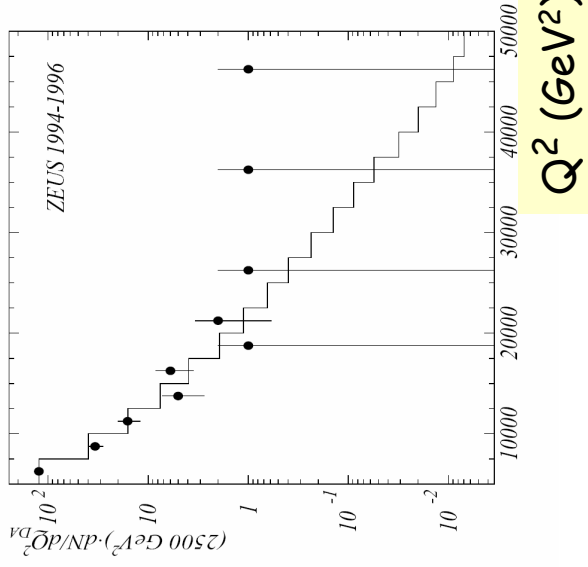
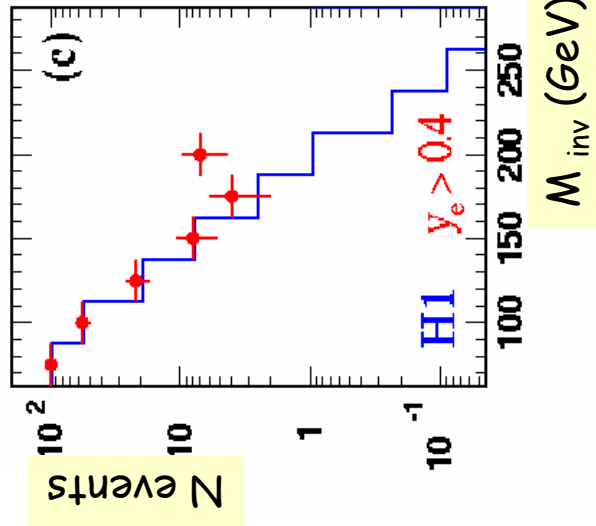


Euro-GDR SUSY meeting,
 Barcelona, 2nd-5th November 2005

Beyond the Standard Model at HERA

Emmanuelle PEREZ

DESY & CEA-Saclay, DSM / DAPNIA / Spp

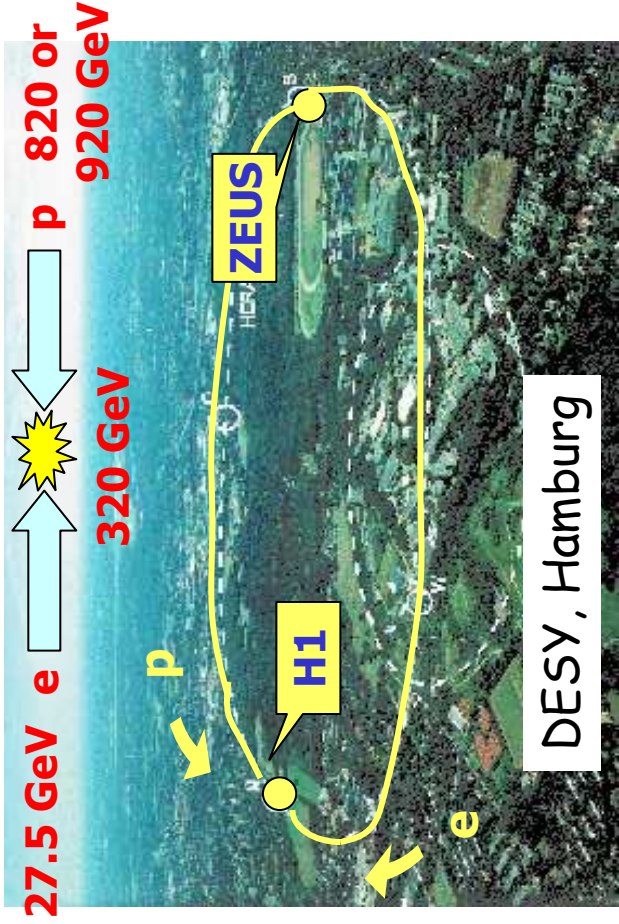


Remember :
 H1, Z. Phys. C74 (1997) 191
 ZEUS, Z. Phys. C74 (1997) 207

Large interest in the community.
 300 citations each, show that:

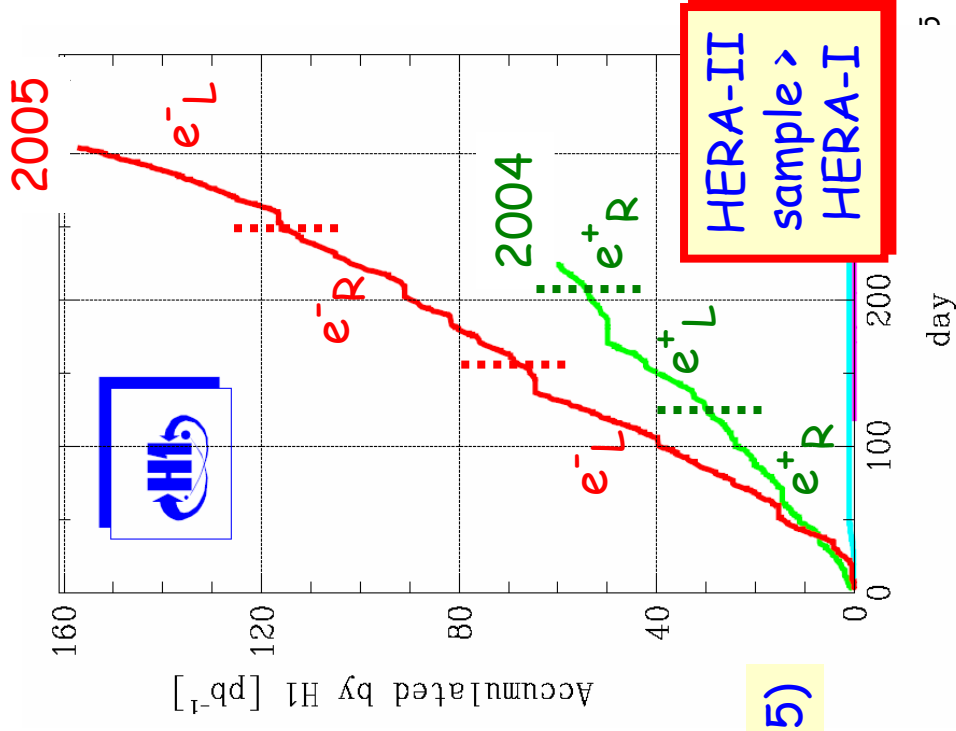
Yes, BSM surprises might
 come from HERA !

H1 and ZEUS at HERA



"HERA II" : started in 2003

- Lumi upgrade
- longitudinal e polarisation
- detector upgrades



"HERA I" : 1994-2000, 120 pb^{-1} per exp.

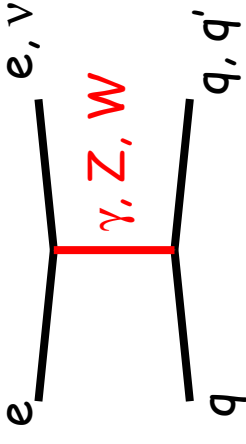
Year	\sqrt{S} (GeV)	Beam	$\int L_{\text{physics}}$ (pb^{-1})
94 - 97	300	e^+p	≈ 40
98 - 99	320	e^-p	≈ 15
99 - 00	320	e^+p	≈ 65

HERA I+II analyses : up to $\approx 200 \text{ pb}^{-1}$ (summer 05)

Data taking until mid-07 $\rightarrow 700 \text{ pb}^{-1}$ per exp.

Introduction & Outline

- Searches for new currents affecting the DIS process
 - Charged current DIS
 - Neutral current DIS



- Model dependent searches for new particles :

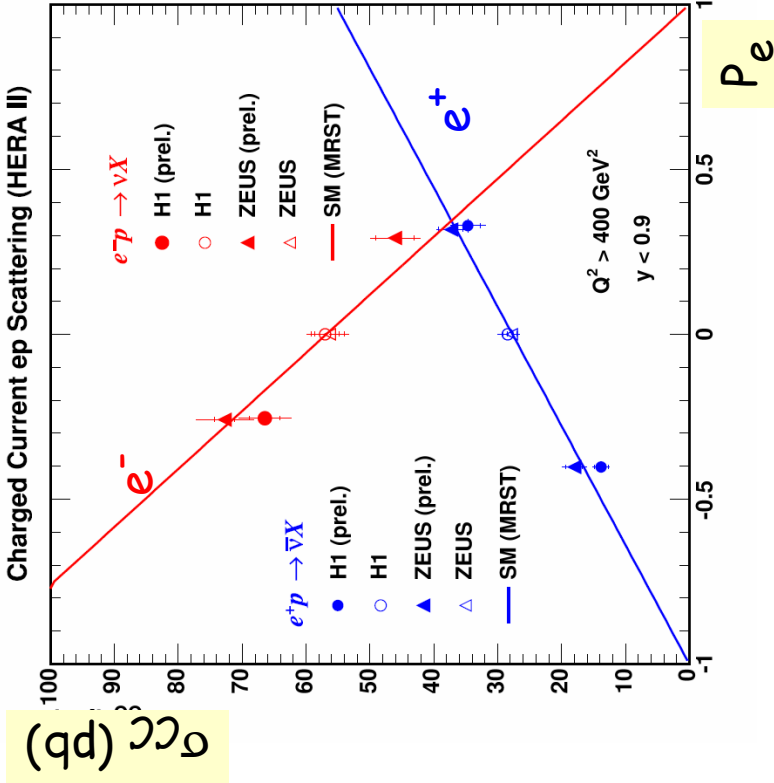
Since HERA is not an annihilation machine, the cross-section is small for (heavy) pair-produced new particles.

- Investigate **single particle production** instead
- The limits depend on the coupling of the new particle to SM ones, i.e. no “absolute” mass limits in contrast to LEP, Tevatron.
- In case of a discovery: information not only on M but also on this coupling

Examples : Leptoquarks, Rp-violating SUSY, excited fermions.

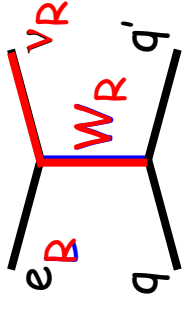
- Model independent searches for new physics :
 - Study SM processes with a low cross-section
 - investigate all possible final states, compare data to SM expectation

CC DIS and new W' bosons



Future HERA sensitivity might reach $\sim 350 \text{ GeV}$ (high lumi, high precision on polarisation measurement)

i.e. unlikely to discover a W_R at HERA-II - but nice textbook plot !

