Beyond the Standard Model

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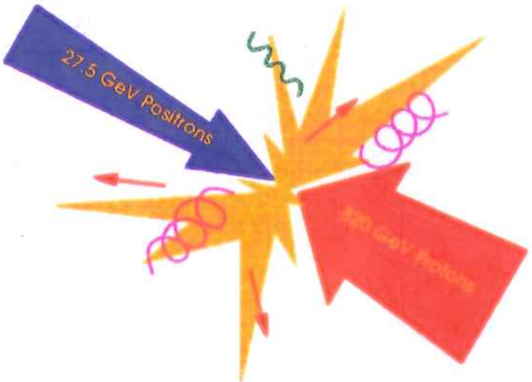
for

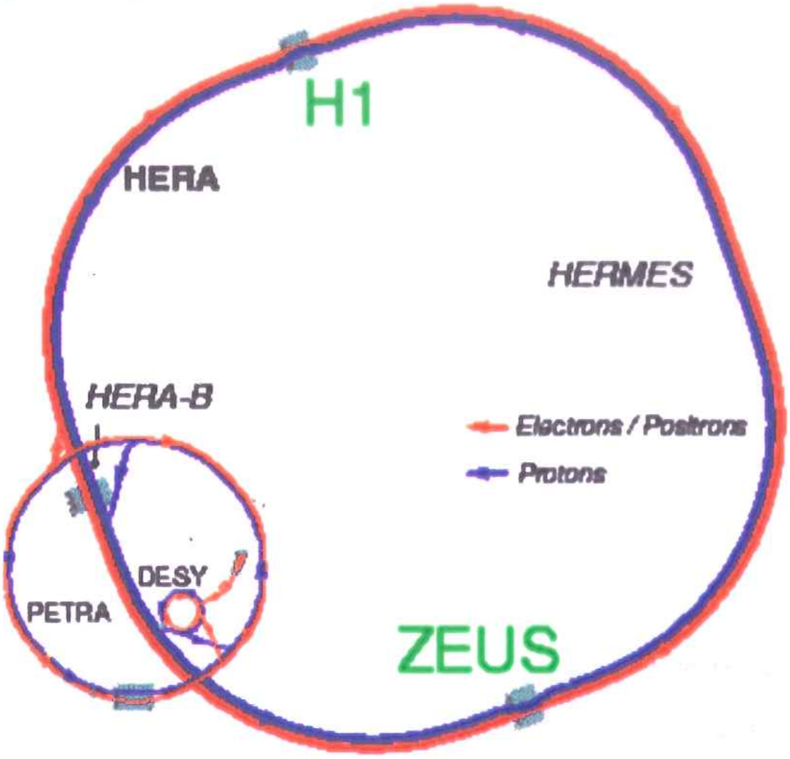
H1 & ZEUS

Contents

HERA

HERA is the unique e-p collider in the world

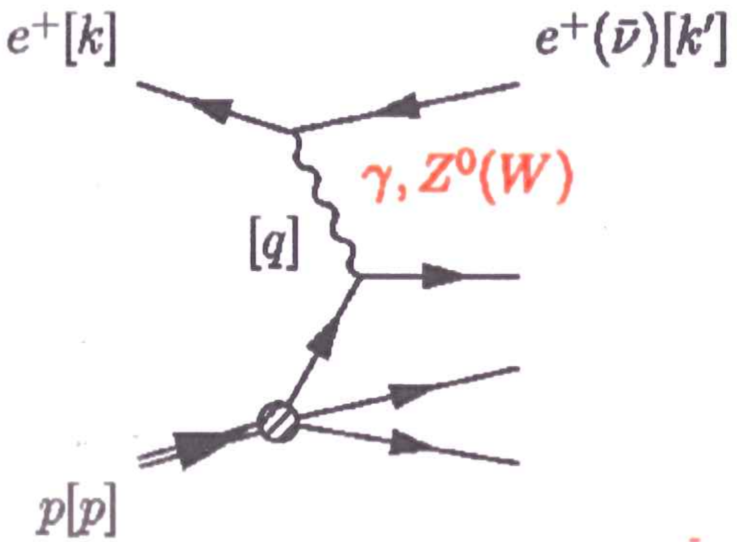




Running conditions

year	e^+/e^-	$E_e \times E_p$ ($\sqrt{s}$) (GeV)	$\mathcal{L}(pb^{-1})$
1993	e^-	26.7×820 ($\simeq 300$)	0.5
1994-1997	e^+	27.5×820 ($\simeq 300$)	37 (H1) 47 (ZEUS)
1998-1999	e^-	27.5×920 ($\simeq 320$)	$\simeq 14$

HERA ep kinematics



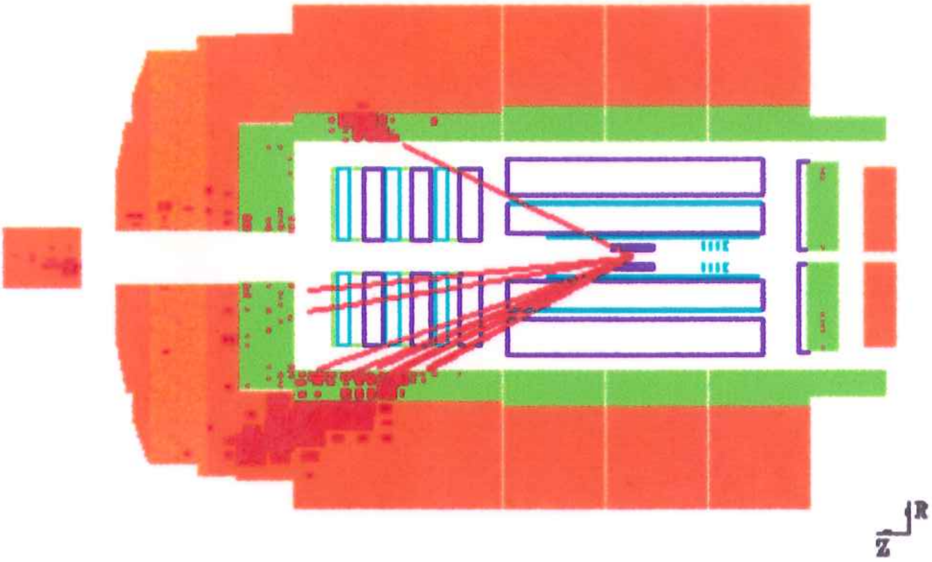
$$Q^2 = -(k - k')^2 = sxy$$

$$x = \frac{Q^2}{2(p.q)} \Rightarrow M = \sqrt{sx}$$

$$y = \frac{p.q}{p.k} = \frac{1+\cos\theta_e^*}{2}$$

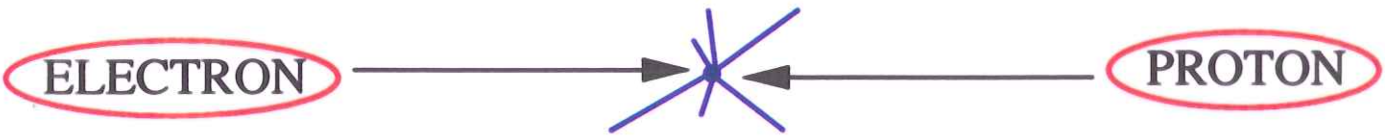
H1 and ZEUS

The main subdetectors of both experiments are the calorimeters



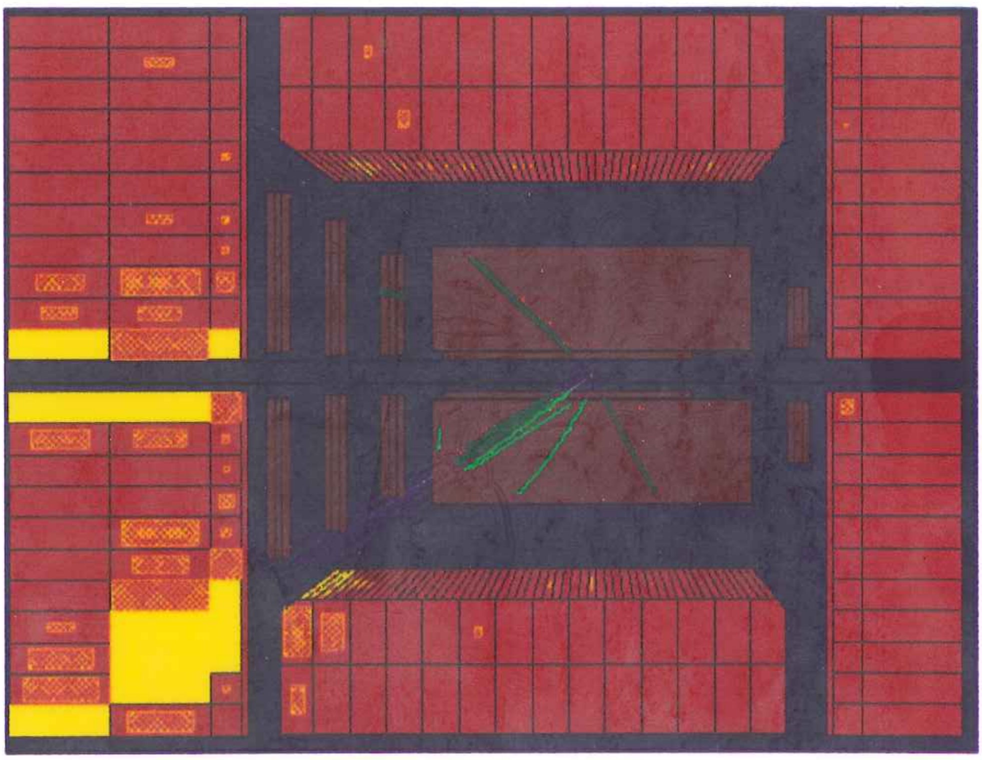
H1 calorimeter

Calo	Liq. Ar
Cells (10^3)	44
σ_θ(mrad)	2-5
$\frac{\sigma_E}{\sqrt{E}}$ (Emg)	12%
$\frac{\sigma_E}{\sqrt{E}}$ (Had)	50%
$\frac{\Delta E}{E}$ (%)	1-3



