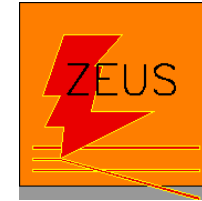


Supersymmetry at HERA



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- **RPV at HERA**
- **Squark Production in RPV SUSY**
 - **General Search**
 - **Bosonic Stop Decays**
 - **Stop Production**
- **Superlight Gravitinos in RPV SUSY**
- **Summary and Outlook**

R-Parity at HERA

- **RPV SUSY:** \Rightarrow Resonant Squark Production via s-channel with masses up to \sqrt{s}

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

- Additional Terms in Superpotential:

$$W_{R_p} = \underbrace{\lambda_{ijk} L_i L_j \bar{e}_k}_{\cancel{R_p}} + \underbrace{\lambda'_{ijk} L_i Q_j \bar{d}_k}_{\cancel{R_p}} + \underbrace{\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k}_{\cancel{R_p}} \dots$$

- allows **Single Production** of SUSY particles
- allows **Decay of LSP** (Lightest Supersymmetric Particle) to SM Particles
- **HERA:** Leading Order Diagrams proceed through 2. term
 \Rightarrow Resonant Production of SUSY Particles possible via λ'_{ijk}

Search for Squark Production in RPV SUSY

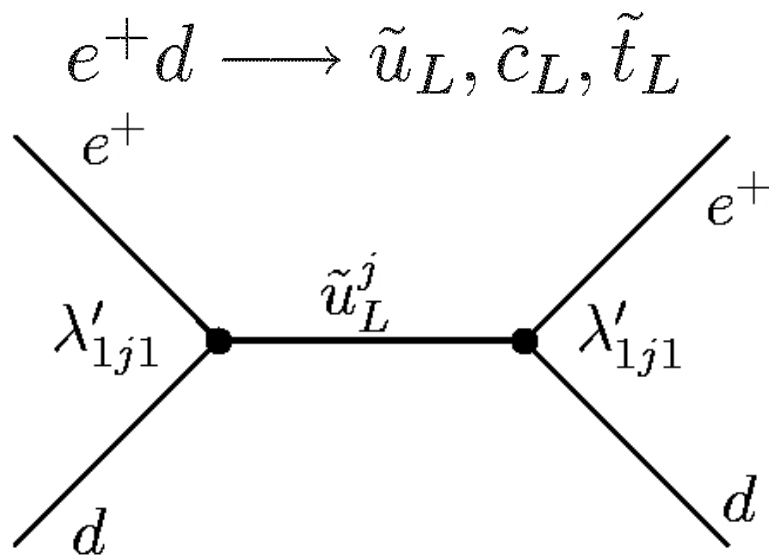
- Squark Masses up to \sqrt{s}

- **Narrow Width Approximation:**

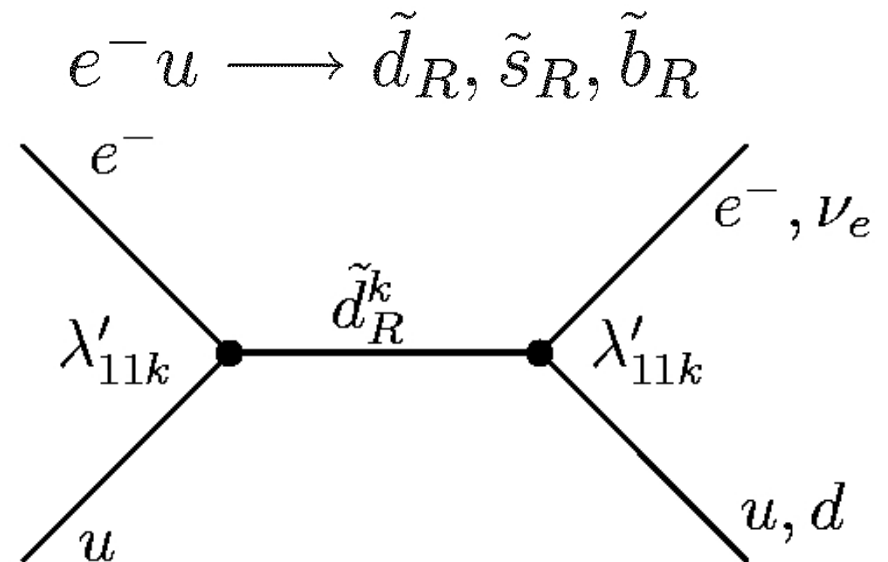
$$\sigma(e^+ p \rightarrow \tilde{u}_L^j) \sim \lambda'_{1jk}{}^2 \cdot d^k \left(x = \frac{M_{\tilde{q}}^2}{s}\right)$$

$$\sigma(e^- p \rightarrow \tilde{d}_R^k) \sim \lambda'_{1jk}{}^2 \cdot u^j \left(x = \frac{M_{\tilde{q}}^2}{s}\right)$$

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



High E_T e + jet (Backg: NC DIS)



