

12th International Conference on
Supersymmetry and Unification of
Fundamental Interactions
June 17-23, 2004
Tsukuba, Japan



Searches for SUSY and Exotics at HERA

Johannes Haller
Physikalisches Institut Heidelberg
now at CERN

(on behalf of H1 and ZEUS)

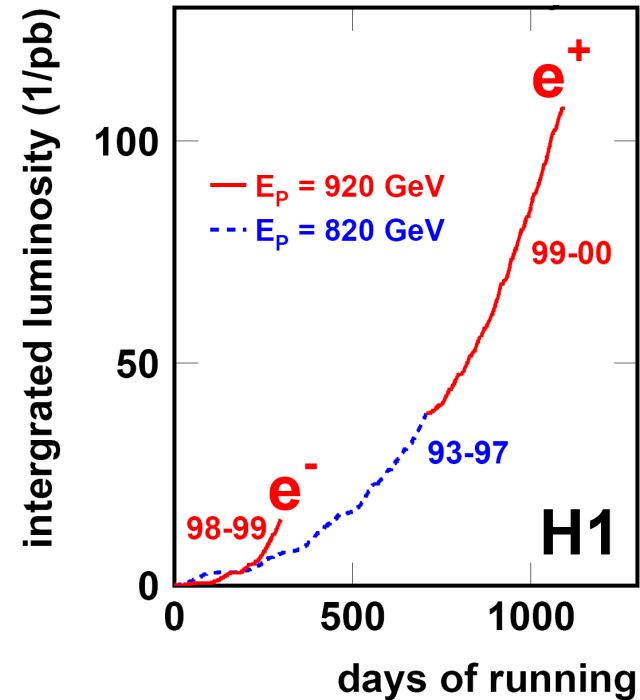
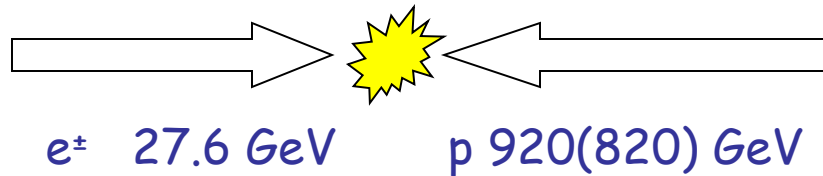
Content of the Talk

- HERA I, luminosities and data sets
- DIS at high Q^2 and LED
- Leptoquarks
- R_p -violating SUSY:
 - Resonant Squark Production
 - Bosonic Decays of Stops
 - Sleptons and GMSB
- Single Top Production
- Outstanding Events:
 - Isolated Leptons
 - Multi-Electrons
- First Results from HERA II

Not covered:

- Excited leptons and quarks
- General search for new physics
- Contact Interactions
- Finite quark radius
- R_p -conserving SUSY
- Doubly charged Higgs
- LFV Leptoquarks
- Magnetic monopoles
- Polarized cross-sections
- ...

HERA I, Luminosities and Data Sets



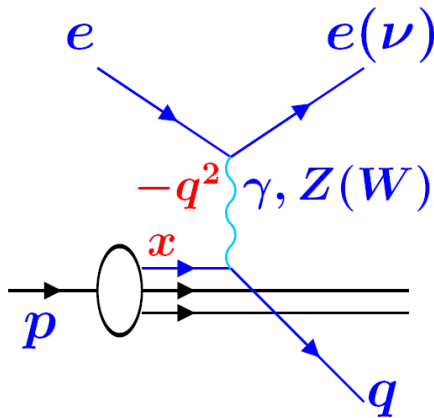
period	collisions	\sqrt{s} (GeV)	luminosity (pb ⁻¹)
93 – 97	e^+p	~ 300	~ 40
98 – 99	e^-p	~ 320	~ 20
99 – 00	e^+p	~ 320	~ 70

- excellent performance during HERA I
- many new results on searches based on HERA I data !
- HERA II data taking on-going (see later)

SM: DIS at high Q^2

HERA is a unique facility to test eq interactions at highest energies !

final HERA I NC/CC cross-section

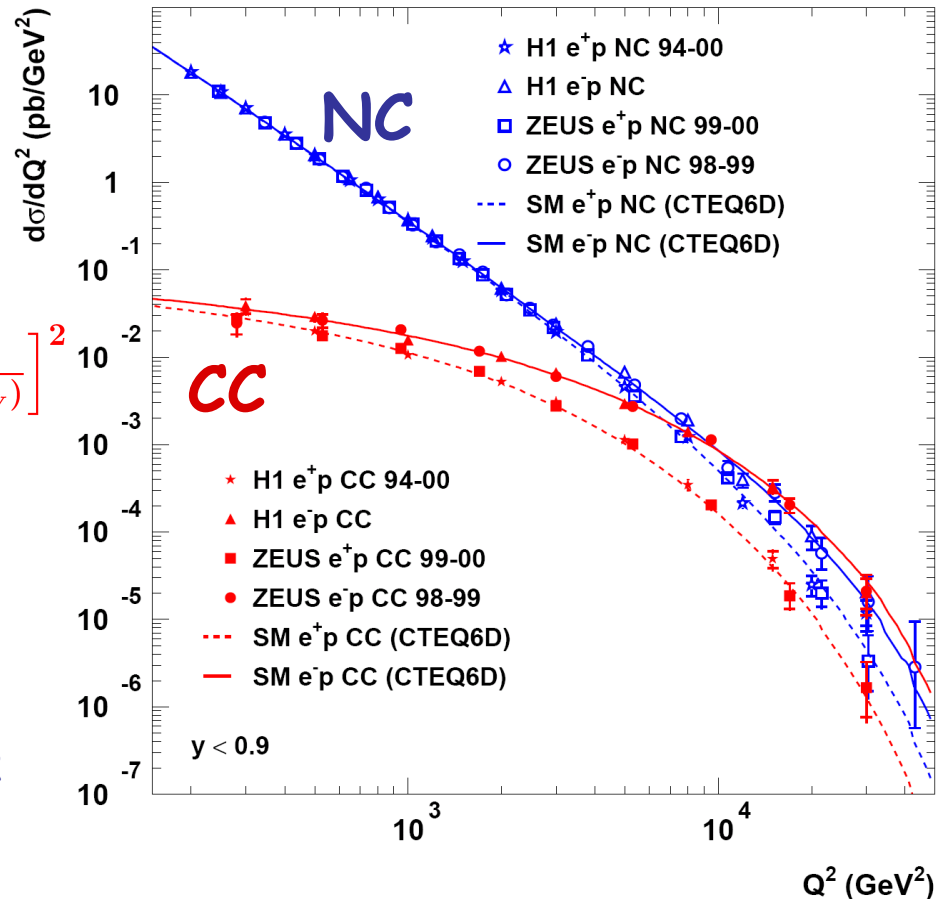


photon
 $\sim 1/Q^4$

W boson
 $\sim \left[\frac{M_W^2}{(Q^2 + M_W^2)} \right]^2$

test of EW sector up to
 $Q^2 \sim 40\,000 \text{ GeV}^2$

→ high spatial resolution:
 current HERA limit on quark
 radius: $0.85 \cdot 10^{-16} \text{ cm}$



