Top Couplings @ Beyond...

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LHC Physics

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Main Topics in this Talk

- Global Fits of Data
- More on Top couplings:
  Top Quarks Polarisations

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

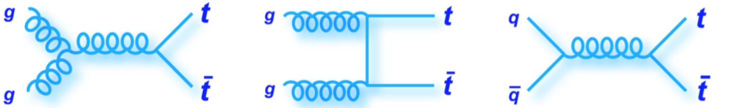
- It may reveal physics beyond the Standard Model
  - V_{tb} could be different from the Standard Model value
  - Anomalous couplings may appear at the vertex
- It may help understand possible other new physics beyond the Standard Model
  - top quarks decay almost exclusively to $t \to W^+ b$
  - understanding 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

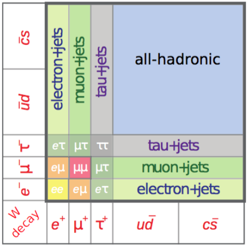
- Production at the LHC:



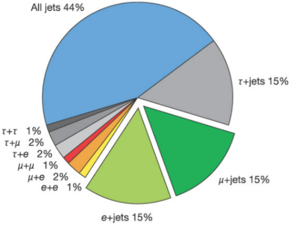
$\sigma(t\bar{t})$=177.3±9.9$^{+4.6}_{-6.0}$ pb @ 7 TeV, $\sigma(t\bar{t})$=252.9±11.7$^{+6.4}_{-8.6}$ pb @ 8 TeV, $\sigma(t\bar{t})$=832$^{+40}_{-46}$ pb @ 13 TeV

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).

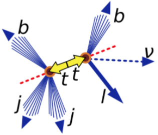
Top pair decay channels



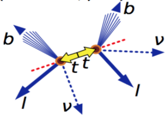
Top pair branching fractions



$\Longrightarrow$ 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

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

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

$V_{\rm R}, g_{\rm R}, g_{\rm L} \Rightarrow$ 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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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.

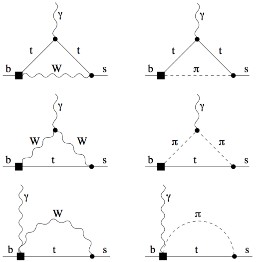


FIG. 1: Diagrams with non-SM $b \to t$ vertices that contribute to $f_7^{g_{L,R}}(x)$. The pseudogoldstone boson is denoted by π.

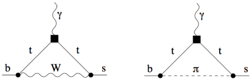


FIG. 2: Diagrams with non-SM $\bar{t}t\gamma$ vertices that contribute to $f_7^{g_R}(x)$.

'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]

LEPTON FLAVOR (UNIVERSALITY) VIOLATION

LEPTON FLAVOR UNIVERSALITY

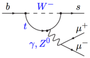
- In the Standard Model (SM), couplings of leptons with gauge bosons are universal (***LFU***).
- Beyond SM physics could couple differently to lepton families.
- LHCb performs LFU tests in:

$$\frac{\Gamma(Z\to\mu^+\mu^-)}{\Gamma(Z\to e^+e^-)} = 1.0001 \pm 0.0024$$

$$\frac{\Gamma(W\to\mu\nu)}{\Gamma(W\to e\nu)} = 0.996 \pm 0.008$$

[PDG 2021]

$b \to s\,\ell\ell$ (loop process)

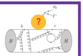


$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2} dq^2}$$

$q^2 = m(\ell\ell)^2$

- *H = K+, K*0, Ks, K*+, ….*
- Rx = 1 in SM, apart from precisely predictable phase space effects.
- Theoretical uncertainty at 10^{-3}, QED effects at % level (arXiv:1605.07633)
- Not affected by QCD effects (ex: charm loops cancels out)

$b \to c\,\ell\nu$ (tree process)



$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c\tau\overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c\ell'\overline{\nu}_{\ell'})}$$

ℓ' = μ (LHCb)

ℓ' = e/μ (B-factories)

- Hc = D, D^*, D_s, Λ_c…
- Semileptonic decays theoretical predictions are precise (% level)
- Large BR.

