How can top quarks help probing the Higgs sector, DM and BSM?

A. Onofre
in coll. R.Santos, J.Aguilar-Saavedra, M.C.N. Fiolhais, A.Ferroglia, R.Capucha, D.Azevedo, P. Martin-Ramiro, J. M. Moreno, J.Martins, P.Chaves
(antonio.onofre@cern.ch)

Workshop on Multi-Higgs Models,
IST, 30th August - 2nd September 2022, Lisbon - Portugal

CERN/FIS-PAR/0029/2019 CERN/FIS-PAR/0037/2021

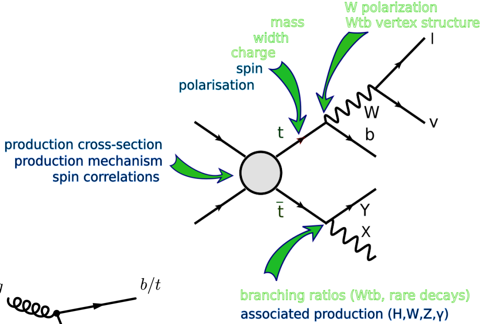
Outline

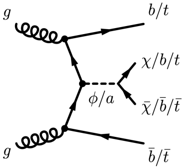
The t-quark and Higgs boson (ϕ) have a quite rich phenomenology. ☞ Understanding the couplings and the connection to BSM, DM etc., is quite important @ LHC

List of Topics Covered

☞ all about couplings and spin correlations

- Many processes available
  impossible to cover all
  concentrate on new results
- a *Template Method* to measure
  $t\bar{t}$ spin correlations, Interferences...
  [Eur.Phys.J.C 82 (2022) 2]
- $t\bar{t}\phi$ production @ LHC
  CP-violation, asymmetries and
  Interferences in $t\bar{t}\phi$
  [arXiv:2208.04271, 8 Aug 2022]
- The $t\bar{t}\phi$ DM searches
  via simplified models





The top quark

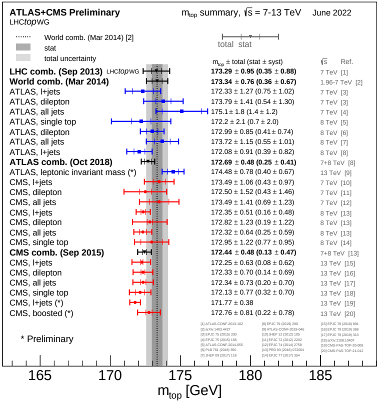
- **The top quark was discovered (CDF,D0)**

  almost 30 years ago

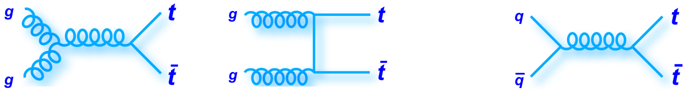
  PRL**74** 2626-2631 (1995);

  PRL**74** 2632-2637 (1995).

- **Properties:**
  - heaviest known fundamental fermion
    $m_t \sim 173\text{GeV}$
  - dominant decay mode: $t \to bW$
    $BR(t \to sW) \leq 0.18\%$
    $BR(t \to dW) \leq 0.02\%$
  - $\Gamma_t^{SM} = 1.42$ GeV
    (including m_b, m_W, α_s, EW corr.)
  - $\tau_t \sim 10^{-25}$s
    $\ll \Lambda_{QCD}^{-1} \sim (100\text{ MeV})^{-1} \sim 10^{-23}$s
    $\Rightarrow$ top decays before hadronization takes place



- **Double Production at the LHC:**

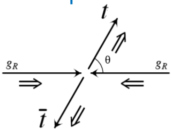


$$g(p_1) + g(p_2) \to t(k_1, s_1) + \bar{t}(k_2, s_2) \qquad q(p_1) + \bar{q}(p_2) \to t(k_1, s_1) + \bar{t}(k_2, s_2)$$

$t\bar{t}$ Production: Top spin correlations

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

$$\sigma = \sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}$$



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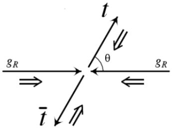
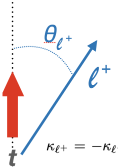


quantum interference effects between polarisation states exist

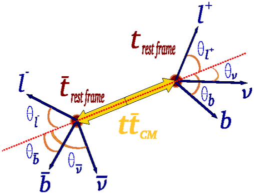
☞ Probe spin correlations using the $\ell^{\pm}$ i.e, $\cos\theta_{\ell^{\pm}}$ ($t\bar{t}$ dileptonic decays)

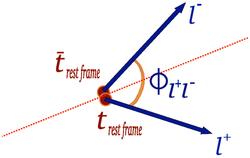
$$pp \to t + \bar{t} + X \to \ell^{+}\ell'^{-} + \text{ jets} + E_T^{\text{miss}}$$



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \kappa_\ell \cos\theta_\ell)$$

$\kappa_{\ell^+} = -\kappa_{\ell^-} = 1$ in the SM at leading order (LO)





$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\Phi_{\ell\ell}} = \frac{1}{2}(1 - D\cos\Phi_{\ell\ell})$$

☞ The $\Delta\Phi_{\ell^+\ell^-}$ also used in LAB frame (does not require $t\bar{t}$ reconstruction)

