wyler (BRW) model

7 scalars, 7 vectors
$BR_{eq} = 1, 1/2$, $BR_{\nu q} = 0, 1/2$



Scalar LQs versus NC DIS

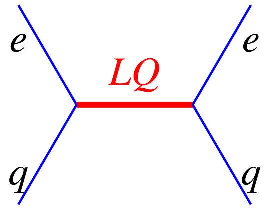
NC DIS



$$\frac{d\sigma}{dy} \sim \frac{1}{y^2}$$

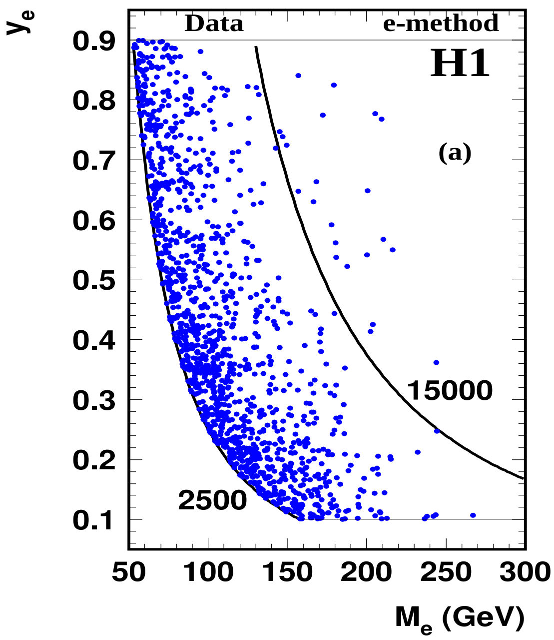
Scalar LQs:

(or $\tilde{q}$ in $R\!\!\!/_P$ SUSY)

