Jet Substructure and New Physics Searches at the LHC

Biplob Bhattacherjee

References: BB, Manoranjan Guchait, Sreerup Raychaudhuri, K. Sridhar
Phys.Rev.D82:055006,2010.
&
BB and Priyotosh Bandyopadhyay
Phys.Rev.D84:035020,2011

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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2. Jet substructure

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

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   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.
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Disadvantage

Unknown initial states, severe backgrounds

Expectations from LHC

Standard Model

predicts the existence of a real scalar $\Rightarrow$ Higgs boson

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Goal:

1. Discover SM Higgs boson

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After discovery(!)

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Verify properties of know particles (top, W, Z)

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Other aspects:

Verify properties of know 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)

Expectations from LHC

Model beyond the Standard Model

Expectations from LHC

Model beyond the Standard Model

Existence of new particles

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Goal:

Try different options

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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

Goal:

Try different options

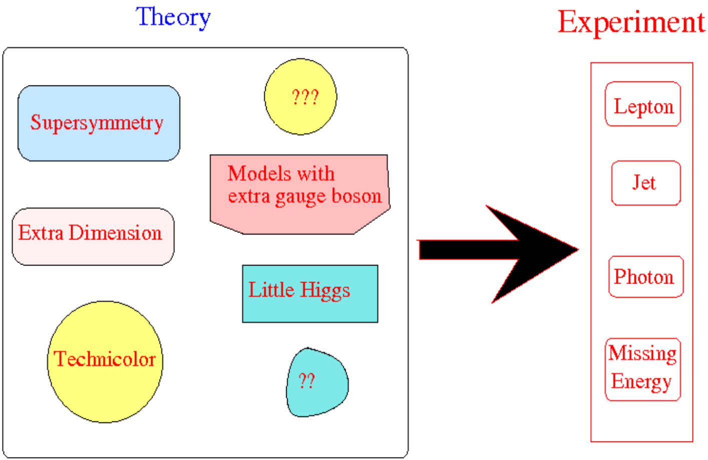
1. Multijet plus missing energy search (SUSY, UED)

2. Search for resonances (models with extra gauge bosons..)

3. ....
After discovery(!)

3. Measure properties of new particles ... decay modes of new particles, predict the model which can accommodate such particles .....

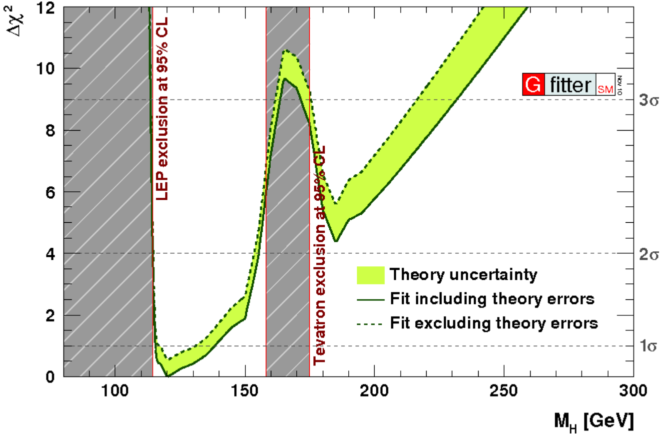
Theory and Experiment



Conventional Search Strategies

Higgs boson in SM

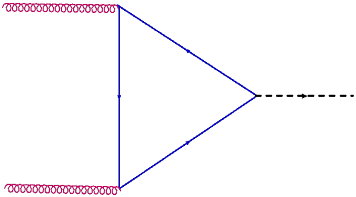
Electroweak precision test
(H. Flcher, M. Goebel, J. Haller, A. Hcker, K. Mnig, J. Stelzer : Gfitter group):



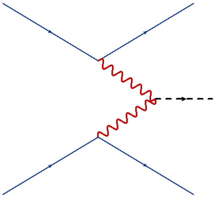
$$m_h = 121^{+17}_{-6}\ \text{GeV}$$

Higgs boson Production in SM

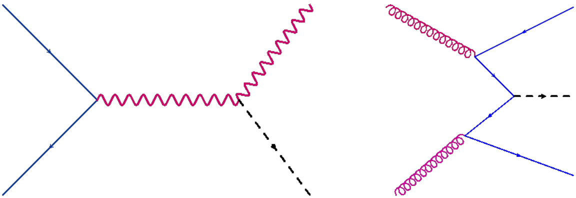
Higgs boson Production in SM



$\sim$ 36 pb (m_h=120 GeV)

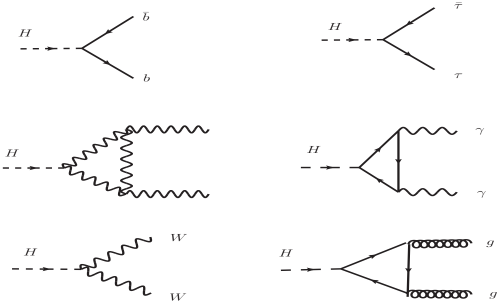


$\sim$ 5 pb (m_h=120 GeV)