ZEUS calorimeter

Calo	Uran. Sc.
Cells (10^3)	6
σ_θ(mrad)	3
$\frac{\sigma_E}{\sqrt{E}}$ (Emg)	18%
$\frac{\sigma_E}{\sqrt{E}}$ (Had)	35%
$\frac{\Delta E}{E}$ (%)	1-3

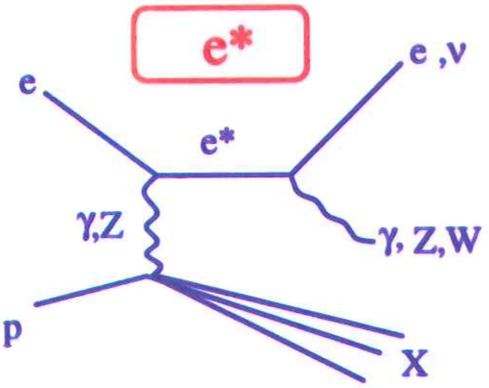


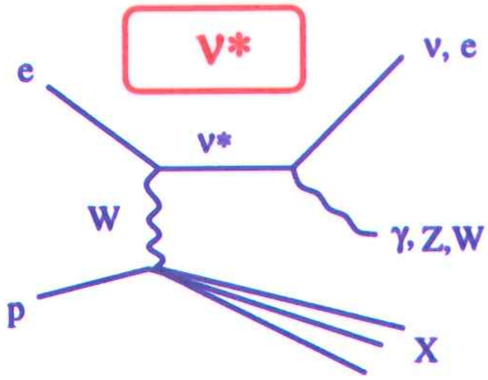
Excited fermions (1)

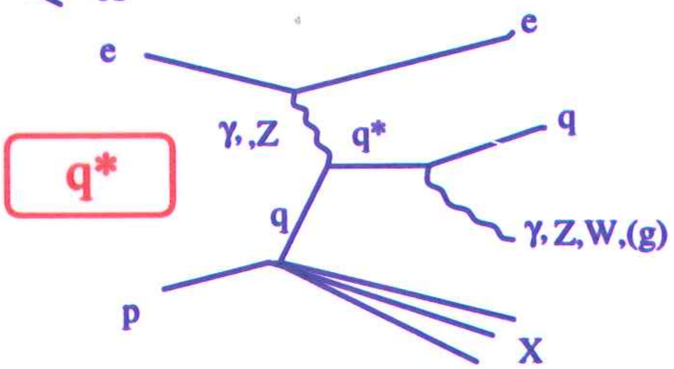
Discovery of excited fermions → Substructure

At HERA search for excited leptons and quarks via a search of resonance production in hard ep scattering

$$e + P \rightarrow f^* + X$$
$$\quad\quad\quad\quad\quad \hookrightarrow f + \gamma,\ Z^0, W$$







The search is based on the Hagiwara-Komamiya-Zeppenfeld model

The excited fermions are L/R weak isodoublets and have spin 1/2

Lagrangian :

$$\mathcal{L} = \frac{1}{\Lambda} \bar{f}^*_R \left[f\,SU(2)_L + f'\,U(1)_Y + f_S\,SU(3)_C \right] f_L$$

Where : - f, f' and fs are the coupling constants of gauge groups

- Λ the compositeness scale ($f/\Lambda = 1/M_{f^*}$)

Assuming : f = f' for e* production (SU(2) and U(1) decays equally)

f = -f' for ν* radiative decays ($\nu^* \rightarrow \nu\gamma$)

fs = 0 for q* production via e/w couplings

Excited fermions (2)

The following decay modes were studied :

f^*	Decay mode	final state	signature
e^*	$e\gamma$	$e\gamma$	2 e.m. clusters
	eZ	eee	3 e.m. clusters
		$e\nu\nu$	e.m. cluster + track, P_t^{miss}
		eqq	e.m. cluster, large E_t^{had} and M^{had}
	νW	$e\nu\nu$	e.m. cluster + track, P_t^{miss}
		νqq	P_t^{miss}, large E_t^{had} and M^{had}
ν^*	$\nu\gamma$	$\nu\gamma$	e.m. cluster and P_t^{miss}
	νZ	νqq	P_t^{miss}, large E_t^{had} and M^{had}
		$ee\nu$	2 e.m. clusters and P_t^{miss}
		$\nu\nu\bar{\nu}$	not considered
	eW	eqq	e.m. cluster, large E_t^{had} and M^{had}
		$ee\nu$	2 e.m. clusters and P_t^{miss}
q^*	$q\gamma$	$q\gamma$	e.m. cluster, large E_t^{had}
	qW	$qe\nu$	P_t^{miss}, e.m. cluster and large E_t^{had}
		$qq\bar{q}$	not considered
	qZ	not considered	
	qg	small Br assumed ($f_s = 0$)	

For all the channels look for high Pt objects (electrons, jets) or high missing Pt

As an example of the analyzed channels the $e^* \longrightarrow e\,\gamma$

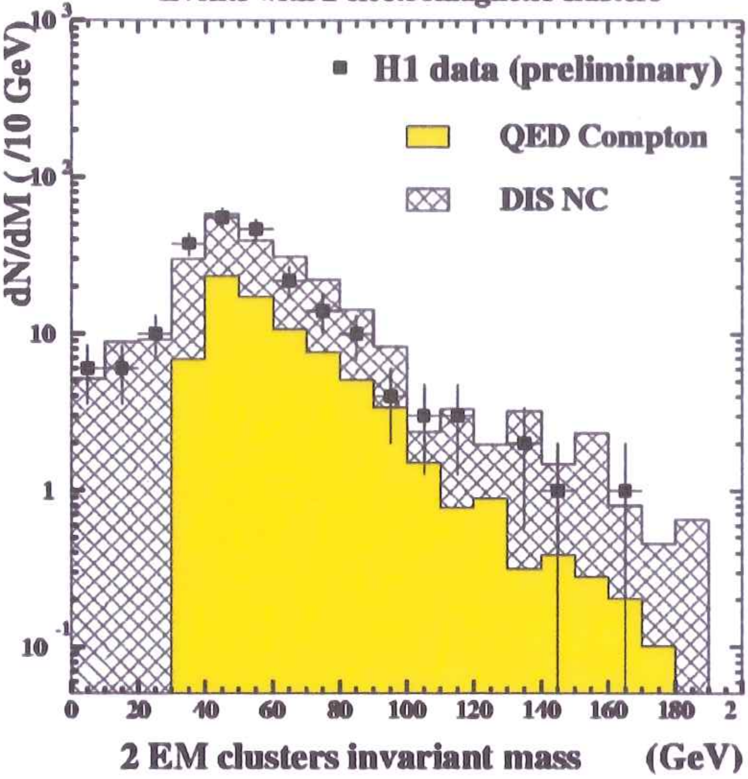
Look for high Et electromagnetic clusters.

The main background is QED Compton and NC DIS

Analysis	$M(e^*)$ range (GeV)	efficiency (%)	# data events	# bckgd events
H1	25-250	27-79	223	239 ± 6
ZEUS	100-250	60-79	60	68 ± 2

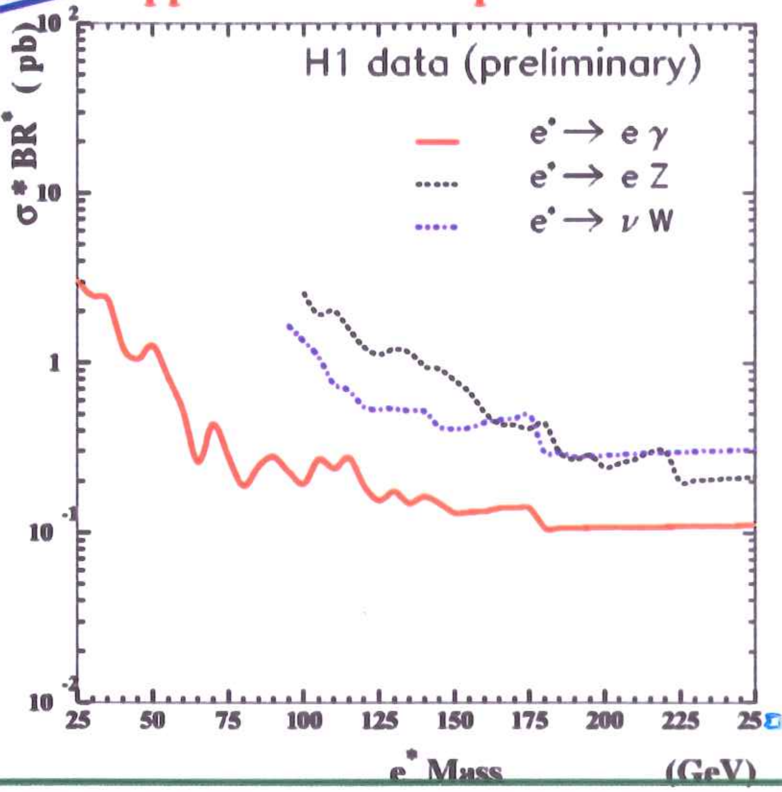
Excited fermions (3)

