Searches for squarks with H1 at HERA

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On behalf of the **H1 Collaboration**

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- SUSY and R–Parity
- Phenomenology of $\not{R}_p$ SUSY in $e^{\pm}p$ scattering
- Squark decays & $\not{R}_p$ SUSY results (DESY-04-025)
  - MSSM exclusion limits
  - mSUGRA exclusion limits
- Bosonic stop decay: Interpretation & exclusion limits (final results)
- Summary and outlook

Supersymmetry (SUSY)

SM particles	spin	SUSY partners	spin
q_L, q_R	$\frac{1}{2}$	$\tilde{q}_L$, $\tilde{q}_R$	0
l_L, l_R	$\frac{1}{2}$	$\tilde{l}_L$, $\tilde{l}_R$	0
$\gamma, Z^0, W^\pm$	1	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	$\frac{1}{2}$
$h^0, H^\pm, H^0, A^0$	0	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\frac{1}{2}$
g	1	$\tilde{g}$	$\frac{1}{2}$

MSSM: 105 parameters, but

– The masses and couplings of $\tilde{\chi}_i^0$, $\tilde{\chi}_j^\pm$ and $\tilde{g}$ are determined by the parameteres

$$\boldsymbol{\mu},\ \boldsymbol{\tan\beta},\ \boldsymbol{M_2}$$

– Gaugino mass parameters M_1, M_2, M_3 unify to $m_{1/2}$ at the GUT scale

– Sfermion masses are free parameters

mSUGRA model:

– m_0 ($m_{1/2}$) common mass for scalar fields (gauginos) at the GUT scale

– REWSB $\rightarrow$ model completely determined by $\boldsymbol{m_0}$, $\boldsymbol{m_{1/2}}$, $\boldsymbol{\tan\beta}$, sign $\boldsymbol{\mu}$, $\boldsymbol{A_0}$

R–Parity and R–Parity violation

Definition: $R_P = (-1)^{3B+L+2S}$

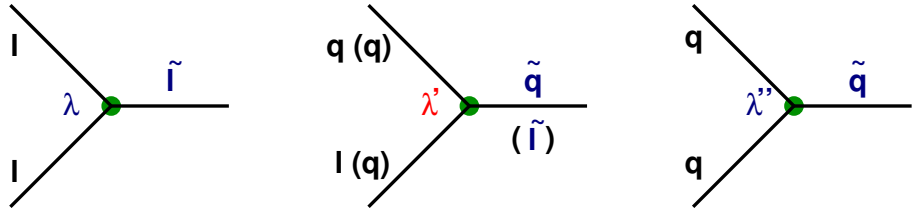
$\rightarrow R_P = 1$ for all SM particles
$\rightarrow R_P = -1$ for all SUSY particles

- The MSSM is R_P–conserving

  $\rightarrow$ all SUSY particles are produced in pairs
  $\rightarrow$ the LSP is stable (candidate for cold dark matter)

The superpotential in the general MSSM has additional $\not{R}_p$ terms:

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



HERA

$\rightarrow$ Resonant production of single SUSY particles
$\rightarrow$ SUSY particles can decay into SM particles ($\Rightarrow$ LSP no more stable)

Phenomenology of $\not{R}_p$ SUSY in $e^{\pm}p$ scattering at HERA

Production of squarks ($\tilde{q}$) in s–channel via λ'_{ijk} with masses up to $\sqrt{s}$

94–97 and 99/00: ~ 106 pb^{-1} $e^+p \Rightarrow \lambda'_{1j1}$: $e^+d \longrightarrow \tilde{u}_L, \tilde{c}_L, \tilde{t}_L$

98/99: ~ 14 pb^{-1} $e^-p \Rightarrow \lambda'_{11k}$: $e^-u \longrightarrow \tilde{d}_R, \tilde{s}_R, \tilde{b}_R$

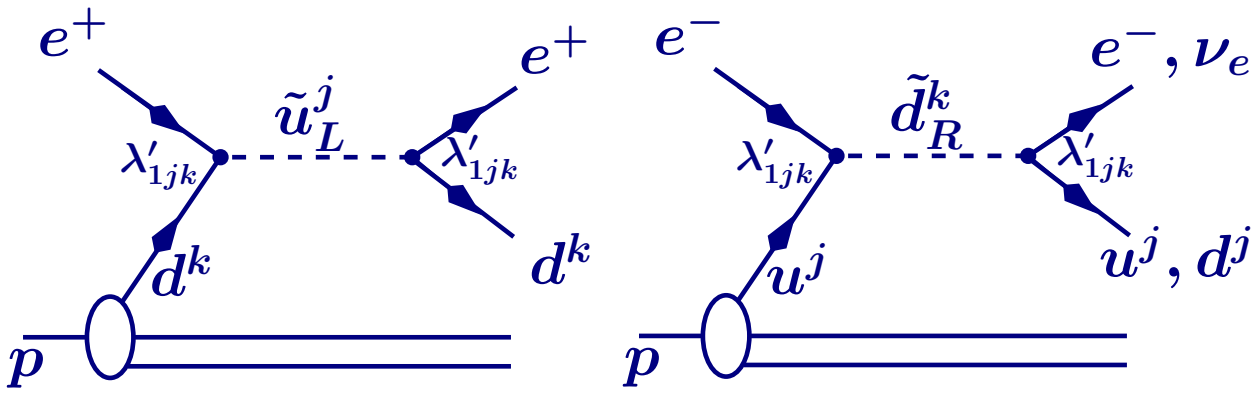
Cross sections in NWA:

$$\sigma(e^+p \to \tilde{u}^j_L) \sim \lambda'^2_{1jk} \cdot d^k(x = \frac{M^2_{\tilde{q}}}{s})$$

$$\sigma(e^-p \to \tilde{d}^k_R) \sim \lambda'^2_{1jk} \cdot u^j(x = \frac{M^2_{\tilde{q}}}{s})$$

Direct $\not{R}_p$ decays:

(Leptoquark–like)



Signature: high P_T $e(\nu)$ + jet $\Rightarrow$ look for NC (CC) –like events at high P_T

