Jet Substructure and New Physics Searches at the LHC

Biplob Bhattacherjee

References: BB, Manoranjan Guchait, Sreerup Raychaudhuri, K. Sridhar
&
BB and Priyotosh Bandyopadhyay

October 6, 2011
Overview of the talk

1. SM and beyond the SM(BSM) search at the LHC

   Conventional Higgs, SUSY, extra dimension search

   Difficulties
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   Conventional Higgs, SUSY, extra dimension search
   Difficulties

2. Jet substructure
   a). Resonance search
   b). top quark in the SUSY cascade
   b). Higgs boson in the SUSY cascade
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   a). Resonance search
   b). top quark in the SUSY cascade
   b). Higgs boson in the SUSY cascade

3. Summary
The Large Hadron Collider

- The Large Hadron Collider (LHC) is the highest energy collider.
- Large Hadron Collider is operating with proton proton CM energy 7 TeV.
- It has already collected about $4 \text{ fb}^{-1}$ of data in 2011.
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Higher energy, higher luminosity, multiple initial states, scan over wide energy range
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Higher energy, higher luminosity, multiple initial states, scan over wide energy range

### Disadvantage
Unknown initial states, severe backgrounds
Expectations from LHC

Standard Model predicts the existence of a real scalar ⇒ Higgs boson

Goal:
1. Discover SM Higgs boson
After discovery(!)
2. Measure Higgs boson properties: mass, spin, decay......

Other aspects:
Verify properties of known particles (top, W, Z)
1. Measurement of cross sections and compare with SM expectation
2. Precise measurement of decay properties of SM particles (e.g., decay width of top quark)
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Goal:
1. Multijet plus missing energy search (SUSY, UED)
2. Search for resonances (models with extra gauge bosons...)
3. ................

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Existence of new particles
Expectations from LHC

Model beyond the Standard Model

Existence of new particles

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Try different options
Expectations from LHC

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Theory and Experiment

Theory

- Supersymmetry
- Extra Dimension
- Technicolor
- Models with extra gauge boson
- Little Higgs
- ???

Experiment

- Lepton
- Jet
- Photon
- Missing Energy
- ???
Conventional Search Strategies
Higgs boson in SM
Electroweak precision test
(H. Flcher, M. Goebel, J. Haller, A. Hcker, K. Mnig, J. Stelzer : Gfitter group):

\[ m_h = 121^{+17}_{-6} \text{ GeV} \]
Higgs boson Production in SM

\[ \sim 36 \text{ pb} \quad (m_h=120 \text{ GeV}) \sim 5 \text{ pb} \quad (m_h=120 \text{ GeV}) \sim 3 \text{ pb} \quad (W_h+Z_h+QQ_h) \quad (m_h=120 \text{ GeV}) \]
Higgs boson Production in SM

\[ \sim 36 \text{ pb} \ (m_h=120 \text{ GeV}) \]

\[ \sim 5 \text{ pb} \ (m_h=120 \text{ GeV}) \]

\[ \sim 3 \text{ pb} \ (Wh+Zh+QQh) \ (m_h=120 \text{ GeV}) \]
Higgs boson decay

For $M_H = 120$ GeV

$Br(H \rightarrow b\bar{b}) = 0.7$ (large)

$Br(H \rightarrow \tau\bar{\tau}) = 0.07$

$Br(H \rightarrow \gamma\gamma) \sim 10^{-3}$ (very small)
Higgs boson search prospect

\[ \sigma(gg \rightarrow H \rightarrow b\bar{b}) \sim 20 \text{ pb (Highest cross section)} \]
Higgs boson search prospect

\[ \sigma(gg \rightarrow H \rightarrow b\bar{b}) \sim 20 \text{ pb} \] (Highest cross section)

Compare with \( \sigma(b\bar{b}) \sim 500 \mu b \)

**Enormous QCD background** \( \Rightarrow \) No chance to look at fully hadronic state

1. \((M_h > 140 \text{ GeV})\) \(H \rightarrow WW \rightarrow l\nu l\nu\)
2. \((M_h > 2M_Z)H \rightarrow ZZ \rightarrow 4 \text{ leptons (gold plated channel)}\)
3. \((M_h < 140 \text{ GeV})H \rightarrow \gamma\gamma\) is the best channel \((\text{BR} \sim 10^{-3})\)

Huge di-photon background, excellent mass resolution required to extract narrow peak. need good amount of data
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Huge di-photon background, excellent mass resolution required to extract narrow peak. Need good amount of data

Difficult scenario

There are scenarios where \( M_H \sim 115 – 120 \text{ GeV} \) and \( H \rightarrow \gamma\gamma \) branching is smaller than SM branching.

