Double Higgs Production at the 14 TeV LHC and 100 TeV pp-collider

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Based on arXiv: 1611.09336, in collaboration with
Qing-Hong Cao, Bin Yan, Dong-Ming Zhang, Hao Zhang

IAS Program at HKUST, Jan. 25, 2017

Motivations

- The Higgs potential is still undetermined

$$V(h) = \frac{1}{2} m_h^2 v^2 + \lambda v h^3 + \frac{1}{4} \tilde{\lambda} h^4$$

$$m_h = 125\text{GeV}$$
$$v = (2G_F)^{-1/2}$$

SM: $\lambda = \tilde{\lambda} = \lambda_{\text{SM}} = m_h^2/(2v^2)$

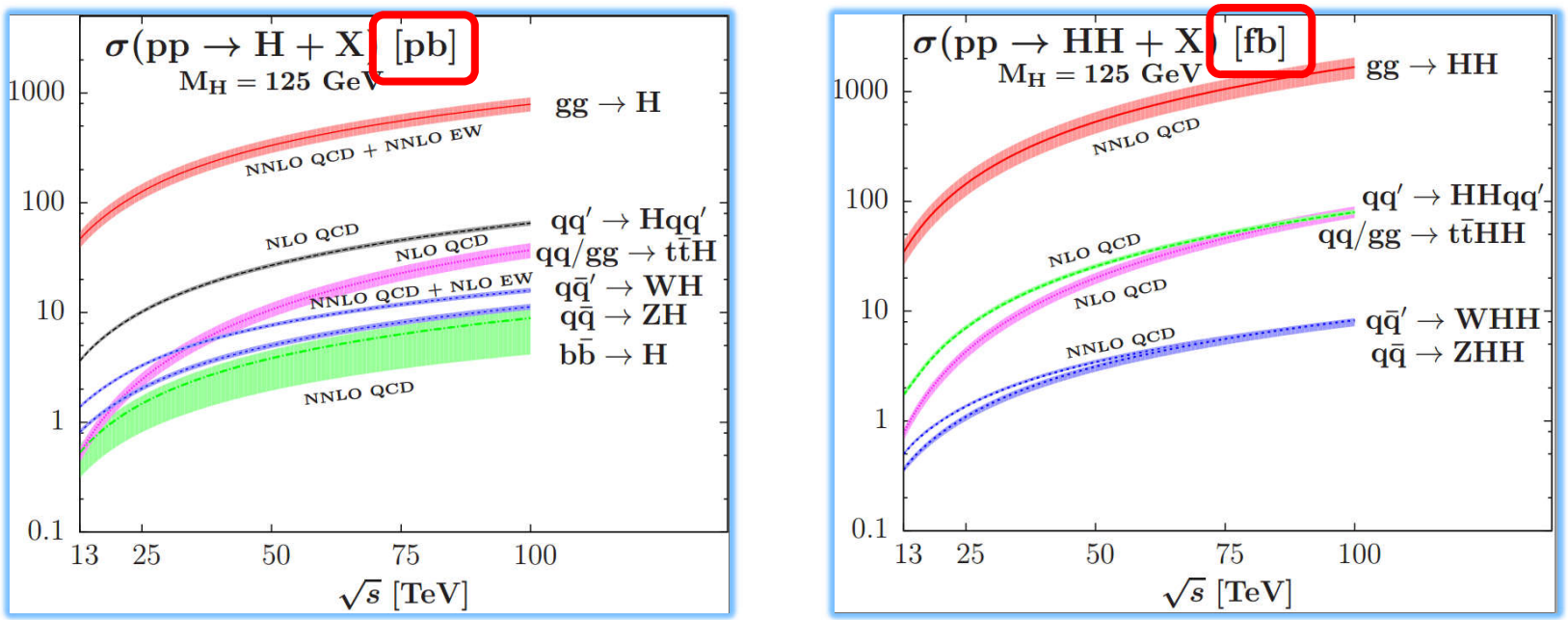
- λ and $\tilde{\lambda}$ can vary independently, for example by adding a higher dimensional operator $\left(H^\dagger H\right)^3$
- So it is necessary to probe λ and $\tilde{\lambda}$ <u>directly</u> in multi-Higgs production
- The measurements of $\tilde{\lambda}$ in triple Higgs production is much more challenging than and depends on the measurements of λ in double Higgs production

T. Plehn, M. Rauch, Phys.Rev. D72, 053008 (2005)

Pioneering works (before Higgs discovery):
F. Gianotti, M.L. Mangano, T. Virdee, et. al, hep-ph/0204087, Eur.Phys.J. C39 (2005) 293
U. Baur, T. Plehn, D. L. Rainwater, Phys.Rev.Lett. 89, 151801 (2002); Phys.Rev. D67, 033003 (2003); Phys.Rev. D 68, 033001 (2003); Phys.Rev. D 69, 053004 (2004); Phys.Rev. D69 (2004) 053004
M. J. Dolan, C. Englert, M. Spannowsky, JHEP 1210 (2012) 112
Theoretical status (after Higgs discovery)
J. Baglio, A. Djouadi, R. Grober, M.M. Muhlleitner, J. Quevillon, M. Spira, JHEP 1304 (2013) 151

Motivations

- The cross section of double Higgs production in the SM is small



Baglio, Djouadi, Quevillon, Rep. Prog. Phys. 79 (2016) 116201

- However, it has received a lot of attention after the Higgs boson was discovered since it is very sensitive to NP

Motivations

- $gg \to hh$:

Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer, JHEP08(2012)154

Chuan-Ren Chen, Ian Low, Phys.Rev. D90, 013018 (2014)

Goertz, Papaefstathiou, Yang, Zurita, JHEP 1504 (2015) 167

Dawson, Ismail, Low, Phys.Rev. D91, 115008 (2015)

Chih-Ting Lu, Jung Chang, Kingman Cheung, Jae Sik Lee, JHEP 1508 (2015) 133

Azatov, Contino, Panico, Son, Phys.Rev. D92, 035001 (2015)

Qing-Hong Cao, Bin Yan, Dong-Ming Zhang, Hao Zhang, Phys.Lett. B752 (2016) 285

Ligong Bian, Ning Chen JHEP 1609 (2016) 069

Hong-Jian He, Jing Ren, Weiming Yao, Phys. Rev. D 93, 015003 (2016)

- $qq' \to hhqq'$:

Bishara, Contino, Rojo, 1611.03860

- $q\bar{q}/gg \to t\bar{t}hh$:

Tao Liu, Hao Zhang, 1410.1855

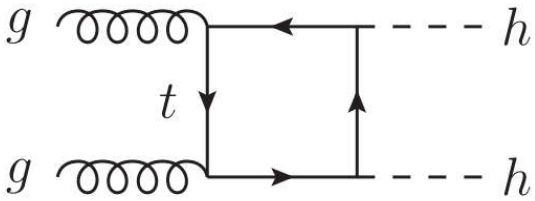
Ning Liu, Yanming Zhang, Jinzhong Han, Bingfang Yang, JHEP 1509 (2015) 008

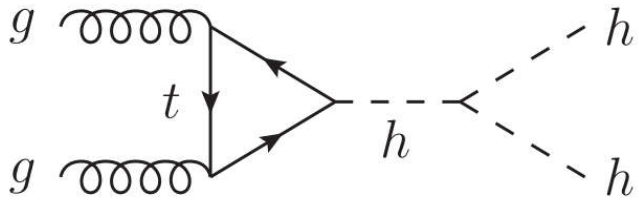
- $q\bar{q}' \to Vhh$:

Qing-Hong Cao, Yandong Liu, Bin Yan, 1511.03311

Motivations

- I will focus on $gg \to hh$
- In the SM, there is large cancellation between

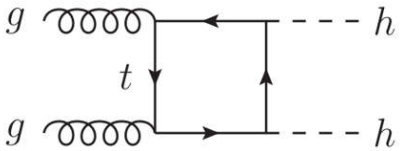




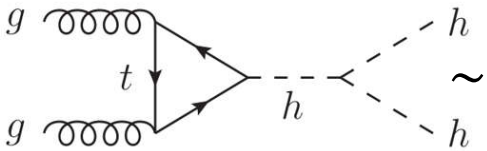
Low energy theorem

B. A. Kniehl, M. Spira Z.Phys. C69 (1995) 77 A. Pierce, J. Thaler, L-T Wang JHEP 0705 (2007) 070

$$\frac{\alpha_s}{24\pi} G^{a,\mu\nu} G^a_{\mu\nu} \log\left(1 + \frac{h}{v}\right)$$



$$\sim \frac{\alpha_s}{12\pi} G^{a,\mu\nu} G^a_{\mu\nu} \frac{h}{v}$$



$$\sim -\frac{\alpha_s}{24\pi} G^{a,\mu\nu} G^a_{\mu\nu} \frac{h^2}{v^2}$$

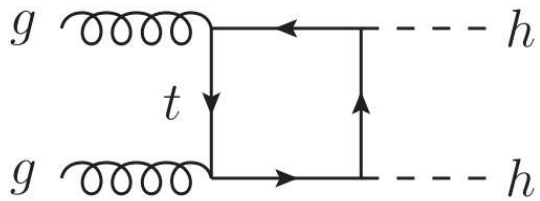
- The current constraint on gluon fusion double Higgs production (8 TeV)

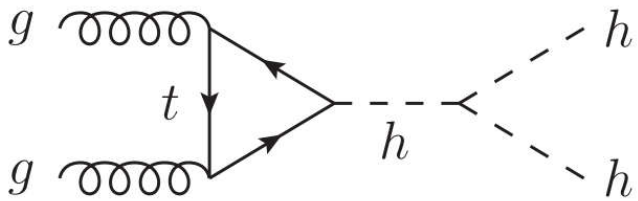
ATLAS Phys.Rev. D92, 092004 (2015)

$$\sigma_{hh} \leq 0.69\text{Pb} \sim 70\sigma_{hh}^{SM}$$

Motivations

- NP enters in double Higgs production in different ways





- A model independent way to study the NP effects is EFT

Goertz, Papaefstathiou, Yang, Zurita, JHEP 1504 (2015) 167

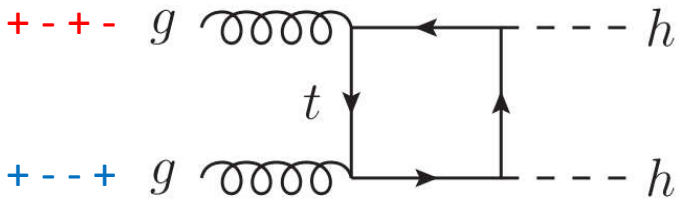
$$\mathcal{L}_{\text{eff}} = -\frac{m_t}{v}\bar{t}(c_t + \tilde{c}_t\gamma_5)th - \frac{m_t}{2v^2}\bar{t}(c_{2t} + \tilde{c}_{2t}\gamma_5)th^2 - c_{3h}\frac{m_h^2}{2v}h^3$$
$$+\frac{\alpha_s h}{12\pi v}\left(c_g G^A_{\mu\nu}G^{A,\mu\nu} + \tilde{c}_g G^A_{\mu\nu}\tilde{G}^{A,\mu\nu}\right) + \frac{\alpha_s h^2}{24\pi v^2}\left(c_{2g} G^A_{\mu\nu}G^{A,\mu\nu} + \tilde{c}_{2g} G^A_{\mu\nu}\tilde{G}^{A,\mu\nu}\right)$$

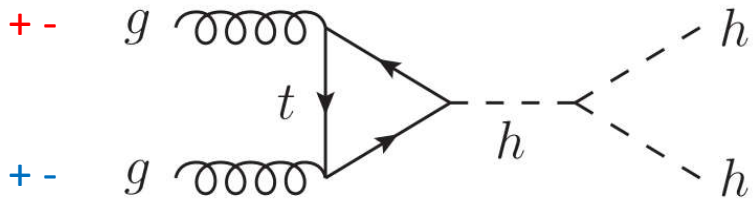
- $c_t = c_{3h} = 1$ and others=0 in the SM

Chih-Ting Lu, Jung Chang, Kingman Cheung, Jae Sik Lee, JHEP 1508 (2015) 133

- $\mathcal{O}_{HG} = H^\dagger H G^A_{\mu\nu}G^{A,\mu\nu}$
  $\tilde{\mathcal{O}}_{HG} = H^\dagger H G^A_{\mu\nu}\tilde{G}^{A,\mu\nu}$ $\Rightarrow$ $c_g = c_{2g}$, $\tilde{c}_g = \tilde{c}_{2g}$