$\sim$ 3pb (Wh+Zh+QQh) (m_h=120 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

$\sigma(gg \to H \to b\bar{b}) \sim$ 20 pb (Highest cross section)

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

Enormous QCD background $\Rightarrow$ No chance to look at fully hadronic state

1. $(M_h > 140$ GeV$)$ $H \to WW \to l\nu l\nu$
2. $(M_h > 2\ M_Z) H \to ZZ \to 4$ leptons (gold plated channel)
3. $(M_h < 140$ GeV$) H \to \gamma\gamma$ is the best channel (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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Difficult scenario

There are scenarios where $M_H \sim 115 - 120$ GeV and $H \to \gamma\gamma$ 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. $q\bar{q} \to t\bar{t}$ (85 % at Tevatron and 15 % at LHC)
2. $gg \to t\bar{t}$ (15 % at Tevatron and 85 % at LHC)

$\sigma \sim$ 7 pb (Tevatron)
$\sigma \sim$ 140 pb (LHC - 7TeV)
$\sigma \sim$ 800 pb (LHC - 14TeV)

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Electroweak single production

1. $qb \to t\bar{q}$ 2. $q\bar{q} \to t\bar{b}$ 3. $g\bar{q} \to tW$

$\sigma \sim$ 3 pb (Tevatron)
$\sigma \sim$ 300 pb (LHC - 14TeV)

Top quark decay

Within SM

$M_t > M_b + M_W \Rightarrow$ dominant 2 body decay mode t $\rightarrow$ b W (Br 100%)

t $\rightarrow$ W s, W d CKM suppressed

t $\rightarrow$ u/c Z is not allowed at the tree level

$\Gamma_{top} \sim 1.4$ GeV

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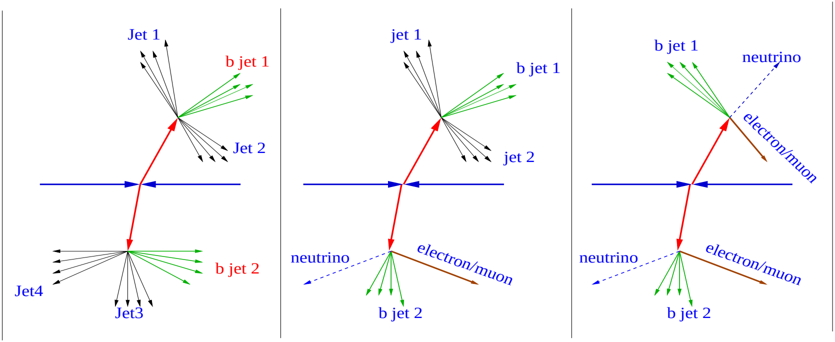
Final states of top quark is determined by W decay products

Br (W $\rightarrow$ q q$'$) = 67%
Br (W $\rightarrow$ l ν) = 11% for each l=e,μ,τ

1. top $\Rightarrow$ b jet + e/μ + MET(ν)
2. top $\Rightarrow$ b jet + 2 light jets
3. top $\rightarrow$ b jet+ τ jet + MET

Final states from top quark pair



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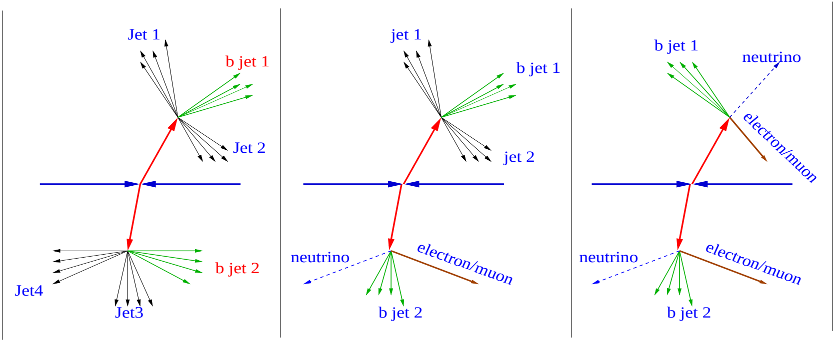

1. Fully hadronic
Br$\sim$ 45%
Huge bkg

2. lepton + jets
Br$\sim$ 30%
Moderate bkg

3. dilepton + jets
Br$\sim$ 5%
Low bkg

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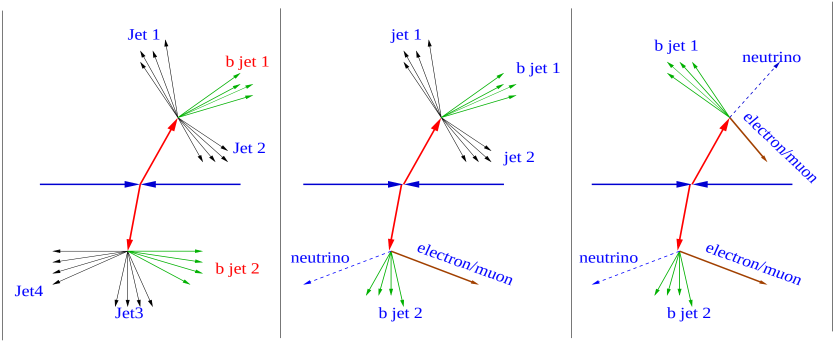

