Can We See a Light Higgs in $WW^* \rightarrow jjl\nu$?

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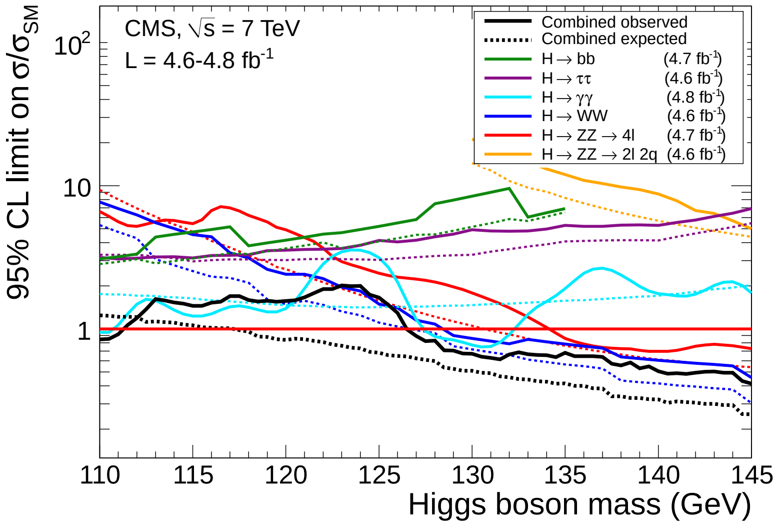
Based on work with C. Kao

Executive Summary

- Yes, eventually. Probably not this year.

Motivation

We were all excited by the prospect of an excess of events in 2011 data at both ATLAS and CMS that could correspond to a Higgs with mass ~ 125 GeV. The excess was primarily in $\gamma\gamma$, with some surplus in $ZZ->4l$ as well.



If we can see ZZ^* then WW^* should have a comparable or better rate since W^* is less off-shell than Z^*.

Taking into account the ‘look elsewhere’ effect, the ZZ^* excess appears to be unremarkable. Nonetheless, the question remains: Will we be able to see WW^* in the foreseeable future with a light Higgs?

Signal Modes

WW^* has 3 modes of decay: leptonic ($l\nu l\nu$), semi-leptonic($jjl\nu$), and fully hadronic ($jjjj$).

All-leptonic mode has been searched for at detectors. No significant excess seen so far. [CMS Collaboration,2012 1202.1489 [hep-ex]]

- \+ Weak backgrounds, no jets.
- \- Two neutrinos limit ability to reconstruct a resonant mass.

Semi-leptonic mode generally viewed as unfavorable at lower masses. [Han, Turcot & Zhang, 1999 9812275 [hep-ph]; Menon & Sullivan, 2010 1006.1078 [hep-ph]]

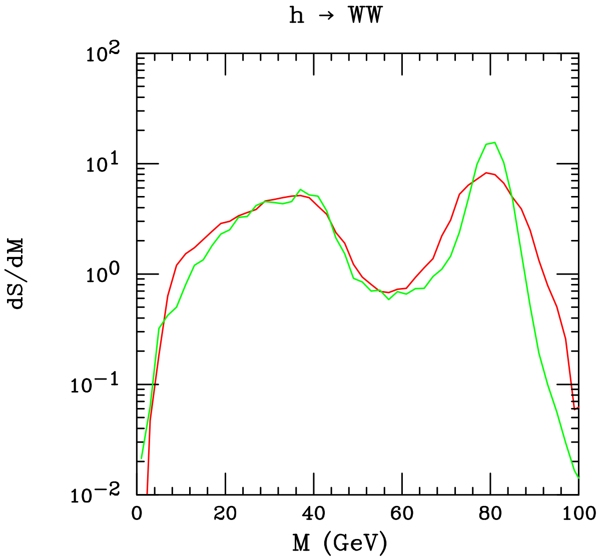
- \- Large QCD backgrounds.
- \+ One neutrino allows for better reconstruction of events.

We consider prospects for the latter in this talk.

Strategy

Primary background will be Wjj generated by QCD processes.

For $M_h \sim 125$ GeV, resonant production of the Higgs requires one of the signal W's to be far off shell, $M_{W*} \sim 45$ GeV. Invariant mass distribution for $W_{l\nu}$ or W_{jj} will have two modes.



The background is dominated by an on-shell $W_{l\nu}$ and a smoothly falling jj distribution.

