

Scalar boson self-coupling



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Mainly based on:

Andreas Papaefstathiou, Li Lin Yang, JZ: PRD 87 (2013) 011301 [arXiv 1209.1489]

Florian Goertz, Andreas Papaefstathiou, Li Lin Yang, JZ:

JHEP 1306 (2013) 016 [arXiv: 1301.3492] + work in progress

Rencontres du Vietnam 2014, 11th August 2014.

Scalar boson (H) potential: self couplings

After EWSB :
$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH}vH^3 + \frac{1}{4}\lambda_{HHHH}H^4 .$$

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Plehn, Rauch, Phys. Rev D 72, 053008.
↓
Linear Collider? TESLA TDR (hep-ph/0106315) $\sim 1000 \text{ fb}^{-1}$ for 20% accuracy.

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Linear Collider? TESLA TDR (hep-ph/0106315) $\sim 1000 \text{ fb}^{-1}$ for 20% accuracy.
- **Trilinear coupling (double scalar boson production): this talk!**
 - In the SM : $\lambda_{HHH}^{SM} = \lambda_{HHHH}^{SM} = (M_H^2/2v^2) \approx 0.13 \longrightarrow$ We want to verify it!
 - Throughout the talk: $\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$ and $y_t = g_{Ht\bar{t}}/g_{Ht\bar{t}}^{SM}$.

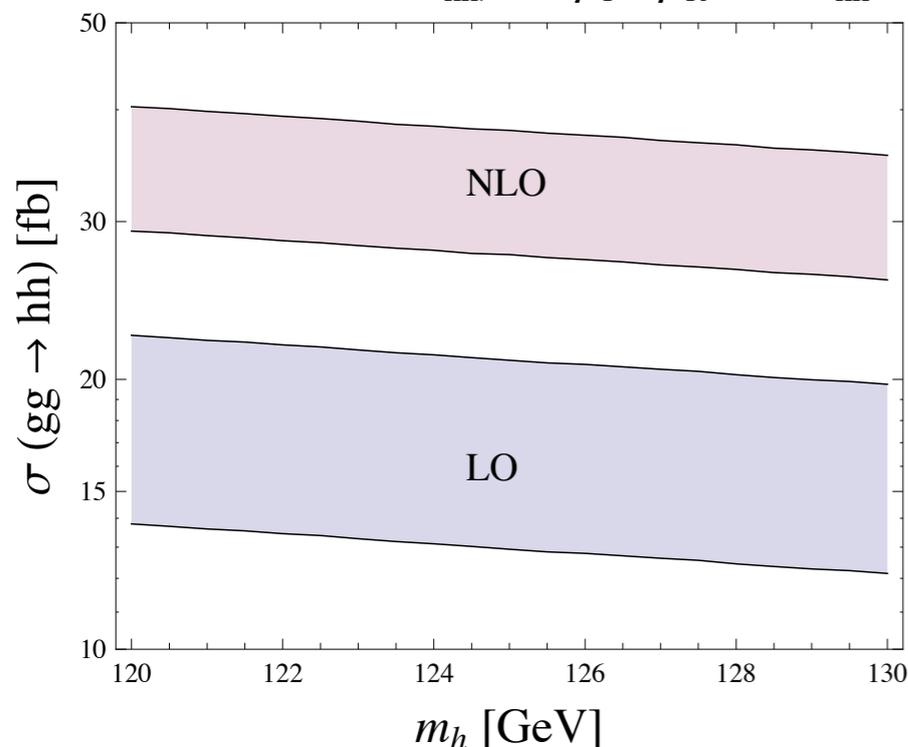
Disclaimer: No BSM in this talk! (rather active field in the recent past, incomplete list below)

Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer [1205.5444]; Gillioz, Grober, Grojean, Muhlleitner, Salvioni [1206.7120]; Kribs, Martin [1207.4496]; Dawson, Furlan, Lewis [1210.6663]; Dolan, Englert, Spannowsky [1210.8166]; Englert, Re, Spannowsky [1302.6506]; Goutzevich, Oliveira, Rojo, Rosenfeld, Salam, Sanz [1303.3663]; Craig, Galloway, Thomas, [1305.2424]; Killick, Kumar, Logan, [1305.7236]; Gupta, Rzehak, Wells, [1305.6397]; Nhung, Muhlleitner, Streicher, Walz [1306.3926]; Choi, Englert, Zerwas [1308.784]; Nishiwaku, Noyogi, Shivaji [1309.6907]; Liu, Wang, Zhu [1310.3634]; Ramsey-Musolf, No [1310.6035]; Enkhbat [1311.4445]; Heng, Shang, Zhang, Zhu [1312.4260], Hespel, Lopez-Val, Vryonidou [1407.0281], Bhattacharjee, Choudhury [1407.6866] + many others

Scalar boson pairs: production and decay

Cross sections, events and decay rates @ 14 TeV LHC

$\sqrt{s} = 14 \text{ TeV}, m_{hh}/2 < \mu_F = \mu_R < 2 m_{hh}$



Cross sections

- Gluon fusion is dominant ($> 90\%$) in 120-130 GeV, VBF also interesting.
- K-fac ~ 2 (2.3) LO (NLO), th. unc. 30 (20) [8] % @ LO (NLO) [NNLO].

LO: Glover, van der Bij, Nucl. Phys. B **309**, 282 (1988); Plehn, Spira and Zerwas, Nucl. Phys. B **479**, 46 (1996), [Erratum B **531**, 655 (1998)]

NLO heavy top : Dawson, Dittmaier and Spira, Phys. Rev. D **58**, 115012 (1998).

NLO exp. top mass: Grigo, Hoff, Melnikov and Steinhauser, 1305.7340

NNLL+NLO : D. Shao, C. Li, H. Li, J. Wang, 1301.1245.

