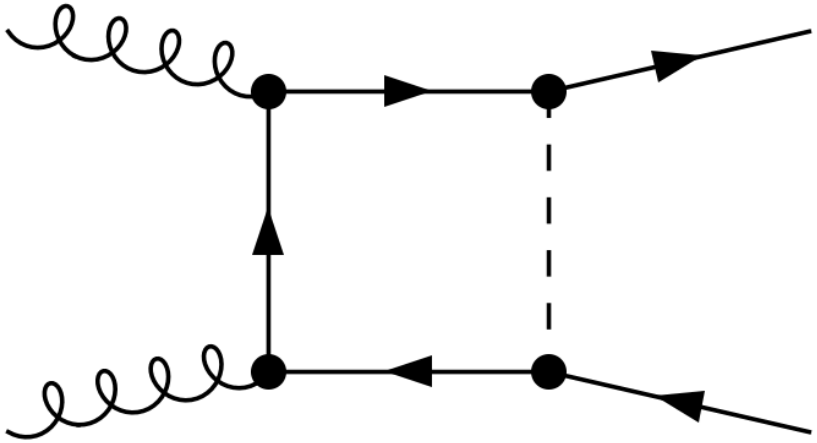
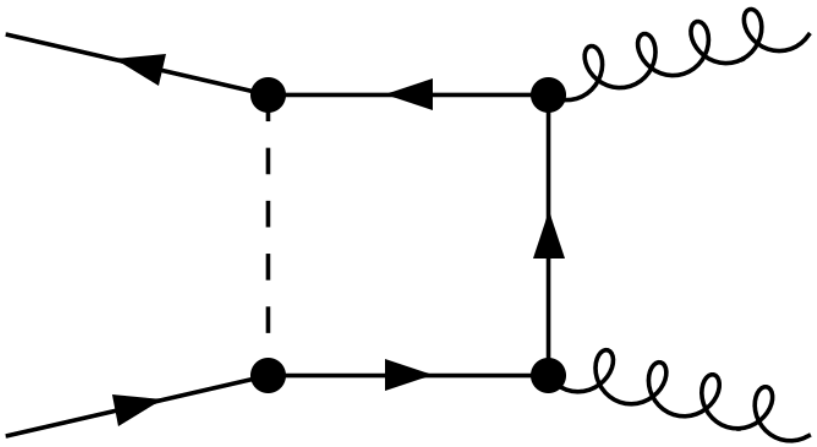
Spin-Density Matrices as probes of CP violation in top-Higgs interactions







Marcel Yáñez Reyes

Work in collaboration with: Eren Erdogan, Kirtimaan Mohan and Keping Xie. [arXiv:2607.28761].

21st PIKIMO Meeting
PITT-PAC, 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.

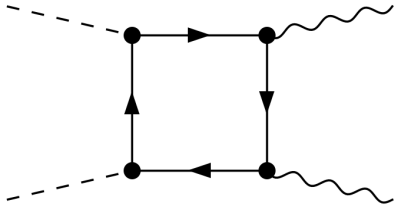
Sakharov's Conditions [Sakharov 1991 *Sov. Phys. Usp.* **34** 392] for baryogenesis:

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;

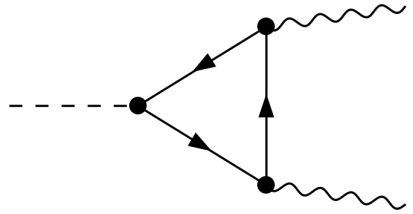


General approaches to parametrize CP violation in the Yukawa sector

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



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



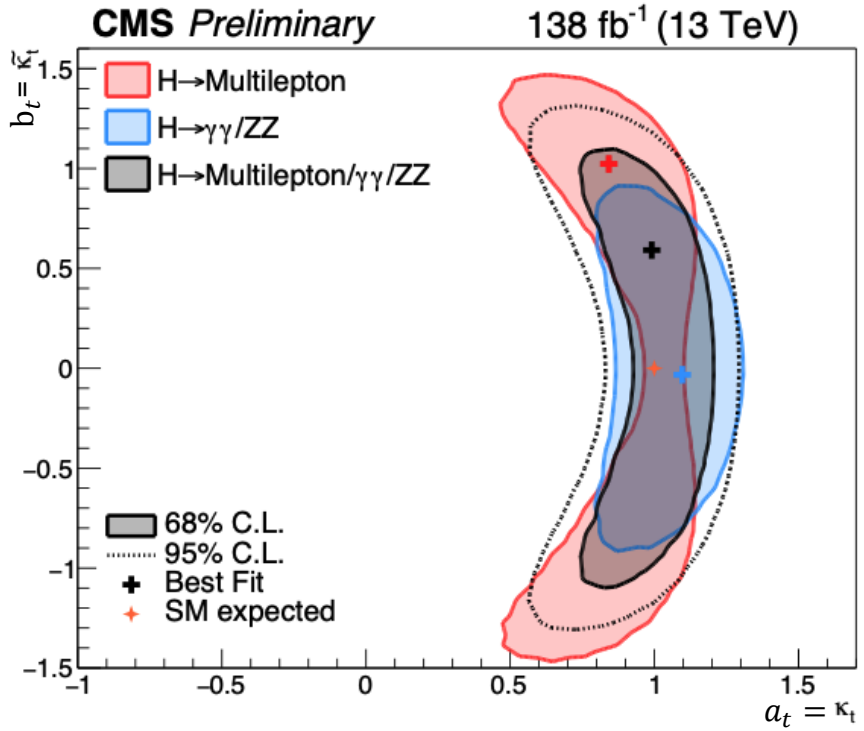
People have studied this model since the 90s [C. Schmidt and M. Peskin, Phys. Rev. Lett. 69, 410 (1992)] and have studied its signals at the LHC [See 2208.02686, 2303.05974 and related]

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

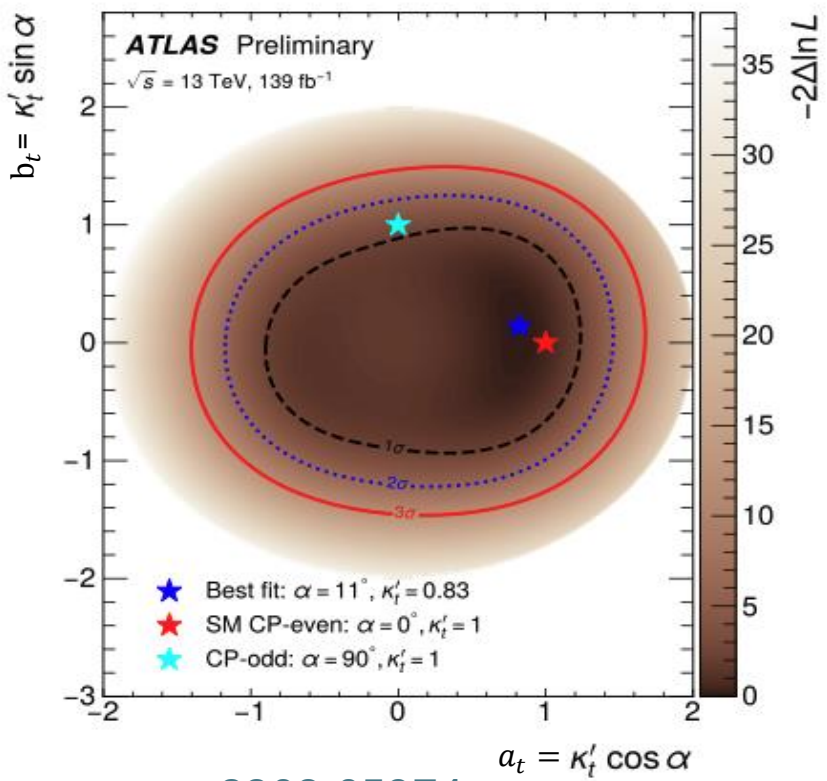
a_t	b_t	Type of Higgs
1	0	SM
$\neq 0$	$\neq 0$	BSM-mixed CP state
0	$\neq 0$	BSM pure pseudoscalar

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

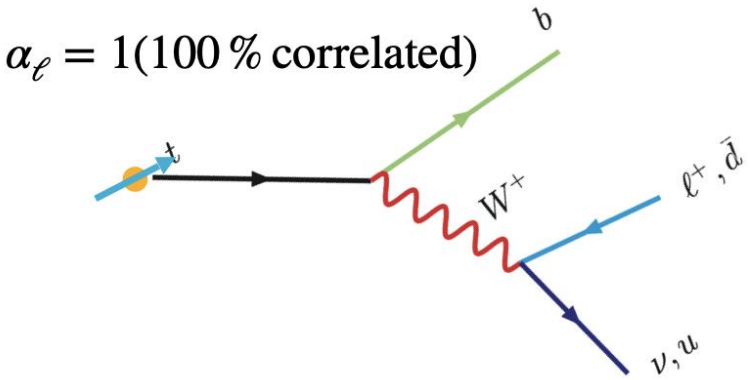


2303.05974

See Hannah Arnold's talk at DPF 26 for up to date constrains

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

- Can we look at other channels to complement constrains on these couplings? Can we use Quantum Information based quantities 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)

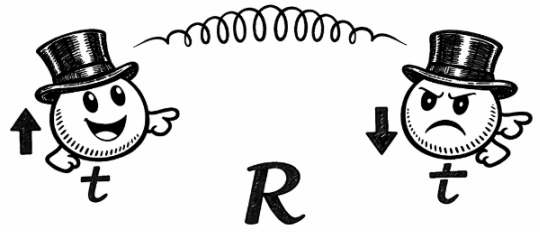


Picture taken from: Fabio Maltoni's talk - PHENO 26

Quantum information quantities for CP-odd searches

Bernreuther et al. [Nuclear Physics B,Volume 388, Issue 1,1992] proposed searching for CP odd interactions by characterizing entanglement in $2 \to 2$ processes, specifically with a top quark pair in the final state.

