Double Higgs Production at the LHC

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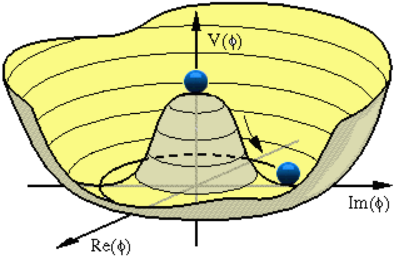
(w/ Alan Barr), 1310.1084 (w/ Nico Greiner), in progress

Measuring Higgs Couplings

- Can we measure double Higgs production at the LHC?
- Can we measure the Higgs self-coupling at the LHC?
- Can we learn about New Physics?

Why Think About Self Couplings?

- $$\mathcal{L} \supset \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{2v^2} h^4$$
- Standard Model trilinear is $\lambda_{SM} = m_h^2/2v$
- Measuring the Higgs self couplings directly probes the structure of the Higgs potential

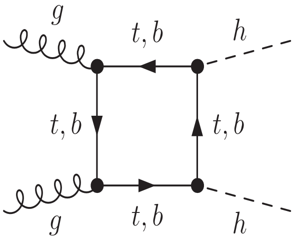


Higgs pair production

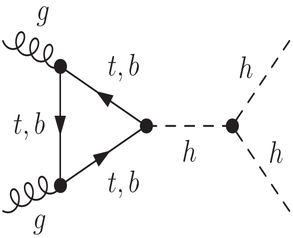
Effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{1}{4}\frac{\alpha_s}{3\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

$$\mathcal{L} \supset +\frac{1}{4}\frac{\alpha_s}{3\pi v} G^a_{\mu\nu} G^{a\,\mu\nu} h - \frac{1}{4}\frac{\alpha_s}{6\pi v^2} G^a_{\mu\nu} G^{a\,\mu\nu} h^2$$

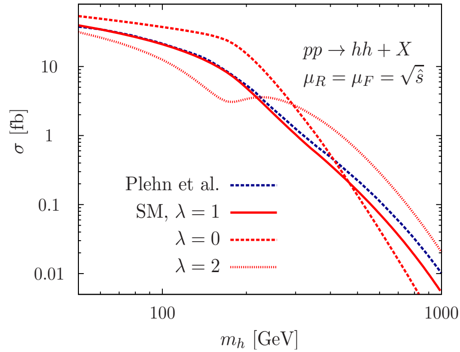


(a)



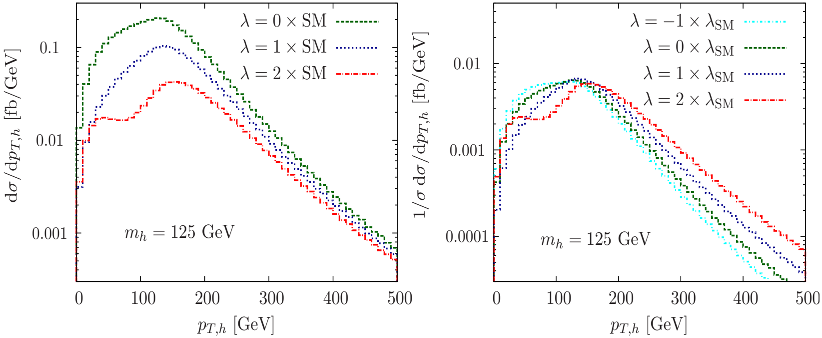
(b)

Inclusive Cross-section



- LO: 16 fb ($\sim$ 1500 times smaller than single Higgs production)
- NLO: 33 ± 5 fb. NNLO: 40 ± 3.5 fb
- Diagram (b) resonantly enhanced when $s \simeq 4m_t^2$

p_T distributions



- Naturally boosted $p_{T,h} \gtrsim 100$ GeV
- Max sensitivity at $p_{T,h} \sim 100$ GeV

Rare decay search strategy: $bb\gamma\gamma$

- $bb\gamma\gamma$: Constraints possible with a lot of luminosity[a]
- Suffers from small $BR(h \to \gamma\gamma)$
- Claim $40 - 50\%$ uncertainty on λ_{hhh} with 3ab^{-1}

