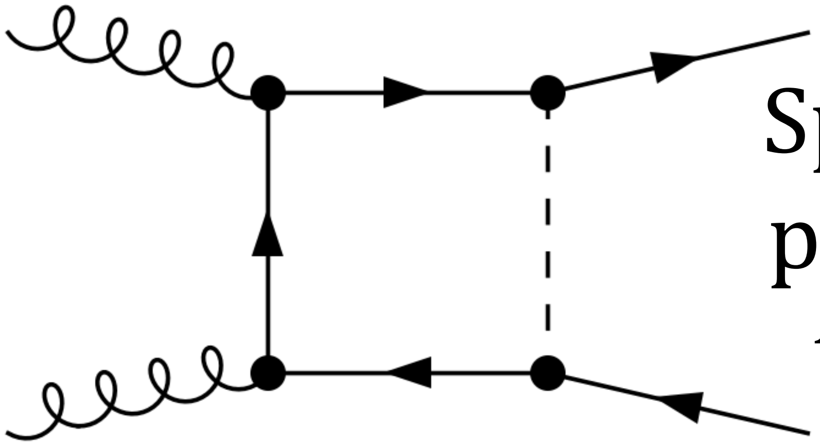
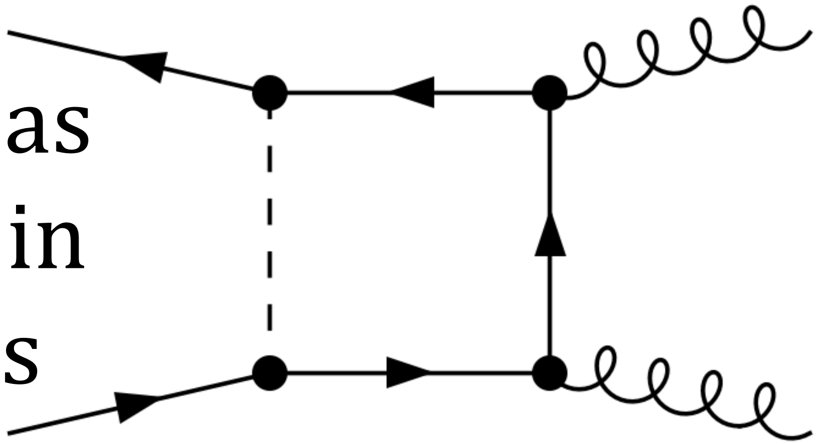


Spin-Density Matrices as probes of CP violation in top-Higgs interactions



Marcel Yáñez Reyes

Michigan State University

Work in collaboration with: Eren Erdogan, Kirtimaan Mohan, Scarlett Rebolledo and Keping Xie

Phenomenology 2026 Symposium
University of Pittsburgh

Need for BSM physics – Lack of anti-matter

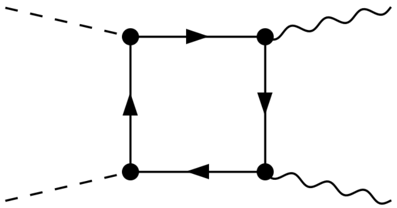
The matter antimatter asymmetry of our universe is an established problem, with several independent sources of evidence.

Sakharov's Conditions [Sakharov 1991 *Sov. Phys. Usp.* **34** 392] for baryogenesis:

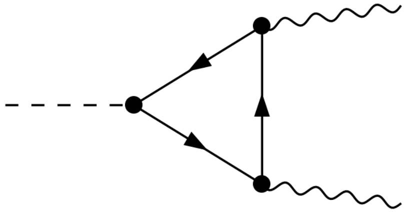
1. Baryon number must be violated.
2. C and CP symmetries must be violated.
3. The universe must undergo a state that is away from thermal equilibrium;

General approaches to parametrize CP violation in the Yukawa sector

We focus on the description of the SM and just one operator that emerges from pseudoscalar interactions between the top quark and the Higgs. This simplified model characterized by Higgs-Top CP (HTCP) odd states is given by



$$\mathcal{L}_{t\bar{t}H} \rightarrow \mathcal{L}_{t\bar{t}HCP} = -\frac{Y_t}{\sqrt{2}}\bar{t}(a_t \mathrm{h} + i b_t \gamma_5 \mathrm{h})t,$$



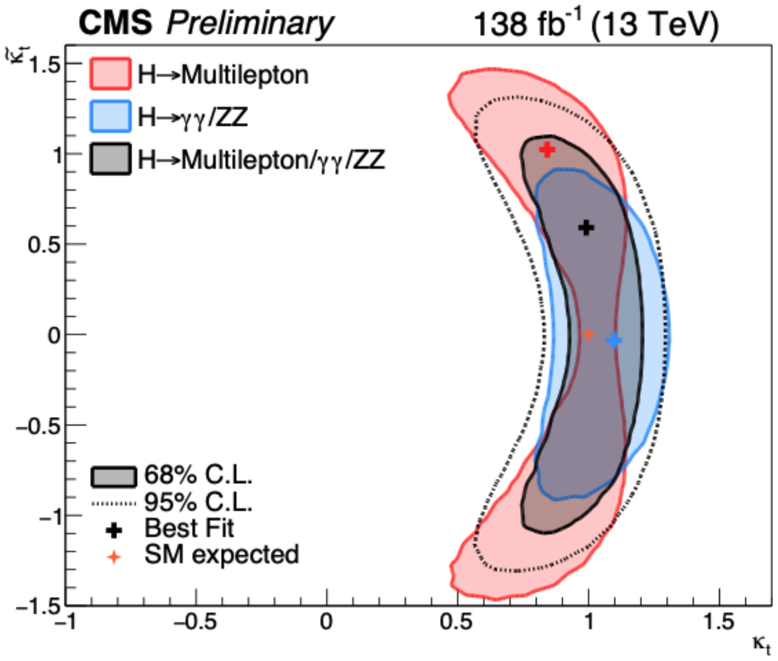
People have studied this model since the 90s [C. Schmidt and M. Peskin, Phys. Rev. Lett. 69, 410 (1992)] and have studied its signals at the LHC [See 2208.02686, 2303.05974 and related]

The most accessible of these Yukawa couplings is the Higgs-top coupling given the large value of the top quark mass.

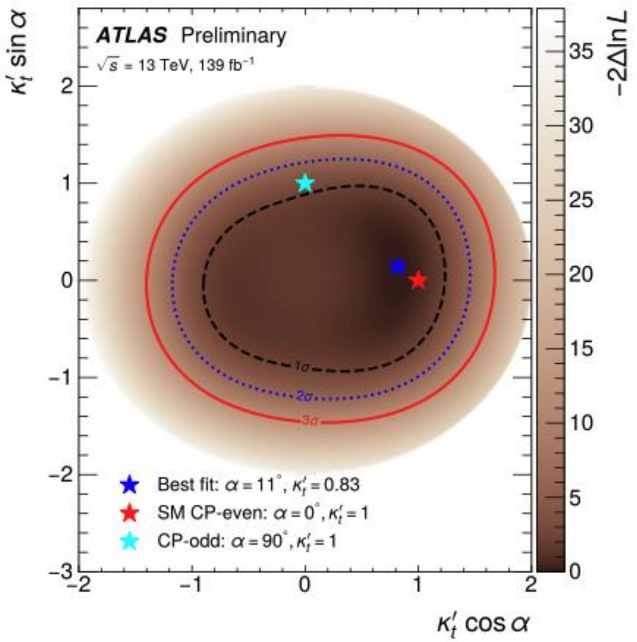
a_t	b_t	Type of Higgs
1	0	SM
$\neq 0$	$\neq 0$	BSM-mixed CP state
0	$\neq 0$	BSM pure pseudoscalar

Constrains on HTCP

Multiple studies have constrained CP violation directly in VBF, $h\gamma\gamma$, hZZ, ht and $h\bar{t}t$. Modern bounds have been set for a_t and b_t. From 2024 in ATLAS and 2023 CMS:



