Summary of LHC SUSY and Exotic search results

Sanjay Padhi

(On behalf of the ATLAS and CMS Collaborations)

FNAL LPC/University of California, San Diego
Amazing LHC!!!

Similar performance by ATLAS as well

- first MinBias / UE studies, particle multiplicities
- first incl. b x-section, 8/nb $\delta \sim 15\%$
- first incl. jet x-section, PF jets 60/nb $\delta \sim 20-30\%$
- first incl. W/Z x-sections, 200/nb $\Delta \sim 6.5$ GeV
- first incl. $J/\psi$ x-section, 100/nb $\delta \sim 20\%$
- first $WW$ x-section, 36/pb $\Delta \sim 40\%$
- first particle discovered by CMS: $\Xi_b$
- BSM searches continue, limits pushed
- first spin parity analysis of the boson, 17/fb
- a new boson is announced, 5/fb
- going more differential, e.g. $Z/W + j,b,c$
- first significant limit on $B_s \rightarrow \mu \nu$, $BR<1.9\times10^{-8}$
- first ZZ x-section, 1.1/fb $\delta \sim 40\%$
- first $q^*, Z^*, W$ limits, 3-36/pb >1.6, 1.1, 1.4 TeV
- first SUSY limits, 36/pb $-q$, $-g > 500-600$ GeV
- repeating the program at 8 TeV
- first top x-section, 3/pb $\delta \sim 40\%$
- first single top x-section, t-channel, 36/pb $\delta \sim 36\%$

From G. Dissertori (ETH)

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC
Outline

- Re-discovery of the Standard Model
- Search for Supersymmetry (SUSY) at the LHC
  - Searches in SUSY Colored Sector
  - Searches in SUSY Electroweak sector
  - R-parity violating searches
- Search for Exotic (non SUSY) signatures at the LHC
  - Dark Matter
  - New Physics with resonances
  - Top and Bottom like beyond SM signatures
- Summary and Conclusion
Re-discovery of the SM at the energy frontier

Similar results from CMS as well

**ATLAS** Preliminary

LHC pp $\sqrt{s} = 7$ TeV
- Theory
- Data ($L = 0.035 - 4.6$ fb$^{-1}$)

LHC pp $\sqrt{s} = 8$ TeV
- Theory
- Data ($L = 5.8 - 20$ fb$^{-1}$)

Search for Supersymmetry (SUSY) at the LHC
SUSY search strategy was driven by cross section and thus luminosity


Early analyses were dominated by broad inclusive searches
- mainly gluino and squark production

Increase in luminosity gave access to rarer channels
- Also with added motivation from Natural SUSY paradigm

It was quickly realized to develop exclusive search modes to cover full spectrum
Various constrained SUSY models like mSUGRA. CMSSM were severely put under pressure by the LHC limits!

Experiments were bound to define new benchmarks and use simplified SUSY models in order to present the results and its interpretation.

Aided by the discovery of a Higgs boson, the focus of the experimental search strategy and corresponding interpretation moves towards "Natural SUSY" scenarios:

- Expect to see dedicated 3rd generation searches

- Electroweak studies (also with Higgs in the final state)

The goal from the experiments was to leave no stone unturned.
The LHC has pushed the mass scale in constraint SUSY models to a new level!
Inclusive search for 1\textsuperscript{st} and 2\textsuperscript{nd} generation squarks

Simplified models: captures bulk of characteristics of real models

Assume 100% BR in both legs.

Normalize using SUSY NLO+NLL cross sections

Clean representation of potential (Not sure about the theory)

"Remember the gaps"

See talk by S. Paramesvaran in the parallel session
Inclusive search for 1\textsuperscript{st} and 2\textsuperscript{nd} generation squarks

\begin{align*}
\tilde{q} \rightarrow q \chi_1^0 & \quad \text{CMS-PAS-SUS-13-012} \\
\tilde{b} \rightarrow b \chi_1^0 & \quad \text{ATLAS-CONF-2013-053} \\
\tilde{t} \rightarrow t \chi_1^0 & \quad \text{ATLAS-CONF-2013-037}
\end{align*}
Inclusive search for 1\textsuperscript{st} and 2\textsuperscript{nd} generation squarks

ATLAS and CMS 1st & 2nd generation squark limits are only better than the 3\textsuperscript{rd} generation when assuming BR=100%! Eight-fold mass degeneracy!!

