Higgs Sematary

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Based on AA,Krohn,Shelton,Thallapillil,Wang [0905.xxxx] ,

Pet Sematary

The concept of *sematary* was introduced by Stephen King in a paper from 1983

- *Pet Sematary* (misspelled cemetary) refers to an ancient burial ground of the Micmacs, a Native American tribe
- At the back of the sematary there is the so-called *deadfall*: a pile of tree and bush limbs that form a barrier
- Animals or people buried beyond the deadfall come back to life next day
- Although they remain *a little dead*...

In this talk I will apply similar concepts to Buried Higgs

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Outline

Why bother with Higgs physics?

Why Higgs?

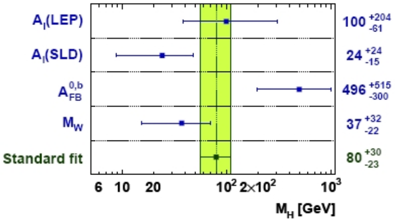
- Higgs boson provides the *simplest* mechanism to unitarize the scattering amplitude of longitudinally polarized W and Z bosons
- Electroweak precision observables suggest that Higgs exists and couples to W and Z mass with roughly the SM strength
- The LHC should settle the case once and for all

Why non-standard Higgs?

- Higgs is expected to couple strongly to (at least) new physics states playing part in electroweak symmetry breaking
- Both production cross section and branching fractions can easily be (and often are) modified by new physics
- Especially for a light Higgs, the couplings to kinematically available SM states are tiny, e.g. $y_b \sim m_b/v_{EW} \sim 0.02$, and therefore branching fractions can be dramatically altered by new physics
- Measuring Higgs properties may be the shortest path to new physics

Trouble with SM Higgs

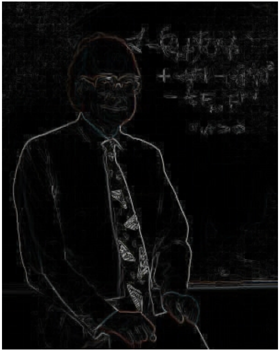
- Experimental:
- Electroweak fit from Gfitter: $m_h = 80^{+30}_{-23}$. Tension with the LEP limit $m_h > 114.4\,\mathrm{GeV}$.
  - Leptonic observables and W mass alone prefer a very light Higgs, of order 60 GeV!
  - Only the $Z \to bb$ forward-backward asymmetry pushes the Higgs mass toward larger values



- Experimental: $\sim 2\sigma$ excess of $H \to \bar{b}b$ like events at $m_h \approx 100$ GeV
- Mixed: If tau data instead of electron data used for $\Delta\alpha_{had}$ in the electroweak fit, the best fit Higgs mass further decreases Passera,Marciano,Sirlin [1001.4528]
- Theoretical: In many extensions of the SM, in particular in the MSSM or simplest little Higgs theories, $m_{Higgs} \approx m_Z$ preferred by naturalness, while $m_{Higgs} \geq 115$ GeV leads to the *little hierarchy problem*

So maybe Higgs IS lighter than 115 GeV?

- One possibility: suppressed coupling to Z boson, so that it was not produced at LEP. But then electroweak fit is not improved even if Higgs is light
- More exciting possibility: Higgs was copiously produced at LEP, but it escaped our attention.



Summary of LEP Higgs constraints

Assuming SM production cross section, and $BR(H \to xx) = 1$

Decay Channel	**Limit**	
$h \to \not{E}$	114 GeV	
$h \to \tau\overline{\tau}$	115 GeV	
$h \to jj$	113 GeV	
$h \to WW^*$ or ZZ^*	110 GeV	
$h \to AA \to 4b$	110 GeV	
$h \to AA \to 4\tau$	110 GeV	(new!)
$h \to AA \to 4c, 4g$	86 GeV	
$h \to$ anything	82 GeV	

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

- Invisible and two-body decay channels very well constrained
- Constraints on four- and more body decay channels typically not much better than the model independent OPAL constraint, with the exception of the 4b and 4τ channels
- Typically, the multiparticle channels are weakly constrained not because of fundamental reasons but because nobody bothered to look

