

# Probing Higgs Width and Top Quark Yukawa Coupling

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# Outline

- Motivation
- Top Quark Yukawa Coupling Measurement
- Higgs Width and Higgs Rare Decays Constraints
- Summary

# Motivation

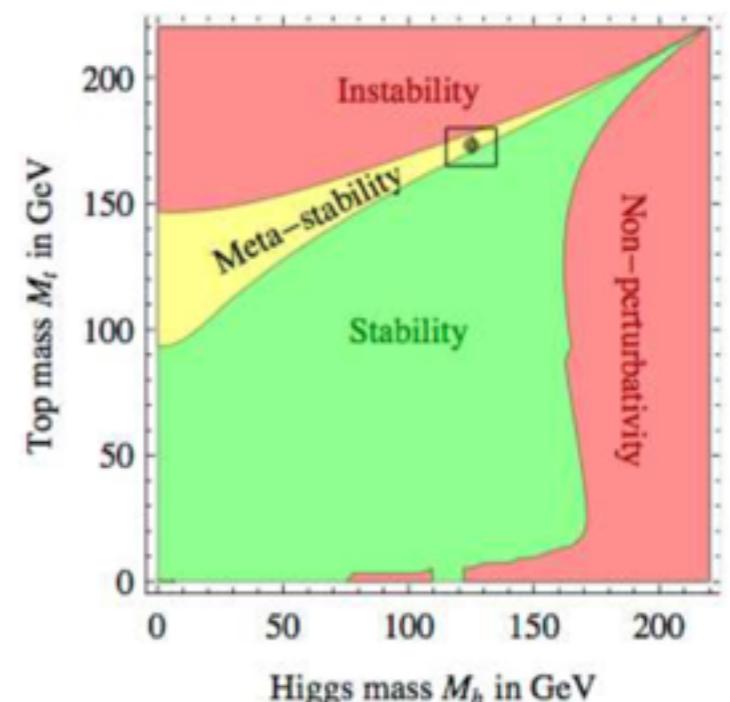
## \* Hierarchy/Naturalness

$$\begin{aligned}
 m_H^2 &= \int_0^{\lesssim \Lambda_{\text{SM}}} dE \frac{dm_H^2}{dE}(E; p_{\text{true}}) + \int_{\lesssim \Lambda_{\text{SM}}}^\infty dE \frac{dm_H^2}{dE}(E; p_{\text{true}}) \\
 &= \delta_{\text{SM}} m_H^2 + \delta_{\text{BSM}} m_H^2, \quad \Lambda_{\text{SM}} : \text{SM invalidating/NP scale}
 \end{aligned}$$

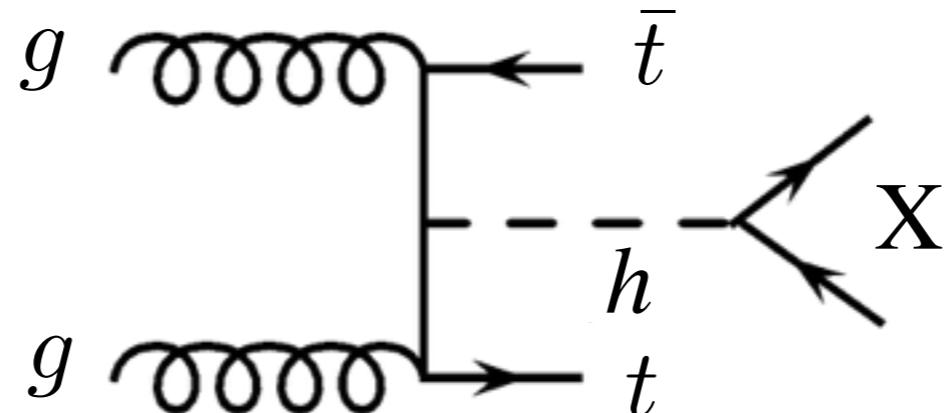
$$\delta_{\text{SM}} m_H^2 = \frac{3y_t^2}{8\pi^2} \Lambda_{\text{SM}}^2 + \frac{g_W^2}{16\pi^2} \Lambda_{\text{SM}}^2 + \frac{\lambda}{16\pi^2} \Lambda_{\text{SM}}^2$$

## \* Vacuum stability

$$\beta_\lambda = \frac{1}{16\pi^2} (-3y_t^4) + \frac{1}{16\pi^2} (\mathcal{O}_{\text{NP}})$$



# Top Quark Yukawa Coupling: tth



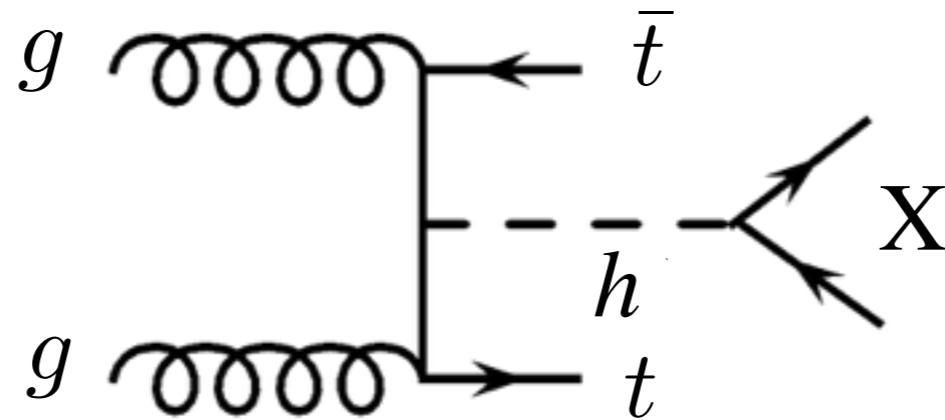
Channel	LHC Run I comb.	$bb$ $12.9 \text{ fb}^{-1}$	multi- leptons	$\tau_h + X$	$\gamma\gamma$	$ZZ(4l)$
$\mu = \sigma_{ttH}/\sigma_{SM}$	$2.3^{+0.7}_{-0.6}$	$-0.2 \pm 0.8$	$1.5 \pm 0.5$	$0.7^{+0.6}_{-0.5}$	$2.2^{+0.9}_{-0.8}$	$0.0^{+1.2}_{-0.0}$

