Searches for New Physics at HERA

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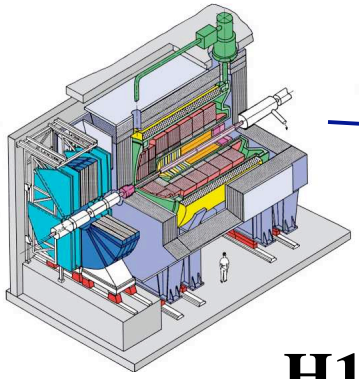
On behalf of the H1 and ZEUS Collaborations

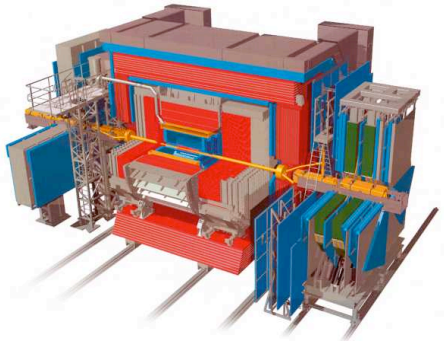
Outline

- Introduction to HERA
- Rare SM Processes
  - Isolated Leptons and Missing Transverse Momentum
  - Multi Lepton Events
  - General Search for New Phenomena
- Searches for BSM Physics
  - Leptoquark Production and Lepton Flavour Violation
  - SUSY and R-parity Violating Squark production
  - Bosonic Stop Decays in R-parity Violating SUSY
  - Search for Gaugino Production
  - Light Gravitinos in Events with Photons and Missing Transverse Momentum
- Summary of Results

HERA and the H1 and ZEUS Experiments

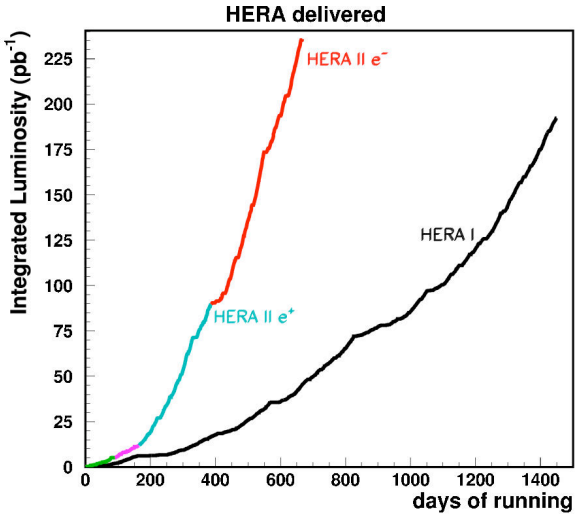


H1

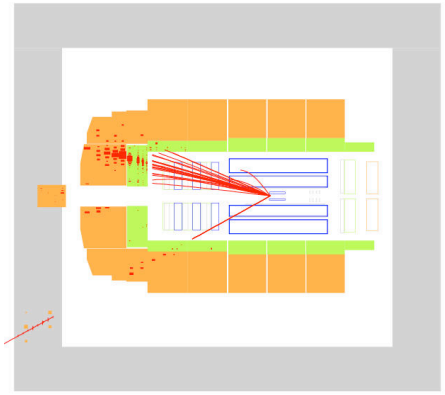


ZEUS

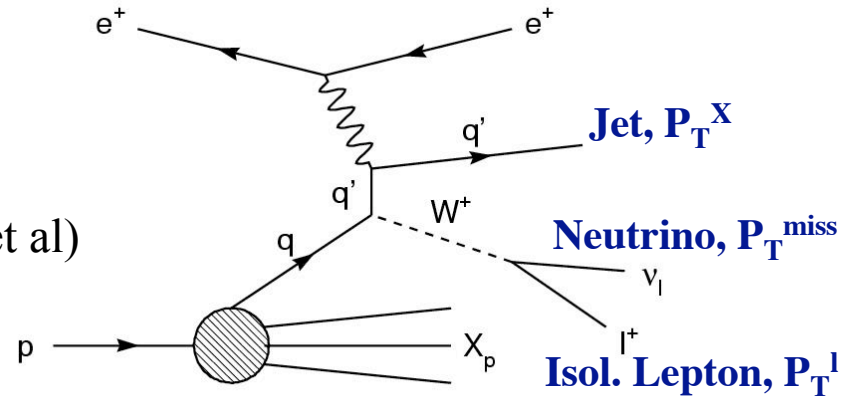
- At the HERA collider in Hamburg, Germany 920 GeV protons are collided with 27.6 GeV electrons or positrons, at a centre of mass 319 GeV
- Physics programme: Measure the structure of the proton, SM constraints and search for physics beyond the SM
- About 120 pb^{-1} of data collected by each experiment during HERA I phase (1992-2000)
- HERA II phase underway since 2003 with longitudinally polarised e beam, luminosity doubled by both experiments, much more data expected before 2007



Isolated Leptons and Missing P_T



- Experimental signature
  - Isolated lepton
  - Missing transverse momentum
  - Hadronic jet
- SM processes
  - Signal: Real W production, $\sigma \sim 1$ pb^{-1}
  - MC: EPVEC (Baur et al) + NLO (Spira et al)
  - Main SM backgrounds from NC and CC DIS and di-lepton production



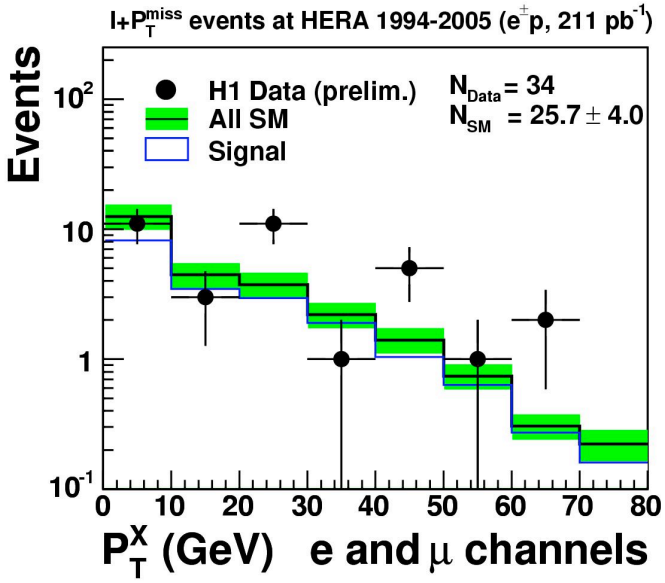
- Results from HERA I
  - Excess observed at high P_T^X in electron and muon channels by H1, not confirmed by ZEUS
  - Slight excess observed in tau channel (not covered here) by ZEUS, not confirmed by H1

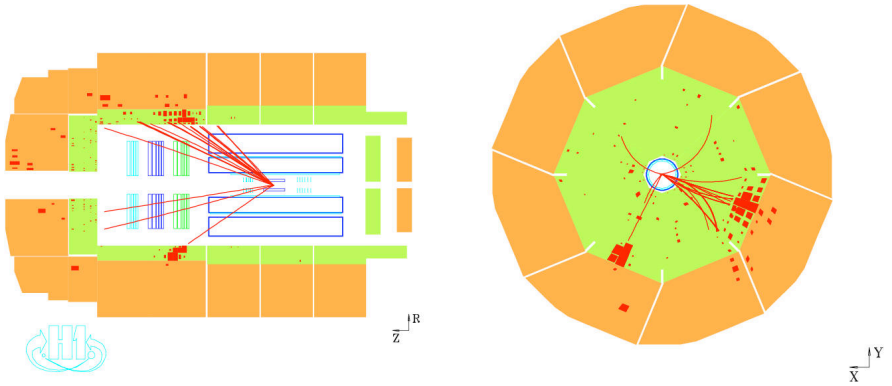
Isolated Leptons and Missing P_T

H1 Preliminary		Electron obs./exp. (Signal contribution)	Muon obs./exp. (Signal contribution)	Combined obs./exp. (Signal contribution)
1994-2004 e^+p 158 pb^{-1}	Full Sample	19 / 14.60 ± 2.03 (70%)	9 / 3.88 ± 0.63 (84%)	28 / 18.48 ± 2.66 (73%)
	$P_T^X > 25$ GeV	9 / 2.32 ± 0.44 (80%)	6 / 2.29 ± 0.38 (84%)	15 / 4.61 ± 0.82 (82%)
1998-2005 e^-p 53 pb^{-1}	Full Sample	6 / 5.78 ± 0.89 (62%)	0 / 1.47 ± 0.47 (76%)	6 / 7.25.± 1.36 (65%)
	$P_T^X > 25$ GeV	2 / 0.90 ± 0.15 (71%)	0 / 0.91 ± 0.16 (73%)	2 / 1.81 ± 0.31 (72%)
1994-2005 $e^\pm p$ 211 pb^{-1}	Full Sample	25 / 20.38 ± 2.92 (68%)	9 / 5.35 ± 1.10 (82%)	34 / 25.73 ± 4.02 (71%)
	$P_T^X > 25$ GeV	11 / 3.22 ± 0.59 (77%)	6 / 3.20 ± 0.54 (81%)	17 / 6.42 ± 1.13 (79%)

- Excess continues to be seen by H1 high P_T^X in the HERA II e^+p data
- No clear excess seen in e^-p data (lower statistics)
- Fewer muon events in the HERA II data