\begin{itemize}
  \item \textbf{Direct squark}
  \[ m_{\text{SUSY}} = m_{\tilde{q}} \]
  \[ \tilde{q} \rightarrow q \chi_1^0 \text{CMS-PAS-SUS-13-012 (8x mass)} \]
  \[ \tilde{u}_L \rightarrow q \chi_1^0 \text{CMS-PAS-SUS-13-012} \]
  \[ \tilde{b} \rightarrow b \chi_1^0 \text{ATLAS-CONF-2013-053} \]
  \[ \tilde{t} \rightarrow t \chi_1^0 \text{ATLAS-CONF-2013-037} \]
\end{itemize}

\textbf{CMS-SUS-PAS-13-012}

Signature: Jets + \text{E}_T^{\text{miss}}

Limit assumes only one light squark (e.g. \( u_L \)) and decoupled gluino (as before).
Inclusive search for gluinos cascade decays (via squarks)

Hadronic searches probes:
- Gluino masses up to 1.2 TeV
- "Compressed regions" better covered
  - in inclusive Jet/MET study
Inclusive search for gluinos cascade decays (via stops)

Gluino via stops:

- Gluino masses up to 1.3 TeV using 1-lepton analysis
- A large “compressed” region available for future studies
Inclusive search for gluinos cascade decays (via stops and sbottoms)

Gluino via stops or sbottoms:

- Gluino masses up to 1.32 TeV using One lepton analysis
- A large “compressed” region available for future studies

\[ \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0 \]
Inclusive search for gluinos cascade decays

See talk by L. Morvaj & A. Tudorache in the parallel session

Probe using inclusive signatures (See next)
Inclusive search for gluinos cascade decays

Low \( \frac{m_{\text{SUSY}} - m_{\text{LSP}}}{m_{\text{SUSY}}} \) (Compressed region)  \text{ATLAS-CONF-2013-062, ATLAS-CONF-2013-007}

Use loose/medium signal regions to probe topologies with \( m_{\text{SUSY}} \sim m_{\text{LSP}} \)
- In this region, jets from gluinos/squarks are very light (relaxed Meff cuts)
- Large SM backgrounds

- Sensitive to Initial State Radiation (ISR) jets boosted by heavy particle production

Significantly less stronger limits ....
Third generation searches

Mind the gap! $\Delta m = m(\tilde{t}) - m(\chi^0)$

- $\Delta m < m(W)$
- $m(W) < \Delta m < m(t)$
- $\Delta m > m(t)$

$\tilde{t} \rightarrow bW^* \tilde{\chi}_1$
$\tilde{t} \rightarrow c\tilde{\chi}_1$
$\tilde{t} \rightarrow b\tilde{\chi}_1$
$\tilde{t} \rightarrow bW^* \tilde{\chi}_1$
$\tilde{t} \rightarrow t\tilde{\chi}_1$ (on-shell top)
$\tilde{t} \rightarrow t\tilde{\chi}_1$ (off-shell top)

BR=100%
all limits are observed nominal
95% CLs limits
RP conserved

$m_{\text{SUSY}}$ [GeV]
Direct stop pair production

See talk by D. Hare in the parallel session

Covers a large range of mass scale.
Excluded regions up to 750 GeV (100% BR)
Direct stop pair production

See talk by D. Guest in the parallel session

**ATLAS Preliminary**

- Observed limits
- Expected limits

All limits at 95% CL

CDF 2.6 fb$^{-1}$ [1203.4171]

\[ \tilde{t}_1 \rightarrow b \tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow W^{(*)} \tilde{\chi}_1^0 \]

New analyses: stop → charm LSP, stop2 → stop1+Z

\[
\begin{align*}
\tilde{t}_1 &\rightarrow c \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \\
\end{align*}
\]

\[ m_{\tilde{t}_1}[\text{GeV}] \]

\[ m_{\tilde{\chi}_1^0}[\text{GeV}] \]

\[ m_{\tilde{\chi}_1^\pm}[\text{GeV}] \]

\[ m_{\tilde{\chi}_1^0} = m_{\tilde{t}_1} + 5 \text{ GeV} \]

\[ m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1} + 10 \text{ GeV} \]

\[ m_{\tilde{\chi}_1^0} = 2 \times m_{\tilde{\chi}_1^0} \]

