Search for New Phenomena at Colliders

E. Nagy (CPPM) for the CDF, D0 (Tevatron) and H1, ZEUS (HERA) Collaborations
In spite of the great success of the SM we still miss an ultimate theory (TOE) which would provide unification of all the 4 known forces (gravity!) into a finite (renormalizable) theory.

Therefore, new, BSM physics is expected at some energy scale $M_X$.

The questions are: what is the TOE and what is $M_X$?

Today only elements of such a theory are proposed for experimental tests. In the present talk: some arbitrary choice of topics addressed by two active colliders: Tevatron and HERA.
• Extra Dimensions
• Super Symmetry
• Z’, Lepto-Quarks, Beyond SM Higgses
• Substructure (Contact Interactions, Excited Leptons)
• Anomalies

Frequently, the same event topology (e.g. high mass di-leptons) allows to test several theoretical models

For $M_X$ the natural value is $M_{Pl}$ to unify gravity. However this leads to « unnatural » fine tuning of scalar masses (problem of hierarchy).
Some of the above topics present solution to this problem.
>3 times more luminosity than in Run I; soon $\mathcal{L}$ is $10^{32}\text{cm}^{-2}\text{s}^{-1}$ and counted in $\text{fb}^{-1}$

~ 200 pb$^{-1}$ and only most recent results from Run II reported here
HERA II will deliver ~10 times more luminosity (at present ~70 pb⁻¹) + longitudinal polarisation of e-beam

Results mainly from HERA I
Extra Dimensions (ED)

- ED’s provide framework for unification with gravity (Th. Klauza, 1919)
- ED’s are compact since not seen (O. Klein, 1926)
- Compact ED’s generate replica of particles (KK-tower) propagating in them
- In string theories, ED’s restore QM probabilities in the range [0,1].
- ED’s can be large (LED: $R >> \text{TeV}^{-1}$) – if only gravity can propagate in them
- LED can explain why gravity is weak: $1/G \sim M_{Pl}^2 \sim M_s^{n+2} R^n$ and can solve the hierarchy problem: $M_s \sim M_W$
- LED can be tested by gravity experiments ($n<3$) but also at colliders through virtual effects or direct emission of KK gravitons ($n>2$).
- Smaller ED’s ($R \sim \text{TeV}^{-1}$) can also be tested at colliders (interference of KK states)
- Randall-Sundrum model (1 small ED of size $R \sim 1/M_{\text{GUT}}$ with a metric damped by $e^{-kR\phi}$) predicts graviton resonances ($S=2$) of $k \sim 1$. 
Determination of $M_s$ of LED

Look for effects of virtual gravitons in high mass lepton (photon) pairs

\[
\frac{d^2\sigma}{dMd \cos \theta^*} = f_{SM} + f_{int} \eta_G + f_{KK} \eta_G^2
\]

\[
\eta_G = \frac{2\lambda}{\pi} \frac{1}{M_S^4} \quad ; \quad \lambda = \pm 1 \quad (Hewett)
\]
Select:
- 2 (and only 2) high pT em objects: pT>25 GeV
- Precisely determined vertex

Compare:
- SM and instrumental (mis-ID) background

Extract limit:

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$\eta$(TeV^{-4})</th>
<th>$M_s$(TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>0.292</td>
<td>1.22</td>
</tr>
<tr>
<td>-1</td>
<td>-0.432</td>
<td>1.10</td>
</tr>
</tbody>
</table>
Limit on $M_S$ from HERA

$$\eta = \lambda / M_S^4$$

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>H1</th>
<th>ZEUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>0.82</td>
<td>0.78</td>
</tr>
<tr>
<td>-1</td>
<td>0.78</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Total of ~12500 CC+CP candidates in 200 pb$^{-1}$ data

**CDF ee limit**

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$\eta(\text{TeV}^{-4})$</th>
<th>$M_S(\text{TeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>1.17</td>
<td>0.961</td>
</tr>
<tr>
<td>-1</td>
<td>1.05</td>
<td>0.987</td>
</tr>
</tbody>
</table>

PIC Boston, June 2004

E. Nagy: Searches for New Phenomena at Colliders
Determination of $M_d$ from KK graviton emission

**Signature is Monojet + MET**

- **Selection:**
  - Leading jet $p_T > 150$ GeV
  - 2nd jet $p_T < 50$ GeV
  - MET $> 150$ GeV
  - Lepton (e,μ) veto

**Main Background:**
- $Z(\rightarrow \nu\nu)+nj$
- $W(\rightarrow l\nu)+nj$

**Main uncertainty:**
- Jet energy scale
Determination of $M_C$ of TeV$^{-1}$-size (Longitudinal) ED

- Fermions are confined in the ordinary 3d world.
- Gauge bosons can propagate in 3+$delta$ brane of $delta$ compact ED.
- Look for effects of KK replica of gauge bosons in high mass lepton pairs and determine the scale $M_C$ of ED.

