WHAT CAN WE LEARN FROM MEASUREMENT OF DOUBLE HIGGS PRODUCTION ?

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snowmass : seattle energy frontier workshop
Jun 30, 2013

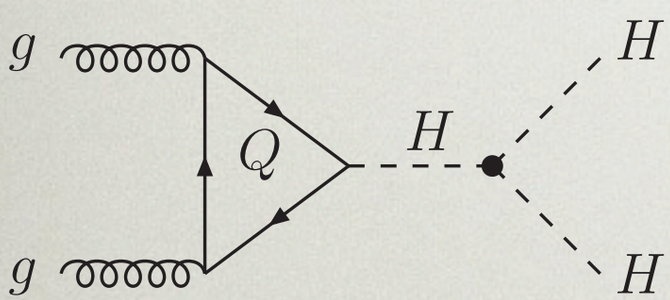
Outline

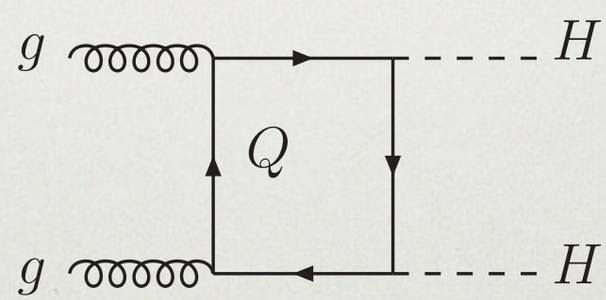
- Trilinear Self Coupling at Colliders
- Other Accessible Couplings - tthh, hhVV
- Effects of New Colored Particles
- Resonant vs Non Resonant Contributions to di-Higgs

Higgs trilinear self-coupling

Self Coupling at LHC

- In the Standard Model (SM) the trilinear and quartic higgs self couplings are fixed by the Higgs mass
- Former is accessible via di Higgs production at LHC
- Gluon fusion is the most promising production mode (10 - 30 times higher than the others)





$$\sigma^{NLO}_{8\mathrm{TeV}} = 8 \text{ fb}$$

$$\sigma^{NLO}_{14\mathrm{TeV}} = 34 \text{ fb}$$

Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira arXiv : 1212.5581

Note: Destructive Interference. For self coupling = 2xSM the cross section at 14 TeV is 16 fb

Self Coupling at LHC

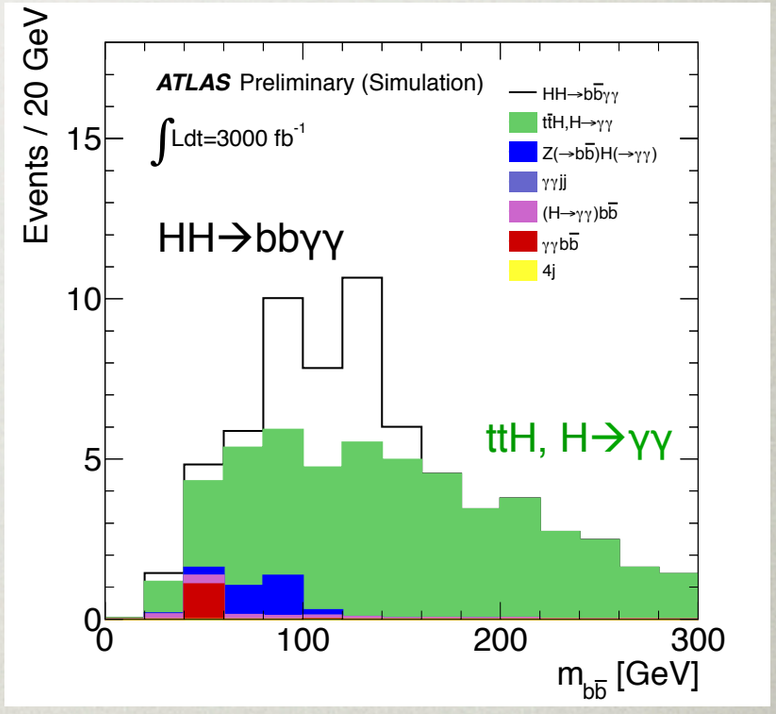
- Boosted Jet + Substructure techniques have improved signal significance

Butterworth, Davison, Rubin, Salam [0802.2470] , Dolan, Englert, Spannowsky [1206.5001]
Papaefstathiou, Yang, Zurita [1209.1489]

- Promising decay modes

$$hh \to b\bar{b}\gamma\gamma \qquad hh \to b\bar{b}\tau^+\tau^- \quad hh \to b\bar{b}W^+W^-$$

- ATLAS $hh \to b\bar{b}\gamma\gamma$: 3 sigma sig.
- Expected to obtain 30% precision on λ after including additional decay modes with 3000 fb^{-1}



Pippa Wells, LP2013 conference talk

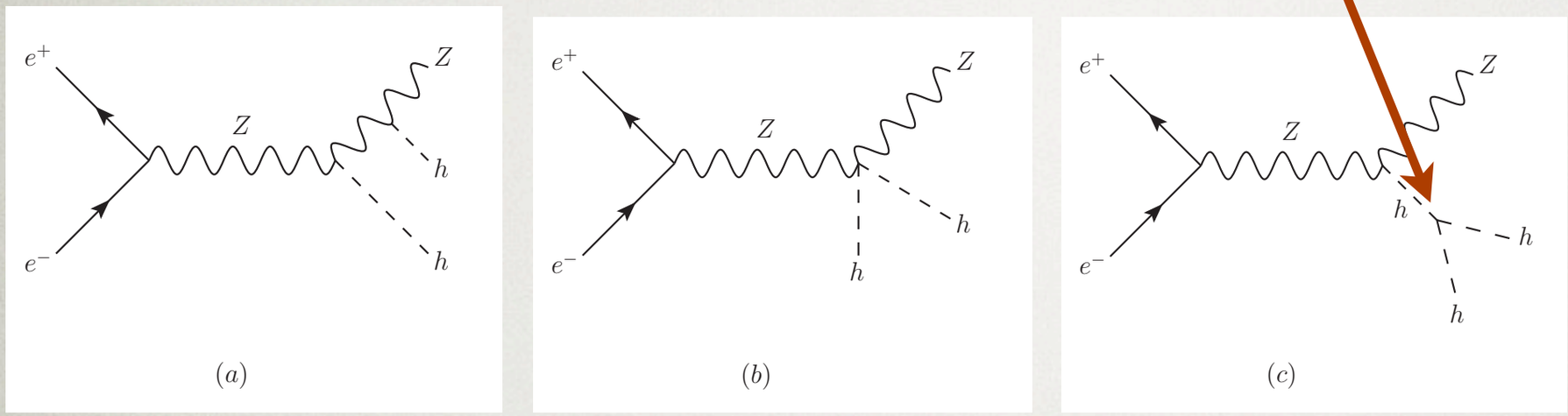
Self Coupling at LHC

- Can also be constrained by considering ratio of di-Higgs to single higgs production via gluon fusion Goertz, Papaefstathiou,Yang, Zurita [arXiv : 1301.3492]
- With 3000 fb^{-1} the 1 sigma uncertainty is +30% and -20%
- This result would vary if the top yukawa is different or if new particles are present in the loops

Self Coupling at ILC

$e^+e^- \to Zhh$ (500 GeV)

