Single-spin measurements and heavy new physics in the $e^+e^- \to t\bar{t}$ process at an FCC-ee

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Northwestern University&CFNS

H.C., Petriello, arXiv:2511.01994

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Outline

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Why Expect New Physics

- The Standard Model has been tested with remarkable precision

Observable	Measurement	SM
M_Z [GeV]	91.1876 ± 0.0021	91.1884 ± 0.0019
Γ_Z [GeV]	2.4955 ± 0.0023	2.4940 ± 0.0009
$\sin^2 \theta^{\ell}_{\mathrm{eff}}$	0.2324 ± 0.0012	0.23161 ± 0.00004

[Particle Data Group]

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Why Expect New Physics

- The Standard Model has been tested with remarkable precision
- Successfully describes strong, and electroweak interactions
- Expected to break down at some higher energy scale

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[Particle Data Group]

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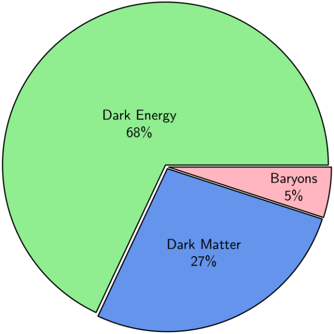
Why the Standard Model is Incomplete

- **Cosmological evidence:** dark matter and dark energy point to physics beyond the SM



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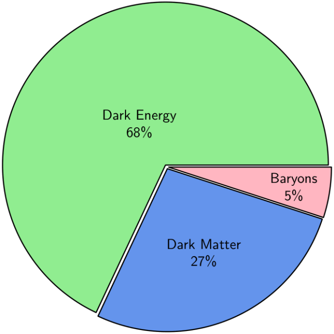

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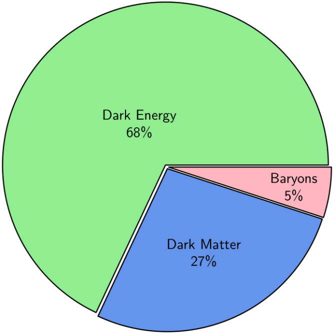
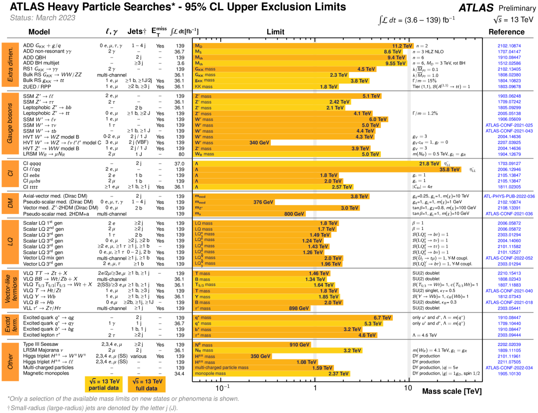
Why the Standard Model is Incomplete

- **Cosmological evidence:** dark matter and dark energy point to physics beyond the SM
- **Particle physics evidence:** neutrinos have non-zero masses
- This requires an extension of the SM



Direct Searches for New Physics at the LHC

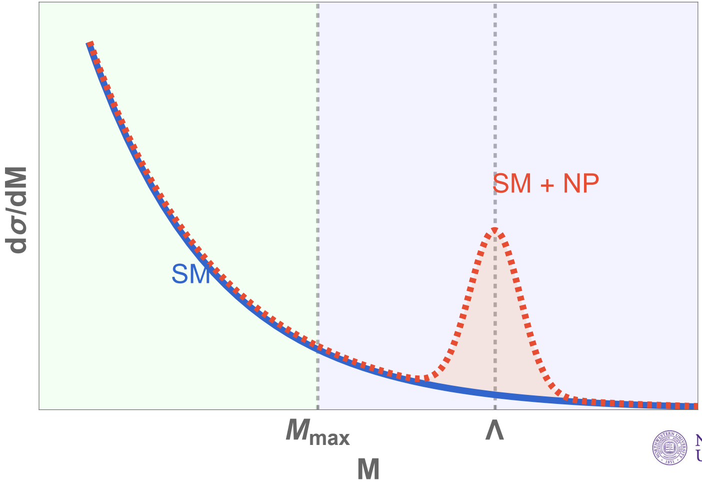
- Absence of direct discovery of new physics at the LHC
- Scale of new physics lies above the energies currently accessible at colliders



[ATLAS]

Standard Model Effective Field Theory

New physics exist at scale $\Lambda \gg$ Maximum energy from collider M_{max}.
We need to exploring indirect effects via precision measurements



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Standard Model Effective Field Theory

As $\Lambda \gg M_{max}$, their effects can be captured by Standard Model Effective Field Theory (SMEFT)
SMEFT: An EFT that describes the indirect effects of heavy new physics at low energies, it extend SM with higher-dimension operators suppressed by Λ built from Standard Model fields and respecting its gauge symmetries.

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_j \frac{C_j^{(6)}}{\Lambda^2}\mathcal{O}_j^{(6)} + \dots$$

- Dim-5: lepton number violation $\rightarrow$ neutrino masses (irrelevant here)
- Dim-6: leading contributions to top-quark production

$$\sigma \sim |M_{SM}|^2 + \frac{2}{\Lambda^2} Re|M_{SM} M_6^\star|^2 + \frac{1}{\Lambda^4}|M_6|^2 + \dots$$

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What can SMEFT teach us?

Analyzing precision data within the SMEFT framework allows for two complementary outcomes.