Large Extra Dimensions

models with LEDs (ADD scenario):

cure hierarchy problem:

$$M_p^2 = R^n M_S^{2+n}$$

M_S = effective Planck scale

R = size of n compact extra dimensions

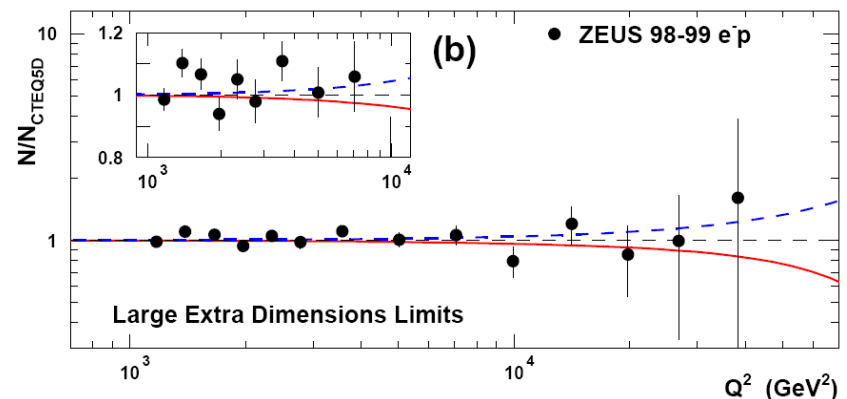
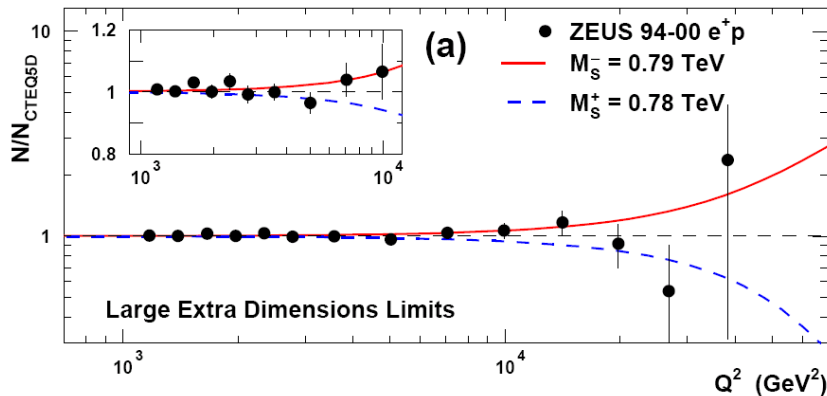
- $e q \rightarrow e q$:
- virtual KK 'graviton' exchange interferes with γ, Z^0 exchange
 - effective contact interaction with coupling $\eta = 1/M_S^4$

[Arkani-Hamed, Dimopoulos, Dvali, Phys. Lett. B429 (1998) 263.]

[H1, Phys. Lett. B568 (2003) 35.]

[ZEUS, subm. to Phys. Lett. B, hep-ex/0401009]

expect deviations from SM in NC DIS at high Q^2



no significant deviation from SM at high Q^2 stat. error dominant !

limit on eff. Planck scale:

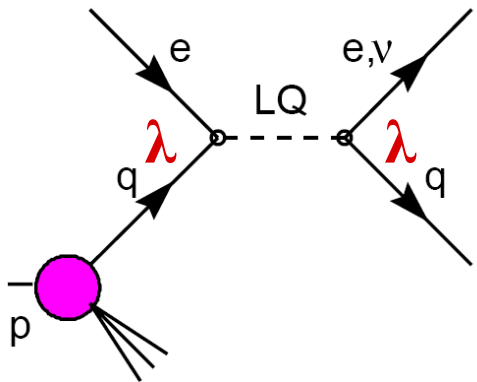
$$M_S > 0.8 \text{ TeV}$$

similar methods allow to set constraints on:
 eeqq Contact Interactions, finite quark radius, heavy
 Leptoquarks

Leptoquarks

- symmetry between the lepton & quark sector in the SM
- LQs appear in many extensions of SM:
 - GUT-like theories, Superstring-'inspired' E_6 -models, Technicolor-like theories, Compositeness models, ...
- general effective theory: BRW model: $\beta(eq) = 0, \frac{1}{2}$ or 1. [Buchmüller, Rückl, Wyler, Phys. Lett. B191 (1987) 442.]

single LQ production at HERA depends on λ (lepton-quark-LQ coupling)



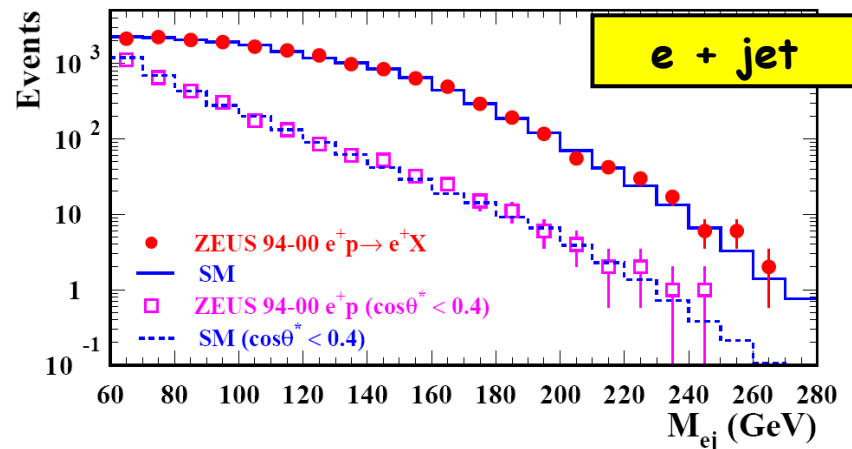
topology	SM background
$e + \text{jet}$	NC DIS
$\nu + \text{jet}$	CC DIS

exploit angular distr. to reduce SM bgr.

search for resonance in M spectra

ZEUS

for both $e + \text{jet}$ and $\nu + \text{jet}$:
no resonance observed in full HERA I data set



Leptoquarks: Exclusion Limits

BRW model: β fixed

example: $S_{0,L}$ $\beta(eq) = \beta(vq) = 0.5$

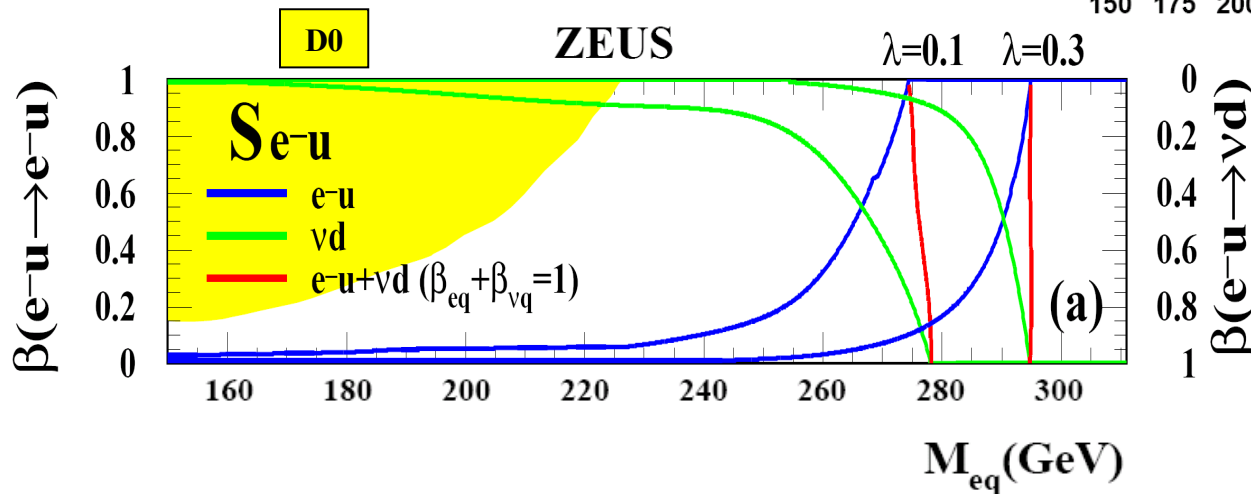
Tevatron: LQ pair production,
independent of λ .

LEP: t-channel LQ contribution
to hadr. cross-section,
strongly dependent on λ .