\[ L_{\text{int}} = 20 - 21 \text{ fb}^{-1} \quad \sqrt{s} = 8 \text{ TeV} \]

\[ L_{\text{int}} = 4.7 \text{ fb}^{-1} \quad \sqrt{s} = 7 \text{ TeV} \]

\[ 0L, \text{ ATLAS-CONF-2013-024} \]

\[ 1L, \text{ ATLAS-CONF-2013-037} \]

\[ 2L, \text{ ATLAS-CONF-2013-065} \]

\[ 2L, \text{ ATLAS-CONF-2013-048} \]

\[ 0L, \text{ ATLAS-CONF-2013-048} \]

\[ 0L, \text{ ATLAS-CONF-2013-068} \]

\[ 0L, \text{ ATLAS-CONF-2013-068} \]

\[ 0L, \text{ ATLAS-CONF-2013-048} \]

\[ 1L, \text{ ATLAS-CONF-2013-037, ATLAS-CONF-2013-063} \]

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\[ 1L, \text{ ATLAS-CONF-2013-037, ATLAS-CONF-2013-063} \]
Direct sbottom pair production

Sbottom mass up to 650 GeV is excluded
In pure EW sector these limits are weak: opportunity to explore using 13/14 TeV LHC

100% BR usually not realized
Enriched leptonic final state
SUSY Electroweak production

Enriched leptonic final states

Limits are weak in M1, M2 and \( \mu \) space – See arXiv:1309.7342

Direct slepton production

See talk by S. Williams in the parallel session
\[
\Delta L_{RPV} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \ldots
\]

Lepton enriched final states
(With no MET) SUS-13-003

Probes stops in RPV mode up to 1.1 TeV (ATLAS Similar)
Same sign dilepton study can also constrain RPV gluino decays

Gluino mass up to 950 GeV can be excluded

ATLAS: See talk by Benitez in the parallel session
Search for Exotic (non SUSY) signatures at the LHC
Dark Matter and Monojets

Pair-production of DM (χ) characterized by a contact interaction effective theory

Derived limits using LHC data and compared to direct-detection experiments

ATLAS & CMS results are similar for 7 TeV, improved with 8 TeV

Started to extend simple contact interaction scenarios to new operators – scan over mediator mass

See talk by Olschewski/McKee

See talk by P. Sorensen in the parallel session
Mono-lepton Dark Matter

Consider two couplings and interferences

Vector- and axial-vector like couplings considered

Unlike monojets, they have interference effects

Parameterize interference effects by $\zeta$ (See $W^+$ right)

First LHC results on “monolepton” dark matter
New Physics with resonances – di-leptons

Event selection

- ATLAS: Isolated leptons with $p_T(e_1, e_2) > (40, 30) \text{ GeV}$, $p_T(\mu_1, \mu_2) > 25 \text{ GeV}$
- CMS: Isolated leptons with $p_T(e_1, e_2) > 35 \text{ GeV}$, $p_T(\mu_1, \mu_2) > 45 \text{ GeV}$

Backgrounds

- $Z/\gamma^*, \text{ttbar}, tW, VV, Z \rightarrow \tau\tau$, multi-jet with fakes
- estimated using functional fits

Limits set on variety of narrow resonance models
The highest-mass central dijet very well measured event. Two central jets with invariant mass of 4.7 TeV

\[ m_{jj} = 4.7 \text{ TeV} \]
\[ P_T (j_1, j_2) = 2.3 - 2.2 \text{ TeV} \]
\[ E_T^{\text{miss}} = 47 \text{ GeV} \]
Search dijet spectrum for narrow resonances

- Background fit to smooth

\[ \frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^P_1}{x^{P_2+P_3\ln(x)}} \]

<table>
<thead>
<tr>
<th>M(q^*) 95% CL</th>
<th>Luminosity</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS 2011</td>
<td>4.8</td>
<td>&gt; 3.09 TeV</td>
<td>&gt; 3.55 TeV</td>
</tr>
<tr>
<td>CMS 2011</td>
<td>5.0</td>
<td>&gt; 3.27 TeV</td>
<td>&gt; 3.05 TeV</td>
</tr>
<tr>
<td>ATLAS 2012</td>
<td>13.0</td>
<td>&gt; 3.70 TeV</td>
<td>&gt; 3.84 TeV</td>
</tr>
<tr>
<td>CMS 2012</td>
<td>19.6</td>
<td>&gt; 3.75 TeV</td>
<td>&gt; 3.50 TeV</td>
</tr>
</tbody>
</table>