For unpolarized beams

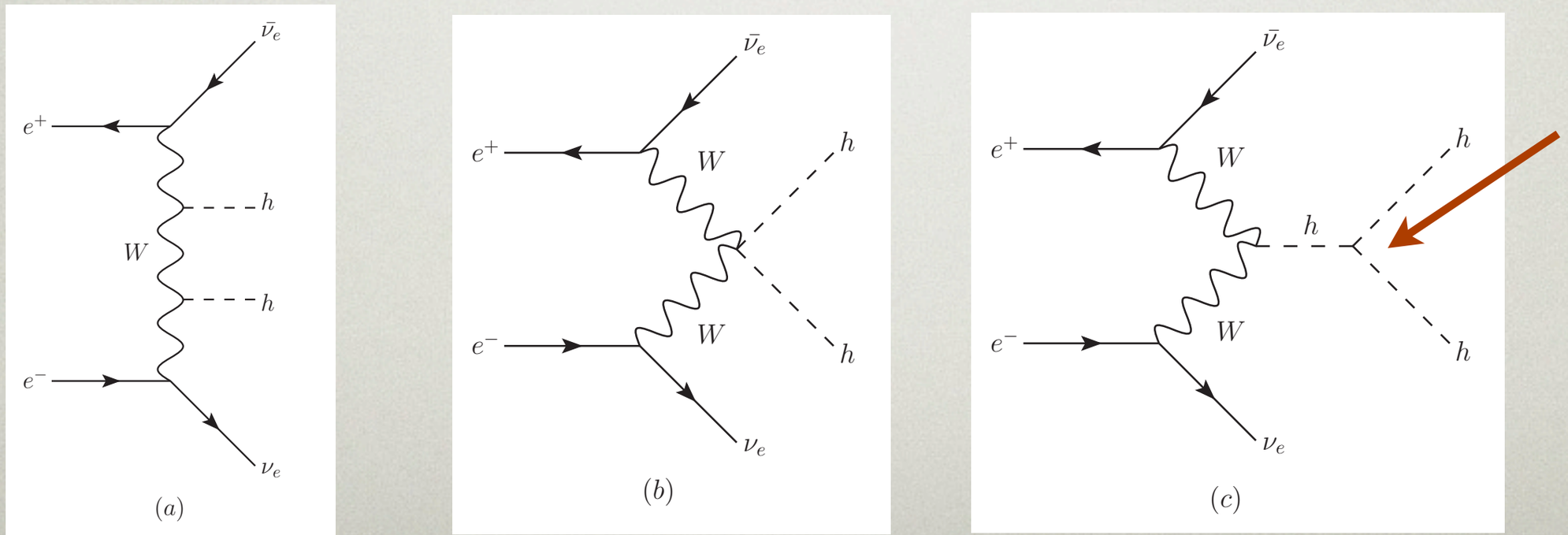


$$\sigma_{500}^{Zhh} = 0.16 \text{ fb}$$

$$\sigma_{1000}^{Zhh} = 0.12 \text{ fb}$$

$$\sigma_{1000}^{\text{WBF}} = 0.07 \text{ fb}$$

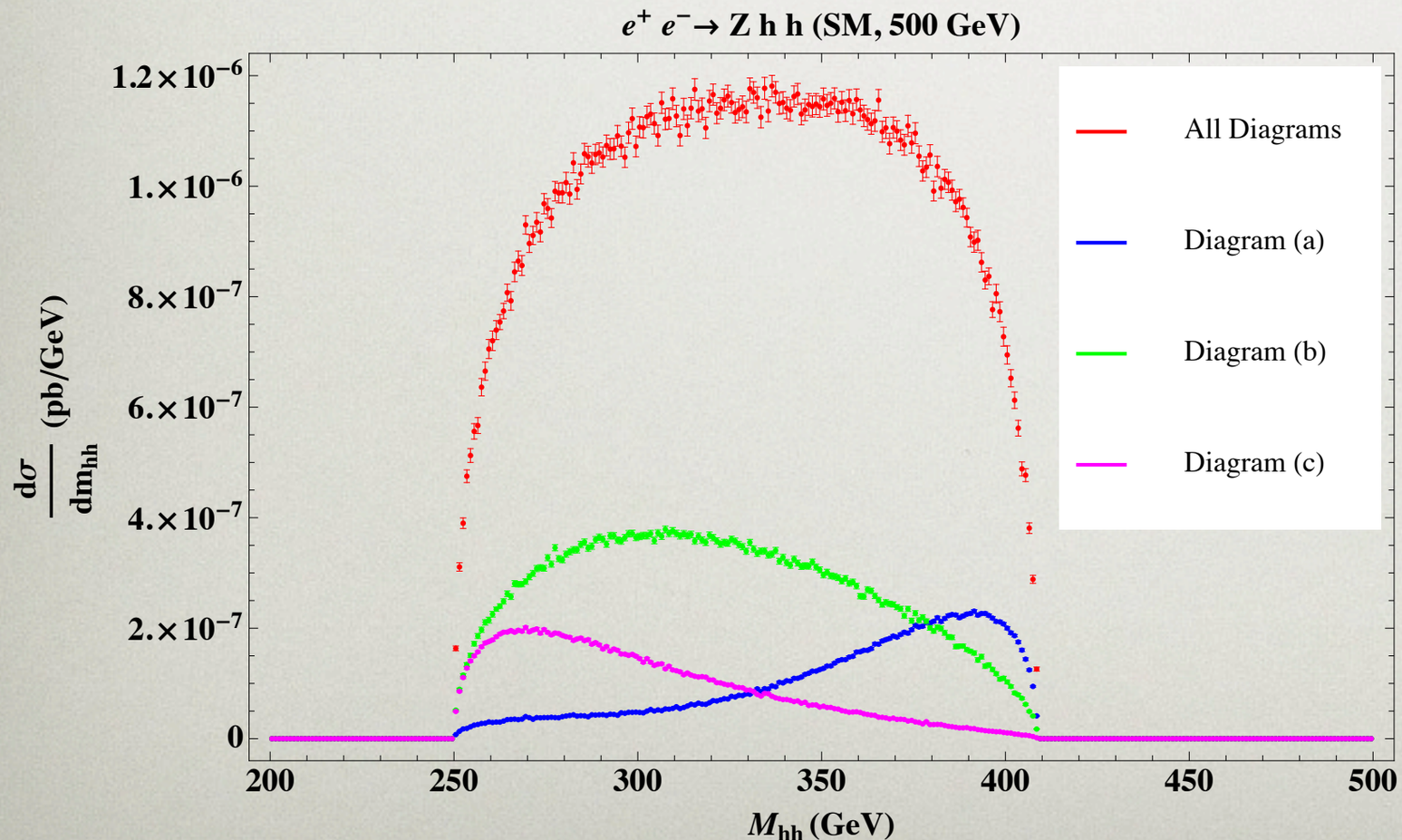
$e^+e^- \to \nu\bar{\nu}hh$ (1 TeV) WBF and $Z(\to \nu\bar{\nu})hh$

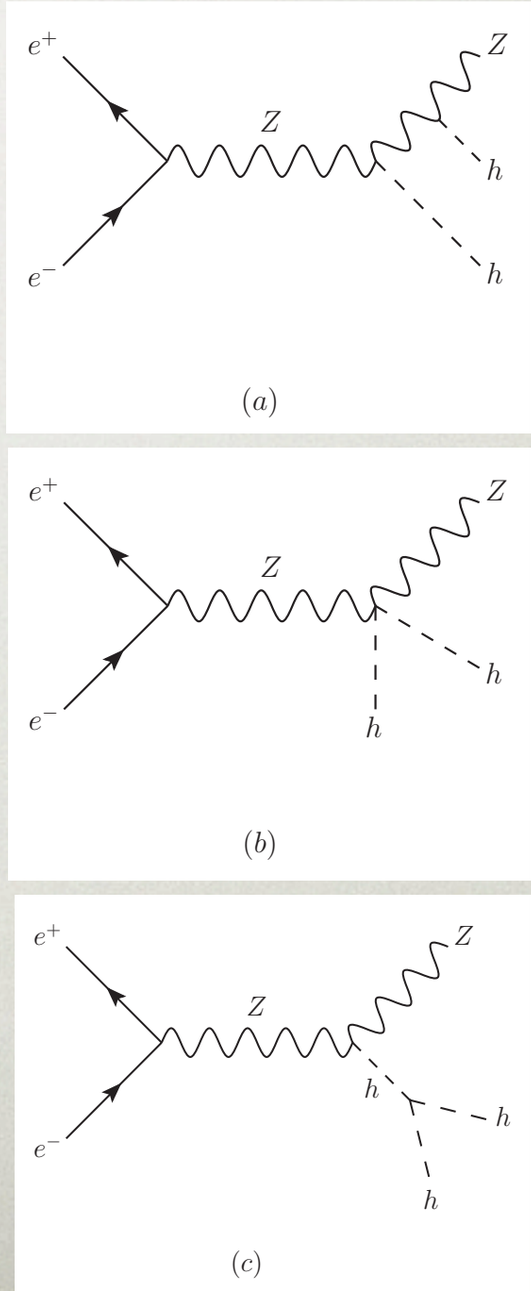


Self Coupling at ILC

- Measuring the cross sections allows us to constrain λ
- In addition weighting events based on hh invariant mass can improve sensitivity to λ

