Unitarity and CPV in the Higgs sector

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

Probing Top-Higgs interactions at the LHC, Benasque, 30/5/2018

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.
- It is **important to constrain CPV Higgs couplings experimentally or theoretically as model independent as possible**.
- 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 study model-independently the CPV Higgs interactions.
- Unitarity provides non-trivial and model-independent constraints on the Wilson coefficients of the EFT operators.

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 (exception: QCD θ-term → Michihisa's talk).
- After EW symmetry breaking, we consider the following CP violating operators in the Higgs sector up to D=5:

$$\left.\begin{aligned} \mathcal{O}_{hff} &= h\bar{\psi}_f \gamma_5 \psi_f \\ \mathcal{O}_{hhZ} &= h(\partial_\mu h) Z^\mu \end{aligned}\right\} \quad D = 4$$

$$\left.\mathcal{O}_{hF\tilde{F}} = hF_{\mu\nu}\tilde{F}^{\mu\nu} \quad \right\} \quad D = 5$$

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

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

broken phase | **symmetric phase**

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

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

$$h(\partial_\mu h) Z^\mu \longleftarrow S |D_\mu H_i|^2 \ni v S Z_\mu \partial^\mu A$$

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

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

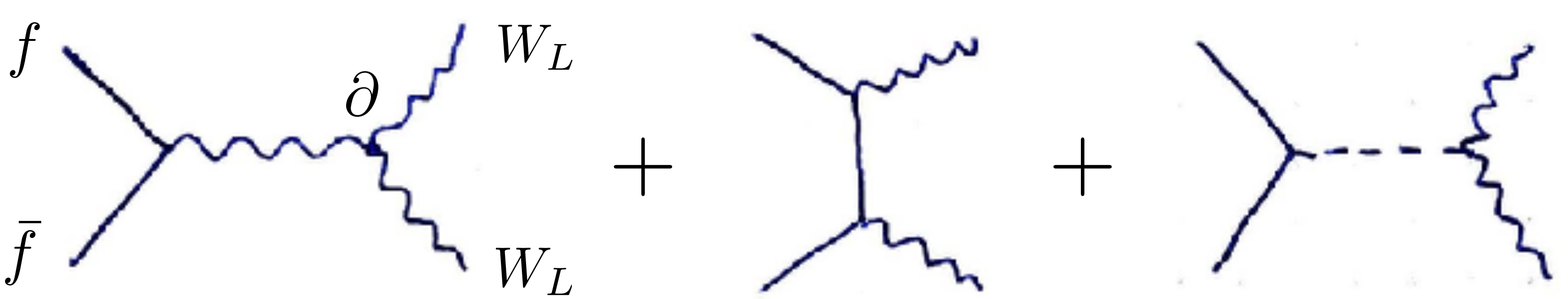
$$S^\dagger S = \mathbb{1} \longmapsto |a_\ell(s)| \leq 1$$

- This places a non-trivial constrains among couplings because the Matrix element naively grows as the energy increases.

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

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

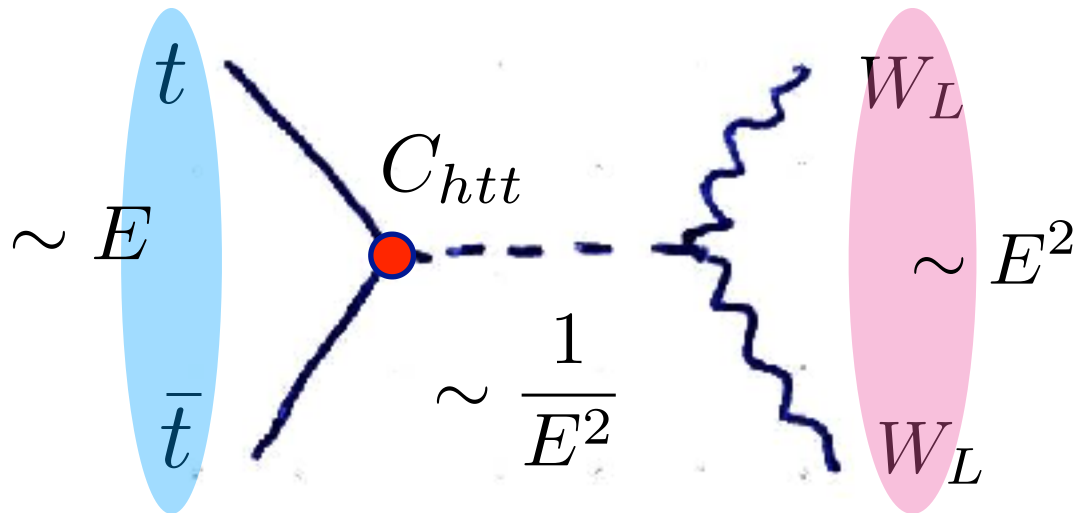
high energy behaviour must be regulated



$\sim E^2$ $\sim E^2$ $\sim E$

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

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



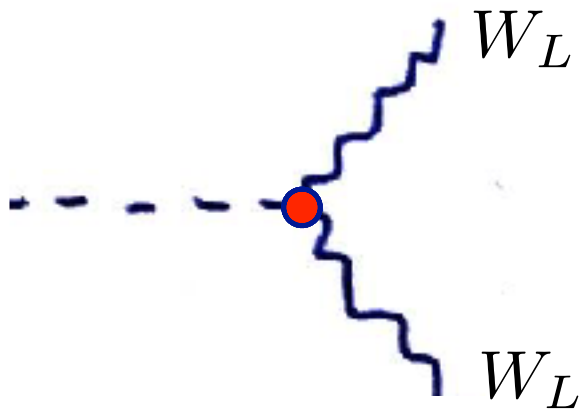
$\Rightarrow \sim C_{htt}\sqrt{s}$

$$|a_\ell(s)| \le 1 \quad \Rightarrow \quad |C_{htt}| < 1.24 \;\; \text{for} \;\; \Lambda = 5\,\text{TeV}$$

$$\Lambda = \sqrt{s}$$

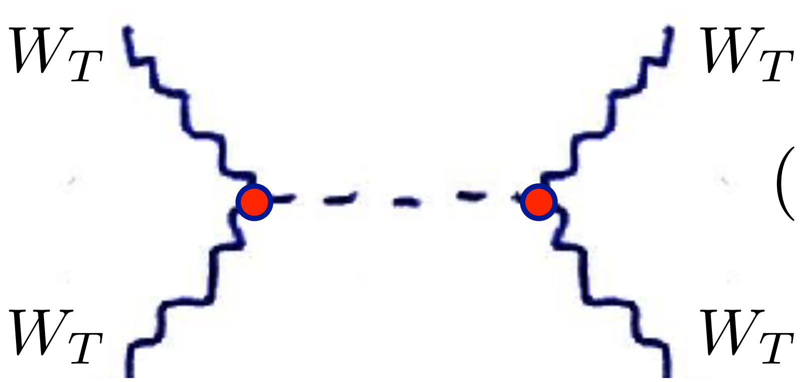
$$\mathcal{O}_{hF\tilde{F}} = hF_{\mu\nu}\tilde{F}^{\mu\nu}$$

Longitudinal contribution cancels



$$\sim \epsilon_{\mu\nu\rho\sigma} p_1^\mu p_2^\nu \epsilon_L^\rho(p_1)\epsilon_L^\rho(p_2) = 0 \qquad (\text{up to } \mathcal{O}(m_W/E))$$

Most stringent constraint arises from transverse scattering



$$(+t+u) \quad = \frac{4|C_{hWW}|^2}{v^2}\frac{s(s-m_W^2)}{s-m_h^2} \sim |C_{hWW}|^2 s$$

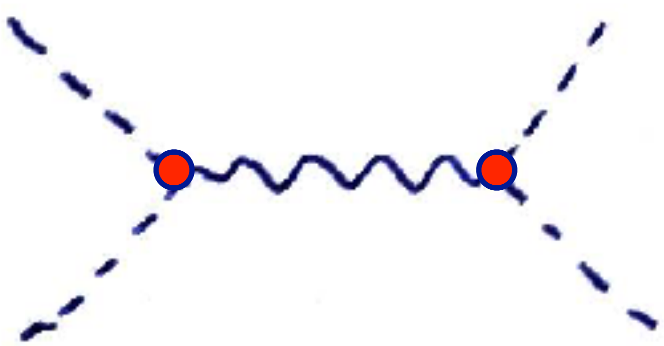
$$|a_\ell(s)| \leq 1 \quad \Rightarrow \quad |C_{hWW}| \leq 0.26 \quad \text{for } \underset{\sqrt{s}}{\underset{\parallel}{\Lambda}} = 5\,\text{TeV}$$

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

- does not contribute to the high energy behaviour for:

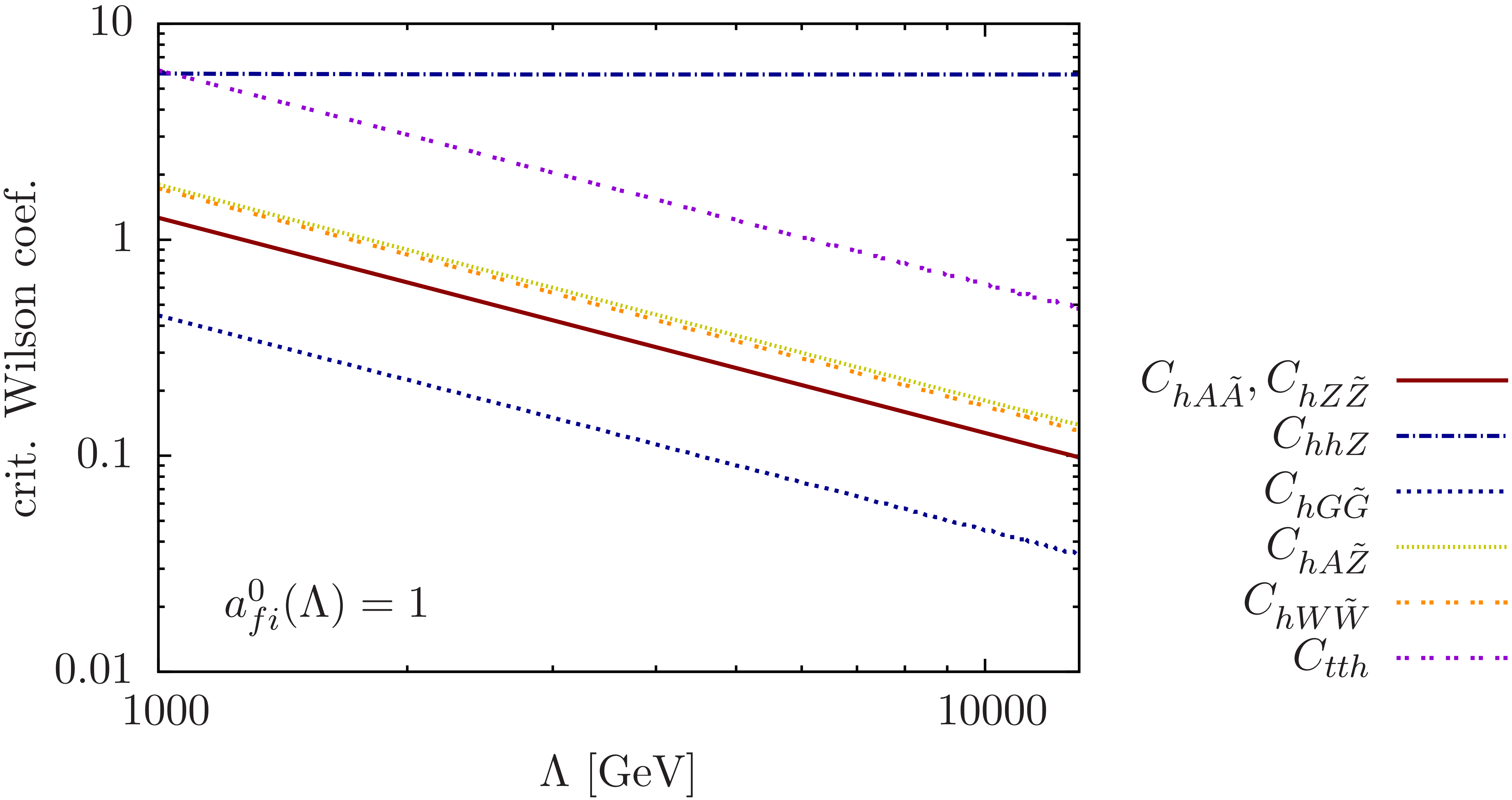
$$tt \to hh, \;\; hh \to VV, \;\; hh \to hV, \;\; VV \to hV$$

- most sensitive process is $hh \to hh$

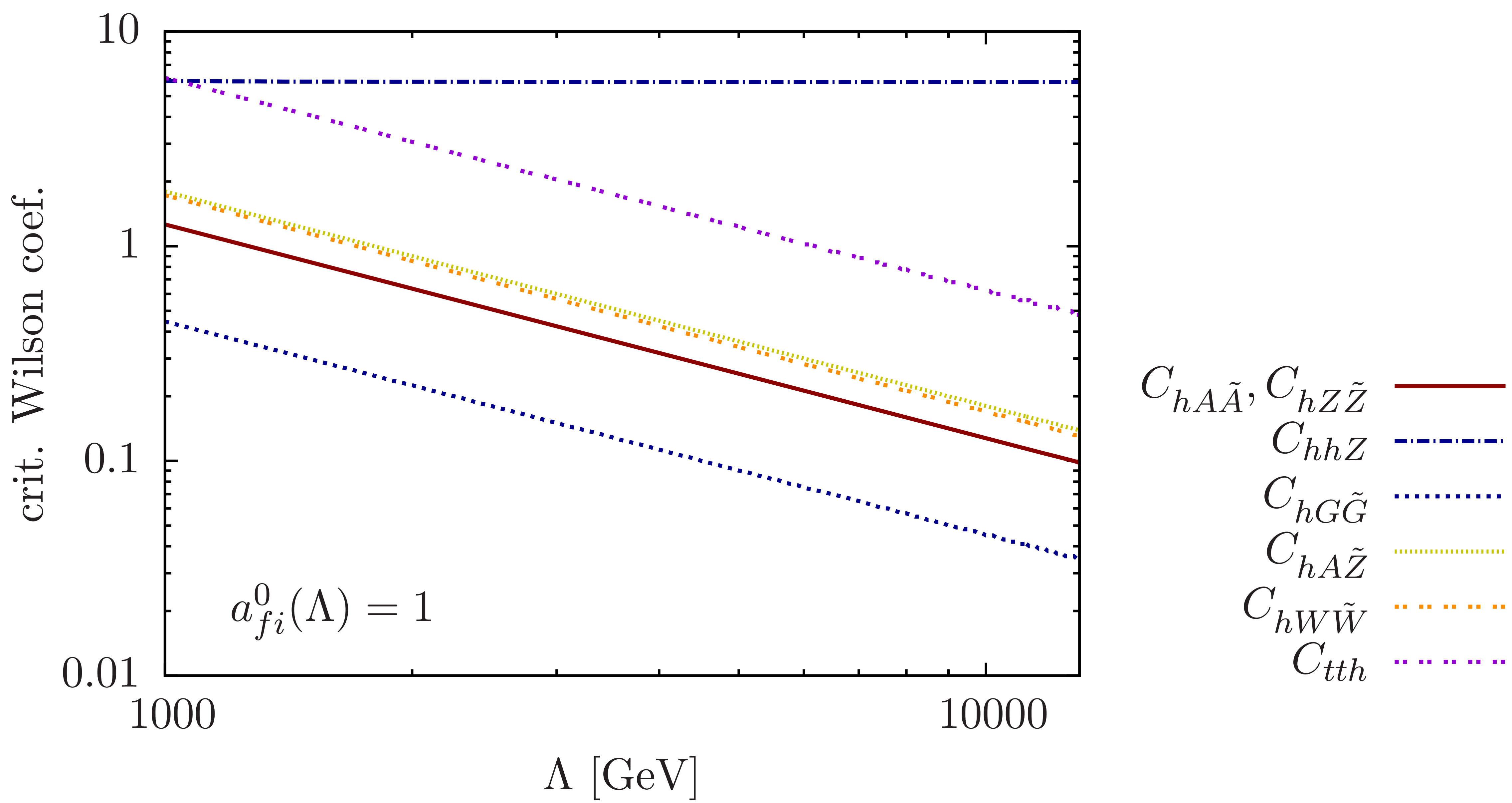


$$(+t+u) \qquad \sim |C_{hhZ}|^2$$

$$|a_\ell(s)| \leq 1 \quad \Rightarrow \quad |C_{hhZ}| \leq 5.82 \quad \text{for any } \Lambda = \sqrt{s}$$