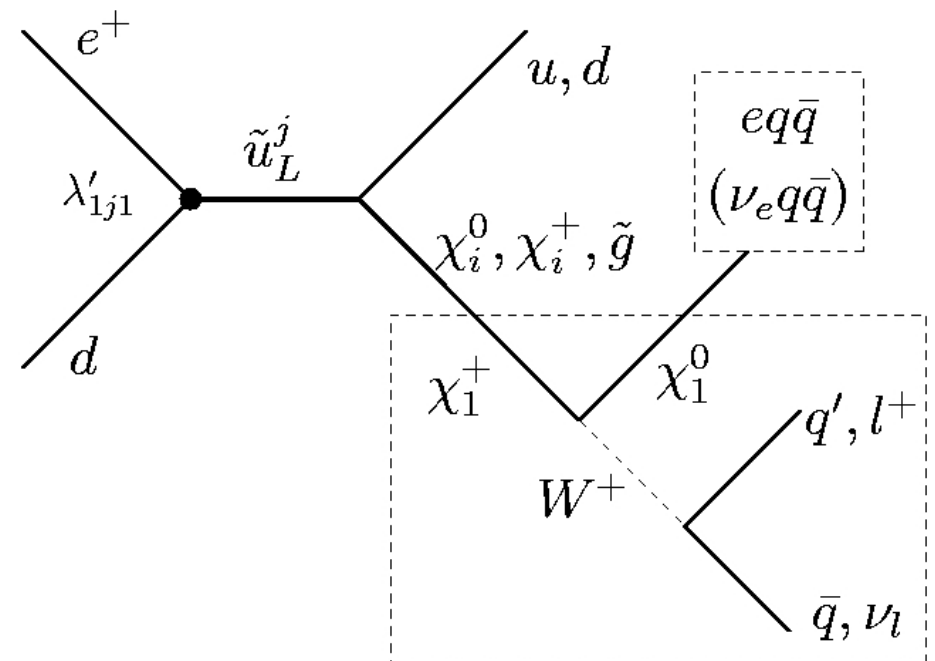
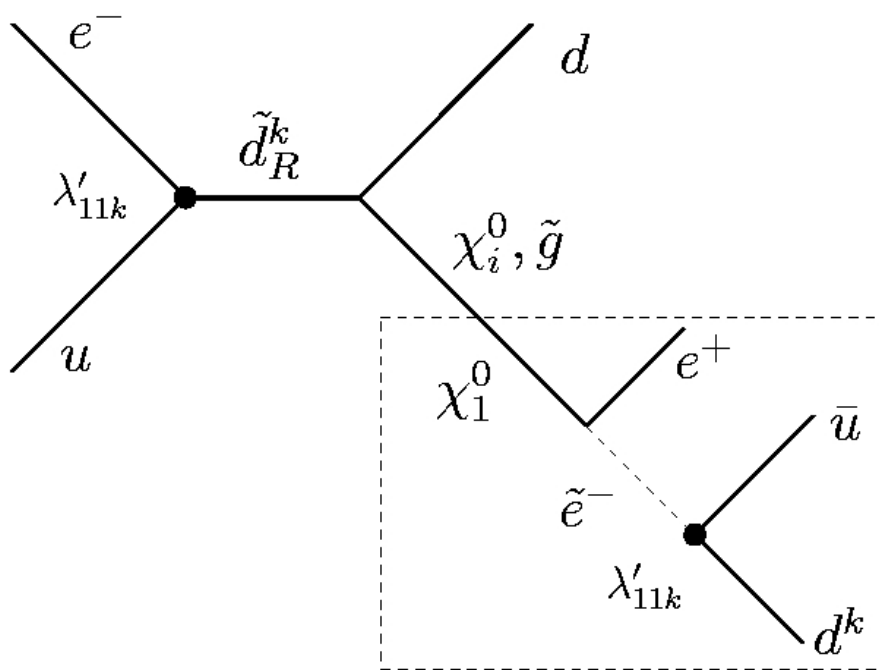
High E_T ν + jet (Backg: CC DIS)

Gauge Decays

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

Subsequent Gaugino Decay via cascade: **Large variety of final states**

- $e^{+/-}$ + **multiple jets** (Backg: NC DIS)
- $e^{-/+}$ „wrong sign“ + **multiple jets** (Backg: bg-free!“)
- ν + **multiple jets** (Backg: CC DIS)
- $e(\nu) + l$ + **multiple jets** (Backg: small contrib. from NC, CC)

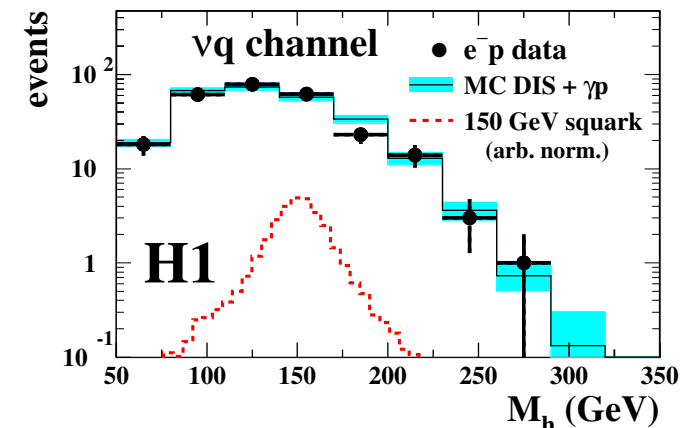
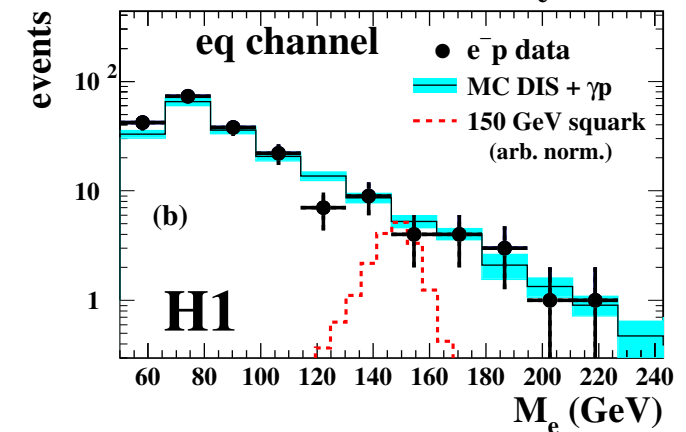
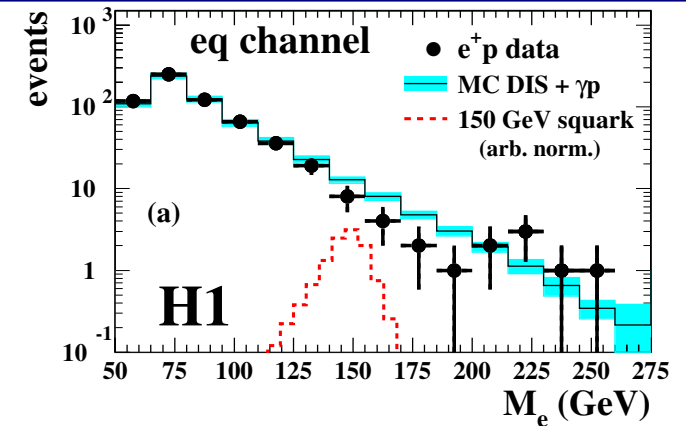


- In this Search: Almost full coverage of BR's (**depend on parameters**)

Squark Production: lq -channel

- H1, Data: $64.3 \text{ pb}^{-1} e^+p$, $13.5 \text{ pb}^{-1} e^-p$
- Selection
 - Exclusive Selection for each channel
 - High Q^2, y
 - eq-channel:
 - * $P_{T,e} > 16 \text{ GeV}$, isolated
 - vq-channel:
 - * $P_{T,miss} > 30 \text{ GeV}$
 - * No Lepton $p_T > 5 \text{ GeV}$ found
- Resonance in M_{inv} (M_h) at Squark Mass
expected for Signal - Resolution 3-6 (15) GeV
- Typical Efficiencies: 30-60%
- **No „wrong sign electron“ found**