Interference of KK states

- Same selection as above + trackmatch of at least 1 em object
- Data is compatible with SM
- $M_C > 1.12$ TeV @ 95%
Search for Randall-Sundrum resonances in high mass di-lepton states

CDF Run II Preliminary

<table>
<thead>
<tr>
<th>CDF Run</th>
<th>L(pb⁻¹)</th>
<th>M₉₉% CL (k/Mₚ=0.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIA (winter '04)</td>
<td>200</td>
<td>ee: 620, µµ: 605</td>
</tr>
</tbody>
</table>

PIC Boston, June 2004

E.Nagy: Searches for New Phenomena at Colliders
SUper SYmmetry

Symmetry of Nature for Boson<->Fermion interchange
   Basic ingredient for unification with gravity (SuperString/M-theory)
   The only nontrivial extension of the Lorentz-Poincaré group
   Provides elegant solution for the hierarchy problem

Minimal extension of the SM: MSSM
   every SM particle has $\Delta S = \pm 1/2$ partner
   $R = (-1)^{3B+2L+S} = +1$ (SM); = -1 (SUSY)
   2nd Higgs doublet is needed
   
   $q, l \Leftrightarrow q, \bar{l}$
   
   $g \Leftrightarrow g$

   $\gamma, Z, h, H, A \Leftrightarrow \chi^0_{1,...,4}$

   $W^\pm, H^\pm \Leftrightarrow \chi^\pm_{1,2}$

   If SUSY were exact: only 1 additional parameter ($\mu$) needed
SUSY is a broken symmetry since nobody has seen the partners
many more parameters describe breaking
with additional hypotheses they are reduced in the 2 models treated here
gravitation mediated (mSUGRA) model to 5 \((m_0, m_{1/2}, \tan \beta, \sgn, A_0)\)
gauge mediated (GMSB) model to 6 \((\Lambda, M_m, N_5, \tan \beta, \sgn, C_{grav})\) parameters.

R-parity is approximately conserved:
severe limits on B- and L-violating processes
SUSY partners are pair produced
LSP is stable (neutral and weakly interacting)

Basic signature is MET (LSP), + multiple jets and leptons
from cascade decays

Main bg is t tb and gauge boson pair production

Small violation of R-parity is not excluded:
allows single resonant formation of SUSY particles
many more jets/leptons in final state
additional couplings (48)

At Tevatron both RPC and RPV can be studied
HERA is competitive only for RPV processes
The “golden” signature: chargino ($\chi_1^{\pm}$) and neutralino ($\chi_2^0$) pair production

The signatures exploited by D0:
MET from $\chi_1^0$ and $\nu + 3$ leptons (e,\(\mu\),l/e,e,l) or $2$ leptons ($\mu$, $\mu$) of same sign

D0 has searched beyond the stringent mSUGRA LEP limit and has chosen the following parameter region:

$$72 \leq m_0 \leq 88 \text{ GeV}; 165 \leq m_{1/2} \leq 185 \text{ GeV}; \tan\beta = 3; \mu > 0; A_0 = 0$$

$$m_{\chi_1^\pm} \approx m_{\chi_2^0} \approx 2 m_{\chi_1^0} \approx m_{\tilde{l}}$$
**e+ μ +l**

High quality, isolated electron: $p_T > 12$ GeV
Muon: $p_T > 8$ GeV
Charged track

Jet veto
$m_T^{\text{min}} > 15$ GeV
$15 < m_{e\mu} < 100$ GeV
MET signif $> 25$ GeV
$p_T > 3$ GeV
0 data – $0.54 \pm 0.25$ bg

