Limits on Top-Higgs Interaction from Multi-Top Final States

Qing-Hong Cao
Peking University

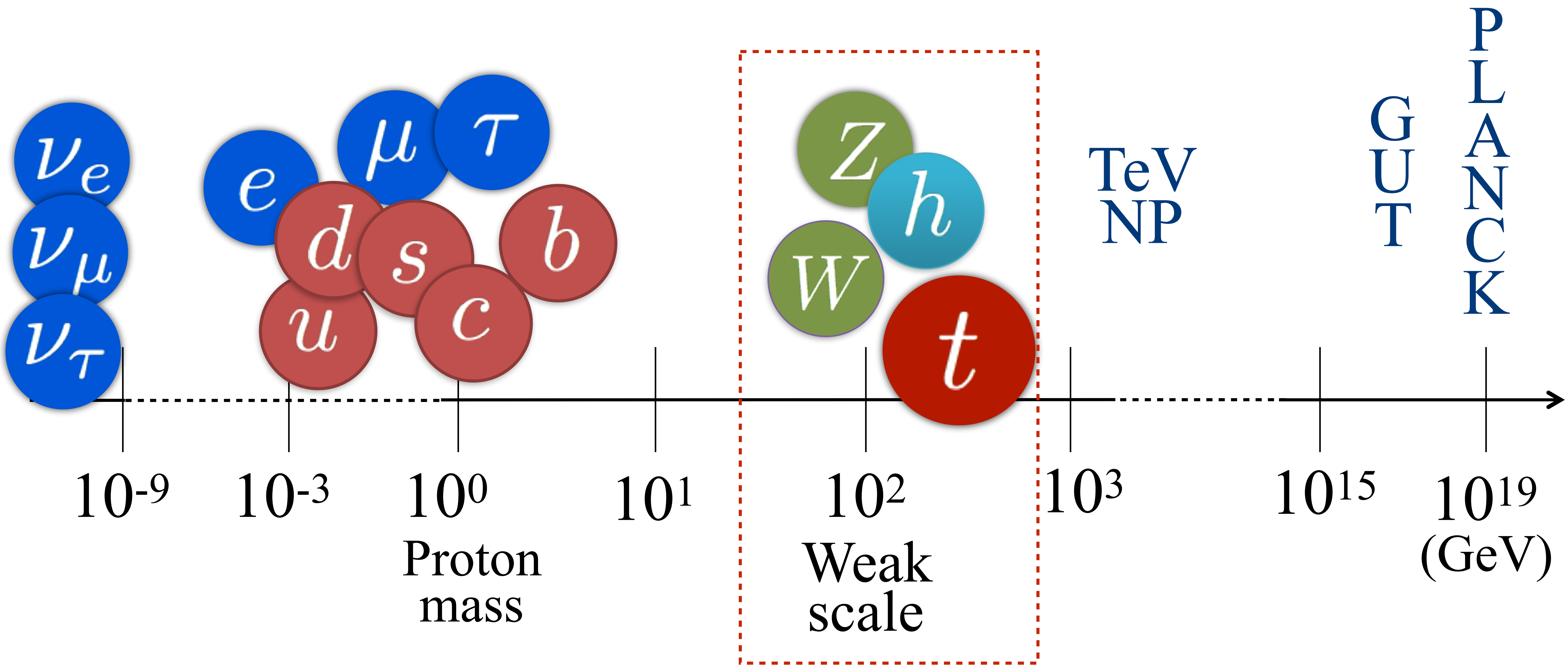
20/09/2018

In collaboration with
Shao-Long Chen and Yandong Liu, 1602.01934;
Shao-Long Chen, Yandong Liu, Rui Zhang, Ya Zhang, in preparation

Two outstanding puzzles in SM

Origins of EWSB and Flavor breaking

(*W/Z Mass*) (*Fermion Mass*)

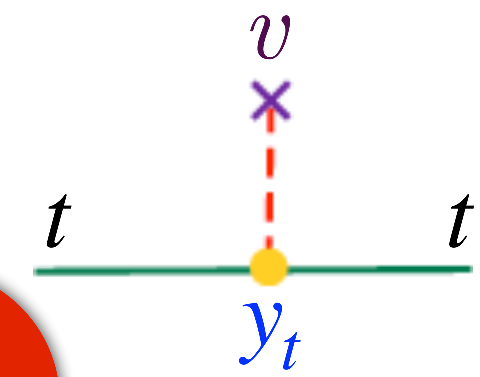


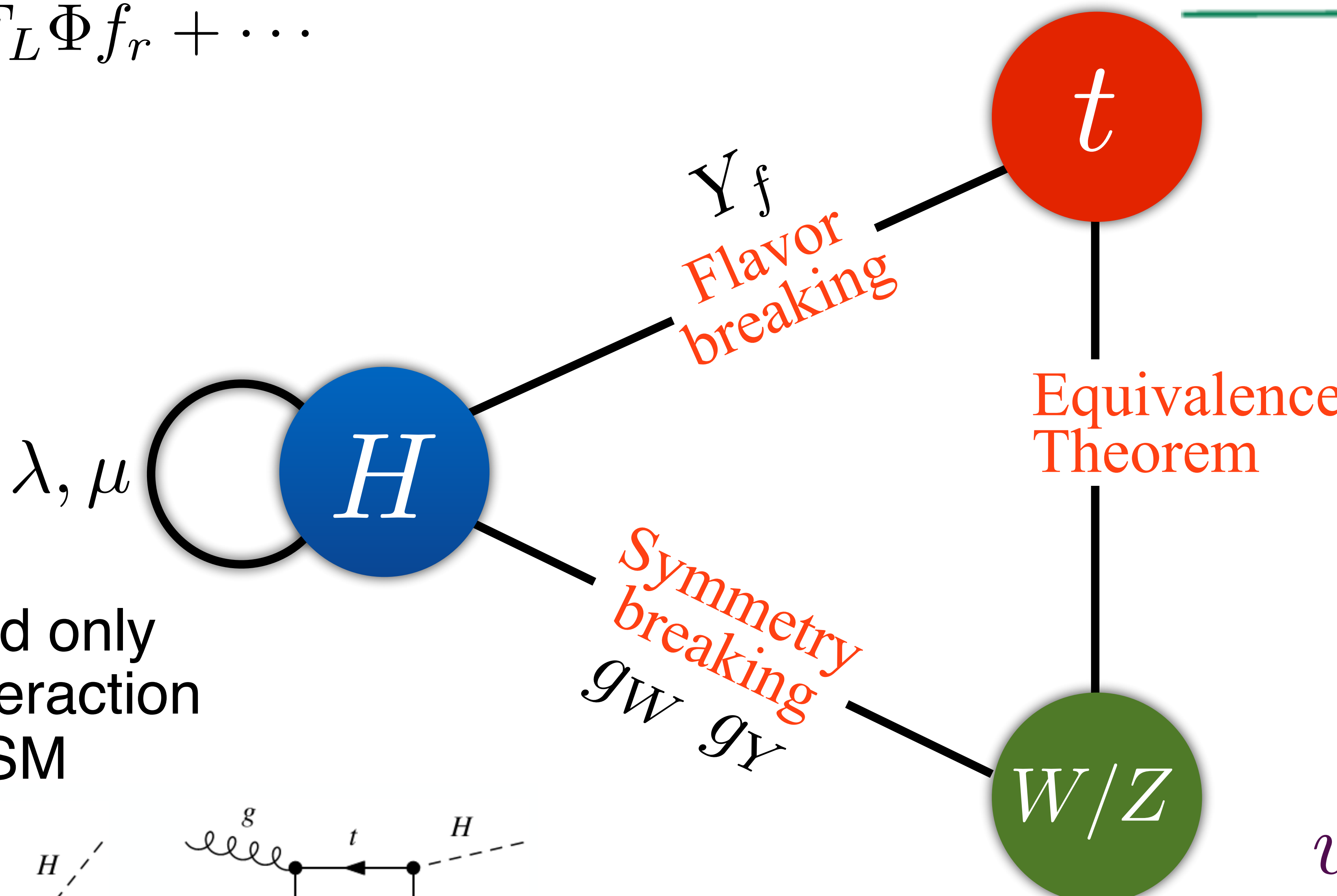
Top quark is not heavy! It is naturally around weak scale.

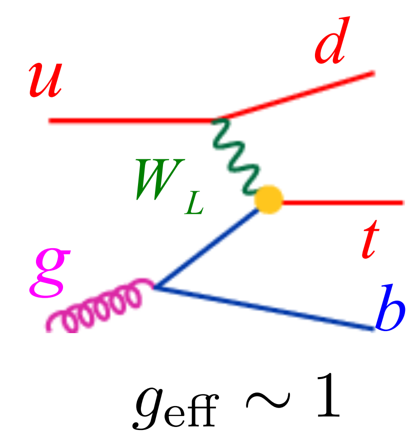
Q: why are the other quarks and leptons so light?

