The Beyond the SM Landscape

The Standard Model

- SU(3)_c x SU(2)_L x U(1)_Y
- The Higgs mechanism
- 3 generations of quarks and leptons
- The Poincaré group
- In 4 dimensions

Test Beyond the SM hypotheses

- New substructures? (compositness)
- Quarks ↔ leptons (Lepto-quarks?)
- Enlarge the gauge group (Z', W'?)
- Alternative EWSB mechanisms
- A 4^{th} dimension?
- Extend Poincaré → Supersymmetry
- (...)

Test the SM → BSM-independent

- New resonances?
- Topologies with low SM background
- Topologies with specific particle(s)
- General searches
The Experimental Tools

Present and past colliders at the energy frontier

- **LEP**
  - $\sqrt{s} = 210$ GeV,
  - $\sim 0.9$ fb$^{-1}$ / exp.
  - Results still complementary

- **Tevatron**
  - $\sqrt{s} = 1.96$ TeV,
  - Up to $\sim 4$ fb$^{-1}$ in analyses
  - $\sim 6$ fb$^{-1}$ on tape

- **HERA**
  - $\sqrt{s} = 320$ GeV,
  - $\sim 0.5$ fb$^{-1}$ / exp.
  - Stopped mid-2007
Deeper into Matter Structure

- Repeat the history: diffusion of point-like particles on matter
  - Atom → Nucleus → Nucleon → Quark (→ ?)
  - DIS scattering of e on q

- A finite size of quarks EW charge distribution

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

\[
R_q < 0.63 \times 10^{-18} \text{ m (ZEUS)}
\]

\[
R_q < 0.74 \times 10^{-18} \text{ m (H1)}
\]
Compositness

- A direct manifestation of new substructures
  - Existence of fermion excited states
  - Searches via decays to fermion+ boson

- ep colliders well suited
  - A complete scan performed by H1 at HERA, using all data
  - $\nu^*, e^*$ and $q^*$ searched for

\[ \sqrt{s} = 200 < M_{l^*} < 300 \text{ GeV} \]

- For $l^*$: HERA has the best sensitivity in $\sqrt{s}_{\text{LEP}} = 200 < M_{l^*} < 300$ GeV
- For $q^*$: complementary to Tevatron for small $f_s$
Lepto-quarks

- Leptoquarks: connect lepton and quark sectors
- HERA was ideal to search for 1st generation LQs
  - Single production possible up to the kinematic limit
  - Look for lepton-quark resonances in e+jet, ν+jet
  - Sensitivity via u-channel beyond 320 GeV

\[ F = L + 3B \quad \beta = \text{BR}(\text{LQ} \to \text{eq}) \]

\[ LQ \to e\nu \]

\[ LQ \to e\nuq \]

\[ S_{0,L} \quad (F=2, \beta = 0.5) \]

New D0 limit

\[ S_{0,L} (e^{+}u, \nu d) \]

H1 prelim. single LQ
H1 (94-00) single LQ
D0 pair prod.
L3 indir. limit

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Searches for New Physics with High Energy Colliders - PIC 2009 - 6
Leptoquarks at the Tevatron

- Searches for pair production
  - No sensitivity to $\lambda$
- All 3 LQs generations accessible
- Now stringent limits on 1$^{\text{st}}$ generation LQs
  - Searches performed in $e\mu e\mu$ and $e\mu \text{MET}+j$
  - Lower sensitivity for small $\beta$

Limits for scalar LQs masses (in GeV):

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>scalar</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>235</td>
</tr>
<tr>
<td>0.5</td>
<td>284</td>
</tr>
<tr>
<td>1</td>
<td>299</td>
</tr>
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</table>
**2\textsuperscript{nd} and 3\textsuperscript{rd} generation Leptoquarks**

- **2\textsuperscript{nd}:** Searches in the $\mu j \mu j$ and $\mu j$ MET (D0)

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$M_{\text{LQ}}^{\text{obs}}$ (GeV)</th>
<th>$M_{\text{LQ}}^{\exp}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>185</td>
<td>181</td>
</tr>
<tr>
<td>0.5</td>
<td>270</td>
<td>272</td>
</tr>
<tr>
<td>1</td>
<td>316</td>
<td>316</td>
</tr>
</tbody>
</table>