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



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.

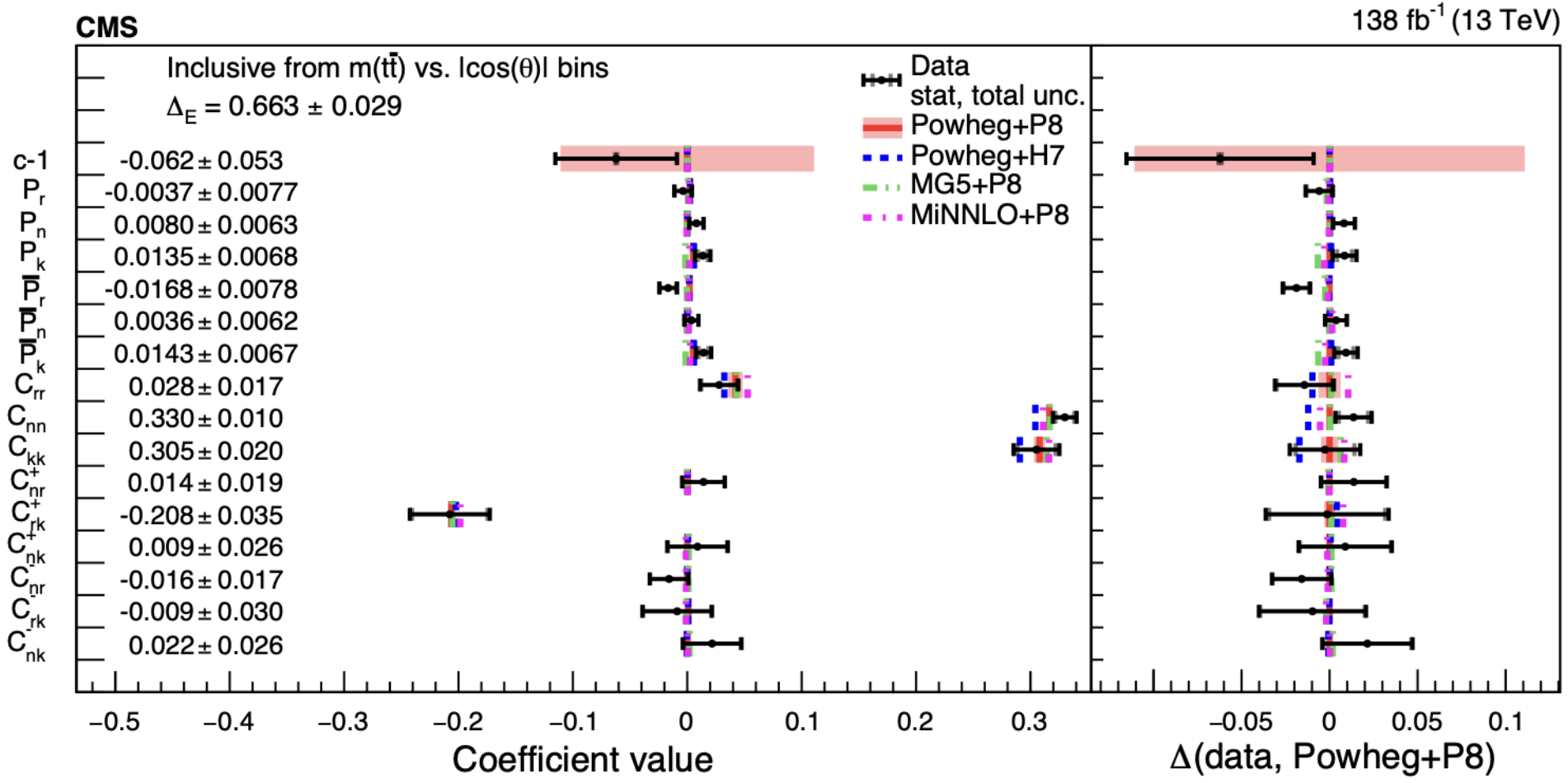
For a pair of top quarks: $R^I = f_I\left[\tilde{A}^I\,(\mathbb{1}\otimes\mathbb{1}) + \tilde{B}_i^{I+}(\sigma^i\otimes\mathbb{1}) + \tilde{B}_i^{I-}(\mathbb{1}\otimes\sigma^i) + \tilde{C}_{ij}^I(\sigma^i\otimes\sigma^j)\right]$

- $\tilde{\mathrm{A}}$ is related to the differential cross section via $\frac{d\sigma}{d\Omega ds} = f_I\beta\tilde{A}^I(s,k_1),$ *where* $\beta = \sqrt{1-4m_t^2/s}$ *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 $C_{ij}^I = \frac{\tilde{C}_{ij}^I}{\tilde{A}^I}$. These are called Fano coefficients.

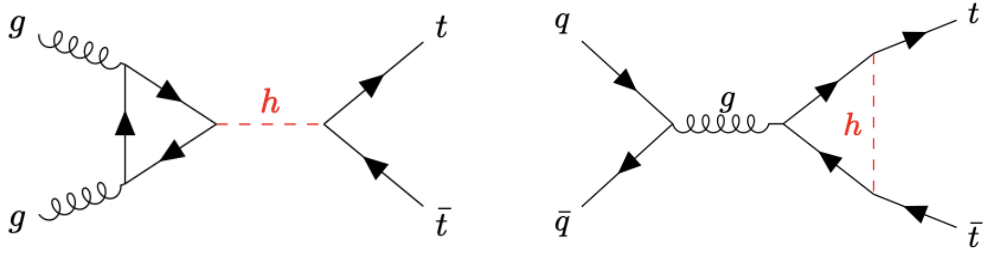
- Our work [Mohan, Erdogan, Xie, MYR arXiv:2607.28761]: Compute the dominant one loop EW corrections to the spin density matrix ρ of the processes $gg \to \bar{t}t$ and $\bar{q}q \to \bar{t}t$, which allows to use Fano coefficient measurements [CMS collaboration 2409.11067] to constrain a_t and b_t of the HTCP model.



Combining both channels to constrain HTCP

Following the standard kinematic approach presented in [Cheng, Han, Low 2410.08303] we add the two production channels via luminosity weights:

$$R^{\alpha}(a_t, b_t) = R^{\alpha,\mathrm{SM}} + \Delta R^{\alpha}(a_t, b_t), \quad \alpha = \{gg, q\bar{q}\}$$



Hence, for a binned analysis [CMS, 2409.11067] where k denotes the bin width we obtain the integrated spin production matrix as:

$$\mathcal{R}_k^{\alpha}(a_t, b_t) = \int_k W^{\alpha}\, R^{\alpha}(a_t, b_t)\, d\beta\, d\cos\theta. \quad \text{With} \quad W^{\alpha}(\beta, \cos\theta) = \frac{dL^{\alpha}}{d\tau}\, \frac{\beta^2}{16\pi s\,(1-\beta^2)}, \quad \tau = m_{t\bar{t}}^2/s$$

Which leads us to the following per bin weighted density matrix prediction, directly comparable to the CMS data:

$$\rho_k(a_t, b_t) = \frac{\rho_k^{\mathrm{SM}} + \frac{\Delta\mathcal{R}_k(a_t, b_t)}{4\sigma_k^{\mathrm{SM}}}}{1 + \frac{\mathrm{Tr}[\Delta\mathcal{R}_k(a_t, b_t)]}{4\sigma_k^{\mathrm{SM}}}}. \quad \text{Where we used,} \quad \frac{\mathrm{Tr}[\mathcal{R}_k(a_t, b_t)]}{4} = \sigma_k = \sigma_k^{\mathrm{SM}} + \frac{\mathrm{Tr}[\Delta\mathcal{R}_k(a_t, b_t)]}{4}.$$

