# Probing CP couplings in $t\bar{t}x$ production at the Run3 of the LHC.

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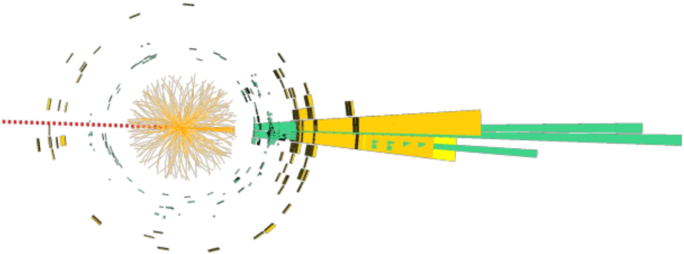

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Prof. Dr. Miguel Fiolhais (The City University of New York)
Prof. Dr. Ricardo Gonçalo (University of Coimbra).

# Motivation: CP-odd component of Higgs

Higgs coupling with SM particles $\mathcal{L} = -y_t \bar{t}(\kappa + i\gamma^5 \tilde{\kappa}) th$

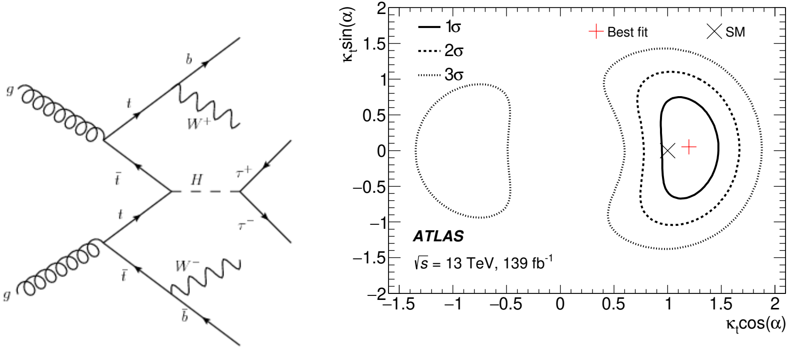



Figure 1: Exclusion limits for Higgs bosons interactions associated with the top quark (right), Feynman diagram for the production of the Higgs boson in association with a pair of top quarks (left). (ATLAS col.) [1].

# What can we say for the $t\bar{t}x$ case?

Spoiler alert: Dark Matter

# Dark Matter models

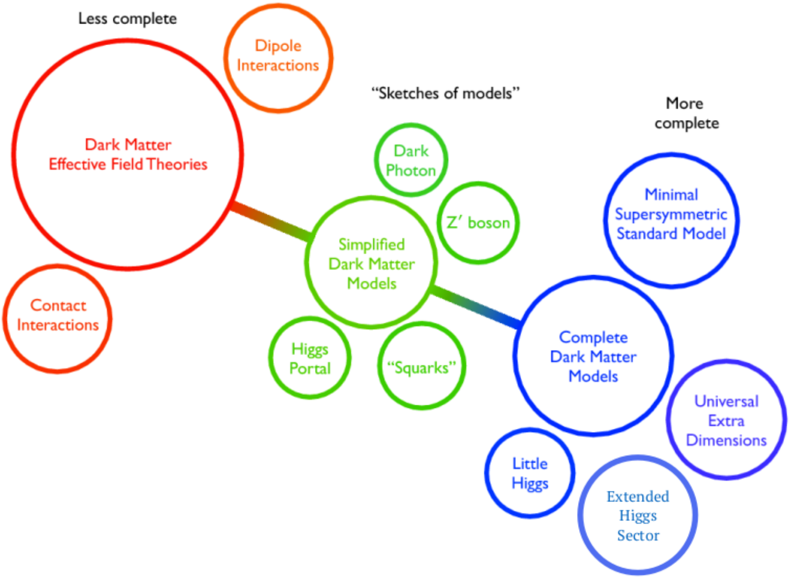



Figure 2: Landscape for particle-like DM models (ATLAS col.) [2].

