Rp-violating SUSY and Exotics at HERA

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Outline:

- **Introduction:**
- **Searches and discovery prospects:**

  Covered (partly):

  Leptoquarks, $\not{R}_p$-SUSY, FCNCs, Doubly Charged Higgs, Contact Interactions, Extra Dimensions

  Uncovered (mostly):

  L-Flavour Violation, Technicolour, R_p conserving SUSY, W_R Currents, Bileptons, Excited fermions, ...

- **Summary**

Introduction[1]

(1) Why bother in general ?

- Although remarkably confirmed (e.g. at colliders), the SM remains unsatisfactory (# arbitrary parameters; partial "unification", etc.)
- Fundamental questions remain to be answered :
  How do particle acquire masses ?
  How to "explain" the symmetry between L and Q sectors
  How to "explain" the threefold "replica" of fermion generations ?
- There $\exists$ a **strong** prejudice (more or less a necessity) for new physics "close to" EW unification scale
  SUSY matter $\lesssim \mathcal{O}(1\ \mathrm{TeV})$? String scale $\lesssim \mathcal{O}(10\ \mathrm{TeV})$?
- Scales from 1 to 10 TeV are being or will be best probed in "complementary" collider facilities:

Collider	Beams	$\sqrt{s}$	$\int \mathcal{L}dt$	Years
LEP_I	e^+e^-	M_Z	$\sim 160\ \mathrm{pb}^{-1} \otimes 4$	1989-95
LEP_{II}	e^+e^-	$> 2 \times M_W$	$\sim 700\ \mathrm{pb}^{-1} \otimes 4$	1996-00
HERA_I	$e^{\pm}p$	$\lesssim 320$ GeV	$\mathcal{O}(100\ \mathrm{pb}^{-1}) \otimes 2$	1994-00
$\mathrm{Tevatron}_I$	$p\bar{p}$	1.8 TeV	$\mathcal{O}(100\ \mathrm{pb}^{-1}) \otimes 2$	1992-96
HERA_{II}	$e^{\pm}_{L,R}p$	~ 320 GeV	$\sim 1\ \mathrm{fb}^{-1} \otimes 2$?	2002-06
$\mathrm{Tevatron}_{IIa}$	$p\bar{p}$	2.0 TeV	$\sim 3\ \mathrm{fb}^{-1} \otimes 2$?	2002-06 ?

$\mathrm{Tevatron}_{IIb}$ (?) $\gtrsim$2007, LHC $\gtrsim$2007 ?, TESLA LC ? $\gtrsim$2012 ? ...

Introduction$^{(2)}$

(1) Why bother at HERA ?

HERA$_I$ (1994-00): $e^{\pm}p$ $E_e = 27.5$ GeV $Ep = 820$ to 920 GeV
$\sqrt{s_{ep}} = 300$ to 318 GeV $\mathcal{L} \sim \mathcal{O}(100)$ pb$^{-1} \times 2$

HERA$_{II}$ (2002-06): $e^{\pm}_{L,R}p$ $E_e = 27.6$ GeV $Ep \gtrsim 920$ GeV
$\sqrt{s_{ep}} \gtrsim 320$ GeV $\mathcal{L} \sim \mathcal{O}(1)$ fb$^{-1} \times 2$

Two general purpose experiments: H1 and ZEUS

Standard Model physics: proton structure, EW couplings, QCD dynamics

Beyond the Standard Model:

HERA$_{II}$ provides a complementary window on:

- Physics of theories addressing the hierarchy problem ($\not{R}_p$ Yukawa sector of SUSY; Technicolour, Virtual G exchange ...)
- Physics of new theories pertinent for the apparent structure and symmetries of matter (leptoquarks, SM extensions, LFV, FCNCs)
- Models relevant for the threefold "replica" of fermions (excited fermions, Contact Interactions)

∘ Admittedly, considering existing constraints and current knowledge, HERA$_{II}$ will have essentially nothing to say on extra Z's; sparticles and Higgses in MSSM, mSUGRA, GMSB or AMSB theories...; anomalous TGB vertices; etc. ...

Leptoquarks at Colliders

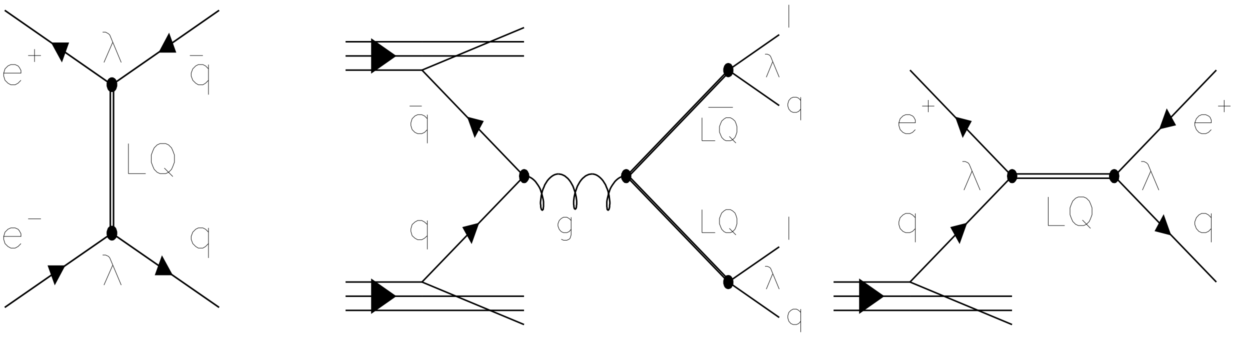
- LQs are colour triplet bosons (scalars S or vectors V) carrying L and B numbers and fractional Q_{em}
- LQs appear naturally in:
  GUT-like theories, Superstring-"inspired" E_6 models,
  Technicolour-like theories, Compositeness models
- Büchmuller-Rückl-Wyler LQ "minimal" model $\leftrightarrow$
  assume (chiral) couplings invariant under SM gauge interactions; interactions **only** with SM fermions and gauge bosons; etc.
  $\Rightarrow$ Scalars and Vectors each forming 5 Isospin families:

	Scalars	Vectors
F=2	$(S_{0,R},\ S_{0,L}),\ \tilde{S}_{0,R},\ S_{1,L}$	$(V_{1/2,R},\ V_{1/2,L}),\ \tilde{V}_{1/2,L}$
F=0	$S_{1/2,L},\ (\tilde{S}_{1/2,L}\ \tilde{S}_{1/2,R})$	$V_{0,L},\tilde{V}_{0,R},\ V_{1,L}$

- Non-minimal models: non-standard decays allowed $\leftrightarrow$
  arbitrary β_{eq} for 1^{rst} generation leptoquarks
  e.g. LQ with LFV couplings; e.g. $\tilde{u}_L \leftrightarrow \tilde{S}_{1/2,L}$ $\tilde{d}_R \leftrightarrow S_{0,L}$

At various colliders:

LEP Tevatron HERA



At HERA: ◦ $e^-p \rightarrow S_0\,;\ \tilde{S}_0\,;\ S_1$ $e^+p \rightarrow \bar{S}_{1/2}\,;\ \bar{\tilde{S}}_{1/2}$
◦ All LQ types can be distinguished through $e^{\pm}_{L,R}$

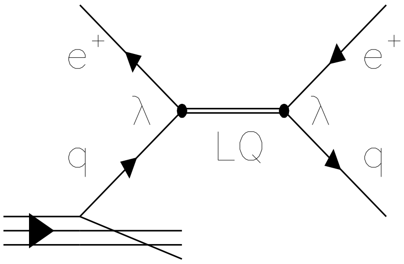
Search for Leptoquarks at HERA

Previously published: $F = 0$ e^+p; $\mathcal{L} \simeq 37$ pb^{-1} H1 Collab. EPJ C11 (1999) 447

$F = 2$ e^-p; $\mathcal{L} \simeq 15$ pb^{-1} H1 Collab. PLB 523 (2001) 234

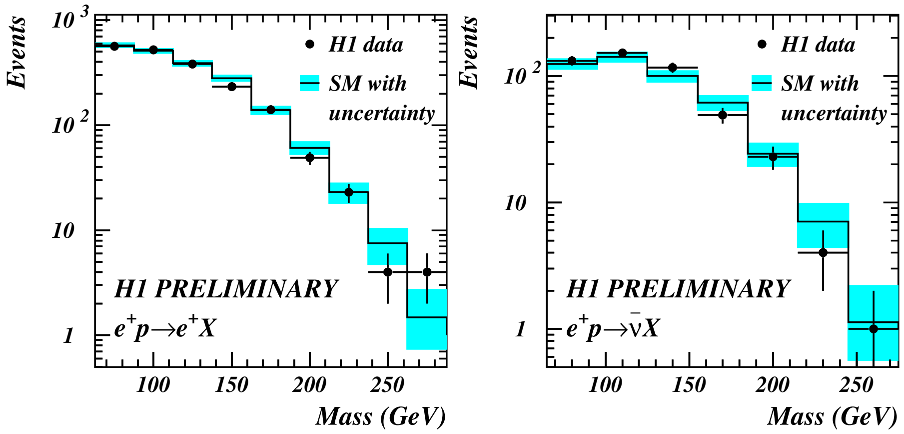
$F = 0$ e^+p; $\mathcal{L} \simeq 48$ pb^{-1} ZEUS Collab. EPJ C16 (2000) 253

PRD 63 (2001) 052002



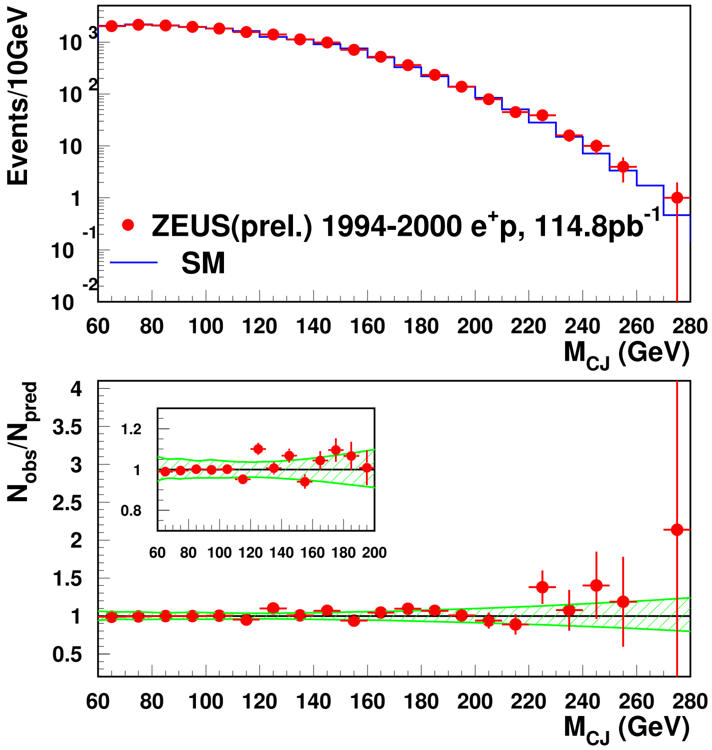
∘ LQ interaction interferes with with SM boson t-channel exchange