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



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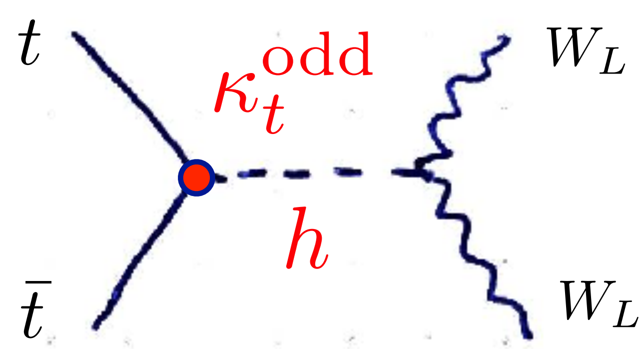
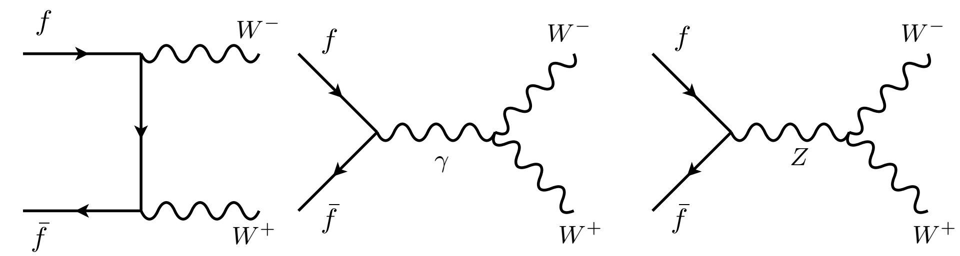
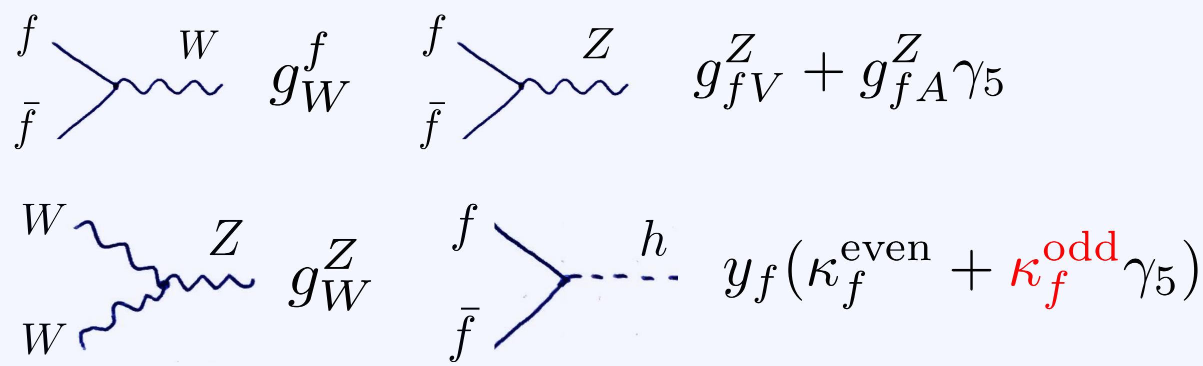






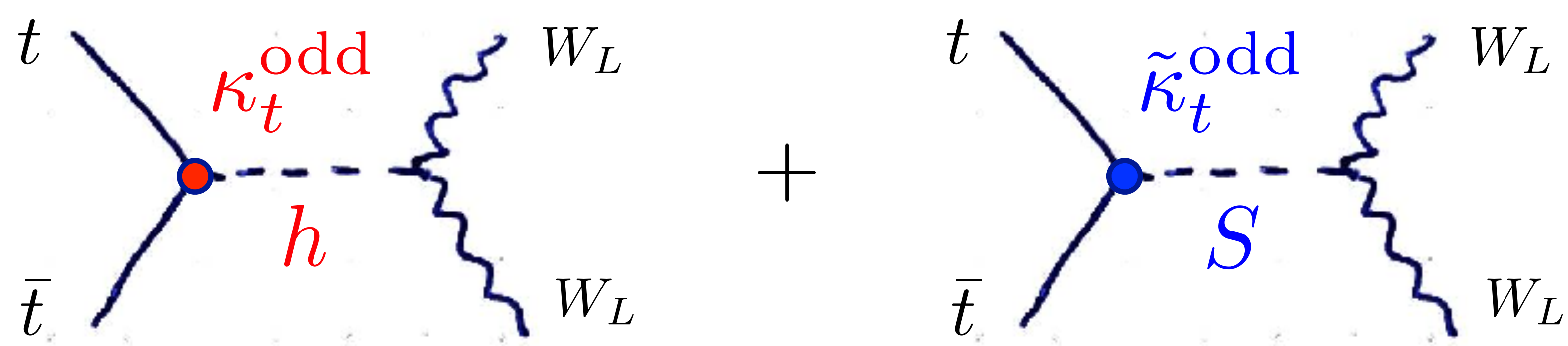
$$C_{tth} = \kappa_t^{\mathrm{odd}} / y_t$$

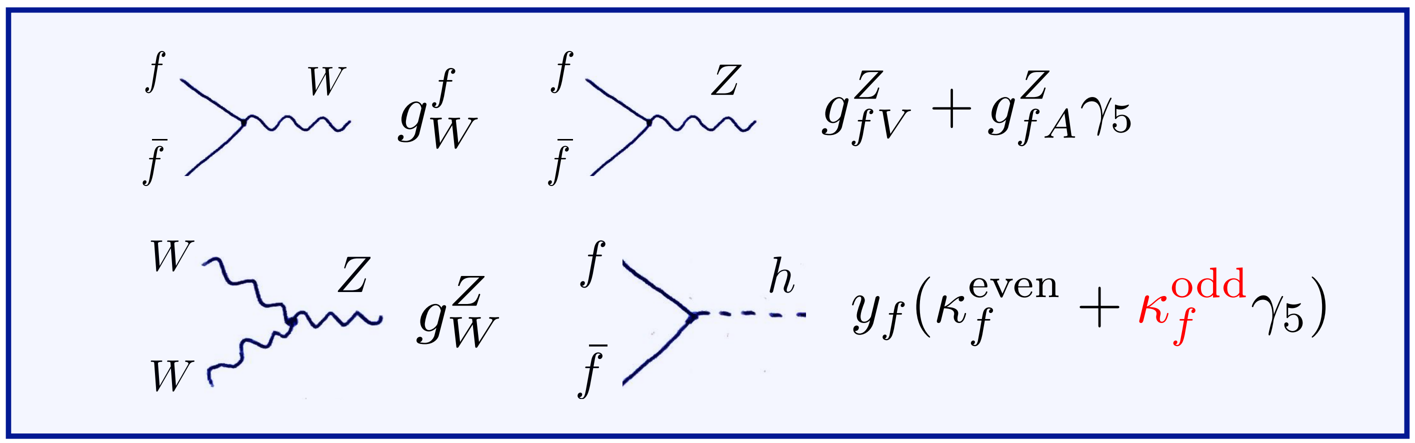
$$\mathcal{M}(tt \to W_L W_L) \overset{E \gg m_t}{=} \frac{g_W^h}{2m_W^2} \underbrace{\bar{v}(p_2)\gamma_5 u(p_1)}_{\sim E} \underbrace{\left[(g_W^f)^2 + 2 g_W^Z g_{fA}^Z + i\,(g_W^h \kappa_t^{\mathrm{odd}})\right]}_{\text{must vanish (sum rule)}}$$

$\sim E$

must vanish (sum rule)

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





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

$$\mathcal{M}(tt \to W_L W_L) \overset{E \gtrsim m_t}{=} \frac{g_W^h}{2m_W^2}\underbrace{\bar{v}(p_2)\gamma_5 u(p_1)}_{\sim E}\Big[\underbrace{(g_W^f)^2 + 2g_W^Z g_{fA}^Z + i\big(g_W^h \kappa_t^{\rm odd} + g_W^S \tilde{\kappa}_t^{\rm odd}\big)}_{\text{must vanish (sum rule)}}\Big]$$

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

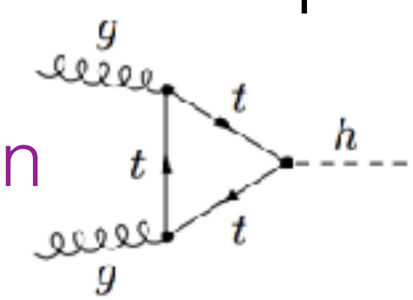
- The modification of tth coupling is constrained by the Higgs measurements.