Quantum tomography as a probe of CP violation in the Higgs top sector

$$\rho_k(a_t, b_t) = \frac{\rho_k^{\mathrm{SM}} + \frac{\Delta\mathcal{R}_k(a_t,b_t)}{4\sigma_k^{\mathrm{SM}}}}{1 + \frac{\mathrm{Tr}[\Delta\mathcal{R}_k(a_t,b_t)]}{4\sigma_k^{\mathrm{SM}}}}.$$

We can then use:

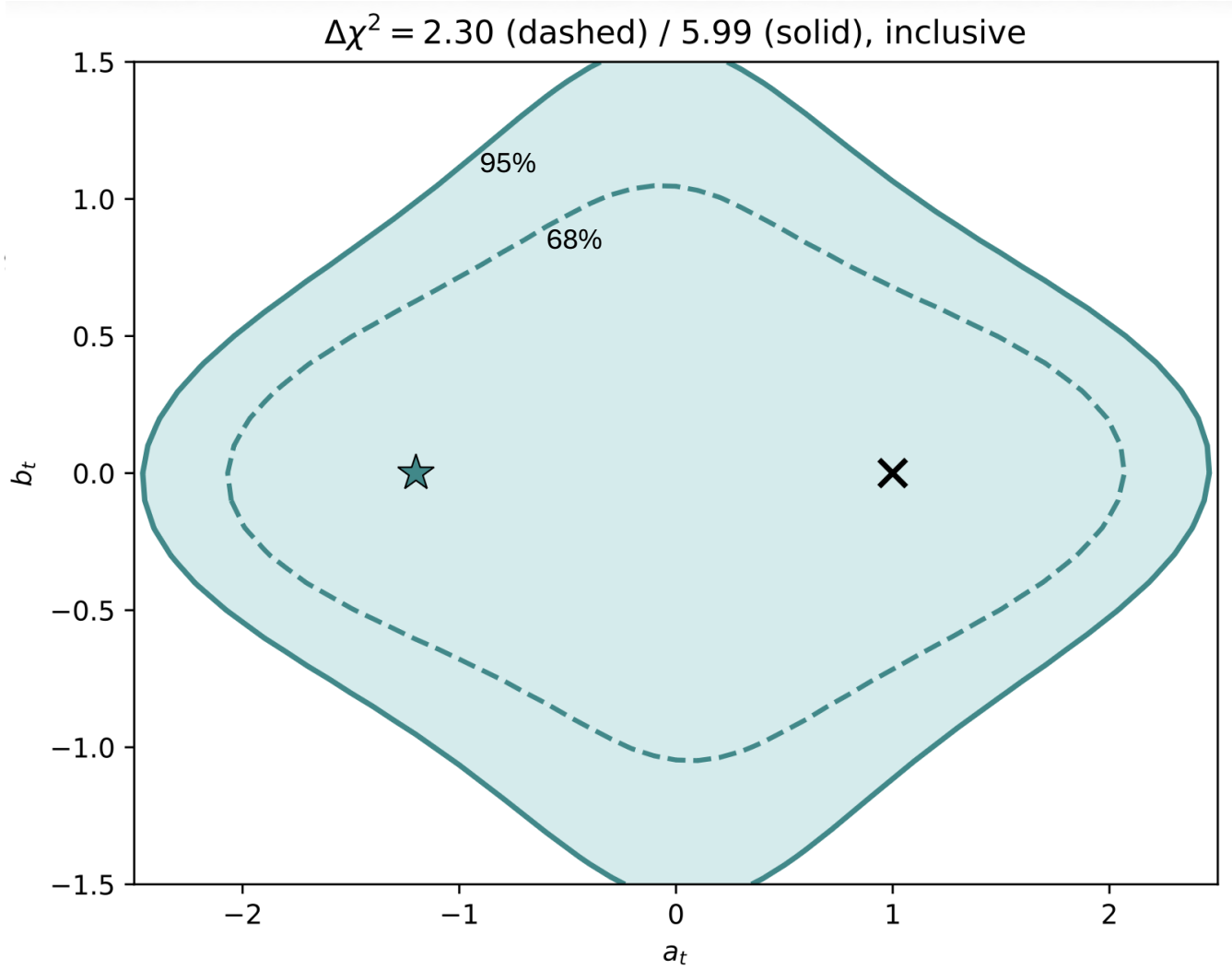
$$\rho = \frac{1}{4}\Big(\mathbb{1}\otimes\mathbb{1} + B_i^+\,\sigma_i\otimes\mathbb{1} + B_i^-\,\mathbb{1}\otimes\sigma_i + C_{ij}\,\sigma_i\otimes\sigma_j\Big)$$

And extract all fifteen independent Fano coefficients $Q_m(a_t, b_t)$, hence defining

$$\chi^2(a_t, b_t) = \sum_{m,n} \Delta Q_m\,(V^{-1})_{mn}\,\Delta Q_n,$$

Where $\Delta Q_m = Q_m(a_t, b_t) - Q_m^{\mathrm{obs}}$, along with the 15x15 covariance matrix V reported by [CMS, 2409.11067].

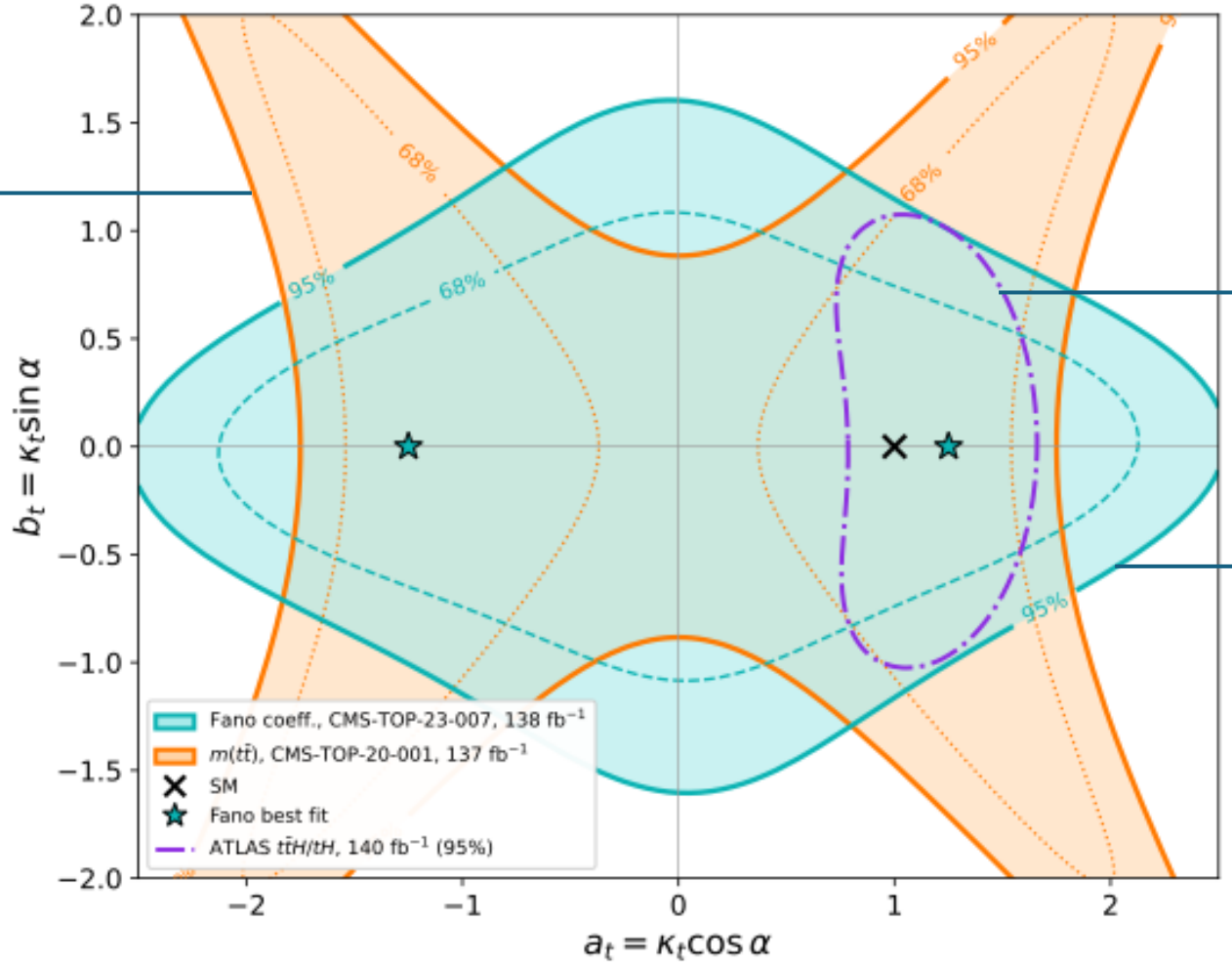
$$\Delta\chi^2(a_t, b_t) = \chi^2(a_t, b_t) - \chi^2_{\mathrm{min}} > \Delta\chi^2_{\mathrm{CL}}\,,$$



After minimization and two parameter subtraction we get the constrain plot on the right.

