Top Couplings @ Beyond...

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LHC Physics

Course on Physics at the LHC, 6th April, 2021

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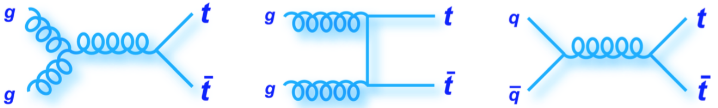
Why is it necessary a precise model-independent measurement of the Wtb vertex structure?

- 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

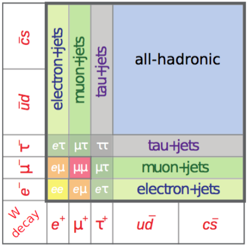
- Production at the LHC:



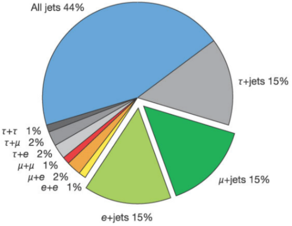
$\sigma(t\bar{t})$=177.3$\pm$9.9$^{+4.6}_{-6.0}$ pb @ 7 TeV, $\sigma(t\bar{t})$=252.9$\pm$11.7$^{+6.4}_{-8.6}$ pb @ 8 TeV, $\sigma(t\bar{t})$=832$^{+40}_{-46}$ pb @ 13 TeV

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).

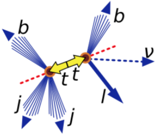
Top pair decay channels



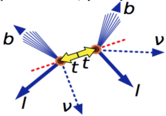
Top pair branching fractions



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

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B-physics constraints to *Wtb* vertex

IFT-2/2008

Anomalous Wtb coupling effects in the weak radiative B-meson decay

Bohdan Grzadkowski and Mikołaj Misiak
Institute of Theoretical Physics, University of Warsaw, PL-00-681 Warsaw, Poland and
Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland
(Dated: February 7, 2008)

We study the effect of anomalous Wtb couplings on the $\bar{B} \to X_s \gamma$ branching ratio. The considered couplings are introduced as parts of gauge-invariant dimension-six operators that are built out of the Standard Model fields only. One-loop contributions from the charged-current vertices are assumed to be of the same order as the tree-level flavour-changing neutral current ones. Bounds on the corresponding Wilson coefficients are derived.

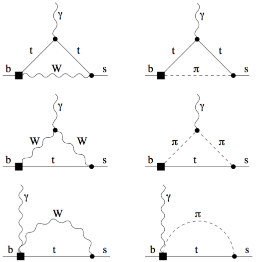


FIG. 1: Diagrams with non-SM $b \to t$ vertices that contribute to $f_7^{g_{L,R}}(x)$. The pseudogoldstone boson is denoted by π.

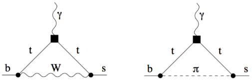


FIG. 2: Diagrams with non-SM $\bar{t}t\gamma$ vertices that contribute to $f_7^{g_R}(x)$.

't Hooft gauge. The relevant Feynman diagrams with non-SM $b \to t$ vertices are shown in Fig. 1. In addition, analogous six diagrams with non-SM $t \to s$ vertices and two diagrams with non-SM $\bar{t}t\gamma$ vertices (Fig. 2) occur in the case of $f_7^{g_R}$(x). In the case of $f_7^{g_L}$(x), there are also diagrams where the intermediate t-quark gets replaced by u or c. The functions $f_8^{g_{L,R}}(x)$ have been found by replacing the external photon by the gluon in the diagrams like the ones in the first row of Fig. 1.