$\uparrow$   
**4.4 $\sigma$  obs**  
**2.0 $\sigma$  exp**

$\uparrow$   
**3.3 $\sigma$  obs**  
**2.5 $\sigma$  exp**

$\uparrow$   
**3.3 $\sigma$  obs**  
**1.5 $\sigma$  exp**

# Top Quark Yukawa Coupling: tth



$$\kappa_t = \frac{y_t}{y_t^{\text{SM}}}$$

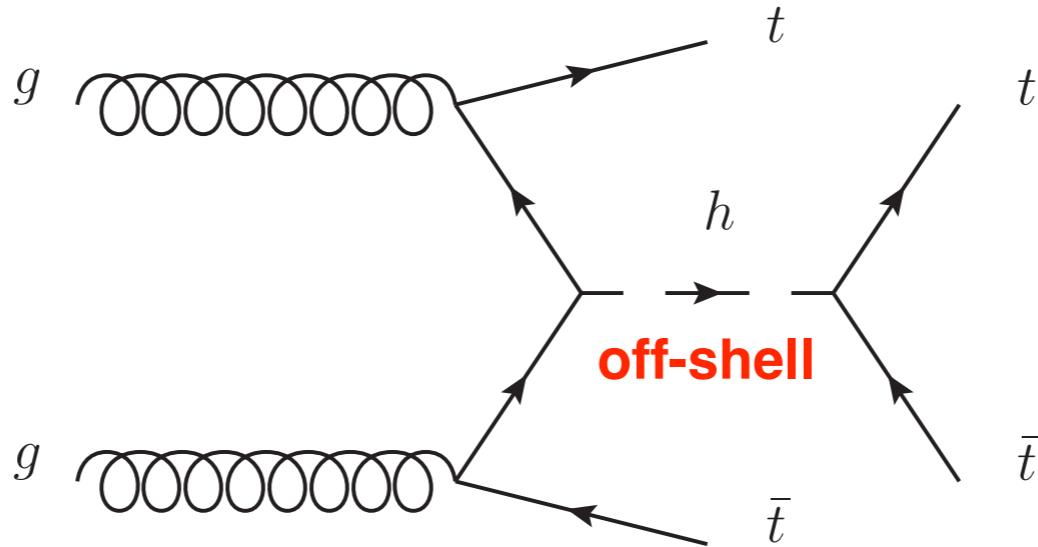
$$\kappa_X = \frac{y_X}{y_X^{\text{SM}}}$$

$$\hat{\sigma} = \sigma(gg \rightarrow t\bar{t}h) \times \frac{\Gamma(h \rightarrow X)}{\Gamma_{\text{total}}} = \frac{\kappa_t^2 \kappa_X^2}{\Gamma_{\text{total}}/\Gamma_{\text{SM}}} \hat{\sigma}_{\text{SM}}$$

$$\mu \equiv \frac{\hat{\sigma}}{\hat{\sigma}_{\text{SM}}} = \frac{\kappa_t^2 \kappa_X^2}{\Gamma_{\text{total}}/\Gamma_{\text{SM}}^{\text{total}}} \quad \frac{\Gamma_{\text{total}} = \Gamma_{\text{SM}}^{\text{total}}}{\kappa_X = 1} \rightarrow \mu = \kappa_t^2$$

Can we measure/constrain the top quark Yukawa coupling directly?

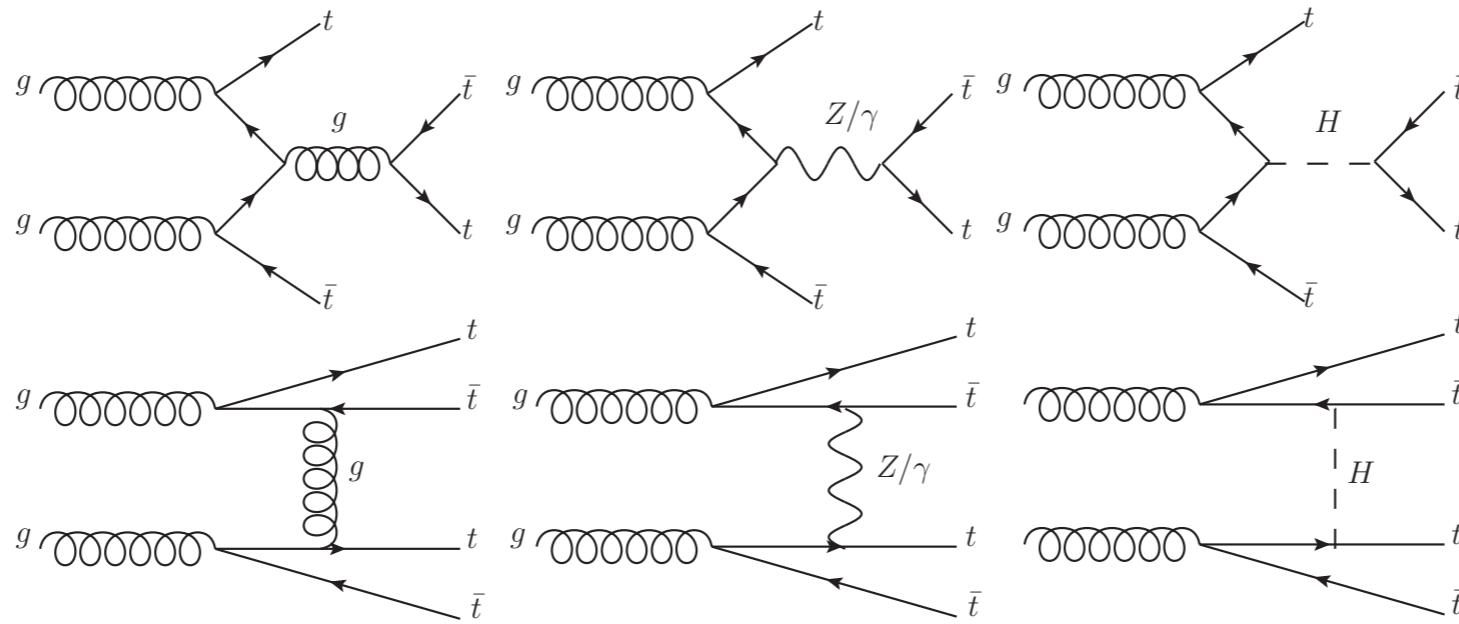
# Top Quark Yukawa Coupling: tt



$$\hat{\sigma}(pp \rightarrow t\bar{t}h^* \rightarrow t\bar{t}t\bar{t}) \propto \kappa_t^4 \hat{\sigma}(pp \rightarrow t\bar{t}h^* \rightarrow t\bar{t}t\bar{t})^{\text{SM}}$$

- \* No other assumption about Higgs boson
- \* Sensitive to top quark Yukawa coupling

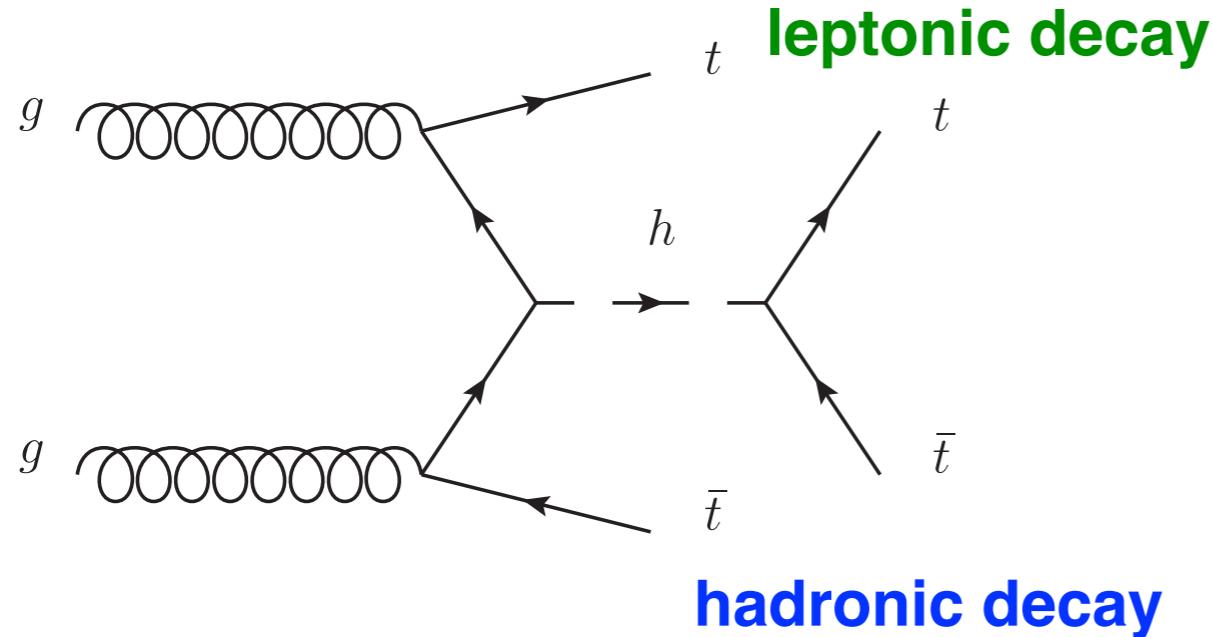
# Top Quark Yukawa Coupling: tt tt



$$\sigma(t\bar{t}tt) = \sigma^{\text{SM}}(t\bar{t}tt)_{g+Z/\gamma} + \kappa_t^2 \sigma^{\text{SM}}(t\bar{t}tt)_{\text{int}} + \kappa_t^4 \sigma^{\text{SM}}(t\bar{t}tt)_h$$