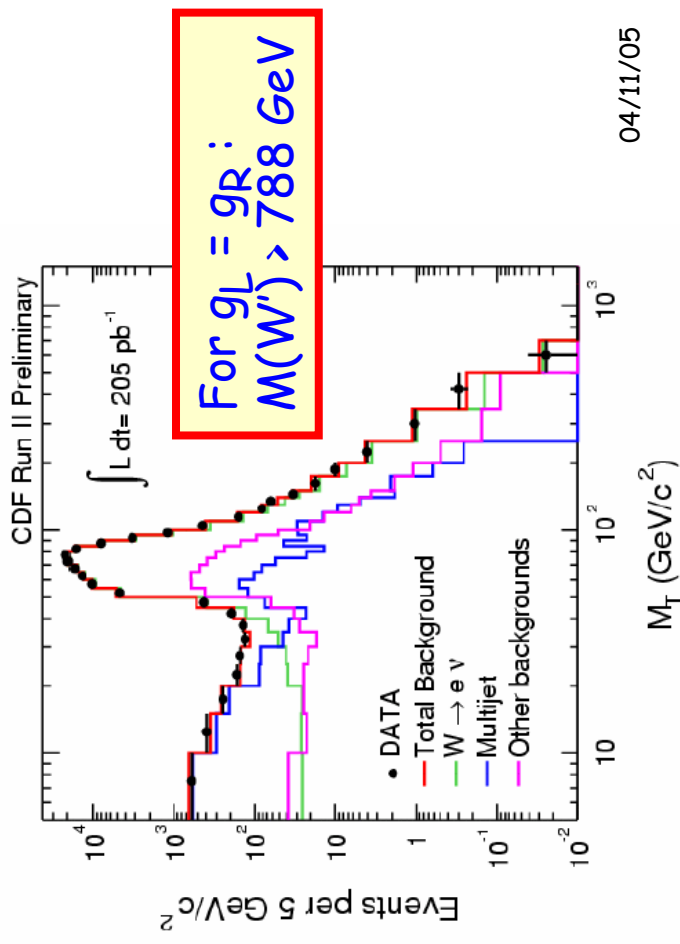


$$\sigma_{CC}(e^\pm, SM) \sim (1 \pm P_e)$$

CC DIS with polarised e beam a priori sensitive to right-handed W bosons (provided that ν_R is light and stable)

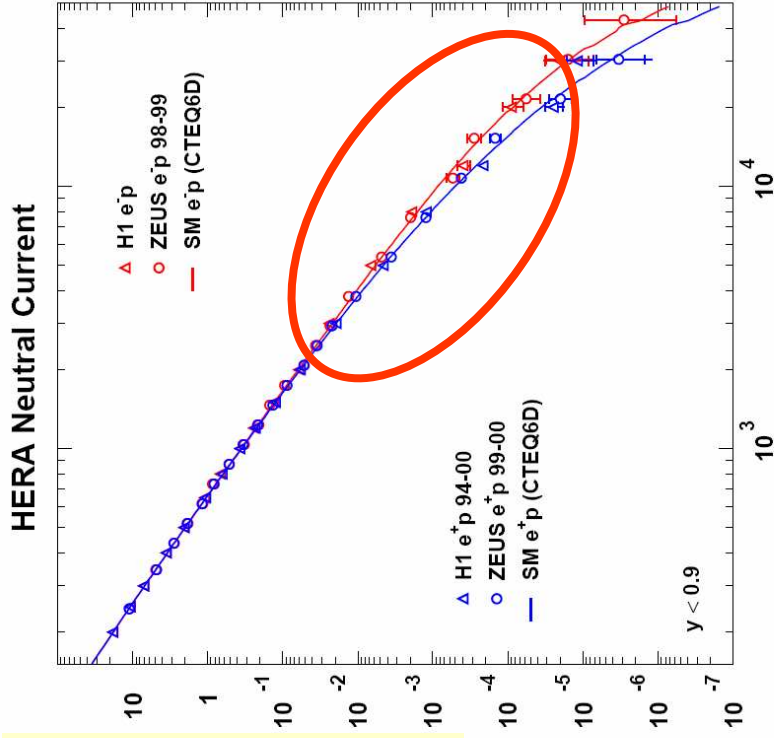
Extrapolations to $P_e = \pm 1$ consistent with no W_R

Corresponding bound on $M(W_R)$ if $g_L = g_R$? Well, much below that reached at Tevatron...



NC DIS at high Q^2

$d\sigma/dQ^2$ (pb/GeV²)



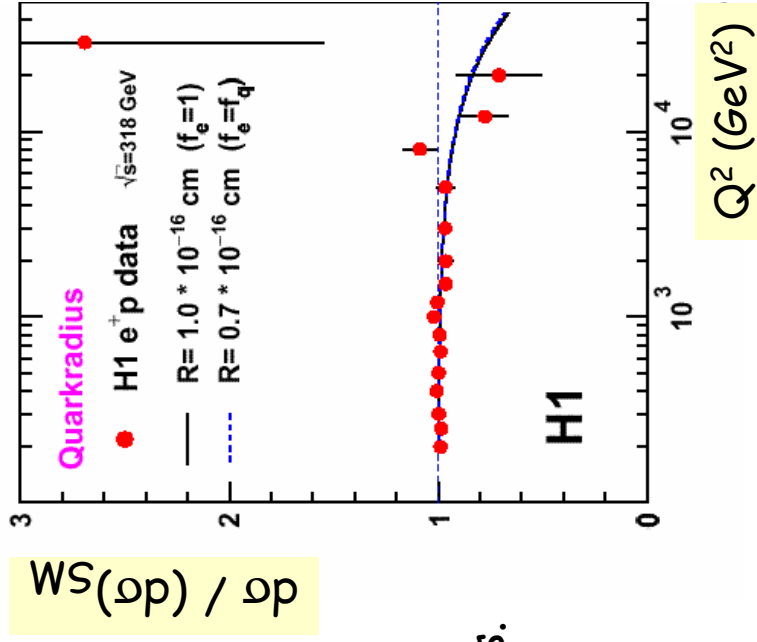
Q^2 (GeV²)

Measurements up to ~ 40000 GeV²
 Typical current precision : $\sim 3\%$ at 1000 GeV², $\sim 10\%$ at 10000 GeV² where largely dominated by statistical errors.

Already provides a lot of information !

First simple example :

Remind that DIS is the golden process to study the structure of matter.



assign a finite size to the EW charge distributions.

$$f(Q^2) = 1 - \frac{R_q^2}{6} Q^2$$

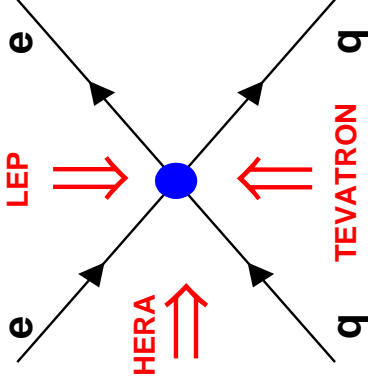
$$R_q < 0.85 \cdot 10^{-18} \text{ m}$$

ZEUS, DESY 03-218; H1, DESY 03-052

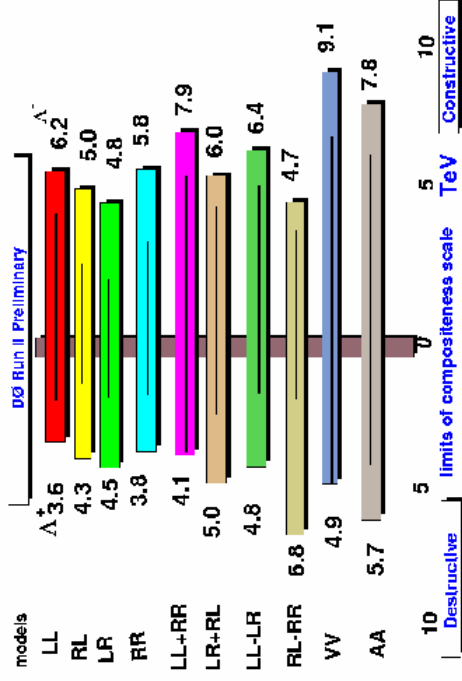
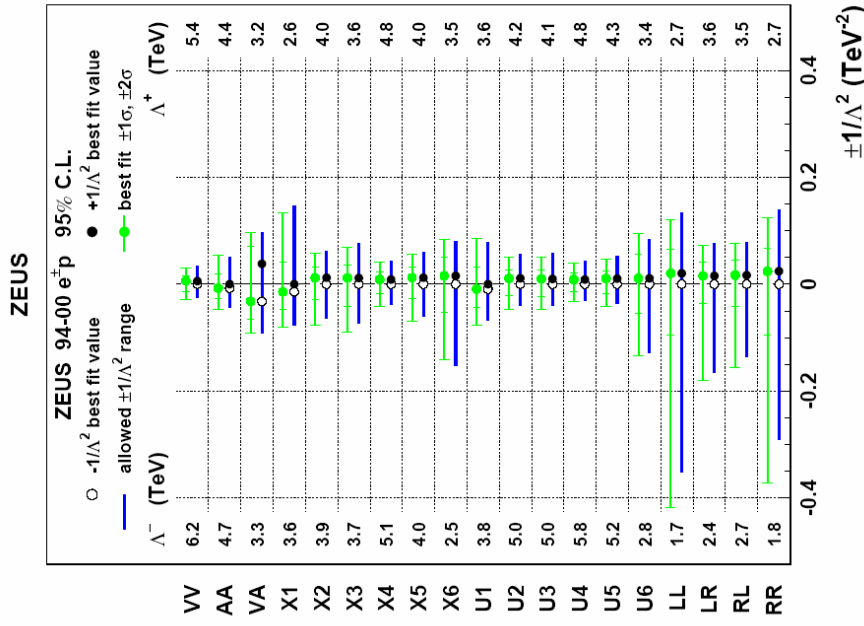
New Physics in $e\bar{q} \rightarrow e\bar{q}$ amplitude

- a) general contact interactions : assume that the scale Λ of NP is large, parameterize the effects of NP as a four-fermion interaction :

$$L = \sum_{i,j=L,R} \mathcal{E}_{i,j} \frac{4\pi}{\Lambda^2} (\bar{e}_i \gamma^\mu e_j) (\bar{q}_j \gamma_\mu q_i)$$



Typical bounds $\Lambda > 5$ TeV



Similar sensitivity achieved at Tevatron from Drell-Yan

- b) t-channel exchange of Kaluza-Klein gravitons
 c) u-channel exchange of a particle coupling to (e,q) i.e. a "leptoquark"

L and B together: Leptoquarks

Apparent symmetry between the lepton & quark sectors ?
 Exact cancellation of QED triangular anomaly ?

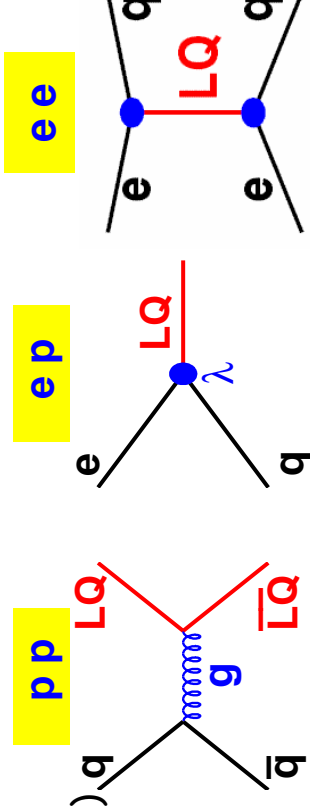
- LQs appear in many extensions of SM

(enlarged gauge structure, compositeness, technicolor...)