$t\bar{t}$ Production: Top spin correlations

☞ Measurements with respect to $\{\hat{r}_t, \hat{k}_t, \hat{n}_t\}$ axis [JHEP12(2015)026]

The (four-fold) normalised cross section distribution:

$$\frac{1}{\sigma}\frac{d^4\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}(1 + \mathbf{B_1}\cdot\hat{\ell}_1 + \mathbf{B_2}\cdot\hat{\ell}_2 - \hat{\ell}_1\cdot C\cdot\hat{\ell}_2)$$

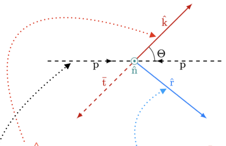
$d\Omega = d\cos\theta d\phi$ $\quad$ B_1 (B_2) = top (anti-top) vector spin polarisations $\quad$ C = spin correlation matrix

$\hat{\ell}_1$ ($\hat{\ell}_2$) = the $\hat{\ell}^+$ ($\hat{\ell}^-$) directions in the $t(\bar{t})$ system

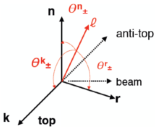
Different polar axes $\hat{\mathbf{a}}$ and $\hat{\mathbf{b}}$ can be used, and particles defined with respect to them:

$z_1 = \cos\theta_+ = \hat{\ell}^+ \cdot \hat{\mathbf{a}}$ $\qquad$ $z_2 = \cos\theta_- = \hat{\ell}^- \cdot \hat{\mathbf{b}}$

The **B** and ***C*** functions are defined in the $\{\hat{r}, \hat{k}, \hat{n}\}$ basis:



$\hat{k}$ = top quark flight direction in $t\bar{t}$ system



$$\hat{\mathbf{p}}_p = (0,0,1)\,,\quad \hat{\mathbf{r}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p - y_p\hat{\mathbf{k}})\,,\quad \hat{\mathbf{n}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p \times \hat{\mathbf{k}})\,,$$

$$y_p = \hat{\mathbf{p}}_p \cdot \hat{\mathbf{k}}\,,\qquad r_p = \sqrt{1-y_p^2}\,.$$

Why these axis choice?

Correlation		sensitive to
$C(n,n)$	c^I_{nn}	P-, CP-even
$C(r,r)$	c^I_{rr}	P-, CP-even
$C(k,k)$	c^I_{kk}	P-, CP-even
$C(r,k)+C(k,r)$	c^I_{rk}	P-, CP-even
$C(n,r)+C(r,n)$	c^I_{rn}	P-odd, CP-even, absorptive
$C(n,k)+C(k,n)$	c^I_{kn}	P-odd, CP-even, absorptive
$C(r,k)-C(k,r)$	c^I_n	P-even, CP-odd, absorptive
$C(n,r)-C(r,n)$	c^I_k	P-odd, CP-odd
$C(n,k)-C(k,n)$	$-c^I_r$	P-odd, CP-odd
$B_1(n)+B_2(n)$	$b^{I+}_n + b^{I-}_n$	P-, CP-even, absorptive
$B_1(n)-B_2(n)$	$b^{I+}_n - b^{I-}_n$	P-even, CP-odd
$B_1(r)+B_2(r)$	$b^{I+}_r + b^{I-}_r$	P-odd, CP-even
$B_1(r)-B_2(r)$	$b^{I+}_r - b^{I-}_r$	P-odd, CP-odd, absorptive
$B_1(k)+B_2(k)$	$b^{I+}_k + b^{I-}_k$	P-odd,CP-even
$B_1(k)-B_2(k)$	$b^{I+}_k - b^{I-}_k$	P-odd, CP-odd, absorptive
$B_1(k^*)+B_2(k^*)$	$b^{I+}_k + b^{I-}_k$	P-odd,CP-even
$B_1(k^*)-B_2(k^*)$	$b^{I+}_k - b^{I-}_k$	P-odd, CP-odd, absorptive
$B_1(r^*)+B_2(r^*)$	$b^{I+}_r + b^{I-}_r$	P-odd, CP-even
$B_1(r^*)-B_2(r^*)$	$b^{I+}_r - b^{I-}_r$	P-odd, CP-odd, absorptive

$t\bar{t}$ Production: Top spin correlations

☞ CMS Measurements [Phys. Rev. D 100 (2019) no.7, 072002]

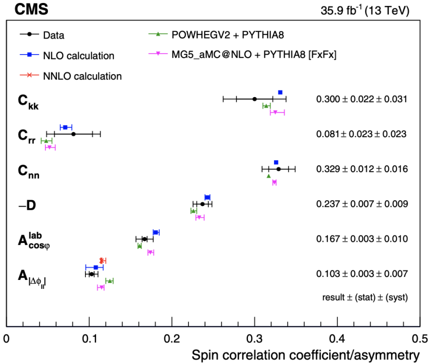
for each 15 coefficient **B**$_1$,**B**$_2$, **C** single differential distributions are used