Hidden Higgs models

- $H \to 4b, 4\tau$ in NMSSM, Dermisek,Gunion [hep-ph/0502105,hep-ph/0611142] , now excluded for $m_h < 110$ GeV apart from a small $\tan\beta$ corner
- $H \to 6j$ in R-parity violating MSSM Carpenter,Kaplan,Rhee [hep-ph/0607204] , open for $m_h > 82$ GeV
- $H \to 4j$ (Buried Higgs) in SUSY Little Higgs Bellazzini,Csaki,AA,Weiler [0906.3026] , open for $m_h > 86$ GeV
- $H \to 4c$ (Charming Higgs) in SUSY Little Higgs Bellazzini,Csaki,AA,Weiler [0910.0345] , open for $m_h > 86$ GeV
- $H \to$ lepton jets in MSSM+light hidden sector AA,Ruderman,Volansky,Zupan [1002.2952] open for $m_h \gtrsim 100$ GeV
- $H \to$ displaced vertices in SM+light RH neutrino Graesser [0705.2190] , open for $m_h > 82$ GeV

To take home...

- It is conceivable that Higgs decays to a complicated multiparticle final states
- If Higgs is lighter than 110 GeV that is the only option in view of LEP limits
- Even if Higgs was not at LEP, it is conceivable that non-standard Higgs decay are present, as the leading or subleading channel
- These final states are usually difficult for the LHC, and would be missed unless specifically targeted

Are we prepared?

Outline

Little SUSY

- Supersymmetric little Higgs models (aka little Susy)
- The MSSM extended to include $SU(3)$ global symmetry spontaneously broken to $SU(2)$ at the scale $f \gtrsim v_{EW}$
- Higgs doublets $H_{u,d}$ embedded in triplets $\mathcal{H}_{u,d}$ transforming under global $SU(3)$
- 5 Goldstone bosons from $SU(3) \to SU(2)$ breaking, 3 of which get eaten by W and Z after EW breaking

Two physical pGB scalars h and η embedded in the triplets as

$$\mathcal{H}_u \approx f \sin\beta \begin{pmatrix} 0 \\ \sin((\tilde{v}+h)/f) \\ e^{i\eta/f}\cos((\tilde{v}+h)/f) \end{pmatrix} \qquad \mathcal{H}_d^T \approx f \cos\beta \begin{pmatrix} 0 \\ \sin((\tilde{v}+h)/f) \\ e^{-i\eta/f}\cos((\tilde{v}+h)/f) \end{pmatrix}.$$

- Global symmetry breaking f generated radiatively
- Electroweak breaking scale $v_{EW} = f\sin(\tilde{v}/f)$ from (also radiative) vacuum misalignment
- The pGB scalar h identified with the SM Higgs boson
- The pGB pseudoscalar η is a new singlet with protected mass (so can be v. light!)

Higgs Decays

From the kinetic terms, interaction vertex between the PGBs

$$\frac{\cos^2((\tilde{v}+h/\sqrt{2})/f)}{\cos^2(\tilde{v}/f)}(\partial_\mu\eta)^2 \rightarrow -h(\partial_\mu\eta)^2\frac{\sqrt{2}v_{EW}}{f^2}$$

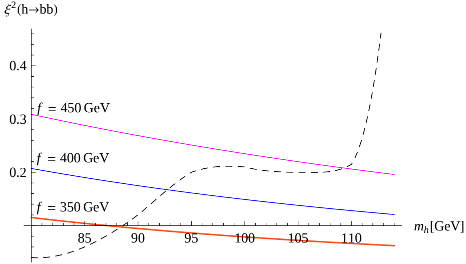
The decay width into two singlets

$$\Gamma_{h\rightarrow\eta\eta} \approx \frac{1}{64\pi}\frac{m_h^3 v_{EW}^2}{f^4}$$

as compared to the width into bees

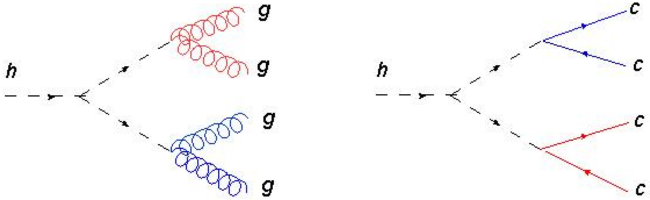
$$\Gamma_{h\rightarrow b\bar{b}} \approx \frac{3}{16\pi}\frac{m_h m_b^2}{v_{EW}^2}$$