Isolated Leptons and Missing P_T



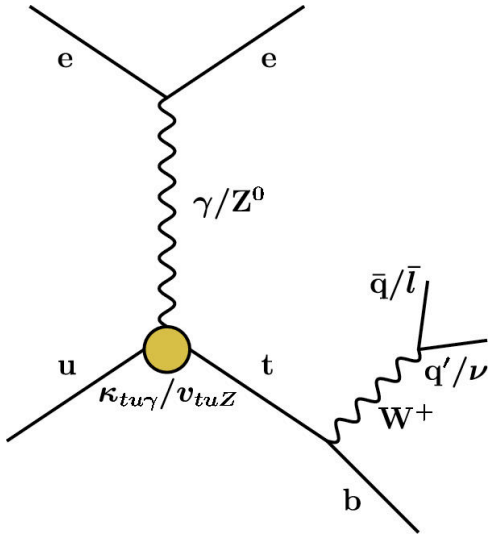


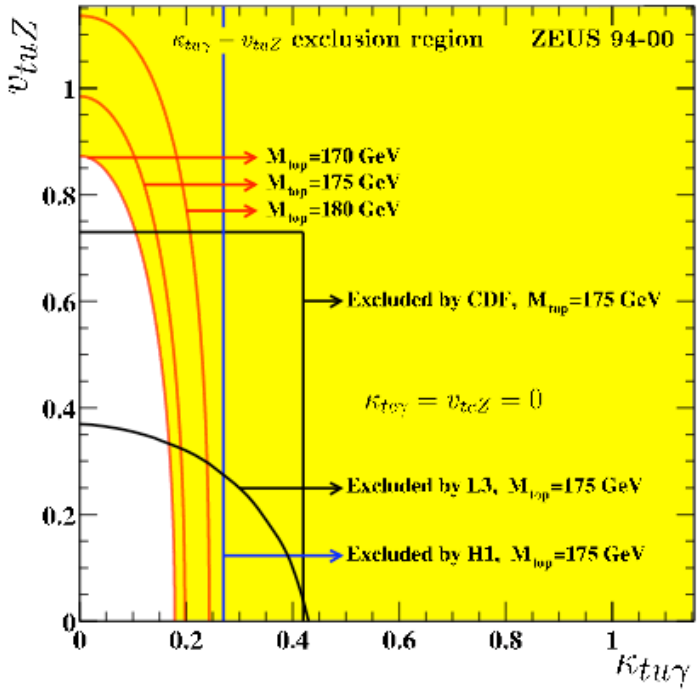
H1 HERA II isolated lepton event at large P_T^X

Isolated e candidates	$12 < P_T^X < 25$ GeV	$P_T^X > 25$ GeV
ZEUS (prel.) HERA I 99-00 (66 pb^{-1})	1 / 1.04 ± 0.11 (57%)	1 / 0.92 ± 0.09 (79%)
ZEUS (prel.) HERA II 03-04 (40 pb^{-1})	0 / 0.46 ± 0.10 (64%)	0 / 0.58 ± 0.09 (76%)

- H1 excess not confirmed by ZEUS in new electron channel analysis
- More data needed to resolve these intriguing events!

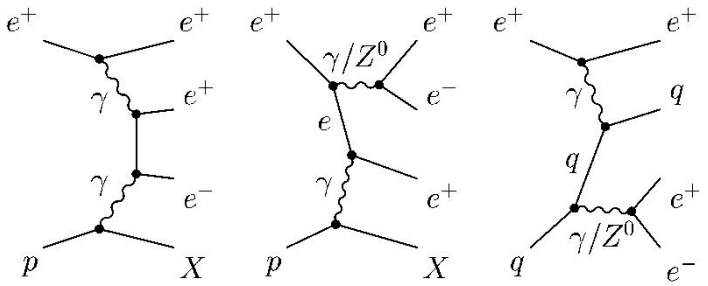
Source - Single Top Production via FCNC?





- Single top production in SM is negligible at HERA
  - production via FCNC anomalous tuγ coupling: sensitivity at HERA
- Sub-selection of isolated lepton event analysis - no significant excess seen by H1 or ZEUS in the data - derive limits
- Limits do not rule out FCNC as explanation of isolated lepton events!

Multi Lepton Events at H1

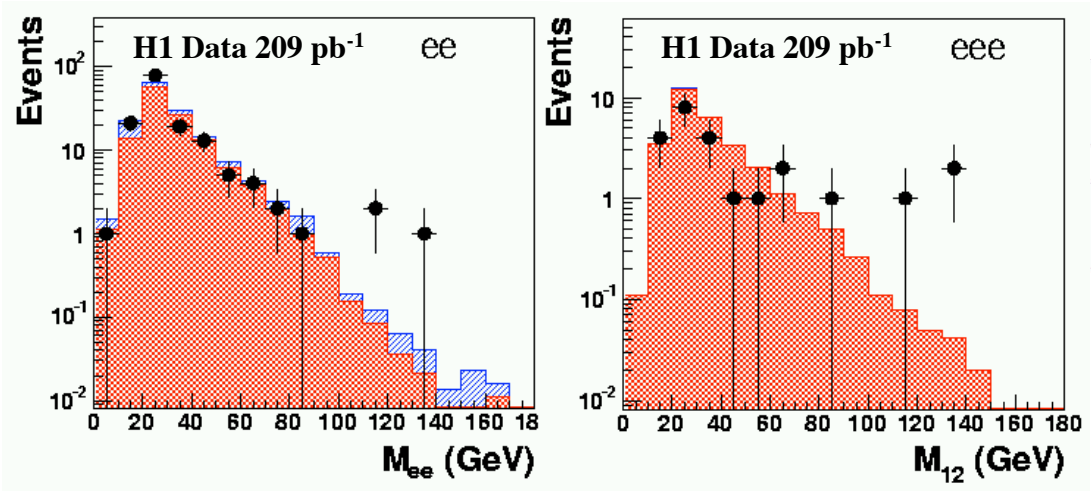


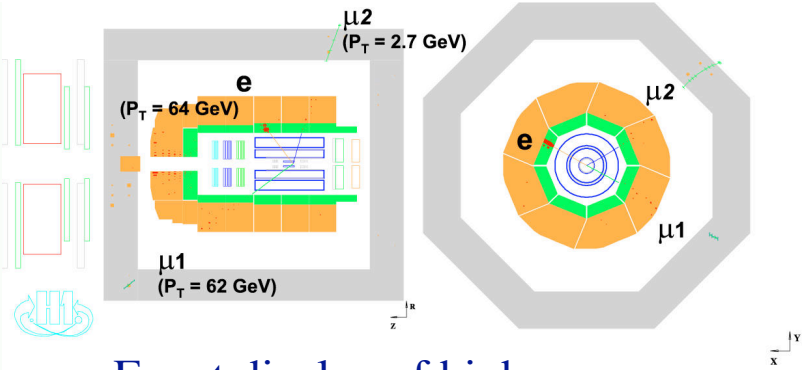
- Main production mechanism at HERA from γ-γ interactions (elastic and inelastic) - modelled by GRAPE
- H1 analysis uses HERA I+II data, (209 pb^{-1}) and examines ee, μμ, eμ, eee and eμμ topologies - search for events containing at least 2 high P_T electrons or muons - clean topology

Selection	Data	SM	Pair Production	NC DIS + Compton
ee	190	196 ± 29	163 ± 17	33 ± 20
μμ	82	85 ± 16	85 ± 16	-
eμ	106	99 ± 13	61 ± 5	38 ± 10
eee	37	39 ± 4	39 ± 4	0.1 ± 0.1
eμμ	50	51 ± 8	51 ± 8	-

- Data in agreement with SM in all event classes

Multi Lepton Events at H1

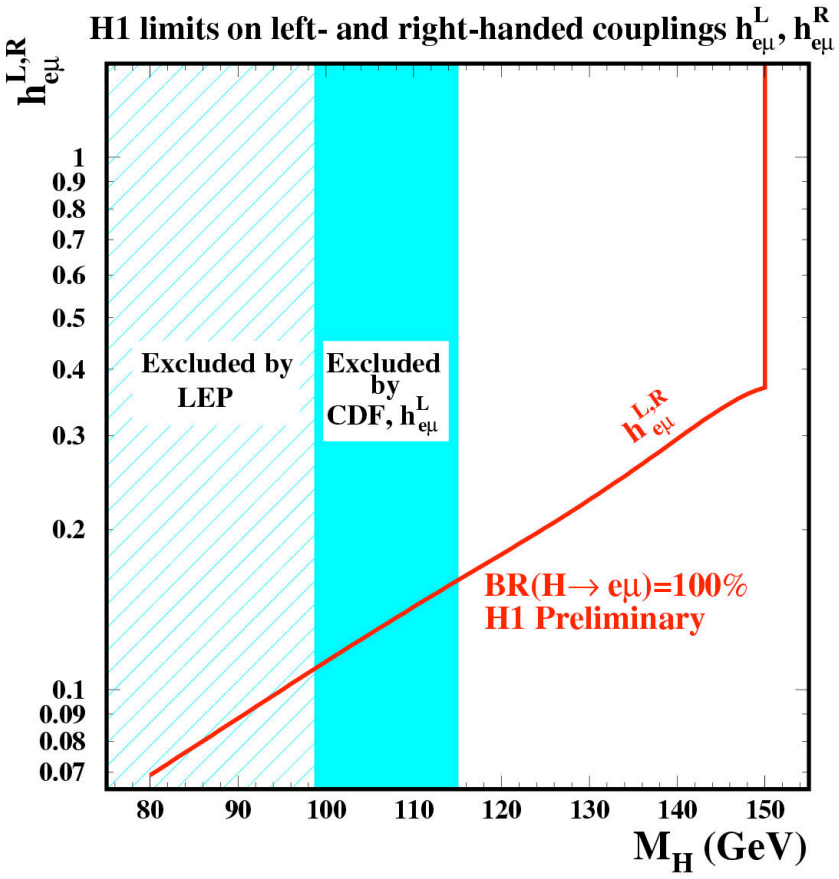


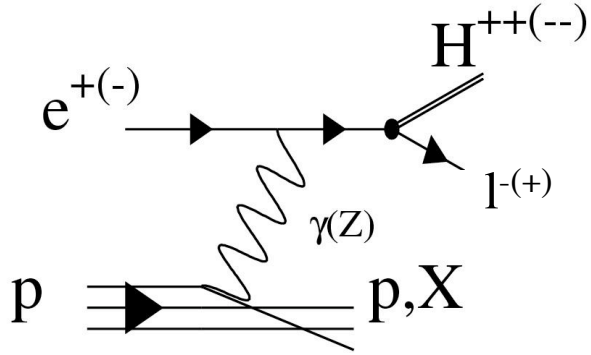


Event display of high mass eμμ event observed in HERA II data

- At low mass combinations, good agreement with the SM
- Interesting events seen a large mass combinations (M > 100 GeV)
- 3 ee events (SM: 0.44 ± 0.10) and 3 eee events (SM: 0.29 ± 0.06) observed in HERA I data
- 2 eμμ events observed in HERA II data at high mass

Source - Doubly Charged Higgs Production?





