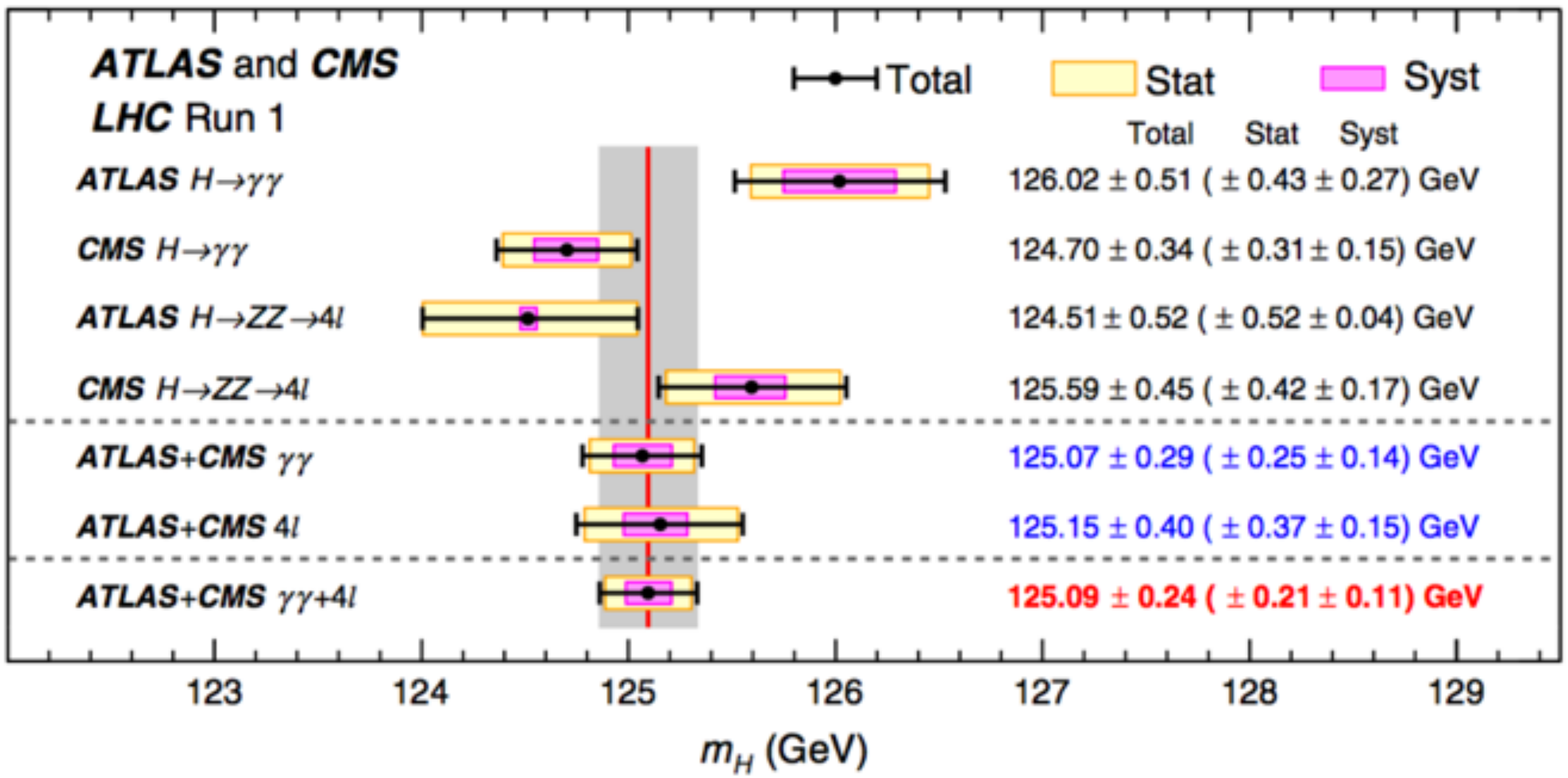
New physics searches in top yukawa sector

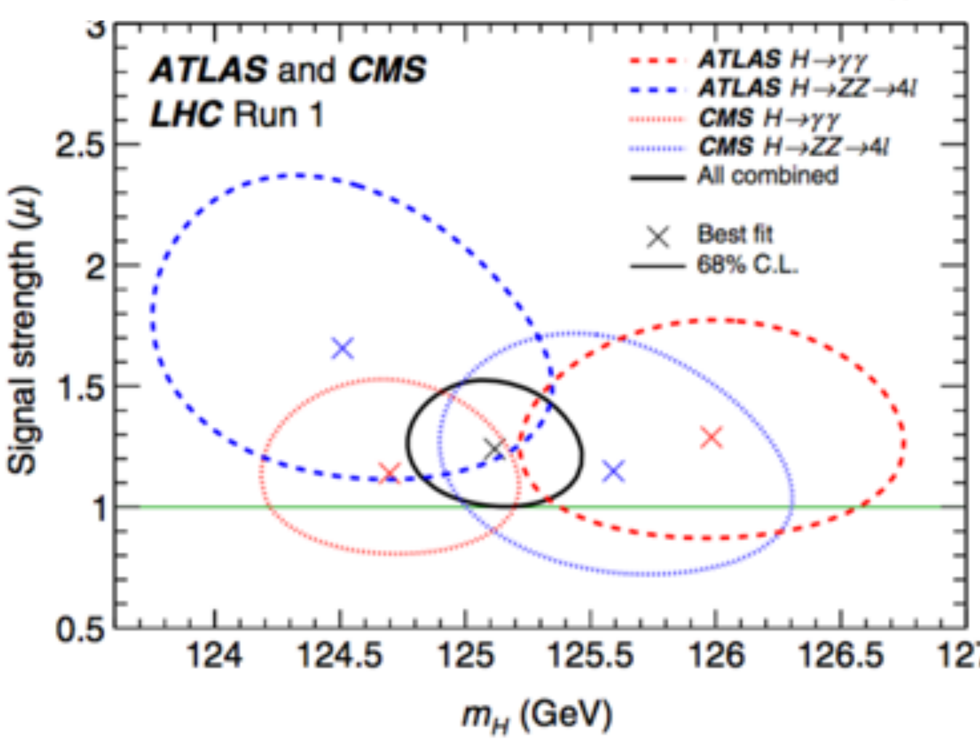
Michihisa Takeuchi (Kavli IPMU)

2016. 3. 14 at Nagoya

Higgs combined results from LHC run 1

PhysRevLett.114.191803

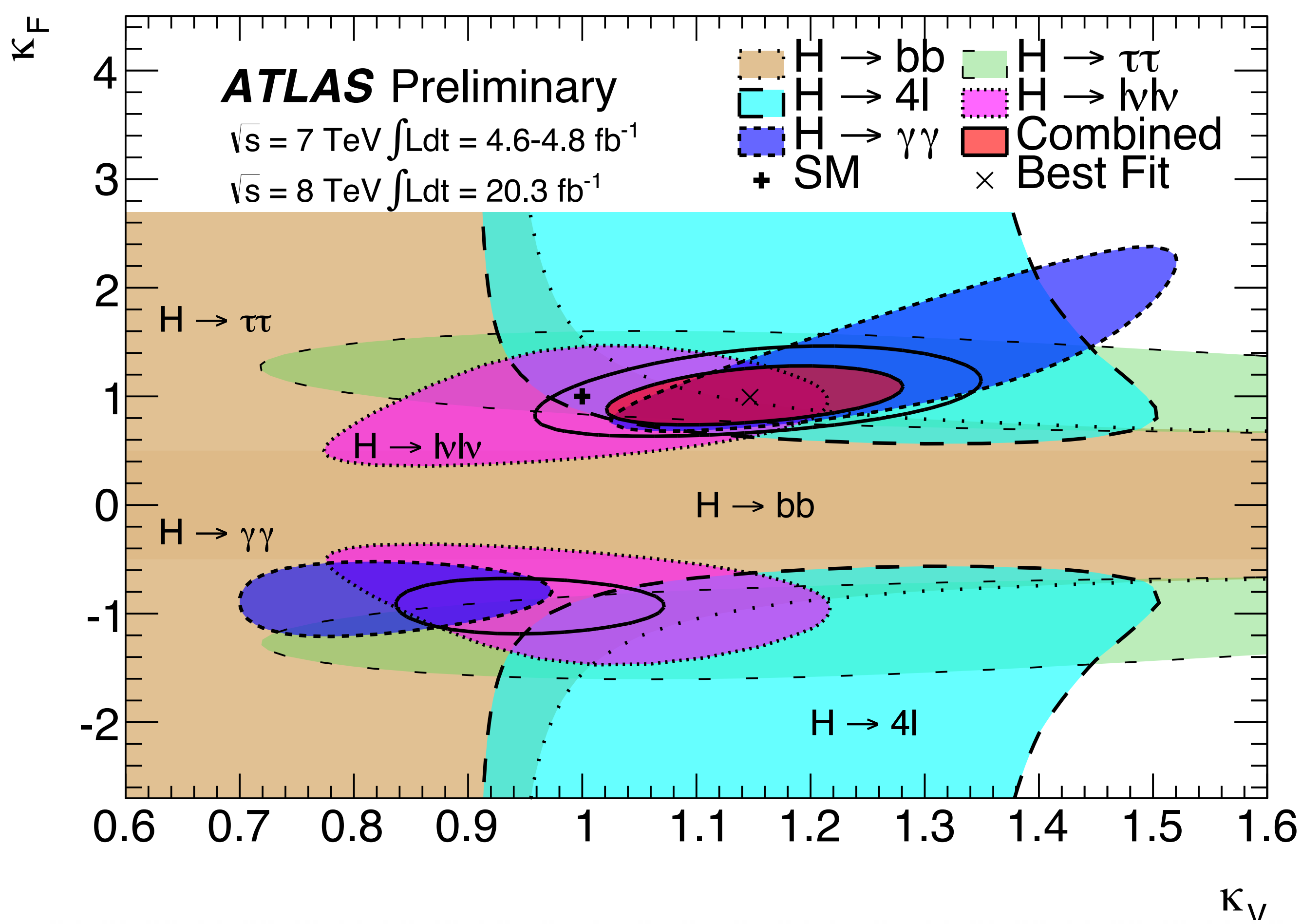




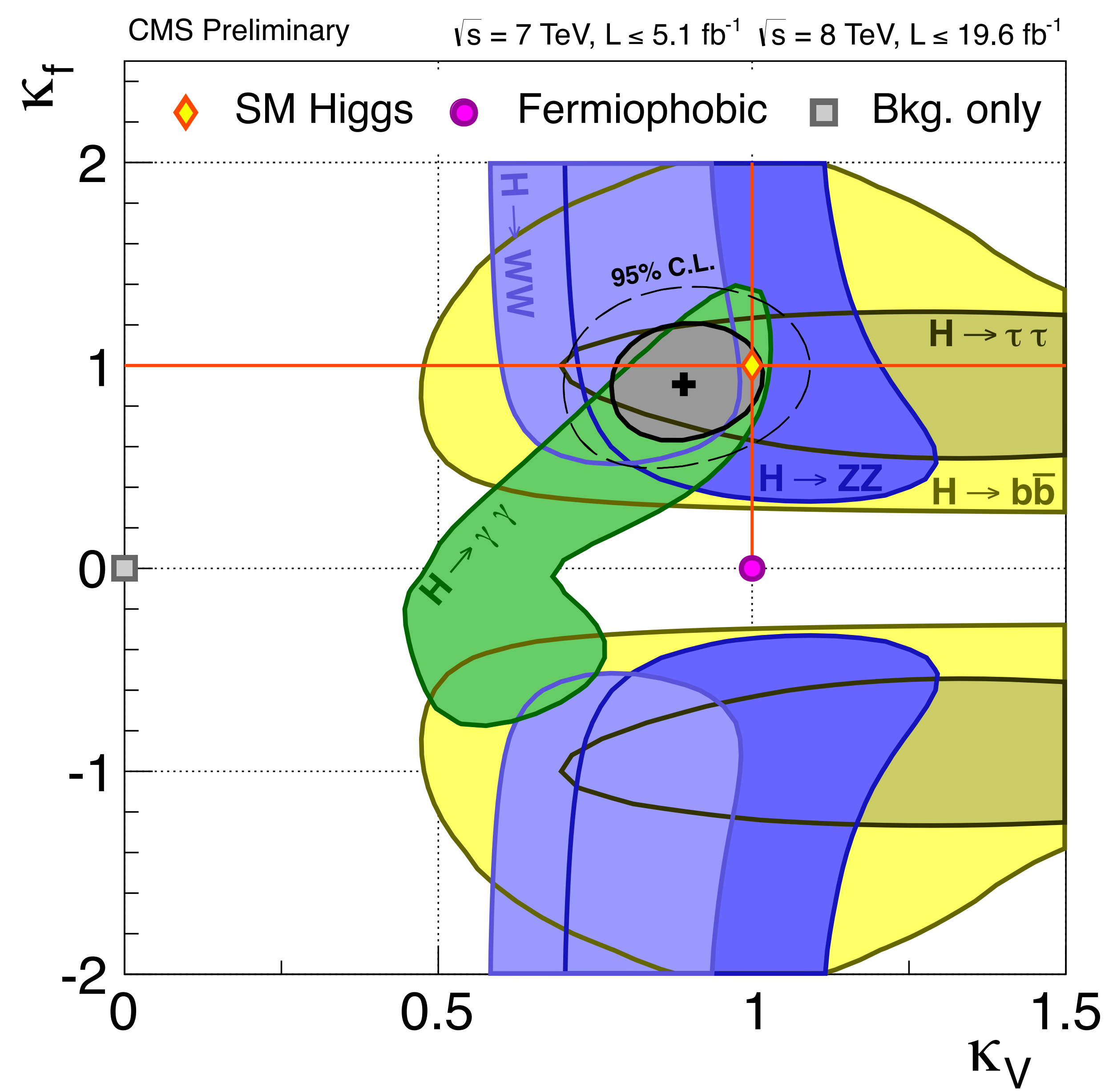
125 GeV with 0.2% error

Higgs coupling fit

ATLAS-CONF-2014-009



CMS-Hig-13-005



ATLAS: κ_V [1.05,1.22] at 68% CL - κ_F [0.76,1.18] at 68% CL

CMS: κ_V [0.74,1.06] at 95% CL - κ_F [0.61,1.33] at 95% CL

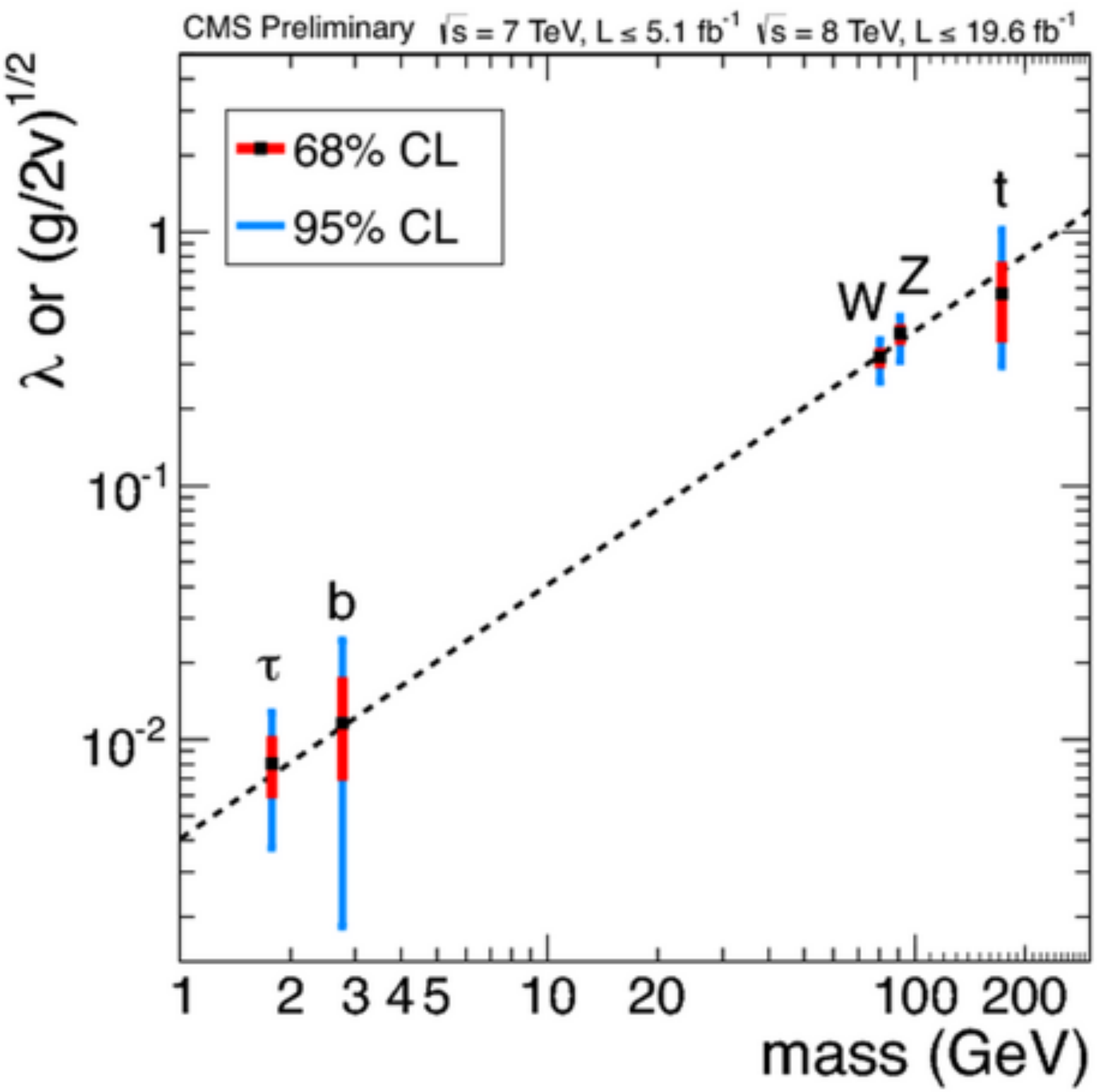
$$\text{production} : ggF, VBF, VH$$

$$\text{decay} : \gamma\gamma, ZZ, WW, bb, \tau\tau$$

$$\kappa_g, \kappa_\gamma, \kappa_Z, \kappa_W, \kappa_b, \kappa_\tau$$

SM compatible in 10-20%

ttH coupling and ggH coupling



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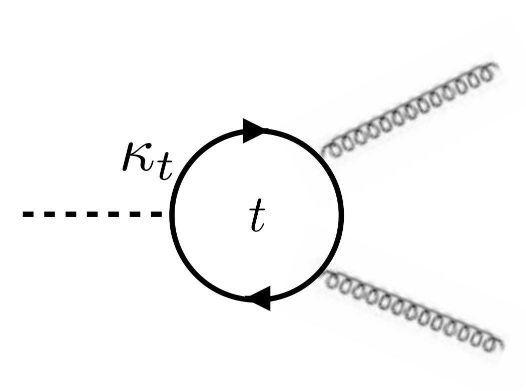
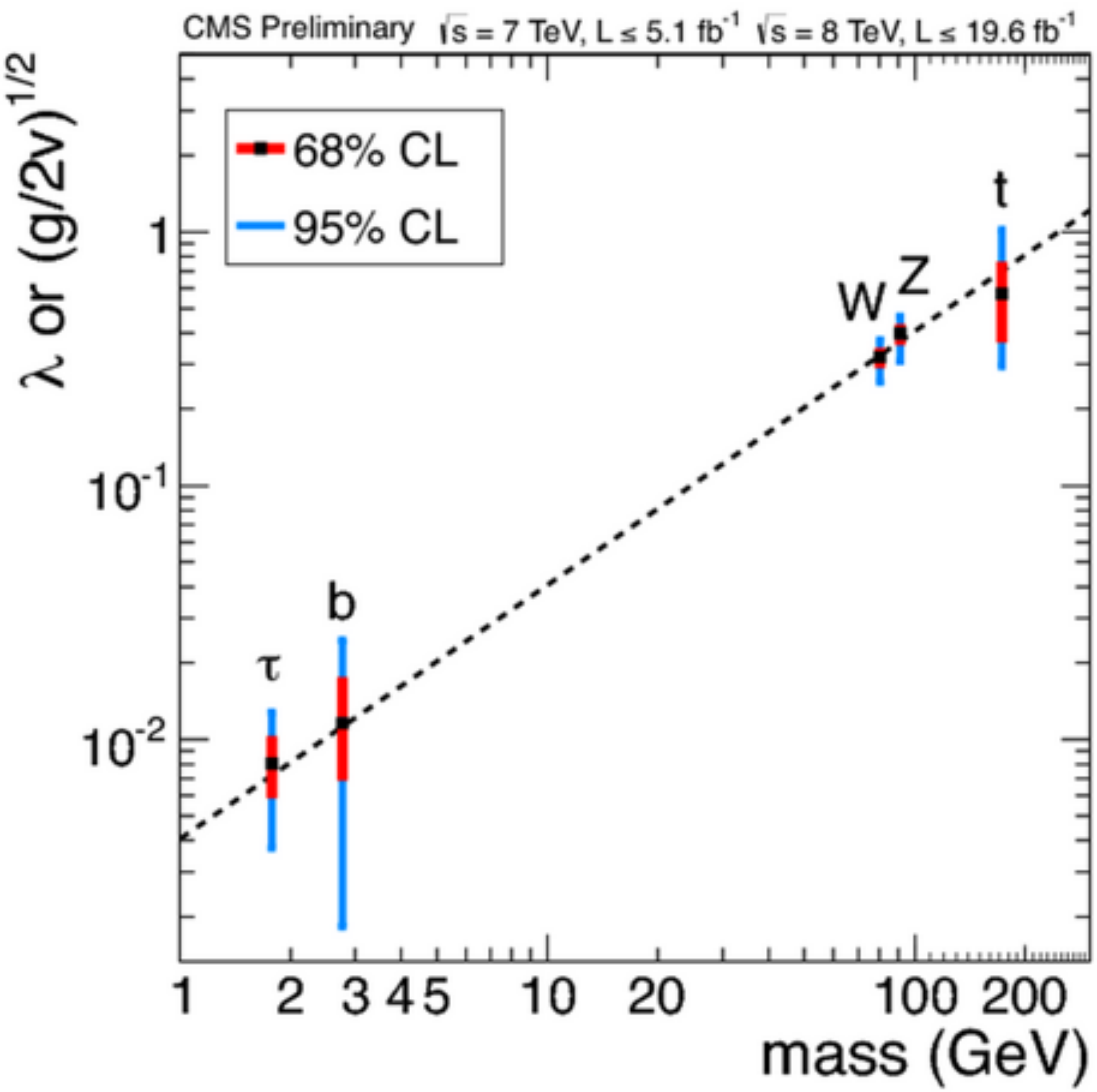
$\kappa_g = \kappa_t$ is often assumed