- **Connect lepton & quark sectors**

- **Scalar or Vector** color triplet bosons

- Carry both L and B, frac. em. charge



λ (unknown) coupling lepton-quark-LQ

→ Classified by **Buchmuller, Ruckl and Wyler** according to their quantum nbs

Assumptions : LQs couple only to SM fermions and bosons

pure chiral couplings

family diagonal couplings

BRW model : if LQs \subset isospin multiplet are degenerate :

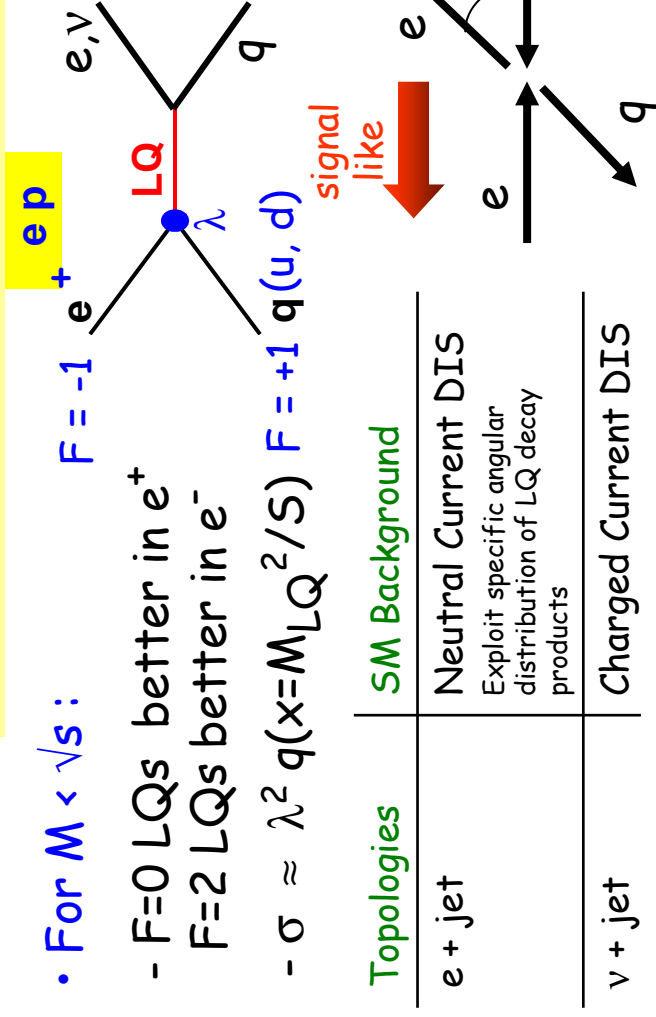
$$\begin{cases} \beta(LQ \rightarrow lq) & = 1 \text{ or } 1/2 \\ \beta(LQ \rightarrow \nu_l q) & = 0 \text{ or } 1/2 \end{cases}$$

→ (Some of) BRW assumptions relaxed \Rightarrow "generic models"

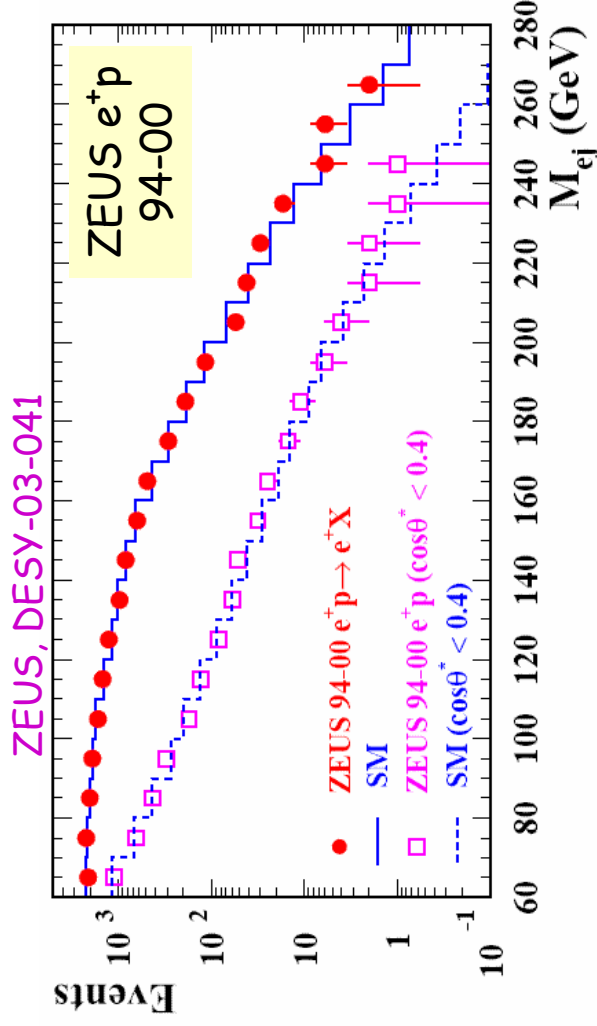
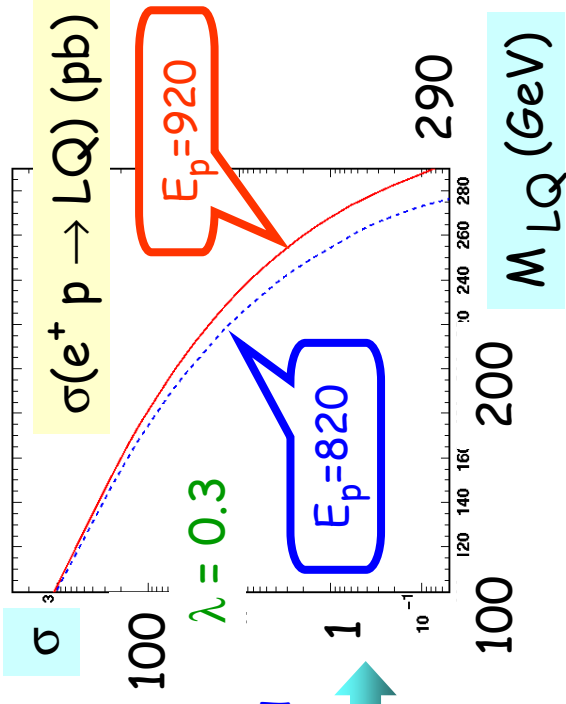
→ $\beta_l = \beta(LQ \rightarrow lq)$ and $\beta_\nu = \beta(LQ \rightarrow \nu_l q)$ free parameters

Leptoquarks at HERA

- For $M < \sqrt{s}$:
 - $F=0$ LQs better in e^+
 - $F=2$ LQs better in e^-
- $\sigma \approx \lambda^2 q(x=M_{LQ}^2/S)$ $F = +1$ $q(u, d)$



Topologies	SM Background
$e + \text{jet}$	Neutral Current DIS Exploit specific angular distribution of LQ decay products
$\nu + \text{jet}$	Charged Current DIS



Look for a resonant peak in M spectra

- For $M > \sqrt{s}$:
 - cf contact interactions, look for deviations at high Q^2 .
 - u-channel + interference with DIS.

No excess observed neither in the NC nor in the CC channel.

Existing Bounds on 1st Generation LQs

For $\beta = \text{BR}(LQ \rightarrow eq) = 1$:

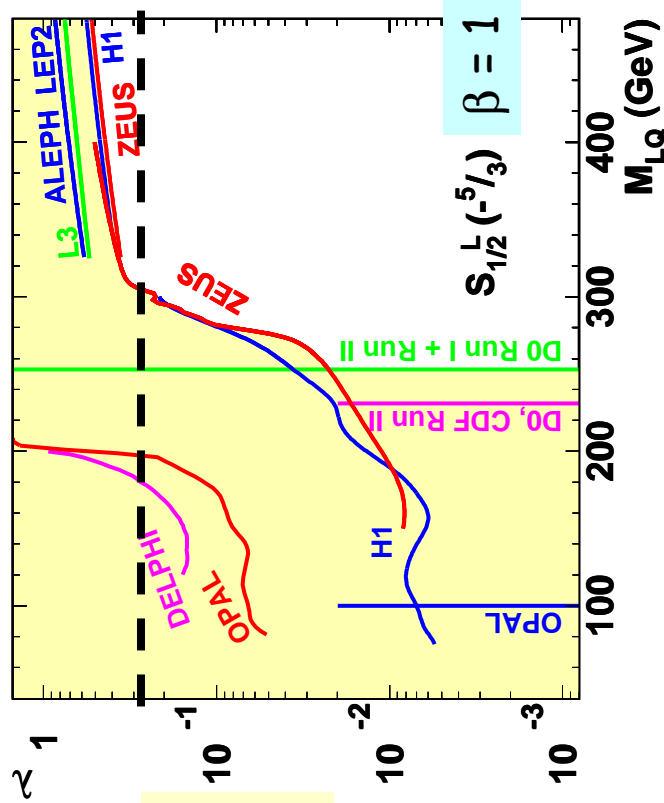
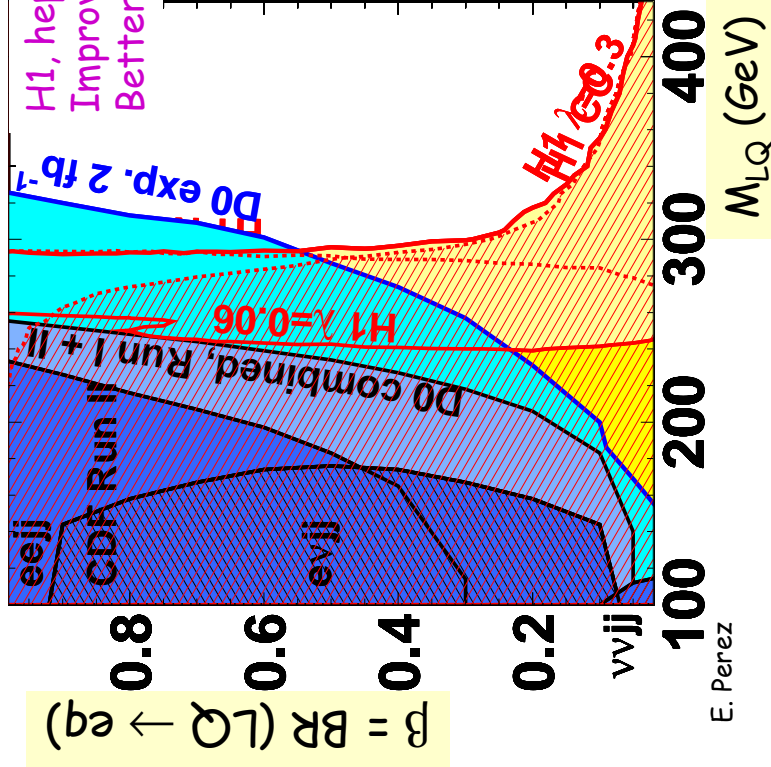
DO Run II + D0 Run I: $M > 256 \text{ GeV}$

For $\lambda = \sqrt{4\pi\alpha_{em}} \approx 0.3$: HERA rules out LQ masses $< \approx 290 \text{ GeV}$

$\beta \neq 1$ at TEVATRON:

eeqq	evqq	vvqq
Z/DY + jj	W + jj	W/Z + jj
QCD	QCD	QCD

difficult, large backgrounds



- Tevatron probes large masses for large β ($LQ \rightarrow eq$) independently of λ .
But large β ($LQ \rightarrow \nu q$) is difficult.
- HERA better probes LQs with small β provided that λ not too small

→ Complementarity of both facilities

ep as the golden machine to study LQs

In case a signal is observed : spin is easily determined by looking at the angular distributions (no combinatorial background, large acceptance)

Further determination of some of the LQ quantum numbers :

$F = 0$ or 2 ? Compare rates in e^-p and e^+p

Chiral couplings ? Play with polarisation of lepton beam

Couples to ν ? Easy to see since good S/B in νj channel

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

i.e. HERA would be the ideal machine to study LQs, if discovered

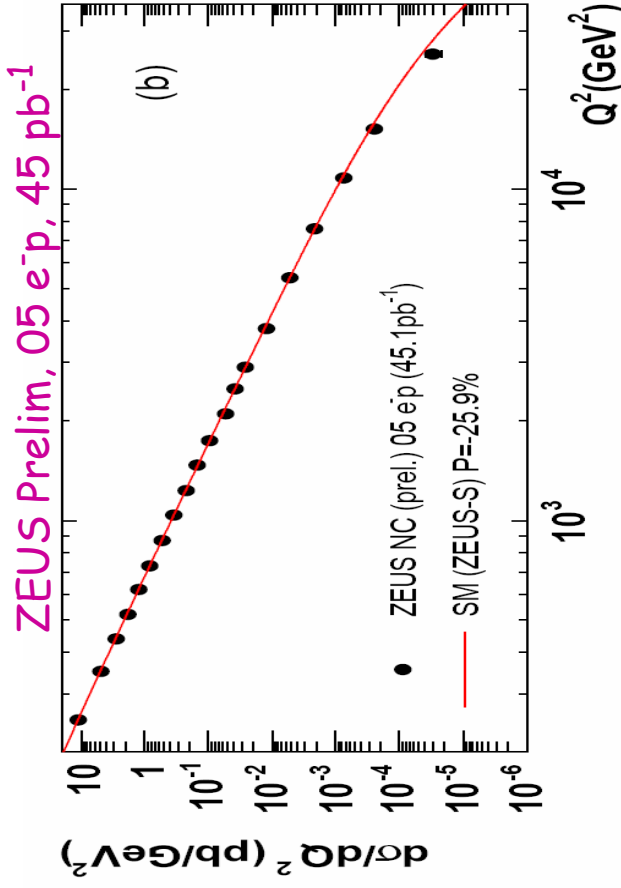
LQ prospects

Taking into account our bounds (obtained from 100 pb⁻¹ of e⁺ p data):
 Can we still hope to observe a LQ signal at HERA-II?

e.g. for a F=0 LQ which would manifest itself as a resonance i.e. $M < \sim 280$ GeV:

Total e ⁺ p luminosity	$\sigma_{\text{prod}} = \text{current limit}$	$\sigma_{\text{prod}} = 0.5 * \text{limit}$
350 pb ⁻¹	$\sim 4 \sigma$	$\sim 2.5 \sigma$
700 pb ⁻¹ (i.e. H1 + ZEUS)	$> 5 \sigma$	$\sim 3.5 \sigma$

(my crude estimates, depend a bit on the LQ mass, numbers to be taken with care...)



