# Top Quark Polarizations & Couplings

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Course on Physics at the LHC, $3^{th}$ April 2023, Lisbon

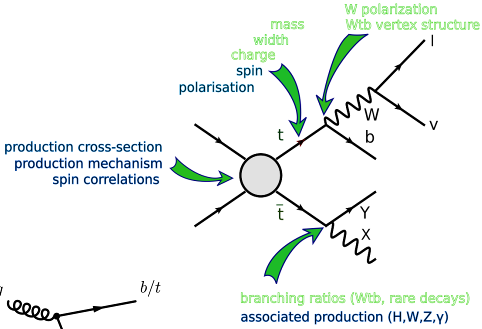
CERN/FIS-PAR/0029/2019 CERN/FIS-PAR/0037/2021

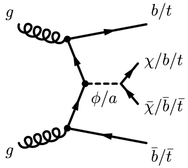
The top-quark and Higgs boson ($\phi$) have a quite rich phenomenology. ☞ Understanding the couplings and the connection to BSM, DM etc., is quite important @ LHC

## List of Topics Covered

☞ all about $t$ spin and spin correlations

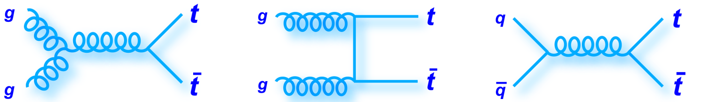
- Data fits, fits and more fits...
- a *Template Method* to measure $t\bar{t}$ spin correlations, Interferences... [Eur.Phys.J.C 82 (2022) 2]
- $t\bar{t}\phi$ production @ LHC CP-violation, asym. and Interferences in $t\bar{t}\phi$ [arXiv:2208.04271, 8 Aug 2022]
- The $t\bar{t}\phi$ DM searches via simplified models low to high mass



# $t\bar{t}$ production at the LHC

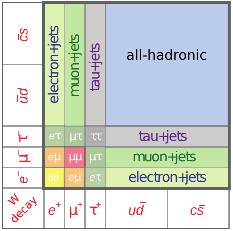
- Production at the LHC:



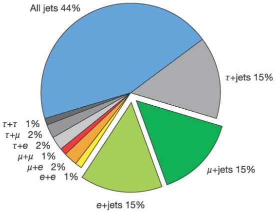

$\sigma(t\bar{t})$=177.3$\pm$9.9$^{+4.6}_{-6.0}$ pb @ 7 TeV, $\sigma(t\bar{t})$=252.9$\pm$11.7$^{+6.4}_{-8.6}$ pb @ 8 TeV, $\sigma(t\bar{t})$=832$^{+40}_{-46}$ pb @ 13 TeV

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).

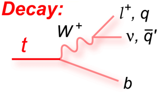
Top pair decay channels



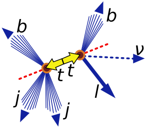

Top pair branching fractions



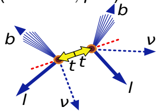

**Decay:**



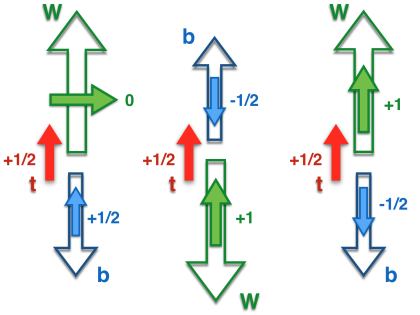

$\Longrightarrow$ Lepton+jets ($\sim$ 30%): ($\ell = e^{\pm}, \mu^{\pm}$)




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



## ☞ 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

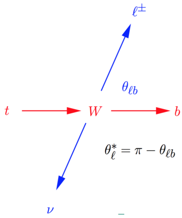
$F_0^{SM} = 0.687 \pm 0.005$

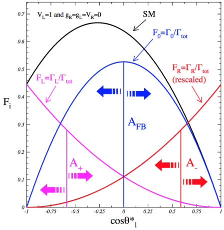
$F_L^{SM} = 0.311 \pm 0.005$

$F_R^{SM} = 0.0017 \pm 0.0001$

@ NNLO QCD calculation, PRD**81**(2010)111503

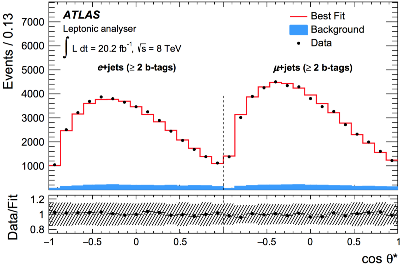
$(F_0 + F_L + F_R = 1)$




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

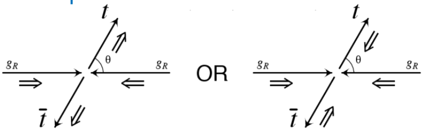
EPJC**77**(2017)264



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

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

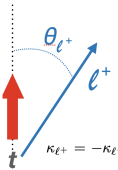
$$\sigma = \sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}$$




quantum interference effects between polarisation states exist

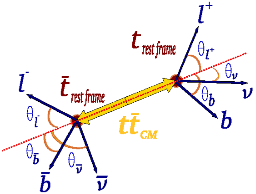
☞ Probe spin correlations using the $\ell^{\pm}$ i.e, $\cos\theta_{\ell^{\pm}}$ ($t\bar{t}$ dileptonic decays)

