Search for New Physics at HERA

Chi Nhan Nguyen – DESY

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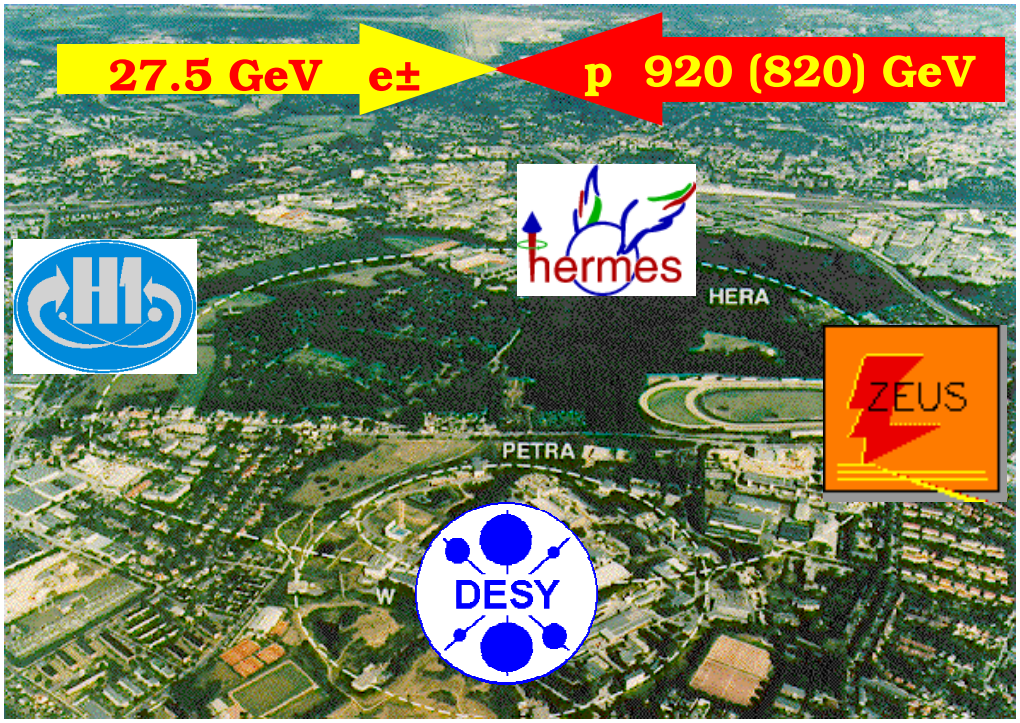
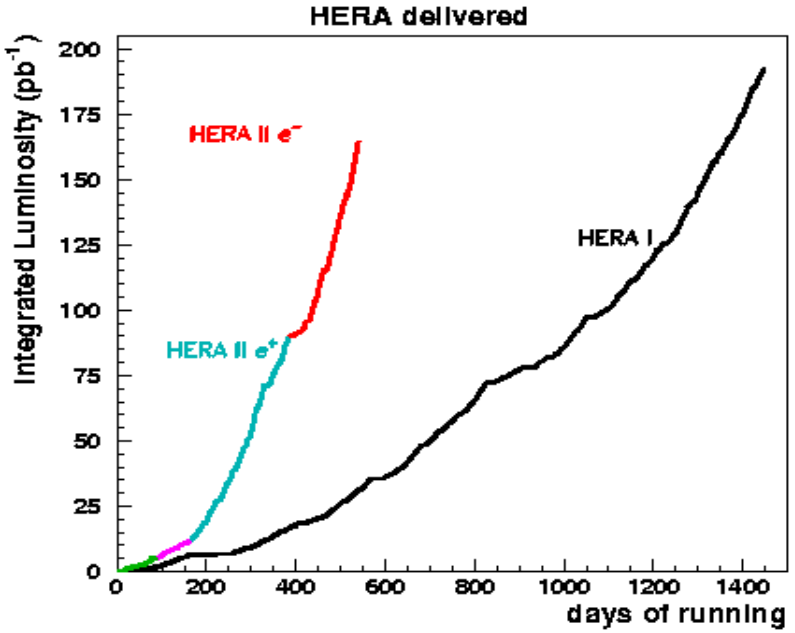
- HERA, H1 & ZEUS

- Isolated Leptons
- RPV Supersymmetry
- Leptoquarks

- Summary & Outlook

HERA





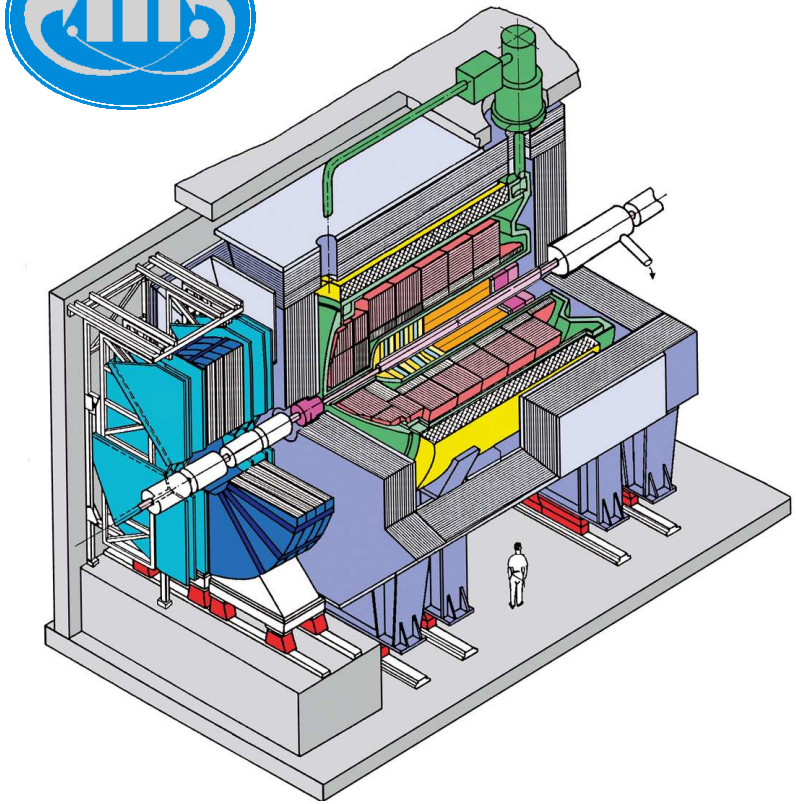
- HERA: e± p collider in Hamburg, Germany
- Leptons: 27.5 GeV Protons: 920 GeV
- CMS-Energy: 320 GeV

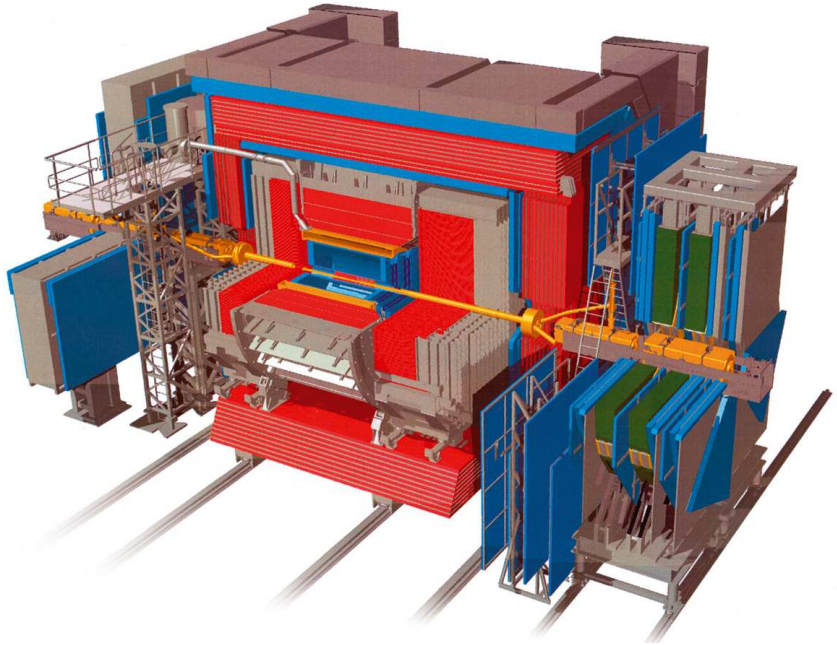
- Luminosity: since 1994
- Extensive Upgrade: 2000-2002

- After some background problems: Very good performance since 2003

- Luminosity increased
- Delivered int. luminosity will extend HERA I int. Luminosity soon
- Polarised lepton beam