ttH is indirectly measured by ggH coupling



ttH coupling and ggH coupling



$$\text{production} : ggF, VBF, VH$$

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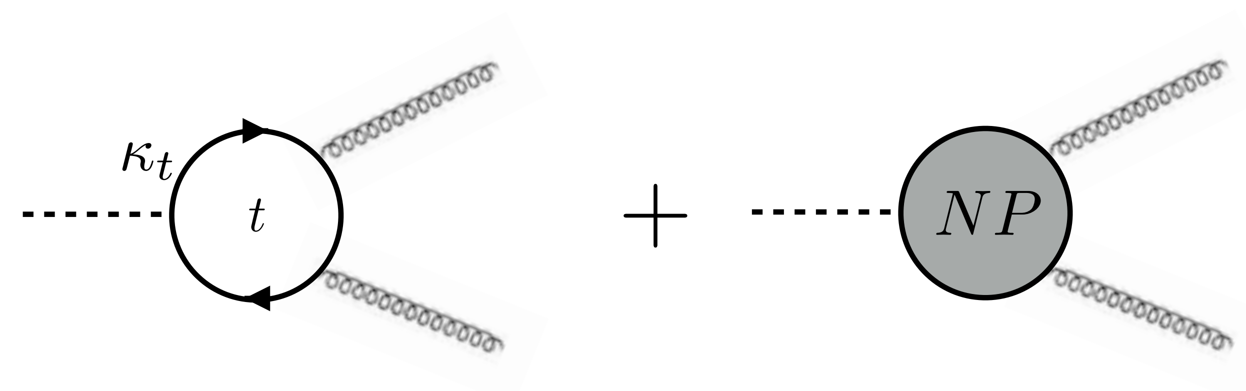
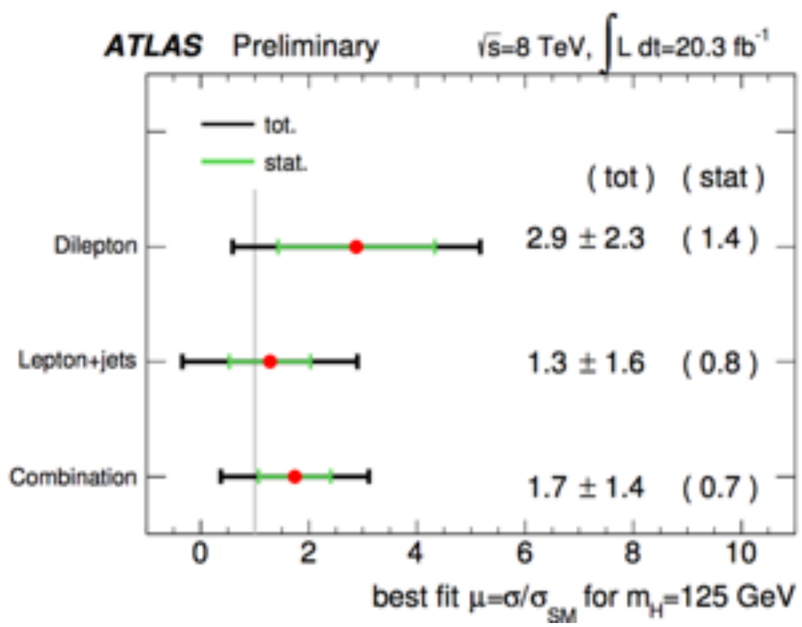


However, κ_g can include new particle effects $\kappa_g = \kappa_t + \kappa_g^{NP}$

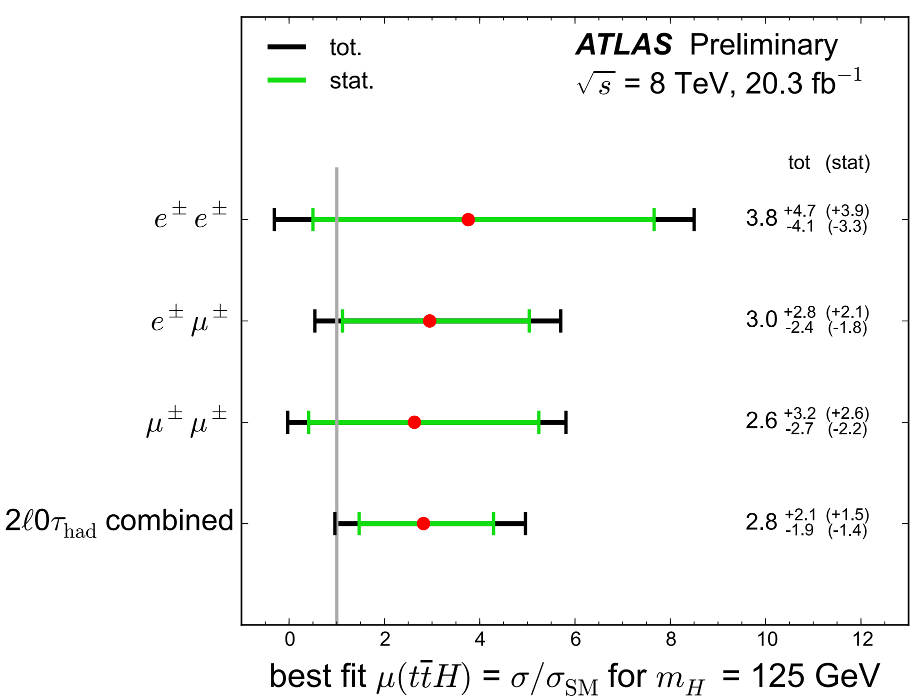
We want to measure κ_g and κ_t independently

ttH coupling direct measurement

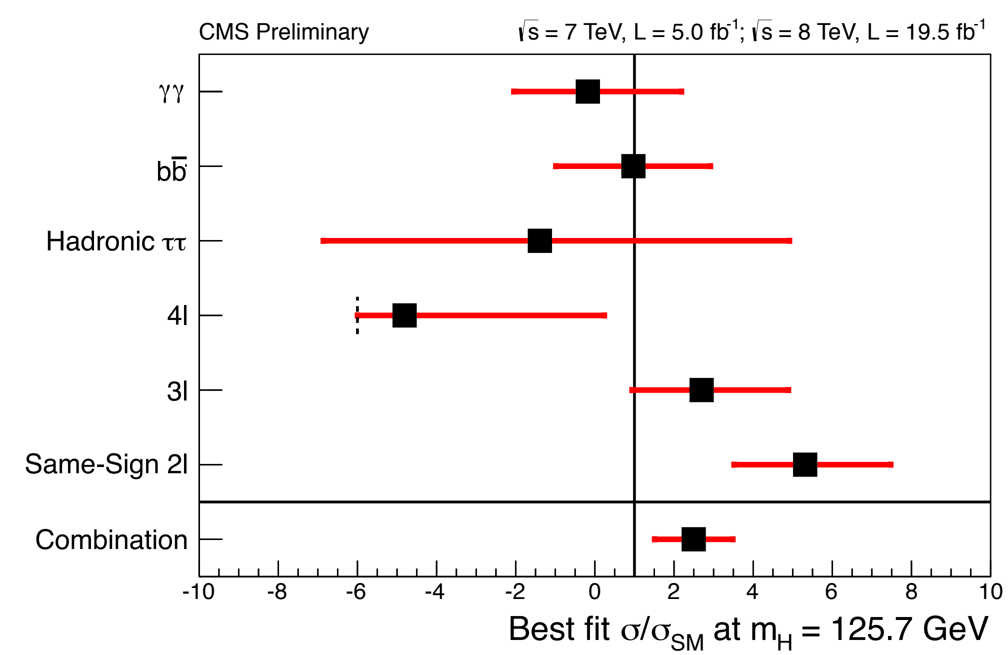


ATLAS-CONF-2014-011

ttH Channel	$\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)
$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$
$b\bar{b}$	$+1.0^{+1.9}_{-2.0}$
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$
4l	$-4.8^{+5.0}_{-1.2}$
3l	$+2.7^{+2.2}_{-1.8}$
Same-sign 2l	$+5.3^{+2.2}_{-1.8}$
Combined	$+2.5^{+1.1}_{-1.0}$

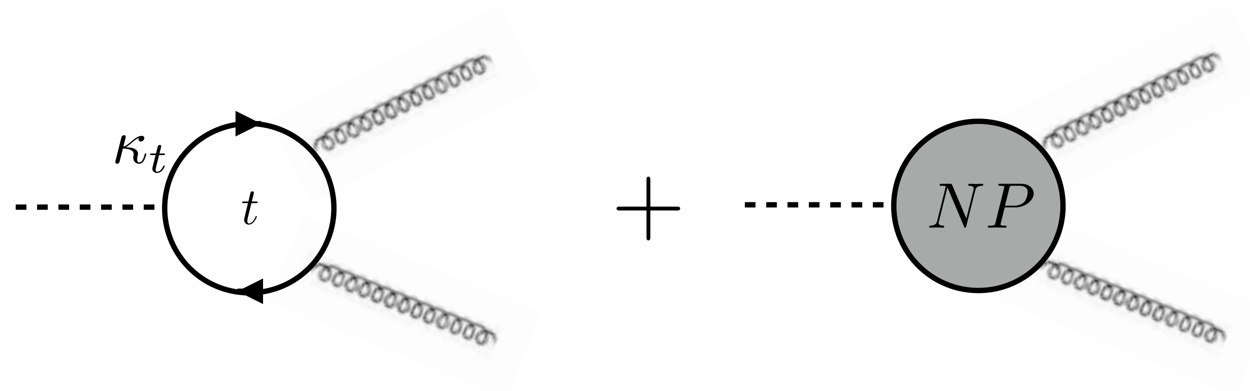


ATLAS-CONF-2015-006



ttH coupling directly starts constrained weakly non 0 at 1-2 sigma

HL-LHC: $\sim 10\%$ for all couplings



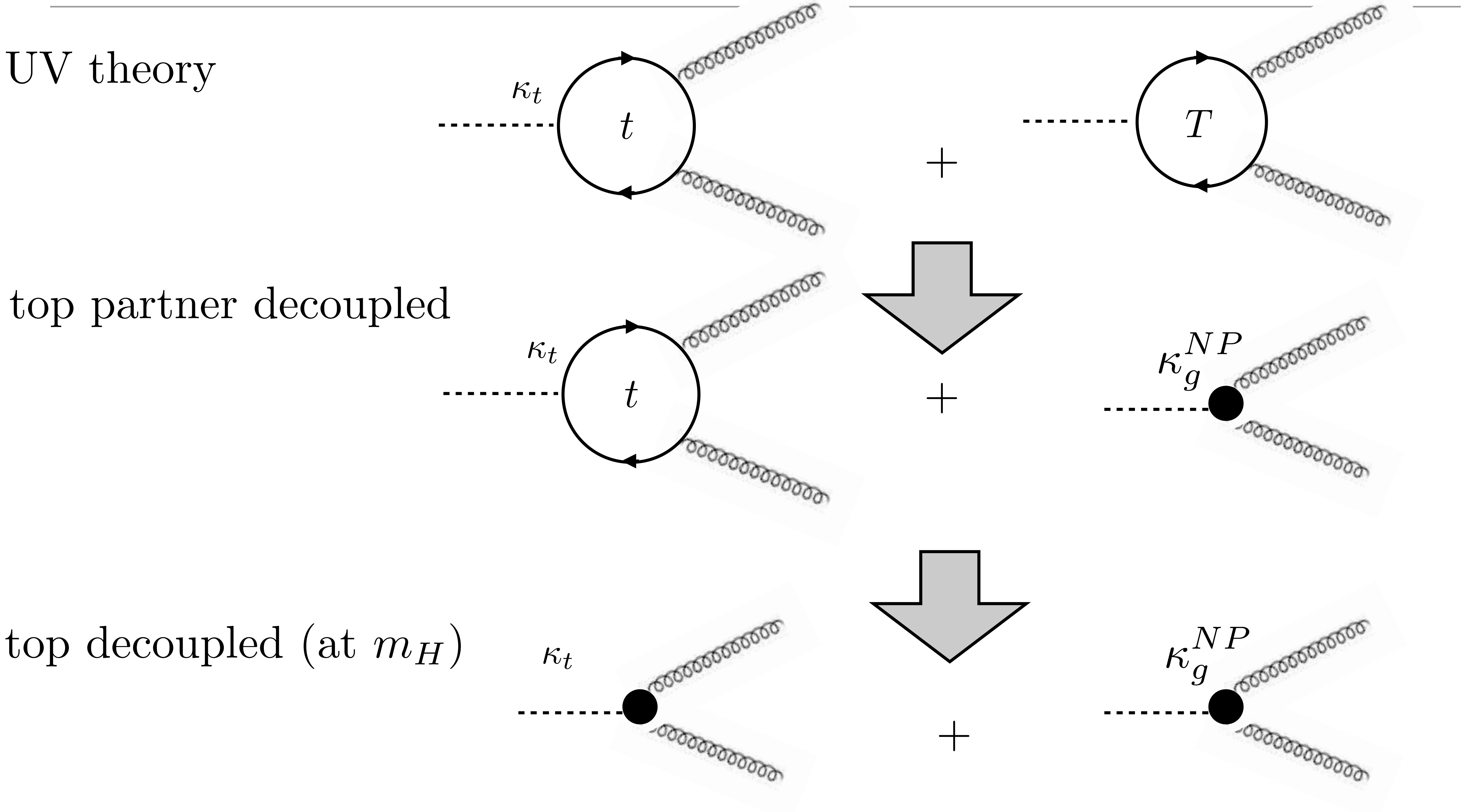
$$\text{We have measured } \kappa_g^{\text{eff}} = \kappa_t + \kappa_g^{NP} \text{ but}$$

$$\text{want to measure } \kappa_g^{NP} \text{ and } \kappa_t \text{ separately}$$

one option: ttH measurement

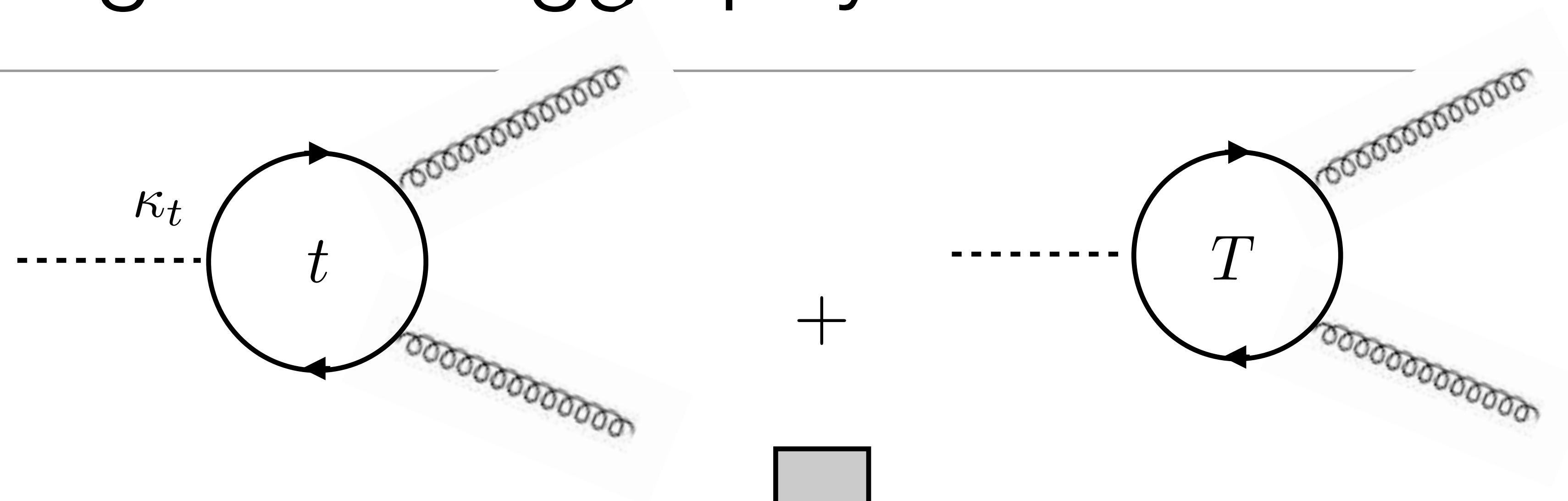
another option: **Boosted Higgs shapes**

Effective Lagrangian for higgs physics



Effective Lagrangian for higgs physics

UV theory



top partner decoupled

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \kappa_t \frac{m_t}{v}\bar{t}th + \kappa_g^{NP}\frac{\alpha_s}{12}\frac{h}{v}G^a_{\mu\nu}G^{\mu\nu a}$$

top decoupled (at m_H)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + (\kappa_t + \kappa_g^{NP})\frac{\alpha_s}{12}\frac{h}{v}G^a_{\mu\nu}G^{\mu\nu a}$$

what we measure in inclusive $H \to gg$ is $\kappa_g^{\rm eff} = \kappa_t + \kappa_g^{NP}$

Ex. Composite Higgs model, natural SUSY

Interestingly, $\kappa_t + \kappa_g = 1 - \mathcal{O}(\xi)$ in many CH models ($\xi = v^2/f^2$)

$SO(5)/SO(4)$ **minimal composite Higgs model**

$$\kappa_g^{\text{eff}} = \kappa_t + \kappa_g = 1 - \tfrac{3}{2}\xi$$

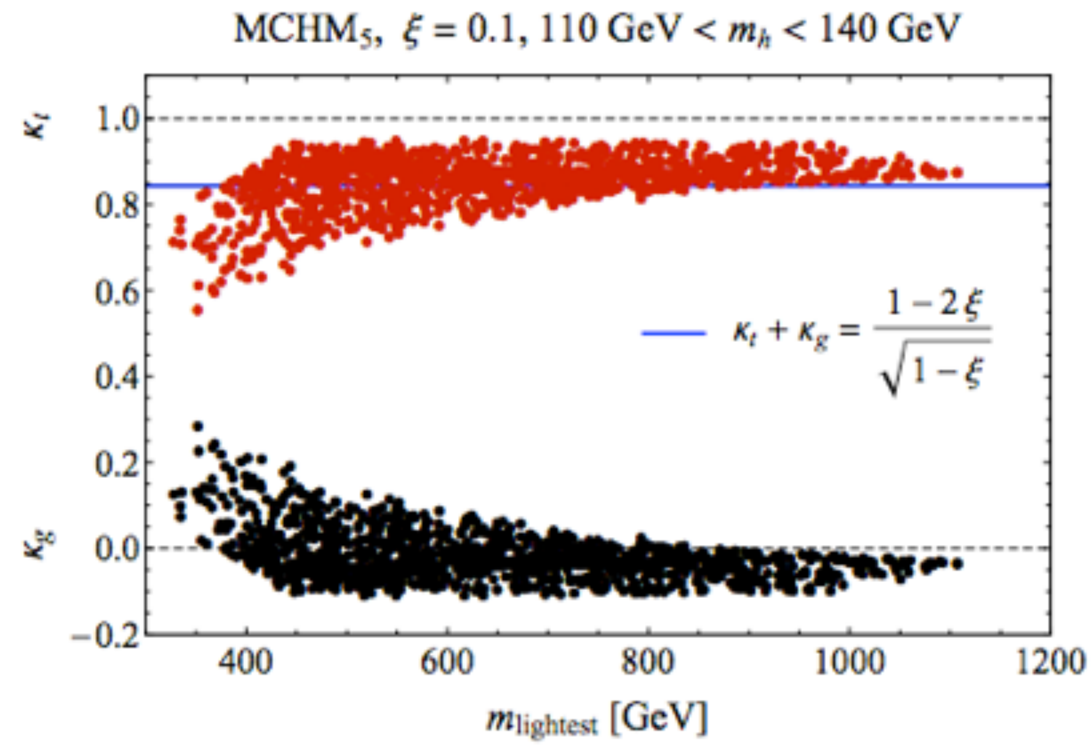
independent of top partner mass m_T

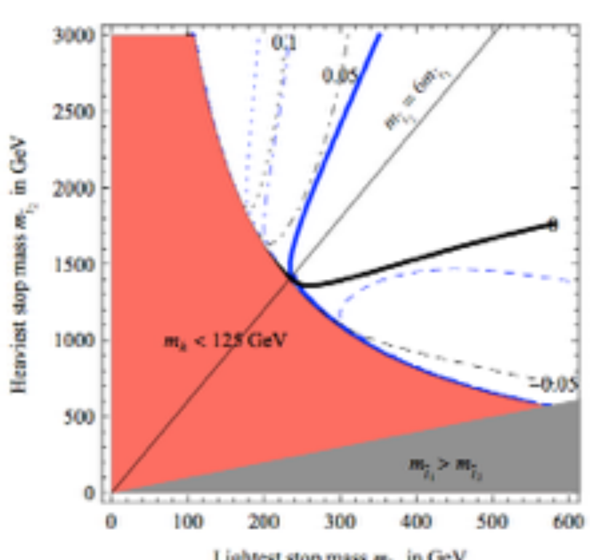
$$(\bar{t}_L\, \bar{T}_L) \begin{pmatrix} \frac{y_t h}{\sqrt{2}} & \Delta \\ 0 & M \end{pmatrix}_{h=v} \begin{pmatrix} t_R \\ T_R \end{pmatrix}$$

diagonalize

$$\longrightarrow \quad h\bar{t}t : \frac{m_t}{v}\cos^2(\theta_R), \quad h\overline{T}T : \frac{M_T}{v}\sin^2(\theta_R)$$

$$\theta_R = \frac{1}{2}\arcsin\left(\frac{2m_t M_T \eta}{M_T^2 - m_t^2}\right)$$





$$m_h^2 = m_Z^2\cos^2 2\beta + \frac{3y_t m_t^2}{4\pi^2}\left[\log\frac{m_S^2}{m_t^2} + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] + \cdots$$

$$X_t = \frac{A_t + \mu\cot\beta}{m_S},\ m_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$m_S \sim 500$ GeV and $X_t \sim \sqrt{6}$

$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{SM}} = (1 + \Delta_t)^2$$

$$\Delta_t \sim \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{X_t^2}{m_S^2}\right)$$