ATLAS Preliminary
\[ \int L \, dt = 13.0 \, fb^{-1} \]
\[ \sqrt{s} = 8 \, TeV \]

Limits also set on qq, gg and bg (Z', G_{RS} and b* models) in 0, 1 and 2 b-tags
Search for heavy resonance decaying to ttbar pairs in e and $\mu$ + jets ($X \rightarrow \text{ttbar}$)

Many models favor such resonances: $Z'$, top-color, bulk RS (KK gluon)

Search regions: Resolved jets and high lorentz boost (> 1 TeV)

Combination of MC and data-driven used

SM ttbar, Single top (+Wjets) bkg (after b-tag)

<table>
<thead>
<tr>
<th>M($Z'$ or gKK) 95%</th>
<th>Luminosity</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS $Z'$</td>
<td>14.3</td>
<td>&gt; 1.9 TeV</td>
<td>&gt; 1.8 TeV</td>
</tr>
<tr>
<td>CMS $Z'$</td>
<td>19.6</td>
<td>&gt; 2.0 TeV</td>
<td>&gt; 2.1 TeV</td>
</tr>
<tr>
<td>ATLAS gKK</td>
<td>14.3</td>
<td>&gt; 2.1 TeV</td>
<td>&gt; 2.0 TeV</td>
</tr>
<tr>
<td>CMS gKK</td>
<td>19.6</td>
<td>&gt; 2.2 TeV</td>
<td>&gt; 2.5 TeV</td>
</tr>
</tbody>
</table>

See talk by S. Liu
New Physics with resonances – ttbar (hadronic decays)

In hadronic mode the main challenge includes boosted top tagging

Top-tagging: requirement on # of subjets, jet mass and min. pair mass (W)

**ATLAS:** Fat CA (R = 1.5) jets, split and re-cluster (HEPTopTagger)

**CMS CA (R=0.8) Top-tagger**

Main backgrounds: ttbar, multijets, etc.

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*Limits on $M(G_{KK}) < 1.8$ TeV, $M(Z') < 2.5$ TeV*
New Physics with resonances – di-bosons (WZ)

$W' / \rho_{TC} \rightarrow WZ \rightarrow 3l + \text{MET}$

Analysis approach:

- Compute $M_{wz}$, taking MET into account
- Main background from SM WZ process
- Cuts are optimized for each signal regions

ATLAS: $< 1.18$ TeV @ 95% CL
CMS: $(0.17 - 1.45)$ TeV @ 95% CL

See talk by Endner/Varol in the parallel session
New Physics with resonances – di-bosons (WW/ZZ - leptonic)

Search for WW/ZZ resonance at high mass
Identify boosted in W-jets (CMS N-subjetiness)
Study performance of W-tagging in data (See next slide)

ATLAS (ZZ → lν jj), Bkg: Fit to the data

RS Graviton:
ATLAS (ZZ): mass < 850 GeV (excluded)
CMS (WW): Limit 70 – 3 fb (0.8 - 2.5) TeV
New Physics with resonances: di-bosons (WW/WZ/ZZ hadronic)

- $G_{RS} \to WW/ZZ$ and $W' \to WZ$ in dijets
  - Fully hadronic $VV$ decays, $W \to jj$ and/or $Z \to jj$
  - Jets from $W/Z$ typically boosted and merged into a single jet
  - QCD only significant background, suppressed by $|\eta_{jet1} - \eta_{jet2}| < 1.3$

- Each jet is required to pass the “W/Z-tagger”
  - pruned jet mass: $70 < M_{jet} < 100 \text{ GeV}/c^2$
  - $N$-subjettiness (same as previous): $\tau_{21} < 0.5$ for high purity, and $0.5 < \tau_{21} < 0.75$ for low

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**Graph 1:**
- CMS Preliminary, 19.8 fb$^{-1}$, $\sqrt{s} = 8\text{ TeV}$
- $\sigma \times BR(X \to qZ)$ (pb)
- $\sigma \times BR(X \to WZ)$ (pb)
- Resonance mass (TeV)

**Graph 2:**
- CMS Preliminary, 19.8 fb$^{-1}$, $\sqrt{s} = 8\text{ TeV}$
New Physics with resonances: di-bosons (WW/WZ/ZZ hadronic)