Testing the SM at weak scale

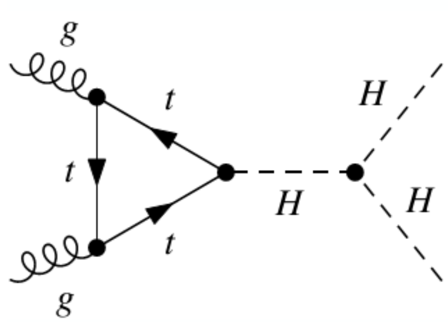
$$\mathcal{L} = \left(D_\mu\Phi\right)^\dagger\left(D^\mu\Phi\right) - \mu^2\Phi^\dagger\Phi + \lambda\left(\Phi^\dagger\Phi\right)^2$$
$$+ y_f \bar{F}_L \Phi f_r + \cdots$$

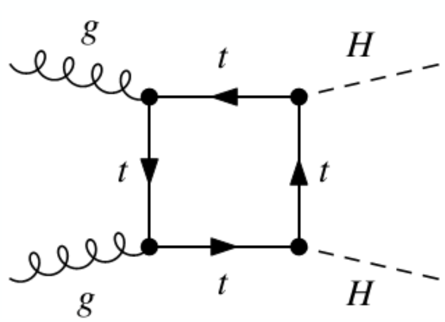


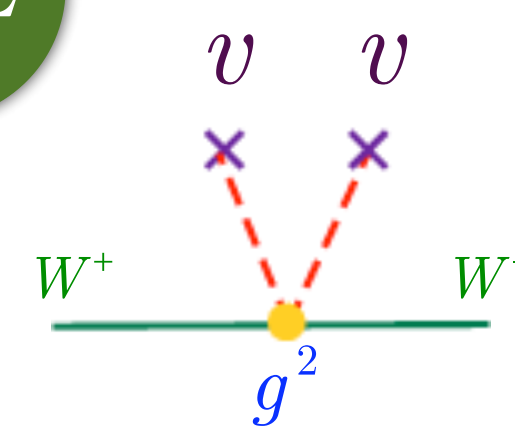




one and only
self-interaction
in the SM

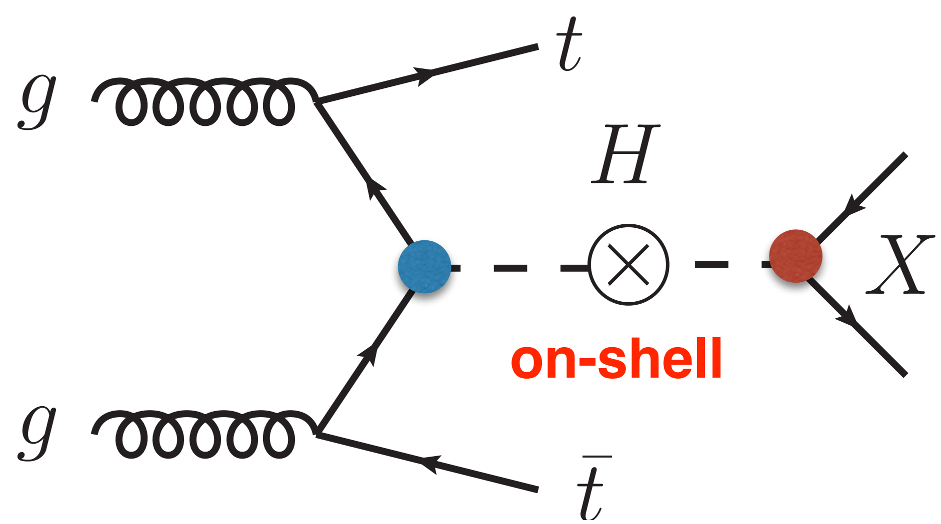






Top-quark Yukawa coupling

directly measured from the $t\bar{t}H$ production



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

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

Narrow width approximation

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

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

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

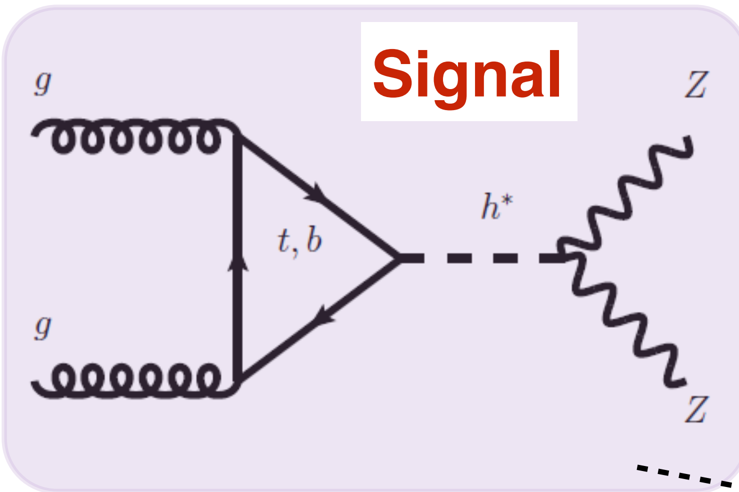
Q1: can we determine κ_t without those assumptions?

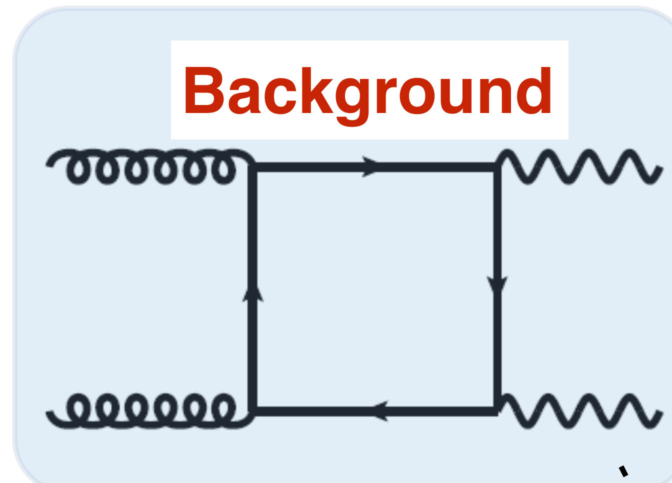
Higgs boson width

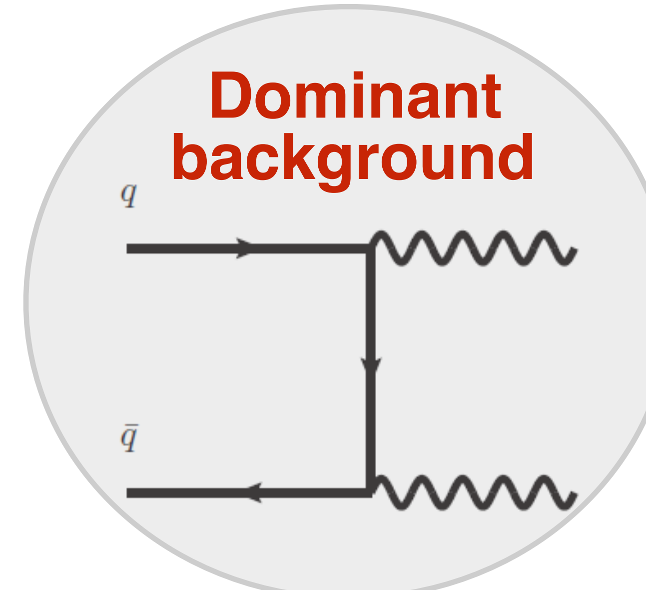
Caola, Melnikov (2013)

Higgs on-shell production

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

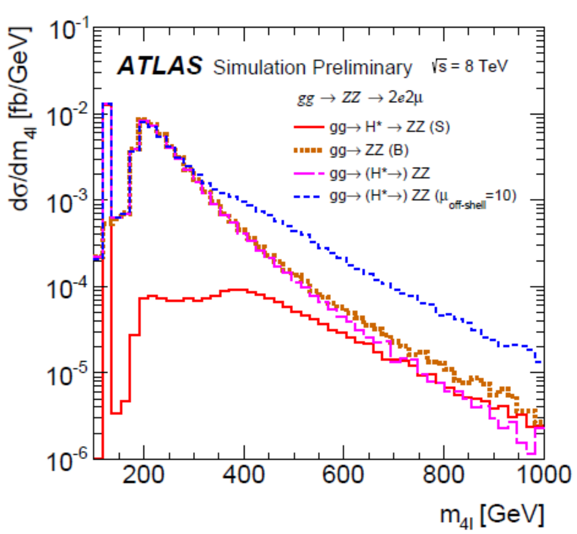






Higgs off-shell production

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

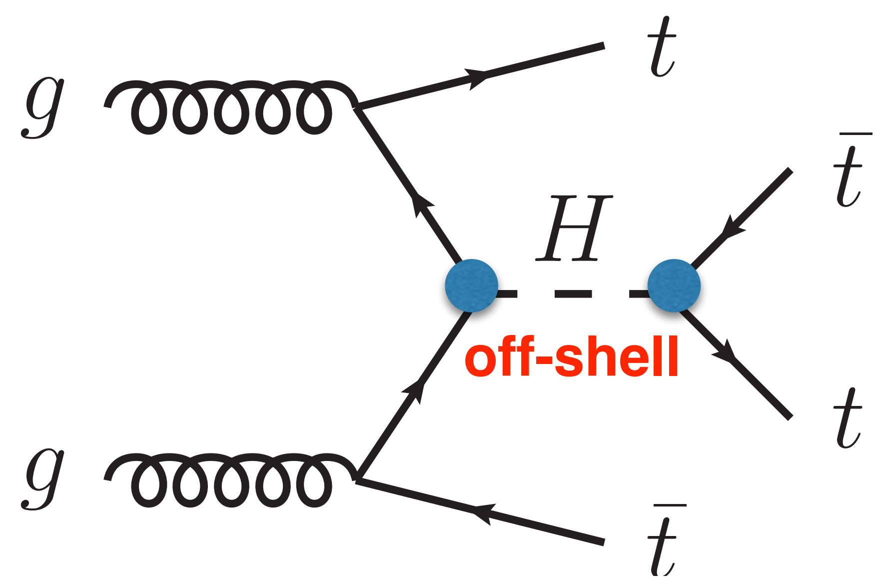


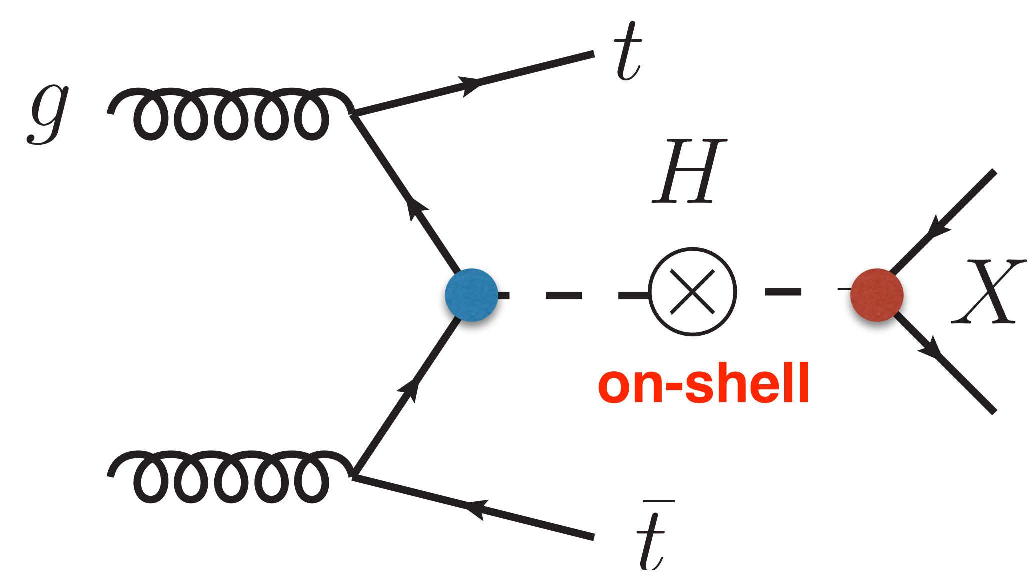
The combination of both on-shell and off-shell measurements of signal strength achieve a significantly higher sensitivity to the total width

Q2: alternative way to measure the Higgs boson width?