Partial wave analysis

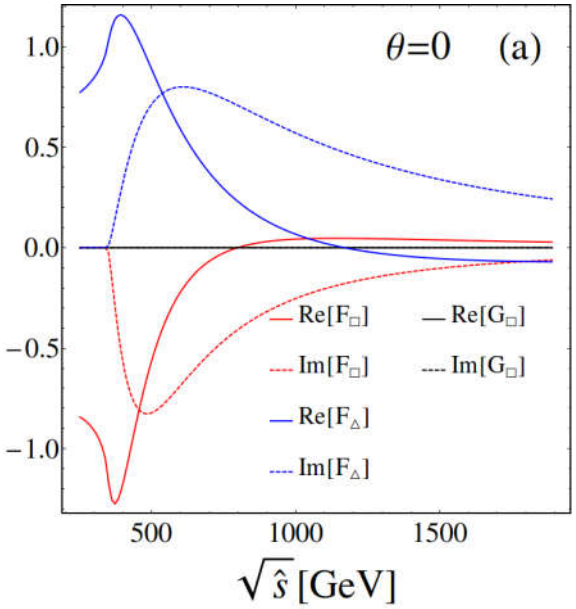


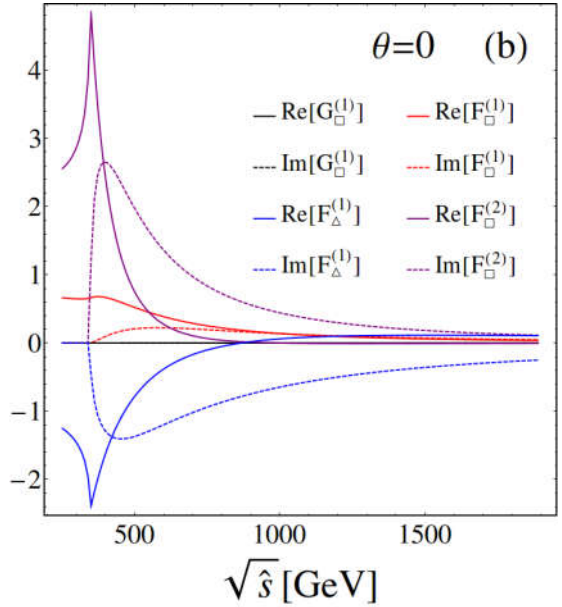


J_z=0,2 $\quad d^0_{0,0}, d^1_{0,0}, d^2_{0,0}, d^2_{2,0}$

J_z=0 $\quad d^0_{0,0}$

$$\mathcal{M}_{hh} = -\frac{\alpha_s \hat{s}\delta^{ab}}{4\pi v^2}\epsilon^a_\mu(p_1)\epsilon^b_\nu(p_2)\left\{\left[c_t^2 F_\square + \tilde{c}_t^2 F_\square^{(1)} + \frac{3m_h^2}{\hat{s}-m_h^2}c_{3h}\left(c_t F_\Delta + \frac{2}{3}c_g\right) + \frac{2}{3}c_g + c_{2t}F_\Delta\right]A^{\mu\nu}\right.$$
$$\left. + \left(c_t^2 G_\square + \tilde{c}_t^2 G_\square^{(1)}\right)B^{\mu\nu} - \left[c_t\tilde{c}_t F_\square^{(2)} + \frac{3m_h^2}{\hat{s}-m_h^2}c_{3h}\left(\tilde{c}_t F_\Delta^{(1)} + \frac{2}{3}\tilde{c}_g\right) + \frac{2}{3}\tilde{c}_g + \tilde{c}_{2t}F_\Delta^{(1)}\right]C^{\mu\nu}\right\}$$





$$C^{\mu\nu} = \frac{p_1^\rho p_2^\sigma}{p_1\, p_2}\varepsilon^{\mu\nu\rho\sigma}$$

LET for $\sqrt{\hat{s}} \ll m_t$ but <u>effective</u> around the threshold $\sqrt{\hat{s}} \sim 2m_h$:

$$F_\square \to -\frac{2}{3}, G_\square \to 0, F_\Delta \to \frac{2}{3}$$
$$F_\square^{(1)} \to \frac{2}{3}, F_\square^{(2)} \to 2,$$
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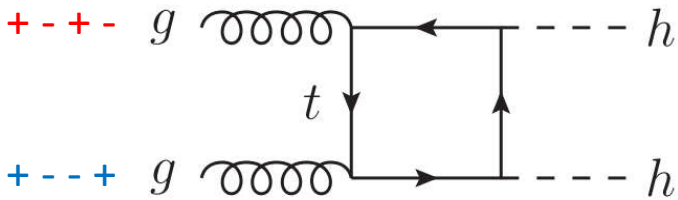
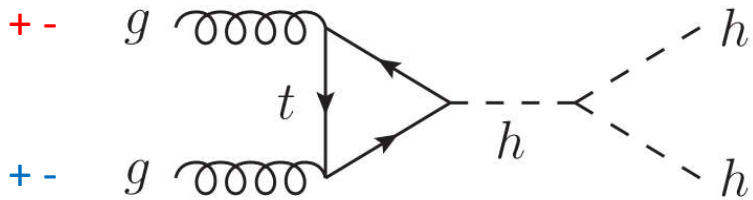
S. Dawson, I. Low, et. al.

Partial wave analysis





J_z=0,2 $\quad d^0_{0,0}, d^1_{0,0}, d^2_{0,0}, d^2_{2,0}$

J_z=0 $\quad d^0_{0,0}$

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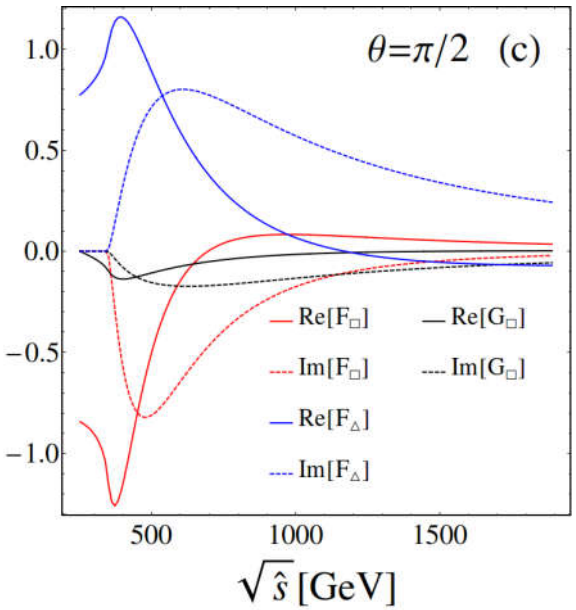
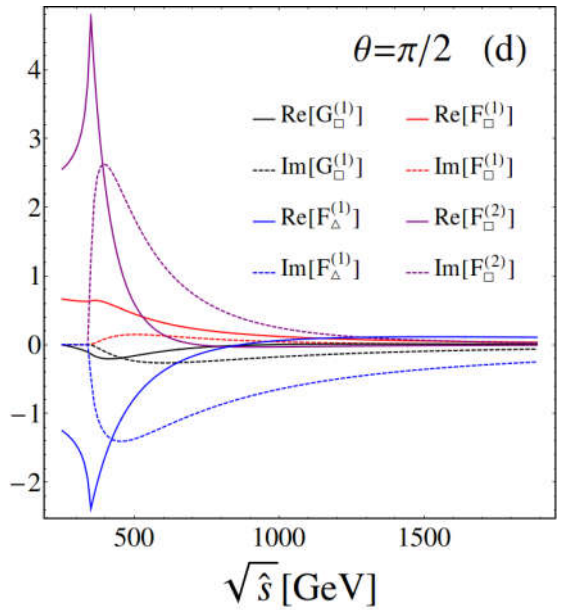
$$\left. + \left(c_t^2 G_\square + \tilde{c}_t^2 G_\square^{(1)}\right)B^{\mu\nu} - \left[c_t\tilde{c}_t F_\square^{(2)} + \frac{3m_h^2}{\hat{s}-m_h^2}c_{3h}\left(\tilde{c}_t F_\Delta^{(1)} + \frac{2}{3}\tilde{c}_g\right) + \frac{2}{3}\tilde{c}_g + \tilde{c}_{2t}F_\Delta^{(1)}\right]C^{\mu\nu}\right\}$$





$$C^{\mu\nu} = \frac{p_1^\rho p_2^\sigma}{p_1\, p_2}\varepsilon^{\mu\nu\rho\sigma}$$

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$$G_\square^{(1)} \to 0, F_\Delta^{(1)} \to -1$$

