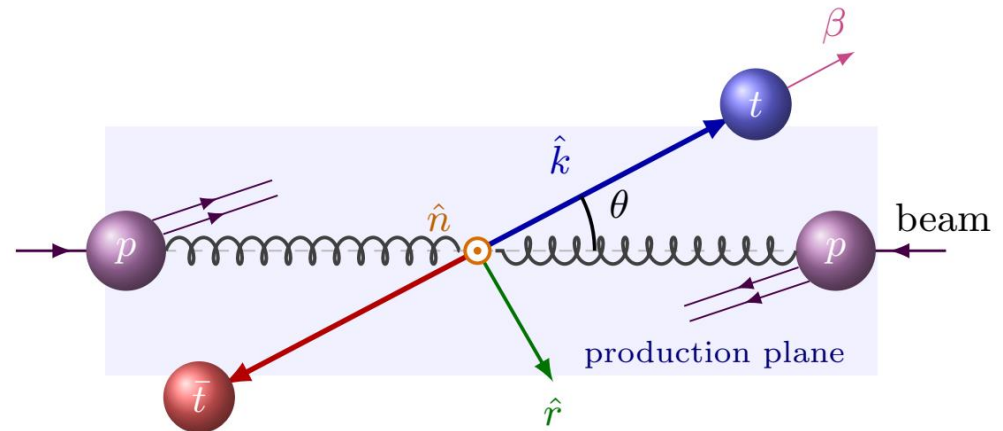


Quantum Tomography of Top Quarks as a Probe of Charge-Parity Violation in Higgs-top interactions.

Kirtimaan Mohan
MSU, HEP Seminar
Sep 28, 2026



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Outline

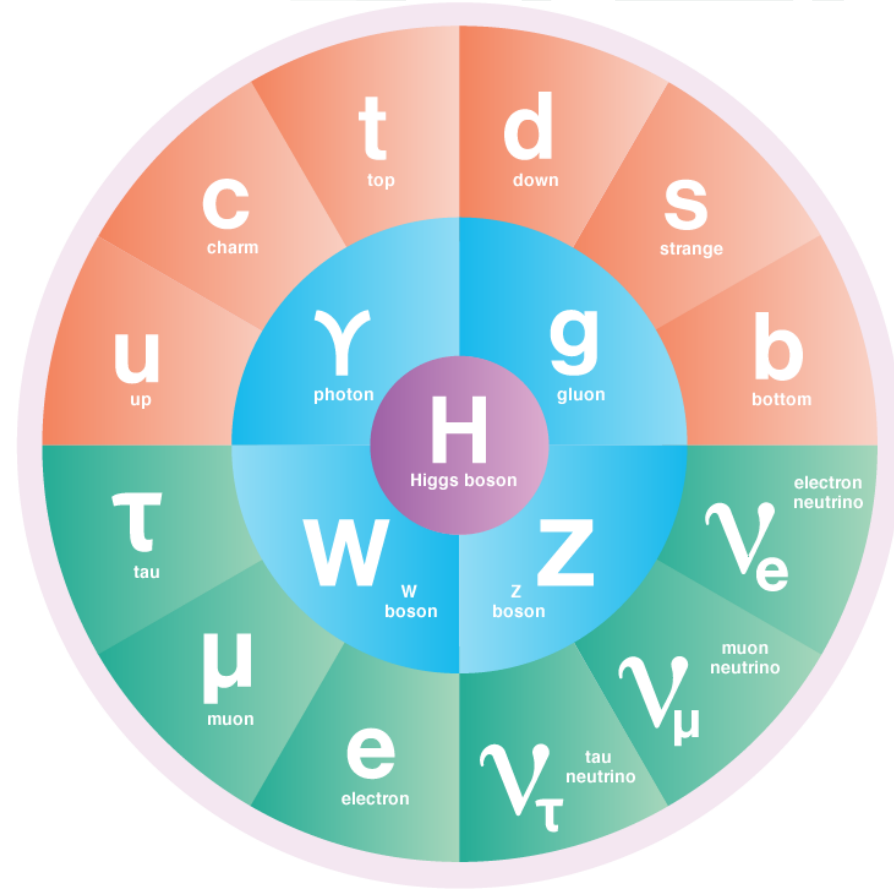
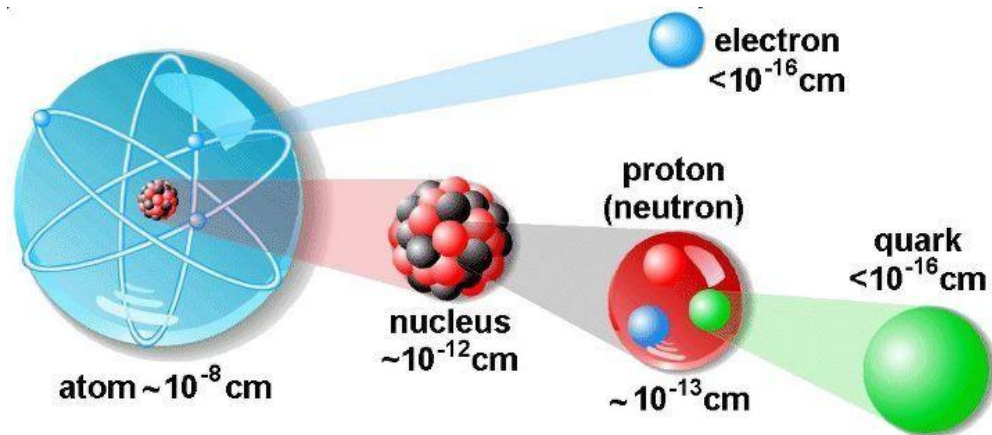


- Motivation For CP violation in Higgs sector
 - Baryon Asymmetry
 - Vacuum Structure of the scalar sector
- CP violation in Higgs-top interactions
 - Higgs + 1 jet
 - Higgs + 2 jet
 - Quantum Tomography of Top quark pairs

What we know about matter and its interactions?

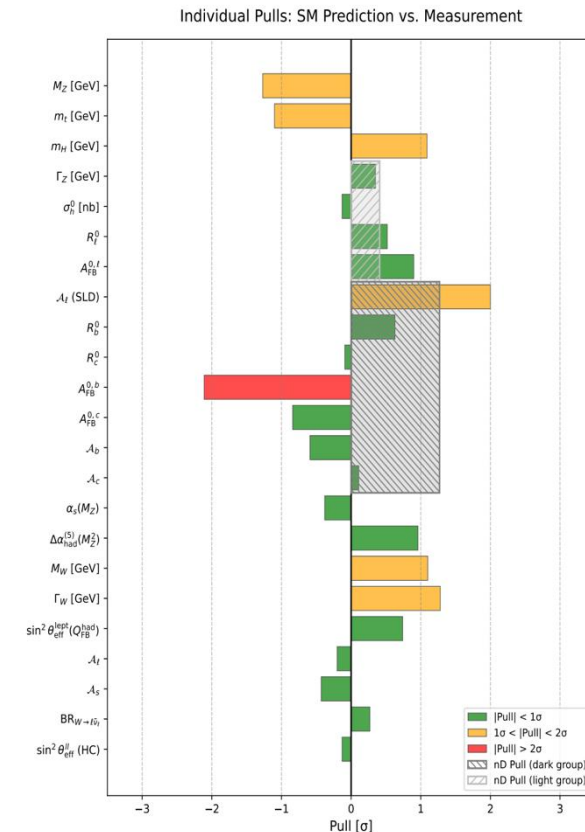
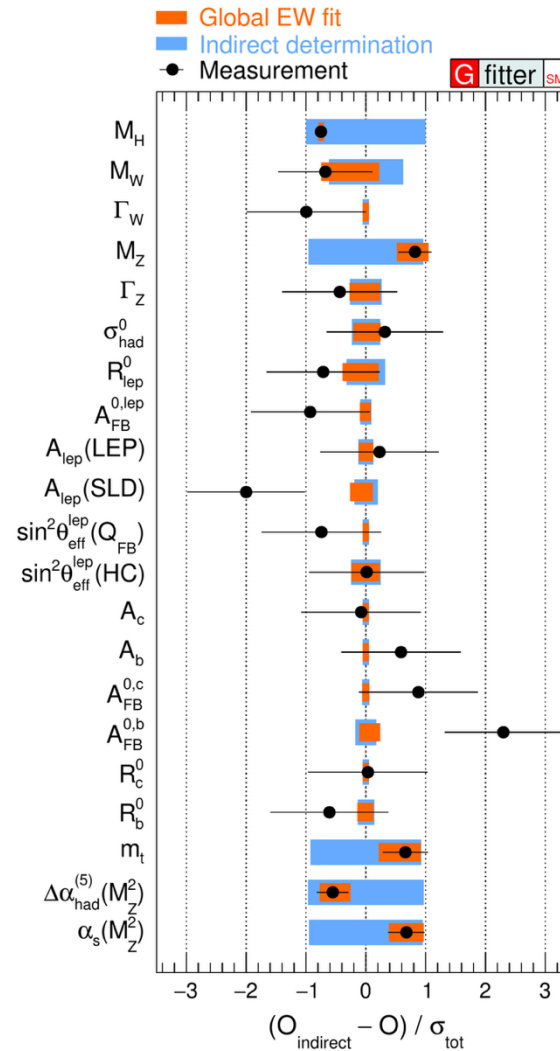
The Standard Model (SM):

- 17 particles
- 18 parameters (25 including neutrino mass)
- Explains everything very precisely... almost



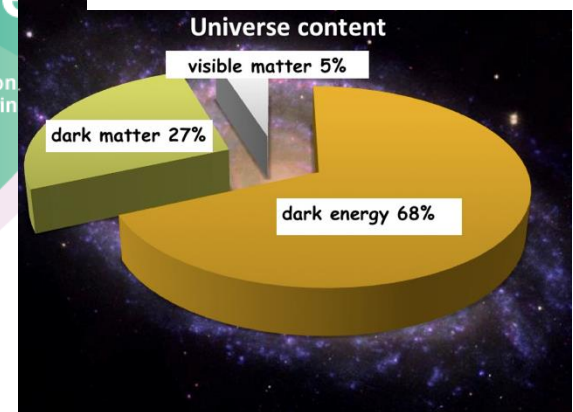
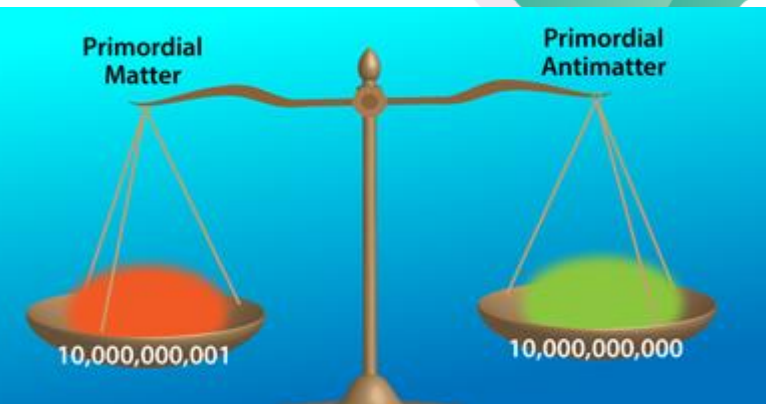
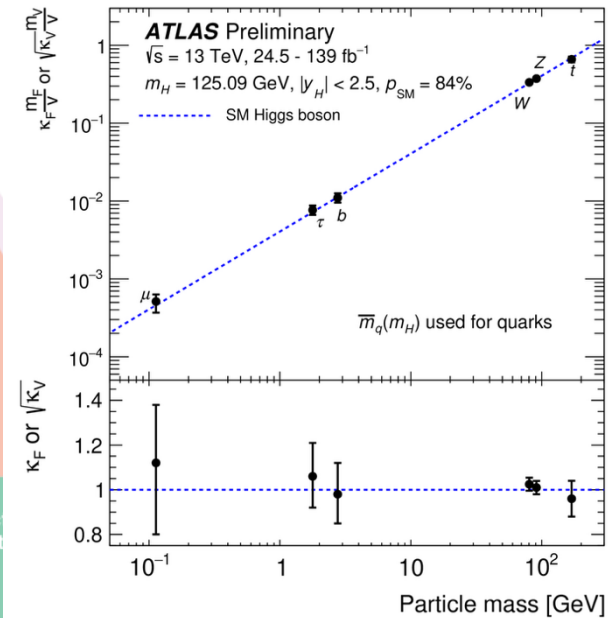
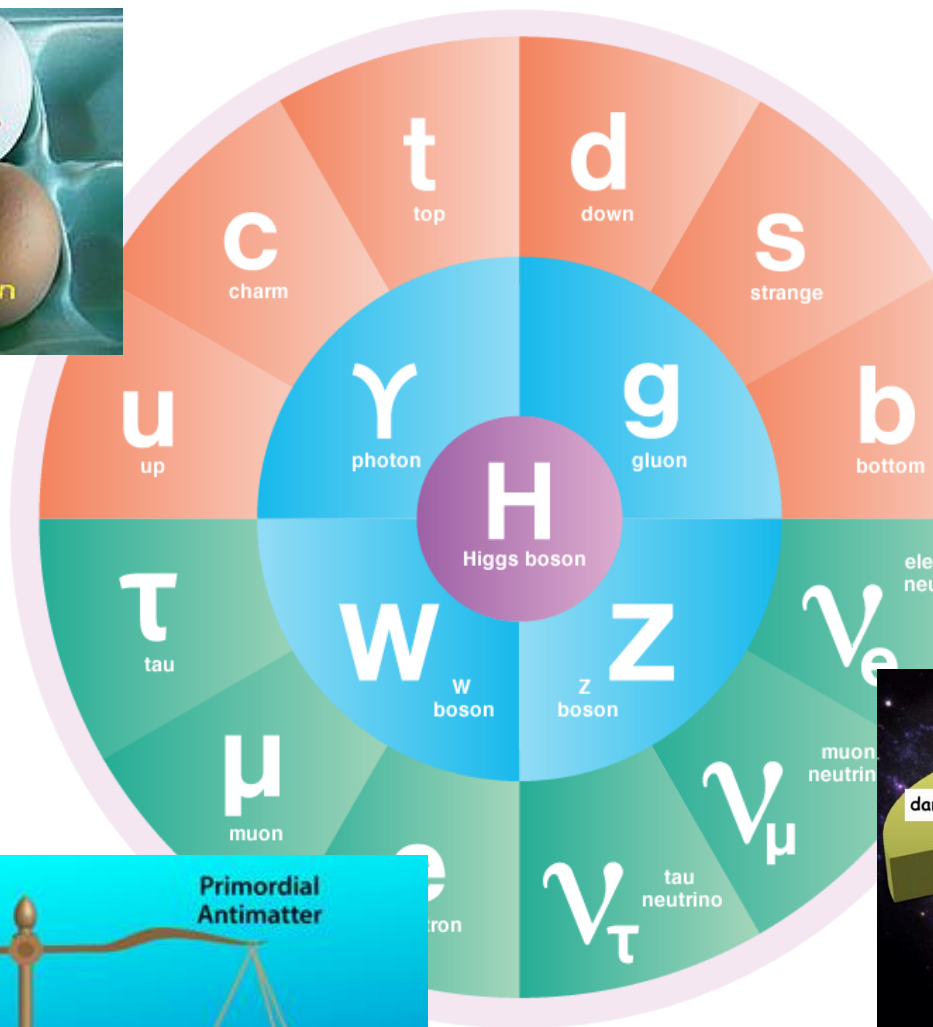
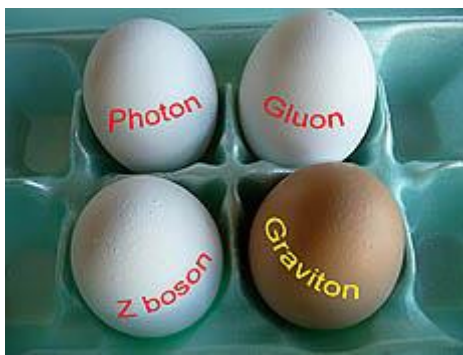
Experimental tests of the SM

Electroweak precision fits of the standard model indicate that it fits experimental data well.