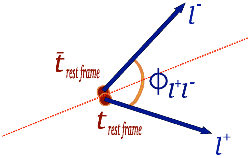
$$pp \to t + \bar{t} + X \to \ell^{+}\ell'^{-} + \text{ jets} + E_T^{\text{miss}}$$




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

$\kappa_{\ell+} = -\kappa_{\ell-} = 1$ 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:

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

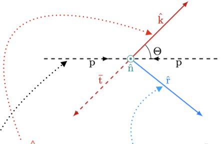
$d\Omega = d\cos\theta d\phi$ $\quad$ $B_1$ ($B_2$) = top (anti-top) vector spin polarisations $\quad$ $C$ = spin correlation matrix

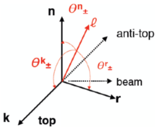
$\hat{\ell}_1$ ($\hat{\ell}_2$) = the $\hat{\ell}^+$ ($\hat{\ell}^-$) directions in the $t(\bar{t})$ system

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

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

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]

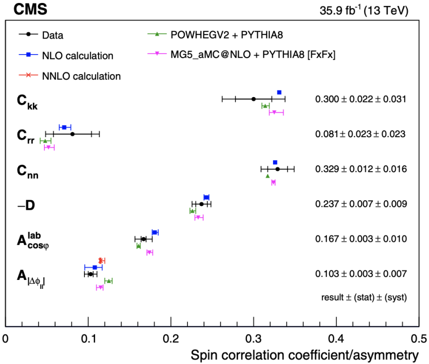
for each 15 coefficient **$B_1$,$B_2$, C** single differential distributions are used

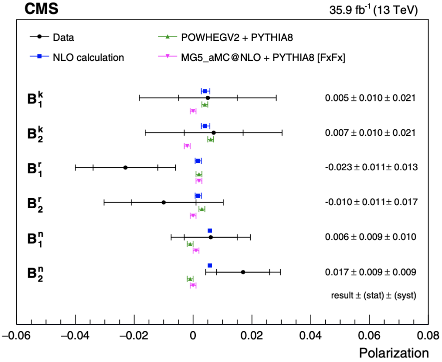
Integrating over the azimuthal angles (for each axis ***i,j***)

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

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

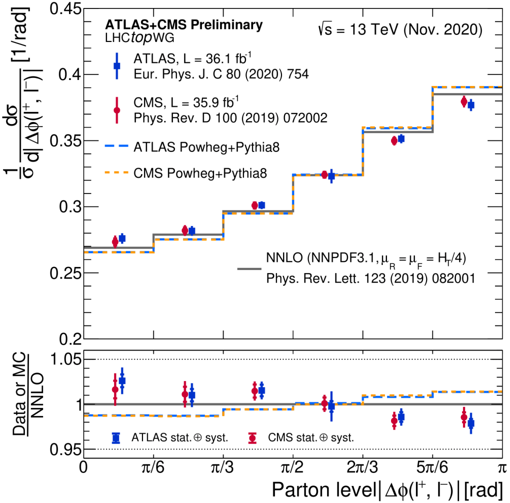
$\theta_1^i$ ($\theta_2^j$) = $\ell^+$ ($\ell^-$) directions in the $t$($\bar{t}$) system, with respect to $i$($j$) axis ($\hat{r}$,$\hat{k}$,$\hat{n}$)



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

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




☞ ATLAS and CMS data compared to calculations at NNLO.

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

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

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

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

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

$\theta_1^i$ ($\theta_2^j$) = $\ell^+$ ($\ell^-$) 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

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

Interference Term (small but not zero!)

