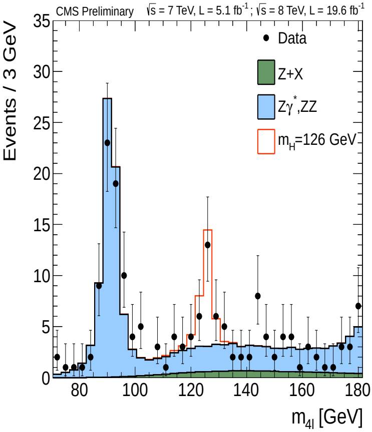
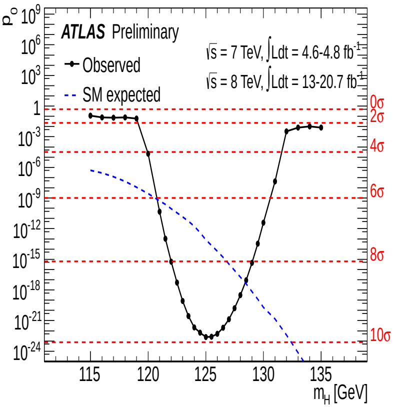
New (and Old) Physics in Double Higgs Production

Matthew Dolan

IPPP
University of Durham
with Christoph Englert & Michael Spannowsky, 1206.5001,1210.8166

Habemus Higgs!





Measuring Higgs Couplings

- 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?
- What could 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

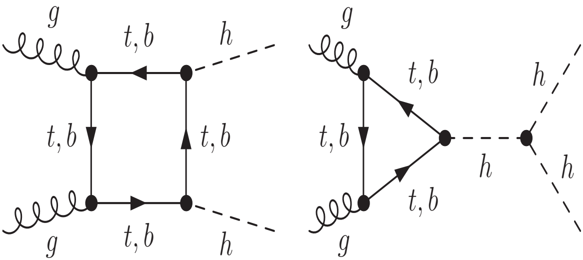
$$\frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4$$

- where

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

Higgs Self Couplings

- Can we measure double Higgs production at the LHC?
- Can we measure the Higgs self-coupling at the LHC?



(a) (b)

Higgs pair production

Effective Lagrangian

- Heavy top quark limit

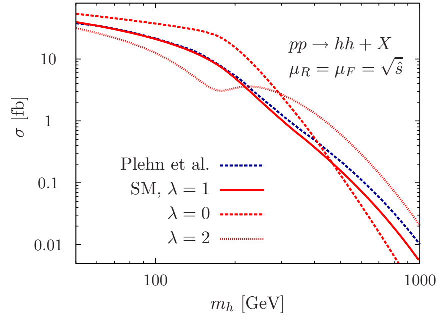
$$\mathcal{L}_{\mathrm{eff}} = \frac{1}{4}\frac{\alpha_s}{3\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

- Expanding gives

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

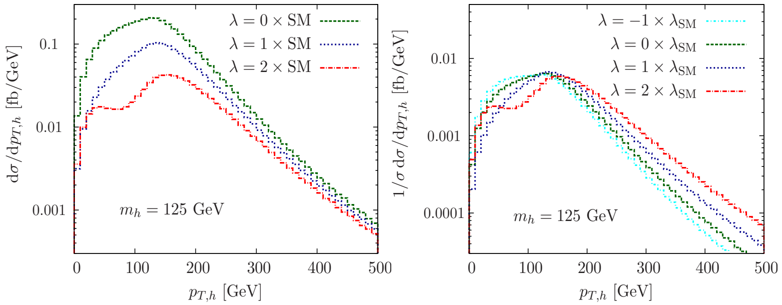
- Interference effects important.
- Fails to reproduce full kinematics when $Q^2 \gtrsim m_t^2 \implies$ need to implement full matrix element.

Cross-section



- Relatively large dependence on λ at $m_h \approx 125$
- Diagram (b) resonantly enhanced when $s \simeq 4m_t^2$
- Ameliorates s-channel suppression.
- SM x-sec (LO): 16fb

p_T distributions



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

Search strategies

- $hh \to W^+W^-W^+W^-$ already considered: doesn't work below $m_h \sim 2m_W$
- $bb\gamma\gamma$: Constraints possible with a lot of luminosity
- Suffers from small $BR(h \to \gamma\gamma)$
- Anything else: Huge backgrounds

What's changed?