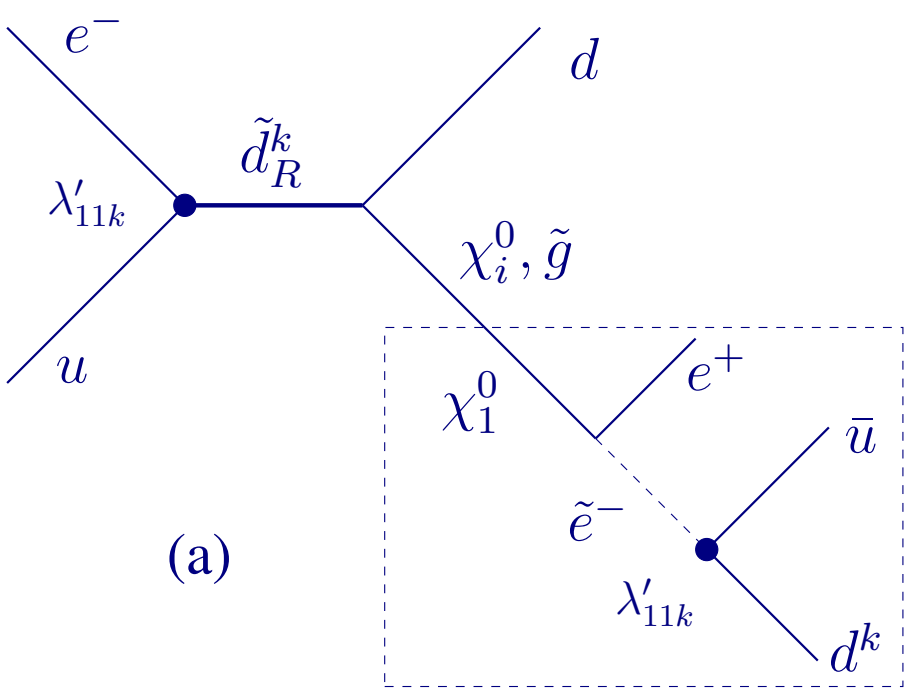
$\rightarrow$ only $\tilde{d}^k_R$ (e^-p collisions) can decay to νq

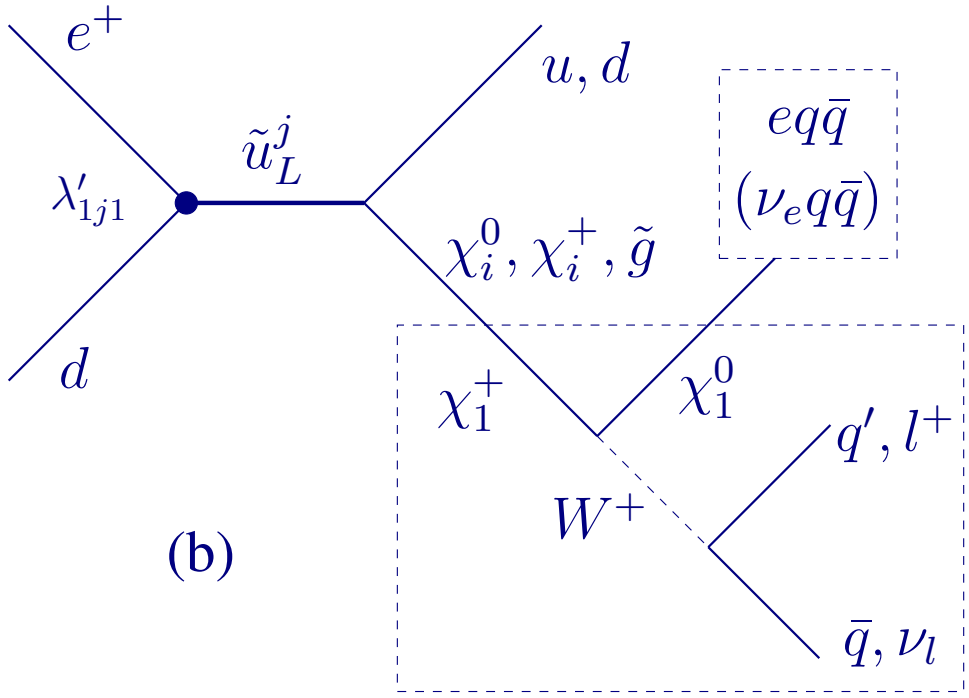
Squark gauge decay into quark + gaugino

$$\tilde{q} \to \tilde{\chi}_i^0 q \qquad \tilde{q} \to \tilde{\chi}_i^\pm q' \qquad \tilde{q} \to \tilde{g} q$$

Subsequent gaugino decay:

$\to$ $\not{R}_p$ gaugino decays into 2 quarks $+(e^\pm$ or $\nu_e)$
$\to$ $\tilde{\chi}_i^0$ with $i > 1$, $\tilde{g}$ decays into lighter $\tilde{\chi}$ and 2 fermions



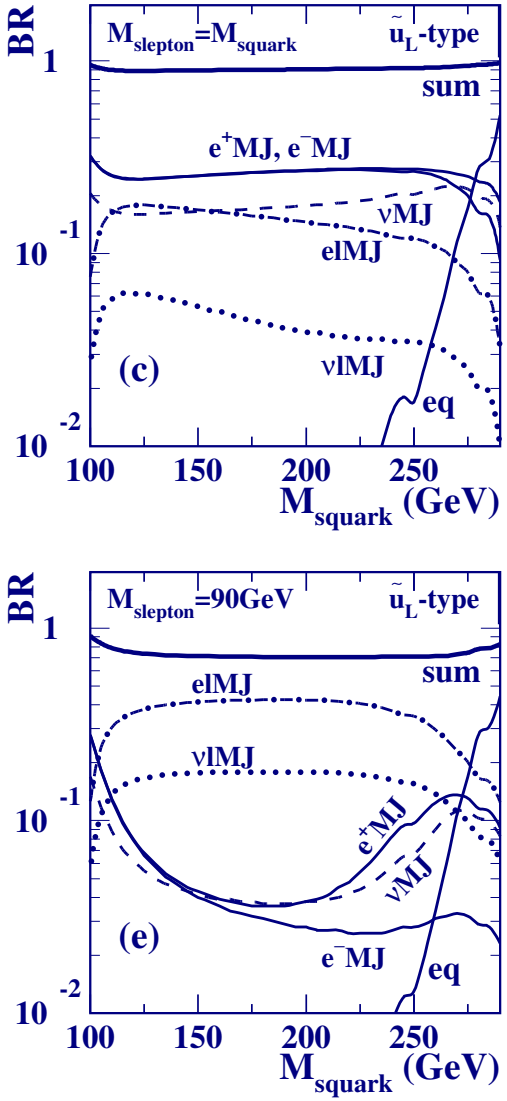


$\Rightarrow$ Large variety of decay modes with lepton(s) + multiple jets

Squark decay modes

Channel	Decay process	Event topology
eq	$\tilde{q} \xrightarrow{\lambda'} eq$	high p_T e + 1 jet
νq	$\tilde{d}^k_R \xrightarrow{\lambda'} \nu_e d$	missing p_T + 1 jet
$e^{\pm}MJ$	$\tilde{q} \to qX$ $\quad X \xrightarrow{\lambda'} e^{\pm}\bar{q}q$ $X \to q\bar{q}\ Y$ $Y \xrightarrow{\lambda'} e^{\pm}\bar{q}q$	e (both charges) + multiple jets
νMJ	$\tilde{q} \to qX$ $\quad X \xrightarrow{\lambda'} \nu\bar{q}q$ $X \to q\bar{q}\ Y$ $X \to \nu\bar{\nu}\ Y$ $Y \xrightarrow{\lambda'} \nu\bar{q}q$	missing p_T + multiple jets
$elMJ$	$\tilde{q} \to qX$ $\quad X \to \ell\nu_\ell\ Y$ $X \to \ell^+\ell^-\ Y$ $X \to e^+e^-\ Y$ $Y \xrightarrow{\lambda'} e^{\pm}\bar{q}q, \nu\bar{q}q$	e + ℓ (e or μ) + multiple jets
νlMJ	$\tilde{q} \to qX$ $\quad X \to \ell\nu_\ell\ Y$ $X \to \nu\bar{\nu}\ Y$ $X \to \mu^+\mu^-\ Y$ $Y \xrightarrow{\lambda'} \nu\bar{q}q, e\bar{q}q$	ℓ (e or μ) + missing p_T + multiple jets