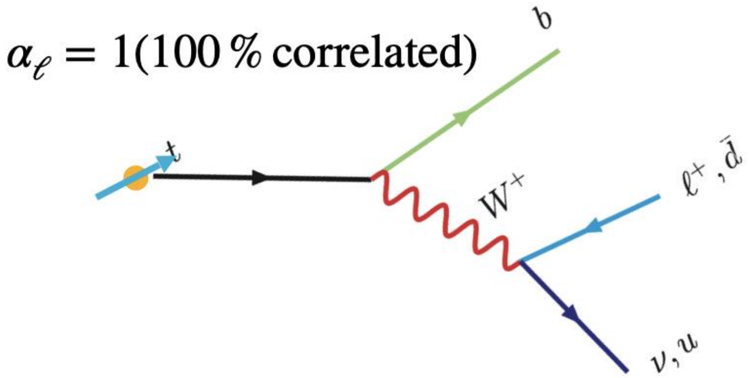
2208.02686



2303.05974

Probing HTCP with $pp \to \bar{t}t$

- Can we look at other channels to complement constrains on these couplings? Can we use Quantum Information based observables to achieve this?
- One of the "standard candle" processes at the LHC with an estimate of $\sim 10^8$ events using run 2 data only [PDG, Review of Particle Physics (2024), ATLAS 2006.13076].
- Short lifetime of top quark allows it to decay before hadronizing. This habilitates the use of perturbation theory to accurately study its properties [PDG, Review of Particle Physics (2024)].
- Decaying lepton direction is highly correlated with top spin (spin analyzing power is exactly 1)

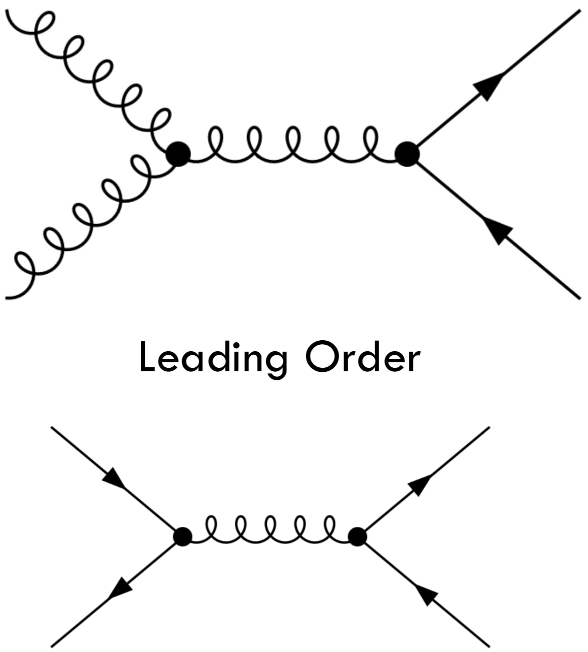


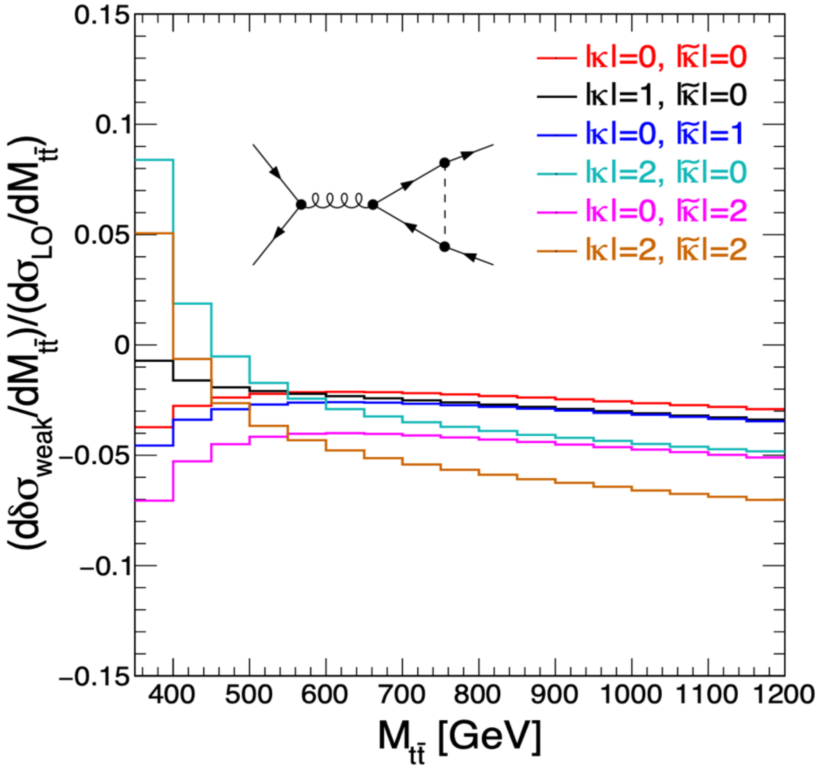
Picture taken from: Fabio Maltoni's talk - PHENO 26

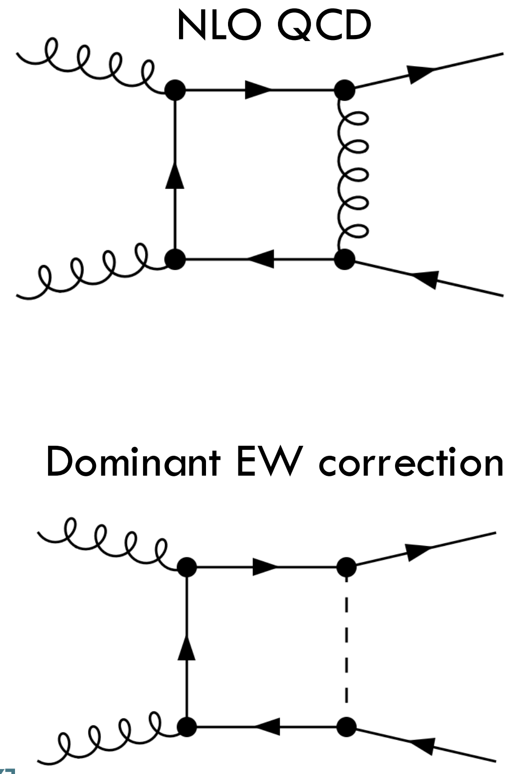
Relevant kinematic observables

$$\mathcal{L}_{t\bar{t}HCP} = -\frac{Y_t}{\sqrt{2}}\bar{t}(a_t \mathrm{h} + i b_t \gamma_5 \mathrm{h})t, \qquad \delta_{weak} = \frac{d\sigma_{NLOQCD+\mathrm{H}} - d\sigma_{NLOQCD}}{d\sigma_{NLOQCD}}.$$

There are noticeable differences in certain kinematic observables when comparing different values of couplings in the HTCP model:







[Martini, Pan, Schultze and Xiao 2104.04277]

