Double Higgs production at the 14 TeV LHC and 100 TeV hadron colliders

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Outline

- Motivations
- Effective Lagrangian
- Sensitivity on NP from Double Higgs production
- Conclusions

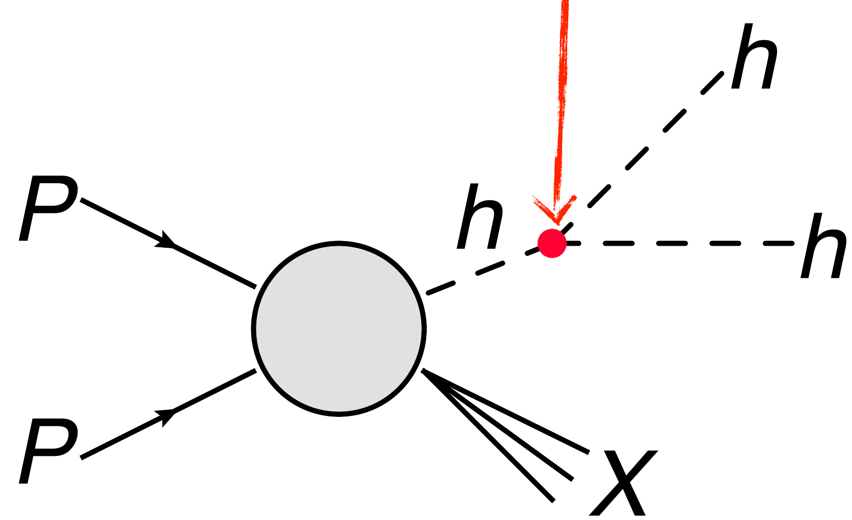
Motivations

- The Higgs potential is still undetermined.

$$m_h,\ v \quad \not\Longrightarrow \quad V(H)$$

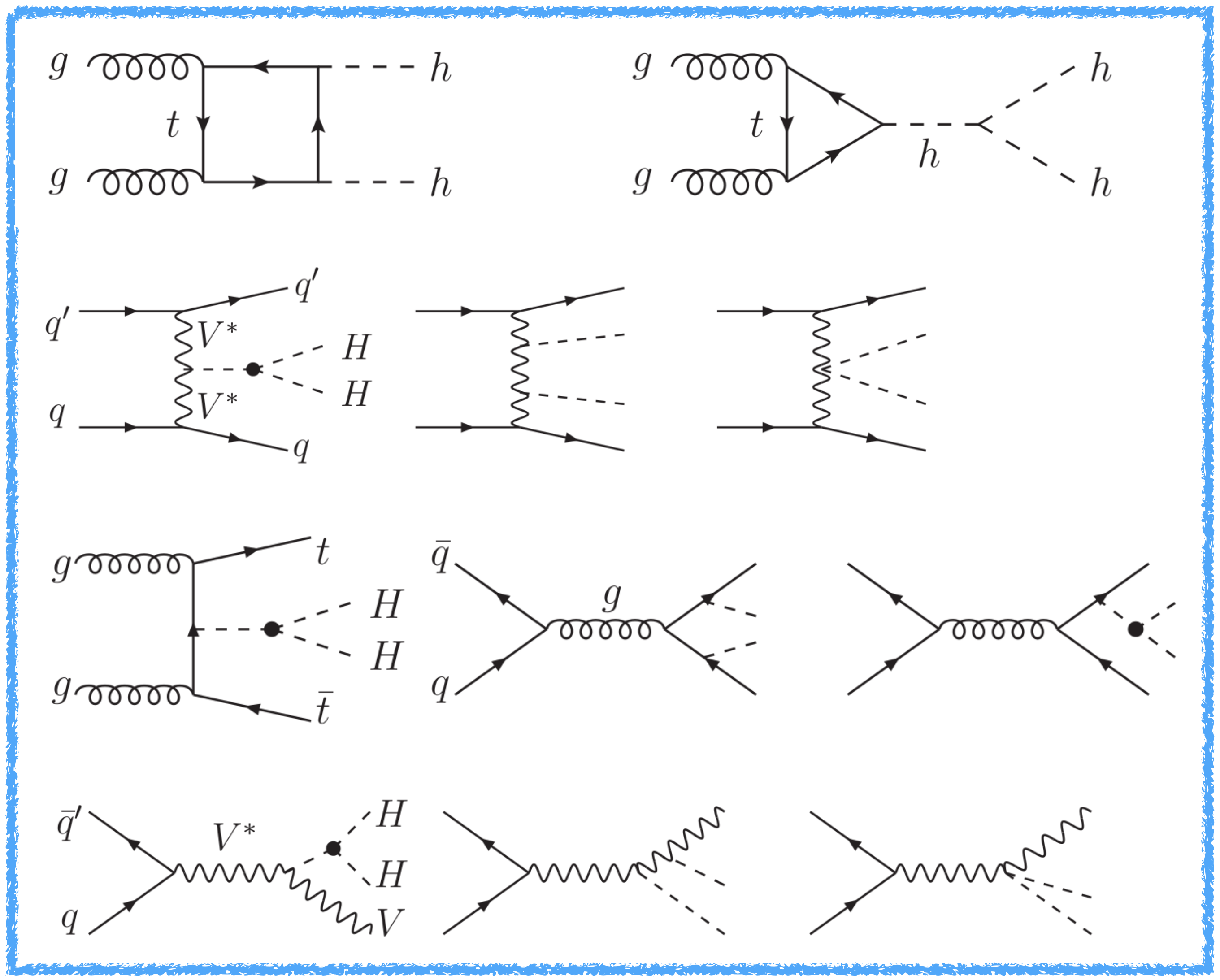
$$V'(H) = \mu^2|H|^2 + \lambda_4|H|^4 + \frac{\lambda_6}{\Lambda^2}|H|^6$$ degeneracy!

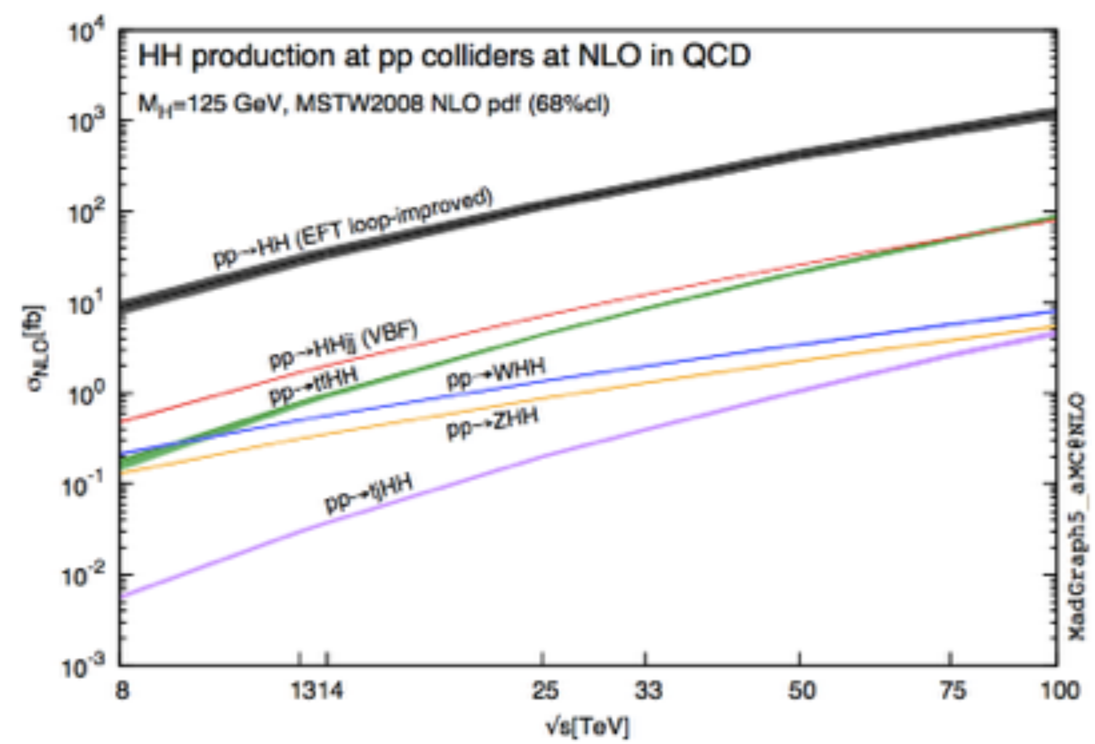
- We should measure the Higgs-trilinear coupling to distinguish the degeneracy of the Higgs potential.



Motivations

- The cross section is very small in the SM, making NP very sensitive.





R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, M. Zaro Phys.Lett. B732 (2014) 142

11.8 fb (8 TeV), 37.95 fb (13 TeV)
45.05 fb (14 TeV), 1749 fb (100 TeV)
LHC Higgs Cross Section Working Group (2016)

Cancellation in the SM!

Motivations

- To motivate why to study the Double Higgs at 100 TeV hadron colliders.

- 14 TeV LHC: $\sigma(gg \to hh) \sim 40 \text{ fb}$
  - ATLAS's result: $S/\sqrt{S+B} \sim 1.2$ @3000 fb^{-1} HL-LHC

    ATL-PHY-PUB-2014-019 (2015).

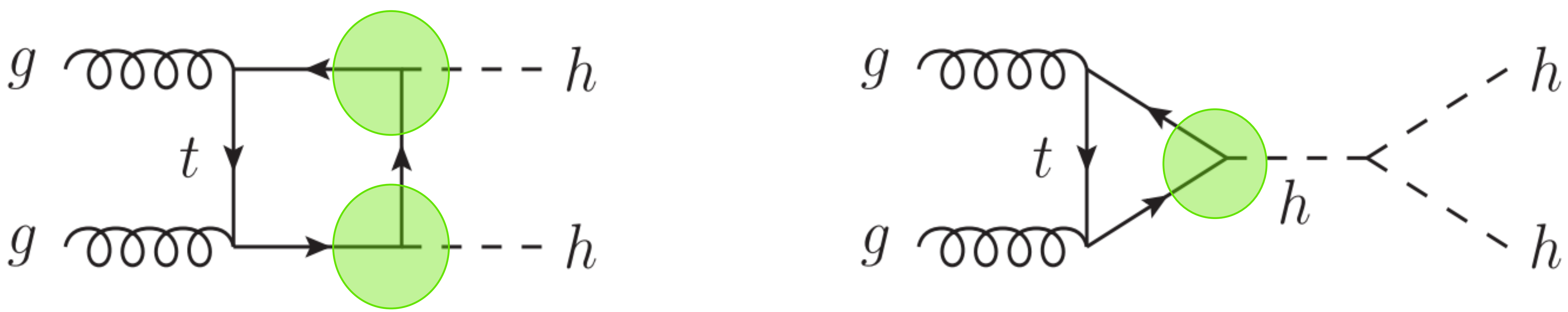
- 100 TeV hadron colliders: $\sigma(gg \to hh) \sim 1700 \text{ fb}$
  - Result: $S/\sqrt{S+B} \sim 61$ @30 ab^{-1} 100 TeV hadron colliders

    R. Contino, et. al, Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies.

  $\Longrightarrow S/\sqrt{S+B} \sim 5$ @200 fb^{-1} 100 TeV hadron colliders

Effective Lagrangian

$$\mathcal{L}_{\rm eff} = -\frac{m_t}{v}\bar{t}(c_t + i\tilde{c}_t\gamma_5)th - \frac{m_t}{v^2}\bar{t}(c_{2t} + i\tilde{c}_{2t}\gamma_5)th^2 + \frac{\alpha_s h}{12\pi v}(c_g G^A_{\mu\nu}G^{\mu\nu}_A + \tilde{c}_g G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A)$$
$$+ \frac{\alpha_s h^2}{24\pi v^2}(c'_g G^A_{\mu\nu}G^{\mu\nu}_A + \tilde{c}'_g G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A) - c_{3h}\frac{m_h^2}{2v}h^3$$



