Resolving the degeneracy in the single Higgs production with Higgs pair production:

from LHC to 100TeV *pp* collider

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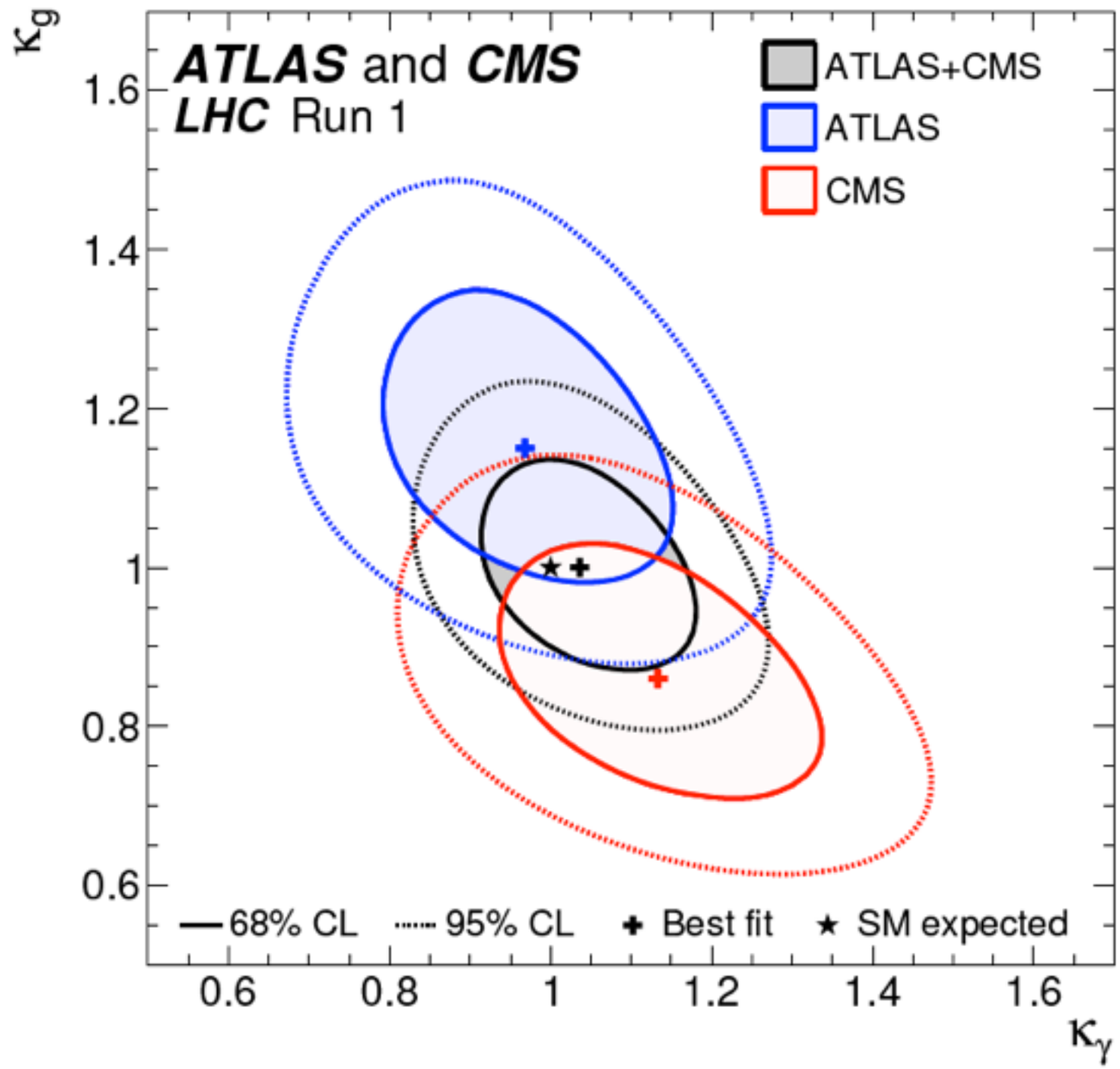
For CLHCP2016, Dec 16-19, 2016, Beijing

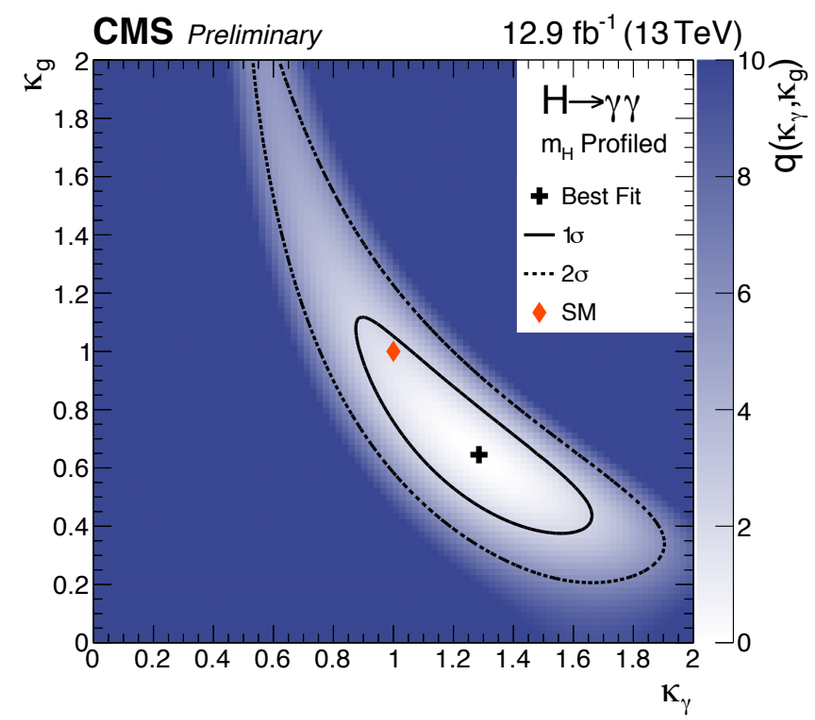
Base on the works PLB752(2016)285 and arXiv:1611.09336[hep-ph] in collaboration with Qing-Hong Cao, Gang Li, Bin Yan and Dong-Ming Zhang

The degeneracy in the single Higgs production



$$\kappa_g \equiv \frac{\Gamma(H \to gg)}{\Gamma(H \to gg)_{SM}}$$

$$\kappa_\gamma \equiv \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to \gamma\gamma)_{SM}}$$



ATLAS and CMS collaboration, JHEP08(2016)045;
CMS collaboration, CMS PAS HIG-16-020.

The degeneracy in the single Higgs production

- With more and more data, the contour will become smaller and smaller.
- Will the Higgs boson be more and more SM-like?