S. Dawson, I. Low, et. al.

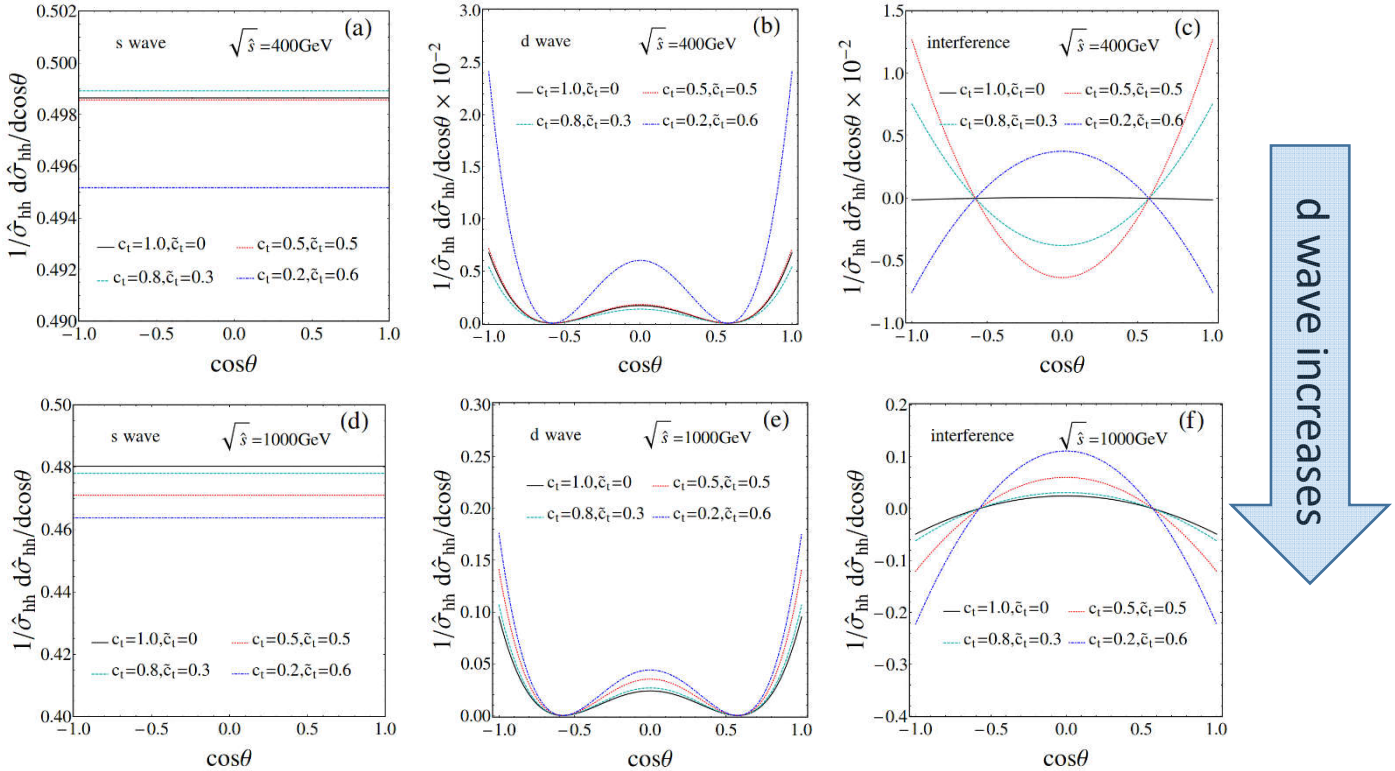
Partial wave analysis

- The $gg \to hh$ is dominated by s wave?
- Yes!

$$\mathcal{M}_{hh} = \sum_{\ell=0,2} \mathcal{M}_\ell(\hat{s}) P_\ell(\cos\theta)$$

$\ell = 0$, s wave, $\ell = 2$, d wave

$$\frac{d\hat{\sigma}_{hh}}{d\cos\theta} = \hat{\sigma}_0(\hat{s}) + \hat{\sigma}_2(\hat{s}) P_2(\cos\theta)^2 + \hat{\sigma}_{\text{int}}(\hat{s}) P_2(\cos\theta)$$



d wave increases

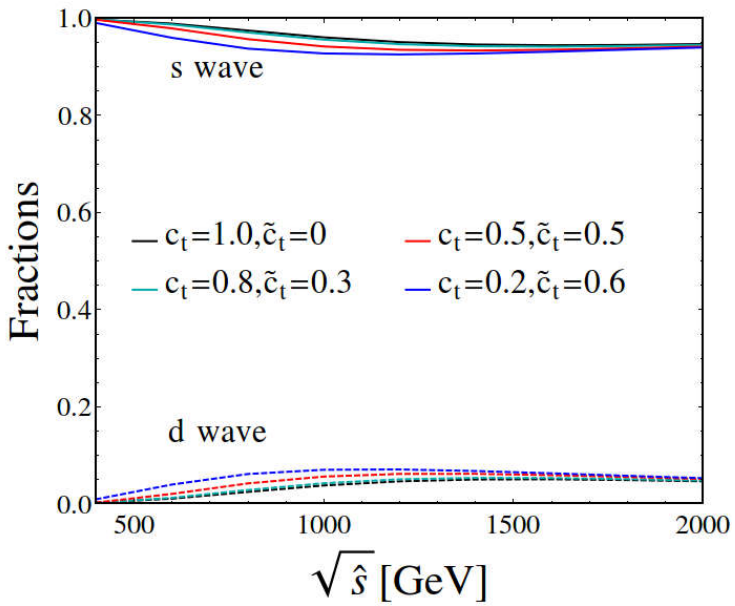
Partial wave analysis

- The $gg \to hh$ is dominated by s wave?
- Yes!

$$\mathcal{M}_{hh} = \sum_{\ell=0,2} \mathcal{M}_\ell(\hat{s}) P_\ell(\cos\theta)$$

$\ell = 0$, s wave, $\ell = 2$, d wave

$$\int d\cos\theta \frac{d\hat{\sigma}_{hh}}{d\cos\theta} = \int d\cos\theta \, [\hat{\sigma}_0(\hat{s}) + \hat{\sigma}_2(\hat{s}) P_2(\cos\theta)^2]$$



The d-wave contribution is at most 10%

Cut efficiency function

- The $gg \to hh$ is dominated by s wave
- So what?
- We consider $gg \to hh \to b\bar{b}\gamma\gamma$. Owing to the (pseudo)scalar feature of the Higgs boson, there is no spin correlation among the initial and final state particles, thus $p_T^b, p_T^\gamma, \eta_b, \eta_\gamma$ mainly depend on m_{hh}
- Therefore, the cut efficiency is insensitive to the Higgs effective couplings

$$\Rightarrow \frac{d\sigma_{\text{cut}}}{dm_{hh}} = \frac{d\sigma}{dm_{hh}} \times \boldsymbol{A(m_{hh})} \qquad \sigma_{\text{cut}} = \int dm_{hh} \frac{d\sigma}{dm_{hh}} \times \boldsymbol{A(m_{hh})}$$

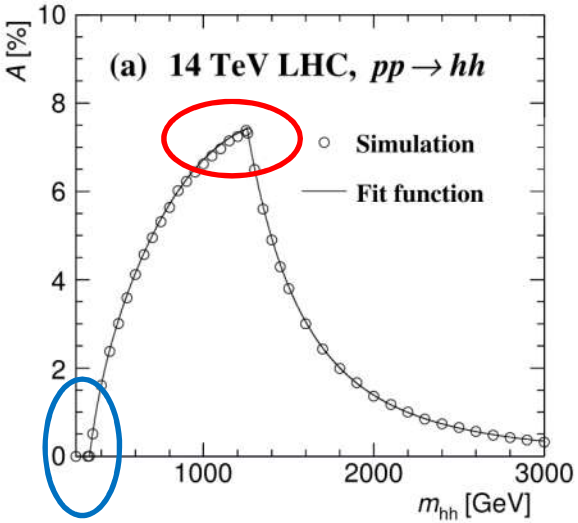
$\boldsymbol{A(m_{hh})}$: cut efficiency function, which can be derived analytically with the parameter obtained by fitting

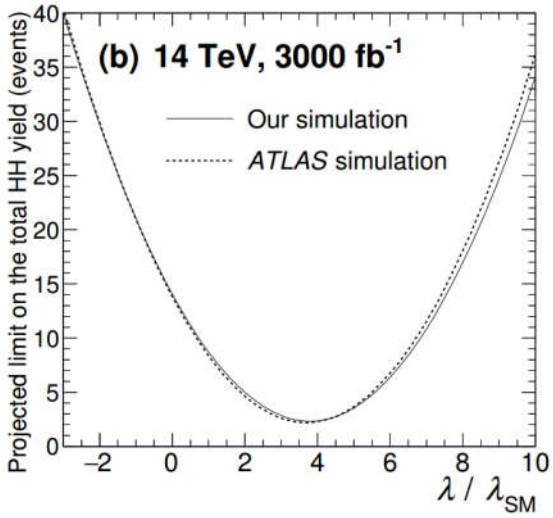
- Does this method work? Yes!