Effective Lagrangian

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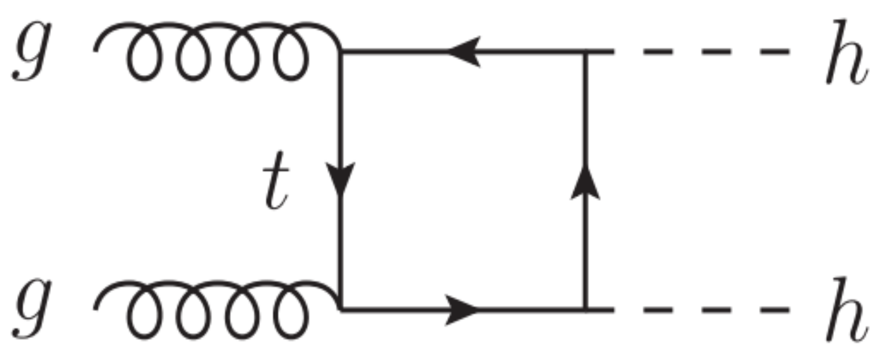

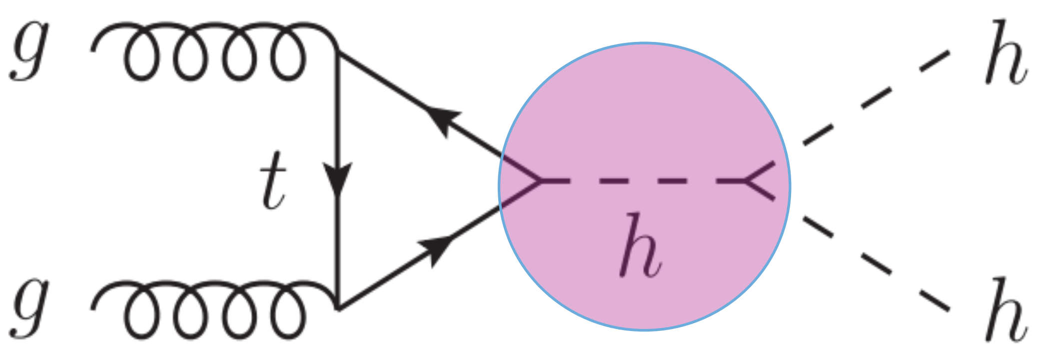

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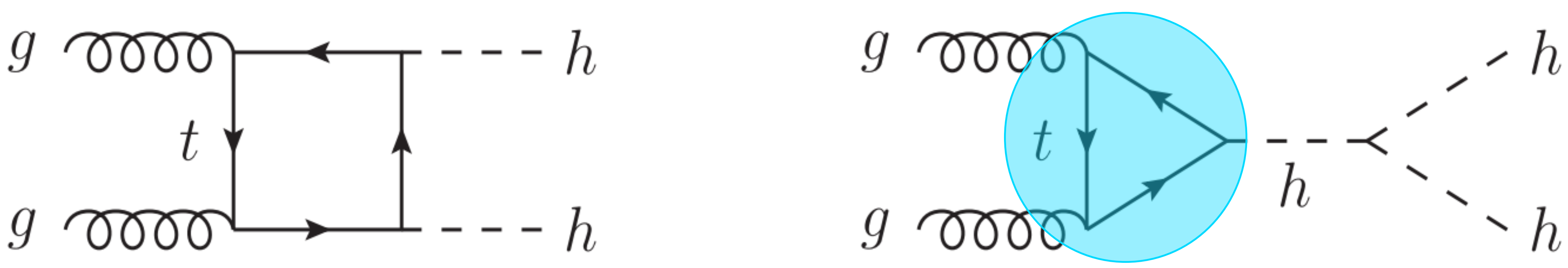

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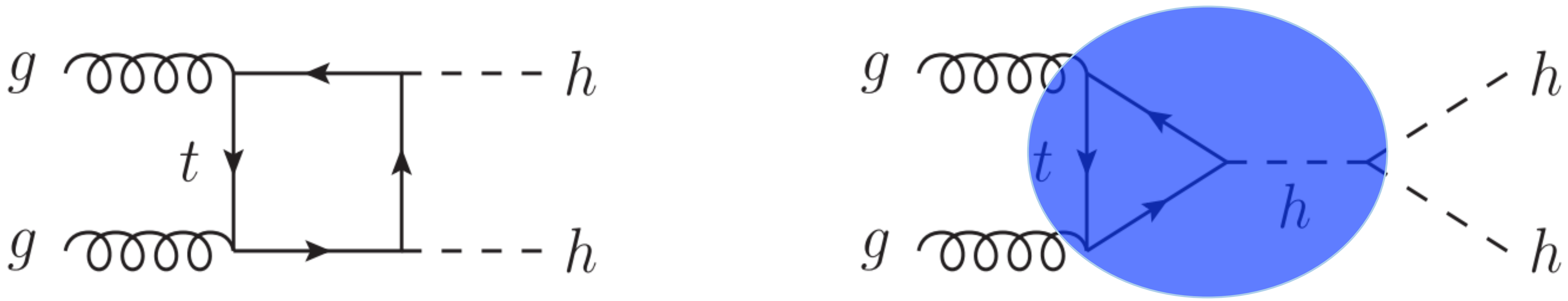

Effective Lagrangian

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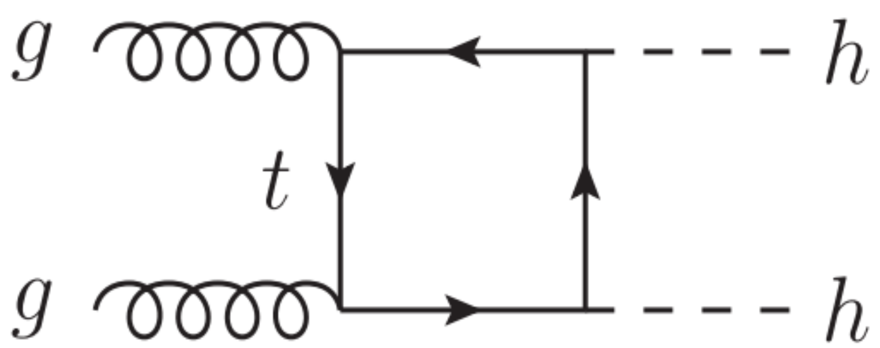

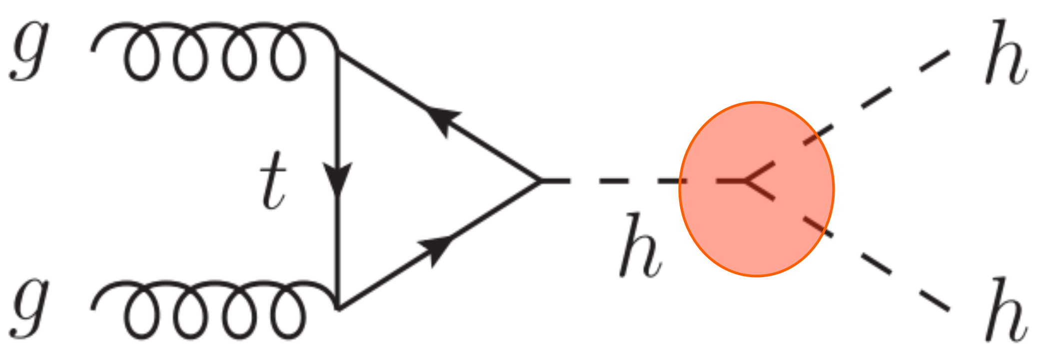

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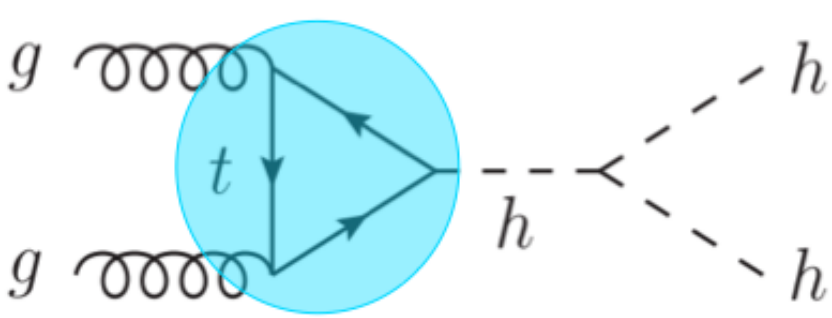
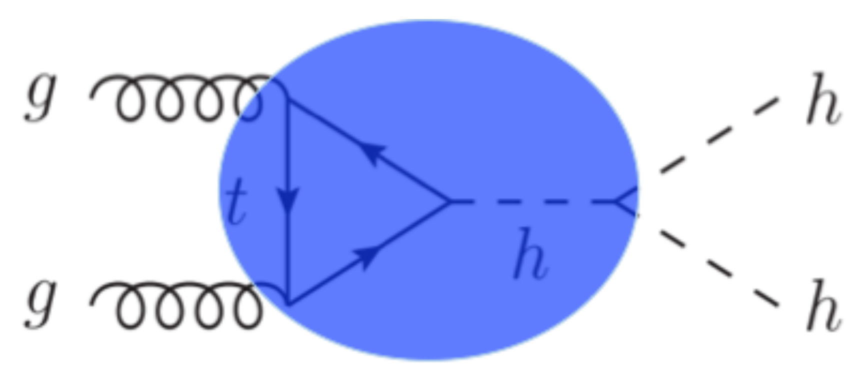
Assumption:

$$\mathcal{O}_{HG} = H^\dagger H G^A_{\mu\nu}G^{\mu\nu}_A$$
$$\tilde{\mathcal{O}}_{HG} = H^\dagger H G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A$$

$$\Rightarrow \quad c'_g = c_g, \qquad \tilde{c}'_g = \tilde{c}_g$$





Sensitivity on NP from Double Higgs production

- Tensor basis expansion

$$\mathcal{M}_{hh} = -\frac{\alpha_s \hat{s}\delta^{ab}}{4\pi v^2}\epsilon_\mu(p_a)\epsilon_\nu(p_b)\Bigg\{ \left[c_t^2 F_\square + \tilde{c}_t^2 F_\square^{(1)} + \frac{3m_H^2}{\hat{s} - m_H^2} c_{3h}\left(c_t F_\triangle + \frac{2}{3}c_g\right) + \frac{2}{3}c_g + c_{2t}F_\triangle\right] A^{\mu\nu}$$

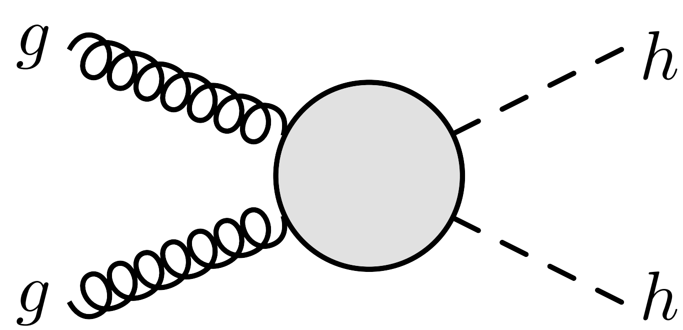
$$+ \left(c_t^2 G_\square + \tilde{c}_t^2 G_\square^{(1)}\right) B^{\mu\nu} - \left[c_t \tilde{c}_t F_\square^{(2)} + \frac{3m_H^2}{\hat{s} - m_H^2}c_{3h}\left(\tilde{c}_t F_\triangle^{(3)} + \frac{2}{3} \tilde{c}_g\right) + \frac{2}{3} \tilde{c}_g + \tilde{c}_{2t} F_\triangle^{(3)}\right] C^{\mu\nu}\Bigg\}$$

