# A Lone Higgs Scenario and Higgs Pair Production

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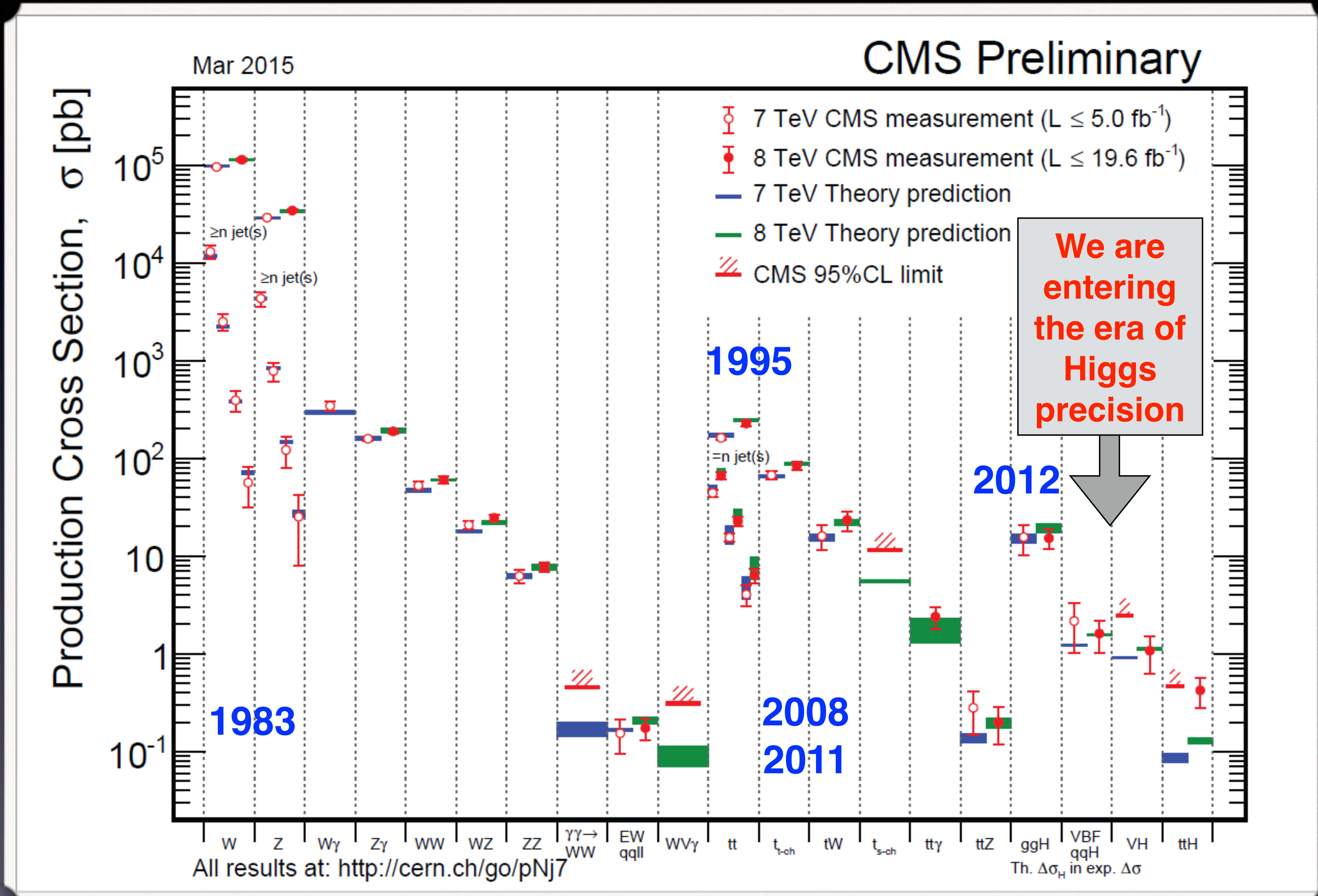
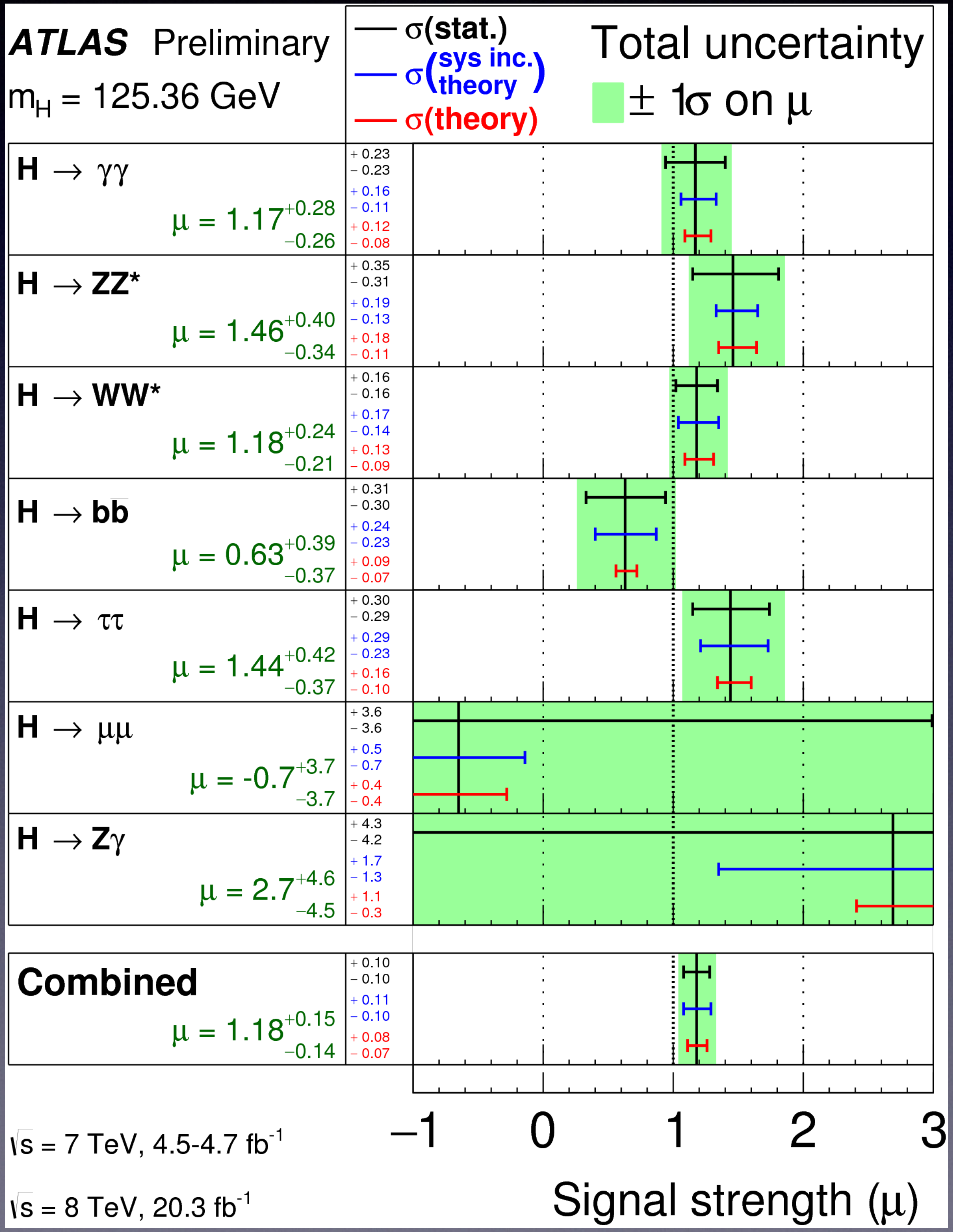
In collaboration with
1) Bin Yan, Dong-Ming Zhang, Hao Zhang, arXiv:1508.xxxxx
2) Hao-ran Wang, Ya Zhang, arXiv:1505.00654