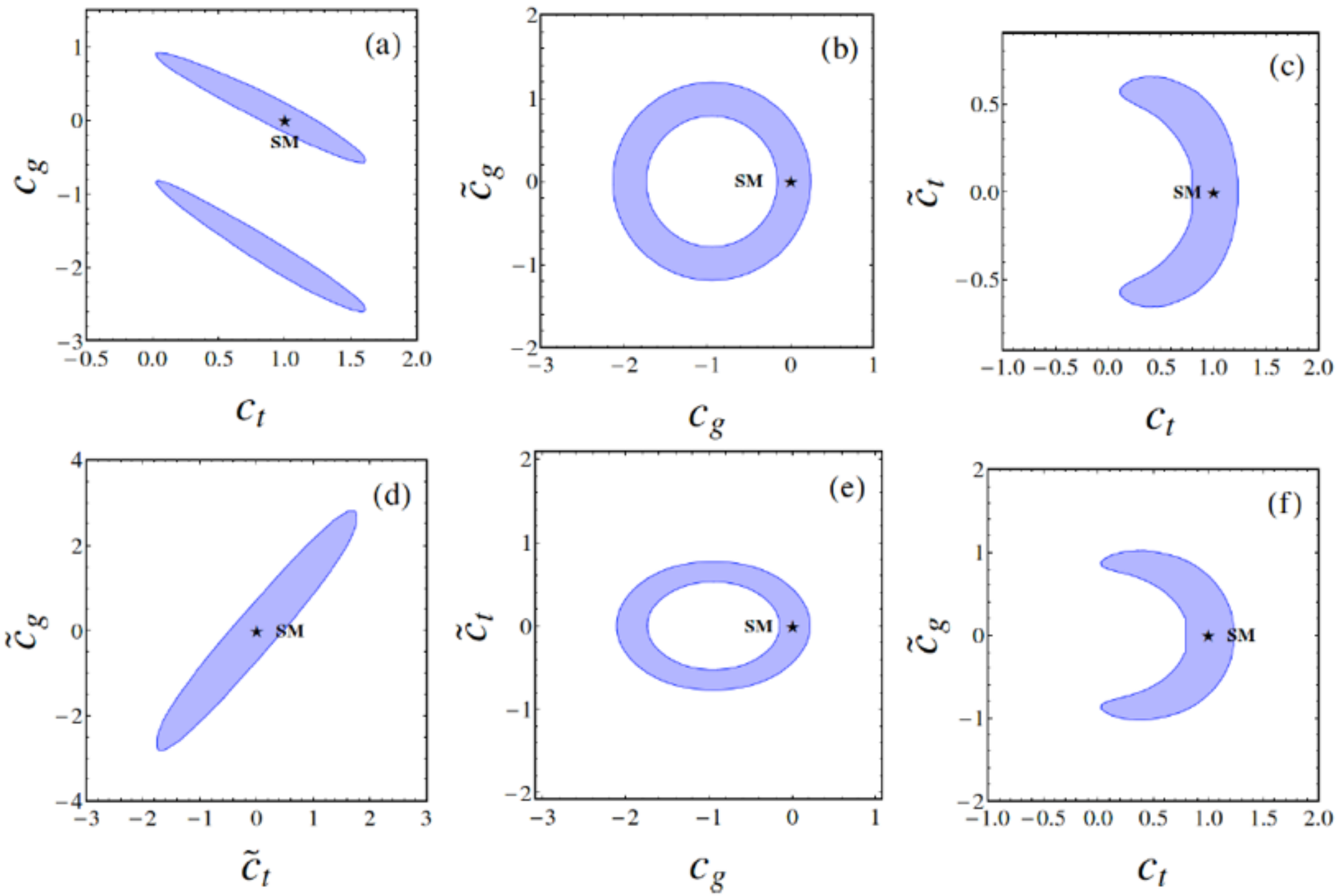
$$\mathcal{L}_{\rm eff} = -\frac{m_t}{v}\bar{t}(c_t + i\tilde{c}_t\gamma_5)th - \frac{m_t}{2v^2}\bar{t}(c_{2t} + i\tilde{c}_{2t}\gamma_5)th^2 + \frac{\alpha_s h}{12\pi v}(c_g G^A_{\mu\nu}G^{A,\mu\nu} + \tilde{c}_g G^A_{\mu\nu}\tilde{G}^{A,\mu\nu})$$
$$+ \frac{\alpha_s h^2}{24\pi v^2}(c_{2g} G^A_{\mu\nu}G^{A,\mu\nu}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

- The relation between c_g and c_{2g} is model-dependent. For example, for new physics does not carry the SM $SU(2)_L$ quantum number, we have c_g=c_{2g}.

$$\frac{\alpha_s}{12\pi v^2}\left(H^\dagger H\right)(c_g G^A_{\mu\nu}G^{A,\mu\nu} + \tilde{c}_g G^A_{\mu\nu}\tilde{G}^{A,\mu\nu})$$

The degeneracy in the single Higgs production

- The degeneracy in the single Higgs production.



The degeneracy in the single Higgs production

- Resolving the degeneracy with Higgs pair production.

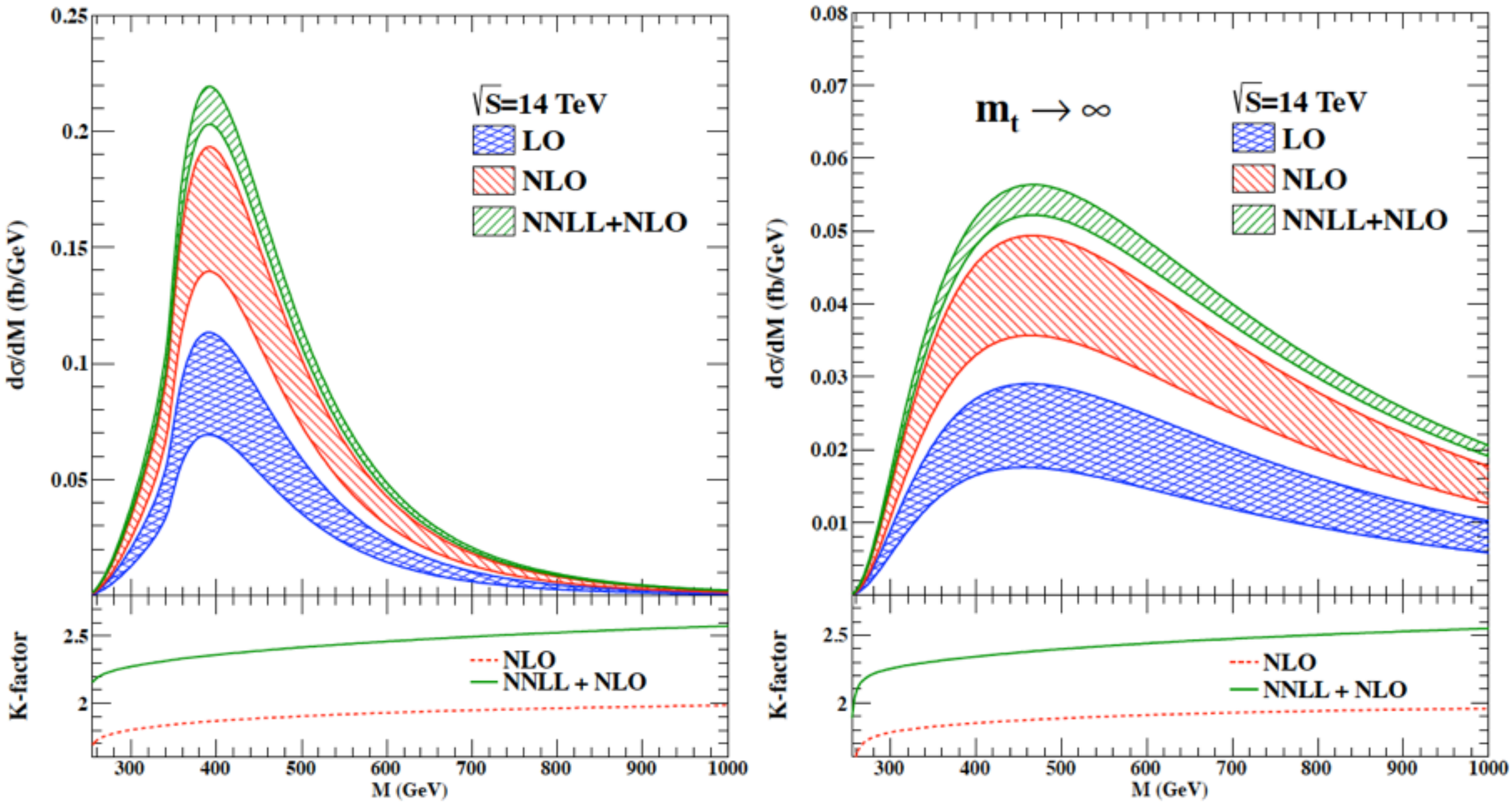
$$\mathcal{M}_h = -\frac{\alpha_s \hat{s}\delta^{ab}}{4\pi v}[(c_t F_\triangle + \frac{2}{3}c_g)A^{\mu\nu} - (\tilde{c}_t F_\triangle^{(1)} + \frac{2}{3}\tilde{c}_g)C^{\mu\nu}]\epsilon_\mu^a(p_1)\epsilon_\nu^b(p_2)$$

htt triangle | hgg EFT | htt triangle | hgg EFT

$$\begin{aligned}\mathcal{M}_{hh} &= -\frac{\alpha_s \hat{s}\delta^{ab}}{4\pi v^2}\epsilon_\mu(p_a)\epsilon_\nu(p_b)\{[c_t^2 F_\square + \tilde{c}_t^2 F_\square^{(1)} + \frac{3{m_h}^2}{\hat{s}-{m_h}^2}c_{3h}(c_t F_\triangle + \frac{2}{3}c_g) + \frac{2}{3}c_g + c_{2t}F_\triangle]A^{\mu\nu} \\ &+ (c_t^2 G_\square + \tilde{c}_t^2 G_\square^{(1)})B^{\mu\nu} - [c_t\tilde{c}_t F_\square^{(2)} + \frac{3{m_h}^2}{\hat{s}-{m_h}^2}c_{3h}(\tilde{c}_t F_\triangle^{(1)} + \frac{2}{3}\tilde{c}_g) + \frac{2}{3}\tilde{c}_g + \tilde{c}_{2t}F_\triangle^{(1)}]C^{\mu\nu}\}.\end{aligned}$$

The degeneracy in the single Higgs production

- Total cross section at *pp* collider.