$$A^{\mu\nu}B_{\mu\nu} = B^{\mu\nu}C_{\mu\nu} = A^{\mu\nu}C_{\mu\nu} = 0$$

$$\text{CP odd}: \quad C^{\mu\nu}$$

$$\text{CP even}: \quad A^{\mu\nu}, \quad B^{\mu\nu}$$

since gluon has spin 1,



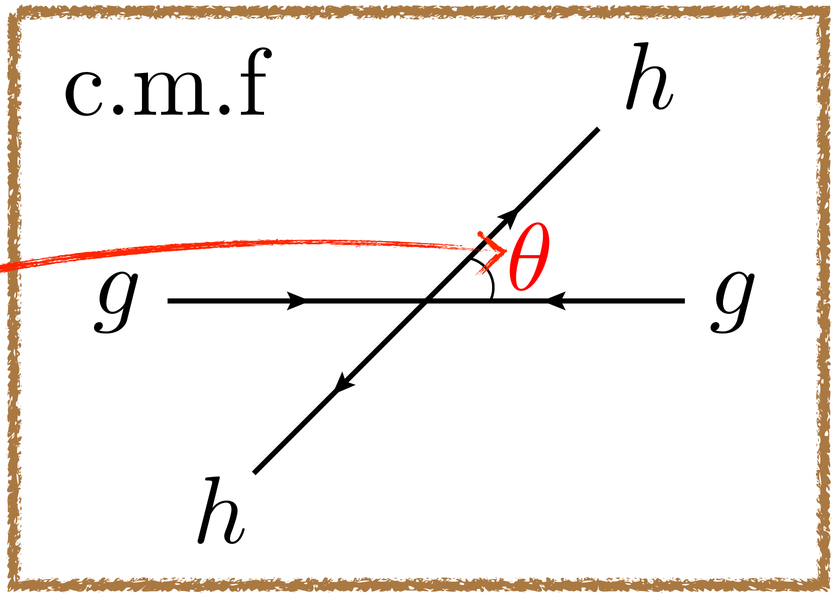
~spin-0 and spin-2

We have to expand the amplitude in the partial wave basis

Sensitivity on NP from Double Higgs production

- Partial-Wave basis expansion

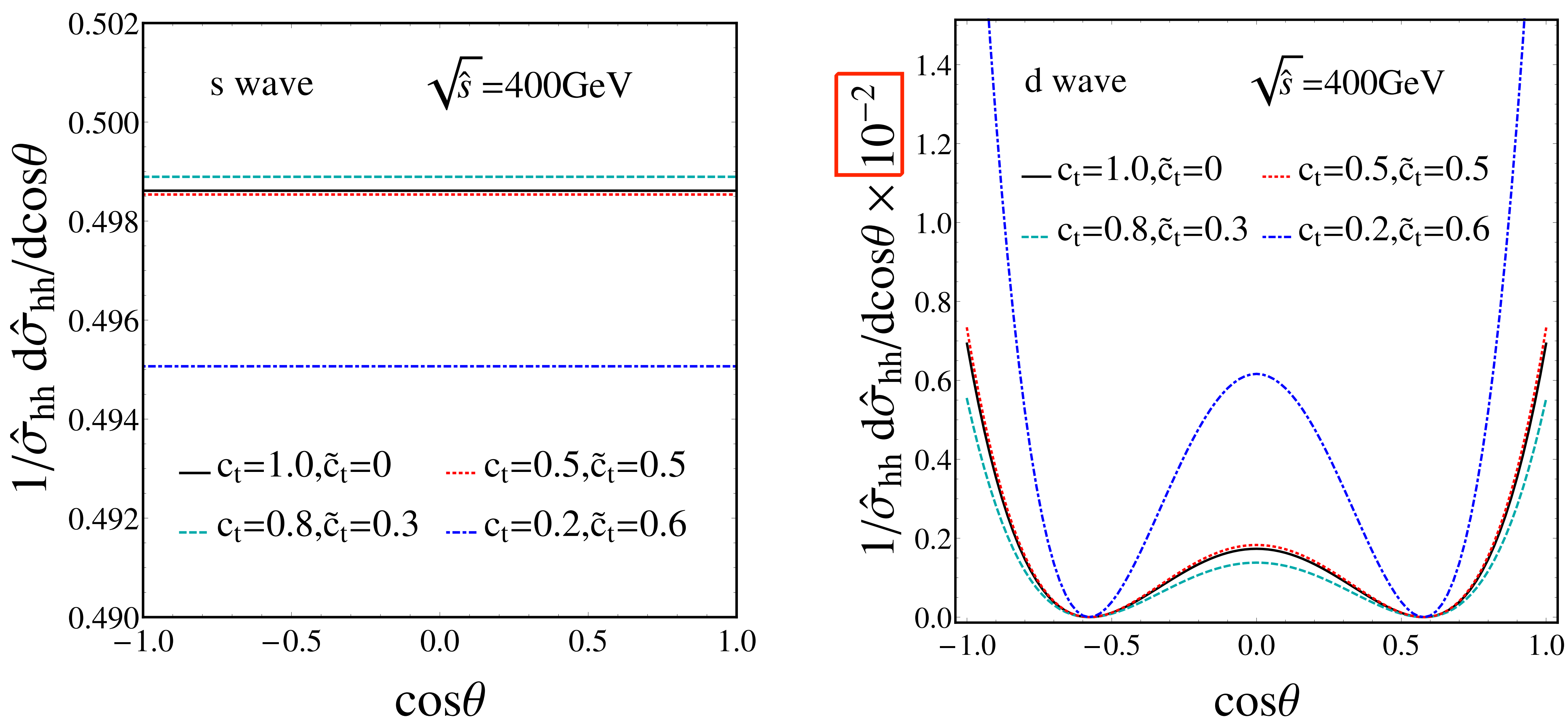
$$\mathcal{M}_{hh}(\hat{s},\theta) = \sum_{l=0,2} \mathcal{M}_l(\hat{s}) P_l(\cos\theta)$$



$$\frac{d\sigma(\hat{s})}{d\cos\theta} = \left|\tilde{\mathcal{M}}_0(\hat{s})\right|^2 P_0(\cos\theta)^2 + \left|\tilde{\mathcal{M}}_2(\hat{s})\right|^2 P_2(\cos\theta)^2$$

s-wave d-wave

Sensitivity on NP from Double Higgs production



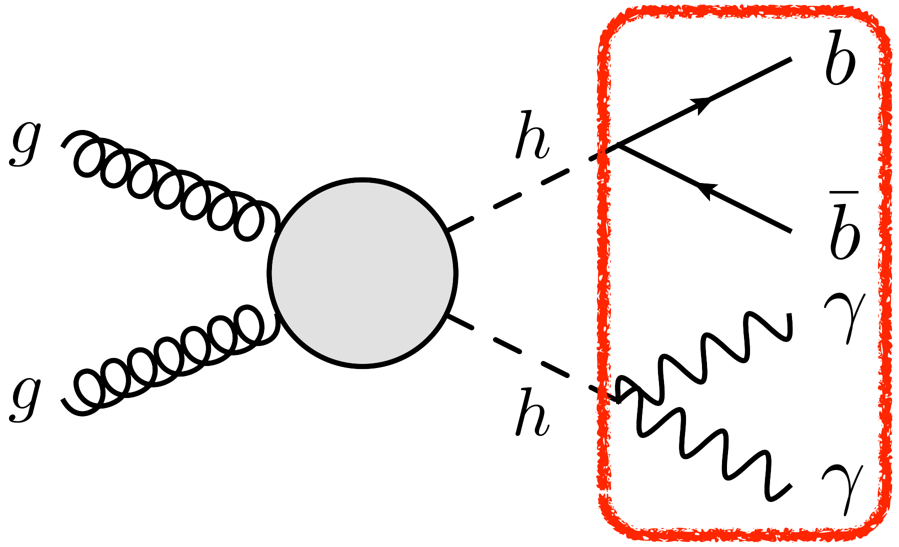
s-wave dominant!

Sensitivity on NP from Double Higgs production

Based on $\mathcal{M}_{hh}(\hat{s},\theta) \approx \mathcal{M}_{hh}(\hat{s})$

- We can use a universal cut efficiency function $A(\hat{s})$ to mimic the simulation on any of the NP signals.

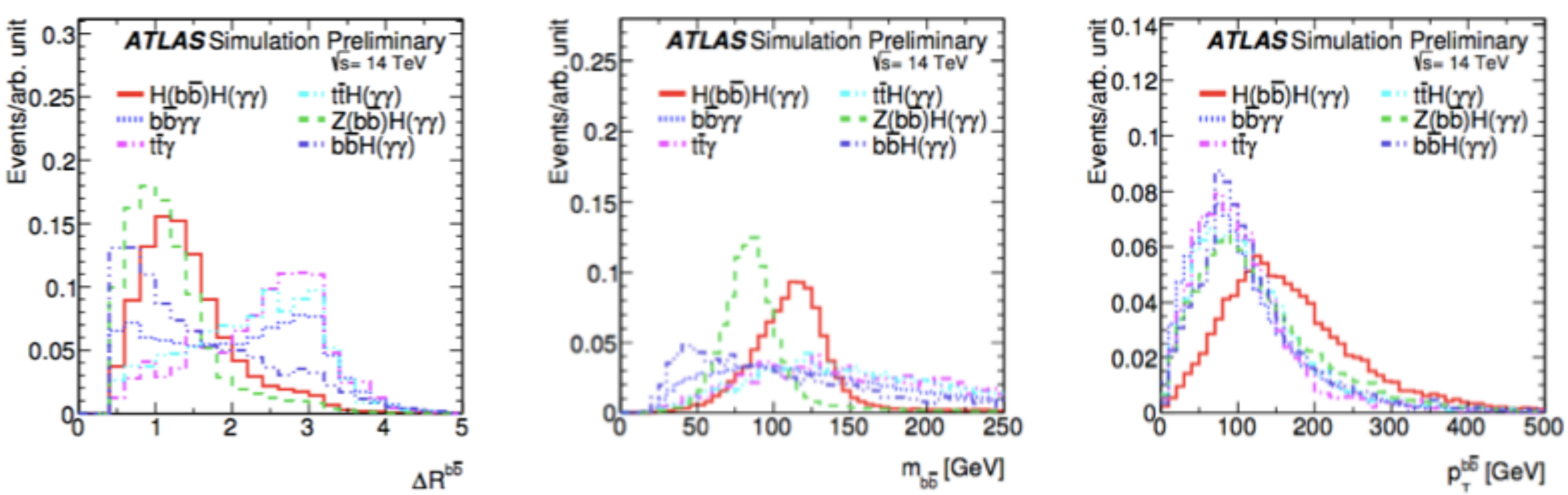
- Previous study:
  - 14 TeV HL-LHC ATL-PHY-PUB-2014-019 (2015).
  - 100 TeV 30 ab^{-1} hadron colliders R. Contino, et. al, Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies.