**e+e+l**

High quality, isolated electrons: $p_T > 8, 12$ GeV

Jet veto
$m_T^o > 15$ GeV
$m_{ee} < 60$ GeV
$\Delta \phi_{ee} < 2.8$
MET $> 20$ GeV
$p_T^3 \times \text{MET} > 250$ GeV
1 data – $0.27 \pm 0.42$ bg
High quality, isolated like-sign muons:
\( p_T^1 > 11 \text{ GeV}, \ p_T^2 > 5 \text{ GeV} \)
\( \text{MET} > 15 \text{ GeV} \)
\( m_{\mu\mu} < 80 \text{ GeV} \)
\( \Delta \phi_{\mu\mu} < 2.7 \) (if \( p_T^2 < 11 \text{ GeV} \))
\( \Delta \phi_{\text{MET},\mu}^{\text{min}} > 0.5 \) (if \( p_T^2 < 11 \text{ GeV} \))
\( \Delta \phi_{\text{MET},\mu}^{\text{max}} < 2.4 \) (if \( p_T^2 < 11 \text{ GeV} \))
\( \Delta \phi_{\text{MET},j} < 2.4 \)

1 data – 0.13±0.06 bg

Combined 3l+MET

Great improvement wrt Run I
Sensitivity very near to mSUGRA prediction

Bg is mainly heavy flavour
Estimated from OS pairs
Search for $q \rightarrow q + \chi_1^0$, $g \rightarrow q \bar{q} \chi_1^0$ in jet + MET

At least 2 jets:
- $p_T > 60$ GeV
- lepton veto
- $\Delta \phi_{\text{METj}}^\text{min} > 30^\circ$
- $\Delta \phi_{\text{METj}}^\text{max} < 165^\circ$
- $\text{MET} > 175$ GeV
- $H_T = \Sigma p_T > 275$ GeV
- 4 data – 2.67±0.95 bg
- Bg mainly $Z \rightarrow v v + n j$

$m_{\text{SUGRA}}$

$m_0 = 25$ GeV; $100 \leq m_{1/2} \leq 140$ GeV; $\tan \beta = 3$; $\mu < 0$; $A_0 = 0$
GMSB

Di-Photons+MET

CDF Run II Preliminary (202 pb$^{-1}$)

Events/5 GeV

- Data
- QCD & fake photon
- SM $\gamma\gamma$ production
- $\tau\tau$ background

$E_\gamma > 13$ GeV
$\eta < 1.1$
$\not\!p_T > 45$ GeV
$10^\circ < \Delta \phi (\not\!p_T, \gamma) < 170^\circ$
Calorimeter timing

Getting NLSP = $\chi^0_1$

$\tilde{L}SP = \tilde{G}$

Signal is at high MET:
MET > 40 GeV
Data: 1 Bg: 2.5±0.5

Expected signal vs $M=2\Lambda$ messenger mass scale

Best limit on: $\Lambda > 78.8$ TeV
$m_{\chi_0} > 105$ GeV, $m_{\chi^\pm} > 192$ GeV
R-parity violation

Introduces 48 new L and B violating Yukawa couplings:

\[ L = \lambda_{ijk} L_i L_j \tilde{E}_k + \lambda'_{ijk} L_i Q_j \tilde{D}_k + \lambda''_{ijk} U_i D_j \tilde{D}_k \]

with more leptons, jets in the final state

Single sparticle production and decay depends on coupling \( \lambda \)

Decay of the LSP (\( \chi_1^0 \)) – if fast, does not depend on coupling \( \lambda \)
Look for signal in multiple event topology (H1). Below an exemple of the lepton-jet(s) inv mass spectrum

**No deviation from the SM -> Limits on** $\lambda_{ij1}$ and $m_0$, $m_{sq}$, $\tan\beta$
**R-parity violation in GMSB (H1)**

**Signature:** MET>25 GeV, and an isolated $\gamma$ ($p_\gamma>25$ GeV)

1 event found, $2.55\pm1.30$ expected

Limits on $\lambda'_{1j1}$, $m_{\text{NLSP}}$, $m_{\text{sel}}$
CDF: agreement of the high mass di-lepton spectra with the SM is transformed into limits on $\lambda'$ and $m_{\text{snu}}$