D. Y. Shao, C. S. Li, H. T. Li, and J. Wang, JHEP 1307 (2013) 169;
S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, U. Schubert, and T. Zirke, PRL117(2016)079901.

The degeneracy in the single Higgs production

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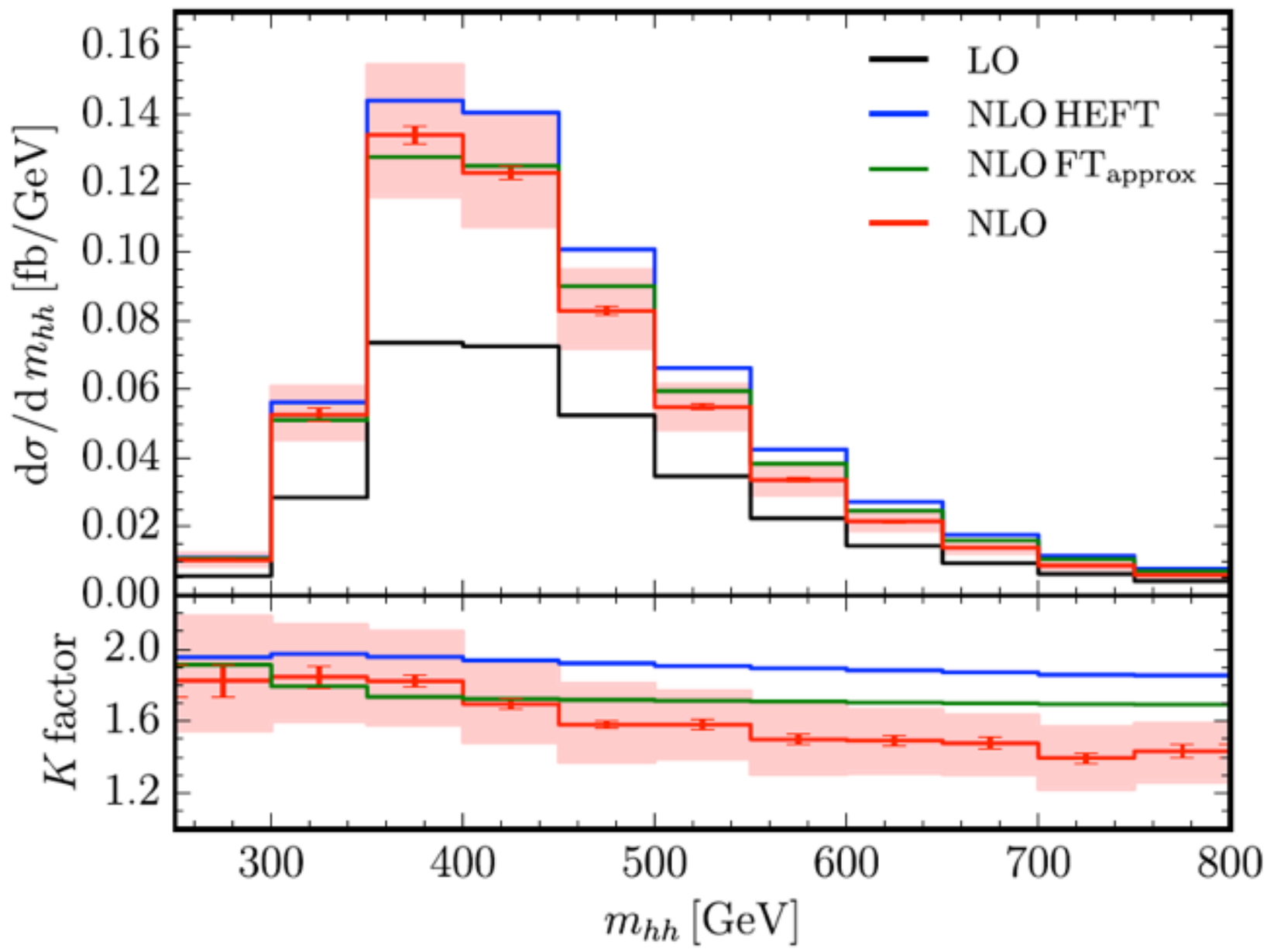

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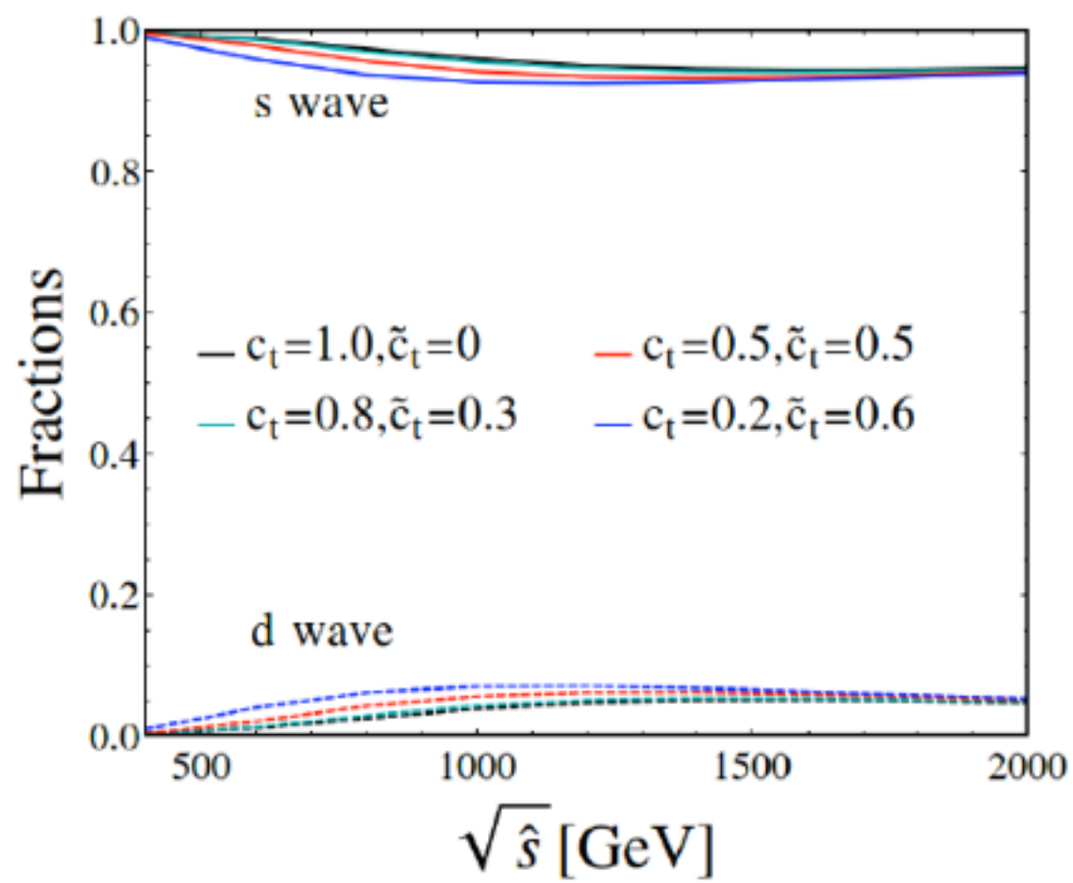
Resolving the degeneracy