Four top-quark production

QHC, Chen, Liu, 1602.01934





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

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

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

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

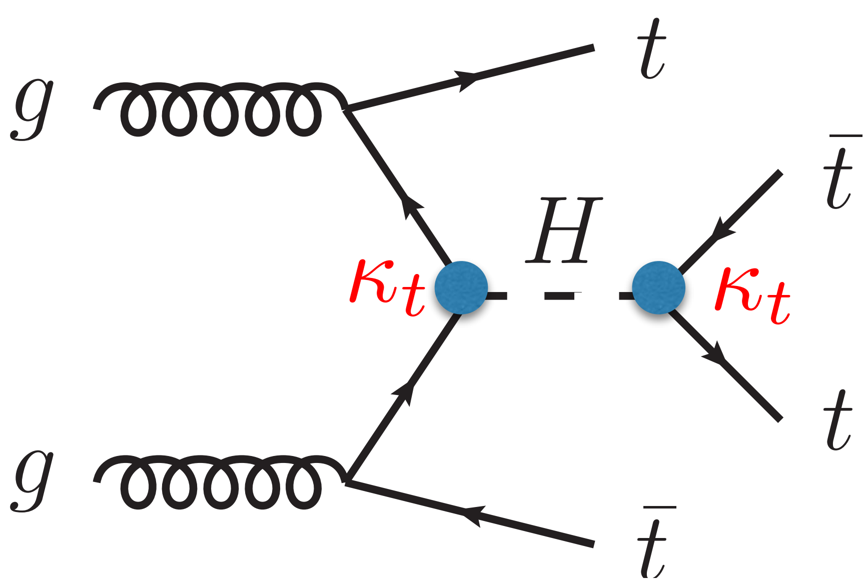
$X = \gamma\gamma, \mu^+\mu^-, ZZ^*, \cdots$

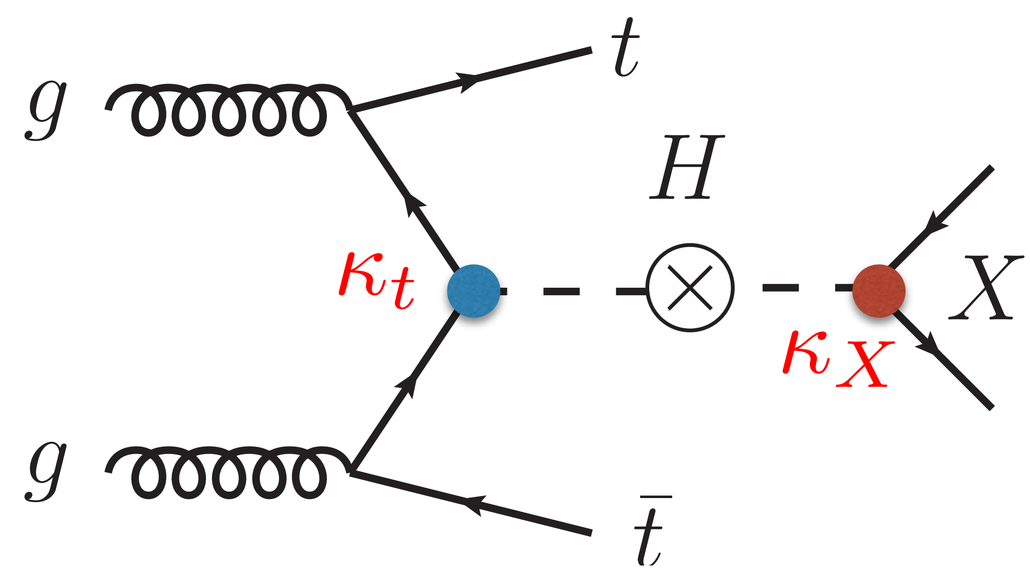
$\mu^{\gamma\gamma}_{t\bar{t}H} = 1.00 \pm 0.38$ $\quad \mu^{ZZ}_{t\bar{t}H} = 1.00 \pm 0.49$

$\mu^{\mu\mu}_{t\bar{t}H} = 1.00 \pm 0.74$ $\quad \mu^{\rm combo}_{t\bar{t}H} = 1.00 \pm 0.30$

ATLAS-PHYS-PUB-2014-016
14TeV LHC, 300fb^{-1}

Two scenarios



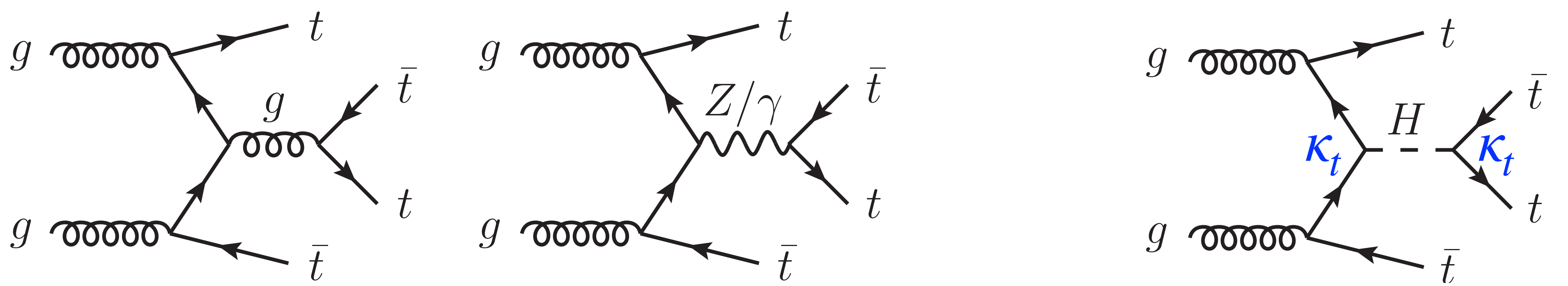


$$\hat{\sigma}(pp \to t\bar{t}t\bar{t}) \propto \kappa_t^4$$

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

1) $\Gamma_H \simeq \Gamma_H^{\rm SM}$	**2)** $\kappa_X \simeq 1$
Rare modes $(\gamma\gamma, \mu^+\mu^-)$	Major modes $(b\bar{b}, WW^*)$
$\kappa_t^2 \kappa_X^2 = \mu^X_{t\bar{t}H}$	$\frac{\kappa_t^2}{R_\Gamma} = \mu^X_{t\bar{t}H}$

Measuring κ_t from four top-quark production



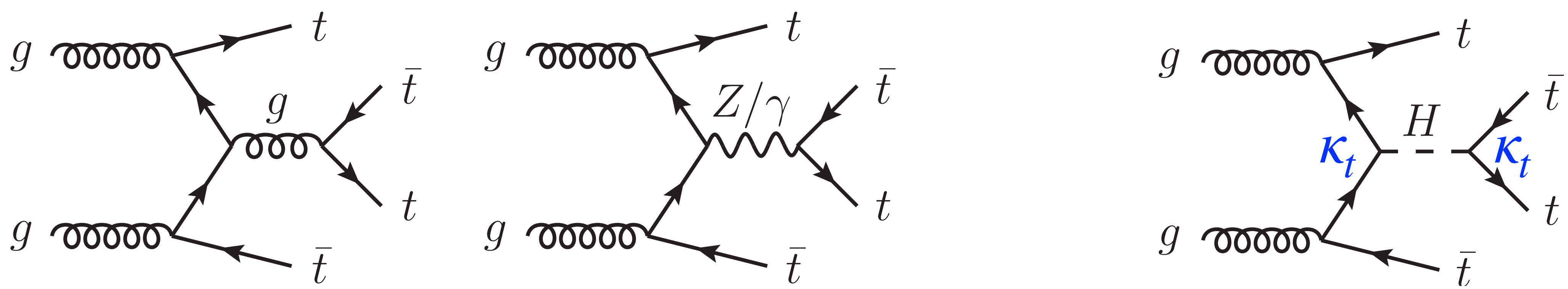
$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g/Z/\gamma} + \kappa_t^2\sigma^{\mathrm{SM}}_{\mathrm{int}} + \kappa_t^4\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_H$$

	8 TeV	1.344	-0.224	0.171
LO	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

in unit of fb

NLO corrections: Bevilacqua, Worek (2012);
Alwall et al (2014); Frederix, Pagani, Zaro (2017)

Measuring κ_t from four top-quark production



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

		$\sigma^{SM}(t\bar{t}t\bar{t})_{g/Z/\gamma}$	σ^{SM}_{int}	$\sigma^{SM}(t\bar{t}t\bar{t})_H$
LO	8 TeV	1.344	-0.224	0.171
	13 TeV	9.997	[illegible]	[illegible]
	14 TeV	13.14	[illegible]	[illegible]
	27 TeV	115.1	[illegible]	[illegible]
	100 TeV	3276	-356.9	273.1