Our final results for $f_i^{g_{L,R}}(x)$ read:

[EPJC57 (2008) 183]

B-physics constraints to Wtb vertex

$$BR(\bar{B} \to X_s\gamma) = \left(3.55 \pm 0.24 \,^{+0.09}_{-0.10} \pm 0.03\right) \times 10^{-4}$$

[hep-ex/0603003]

$$\begin{aligned} BR(B \to X_s\gamma) \times 10^4 &= (3.15 \pm 0.23) - 4.14\,(V_L - V_{tb}) + 411\, V_R \\ &- 53.9\, g_L - 2.12\, g_R - 8.03\, C_7^{(p)}(\mu_0) \\ &+ \mathcal{O}\left[\left(V_L - V_{tb}, V_R, g_L, g_R, C_7^{(p)}\right)^2\right] \end{aligned}$$

$$\mathcal{O}\left[(V_L - V_{tb}, V_R, \ldots)^2\right] \simeq 1.32(V_L - V_{tb})^2 - 262(V_L - V_{tb})V_R + 12970\, V_R^2 + \ldots$$

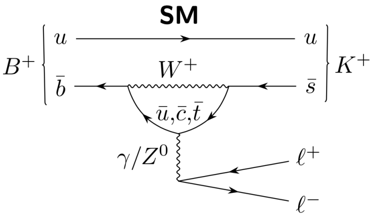
	$V_L - V_{tb}$	V_R	g_L	g_R	$C_7^{(p)}(\mu_0)$
upper bound	0.04	0.0024	0.003	0.08	0.02
lower bound	−0.24	−0.0004	−0.018	−0.46	−0.12

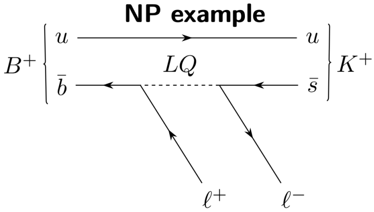
[EPJC57 (2008) 183]

B Mesons Rare Decays

$B^+ \to K^+\ell^+\ell^-$ and related decays

- Occur through $b \to s\ell^+\ell^-$ transition but in contrast to $B^0_s \to \ell^+\ell^-$, contain a hadron in the final state.
  e.g $B^+ \to K^+\ell^+\ell^-$, $B^0 \to K^{*0}\ell^+\ell^-$, $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda^*\ell^+\ell^-$...





- Offer multitude of observables complementary to $B^0_s \to \ell^+\ell^-$ measurements.

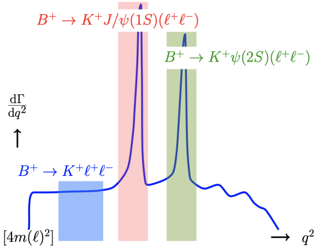
[K.A.Petridis, CERN talk, March 23, 2021]

Measurement Strategy

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = \frac{N^{\mathrm{rare}}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}\ \varepsilon^{\mathrm{rare}}_{e^+e^-}}{N^{\mathrm{rare}}_{e^+e^-}\ \varepsilon^{J/\psi}_{e^+e^-}}$$

$\rightarrow R_K$ is measured as a **double ratio** to cancel out most systematics

- Rare and J/ψ modes share identical selections apart from cut on q^2
- Yields determined from a fit to the invariant mass of the final state particles
- Efficiencies computed using simulation that is calibrated with control channels in data



($q^2 \equiv$ dilepton invariant mass squared)

[K.A.Petridis, CERN talk, March 23, 2021]

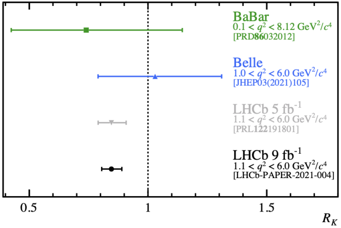
B Mesons Rare Decays

R_K with full Run1 and Run2 dataset

[LHCb-PAPER-2021-004]**Submitted to Nature Physics**

$$R_K = 0.846 \, ^{+0.042}_{-0.039} \, (\text{stat}) \, ^{+0.013}_{-0.012} \, (\text{syst})$$

- p-value under SM hypothesis: 0.0010
  $\rightarrow$ Evidence of LFU violation at 3.1σ