with

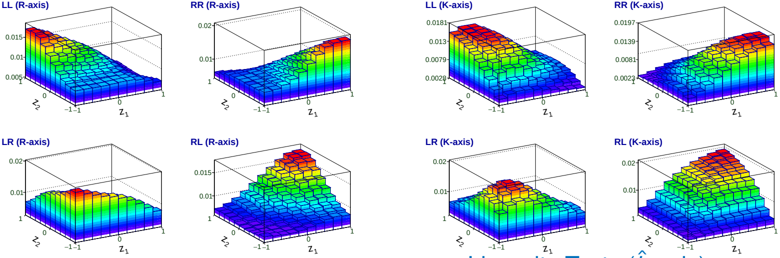
$$\varepsilon = \bar{\sigma}/\sigma$$

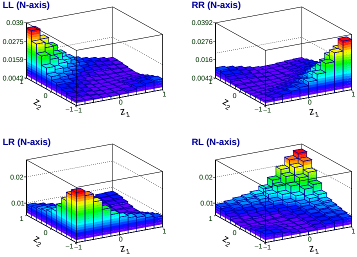
$$\varepsilon_{XX'} = \bar{\sigma}_{XX'}/\sigma_{XX'}$$

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

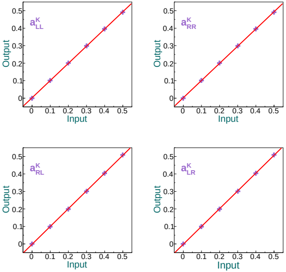
**$a_{XX'}$ = $a_{RR}$, $a_{LL}$, $a_{RL}$ and $a_{LR}$ are the Parton Level spin correlation fractions**
**(no need for unfolding!)**

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

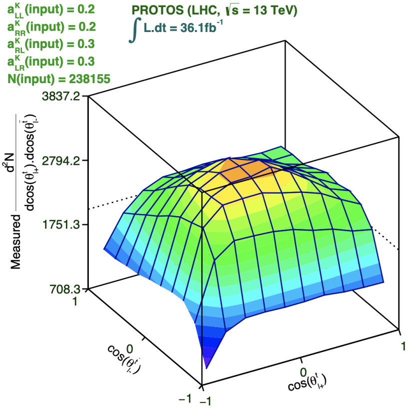


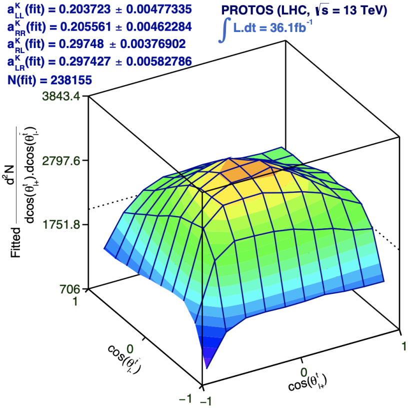




## Linearity Tests ($\hat{k}$ axis)



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

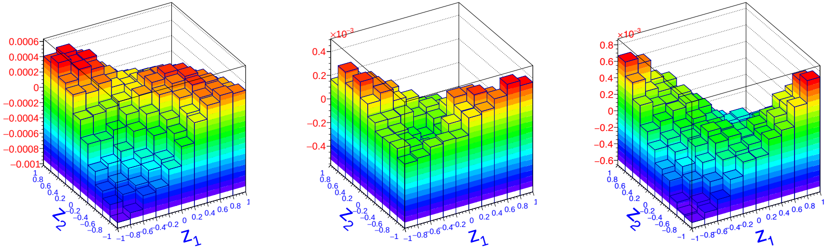


☞ Interference effects can also be measured in all axes $\{\hat{r},\hat{k},\hat{n}\}$

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

**R-axis** **K-axis** **N-axis**




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

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

## 2D Template Fit Results

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

### Top quark Polarizations

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

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

| K | SM | |
|---|---|---|
| | Prediction | Fit |
| $a_{LL}$ | $0.335 \pm 0.001$ | $0.337 \pm 0.006$ |
| $a_{RR}$ | $0.336 \pm 0.003$ | $0.330 \pm 0.005$ |
| $a_{LR}$ | $0.165 \pm 0.003$ | $0.167 \pm 0.007$ |
| $a_{RL}$ | $0.165 \pm 0.002$ | $0.160 \pm 0.004$ |
| $C_{kk}$ | $0.340 \pm 0.002$ | $0.340 \pm 0.019$ |
| $P_t$ | $0.001 \pm 0.002$ | $-0.014 \pm 0.008$ |
| $P_{\bar{t}}$ | $0.001 \pm 0.002$ | $0.000 \pm 0.008$ |

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

## 2D Template Fit Results

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

**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

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

($d_A$ set to zero)

| N | CMDM | |
|---|---|---|
| | Prediction | Fit |
| $a_{LL}$ | $0.358 \pm 0.001$ | $0.363 \pm 0.004$ |
| $a_{RR}$ | $0.358 \pm 0.001$ | $0.352 \pm 0.004$ |
| $a_{LR}$ | $0.142 \pm 0.0003$ | $0.138 \pm 0.004$ |
| $a_{RL}$ | $0.142 \pm 0.001$ | $0.136 \pm 0.004$ |
| $C_{nn}$ | $0.433 \pm 0.002$ | $0.442 \pm 0.010$ |
| $P_t$ | $-0.001 \pm 0.002$ | $-0.014 \pm 0.009$ |
| $P_{\bar{t}}$ | $0.000 \pm 0.001$ | $-0.009 \pm 0.009$ |