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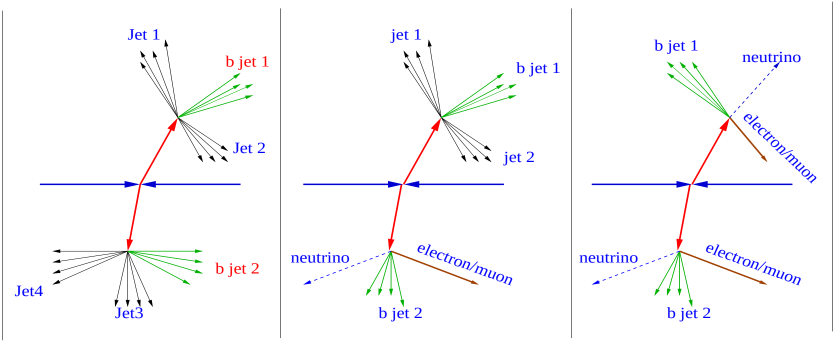

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Compromise between statistics and background

lepton+jets channel $\Longleftrightarrow$ Golden channel for analysis

Top quark reconstruction in lepton jet channel

Consider the channel $t\,\bar{t} \rightarrow \mathrm{b\,W\,b\,W} \rightarrow \mathrm{b\,l}\,\nu\,\mathrm{b\,q\,q}'$

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*

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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 $\Longleftrightarrow$ more then 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_{jjb1}) and (M_{jjb2}).
- choose the right combination $|M_{jjb} - M_t| < 20$ GeV

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Hadronically decaying top is reconstructed.

Leptonic top reconstruction

Assumption: Missing transverse energy only comes from the neutrino

$$p_{T_\nu} = \not{p}_T$$

$$p_{X_\nu} = \not{p}_X \quad \text{and} \quad p_{Y_\nu} = \not{p}_Y$$

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$$\alpha p_{z_\nu} + \beta p_{z_\nu} + \gamma = 0 \qquad \text{Two values of } p_{z_\nu}$$

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Problem: In 10-20% cases p_{z_ν} 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 $M_{bl\nu} = (p_l + p_\nu + p_b)^2$
$|M_{bl\nu} - M_t| < 40$ GeV.

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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 $t\bar{t}$

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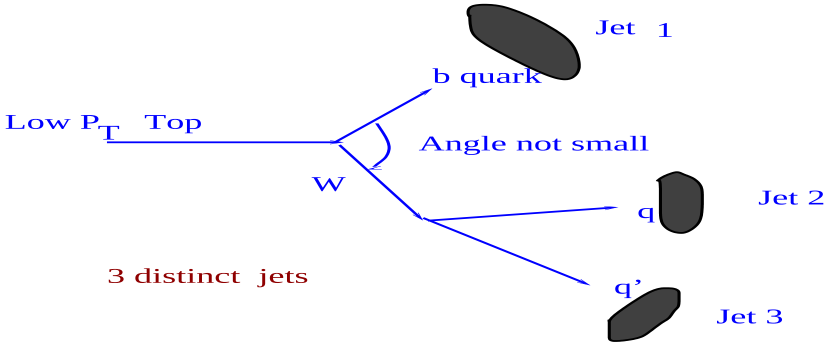
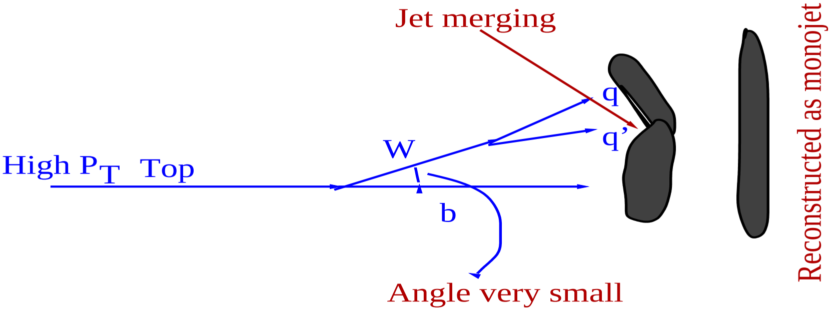
Answer: No

Usual scenario



Difficulties



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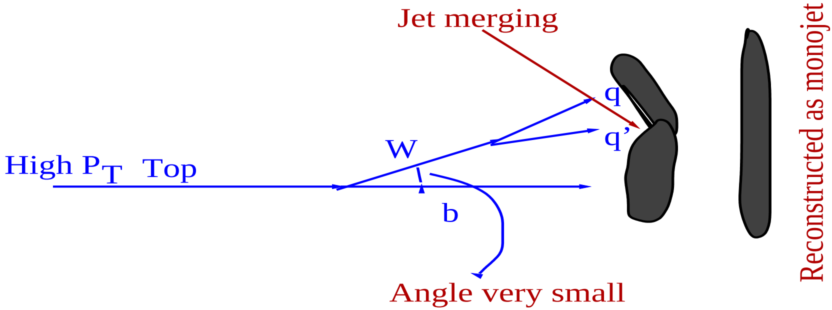