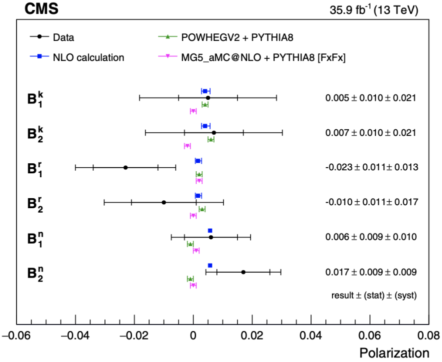
Integrating over the azimuthal angles (for each axis ***i,j***)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1^i\, d\cos\theta_2^j} = \frac{1}{4}\left(1 + B_1^i\cos\theta_1^i + B_2^j\cos\theta_2^j - C_{ij}\cos\theta_1^i\cos\theta_2^j\right)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i} = \frac{1}{2}(1 + B_1^i\cos\theta_1^i),$$
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_2^i} = \frac{1}{2}(1 + B_2^i\cos\theta_2^i),$$
$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 - C_{ij}x)\ln\left(\frac{1}{|x|}\right),$$
$$x = \cos\theta_1^i\cos\theta_2^j.$$

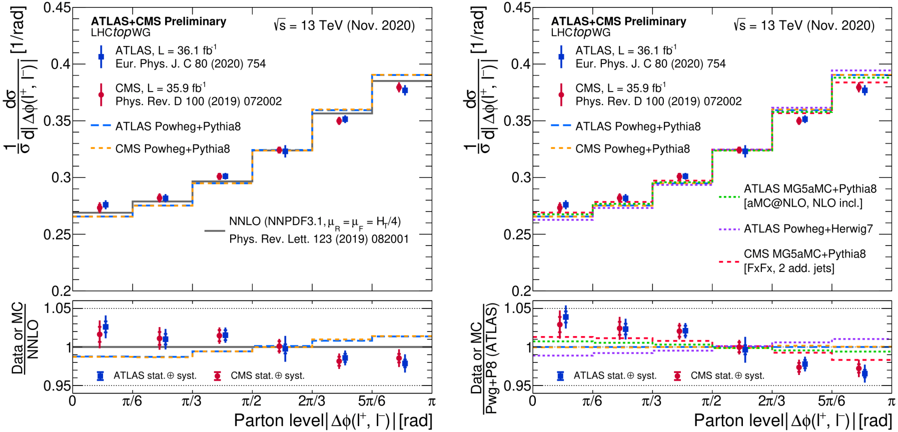
θ_1^i (θ_2^j) = ℓ^+ (ℓ^-) directions in the $t(\bar{t})$ system, with respect to $i(j)$ axis ($\hat{r},\hat{k},\hat{n}$)





$t\bar{t}$ Production: Top spin correlations

☞ Using the Normalized Differential $|\Delta\phi_{\ell^+\ell^-}|$ Distribution (LAB system)



☞ ATLAS and CMS data compared to calculations at NNLO on the left, and different MC simulations on the right.

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

☞ Double Differential Normalized Distributions [Eur.Phys.J.C 82 (2022) 2]

Defining (with respect to any of the axis ***i,j={r,k,n}***)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1^i\, d\cos\theta_2^j} = \frac{1}{\sigma}\frac{d\sigma}{dz_1 dz_2} = f(z_1,z_2) \quad \text{and} \quad f_{XX'}(z_1,z_2) = \frac{1}{\sigma_{XX'}}\frac{d\sigma_{XX'}}{dz_1 dz_2} \quad \text{with} \quad X, X' = L, R$$

θ_1^i (θ_2^j) = ℓ^+ (ℓ^-) directions in the t($\bar{t}$) system, with respect to i(j) axis ($\hat{r},\hat{k},\hat{n}$)

the **Normalised Double Differential Distribution** can be defined (at parton level)

$$f(z_1,z_2) = \sum_{XX'} a_{XX'} f_{XX'}(z_1,z_2) \quad \text{with} \quad \sum_{XX'} a_{XX'} = 1$$

Phase Space cuts (p_T, η, etc.) affect the Polarizations differently

$$\frac{d\bar{\sigma}}{dz_1 dz_2} = \sum_{X,X'} \frac{d\bar{\sigma}_{XX'}}{dz_1 dz_2} + \ldots$$

(the ***bar*** = quantities **after cuts**)

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

with $\varepsilon = \bar{\sigma}/\sigma$

$\varepsilon_{XX'} = \bar{\sigma}_{XX'}/\sigma_{XX'}$

Interference Term (small but not zero!)

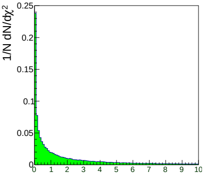
$\bar{f}_{XX'}(z_1,z_2)$, $\bar{f}(z_1,z_2)$ } **2D Templates after cuts**

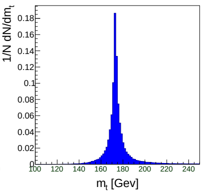
$a_{XX'}$ = a_{RR}, a_{LL}, a_{RL} and a_{LR} are the Parton Level spin correlation fractions (no need for unfolding!)