Advent of boosted techniques.

Unboosted and Boosted searches

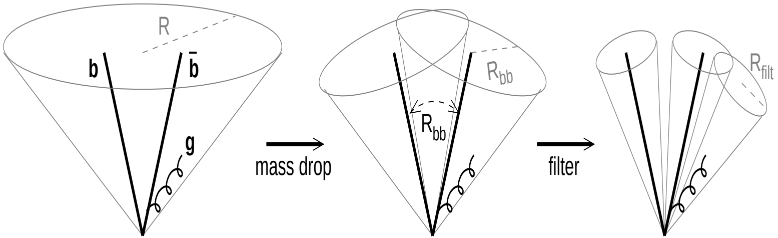
Strategy

- 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	$8.3 \cdot 10^{-5}$

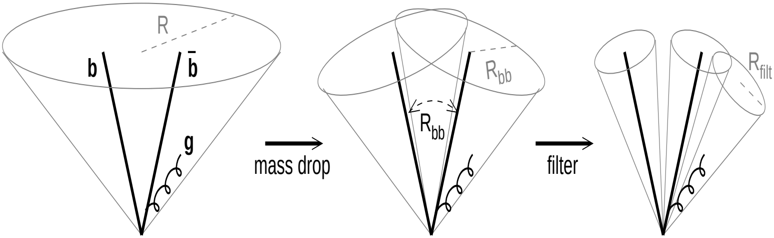
Substructure techniques: BDRS

- Look for C/A fatjets with $R \approx 1.5$
- Undo last clustering, and if $m_{j_1} < \mu m_j$ ($\mu \sim 0.67$) and splitting not too asymmetric:
- Then j is heavy particle neighbourhood



BDRS: II

- Reduce R to R_{filt} to filter away UE but keep radiation from Higgs decay
- $R_{filt} = \min(0.3, R_{b\bar{b}}/2)$



Boosted Kinematics: $(\mathrm{BDRS})^2$

Comments

- Can gain sensitivity in main decay channels.
- But lose some sensitivity to modifications of trilinear coupling.

	$\lambda = 1$	$b\bar{b}b\bar{b}$ [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	$9.6 \cdot 10^{-3}$

Boosted regime: $bb\tau\tau$

Consider $bb\tau\tau$

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

	$\xi = 1$	$b\bar{b}\tau\tau$ (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($m_{b\bar{b}}$)	0.26	9.65	$2.7 \cdot 10^{-2}$
double b-tag	0.095	0.15	0.49

Boosted regime: $bb\tau\tau$

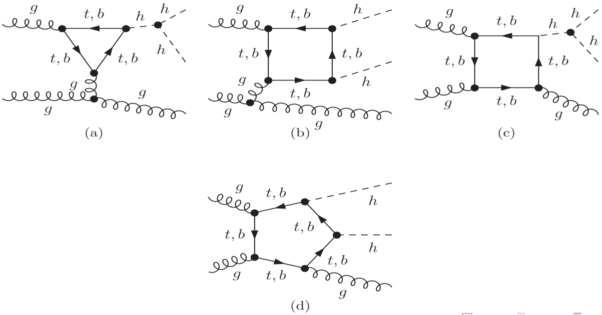
Consider $bb\tau\tau$

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

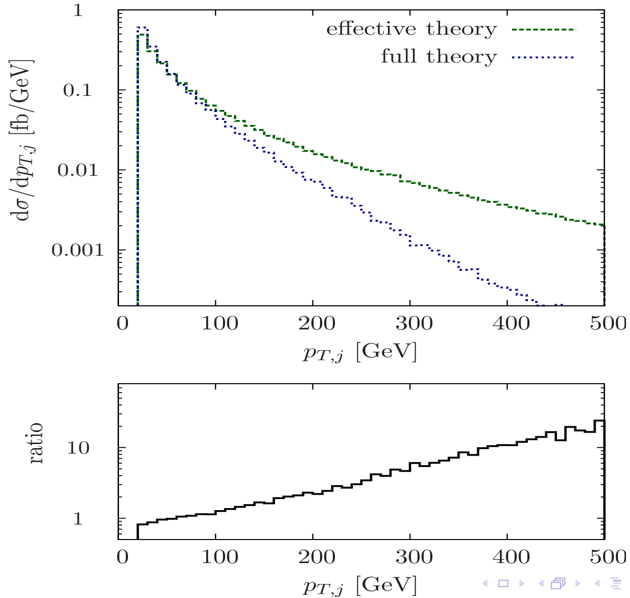
	$\xi = 1$	$b\bar{b}\tau\tau$ (BG)	ratio to $\xi = 1$
x-section pre-cuts	28.34	873076	$3.2 \cdot 10^{-5}$
Higgs from τs	1.94	1512	$1.9 \cdot 10^{-3}$
fatjet cuts	1.09	225	$4.8 \cdot 10^{-3}$
Higgs-rec($m_{b\bar{b}}$)	0.26	9.65	$2.3 \cdot 10^{-2}$
double b-tag	0.095	0.15	0.49

