Double Higgs Production at the LHC

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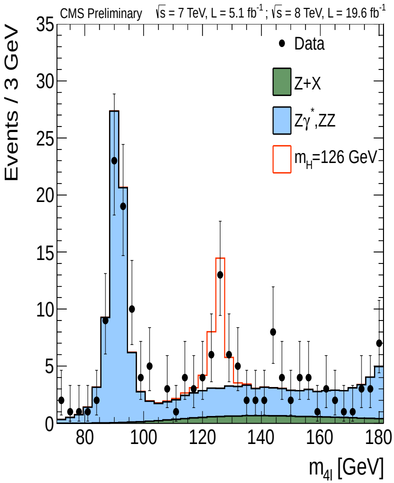
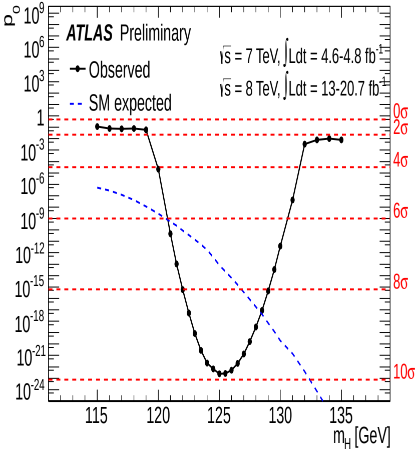
Obligatory Experimental Higgs Slide





Measuring Higgs Couplings

Things we can measure

- Couplings to fermions: $b\bar{b}$, $t\bar{t}$, $\tau\tau$.
- Couplings to massive VBs: ZZ, WW, VBF, associated production.
- Couplings to massless VBs: $\gamma\gamma$, g-fusion.
- Couplings to itself.

This talk

- 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?

The SM Higgs Lagrangian

- SM Higgs Lagrangian

$$V(H^\dagger H) = \mu^2 H^\dagger H + \eta (H^\dagger H)^2$$

- In unitary gauge get

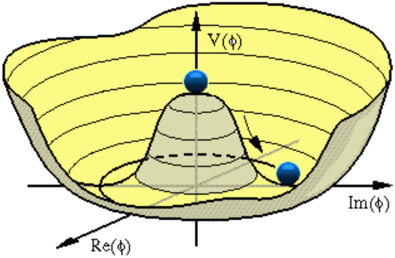
$$\frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4$$

- where

$$m_h^2 = \eta v^2/2 \qquad v^2 = -\mu^2/\eta$$

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

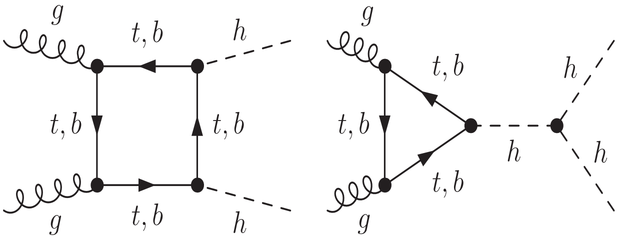


Higgs pair production

Effective Lagrangian

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

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



(a) (b)

Higgs Pair Production

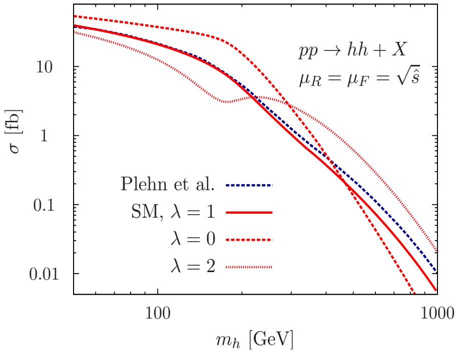
Effective Lagrangian

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

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

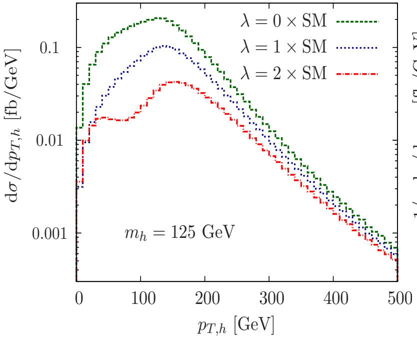
- Interference effects important.
- Fails to reproduce full kinematics when $Q^2 \gtrsim m_t^2$