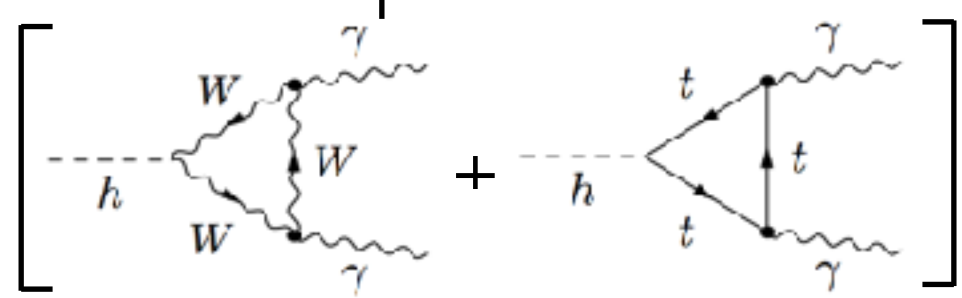
$$\mathcal{L}_t = -\frac{m_t}{v}(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t)H \qquad \text{SM: } (\kappa_t, \tilde{\kappa}_t) = (1,0)$$

CPV ($\uparrow$ $\tilde{\kappa}_t$)

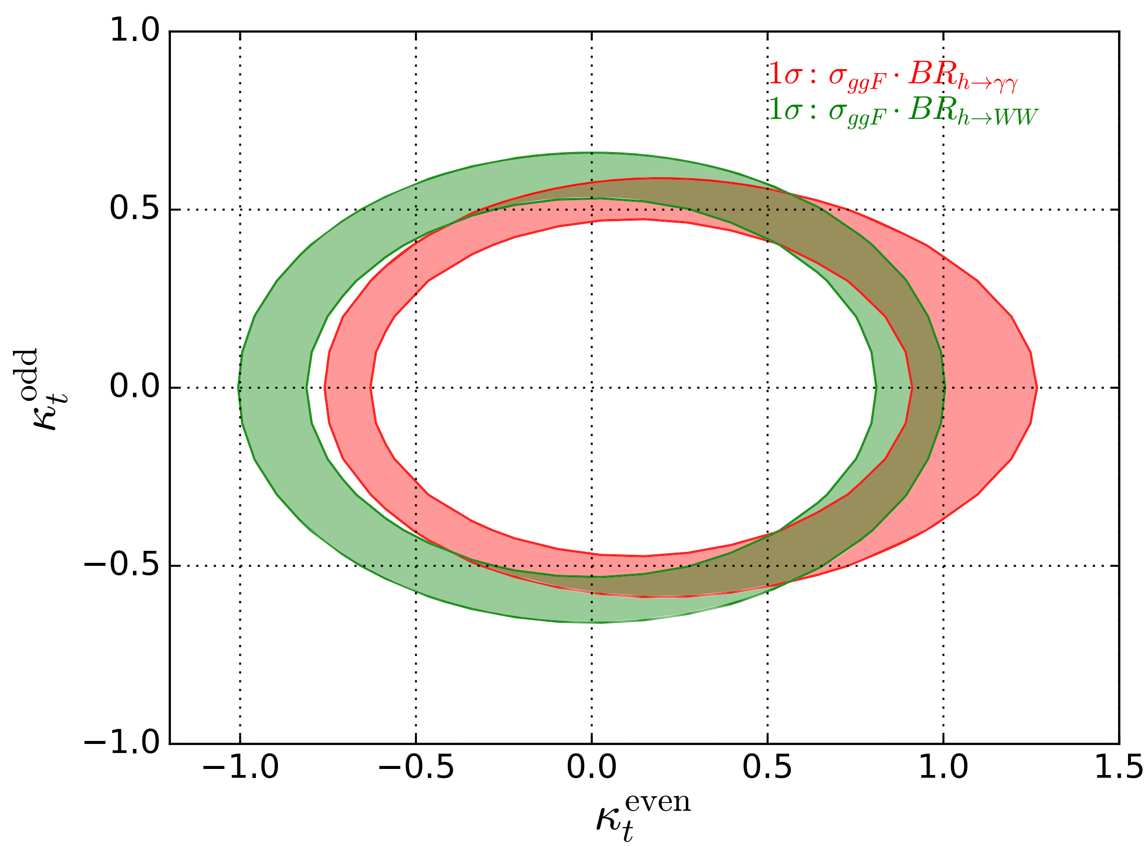
$$\mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi} c_g b_g G^a_{\mu\nu} G^{\mu\nu a} + \frac{\alpha_{em}}{8\pi} c_\gamma b_\gamma F_{\mu\nu} F^{\mu\nu}\right]\left(\frac{H}{v}\right) \qquad \text{SM: } (c_g, c_\gamma) = (1,1)$$

Production



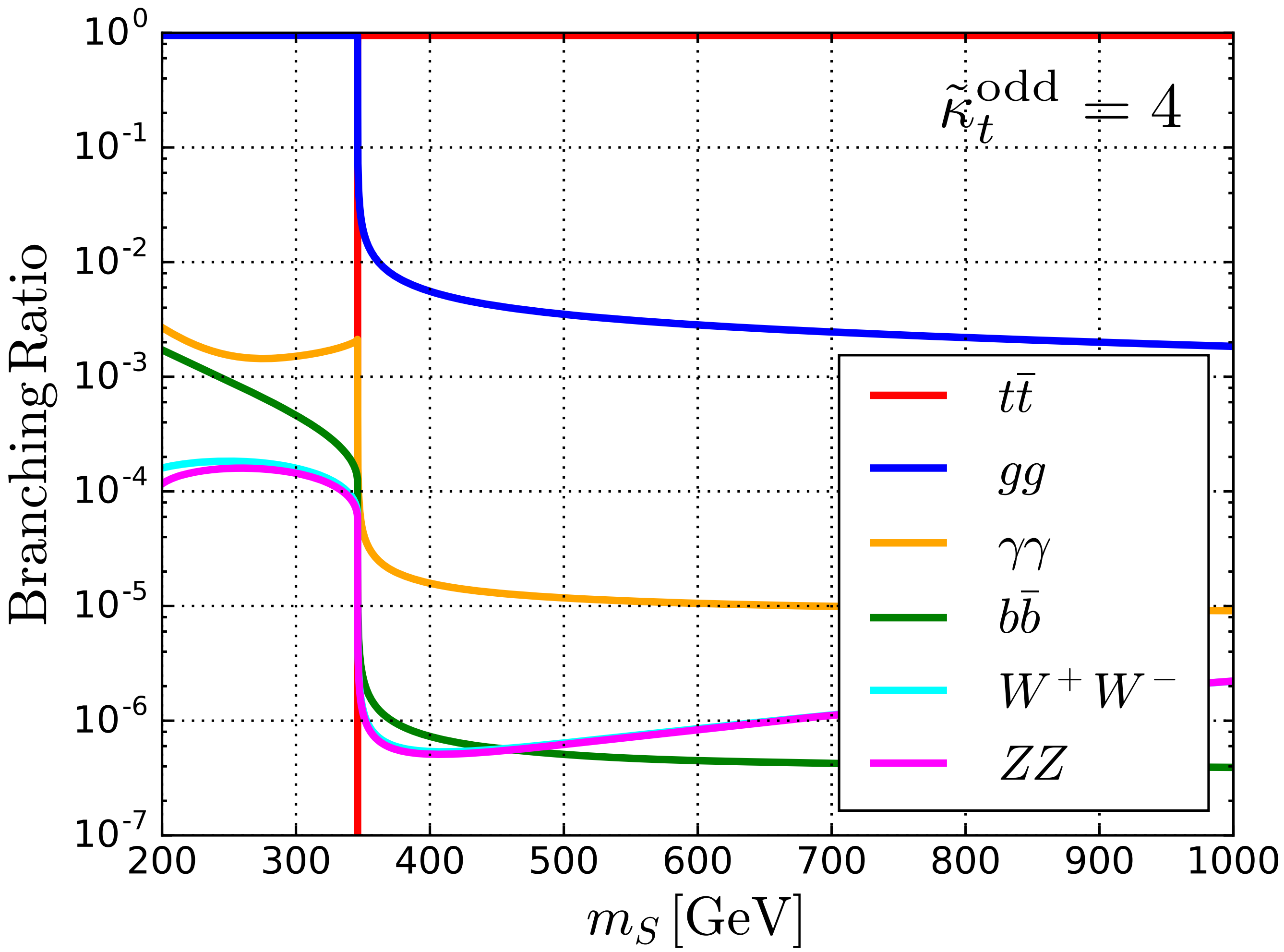


Decay



$$|\kappa_t^{\text{odd}}| < 0.5$$

Properties of S: Decay



unitarity sum-rule:

$$g_W^S \tilde{\kappa}_t^{\rm odd} = -g_W^h \kappa_t^{\rm odd}$$

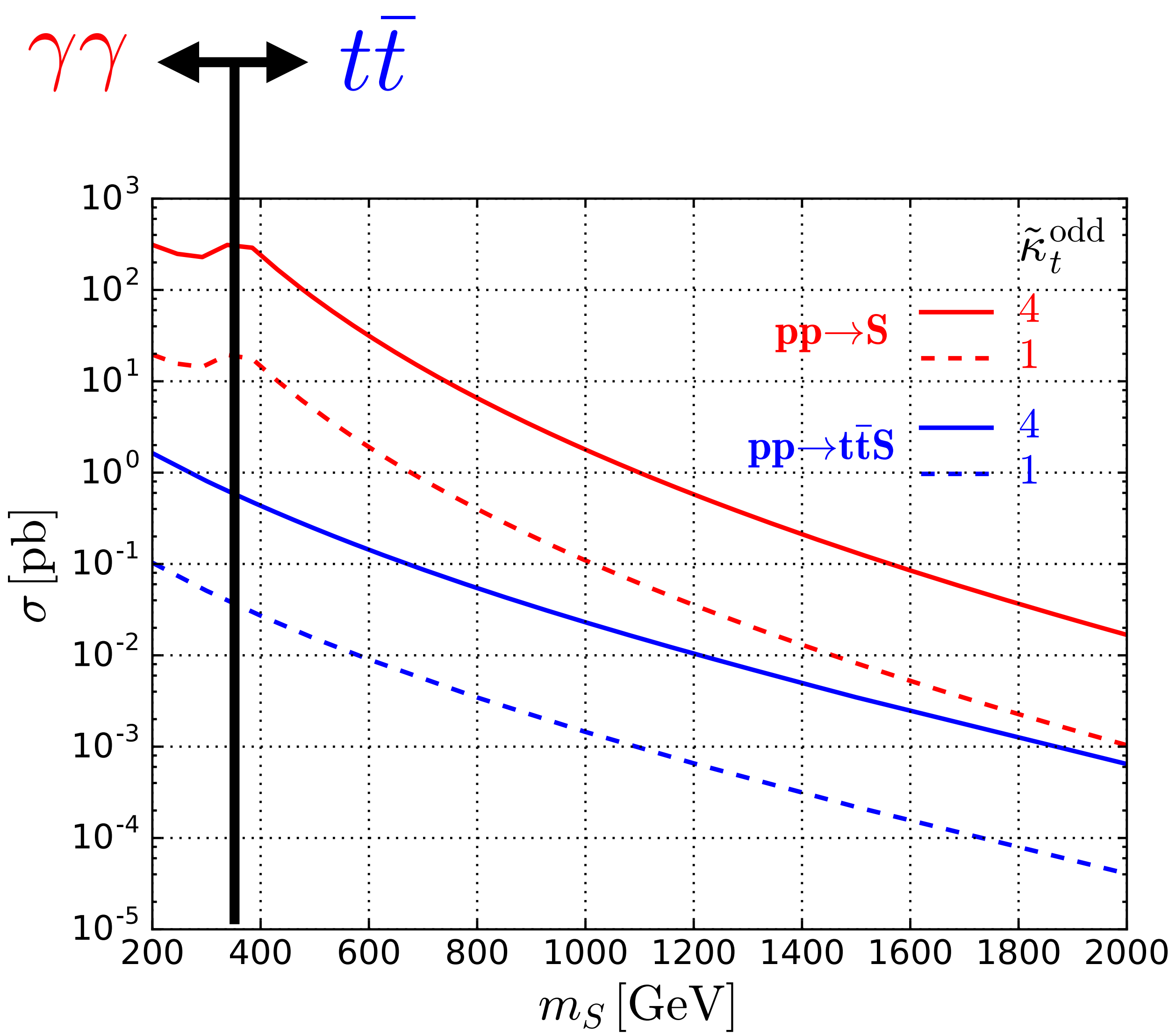
Higgs measurement:

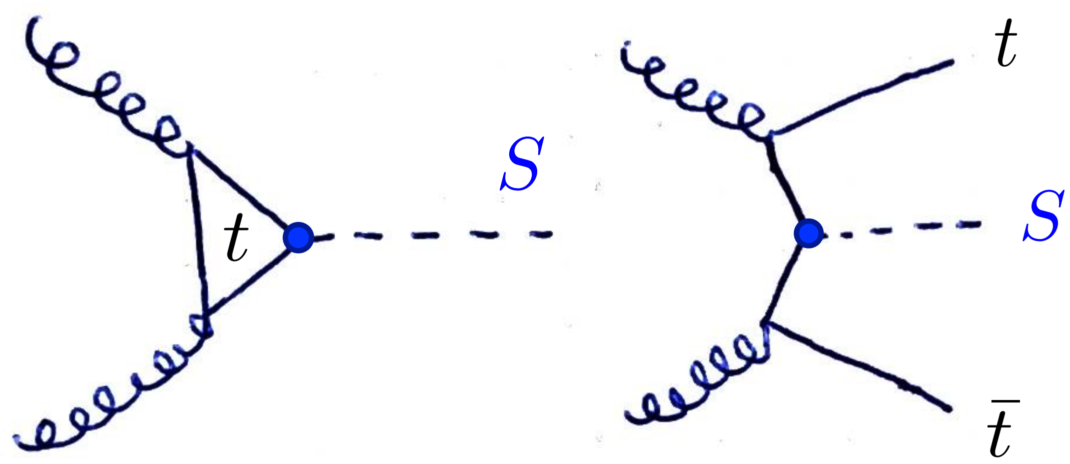
$$|\kappa_t^{\rm odd}| < 0.5$$

$$S \to gg \ (\sim 100\%), \ \gamma\gamma \ (\text{a few permille}) \qquad \cdots \qquad m_S < 345\,\text{GeV}$$

$$S \to t\bar{t} \ (\sim 100\%), \ gg \ (\text{permille level}) \qquad \cdots \qquad m_S \geq 345\,\text{GeV}$$

Properties of S: Production





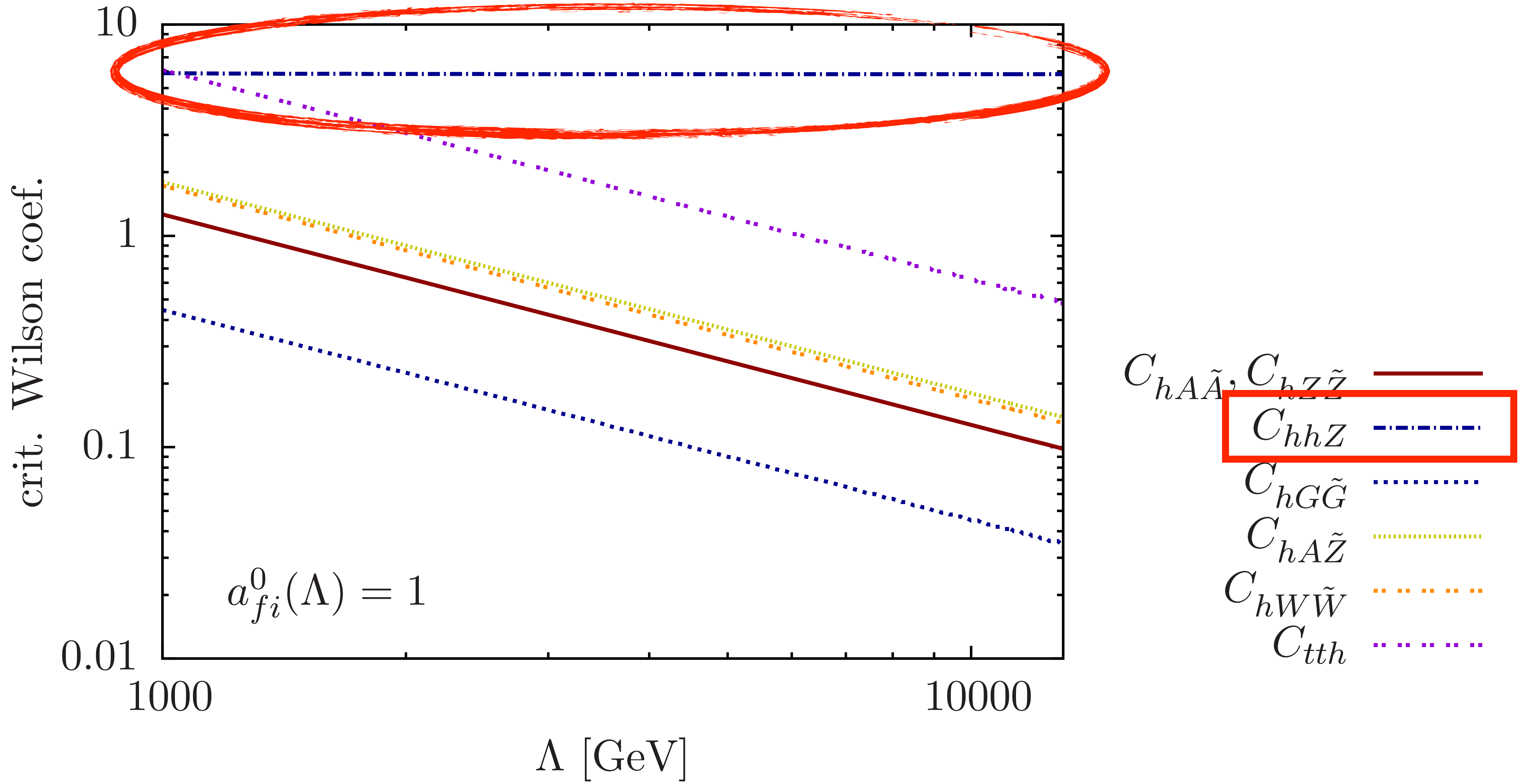
- CMS diphoton [1609.02507]

