Higgs Decay to Light Jets

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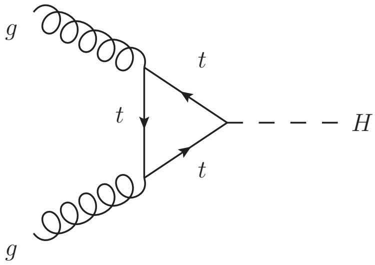
Motivation

- Currently, the best understood Higgs detection channels are mostly EW
- $ht\bar{t}$ can be measured via loop (and other) processes
- b-tagging may allow us to see $h \rightarrow b\bar{b}$ up to 5σ at $14 TeV$ and $\sim$hundred fb^{-1}
- c-tagging could set bounds of the $hc\bar{c}$ coupling at $\sim 6.5 \times SM$

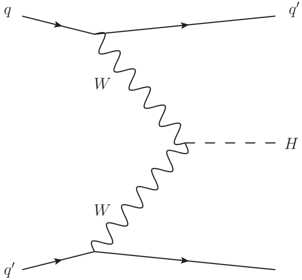
- **We looked for a way to study Higgs decay to a pair of light, untagged jets ($h \rightarrow jj$).**

Higgs Production at the LHC

- *pp* collider → collisions between quarks and gluons
- Primary Higgs production mode is gluon-gluon fusion (≈ 86%)
- Second largest production channel from Vector Boson Fusion (≈ 7%)



Gluon-gluon fusion via top quarks



VBF fusion via top quarks

Higgs Decays

process	BR	process	BR
$H \to \bar{b}b$	58.2%	$H \to ZZ^*$	2.7%
$H \to WW^*$	21.6%	$H \to \gamma\gamma^\Diamond$	0.23%
$H \to gg^\Diamond$	8.18%	$H \to Z\gamma$	0.15%
$H \to \tau^+\tau^-$	6.4%	$H \to \bar{q}q$	<0.03%
$H \to \bar{c}c$	2.89%		

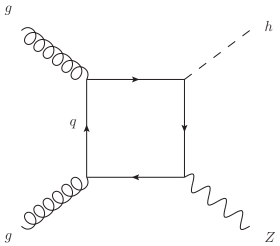
Higgs branching ratios at $m_H \approx 125 GeV$.
($^\Diamond$) indicates a loop process.
Here $q = \{u, d, s\}$.

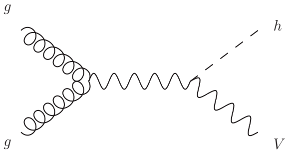
$h \to$ light jets

Strategy: Use associated production with vector boson.

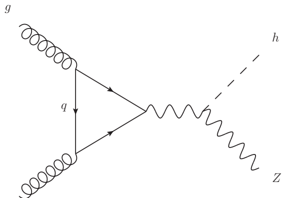
- Production:
  - $pp \to hV$ (LO)
  - $gg \to hZ$ (NLO)
- Decays: $h \to gg$ plus
  - $Z \to \ell\ell$ ($\ell = \{e^{\pm}, \mu^{\pm}\}$)
  - $W \to \ell\nu$
  - $Z \to \nu\nu$

$\to$ The leptonic W/Z decay serves as effective trigger





$gg \to hV$



$gg \to hZ$ (NLO)

Simulation

MadGraph to simulate events:

- Production/decay of tree level diagrams was done in-line
- Production/decay of loop diagrams was done using @NLO+MadSpin
- LHE (parton level) events were showered via Pythia
- Used the Delphes detector simulator (generic LHC)

Dominant backgrounds:

- Primary background for all channels was $pp \to Vjj$
- $t\bar{t} \to l\nu jjbb$ was also significant in the one-lepton ($W \to \ell\nu$) channel.