[a] Baur *et al* 2003, Yao 1308.6302, Barger *et al.* 1311.2931

bb$\gamma\gamma$: ATLAS-PHYS-PUB-2014-019 (3 weeks ago)

For 3000fb^{-1}:
"After event selection, a signal yield of around 8 events is obtained for the Standard Model scenario, corresponding to a signal significance of 1.3σ"

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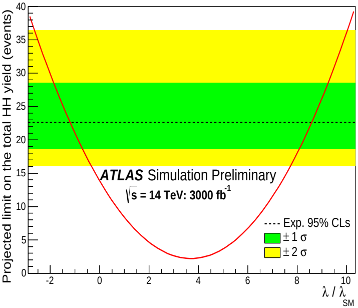
"After event selection, a signal yield of around 8 events is obtained for the Standard Model scenario, corresponding to a signal significance of 1.3σ"

- Excludes $8.7 \lesssim \lambda/\lambda_{SM} \lesssim -1.3$



Unboosted and Boosted searches

Strategy

- Small cross-section: $\sigma^{NLO}(hh) = 28.4$ fb.
- So focus on largest branching ratios: *bb* (60%), *WW* (20%), $\tau\tau$ (6%).
- Unboosted *bbbb*, *bbWW*: Not possible due to 4*b* and $t\bar{t}$ backgrounds.

	$\lambda = 1$ (fb)	$b\bar{b}WW$	ratio to $\lambda = 1$
1 isolated lepton	3.76	254897	$1.5 \cdot 10^{-5}$
MET + jet cuts	0.85	66595	$1.2 \cdot 10^{-5}$
had-W recon	0.33	38153	$0.9 \cdot 10^{-5}$
kinematic Higgs recon	0.017	205	$8.3 \cdot 10^{-5}$

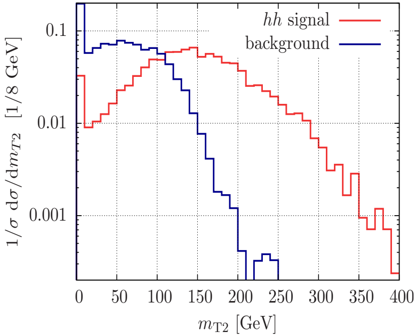
AugMT2ing DiHiggs Searches: $b\bar{b}\tau\tau$

- Can use the m_{T2} variable to supress $t\bar{t}$ backgrounds
- $m_{\mathrm{T2}} = \min_{\mathbf{c}_{\mathrm{T}}+\mathbf{c}'_{\mathrm{T}}=\mathbf{p}^{\Sigma}_{\mathrm{T}}} \{\max(m_{\mathrm{T}}, m'_{\mathrm{T}})\}$

- Take b's as visible particles, and $p_{T,W} + p_{T,W'}$ as 'invisible momentum'
- m_{T2} constructed from momenta of t decay products and $\not{p}_{\mathrm{T}}$ has maximum at m_t
- Signal does not

- Also use $p_{\mathrm{T},b\bar{b}}$

[Barr, MJD, Englert, Spannowsky '13]



AugMT2ed DiHiggs: some results

Analysis results

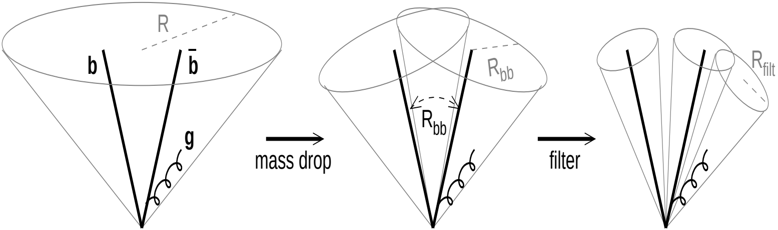
cross section [fb]	hh	S/B
Before cuts	13.89	1.06×10^{-3}
After trigger	1.09	0.463×10^{-3}
After event selection	0.248	0.578×10^{-3}
After $m(\tau^+\tau^-)$ cut	0.164	1.46×10^{-3}
After $m(b\bar{b})$ cut	0.118	3.98×10^{-3}
After $p_{\mathrm{T},b\bar{b}} > 175$ GeV cut	0.055	0.105
After $m_{\mathrm{T2}} > 125$ GeV cut	0.047	0.250