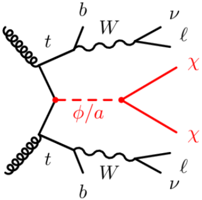
# Simplified Dark Matter models (SDMm)

- Dark matter simplified models: around 5-7 parameters: $(g_q,\ g_\ell,\ g_\chi, \Gamma, M_X,\ M_{V,\phi}, \Lambda)$
- New observables has been introduced for the Higgs pseudoscalar component [3].

$$\mathcal{L} = -y_t \bar{t}(\kappa + i\gamma^5 \tilde{\kappa}) t\phi \quad (1)$$

$$\mathcal{L} = -y_t \gamma^\mu \bar{t}(\kappa + i\gamma^5 \tilde{\kappa}) t\phi_\mu \quad (2)$$

$$\mathcal{L} = -\frac{1}{4\Lambda}[i\bar{t}(\gamma^\mu \partial_\nu + \gamma^\nu \partial_\mu)t - i(\gamma^\mu \partial_\nu \bar{t} + \gamma^\mu \partial_\nu \bar{t})t]\phi^\nu_\mu \quad (3)$$




Total cross-section can be decomposed:

$$\sigma^T_{t\bar{t}\phi} = \sigma_{\text{CP-even}} \cos^2(\alpha) + \sigma_{\text{CP-odd}} \sin^2(\alpha) \ \ \text{LO} \quad (4)$$

Parton level distributions are used to test observables such as:

$$b_2 = \frac{\vec{p}_t \cdot \vec{p}_{\bar{t}}}{|\vec{p}_t||\vec{p}_{\bar{t}}|} \quad , \quad b_3 = \frac{p^x_t p^x_{\bar{t}}}{|\vec{p}_t||\vec{p}_{\bar{t}}|} \quad , \quad b_4 = \frac{p^z_t p^z_{\bar{t}}}{|\vec{p}_t||\vec{p}_{\bar{t}}|} \quad (5)$$

# How do I simulated events with theses models?

# MC simulation of DM models

However, for a fast Monte Carlo simulation (MC) pipeline for modeling DM passes by the following steps:

Events generation and parton level reconstruction

- Models: (i.e. `UFO`, `DMsimp`, etc.)
- Events generation: `MadGraph`
- Detector parameters `Delphes`
- Reconstruction of the kinematic variables (i.e. likelihood estimators) [4].

Confidence limits determination

- Input distributions for reconstructed variables.
- Transformation in number of events, including branching ratios.
- Addition of background previously estimated.
- Likelihood computation (varying parameters).
- Confidence regions.

- Background + Signal:

$$\mathcal{L}_{\text{total}=b+s} = \Pi_i^N \text{Pois}(N_i|s_i + b_i)P_n(\theta) \tag{6}$$

- Signal:

$$\mathcal{L}_{\text{total}=s} = \Pi_i^N \text{Pois}(N_i|s_i)P_n(\theta) \tag{7}$$