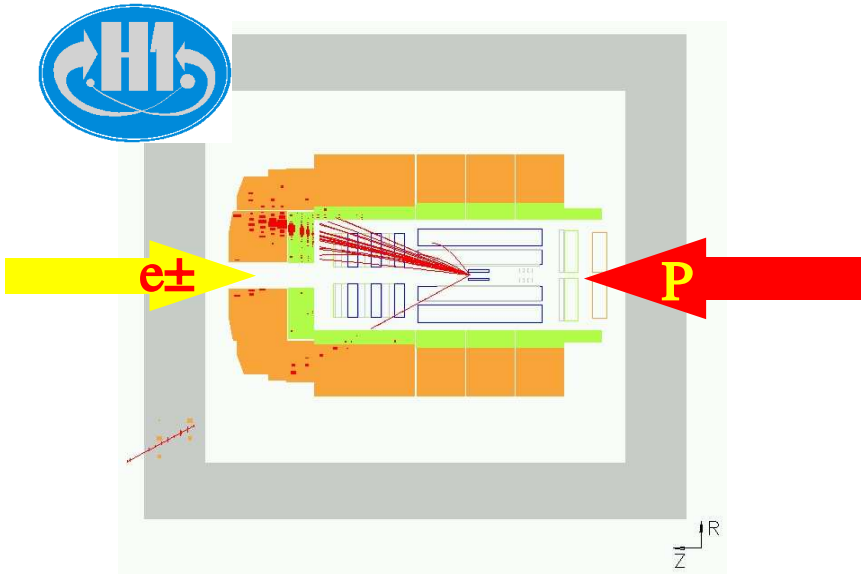
H1 & ZEUS

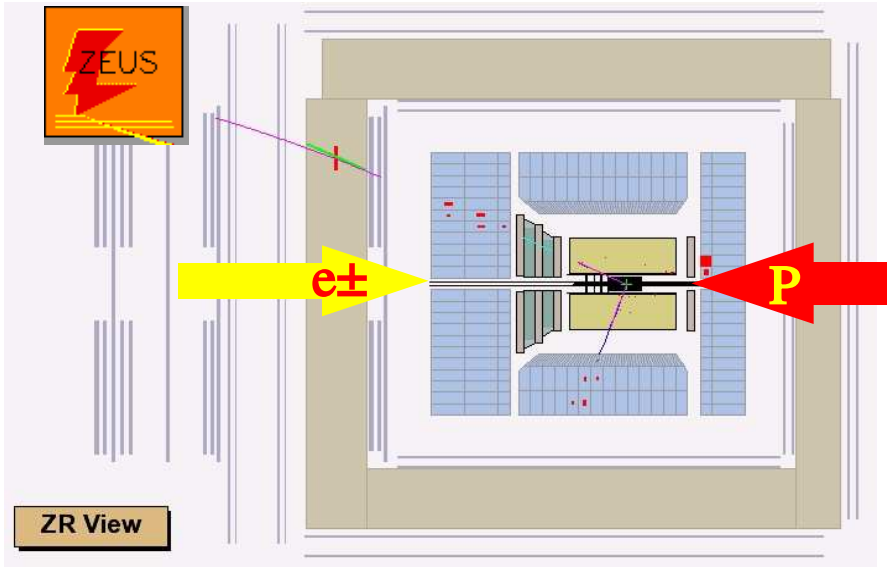




- Two colliding beam experiments: H1 & ZEUS
- Multi-purpose detectors

H1 & ZEUS: Main Components



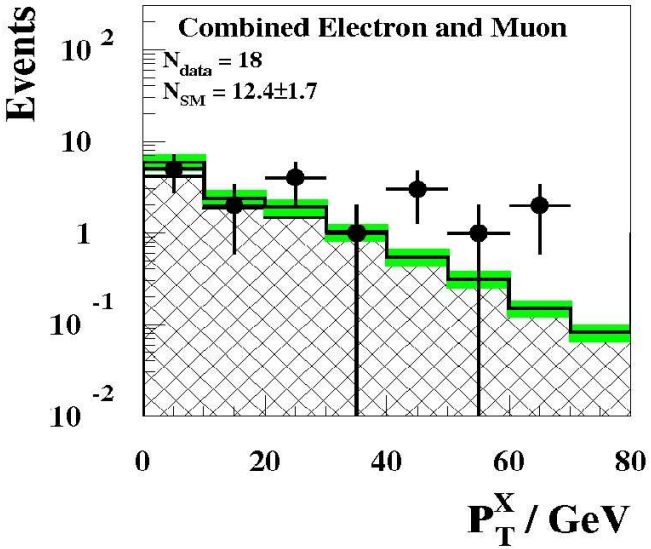


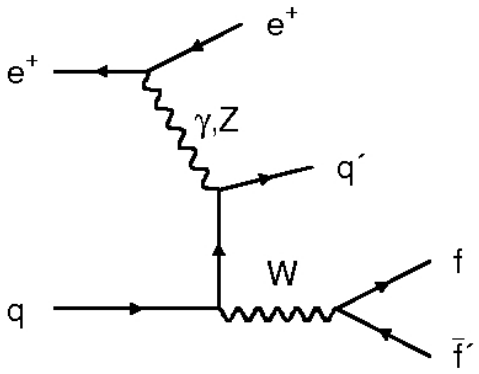
- Calorimeter: LAr, $4° < \theta < 154°$
  - EMC $\Delta E/E = 12\%/\sqrt{(E/GeV)} \oplus 1\%$
  - HAC $\Delta E/E = 50\%/\sqrt{(E/GeV)} \oplus 2\%$
- Tracking Detectors:
  - Forward $7° < \theta < 25°$
  - Central $25° < \theta < 155°$
- Muon System:
  - Instr. Solenoid (1.15 T) $4° < \theta < 171°$
  - Muon Spectrometer $3° < \theta < 17°$

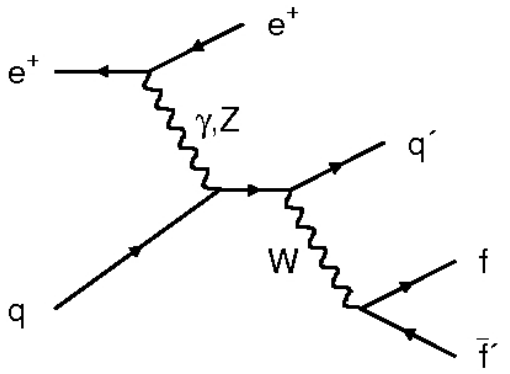
- Calorimeter: Uranium Scintillator
  - EMC $\Delta E/E = 18\%/\sqrt{(E/GeV)} \oplus 1\%$
  - HAC $\Delta E/E = 35\%/\sqrt{(E/GeV)} \oplus 1\%$
- Tracking System:
  - Central $15° < \theta < 164°$
  - Inner (HERA2) $7° < \theta < 158°$
- Muon Detectors:
  - Instrumented hermetic Yoke (1.4 T)
  - Tube Chambers $5° < \theta < 171°$

Isolated Lepton & Missing tr. Momentum

- Model independent Search: Events with isolated high-Pt lepton and large missing transverse momentum
- Main SM Background with scalable cross section: : Single W Boson Production





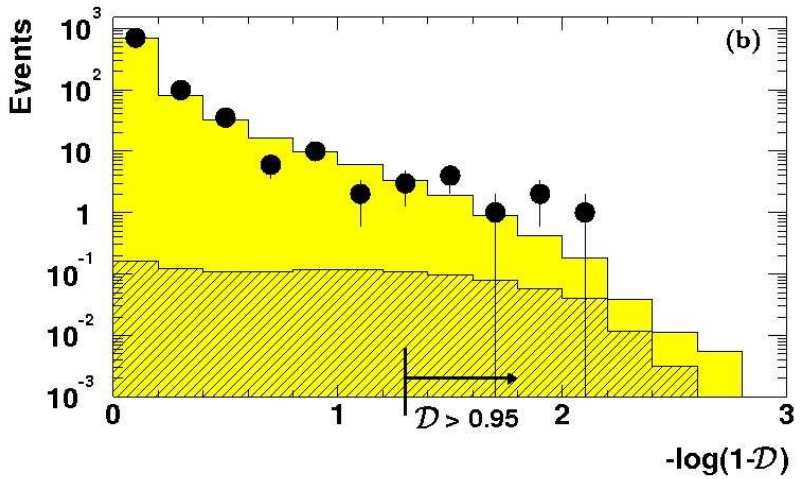


1994-2000 $e^{\pm}p$		Electron obs./exp. ($W^{\pm}$ contrib.)	Muon obs./exp. ($W^{\pm}$ contrib.)
H1 118.4 pb^{-1}	Full Sample	11 / 11.54±1.50 (71%)	8 / 2.94±0.50 (86%)
	$P_T^X > 25$ GeV	5 / 1.76±0.30 (82%)	6 / 1.68±0.30 (88%)
	$P_T^X > 40$ GeV	3 / 0.66±0.13 (80%)	3 / 0.64±0.14 (92%)
ZEUS 130.2 pb^{-1}	Full Sample	24 / 20.6 $^{+1.7}_{-4.6}$ (17%)	12 / 11.9$^{+0.6}_{-0.7}$ (16%)
	$P_T^X > 25$ GeV	2 / 2.90$^{+0.59}_{-0.32}$ (45%)	5 / 2.75$^{+0.21}_{-0.21}$ (50%)
	$P_T^X > 40$ GeV	0 / 0.94$^{+0.11}_{-0.10}$ (61%)	0 / 0.95$^{+0.14}_{-0.10}$ (61%)