Dileptonic Signal Reconstruction:

☞ $gg, q\bar{q} \rightarrow t\bar{t} \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)$

PROTOS signal samples for SM and pure $t_R\bar{t}_R$, $t_L\bar{t}_L$, $t_R\bar{t}_L$, $t_L\bar{t}_R$ (all r,k,n axes) $\oplus$ DELPHES





☞ Constrained Kinematic fit

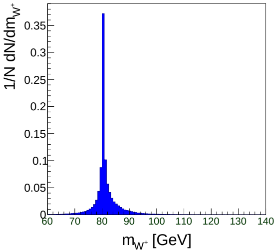
I- Mass constraints:

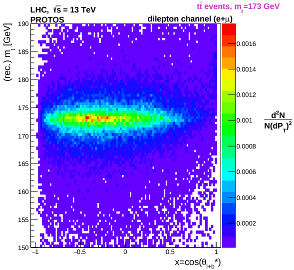
(1) $(p_{W^+} + p_b)^2 = m_t^2$

(2) $(p_{W^-} + p_{\bar{b}})^2 = m_{\bar{t}}^2$

(3) $(p_{\ell^+} + p_\nu)^2 = m_{W^+}^2$

(4) $(p_{\ell^-} + p_{\bar{\nu}})^2 = m_{W^-}^2$





II- Missing Transverse Energy:

(1) $p_x^\nu + p_x^{\bar{\nu}} = \not{E}_x$

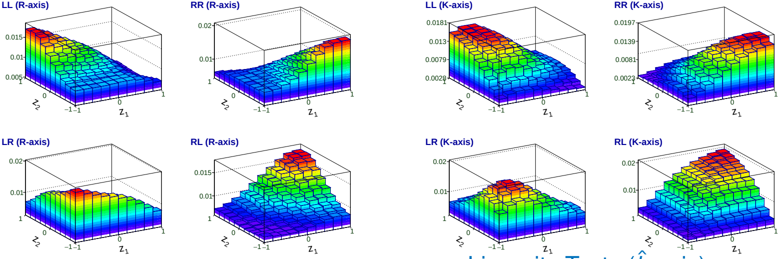
(2) $p_y^\nu + p_y^{\bar{\nu}} = \not{E}_y$

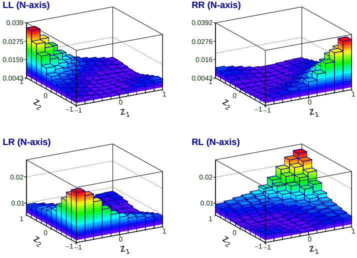
III- χ^2 Minimization:

(1) $$\chi^2 = \frac{(m_t^{rec} - m_t)^2}{\Gamma_t^2} + \frac{(m_{\bar{t}}^{rec} - m_{\bar{t}})^2}{\Gamma_{\bar{t}}^2} + \frac{(m_{W+}^{rec} - m_{W+})^2}{\Gamma_{W+}^2} + \frac{(m_{W-}^{rec} - m_{W-})^2}{\Gamma_{W-}^2} + \frac{(p_t^T - p_{\bar{t}}^T)^2}{(\sigma_p^T)^2}$$

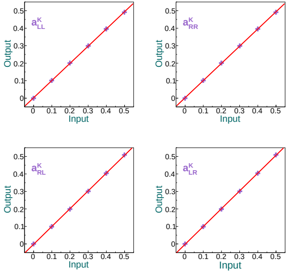
☞ m_W=80.4 GeV, m_t=173 GeV, Γ_t=11.5 GeV, Γ_W=7.5 GeV, σ_p^T=20 GeV

☞ Double Differential Normalized Templates in $\{\hat{r},\hat{k},\hat{n}\}$ axes

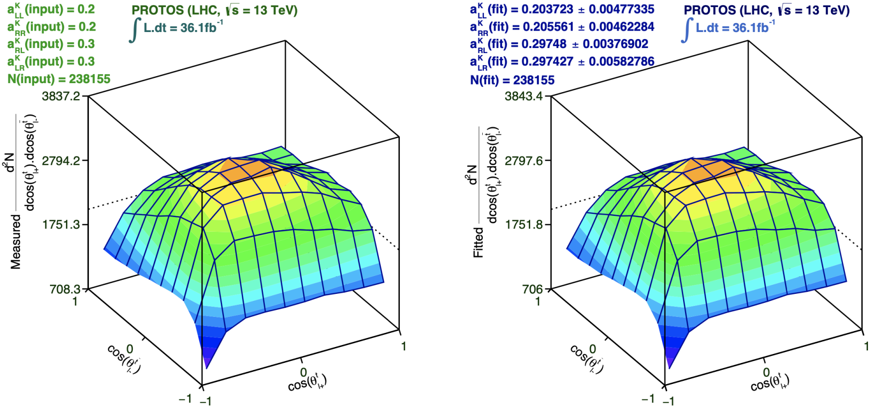




Linearity Tests ($\hat{k}$ axis)



☞ Template 2D fit example in $\hat{k}$ axis (from linearity tests)

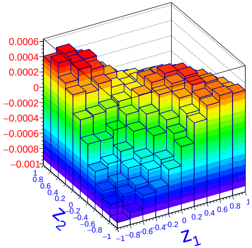


$t\bar{t}$ Production: Top spin correlations with a Template Method

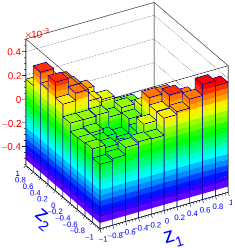
☞ Interference effects can also be measured in all axes $\{\hat{r},\hat{k},\hat{n}\}$

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

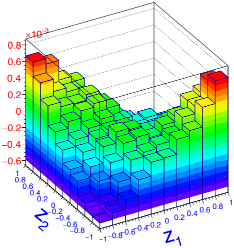
R-axis



K-axis



N-axis



☞ BSM interference effects are different from the SM in all $\{\hat{r},\hat{k},\hat{n}\}$ axes