e^+p collisions



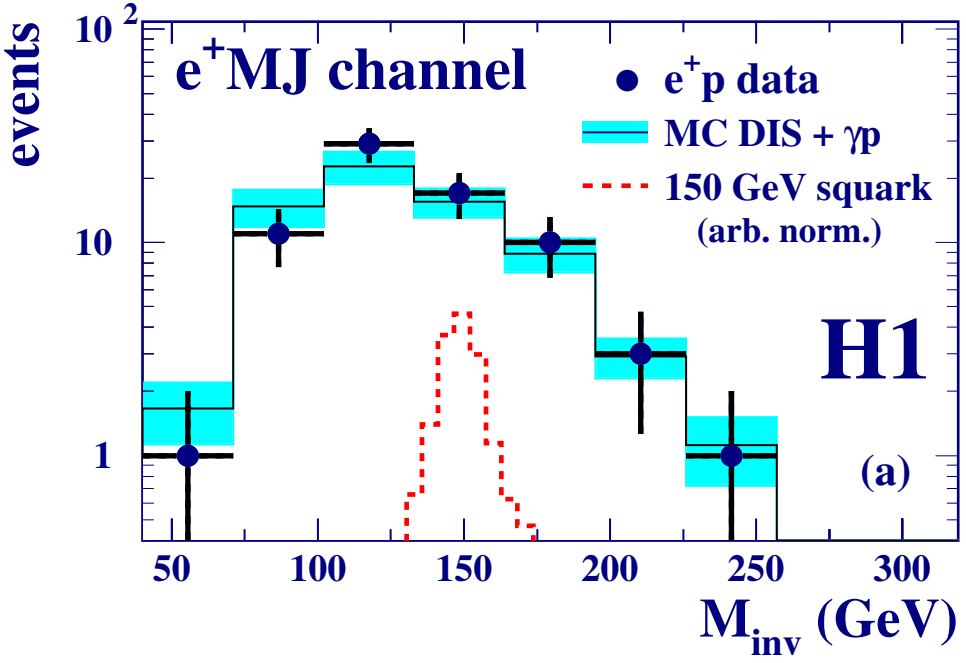
almost full coverage of BR's !

Gauge decay into quark + gaugino: H1 e^+p analysis

Selection cuts: $\gtrsim 2$ jets with $P_T^{jet} > 15\,\text{GeV}$
angular cuts

eMJ + X selection

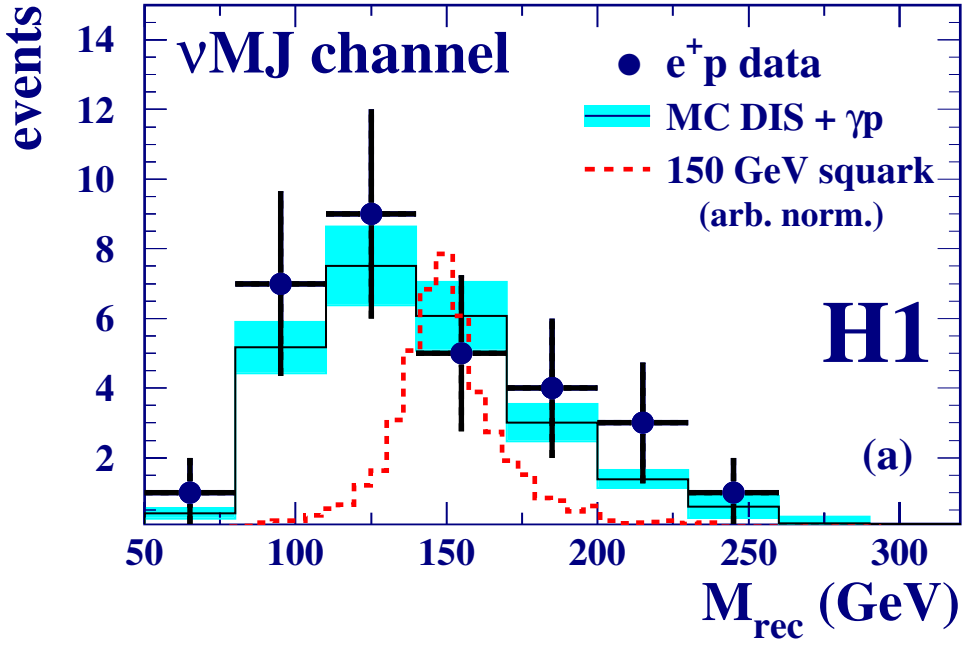
$P_T^e > 6\,\text{GeV}$, high y_e
angular cuts



typical efficiencies: $30 - 50\%$

νMJ+ X selection

$\not{P}_T > 26\,\text{GeV}$



typical efficiencies: $30 - 60\%$

Squark decay modes

Channel	Event topology	e^+p data (SM)	e^-p data (SM)
eq	high p_T e + 1 jet	632 (628 ± 46)	204 (192 ± 14)
νq	missing p_T + 1 jet	–	261 (269 ± 21)
$e^{\pm}MJ$	e (both charges) + multiple jets	e^+MJ: 72 (67.5 ± 9.5) e^-MJ: 0 (0.20 ± 0.14)	e^+MJ: 20 (17.9 ± 2.4) e^-MJ: 0 (0.06 ± 0.02)
νMJ	missing p_T + multiple jets	30 (24.3 ± 3.6)	12 (10.1 ± 1.4)
$elMJ$	e + ℓ (e or μ) + multiple jets	$eeMJ$: 0 (0.91 ± 0.51) $e\mu MJ$: 0 (0.91 ± 0.38)	$eeMJ$: 0 (0.13 ± 0.03) $e\mu MJ$: 0 (0.20 ± 0.04)
νlMJ	ℓ (e or μ) + missing p_T + multiple jets	νeMJ: 0 (0.74 ± 0.26) $\nu\mu MJ$: 0 (0.61 ± 0.12)	νeMJ: 0 (0.21 ± 0.07) $\nu\mu MJ$: 0 (0.16 ± 0.03)

all decay modes checked in detail $\Rightarrow$ **no deviation from SM expectation**