K. Fujii, Higgs Snowmass Workshop 2013,
http://physics.princeton.edu/snowmass





Self Coupling at ILC

$e^+e^- \to Zhh$ (500 GeV)

$P(e^-, e^+) = (-0.8, +0.3)$

2000 fb^{-1}

$$\frac{\Delta\sigma}{\sigma} = 26.7\% \qquad \frac{\Delta\lambda}{\lambda} = 48\%$$

- Improved precision after reweighting $\frac{\Delta\lambda}{\lambda} = 44\%$

$e^+e^- \to \nu\bar{\nu}hh$ (1 TeV)

$P(e^-, e^+) = (-0.8, +0.2)$

2000 fb^{-1}

$$\frac{\Delta\sigma}{\sigma} = 23\% \qquad \frac{\Delta\lambda}{\lambda} = 20\%$$

- Improved precision after reweighting $\frac{\Delta\lambda}{\lambda} = 18\%$

J. Tian, LC-REP-2013-003

Self coupling at CLIC

- $e^+e^- \to \nu\bar{\nu}hh$ at 1.4 TeV and 3 TeV
- 120 GeV Higgs, Unpolarized beams
- 1.4 TeV (1500 fb^{-1})

$$\sigma^{1400} = 0.16 \text{ fb}$$

$$\sigma^{3000} = 0.63 \text{ fb}$$

$$\frac{\Delta\sigma}{\sigma} \approx 25\% \qquad \frac{\Delta\lambda}{\lambda} \approx 30 - 35\ \%$$

- 3 TeV (2000 fb^{-1})

$$\frac{\Delta\sigma}{\sigma} \approx 10\% \qquad \frac{\Delta\lambda}{\lambda} \approx 15 - 20\ \%$$

For 126 GeV Higgs the cross section uncertainties increase by a few % and their effect on the self-coupling uncertainty is being studied

Lastowicka, Strube - Higgs Self Coupling Studies (Preliminary) -LCWS2012

Self Coupling at PLC

- Photon Linear Collider (PLC) could measure the di-Higgs signal to 5 sigma significance with 5 yrs of running at ~ 270 GeV (study done for 120 GeV)

Kawada et. al , arXiv : 1205.5292

- Corresponding precision on self-coupling is yet to be studied

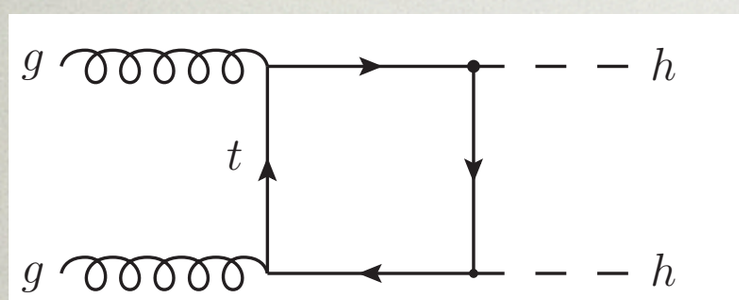
Other accessible couplings

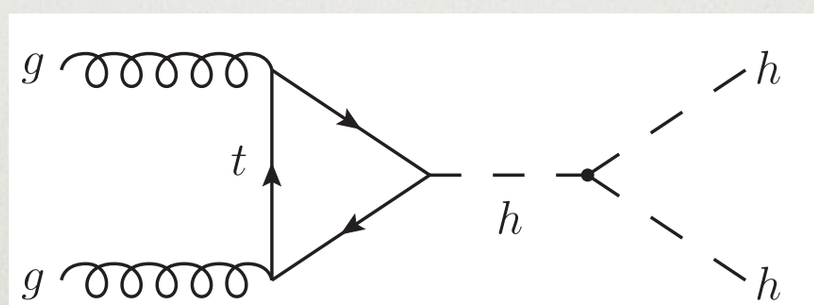
$tthh$

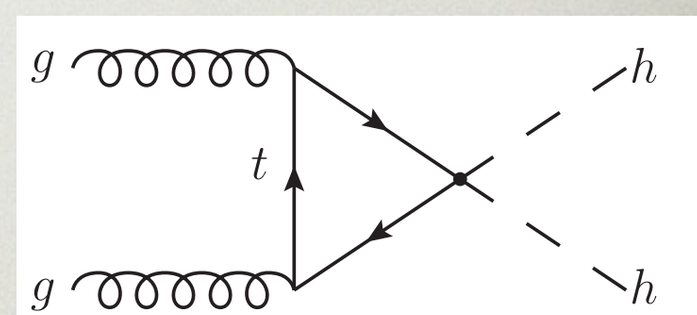
$hhVV$

tthh as sign of Composite Higgs

- EWSB triggered by strong dynamics at the TeV scale the
- Scenario where the additional scalars aren't light
- di-Higgs can be increased by an order of magnitude







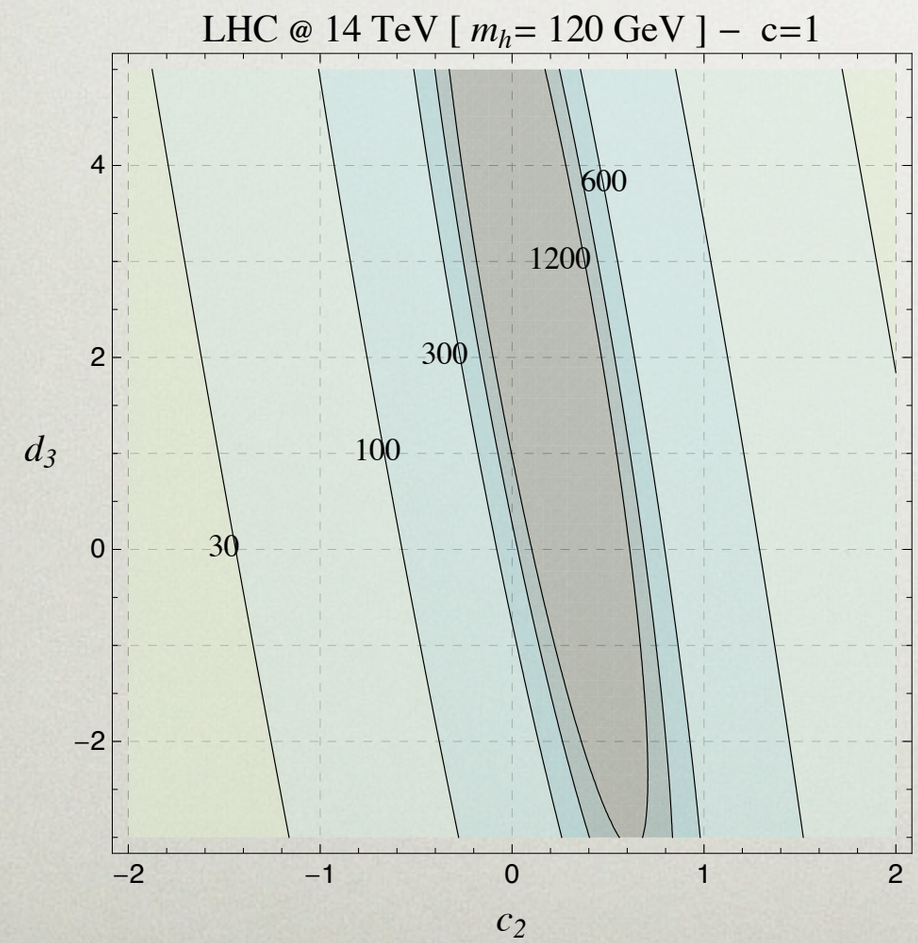
Contino,Ghezzi,Moretti,Panico,Piccinini,Wulzer, arXiv : 1205.5444