$t\bar{t}$ Production: Top spin correlations with a Template Method

☞ Results for the SM and CMDM in all $\{\hat{r},\hat{k},\hat{n}\}$ axes

2D Template Fit Results

Spin correlations parameter C_{ii}

$C_{ii} = a_{RR} + a_{LL} - a_{RL} - a_{LR}$

Top quark Polarizations

$P_t = a_{RR} + a_{RL} - a_{LR} - a_{LL}$

$P_{\bar{t}} = a_{RR} + a_{LR} - a_{RL} - a_{LL}$

Sample with large top quark **anomalous chromomagnetic dipole moment (CMDM)** d_V=0.036 also used as a test

$$\mathcal{L} = -\frac{g_s}{m_t}\bar{t}\sigma^{\mu\nu}(d_V + id_A\gamma_5)\frac{\lambda^a}{2}tG^{\mu\nu}_a$$

(d_A set to zero)

take home message:

Fits are very sensitive to Interference terms in Spin Correlations

may be probed @ LHC (RUN3) without unfolding!

K	SM Prediction	SM Fit	CMDM Prediction	CMDM 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_{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

R	SM Prediction	SM Fit	CMDM Prediction	CMDM Fit
a_{LL}	0.258 ± 0.001	0.254 ± 0.006	0.290 ± 0.002	0.291 ± 0.006
a_{RR}	0.259 ± 0.002	0.264 ± 0.006	0.289 ± 0.002	0.290 ± 0.006
a_{LR}	0.242 ± 0.001	0.236 ± 0.006	0.210 ± 0.001	0.210 ± 0.006
a_{RL}	0.241 ± 0.002	0.241 ± 0.006	0.211 ± 0.001	0.201 ± 0.006
C_{rr}	0.036 ± 0.002	0.041 ± 0.019	0.159 ± 0.002	0.170 ± 0.019
P_t	0.0004 ± 0.0005	0.015 ± 0.010	-0.001 ± 0.004	-0.011 ± 0.010
$P_{\bar{t}}$	0.002 ± 0.002	0.006 ± 0.010	-0.001 ± 0.003	0.008 ± 0.009

N	SM Prediction	SM Fit	CMDM Prediction	CMDM Fit
a_{LL}	0.333 ± 0.001	0.329 ± 0.004	0.358 ± 0.001	0.363 ± 0.004
a_{RR}	0.334 ± 0.002	0.329 ± 0.004	0.358 ± 0.001	0.352 ± 0.004
a_{LR}	0.166 ± 0.001	0.164 ± 0.004	0.142 ± 0.0003	0.138 ± 0.004
a_{RL}	0.167 ± 0.002	0.169 ± 0.004	0.142 ± 0.001	0.136 ± 0.004
C_{nn}	0.336 ± 0.002	0.325 ± 0.010	0.433 ± 0.002	0.442 ± 0.010
P_t	0.002 ± 0.001	0.005 ± 0.009	-0.001 ± 0.002	-0.014 ± 0.009
$P_{\bar{t}}$	0.000 ± 0.002	-0.005 ± 0.008	0.000 ± 0.001	-0.009 ± 0.009

TABLE III. Theory predictions and best-fit values for various polarisation coefficients in the SM and CMDM data samples. For the theory predictions, the quoted uncertainty corresponds to the Monte Carlo statistical uncertainty.

EW Loop corrections in $t\bar{t}$ Production @ the LHC
[Phys. Rev. D 104, 055045 (2021)]

$t\bar{t}$ Production: Loop corrections sensitive to top Yukawa couplings

☞ EW loops in $t\bar{t}$ production are sensitive to the Higgs CP nature (k,$\tilde{k}$)
Phys. Rev. D 104, 055045 (2021)

Effective Lagrangian for top quark Higgs boson interaction

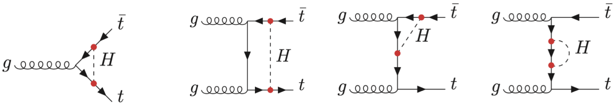
$$\mathcal{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\,(\kappa + \mathrm{i}\,\tilde{\kappa}\gamma_5)\,\psi_t\,H,$$

k($\tilde{k}$) = CP-even (CP-odd) components

SM (pure CP-even): $k=1$ and $\tilde{k} = 0$

BSM, pure CP-odd: $k=0$ and $\tilde{k} = 1$

s- and *t*-channels contributions considered



(*s*-channel) (*t*-channel)

Interference terms of the tree level with Higgs-loop diagrams

proportional to: (k^2 + $\tilde{k}^2$) or (k^2 - $\tilde{k}^2$)

→ no sensitivity to mixed terms or signs

→ CP-odd roughly 40% of CP-even $\sigma(\kappa,\tilde{\kappa})_{t\bar{t}H} = \sigma_{\mathrm{SM}}^{t\bar{t}H}\left(|\kappa|^2 + 0.39|\tilde{\kappa}|^2\right)$

☞ EW loops in $t\bar{t}$ production are sensitive to the Higgs CP nature (k,$\tilde{k}$)

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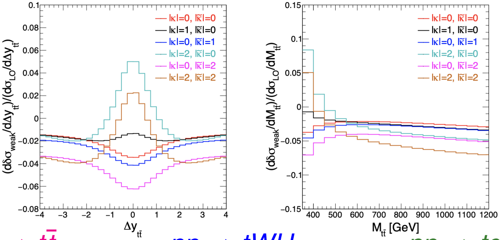
strong dependence of Δy, $M_{t\bar{t}}$ with k, $\tilde{k}$