Events with 2 electromagnetic clusters



For all the other channels the observed number of events is compatible with the background. Both experiments deduce no evidence of e*, ν* and q*

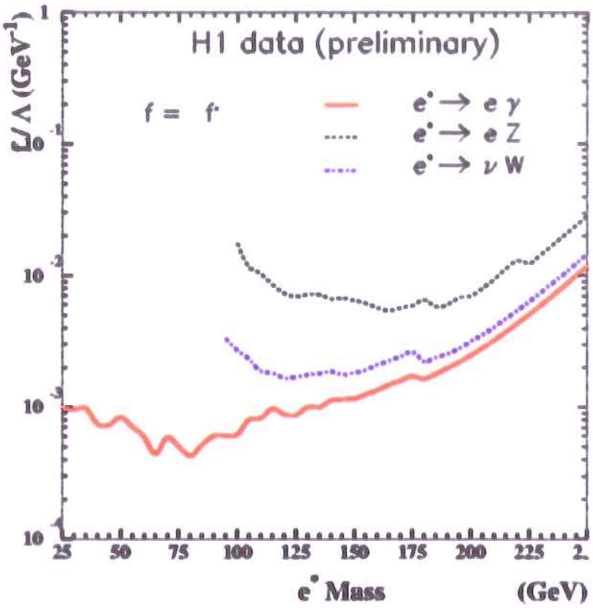
→ Upper limits on f* production cross sections



σ * Br (e* → e γ) < 0.1 Pb for M(e*) = 250 GeV

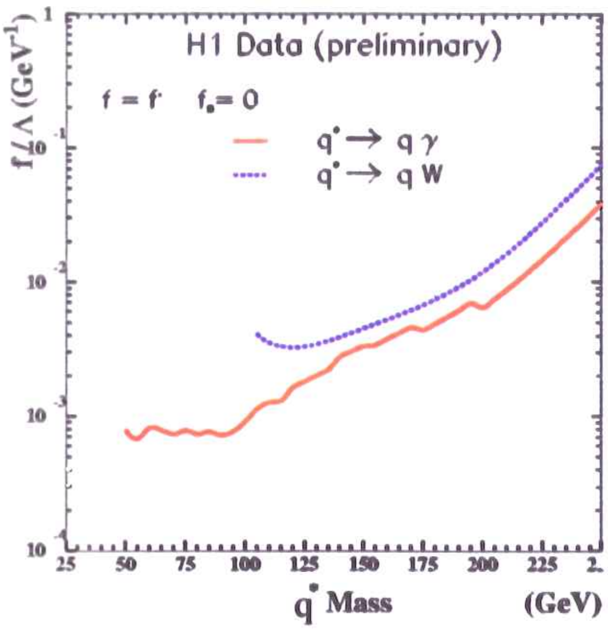
Excited fermions (4)

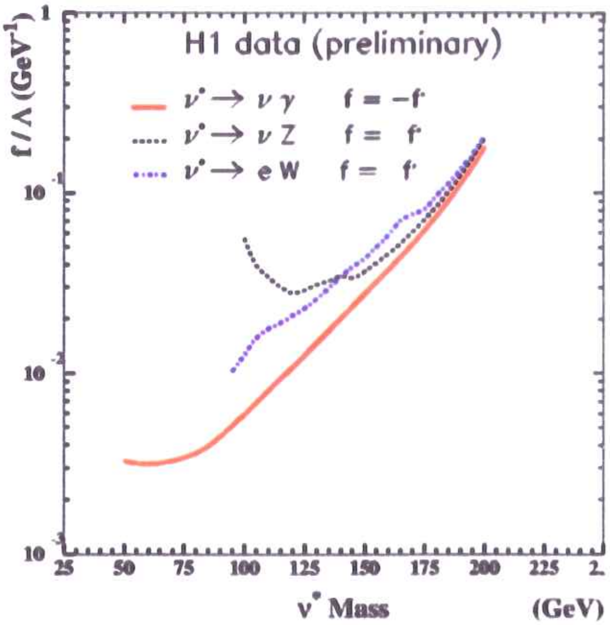
$f/\Lambda < 0.6\ 10^{-3}$ – $1.0\ 10^{-2}$: excluded regions above the curves



if $f/\Lambda = 1/M(e^*)$ ⟶ $M(e^*) > 222$ GeV

As for e* the ν* and q* f/Λ upper limits are extracted (95% CL)





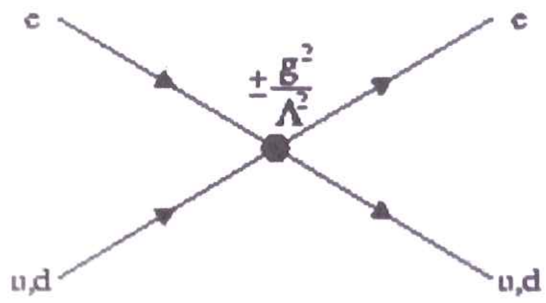
If $f/\Lambda > 0.08\ 10^{-2}$ to $1.9\ 10^{-2}$ (GeV^{-1})
60 < M(q*) (GeV) < 230 : excluded

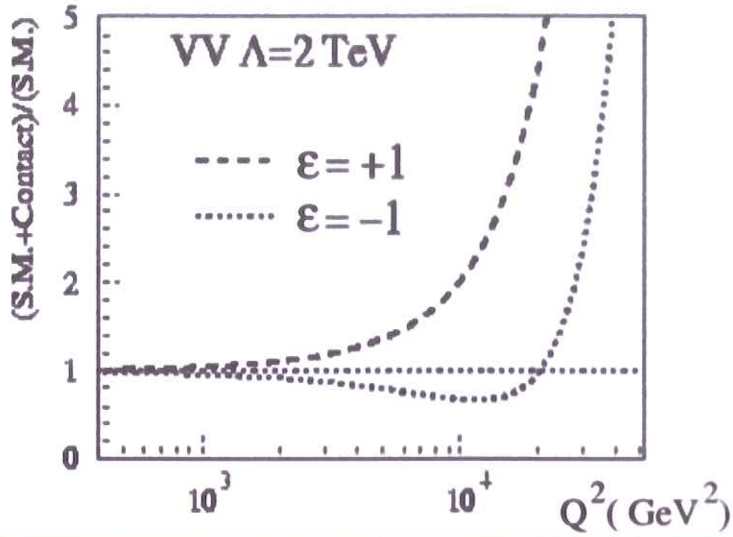
If $f/\Lambda > 0.3\ 10^{-2}$ to $9\ 10^{-2}$ (GeV^{-1})
60 < M(ν*) (GeV) < 180 : excluded

With $\Lambda = M(q^*)$ and $f = f' = fs = 1$, the Tevatron excludes $M(q^*) < 760$ GeV

Contact interactions (1)

Interactions where the intermediate particles are heavier than the kinematical limit : M >> 300 GeV. Deviation from SM to be observed via distortions of the Q^2 distributions at high Q^2.





$$\mathcal{L}_{CI} = \frac{g^2}{\Lambda^2}\left[\sum_{q=u,d}^{ab=L,R} \epsilon^q_{ab}(\bar{e}_a\gamma^\mu e_a)(\bar{q}_b\gamma_\mu q_b)\right], \quad (\epsilon^q_{ab} = \pm 1, 0 \; g^2 = 4\pi)$$

Only vector terms considered. Strong limits beyond HERA sensitivity exclude scalar and tensor terms.

Atomic parity violation + SU(2) invariance : 30 CI scenarios

CI type	ϵ^u_{LL}	ϵ^u_{LR}	ϵ^u_{RL}	ϵ^u_{RR}	ϵ^d_{LL}	ϵ^d_{LR}	ϵ^d_{RL}	ϵ^d_{RR}
VV	+	+	+	+	+	+	+	+
AA	+	-	-	+	+	-	-	+
VA	+	-	+	-	+	-	+	-
X1	+	-	0	0	+	-	0	0
X2	+	0	+	0	+	0	+	0
X3	+	0	0	+	+	0	0	+
X4	0	+	+	0	0	+	+	0
X5	0	+	0	+	0	+	0	+
X6	0	0	+	-	0	0	+	-
U1	+	-	0	0	0	0	0	0
U2	+	0	+	0	0	0	0	0
U3	+	0	0	+	0	0	0	0
U4	0	+	+	0	0	0	0	0
U5	0	+	0	+	0	0	0	0
U6	0	0	+	-	0	0	0	0

Contact interactions (2)

$\Lambda(^{+}_{-})$ values obtained by fitting the NC data with MC (SM+CI) .