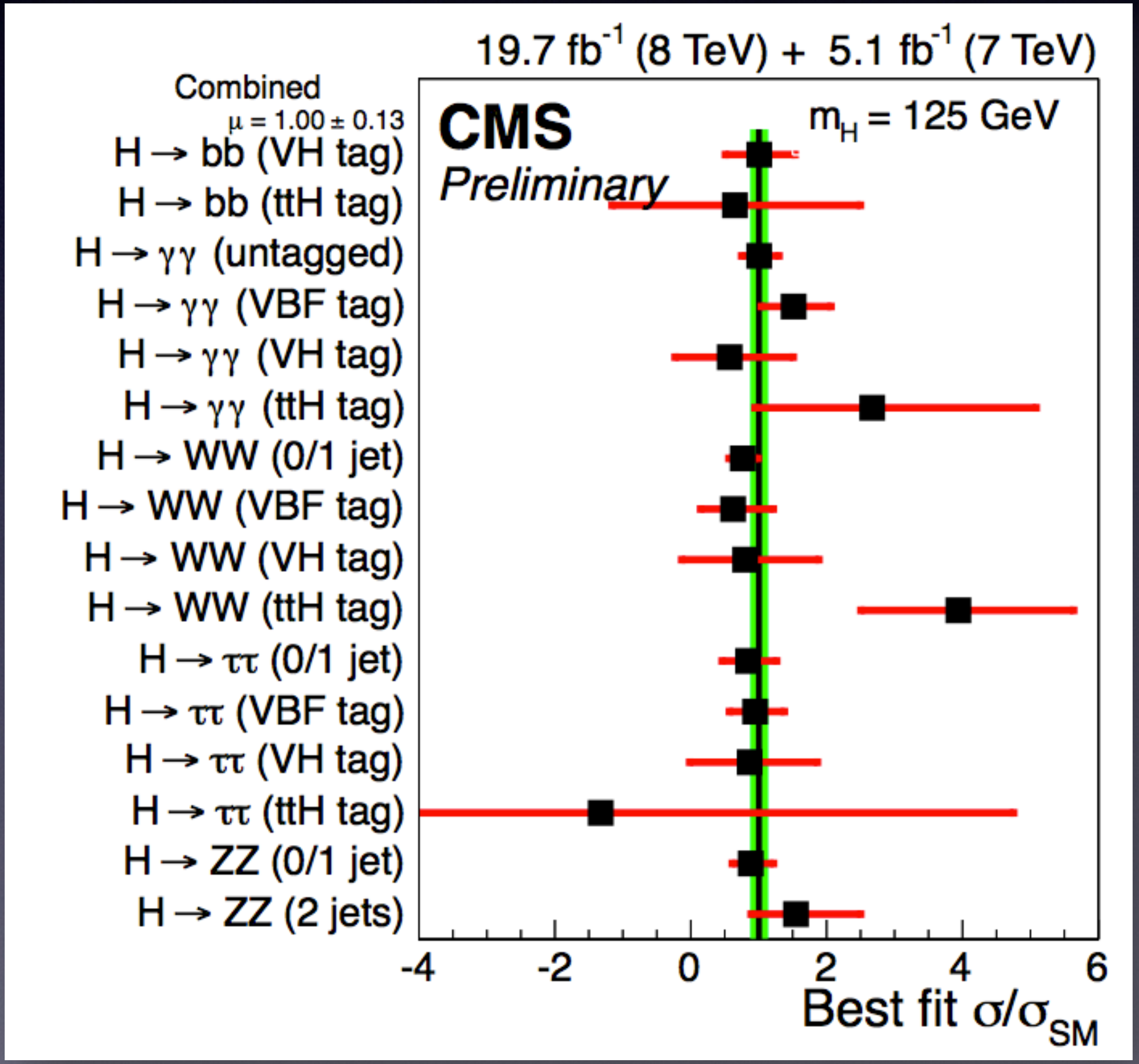
# LHC: A Precision Machine



# Era of Higgs Precision

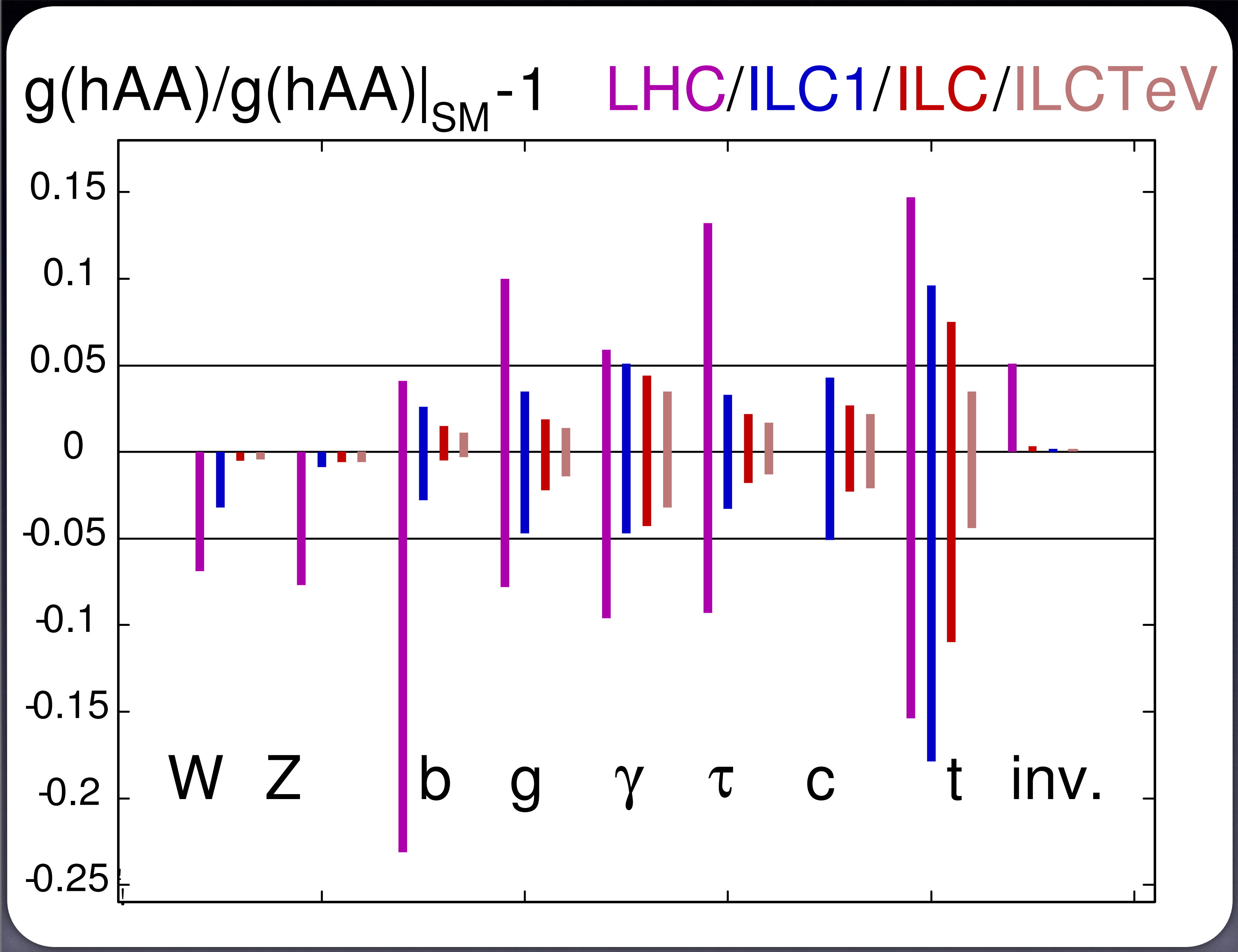
## Higgs boson coupling measurements



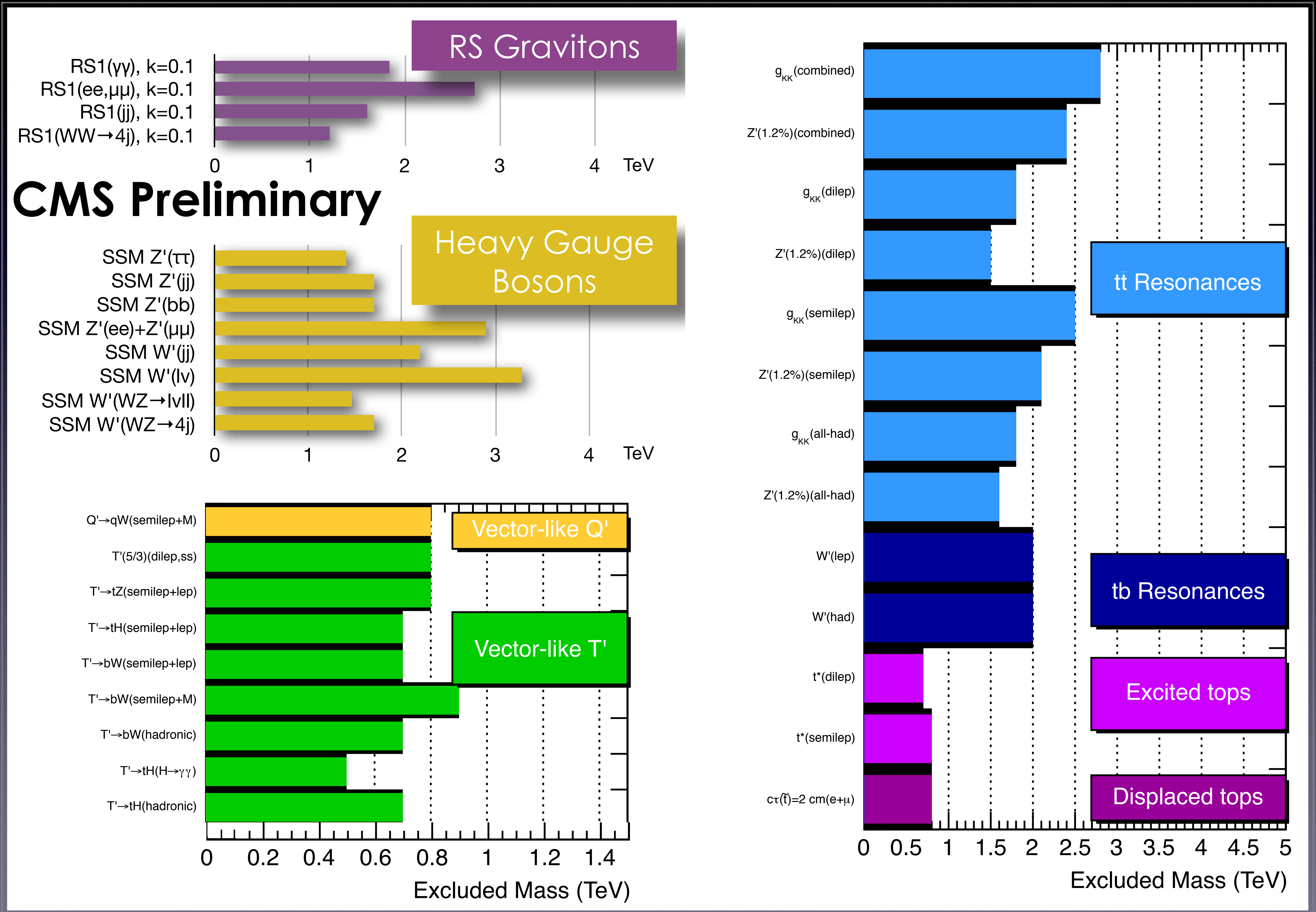
# Era of Higgs Precision

## Higgs boson coupling strength measurements




**The sign of each coupling is also important**

# New Physics? No Hint At All!



# A Lone Higgs Scenario
# ( nightmare scenario )

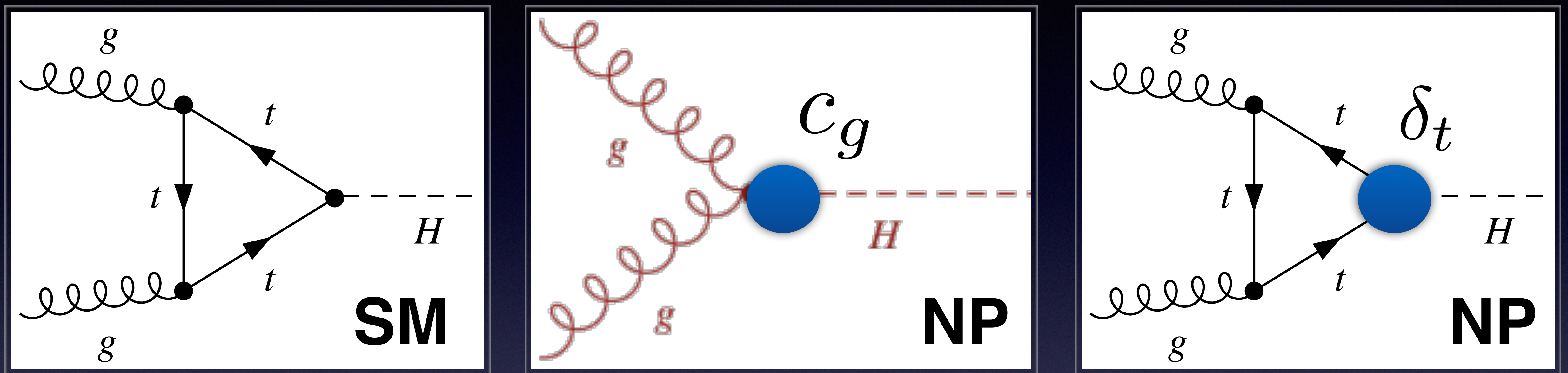
- What if we end up with a SM-like Higgs boson and nothing else at the LHC Run-2 (13TeV and ~300$fb^{-1}$)?

- Does it mean the new physics scale must be very high?

- If yes, we will go for a high energy machine if money is not the issue.

- If not, luckily for us, then where is the NP particles?
  Or, what can we learn from the data? Any loophole?