- **3\textsuperscript{rd}:** Searches in the $\tau b \tau b$ and $bb + \text{MET}$

$\Rightarrow$ For $\beta=0$: $M_{\text{LQ}} > 214$ GeV

$\Rightarrow$ Charge 4/3, $\beta(\text{LQ} \rightarrow \tau b) = 1$, $M_{\text{LQ}} > 210$ GeV

$\Rightarrow$ Charge 1/3, $\beta(\text{LQ} \rightarrow \nu b) = 1$, $M_{\text{LQ}} > 252$ GeV
SuperSymmetry

- Relates fermion ⇔ bosons \(\Rightarrow \) 1 supersymmetric partner for each SM particle
- New quantum number: R-parity, \(R_p = (-1)^{3(B-L)+2S}\)
- Superpartners should be heavy (not observed) \(\Rightarrow\) SUSY is broken
- Minimal field content of the MSSM (Minimal SUSY):

\[
\begin{array}{|c|c|c|}
\hline
\text{spin 0} & \text{spin 1/2} & \text{spin 1} \\
\hline
\text{squarks: } \tilde{q}_R, \tilde{q}_L & q & \\
\hline
\text{gluinos: } \tilde{g} & g & \\
\hline
\text{sleptons: } \tilde{\ell}_R, \tilde{\ell}_L & \ell & \\
\hline
\text{neutralinos: } \tilde{\chi}^0_{i=1-4} & Z^0, \gamma & \\
\hline
\text{Higgs: } H^\pm & \text{charginos: } \tilde{\chi}^{\pm}_{i=1-2} & W^\pm \\
\hline
\end{array}
\]

\(\Rightarrow\) A priori > 100 parameters

\(\Rightarrow\) Need to define a specific breaking scheme
Some SUSY models

• mSUGRA: gravity mediated SUSY breaking

  ➔ \text{M}_0, \text{m}_{1/2}, \text{A}_0, \text{tan} \beta, \text{sign}(\mu)

  \text{M}_0: \text{common scalar mass at GUT scale}
  \text{M}_{1/2}: \text{common gaugino mass at GUT scale}
  \text{A}_0: \text{common trilinear coupling at GUT scale}
  \text{sign}(\mu): \text{sign of higgsino mass parameter}
  \text{tan} \beta: \text{ratio of Higgs vev's}

• Rp conserved

  ➔ SUSY particles pair-produced
  ➔ Cascade decay to the lightest sparticle (LSP)
  ➔ If LSP = neutralino ➔ Missing transverse energy (MET)

• Rp not conserved

  ➔ Single production of sparticles possible

• GMSB: gauge mediated SUSY breaking

  ➔ The LSP is a light gravitino
  ➔ The phenomenology depends and the next-to-LSP and its lifetime
Squarks and gluinos

- One of the main stream at the Tevatron: squarks and gluinos produced via strong interaction
  - Signature: 2-4 jets + MET
  - Large cross section, large background

\[
\begin{align*}
  p\bar{p} &\rightarrow \tilde{g}\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}^0 q\tilde{\chi}^0 X \\
  p\bar{p} &\rightarrow \tilde{g}\tilde{q} \rightarrow q\tilde{q}\tilde{\chi}^0 q\tilde{\chi}^0 X \\
  p\bar{p} &\rightarrow \tilde{g}\tilde{g} \rightarrow q\tilde{g}\tilde{\chi}^0 q\tilde{\chi}^0 X
\end{align*}
\]

- gluinos: \( m > 208 \text{ GeV} \) (CDF), 308 GeV (D0) (for all squarks masses)
- squarks: \( m > 380 \text{ GeV} \) (CDF, D0) (for all gluinos mass)
- In mSUGRA: regions not accessed by LEP excluded
Stop

- Stop and sbottom expected to be light
- For light stop $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ not allowed
  - Dominant decay mode depends on other SUSY masses
  - If stop is next-to-LSP: $\tilde{t} \rightarrow c + \tilde{\chi}_1^0$

- New CDF analysis exploiting charm tagging (reduces background from bottom jets)
Stop searches in the di-lepton channel