∘ Background reduction: $\cos(\theta_e^*)$ spectra distinct from SM DIS



NEW (prelim. DIS 2002)

H1 use all $e^\pm p$ data

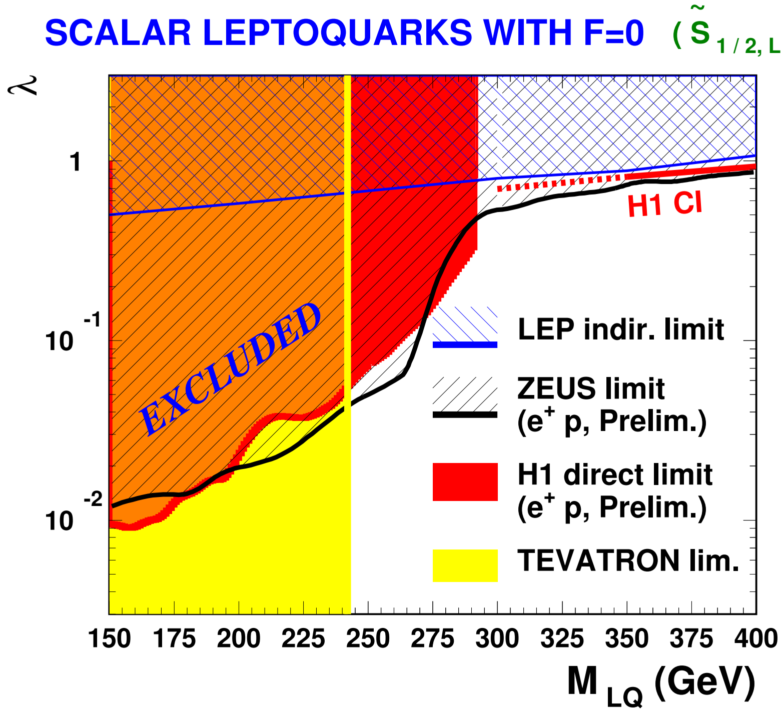


NEW (prelim. DIS 2002)

ZEUS use all $e^\pm p$ data

No deviation from SM expectation !

Search for Leptoquarks at HERA



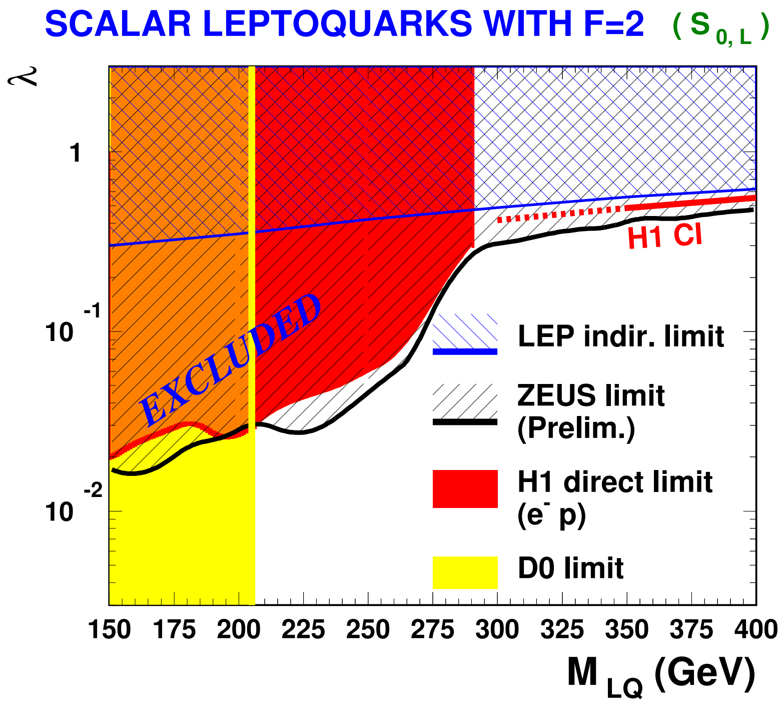
e^+p

$Q_{em} = -2/3$ $\beta_{eq} = 100\%$

Tevatron: $M \gtrsim 245$ GeV

HERA: $(\lambda = 0.3)$ $M \gtrsim 290$ GeV

$(\lambda = 0.1)$ $M \gtrsim 270$ GeV



e^-p

$\beta_{eq} = \beta_{\nu q} = 50\%$

Sensitivity ↑ by combining

NC-like and CC-like events

Tevatron: $M \gtrsim 204$ GeV

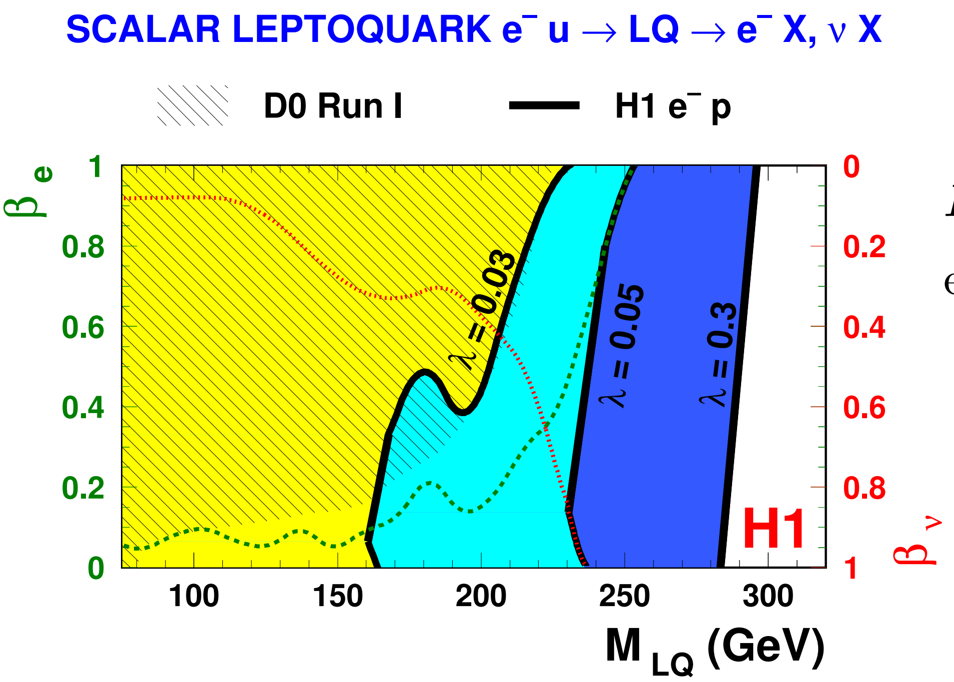
HERA: $(\lambda = 0.3)$ $M \gtrsim 300$ GeV

$(\lambda = 0.1)$ $M \gtrsim 270$ GeV

Recall: $M < \sqrt{s}$ $\lambda \ll 1 \Rightarrow \sigma \propto \lambda^2$

$M \gg \sqrt{s} \Rightarrow \sigma \propto \lambda^4$

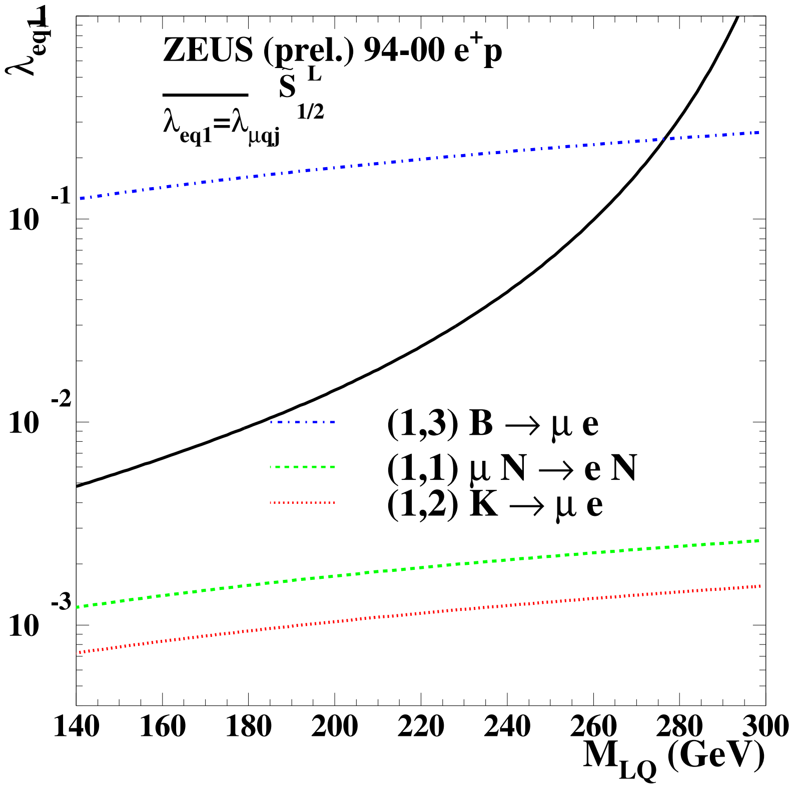
Search for Leptoquarks at HERA



$F = 2$

e.g. $S_{0,L}$

- At Tevatron: ◦ Best sensitivity for $\beta_{eq} \to 1$
- Best cases at HERA are for LQs in non-minimal minimal models (non-standard decays allowed ↔ arbitrary β_{eq}) with $\beta_{eq} \ll 1$



- Unique sensitivity and striking signal for LFV at HERA possible through s-, t- or u-channel exchange of new eq bosons with mixed $\lambda_{eq_i} \times \lambda_{\mu q_j}$ or $\lambda_{eq_i} \times \lambda_{\tau q_j}$

(see || session talk by D. Danheim)

$M \gtrsim 280$ GeV for $\lambda_{eq_1} = 0.3$

Extra Dimensions at Colliders

- Problem of hierarchy between EW and Planck scale $\leftrightarrow$ possibly finds solutions in theories with extra dimensions
- There $\exists$ many viable $4+n$ dimensional scenarios

  e.g. ADD = Arkani-Hamed, Dimopoulos, Dvali PLB 429 (1998) 263;