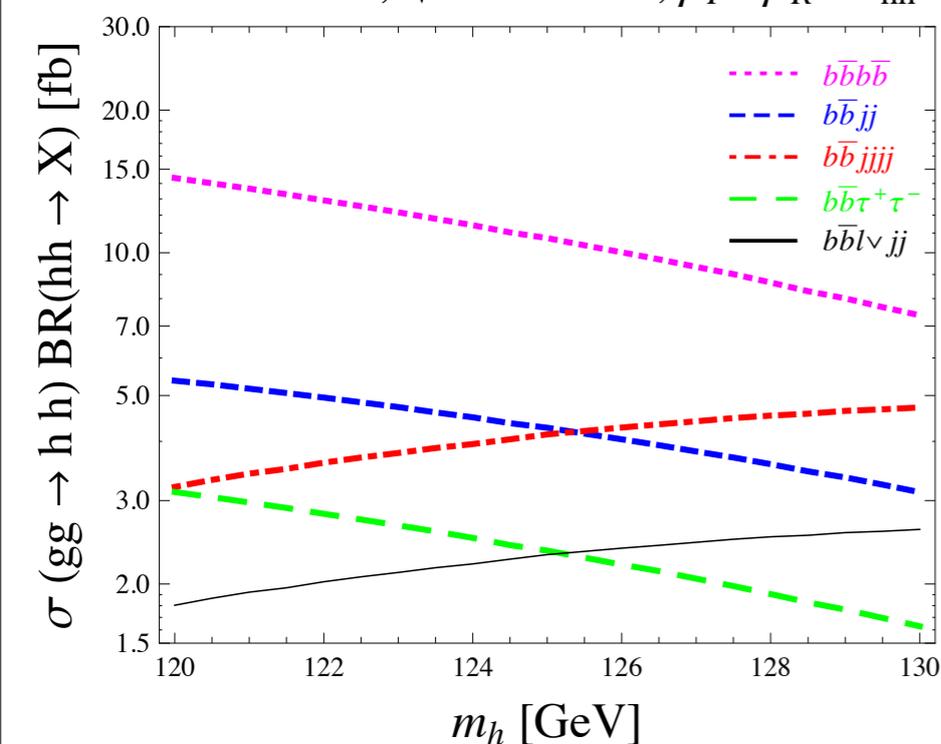
NNLO heavy top: De Florian, Mazzitelli, 1305.5206, 1309.6594

A. Papaefstathiou, L. L. Yang, JZ, 1209.1489

Cross sections computed with HPAIR

(<http://people.web.psi.ch/spira/hpair/>)

CT10NLO, $\sqrt{s} = 14 \text{ TeV}, \mu_F = \mu_R = m_{hh}$



Event generation

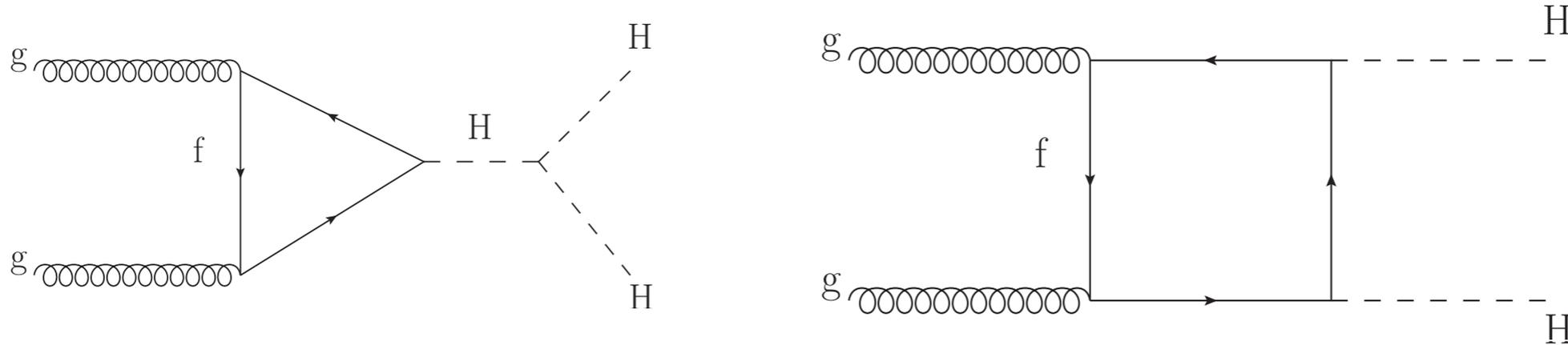
- Events can be generated with MG5 and Herwig++ (public).
- Matching to PS @ NLO:
 - MG5_aMC@NLO: Frederix et al, 1401.7340.
 - Open Loops + Herwig++: Maierhöfer, Papaefstathiou, 1401.0007

Total rates

- Hadronic decays dominate.
- Total rate for $b\bar{b}\tau^+\tau^-$ and $b\bar{b}l\nu jj \sim 2.4 \text{ fb}$. $b\bar{b}\gamma\gamma \sim 0.087 \text{ fb}$.

A. Papaefstathiou, L. L. Yang, JZ, PRD 87 (2013) 011301

Dissecting HH cross section



2 topologies, each with 2 Lorentz structures (1 and 2):

$$\sigma_{LO} = |\alpha_1 C_{tri}^{(1)} + \beta_1 C_{box}^{(1)}|^2 + \gamma_1^2 |C_{box}^{(2)}|^2 \quad \text{SM:} \quad \begin{aligned} \alpha_1 &= y_t \lambda \\ \beta_1 &= \gamma_1 = y_t^2 \end{aligned}$$

Our fit: $\sigma_{HH}^{\text{NLO}} [\text{fb}] = 9.66 \lambda^2 y_t^2 - 46.9 \lambda y_t^3 + 70.1 y_t^4 + \mathcal{O}(\lambda y_b y_t^2)$.

(MSTW2008)

Goertz, Papaefstathiou, Yang, JZ (arXiv: 1301.3492)

- Triangle diagram subdominant due to off-shell s-channel Higgs boson.
- Minimum for $\lambda \sim 2.4 y_t$.
- Cross section is very sensitive to actual value of y_t .
- Bottom loop effects 0.2 % in the SM (up to 2% for currently allowed ranges).

Final states @ 14 TeV LHC

Process	S (600 fb^{-1})	B (600 fb^{-1})	σ
$b\bar{b}\tau^+\tau^-$	50	104	4.5
$b\bar{b}W^+W^-$	12	8	4.1
$b\bar{b}\gamma\gamma$	9	11	2.4
$b\bar{b}\gamma\gamma$	6	12.5	1.5
$b\bar{b}b\bar{b}$	50	2500	1.0

Dolan, Englert, Spannowsky, 1206.5001

Papaefstathiou, L. L. Yang, JZ, 1209.1489.

Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira:1212.5581

Baur, Plehn, Rainwater, Phys.Rev. D69 (2004) 053004

Ferreira de Lima, Papaefstathiou, Spannowsky:1404.7139.

- Benefits from new techniques in jet physics:

$b\bar{b}\tau^+\tau^-$, $b\bar{b}W^+W^-$ exploit jet substructure.