Sensitivity on NP from Double Higgs production

- 14 TeV HL-LHC ATL-PHY-PUB-2014-019 (2015)
  - Event Selections

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



Sensitivity on NP from Double Higgs production

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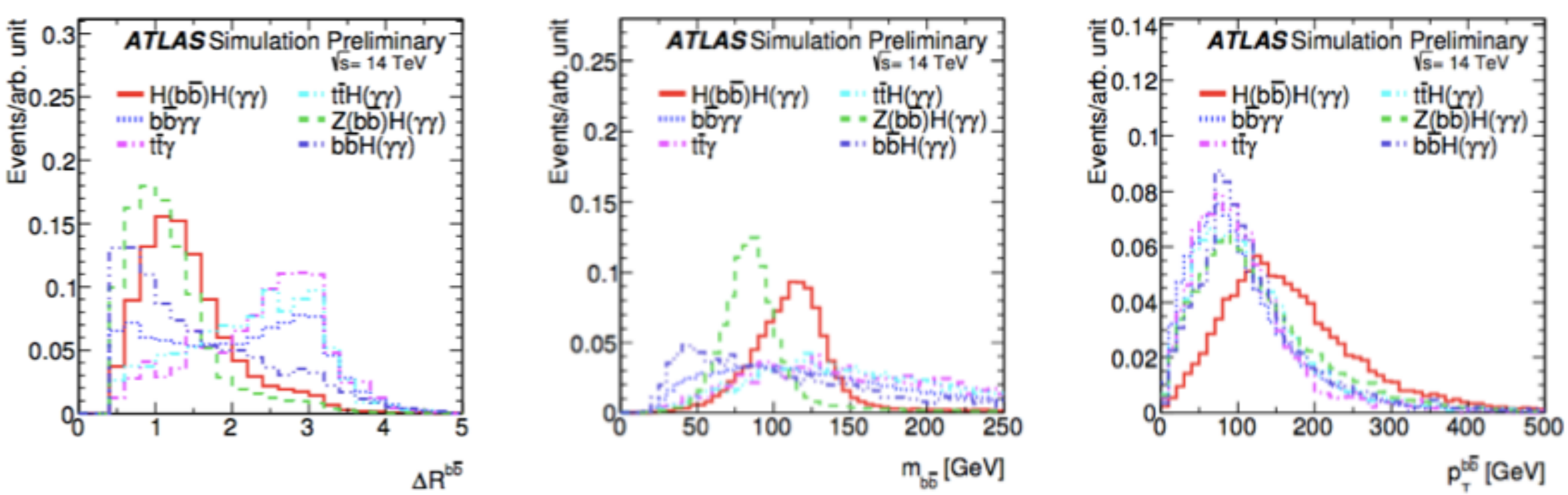
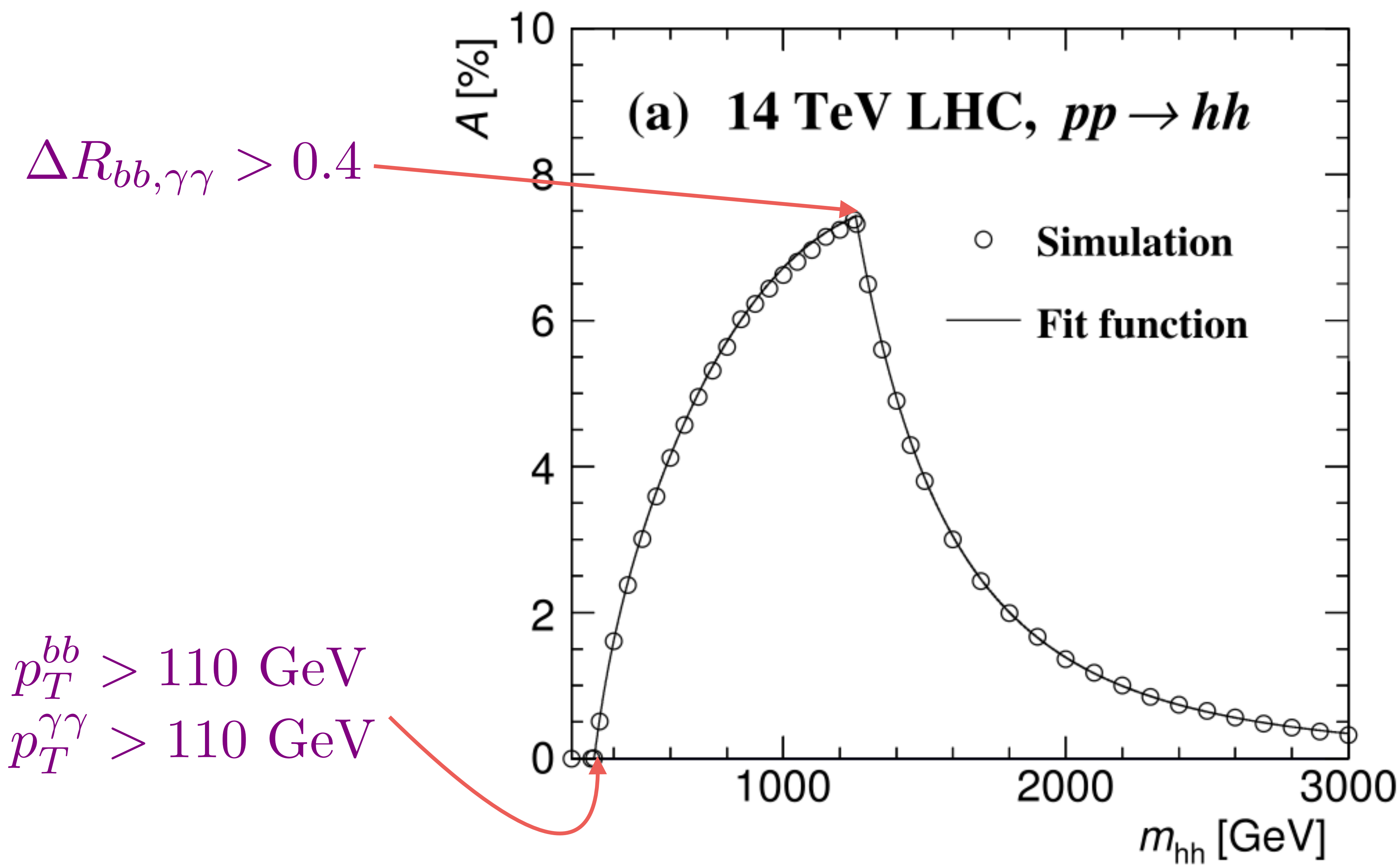
- Results

Background : 47.1 ± 3.5
Signal : 8.4 ± 0.1



Sensitivity on NP from Double Higgs production



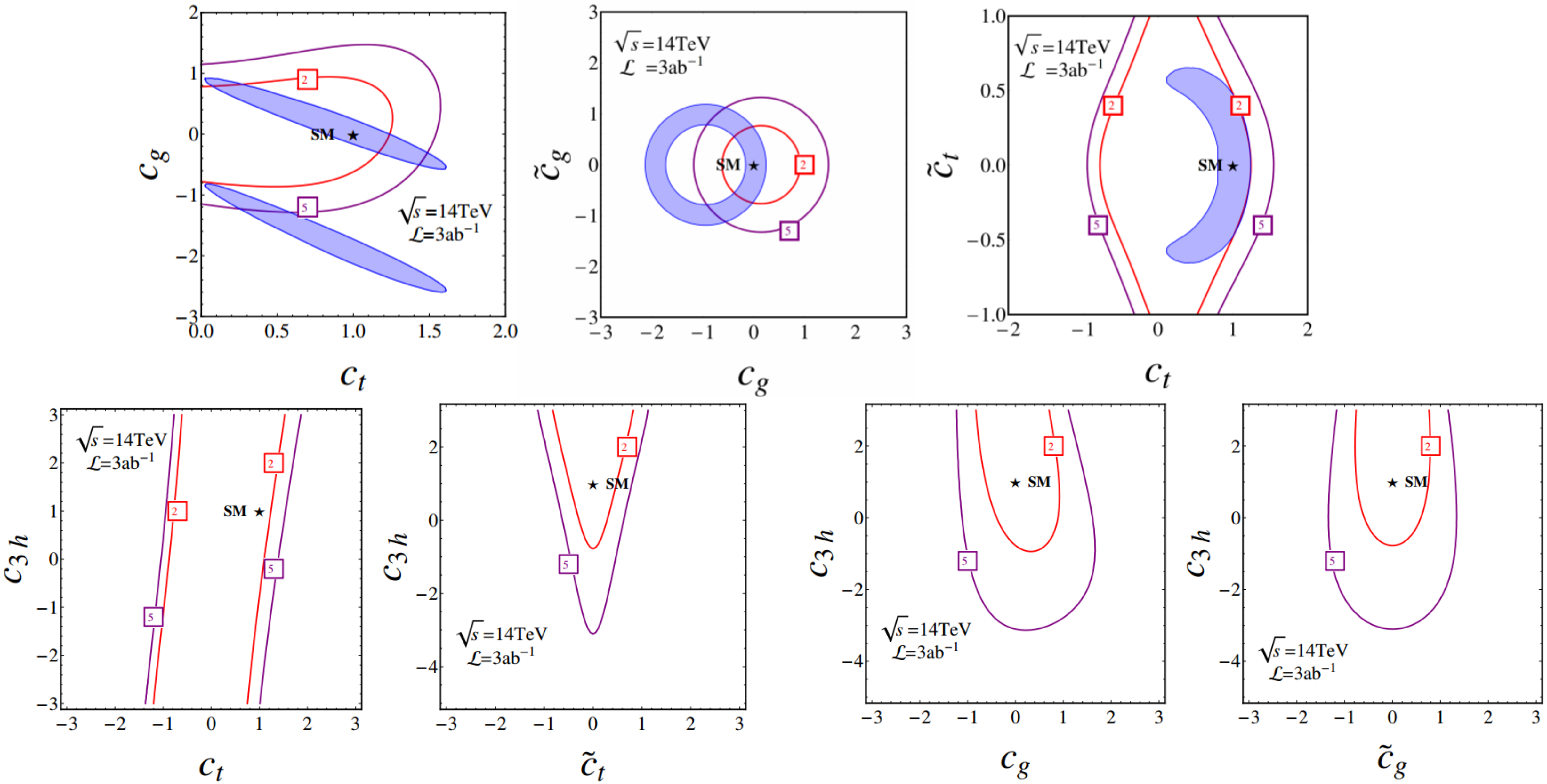
S-wave dominant!

NP Signal: $\sigma_{\rm cut}^{\rm NP} = \int dm_{hh} \frac{d\sigma}{dm_{hh}} \mathcal{A}(m_{hh})$

$\text{Background}: \ 47.1 \pm 3.5$

Sensitivity on NP from Double Higgs production

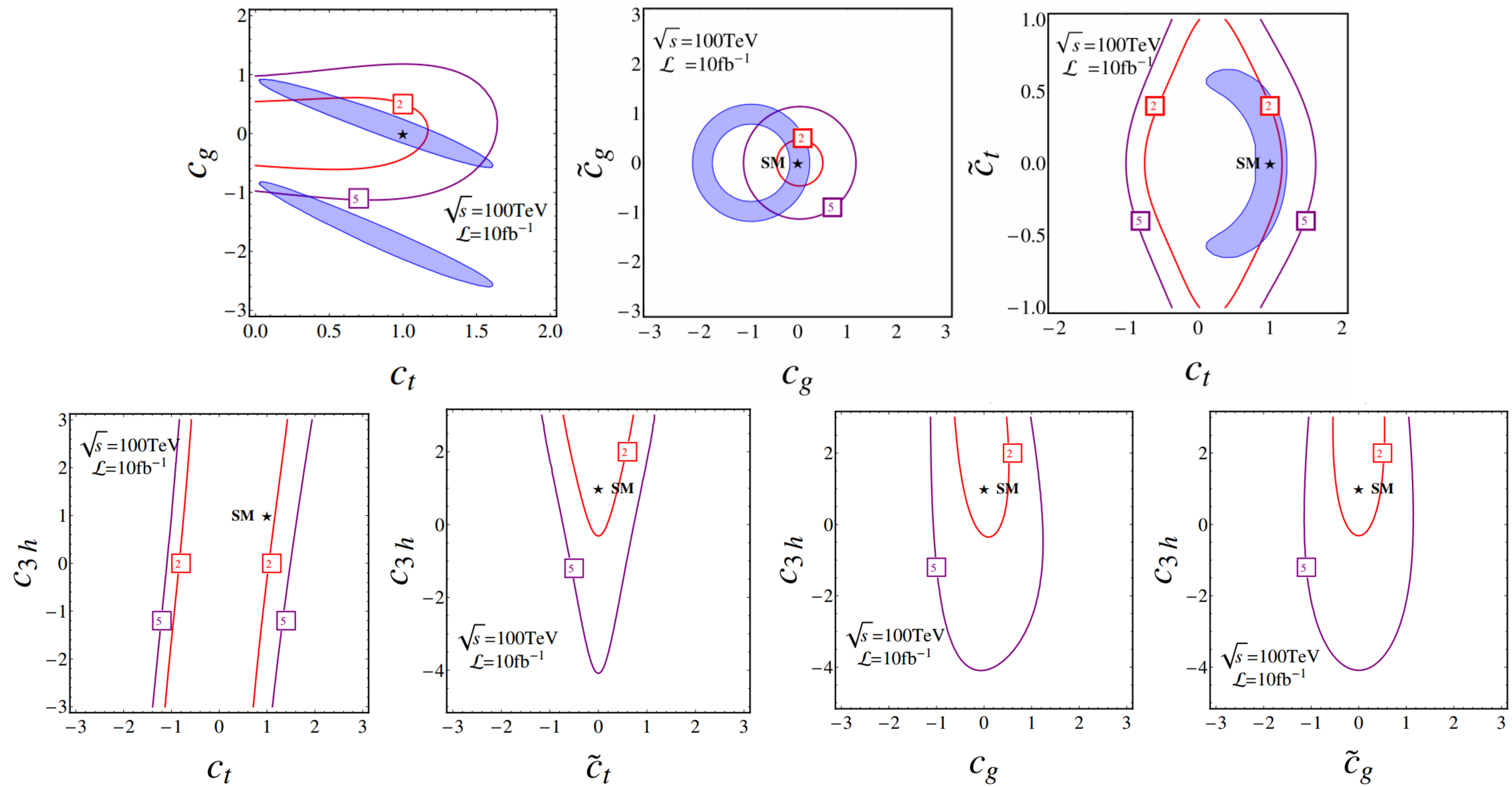
- 2σ Exclusion limit and 5σ discovery limit @14 TeV HL-LHC



The SM double Higgs production can not be discovered, but some parameter space can be excluded.