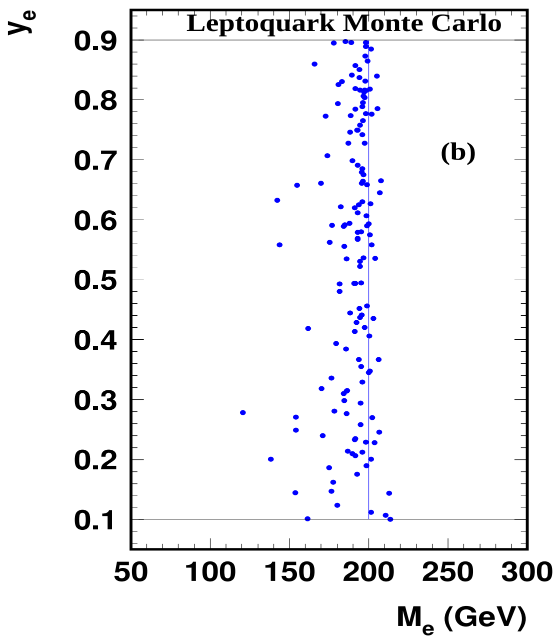


$$\left.\frac{d\sigma}{dy}\right|_{\text{scalar}} \to \text{flat}$$

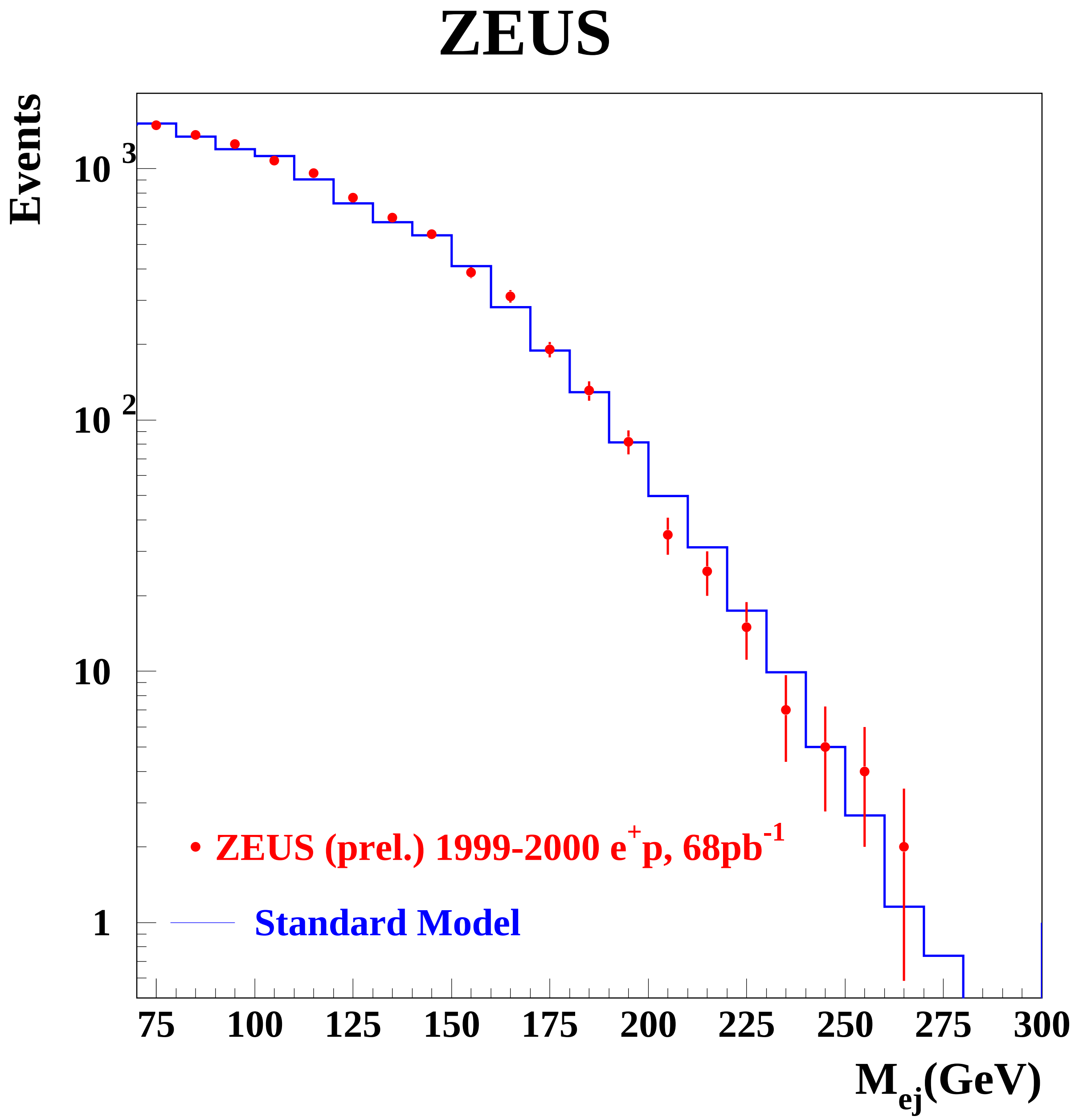
H1 data 94-97



Monte carlo

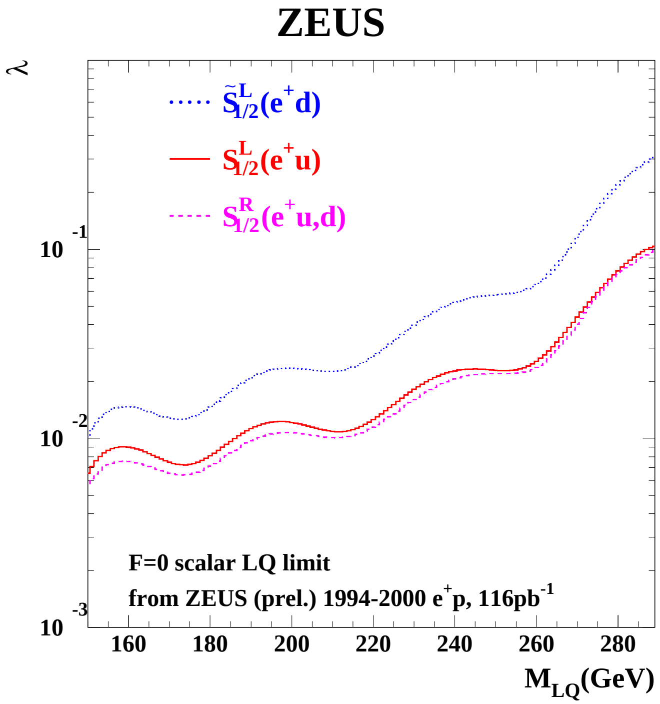


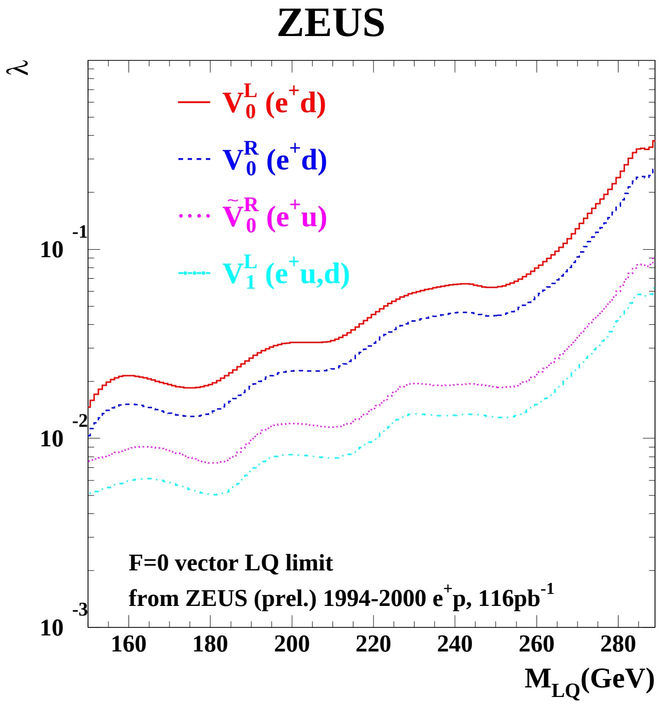
$\Rightarrow$ **Same final states but different y (angular) distributions**



No excess is observed in the eq mass spectra.

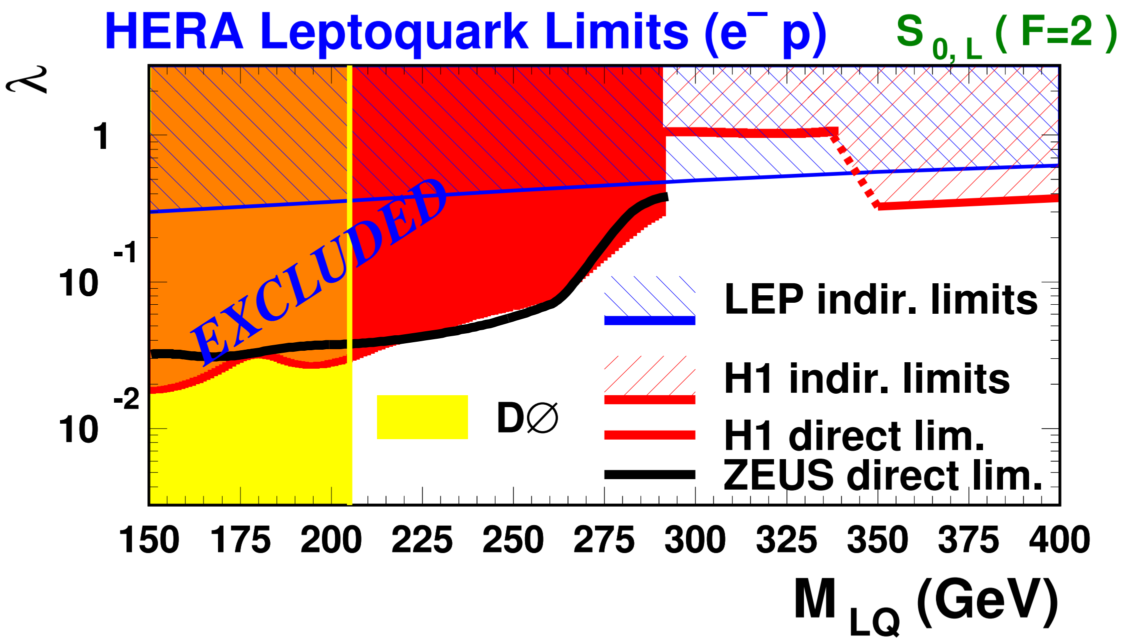
New preliminary results: combined 1994-2000 e^+p data