Butterworth, Davison, Rubin, Salam, Phys.Rev.Lett. 100 (2008) 242001

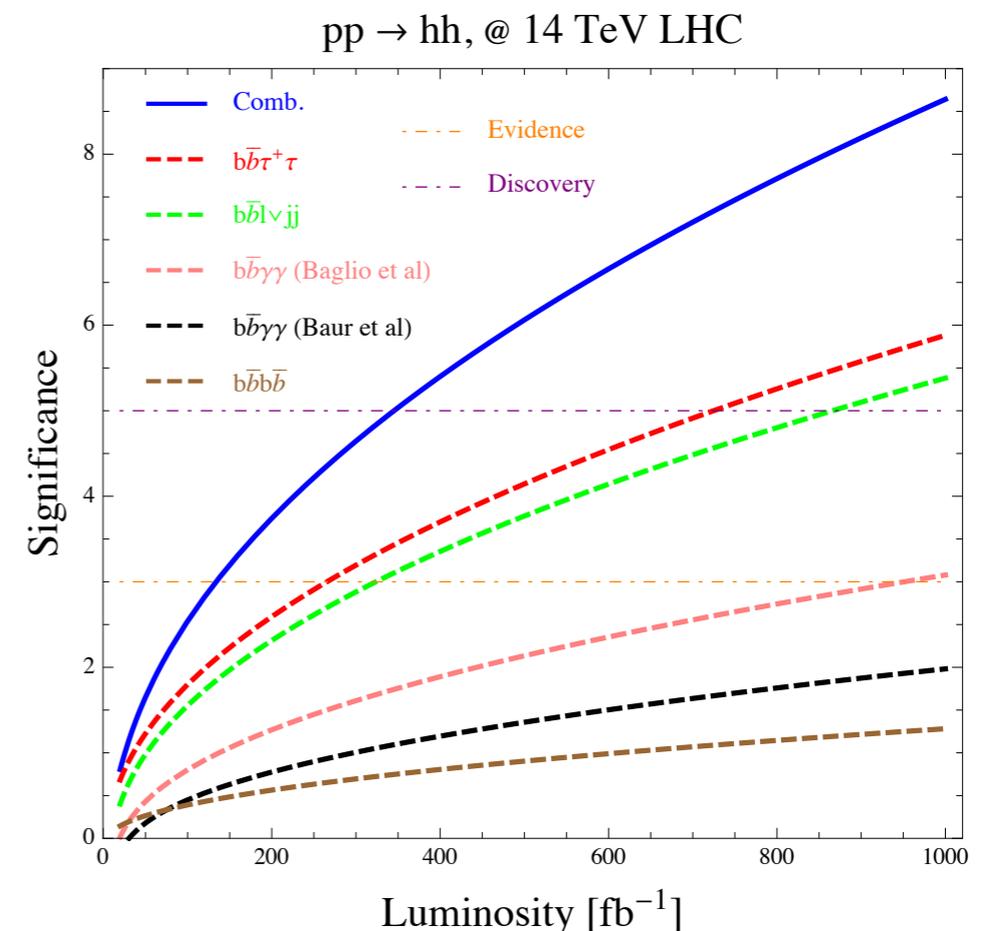
$b\bar{b}b\bar{b}$ based on shower deconstruction.

Soper, Spannowsky, 1102.3480.

- What if we combine channels?

Channel	Evidence	Discovery
$b\bar{b}\tau^+\tau^-$	270 fb^{-1}	730 fb^{-1}
Combination	140 fb^{-1}	350 fb^{-1}

Goertz, Papaefstathiou, Yang, JZ, in progress



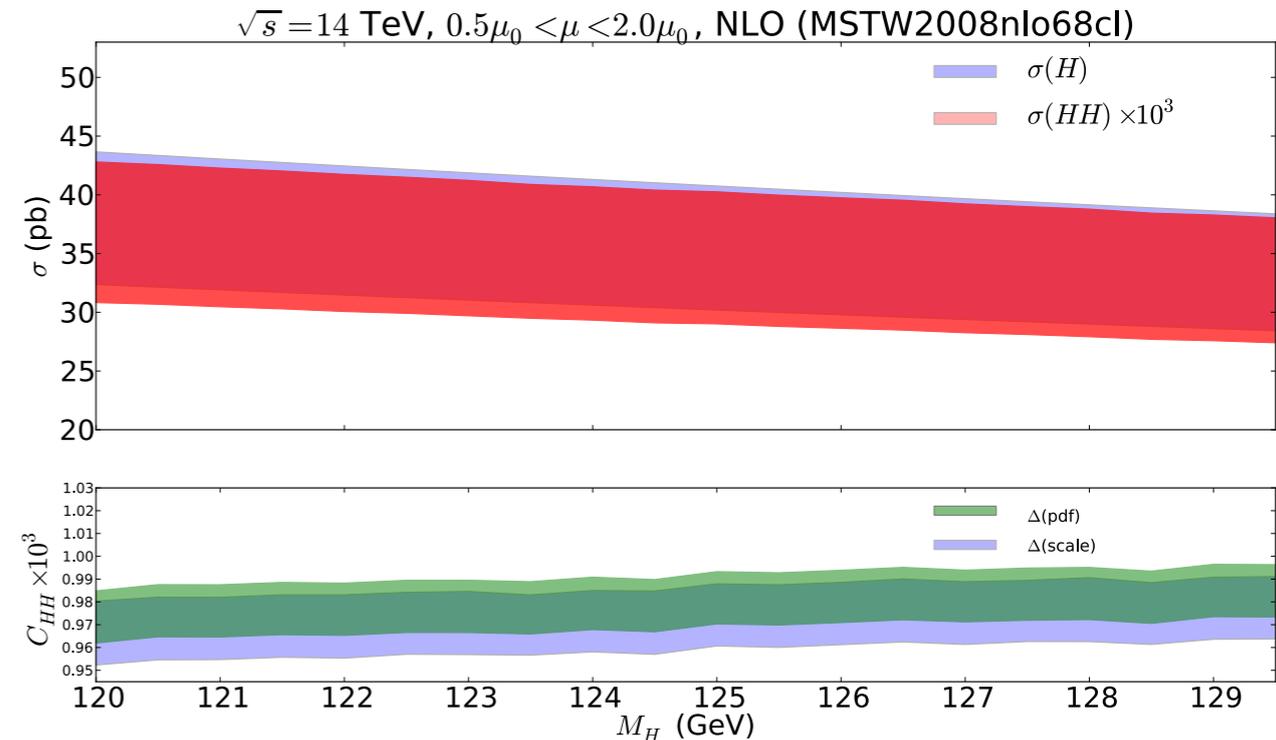
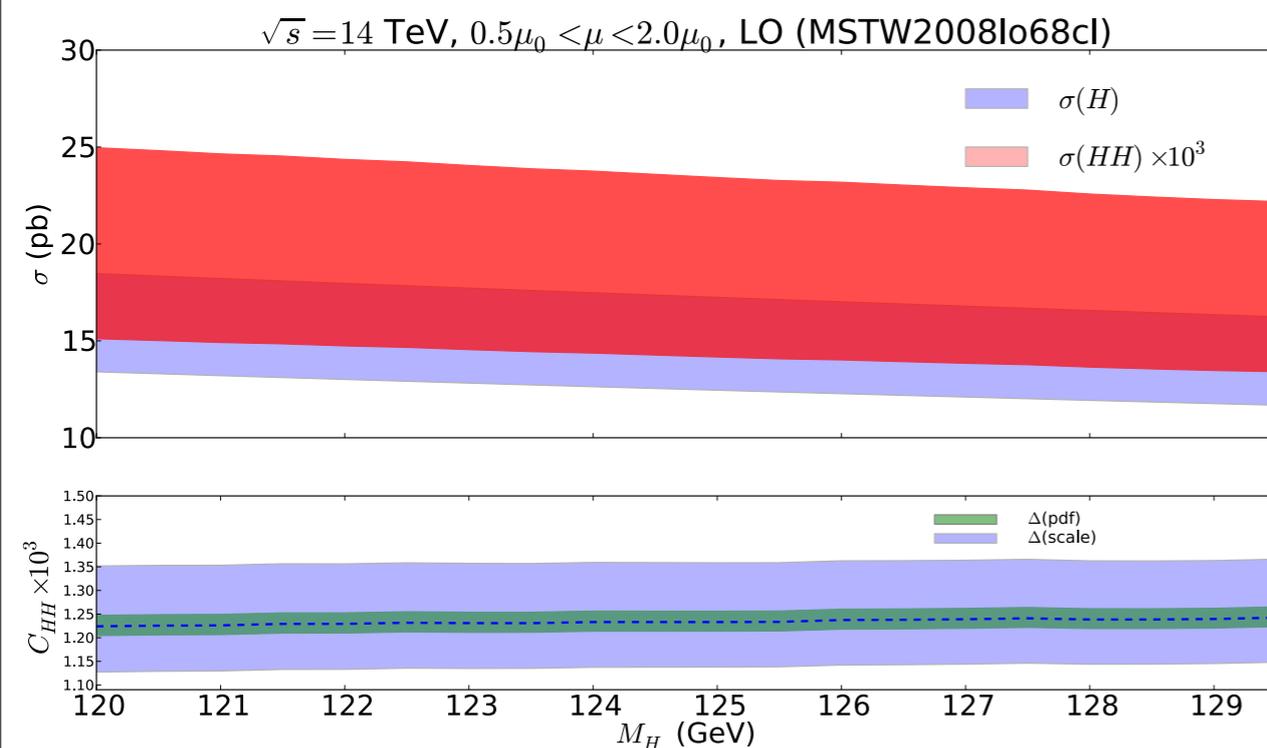
**Double to single scalar
boson cross section ratio**

