Top Couplings @ Beyond...

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LHC Physics

Course on Physics at the LHC, 30th March, 2020

Cofinanciado por:

Main Topics in this Talk

- Global Fits of Data
- More on Top couplings:
  Top-Higgs Yukawa Couplings

....a change in analysis strategy
to improve performance,
required?

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Why is it necessary a precise model-independent measurement of the Wtb vertex structure?

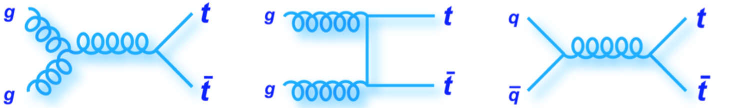
- It may reveal physics beyond the Standard Model
  - V_{tb} could be different from the Standard Model value
  - Anomalous couplings may appear at the vertex
- It may help understand possible other new physics beyond the Standard Model
  - top quarks decay almost exclusively to $t \to W^+ b$
  - understanding the structure of the Wtb vertex helps revealling possible non-standard $t\bar{t}$ production at LHC, $Zt\bar{t}/\gamma t\bar{t}$ couplings at ILC, etc.
  - important for B and K physics (indirect limits on anomalous couplings, see later)

The Wtb vertex must be determined by a global fit to several observables:

- Several, theorectically equivalent, observables studied for $t\bar{t}$ production at LHC (not all explored yet @ LHC)
- Single top cross section usefull (sensitive to V_{tb} and anomalous couplings)
- Indirect limits from $b \to s\gamma$ available (not used)
- The most general CP-conserving vertex for top quarks on-shell is used
- All couplings are allowed to vary freely in TopFit to find the allowed regions for a given CL

Global Fits of Data

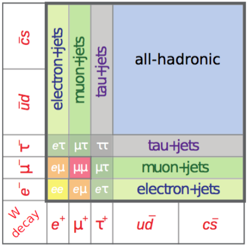
- Production at the LHC:



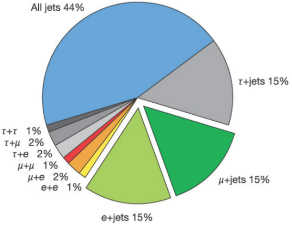
$\sigma(t\bar{t})$=177.3$\pm$9.9$^{+4.6}_{-6.0}$ pb @ 7 TeV, $\sigma(t\bar{t})$=252.9$\pm$11.7$^{+6.4}_{-8.6}$ pb @ 8 TeV, $\sigma(t\bar{t})$=832$^{+40}_{-46}$ pb @ 13 TeV

NNLO+NNLL, m_t =172.5 GeV PLB **710** 612 (2012), PRL **109** 132001(2012), JHEP **1212** 054(2012), JHEP **1301** 080(2013), PRL**110** 252004 (2013).

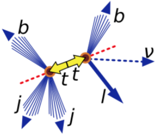
Top pair decay channels



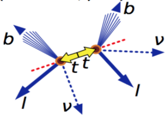
Top pair branching fractions



$\Longrightarrow$ Lepton+jets ($\sim$ 30%): ($\ell = e^{\pm}, \mu^{\pm}$)



$\Longrightarrow$ Dilepton ($\sim$ 5%): ($\ell = e^{\pm}, \mu^{\pm}$)



The Wtb vertex structure

Effective *Wtb* vertex from dim-6 operators

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_{\mathrm{L}}P_L + V_{\mathrm{R}}P_R)\,t\,W^-_{\mu}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_{\mathrm{L}}P_L + g_{\mathrm{R}}P_R)\,t\,W^-_{\mu} + \mathrm{h.c.}$$

$V_{\mathrm{L}} \equiv V_{tb} \sim 1$ (within SM)

$V_{\mathrm{R}}, g_{\mathrm{R}}, g_{\mathrm{L}} \Rightarrow$ anomalous couplings

[EPJC50 (2007) 519, NPB804 (2008) 160, NPB812 (2009) 181]

How to probe anomalous couplings in the *Wtb* vertex?