Thus we choose to focus on the signal events with W_{jj} on shell and $W_{l\nu}$ well below nominal M_W.

Reconstructing the Event

We have one neutrino with a significant fraction of the total momentum. We assume $MET = p(\nu)_T$ but $p(\nu)_z$ is unknown.

Consider

$$\begin{aligned} M_T(W)^2 &\equiv (E(l)_T + E(\nu)_T)^2 - (\overline{p}(l)_T + \overline{p}(\nu)_T)^2 \\ &\simeq (|p(l)_T| + |p(\nu)_T|)^2 - (p(l)_T + p(\nu)_T)^2. \end{aligned}$$

This mass corresponds to the value we get from minimizing $M_W(p(\nu)_z)$ with respect to $p(\nu)_z$.

$$p(\nu)_z = \frac{p(l)_z p(\nu)_T}{\sqrt{E(l)^2 - p(l)_z^2}}.$$

This principle can be easily generalized to the invariant mass of any number of particles.

Cluster Mass

Minimizing $M_h(p(\nu)_z) \equiv (p(j) + p(j') + p(l) + p(\nu))^2$ yields the Cluster Mass:

$$M_c(h)^2 \equiv (\sqrt{M_{jj'l}^2 + p(\nu)_T^2} + p(\nu)_T)^2.$$

This is equivalent to choosing

$$p(\nu)_z = \frac{p(jj'l)_z p(\nu)_T}{\sqrt{E(jj'l)^2 - p(jj'l)_z^2}}.$$

Since we are at a minimum, minor variations in $p(\nu)_z$ do not have a strong effect on the mass distributions.

Weighted Average

Since we are searching for a peak at the low end of the spectrum generated by our signal, choosing a minimum $M(W)_{l\nu}$ or $M(h)$ does a good job reproducing the actual peak.

In fact, we can choose a weighted function

$$p(\nu)_z = \frac{(p(jj'l)_z * M_T(W)^2 + p(l)_z * M_c(h)^2)p(\nu)_T}{\sqrt{(E(jj'l) * M_T(W)^2 + E(l) * M_c(h)^2)^2 - (p(jj'l)_z * M_T(W)^2 + p(l)_z * M_c(h)^2)}}$$

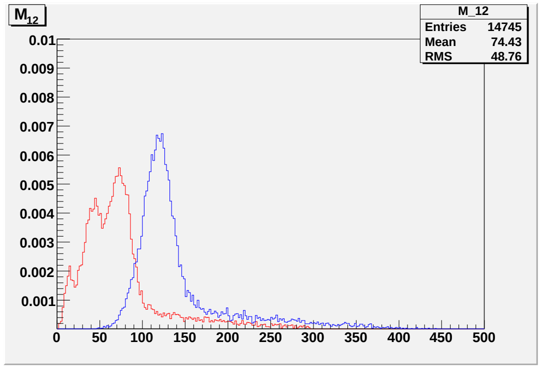
which minimizes the product $M_h * M_w$.

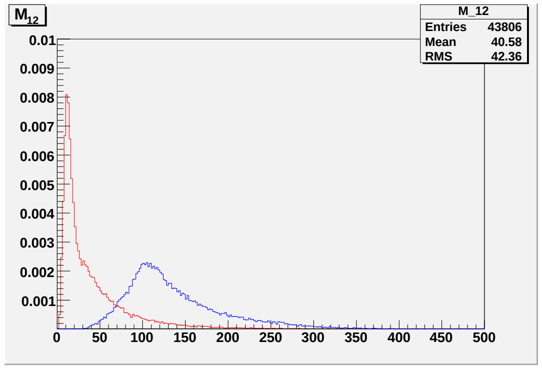
This does a better job of reproducing both the $M_{l\nu}$ and $M_{jjl\nu}$ curves accross the entire spectrum with one choice of $p(\nu)_z$.

In practice, after cuts all three choices of $p(\nu)_z$ will give very similar mass distributions.