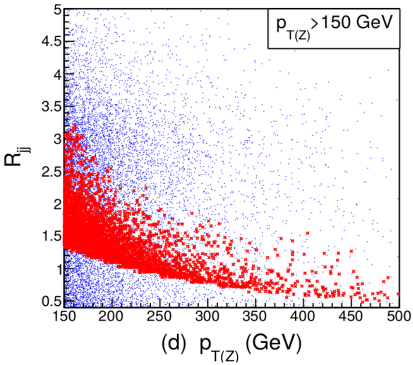
Analysis

Analysis:

- Selected generator-level cuts used to minimize divergences and increase event generation statistics.
- Used Root for analysis with in-house code to check/confirm Root results

Jet cuts:

- At least two jets,
  $p_{T(j)} > 30 GeV$, $|\eta_j| < 2.5$
- Higgs mass reconstruction
  $95 < m_{jj} < 150 GeV$
- $R_{jj} < 1.4$



$R_{jj} - p_T$ distribution

Analysis

VB cuts

- $Z \to \ell\ell$
  - Two hard leptons, same flavor, opposite sign, $p_{T(\ell)} > 30 GeV$, $|\eta_\ell| < 2.5$
  - $p_{T(V)} > 200 GeV$
  - Z mass reconstruction $70 < m_{\ell\ell} < 110 GeV$
- $W \to \ell\nu$
  - One hard lepton $p_{T(\ell)} > 30 GeV$, $|\eta_\ell| < 2.5$
  - $p_{T(V)} > 200 GeV$
  - $\not{E}_T > 30 GeV$
- $Z \to \nu\nu$
  - lepton veto: $p_{T(\ell)} > 30 GeV$, $|\eta_\ell| < 2.5$
  - $\not{E}_T > 200 GeV$

Results

$$\mathcal{S} = \frac{\sigma_{sig} \times \mathscr{L}}{\sqrt{\sigma_{bkgd}}}$$

σ (fb)	$\ell^+\ell^- + jj$	$\ell^\pm + \not{E}_T + jj$	$\not{E}_T + jj$	combined
Vh signal	7.0×10^{-2}	4.1×10^{-1}	3.6×10^{-1}	
Vjj background	2.4×10^{2}	2.5×10^{3}	1.6×10^{3}	
$\mathcal{S}$ @ $\mathscr{L} = 3000 fb^-1$	0.25	0.61	0.49	0.82

Table : Signal significance achieved from each channel and combined results.

Results

$$\mathcal{S}_{j'} = \frac{\mathcal{S}_q}{74\%} = 1.1\sigma$$

	$h \to b\bar{b}$	$h \to c\bar{c}$	$h \to jj$
bb-tag	99.6%	0.4%	0%
cc-tag	90.4%	9.6%	0%
un-tag j'	16%	10%	74%

Table : Fraction of SM decay channels

NOTE: $\mathcal{S}_b = 11$, $\mathcal{S}_c = 1.35$

Results

Signal strength:

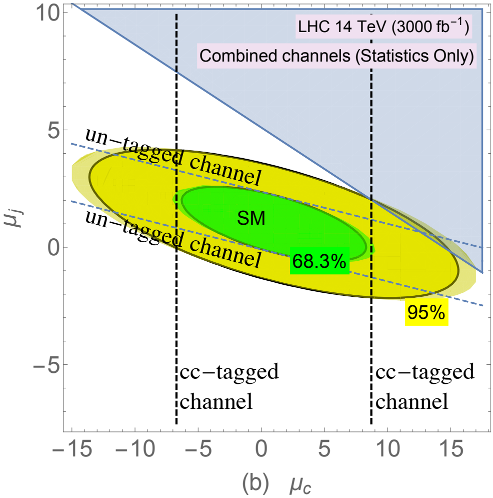
$$\mu_i = \frac{BR(h \to ii)}{BR^{SM}(h \to ii)}$$

Contour constraint on correlation between $\{\mu_j, \mu_c, \mu_b\}$:

$$\mathcal{S}^2 > \sum_a \frac{(\sum_i e_{ai}\ \mu_i - 1)^2}{(1/\mathcal{S}_a)^2}$$