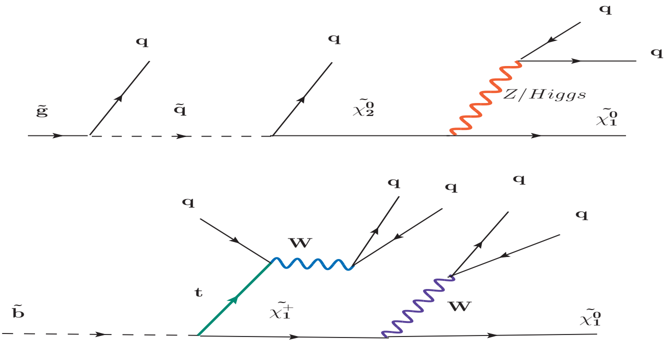
Difficulties

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

Supersymmetry search

R parity Conserving MSSM

Typical search channel: Multijet + leptons + missing energy



Difficulties in conventional search

Higgs search

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

High mass resonance

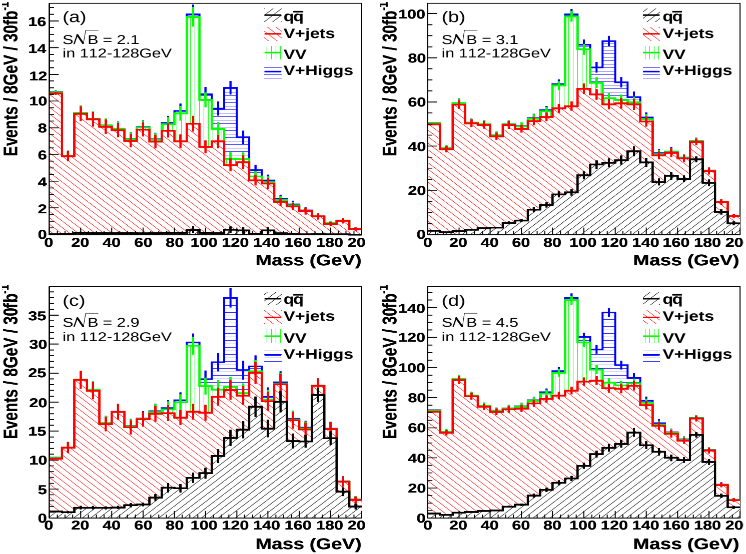
For $X \to t\bar{t}$ with $M_X \sim 1\,TeV$ conventional method gives poor result

SUSY search

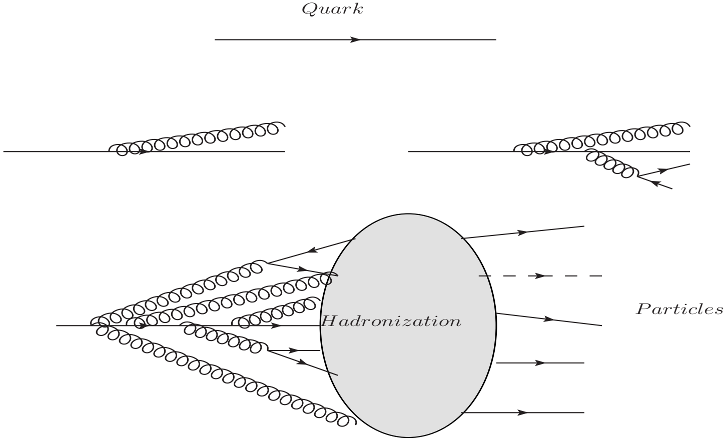
Can be discovered by conventional methods
Understanding of detailed decay modes can be very difficult

Higgs discovery using substructure analysis

(Butrerworth et al., arXiv:0802.2470v2)