- $G_{RS} \rightarrow WW/ZZ$ and $W' \rightarrow WZ$ in dijets
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- $G_{RS1}$ ($k/M_{PL}=0.1$) $\rightarrow WW(ZZ)$ excluded in mass range 1.0 to 1.59(1.17) TeV
- $W' \rightarrow WZ$ excluded in mass range 1.0 to 1.73 TeV
- $q^* \rightarrow qW(qZ)$ excluded in mass range 1.0 to 3.23(3.00) TeV
Top and Bottom like beyond SM signatures

**Vector-Like** $T' \rightarrow tZ/tH/bW$

GIM mechanism is broken, tree level FCNC arises

Vector like multiplets with new charge

Mixing primarily with 3$^{\text{rd}}$ gen. (but not required)

**ATLAS**: $Ht+X$, $Wb+X$, $Zb/t+X$, SS.

**CMS**: 1lep, OS, SS and multi-leptons (+jets)

$\text{BR}(T' \rightarrow bW/tH/tZ) = 50/25/25\%$

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**CMS preliminary** $\sqrt{s}=8$ TeV 19.6 $fb^{-1}$

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**Observed T Quark Mass Limit [GeV]**

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**Limits between 690 and 782 GeV**

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**Nov. 22nd, 2013, “PASCOS 2013, 20-26 Nov. 2013, Taipei, Taiwan”**
Top and Bottom like beyond SM signatures

See talk by Panizzi in the parallel session

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**ATLAS Preliminary**

Status: Lepton-Photon 2013

- $\sqrt{s} = 8$ TeV,
- $\int L \, dt = 14.3 \, fb^{-1}$

![Graphs showing BR(T → Ht) for different values of m_T](image)

- $m_T = 350$ GeV
- $m_T = 400$ GeV
- $m_T = 450$ GeV
- $m_T = 500$ GeV
- $m_T = 550$ GeV
- $m_T = 600$ GeV
- $m_T = 650$ GeV
- $m_T = 700$ GeV
- $m_T = 750$ GeV
- $m_T = 800$ GeV
- $m_T = 850$ GeV

- SU(2) (T,B) doublet
- SU(2) singlet

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Sanjay Padhi

Top and Bottom like beyond SM signatures

Vector like b quarks $\rightarrow tW, bZ$ and $bH$ final states

Multi-leptons ($> 2$) + jets study ($bZbZ; tWtW; bHbH; bZtW; bZbH; \text{and } tWbH$)

SM Higgs with mass of 125 GeV is assumed

Both on- and off-shell Z mass ranges are considered

Main backgrounds: $tt\bar{t}$, dibosons and rare decays

$b \rightarrow tW$ (50%), $bZ$ (25%), $bH$ (25%)

Exclusion : 520 - 785 GeV
Top and Bottom like beyond SM signatures

See talk by Panizzi in the parallel session
### Summary of SUSY processes with mass scale excluded

#### ATLAS SUSY Searches - 95% CL Lower Limits

**Status:** SUSY 2013

<table>
<thead>
<tr>
<th>Model</th>
<th>( \xi, \mu, \tau, \gamma )</th>
<th>Jets</th>
<th>( \sum E_T ) [fb]</th>
<th>Mass limit [TeV]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSM</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>( (4.6 - 22.9) \times 10^{-1} ) fb(^{-1} )</td>
</tr>
<tr>
<td>MSUGRA/CMSM</td>
<td>1 ( e, \mu )</td>
<td>3-6 jets</td>
<td>Yes</td>
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<td>MSUGRA/CMSM</td>
<td>0</td>
<td>7-10 jets</td>
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<td>( (4.6 - 22.9) \times 10^{-1} ) fb(^{-1} )</td>
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<tr>
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</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1\( \sigma \) theoretical signal cross section uncertainty.*
Summary of SUSY processes with mass scale excluded

Summary of CMS SUSY Results* in SMS framework

SUSY 2013

m(mother)-m(LSP)=200 GeV

m(LSP)=0 GeV

<table>
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<tr>
<th>Process</th>
<th>m(mother) [GeV]</th>
<th>m(LSP) [GeV]</th>
<th>Limit [fb]</th>
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CMS Preliminary

For decays with intermediate mass,
m_{intermediate} = x_{m_{mother}} (1-x) m_{LSP}