95%CL upper bounds @ $3000 fb^{-1}$:

- $BR(h \to jj) \leq 4 \times BR^{SM}(h \to gg)$
- $BR(h \to c\bar{c}) \leq 15 \times BR^{SM}(h \to c\bar{c})$



$\mu_c - \mu_j$ with $\mu_b = 1$ fixed

Results

Extrapolated upper bounds at 95% CL on the light-quark Yukawa couplings:

$\mathcal{L}(\mathrm{fb}^{-1})$	$\overline{\kappa}_{\mathrm{u}}$ (κ_{u})	$\overline{\kappa}_{\mathrm{d}}$ (κ_{d})	$\overline{\kappa}_{\mathrm{s}}$ (κ_{s})
300 (un-tagged $\mathrm{j'j'}$)	1.3	1.3	1.3
3000 (un-tagged $\mathrm{j'j'}$)	0.6	0.6	**0.6**
Current Global Fits	0.98	0.97	0.70
h kinematics - 300	0.36	0.41	
h kinematics - 3000			1

$$\overline{\kappa}_{\mathrm{q}} = \frac{\mathrm{y_q}}{\mathrm{y_b^{SM}}} \text{ for } \mathrm{q} = \{\mathrm{u}, \mathrm{d}, \mathrm{s}\}$$

Conclusions

Summary:

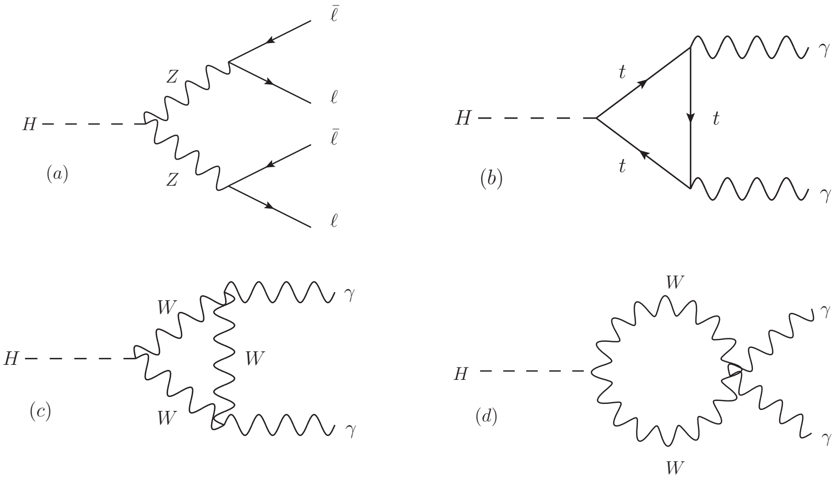
- Achieve a combined significance of $\mathcal{S} = 1.1\sigma$ for the untagged light jet channel
- 95%CL upper bounds @ $3000\mathrm{fb}^{-1}$:
  - $BR(h \to jj) \leq 4 \times BR^{SM}(h \to gg)$
  - $BR(h \to c\bar{c}) \leq 15 \times BR^{SM}(h \to c\bar{c})$
- indirect bounds on light quark Yukawa couplings

Further work:

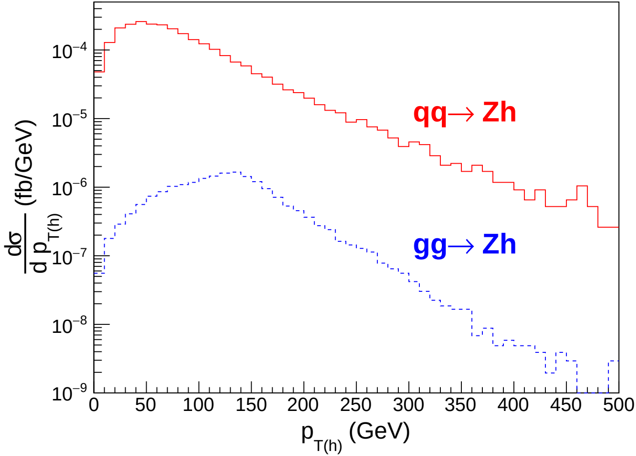
- Include other production channels (VBF & $t\bar{t}h$)
- Include single-tagged categories