- Production of H^{++} boson with decay to leptons
- Sub-selection of multi lepton events
  - select same charge as beam for two high P_T leptons in final state
- Only one ee event compatible
  - doubly charged Higgs unlikely
- Limits derived on all relevant higgs couplings h_{ee}, $h_{e\mu}$, $h_{e\tau}$
- Improved limits on $h_{e\mu}$ from HERA!

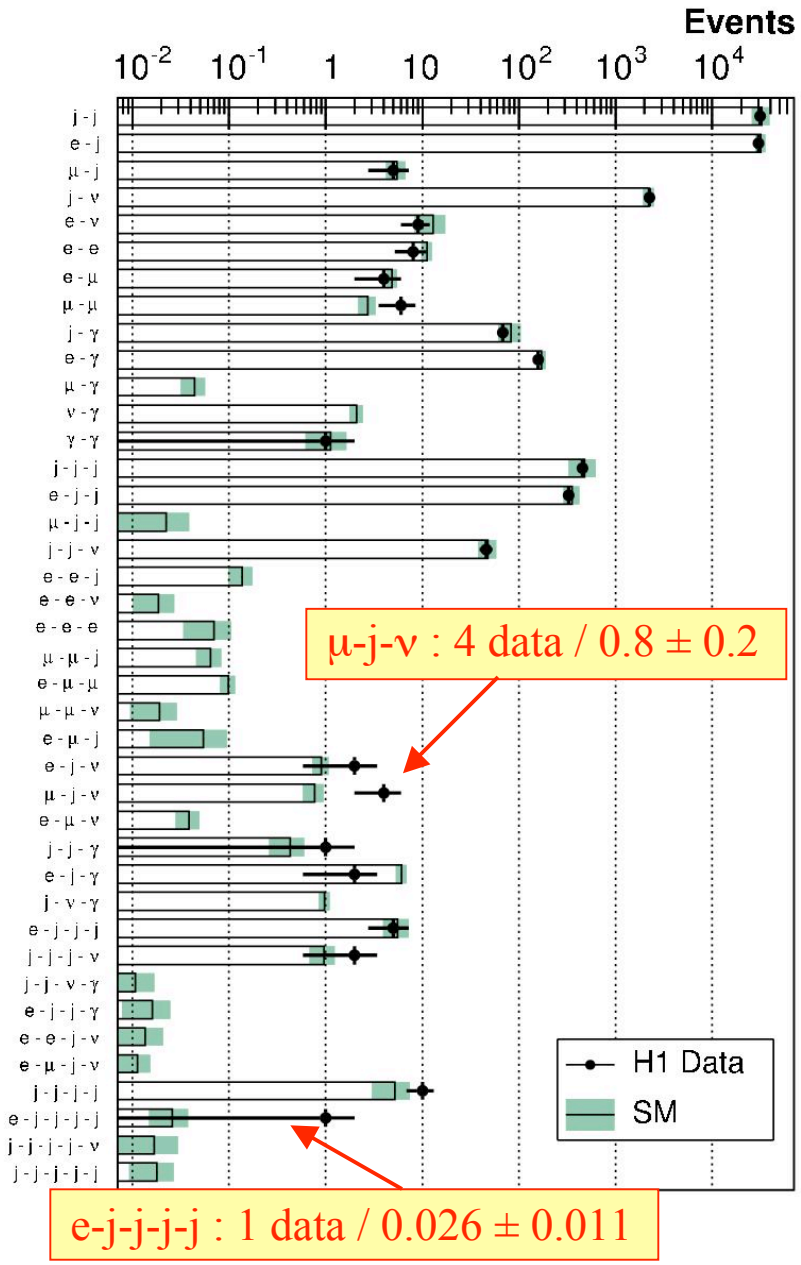
H1 General Search

- Presents a general picture of the H1 HERA I data at high P_T - and the consistency with the SM
- Look for isolated, high P_T particles: e, μ, γ, jet, ν

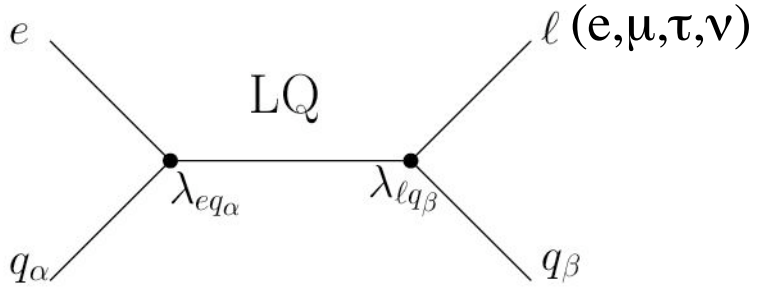
Selection Criteria:

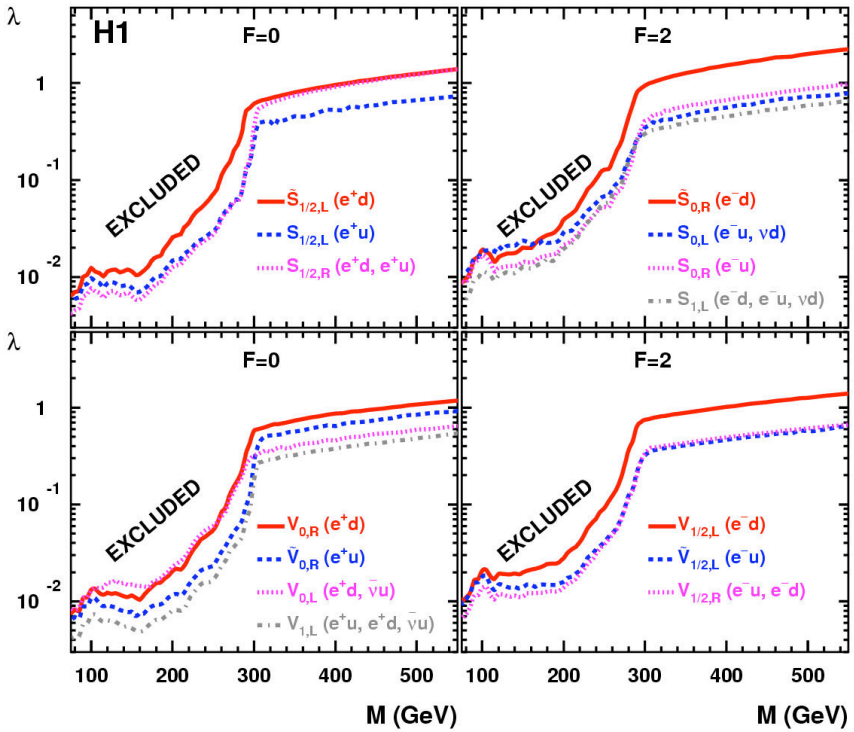
$P_T^{part} > 20$ GeV, $10 < \theta^{part} < 140$, $D(\eta\text{-}\phi)^{part} > 1.0$

- Events classed into exclusive channels (≥ 2 particles): e-j, j-j, j- ν, e-j-j and so on…
- Overall agreement with the SM observed!