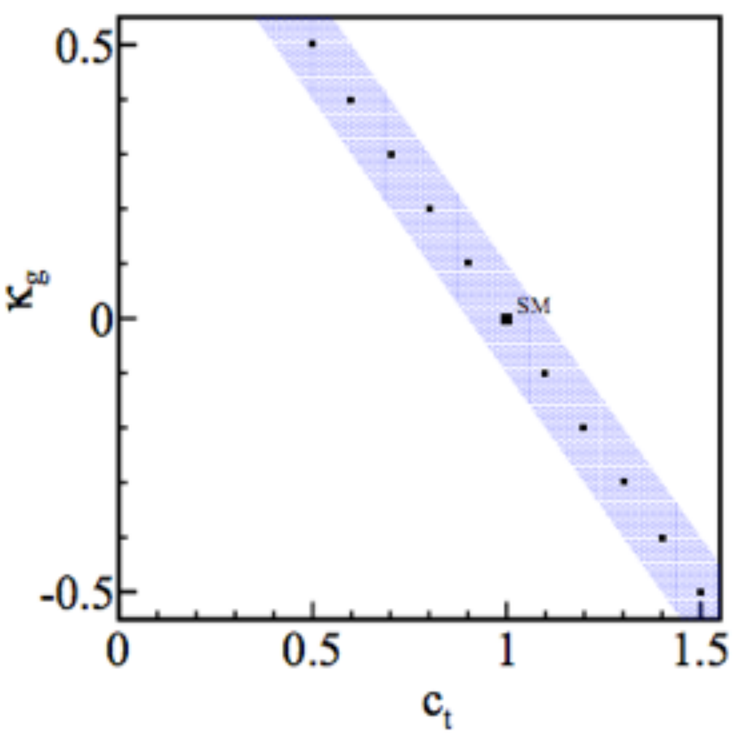
With $X_t^2 \sim 6$, $m_{\tilde{t}_2} = 6m_{\tilde{t}_1}$ gives $\Delta_t \sim 0$

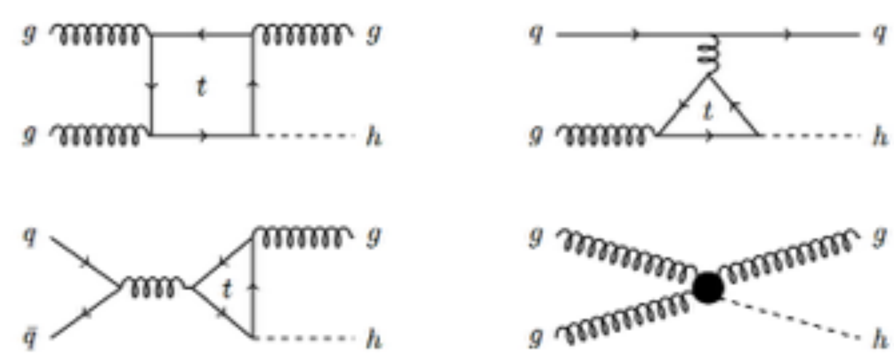
Antonio Delgado, Gian F. Giudice, Gino Isidori, Maurizio Pierini, Alessandro Strumia

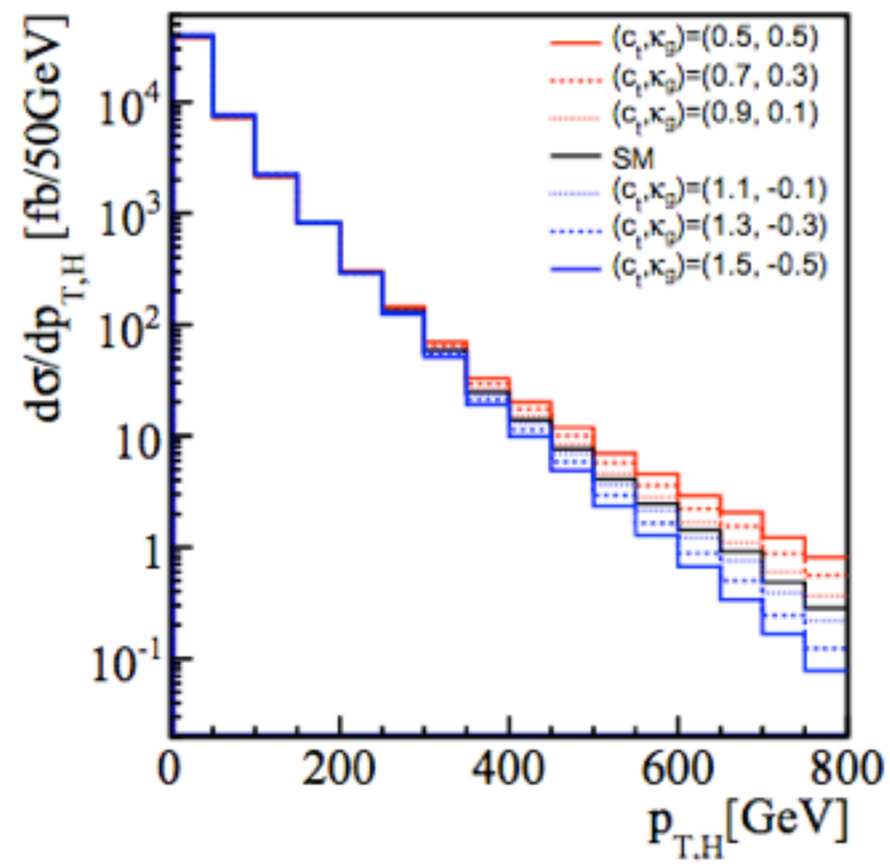
Off-shell gluon breaks top loops

arXiv:1405.4295 M. Schlaffer, M. Spannowsky, MT, A. Weiler, C. Wymant

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - c_t \frac{m_t}{v}\bar{t}th + \kappa_g \frac{\alpha_s}{12}\frac{h}{v} G^a_{\mu\nu}G^{\mu\nu a} \qquad \mathcal{M}(c_t, \kappa_g) = c_t \mathcal{M}(m_t) + \kappa_g \mathcal{M}(\infty)$$







on-shell gluon amplitude has only scale m_H
(only τ_X is sensitive to the mass but very weak)

gluon off-shellness can probe the mass scale in the loop. p_T/m_t

$H + \mathrm{j}:\quad p_{T,H}$ distribution is the observable

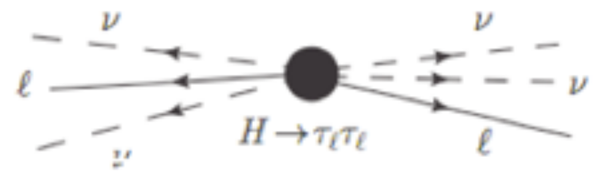
$\kappa_g > 0$ enhance in high $p_{T,H}$
$\kappa_g < 0$ deficit in high $p_{T,H}$

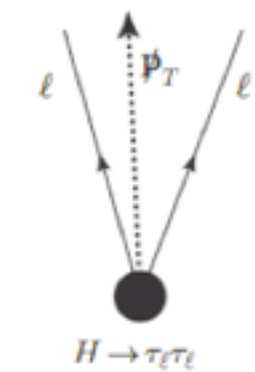
boost helps, M_col distribution

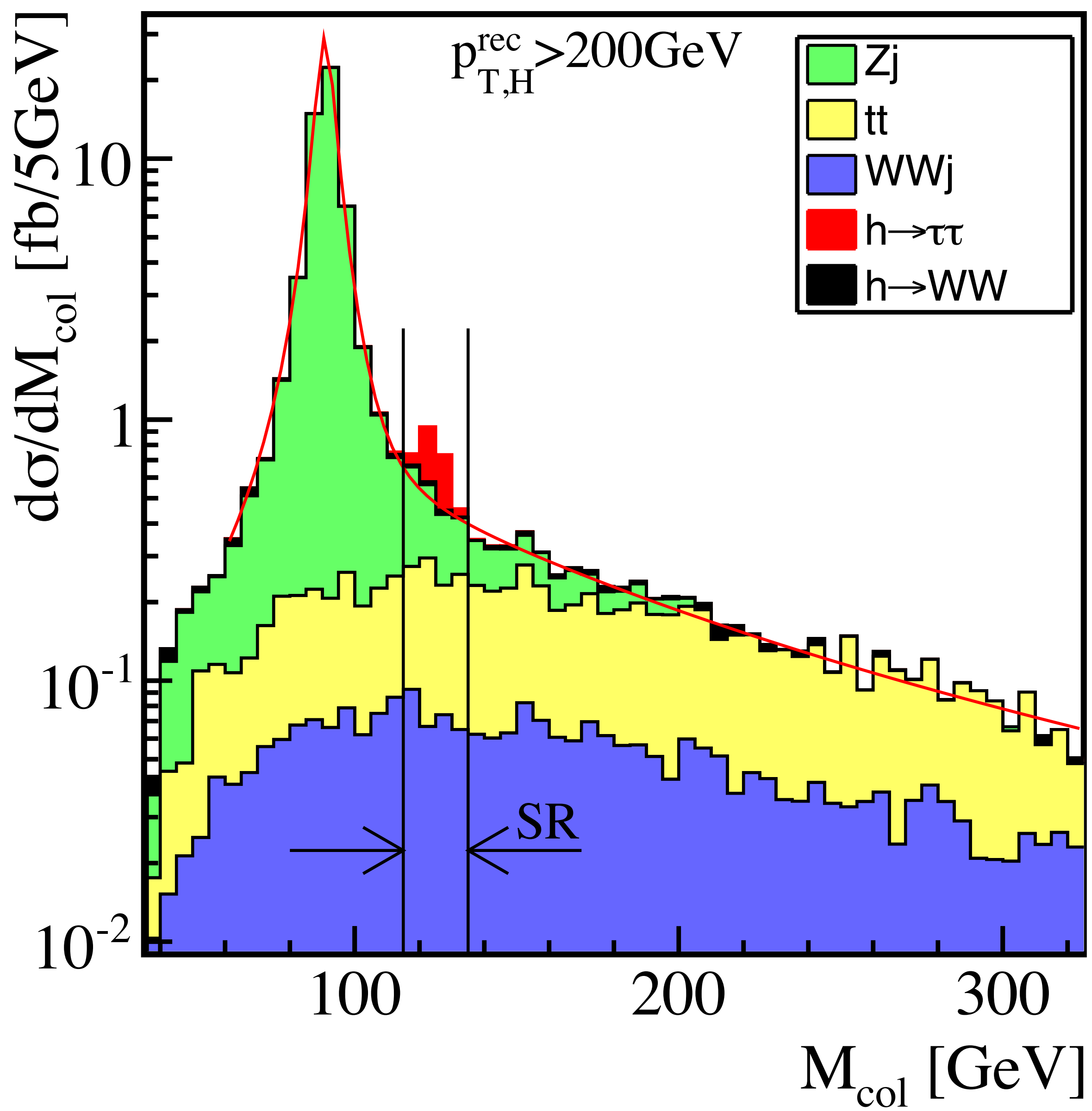
Collinear approx.

$$\not{\mathbf{p}}_T = \mathbf{p}_{T,\nu_1} + \mathbf{p}_{T,\nu_2}$$

$$\mathbf{p}_{\nu_1} = \alpha_1 \mathbf{p}_{\ell_1},\ \mathbf{p}_{\nu_2} = \alpha_2 \mathbf{p}_{\ell_2} \qquad (\alpha_1, \alpha_2 > 0)$$







$$p_{\rm col} = p_{\nu_1} + p_{\nu_2} + p_{\ell_1} + p_{\ell_2}$$

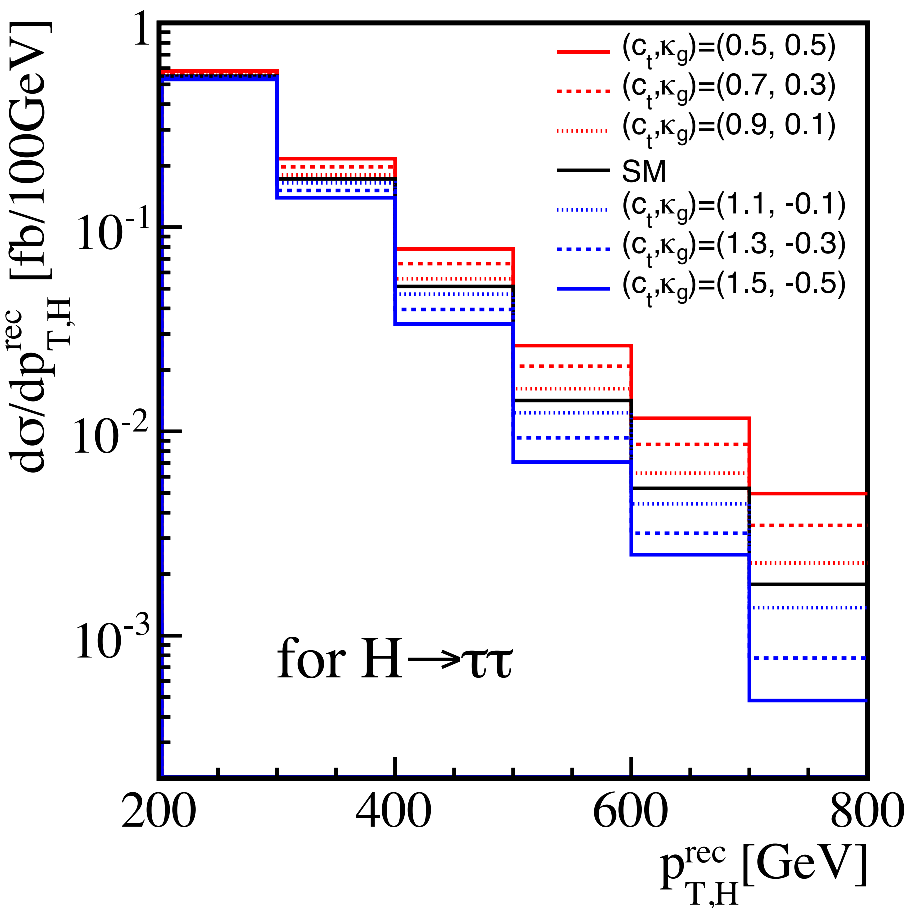
$$M_{\rm col}^2 = p_{\rm col}^2$$

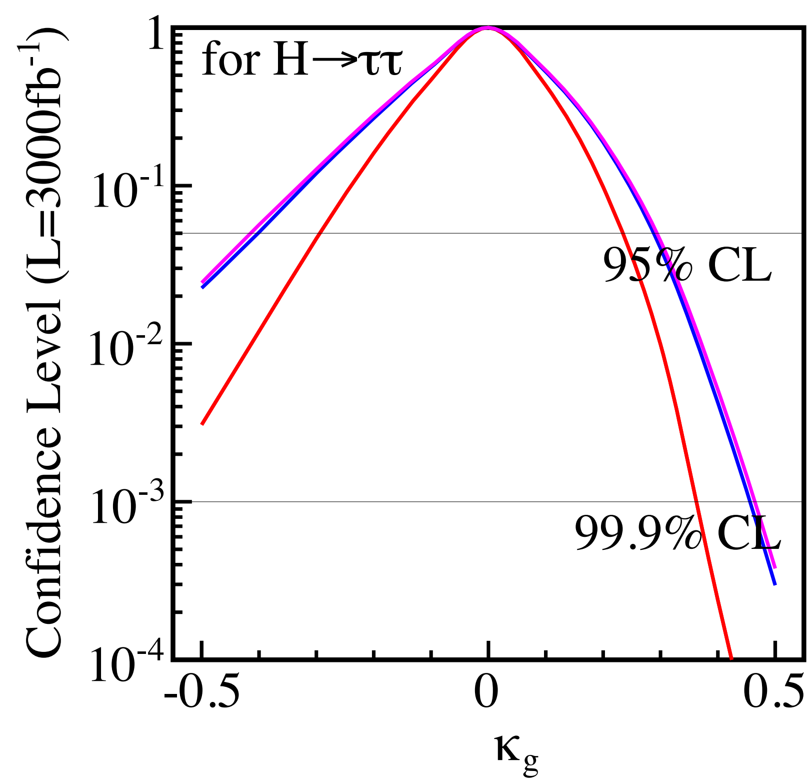
thanks to $m_\tau \ll m_H$

We see also $m_Z \to \tau\tau$ peak

New physics sensitivity

arXiv:1405.4295 M. Schlaffer, M. Spannowsky, MT, A. Weiler, C. Wymant





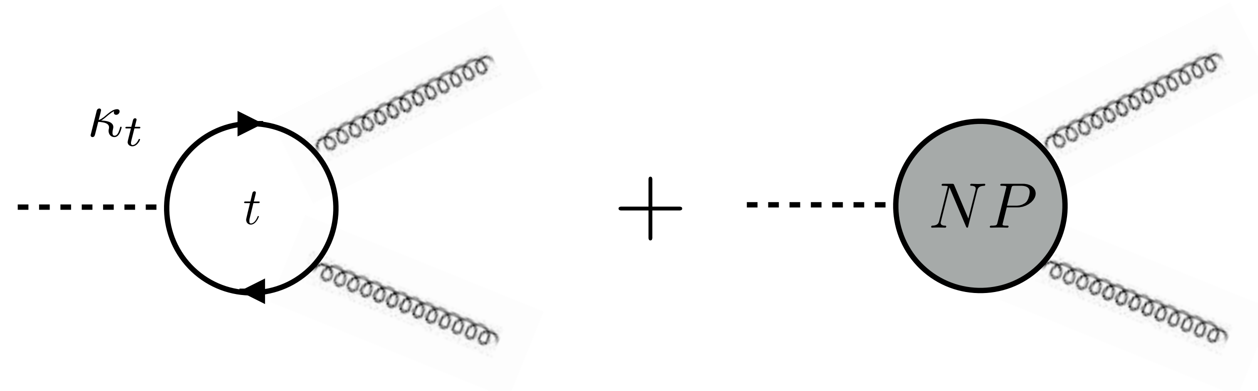
by comparing $p_{T,H}$ distribution,

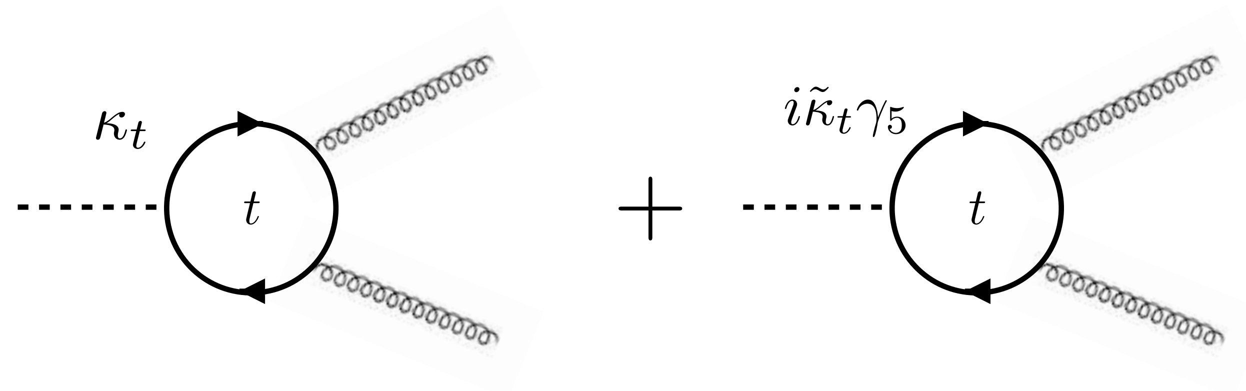
with 3000 fb^{-1}, $\kappa_g < -0.29$ and $\kappa_g > 0.24$ excluded

with 10% sys. err., $\kappa_g < -0.4$ and $\kappa_g > 0.3$ excluded

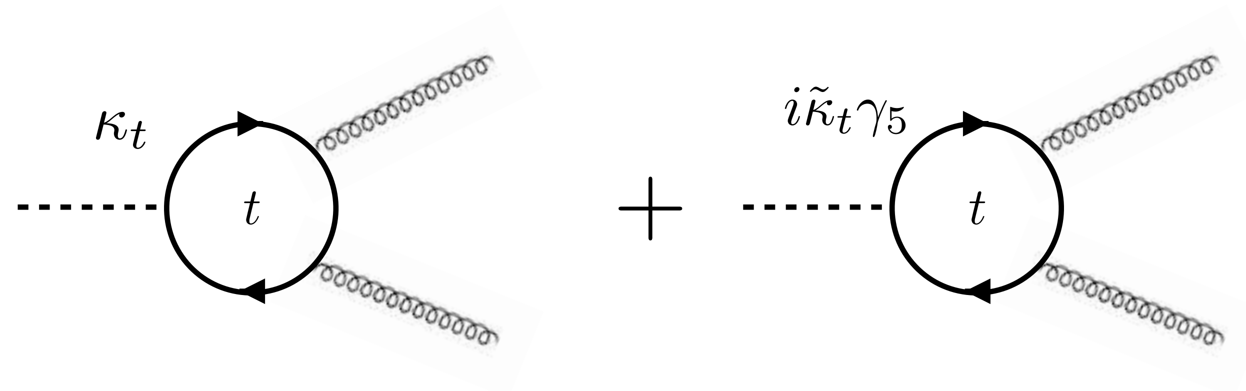
cf.) compared with $\Delta\kappa_t$ by $t\bar{t}H : 0.15(300\text{fb}^{-1}), 0.12(3\text{ab}^{-1})$

weaker but independent information


κ_t
t
$+$
NP



What about $i\bar{t}\gamma_5 t h$?

