

Probing CP violating effective operators at colliders

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Christoph Englert, Karl Nordström, KS, Michael Spannowsky: Phys. Rev. D95 [1611.05445]

John Ellis, Dae Sung Hwang, KS, Michihisa Takeuchi: JHEP 1404 [1312.5736]

Introduction

- The data at the LHC indicates the SM is very promising.
- The SM fails to give a quantitative explanation of baryon asymmetry of the Universe. **Baryogenesis requires additional CP phases** and it is important to find them.
- The Higgs sector has not been well tested experimentally.
- It is **important to constrain CPV Higgs couplings experimentally or theoretically in a model independent way**.
- In particular, the **interaction between Higgs and top quark is strongly related to the fine-tuning problem as well as the stability of the EW vacuum**.
- No new particle has been found so far at the LHC. **EFT approach** is desirable to model-independently study the anomalous CP violating Higgs coupling.

Plan

1. Constraining anomalous Higgs couplings *theoretically* with **unitarity**.
2. Study measurements of the CPV Higgs-top coupling in $pp \rightarrow ttH$ and tHj processes at **colliders**.

EFT approach

- Effective Field Theory (EFT) provides a powerful framework to study new type of interactions among the SM degrees of freedom.
- The SM considers all possible D=4 terms that are consistent with Lorentz and gauge symmetry (except for the QCD θ term).
- After EW symmetry breaking, we consider the following CP violating operators in the Higgs sector up to D=5:

$$\left. \begin{array}{l} \mathcal{O}_{hff} = h\bar{\psi}_f\gamma_5\psi_f \\ \mathcal{O}_{hhZ} = h(\partial_\mu h)Z^\mu \\ \mathcal{O}_{hF\tilde{F}} = hF_{\mu\nu}\tilde{F}^{\mu\nu} \end{array} \right\} \begin{array}{l} D=4 \\ \\ D=5 \end{array}$$

$$\tilde{F}^{\mu\nu} \equiv \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$$

- The operators in broken phase may be generated from the $SU(2) \times U(1)$ symmetric higher dimensional operators.

broken phase

symmetric phase

$$h F_{\mu\nu} \tilde{F}^{\mu\nu} \longleftrightarrow (H^\dagger H) F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$h \bar{\psi}_f \gamma_5 \psi_f \longleftrightarrow (H^\dagger H) \bar{\Psi}_L H \psi_R + \text{h.c.}$$

$$h(\partial_\mu h)Z^\mu \longleftrightarrow S|D_\mu H_i|^2 \ni v S Z_\mu \partial^\mu A \quad \textbf{2HDM + 1 singlet}$$

$$h = \sin \alpha (\cos \beta S + \sin \beta A) + \cos \alpha (\cdots)$$

- We work on the following effective Lagrangian:

$$\mathcal{L} = \mathcal{L}^{\text{SM}} + C_{hhZ} h(\partial_\mu h)Z^\mu + C_{htt} h \bar{t} \gamma^5 t + \sum_{F,\tilde{F}} \frac{C_{hF\tilde{F}}}{v} \mathcal{O}_5^{hF\tilde{F}}$$

Unitarity Constraints

- Unitarity of S-matrix requires partial amplitudes to be less than 1

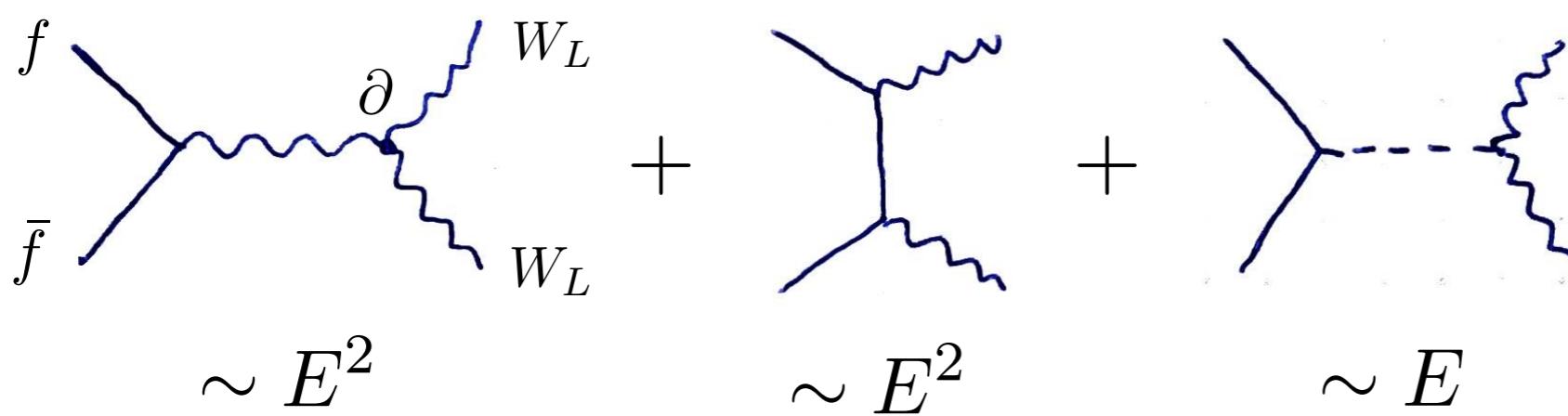
$$a_\ell(s) \equiv \frac{1}{32\pi} \int d\cos\theta \mathcal{M}(s, \cos\theta) P_\ell(\cos\theta)$$

$$S^\dagger S = \mathbb{1} \longrightarrow |a_\ell(s)| \leq 1$$

- This places a non-trivial constraints among coupling because the Matrix elements naively grows as energy.

longitudinal polarisation vector: $\epsilon_L(p_W) \sim E_W/m_W$

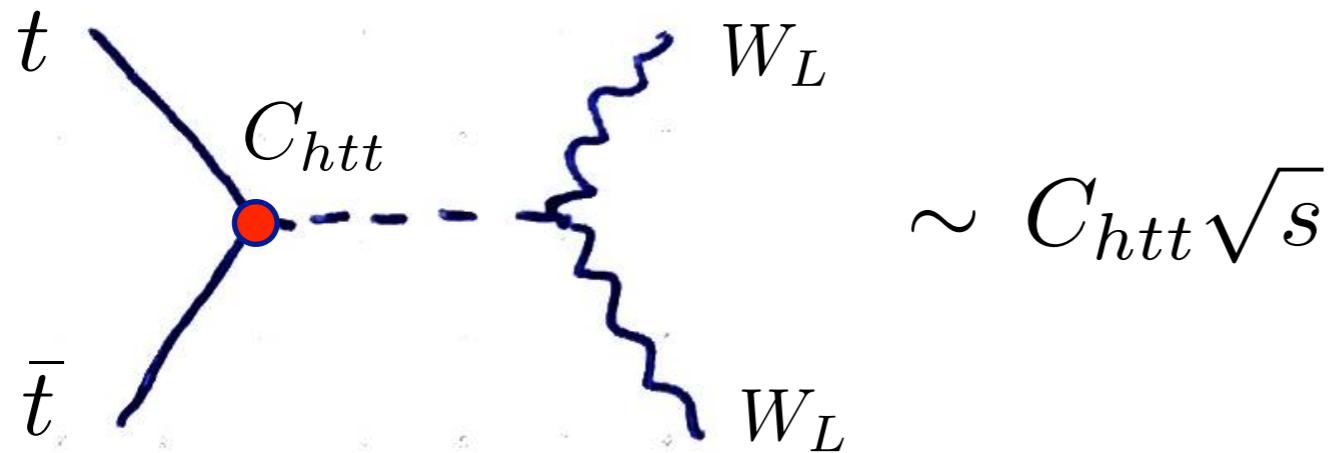
fermion spinor: $u(p_f) \sim \sqrt{E_f}$



**high energy
behaviour regulated**

$$\sim E^0 + E^{-1} + \dots$$

$$\mathcal{O}_{hff} = h\bar{\psi}_f \gamma_5 \psi_f$$

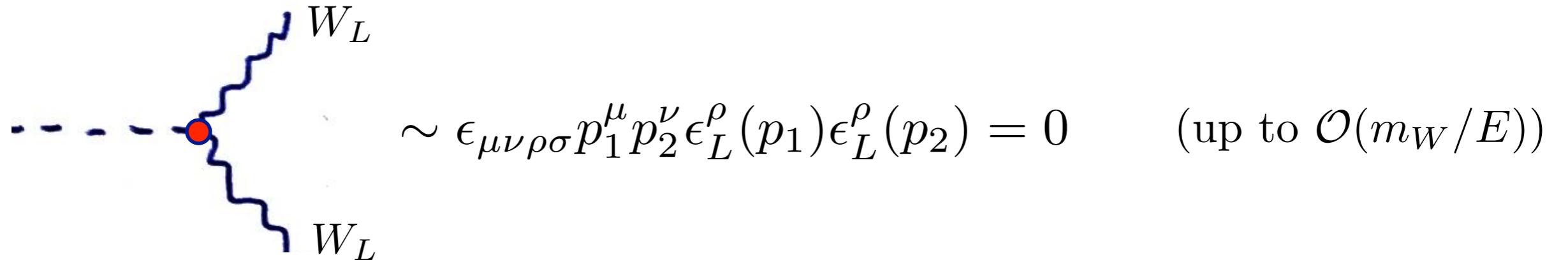


$$\sim C_{htt} \sqrt{s}$$

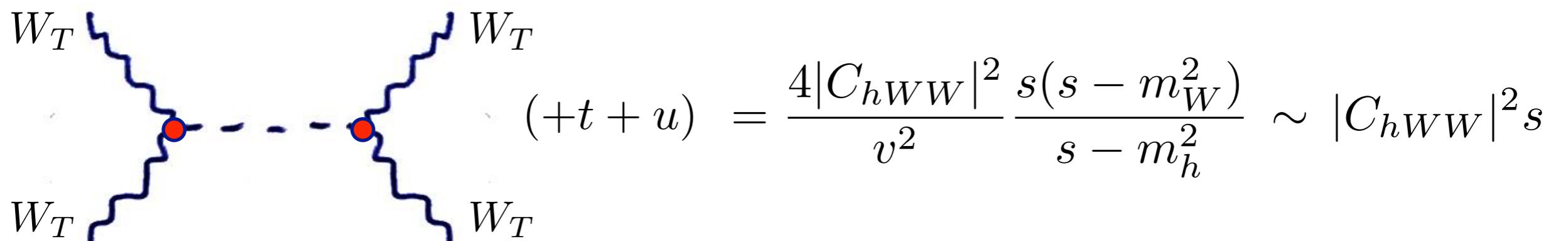
$$|a_\ell(s)| \leq 1 \quad \rightarrow \quad |C_{htt}| < 1.24 \quad \text{for } \Lambda = 5 \text{ TeV}$$

$$\mathcal{O}_{hF\tilde{F}} = h F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Longitudinal contribution cancels



Most stringent constraint arises from transverse scattering



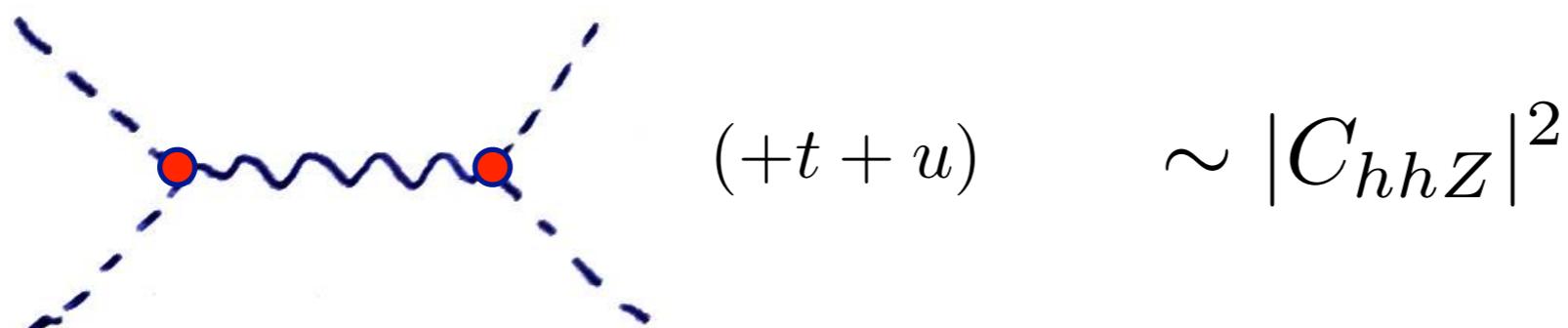
$$|a_\ell(s)| \leq 1 \quad \rightarrow \quad |C_{hWW}| \leq 0.26 \quad \text{for } \Lambda = 5 \text{ TeV}$$

$$\mathcal{O}_{hhZ} = h(\partial_\mu h) Z^\mu$$

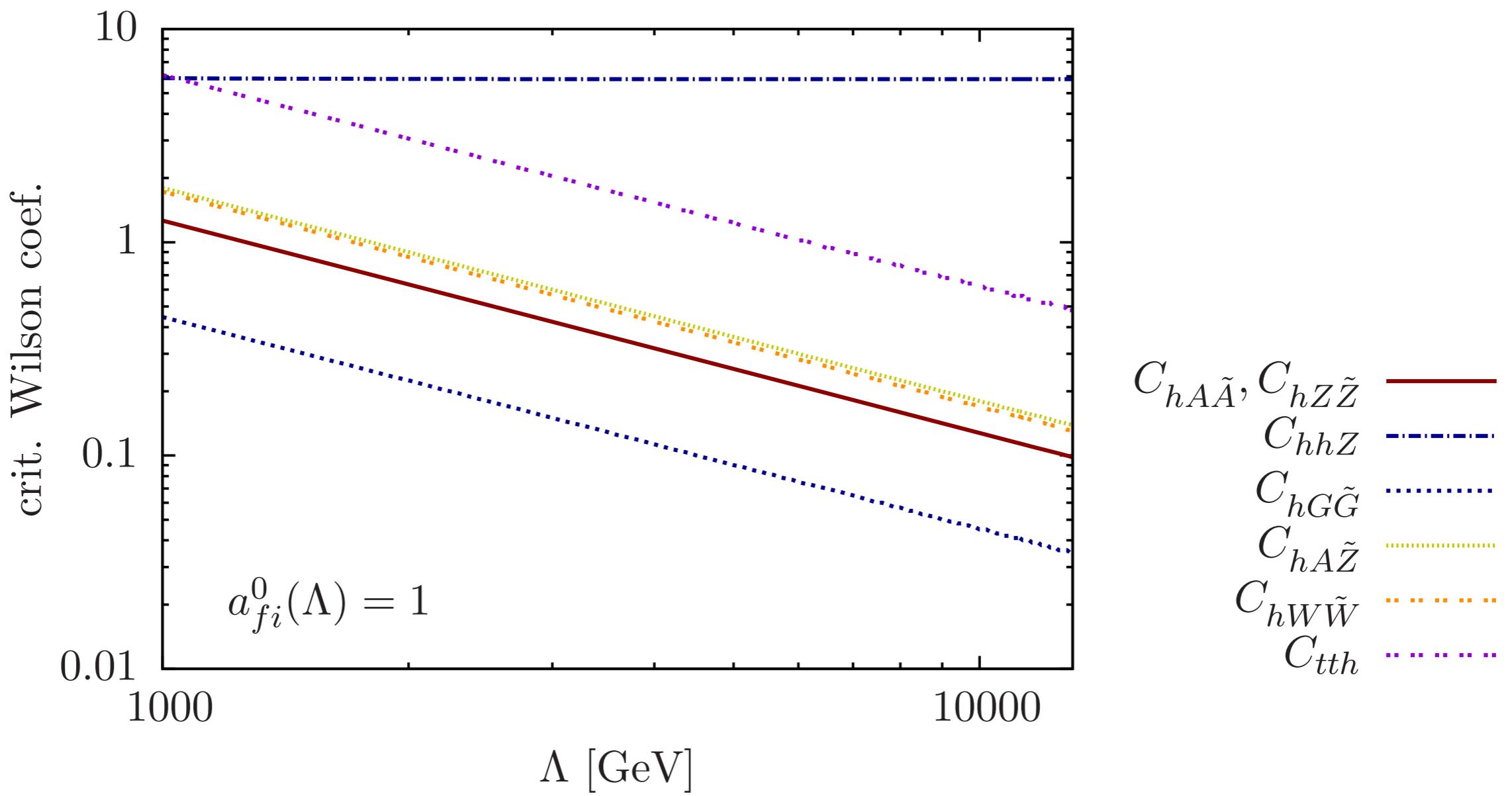
- does not contribute to the high energy behaviour for:

$$tt \rightarrow hh, \quad hh \rightarrow VV, \quad hh \rightarrow hV, \quad VV \rightarrow hV$$