Cut efficiency function

- At the 14 TeV LHC, ATL-PHYS-PUB-2014-019

$$p_T^{b_1} > 40 \text{ GeV}, \; p_T^{b_2} > 25 \text{ GeV}, \; |\eta^b| < 2.5,$$
$$p_T^{\gamma} > 30 \text{ GeV}, \; |\eta^{\gamma}| < 1.37 \text{ or } 1.52 < |\eta^{\gamma}| < 2.37,$$
$$\Delta R_0 < \Delta R_{bb,\gamma\gamma} < 2.0 \;, \; \Delta R_{b\gamma} > \Delta R_0, \quad \Delta R_0 = 0.4 \;,$$
$$100 \text{ GeV} < m_{bb} < 150 \text{ GeV}, \; p_T^{bb} > 110 \text{ GeV},$$
$$123 \text{ GeV} < m_{\gamma\gamma} < 128 \text{ GeV}, \; p_T^{\gamma\gamma} > 110 \text{ GeV}$$





- Similar at the 100 TeV pp-collider

m_{hh} distribution

$$\mathcal{M}_{hh} = -\frac{\alpha_s \hat{s}\delta^{ab}}{4\pi v^2}\epsilon^a_\mu(p_1)\epsilon^b_\nu(p_2)\left\{\left[c_t^2 F_\square + \tilde{c}_t^2 F_\square^{(1)} + \frac{3m_h^2}{\hat{s}-m_h^2}c_{3h}\left(c_t F_\Delta + \frac{2}{3}c_g\right) + \frac{2}{3}c_g + c_{2t}F_\Delta\right]A^{\mu\nu}\right.$$
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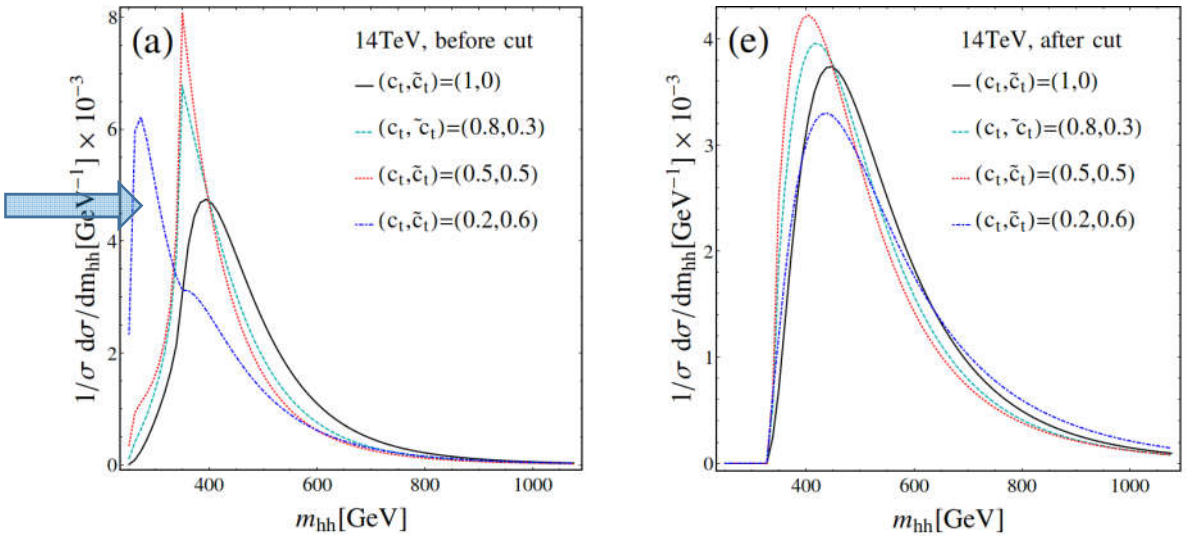
- LET:

$$F_\square \to -\frac{2}{3}, G_\square \to \mathcal{O}\left(\frac{\hat{s}}{m_t^2}\right), F_\Delta \to \frac{2}{3}$$
$$F_\square^{(1)} \to \frac{2}{3}, F_\square^{(2)} \to 2, G_\square^{(1)} \to \mathcal{O}\left(\frac{\hat{s}}{m_t^2}\right), F_\Delta^{(1)} \to -1$$



