Searches for new Physics at HERA

HERA:

\[ p \ (920 \text{ GeV}) \quad e \ (27.6 \text{ GeV}) \]

- HERA data & experiments
- Model – independent Search
- Single top & lepton + \( P_{T,\text{miss}} \)
- Supersymmetry
- Contact Interactions
- Excited Fermions
HERA Performance

**HERA— I:** 1992 - 2000
- ~120 pb$^{-1}$ per experiment, mostly e$^+$p

**HERA— II:** 2003 - 2007
- Recently: very good conditions
  - low background, stable beam conditions
  - high data taking efficiencies, low thresholds
  - no major problems on central detectors
- polarisation
  - average ~ 40%
- electron & positron running
  - ~184 pb$^{-1}$ e$^-p$
  - ~294 pb$^{-1}$ e$^+p$
- luminosity HERA I & II
  - ~478 pb$^{-1}$ per experiment, ~90% at 320 GeV
- end of HERA running in June, 2007 → final data set
HERA Experiments: H1 & ZEUS

multi-purpose detectors

Tracking (B-Feld: 1.15 ... 1.5 Tesla)
- 3 layers silicon vertex detectors
- central drift chambers (~60 hits)
- forward straw tubes or drift chambers

Calorimeters: hermetic up to $\eta < 3.5..4$

ZEUS: Uran-Szint. $\rightarrow$ compensating
- electrons: $18%/\sqrt{E}$
- hadrons: $35%/\sqrt{E}$

H1: Liquid Argon $\rightarrow$ high granularity
- electrons: $11%/\sqrt{E}$
- hadrons: $50%/\sqrt{E}$

Jets from tracks + calor. for $\eta < 1.5$
Muon chambers in return yoke

$\sim 10^8$ ep collisions triggered by H1 & ZEUS
- 96 ns BC $\rightarrow$ 100 Hz trigger rate
- Thresholds: $P_T > 5 \ldots 10$ GeV for electrons and jets
- Luminosity: $\sim 1.6 \ldots 3.5$ % precision
- Polarisation: $\sim 3 \ldots 5$ % precision
**HERA data**

**Neutral current: \( \gamma, Z \)**

- \[ Q^2 = 25030 \text{ GeV}^2, \ y = 0.50, \ M = 211 \text{ GeV} \]

**Calorimeter E-scales:**
- Kinematic constraints
- on \( P_T \) and long. momentum
- \( \theta_e, \theta_{\text{hadrons}} \rightarrow E_e, P_T, P_{T, \text{Hadronen}} \)
- (c.f. \( \gamma + \text{jet calibration at LHC} \))
- \( \rightarrow 1\% \text{ for electrons, } 2...3 \% \text{ for jets} \)

**Charged current: \( W \)**

- \( Q^2 \text{ up to } \sim 40000 \text{ GeV}^2 \)
- \( \rightarrow \text{resolution } \sim 0.001 \text{ fm} \)
**HERA data**

**Inclusive measurements**
- used for PDF determinations (low Q^2)
- Contact interaction analysis (high Q^2)
- Squarks in RP violating SUSY, leptoquarks
- dominant sources of background for many searches, systematics ~2%

**Neutral Current**

**Charged Current**

**Polarisation**

HERA combined (new analysis):

\[ \alpha_s(M_Z) = 0.1198 \pm 0.0019 \text{ (exp.)} \pm 0.0026 \text{ (th.)} \]
Model – independent Search (H1)

HERA: highest energy with lepton in the initial state

e+q: no pair production, but single production of new particles

high precision on SM processes

Model independent search

• Inclusive search for particles at high $P_T$
• Electrons, Photons, Muons, Hadronic Jets, Neutrinos (PTmiss)
• phase space for all:
  • $P_T > 20$ GeV
  • $10^\circ < \theta < 140^\circ$
• All combinations: ee, $e\gamma$, $e\mu$, ej, ...jj, ejj, ej$\nu$ → event classes
• Mass and $\sum P_T$ (Jacobi-peak)
• Comparison to SM (LO+PS + K-factors from NLO)
  → look for deviations (max. deviations)
• Statistical interpretation via monte carlo experiments → probability
Model – independent Search

Precision:
→ Systematics: few %
→ Statistics: limited at large M, PT and large multiplicity
→ Theory: uncertainty large for multi-jet channels

Distribution for data follows expectation
→ Excellent understanding of most final states at HERA

Exception: Largest deviation for $\mu j \nu$ channel

$e^+p$: H1 observation: 21 / 8.9 ±1.5 events (3.0$\sigma$)
ZEUS: no events in excess of SM
$e^-p$: H1 and ZEUS: Agreement with SM
**Lepton + P_{Tmiss} + X**