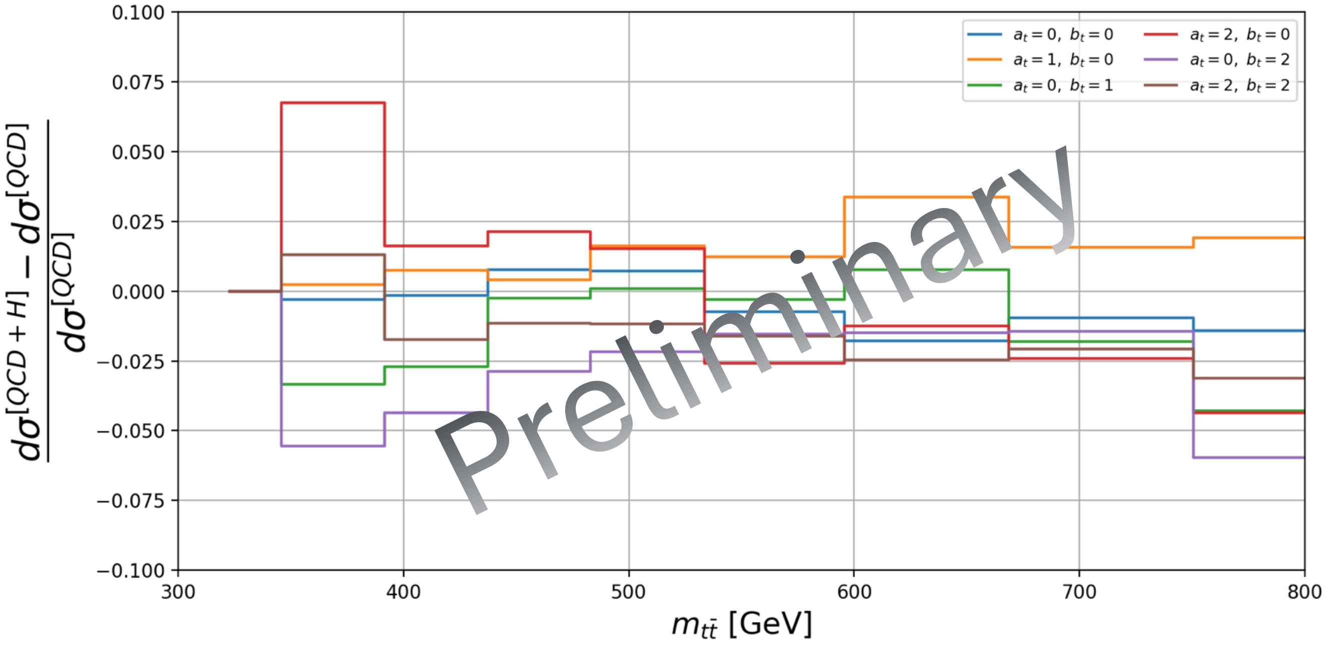
Incorporating NLO electroweak effects in the model

- We have simulated $\mathrm{pp} \to \bar{\mathrm{t}}\mathrm{t}$ at NLO in QCD and dominant EW corrections with MG5_aMC@NLO and CT18NNLO PDFs at the hard scattering level.

- We compute the impact of the dominant electroweak corrections through δ_{weak} .

- Our results fully reproduce the threshold and tail effects in the kinematic distribution presented in [Martini, Pan, Schultze and Xiao 2104.04277]

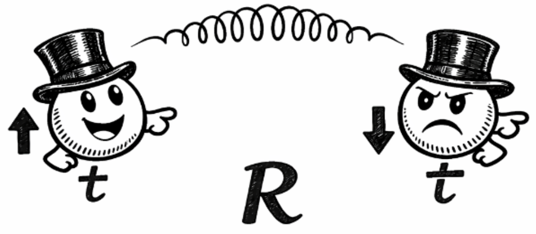
$$\delta_{weak} = \frac{d\sigma_{NLOQCD+\mathrm{H}} - d\sigma_{NLOQCD}}{d\sigma_{NLOQCD}}$$



Quantum information observables for CP-odd searches

Bernreuther et al. [*Nuclear Physics B,Volume 388, Issue 1,1992*] *proposed searching for CP odd interactions by measuring entanglement in* $2 \to 2$ *processes, specifically with a top quark pair in the final state. In this context, the central ingredient is the spin production density matrix, defined by*

$$R_{i_1 i_2 j_1 j_2} = \frac{1}{N_a N_b} \sum_{\substack{\text{spin in } \{a,b\} \\ \text{colors}}} \mathcal{M}_{i_1 j_1} \mathcal{M}^*_{i_2 j_2} \,,$$



Sketch generated using Microsoft Copilot AI

where $\mathcal{M}_{ij} = \langle t(k_1, i)\bar{t}(k_2, j)|T|a(p_1)b(p_2)\rangle$ is the respective transition matrix element. $N_{a,b}$ corresponds to the number of degrees of freedom in particles a and b of the initial state, respectively. $\{i,j\}$ correspond to spin indices of the outgoing top and anti-top, respectively.

We want to study the R matrix in view of quantum information language, which has sparked resurgence of interest in this picture due to recent development in the area.

See Fabio Maltoni’s talk

$$R^I = f_I\left[\tilde{A}^I\,(\mathbb{1}\otimes\mathbb{1}) + \tilde{B}_i^{I+}(\sigma^i\otimes\mathbb{1}) + \tilde{B}_i^{I-}(\mathbb{1}\otimes\sigma^i) + \tilde{C}_{ij}^I(\sigma^i\otimes\sigma^j)\right]$$

We highlight the direct relation of the R matrix pieces to physical quantities:

- Ã is related to the differential cross section via $\frac{d\sigma}{d\Omega ds} = f_I\beta\tilde{A}^I(s,k_1),$ *where* $\beta = \sqrt{1-4m_t^2/s}$ *is the velocity of the top quark pair*.
- $\tilde{B}_i^{I\pm}$ are related to the degree of top and anti top polarization.
- $\tilde{C}_{ij}^I$ coefficients capture the correlations between the top and anti-top subsystems.
- Furthermore, the normalized R matrix corresponds to the density matrix describing the quantum state of the system

$$\rho \equiv \frac{R^I}{Tr[R^I]} = \frac{1}{4}\left[(\mathbb{1}\otimes\mathbb{1}) + B_i^{I+}(\sigma^i\otimes\mathbb{1}) + B_i^{I-}(\mathbb{1}\otimes\sigma^i) + C_{ij}^I(\sigma^i\otimes\sigma^j)\right]$$

Where we defined $B_i^{I\pm} = \frac{\tilde{B}_i^{I\pm}}{\tilde{A}^I}$ and $C_{ij}^I = \frac{\tilde{C}_{ij}^I}{\tilde{A}^I}$.

Reproducing known results - Concurrence

For a pair of qubits with density matrix ρ the concurrence observable is positive if and only if there is entanglement in the system [Hill and Wootters 9703041]

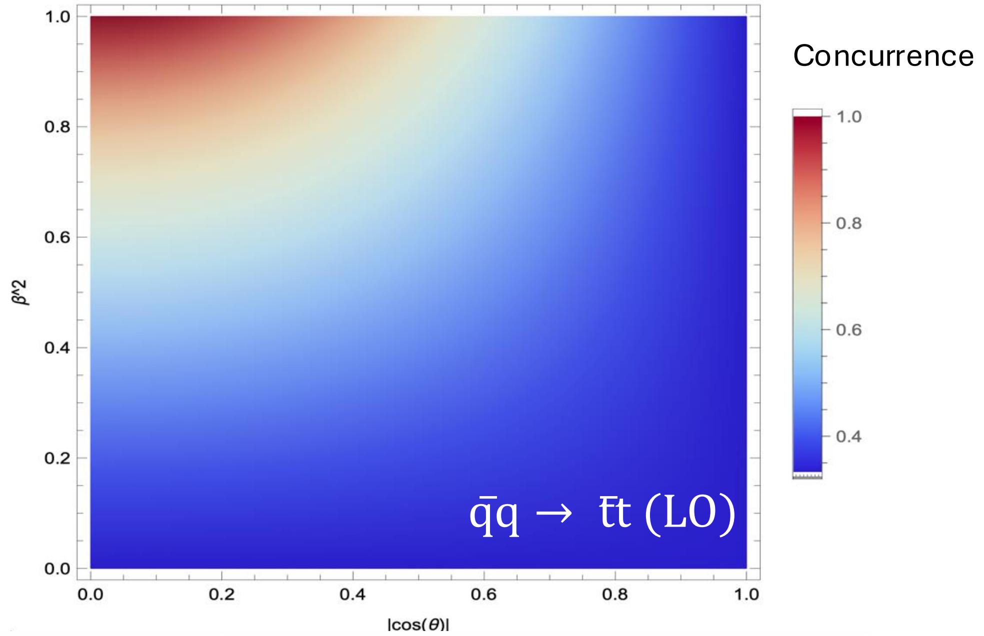
$$C(\rho) = \max(0,\ \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)\,,$$