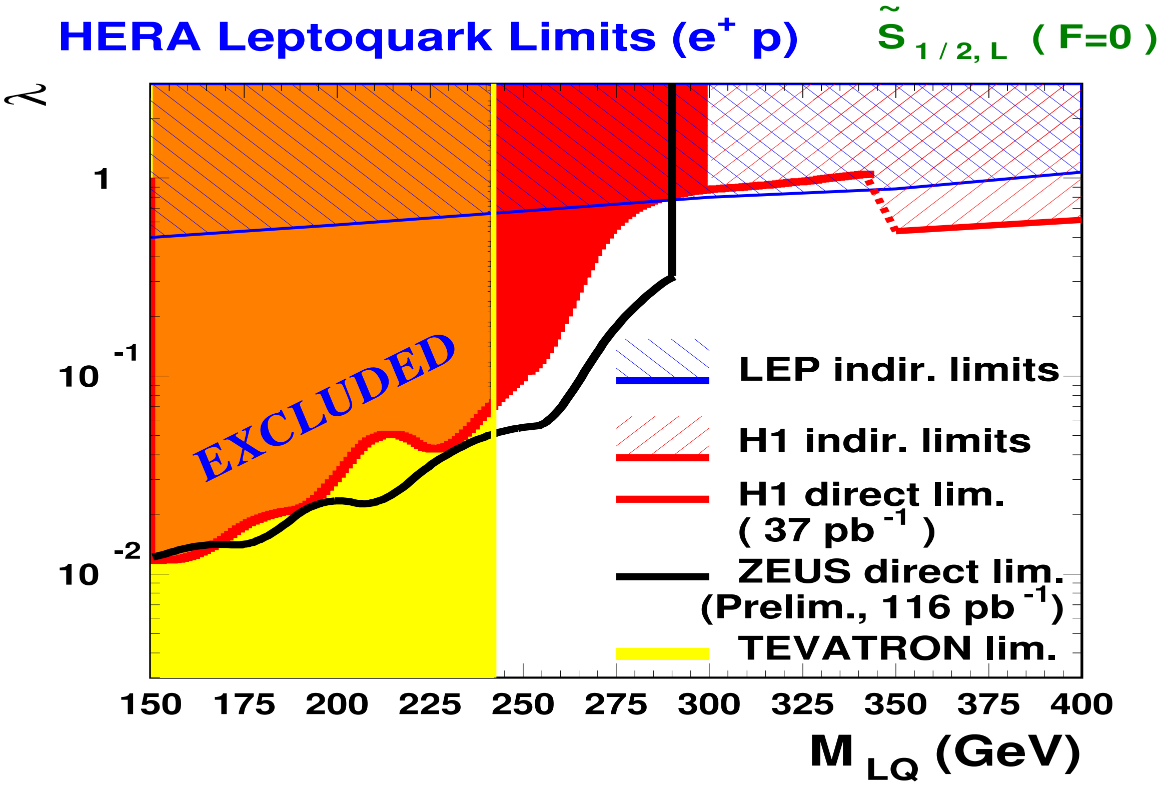




For $\lambda = 0.03$ (i.e. a coupling 100 times smaller than α_{em})
1994-2000 combined: M_{LQ} up to 275 GeV excluded
Improved by 25 GeV with respect to 1994-1997 alone

Leptoquarks in BRW model



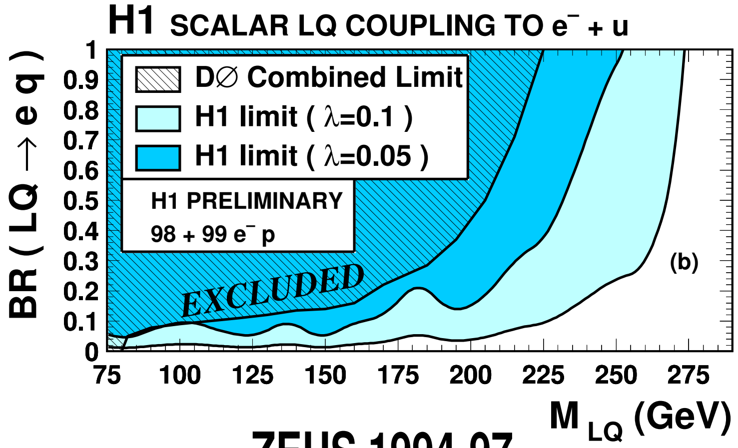


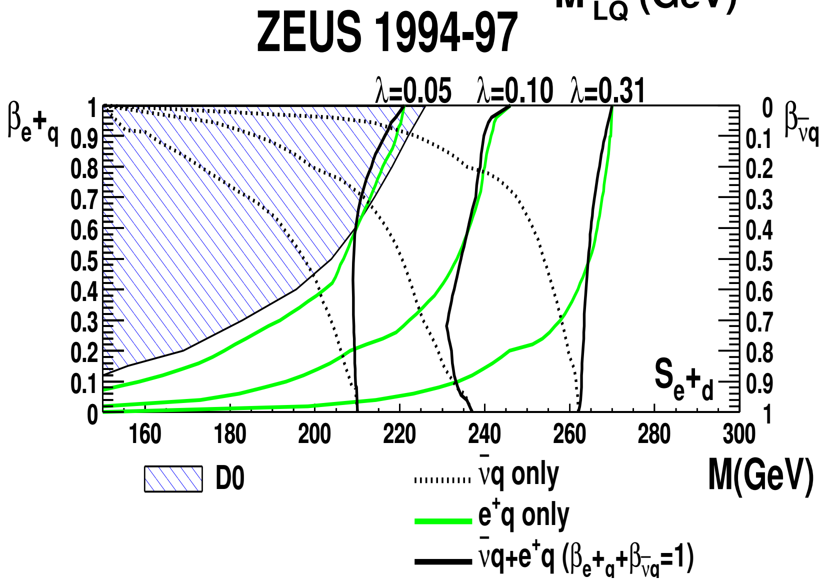
Leptoquarks

General LQ model

β free

$\Rightarrow$ study β vs M$_{LQ}$
for fixed λ





NC and CC
combined

$\Rightarrow$ limits on M$_{LQ}$
independent on β

$\beta_{eq} + \beta_{\nu q} \equiv 1$

Production of Squarks

Minimal Supersymmetric Standard Model (MSSM):

