Limiting Top-Higgs Interaction and Higgs Width from multi-Top Productions

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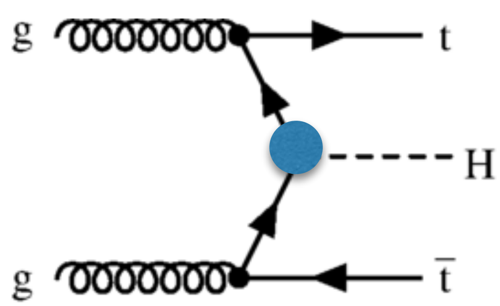
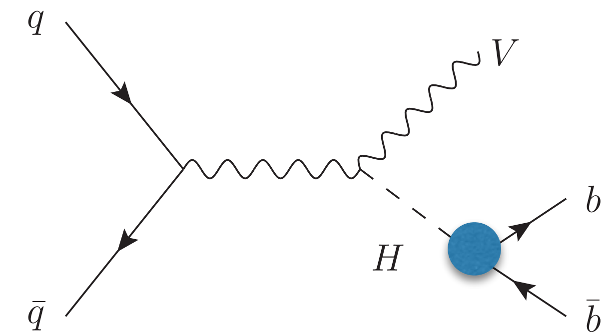
Observation of Higgs-Top and Higgs-Bottom couplings



$$\mu_{ttH} = 0.96^{+0.34}_{-0.31}$$

CMS-PAS-HIG-18-019

Size, CP-phase



$$\mu_{VH} = 1.01 \pm 0.12^{+0.16}_{-0.15}$$

ATLAS, 1808.08238

Size, CP-phase

Higgs-boson width

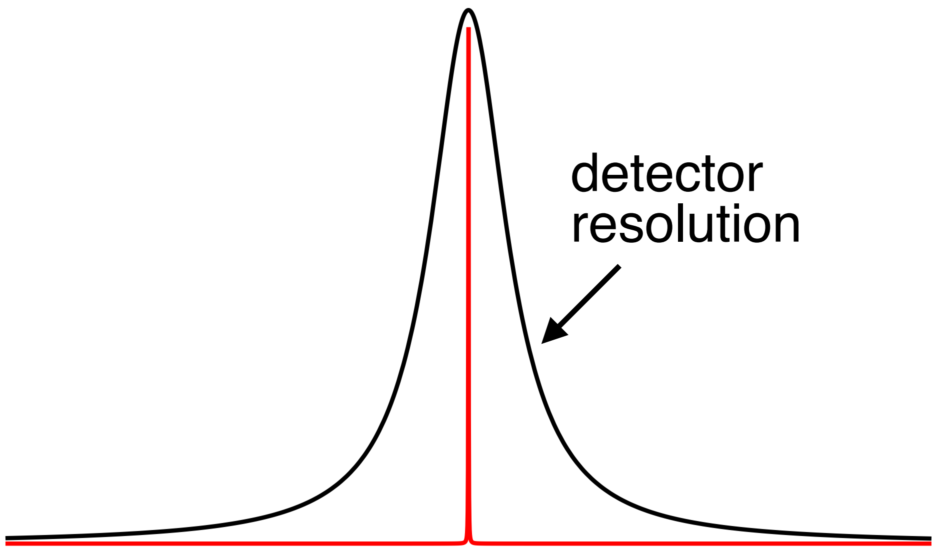
$$\begin{cases} \Gamma_H > \Gamma_H^{SM} \\ \Gamma_H < \Gamma_H^{SM} \end{cases}$$

Invisible decay, scalar extension, ….

Scalar mixing, composite Higgs …

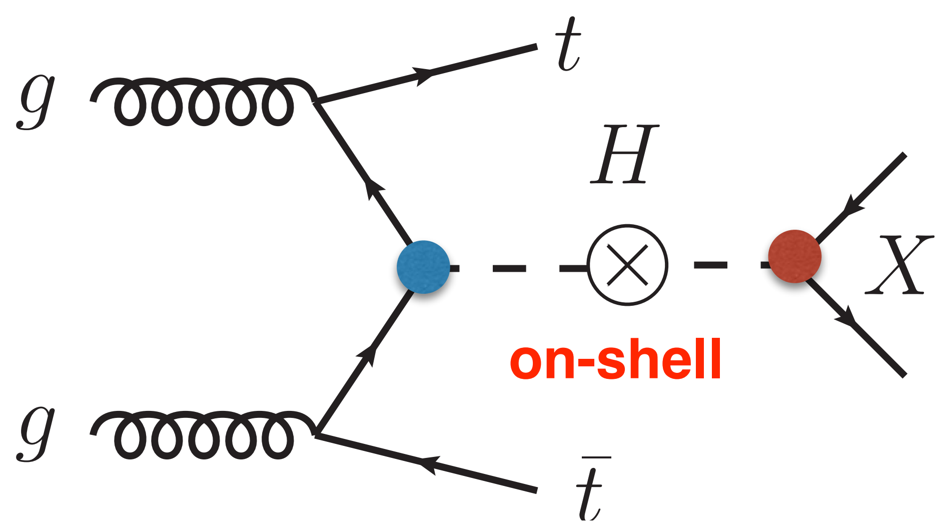
$$\Gamma_H^{SM} = 4 \text{ MeV}$$

$$\frac{\Gamma_H^{SM}}{m_H} = 0.000032$$



One can only obtain a range but not precise value of Higgs with

Top-quark Yukawa coupling



$b \quad W^* \quad Z^* \quad \tau^- \quad \mu^- \quad \gamma$

$\bar{b} \quad W \quad Z \quad \tau^+ \quad \mu^+ \quad \gamma$

Narrow width approximation

$$\hat{\sigma} = \sigma(gg \to t\bar{t}H) \times \frac{\Gamma(H \to X)}{\Gamma_H} = \frac{\kappa_t^2 \kappa_X^2}{\Gamma_H/\Gamma_H^{\rm SM}} \hat{\sigma}_{\rm SM}$$

$$\kappa_t = \frac{y_t}{y_t^{\rm SM}} \qquad \kappa_X = \frac{y_X}{y_X^{\rm SM}}$$

signal strength

$$\mu \equiv \frac{\hat{\sigma}}{\hat{\sigma}_{\rm SM}} = \frac{\kappa_t^2 \kappa_X^2}{\Gamma_H/\Gamma_H^{\rm SM}} \xrightarrow[\kappa_X = 1]{\Gamma_H = \Gamma_H^{\rm SM}} \mu = \kappa_t^2$$

Higgs width affects all the Higgs measurements.

Q1: can we determine κ_t without those assumptions?

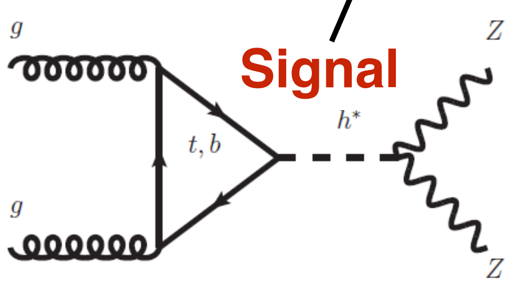
Higgs boson width measurement

Caola, Melnikov (2013)

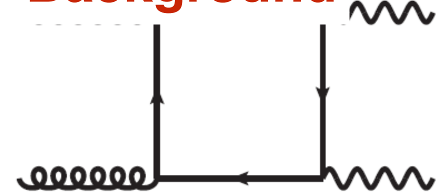
Higgs on-shell production

$$\sigma \sim \frac{g_{ggh}^2\, g_{hzz}^2}{m_h\, \Gamma_h}$$

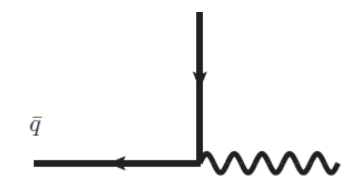
Signal



Background

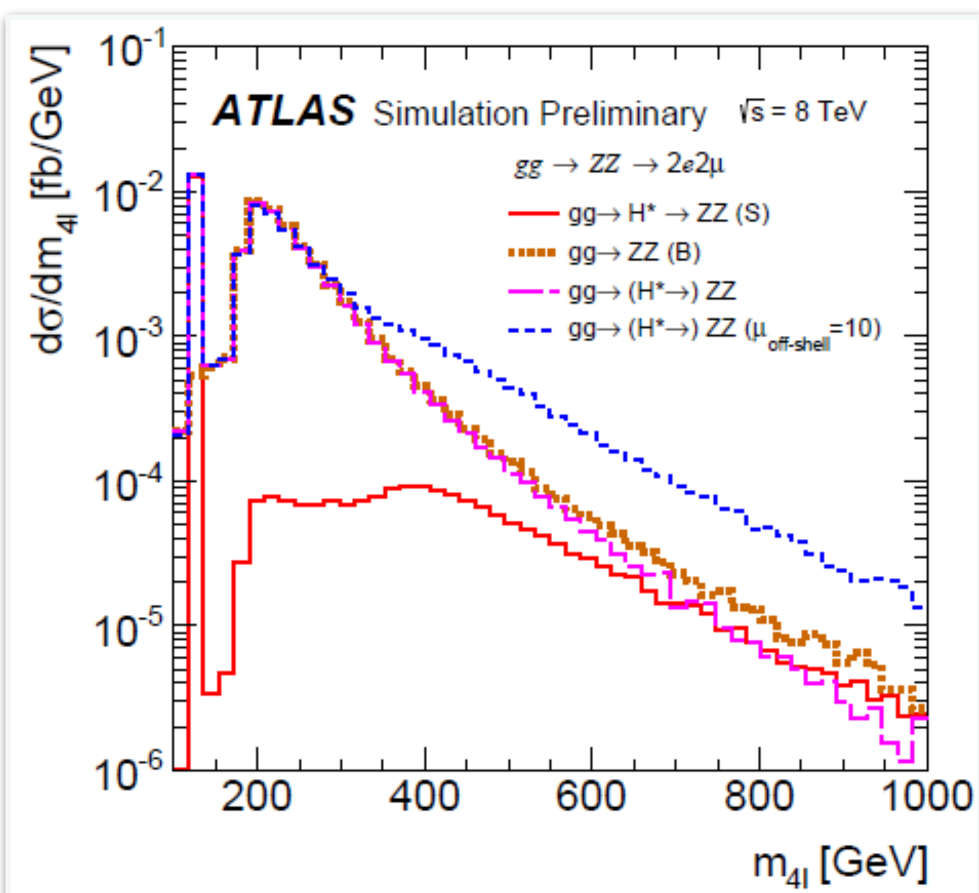


Dominant background



Higgs off-shell production

$$\frac{d\sigma}{dM_{ZZ}^2} \sim \frac{g_{ggh}^2 g_{hZZ}^2}{(M_{ZZ}^2 - m_h^2)^2}\, |M_1|^2 + \frac{g_{ggh} g_{hZZ}}{(M_{ZZ}^2 - m_h^2) M_{ZZ}^2}\, |M_1\, M_2^*|$$