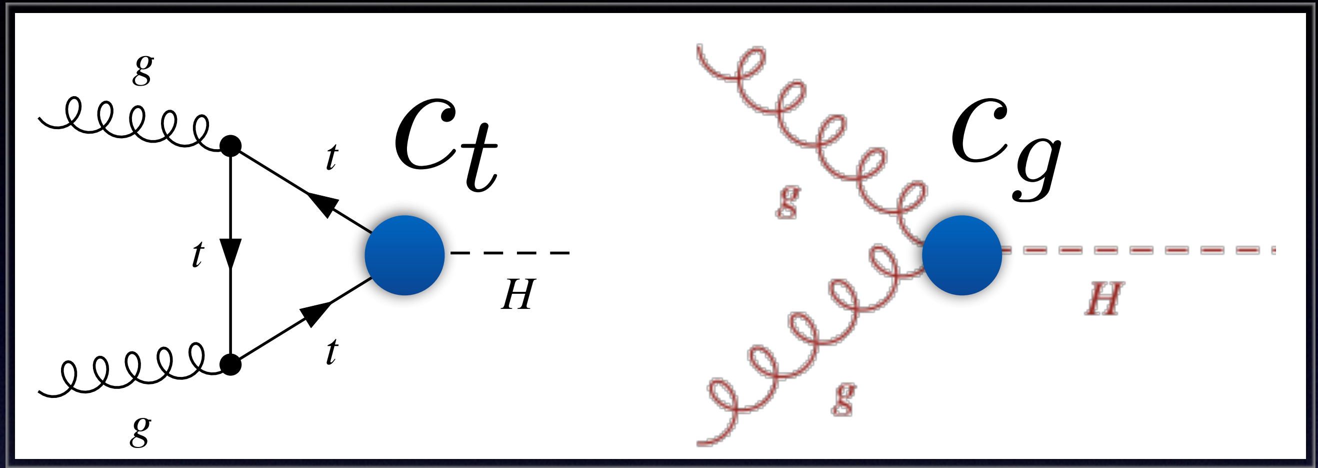
# Single Higgs Production

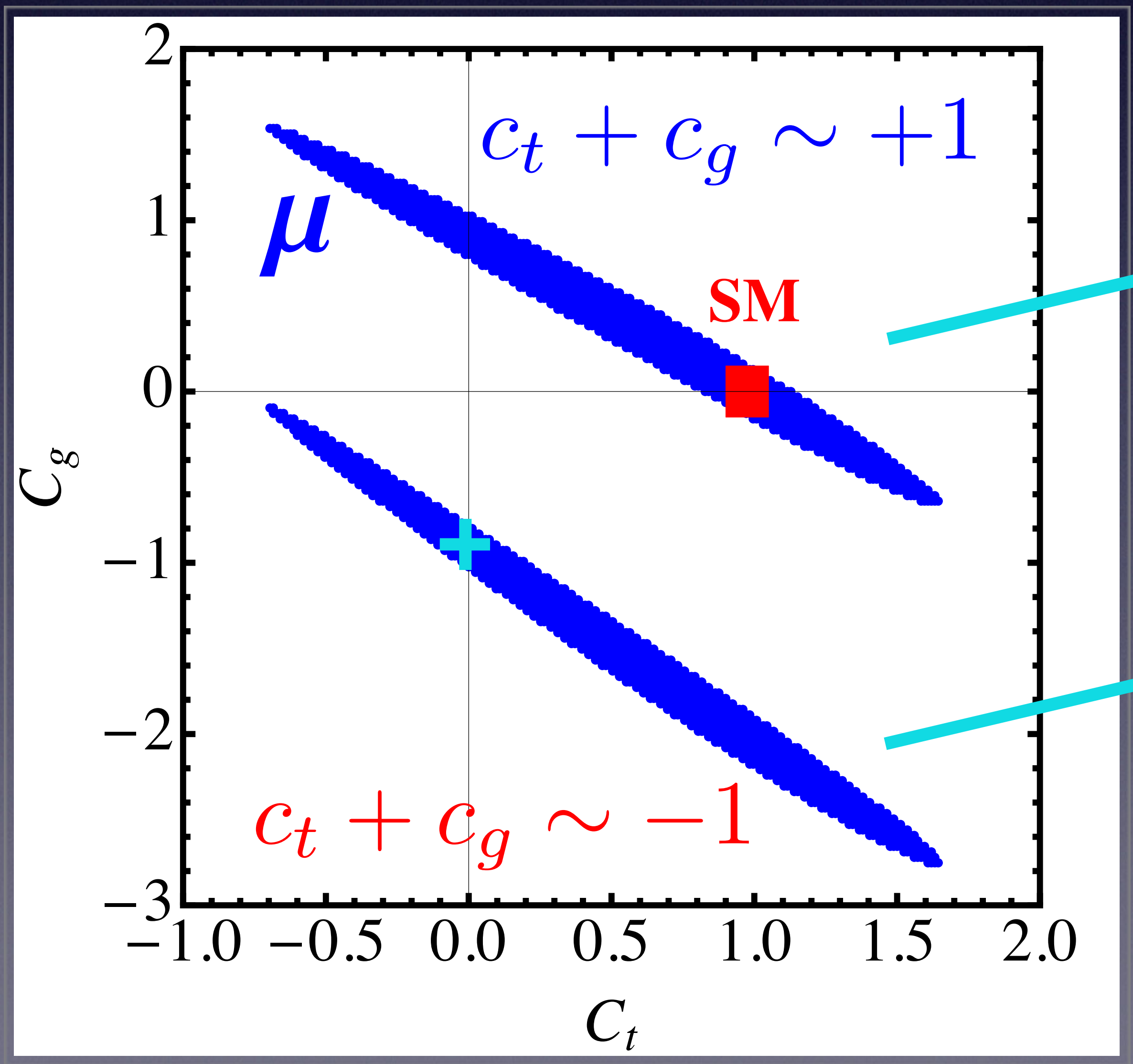



$$\mathcal{L} \sim \frac{m_t c_t}{v} H \bar{t}_L t_R + \frac{\alpha_s c_g}{12\pi v} H G^a_{\mu\nu} G_a^{\mu\nu} + h.c.$$

$$c_t \equiv 1 + \delta_t$$

# A Lone Higgs and Faked-No-New-Physics Scenario




$\mathcal{M}_{\rm NP} + \mathcal{M}_{\rm SM} \sim +\mathcal{M}_{\rm SM}$

$\mathcal{M}_{\rm NP} \sim 0 \quad \Lambda_{\rm NP}$ 很高

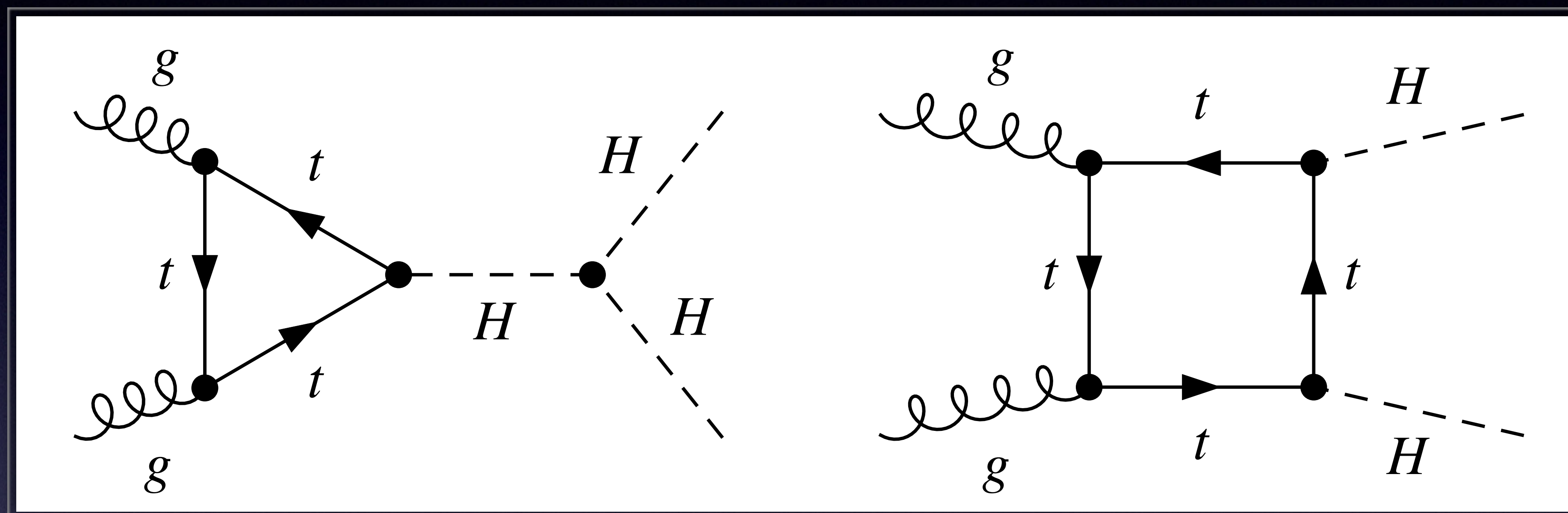
$\mathcal{M}_{\rm NP} + \mathcal{M}_{\rm SM} \sim -\mathcal{M}_{\rm SM}$

(Faked-No-New-Physics)

It is interesting,
but how to rule it out?

# Higgs Pair Production

The best channel to measure the Higgs self interaction




$HH \to b\bar{b}, b\bar{b}$ Papaefstathiou, L. L. Yang, J. Zurita, 1209.1489

$HH \to b\bar{b}, W^+W^-$ Ferreira de Lima, Papaefstathiou, Spannowsky, 1404.7139

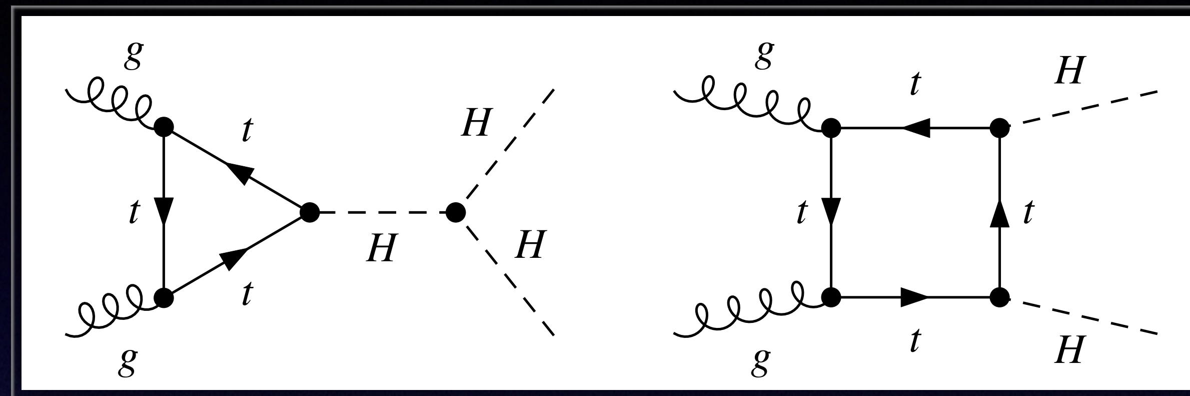
$HH \to W^+W^-, W^+W^-$ Q. Li, Z. Li, Q.-S. Yan, X. Zhao, 1503.07611

$HH \to b\bar{b}, \tau^+\tau^-$ Dolan, Englert, Spannowsky, 1206.5001

$HH \to b\bar{b}, \gamma\gamma$ H.-J. He, J. Ren, and W. Yao (2015), 1506.03302

# Higgs Pair Production

## The two diagrams cancel each other out and yield a tiny rate

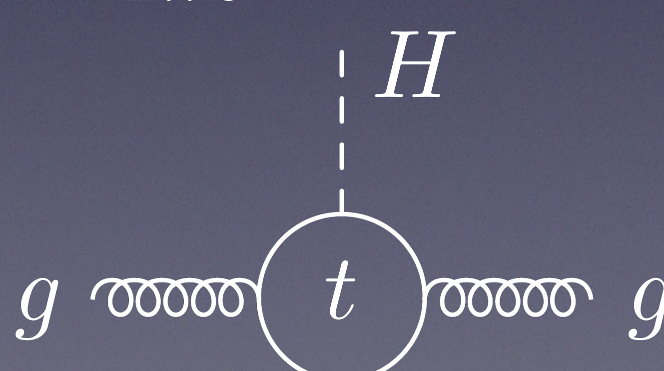


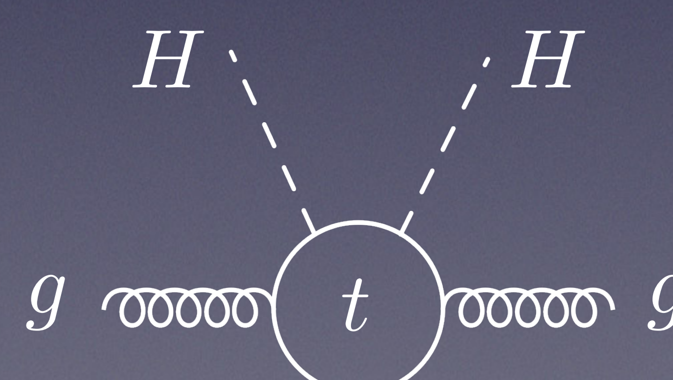

**Low Energy Theorem** Dawson and Haber (1989)


$$\sim -\frac{\alpha_s}{24\pi} G^a_{\mu\nu} G^{\mu\nu}_a \log \frac{\Lambda^2}{m_t^2}$$

$$y_t \frac{\partial}{\partial m_t}, y_t^2 \frac{\partial^2}{\partial m_t^2}$$

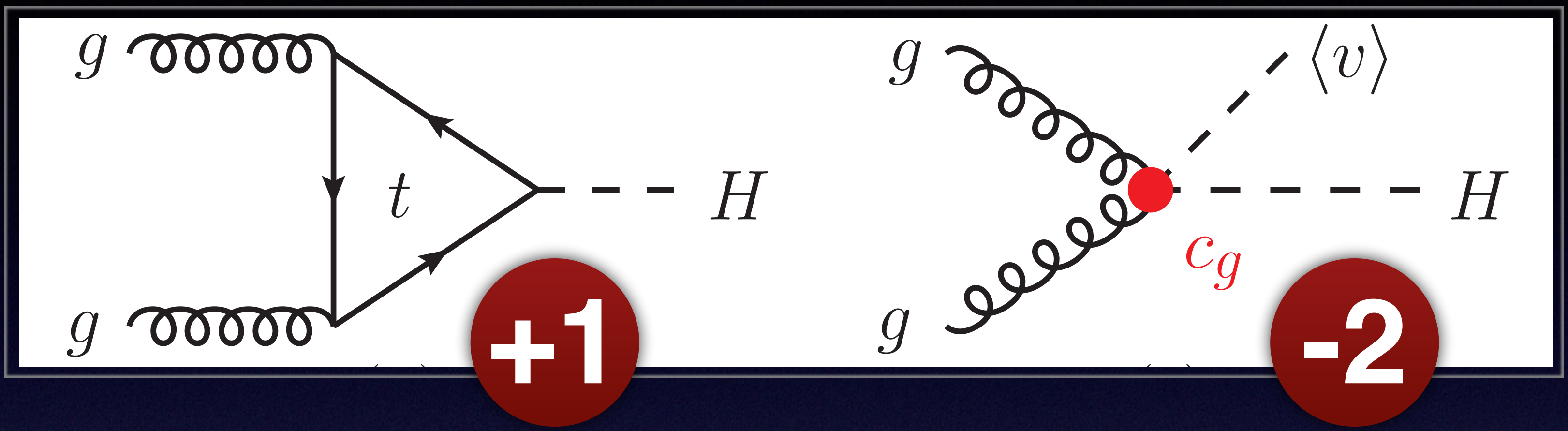
$$\frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{\mu\nu}_a H \quad - \quad \frac{\alpha_s}{24\pi v} G^a_{\mu\nu} G^{\mu\nu}_a H^2$$