- *s*-wave dominant!

$$\mathcal{M}_{hh}(\hat{s},\theta) = \sum_{\ell=0,2}(2\ell+1)\mathcal{M}_\ell(\hat{s})P_\ell(\cos\theta),$$

$$\sigma_0 = \int_{\tau_0}^1 d\tau \int_\tau^1 \frac{dx}{x} f_g(x;\mu_F^2) f_g(\frac{\tau}{x};\mu_F^2) \int_{-1}^1 d\cos\theta \hat{\sigma}_0(\tau s) P_0(\cos\theta)^2,$$

$$\sigma_2 = \int_{\tau_0}^1 d\tau \int_\tau^1 \frac{dx}{x} f_g(x;\mu_F^2) f_g(\frac{\tau}{x};\mu_F^2) \int_{-1}^1 d\cos\theta \hat{\sigma}_2(\tau s) P_2(\cos\theta)^2,$$



Resolving the degeneracy

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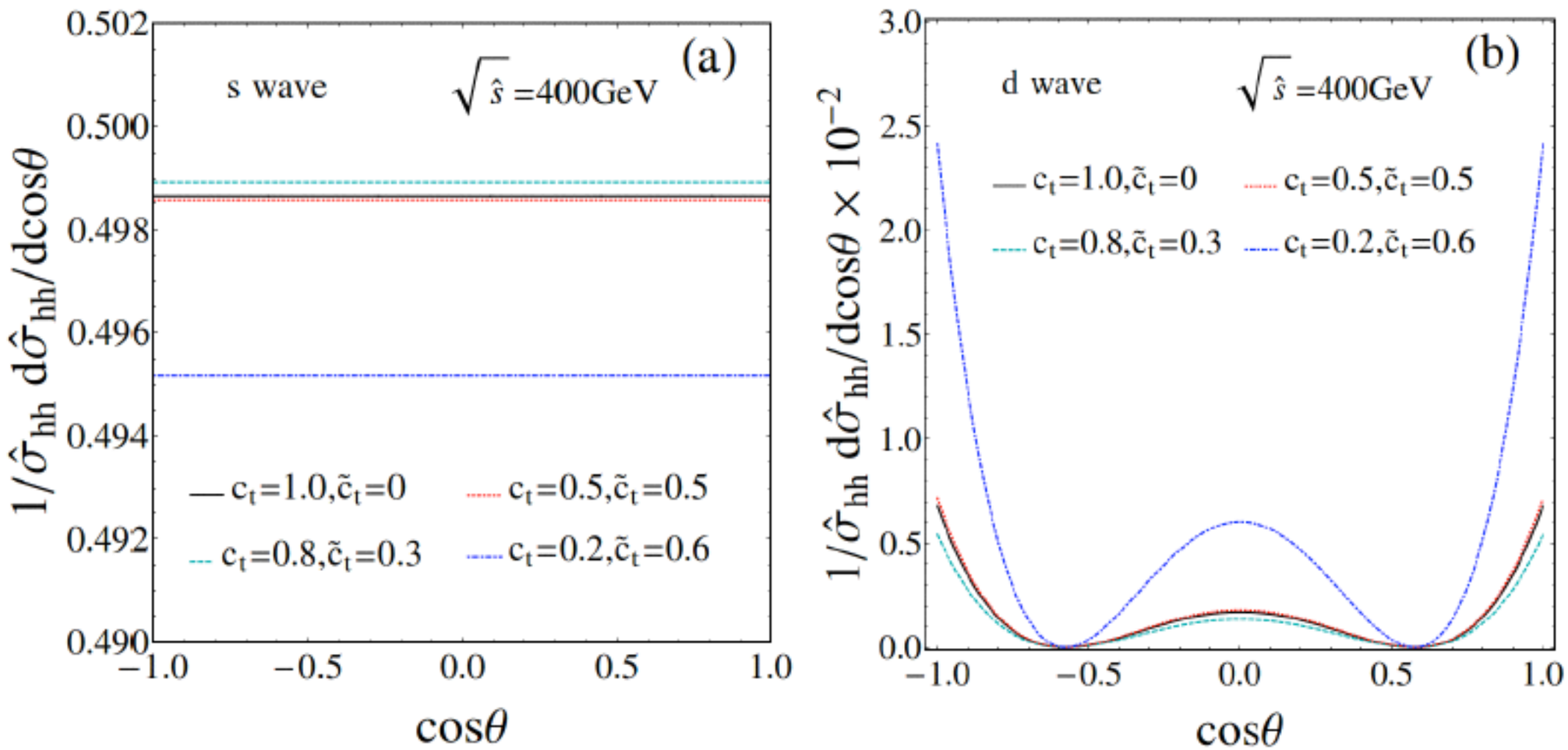


Resolving the degeneracy

- From parton level to detector level.

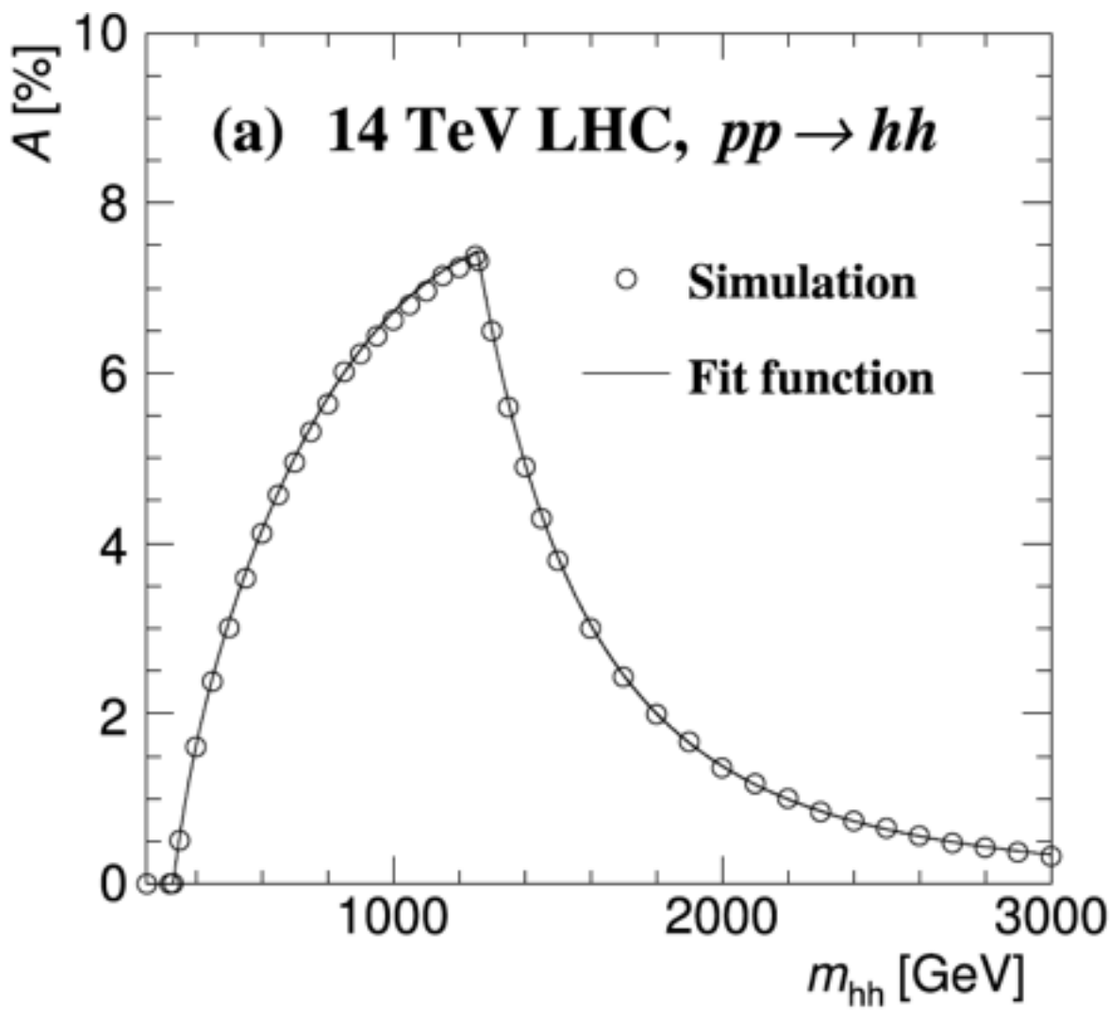
$$\sigma_{\text{after cuts}} = \int dm_{hh} \frac{d\sigma}{dm_{hh}} \mathcal{A}(m_{hh}, S, \mu_f)$$