→ Yes if the coupling is not too far from our present limits.

→ Excess might be significant only by combining H1 and ZEUS.
 Work starting in this direction (combining HERA-I limits)

NB : so far HERA-II still looks very much SM-like ...

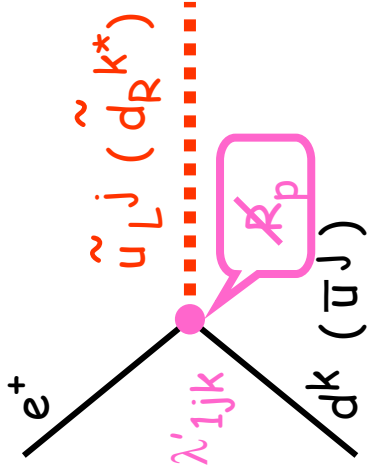
Beyond minimal LQs: SUSY quarks

In supersymmetric models with R-parity violation, squarks could be produced at HERA similarly to leptoquarks.

R_p = +1 for SM particle, -1 for SUSY particle

R_p-violation allows: slepton-lepton-quark (λ), squark-quark-quark (λ'')

squark-lepton-quark and slepton-quark-quark (λ') →
decay of the Lightest Susy Particle (LSP)



e^+ and e^- probe different squarks & couplings

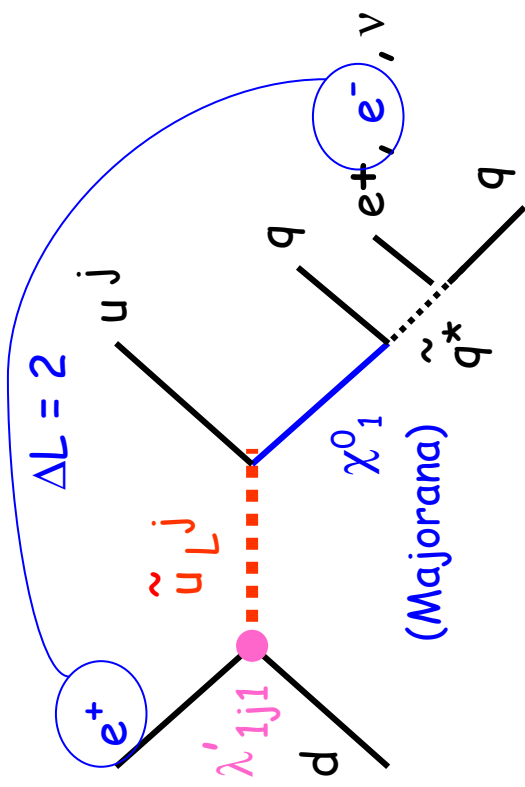
Of main interest:

$e^+ d \rightarrow \tilde{u}_L^j$ via λ'_{1j1}

$e^- u \rightarrow \tilde{d}_R^k$ via λ'_{11k}

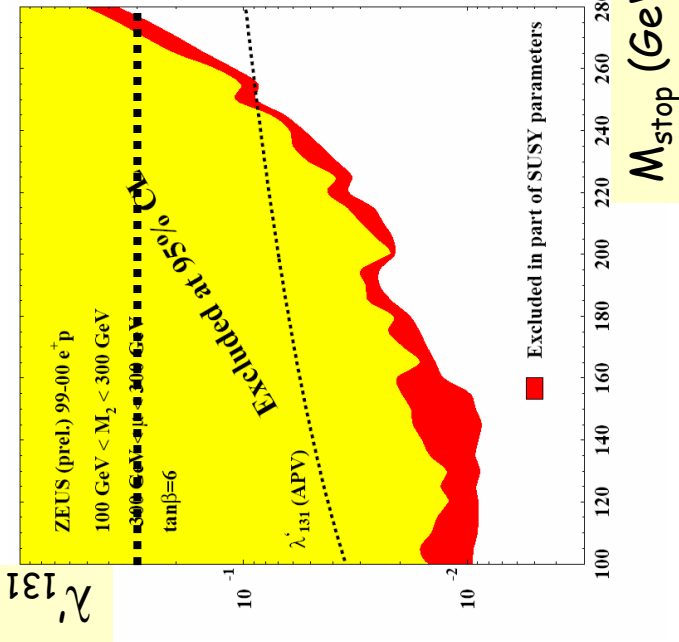
In addition to the "LQ-like" decays, also "gauge" decays. Some of them lead to spectacular signatures.

- e^+ + multi-jets NC DIS
- e^- + multi-jets \approx bckgd free
- ν + multi-jets CC DIS
- $e(\nu) + l +$ multi-jets..... small SM bckgd



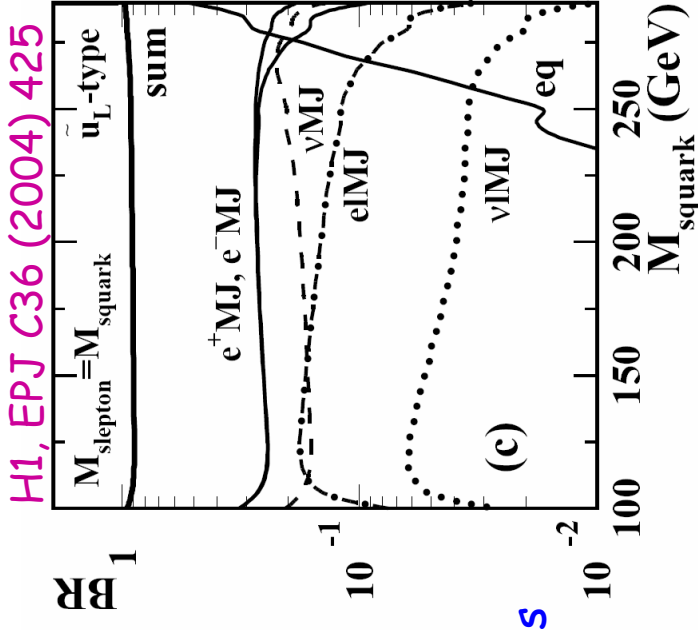
Constraints within the MSSM

- H1, EPJ C36 (2004) 425 : all squark types, all decay modes
- ZEUS Prelim : stop in stop \rightarrow eq and stop \rightarrow b χ^+



Consider first an “unconstrained model” :
 sfermion & gaugino sectors are not related,
 i.e. $M_{\tilde{f}}$ are free parameters

Scan on the parameters which determine
 the other masses & branchings : limits do not depend
 much on the MSSM parameters.



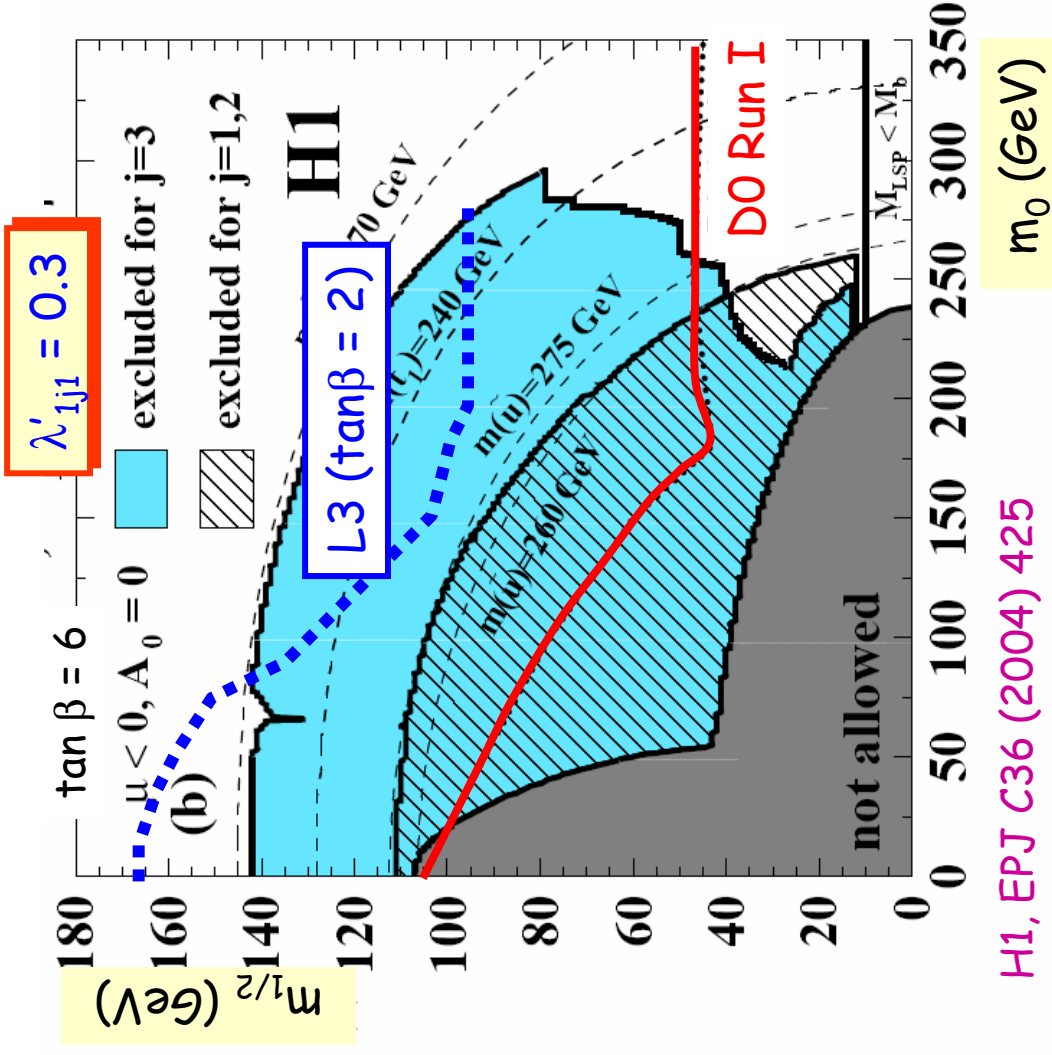
Because S/B is good in
 all channels.