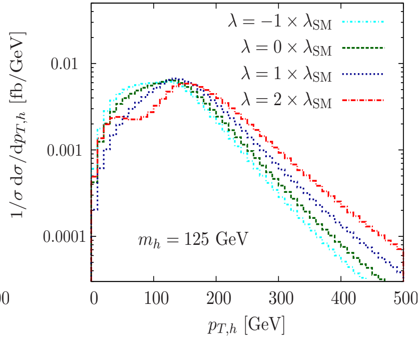
Inclusive Cross-section



- 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



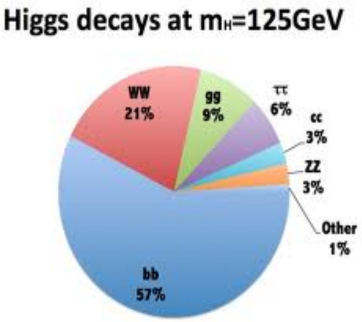


- Naturally boosted $p_{T,h} \gtrsim 100$ GeV
- Max sensitivity at $p_{T,h} \sim 100$ GeV

Hunting for a Higgs

- The Higgs is unstable and decays
- Need to hunt for its decay products and reconstruct it from them

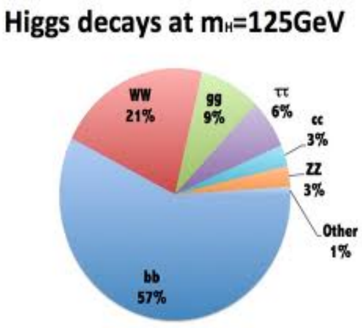
- Largest branching ratio $b\bar{b}$ difficult to observe due to large background
- $\gamma\gamma$ and $ZZ \rightarrow 4l$: Low BR but low backgrounds (discovery modes)
- WW and $\tau\tau$: Also measured already at 8 TeV

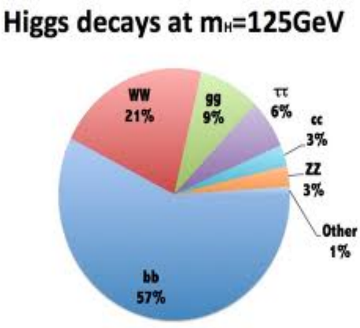


Hunting for Higgses

Balance between

- Having as much pie as possible
- Pie slice is easy to find





Search strategies

- $hh \rightarrow W^+W^-W^+W^-$: 2$l$ and 3l cases studied, no constraints when $m_h \lesssim 2m_W$[a]
- $bb\gamma\gamma$: Constraints possible with a lot of luminosity[b]
- Claim 40% uncertainty on λ_{hhh} with 3ab^{-1}
- Suffers from small $BR(h \rightarrow \gamma\gamma)$

[a] Baur *et al* 2003
[b] Baur *et al* 2003, Barger *et al* 2013

bb$\gamma\gamma$: From ATLAS Hi-Lumi Study (Withdrawn!)

"On applying this selection, a signal yield of approximately 11 is obtained, with ttH being the dominant background, contributing approximately 14 events."

Unboosted and Boosted searches

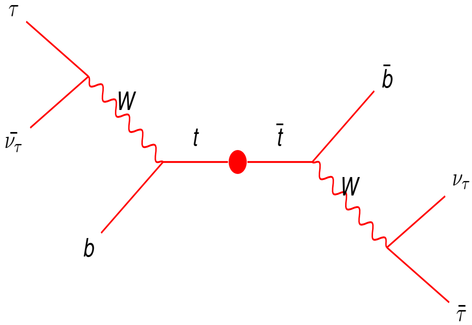
Strategy

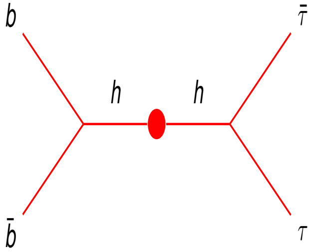
- Small cross-section: $\sigma^{NLO}(hh) = 28.4$ fb.
- So focus on largest branching ratios: *bb* (60%), *WW* (20%), $\tau\tau$ (6%).
- Unboosted *bbbb*, *bbWW*: Not possible due to 4*b* and $t\bar{t}$ backgrounds.

	$\lambda = 1$	$b\bar{b}WW$	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

- We want to keep as much pie as possible
- $bb\tau\tau$: Can exploit kinematic differences between signal and $t\bar{t}$ background.