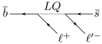
LEPTON FLAVOR VIOLATION

- Charged lepton flavor violation (**LFV**), strongly suppressed in SM (rate ~10^{-54})
- LFV is expected in leptoquarks and generic Z' models

  [PRD 97 (2018) 075004, PRD 97 (2018) 015019, PRD 92 (2015) 054013)]
- Could be enhanced in *b* decays as consequence of LFU violation

  [PRL144 (2015) 091801]

$b \to s\,\ell\ell'$



arXiv:1609.08895v2

$$\mathcal{B}(B\to K\mu^\pm e^\mp) \sim 3\cdot 10^{-8}\left(\frac{1-R_K}{0.23}\right)^2, \quad \mathcal{B}(B\to K(e^\pm,\mu^\pm)\tau^\mp) \sim 2\cdot 10^{-8}\left(\frac{1-R_K}{0.23}\right)^2$$

$$\frac{\mathcal{B}(B_s\to\mu^+e^-)}{\mathcal{B}(B_s\to\mu^+\mu^-)_{\rm SM}} \sim 0.01\left(\frac{1-R_K}{0.23}\right)^2, \quad \frac{\mathcal{B}(B_s\to\tau^+(e^-,\mu^-))}{\mathcal{B}(B_s\to\mu^+\mu^-)_{\rm SM}} \sim 4\left(\frac{1-R_K}{0.23}\right)^2.$$

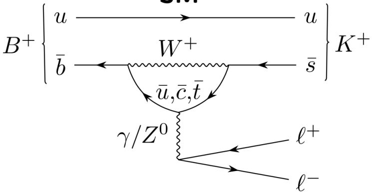
Moriond QCD 2022 – 19-26 March 2022 Francesco Polci (LPNHE CNRS/IN2P3, Sorbonne Université,CERN) 1

[Francesco Polci, Moriond QCD, 19-26 March, 2022]

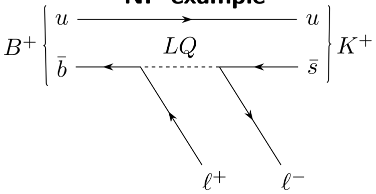
$B^+ \to K^+\ell^+\ell^-$ and related decays

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

SM



NP example



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

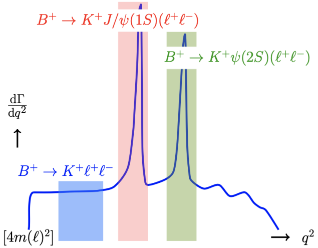
[K.A.Petridis, CERN talk, March 23, 2021]

Measurement Strategy

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

$\to$ 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)

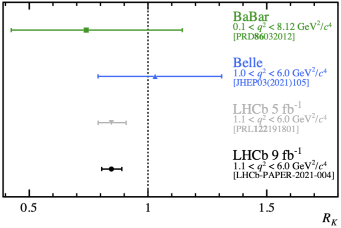
[K.A.Petridis, CERN talk, March 23, 2021]

R_K with full Run1 and Run2 dataset

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

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

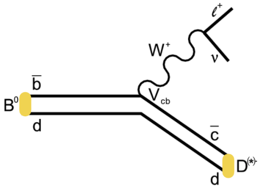
- *p*-value under SM hypothesis: 0.0010
  $\rightarrow$ Evidence of LFU violation at 3.1σ



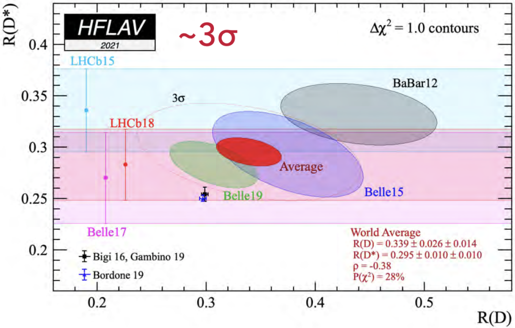
[K.A.Petridis, CERN talk, March 23, 2021]

FLAVOR ANOMALIES & LEPTON NON-UNIVERSALITY

CKM-FAVORED TREE-LEVEL DECAYS ($\tau \neq \mu, e$)