Cross section ratio

$$C_{HH} = \frac{\sigma(gg \rightarrow HH)}{\sigma(gg \rightarrow H)} \equiv \frac{\sigma_{HH}}{\sigma_H}$$

Djouadi, arXiv 1208.3436

- The bulk of the QCD corrections for both processes comes from real radiation from initial state gluons, hence we expect the ratio to be more stable against higher order corrections.
- Moreover, common systematic uncertainties will cancel out (i.e luminosity).



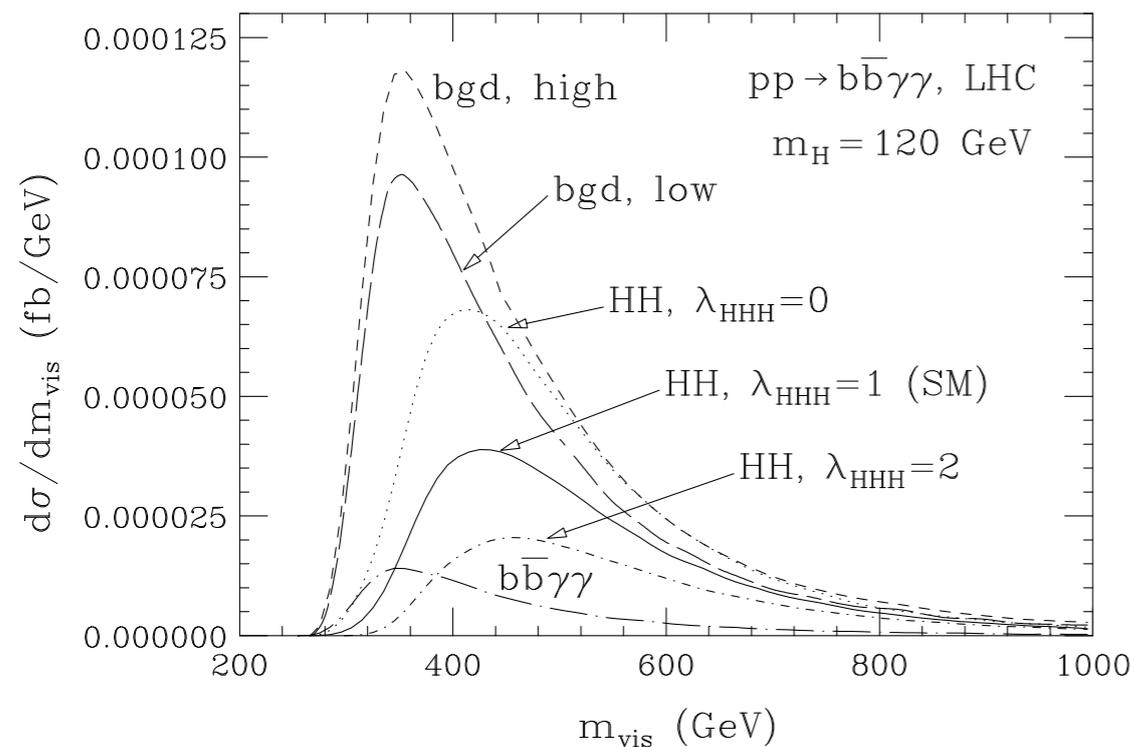
F. Goertz, A. Papaefstathiou, L. L. Yang, JZ (arXiv: 1301.3492)

	LO	NLO
σ_H	20 % (scale)	16 % (scale)
σ_{HH}	25 % (scale)	17 % (scale)
C_{HH}	9 % (scale) 2-3% (PDF)	1.5 % (scale) 2 % (PDF)

Scalar boson self coupling at the LHC

Measuring the scalar boson self coupling

1- Traditional method: fitting a distribution



- A few events in a few bins: poor statistics.