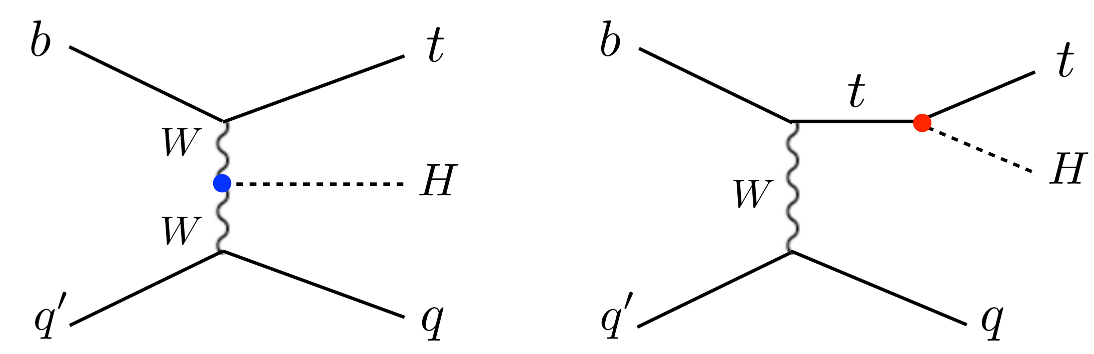


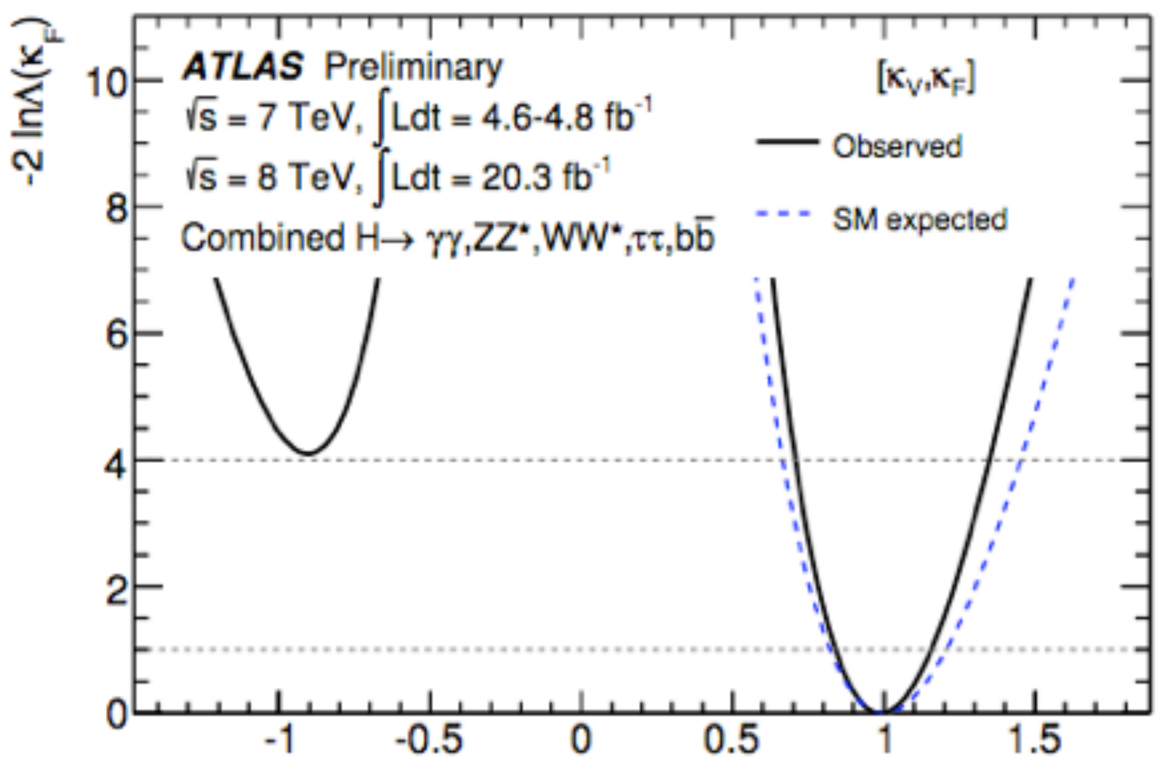
What about $i\bar{t}\gamma_5 th$?

$$-\kappa_t \frac{m_t}{v}\bar{t}th + \kappa_g \frac{\alpha_s}{12\pi}\frac{h}{v}G^a_{\mu\nu}G^{\mu\nu\,a} + i\tilde{\kappa}_t\frac{m_t}{v}\bar{t}\gamma_5 th + \tilde{\kappa}_g\frac{\alpha_s}{8\pi}\frac{h}{v}G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu} + \mathcal{L}_{\rm QCD}\,,$$

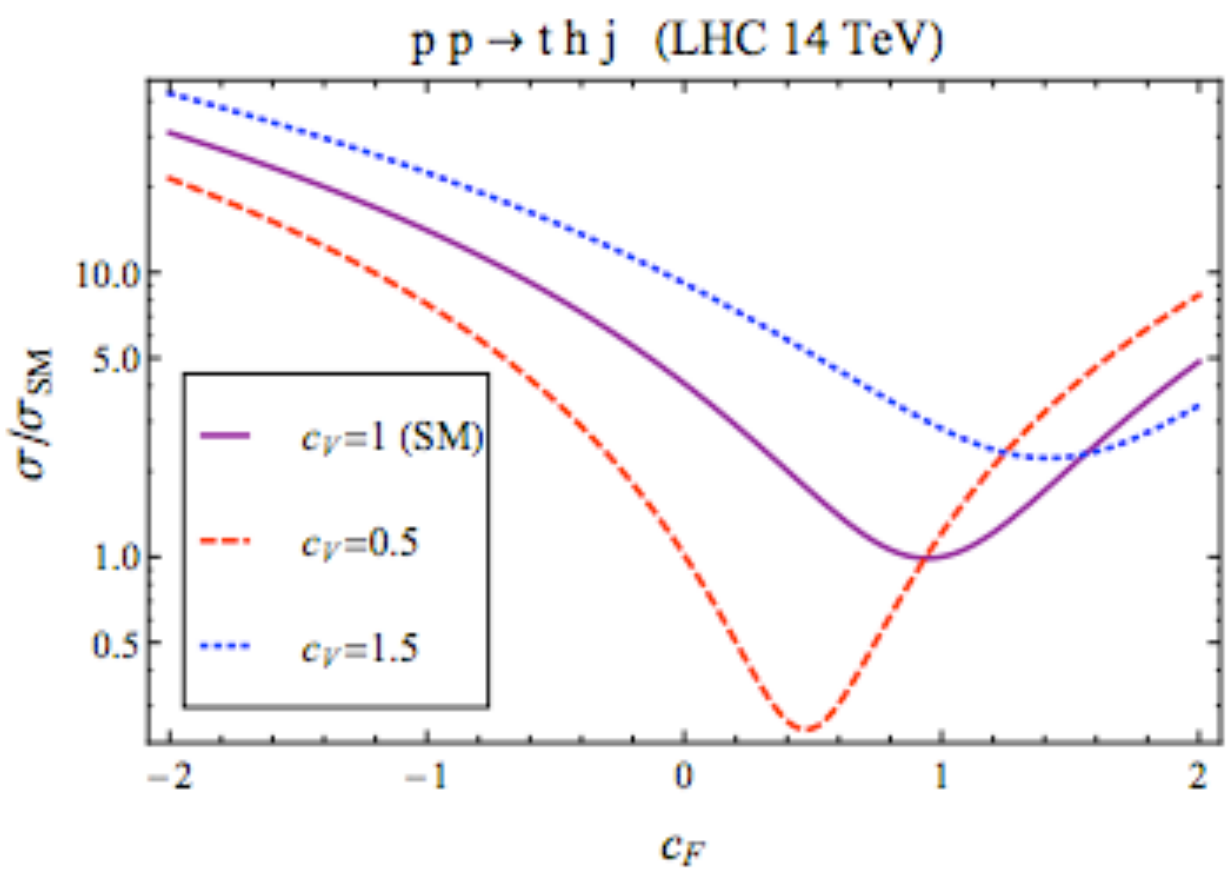
What if ct = -1 ?

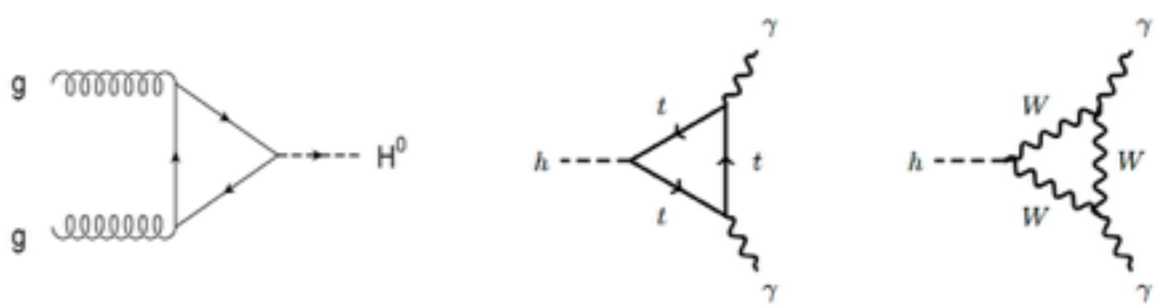
$\kappa_t = -1$ is excluded in 2σ (SM:$\kappa_t = 1$)





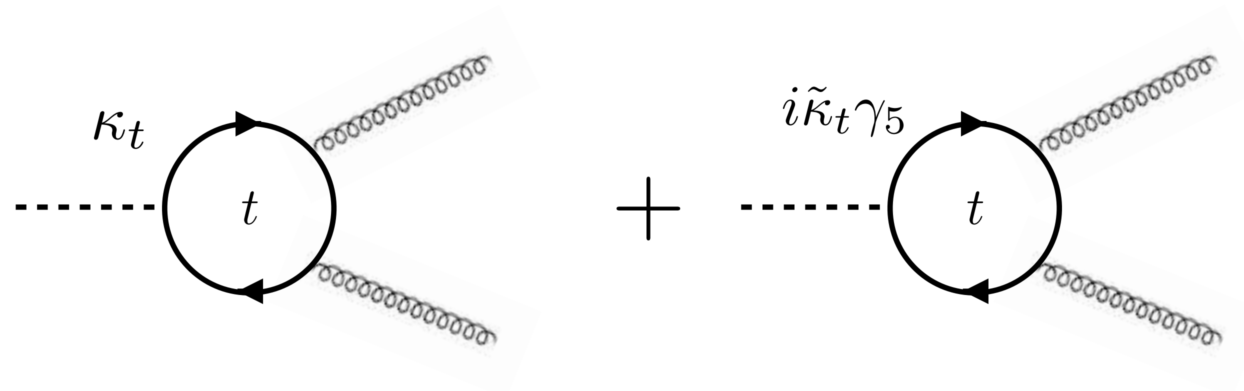
$\sigma(tH)$ would be enhanced by interfere





$\mu_{gg} \propto |\kappa_t|^2, \mu_{\gamma\gamma} \propto |\kappa_V - \epsilon\kappa_t|^2$

taken from JHEP 1305 (2013) 022



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$$-\kappa_t \frac{m_t}{v}\bar{t}th + \kappa_g \frac{\alpha_s}{12\pi}\frac{h}{v}G^a_{\mu\nu}G^{\mu\nu\,a} + i\tilde{\kappa}_t\frac{m_t}{v}\bar{t}\gamma_5 th + \tilde{\kappa}_g\frac{\alpha_s}{8\pi}\frac{h}{v}G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu} + \mathcal{L}_{\rm QCD}\,,$$

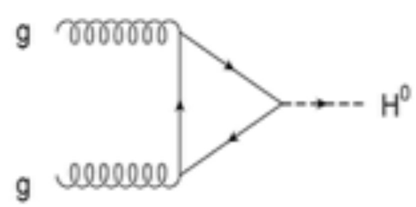
Consistent parameters to Higgs signal strengths?

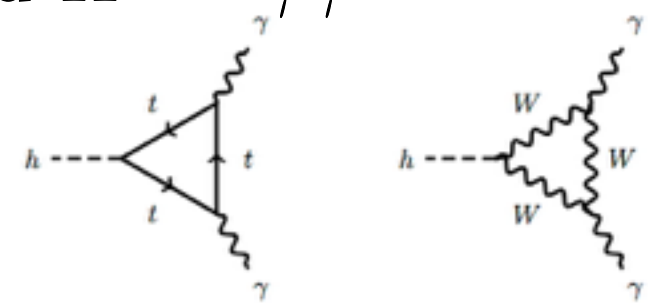
$\sigma(ttH), \sigma(tH)$?

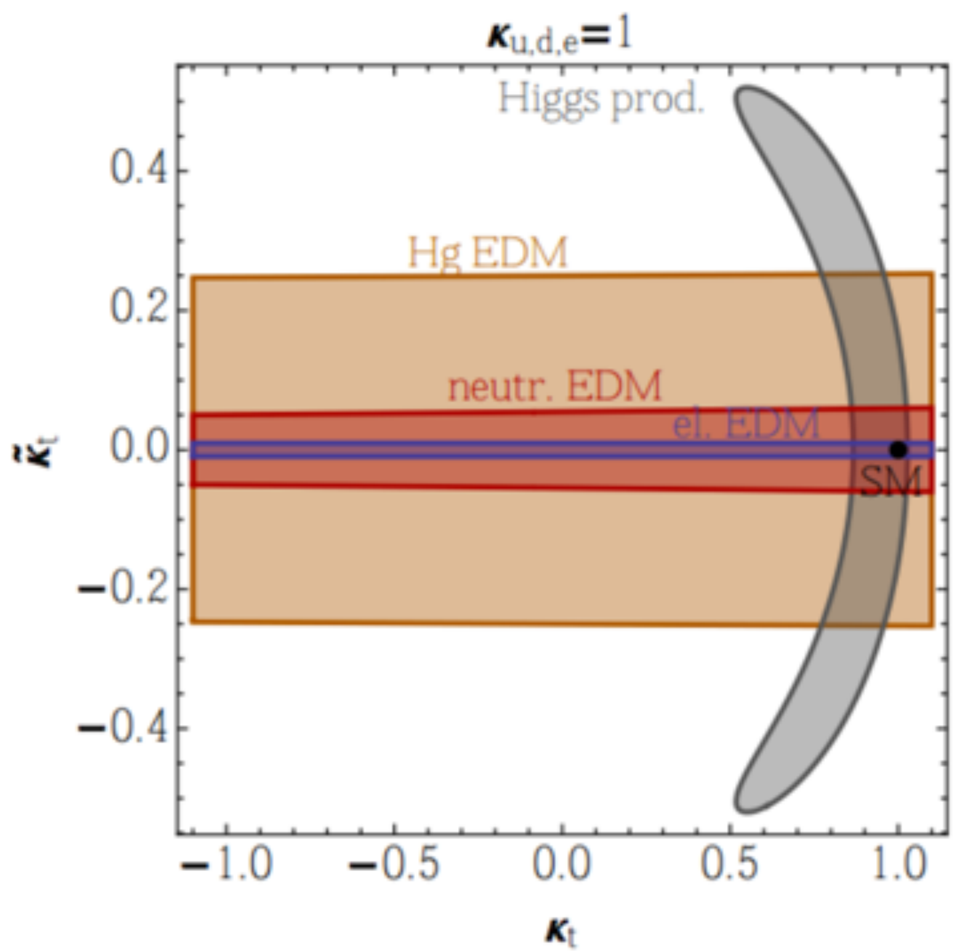
CPV ttH coupling

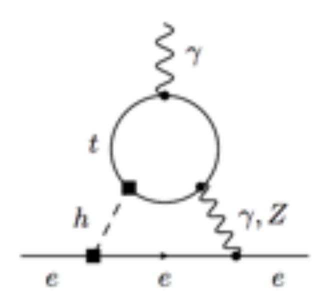
$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

weakly constrained by $H \to gg$ and $H \to \gamma\gamma$









$$\mathrm{SM}: \kappa_t = 1, \tilde{\kappa}_t = 0$$

$$\kappa_{g,\mathrm{WA}} = 0.91 \pm 0.08\,, \qquad \kappa_{\gamma,\mathrm{WA}} = 1.10 \pm 0.11\,,$$

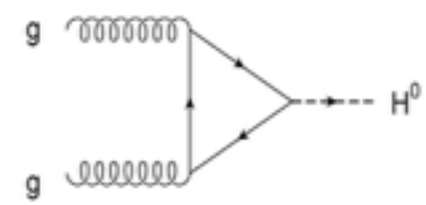
[Joachim Brod,Ulrich Haisch and Jure Zupan]

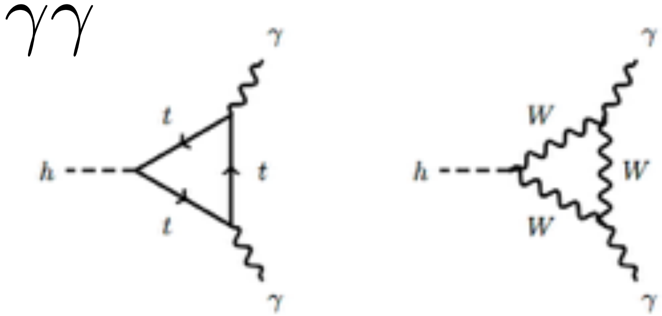
strongly constrained by EDM $\quad |\tilde{\kappa}_t| < 0.01$

CPV ttH coupling

[arXiv:1312.5736[hep-ph] J. Ellis, D. Hwang, K. Sakurai, MT]

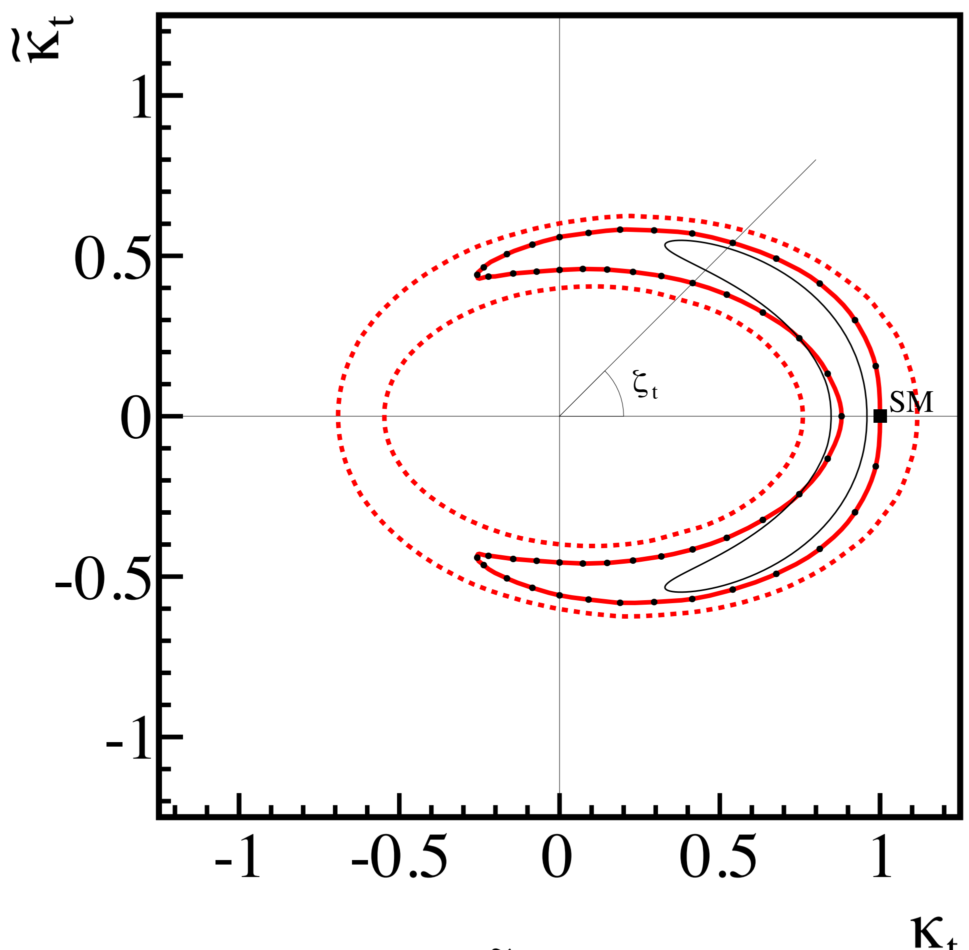
weakly constrained by $H \to gg$ and $H \to \gamma\gamma$

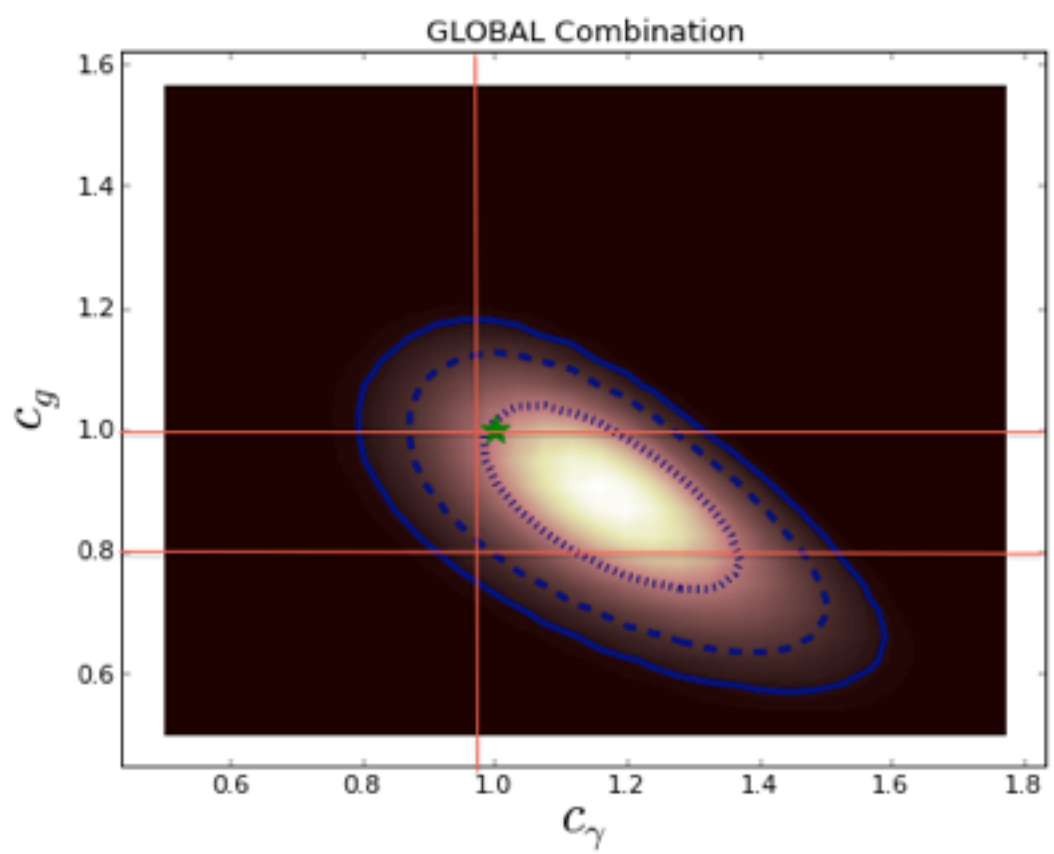




$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

$$\text{SM} : \kappa_t = 1, \tilde{\kappa}_t = 0$$



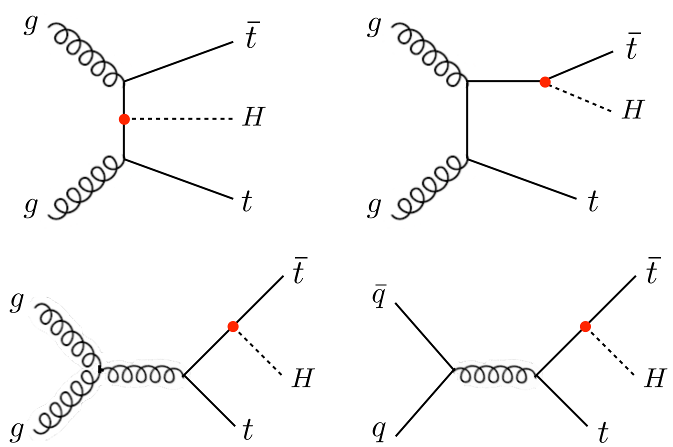


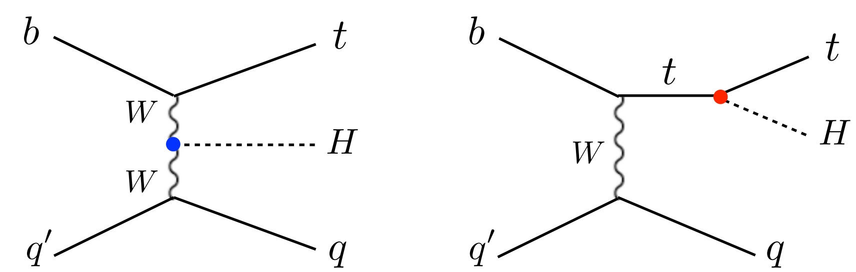
$$\zeta_t = \arctan \frac{\tilde{\kappa}_t}{\kappa_t}$$