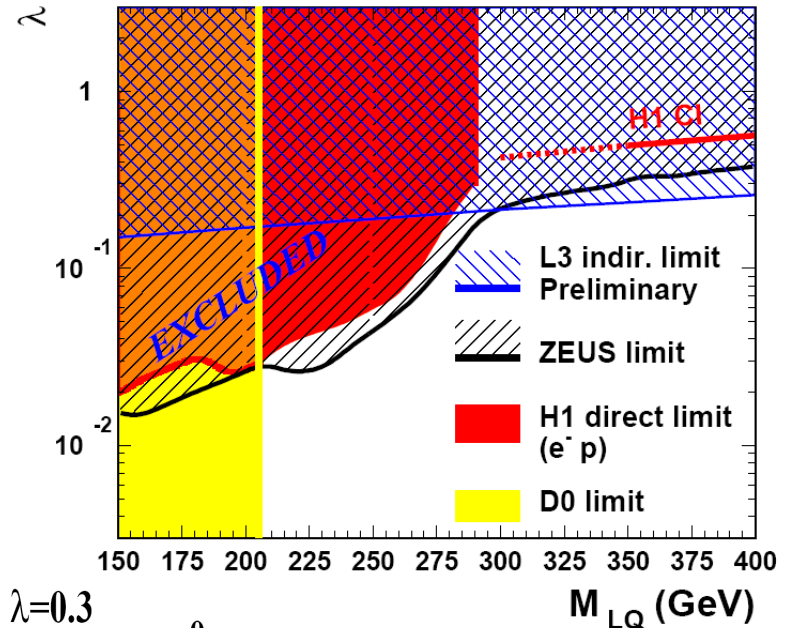
[H1, prelim., EPS03]

[ZEUS, Phys. Rev. D68 (2003) 052004]

generic LQ models: β free



SCALAR LEPTOQUARKS WITH F=2 ($S_{0,L}$)



HERA limits:

- dependent on λ
- independent of $\beta(eq)$
- stringent for small $\beta(eq)$

Resonant Production of Squarks

general superpotential has R_p -violating terms :

$$R_p = (-1)^{3B+L+2S}$$

$$W_{R_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

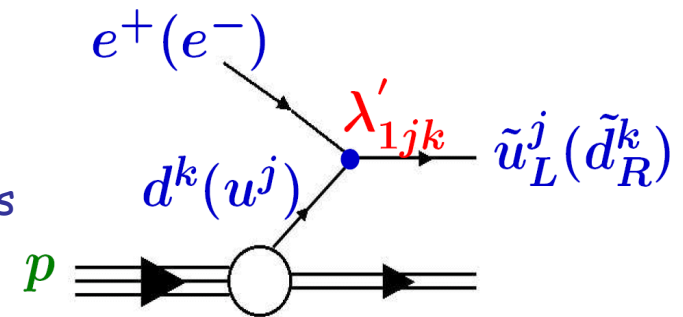
For proton stability: $\lambda' \cdot \lambda'' = 0$ sufficient

main consequences for colliders:

1. fundamental instability of SUSY matter (LSP decay)
 - indirect sensitivity to λ , λ' , λ'' from sparticle pair production
 - resonant production of sparticles at colliders.

HERA: single squark production via λ'_{1jk}

e^+p , e^-p : all flavors can be probed
e.g. stop production via λ'_{131} in e^+p collisions



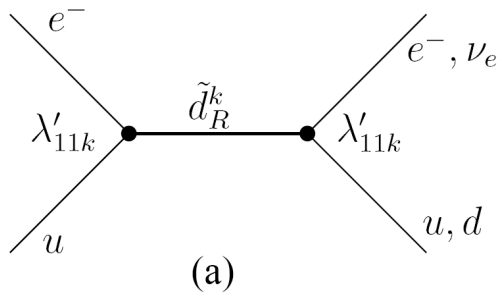
best discovery reach for SUSY at HERA

Squarks: Decay Modes

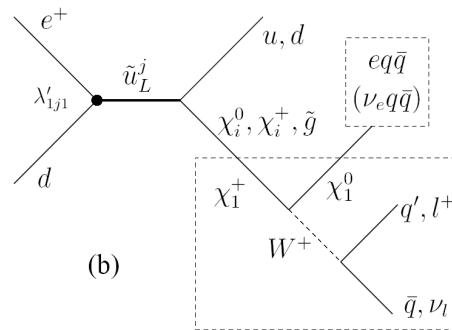
$\lambda' \neq 0$ opens a large variety of squark decay modes.

LSP decay: $\chi_1^0 \rightarrow e^\pm q \bar{q}$ ($\nu q \bar{q}$)

R_p-violating decay:

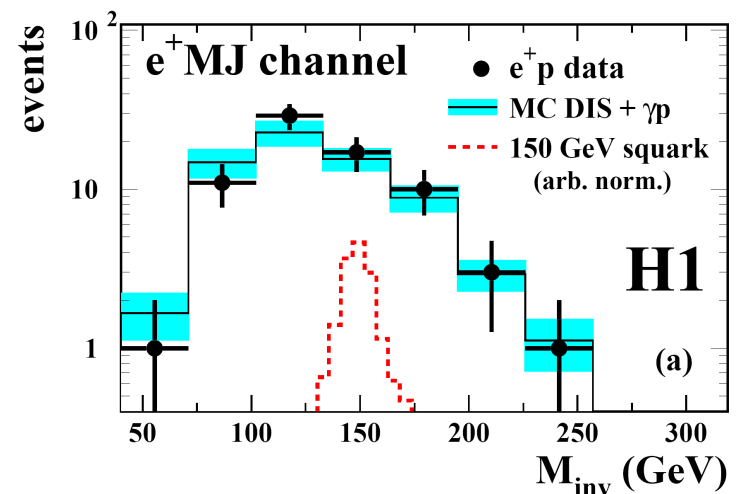


example of gauge decays:



many final states considered to reduce dependence on SUSY parameters (e.g. μ , $\tan\beta$, M_2 , λ' , M_{squark} , ...)
 $\rightarrow \text{BR}_{\text{tot}} \sim 1$

Channel	e^+p collisions		e^-p collisions	
	Data	SM expectation	Data	SM expectation
eq	632	628 ± 46	204	192 ± 14
νq	—	—	261	269 ± 21
eMJ (“right” charge)	72	67.5 ± 9.5	20	17.9 ± 2.4
eMJ (“wrong” charge)	0	0.20 ± 0.14	0	0.06 ± 0.02
$eeMJ$	0	0.91 ± 0.51	0	0.13 ± 0.03
$e\mu MJ$	0	0.91 ± 0.38	0	0.20 ± 0.04
$\nu e MJ$	0	0.74 ± 0.26	0	0.21 ± 0.07
νMJ	30	24.3 ± 3.6	12	10.1 ± 1.4
$\nu\mu MJ$	0	0.61 ± 0.12	0	0.16 ± 0.03