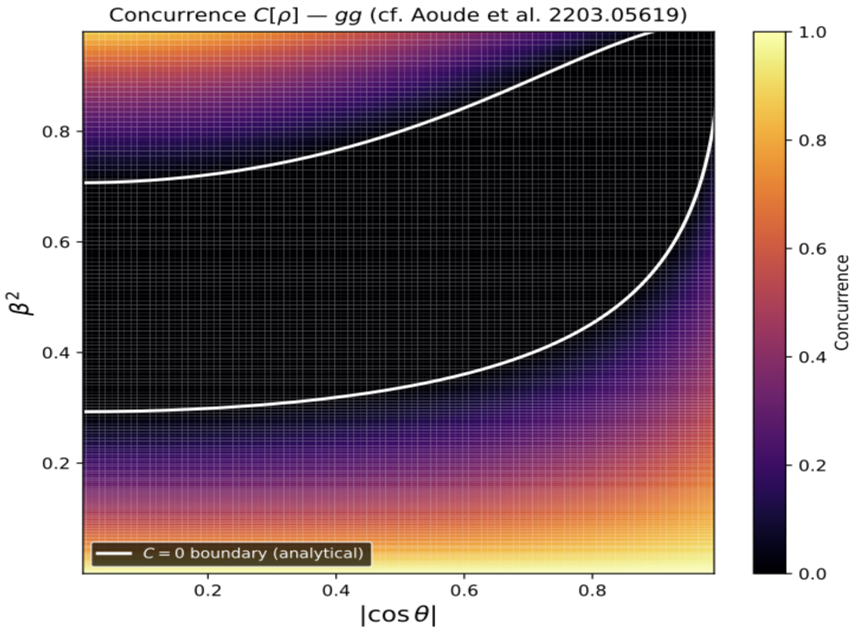
Where the set λ_i are the square root of the eigenvalues of the matrix:

$$W = \rho\,\tilde{\rho},$$ where $\tilde{\rho}$ is defined as

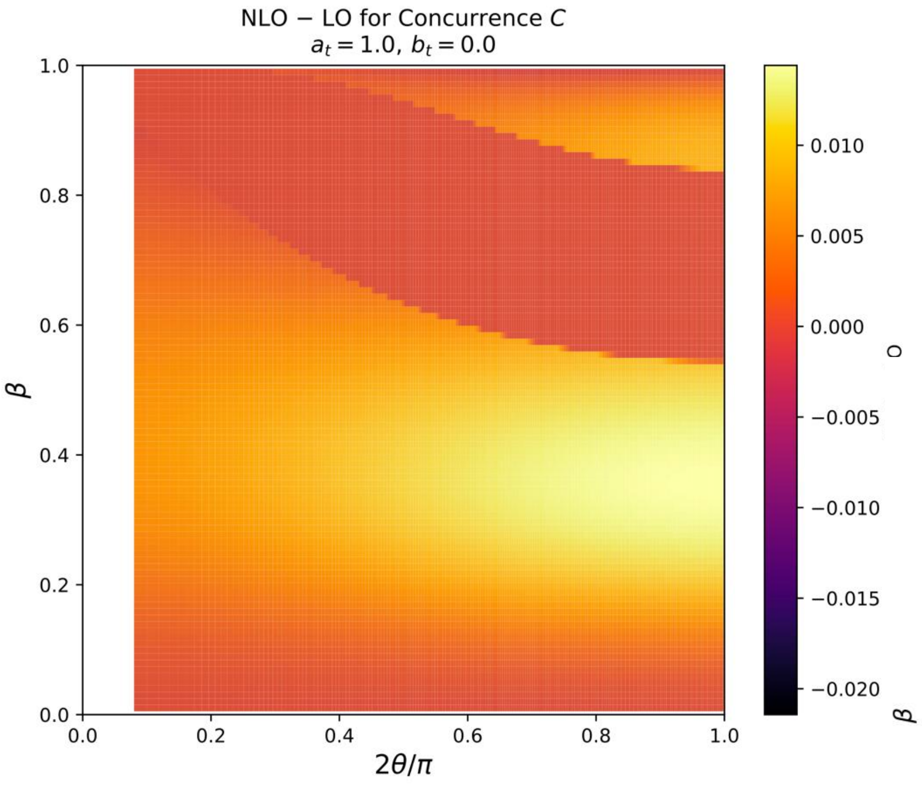
$$\tilde{\rho} = (\sigma_y \otimes \sigma_y)\,\rho^*\,(\sigma_y \otimes \sigma_y).$$

We have computed this quantity for $gg \to \bar{t}t$ and $\bar{q}q \to \bar{t}t$, reproducing known results for the SM reported in [Aoude, Madge, Maltoni and Mantani 2203.05619].

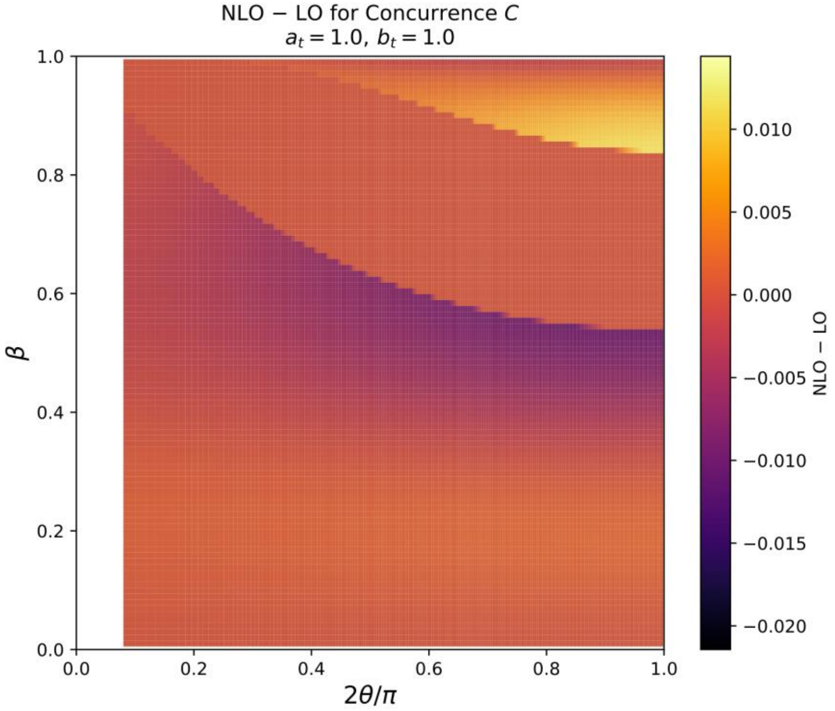




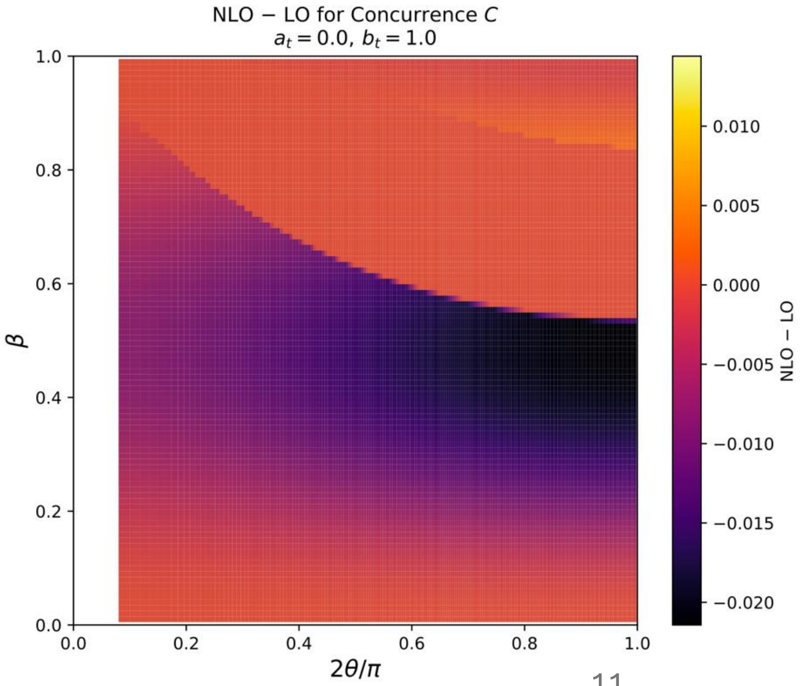
Concurrence differences between these radically different models reach 4%, proving Concurrence is sensitive to CP violating Higgs-top Yukawas.