$pp \to t\bar{t}$ $pp \to tWH$ $pp \to tqH$

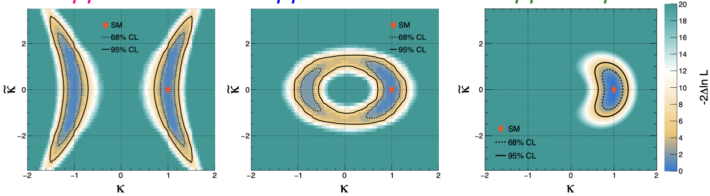


FIG. 7: Two dimensional likelihood scans of κ and $\tilde{\kappa}$ in the $pp \to t\bar{t}$ (left) and $pp \to tWH$ (middle) and $pp \to tqH$(right) processes at a luminosity of 300 fb^{-1}. The expected 68% and 95% CL regions are presented as contours with dashed and solid black lines, respectively.

☞ Experimental results on the Higgs CP nature $(k, \tilde{k})$

Effective Lagrangian for top quark Higgs boson interaction

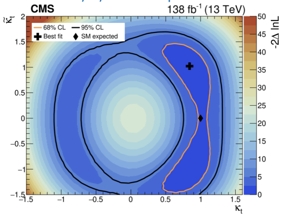
$$\mathcal{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\,(\kappa + i\tilde{\kappa}\gamma_5)\,\psi_t\,H,$$

$k(\tilde{k})$ = CP-even (CP-odd) components

SM (pure CP-even): $k=1$ and $\tilde{k}=0$ BSM, pure CP-odd: $k=0$ and $\tilde{k}=1$

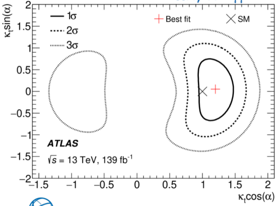
Mixing angle (α) parametrisation: $k=k_t\cos(\alpha)$ and $k=\tilde{k}_t\sin(\alpha)$

ttH,tH, H→multilepton



Phys. Rev. Lett. 125 (2020) 061802

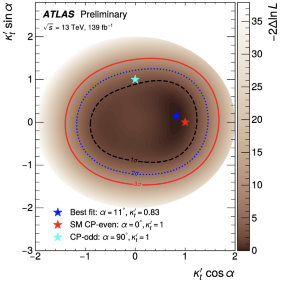
ttH, H→γγ



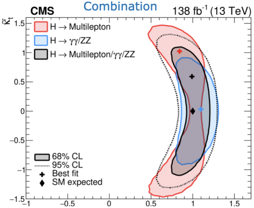
ATLAS EXPERIMENT

ATLAS-CONF-2022-016

ttH, H→bb



Combination



CMS-HIG-21-006 ; CERN-EP-2022-157

Can we probe CP violation and Interference Effects in associated Higgs production @ the LHC ?
[arXiv:2208.04271, JHEP 4 (2014), JHEP 01 (2022) 158]

☞ Probing the top quark - Higgs boson vertex CP nature

Effective Lagrangian for top quark Higgs boson interaction

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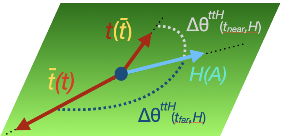
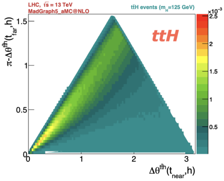
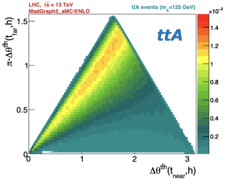
Mixing angle (α) parametrisation: $k=k_t\cos(\alpha)$ and $k=\tilde{k}_t\sin(\alpha)$

The role of *ttH* CM system is quite important [Phys. Rev. D**100**, 075034 (2019)]



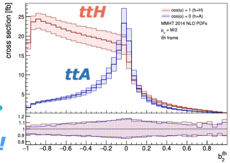
ttH centre-of-mass system

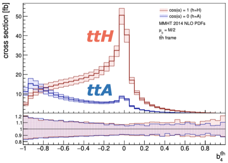




The role of *top quarks* is also very important

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



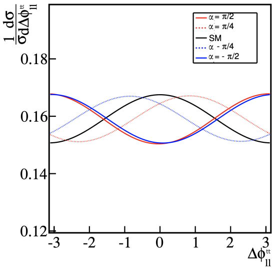


$$b_4^f(i,j) = \frac{p_{i,z}^f\ p_{j,z}^f}{|\vec{p}_i^{\,f}||\vec{p}_j^{\,f}|}$$

Spin-parity sensitivity is clear !