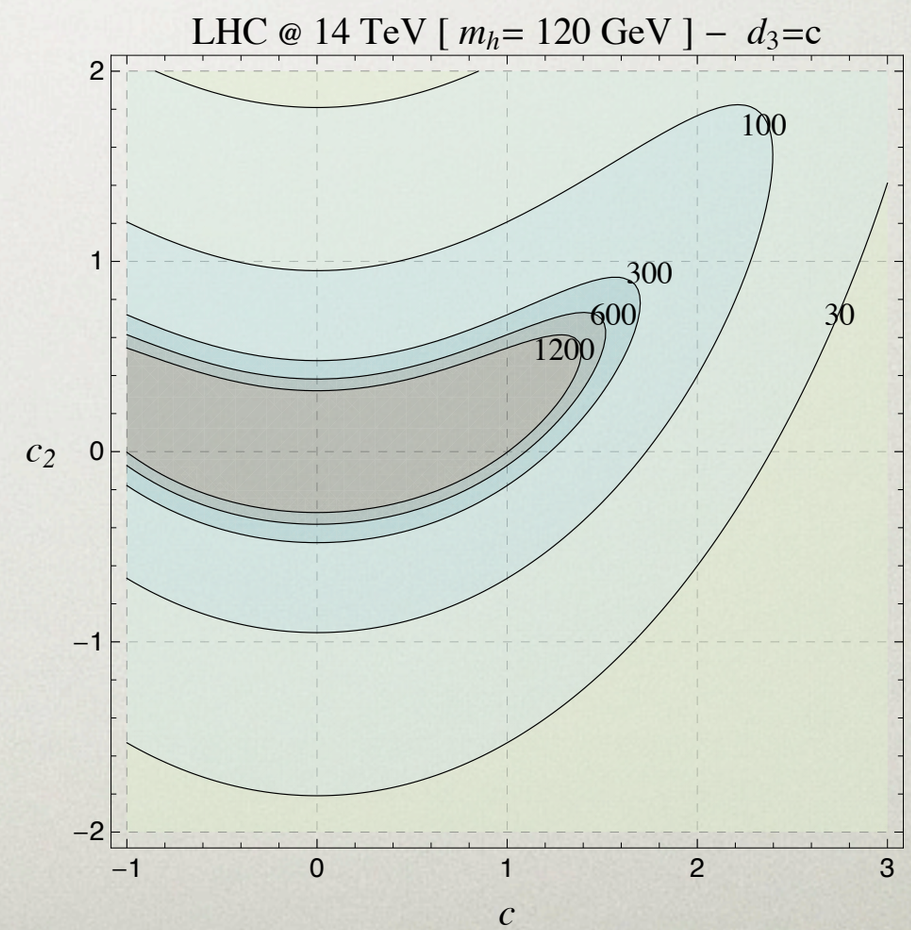
tthh as sign of Composite Higgs

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma)\left(1 + 2a\,\frac{h}{v} + \ldots\right) + \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + \ldots$$

$$- m_t\,\bar{q}_L^i \Sigma_{i1} t_R \left(1 + c_t\,\frac{h}{v} + c_2\,\frac{h^2}{v^2} + \ldots\right) - m_b\,\bar{q}_L^i \Sigma_{i2} b_R \left(1 + c_b\,\frac{h}{v} + \ldots\right) + h.c.\,,$$

Curves of discovery luminosity (in fb^{-1}) $\quad pp \to hh \to \gamma\gamma b\bar{b}$



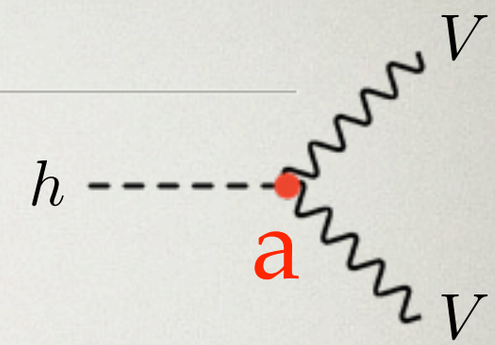


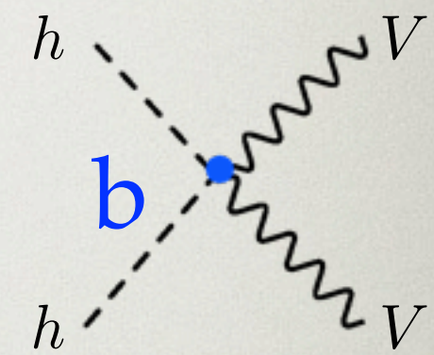
$c_t = c_b = c$

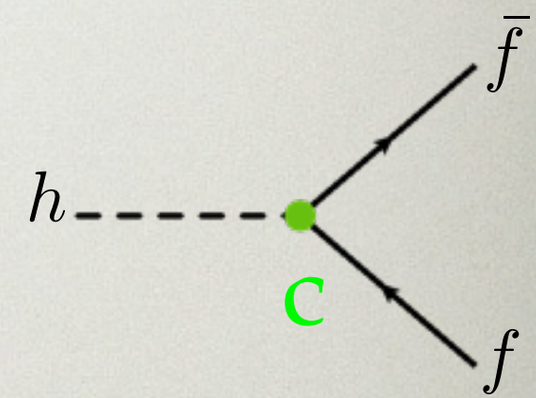
Contino,Ghezzi,Moretti,Panico,Piccinini,Wulzer, arXiv : 1205.5444

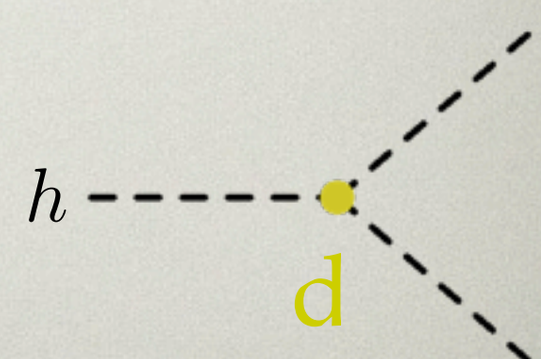
Extracting *hhVV* at ILC

- Extended Higgs sectors with Higgs mixing
- The EW quantum numbers of the scalar the Higgs mixes with are not determined by the 3 pt. couplings in general
- *hhVV* depends on isospin and hypercharge and can therefore help determine EW quantum numbers of the other scalar