- indirect limits from *B*-physics
- measurements of single top quark production: cross-section and angular distibutions
- measurements of $t\bar{t}$ production: angular distributions of top quark decays

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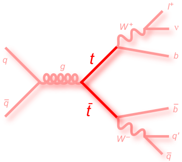
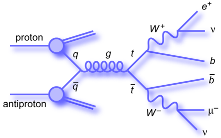
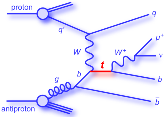
Main objective: extend the studies already performed at the LHC on top quark Anomalous Couplings/EFT in $t \rightarrow Wb$ decays to HL-LHC/HE-LHC

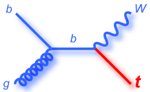
Several processes under study to probe the *Wtb* vertex[1]:

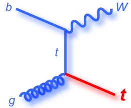
- Top quark pair production ($t\bar{t}$)
  - (i) semileptonic channel
  - (ii) dileptonic decays
- single top quark physics
  - (i) *t*-channel (single lepton)
  - (ii) *Wt*-channel (dileptonic decay)
- EFT/anomalous couplings studied associated to the *Wtb* vertex









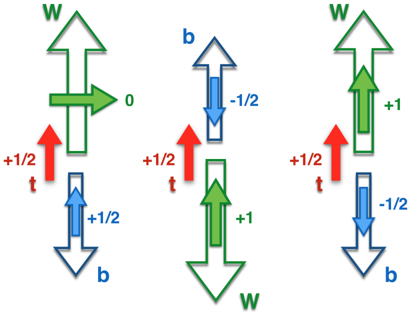


[1] JHEP**1206**(2012)088, EPJC**77**(2017)264, JHEP**04**(2017)124, JHEP**04**(2016)023, JHEP**12**(2017)017, PLB**717**(2012)330, PRD**90**(2014)112006, PLB**716**(2012)142, PLB**756**(2016)228, EPJC**77**(2017)531, JHEP**01**(2016)064, JHEP**04**(2017)086, JHEP**01**(2018)63, EPJC**78**(2018)186

Top quark pair production

Top quark pair production ($t\bar{t}$)

☞ Observable(s): angular distribution(s) $\cos\theta^*_\ell$ $[F_0, F_L, F_R]$



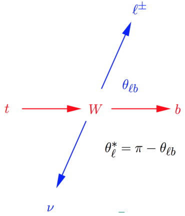
F_0
W Longitudinal fraction

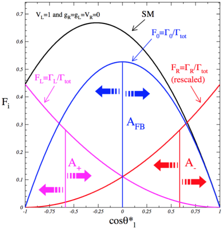
F_L
W Left-Handed fraction

F_R
W Right-Handed fraction

$$F_0^{\rm SM} = 0.687 \pm 0.005$$
$$F_L^{\rm SM} = 0.311 \pm 0.005$$
$$F_R^{\rm SM} = 0.0017 \pm 0.0001$$

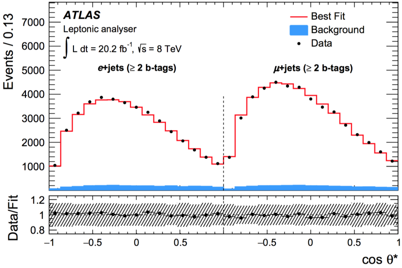
@ NNLO QCD calculation, PRD**81**(2010)111503
($F_0 + F_L + F_R = 1$)



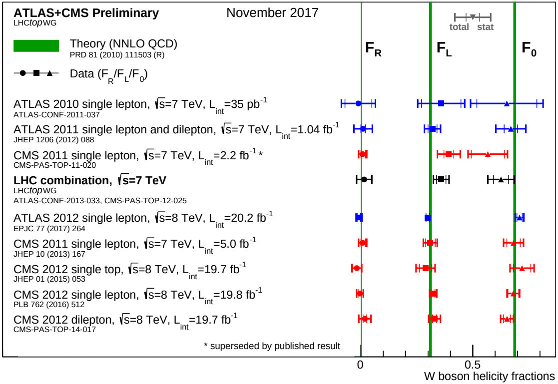


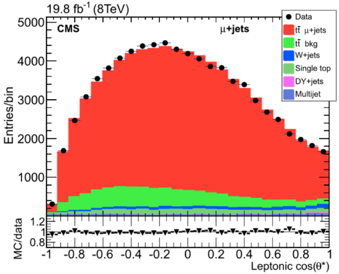
$$\frac{1}{N}\frac{dN}{d\cos\theta^*_\ell} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta^*_\ell}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\theta^*_\ell}{2}\right)^2 + F_R\left(\frac{1+\cos\theta^*_\ell}{2}\right)^2\right]$$

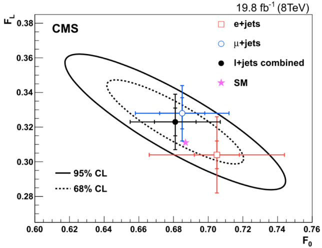
EPJC**77**(2017)264



Summary of W-boson helicity meas. @ LHC







$\Delta F_0/F_0$ ~2.7% (3.7× theo. unc.)