**Goal: Propose new observables for real measurements.**

# Higgs CP-sensitive observables results

# CP-sensitive variables in the context of Dark Matter

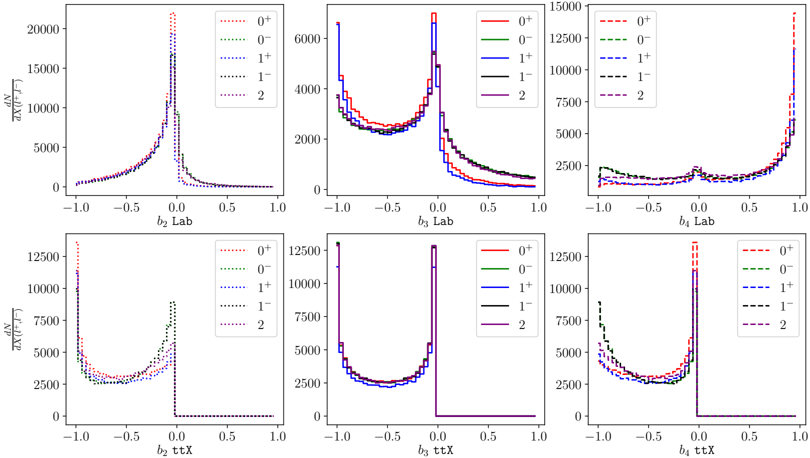



Figure 3: Events distributions for the $b_2$ (upper left), $b_3$ (upper middle), $b_4$ (upper right) in the laboratory frame, against the $b_2$ (lower left), $b_3$ (lower middle), $b_4$ (lower right) in the $t\bar{t}X$ reference frame for a SDMm with mediator mass of 1 GeV for several cases of CP and mediator spin.

# CP-sensitive variables in the context of Dark Matter

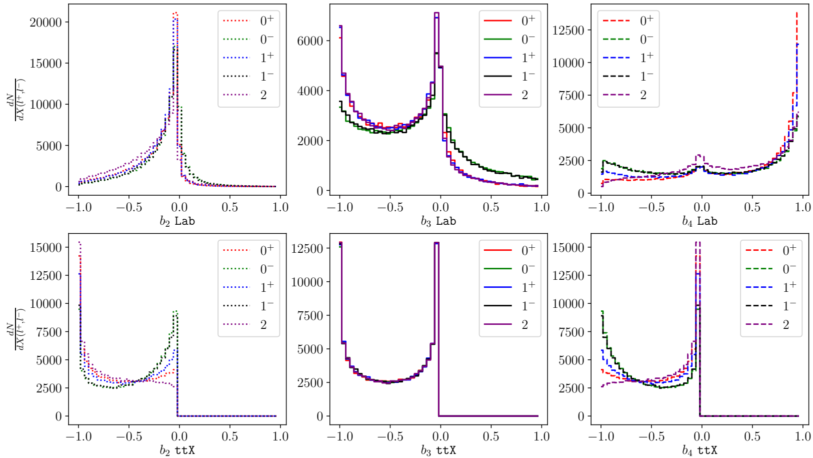



Figure 4: Events distributions for the $b_2$ (upper left), $b_3$ (upper middle), $b_4$ (upper right) in the laboratory frame, against the $b_2$ (lower left), $b_3$ (lower middle), $b_4$ (lower right) in the $t\bar{t}X$ reference frame for a SDMm with mediator mass of 10 GeV for several cases of CP and mediator spin.

# CP-sensitive variables in the context of Dark Matter

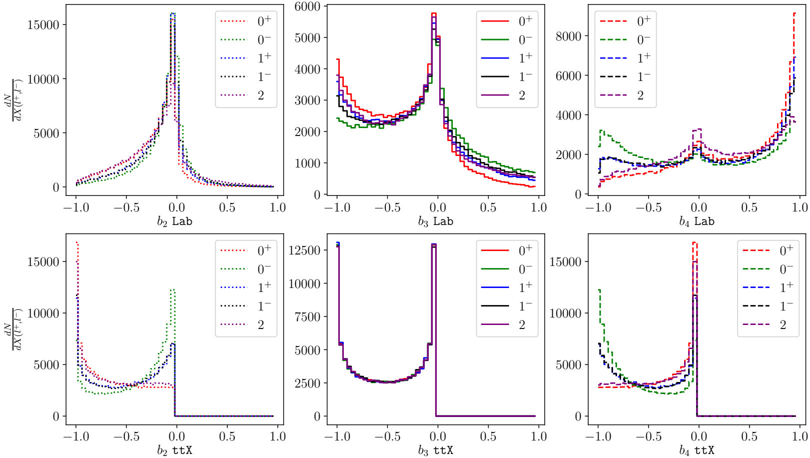



Figure 5: Events distributions for the $b_2$ (upper left), $b_3$ (upper middle), $b_4$ (upper right) in the laboratory frame, against the $b_2$ (lower left), $b_3$ (lower middle), $b_4$ (lower right) in the $t\bar{t}X$ reference frame for a SDMm with mediator mass of 100 GeV for several cases of CP and mediator spin.

