

Searches for New Physics at HERA

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On behalf of the H1 and ZEUS
collaborations

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LISHEP 2009, Rio de Janeiro
January 19th, 2009

- 1 Collider and Experiments
- 2 Inclusive DIS
- 3 Model-Independent Searches
- 4 Model-Based Searches
- 5 Summary

Collider and Experiments

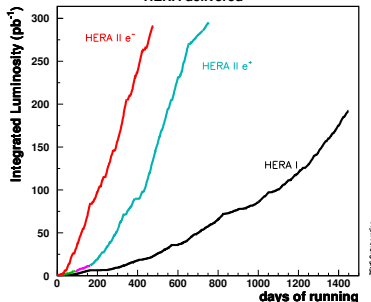
Overview

- 1 Collider and Experiments
 - HERA
 - ep Physics
 - H1 and ZEUS
 - BSM Searches at HERA
- 2 Inclusive DIS
- 3 Model-Independent Searches
- 4 Model-Based Searches
- 5 Summary

HERA *ep* Collider



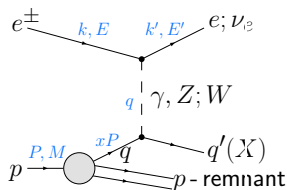
HERA delivered



- World's only *ep* collider, located at DESY Hamburg
- 6.3 km circumference
- Two *ep* collision experiments: H1 and ZEUS
- Operated 1992–2007, upgrade in 2000/01
→ luminosity, detectors
- Almost 0.5 fb^{-1} /experiment

ep Physics: Deep Inelastic Scattering (DIS)

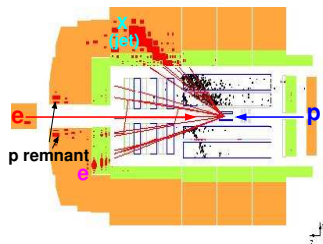
Dominant process at high transverse momentum (sensitive to new physics):



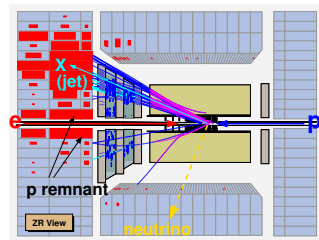
virtuality of exchanged boson: $Q^2 = -q^2$

fractional e-energy loss: $y = \frac{q \cdot P}{k \cdot P}$

p-momentum fraction carried by quark: $x = \frac{Q^2}{2yME}$



neutral current (NC), $Q^2 = 41000 \text{ GeV}^2$

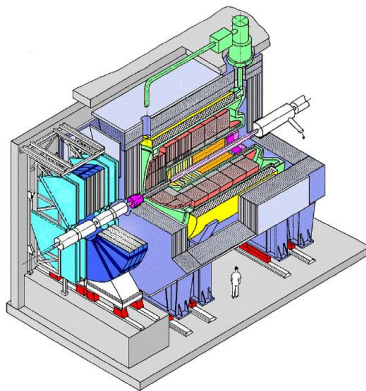


charged current (CC), $Q^2 = 16400 \text{ GeV}^2$

H1

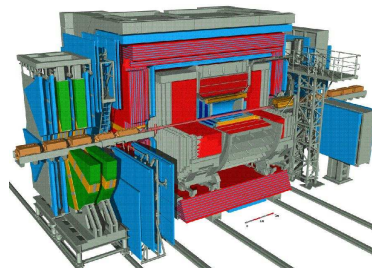
ZEUS

Goal: Identify and measure e , μ , jets, γ , p_T^{miss}



$e \rightarrow$ $\leftarrow p$

Liquid Argon Calorimeter
optimised for scattered lepton



$e \rightarrow$ $\leftarrow p$

Uranium-Scintillator Calorimeter
optimized for hadronic final state

Beyond the Standard Model Searches at HERA

Inclusive DIS

- NC: quark radius, contact interactions, extra dimensions
- CC: polarisation dependence

Model-Independent Searches

- Isolated leptons, missing p_T
- High- p_T multileptons
- General searches

Model-Based Searches

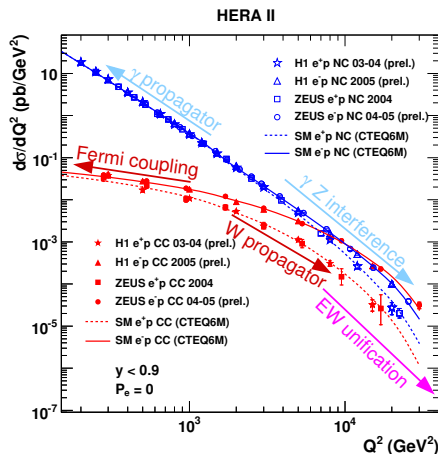
- Leptoquarks, LFV
- Excited leptons
- Single top production
- SUSY
- Magnetic monopoles

Inclusive DIS

Overview

- 1 Collider and Experiments
- 2 Inclusive DIS**
 - High Q^2 Cross Sections
 - Polarisation Dependence of Charged Current Cross Sections
 - Quark Structure
 - Contact Interactions
 - Extra Dimensions
- 3 Model-Independent Searches
- 4 Model-Based Searches
- 5 Summary