$\Delta F_L/F_L$ ~5% (3.1× theo. unc.)

F_R=-0.008±0.014

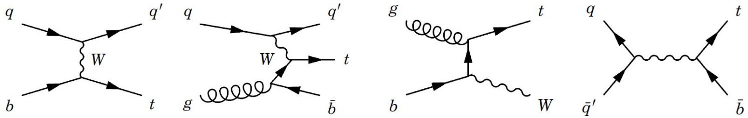
- [arXiv:hep-ph0605190v2 18 Mar 2007]

the modulus of the W boson three-momentum in the top quark rest frame. The total top width is

$$\begin{aligned}\Gamma \;=\; & \frac{g^2|\vec{q}|}{32\pi}\frac{m_t^2}{M_W^2}\left\{\left[|V_L|^2+|V_R|^2\right]\left(1+x_W^2-2x_b^2-2x_W^4+x_W^2x_b^2+x_b^4\right)\right.\\ & -12x_W^2x_b\,\mathrm{Re}\,V_LV_R^*+2\left[|g_L|^2+|g_R|^2\right]\left(1-\frac{x_W^2}{2}-2x_b^2-\frac{x_W^4}{2}-\frac{x_W^2x_b^2}{2}+x_b^4\right)\\ & -12x_W^2x_b\,\mathrm{Re}\,g_Lg_R^*-6x_W\mathrm{Re}\,\left[V_Lg_R^*+V_Rg_L^*\right]\left(1-x_W^2-x_b^2\right)\\ & \left.+6x_Wx_b\,\mathrm{Re}\,\left[V_Lg_L^*+V_Rg_R^*\right]\left(1+x_W^2-x_b^2\right)\right\}\,. \qquad (4)\end{aligned}$$

Single top quark production

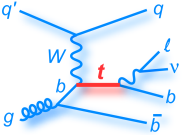
Single top quark production



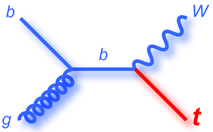
$$\sigma = \sigma_{SM} \left(V_L^2 + \kappa^{V_R} V_R^2 + \kappa^{V_L V_R} V_L V_R + \kappa^{g_L} g_L^2 + \kappa^{g_R} g_R^2 + \kappa^{g_L g_R} g_L g_R + \dots \right)$$

- the κ factors determine the dependence on anomalous couplings
- the κ factors are, in general, different for t and $\bar{t}$ production
- the measurement of the single top production cross-section allows to obtain a measurement of V_L ($\equiv V_{tb}$) and bounds on anomalous couplings

- Processes currently under study:



t-channel

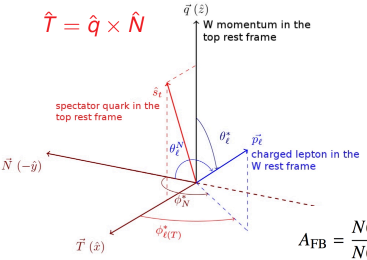


(*Wt*-prod.)

☞ Observables: 2D angular distributions in *t*-channel production as a function of 6 spin observabels $< S_{1,2,3} >$, $< T_0 >$, $< A_{1,2} >$ [PRD **93** (2016) 011301]

$\hat{N} = \hat{s}_t \times \hat{q}$

$\hat{T} = \hat{q} \times \hat{N}$



1) Double-differential distribution:

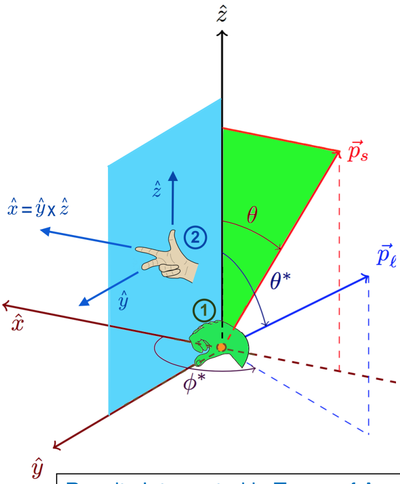
$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_\ell^*)d\phi_\ell^*} = \frac{3}{8\pi}\left\{\frac{2}{3} + \frac{1}{\sqrt{6}}\langle T_0\rangle\left(3\cos^2\theta_\ell^* - 1\right) + \langle S_3\rangle\cos\theta_\ell^* + \langle S_1\rangle\cos\phi_\ell^*\sin\theta_\ell^* + \langle S_2\rangle\sin\phi_\ell^*\sin\theta_\ell^* - \langle A_1\rangle\cos\phi_\ell^*\sin 2\theta_\ell^* - \langle A_2\rangle\sin\phi_\ell^*\sin 2\theta_\ell^*\right\}.$$