# CP-sensitive variables in the context of Dark Matter

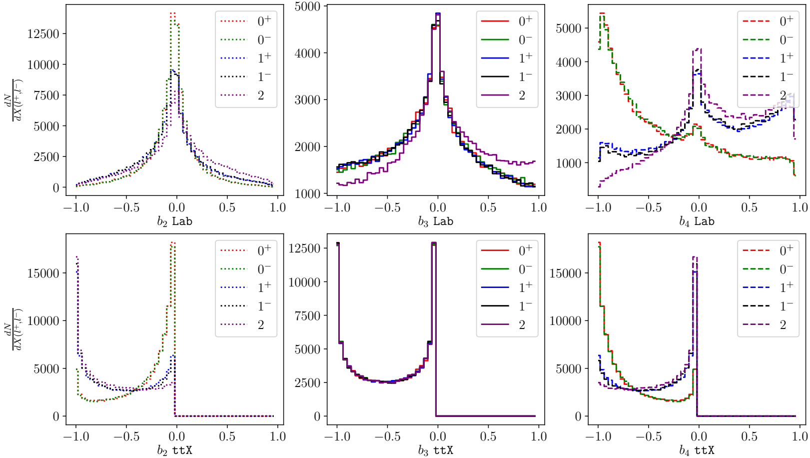



Figure 6: Events distributions for the $b_2$ (upper left), $b_3$ (upper middle), $b_4$ (upper right) in the laboratory frame, against the $b_2$ (lower left), $b_3$ (lower middle), $b_4$ (lower right) in the $t\bar{t}X$ reference frame for a SDMm with mediator mass of 1000 GeV for several cases of CP and mediator spin.

# MC simulation of DM models: CP-nature (LO)

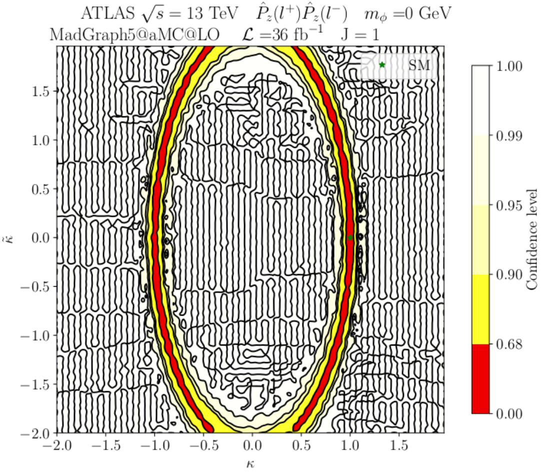



Figure 7: Example of an exclusions limit for the HC−UFO at leading order. The particle mediator considered is spin 1 and limits are compute using the $b_4$ observable in the $t\bar{t}X$ frame after adding the SM background.

# How useful are observables?

Very much. ML method can be used to optimize a given observable (Kamenich et. al.: [5]):

$$\text{loss}(\boldsymbol{\alpha}) = \left(\frac{\text{mean}(\mathcal{F}(\boldsymbol{X};\boldsymbol{\alpha}))}{\text{std}(\mathcal{F}(\boldsymbol{X};\boldsymbol{\alpha}))/\sqrt{N}}\right)^{-2}, \tag{8}$$

$$\omega_6 \sim [(p_{\ell^-} \times p_{\ell^+}) \cdot (p_b + p_{\bar{b}})]\,[(p_{\ell^-} - p_{\ell^+}) \cdot p_b + p_{\bar{b}})] \tag{9}$$

$$\omega_{14} \sim [(p_{\ell^-} \times p_{\ell^+}) \cdot (p_b - p_{\bar{b}})]\,[(p_b - p_{\bar{b}}) \cdot (p_{\ell^-} - p_{\ell^+})] \tag{10}$$