[arXiv:1803.01853](https://arxiv.org/abs/1803.01853), [arXiv:2511.16534](https://arxiv.org/abs/2511.16534)

Lingering Questions



Lingering questions



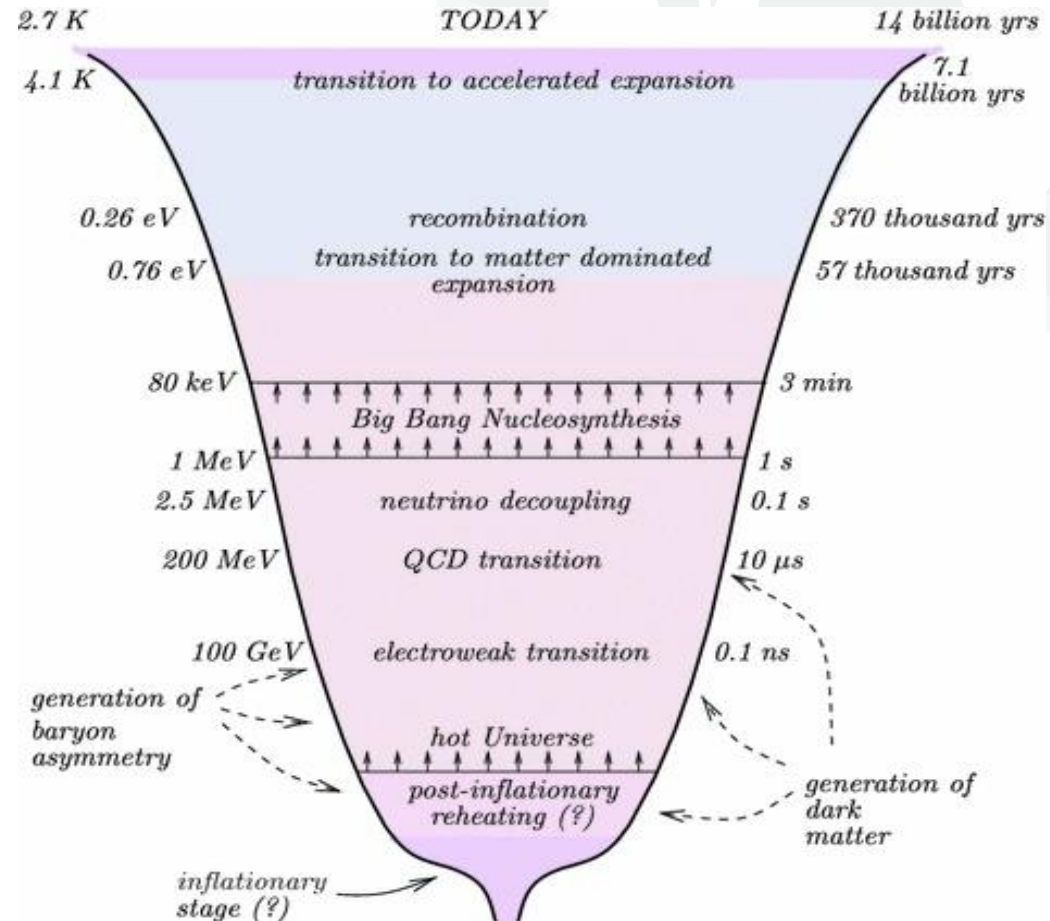
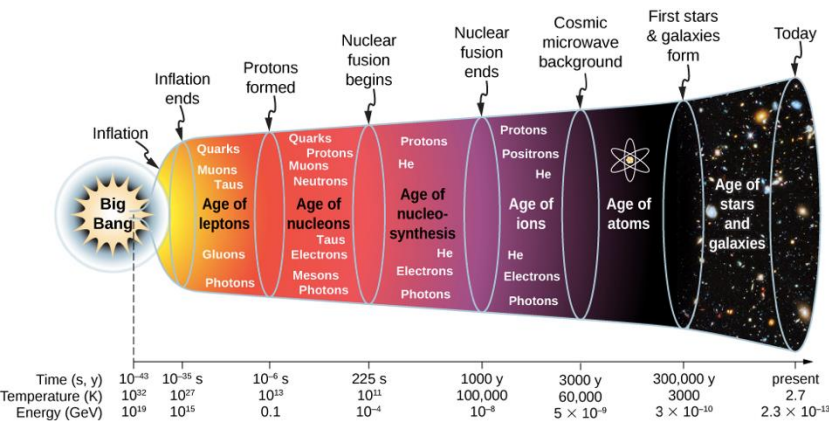
1. Dark Matter
2. Matter- Anti-Matter Asymmetry
3. Neutrino Masses
4. Mass hierarchy
5. Unifying Gravity
6. Hierarchy problem
7. Other smaller Anomalies

Baryon Asymmetry and Thermal history of the universe

Baryon asymmetry:

$$\eta_B = \frac{(n_b - n_{\bar{b}})}{n_\gamma} \simeq 6 \times 10^{-10}$$

- Where did this come from?



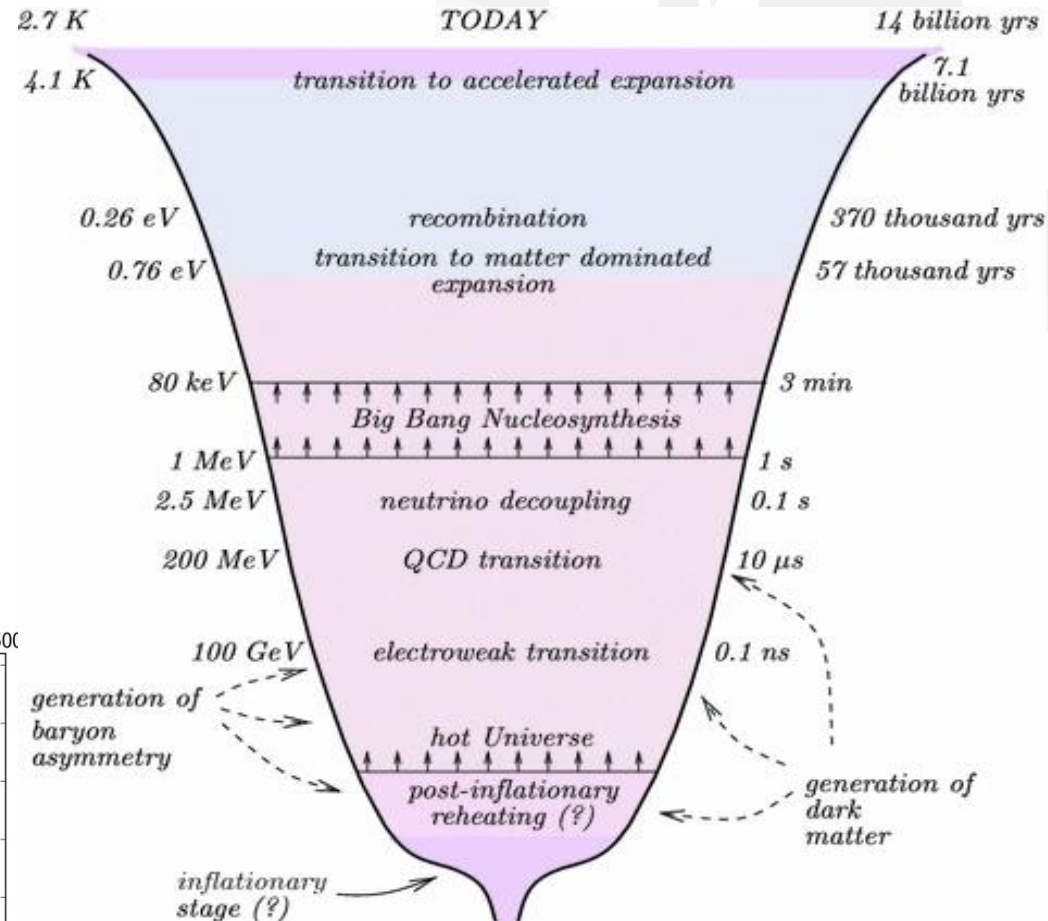
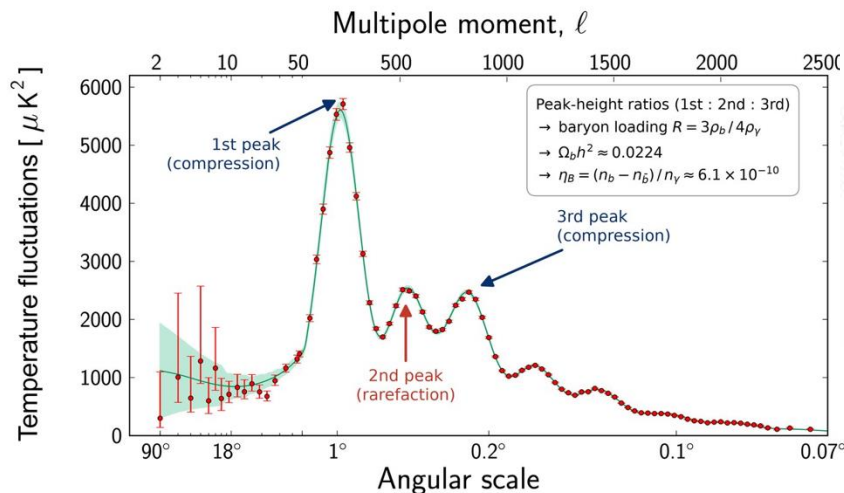
Source: [arXiv:1612.07933](https://arxiv.org/abs/1612.07933)

Baryon Asymmetry and Thermal history of the universe

Baryon asymmetry:

$$\eta_B = \frac{(n_b - n_{\bar{b}})}{n_\gamma} \simeq 6 \times 10^{-10}$$

- Baryon Acoustic oscillations can be seen at various points in the thermal history
- At recombination Baryons and photons decouple and the CMB power spectrum leaves behind an imprint of the baryon to photon density



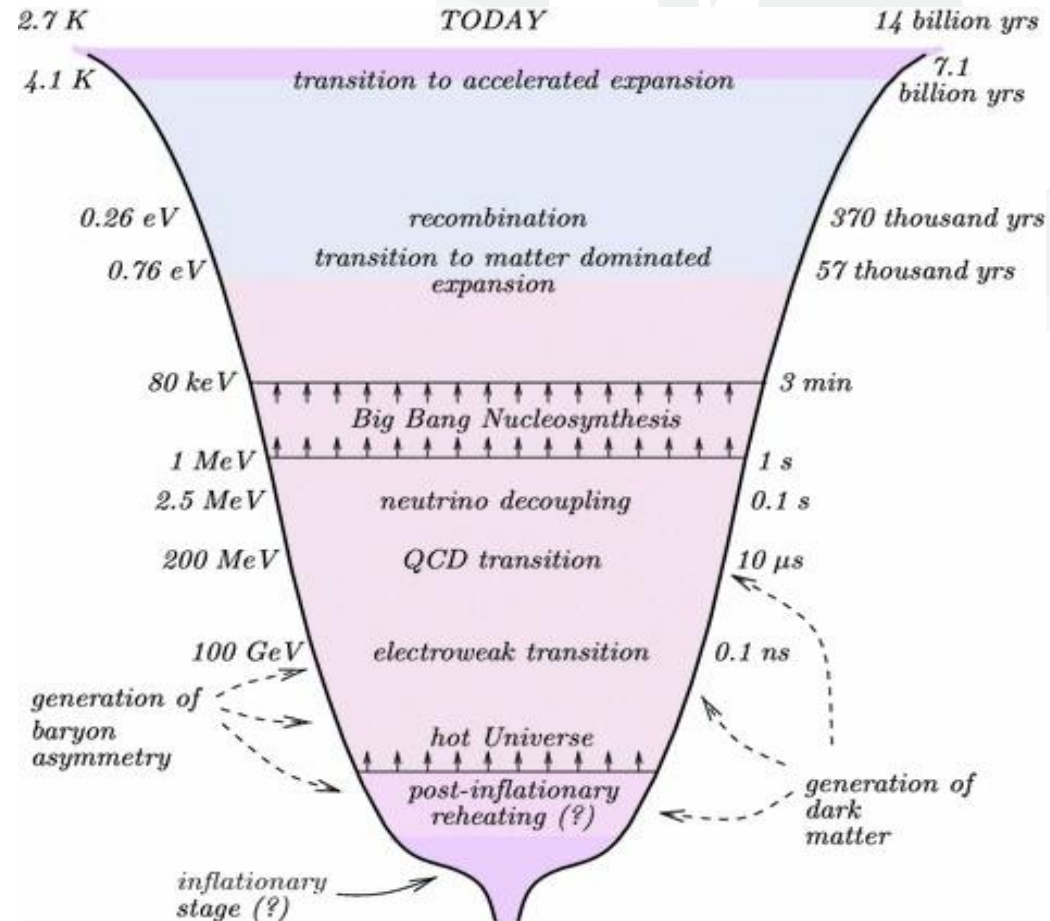
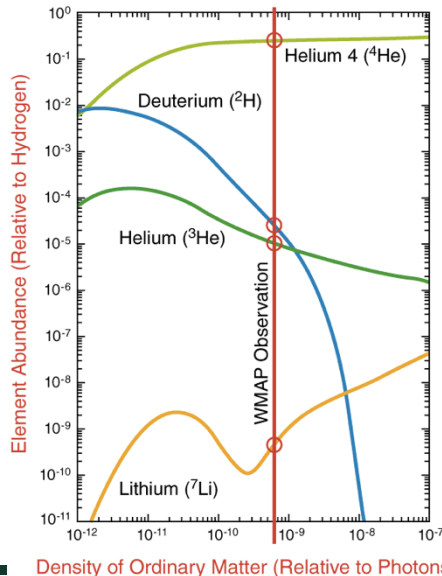
Source: <https://www.esa.int/>

Baryon Asymmetry and Thermal history of the universe

Baryon asymmetry:

$$\eta_B = \frac{(n_b - n_{\bar{b}})}{n_\gamma} \simeq 6 \times 10^{-10}$$

- Baryon Acoustic oscillations can be seen at various points in the thermal history
- The primordial abundance of various elements which were created during big bang nucleosynthesis also tell us the value of η_B - and these agree well.



Source: [arXiv:1612.07933](https://arxiv.org/abs/1612.07933)

Baryogenesis: How we generate an excess of Baryons over anti-Baryons

Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)

Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).

Also S7, pp. 85–88]

Usp. Fiz. Nauk **161**, 61–64 (May 1991)

Sakharov's conditions for Baryogenesis:

1. Baryon number violating processes:

SM (B+L) symmetry is violated by $SU(2)_L$

2. Charge-Parity violation:

SM violates CP symmetry: Complex Yukawa mass matrices

3. Departure from Thermal equilibrium:

The Higgs: Phase transitions of the electroweak vacuum.

Из записки С. Окубо
при доброй температуре
для Вселенной сшита шуба
по ее кривой фигуре

Literal translation: Out of S. Okubo's effect
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

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Sakharov's conditions for Baryogenesis:

1. Baryon number violating processes:

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2. Charge-Parity violation:

SM violates CP symmetry: Complex Yukawa mass matrices

Unfortunately, not enough CP violation ($\eta_B \simeq 10^{-26}$) ([arXiv: hep-ph/9404302](https://arxiv.org/abs/hep-ph/9404302))

3. Departure from Thermal equilibrium:

The Higgs: Phase transitions of the electroweak vacuum.