On-shell versus off-shell measurements of signal strength

⬇

a significant sensitivity to Higgs width

Recent measurements of Higgs width

Direct measurements:

CMS, 1706.09936 (13TeV, 35.9fb^{-1})

$$gg \to H \to ZZ^* \to 4\ell$$

$$\Gamma_H < 1.10 \text{ GeV}$$

CMS, 1605.02329 (7+8TeV)

ATLAS, 1808.01191 (13TeV, 36.1fb^{-1})

$$gg \to H \to WW^* \to 2\ell + \text{MET}$$

$$\Gamma_H < 13 \text{ MeV} \qquad \Gamma_H < 14.4 \text{ MeV}$$

Indirect measurement through invisible decay:

ATLAS, 1809.06682 (13TeV, 36.1fb^{-1})

$$\text{Br}(\text{H} \to \text{inv}) \leq 0.37 \equiv \text{Br}_{\text{inv}}^{\text{Max}} \xrightarrow{\Gamma_H = \Gamma_H^{\text{known}} + \Gamma_H^{\text{inv}}} \Gamma_H \leq \frac{\Gamma_H^{\text{Known}}}{1 - \text{Br}_{\text{inv}}^{\text{Max}}}$$

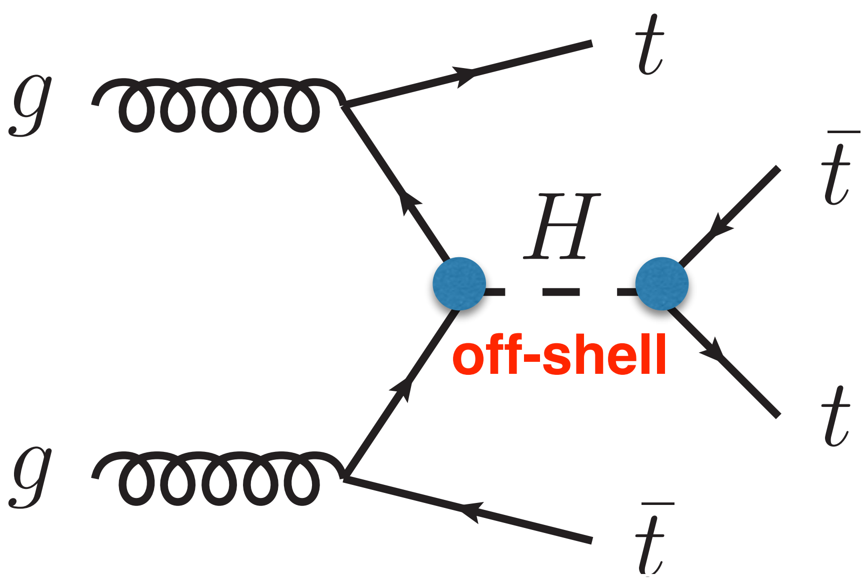
$$\Big\downarrow \; \Gamma_H^{\text{Known}} = \Gamma_H^{\text{SM}}$$

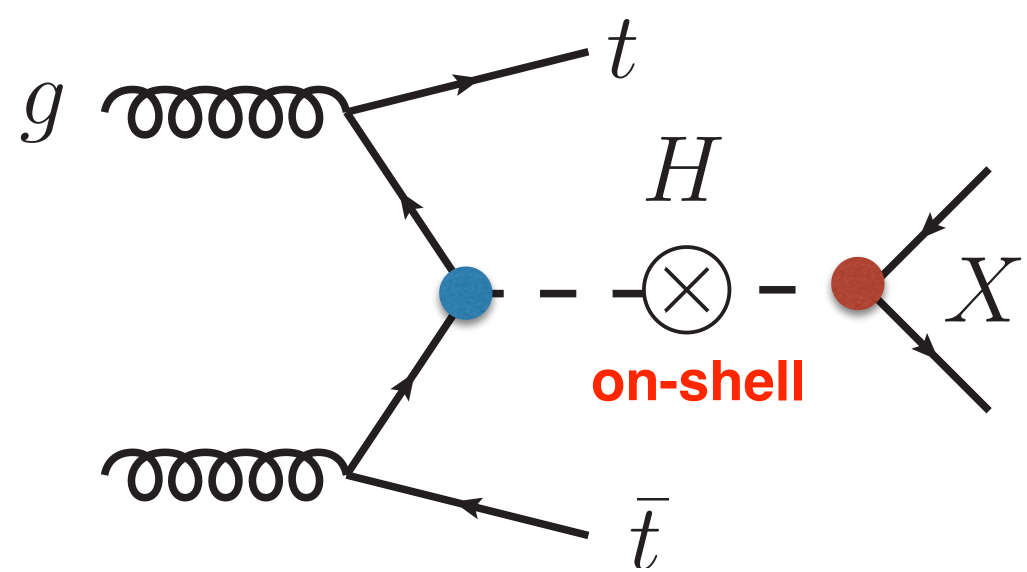
$$\Gamma_H \leq \frac{\Gamma_H^{\text{SM}}}{1 - \text{Br}_{\text{inv}}^{\text{Max}}} = 1.6\Gamma_H^{\text{SM}} = 6.4 \text{ MeV}$$

Q2: alternative way to measure Higgs width?

Four top-quark production

QHC, Chen, Liu, 1602.01934





$$\hat{\sigma}(pp \to t\bar{t}H \to t\bar{t}t\bar{t})$$

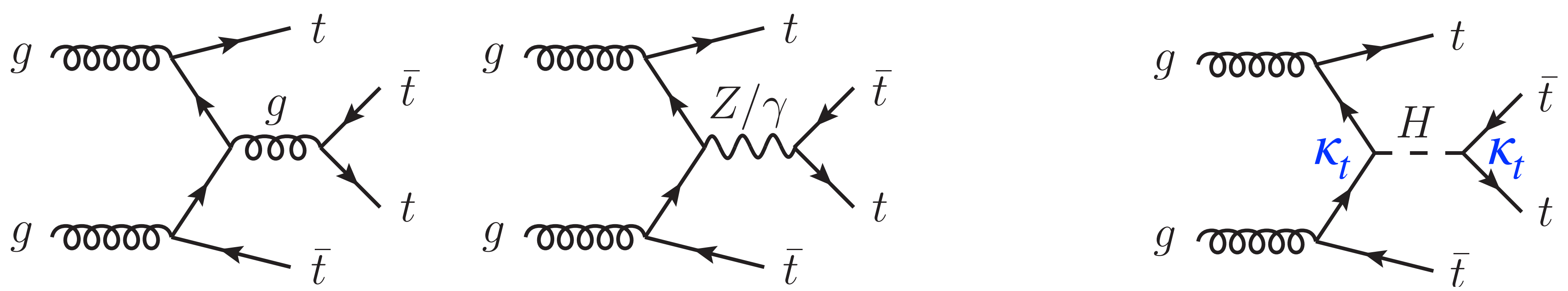
$$\propto \kappa_t^4 \times \hat{\sigma}(pp \to t\bar{t}H \to t\bar{t}t\bar{t})_{\rm SM}$$

$$\hat{\sigma}(pp \to t\bar{t}H \to t\bar{t}X)$$

$$\propto \underbrace{\frac{\kappa_t^2 \kappa_X^2}{\Gamma_H/\Gamma_H^{\rm SM}}}_{\mu^X_{t\bar{t}H}} \times \hat{\sigma}(pp \to t\bar{t}H \to t\bar{t}X)_{\rm SM}$$

$$\mu^X_{t\bar{t}H} \equiv \frac{\kappa_t^2 \kappa_X^2}{\Gamma_H/\Gamma_H^{\rm SM}} = \frac{\kappa_t^2 \kappa_X^2}{R_\Gamma} \xrightarrow{\kappa_X \simeq 1} \frac{\kappa_t^2}{R_\Gamma} = \mu^X_{t\bar{t}H}$$

Measuring κ_t from four top-quark production



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

LO	8 TeV	1.344	-0.224	0.171	in unit of fb
	13 TeV	9.997	-1.547	1.108	

$\sigma_g^{SM} = 1.216$

$\sigma_{Z/\gamma}^{SM} = 0.412$

$\sigma_{g+Z/\gamma}^{SM} = -0.262$

NLO corrections:

Bevilacqua, Worek (2012)
Alwall et al (2014)
Frederix, Pagani, Zaro (2017)

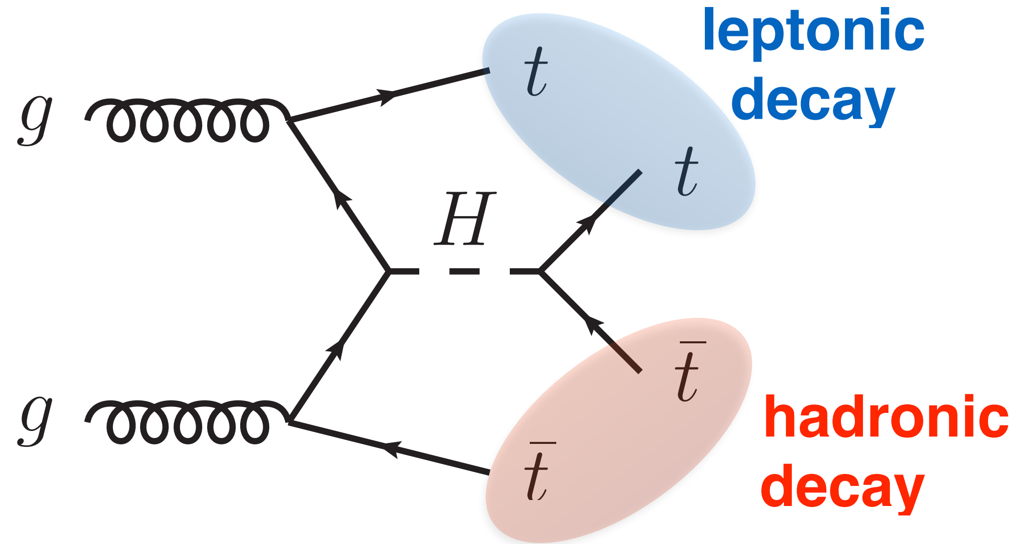
$K_{factor} = 1.58$

significant cancellations between strong and weak interactions

→ **large scale dependence**

Collider simulation

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



Event selections:

$p_T^{j,l} \geq 20\text{GeV}$

$|\eta^{j,l}| < 2.5$

$N_{l^\pm} = 2$

$N_{b-\text{jets}} \geq 3$

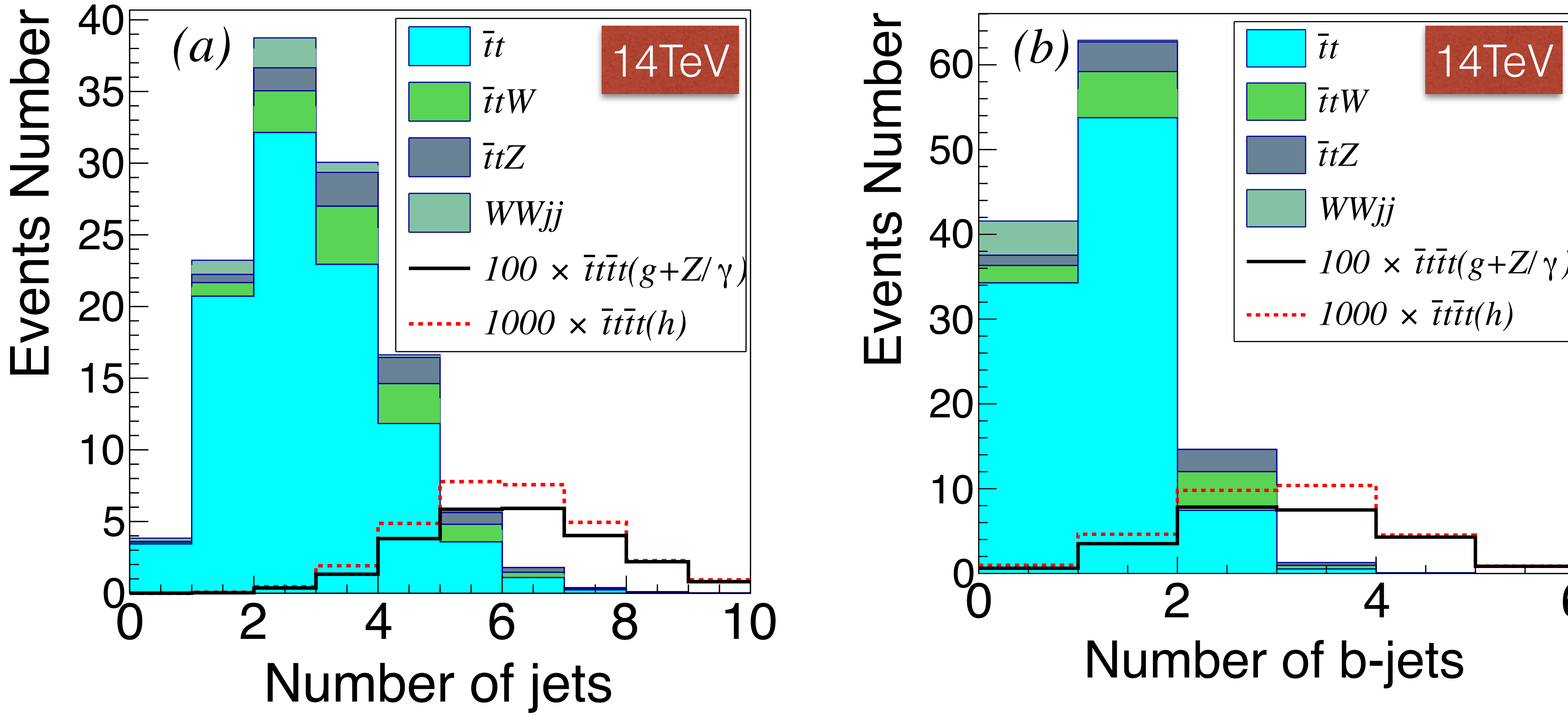
13-14TeV	27TeV	100TeV
$N_{\text{jets}} \geq 5$	$N_{\text{jets}} \geq 6$	$N_{\text{jets}} \geq 6$
$\not{E}_T \geq 100\text{GeV}$	150GeV	150GeV
$\text{M}_T \geq 100\text{GeV}$		
$H_T \geq 700\text{GeV}$	700GeV	800GeV

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

$K_F^{t\bar{t}W^+} = 1.22$ $K_F^{t\bar{t}W^-} = 1.27$ $K_F^{t\bar{t}Z} = 1.49$ $K_F^{W^+W^+jj} = 0.9$ $K_F^{t\bar{t}} = 1.4$ @14TeV

Collider simulation

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

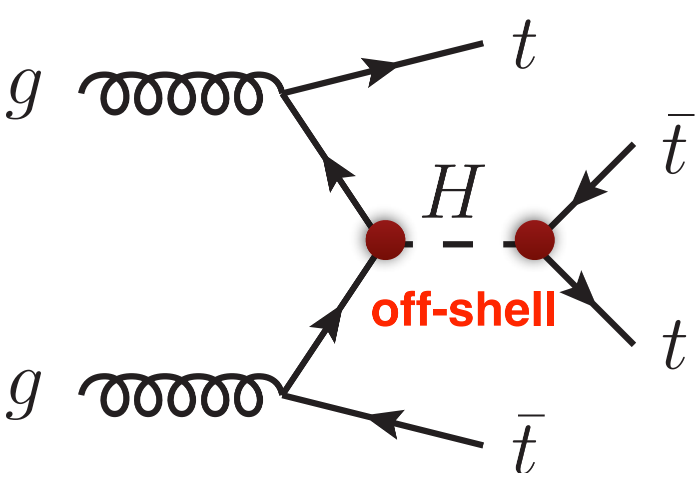


Not adequate to claim a discovery of κ_t at LHC but could set a bound

$\kappa_t \leq 1.34$ @ 13 TeV LHC (300fb^{-1})