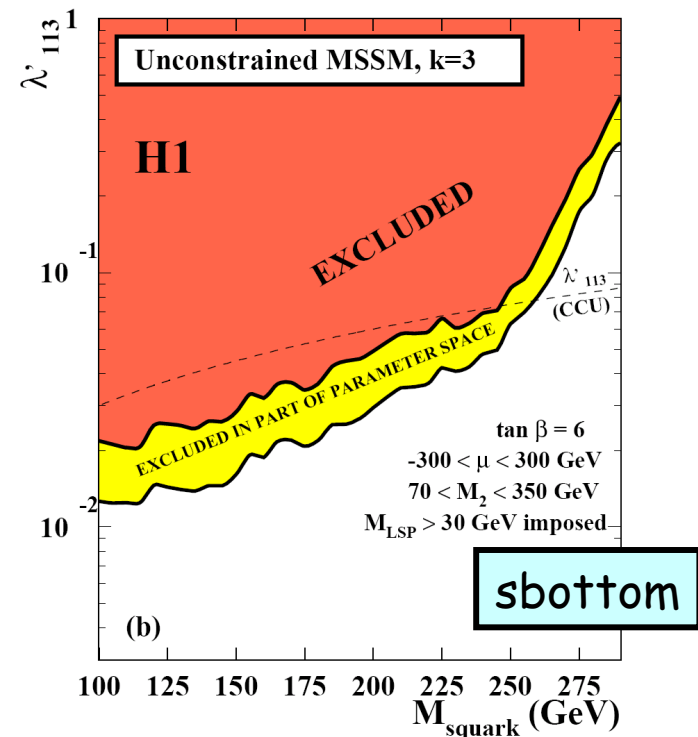
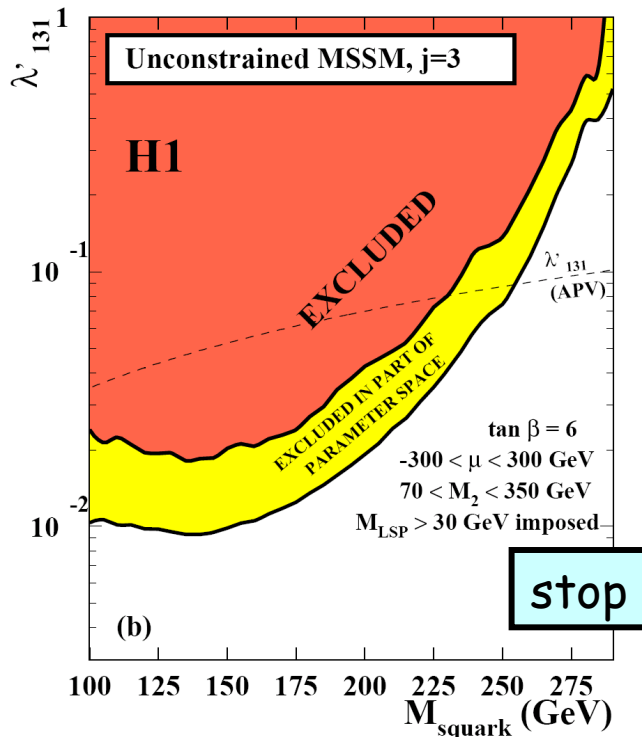


[H1, subm. to Eur. Phys. J. C, hep-ex/0403027]

all channels in agreement with SM expectation

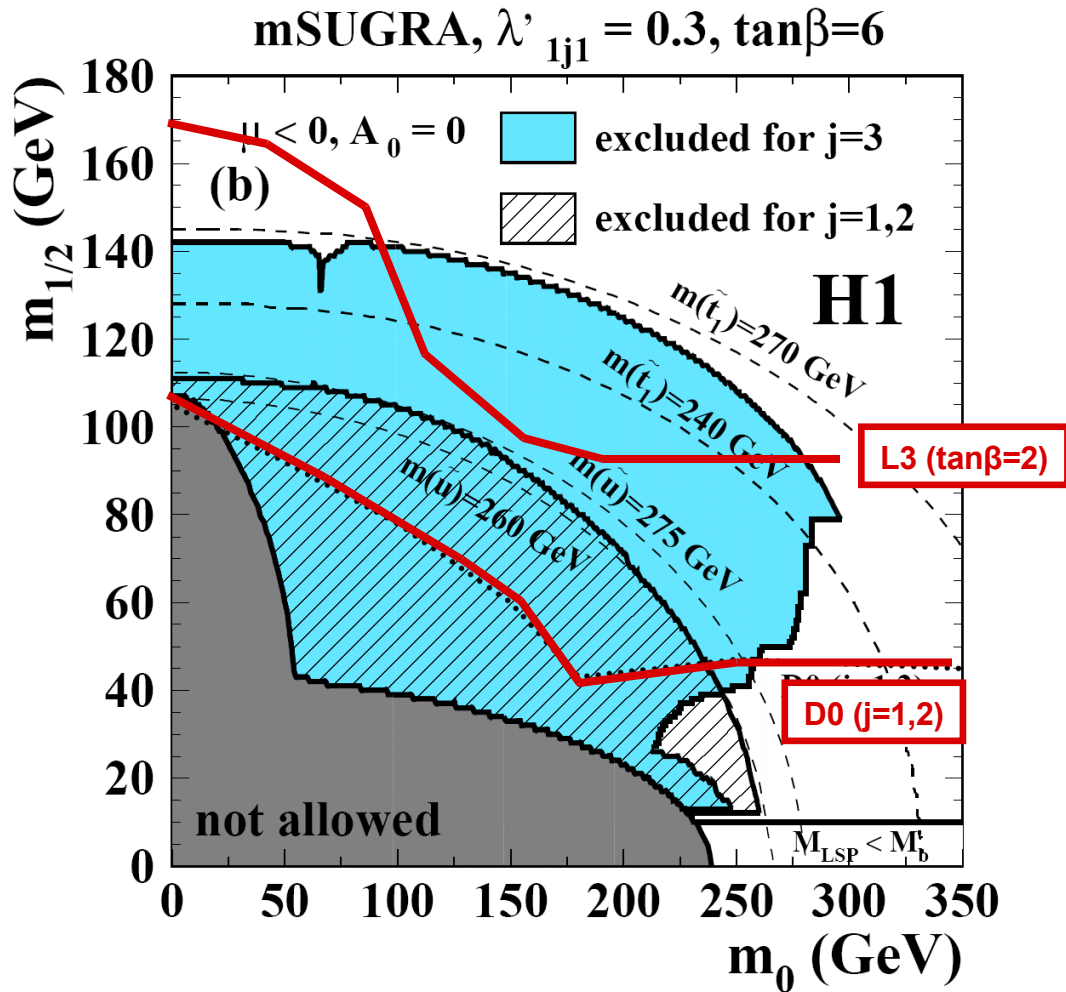
Squarks: Exclusion Limits

constraints on $\lambda'(M_{\text{squark}})$: e.g. third generation ($j=3, k=3$)



- For $\lambda'=0.3$ (e.m. strength) squarks up to 280 GeV are ruled out
- small couplings: improvement of indirect low-energy limits

Squarks: mSUGRA Interpretation



HERA limits follow squark isomass curve

for $\lambda' = 0.3$: squark masses up to 275 GeV ruled out

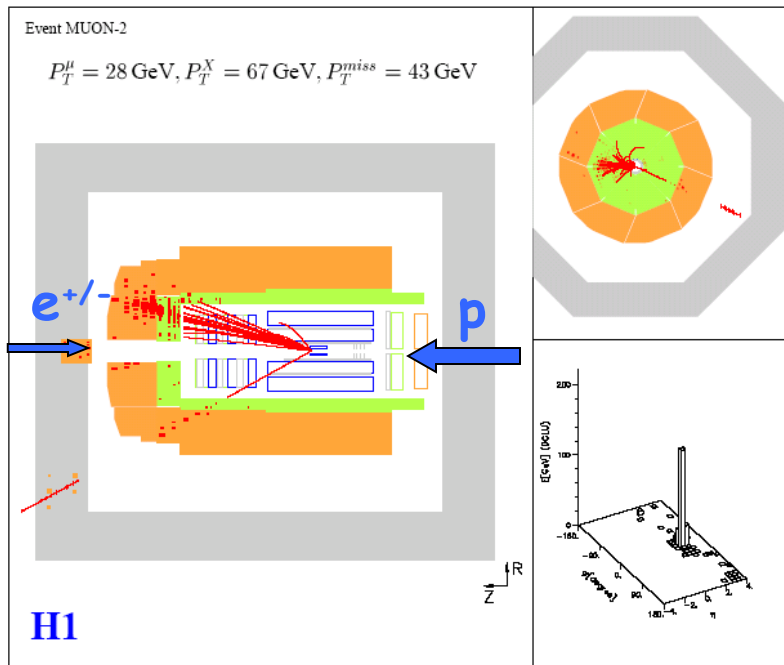
HERA sensitivity comparable with LEP and Tevatron bounds