High Q^2 Cross Sections



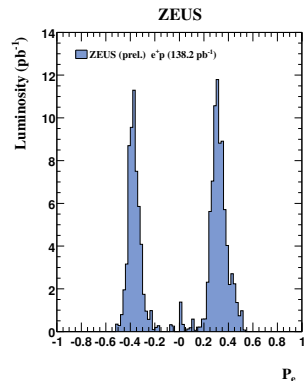
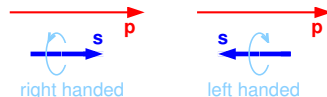
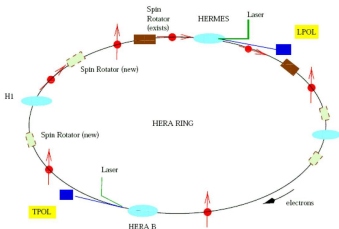
- NC: γ/Z^0 exchange
- CC: W^\pm exchange

$$\frac{d\sigma}{dQ^2} \propto \text{propagator}^2$$

- γ propagator $\propto \frac{1}{Q^2}$
- W propagator $\propto \frac{1}{M_W^2 + Q^2}$
- NC: γZ^0 interference
- For high Q^2 cross sections get similar
→ Electroweak unification
- Excellent agreement with SM, new physics would cause deviations at high Q^2

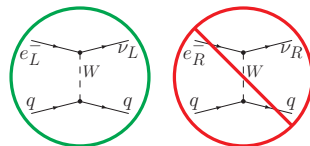
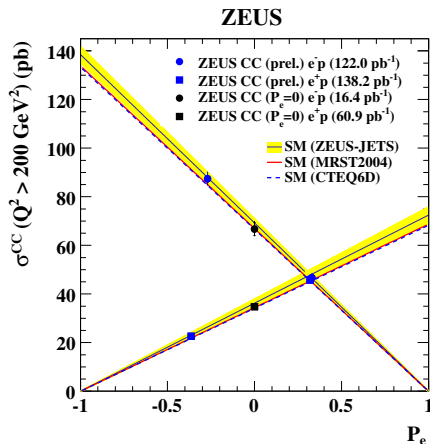
Polarised e^\pm

- Transverse polarisation of e^\pm beam by Sokolov-Ternov effect
→ No effect on physics
- Longitudinal polarisation by spin rotators at the experiments
- Polarisation typically 30% – 40%
- Monitoring by compton backscattering of laser beams



$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

Polarisation Dependence of CC Cross Sections

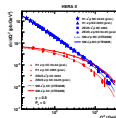
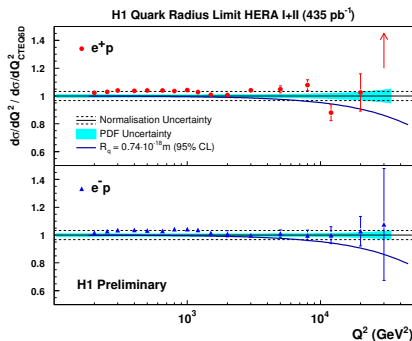


- Total cross sections for charged current DIS should depend linearly on longitudinal polarisation, going to zero for $P_{e^+} = -1$ and $P_{e^-} = 1$
- No deviation from Standard Model found

Quark (Sub)Structure

Finite quark size R_q (RMS of electroweak charge distribution)
 \Rightarrow NC cross section modified by form factor:

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot \left(1 - \frac{R_q^2}{6} Q^2\right)^2$$



\rightarrow Ratio NC to SM

95% CL limits:

ZEUS $R_q < 0.67 \cdot 10^{-18} \text{m}$

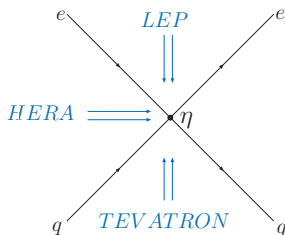
H1 $R_q < 0.74 \cdot 10^{-18} \text{m}$

Quarks radius $< \frac{1}{1000}$ proton radius

Contact Interactions

Some new interactions at higher scale $\Lambda \gg \sqrt{s}$ can be effectively described as low-energy 4-fermion contact interactions with coupling $\eta \propto \pm \Lambda^{-2}$.

History: Fermi's 4-fermion coupling ($\eta \propto g_F \propto \frac{g^2}{M_W^2}$), later: W boson



Examples:

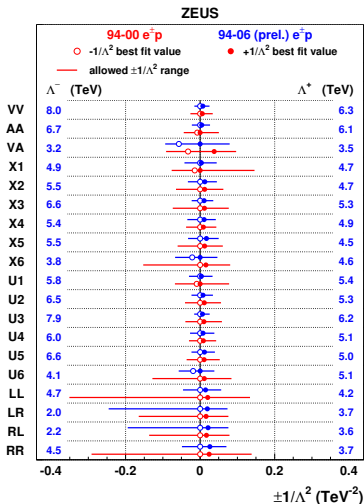
- Exchange of extra gauge bosons
- Exchange of leptoquarks or squarks
- Compositeness
- Gravitational effects from extra dimensions

Different helicity and flavour structures in the Lagrangian

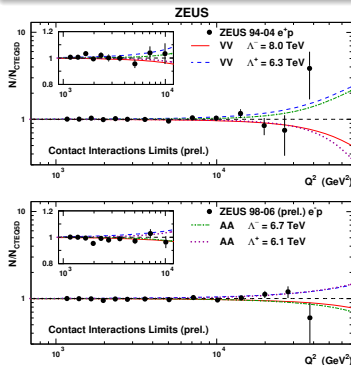
$$\mathcal{L}_{CL} = \sum_{\alpha, \beta=L,R} \sum_{q=u,d} \eta_{\alpha\beta}^{eq} (\bar{e}_{\alpha} \gamma^{\mu} e_{\alpha}) (\bar{q}_{\beta} \gamma_{\mu} q_{\beta})$$