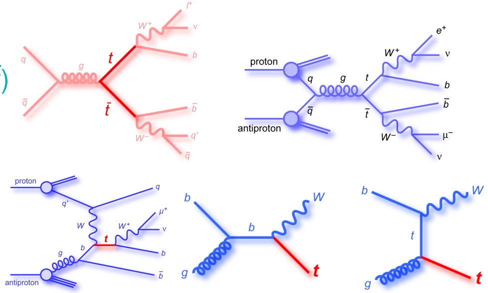
[K.A.Petridis, CERN talk, March 23, 2021]

Global Fits of Data

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

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

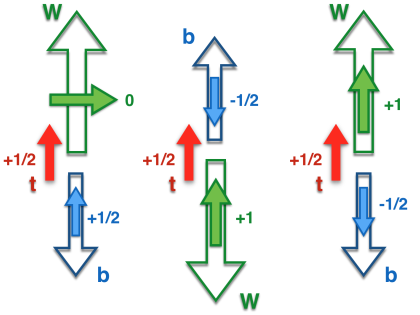
- Top quark pair production ($t\bar{t}$)
  - (i) semileptonic channel
  - (ii) dileptonic decays
- single top quark physics
  - (i) t-channel (single lepton)
  - (ii) Wt-channel (dileptonic decay)
- EFT/anomalous couplings studied associated to the Wtb vertex



[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

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



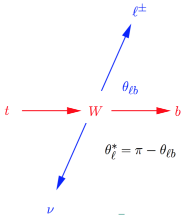
F_0
W Longitudinal fraction

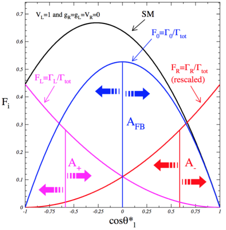
F_L
W Left-Handed fraction

F_R
W Right-Handed fraction

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

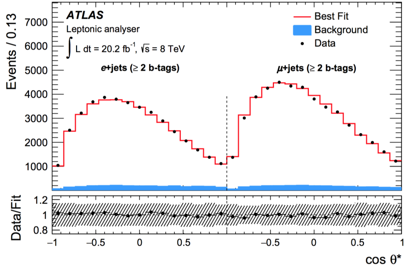
@ NNLO QCD calculation, PRD**81**(2010)111503
($F_0 + F_L + F_R = 1$)





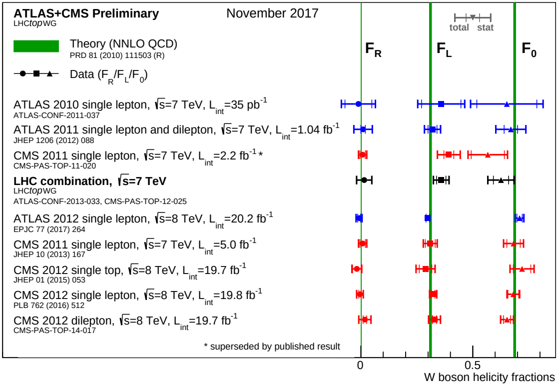
$$\frac{1}{N}\frac{dN}{d\cos\theta^*_\ell} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta^*_\ell}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\theta^*_\ell}{2}\right)^2 + F_R\left(\frac{1+\cos\theta^*_\ell}{2}\right)^2\right]$$

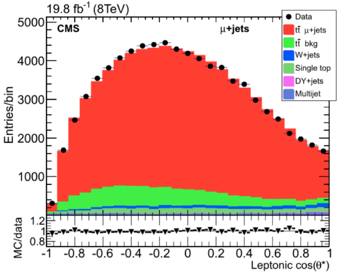
EPJC**77**(2017)264

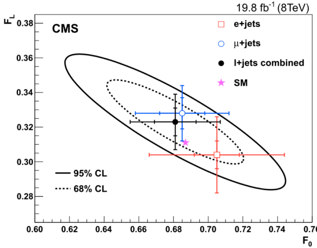


Top quark pair production ($t\bar{t}$)