Events with Isolated Leptons

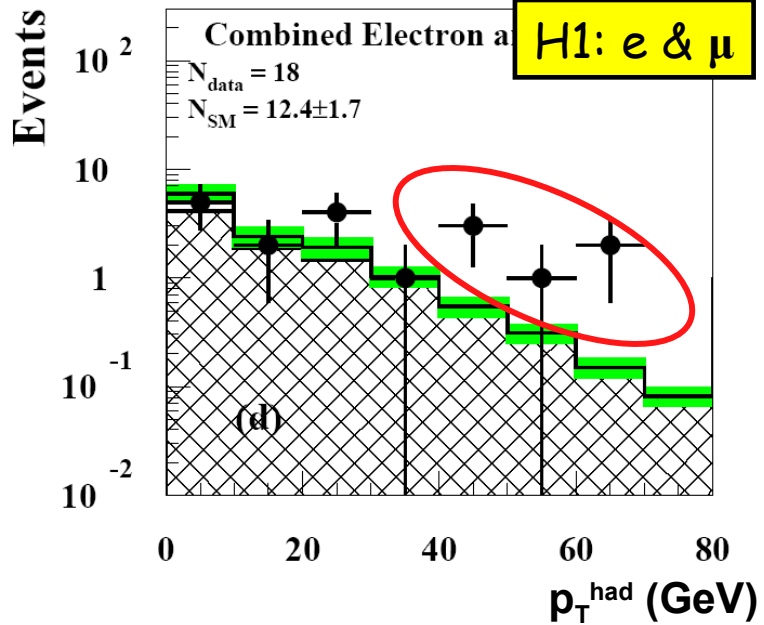
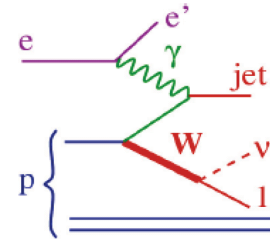
H1 observes excess of spectacular events

- isolated e or μ with high p_T
- $p_{T,miss}$
- jet with high p_T

$$e^+p \rightarrow \mu^+X$$



main SM contribution from W production:



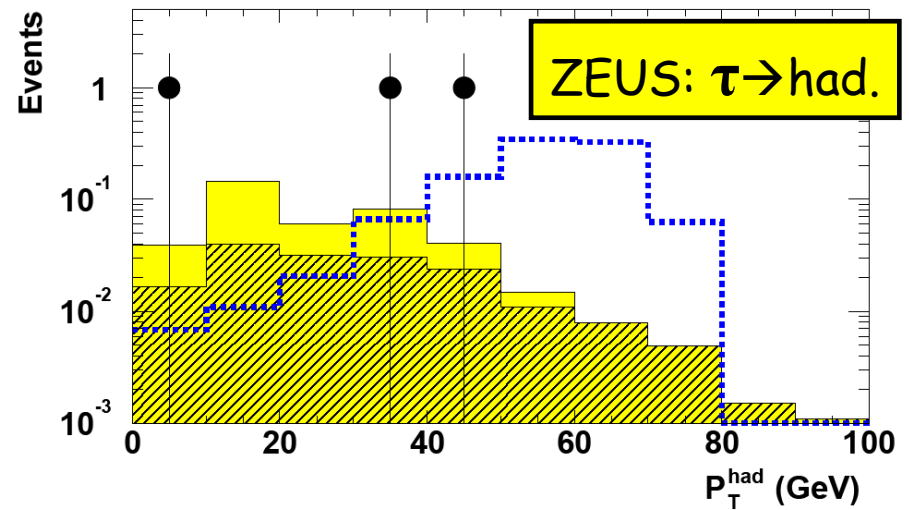
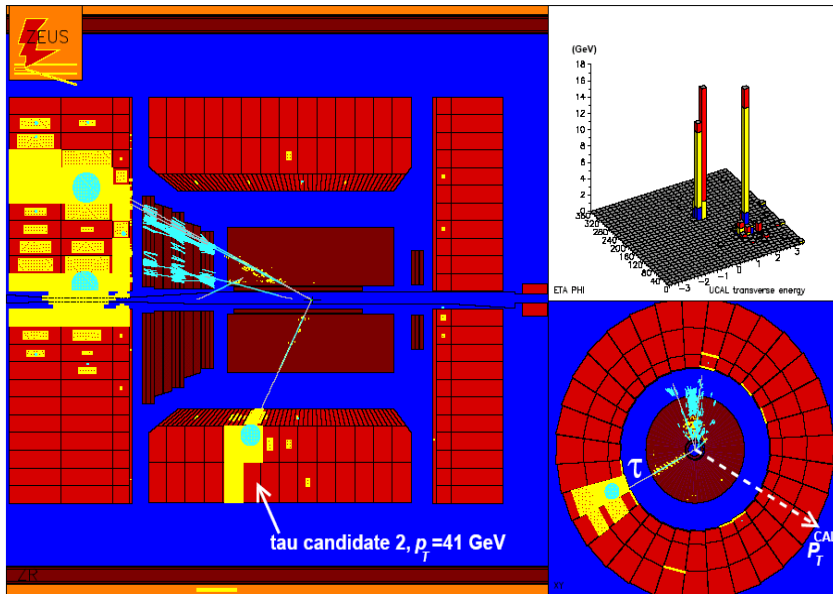
not confirmed by ZEUS

Events with Isolated Leptons

τ search performed by ZEUS:

- selects isolated taus decaying to hadrons
- pencil-like jets

3 events found, 0.40 ± 0.13 exp.



not confirmed by a preliminary H1 analysis

Events with Isolated Leptons

current situation: **observed** / expected

H1	electron	muon	tau (prelim)
$p_T^x > 25 \text{ GeV}$	5 / 1.8 ± 0.3	6 / 1.7 ± 0.3	0 / 0.53 ± 0.10
$p_T^x > 40 \text{ GeV}$	3 / 0.7 ± 0.1	3 / 0.6 ± 0.1	0 / 0.22 ± 0.05

ZEUS	electron	muon	tau
$p_T^x > 25 \text{ GeV}$	2 / 2.9 ± 0.6	5 / 2.8 ± 0.2	2 / 0.20 ± 0.05
$p_T^x > 40 \text{ GeV}$	0 / 0.9 ± 0.1	0 / 0.9 ± 0.1	1 / 0.07 ± 0.02

- interpretation unclear
- need more data from HERA II

e/m : [H1, Phys. Lett. B561 (2003) 241.]
 [ZEUS, Phys. Lett. B559 (2003) 153.]

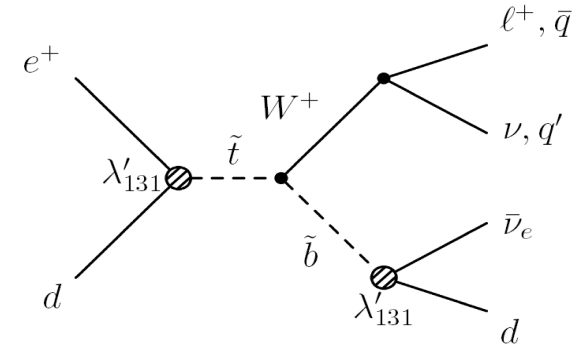
tau: [H1, prelim., DIS04]
 [ZEUS, Phys. Lett. B583 (2004) 1.]