	8 TeV	13 TeV	14 TeV
$\sigma^{\text{SM}}(t\bar{t}tt)_{g+Z/\gamma}:$	1.344 fb,	9.997 fb,	13.140 fb,
$\sigma^{\text{SM}}(t\bar{t}tt)_H:$	0.171 fb,	1.168 fb,	1.515 fb,
$\sigma^{\text{SM}}(t\bar{t}tt)_{\text{int}}:$	-0.224 fb,	-1.547 fb,	-2.007 fb.

# Collider Simulation



**Event Topology: same-sign charged leptons plus multi-jet (b-jet)**

Backgrounds:

$$t\bar{t}Z/W, W^\pm W^\pm jj, t\bar{t}$$

Event selection:

$$\begin{aligned} p_T^{j,l} &\geq 20 \text{ GeV}, |\eta^{j,l}| < 2.5, \\ N_{l^\pm} &= 2, \\ N_{\text{jets}} &\geq 5, N_{b-\text{jets}} \geq 3, \\ E_T &\geq 100 \text{ GeV}, \\ m_T &\geq 100 \text{ GeV}, \\ H_T &\geq 700 \text{ GeV}. \end{aligned}$$

$$\kappa_t \leq 1.94 \text{ @ 14 TeV LHC } \mathcal{L} = 100 \text{ fb}^{-1}$$

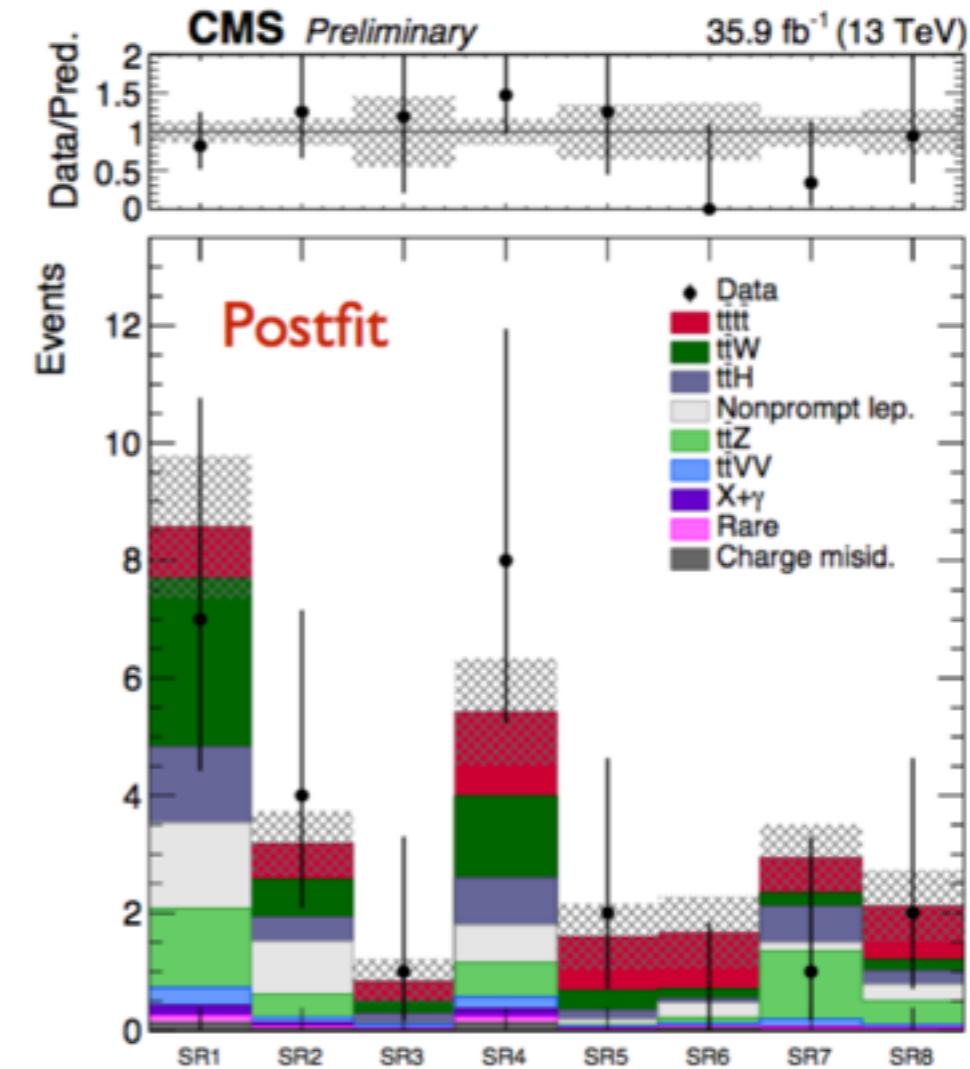
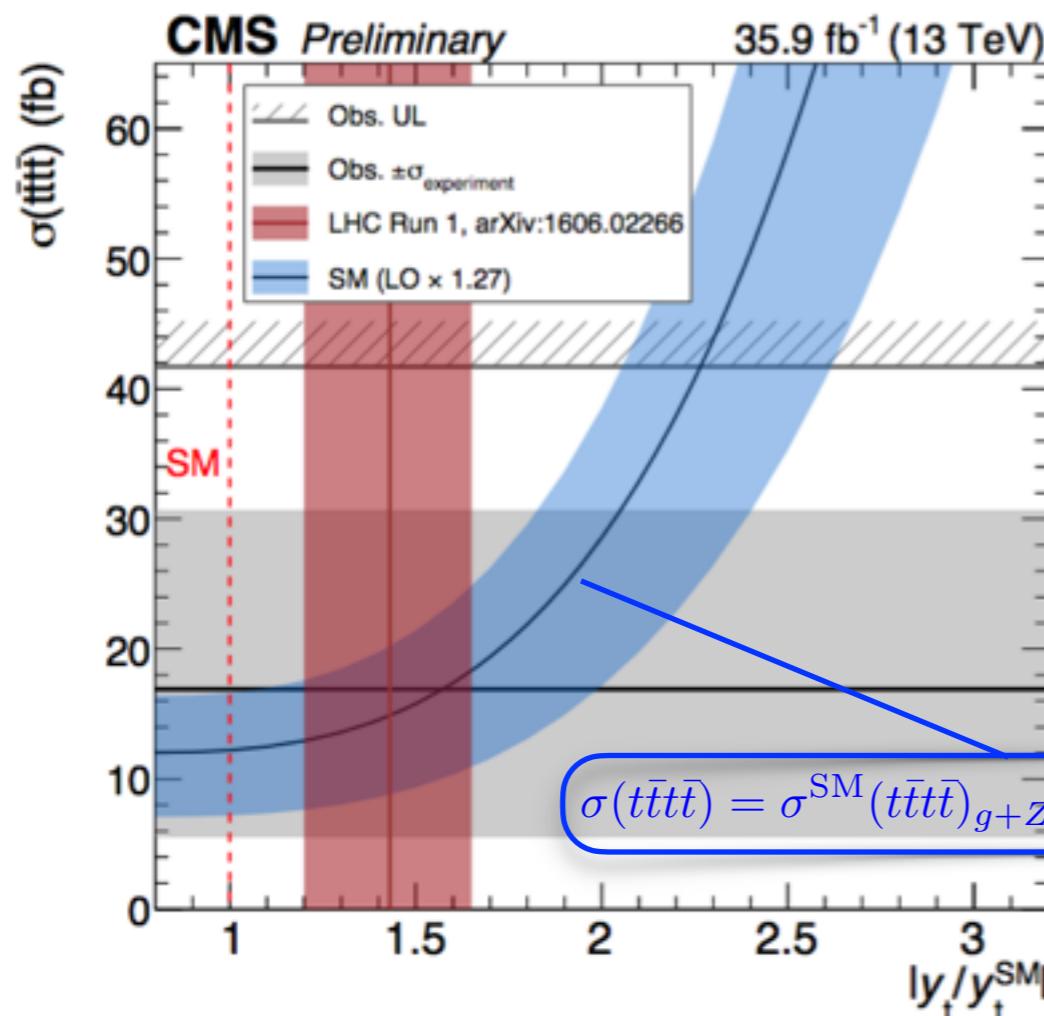
$$\kappa_t \leq 1.34 \text{ @ 14 TeV LHC } \mathcal{L} = 300 \text{ fb}^{-1}$$