For $m_H = 125 \text{ GeV}$ the electroweak phase transition is a smooth crossover
([arXiv: 1508.07161](https://arxiv.org/abs/1508.07161))

For a review see Morrissey and Musolf 2012

Мы зорречка С. Окубо
при доброй температуре
для Вселенной шитья шубы
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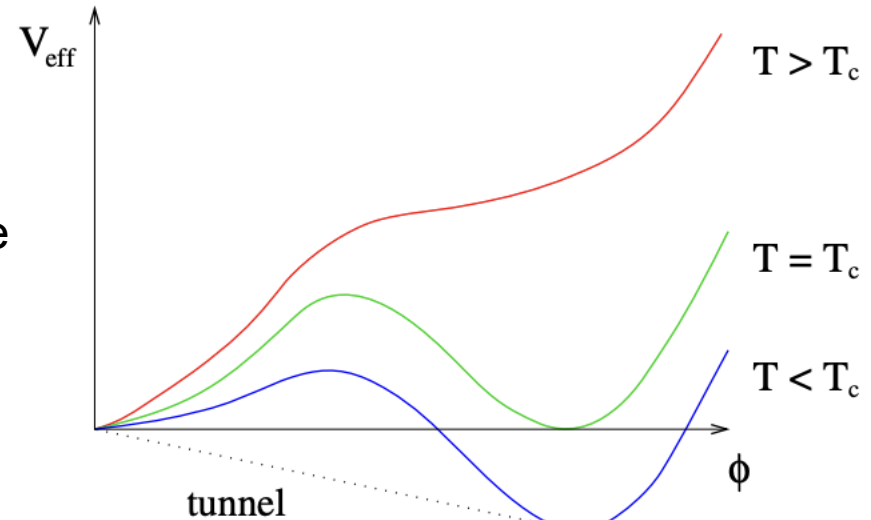
Electroweak Phase Transition

The Higgs potential changes with temperature:

- At high temperatures ($T_c \sim 160 \text{ GeV}$) the SM is in its symmetric phase ($SU(2)_L \times U(1)_Y$)
- Symmetry is broken ($U(1)_{em}$) at low temperatures
($v = 0$) $\rightarrow$ ($v = 246$)

For a 125 GeV Higgs the transition
($v = 0$) $\rightarrow$ ($v = 246$)

is a **smooth cross-over** and does not lead to bubble nucleation which gives rise to the out of thermal equilibrium condition.



Strong first order phase transitions can happen if there are additional scalars that couple to the Higgs.

Aside: 2HDM



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The Two Higgs doublet model

$$\begin{aligned} V_H = & m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - (m_{12}^2 \phi_1^\dagger \phi_2 + \text{h.c.}) \\ & + \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1) (\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2) (\phi_2^\dagger \phi_1) \\ & + \left[\frac{1}{2} \lambda_5 (\phi_1^\dagger \phi_2)^2 + \lambda_6 (\phi_1^\dagger \phi_1) (\phi_1^\dagger \phi_2) + \lambda_7 (\phi_2^\dagger \phi_2) (\phi_1^\dagger \phi_2) + \text{h.c.} \right]. \end{aligned}$$

Add an additional Higgs doublet to the SM and you get the 2HDM.

- Consists of one 2 neutral higgs, 2 charged higgs and one pseudoscalar.

The 2HDM is able to solve both problems.

- E.g. complex mass terms in m_{12} provide additional sources of CP violation
- Further, additional bosons give rise to strong first order transitions (Sakharov's out of equilibrium condition)

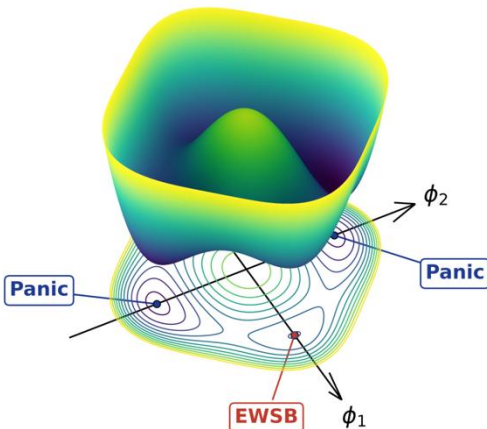
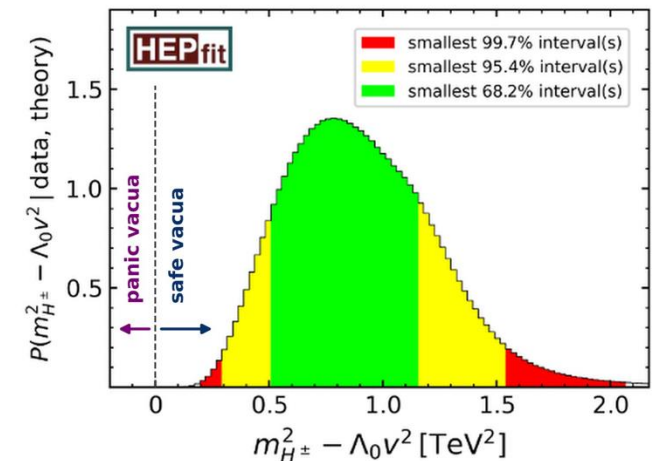
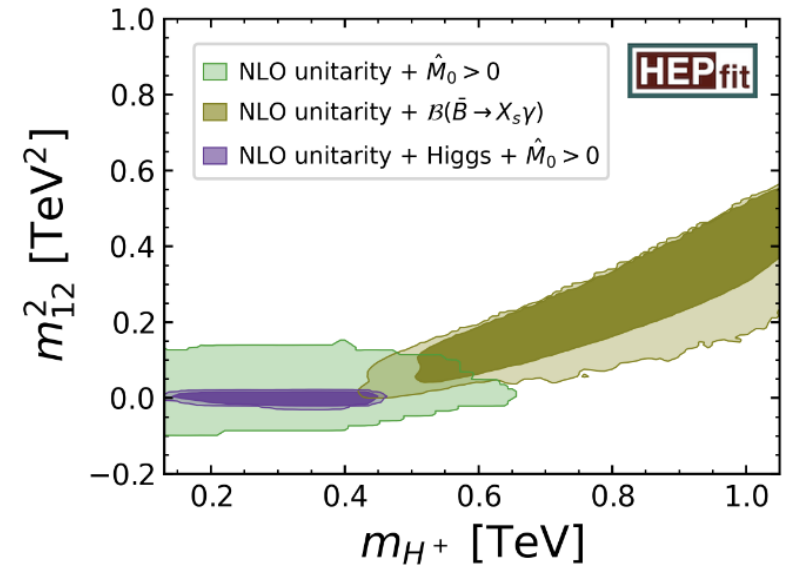
Additional minima of the 2HDM

With additional scalars comes additional minima:

Panic Vacua: Some of these minima can be charge or CP violating, and some can lead to different values of the vev.

We need to be careful using this model and avoid masses and coupling values that would lead additional minima deeper the EWSB minimum with a tunneling rate larger than the age of the universe.

Fortunately, we were able to show through a Bayesian Global fit that current data indicates that most vacua are safe, Panic Vacua ruled out at greater than 5σ



[arXiv:2607.18380](https://arxiv.org/abs/2607.18380), D. Chowdhury, KM, P. Mondal, S. Samanta

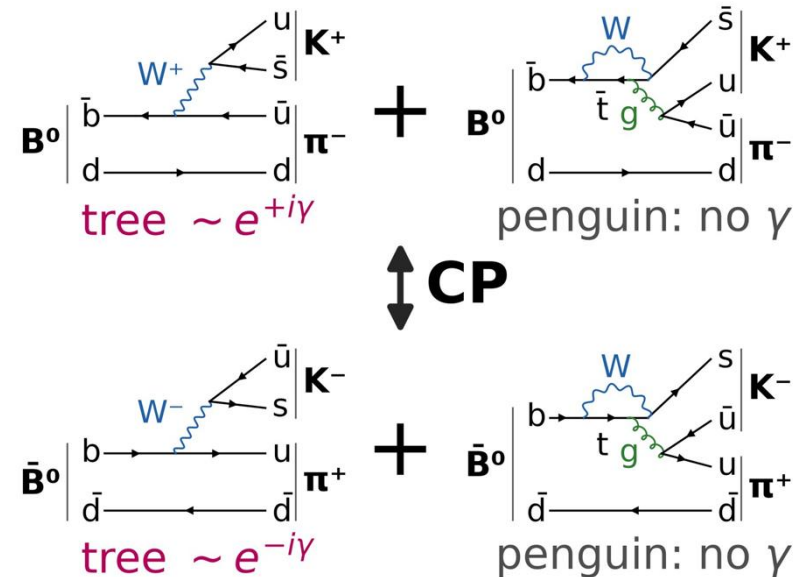
CP violation in Higgs-top interactions



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CP violation: what is it?

- **C**: Charge conjugation operation, transforms particles to anti-particles
- **P**: Spatial inversion $(x, y, z) \rightarrow (-x, -y, -z)$
- If CP is a symmetry of the SM, then we would expect the rates of reactions for particles and anti particles to be the same.



$$\frac{\Gamma(B^0 \rightarrow K^+ \pi^-)}{\Gamma(\bar{B}^0 \rightarrow K^- \pi^+)} \approx 1.17$$

Additional CP violation in the Higgs Sector

- Many possible extensions of the Higgs sector of SM allow for additional for sources of CP violation.
- Rather than studying this for each individual model, we will focus on a phenomenological model, where a CP violating piece is introduced in the top an higgs Yukawa coupling.
- Caveat: This is only approximate and works when additional BSM states are a lot more massive.

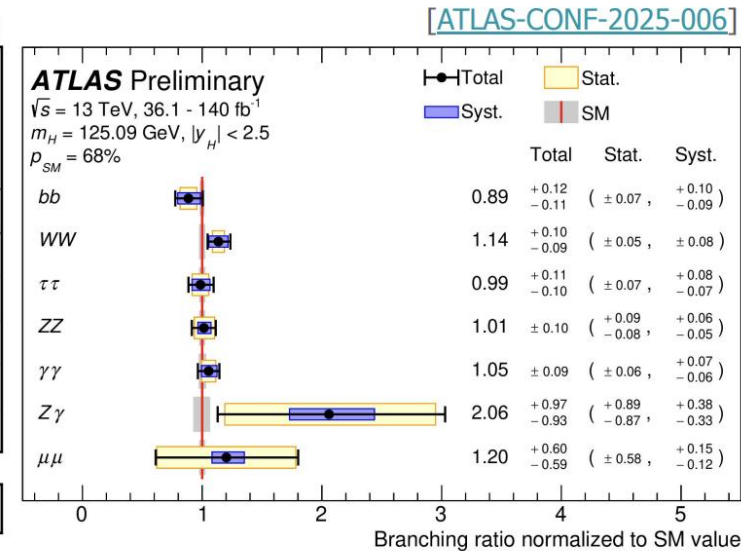
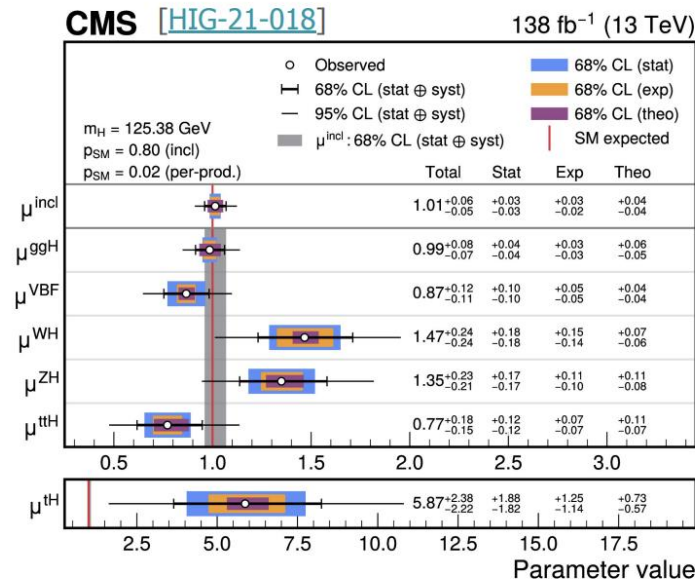
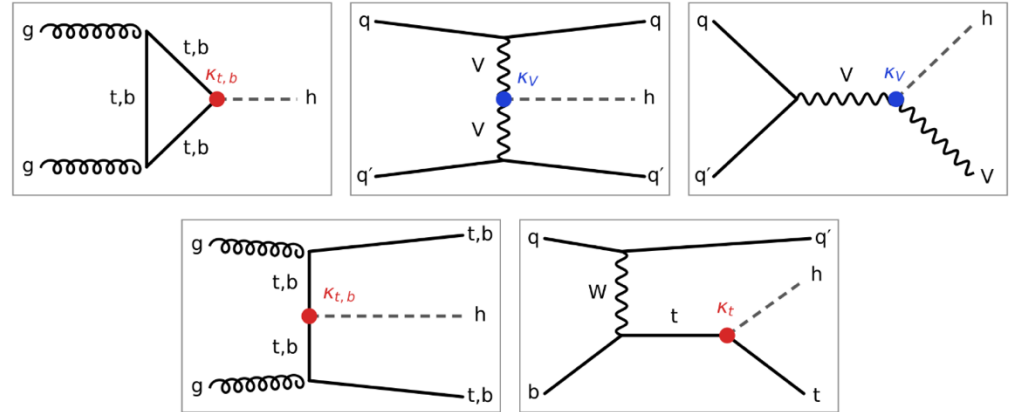
Standard Model $\Rightarrow (a_t = 1, b_t = 0)$

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

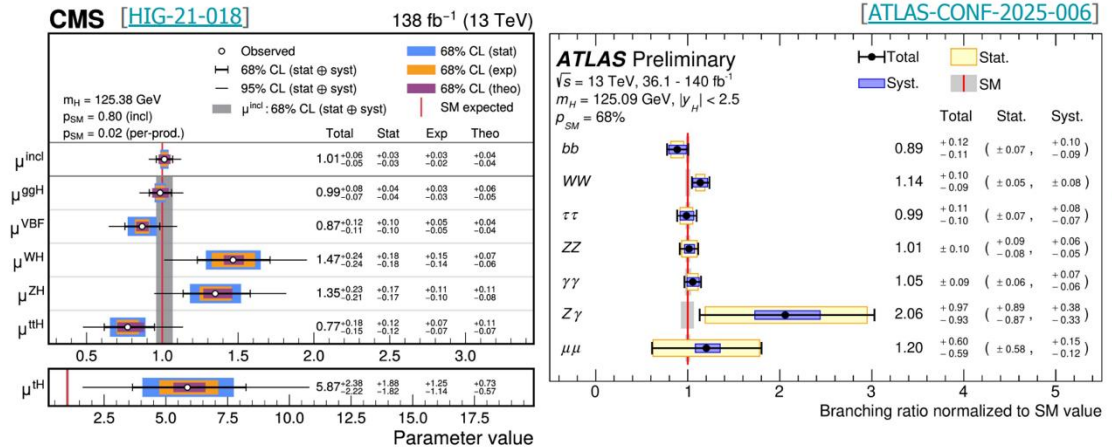
$$\mathcal{L}_{ht\bar{t}} \supset -\frac{m_t}{v} h \bar{t} \kappa_t (\cos \alpha + i \sin \alpha \gamma_5) t$$

Constraints from Higgs rates alone

Higgs production rates (signal strengths) at LHC can constrain CP violation in Higgs top interactions