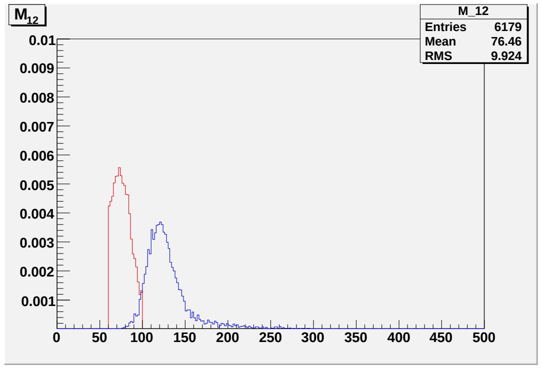
Useful Cuts

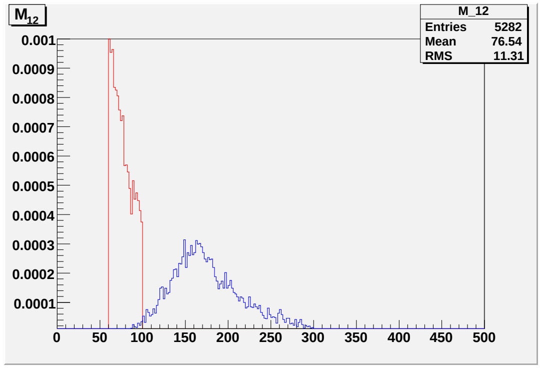
After setting $p(\nu)_z$ as described, we can reconstruct all the kinematics of our event. Our most powerful cuts will be selecting $M_{jj} \sim M_W$ and $M_{jjl\nu} \sim M_h$.





Selecting for on-shell hadronic W.





Angular Correlations

Because we are looking for a scalar decaying to two vector bosons, which then each decay via left-handed couplings, there are angular correlations which might prove useful. [cf. Dobrescu & Lykken, 2009 0912.3543 [hep-ph]]

Generally, this means that the up (down)-type quark will tend to be anti-aligned with the charged (neutral) lepton.

We don't know which jet comes from the up-type quark, but the planes of each W-decay will tend to align. This can be parameterized by:

- ϕ: The angle between the $l\nu$ and jj' planes in the rest frame of the Higgs.
- θ^l: The angle between the l momentum and the direction of the $W_{l\nu}$ boost in the rest frame of $W_{l\nu}$.
- θ^j: The angle between the leading jet momentum and the direction of the W_{jj} boost in the rest frame of W_{jj}.

The signal is maximized for $\phi \simeq 0, \pi$, $\theta^j, \theta^l \sim \frac{\pi}{2}$.

Simulation

- We generate signal and background events using MadGraph/MadEvent. ISR can play a significant role. To handle this consistently we make use of a matching scheme (MLM matching) to merge showering effects with matrix element calculations including up to 3 jets.
- Events are fed through Pythia 6.4 for showering and hadronization. Reconstruction is done with the Delphes detector simulator. We use a Cambridge-Aachen algorithm with 0.5 cone size for jet reconstruction.
- We apply a simulated Jet Energy correction based on the average energy loss (as a function of $|\overline{p}|$ and η) from a comparison of Monte Carlo generated events at parton and jet level.
- We select the leading two jets (in p_T) and the leading electron as our candidate particles with a neutrino inferred as above. For the results below we set $M_h = 125$ GeV with Standard Model couplings.
- We assume l includes electrons and muons but not taus.

Cuts

- $65 < M_{jj} < 95$ GeV
- $M_{jjl\nu} < 130$ GeV
- $M_{l\nu} < 40$ GeV
- $p_T(j_1), p_T(j_2) > 30, 20$ GeV
- $MET < 35$ GeV
- $E^0_{l\nu} < 45$ GeV (Energy of $W_{l\nu}$ in frame of h^0)
- $\Delta R_{jl} > 0.2$

We find that including cuts on the angular correlations or tightening the cuts above can improve the ratio of S/B but will lower the statistical significance $S/\sqrt{B}$.

n.b. The two jets are typically well separated in our signal, $\Delta R_{jj} \gtrsim 2$. However, after the above cuts the background jets are also usually separated.

Results

Events per fb^{-1}

At 8 TeV

Signal	Wjj	WW	$t\bar{t}$
22.6	3130	55.8	12.9

Significance with 16fb^{-1}: 1.6σ

At 14 TeV

Signal	Wjj	WW	$t\bar{t}$
46.3	3930	79.0	31.2

Data required for 5σ discovery: 46.8fb^{-1}

$WW \rightarrow jjl\nu$ (on this analysis) will not lead to a discovery in this channel with 2012 running. We may see a weak hint which could contribute to a combined signal or limit.