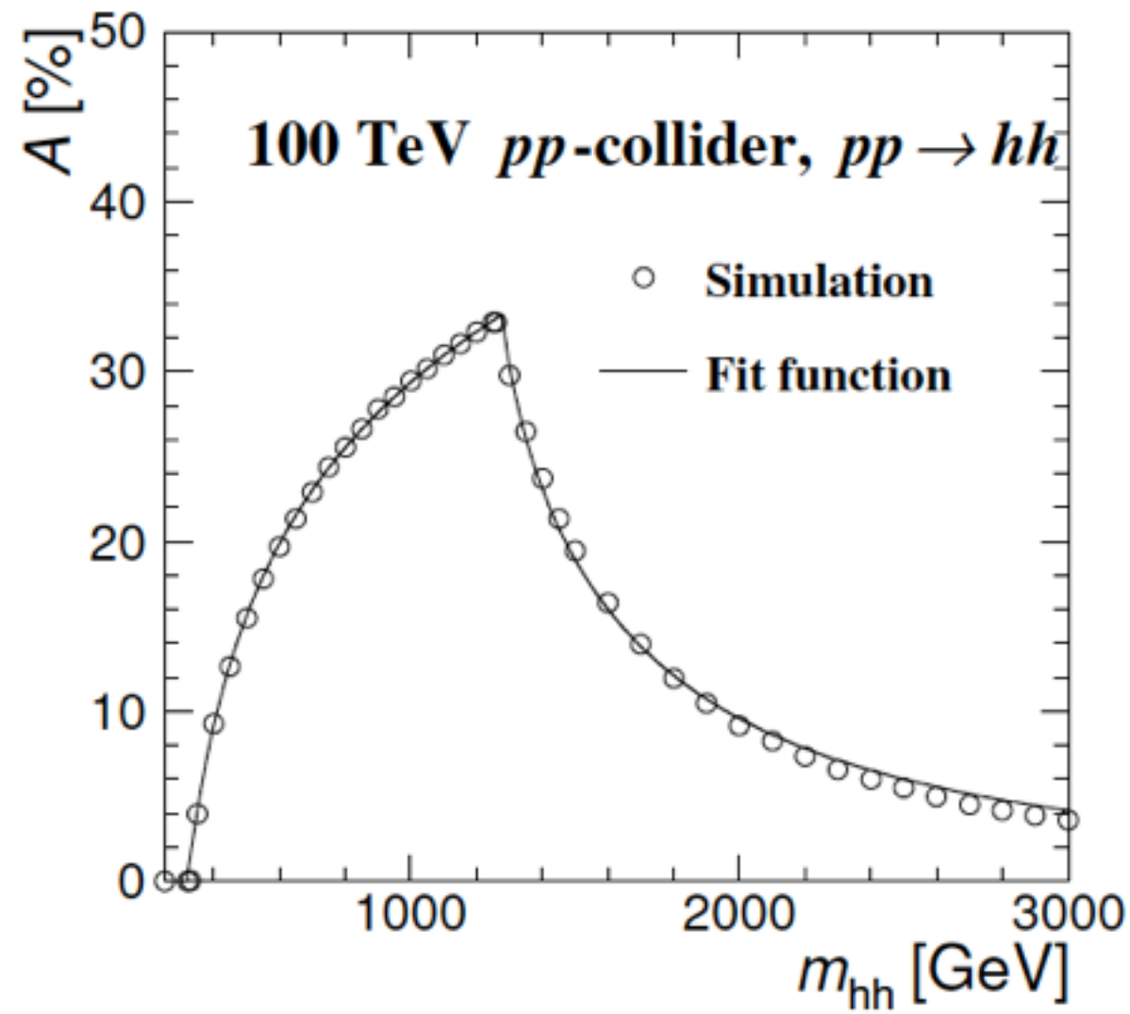
Cut acceptance function

- For s-wave process, the cut acceptance function does not depend on the detail of the angular distribution when we integrate it out.
- The total cross section after cut can be calculated without simulation point by point in the parameter space in NP model.
- We only need to know the cut acceptance function!

Resolving the degeneracy

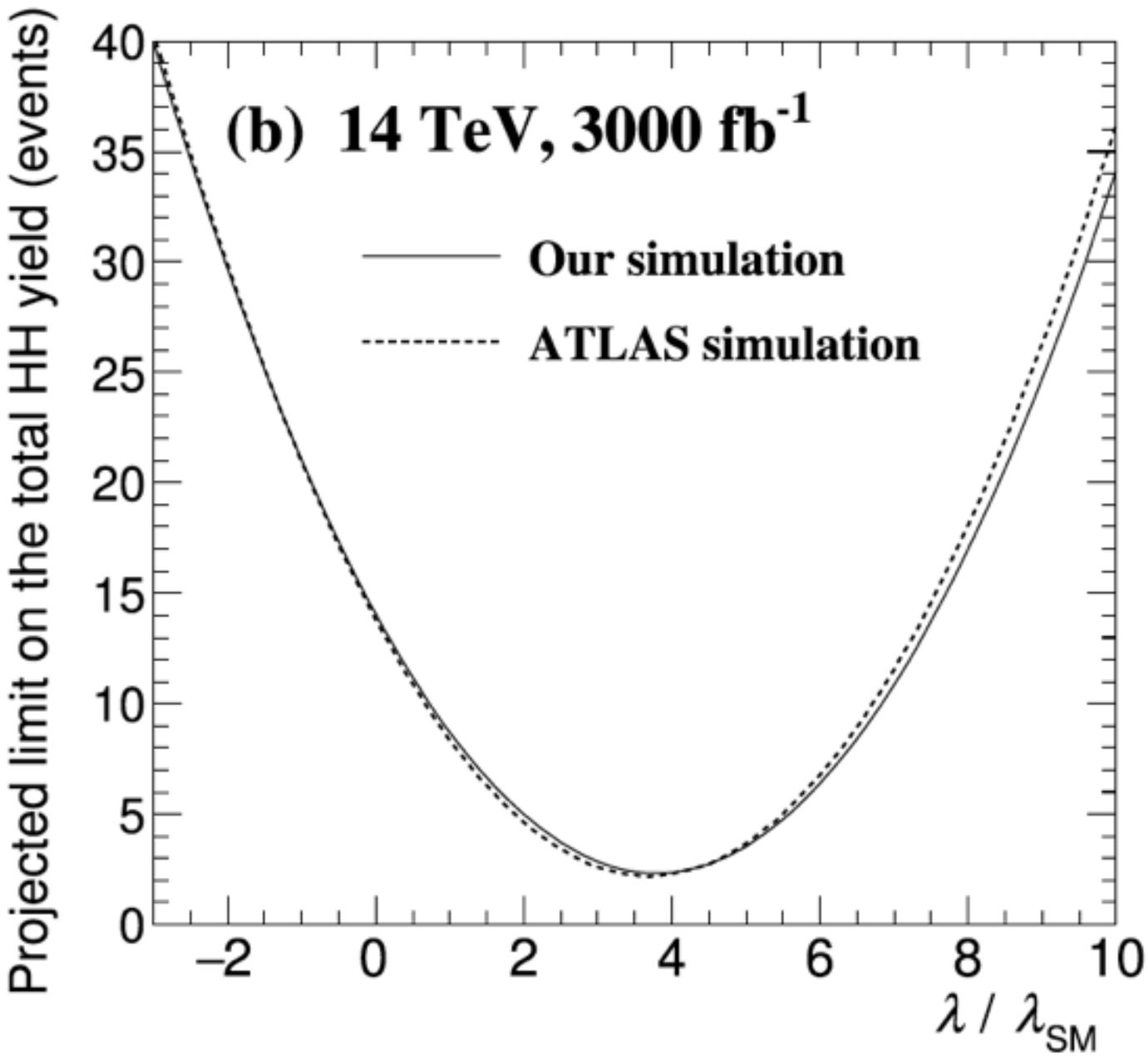
- From parton level to detector level.