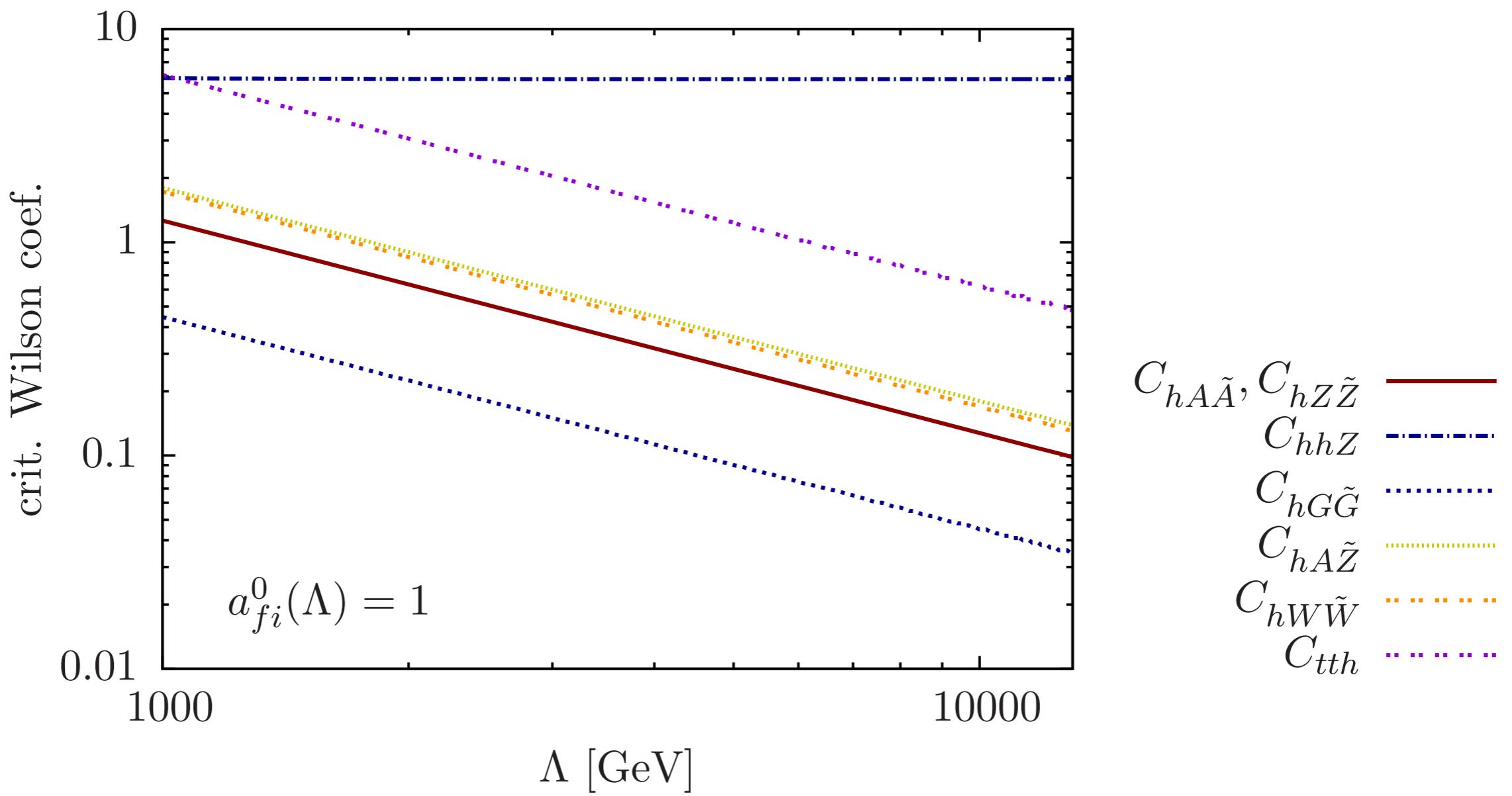
- most sensitive process is $hh \rightarrow hh$



$$|a_\ell(s)| \leq 1 \quad \xrightarrow{\hspace{1cm}} \quad |C_{hhZ}| \leq 5.82 \quad \text{for any } \Lambda$$

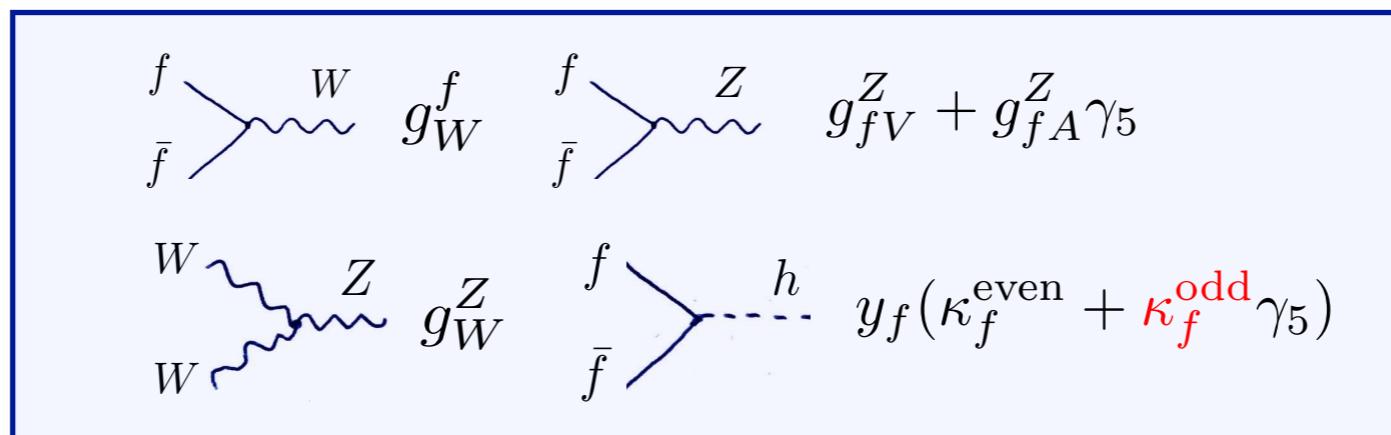
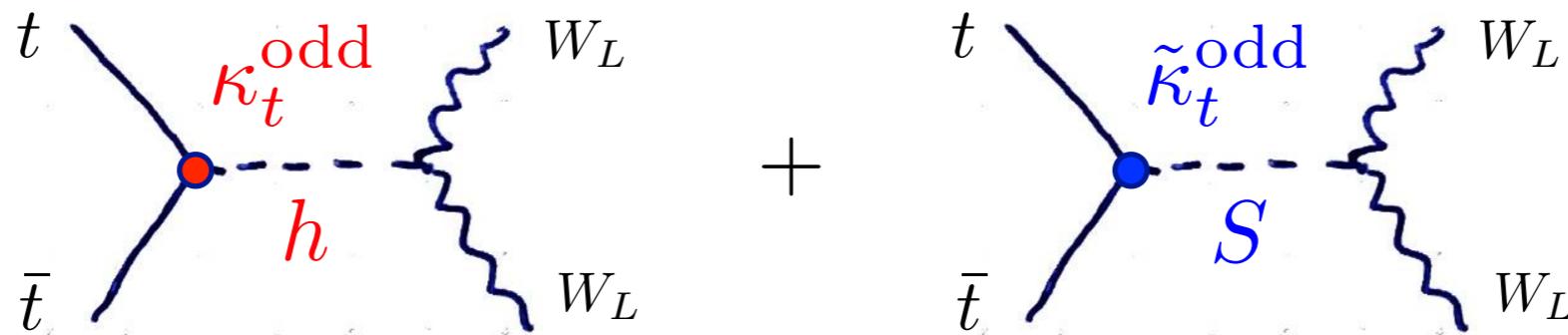


Wilson coefficient	Most sensitive channel	Scaling of $ \mathcal{M} $ at large s	Limit at $\Lambda = 5$ TeV
C_{tth}	$t\bar{t} \rightarrow W_L^+ W_L^-$	$C_{tth}\sqrt{s}$	1.24
$C_{hF\tilde{F}}$	$V_T V_T \rightarrow V_T V_T$	$C_{hF\tilde{F}}^2 s$	0.26
$C_{hG\tilde{G}}$	$g_T g_T \rightarrow g_T g_T$	$C_{hG\tilde{G}}^2 s$	0.09
$C_{hA\tilde{Z}}$	$Z_T A_T \rightarrow Z_T A_T$	$C_{hA\tilde{Z}}^2 s$	0.36
C_{hhZ}	$hh \rightarrow hh$	C_{hhZ}^2	5.82



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Bad high energy behaviour may be amended by an extra state S



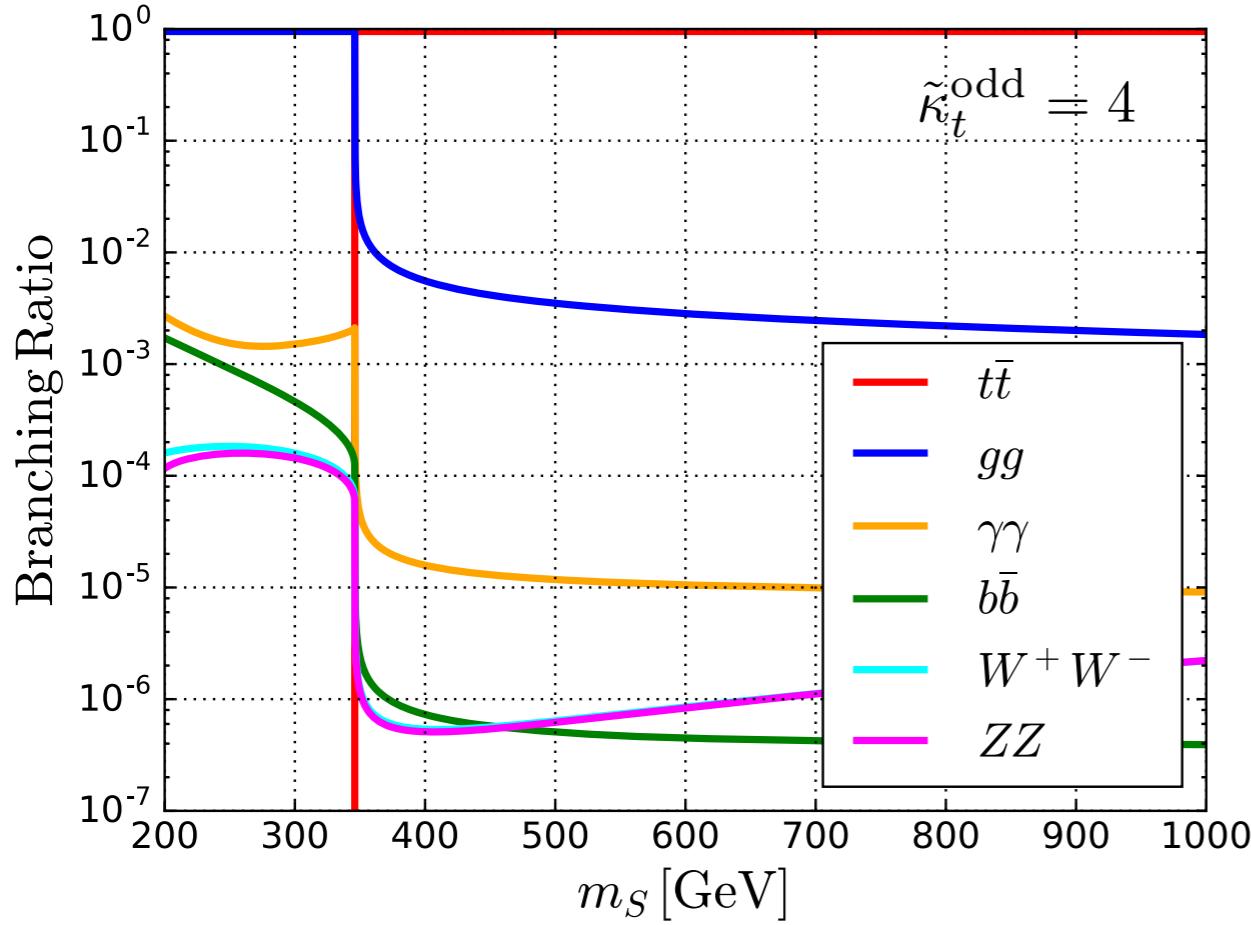
$$C_{tth} = \kappa_t^{\text{odd}} / y_t$$

$$\mathcal{M}(tt \rightarrow WLWL) \stackrel{E \gg m_t}{=} \underbrace{\frac{g_W^h}{2m_W^2} \bar{v}(p_2) \gamma_5 u(p_1)}_{\sim E} \left[(g_W^f)^2 + 2g_W^Z g_{fA}^Z + i(g_W^h \kappa_t^{\text{odd}} + g_W^S \tilde{\kappa}_t^{\text{odd}}) \right]$$

must vanish (sum rule)

A new state is necessary and must satisfy $g_W^S \tilde{\kappa}_t^{\text{odd}} = -g_W^h \kappa_t^{\text{odd}}$

Production and decay



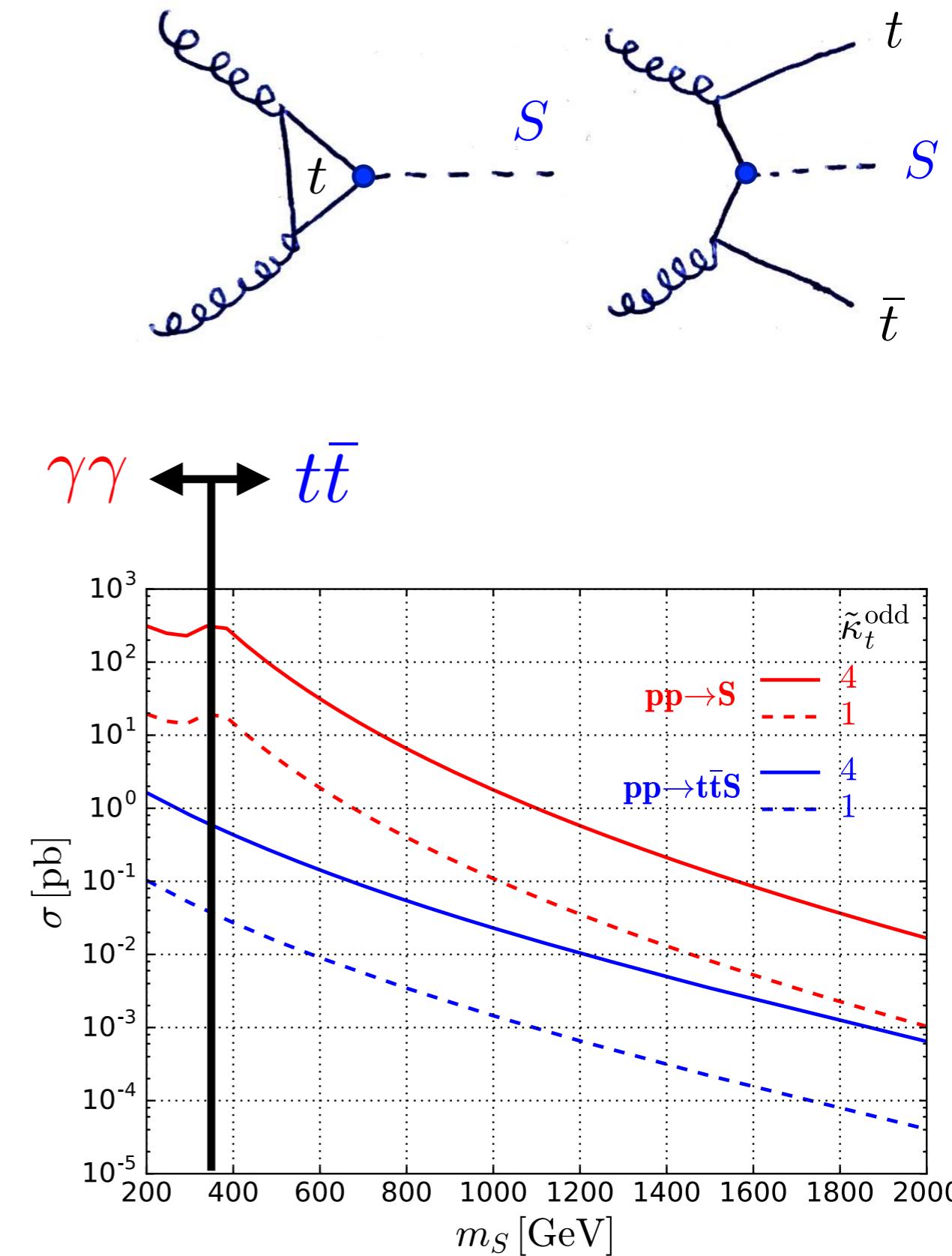
- CMS diphoton [1609.02507]