Baur, Plehn, Rainwater, Phys.Rev. D69 (2004) 053004

(see also Chen, Low, I405.7040)

2- Alternative: event count (more “shape-independent”)

- We measure N events, and we expected B background events.
- Assuming Gaussian distribution, $S = N - B$, $\Delta S = \sqrt{N + B}$.
- We draw 1σ and 2σ exclusion contours (68 % and 95 % C.L.).

Exploiting the ratio

$$\begin{aligned} \sigma_{HH}^{b\bar{b}xx} &\equiv \sigma_{HH} \times 2 \times \text{BR}(b\bar{b}) \times \text{BR}(xx) \\ \sigma_H^{b\bar{b}} &\equiv \sigma_H \times \text{BR}(b\bar{b}) \end{aligned} \quad \longrightarrow \quad \text{Measured quantities}$$

$$C_{HH}^{\text{exp.}} = \left. \frac{\sigma_{HH}^{b\bar{b}xx}}{\sigma_H^{b\bar{b}} \times 2 \times \text{BR}(xx)} \right|_{\text{exp.}}$$

- **Uncertainties assumed:**

$y_t \sim 20\%$ after 300/fb at 14 TeV LHC.

$h \rightarrow (\tau^+ \tau^-, W^+ W^-, \gamma\gamma) = (12, 12, 16)\%$

CMS collaboration,

“CMS at the High Energy Frontier”

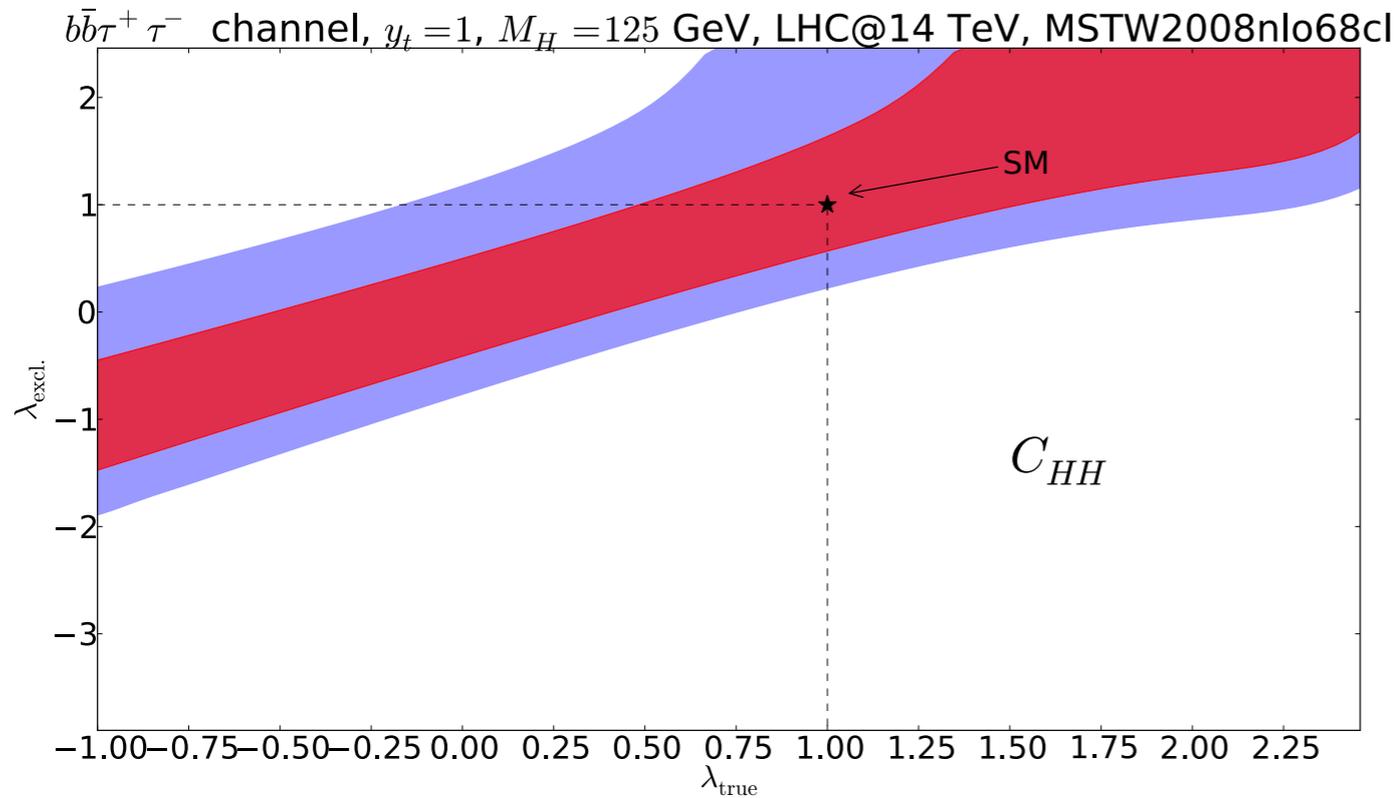
(Contribution to the Update of the European Strategy for Particle Physics, Aug 2012)

- **Assume no further improvement beyond 300/fb (conservative).**

- **Combine all errors in quadrature:**

$$\left(\frac{\Delta C_{HH}}{C_{HH}} \right)^2 = \left(\frac{\Delta \sigma_{HH}^{b\bar{b}xx}}{\sigma_{HH}^{b\bar{b}xx}} \right)^2 + \left(\frac{\Delta \text{BR}(xx)}{\text{BR}(xx)} \right)^2 + \left(\frac{\Delta \sigma_H^{b\bar{b}}}{\sigma_H^{b\bar{b}}} \right)^2 + (\text{“theory” errors})^2.$$

