Beyond MSSM: Higgs cascade decays

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- In the SM Higgs decays most readily to the pair of the heaviest kinematically available particles
- In the presence of new physics this can be dramatically altered
- MSSM and its extensions contain a lot of new particles that could mess with the Higgs sector
- Many possibilities: enhanced decays to 2τ, invisible decays etc.
- One new dramatic possibility: cascade decays to many-body final states via new intermediate particles

A selection (far from complete!) of SUSY models with cascade Higgs decay

- $H \to 4b, 4\tau$ in NMSSM, Dermisek,Gunion [hep-ph/0502105,hep-ph/0611142]
- $H \to 6j$ in R-parity violating MSSM Carpenter,Kaplan,Rhee [hep-ph/0607204]
- $H \to 4g$ (Buried Higgs) in SUSY Little Higgs Bellazzini,Csaki,AA,Weiler [0906.3026]
- $H \to 4c$ (Charming Higgs) in SUSY Little Higgs Bellazzini,Csaki,AA,Weiler [0910.0345]
- $H \to$ lepton jets in MSSM+light hidden sector AA,Ruderman,Volansky,Zupan [1002.2952]

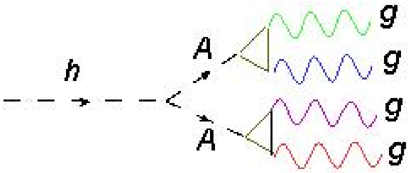
Decay Channel	Exp.	**Limit**
$h \to AA \to 4b$	LEP, hep-ex/0602042	110 GeV
$h \to AA \to 4\tau$	ALEPH, 1003.0705	$\sim$ 110 GeV
$h \to AA \to 4\mu, 2\mu 2\tau$	D0, 0905.3381	-
$h \to AA \to 4\mu, 4e$	RECAST, 1010.2506	$\sim$ 115 GeV
$h \to AA \to 4c, 4g$	OPAL, hep-ex/0209068	86 GeV
$h \to$ anything	OPAL, hep-ex/0206022	82 GeV

see Chang,Dermisek,Gunion,Weiner [0801.4554] for review

- Most searches for Higgs cascade decays are pretty recent
- In some case mass limits are weak because the channel did not receive enough attention

Case study: $H \to 4g$, Bellazzini,Csaki,AA,Weiler [0906.3026]

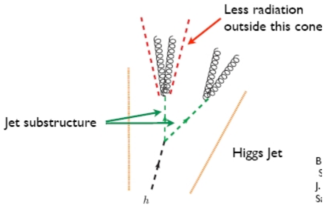
- Higgs dominantly decays to a pair of pseudoscalars A with $m_A < 10$ GeV
- A has sizable Yukawa couplings to the third generation quarks and tiny coupling to light quarks and to leptons
- For $m_A > 10$ GeV it dominantly decays to 2 b-quarks (not considered here)
- For $m_A < 10$ GeV it dominantly decays via loop of off-shell bottom quark to 2 gluons
- In effect, the leading Higgs decay is the cascade $h \to AA \to 4g$



- In this model the branching into standard LHC discovery final states like $h \to \gamma\gamma$ $h \to bb$ or $h \to \tau\tau$ is strongly suppressed

Buried Forever?

- Because $m_A \ll m_h$, A is boosted, and the 2 gluons from its decay will merge into 1 jet
- The signature of buried Higgs is 2 jets of low invariant mass $\sim m_A \lesssim 10$ GeV
- At the LHC, it semes hopeless at first sight:
  - Gluon fusion $gg \to h$ completely swamped by dijet background
  - VBF channels suffers because of the central jet veto
  - The associated production Vh or tth more promising, but the backgrounds from $V + jets$ and $tt + jets$ are many orders of magnitude larger than the signal
- Nevertheless...



jet substructure may save the day! Chen et al [1006.1151] , AA,Krohn,Shelton,Thallapillil,Wang [1006.1650]

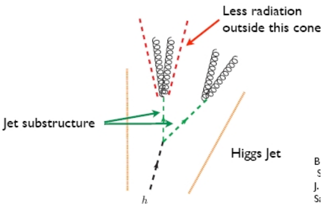
How to dig him out

AA,Krohn,Shelton,Thallapillil,Wang [1006.1650] looks at the following 2 channels

- Higgstrahlung: $W + h$
  - At LHC 14 TeV, $\sigma_{Wh} \sim 3$ pb for $m_h \sim 100$ GeV
  - Look at leptonic W boson decays
  - Main background: W+jets, $\sigma_W \sim 200$ nb
- Associated production with top quarks: $t\bar{t}h$
  - At LHC 14 TeV, $\sigma_{tth} \sim 1$ pb, for $m_h \sim 100$ GeV.
  - Look at dileptonic tops
  - Final state: 2 leptons (e or μ), 2 tagged b-jets, and at least 2 ordinary jets
  - Main background: tt+jets, $\sigma_{tt+jets} \sim 1000$ pb, $S/B \sim 1/1000$
  - Note: contrary to the SM case no pesky combinatorics!
  - Other backgrounds like ttZ, Zbb are by far subdominant

Assume SM production cross section and 100 percent branching fraction into 4 gluons (caution: both can be suppressed in specific models). Assume $m_A < 10$ GeV so the two gluons to which A decays merge into 1 jet, see Kaplan,McEvoy [1102.0704] for the large m_A case

Unburied Higgs



- LHC is a very jetty place, and brute force kinematic cuts are not enough
- Concentrate on the kinematic regime where Higgs is boosted, $p_T(h) \gtrsim 150$ GeV, so that 2 jets from Higgs decay are approximately collimated and appear as one fat jet in the detector
- Then study the jet substructure, to identify the characteristic kinematics and color flow of buried Higgs. It turns out for QCD it is not easy to fake that substructure
- Jet substructure tools successfully earlier applied for the SM Higgs in the $W(H \to b\bar{b})$ channel Butterworth et al [0802.2470] and $t\bar{t}h$ channel, Plehn et al [0910.5472] .

