Workgroup-I
exotics subgroup summary -I

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Flavour in the era of the LHC
26-28 March 2007
5 meetings between November 2005 and March 2007

Non-supersymmetric models beyond SM

- 20 contributions,
- Both theoretical and phenomenological studies,
- ~50 pages for the yellow report
Non-SUSY BSM Chapter

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Thank you to all ..
Motivations

- SM is like your old car: *you know it has problems*!
  - Hierarchy problem: $\delta H \sim M_H$
  - Non-unification for EW and Strong Forces
  - Seemingly arbitrary fermion mass & mixings
  - Unknown source of baryogenesis

- LHC is to start soon:
  - at the end of 2007 $\sqrt{s}=0.9$ TeV
  - In 2008 LHC will provide $\sqrt{s}=14$ TeV,
    - few years at 10 fb$^{-1}$/yr: low luminosity
    - then 100 fb/yr: nominal or design luminosity

- What flavour physics can be done at this new era?
  - What are the extensions to SM?
“Exotic” models

A brief summary of popular models:

- **Grand Unified Theories:**
  - SM gauge group is embedded into a larger one like SO(10), to unify EW and QCD.
  - additional fermions and bosons predicted.

- **Little Higgs models:**
  - spontaneously broken global symmetry to impose a cut-off ~10 TeV.
  - additional bosons and quarks introduced to cure the hierarchy problem.

- **Extra Dimensions:**
  - Low Planck scale in d dimensional theory solves the hierarchy problem between EW and Gravitational couplings.
  - Excitations of SM bosons and fermions are predicted.

*These models do **not** exclude supersymmetry.*
0. Introduction

1. Searches for scalars
   1.1. Babu-Zee model

2. Searches for quarks
   2.1. iso-singlet quarks
   2.2. iso-doublet quarks

3. Searches for leptons
   3.1. heavy neutrinos

4. Searches for vector bosons
   4.1. Z’ searches
   4.2. W’ searches

5. Conclusions
1. Searches for scalars

Relevant Models

- **2HDM**
  - A 2\textsuperscript{nd} Higgs doublet to induce baryogenesis
  - CPV H can be searched via top quarks \(\text{(see top sub-group report)}\)

- **Little Higgs**
  - A Higgs triplet to cancel its own loop contribution to \(m_H\)
  - Higgs correction is small, new Higgs might be inaccessible

- **Babu-Zee model**
  - Two new scalars to induce the \(\nu\) masses at 2-loop level.
  - New scalars can be accessible at the LHC
1.1 Babu-Zee model

- $h^+$ and $k^{++}$, couple to leptons, give Majorana $\nu$ mass.
- $\nu$ data predicts $M_{h,k} \sim O(0.1 - 1.0 \text{ TeV})$
- Signature: $q\bar{q} \rightarrow \gamma^*, Z^* \rightarrow k^{--}k^{++}$
  $k^{\pm\pm} \rightarrow h^\pm h^\pm$
  $k^{\pm\pm} \rightarrow \ell^\pm\ell^\pm$
  BR($k\rightarrow hh$) model dependent values [0.1 - 0.8] scanned

- $\sigma_{\text{pair production for } k, h}$
  PRD67, 073010

Excluded by $\mu \rightarrow e\gamma \tau \rightarrow 3\mu$
2. Searches for quarks

Relevant Models

- Iso-singlets predicted in
  - GUTs, Little Higgs, EDs
  - W, Z, H vertex modified
  - $\gamma, g$ vertex same as SM

- Iso-doublets: the 4th SM-like family
  - not yet ruled out for $m_\nu > m_Z/2$

- Extra Dimensions
  - KK excitations of known quarks
  - additional quarks with $Q = 1/3, 2/3, 5/3$

Iso-singlet quark pair production at LHC (tree level)
<table>
<thead>
<tr>
<th>$Q_e$</th>
<th>$l_3=0$ singlet</th>
<th>$l_3=\pm 1/2$ doublet</th>
<th>$Q_e = l_3 + \frac{1}{2}Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1/3</td>
<td>E6, $D$</td>
<td>$4^{th}$ Fam, $d_4/b'$</td>
<td>$g_V = l_3 - 2\sin^2\theta_w$</td>
</tr>
<tr>
<td>2/3</td>
<td>LH, $T$</td>
<td>$4^{th}$ Fam* $u_4$</td>
<td>$g_A = l_3$</td>
</tr>
<tr>
<td>5/3</td>
<td>EDs,</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*LHC relevant material is also in ATLAS TDR
2.1 Iso-singlets $Q = -1/3$