*Observed limits, theory uncertainties not included

Only a selection of available mass limits

Probe "up to" the quoted mass limit

Nov. 22nd, 2013, “PASCOS 2013, 20-26 Nov. 2013, Taipei, Taiwan” 43

Sanjay Padhi
RPV Studies and excluded mass ranges

Summary of CMS RPV SUSY Results

\[ \tilde{g} \to q\bar{q}l\nu \, \lambda_{122} \]
\[ \tilde{g} \to q\bar{q}l\nu \, \lambda_{123} \]
\[ \tilde{g} \to q\bar{q}l\nu \, \lambda_{233} \]
\[ \tilde{g} \to qf\bar{\tau}l \, \lambda'_{231} \]
\[ \tilde{g} \to qf\bar{\tau}l \, \lambda'_{233} \]
\[ \tilde{g} \to qqqq \, \lambda''_{112} \]
\[ \tilde{g} \to qqqq \, \lambda''_{113} \]
\[ \tilde{q} \to q\bar{q}l\nu \, \lambda_{122} \]
\[ \tilde{q} \to q\bar{q}l\nu \, \lambda_{123} \]
\[ \tilde{q} \to q\bar{q}l\nu \, \lambda_{233} \]
\[ \tilde{q} \to qf\bar{\tau}l \, \lambda'_{231} \]
\[ \tilde{q} \to qf\bar{\tau}l \, \lambda'_{233} \]
\[ q_R \to qqqq \, \lambda''_{112} \]
\[ t_R \to \mu\nu\tau \, \lambda_{122} \]
\[ t_R \to \mu\nu\tau \, \lambda_{123} \]
\[ t_R \to \mu\nu\tau \, \lambda_{233} \]
\[ t_R \to t\bar{b}\tau \, \lambda'_{233} \]

Prompt LSP decays

\[ \sqrt{s} = 7 \text{ TeV} \]
\[ \sqrt{s} = 8 \text{ TeV} \]

CMS Preliminary

Mass scales [GeV]

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe "up to" the quoted mass limit

Nov. 22nd, 2013, “PASCOS 2013, 20-26 Nov. 2013, Taipei, Taiwan” 44

Sanjay Padhi
Summary of exotic processes with mass scale probed

**Extra dimensions**
- Large ED (ADD): monojet + $E_{T,miss}$
- Large ED (ADD): monophoton + $E_{T,miss}$
- Large ED (ADD): diphoton + dilepton, $m_{T,miss}$
- UED: diphoton + $E_{T,miss}$
- $S^T_{B,ED}$: dilepton, $m_{T,miss}$
- RS1: dilepton, $m_{T,miss}$
- RS1: WW resonance, $m_{T,miss}$
- Bulk RS: ZZ resonance, $m_{T,miss}$
- ADD BH ($M_{1H}/M_{0,3}$): SS dimuon, $N_{stop}$, stop
- ADD BH ($M_{1H}/M_{0,3}$): leptons + jets, $\Sigma p_T$
- Quantum black hole: djet, $F(m_T)$
- qqgg contact interaction: $Z(m_T)$
- cqql CI: $e^+e^-$, $m_{T,miss}$
- uutt CI: SS dilepton + jets + $E_{T,miss}$
- $Z'(SSM): N_{eL,miss}$
- $Z'(SM): m_T$
- $Z'$ (loopholophic color): $t\bar{t}$ + 1+jets, $m_{T,miss}$
- W (SSM): $m_{T,miss}$
- $W'$ ($\to l\nu$, $g \to g$, $m_{T,miss}$)
- Scalar LQ pair (β1): $k_{\nu}$, $m_{T,miss}$
- Scalar LQ pair (β1): $k_v$, $m_{T,miss}$
- Scalar LQ pair (β1): $k_{\nu}$, $m_{T,miss}$
- Vector-like quark: $T\to Ht+X$
- Vector-like quark: $C, C^*$
- Excited quarks: dijet, $m_{T,miss}$
- Excited quarks: $W+T$ resonance, $m_{T,miss}$
- Techni-hadrons (LSTC): dilepton, $m_{T,miss}$
- Techni-hadrons (LSTC): WZ resonance, $m_{T,miss}$
- Major neutr. (LSRM, no mixing): $2\nu$ + jets
- Heavy neutrino $\nu_L$ (type III seesaw): $Z$ resonance, $m_{T,miss}$
- Higgs ($D$ prod., BR($H^+\to l\nu$)): SS ee ($\mu\nu$), $m_{T,miss}$
- Color octet scalar: dijet resonance, $m_{T,miss}$
- Multi-charged particles (D$^+$ prod.): highly ionizing tracks
- Magnetic monopole (D$^+$ prod.): highly ionizing tracks