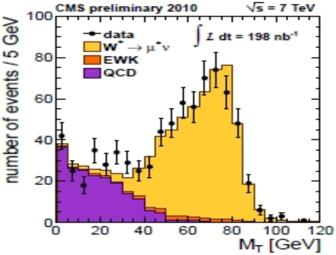




Exploiting Event Kinematics

Reconstructing Semi-Invisible Particle Decays

- $M_T^2 = 2E_{T,1}E_{T,2}(1 - \cos\phi)$ (for massless daughters)
- Satisfies $M_T \leq M_X$



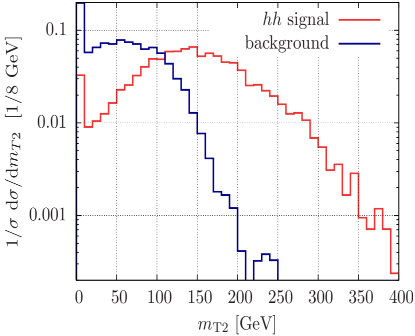
AugMT2ing DiHiggs Searches

- Can generalise transverse mass to pair production: m_{T2}
- $m_{\mathrm{T2}} = \min_{\mathbf{c}_\mathrm{T}+\mathbf{c}'_\mathrm{T}=\mathbf{p}_\mathrm{T}^\Sigma} \{\max(m_\mathrm{T}, m'_\mathrm{T})\}$

- 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
- Not the case for signal

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

[Barr, MJD, Englert, Spannowsky '13]



DiHiggs:some results

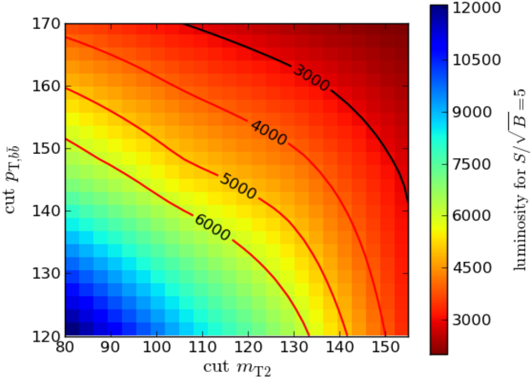
Analysis results

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 still be further optimised: substructure etc.
- Can gain further sensitivity using $hh + 1$j final state
- Being studied by ATLAS and CMS

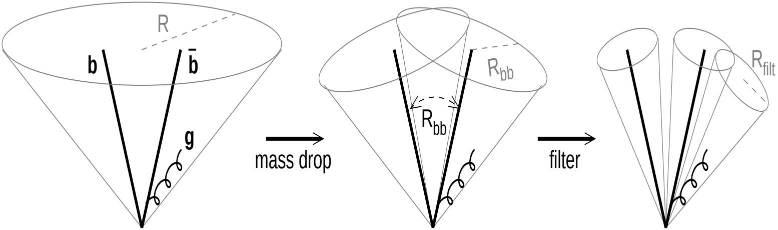
Observing dihiggs production



- Luminosity in fb^{-1} required for $S/\sqrt{B} = 5$

Exploit kinematics II

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



Boosted Kinematics: (BDRS)^2

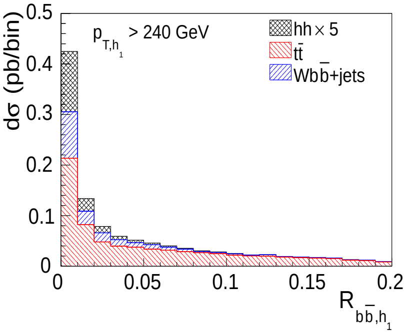
	$\lambda = 1$	$b\bar{b}b\bar{b}$ [QCD]	ratio to $\lambda = 1$
x-sec pre-cuts	28.42	21342	$1.3 \cdot 10^{-3}$
fatjet cuts	8.23	4800	$1.7 \cdot 10^{-3}$
1^{st} Higgs rec+2b	1.02	237.3	$4.2 \cdot 10^{-3}$
2^{nd} Higgs rec+2b	0.094	9.78	$9.6 \cdot 10^{-3}$

Comments

- Can gain sensitivity in main decay channels.
- Can think about $b\bar{b}WW$ and $b\bar{b}\tau\bar{\tau}$ again