$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}\,; \quad \ell = e, \mu$$



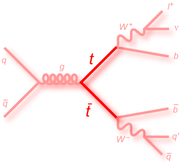
- need **tree-level new physics** without much CKM-like suppression
- difficult to account for effects much bigger than $v^2/\Lambda^2 \sim$ few %

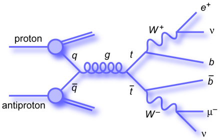
[Mathias Neubert, Moriond QCD, 19-26 March, 2022]

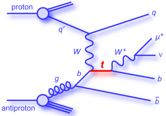
Main objective: extend the studies already performed at the LHC on top quark Anomalous Couplings/EFT in $t \to Wb$ decays to HL-LHC/HE-LHC

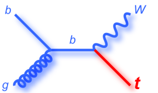
Several processes under study to probe the *Wtb* vertex[1]:

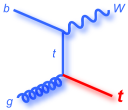
- Top quark pair production ($t\bar{t}$)
  - (i) semileptonic channel
  - (ii) dileptonic decays
- single top quark physics
  - (i) *t*-channel (single lepton)
  - (ii) *Wt*-channel (dileptonic decay)
- EFT/anomalous couplings studied associated to the *Wtb* vertex







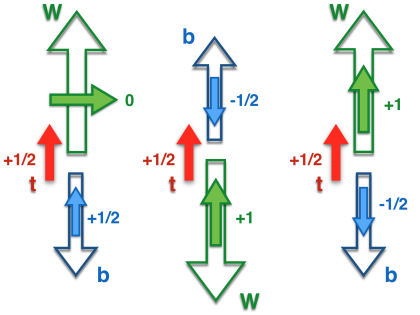




[1] JHEP**1206**(2012)088, EPJC**77**(2017)264, JHEP**04**(2017)124, JHEP**04**(2016)023, JHEP**12**(2017)017, PLB**717**(2012)330, PRD**90**(2014)112006, PLB**716**(2012)142, PLB**756**(2016)228, EPJC**77**(2017)531, JHEP**01**(2016)064, JHEP**04**(2017)086, JHEP**01**(2018)63, EPJC**78**(2018)186

Top quark pair production

☞ Example of Decay Observable: $\cos\theta^*_\ell$ $[F_0, F_L, F_R]$



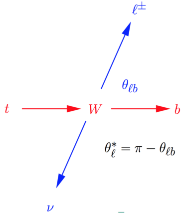
F_0 — W Longitudinal fraction

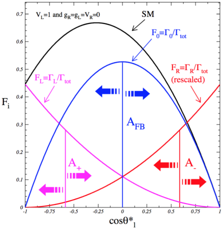
F_L — W Left-Handed fraction

F_R — W Right-Handed fraction

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

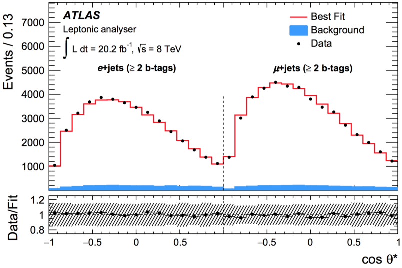
@ NNLO QCD calculation, PRD**81**(2010)111503
($F_0 + F_L + F_R = 1$)





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

EPJC**77**(2017)264



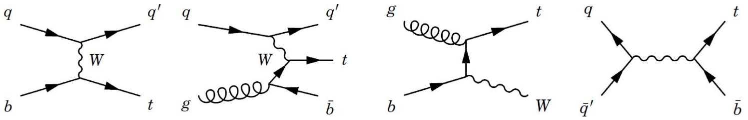
- [arXiv:hep-ph0605190v2 18 Mar 2007]