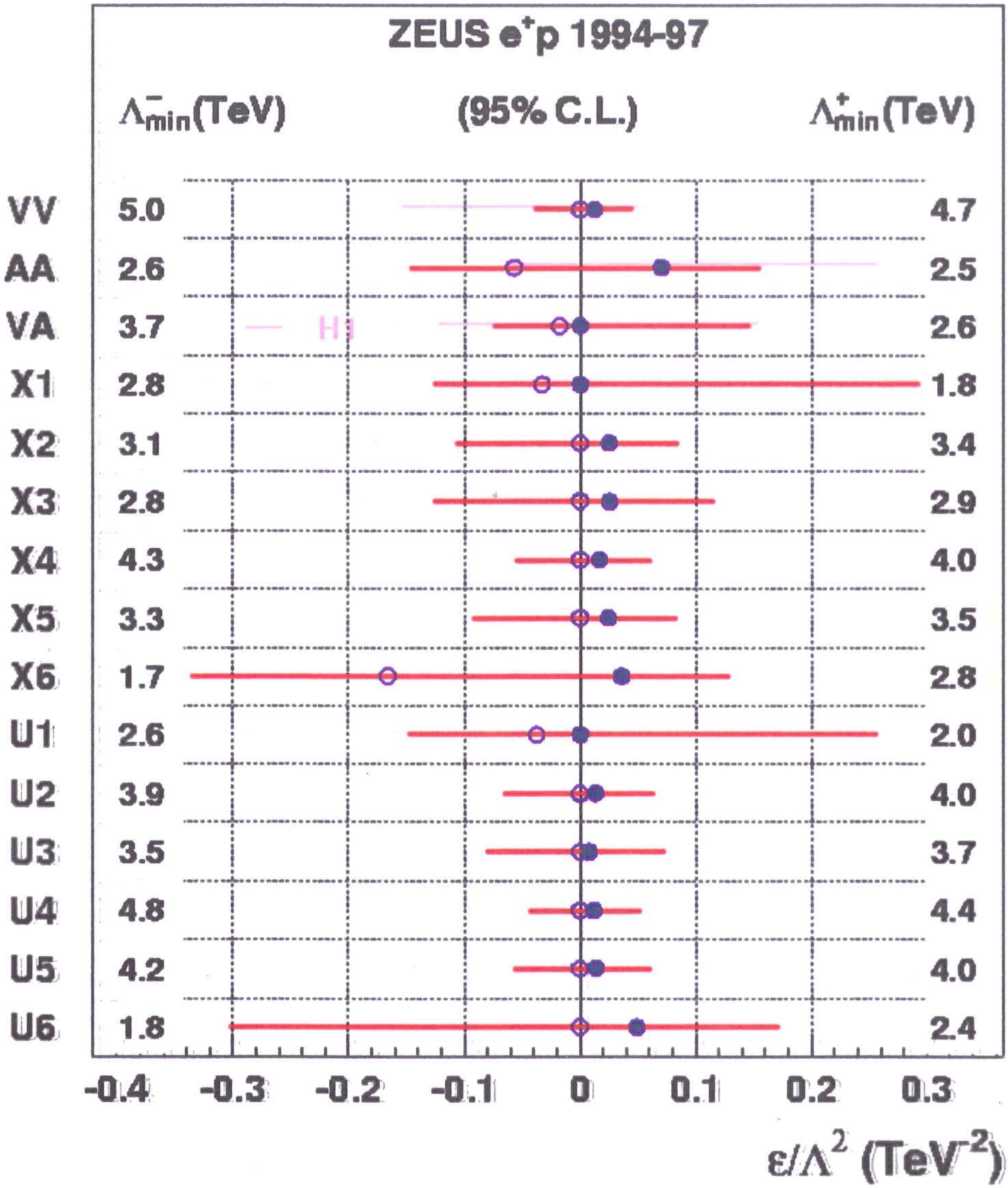
CI type	Λ ranges (TeV) at 95% CL						
	ZEUS	H1 (prel)	CDF	D0	ALEPH (prel)	L3 (prel)	OPAL
VV +	4.7	4.5	3.5	4.9	6.7	3.8	4.1
VV -	⇒ 5.0	2.5	5.2	6.1	7.4	5.0	5.7
AA +	2.6	2.0	3.8	4.7	7.4	5.6	6.3
AA -	3.7	3.8	4.8	5.5	8.2	3.5	3.8
VA +	2.8	2.6	-	-	-	-	-
VA -	2.8	2.8	-	-	-	-	-
X1 +	1.8	-	-	3.9	-	-	-
X1 -	2.8	-	-	4.5	-	-	-
X2 +	3.4	-	-	-	-	-	-
X2 -	3.1	-	-	-	-	-	-
X3 +	2.9	-	-	4.2	6.9	4.0	4.4
X3 -	2.8	-	-	5.1	7.7	3.4	3.8
X4 +	4.0	-	-	3.9	2.9	2.9	3.1
X4 -	4.3	-	-	4.4	4.5	4.8	5.5
X5 +	3.5	-	-	-	-	-	-
X5 -	3.3	-	-	-	-	-	-
X6 +	2.8	-	-	4.0	-	-	-
X6 -	⇒ 1.7	-	-	4.3	-	-	-
U1 +	2.0	-	-	-	-	-	-
U1 -	2.6	-	-	-	-	-	-
U2 +	4.0	-	-	-	-	-	-
U2 -	3.9	-	-	-	-	-	-
U3 +	3.7	-	-	-	-	6.1	4.1
U3 -	3.5	-	-	-	-	4.9	5.8
U4 +	4.4	-	-	-	-	2.1	2.3
U4 -	4.8	-	-	-	-	2.9	3.2
U5 +	4.0	-	-	-	-	-	-
U5 -	4.2	-	-	-	-	-	-
U6 +	2.4	-	-	-	-	-	-
U6 -	1.8	-	-	-	-	-	-

X2,X5,U1,U2,U5 and U6 done only by ZEUS

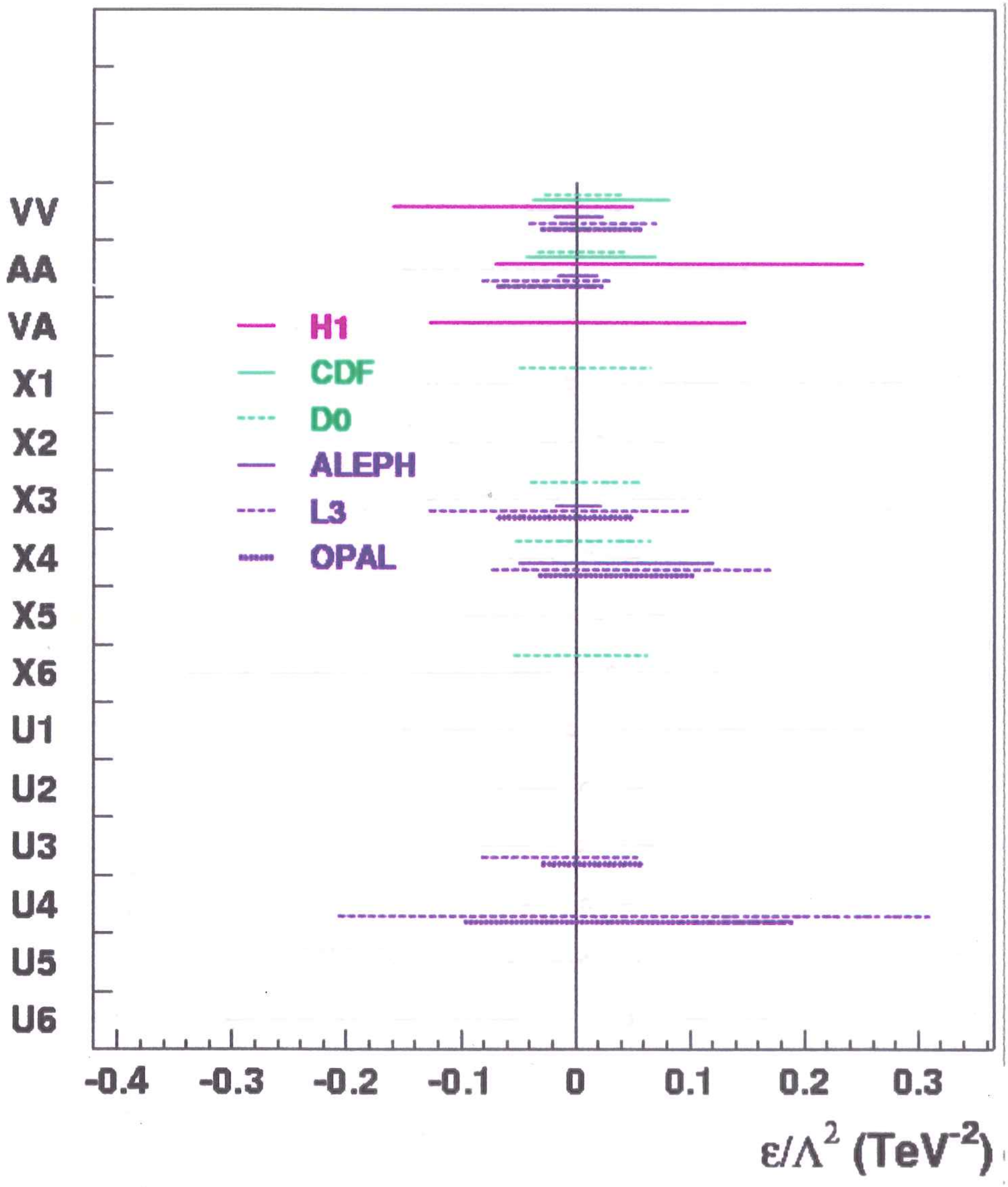
No indication for existence of contact interactions