The Higgs boson discovery may be challenging at the LHC
Top quark production in Tevatron/LHC

Strong pair production

1. $q\bar{q} \rightarrow t\bar{t}$ (85 % at Tevatron and 15 % at LHC)
2. $gg \rightarrow t\bar{t}$ (15 % at Tevatron and 85 % at LHC)

\[ \sigma \sim 7 \text{ pb (Tevatron)} \]
\[ \sigma \sim 140 \text{ pb (LHC - 7TeV)} \]
\[ \sigma \sim 800 \text{ pb (LHC - 14TeV)} \]
### Top quark production in Tevatron/LHC

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\sigma \sim 7 \text{ pb (Tevatron)} \\
\sigma \sim 140 \text{ pb (LHC - 7TeV)} \\
\sigma \sim 800 \text{ pb (LHC - 14TeV)}
\]

#### Electroweak single production

1. $qb \rightarrow t\bar{q}$
2. $q\bar{q} \rightarrow t\bar{b}$
3. $gq \rightarrow tW$

\[
\sigma \sim 3 \text{ pb (Tevatron)} \\
\sigma \sim 300 \text{ pb (LHC - 14TeV)}
\]
Top quark decay

Within SM

\[ M_t > M_b + M_W \Rightarrow \text{dominant 2 body decay mode } t \rightarrow b W \ (\text{Br } 100\%) \]

\[ t \rightarrow W s, W d \text{ CKM suppressed} \]

\[ t \rightarrow u/c \ Z \text{ is not allowed at the tree level} \]

\[ \Gamma_{top} \sim 1.4 \text{ GeV} \]
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Final states of top quark is determined by W decay products

\[ \text{Br } (W \rightarrow q\ q') = 67\% \]
\[ \text{Br } (W \rightarrow l\ \nu) = 11\% \text{ for each } l=e,\mu,\tau \]

1. top \Rightarrow b\ jet + e/\mu + \text{MET}(\nu)
2. top \Rightarrow b\ jet + 2 \text{ light jets}
3. top \rightarrow b\ jet + \tau\ jet + \text{MET}
Final states from top quark pair

1. Fully hadronic
2. Lepton + jets
3. Dilepton + jets

Br \sim 45\% Br \sim 30\% Br \sim 5\%

Huge bkg Moderate bkg Low bkg

Compromise between statistics and background

lepton+jets channel \Leftarrow \Rightarrow Golden channel for analysis
Final states from top quark pair

1. Fully hadronic
   Br $\sim 45\%$
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Compromise between statistics and background

lepton+jets channel ⇐⇒ Golden channel for analysis
Top quark reconstruction in lepton jet channel

Consider the channel

\[ t \bar{t} \rightarrow bWbW \rightarrow b \ell \nu bqq' \]

Select signal like events:

- events with one high \( p_T \) isolated electron/muon
- 4 or more jets
- good amount of missing transverse energy
- it must contain one or two \( b \)-tagged jets
Consider the channel \( t \bar{t} \rightarrow b \, W \, b \, W \rightarrow b \, l \, \nu \, b \, q \, q' \)

Select signal like events:

- events with one high \( p_T \) isolated electron/muon
- 4 or more jets
- good amount of missing transverse energy
- it must contain one or two \( b \)-tagged jets

*Using these information it is possible to calculate 4-momenta of both top quarks.*
Hadronic top reconstruction

- Identify two light jets coming from the decay of W boson
- ISR/FSR $\iff$ more than two jets are often present
- Choose correct combination $|M_{jj} - M_W| < 20$ GeV
- If the previous inequality satisfies combine jj with one of the b jets $(M_{jjb_1})$ and $(M_{jjb_2})$.
- Choose the right combination $|M_{jjb} - M_t| < 20$ GeV
Hadronic top reconstruction

- Identify two light jets coming from the decay of $W$ boson
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Hadronically decaying top is reconstructed.
Leptonic top reconstruction