Contact Interactions

Limits for 19 Different Coupling Structures

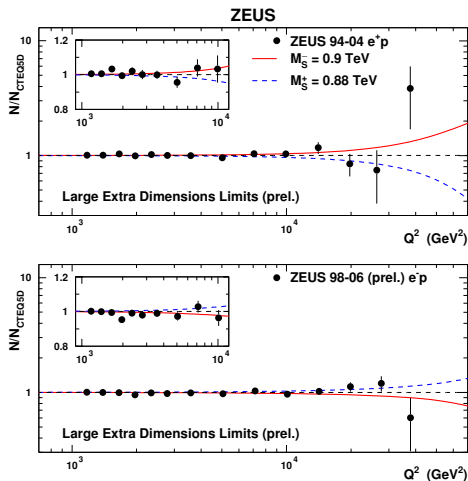


| | η_{LL} | η_{LR} | η_{RL} | η_{RR} |
|-----|-------------|-------------|-------------|-------------|
| VV | $+\eta$ | $+\eta$ | $+\eta$ | $+\eta$ |
| AA | $+\eta$ | $-\eta$ | $-\eta$ | $+\eta$ |
| ... | ... | ... | ... | ... |



ZEUS (94-06) $\Lambda = 2.0 - 8.0$ TeV
H1 (94-00) $\Lambda = 1.6 - 5.5$ TeV

Extra Dimensions



- Arkani-Hamed-Dimopoulos-Dvali: $D = 4 + n$ dimensions
- Extra dimensions compactified to radius R
- Usual Planck scale M_p only effective scale arising from the fundamental Planck scale, $M_p^2 \propto R^n M_S^{2+n}$
- Gravity comparable to other interactions
- $\eta_G = \lambda/M_S^4$, (coupling $\lambda \approx \pm 1$)
- 95% CL limit:
 $M_{S\pm} > 0.9 \text{ TeV}$

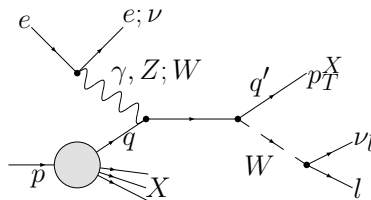
Model-Independent Searches

Overview

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 - Isolated Leptons
 - Multi-Leptons
 - General Search
- 4 Model-Based Searches
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Isolated Leptons and Missing p_T

- Reminder: in DIS *either* isolated lepton *or* missing p_T
- Events with isolated high energetic leptons and missing transverse momentum are very rare
- Main SM source: Single W production ($\sigma \approx 1.3 \text{ pb}$)



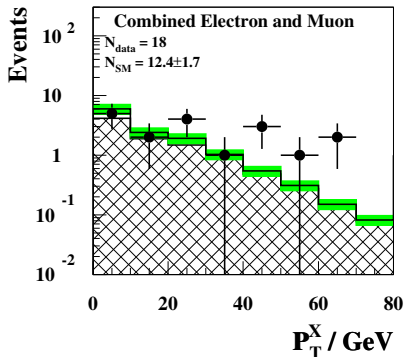
Excess at high hadronic transverse momentum $p_T^X \rightarrow$ new physics?

Isolated Leptons and Missing p_T

H1 Excess

H1 saw excess at high transverse momentum p_T^X in e^+p , nothing in e^-p :

H1 HERA-I

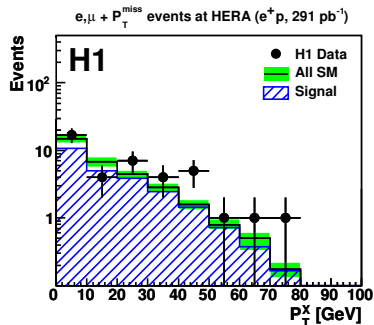


$p_T^X > 25 \text{ GeV}$:

Observed: 10

Expected: 2.92 ± 0.49

H1 all HERA



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

Observed: 17

Expected: 8.0 ± 1.3

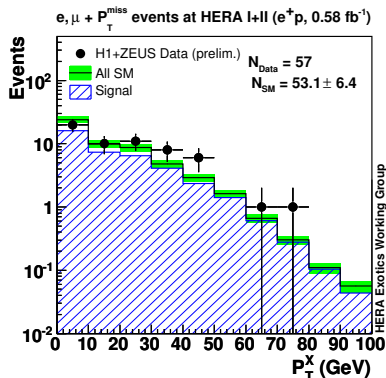
Isolated Leptons and Missing p_T

H1 and ZEUS Combined

- ZEUS never saw this excess
- No excess in e^-p either
- H1 and ZEUS have made a combined analysis based on a common phase space
- Combination of H1 and ZEUS data eliminates excess
→ statistical fluctuation(?)

W^\pm production cross section:

| | |
|------|--|
| SM | $1.2 \pm 0.2 \text{ pb}$ |
| ZEUS | $0.89^{+0.25}_{-0.22}(\text{stat.}) \pm 0.10(\text{syst.}) \text{ pb}$ |
| H1 | $1.23 \pm 0.25(\text{stat.}) \pm 0.22(\text{syst.}) \text{ pb}$ |



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

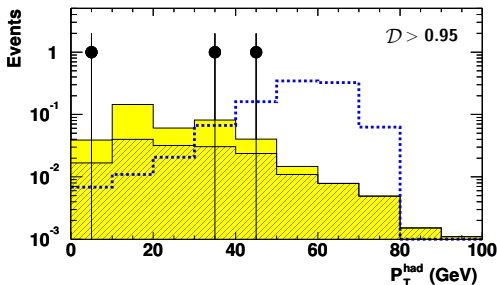
Observed: 23

Expected: 14.6 ± 1.9

Isolated Taus and Missing p_T

ZEUS Excess

ZEUS saw excess at high transverse momentum p_T^X in e^+p :

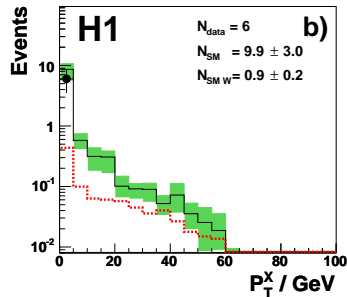


ZEUS HERA-I data:

Observed: 3

Expected: 0.40 ± 0.13

ZEUS analysis of full HERA data ongoing.