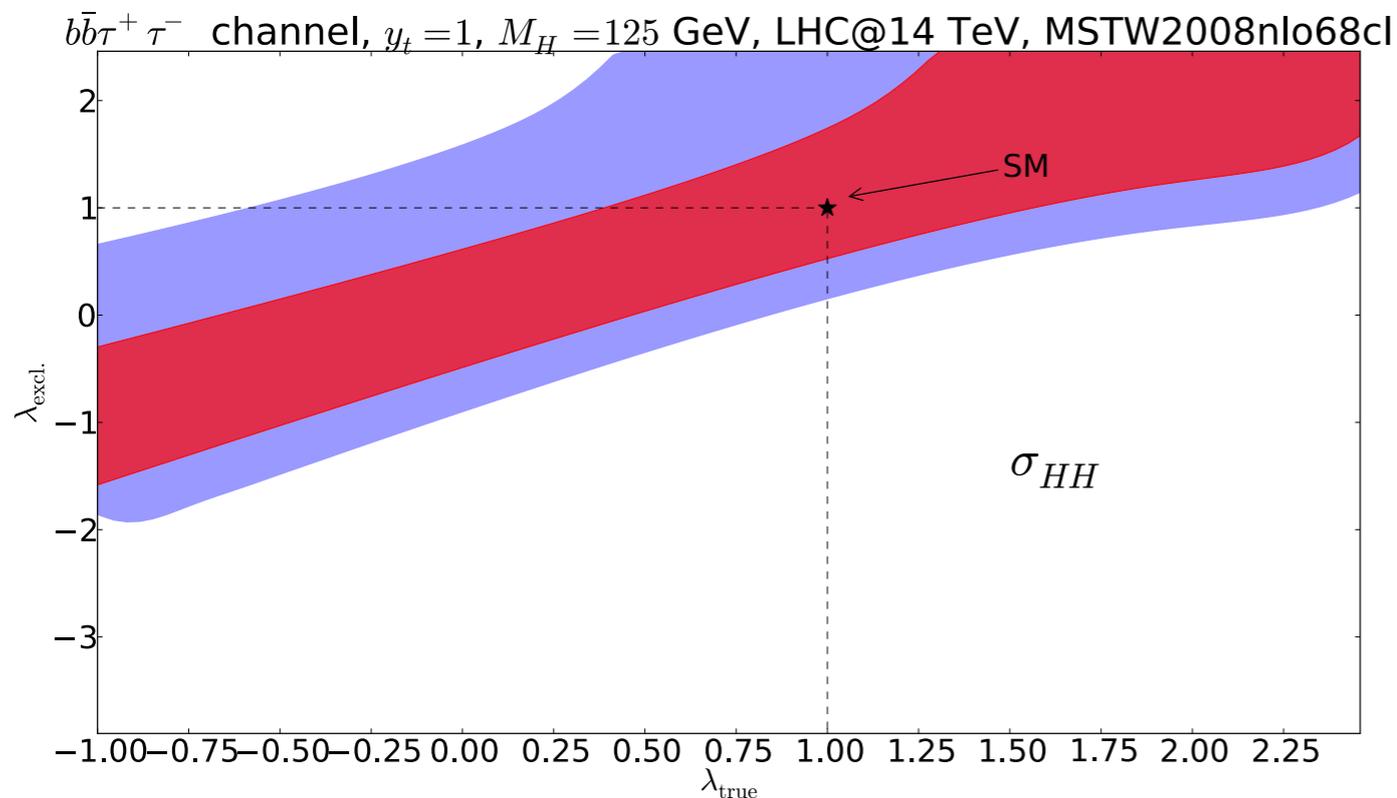
Constraining the self-coupling



- Given an assumption for the “true” value of the self-coupling (λ_{true}) what is the constraint we can impose on λ ?

$$1\sigma : \lambda \in (0.57 - 1.64)$$

$$2\sigma : \lambda \in (0.22 - 4.70)$$



$$1\sigma : \lambda \in (0.54 - 1.78)$$

$$2\sigma : \lambda \in (0.17 - 4.75)$$

Exclusion intervals

Process	600 fb ⁻¹ (2σ)	600 fb ⁻¹ (1σ)	3000 fb ⁻¹ 2σ	3000 fb ⁻¹ 1σ
$b\bar{b}\tau^+\tau^-$	(0.22, 4.70)	(0.57, 1.64)	(0.42, 2.13)	(0.69, 1.40)
$b\bar{b}W^+W^-$	(0.04, 4.88)	(0.46, 1.95)	(0.36, 4.56)	(0.65, 1.46)
$b\bar{b}\gamma\gamma$	(-0.56, 5.48)	(0.09, 4.83)	(0.08, 4.84)	(0.48, 1.87)

Table 1: The expected limits at 1σ and 2σ confidence levels, provided that λ_{true} and $y_{t,\text{true}}$ have their SM values: $\lambda_{\text{true}} = 1$, $y_{t,\text{true}} = 1$. The results have been derived using C_{HH} and are shown for 600 fb⁻¹ and 3000 fb⁻¹.

Naive combination, $\sqrt{s} = 14$ TeV, 3000 fb⁻¹, gives $\pm 20\%$.

(adding 4b channel, not shown here)