Higgs production with a hard hadronic jet

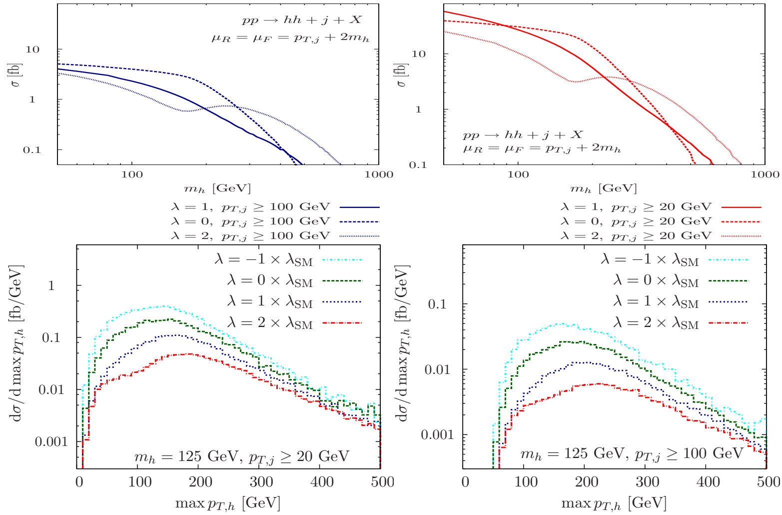
- Want to decorrelate $p_{T,h}$ with suppression of triangle diagram
- Motivates studying $pp \rightarrow hh + j$



Effective theory vs full theory for *hhj*.



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



Comments on $pp \to hh + j$

- 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 $pp \to hh$.

- Sensitivity to λ comes from configs with two Higgs bosons close to each other and central.
- Hadronic decay products likely to overlap $\to$ to reconstruct hh system rely on substructure techniques.
- Cost in cross-section: $\sigma(pp \to hh + j) \simeq$ few fb^{-1}

Analysis details

- Two τ-jets with $100 < m_{\tau\tau} < 150$ + 1-fatjet
- Apply Higgs-tagger and require $115 < m_{h-jet} < 135$, $p_{T,h} > 150$ GeV.
- $m_{hh} > 400$ GeV for rejecting $t\bar{t}$ background.

Higgs-tagger

- Modify BDRS similar to 0910.5472[1]

[1] Plehn,Salam,Spannowsky

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

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	$4.8 \cdot 10^{-3}$
$m_{\tau\tau} \approx m_h$ + fatjets	0.16	3.1	$5.1 \cdot 10^{-2}$
kin. Higgs rec.	0.04	0.153	0.26
2b + hh inv. mass + $p_{T,j}$ cuts	0.006	0.0037	1.54

New Physics in Double Higgs Production

- Can we use double Higgs production as a probe of new physics?