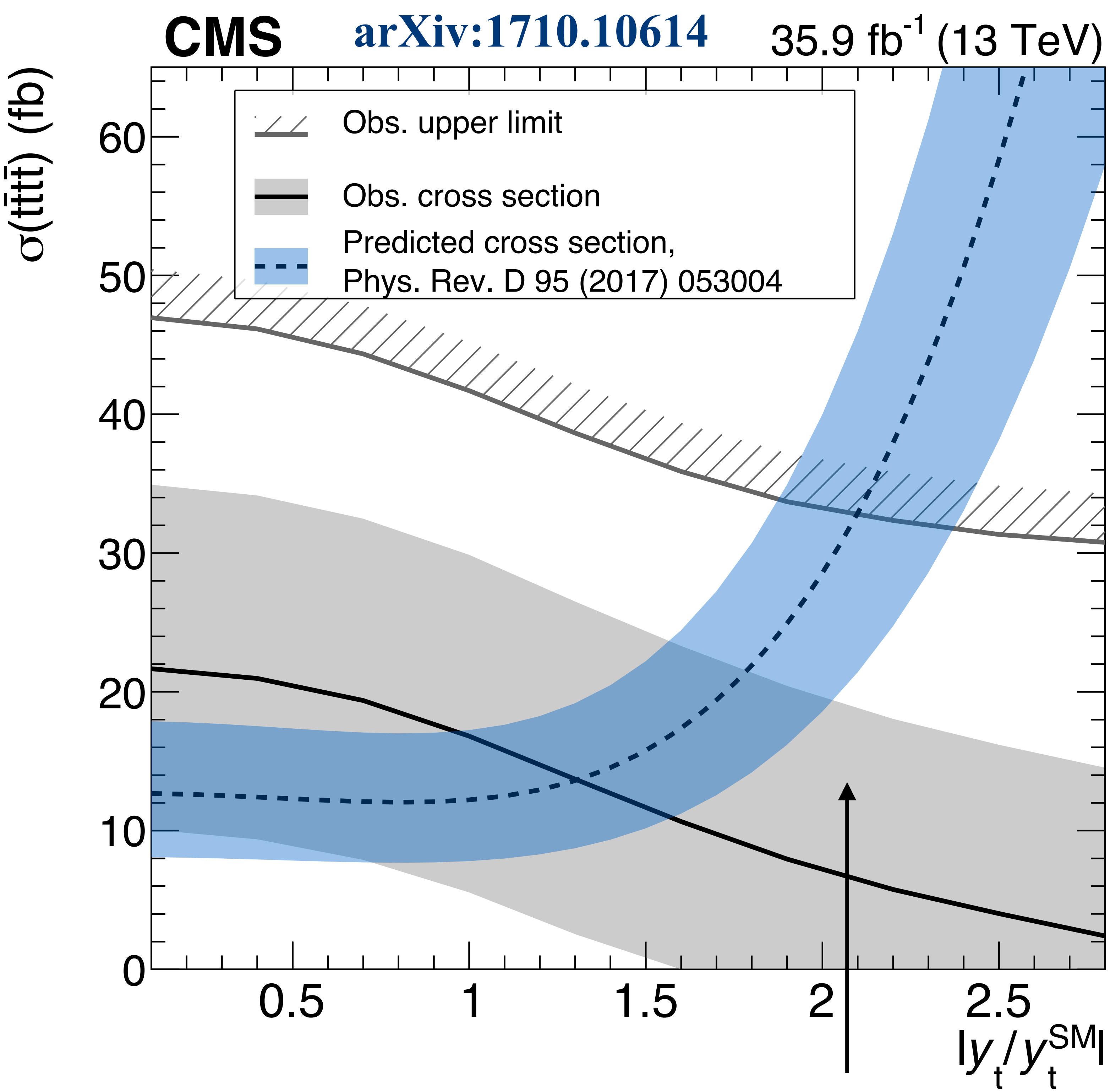
Sizing up top-quark interaction with Higgs

Four-top production



QHC, Chen, Liu
PRD95 (2017) 053004

No assumptions made on how Higgs-boson decays



$y_t/y_t^{SM} \leq 2.1$

$$\frac{\kappa_t^2}{R_\Gamma} = \mu_{t\bar{t}H}$$ assume $\kappa_X \simeq 1$ and invisible width

$\Gamma_H \leq 6.8\ \Gamma_H^{SM}$

13TeV LHC (35.9fb[-1])

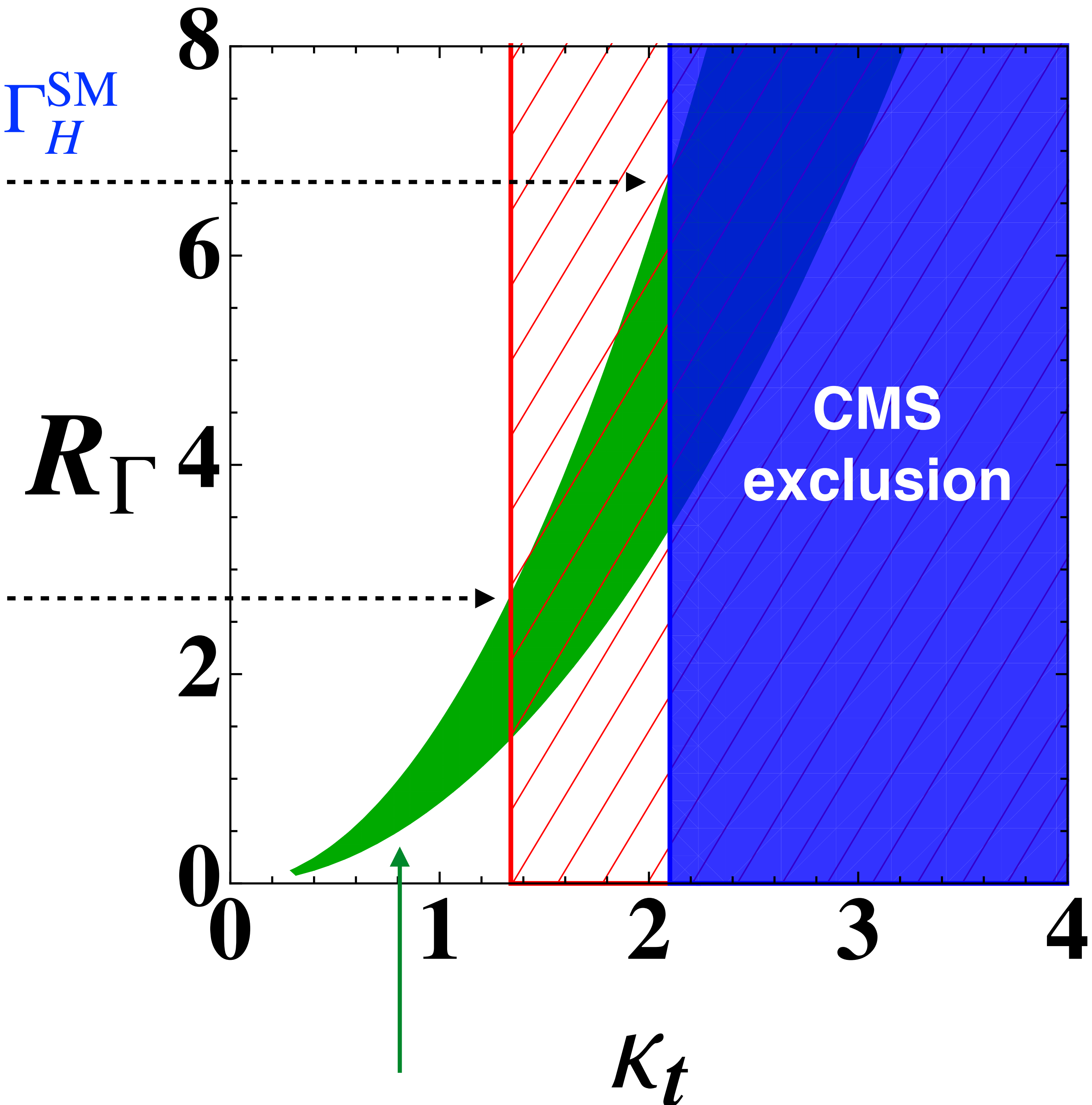
$\kappa_t \leq 2.1$

13TeV LHC (300fb[-1])

$\kappa_t \leq 1.34$

$\Gamma_H \leq 2.8\ \Gamma_H^{SM}$

$\sim 11\text{MeV}$



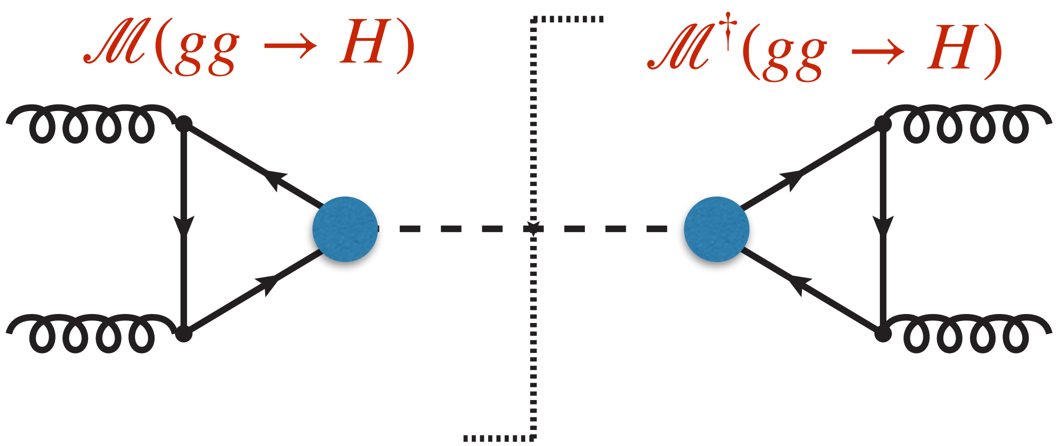
$\mu_{t\bar{t}H} = 0.96^{+0.34}_{-0.31}$