Mass scale range is 1.7 to 5. Tev

Contact interactions (3)



Contact interactions (3)



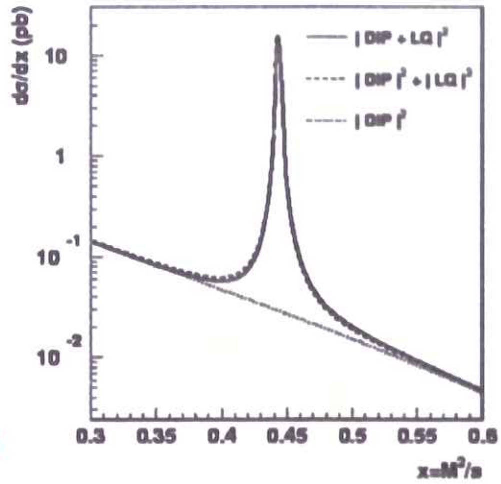
Leptoquarks (1)

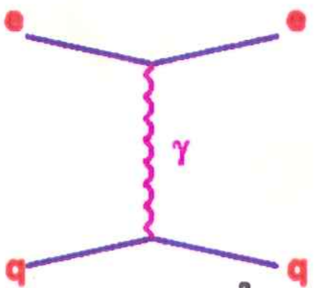
Leptoquarks : Bosons (scalars (S) and vectors (V)) coupling lepton-quark pairs. Appear in GU Theories, Superstring E6 models and in compositeness.

Such events are indistinguishible from NC/CC HERA events.

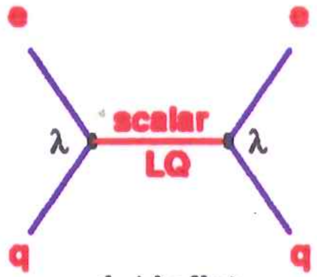
But the $d\sigma / dx$ distribution must present a narrow resonance at

$$x = M_{LQ}^2 / s$$





$d\sigma/dy$ in $1/y^2$



$d\sigma/dy$ flat

Distinguish processes either by optimizing a y cut $y > y_{cut}(M)$

Or by angular distributions given : $y = 1/2(1+\cos\theta^*)$

Use of the Buchmüller-Rückl-Wyler model (fixed branching ratio β)

F = 2	prod/decay	β	F = 0	prod/decay	β
${}^{-1/3}S_0^*$	$e_R^+\bar{u}_R \rightarrow e^+\bar{u}$	1/2	${}^{-5/3}S_{1/2}^*$	$e_L^+u_L \rightarrow e^+u$	1
	$\rightarrow \bar{\nu}_e\bar{d}$	1/2		$e_R^+u_R \rightarrow e^+u$	1
	$e_L^+\bar{u}_L \rightarrow e^+\bar{u}$	1	${}^{-2/3}S_{1/2}^*$	$e_L^+d_L \rightarrow e^+d$	1
${}^{-4/3}\tilde{S}_0^*$	$e_L^+\bar{d}_L \rightarrow e^+\bar{d}$	1	${}^{-2/3}\tilde{S}_{1/2}^*$	$e_R^+d_R \rightarrow e^+d$	1
${}^{-4/3}S_1^*$	$e_R^+\bar{d}_R \rightarrow e^+\bar{d}$	1			
${}^{-1/3}S_1^*$	$e_R^+\bar{u}_R \rightarrow e^+\bar{u}$	1/2			
	$\rightarrow \bar{\nu}_e\bar{d}$	1/2			

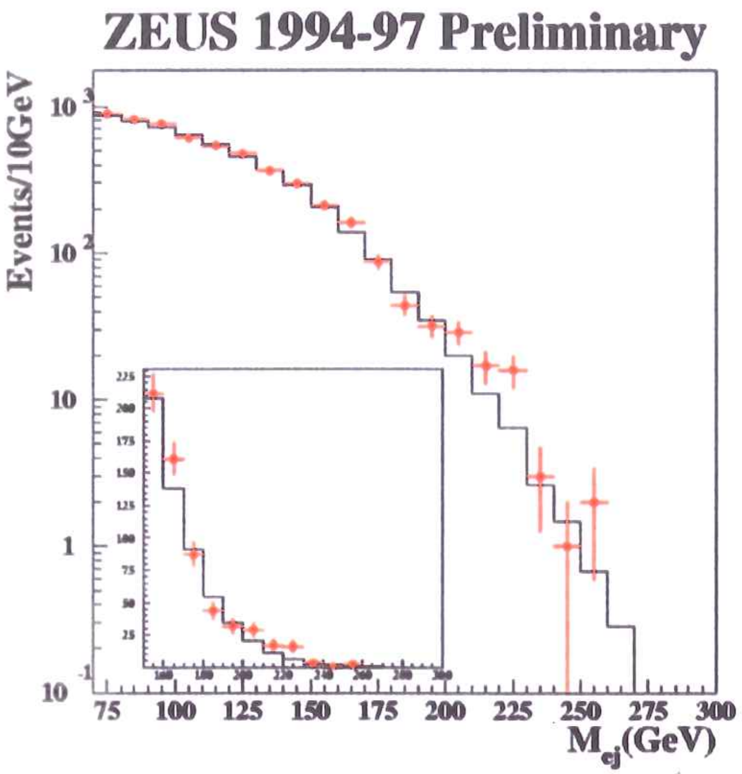
F = 3B + L

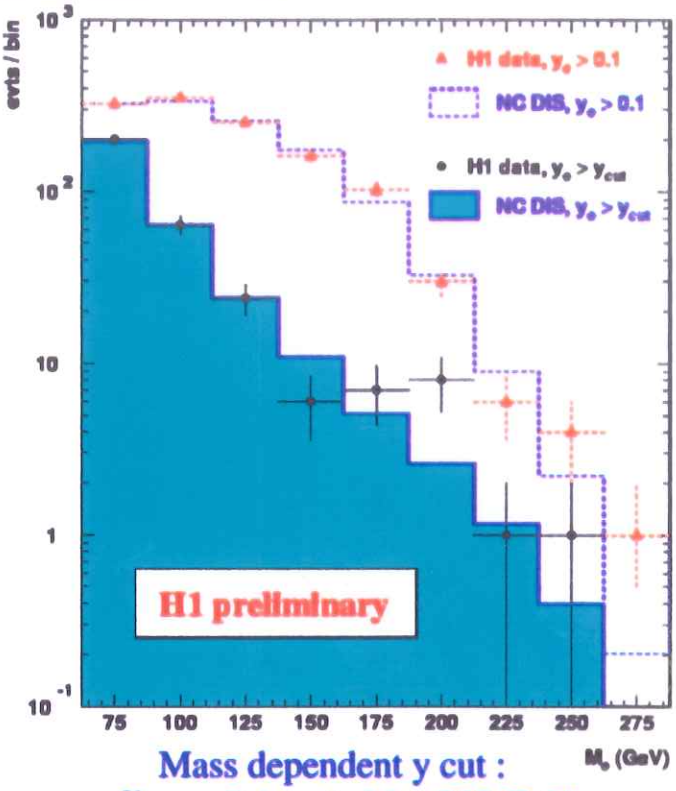
λ :Yukawa coupling

$$\sigma(eq \rightarrow LQ \rightarrow eq) \;\alpha\; \lambda^2 \beta\, q(x)$$

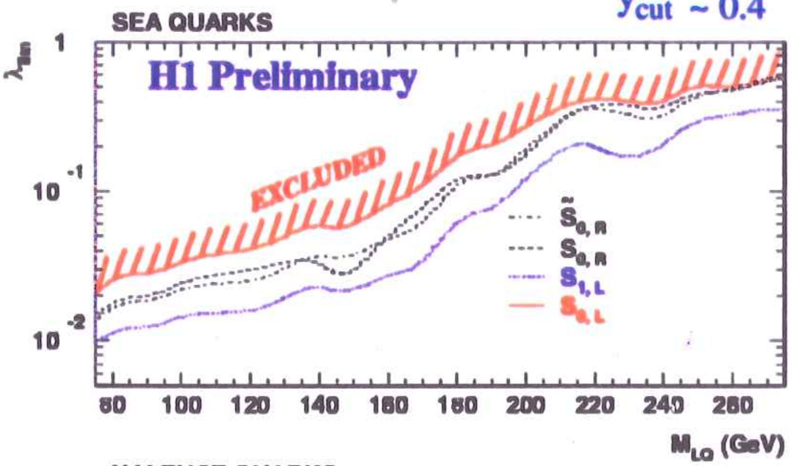
Constrain λ with a known β or fix λ and set constrains on β

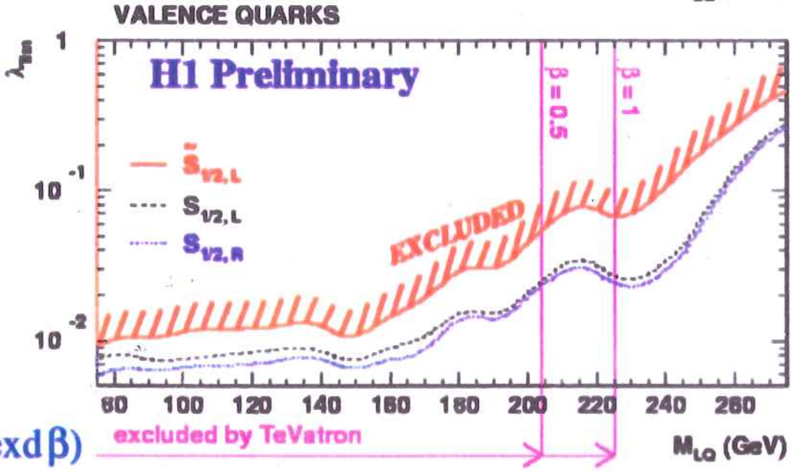
Leptoquarks (2)





