"New Trends in HERA Physics"
Ringberg, 2nd-7th October 2005

Beyond the Standard Model at HERA

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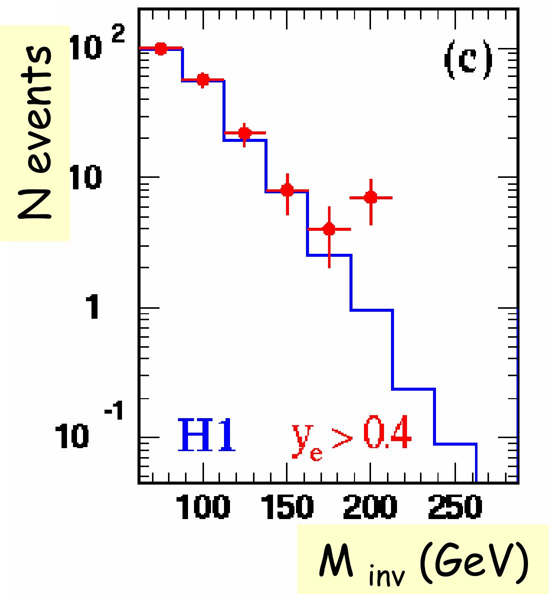
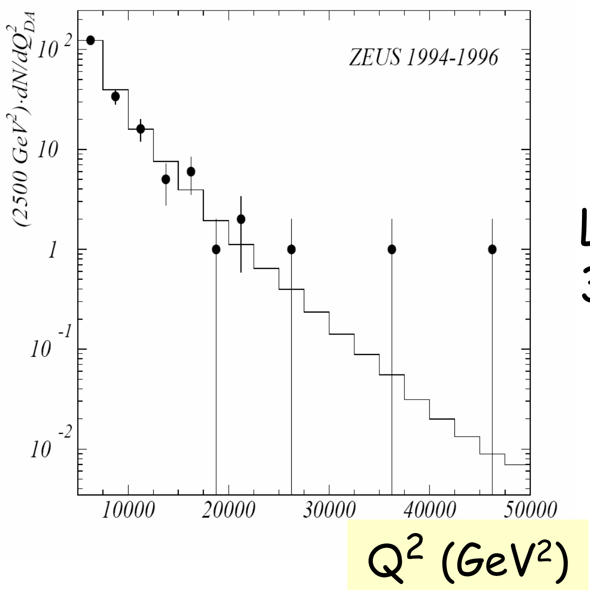




Remember :
H1, Z. Phys. C74 (1997) 191
ZEUS, Z. Phys. C74 (1997) 207

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

Yes, BSM surprises might come from HERA !

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

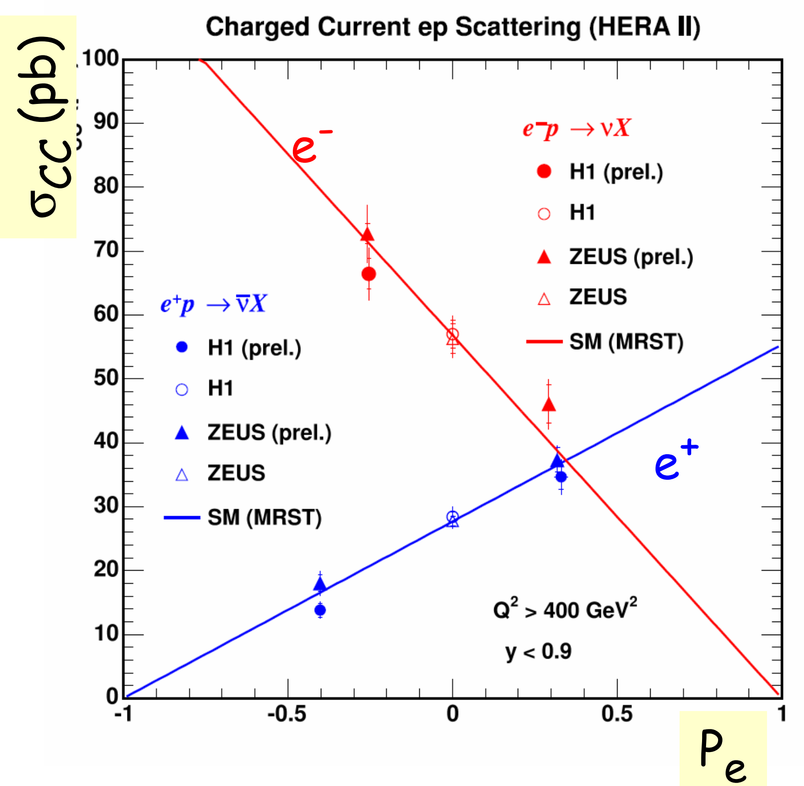
  → The limits depend on the coupling of the new particle to SM ones, i.e. no "absolute" mass limits in contrast to LEP, Tevatron.

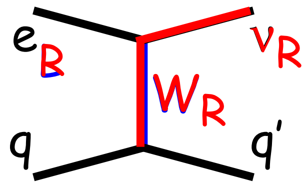
  → In case of a discovery: information not only on M but also on this coupling

  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



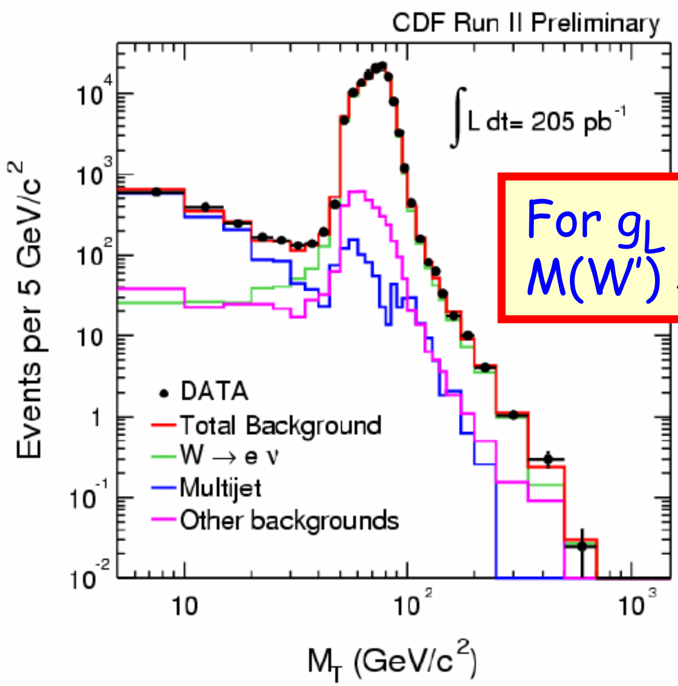


$\sigma_{CC}(e^{\pm},SM) \sim (1 \pm P_e)$

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…

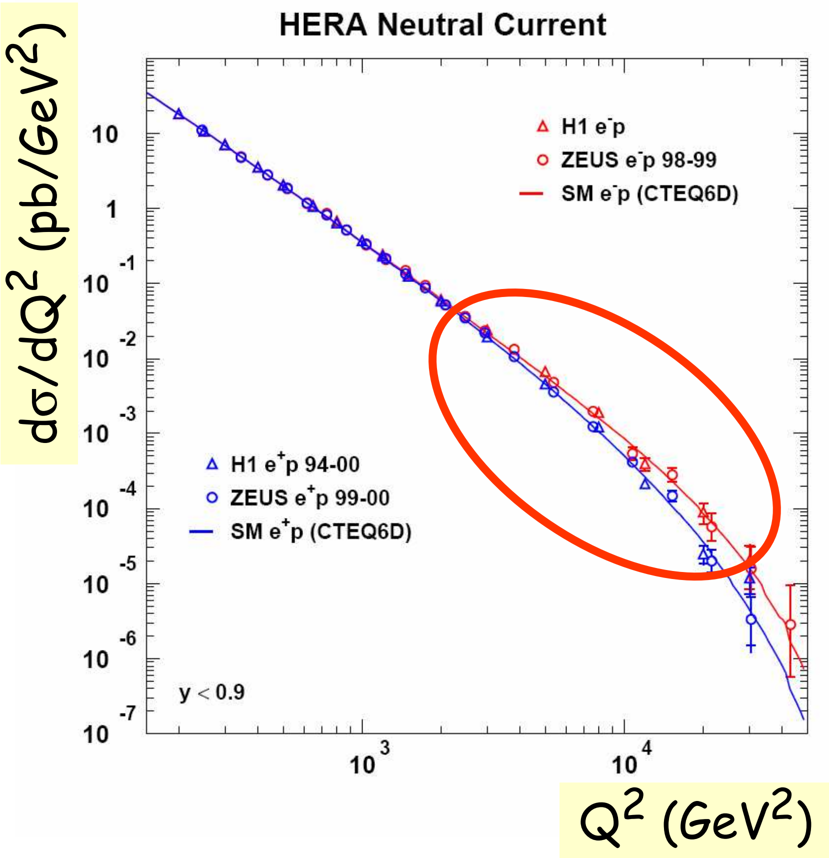


For $g_L = g_R$:
$M(W') > 788$ GeV

Future HERA sensitivity might reach ~ 350 GeV (high lumi, high precision on polarisation measurement)

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

NC DIS at high Q2

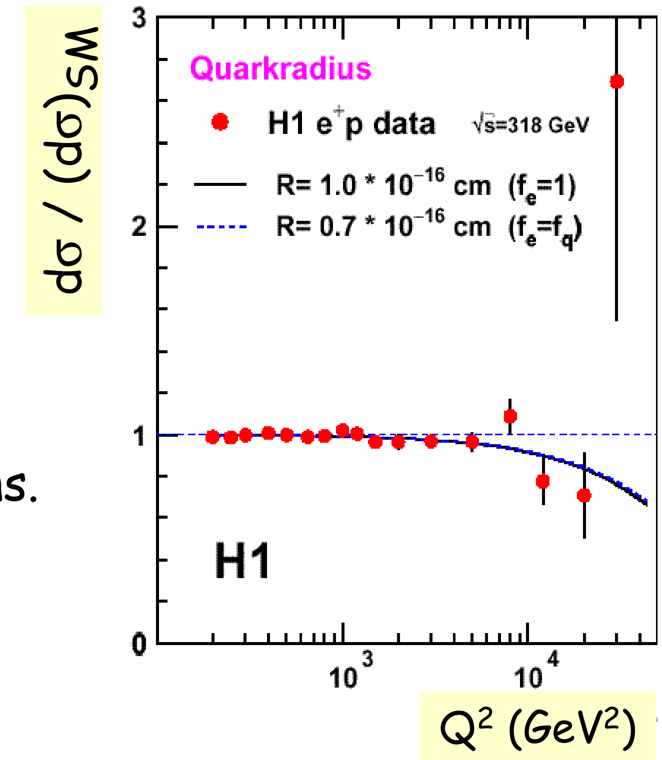


Measurements up to ~ 40000 GeV^2
Typical current precision : ~ 3% at 1000 GeV^2, ~ 10% at 10000 GeV^2 where largely dominated by statistical errors.