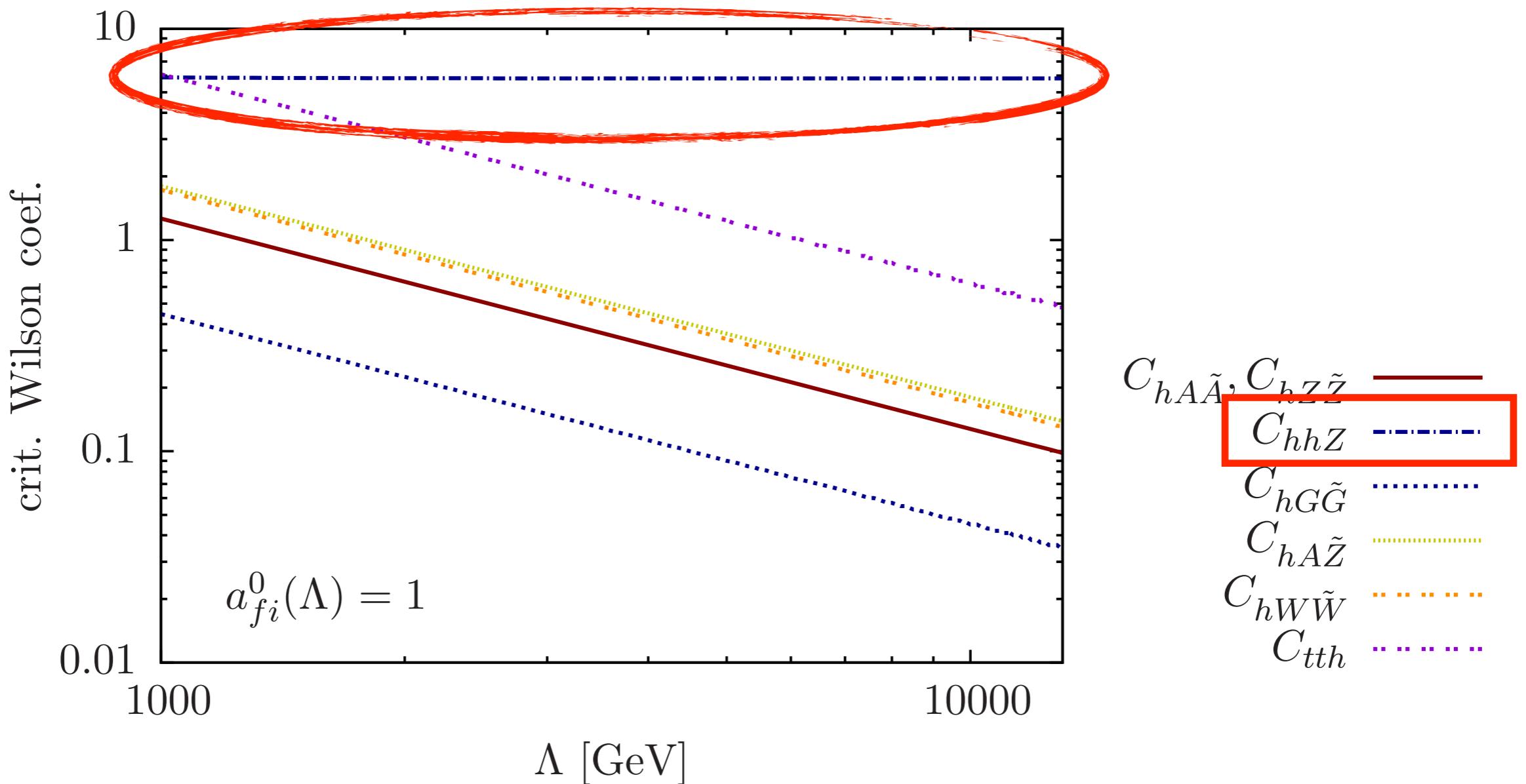
$$\sigma \cdot \text{BR}_{\gamma\gamma} < 10 \text{ fb}$$

- A \rightarrow ttbar, 2HDM [ATLAS-CONF-2016-073]

$$|\tilde{\kappa}_t^{\text{odd}}| \lesssim 1.7 \quad (m_S = 750 \text{ GeV})$$

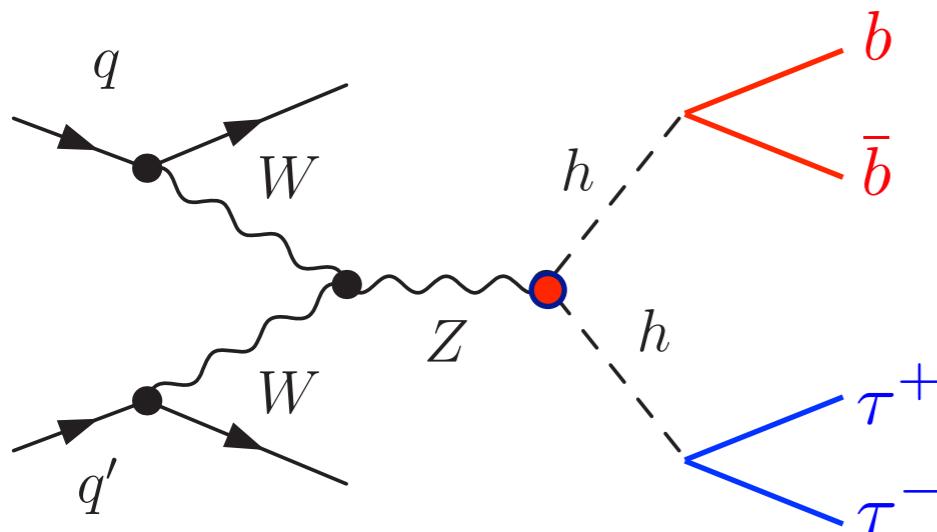
$$|\tilde{\kappa}_t^{\text{odd}}| \lesssim 1 \quad (m_S = 500 \text{ GeV})$$





Wilson coefficient	Most sensitive channel	Scaling of $ \mathcal{M} $ at large s	Limit at $\Lambda = 5$ TeV
C_{tth}	$t\bar{t} \rightarrow W_L^+ W_L^-$	$C_{tth}\sqrt{s}$	1.24
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$$\mathcal{O}_{hhZ} = h(\partial_\mu h) Z^\mu$$

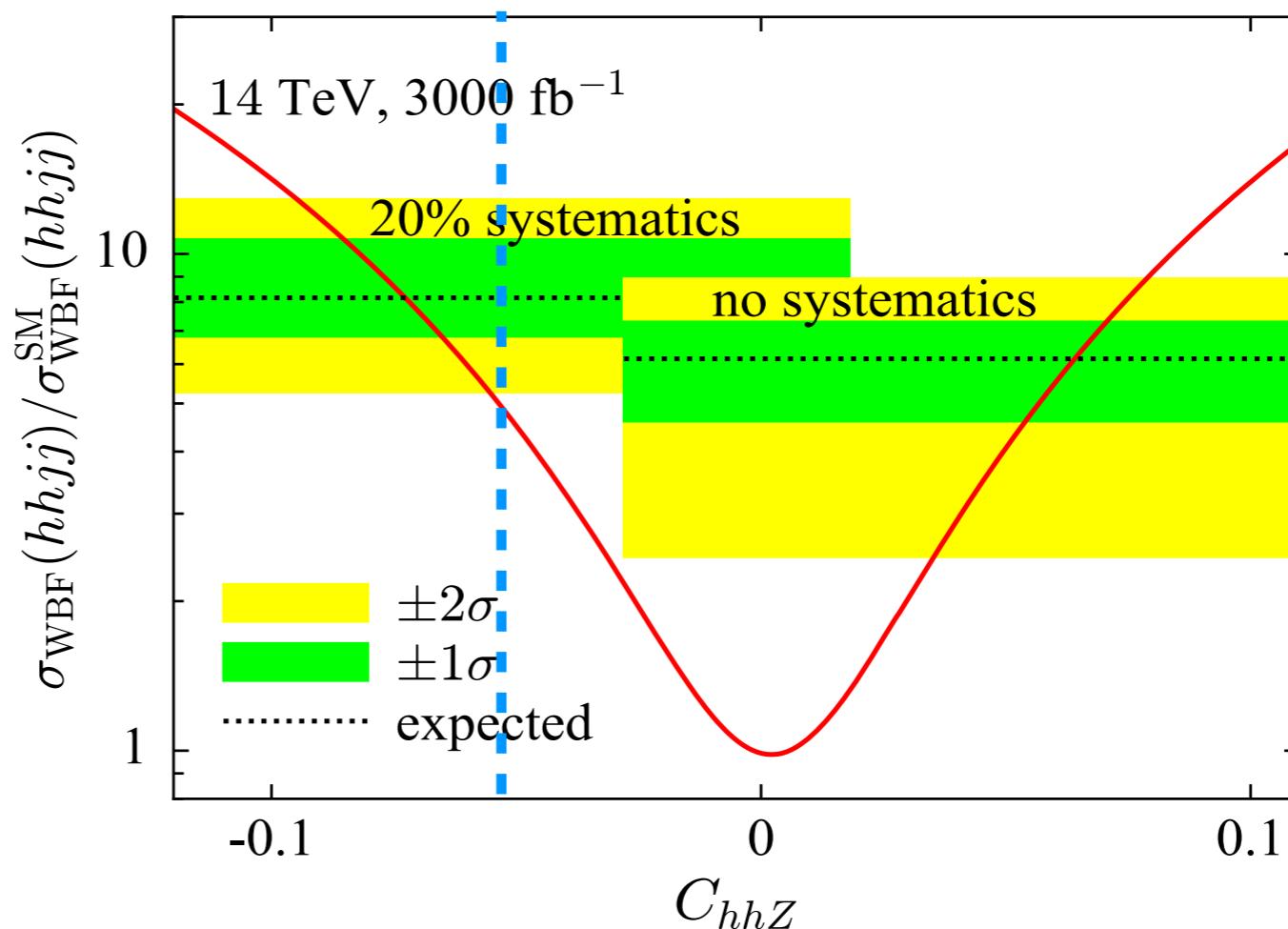


projected sensitivity
@ HL-LHC 3ab⁻¹

$$|C_{hhZ}| \lesssim 0.06$$

Event selection (**bbττ** channel)

- 2 taus with $p_T > 29, 20\text{GeV}$, $|\eta|<2.5$ ($\epsilon_\tau=70\%$)
- 2 jets (not b nor τ) with $p_T > 25\text{GeV}$, $|\eta|<4.5$
- $\Delta\eta(j_1, j_2) > 5$
- 2 hardest jets to be b -tagged and $|\eta|<2.5$ ($\epsilon_b=70\%$)
- $|m_{bb} - m_h|<15\text{GeV}$, $|m_{\tau\tau} - m_h|<25\text{GeV}$, $m_{hh}>400\text{GeV}$



Probing CPV Higgs-top interaction via $pp \rightarrow ttH$ and tHj processes at colliders

Anomalous top-Higgs coupling

- We parametrise the top-Higgs coupling as:

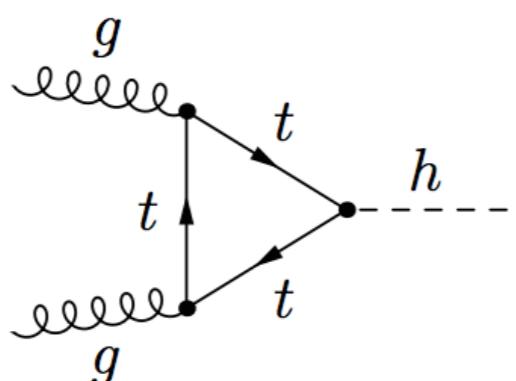
$$\mathcal{L}_t = -\frac{m_t}{v} (\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t) H$$

↑
CPV

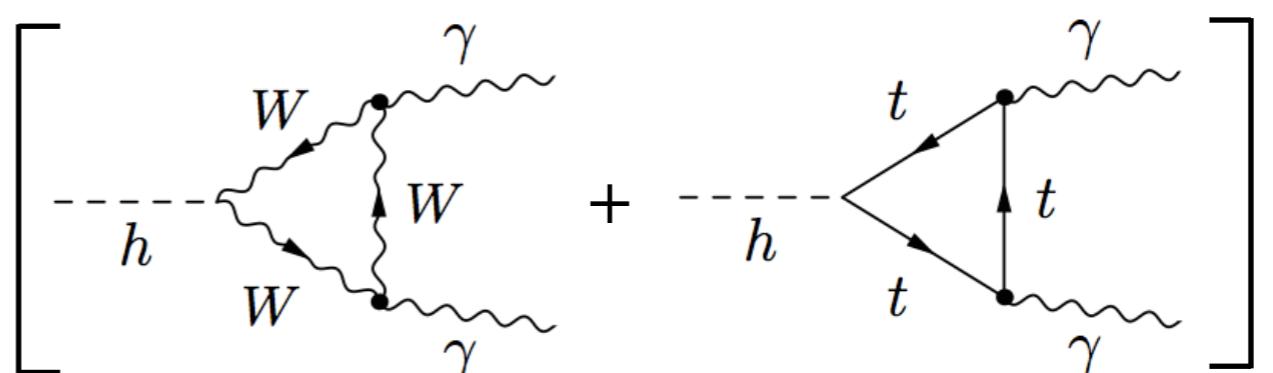
- The top-Higgs coupling enters the Higgs production and decay:

$$\mathcal{L}_\Delta = - \left[\frac{\alpha_s}{8\pi} c_g b_g G_{\mu\nu}^a G^{\mu\nu a} + \frac{\alpha_{em}}{8\pi} c_\gamma b_\gamma F_{\mu\nu} F^{\mu\nu} \right] \left(\frac{H}{v} \right)$$