SM



Mixed CP



Pure CP

Reproducing known results - Magic

Magic quantifies how much non-stabilizer structure is present in a state or operation. Defined as:

$$M_2(\rho) = -\log_2 \left(\frac{\sum_{P \in \mathcal{P}_n} \mathrm{Tr}^4(\rho P)}{\sum_{P \in \mathcal{P}_n} \mathrm{Tr}^2(\rho P)} \right),$$

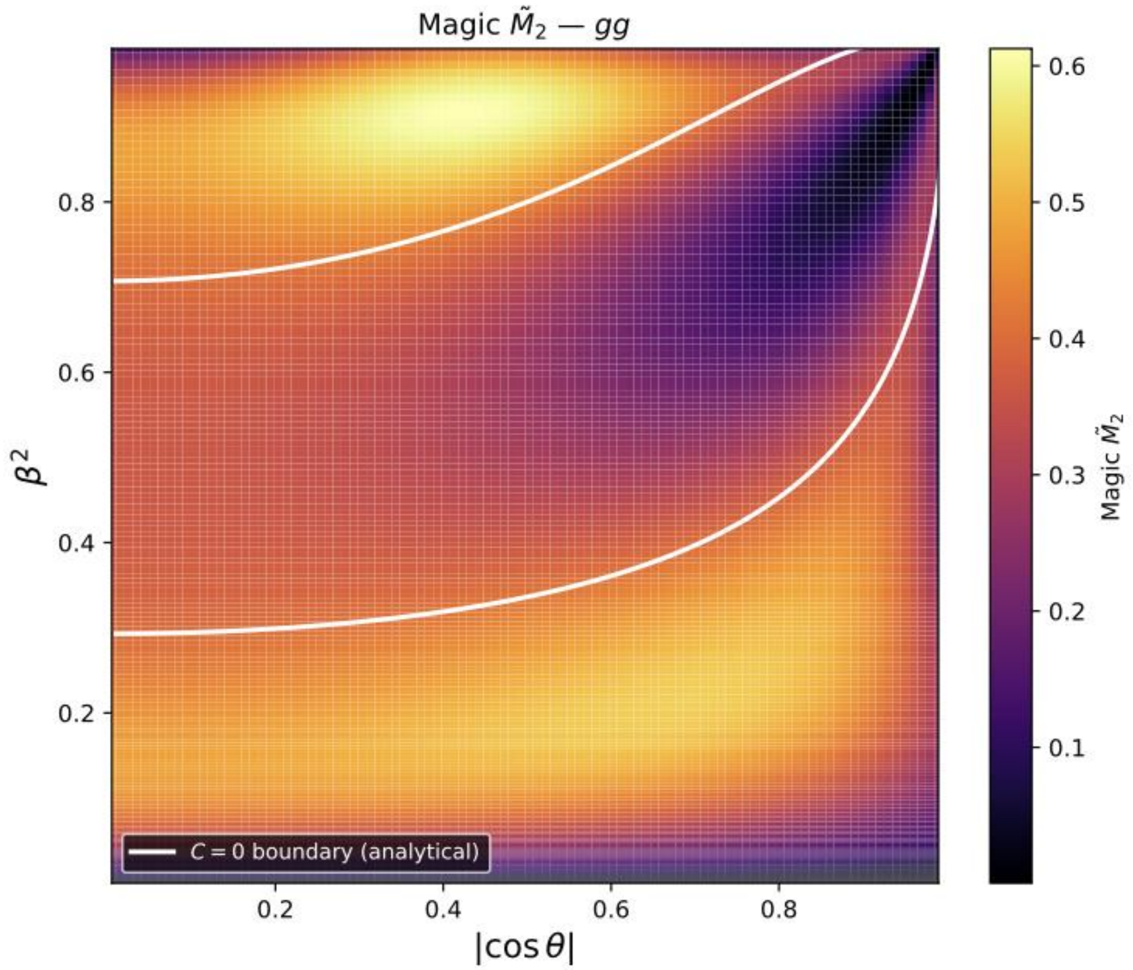
where

$$\mathcal{P}_n = P_1 \otimes P_2 \otimes \ldots \otimes P_N, \quad P_a \in \{\sigma_1, \sigma_2, \sigma_3, I\},$$

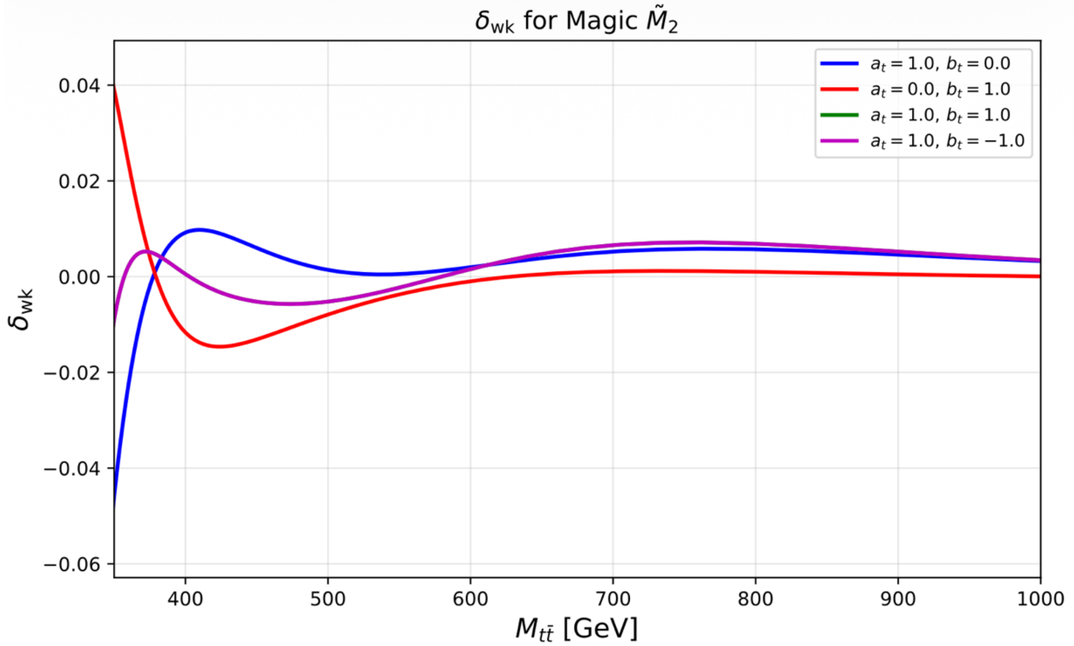
which in terms of Fano coefficients yields

$$M_2(\rho^I) = -\log_2 \left(\frac{1 + \sum_i \left[(B_i^{I+})^4 + (B_i^{I-})^4\right] + \sum_{i,j} (C_{ij}^I)^4}{1 + \sum_i \left[(B_i^{I+})^2 + (B_i^{I-})^2\right] + \sum_{i,j} (C_{ij}^I)^2} \right)$$

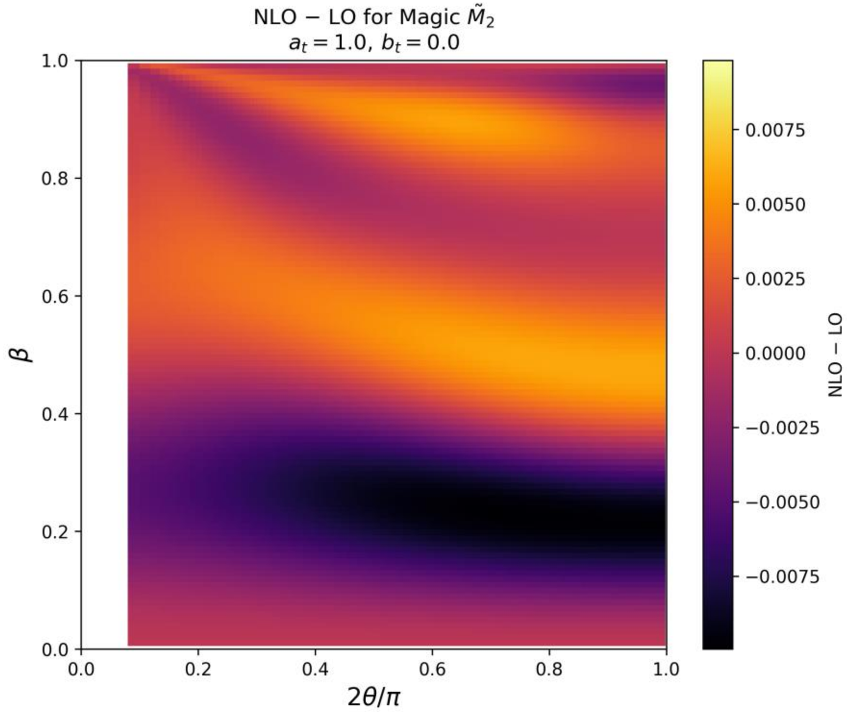
This quantity describes how far away the system is from being efficiently simulated classically with stabilizer methods.

