

Quantum Tomography of Top Quarks as a Probe of Charge–Parity Violation

The measured $t\bar{t}$ spin density matrix as a constraint on the top Yukawa

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What is new

- CMS has measured **all 15** parameters of the $t\bar{t}$ two-qubit spin density matrix
 $\Rightarrow$ a full *quantum-state tomography*.
- We compute the **first complete renormalized** one-loop Higgs-induced $t\bar{t}$ production density matrix for a CP-violating top Yukawa.
- Confronting the two gives the **first tomography-based** bound on the CP structure of y_t .

Headline numbers

For $a_t = 1$ (SM-like scalar coupling):

$$-1.40 < b_t < 1.23 \quad (95\% \text{ CL, spin only})$$

$$-1.01 < b_t < 1.26 \quad (95\% \text{ CL, spin} + m_{t\bar{t}})$$

Comparable to direct $t\bar{t}H/tH$ limits — and
independent of them.

The quantum state itself becomes a precision observable.

1. Why CP violation in the top Yukawa?
2. Quantum tomography of $t\bar{t}$ at the LHC
3. How CP violation enters the density matrix
4. Renormalizing the CP-odd sector
5. From amplitudes to a constraint
6. Results
7. Discussion and outlook

Why CP violation in the top Yukawa?

- Sakharov (1967): baryogenesis requires C and CP violation.
- The CKM phase is **orders of magnitude too small** to generate the observed baryon asymmetry.

⇒ New sources of CP violation are *required*.

- The Higgs couples most strongly to the top quark
⇒ a natural place for a new CP-odd phase to hide.
- Weinberg (1989, 1990): CP violation in the Higgs sector is a well-motivated, minimally-tuned possibility.

The phenomenological Lagrangian

$$\mathcal{L}_{h\bar{t}t} = -\frac{m_t}{v} h \bar{t} (a_t + i b_t \gamma_5) t$$

- a_t : scalar (CP-even);
 b_t : pseudoscalar (CP-odd)
- SM: $(a_t, b_t) = (1, 0)$
- $a_t b_t \neq 0 \iff$ **CP violation**
- Often written $(a_t, b_t) = \kappa_t (\cos \alpha, \sin \alpha)$

Where is (a_t, b_t) constrained today?

Direct: $t\bar{t}H$ and tH production

- Tree level: the CP structure imprints directly on the *rate* and on $t\bar{t}H/tH$ interference.
- ATLAS & CMS, $H \rightarrow \gamma\gamma$ and multilepton.
- ATLAS Run 2: $|b_t| \approx 1.1$ at $a_t = 1$ (95% CL, 2D).

Indirect: electric dipole moments

- Nominally *much* stronger ...
- ... but assume SM-like Higgs couplings to light fermions and *no cancellations* among contributions.

What about plain $t\bar{t}$ production?

- Rates & kinematics: Higgs loops shift $\sigma(m_{t\bar{t}})$ — but only through a_t^2 and b_t^2 .
- ⇒ cross sections are blind to CP violation (no $a_t b_t$ dependence).
- Spin correlations *are* sensitive (Schmidt–Peskin '92; Bernreuther–Brandenburg '93,'94)...
 - ... but those analyses kept only the UV-finite parts of the one-loop structure functions.

This talk: do it completely, and use the tomographic data.

Quantum tomography of $t\bar{t}$ at the LHC

- Top decays *before* it hadronizes $\Rightarrow$ spin information survives into the decay products.
- t and $\bar{t}$ spins form a genuine **two-qubit state**.
- Production spin density matrix from helicity amplitudes:

$$R_{\lambda\lambda',\bar{\lambda}\bar{\lambda}'} = M_{\lambda\bar{\lambda}} M_{\lambda'\bar{\lambda}'}^*$$

(summed over final helicities, averaged over initial colours).

- $\text{Tr } R \propto d\sigma$; $\rho = R / \text{Tr } R$ is a unit-trace two-qubit density operator.

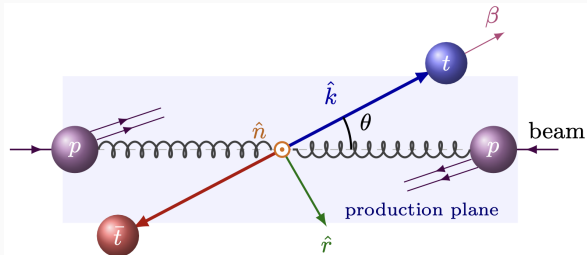
Fano decomposition: 15 real numbers

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

- $B_i^+ \equiv P_i$: top polarization (3)
- $B_i^- \equiv \bar{P}_i$: antitop polarization (3)
- C_{ij} : spin-spin correlations (9)

Measuring all 15 = quantum-state tomography.