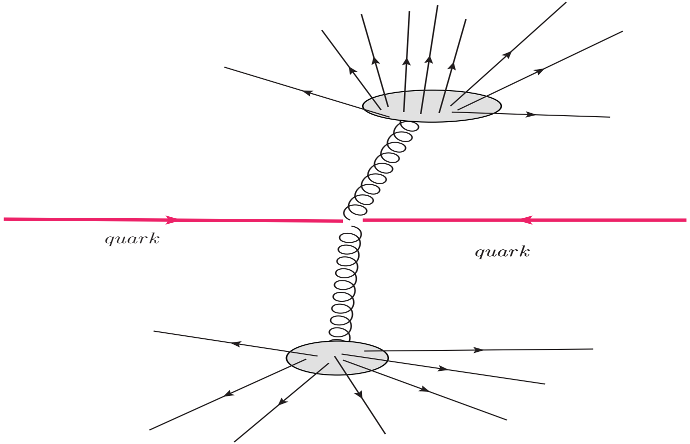


Jets

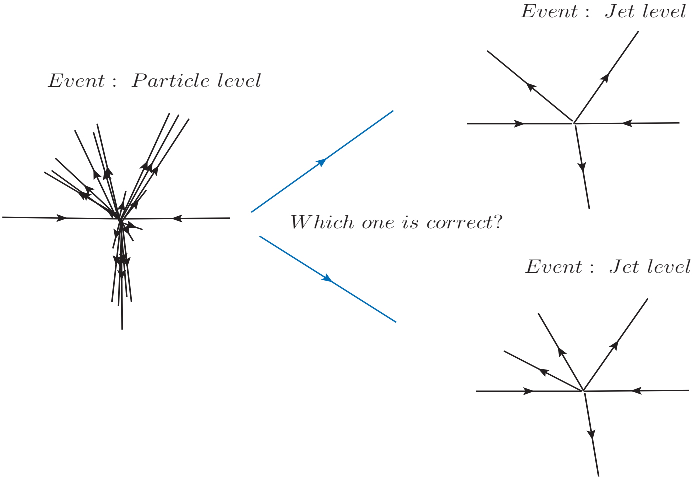


$Jets : Narrow\ cones\ of\ hadrons\ or\ other\ particles$

Jets



Jets


Event : Particle level
Which one is correct?
Event : Jet level
Event : Jet level

Jet formation algorithm

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

$$\{p_i\} \Longrightarrow J_i$$

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

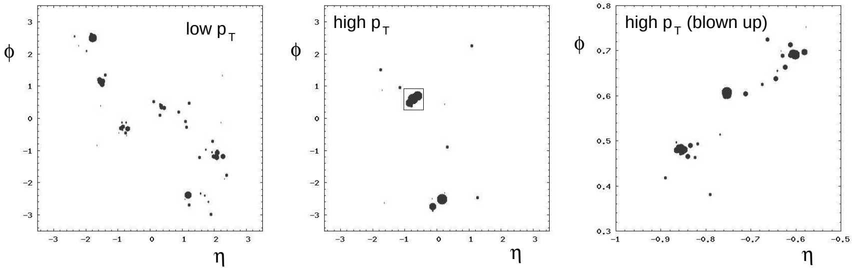
Calculate $d_{ij}= \min(p_{Ti}^{2n}, p_{Tj}^{2n})\ \frac{\Delta R_{ij}}{R^2}$ and $d_{iB} = p_T^{2n}$

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



Jet substructure

Kaplan, et al. , Phys.Rev.Lett.101:142001,2008

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 in our analysis).
- The objects are not too close, i.e. $|\delta\eta|, |\delta\phi| > \delta_r$ (= 0.1 in our analysis).

After de-clustering we shall get subjets .

Top Jet

- 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.

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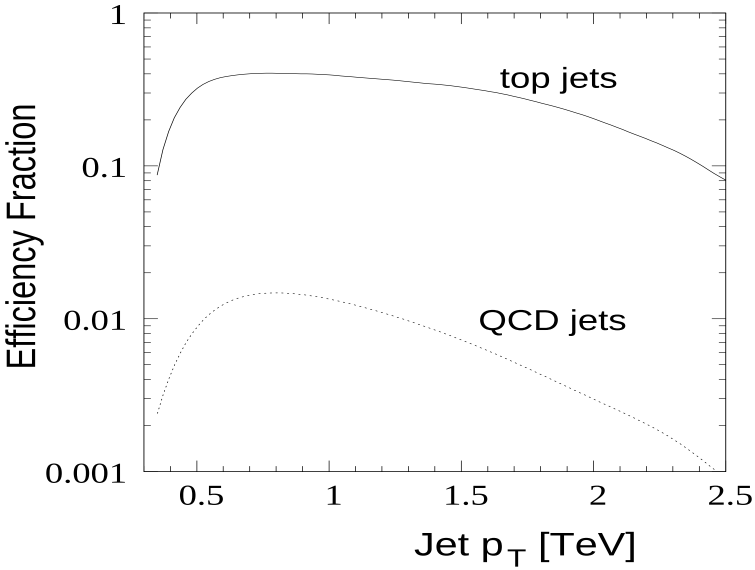
Background

QCD dijet cross section is huge.

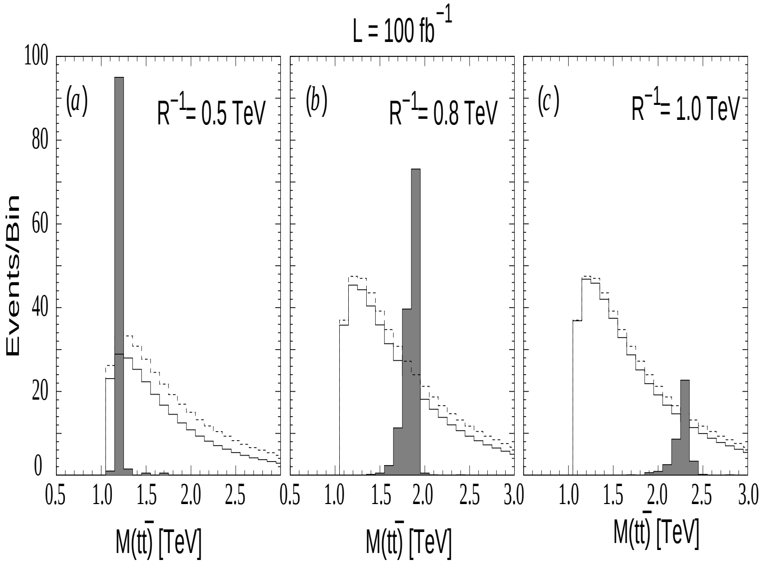
QCD can produce jets with substructure.