No deviation from SM expectation



Search for Squark Production: Summary

Channel	e^+p collisions		e^-p collisions		Efficiency
	Data	SM expectation	Data	SM expectation	
eq	632	628 ± 46	204	192 ± 14	30 – 50 %
νq	—	—	261	269 ± 21	40 – 60 %
eMJ (“right” charge)	72	67.5 ± 9.5	20	17.9 ± 2.4	15 – 50 %
eMJ (“wrong” charge)	0	0.20 ± 0.14	0	0.06 ± 0.02	10 – 30 %
$eeMJ$	0	0.91 ± 0.51	0	0.13 ± 0.03	15 – 45 %
$e\mu MJ$	0	0.91 ± 0.38	0	0.20 ± 0.04	15 – 35 %
νeMJ	0	0.74 ± 0.26	0	0.21 ± 0.07	15 – 40 %
νMJ	30	24.3 ± 3.6	12	10.1 ± 1.4	10 – 60 %
$\nu\mu MJ$	0	0.61 ± 0.12	0	0.16 ± 0.03	15 – 50 %

• Measurements in all Channels are compatible with SM

⇒ Calculation of Exclusion Limits

Squark Production: Constraints on MSSM

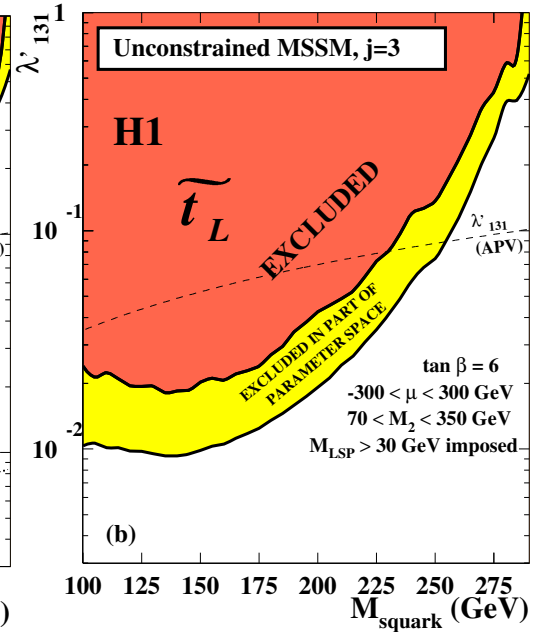
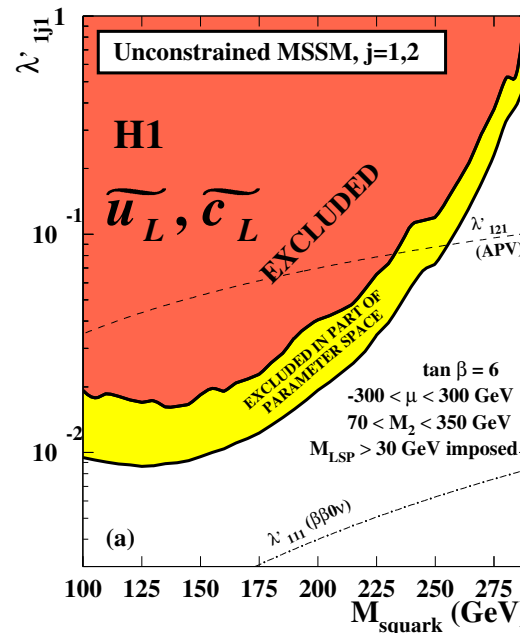
• MSSM Parameter Scan:

- $\tan \beta = 6$
- $70 \text{ GeV} < M_2 < 350 \text{ GeV}$
- $-300 \text{ GeV} < \mu < 300 \text{ GeV}$
- $M_{\tilde{t}} = 90 \text{ GeV}$

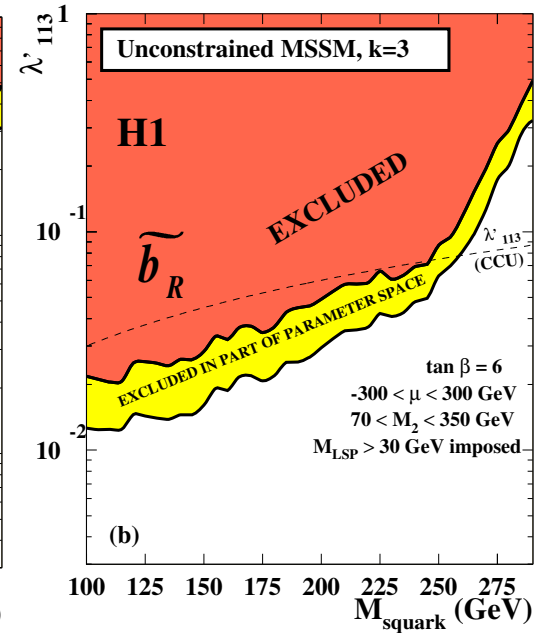
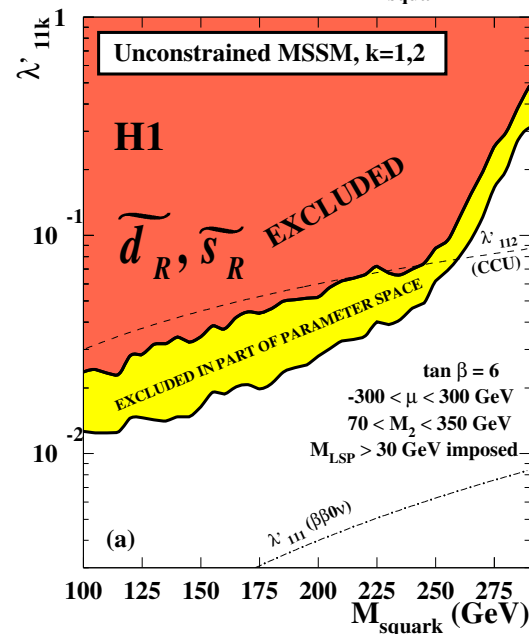
• Limits almost independent of SUSY Parameters

- $\lambda'_{ijl} = 0.3$ ($\lambda'_{llk} = 0.3$) $\sim \sqrt{4 \pi \alpha_{em}}$:
- $M_{\tilde{q}} < 275 \text{ GeV}$ (280 GeV)

e+p:



e-p:



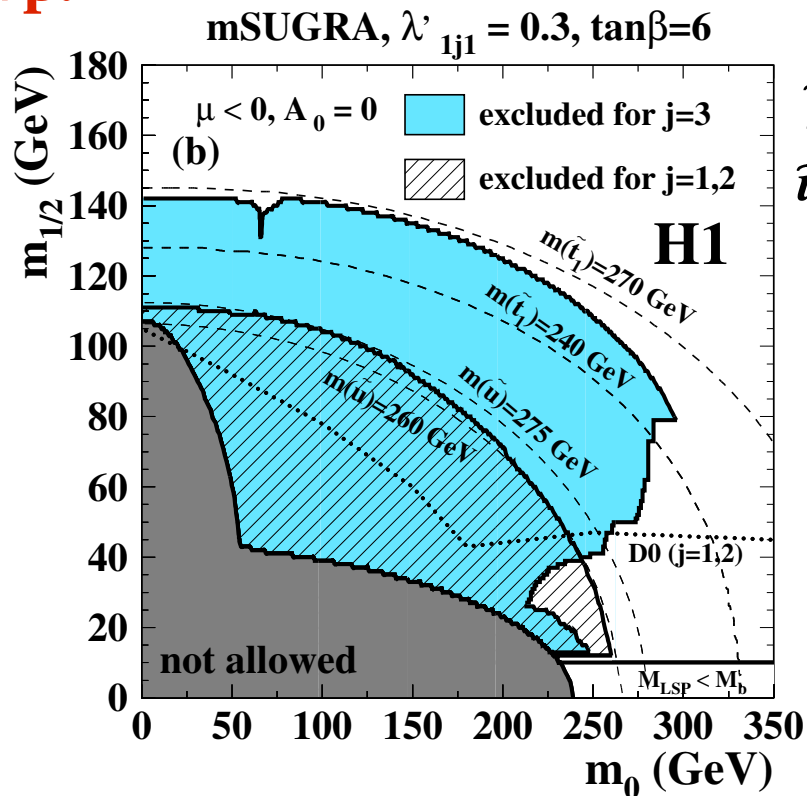
Squark Production: Constraints on mSUGRA

• mSUGRA Parameters:

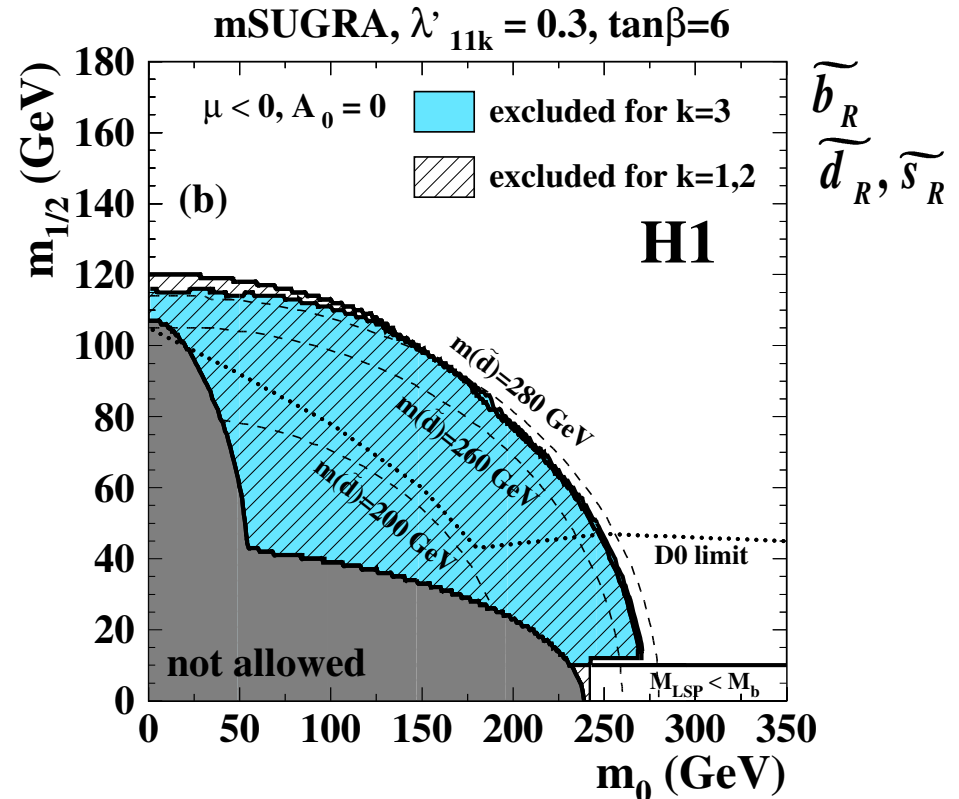
- $\tan \beta = 6$
- $\text{Sign}(\mu) = -1$
- $A_0 = 0$
- $\lambda'_{ijl} = 0.3$ ($\lambda'_{1lk} = 0.3$) $\sim \sqrt{4 \pi \alpha_{em}}$

- Limits follow squark isomass curves
- $M_{\tilde{q}}$ up to ~ 280 GeV excluded
- Medium $\tan \beta$: HERA more sensitive than Tevatron

e+p:



e-p:



Bosonic Stop Decays in RPV SUSY

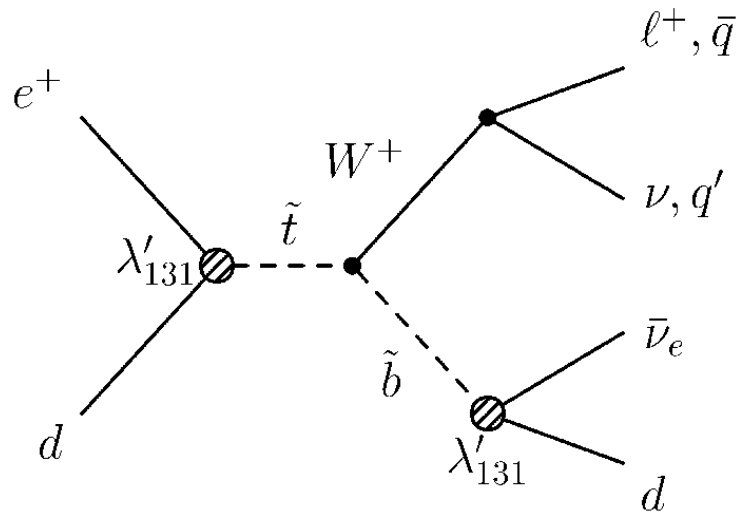
- Large Mixing in 3. generation possible:

\tilde{b} or \tilde{t} can be rather light through large mixing:
$$\begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{\tilde{f}} & \sin \theta_{\tilde{f}} \\ -\sin \theta_{\tilde{f}} & \cos \theta_{\tilde{f}} \end{pmatrix} \begin{pmatrix} \tilde{f}_L \\ \tilde{f}_R \end{pmatrix}$$

$$m_{\tilde{t}_1}^2 = \frac{1}{2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 - \sqrt{(m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)^2 + 4m_t^2 a_t^2}) \quad a_t^2 = A_t - \mu \cot \beta$$

Motivation: Excess in isolated high pt lepton events at H1 (Talk by A. Schoening) 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 + $p_{T,miss}$



Assumptions (choice of MSSM Parameters):

$$M_{\tilde{b}} < M_{\tilde{t}}$$

$\tilde{t} \rightarrow \tilde{q} \chi$: kinematically forbidden

$$M_{\tilde{t}} > M_{\tilde{b}} + M_W$$

otherwise $\tilde{t} \rightarrow ed$ dominant

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

Bosonic Stop Decays: Mass Spectra

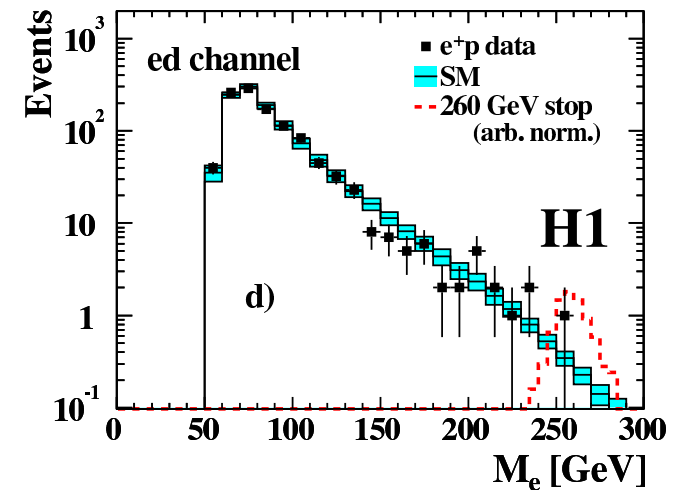
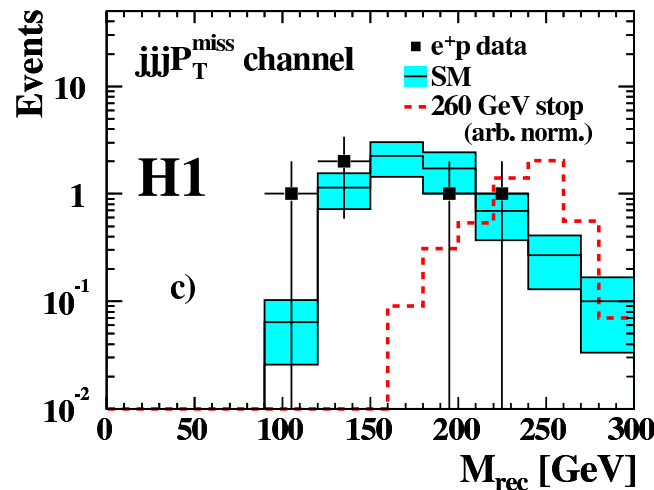
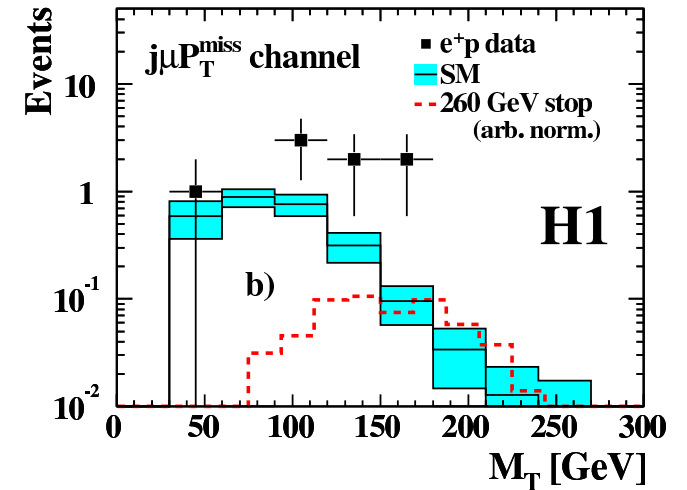
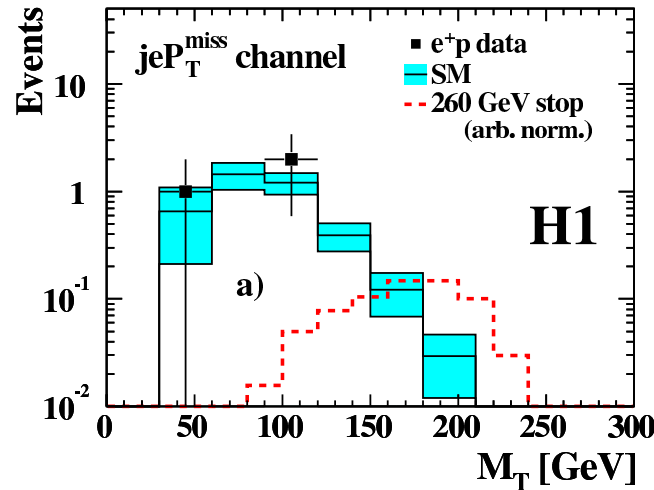
- Selection $j\ell P_{T,miss}-(jjj)P_{T,miss}$ -channel:

- $P_{T,e(\mu)} > 10$ GeV
- $P_{T,jet} > 10$ GeV (20, 15, 10 GeV)
- $P_{T,miss} > 12$ GeV (25 GeV)
- Angular Cuts