note: anti-correlation

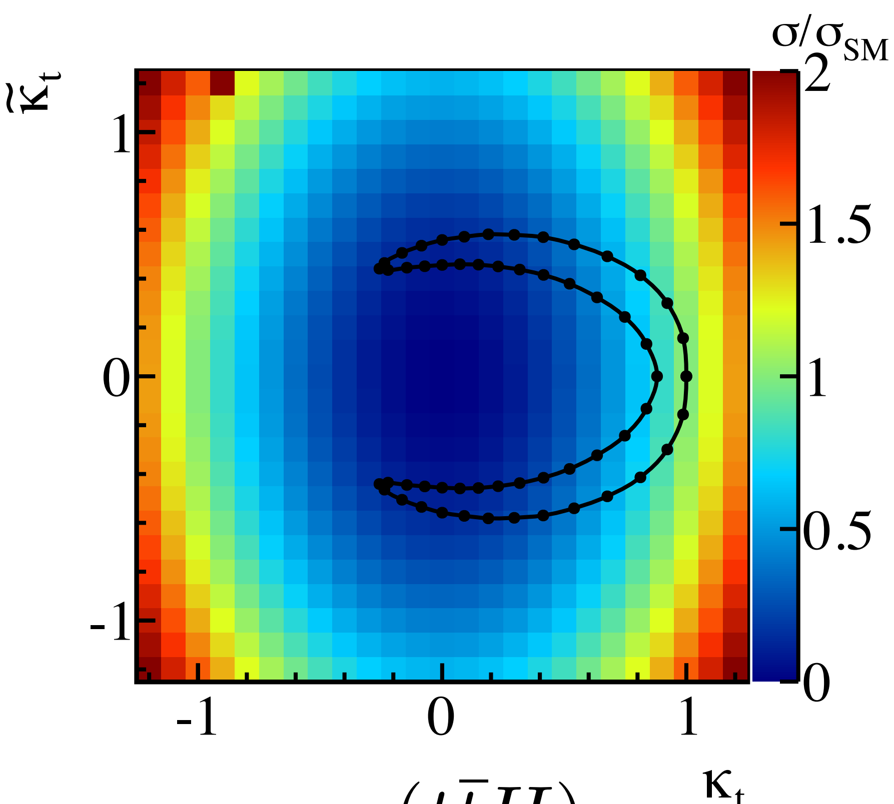
ttH, tHj production rate [arXiv:1312.5736[hep-ph] J. Ellis, D. Hwang, K. Sakurai, MT]

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

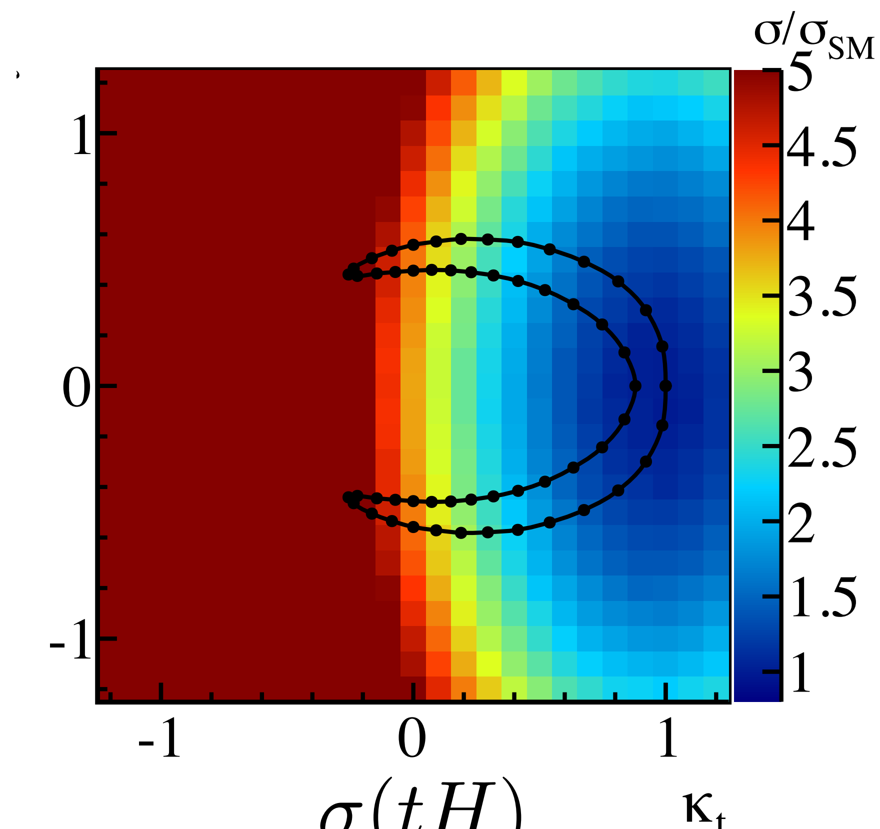




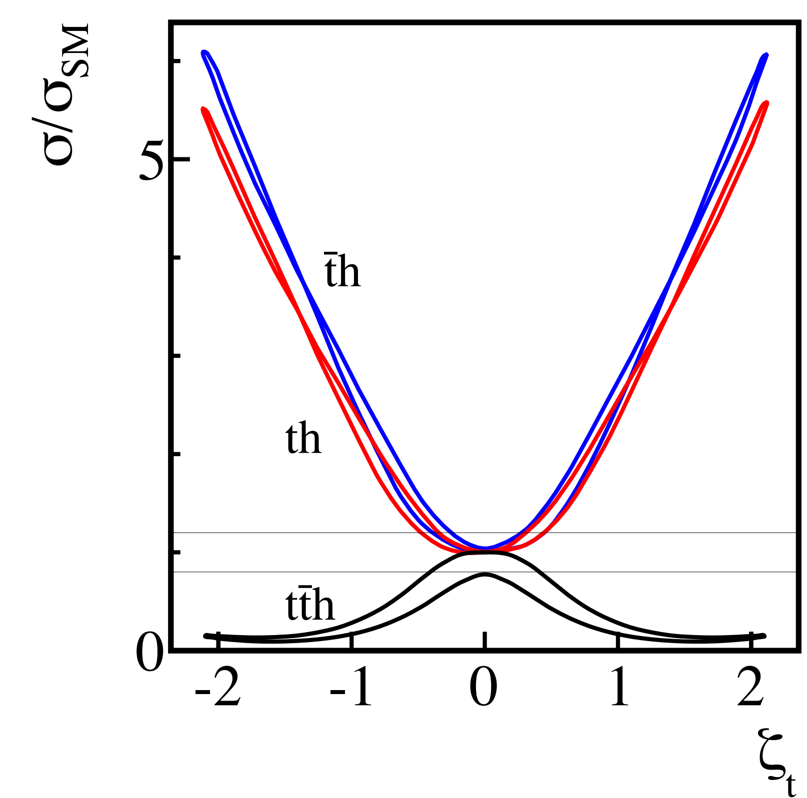
20% $\sigma(t\bar{t}H)$ measurement
determine $\zeta_t < 30°$



$\sigma(t\bar{t}H)$

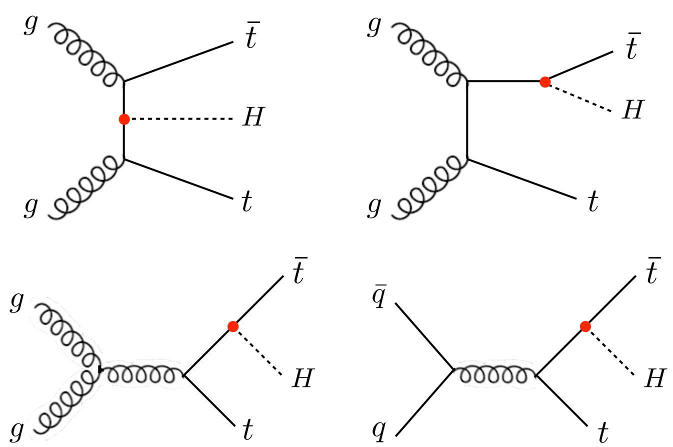


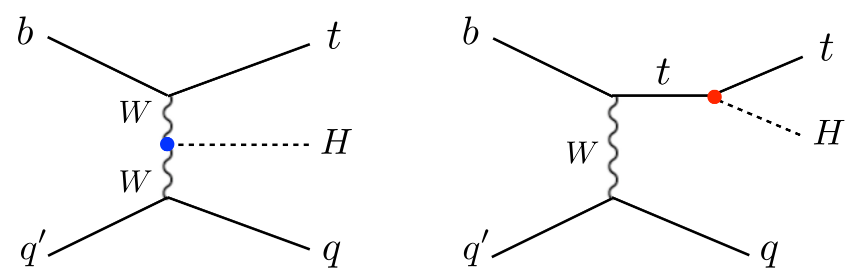
$\sigma(tH)$



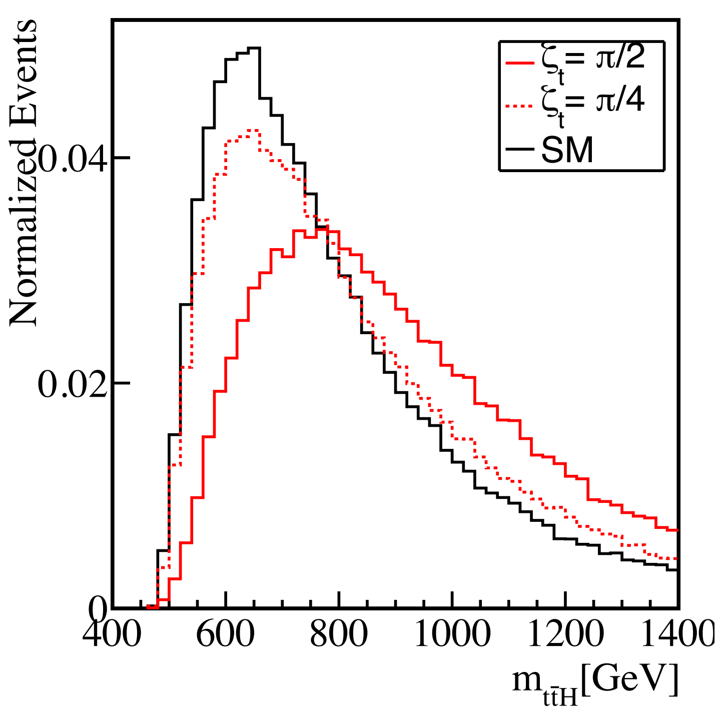
ttH, tHj invariant masses [arXiv:1312.5736[hep-ph] J. Ellis, D. Hwang, K. Sakurai, MT]

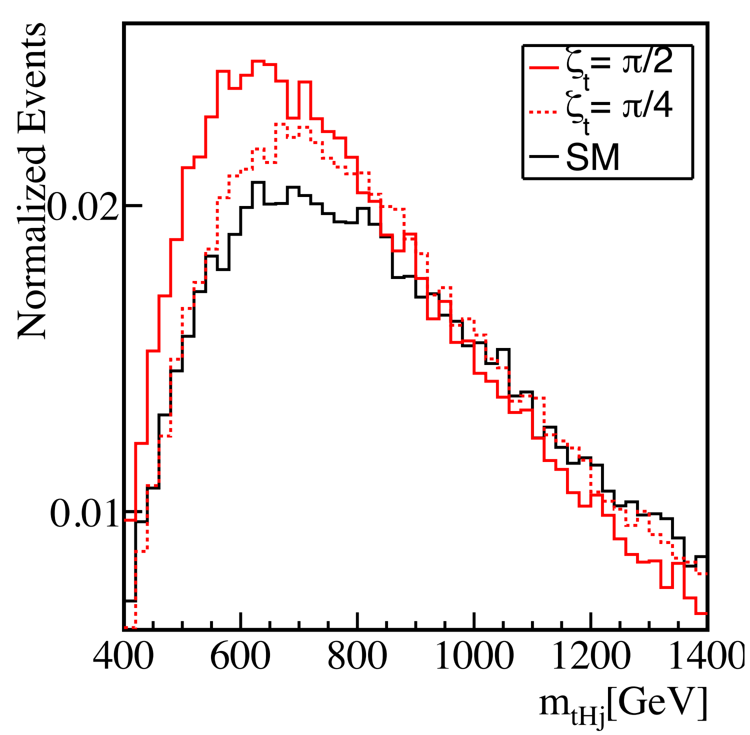
$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

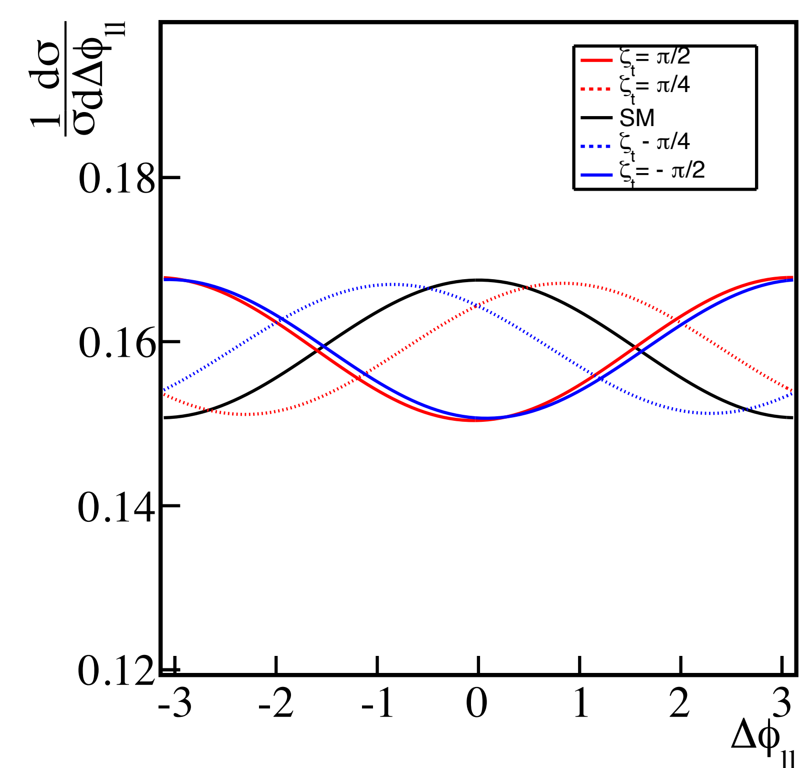




$$\alpha \equiv \mathrm{sgn}\left(\vec{p}_t^{\,t\bar{t}} \cdot (\vec{p}_{\ell^-}^{\,t\bar{t}} \times \vec{p}_{\ell^+}^{\,t\bar{t}})\right).$$



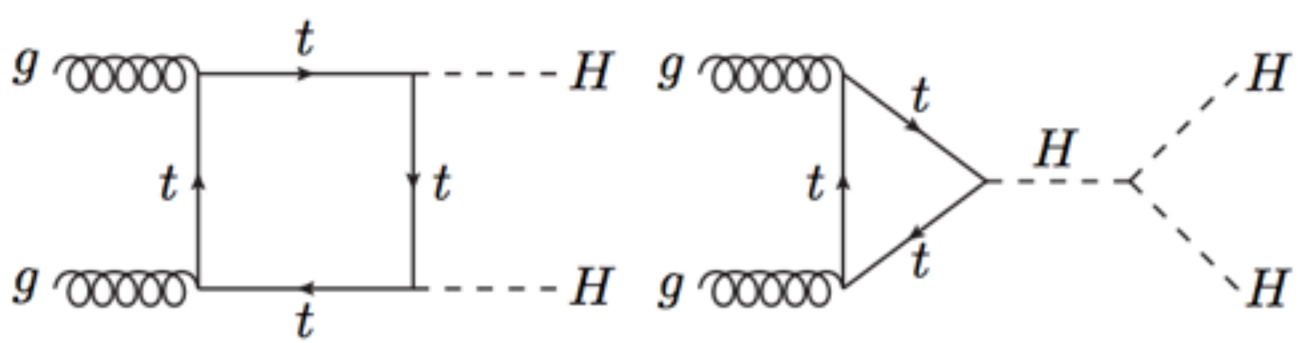


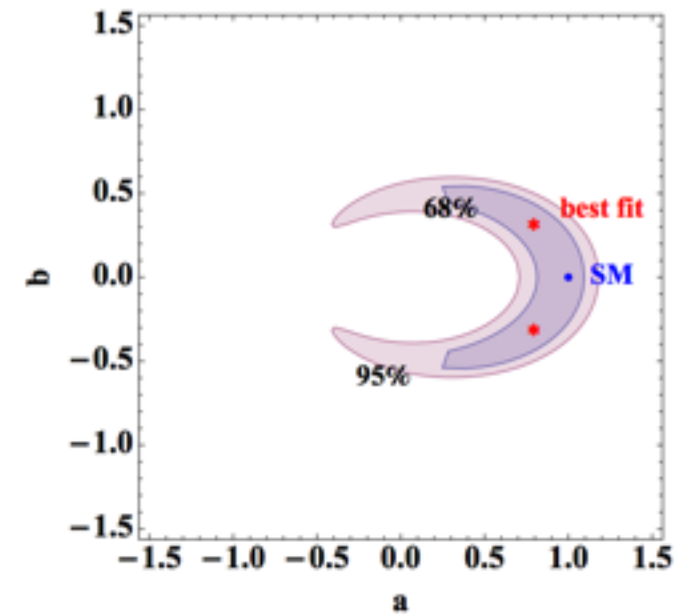


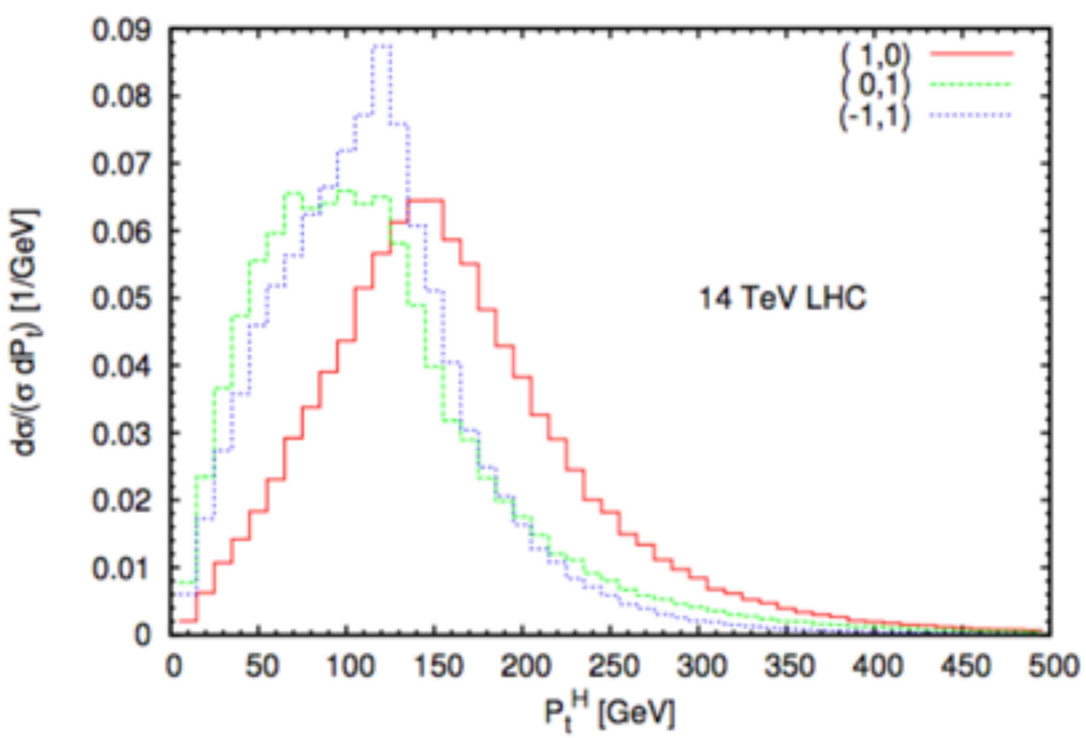
HH invariant masses

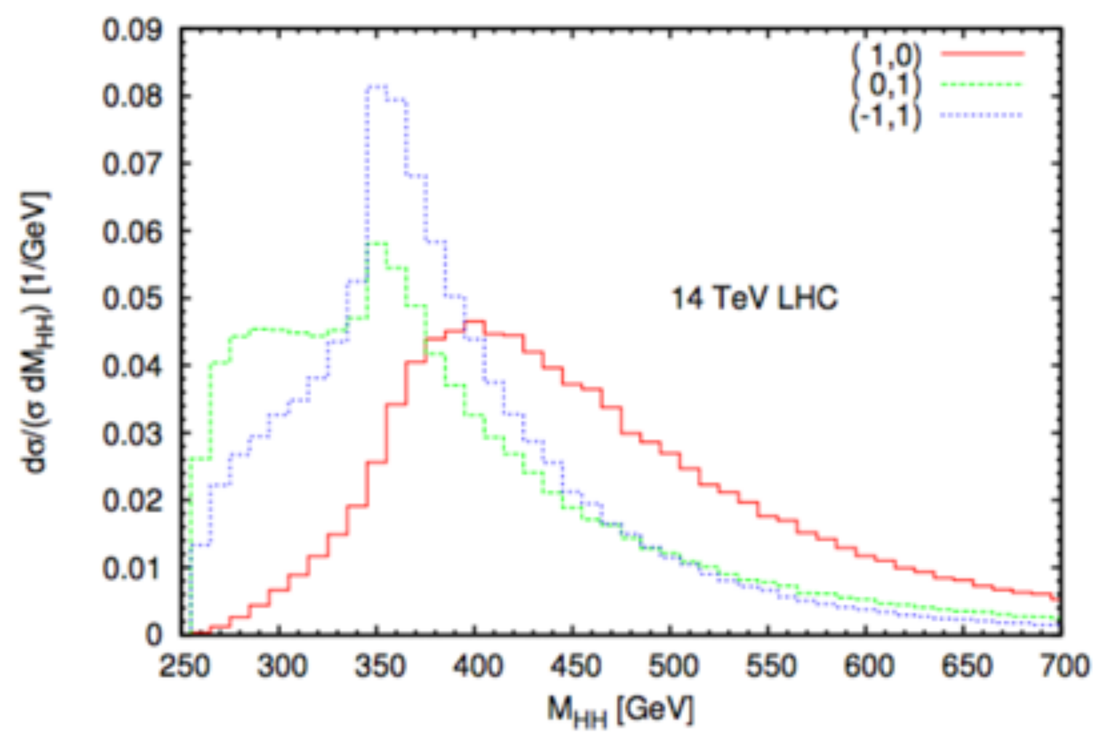
arXiv:1309.6907 [Kenji Nishiwaki, Saurabh Niyogi, Ambresh Shivaji]