Leptoquark Production

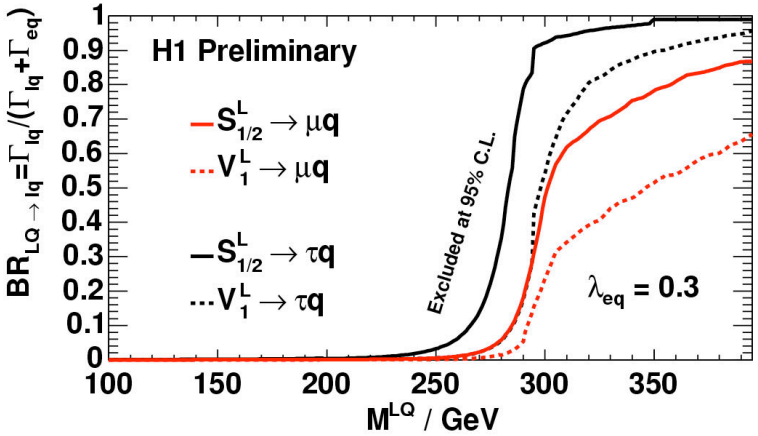




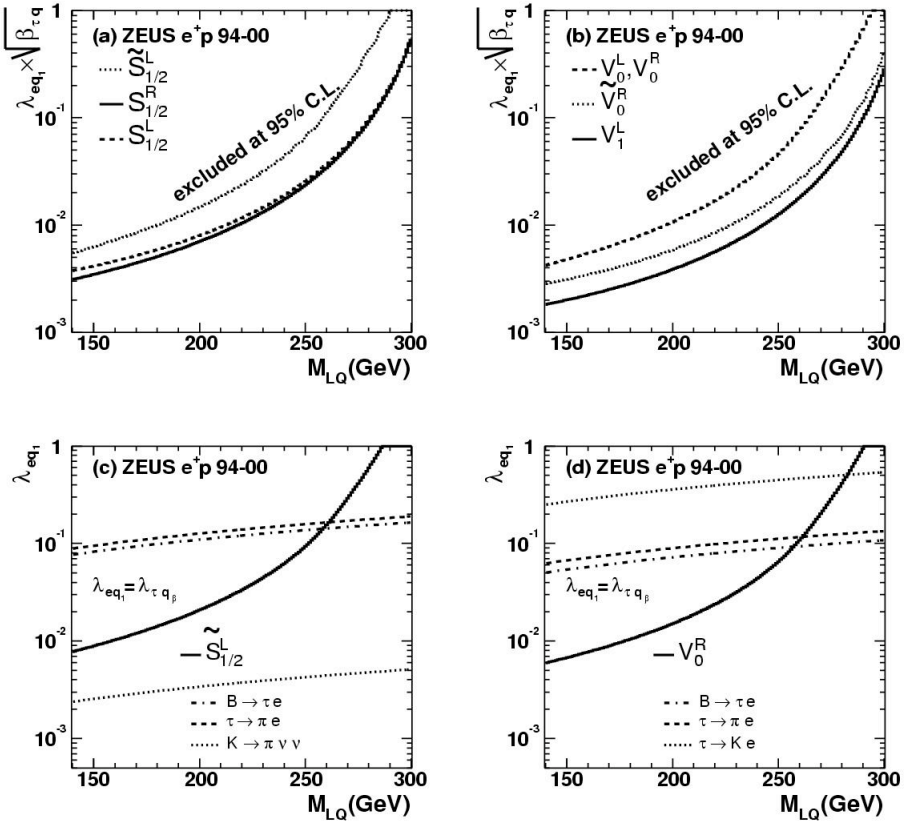
- Search for 7 scalar and 7 vector LQs (bosons with baryonic and leptonic quantum numbers)
  - Fermion number F = 3B + L (= 0 e^+p, 2 e^-p)
- DIS at HERA:
  - NC: ep → eX
  - CC: ep → νX
- First generation of LQs: decay to e, ν
  - look for enhancement in mass spectra of NC and CC interactions
- No signal seen: derive limits on the 14 different LQ types as a function of mass
- For M < 300 GeV: resonant production
- For M > 300 GeV: contact interactions

Leptoquark Production with LFV

- Can also look for lepton flavour violating leptoquarks
  - Look for final state muon or tau + jet
  - Convention: $\lambda_{eq} = \lambda_{\mu q'}$ or $\lambda_{eq} = \lambda_{\tau q'}$
- No signal seen: again, derive limits
- ZEUS: tau channel (F=0), masses up to 299 GeV excluded for $\lambda_{eq} = 0.3$
- H1: variable LQ coupling strength for fixed $\lambda_{eq} = 0.3$, masses up to 350 GeV excluded for BR(μ) of 0.5



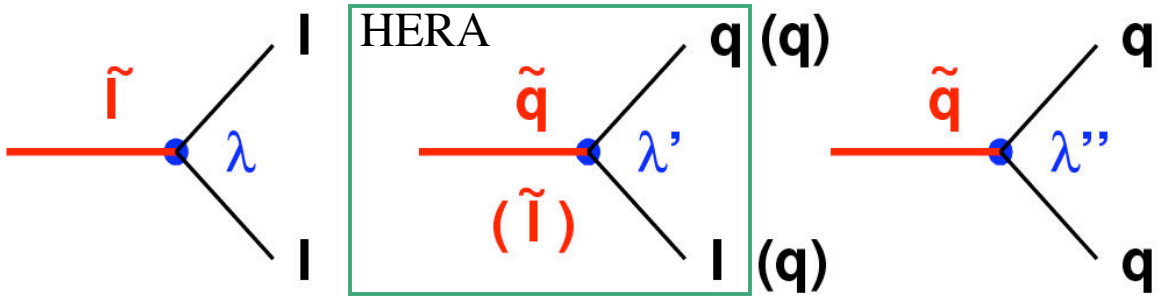
ZEUS



SUSY and R-parity

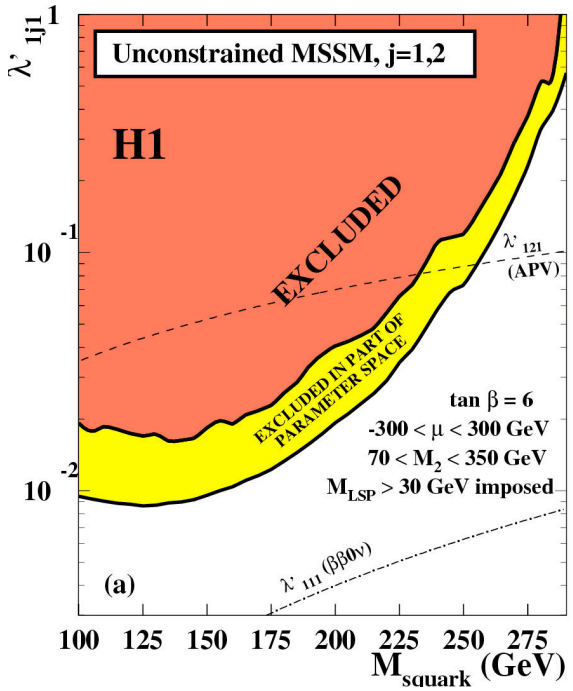
- The most general SUSY (MSSM) model allows Yukawa couplings between two SM fermions and a sfermion, squark or slepton, introducing R-parity violation
  - $R_p = (-1)^{3B + L + 2S}$ (= 1 for SM particles, -1 for SUSY particles)

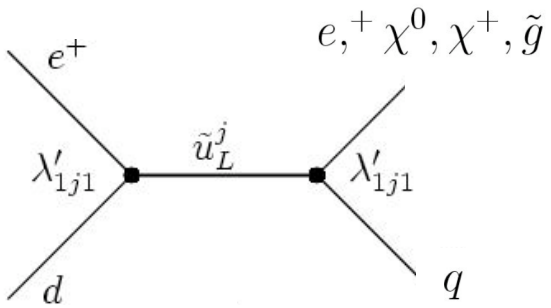
$$W_{\not R_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i D_j \bar{D}_k$$

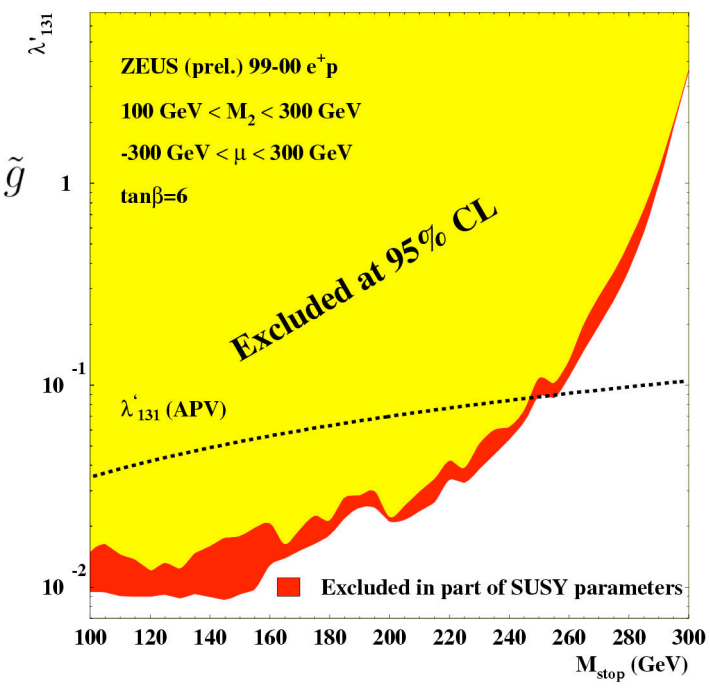


- At HERA the resonant production of single SUSY particles is possible through e-q fusion

Search for Squark Production in R-parity Violating SUSY



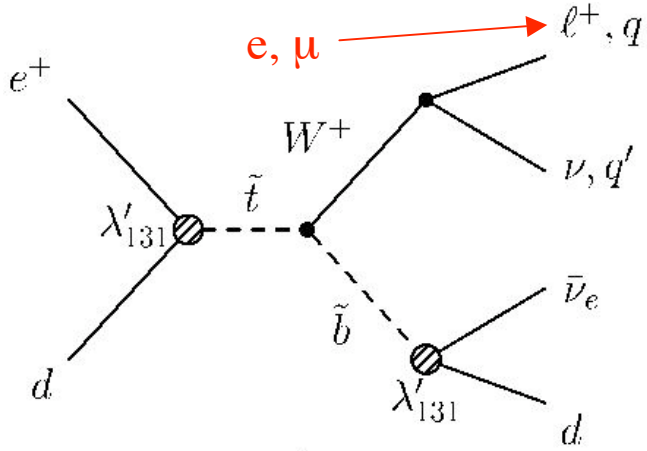




- A complete search for resonant production of squarks of all flavours via the Yukawa coupling λ' has been performed by H1 and ZEUS
- No evidence for squark production found
- At 95% C.L. squarks of all flavours with masses up to 280 GeV excluded for a coupling of electromagnetic strength