$\sigma^{SM}_g = 1.216$

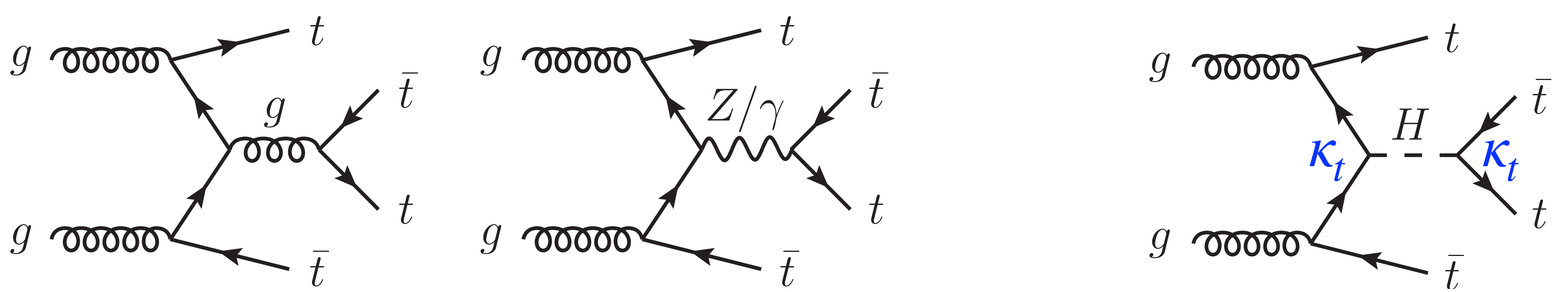
$\sigma^{SM}_{Z/\gamma} = 0.412$

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

NLO corrections: Bevilacqua, Worek (2012); $K_{factor} = 1.27$

Alwall et al (2014); Frederix, Pagani, Zaro (2017)

Measuring κ_t from four top-quark production



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

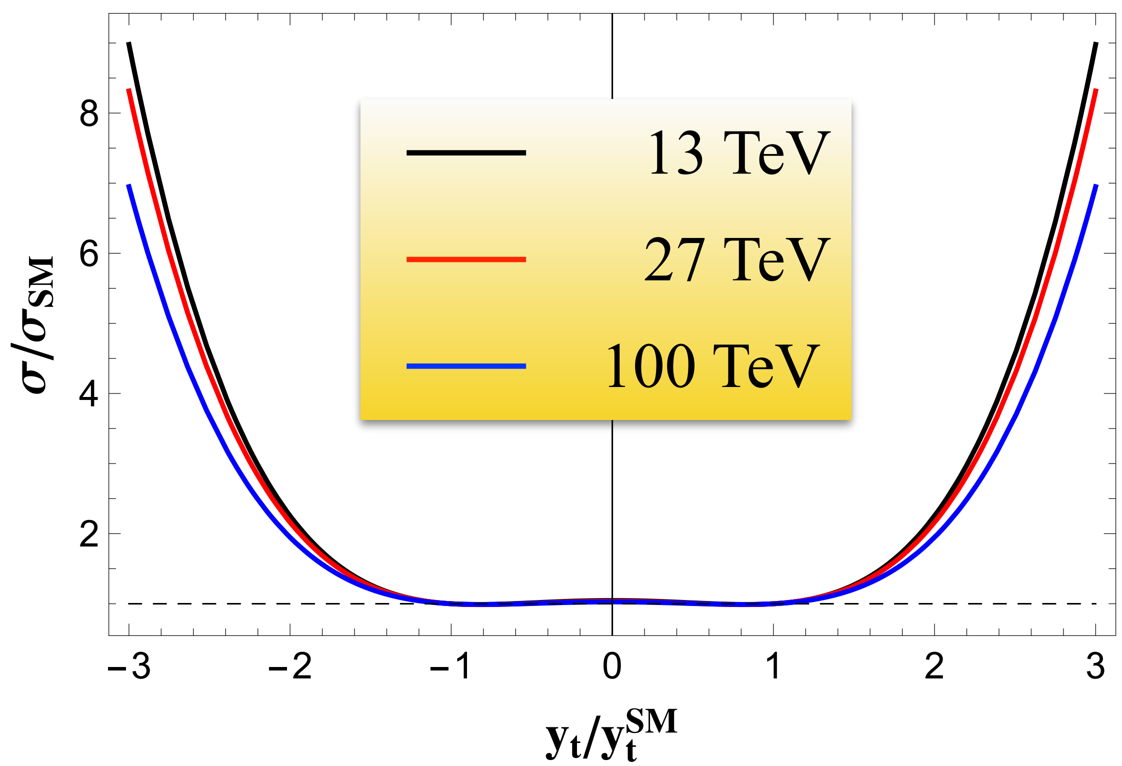
LO	8 TeV	1.344	-0.224	0.171
	13 TeV	9.997	-1.547	1.108
	14 TeV	13.14	-2.007	1.515
	27 TeV	115.1	-15.57	11.73
	100 TeV	3276	-356.9	273.1
	Relative ratio	**8~12**	**-1.3**	**1**