**Fits are very sensitive to Interference terms in Spin Correlations**

**may be probed @ LHC (RUN3) without unfolding!**

## 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

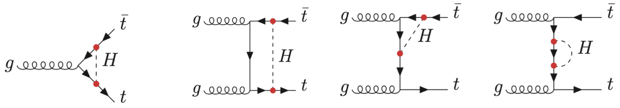
$$\mathcal{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\,(\kappa + i\,\tilde{\kappa}\gamma_5)\,\psi_t\,H,$$

$k$($\tilde{k}$) = 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 $\sigma(\kappa,\tilde{\kappa})_{t\bar{t}H} = \sigma^{t\bar{t}H}_{\rm SM}\left(|\kappa|^2 + 0.39|\tilde{\kappa}|^2\right)$

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

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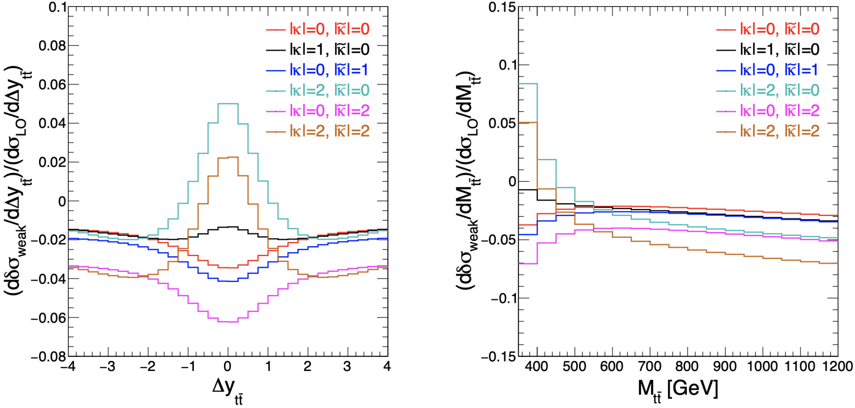


## ☞ Experimental results on the Higgs CP nature $(k,\tilde{k})$

### Effective Lagrangian for top quark Higgs boson interaction

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

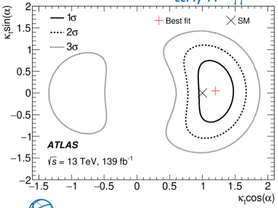
$k(\tilde{k})$ = CP-even (CP-odd) components

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

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

Phys. Rev. Lett. 125 (2020) 061802

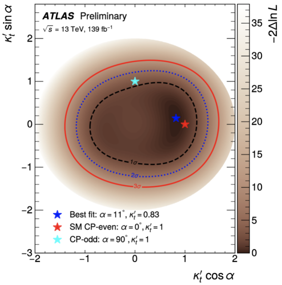
ttH, H→γγ



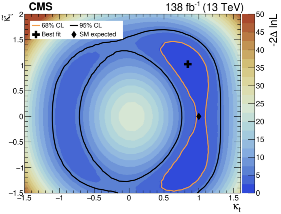

ATLAS EXPERIMENT

ATLAS-CONF-2022-016

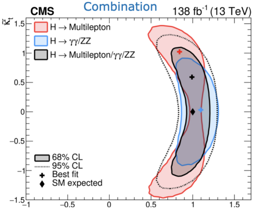
ttH, H→bb




ttH,tH, H→multilepton




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

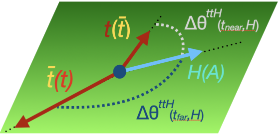
$$\mathcal{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\,(\kappa + \mathrm{i}\,\tilde{\kappa}\gamma_5)\,\psi_t\,H,$$

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

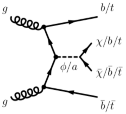
SM (pure CP-even): $k=1$ and $\tilde{k}=0$ BSM, pure CP-odd: $k=0$ and $\tilde{k}=1$

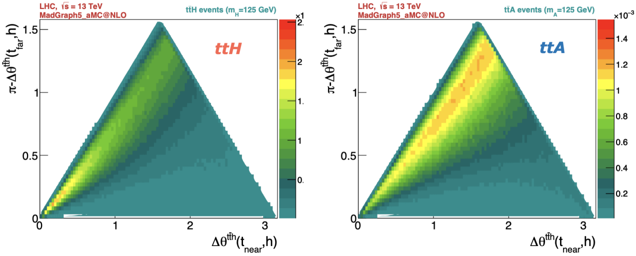
**Mixing angle ($\alpha$) parametrisation: $k=k_t\cos(\alpha)$ and $k=\tilde{k}_t\sin(\alpha)$**