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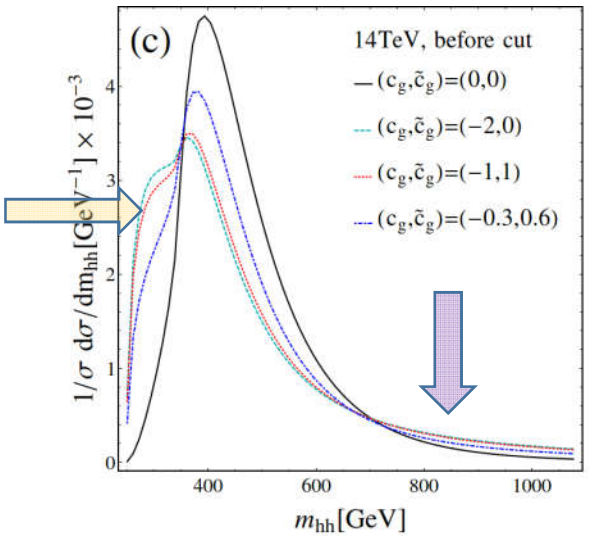
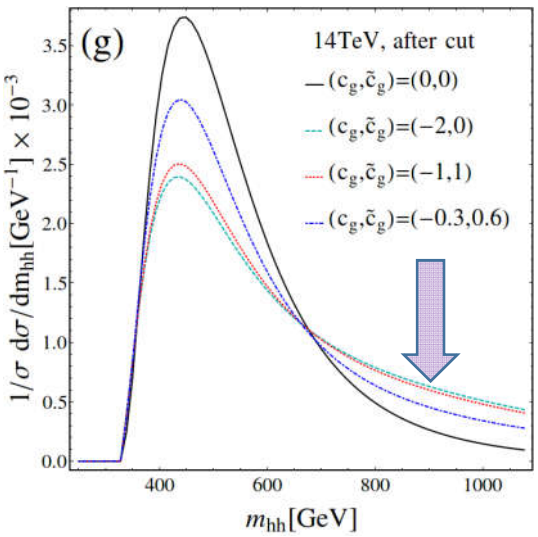
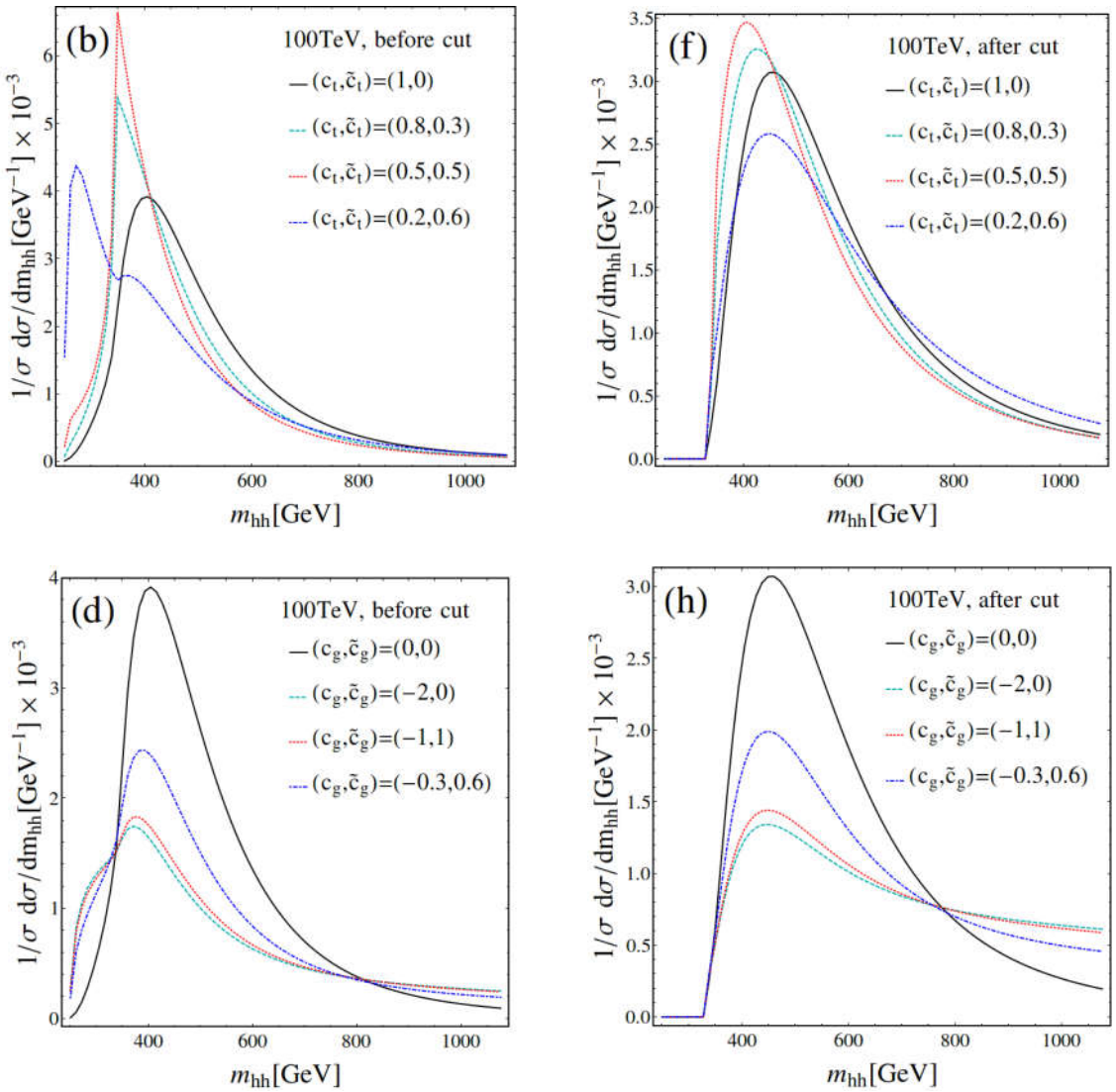




m_{hh} distribution



Cross section

$$\frac{\sigma(pp \to hh \to b\bar{b}\gamma\gamma)}{\sigma(pp \to hh \to b\bar{b}\gamma\gamma)} = \mu_{hh} \times \mu_{bb} \times \mu_{\gamma\gamma}$$

- $\mu_{hh} = \frac{\sigma_{hh}}{\sigma_{hh}^{\mathrm{SM}}}$

$$\begin{aligned}\mu_{hh} = {} & A_1 c_{3h}^2 c_g^2 + A_2 c_{3h}^2 c_g c_t + A_3 c_{3h}^2 c_t^2 + A_4 c_{3h} c_g^2 + A_5 c_{3h} c_g c_t^2 + A_6 c_{3h} c_g c_t + A_7 c_{3h} c_g \tilde{c}_t^2 \\ & + A_8 c_{3h} c_t^3 + A_9 c_{3h} c_t \tilde{c}_t^2 + A_{10} c_g^2 + A_{11} c_g c_t^2 + A_{12} c_g \tilde{c}_t^2 + A_{13} c_t^4 + A_{14} c_t^2 \tilde{c}_t^2 + A_{15} \tilde{c}_t^4 \\ & + A_{16} c_{3h}^2 \tilde{c}_g^2 + A_{17} c_{3h}^2 \tilde{c}_g \tilde{c}_t + A_{18} c_{3h}^2 \tilde{c}_t^2 + A_{19} c_{3h} \tilde{c}_g^2 + A_{20} c_{3h} \tilde{c}_g c_t \tilde{c}_t + A_{21} c_{3h} \tilde{c}_g \tilde{c}_t \\ & + A_{22} \tilde{c}_g^2 + A_{23} \tilde{c}_g c_t \tilde{c}_t + A_{24} c_{2t}^2 + A_{25} c_{2t} c_{3h} c_g + A_{26} c_{2t} c_{3h} c_t + A_{27} c_{2t} c_g + A_{28} c_{2t} c_t^2 \\ & + A_{29} c_{2t} \tilde{c}_t^2 + A_{30} c_t \tilde{c}_t \tilde{c}_{2t} + A_{31} c_{3h} \tilde{c}_t \tilde{c}_{2t} + A_{32} c_{3h} \tilde{c}_g \tilde{c}_{2t} + A_{33} \tilde{c}_{2t}^2 + A_{34} \tilde{c}_g \tilde{c}_{2t}.\end{aligned}$$

- μ_{hh} has no dependence on odd-number-power $\tilde{c}_i$
- μ_{hh} have sensitivities on $c_t, \tilde{c}_t, c_g, \tilde{c}_g, c_{2t}, \tilde{c}_{2t}, c_{3h}$

$$\kappa_g^2 = \frac{\left|c_t F_\Delta + \frac{2}{3} c_g\right|^2 + \left|\tilde{c}_t F_\Delta^{(1)} + \frac{2}{3} \tilde{c}_g\right|^2}{|F_\Delta|^2}$$

$$\kappa_\gamma^2 = \frac{\left|F_1(\tau_W) + \frac{4}{3} c_t F_\Delta\right|^2 + \left|\frac{4}{3} \tilde{c}_t F_\Delta^{(1)}\right|^2}{\left|F_1(\tau_W) + \frac{4}{3} F_\Delta\right|^2}$$

Cross section

$$\frac{\sigma(pp \to hh \to b\bar{b}\gamma\gamma)}{\sigma(pp \to hh \to b\bar{b}\gamma\gamma)} = \mu_{hh} \times \mu_{bb} \times \mu_{\gamma\gamma}$$

partial width to diphoton

$$\mu_f \equiv \mu_{bb} \times \mu_{\gamma\gamma} = \frac{\kappa_\gamma^2}{\left[1 + (\kappa_g^2 - 1)\mathrm{BR}_g^{\mathrm{SM}} + (\kappa_\gamma^2 - 1)\mathrm{BR}_\gamma^{\mathrm{SM}}\right]^2}$$