Comments

- Corresponds to $\sim 60\%$ sensitivity to λ_{SM} with 3000fb^{-1} LHC
- Can gain further sensitivity using $hh + 1$j final state

Exploiting boosted kinematics

- Signal has $b\bar{b}$ and $\tau\bar{\tau}$ systems approximately back-to-back
- $t\bar{t}$ background more likely to have collimated $b\tau$
- Promising place to use jet substructure techniques



Boosted regime: $bb\tau\tau$

Higgs reconstruction

- Two hadronic taus reconstructing m_h
- One fatjet with BDRS cuts reconstructing m_h

	$\lambda = 1$	$b\bar{b}\tau\tau$ (BG)	ratio to $\lambda = 1$
x-section pre-cuts	28.34	873076	$3.2 \cdot 10^{-5}$
Higgs from τs	1.94	1512	$1.3 \cdot 10^{-3}$
fatjet cuts	1.09	225	$4.8 \cdot 10^{-3}$
Higgs rec & tags	0.095	0.15	0.49

- Expect 95 signal events with 1000fb^{-1} in SM.
- Expect 148 events for $\lambda = 0$; 53 events for $\lambda = 2$.

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$b\bar{b}W^+W^-$ also studied

- BDRS cuts on $b\bar{b}$, 1 leptonic W, 1 hadronic.
- 4.6 signal, 2.6 background events in 600 fb^{-1}

Multi-b final states

$pp \to hh \to b\bar{b}b\bar{b}$

- Two BDRS fatjets & shower deconstruction[a]
- Constrains $\lambda \lesssim 1.2 \times \lambda_{SM}$ at 95% C.L

[a] de Lima, Papaefstathiou, Spannowsky 1404.7139

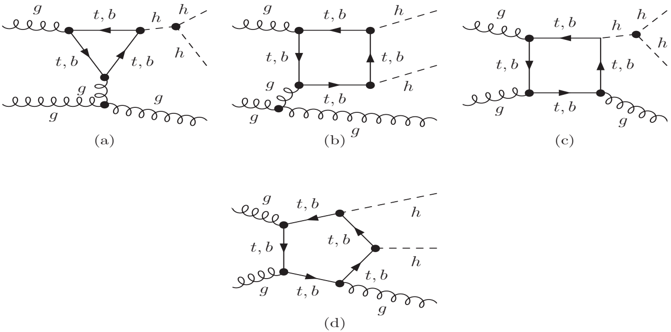
$pp \to t\bar{t}hh \to t\bar{t}b\bar{b}b\bar{b}$

- 5-6 b-tags [a]
- Constrains $\lambda \lesssim 2.51 \times \lambda_{SM}$ at 95% C.L

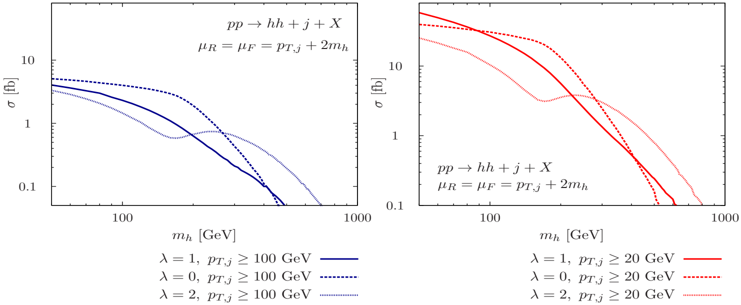
[a] Englert *et al.* 1409.8074; Liu & Zhang 1410.1855;

Dihiggs + hard jet production

- Want to decorrelate $p_{T,h}$ with suppression of triangle diagram
- Motivates studying $pp \to hh + j$



$\sigma(pp \to hh + 1j)$



- Left: $p_{\mathrm{T,j}} > 100$ GeV. Right: $p_{\mathrm{T,j}} > 20$ GeV
- Large dependence on λ: $\Delta\sigma/\sigma_{SM} \simeq 100\%$ for $\lambda \in [0, 2\lambda_{SM}]$
- Compare $\Delta\sigma/\sigma_{SM} \simeq 45\%$ for $pp \to hh$.
- Cost in cross-section: $\sigma(pp \to hh + j) \simeq$ few fb^{-1}