- H1 observes excess in muon-channel and in electron channel at large hadronic transverse momentum
- ZEUS sees no excess

Isolated Tau & Missing tr. Momentum

- H1 and ZEUS: Tau-Channel ⇒ 1-prong hadronic decays of tau ⇒ pencil-like jets
- H1: Conventional cuts
- ZEUS: Discriminant method based on multi-dim. pdf



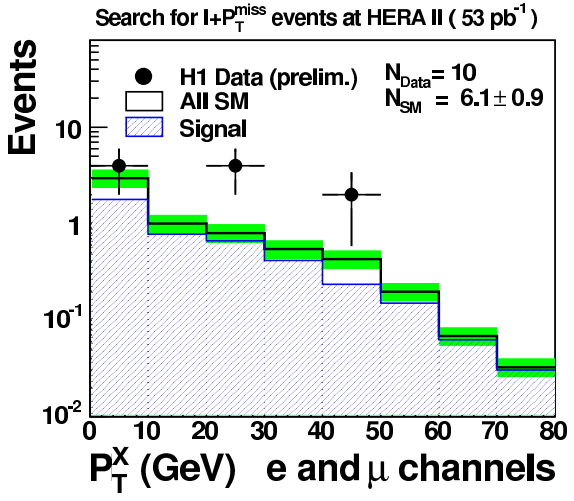
1994-2000 $e^{\pm}p$		Electron obs./exp. ($W^{\pm}$ contrib.)	Muon obs./exp. ($W^{\pm}$ contrib.)	Tau (H1:108 pb^{-1}) obs./exp. ($W^{\pm}$ contrib.)
H1	Full Sample	11 / 11.54±1.50 (71%)	8 / 2.94±0.50 (86%)	5 / 5.81±1.36 (15%)
	$P_T^X > 25$ GeV	5 / 1.76±0.30 (82%)	6 / 1.68±0.30 (88%)	0 / 0.53±0.10 (49%)
118.4 pb^{-1}	$P_T^X > 40$ GeV	3 / 0.66±0.13 (80%)	3 / 0.64±0.14 (92%)	0 / 0.22±0.05 (54%)
ZEUS	Full Sample	24 / 20.6 $^{+1.7}_{-4.6}$ (17%)	12 / 11.9$^{+0.6}_{-0.7}$ (16%)	3 / 0.40$^{+0.12}_{-0.13}$ (49%)
	$P_T^X > 25$ GeV	2 / 2.90$^{+0.59}_{-0.32}$ (45%)	5 / 2.75$^{+0.21}_{-0.21}$ (50%)	2 / 0.20$^{+0.05}_{-0.05}$ (49%)
130.2 pb^{-1}	$P_T^X > 40$ GeV	0 / 0.94$^{+0.11}_{-0.10}$ (61%)	0 / 0.95$^{+0.14}_{-0.10}$ (61%)	1 / 0.07$^{+0.02}_{-0.02}$ (71%)

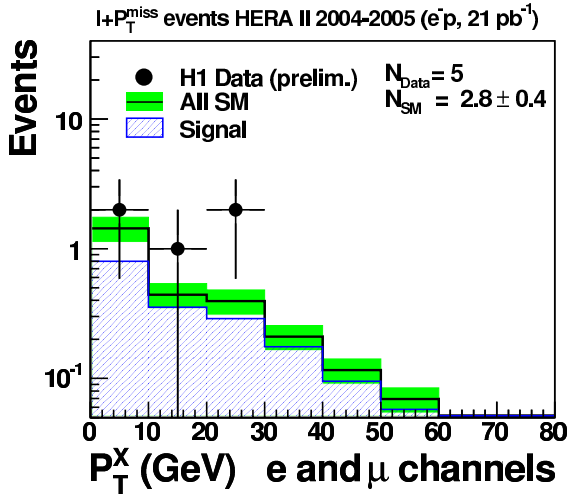
- H1: no excess
- ZEUS: slight excess

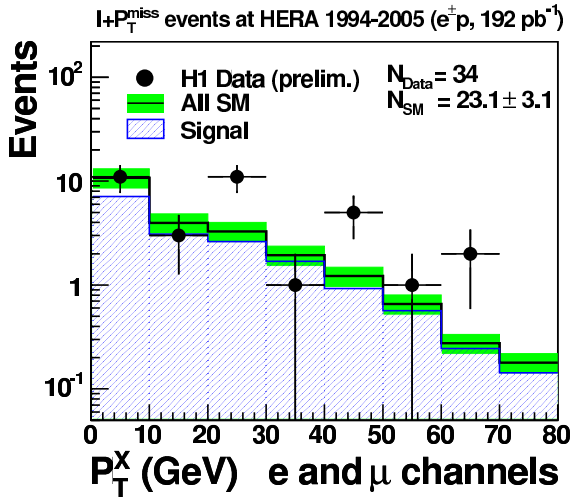
- <u>Need new Data to clear the puzzle</u>

Isolated Lepton & Missing tr. Momentum: HERA II

- H1: HERA II e±p data (53 + 21 = 64 pb^{-1}) : > 50% HERA I
- Preliminary results for Electron- and Muon-channel



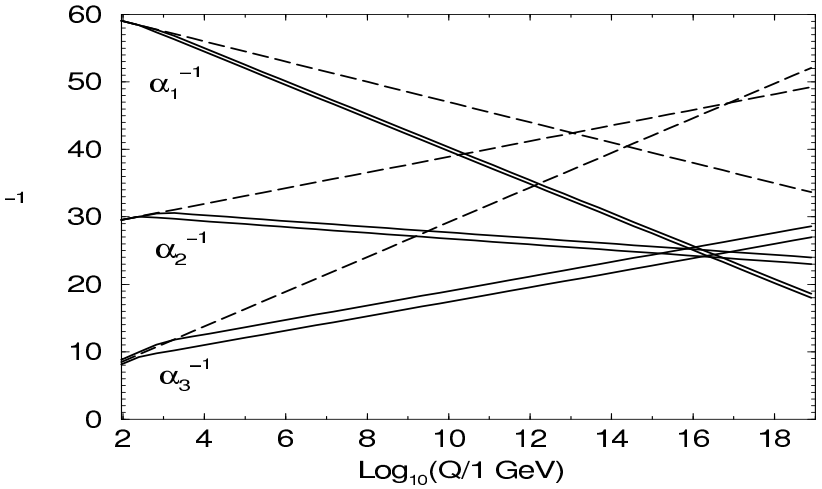




- H1: still excess in Electron- and Muon-channel
- Waiting for ZEUS HERA2 results,
  the tau-channel in HERA2 and even more data from HERA2!

SUSY Introduction

- **Supersymmetry**
  - Symmetry between fermions and bosons:
    Q |Boson> = |Fermion>; Q |Fermion> = |Boson>
  - Can lead e.g. to unification of coupling constants
  - Leads to additional particles with unknown mass spectrum and couplings



Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	+1	$h^0\ H^0\ A^0\ H^\pm$	$H_u^0\ H_d^0\ H_u^+\ H_d^-$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$ $\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$ $\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$	" " " " $\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$ $\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$ $\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$	" " " " $\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$
charginos	1/2	−1	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$
gluino	1/2	−1	$\tilde{g}$	" "
gravitino/ goldstino	3/2	−1	$\tilde{G}$	" "

RPV SUSY at HERA

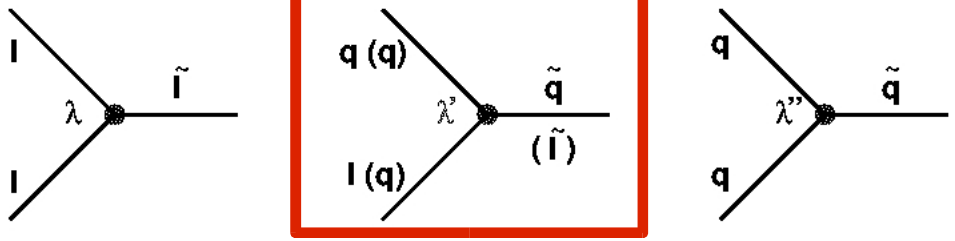
- Often RPC assumed to reduce phenomenology
- HERA: Ideal place to look for RPV ⇒ all results presented: RPV SUSY