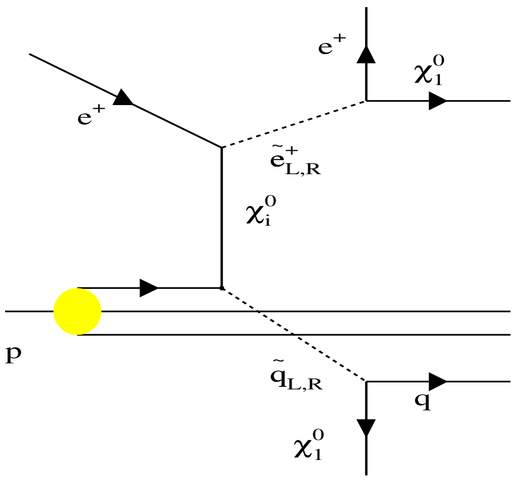
- **R-parity:** $R_p = (-1)^{3B+L+2S}$ **(= 1,-1 for particles , sparticles)**
- R_p**-conservation** $\Rightarrow$ **associated $\tilde{e}\tilde{q}$-production**

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

LSP=χ_1^0 stable $\Rightarrow$ undetected

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

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



R-parity violating $(\not{R}_p)$ SUSY:

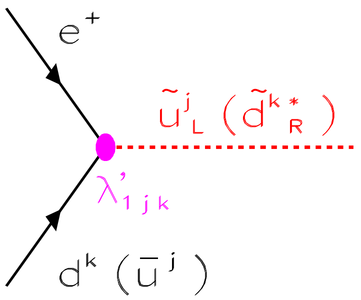
$\not{R}_p$ part of SUSY superpotential

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

$$\hookrightarrow \not{L}$$

- **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 :**

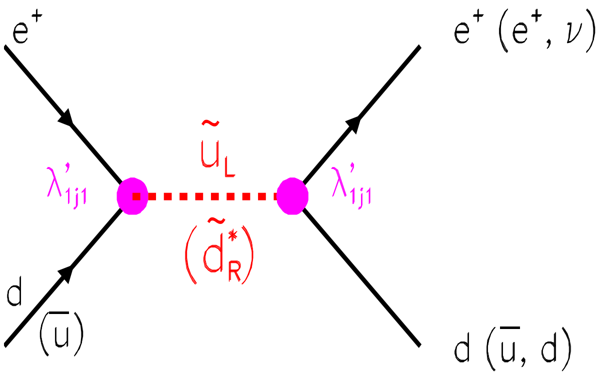
$$e^+ d \rightarrow \tilde{u}_L, \tilde{c}_L, \tilde{t}_L$$

Cross section :

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

Squark Decays

$R\!\!\!/_p$ Decays (Leptoquark-like):

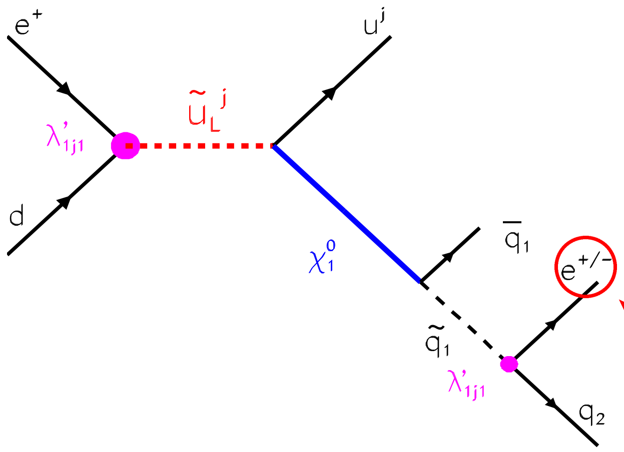


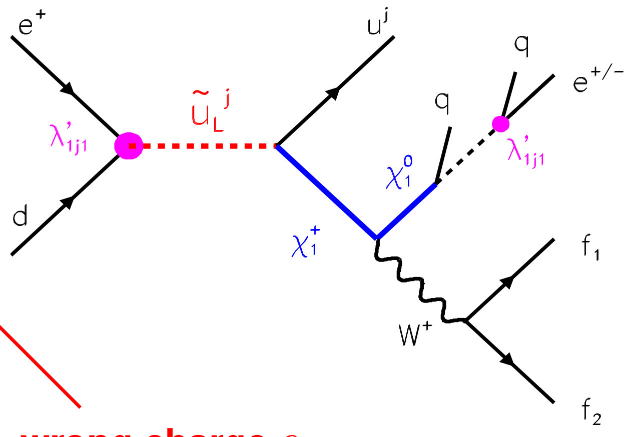
Signature :

High P_T e (ν) + jet

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

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





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

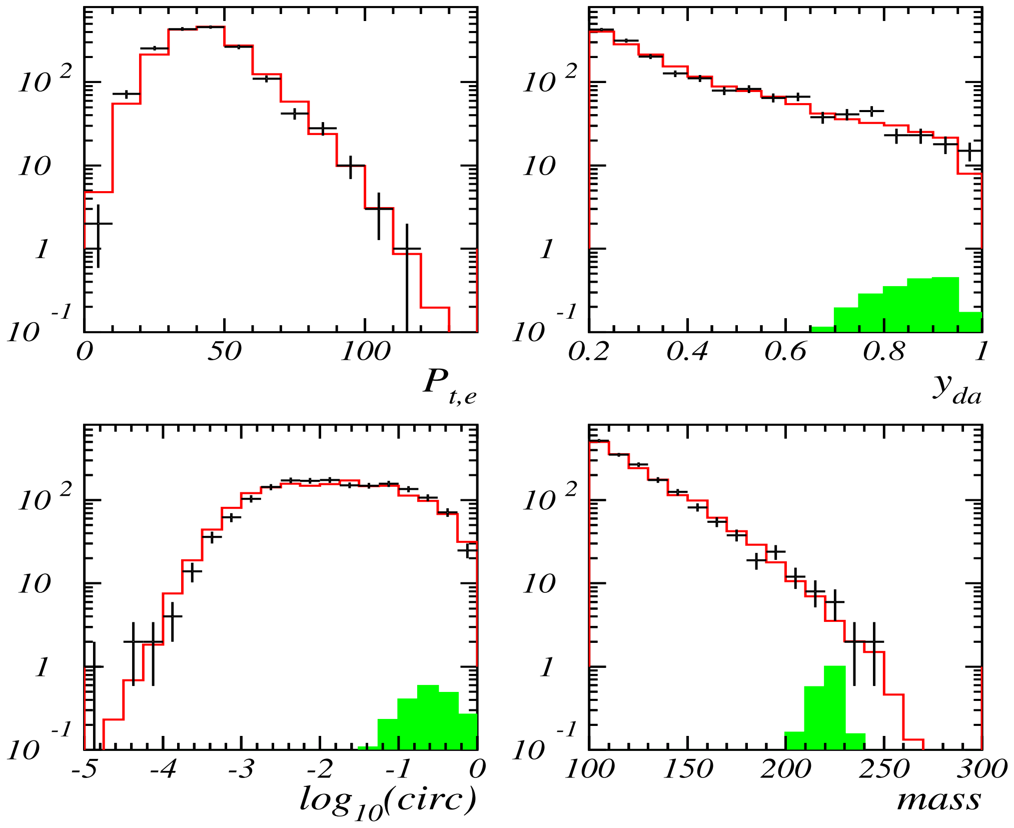
The analyses cover $\sim$ 100 % of the $\tilde{q}$ decay modes