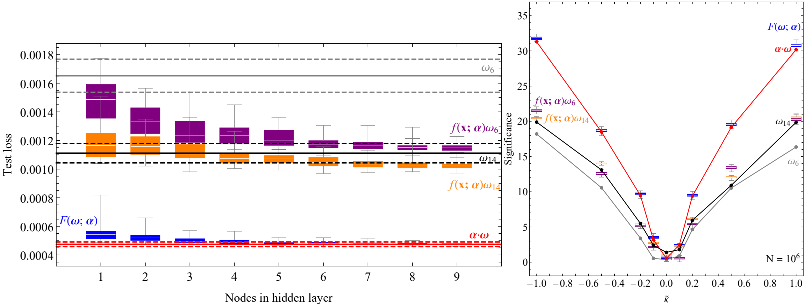



Figure 8: Scanning for the loss function for a sample o Higgs events with coupling constants to quarks normalized to 1 $\kappa, \tilde{\kappa} = 1$ inside a artificial Neutral Network for the CP-odd observables $\omega_6$ and $\omega_{14}$.

# Summary

What we have learned:

- It is possible to probe the CP components in the context of simplified Dark Matter models (LO).
- Monte Carlo simulation pipeline based in parton-level distribution is fully functional.
- Some of the Higgs related variables (i.e. $b_2$, $b_3$, $b_4$) show sensitivity for the simplified dark matter models mass and spin.
- Some observables are not really sensitive but still useful.
- New observables (ongoing work: stay tuned!)

What we will learn:

- Explore exclusion limits for NLO variables.
- Phenomenological studies in ATLAS.
- Classifying events from Backgrounds (ML).
- How to improve parameter space coverage (ML).
- Recovering the input given parameters by using regression algorithms (ML).

Thanks!

# Backup

# WIMP-like DM

WIMP-like (i.e., particle-like) DM production relies on one or more visible particles produced in association with the invisible DM candidate.

- Axions.
- Two-Higgs-doublet.
- **Pseudoscalar/vector/tensor mediators to DM**.
- Supersymmetry.
- Gravitinos, etc.

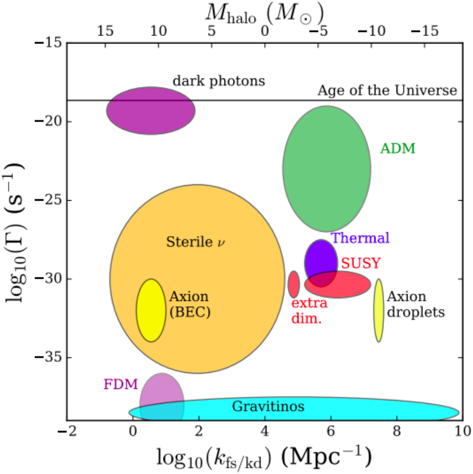



Figure 9: Allowed parameter space of the currently most popular dark matter candidates[6].

Many more complicated models!

# Detection of DM

- Indirect detection: CTA, HESS, AMS, PAMELA.
- Direct detection: Zeplin, Xenon, LUX, CoGeNT, DAMA/LIBRA.
- Collision: FCC, LHC, 100-TeV collider.
- Astrophysical observation: Galaxy surveys.