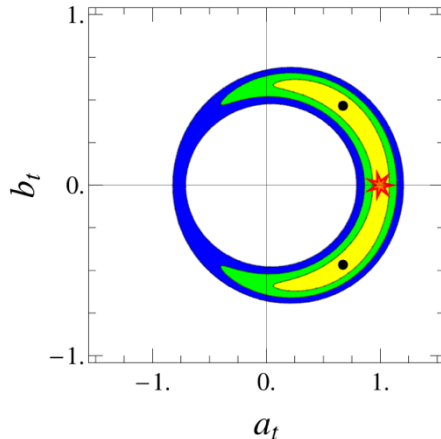


Constraints from Higgs rates alone

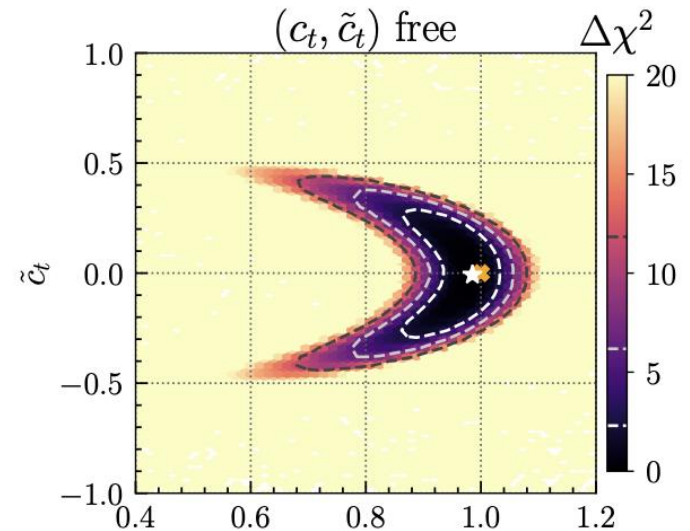


$$\mathcal{L}_{ht\bar{t}} \supset -\frac{m_t}{v} h \bar{t} (a_t + i b_t \gamma_5) t$$

$$\Gamma_{gg}/\Gamma_{gg}^{SM} \simeq (a_t + \kappa_{gg})^2 + 2.29 (b_t + \tilde{\kappa}_{gg})^2$$

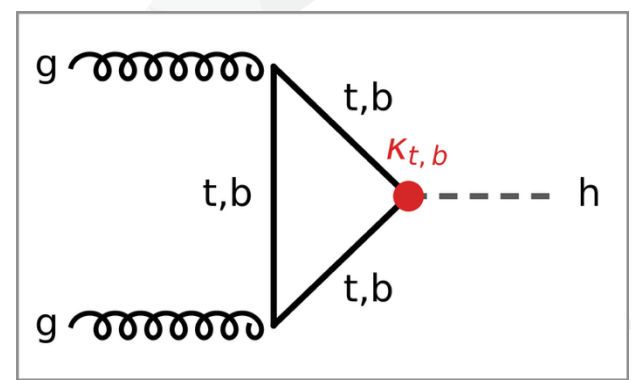


[arXiv:1501.03157](https://arxiv.org/abs/1501.03157) F.
 Boudjema, R. Godbole,
 D. Guadagnoli, KM



[arXiv:2202.11753](https://arxiv.org/abs/2202.11753)

Linear dependence on b_t



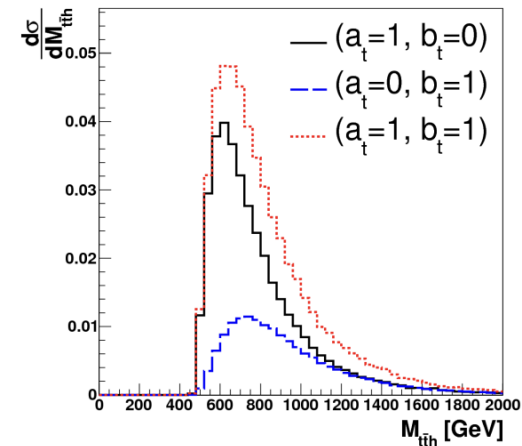
Can these constraints be improved further?

- Higgs rate information is low hanging fruit. Not the most sensitive for small values of b_t

$$|M|^2 = a_t^2 \left| M_{a_t} \right|^2 + b_t^2 \left| M_{b_t} \right|^2 + 2 \operatorname{Re}[a_t b_t M_{a_t} M_{b_t}^\dagger]$$

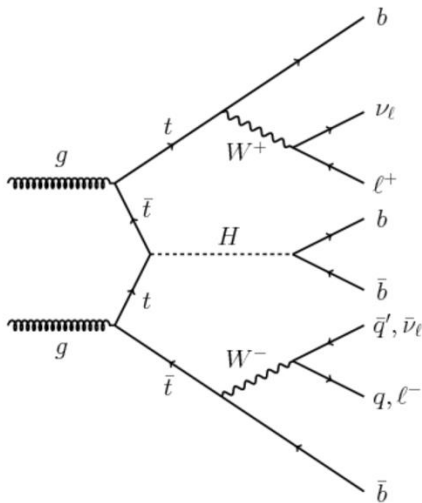
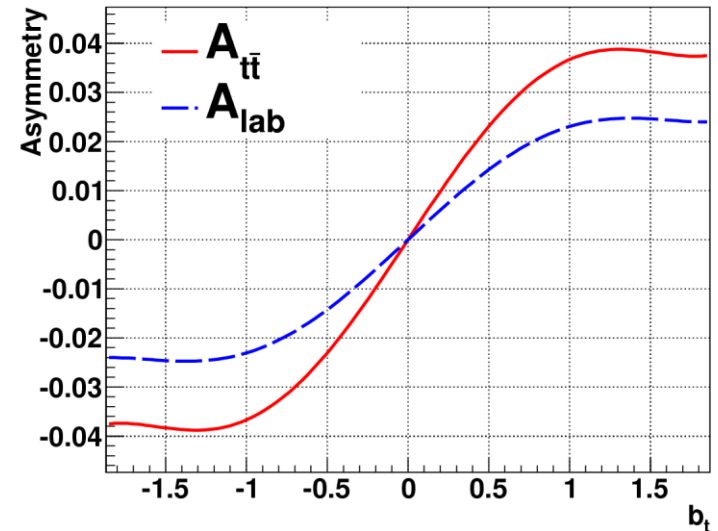
- Terms linearly dependent on b_t will be more sensitive when $a_t \gg b_t$
- Since the linear term is odd under CP, it will not contribute to the rate.
- Here we will need more than just the rate information.
- We also need CP-odd observables sensitive to linear parts of the amplitude.

Direct constraints using ttH



CP-odd asymmetry

Asymmetry of lab variables is smaller but easier to construct in addition to having smaller systematic uncertainties.

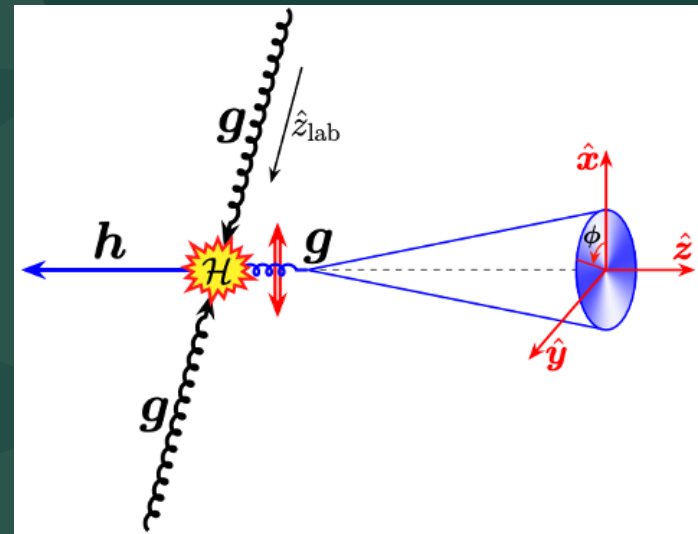


$$A_{\text{lab}} = \frac{\sigma(\beta \times \Delta\theta^{\ell h}(\ell^-, \ell^+) > 0) - \sigma(\beta \times \Delta\theta^{\ell h}(\ell^-, \ell^+) < 0)}{\sigma(\beta \times \Delta\theta^{\ell h}(\ell^-, \ell^+) > 0) + \sigma(\beta \times \Delta\theta^{\ell h}(\ell^-, \ell^+) < 0)}.$$

[arXiv:1501.03157](https://arxiv.org/abs/1501.03157) F. Boudjema, R. Godbole, D. Guadagnoli, KM

Probes of CP violation in Higgs +1 jet

Z. Yu, KM, C.-P. Yuan



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Linear gluon polarization

Z. Yu, KM, C.-P. Yuan, arXiv:[2211.00845](https://arxiv.org/abs/2211.00845)

□ Density matrix

$$\rho_{\lambda\lambda'} = \frac{1}{2}(1 + \boldsymbol{\xi} \cdot \boldsymbol{\sigma})_{\lambda\lambda'} = \frac{1}{2} \begin{pmatrix} 1 + \xi_3 & \xi_1 - i\xi_2 \\ \xi_1 + i\xi_2 & 1 - \xi_3 \end{pmatrix}$$

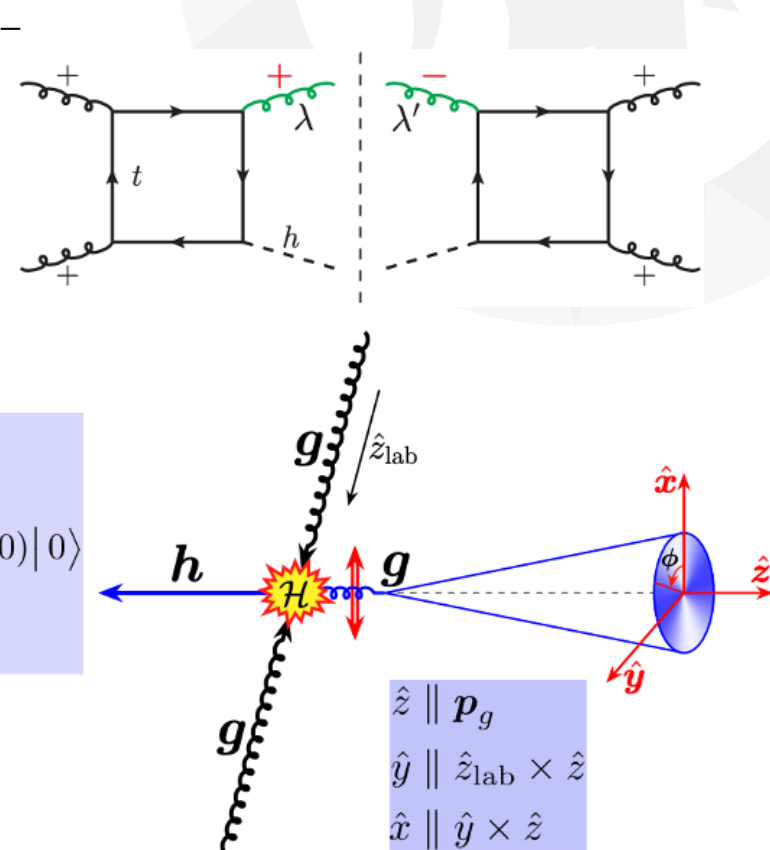
ρ_{+-} (indicated by a green arrow pointing to the off-diagonal element)

□ Polarized gluon jet function

$$\frac{d\sigma_w}{dy_g dp_T^2 dm_J^2 d\phi} = \frac{\mathcal{L}(\tau)}{16\pi\tau s^2} \frac{\sqrt{\hat{s}}}{E_h} |\overline{\mathcal{M}}|^2 \frac{dJ(\boldsymbol{\xi}, m_J^2, \phi)}{d\phi}$$

$$\begin{aligned} \frac{dJ}{d\phi} &= \frac{1}{2\pi N_{c,g} (k^+)^2} \sum_X \int d^4x e^{ik \cdot x} [\rho_{\lambda\lambda'}(\boldsymbol{\xi}) O(\phi, X)] \\ &\quad \times \varepsilon_{\lambda'\nu}^* \langle 0 | W_{ac}^n(\infty, x) G_c^{+\nu}(x) | X \rangle \varepsilon_{\lambda\mu} \langle X | W_{ab}^n(\infty, 0) G_b^{+\mu}(0) | 0 \rangle \\ &= \frac{\alpha_s T_F}{6\pi^2 m_J^2} \left[1 + \frac{1}{2} (\xi_1 \cos 2\phi + \xi_2 \sin 2\phi) \right] \quad (\text{quark tagged}) \end{aligned}$$

$$O(\phi, X) = \frac{1}{\sum_{i \in X} p_{i,T}} \sum_{i \in X} p_{i,T} \delta(\phi - \phi_i)$$



Linear gluon polarization: CP property

Z. Yu, KM, C.-P. Yuan, arXiv:[2211.00845](https://arxiv.org/abs/2211.00845)

□ $\xi_{1,2}$ = differences of linear polarizations along orthogonal directions

$$\xi_1 = \langle \pi/2 | \rho | \pi/2 \rangle - \langle 0 | \rho | 0 \rangle = \rho_{yy} - \rho_{xx}$$

$$\xi_2 = \langle 3\pi/4 | \rho | 3\pi/4 \rangle - \langle \pi/4 | \rho | \pi/4 \rangle = \rho_{\frac{3\pi}{4}, \frac{3\pi}{4}} - \rho_{\frac{\pi}{4}, \frac{\pi}{4}}$$

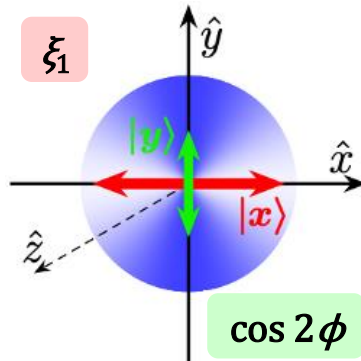
- **C**: trivial on gluon state
- **P**: reflection about the scattering plane ($\hat{x}\hat{z}$)



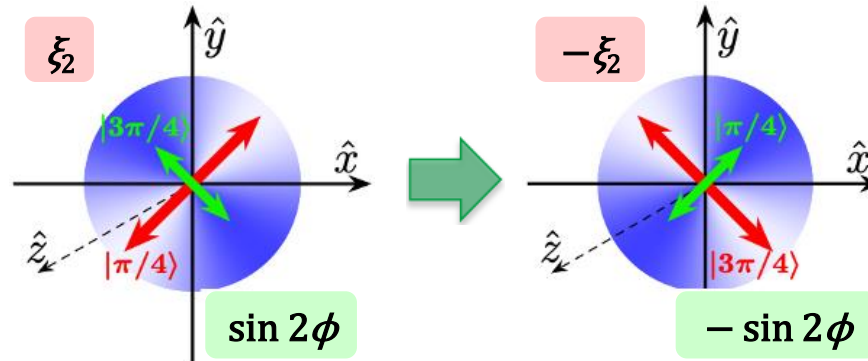
$$\begin{aligned} \hat{P}|x\rangle &= |x\rangle \\ \hat{P}|y\rangle &= |y\rangle \end{aligned}$$

$$\begin{aligned} \hat{P}|\pi/4\rangle &= |3\pi/4\rangle \\ \hat{P}|3\pi/4\rangle &= |\pi/4\rangle \end{aligned}$$