$$b_W^\chi = 2\left[T(T+1) - \frac{Y^2}{4}\right], \qquad b_Z^\chi = Y^2.$$

$$b_V = \cos^2\theta + b_V^\chi \sin^2\theta.$$

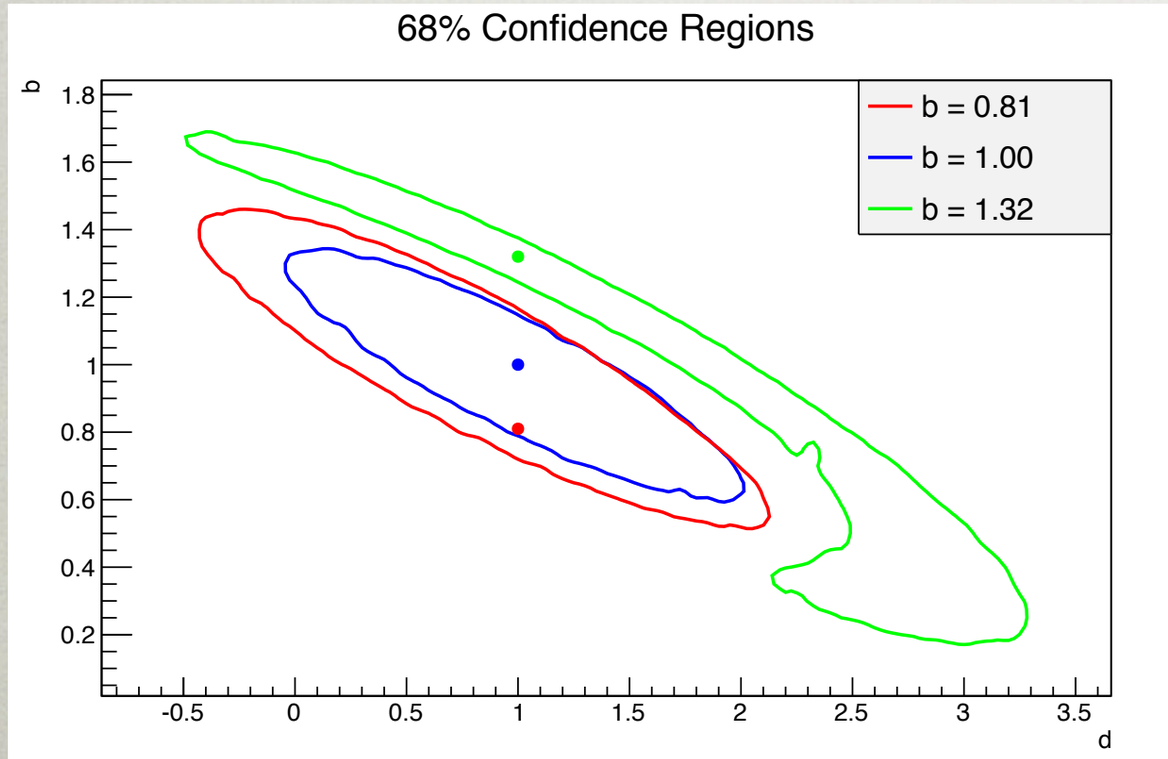
Killick, KK, Logan, arXiv : 1305.7236

Extracting $hhVV$ at ILC

- Accessible at ILC via di-Higgs
- Same cross sections that are used to extract the self-coupling (d) can be used to extract hhVV (b) simultaneously

$$e^+e^- \to Zhh \quad (500\ \text{GeV})$$

$$e^+e^- \to \nu\bar{\nu}hh \quad (1\ \text{TeV})$$



Red - SM + real singlet scalar

Blue - SM + additional doublet

Green - SM + complex triplet + real triplet (Georgi-Machacek model)

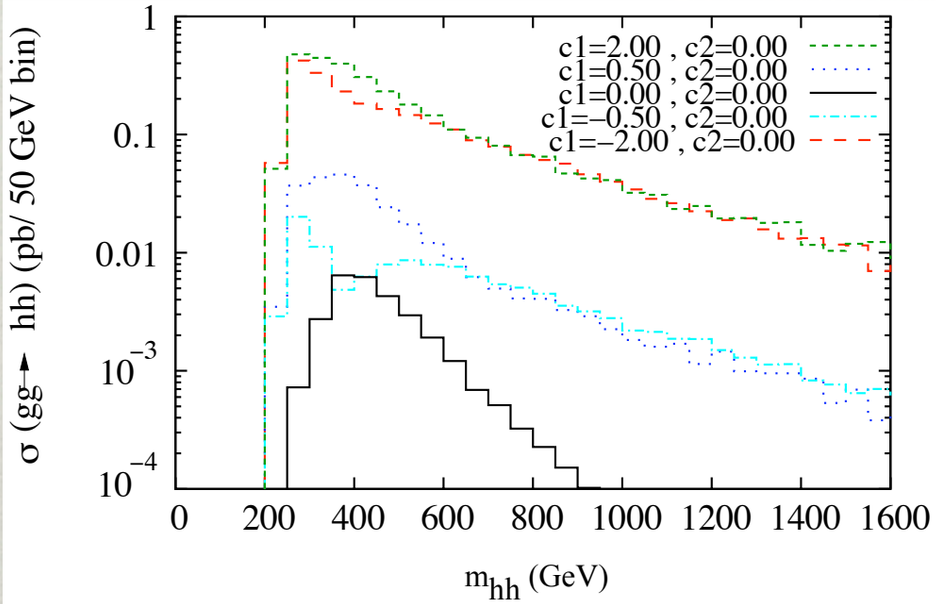
Effects of New Colored Particles

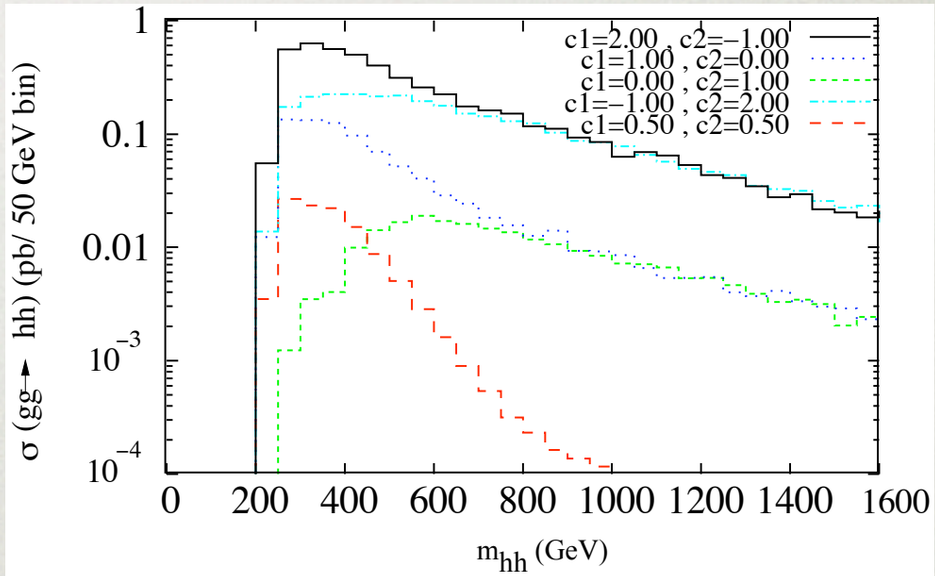
Constraints on dimension 6 operators

$$\mathcal{O}_1 = c_1 \frac{\alpha_s}{4\pi v^2} G^a_{\mu\nu} G^{\mu\nu}_a H^\dagger H \qquad \mathcal{O}_2 = c_2 \frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{\mu\nu}_a \log\left(\frac{H^\dagger H}{v^2}\right)$$

$$\mathcal{O}_1 \supset \frac{c_1 \alpha_s}{4\pi} G_{\mu\nu} G^{\mu\nu} \left(\frac{h}{v} + \frac{h^2}{2v^2}\right) \qquad \mathcal{O}_2 \supset \frac{c_2 \alpha_s}{4\pi} G_{\mu\nu} G^{\mu\nu} \left(\frac{h}{v} - \frac{h^2}{2v^2}\right)$$

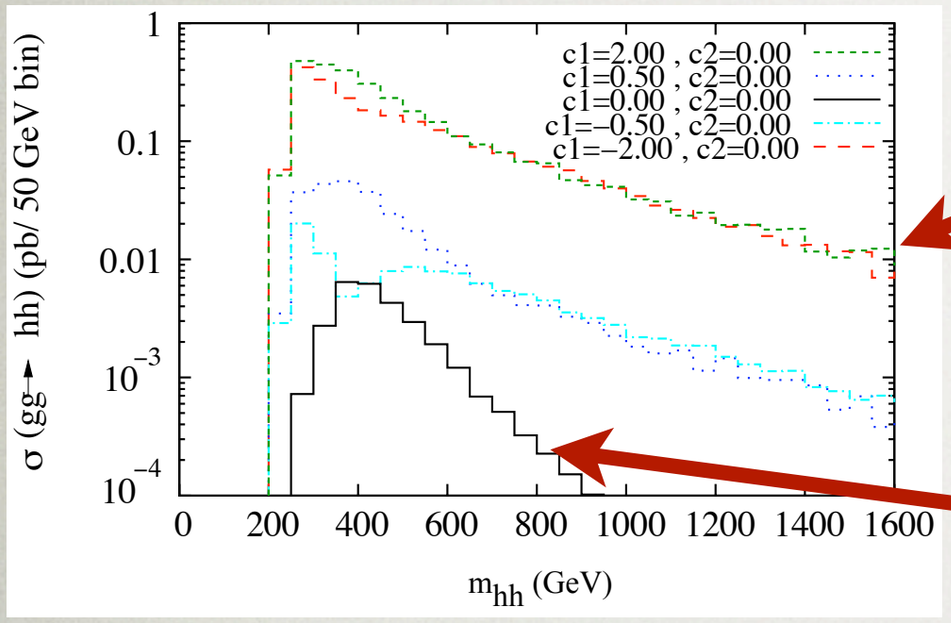
- c1 and c2 can be determined by measuring higgs and di-Higgs production