• For $\lambda' = 0.3$ ($\lambda'^2 / 4\pi = \alpha_{em}$) :
 squarks can be ruled out up to $\approx 270 - 280$ GeV

- HERA's sensitivity extends beyond the indirect limits from low energy exp. for \tilde{c}_L and \tilde{t}_L

Constraints within mSUGRA

A more constrained SUSY model, with only 5 parameters.
 Interpretation within mSUGRA useful when comparing to other experiments.



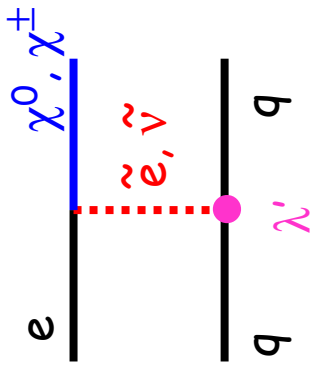
For intermediate m_0 ,
 excluded domain not ruled
 out by LEPII

DO bound (Run I) : moderate, again
 because of large branching in
 $E_{T,miss} + jets$

NB: Tevatron RunI : different
 frameworks, but typical
 sensitivities on stop $\approx 130 \text{ GeV}$.
 RunII: $\approx 200\text{-}250 \text{ GeV}$

Discovery potential for RpV stop
 at HERA with larger L!

If squarks are very heavy



Gauginos production via slepton exchange.

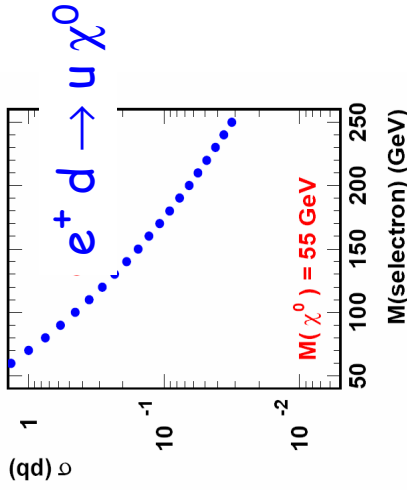
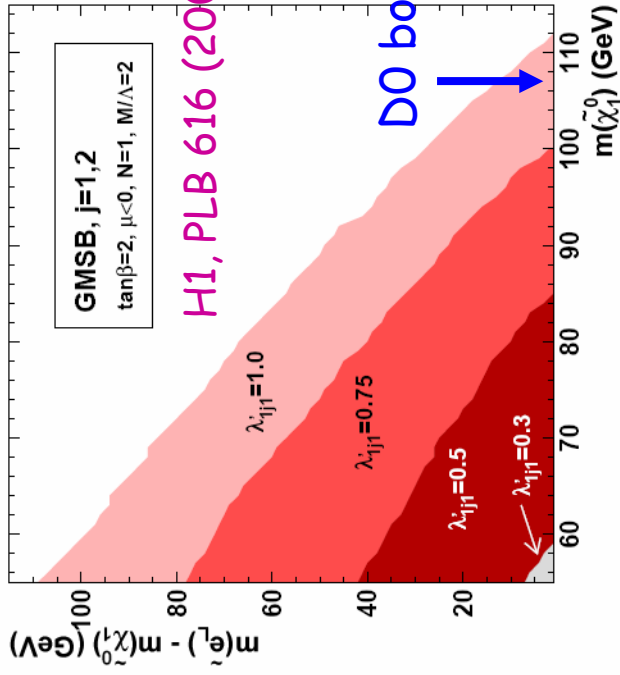
Example σ , for a coupling $\lambda' = 0.5 \rightarrow$

Considered at HERA in two scenarios :

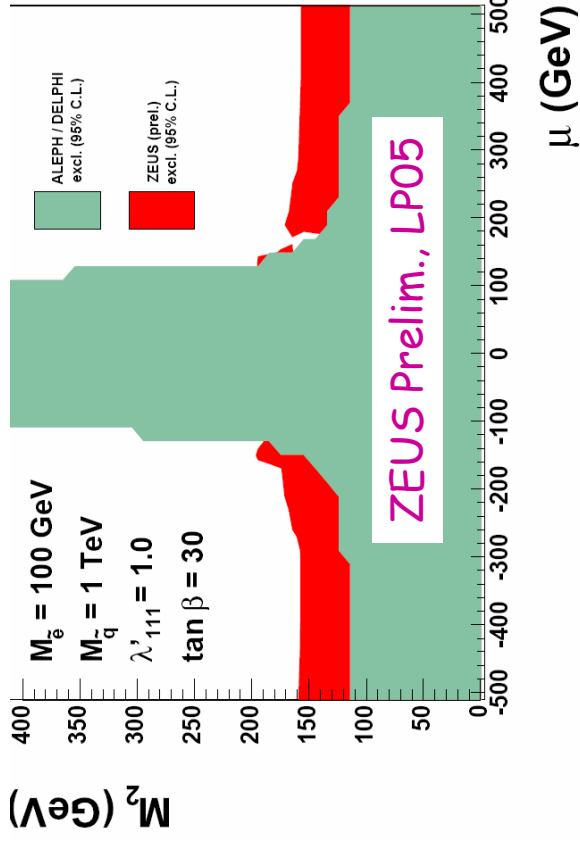
“GMSB” like :

$\chi \rightarrow \gamma + \text{gravitino}$, i.e. $\gamma + E_{T, \text{miss}}$

\rightarrow Study of radiative CC DIS



“mSUGRA” like : $\chi \rightarrow e$ or $\nu + 2$ quarks



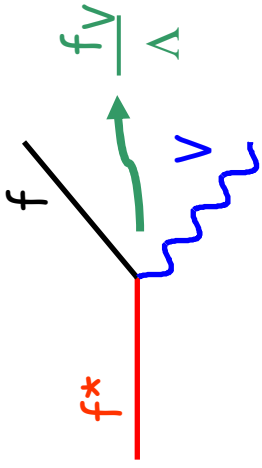
In both cases: slightly extend beyond limits set by LEP/Tevatron.

A new scale of matter ? I+V resonances ?

- Unambiguous signature : direct observation of excited states

(chiral) magnetic coupling $\rightarrow (GeV)^{-1}$

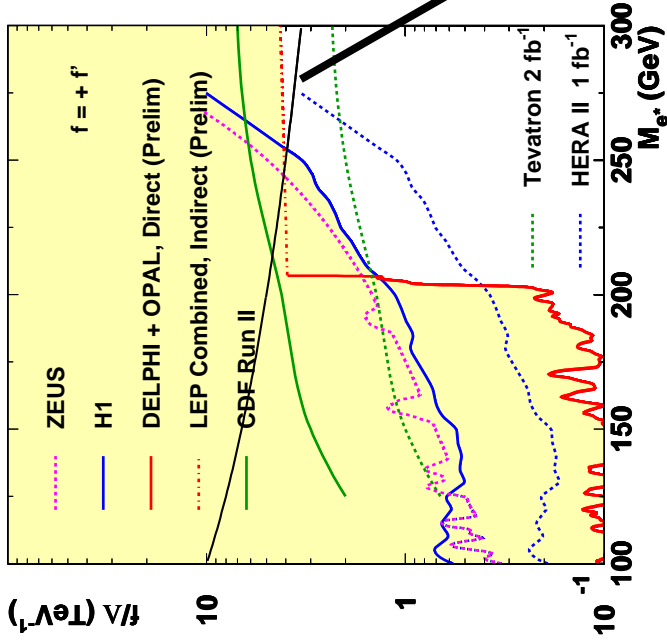
$\Lambda \approx$ compositeness scale



Relative strength of γ, Z
and g couplings $\rightarrow f, f', f_s$

Hagiwara et al, ZPC 29 (1985) 115.
Boudjema et al, ZPC 57 (1993) 425.

\rightarrow Pair production of f^* in e^+e^- and pp ; single production depends on coupling



- Searches for singly produced excited fermions, e.g. $e^* \rightarrow e \gamma$, search for a ($e\gamma$) resonance

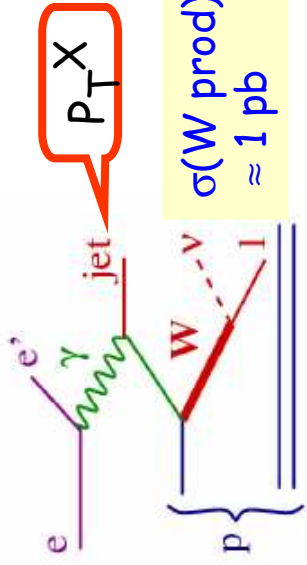
- $Z/DY + \gamma$ at Tevatron
- radiative Bhabha at LEP
- radiative DIS, QED Compton at HERA

NB: e^- data very sensitive to v^* .
HERA II will improve a lot w.r.t our HERA I results.

For $f/\Lambda = 1/M(e^*)$:

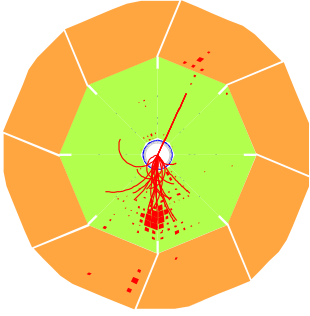
$\rightarrow M(e^*) > 250 GeV$

W Production



$\sigma(W \text{ prod}) \approx 1 \text{ pb}$

HERA I: excess (H1) of **observed** evts at high P_T^X w.r.t. **SM** expectation

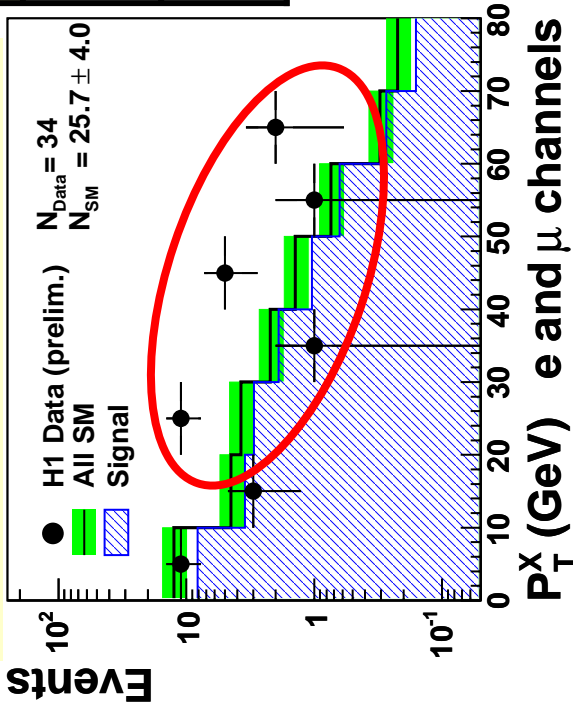


H1, PLB 561 (2003) 241

H1 ep data, 118 pb^{-1}	Combined e & μ
$P_T^X > 25 \text{ GeV}$	11 / 3.4 ± 0.6

$e p \rightarrow l + \text{jet} + P_{T,\text{miss}}$

H1 prelim 94-05, $e^\pm p$, 211 pb^{-1}



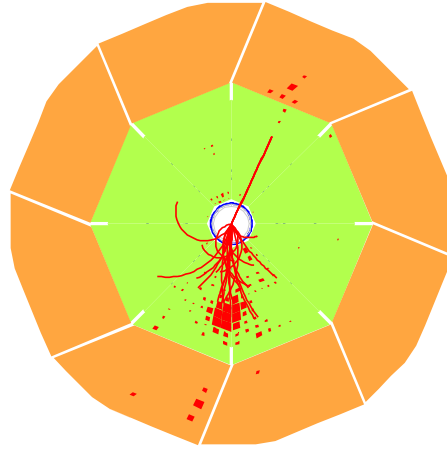
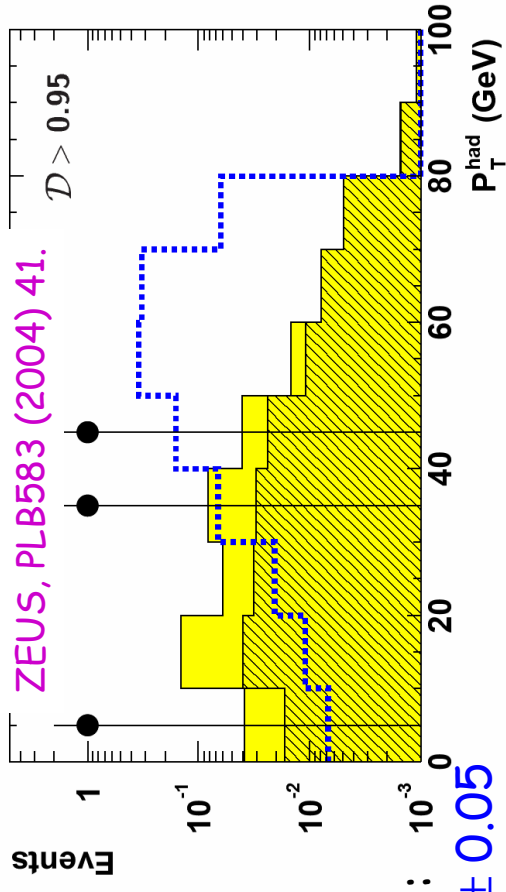
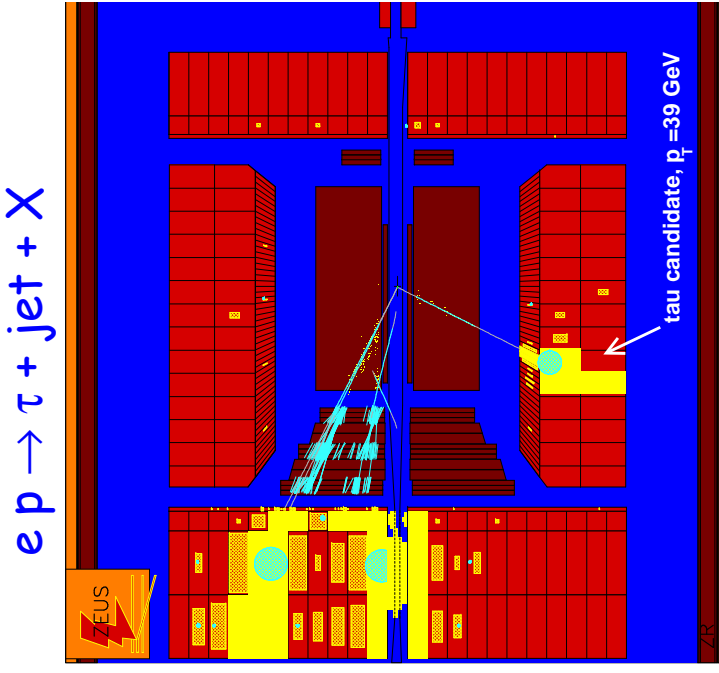
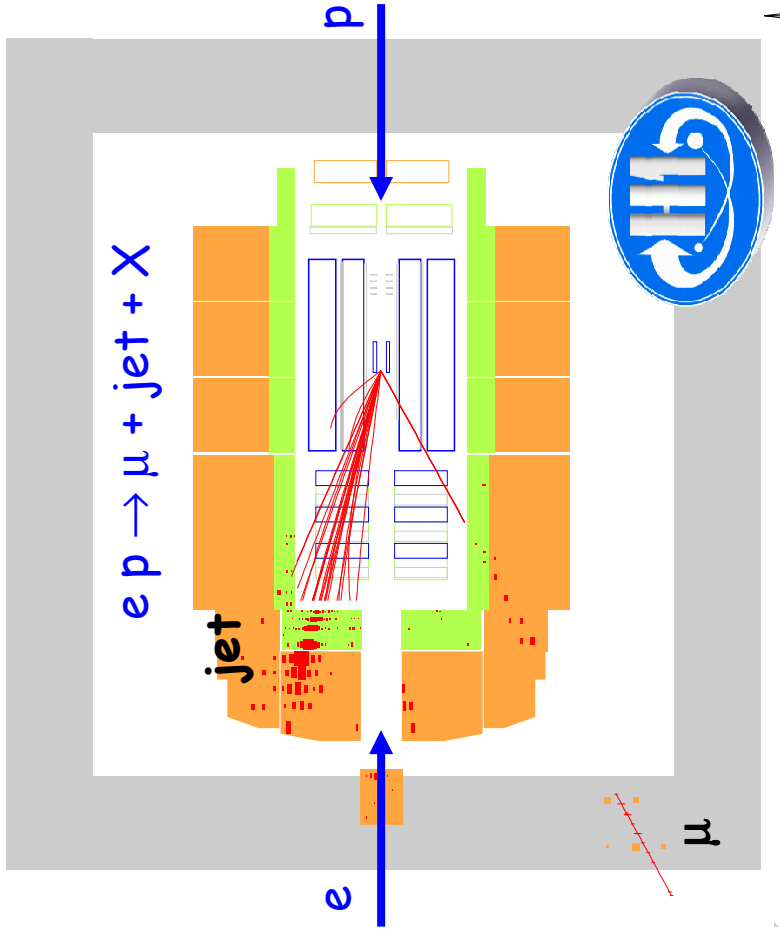
Such evts are still observed in HERA II H1 data...

$P_T^X > 25 \text{ GeV}$	e channel	μ channel	Combined e & μ
H1 94-05 211 pb^{-1}	11 / 3.2 ± 0.6	6 / 3.2 ± 0.6	17 / 6.4 ± 1.1
ZEUS 99-04 106 pb^{-1}	1 / 1.5 ± 0.18		

But still do not show up in ZEUS data...

- no new μ evt in H1 in analyzed HERA II data
- new ZEUS analysis : close to H1 cuts, high W purity
- ZEUS & H1 expectations agree...

HERA events with isolated lepton + $P_{T,miss}$



No high P_{T^X}
 τ event seen
in H1

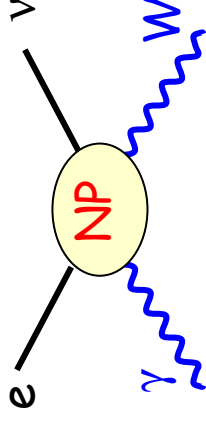
ZEUS τ

@ $P_{T^X} > 25 \text{ GeV}$: $N_{\text{obs}} = 2$, $N_{\text{exp}} = 0.2 \pm 0.05$

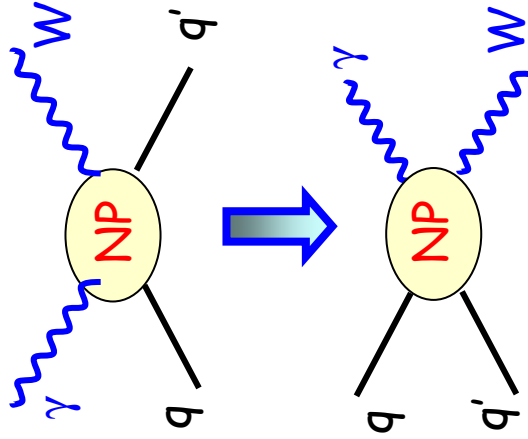
Fluctuation ? New Physics ?

- Non SM W production in $e\gamma$?

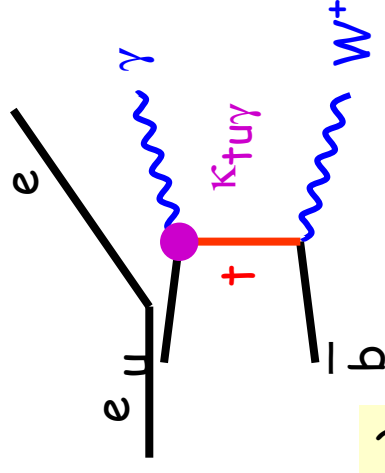
Most likely, something should have been seen at LEP! (NB: unlikely to produce large $P_{T, had}$ at HERA)



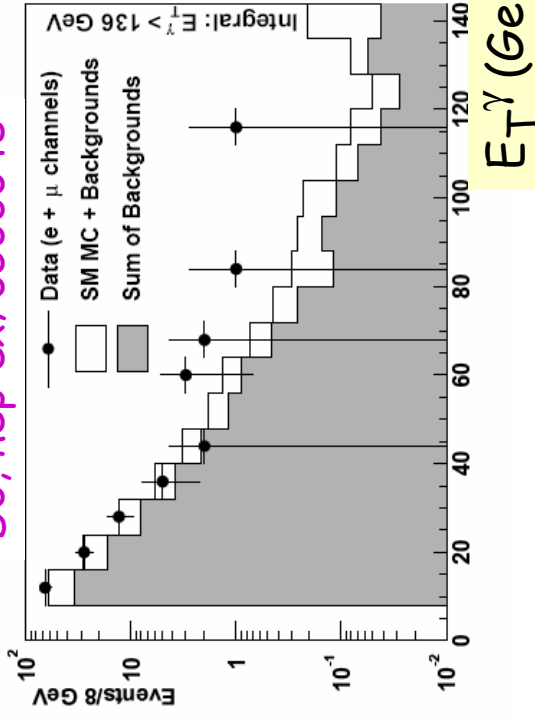
- New physics in γq ?



But NP might not be seen in $W\gamma$ if q' is a b, e.g. FCNC coupling to the top quark?



DO, hep-ex/0503048



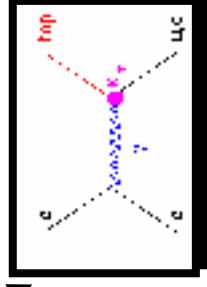
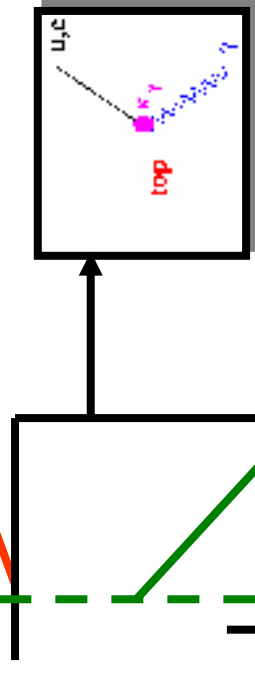
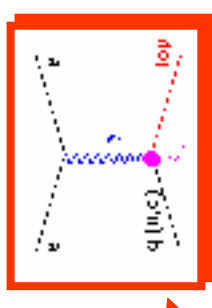
$W\gamma$ at Tevatron agrees with SM...

$K_{t\gamma}$ leads to single top production at HERA (LEP, Tevatron)

FCNC couplings $tq\gamma$, tqZ (tqg) where $q = u, c$ can be searched for in single top prod. at LEP & HERA, in $t \rightarrow qV$ decays in $t\bar{t}$ pairs at Tevatron.

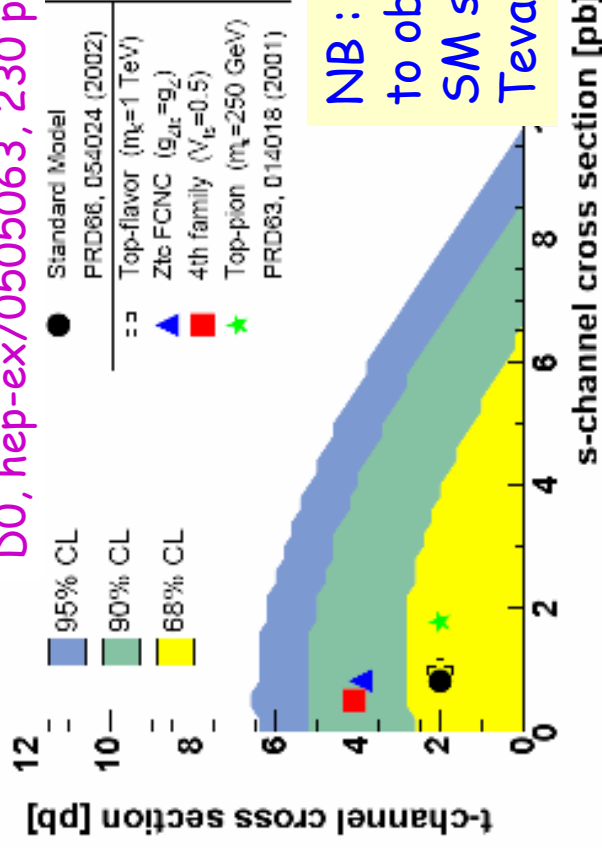
H1, EPJ. C33 (2004) 9

ZEUS, PLB 559 (2003) 153.