$\xi_1 \rightarrow \xi_1$: CP even



$\xi_2 \rightarrow -\xi_2$: CP odd



$\sin 2\phi$

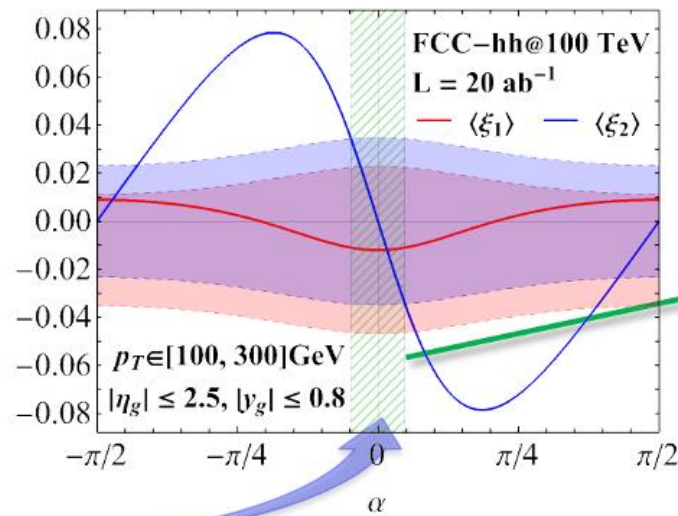
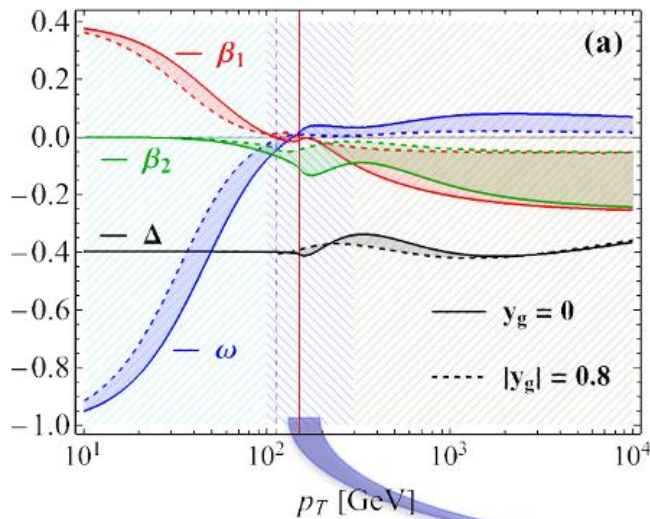


$-\sin 2\phi$

Constraining the CP phase with Jet substructure

$$\xi_1 = \frac{\omega + \beta_1 \cos 2\alpha}{1 + \Delta \cos 2\alpha}, \quad \xi_2 = \frac{\beta_2 \sin 2\alpha}{1 + \Delta \cos 2\alpha}$$

$$\langle \xi_i(\alpha) \rangle = \frac{1}{\sigma(\alpha)} \int dy_g dp_T [\xi_i(p_T, y_g, \alpha)] \frac{d\sigma(\alpha)}{dy_g dp_T}$$

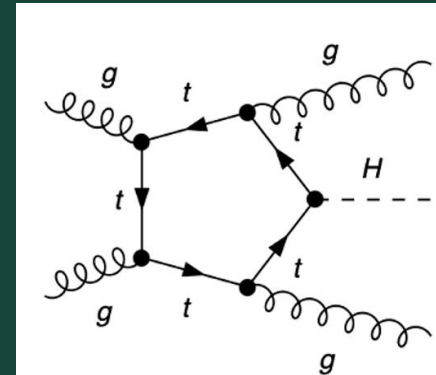


- $h \rightarrow \gamma\gamma$ channel
- $g \rightarrow b\bar{b}, c\bar{c}$

$$|\alpha| \leq 8.6^\circ$$

CP violation in Hjj

WIP: J. Huston, P. Kafle, KM,
N. Parekh, M. Yáñez



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Higgs + 2 jets

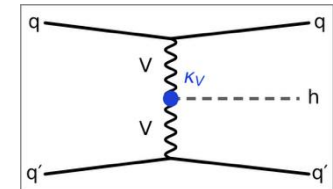
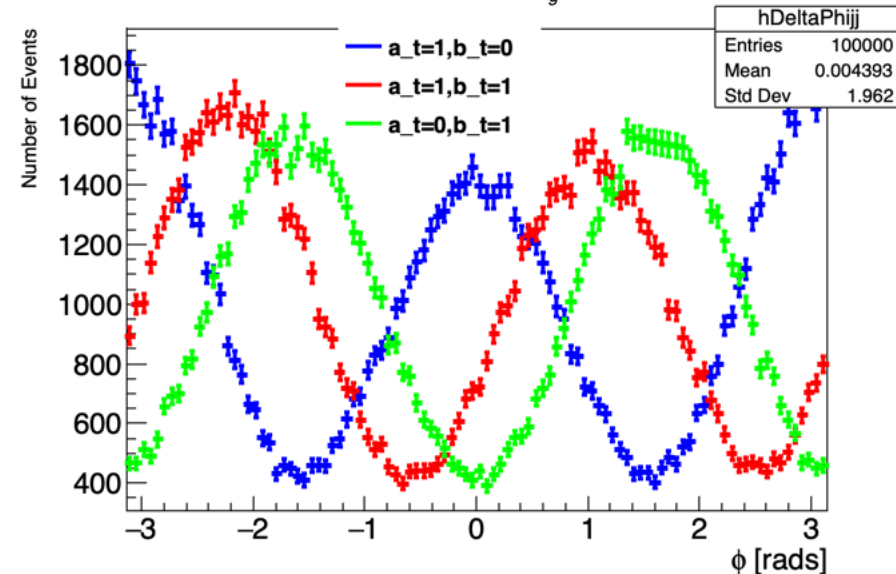
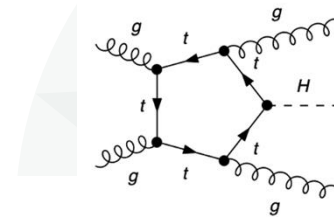
It is well known that Higgs + 2 jet production is sensitive to CP violating top-Higgs interactions

Specifically, the azimuthal angle separation between two jets

$$\frac{d\sigma}{d\phi_{jj}} \propto a_t b_t \sin(\Delta\phi_{jj})$$

The same is true about VBF and CP violating hVV couplings.

ATLAS used the optimal observable to place constraints on hVV couplings using the optimal observable method.



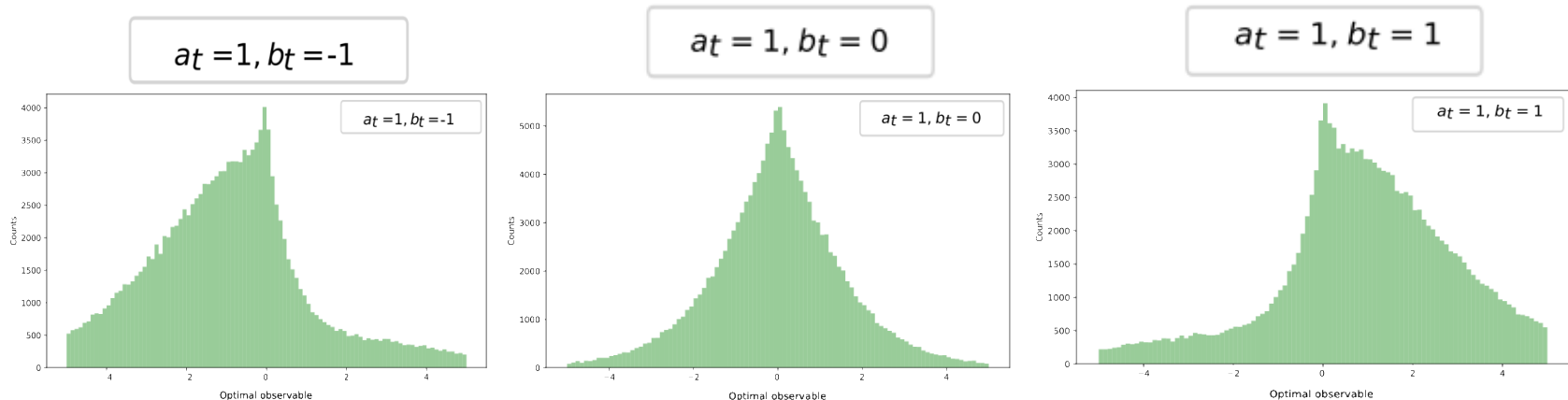
Optimal Observable

$$|M|^2 = a_t^2 |M_{a_t}|^2 + b_t^2 |M_{b_t}|^2 + 2 \operatorname{Re}[a_t b_t M_{a_t} M_{b_t}^\dagger]$$

$$OO_1 = \frac{2 \operatorname{Re}[M_{a_t} M_{b_t}^\dagger]}{|M_{a_t}|^2}$$

$$OO_2 = \frac{|M_{b_t}|^2}{|M_{a_t}|^2}$$

By definition these are the most constraining observables

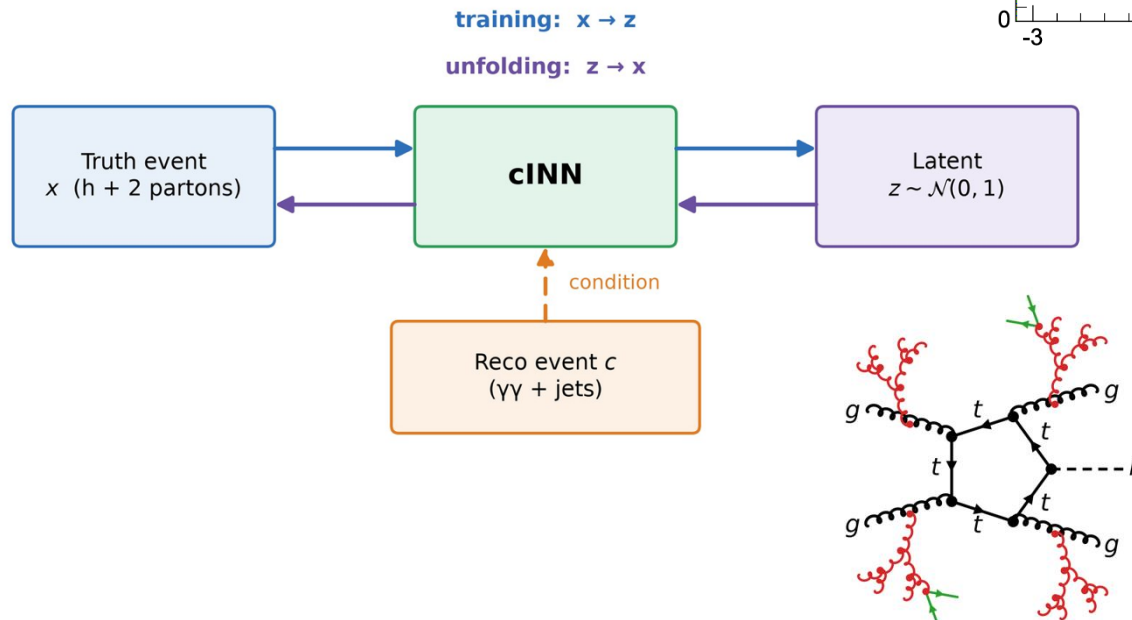
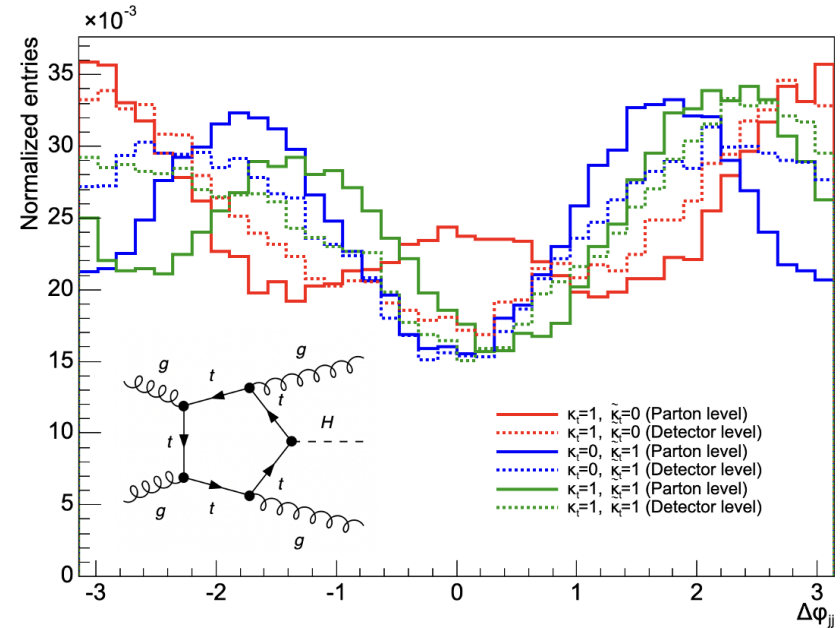


Unfolding

Detector level effects and additional jet radiation wash out some of these differences.

Unfolding these effects will help us recover sensitivity.

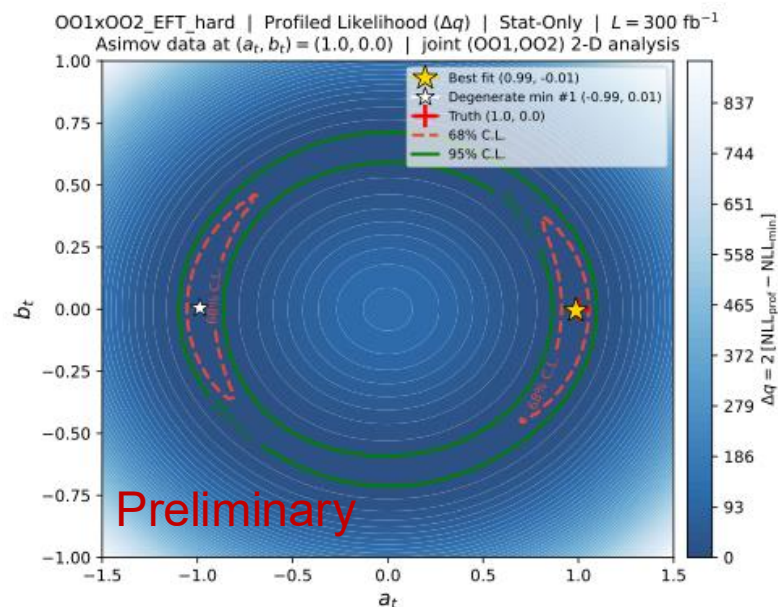
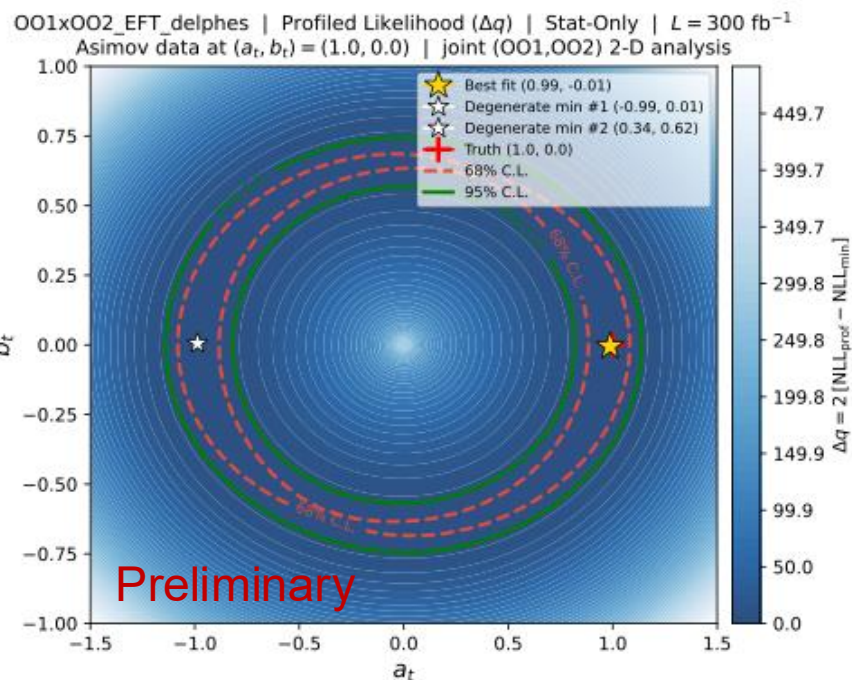
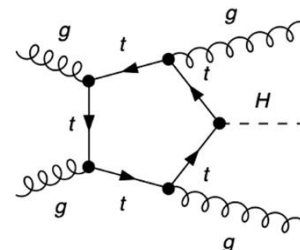
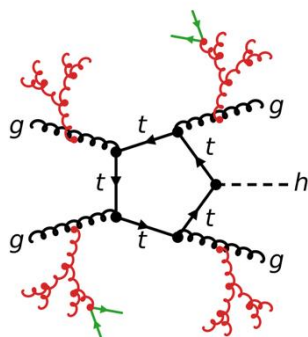
We have used a Conditional Invertible Neural Network (cINN) for unfolding with some promising results.