# Results

Nick Amin's slide at Top 2017

1710.10614

- After the fit to data in the signal + control regions, the four top cross-section is measured to be  $16.9^{+13.8}_{-11.4}$  fb, with an observed (expected) significance wrt the bg-only hypothesis of  $1.6\sigma$  ( $1.0\sigma$ )
- Additionally, this measurement is used to constrain the top Yukawa coupling  $|y_t/y_t^{\text{SM}}| < 2.1$  at 95% confidence, as motivated by Cao, et al. in Phys. Rev. D 95 (2017) 053004



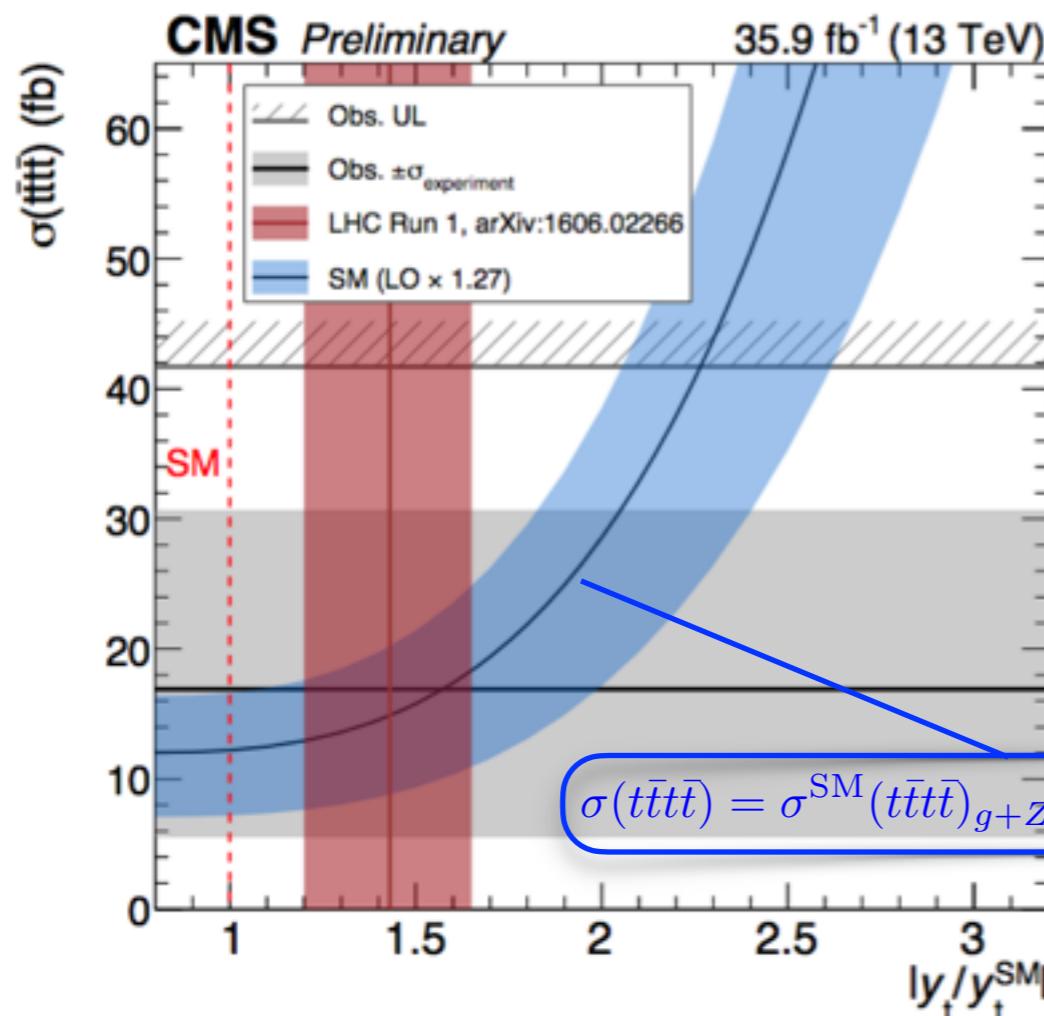
$N_{\text{lep}}$	$N_b$	$N_{\text{jets}}$	Region
2	2	6	SR1
	7	7	SR2
	$\geq 8$	$\geq 8$	SR3
	5, 6	$\geq 7$	SR4
3	$\geq 7$	$\geq 7$	SR5
	$\geq 4$	$\geq 5$	SR6
	2	$\geq 5$	SR7
	$\geq 3$	$\geq 4$	SR8