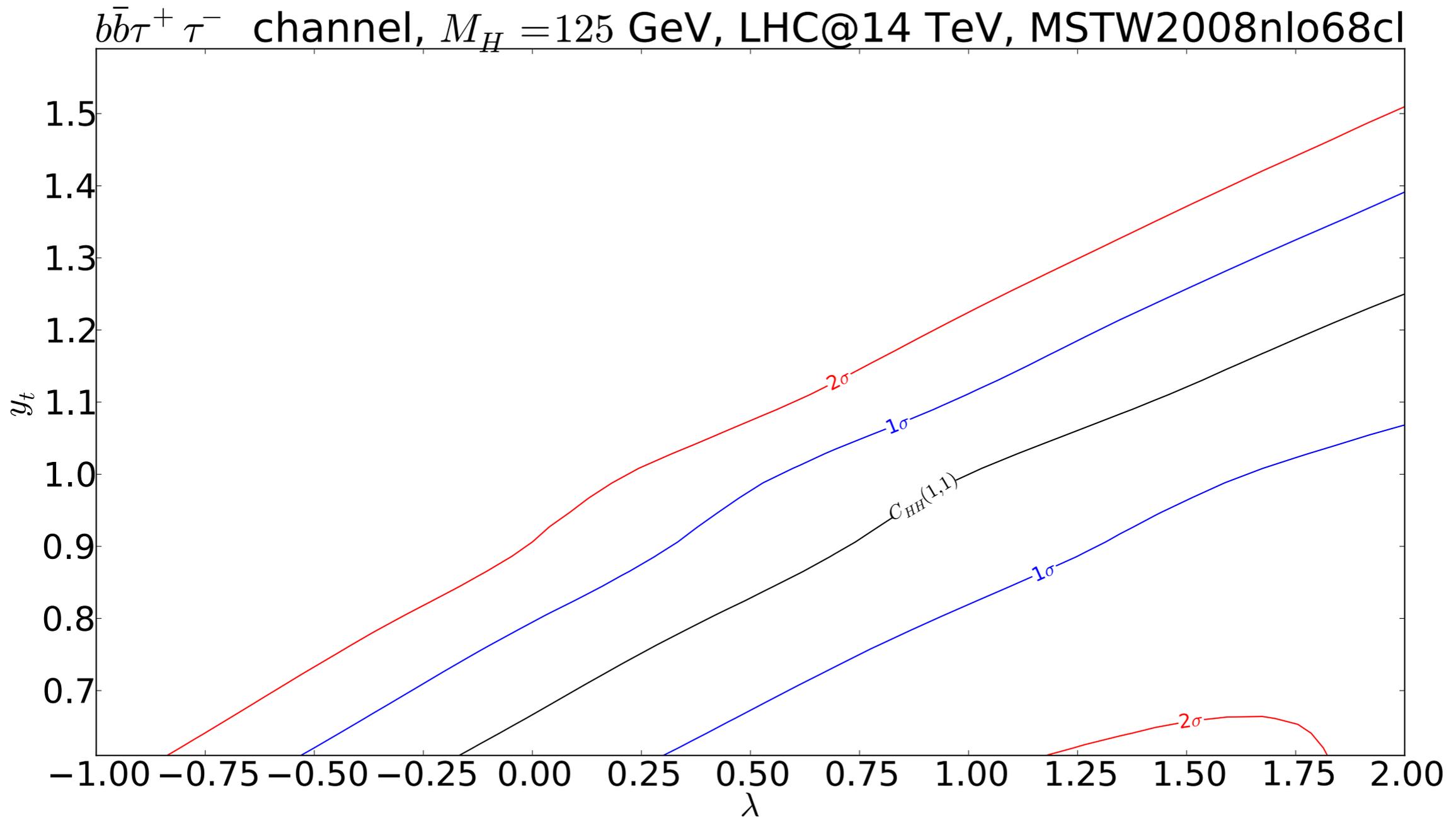
- **Compare to:**

LHC: (0.26-1.94) $\sqrt{s} = 14$ TeV, 600 fb⁻¹ (1σ) [Baur, Plehn, Rainwater, Phys.Rev. D69 \(2004\) 053004](#)

ILC: (0.76-1.24) $\sqrt{s} = 1$ TeV, 1000 fb⁻¹

[T. Barklow, et al, "Physics at the International Linear Collider", to be published in the ILC Detailed Baseline Design Report \(2012\).](#)

Varying Yukawa top



F. Goertz, A. Papaefstathiou, L. L. Yang, JZ (arXiv: 1301.3492)

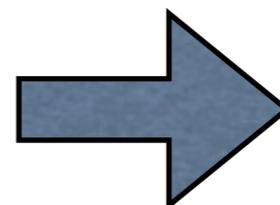
1σ

$$y_t = 0.85$$

$$\lambda \in (0.2 - 1.1)$$

$$y_t = 1.15$$

$$\lambda \in (1.1 - 2.5)$$



No overlap!

Scalar boson pair production in Effective Field Theory (HEFT)

Lagrangian and couplings

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\bar{c}_H}{2v^2} (\partial^\mu |H|^2)^2 - \frac{\bar{c}_6}{v^2} v |H|^6 + \left\{ -\frac{\bar{c}_u}{v^2} y_u |H|^2 \bar{Q}_L H^c u_R - \frac{\bar{c}_d}{v^2} y_d |H|^2 \bar{Q}_L H d_R - \frac{\bar{c}_l}{v^2} y_l |H|^2 \bar{L}_L H e_R + \text{h.c.} \right\}$$

$$+ \frac{\alpha_s \bar{c}_g}{4\pi v^2} |H|^2 G_{\mu\nu}^a G_a^{\mu\nu} + \frac{g'^2 \bar{c}_\gamma}{v^2} |H|^2 B_{\mu\nu} B^{\mu\nu} + \frac{ig \bar{c}_{HW}}{v^2} (D^\mu H)^\dagger \sigma_k (D^\nu H) W_{\mu\nu}^k$$

$$+ \frac{ig' \bar{c}_{HB}}{v^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} + \frac{i\bar{g} \bar{c}_W}{2v^2} (H^\dagger \sigma_k \overleftrightarrow{D}^\mu H) D^\nu W_{\mu\nu}^k + \frac{ig' \bar{c}_B}{2v^2} (H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu}$$

See (recent) e.g: Passarino (1209.5538), Buchalla, Cata, Krause (1307.5017), Alloul, Fuks, Sanz (1310.5150) and refs therein.

$$\bar{c}_{HB} = -\bar{c}_{HW} = \bar{c}_W = -\bar{c}_B \quad \text{Elias-Miro, Espinosa, Masso, Pomarol (1308.1879).}$$

“Extended kappa framework” for double scalar boson production:

$$\mathcal{L} \supset -\frac{m_h^2}{2v} \kappa_\lambda h^3 - \frac{m_h^2}{8v^2} \kappa_{hh} h^4 + \left(\kappa_g \frac{h}{v} + \kappa_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu}^a G_a^{\mu\nu} - \sum_{f=b,t,\tau,\dots} \frac{m_f}{v} \bar{f}_L f_R \left(\kappa_f \frac{h}{v} + \kappa_{2f} \frac{h^2}{v^2} \right)$$

$$\kappa_\lambda = 1 - \frac{3}{2} \bar{c}_H + \bar{c}_6$$

$$\kappa_{hh} = 1 - \frac{25}{3} \bar{c}_H + 6\bar{c}_6$$

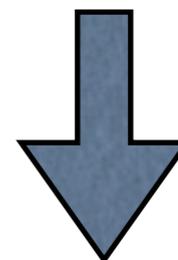
$$\kappa_g = \kappa_{2g} = \frac{\alpha_s \bar{c}_g}{4\pi}$$

$$\kappa_f = 1 - \frac{\bar{c}_H}{2} + \bar{c}_f$$

$$\kappa_{2f} = \frac{3\bar{c}_f - \bar{c}_H}{2}$$

Process	Tree
$h \rightarrow bb$	\bar{c}_H, \bar{c}_d
$h \rightarrow \tau\tau$	\bar{c}_H, \bar{c}_l
$h \rightarrow \gamma\gamma$	\bar{c}_γ
$h \rightarrow WW$	$\bar{c}_H, \bar{c}_{HW}, \bar{c}_W$
$gg \rightarrow h$	$\bar{c}_H, \bar{c}_g, \bar{c}_t$
$gg \rightarrow hh$	$\bar{c}_H, \bar{c}_g, \bar{c}_t, \bar{c}_6$

Only place where \bar{c}_6 shows up!