As long as v_{EW}/f not too small and m_h large enough, the singlet wins



Buried in QCD backyard

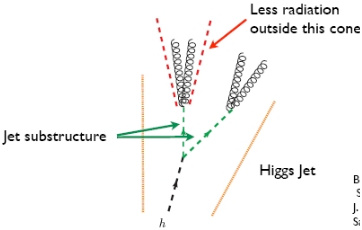
- Pseudoscalar η, being a singlet, couples to SM fermions via their mixing with heavy partner fermions
- Couplings of η to SM fermions depend on fermion representations under global SU(3), masses of heavy fermionic partners of SM fermions, etc.
- Several phenomenologically distinct realizations of Hidden Higgs
  - Gluophilic (Buried) Higgs: for $m_\eta < 10$ GeV the loop coupling of η to 2 gluons dominates the branching fraction. Then Higgs decays as $h \to \eta\eta \to 4g$
  - Charming Higgs: η has no couplings to up-type quarks or leptons. Then for $2\,\mathrm{GeV} < m_\eta < m_h/2$, Higgs decays as $h \to \eta\eta \to 4c$



- Typically, branching into standard LHC discovery final states like $h \to \gamma\gamma$ or $h \to \tau\tau$ is strongly suppressed

Buried Forever?

- At LEP, the current limit of 86 GeV could easily be improved by a dedicated analysis (probably all the way until 110 GeV).
- At LHC, at first sight seems difficult:
  - Gluon fusion $gg \to h$ completely swamped by dijet background
  - VBF channels suffers because of the central jet veto
  - For Vh or tth the backgrounds $V + jets$ and $tt + jets$ are many orders of magnitude larger
- Nevertheless...



jet substructure and superstructure may help! AA,Krohn,Shelton,Thallapillil,Wang [1005.xxxx]

Outline

Digging directions

- Higgstraglung: Zh, Wh (background Z + jets, W + jets)
  - At LHC 14 TeV, $\sigma_{Wh} \sim 3$ pb, $\sigma_{Zh} \sim 1$ pb, for $m_h \sim 100$ GeV
  - Look at leptonic wector boson decays
  - Main background: W+jets, $\sigma_W \sim 200$ nb, Z+jets, $\sigma_Z \sim 60$ nb,
- Associated production 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), 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

`This talk:` ttH channel only (similar techniques and final signal significance in Vh channel). Assume SM production cross section and 100 percent branching fraction into 4 gluons (caution: in buried Higgs model both are suppressed by ~ 0.8)

Tools for the LHC

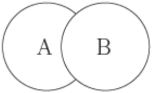
LHC is a difficult environment for precision jet physics. Modern tools needed to dig for Higgs

- **Jet algorithms that enable peering into event at several scales**
  - Sequential jet algorithms: kT, C/A, anti-kT (see Salam [0906.1833] for review)
- Kinematic variables that can tell Higgs cascade decay from QCD showers
- Cleaning the contamination from pile-up and underlying event

Sequential jet algorithms

- k_T algorithm

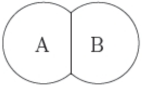
$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = p_{Ti}^2$$



k_T

- C/A algorithm

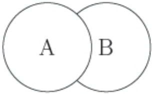
$$d_{ij} = \left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = 1$$



C/A

- anti-k_T algorithm

$$d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = p_{Ti}^{-2}$$



anti$-k_T$

$$(\Delta R)^2 \equiv (\Delta\eta)^2 + (\Delta\phi)^2$$

$$p_T^A > p_T^B$$

Tools for the LHC

LHC is a difficult environment for precision jet physics. Modern tools needed to dig for Higgs

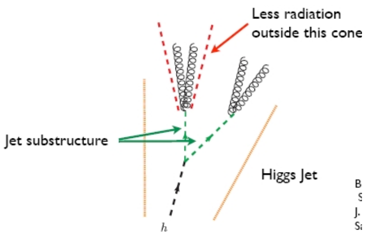
- Jet algorithms that enable peering into event at several scales
- **Kinematic variables that can tell Higgs cascade decay from QCD showers**
  - Energy and momentum sharing between jets (see also z, sphericity tensor Thaler,Wang [0806.0023] , planar flow Almeida et al0810.0934 in the context of top id)
  - Mass drop (see also mass drop Butterworth,Davison,Rubin,Salam [0802.2470] in the context of SM Higgs searches)
  - Color flow variables (see also pull Gallicchio,Schwartz [1001.5027])
- Cleaning the contamination from pile-up and underlying event