2) A_{FB} and A_{EC} Asymmetries:

$$A_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)} \qquad A_{EC} = \frac{N(|\cos\theta| > \frac{1}{2}) - N(|\cos\theta| < \frac{1}{2})}{N(|\cos\theta| > \frac{1}{2}) + N(|\cos\theta| < \frac{1}{2})}$$

Single top quark production

- Triple-differential (3D) decay rates of polarised top quarks
  - ☞ define specific coordinate system (in t centre-of-mass):



1) System Definition (in t-system):

$$\hat{z} = \hat{p}^*_W = \vec{p}^{\,*}_W / |\vec{p}^{\,*}_W|, \quad \vec{p}^{\,*}_s\text{=spectator quark mom.}$$

$$\hat{y} = \hat{p}^*_s \times \hat{p}^*_W, \qquad \hat{x} = \hat{y} \times \hat{p}^*_W$$

2) Triple-differential distribution:

$$\begin{aligned}
\varrho(\theta,\theta^*,\phi^*;P) = \frac{1}{N}\frac{d^3N}{d(\cos\theta)d\Omega^*} &= \frac{1}{8\pi}\Big\{\frac{3}{4}\left|A_{1,\frac{1}{2}}\right|^2(1+P\cos\theta)(1+\cos\theta^*)^2 \\
&+ \frac{3}{4}\left|A_{-1,-\frac{1}{2}}\right|^2(1-P\cos\theta)(1-\cos\theta^*)^2 \\
&+ \frac{3}{2}\left(\left|A_{0,\frac{1}{2}}\right|^2(1-P\cos\theta)+\left|A_{0,-\frac{1}{2}}\right|^2(1+P\cos\theta)\right)\sin^2\theta^* \\
&- \frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1+\cos\theta^*)\,\mathrm{Re}\left[e^{i\phi^*}A_{1,\frac{1}{2}}A^*_{0,\frac{1}{2}}\right] \\
&- \frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1-\cos\theta^*)\,\mathrm{Re}\left[e^{-i\phi^*}A_{-1,-\frac{1}{2}}A^*_{0,-\frac{1}{2}}\right]\Big\} \\
&= \sum_{k=0}^{1}\sum_{l=0}^{2}\sum_{m=-k}^{k} a_{k,l,m}M^m_{k,l}(\theta,\theta^*,\phi^*)\,,
\end{aligned}$$

A_{λ_W,λ_b} = helicity amplitudes $\qquad M^m_{k,l}(\theta,\theta^*,\phi^*) = \sqrt{2\pi}Y^m_k(\theta,0)Y^m_l(\theta^*,\phi^*)$

Results Interpreted in Terms of Anomalous Couplings (V_R, g_L, g_R) ☞ **next slide**

EFT/anomalous Couplings

General Wtb vertex

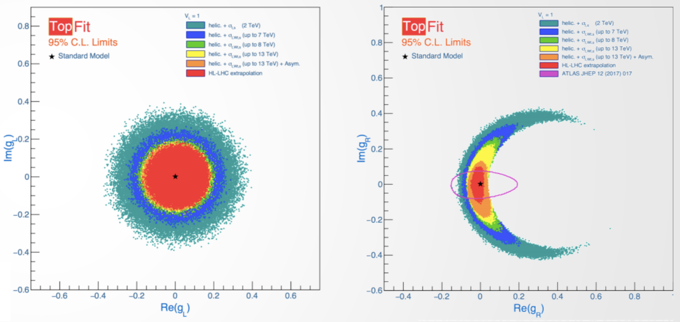
Eur.Phys.J. C50 (2007) 519-533

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-}$$

vector (V_R) and tensor like couplings (g_L, g_R) zero @ tree level in SM

☞ EFT parameters: anomalous couplings described by effective operators $\mathcal{O}_{uW}$,$\mathcal{O}_{dW}$, $\mathcal{O}_{\phi q}^{(3)}$ and $\mathcal{O}_{\phi ud}$ i.e., constraints on anomalous couplings equivalent to constraints on EFT parameters (a more integrating framework) [arXiv:1802.07237]