Bosonic Stop Decays: Phenomenology

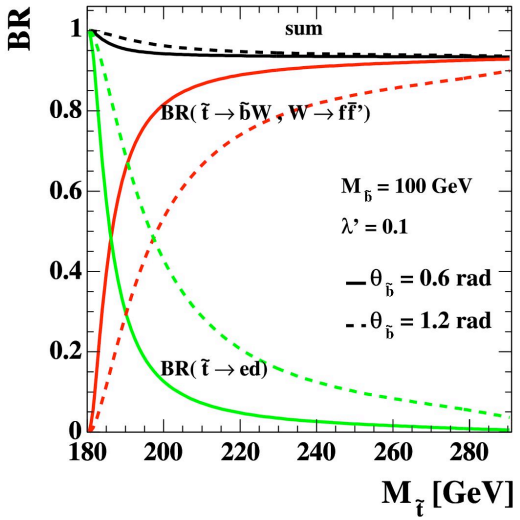
$$W_{\not R_p} \sim \lambda'_{131} e_L \tilde{t}_L \bar{d}_R + \lambda'_{131} \nu_{e,L} \tilde{b}_L \bar{d}_R$$



- Resonant production of a stop quark and the R-parity violating bosonic decay of stop and sbottom quarks via the λ'_{131} coupling - complimentary to previous searches for squark production analysis
- Stop and sbottom quarks assumed the lightest in this model, where $M_{\tilde{t}} > M_{\tilde{b}}$
- Kinematic range of real bosonic decays:

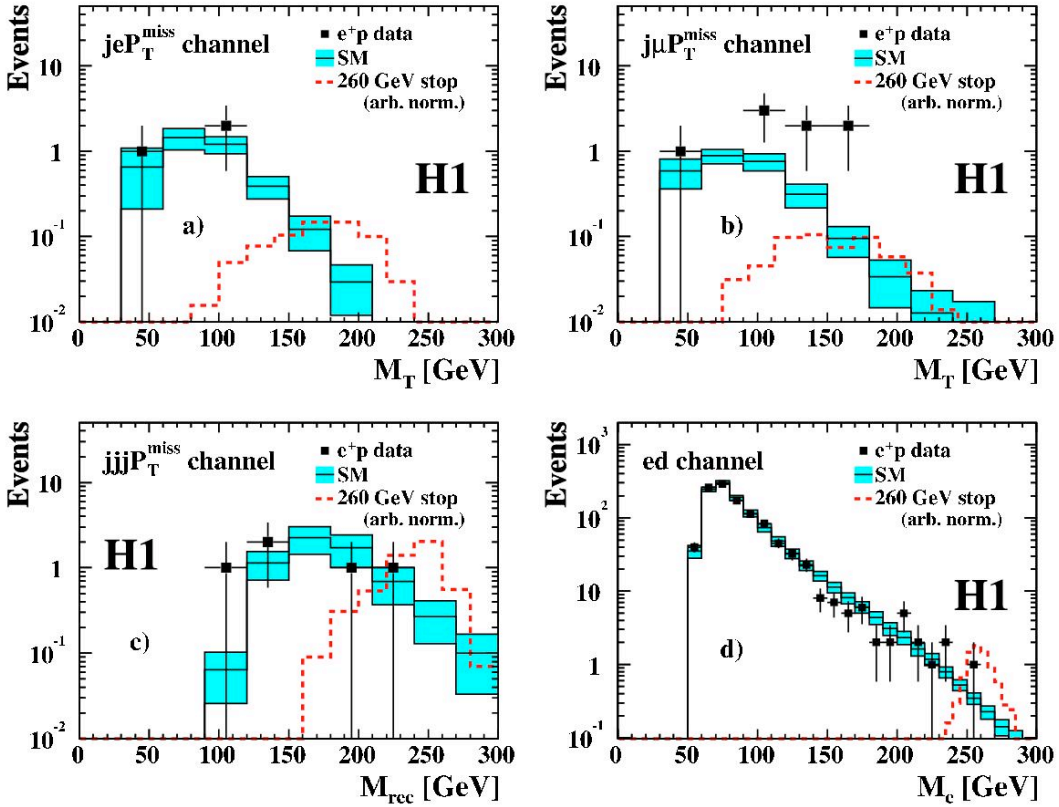
$$M_{\tilde{t}} > M_{\tilde{b}} + M_W$$

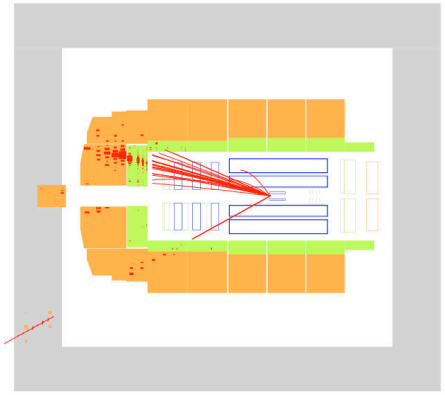
- The decay mode $\tilde{t} \rightarrow ed$ is also analysed, which dominates for $M_{\tilde{t}} \leq M_{\tilde{b}} + M_W$
- Almost full coverage of branching ratios achieved by analysing these 4 channels



Bosonic Stop Decays: Kinematic Selection

Total e^+p Luminosity Analysed: 106 pb^{-1} e^+p





Event Signature:

Jet + lepton + P_T^{miss} or 3 jets + P_T^{miss}

High P_T Leptons seen at HERA!

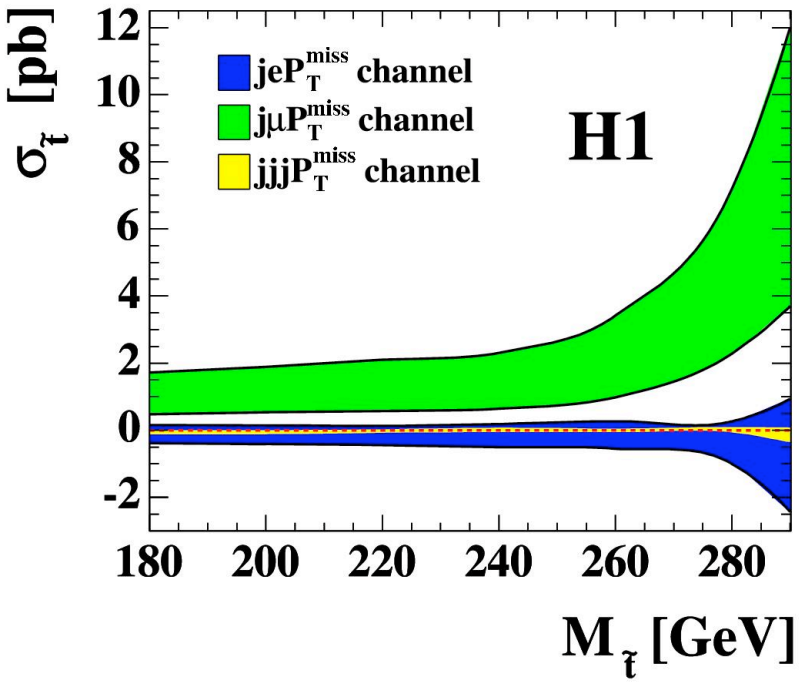
- Bosonic Stop Decay Channels:
  - $P_T^{lepton} > 10$ GeV
  - $P_T^{miss} > 12$ (25) GeV
  - $P_T^{jet(s)} > 10$ (20,15,10) GeV
- R-parity Violating $\tilde{t} \rightarrow ed$ Channel:
  - $P_T^{lepton} > 20$ GeV
  - $P_T^{jet} > 20$ GeV
- Selection efficiencies of 30 - 50%

Slight excess observed in muon channel, but no significant deviation from SM

Stop Production Cross Section

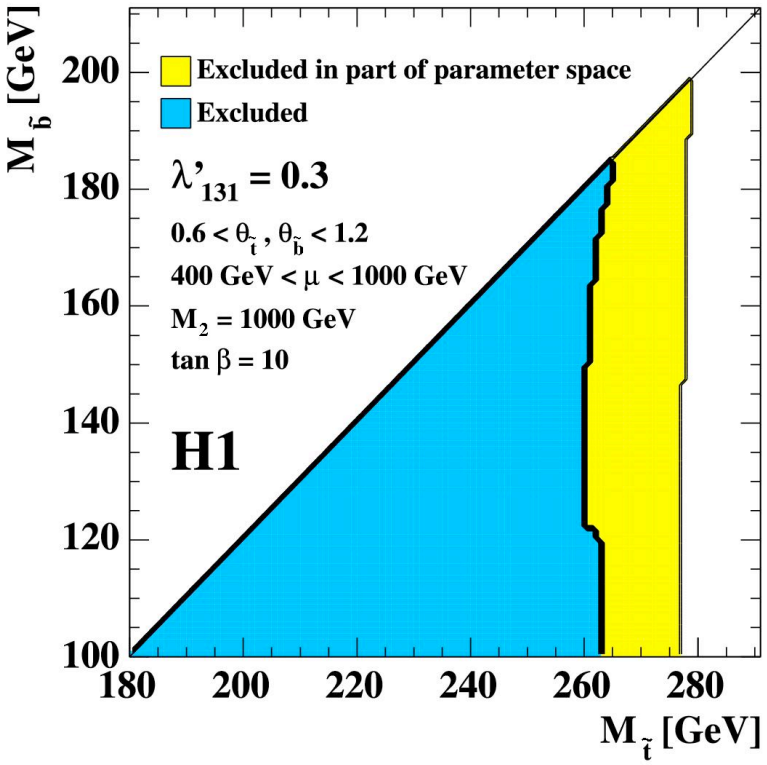
- Assuming the presence of a stop mass, determine an allowed 1 sigma range $\Delta\sigma_{\tilde{t}}$ for the stop production cross section