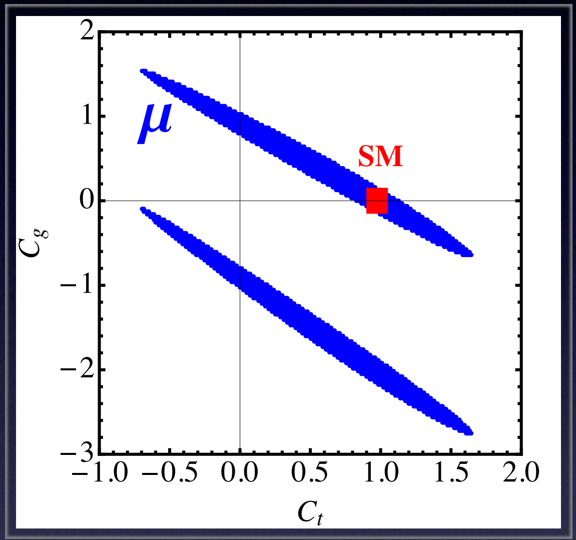



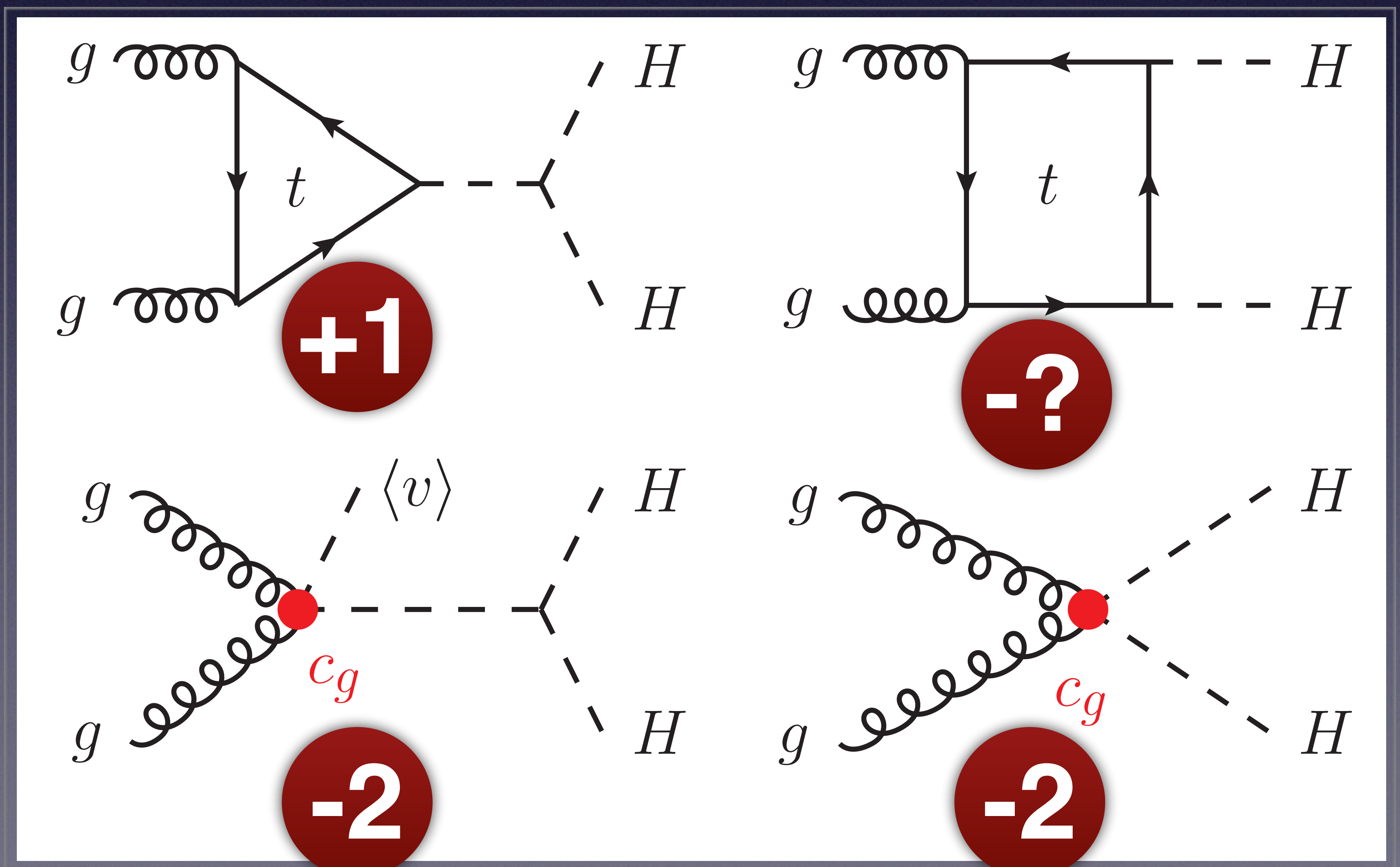

*But* Higgs pair is a powerful tool to exclude NP models

# Single Higgs versus Double Higgs




$$O_G = \frac{c_g}{\Lambda^2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$




In the FNNP:

$$c_g + c_t \simeq -1$$

$$\mathcal{M}_{\rm NP} \sim -2\mathcal{M}_{\rm SM}$$

**Large enhancement to HH pair production**

# Higgs Effective Field Theory

$$O_{\phi t} = \phi^\dagger \phi \bar{q}_L \tilde{\phi} t_R, \qquad O_{\phi g} = \phi^\dagger \phi G^a_{\mu\nu} G^{\mu\nu}_a,$$

$$O_{\phi 1} = \frac{1}{2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi), \qquad O_{\phi 2} = (\phi^\dagger\phi)^3,$$

$$O_{\phi D} = (D_\mu\phi)^\dagger \phi \phi^\dagger D^\mu \phi.$$

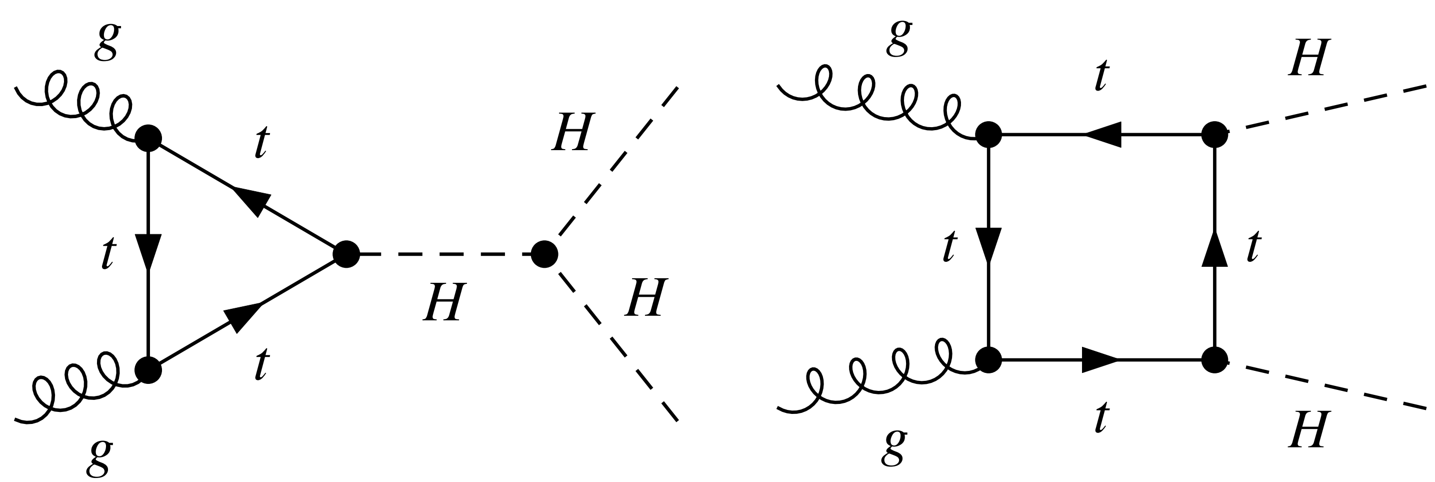
$$\mathcal{L}_{relevant} = -\frac{m_H^2}{2v} c_3 H^3 - \frac{m_t}{v} c_t \bar{t}_L t_R H - \frac{m_t}{v^2} c_{2H} \bar{t}_L t_R H^2 + \frac{\alpha_s c_g}{12\pi v} H G^a_{\mu\nu} G^{\mu\nu}_a + \frac{\alpha_s c_g}{24\pi v^2} H^2 G^a_{\mu\nu} G^{\mu\nu}_a + h.c.$$

$$c_3 = 1 + \frac{C_{\phi 2} v^2}{\lambda \Lambda^2}, \qquad c_t = 1 + \frac{C_{\phi t} v^2}{y_t \Lambda^2},$$

$$c_{2H} = \frac{3}{2}(c_t - 1), \qquad c_g = \frac{12\pi C_{\phi g} v^2}{\alpha_s \Lambda^2}.$$

# Higgs pair production in the SM

S. Dawson, A. Ismail, and I. Low, 1504.05596




$$|\mathcal{M}|^2_{SM} = (N_c^2 - 1)\frac{\alpha_s^2}{8\pi^2}\frac{\hat{s}^2}{v^4}\left\{\left|\frac{3m_H^2}{\hat{s} - m_H^2}F_\triangle(\hat{s}, \hat{t}, m_H^2, m_t^2) + F_\square(\hat{s}, \hat{t}, m_H^2, m_t^2)\right|^2 + \left|G_\square(\hat{s}, \hat{t}, m_H^2, m_t^2)\right|^2\right\}$$