The spin-analysis frame $\{\hat{n}, \hat{r}, \hat{k}\}$



- Frame attached **event by event** in the $t\bar{t}$ rest frame.
- $\hat{k}$: along the top momentum
 $\hat{r}$: in the production plane
 $\hat{n}$: normal to the production plane
- Event kinematics: top velocity β and scattering angle θ .
- Helicity amplitudes must be **rotated** into this common basis (t and $\bar{t}$ momenta are antiparallel!).
- We adopt the CMS conventions, including the $\text{sgn}(\cos\theta)$ folding defining $\hat{n}, \hat{r}$.

CMS-TOP-23-007 — PRD 110 (2024) 112016
[2409.11067]

- ℓ +jets, $\sqrt{s} = 13$ TeV, full Run 2.
- All **15 Fano coefficients**, *unfolded*, with the **full covariance matrix**.
- Inclusive *and* in 4 bins of $m_{t\bar{t}}$ (and $\cos\theta$).
- Plus a per-bin normalization c (expected value 1) $\Rightarrow$ a proxy for the $m_{t\bar{t}}$ shape.
- $4 \times (15 + 1) = 64$ correlated quantities.

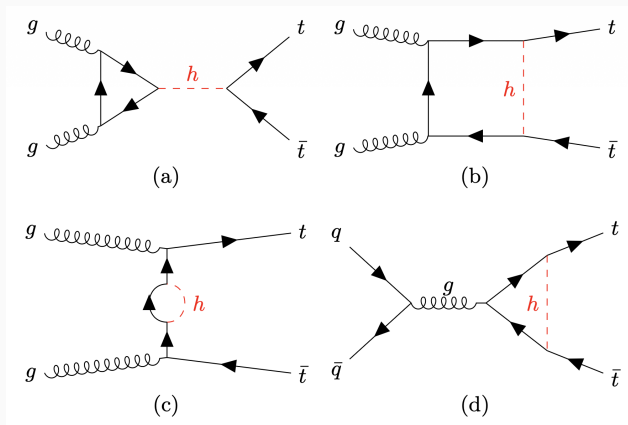
- So far used for *quantum* properties of the state:
 - entanglement (CMS, ATLAS)
 - Bell non-locality
 - “magic” (non-stabilizerness)
- Near threshold: spin singlet $\Rightarrow$ maximally entangled.
At large $m_{t\bar{t}}$: approaches a triplet configuration.

Our point

The same data, and the same covariance, constrain new physics — here CP violation in y_t .

How CP violation enters the density matrix

(a_t, b_t) enter at one loop



- At LO the $t\bar{t}$ spin state is **pure QCD**: P- and CP-even, no discontinuities.
- (a_t, b_t) first enter through the **interference** of the tree QCD amplitude with virtual Higgs exchange.
- Both loop particles massive $\Rightarrow$ **IR finite**.
- Relative size: $\frac{y_t^2}{16\pi^2}$, $y_t = \frac{2m_t}{v}$.
- Additive shift of the production density matrix:

$$\Delta R(a_t, b_t)$$

Dispersive vs. absorptive: a symmetry classification

The shift $\Delta R(a_t, b_t)$ splits into two physically distinct pieces:

- **Dispersive**: the real (principal-value) part of the loop — present already *below* any threshold.
- **Absorptive**: the discontinuity across a branch cut, i.e. **on-shell intermediate states** $\Rightarrow$ imaginary parts of the helicity amplitudes.

They populate *different* Fano coefficients, in a pattern fixed by CP and naive time reversal T_N (reverse all momenta and spins, do *not* swap in and out states).

Two independent CP-odd handles

C_{nr}^- dispersive | $P_k - \bar{P}_k$ absorptive

The selection rules

- CP-even coefficients (incl. diagonal C_{ii}): corrections $\propto a_t^2, b_t^2$.
- **Every CP-odd coefficient is linear in $a_t b_t$** — it vanishes unless *both* couplings are present.
- C_{nr}^-, C_{nk}^- (antisymmetric, $C_{ij}^- = C_{ij} - C_{ji}$): T_N -odd $\Rightarrow$ **dispersive** parts suffice.
- $P_k - \bar{P}_k$: T_N -even; odd under $CPT_N \Rightarrow$ by CPT it is **purely absorptive**.