Sensitivity on NP from Double Higgs production

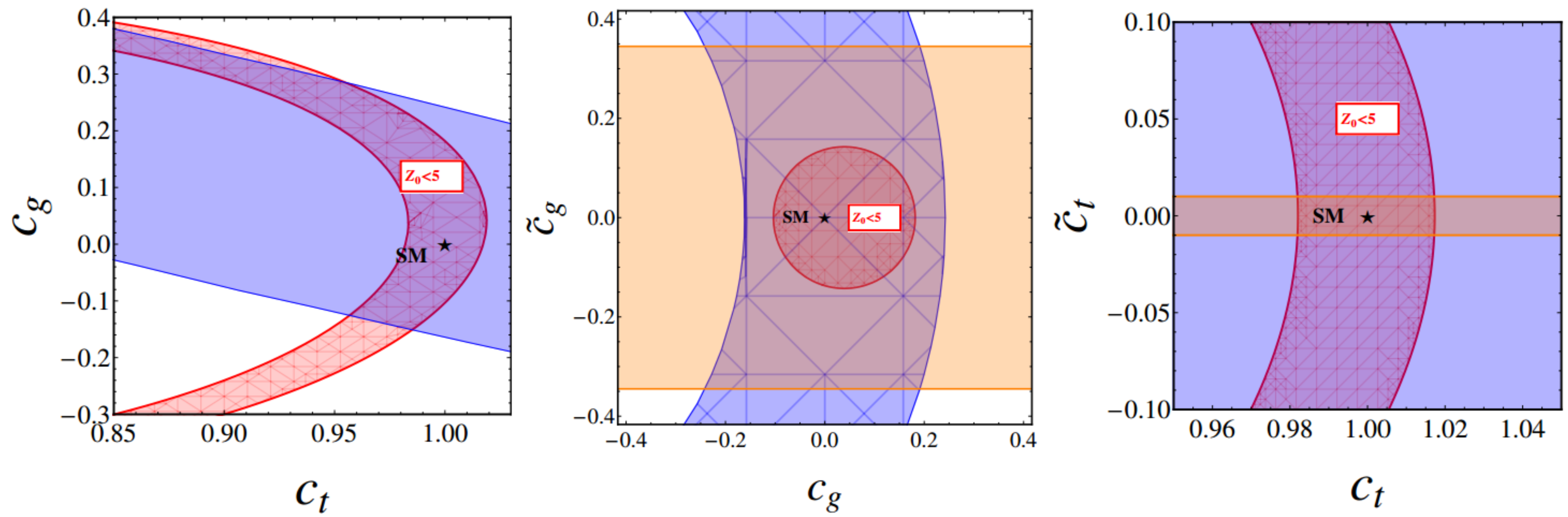
- 2σ Exclusion limit and 5σ discovery limit @100 TeV 10 fb^{-1} hadron colliders



Comparable to the 14 TeV HL-LHC results

Sensitivity on NP from Double Higgs production

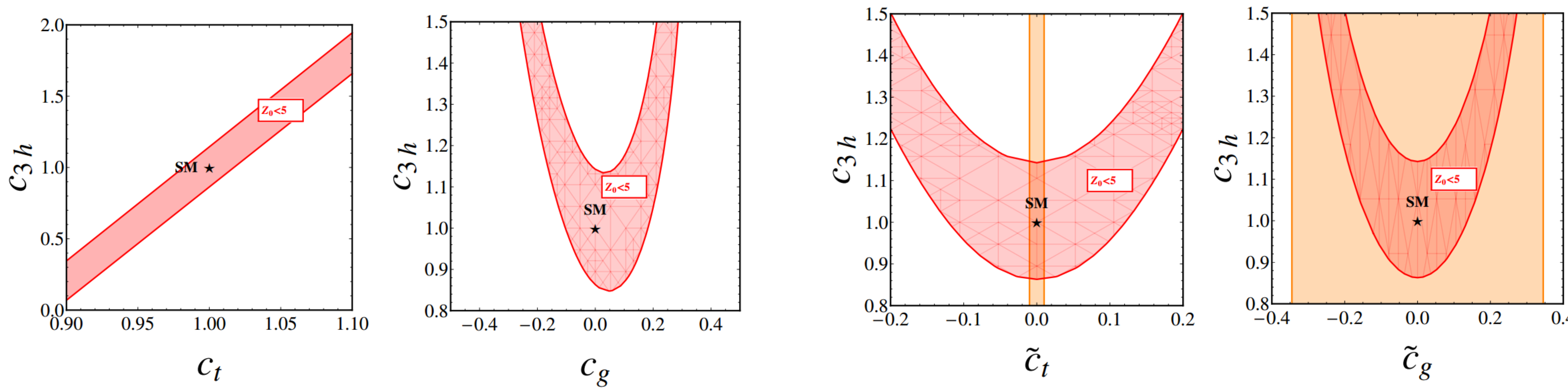
- 5 σ discovery significance @100 TeV 30 ab^{-1}, hadron colliders considering the SM double Higgs is the background



EDMs

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

$|\tilde{c}_g| < 0.345$



NP deviates from SM with 1~2% can be discovered!

Conclusions

- Double Higgs production is essential to measure the Higgs-trilinear coupling and also very sensitive to NP.

- Using the effective Lagrangian approach and based on the s-wave dominant signature of the NP, we have studied the sensitivity on NP at 14 TeV LHC and 100 TeV hadron colliders.

- The sensitivity can be comparable between 14 TeV HL-LHC and 100 TeV 10 fb^{-1} hadron colliders.

- NP deviates from SM with 1~2% can be discovered at 100 TeV 30 ab^{-1} hadron colliders.

Backups

Single Higgs Production

$$\mathcal{L}_{\text{eff}} = -\frac{m_t}{v}\bar{t}(c_t + i\tilde{c}_t\gamma_5)th - \frac{m_t}{v^2}\bar{t}(c_{2t} + i\tilde{c}_{2t}\gamma_5)th^2 + \frac{\alpha_s h}{12\pi v}(c_g G^A_{\mu\nu}G^{\mu\nu}_A + \tilde{c}_g G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A)$$
$$+ \frac{\alpha_s h^2}{24\pi v^2}(c'_g G^A_{\mu\nu}G^{\mu\nu}_A + \tilde{c}'_g G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A) - c_{3h}\frac{m_h^2}{2v}h^3$$

Constraints from Single Higgs Measurements

$$\mathcal{L}_{\rm eff} = -\frac{m_t}{v}\bar{t}(c_t + i\tilde{c}_t\gamma_5)th - \frac{m_t}{v^2}\bar{t}(c_{2t} + i\tilde{c}_{2t}\gamma_5)th^2 + \frac{\alpha_s h}{12\pi v}(c_g G^A_{\mu\nu}G^{\mu\nu}_A + \tilde{c}_g G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A)$$
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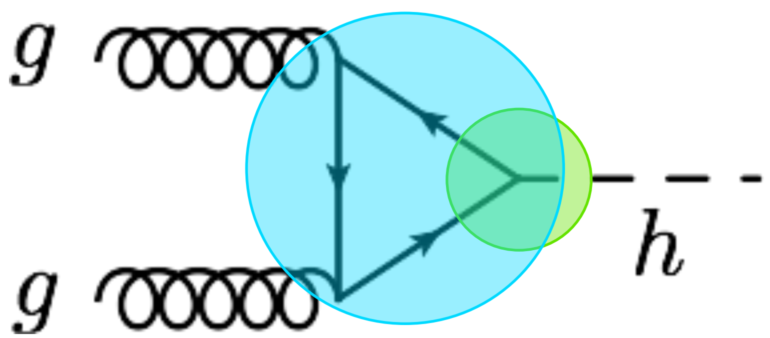
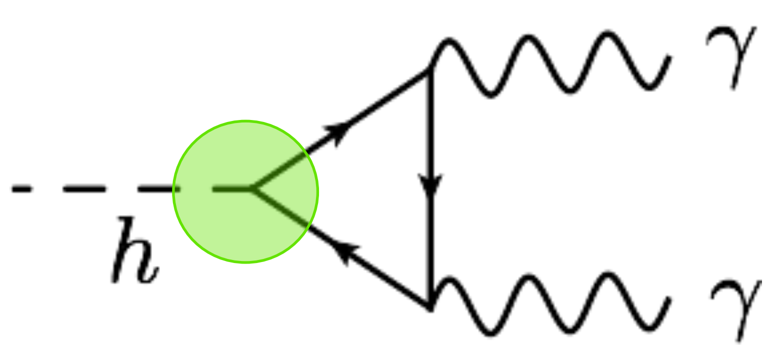
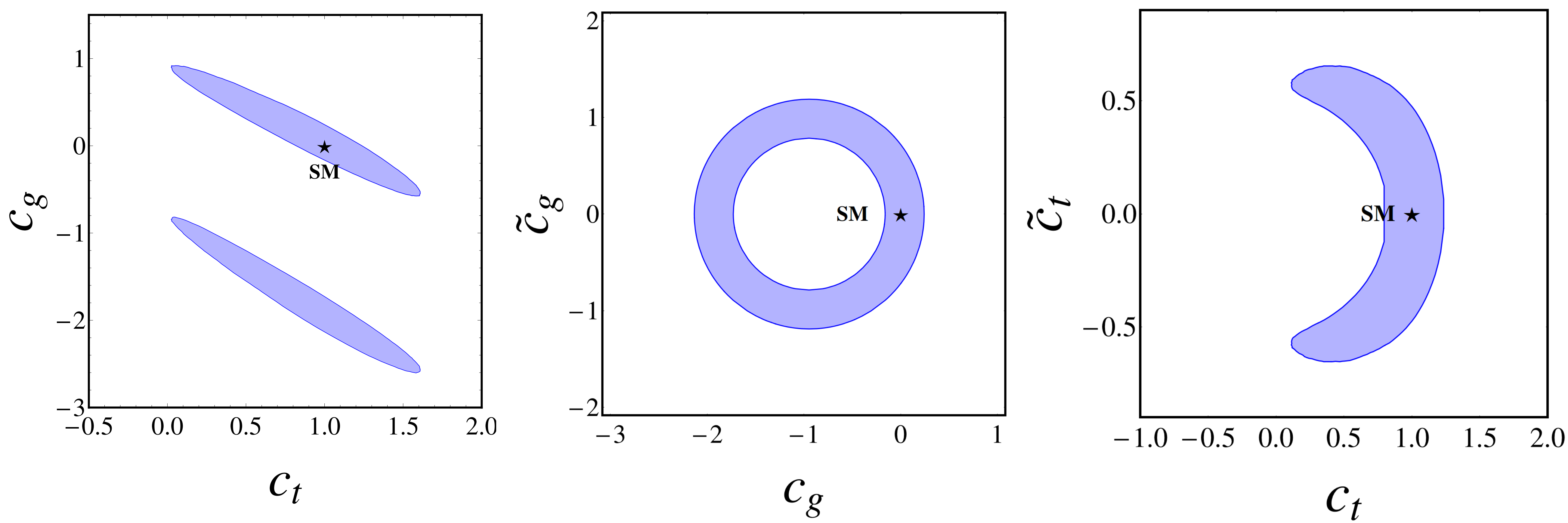


$$\mu_{gg} \equiv \frac{\sigma(gg\to h)}{\sigma(gg\to h)_{\rm SM}} = \frac{|c_t F^{\rm even}_{1/2}(\tau_t) + \frac{2}{3}c_g|^2 + |\tilde{c}_t F^{\rm odd}_{1/2}(\tau_t) + \frac{2}{3}\tilde{c}_g|^2}{|F^{\rm even}_{1/2}(\tau_t)|^2}$$
$$= (c_t + 0.969 c_g)^2 + (-1.521\tilde{c}_t + 0.969\tilde{c}_g)^2$$



$$\mu_{\gamma\gamma} \equiv \frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{\rm SM}} = \frac{|2F_1(\tau_W) + \frac{8}{3}c_t F^{\rm even}_{1/2}(\tau_t)|^2 + |\frac{8}{3}\tilde{c}_t F^{\rm odd}_{1/2}(\tau_t)|^2}{|2F_1(\tau_W) + \frac{8}{3}F^{\rm even}_{1/2}(\tau_t)|^2}$$
$$= (-0.28 c_t + 1.28)^2 + (0.43\tilde{c}_t)^2$$