<table>
<thead>
<tr>
<th>$\lambda'^2 \cdot Br$</th>
<th>CC (GeV)</th>
<th>CP (GeV)</th>
<th>CC+CP (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.1$</td>
<td>830</td>
<td>710</td>
<td>840</td>
</tr>
<tr>
<td>$0.01$</td>
<td>650</td>
<td>550</td>
<td>660</td>
</tr>
<tr>
<td>$0.001$</td>
<td>400</td>
<td>340</td>
<td>400</td>
</tr>
</tbody>
</table>
**Z’**

Z’ is predicted in several extensions of the SM E₆ and little Higgs models are considered here

\[ E₆ \rightarrow \text{SO}(10) \times U(1)_ψ \rightarrow \text{SU}(5) \times U(1)_χ \times U(1)_ψ \rightarrow \text{SU}(3) \times \text{SU}(2) \times U(1)_γ \ U(1)_χ \ U(1)_ψ \]

\[ Z'(θ) = Z_ψ \cos θ + Z_χ \sin θ \]

<table>
<thead>
<tr>
<th>θ</th>
<th>0°</th>
<th>90°</th>
<th>37.76°</th>
<th>-37.76°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z’</td>
<td>Z_ψ</td>
<td>Z_χ</td>
<td>Z_η</td>
<td>Z_₁</td>
</tr>
</tbody>
</table>
$DØ \int L dt = 200 \text{ pb}^{-1}$

**Limits for $e^+e^-$ (in GeV)**

**SM Couplings**
- CDF: 750
- $DØ$: 780

$E_6$:
- $Z_1$, $Z\chi$, $Z\psi$, $Z\eta$
  - CDF: 570, 610, 625, 650
  - $DØ$: 575, 640, 650, 680

**Similar, somewhat smaller limits for $\mu^+\mu^-$**
**Little Higgs**

Proposes new fermions and bosons to solve the hierarchy problem. Contrary to SUSY, here the quadratically divergent diagrams are cancelled by the same type of particle (fermion-loops by fermion-loops, etc.). $Z_H$ is one of the new bosons to cancel divergent boson loop. Its coupling is parametrized by $\Theta$. CDF establishes limits on the mass of $Z_H$ and $\Theta$ in both of ee and $\mu\mu$ final states.

- **ee**: $M(Z_H) > 800$ GeV/$c^2$ for $\cot\theta = 1.0$
- **$\mu\mu$**: $M(Z_H) > 755$ GeV/$c^2$ for $\cot\theta = 0.9$
**Lepto-Quarks**

Hypothetical bosons (scalars or vectors) carrying both L and B. Proposed in several extensions of SM based on Q-L symmetry. HERA is an ideal machine to produce 1st generation LQ’s. No deviation is found wrt SM -> Limits on $M_{LQ}$ and coupling $\lambda$.
ZEUS has also searched for tau's in the final state:
Lepton Flavour Violation

No events have been found:
limits on $\lambda_{eq1} = \lambda_{qaj}$ vs $M_{LQ}$
1st generation Lepto-Quarks at Tevatron

Dominantly produced in pairs of the same generation (avoid topology of FCNC or LFV) Production is ~independent of $\lambda$

Final state is characterized by 2j+2l lepton can be charged or neutral with BR $\beta$

-> possible final states: 2j+2l, 2j+1+MET, 2j+MET

**2j+2e channel:**
- 2j $E_T>$ 20 GeV
- 2e $E_T>$ 25 GeV
- Z-veto
  \[ S_T = \sum E_T^{j} + \sum E_T^{e} > 450 \text{GeV} \]

0 data, 0.4±0.1 bg

**2j+ev channel:**
- 2j $E_T>$ 25 GeV
- 1e $E_T>$ 25 GeV
- MET>30 GeV
- W-veto: $m_T>$ 130 GeV
- $S_T>$ 330 GeV

2 data, 4.7±0.9 bg

---

**D0 MLQ1 limits in GeV**

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>0.1</th>
<th>0.5</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run I</td>
<td>110</td>
<td>204</td>
<td>225</td>
</tr>
<tr>
<td>Run II</td>
<td>155</td>
<td>213</td>
<td>238</td>
</tr>
</tbody>
</table>
Similar analyses of CDF - also in the jjMET channel