$P_k - \bar{P}_k \neq 0$ requires CP violation *and* particles light enough to go on shell — here the top and the Higgs themselves.

Which coefficients actually carry the signal?

Fano coefficient	CP	Origin	Pull at $(a_t, b_t) = (1, 1)$
C_{nr}^- (antisym.)	odd	dispersive	0.8σ
$P_k, \bar{P}_k$	odd	absorptive	$\sim 0.6 \sigma$
C_{nn}	even	a_t^2, b_t^2	$\sim 0.4 \sigma$
C_{nk}^- (antisym.)	odd	dispersive	small
other $C_{ij}, B_i^\pm$	mixed	—	below sensitivity

- Pull $\equiv \delta Q_m / \sigma_m$ with $\delta Q_m = Q_m(a_t, b_t) - Q_m^{\text{SM}}$ and $\sigma_m = \sqrt{V_{mm}}$ the uncorrelated per-coefficient uncertainty.
- All Fano coefficients vary across the (a_t, b_t) plane — but only a handful are measured precisely enough to matter.
- The fit therefore bounds the dispersive and absorptive CP-odd contributions *simultaneously*.

Renormalizing the CP-odd sector

The top self-energy acquires a pseudoscalar structure

The one-loop Higgs-exchange correction is **UV divergent**. Renormalize m_t and the top field in the *on-shell* scheme. The 1PI two-point function decomposes as

$$\Sigma_t(p) = \not{p} \Sigma_V(p^2) + m_t \Sigma_S(p^2) + i m_t \gamma_5 \Sigma_P(p^2)$$

with, for the Higgs loop,

$$\Sigma_V = -\frac{a_t^2 + b_t^2}{16\pi^2} \frac{m_t^2}{v^2} B_1,$$

$$\Sigma_S = \frac{a_t^2 - b_t^2}{16\pi^2} \frac{m_t^2}{v^2} B_0,$$

$$\Sigma_P = \frac{a_t b_t}{8\pi^2} \frac{m_t^2}{v^2} B_0,$$

$$B_{0,1} \equiv B_{0,1}(p^2, m_t, m_H).$$

- Σ_V, Σ_S : CP even, same Lorentz structure as in the SM (known: Maltoni–Pagani–Tentori; Martini et al.).
- $\Sigma_P \propto a_t b_t$: **new**, present only when both couplings are nonzero.
- Mass counterterm stays *real and CP even*:

$$\delta m_t = \frac{m_t^2}{16\pi^2 v^2} \left[a_t^2 (B_0 - B_1) - b_t^2 (B_0 + B_1) \right]$$

evaluated at $p^2 = m_t^2$.

$\Rightarrow$ the CP-odd $a_t b_t$ dependence sits *entirely* in the field renormalization.

The pseudoscalar form factor is absorbed by the **field** renormalization:

$$\text{Im } \delta Z_t^{L,R} = \mp \widetilde{\text{Re}} \Sigma_P(m_t^2) = \mp \frac{a_t b_t}{8\pi^2} \frac{m_t^2}{v^2} \left[\widetilde{\text{Re}} B_0 \right]_{p^2=m_t^2}$$

- $\widetilde{\text{Re}}$: keep imaginary parts of *couplings*, discard absorptive parts of loop integrals.
- An imaginary axial δZ is a **chiral rotation** of the top field — equivalent to a $\bar{t} i \gamma_5 t$ mass term, forced by consistency of a CP-violating two-point function.
- **No new independent counterterms** are required.

Why this matters

- Earlier work kept only UV-finite pieces (Schmidt–Peskin; Bernreuther–Brandenburg).
 - The finite $a_t b_t$ remainder **does not shift the cross section** — but it *does* enter the spin density matrix.
 - The top self-energy is the *only* counterterm carrying $a_t b_t$.
- ⇒ **first complete renormalized production density matrix**: dispersive *and* absorptive CP-odd observables.