C-tagging

Menon and Sullivan have advocated the development of c-tagging algorithms which might enhance this channel (and others). [Menon & Sullivan, 2010]

- If we focus on the signal with a c-quark in the final state, then we start with half the signal rate since we exclude $W \to ud$ decays. However, the Wjj background is dominated by light quark jets and gluons. The Wcj component is roughly $\sim \frac{1}{6}$ the total before cuts.
- Additionally, if we can identify the c-originating jet, we can improve on the angular correlations since we know which jet should align or anti-align with the charged lepton.

Is c-tagging possible?

In fact, we already have a weak version of c-tagging. B-tagging algorithms will (mis)tag c-jets at a much higher rate than light-quark jets.

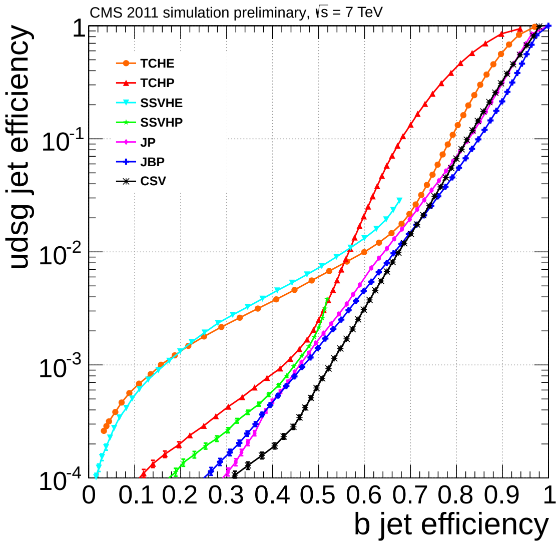
E.g., for a b-jet efficiency of $\sim 55\%$, c-jets will be tagged at a rate of $10 - 15\%$ while light jets ($udsg$) are tagged at $\lesssim 1\%$.

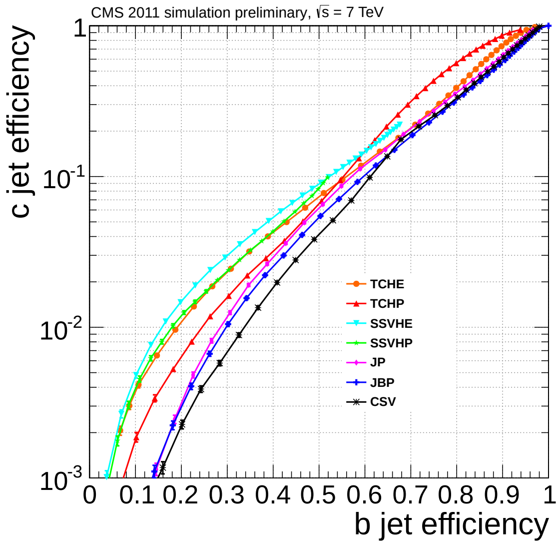
Acceptance can be tuned by adjusting algorithm cut parameter. As we increase the b-jet efficiency we also increase the acceptance of c-jets.

Even 100% acceptance of b-jets is not a problem for us since we are primarily concerned with rejecting a background dominated by light jets.

However, we would require both high c-jet acceptance and good rejection of light jets.

Current B-Tagging Performance





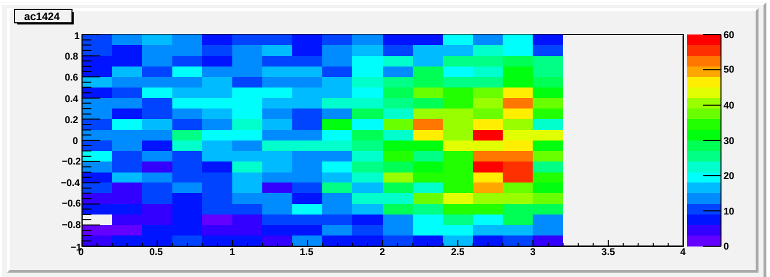
For current b-tagging algorithms, high acceptance does not provide sufficient discrimination against light jets.