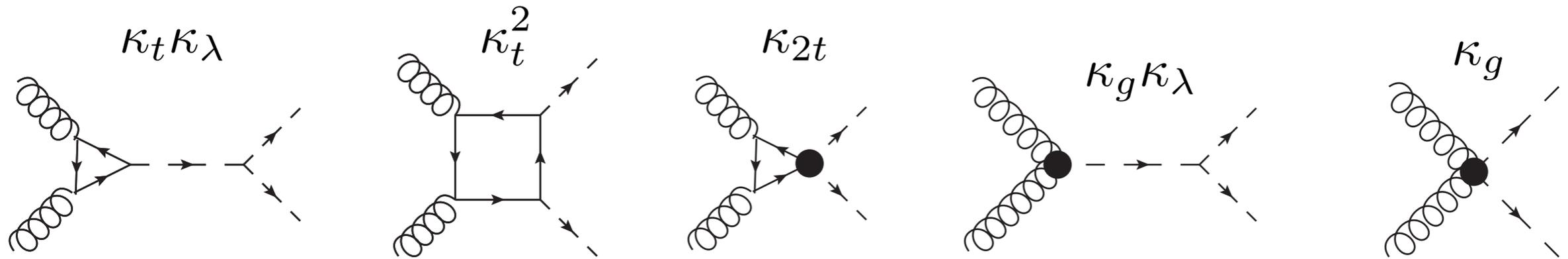


Varying the trilinear coupling only is consistent with the EFT framework

EFT analysis

BRs computed with eHDECAY [Contino, Ghezzi, Grojean, Mühlleitner, Spira, 1303.3876, 1403.3381](#).

Compatibility with scalar boson data using HiggsBounds and HiggsSignals [Bechtle et al, 1311.0055, 1305.1933](#).



Our fit
(MSTW)

$$\frac{\sigma(gg \rightarrow hh)}{\sigma(gg \rightarrow hh)_{\text{SM}}} = 2.1\kappa_t^4 - 1.4\kappa_t^3\kappa_\lambda + 0.3\kappa_t^2\kappa_\lambda^2 + \kappa_g^2(0.05\kappa_\lambda^2 - 0.03\kappa_\lambda + 24.4) - 8.3\kappa_g\kappa_t^2 + \kappa_g\kappa_\lambda(2.8\kappa_t^2 - 0.5\kappa_\lambda\kappa_t + 1.5\kappa_t - 2.2\kappa_{2t}) + \kappa_{2t}(21.7\kappa_g + 3.1\kappa_\lambda\kappa_t - 8.8\kappa_t^2 + 8.9\kappa_{2t})$$

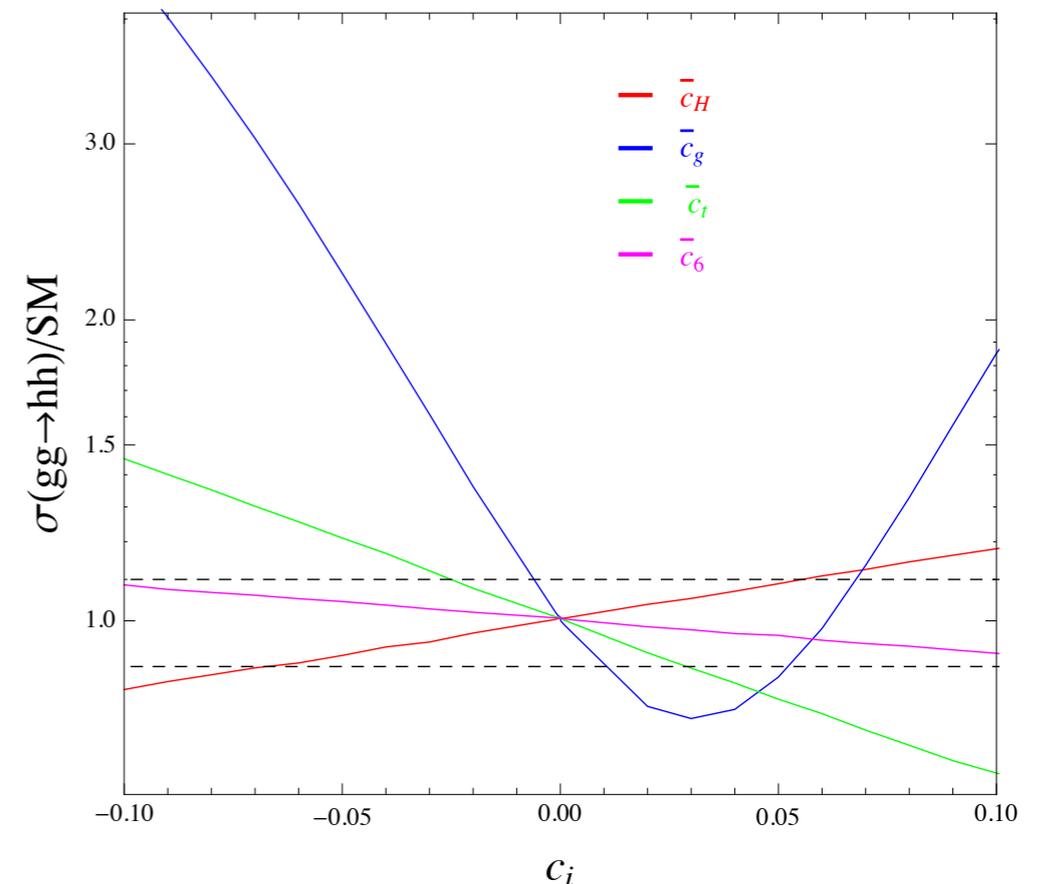
Linearizing:

$$\frac{\sigma(gg \rightarrow hh)}{\sigma(gg \rightarrow hh)_{\text{SM}}} = 1 + 1.6c_h - 0.8c_6 - 4.5c_g - 3.7c_t + \mathcal{O}(c_i^2)$$

Large variations in the cross section
still allowed by current SB data

Still a lot of room for surprises!

Goertz, Papaefstathiou, Yang, JZ, in preparation.



Conclusions

- We have considered the double to single scalar boson cross section ratio, C_{HH} at the 14 TeV LHC, including scale and PDF uncertainties.
- The ratio is very stable under scale variation (1.5 % @ NLO), while the cross section itself has a 20 % theory uncertainty.
- We have derived exclusion limits for the trilinear scalar boson self coupling using the available channels, obtaining a 20% accuracy for the SM case.
- To measure it is crucial to know y_t with a high accuracy .
- The channels used here have to be studied in more realistic environment (including detector simulation, underlying event, pile up, efficiencies, etc...)
- We have shown preliminary results for the EFT analysis, large effects still allowed in spite of a “SM-look-alike” scalar boson.