- Resonant Production: Higgs Portal and Supersymmetry
- Non-Resonant Production: Pseudo-dilatons and Composite Higgs

The Higgs Portal

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

- Higgs Portal Potential:

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

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

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

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

Cross-sections

- Visible and hidden sector Higgses mix:

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

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

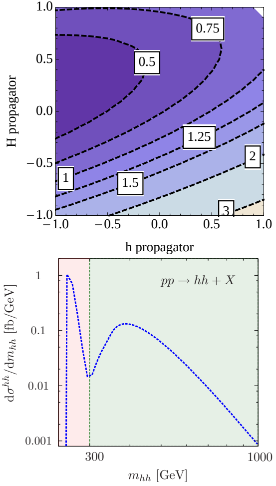
$$pp \to hh + X \quad : \quad 44.4 \text{ fb} \tag{1a}$$

$$pp \to Hh + X \quad : \quad 5.57 \text{ fb} \tag{1b}$$

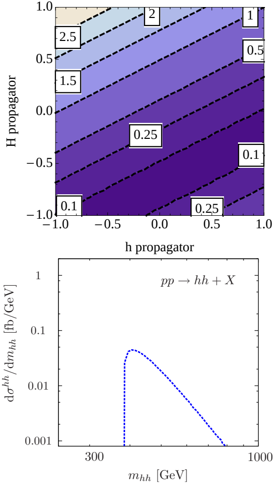
$$pp \to HH + X \quad : \quad 667 \text{ ab} \tag{1c}$$

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

Cross-section scans



(a) σ/σ(portal) for $pp \to hh + X$



(b) σ/σ(portal) for $pp \to hH + X$

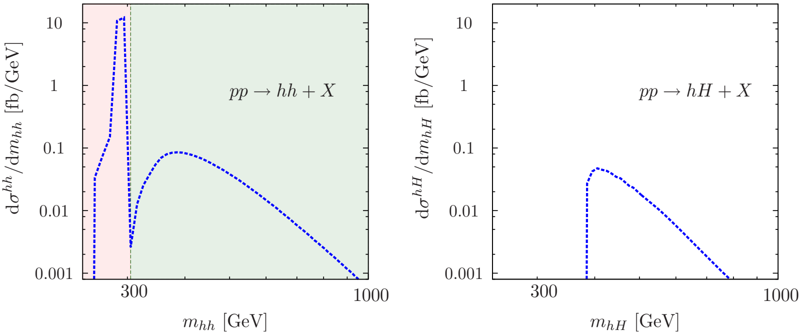
Supersymmetry at low $\tan\beta$

- 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, $BR(H \to hh) = 47\%$

SUSY production plots



(c) *hh* final state (d) *Hh* final state

- Can separate resonant peak due to $H \to hh$ with invariant mass cut

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)
- Holographically identify this with radion
- Composite Higgs

Pseudo-dilaton couplings

- Dilaton couples to trace of EM tensor:

$$T^{\mu}_{\mu} \sim m_W^2 W^+_{\mu} W^{-\,\mu} + \frac{m_w^2}{\cos^2\theta_w} Z_{\mu} Z^{\mu} + \sum_f m_f \bar{f} f + \dots \quad (2)$$

- Like Higgs, couplings rescaled by v/f
- Effective couplings to massless particles:

$$\mathcal{L}^{D5}_{\chi,\text{massless}} = \frac{\alpha_{EM}}{8\pi f} c_{EM} \chi F_{\mu\nu} F^{\mu\nu} + \frac{\alpha_S}{8\pi f} c_S \chi G^a_{\mu\nu} G^{a\mu\nu}$$

Pseudo-dilaton production

Fully composite SM

- Anomaly co-efficients given by β-functions: $c_s = 11 - 2/3n_f$, $c_{EM} = -17/9$
- Fits give $f \sim 850$ GeV

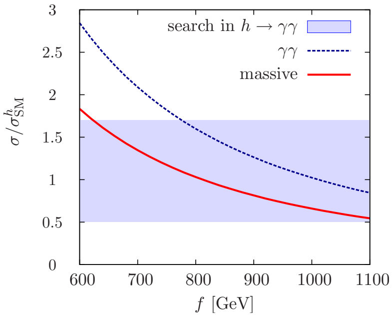
Fourth family model

- Have $c_S = 4/3$, $c_{EM} = -1.2$
- Get $f \sim 570$ GeV

Pseudo-dilaton production

Composite SM

- Anomaly co-efficients given by β-functions: $c_s = 11 - 2/3n_f$, $c_{EM} = -17/9$
- Fits give $f \sim 850$ GeV