Bosonic stop Decay

possible SUSY explanation of isolated leptons:

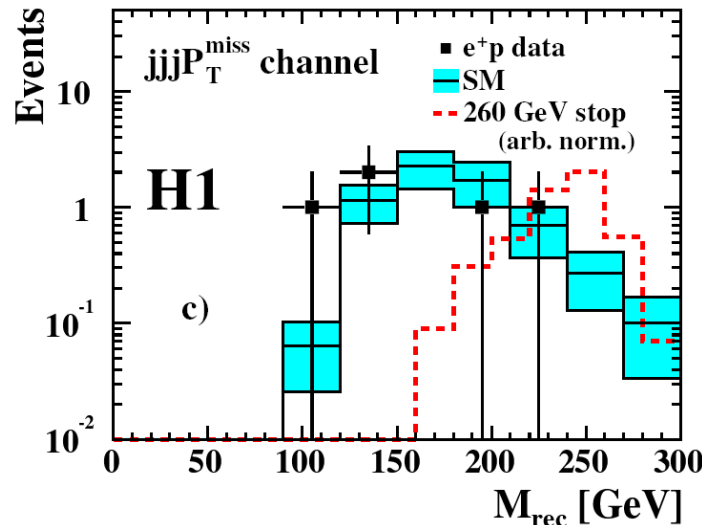
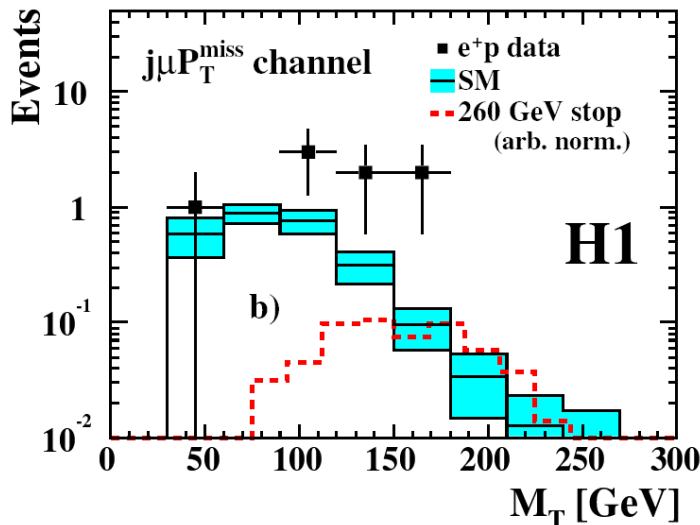
[T. Kon et al, Mod. Phys. Lett. A12 (1997) 3143.]

1. sbottom is significantly lighter than stop
2. decay to gauginos kinematically forbidden



signature: 3 jets + $p_{T,miss}$
jet + l + $p_{T,miss}$

H1	$j e p_{T,miss}$	$j \mu p_{T,miss}$	$j j j p_{T,miss}$	$e j$
data	3	8	5	1100
SM exp.	3.8 ± 0.9	2.7 ± 0.5	6.2 ± 1.7	1120 ± 131

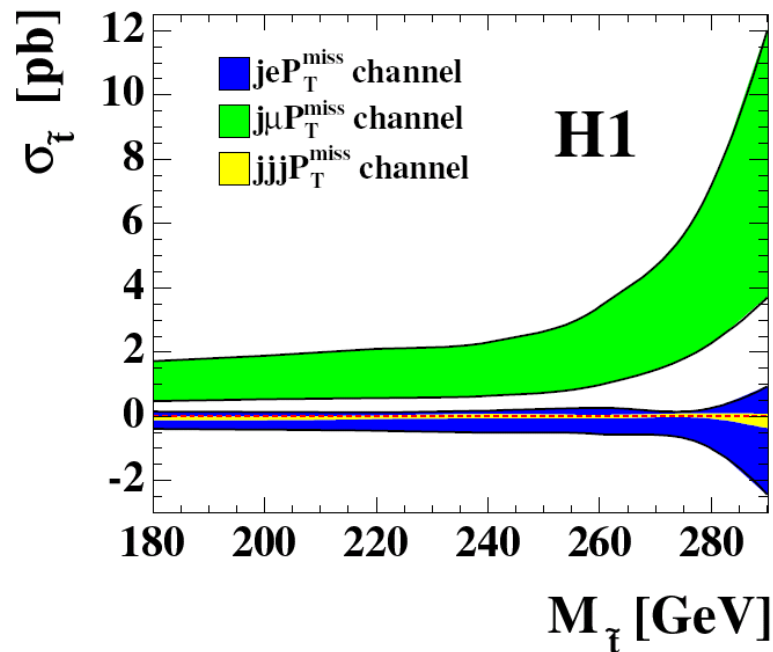


excess in
 $j \mu p_{T,miss}$ not
confirmed by
other channels

[H1,
subm. to Phys. Lett. B,
hep-ex/0405070]

Bosonic stop Decay: Interpretation

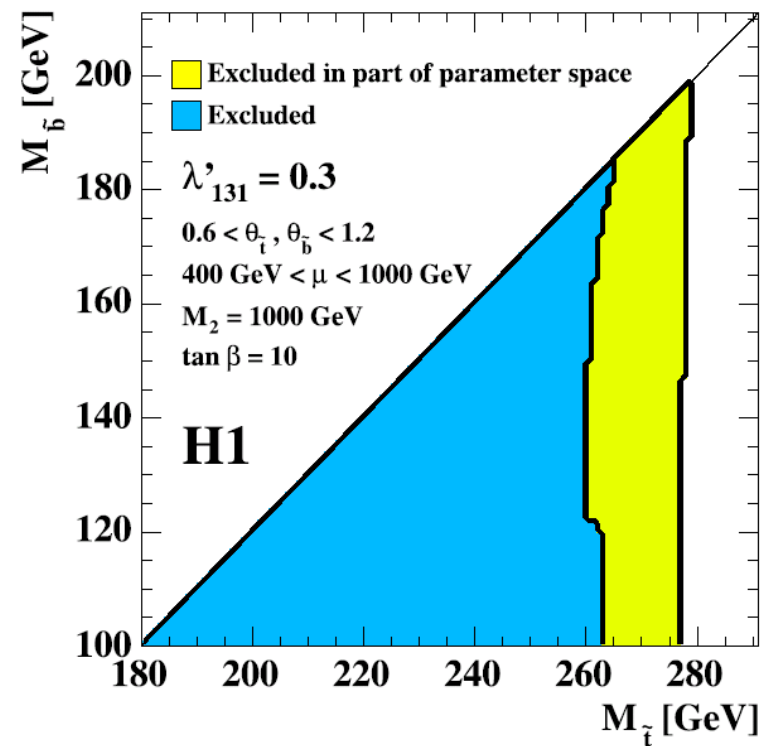
allowed signal cross sections ($\sigma \pm \Delta\sigma$)



all channels (except $\text{j}\mu\text{P}_{T,\text{miss}}$)
consistent with non-observation

→ Isolated lepton events can hardly
be interpreted as scalar tops.

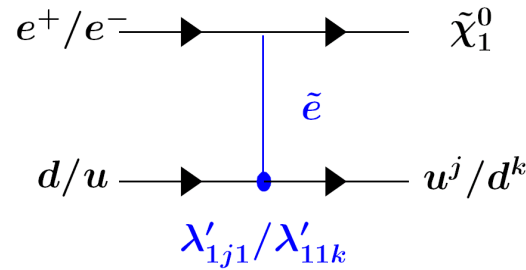
excluded ($M_{\text{stop}}, M_{\text{sbottom}}$) area



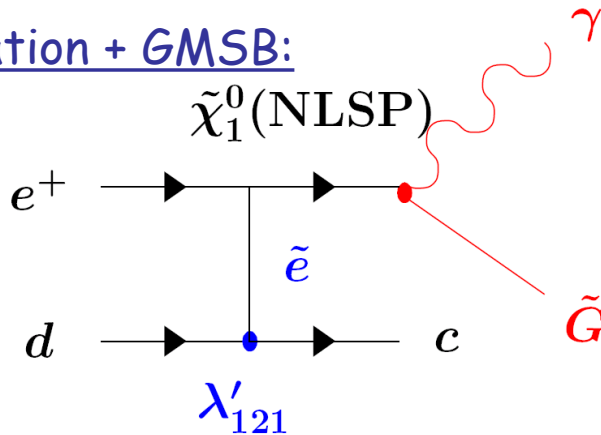
stops up to 275 GeV
excluded for $\lambda'_{131} = 0.3$