**New quarks**
- 4th generation: $b' \to WWbWb$
- Vector-like quark: $T' \to Ht+X$
- Vector-like quark: $C, C^*$
- Excited quarks: dijet, $m_{T,miss}$
- Excited quarks: $W+T$ resonance, $m_{T,miss}$
- Techni-hadrons (LSTC): dilepton, $m_{T,miss}$
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- Magnetic monopole (D$^+$ prod.): highly ionizing tracks

**ATLAS Exotics Searches** - 95% CL Lower Limits (Status: May 2013)

**Mass scale [TeV]**

---

Sanjay Padhi

Summary and Conclusion

BSM results from ATLAS and CMS show the breath of physics analyses

First 35 pb$^{-1}$ (2010)
- Observed all SM particles
- Validated data-driven methods for new physics searches
- First SUSY/EXO searches → Significant coverage beyond Tevatron!

Up to 5 fb$^{-1}$ using 7 TeV (2011)
- Excluded “SUSY with/using MET” and EXO up to a ~TeV mass scale

20 fb$^{-1}$ at 8 TeV (2012)
- Discovery of Higgs boson (hence understanding Natural SUSY took precedence)
- No new physics in the direct stop/sbottom sector
- “Partially” sensitive to pure SUSY electroweak sector
- Several RPV searches are ongoing or getting completed.
- Large number of BSM searches result in vast number of topologies/theoretical scenarios.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

13/14 TeV LHC will enter to a new mass scale territory!
Backup slides
Re-Discovery of the Standard Model
Naturalness in Supersymmetry

\[ \frac{1}{2} M_Z^2 = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u) \tan^2 \beta}{(\tan^2 \beta - 1)} - \mu^2. \]

“Tuned” due to the Higgs mass - Colored sector

- Individual terms on right side should be comparable in magnitude
- “Large” cancellations are “unnatural”
- \( |\mu| \) can be a measure of naturalness

\[ \Sigma \text{- arises from radiative correction} \quad \Sigma_u \sim \frac{3 f_v^2}{16 \pi^2} \times \left( m_{t_i}^2 \right) \left( \ln \left( \frac{m_{t_i}^2}{Q^2} \right) - 1 \right) \]

For, \( \Sigma \approx 1/2 M_Z^2 \rightarrow m_{t_i} \approx 500 \text{ GeV} \)

Assuming \( \mu \approx 150 \text{ (200) GeV} \rightarrow \text{Mass(stop)} \approx 1 \text{ (1.5) TeV} \)

Other heavier Higgs can easily be in the TeV mass range and is perfectly natural:

\[ m_A^2 \approx 2 \mu^2 + m_{H_u}^2 + m_{H_d}^2 + \Sigma_u + \Sigma_d \]
The key equations:

\[ \frac{m_h^2}{2} \approx -|\mu|^2 + m_u^2 + \ldots \]

\[ \delta m_u^2 \approx -\frac{3y_t^2}{8\pi^2} (m_{tL}^2 + m_{tR}^2 + A_t^2) \log \frac{M}{m_{\tilde{t}}} \]

\[ \delta m_{\tilde{t}}^2 \approx \frac{8\alpha_s}{3\pi} m_{\tilde{g}}^2 \log \frac{M}{m_{\tilde{t}}} \]

to be made more precise in any given SB-mediation scheme

see Dimopoulos, Giudice for SUGRA-mediation
Naturalness in Supersymmetry

\[ \frac{1}{2} M_Z^2 = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u) \tan^2 \beta}{(\tan^2 \beta - 1)} \]

\[ \mu^2. \]

\[ \tilde{t}_1, \tilde{t}_2, \tilde{b}_L \leftrightarrow \text{strongest coupling to the Higgs system} \]

\[ (\mu \leftrightarrow M_Z \text{ at tree level}) \]

\[ \tilde{q}_1, \tilde{q}_2, \tilde{b}_R \] heavy enough (≥ \( \tilde{g} \)) to be ~ irrelevant