MET+Jets channel:
>2j (j^{1,2} central w/4 tracks)
Jets and MET shouldn’t be aligned
e/µ-veto
MET>60 GeV
80<ΔΦ(j^{1,2})<165°
124 data, 118±13 bg
78<M_{LQ}<117 GeV excluded

CDF M_{LQ1} limits in GeV

<table>
<thead>
<tr>
<th>β</th>
<th>Run I</th>
<th>Run II</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>182</td>
<td>135</td>
</tr>
<tr>
<td>0.5</td>
<td>220</td>
<td>197</td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td>230</td>
</tr>
</tbody>
</table>
2nd generation Lepto-Quarks at Tevatron

jj+µµ channel:
2µ p_T>25 GeV
2j E_T^{1,2}>30, 15 GeV
Z-veto
Topological cuts (see Fig.)
2 data, 3.2±1.2 bg
M_{LQ}<240 GeV excluded

CDF Run II Preliminary (198 pb⁻¹)

Search for 2nd Generation Scalar Leptoquarks, β=1

M_{LQ} > 240 GeV/c²

MLQ<186 GeV excluded (L=104 pb⁻¹)

E.Nagy: Searches for New Phenomena at Colliders
Beyond SM Higgses

On the way to discover $H_{SM}$ ...
... one may find BSM Higgses

- $H \to \gamma\gamma$
- $H \to WW$
- Neutral SUSY/2-Doublets: $h, H, A$
- $H^{++/-}$
In some extensions of the SM $\text{BR}(H\rightarrow\gamma\gamma)$ can be $\sim 1$ (e.g. Fermiophobic or Topcolor Higgs)

Select 2 isolated photons:

- $p_T^{1,2} > 25$ GeV
- $p_T^{\gamma\gamma} > 35$ GeV

Estimate background:

- Instrumental
- $\text{DY, } \gamma\gamma$

Determine limit on BR:

- sliding window technique
**H->WW->2l+MET**

**ee (OS) channel:**
- $p_T^{1,2}>12.8$ GeV
- MET $>$ 20 GeV
- METsig $>$ 15 GeV$^{1/2}$
- $\Sigma p_T +$ MET $>$ 100 GeV
- $12 < M_{ee} < 80$ GeV
- Jet-veto
- $\Delta\phi_{ee} < 1.5$
- 2 data, $2.7\pm0.4$ bg

**e$\mu$ (OS) channel:**
- $p_T^{e,\mu}>12.8$ GeV
- MET $>$ 20 GeV
- METsig $>$ 15 GeV$^{1/2}$
- $\Sigma p_T +$ MET $>$ 90 GeV
- $M_T^{\min} < 20$ GeV
- Jet-veto
- $\Delta\phi_{e\mu} < 2.0$
- 2 data, $3.1\pm0.3$ bg

**$\mu\mu$ (OS) channel:**
- $p_T^{1,2}>20,10$ GeV
- MET $>$ 30 GeV
- MET $+10+0.75\times p_T^1$ GeV
- Jet-veto
- Z-veto
- $\Delta\phi_{\mu\mu} < 2.0$
- 2 data, $3.1\pm0.3$ bg

PIC Boston, June 2004

E.Nagy: Searches for New Phenomena at Colliders
H, h, A (φ)  \[ gg, qq \rightarrow \varphi + b\bar{b} \rightarrow b\bar{b}b\bar{b} \text{ or } gb \rightarrow b\varphi \rightarrow b\bar{b}b \]

Background:
Multijet fakes (estimated from data)
HF + fakes (estimated from data and MC)
Bg is normalized to data outside the signal
Limits for \( m_A = m_h < 135 \) or \( m_A = m_H > 135 \) GeV
and for \( \tan \beta \) are calculated

\[ \sigma_\varphi \sim \tan^2 \beta \]

Select:
\( >2j \quad E_\text{T} > 20 \text{ GeV}, \quad E_\text{T} > 15 \text{ GeV} \)
with well defined vertex (>3 tracks)
Apply b-tag with SVT algorithm
\( \epsilon_{\text{tag}} = 0.75, \quad \epsilon_{\text{btag}} = 0.51, \quad \epsilon_{\text{ctag}} = 1/4 \epsilon_{\text{btag}}, \quad \text{fake}=0.02 \)
**H++/--**

Predicted in L-R symmetric, Triple Higgs, Little Higgs, etc. models

**Signature is multilepton (SS) events**

At HERA one searched for multi-\(e\) events (in general):