# Results

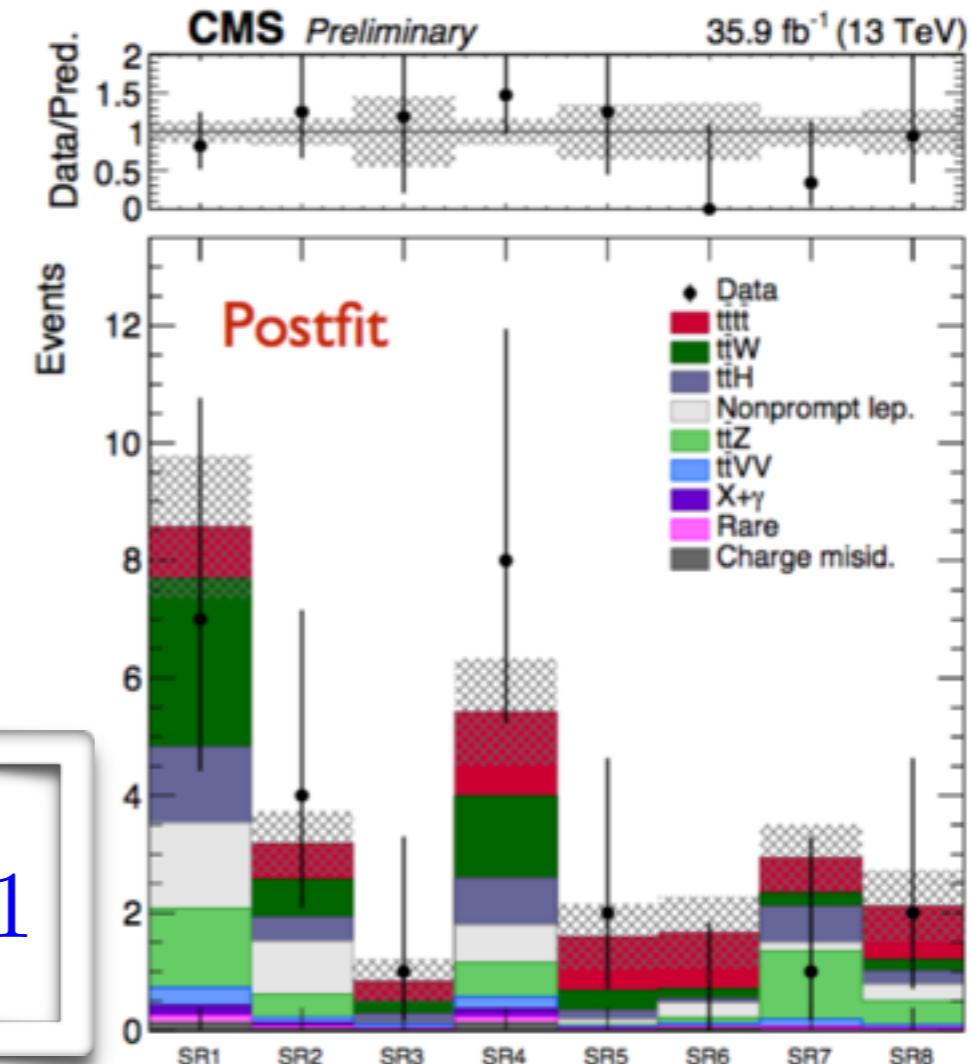
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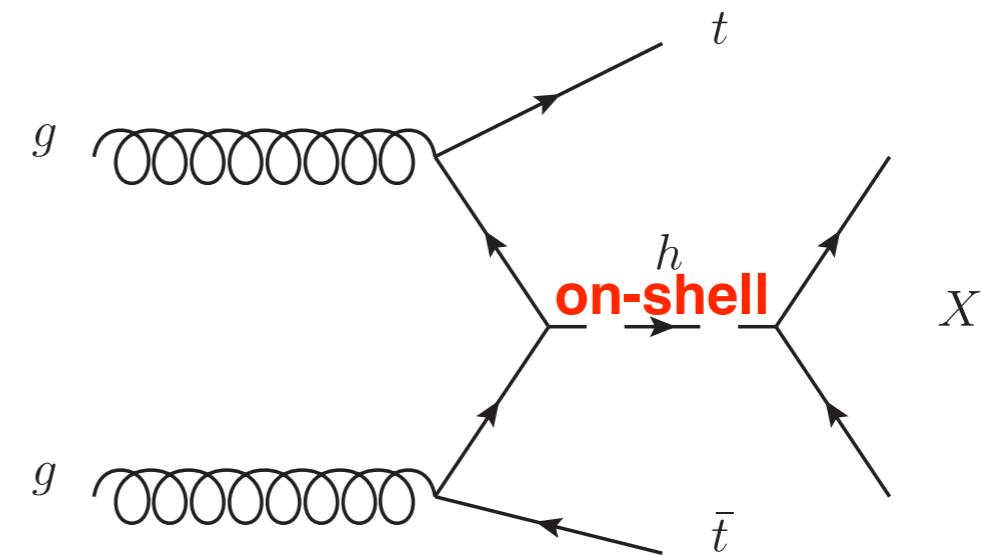
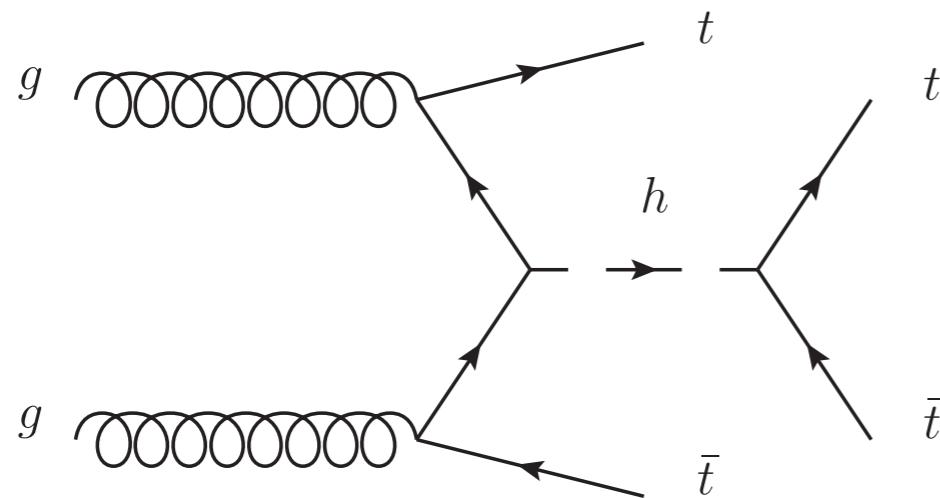
$$\kappa_t < 2.1$$



	$N_{\text{lep}}$	$N_b$	$N_{\text{jets}}$	Region
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$\geq 3$	2	$\geq 5$		SR7
	$\geq 3$	$\geq 4$		SR8

# 14 TeV LHC

$300 \text{ fb}^{-1}$



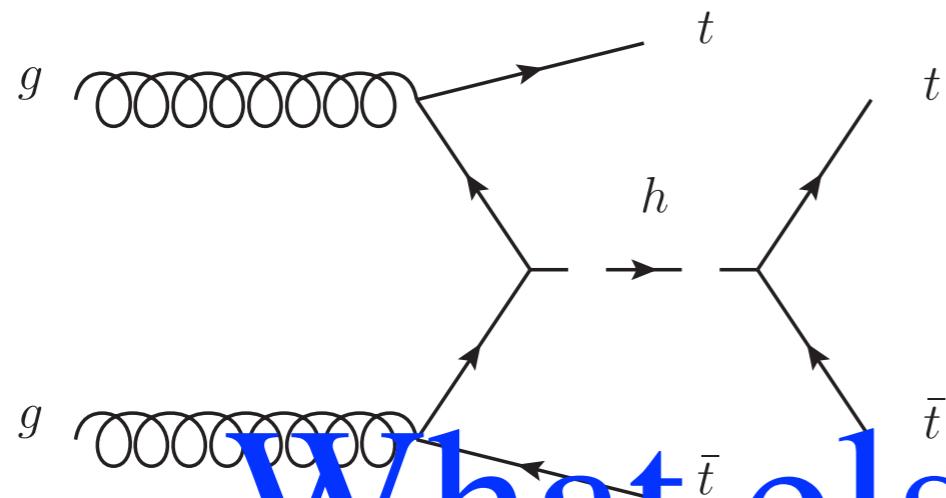
$\kappa_t < 1.34$

X	signal strength $\bar{\mu}_{t\bar{t}h}^X$
$\gamma\gamma$	$1.00 \pm 0.38$
$ZZ$	$1.00 \pm 0.49$
$\mu\mu$	$1.00 \pm 0.74$
combined	$1.00 \pm 0.32$