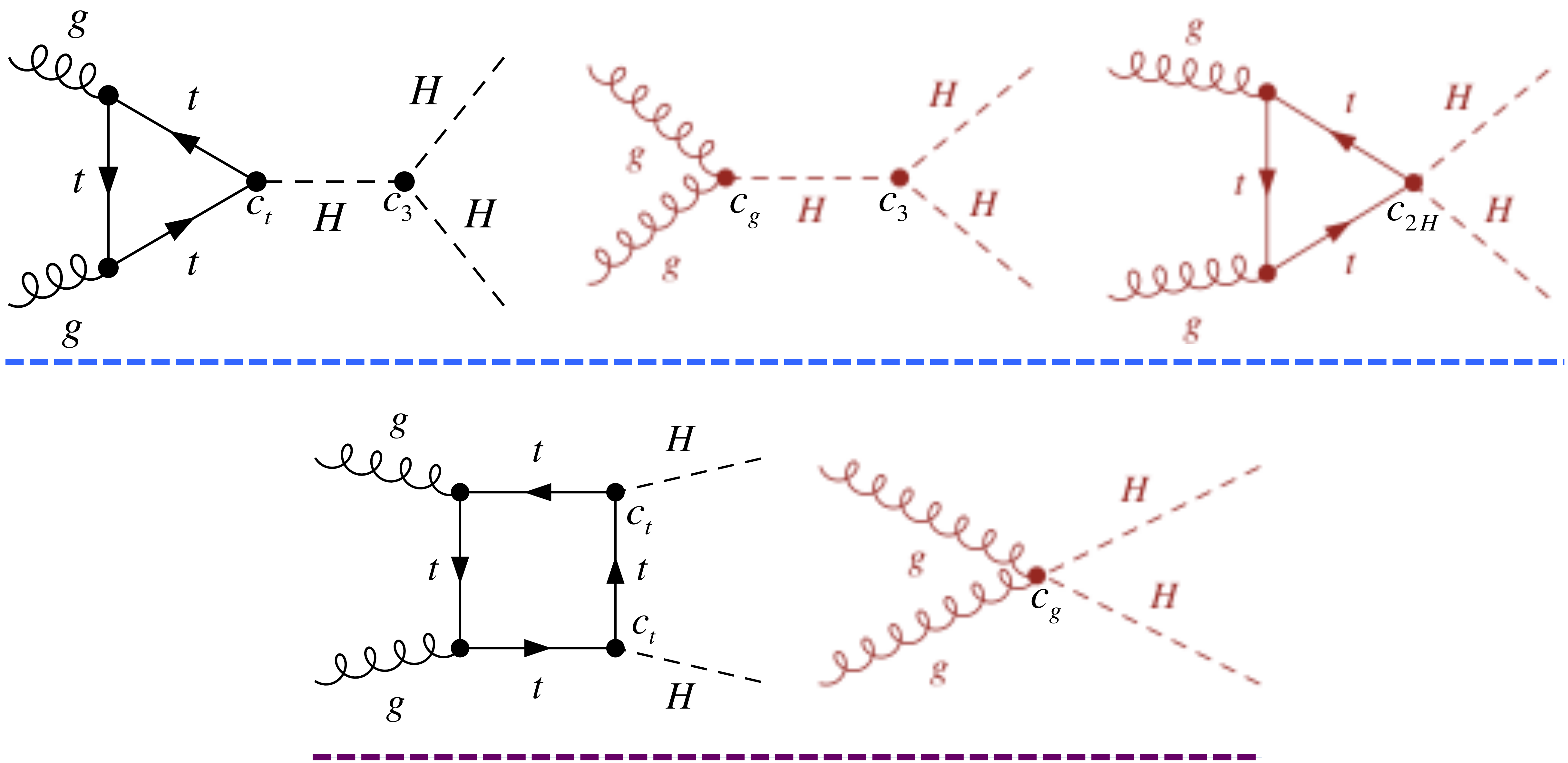
$$F_\triangle(m_t \to \infty) = \frac{2}{3} \qquad F_\triangle \sim d^0_{00}$$

$$F_\square(m_t \to \infty) = -\frac{2}{3} \qquad F_\square \sim d^0_{00}, d^2_{20}$$

$$G_\square(m_t \to \infty) = 0 \qquad G_\square \sim d^2_{20}$$

**s-wave dominates**

# Higgs pair production in NP




$$M_{NP} \sim \frac{3m_H^2}{\hat{s} - m_H^2} c_3 \left( c_t F_\triangle + \frac{2}{3} c_g \right) + 3(c_t - 1) F_\triangle + c_t^2 F_\Box + \frac{2}{3} c_g$$

S. Dawson, A. Ismail, and I. Low, 1504.05596

# Enhanced $HH$ production in FNNP

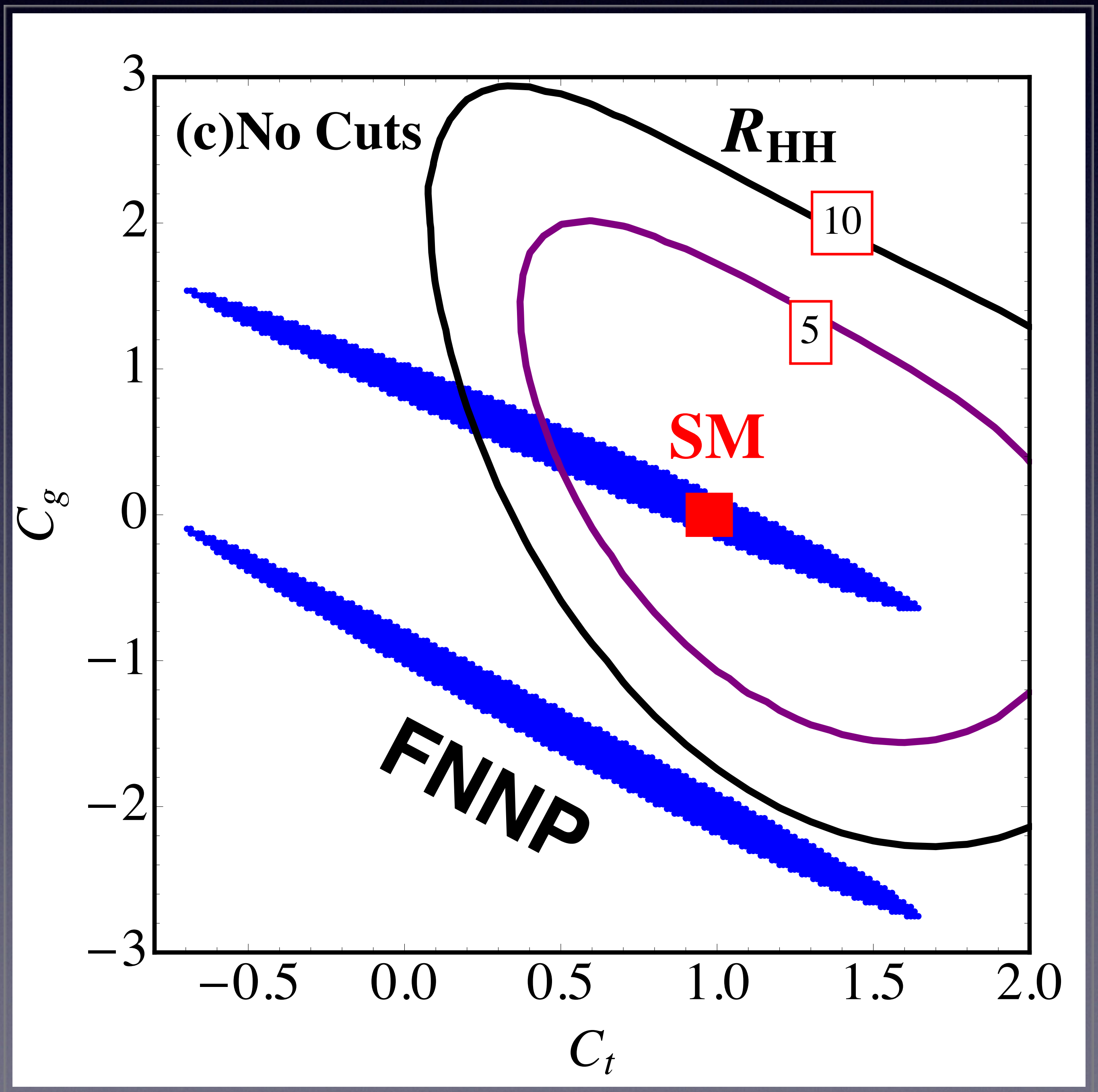
$$\mathcal{M}_{\rm SM} + \mathcal{M}_{\rm NP} \sim \frac{3m_H^2}{\hat{s} - m_H^2}\left(c_t F_\triangle + \frac{2}{3}c_g\right) + 3(c_t - 1)F_\triangle + c_t^2 F_\Box + \frac{2}{3}c_g$$

$$F_\triangle(m_t \to \infty) = \frac{2}{3}$$

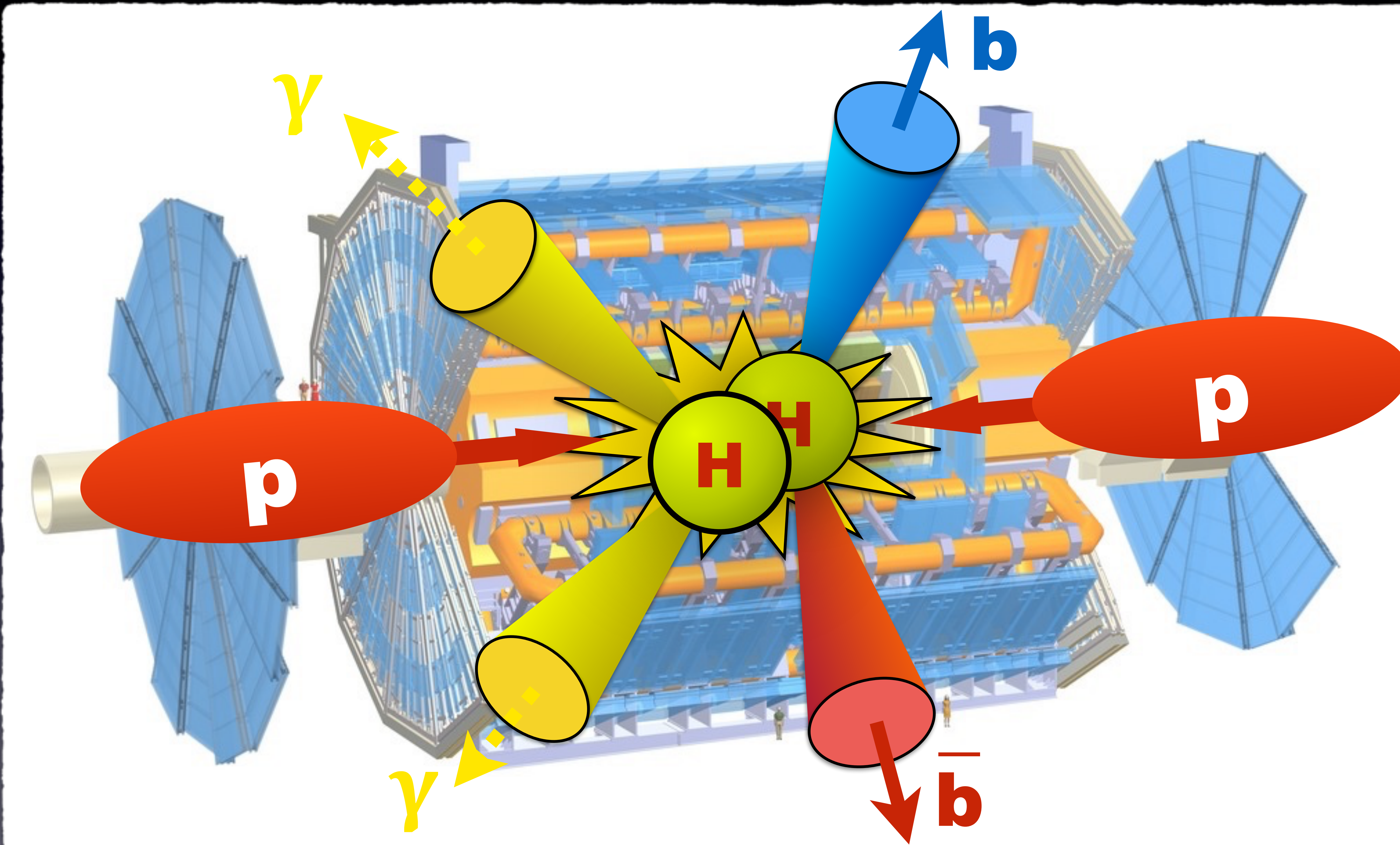
$$F_\Box(m_t \to \infty) = -\frac{2}{3}$$

$$R_{HH} = \frac{\sigma(pp \to HH)_{\rm NP}}{\sigma(pp \to HH)_{\rm SM}}$$

Large enhancement
(easy to be excluded)