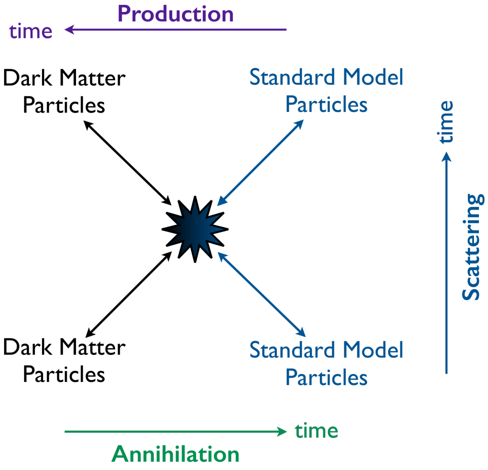



Figure 10: Production of DM particles and possible detection methods [7].

# Detection of DM

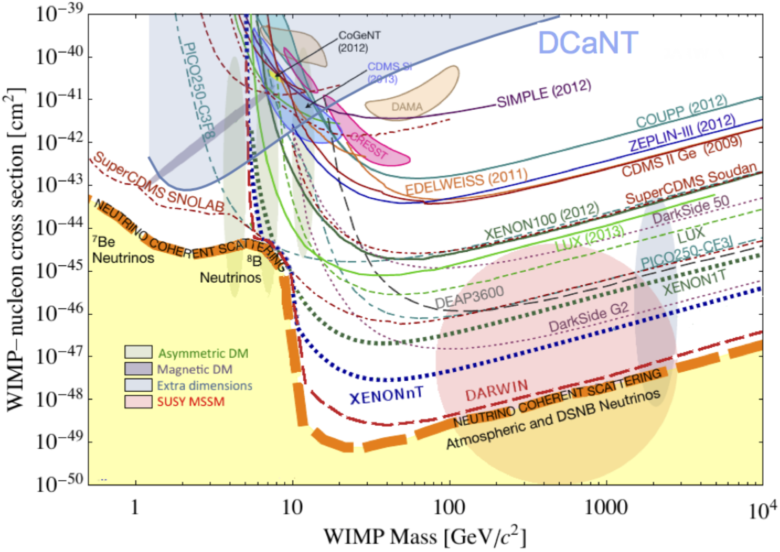



Figure 11: WIMP-nucleon spin-independent cross section limits for current DM direct detection experiments [8].

# Direct detection: ATLAS

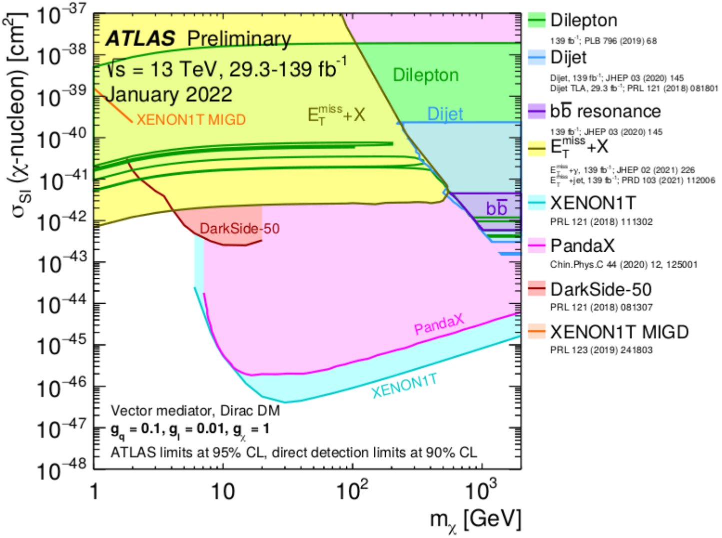



Figure 12: WIMP-nucleon scattering cross-section results compared with direct detection limits to date from Dark-Side-50, XENON1T and PandaX experiments [9].