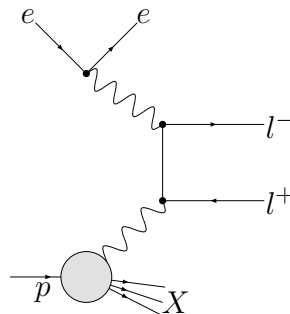
H1 full HERA data:

Observed: 6

Expected: 9.9 ± 3.0

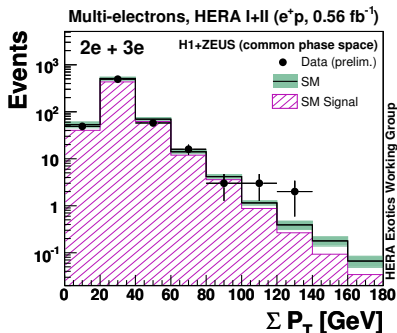
High- p_T Multi-Leptons

- Main mechanism: Bethe-Heitler
($\gamma\gamma \rightarrow e^+e^-$)
→ precisely calculable in QED
- Steep fall-off with p_T
Deviations could hint to new physics
- Search for events with at least 2
isolated high- p_T leptons
- Topologies: ee , eee , $e\mu$, $\mu\mu$, $e\mu\mu$



High- p_T Multi-Leptons

Multi-Electrons H1 and ZEUS Combined



No significant excess in combination.

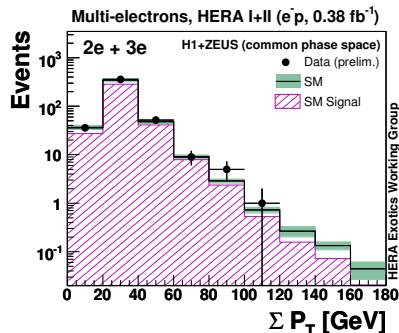
$\Sigma p_T > 100 \text{ GeV}$:

Observed:

5

Expected:

1.82 ± 0.21



$\Sigma p_T > 100 \text{ GeV}$:

Observed:

1

Expected:

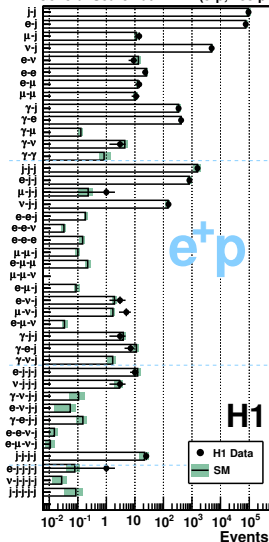
1.19 ± 0.14

General Search

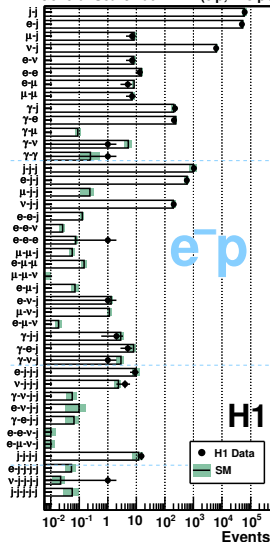
Method

- Look for objects (e , μ , γ , jet, ν) with $p_T > 20$ GeV
- Count events in distinct event classes
- Compare to SM
- No significant deviations (largest in ee)
- Excellent understanding of HERA data

H1 General Search at HERA (e^+p , 285 pb^{-1})

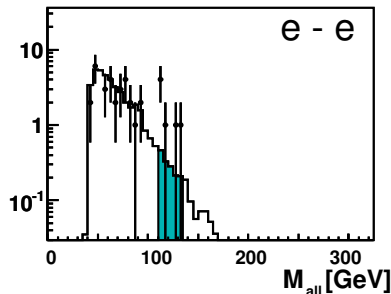
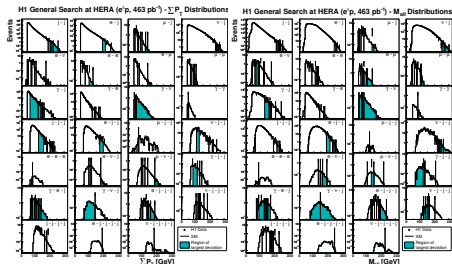


H1 General Search at HERA (e^-p , 178 pb^{-1})

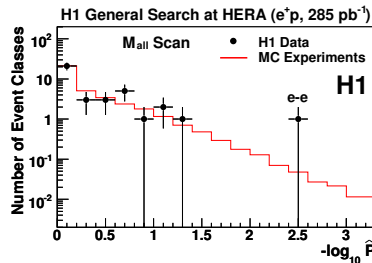


General Search

Distributions and Significance



- Mass and $\sum p_T$ distributions
 - statistical search algorithm
 - region of greatest deviation ($e-e$)
 - significance?
 - quantify as probability
- Probability for the given number of event classes with deviations: 12%



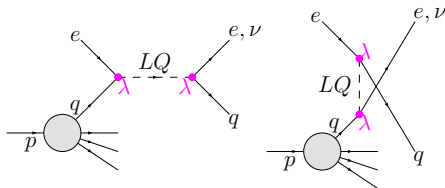
Model-Based Searches

Overview

- 1 Collider and Experiments
- 2 Inclusive DIS
- 3 Model-Independent Searches
- 4 Model-Based Searches**
 - Leptoquarks
 - Excited Leptons and Quarks
 - Single Top
 - R -Parity Violating SUSY
 - Magnetic Monopoles
- 5 Summary