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.

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

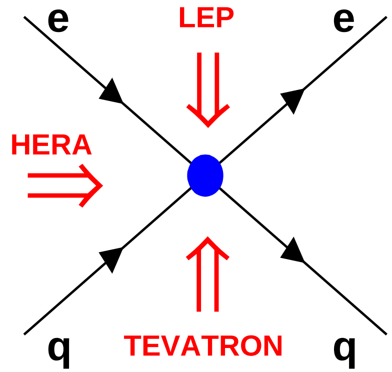
$R_q < 0.85 \cdot 10^{-18}$ m

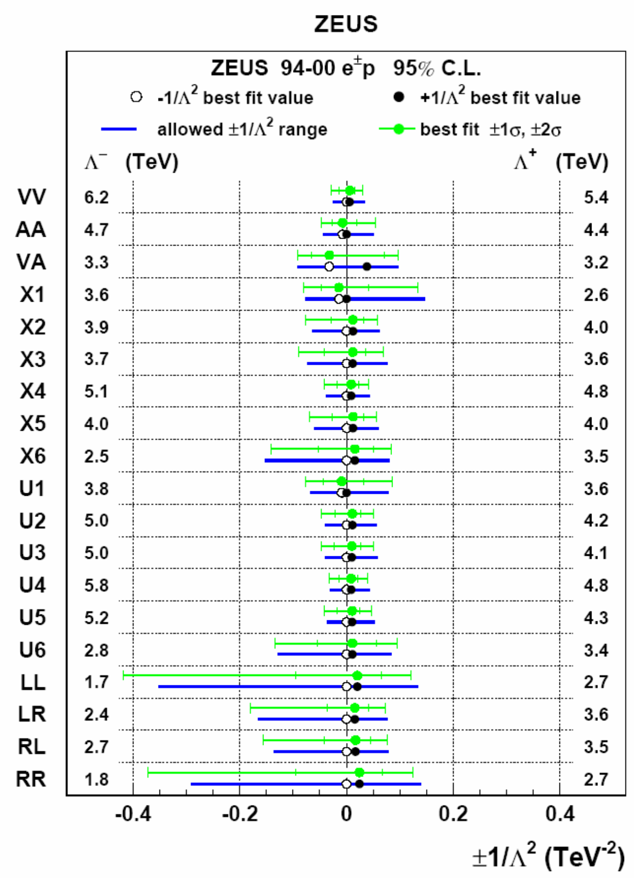
ZEUS, DESY 03-218; H1, DESY 03-052

New Physics in eq → eq amplitude

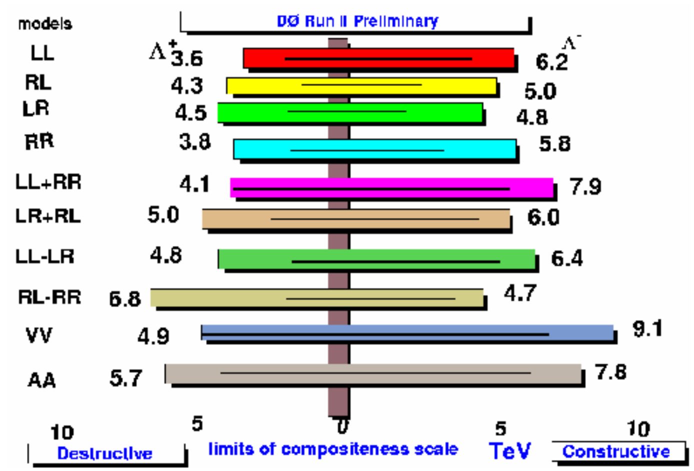
a) general contact interactions : assume
that the scale Λ of NP is large, parameterize
the effects of NP as a four-fermion interaction :

$$L = \sum_{i,j=L,R} \varepsilon_{i,j}^{e,q} \frac{4\pi}{\Lambda^2} (\bar{e}_i \gamma^\mu e_i)(\bar{q}_j \gamma_\mu q_j)$$





Typical bounds $\Lambda > 5$ TeV



Similar sensitivity achieved at Tevatron from Drell-Yan

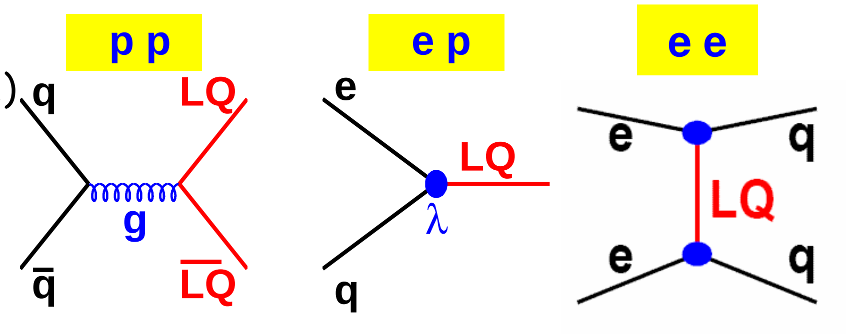
b) t-channel exchange of Kaluza-Klein gravitons
c) u-channel exchange of a particle coupling to (e,q)
i.e. a "leptoquark"

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) Yukawa 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

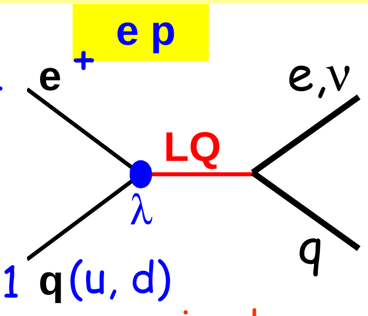
BRW model : if LQs ⊂ isospin multiplet are degenerate :

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

→ (Some of) BRW assumptions relaxed ⇒ "generic models"
→ $\beta_l = \beta(LQ \to l\, q)$ and $\beta_\nu = \beta(LQ \to \nu\, q)$ free parameters

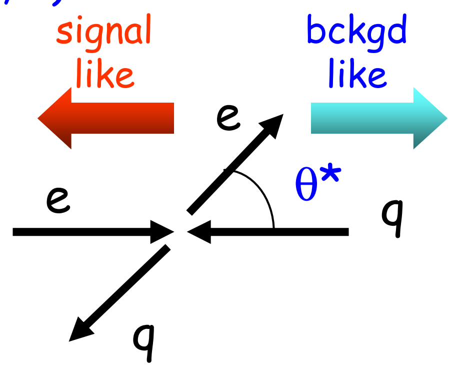
Leptoquarks at HERA

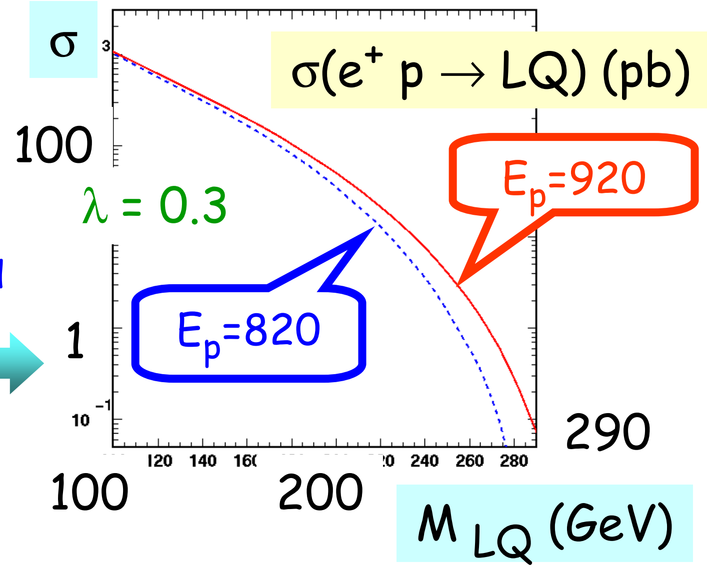
- For $M < \sqrt{s}$:

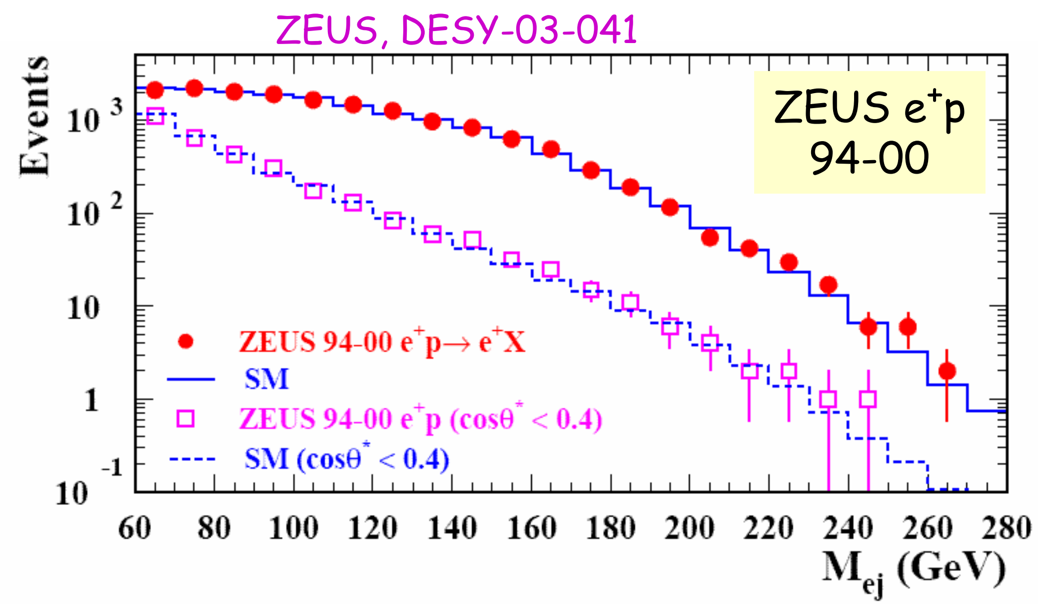


- F=0 LQs better in e^+
  F=2 LQs better in e^-
- $\sigma \approx \lambda^2 q(x=M_{LQ}^2/S)$