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

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

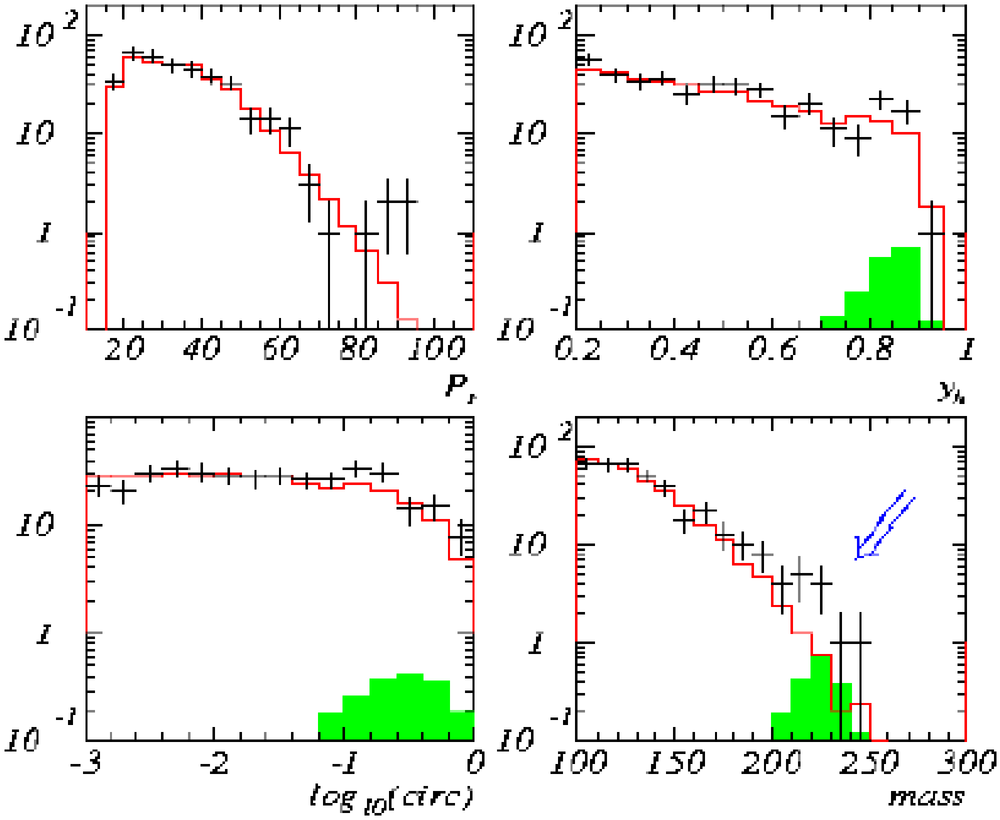
- **Good agreement with SM expectation**
- **No wrong-charge electron event found by ZEUS and H1 !**

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

Main preselection cuts:

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

$\mathbf{M} > 100$ GeV



Observed data events: 377

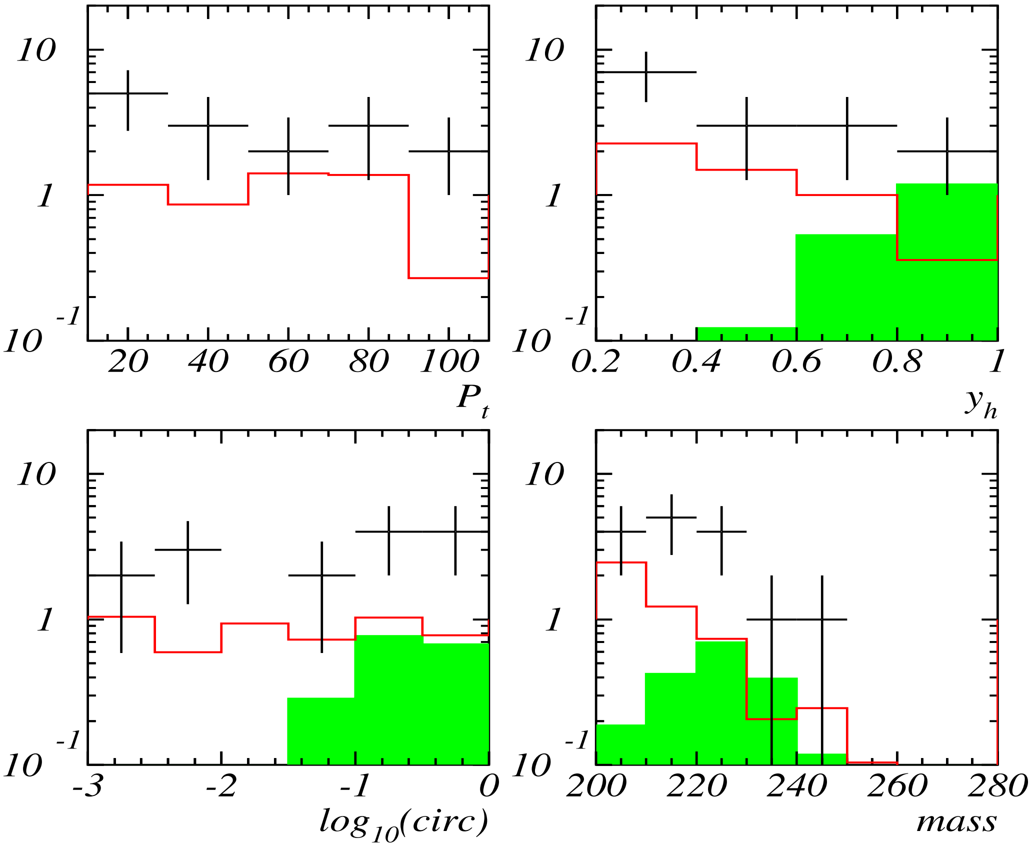
Total SM expectation: 352

Hypothetical signal of a 220 GeV squark

Slight excess at $\mathbf{M} > 200$ 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