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




*ttH* centre-of-mass system



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

## ☞ Probing the top quark - Higgs boson vertex CP nature

### Effective Lagrangian for top quark Higgs boson interaction

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

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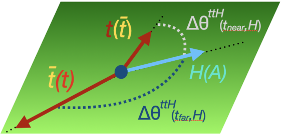
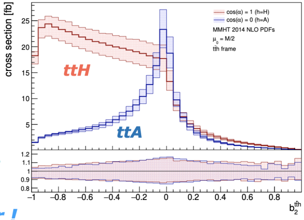


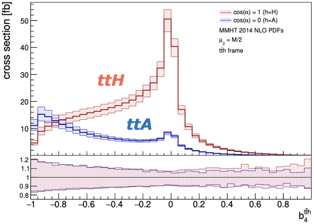

*ttH* centre-of-mass system

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

- **The role of *top quarks* is also very important**

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




***Spin-parity sensitivity is clear !***

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

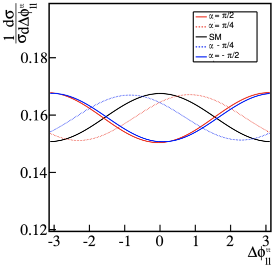
- Probing the top quark - Higgs boson vertex CP nature
- Pheno study with $t\bar{t}\phi$ $2\ell$ events i.e., $t\bar{t}\phi \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu_\ell})(b\bar{b})$
- Event Generation+Simulation @ 13 TeV (RUN2)
  - MadGraph5_aMC@NLO for $t\bar{t}\phi, \phi = A, H$ and $t\bar{t}b\bar{b}$ (@ 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)



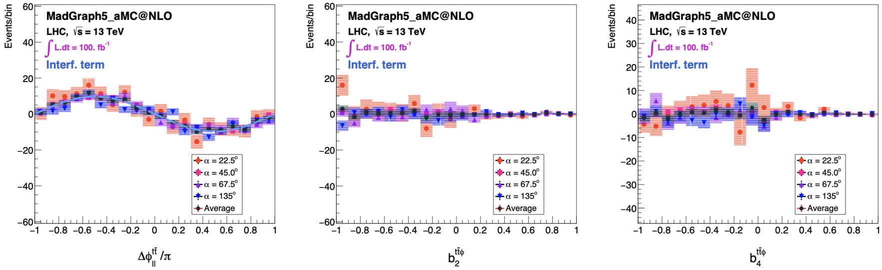

- Observables sensitive to mixing

  (5) $\Delta\phi_{ll}^{t\bar{t}} = \text{sgn}[\hat{p}_t \cdot (\hat{p}_{l^+} \times \hat{p}_{l^-})] \arccos[(\hat{p}_t \times \hat{p}_{l^+}) \cdot (\hat{p}_t \times \hat{p}_{l^-})]$
- Differential cross section and Interference term

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

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

**Reconstructed Interference Differential Distributions**
**(NLO parton level)**




## ☞ Differential cross section and Interference term

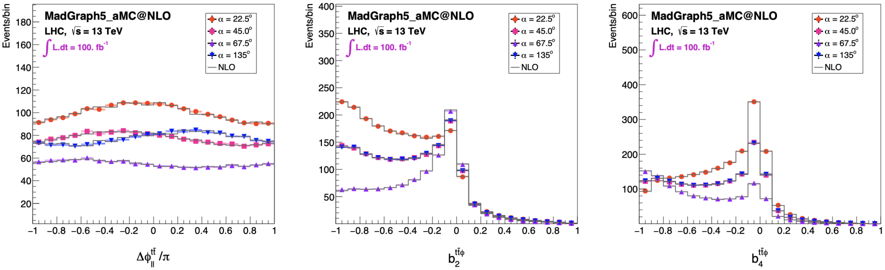
$$d\sigma_{t\bar{t}\phi} = \kappa^2\ d\sigma_{\text{CP-even}} + \tilde{\kappa}^2\ d\sigma_{\text{CP-odd}} + \kappa\tilde{\kappa}\ d\sigma_{\text{int}}$$

solving for $d\sigma_{\text{int}}$ we get:

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

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

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




☞ Differential cross section and Interference term

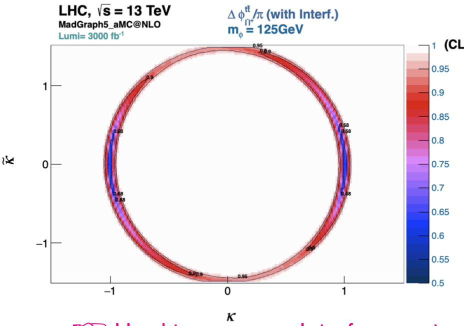
$$d\sigma_{t\bar{t}\phi} = \kappa^2\ d\sigma_{\text{CP-even}} + \tilde{\kappa}^2\ d\sigma_{\text{CP-odd}} + \kappa\tilde{\kappa}\ d\sigma_{\text{int}}$$