Interpretation of the data in the MSSM

relevant SUSY parameters:

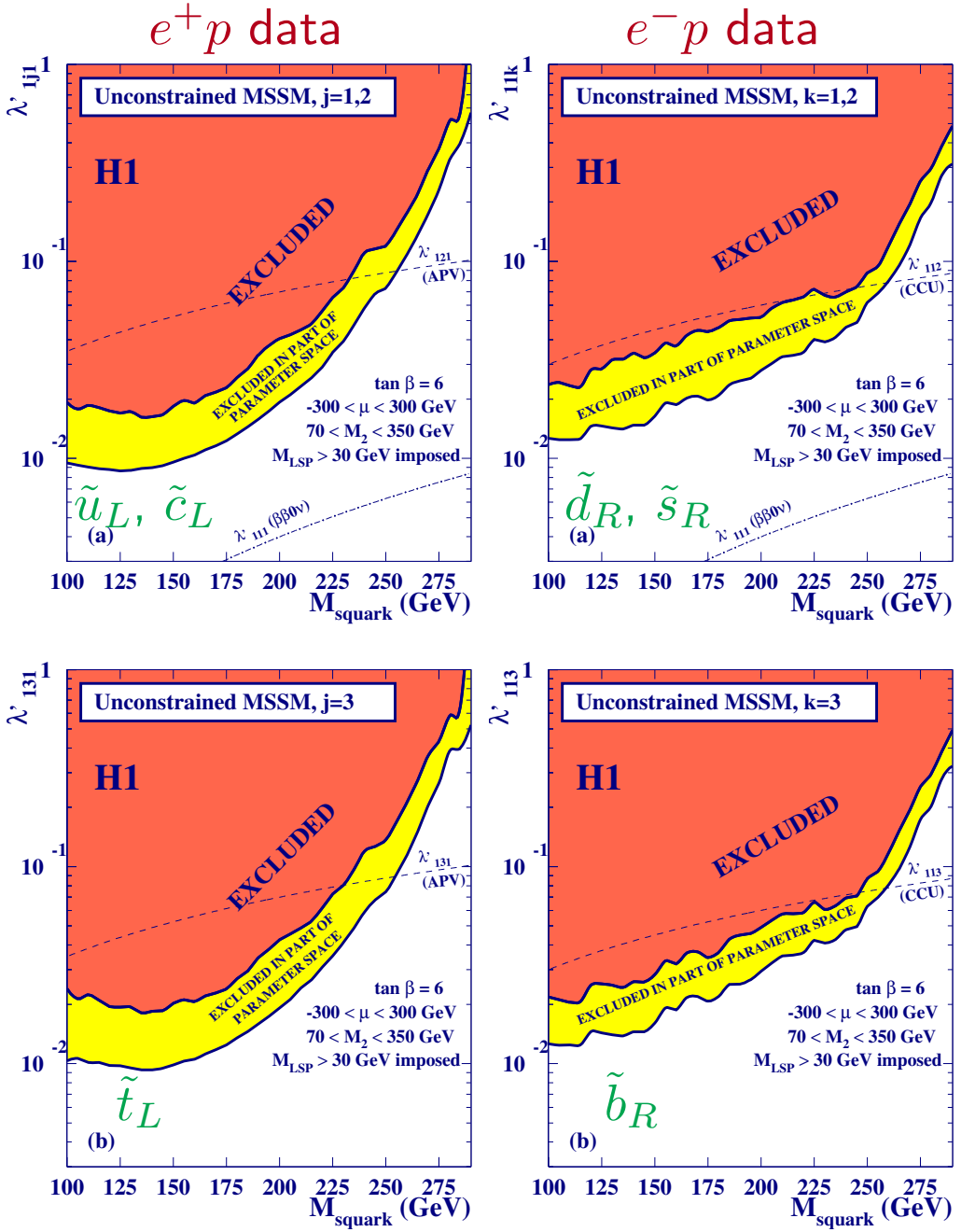
$M_2,\ \mu,\ \tan\beta,\ \lambda'_{1jk},\ M_{\tilde{q}}$

Squark masses and couplings are free parameters

$\Rightarrow$ **set limits on λ'_{1jk} vs. $M_{\tilde{q}}$**

$\Rightarrow$ **SUSY parameter scan**

$$\tan\beta = 6$$
$$-300 < \mu < 300\,\text{GeV}$$
$$-70 < M_2 < 350\,\text{GeV}$$