- If sneutrinos lighter than stop: dominant decay $\tilde{t} \rightarrow b + \ell + \tilde{\nu}$ with $\tilde{\nu} \rightarrow \nu + \tilde{\chi}_1^0$

  ➔ Signature similar to $t\bar{t}$ di-leptons but with soft leptons and different kinematics

  ➔ Most sensitive channel: $2b + e + \mu +$ MET

- D0: $3.1 \text{ fb}^{-1}$, $e\mu$ channel only
- CDF: $1.1 \text{ fb}^{-1}$, all channels

  ➔ Difficult backgrounds: QCD multi-jets, lepton+fake, similar topologies ($Z \rightarrow \tau\tau$, $t\bar{t}$, WW)

  ➔ Exclusion limits above top mass: $M(\text{stop}) > 180 - 200$ GeV
Stop searches in top-like events

- If chargino is lighter than stop: top-like decays dominant
  $$\tilde{t} \rightarrow b\tilde{\chi}^+ \rightarrow b\ell\nu\tilde{\chi}^0$$
  ➔ Search stop in lepton+jet top sample (D0)
  ➔ Search stop in top di-lepton sample (CDF)
  ➔ Differences in mass distribution of stop and kinematics

- Extract limits in 3D-space: $$m_{\tilde{t}}, \ m_{\tilde{\chi}^\pm}, \ m_{\tilde{\chi}^0}$$
**Sbottom**

- At large $\tan\beta$, sbottom may be the lightest colored particle
- Decay: $\tilde{b} \rightarrow b + \tilde{\chi}_1^0$
  - 2 b-jets + MET
  - Visible energy in the event depends on $\tilde{b} - \tilde{\chi}_1^0$ mass difference $\Delta m$

$\Rightarrow$ sbottom up to masses $\sim 250$ GeV are excluded
Sbottom: an alternative way

- If sbottom is light enough, it will be produced via gluino decay
- For similar masses gluino cross section is larger than sbottom cross section

➔ 4 b-jets + MET
➔ Low background signature
➔ But large model dependences
➔ Dependence on gluino mass

➔ Competitive results for $M(\text{gluino}) \sim M(\text{sbottom})$
Search for Charginos and Neutralinos

- One of the golden channel at Tevatron for SUSY: \( \tilde{\chi}^\pm \tilde{\chi}_2^0 \rightarrow 3\ell + \text{MET} \)
  - Cross section (EW) relatively small
  - Low \( P_T \) leptons
  - But clean signature: 3 leptons + MET

- Chargino masses up to 176 GeV probed
- Sensitivity degrades with increasing tan \( \beta \)
**Rp-Violating SUSY at the Tevatron**

- If RpV, resonant production of sneutrino possible
  - Very clean topologies: 2 isolated leptons $e\mu$, $e\tau$, $\mu\tau$
  - Low SM background ($WW, ZZ/\gamma^* \rightarrow \tau\tau$)
- D0: $e\mu$ channel with 4.1 fb$^{-1}$
- CDF: 1 fb$^{-1}$ only but $e\tau$ and $\mu\tau$ also investigated

Limits beyond LEP results
If RpV, resonant production of squarks possible at HERA

- \( e^{-j}, \nu^{-j} \) decays and cascade decays via gauginos

  Many topologies to search for

- Limits derived on squark mass and \( \lambda'_{1j1} \) and \( \lambda'_{11k} \) with \( j, k = 1, 2 \)

- For \( \lambda' = 0.3 \)

  - u-type squarks excluded up to 275 GeV
  - d-type squarks up to 290 GeV
In GMSB, usually, allows neutralino decay in a photon and a gravitino (LSP)

\[ \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \quad (\tau_{\tilde{\chi}_1^0} < 2 \text{ ns}) \]

Final states with 2 \( \gamma \) + MET

\[ m(\tilde{\chi}_1^0) > 125 \text{ GeV} \]
\[ m(\tilde{\chi}_1^\pm) > 229 \text{ GeV} \]

CDF Run II Preliminary

\[ m(\tilde{\chi}_1^0) > 149 \text{ GeV} \quad (\tau_{\tilde{\chi}_1^\pm} = 0 \text{ ns}) \]
Large Extra Dimensions?