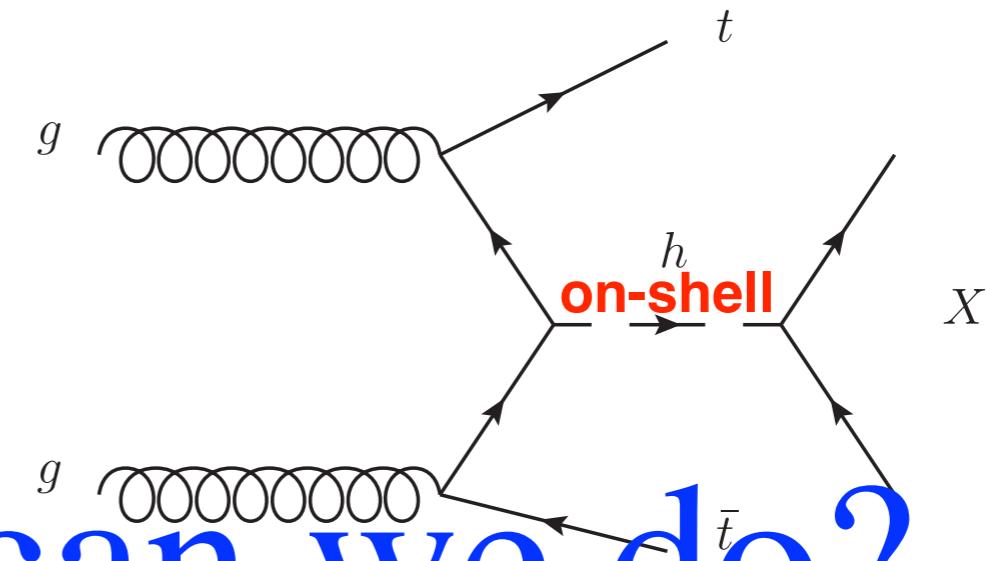
Projection from ATLAS

# 14 TeV LHC

300 fb<sup>-1</sup>



What else can we do?

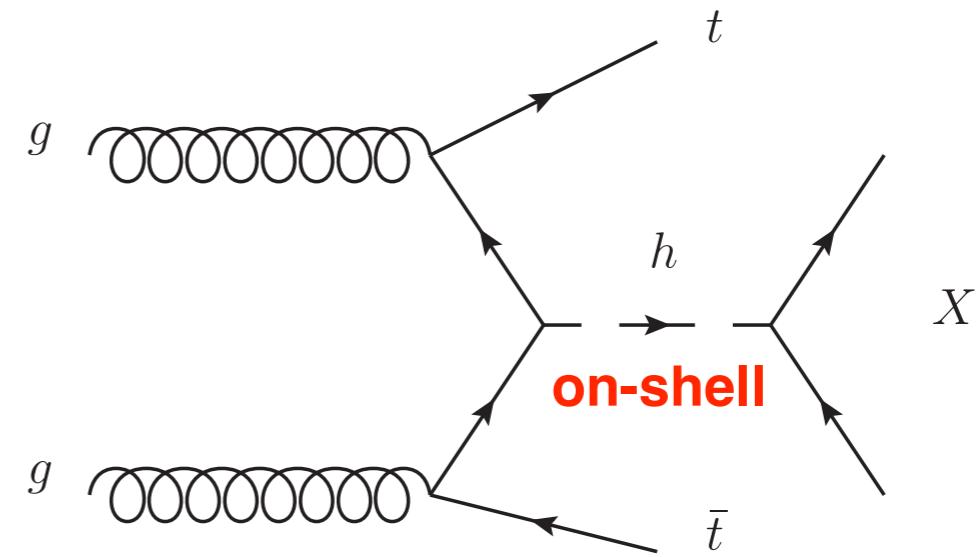
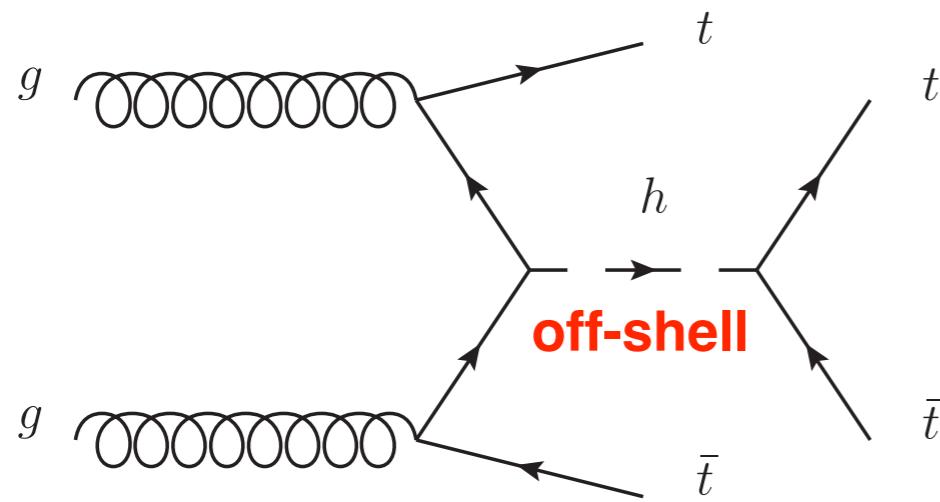


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Projection from ATLAS

# tth and tt<sub>tt</sub>



$$\hat{\sigma}(pp \rightarrow t\bar{t}h \rightarrow t\bar{t}t\bar{t})$$

$$\propto \kappa_t^4 \hat{\sigma}(pp \rightarrow t\bar{t}h \rightarrow t\bar{t}t\bar{t})^{\text{SM}}$$

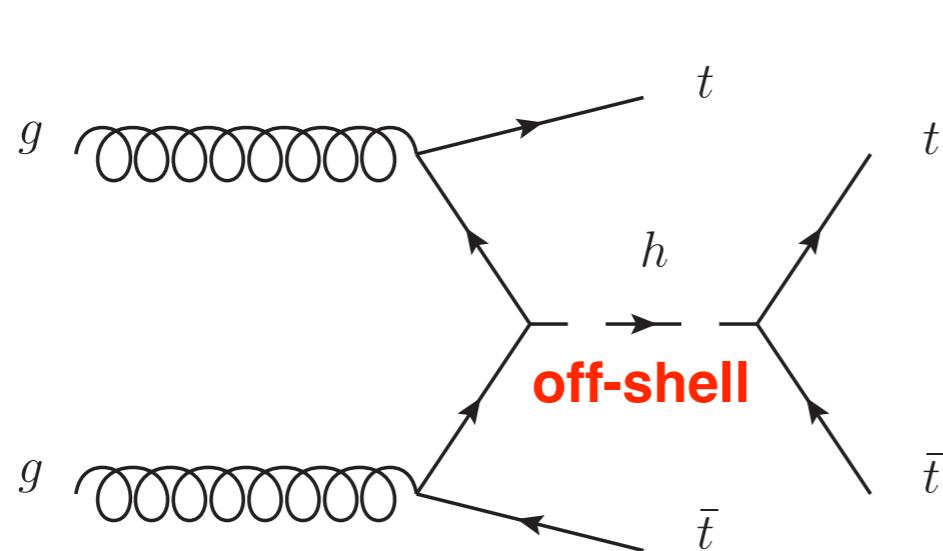
$$\hat{\sigma}(pp \rightarrow t\bar{t}h \rightarrow t\bar{t}X)$$

$$\propto \frac{\kappa_t^2 \kappa_X^2}{\Gamma_h^{\text{total}} / \Gamma_h^{\text{total SM}}} \hat{\sigma}(pp \rightarrow t\bar{t}h \rightarrow t\bar{t}X)^{\text{SM}}$$