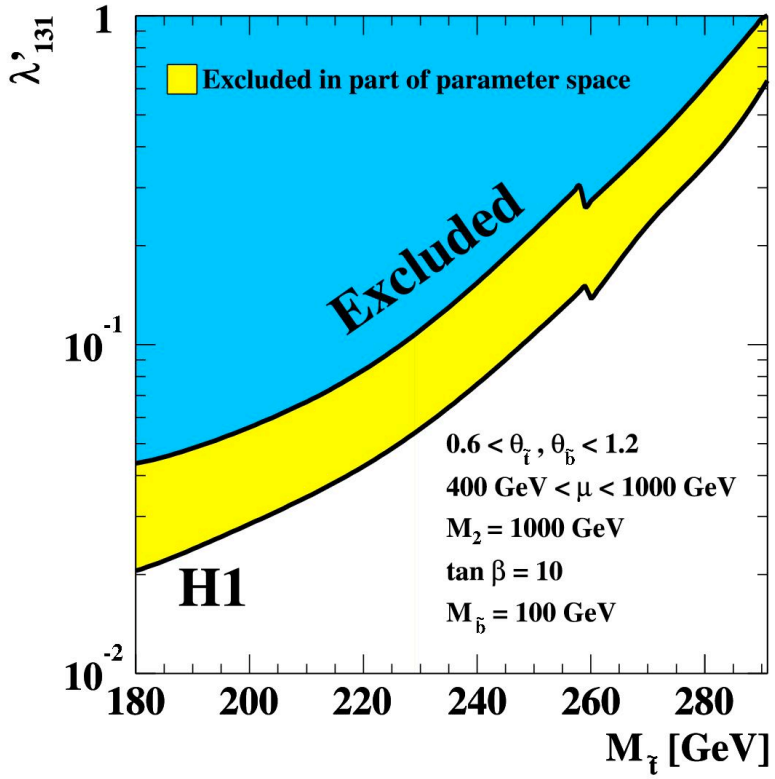
$$\sigma_{\tilde{t}}(M_{\tilde{t}}) = \frac{N_{Data} - N_{SM}}{\varepsilon \cdot BR \cdot \mathcal{L}}$$



- Discrepancy in μjP_T^{miss} channel is not confirmed by other channels
- Probability that observed rate of $jjjP_T^{miss}$ channel fluctuates up to a level compatible with μjP_T^{miss} channel is ~ 1%
- Bosonic stop production does not explain the observed H1 high P_T isolated lepton events

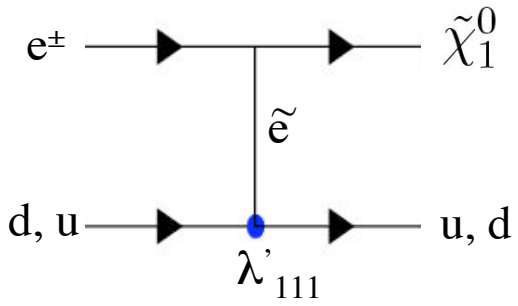
Stop Production Limits

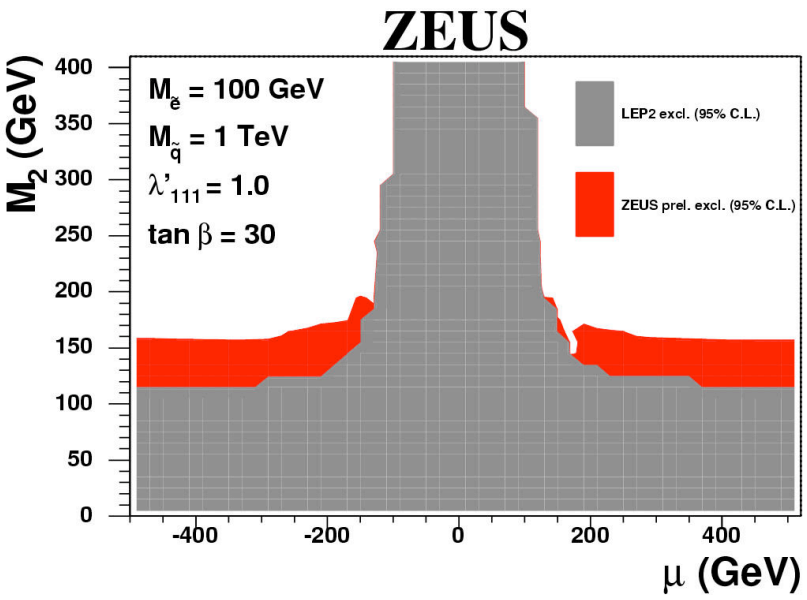




- Perform 5 SUSY parameter scan: $M_{\tilde{t}}$, $M_{\tilde{b}}$, $0.6 < \theta_{\tilde{t},\tilde{b}} < 1.2$, $400 < \mu < 1000$
- For λ'_{131} of electromagnetic strength, stop masses up to 275 GeV are excluded
- For $M_{\tilde{b}} = 100$ GeV, at a $M_{\tilde{t}}$ of 275 GeV, the allowed domain is $\lambda'_{131} \leq 0.3$
- Complementary results to previous HERA searches for squark production

Search for Gaugino Production

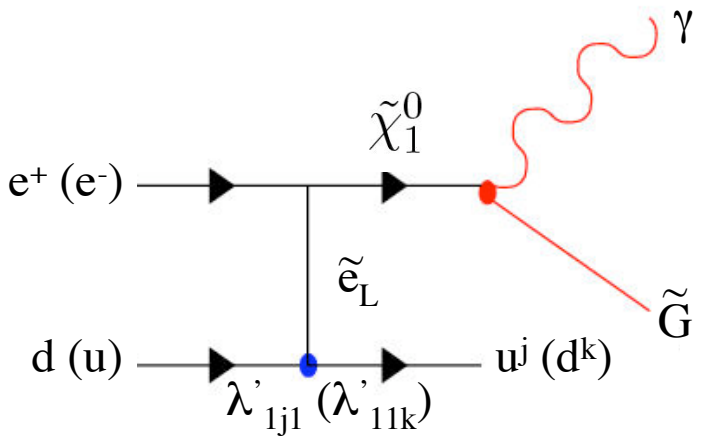




- Search performed by ZEUS for the production of a neutralino $\tilde{\chi}_1^0$ via t channel selectron exchange
- The neutralino subsequently decays via cascade to an electron or positron and quark pair
- Main SM background due to dijet events in NC DIS
- No deviation from the SM observed: perform SUSY parameter scan in the MSSM framework to constrain μ and M_2
- Exclusion limits at 95% C.L. for tanβ = 30, $M_{\tilde{e}}$ = 100 GeV and λ'_{111} = 1.0 are extended with respect to previous limits set by LEP experiments

Light Gravitinos: Phenomenology

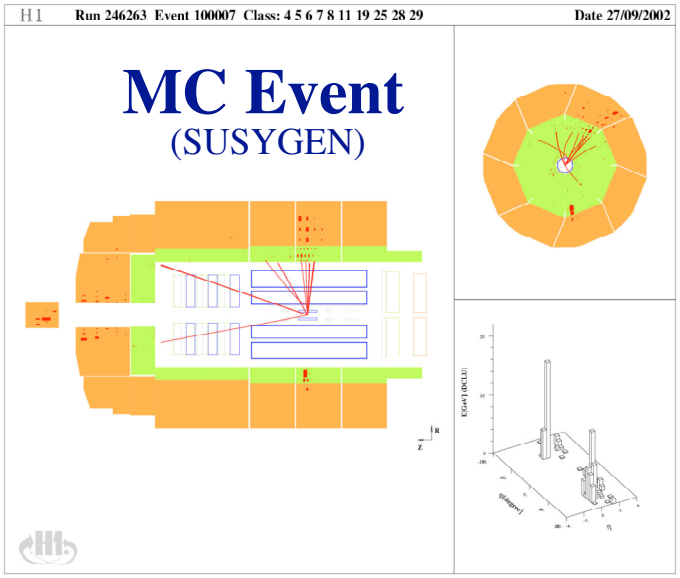
$$W_{\not R_p} \sim -\lambda'_{1jk}\tilde{e}_L u^j_L \bar{d}^k_R$$



- Main difference to other SUSY models is the mass of the Gravitino ($\tilde{G}$), which is small ($< 10^3$ eV) and is the lightest SUSY particle (LSP)
- The single production of a neutralino has been investigated in this model, mediated by selectron exchange (while previous analyses assumed squarks within the kinematic limit)
- The analysis is completely independent of the squark sector
- Different couplings tested with e^+ and e^- data
- GMSB models typically have 6 new parameters compared to the SM:

Λ : Mass scale of SUSY particles	$\tan\beta$: ratio of Higgs vacuum expectation values
M : Mass of "messenger" particles ($m_{\tilde{e}}$, $m_{\tilde{\chi}}$)	sign(μ) : sign of Higgs mixing parameter
N : Number of messenger particles	$\sqrt{F}$: SUSY breaking scale (related to $m_{\tilde{G}}$)