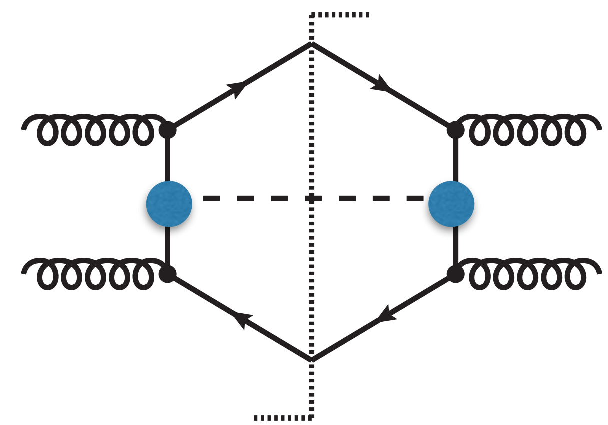
CMS-PAS-HIG-18-019

Q3: CP property of top-Higgs interaction

$$\mathscr{L}_{Ht\bar{t}} = -\frac{m_t}{v} H\bar{t}(a_t + i b_t \gamma_5)t$$

Boudjema, Godbole, Guadagnoli, Mohan, 1501.03157





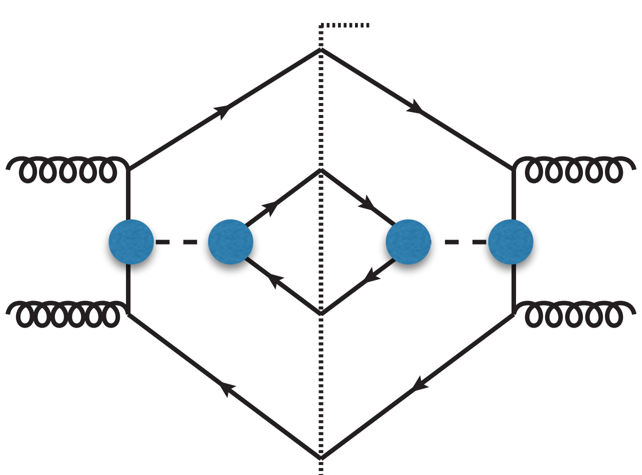
$$\frac{\sigma(gg \to H)}{\sigma(gg \to H)_{\rm SM}} \sim a_t^2 + 2.26 b_t^2$$

pseudo-scalar dominates

$$\frac{\sigma(gg \to t\bar{t}H)}{\sigma(gg \to t\bar{t}H)_{\rm SM}} \sim a_t^2 + 0.46 b_t^2$$

@13TeV

scalar dominates



CP-odd (a=0, b=1)

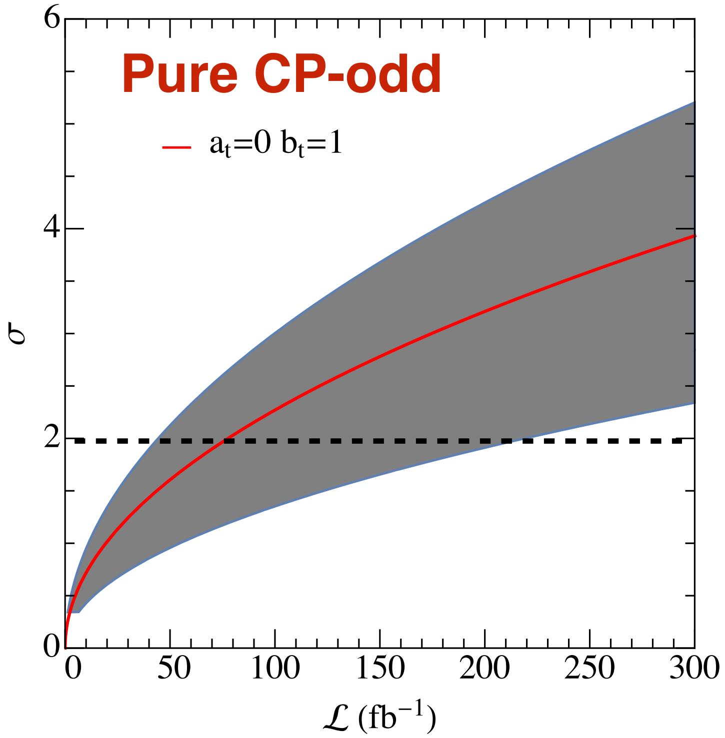
$$\sigma(t\bar{t}t\bar{t}) = 9.997 + 2.807 \times b_t^2 + 1.788 \times b_t^4$$

CP-even (a=1, b=0)

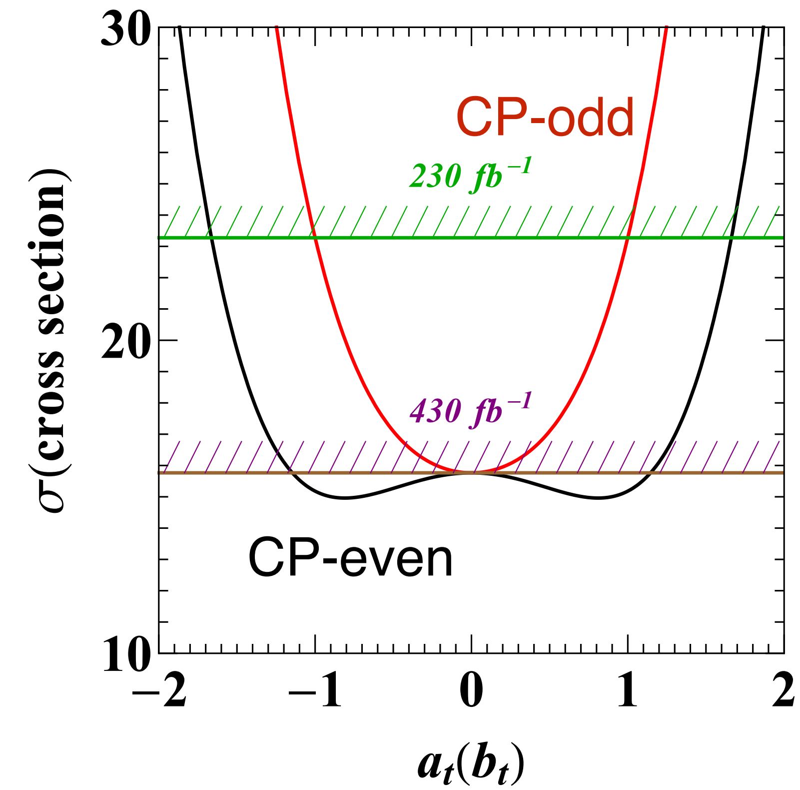
$$\sigma(t\bar{t}t\bar{t}) = 9.997 - 1.547 \times a_t^2 + 1.108 \times a_t^4$$

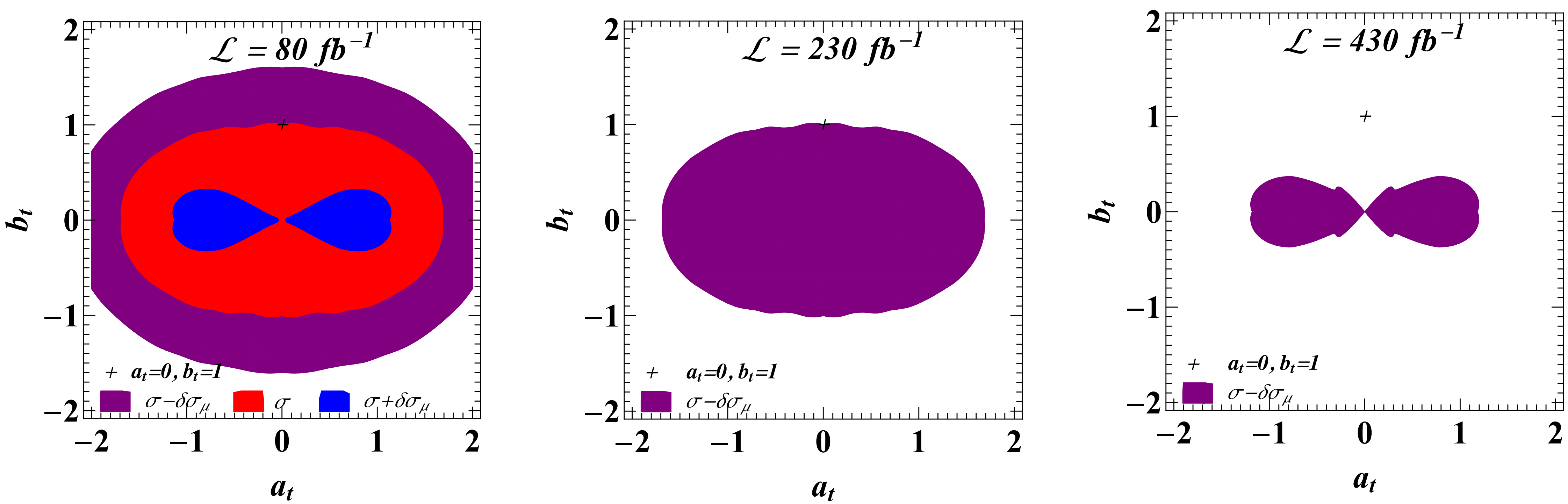
Potential of four-top measurements

Exclusion significance



large scale dep. ~50%





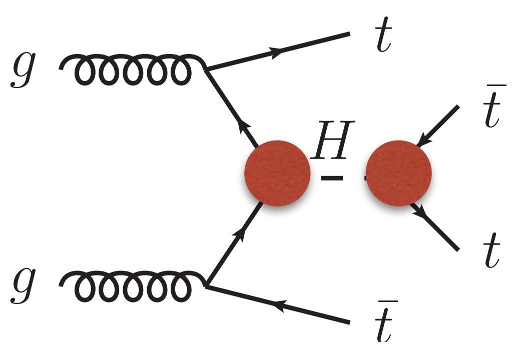
13TeV

230fb^{-1}: excludes a pure CP-odd Htt coupling with b_t=1

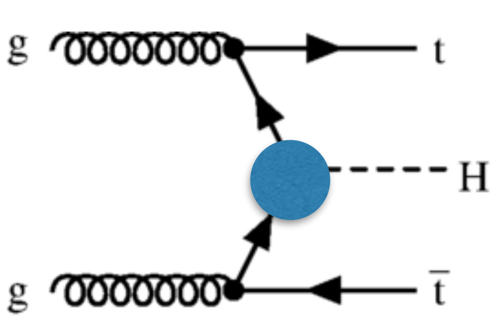
430fb^{-1}: excludes a pure CP-odd Htt coupling entirely (any b_t)