Future
HERA &
Tevatron
sensitivities

D0, hep-ex/0505063, 230 pb⁻¹



Isolated lepton events (2)

H1 Preliminary, 211 pb-1 obs. / exp.

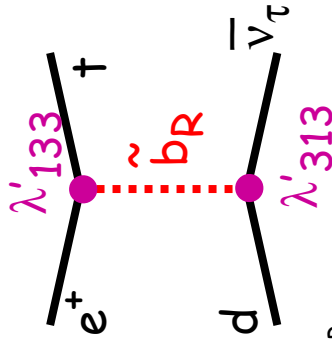
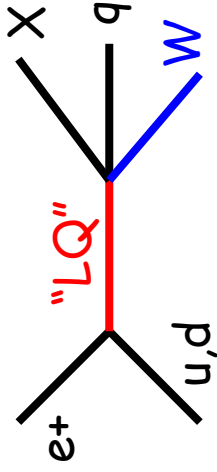
$P_T^X > 25$ GeV	e channel	μ channel	Combined e & μ
Electrons, 98-05 53 pb-1	2 / 0.9 ± 0.2	0 / 0.9 ± 0.2	2 / 1.8 ± 0.3
Positrons, 94-04 158 pb-1	9 / 2.3 ± 0.4	6 / 2.3 ± 0.4	15 / 4.6 ± 0.8

H1 excess not seen in $e^- p!$

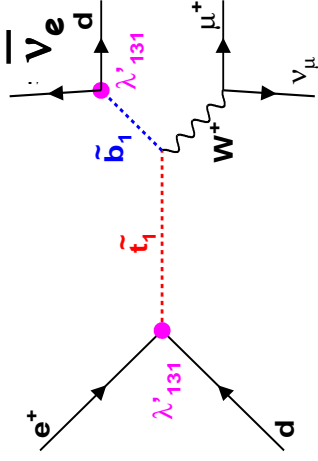
3.4 σ effect...

Might be a 3.4 σ fluctie. But if NP, likely to appear soon at the Tevatron as well ...

Possible explanations ??

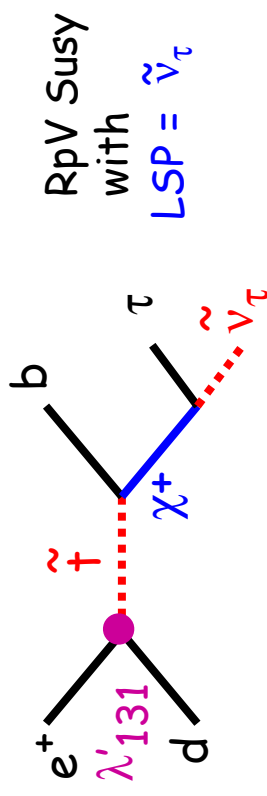


Two RpV couplings with 3rd gene. fields (Not too much $P_{T,miss}$ in that case)



H1, PLB 599 (2004) 159

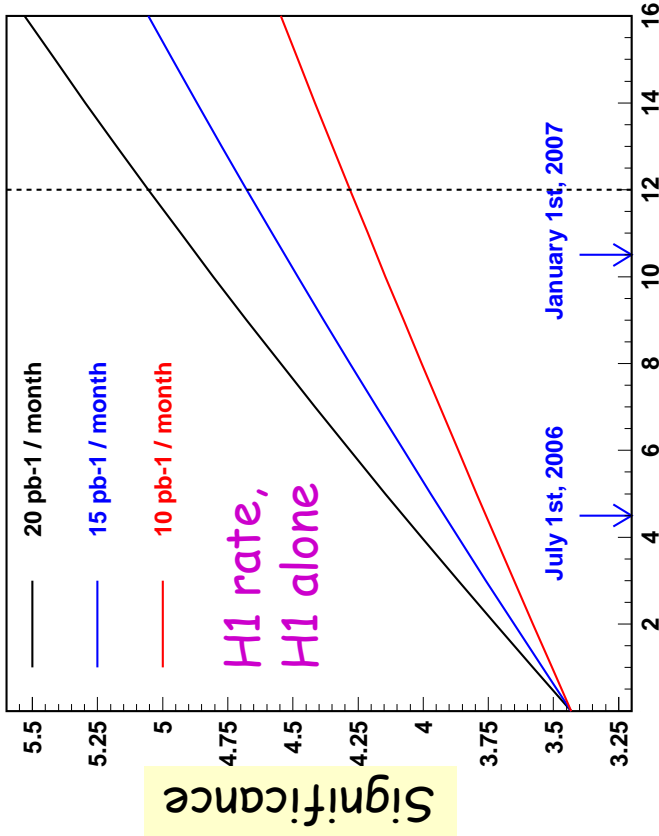
Unlikely because of the had. channel ($j\bar{j} + P_{T,miss}$ in that case, good S/B)



There are possibilities. First clarify the excess !!

Isolated leptons: extrapolations

Isolated leptons: extrapolations for e^+

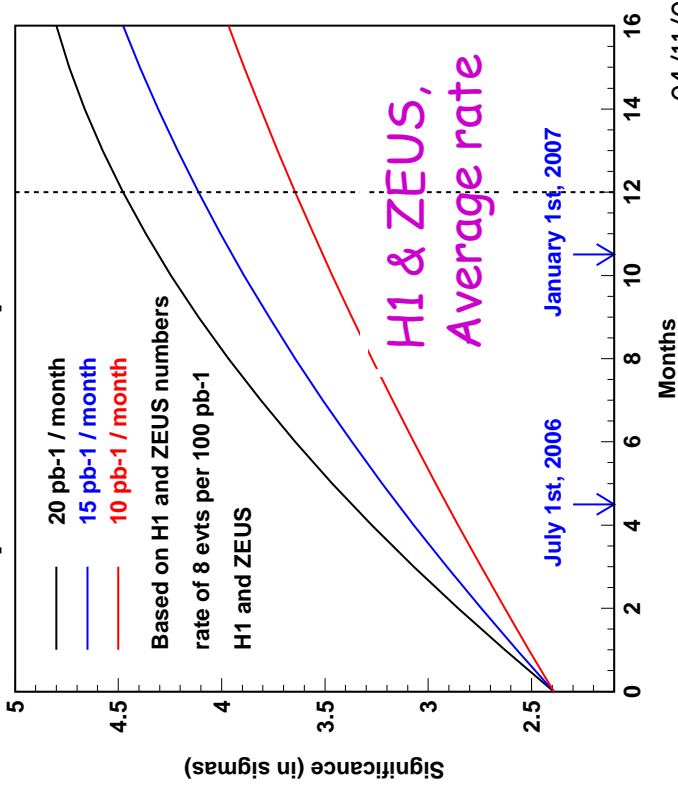


Feb 06

Months (data to come)

- Assume that the events continue to show up at the rate observed in H1 :
- A 4.5σ effect possible with ~ 8 months of additional e^+ luminosity if $20 \text{ pb}^{-1}/\text{month}$
- Take instead the average rate from H1 and ZEUS (e channel), i.e. $4 \text{ evts} / 100 \text{ pb}^{-1}$

Take the same rate for the μ channel
Isolated leptons: extrapolations for e^+



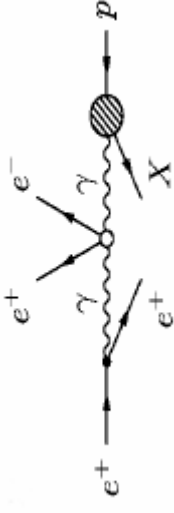
A 4σ effect could be within our reach.
More if we are more lucky.

Let's collect the data and see !!
The fluctie might go away, but this is our best chance for a discovery.

Anomalous multilepton production ?

If anomalous W production: what about anomalous Z ??

Events with ≥ 2 leptons in final state. Mainly produced via $\gamma\gamma$. Cross-section ~ 1 pb for central l , $P_T > \sim 5$ GeV



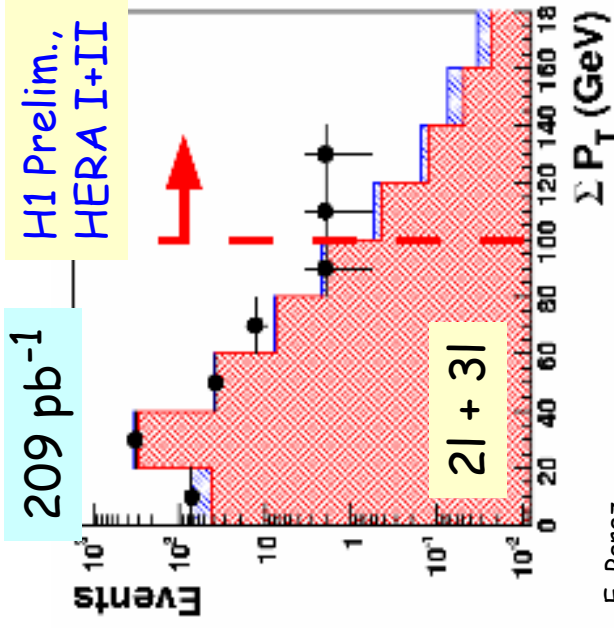
H1 data 94-00 : excess of $2e+3e$ events at high M_{12} = mass of two highest $P_T e$
 No such excess seen in ZEUS HERA-I data

H1 94-00 data obs. / exp.

selection	expt	H1 (115 pb ⁻¹)
$2e, M_{12} > 100$ GeV	3	0.30 ± 0.04
$3e, M_{12} > 100$ GeV	3	0.23 ± 0.04

H1, EPJ C31 (2003) 17

H1 analysis extended to include 03-05 data :



Extended to other $2l$ & $3l$ topologies :

Now $ee, \mu\mu, e\mu, eee, e\mu\mu$ are considered

- no new $2e / 3e$ evt at $M_{12} > 100$ GeV (but one high mass $3e$ event ...)
- one $e\mu\mu$ evt at $M_{\mu\mu} > 100$ GeV, one at $M_{e\mu} > 100$ GeV

Altogether, at $\Sigma P_T > 100$ GeV :

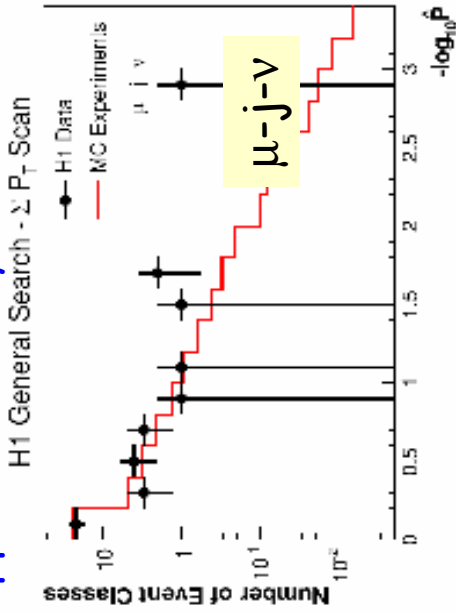
$N_{obs} = 4, N_{exp} = 0.81 \pm 0.14$

"Signature Based" Searches for NP

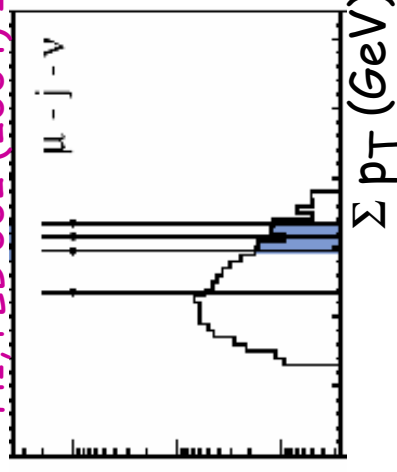
- (Quasi) "model-independent" search for new physics :
 - definition of objects (e, μ , ν , γ , jet, W, Z, ...)
 - look at data vs SM in all "channels" with > 1 object
 - in each channel, find the part of ϕ space with largest deviation (e.g. in M , Σp_T)
 - quantify the agreement using "Gedanken" (Mock, MC) expts