$t\bar{t}H$, tH Production @ the LHC

- Probing the top quark - Higgs boson vertex CP nature
- Pheno study with $t\bar{t}\phi$ 2ℓ events i.e., $t\bar{t}\phi \to (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu_\ell})(b\bar{b})$
- Event Generation+Simulation @ 13 TeV (RUN2)
  - MadGraph5_aMC@NLO for $t\bar{t}\phi, \phi = A, H$ and $t\bar{t}b\bar{b}$ (@ NLO)
    Backgrounds @ LO with MLM: $t\bar{t} + jets$, $t\bar{t}V + jets$, Single t,
    $W(Z)$+jets, $W(Z)b\bar{b}$+jets, VV+jets
    $t\bar{t}\phi$ signals for: $\alpha = 0^o, 22.5^o, 45^o, 67.5^o, 90^o, 135^o$ and 180^o
  - MadSpin $\oplus$ Pythia $\oplus$ DELPHES
  - MadAnalysis5, $N_{jets} \geq 4$ $\oplus$ $N_{lep} \geq 2$
    ($p_T \geq 20$ GeV, $|\eta| \leq 2.5$)



- CP-observables [arXiv:2208.04271]

  (1) $b_2^{t\bar{t}\phi} = (\vec{p}_t \times \hat{k}_z).(\vec{p}_{\bar{t}} \times \hat{k}_z)/(|\vec{p}_t|.|\vec{p}_{\bar{t}}|)$

  (2) $b_4^{t\bar{t}\phi} = (p_t^z.p_{\bar{t}}^z)/(|\vec{p}_t|.|\vec{p}_{\bar{t}}|)$

  (3) $\sin(\theta_\phi^{t\bar{t}\phi}) * \sin(\theta_{\bar{t}}^{t\bar{t}})$

  (4) $\sin(\theta_\phi^{t\bar{t}\phi}) * \sin(\theta_{b_{\bar{t}}}^{\bar{t}})$ (seq. boost)

- Observables sensitive to mixing

  (5) $\Delta\phi_{ll}^{t\bar{t}} = \mathrm{sgn}[\hat{p}_t \cdot (\hat{p}_{l^+} \times \hat{p}_{l^-})] \arccos[(\hat{p}_t \times \hat{p}_{l^+}) \cdot (\hat{p}_t \times \hat{p}_{l^-})]$

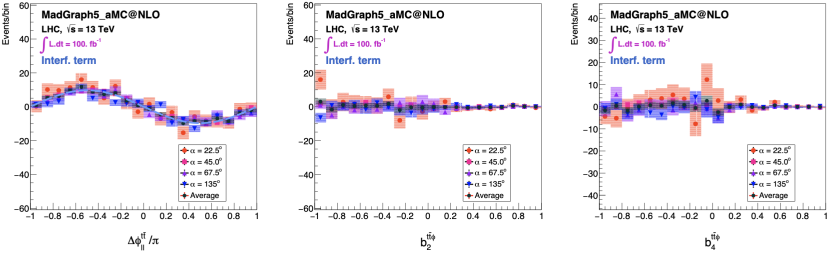
- Differential cross section and Interference term

$$d\sigma_{t\bar{t}\phi} = \kappa^2\ d\sigma_{\text{CP-even}} + \tilde{\kappa}^2\ d\sigma_{\text{CP-odd}} + \kappa\tilde{\kappa}\ d\sigma_{\text{int}}$$

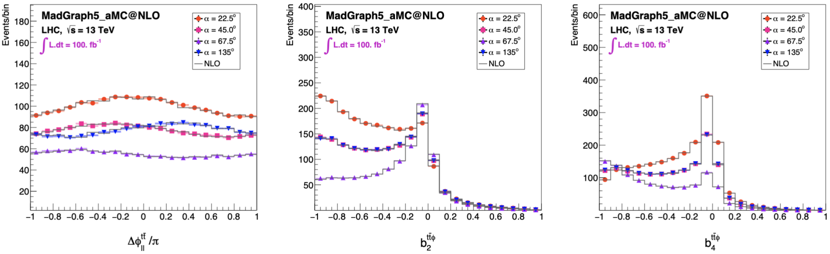
$t\bar{t}H$, tH Production @ the LHC

☞ Probing the top quark - Higgs boson vertex CP nature (Interf. Terms)

Reconstructed Interference Differential Distributions (NLO parton level)

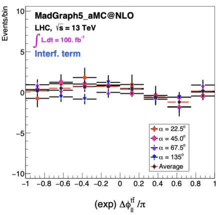


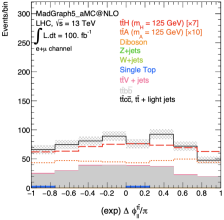
Reconstructed Differential Distributions w/Int. compared to NLO parton level distributions



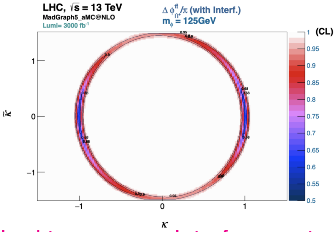
☞ Probing the top quark - Higgs boson vertex CP nature (Interf. Terms)

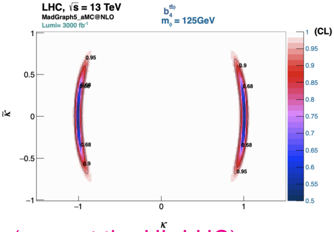
Expected Interference Differential Distributions (after cuts+Kin.Rec.)