# Simplified Dark Matter models

| Short description | Acronym | Symbol | $J^P$ | Charge | Signatures (Sec. 4) |
|---|---|---|---|---|---|
| Vector/axial-vector mediator | V/AV | $Z'_V/Z'_A$ | $1^{\mp}$ | × | jet/$\gamma/W/Z$+$E_T^{miss}$, difermion resonance |
| Vector baryon-number-charged mediator | VBC | $Z'_B$ | $1^-$ | baryon-number | $h + E_T^{miss}$ |
| Vector flavour-changing mediator | VFC | $Z'_{VFC}$ | $1^-$ | flavour | $tt$, $t + E_T^{miss}$ |
| Scalar/pseudo-scalar mediator | S/PS | $\phi/a$ | $0^{\pm}$ | × | jet+$E_T^{miss}$, $t\bar{t}/b\bar{b}$+$E_T^{miss}$ |
| Scalar colour-charged mediator | SCC$_{q/b/t}$ | $\eta_{q/b/t}$ | $0^+$ | colour, 2/3 electric-charge | jet+$E_T^{miss}$, $b + E_T^{miss}$, $t + E_T^{miss}$ |
| Two-Higgs-doublet plus vector mediator | 2HDM+$Z'_V$ | $Z'_V$ | $1^-$ | × | $h + E_T^{miss}$ |
| Two-Higgs-doublet plus pseudo-scalar mediator | 2HDM+$a$ | $a$ | $0^-$ | × | $W/Z/h + E_T^{miss}$, $t\bar{t}/b\bar{b}$+$E_T^{miss}$, $h$(inv), $t\bar{t}t\bar{t}$ |
| Dark energy | DE | $\phi_{DE}$ | $0^+$ | × | jet+$E_T^{miss}$, $t\bar{t}$ +$E_T^{miss}$ |

Figure 13: DM mediator-based simplified models considered by ATLAS col. [10]

# Maximum likelihood estimators

Likelihood profiles are Poisson-like distributions for two different cases:

- Background + Signal:

$$\mathcal{L}_{\text{total}=b+s} = \Pi_i^N \text{Pois}(N_i|s_i + b_i)P_n(\theta) \quad (11)$$

- Signal:

$$\mathcal{L}_{\text{total}=s} = \Pi_i^N \text{Pois}(N_i|s_i)P_n(\theta) \quad (12)$$

Where $N_i$ is the number of events in the i-bin, $b_i$ is the background signal, $s_i$ is the signal and $P_n(\theta)$ is the distribution for nuisance parameters.

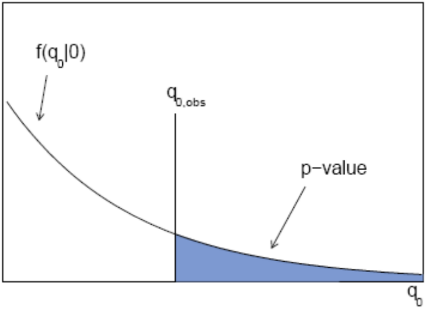



Figure 14: P-val determination from a distribution [11].

Confidence level determination criteria:

$$CDF: \quad Z = \Phi^{-1}(1-p) \quad (13)$$

# MC simulation of DM models (LO)

Constrain the couplings in the lagrangian for scalar mediators:

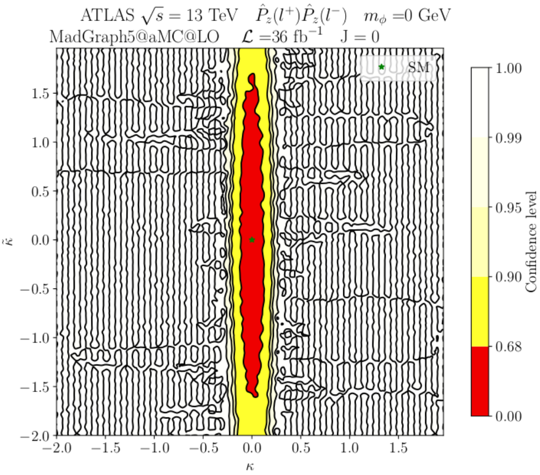



Figure 15: Exclusions limits for the HC-UFO at leading order for the spin 0 mediator in the total cross-section signal for $b_4$ distribution in the $t\bar{t}X$ frame in signal only case.