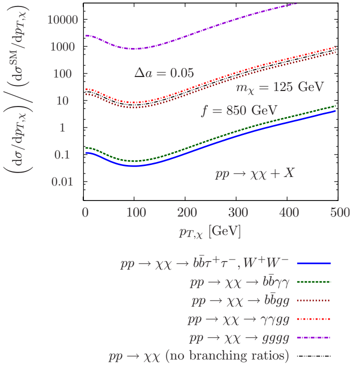
Higher-dimensional interactions

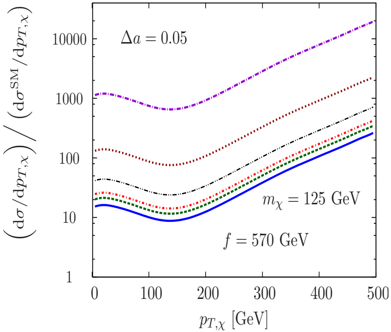
- Box diagrams: effective D6 interactions
- New anomalous derivative interactions

$$\mathcal{L}^{D7,D8} \supset 2(a_{UV} - a_{IR})(2(\partial\chi)^2\Box\chi - (\partial\chi)^4).$$

- Will be more important in boosted regime
- Could allow to probe anomaly coefficients (if measurable)

Cross-sections





- L: Composite SM
- R: Four-family model

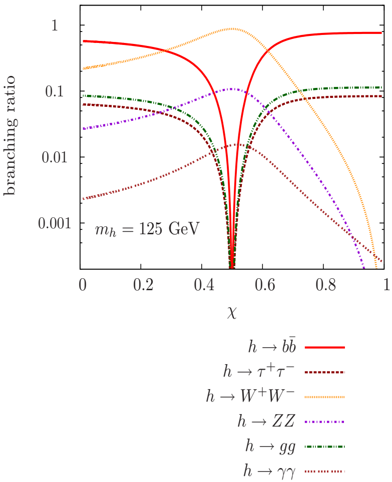
Composite Higgs

- 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 take $\xi = 0.25$ for our study

Di-higgs Phenomenology

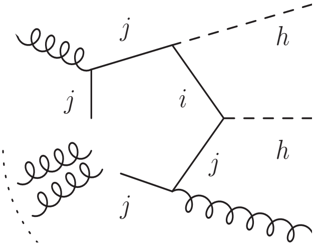
- Consider adding set of vector-like fermions Ψ forming a 5 of $SO(5)$
- Decomposes as $5_{2/3} = (2,2)_{2/3} + (1,1)_{2/3}$
- Non-linear Higgs field Σ
- Masses come from mixing in Lagrangian:

$$-\mathcal{L}_m = yf(\bar{\psi}_L\Sigma^T)(\Sigma\psi_R) + m_0\bar{\psi}_L\psi_R + \Delta_L\bar{q}_L Q_R + \Delta_R\bar{\widetilde{T}}_L t_R + \text{h.c.} \quad (3)$$

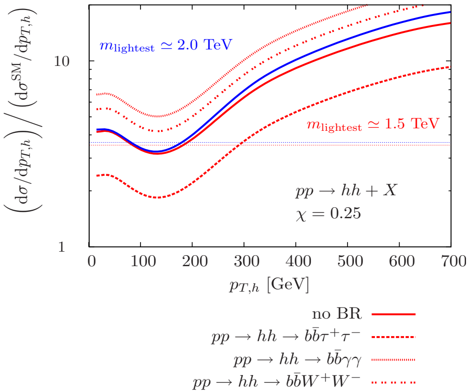
Fermion masses

Generated by mixing operators

- Get non-diagonal interactions $f_i f_j h$ and $f_i f_j hh$
- Contribute to dihiggs production.
- Higgs trilinear $L_h \supset \frac{1-2\xi}{\sqrt{1-2\xi}} h^3$



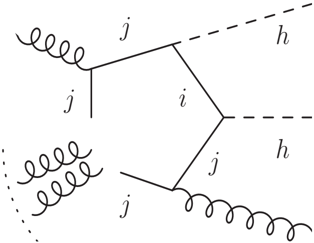
Composite Higgs p_T distributions



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

Dihiggs +jet

- 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 above.



Summary

- Trilinear coupling an important measurement of EWSB (and possibly signal of new physics).
- Interesting prospects in boosted $bb\tau\tau$, boosted $bb\tau\tau + j$ final state.
- New Physics: Resonant enhancements in portal and SUSY
- Non-resonant: can enhance or decrease σ depending on UV model.