R_p -viol. SUSY with Sleptons and Gravitinos

if $M_{\text{squark}} \gg M_{\text{slepton}}$: λ' can still be probed via slepton exchange:



R_p -violation + GMSB:



signature:

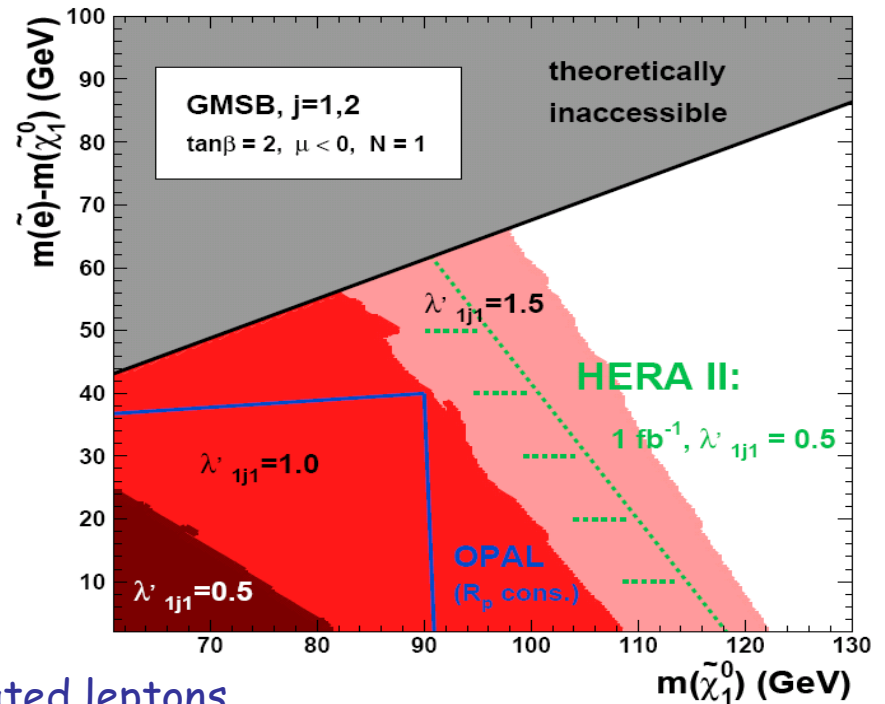
isolated $\gamma + p_{T,\text{miss}} + \text{jet}$

no deviation from SM [H1, prelim., DIS04]

obs.: 1 exp.: 3.1 ± 0.3

analogous: $e^+d \rightarrow u\chi^+$; $\chi^+ \rightarrow \tilde{G}W^+$ recall: isolated leptons

H1 preliminary: e^+p

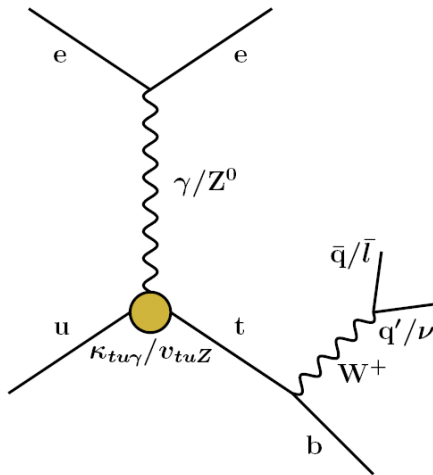


Production of single top Quarks

another possible explanation of isolated leptons

[H1, Eur. Phys. J. C33 (2004) 9.]
 [ZEUS, Phys. Lett. B559 (2003) 153.
 and add. DESY-03-188]

FCNC couplings to top quark ($\kappa_{tu\gamma}$, ν_{tuZ})



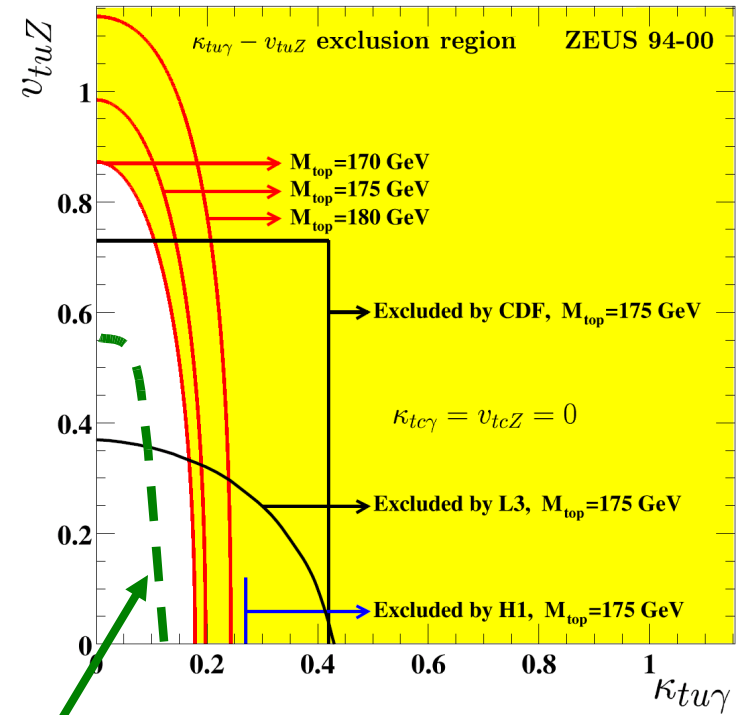
dedicated searches performed at HERA

leptonic channels: • isolated lepton events
 • $E_{T,miss}$ + lepton + jet

hadronic channel: • no deviation from SM
 • low sensitivity due to QCD background

exclusion limits:

ZEUS



exp. reach of HERA II

Observation of Multi-Electron Events

search for events with several leptons in final state

good agreement with SM found
in muon and tau channels

e: [H1, Eur. Phys. J. C31 (2003) 17.]

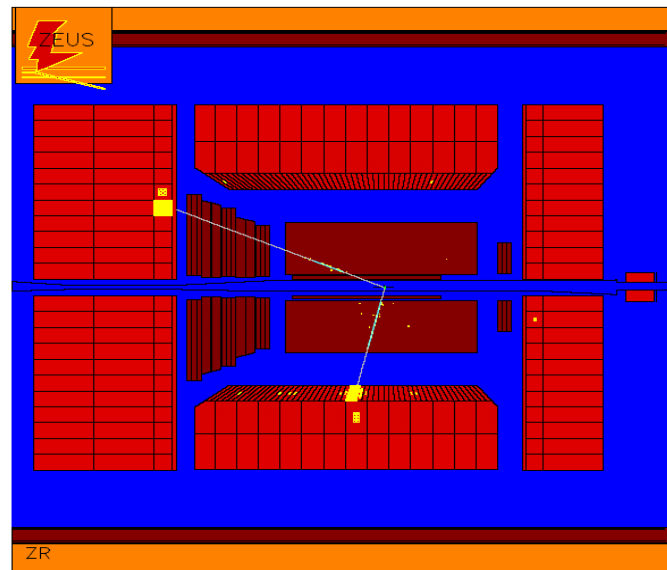
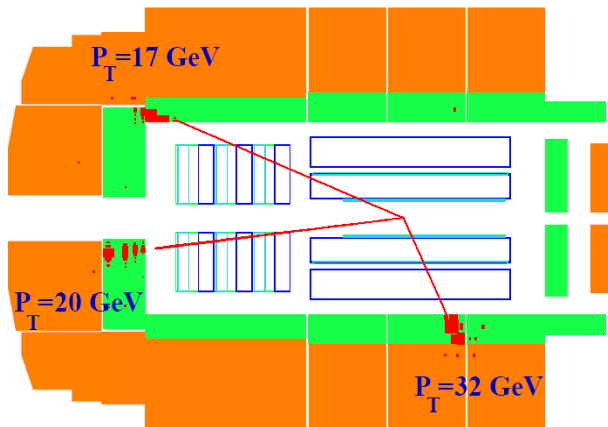
[ZEUS, prelim., ICHEP02]

mu: [H1, Phys. Lett. B583 (2004) 28.]