# MC simulation of DM models (LO)

For axial/vector mediators:

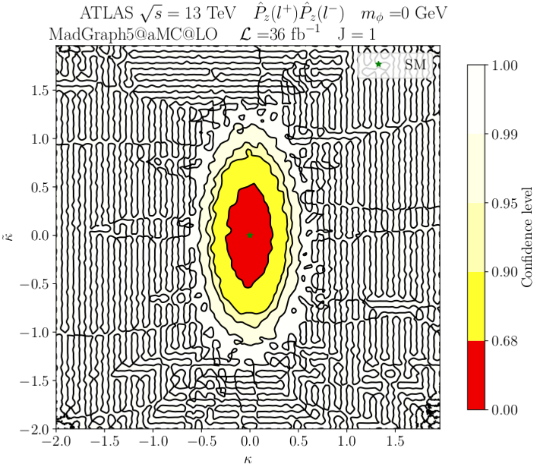



Figure 16: Exclusions limits for the HC-UFO at leading order for the spin 1 mediator in the total cross-section signal for $b_4$ distribution in the $t\bar{t}X$ frame in signal only analysis.

# MC simulation of DM models: CP-nature (LO)

Constraining the couplings in the Lagrangian for scalar mediators:

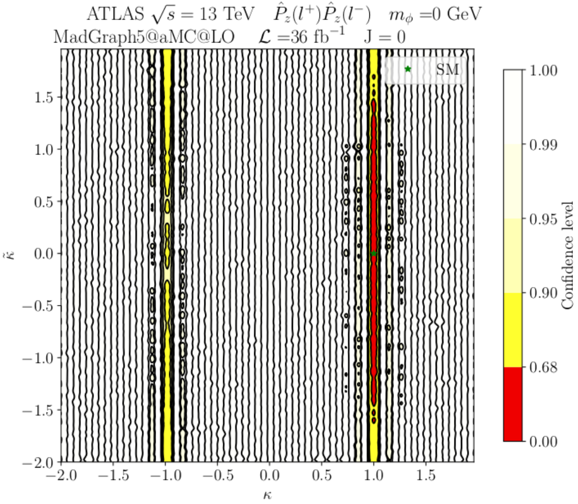



Figure 17: Exclusions limits for the `HC-UFO` at leading order for the spin 0 mediator in the total cross-section signal for $b_4$ distribution in the $t\bar{t}X$ frame in signal+SM background.

# MC simulation of DM models

We can use parton level distributions for simplified Dark Matter models (i.e HC-UFO) [12]:

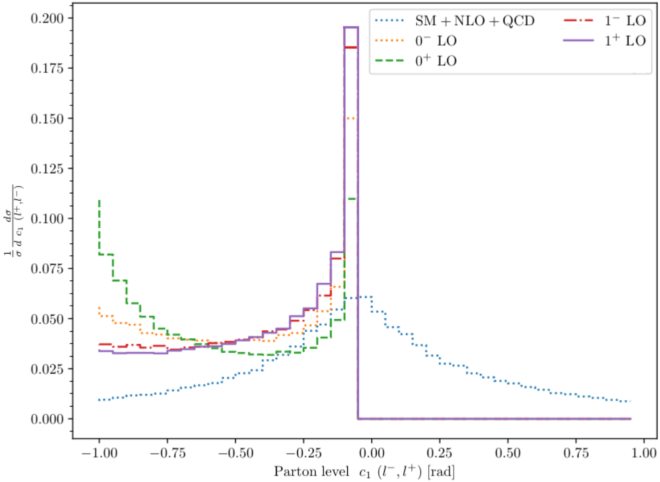



Figure 18: Normalized differential cross-section for the HC-UFO@LO for the $b_4$ observable in the $t\bar{t}\phi$ frame against the SM case for the same observable.

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