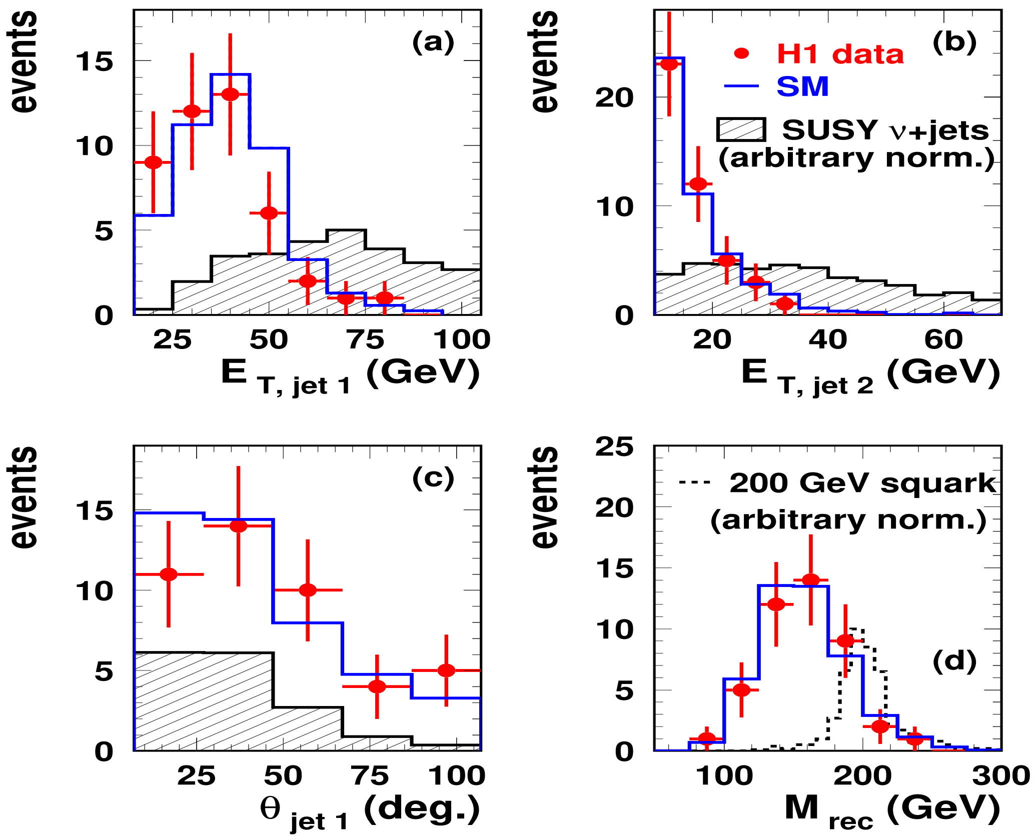
- **Excess <u>not</u> confined to signal region in y_h and circularity**
- **Reasons for this excess under investigation**

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 , $\theta_{jet1} > 10°$

- 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

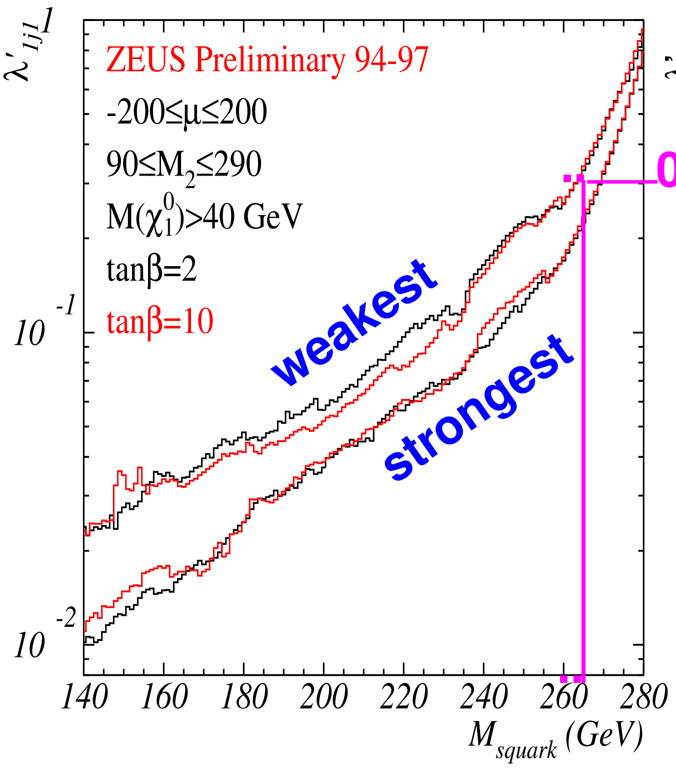
Results in the Unconstrained MSSM

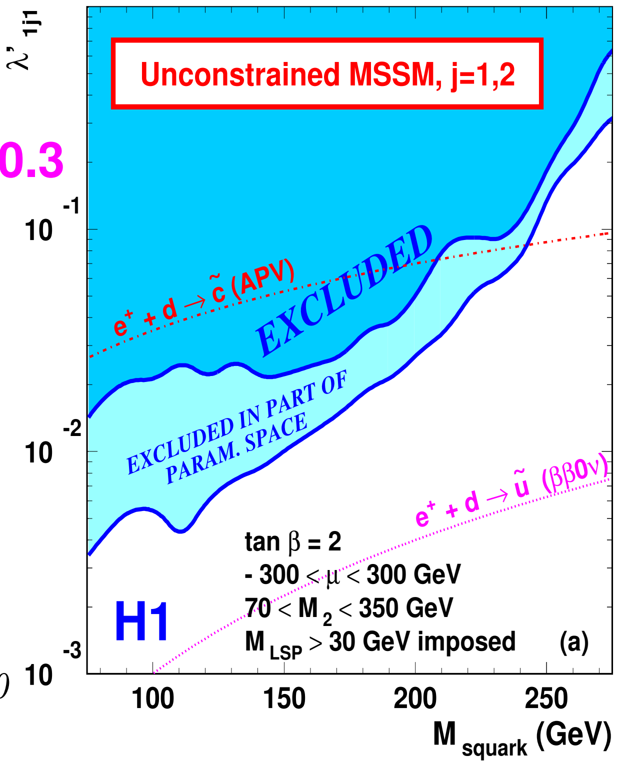
Unconstrained (phenomenological) MSSM:

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**





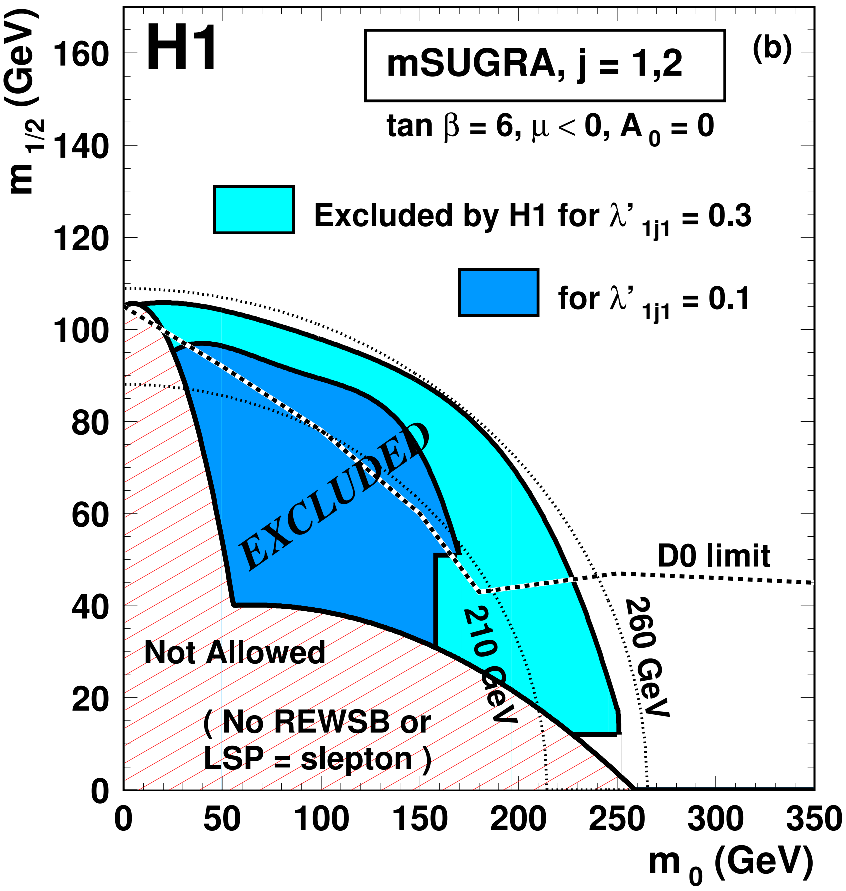
- **Limits are widely model independent**
- $\lambda'_{1j1} = 0.3$ **(em. strength)** $\rightarrow$ **masses** $M_{\tilde{q}}$ **up to 260 GeV can be ruled out**
- **For $\tilde{c}$ (and $\tilde{t}$) production HERA limits better than indirect bounds from low energy experiments**

Results in Constrained MSSM Models (1)

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

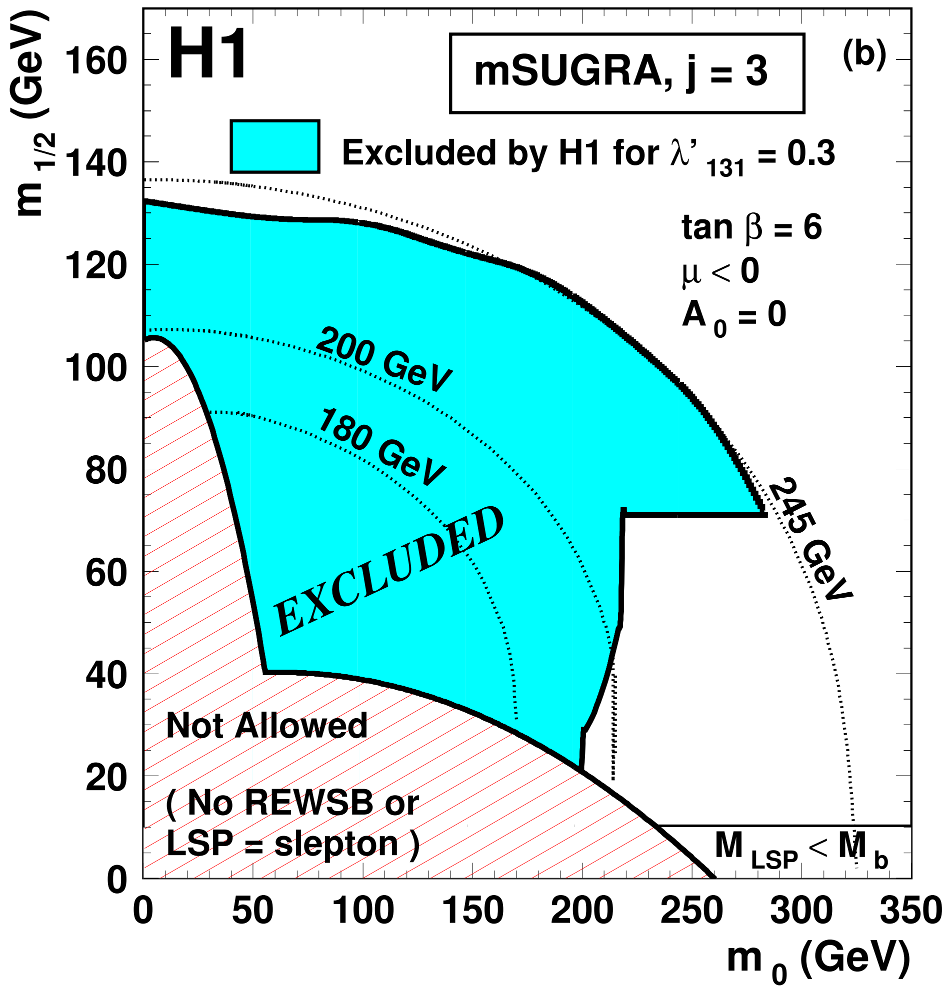
  Assume in addition that electroweak symmetry breaking driven by radiative corrections