- E$_6$ model introduces new particles:

$$SUC(3) \times SU_W(2) \times U_Y(1) \subset E_6$$

- One iso-singlet quark per family:

$$\begin{pmatrix}
  u_L \\
  d_L
\end{pmatrix}, u_R, d_R, D_L, D_R \begin{pmatrix}
  c_L \\
  s_L
\end{pmatrix}, c_R, s_R, S_L, S_R \begin{pmatrix}
  t_L \\
  b_L
\end{pmatrix}, t_R, b_R, B_L, B_R$$

Assumptions:

1. In-family mixing bigger than between family mixing
2. D quark is the lightest, like SM: most accessible in LHC
3. E$_6$ gauge bosons heavy & don’t interact w/ SM bosons

$$D \rightarrow Z d \quad D \rightarrow W u$$

<table>
<thead>
<tr>
<th>BR</th>
<th>33%</th>
<th>66%</th>
<th>if there is no Higgs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25%</td>
<td>50%</td>
<td>if Higgs is light</td>
</tr>
</tbody>
</table>
Discovery for $Q = -1/3$

- uses pp$\rightarrow$DD pair production
  - independent of d-D mixing angle
  - with both the D$\rightarrow$Zd and Z decays leptonically (e,μ)
  - signal is 4 leptons + 2 jets
- ATLAS FastMC based study with simple cuts
- $m_D$ scan up to 1.2 TeV, channel efficient up to $\sim 1$ TeV

### high event yield for low masses
$m_D = 600$ GeV
$\int Lumi = 100$ fb$^{-1}$

### optimized cuts for high masses
$m_D = 1$ TeV
$\int Lumi = 100$ fb$^{-1}$
Estimation for other D mass values using only $D \rightarrow Z_d$ channel

- **1 fb$^{-1}$**
  - $3\sigma : m_D \approx 500$ GeV
  - $5\sigma : m_D \approx 350$ GeV

- **10 fb$^{-1}$**
  - $3\sigma : m_D \approx 750$ GeV
  - $5\sigma : m_D \approx 650$ GeV

- **100 fb$^{-1}$**
  - $3\sigma : m_D \approx 940$ GeV
  - $5\sigma : m_D \approx 1050$ GeV

Graph showing the discovery reach for different mass values of the D quark with Tevatron run.
Mixing for $Q=-1/3$

- Jet associated single production & decay
  - $pp \rightarrow jD \rightarrow jjZ$ where leptonic $Z$ decays are considered
- Production $\sigma \sim (\sin\Phi)^2$, where $\Phi = d-D$ mixing angle
  - Good for measuring $\sin\Phi$
- Generator level study with cuts

- $3\sigma$ signals can be rescaled for different $\sin\Phi$ values at any mass
- $30, 100, 300 \& 1000$ fb$^{-1}$ reach limits are given
- With $300$ fb$^{-1}$ current mixing limits could be enhanced 2 times
Higgs searches & $Q = -\frac{1}{3}$

- $d$-$D$ mixing leads to $dDh$ vertex at tree level
- this can be exploited for a double discovery: light $H$ & $D$
- pair production mode considered for ATLAS using FastMC
  - $m_D = 250$ - 1000 GeV range scanned

```latex
\begin{tabular}{|c|c|c|c|}
\hline
$D_1$ & $D_2$ & BR & expected final state \\
\hline
$D \rightarrow h j$ & $D \rightarrow h j$ & 0.029 (0.053) & $2j \ 4j_b$ \\
$D \rightarrow h j$ & $D \rightarrow Z j$ & 0.092 (0.120) & $2j \ 2j_b \ 2l$ \\
$D \rightarrow h j$ & $D \rightarrow W j$ & 0.190 (0.235) & $2j \ 2j_b \ l \ E_T,miss$ \\
\hline
\end{tabular}
```