Topologies	SM Background
e + jet	Neutral Current DIS Exploit specific angular distribution of LQ decay products
ν + 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 β = BR(LQ $\rightarrow$ eq) = 1 :

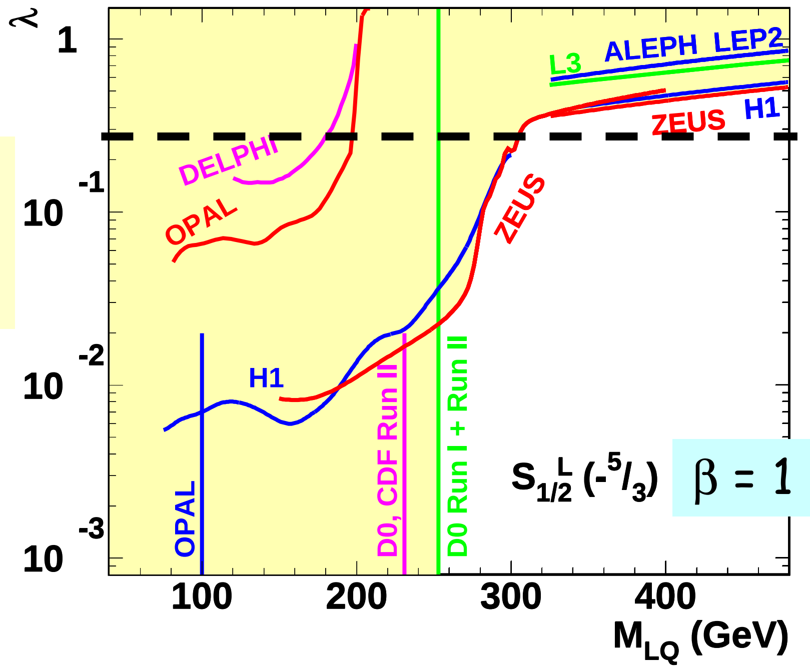
DO Run II + DO Run I : M > 256 GeV

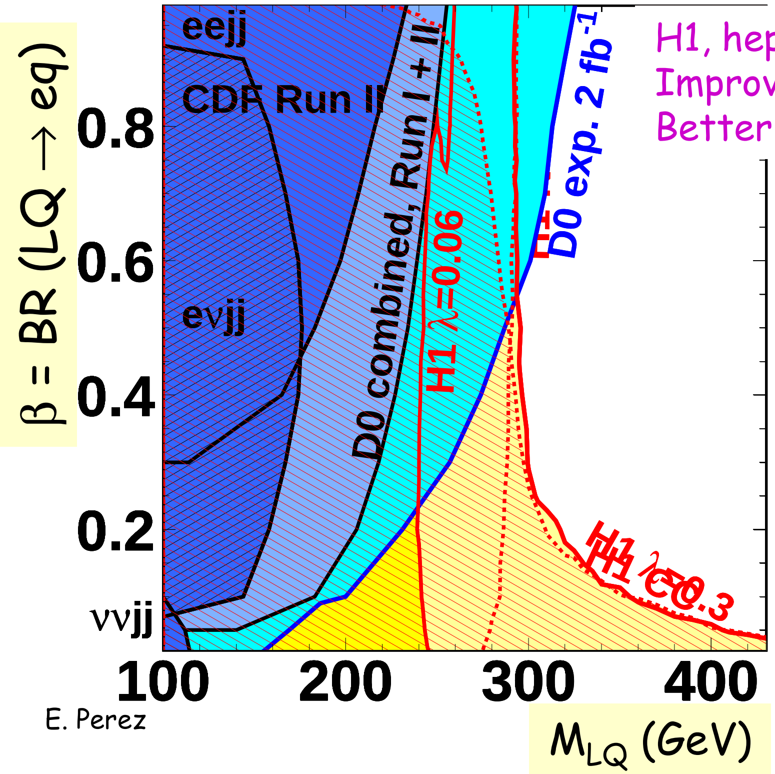
For $\lambda = \sqrt{4\pi\alpha_{em}} \approx 0.3$: HERA rules out LQ masses < ≈ 290 GeV

$\beta \neq 1$ at TEVATRON :

eeqq	eνqq	ννqq
Z/DY + jj QCD	W + jj	W/Z + jj QCD

difficult, large backgrounds





H1, hep-ex/0506044
Improved method,
Better sensitivity

- Tevatron probes large masses for large β (LQ $\rightarrow$ eq) independently of λ.
  But large β (LQ $\rightarrow$ νq) is difficult.

- HERA better probes LQs with small β provided that λ not too small

$\rightarrow$ 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

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

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

LQ prospects

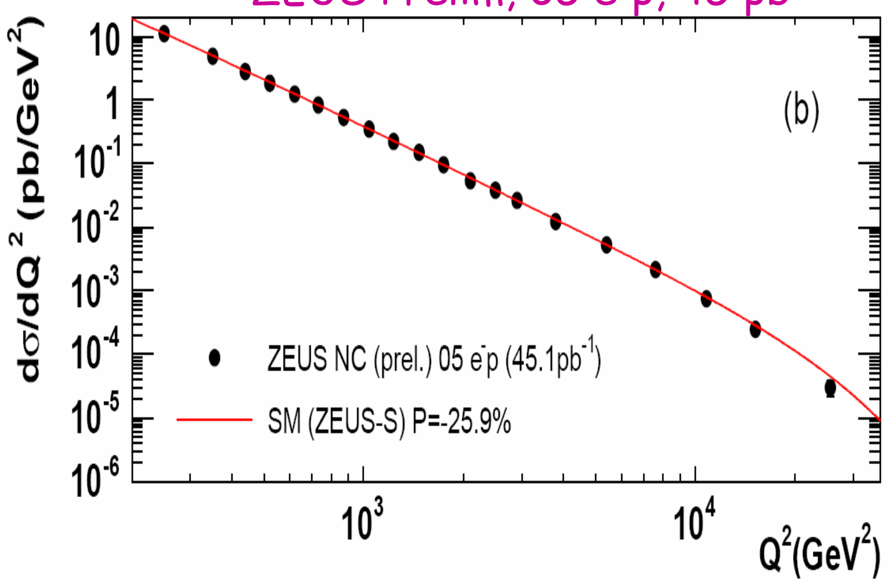
Taking into account our bounds (obtained from 100 pb^{-1} of e^+ p data) :
Can we still hope to observe a LQ signal at HERA-II ?

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

Total e^+p luminosity	σ_{prod} = current limit	σ_{prod} = 0.5 * limit
350 pb^{-1}	~ 4 σ	~ 2.5 σ
700 pb^{-1} (i.e. H1 + ZEUS)	> 5 σ	~ 3.5 σ

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

ZEUS Prelim, 05 e^-p, 45 pb^{-1}



→ 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 ...

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..)

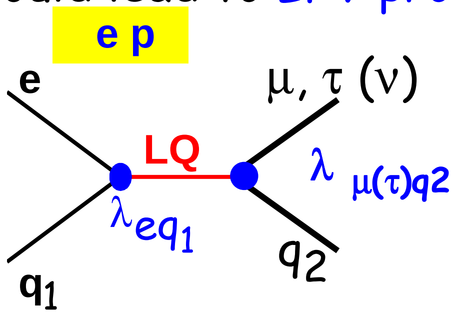
- Unlikely that a significant NP effect might have "faked" DGLAP in fits using several datasets (eN, μN, νN)

- 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 $\rightarrow$ J. Meyer's talk

- e.g. for (high mass) LQ exchange: no full NLO calculation for $|\mathrm{DIS} + \mathrm{LQ}|^2$, but already a LO fit would be informative.

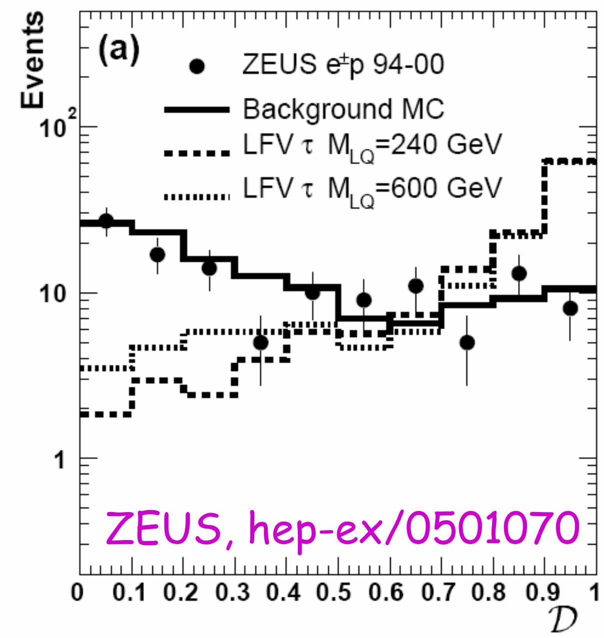
Lepton Flavor Violating LQs

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

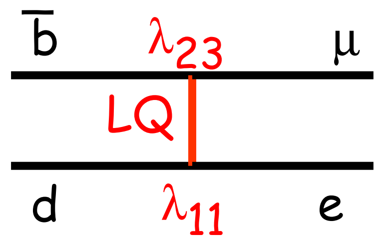


- Constraints obtained on (M_{LQ}, λ_e, $\lambda_{\mu(\tau)}$) for $M < \sqrt{s}$
- For very large masses : bounds on $\lambda_{eq}\, \lambda_{lq} / M^2_{LQ}$

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

ed → μb	1 3	*	$B \to \mu\bar{e}$ 0.4 **1.8**	$B \to \mu\bar{e}$ 0.4 **1.9**
eb → μs	3 2	*	$B \to \tau\bar{e}X$ 14 **11**	$B \to \tau\bar{e}X$ 14 **10**