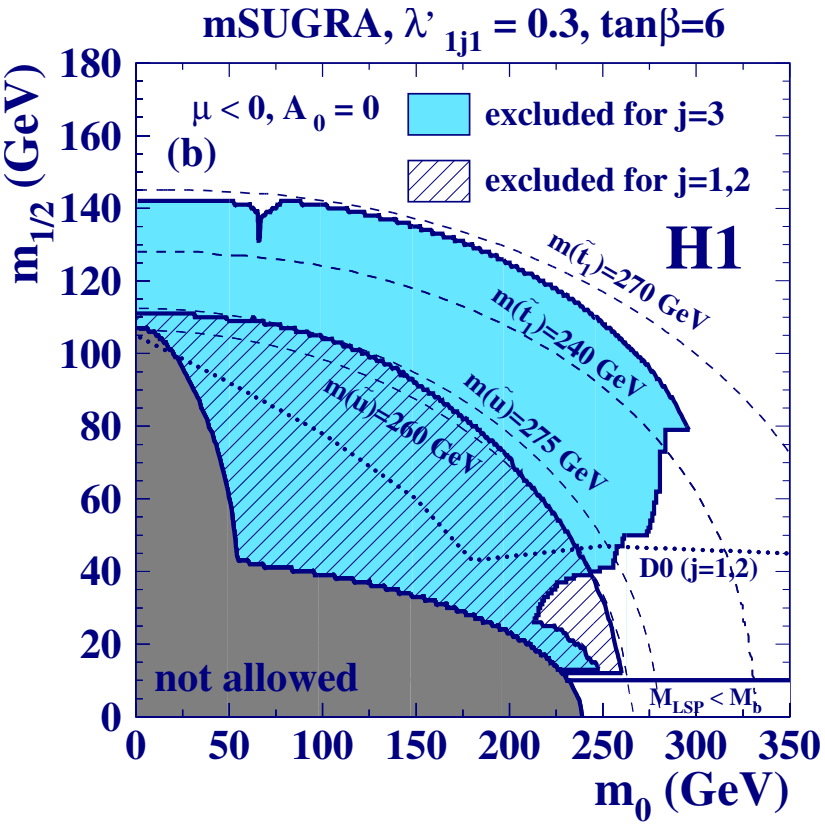


Interpretation of the data in the mSUGRA model

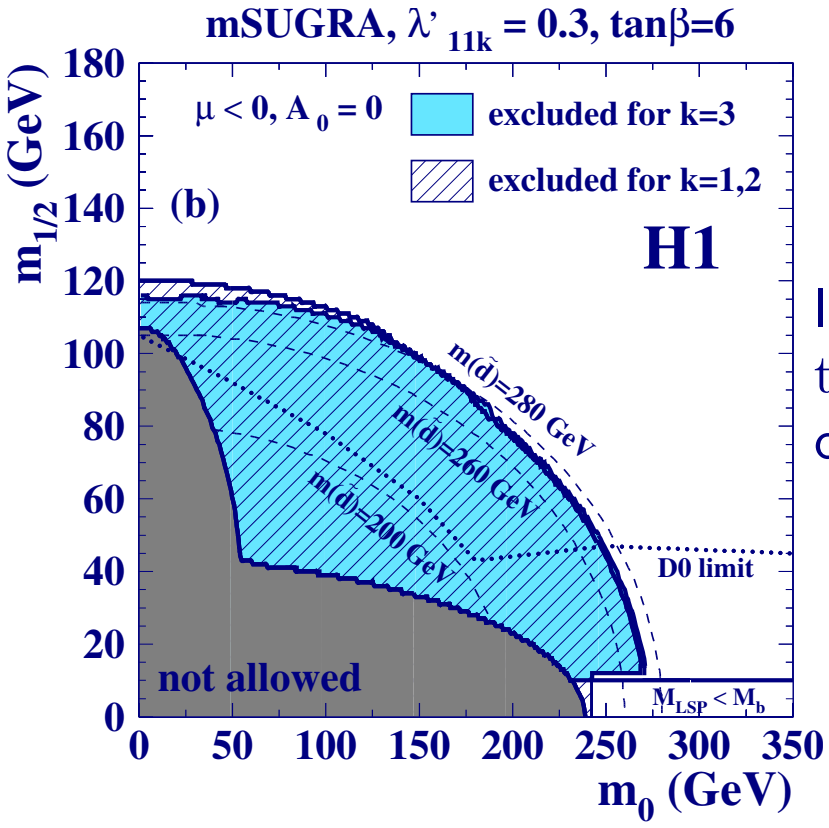
Only five parameters: $\tan\beta$, $m_{1/2}$, m_0, A_0, sign μ

set limits for $\lambda'_{1j1}, \lambda'_{11k} = 0.3$ (e.m. coupling):

e^+p data



e^-p data



limits for $\tan\beta = 2$ comparable

HERA sensitivity follows isomass curve:

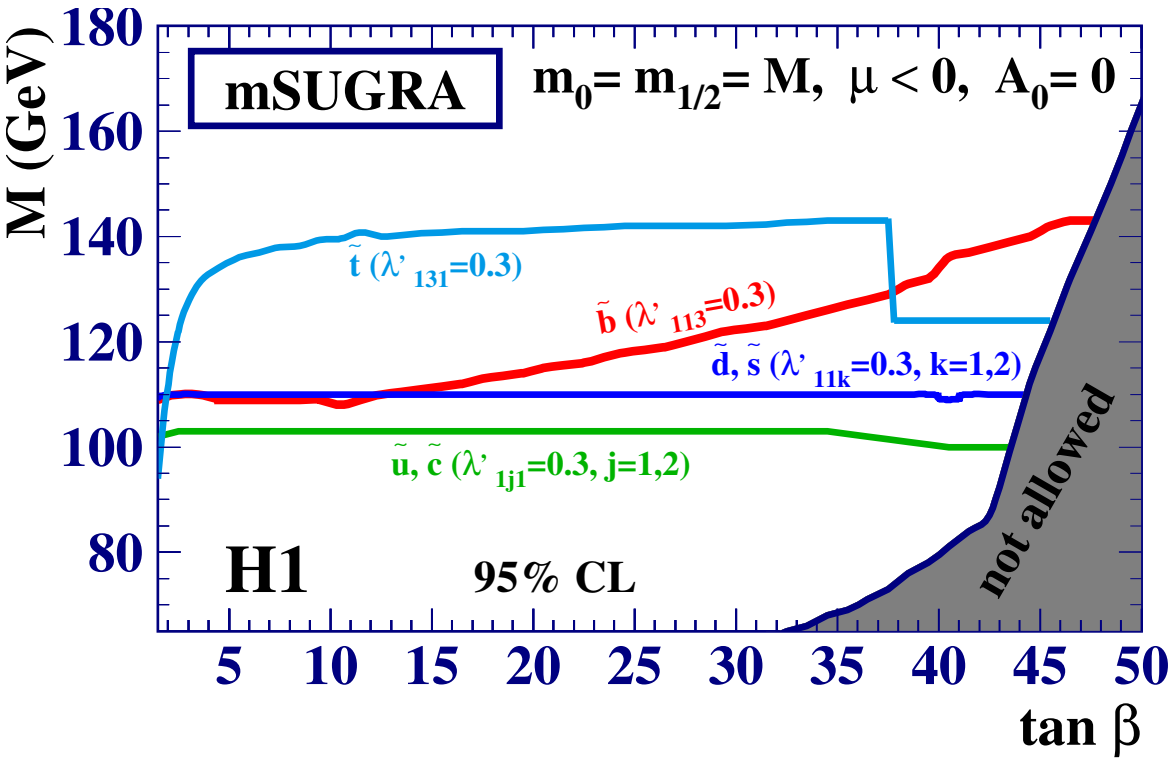
$\tilde{u}$, $\tilde{c}$, $\tilde{t}$ excluded up to 275 GeV;

$\tilde{d}$, $\tilde{s}$, $\tilde{b}$ excluded up to 285 GeV

mSUGRA limits

Large part of SUSY parameter space excluded for small $\tan\beta$ by MSSM Higgs search at LEP

exclusion limits assuming $m_0 = m_{1/2} = M$ vs. $\tan\beta$:



$\tilde{u}$, $\tilde{c}$: constant $\rightarrow$ small mixing

$\tilde{d}$, $\tilde{s}$: constant $\rightarrow$ small mixing; larger cross section

$\tilde{b}$: mixing important for $\tan\beta \gtrsim 10$

$\tilde{t}$: mixing important for all $\tan\beta$; τ final states for $\tan\beta \gtrsim 37$

Bosonic stop decay $\tilde{t} \to \tilde{b}W$

In the third generation: M_q not negligible $\Rightarrow$ large mixing between $\tilde{q}_L$ and $\tilde{q}_R$:

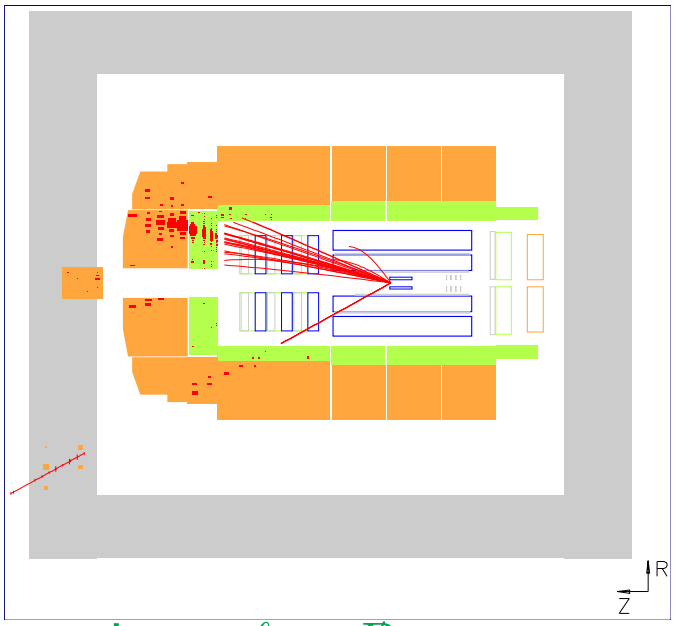
$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{q}} & \sin\theta_{\tilde{q}} \\ -\sin\theta_{\tilde{q}} & \cos\theta_{\tilde{q}} \end{pmatrix} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix}$$

$\tilde{q} = \tilde{b}, \tilde{t}$: presumably the lightest squarks

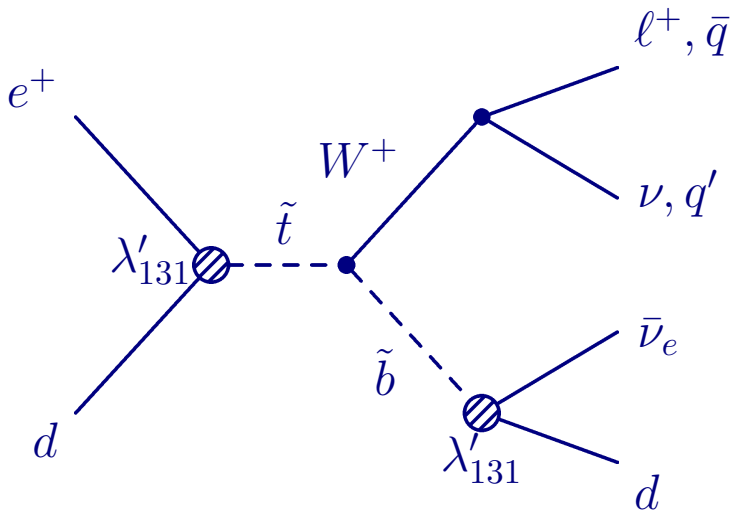
$M_{\tilde{b}} < M_{\tilde{t}}$ (different from 'usual' MSSM)

$\tilde{q} \not\to q'\tilde{\chi}$ (kinematically not accessible)

$\theta_{\tilde{t}}$ and $\theta_{\tilde{b}}$ are free parameters



$\to$ bosonic stop decay $\tilde{t} \to \tilde{b}W$



Signature: 3 jets + $\not{P}_T$ or jet + ℓ + $\not{P}_T$

$\longrightarrow$ high P_T lepton events observed at H1

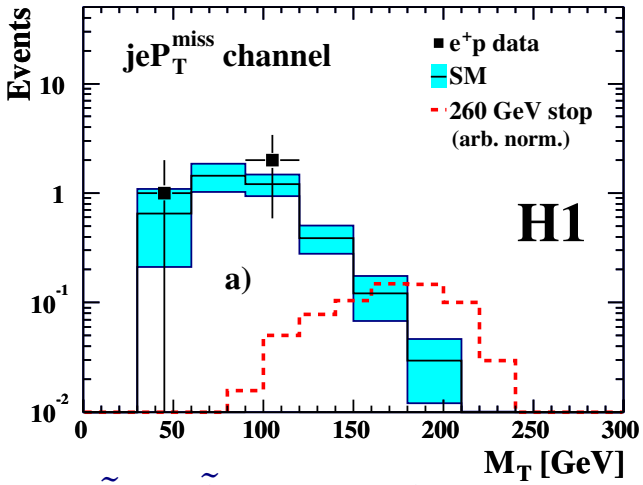
Interpretation of these events as decay products from bosonic stop decays (T. Kon et al., Mod. Phys. Lett. A12 (1997) 3143)

kinematic range: $M_{\tilde{t}} > M_{\tilde{b}} + M_W$

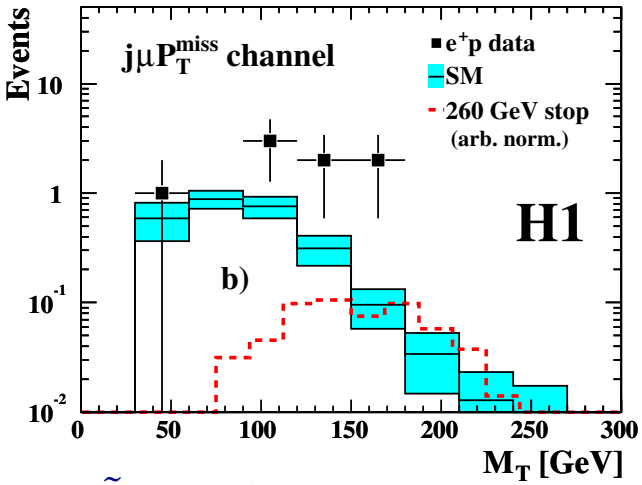
virtual W decay strongly suppressed & the direct $\not{R}_p$ decay $\tilde{t} \to ed$ dominates for $M_{\tilde{t}} \lesssim M_{\tilde{b}} + M_W$

Bosonic stop decay: H1 analysis

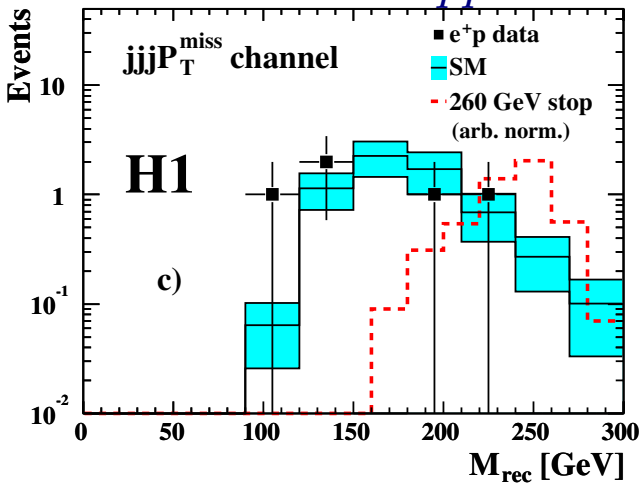
$\tilde{t} \to \tilde{b}W \to \nu d\, e\nu$