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



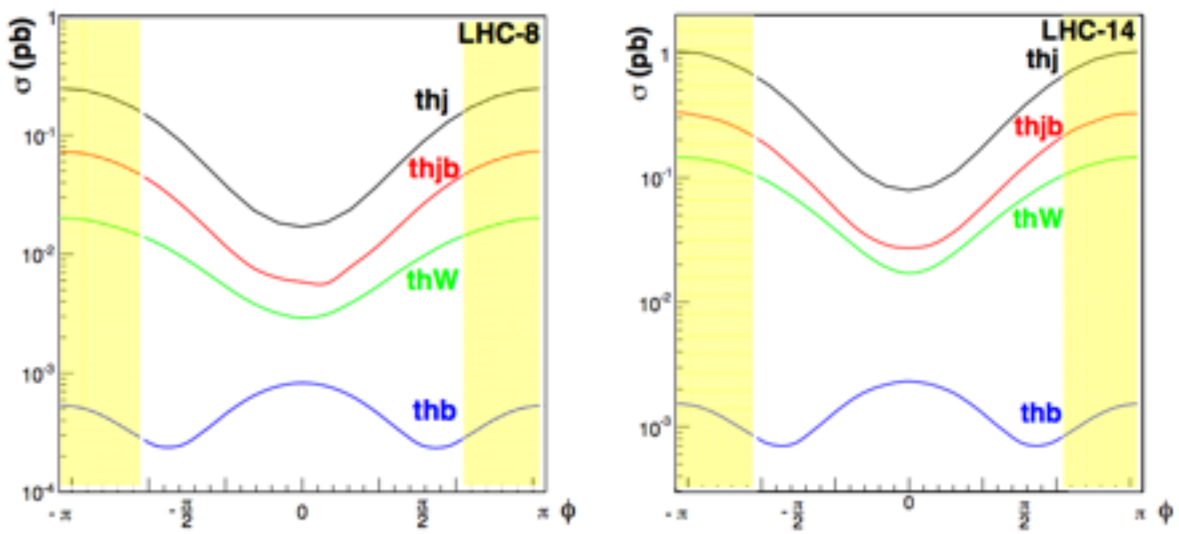






other processes, other observables

[Jung Chang, Kingman Cheung, Jae Sik Lee and Chih-Ting Lu]



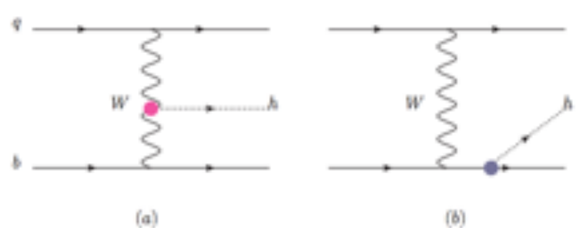


Figure 1. Contributing Feynman diagrams for $qb \to thq'$.

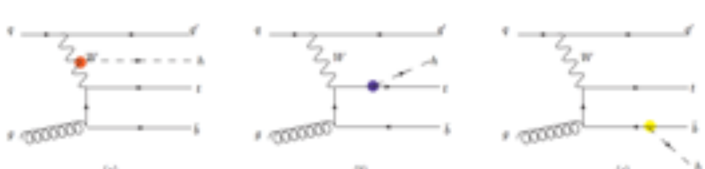


Figure 2. Some of the contributing Feynman diagrams for $qg \to thq'\bar{b}$.

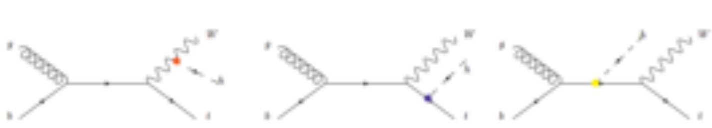


Figure 3. Some of the contributing Feynman diagrams for $gb \to thW^-$.

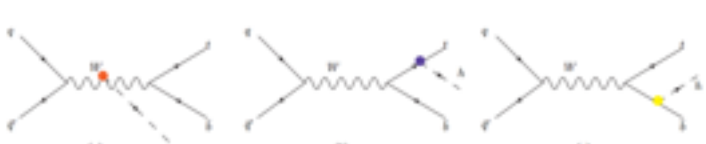


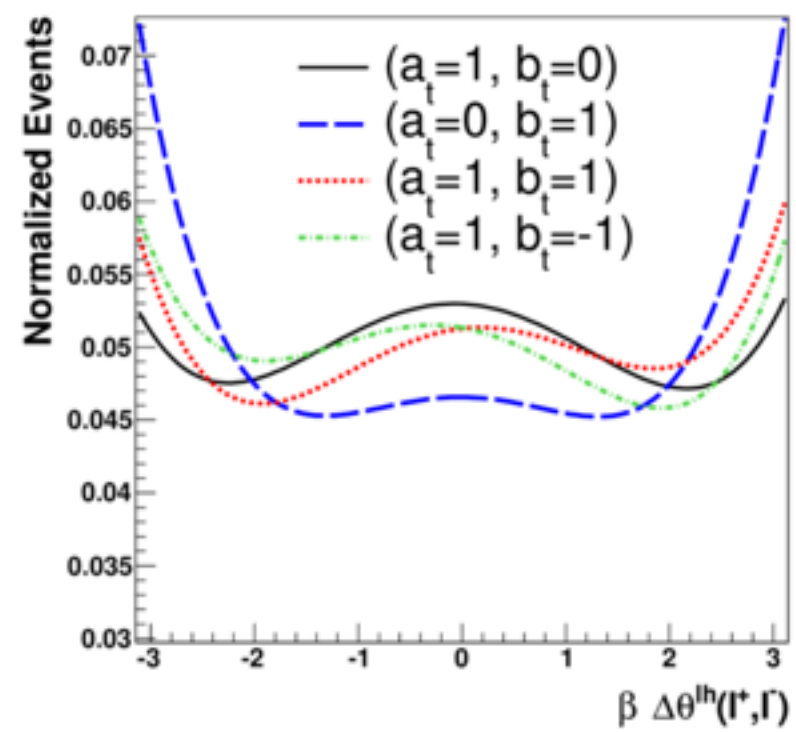
Figure 4. Contributing Feynman diagrams for $q\bar{q}' \to th\bar{b}$.

[Fawzi Boudjema, Rohini M. Godbole, Diego Guadagnoli, Kirtimaan A. Mohan]

$$\alpha \equiv \text{sgn}\left(\vec{p}_t^{\,t\bar{t}} \cdot (\vec{p}_{\ell^-}^{\,t\bar{t}} \times \vec{p}_{\ell^+}^{\,t\bar{t}})\right).$$

defined with lab frame observables

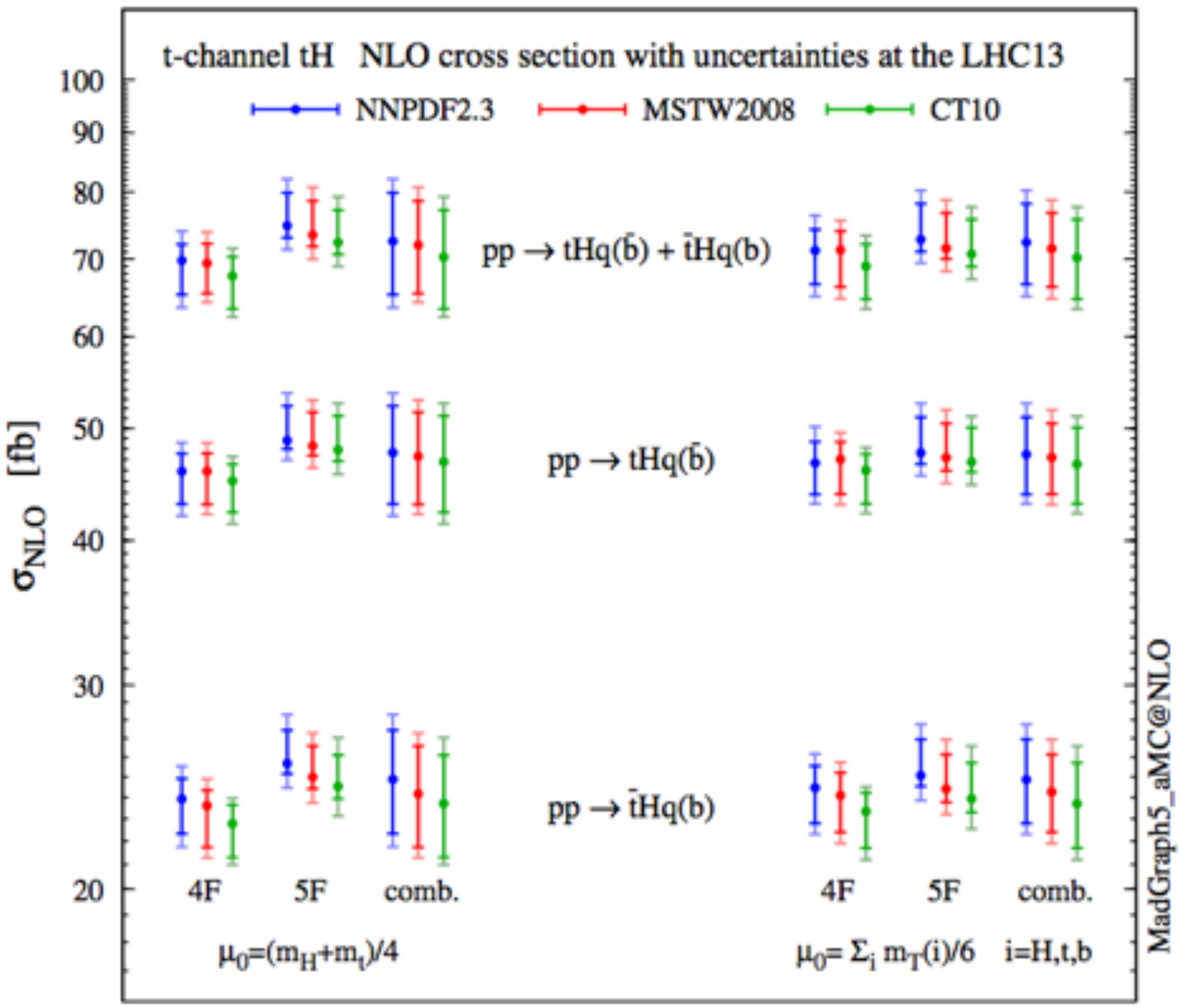
$$\beta \equiv \text{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})\right).$$

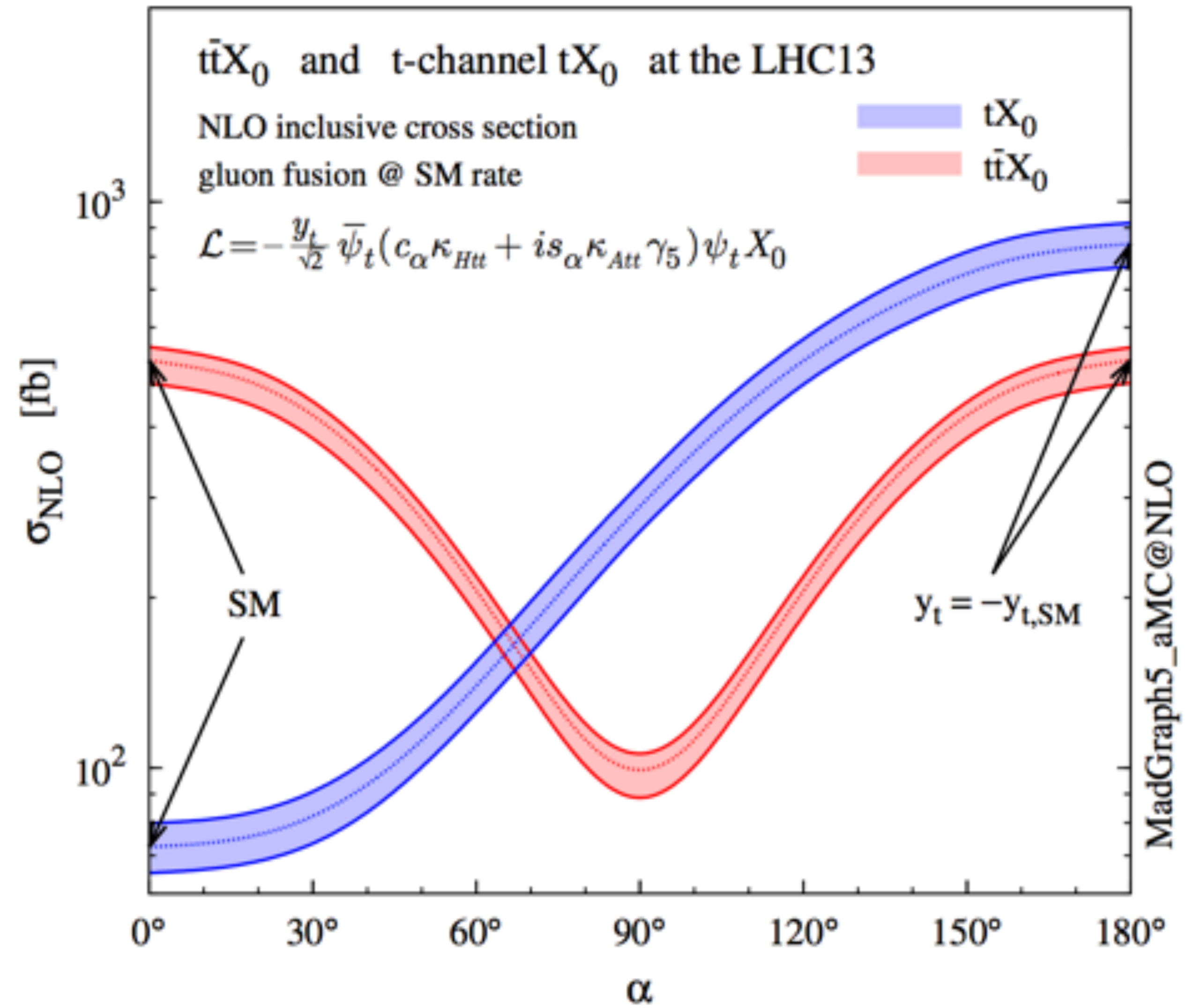


NLO prediction

[Federico Demartin, Fabio Maltoni, Kentarou Mawatari, Marco Zaro]

arxiv:1504.00611



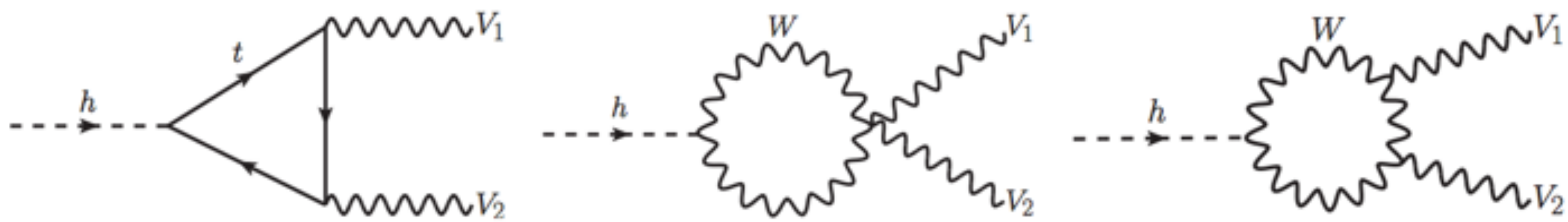


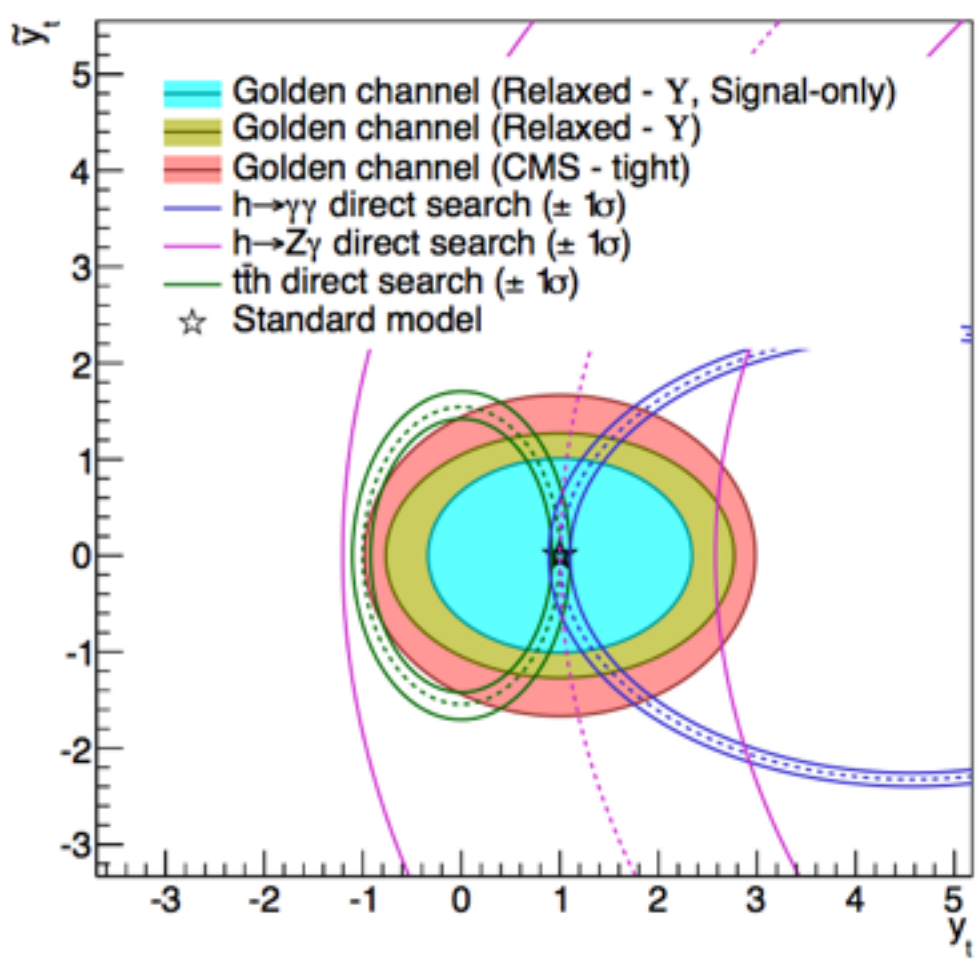
NLO in QCD is available, more reliable prediction possible.