→ Better constrained by $B_d \to e\mu$ (Belle)



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

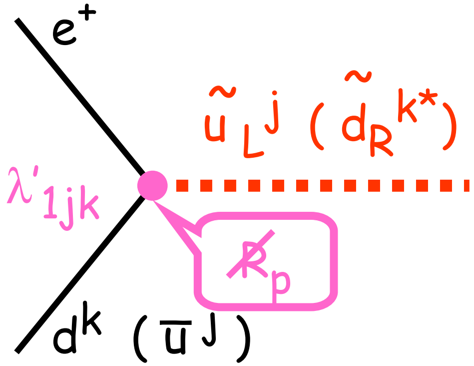
E. Perez

Beyond minimal LQs: SUSY quarks

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

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

Rp-violation allows : slepton-lepton-lepton (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

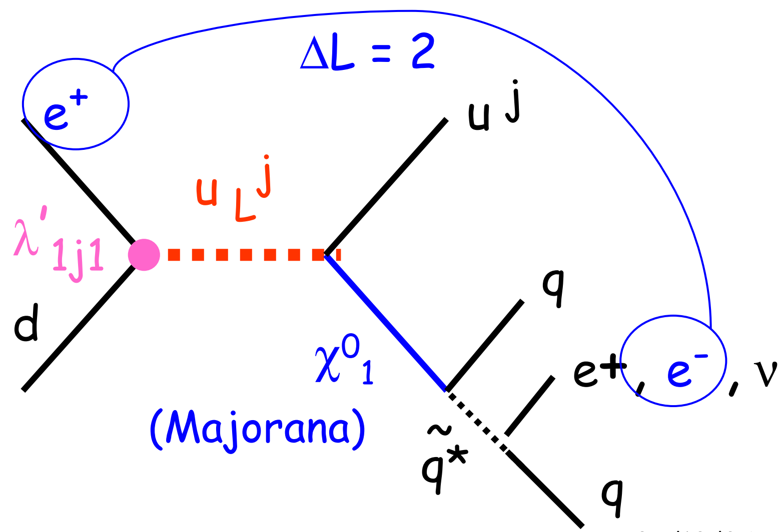
Of main interest :

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

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

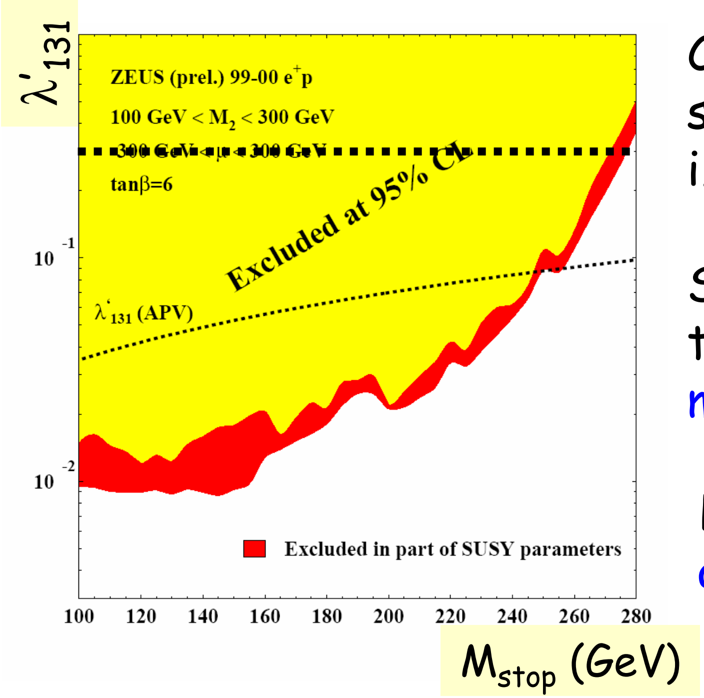
In addition to the "LQ-like" decays, also "gauge" decays. Some of them lead to spectacular signatures.

- e^+ + multi-jets .... NC DIS
- e^- + multi-jets .... ≈ bckgd free
- ν + multi-jets .... CC DIS
- e (ν) + 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 → eq and stop → b χ^+

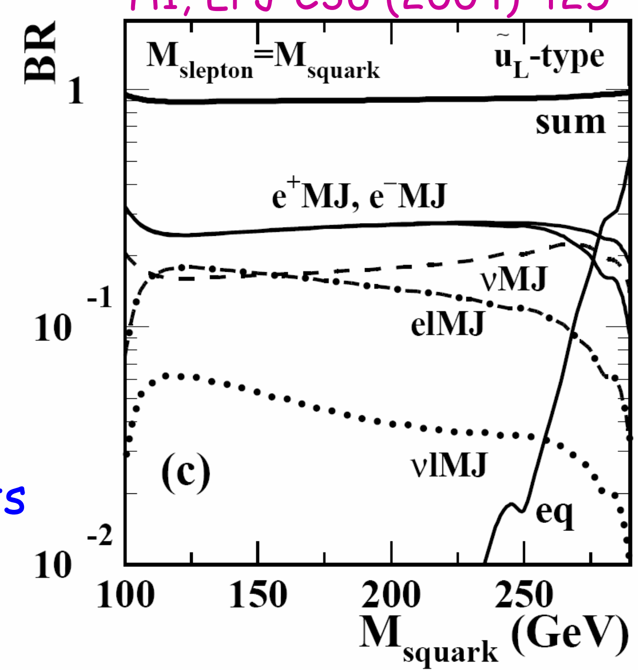


Consider first an "unconstrained model" : sfermion & gaugino sectors are not related, i.e. $M_{\tilde{f}}$ are free parameters

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.

H1, EPJ C36 (2004) 425

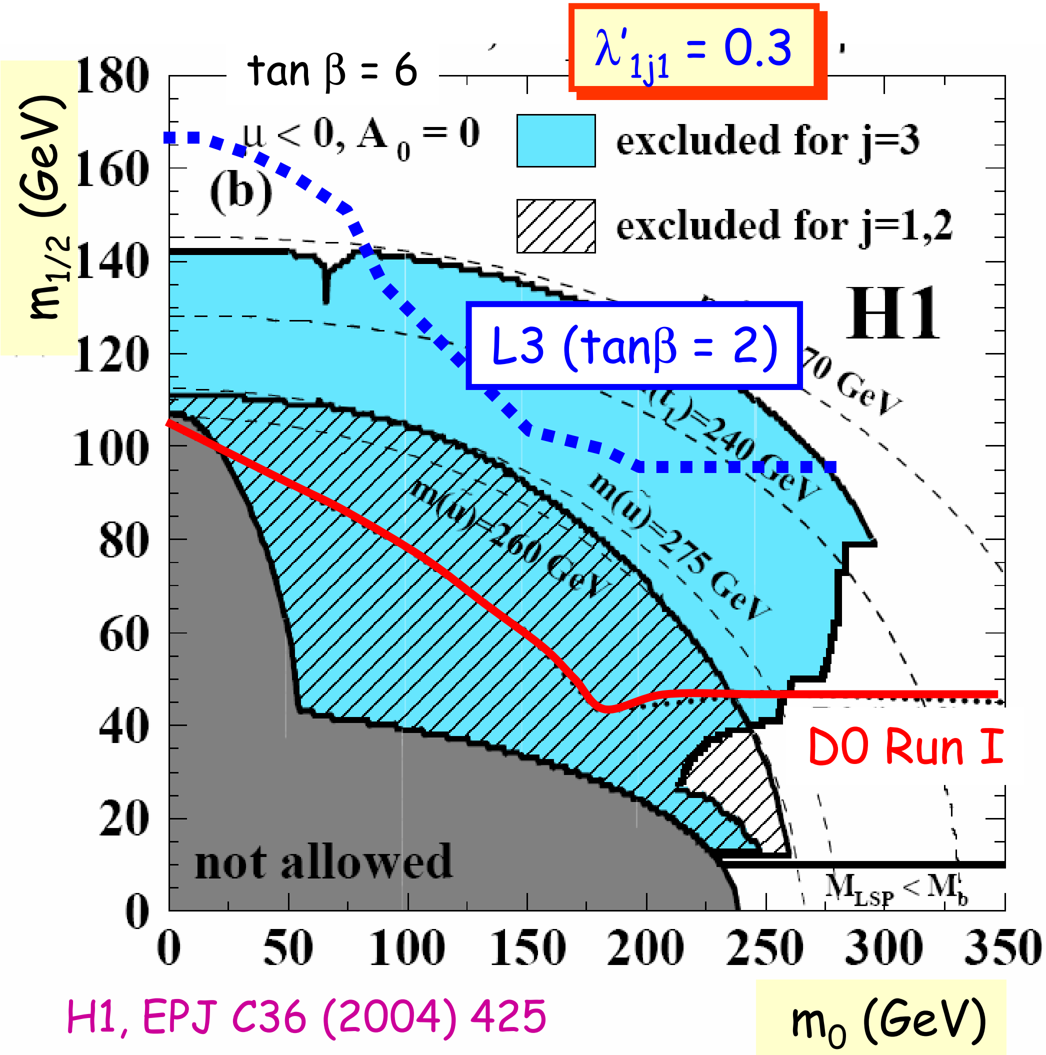


- For $\lambda' = 0.3$ ($\lambda'^2 / 4\pi = \alpha_{em}$) :
  squarks can be ruled out up to ≈ 270 - 280 GeV

- 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.



H1, EPJ C36 (2004) 425

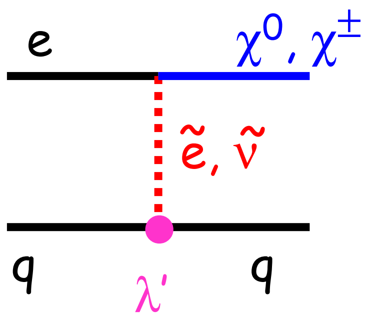
For intermediate m_0, excluded domain not ruled out by LEPII

D0 bound (Run I) : moderate, again because of large branching in $E_{T,miss}$ + jets

NB: Tevatron RunI : different frameworks, but typical sensitivities ≈ 130 GeV.
RunII: ≈ 200-250 GeV

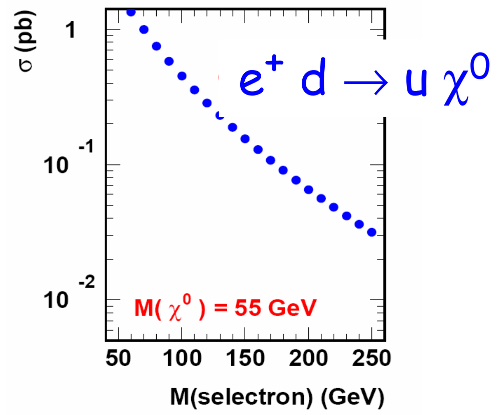
Discovery potential for RpV stop at HERA with larger L !