Constraints from Single Higgs Measurements



$$\mu_{gg} = (c_t + 0.969 c_g)^2 + (-1.521 \tilde{c}_t + 0.969 \tilde{c}_g)^2$$

$$\mu_{\gamma\gamma} = (-0.28 c_t + 1.28)^2 + (0.43 \tilde{c}_t)^2$$

EDMs

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

$|\tilde{c}_g| < 0.345$

Brod, Joachim and Haisch, Ulrich and Zupan, Jure, 1310.1385

Sensitivity on NP from Double Higgs production

$$\mathcal{O}_{Ht} = H^\dagger H \bar{q}_L \tilde{H} t_R$$
$$c_{2t} = \frac{3}{2}(c_t - 1)$$

$$\mathcal{O}_H = \frac{1}{2}\partial_\mu (H^\dagger H)\partial^\mu (H^\dagger H)$$
$$\mathcal{L}_{kin} = \frac{1}{2}(1 + \frac{c_H v^2}{\Lambda^2})\partial_\mu H \partial^\mu H$$
$$H' = \sqrt{1 + \frac{c_H v^2}{\Lambda^2}} H \approx (1 + \frac{c_H v^2}{2\Lambda^2}) H - \frac{c_H v^2}{8\Lambda^2} H^2$$

$$\bar{q}_L \tilde{H} t_R \to \bar{q}_L \left[\left(1 + \frac{c_H v^2}{2\Lambda^2} \right) \tilde{H} - \frac{c_H v^2}{8\Lambda^2} H^2 \right] t_R$$
$$c_{2t} \neq \frac{3}{2}(c_t - 1)$$

$$\mathcal{O}_{HG} = H^\dagger H G^A_{\mu\nu} G^{\mu\nu}_A$$
$$\tilde{\mathcal{O}}_{HG} = H^\dagger H G^A_{\mu\nu} \tilde{G}^{\mu\nu}_A$$

$\Rightarrow$

$$c'_g = c_g$$
$$\tilde{c}'_g = \tilde{c}_g$$

Sensitivity on NP from Double Higgs production

- Tensor basis expansion

$$\mathcal{M}_{hh} = -\frac{\alpha_s \hat{s} \delta^{ab}}{4\pi v^2} \epsilon_\mu(p_a)\epsilon_\nu(p_b) \Bigg\{ \left[c_t^2 F_\Box + \tilde{c}_t^2 F_\Box^{(1)} + \frac{3m_H^2}{\hat{s} - m_H^2} c_{3h} \left(c_t F_\triangle + \frac{2}{3} c_g \right) + \frac{2}{3} c_g + c_{2t} F_\triangle \right] A^{\mu\nu}$$

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

numerically very small

- Helicity basis expansion

$$\mathcal{M}_{hh} = \mathcal{M}_{+-} + \mathcal{M}_{-+} + \mathcal{M}_{++} + \mathcal{M}_{--}$$

$\mathcal{M}_{+-} \supset B^{\mu\nu}$	$\mathcal{M}_{++},\ \mathcal{M}_{--} \xrightarrow{m_t \to +\infty} \#$ (non-decoupling limit)
$\mathcal{M}_{-+} \supset B^{\mu\nu}$	$\mathcal{M}_{+-},\ \mathcal{M}_{-+} \xrightarrow{m_t \to +\infty} 0$ (decoupling limit)
$\mathcal{M}_{++} \supset A^{\mu\nu} + iC^{\mu\nu}$	$\mathcal{M}_{+-},\ \mathcal{M}_{-+} \sim G_\Box,\ G_\Box^{(1)} \sim \frac{p_T^2}{m_t^2}$
$\mathcal{M}_{--} \supset A^{\mu\nu} - iC^{\mu\nu}$	

$$A^{\mu\nu} = g^{\mu\nu} - \frac{p_a^\nu p_b^\mu}{p_a \cdot p_b} \qquad C^{\mu\nu} = \frac{p_{a\rho} p_{b\sigma}}{p_a \cdot p_b} \varepsilon^{\mu\nu\rho\sigma}$$

$$B^{\mu\nu} = g^{\mu\nu} + \frac{p_c^2 p_a^\nu p_b^\mu}{p_T^2 p_a \cdot p_b} - \frac{2 p_b \cdot p_c p_a^\nu p_c^\mu}{p_T^2 p_a \cdot p_b} - \frac{2 p_a \cdot p_c p_b^\mu p_c^\nu}{p_T^2 p_a \cdot p_b} + \frac{2 p_c^\mu p_c^\nu}{p_T^2}$$

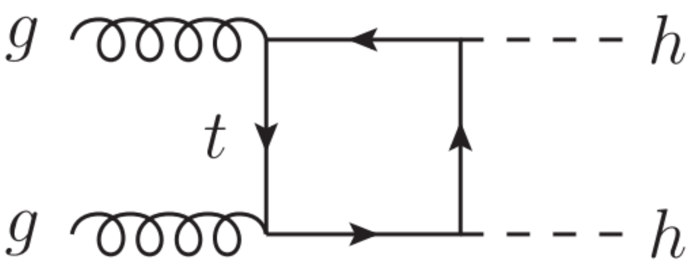
$$
\begin{aligned}
F_{\Box} &= \frac{2m_t^2}{\hat{s}}\{m_t^2(8m_t^2-\hat{s}-2m_H^2)(D_0^t+D_0^u+D_0^{tu})+p_T^2(4m_t^2-m_H^2)D_0^{tu} \\
&+2+4m_t^2C_0^s+\frac{2}{\hat{s}}(m_H^2-4m_t^2)[(\hat{t}-m_H^2)C_0^t+(\hat{u}-m_H^2)C_0^u]\}, \\
G_{\Box} &= \frac{m_t^2}{\hat{s}}\{2(8m_t^2+\hat{s}-2m_H^2)[m_t^2(D_0^t+D_0^u+D_0^{tu})-C_0^{sm}]-2[\hat{s}C_0^s+(\hat{t}-m_H^2)C_0^t+(\hat{u}-m_H^2)C_0^u] \\
&+\frac{1}{\hat{s}p_T^2}[\hat{s}\hat{u}(8\hat{u}m_t^2-\hat{u}^2-m_H^4)D_0^u+\hat{s}\hat{t}(8\hat{t}m_t^2-\hat{t}^2-m_H^4)D_0^t+(8m_t^2+\hat{s}-2m_H^2) \\
&[\hat{s}(\hat{s}-2m_H^2)C_0^s+\hat{s}(\hat{s}-4m_H^2)C_0^{sm}+2\hat{t}(m_H^2-\hat{t})C_0^t+2\hat{u}(m_H^2-\hat{u})C_0^u]]\}, \\
F_{\Box}^{(1)} &= \frac{2m_t^2}{\hat{s}^2}\{m_H^2(2\hat{t}C_0^t+2\hat{u}C_0^u-\hat{t}\hat{u}D_0^{tu})-2m_H^4(C_0^t+C_0^u)+m_H^6D_0^{tu} \\
&+\hat{s}[2+m_t^2[4C_0^s-(D_0^t+D_0^u+D_0^{tu})(\hat{t}+\hat{u})]]\} \\
G_{\Box}^{(1)} &= \frac{m_t^2}{2\hat{s}}\{\frac{2}{m_H^4-\hat{t}\hat{u}}[-\hat{s}(2m_H^4+\hat{t}^2+\hat{u}^2)C_0^s+2(m_H^2-\hat{t})(m_H^4+\hat{t}^2)C_0^t+2(m_H^2-\hat{u})(m_H^4+\hat{u}^2)C_0^u \\
&-(\hat{t}+\hat{u})(2m_H^4-\hat{t}^2-\hat{u}^2)C_0^{sm}+\hat{s}\hat{t}(\hat{t}^2+m_H^4)D_0^t+\hat{s}\hat{u}(\hat{u}^2+m_H^4)D_0^u] \\
&-4m_t^2(\hat{t}+\hat{u})(D_0^t+D_0^u+D_0^{tu})\}, \\
F_{\Box}^{(2)} &= 4m_t^4(D_0^t+D_0^u+D_0^{tu}), \\
F_{\triangle} &= \frac{2m_t^2}{\hat{s}}[2+(4m_t^2-s)C_0^s], \\
F_{\triangle}^{(3)} &= 2m_t^2C_0^s.
\end{aligned}
$$

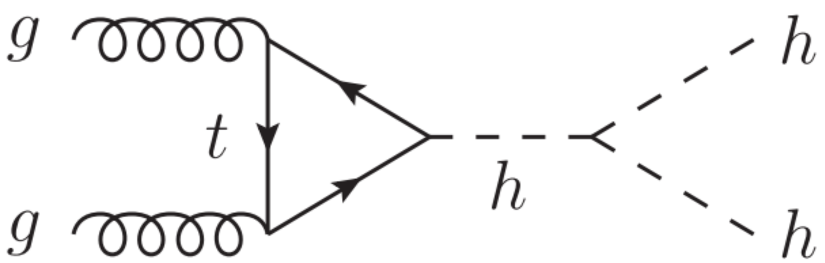
Sensitivity on NP from Double Higgs production

- Physical reason

  $m_t \to +\infty$

  - s-wave has non-decoupling effect
  - d-wave has decoupling effect





Sensitivity on NP from Double Higgs production

$$\mathcal{M}_{hh}(\hat{s},\theta) \approx \mathcal{M}_{hh}(\hat{s})$$

- Any NP doesn't change the distribution of the Higgs pair, neither of the distribution of the decay final state due to the scalar signature of the Higgs boson.

- For a specific decay final state and kinematic cuts, cut efficiency will be universal for all NP at a given $\hat{s}$

- We can use a universal cut efficiency function $A(\hat{s})$ to mimic the simulation on any of the NP signal.

Sensitivity on NP from Double Higgs production

- Previous searches for double Higgs production at 8 TeV and 13 TeV LHC

- 8 TeV, non-resonant hh production

  $b\bar{b}\gamma\gamma \leq 2.2$ pb ATLAS Phys. Rev. Lett. 114, 081802 (2015)
  $b\bar{b}b\bar{b} \leq 0.62$ pb ATLAS Eur. Phys. J. C75, 412 (2015)
  $b\bar{b}\tau^+\tau^- \leq 1.6$ pb ATLAS Phys. Rev. D92, 092004 (2015)
  $\gamma\gamma W^+W^- \leq 11$ pb ATLAS Phys. Rev. D92, 092004 (2015)
  the combined result: $\sigma_{hh}(8\text{ TeV}) \leq 0.69\text{ pb} \simeq 70\ \sigma_{hh}^{SM}(8\text{ TeV})$ ATLAS Phys. Rev. D92, 092004 (2015)

- 13 TeV, non-resonant hh production

  $b\bar{b}\gamma\gamma \leq 3.76$ pb ATLAS-CONF-2016-004 (2016)
  $b\bar{b}b\bar{b} \leq 3.9$ pb ATLAS-CONF-2016-017
  $b\bar{b}\tau^+\tau^- \leq 8.8$ pb CMS-PAS-HIG-16-012