- $R_p=(-1)^{3B+L+2S}$ multiplicative, discrete Symmetry:

  +1 (SM Particles) -1 (SUSY Particles)

  - Additional Terms in Superpotential:

$$W_{\not R_p} = \underbrace{\lambda_{ijk} L_i L_j \bar{e}_k}_{\not L} + \underbrace{\lambda'_{ijk} L_i Q_j \bar{d}_k}_{\not L} + \underbrace{\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k}_{\not B} \ldots$$



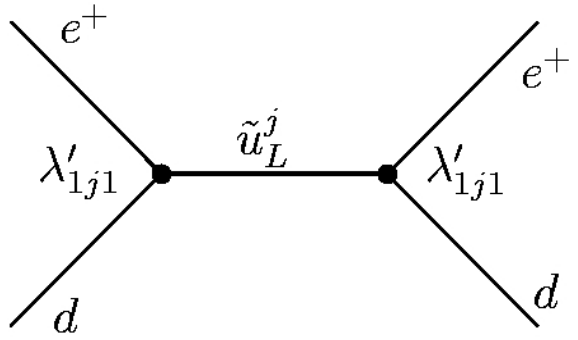
  - allows Single Production of SUSY particles
  - allows Decay of LSP (Lightest Supersymmetric Particle) to SM Particles

- HERA: Leading Order Diagrams proceed through 2. term via Yukawa coupling (e.g. Resonant squark production)

HERA: RPV Search Guideline

1. Resonant Squark Production: Masses up to

$\sqrt{s}$ = 320 GeV kinematically accessible



2. Stop production:

Large Mixing in 3. generation possible:

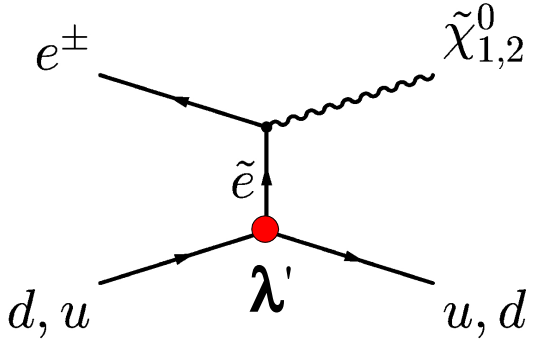
$\tilde{b}$ or $\tilde{t}$ can be rather light through large mixing

$$\begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{f}} & \sin\theta_{\tilde{f}} \\ -\sin\theta_{\tilde{f}} & \cos\theta_{\tilde{f}} \end{pmatrix} \begin{pmatrix} \tilde{f}_L \\ \tilde{f}_R \end{pmatrix}$$

$$m^2_{\tilde{t}_1} = \tfrac{1}{2}(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} - \sqrt{(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4m_t^2 a_t^2}) \qquad a_t^2 = A_t - \mu\cot\beta$$

3. t-channel processes:

Probing λ'_{ijk} independent of squark masses

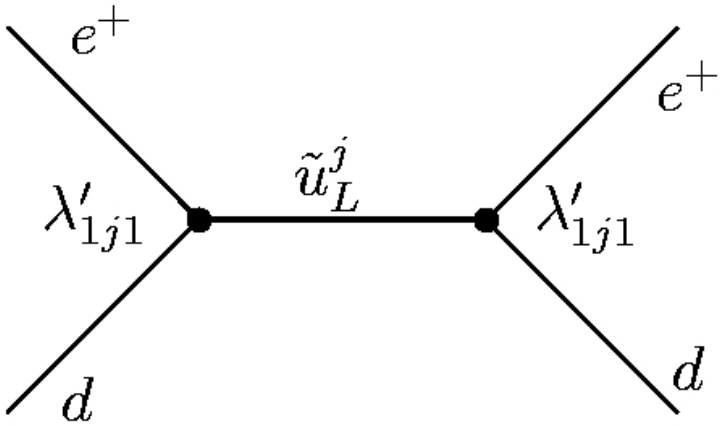


RPV Squark Production

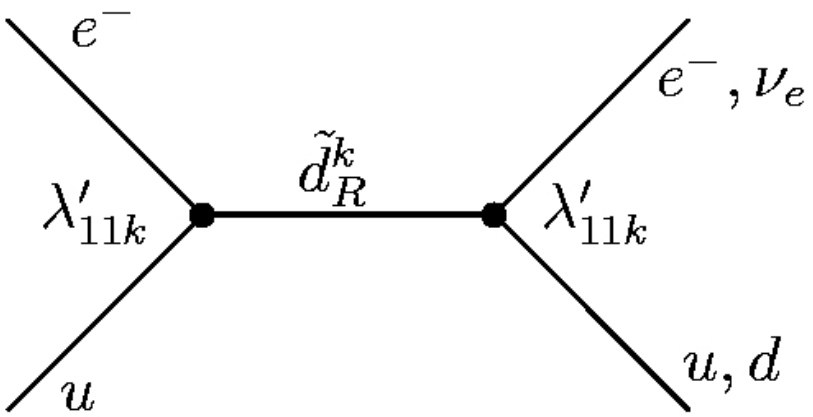
- RPV: Squark Masses up to $\sqrt{s}$ = 320 GeV kinematically accessible

- Electrons and Positrons probe different squarks and couplings
- Direct RPV decays (like scalar Leptoquark):

$$e^+ d \longrightarrow \tilde{u}_L, \tilde{c}_L, \tilde{t}_L$$



$$e^- u \longrightarrow \tilde{d}_R, \tilde{s}_R, \tilde{b}_R$$



High E_T e + jet (Backg: NC DIS)

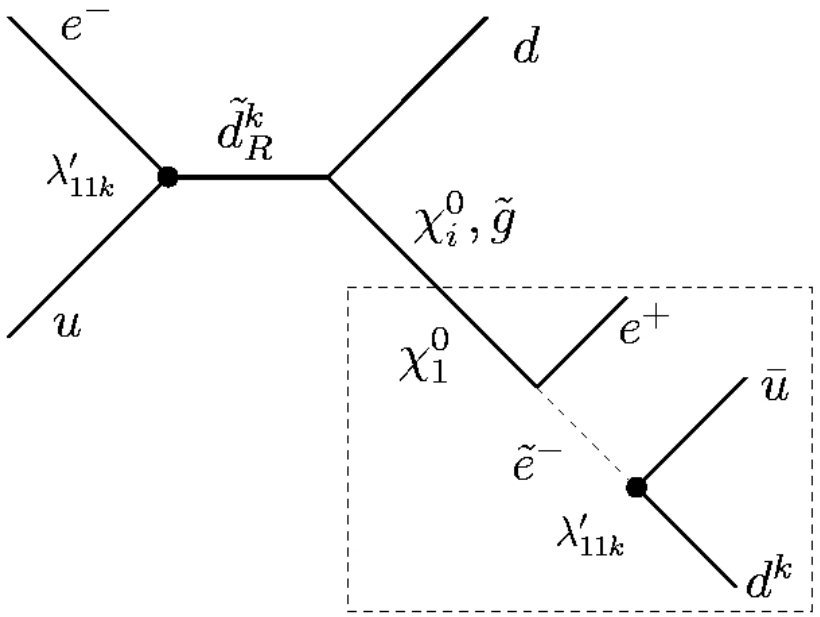
High E_T ν + jet (Backg: CC DIS)

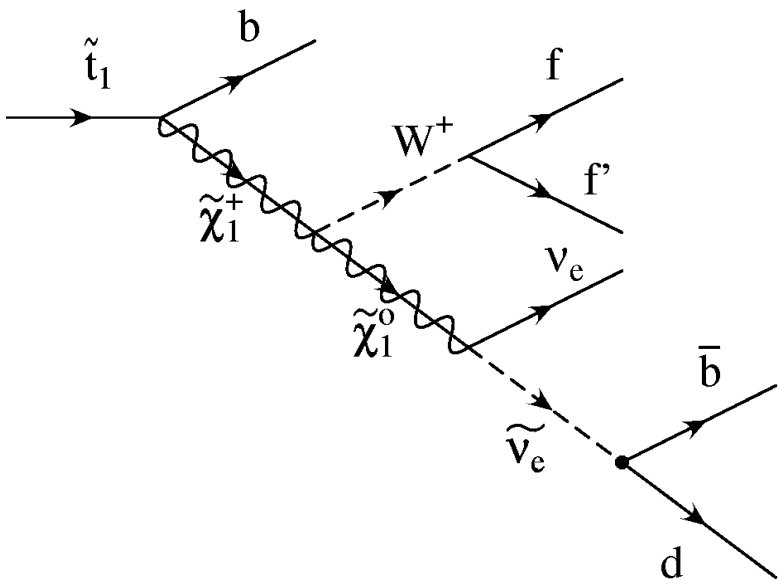
Squarks: Gauge Decays

- Gauge Decay of squarks: $\tilde{q} \to \tilde{\chi}_i^0 q$ $\tilde{q} \to \tilde{\chi}_i^{\pm} q'$ $\tilde{q} \to \tilde{g} q$