UNFOLD

Additional radiation reduces sensitivity

WIP: J. Huston, P. Kafle, KM, N. Parekh, M. Yáñez

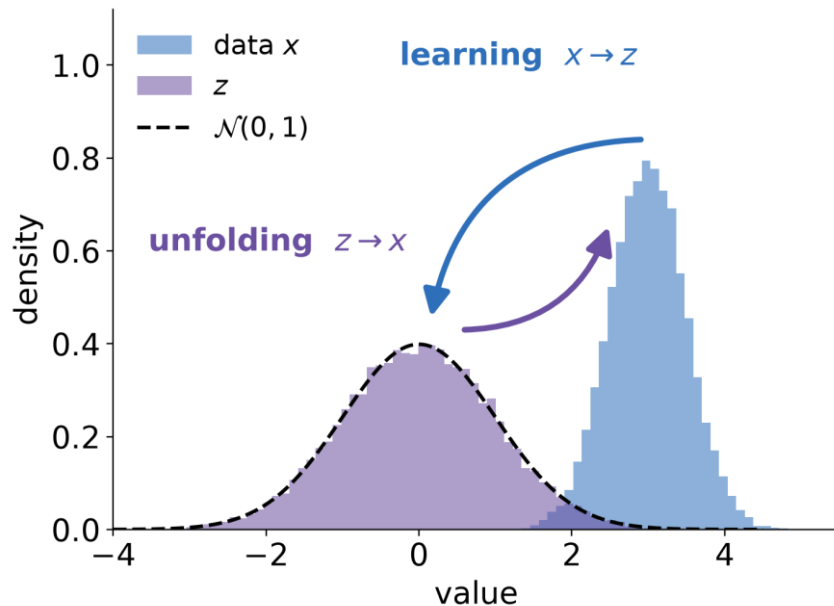


Single layer flow: learning and conditioning with a toy model

$$p(z | c) = \mathcal{N}(z; 0, 1) = (2\pi)^{-1/2} e^{-z^2/2}$$

$$p(x | c) = p(z | c) \left| \frac{\partial z}{\partial x} \right| = (2\pi)^{-1/2} e^{s(c)} e^{-\frac{1}{2}(e^{s(c)}x + t(c))^2} = \mathcal{N}(x; \mu(c), \sigma(c))$$

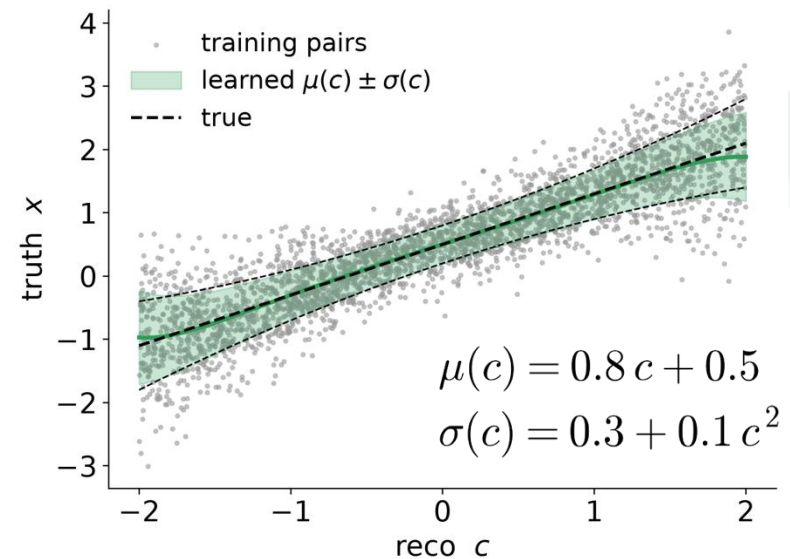
No condition



$$z = e^s x + t \quad \mathcal{L} = \left\langle \frac{1}{2} z^2 - s \right\rangle$$

$$e^s = \frac{1}{\sigma}, \quad t = -\frac{\mu}{\sigma}$$

Conditioned on detector level events (reco c)

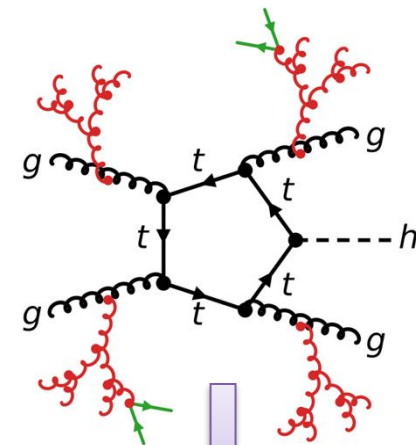
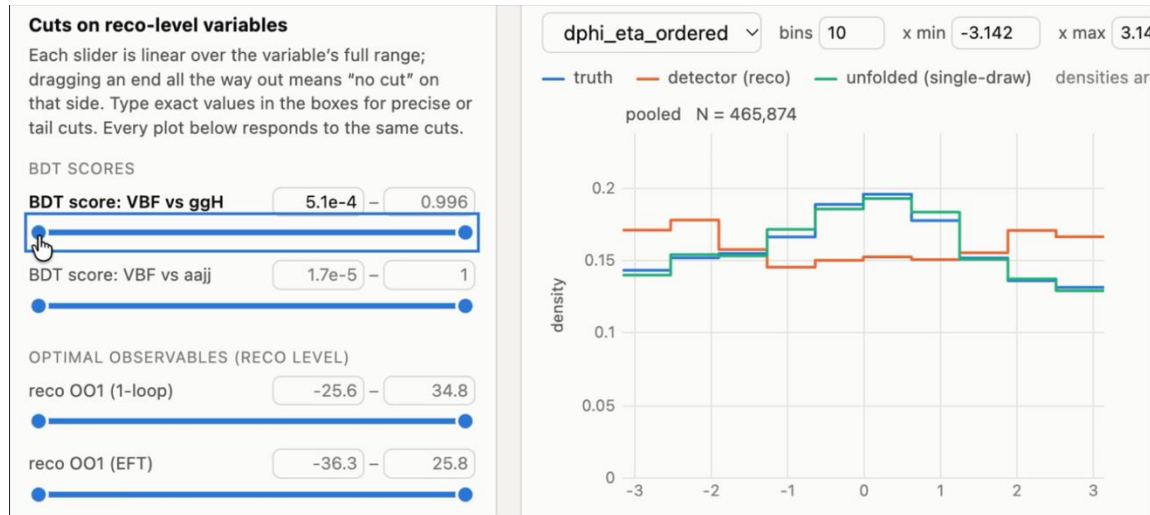


$$z = e^{s(c)} x + t(c) \quad x = \mu(c) + \sigma(c) z$$

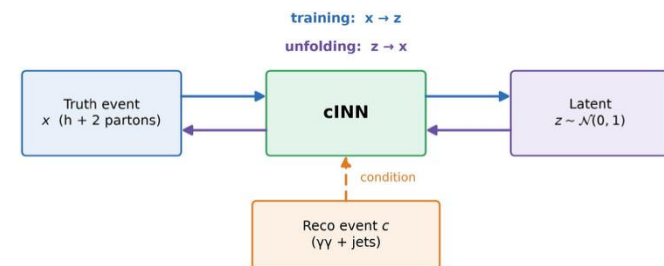
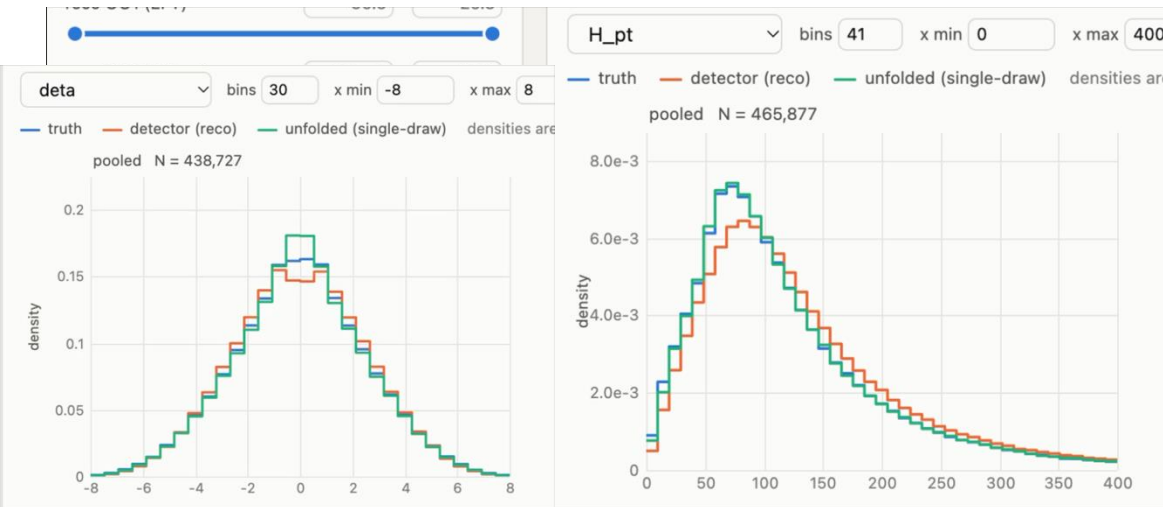
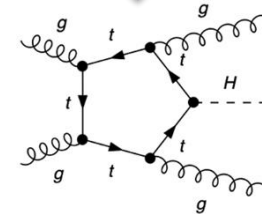
$$e^{s(c)} = \frac{1}{\sigma(c)}, \quad t(c) = -\frac{\mu(c)}{\sigma(c)}$$

Unfolding at work

<https://unfolding-hjj.web.cern.ch/>



unfold

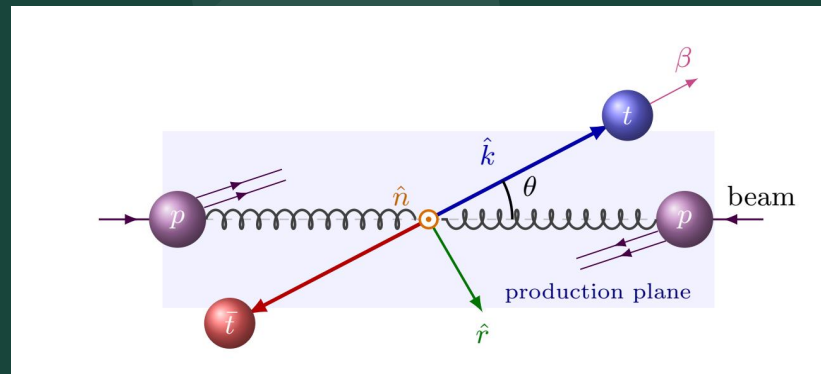


WIP: J. Huston, P. Kafle, KM, N. Parekh, M.

Yáñez

Quantum Tomography of Top Quarks

E. Erdogan, KM, K. Xie, M. Yáñez

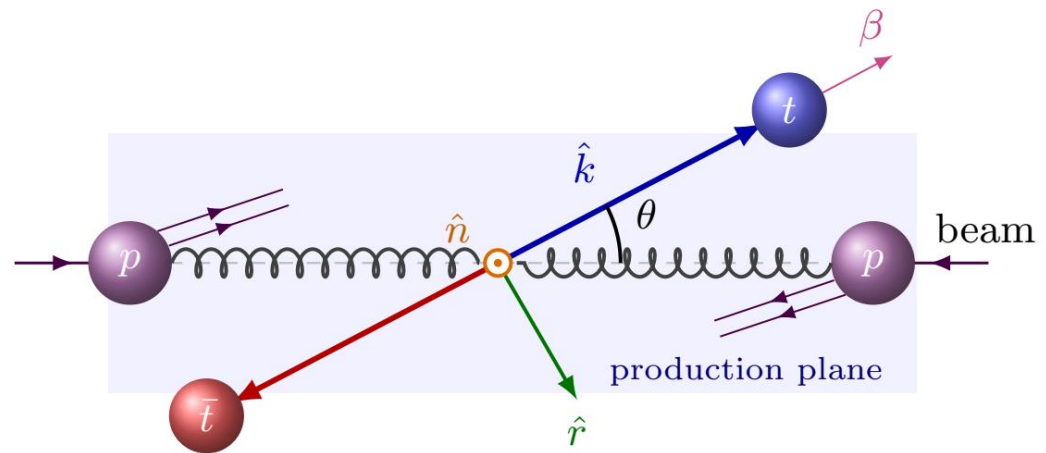


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$t\bar{t}$ & CP violation

Top quark pairs are produced in abundance at LHC (billions of events)

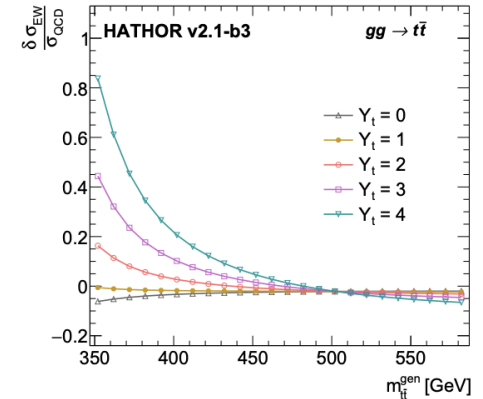
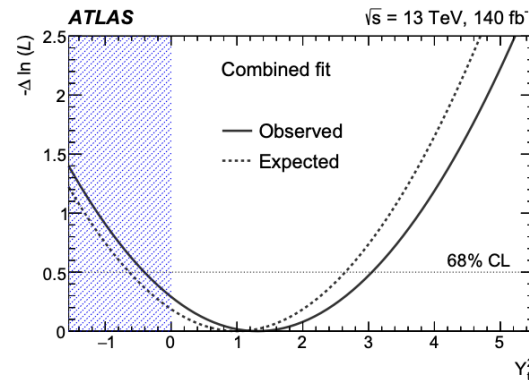
Can we exploit the large cross-section and probe CP-violation?



Constraints from differential cross-section

[arXiv:2509.16039](https://arxiv.org/abs/2509.16039) (ATLAS), [arXiv:2009.07123](https://arxiv.org/abs/2009.07123) (CMS)

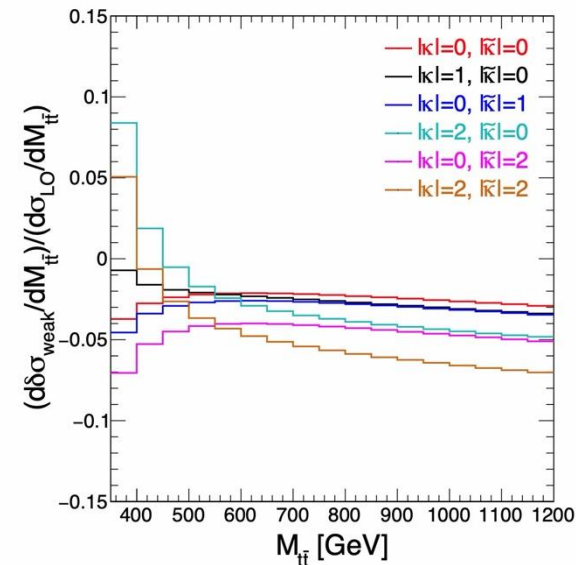
ATLAS and CMS constrain the value of $(a_t \lesssim 2.1)$ alone using the $m_{t\bar{t}}$ distribution.



What about b_t ?