Assumption: Missing transverse energy only comes from the neutrino

\[ p_{T\nu} = p_T \]

\[ p_{X\nu} = p_X \quad \text{and} \quad p_{Y\nu} = p_Y \]

\[ M_{bl\nu} = (p_l + p_{\nu} + p_b)^2 \]

\[ |M_{bl\nu} - M_t| < 40 \text{ GeV}. \]

Leptonically decaying top is reconstructed.
Leptonic top reconstruction

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\( p_{Z\nu} \) is unknown ⇔ we need another equation

\[ M_W^2 = (p_l + p_\nu)^2 \]
\[ \alpha p_{Z\nu} + \beta p_{Z\nu} + \gamma = 0 \quad \text{Two values of } p_{Z\nu} \]
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Problem: In 10-20% cases \( p_{z\nu} \) is not real

Cause: neutrino transverse energy is overestimated

Solution: reduce neutrino transverse energy by steps of 0.1 GeV until a real solution is found.

Final step: calculate \( M_{bl\nu} = (p_l + p_\nu + p_b)^2 \)

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Leptonically decaying top is reconstructed.
An example of BSM scenario

Suppose we have a new particle $X$ with mass $M_X \sim 2$ TeV. The dominant decay mode of the new particle is $t\bar{t}$

$$q\bar{q} \rightarrow X \rightarrow t\bar{t}$$
An example of BSM scenario

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$$q\bar{q} \to X \to t\bar{t}$$

Question: Is it possible to discover particle $X$ by using conventional top tagging methods?
An example of BSM scenario

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$$q\bar{q} \rightarrow X \rightarrow t\bar{t}$$

Question: Is it possible to discover particle $X$ by using conventional top tagging methods?

Answer: No
Usual scenario

- Top quark
- Low $P_T$
- Angle not small
- 3 distinct jets
- $b$ quark
- $W$
- $q$
- $q'$

Jet 1
Jet 2
Jet 3
Difficulties

1. Leptons are not isolated
2. Number of jets may be less than 4 (jet merging)
3. B-tagging for high energy jet efficiency is very poor
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Supersymmetry search

R parity Conserving MSSM

Typical search channel: Multijet + leptons + missing energy

\[ \tilde{g} \rightarrow q \tilde{q} \]
\[ \tilde{q} \rightarrow \tilde{\chi}_2^0 q \]

\[ \tilde{t} \rightarrow W t \tilde{\chi}_1^\pm \]
\[ \tilde{b} \rightarrow Z/Higgs \tilde{\chi}_1^0 \]

Discovery possible, identification of t/h/W/Z may not be possible in the decay chain
Difficulties in conventional search

Higgs search

For light Higgs, the only option is the di-photon channel. There are BSM scenarios where $H \rightarrow \gamma\gamma$ can be very small. Conclusion: Light Higgs boson may be challenging at the LHC.

High mass resonance

For $X \rightarrow t\bar{t}$ with $M_X \sim 1\text{ TeV}$ conventional method gives poor result

SUSY search

Can be discovered by conventional methods
Understanding of detailed decay modes can be very difficult
Higgs discovery using substructure analysis

(Butterworth et al., arXiv:0802.2470v2)
Jets: Narrow cones of hadrons or other particles

Quark

Hadronization

Particles

Jets: Narrow cones of hadrons or other particles
Jets

Jet Substructure and New Physics Searches at the LHC

B. Bhattacharjee (IPMU)

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Jet Substructure and New Physics Searches at the LHC

Which one is correct?

Event: Particle level

Event: Jet level
Jet formation algorithm

We have 4 momenta of particles $\Rightarrow$ Jets are formed

$$\{p_i\} \Rightarrow J_i$$

It depends on jet formation algorithm
Jet algorithm depends on parameters

2 broad classes:
a). Cone type jet
b). Sequential recombination
Sequential jet formation algorithm

Take two particles i and j

Calculate $d_{ij} = \min(p_{T_i}^{2n}, p_{T_j}^{2n}) \ \frac{\Delta R_{ij}}{R^2}$ and $d_{iB} = p_T^{2n}$

where

$\Delta R_{ij} = \sqrt{(\phi_i - \phi_j)^2 + (y_i - y_j)^2}$ and $y_i = \frac{1}{2} \log \frac{E_i + p_{zi}}{E_i - p_{zi}}$

1. calculate minimum of $d_{ij}$ and $d_{iB}$
2. If $d_{iB}$ is minimum declare i-th particle as a jet
2. If $d_{ij}$ is minimum combine them
Boosted top: A closer look

low $p_T$

high $p_T$

high $p_T$ (blown up)
Jet substructure


The clustering process mentioned above is reversed, starting from the last two four-vectors to be merged. Final transverse momentum $p_T^{(J)} = p_T + p'_T$ Calculate the fractions $p_T/p_T^{(J)}$ and $p'_T/p_T^{(J)}$.