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

General Wtb vertex

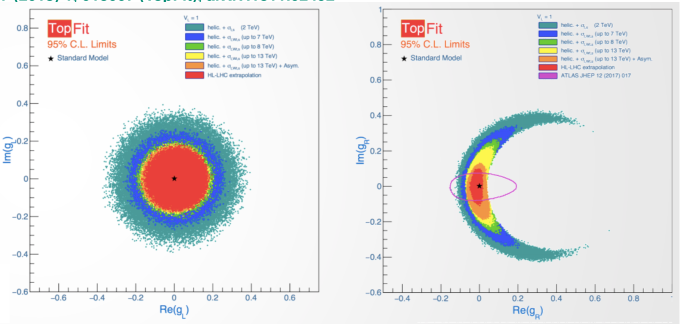
Eur.Phys.J. C50 (2007) 519-533

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R}\right)t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R}\right)t\,W_{\mu}^{-}$$

vector ($V_{\rm R}$) and tensor like couplings ($g_{\rm L}$, $g_{\rm R}$) 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

EFT/anomalous Couplings

[Improvements from Theory]

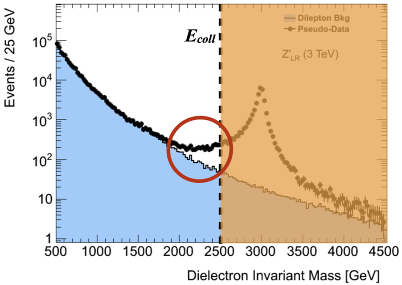
- Effective Field Theory approach (EFT):

EFT

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

SM
Precision measurements

BSM
Explicit Models



[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}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		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:

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

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

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

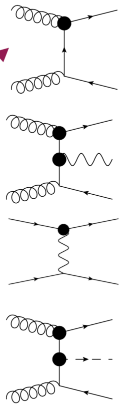
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

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

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

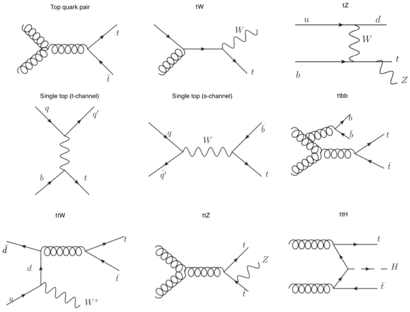
$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$

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



[Improvements from Theory]

☞ Towards a Global SMEFT Fit:

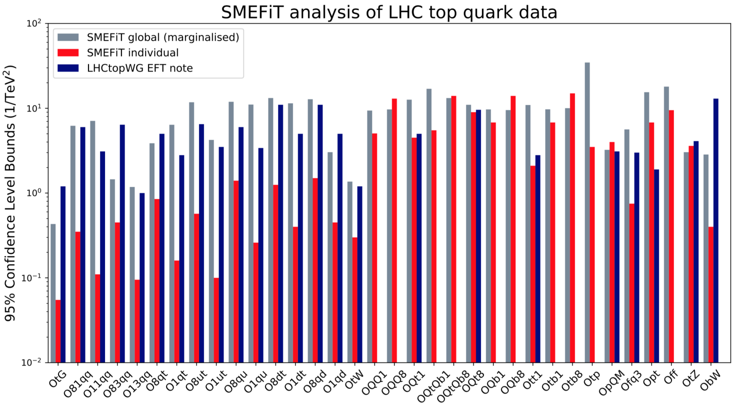


- Maltoni et al., arXiv:1901.05965
- 34 d.o.f., $\geq$ 100 observables

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]

SMEFiT

OUTP-20-05P
Nikhef-2020-020
CP3-21-12
MCNET-21-07
MAN/HEP/2021/004

Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC

The SMEFiT Collaboration:

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Abstract

We present a global interpretation of Higgs, diboson, and top quark production and decay

Constraints from Global Fits

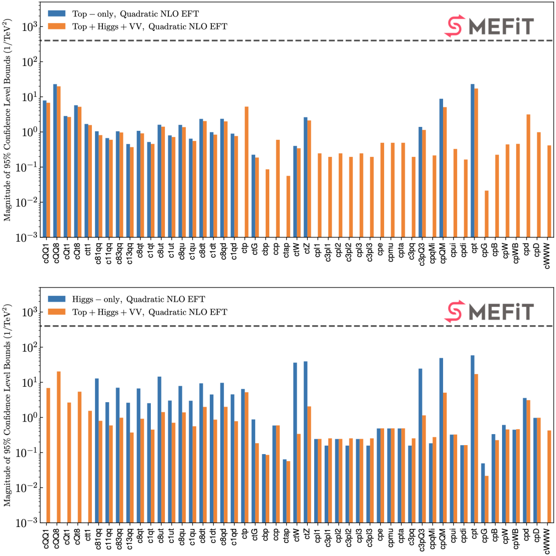


Figure 5.9. Same as upper panel of Fig. 5.4 now comparing the global fit results with those obtained in a top-only (upper) and Higgs-only (lower panel) fits.