  RS = Randall, Sundrum PRL 83 (1999) 3370

Various scenarios $\Leftrightarrow$ model dependent effects at HEP colliders

- ADD scenario: SM particles in 4d $\leftrightarrow$ gravitons in (4+n)d

  $M_p^2 = R^n M_s^{2+n}$ $\quad n \geq 2 \quad M_p \sim 10^{19}$ GeV

  R = size of the n compact extra dimensions

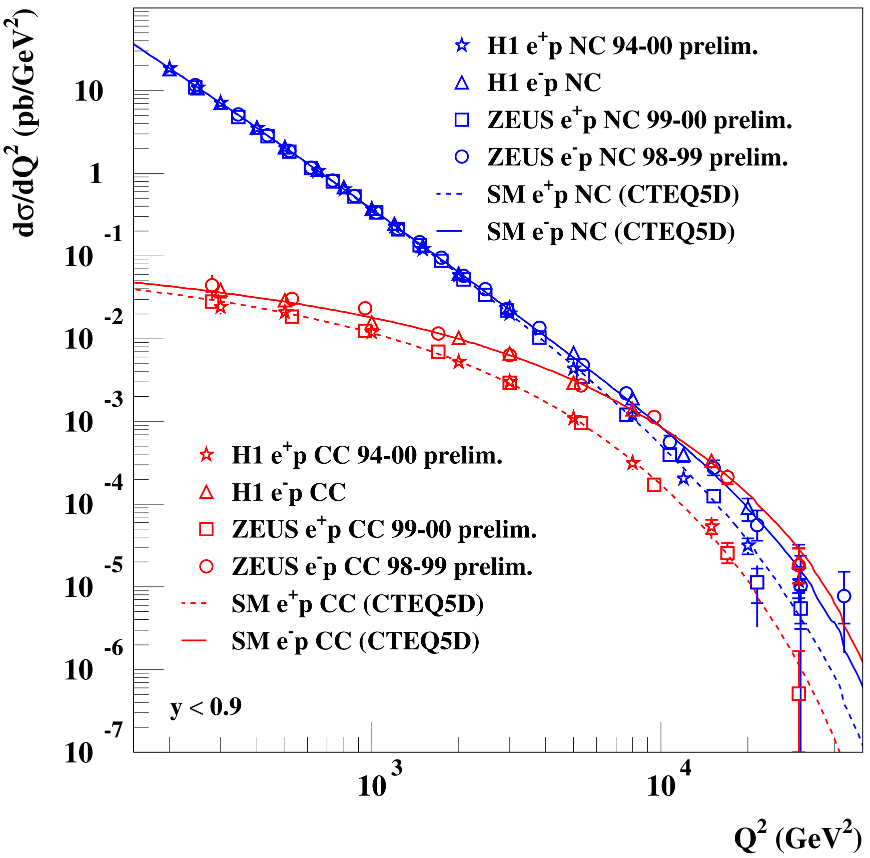
  M_S = gravitional scale in $4+n$ dimensions

$\Rightarrow$ "tower" of massive Kaluza-Klein excitation states !

$\Rightarrow$ virtual "graviton" exchange interferes with γ, Z exhange with an effective (contact interaction) coupling $\eta_G = \lambda / M_S^4$

- Observable effects in $e^+e^- \to f\bar{f}$, $\quad q\bar{q} \to l\bar{l}$, $\quad eq \to lq'$

  e.g. Expect deviations from SM in high Q^2 DIS scattering at HERA:

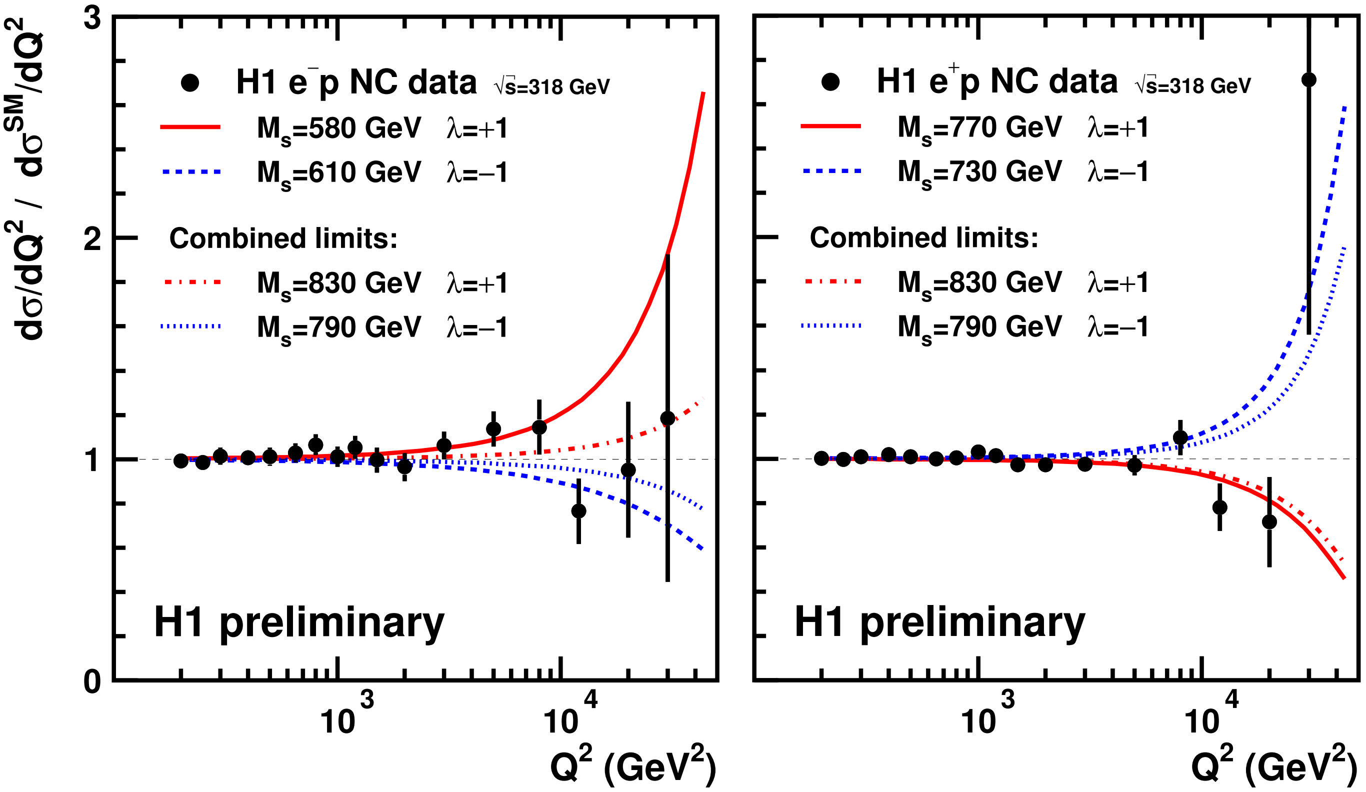


Search for Extra Dimensions at HERA

Published: H1 Collab. PLB 479 (2000) 358

NEW: Using all available $e^{\pm}p$ data:

H1 prelim.- Val. d'Aoste 2002 **ZEUS prelim.** - EPS HEP 2001



HERA$_I$, Tevatron$_I$ and LEP$_{II}$ results:

95% CL limit on M_S [TeV]					
λ	H1	ZEUS	CDF[a]	D0[b]	LEP Combined[c]
+1	0.83	0.81	0.96	1.21	1.26
-1	0.79	0.82	0.94	1.13	0.96

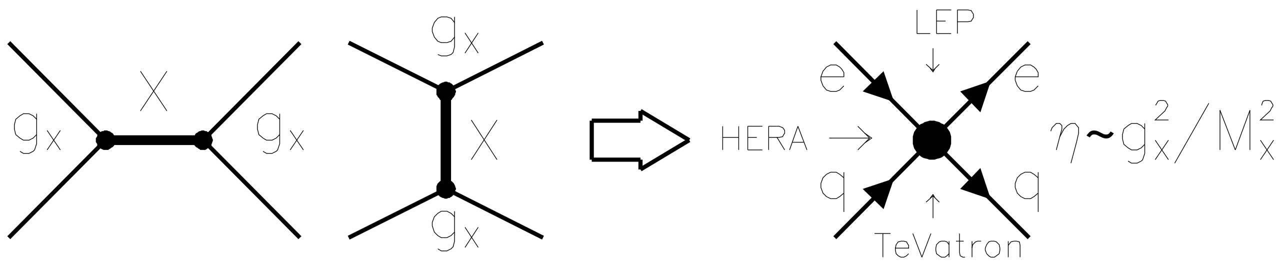
Results conversion from Hewett (H) to Giudice, Rattazi, Wells (GRW) formalism via $M_{GRW}^4 = (\pi/2) M_H^4$

[a] J. Carlson, APS Meeting (May 2001) [b] DØ Collab., PRL 86 (2001) 1156

[c] From D. Bourilkov, A+D+L+O experiments for LEP$_{II}$ $\sqrt{s}$ up to 189 GeV

Contact Interactions

- Interference of (very) heavy bosonic particle X with SM fields in virtual exchange $\leftrightarrow$ for $M_X \gg \sqrt{s}$ the s-, t- or u- channel propagators contract to pointlike four fermion CI with eff. coupling η $[mass^{-2}]$



$$\mathcal{L}_{CI} = \sum_{q=u,\,d} \eta^q_{LL}\,(\bar{e}_L\gamma_\mu e_L)(\bar{q}_L\gamma^\mu q_L) + \eta^q_{LR}\,(\bar{e}_L\gamma_\mu e_L)(\bar{q}_R\gamma^\mu q_R)$$
$$+\eta^q_{RL}\,(\bar{e}_R\gamma_\mu e_R)(\bar{q}_L\gamma^\mu q_L) + \eta^q_{RR}\,(\bar{e}_R\gamma_\mu e_R)(\bar{q}_R\gamma^\mu q_R)$$

$\eta_{ij} \equiv \pm\epsilon g^2/\Lambda^2_{ij}$ $\qquad i, j = R, L$
g = coupling strength $= 4\pi$; $\quad \Lambda_{ij}\,scale \equiv M_x$
APV requires $\eta^q_{LL} + \eta^q_{LR} - \eta^q_{RL} - \eta^q_{RR} = 0$