Leptoquarks: The Buchmüller-Rückl-Wyler Model

- Scalar or vector color triplet bosons
- Fermion number $F = L + 3B = 0, 2$
- Valence quarks in p : $F = 0(2)$ production preferred for $e^+p(e^-p)$
- SM symmetries conserved
- Flavour diagonal (no FCNC)
- 7 scalar and 7 vector leptoquarks couple to $e_L q$ or $e_R q$
- 4 of these leptoquarks couple also to νq
- Resonant production in s channel or interaction in u channel



- Contact interaction description at high masses
- Single events indistinguishable from NC/CC

Parameters

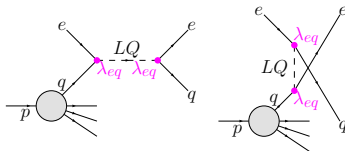
Coupling λ , mass M_{LQ}

Leptoquarks

1st Generation, No Lepton Flavour Violation

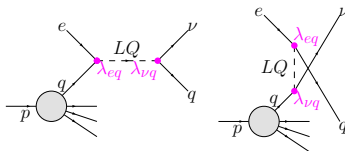
NC channel

e, jet

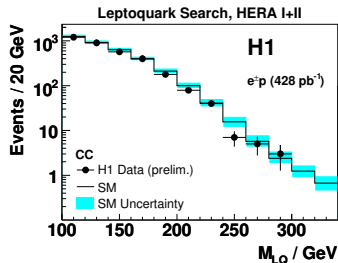
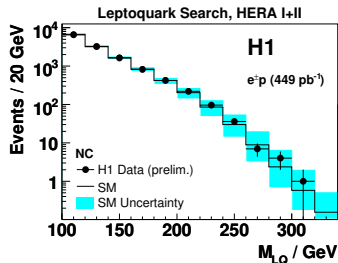


CC channel

$p_T^{\text{miss}}, \text{jet}$



Resonant production only for $M_{LQ} = x\sqrt{s}$



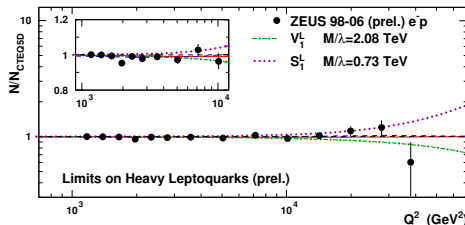
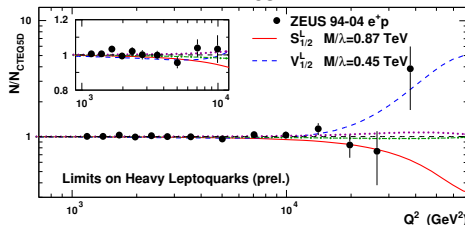
Leptoquarks

Limits

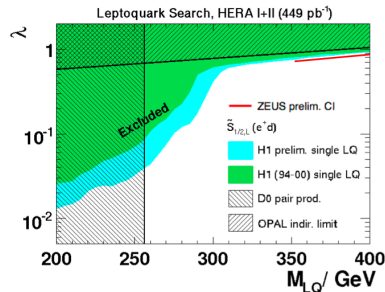
Heavy leptoquarks: contact interaction

(only sensitive to M_{LQ}/Λ)

ZEUS



- No deviation from Standard Model found
→ limits on M_{LQ}/λ

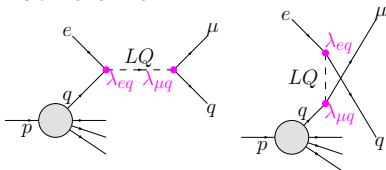


For e.m.-strength coupling:
 $M_{LQ} \lesssim 300 \text{ GeV}$ excluded.

Leptoquarks: 1st and 2nd Generation, with LFV

- Via leptoquark exchange also flavour violation can happen

Muon-channel:

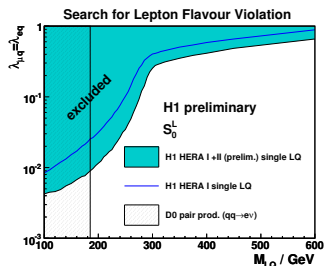
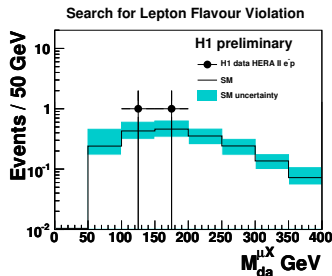


For e.m.-strength coupling

$$\lambda_{eq} = \lambda_{e\mu} = 0.3:$$

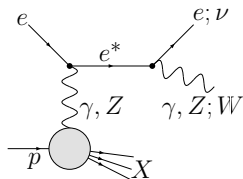
$F = 2$ LQs with

$M_{LQ} \lesssim$ up to 430 GeV excluded.