# Collider Simulation



# Collider Signature and Cuts

Signature: two b-quarks and two photons

| Event Selection Criteria |
| --- |
| $\geq 2$ isolated photons, with $p_T > 30$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$ |
| $\geq 2$ jets identified as $b$-jets with leading/subleading $p_T > 40/25$ GeV, $\lvert\eta\rvert < 2.5$ |
| No isolated leptons with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$ |
| $< 6$ jets with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$ |
| $0.4 < \Delta R^{b\bar{b}} < 2.0$, $0.4 < \Delta R^{\gamma\gamma} < 2.0$, $\Delta R^{\gamma b} > 0.4$ |
| $100 < m_{b\bar{b}} < 150$ GeV, $123 < m_{\gamma\gamma} < 128$ GeV |
| $p_T^{\gamma\gamma}$, $p_T^{b\bar{b}} > 110$ GeV |

Cuts used to suppress the Huge SM backgrounds

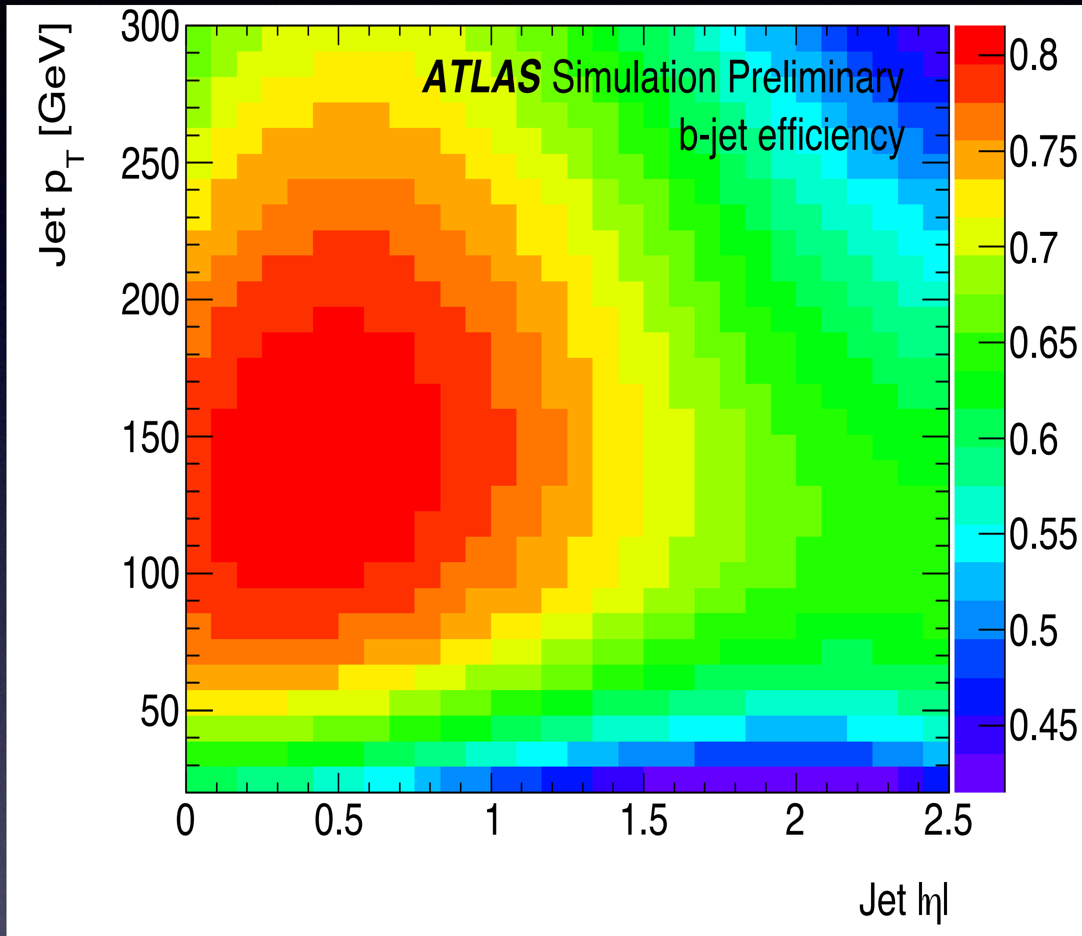
ATL-PHYS-PUB-2014-019

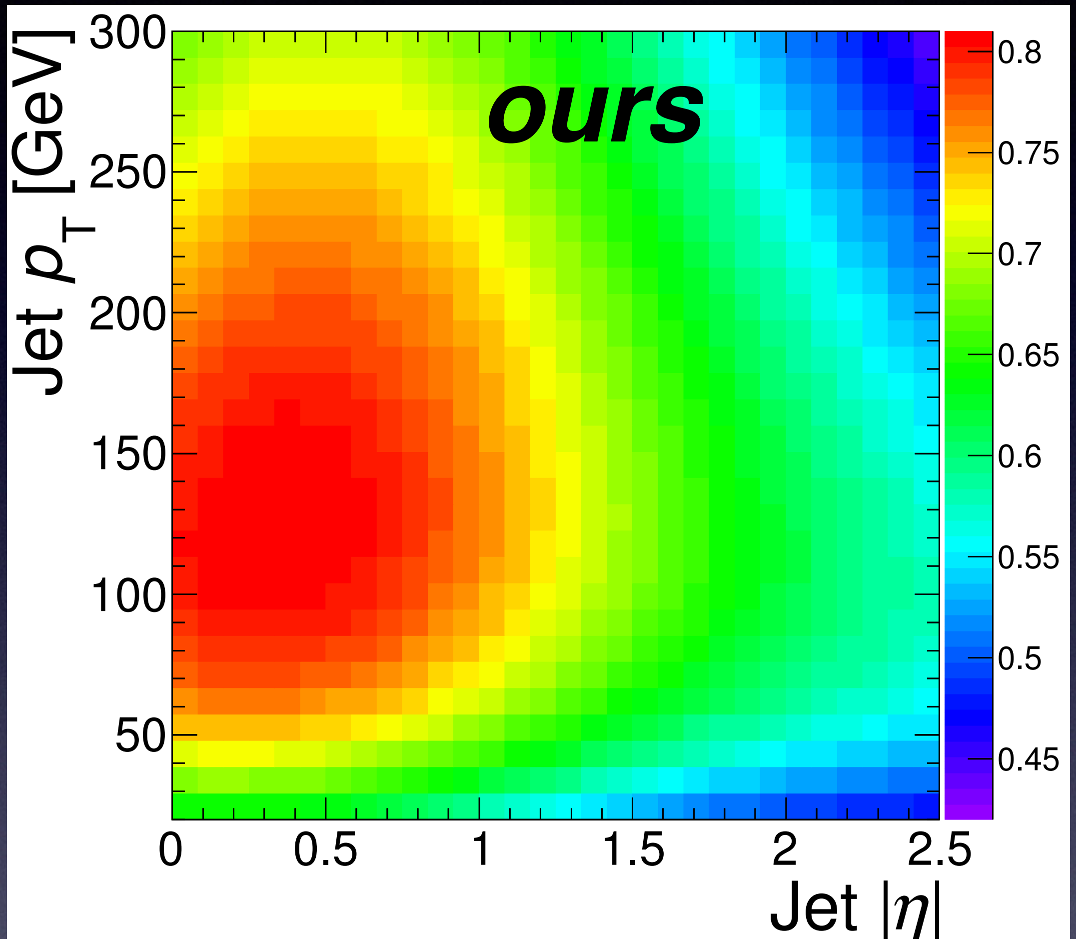
Q: How much luminosity is needed to exclude the FNNP scenario?

# Collider Simulation: Detector Effects

## b-tagging efficiency

ATL-PHYS-PUB-2013-009



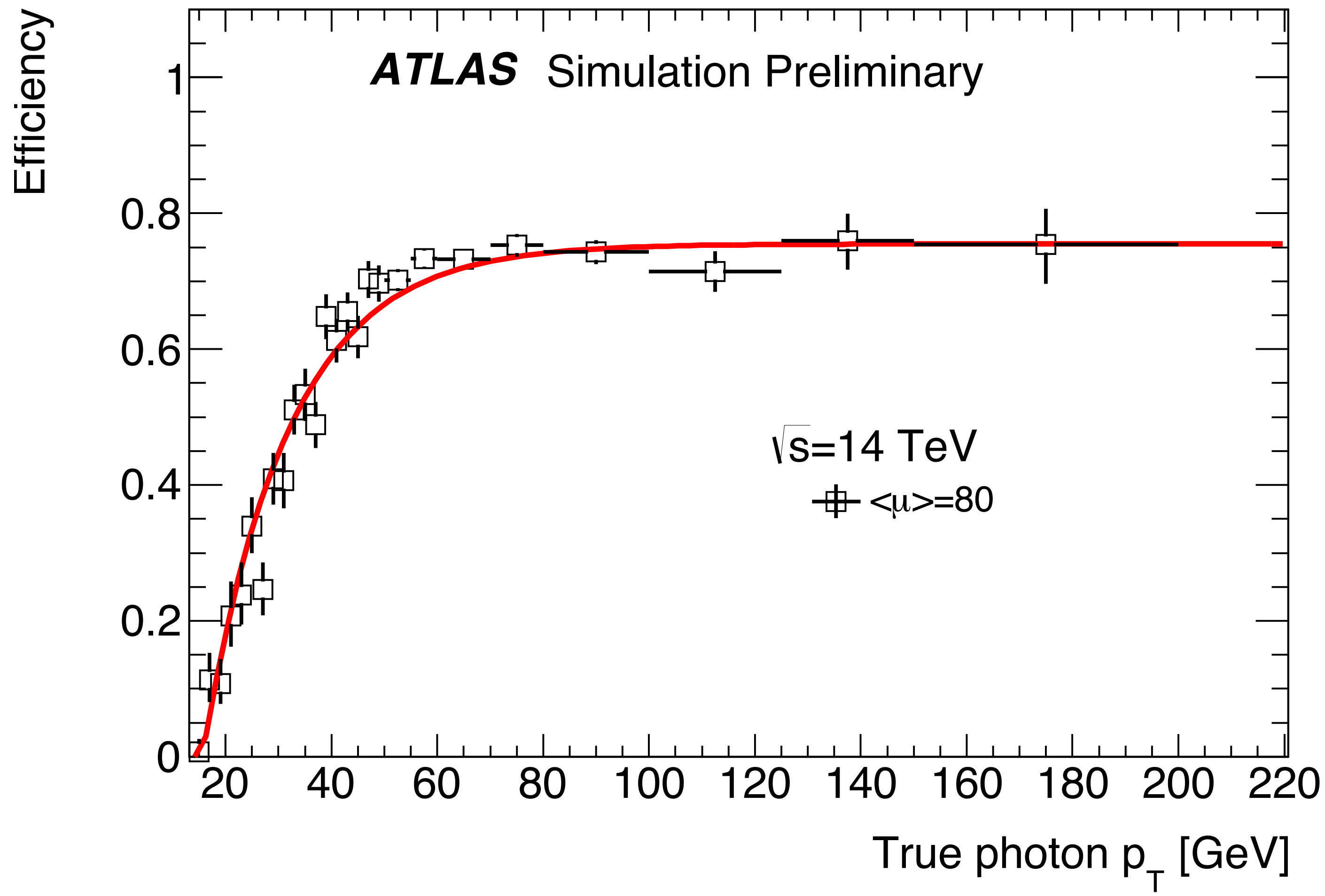

*Our fitting function*

$$\epsilon_b\left(p_{\rm T},\eta\right) = 0.85\tanh\left(\frac{p_{\rm T}+50{\rm GeV}}{75{\rm GeV}}\right)\tanh\left(\frac{450{\rm GeV}}{p_{\rm T}+80{\rm GeV}}\right)\exp\left(-\frac{|\eta|^3 p_{\rm T}}{2.2{\rm TeV}}\right)$$
$$\times\left[0.75+0.25\exp\left(-\frac{\left(|\eta|-\sqrt{p_{\rm T}/1{\rm TeV}}\right)^2}{1.6}\right)\right].$$