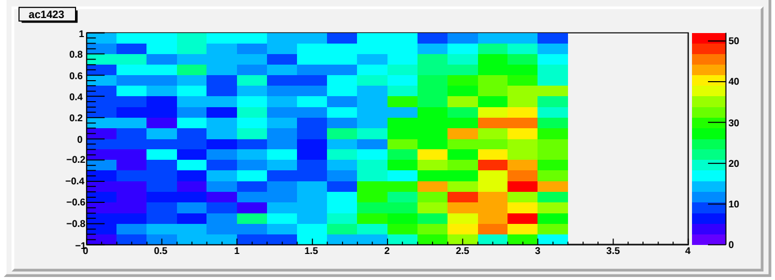
New algorithms designed to single out c-jets from light jets would be needed.

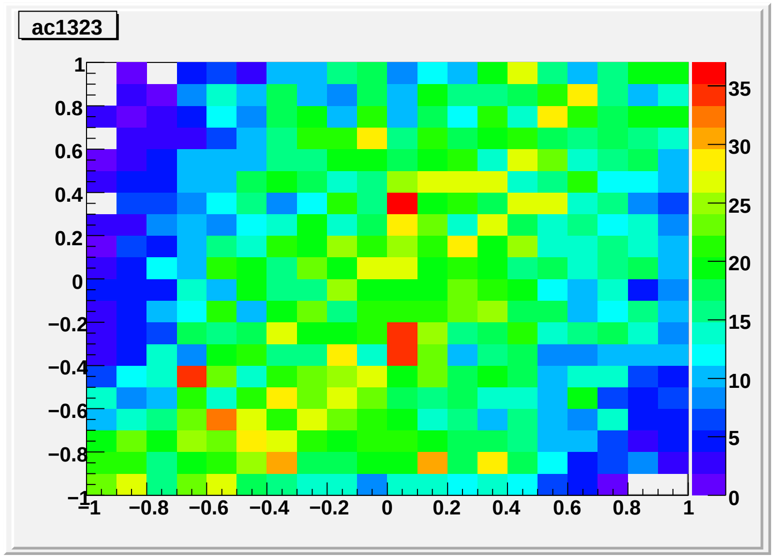
C-tagging Cuts

Angular cuts provide a marginal improvement in statistical significance, but raise $\frac{S}{B}$ and provide a large reduction in non-Wcj backgrounds.

- $\phi > 1.6$
- $\cos\theta^l < 0.85$
- $\cos\theta^j < 0.85$
- $0.9\cos\theta^l - 1 < \cos\theta^j < 2\cos\theta^l + 1$







C-tagging Prospects (Ideal)

With essentially perfect c-tagging (100% acceptance of c-jets, $\lesssim 1\%$ mis-tagging of light jets) we would have notable ($\sim 60\%$) gain in significance.

8 TeV:

Signal	Wcj	WW	$t\bar{t}$
5.6	66.1	5.4	∼1

2.6σ significance with 16fb^{-1}.

14 TeV:

Signal	Wcj	WW	$t\bar{t}$
11.8	160	8.8	10

Discovery with 32fb^{-1}.

Also note improved $\frac{S}{B}$.

C-tagging Prospects (More Realistic)

However, for a more moderate c-tagging model with 50% acceptance, we find only a small gain in statistical significance. We assume 1% mis-tagging for light jets as an illustration.

This case would retain improvement in $\frac{S}{B}$ compared to the untagged case.

8 TeV:

Signal	Wcj	Wjj	WW	$t\bar{t}$
2.9	34.4	5.4	5.7	1

1.7σ significance with 16fb^{-1}.

14 TeV:

Signal	Wcj	Wjj	WW	$t\bar{t}$
6.1	83.2	11.6	9.1	10.

Discovery with 76.5fb^{-1}.

Longer Summary

- The channel $h \to WW \to jjl\nu$ is difficult but not impossible to see for a ~ 125 GeV Higgs. After 2012 running at the LHC we could see a hint in this channel but it will likely take a few 10's of femtobarns at 14 TeV running to reach discovery levels.
- Jet energy resolution is a major limiting factor in our analysis. Since jets are typically $p_T < 40$ GeV we are sensitive to jet-energy corrections and loss of resolution for M_{jj} and $M_{jjl\nu}$. Use of Particle Flow jets or other refinements may improve our results significantly.
- We also consider the prospects for this channel with c-tagging as suggested by Sullivan and Menon. With excellent c-tagging we could see $\sim 60\%$ improvement in our significance. With mid-range c-tagging capabilities we would see only modest gains.