Sensitivity on NP from Double Higgs production

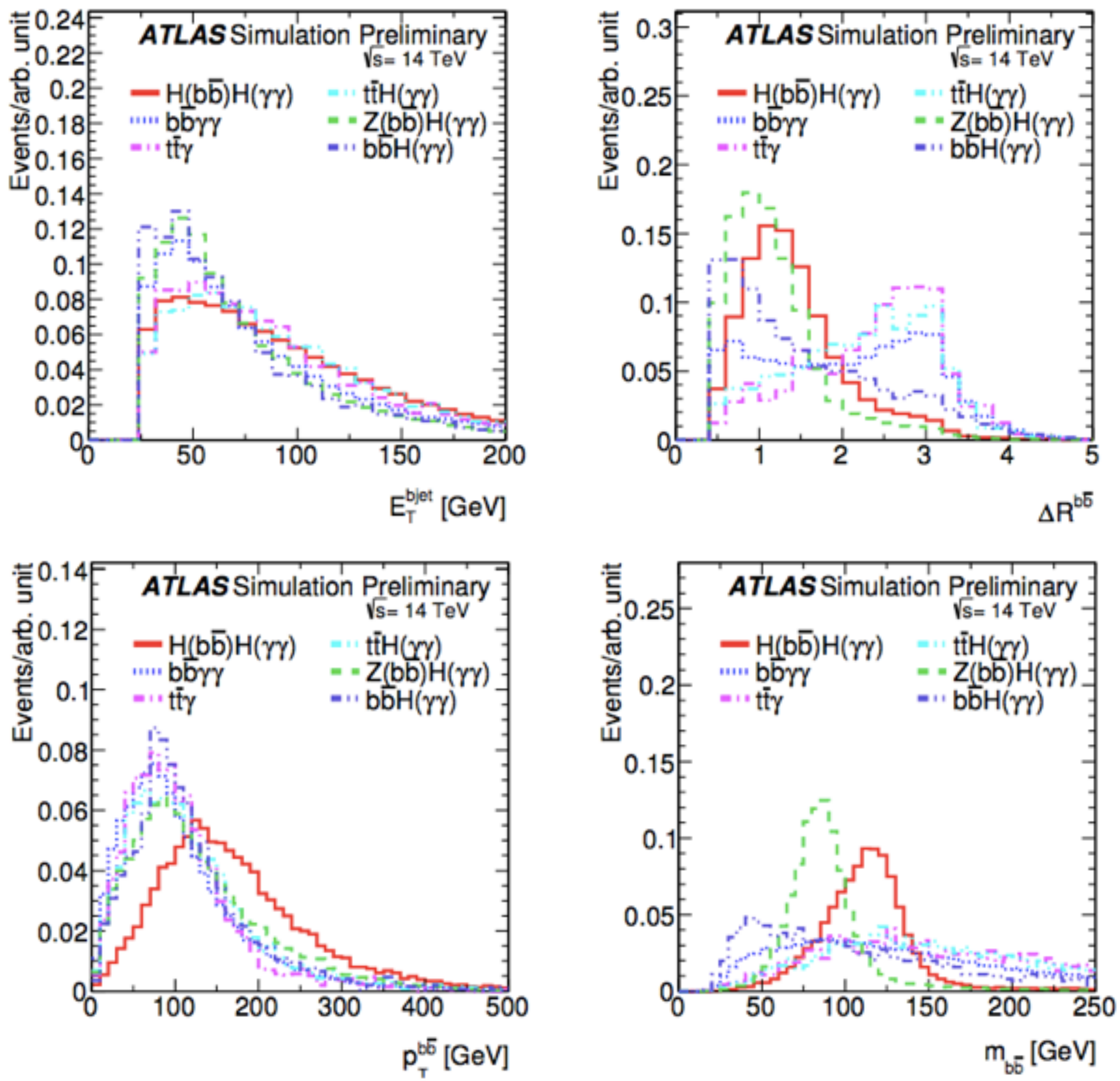
- 14 TeV HL-LHC   ATL-PHY-PUB-2014-019 (2015).
  - Irreducible backgrounds:

    $b\bar{b}\gamma\gamma,\ t\bar{t}h(\gamma\gamma),\ Z(b\bar{b})h(\gamma\gamma),\ b\bar{b}h(\gamma\gamma)$

  - Reducible backgrounds:

    $jj\gamma\gamma,\ c\bar{c}\gamma\gamma,\ b\bar{b}\gamma j,\ t\bar{t},\ t\bar{t}\gamma$

Sensitivity on NP from Double Higgs production

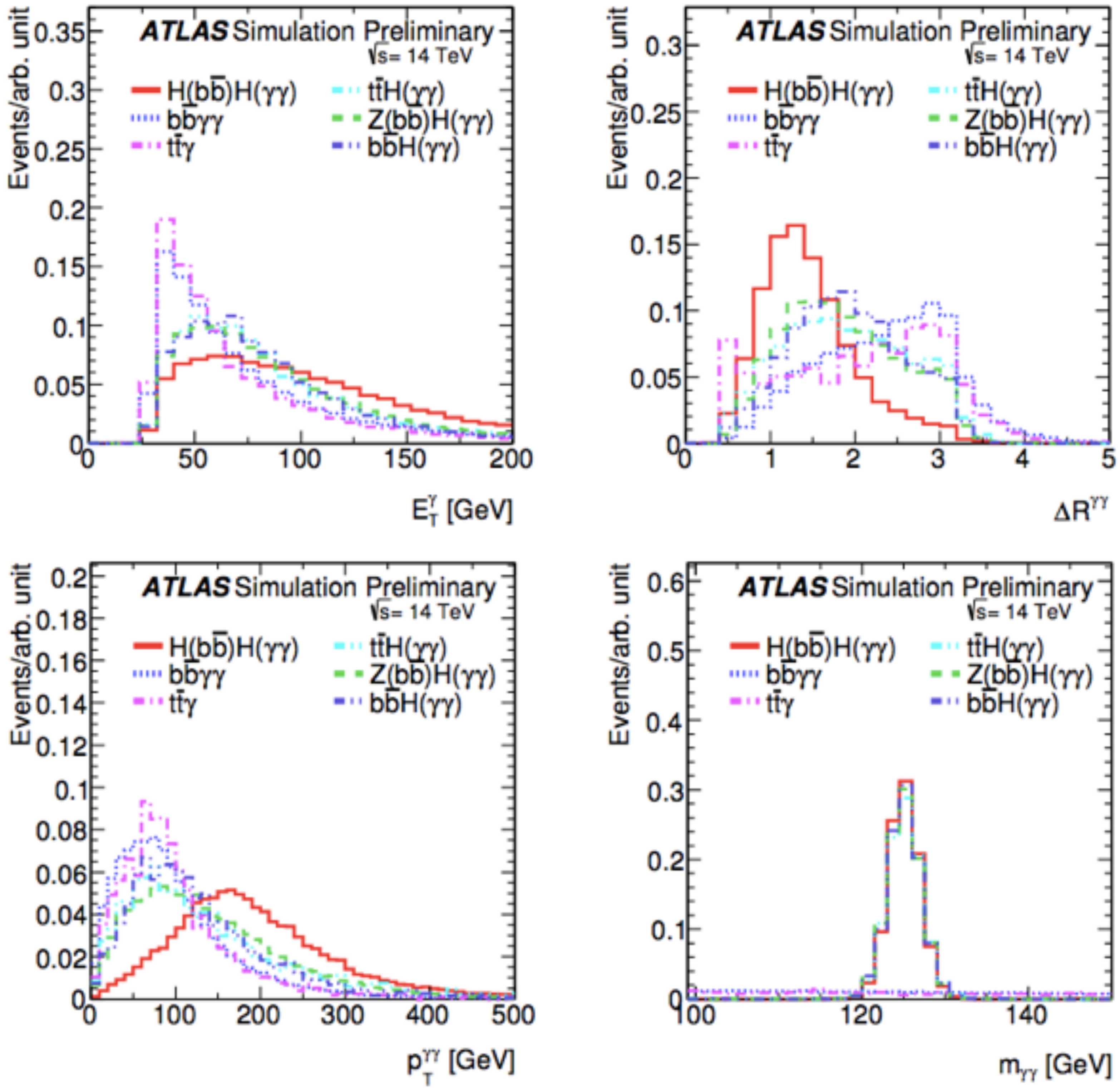


$0.4 < \Delta R_{bb} < 2.0$

$p_T^{bb} > 110$ GeV

100 GeV $< m_{bb} < 150$ GeV

Sensitivity on NP from Double Higgs production



$$0.4 < \Delta R_{\gamma\gamma} < 2.0$$

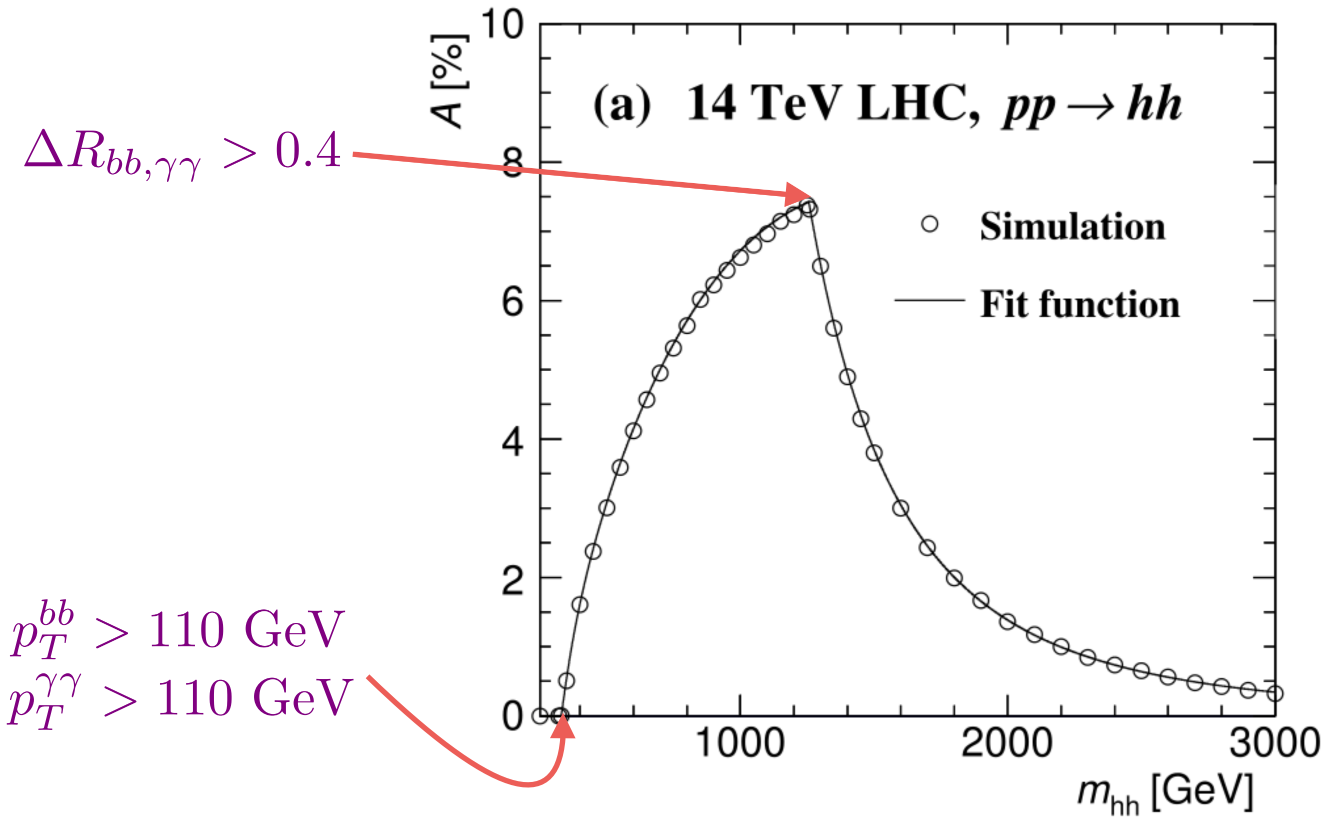
$$p_T^{\gamma\gamma} > 110 \text{ GeV}$$

$$123 \text{ GeV} < m_{\gamma\gamma} < 128 \text{ GeV}$$

Expected yields (3000 fb^{-1}) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=1)$	8.4±0.1	6.7±0.1	1.8±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=0)$	13.7±0.2	10.7±0.2	3.1±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=2)$	4.6±0.1	3.7±0.1	0.9±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=10)$	36.2±0.8	27.9±0.7	8.2±0.4
$b\bar{b}\gamma\gamma$	9.7±1.5	5.2±1.1	4.5±1.0
$c\bar{c}\gamma\gamma$	7.0±1.2	4.1±0.9	2.9±0.8
$b\bar{b}\gamma j$	8.4±0.4	4.3±0.2	4.1±0.2
$b\bar{b}jj$	1.3±0.2	0.9±0.1	0.4±0.1
$jj\gamma\gamma$	7.4±1.8	5.2±1.5	2.2±1.0
$t\bar{t}(\geq 1$ lepton)	0.2±0.1	0.1±0.1	0.1±0.1
$t\bar{t}\gamma$	3.2±2.2	1.6±1.6	1.6±1.6
$t\bar{t}H(\gamma\gamma)$	6.1±0.5	4.9±0.4	1.2±0.2
$Z(b\bar{b})H(\gamma\gamma)$	2.7±0.1	1.9±0.1	0.8±0.1
$b\bar{b}H(\gamma\gamma)$	1.2±0.1	1.0±0.1	0.3±0.1
Total Background	47.1±3.5	29.1±2.7	18.0±2.3
$S/\sqrt{B}(\lambda/\lambda_{SM}=1)$	1.2	1.2	0.4

Table 4: Expected yields in 3000 fb^{-1} for all events, events with both photons in the barrel calorimeter region ("barrel") and events with at least one photon in the endcap calorimeter region ("end-cap"). The quoted errors are from MC statistics only. The final two rows show the total background and the resulting signal significance, $S/\sqrt{B}$, in 3000 fb^{-1} ; combining the "barrel" and "endcap" categories in quadrature the final significance reaches $\sim 1.3\sigma$.