Event Generation

- Signal and background are generated with `MadGraph` pipelined to `Pythia 6.4` and `Slowjet`
- ISR, showering, pile-up and underlying event included
- 3 signal samples: $m_h = 80, 100, 120$, and $m_A = 8$ GeV
- The $t\bar{t}$+jets background is matched using MadGraphs native kT-MLM procedure
- Jet clustering is done in `FastJet` and `SlowJet` using the anti-kT scheme (similar results with C/A)
- Results robust under changing model of parton shower (Pythia virtuality-ordered) and choice of matching scheme (shower-kT)

`This talk:` ttH channel only (similar techniques and final signal significance in Wh channel). For each generated signal and background event

- Cluster all particles into jets of size $R = 0.4$ using the anti-kT algorithm
- Preselection of the dileptonic top sample: events with 2 identified opposite sign leptons + 2 identified b-jets
- Drop leptons and identified b-jets and further cluster remaining untagged jets into fat jets of size $R = 1.5$.
- Trim the fat jets to remove contamination from unrelated soft activity
- Select the hardest fat jet with at least 2 subjets and cut $p_T \gtrsim 130$ GeV
- Find 2 hardest subjets, and cut on their $p_T \gtrsim 40$ GeV

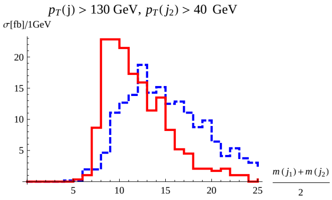
- Signal has 2 subjets with the same and low invariant mass
- QCD radiation favors mass hierarchy and sligthly larger jet masses (after pT cuts)

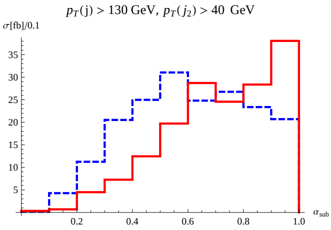
Mean invariant mass:

$$\overline{m} = \frac{m(j_1) + m(j_2)}{2}$$

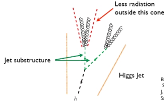
Mass democracy:

$$\alpha_{sub} = \mathrm{Min}(m(j_1)/m(j_2), m(j_2)/m(j_1))$$





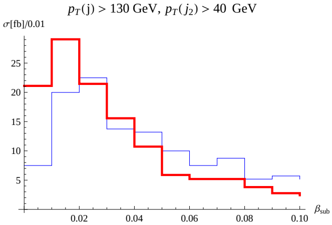
Background (Blue) x 1, Signal(Red) x 100

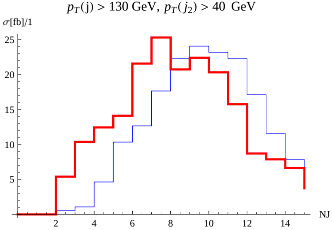


- Signal is color singlet until pseudoscalar decay at $\sim$ 10 GeV: expect less radiation between jets

$$\beta_{sub} = \frac{p_T(j_3)}{p_T(j_1) + p_T(j_2)}$$

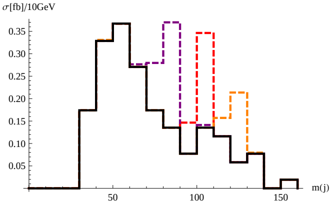
$NJ(j, p_{th})$ = Number of subjets with $p_T > p_{th}$ inside the hardest fat jet





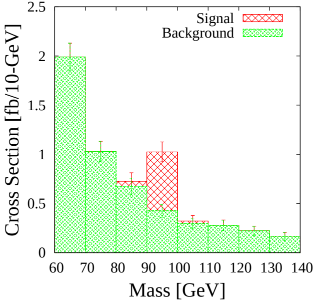
Background (Blue) x 1, Signal(Red) x 100

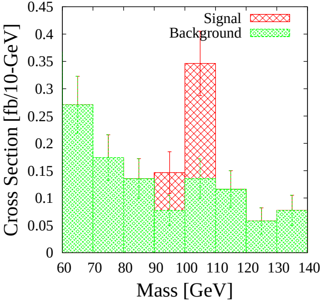
- Cut on mass democracy $\alpha_{sub} \gtrsim 0.7$ on color flow $\beta_{sub} \lesssim 0.03$,
- After all cuts, signal displays a clear peak in the invariant mass of the fat jet, while background sharply drops at high masses



Background (black)
Signal + Background (purple $m_h = 80$ GeV, red $m_h = 100$ GeV, orange $m_h = 120$ GeV)

Similar significance in the W+h channel, with a larger cross section after cuts but worse S/B





Significance, assuming 100 fb-1 as $\sqrt{s} = 14$ TeV

		$m_h = 80\,\mathrm{GeV}$	$m_h = 100\,\mathrm{GeV}$	$m_h = 120\,\mathrm{GeV}$
$pp \to hW$	$S/\sqrt{B}$	6.6	7.8	7.0
	S/B	0.34	0.90	0.80
$pp \to ht\bar{t}$	$S/\sqrt{B}$	6.1	6.1	7.1
	S/B	1.1	1.3	2.5

Conclusions

- Higgs may turn out to be standard and boring, but it may well be a vicious beast
- Each case study usually leads to developing new collider tools and tightens our nets
- With the help from methods of jet substructure a light Higgs boson decaying via a cascade $h \to AA \to 4g$ into 2 light jets can be discovered at the LHC with sufficiently large integrated luminosity