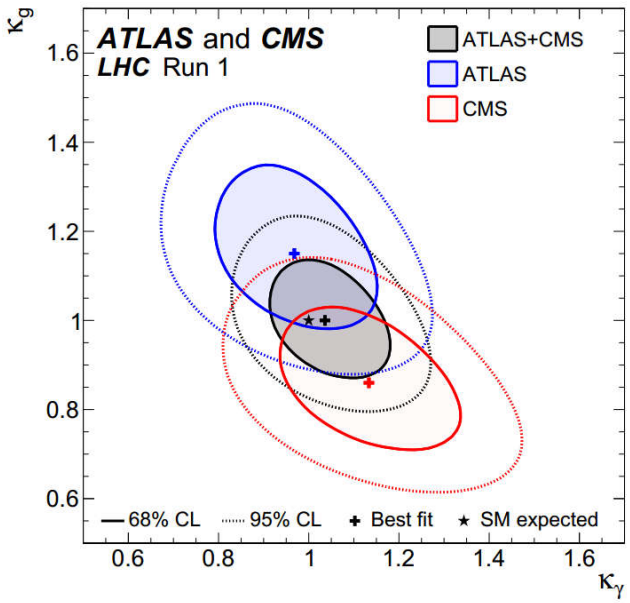
$\mathrm{BR}_g^{\mathrm{SM}}$=8.187%
$\mathrm{BR}_\gamma^{\mathrm{SM}}$=0.227%

total width

- μ_f can be modified significantly with a large κ_g
- Since $F_\Delta \to \frac{2}{3}, F_\Delta^{(1)} \to -1$ and

$$\kappa_g^2 = \frac{\left|c_t F_\Delta + \frac{2}{3} c_g\right|^2 + \left|\tilde{c}_t F_\Delta^{(1)} + \frac{2}{3}\tilde{c}_g\right|^2}{|F_\Delta|^2}$$

large κ_g means large $c_g, |\tilde{c}_g|$



ATLAS+CMS JHEP 1608 (2016) 045

Sensitivities to Higgs effective couplings

- We follow the analysis at the HL-LHC by *the ATLAS Collaborarion* and the analysis at the 100 TeV pp-collider in *Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies*

ATL-PHYS-PUB-2014-019
Contino et al., 1606.09408

- We use the cut efficiency functions $A(m_{hh})$ to mimic the experimental cuts and detector effects

$$\frac{d\sigma_{\text{cut}}}{dm_{hh}} = \frac{d\sigma}{dm_{hh}} \times \boldsymbol{A(m_{hh})} \qquad \sigma_{\text{cut}} = \int dm_{hh} \frac{d\sigma}{dm_{hh}} \times \boldsymbol{A(m_{hh})}$$

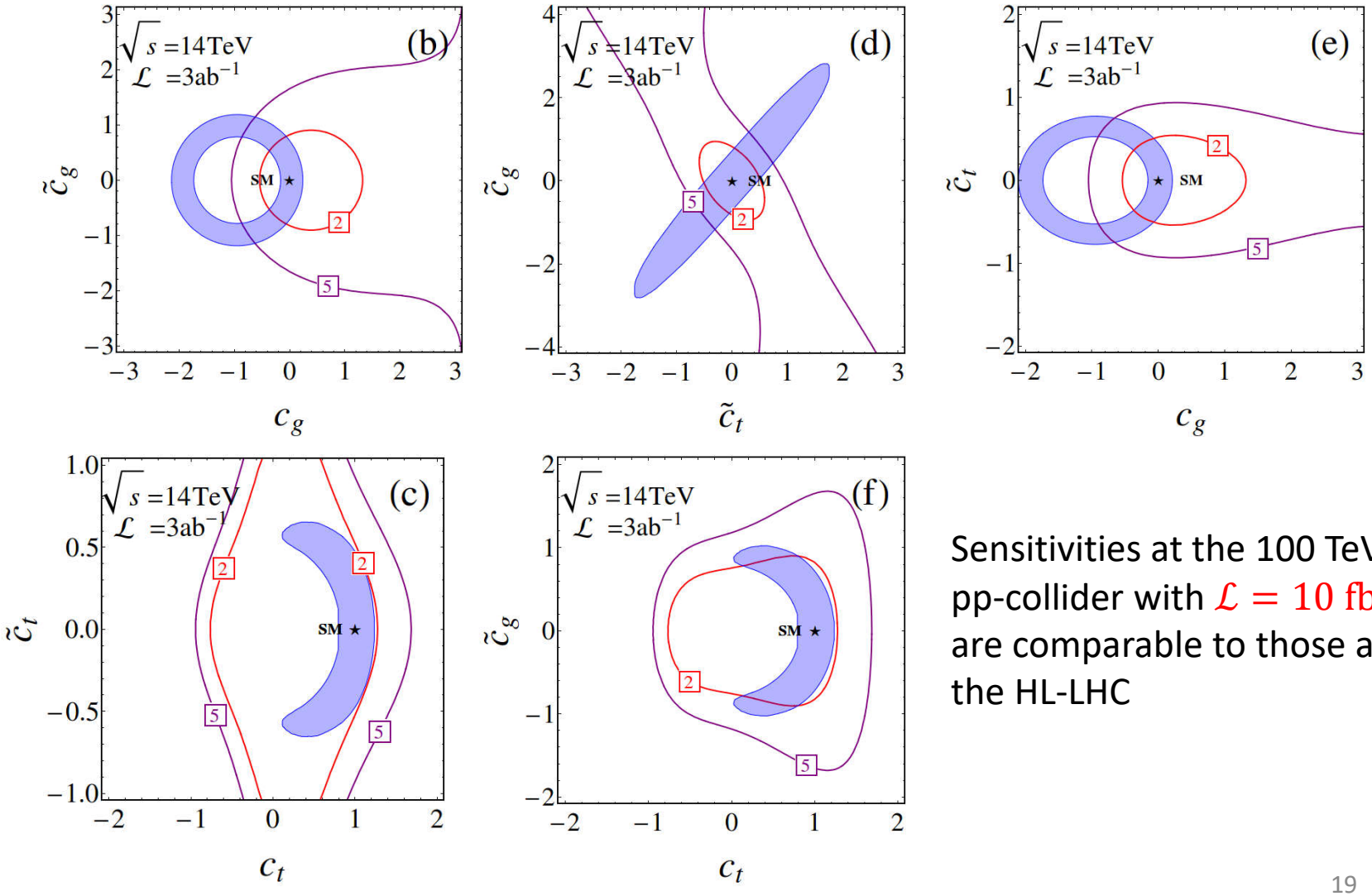
- We can extract the sensitivities on the Higgs effective couplings from the exclusion limit/discovery potential of (non-SM) double Higgs production
- On the other hand, we have included the constraints on the Higgs effective couplings from the measurements of κ_g and κ_γ (and EDMs)

$$|\tilde{c}_t| < 0.01, |\tilde{c}_g| < 0.01$$

J. Brod, U. Haisch, J. Zupan, JHEP 11, 180 (2013), 1310.1385
Y. T. Chien, V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti (2015)