Results for $b\bar{b}\tau\tau j$

- S/B improves relative to $bb\tau\tau$ w/out hard jet
- But cross-section very small.

fb	$\xi = 1$	$b\bar{b}\tau^+\tau^- j$ (BG)	ratio to $\xi = 1$
x-sec precuts	3.24	174	$1.9 \cdot 10^{-2}$
2 τs	0.22	45	$4.8 \cdot 10^{-3}$
$m_{\tau\tau} \approx m_h$ + fatjet	0.16	3.1	$5.1 \cdot 10^{-2}$
kin. Higgs rec. + $2b$	0.04	0.153	0.26
hh inv. mass + $p_{T,j}$ cuts	0.006	0.0037	1.54

Dihiggs +2 jet production[1]

Why study $hh + 2j$? When will this ever end?

- Leading process sensitive to W^+W^-hh and $ZZhh$ interactions through vector boson fusion
- Given by $g_{WWhh} = e^2/(2s_w^2)$ and $g_{ZZhh} = e^2/(2s_w^2 c_w^2)$

But...

- This process also gets contributions from gluon fusion at $\mathcal{O}(\alpha_s^4\alpha^2)$ which must be calculated and kept under control

[1] MJD,Englert,Greiner,Spannowsky 1310.1084 + in progress

Calculating the gluon fusion component

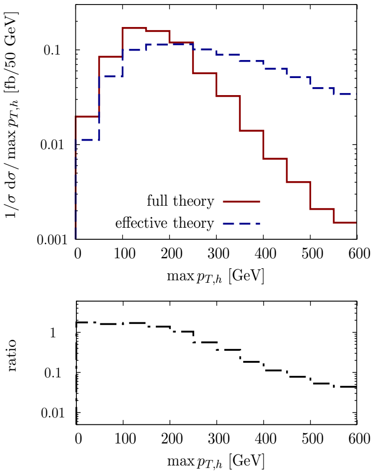
What about our old friend?

$$\mathcal{L}_{\text{eff}} = \frac{1}{4}\frac{\alpha_s}{3\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

Momentum transfers are again $p_{T,h} \sim m_t$ and so kinematic information is lost when $m_t \to \infty$

- Need to incorporate full loop contributions
- This is challenging, particularly for the $gg \to hhgg$ case with $\mathcal{O}(10^3)$ Feynman diagrams: up to 1 minute per phase space point
- Not promising for traditional Monte Carlo approaches
- Instead opt for a reweighting procedure

Reweighted vs. EFT



Comments

- Shows $p_{T,h_{max}}$ from $gg \to hhgg$
- Similar behaviour as in *hh* and *hhj* production
- At large momentum transfers massive quark loops are resolved and EFT overestimates

Results

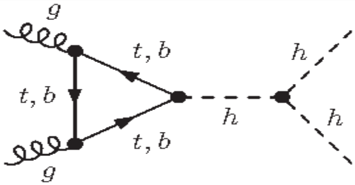
Analysis cuts

- Require $p_{T,j} > 25$ GeV and $|\eta_j| < 4.5$
- Require two *b* jets, and two extra (non-τ jets)
- No m_{T2}-based cuts or MET-based cuts used $\rightarrow$ room for optimisation

	Signal with $\xi \times \lambda$			Background		S/B
	$\xi = 0$	$\xi = 1$	$\xi = 2$	$t\bar{t}jj$	Other BG	ratio to $\xi = 1$
tau selection cuts	0.212	0.091	0.100	3101.0	57.06	0.026×10^{-3}
Higgs rec. from taus	0.212	0.091	0.100	683.5	31.92	0.115×10^{-3}
Higgs rec. from *b* jets	0.041	0.016	0.017	7.444	0.303	1.82×10^{-3}
2 tag jets	0.024	0.010	0.012	5.284	0.236	1.65×10^{-3}
incl. GF after cuts/re-weighting	0.181	0.099	0.067	5.284	0.236	$1/61.76$

DiHiggs BSM Implications[2]

- Is this final state of interest for Beyond the Standard Model physics?
- How can BSM physics alter SM di-higgs phenomenology?