Boosted bbW^+W^{-1}

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



[1] Papaefstathiou, Yang, Zurita, 1209.1489

Boosted regime: $bb\tau\tau$

Higgs reconstruction

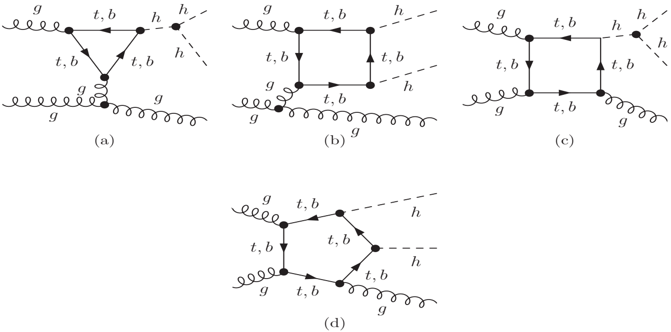
- Two hadronic taus reconstructing m_h
- One fatjet with BDRS cuts reconstructing m_h

	$\lambda = 1$	$b\bar{b}\tau\tau$ (BG)	ratio to $\xi = 1$
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

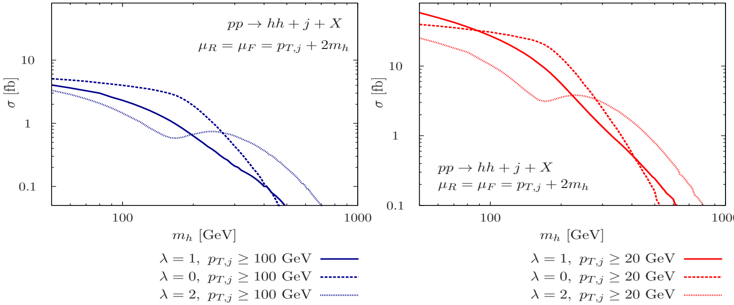
- Expect 95 signal events with 1000fb^{-1} in SM.
- Expect 148 events for $\lambda = 0$; 53 events for $\lambda = 2$.

Dihiggs + jet production

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

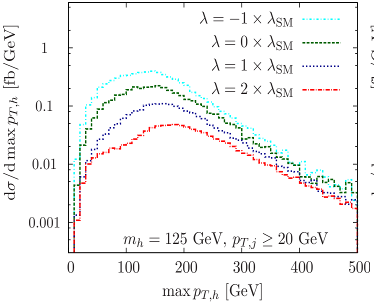


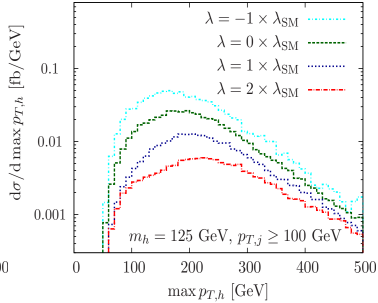
$\sigma(pp \to hh + 1j)$



- 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}

Comments on $pp \to hh + 1j$





- Sensitivity to λ comes from configs with two Higgs bosons close to each other and central.
- Hadronic decay products may overlap $\to$ to reconstruct *hh* system rely on substructure techniques.

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

- $b\bar{b}b\bar{b}j$: S/B still $\sim 10^{-3}$
- S/B improves relative to $bb\tau\tau$
- 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

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

Calculating the gluon fusion component

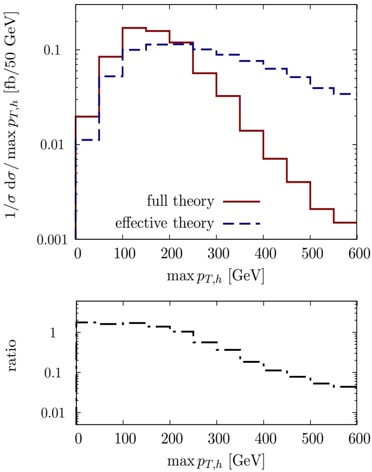
What about our old friend?

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

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 1000 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

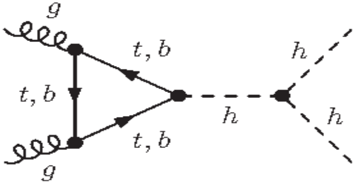
Analysis cuts

- 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

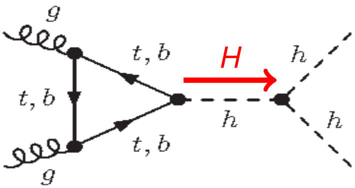
- What is the relevance of this for Beyond the Standard Model physics?
- How can BSM physics alter SM di-higgs phenomenology?