Mass dependent y cut :
y_{cut} ~ 0.4 at M ~ 200 GeV





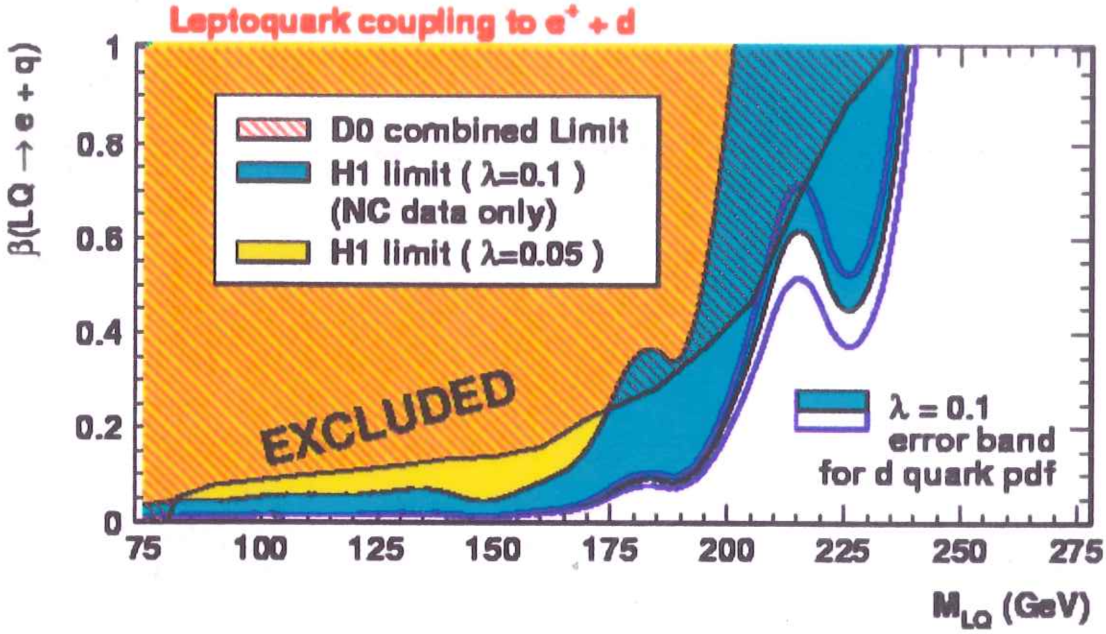
In BRW model (fiexd β)

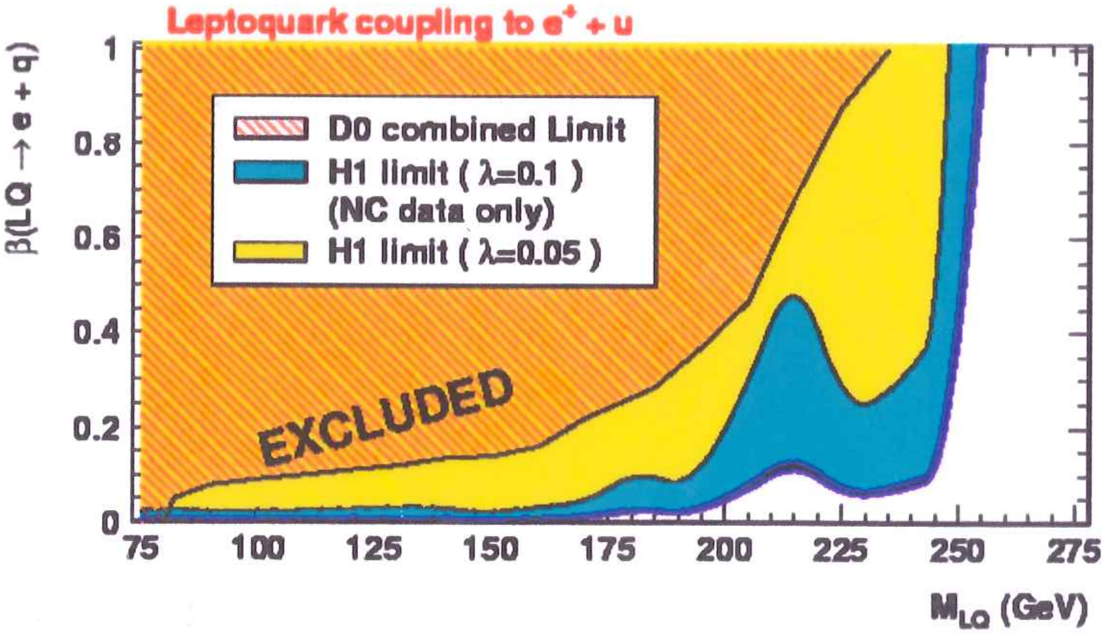
For $\lambda \simeq \sqrt{4\pi\alpha_{em}}$ $M_{LQ} > 200$ (255) GeV for F = 2 (0)

Leptoquarks (3)

Leptoquarks with free branching ratios : fix λ and constrain β

H1 Preliminary





Unexplored domain now covered by H1

Competition with TeVatron : $\lambda = 0.1$ corresponds to ~ 0.1 α_{em}

For even smaller λ, still high discovery potential for HERA

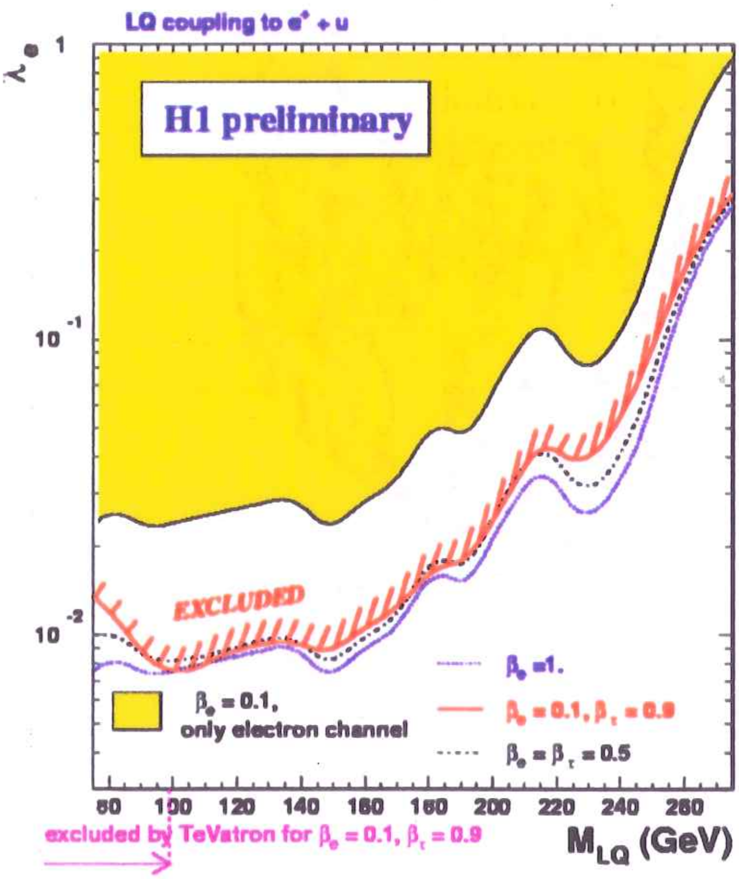
Provided that $\beta << 1$

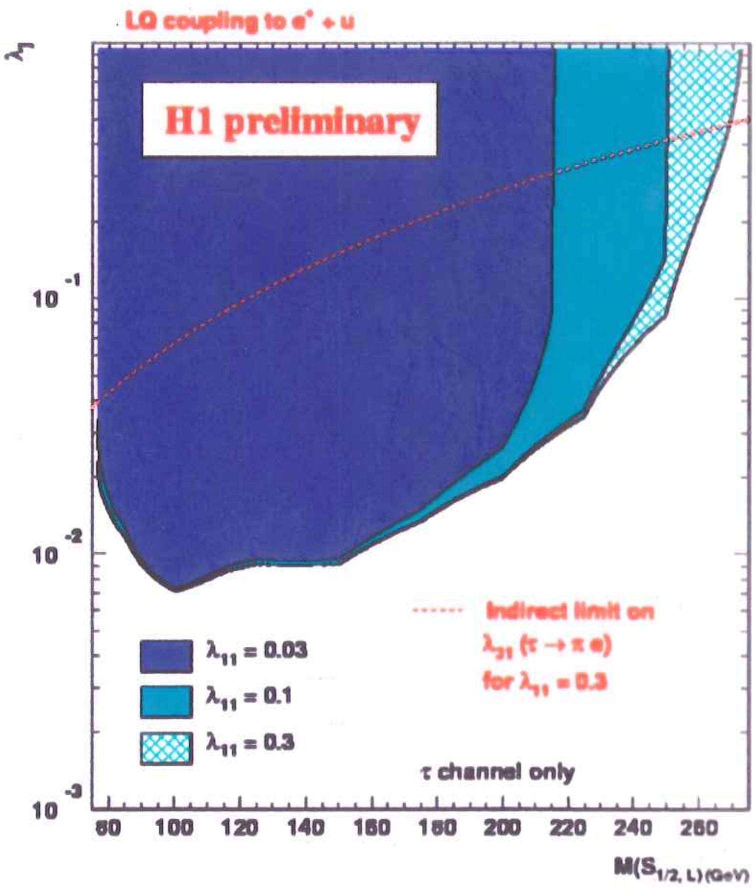
Leptoquarks (4)