Expected Exclusion CLs using Differential Distributions w/Interference

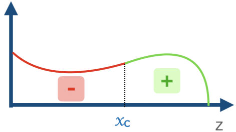




☞ Hard to measure Interference terms (even at the HL-LHC)

☞ Probing the top quark - Higgs boson vertex CP nature using Asymmetries

Asymmetries from angular distributions, defined as:



$$A_c[Z] = \frac{\sigma(Z > x_c) - \sigma(Z < x_c)}{\sigma(Z > x_c) + \sigma(Z < x_c)} = \frac{+ \; - \; -}{+ \; + \; -}$$

$$A_c[Z] = A\kappa^2 + B\tilde{\kappa}^2 + \ldots$$

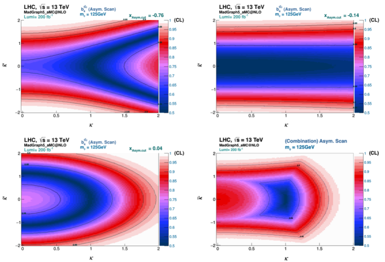
$$A \propto \int_{x_c}^{+1} d\sigma_{\text{CP-even}} - \int_{-1}^{x_c} d\sigma_{\text{CP-even}} \quad \text{and} \quad B \propto \int_{x_c}^{+1} d\sigma_{\text{CP-odd}} - \int_{-1}^{x_c} d\sigma_{\text{CP-odd}}$$

Choose x_c when ttH/ttA $A_c[z]$ differences are maximum:

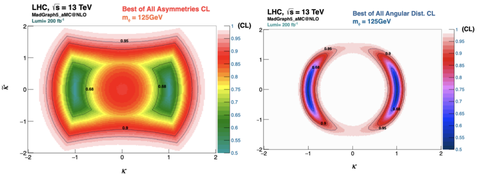
Asymmetries	x_c	MadGraph5 @ NLO+Shower (no cuts applied) $t\bar{t}\phi$ signal mixing angle α (deg.) 0.0°	22.5°	45.0°	67.5°	90.0°	135.0°	180.0°	$t\bar{t}b\bar{b}$
$A_c[b_2^{t\bar{t}\phi}]$	−0.30	−0.35	−0.31	−0.15	+0.15	+0.34	−0.14	−0.36	−0.17
$A_c[b_4^{t\bar{t}\phi}]$	−0.50	+0.41	+0.37	+0.22	−0.04	−0.22	+0.22	+0.41	+0.33
$A_c[\sin(\theta_\phi^{t\bar{t}\phi}) * \sin(\theta_{\bar{t}}^{t\bar{t}})]$	+0.70	−0.27	−0.26	−0.20	−0.09	−0.03	−0.20	−0.27	−0.56
$A_c[\sin(\theta_\phi^{t\bar{t}\phi}) * \sin(\theta_{\bar{b}_{\bar{t}}}^{\bar{t}})]$ (seq. boost)	+0.60	+0.05	+0.05	+0.07	+0.09	+0.11	+0.06	+0.05	−0.38

Table 1: Asymmetries for the $t\bar{t}\phi$ signal as a function of the mixing angle α, as well as for the dominant background $t\bar{t}b\bar{b}$ at NLO+Shower (without any cuts), are shown for several observables. Significant differences between the asymmetries for the pure scalar ($\alpha = 0.0°$) and pseudo-scalar ($\alpha = 90.0°$) cases are observed for several asymmetries.

CLs change with x_c (200 fb^{-1})

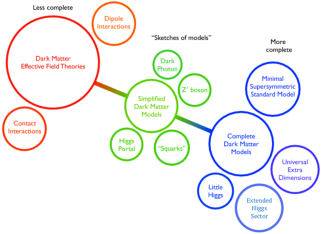


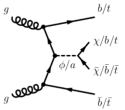
CLs using Asym. vs Ang.Dist. (200 fb^{-1})

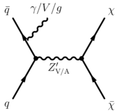


☞ Normalized Differential Distributions

DM Effects in $t\bar{t}$ Spin Observables



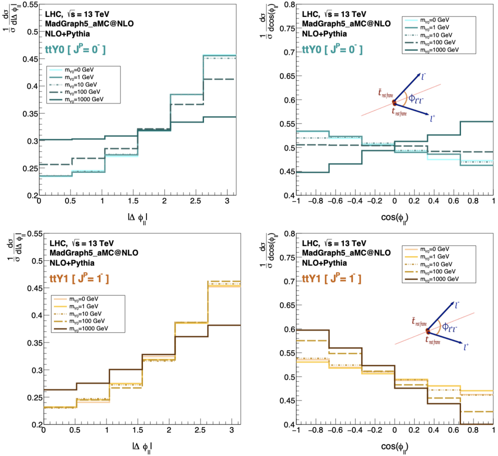




Scalar/pseudo-scalar **Vector/Axial-vector**

Note: reconstruct only the $t\bar{t}$ system and study spin-parity effects in exp. observables

Spin Correlations Observables in $t\bar{t}$ Events @ LHC



Conclusions

- RUN 2 ☞ top quark + Higgs boson precision physics (spin, parity, spin correlations in $t\bar{t}$, BSM...) quite remarkable for an Hadronic Collider ...RUN 3 data will improve the situation; ☞ sensitivity to small contributions (NNLO, interferences, etc.) will (progressively) be more and more important
- Need to measure the nature of the top quark Higgs boson couplings and search for additional sources of CP-violation (direct $t\bar{t}\phi$ measurements are crucial)
- This search can indeed be extend to DM with the significant amount of luminosity expected at RUN3
- But spin physics requires: monitoring the parameter space and finding CP-even and CP-odd angular distributions that can help distinguishing background from signal and also between different signals (probably a combination of those would be best.....)
- CP Asymmetries play an important role at RUN3