Subsequent Gaugino Decay via cascade: Large variety of final states

- e+/- + multiple jets (Backg: NC DIS)
- ν + multiple jets (Backg: CC DIS)
- e (ν) + l + multiple jets (Backg: NC/CC)



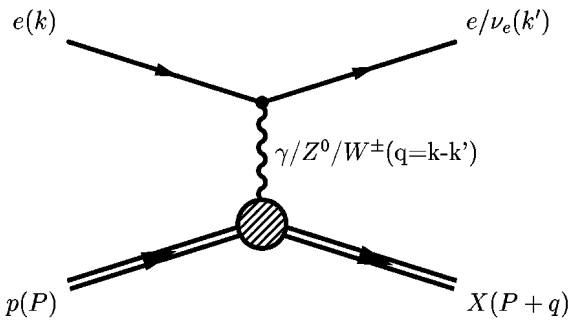


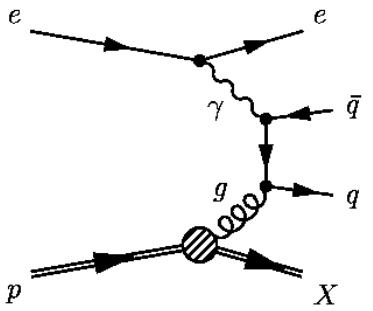
- Searches cover all of these topologies: Allmost full coverage of BR's

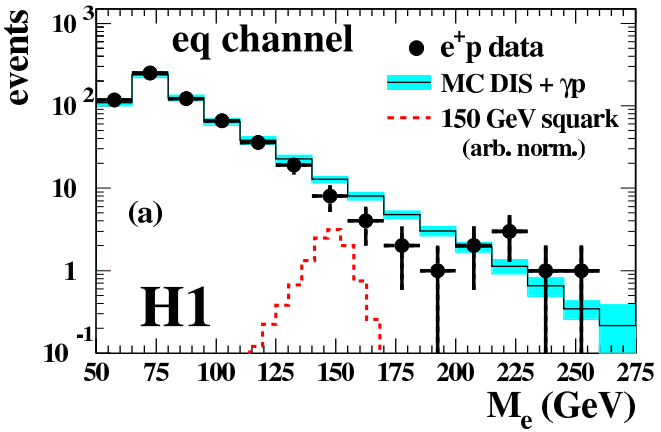
Squarks: lq-Channel

Main Background:

- Neutral Current
  Deep Inelastic Scattering (NC DIS)
- Charged Current DIS (CC DIS)
- Photoproduction (PhP)







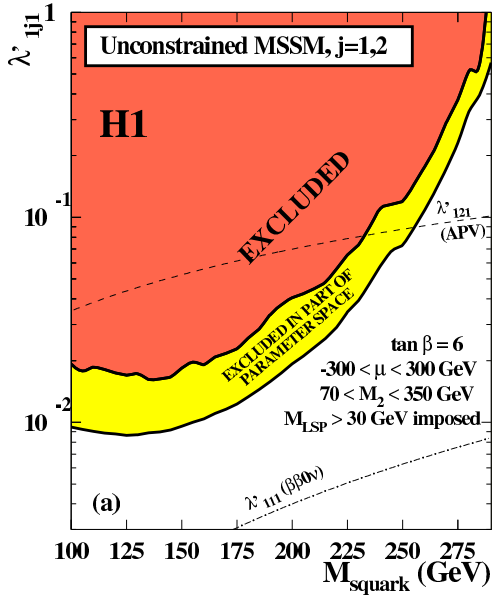
- Resonance at Squark Mass expected for Signal

No deviaton from SM expectation in all channels

Squarks: MSSM Constraints

- MSSM Parameter Scan:
  - $\tan\beta = 6$
  - $70\ \text{GeV} < M_2 < 350\ \text{GeV}$
  - $-300\ \text{GeV} < \mu < 300\ \text{GeV}$

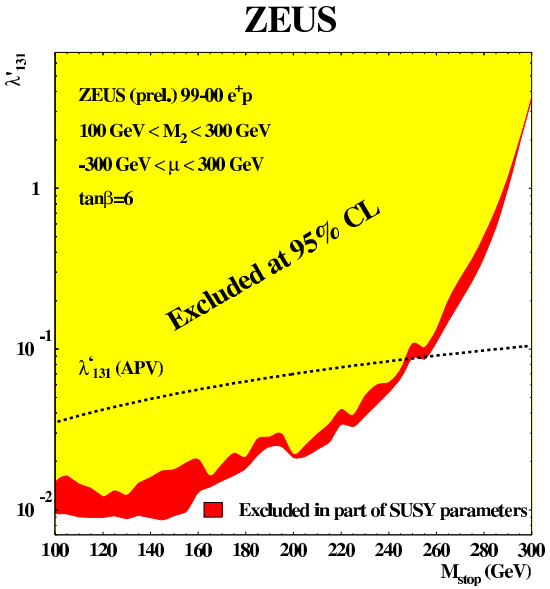
$\tilde{u}_L, \tilde{c}_L$



- Exclusion Limits at 95% CL
- Limits almost independent of SUSY Parameters

- Strongest bounds on λ' for 2. and 3. family squarks

$\tilde{t}_L$

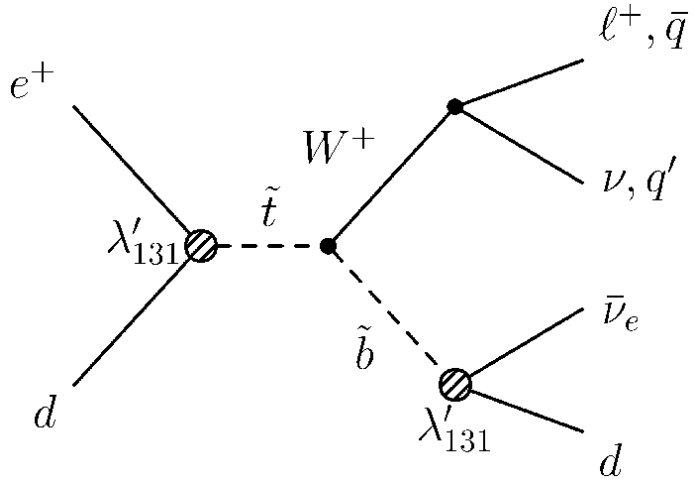


- $\lambda'_{1\,j1} = 0.3\,(\lambda'_{11\,k} = 0.3) \sim \sqrt{4\pi\alpha_{em}}$:
  $M_{\tilde{q}} < 275\,GeV\,(280\,GeV)$

Bosonic Stop Decays

Motivation: Excess of isolated high pt lepton events at H1 (earlier in this talk) can be explained by bosonic stop decays
[T. Kon et al., Mod. Phys. Lett. A12 (1997) 3143]

Signature: 3 jets + $p_{T,miss}$ or jet + lepton + $p_{T,miss}$



H1, Data 1994-2000:
67.9 pb^{-1} ($\sqrt{s}$ = 319 GeV), 37.9 pb^{-1} ($\sqrt{s}$ = 301 GeV)