QCD jets may generate fake top jets.

Efficiency vs mistagging rate



Implication: UED model(cont)



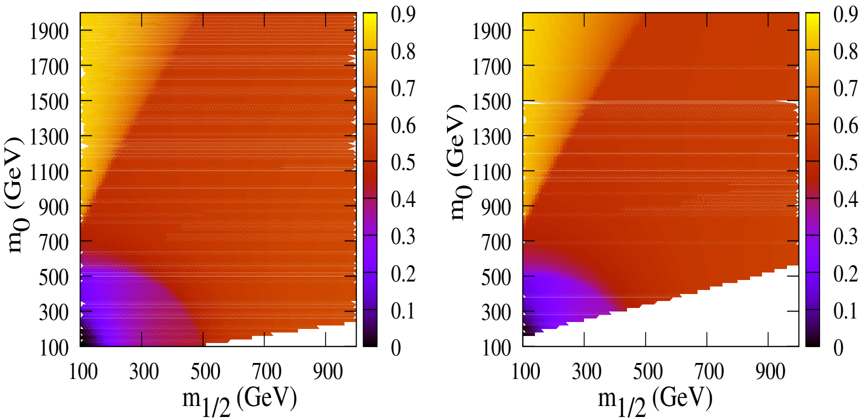
Top quark in SUSY cascade

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

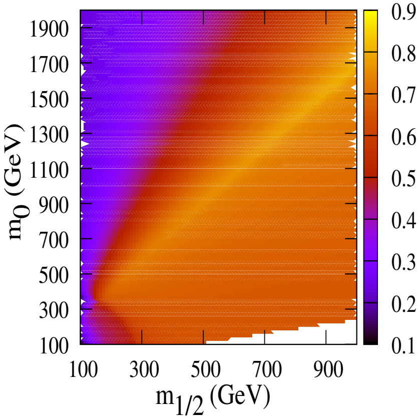
It may be the only new physics signal in some cases. Example: Focus point region in cMSSM

$\tilde{t}_1 \to t\, \tilde{\chi}_i^0 / \tilde{g}$



$\tan\beta = 10$ $\tan\beta = 50$

$\tilde{b}_1 \to t\,\tilde{\chi}_i^-$



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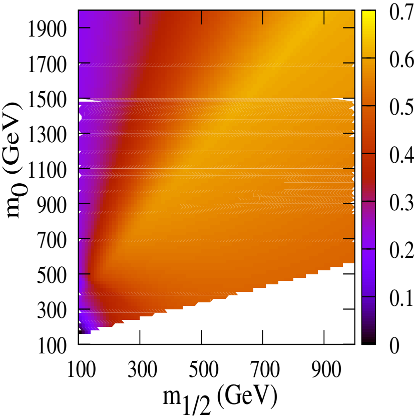
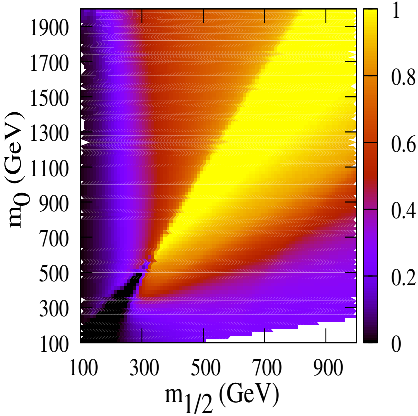


$\tan\beta = 50$

$\tilde{g}$ two body and three body decay to top quark



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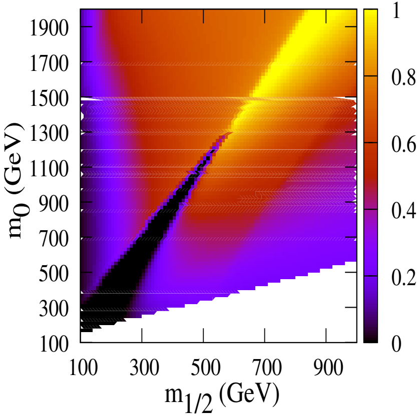
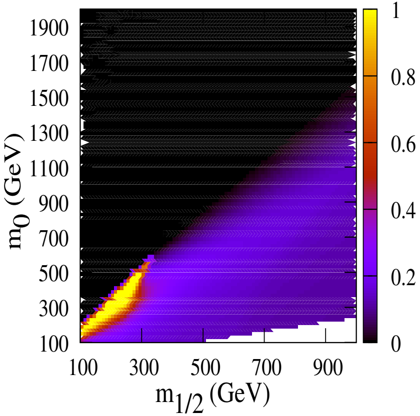
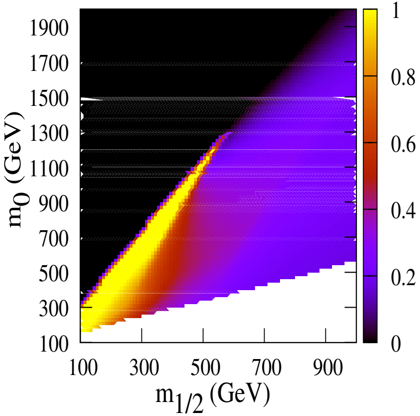