in unit of fb

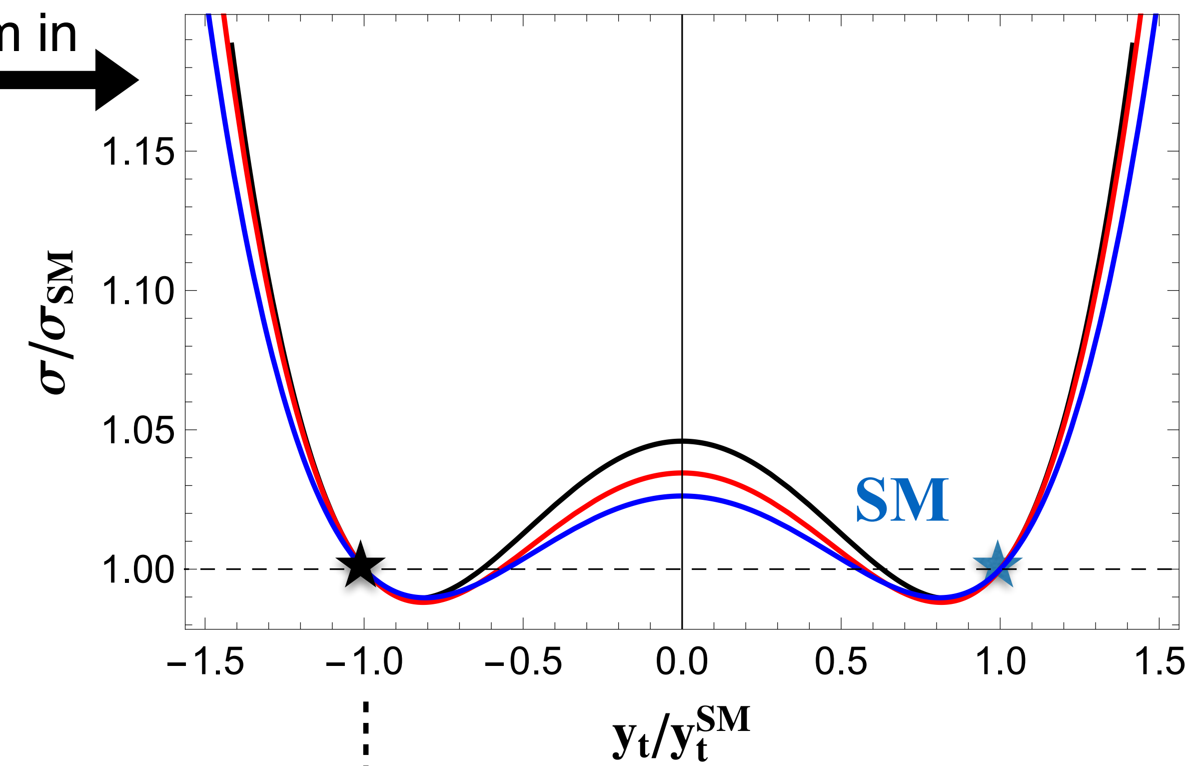
cancel out around SM $\kappa_t = 1$

Dependence of $\sigma/\sigma_{\mathrm{SM}}$ on κ_t

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

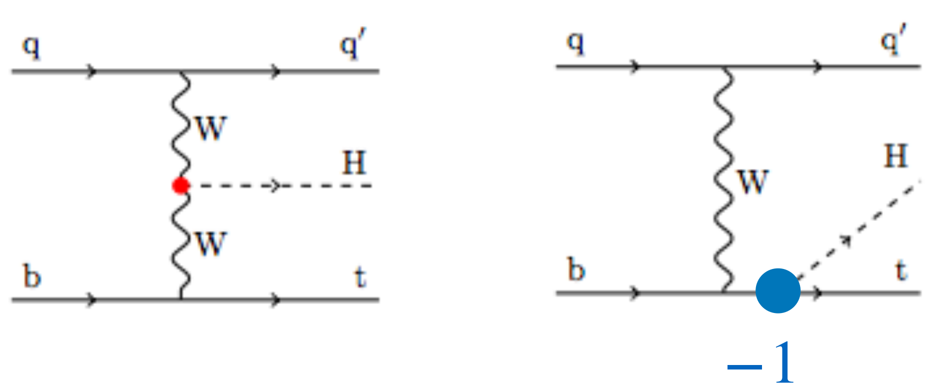


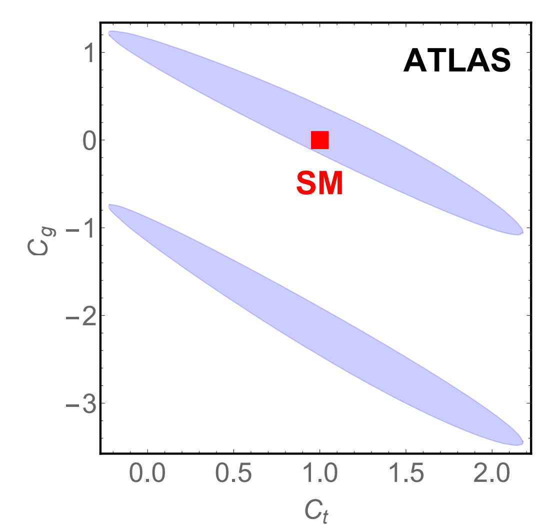
Zoom in



Not supported by global fitting

Htq production enhanced



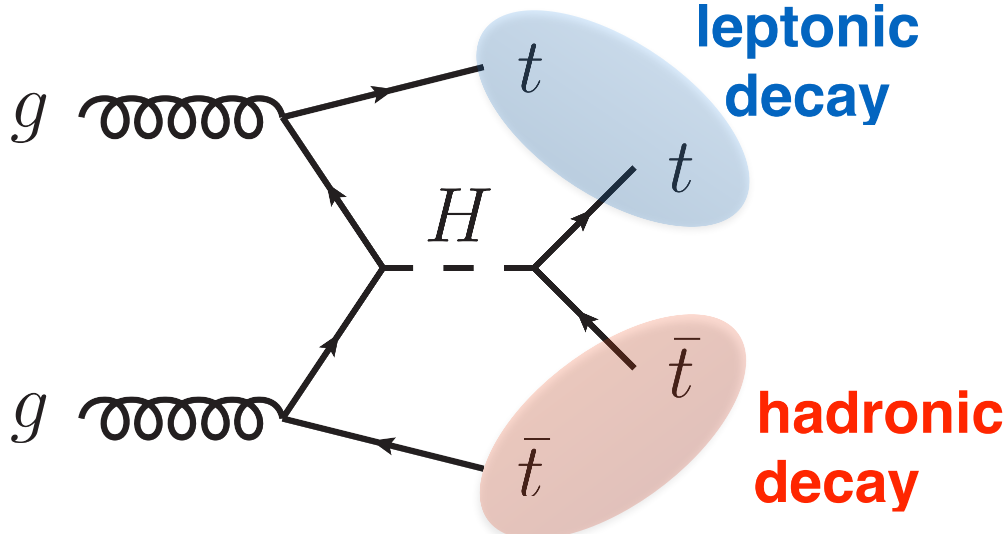


Look and not finding >>> Not looking

Consider $\kappa_t > 0$ in our study

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

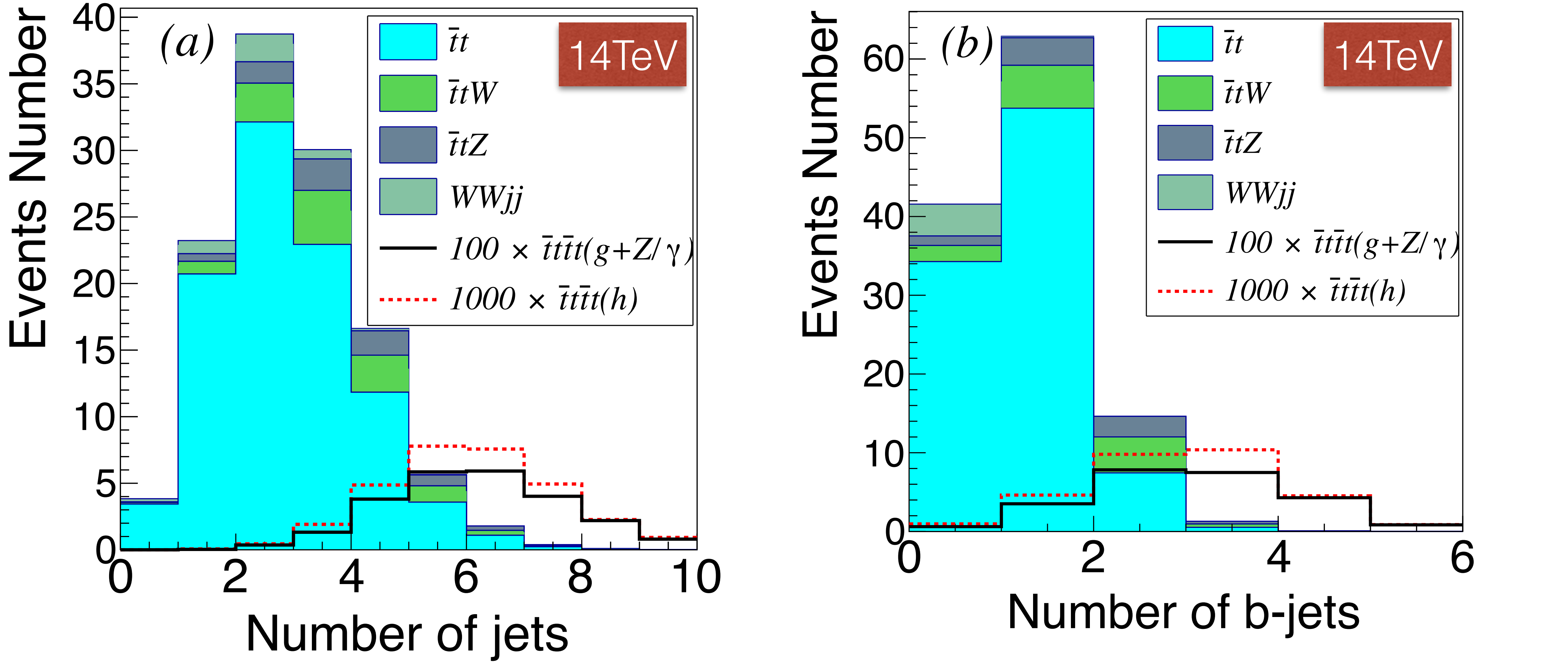
Backgrounds:

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

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

14 TeV: $\kappa_t \leq 1.34$ (300 fb^{-1})

27 TeV: $\kappa_t \leq 1.17$ (10 ab^{-1}), $\kappa_t \leq 1.14$ (20 ab^{-1}), $\kappa_t \leq 1.12$ (30 ab^{-1})

100 TeV: easy to reach a 5σ discovery —> precision measurement

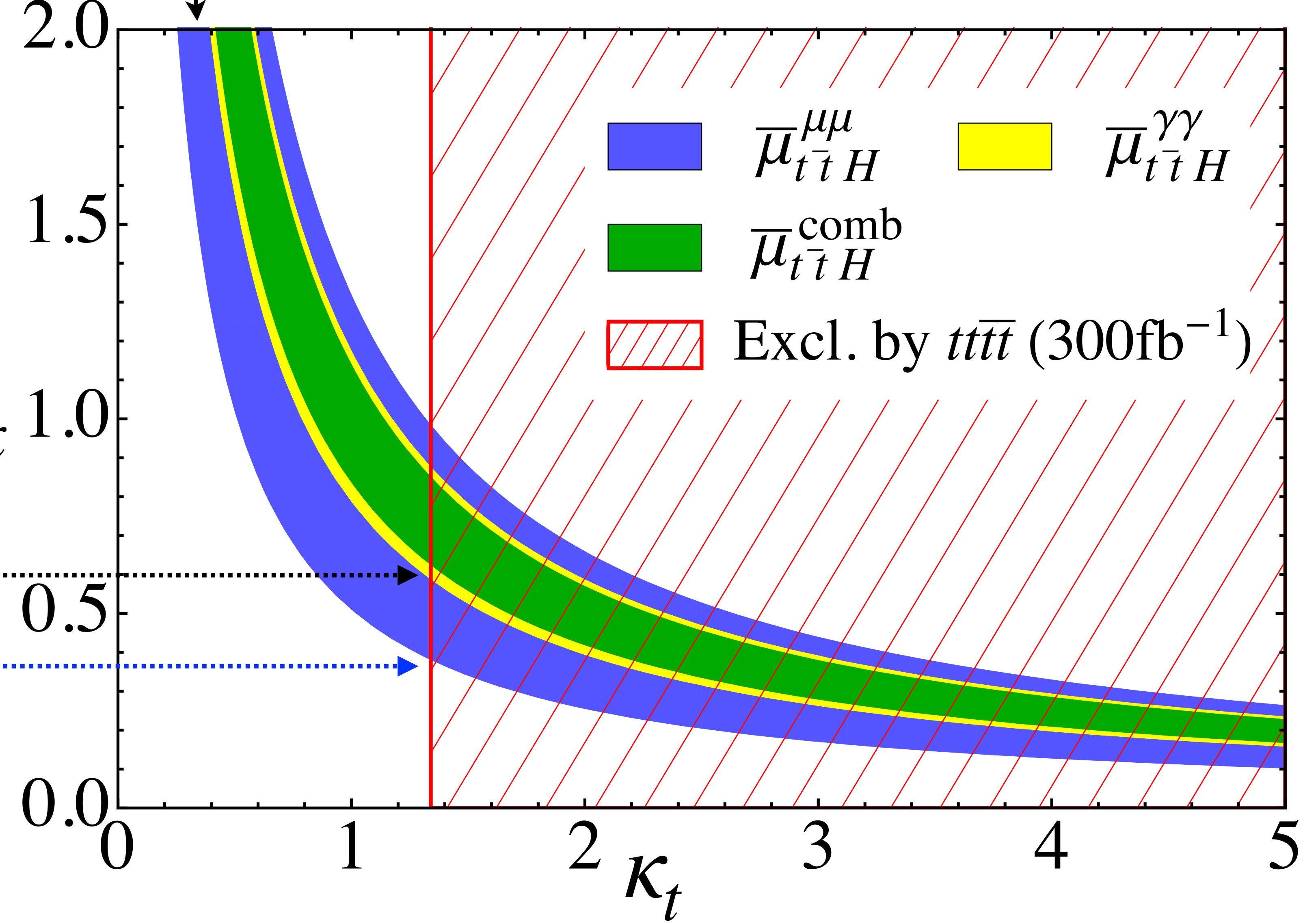
Scenario-I : $\kappa_t^2 \kappa_X^2 = \mu_{t\bar{t}H}^X$