If squarks are very heavy ?



Gaugino production via slepton exchange.

Example σ, for a coupling λ′ = 0.5 →

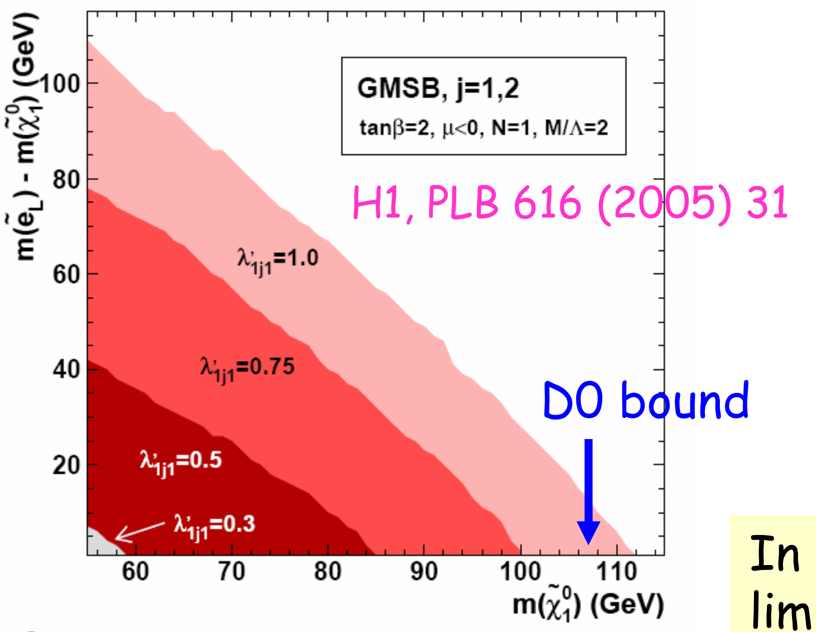


Considered at HERA in two scenarios :

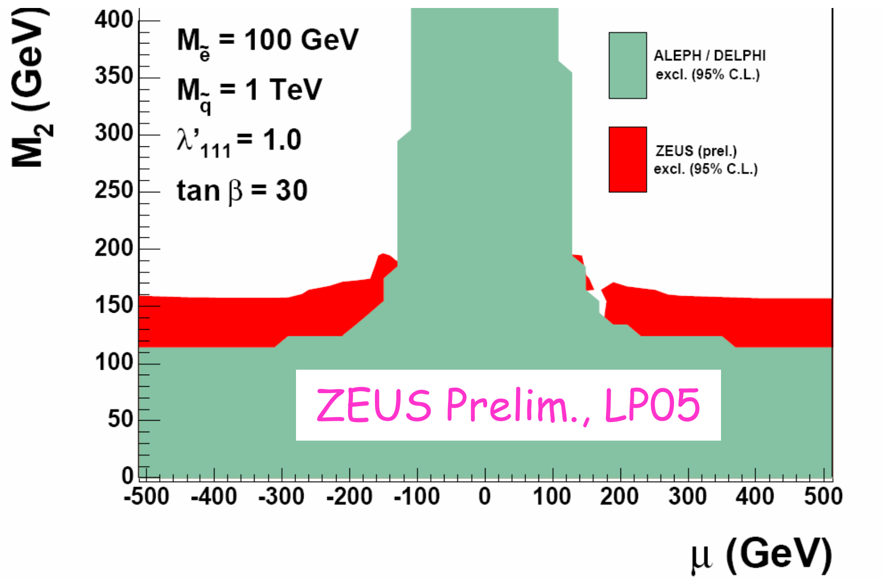
"GMSB" like :

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

→ Study of radiative CC DIS



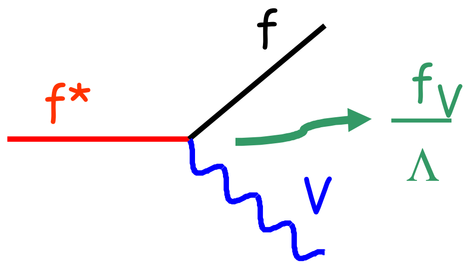
"mSUGRA" like : $\chi \to e$ or ν + 2 quarks



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

A new scale of matter ? l+V resonances ?

- Unambiguous signature : direct observation of excited states



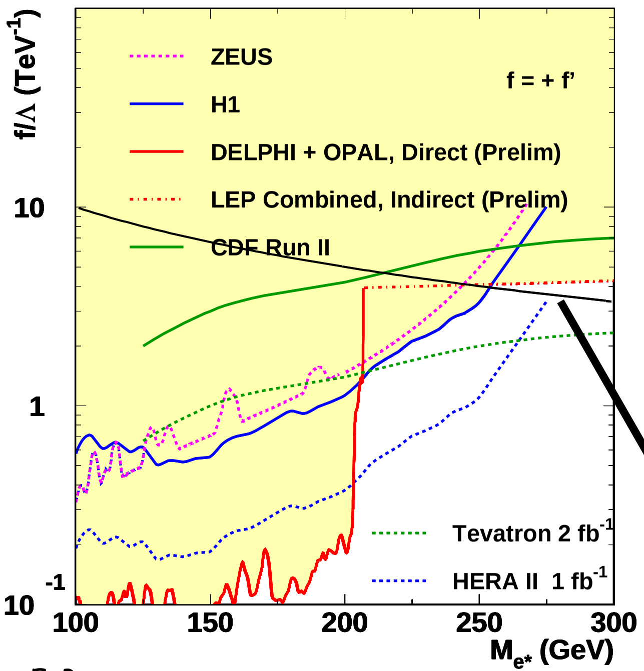
(chiral) magnetic coupling $\rightarrow$ (GeV) $^{-1}$

$\Lambda \approx$ 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 γ, search for a (eγ) resonance

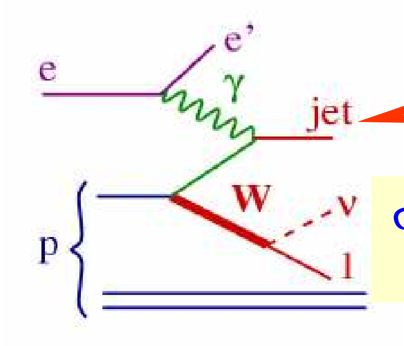
  - Z/DY + γ at Tevatron
  - radiative Bhabha at LEP
  - radiative DIS, QED Compton at HERA

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

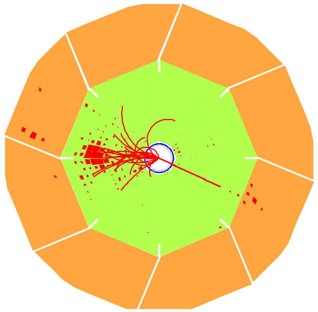
For f/Λ = 1/M(e*) :

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

W Production



σ(W prod) $\approx$ 1 pb



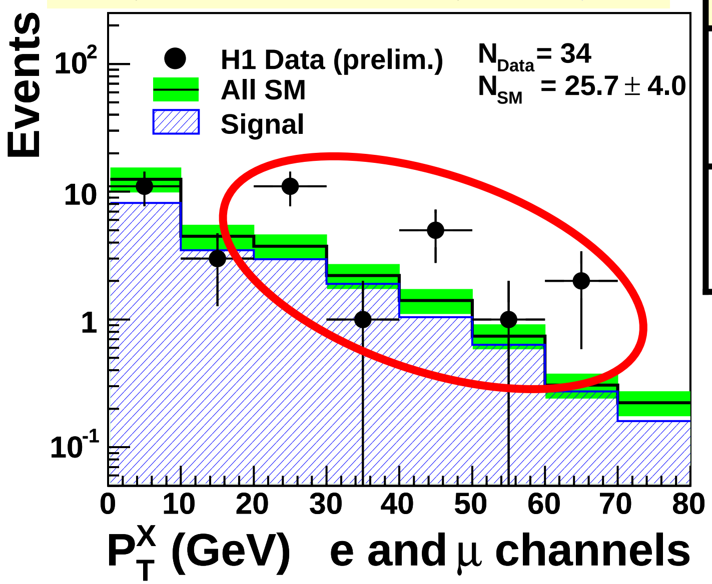
HERA I : excess (H1) of observed evts at high P_T^X w.r.t. SM expectation

H1, PLB 561 (2003) 241

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

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

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



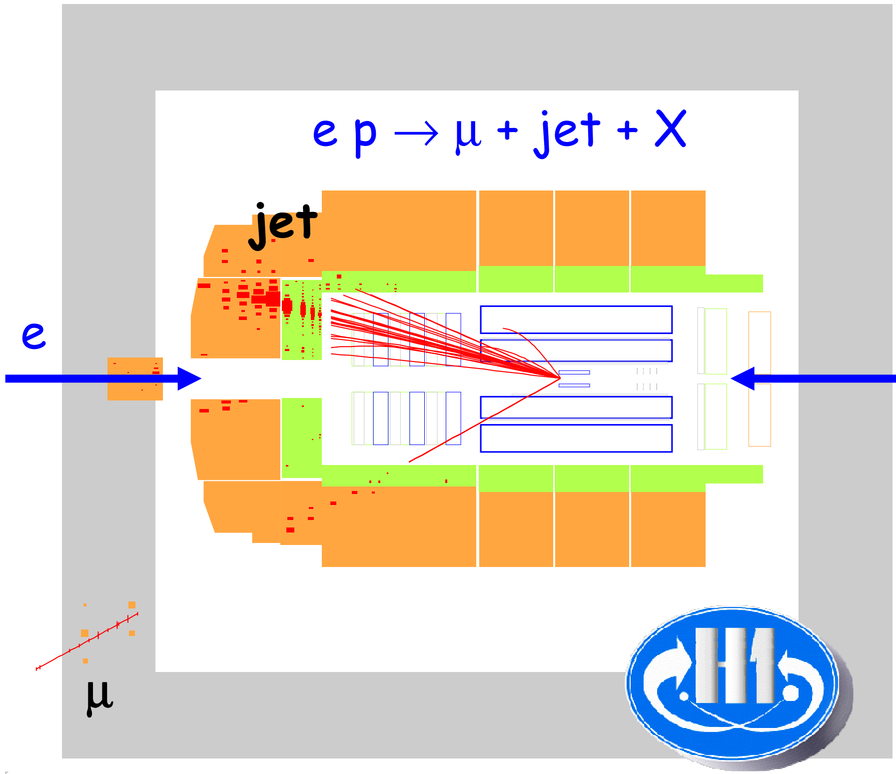
Such evts are still observed in HERA II H1 data...