PRD 97 (2018) 1, 013007 (TopFit), arXiv:1811.02492

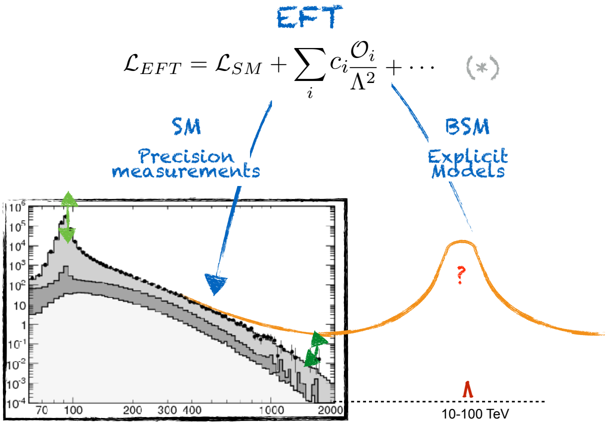


Fits Using:

σ, W_{hel}, A_{FB} @ 7,8,13 TeV

[Improvements from Theory]

☞ Effective Field Theory approach (EFT):



[Improvements from Theory]

☞ Effective Field Theory approach (EFT):

- Dimension 6 Operators:

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		*B*-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- Buchmuller, Wyler Nucl.Phys. **B268** (1986) 621-653, Grzadkowski et al arxiv:1008.4884

[Improvements from Theory]

☞ Effective Field Theory approach (EFT):

- Example of top quark operators:

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

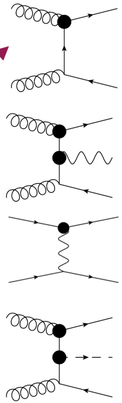
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

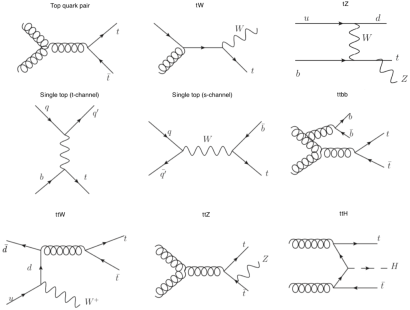
$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)(\bar{Q}t)\,\tilde{\phi}$$



+ Four-Fermion Operators
+ non-top operators (mixing)

[Improvements from Theory]

☞ Towards a Global SMEFT Fit:

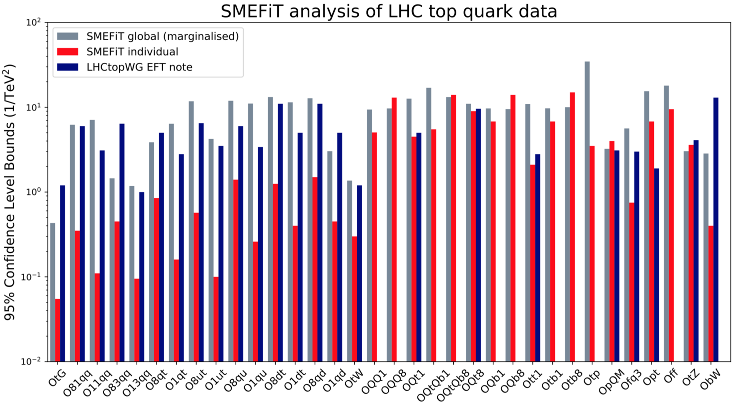


- Maltoni et al., arXiv:1901.05965
- 34 d.o.f., $\geq$ 100 observables

Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1									✓
OQb8									✓
Ott1								✓	
Otb1									✓
Otb8									✓
OQtQb1									(✓)
OQtQb8									(✓)
O81qq	✓				✓	✓	✓	✓	✓
O11qq	[✓]				[✓]	[✓]	[✓]	✓	✓
O83qq	✓	[✓]		[✓]	✓	✓	✓	✓	✓
O13qq	[✓]	✓		✓	[✓]	[✓]	[✓]	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	[✓]				[✓]	[✓]	[✓]	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	[✓]					[✓]	[✓]	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	[✓]					[✓]	[✓]	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	[✓]					[✓]	[✓]	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	[✓]					[✓]	[✓]	✓	✓
OtG	✓		✓		✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)	(✓)					
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓					
OpQM				✓		✓			
Opt				✓		✓			
Otp							✓		

[Improvements from Theory]

☞ Towards a Global SMEFT Fit: Results



- Maltoni et al., arXiv:1901.05965 [LHCTopWG EFT note, arXiv:1802.07237]

Main Topics in this Talk

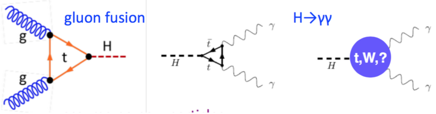
- Global Fits of Data
- More on Top couplings:
  Top-Higgs Yukawa Couplings

....a change in analysis strategy
to improve performance,
required?

all about top quark-Higgs Couplings!