# Collider Simulation: Detector Effects

**Photon-identification: (From ATL-PHYS-PUB-2013-009)**

$$\epsilon_\gamma\left(p_{\mathrm{T}}\right) = 0.76 - 1.98\exp\left(-\frac{p_{\mathrm{T}}}{16.1\mathrm{GeV}}\right)$$




**Photon energy resolution: (From ATL-PHYS-PUB-2013-009)**

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

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

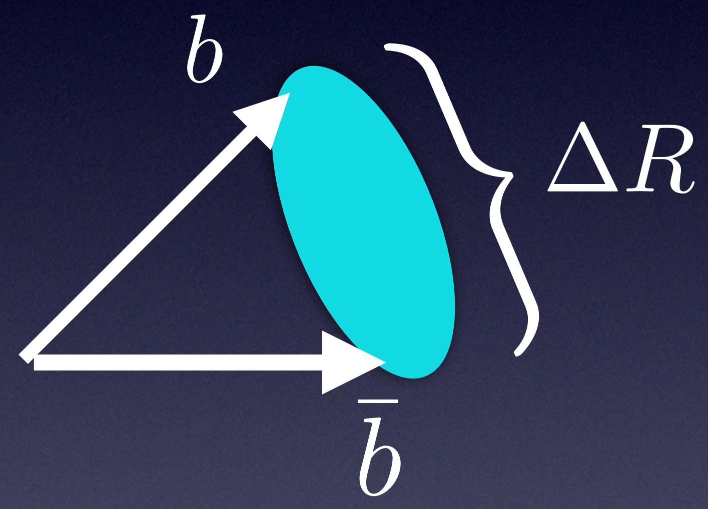
# Collider Simulation: Cut Analysis

- We use the cuts in ATL-PHYS-PUB-2014-019.
- Parton-level simulation. Two b-jets (the leading b-jet $p_T$>40GeV), two photons ($p_T$>30GeV).

$$0.4 < \Delta R_{b\bar{b}} < 2.0$$

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

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




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

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

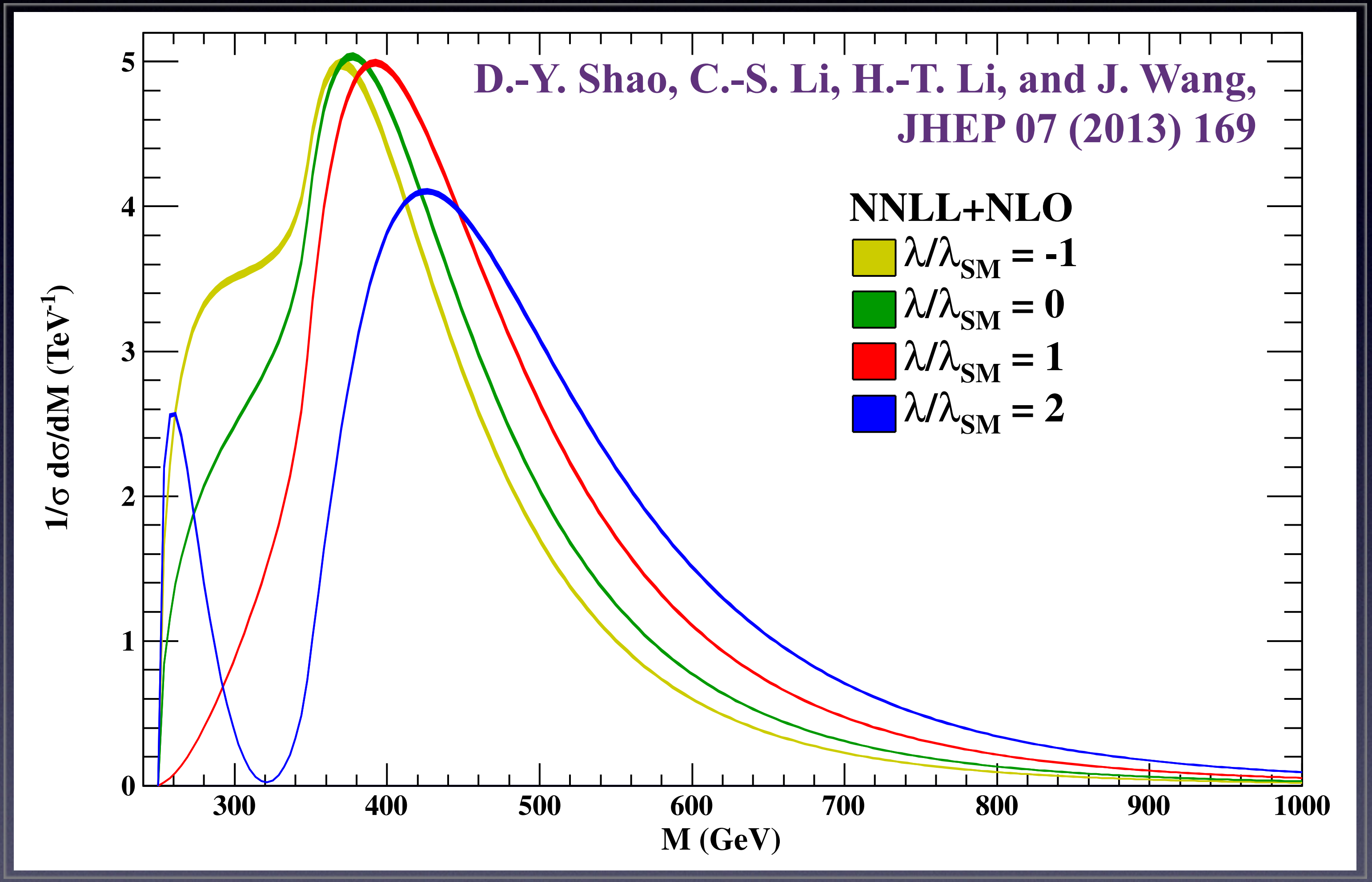
$$p_T^{\gamma\gamma} > 110 \text{ GeV}$$

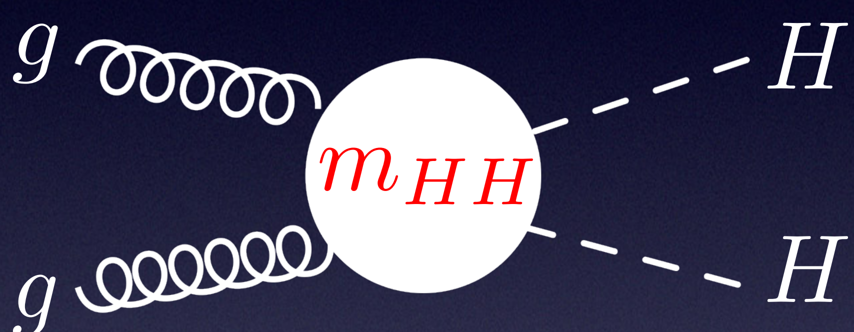
$$p_T^{b\bar{b}} > 110 \text{ GeV}$$

Energetic Higgs boson

# Collider Simulation: Cut Efficiency

Higgs pair production is mainly through the ***s*-wave** scattering



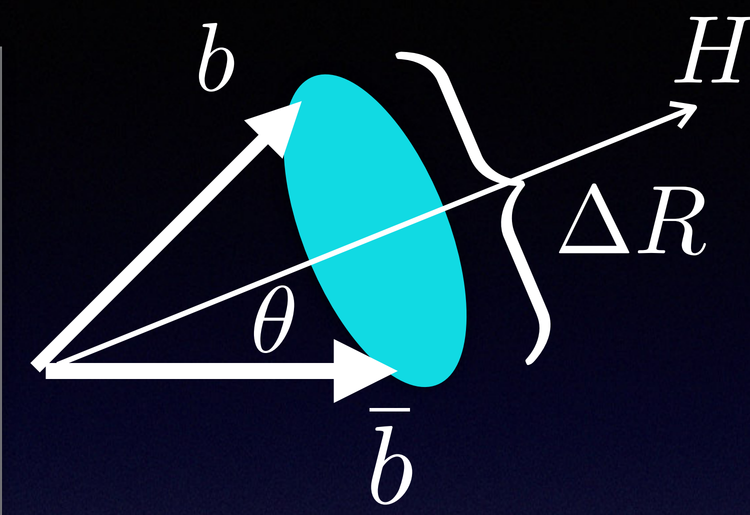

$$\sigma_{\text{after cuts}} = \int dm_{HH}\ \frac{d\sigma}{dm_{HH}} \otimes \mathcal{A}(m_{HH}, E_{\text{cm}}, \mu_f)$$

**Cut Efficiency Function**

**Encoding PDFs and cuts**

# Key of Cut Efficiency: $\Delta R$ cut

$$
\begin{aligned}
\Delta R^2 = \arccos^2\Big\{ & \Big[(1-z^2)\left(\beta_T^2-\cos^2\phi-\sin^2\phi\tanh^2\eta\right)-z^2\,\mathrm{sech}^2\eta+2z\sin\phi\tanh\eta \\
& \times\sqrt{(1-z^2)\left(\beta_T^2+\mathrm{sech}^2\eta\right)}\Big]\Big[(1-z^2)\cos^2\phi+\Big(\beta_T-\sqrt{1-z^2}\sin\phi\tanh\eta \\
& +z\sqrt{\beta_T^2+\mathrm{sech}^2\eta}\Big)^2\Big]^{-\frac{1}{2}}\Big[(1-z^2)\cos^2\phi+\Big(\beta_T+\sqrt{1-z^2}\sin\phi\tanh\eta \\
& -z\sqrt{\beta_T^2+\mathrm{sech}^2\eta}\Big)^2\Big]^{-\frac{1}{2}}\Big\}+\Big\{\ \mathrm{arcsinh}\Big\{\Big[\sinh\eta\Big(\beta_T+z\sqrt{\beta_T^2+\mathrm{sech}^2\eta}\Big)+\sin\phi \\
& \times\ \mathrm{sech}\eta\sqrt{1-z^2}\Big]\Big[(1-z^2)\cos^2\phi+\Big(\beta_T-\sqrt{1-z^2}\sin\phi\tanh\eta \\
& +z\sqrt{\beta_T^2+\mathrm{sech}^2\eta}\Big)^2\Big]^{-\frac{1}{2}}\Big\}+\ \mathrm{arcsinh}\Big\{\Big[\sinh\eta\Big(-\beta_T+z\sqrt{\beta_T^2+\mathrm{sech}^2\eta}\Big)+\sin\phi \\
& \times\ \mathrm{sech}\eta\sqrt{1-z^2}\Big]\Big[(1-z^2)\cos^2\phi+\Big(\beta_T+\sqrt{1-z^2}\sin\phi\tanh\eta \\
& -z\sqrt{\beta_T^2+\mathrm{sech}^2\eta}\Big)^2\Big]^{-\frac{1}{2}}\Big\}\Big\}^2,
\end{aligned}
$$