- If gravity propagates in 4+n dimensions, the fundamental Planck scale $M_D$ could be small
  \[ M_{Pl}^2 = 8\pi R^n M_D^{n+2} \]

- Real graviton emission
  the Tevatron:
  \[ g + G_{KK} \Rightarrow \text{mono jet} + \text{MET} \]
  \[ \gamma + G_{KK} \Rightarrow \gamma + \text{MET} \]
  \[ \Rightarrow \text{Directly sensitive to } M_D \]

- CDF: combine both, D0 only $\gamma$

- Lower limits on $M_D$ in GeV:

<table>
<thead>
<tr>
<th>$n$</th>
<th>CDF</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1400</td>
<td>970</td>
</tr>
<tr>
<td>6</td>
<td>940</td>
<td>831</td>
</tr>
</tbody>
</table>
Indirect LED Searches at the Tevatron

- Virtual KK gravitons exchange
  - Enhancement of the production of fermion or boson pairs
  - the Drell-Yann or di-photon cross sections
  - di-jets

- Sensitivity on the effective Planck scale $M_s$ (ultraviolet cutoff)
  - **D0**: combining di-e and di-$\gamma$:
    $M_s > 1.62$ TeV (GRW formalism)
  - **CDF**: di-jets:
    $M_s > 1.66$ TeV (GRW)
    - Uses jet angular distributions
      $\chi = \exp(|y_1-y_2|)$

[D0, PRL 102(2009)051601] [arXiv:0906.4819]
Indirect LED Searches at HERA

- At HERA: graviton exchange can affect $\text{eq} \rightarrow \text{eq}$ scattering

  » Contact interaction term with an effective coupling:

$$\eta_G = \pm \frac{1}{M_S^2}$$

  » Look for deviations in the $\text{ep}$ NC DIS cross section

  - Limit from all ZEUS data: $M_S(\pm 1) = 0.94 \text{ TeV}$
Signature Based Searches

• Facing the large variety of BSM models ….

➔ Tendency to develop more general signature based searches
➔ Different possible BSM interpretations of a same signal

• Look for new narrow resonances
• Topologies with low SM expectation
• Topologies specific particles
• More general: all possible final states …
Di-electron Resonances

- $e^+ e^-$ resonance $\rightarrow$ new $Z'$ boson?

$\Rightarrow$ CDF fluctuation at 240 GeV not confirmed by D0

$\Rightarrow$ $M_{Z'} < 963$ GeV excluded.
• Use $m^{-1}$ for a constant resolution

- Data well described
- Z' excluded up to 1030 GeV
- Limits set also on other models
Di-jet resonances

- Investigate the di-jet distribution
- Poorer resolution than for leptons
- Large QCD background
  - Good agreement with NLO pQCD predictions
  - Excited quarks excluded up to 870 GeV (f=f'=fs)
  - W' up to 840 GeV
  - Z' up to 740 GeV

\[ \begin{align*}
\text{CDF Run II Data (1.13 fb}^{-1} \text{)} & \quad \text{Fit} \\
300 \text{ GeV/c}^2 & \quad 500 \text{ GeV/c}^2 \\
700 \text{ GeV/c}^2 & \quad 900 \text{ GeV/c}^2 \\
1100 \text{ GeV/c}^2 & \\
\end{align*} \]
Heavy resonances: $X \rightarrow VV$

- Search for $X \rightarrow WW/ZZ \rightarrow (ev)(jj)$ by CDF
- Analysis based on SM di-boson production studies
  - Look for possible excess ($e + 2$ jets + MET)
- Selection: $W \rightarrow ev$ with 2 solutions
  - di-jets in $[65, 95]$ for WW
  - di-jets in $[70, 105]$ for WZ
- Small fluctuation in WW at $\sim 600$ GeV
- Limit set within different models
Isolated Leptons at HERA

- Events with high $P_T$ $e$, $\mu$, $P_T^{\text{miss}}$ and hadronic system ($P_T^X$)
  
  $\Rightarrow$ H1, for $P_T^X > 25$ GeV, in e+p only an excess of data events ($2.4\sigma$)