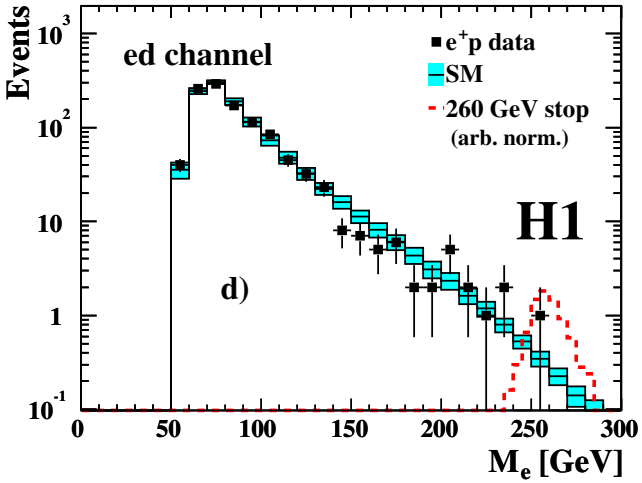
$\tilde{t} \to \tilde{b}W \to \nu d\, \mu\nu$

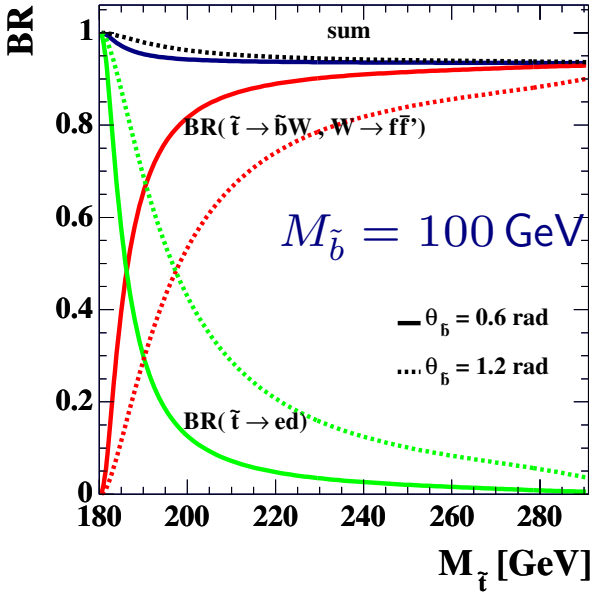


$\tilde{t} \to \tilde{b}W \to \nu d\, q\bar{q}$



$\tilde{t} \to ed$





almost full coverage of BR's

Selection cuts:

$P_T^{\ell} > 10\,\text{GeV}$
$P_T^{Jet} > 10(20, 15)\,\text{GeV}$
$\not{P}_T > 12(25)\,\text{GeV}$

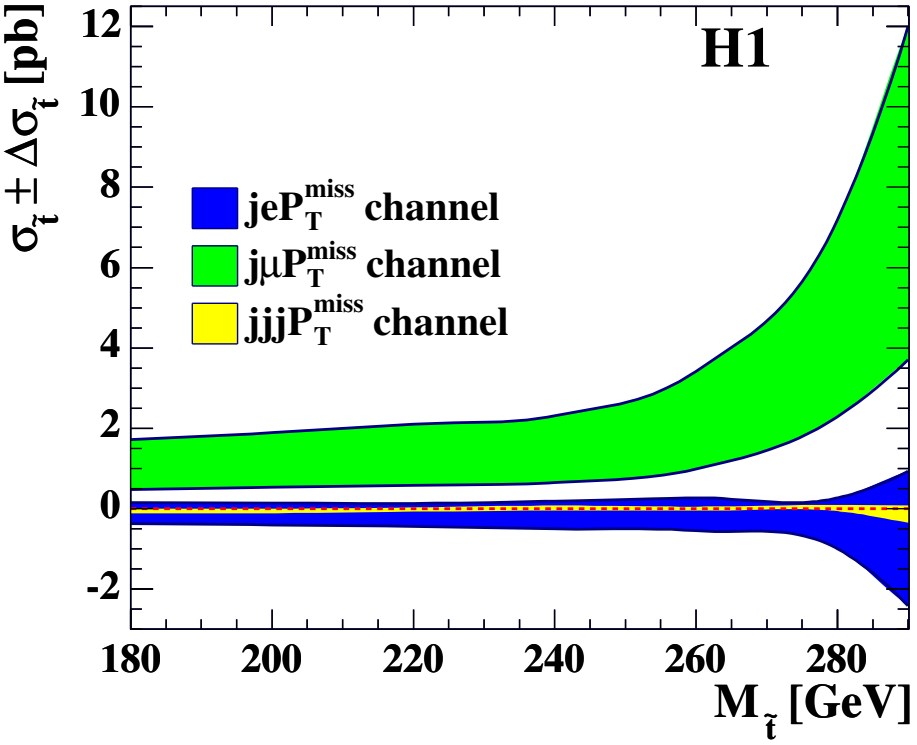
typical efficiencies: $30 - 50\%$

$\to$ slight excess in $j\mu\not{P}_T$ channel but

no significant deviation from SM expectation

Bosonic stop decay: Interpretation of high P_T lepton events

For each channel: calculate cross section $\sigma_{\tilde{t}}(M_{\tilde{t}}) = \frac{N_{Data} - N_{SM}}{\epsilon \cdot BR \cdot \mathcal{L}}$



- Slight discrepancy between data and SM only observed in the $j\mu \not{P}_T$ channel but not confirmed in the $jjj \not{P}_T$ or $je \not{P}_T$ channels
- The probability that the event rate in the $jjj \not{P}_T$ channel fluctuates such that it is comparable with the cross section in the $j\mu \not{P}_T$ channel is $\sim 0.5\% - 1\%$

$\Rightarrow$ The high P_T lepton candidates cannot be interpreted as scalar tops.

$\Rightarrow$ Set limits on SUSY parameters!