Assume $\Gamma_H = \Gamma_H^{SM}$ rare decays

14TeV LHC (300fb^{-1})

$\kappa_t \leq 1.34$

$gg \to t\bar{t}H,\ H \to \gamma\gamma/\mu^+\mu^-$



$\kappa_{\gamma\gamma} \geq 0.59$

$\kappa_{\mu\mu} \geq 0.38$

Lower bounds on rare decays

$\mu_{t\bar{t}H}^{\gamma\gamma} = 1.00 \pm 0.38$ $\quad$ $\mu_{t\bar{t}H}^{ZZ} = 1.00 \pm 0.49$

$\mu_{t\bar{t}H}^{\mu\mu} = 1.00 \pm 0.74$ $\quad$ $\mu_{t\bar{t}H}^{combo} = 1.00 \pm 0.30$

ATLAS-PHYS-PUB-2014-016

14TeV LHC, 300fb^{-1}

Scenario-II : $\frac{\kappa_t^2}{R_\Gamma} = \mu_{t\bar{t}H}$

Assume $\kappa_X \simeq 1$

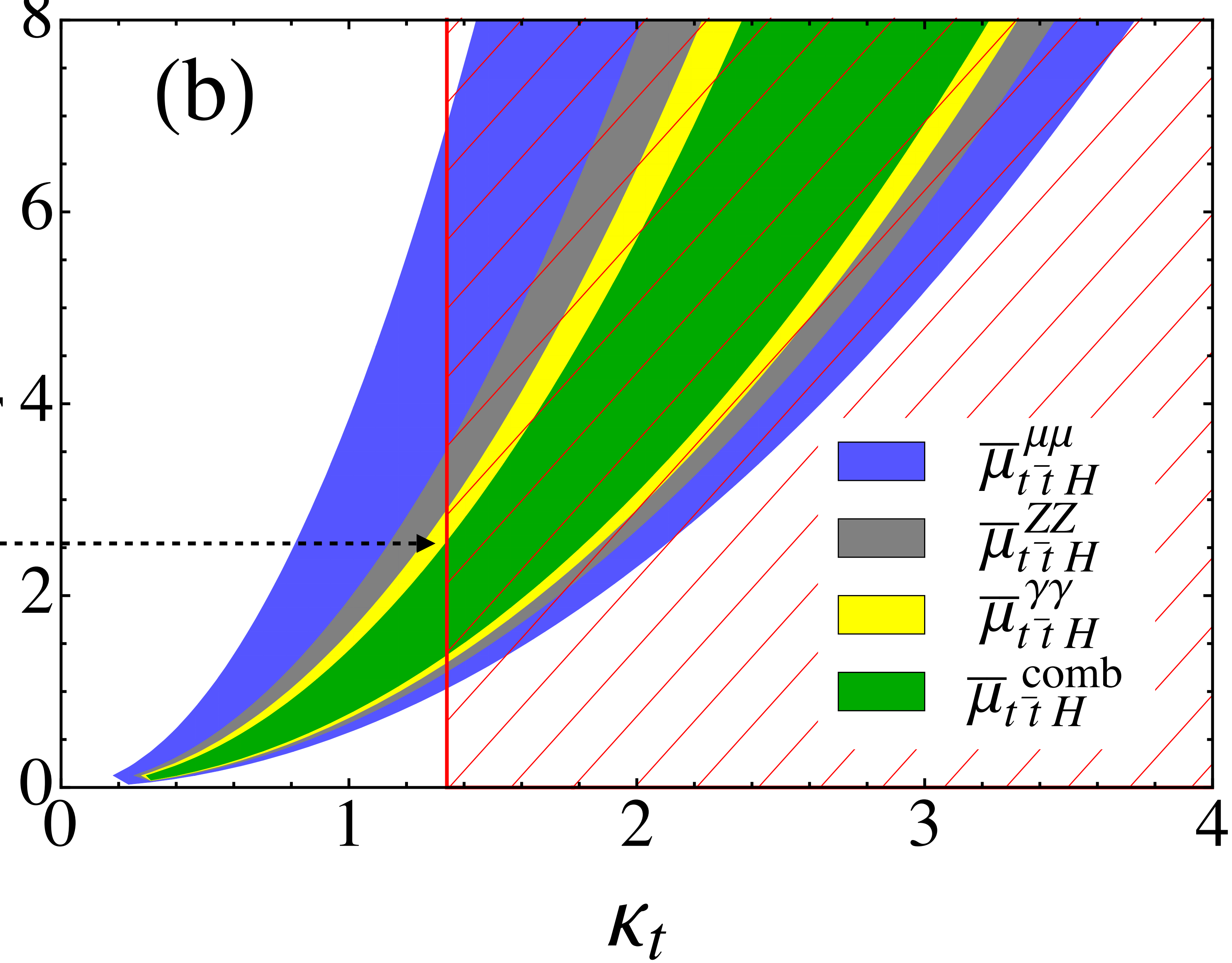
Invisible width

14TeV LHC (300fb^{-1})

$\kappa_t \leq 1.34$

$\Gamma_H \leq 2.5\ \Gamma_H^{SM}$

$\sim$ 10MeV



$\mu_{t\bar{t}H}^{\gamma\gamma} = 1.00 \pm 0.38$ $\quad$ $\mu_{t\bar{t}H}^{ZZ} = 1.00 \pm 0.49$

$\mu_{t\bar{t}H}^{\mu\mu} = 1.00 \pm 0.74$ $\quad$ $\mu_{t\bar{t}H}^{combo} = 1.00 \pm 0.30$

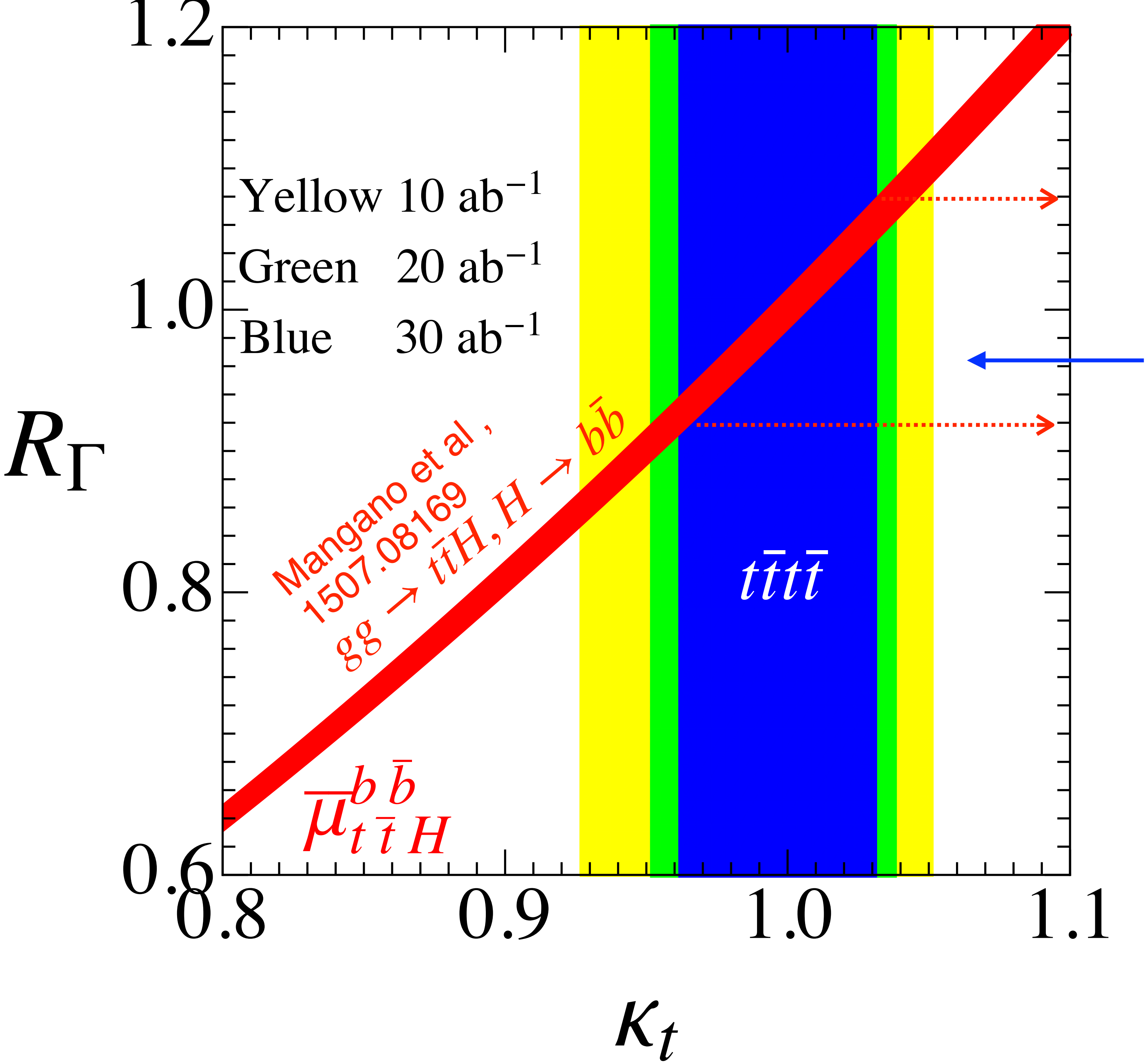
ATLAS-PHYS-PUB-2014-016

14TeV LHC, 300fb^{-1}

Potential at the 100TeV FCC-HH/SppC

$$\frac{\kappa_t^2}{R_\Gamma} = \mu_{t\bar{t}H} \qquad \kappa_b = 1$$

FCC-HH report, 1606.09408



Four-top production reaches 5sigma discovery with an integrated luminosity of 9fb^{-1} .