A. Pierce, J. Thaler, L.-T. Wang, arXiv : 0609049

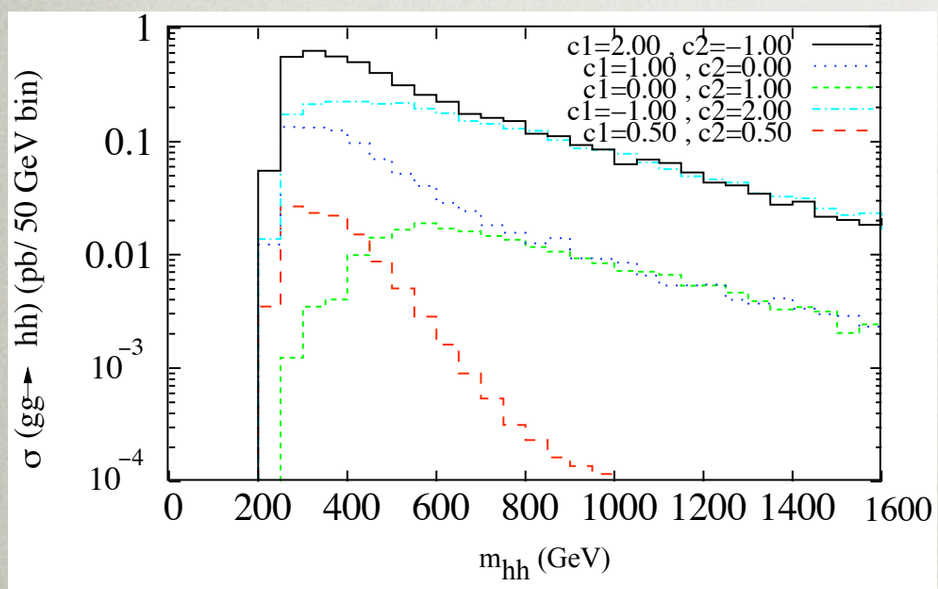
Constraints on dimension 6 operators



Long Tail compared to SM

Tail size governed by $|c_1 - c_2|$

SM



Single Higgs prodn. fixed by fixing c1 + c2

di-Higgs prodn. can help disentangle c1 & c2

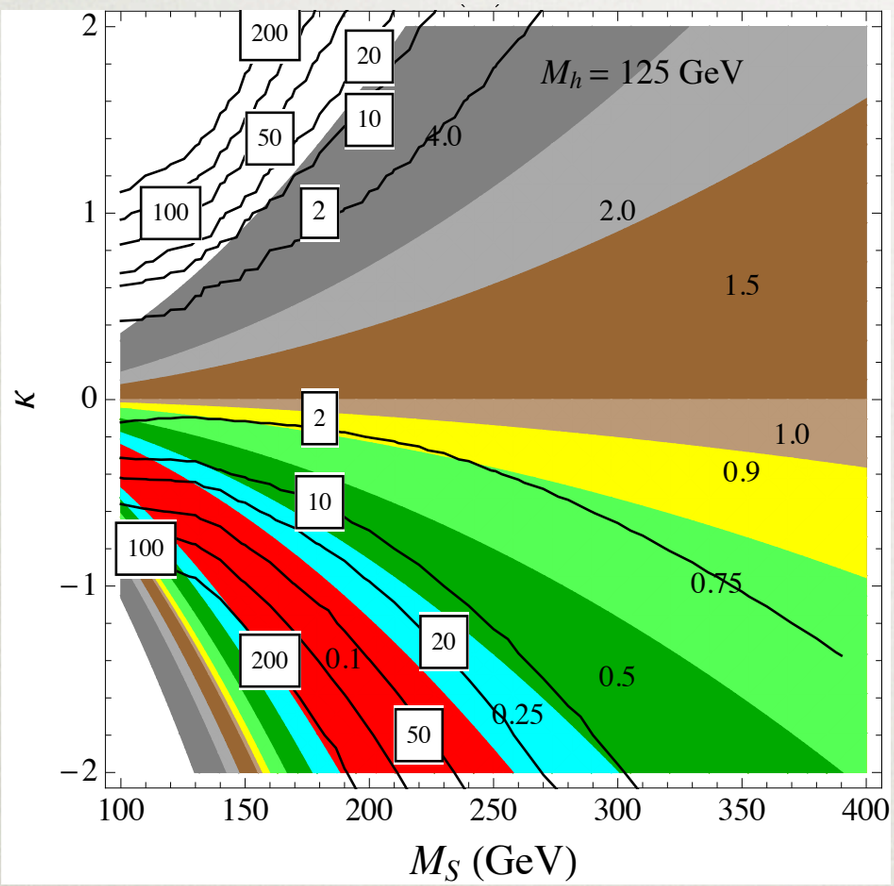
Hopefully the di-Higgs inv mass shape will emerge after several hundred fb^{-1} of data

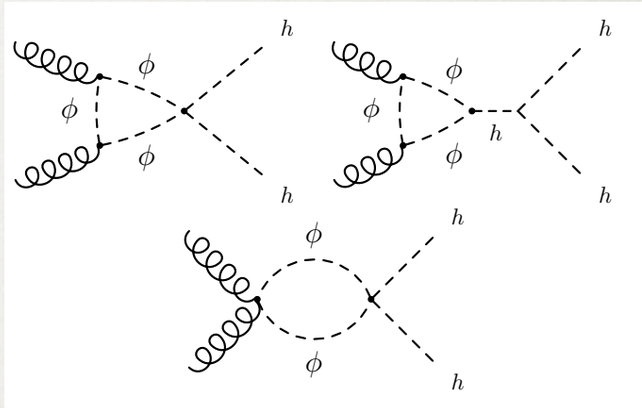
A. Pierce, J. Thaler, L.-T. Wang, arXiv : 0609049

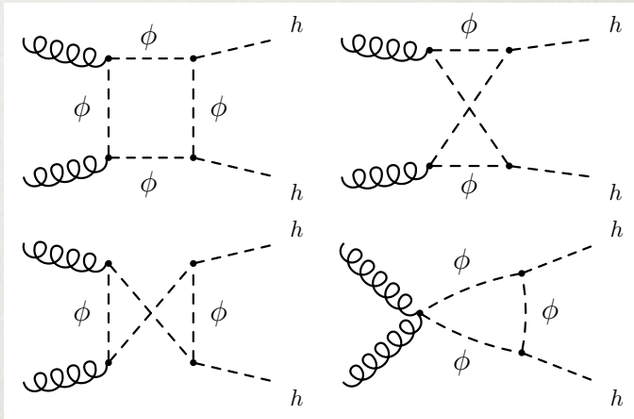
Effects of New Colored Particles

- SM + Real color octet scalars

$$\mathcal{L}_r = \frac{1}{2}(D_\mu \phi_i)^2 - \frac{1}{2} m_i^2 \phi_i^2 - \frac{\kappa_i}{2} \phi_i^2 H^\dagger H$$