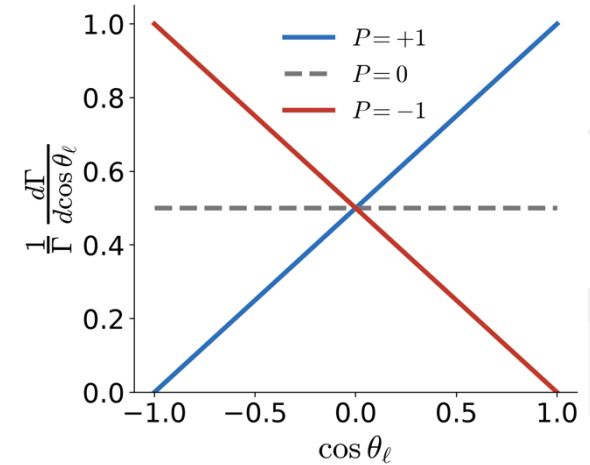
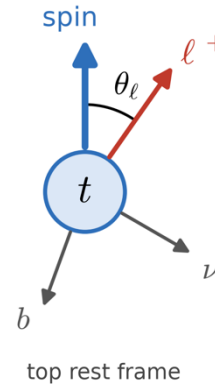
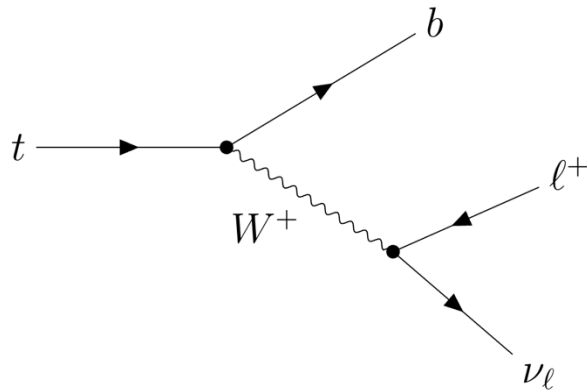


What about spin information?



[arXiv:2104.04277](https://arxiv.org/abs/2104.04277)

Top quark spin can be measured at LHC



One top: polarization B

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_i} = \frac{1}{2} (1 + \alpha_i |\mathbf{B}| \cos \theta_i), \quad \alpha_{\ell^+} = \alpha_{\bar{d}} \simeq 1, \quad \alpha_b \simeq -0.39$$

Top pair: polarizations and spin correlations

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2} \left(1 + \mathbf{B} \cdot \hat{\ell}_+ - \bar{\mathbf{B}} \cdot \hat{\ell}_- - \hat{\ell}_+ \cdot \mathbf{C} \cdot \hat{\ell}_- \right)$$

$$\tau_t = \frac{1}{\Gamma_t} \approx 5 \times 10^{-25} \text{ s} \ll \tau_{\text{had}} \sim \frac{1}{\Lambda_{\text{QCD}}} \approx 3 \times 10^{-24} \text{ s} \ll \tau_{\text{spin}} \sim \frac{m_t}{\Lambda_{\text{QCD}}^2} \approx 3 \times 10^{-21} \text{ s}$$

$t\bar{t}$ density matrix – 2 qubit system

One qubit $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \longrightarrow \rho = |\psi\rangle\langle\psi| = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix} = \frac{1}{2}(\mathbb{I} + \mathbf{B} \cdot \boldsymbol{\sigma})$

$$\mathbf{B} = (2 \operatorname{Re} \alpha^* \beta, 2 \operatorname{Im} \alpha^* \beta, |\alpha|^2 - |\beta|^2), \quad |\mathbf{B}| \leq 1$$

$$|\mathbf{B}| = 1 \text{ pure;} \quad \text{ensemble } \rho = \sum_k p_k |\psi_k\rangle\langle\psi_k| : |\mathbf{B}| < 1$$

Two qubits: t and $\bar{t}$

$$\rho_{t\bar{t}} = \frac{1}{4} \left(\mathbb{I} \otimes \mathbb{I} + \underbrace{B_i \sigma_i \otimes \mathbb{I}}_{\mathbf{B} \ (t)} + \underbrace{\bar{B}_j \mathbb{I} \otimes \sigma_j}_{\bar{\mathbf{B}} \ (\bar{t})} + \underbrace{C_{ij} \sigma_i \otimes \sigma_j}_{C \text{ (correlations)}} \right) = 15$$

LHC: $B \approx 0$ (QCD conserves parity), so the information sits mostly in C

antitop

	1	σ_n	σ_r	σ_k
1	1	$\bar{B}_n$	$\bar{B}_r$	$\bar{B}_k$
σ_n	B_n	C_{nn}	C_{nr}	C_{nk}
σ_r	B_r	C_{rn}	C_{rr}	C_{rk}
σ_k	B_k	C_{kn}	C_{kr}	C_{kk}

top

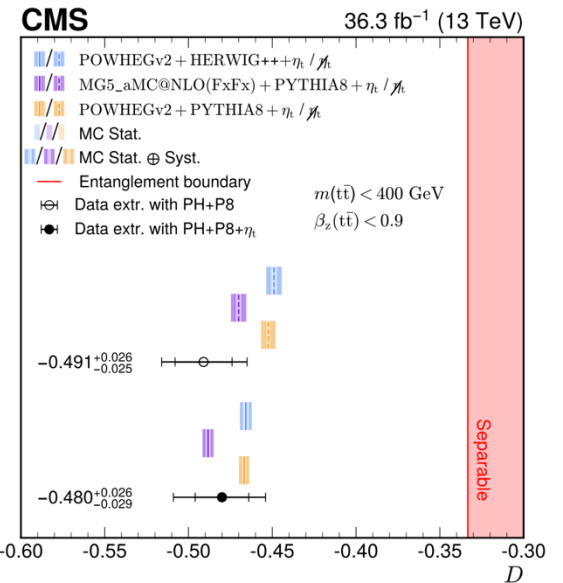
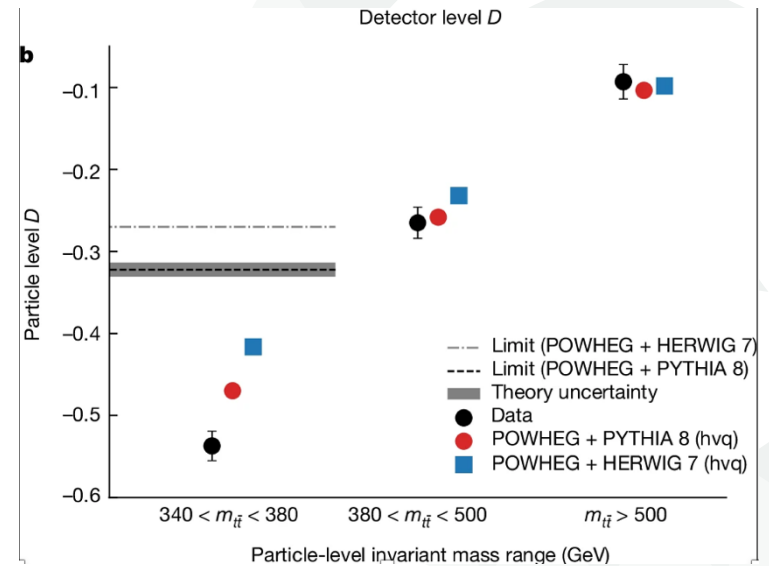
$3 (B) + 3 (\bar{B}) + 9 (C) = 15$

Entangled top quarks @ LHC

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D \cos\varphi), \quad \cos\varphi = \hat{\ell}_+ \cdot \hat{\ell}_-$$

$$D = \frac{\text{tr } C}{3}, \quad \text{separable} \Rightarrow D \geq -\frac{1}{3}$$

$$\text{product state: } C_{ij} = v_i \bar{v}_j \Rightarrow \text{tr } C = \mathbf{v} \cdot \bar{\mathbf{v}} \geq -1, \quad |\mathbf{v}|, |\bar{\mathbf{v}}| \leq 1$$



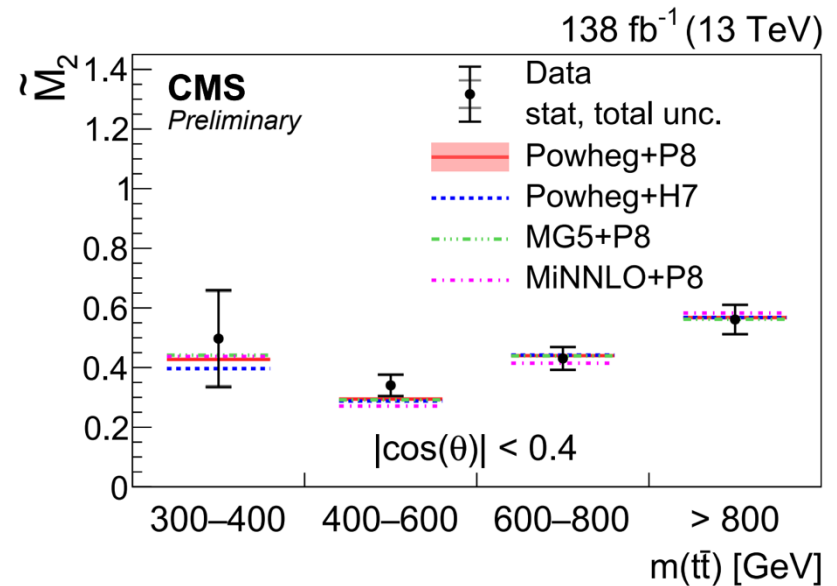
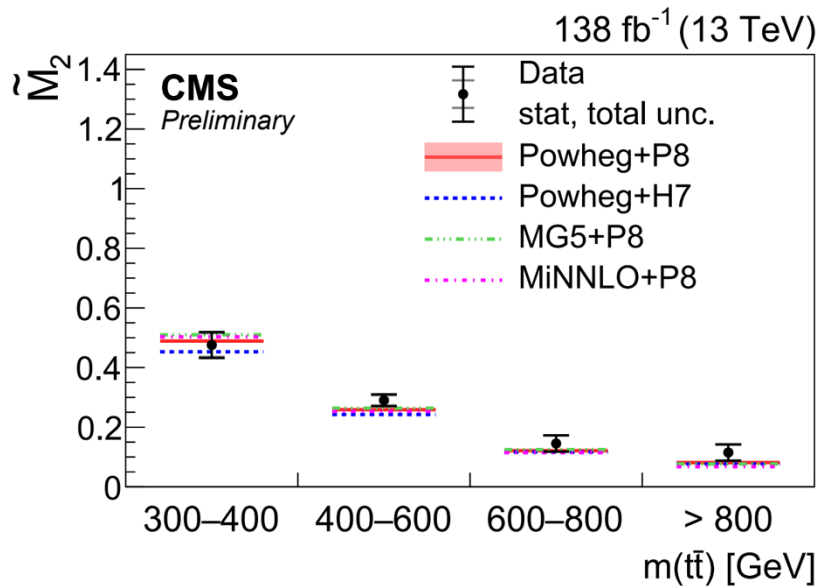
[arXiv:2311.07288](https://arxiv.org/abs/2311.07288) [arXiv:2406.03976](https://arxiv.org/abs/2406.03976)
[arXiv:2409.11067](https://arxiv.org/abs/2409.11067)

Magic: measured at CMS

- Stabilizer states: can be classically simulated (Gottesman–Knill Theorem)
- Magic: distance from the stabilizer states
- Singlet: maximally entangled, zero magic

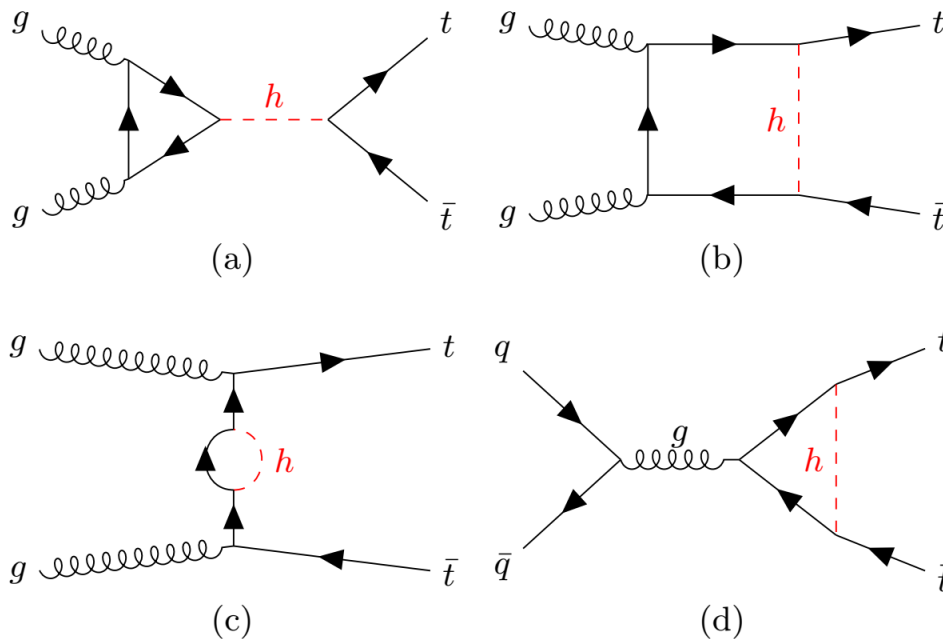
$$\tilde{M}_2 = 0 \text{ (stabilizer state)}, \quad \tilde{M}_2^{\max} = \log_2 \frac{16}{7} \approx 1.19$$

$$\tilde{M}_2 = -\log_2 \frac{1 + \sum_i B_i^4 + \sum_j \bar{B}_j^4 + \sum_{ij} C_{ij}^4}{1 + \sum_i B_i^2 + \sum_j \bar{B}_j^2 + \sum_{ij} C_{ij}^2}$$



[CMS-PAS-TOP-25-001](#) [arXiv:2510.13743](#) [arXiv:2406.07321](#)

Calculating CP violating quantum corrections to top pair production



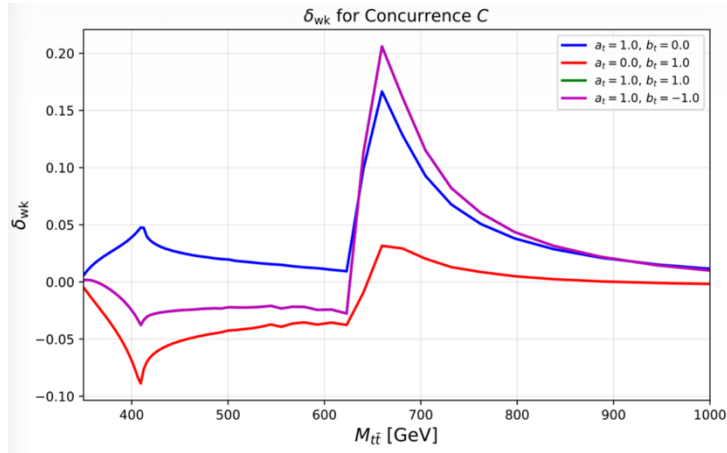
$$\Delta R / R \sim y_t^2 / 16\pi^2 \approx 0.6\%$$

- Complete renormalized one-loop correction
- Full production density matrix
- gg and $q\bar{q}$ initial states