DiHiggs BSM Implications

Resonant

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



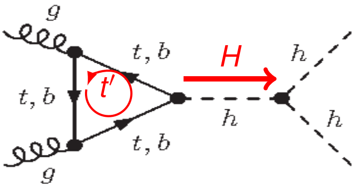
DiHiggs BSM Implications

Resonant

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

Non-Resonant

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

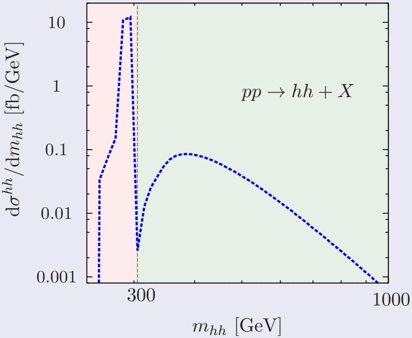


DiHiggs BSM Implications

Resonant: SUSY

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

[MJD, Englert, Spannowsky '12]



Supersymmetry at low tan β

- For tan $\beta \sim 2-3$ and $2m_h < m_H < 2m_t$, H has a large BR $H \to hh$.
- Can happen in NMSSM with moderate λ, splittish SUSY scenarios.

$$\lambda_{hhh} = 3\cos 2\alpha \, \sin(\beta+\alpha)$$
$$\lambda_{Hhh} = 2\sin 2\alpha \, \sin(\beta+\alpha) - \cos 2\alpha \, \cos(\beta+\alpha)$$

- Way to reconstruct α and $\beta = v_u/v_d$
- $m_H = 290$ GeV, $\sigma(pp \to hh) = 246$ fb, $BR(H \to hh) = 47\%$

The Higgs Portal

$\Phi_H^\dagger \Phi_H$ is a singlet

- Higgs Portal Potential:

$$V = m_H^2 |\Phi_H|^2 + \lambda_H |\Phi_H|^4 + m_S^2 |\Phi_S|^2 + \lambda_S |\Phi_S|^4 + \eta_\chi |\Phi_H|^2 |\Phi_S|^2$$

- 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

Cross-sections

- Visible and hidden sector Higgses mix:

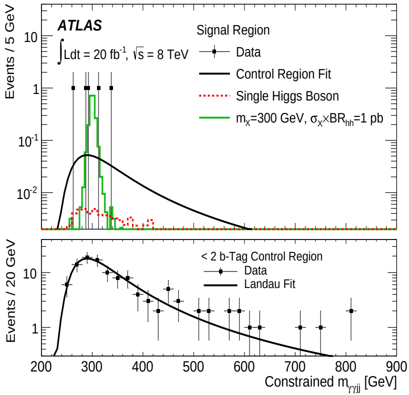
$$h = \cos\chi\, H_s + \sin\chi\, H_h$$
$$H = -\sin\chi\, H_s + \cos\chi\, H_h\,,$$

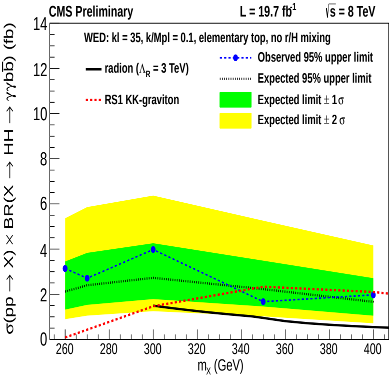
- $m_h = 125$ GeV, $m_H = 255$ GeV
- Find cross-sections:

$$pp \to hh + X \quad : \quad 44.4 \text{ fb} \qquad (1a)$$
$$pp \to Hh + X \quad : \quad 5.57 \text{ fb} \qquad (1b)$$
$$pp \to HH + X \quad : \quad 667 \text{ ab} \qquad (1c)$$

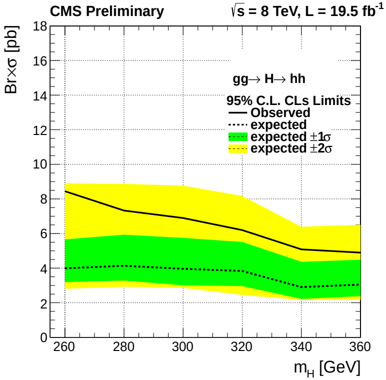
- $\sigma(pp \to hh + j) = 10.1$ fb, $p_{T,j} > 80$ GeV