$\tan\beta = 50$

$\tilde{g} \to \tilde{b}_1 b$



$\tan\beta = 10$



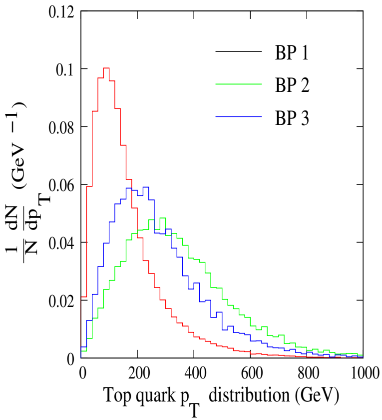
$\tan\beta = 50$

Top quark in SUSY cascade(CMSSM)

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

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

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



Result

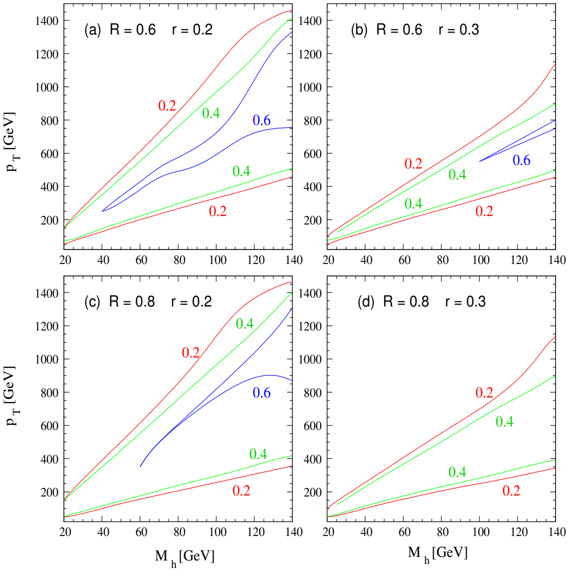
No.		$\tilde{t}_1\tilde{t}_1$ (30 fb^{-1})	$\tilde{b}_1\tilde{b}_1$ (30 fb^{-1})	$\tilde{g}\tilde{g}$ (30 fb^{-1})	$\tilde{g}\tilde{q}$ (30 fb^{-1})	Total (30 fb^{-1})
1	BP1	15	6	142	618	992
2	BP2	8	3	110	336	591
3	BP3	7	5	42	282	463

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.

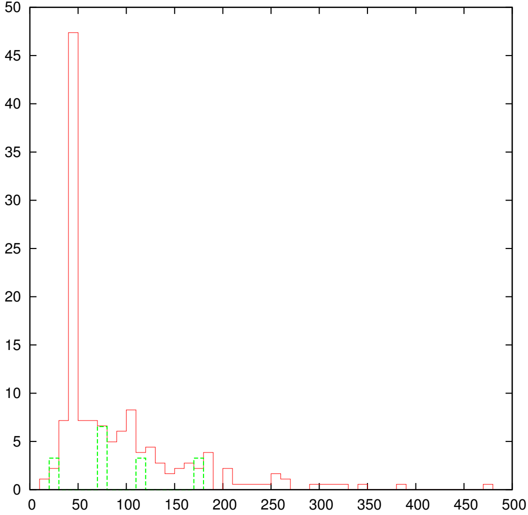
Higgs production in the SUSY cascade

- Higss boson can be produced in the SUSY cascade.
- Higss boson may get sufficient boost in a decay chain $\rightarrow$ decay producs 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 ($\sim$ 20-60 GeV).