Global analysis of multi-top productions

13TeV LHC

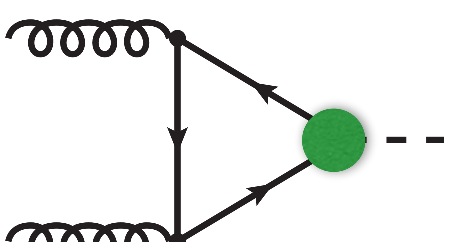


$$\sigma(t\bar{t}t\bar{t}) = 9.998 - 1.522a_t^2 + 2.883b_t^2 + 1.173a_t^4 + 2.713a_t^2b_t^2 + 1.827b_t^4$$



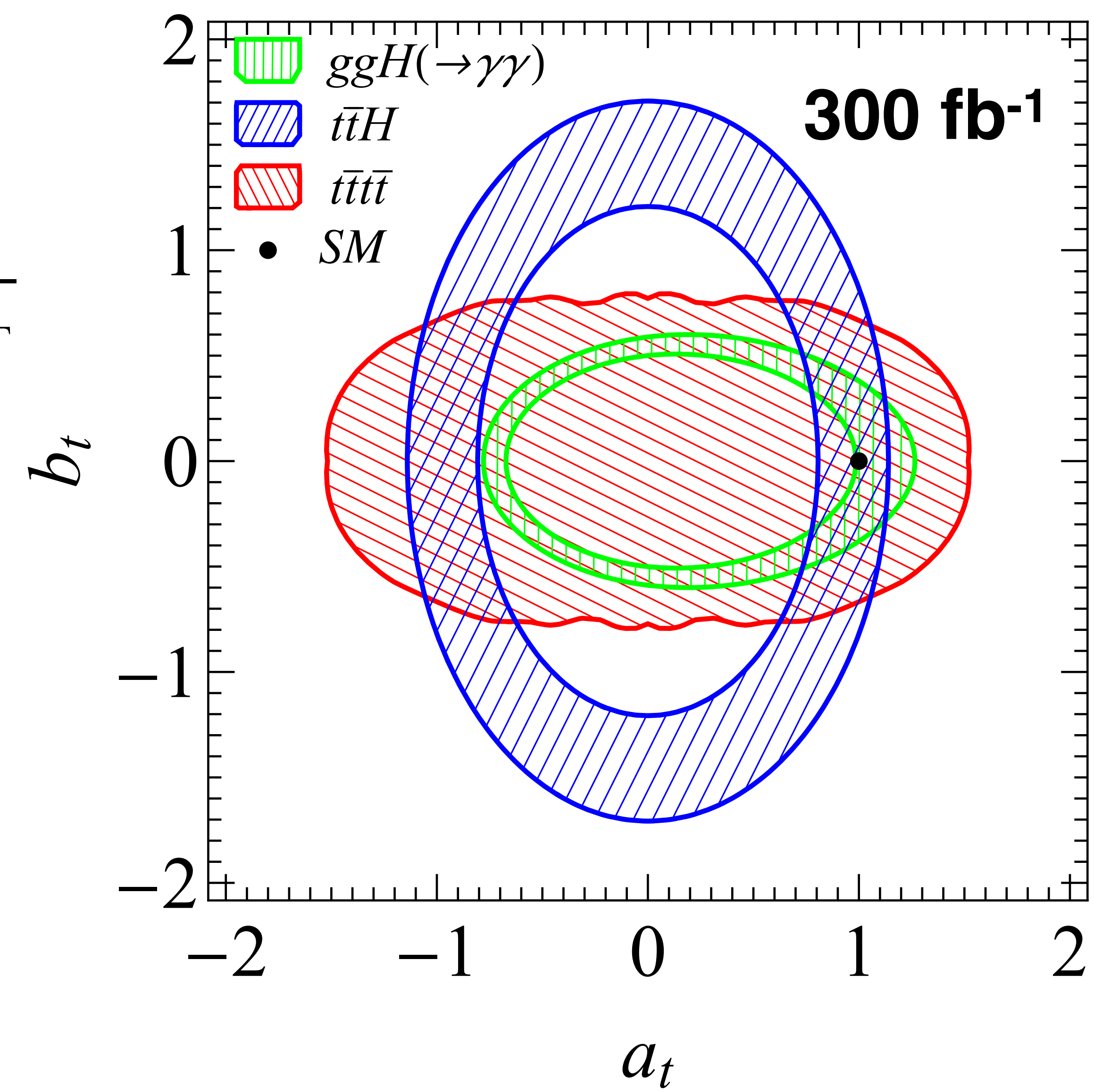
$$\frac{\sigma(gg \to t\bar{t}H)}{\sigma(gg \to t\bar{t}H)_{\rm SM}} = \left(a_t^2 + 0.46b_t^2\right)\frac{1}{R_\Gamma}$$

$$\mu_{t\bar{t}H} = 0.96^{+0.34}_{-0.31}$$



$$\frac{\sigma(gg \to H \to \gamma\gamma)}{\sigma(gg \to H \to \gamma\gamma)_{\rm SM}} = (a_t^2 + 2.26b_t^2) \times \frac{0.035(-7.2 + 1.83a_t^2) + 0.27b_t^2}{R_\Gamma}$$

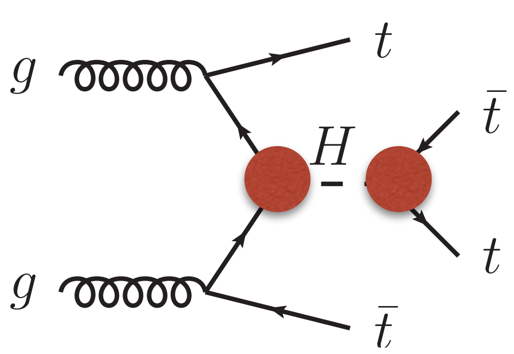
$$\mu_{gg\to H\to\gamma\gamma} = 1.16^{+0.21}_{-0.18}$$



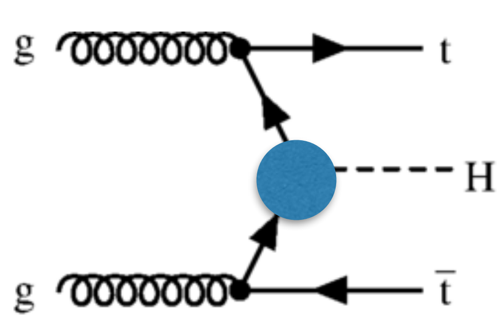
$$0.73 < a < 1.14$$
$$-0.51 < b < 0.51$$

Global analysis of multi-top productions

13TeV LHC



$$\sigma(t\bar{t}t\bar{t}) = 9.998 - 1.522a_t^2 + 2.883b_t^2 + 1.173a_t^4 + 2.713a_t^2b_t^2 + 1.827b_t^4$$



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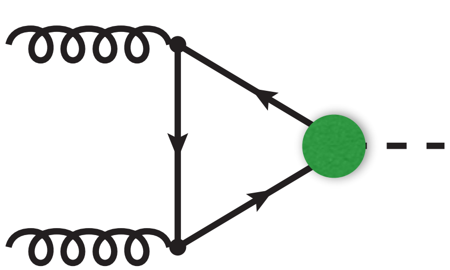
$$\mu_{t\bar{t}H} = 0.96^{+0.34}_{-0.31}$$



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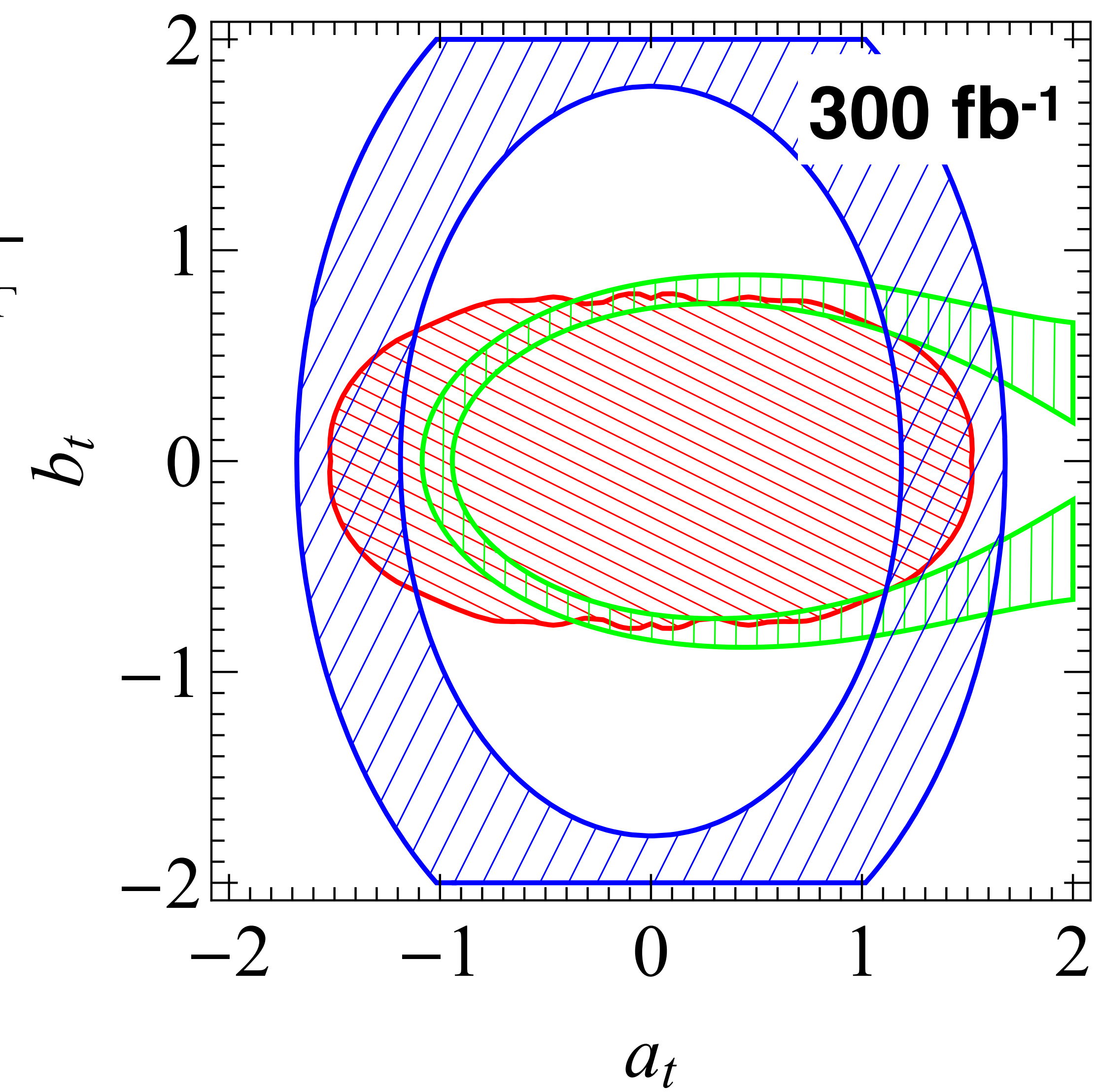
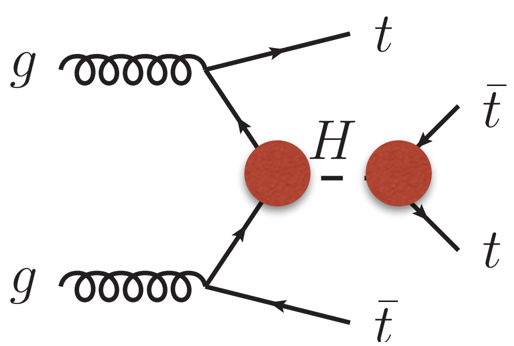