  $\Rightarrow$ Not confirmed in ZEUS analysis

- H1+ZEUS combined data: $0.98 \text{ fb}^{-1}$

- For $P_T^X > 25$ GeV, in e+p:
  
  data/SM: $23 / 14.02 \pm 1.94$

\[ \Rightarrow \text{In e+p: } 1.9\sigma \text{ positive fluctuation of data, driven by H1 events} \]
Multi-Leptons at HERA

- Low and well controlled SM contribution
- Mainly produced via $\gamma-\gamma$ in the SM
- Look for events with at least 2 isolated high-$p_T$ leptons ($e, \mu$)
  ➔ $ee, eee, e\mu, \mu\mu, e\mu\mu$
- H1+ZEUS combined analysis (0.94 fb$^{-1}$)
  ➔ $\Sigma p_T$: hardness of the events

⇒ Striking events observed for $\Sigma p_T > 100$ GeV by H1 and ZEUS
⇒ Only in e+p: $7 / 1.94 \pm 0.17$

⇒ Probability of 0.4% (2.6σ)
Signature Based Searches with Photons

- Various topologies with high $P_T$ photons investigated by CDF
  - Model independent

- $\gamma\gamma + X$, $X = e, \mu, \tau, \gamma$, MET with up to 2 fb$^{-1}$

- lepton + $\gamma$ + b-jet + MET

<table>
<thead>
<tr>
<th># events</th>
<th>$e\gamma bE_T$</th>
<th>$\mu\gamma bE_T$</th>
<th>$(e + \mu)\gamma bE_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted</td>
<td>18.4 ± 2.4</td>
<td>12.6 +1.9</td>
<td>31.0 +4.1</td>
</tr>
<tr>
<td>Observed</td>
<td>16</td>
<td>12</td>
<td>28</td>
</tr>
</tbody>
</table>

- $\gamma +$ jet + b-jet + MET
  - $617$ (obs.) / $607 \pm 114$ (exp.)

All consistent with SM expectations
The most general signature based search: investigate ALL possible topologies

- Search for deviations to the SM in many (all) final states
- Independent of any BSM assumptions: no specific selections
  - More general
  - Lower sensitivity than dedicated searches

- Allow a statistical quantification of observed discrepancies

- Performed by H1, CDF and D0, using different strategies
Investigate all high $P_T$ topologies

- Pioneered by H1, full HERA data, 463 pb$^{-1}$
- Isolated particles
  - $e, \gamma, \mu, \text{jet, } \nu$
- A common phase space
  - $P_{T\text{part}} > 20 \text{ GeV}$
  - $10 < \theta_{\text{part}} < 140 \text{ deg.}$

Good agreement with SM in most classes

- Good understanding of the detector and of SM processes

[H1, PLB 674(2009)257]
• Look for regions of data/SM discrepancies in 1D distributions:
  ➔ $\sum p_T, M_{\text{all}}$
  ➔ Topological variables: angle and energy sharing

- Largest deviation observed in e+p, in e-e channel for $M_{\text{all}} (\sim 2.5\sigma)$
- Global probability to observe such deviation in one of the channels: 12%
General Search at the Tevatron

- Also performed by CDF and D0
  - A common framework used by CDF and D0
  - CDF: all topologies (399)
  - D0: only topologies with 1 lepton (180)

- Adjust the SM simulation to data at low energies
  - $O(40)$ k-factors used, determined in a dedicated algorithm
  - Check data/SM discrepancies at high energies
• Check data/SM in rate and shape of distribution

Most significant discrepancies found:
- attributed to QCD and detector simulation deficits

• Look for bumps in $\sum p_T$ distributions

QCD mis-modeling

CDF Run II Data
Other
Pythia $jj$ : 0.1%
Overlaid events : 0.2%
Pythia $bg$ : 4.7%
Pythia $jj$ : 94.9%
Summary

- Beyond the SM: we are searching for the unknown …
  ➔ A large variety of possibles searches

- A large domain already explored using high energy colliders
  ➔ Following model hints
  ➔ More generic tests of the SM validity

- Yet, no evidence for new physics at colliders

- Soon, a new tool for physicists to play with: the LHC
  ➔ Should open new windows on our universe

humanity has not seen most exciting moment since my first electric train