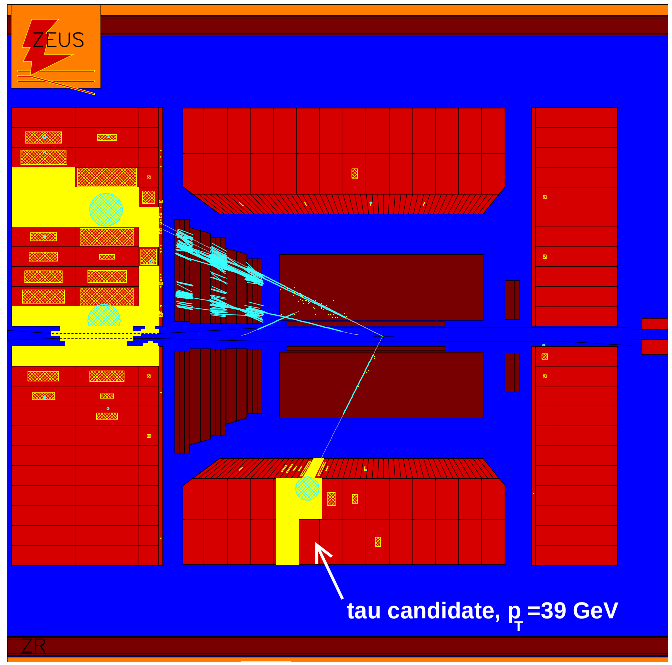
P_T^X > 25 GeV	e channel	μ channel	Combined e & μ
H1 94-05 211 pb-1	11 / 3.2 ± 0.6	6 / 3.2 ± 0.6	17 / 6.4 ± 1.1
ZEUS 99-04 106 pb-1	1 / 1.5 ± 0.18		

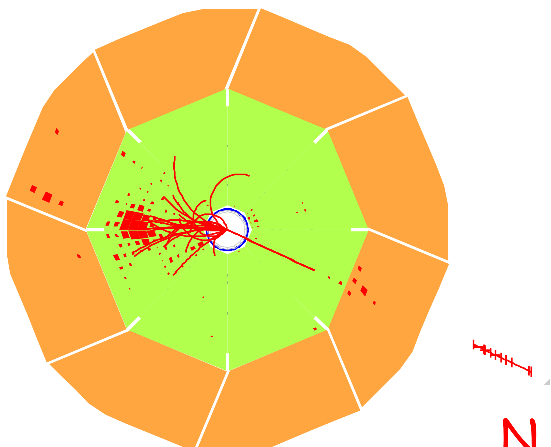
But still do not show up in ZEUS data...

- 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...

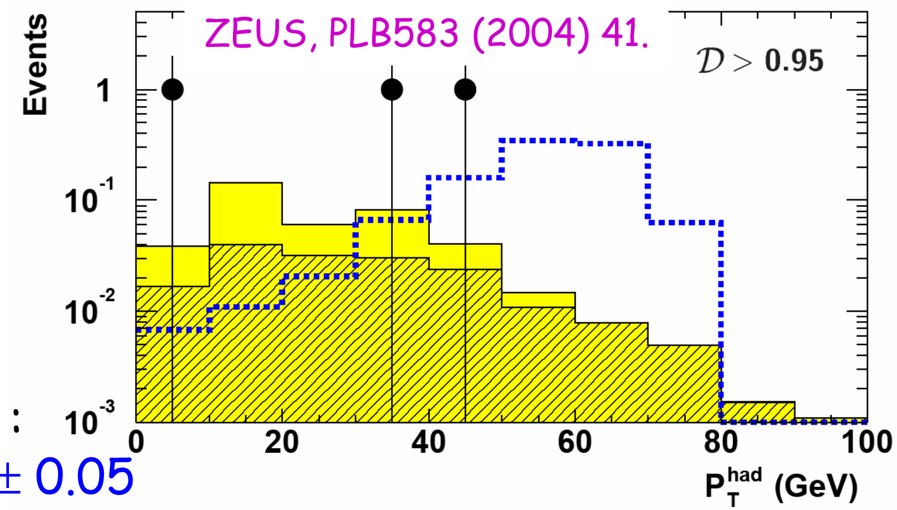
HERA events with isolated lepton + $P_{T,miss}$







No high P_T^X τ event seen in H1



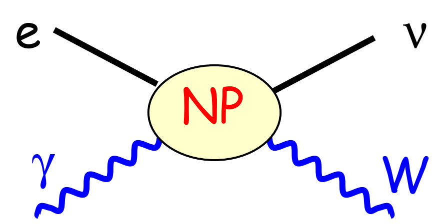
ZEUS τ

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

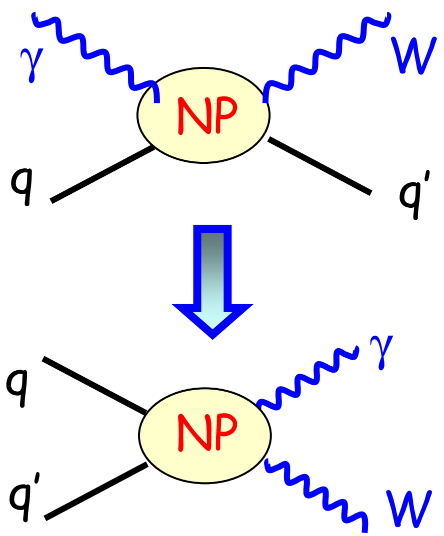
Fluctuation ? New Physics ?

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

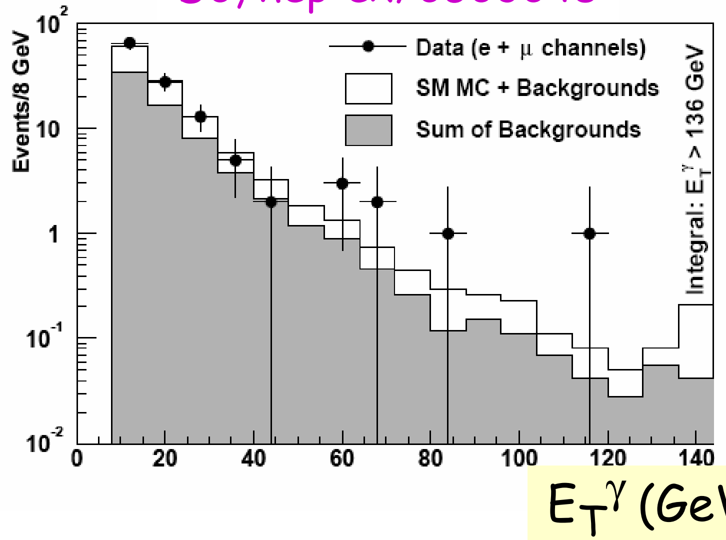
Most likely, something should have been seen at LEP ! (NB: unlikely to produce large $P_{T,had}$ at HERA)



- New physics in γq ?

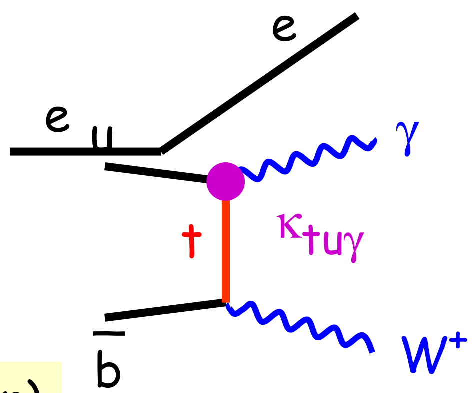


D0, hep-ex/0503048



$W\gamma$ at Tevatron agrees with SM…

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



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

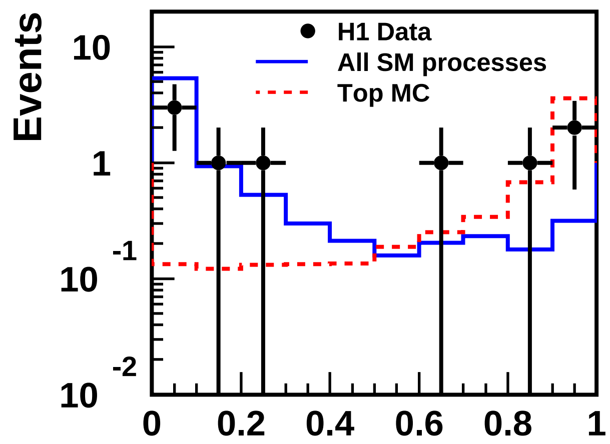
H1 dedicated top search (HERA I)

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

- the lepton charge : valence quark $\rightarrow$ u $\rightarrow$ t (not $\bar{t}$) $\rightarrow \oplus$
- angular distributions : cos θ_W (cf W helicity in top decays)
- exploit the large expected $P_{T,jet}$ & $M_{l\nu b}$

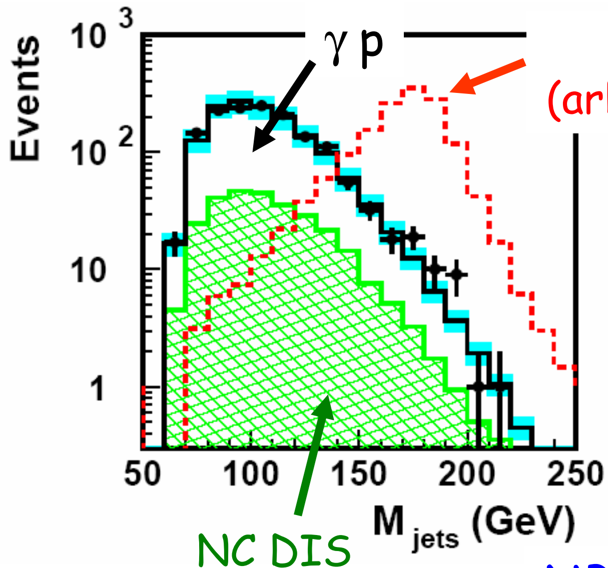
H1 Collab., EPJ. C33 (2004) 9

ELECTRON CHANNEL



5 (3e + 2μ) 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).