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

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

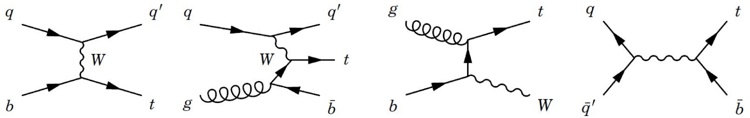
- [arXiv:hep-ph0605190v2 18 Mar 2007]

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

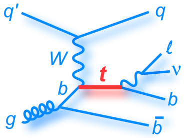


$$\sigma = \sigma_{SM}\left(V_L^2 + \kappa^{V_R} V_R^2 + \kappa^{V_L V_R} V_L V_R + \kappa^{g_L} g_L^2 + \kappa^{g_R} g_R^2 + \kappa^{g_L g_R} g_L g_R + \dots\right)$$

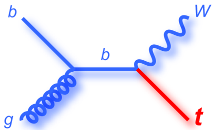
- the κ factors determine the dependence on anomalous couplings
- the κ factors are, in general, different for t and $\bar{t}$ production
- the measurement of the single top production cross-section allows to obtain a measurement of V_L ($\equiv V_{tb}$) and bounds on anomalous couplings

Single top quark production

- Processes currently under study:



t-channel

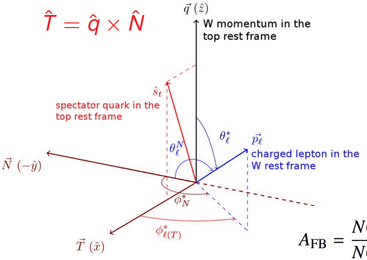


(*Wt*-prod.)

☞ 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:

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

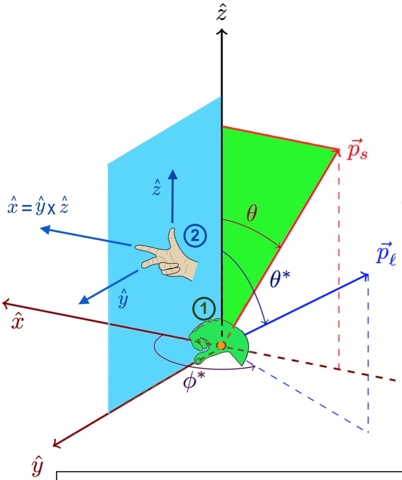
2) A_{FB} and A_{EC} Asymmetries:

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

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

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):

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

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

2) Triple-differential distribution:

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

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

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

EFT/anomalous Couplings

General Wtb vertex

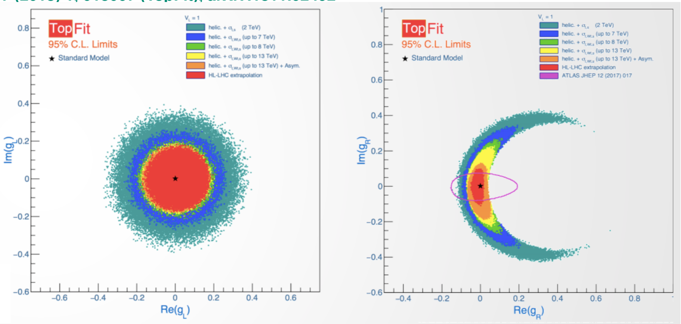
Eur.Phys.J. C50 (2007) 519-533

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

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

☞ EFT parameters: anomalous couplings described by effective operators $\mathcal{O}_{uW}$,$\mathcal{O}_{dW}$, $\mathcal{O}^{(3)}_{\phi q}$ 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:

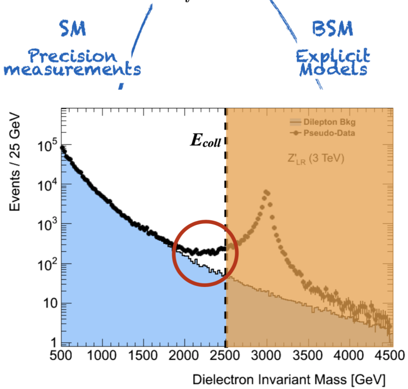
σ, W_{hel}, A_{FB} @ 7,8,13 TeV

[Improvements from Theory]

☞ Effective Field Theory approach (EFT):

EFT

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i c_i \frac{\mathcal{O}_i}{\Lambda^2} + \cdots \quad (*)$$



[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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	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:

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

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

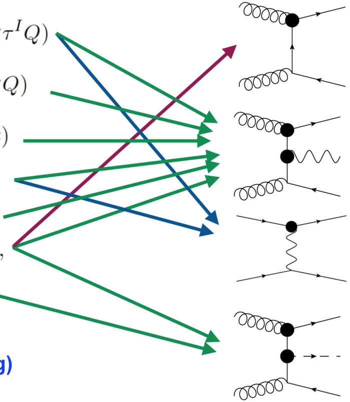
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right) (\bar{t}\gamma^\mu t)$$

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

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

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

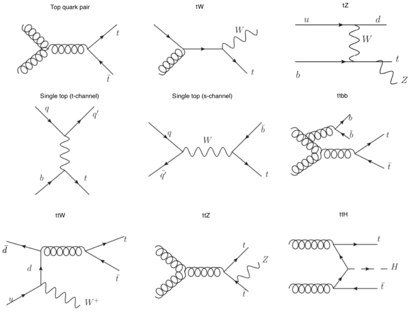
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\,\tilde{\phi}$$



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

[Improvements from Theory]

☞ Towards a Global SMEFT Fit:

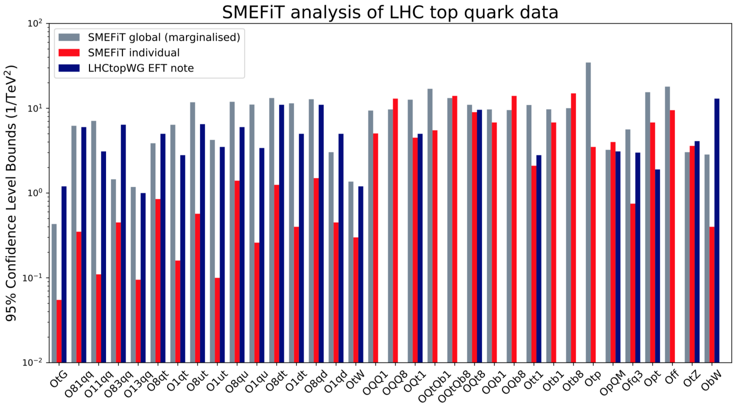


- Maltoni et al., arXiv:1901.05965
- 34 d.o.f., $\geq$ 100 observables

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



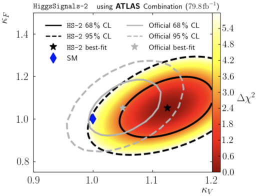
- Maltoni et al., arXiv:1901.05965 [LHCTopWG EFT note, arXiv:1802.07237]

Simplified Likelihoods

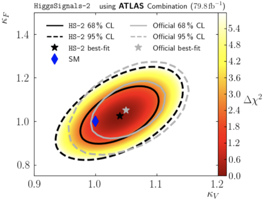
- On the (practical) importance of correlations:
  - ✓ **Example:** Interpreting ATLAS Run 2 Higgs STXS in terms of SM coupling modifiers