Light Gravitinos: Kinematic Selection

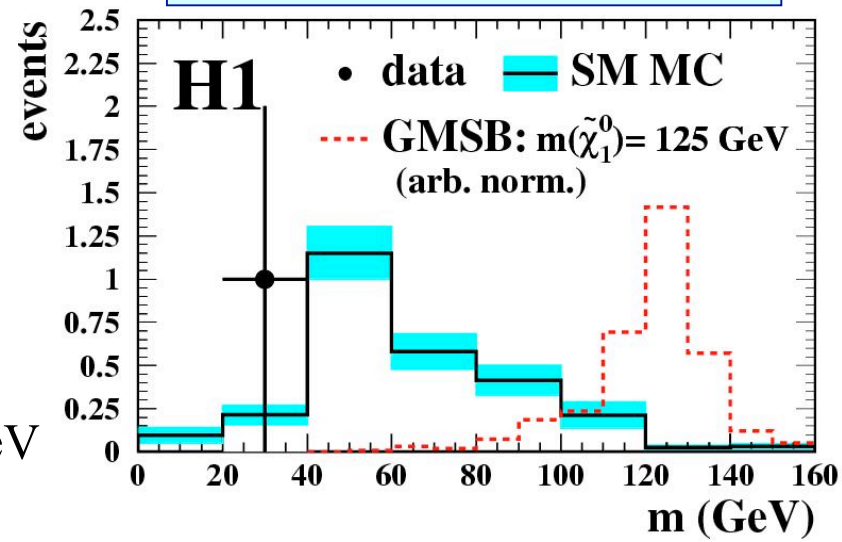


Event Signature:

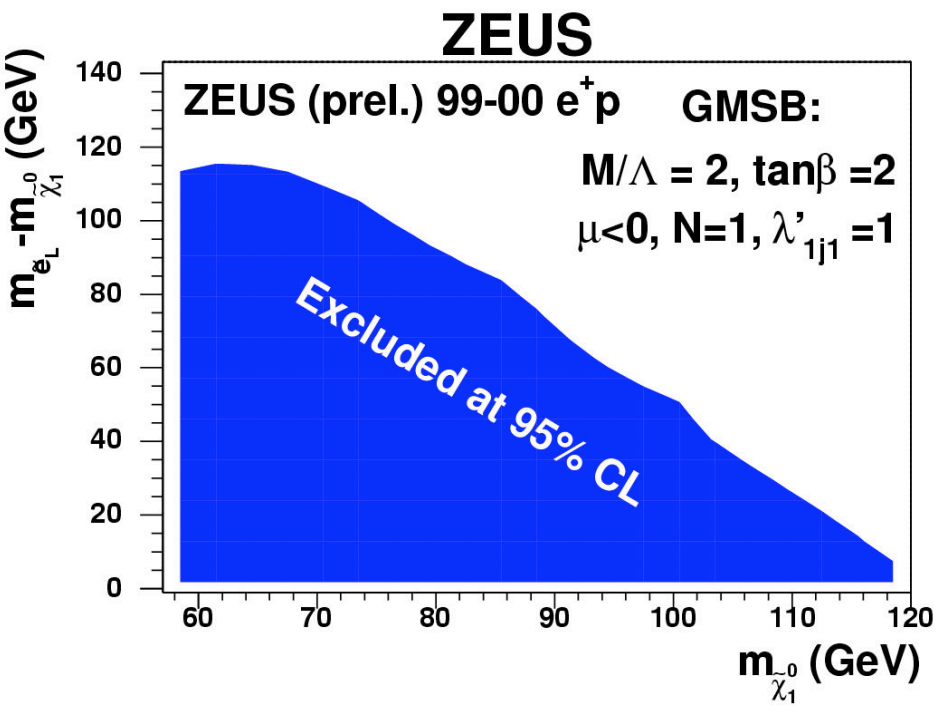
$\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ occurs with unobservably small lifetime: expect photon + jet + P_T^{miss}

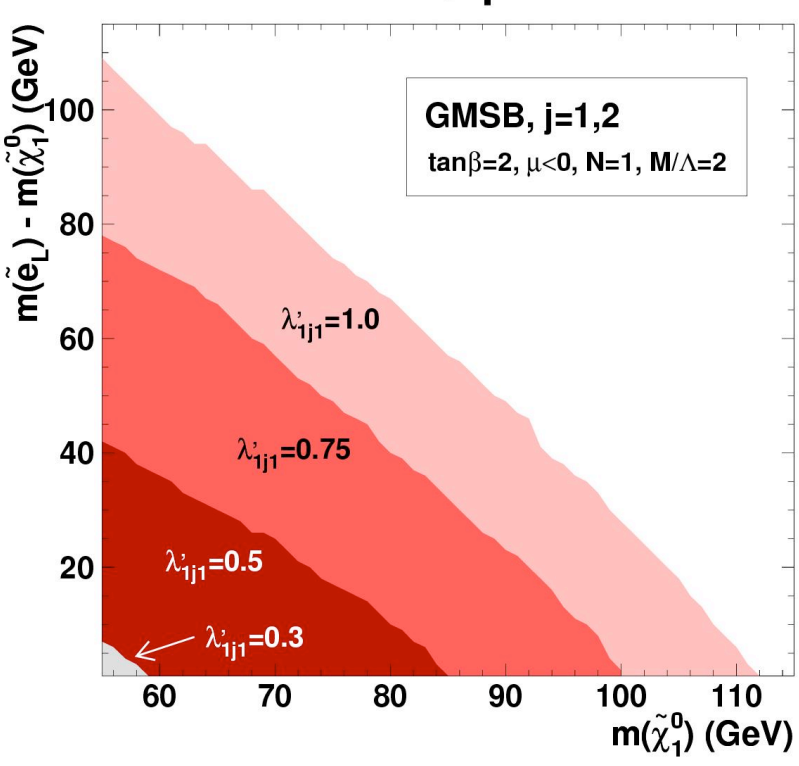
- Main SM background: radiative CC
- Event Selection:
  $P_T^{photon} > 15$ GeV (isolated, no associated track)
  $P_T^{jet} > 5$ GeV
  $P_T^{miss} > 25$ GeV (from Gravitino)
  $\Sigma (E - P_z) > 15$ GeV (against CC DIS)
- Selection efficiencies of 10 - 35%
- e^+p : No candidate observed (1.8 ± 0.2 SM)
- e^-p : One candidate observed (1.2 ± 0.2 SM)
- Assume one non-interacting particle: reconstructed neutralino mass, m = 36 ± 4 GeV

Total Luminosity Analysed:
64 pb^{-1} (e^+p), 14 pb^{-1} (e^-p)



Gravitino Exclusion Limits





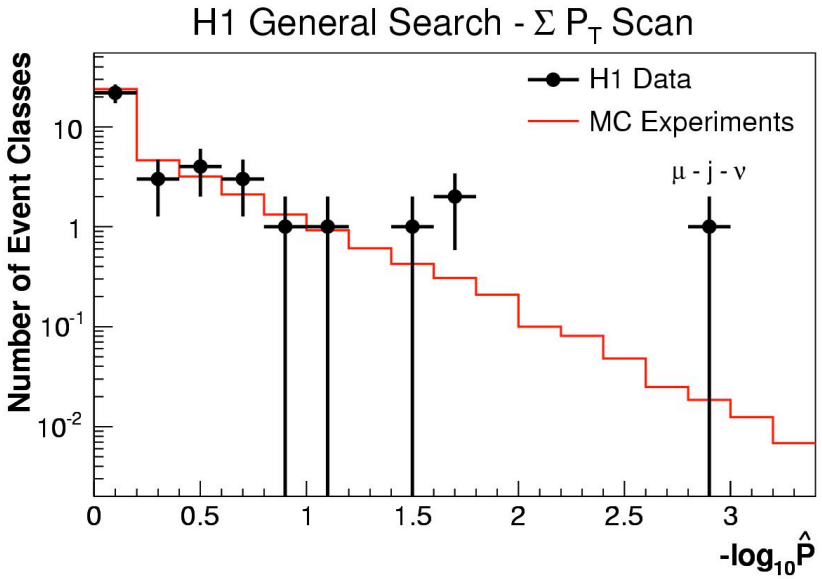
- For small Δm: neutralino masses up ~ 120 GeV are excluded for $\lambda' = 1.0$
- For masses close to 55 GeV, couplings $\lambda'_{1j1} > 0.3$ and $\lambda'_{11k} > 0.5$ are excluded
- First HERA limits on R-parity violating SUSY independent of squark sector

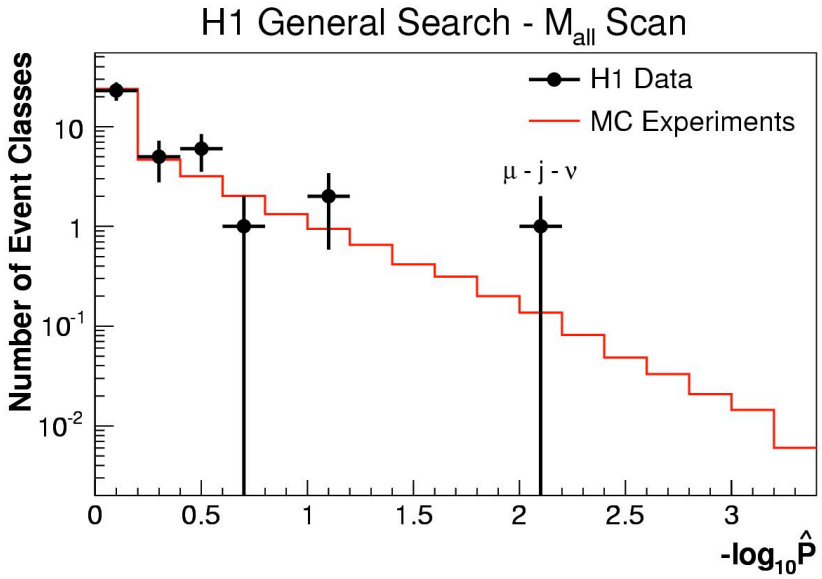
Summary of Results

- Many searches for new physics performed at HERA by the H1 and ZEUS collaborations - including data from the new HERA II phase
- Interesting events observed by H1 containing isolated leptons and missing P_T - but not confirmed by ZEUS - Single top not ruled out!
- Interesting high mass events containing multiple high P_T leptons also observed, but no evidence of Higgs double boson
- No evidence seen in searches for a large selection of exotic particles: leptoquarks, squarks, gauginos, bosonic stop decays and light gravitinos - competitive limits derived on such BSM scenarios, often ruling out particle masses up to 300 GeV
- More incoming data from HERA II expected to resolve the isolated lepton story