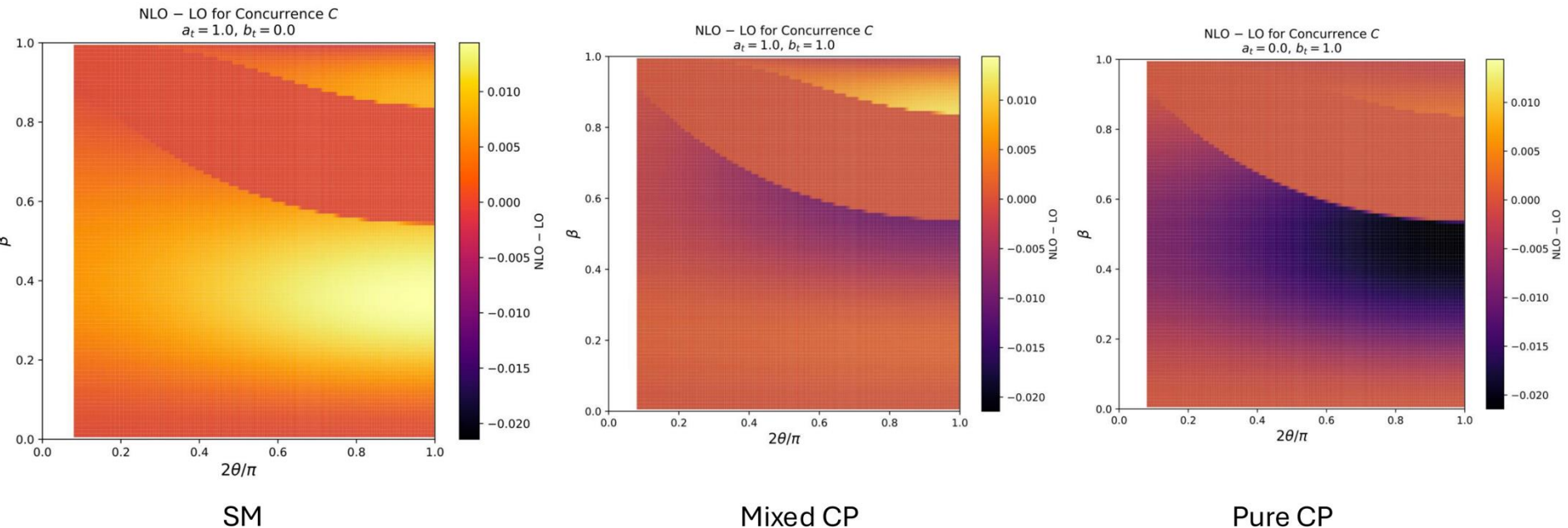
Earlier Partial Calculations:

[C. Schmidt & M. Peskin \(1992\)](#), [arXiv:hep-ph/9312210](#), [arXiv:2406.06694](#)

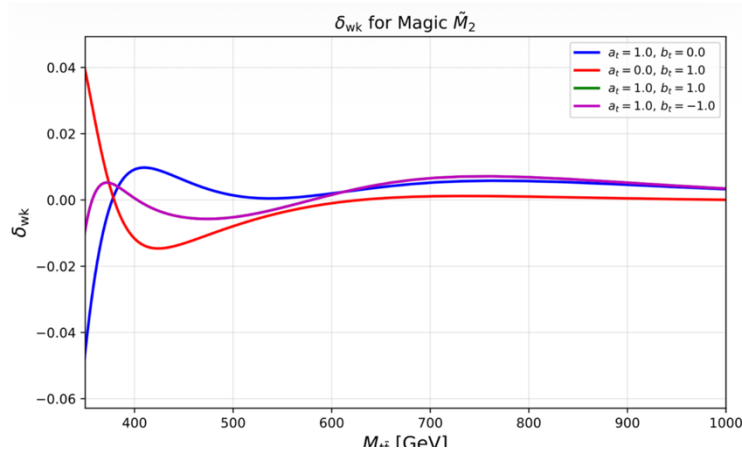
CP-odd Higgs: impact on entanglement



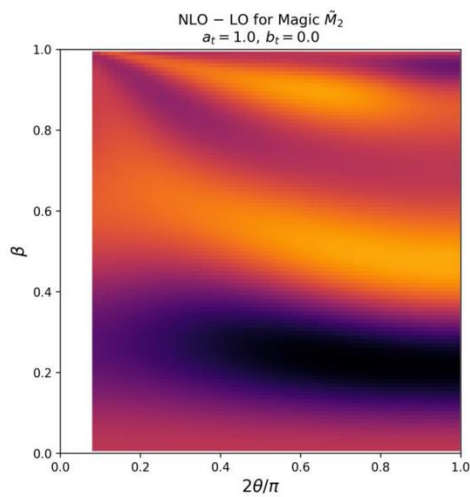
- Concurrence differs by up to $\sim 4\%$ between SM, mixed and pure CP-odd
- $b_t = +1$ and $b_t = -1$: identical curves



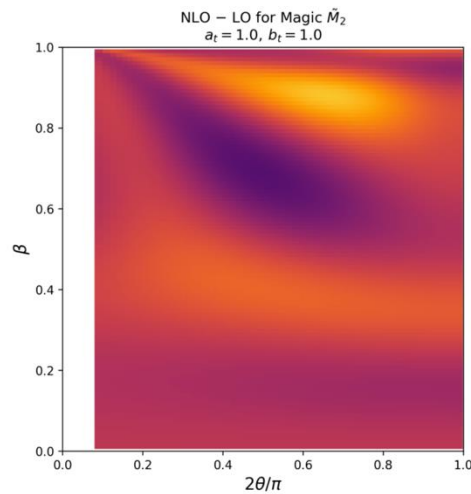
CP-odd Higgs: impact on magic



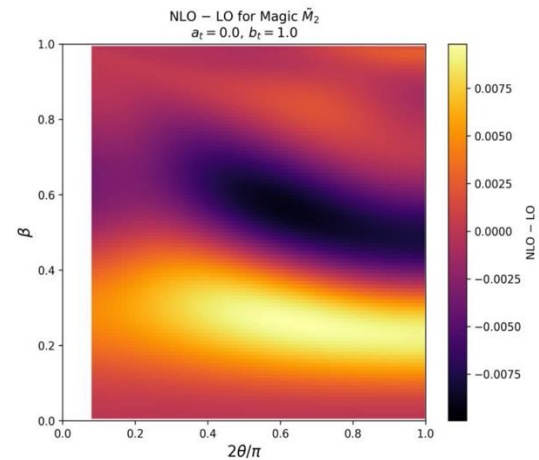
Quantum observables are sensitive to scalar and pseudoscalar interactions! But they are not odd under CP



SM



Mixed CP



Pure CP

[M. Yáñez, DPF 2026; arXiv:2607.28761](#)

Full Quantum Tomography of top quarks

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

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

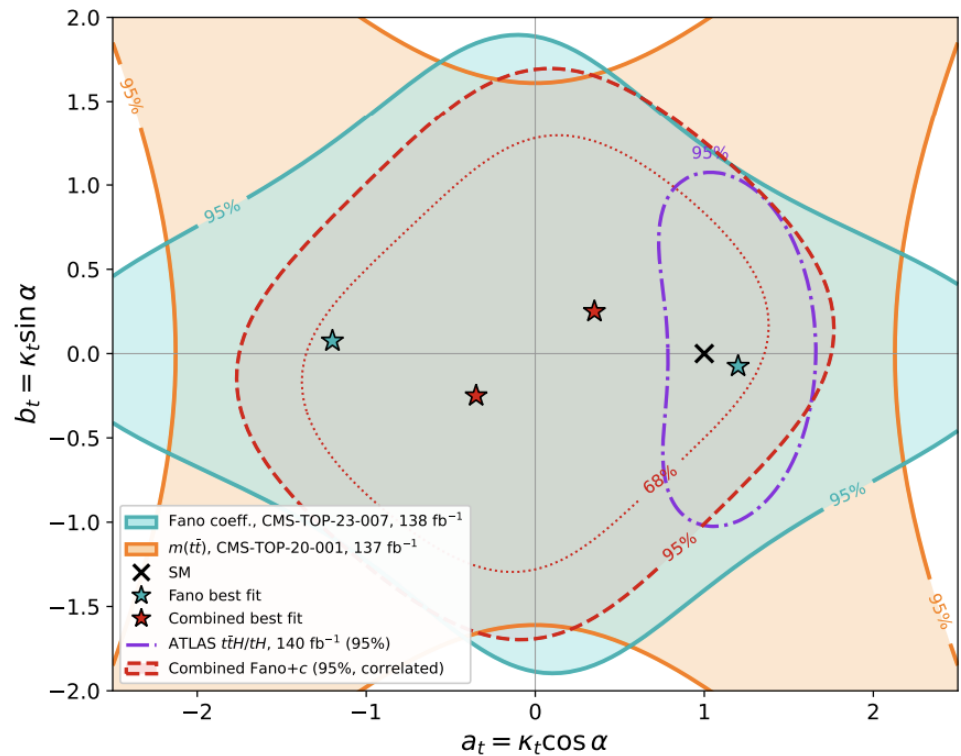
And extract all fifteen independent Fano coefficients $Q_m(a_t, b_t)$, hence defining

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

Where we define $\Delta Q_m = Q_m(a_t, b_t) - Q_m^{\text{obs}}$, and use the 15x15 covariance matrix. V reported by CMS.

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

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



- Differential $m(t\bar{t})$ cross section ([arXiv:2108.02803](https://arxiv.org/abs/2108.02803)): open along flat directions, blind to the sign of b_t ; overlaid, not combined
- Tomography closes the flat directions and is sensitive to the sign of $a_t b_t$
- ATLAS $t\bar{t}H/tH$ ([arXiv:2606.04855](https://arxiv.org/abs/2606.04855)): comparable reach, independent directions
- Binning is not optimized and further sensitivity is expected for finer binning.

Outlook

- CP violation is an important ingredient to explain the Baryon Asymmetry of the Universe.
- Additional Sources of CP violation can be added by extending the Higgs sector
- Additional scalars also help with strong first order phase transitions; another ingredient for Baryogenesis.
- Extending the Higgs sector and adding in CP violation, usually results in CP violating top-Higgs interactions
- Major program of LHC is to constrain/uncover such sources of CP violation.
- Here we looked at CP violation in Higgs + 1jet , Higgs +2 jet production and top quark pair production at LHC as a way of probing such interactions
- $t\bar{t}$ quark differential cross-sections ($m_{t\bar{t}}$) can probe some aspects.
- Quantum Information observables such as Magic and Concurrence also display sensitivity.
- Quantum tomography significantly improves constraints in flat directions as they contain observables that are odd under CP.
- WIP: Implementing constraints for a variety of models: 2HDM, Radion, Dark Matter....

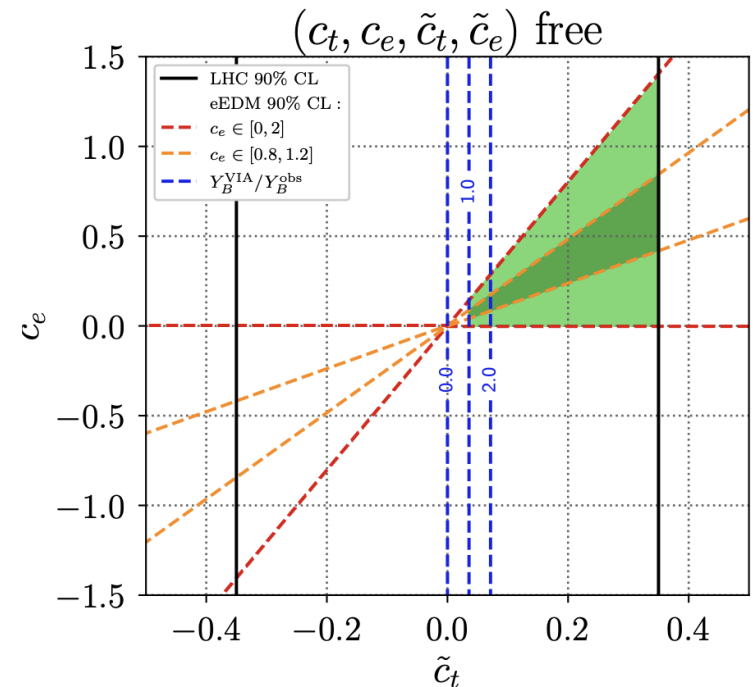
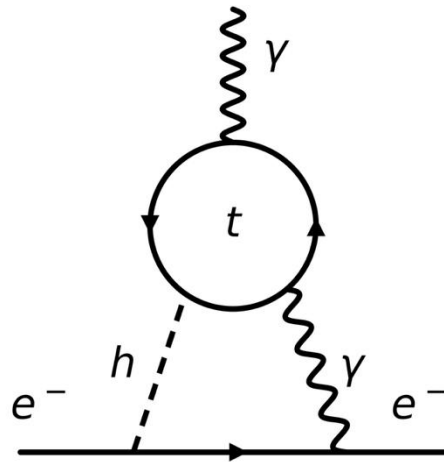
Backup



Constraints from EDM

$$\begin{aligned} \frac{d_e}{d_e^{\text{ACME}}} = & c_e (870.0\tilde{c}_t + 3.9\tilde{c}_b + 2.8\tilde{c}_c + 0.01\tilde{c}_s + 8 \cdot 10^{-5}\tilde{c}_u + 7 \cdot 10^{-5}\tilde{c}_d + 3.4\tilde{c}_\tau + 0.03\tilde{c}_\mu) \\ & + \tilde{c}_e (610.1c_t + 3.1c_b + 2.3c_c + 0.01c_s + 7 \cdot 10^{-5}c_u + 6 \cdot 10^{-5}c_d + 2.8c_\tau + 0.02c_\mu \\ & - 1082.6c_V) \\ & + 2 \cdot 10^{-6}c_e\tilde{c}_e \end{aligned}$$

$$d_e^{\text{ACME}} = 1.1 \cdot 10^{-29} e \text{ cm}$$



[arXiv:2202.11753](https://arxiv.org/abs/2202.11753)

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:

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

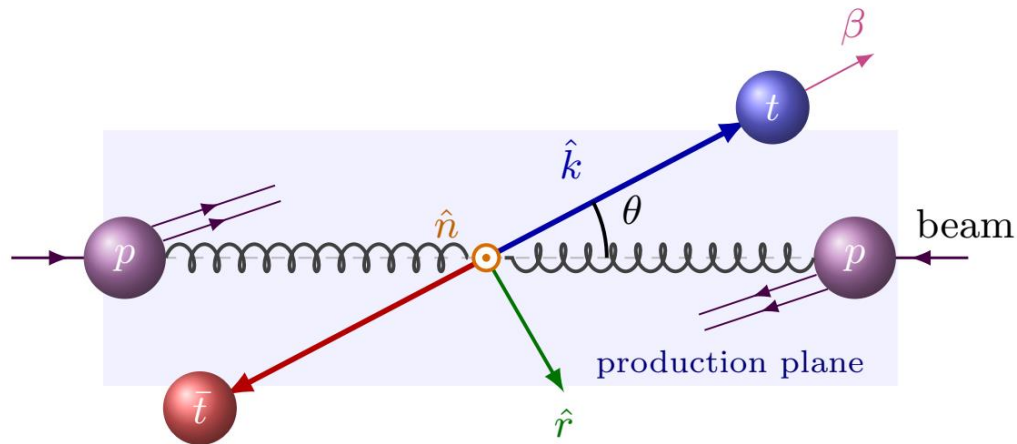
Hence, for a binned analysis [\[CMS, 2409.11067\]](#) where k denotes the bin width we obtain the integrated spin production matrix as:

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

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

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

Spin axes {n, r, k}



- $\hat{n}$: normal to the production plane
- $\hat{r}$: in the plane, transverse
- $\hat{k}$: top direction
- Axis order {n, r, k}

CP violation lives inside the density matrix

observable	CP	depends on	one-loop origin
cross section $\sigma \propto \text{Tr } R$	even	a_t^2, b_t^2	not sensitive to CP
C_{nn}, C_{rr}, C_{kk}	even	a_t^2, b_t^2	
C_{nr}^-, C_{nk}^-	odd	$a_t b_t$	dispersive part
$P_k - \bar{P}_k$	odd	$a_t b_t$	absorptive part

$$C_{ij}^- = C_{ij} - C_{ji}. \quad \text{Main CP-odd observable: } C_{nr}^-$$

Backup: significance of every coefficient

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