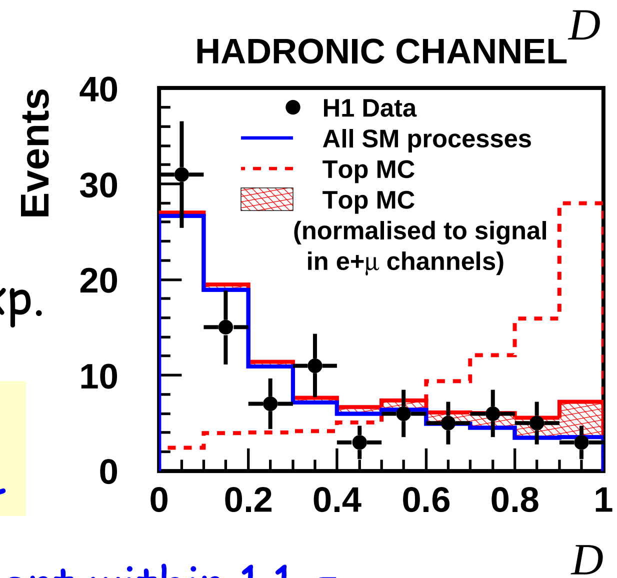


Good understanding of MJ production

Final selection :
18 candidates, 20.2 ± 3.6 exp.

Combined bound :
σ(top) < 0.55 pb @ 95% CL

HADRONIC CHANNEL

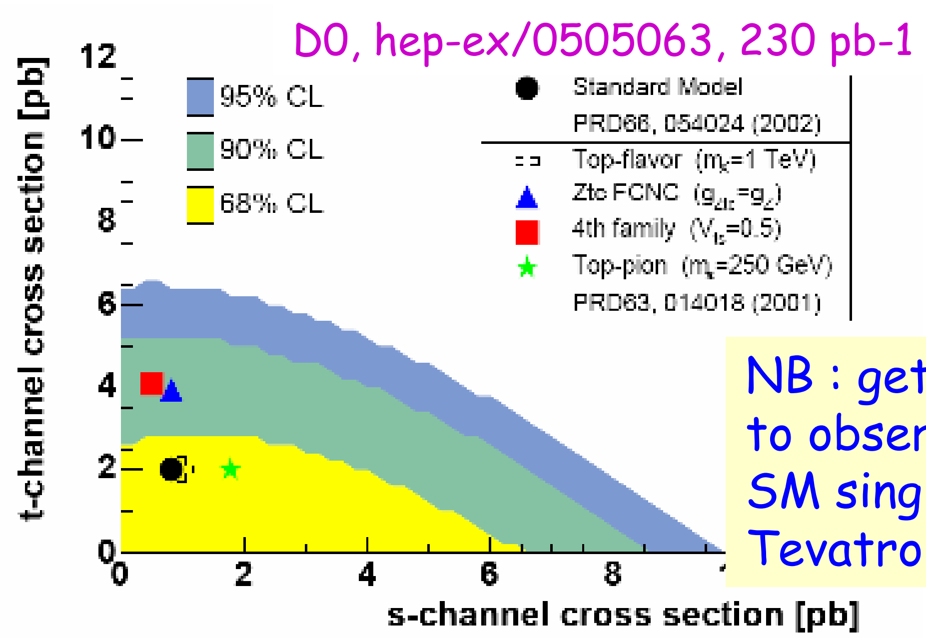


NB : lep & had. channels consistent within 1.1 σ

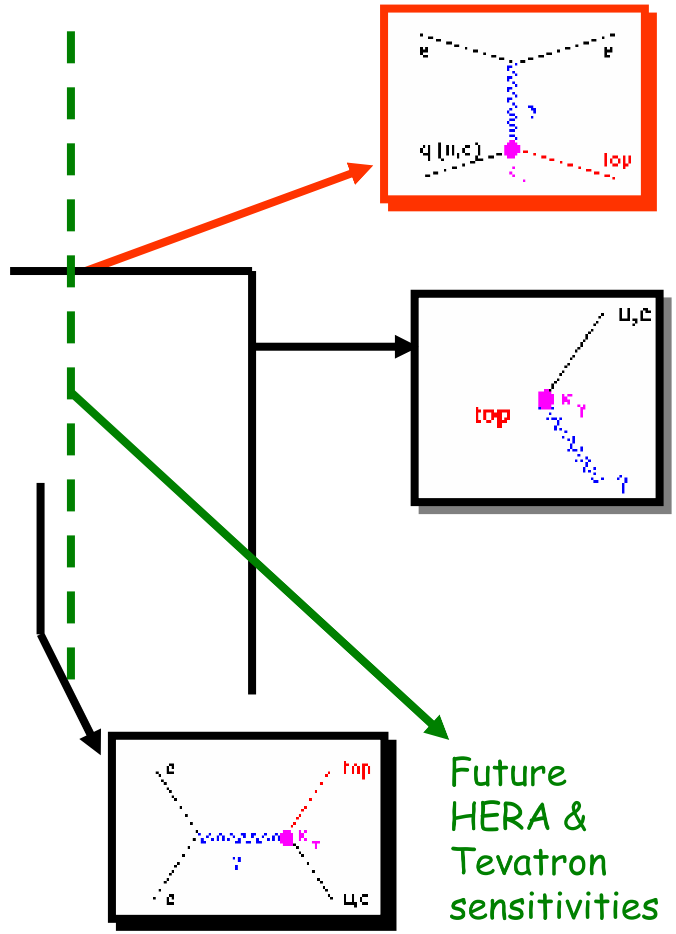
FCNC couplings $tq\gamma$, tqZ (tqg) where q = u,c can be searched for in single top prod. at LEP & HERA, in $t \rightarrow qV$ decays in $t\bar{t}$ pairs at Tevatron.

H1, EPJ. C33 (2004) 9
ZEUS, PLB 559 (2003) 153.

D0, hep-ex/0505063, 230 pb-1



NB : getting close to observe SM single top at Tevatron !



Isolated lepton events (2)

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

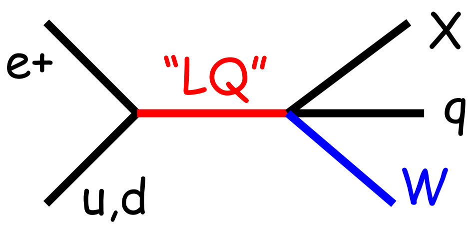
$P_T^X > 25$ GeV	e channel	μ channel	Combined e & μ
Electrons, 98-05 53 pb-1	2 / 0.9 ± 0.2	0 / 0.9 ± 0.2	2 / 1.8 ± 0.3
Positrons, 94-04 158 pb-1	9 / 2.3 ± 0.4	6 / 2.3 ± 0.4	15 / 4.6 ± 0.8

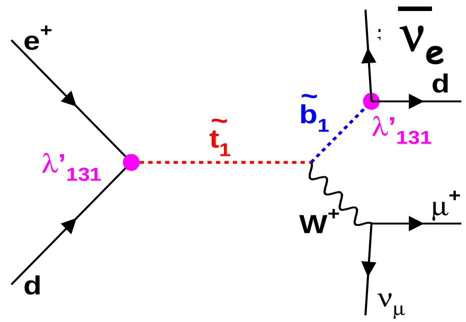
H1 excess not seen in $e^- p$!

3.4 σ effect…

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

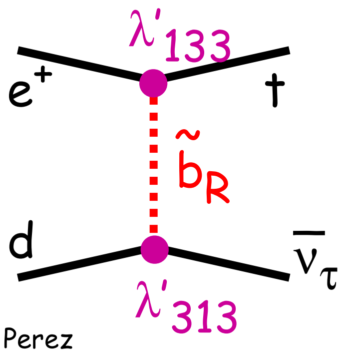
Possible explanations ??



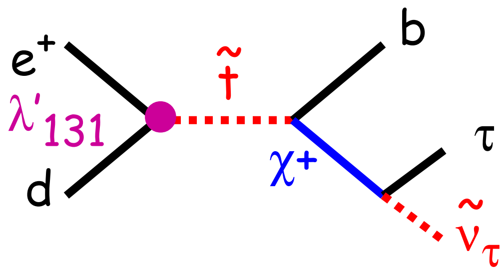


H1, PLB 599 (2004) 159

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



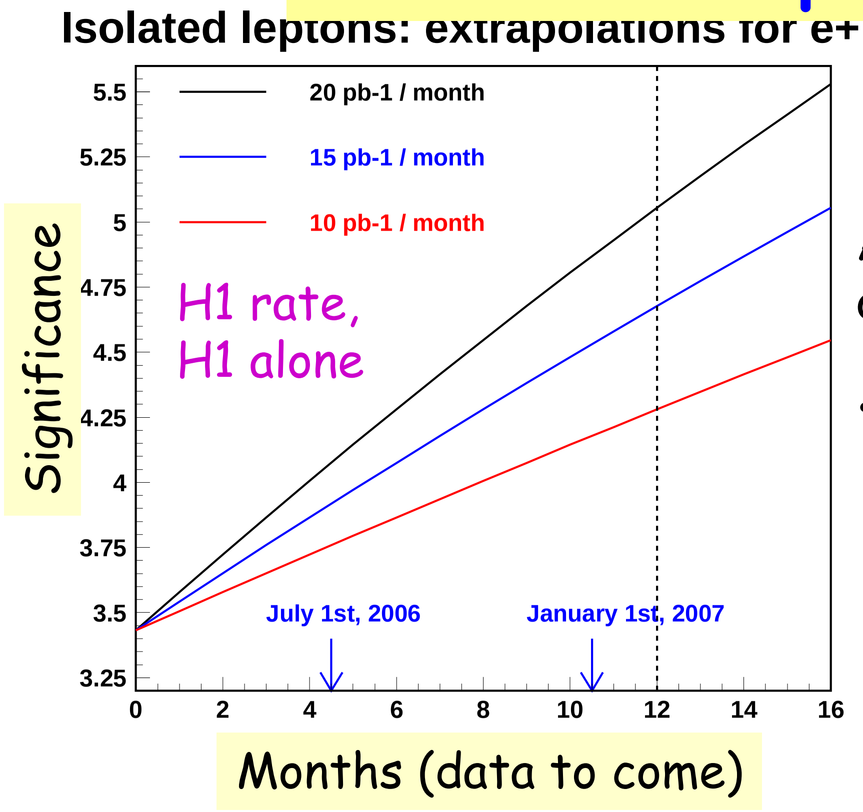
Two RpV couplings with 3rd gene. fields (Not too much $P_{T,miss}$ in that case)



RpV Susy with LSP = $\tilde{\nu}_\tau$

There are possibilities. First clarify the excess !!