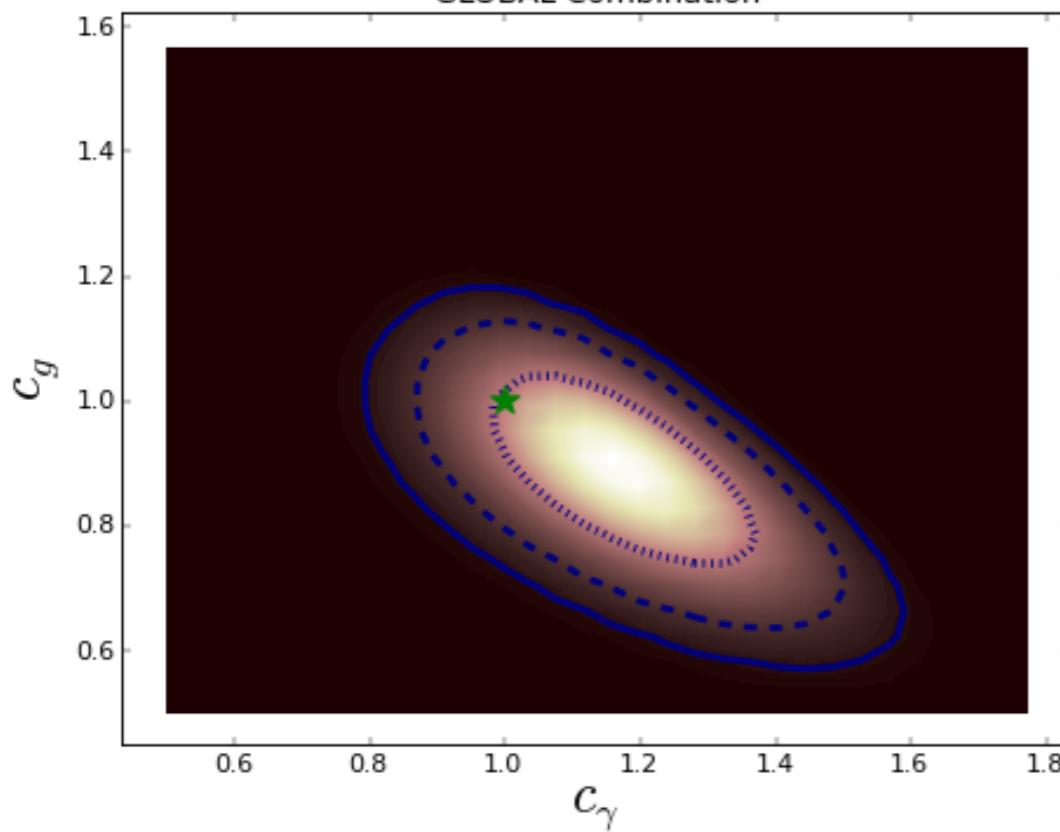
Production



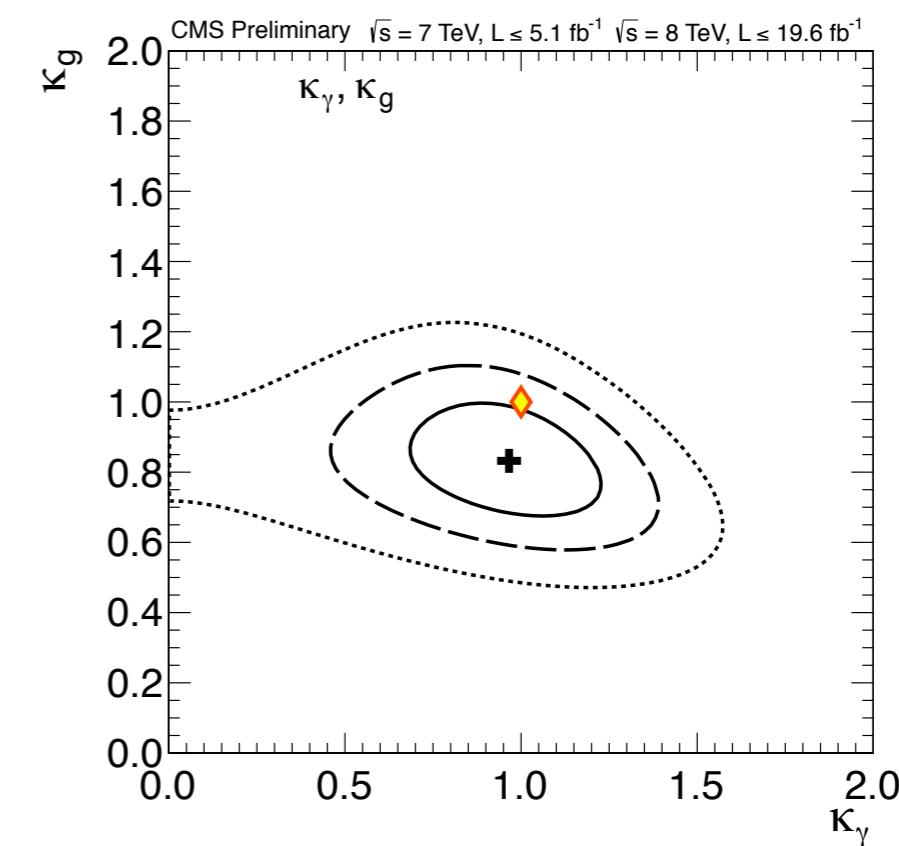
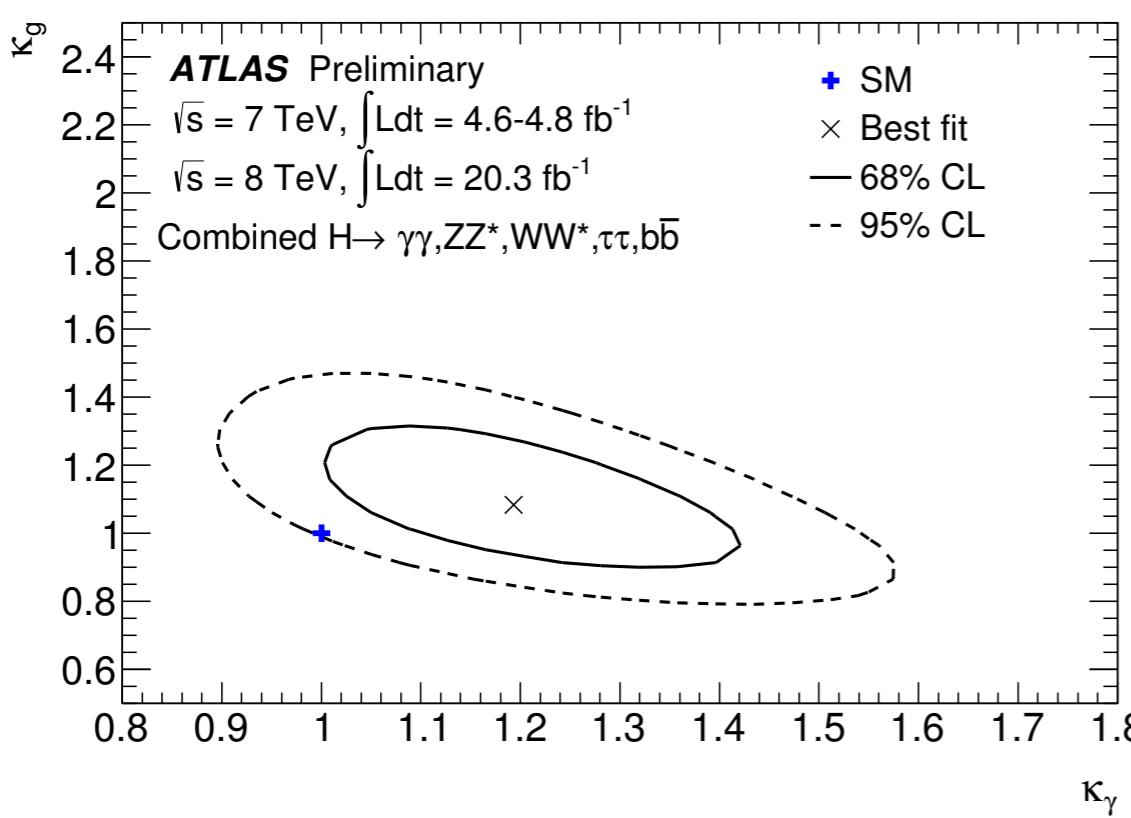
Decay



GLOBAL Combination



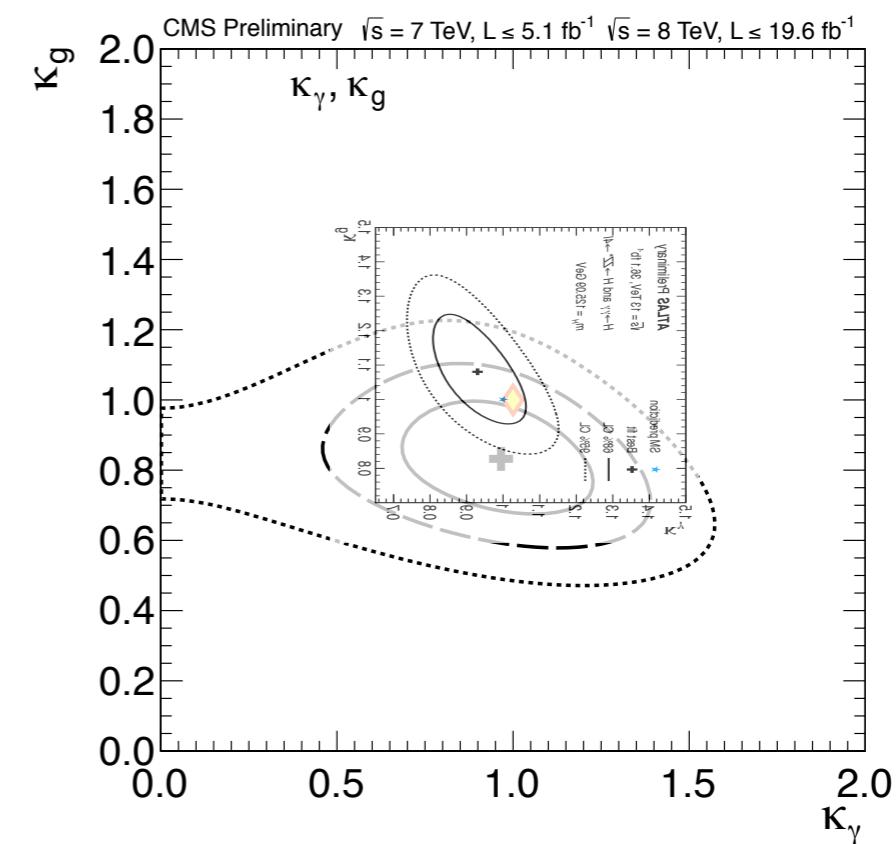
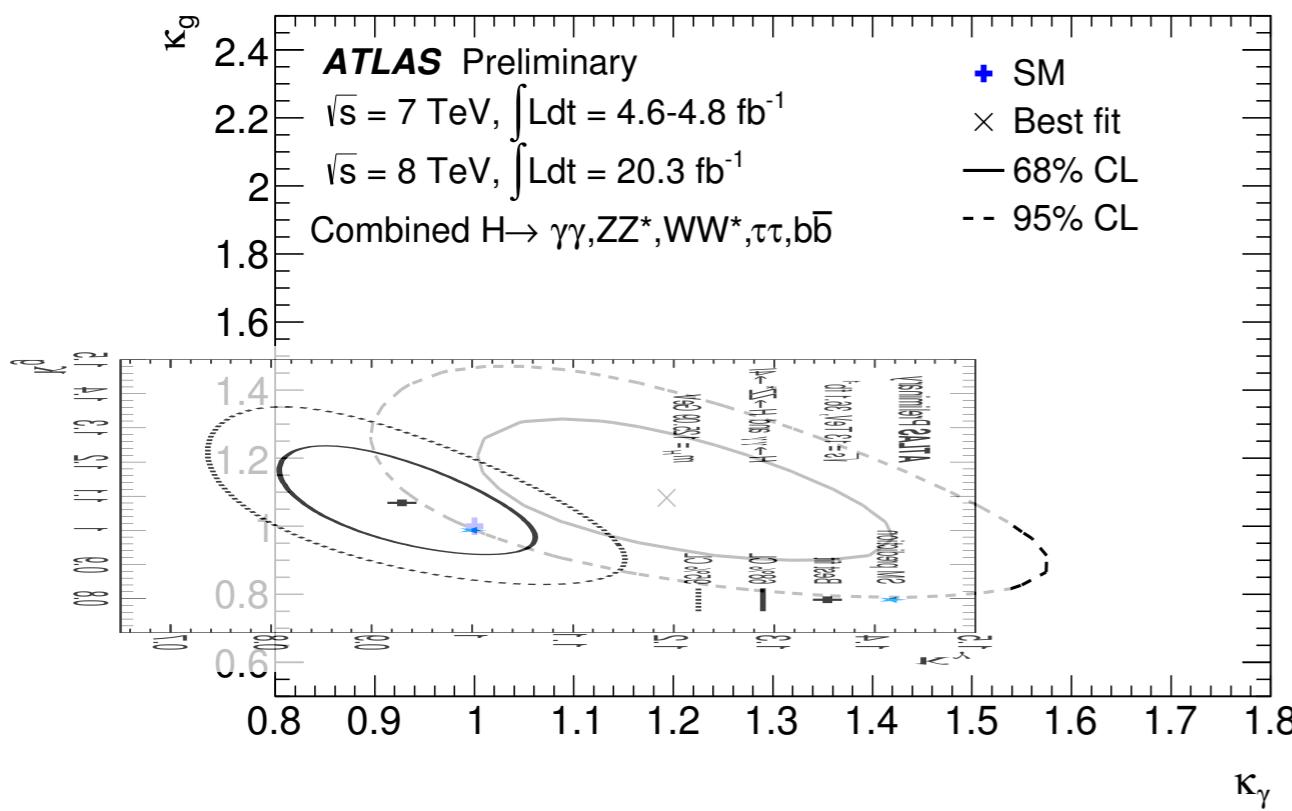
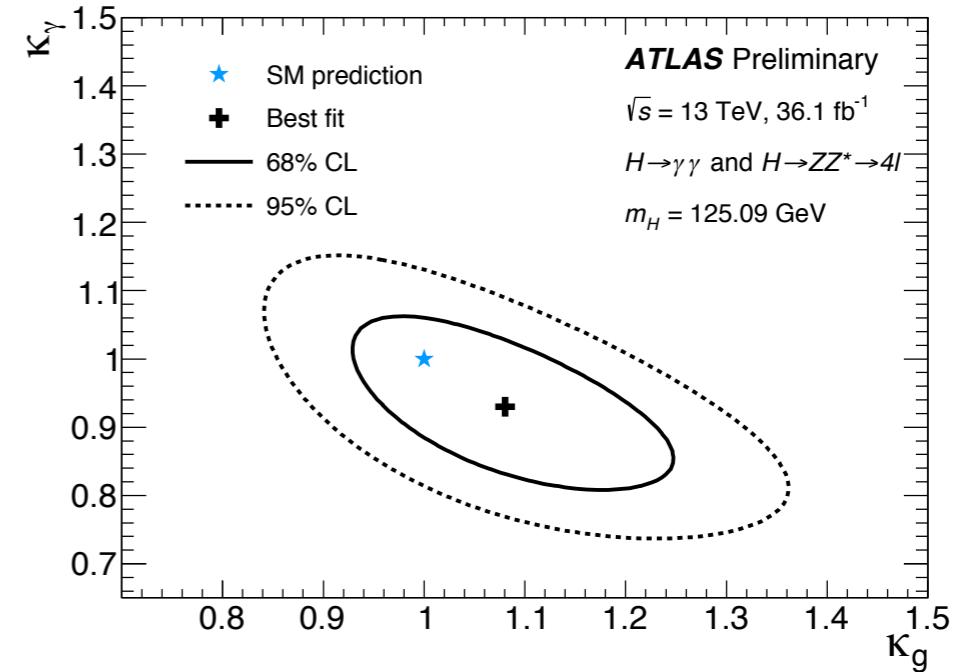
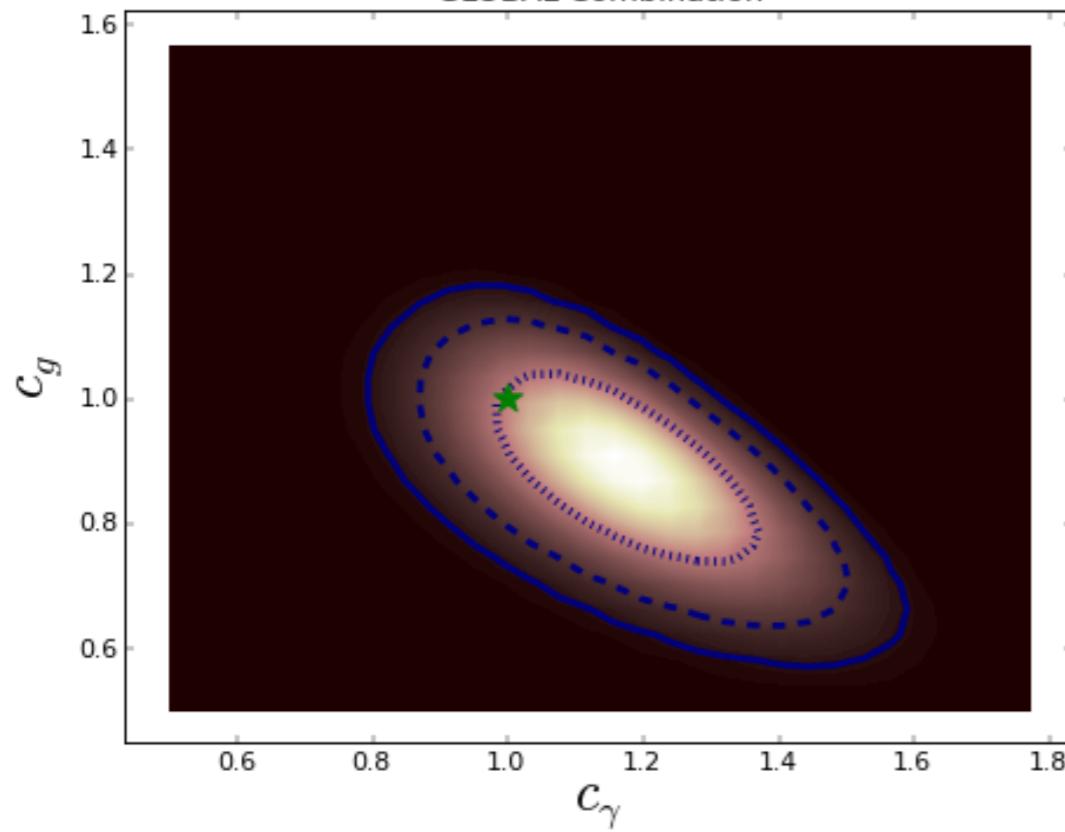
Constraints on ggH and $\gamma\gamma$ H couplings



$$\kappa_g^2(\kappa_b, \kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}}$$