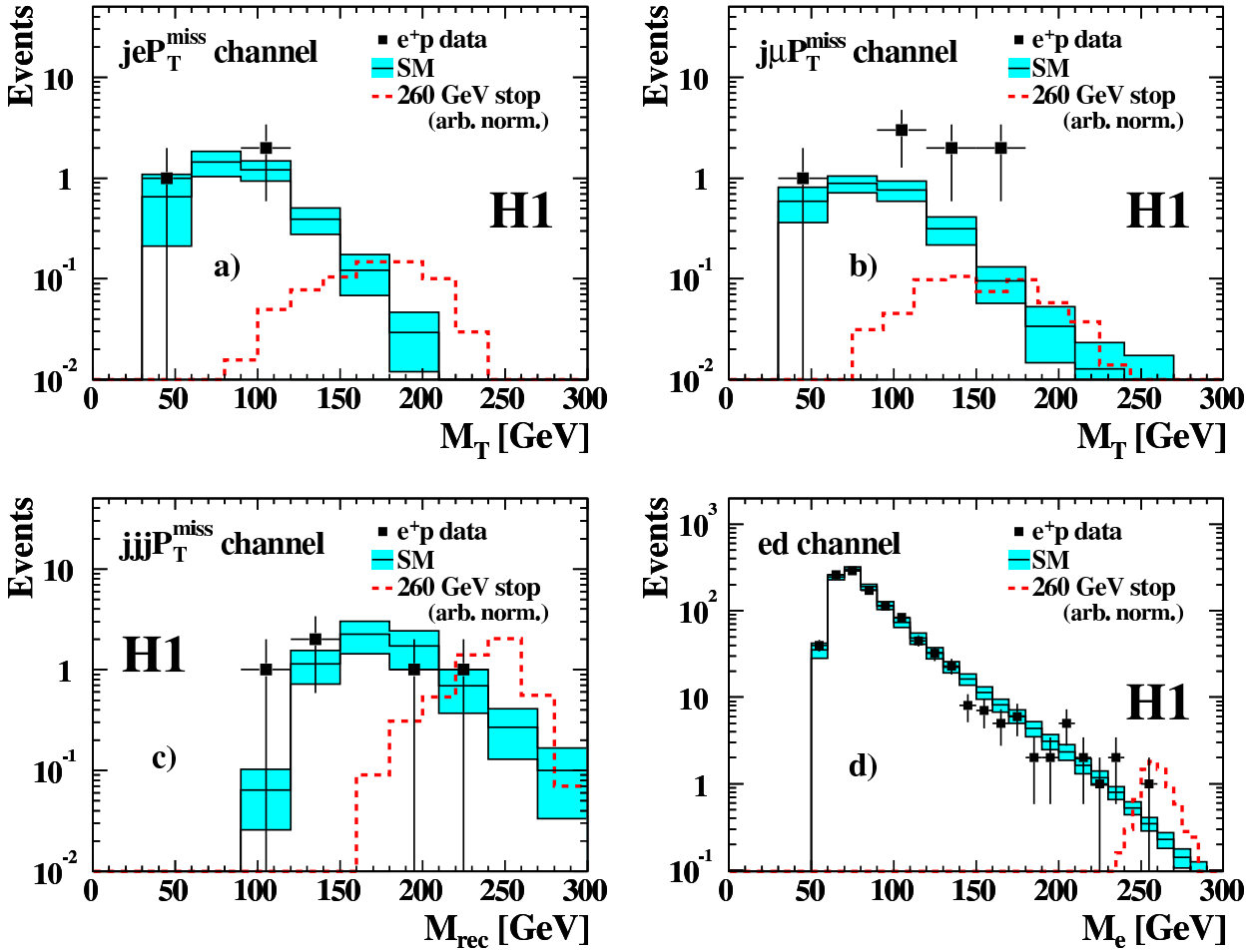
Bosonic Stop Decays: Selection

- Slight excess in

  $j\mu P_{T,miss}$ channel

Significance study:
Isolated high-Pt leptons cannot be interpreted as bosonic stop decays!

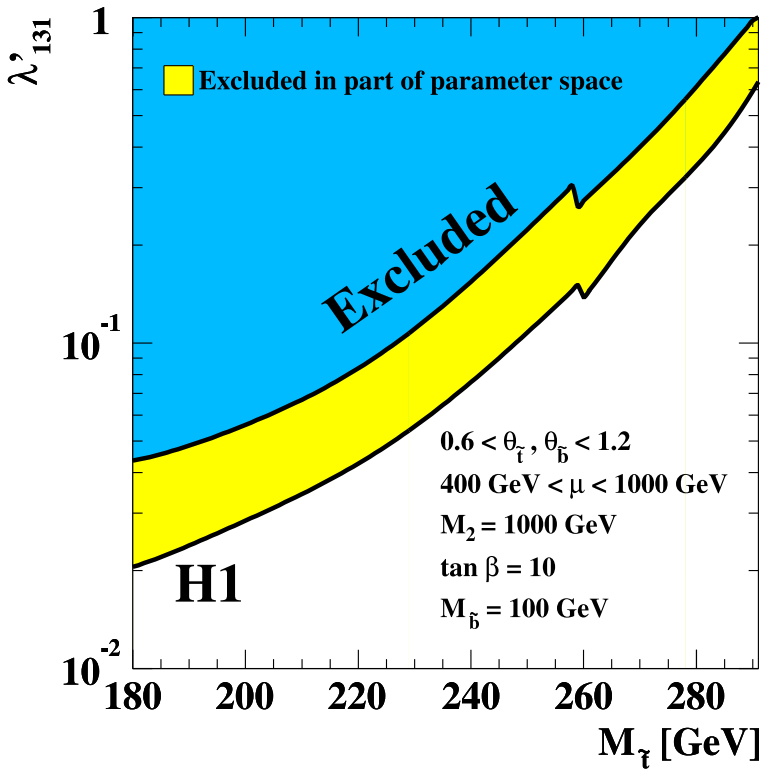
→ Constraining MSSM parameters



Bosonic Stop Decays: Limits

- MSSM Parameter Scan:
  - $\tan\beta = 10$
  - $M_2 = 1000$ GeV
  - $400 < \mu < 1000$ GeV
  - $0.6 < \theta_{\tilde{t},\tilde{b}} < 1.2$

- Similar Results for
  $\tan\beta = 2$ and
  $M_2 = 400$ GeV



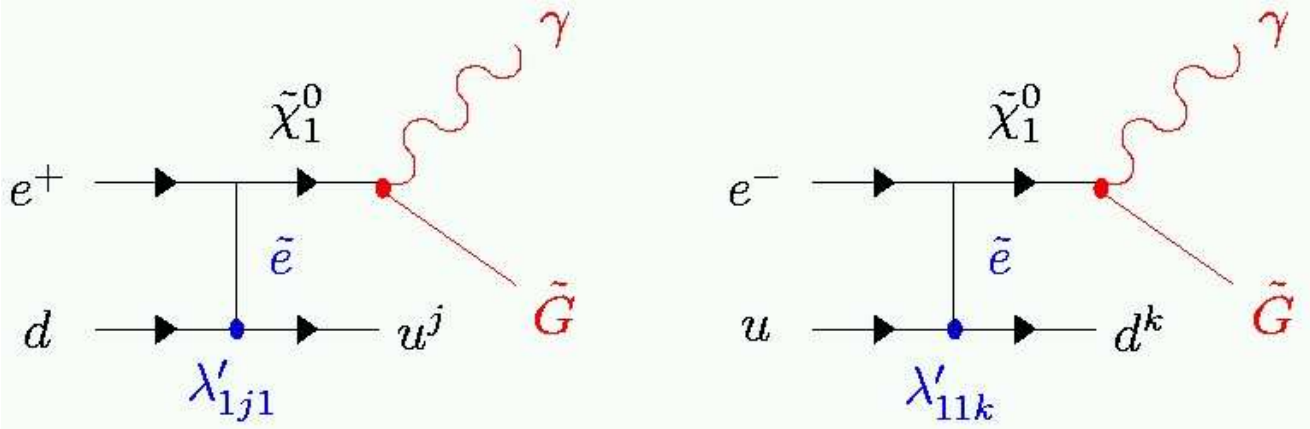
⇒ Stop masses up to ~275 GeV excluded for

$\lambda'_{131} = 0.3$

Light Gravitinos

- GMSB
  - Gravitino is LSP (< 1 GeV), NLSP: Neutralino, short lifetime

- Neutralino production via t-channel selectron exchange
  - ⇒ Independent of squark masses (strong constrains by Tevatron)
  - ⇒ Depend on selectron and neutralino masses (lower constrains by LEP)



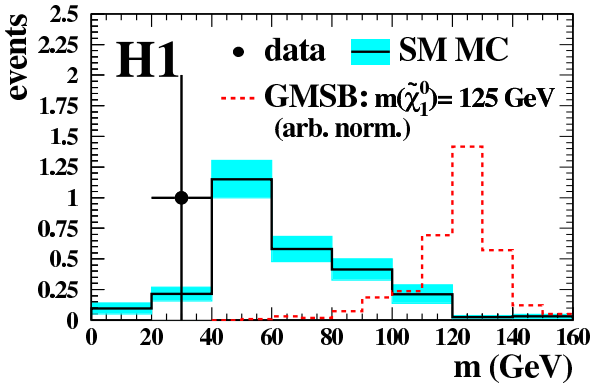
- Signature:
  - Isolated photon, jet and $P_{T,miss}$