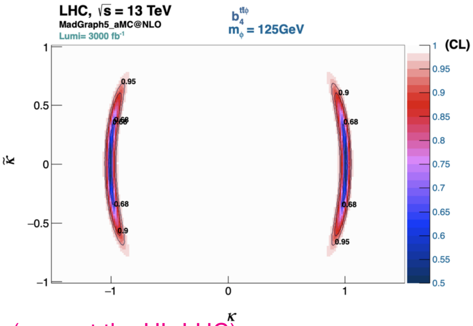
solving for $d\sigma_{\text{int}}$ we get:

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

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

## Expected Exclusion CLs using Differential Distributions w/ Interference



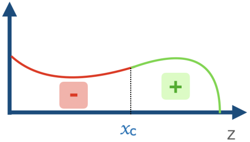




☞ Hard to measure Interference terms (even at the HL-LHC):

...need to study other channels and observables

## ☞ Idea for RUN 3: use Asymmetries

Asymmetries from angular distributions, defined as:




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


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

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

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

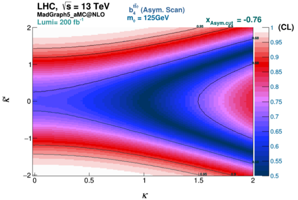
| Asymmetries | $x_c$ | MadGraph5 @ NLO+Shower (no cuts applied) $t\bar{t}\phi$ signal mixing angle $\alpha$ (deg.) 0.0° | 22.5° | 45.0° | 67.5° | 90.0° | 135.0° | 180.0° | $t\bar{t}b\bar{b}$ |
|---|---|---|---|---|---|---|---|---|---|
| $A_c[b_2^{t\bar{t}\phi}]$ | −0.30 | −0.35 | −0.31 | −0.15 | +0.15 | +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 |

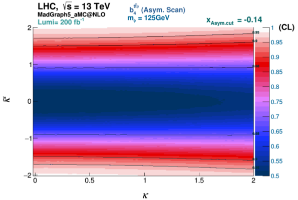
Table 1: Asymmetries for the $t\bar{t}\phi$ signal as a function of the mixing angle $\alpha$, as well as for the dominant background $t\bar{t}b\bar{b}$ at NLO+Shower (without any cuts), are shown for several observables. Significant differences between the asymmetries for the pure scalar ($\alpha =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

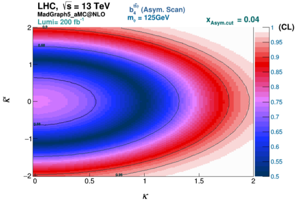
# $t\bar{t}H$, $tH$ Production @ the LHC

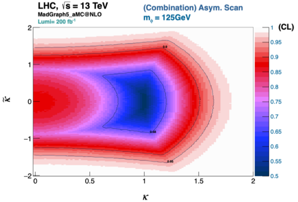
☞ Idea for RUN 3: use Asymmetries

CLs change with the cut-off definition for the asymmetry $x_c$ (200 fb$^{-1}$)



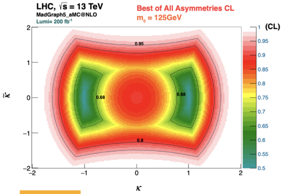



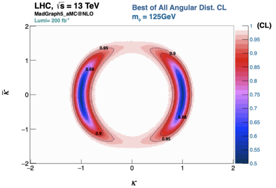




CLs using Asym. vs Ang.Dist. (200 fb$^{-1}$)

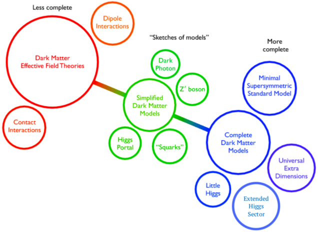
Asym

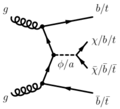



Angular

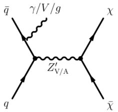


## DM Effects in $t\bar{t}$ Spin Observables




Scalar/pseudo-scalar




Vector/Axial-vector

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

## Interaction Lagrangians for Spin 0 and 1 Mediators

**Spin-0 mediator model**

$$\mathcal{L}^{Y_0}_{X_D} = \bar{X}_D (g^S_{X_D} + i g^P_{X_D} \gamma_5) X_D \, Y_0$$

pure scalar: $g^S{}_{XD}= g^S{}_{u33}=1$, $g^P{}_{XD}= g^P{}_{u33}=0$

pure pseudo-scalar: $g^S{}_{XD}= g^S{}_{u33}=0$, $g^P{}_{XD}= g^P{}_{u33}=1$

**Spin-1 mediator model**

$$\mathcal{L}^{Y_1}_{X_D} = \bar{X}_D \gamma_\mu (g^V_{X_D} + g^A_{X_D} \gamma_5) X_D \, Y_1^\mu$$