**W production in SM:**
small $P_{T,X}$ of hadrons

**SUSY with $R_p$ violation**
Single stop production

**H1:** events with unexpected large $P_{T,X} > 25$ GeV

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$W$ production in SM:
- Small $P_{T,X}$ of hadrons

SUSY with $R_p$ violation:
- Single stop production

**H1:**
- Events with unexpected large $P_{T,X} > 25$ GeV

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**e, $\mu + P_{T,miss}$, $e^+p$ data**

- **H1:** $3 \sigma$
- **H1+ZEUS:** $1.8 \sigma$

→ not confirmed by ZEUS

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**Peter Schleper, Hamburg University**

**LHC 2008**

**Searches at HERA**
Single Top

- parameterize tu-vertex by effective couplings $\kappa_{tuY}$ and $v_{tuZ}$
- explicit reconstruction of top mass

**RP violating SUSY**

![Diagram showing SUSY processes involving $\gamma$, $e_i$, $\lambda'_{13k}$, $t$, $d_k$, $\lambda'_{11k}$, $u$, and $\nu_{t\ell}$.]

-H1 Preliminary (HERA I+II)

- Excluded
- Excl. by ZEUS
- Excl. by CDF
- Excl. by L3

CDF Note 9202
$Br(t\to Zq) < 3.7\%$

$\kappa_{tuy} = v_{tzu} = 0$

$m_t = 175 \text{ GeV}$

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Searches at HERA
Supersymmetry: R-parity violating

\( \mathcal{R}_p \) conserved:
- \( e^+q \rightarrow \text{selectron-squark} \)
- \( E_{\text{CMS}} \) too small (Tevatron constrains)

\( \mathcal{R}_p \) violation:
- \( e^+q \rightarrow \text{squark} \) (s-channel resonance + u-channel)
- irreducible background / interference with deep inelastic \( e^+q \rightarrow e^+q \)

\[ W_{\mathcal{RPV}} = \lambda'_{ijk} L_i Q_j \tilde{D}_k \]

\( e^+d \rightarrow \tilde{u}_{j,L} \rightarrow e^+d \)
\( e^-u \rightarrow \tilde{d}_{k,R} \rightarrow e^-u \)
\( e^-u \rightarrow \tilde{d}_{k,R} \rightarrow \nu d \)

No significant deviation from standard model expectation observed
Squarks in $R_P$ viol. SUSY

if decays via $\lambda'$ dominate, BR($R_P$-viol.=1)
- mass range up to & beyond $E_{CMS}$ due to interference
- signature same as for some leptoquarks

If squark decays into gauginos are possible
- 3-body decays of gauginos into e+jets
- scan of mSUGRA parameter space

Similar results for couplings with lepton flavour violation
Contact Interactions

Standard Model + 4-Fermion interaction

\[ L_{CI} = \sum_{i,j=L,R; a=u...b} \eta_{ij}^e (\bar{e}_i \gamma^\mu e_i)(\bar{q}_j \gamma_\mu q_j) \]

Compositeness

\[ \eta_{ij} = \epsilon_{i,j} \frac{4\pi}{\Lambda^2} \]

Quark radius

\[ (1 - \frac{R^2_q}{6} Q^2) \]

Leptoquark (M > E_{CMS})

\[ \eta \sim (\lambda/M_{LQ})^2 \]

Squarks in R_p-viol.

\[ \eta_G \sim 1/M_S^4 \]

Large Extra Dimensions

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Searches at HERA
Contact Interactions

ZEUS ep data
- HERA I \( \sqrt{s} = 300 \text{ GeV} \) 1994-2000 128 pb\(^{-1}\)
  - unpolarized e\(^+\) (112 pb\(^{-1}\)) and e\(^-\) data sets
- HERA II \( \sqrt{s} = 318 \text{ GeV} \) 2003-2005 146 pb\(^{-1}\)
  - polarization e\(^-\) −0.27, +0.33, e\(^+\) −0.41, +0.32

Measurement via 2-angle method:
- Resolution \( \ll \) Binning
- Results limited by statistics
Contact Interactions

Typical Range of Contact Interaction scales:

2 … 8 TeV

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Leptoquarks (indirect)

Leptoquark masses excluded for:
- Indirect search
  \[ M / \lambda' > 0.3 \ldots 2 \text{ TeV} \]
- Direct searches for peak in \( M_{\text{eq}} \)
  \( M < 300 \text{ GeV} \Rightarrow \lambda < 0.01 \)