From amplitudes to a constraint

Building the prediction

1. Additive shift, channel by channel

$$R_\alpha(a_t, b_t) = R_{\alpha, \text{SM}} + \Delta R_\alpha(a_t, b_t), \quad \alpha = \{gg, q\bar{q}\}$$

$$\Delta R_\alpha = R_{\alpha, h t \bar{t}}(a_t, b_t) - R_{\alpha, h t \bar{t}}(1, 0)$$

- $R_{\alpha, \text{SM}}$: the CMS SM prediction (NLO QCD + PS, normalized to NNLO).
- No re-simulation: CMS results are **unfolded**, and the Fano coefficients are *linear* in ρ .

2. Bin integration with parton luminosity

$$W_\alpha(\beta, \cos \theta) = \frac{dL_\alpha}{d\tau} \frac{\beta^2}{16\pi s (1 - \beta^2)}, \quad \tau = \frac{m_{t\bar{t}}^2}{s}$$

$$\mathcal{R}_k^\alpha(a_t, b_t) = \int_k W_\alpha R_\alpha d\beta d\cos\theta$$

3. Combine channels before extracting coefficients

$$\mathcal{R}_k = \sum_\alpha \mathcal{R}_k^\alpha$$

- Coefficients come from the *normalized* matrix $\Rightarrow$ channels cannot be averaged coefficient-by-coefficient.
- gg dominates: $q\bar{q}$ is $\sim 16\times$ smaller near threshold.

4. Normalize

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

$$\sigma_k^{\text{SM}} = f_k \times 832^{+40}_{-46} \text{ pb (NNLO+NNLL)}, \mu_{R,F} = H_T/2, \\ m_t = 172.5 \text{ GeV, NNPDF3.1 NNLO.}$$

Implementation A — analytic

- FeynArts + FormCalc: renormalized one-loop amplitudes and the density matrices built from them.
- Loop integrals with LoopTools.

Implementation B — fully numerical

- Renormalized model (incl. the CP-odd counterterms) generated with FeynRules + NLOCT.
- Virtual amplitudes from MadGraph5_aMC@NLO / MadLoop.

The two yield identical constraints.

The χ^2

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

$$\Delta Q_m = Q_m(a_t, b_t) - Q_m^{\text{obs}}$$

with V the full published experimental covariance.

- Symmetry: the density matrix depends on (a_t, b_t) only through a_t^2 , b_t^2 and $a_t b_t$.

⇒ every fit is invariant under $(a_t, b_t) \rightarrow (-a_t, -b_t)$: two mirror minima.

Three fits, three kinds of information

$\chi^2_{m_{t\bar{t}}}$ — kinematics only

- Trace of the same $\Delta\mathcal{R}_k \Rightarrow$ shift of $d\sigma/dm_{t\bar{t}}$.
 - Compared with the CMS differential $m_{t\bar{t}}$ measurement [2108.02803] and its covariance.
 - Depends only on a_t^2, b_t^2 .
- $\Rightarrow$ **blind to CP violation.**

$\chi^2_{\text{Fano-inc}}$ — spin only

- The 15 Fano coefficients measured *inclusively*.
 - Full 15×15 covariance.
 - Sensitive to $a_t b_t$ through $C_{nr}^-, P_k, \bar{P}_k$.
- $\Rightarrow$ closes the $a_t^2 \simeq b_t^2$ directions.

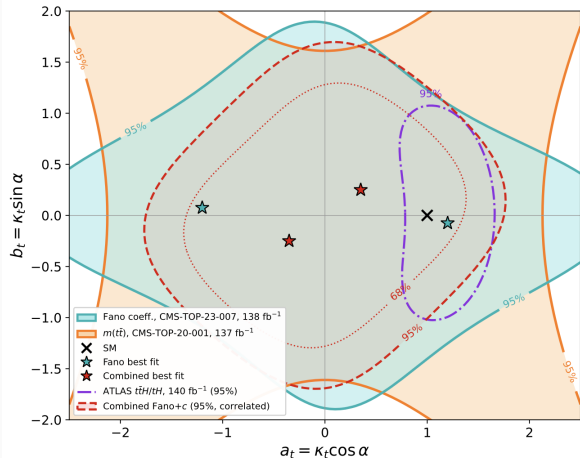
$\chi^2_{\text{Fano-diff}}$ — combined

- 15 coefficients in 4 $m_{t\bar{t}}$ bins *plus* the per-bin normalization c .
 - $c(a_t, b_t) = \nu \left(1 + \frac{\Delta\sigma_k}{\sigma_k^{\text{SM}}} \right)$, ν a floating nuisance parameter.
- $\Rightarrow$ uses the $m_{t\bar{t}}$ *shape*, not the absolute rate (no large scale uncertainty).
- Full 64×64 covariance.