  $\Rightarrow$ 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

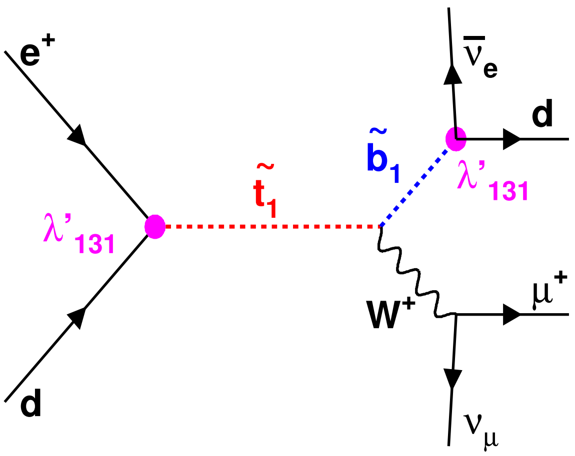
Results in Constrained MSSM Models (2)



- 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

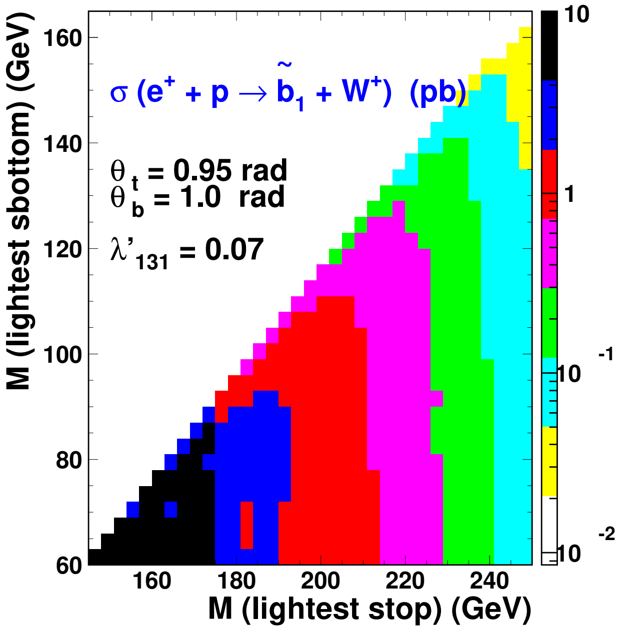


Possible $R\!\!\!/_p$ $\tilde{b}$ decay:
$\tilde{b} \rightarrow \nu d$
[T.Kon, Mod.Phys.Lett.A12(1997)]

Limit on coupling:

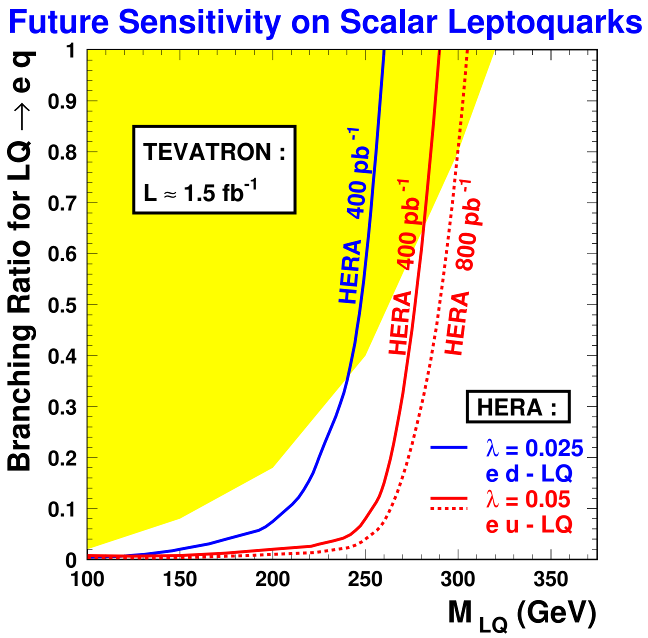
$\lambda'_{131} < 0.07$ (APV)
at $M_{\tilde{t}_1} = 200$ GeV
$\Rightarrow$ expect $\sim$ 100 events $\tilde{t} \rightarrow \tilde{b}W$
$\Rightarrow$ a few events in leptonic channel

ℓ + jet + p_T^{miss}



$\Rightarrow$ Dedicated stop analysis in under way !

Future sensitivities on 1st generation LQs



- Tevatron RunIIa (2 fb^{-1}) : probe large masses for large β_e independently of λ
- HERA better probes LQs with small β_e (need λ not too small)

$\Longrightarrow$ complementarity of both facilities

After 2004 : Tevatron $\rightarrow \sim$ 400 GeV with 10 fb^{-1}

At HERA : e^+ / e^- + polarisation could help in disentangling the LQ types

in BRW model :
NC + CC brings additional information

	$S_{0,L}$	$S_{1,L}$	$\tilde{S}_{0,R}$	$S_{0,R}$	$S_{1/2,L}$	$\tilde{S}_{1/2,L}$	$S_{1/2,R}$
$S_{0,L}$		β_ν	P_e	P_e			
$S_{1,L}$	β_ν		P_e	P_e		e^+/e^-	
$\tilde{S}_{0,R}$	P_e	P_e		P_p			
$S_{0,R}$	P_e	P_e	P_p				
$S_{1/2,L}$						P_p	P_e
$\tilde{S}_{1/2,L}$			e^+/e^-		P_p		P_e
$S_{1/2,R}$					P_e	P_e	

Summary

- 200 pb^{-1} of $e^{\pm}p$ data colleced at HERA
- Sensitivity at HERA is high
  Searches at HERA are complimentary to TEVATRON and LEP
- No evidence for new physics found
- ...mystery of isolated lepton events
  (see L.Bellagam talk)
- HERA upgrade.
  about 1 fb^{-1}/detector by 2005

keep searching at HERA