Pot Stirring: $H \to hh \to bb\gamma\gamma$





Pot Stirring: CMS $H \to hh$ multileptons



Pseudo-Nambu-Goldstoneism

- Strong interactions can provide a (partial) cure to the naturalness problem
- Need a light scalar degree of freedom
- Can happen if PNG of some broken symmetry

Examples

- Pseudo-dilaton (PNG of scale symmetry)
- Composite Higgs

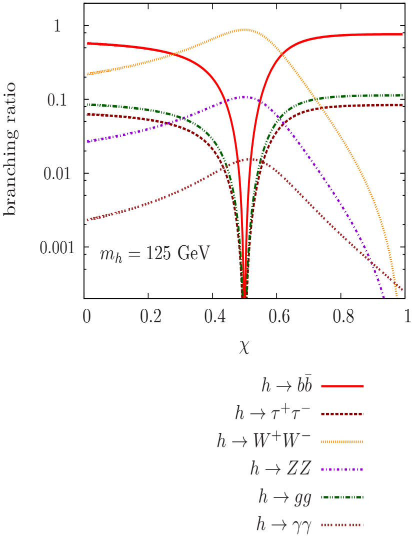
Composite Higgs

- Gauge EW interactions as subgroup of larger broken symmetry group e.g.

$$SO(5) \to SO(4) \simeq SU(2)_L \times SU(2)_R$$

- NG bosons which arise from symmetry breaking get masses from Coleman-Weinberg
- Deviations from SM behaviour measured by $\xi = v/f$, $f \sim$ pion decay constant

Composite Higgs BRs



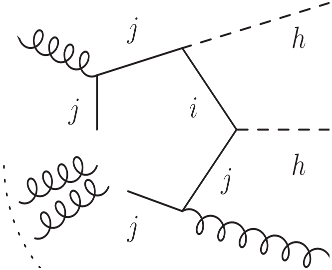
Comments

- Can have highly modified branching ratios relative to SM
- We tooks $\xi = 0.25$ for our study
- This value was allowed in late 2012

Fermion masses

Generated by mixing operators

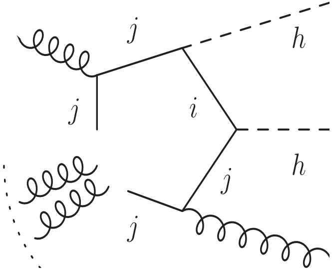
- Get non-diagonal interactions $f_i f_j h$ and $f_i f_j hh$
- Non-SM trilinear $L_h \supset \frac{1-2\xi}{\sqrt{1-\xi}} h^3$
- Top-partners in loop



Composite Higgs Phenomenology

Cross-sections

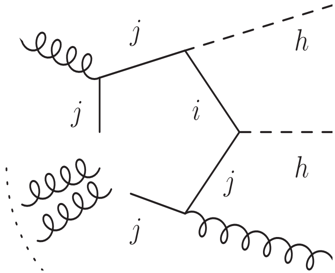
- Cross-section increased by $3 - 4 \times$SM
- σ enhanced at high p_T due to new fermions



Dihiggs +jet

Comparison with Standard Model

- Get $\sigma(pp \to hh + j) = 13$ fb for $p_{T,j} > 80$ GeV - $4.6 \times \sigma_{SM}$
- Would correspond to $S/B \simeq 7$ for $bb\tau\tau + j$ search considered earlier



Summary

Standard Model

- Trilinear coupling a crucial measurement of EWSB
- Good prospects in boosted $bb\tau\tau$, boosted $bb\tau\tau + j$ final states
- Can also use $bb\gamma\gamma$ and maybe $bbWW$
- Possible lifetime measurement of λ_{hhh}^{SM} to 30-50% accuracy?
- Prospects at 100 TeV machine?

Beyond the Standard Model

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

Backups

Modified tagger

- Hadronically more active final state
- Undo clustering, if $m_{j_1} > 0.8 m_j$ discard m_{j_2}, else keep both.
- If $m_{j_i} < 30$ GeV, add to list of substructures, else further decompose.

- Do filtering
- Keep three hardest filtered subjets.
- Call two hardest filtered subjets with mass closest to 125 GeV a Higgs candidate and b-tag