Spin and kinematics are sensitive along **independent directions** of the (a_t, b_t) plane.

Results

Constraints in the (a_t, b_t) plane



$(a_t, b_t) = \kappa_t(\cos \alpha, \sin \alpha)$, CMS Run 2.

- orange, $\chi^2_{m_{t\bar{t}}}$ (CMS-TOP-20-001): rate and kinematics only. Bounds the *magnitude* of the couplings, but stays *open* along $a_t^2 \simeq b_t^2$ — precisely the CP-violating direction.
- teal, $\chi^2_{\text{Fano-inc}}$ (CMS-TOP-23-007): spin information alone *closes* that direction.
- - red dashed, $\chi^2_{\text{Fano-diff}}$: spin + $m_{t\bar{t}}$ shape with their correlations — the tightest of the three.
- · - ATLAS $t\bar{t}H/tH$, same Run 2 dataset [2606.04855].
- × SM; ★ best fits — each appears *twice*, since every fit is invariant under $(a_t, b_t) \rightarrow (-a_t, -b_t)$.

SM consistent with the data at 68% CL in all three fits.

Fit	Information	Best fit (a_t, b_t)	Allowed b_t at $a_t = 1$ (95% CL)
$\chi^2_{m_{t\bar{t}}}$	$d\sigma/dm_{t\bar{t}}$ only	—	open along $a_t^2 \simeq b_t^2$
$\chi^2_{\text{Fano-inc}}$	15 inclusive Fano coeff.	(1.20, -0.08)	$-1.40 < b_t < 1.23$
$\chi^2_{\text{Fano-diff}}$	15 coeff. $\times$ 4 $m_{t\bar{t}}$ bins + c	(0.35, 0.25)	$-1.01 < b_t < 1.26$
$\chi^2_{\text{Fano-diff}}$ at 68% CL: $-0.50 < b_t < 0.83$			
ATLAS $t\bar{t}H/tH$, $H \rightarrow \gamma\gamma$, same dataset: $ b_t \approx 1.1$ at $a_t = 1$ (95% CL)			

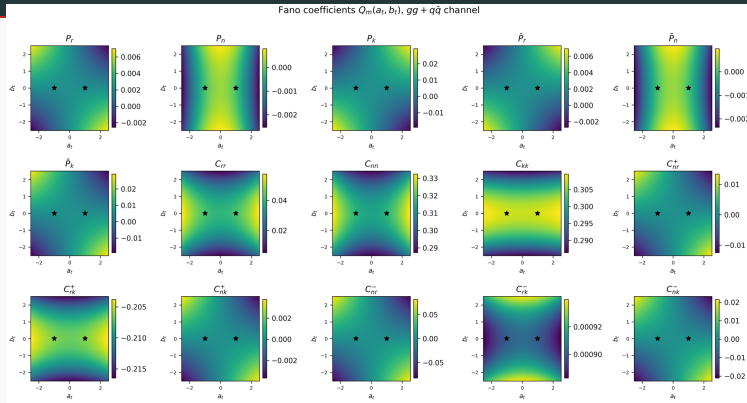
Take-away

- Sensitivity **comparable** to the leading direct probe.
- **Independent** of it: loop level, spin based, different systematics.
- The two can be *combined*.

And this is not optimized

The CMS binning was chosen to map *quantum* properties of the state, not to search for these loop-induced shifts. Finer $m_{t\bar{t}}$ bins near threshold — where the corrections are largest — should do better.