Top Yukawa coupling precision (stat. uncertainty only)

$$\mathcal{L} = 30 \text{ ab}^{-1}$$

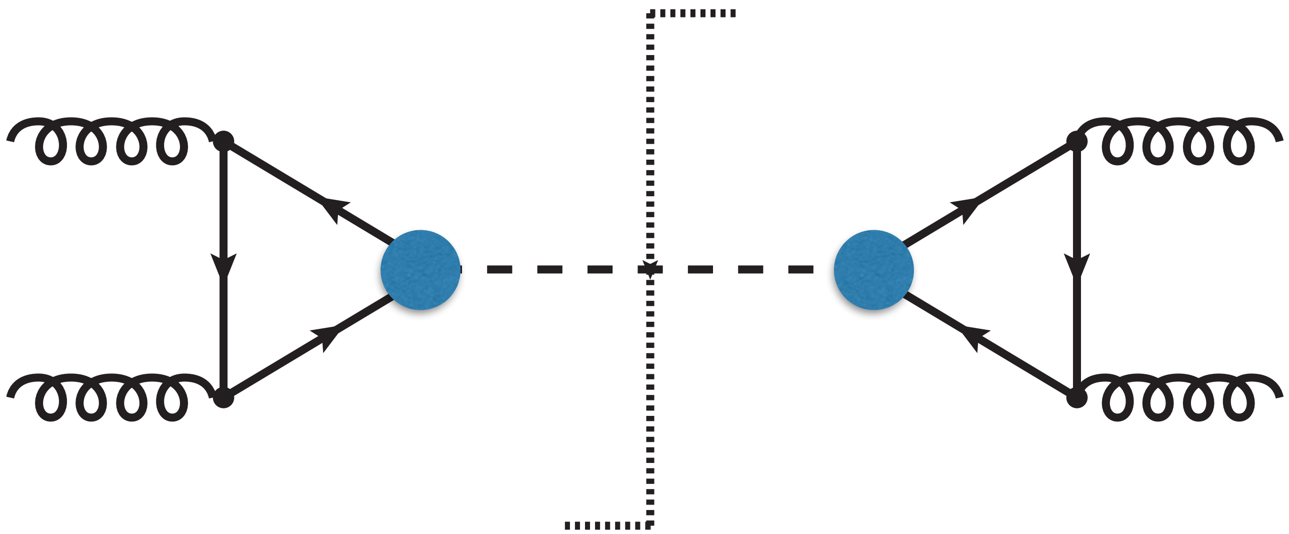
$$0.91\ \Gamma_H^{SM} \leq \Gamma_H \leq 1.08\ \Gamma_H^{SM}$$

$$0.962 \leq \kappa_t \leq 1.031$$

Q3: CP property of top-Higgs interaction

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

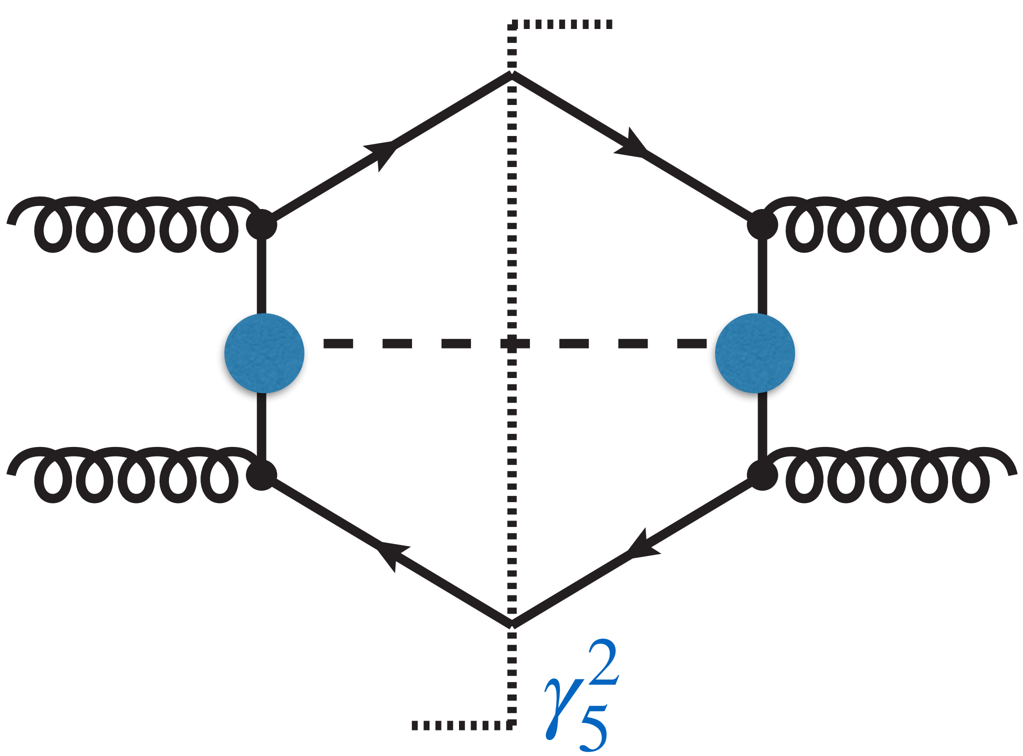
Boudjema, Godbole, Guadagnoli, Mohan, 1501.03157



$\mathrm{Tr}(\cdots\gamma_5)\mathrm{Tr}(\cdots\gamma_5)$

$$\frac{\sigma(gg \to H)}{\sigma(gg \to H)_{\rm SM}} \sim a_t^2 + 2.29 b_t^2$$

↑ pseudo-scalar dominates



$$\frac{\sigma(gg \to t\bar{t}H)}{\sigma(gg \to t\bar{t}H)_{\rm SM}} \sim a_t^2 + 0.42 b_t^2 \quad \text{(14TeV)}$$

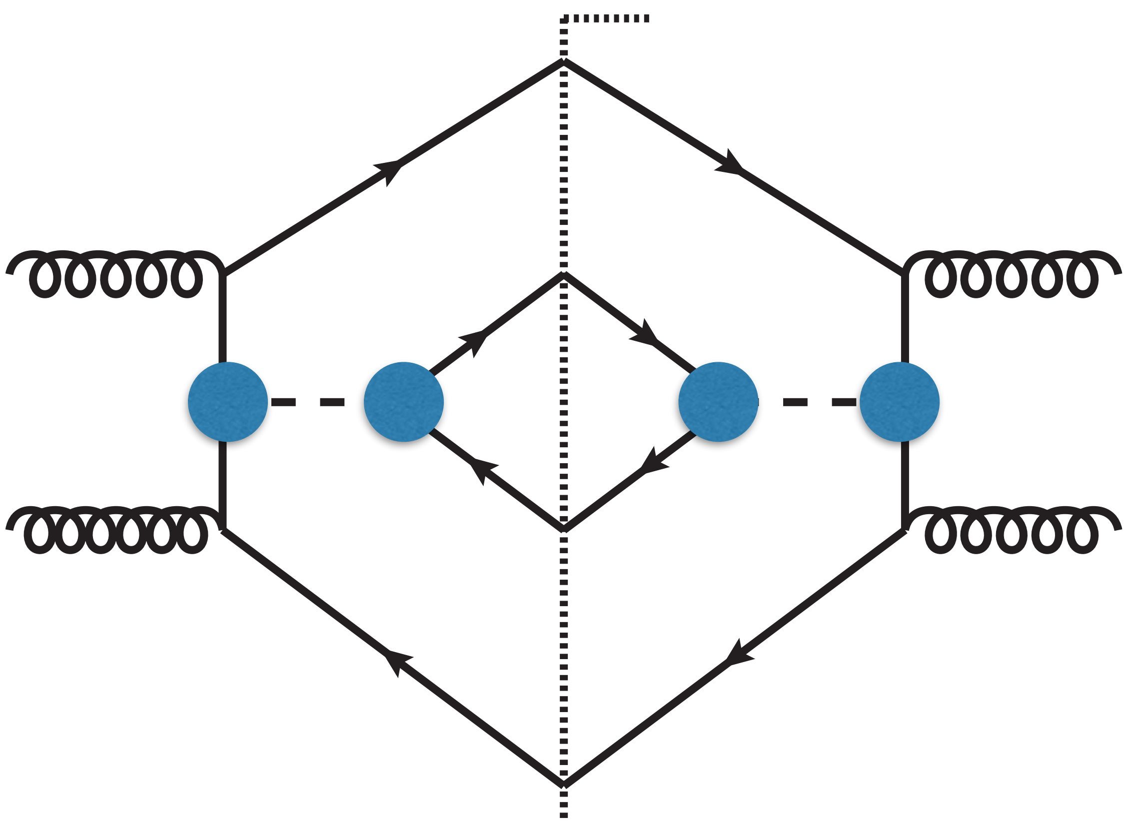
$$\sim a_t^2 + 0.31 b_t^2 \quad \text{(8TeV)}$$