- the top quark has the biggest coupling to the Higgs SM boson ($Y_t \sim 1.$)
- precision measurements of top quark Yukawa couplings are really important
- .....as well as deviations !!!
- need also to understand the nature of the coupling ($h = H, A$)
- indirect constraints are important (involve several contributions)

top-Higgs interactions contribute to the loops



probing CP-even(a) -odd(d) nature of couplings in $t\bar{t}H$,

$$L_{hf\bar{f}} \sim [a_f + ib_f\gamma_5] \sim [cos(\alpha) + isin(\alpha)\gamma_5]$$

PRL **76**, 24 (1996)
J.F.Gunion, Xiao-Gang He

$$a_1, a_2, b_1, b_2, b_3 \ldots b_4 = \frac{p_t^z p_{\bar{t}}^z}{|p_t||p_{\bar{t}}|}$$

PRD **92**, 1 (2015)
F.Boudjema, R.M.Godbole, D.Guadagnoli, K.A.Mohan

$$\Delta\phi^{t\bar{t}}(l+, l-),\ \beta_{b\bar{b}}\Delta\theta^{lh}(l+, l-)$$

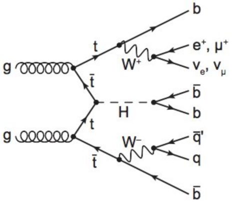
$$\beta \equiv \mathrm{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})\right)$$

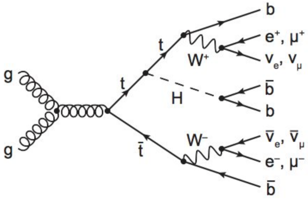
$$\cos(\Delta\theta^{\ell h}(\ell^+, \ell^-)) = \frac{(\vec{p}_h \times \vec{p}_{\ell^+}) \cdot (\vec{p}_h \times \vec{p}_{\ell^-})}{|\vec{p}_h \times \vec{p}_{\ell^+}||\vec{p}_h \times \vec{p}_{\ell^-}|}$$

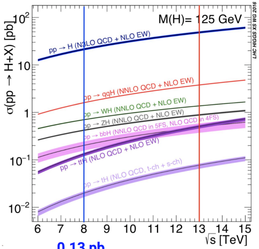
- need to understand $t\bar{t}H$ production and decay

arXiv:1611.00049v2, A.Broggio,A.Ferroglia,B.D.Pecjak,L.L.Yang

Top-Higgs Yukawa Couplings

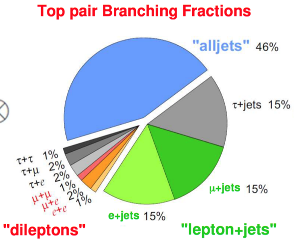






0.13 pb **0.50 pb**

⊗



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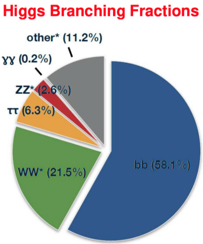
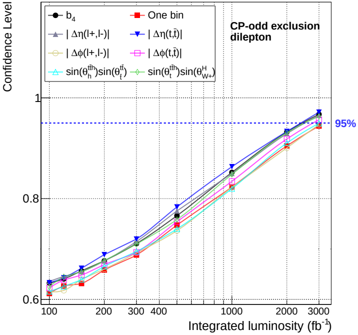
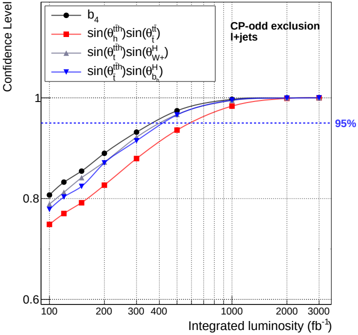


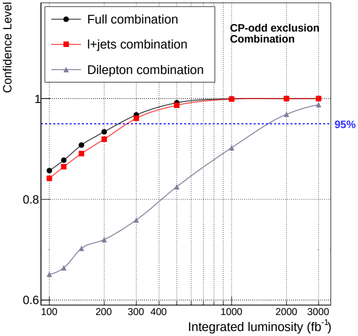
Top-Higgs Yukawa Couplings

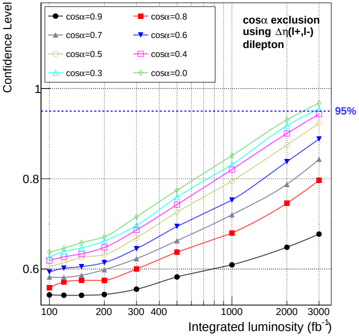




Direct Dileptonic exclusion limits as a function of luminosity [arXiv:1902.00134v2]