H1 finds 6 multi-\(e\) events with \(M_{12}>100\) GeV (0.54±0.6 expected)

No excess for ZEUS: 2 found (1.2±0.1 expected)

However only 1 event of H1 agrees with H++/-- topology

Limit on coupling \(h_{ee}\) vs \(M_H\)

---

PIC Boston, June 2004

E.Nagy: Searches for New Phenomena at Colliders
**D0 selected events in the $2\mu$ channel:**
At least 2 isolated muons, $p_T>15$ GeV of same charge with $\Delta\Phi<0.8$ (anti-Z)
Bg mainly HF and Z (wrong charge id)
3 events observed, $1.5\pm0.4$ expected

**CDF selected events in the $ee$, $e\mu$ and $\mu\mu$ channels**

**Predicted background**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>$1.8^{+0.8}_{-0.6}$</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>$0.8^{+0.6}_{-0.5}$</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>$0.9^{+0.4}_{-0.4}$</td>
</tr>
</tbody>
</table>

0 events observed

![Graphs showing data and predicted background for $ee$, $e\mu$, and $\mu\mu$ channels.](image)

<table>
<thead>
<tr>
<th>Mass Limit</th>
<th>CDF 240 pb$^{-1}$</th>
<th>D0 113 pb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{L}^{++}$</td>
<td>~102-113</td>
<td>135</td>
</tr>
<tr>
<td>$H_{R}^{++}$</td>
<td></td>
<td>113</td>
</tr>
<tr>
<td>$ee$</td>
<td>135</td>
<td>118.4</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>135</td>
<td>98.2</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>115</td>
<td></td>
</tr>
</tbody>
</table>
Substructure of quarks and leptons

A possible substructure manifests itself by:

• Excited states of quarks and leptons
• Finite size of quarks and leptons
• Contact interaction of $q$’s / $l$’s of scale $\Lambda > > \sqrt{s}$
Excited Leptons at the Tevatron (CDF)

Contact interaction

Gauge mediated interaction

Select eey events:

$E_T^{e_1}, E_T^{e_2}, E_T^\gamma > 25$ GeV

Z-veto

3 events observed

Run=167866 Event=443088

$\gamma$-jet

$\gamma\gamma$-jet

W($\to$ ee)+jet

Multi-jet

\[ M_{e\gamma} = 256 $\text{GeV}$ \]

\[ M_{e\gamma} = 220 $\text{GeV}$ \]

\[ M_{e\gamma} = 64 $\text{GeV}$ \]

\[ M_{e\gamma} = 344 $\text{GeV}$ \]

Expected background events:

\begin{tabular}{|c|c|}
\hline
Source & Events \\
\hline
$Z(ee)\gamma$ & $2.56 \pm 0.24$ \\
$Z(ee)+jet$ & $0.24 \pm 0.04$ \\
$W(e\nu)Z(ee)$ & $0.11 \pm 0.01$ \\
$Z(ee)Z(ee)$ & $0.038 \pm 0.004$ \\
Multi-jet & $0.035 \pm 0.005$ \\
$tt$ & $0.015 \pm 0.005$ \\
$\gamma\gamma$-jet & $0.008 \pm 0.005$ \\
$W(e\nu)+jet$ & $0.004 \pm 0.005$ \\
Total & $3.01 \pm 0.28$ \\
\hline
\end{tabular}
Excited Leptons at the Tevatron (CDF)

- Contact Interaction Model
- Gauge Mediated Model

Λ - compositness scale
f – relative coupling strength to SU$_{2L}$ gauge boson
Contact Interactions

Deviation from the SM of inclusive ep->eX is parametrized as:

\[ L = \frac{4\pi}{\Lambda^2} \sum_{q=u,d} \sum_{\alpha,\beta=L,R} \eta_{e,q}^\alpha (\bar{e}_\alpha \gamma^\mu e_\alpha) (\bar{q}_\beta \gamma^\mu q_\beta); \quad \eta_{e,q} = 0,\pm 1 \]