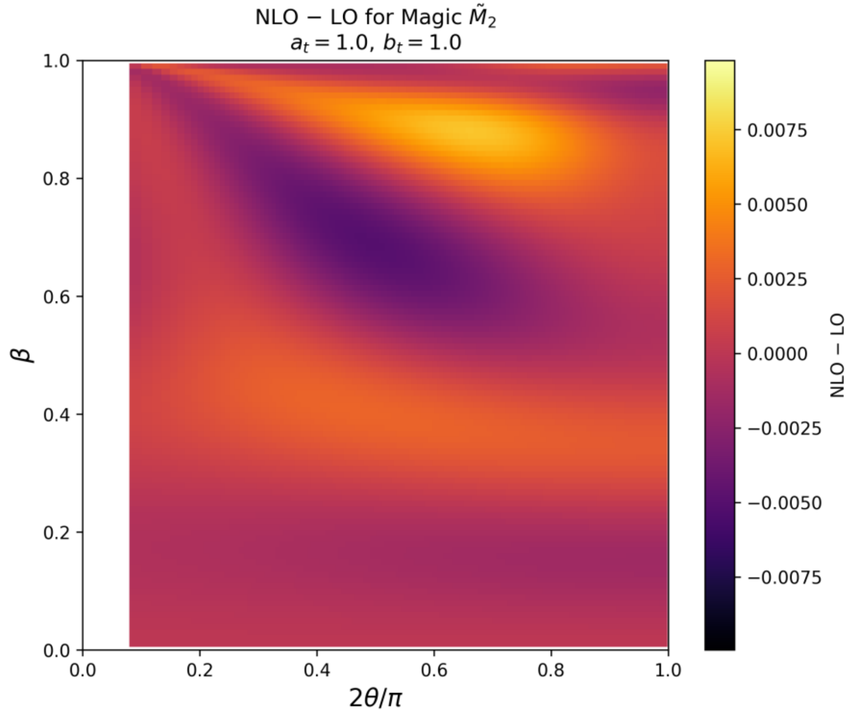


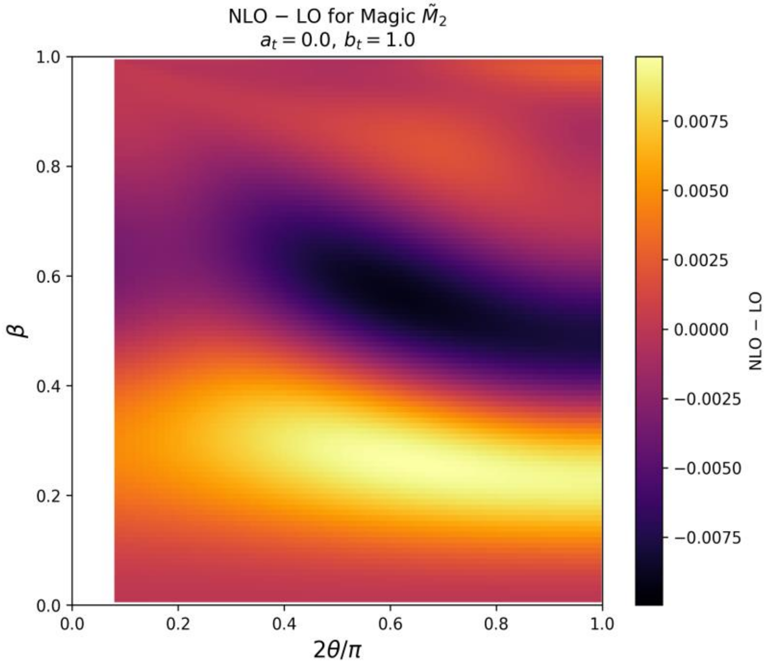
See White^2, 2412.07479, Aoude, Banks, White^2, 2505.12522, and Durupt, Maltoni, Mattelaer 2510.17730



Quantum observables are sensitive to scalar and pseudoscalar interactions, but they are not odd under CP







$pp \to \bar{t}t$ in HTCP so far

- Reproduced existing known behavior of CP- even observables.

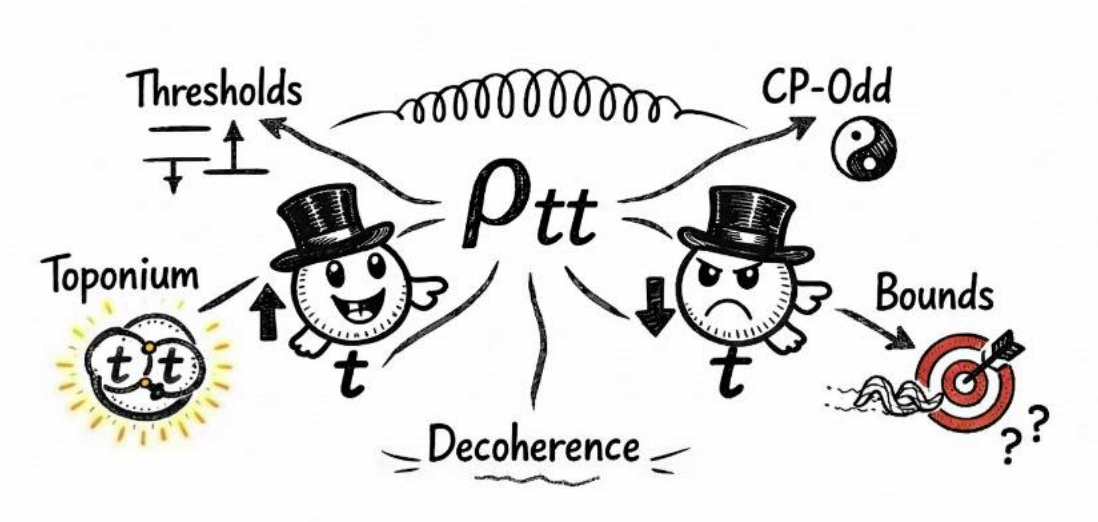
- Computed the dominant one loop EW corrections to the spin density matrix ρ of the processes $gg \to \bar{t}t$ and $\bar{q}q \to \bar{t}t$, habilitating the computation and simulation of quantum entanglement observables in these processes for the HTCP model.

Process	Analytical computation of helicity amplitudes at NLO	Numerical computation of helicity amplitudes at NLO in MG5	Analytical computation of ρ and QI observables	Numerical simulation of ρ and QI observables
$gg \to t\bar{t}$	☑	☑	☑	~ (WIP)
$\bar{q}q \to t\bar{t}$	☑	☑	☑	~ (WIP)

- Can these QI based observables be used to constrain a_t and b_t? We can see that they are sensitive to these couplings, but including recent CMS bounds is WIP.

Future directions

- Can we include threshold effects (toponium/resummation) to our HTCP computations?
- Are there quantum observables that are odd under CP and we could compute? Would these perform better than the ones presented here?
- Can we use the above observables to tighten bounds on a_t and b_t when using available LHC data?
- How does soft/collinear effects alter this picture in terms of the decoherence? See F. Maltoni's work!