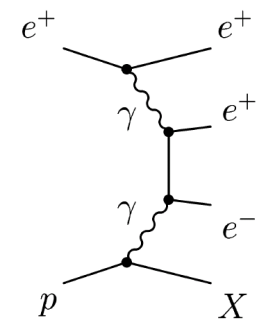
[ZEUS, prelim., ICHEP02]

tau: [H1, prelim., DIS04]

excess observed in electron channel at high invariant mass

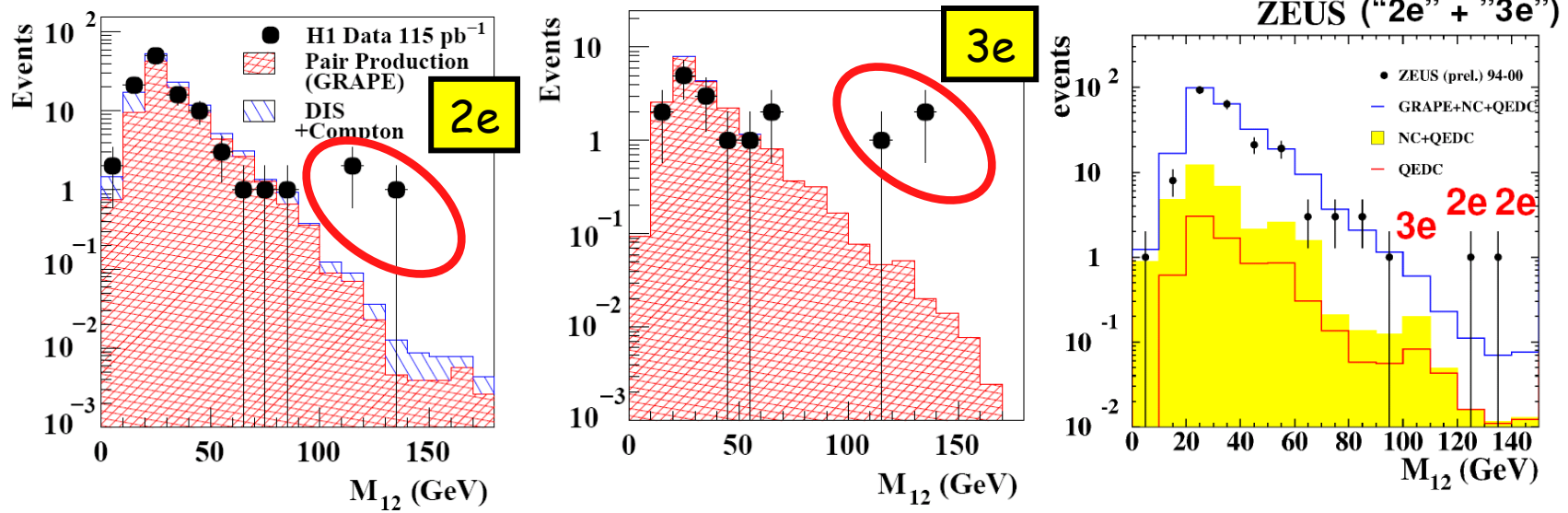


main SM
contribution
from $\gamma\text{-}\gamma$
collisions:



Observation of Multi-Electron Events

excess in multi-electron channel at high invariant mass



M_{12} = mass of two highest p_T electrons

event numbers in electron channel: **observed/expected**

selection	H1 (115 pb ⁻¹)	ZEUS (130 pb ⁻¹) [prelim.]
2e, $M > 100$ GeV	3 / 0.30 ± 0.04	2 / 0.77 ± 0.08
3e, $M > 100$ GeV	3 / 0.23 ± 0.04	0 / 0.37 ± 0.04

need more data

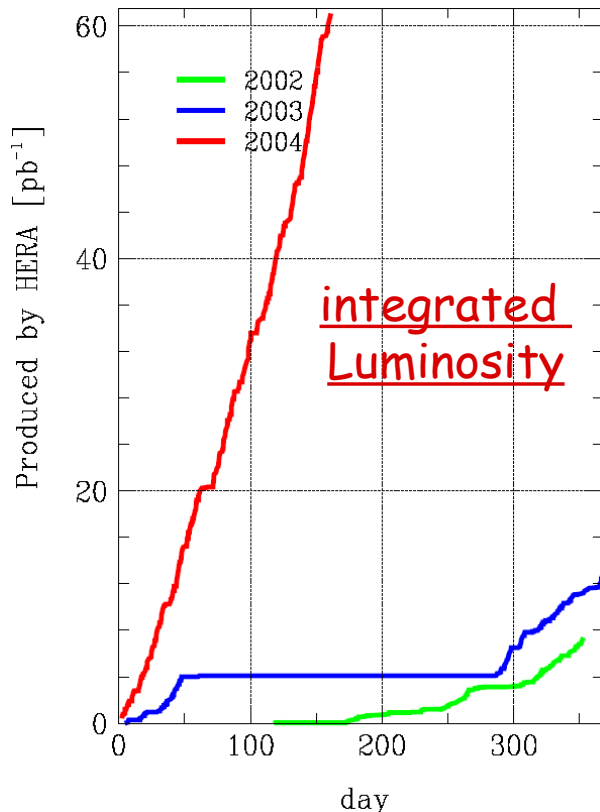
First Results from HERA II

background problems are solved !

[H1, prelim., DIS04]

HERA runs with 3 times higher luminosity

- expected: $\sim 700 \text{ pb}^{-1}$ by mid 2007
- P_e up to 50% achieved



multi-electrons:

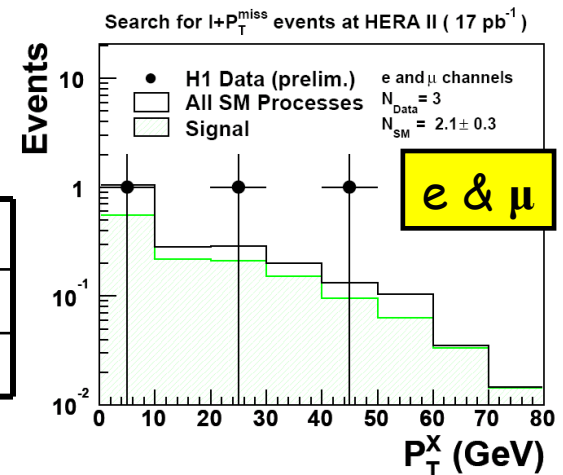
based on 17 pb^{-1}

	data	SM exp.
'2e'	10	15.8 ± 1.7
'3e'	2	3.0 ± 0.4

isolated leptons:

$p_T^X > 25 \text{ GeV}$

	data	SM exp.
e	2	0.34 ± 0.07
μ	0	0.29 ± 0.08



more data from HERA II needed

Conclusion

- HERA is a unique facility to search for new physics.
- A large variety of searches for SUSY and exotics has been performed with HERA I data (CI, LED, single top, finite quark radius, excited leptons, excited quarks, leptoquarks, resonant squark production, bosonic stop decay, magnetic monopoles, LFV, ...).
- Outstanding events have been observed (isolated leptons, multi-electrons). More data are needed for clarification.
- Background problems after the HERA II upgrade are solved.
- The high luminosity runs of HERA II have started.
- $\sim 700 \text{ pb}^{-1}$ are expected by mid 2007.
- First results from HERA II are available now, more to come !