Top-Higgs Yukawa Couplings



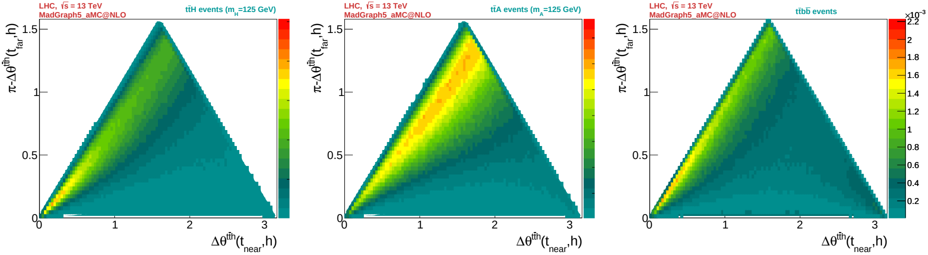


Direct Semileptonic+Dileptonic exclusion limits as a function of luminosity [arXiv:1902.00134v2]

Semileptonic channel roughly $\times$5 better than Dileptonic

The role of $t\bar{t}H$ centre-of-mass system

[Phys. Rev. **D** 100, 075034 (2019)]

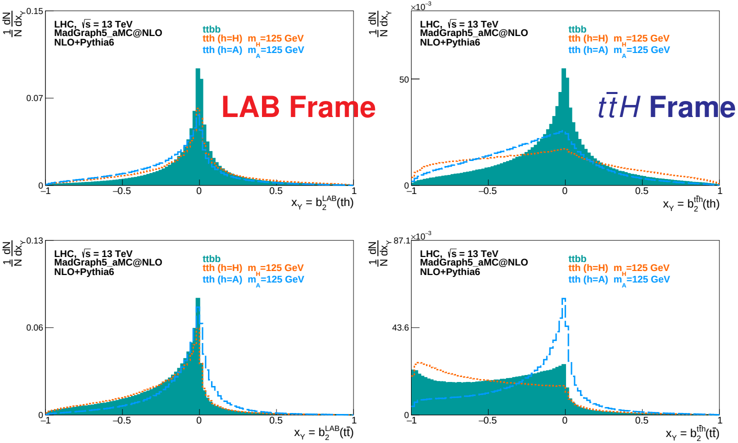


$$b_2^f(i,j) = \frac{(\vec{p}_i^{\,f} \times \hat{k}_z).(\vec{p}_j^{\,f} \times \hat{k}_z)}{|\vec{p}_i^{\,f}||\vec{p}_j^{\,f}|},$$

$$b_4^f(i,j) = \frac{p_{i,z}^f \; p_{j,z}^f}{|\vec{p}_i^{\,f}||\vec{p}_j^{\,f}|},$$

The role of $t\bar{t}H$ centre-of-mass system: the b_2 variable

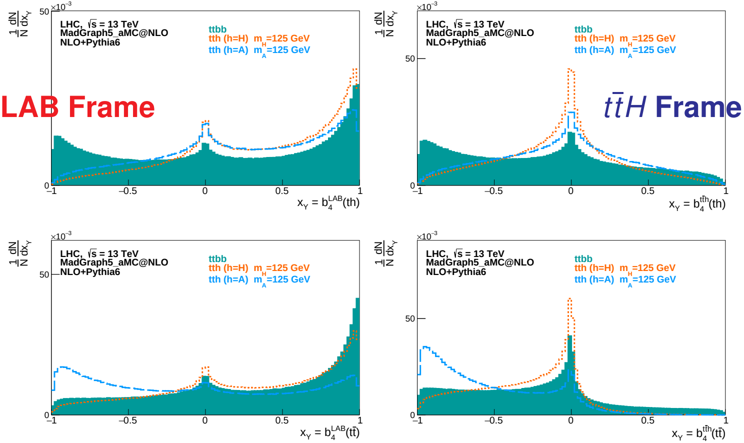
[Phys. Rev. **D** 100, 075034 (2019)]