$R_\Gamma < 2.17$

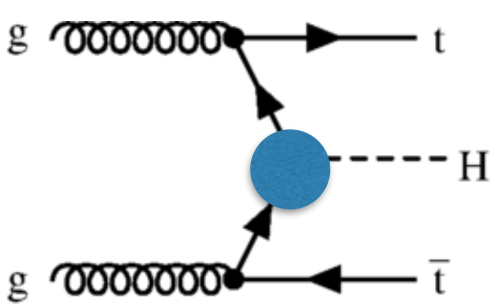
Global analysis of multi-top productions

@ HL-LHC



$$\sigma(t\bar{t}t\bar{t}) = 9.998 - \underline{1.522a_t^2 + 2.883b_t^2 + 1.173a_t^4 + 2.713a_t^2b_t^2 + 1.827b_t^4}$$

assume $\mu^{H}_{t\bar{t}t\bar{t}} = 1.00^{+0.50}_{-0.50}$



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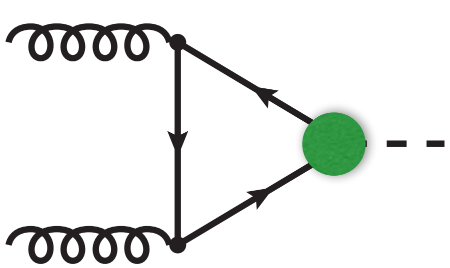
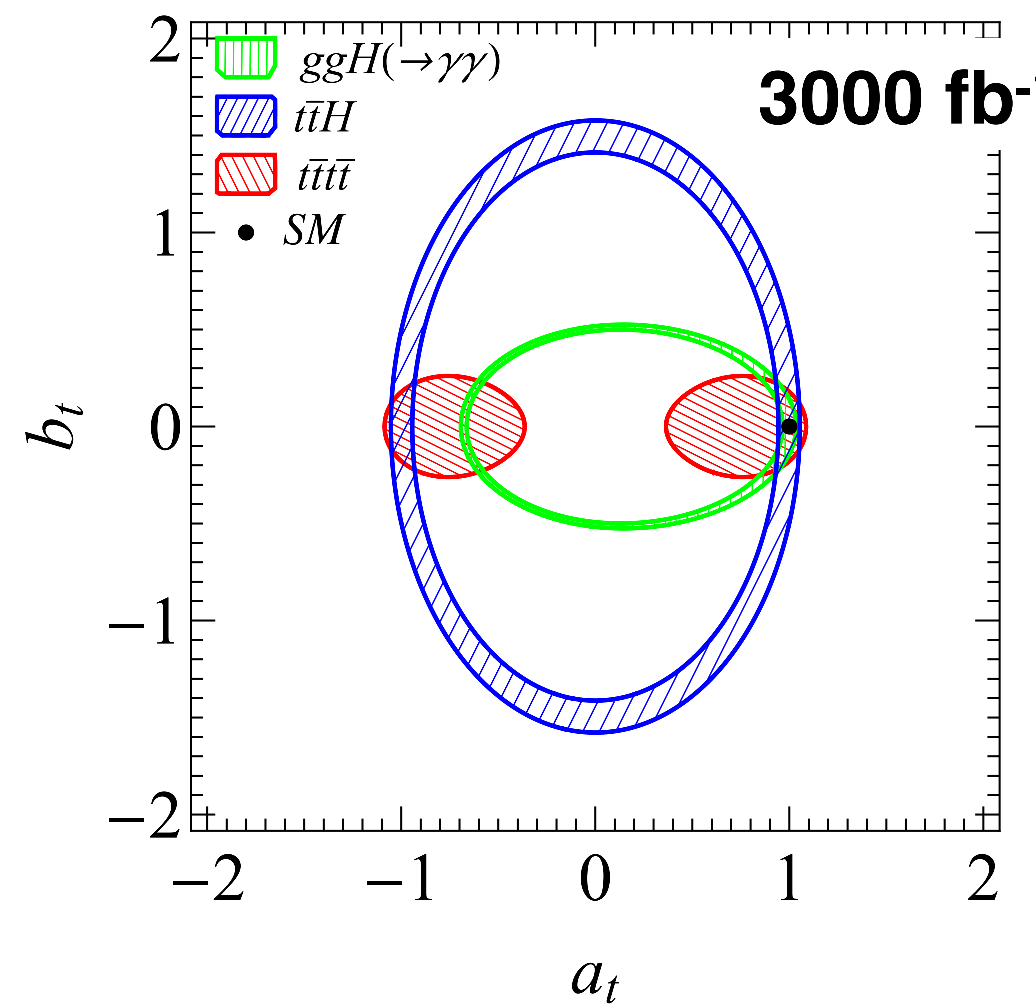


$$\frac{\sigma(gg \to H \to \gamma\gamma)}{\sigma(gg \to H \to \gamma\gamma)_{\rm SM}}$$

$$= (a_t^2 + 2.26b_t^2)$$

$$\times \frac{0.035(-7.2 + 1.83a_t^2) + 0.27b_t^2}{R_\Gamma}$$

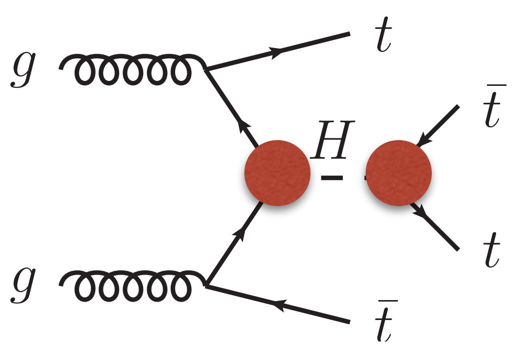
$$\mu_{gg\to H\to\gamma\gamma} = 1.00^{+0.05}_{-0.05}$$



$$0.93 < a < 1.03$$
$$-0.22 < b < 0.22$$

Global analysis of multi-top productions

@ HL-LHC



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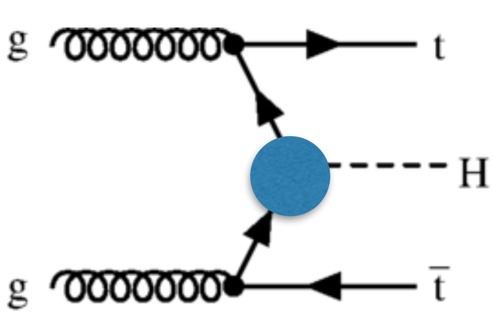
assume $\mu^H_{t\bar{t}t\bar{t}} = 1.00^{+0.5}_{-0.5}$



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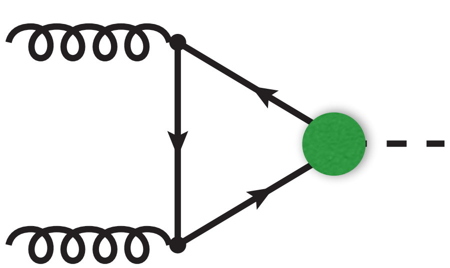