Quantum tomography as a probe of CP violation in the Higgs top sector

Differential cross section constraint using the methodology of [Maltoni, Pagani, Tentori 2406.06694] and data from [CMS 2108.02803] . 95% C.L



[ATLAS 2303.05974]
ttH + tH 95%

Fano coefficient one loop computation 95% C.L. (this work's method)

This establishes top quark quantum tomography as a new and complementary probe of CP violation in the Higgs sector!

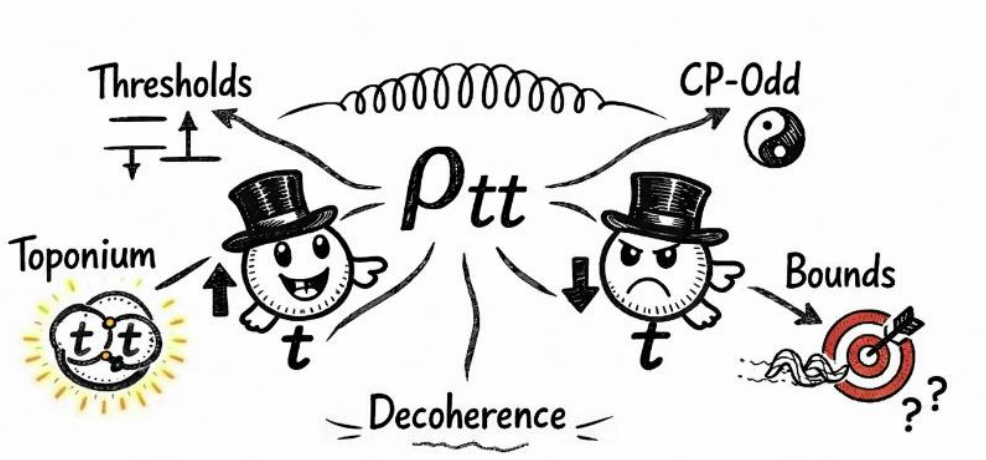
Future directions

- Can we include threshold effects (toponium/resummation) to our HTCP computations? See Artemiy Filippov's talk later today!

- Are there quantum observables that are odd under CP and we could compute? Would these perform better than the ones presented here?

- How does soft/collinear effects alter this picture in terms of the decoherence?

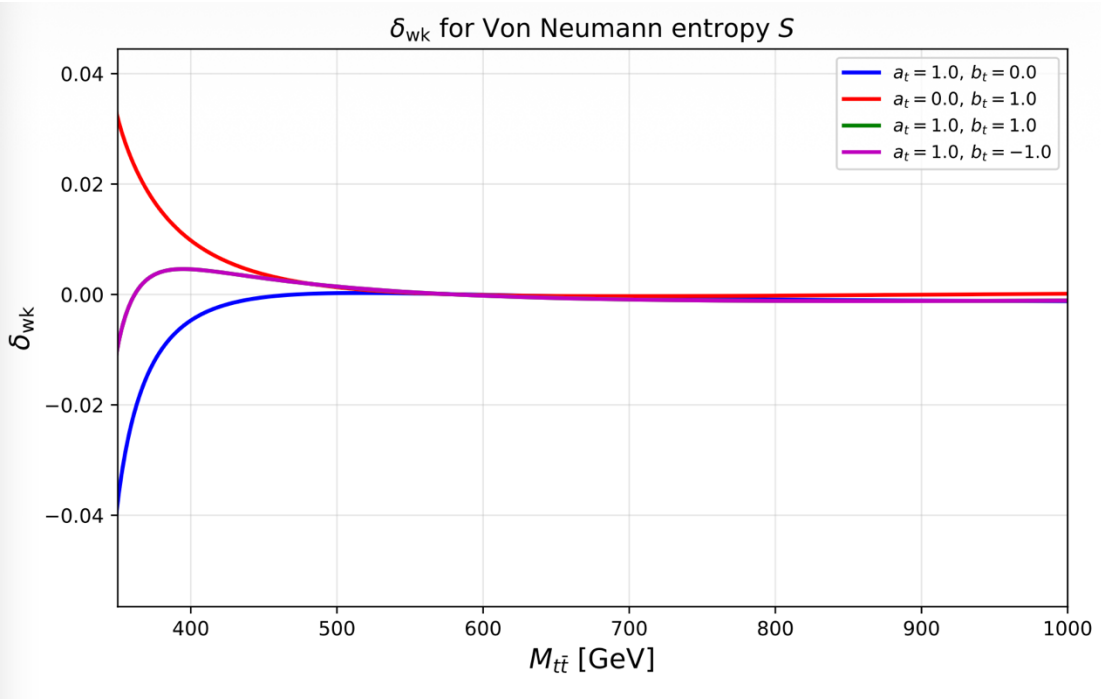
- How do we map these constrains to SMEFT operators? How does this compete with electron EDM constraints? See also the recent article

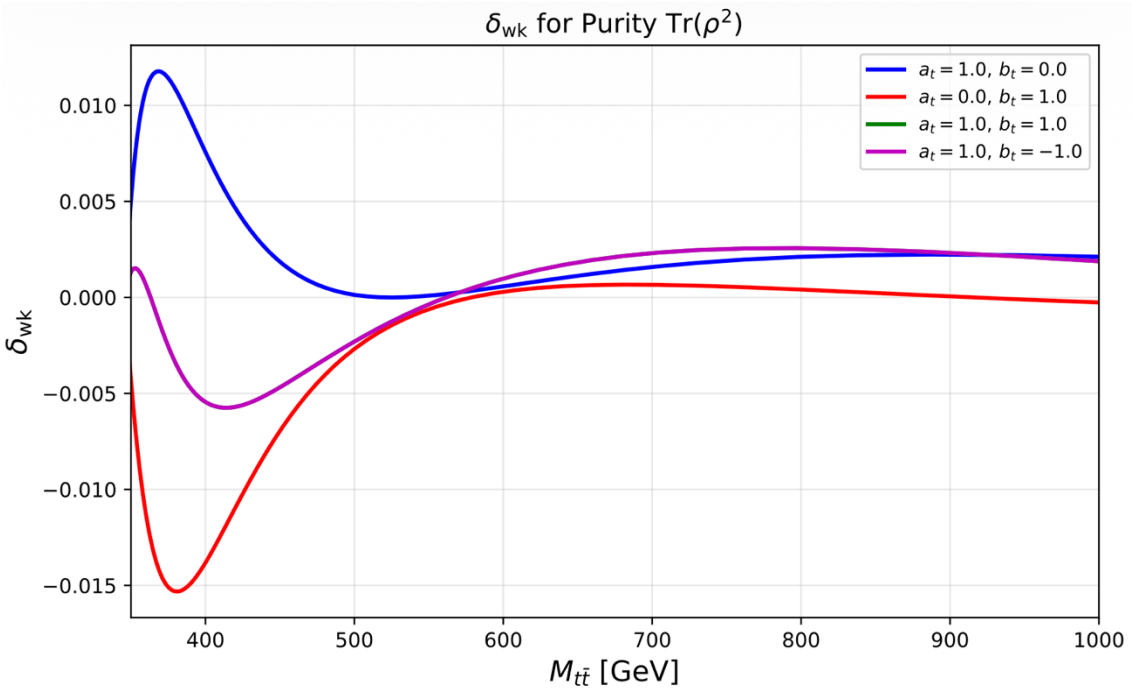



Thank you!

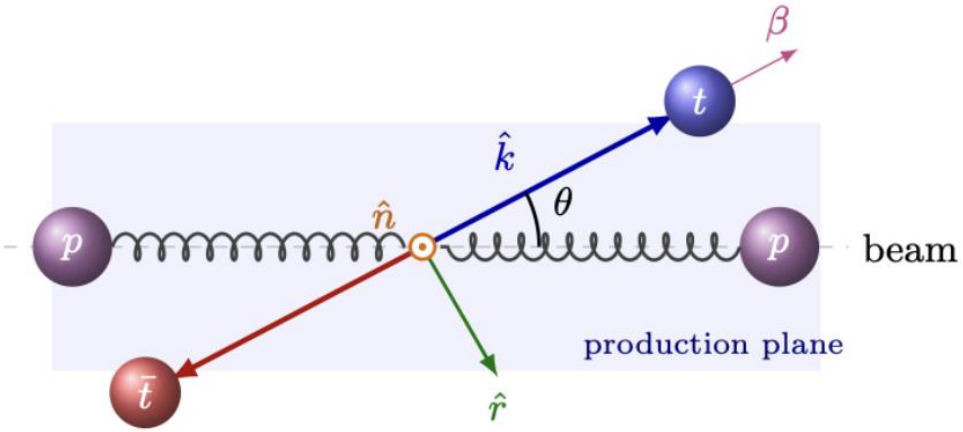
- We have crosschecked several other QI observables with our framework, including:

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 $t\bar{t}$ 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).