No deviation (ZEUS, H1) is transformed to limits on \( \Lambda \):

\[ \text{No deviation (ZEUS, H1) \Rightarrow \Lambda^- < 6.4 \text{ TeV}, \Lambda^+ < 3.4 \text{ TeV}} \]

and also to limits on q-radius:

\[ R_q < 1.0 \times 10^{-18} \text{ m (H1)} \]
\[ R_q < 0.85 \times 10^{-18} \text{ m (ZEUS)} \]

\[ \frac{d\sigma}{dQ^2} = \frac{d\sigma^{\text{SM}}}{dQ^2} (1 - \frac{R_q^2}{6}); \quad \text{(for pointlike electron)} \]
General search for deviations from the SM
pioneered by D0, here carried out by H1

Select events with at least 2 isolated objects: $e$, $\mu$, $j$, $\gamma$, $\nu$ with $P_T > 20$ GeV
to look for large deviation from SM in $M_{all}$ and $\sum p_T$

HERA I

**Events**

| $e - j$ | $e - \gamma$ | $e - \nu$ | $\mu - j$ | $\mu - \gamma$ | $\mu - \nu$ | $\nu - j$ | $\nu - \gamma$ | $\nu - \mu$ | $j - j$ | $j - \gamma$ | $j - \nu$ | $\gamma - j$ | $\gamma - \gamma$ | $\gamma - \nu$ | $\gamma - \mu$ | $\nu - \nu$ | $\nu - \gamma$ | $\nu - \mu$ | $j - j$ | $\gamma - j$ | $\gamma - \gamma$ | $\gamma - \nu$ | $\gamma - \mu$ | $\nu - \nu$ |
| $10^{-1}$ | 1 | 10 | 10$^2$ | 10$^3$ | 10$^4$ |

H1 General Search

HERA II

**Events**

| $e - j$ | $e - \gamma$ | $e - \nu$ | $\mu - j$ | $\mu - \gamma$ | $\mu - \nu$ | $\nu - j$ | $\nu - \gamma$ | $\nu - \mu$ | $j - j$ | $j - \gamma$ | $j - \nu$ | $\gamma - j$ | $\gamma - \gamma$ | $\gamma - \nu$ | $\gamma - \mu$ | $\nu - \nu$ | $\nu - \gamma$ | $\nu - \mu$ | $j - j$ | $\gamma - j$ | $\gamma - \gamma$ | $\gamma - \nu$ | $\gamma - \mu$ | $\nu - \nu$ |
| $10^{-2}$ | $10^{-1}$ | 1 | 10 | 10$^2$ | 10$^3$ |

H1 General Search (Hera-II)

**Largest deviation**
in $\mu - j - \nu$

PIC Boston, June 2004

E.Nagy: Searches for New Phenomena at Colliders
Excess of isolated leptons at HERA

5 H1 events are compatible with FCNC single top production: 
\[ \sigma(ep\rightarrow etX) = 0.29\pm0.15 \, \text{pb} \]
Alternatively, upper limit on: 
\[ k_{tuy} < 0.27 @ 95\% \text{CL} \]
ZEUS is compatible with SM: limit on \( v_{tuz} \) vs \( k_{tuy} \)

Is the tau excess of ZEUS a sign of stop decay at large tan\( \beta \)?

---

PIC Boston, June 2004

E.Nagy: Searches for New Phenomena at Colliders
Conclusions

The performances of both Tevatron and HERA improve steadily allowing to test experimentally many new ideas in the search for an ultimate theory

Although some anomalies observed already, no conclusive sign of new, BSM physics yet

More results are expected soon...
Apologies for subjects I haven’t had time to present here

Acknowledgments for help in preparing this material

to colleagues of the D0, CDF, H1 and ZEUS collaborations
and especially to
Elisabetta Gallo (ZEUS) and
Jianming Qian (D0)
Backup slides
The CDF upgraded detector

- Muon System
- Central Calorimeter
- Solenoid
- Silicon Microstrip Tracker
- Plug Calorimeter
- Time-of-Flight
- Drift Chamber
- Front End Electronics
- Pipelined Triggers / DAQ
- Online & Offline Software

New
Old
Partly New
The D0 upgraded detector
The H1 detector
The ZEUS detector
Extra Dimensions
Highest DiEm Masses

$M_{ee} = 475 \text{ GeV}$

$\cos \Theta^* = 0.01$

$M_{\gamma\gamma} = 435 \text{ GeV}$

$\cos \Theta^* = 0.02$
Analogous study for stop (H1) assuming $m_{st} > m_{sb}$
Doesn’t explain isolated lepton events -> Limits on $\lambda_{131}$ and $m_{st}$

![Diagram](image)

**Figure:**
- A graph showing excluded regions in the parameter space for $\lambda_{131}$.
- Plots for the H1 channel with distributions of $M_1$ and $M_3$.