Sensitivities to Higgs effective couplings

- 2σ exclusion and 5σ discovery of double Higgs production

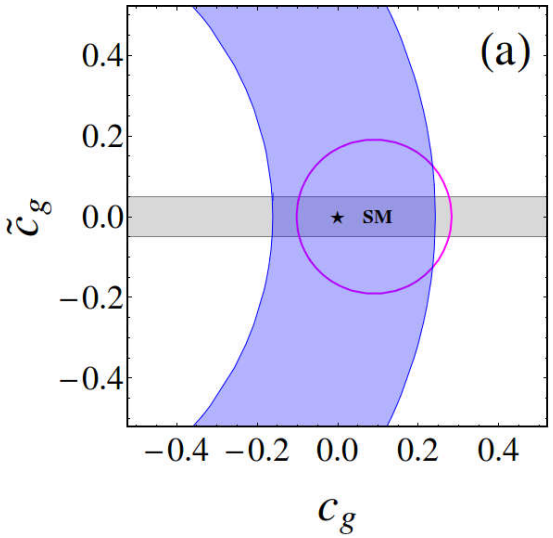


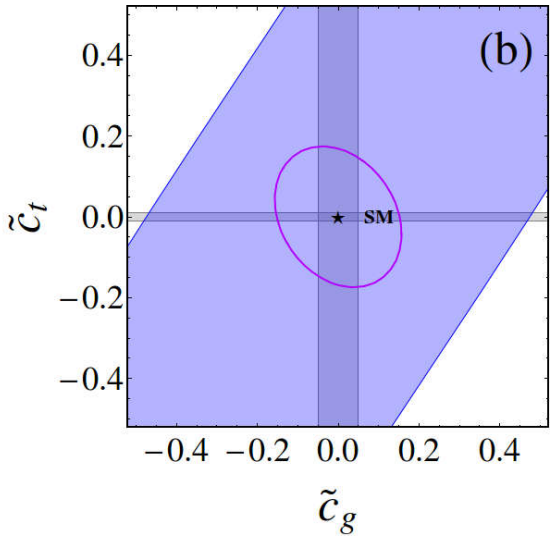
Sensitivities at the 100 TeV pp-collider with $\mathcal{L} = 10\ \mathrm{fb}^{-1}$ are comparable to those at the HL-LHC

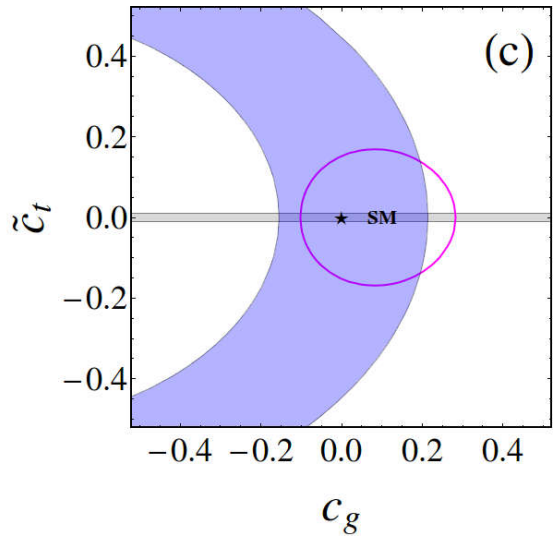
$\mathcal{L} = 30\text{ab}^{-1}$

Sensitivities to Higgs effective couplings

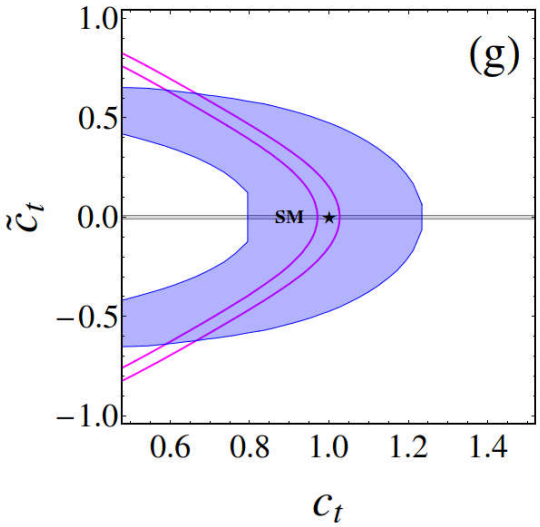
5σ discovery of NP, where the SM hh is treated as bkg

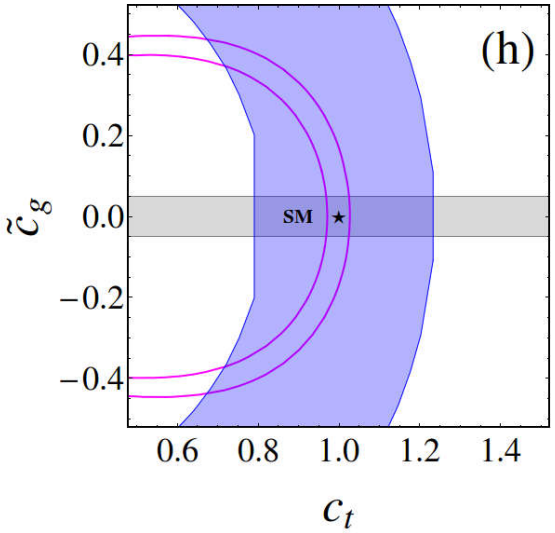






$3.7c_g^2 - 0.29c_g + 3.7\tilde{c}_g^2 \geq 0.1$ $3.7\tilde{c}_g^2 + 1.4\tilde{c}_g\tilde{c}_t + 4.5\tilde{c}_t^2 \geq 0.1$ $3.7c_g^2 - 0.29c_g + 4.5\tilde{c}_t^2 \geq 0.1$





Additional CP-violating interaction has to be included to respect the strict EDM constraints if double Higgs production in NP models is discovered outside the grey region

Summary

- $gg \to hh$ with CP violation is parametrized in the EFT approach
- $gg \to hh$ is dominated by s wave
- We use the cut efficiency function to mimic the experimental cuts and detector effects at the HL-LHC and the 100 TeV pp-collider
- We investigate the sensitivities to the Higgs effective couplings, especially we provide the analytical expressions corresponding to the 5σ discovery of NP

Backup slides

Higgs self-coupling in 2HDM

- Two-Higgs-doublet model: in the decoupling limit $\cos(\beta - \alpha) \to 0$

$$\boxed{\lambda_3 = \frac{3m_h^2}{v}\left(1 + \cos^2(\beta - \alpha)\left(\frac{3}{2} - \frac{2M^2}{m_h^2}\right)\right)} \qquad M^2 = \frac{m_3^2}{s_\beta c_\beta}$$

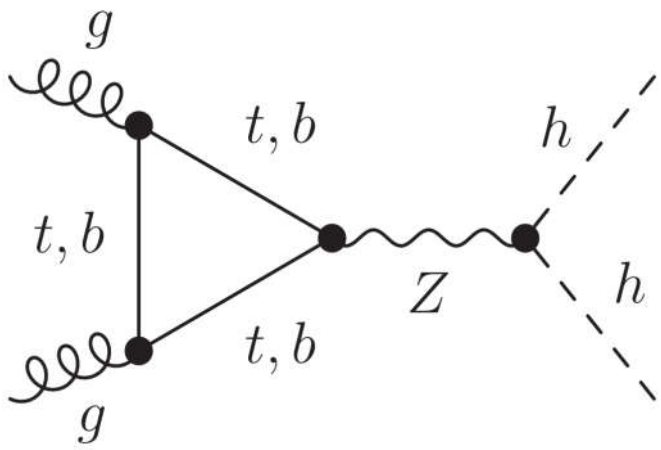
V. Barger, L. L. Everett et al, PRD 90 (2014) 095006
S. Kanemura, Y. Okada, E. Senaha, C.-P. Yuan, Phys.Rev. D70, 115002 (2004)

$\boldsymbol{gg \to hh}$: spin 1

- For a CP-mixed Higgs boson

$$\mathcal{O}_4^{hhZ} = h(\partial_\mu h)Z^\mu$$

C. Englert, K. Nordström, K. Sakurai, M. Spannowsky, 1611.05445



It originates from a dimension-8 operator for a linearly-realized model

M.B. Gavela, J. Gonzalez-Fraile, M.C. Gonzalez-Garcia, L. Merlo, S. Rigolin, J. Yepes, JHEP 1410 (2014) 044