Effeciency plot



Jet mass distribution 10fb^{-1}, M_{h_1}=40 GeV

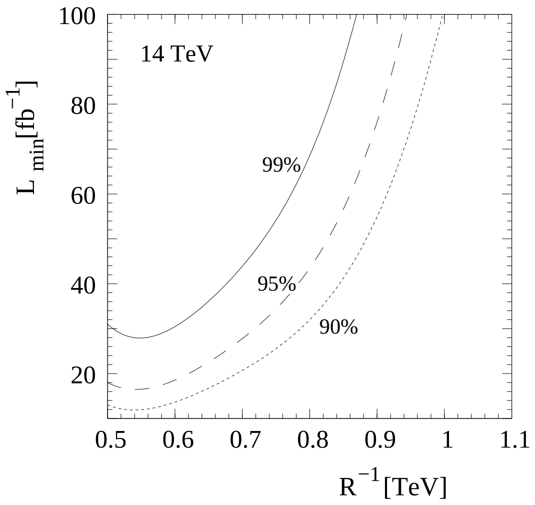


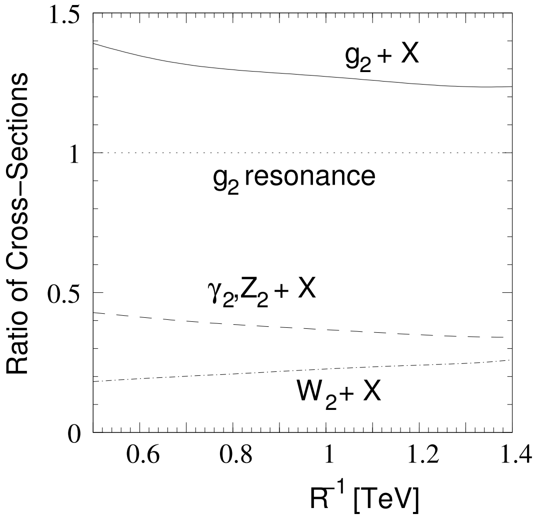
Summary

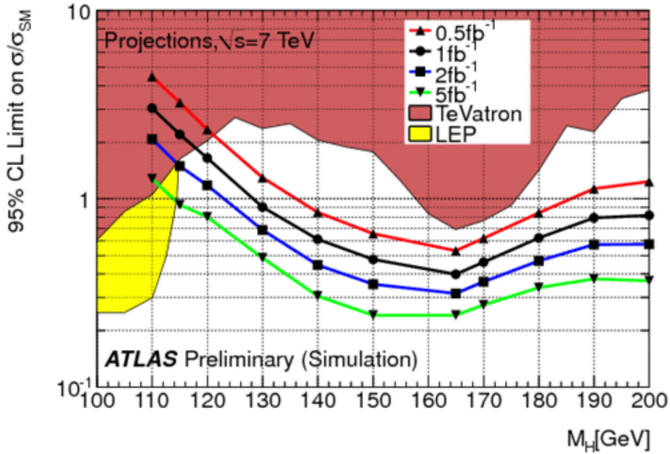
- We expecting new physics at the LHC.
- The form of new physics is not known $\rightarrow$ search in different channels, techniques.
- conventional methods may give poor results
- Jet substructure method is a very useful method which can be used in various new physics searches.
- Many new ideas are coming ....

Thank you

Back up slides


14 TeV
99%
95%
90%
L min[fb −1]
R −1[TeV]
0.5
0.6
0.7
0.8
0.9
1
1.1
20
40
60
80
100


1.5
1
0.5
0
0.6
0.8
1
1.2
1.4
Ratio of Cross–Sections
R^-1 [TeV]
g2 + X
g2 resonance
γ2,Z2 + X
W2+ X



95% CL Limit on σ/σ_SM
Projections,√s=7 TeV
0.5fb-1
1fb-1
2fb-1
5fb-1
TeVatron
LEP
ATLAS Preliminary (Simulation)
10
1
10-1
100
110
120
130
140
150
160
170
180
190
200
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

$$\overline{f_0} f_0 V_2 \longrightarrow (-ig\gamma^\mu T_a P_+) \frac{\sqrt{2}}{2} \left(\frac{\bar{\delta}(m_{V_2}^2)}{m_2^2} - 2\frac{\bar{\delta}(m_{f_2})}{m_2} \right)$$

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/γ_2 production.

Decay modes

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

Conclusion: g_2 can not be detected at the LHC.

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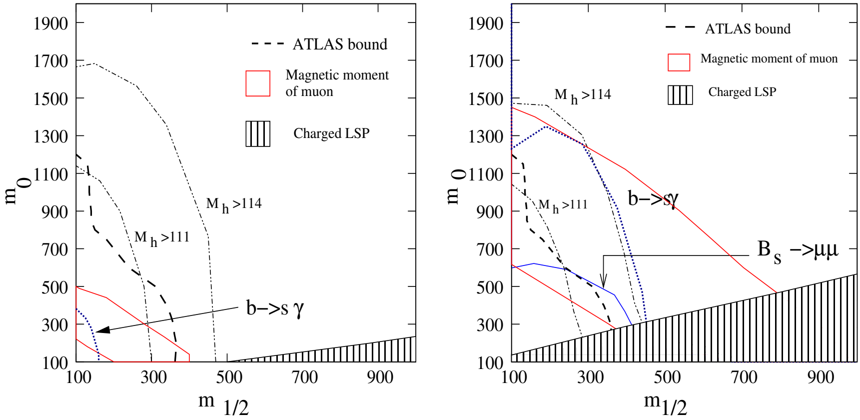
Conclusion: g_2 can not be detected at the LHC.

What is the status of $g_2 \to t\bar{t}$?

Bounds on cMSSM



$\tan\beta = 10$ $\tan\beta = 50$