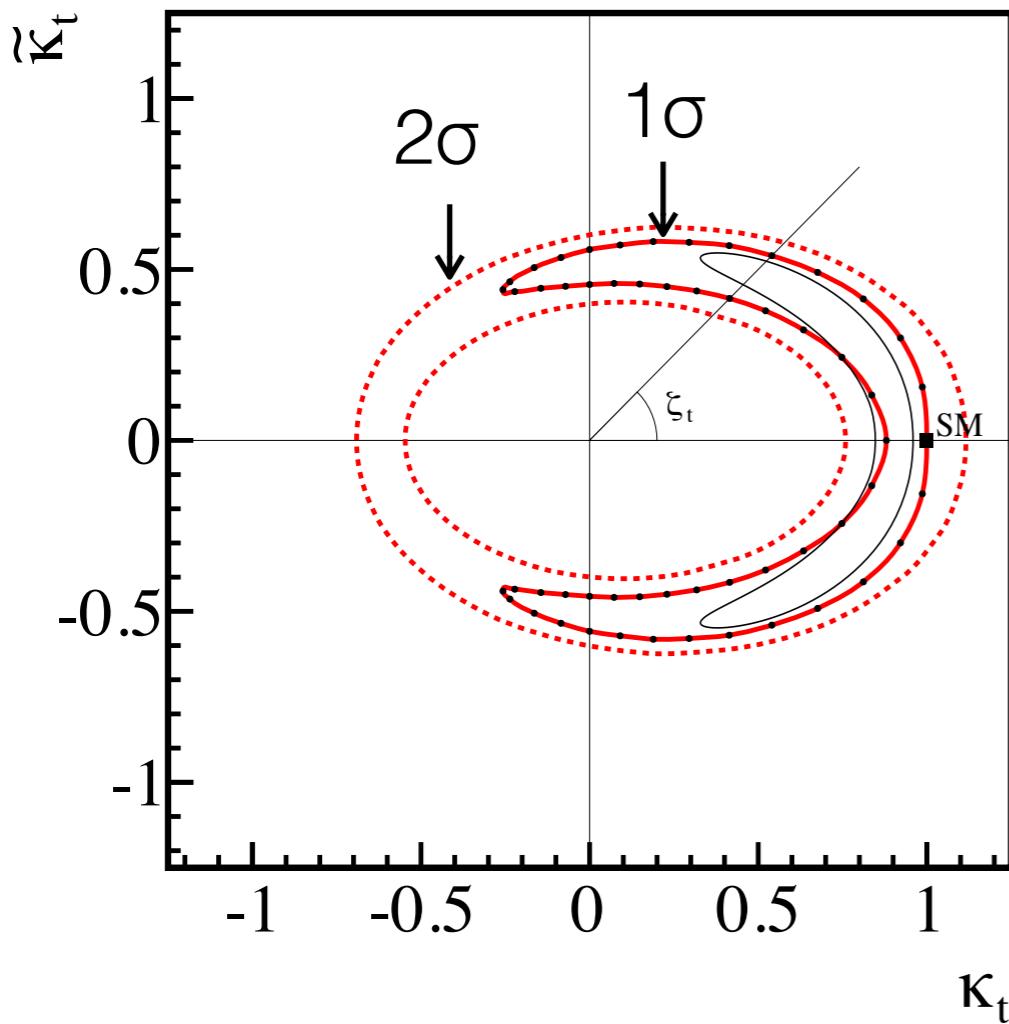
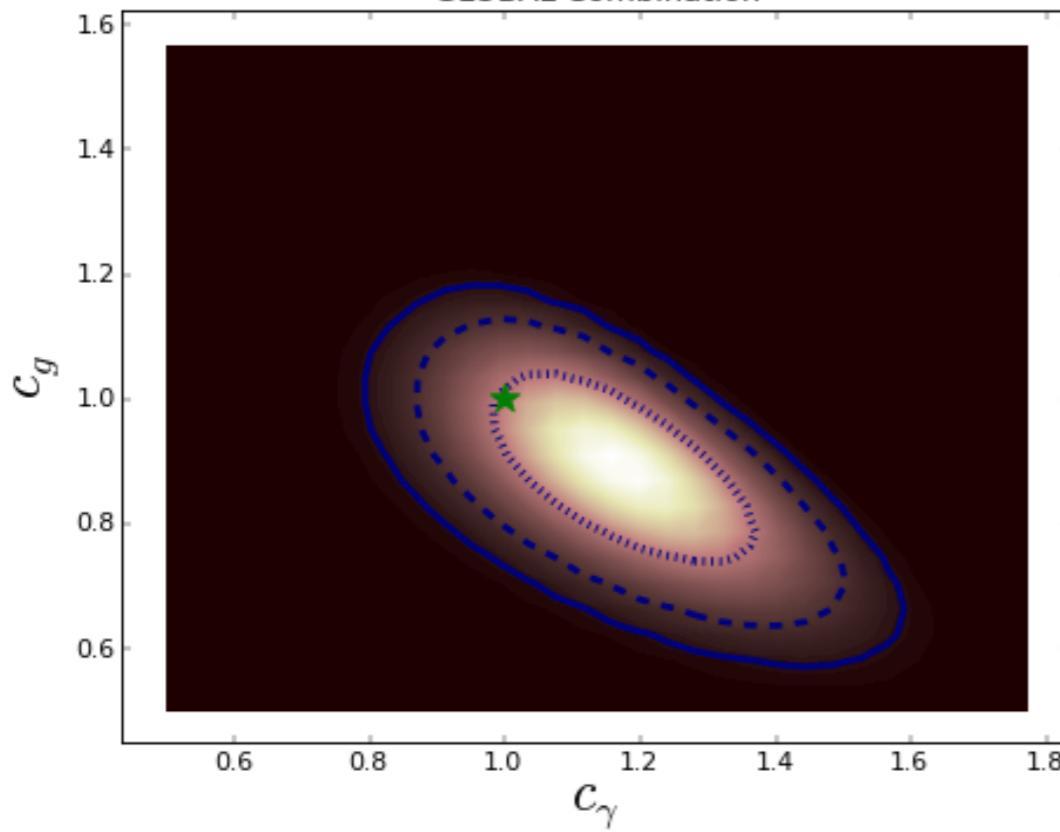
GLOBAL Combination



$$\kappa_g^2(\kappa_b, \kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}}$$

GLOBAL Combination



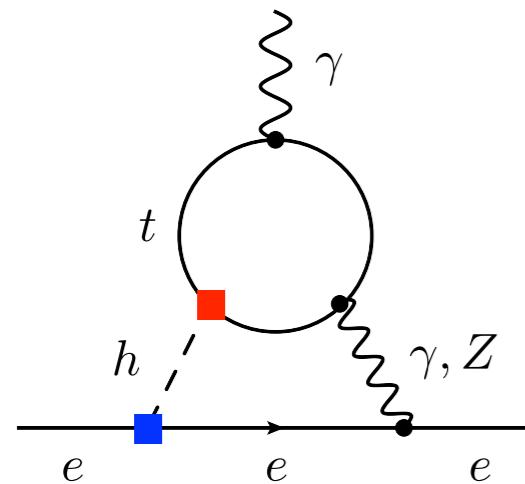
$$\mathcal{L}_\Delta = - \left[\frac{\alpha_s}{8\pi} \textcolor{red}{c_g} b_g G_{\mu\nu}^a G^{\mu\nu a} + \frac{\alpha_{em}}{8\pi} \textcolor{blue}{c_\gamma} b_\gamma F_{\mu\nu} F^{\mu\nu} \right] \left(\frac{H}{v} \right)$$

$$\mathcal{L}_t = - \frac{m_t}{v} (\textcolor{blue}{\kappa_t} \bar{t} t + i \tilde{\kappa}_t \bar{t} \gamma_5 t) H$$

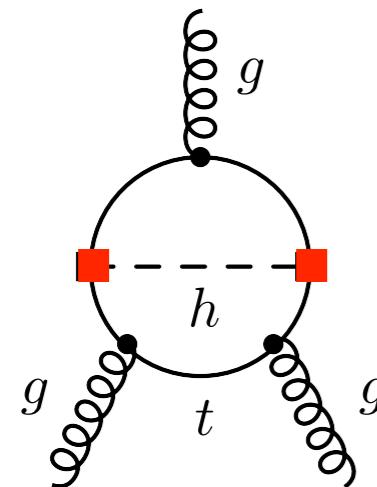
- The CPV phase ζ_t is largely arrowed.
- Due to the interference in c_γ , the constraints for $\kappa_t > 0$ and < 0 are not symmetric. $\zeta_t = \pi$ is excluded at 1σ .

EDM constraint

CP violating ttH coupling contributes to the electron and neutron EDMs via 2-loop diagrams: **J.Brod, U.Haischb, J.Zupan [1310.1385]**



$$\left| \frac{d_e}{e} \right| < 8.7 \cdot 10^{-29} \text{ cm} \rightarrow |\tilde{\kappa}_t| < 0.01$$



$$\left| \frac{d_n}{e} \right| < 2.9 \cdot 10^{-26} \text{ cm} \rightarrow |\tilde{\kappa}_t| < [0.03, 0.10]$$

These constraints can be avoided once other contributions are considered, e.g. suppressed eeh coupling, SUSY contributions.

We do not consider these model-dependent constraints in this talk.

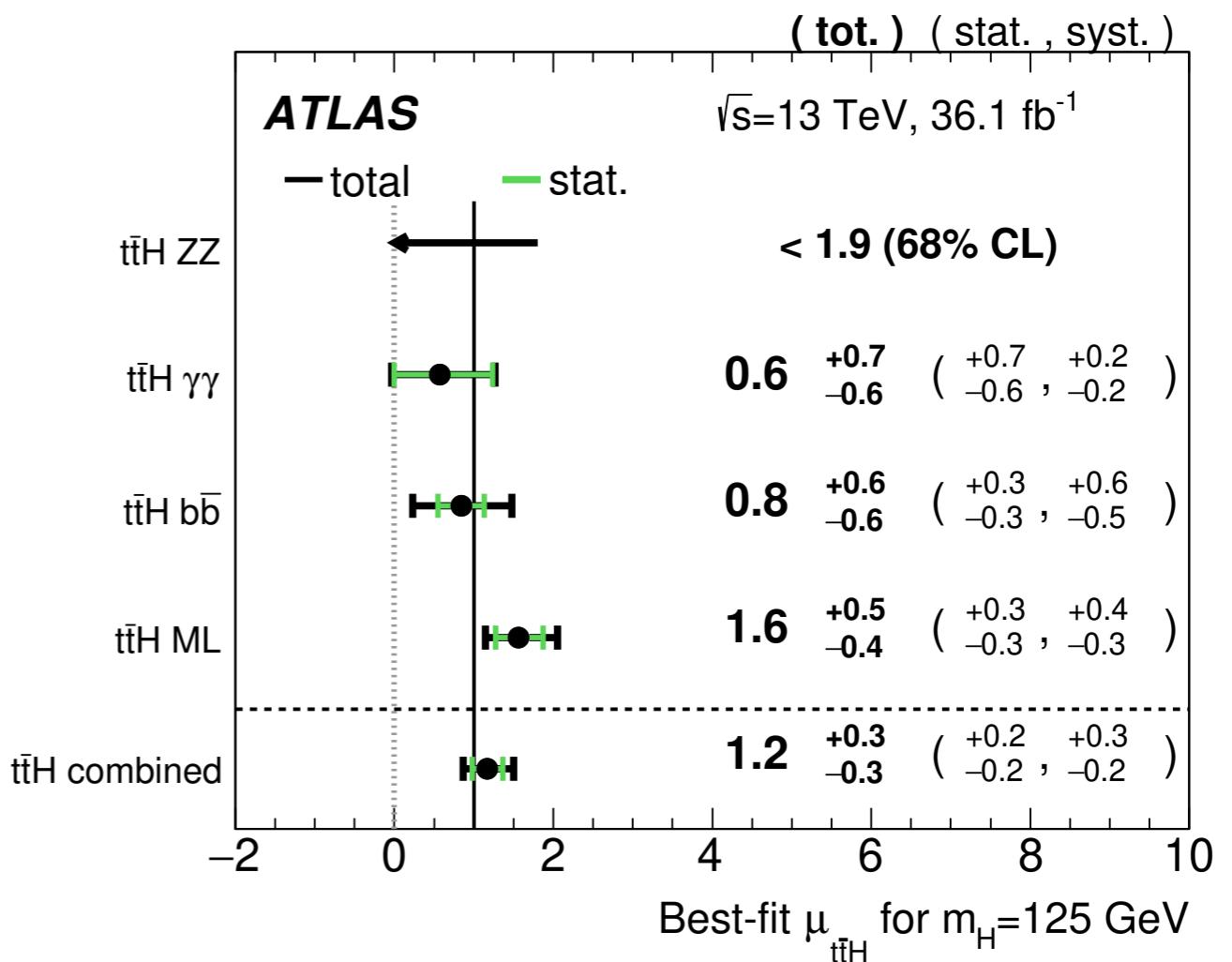
ttH and tHj

- If the anomalous top-Higgs couplings exist, the effect should be seen in $pp \rightarrow \bar{t}tH$ and $pp \rightarrow tHj (\bar{t}Hj)$.
- Cross sections are small:

$\sigma(ttH) \sim 507 \text{ fb}$

$\sigma(tHj) \sim 47 \text{ fb}, \sigma(\bar{t}Hj) \sim 25 \text{ fb}, \sigma(tHj) + \sigma(\bar{t}Hj) \sim 72 \text{ fb}$

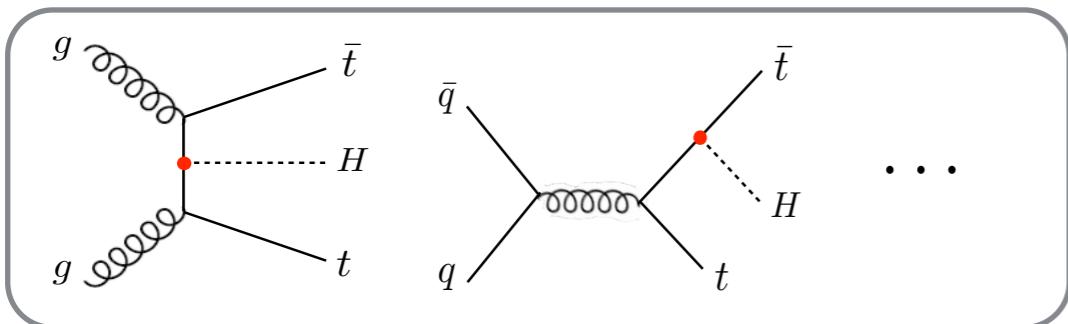
- ttH: **>3 σ evidence**
- tHj, tbarHj: statistics not enough



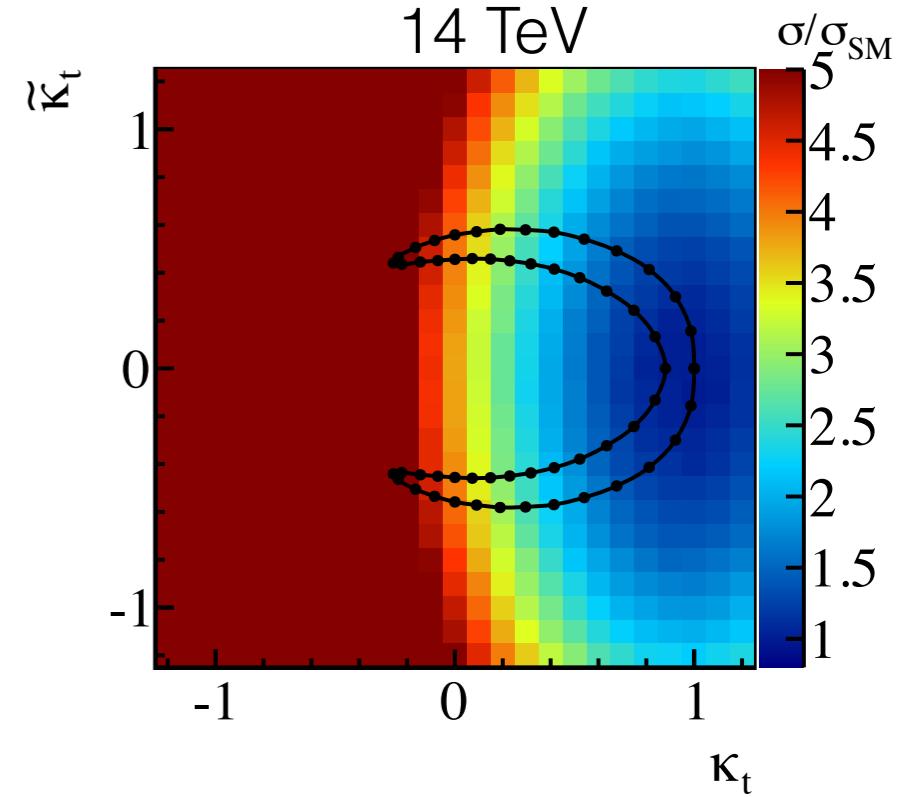
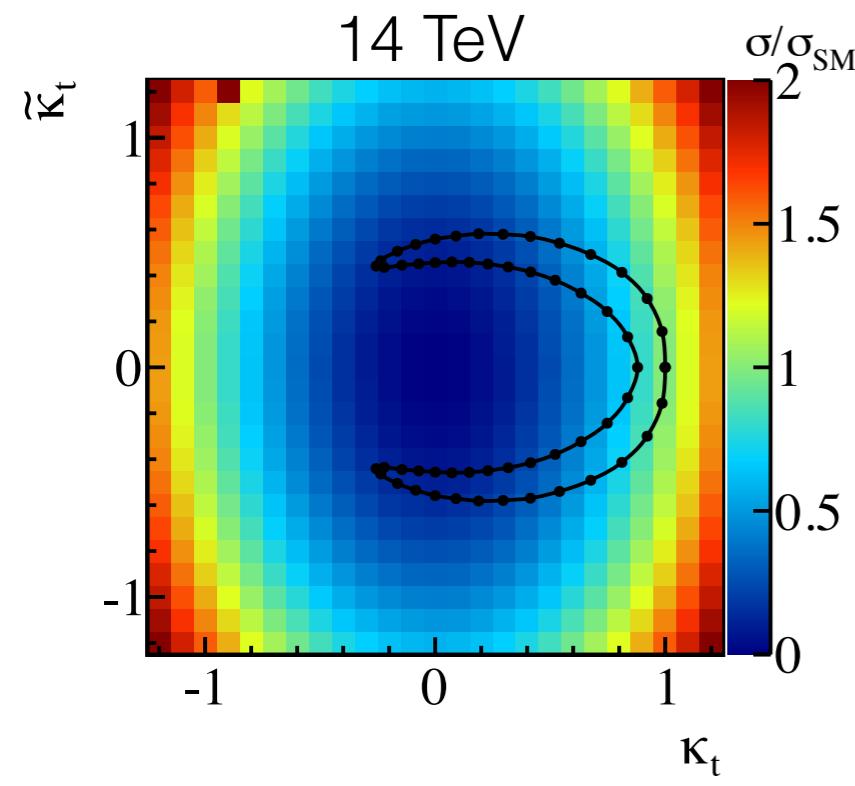
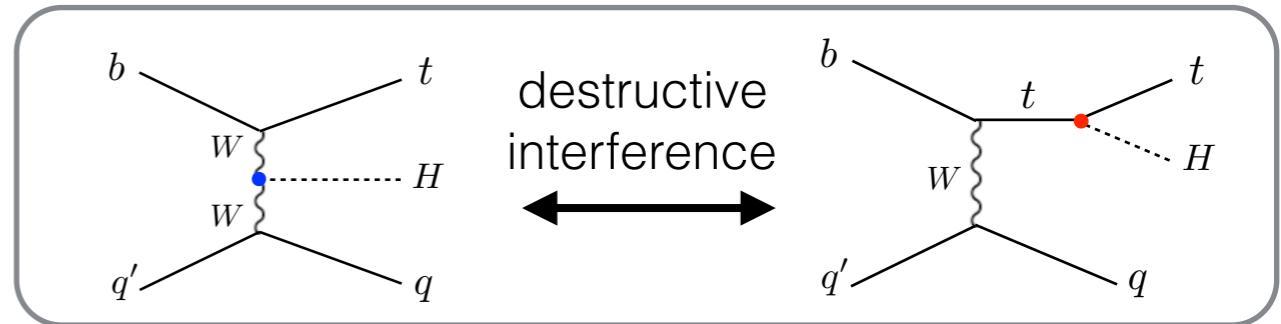
Cross Section

- How are the cross sections affected by the anomalous top-Higgs coupling?