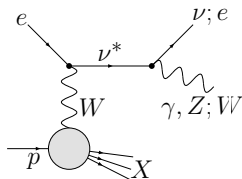


Excited Leptons and Quarks

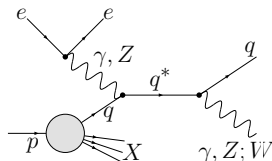
- Models with composite leptons and quarks provide explanations for three-family structure and mass hierarchy
- Allow excited states for then not-quite-so-fundamental fermions



Excited electrons



Excited neutrinos



Excited quarks

Effective Lagrangian

$$\mathcal{L}_{\text{int.}} = \frac{1}{2\Lambda} \bar{F}_R^* \sigma^{\mu\nu} \left[g f \frac{\tau^a}{2} W_{\mu\nu}^a + g' f' \frac{Y}{2} B_{\mu\nu} + g_s f_s \frac{\lambda^a}{2} G_{\mu\nu}^a \right] F_L + \text{h.c.}$$

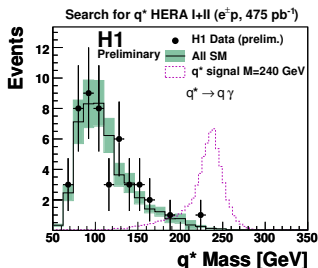
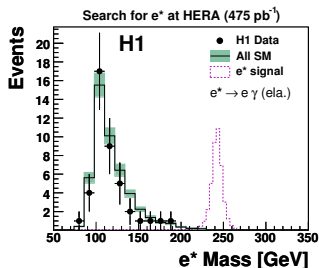
Parameters

Couplings

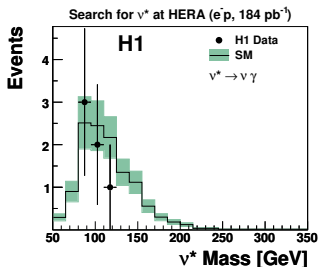
 f, f' Scale Λ

Excited Leptons and Quarks

Mass Spectrum

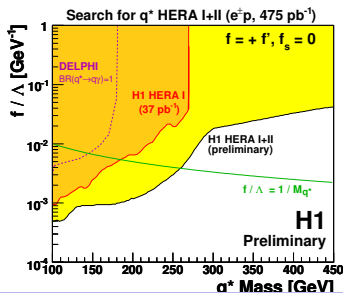
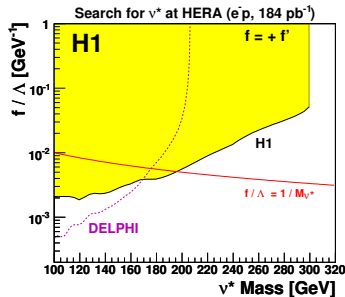
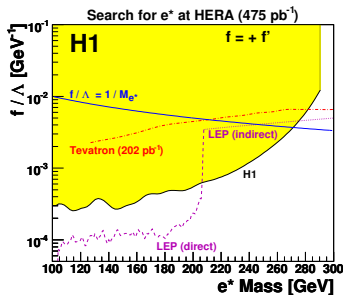


f^* signal for
 $M_{f^*} = 240 \text{ GeV}$
 (arbitrary
 normalization)



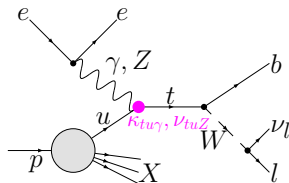
- Other decay channels also investigated (not shown here)
- No excess in any channel
- Limits were derived

Excited Quarks and Leptons: Limits



- Derived mass-dependent limits on ratio of the coupling f to the compositeness scale Λ
- Shown is case $f = f'$ (other limits also calculated)
- $f_5 = 0$ (else no sensitivity), complementary to Tevatron

Single Top

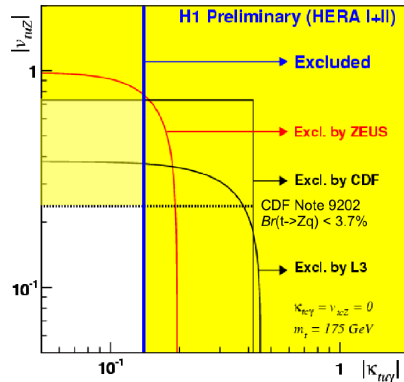


- Single top production in SM kinematically possible
... but cross section $< 1 \text{ fb}$
- FCNC interactions for top in some BSM theories
 - Magnetic coupling $\kappa_{t\gamma}$
 - Anomalous t production sizable

Parameters

Coupling $\kappa_{t\gamma}$

Multi-variate discriminant method:



95%-CL upper limit: $\kappa_{t\gamma} < 0.14$

R-Parity Violating SUSY

Overview

R parity

$$R_P = (-1)^{3(B-L)+2S} = \begin{cases} +1 & \text{for SM particles} \\ -1 & \text{for SUSY particles} \end{cases}$$

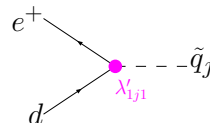
- Multiplicative, discrete
- R_P no mandatory symmetry, possibly accidental symmetry of SM

R_P violation

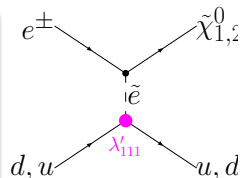
- Additional trilinear terms in superpotential (ingredient of SUSY-Lagrangian):

$$W_{\text{RPV}} = \lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k + \dots$$
- Single-production of superpartners
- Lepton/baryon number violation

RPV examples:



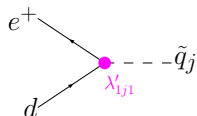
Squark production



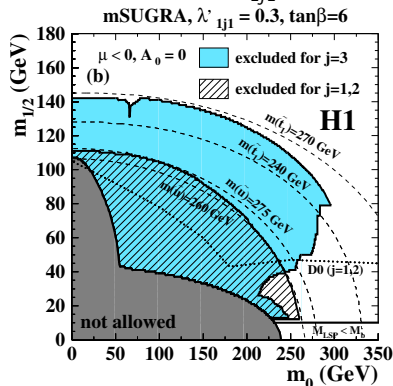
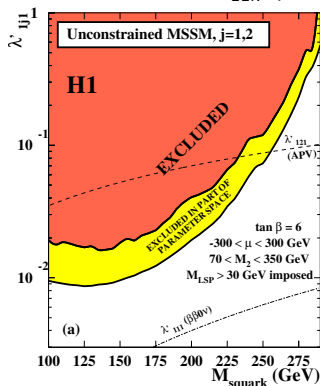
Gaugino production