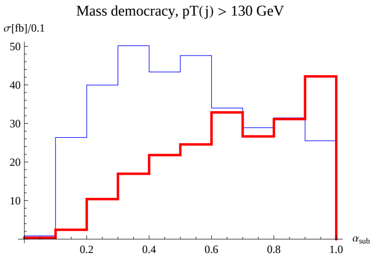
Substructure variables

- Signal has 2 subjets with the same invariant mass
- QCD radiation favors mass hierarchy

Mass democracy:

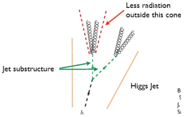
$$\alpha_{sub} = \mathrm{Min}(m(j_1)/m(j_2), m(j_2)/m(j_1))$$





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

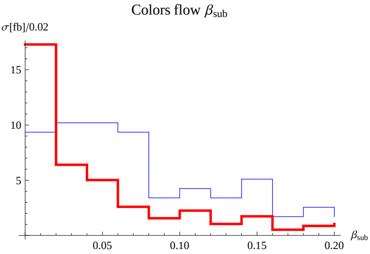
Color flow variables

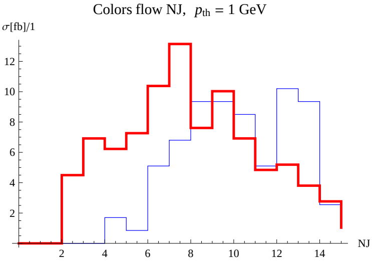


- Signal is color singlet until pseudoscalar decay at $\sim$ 10 GeV: expect less radiation between jets

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

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





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

Tools for the LHC

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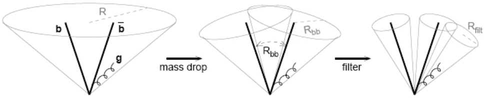
- Jet algorithms that enable peering into event at several scales
- Kinematic variables that can tell Higgs cascade decay from QCD showers
- **Cleaning the contamination pile-up and underlying event**
  - Filtering Butterworth,Davison,Rubin,Salam [0802.2470]
  - Pruning Ellis,Vermilion,Walsh [0912.0033]
  - Trimming Krohn,Thaler,Wang [0912.1342]
    - ★ Remove all subjets with $p_T(j_i)$ less than $\sim$ 10 percent of the fat jet $p_T(j)$

Success for SM Higgs

Jet substructure tools successfully applied for boosting the LHC sensitivity to the $Z(H \to b\bar{b})$ channel Butterworth et al [0802.2470]

- Cluster jets with C/A into cones of size $R = 1.2$ and $p_T(j) > 200$
- Deconstruct the jets and look for mass dropping $\min(m(j_1), m(j_2)) \lesssim \mu m(j)$ and symmetric $\Delta R_{12} \min(p_{T1}^2, p_{T2}^2)/m^2(j) > y_{cut}$ configurations
- Clean up soft contamination: find subjets at scale $R \sim 0.3$ and keep only the hardest three
- Ligth Higgs signal with $\sim 4.5\sigma$ after 30 inverse fb
- Techniques validated by ATLAS and CMS
- Also applied to the tth channel, Plehn,Salam,Spannowsky [0910.5472] , with the resulting significance of $\sim 5\sigma$ after 100 inverse fb



Outline

Event Generation

- Signal and background are generated with `MadGraph` pipelined to `Pythia 6.4`
- 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)

Analysis - Preselection

To select the dileptonic top sample...

- Required two opposite sign leptons ($p_T(e) > 15$ GeV, $p_T(\mu) > 10$ GeV).
- To reduce the Z+jets contribution, we veto events with same flavor leptons that reconstruct the Z mass, $|m(l^+l-) - m_Z| > 10$
- Require two b-tagged jets with $p_T > 20 GeV$
- No missing energy cut applied (no need to)
- These cuts select events containing $t\bar{t}$ with both tops decaying leptonically. Contribution from $Zb\bar{b}$ is at the 5 percent level after these cuts
- Efficiency similar for signal and background, of order 15 percent, assuming b-tagging efficiency 0.6.