Resolving the degeneracy

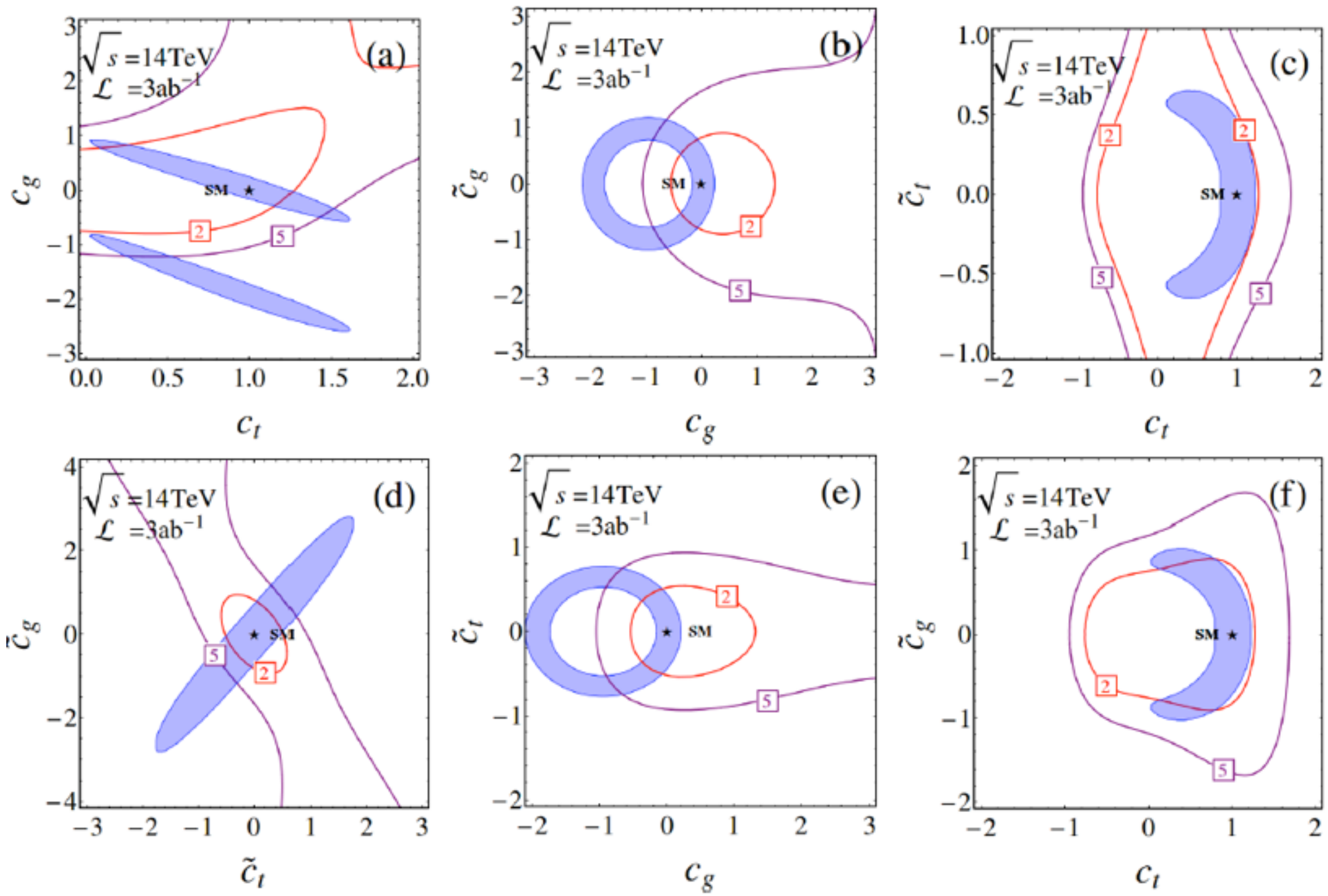
- Reproducing the ATLAS result perfectly!



ATLAS collaboration, ATL-PHYS-PUB-2014-019.

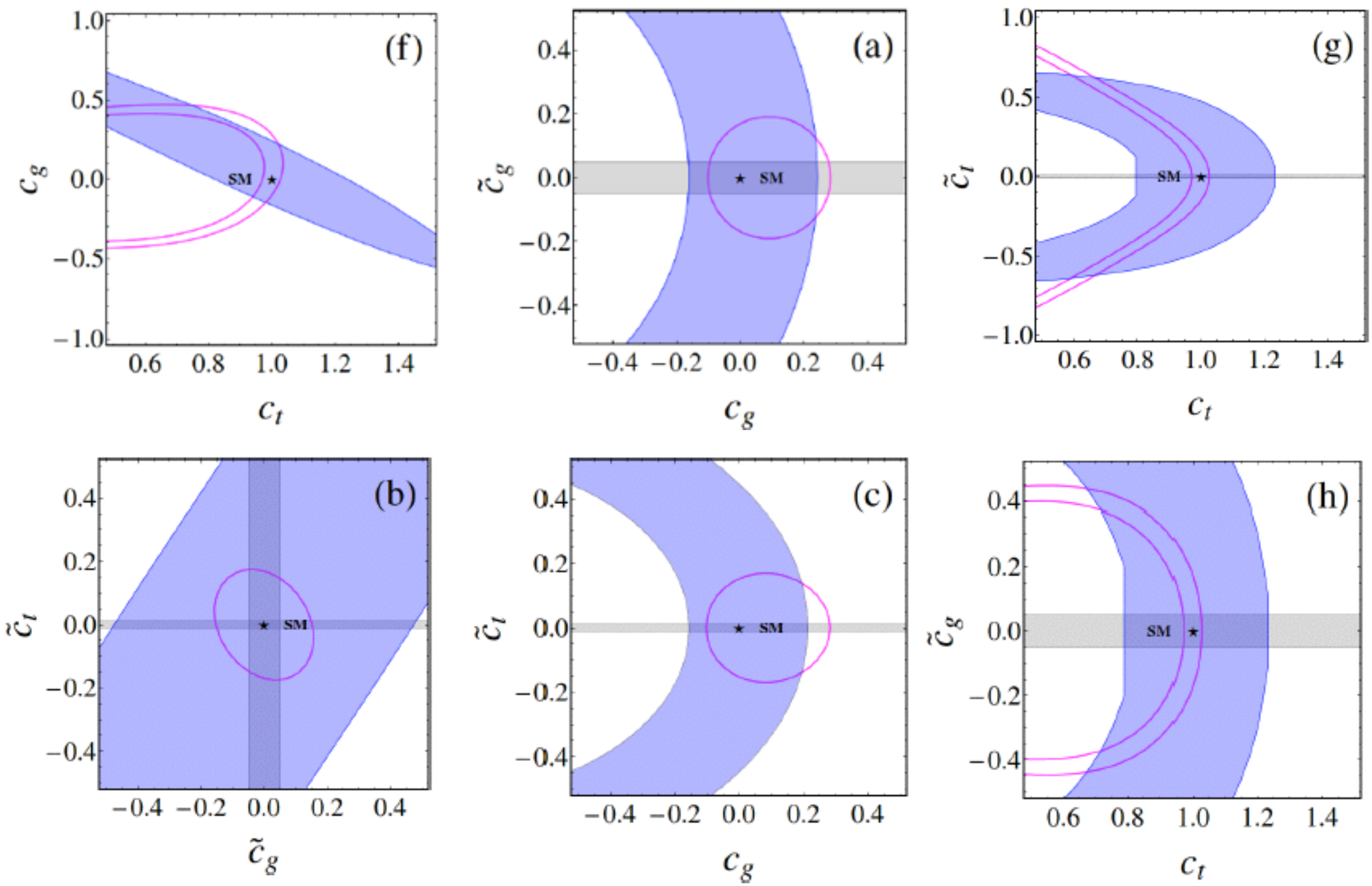
Resolving the degeneracy

- Resolving the degeneracy at 14TeV LHC.