R-Parity Violating SUSY

Squark Searches

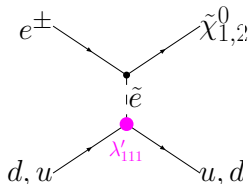


- Resonantly produced squarks decay (RPV or gauge coupling) \rightarrow Many final states, various combinations of e, μ, ν, q
- Limits derived in “phenomenological MSSM” and mSUGRA λ'_{11k} (not shown) limits very similar to λ'_{1j1} limits



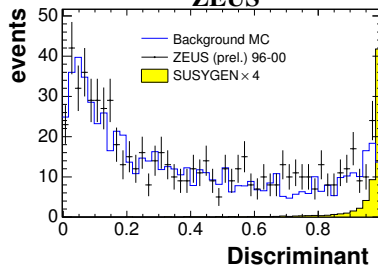
R-Parity Violating SUSY

Gaugino Search

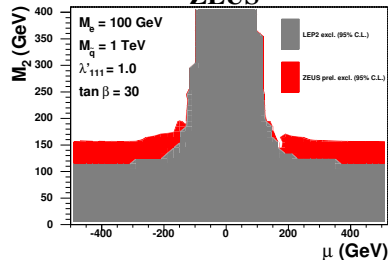


- Independent of squark masses
- Gaugino decay via $\tilde{e}/\tilde{\nu}$ to $qqe/qq\nu$
- Signature: 3 jets + e or p_T^{miss}
- Discriminant method for S/B optimisation

ZEUS

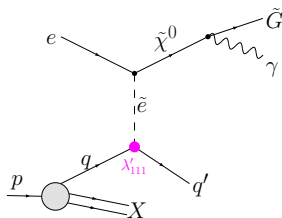


ZEUS

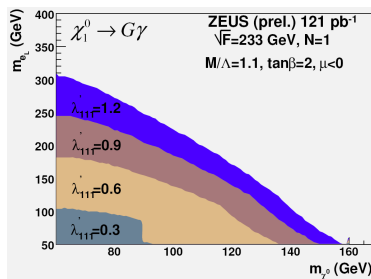
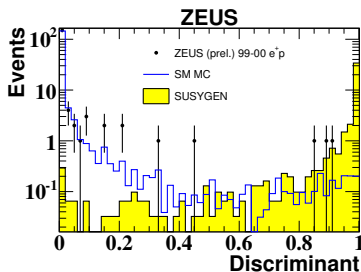


R-Parity Violating SUSY

Gravitino Search

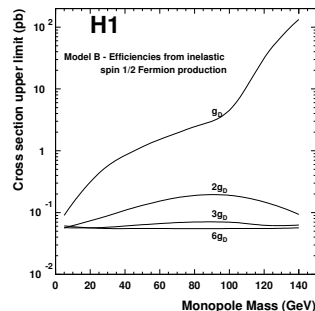
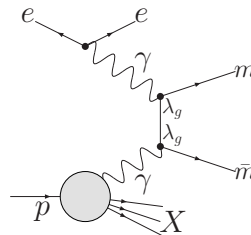
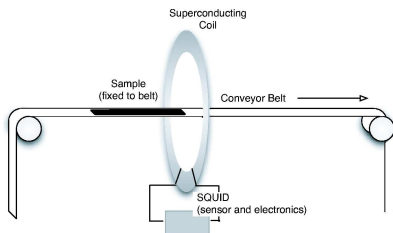


- SUSY-breaking model: GMSB (gravitino \tilde{G} is LSP)
- Gaugino decay to $\gamma\tilde{G}$
- Light gravitino behaves like a neutrino
- Signature: γ , jet, p_T^{miss}
- Discriminant method for S/B optimisation



Magnetic Monopoles

- Dirac monopoles with large magnetic charge \rightarrow highly ionizing
- $\lambda_D = \frac{g_D}{\sqrt{4\pi}}$
- Predicted to be light by some models
- Could be trapped in beampipe (AI)
- 1994-97 beampipe was cut into strips and passed through superconducting coil



Summary

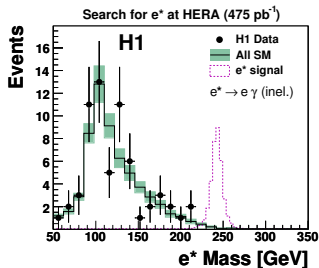
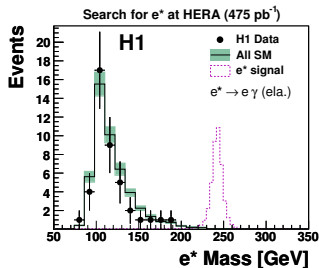
- HERA finished data taking two years ago
- Many searches for physics beyond the Standard Model:
 - Quark structure
 - Contact interactions
 - Extra dimensions
 - Leptoquarks
 - Excited leptons and quarks
 - Single top
 - R -Parity violating SUSY
 - Magnetic monopoles
- No evidence for BSM physics → strong limits
- In inclusive searches,
 - NC cross sections
 - CC cross sections
 - Isolated leptons
 - Multiple leptons
 - General topologies
- No significant deviations from SM
- Some final analyses and combination efforts still ongoing