**Legend:**
- Excluded in part of parameter space:
- $0.6 < \theta_t, \theta_b < 1.2$
- $400 \text{ GeV} < \mu < 1000 \text{ GeV}$
- $M_3 = 1000 \text{ GeV}$
- $\tan \beta = 10$
- $M_1 = 100 \text{ GeV}$

**Note:**
- PIC Boston, June 2004
- E.Nagy: Searches for New Phenomena at Colliders

53
$Z' \rightarrow \mu\mu$

**CDF Run II Preliminary (200 pb$^{-1}$)**

- $\sigma Br(Z' \rightarrow l\bar{l})$ limit (95% C.L.)
- $\sigma Br(Z' \rightarrow l\bar{l})$ LO = 13

<table>
<thead>
<tr>
<th>$Z'$ Mass (GeV/c$^2$)</th>
<th>570 GeV ($Z_{I}$)</th>
<th>610 GeV ($Z_{E}$)</th>
<th>625 GeV ($Z_{S}$)</th>
<th>650 GeV ($Z_{N}$)</th>
<th>750 GeV ($Z'$ SM coupling)</th>
</tr>
</thead>
</table>

**ee $Z'_SM$**

<table>
<thead>
<tr>
<th>CDF Run</th>
<th>L(pb$^{-1}$)</th>
<th>Mass limit @95%CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA ('92-93)</td>
<td>20</td>
<td>505</td>
</tr>
<tr>
<td>IB ('94-'95)</td>
<td>90</td>
<td>640</td>
</tr>
<tr>
<td>IIa (winter '04)</td>
<td>200</td>
<td>750</td>
</tr>
</tbody>
</table>

(D0 Run II limit: 780 GeV/c$^2$)

**CDF Run II Preliminary**

<table>
<thead>
<tr>
<th>Model</th>
<th>Run I</th>
<th>Run II (winter '04)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'_{SM}$</td>
<td>590</td>
<td>735</td>
</tr>
<tr>
<td>$Z_{Y}$</td>
<td>495</td>
<td>600</td>
</tr>
<tr>
<td>$Z_{X}$</td>
<td>500</td>
<td>580</td>
</tr>
<tr>
<td>$Z_{N}$</td>
<td>520</td>
<td>635</td>
</tr>
<tr>
<td>$Z_{I}$</td>
<td>480</td>
<td>530</td>
</tr>
</tbody>
</table>

**CDF Run II Preliminary (200 pb$^{-1}$)**

<table>
<thead>
<tr>
<th>$\sigma Br(Z' \rightarrow \mu\bar{\mu})$ limit (95% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma Br(Z' \rightarrow \mu\bar{\mu})$ LO = 13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'$ Mass (GeV/c$^2$)</td>
</tr>
<tr>
<td>$\sigma Br(Z' \rightarrow \mu\bar{\mu})$ (LO = 13)</td>
</tr>
</tbody>
</table>

PIC Boston, June 2004

E.Nagy: Searches for New Phenomena at Colliders
Excited Leptons
Excited Leptons at the Tevatron (CDF)

- Contact Interaction Model depends on $M_{e^*}$ and $\Lambda$
- $M_{e^*} < \Lambda$

- No published limits

- Gauge mediated model depends on $M_{e^*}$ and $f/\Lambda$


CDF Run II Preliminary $\int L \cdot dt = 200$ pb$^{-1}$

95% C.L. Exclusion Region

$\frac{H}{\Lambda}$ (GeV$^{-1}$) vs. $M_{e^*}$ (GeV)

- 95% C.L. Exclusion Region
- $\Gamma_{ee} = 0.1$ Full BW Width
- CDF Run II
- ZEUS (1994-1997)
- H1
- L3
Multi-e events at HERA II

H1 Preliminary

Multi-electron Analysis Hera-II, (17 pb$^{-1}$)

Events vs. $M_{12}$ (GeV)

H1 Data (prelim.)
Pair Production
NC-DIS
Compton

2e

3e