The de-clustering procedure is possible if both of the following situations is encountered:

- Both the de-clustered four-vectors have $p_T/p_T^{(J)} > \delta_p (= 0.05 \text{ in our analysis})$.
- The objects are not too close, i.e. $|\delta \eta|, |\delta \phi| > \delta_r (= 0.1 \text{ in our analysis})$.

After de-clustering we shall get subjets.
We select 2 jets with $p_T$ greater than 500 GeV

- The jet mass of a jet should be around $M_t$.
- The number of subjets must be greater than 3 (it can be up to four)
- The invariant mass of one combination of two jets must be of the order of $M_W$.

We then construct dijet invariant mass.
Top Jet

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- The jet mass of a jet should be around $M_t$.
- The number of subjets must be greater than 3 (it can be up to four)
- The invariant mass of one combination of two jets must be of the order of $M_W$.

We then construct dijet invariant mass.

Background

QCD dijet cross section is huge.

QCD can produce jets with substructure.

QCD jets may generate fake top jets.
Efficiency vs mistagging rate

Efficiency Fraction

Jet p$_T$ [TeV]

top jets

QCD jets

0.001 0.01 0.1 1

0.5 1 1.5 2 2.5
Implication: UED model (cont)

L = 100 fb$^{-1}$

(a) $R^{-1} = 0.5$ TeV

(b) $R^{-1} = 0.8$ TeV

(c) $R^{-1} = 1.0$ TeV

Events/Bin

$M(\bar{t}t)$ [TeV]

B. Bhattacharjee (IPMU)
Top quark in SUSY cascade

Top quark can be produced in the SUSY decay chains.

1. $\tilde{t}_1, \tilde{t}_2 \rightarrow t \tilde{\chi}_i^0 / \tilde{g}$
2. $\tilde{b}_1, \tilde{b}_2 \rightarrow t \tilde{\chi}_i^-$
3. $\tilde{g} \rightarrow t \tilde{t}_1, \tilde{t}_2$
4. $\tilde{g} \rightarrow t \tilde{\chi}_i^0 + X$

It may be the only new physics signal in some cases. Example: Focus point region in cMSSM
\[ \tilde{t}_1 \rightarrow t \tilde{\chi}_i^0 / \tilde{g} \]

\[ \tan \beta = 10 \]

\[ \tan \beta = 50 \]
\[ \tilde{b}_1 \rightarrow t \chi_i^- \]

\[ \tan \beta = 10 \]

\[ \tan \beta = 50 \]
\( \tilde{g} \) two body and three body decay to top quark

\[
\begin{align*}
\tan \beta &= 10 \\
\tan \beta &= 50
\end{align*}
\]
$\tilde{g} \rightarrow \tilde{b}_1 b$

$\tan \beta = 10$

$\tan \beta = 50$
Top quark in SUSY cascade (CMSSM)

$m_0 = 600$ GeV $m_{1/2} = 350$ GeV $A_0 = 0$ GeV $\mu > 0$ and $\tan \beta = 10$

$m_0 = 900$ GeV $m_{1/2} = 400$ GeV $A_0 = 0$ GeV $\mu > 0$ and $\tan \beta = 50$

$m_0 = 540$ GeV $m_{1/2} = 490$ GeV $A_0 = 0$ GeV $\mu > 0$ and $\tan \beta = 50$
Result