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

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

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

Reproducing known results - Concurrence

For the density matrix in the helicity basis the condition:

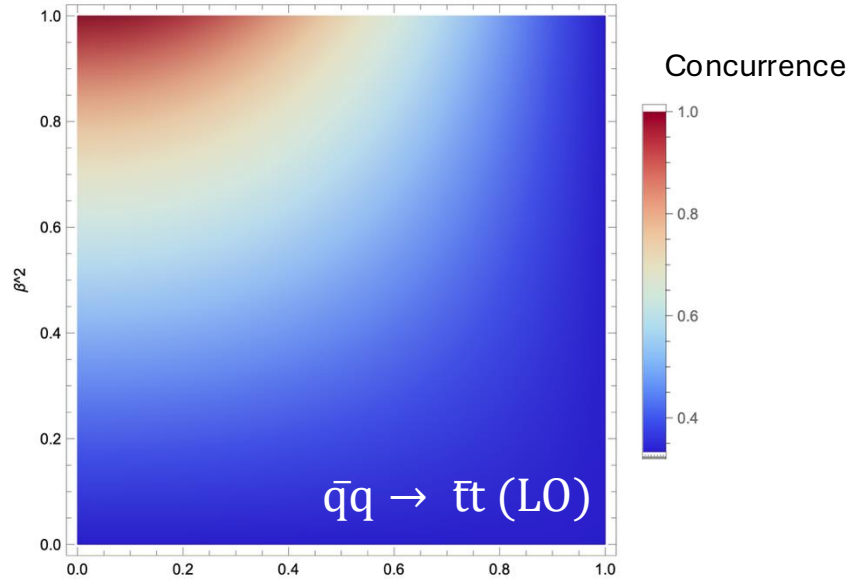
$$\Delta \equiv -C_{nn} + |C_{kk} + C_{rr}| > 1$$

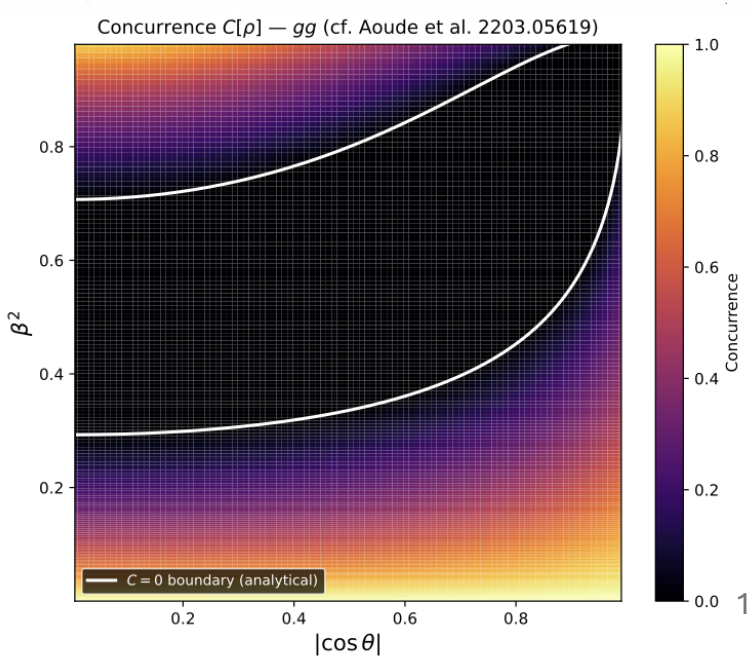
Is sufficient and necessary for entanglement in accordance with the Peres-Horedecki criterion (PHC) [Horodecki^3 9605038, Peres 9604005].

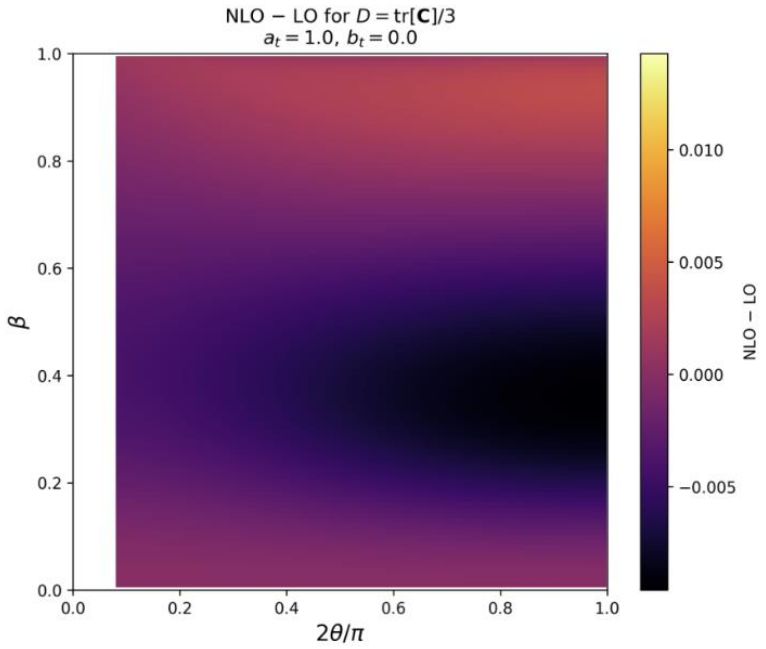
The degree of entanglement in the $\bar{t}t$ system is quantified by the concurrence, defined via

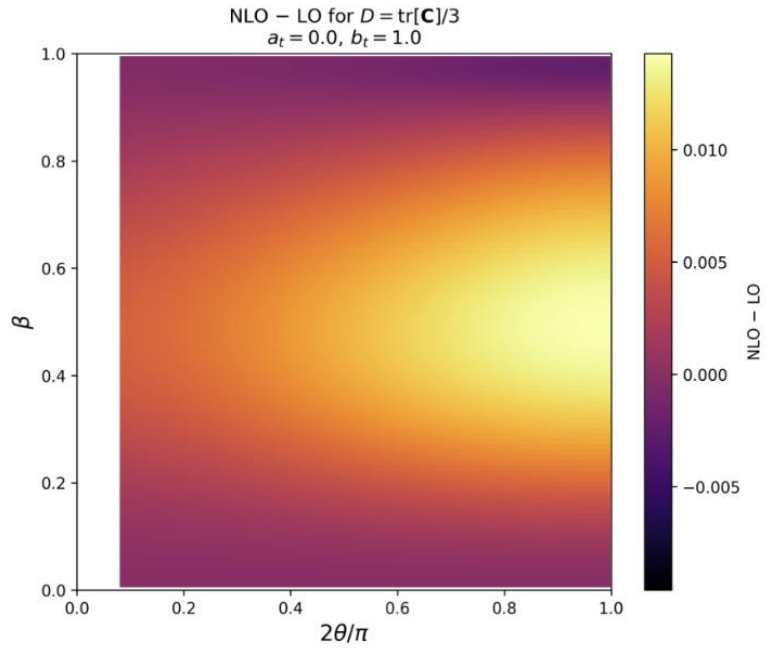
$$C[\rho] = max(\frac{\Delta}{2}, 0)$$

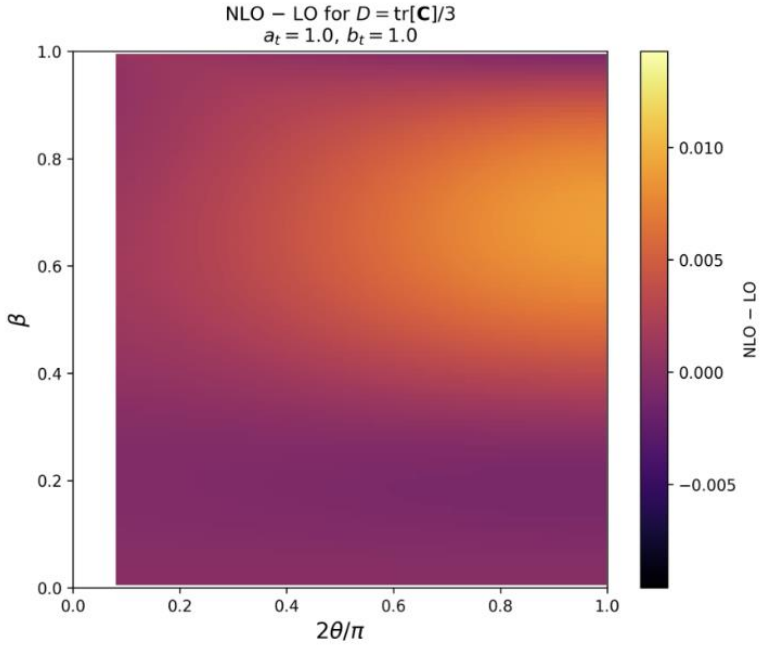
We have computed this quantity for $gg \to \bar{t}t$ and $\bar{q}q \to \bar{t}t$, reproducing known results for the SM reported in [Aoude, Madge, Maltoni and Mantani 2203.05619].