- $5\sigma$ Higgs discovery in $DD \rightarrow Whjj$ channel can be made using 100 fb$^{-1}$ if $m_D < 700$ GeV
- If $m_D < 630$ GeV, this channel becomes as efficient as $h \rightarrow \gamma\gamma$. (i.e. 8$\sigma$ in 100 fb$^{-1}$)

\[ \int Lumi = 10 \text{ fb}^{-1} \]
\[ m_D = 250 \text{ GeV} \]
\[ m_H = 120 \text{ GeV} \]
Up type quark T, predicted by LH & GUT models

T decays via W, Z & H (BR similar to -1/3 quark) to b and t quarks.

pair production considered with all decay modes with at least 1 W decaying leptonically

ATLAS FastMC based study for \( m_T = 1 \) TeV and light Higgs

main background from tt only

<table>
<thead>
<tr>
<th>TT decay</th>
<th>signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>WbWb</td>
<td>( \ell \nu \ bb \ jj )</td>
</tr>
<tr>
<td>WbHt</td>
<td>( \ell \nu \ bbbb \ jj )</td>
</tr>
<tr>
<td>WbZt</td>
<td>( \ell \nu \ bb \ jjjj )</td>
</tr>
</tbody>
</table>
5σ reach for $T$ mass

- TT & Tj used for $\int L = 300$ fb$^{-1}$ data for only $T \to Wb$
  - $\sigma_{Tj} \sim |V_{Tb}|^2$ where $V_{Tb} \sim O(m_t/m_T)$
  - background tt only

up to 1.1 TeV using TT
above this curve using Tj

upper bound from EW precision data, $T$ parameter

$T = 0.117$ (U = 0)
$T = 0.050$

$\sigma_{Tj} \sim |V_{Tb}|^2$
For a light Higgs $T$ quark’s decays provide a large $\sigma$ enhancement.

- pair production study with pythia using signals: $T\bar{T} \rightarrow WbHt$
- main background $tt$ & $tt\, nj$ where $n=1,2,3,4,5$.

$$T\bar{T} \rightarrow HtHt$$
$$T\bar{T} \rightarrow HtZt$$

Expected signature: $\ell\nu \geq 4b_j \, 2j$

Example at $m_T=500$ GeV, $M_H=115$ GeV, $\int L=30$ fb$^{-1}$

**Log likelihood for 4b case**

<table>
<thead>
<tr>
<th>#b$_j$</th>
<th>Higgs signal significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>6.43</td>
</tr>
<tr>
<td>5</td>
<td>6.02</td>
</tr>
<tr>
<td>6</td>
<td>5.63</td>
</tr>
<tr>
<td>combined</td>
<td>10.45</td>
</tr>
</tbody>
</table>
singlets from EDs

- RS model with extended EW gauge group
- additional symmetries allows quarks $m \sim O(100)\text{GeV}$ w/ $Q = -1/3, 2/3, 5/3$
  - $q$: KK excitation of $b$ with $BR(q \rightarrow W t) \sim 50\%$ for $m_H \sim 300\text{GeV}$
- Focus on $qq$ pair prod.: $2x(q \rightarrow Wt) \rightarrow 4W \ 2b$
  - pythia level study w/ at least 1 $W$ decaying leptonically
  - main SM background has 2 $W$
  - $m_q = 500 \text{ GeV}$ & $m_H = 300 \text{ GeV}$

promising results
10 fb$^{-1}$ MC

after elimination of 1$^{st}$ hadronic $W$

bg from $tt$ and $ttH$ events
2.2 Iso-doublets

- A 4th family with heavy quarks and leptons (>200GeV)
- Could explain the observed fermion mixing & mass values, CP violation in b-s transitions
  - Not yet ruled out experimentally
- Study of channels of interest for new quark

<table>
<thead>
<tr>
<th>mixing</th>
<th>pair prod. signal</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>b' → c/u W</td>
<td>cc/uu WW</td>
<td>See next slide</td>
</tr>
<tr>
<td>b' → cW, bZ/H</td>
<td>cbWZ/H</td>
<td>FCNC, could get H as a bonus</td>
</tr>
<tr>
<td>b' → tW</td>
<td>ttWW or bb4W</td>
<td>Same signal as ED KK quarks</td>
</tr>
<tr>
<td>b' → tW, bZ/H</td>
<td>bb WW Z/H</td>
<td>b-jet to distinguish from row 2</td>
</tr>
</tbody>
</table>
4th family - discovery