Resolving the degeneracy

- From 14 TeV LHC to 100 TeV *pp* collider 30ab^{-1}.



Summary

- Some NP model might predict the same results with the SM in the single Higgs processes.

SM single Higgs result $\not\Rightarrow$ SM-like Higgs

- A precise measurement of the single Higgs processes can not resolve this degeneracy.
- The measurement of the Higgs pair process can help us resolve the degeneracy.
- At 100 TeV *pp* collider, a precise measurement of the Higgs pair processes is possible, and can help us understand the properties of the Higgs boson.

Thank you!

Back up

$$
\begin{aligned}
\frac{d^2\sigma}{dm_{hh}d\eta} &= \frac{m_{hh}}{S}\int dx_1 dx_2 \left|\frac{\partial\hat{\eta}}{\partial\eta}\right| H\left(m_{hh},\hat{\eta}\left(m_{hh},\eta,\frac{x_1}{x_2}\right),\mu_r\right) f_{g/p}\left(x_1,\mu_f\right) f_{g/p}\left(x_2,\mu_f\right)\delta\left(x_1x_2S-m_{hh}^2\right) \\
&= \int_{m_{hh}^2/S}^1 \frac{m_{hh}dx_1}{x_1S^2} H\left(m_{hh},\hat{\eta}\left(m_{hh},\eta,\frac{x_1^2S}{m_{hh}^2}\right),\mu_r\right) f_{g/p}\left(x_1,\mu_f\right) f_{g/p}\left(\frac{m_{hh}^2}{x_1S},\mu_f\right)\left|\frac{\partial\hat{\eta}}{\partial\eta}\right|.
\end{aligned}
$$

$$
\frac{\partial\hat{\eta}}{\partial\eta} = \frac{\sqrt{\Delta^2+4x_1x_2\beta^2\mathrm{sech}^2\hat{\eta}}}{\left(x_1+x_2\right)\beta+\left(x_1-x_2\right)\tanh\hat{\eta}},
$$

$$
\begin{aligned}
\tilde{\Sigma}\left(\tilde{m}_{hh},S,\mu_f\right) &\equiv \int dm_{hh}\int_{\tilde{m}_{hh}^2/S}^1 \frac{dx_1}{x_1} f_{g/p}\left(\frac{\tilde{m}_{hh}^2}{x_1S},\mu_f\right) f_{g/p}\left(x_1,\mu_f\right) \\
&\quad\times\int d\eta\left|\frac{\partial\hat{\eta}}{\partial\eta}\right|_{\tilde{m}_{hh},\eta,x_1}\epsilon\left(m_{hh},\tilde{m}_{hh},x_1,\eta\right),
\end{aligned}
$$

$$
\frac{d\sigma}{dm_{}} \qquad\qquad \frac{\hat{\eta}}{\eta}\Big|_{m_{hh},\eta,x_1}
$$

$$
\sigma_{\text{after cuts}} = \int d\tilde{m}_{hh}\frac{\tilde{m}_{hh}}{S^2}H\left(\tilde{m}_{hh},\mu_r\right)\tilde{\Sigma}\left(\tilde{m}_{hh},S,\mu_f\right).
$$

$$
\begin{aligned}
\sigma_{\text{after cuts}} &= \int dm_{hh}d\tilde{m}_{hh}\frac{\tilde{m}_{hh}}{S^2}H\left(\tilde{m}_{hh},\mu_r\right)\int_{\tilde{m}_{hh}^2/S}^1\frac{dx_1}{x_1}f_{g/p}\left(\frac{\tilde{m}_{hh}^2}{x_1S},\mu_f\right)f_{g/p}\left(x_1,\mu_f\right) \\
&\quad\times\int d\eta\left|\frac{\partial\hat{\eta}}{\partial\eta}\right|_{\tilde{m}_{hh},\eta,x_1}\epsilon\left(m_{hh},\tilde{m}_{hh},x_1,\eta\right).
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\sigma}{dm_{hh}} &= \frac{m_{hh}}{S^2} H\left(m_{hh},\mu_r\right) \int_{m_{hh}^2/S}^1 \frac{dx_1}{x_1} f_{g/p}\left(\frac{m_{hh}^2}{x_1 S},\mu_f\right) f_{g/p}\left(x_1,\mu_f\right) \int d\eta \left|\frac{\partial\hat{\eta}}{\partial\eta}\right|_{m_{hh},\eta,x_1} \\
&\equiv \frac{m_{hh}}{S^2} H\left(m_{hh},\mu_r\right) \Sigma\left(m_{hh},S,\mu_f\right).
\end{aligned}
$$

$$
\begin{aligned}
\sigma_{\text{after cuts}} &= \int dm_{hh} d\tilde{m}_{hh} \frac{\tilde{m}_{hh}}{S^2} H\left(\tilde{m}_{hh},\mu_r\right) \int_{\tilde{m}_{hh}^2/S}^1 \frac{dx_1}{x_1} f_{g/p}\left(\frac{\tilde{m}_{hh}^2}{x_1 S},\mu_f\right) f_{g/p}\left(x_1,\mu_f\right) \\
&\quad \times \int d\eta \left|\frac{\partial\hat{\eta}}{\partial\eta}\right|_{\tilde{m}_{hh},\eta,x_1} \epsilon\left(m_{hh},\tilde{m}_{hh},x_1,\eta\right).
\end{aligned}
$$

$$
\begin{aligned}
\tilde{\Sigma}\left(\tilde{m}_{hh},S,\mu_f\right) &\equiv \int dm_{hh} \int_{\tilde{m}_{hh}^2/S}^1 \frac{dx_1}{x_1} f_{g/p}\left(\frac{\tilde{m}_{hh}^2}{x_1 S},\mu_f\right) f_{g/p}\left(x_1,\mu_f\right) \\
&\quad \times \int d\eta \left|\frac{\partial\hat{\eta}}{\partial\eta}\right|_{\tilde{m}_{hh},\eta,x_1} \epsilon\left(m_{hh},\tilde{m}_{hh},x_1,\eta\right),
\end{aligned}
$$