$pp \rightarrow \bar{t}tH$



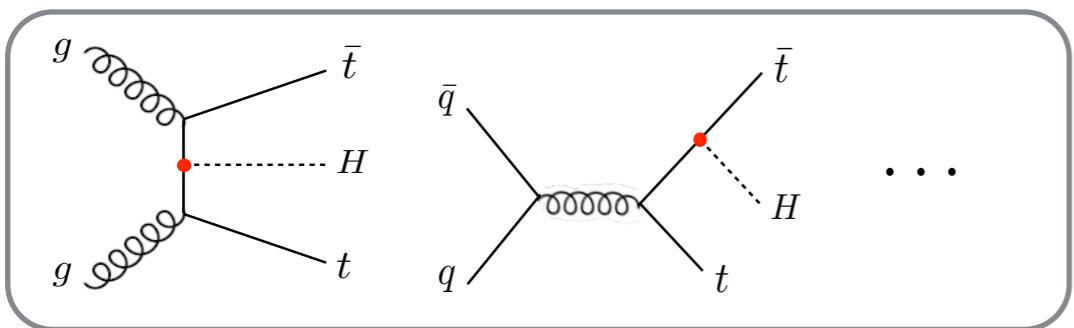
$pp \rightarrow tHj (\bar{t}Hj)$



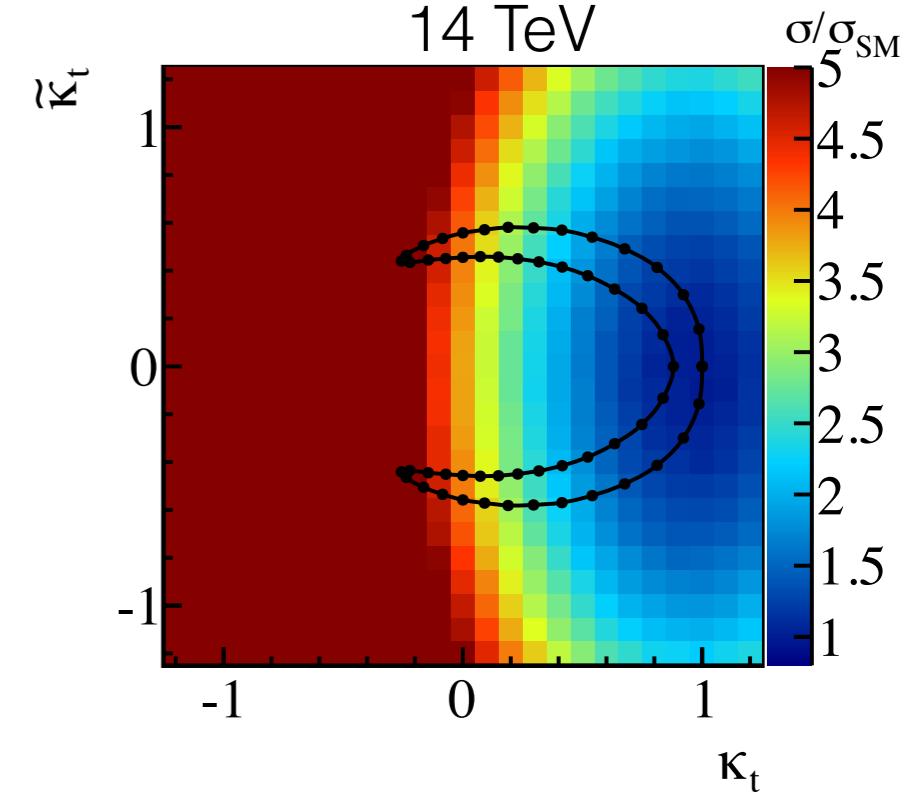
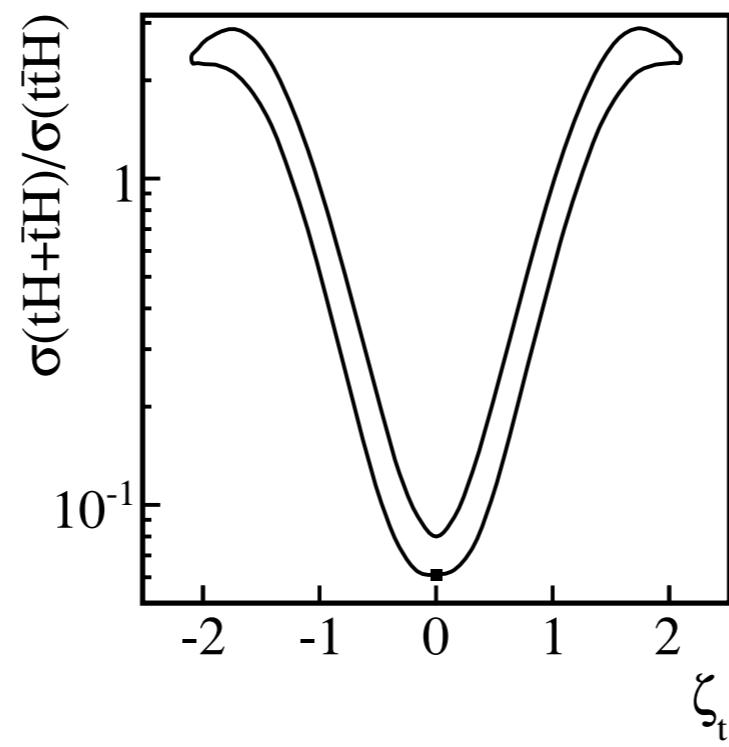
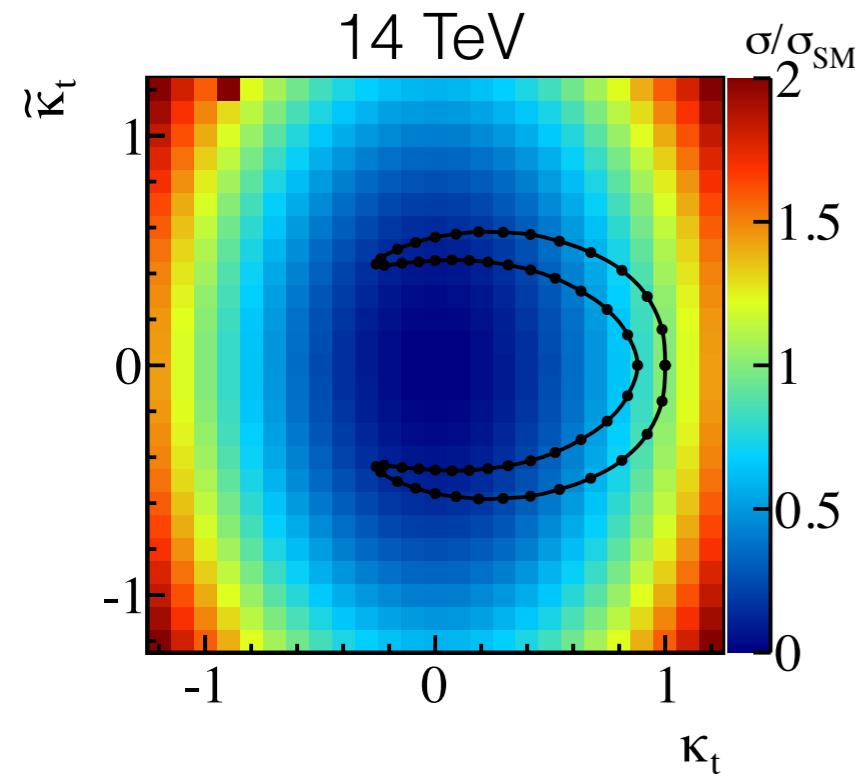
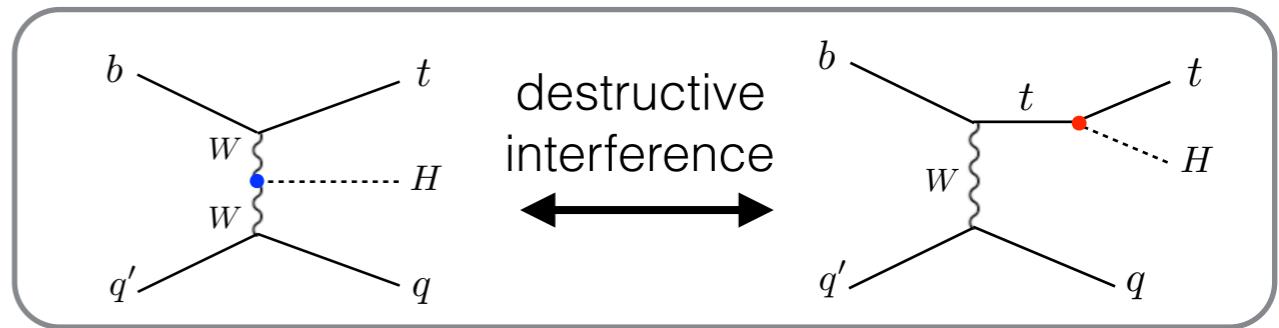
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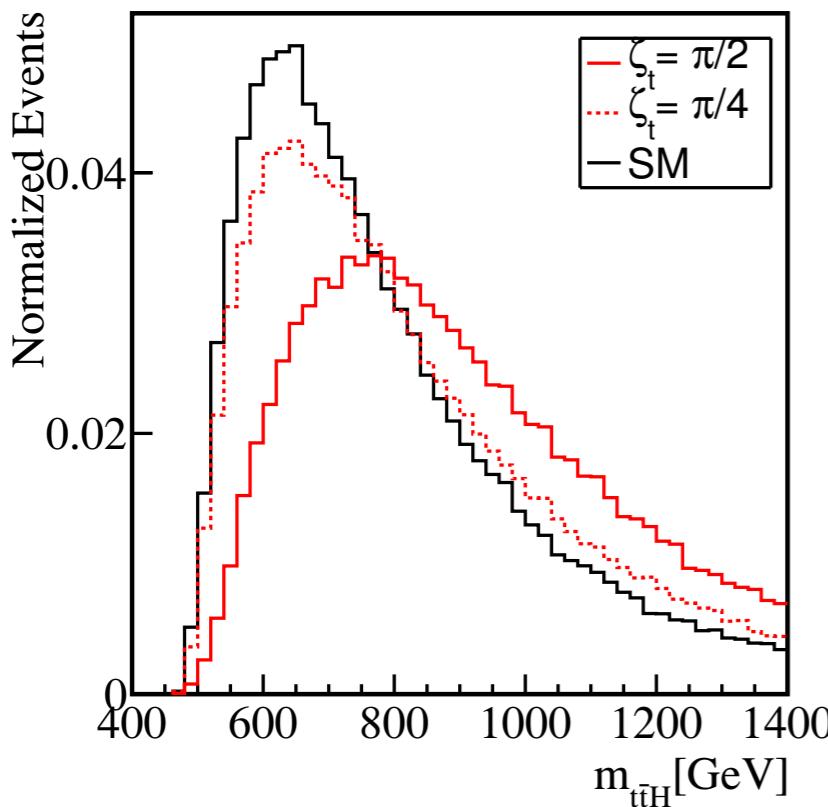
$pp \rightarrow tHj (\bar{t}Hj)$



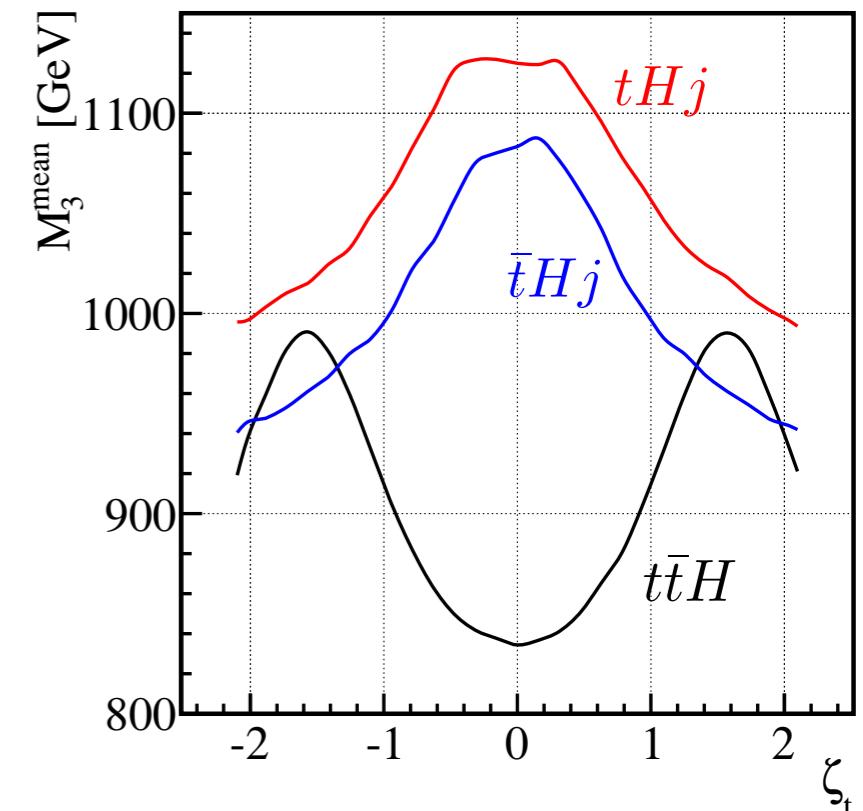
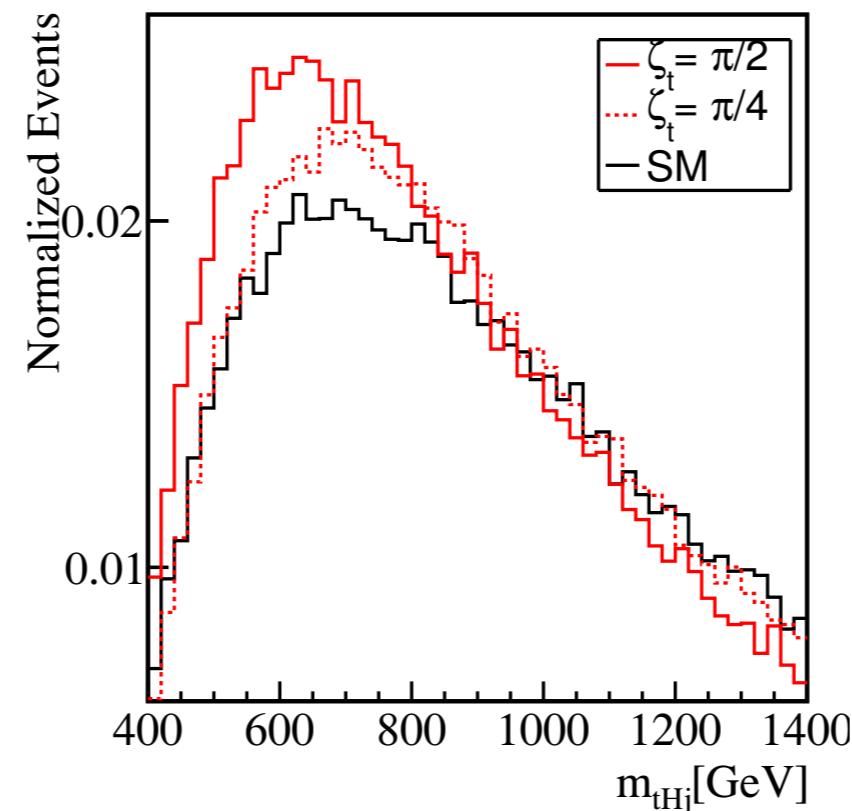
- For $\zeta_t > 1.2$, $\sigma(tHj)$ can become larger than $\sigma(\bar{t}tH)$.