Backup Slides

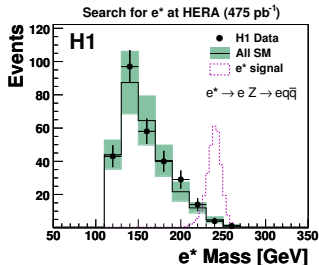
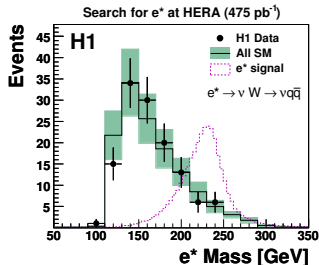
Backup slides

► [Back to title](#)

Excited Electrons: Mass Spectrum

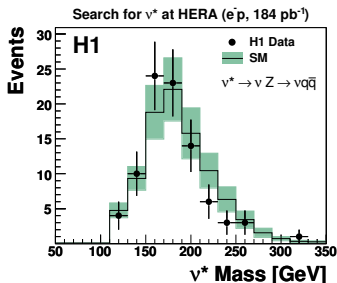
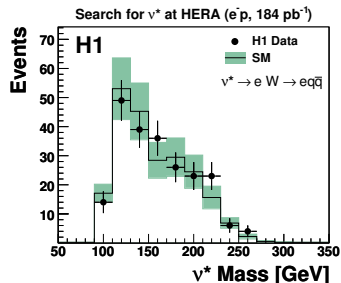
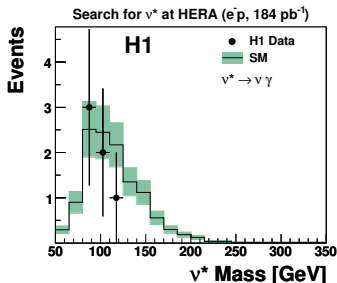


e^* signal for
 $M_{e^*} =$
 240 GeV
 (arbitrary
 normalization)



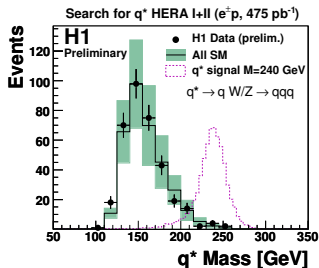
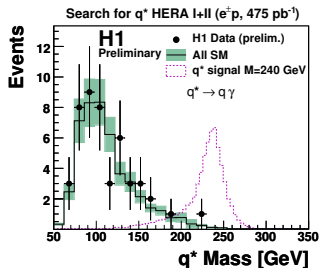
No excess
 → set limits

Excited Neutrinos: Mass Spectrum

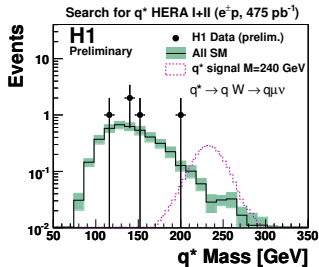
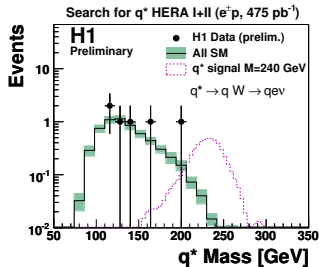


- Good description of SM
- No excess in any of the neutrino channels
- Set limits

Excited Quarks: Mass Spectrum

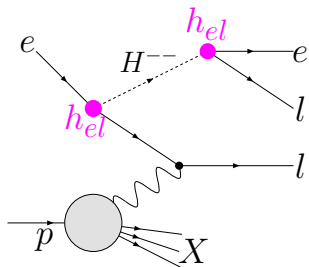


q^* signal for
 $M_{q^*} =$
 240 GeV
 (arbitrary
 normalization)



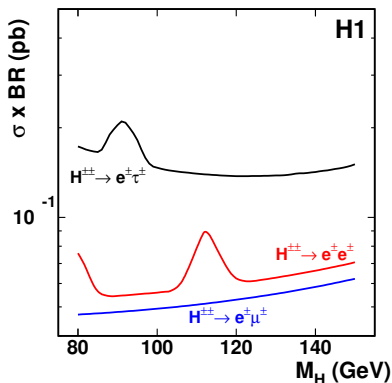
No excess
 \rightarrow set limits

Doubly Charged Higgs



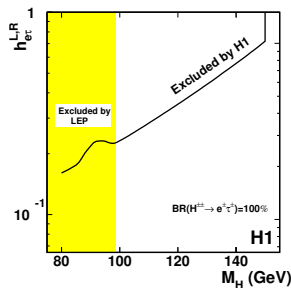
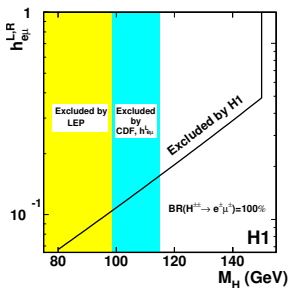
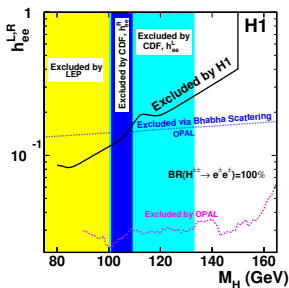
- In some BSM theories doubly-charged higgs
- Yukawa couplings $h_{ll}^{R,L}$ a priori unknown

95%-CL upper limits on cross section for $H^{\pm\pm}$ production:



Doubly Charged Higgs

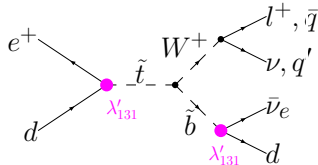
Limits on Couplings



- Limits for exclusive couplings extend partly beyond LEP/TEVATRON

R-Parity Violating SUSY

Bosonic Stop Decay Search



- Complementary mass spectrum to previous squark search
- Stop mass up to 275 GeV excluded