Top-Higgs Yukawa Couplings

The role of $t\bar{t}H$ centre-of-mass system: the b_4 variable

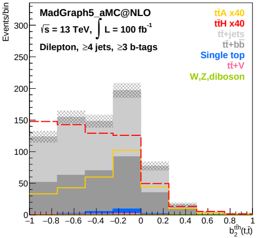
[Phys. Rev. **D** 100, 075034 (2019)]

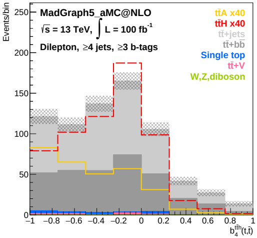


Top-Higgs Yukawa Couplings

The role of $t\bar{t}H$ centre-of-mass system: the b_2 and b_4 variables [Phys. Rev. **D** 100, 075034 (2019)]

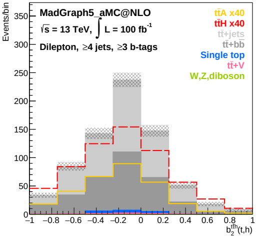
$b_2^{t\bar{t}h}(t\bar{t})$

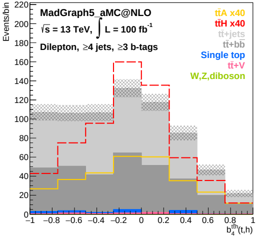




$b_4^{t\bar{t}h}(t\bar{t})$

$b_2^{t\bar{t}h}(th)$





$b_4^{t\bar{t}h}(th)$

The role of $t\bar{t}H$ centre-of-mass system: b_2 and b_4

[Phys. Rev. **D** 100, 075034 (2019)]

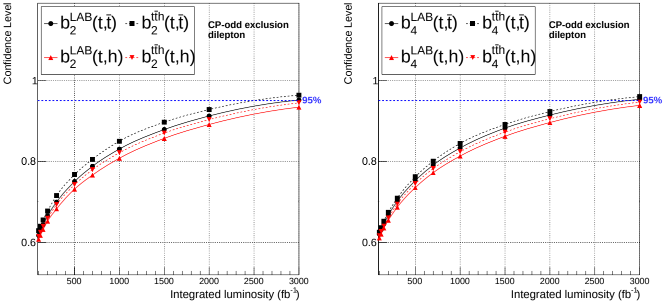
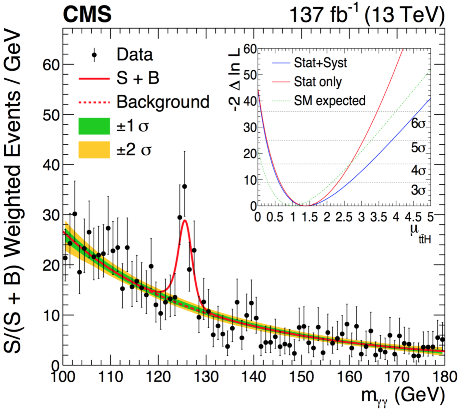


Figure: Expected CLs, assuming the SM (including the scalar Higgs), for exclusion of the pure CP-odd scenario for dileptonic $t\bar{t}h$ ($h \to b\bar{b}$).

b_2^f (in the $t\bar{t}h$) requires 250 fb^{-1} less lumin. for the same CL, when comp. to LAB



CMS CERN-EP-2020-028
2020/03/25

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t,$$

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t).$$

To conclude, we presented the first single-channel observation of the $t\bar{t}H$ process and the first measurement of the CP structure of the Htt coupling using the $H \to \gamma\gamma$ channel. The cross section of the $t\bar{t}H$ process is measured to be $\sigma_{t\bar{t}H}\mathcal{B}_{\gamma\gamma} = 1.56^{+0.34}_{-0.32}$ fb, corresponding to $1.38^{+0.36}_{-0.29}$ times the SM prediction, with a significance of 6.6σ. The data disfavor the pure CP-odd model of the Htt coupling at 3.2σ, and a possible fractional CP-odd contribution is constrained to be $f_{CP}^{Htt} = 0.00 \pm 0.33$ at 68% CL.

Global Fits to Data (up to the HL-LHC):

1) global analysis approach
2) full kinematical reconstruction
3) angular distributions identified in several signal regions
4) fit the Standard Model and extract EFT wilson coefficients
5) need to go global !!!

Top-Higgs Yukawa Couplings (contribution to the HL-LHC):

1) many new angular observables available
2) sensitivity of the semileptonic final state better (factor 5) then dileptonic
3) combination allow probing top quark Yukawa coupling in the fermionic sector