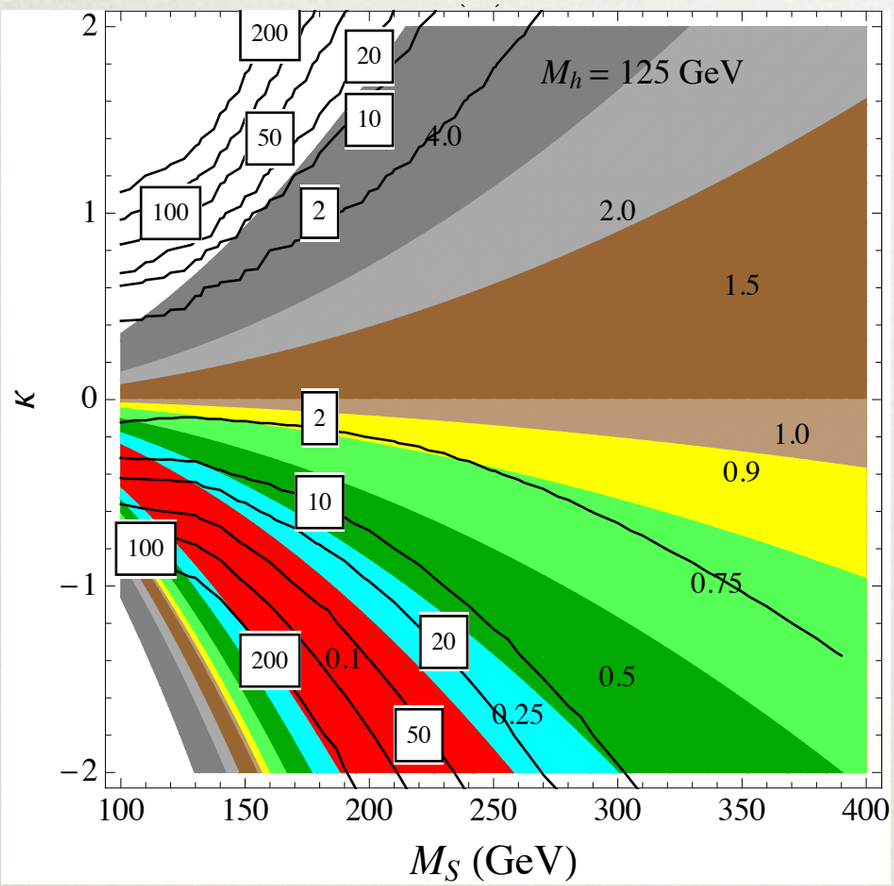
G. Kribs,A. Martin, arXiv : 1207.4496

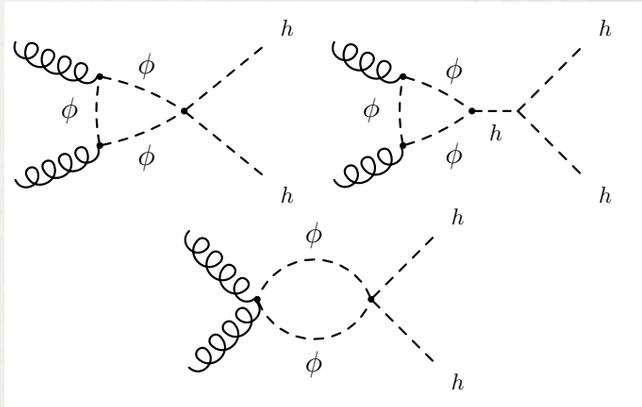
Light colored scalars can enhance di-Higgs considerably for negative κ even if single Higgs is within 10% of SM

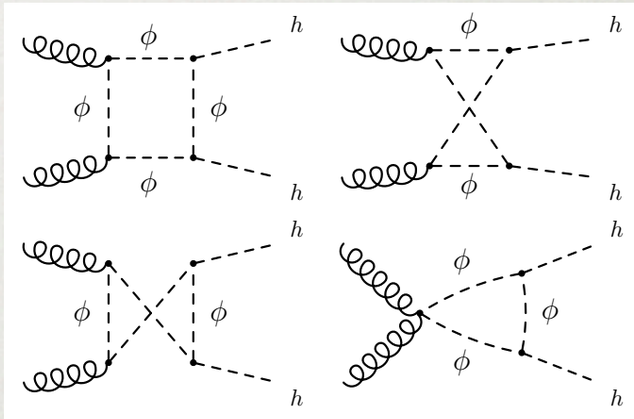
Effects of New Colored Particles

- SM + Real color octet scalars

$$\mathcal{L}_r = \frac{1}{2}(D_\mu \phi_i)^2 - \frac{1}{2} m_i^2 \phi_i^2 - \frac{\kappa_i}{2} \phi_i^2 H^\dagger H$$







G. Kribs,A. Martin, arXiv : 1207.4496

- Not all models that are consistent with SM for single Higgs production can lead to enhanced di-Higgs however

Effects of New Colored Particles

S. Dawson, E. Furlan, I. Lewis, arXiv :1210.6663

- Extended Quark Sector
- Restrict $gg \to h$ to deviate by 10% at most
- In two cases the $gg \to hh$ is found to be close to SM di-Higgs rate
- SM + vector singlet
- SM + mirror quarks (no mixing)

$$\psi_L^1 = \begin{pmatrix} \mathcal{T}_L^1 \\ \mathcal{B}_L^1 \end{pmatrix}, \quad \mathcal{T}_R^1, \mathcal{B}_R^1; \qquad \psi_R^2 = \begin{pmatrix} \mathcal{T}_R^2 \\ \mathcal{B}_R^2 \end{pmatrix}, \quad \mathcal{T}_L^2, \mathcal{B}_L^2.$$

SM charge assignments

SM charge assignments swapped for left and right handed fields

Observing enhanced di-Higgs and SM-like single Higgs production would help rule out models that cannot produce such enhancements

Resonant and Non Resonant Contributions to di-Higgs

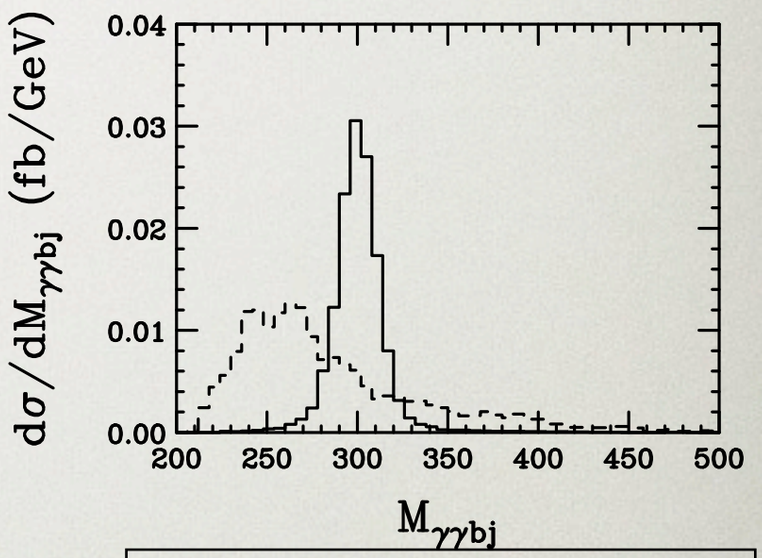
Resonant Contributions to diHiggs

Higgs Portal Scenario

- Heavier Higgs (300 GeV) can be discovered in $H \to hh \to \gamma\gamma b\bar{b}$

M. Bowen,Y. Cui, J.D. Wells, arXiv : 0701035

	Point 1	Point 2	Point 3
s_ω^2	0.5	0.5	0.5
m_h (GeV)	115	175	225
m_H (GeV)	300	500	500
$\Gamma(H \to hh)$ (GeV)	2.1	17	17
$BR(H \to hh)$	0.33	0.33	0.33