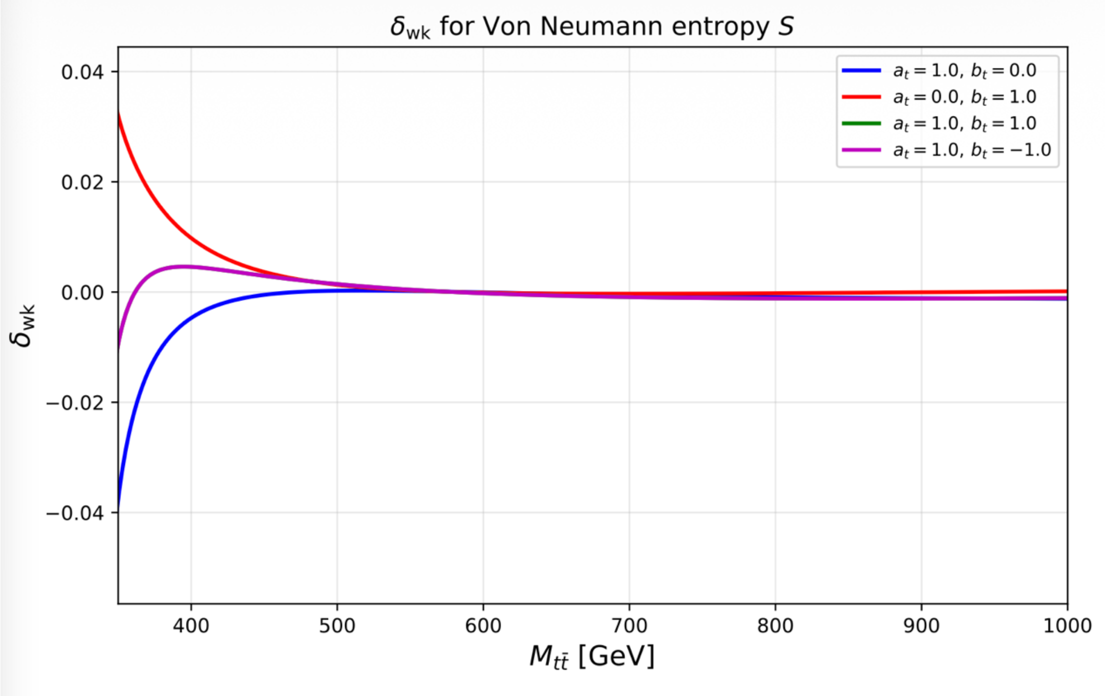


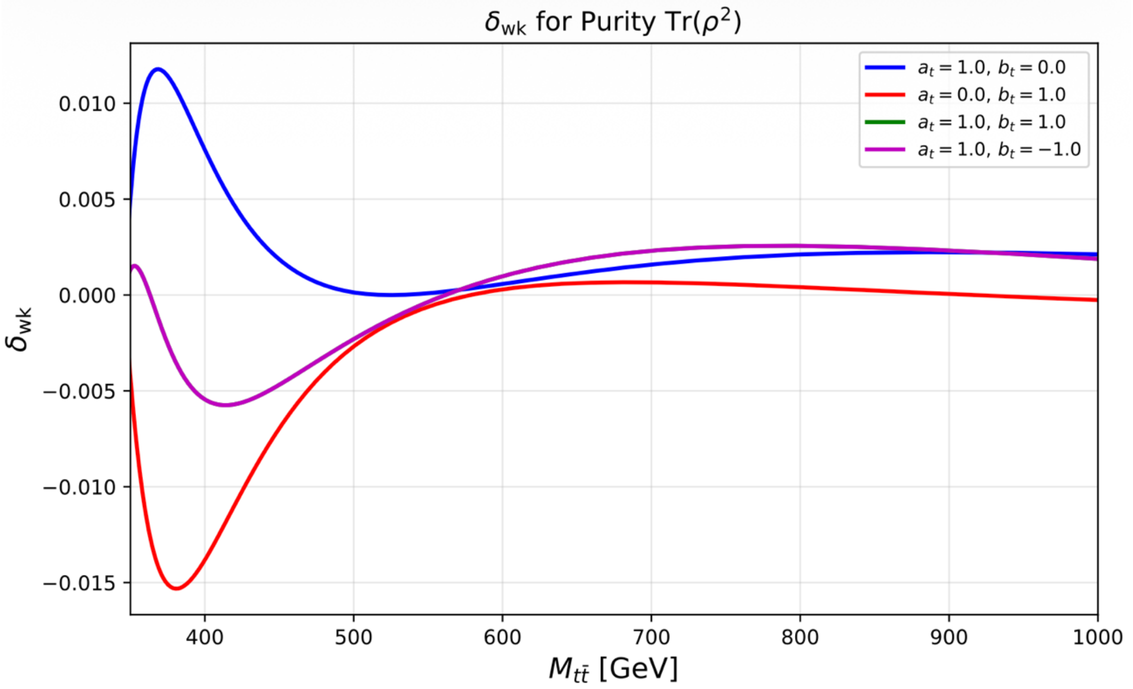
Sketch generated using Microsoft Copilot AI


Thank you!

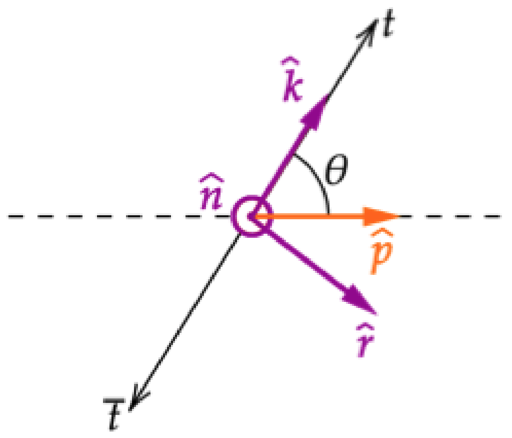
- We have crosschecked several other QI observables with our framework, including:

Von Neumann entropy, entanglement of formation, CHSH inequality parameters, D parameter from concurrence, Purity, Negativity. All these definitions crosschecked against Durupt, Maltoni, and Mattelaer [2510.17730]





Helicity basis for rho



- Of course, we need to pick a vector basis in Lorentz space to be able to compute phenomenologically relevant quantities. We do this by picking the top quark's flight direction as the z-axis
- $\hat{k}$ = top direction, $\hat{r} = \frac{\hat{p} - \hat{k}\cos(\theta)}{\sin(\theta)}$, $\hat{n} = \frac{\hat{p} \times \hat{k}}{\sin(\theta)}$
- where $\hat{p}$ corresponds to the beam direction, and θ is the scattering angle of the top quark with respect to $\hat{p}$ in the $\bar{t}t$ rest frame, such that $\cos(\theta) = \hat{k} \cdot \hat{p}$

HTCP renormalization in the on-shell scheme

- The modification that we insert into the Lagrangian has consequences for the renormalization of the model.
- Using the following definition for the bare top quark field and mass:

$$t_0 = t\left(1 + \frac{1}{2}(\delta Z_L^t + \delta Z_R^t)\right) = t\left(1 + \frac{1}{2}\delta Z_t\right)$$

$$m_0 = m_t + \delta m_t$$

- We get the following renormalization constants when using the on-shell renormalization scheme for the top quark self energy functions (This was not reported in the literature).

$$\delta Z_L^t = -(a_t^2 + b_t^2 - 2ia_t b_t)\,\mathrm{Re}\big[\Sigma_L^t(m_t^2)\big] - 2(a_t^2 + b_t^2)\,m_t^2\ \frac{\partial}{\partial p^2}\,\mathrm{Re}\big[\Sigma_L^t(p^2) + \Sigma_S^t(p^2)\big]\Big|_{p^2=m_t^2}$$