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

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

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

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



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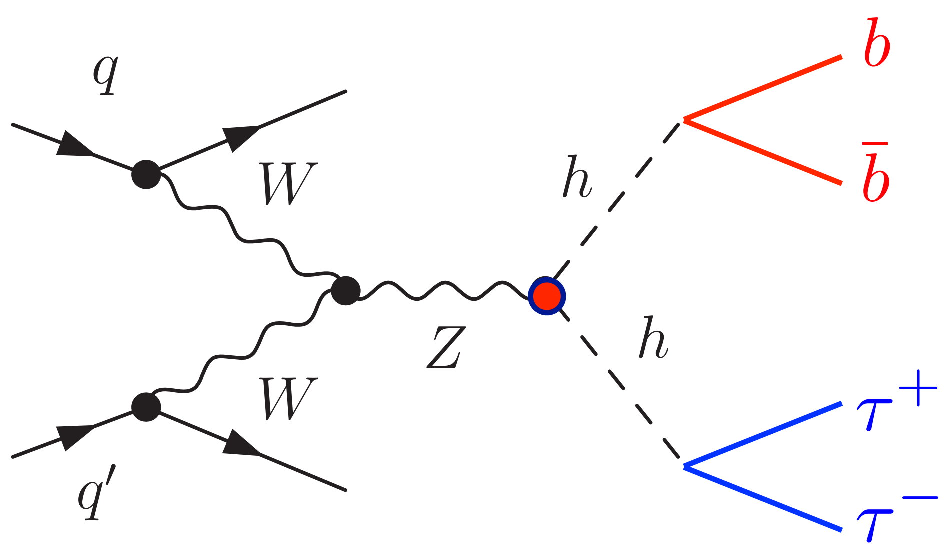
$$\mathcal{O}_{hhZ} = h(\partial_\mu h)Z^\mu$$

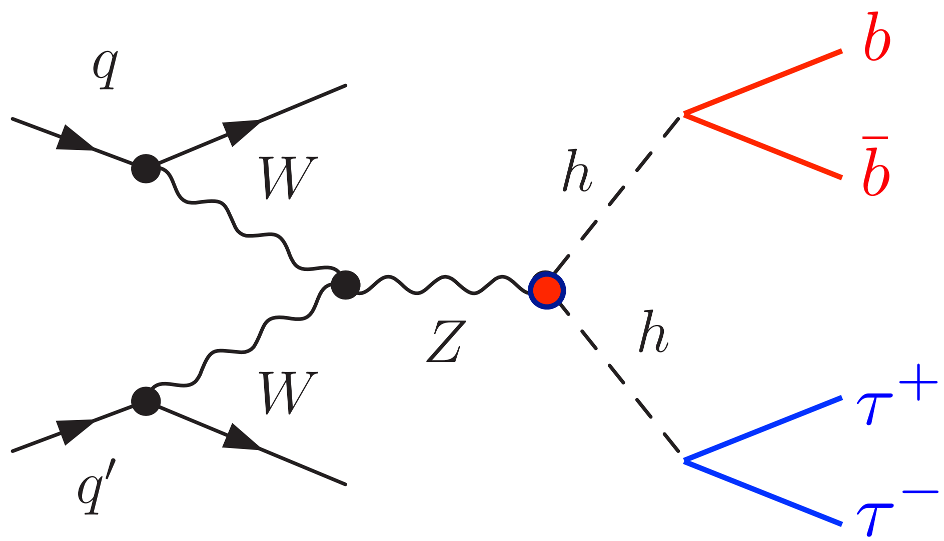


Event selection (bbττ channel)

- 2 taus with p_T > 29, 20GeV, $|\eta|<2.5$ (ε_τ=70%)
- 2 jets (not *b* nor τ) with p_T > 25GeV, $|\eta|<4.5$
- $\Delta\eta(j_1, j_2) > 5$
- 2 hardest jets to be *b*-tagged and $|\eta|<2.5$ (ε_b=70%)
- $|m_{bb} - m_h|<15$GeV, $|m_{\tau\tau} - m_h|<25$GeV, $m_{hh}>400$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	$1/12.60$

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

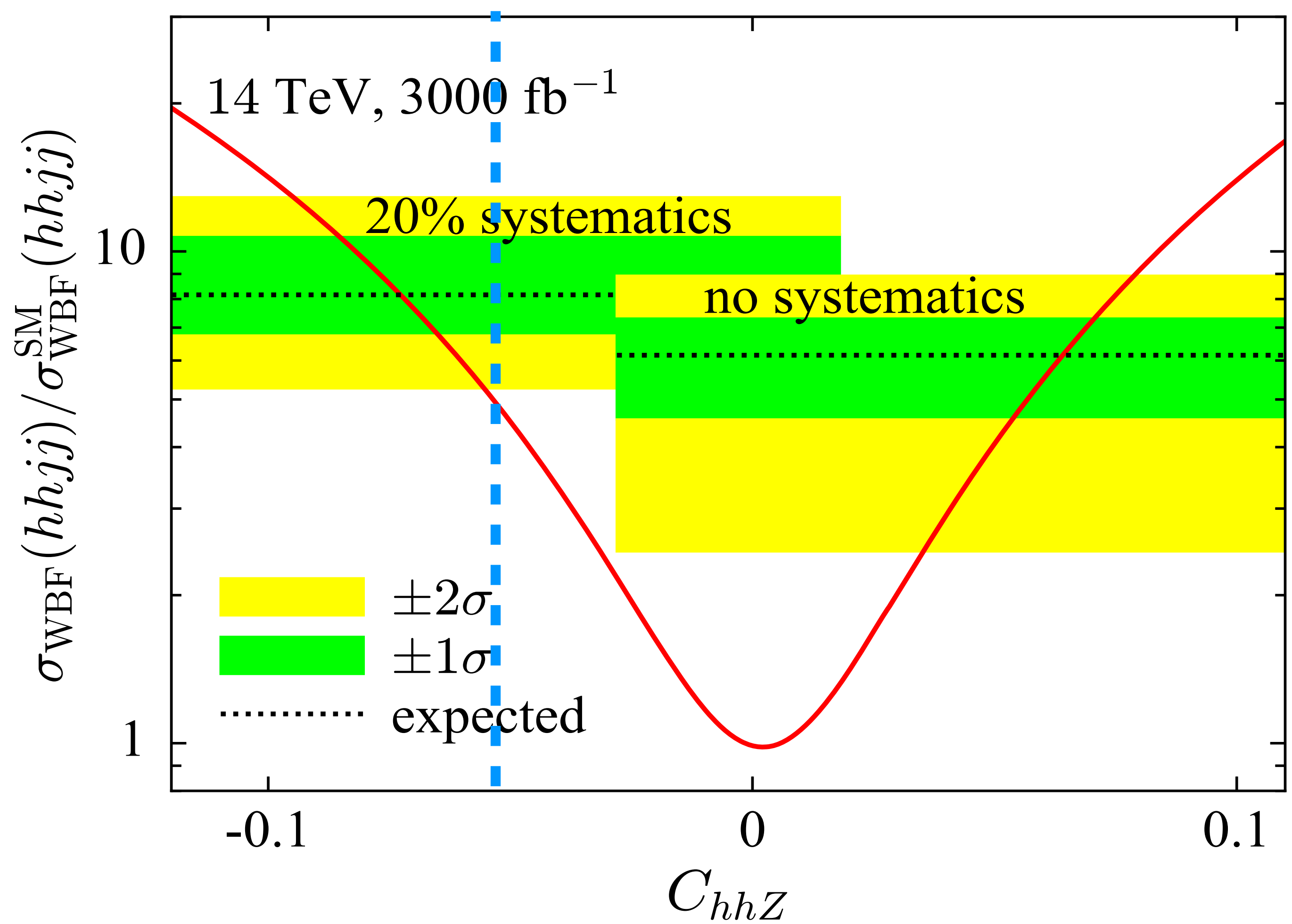


Event selection (bbττ channel)