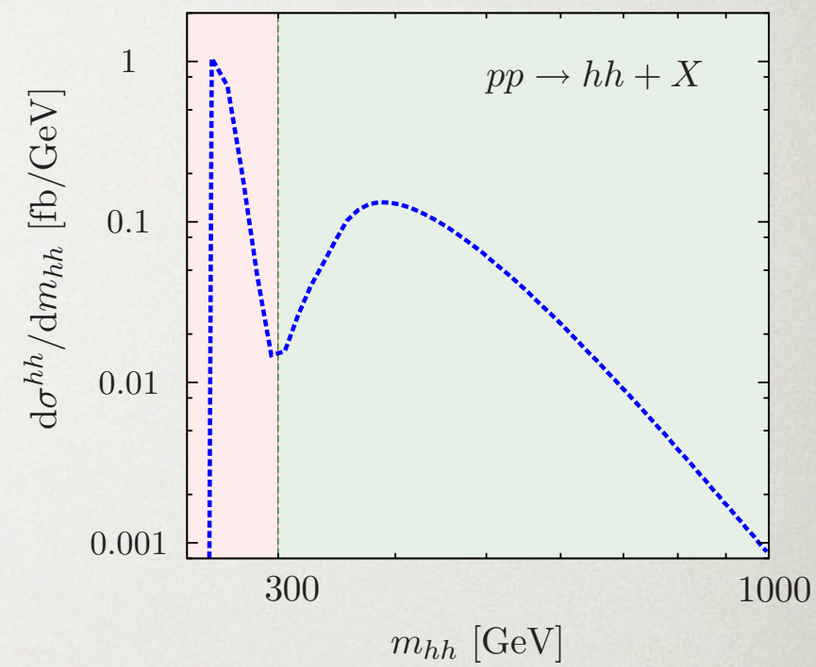


Bowen,Cui,Wells, 0701035

Resonanct Contributions to diHiggs

Higgs Portal Scenario

- Measuring tot. cross section and cross section close resonance can help measure λ_{hhh} and λ_{Hhh} and hence constrain the Portal Lagrangian



$pp \to hh + X \quad : \quad 44.4$ fb

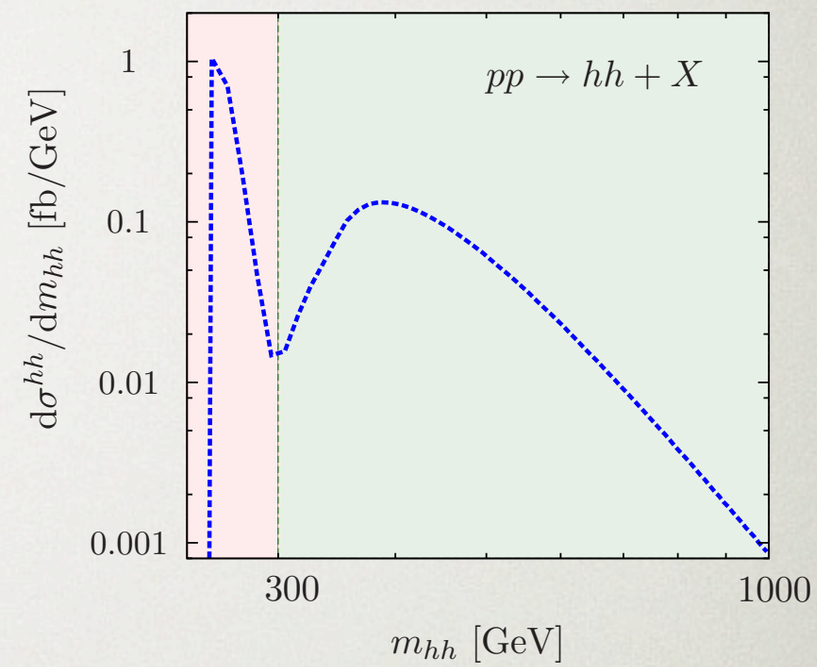
mH =255 GeV

Dolan, Englert, Spannowsky, arXiv : 1210.8166

Resonance Contributions to diHiggs

Higgs Portal Scenario

- Measuring tot. cross section and cross section close resonance can help measure λ_{hhh} and λ_{Hhh} and hence constrain the Portal Lagrangian



$pp \to hh + X \quad : \quad 44.4$ fb

mH =255 GeV

Dolan, Englert, Spannowsky, arXiv : 1210.8166

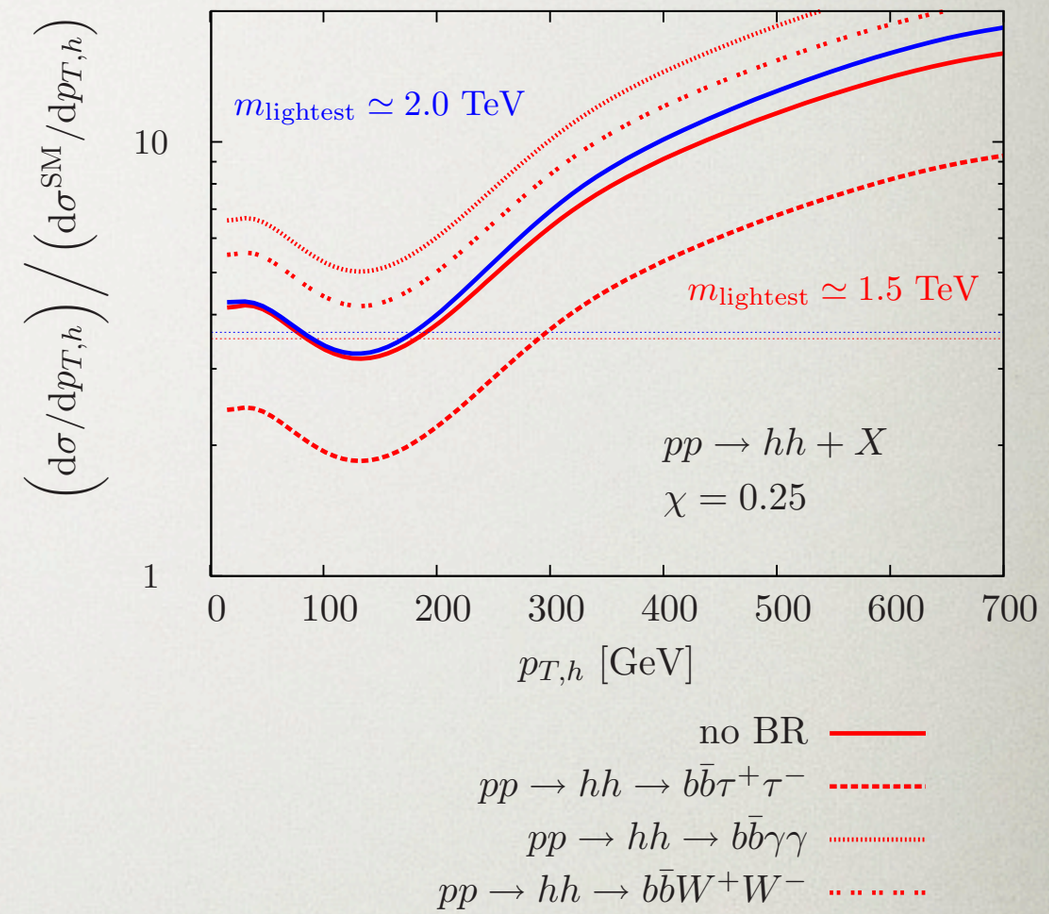
MSSM at small $\tan\beta$

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

- Measuring the above allows a reconstruction of α and β

Higgs as pNGB

- In Composite Higgs models deviations from SM couplings are parametrized in terms of $\xi = v^2/f^2$
- Enhanced hh and hh+jet possible
- non-trivial phase space dependence



$$\xi = 0.25$$

$$\sigma(hh)/\sigma^{\text{SM}}(hh) \sim 3$$

Dolan, Englert, Spannowsky, arXiv : 1210.8166

Summary

- di-Higgs production provides a window to the EWSB sector
- Access to *hhh, tthh, hhVV* couplings
- Constrains higher dimensional operators
- Distinguish models based on their effect on single vs di-Higgs production
- Resonant and Non Resonant contributions can be studied via di-Higgs and di-Higgs + jet final states