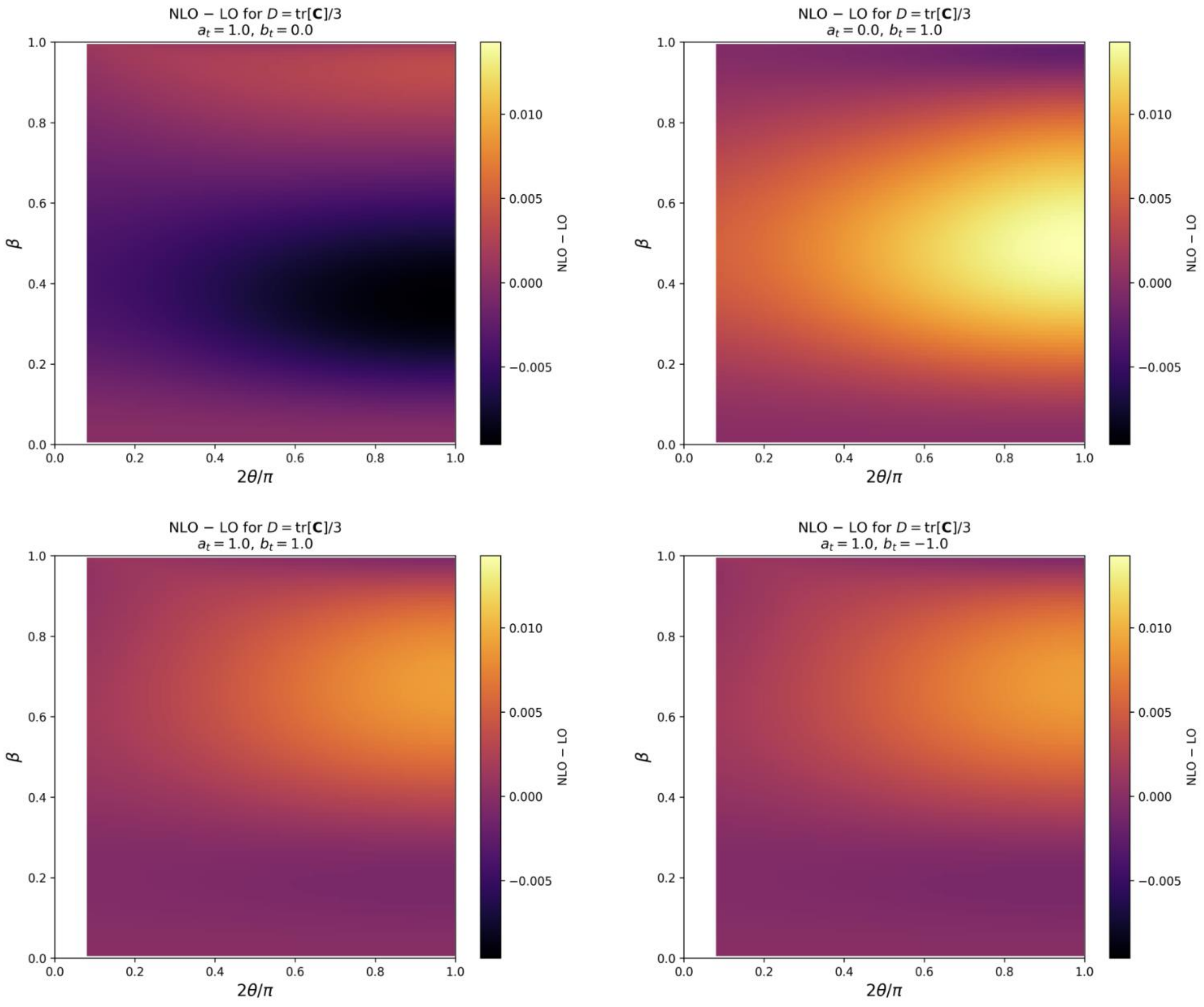
$$\delta Z_R^t = -(a_t^2 + b_t^2 + 2ia_t b_t)\,\mathrm{Re}\big[\Sigma_R^t(m_t^2)\big] - 2(a_t^2 + b_t^2)\,m_t^2\ \frac{\partial}{\partial p^2}\,\mathrm{Re}\big[\Sigma_R^t(p^2) + \Sigma_S^t(p^2)\big]\Big|_{p^2=m_t^2}$$

$$\delta m_t = \frac{(a_t^2 + b_t^2)}{2}\,m_t\,\mathrm{Re}\left[\Sigma_L^t(m_t^2) + \Sigma_R^t(m_t^2) + 2\Sigma_S^t(m_t^2)\right]$$

The difference is visible already at the $1/\varepsilon$ pole level. From the NLOCT model file (`SMCPMinYQEDreno.nlo`), the Yukawa contribution to the $1/\varepsilon$ piece of the top self-energy counterterm (setting $g_s \to 0$) is:

$$\frac{-i\, m_t^2}{32\pi^2 v^2 \varepsilon}\, \mathrm{IPL}[\{t, H\}] \left[2(a_t - ib_t)^2\, m_t\, \omega_- + 2(a_t + ib_t)^2\, m_t\, \omega_+ + (a_t^2 + b_t^2)\, (\not{p}\, \omega_- + \not{p}\, \omega_+)\right]. \quad (15)$$

The $\not{p}$ (wavefunction) pieces are proportional to $(a_t^2 + b_t^2)$ and carry no $a_t b_t$ cross terms. The mass-type pieces, however, have *different* coefficients for ω_- and ω_+: expanding $(a_t \mp ib_t)^2 = a_t^2 \mp 2i\, a_t b_t - b_t^2$ shows that the $a_t b_t$ interference enters the mass counterterm with opposite signs for the two chiralities.


NLO − LO for $D = \mathrm{tr}[\mathbf{C}]/3$
$a_t = 1.0$, $b_t = 0.0$
NLO − LO for $D = \mathrm{tr}[\mathbf{C}]/3$
$a_t = 0.0$, $b_t = 1.0$
NLO − LO for $D = \mathrm{tr}[\mathbf{C}]/3$
$a_t = 1.0$, $b_t = 1.0$
NLO − LO for $D = \mathrm{tr}[\mathbf{C}]/3$
$a_t = 1.0$, $b_t = -1.0$
β
$2\theta/\pi$
NLO − LO
0.010
0.005
0.000
−0.005

D parameter

Implications for the (a_t, b_t) analysis

Since the CMS theory prediction already includes the SM Higgs-mediated contribution via the HATHOR electroweak corrections, the Fano coefficients $F_i^{\mathrm{SM,\,theory}}$ in the HEPData tables incorporate $gg \to H^* \to t\bar{t}$ interference evaluated at the SM Yukawa coupling $(a_t, b_t) = (1, 0)$.

Our Born-level $pp \to t\bar{t}$ calculation (using the `ppttQCDQQED_SM_nob_SO` process) includes the same Higgs-mediated one-loop contribution with a parametrically variable Yukawa coupling. The shift due to non-SM values of (a_t, b_t) modifies exactly this piece of the calculation, while leaving all other contributions (NLO QCD, W/Z loops, toponium) unchanged.

$$\frac{R_{ij}(a_t, b_t)}{4\tilde{A}^{\mathrm{CMS}}} = \rho_{ij}^{\mathrm{CMS}} + \frac{\tilde{A}^{\mathrm{our}}(a_t, b_t)}{\tilde{A}^{\mathrm{CMS}}}\,\rho_{ij}^{\mathrm{our}}(a_t, b_t) - \frac{\tilde{A}^{\mathrm{our}}(1,0)}{\tilde{A}^{\mathrm{CMS}}}\,\rho_{ij}^{\mathrm{our}}(1,0)\,,$$

Reproducing known results - Concurrence

For the density matrix in the helicity basis the condition:

$$\Delta \equiv -C_{nn} + |C_{kk} + C_{rr}| > 1$$

Is sufficient and necessary for entanglement in accordance with the Peres-Horedecki criterion (PHC) [Horodecki^3 9605038, Peres 9604005].

The degree of entanglement in the $\bar{t}t$ system is quantified by the concurrence, defined via

$$C[\rho] = max(\frac{\Delta}{2}, 0)$$

We have computed this quantity for $gg \to \bar{t}t$ and $\bar{q}q \to \bar{t}t$, reproducing known results for the SM reported in [Aoude, Madge, Maltoni and Mantani 2203.05619].