The fifteen coefficients across the (a_t, b_t) plane

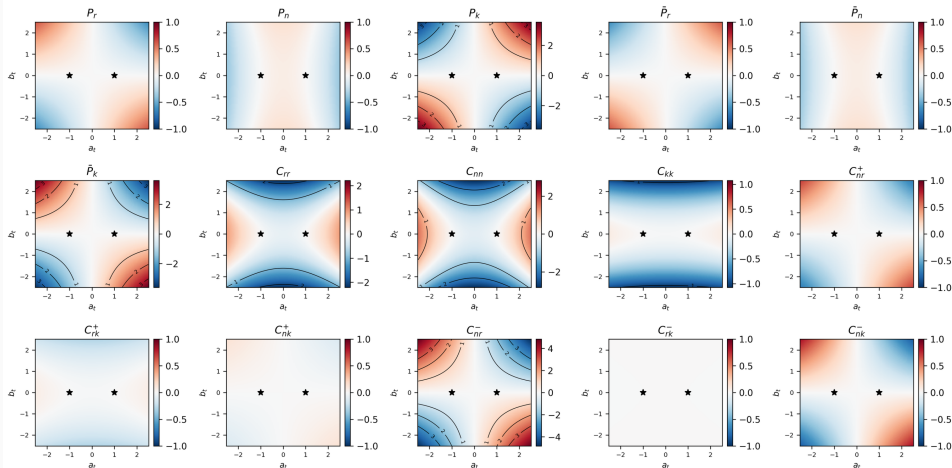


- $Q_m(a_t, b_t)$ themselves, *not* shifts, for the combined $gg + q\bar{q}$ matrix. **Every panel has its own scale** — read the numbers, not the colours.
- Diagonal correlations are large and QCD-dominated ($C_{nn}, C_{kk} \simeq 0.3$, $C_{rk}^+ \simeq -0.21$); the Higgs loop modulates them only at the percent level, as $y_t^2/16\pi^2$ demands.

- The shapes read off the coupling structure: **saddles symmetric about both axes** are the a_t^2, b_t^2 entries; **diagonal patterns** ($P_r, P_k, \bar{P}_k, C_{nr}^-, C_{nk}^-$) are the $a_t b_t$ ones, and vanish on either axis.
- Polarizations are $10^{-2} - 10^{-3}$, but LO QCD produces *none*: they are Higgs-loop induced outright. **Size is not sensitivity** — divide by the measured errors, next slide.

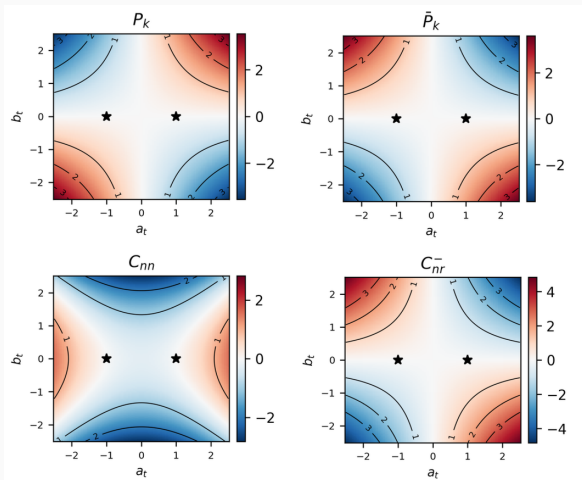
Sensitivity coefficient by coefficient

$(Q_m - Q_m^{\text{SM}})/\sigma_m^{\text{CMS}}, gg + q\bar{q}$ channel



$\delta Q_m/\sigma_m = (Q_m - Q_m^{\text{SM}})/\sqrt{V_{mm}}$; contours at $1\sigma, 2\sigma, 3\sigma$; stars: SM and its mirror. **Four of the fifteen carry essentially all of the sensitivity.**

The four that matter



- C_{nr}^- gives the largest pull, 0.8σ at $(a_t, b_t) = (1, 1)$ — it carries the **dispersive** CP-odd piece and is the single coefficient that drives the bound.
- P_k and $\bar{P}_k$ follow at $\sim 0.6\sigma$. Their **difference** is **purely absorptive**: note the mirrored red/blue quadrants of the two panels.
- C_{nn} , at $\sim 0.4\sigma$, is CP *even* — it responds to a_t^2, b_t^2 and helps fix the coupling magnitude.
- All four vanish along $a_t = 0$ or $b_t = 0$ except C_{nn} : the CP-odd response needs *both* couplings.

Discussion and outlook

What the bound does and does not assume

The implicit assumption

Any *other* new physics is heavy enough to decouple from $t\bar{t}$ production, so that

$$\mathcal{L}_{ht\bar{t}} = -\frac{m_t}{v} h \bar{t} (a_t + i b_t \gamma_5) t$$

is the only non-standard interaction entering the loop.

- Additional new physics in the loop would modify the bounds.

... but the data can tell

- The Fano coefficients are measured **in bins of $m_{t\bar{t}}$ and $\cos\theta$** .
- ⇒ the *shape* of a loop correction across the spectrum is resolved.
- States not far above the $t\bar{t}$ threshold would leave a **distinguishable imprint**.
 - Left to future work.