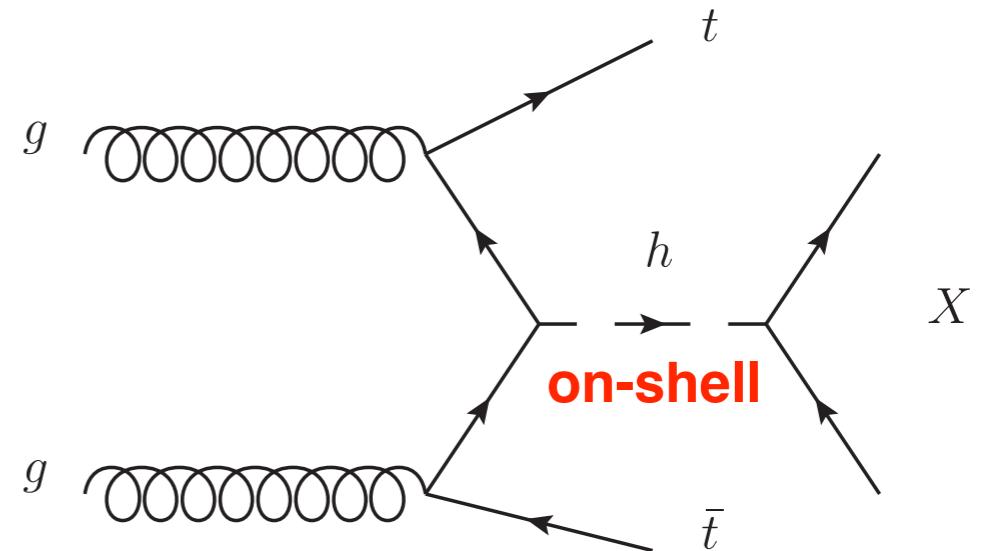
$$\propto \mu_{t\bar{t}h}^X \hat{\sigma}(pp \rightarrow t\bar{t}h \rightarrow t\bar{t}X)^{\text{SM}}$$

$$\frac{\mu_{t\bar{t}h}^X}{\kappa_t^2} = \frac{\kappa_X^2}{\Gamma_h^{\text{total}} / \Gamma_h^{\text{total SM}}}$$

# Case I : Higgs Rare Decays



VS



$$\frac{\mu_{t\bar{t}h}^X}{\kappa_t^2} = \frac{\kappa_X^2}{\Gamma_h^{\text{total}}/\Gamma_h^{\text{total SM}}}$$

Rare decay : Higgs Width  
not dramatically affected

$$\Gamma_h^{\text{total}}/\Gamma_h^{\text{total SM}} \sim 1$$

$$\kappa_t^2 \kappa_X^2 = \bar{\mu}_{t\bar{t}h}^X \quad \kappa_t < \kappa_t^{\text{ul}} \quad \text{from tttt}$$

$$\kappa_X > \frac{\sqrt{\mu_{t\bar{t}h}^X}}{\kappa_t^{\text{ul}}}$$

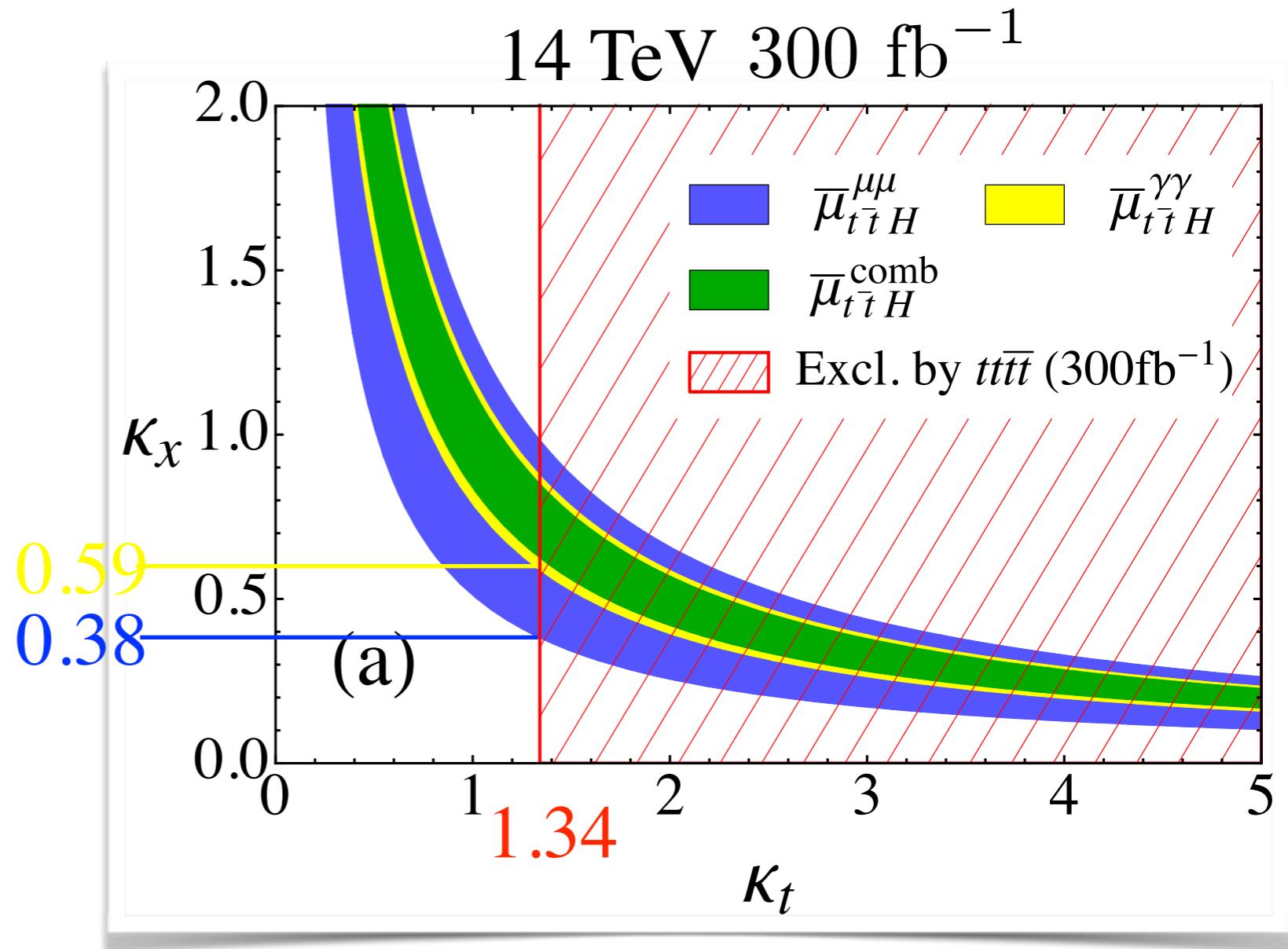
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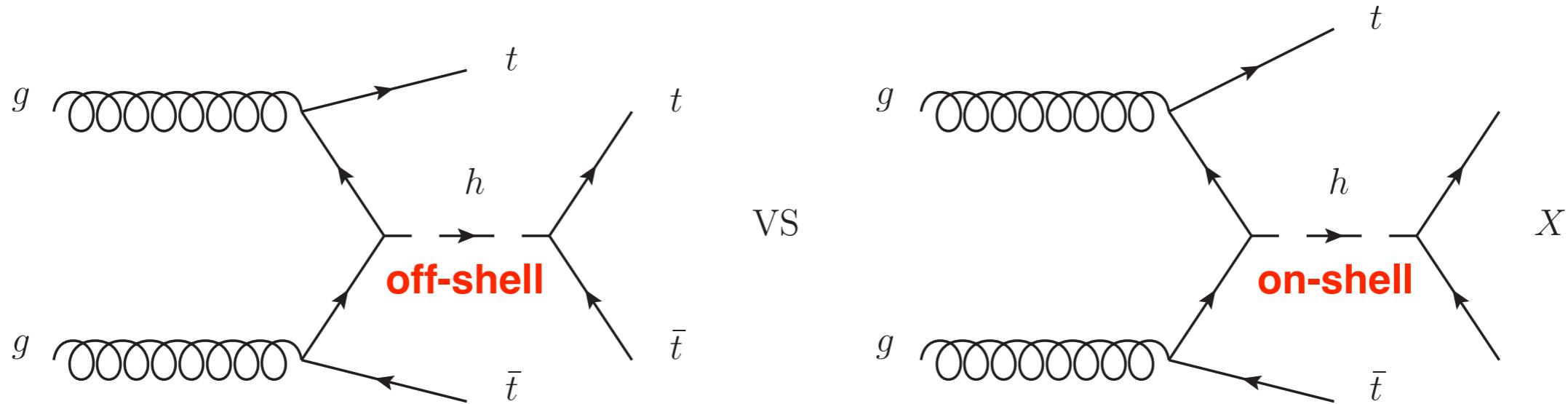
$$\kappa_t < 1.34 \quad \kappa_t^2 \kappa_X^2 = \bar{\mu}_{t\bar{t}h}^X$$