P. Bechtle et al., Eur. Phys. J.C 81 (2021) 2, 145 [arXiv:2012.09197]

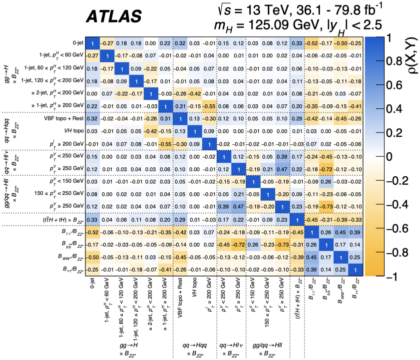
Neglecting Exp. Corr



Including Exp. Corr

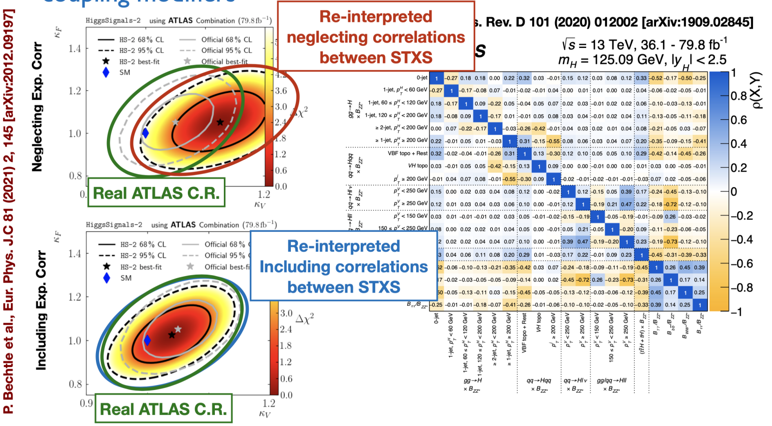


ATLAS coll., Phys. Rev. D 101 (2020) 012002 [arXiv:1909.02845]



Simplified Likelihoods

- On the (practical) importance of correlations:
  - ✓ **Example:** Interpreting ATLAS Run 2 Higgs STXS in terms of SM coupling modifiers



Main Topics in this Talk

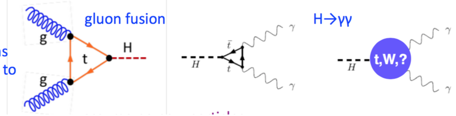
- Global Fits of Data
- More on Top couplings:
  Top-Higgs Yukawa Couplings

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

Top-Higgs Yukawa Couplings

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)



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

$$L_{hf\bar{f}} \sim [k_t + i\tilde{k}_t\gamma_5] \sim [kcos(\alpha) + iksin(\alpha)\gamma_5]$$

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

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

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

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

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

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

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

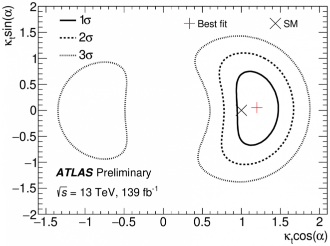
arXiv:1611.00049v2, A.Broggio,A.Ferroglia,B.D.Pecjak,L.L.Yang

Great first episode - first appearance of a constraints on the top CPV angle!

$$pp \to (h \to \gamma\gamma)\bar{t}t$$

$$\mathcal{L}^{CPV}_{\bar{t}th} = -\frac{y_f}{\sqrt{2}}\,\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)\,t\,h$$

All measurements are consistent with the SM expectations, and the possibility of a pure CP-odd coupling between the Higgs boson and top quark is severely constrained. A pure CP-odd coupling is excluded at 3.9σ, and |α| > 43° is excluded at 95% CL.



$$\kappa_t = \kappa\,\cos\alpha$$

$$\tilde{\kappa}_t = \kappa\,\sin\alpha$$

ATLAS collaboration, PRL 125 (2020) 6, 061802

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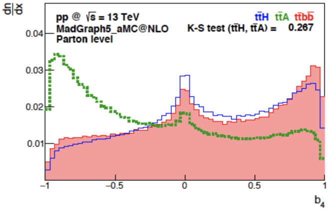
Constraints from Global Fits

The spin averaged cross section of tth productions has terms proportional to a^2+b^2 and to a^2-b^2. Terms a^2-b^2 are proportional to the top quark mass. There are many operators that can distinguish CP-even and CP-odd parts.

$$b_4 = \frac{p_t^z p_{\bar{t}}^z}{p_t p_{\bar{t}}}$$

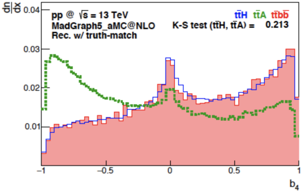
Like a good port wine!