A general method

Any new physics that modifies the production density matrix — loops or effective operators — can be confronted with the measured tomography and its covariance *in the same way*: no event regeneration, no repeated decay simulation. That expensive step is already contained in the experimental analysis.

What we did

1. Computed the **complete renormalized** one-loop Higgs-induced corrections to $gg, q\bar{q} \rightarrow t\bar{t}$ for a CP-violating top Yukawa.
2. Handled the new **pseudoscalar** self-energy structure via an imaginary axial field renormalization — no new counterterms.
3. Predicted the shift in **all 15 Fano coefficients**, dispersive *and* absorptive.
4. Fit the CMS tomographic data with its **full covariance**.

What we found

- C_{nr}^- (dispersive) and $P_k, \bar{P}_k$ (absorptive) drive the sensitivity.
- At $a_t = 1$: $-1.40 < b_t < 1.23$ (spin only) and $-1.01 < b_t < 1.26$ (spin + $m_{t\bar{t}}$ shape), 95% CL.
- **Comparable to, and independent of, direct $t\bar{t}H/tH$ probes.**

The broader point

Quantum-state tomography at colliders is not only a probe of quantum correlations — it is a precision observable for testing the interactions of the Standard Model and its extensions.

Thank you

$$\rho = \frac{1}{4} \left(\mathbb{1} \otimes \mathbb{1} + B_i^+ \sigma_i \otimes \mathbb{1} + B_i^- \mathbb{1} \otimes \sigma_i + C_{ij} \sigma_i \otimes \sigma_j \right), \quad i, j \in \{\hat{n}, \hat{r}, \hat{k}\}$$

- $B_i^+ = P_i$ (3) + $B_i^- = \bar{P}_i$ (3) + C_{ij} (9) = 15 real parameters.
- Antisymmetric combinations: $C_{ij}^- = C_{ij} - C_{ji}$.
- Near threshold: spin-singlet $\Rightarrow$ maximal entanglement.
At large $m_{t\bar{t}}$: spin-triplet configuration.
- Production-level ρ and the ρ reconstructed from decay angular distributions **coincide for quantities linear in ρ** (the Fano coefficients).
They differ for *nonlinear* functions, e.g. entanglement measures. [Cheng, Han, Low, 2410.08303]

$$W_\alpha(\beta, \cos \theta) = \frac{dL_\alpha}{d\tau} \underbrace{\frac{\beta^2}{16\pi s(1-\beta^2)}}_{\text{2-body PS} \times \text{Jacobian}}, \quad \tau = \frac{m_{t\bar{t}}^2}{s}, \quad \sqrt{s} = 13 \text{ TeV}$$

- Two-body phase space $\frac{\beta}{32\pi m_{t\bar{t}}^2}$ times $\frac{d\tau}{d\beta}$.
- $dL_\alpha/d\tau$: parton luminosity, NNPDF3.1 NNLO.
- Integrated production matrix in bin k :

$$\mathcal{R}_k^\alpha(a_t, b_t) = \int_k W_\alpha R_\alpha(a_t, b_t) d\beta d\cos\theta, \quad \mathcal{R}_k = \sum_\alpha \mathcal{R}_k^\alpha$$

- Relation to the cross section:

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

Backup: the combined fit $\chi^2_{\text{Fano-diff}}$

CMS reports, per $m_{t\bar{t}}$ bin, a normalization c whose expected value is unity. We predict

$$c(a_t, b_t) = \nu \left(1 + \frac{\Delta\sigma_k(a_t, b_t)}{\sigma_k^{\text{SM}}} \right)$$

$$\Delta\sigma_k(a_t, b_t) = \sigma_k(a_t, b_t) - \sigma_k(1, 0)$$

- ν : floating nuisance absorbing the overall normalization.

⇒ the fit uses the **shape** of the $m_{t\bar{t}}$ distribution, avoiding the large scale uncertainty of the absolute rate.

- Published covariance correlates all **64** quantities; varying the SM normalization has minimal impact on the contour.

$\chi^2_{m_{t\bar{t}}}$

- Uses $\text{Tr}[\Delta\mathcal{R}_k]$, i.e. the Higgs-induced shift of $d\sigma/dm_{t\bar{t}}$ (following Maltoni–Pagani–Tentori).
- Added to the NNLO SM prediction at its LO normalization.
- χ^2 against the CMS spectrum [2108.02803] with its published covariance.
- Depends only on $a_t^2, b_t^2 \Rightarrow$ **no CP sensitivity**.

Backup: key references

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