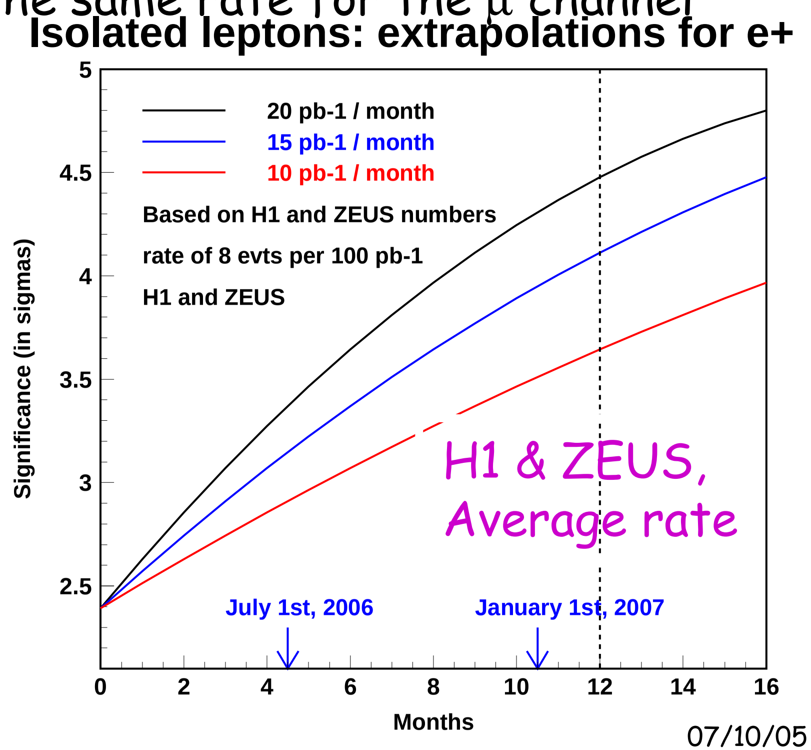
Isolated leptons: extrapolations



- Assume that the events continue to show up at the rate observed in H1 :

A 4.5 σ effect possible with ~ 8 months of additional e^+ luminosity if 20 pb^{-1}/month

- Take instead the average rate from H1 and ZEUS (e channel), i.e. 4 evts / 100 pb^{-1}
  Take the same rate for the μ channel



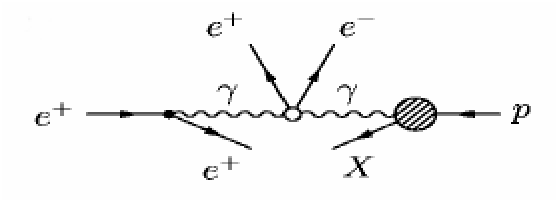
A 4σ effect could be within our reach.
More if we are more lucky.

> 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 γγ. Cross-section ~ 1 pb for central l, Pt > ~ 5 GeV



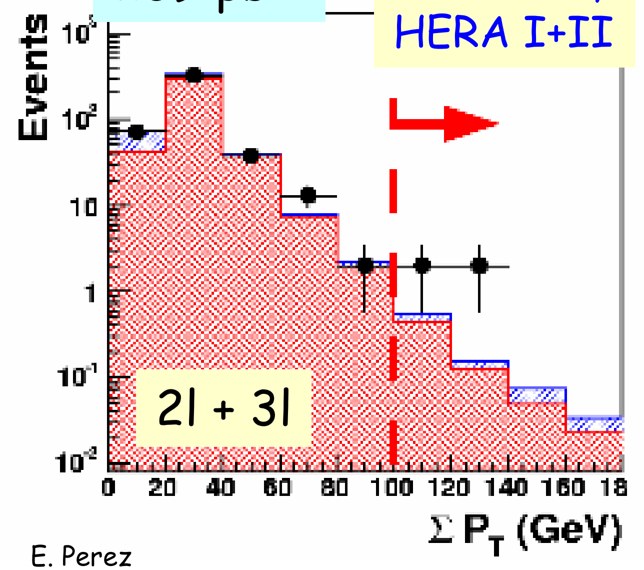
H1 data 94-00 : excess of 2e+3e events at high M_{12} = mass of two highest P_T e
No such excess seen in ZEUS HERA-I data

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, μμ, eμ, eee, eμμ are considered

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

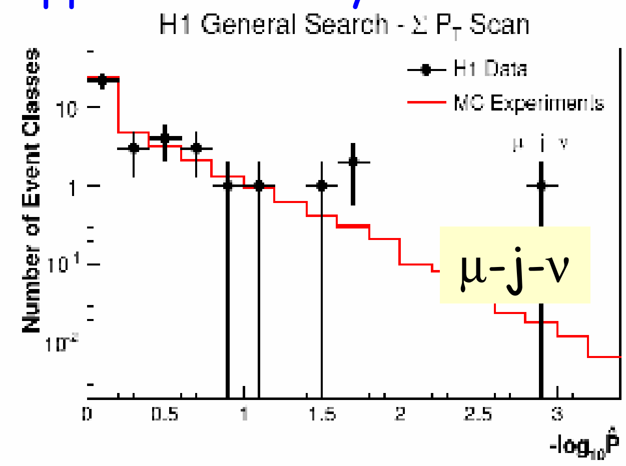
Altogether, at ΣP_T > 100 GeV :
N_{obs} = 4, N_{exp} = 0.81 ± 0.14

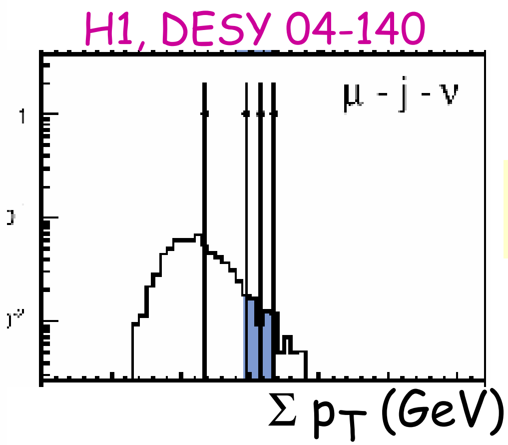
“Signature Based” Searches for NP

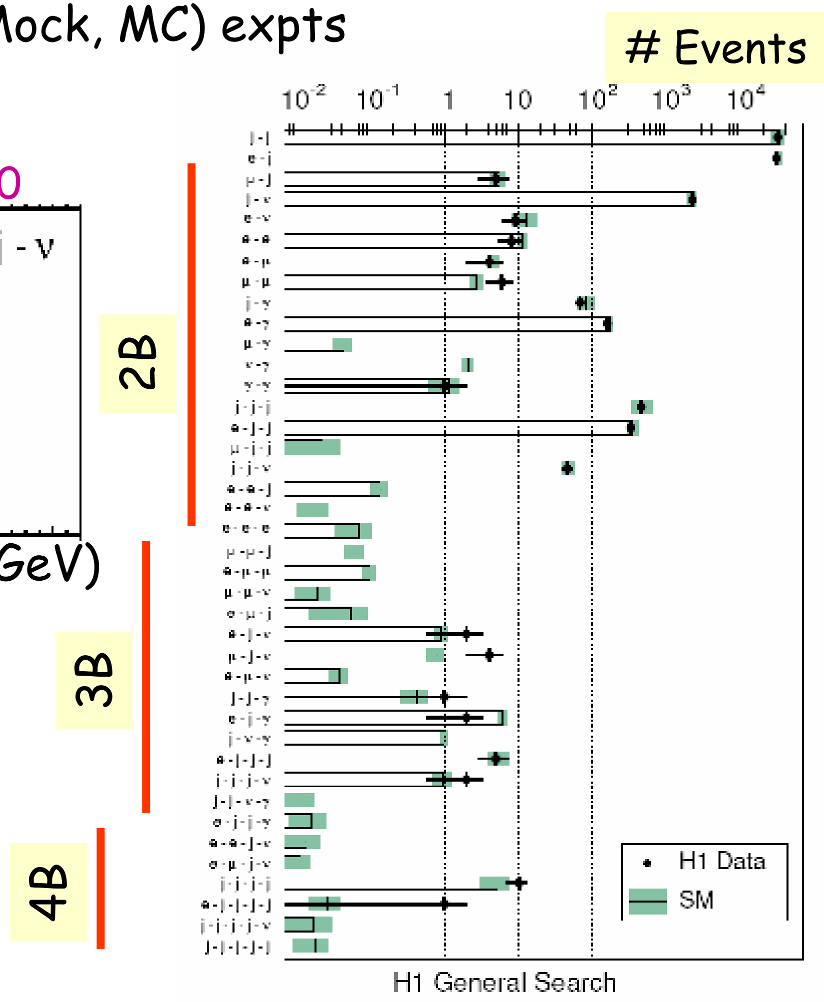
(Quasi) “model-independent” search for new physics :
- definition of objects (e, μ, ν, γ, jet, W, Z, …)
- look at data vs SM in all “channels” with > 1 object
- in each channel, find the part of φ space with largest deviation (e.g. in M, Σp_T)
- quantify the agreement using “Gedanken” (Mock, MC) expts

Pionnered by DZero with the full Run I sample
D0, PRD64, 012004 (2001)

Applied recently to the full sample of H1 data







- 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 !

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)

- 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.
  (cf Higgs at Tevatron ! Hope for a signal only by combining D0 + CDF !)

- To my view our best chance is in the "anomalous W-like events"