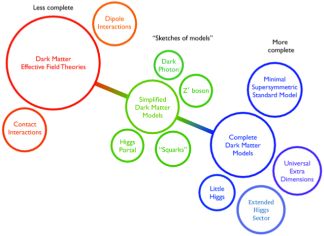
pure vector: $g^V{}_{XD}=1$, $g^V{}_{u33}=0.25$, $g^A{}_{XD}= g^A{}_{q33}=0$

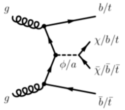
pure axial-vector: $g^V{}_{XD}= g^V{}_{q33}=0$, $g^A{}_{XD}=1$, $g^A{}_{q33}=1$

# DM in $t\bar{t}$ Production @ LHC

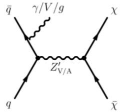
## ☞ Normalized Differential Distributions

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



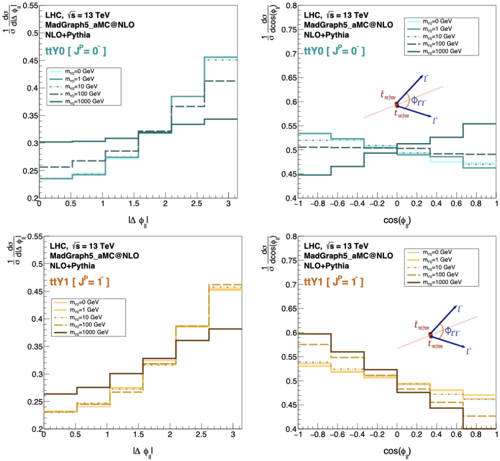

Scalar/pseudo-scalar




Vector/Axial-vector

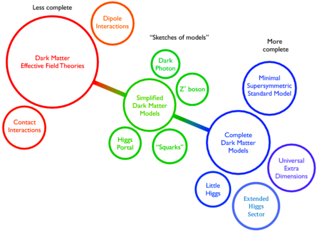
Note: reconstruct only the $t\bar{t}$ system and study spin-parity effects in exp. observables

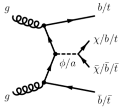
### Spin Correlations Observables in $t\bar{t}$ Events @ LHC



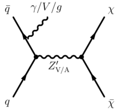
## ☞ Differential Distributions

### Just one simple example



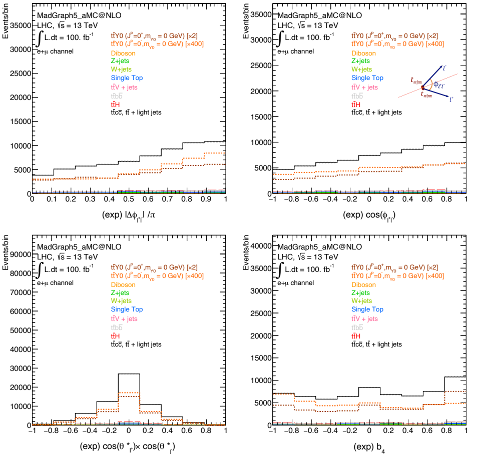

Scalar/pseudo-scalar




Vector/Axial-vector

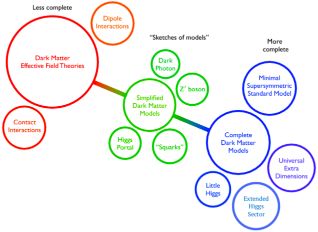
**Note: use $m_\phi=0$, and $m_{DM}=0$**

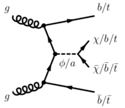
### Spin Correlations Observables in $tt$ Events @ LHC (analysis)