Extra Slides

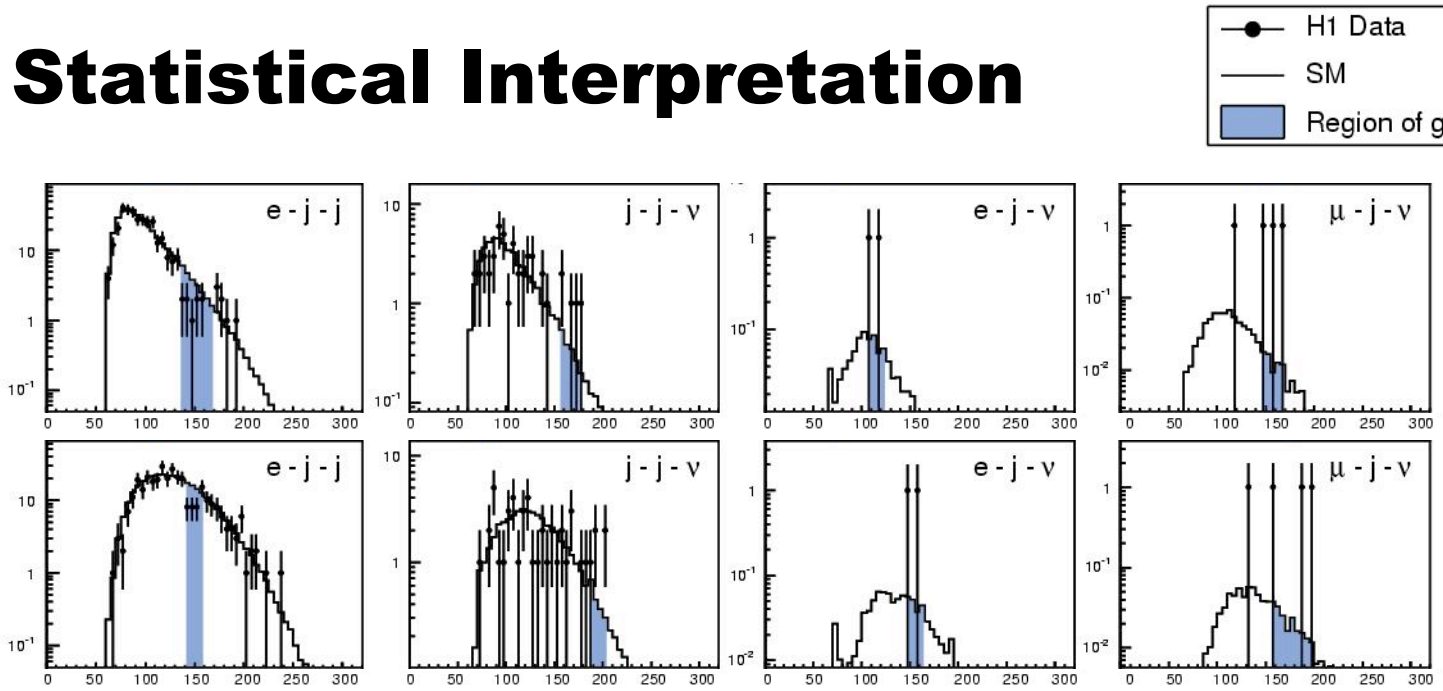
H1 General Search
Statistical Interpretation





- Compare data event classes with prediction with that from many MC experiments, calculated according to the SM expectation
- $\hat{P}$ is then a measure of the significance of the the deviation observed in the data
- In each channel, low values of $-\log_{10}\hat{P}$ indicate good agreement between data/MC
- The global probabilities to find an event class with $\hat{P}$ smaller than that observed in the μ-j-ν channel are 3% (28%) for the ΣP_T (M_T^{all}) distributions

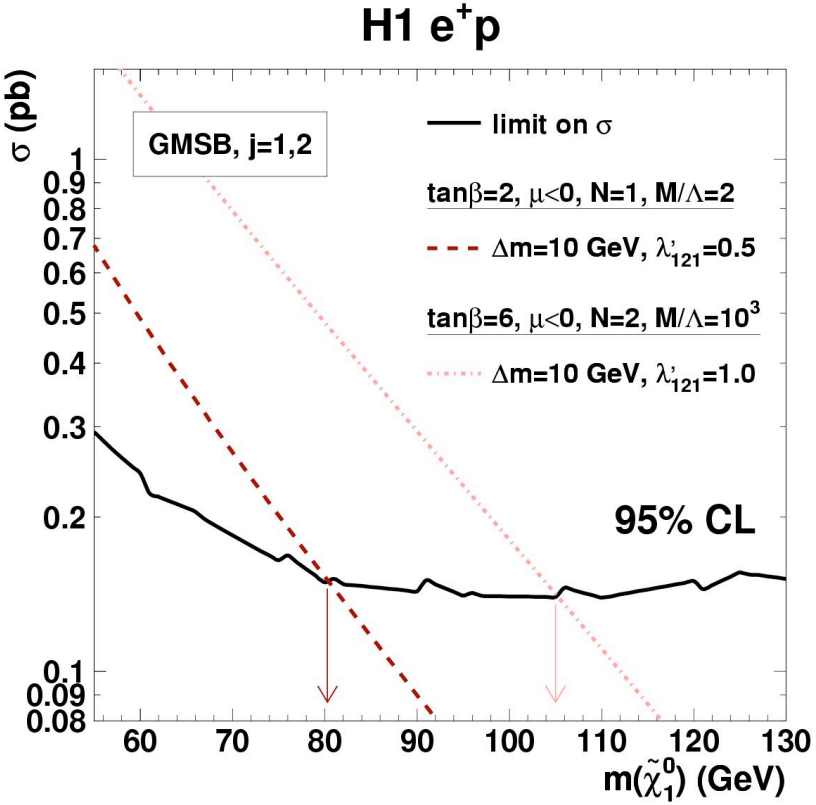
H1 General Search
Statistical Interpretation

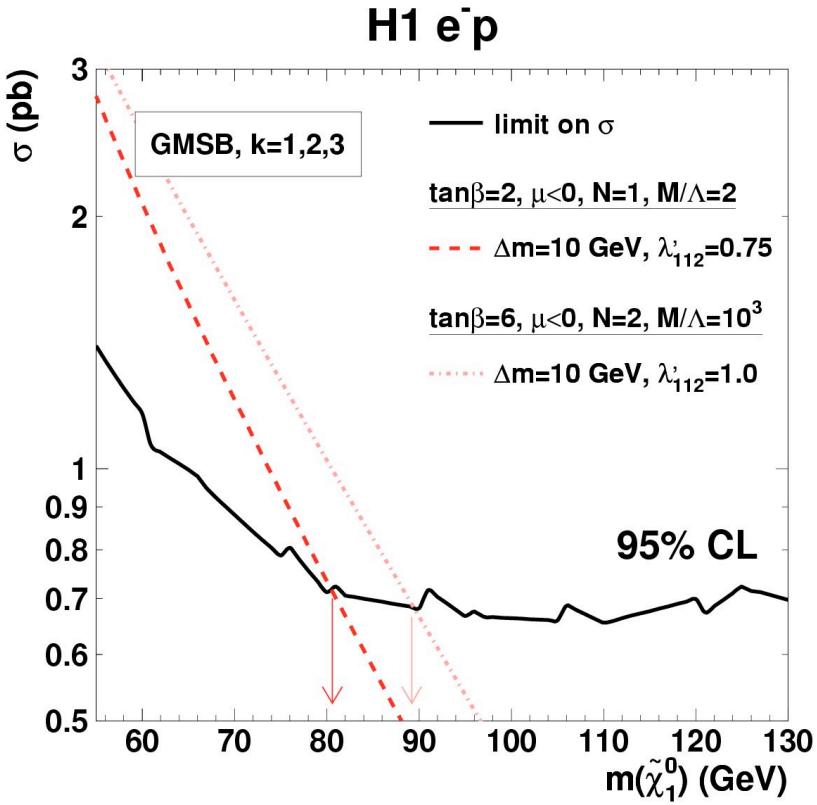


Example Distributions

- Look for deviations in ΣP_T and M_T^{all} distributions
- Determine the region of greatest deviation p_{min} by estimating the probability of upward or downward fluctuations in the distributions
- The method can find narrow resonances and atypical events as well signals spread of large areas of phase space

Gravitino Cross Section Limits





- No significant deviation from SM : derive limits on GMSB model at 95% CL
- Limits less stringent at low neutralino masses due to lower detection efficiency
- For comparison, GMSB cross sections for different couplings λ'_{121} and λ'_{112} with fixed values of tanβ, N and μ