Case where a scalar LQ decays by Lepton Flavour Violation :

LQ $\longrightarrow$ e + q (Branching ratio β_e) ($\beta_e + \beta_\tau < 1$)

LQ $\longrightarrow$ τ + q (Branching ratio β_τ)





For e.m. coupling strength ($\lambda = 0.3$) and $\beta_e = 0.1$

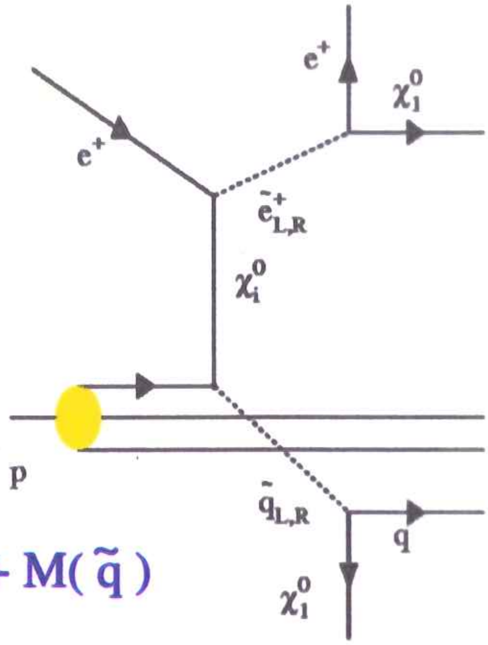
M_{LQ} below 255 (237) GeV are excluded for LQ coupling to e^+u (e^+d)

If $\beta_e \sim 0.1$ and β_τ high : High discovery potential at HERA

TeVatron limit < 100 GeV !!!

SUSY (1)

- The SUSY superpotential : $W_{SUSY} = W_{MSSM} + W_{R\!\!\!/p}$
- The R-parity : $R_P = (-1)^{3B+L+2S}$



MSSM : Conserving R-parity

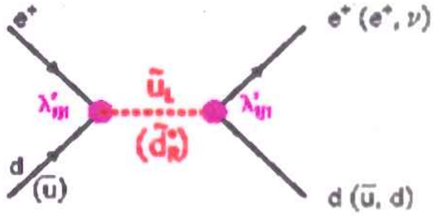
$$\tilde{e}\,(\tilde{q}) \longrightarrow e(q) + \chi_1^0$$

LSP = χ_1^0 stable and undetected

The cross section depends mainly on $M(\tilde{e}) + M(\tilde{q})$

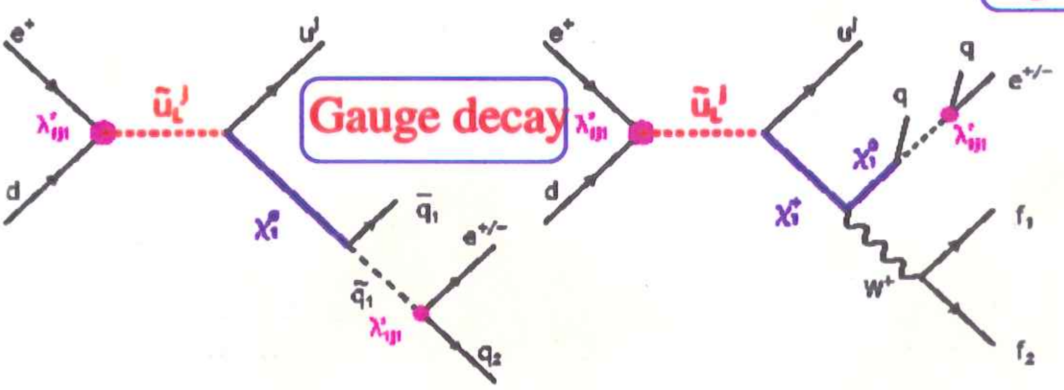
R- parity violation :

$$W_{R\!\!\!/p} = \lambda_{ijk}\, L_i L_j \bar{E}_k + \lambda'_{ijk}\, L_i Q_j \bar{D}_k + \lambda''_{ijk}\, U_i \bar{D}_j \bar{D}_k$$



Rp-violating decay

Single s-fermions production



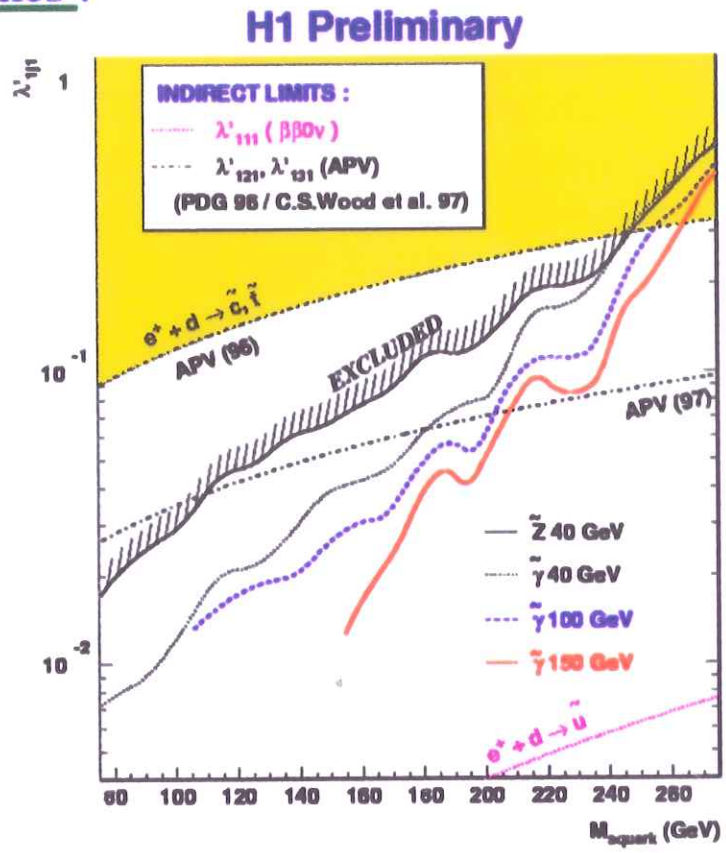
e^+ probe mainly the λ'_{1j1} couplings $\quad e^+ d \longrightarrow \tilde{u}_L, \tilde{c}_L, \tilde{t}_L$

$$\sigma\,(ep \longrightarrow \tilde{u}^j_L)\ \alpha\ \lambda'^2_{1j1}$$

SUSY (2)

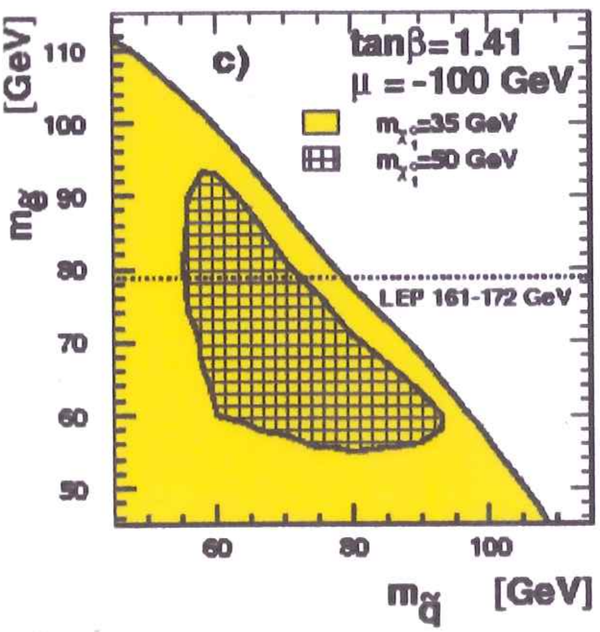
No evidence for squark production ⟶ Limits :

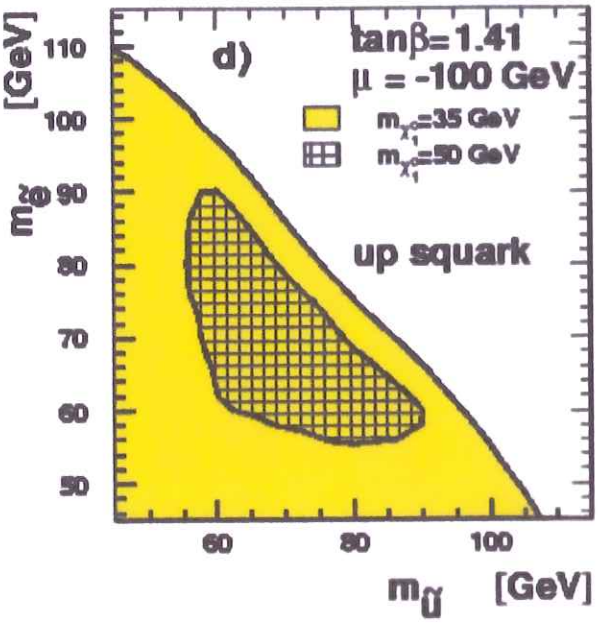
Rp violation searches :