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

projected sensitivity @ HL-LHC 3ab^{-1}

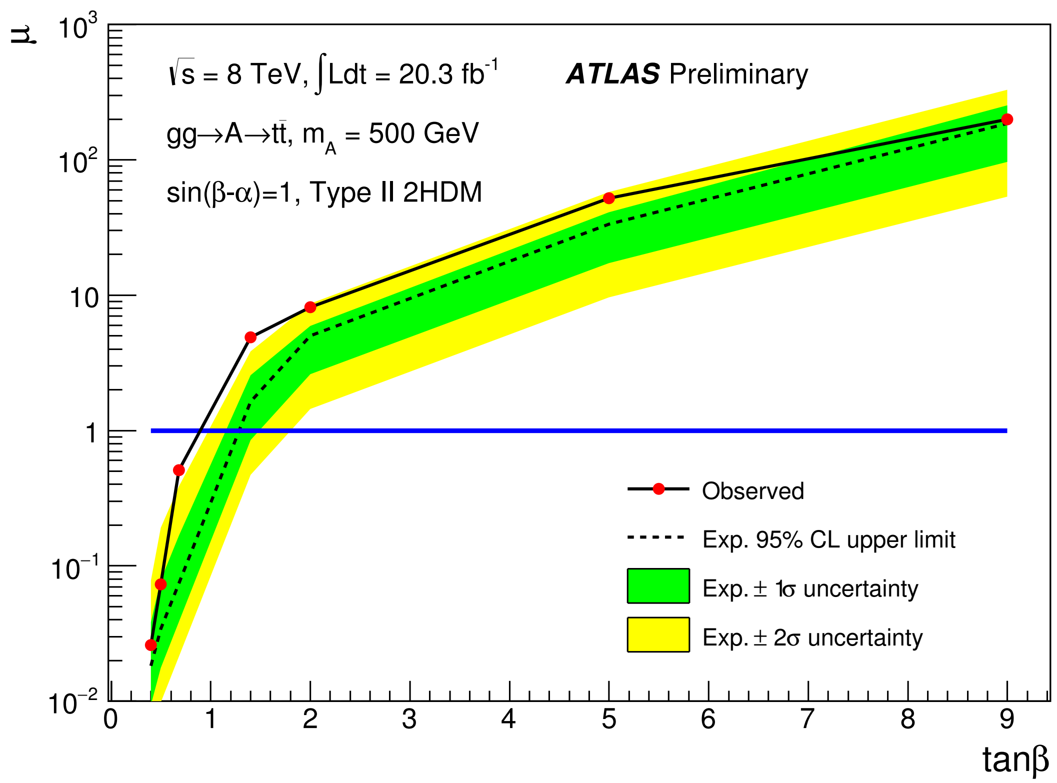
$$|C_{hhZ}| \lesssim 0.06$$

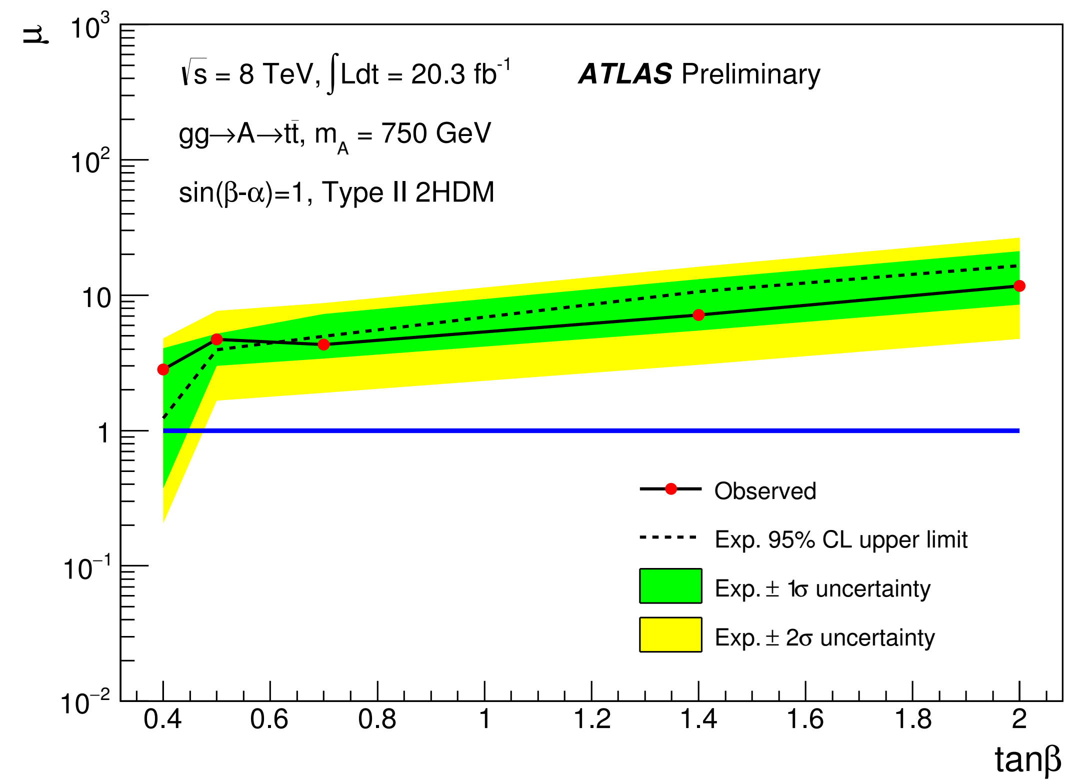


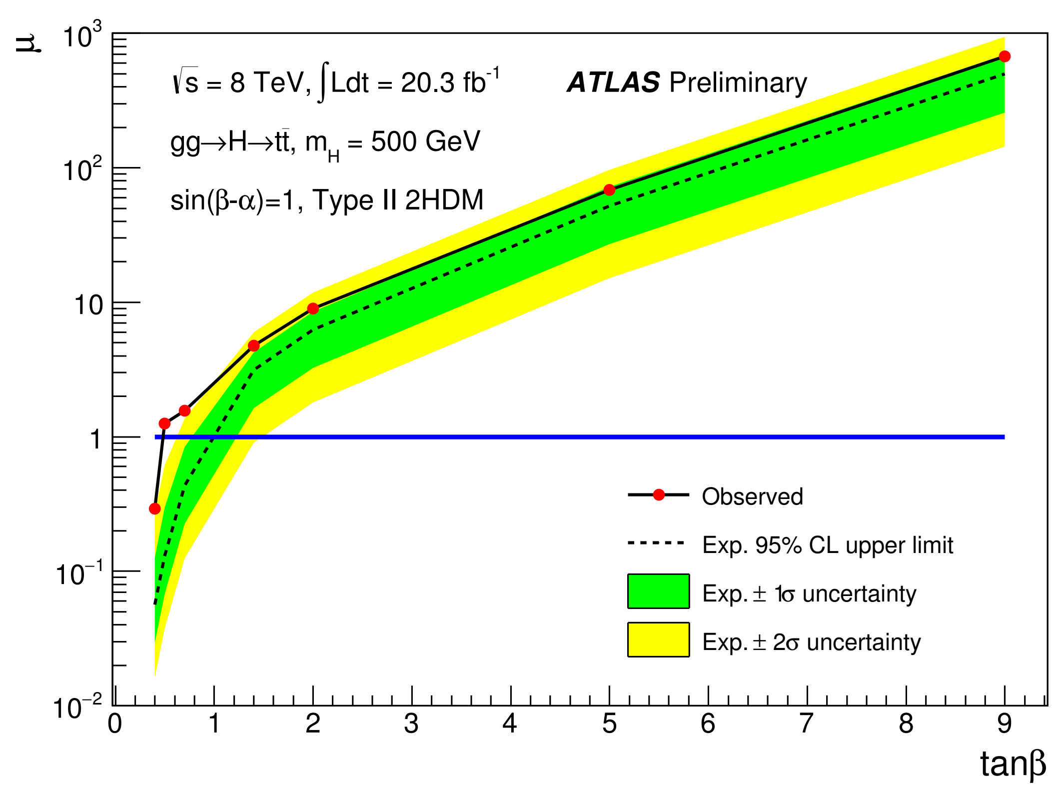
Conclusion

- 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.
- new CPV operators require additional degrees of freedom (new particle) to unitarise S-matrix, and give us information to look for those new particles.
- hhZ operator does not spoil the high energy behaviour of scattering processes, but we can constrain them by looking at WBF double Higgs production.