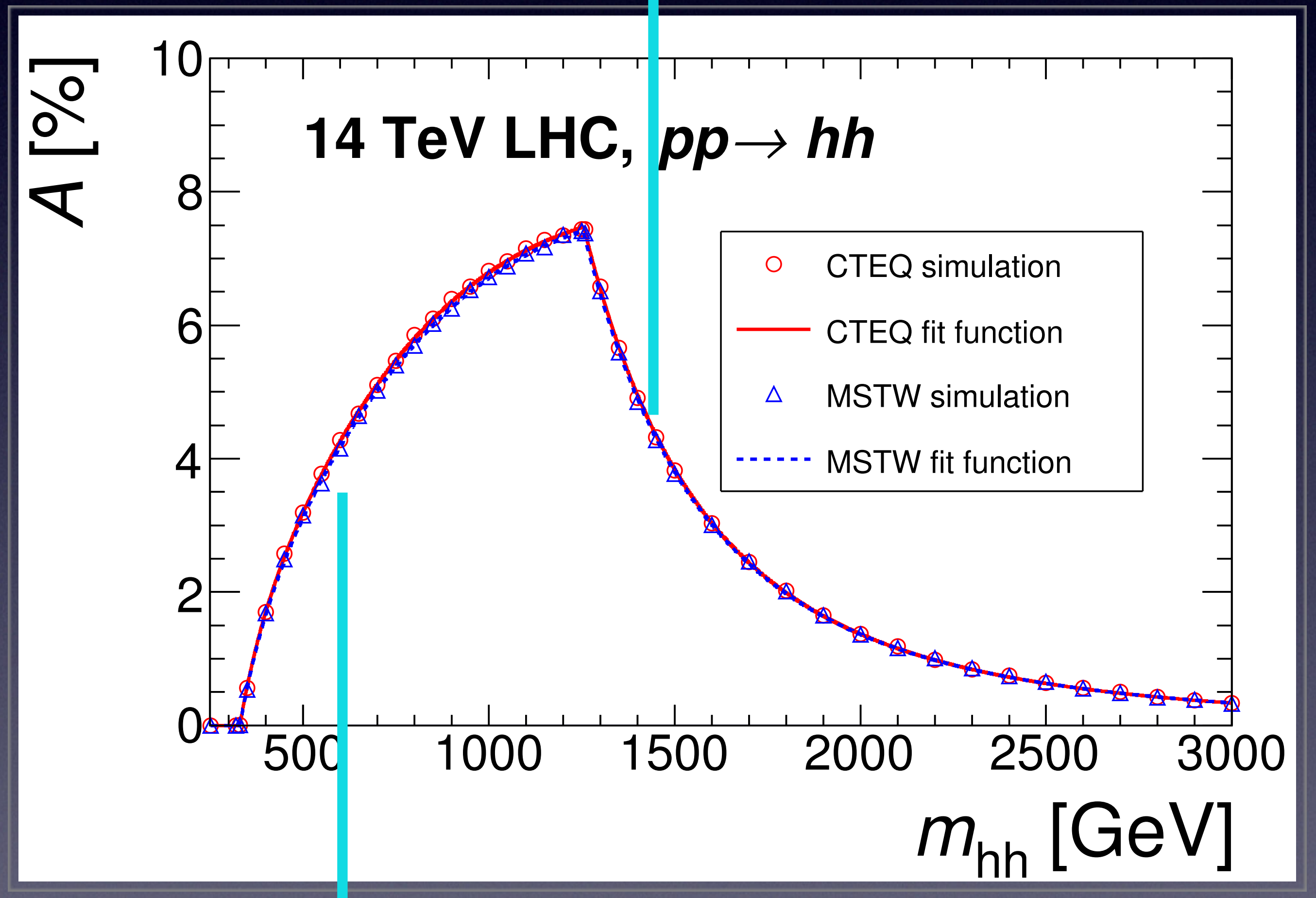



$$\beta_T = p_T^H/m_H \qquad z = \cos\theta$$

$$\beta_T \gg 1 \;\Rightarrow\; \Delta R = \arccos\left[1-\frac{2}{1+(1-z^2)\beta_T^2}\right]$$

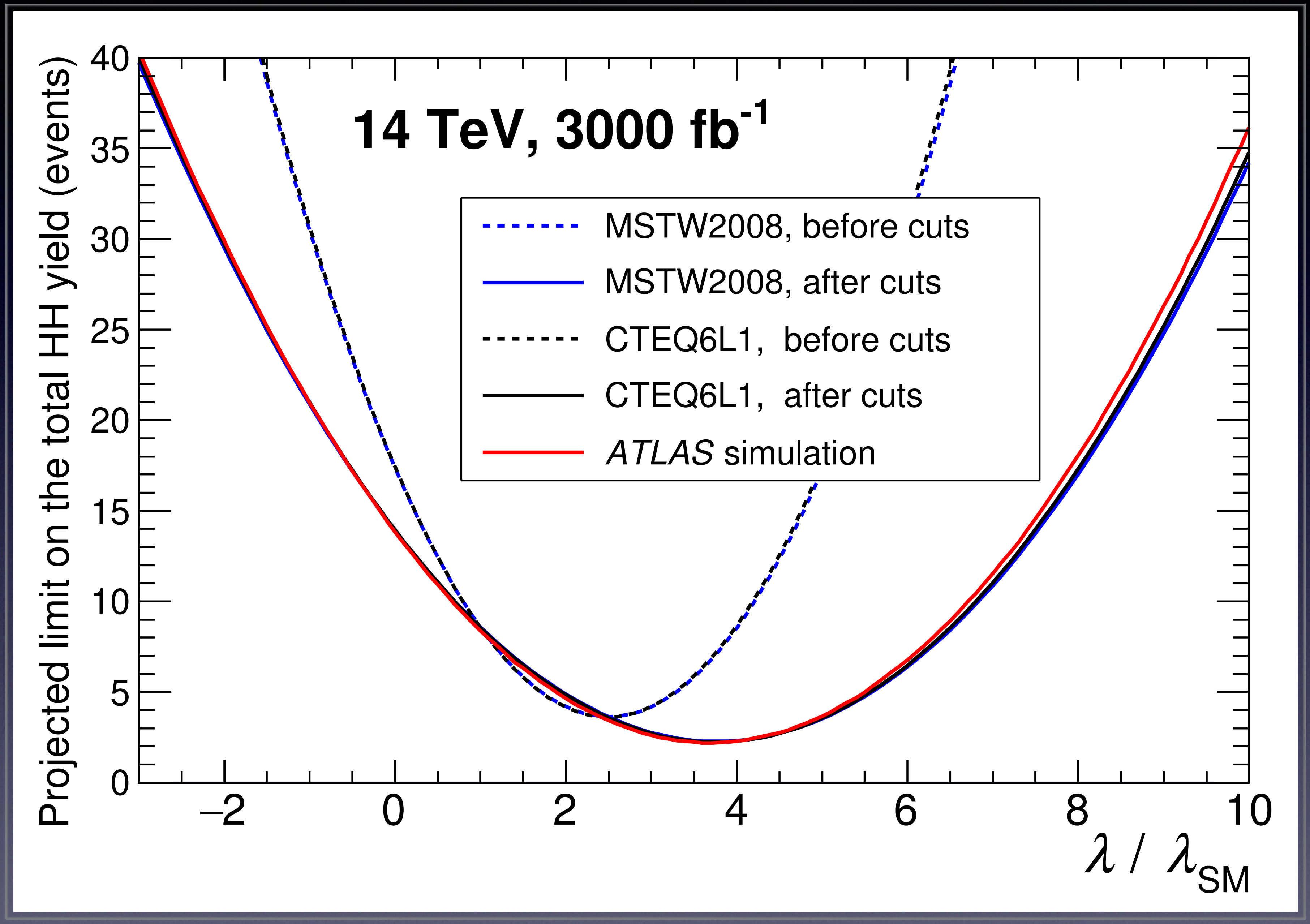
# Cut Efficiency Functions

$$\mathcal{A}(m_{hh}) = c^{\gamma_c}\left[1-\sqrt{\frac{m_{hh}^2(1-\cos\Delta R)-8(m_h-\delta m_h)^2}{(1-\cos\Delta R)\left(m_{hh}^2-4(m_h-\delta m_h)^2\right)}}\right]^{\gamma_c}$$



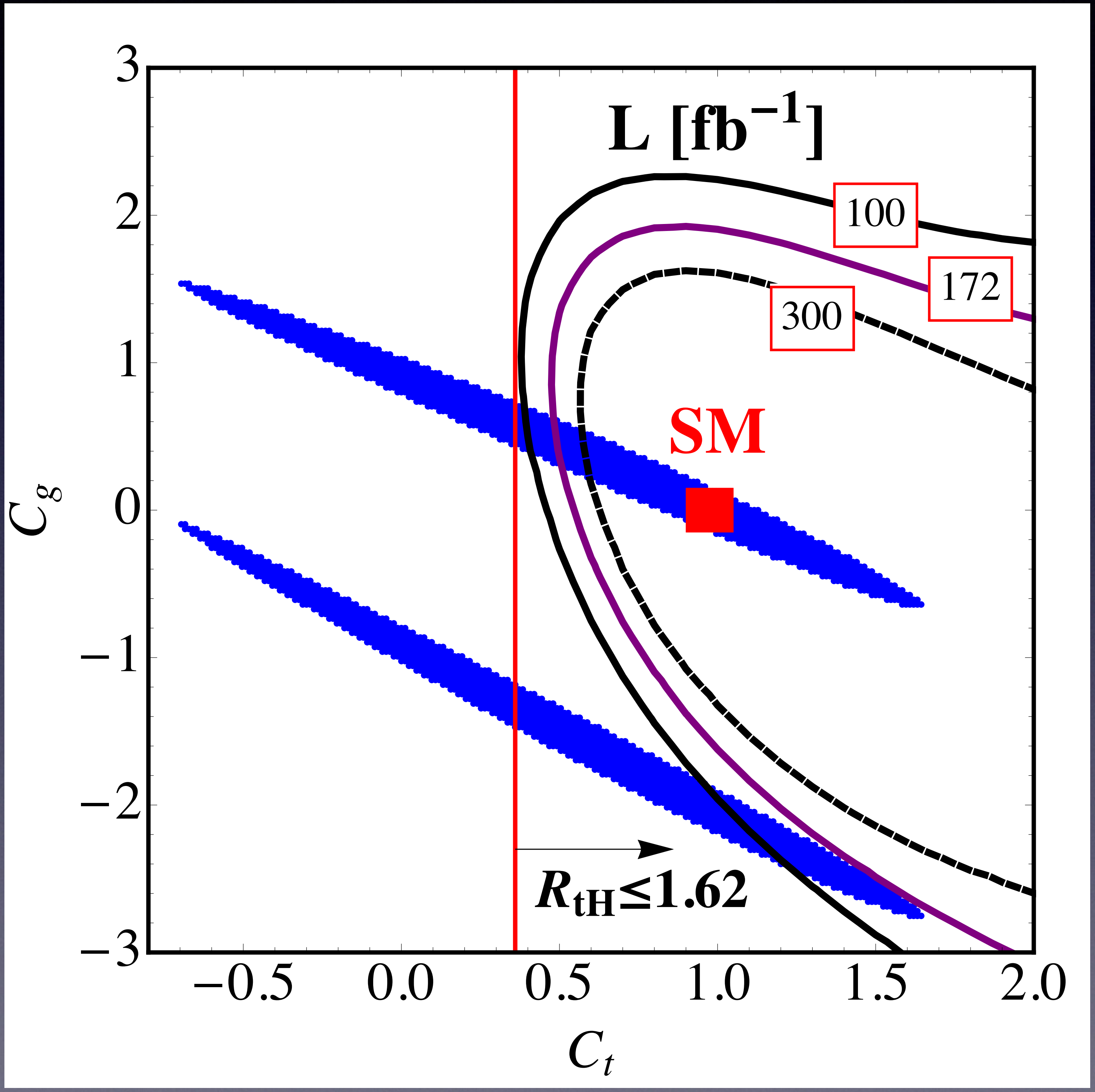

$$\mathcal{A}(m_{hh}) = a_1\left[1-\frac{4p_{T,h}^2}{m_{hh}^2-4(m_h-\delta m_2)^2}\right]^{\beta_a}\left(\frac{m_{hh}}{\sqrt{S}}\right)^{\beta_b}\left[1+a_2\left(\frac{m_{hh}}{\sqrt{S}}\right)\log\left(\frac{2m_{hh}}{\sqrt{S}}\right)\right]$$

# Testing the Cut Efficiency Function




Our cut efficiency function can be generally applied to Higgs pair production in any NP physics as long as the s-wave scattering dominates

# Projected Exclusion Limit




Integrated luminosity needed to reach 95% C.L. Exclusion

Luminosity of ~200fb$^{-1}$ could exclude the FNNP

Good News!
We don't have to wait too long.

# Summary

It is possible that we discover only a SM-like Higgs boson and nothing else at the LHC and even HL-LHC eventually.

——- A lone Higgs scenarios (nightmare scenario)

Higgs pair production is good for probing the Higgs self interaction and excluding the Faked-No-New-Physics scenario.

We obtain a general cut efficiency function for any s-wave dominated Higgs pair production.