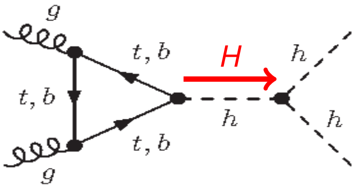


[2] MJD, Englert, Spannowsky 1210.8166

DiHiggs BSM Implications[2]

Resonant

- New (on-shell) resonances
- Two-Higgs doublet models (supersymmetry)
- Higgs-portal models
- Composite models with *hh* resonances



[2] MJD, Englert, Spannowsky 1210.8166

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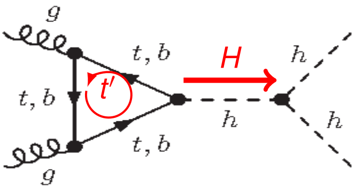


Non-Resonant

- Models with heavy top-partners
- Composite Higgs models
- Pseudo-dilaton models

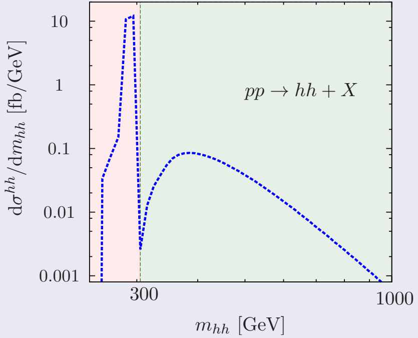
[2]MJD, Englert, Spannowsky 1210.8166

DiHiggs BSM Implications[2]

Resonant: SUSY

- $H \to hh$ can be dominant decay channel!
- Happens for low tan β
- Can separate SM and BSM contributions with m_{hh} cut
- Could allow to bound/reconstruct tan β

[MJD, Englert, Spannowsky '12]



[2] MJD, Englert, Spannowsky 1210.8166

The Higgs Portal

$H^\dagger H$ is a singlet

- Higgs Portal Potential:

$$V = m_H^2|H|^2 + \lambda_H|H|^4 + m_S^2|S|^2 + \lambda_S|S|^4 + \eta_\chi|H|^2|S|^2$$

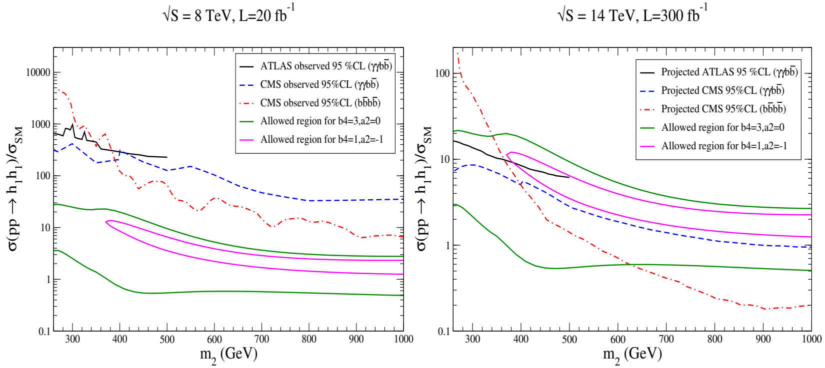
- Φ_S a hidden sector Higgs field
- Visible and hidden sector Higgses mix:

$$\begin{aligned} h &= \cos\chi\, H_s + \sin\chi\, H_h \\ H &= -\sin\chi\, H_s + \cos\chi\, H_h\,, \end{aligned}$$

- Variety of trilinears to possibly study: *hhh*, *Hhh*, *HHh*, *HHH*

The Higgs Portal[3]

- LH: Constraints from current searches
- RH: Projections for Run II



[3] Chen, Dawson, Ian Lewis 1410.5488 (and also 1210.6663)

DiHiggs catching up with single Higgs

Studies of

- Variety of different production mechanisms: gluon fusion, $t\bar{t}hh$, vector boson fusion...
- Variety of different final states: $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, $b\bar{b}WW$, 4bs...
- Current projections: 30-50% accuracy on trilinear from lifetime measurement?
- Field continues to evolve!

Beyond the Standard Model

- Rich BSM phenomenology
- Large resonant and non-resonant enhancements possible in a variety of models