Squarks in R-parity viol. SUSY:
\[ \lambda'_{ijk} L_i Q_j D_k \text{ coupling} \]
\( \tilde{u} \) has same coupling as \( \tilde{S}_{1/2} \)

same limit applies

\[
\begin{array}{|c|c|c|}
\hline
\text{Model} & \text{Coupling Structure} & 95\% \text{ C.L. (TeV)} \\
\hline
S^L_0 & a_{\text{ee}}^{\text{L}} = +\frac{1}{2} & 0.96 \\
S^R_0 & a_{\text{RR}}^{\text{L}} = +\frac{1}{2} & 0.82 \\
\tilde{S}^R_0 & a_{\text{RR}}^{\text{L}} = +\frac{1}{2} & 0.32 \\
S^L_1/2 & a_{\text{LL}}^{\text{L}} = -\frac{1}{2} & 0.88 \\
\tilde{S}^R_1/2 & a_{\text{RL}}^{\text{L}} = a_{\text{LU}}^{\text{L}} = -\frac{1}{2} & 0.46 \\
\tilde{S}^L_1/2 & a_{\text{LL}}^{\text{L}} = -\frac{1}{2} & 0.44 \\
S^L_1 & a_{\text{LL}}^{\text{L}} = +1, a_{\text{LU}}^{\text{L}} = +\frac{1}{2} & 0.74 \\
V^L_0 & a_{\text{LL}}^{\text{L}} = -1 & 0.80 \\
V^R_0 & a_{\text{RR}}^{\text{L}} = -1 & 0.62 \\
\tilde{V}^R_0 & a_{\text{RR}}^{\text{L}} = -1 & 1.33 \\
V^L_1/2 & a_{\text{LL}}^{\text{L}} = +1 & 0.46 \\
\tilde{V}^R_1/2 & a_{\text{RL}}^{\text{L}} = a_{\text{LU}}^{\text{L}} = +1 & 1.00 \\
\tilde{V}^L_1/2 & a_{\text{LL}}^{\text{L}} = +1 & 1.10 \\
V^L_1 & a_{\text{LL}}^{\text{L}} = -1, a_{\text{LU}}^{\text{L}} = -2 & 1.91 \\
\hline
\end{array}
\]
LED’s limited to
• $M_{S(-)} > 0.9$ TeV
• $M_{S(+)} > 0.9$ TeV

Quark Radius limited to
• $R_Q < 0.62 \times 10^{-18}$ m
Excited Leptons (H1)

Effective lagrangian to parameterize compositeness:

- Spin $\frac{1}{2}$, isospin $\frac{1}{2}$, vector currents as SM leptons

\[ L_{F^*F} = \frac{1}{\Lambda} \bar{F}_R^* \sigma^{\mu\nu} \left[ g f \frac{\partial}{\partial \mu} W_\nu + g' f' \frac{\partial}{\partial \mu} B_\nu \right] F_L + h.c. \]

**Λ** compositeness scale

**f, f’** relative strength

for $W_\mu, B_\mu \rightarrow \gamma, Z$

Resonance production for masses $< E_{CMS}$
Excited electrons

Search for $e^*$ HERA I+II ($\sqrt{s} = 320$ GeV, 435 pb$^{-1}$, preliminary)

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>SM</th>
<th>Efficiency $\times$ BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^* \rightarrow \nu W_{\rightarrow qq}$</td>
<td>172</td>
<td>$175 \pm 39$</td>
<td>$\sim 40 %$</td>
</tr>
<tr>
<td>$e^* \rightarrow e Z_{\rightarrow qq}$</td>
<td>351</td>
<td>$318 \pm 64$</td>
<td>$\sim 45 %$</td>
</tr>
<tr>
<td>$e^* \rightarrow e \gamma$</td>
<td>112</td>
<td>$125 \pm 19$</td>
<td>60–70 $%$</td>
</tr>
</tbody>
</table>

Full statistics: No excess seen
Excited Electrons and Neutrinos

HERA: Limits typically 220 ... 280 GeV for $M \sim \Lambda / f$
LEP: $M > 208$ GeV direct search
LEP/Tevatron: indirect limits for $M > 280$ GeV
Conclusion

HERA: final statistics available: 0.5 fb\(^{-1}\) per experiment

Precision dictated by
- luminosity for indirect searches: Contact interactions
- beam energies for direct searches
- experimental errors small in most cases

Model – independent search (H1 full statistics):
- few % level of understanding of ~ ALL final states at HERA
- exception: H1: \(\mu j\nu\) channel for e+ scattering
  ZEUS: not confirmed

Resonance searches on squarks, leptoquarks
- mass limit for small couplings \(\sim 300\) GeV, and beyond via interference

Contact interactions (ZEUS 285 pb\(^{-1}\)):
- limits on scale \(\sim 10 \times E_{\text{CMS}}\) ... up to 7.5 TeV
- improvements from luminosity and polarisation still to come

Excited Leptons (H1 full statistics):
- mass limit \(\sim 220 \ldots 280\) GeV