Higgs Discovery diagrams

Discovery channels for Higgs decay: (a) $h \to 4\ell$; (b-d) $h \to \gamma\gamma$ via quark and vector boson loops



$h \to$ light jets



Higgs p_T distribution for signal processes $qq \to hZ$ and $gg \to hZ$ at the 14 TeV LHC

Generator Level Cuts

Generator Level Cuts:

- $p_{T(j)} > 20 GeV$ (divergences)
- $|\eta_j| < 3$ (divergences)
- $R_{jj} > 0.4$ (divergences)
- $p_{T(V)} > 150 GeV$ (statistics)

Analysis

Cutflow for $hZ \to jj\ell\ell$

cut eff (%)	$q\bar{q} \to Zh$	$gg \to Zh$	$q\bar{q} \to Zjj$
σ (fb)	3.9×10^{-1}	2.0×10^{-1}	$1.2{\times}10^{4}$
2 leptons	59%	52%	40%
$\geq$ 2 jets	51%	49%	32%
$70 < m_{ll} < 110$	50%	49%	31%
$p_{T(\ell\ell)} > 200$ GeV	26%	23%	16%
$R_{j_1 j_2} < 1.4$	21%	12%	5.3%
$95 < m_h < 150$ GeV	14%	7.6%	1.9%
final (fb)	5.4×10^{-2}	1.5×10^{-2}	$2.4{\times}10^{2}$
efficiency	14%	7.6%	1.9%

Analysis

Cutflow for $hW \to jj\ell\not{E}_T$

cut eff (%)	$q\bar{q} \to Wh$	$q\bar{q} \to Wjj$	$t\bar{t} \to \ell\nu jjb\bar{b}$
σ (fb)	2.3	1.0×10^5	1.5×10^4
$\not{E}_T > 30$ GeV	94%	87%	93%
1 lepton	72%	52%	62%
$p_{T(\ell\nu)} > 200$ GeV	39%	24%	26%
≥ 2 jets	35%	20%	22%
$R_{j_1j_2} < 1.4$	27%	6.8%	11%
$95 < m_h < 150$ GeV	18%	2.5%	2.5%
final (fb)	4.1×10^{-1}	2.5×10^3	3.7×10^2
efficiency	18%	2.5%	2.5%

Analysis

Cutflow for $hZ \to jj + \not{E}_T$

cut eff (%)	$q\bar{q} \to Zh$	$gg \to Zh$	$q\bar{q} \to Zjj$
σ (fb)	1.2	6.0×10^{-1}	$3.6{\times}10^4$
$\not{E}_T > 200$ GeV	49%	44%	42%
≥ 2 jets	45%	43%	35%
$R_{j_1 j_2} < 1.4$	36%	25%	12%
$95 < m_h < 150$ GeV	23%	15%	4.5%
final (fb)	2.7×10^{-1}	8.9×10^{-2}	1.6×10^3
efficiency	23%	15%	4.5%

Results

$$\mathcal{S}^2 > \sum_a \chi_a^2 = \sum \frac{(x_a - \overline{x}_a)^2}{\sigma_a^2}$$

$$= \sum_a \frac{(\sum_i \epsilon_{ai}^2 BR_i N_{sig}^{prod} - \sum_i \epsilon_{ai}^2 BR_i^{SM} N_{sig}^{prod})^2}{(\sqrt{N_{bkg}})^2}$$

$$= \sum_a \frac{(\sum_i e_{ai}\ \mu_i - 1)^2}{(1/\mathcal{S}_a)^2}$$