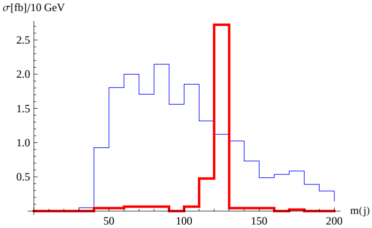
Analysis

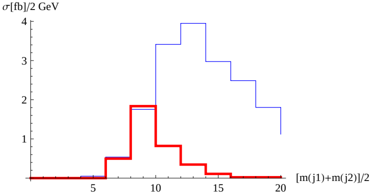
For each generated signal and background event

- Cluster all particles into jets of size $R = 0.4$ using the anti-kT algorithm. Drop leptons and identified b-jets
- Cluster the jets into fat jets of size $R = 1.5$. Drop jets with no substructure (that is, with only one subjet).
- Trim the fat jets to remove contamination from unrelated soft activity
- Select the hardest fat jet and cut $p_T \gtrsim 100$ GeV
- Pray that the fat jet contains all Higgs decay products.
- Find 2 hardest subjets, and cut on the subjet $p_T \gtrsim 50$ GeV and on mass democracy $\alpha_{sub} \gtrsim 0.7$
- Cut on the color flow variables: $\beta_{sub} \lesssim 0.05$, and $NJ \lesssim 10$

Bump Hunting

- The signal has a clear peak in the invariant mass of the fat jet, while background is featureless
- We can further increase the sensitivity to the signal by cutting on the mean invariant mass of the subjets





Background (Blue) x 1, Signal(Red) x 10

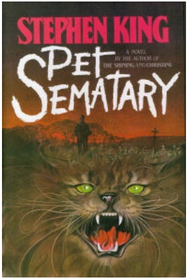
Significance

- Fat jet cuts: $R = 1.5$, $p_T(j) > 130$ GeV, $\alpha_{sub} > 0.7$ GeV,
- Color flow cuts: $\beta_{sub} < 0.05$, $NJ \leq 10$
- Assuming 100 inverse fb

	$\sigma_{tth}[fb]$ $m_h = 80$ GeV	$\sigma_{tth}[fb]$ $m_h = 100$ GeV	$\sigma_{tth}[fb]$ $m_h = 120$ GeV	$\sigma_{tt+jets}[fb]$
After Preselection	12	7	4	6100
After Cuts	0.6	0.5	0.4	20
After Bump Hunting	0.4	0.3	0.2	0.3
Final S/B	1	1	1	
Final $S/\sqrt{B}$	6.6	5.6	5.0	

Outline

Conclusions of Pet Sematary



> *...Louis now completely insane carries Rachel's body to the burial ground, saying that he waited too long with Gage but is confident that Rachel will come back the same as before. Louis waits until nightfall for Rachel to return. Playing solitaire, he hears his resurrected wife walk into the house, and the paper ends with Rachel speaking Darling, her possession, and Louis's fate, unknown...*

Let's hope for happy ending in our case...

Summary of Buried Higgs at the LHC

- There are hints that Higgs may decay into a complicated final state that is difficult to spot at the LHC using traditional techniques
- Example: buried Higgs decaying into 4 gluons

☺ Using jet substructure and color flow allows us to uncover Buried Higgs from the overwhelming QCD background

☺ Still it's not an early discovery: 14 TeV and 100 inverse fb badly needed

What's next?

- Given that we demonstrated the LHC potential to discover difficult Higgs final states, we can proceed to more systematic coverage
- $H \to 4j$ for a heavier pseudoscalar mass (so that the final states has typically 4 separated jets)
- Strategies for $H \to 4b$, $H \to 4c$, $H \to 4\tau$ with light (less than 10 GeV) or heavier (more than 10 GeV) intermediate pseudoscalar

Famous Last Words

- A light (within the LEP reach) Higgs decaying to multiparticle final states is a well-motivated possibility and therefore it should be searched for in colliders
- Even if Higgs is heavier than 115 GeV, it is conceivable that non-standard Higgs decay show up at the LHC, as the leading or subleading channel
- Even if Higgs is completely standard, this kind of scenarios allow to patch up gaps in the experimental sensitivity
- ...and new interesting ideas as well as collider tools are born in the process