ATLAS-CONF-2016-073







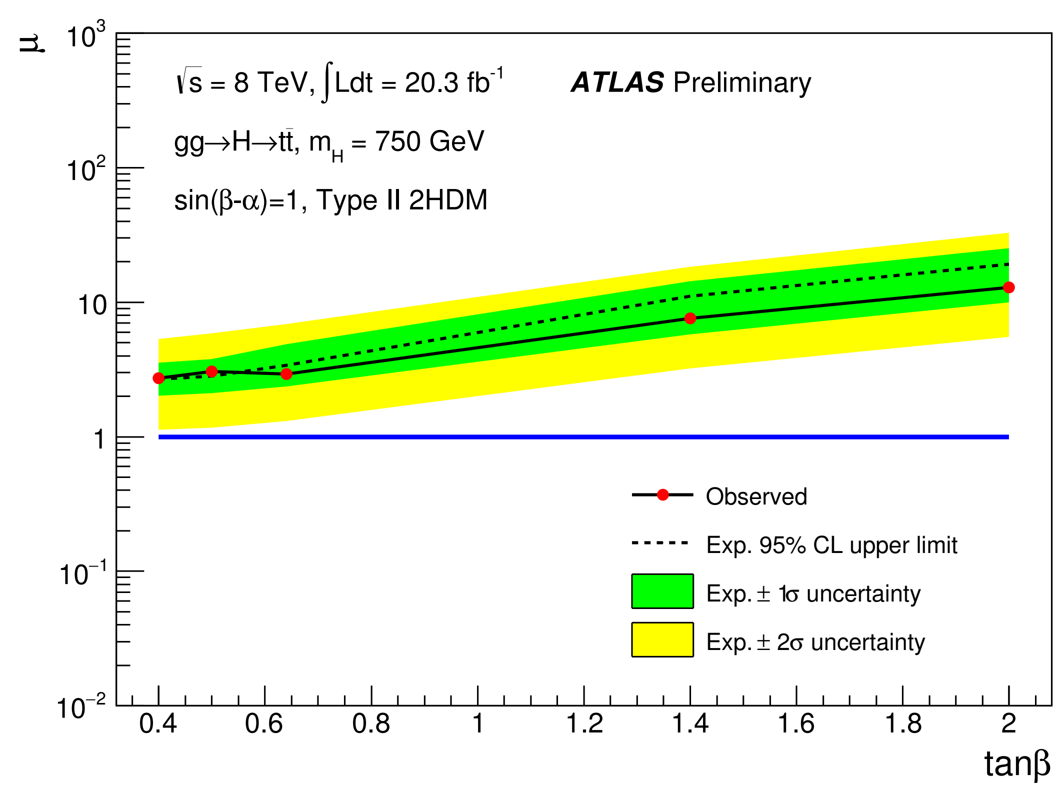
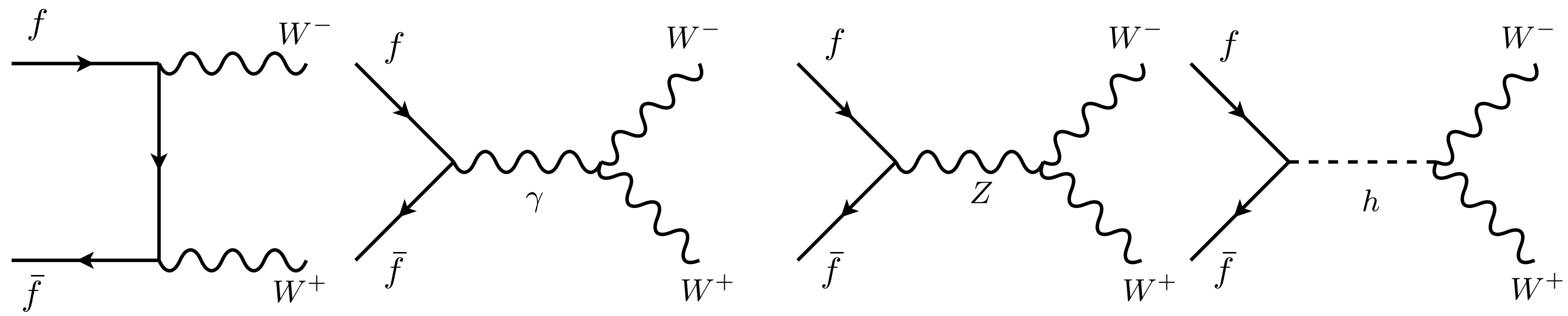
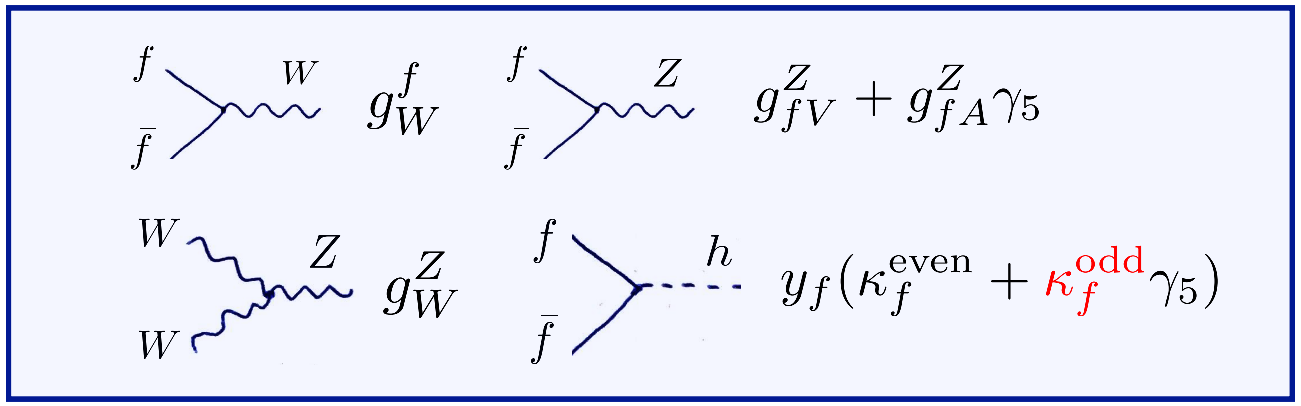


TABLE II. Feynman rules relevant for $f\bar{f} \to W^+W^-$, $P_{L,R}$ denote the right- and left-chirality projectors.

Vertex	Feynman rule	SM
$W^-_\alpha(p)W^+_\beta(k)A_\mu(q)$	$-g^\gamma_W\Gamma_{\alpha,\beta,\mu}(p,k,q)$	$g^\gamma_W = gs_W$
$W^-_\alpha(p)W^+_\beta(k)Z_\mu(q)$	$g^Z_W\Gamma_{\alpha,\beta,\mu}(p,k,q)$	$g^Z_W = gc_W$
$f\bar{f}W^\pm_\mu$	$g^f_W\gamma_\mu P_L$	$g^f_W = g/2$
$f\bar{f}A_\mu$	$-g^f_\gamma\gamma_\mu$	$g^f_\gamma = gs_W Q_f$
$f\bar{f}Z_\mu$	$\gamma_\mu(g^Z_{fL}P_L + g^Z_{fR}P_R)$	$g^Z_{fR} = (g/c_W)(T^f_3 - Q_f s^2_W)$
		$g^Z_{fL} = -(g/c_W)Q_f s^2_W$
		$g^Z_{fV} = (g^Z_{fL} + g^Z_{fL})/2$
		$g^Z_{fA} = (g^Z_{fL} - g^Z_{fL})/2$
$hf\bar{f}$	$-(g^f_h + ig^f_A\gamma_5)$	$g^f_h = gm_f/(2m_W)$
		$g^f_A = 0$
$hW^+_\mu W^-_\nu$	$g^W_h g_{\mu\nu}$	$g^W_h = gm_W$
$hZ_\mu Z_\nu$	$g^Z_h g_{\mu\nu}$	$g^Z_h = (g^2 + g'^2)^{1/2}m_Z$





$$
\begin{aligned}
\mathcal{M}_f^t &= -\frac{(g_W^f)^2}{m_W^2}\bar{v}(p_2)\Big(\not{q}_1 P_L + \frac{m_f}{2}(1-\gamma_5)\Big)u(p_1) + \mathcal{O}(\epsilon) \\
\mathcal{M}_\gamma^s &= \frac{g_W^\gamma g_\gamma^f}{m_W^2}\bar{v}(p_2)\not{q}_1 u(p_1) + \mathcal{O}(\epsilon) \\
\mathcal{M}_Z^s &= -\frac{g_W^Z}{m_W^2}\bar{v}(p_2)\Big(\not{q}_1 g_{fR}^Z + 2\not{q}_1 g_{fA}^Z P_L - m_f g_{fA}^Z\gamma_5\Big)u(p_1) + \mathcal{O}(\epsilon) \\
\mathcal{M}_h^s &= \frac{g_W^h}{2m_W^2}\bar{v}(p_2)\Big(g_h^f + i g_A^f\gamma_5\Big)u(p_1) + \mathcal{O}(\epsilon)\,,
\end{aligned}
$$

$$
\begin{aligned}
(g_W^f)^2 + 2g_W^Z g_{fA}^Z &= 0\colon\ \not{q}_1 P_L, \\
g_W^\gamma g_\gamma^f - g_W^Z g_{fR}^Z &= 0\colon\ \not{q}_1, \\
(g_W^f)^2 - g_W^h g_h^f/m_f &= 0\colon\ \mathbf{1}, \\
(g_W^f)^2 + 2g_W^Z g_{fA}^Z + i g_W^h g_A^f/m_f &= 0\colon\ \gamma_5.
\end{aligned}
$$