$\lambda'_{1j1} < 0.2$ for $M(\tilde{q}) \sim 260$ GeV $\lambda'_{1j1} < 0.02$ for $M(\tilde{q}) \sim 160$ GeV

MSSM searches :

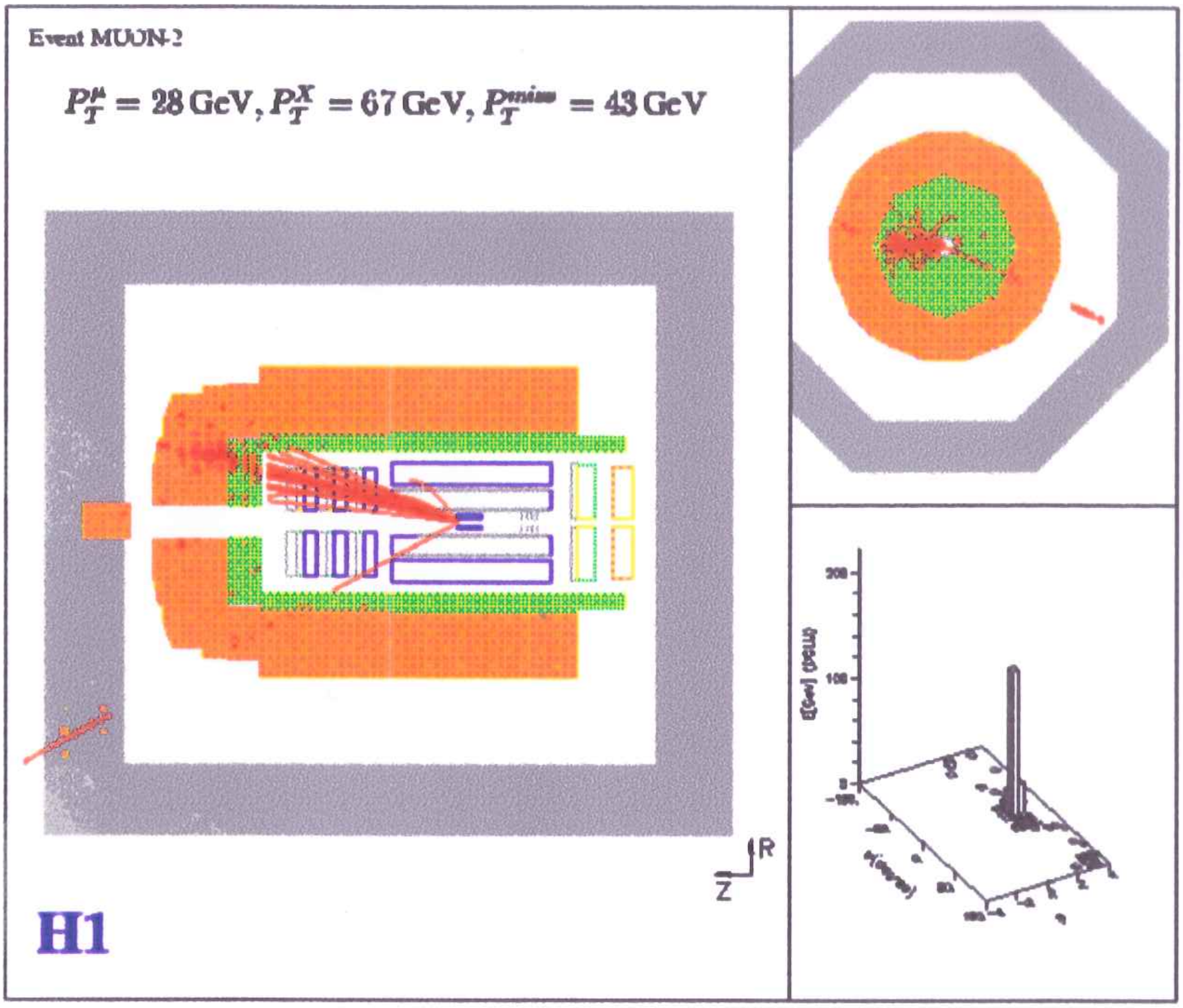




$(M_{\tilde{e}} + M_{\tilde{q}})/2 < 77$ GeV For $M_{\chi_1^0} = 40$ GeV is excluded

Isolated leptons (1)

Since 1994 we observed unusual events with high missing transverse momentum (P_t^{miss}) leptons (electrons or muons). $e^+p \rightarrow \mu^+ X$



- well isolated lepton + missing Pt + acoplanarity ($\Delta\phi \neq 0$)

	electrons		muons	
	Data	Expected	Data	Expected
	94-97 e^+			
H1 (37 Pb^{-1})	1 e^-	2.4 ± 0.5	5 μ ($2\mu^+, 2\mu^-, 1\mu$)	0.8 ± 0.2
ZEUS (47 Pb^{-1})	3 e^+	3.0 ± 0.6	0 μ	0.8 ± 0.3
	98 e^-			
H1 (5.1 Pb^{-1})	0 e	0.37 ± 0.07	0 μ	0.14 ± 0.04
ZEUS (5.1 Pb^{-1})	1 e^+	0.5 ± 0.14	0 μ	0.5 ± 0.14

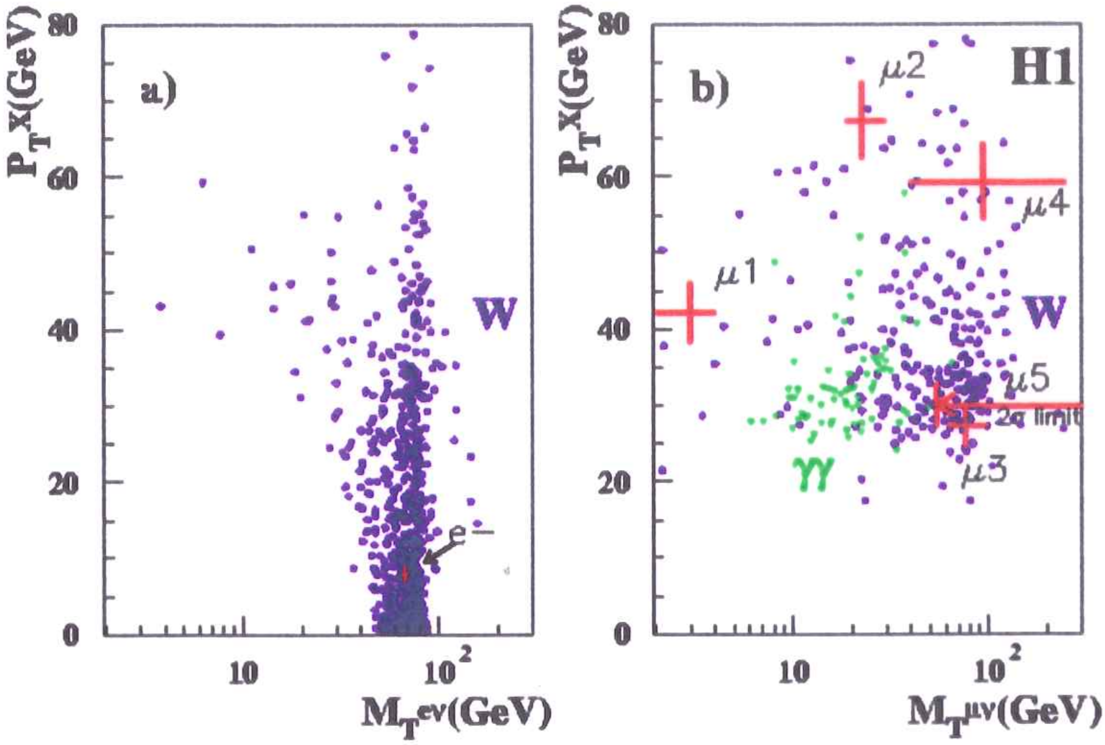
H1 sees a muon events excess while ZEUS does not.

need more luminosity in e^+p and e^-p data.

Isolated leptons (2)

Standard model expectations

(Lumi(MC) = 500 Lumi(data))



→ μ1, μ2, μ4 :
unlikely W production or γ–γ process

→ μ3 compatible with a W
($e^+p \rightarrow e^+\mu^-X$)

Interpretations Beyond the standard model :

- Leptoquark production into μ + jet : unlikely, the kinemtics are incompatible

- SUSY interpretation : R-parity violation single scalar stop quark production :

Compatible with $e^+ d \rightarrow \tilde{t}_1 \rightarrow \tilde{b}_1 + W$

With : $M(\tilde{t}_1) = 205$ GeV and $M(\tilde{b}_1) = 100$ GeV

Kinematics not incompatible for :

$M(\tilde{t}_1) = 200$ GeV and $M(\tilde{b}_1) \sim 90 - 1\ 20$ GeV

HERA in future

- Accumulate about 50 Pb^{-1} up to May 2000

- Luminosity upgrade shutdown fo 9 months

- Start high luminosity regime on spring 2001
  with about 1 fb^{-1} up to 2005