Sensitivity on NP from Double Higgs production

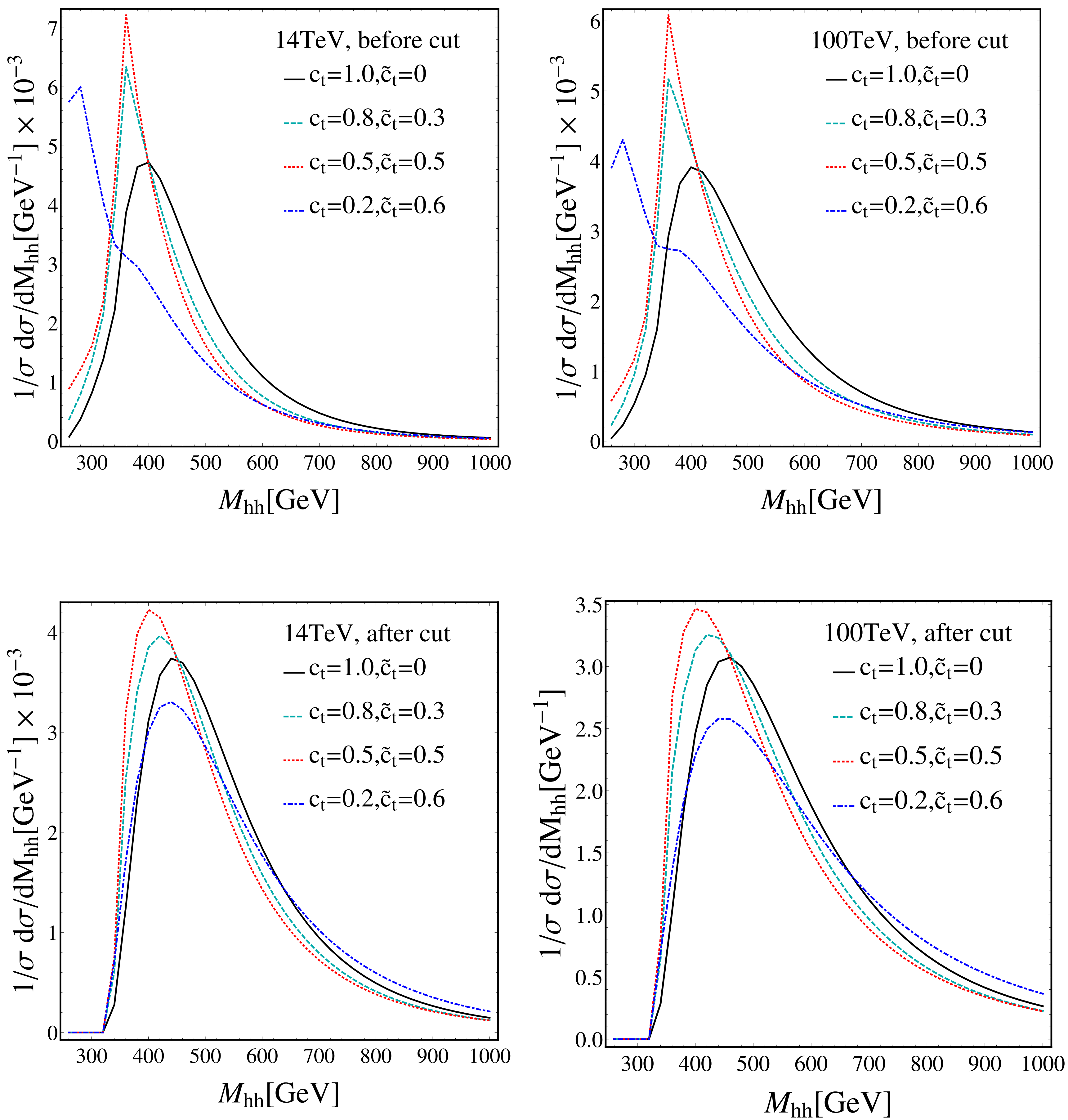


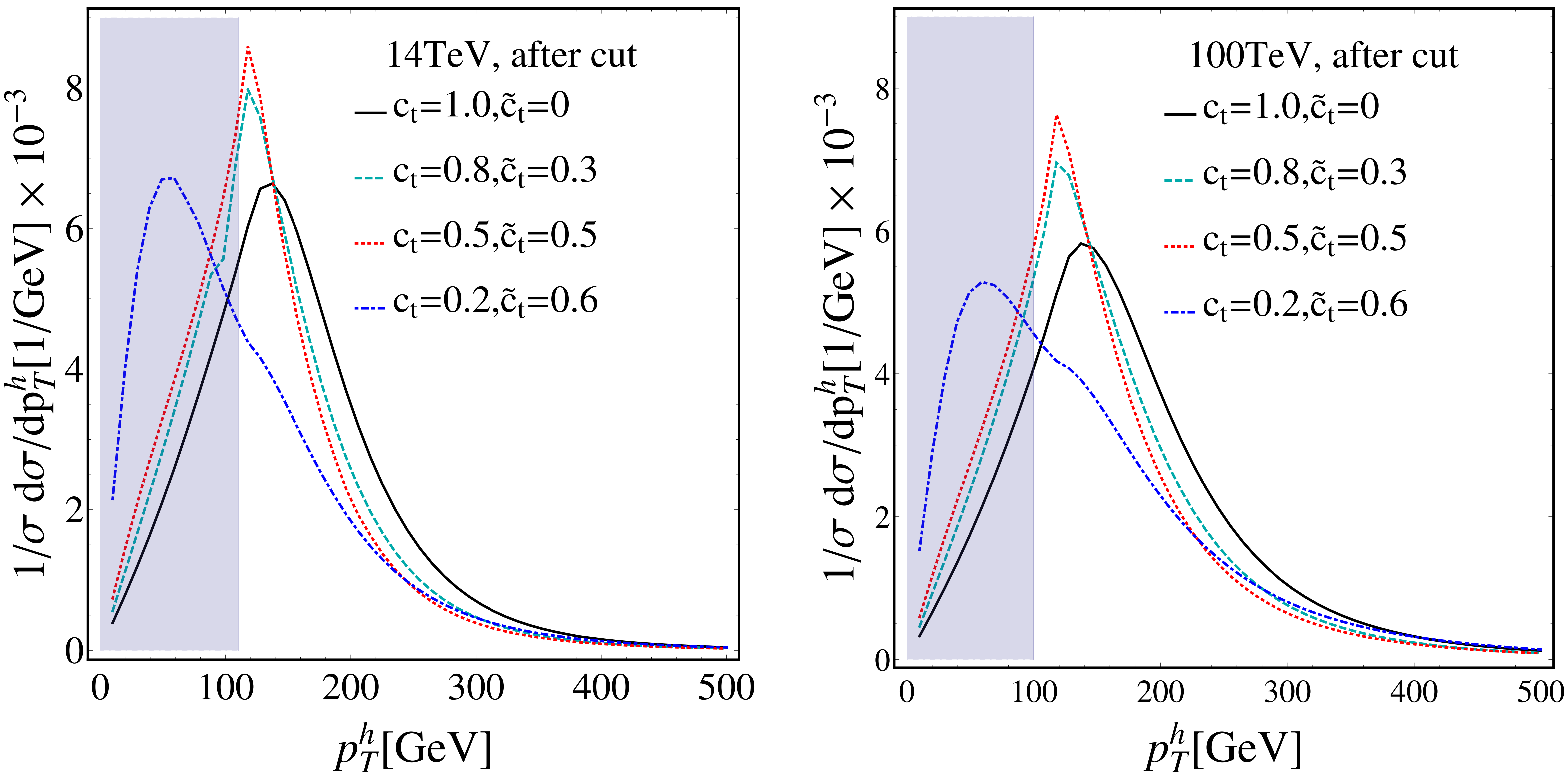
$$\mathcal{A}(M_{hh}) = \begin{cases} c_1 \left[1 - \sqrt{\dfrac{M_{hh}^2 (1-\cos\Delta R_0) - 8\,(m_H - \delta m_1)^2}{(1-\cos\Delta R_0)\left(M_{hh}^2 - 4\,(m_H-\delta m_1)^2\right)}} \right]^{\gamma_c}, & M_{hh} > M_{hh}^{(t)}, \\ c_2 \left[1 - \dfrac{4(p_T^h)^2}{M_{hh}^2 - 4\,(m_H - \delta m_2)^2} \right]^{\beta_a} \left(\dfrac{M_{hh}}{\sqrt{s}} \right)^{\beta_b} \left[1 + \beta_c \left(\dfrac{M_{hh}}{\sqrt{s}} \right) \log \left(\dfrac{2M_{hh}}{\sqrt{s}} \right) \right], & 329.3\ \text{GeV} < M_{hh} < M_{hh}^{(t)}, \\ 0, & M_{hh} < 329.3\ \text{GeV}. \end{cases}$$

$c_1 = 1.1378$, $c_2 = 11.02$, $\delta m_1 = 50$ GeV, $\delta m_2 = 2.5$ GeV, $\gamma_c = 1.675$, $\beta_a = 1.13$, $\beta_b = 1.48$, $\beta_c = 4.88$

S-wave dominant!

$$\sigma_{\rm cut} = \int dm_{hh} \frac{d\sigma}{dm_{hh}} \mathcal{A}(m_{hh})$$


14TeV, before cut
100TeV, before cut
14TeV, after cut
100TeV, after cut
c_t=1.0, c̃_t=0
c_t=0.8, c̃_t=0.3
c_t=0.5, c̃_t=0.5
c_t=0.2, c̃_t=0.6
1/σ dσ/dM_hh[GeV^-1] × 10^-3
1/σ dσ/dM_hh[GeV^-1]
M_hh[GeV]


14TeV, after cut
$c_t=1.0,\tilde{c}_t=0$
$c_t=0.8,\tilde{c}_t=0.3$
$c_t=0.5,\tilde{c}_t=0.5$
$c_t=0.2,\tilde{c}_t=0.6$
$1/\sigma\ d\sigma/dp_T^h[1/\text{GeV}] \times 10^{-3}$
p_T^h[GeV]
0
2
4
6
8
0
100
200
300
400
500
100TeV, after cut
$c_t=1.0,\tilde{c}_t=0$
$c_t=0.8,\tilde{c}_t=0.3$
$c_t=0.5,\tilde{c}_t=0.5$
$c_t=0.2,\tilde{c}_t=0.6$
$1/\sigma\ d\sigma/dp_T^h[1/\text{GeV}] \times 10^{-3}$
p_T^h[GeV]
0
2
4
6
8
0
100
200
300
400
500

Sensitivity on NP from Double Higgs production

- 100 TeV 30 ab^{-1} hadron colliders R. Contino, et. al, Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies.
  - Event Selections

$$\gamma \text{ isolation } R = 0.4$$

$$\text{jets: anti-kt, parameter } R = 0.4$$

$$p_T^{b_1} > 60 \text{ GeV}, \; p_T^{b_2} > 35 \text{ GeV}, \; |\eta^b| < 4.5,$$

$$p_T^{\gamma_1} > 60 \text{ GeV}, p_T^{\gamma_2} > 35 \text{ GeV}, \; |\eta^\gamma| < 4.5,$$

$$p_T(bb) > 100 \text{ GeV}, p_T(\gamma\gamma) > 100 \text{ GeV},$$

$$\Delta R_{bb} < 3.5 \; , \; \Delta R_{\gamma\gamma} < 3.5,$$

$$100 \text{ GeV} < m_{b\bar{b}} < 150 \text{ GeV},$$

$$123 \text{ GeV} < m_{\gamma\gamma} < 128 \text{ GeV},$$

  - Results

$$\text{Background : } \; 27118 \qquad \text{Signal : } \; 12061$$

Sensitivity on SM from Double Higgs production

Precision Measurement (100 TeV)

systematic uncertainty is 0.025
rescaling factor for the total bkg rate is 2.0
then precision on the total cross section is 4.4%