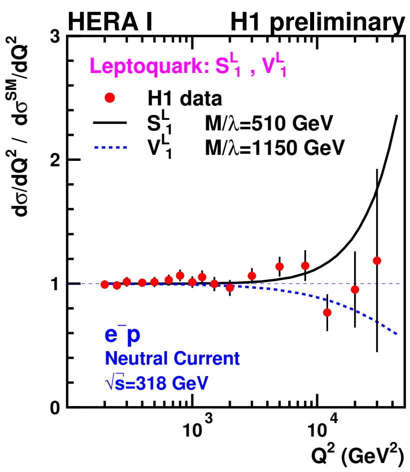
- Various vector and axial vector combinations can be considered

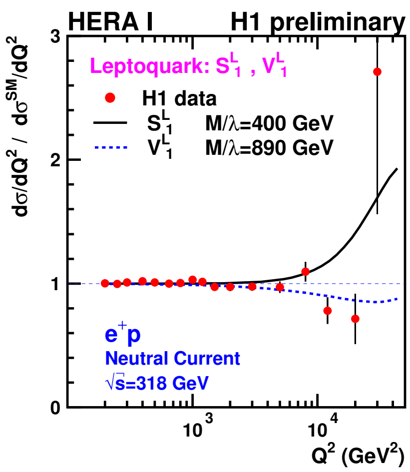
  e.g. Parity conserving Compositeness models with q universality:

  VV= LL + LR +RL + RR   AA= LL- LR - RL + RR ...

  e.g. BRW Leptoquark models (specific chiral couplings to $e-q$ pairs:

  $S_1^L \Rightarrow \epsilon^d_{LL} = 2 \times \epsilon^u_{LL} = +1$





Note: HERA results now profit from distinct sensitivity to e^-p and e^+p data

Search for Contact Interactions at HERA

All available $e^{\pm}p$ data: H1 prelim.- Val. d'Aoste 2002 ZEUS prelim. - EPS HEP 2001

[Recent collider review in M. Kuze, Y. Sirois PPNP (2002)]

Compositeness models:

95% CL limit [TeV]		H1		ZEUS		CDF		DØ	
Model	Coupling structure $[\epsilon_{LL},\epsilon_{LR},\epsilon_{RL},\epsilon_{RR}]$	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+
VV	$[+1, +1, +1, +1]$	5.4	5.1	7.0	6.5	5.2	3.5	6.1	4.9
AA	$[+1, -1, -1, +1]$	3.9	2.5	5.3	4.6	4.8	3.8	5.5	4.7
VA	$[+1, -1, +1, -1]$	2.9	2.9	3.4	3.3				

Leptoquark models:

95% CL limit M_{LQ}/λ_{LQ} [GeV]						
Model	Coupling Structure	H1	ZEUS	ALEPH	L3	OPAL
$S_\circ^L$	$\epsilon_{LL}^u = +\frac{1}{2}$	720	750	640	1240	640
$S_\circ^R$	$\epsilon_{RR}^u = +\frac{1}{2}$	670	690		960	
$\tilde{S}_\circ^R$	$\epsilon_{LL}^d = +\frac{1}{2}$	330	310	220	260	590
$S_{1/2}^L$	$\epsilon_{LR}^u = -\frac{1}{2}$	870	910	-	180	460
$S_{1/2}^R$	$\epsilon_{RL}^d = \epsilon_{RL}^u = -\frac{1}{2}$	370	690		350	630
$\tilde{S}_{1/2}^L$	$\epsilon_{LR}^d = -\frac{1}{2}$	430	500			370
S_1^L	$\epsilon_{LL}^d = 2 \cdot \epsilon_{LL}^u = +1$	480	550	770	640	930

Recall: $S_0^L \sim \tilde{d}_R$ $\tilde{S}_{1/2}^L \sim \tilde{u}_L$

For $\lambda = 1$ some LQs excluded up to ~ 900 GeV for scalars

(~ 1.4 TeV for vectors)

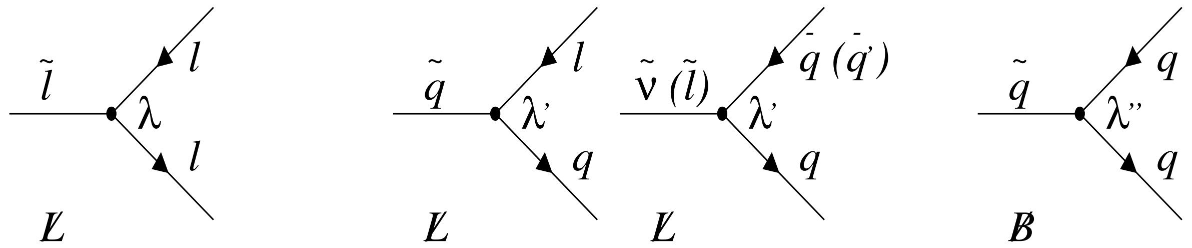
R-Parity Violating SUSY

- The General Superpotential:

$$W = W_{MSSM} + W_{\not{R}_p} \qquad R_p = (-1)^{3B+L+2S} \leftrightarrow +1 \text{ for particles; } -1 \text{ for Sparticles}$$

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

ijk for generation; superfield: L, Q doublets; E, D, U singlets



Proton stability $\Rightarrow \lambda' \times \lambda'' = 0$ sufficient.

Main consequences at colliders of a non-vanishing λ, λ' or λ'':

- Fondamental instablity of SUSY matter $\Rightarrow$ new/distinct decay modes indirect sensitivity to λ, λ' or λ'' or λ'' from sparticle pair production.
- Extended discovery reach in specific cases:

Resonant Production of Sfermions at Colliders			
Collider	Coupling	Sfermion	Elementary Process
e^+e^-	λ_{1j1}	$\tilde{\nu}_\mu, \tilde{\nu}_\tau$	$l_i^+ l_k^- \rightarrow \tilde{\nu}_j$ $\quad i = k = 1\,,\ j = 2, 3$
$p\bar{p}$	λ'_{ijk}	$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	$d_k \bar{d}_j \rightarrow \tilde{\nu}_i$ $\quad i, j, k = 1, \ldots, 3$
		$\tilde{e}, \tilde{\mu}, \tilde{\tau}$	$u_j \bar{d}_k \rightarrow \tilde{l}_{iL}$ $\quad i, k = 1, \ldots, 3\,,\ j = 1, \ldots, 2$
	λ''_{ijk}	$\tilde{d}, \tilde{s}, \tilde{b}$	$\bar{u}_i \bar{d}_j \rightarrow \tilde{d}_k$ $\quad i, j, k = 1, \ldots, 3\,,\ j \neq k$
		$\tilde{u}, \tilde{c}, \tilde{t}$	$\bar{d}_j \bar{d}_k \rightarrow \tilde{u}_i$ $\quad i, j, k = 1, \ldots, 3\,,\ j \neq k$
ep	λ'_{1jk}	$\tilde{d}_R, \tilde{s}_R, \tilde{b}_R$	$l_1^- u_j \rightarrow \tilde{d}_{kR}$ $\quad j = 1, 2$
	λ'_{1jk}	$\tilde{u}_L, \tilde{c}_L, \tilde{t}_L$	$l_1^+ d_k \rightarrow \tilde{u}_{jL}$ $\quad i, j, k = 1, \ldots, 3$

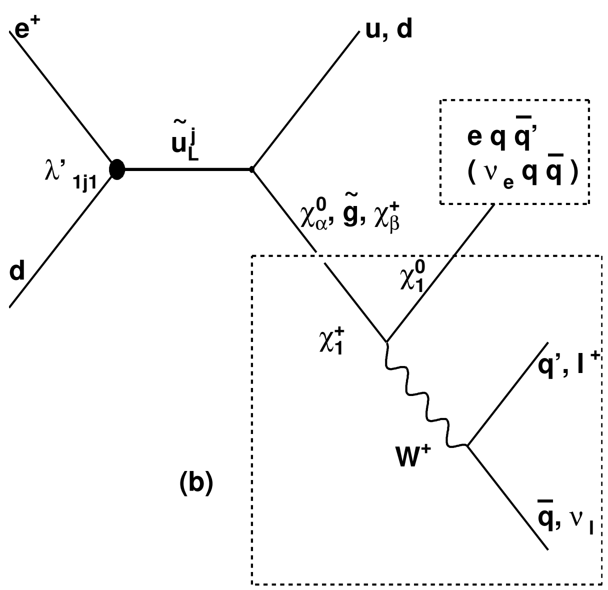
- Best discovery reach for SUSY at HERA = single $\tilde{q}$ prod. through λ'!

Search for $R\!\!\!/_p$-SUSY at HERA

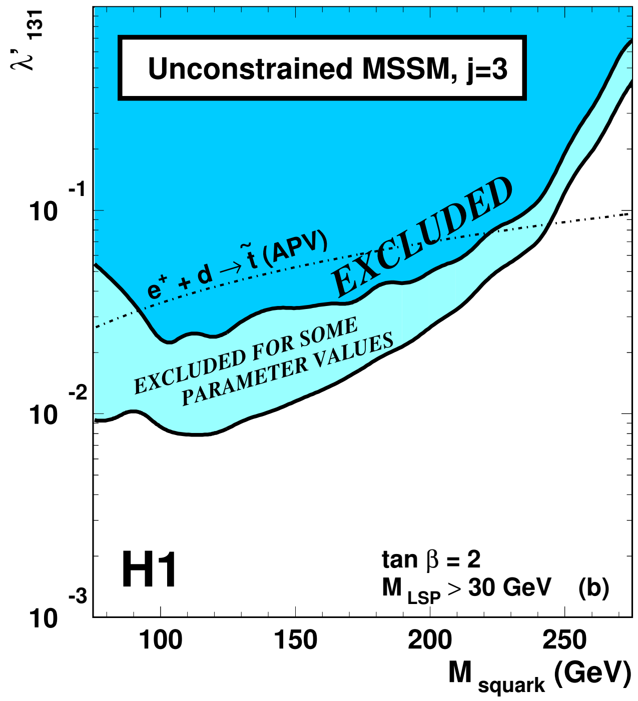
$\tilde{q}$ single production: H1 EPJ C20 (2001) 4 ZEUS prelim. ICHEP (Osaka) 2000

- Different kinds of $\tilde{q}$ produced dominantly for $e^\pm$

  $e^-p \leftrightarrow \lambda'_{11k}$ and $\tilde{d}_R$-like $\tilde{q}$ $e^+p \leftrightarrow \lambda'_{1j1}$ and $\tilde{u}_L$-like $\tilde{q}$ (e.g. the $\tilde{t}$)