- Typical Efficiencies: 30-50%

- Slight excess in

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

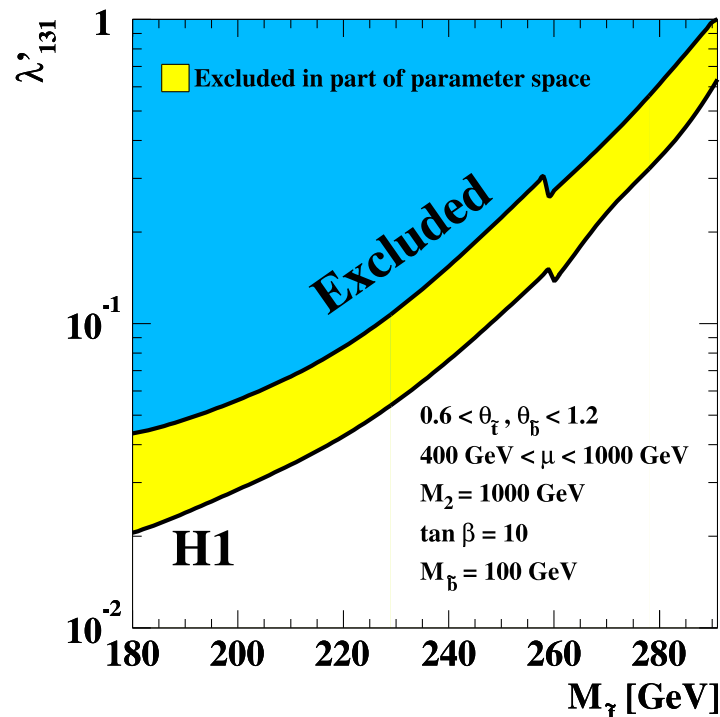
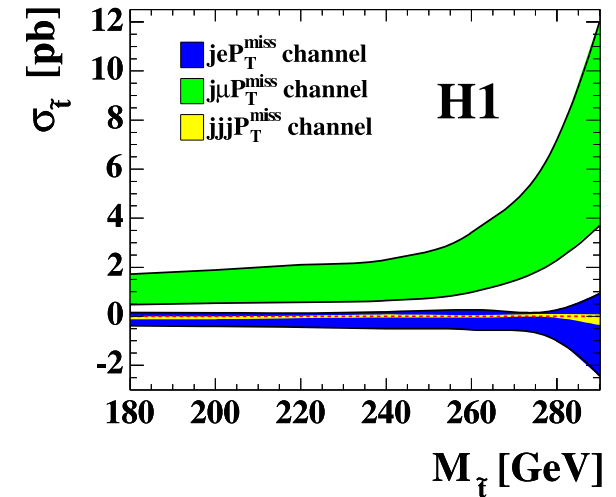


Bosonic Stop Decays: Limits

- **Bands:** allowed cross section regions
- **Probability for fluctuation of $jjjP_{T,miss}$ rates towards rates compatible with $j\mu P_{T,miss}$ cross section is $\sim 1\%$**

\Rightarrow Isolated high P_T leptons cannot be interpreted as bosonic stop decays!

\rightarrow **Constraining MSSM parameters**



MSSM Parameter Scan:

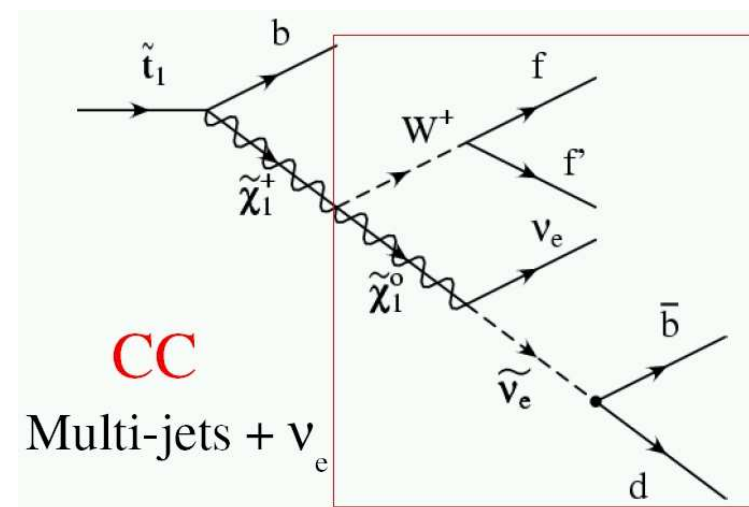
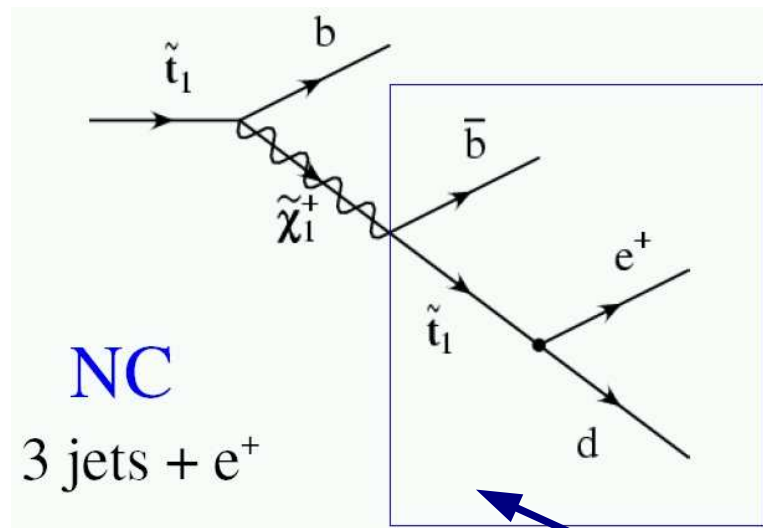
- $\tan \beta = 10$
- $M_2 = 1000 \text{ GeV}$
- $400 < \mu < 1000 \text{ GeV}$
- $0.6 < \theta_{\tilde{t}, \tilde{b}} < 1.2$

\Rightarrow Stop masses up to $\sim 275 \text{ GeV}$ excluded for

- Similar Results for $\lambda'_{131} = 0.3$
 $\tan \beta = 10$ and
 $M_2 = 400 \text{ GeV}$

Stop Production in RPV SUSY

- Gauge decays of stop:



- Assumptions:

- $40 \text{ GeV} < M_{\chi^0} < 100 \text{ GeV}$

- $M_{\chi^0} < M_{\chi^+} < M_{\tilde{t}} < M_{\tilde{b}}$

- $M_{\tilde{t}} - M_{\chi^+} = \Delta M \geq 10 \text{ GeV}$

- Mass of all other sfermions $\sim 1 \text{ TeV}$

- λ'_{131} dominant

Right now: only NC channel analysed

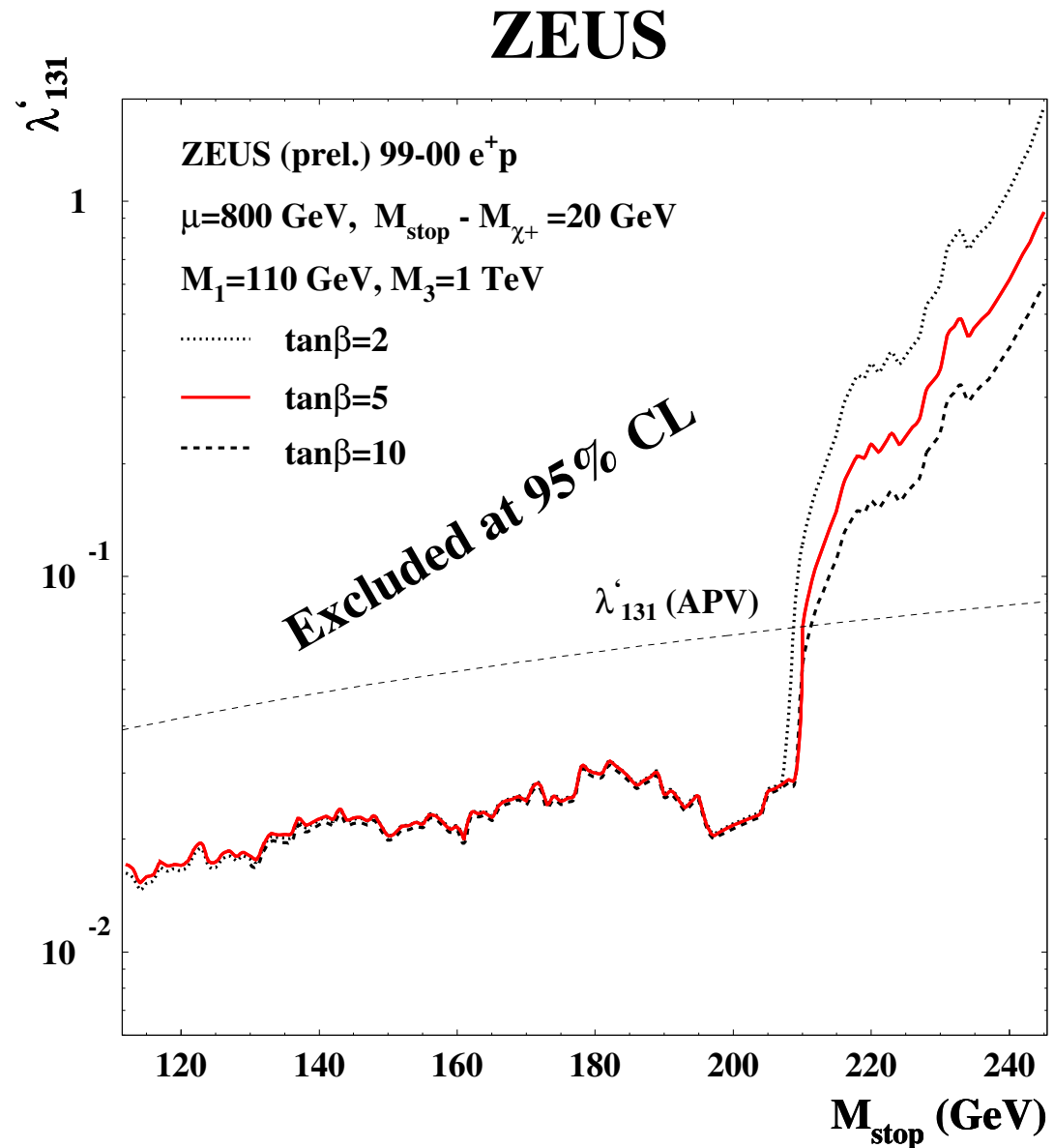
Stop Production: Preliminary Results

- **MSSM Parameter Scan:**

- $\tan\beta = 2, 5, 10$
- $M_1 = 110 \text{ GeV}$
- $M_3 = 1 \text{ TeV}$
- $|\mu| = 600, 800, 1000 \text{ GeV}$
- $\Delta M_{\tilde{t}\chi^+} = 10, 20, 30 \text{ GeV}$

- **Results for each parameter point very similar for stop masses below $\sim 200 \text{ GeV}$**

- **Limits on λ'_{131} improved for stop masses below $\sim 210 \text{ GeV}$**



Superlight Gravitinos

- GMSB

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

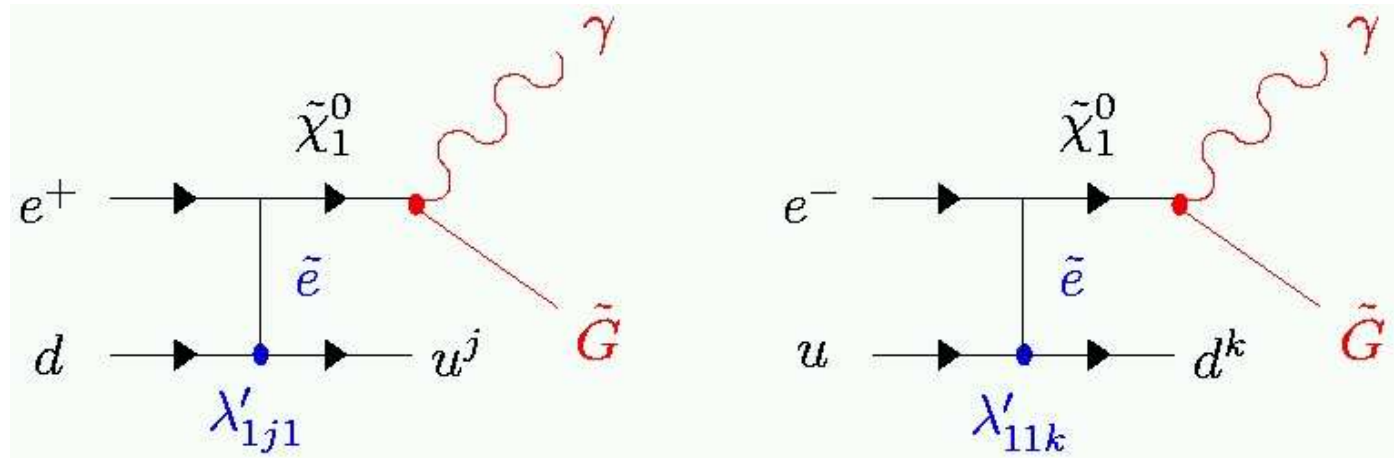
- 6 new Parameters:

- $\text{sign } \mu, \tan \beta$ Λ : Overall mass scale for SUSY Particles
- F_0 : SUSY Breaking Scale, $M(\text{Gravitino}) = F_0/(\sqrt{3} M_P)$
- M : Mass of messenger particle N : Number of messenger particles