Higgs to 4lepton

[Yi Chen, Daniel Stolarski, Roberto Vega-Morales]

arxiv:1505.01168





also sensitive to

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

FCNC in top-sector

LHC: top factory

$$8\text{TeV}: 250 \text{ pb} \to 5,000,000 \text{ top pairs for } 20\text{fb}^{-1}$$

$$14\text{TeV}: 920 \text{ pb} \to 3 \times 10^9 \text{ top pairs for } 3000\text{fb}^{-1}$$

SM predicts extremely small

Immediate NP signature

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

current bounds (arXiv:1311.2028)

Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	7×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	19.5 fb^{-1}, 8 TeV	[130]
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	2.1 fb^{-1}, 7 TeV	[137]
$t \to gu$	3.1×10^{-5}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV	[131]
$t \to gc$	1.6×10^{-4}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV	[131]
$t \to \gamma u$	6.4×10^{-3}	ZEUS $e^{\pm}p \to (t \text{ or } \bar{t}) + X$	474 pb^{-1}, 300 GeV	[134]
$t \to \gamma q$	3.2×10^{-2}	CDF $t\bar{t} \to Wb + \gamma q$	110 pb^{-1}, 1.8 TeV	[132]
$t \to hq$	8.3×10^{-3}	ATLAS $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	20 fb^{-1}, 8 TeV	[135]
$t \to hq$	2.7×10^{-2}	CMS* $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	5 fb^{-1}, 7 TeV	[136]
$t \to$ invis.	9×10^{-2}	CDF $t\bar{t} \to Wb$	1.9 fb^{-1}, 1.96 TeV	[133]

$BR(t \to ch) < 0.56\%$ at 8 TeV

LHC: top factory

$$8\text{TeV}: 250 \text{ pb} \to 5,000,000 \text{ top pairs for } 20\text{fb}^{-1}$$

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$t \to gu$	4×10^{-14}	–	–	$\le 10^{-7}$	$\le 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\le 10^{-4}$	$\le 10^{-8}$	$\le 10^{-7}$	$\le 10^{-6}$	$\le 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\le 10^{-8}$	$\le 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\le 10^{-7}$	$\le 10^{-9}$	$\le 10^{-8}$	$\le 10^{-9}$	$\le 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\le 10^{-5}$	$\le 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\le 10^{-5}$	$\le 10^{-5}$	$\le 10^{-9}$	$\le 10^{-4}$

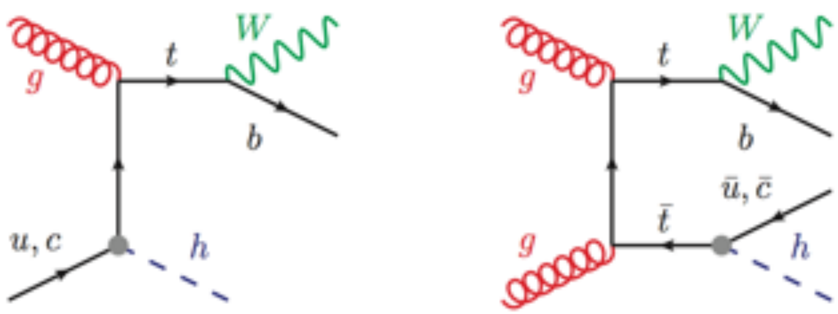
current bounds (arXiv:1311.2028)

future bounds (conservative)

Process	Br Limit	Search	Dataset	Reference
$t \to hq$	2×10^{-3}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	8.3×10^{-3}	ATLAS $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	20 fb^{-1}, 8 TeV	[135]
$t \to hq$	2.7×10^{-2}	CMS* $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	5 fb^{-1}, 7 TeV	[136]
$t \to$ invis.	9×10^{-2}	CDF $t\bar{t} \to Wb$	1.9 fb^{-1}, 1.96 TeV	[133]

$BR(t \to ch) < 0.56\%$ at 8 TeV

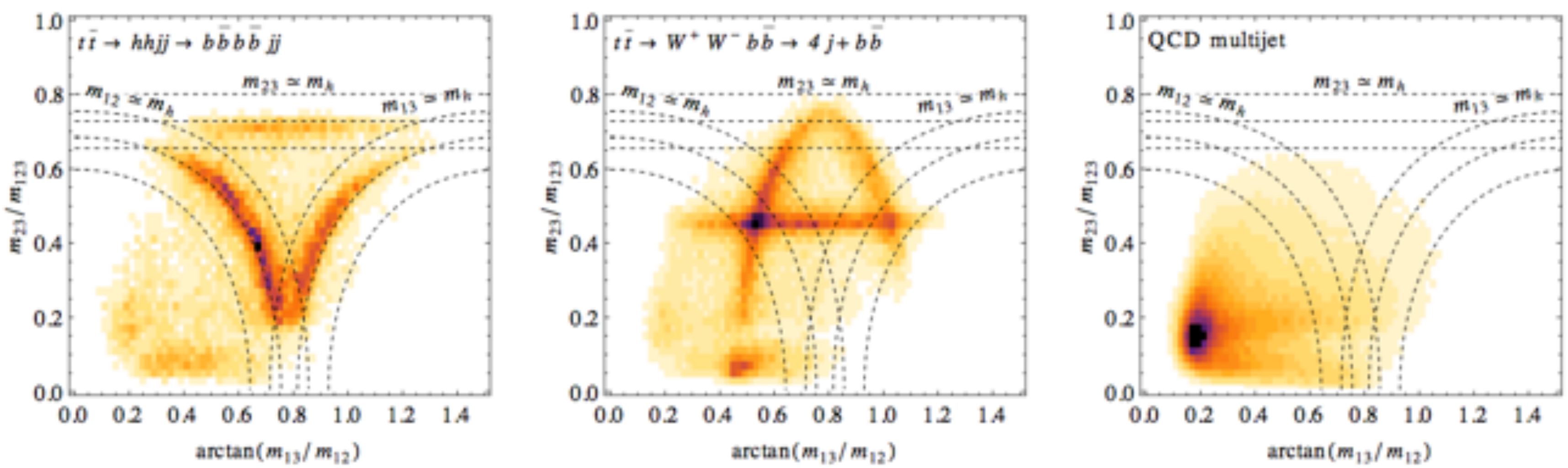
[A. Greljo, J. F. Kamenik, J. Kopp] arXiv:1404.1278



importance of the FC production

$$ug \to th$$

$$BR(t \to uh) < 0.45\% \text{ at } 8 \text{ TeV}$$



HEPTopTagger like $t \to hj$ tagger proposed.

current bounds (arXiv:1311.2028)

future bounds (conservative)

Process	Br Limit	Search	Dataset	Reference
$t \to hq$	2×10^{-3}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	8.3×10^{-3}	ATLAS $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	20 fb^{-1}, 8 TeV	[135]
$t \to hq$	2.7×10^{-2}	CMS* $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	5 fb^{-1}, 7 TeV	[136]
$t \to$ invis.	9×10^{-2}	CDF $t\bar{t} \to Wb$	1.9 fb^{-1}, 1.96 TeV	[133]

$BR(t \to ch) < 0.56\%$ at 8 TeV

Two Higgs doublet models

No tree level FCNC in the SM. Large FCNC is NP signature.

$$\Phi_1 = \begin{pmatrix} H_1^+ \\ \frac{v_1+h_1+iA_1}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H_2^+ \\ \frac{v_2+h_2+iA_2}{\sqrt{2}} \end{pmatrix}$$

$$v_{\rm SM}^2 = v_1^2 + v_2^2$$

$$\tan\beta = v_2/v_1$$

Usually considering Z_2 sym. to suppress FCNC,

$$\mathcal{L} = -\Phi_1 \overline{u}_R [Y_{u1}] Q - \Phi_2 \overline{u}_R [Y_{u2}] Q + \text{h.c.} + \ldots$$

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type-I	+	−	−	−	−	+
Type-II	+	−	−	+	+	+
Type-X	+	−	−	−	+	+
Type-Y	+	−	−	+	−	+

Type *III* to have FCNC, top FCNC is rather less constrained

Φ_1	Φ_2	t_R	c_R	u_R	d_R	ℓ_R	Q_L	L_L
+	−	−	+	+	+	+	+	+

$(\tau_R -)$

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	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type-I	+	−	−	−	−	+
Type-II	+	−	−	+	+	+
Type-X	+	−	−	−	+	+
Type-Y	+	−	−	+	−	+

Type *III* to have FCNC, top FCNC is rather less constrained

Φ_1	Φ_2	t_R	c_R	u_R	d_R	ℓ_R	Q_L	L_L
+	−	−	+	+	+	+	+	+
						$(\tau_R -)$		

There are such well motivated models!

FCNC decay in top-specific Variant Axion Model

Michihisa Takeuchi (Kavli IPMU)
in collaboration with Cheng-Wei Chiang, Hajime Fukuda, Tsutomu Yanagida
JHEP11(2015)057 [arXiv:1507.04354]

Strong CP problem, Domain wall problem

QCD Lagrangian contains the total derivative term: θ-term

$$\mathcal{L}_\theta = \frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

chiral tr. $q \to e^{i\alpha\gamma_5} q$ induces $\theta \to \theta - 2\alpha$
massive fermion mass term is also changed.

$\theta_{\rm eff} = \theta + \arg\det[M^u M^d]$ is invariant under the chiral tr.

Why $\theta_{\rm eff} < 10^{-9}$?

PQ mechanism [R. D. Peccei, H. R. Quinn, PhysRevLett.38.1440]

If the theory has $U(1)_{PQ}$, which spontaneously breakdowns to provide axion, and at least one fermion mass from yukawa coupling,

QCD instanton effects give an axion a potential of the form $1 - \cos(aN/f_a)$ and minimizing it gives $< a >= \theta_{\rm eff} = 0$.

Domain wall problem

for invisible axion model (ZDFS model)

$$U(1)_{PQ} \to Z_N, \quad N = |\sum_i^{N_g} (2q_i + u_i + d_i)|$$

$$N_{DW} = \left| \frac{N}{h_1 + h_2} \right| = N_g$$

[C.Q. Geng, J. N. Ng, PhysRevD.41.3848]

$$V(\Phi_1, \Phi_2, \sigma) = \lambda_1 \left(|\Phi_1|^2 - \frac{v_1^2}{2} \right)^2 + \lambda_2 \left(|\Phi_2|^2 - \frac{v_2^2}{2} \right)^2 + \lambda \left(|\sigma|^2 - \frac{v^2}{2} \right)^2$$
$$+ a\, |\Phi_1|^2 |\sigma|^2 + b\, |\Phi_2|^2 |\sigma|^2 + \left(m\, \Phi_1^\dagger \Phi_2 \sigma + \text{h.c.} \right)$$
$$+ d\, |\Phi_1^\dagger \Phi_2|^2 + e\, |\Phi_1|^2 \, |\Phi_2|^2 .$$

$N_g = 1$ is free from domain wall problem.

Variant Axion model PQ charges: $u_3 = -1, h_2 = -1, \sigma = 1$

[C-R Chen, P. Frampton, F. Takahashi, T. T. Yanagida JHEP1006(2010)059]

top-specific 2HDM

After integrating out the σ field, the effective theory is just a 2HDM.
with Φ_2 only couple with u_{R3}

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)$$

$$L^u = -\Phi_1\overline{u}_{Ra}[Y_{u1}]_{ai}Q_i - \Phi_2\overline{u}_{R3}[Y_{u2}]_iQ_i + \text{h.c.}$$

$$Y_{u1} = \begin{pmatrix} * & * & * \\ * & * & * \\ 0 & 0 & 0 \end{pmatrix}, \quad Y_{u2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}$$

As usual, going to Higgs basis, $\begin{pmatrix} H \\ h \end{pmatrix} = R_{\beta-\alpha}\begin{pmatrix} h^{\text{SM}} \\ h' \end{pmatrix}$

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = R_\beta \begin{pmatrix} \Phi^{\text{SM}} \\ \Phi' \end{pmatrix}, \text{ with } R_\theta = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}, \qquad (1)$$

$$\text{with } \Phi^{\text{SM}} = \begin{pmatrix} G^+ \\ (v_{\text{SM}} + h^{\text{SM}} + iG^0)/\sqrt{2} \end{pmatrix}, \ \Phi' = \begin{pmatrix} H^+ \\ (h' + iA^0)/\sqrt{2} \end{pmatrix}, \qquad (2)$$

$$Y_u^{\text{SM}} = \cos\beta Y_{u1} + \sin\beta Y_{u2}, \qquad Y_u' = -\sin\beta Y_{u1} + \cos\beta Y_{u2} = \begin{pmatrix} -\tan\beta & & \\ & -\tan\beta & \\ & & \cot\beta \end{pmatrix} Y_u^{SM}.$$

top-specific 2HDM

$$L^u = -\Phi_1 \overline{u}_{Ra}[Y_{u1}]_{ai}Q_i - \Phi_2 \overline{u}_{R3}[Y_{u2}]_i Q_i + \text{h.c.}$$

$$Y_{u1} = \begin{pmatrix} * & * & * \\ * & * & * \\ 0 & 0 & 0 \end{pmatrix} \ , \quad Y_{u2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}$$

$$L^u = -\Phi^{\text{SM}} \overline{u}_R [Y_u^{\text{SM}}] Q - \Phi' \overline{u}_R [Y'_u] Q + \text{h.c.}$$

$$Y^{\text{diag}} = VYU^\dagger, u_{R,\text{mass}} = Vu_R, Q_{L,\text{mass}} = UQ_L$$

$$Y_u^{\prime,\text{diag}} = \begin{pmatrix} -\tan\beta & & \\ & -\tan\beta & \\ & & \cot\beta \end{pmatrix} Y_u^{\text{diag}} + (\tan\beta + \cot\beta) H_u Y_u^{\text{diag}},$$

$$H_u \equiv V \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} V^\dagger - \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} \to \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1-\cos\rho & \sin\rho \\ 0 & \sin\rho & \cos\rho - 1 \end{pmatrix}$$

we restrict $c-t$ Flavor violation

top-specific 2HDM

$$L^u = -\Phi_1 \overline{u}_{Ra}[Y_{u1}]_{ai} Q_i - \Phi_2 \overline{u}_{R3}[Y_{u2}]_i Q_i + \text{h.c.}$$

$$Y_{u1} = \begin{pmatrix} * & * & * \\ * & * & * \\ 0 & 0 & 0 \end{pmatrix}, \quad Y_{u2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}$$

$$L^u = -\Phi^{\text{SM}} \overline{u}_R [Y_u^{\text{SM}}] Q - \Phi' \overline{u}_R [Y'_u] Q + \text{h.c.}$$

$$Y^{\text{diag}} = VYU^\dagger, u_{R,\text{mass}} = V u_R, Q_{L,\text{mass}} = U Q_L$$

$$Y_u^{\prime,\text{diag}} = \begin{pmatrix} -\tan\beta & & \\ & -\tan\beta & \\ & & \cot\beta \end{pmatrix} Y_u^{\text{diag}} + (\tan\beta + \cot\beta) H_u Y_u^{\text{diag}},$$

$$H_u \equiv V \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} V^\dagger - \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} \to \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1-\cos\rho & \sin\rho \\ 0 & \sin\rho & \cos\rho - 1 \end{pmatrix}$$

we restrict $c-t$ Flavor violation

in mass eigen basis $\begin{pmatrix} H \\ h \end{pmatrix} = R_{\beta-\alpha} \begin{pmatrix} h^{\text{SM}} \\ h' \end{pmatrix}$

$$\xi_f \equiv \begin{cases} \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) & (\text{for } f = t) \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for } f \neq t) \end{cases}$$

similar expressions in 2HDM

$$\mathcal{L}_Y \equiv -\sum_{f=e,\cdots,u,\cdots,d,\cdots} \xi_f \frac{m_f}{v_{\text{SM}}} h \overline{f} f + \mathcal{L}_{\text{FCNC}}$$

with $\mathcal{L}_{\text{FCNC}} = -a \sum_{f,f'=u,c,t} (H_u)_{ff'} \frac{m_{f'}}{v_{\text{SM}}} h \overline{f}_R f'_L + \text{h.c.}$

$$a \equiv (\tan\beta + \cot\beta)\cos(\beta-\alpha) \; .$$

$$a \sim \tan\beta\cos(\beta-\alpha)$$

FC effect proportional to a and m_{f_L}

top-specific 2HDM

$$L^u = -\Phi_1 \overline{u}_{Ra}[Y_{u1}]_{ai}Q_i - \Phi_2 \overline{u}_{R3}[Y_{u2}]_i Q_i + \text{h.c.}$$

$$Y_{u1} = \begin{pmatrix} * & * & * \\ * & * & * \\ 0 & 0 & 0 \end{pmatrix}, \quad Y_{u2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}$$

$$L^u = -\Phi^{\text{SM}} \overline{u}_R [Y_u^{\text{SM}}] Q - \Phi' \overline{u}_R [Y_u'] Q + \text{h.c.}$$

$$Y^{\text{diag}} = VYU^\dagger, u_{R,\text{mass}} = Vu_R, Q_{L,\text{mass}} = UQ_L$$

$$Y_u^{\prime,\text{diag}} = \begin{pmatrix} -\tan\beta & & \\ & -\tan\beta & \\ & & \cot\beta \end{pmatrix} Y_u^{\text{diag}} + (\tan\beta + \cot\beta) H_u Y_u^{\text{diag}},$$

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similar expressions in 2HDM

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with $\mathcal{L}_{\text{FCNC}} = -a \sum_{f,f'=u,c,t} (H_u)_{ff'} \frac{m_{f'}}{v_{\text{SM}}} h\overline{f}_R f'_L + \text{h.c.}$

model parameter: $a, \rho, \tan\beta$

$$a \equiv (\tan\beta + \cot\beta)\cos(\beta-\alpha)\,.$$

$$a \sim \tan\beta\cos(\beta-\alpha)$$

FC effect proportional to a and m_{f_L}

prediction in VA

Large

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\text{SM}}} h \begin{pmatrix} \bar{c}_R & \bar{t}_R \end{pmatrix} \begin{pmatrix} m_c(1-\cos\rho) & m_t\sin\rho \\ m_c\sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \text{h.c.}$$

Small

top FC decay $t \to ch$

Large

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\rm SM}} h \, (\bar{c}_R \quad \bar{t}_R) \begin{pmatrix} m_c(1-\cos\rho) & m_t \sin\rho \\ m_c \sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \text{h.c.}$$

Small

$\rho = 0 \to$ no FCNC

$$\text{BR}(t \to ch) = \frac{(1-r_h^2)^2}{8(1-r_W^2)^2(1+2r_W^2)|V_{tb}|^2} a^2 \sin^2\rho \simeq (3.24 \times 10^{-2}) a^2 \sin^2\rho \;.$$

current bound:

$BR(t \to ch) < 0.79$ (ATLAS), 1.3(CMS)% — $h \to \gamma\gamma$ arXiv:1403.6293; $h \to \ell s$ arXiv:1404.5801

$BR(t \to ch) < 0.56\%$ at 8 TeV (CMS limit from leptons + di photons) arXiv:1410.2751

$$a^2 \sin^2\rho < 0.17$$

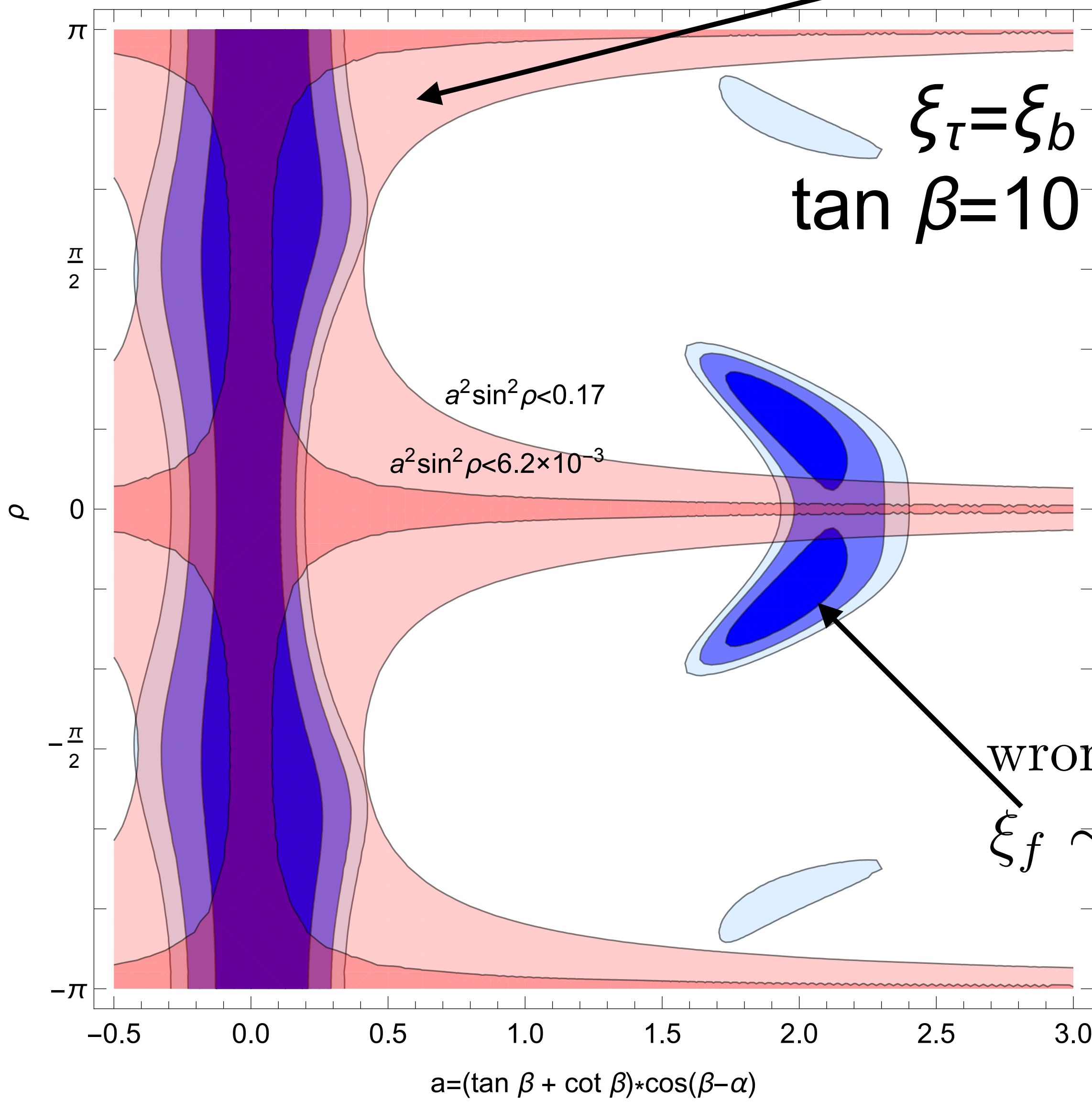
future exp.