$-300 < \mu < 300$ GeV $70 < M_2 < 350$ GeV

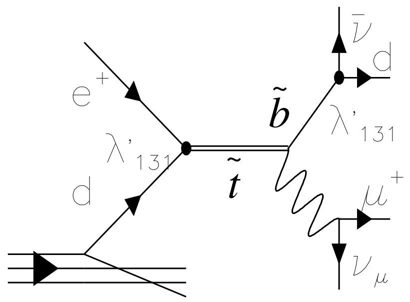


$M_{\tilde{q}} \gtrsim 260$ GeV for $\lambda'_{1j3} = 0.3$

Sensitivity beyond indirect limits

Widely model independent

- The special case of the $\tilde{t}$



- Possibly significant rates both in

  $\tilde{t}_1 \to \tilde{b}_1 + W$ and $\tilde{t}_1 \to ed$

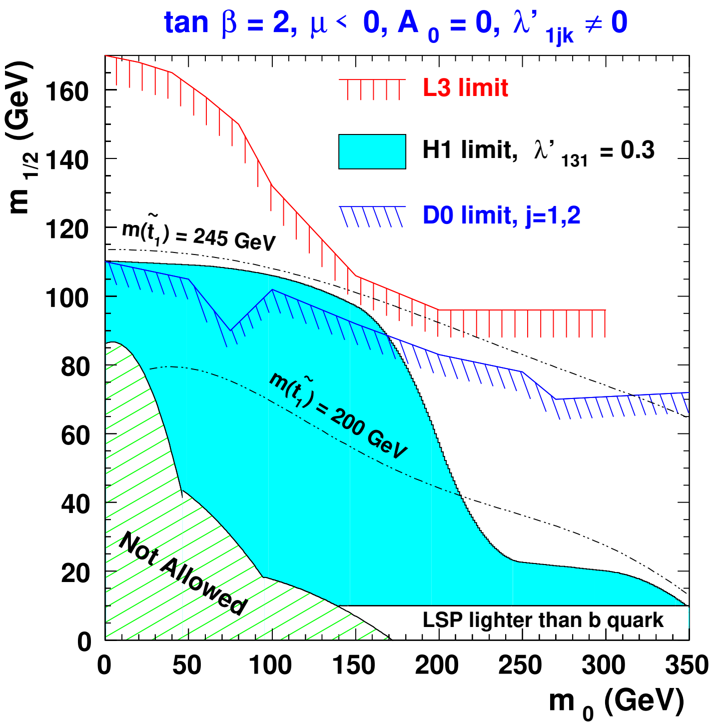
- $\tilde{t}_1 \to \tilde{b}_1 + W \Rightarrow$ outstanding

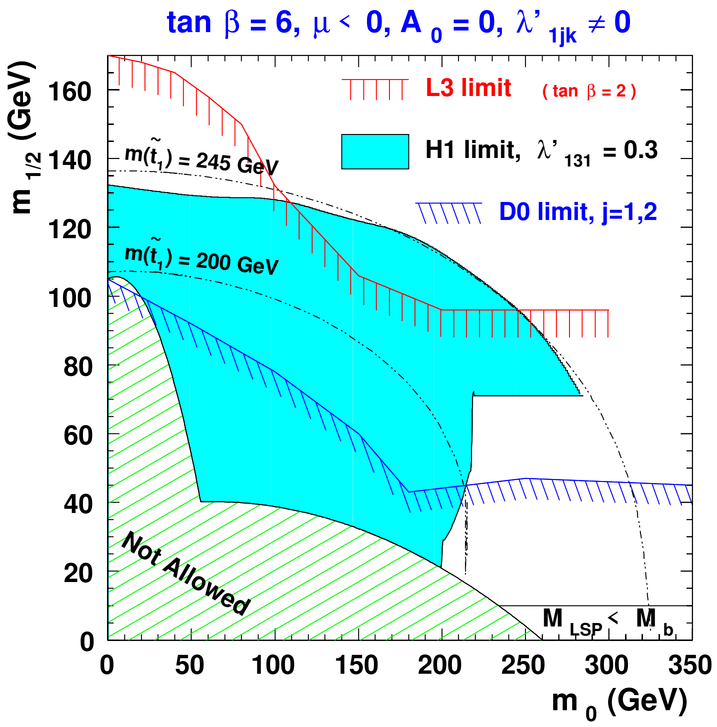
  event topologies: $l^\pm + jet + P\!\!\!/_T$

E. Perez, SUSY 98 & Tools for SUSY 99

Search for $\not{R}_p$-SUSY at HERA

$\tilde{q}$ single production: H1 EPJ C20 (2001) 4 ZEUS prelim. ICHEP (Osaka) 2000





m_0 $(m_{1/2})$ = common scalar (gaugino) mass at GUT scale

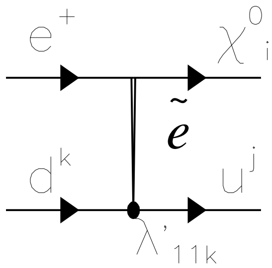
"Not Allowed" $\equiv$ No radiative EW symmetry breaking **or LSP = slepton**

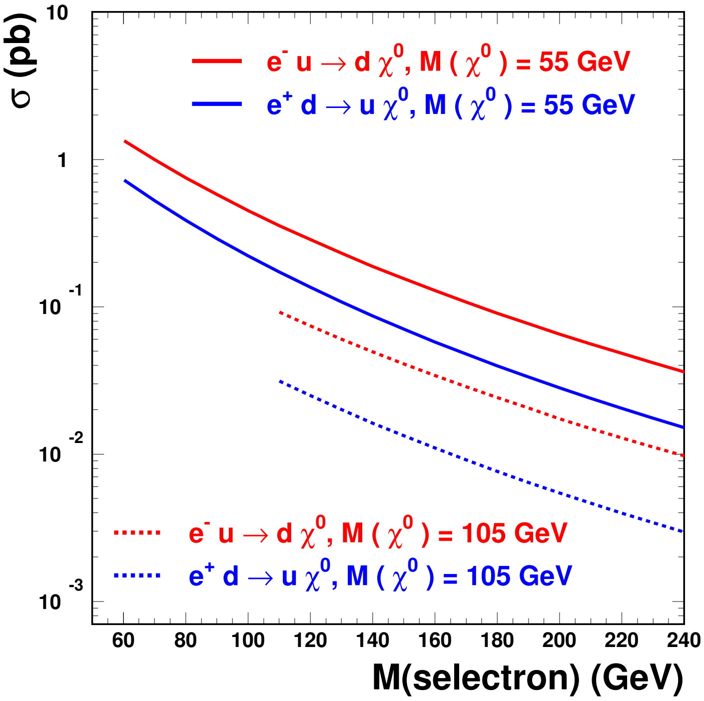
- Best sensitivity at HERA towards larger $\tan\beta$ relative to Tevatron
  (χ_1^0 zino-like $\Rightarrow$ decay in $e^{\pm}q\bar{q}'$ suppressed)
- HERA Limits at larger $\tan\beta$ $\sim$ follow isomass curve

$\not{R}_p$-SUSY with Selectrons at HERA

- If $M_{\tilde{q}} \gg M_{\tilde{l}} \leftrightarrow \lambda'$ can still be probed via $\tilde{l}$ exchange !

Also $\tilde{\chi}^+$ production via $\tilde{\nu}$ exchange





$\not{R}_p$ + MSSM/mSUGRA $\Rightarrow$

$\chi_1^0 \rightarrow e^{\pm} q \bar{q}'$

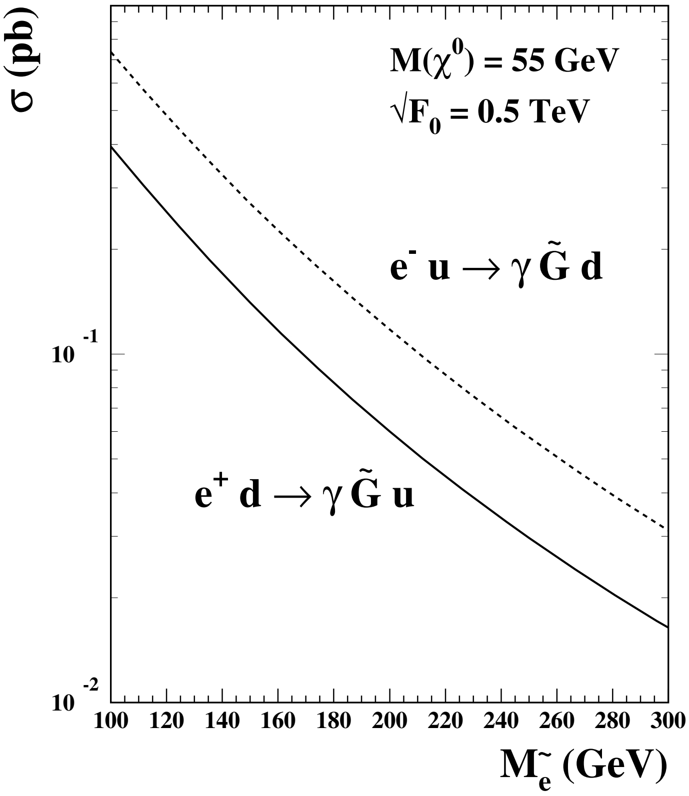
E. Perez, "Tool 99" (Lyon)

χ_1^0 search can be extended for $\tilde{l}^{\pm}$ beyond LEP$_{II}$ reach

Cross-sections here assumes:

$\lambda' = 0.5 \quad \tan\beta = 1$

$\chi^0 \sim \tilde{\gamma}$



$\not{R}_p$ + GMSB $\Rightarrow$ $\chi_1^0 \rightarrow \gamma \bar{G}$

Ch. Schwanenberger (2002)

GMSB: Sensitive to $(\lambda', \sqrt{F_0})$

$\tilde{l}$ masses $100 < M_{\tilde{l}} < 300$ GeV

Cross-sections here assumes:

$\sqrt{F_0} = 0.5$ TeV $\quad \tan\beta = 1$

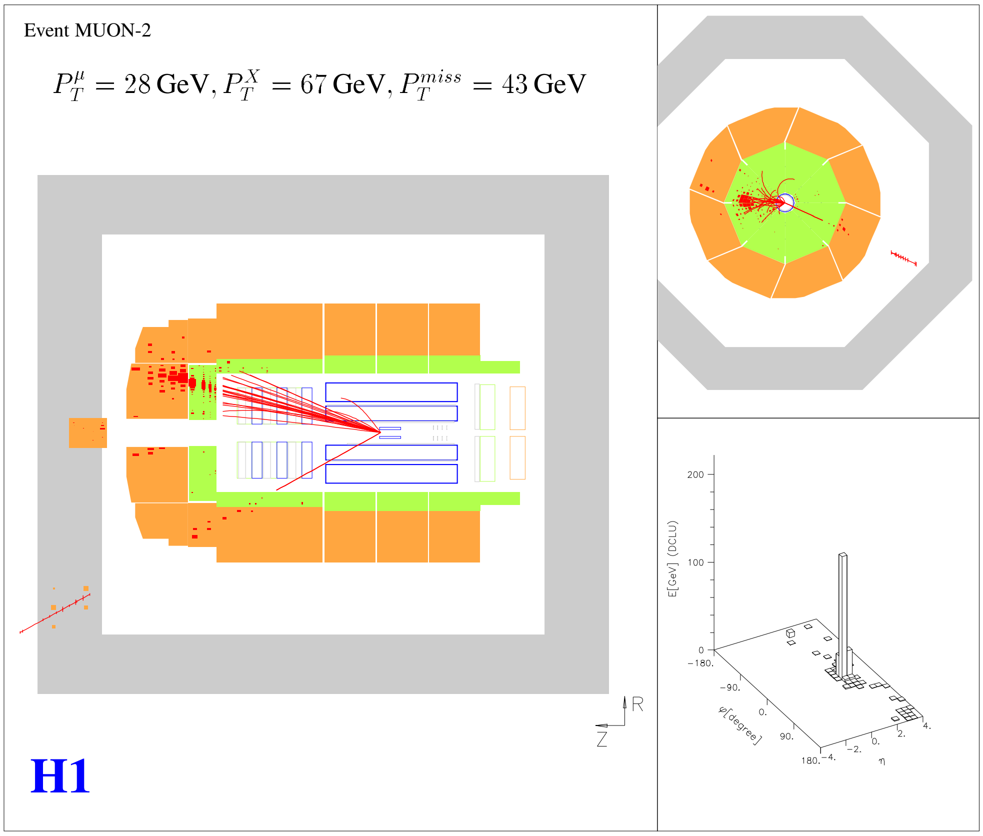
$(\mu, M_1, M_2) = (-60, 50, 80)$ GeV

$M_{\tilde{G}} = F_0 / \sqrt{3} M_P$

$\sqrt{F_0}$ = fund. scale of SUSY breaking

Outstanding Isolated Lepton Topologies at HERA ?

Reminder:



	$P_T^X > 0$ GeV	$P_T^X > 40$ GeV
H1 selection:	18	6
SM expectation:	10.5 ± 2.5	1.0 ± 0.3
ZEUS selection:	10	0
SM expectation:	11.0 ± 1.6	-

Recall: $\not{R}_p$ + MSSM : $e^+ d \rightarrow \tilde{t}_1 \rightarrow \tilde{b} W^+ \,;\; \tilde{b} \rightarrow \bar{\nu} d \quad W^+ \rightarrow l^+ \nu$

$\not{R}_p$ + GMSB : $e^+ d \rightarrow u \chi^+ \,;\; \chi^+ \rightarrow \tilde{G} W^+ \,;\; W^+ \rightarrow l^+ \nu$

...

top FCNC : $e^{\pm} u \rightarrow e t \,;\; t \rightarrow b W^{\pm} \,;\; W^+ \rightarrow l^+ \nu$

...

Flavour Changing Neutral Currents

• FCNCs are absent at tree level in the Standard Model
Neutral Currents are flavour diagional

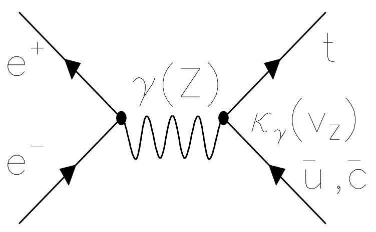
• FCNCs appear ”naturally” (but strongly suppressed !) at one-loop level due to CKM mixing

• In some specific models, FCNC processes in the top sector receive a large contribution beyond the Standard Model rates:

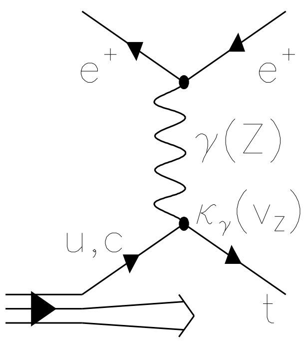
Theory	$\beta(t \to c\gamma, cZ^0)$
Standard Model	$\sim 10^{-13} - 10^{-12}$
Two Higgs Doublet	$\sim 10^{-9} - 10^{-8}$
Supersymmetry	$\sim 10^{-8} - 10^{-6}$
Multiple Higgs Doublet	$\sim 10^{-6} - 10^{-5}$
Quark Singlets	$\sim 10^{-2}$
Composite top quark	$\sim 10^{-2}$
R-Parity Violating SUSY	$\gtrsim 10^{-2}$???

• Because of it’s large mass, the top could be an ideally sentitive to physics beyond the Standard Model

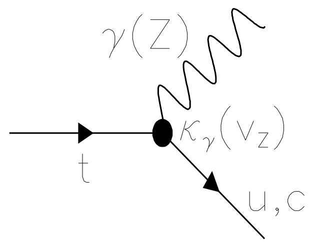
LEP



HERA



Tevatron



Search for FCNCs at HERA

All available $e^{\pm}p$ data; $ep \rightarrow etX$; $t \rightarrow bW$; leptonic and hadronic W decays

H1 prelim.- EPS HEP 2001 + DIS 2002 ZEUS prelim. - EPS HEP 2001

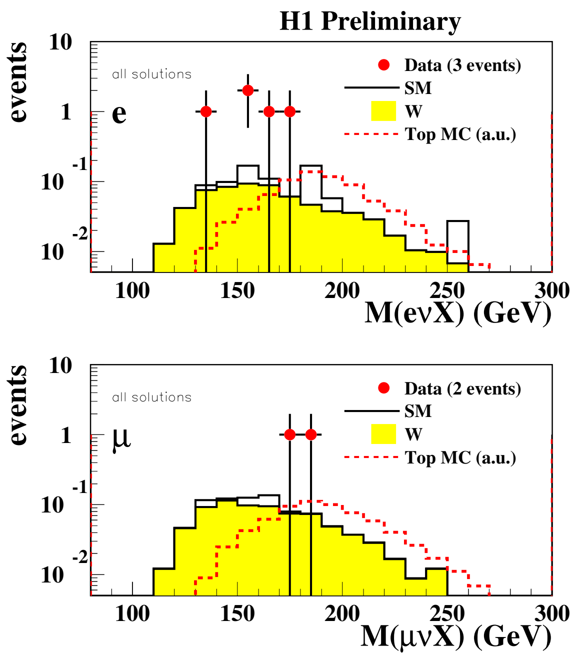
- Single top searches at HERA originally motivated by the finding of outstanding events with "isolated l + large $\not{P}_T$ + high P_T jet"