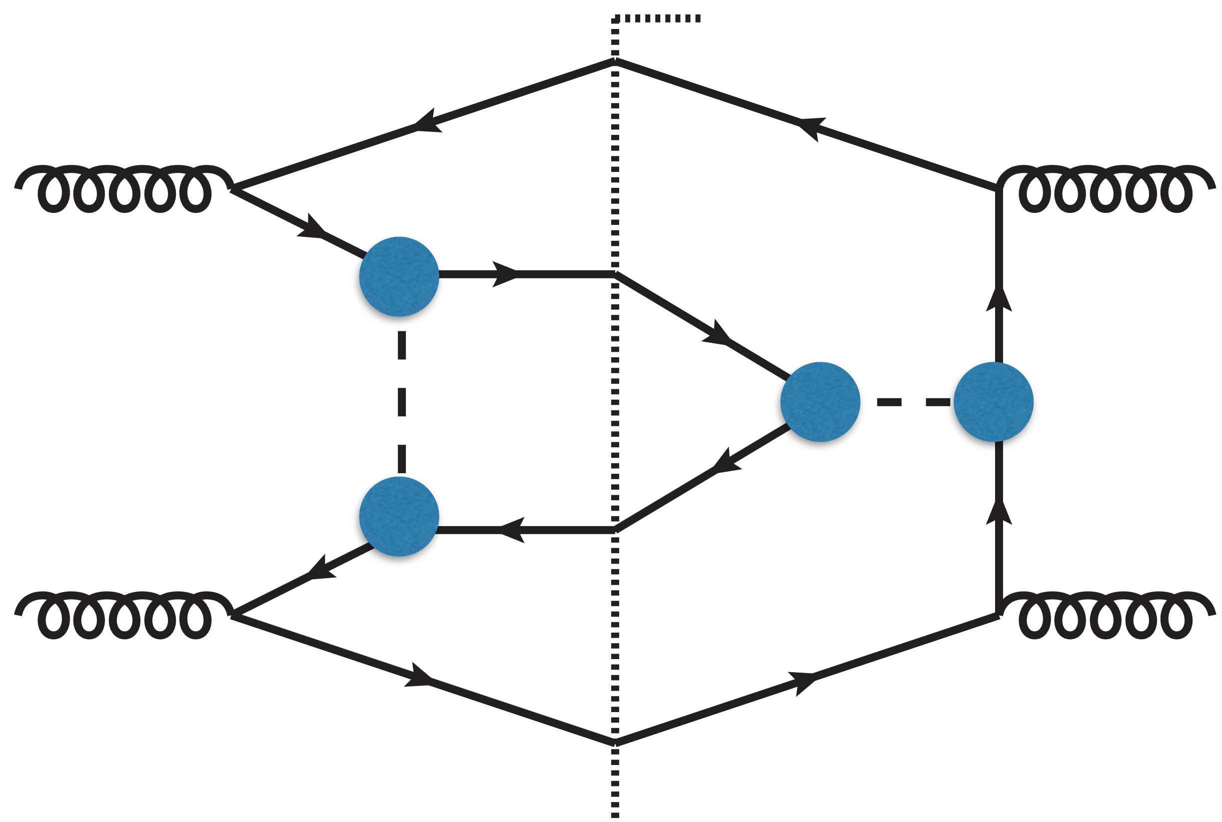
↑ scalar dominates

CP property of top-Higgs interaction

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

Four top-quark production ($gg \to t\bar{t}t\bar{t}$) is complicated.





$$\sigma(t\bar{t}t\bar{t})_{g+H} \propto \#a_t^4 + \#a_t^2 b_t^2 + \#b_t^4 + \#a_t^2 + \#b_t^2 + \#$$

CP property of top-Higgs interaction

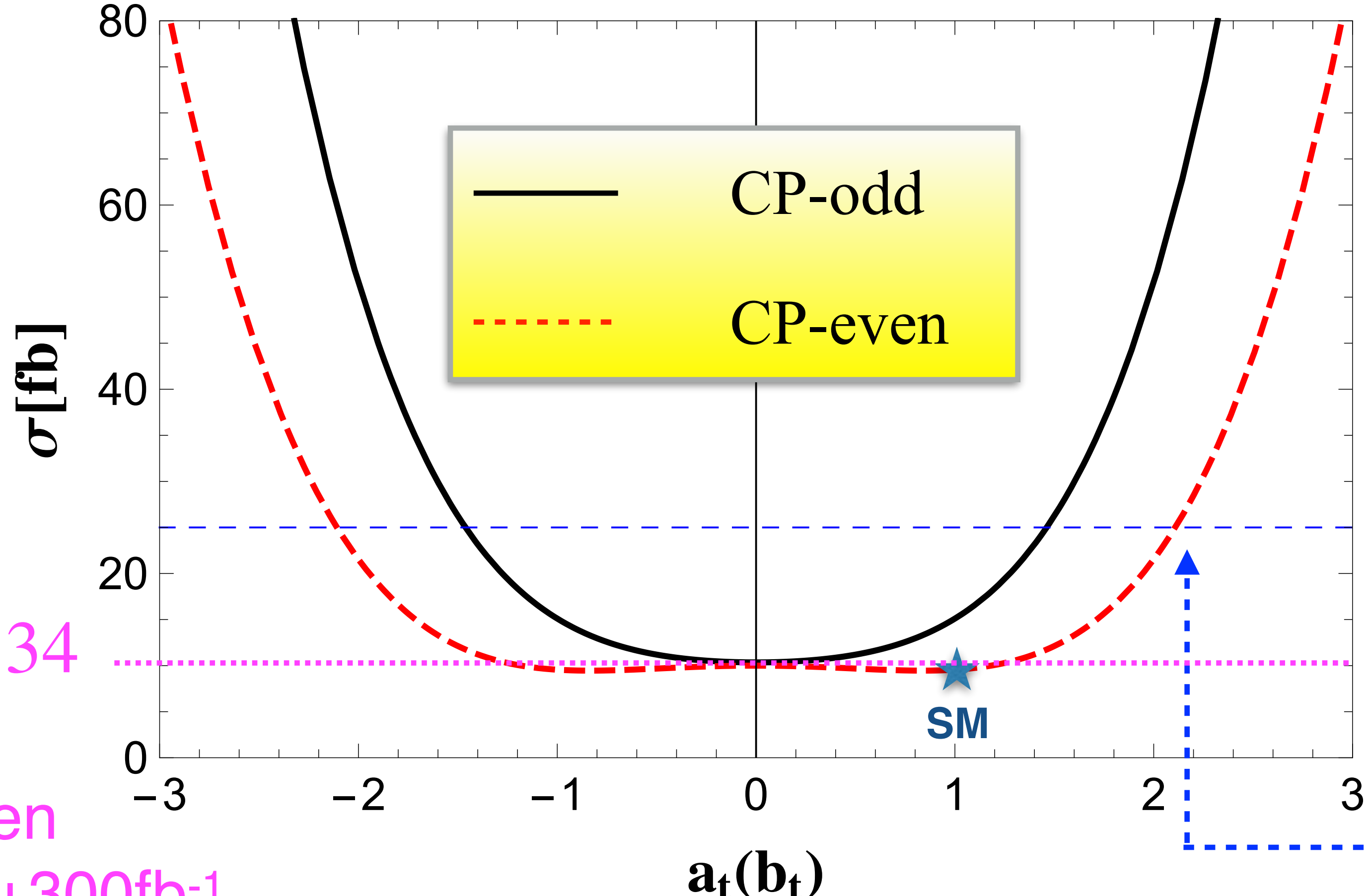
$$\mathscr{L}_{Ht\bar{t}} = -\frac{m_t}{v} H\bar{t}(a_t + i b_t \gamma_5)t$$

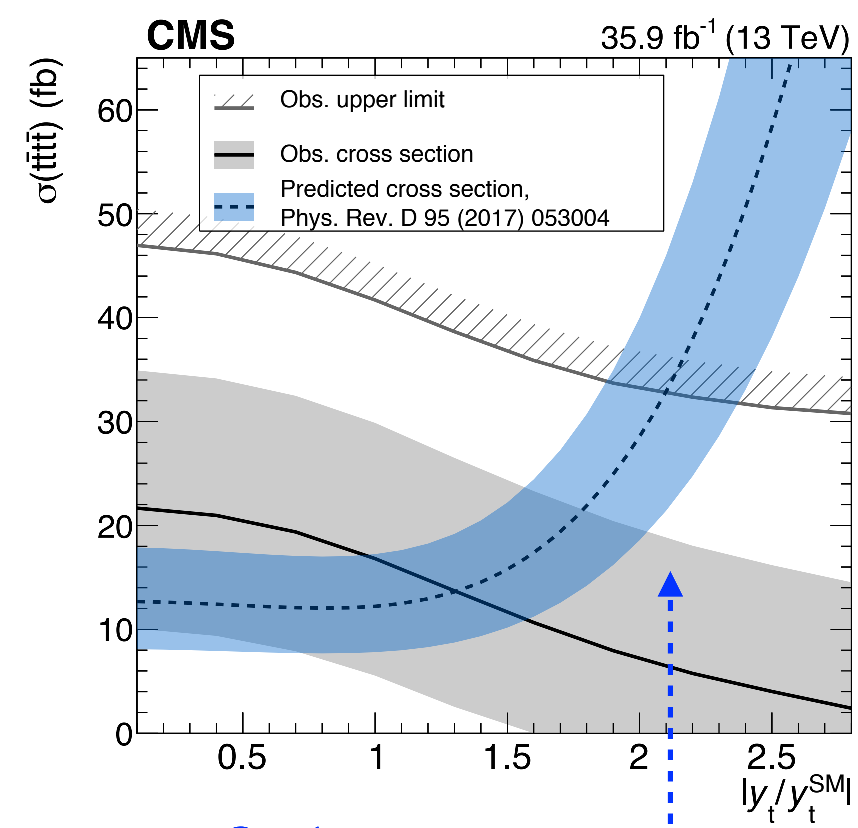
in preparation @13TeV

CP-odd (a=0, b=1) $\sigma(t\bar{t}t\bar{t}) = 9.997 + 2.807 \times b_t^2 + 1.788 \times b_t^4 \ \text{(fb)}$

CP-even (a=1, b=0) $\sigma(t\bar{t}t\bar{t}) = 9.997 - 1.547 \times a_t^2 + 1.108 \times a_t^4 \ \text{(fb)}$

$\kappa_t \leq 1.34$





CP-even 14TeV+300fb^{-1}

almost rule out pure CP-odd

$\kappa_t \leq 2.1$ CP-even

Rough estimation:

$b_t \leq 1.5$ for a pure CP-odd coupling

Summary

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

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

Combining $t\bar{t}t\bar{t}$ production and $t\bar{t}h$ production could constrain $H\gamma\gamma/H\mu^+\mu^-$ couplings or Γ_H .

$$gg \to Ht\bar{t},\ H \to \gamma\gamma/\mu\mu \xrightarrow{\Gamma_H = \Gamma_H^{\rm SM}} g_{H\gamma\gamma}\ /\ Y_\mu$$

$$gg \to Ht\bar{t},\ H \to b\bar{b} \xrightarrow{y_b = y_b^{\rm SM}} \Gamma_H$$

Thank You!