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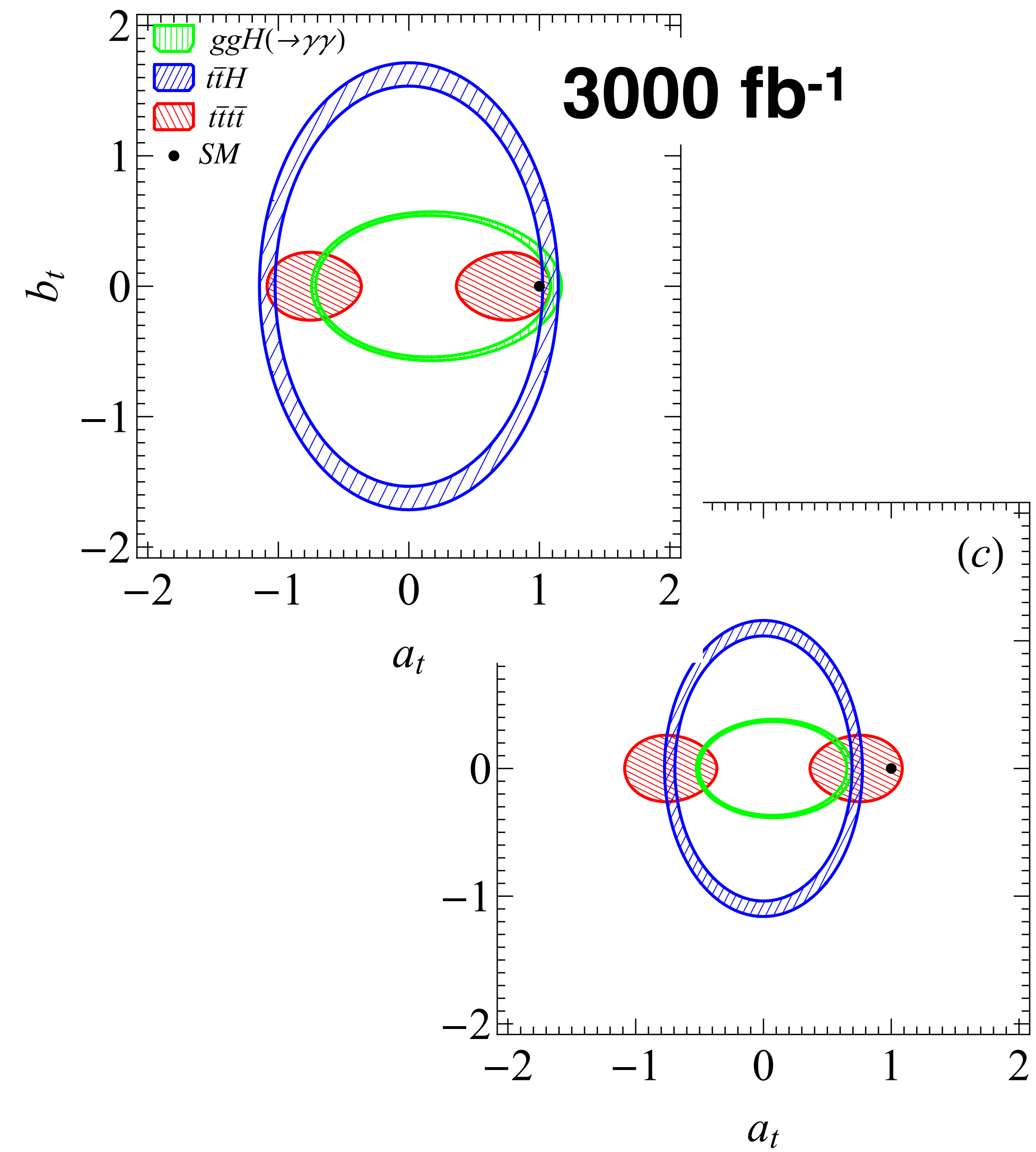
$$= (a_t^2 + 2.26b_t^2)$$

$$\times \frac{0.035(-7.2 + 1.83a_t^2) + 0.27b_t^2}{R_\Gamma}$$

$$\mu_{gg\to H\to\gamma\gamma} = 1.00^{+0.05}_{-0.05}$$



$$0.54 < R_\Gamma < 1.18$$

Summary

The four top-quark production can constrain top-quark Yukawa coupling without assumptions on Higgs boson width or decay branching ratios.

The four top-quark production is sensitive to the CP property of top-Higgs interaction.

$$\mathscr{L}_{Ht\bar{t}} = -\frac{m_t}{v} H\bar{t}(a_t + ib_t\gamma_5)t$$

Global fitting of single-Higgs, $t\bar{t}t\bar{t}$ and $t\bar{t}h$ channels yields

$$0.93 < a < 1.13, \ -0.22 < b < 0.22$$

$$0.54\Gamma_H^{\rm SM} < \Gamma_H \leq 1.18\Gamma_H^{\rm SM}$$

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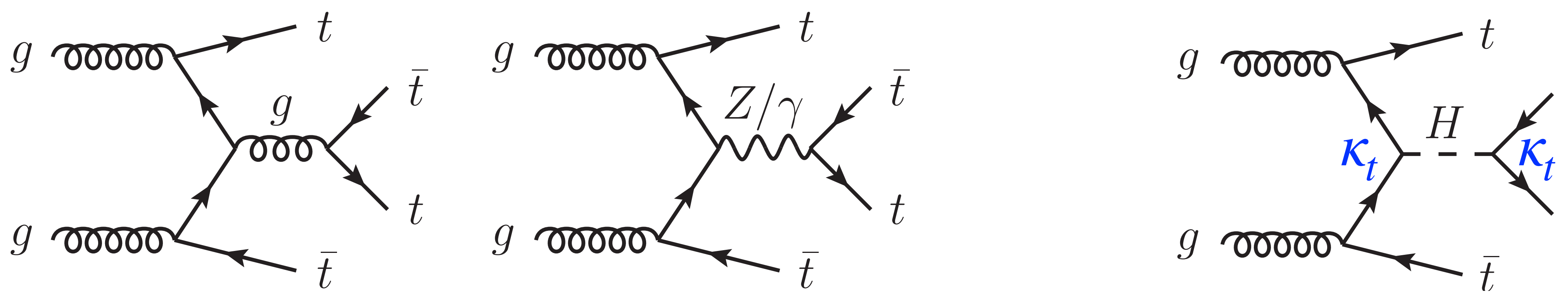
Measuring κ_t from four top-quark production



$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g/Z/\gamma} + \kappa_t^2\sigma_{\rm int}^{\rm SM} + \kappa_t^4\sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$

LO	8 TeV	1.344	-0.224	0.171
	13 TeV	9.997	-1.547	1.108
	14 TeV	13.14	-2.007	1.515
	27 TeV	115.1	-15.57	11.73
	100 TeV	3276	-356.9	273.1
	Relative ratio	**8~12**	**-1.3**	**1**

in unit of fb

cancel out around SM $\kappa_t = 1$

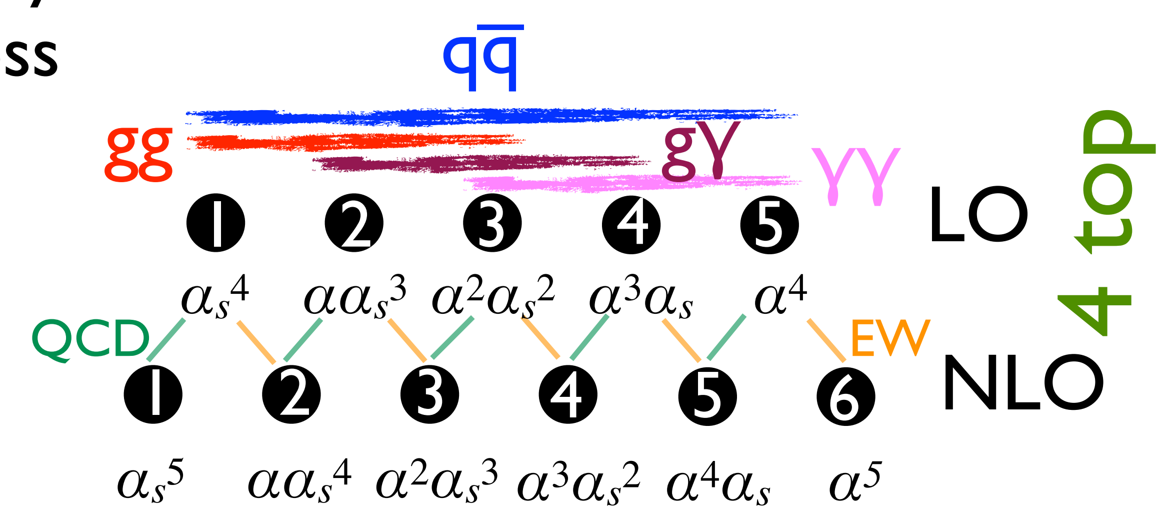
Zaro's talk @ Top2018

Results for 4-top: inclusive results

- The gg-initiated contributions ($LO_{1\to3}$, $NLO_{1\to4}$) are the dominant ones
- $LO_{2,3}$ are large and with different sign
- $NLO_{2,3}$ are sizeable too, and show a very large scale dependence: they are mostly due to QCD-type corrections from $LO_{2,3}$ respectively
- Remarkably, there is an almost complete cancellation between NLO_2 and NLO_3 which is also quite stable w.r.t. the scale choice
- Such a cancelation will be spoiled by e.g. non-SM Yukawa interactions. A LO-based study may not capture the correct behaviour of the cross section

13 TeV

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-26.0	-28.3	-30.5
LO_3	32.6	39.0	45.9
LO_4	0.2	0.3	0.4
LO_5	0.02	0.03	0.05
NLO_1	14.0	62.7	103.5
NLO_2	8.6	-3.3	-15.1
NLO_3	-10.3	1.8	16.1
NLO_4	2.3	2.8	3.6
NLO_5	0.12	0.16	0.19
NLO_6	< 0.01	< 0.01	< 0.01
$NLO_2 + NLO_3$	-1.7	-1.6	0.9



R. Frederix, D. Pagani, and M. Zaro, JHEP 02, 031 (2018), 1711.02116