- 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: Event Selection

• H1, Data: **64.3 pb⁻¹ e⁺p**, **13.5 pb⁻¹ e⁻p**

• Selection

- $P_{T,miss} > 25$ GeV
- $P_{T,jet} > 5$ GeV
- $P_{T,\gamma} > 15$ GeV, isolated
- Angular cuts

• GMSB Parameters:

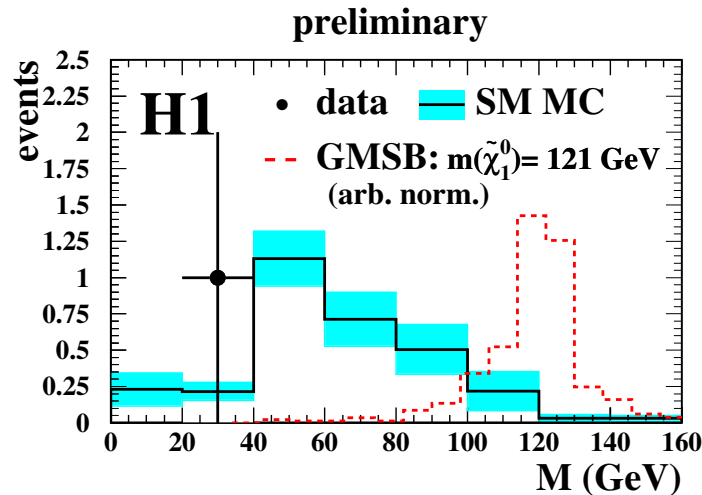
- $\tan \beta = 2, \text{sign}(\mu) = -1$
- $N = 1, \lambda' = 0.5, 1.0, 1.5$
- Λ and M transformed to

$$m_{\tilde{e}_L} = \left(m_{\tilde{e}_R} = m_{\tilde{e}} \right), m_{\tilde{\chi}_1^0},$$

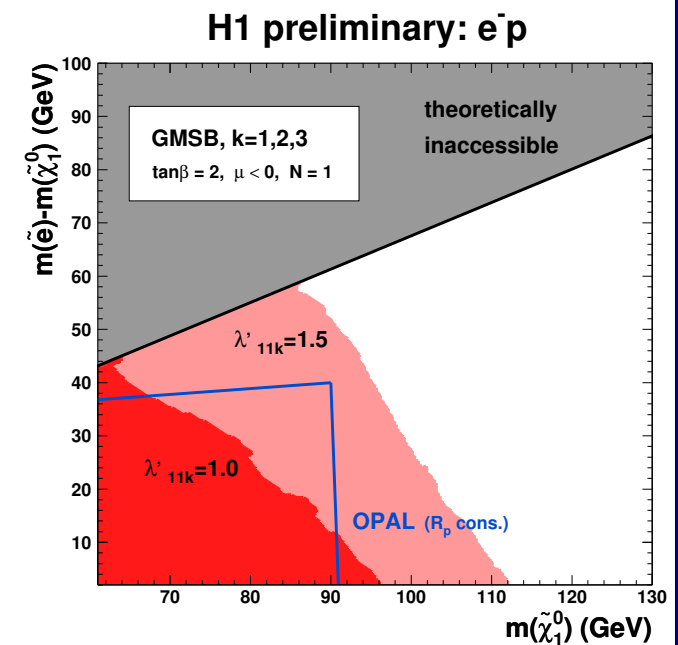
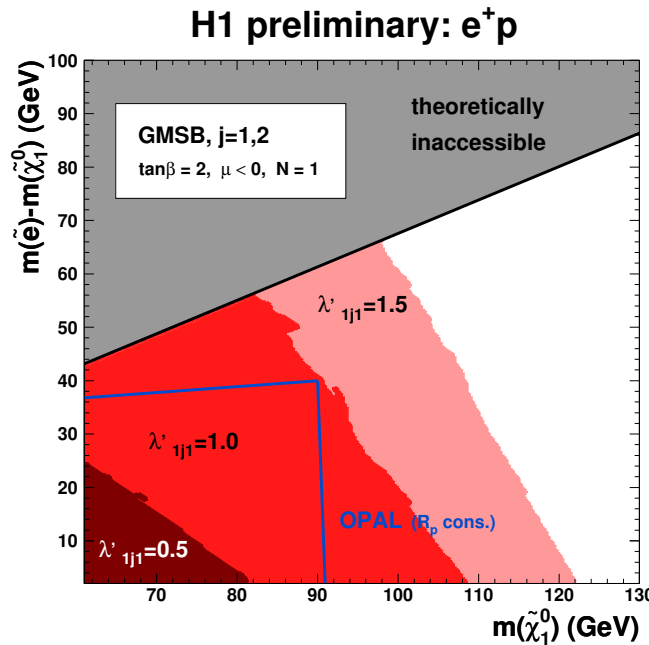
• $\lambda' = 1.0$: $m_{\tilde{\chi}_1^0} > 108$ GeV
and $m_{\tilde{e}} > 138$ GeV
(independ. of squark mass)

• $N=2$ only small effect

• $\tan \beta = 6$ decrease cross section significantly



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



Summary and Outlook

- Squarks in RPV SUSY has been searched in many decay channels
 - Using data $>64 \text{ pb}^{-1} e^+p$ and $>13 \text{ pb}^{-1} e^-p$ at $\sqrt{s} = \sim 320 \text{ GeV}$
 - No deviation from SM found
 - \Rightarrow Significant constraints on MSSM and mSUGRA parameters
 - \Rightarrow Squark masses up to $\sim 280 \text{ GeV}$ excluded for $\lambda'_{ijk} = 0.3$ ($\sim \sqrt{4 \pi \alpha_{em}}$)
 - \Rightarrow Stop masses up to $\sim 275 \text{ GeV}$ excluded for $\lambda'_{131} = 0.3$

- Superlight Gravitinos in GMSB:
 - First time at HERA: Limits on λ'_{ijk} independent of squark masses

- Prospects for HERA2:
 - Polarised beams probe directly:

$$e_R^+ + d_L \rightarrow \tilde{u}_L, \tilde{c}_L, \tilde{t}_L$$

$$e_L^- + u_L \rightarrow \tilde{d}_R, \tilde{s}_R, \tilde{b}_R$$

- Gravitinos:
 - H1 and ZEUS luminosity: $0.5 + 0.5 \text{ fb}^{-1}, \lambda'_{|j|} = 0.5$