Main Topics in this Talk

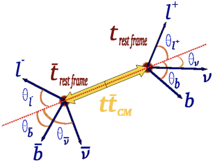
- Global Fits of Data
- More on Top couplings:
  Top Quarks Polarisations

Although produced unpolarised, the t spins are correlated in $t\bar{t}$ events

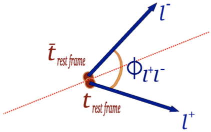
Two spin correl. parameters studied using angular distributions: A and A_D

$$A = \frac{\sigma(t_\uparrow \bar{t}_\uparrow) + \sigma(t_\downarrow \bar{t}_\downarrow) - \sigma(t_\uparrow \bar{t}_\downarrow) - \sigma(t_\downarrow \bar{t}_\uparrow)}{\sigma(t_\uparrow \bar{t}_\uparrow) + \sigma(t_\downarrow \bar{t}_\downarrow) + \sigma(t_\uparrow \bar{t}_\downarrow) + \sigma(t_\downarrow \bar{t}_\uparrow)}$$

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - A|\alpha_1\alpha_2|\cos\theta_1\cos\theta_2), \qquad \alpha_i = \text{spin analysing power of i}$$



$$\frac{1}{N}\frac{dN}{d\cos\Phi} = \frac{1}{2}(1 - A_D|\alpha_1\alpha_2|\cos\Phi)$$



$$A^{SM} = 0.326^{+0.003}_{-0.002}(\mu)^{+0.013}_{-0.001}(PDF), \qquad A_D^{SM} = -0.237^{+0.005}_{-0.007}(\mu)^{+0.000}_{-0.006}(PDF)$$

$$A^{SM} = 0.422, \qquad A_D^{SM} = -0.290 \qquad (m_{t\bar{t}} < 550\ \text{GeV})$$

Nucl.Phys.**B690** (2004) 81, Eur.Phys.J.**C44** (2005) s13-s33

IFT-UAM/CSIC-21-123

A template method to measure the $t\bar{t}$ polarisation

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We develop a template method for the measurement of the polarisation of $t\bar{t}$ pairs produced in hadron collisions. The method would allow to extract the individual fractions of $t_L\bar{t}_L$, $t_R\bar{t}_R$, $t_L\bar{t}_R$ and $t_R\bar{t}_L$ pairs with a fit to data, where L, R refer to the polarisation along any axis. These polarisation fractions have not been independently measured at present. Secondarily, the method also provides the net polarisation of t and $\bar{t}$, as well as their spin correlation for arbitrary axes.

I. INTRODUCTION

The measurement of the top quark properties started shortly after its discovery at the Tevatron [1, 2]. The high statistics achieved at the Large Hadron Collider (LHC) has provided us with a huge dataset of single (anti-)top and $t\bar{t}$ pairs, which can be exploited for precision measurements in the search for any departure from the predictions of the Standard Model (SM). And this will be even more the case at the high-luminosity upgrade (HL-LHC). With such large statistics, the main source of uncertainties in the comparison between theory and experiment are the experimental systematic uncertainties, as well as theoretical uncertainties due to higher-order corrections in perturbation theory [3]. The latter are currently being reduced by two-loop calculations; the former may be reduced, not only with a better knowledge of the

coefficients $a_{XX'}$ from a fit to the measured distribution. Once the effect of hadronisation, detector resolution, kinematical reconstruction of the t and $\bar{t}$ momenta, and phase space cuts are suitably incorporated (details are discussed in Section III), the *parton-level* coefficients $a_{XX'}$ can be extracted by a fit of the measured sample to a combination of the simulated templates. Detailed results are presented in Sections IV and V, and Section VI is devoted to a brief discussion of our results.