Gravitinos: Limits

- H1, Data: 64.3 pb^{-1} e^+p, 13.5 pb^{-1} e^-p

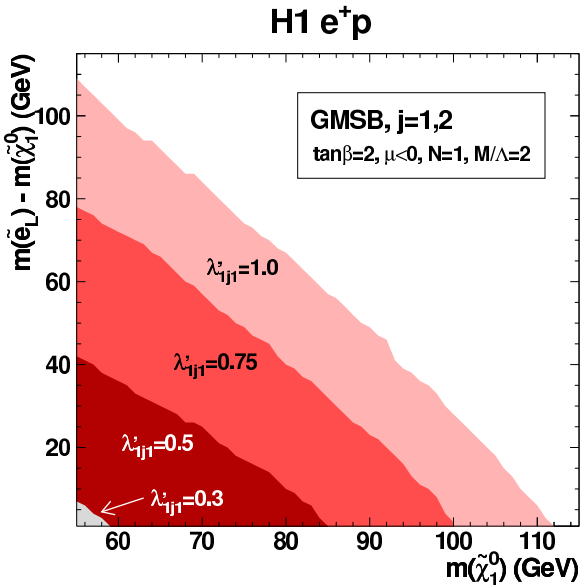
- Selection
  - $P_{T,miss}$
  - 1 Jet
  - isolated photon

- GMSB Parameters:
  - $\tan\beta = 2,6$
  - $sign(\mu) = -1$
  - $N = 1,$
  - $\lambda' = 0.3, 0.5, 0.75, 1.0$
  - M/Λ fixed



- Only one candidate after final cuts
  ⇒ Deriving limits on parameters in GMSB

⇒ Selectron masses up to 164 GeV and neutralino masses up to 112 excluded for $\lambda'_{131} = 1.0$



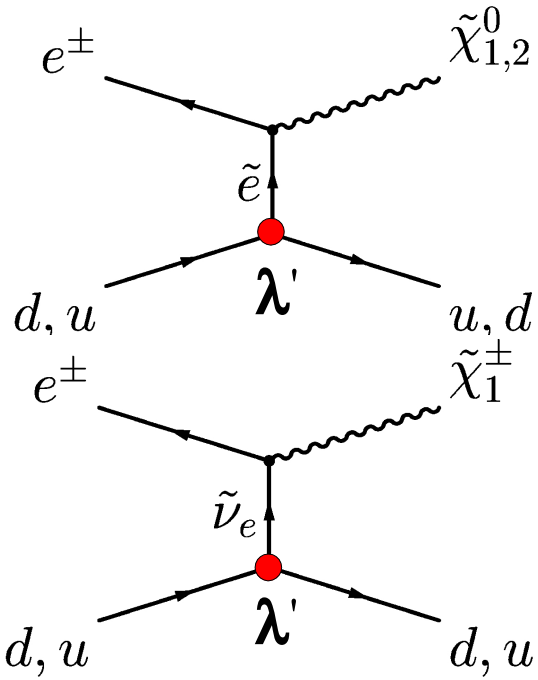
Gaugino Production

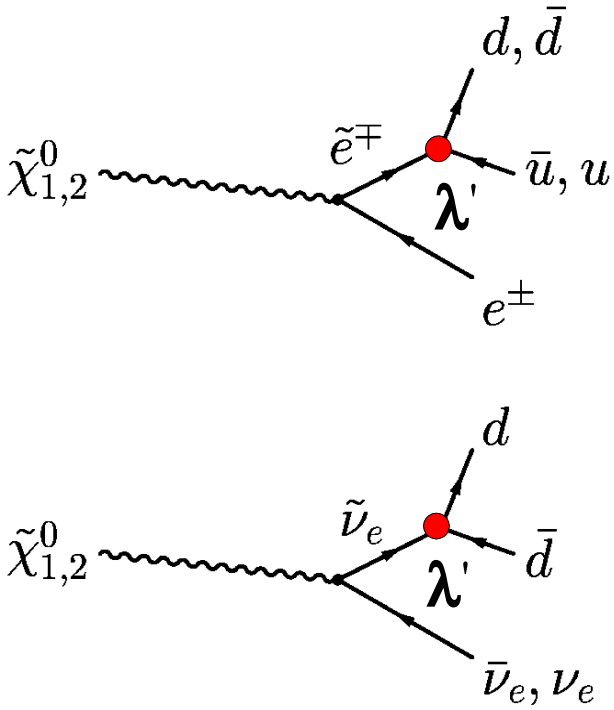
- MSSM: Neutralino assumes to be LSP
- Assuming dominant λ'_{111}, all other Yukawa couplings neglible

ZEUS Data: ~121 pb-1

Selection

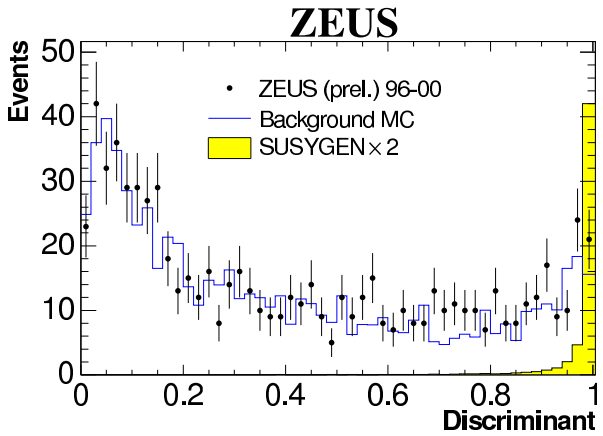
- High $E_T > 75$ GeV
- ≥ 2 Jets:
- Electron candidate

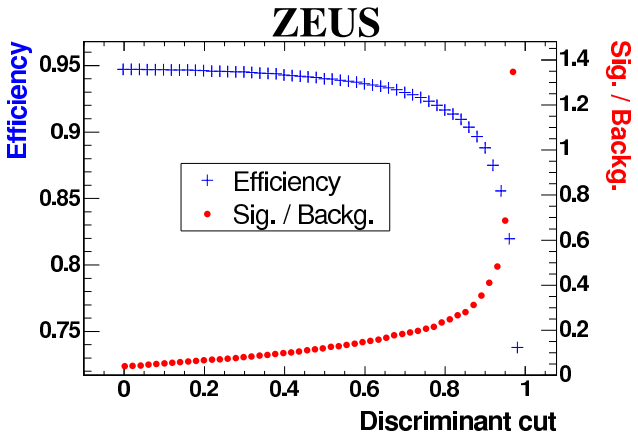




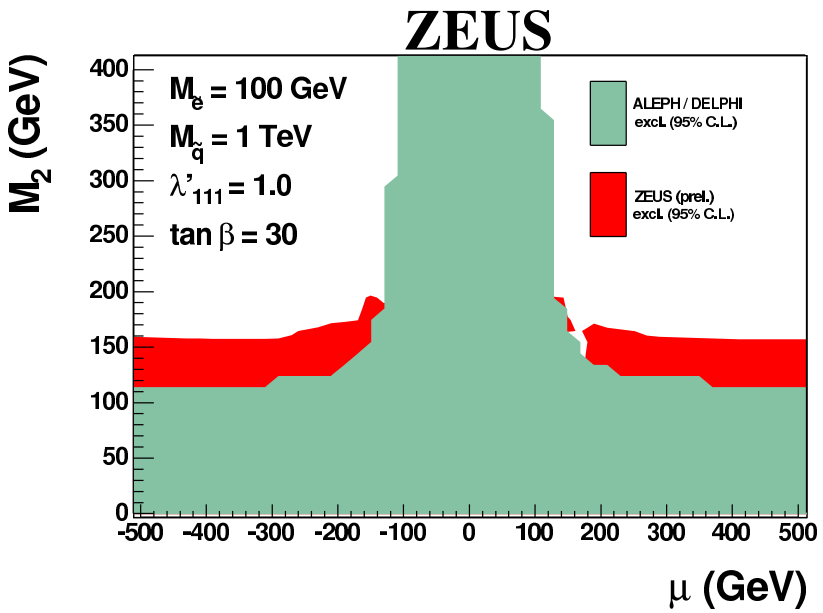
Gaugino Production: Limits

- Discriminant Method based on event topology variables to distinguish signal from background





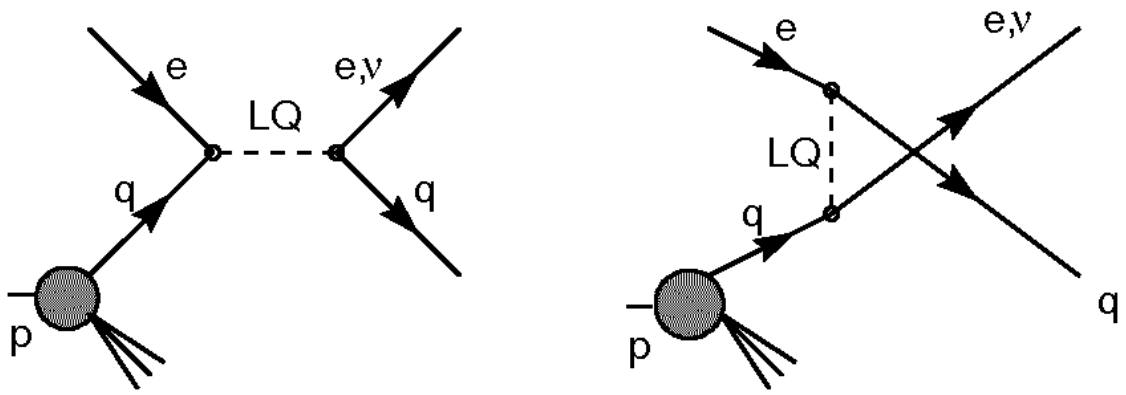
- Limits from MSSM scan:
  - Extend limits from LEP for slepton masses = 100 GeV, large squark masses and large tan β
  - Independent of squark sector
  - ALEPH/DELPHI: Chargino mass > 103 GeV