Invariant Mass

$t\bar{t}H$



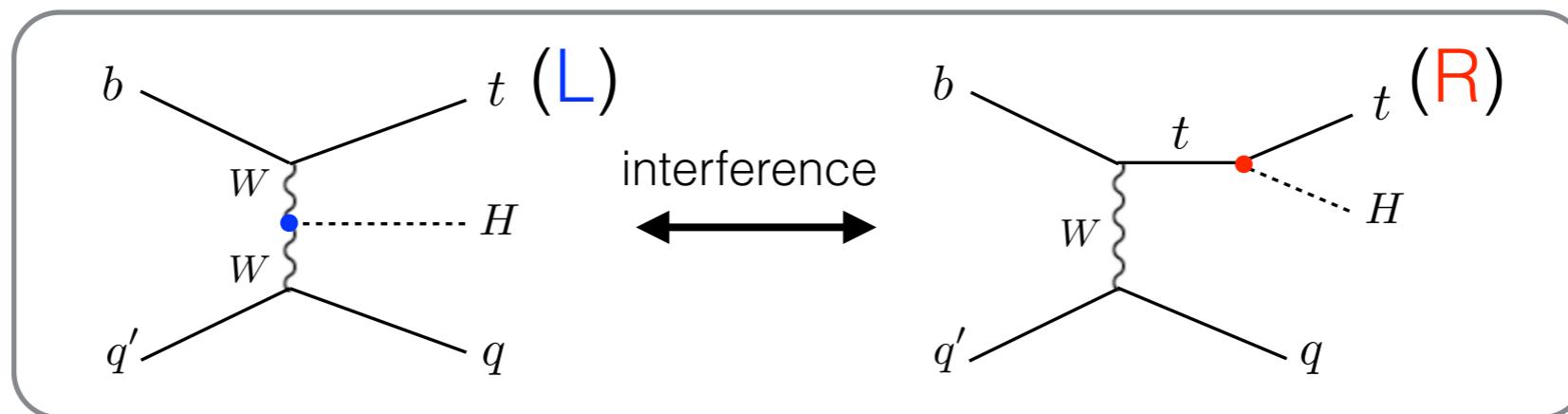
tHj



- For $t\bar{t}H$, the total invariant mass **increases** as increasing the CP phase ζ_t .
- For tHj , the total invariant mass **decreases** as increasing ζ_t .

Spin measurement in tHj

- In the diagram without ttH coupling the top is dominantly **left-handed**, whereas it is **right-handed** in the diagram with ttH. Modification of ttH coupling may affect the top polarisation measurement in tHj.

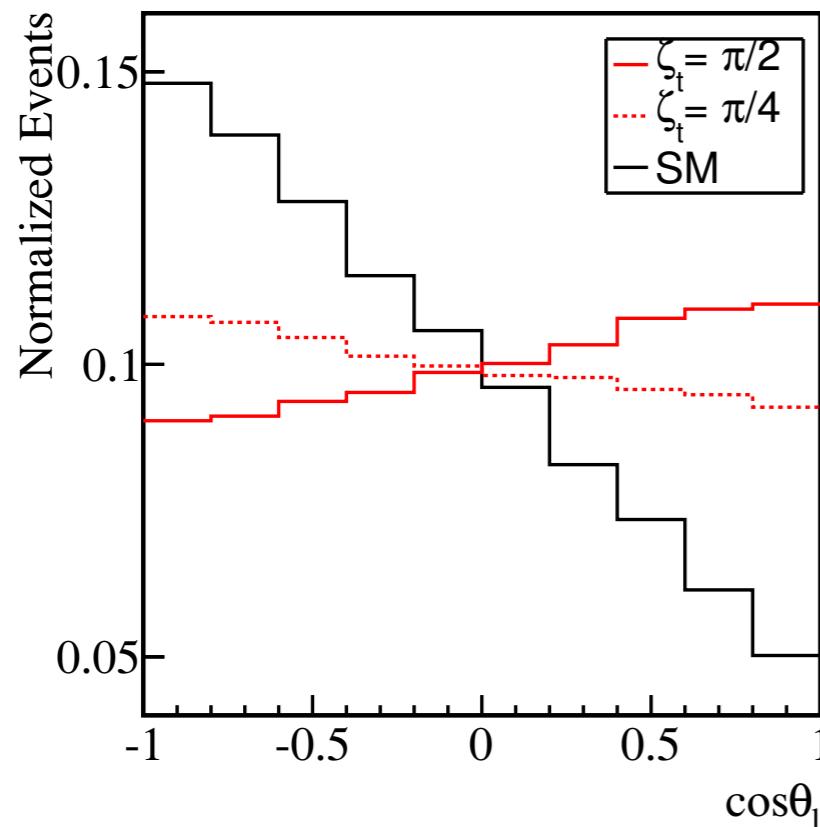


- The top polarisation can be measured by the angle of the lepton w.r.t the top boost direction at the top rest frame.

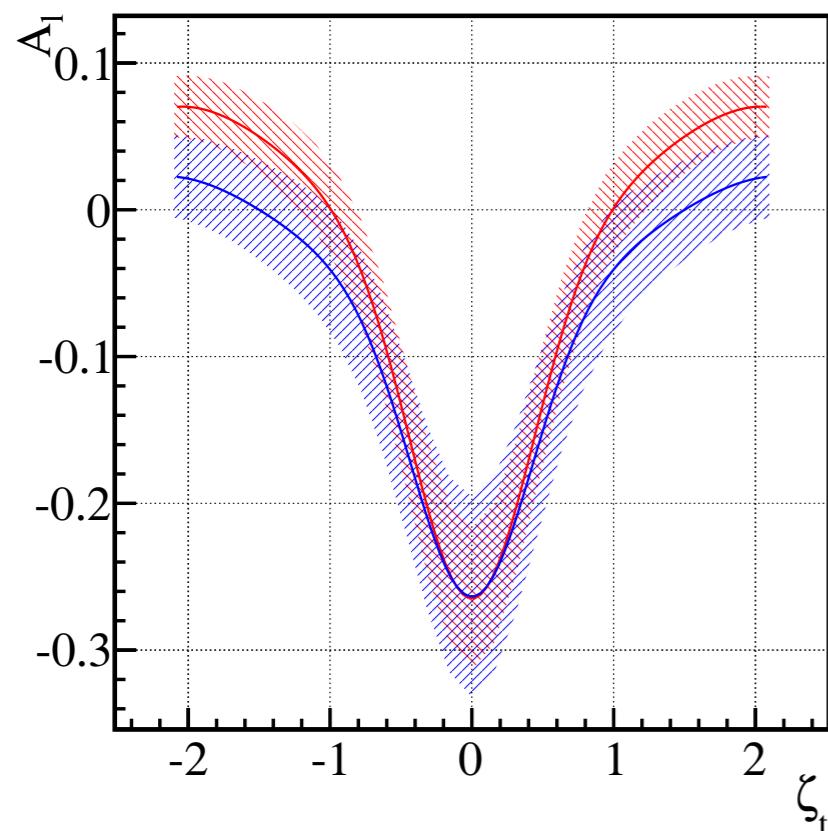
$$\frac{1}{\Gamma_\ell} \frac{d\Gamma_\ell}{d \cos \theta_\ell} = \frac{1}{2} (1 + P_t \cos \theta_\ell)$$

$P_t = \pm 1$ for pure right(left)-handed top

Spin measurement in tHj

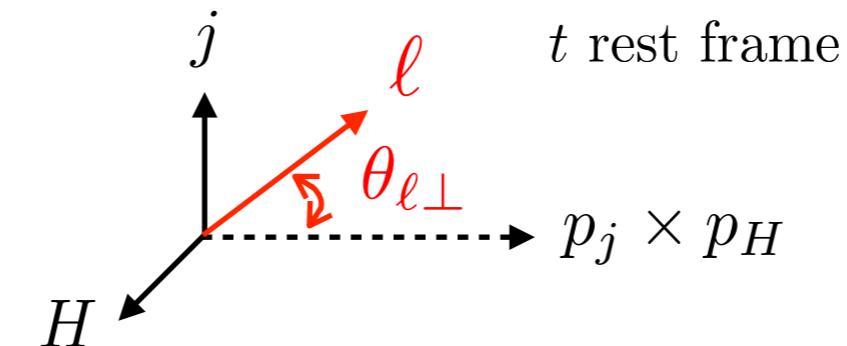
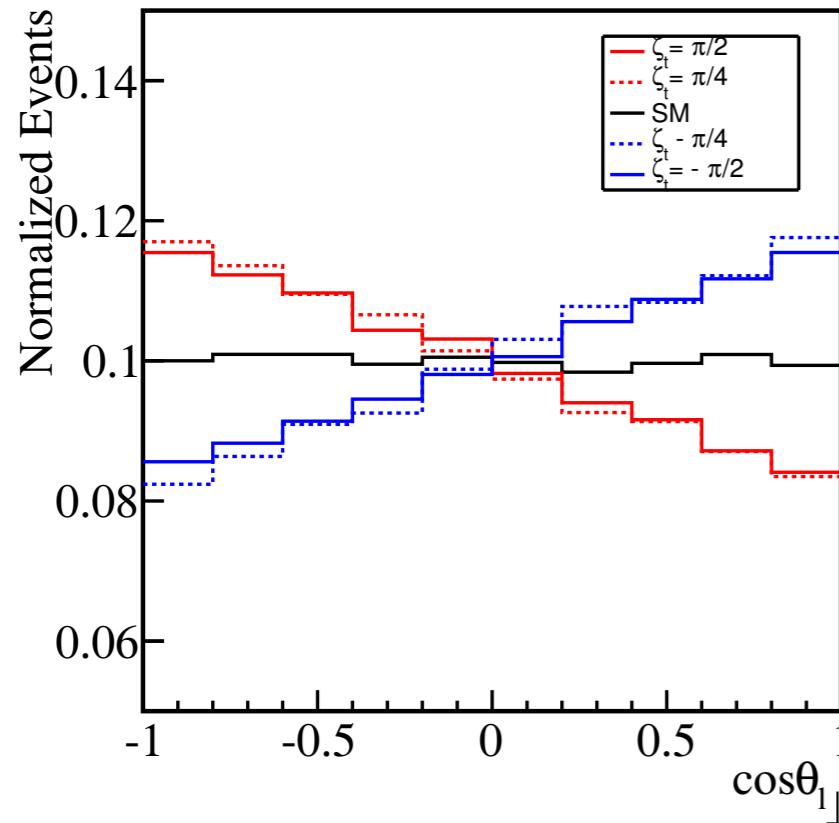


- The $\cos\theta_l$ distribution in the tHj rest frame
- Some dependency of the CP phase
- In SM the lepton prefers the opposite direction to the top boost direction, whereas for $\zeta_t = \pi/2$, it prefers the same direction.

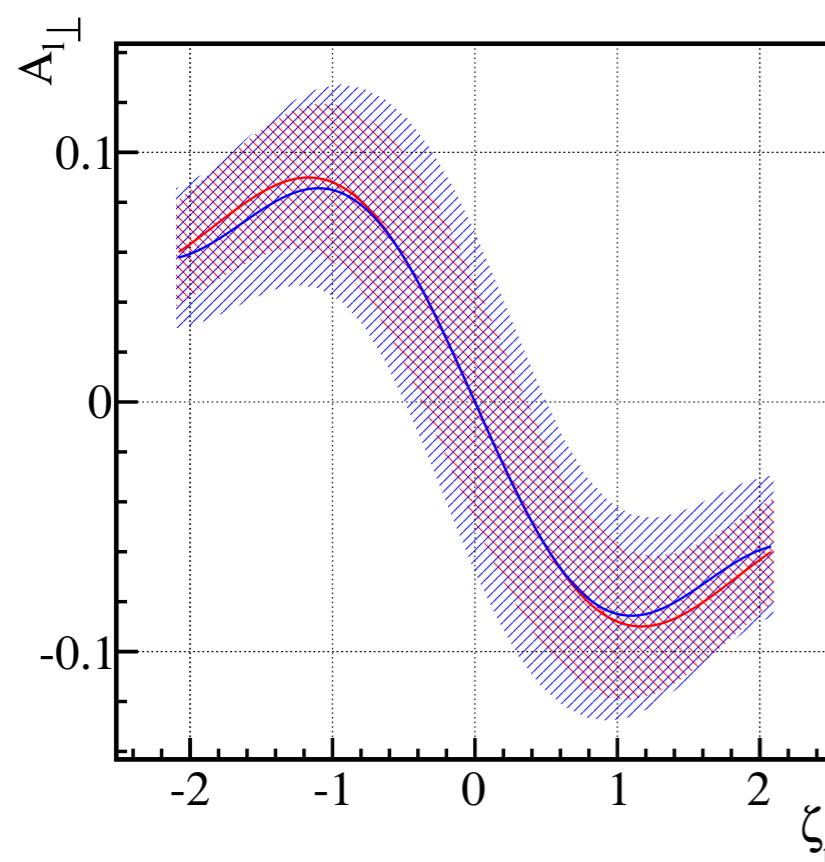


- The asymmetry is an useful measure.
- $$A_\ell = \frac{N(\cos\theta_\ell > 0) - N(\cos\theta_\ell < 0)}{N(\cos\theta_\ell > 0) + N(\cos\theta_\ell < 0)}$$
- tHj and tbarHj. The band is the statistic error assuming 14 TeV LHC with 100 fb^{-1} .
 - $\zeta_t > 0$ and < 0 are not distinguishable.

The angle w.r.t production plane



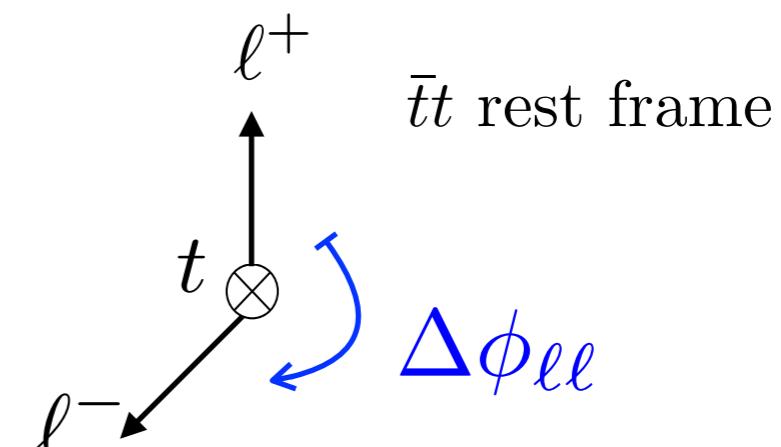
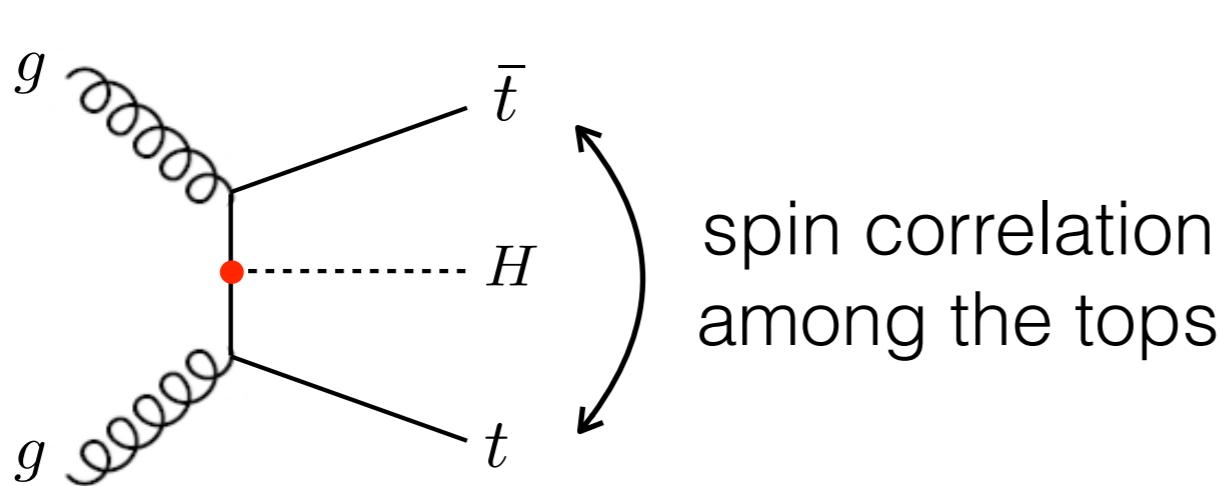
- The SM has a flat distribution => no CPV
- With $\zeta_t \neq 0$, the lepton prefers a particular direction depending on the sign of ζ_t .