- Pair production of the quarks: $d_4$, $u_4$
  - $m_{u4} \sim m_{d4}$ from DMM approach
- Scenario with mixing to 1st or 2nd generations,
  - $pp \rightarrow d_4d_4/u_4u_4 \rightarrow WWjj$
    - One $W$ decays via $e/\mu$ the other via non-b jets: $e/\mu+4j+E_T^{miss}$
- ATLAS fastMC study scanning $m = 250 - 750$ GeV

Width and $\sigma$ pair production

<table>
<thead>
<tr>
<th>$M_{q4}$ (GeV)</th>
<th>250</th>
<th>500</th>
<th>750</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma$ (MeV)</td>
<td>0.01</td>
<td>0.08</td>
<td>0.28</td>
</tr>
<tr>
<td>$\sigma$ (pb)</td>
<td>99.8</td>
<td>2.59</td>
<td>0.25</td>
</tr>
</tbody>
</table>

$m_q = 250$ GeV

$\int L = 1 fb^{-1}$

$s/\sqrt{b} \sim 120$
Quark searches seem promising in LHC;

- Still unexplored channels, unconsidered models, omitted backgrounds & ongoing collaborative work.

What about new leptons & vector bosons? see *part 2*.

High mass also seems to be feasible:

\[ m_q = 750 \text{ GeV} \quad \text{and} \quad \int L = 5 \text{fb}^{-1} \]

\[ s/\sqrt{b} \approx 5 \]

### Necessary \[ \int \text{Luminosity for } 5\sigma \text{ signal} \]

<table>
<thead>
<tr>
<th>( M_q ) (GeV)</th>
<th>250</th>
<th>500</th>
<th>750</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \int L ) (fb(^{-1}))</td>
<td>0.002</td>
<td>1.95</td>
<td>5</td>
</tr>
</tbody>
</table>
Flavour in the era of the LHC

THANK YOU FOR YOUR ATTENTION.
a Workshop on the interplay of flavour and collider physics

QUESTIONS?
First meeting:

CERN, November 7-10 2005

http://mlm.home.cern.ch/mlm/FlavLHC.html

- BSM signatures in B/K/D physics, and their complementarity with the high-pt LHC discovery potential
- Flavour phenomena in the decays of SUSY particles
- Squark/slepton spectroscopy and family structure
- Flavour aspects of non-SUSY BSM physics
- Flavour physics in the lepton sector
- $g - 2$ and EDMs as BSM probes

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QUESTIONS?
D quark pair production

- **Gluons, s channel**
  - Diagram showing gluons interacting to produce a quark pair.

- **Gluons, t channel 1**
  - Diagram showing gluons in a specific interaction channel.

- **Gluons, t channel 2**
  - Diagram showing another gluons interaction channel.

- **Up quarks, s channel**
  - Diagram showing quarks interacting through photon or Z boson.

- **Down quarks, s channel**
  - Diagram showing quarks interacting through photon or Z boson.

- **Up quarks, t channel**
  - Diagram showing quarks interacting through a W boson.

- **Down quarks, t channel 1**
  - Diagram showing quarks interacting through a W boson.

- **Down quarks, t channel 2**
  - Diagram showing quarks interacting through a W boson.
Single D quark production

- Decays involving Z would be easiest to reconstruct:

- \( m_D = 400 \ldots 2000 \) GeV cases are considered using generator level MC (CompHEP) with 2j+Z as the signal (\( \sin \Phi = 0.045 \))

- All SM processes yielding 2j+Z are also considered as background events where j can be any light jet.
is 4th SM family Possible?

Precision EW data consistent with fourth generation with a heavy neutrino.

Example exclusion plot from Novikov, Okun, Rozanov, Vysotsky, PLB 529, 2002, for:

\[ M_{D4} = 200 \text{ GeV} \]
\[ M_{U4} = 220 \text{ GeV} \]
\[ M_{E4} = 100 \text{ GeV} \]

At the minimum,
\[ \chi^2 / \text{d.o.f.} = 21.6 / 12, \quad \text{Ng} = 1.4, \]
\[ M_{v4} = 50 \text{ GeV}, \quad M_H = 116 \text{ GeV}. \]