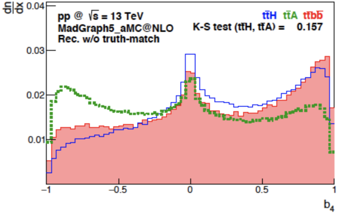


GUNION, HE, PRL77 (1996) 5172

BOUDJEMA, GODBOLE, GUADAGNOLI, MOHAN, PHYS.REV.D 92 (2015) 1, 015019

AMOR DOS SANTOS EAL PRD96 (2017) 013004





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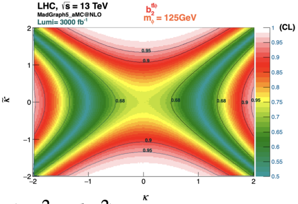
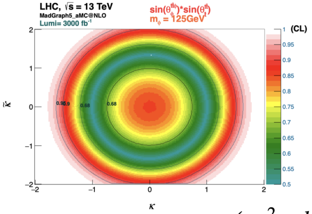
We are testing several variables, combining them, to improve the bounds

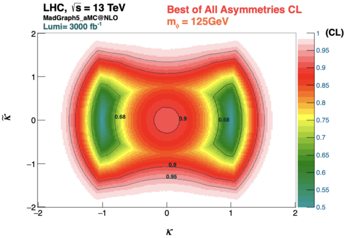




$\propto (a\kappa_t^2 - b\tilde{\kappa}_t^2)$

$\propto (a\kappa_t^2 + b\tilde{\kappa}_t^2)$

Preliminary! - The plug plot



Asymmetries - less systematics

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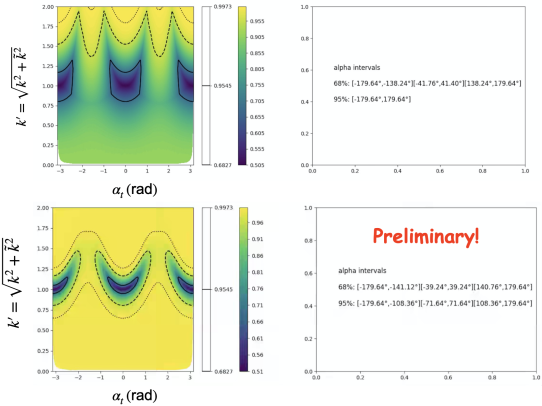
AZEVEDO, CAPUCHA, GOUVEIA, ONOFRE, RS, WORK IN PROGRESS

Rui Santos @ HPNP Special Edition 2021, Japan

Azevedo, Capucha, Gouveia, Onofre, RS, work in progress



More shapes?

Ellis, Hwang, Sakurai, Takeuchi, JHEP 04 (2014) 004

Mileo , Kiers , Szynkman , Crane, Gegner, JHEP 07 (2016) 056

$$\sigma_{\bar{t}t\phi} = \kappa^2 \sigma_{\bar{t}th} + \tilde{\kappa}^2 \sigma_{\bar{t}tA}$$

$$d\sigma(gg \to t(n_t)\bar{t}(n_{\bar{t}})H) = \kappa_t^2 f_1(p_i \cdot p_j) + \tilde{\kappa}_t^2 f_2(p_i \cdot p_j) + \kappa_t \tilde{\kappa}_t \sum_{l=1}^{15} g_l(p_i \cdot p_j)\, \epsilon_l$$

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Conclusions

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