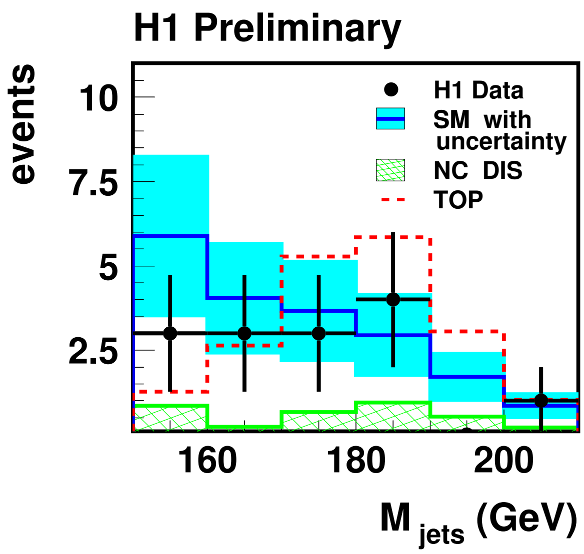
(H1 excess not confirmed by ZEUS

e.g. e-channel had.-channel

$P_T^X > 25$ GeV $P_T^{jet} > 25$ GeV $P_T^{jet} > 40, 25, 20$ GeV

$M_T^{e\nu} > 10$ GeV $\epsilon \sim 40\%$ $\epsilon \sim 30\%$

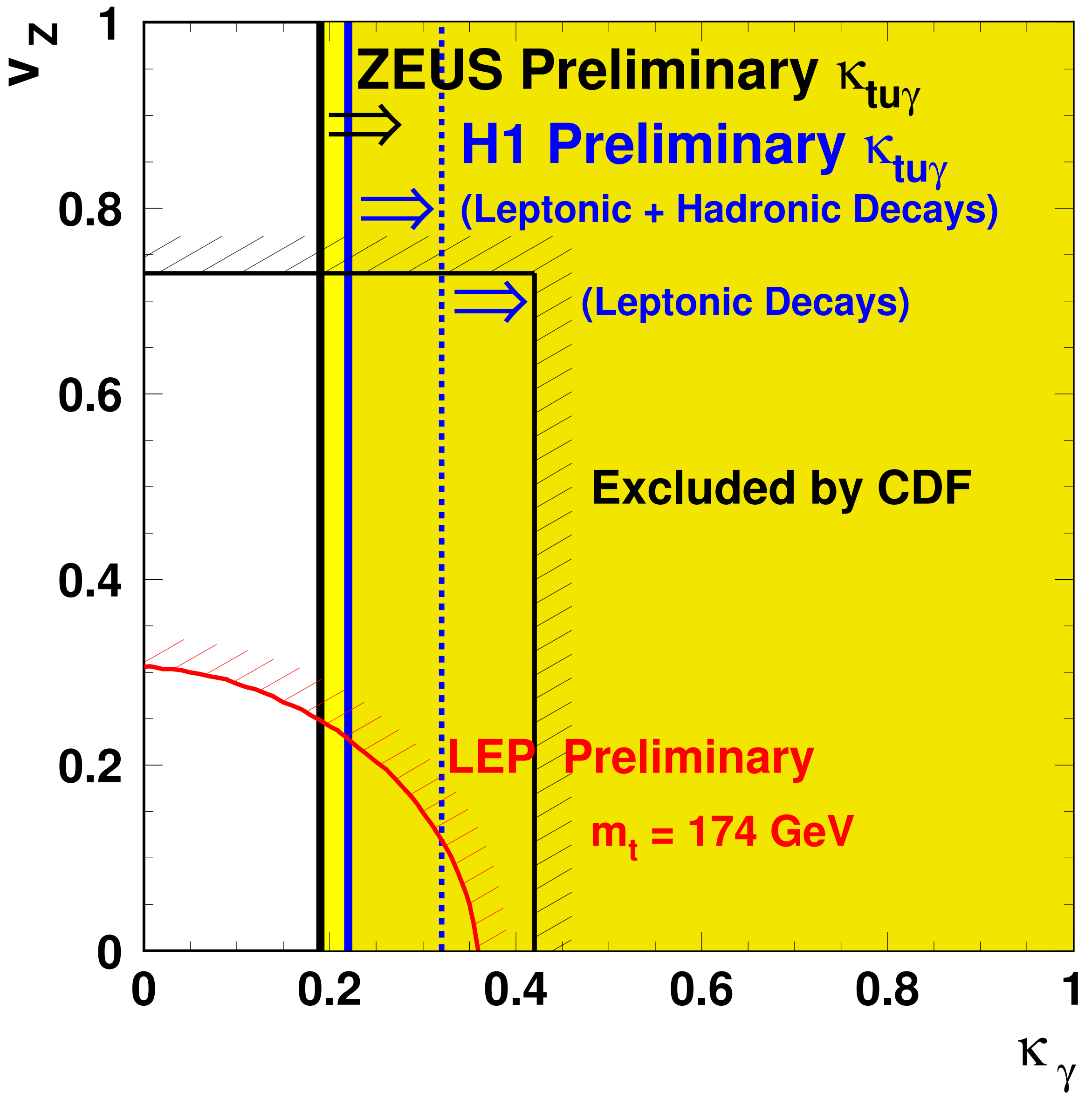




	e-channel	μ-channel	had.-channel
H1 top selection:	3	2	14
SM expectation:	0.75 ± 0.18	0.77 ± 0.21	19.6 ± 7.8
Top efficiency:	37%	45%	27%
ZEUS top selection:	1	1	19
SM expectation:	1.14 ± 0.06	1.29 ± 0.16	~ 20
Top efficiency:		$\sim 21\%$	

Search for FCNCs at HERA

- Sensitivity at HERA comparable/complementary to that of LEP_{II} and $\mathrm{Tevatron}_I$ (... but ADLO combination using full LEP_{II} data still to come !)



- HERA exclusion at 95% CL:

$$\kappa_{tu\gamma} < 0.22 \text{ (H1)} \quad \kappa_{tu\gamma} < 0.19 \text{ (ZEUS)}$$

Doubly Charged Higgs Bosons

M. Kuze, Y. Sirois, PPNP Review (2002)

- **Doubly charged scalar particles** $\Delta^{\pm\pm}$ appear in various models relying on an extension of the EW symmetries beyond SM

  Gauged $U(1)_{B-L}$ (*Pati-Salam* unification of color and lepton numbers);

  Left-Right symmetric models (*Mohapatra et al., Cvetic et al., Huitu et al.*);

  Higgs triplet models (*Georgi et al., Gunion et al.*).

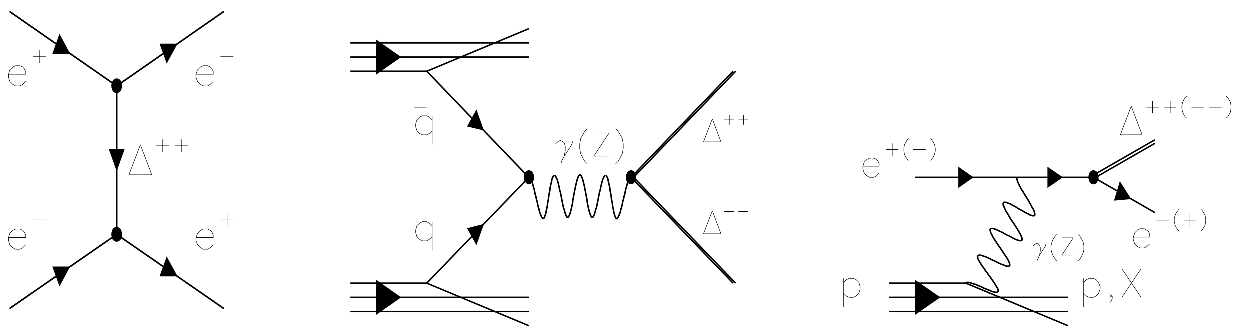
- There $\exists$ strong motivations for light $\Delta^{\pm\pm}$ in SUSY models incorporating $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- SUSY L-R models $\Rightarrow$

  Two Higgs triplets $(\Delta^0, \Delta^-, \Delta^{--})_{L\, or\, R}$ **acting solely in the leptonic sector** ! Do **not couple to ordinary fermion masses** !

  Appear alongside with sparticles, additional $W'^{\pm}$ and Z' bosons;

  Heavy Majorana neutrino N_R^i for each generation i, ...

At Colliders:



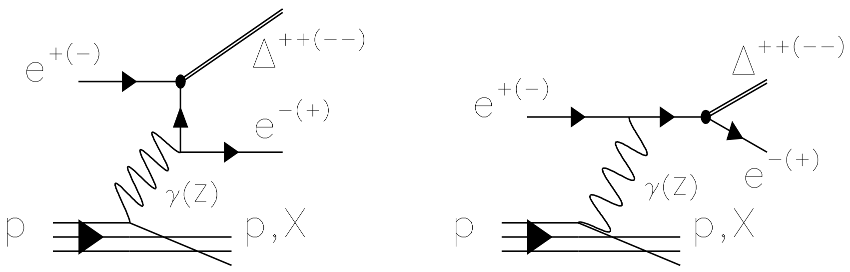
At HERA: e.g. $e^+p \to e^-\Delta^{++}X$; $\Delta^{++} \to l^+l^+$

$\Rightarrow$ striking three lepton event topologies !

Note: ∘ Bosonic decays $\Delta^{--} \to \Delta^- W_R^-$; $\Delta^-\Delta^-$ likely to be closed or disallowed.

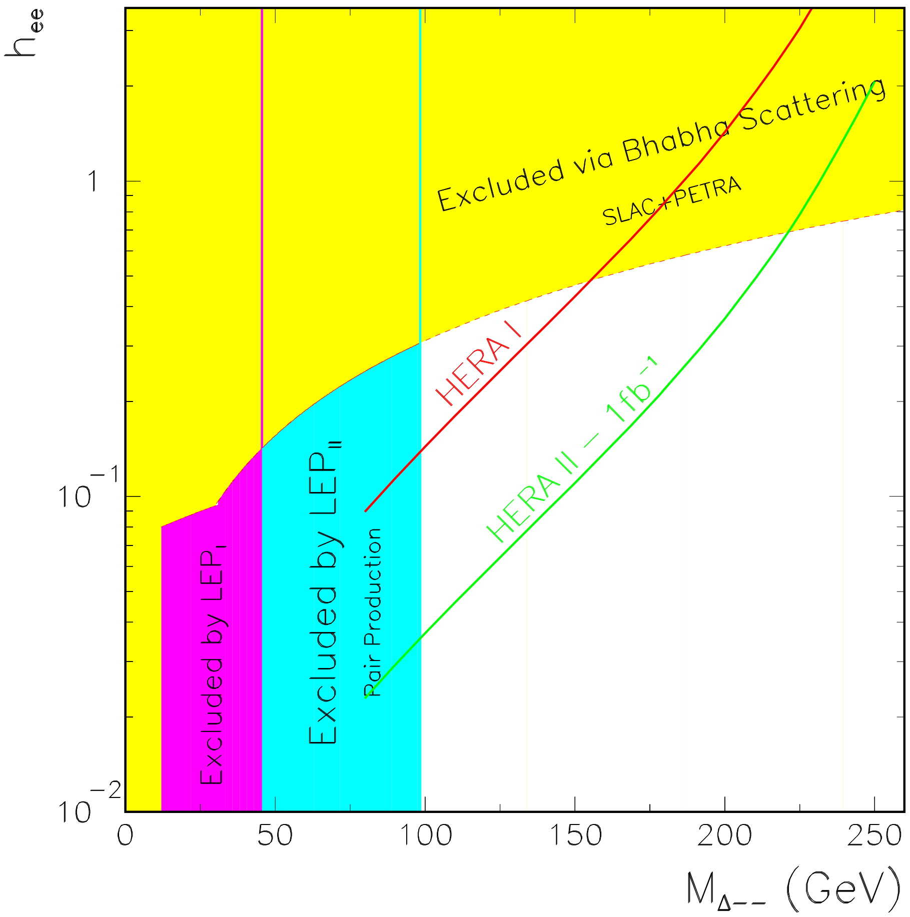
∘ Direct couplings to quarks forbidden by Q conservation

$\Delta^{\pm\pm}$ prospects at HERA



HERA Simulation using PYTHIA + COMPHEP (B. Olivier et al., H1 Collab.)

- Expect: (2/3) "elastic" and (1/3) "inelastic" contributions
- For $M_\Delta \gtrsim 100$ GeV: in $\lesssim 50\%$ cases 1 e lost + 2 e in $20 \lesssim \theta \lesssim 150°$
  $\epsilon_{tot} \simeq 40\%$ to 70% to reconstruct the $\Delta^{\pm\pm}$



HERA prospects assume:

No signal

Negligible background

$\beta(\Delta^{++} \to e^+e^+) = 100\%$

HERA$_I$ $\epsilon_{tot} = 40\%$ (ct)

HERA$_{II}$ $\epsilon_{tot} = 70\%$ (ct+fw)

$\Downarrow$

For $h_{ee} = 0.3$:

$M_\Delta \lesssim 130$ GeV (HERA$_I$)

$M_\Delta \lesssim 190$ GeV (HERA$_{II}$)