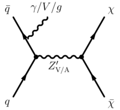
## ☞ CLs exclusions

### Just one simple example




Scalar/pseudo-scalar

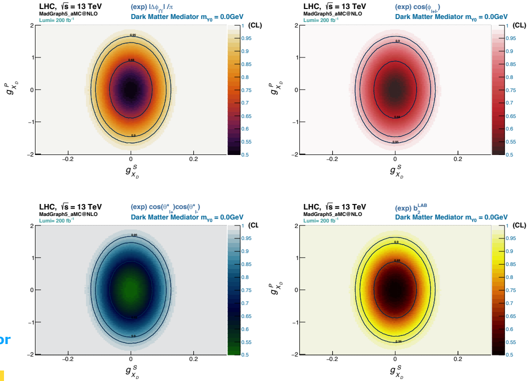



Vector/Axial-vector

**Note: use $m_{\phi}=0$, and $m_{DM}=0$**

**Exclusion Limits for $t\bar{t}$ Events @ LHC (analysis)**

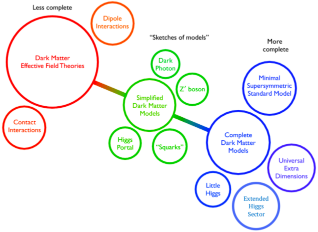
**SM (Null Hyp.)**

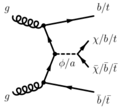


# DM in $t\bar{t}$ Production @ LHC

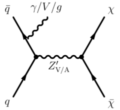
## ☞ CLs exclusions

### Just one simple example




**Scalar/pseudo-scalar**

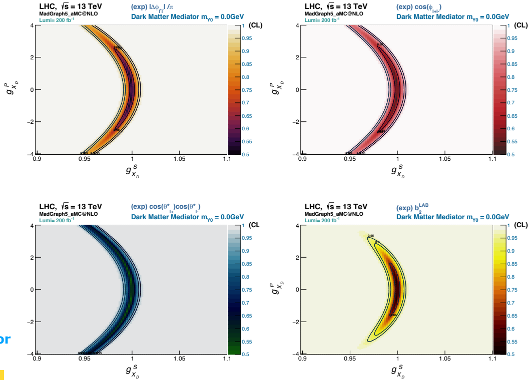



**Vector/Axial-vector**

**Note: use $m_\phi=0$, and $m_{DM}=0$**

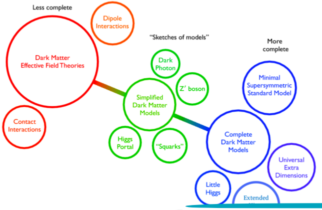
**Exclusion Limits for *tt* Events @ LHC (analysis)**

**SM + $J^P=0^+$ (Null Hyp.)**



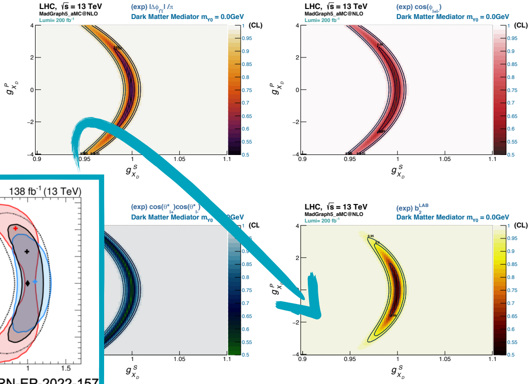
## ☞ CLs exclusions

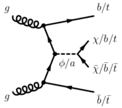
### Just one simple example



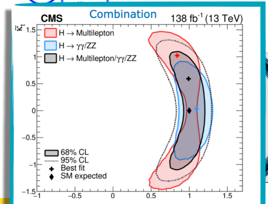

Exclusion Limits for $tt$ Events @ LHC (analysis)

SM + J$^P$=0$^+$ (Null Hyp.)



Scalar/pseudo-scalar



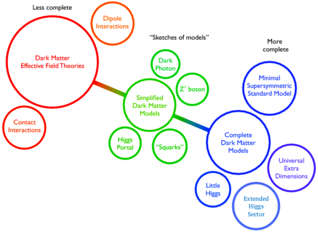

CMS-HIG-21-006 ; CERN-EP-2022-157

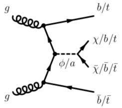
Note: use $m_\phi$=0

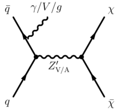
# DM in $t\bar{t}$ Production @ LHC

## ☞ CLs exclusions

### Just one simple example



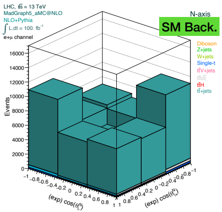



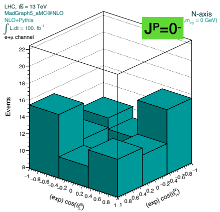

**Scalar/pseudo-scalar** **Vector/Axial-vector**

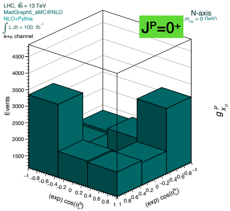
**Note: use $m_{\phi}=0$, and $m_{DM}=0$**

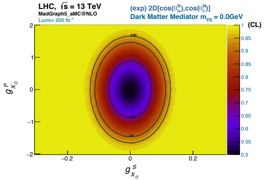
Limits from 2D also good for *tt* Events @ LHC (analysis)

SM (Null Hyp.)



# Conclusions

- RUN 3 has started! ☞ sensitivity to small contributions (NNLO, interferences, etc.) will (progressively) be more and more important

  the LHC is becoming a very precise machine

- Top quark spin observables are indeed quite powerful to probe New Physics
- 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 can play an important role at RUN3