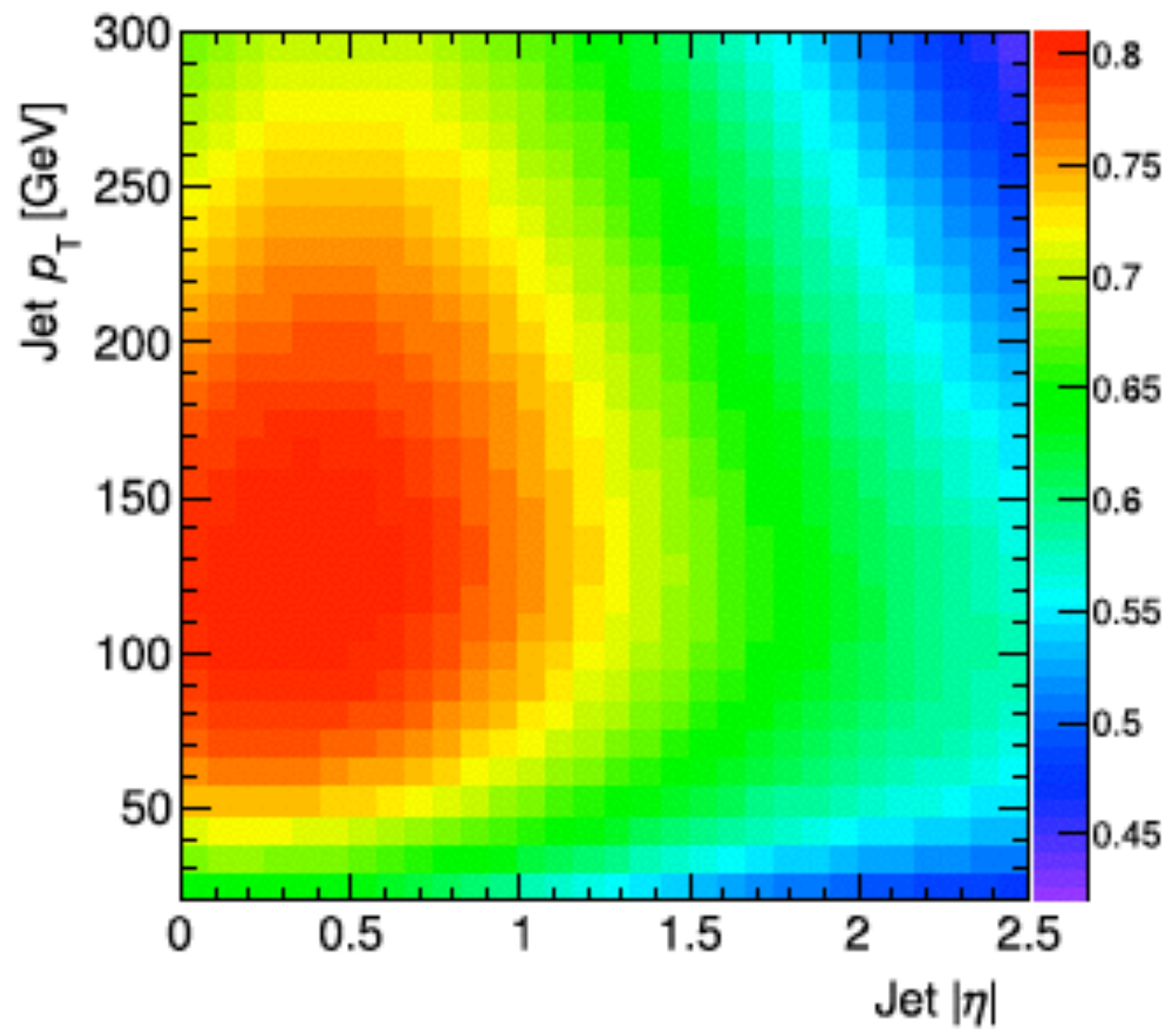
$$
\sigma_{\text{after cuts}} = \int d\tilde{m}_{hh} \frac{\tilde{m}_{hh}}{S^2} H\left(\tilde{m}_{hh},\mu_r\right) \tilde{\Sigma}\left(\tilde{m}_{hh},S,\mu_f\right).
$$

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

$$\epsilon_b\,(p_T, \eta) = 0.85 \tanh\left(\frac{p_T + 50}{75}\right) \tanh\left(\frac{450}{p_T + 80}\right) \times \left[0.75 + 0.25 e^{-\left(|\eta| - \sqrt{p_T/1000}\right)^2/1.6}\right] \times e^{-|\eta|^3 p_T/2200},$$

$$\sigma\,(\text{GeV}) = 0.3 \oplus 0.10 \times \sqrt{E(\text{GeV})} \oplus 0.010 \times E(\text{GeV}), \quad \text{for } |\eta| < 1.37,$$
$$\sigma\,(\text{GeV}) = 0.3 \oplus 0.15 \times \sqrt{E(\text{GeV})} \oplus 0.015 \times E(\text{GeV}), \quad \text{for } 1.52 < |\eta| < 2.37.$$

$$\epsilon_\gamma\,(p_T) = 0.76 - 1.98 \exp\left(-\frac{p_T}{16.1\,\text{GeV}}\right).$$



γ isolation $R = 0.4$, jets: anti-kt, parameter $R = 0.4$, $\Delta R_{bb} < 3.5$, $\Delta R_{\gamma\gamma} < 3.5$,
$p_T^{b_1} > 60$ GeV, $p_T^{b_2} > 35$ GeV, $|\eta^b| < 4.5$, $p_T^{\gamma_1} > 60$ GeV, $p_T^{\gamma_2} > 35$ GeV, $|\eta^\gamma| < 4.5$,
$p_T(bb) > 100$ GeV, $p_T(\gamma\gamma) > 100$ GeV, 100 GeV $< m_{b\bar{b}} <$ 150 GeV, 120.5 GeV $< m_{\gamma\gamma} <$ 129.5 GeV,

$$p_{b\to b} = 0.75,\ p_{c\to b} = 0.1,\ p_{j\to b} = 0.01.$$

$$p_{j\to\gamma} = \alpha \exp(-p_{T,j}/\beta)\ , \alpha = 0.01\ , \beta = 30 \text{ GeV}.$$

$$\epsilon_\gamma(p_T) = \begin{cases} 95\%, & \text{for } |\eta| < 1.5, \\ 90\%, & \text{for } 1.4 < |\eta| < 4, \\ 80\%, & \text{for } 4 < |\eta| < 6. \end{cases}$$

$$\mathcal{A}(M_{hh}) = \begin{cases} c_1 \left[1 - \sqrt{\dfrac{M_{hh}^2 (1-\cos\Delta R_0) - 8\,(m_H - \delta m_1)^2}{(1-\cos\Delta R_0)\left(M_{hh}^2 - 4\,(m_H - \delta m_1)^2\right)}}\right]^{\gamma_c}, & M_{hh} > M_{hh}^{(t)}, \\ c_2 \left[1 - \dfrac{4(p_{\mathrm{T,cut}}^h)^2}{M_{hh}^2 - 4\,(m_H - \delta m_2)^2}\right]^{\beta_a} \left(\dfrac{M_{hh}}{\sqrt{s}}\right)^{\beta_b} \left[1 + \beta_c \left(\dfrac{M_{hh}}{\sqrt{s}}\right) \log\left(\dfrac{2M_{hh}}{\sqrt{s}}\right)\right], & 329.3 \text{ GeV} < M_{hh} < M_{hh}^{(t)}, \\ 0, & M_{hh} < 329.3 \text{ GeV}. \end{cases} \tag{59}$$

The fitting parameters are $c_1 = 1.1378$, $c_2 = 11.02$, $\delta m_1 = 50$ GeV, $\gamma_c = 1.675$, $\delta m_2 = 2.5$ GeV, $\beta_a = 1.13$, $\beta_b = 1.48$, $\beta_c = 4.88$, $\Delta R_0 = 0.4$ and $M_{hh}^t = 1260$ GeV [57].

$$\mathcal{A}(m_{hh}) = \begin{cases} c_1 \left[1 - \sqrt{\dfrac{m_{hh}^2 (1-\cos\Delta R_0) - 8\,(m_h - \delta m_1)^2}{(1-\cos\Delta R_0)\left(m_{hh}^2 - 4\,(m_h - \delta m_1)^2\right)}}\right]^{\gamma_c}, & m_{hh} > M_{hh}^{(t)}, \\ c_2 \left[1 - \dfrac{4(p_{\mathrm{T,cut}}^h)^2}{m_{hh}^2 - 4\,(m_h - \delta m_2)^2}\right]^{\beta_a} \left(\dfrac{2m_h}{m_{hh}}\right)^{\beta_b} \left[1 + \beta_c \left(\dfrac{2m_h}{m_{hh}}\right) \log\left(\dfrac{2m_h}{m_{hh}}\right)\right], & 319.9 \text{ GeV} < m_{hh} < M_{hh}^{(t)}, \\ 0, & m_{hh} < 319.9 \text{ GeV}. \end{cases} \tag{54}$$

where the fitting parameters $\delta m_1 = \delta m_2 = 0.15$ GeV, $\Delta R_0 = 0.4$, $c_1 = 40.30$, $\gamma_c = 0.938$, $c_2 = 8.269$, $\beta_a = 1.241$, $\beta_b = -0.565$, $\beta_c = -2.057$, and $M_{hh}^{(t)} = 1277.5$GeV, in the low detector performance scenario.