Pioneered by DZero with the full Run I sample
 DO, PRD64, 012004 (2001)

Applied recently to the full sample of H1 data



H1, PLB 602 (2004) 14



2B

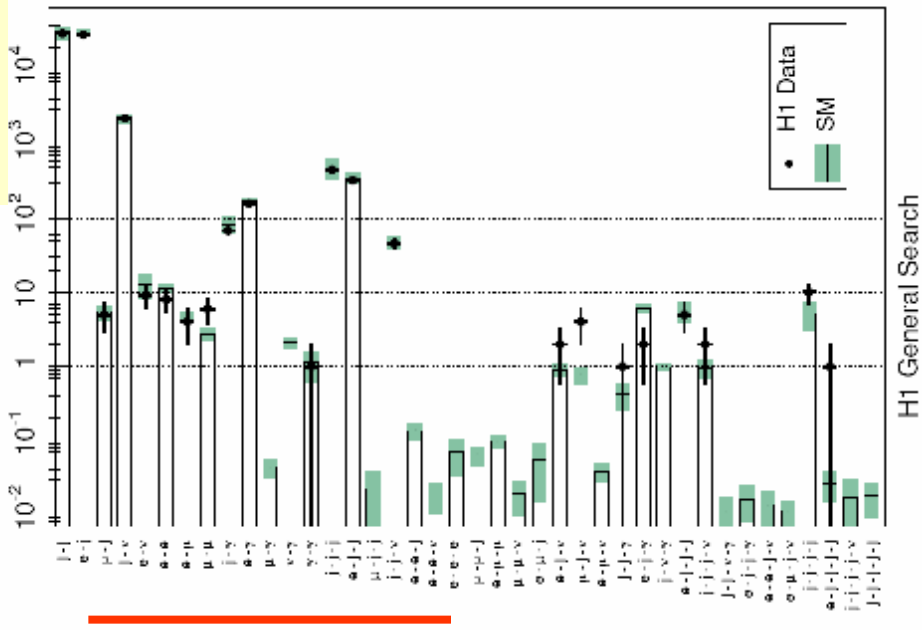
3B

4B

- overall very good agreement H1 data / SM
- retrieves the "lepton-jet- $E_{T,miss}$ " and "multi-electron" anomalies (dedicated analyses might be more sensitive)

Requires a very good understanding of detector & backgrounds !

Events



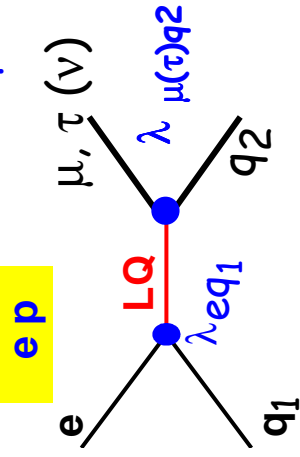
Conclusions

- A lot of activity and a lot of progress in BSM at HERA : more models, more ideas, better understanding of the data, improved analysis techniques (which I had no time to show)
- Many topics not covered, e.g. Lepton Flavor Violation, Doubly-charged Higgses, Magnetic Monopoles
- With LEP & increasing lumi at Tevatron, some searches are becoming "difficult".
But some specific cases where HERA is very well suited, e.g. new particles decaying into ν + jet(s) difficult at Tevatron.
- Discovery potential for e.g. leptoquarks, light stop, excited fermions. Combination H1 + ZEUS might be crucial.
- To my view our best chance is in the "anomalous W-like events"

Backup slides

Lepton Flavor Violating LQs

Possibility to have LQs coupling to fermions of different generations.
 Could lead to LFV processes.



Backgrounds from $\mu\mu$ and CC DIS largely suppressed @ final selection.

τ -id based on a multi-variable analysis

- Constraints obtained on $(M_{LQ}, \lambda_e, \lambda_{\mu(\tau)})$ for $M < \sqrt{s}$

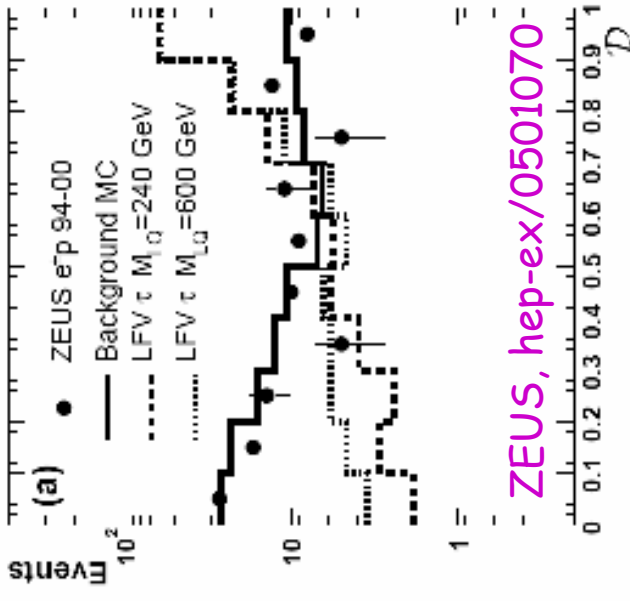
- For very large masses : bounds on $\lambda_{eq} \lambda_{lq} / M^2_{LQ}$

ZEUS bounds on $\lambda_{eq1} \lambda_{\mu q2} / M_{LQ}^2$ in units of TeV^{-2} , for \neq LQ types

	$B \rightarrow \mu e$	$B \rightarrow \mu e$	$B \rightarrow \tau \bar{e} X$	$B \rightarrow \tau \bar{e} X$
$ed \rightarrow \mu b$	1.3	*	0.4	0.4
$eb \rightarrow \mu s$	3.2	*	1.8	1.9
			14	14
			11	10

Better constrained by $B_d \rightarrow e\mu$ (Belle)

$$\frac{\bar{b}}{d} \frac{\lambda_{23}}{\lambda_{11}} \frac{\mu}{e}$$



ZEUS, hep-ex/0501070

Several examples where DIS constraints are competitive with those from rare B decays

New physics in eq & DGLAP ?

- What has been done so far :
 - the *SM expectation* is taken from global fits, which include *high Q^2 HERA data* (94 data for CTEQ5) and other eN data
 - checked that the SM exp. does not change much when using older fits (but the error on it does change a bit..)
- Unlikely that a significant NP effect might have “faked” DGLAP in fits using several datasets (eN, μN , νN)
- Would be nice to quantify still: a *combined fit of pdf's + NP terms*.
Would ensure a *consistency* of NP bounds & pdf's and their errors.
cf the recent H1 fit of pdf's + EW parameter → [H1, hep-ex/0507080](#)
- e.g. for (high mass) LQ exchange: no full NLO calculation for $|DIS + LQ|^2$, but already a LO fit would be informative.

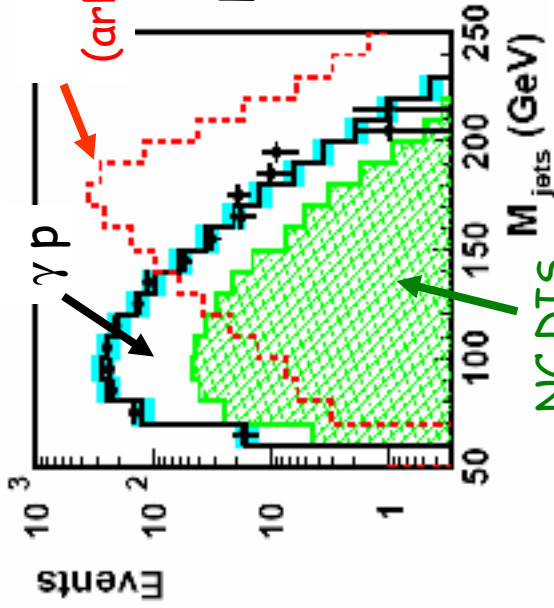
H1 dedicated top search (HERA I)

Excess observed in H1 compatible with top production? Make use of:

- the lepton charge: valence quark $\rightarrow u \rightarrow t(\text{not } \bar{t}) \rightarrow \oplus$ [H1 Collab., EPJ. C33 \(2004\) 9](#)
- angular distributions: $\cos \theta_W$ (cf W helicity in top decays)
- exploit the large expected $P_{T,\text{jet}} & M_{\text{lb}}$

5 ($3e + 2\mu$) of the HERA-I "isolated lepton evts" appear top-like! SM expectation = 1.31 ± 0.22

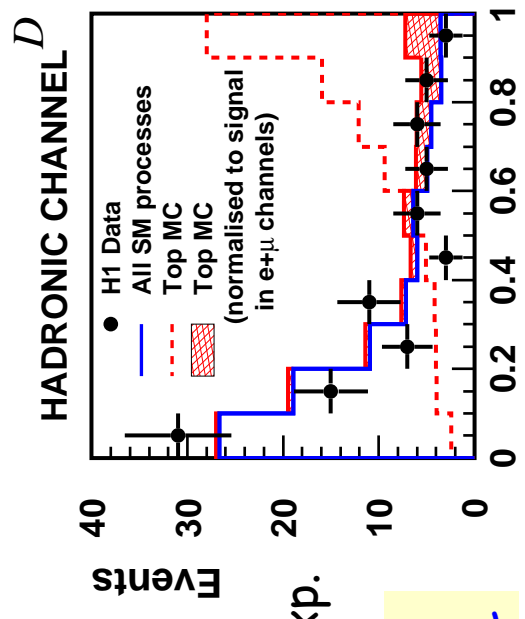
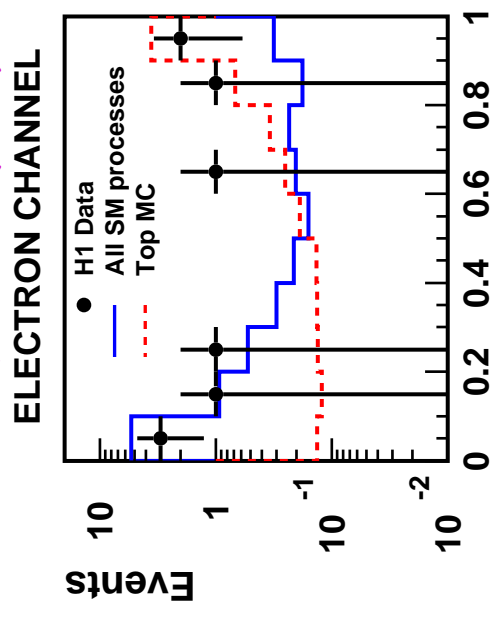
Search also carried out in the 3-jet channel.
Large γp + DIS multijet background (W subleading).



Top (arb. norm.)
Good understanding of MJ production

Final selection:
18 candidates, 20.2 ± 3.6 exp.

Combined bound:
 $\sigma(\text{top}) < 0.55 \text{ pb @ } 95\% \text{ CL}$



NB: lep & had. channels consistent within 1.1 σ