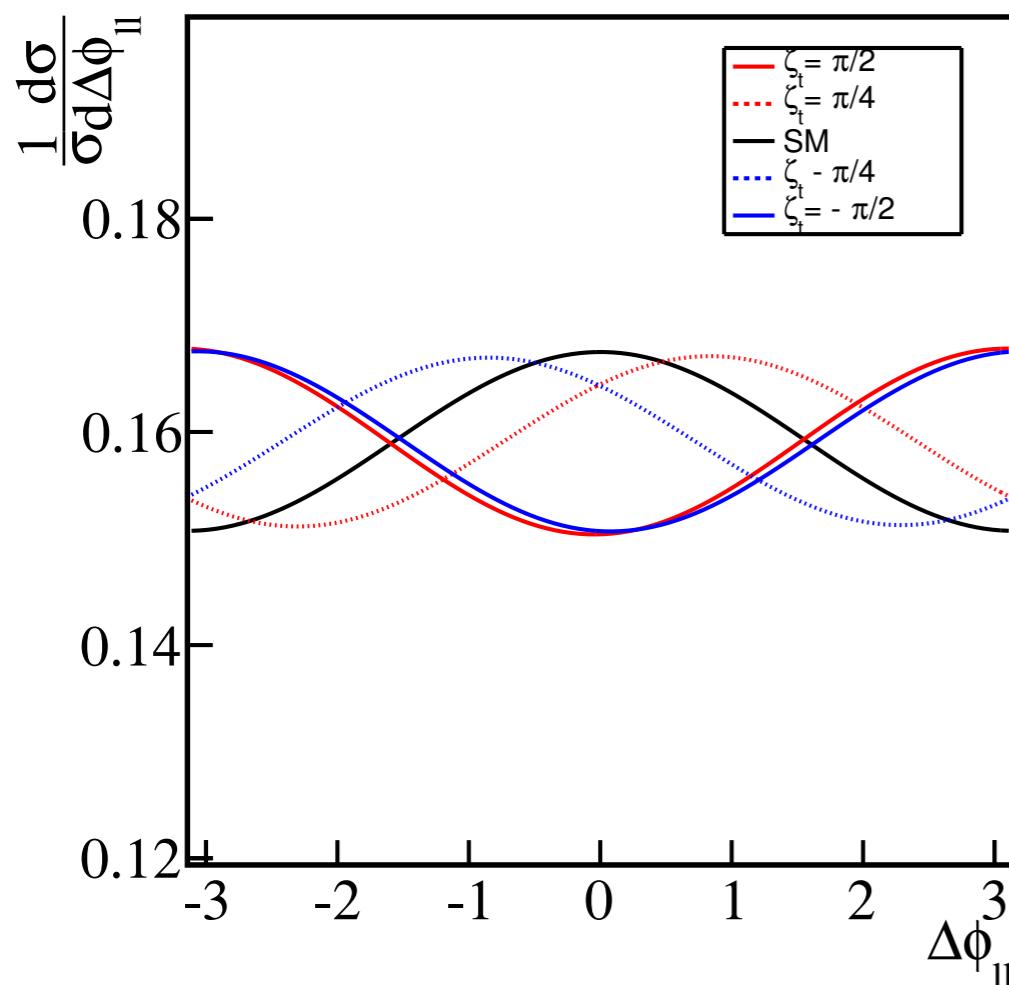
$$A_\ell = \frac{N(\cos\theta_\ell > 0) - N(\cos\theta_\ell < 0)}{N(\cos\theta_\ell > 0) + N(\cos\theta_\ell < 0)}$$

- $\zeta_t > 0$ and < 0 are distinguishable.

Spin Correlation in ttH



The sign is defined by the direction of the top. This is important to capture the CP violation.



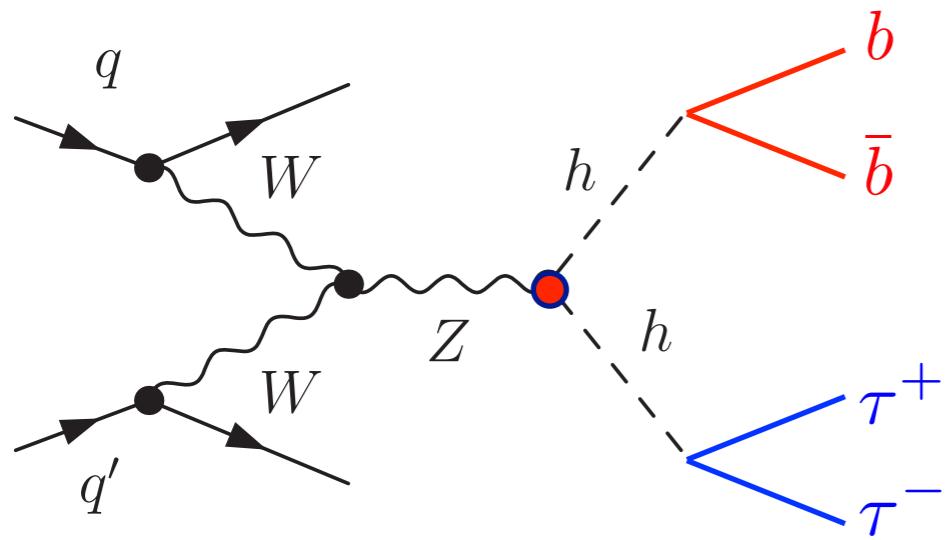
- $\Delta\phi_{\ell\ell}$ can discriminate $\xi_t > 0$ and < 0 .
- The fit shows:

$$\frac{d\sigma}{d\Delta\phi_{\ell\ell}} \propto \cos(\Delta\phi_{\ell\ell} - \delta) + \text{const}$$

$$\delta = 2\xi_t - \sin(2\xi_t)/2$$

Conclusion

- It is important to model independently constrain CPV couplings in the Higgs sector.
- Unitarity provides non-trivial constraints on the strength of effective operators as well as the new physics scale.
- The ratio of the production cross sections of $t\bar{t}H$ and tHj is very sensitive to the modification of the top-Higgs coupling in the SM.
- The lepton angle from the production plane of tHj and the angular correlation in the $t\bar{t}H$ are good variable to measure the CPV in the top-Higgs coupling.



Event selection ($bb\tau\tau$ channel)

- 2 taus with $p_T > 29, 20\text{GeV}$, $|\eta|<2.5$ ($\epsilon_\tau=70\%$)
- 2 jets (not b nor τ) with $p_T > 25\text{GeV}$, $|\eta|<4.5$
- $\Delta\eta(j_1, j_2) > 5$
- 2 hardest jets to be b -tagged and $|\eta|<2.5$ ($\epsilon_b=70\%$)
- $|m_{bb} - m_h|<15\text{GeV}$, $|m_{\tau\tau} - m_h|<25\text{GeV}$, $m_{hh}>400\text{GeV}$

Sample	After selection [fb]
$hhjj$ (WBF)	1.485×10^{-3}
$hhjj$ (GF)	5.378×10^{-4}
$t\bar{t}jj$	1.801×10^{-2}
$t\bar{t}h$	5.658×10^{-5}
$Zhjj$	1.026×10^{-4}
$ZZjj$	7.639×10^{-7}
$ZWWjj$	2.039×10^{-7}
Total background	1.870×10^{-2}
S/B	$1/12.60$

tHj

Scenario	Channel	Obs. Limit (pb)	Exp. Limit (pb)		
			Median	$\pm 1\sigma$	$\pm 2\sigma$
$\kappa_t/\kappa_V = -1$	$\mu\mu$	1.00	0.58	[0.42, 0.83]	[0.31, 1.15]
	$e\mu$	0.84	0.54	[0.39, 0.76]	[0.29, 1.03]
	$\ell\ell\ell$	0.70	0.38	[0.26, 0.56]	[0.19, 0.79]
	Combined	0.64	0.32	[0.22, 0.46]	[0.16, 0.64]
$\kappa_t/\kappa_V = 1$ (SM-like)	$\mu\mu$	0.87	0.41	[0.29, 0.58]	[0.22, 0.82]
	$e\mu$	0.59	0.37	[0.26, 0.53]	[0.20, 0.73]
	$\ell\ell\ell$	0.54	0.31	[0.22, 0.43]	[0.16, 0.62]
	Combined	0.56	0.24	[0.17, 0.35]	[0.13, 0.49]

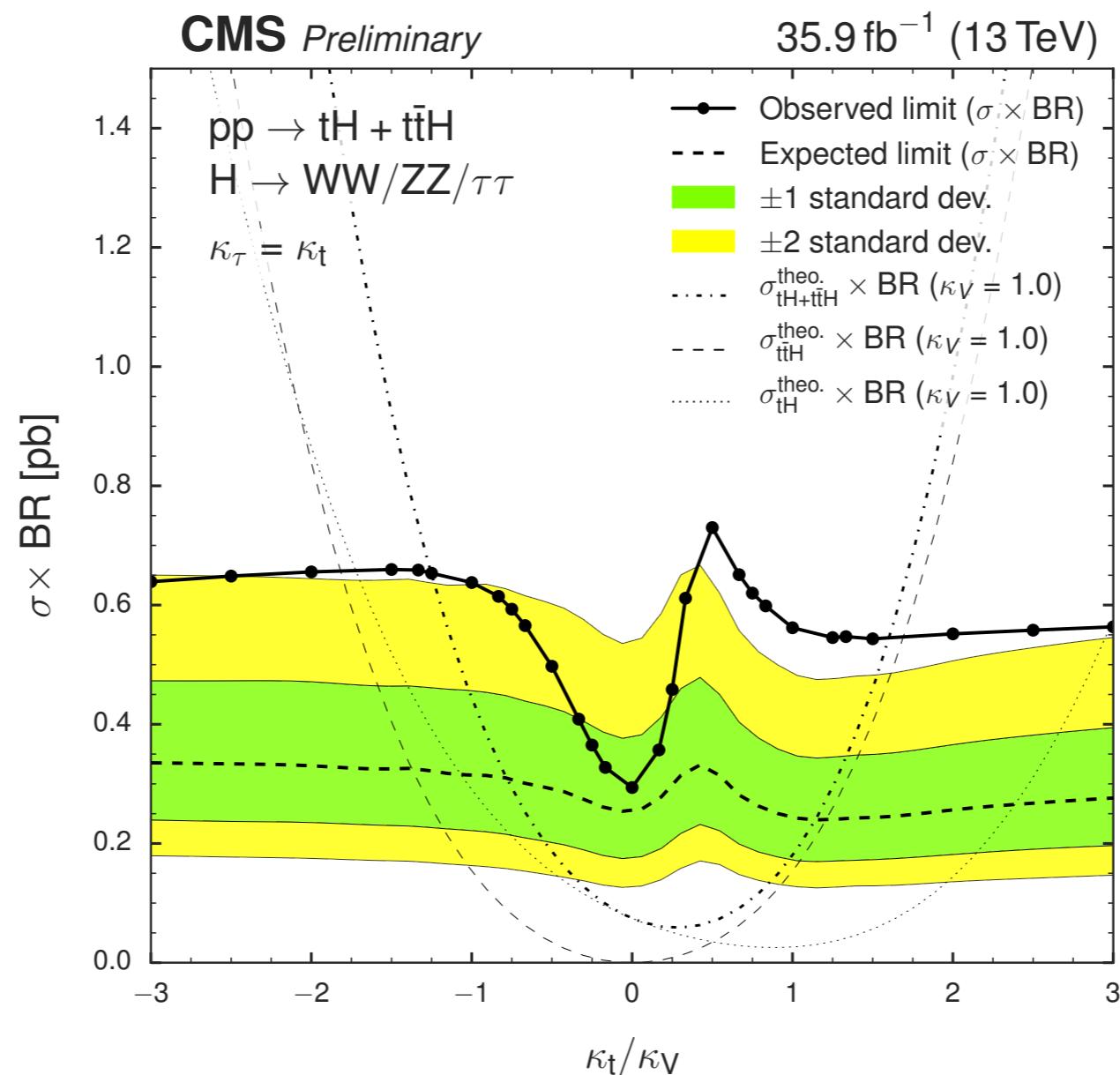
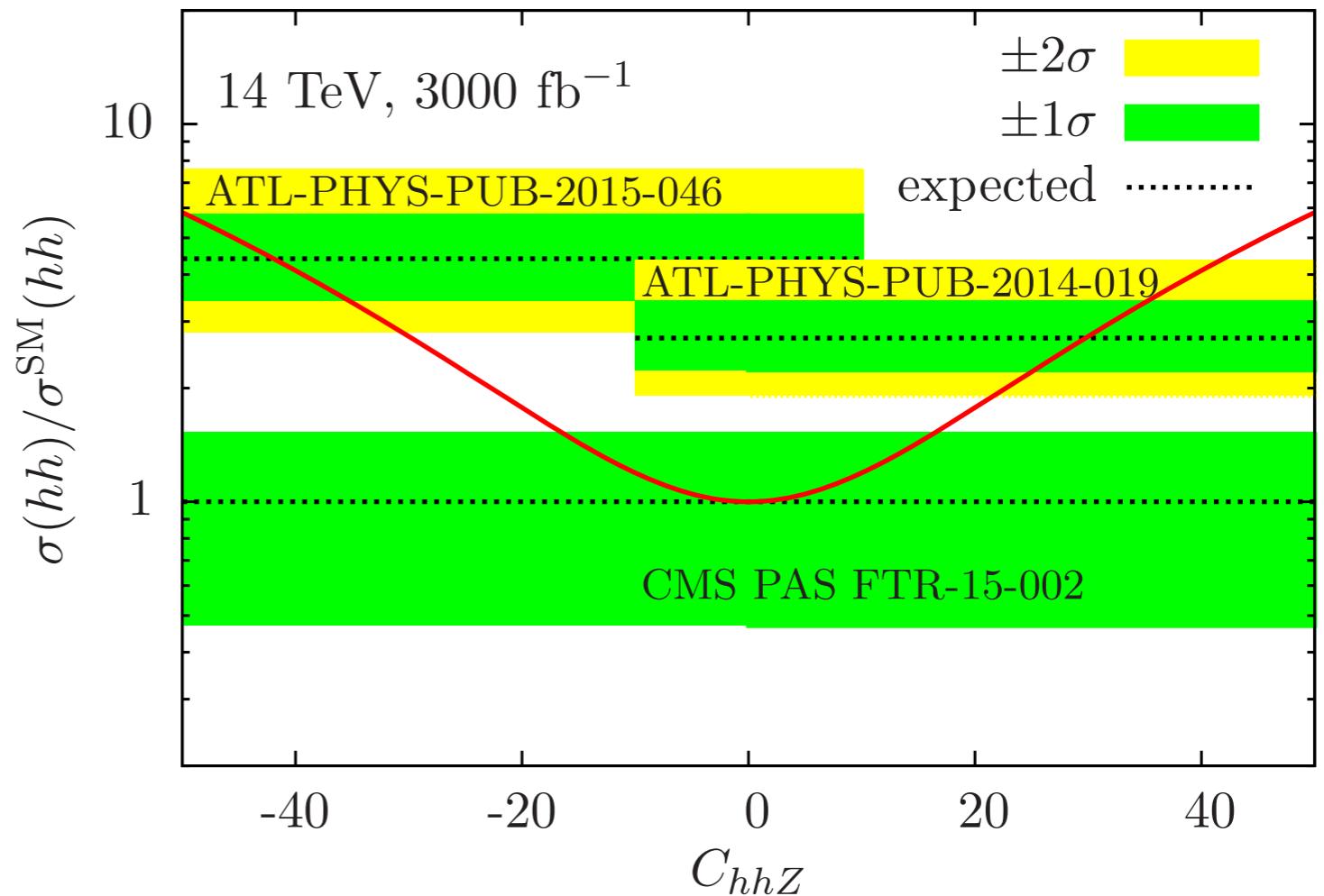
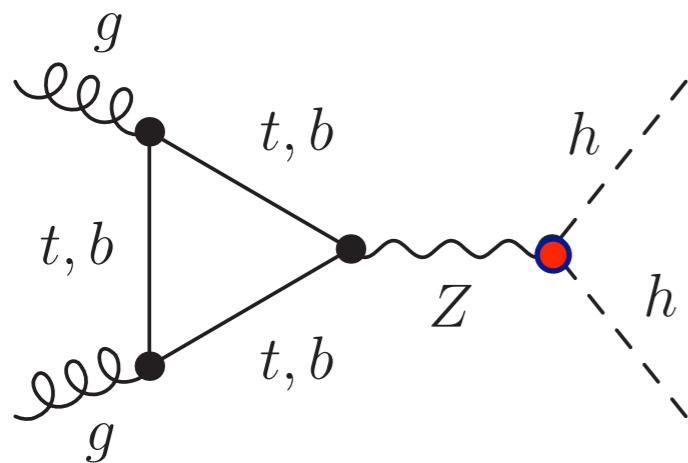


TABLE II. Feynman rules relevant for $f\bar{f} \rightarrow W^+W^-$, $P_{L,R}$ denote the right- and left-chirality projectors.

Vertex	Feynman rule	SM
$W_\alpha^-(p)W_\beta^+(k)A_\mu(q)$	$-g_W^\gamma \Gamma_{\alpha,\beta,\mu}(p, k, q)$	$g_W^\gamma = gs_W$
$W_\alpha^-(p)W_\beta^+(k)Z_\mu(q)$	$g_W^Z \Gamma_{\alpha,\beta,\mu}(p, k, q)$	$g_W^Z = gc_W$
$f\bar{f}W_\mu^\pm$	$g_W^f \gamma_\mu P_L$	$g_W^f = g/2$
$f\bar{f}A_\mu$	$-g_\gamma^f \gamma_\mu$	$g_\gamma^f = gs_W Q_f$
$f\bar{f}Z_\mu$	$\gamma_\mu(g_{fL}^Z P_L + g_{fR}^Z P_R)$	$g_{fR}^Z = (g/c_W)(T_3^f - Q_f s_W^2)$ $g_{fL}^Z = -(g/c_W)Q_f s_W^2$
$h f\bar{f}$	$-(g_h^f + ig_A^f \gamma_5)$	$g_{fV}^Z = (g_{fL}^Z + g_{fR}^Z)/2$ $g_{fA}^Z = (g_{fL}^Z - g_{fR}^Z)/2$ $g_h^f = gm_f/(2m_W)$ $g_A^f = 0$
$h W_\mu^+ W_\nu^-$	$g_h^W g_{\mu\nu}$	$g_h^W = gm_W$
$h Z_\mu Z_\nu$	$g_h^Z g_{\mu\nu}$	$g_h^Z = (g^2 + g'^2)^{1/2} m_Z$

$$\mathcal{O}_{hhZ} = h(\partial_\mu h) Z^\mu$$



$$|C_{hhZ}| \lesssim 16.5$$