II. THE TEMPLATE METHOD

The template method is based on the expansion of the $t\bar{t}$ cross section, which can be written as

[Basic Template Fit]

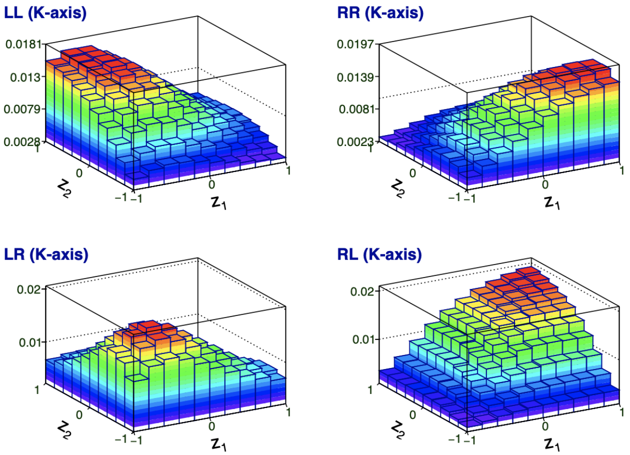
☞ use templates for RR, RL, LR and LL (Protos):

$$\varepsilon \bar{f}(z_1, z_2) = \sum_{XX'} a_{XX'} \varepsilon_{XX'} \bar{f}_{XX'}(z_1, z_2) + \Delta_{\rm int}(z_1, z_2) \,,$$

- Evaluate efficiencies ($\epsilon_{XX'}$) for the different polarisation components
- Evaluate the templates after event selection $\bar{f}_{XX'}$
- Evaluate interference term Δ_{int}
- Extract $a_{XX'}$ (at parton level, without parton level reconstruction)

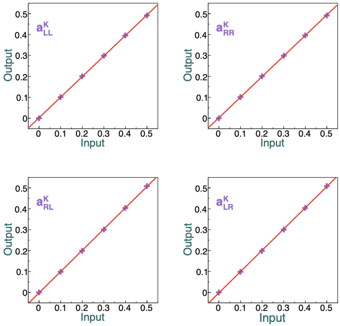
[Templates (in helicity basis K-axis)]

$z_1 = cos(\theta_1)$ and $z_2 = cos(\theta_2)$

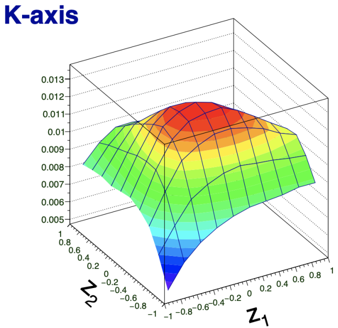


[Templates (in helicity basis K-axis)]

Pull Distributions



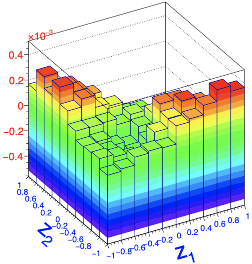
SM reconstruction



[Templates (in helicity basis K-axis)]

SM Δ_{int} Interference

Results



K	SM		CMDM	
	Prediction	Fit	Prediction	Fit
a_{LL}	0.335 ± 0.001	0.337 ± 0.006	0.349 ± 0.001	0.350 ± 0.006
a_{RR}	0.336 ± 0.003	0.330 ± 0.005	0.349 ± 0.001	0.339 ± 0.005
a_{LR}	0.165 ± 0.003	0.167 ± 0.007	0.151 ± 0.001	0.175 ± 0.007
a_{RL}	0.165 ± 0.002	0.160 ± 0.004	0.151 ± 0.001	0.131 ± 0.004
$C_{\rm kk}$	0.340 ± 0.002	0.340 ± 0.019	0.394 ± 0.004	0.383 ± 0.019
P_t	0.001 ± 0.002	-0.014 ± 0.008	0.000 ± 0.001	-0.058 ± 0.008
$P_{\bar{t}}$	0.001 ± 0.002	0.000 ± 0.008	0.001 ± 0.002	0.033 ± 0.008

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 !!!
6) need to include the Flavour Physics (two energy scales ...)

Top Quark Polarisations:

1) new template method
2) no need to recover parton level information
3) interference effects can be probed