<table>
<thead>
<tr>
<th>No.</th>
<th>BP1</th>
<th>$\tilde{t}_1\tilde{t}_1$ (30 fb$^{-1}$)</th>
<th>$\tilde{b}_1\tilde{b}_1$ (30 fb$^{-1}$)</th>
<th>$\tilde{g}\tilde{g}$ (30 fb$^{-1}$)</th>
<th>$\tilde{g}\tilde{q}$ (30 fb$^{-1}$)</th>
<th>Total (30 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BP1</td>
<td>15</td>
<td>6</td>
<td>142</td>
<td>618</td>
<td>992</td>
</tr>
<tr>
<td>2</td>
<td>BP2</td>
<td>8</td>
<td>3</td>
<td>110</td>
<td>336</td>
<td>591</td>
</tr>
<tr>
<td>3</td>
<td>BP3</td>
<td>7</td>
<td>5</td>
<td>42</td>
<td>282</td>
<td>463</td>
</tr>
</tbody>
</table>

Event rates after top tagging for the benchmark points with an integrated luminosity of 30 fb$^{-1}$. The $t\bar{t}$ contribution is 132 events assuming same integrated luminosity.
Higgs production in the SUSY cascade

- Higgs boson can be produced in the SUSY cascade.
- Higgs boson may get sufficient boost in a decay chain → decay products may be collimated.
- Higgs tagging technique can be very useful in this case.
- There are supersymmetric models [CP violating MSSM] in which Higgs boson can be very light (∼ 20-60 GeV).
Effeciency plot

(a) $R = 0.6 \quad r = 0.2$

(b) $R = 0.6 \quad r = 0.3$

(c) $R = 0.8 \quad r = 0.2$

(d) $R = 0.8 \quad r = 0.3$
Jet mass distribution 10fb⁻¹, $M_{h_1}=40$ GeV
Summary

- We expecting new physics at the LHC.
- The form of new physics is not known → search in different channels, techniques.
- Conventional methods may give poor results.
- Jet substructure method is a very useful method which can be used in various new physics searches.
- Many new ideas are coming .............
Thank you
Back up slides
The graph shows the ratio of cross-sections for different processes as a function of $R^{-1}$ [TeV]. The processes include:

- $g_2 + X$
- $g_2$ resonance
- $\gamma_2, Z_2 + X$
- $W_2 + X$

The x-axis represents $R^{-1}$ [TeV], ranging from 0.6 to 1.4, while the y-axis represents the ratio of cross-sections ranging from 0 to 1.5.

The graph indicates the variation of cross-sections for these processes with the inverse of the TeV scale.
Projections, $\sqrt{s}=7$ TeV

95% CL Limit on $\sigma/\sigma_{SM}$

ATLAS Preliminary (Simulation)

$M_{H}[GeV]$
\( n = 2 \) Gauge Bosons

- \( n = 2 \) gauge bosons can couple to two SM fermions via KK number violating coupling
- Need same energy to produce two \( n = 1 \) states or one \( n = 2 \) state
- The production goes through the coupling

\[
\bar{f}_0 f_0 V_2 \rightarrow (-ig\gamma^\mu T_a P^+) \frac{\sqrt{2}}{2} \left( \frac{\delta(m_{V_2}^2)}{m_2^2} - 2 \frac{\delta(m_{f_2}^2)}{m_2} \right)
\]

where \( m_2 = 2/R \), \( T_a \) is the group generator
$n = 2$ KK Gluon ($g_2$)

$n = 2$ Gluon can also be produced as s-channel resonances at the LHC and production cross section is much larger than $Z_2/\gamma_2$ production.

**Decay modes**

- KK number conserving: $g_2 \rightarrow q_1 \bar{q}_1$ or $q_2 \bar{q}$ can provide soft leptons but it may not be useful for detection
- KK number violating: $g_2 \rightarrow q \bar{q}$: **No hope for detection (Huge QCD background. )**  
  $g_2 \rightarrow b \bar{b}$: The b jets must have very high $p_T$. detection efficiency is very low

**Conclusion:** $g_2$ can not be detected at the LHC.
$n = 2$ KK Gluon ($g_2$)

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- KK number conserving: $g_2 \rightarrow q_1 \bar{q}_1$ or $q_2 \bar{q}$ can provide soft leptons but it may not be useful for detection
- KK number violating: $g_2 \rightarrow q\bar{q}$: No hope for detection (Huge QCD background.)
  
  $g_2 \rightarrow b\bar{b}$: The b jets must have very high $p_T$. detection efficiency is very low

**Conclusion:** $g_2$ can not be detected at the LHC.

**What is the status of $g_2 \rightarrow t\bar{t}$?**
Bounds on cMSSM

\[ \tan \beta = 10 \]

\[ \tan \beta = 50 \]