$$\kappa_\gamma > 0.59$$

$$\kappa_\mu > 0.38$$

# Case II : Higgs Width



$$\frac{\mu_{t\bar{t}h}^X}{\kappa_t^2} = \frac{\kappa_X^2}{\Gamma_h^{\text{total}} / \Gamma_h^{\text{total SM}}}$$

Invisible decay:Higgs Width Modified       $\kappa_X \sim 1$

$$\frac{\kappa_t^2}{R_\Gamma} = \mu_{t\bar{t}h} R_\Gamma = \Gamma_h^{\text{total}} / \Gamma_h^{\text{total SM}} \quad \kappa_t < \kappa_t^{\text{ul}} \quad \text{from } tttt$$

$$R_\Gamma < \frac{\kappa_t^{\text{ul}} 2}{\mu_{t\bar{t}h}}$$

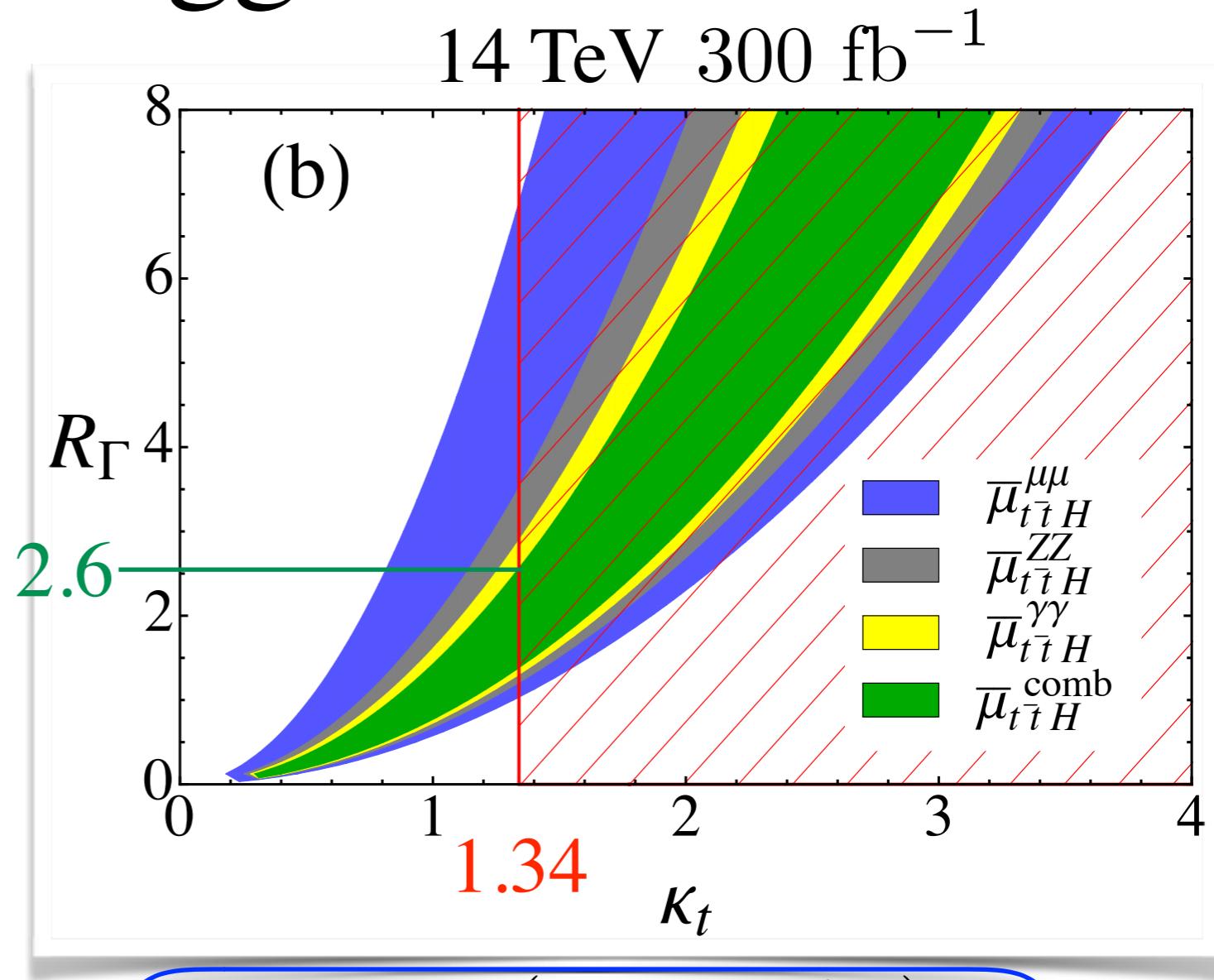
# Case II : Higgs Width

$$R_\Gamma < \frac{\kappa_t^{\text{ul}} 2}{\mu_{t\bar{t}h}} \quad R_\Gamma = \Gamma_h^{\text{total}} / \Gamma_h^{\text{total SM}}$$

X	signal strength $\bar{\mu}_{t\bar{t}h}^X$
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Projection from ATLAS

$$\kappa_t < 1.34 \quad \frac{\kappa_t^2}{R_\Gamma} = \mu_{t\bar{t}h}$$



$$R_\Gamma < 2.9 \text{ ( } \gamma\gamma \text{ mode )}$$

$$R_\Gamma < 3.5 \text{ ( } ZZ \text{ mode )}$$

$$R_\Gamma < 6.9 \text{ ( } \mu^+ \mu^- \text{ mode )}$$

$$R_\Gamma < 2.6 \text{ ( combined )}$$

# Summary

- \* Four top quarks production process used to measure top Yukawa coupling  $\kappa_t < 2.1$
- \* Combining tttt production and tth production:
  - \* Case I: Higgs rare decay
  - \* Case II: Higgs width

Thanks