Bosonic stop decay: exclusion limits in the MSSM

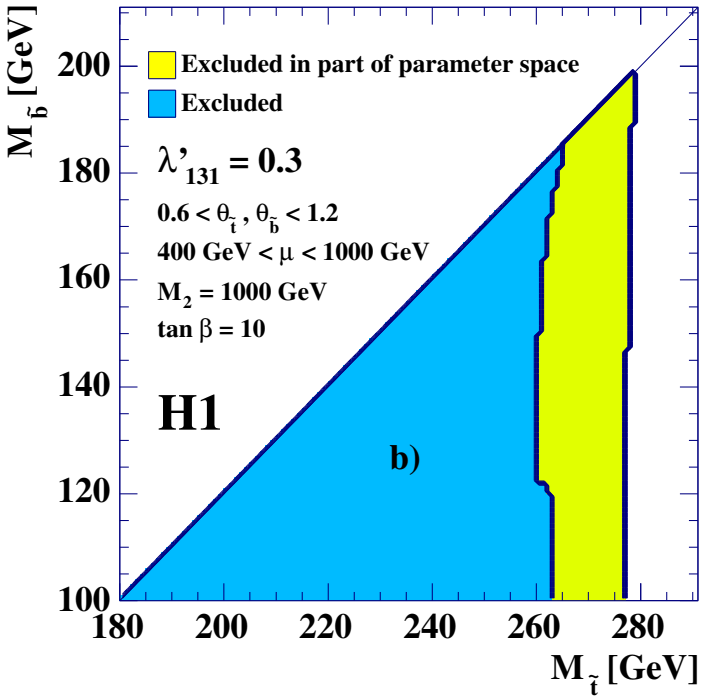
SUSY parameter scan

→ scan also: $M_{\tilde{b}}$ and the mixing angles $\theta_{\tilde{t}}$ (relevant for production cross section)
$\theta_{\tilde{b}}$ (relevant for bosonic stop decay)

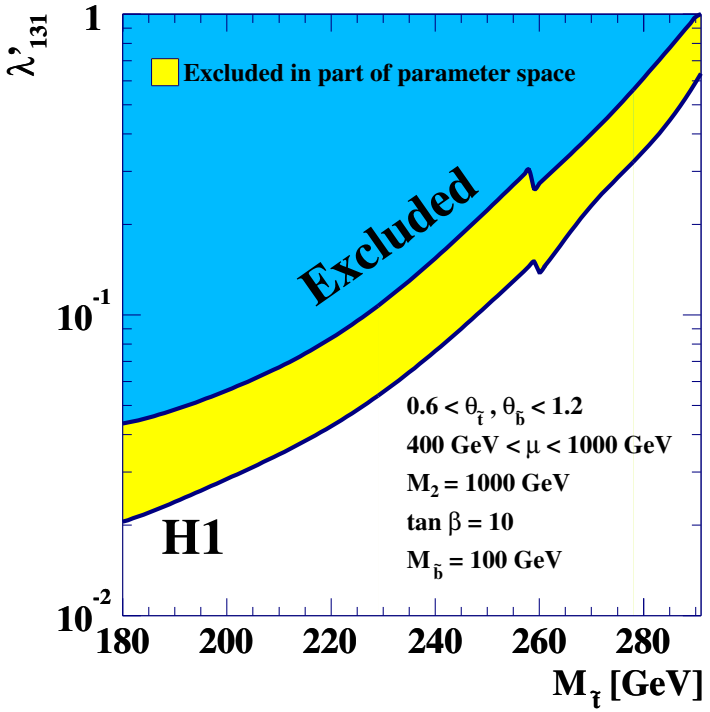
$\tan\beta = 10$
$0.6 < \theta_{\tilde{t}}, \theta_{\tilde{b}} < 1.2$
$400 < \mu < 1000\,\text{GeV}$
$M_2 = 1000\,\text{GeV}$

comparaple results for
$\tan\beta = 10$
$M_2 = 400\,\text{GeV}$

$\lambda'_{131} = 0.3$



$M_{\tilde{b}} = 100\,\text{GeV}$



→ **Stop masses up to $\sim 275\,\text{GeV}$ excluded for $\lambda'_{131} = 0.3$**

Summary & outlook

- Squarks have been searched for in all e^+p and e^-p H1 data ($\mathcal{L}_{int} \approx 120\,\text{pb}^{-1}$)

  $\Rightarrow$ **no evidence for squark production found**

- Limits were derived in the SUSY parameter space

  $\Rightarrow$ **Squark masses up to 275 GeV ($\tilde{u}^j$) and 285 GeV ($\tilde{d}^k$) excluded for $\lambda'_{1jk} = 0.3$**

  mSUGRA limits (on m_0, $m_{1/2}$) are competitive to LEP and TeVatron

- Complementary analysis: bosonic stop decay

  A slight excess in the $j\mu \not{P}_T$ channel is observed, but
  no evidence for stop production found

  $\Rightarrow$ The high P_T lepton events observed at H1 cannot be interpreted as stops.

- **Stop masses up to ~ 275 GeV excluded for $\lambda'_{131} = 0.3$**

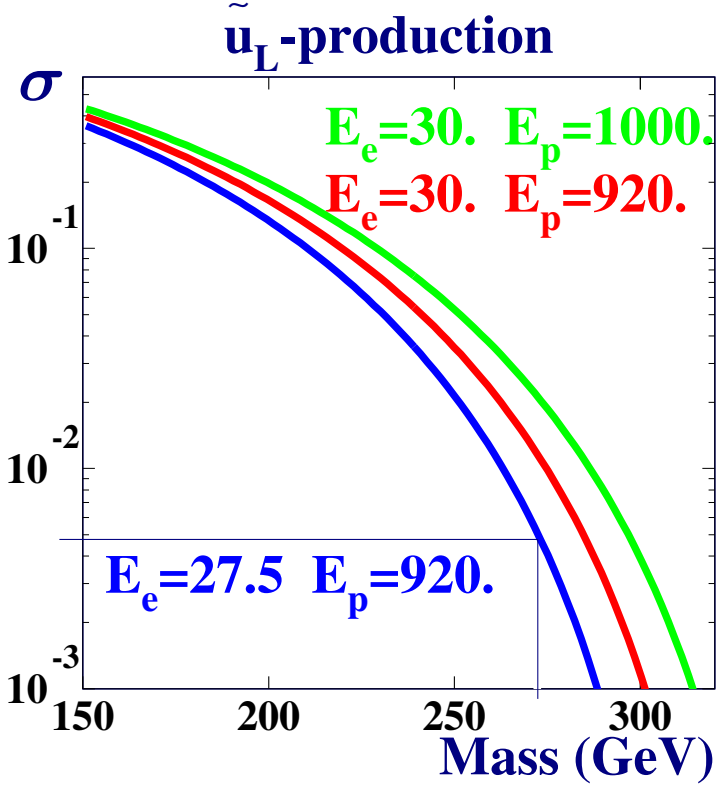
Outlook

- **HERA II**:
  - polarised $e^{\pm}$ beams:

$$e_R^+ + d_L \rightarrow \tilde{u}_L^j$$
$$e_L^- + u_L \rightarrow \tilde{d}_R^k$$

    needed for $\not{R}_p$ SUSY searches at HERA II

  - higher luminosity: ~ 1 fb^{-1} per experiment



- higher $\sqrt{s}$ would also be helpful for $\not{R}_p$ SUSY searches