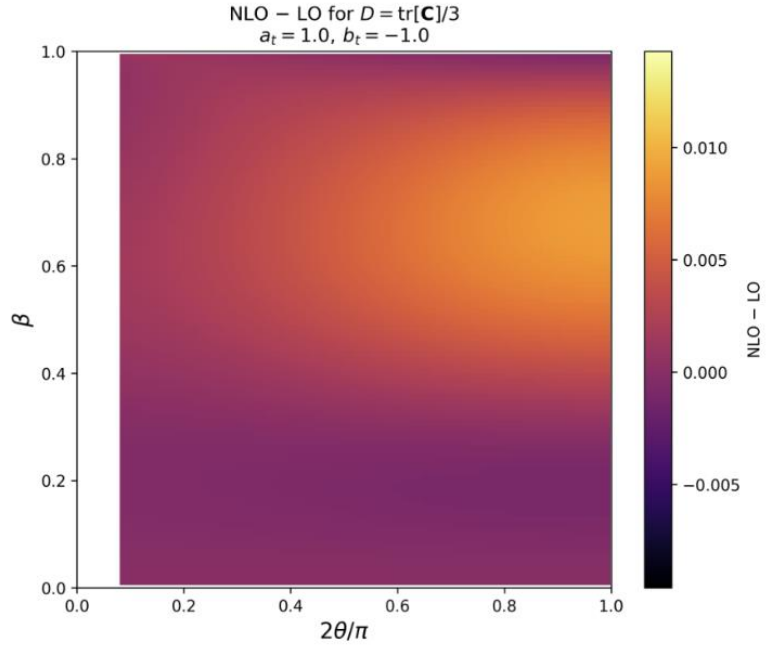












D parameter from concurrence

Reproducing known results - Magic

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

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

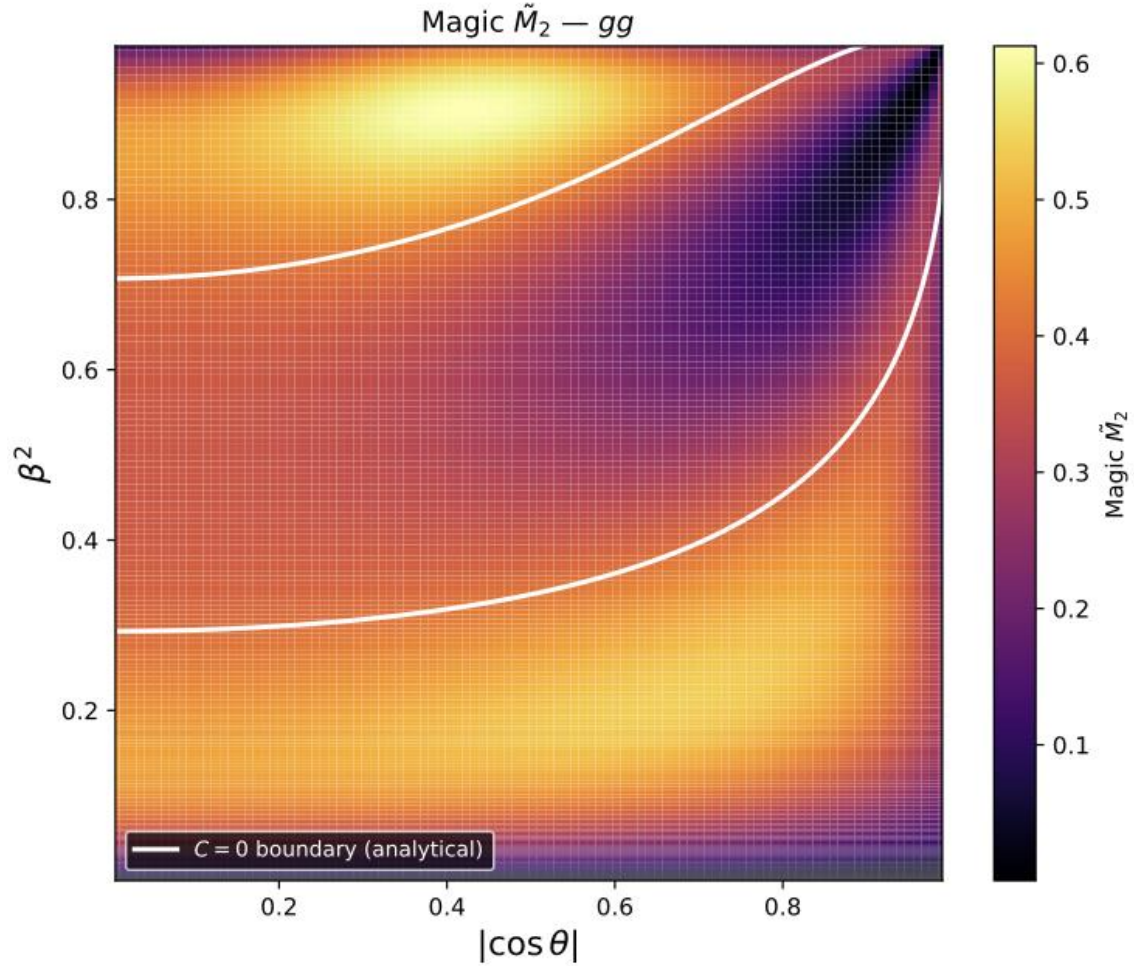
where

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

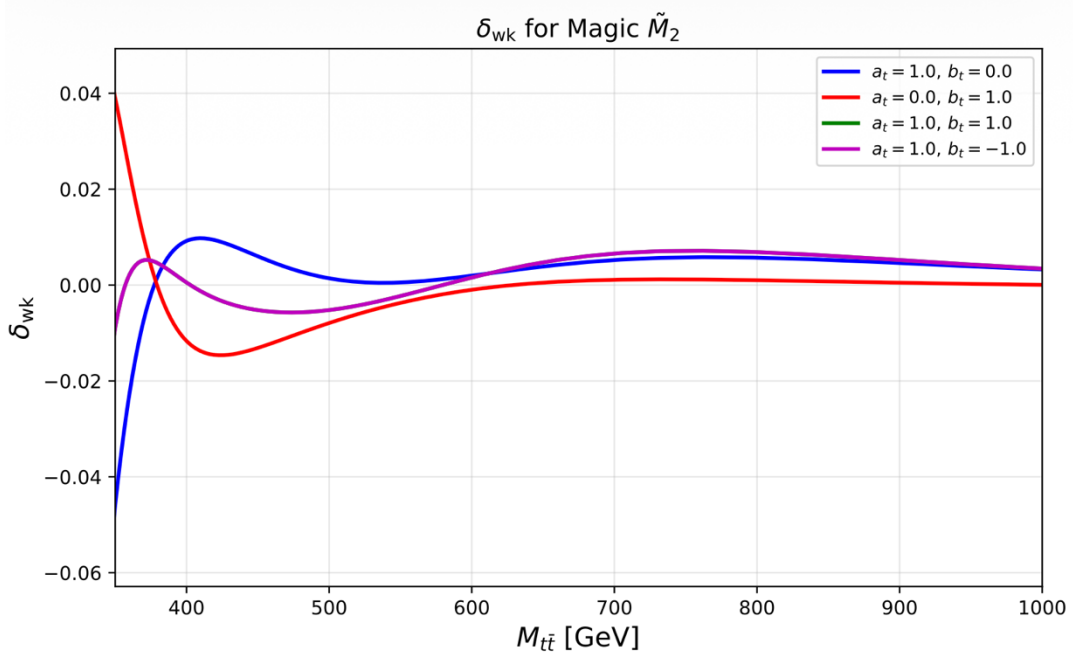
which in terms of Fano coefficients yields