2×10^{-4} (3000 fb^{-1} at 14 TeV) with $h \to \gamma\gamma$

$$a^2 \sin^2\rho < 6.2 \times 10^{-3}$$

Higgs global fit

allowed from $t \to ch$



wrong-sign Yukawa region

$\xi_f \sim -1$ other than top

not sensitive to $\tan\beta$ (for > 5)

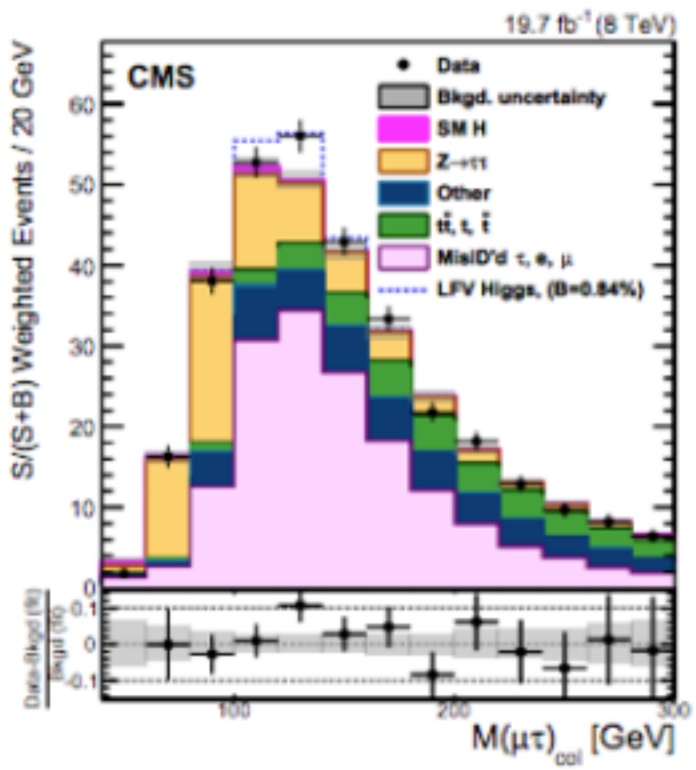
$a \sim \tan\beta\cos(\beta-\alpha)$

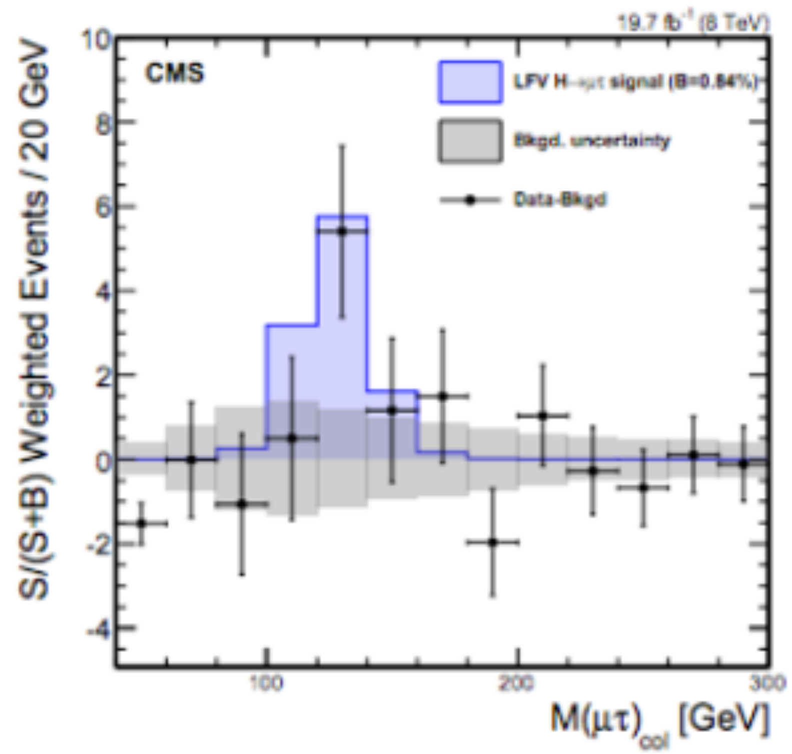
Observable	ATLAS [16]	CMS [17]
$\mu_{ZZ}^{\rm GGF}$	$1.7^{+0.5}_{-0.4}$	$0.883^{+0.336}_{-0.272}$
$\mu_{WW}^{\rm GGF}$	$0.98^{+0.29}_{-0.26}$	$0.766^{+0.228}_{-0.205}$
$\mu_{WW}^{\rm VBF}$	$1.28^{+0.55}_{-0.47}$	$0.623^{+0.593}_{-0.479}$
$\mu_{\gamma\gamma}^{\rm GGF}$	1.32 ± 0.38	$1.007^{+0.293}_{-0.259}$
$\mu_{bb}^{\rm VH}$	0.52 ± 0.40	$1.008^{+0.527}_{-0.499}$
$\mu_{\tau\tau}^{\rm GGF}$	$2.0^{+1.5}_{-1.2}$	$0.843^{+0.423}_{-0.382}$
$\mu_{\tau\tau}^{\rm VBF}$	$1.24^{+0.59}_{-0.54}$	$0.948^{+0.431}_{-0.379}$

$$\xi_f = \begin{cases} \sin(\beta-\alpha) + \left(\cot\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=t)\ , \\ \sin(\beta-\alpha) - \left(\tan\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=c)\ , \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for the others})\ . \end{cases}$$

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\rm SM}} h \left(\bar{c}_R \quad \bar{t}_R\right) \begin{pmatrix} m_c(1-\cos\rho) & m_t\sin\rho \\ m_c\sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \text{h.c.}$$

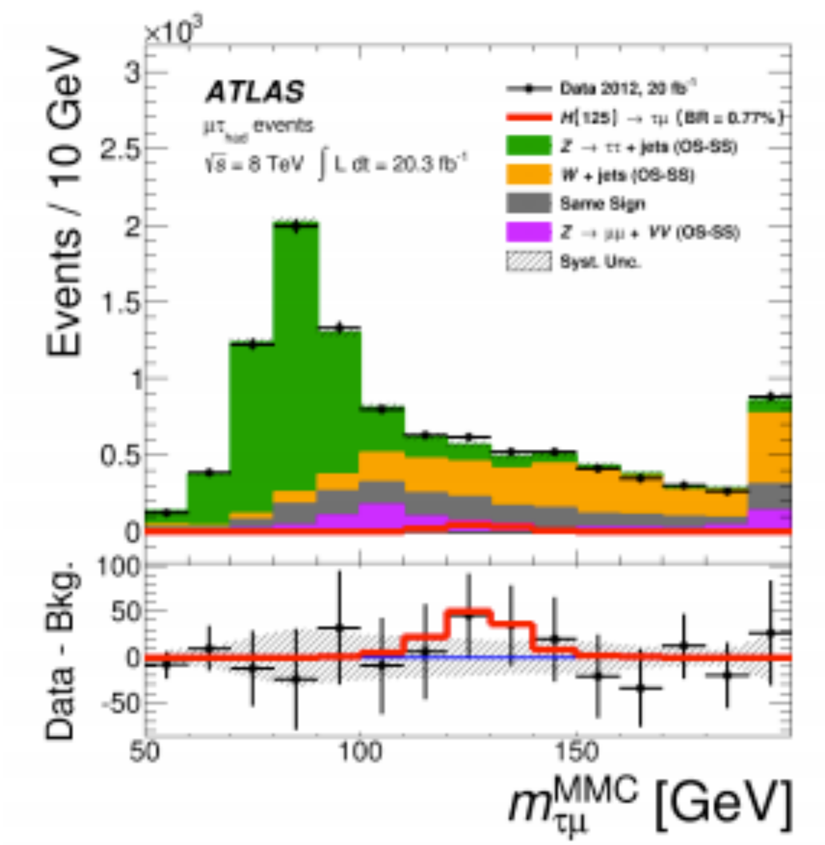
ATLAS and CMS h → $\tau\ \mu$ at 8 TeV





$$BR(h \to \tau\mu) = 0.84^{+0.39}_{-0.37}\%$$

arXiv:1502.07400



$$BR(h \to \tau\mu) = 0.77 \pm 0.62\%$$

arXiv:1508.03372

cf: $BR(h \to \tau\tau) \sim 6\%$

LFV higgs decay $h \to \tau\mu$

Large

$$\mathcal{L}_{\tau\mu} = -\frac{a}{2v_{\rm SM}} h \left(\bar{\mu}_R \quad \bar{\tau}_R\right) \begin{pmatrix} m_\mu(1-\cos\rho_\tau) & m_\tau \sin\rho_\tau \\ m_\mu \sin\rho_\tau & m_\tau(\cos\rho_\tau - 1) \end{pmatrix} \begin{pmatrix} \mu_L \\ \tau_L \end{pmatrix} + \text{h.c.}$$

Small

PQ charge of $\tau = +1$

$$\mathrm{BR_{obs}}(h \to \mu\tau) = \frac{N_{\rm obs}}{\mathcal{L}\ \mathcal{A}\ \sigma_{\rm SM}} = (0.84^{+0.39}_{-0.37})\ \%$$

$$\mathrm{BR_{obs}}(h \to \mu\tau) = \mathrm{BR_{VA}}(h \to \mu\tau)\frac{\sigma_{\rm VA}}{\sigma_{\rm SM}} \simeq {\xi_g}^2 \mathrm{BR_{VA}}(h \to \mu\tau)$$

$$a^2 \sin^2\rho_\tau \sim 0.35$$

$$\mathrm{BR_{VA}}(h \to \mu\tau) \simeq \frac{a^2 \sin^2\rho_\tau}{36.52{\xi_b}^2 + 14.64\sin^2(\beta-\alpha) + 5.44{\xi_g}^2 + 4{\xi_\tau}^2}$$

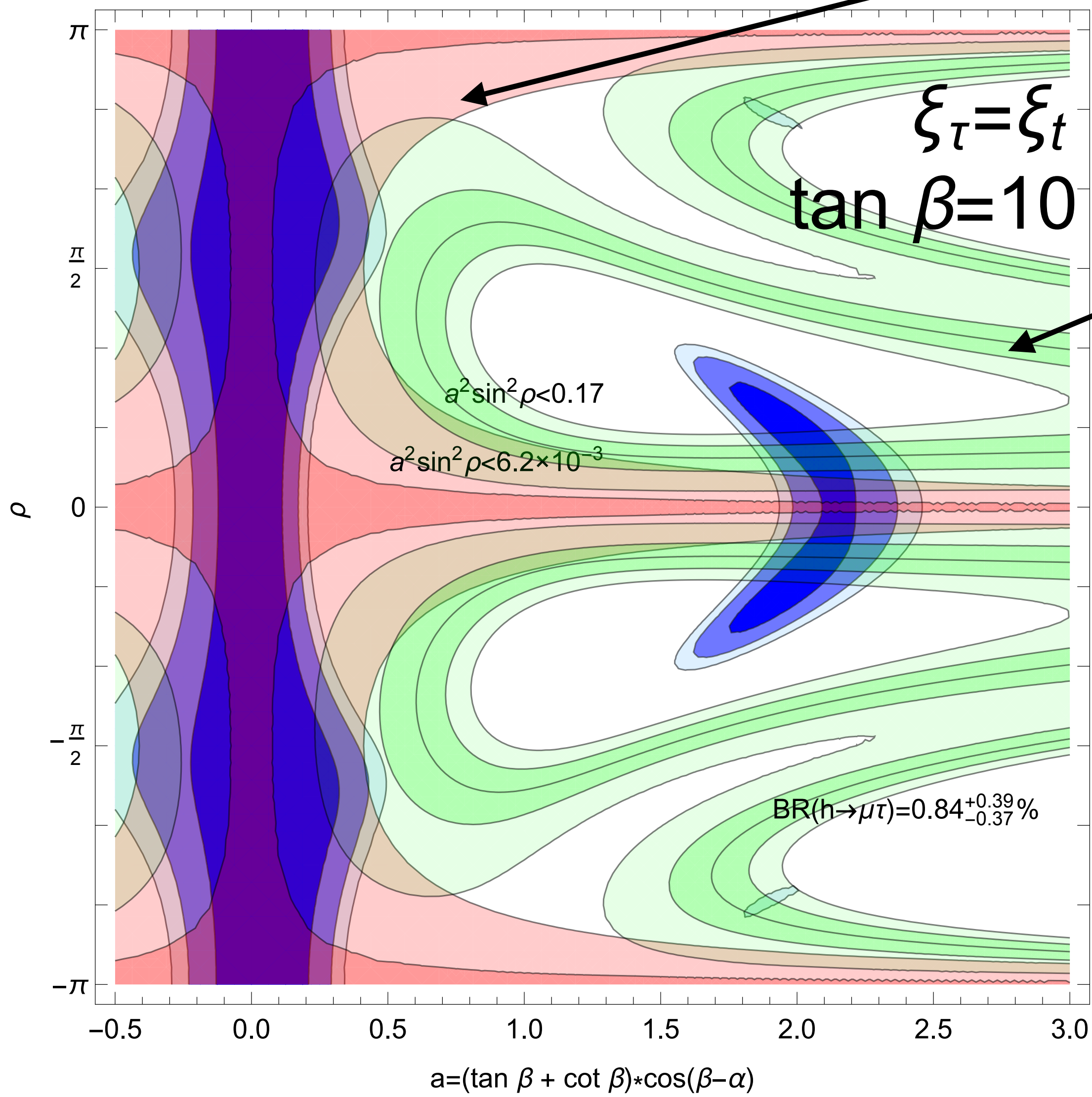
another prediction $h\bar{\mu}_R\tau_L$

always τ_L^- observed $(m_\mu \ll m_\tau)$

τ_L^- visible energy fraction softer.

worth checking the LHC data

Higgs global fit



remark: $\rho = \rho_\tau$ not necessary

but interesting there are the overlapping region

$$\xi_f = \begin{cases} \sin(\beta-\alpha) + \left(\cot\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=t)\ ,\ (\text{for } f=\tau) \\ \sin(\beta-\alpha) - \left(\tan\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=c)\ ,\ (\text{for } f=\mu) \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for the others})\ . \end{cases}$$

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\rm SM}} h \begin{pmatrix} \bar{c}_R & \bar{t}_R \end{pmatrix} \begin{pmatrix} m_c(1-\cos\rho) & m_t\sin\rho \\ m_c\sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \text{h.c.}$$

measuring helicity structure in top FC decay

Large

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\rm SM}} h \begin{pmatrix} \bar{c}_R & \bar{t}_R \end{pmatrix} \begin{pmatrix} m_c(1-\cos\rho) & m_t \sin\rho \\ m_c \sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \text{h.c.}$$

Small

$h\bar{c}_R t_L$: always c_R observed $(m_c \ll m_t)$ in $t \to ch$

from spin conservation, top helicity and direction of c_R is alined.

Spin analyzing power: $$\frac{1}{\Gamma_i}\frac{d\Gamma_i}{d\cos\theta_i} = \frac{1}{2}(1 + \kappa_i P \cos\theta_i)$$

κ_{ℓ^+}	$\kappa_{\bar{d}}$	κ_u	κ_b	κ_c	κ_h
$+1$	$+1$	-0.32	-0.39	$+1$	-1

(LO) $\kappa_f = -\bar{\kappa}_{\bar{f}}$

top from $t\bar{t}$ is unpolarized but Using spin correlation, we can check it.

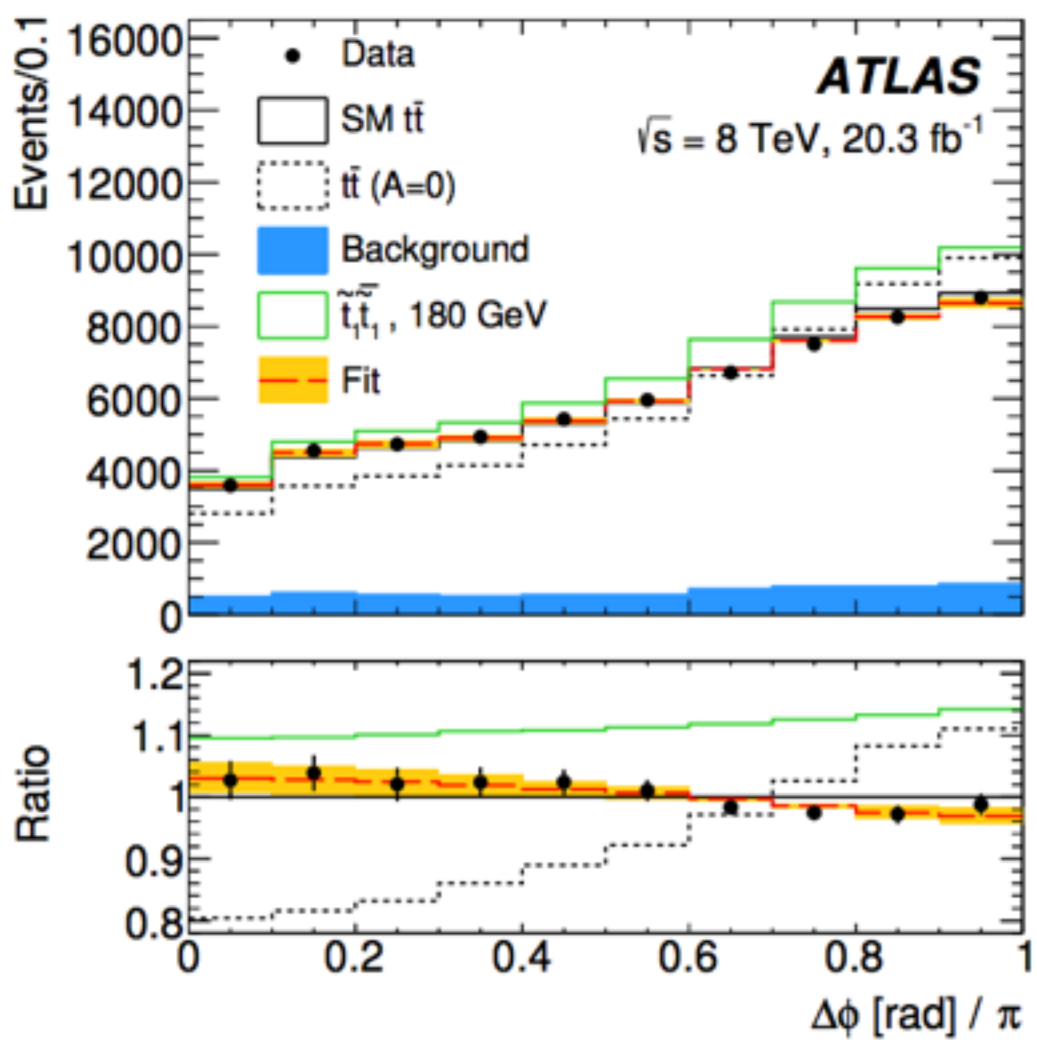
at LHC, helicity basis is known to be a reasonably good spin axis

$$A_{\rm hel} = \frac{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) - N(t_\uparrow \bar{t}_\downarrow) - N(t_\downarrow \bar{t}_\uparrow)}{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) + N(t_\uparrow \bar{t}_\downarrow) + N(t_\downarrow \bar{t}_\uparrow)} \sim 0.35 \quad (14\text{TeV})$$

measuring helicity structure in top FC decay $t \to ch$

$$\frac{1}{\Gamma_i}\frac{d\Gamma_i}{d\cos\theta_i} = \frac{1}{2}(1+\kappa_i P\cos\theta_i)$$

$\kappa_{\ell+}$	$\kappa_{\bar{d}}$	κ_u	κ_b	κ_c	κ_h
$+1$	$+1$	-0.32	-0.39	$+1$	-1



Already measured by ATLAS, CMS

arXiv:1412.4742 CMS-PAS-TOP-13-015

$$A_{\rm hel}^{{\rm SM},8TeV} = 0.318 \pm 0.005$$

$$A_{\rm hel}^{{\rm ATLAS},8TeV} = 0.38 \pm 0.04$$

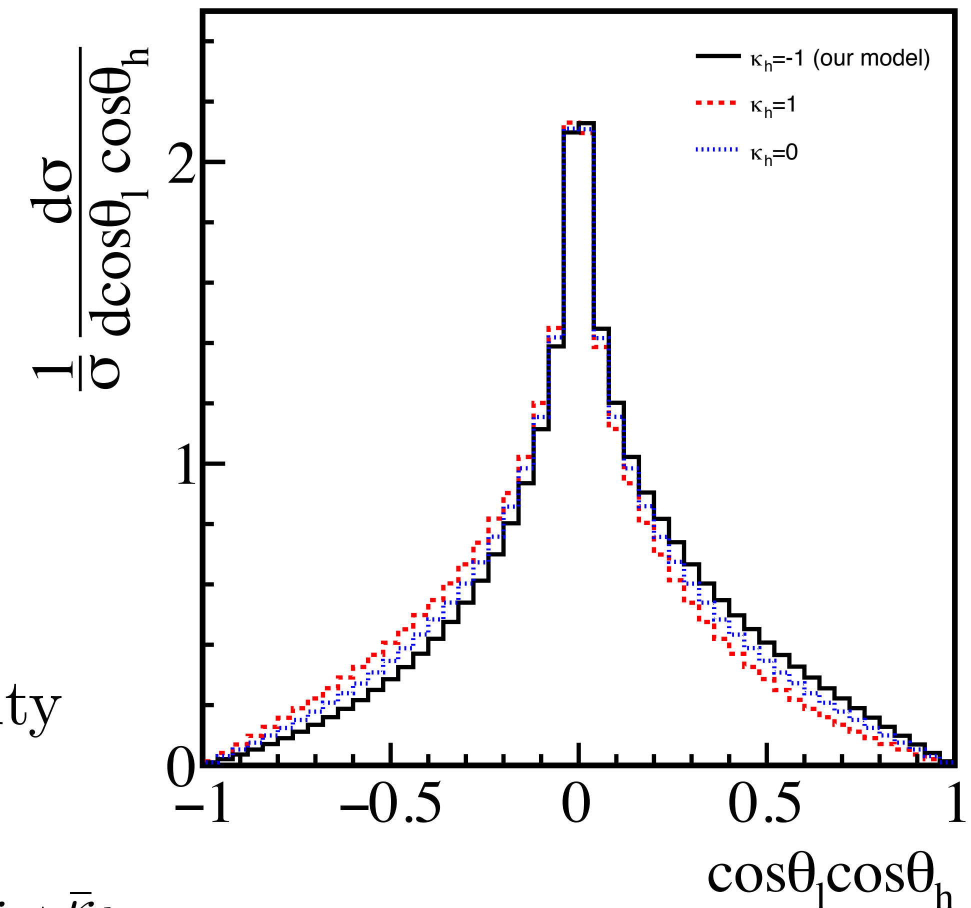
$$A_{\rm hel} = \frac{N(t_\uparrow\bar{t}_\uparrow)+N(t_\downarrow\bar{t}_\downarrow)-N(t_\uparrow\bar{t}_\downarrow)-N(t_\downarrow\bar{t}_\uparrow)}{N(t_\uparrow\bar{t}_\uparrow)+N(t_\downarrow\bar{t}_\downarrow)+N(t_\uparrow\bar{t}_\downarrow)+N(t_\downarrow\bar{t}_\uparrow)} \sim 0.35 \quad (14\text{TeV})$$

measuring helicity structure in top FC decay $t \to ch$

always c_R observed $(m_c \ll m_t)$

$$A_{\rm hel} = \frac{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) - N(t_\uparrow \bar{t}_\downarrow) - N(t_\downarrow \bar{t}_\uparrow)}{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) + N(t_\uparrow \bar{t}_\downarrow) + N(t_\downarrow \bar{t}_\uparrow)} \sim 0.35$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i d\cos\theta_j} = \frac{1}{4}(1 + A_{\rm hel}\,\kappa_i \bar{\kappa}_j \cos\theta_i \cos\theta_j)$$



Finally to provide a rough estimate for the sensitivity

$$A_{\ell h} = \frac{N(\cos\theta_\ell \cos\theta_h > 0) - N(\cos\theta_\ell \cos\theta_h < 0)}{N(\cos\theta_\ell \cos\theta_h > 0) + N(\cos\theta_\ell \cos\theta_h < 0)} = \frac{A_{\rm hel}\kappa_{\ell+}\bar{\kappa}_h}{4} \sim 0.088\bar{\kappa}_h.$$

$\Delta A_{\ell h} \simeq \Delta N/N \simeq 1/\sqrt{N} > 0.088$ → at least 130 signal events needed.

with $\sigma(t\bar{t}) \sim 1$ nb for 3 ab^{-1}, 3×10^9 top pair expecetd

even for $BR(t \to ch) BR(h \to \gamma\gamma) = 2 \times 10^{-4} \times 2.3 \times 10^{-3}$,

~ 500 of $t \to ch_{\to\gamma\gamma}$ events expected

Summary

We consider modified top yukawa couplings and rare top decay.

$$\kappa_t, \tilde{\kappa}_t, \kappa_g$$

We consider top specific 2HDM, which predicts FCNC $t \to ch$

The variant axion model is well motivated to solve strong CP and domain wall problems.

interesting overlapping of the parameter space to explain $h \to \tau\mu$

We predict in general distinct helicity structure in FC higgs couplings.

As top pairs are produced copiously at LHC, we should be able to test it using the spin correlation for a reasonable $BR(t \to ch)$.