Leptoquarks

- **BRW Model**:
  - Particle, which carry both lepton & baryon numbers
  - 14 leptoquarks: Spin, chirality, weak isospin, hypercharge, (F = 3B+L)

- Production and decay via Yukawa coupling λ
- HERA:



LQ species	q	Production	Decay	Branching ratio	Coupling
$S^L_{1/2}$	5/3	$e^+_R u_R$	e^+u	1	λ_L
$S^R_{1/2}$	5/3	$e^+_L u_L$	e^+u	1	λ_R
	2/3	$e^+_L d_L$	e^+d	1	$-\lambda_R$
$\tilde{S}^L_{1/2}$	-2/3	$e^+_R d_R$	e^+d	1	λ_L
V^L_0	2/3	$e^+_R d_L$	e^+d	1/2	λ_L
			$\bar{\nu}_e u$	1/2	λ_L
V^R_0	2/3	$e^+_L d_R$	e^+d	1	λ_R
$\tilde{V}^R_0$	5/3	$e^+_L u_R$	e^+u	1	λ_R
V^L_1	5/3	$e^+_R u_L$	e^+u	1	$\sqrt{2}\lambda_L$
	2/3	$e^+_R d_L$	e^+d	1/2	$-\lambda_L$
			$\bar{\nu}_e u$	1/2	λ_L
S^L_0	-1/3	$e^-_L u_L$	e^-u	1/2	λ_L
			$\nu_e d$	1/2	$-\lambda_L$
S^R_0	-1/3	$e^-_R u_R$	e^-u	1	λ_R
$\tilde{S}^R_0$	-4/3	$e^-_R d_R$	e^-d	1	λ_R
S^L_1	-1/3	$e^-_L u_L$	e^-u	1/2	$-\lambda_L$
			$\nu_e d$	1/2	$-\lambda_L$
	-4/3	$e^-_L d_L$	e^-d	1	$-\sqrt{2}\lambda_L$
$V^L_{1/2}$	-4/3	$e^-_L d_R$	e^-d	1	λ_L
$V^R_{1/2}$	-4/3	$e^-_R d_L$	e^-d	1	λ_R
	-1/3	$e^-_R u_L$	e^-u	1	λ_R
$\tilde{V}^L_{1/2}$	-1/3	$e^-_L u_R$	e^-u	1	λ_L

- Leptoquark: Search for narrow mass resonance

- Main Background: NC & CC DIS

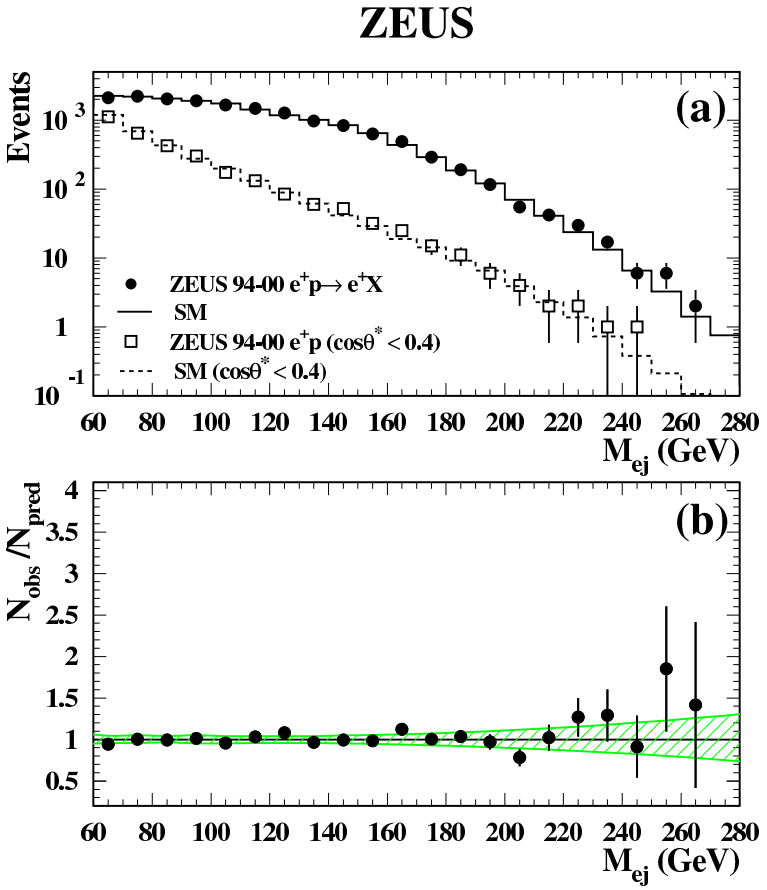
Leptoquarks

- H1 & ZEUS: Data from 1994-2000

- Selection:
  - Inclusive NC & CC DIS
  - High transverse energy
  - Electron candidate or missing transverse momentum
  - At least 1 high Et jet

- Final: Mass resonance

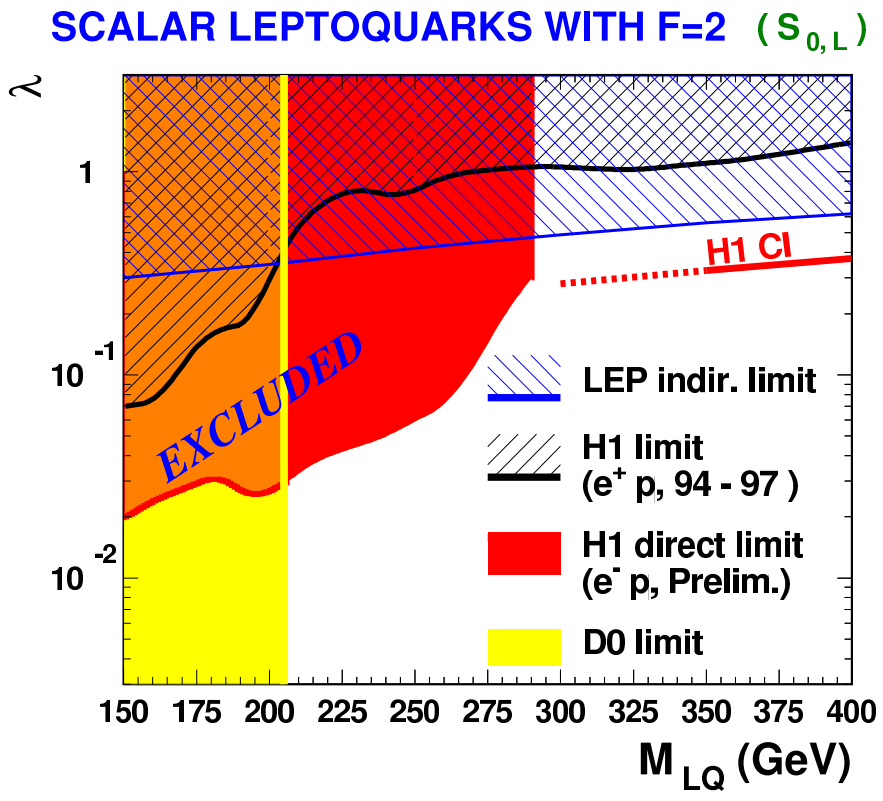
- No excess in data



Leptoquark Limits

- Yukawa coupling limits as a function of the LQ mass for all types of LQ
- Scalar LQ example shown
- Scalar LQ masses up to ~275 GeV can be excluded for

$$\lambda'_{131} = 0.1$$



- <u>H1 & ZEUS: Similar results, which supersede limits from other experiments</u>

Summary & Outlook

Summary

- H1 & ZEUS have searched the HERA I data for new physics
- No hints for Leptoquarks or SUSY could be found
- But excess of high Pt lepton events in data:
  - H1: Electron- & Muon-channel
  - ZEUS: Tau-channel
- H1 already looked into HERA II data:
  High Pt lepton excess remains

Outlook

- Looking forward to analyse HERA II data