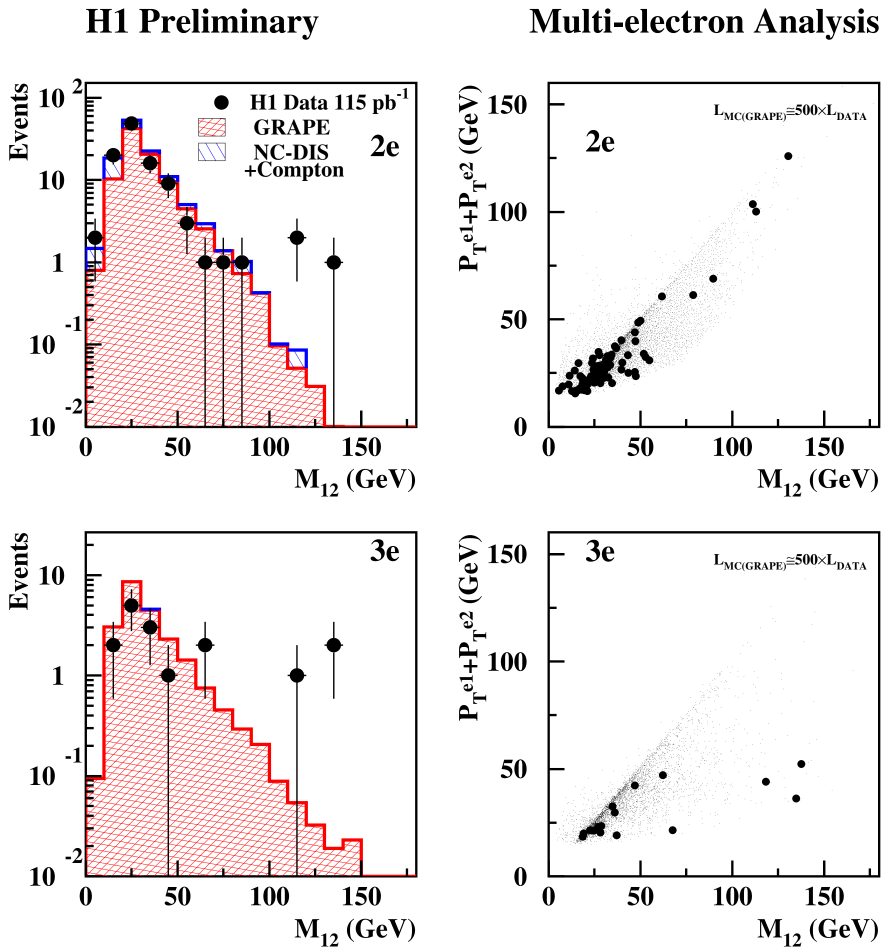
Note: $\exists$ Exhaustive review of constraints (Bileptons): F. Cuypers, S. Davidson (1998)

Outstanding Multi-leptons at HERA

Electrons 115 pb^{-1} $e^{\pm}p$ data (H1 Collab. preliminary DIS 2002)

Muons 70 pb^{-1} $e^{\pm}p$ data (H1 Collab.preliminary DIS 2002)

- SM background: elastic+inelastic $\gamma(e) - \gamma(p)$ collisions + Cabbibo-Parisi ($e\,l$ reaction following $\gamma(p) \to l^+l^-$)



Analysis requires

≥ 2 central "e"

$\left[20 < \theta_e \lesssim 150°\right]$

$P_T(e) > 5, 10$ GeV

3^{rd} "e" unrestricted

- Results at high masses:

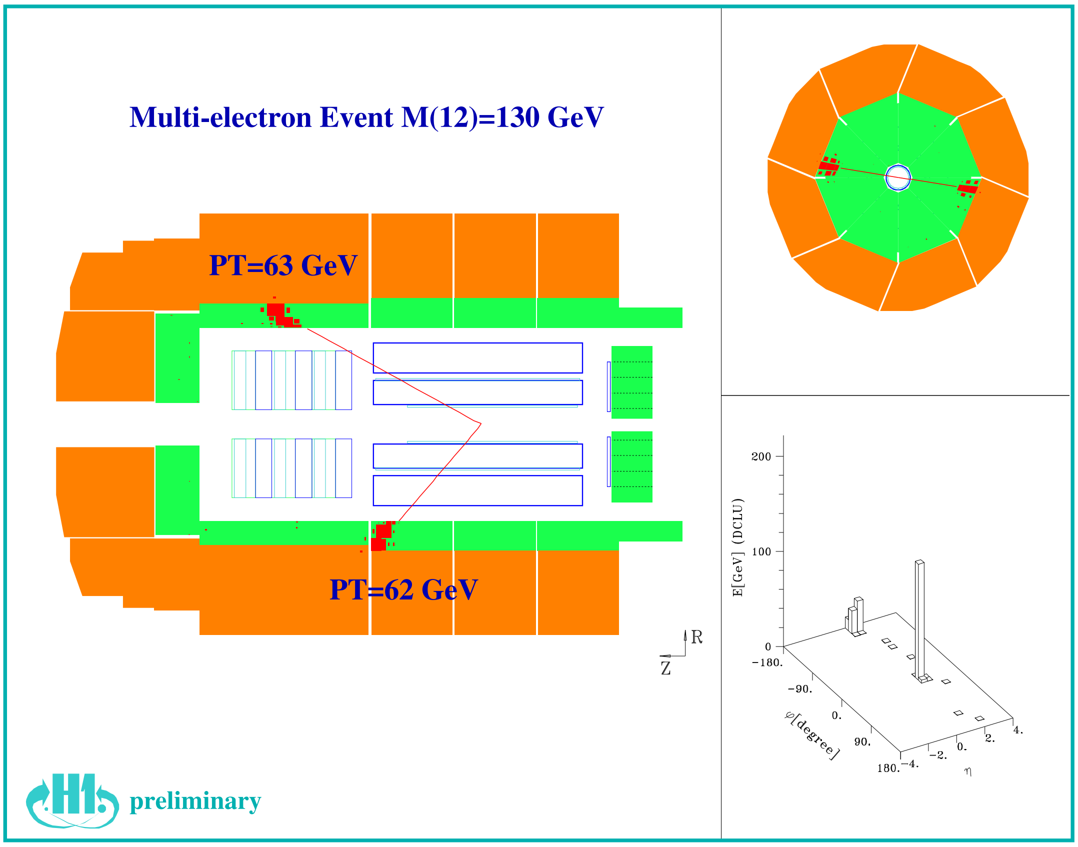
Selection	H1 DATA	SM
Visible 2e $M(12) > 100$	3	0.25 ± 0.05
Visible 3e $M(12) > 100$	3	0.23 ± 0.04

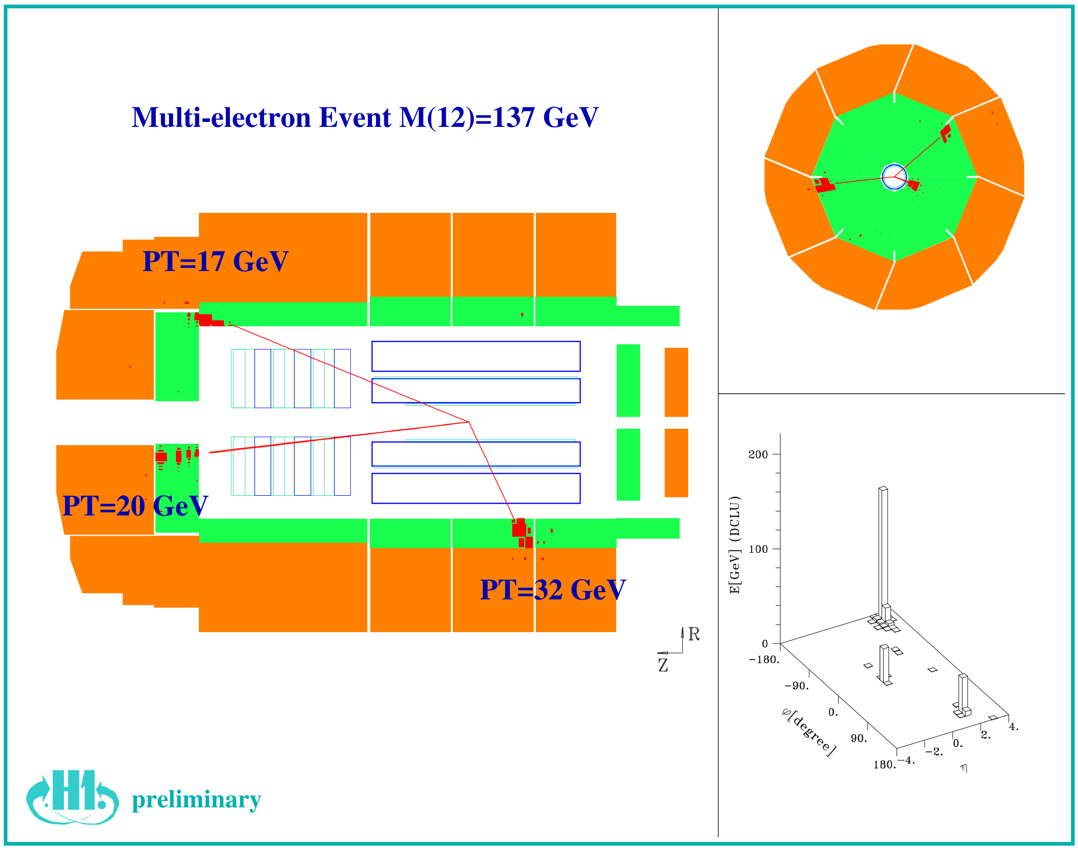
No $\mu\mu$ events seen with $M_{\mu\mu} > 100$ GeV;

Three "2e" events $\leftrightarrow 3 \times \mathcal{L}\epsilon(\mu\mu)/\mathcal{L}\epsilon(ee) \simeq 1\mu\mu$ event

Outstanding Multi-leptons at HERA

(snapshot)





Summary

There do $\exists$ possibly exciting new physics which could lead to acceptable and striking signals at HERA (leptoquarks, LFV, composite fermions, FCNCs, $\not R_p$-SUSY, doubly charged Higgs, Bileptons, contact interactions, extra-dimensions ....

- Rather exhaustive searches have been performed at HERA$_I$ using or combining e^-p data [$\mathcal{O}(10)$ pb^{-1}] and e^+p data [$\mathcal{O}(100)$ pb^{-1}]

- Outstanding event topologies possible (beyond $\exists$ constraints) from (e.g.)
  $\not R_p$-SUSY: $\tilde{t}_1 \to \tilde{b}_1 + W$; $W \to l\nu$
  t-channel slepton exchange
  FCNCs in top sector: $eu \to et$; $t \to Wb$...
  Doubly charged Higgses: $e^+p \to e^-\Delta^{++}X$; $\Delta^{++} \to l^+l^+$

- The upgraded HERA and Tevatron Colliders will offer (≥ 2002) complementary sensitivity to new physics coupling to $e - q$ pairs (leptoquarks, LFV, composite fermions, FCNCs, $\not R_p$-SUSY etc.) in a mass range beyond the reach of LEP$_{II}$

- The discovery reach at HERA$_{II}$ can profit mainly from:
  $\uparrow \mathcal{L}(e^\pm p)$ [$\mathcal{O}(1)$ fb^{-1} $\times 2$] $\uparrow \sqrt{s}_{ep}$ [330 GeV] maybe possible
  Disantangling an eventual signal at HERA$_{II}$ can profit from:
  $e^\pm_{L,R}$ beam $\leftrightarrow$ slightly improved signal/background
  $\leftrightarrow$ distinguish quantum numbers