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

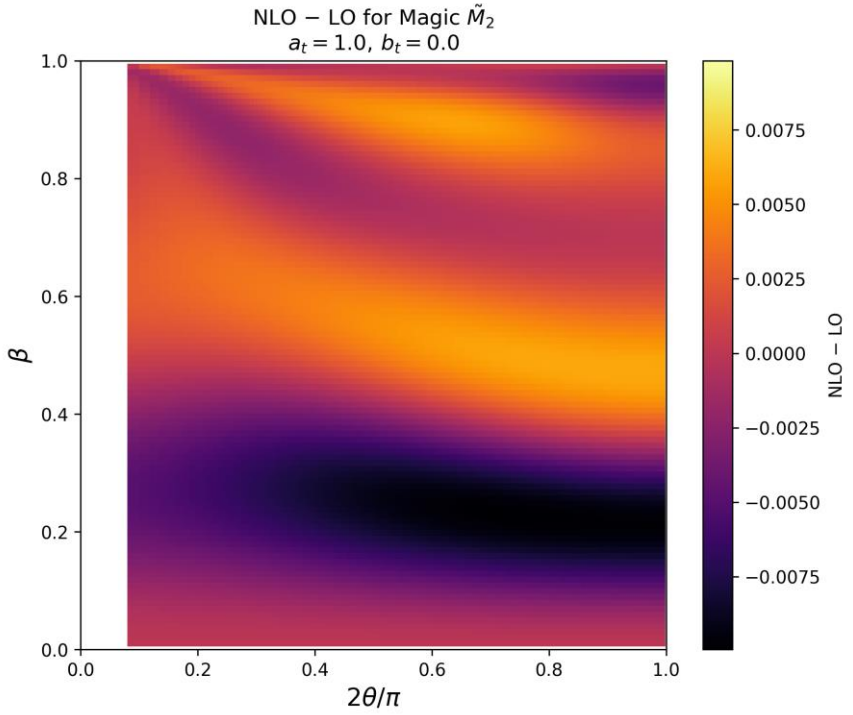
This quantity describes how far away the system is from being efficiently simulated classically with stabilizer methods.

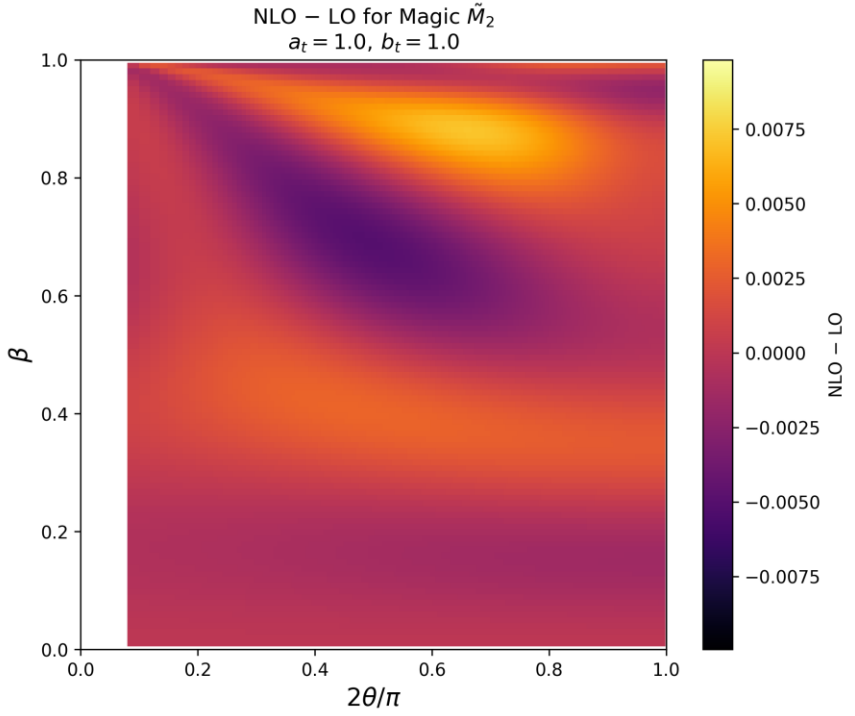


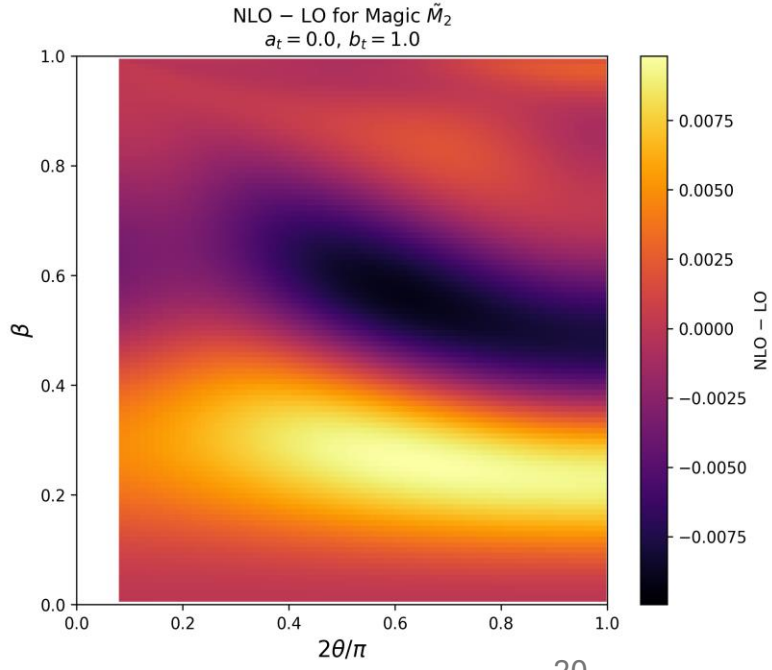
See White^2, 2412.07479, Aoude, Banks, White^2, 2505.12522, and Durupt, Maltoni, Mattelaer 2510.17730



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







Reproducing known results - Concurrence

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

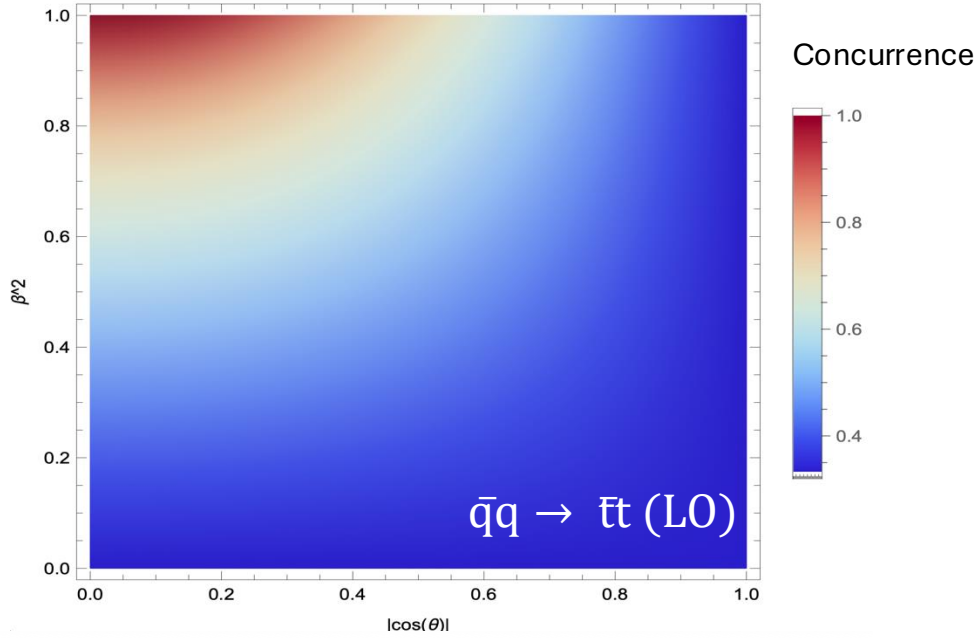
$$C(\rho) = \max(0,\ \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)\,,$$

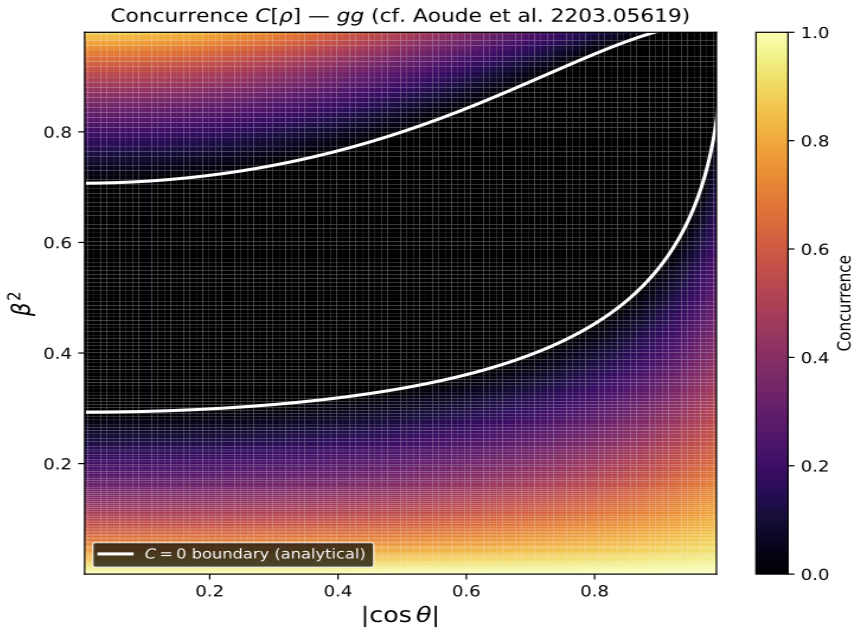
Where the set λ_i are the square root of the eigenvalues of the matrix:

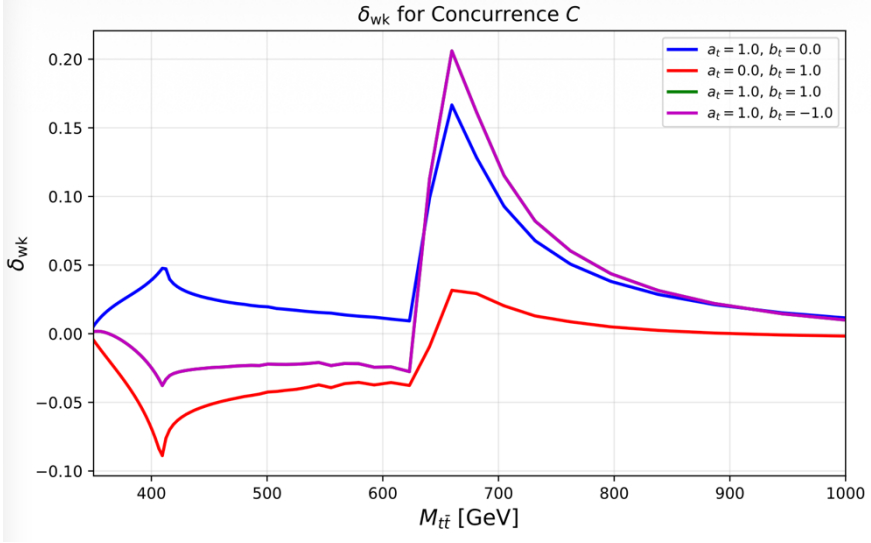
$$W = \rho\,\tilde{\rho}, \quad \text{where } \tilde{\rho} \text{ is defined as}$$

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

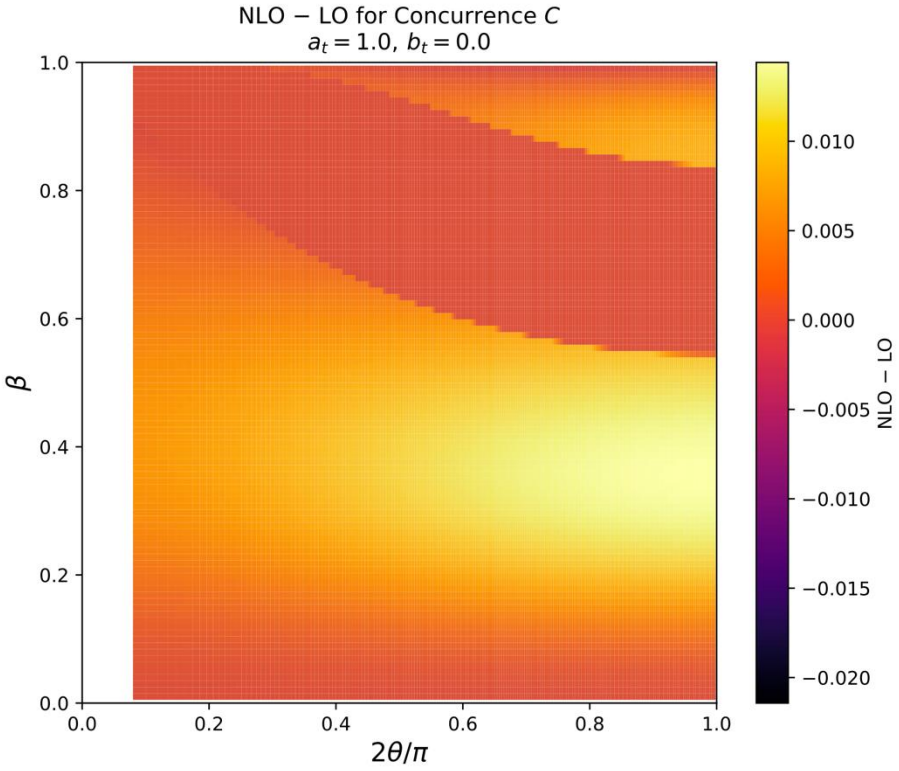
We have computed this quantity for $gg \to \bar{t}t$ and $\bar{q}q \to \bar{t}t$, reproducing known results for the SM reported in [Aoude, Madge, Maltoni and Mantani 2203.05619].



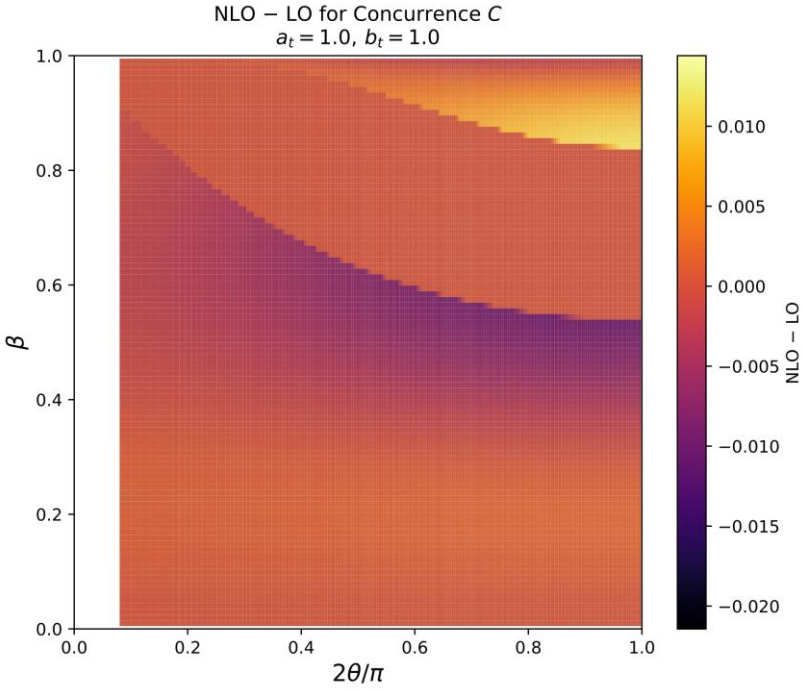




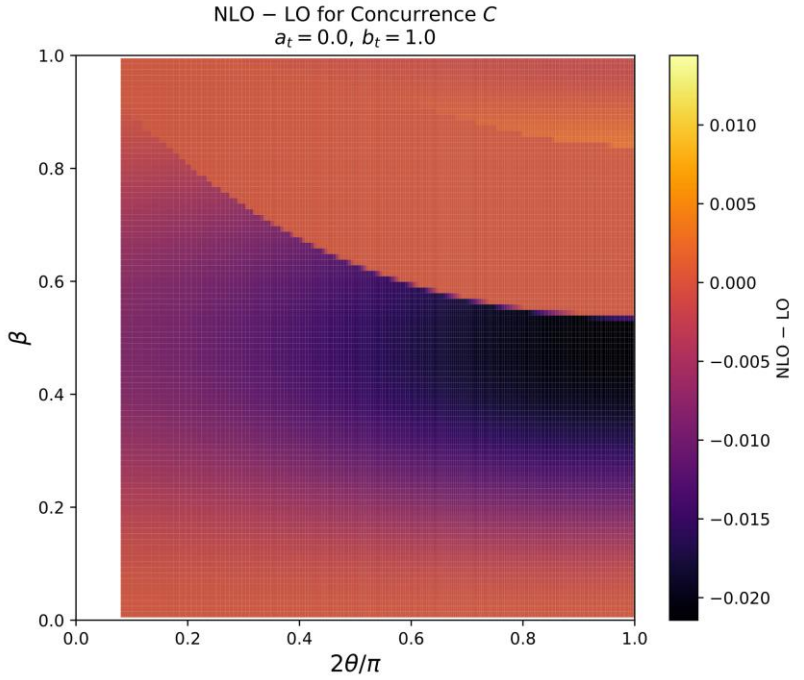
Concurrence differences between these radically different models reach 4%, proving Concurrence is sensitive to CP violating Higgs-top Yukawas.



SM



Mixed CP



Pure CP