Best case: Non-zero Wilson coefficient signals, indicating new physics at a scale not far above current experimental reach, providing a concrete target for future colliders.

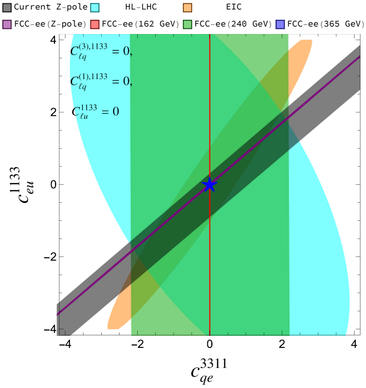
Otherwise: Strong constraints on Wilson coefficients will rule out many new physics models and tell us where to look next, both experimentally and theoretically.

We've seen this strategy before in particle physics. Precision electroweak data pointed to the Higgs mass well before the Higgs was found.

Features of the SMEFT framework

• A board range of NP model can be matched to SMEFT. Determine constraint on SMEFT coefficient is equivalent to determine constraint on the NP model.

• It allows straightforward comparisons of different experiment.



[Bellafronte, Dawson, Giardino, Liu](2025)

We can compare constrains on Wilson coefficient from Different experiments.

An example of flat direction: One experiment can only probe one linear combination of Wilson coefficients; need differnet experiment to break the degeneracy.

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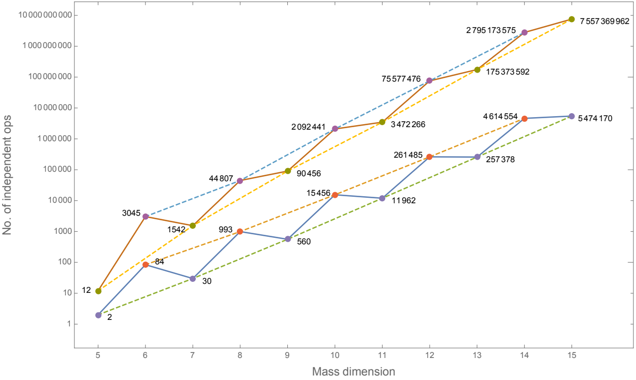
Dimension-Six Operators in SMEFT

Even at dimension six, there is a large SMEFT parameter space.



[Henning, Lu, Melia, Murayama](2015)

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Top Quark: A Unique Window to New Physics

The Heaviest known elementary particle

Top quark mass: 173 GeV, Yukawa coupling ~ 1

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Short Lifetime and Spin Observables

Top quark decays before hadronization.
The spin and other quantum information of the top quark are directly imprinted on its decay products.
$\rightarrow$Enables detailed study of top spin observable and their sensitivity to new physics.

Top-Quark Spin Observables: From LHC to FCC-ee

Spin measurements at the LHC

- Top-quark spin measurements, in particular spin correlations in $t\bar{t}$ production, have already been performed at the LHC
- These measurements have motivated extensive theoretical studies of quantum information aspects of top quarks. [Afik,de Nova](2022), [Maltoni, Severi, Tentori, Vryonidou](2024),...

Motivation for FCC-ee

- Clean e^+e^- environment: electroweak production dominates, QCD corrections to spin observables are small[Brandenburg, Flesch, Uwer](1998)
- Record approximately one million $t\bar{t}$ events during its operation

Recent FCC-ee studies

- Top–antitop quantum information at FCC-ee[Maltoni, Severi, Tentori, Vryonidou](2024)

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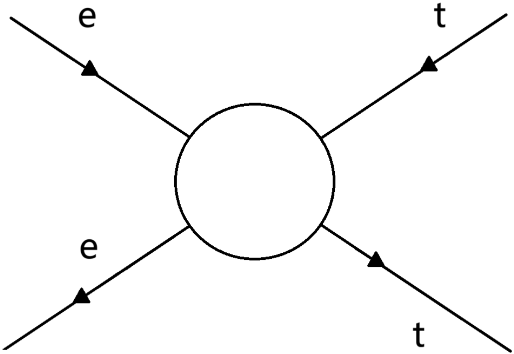
Relevant Dimension-6 Operators for $e^+e^- \to t\bar{t}$

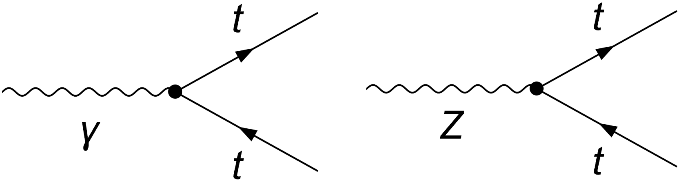
We focus on operators that directly affect $e^+e^- \to t\bar{t}$ near threshold



Relevant Dimension-6 Operators for $e^+e^- \to t\bar{t}$

We focus on

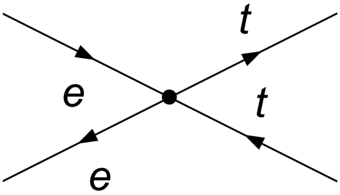
1. Top-Z vertex corrections $((H^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q), \ldots)$
2. Electroweak dipole operators $((\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{H}W^I_{\mu\nu}, \ldots)$



Relevant Dimension-6 Operators for $e^+e^- \to t\bar{t}$

We focus on

1. Top-Z vertex corrections ($(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$, ...)
2. Electroweak dipole operators ($(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{H}W^I_{\mu\nu}$, ...)
3. Four-fermion interactions ($(\bar{Q}\gamma^\mu Q)(\bar{l}\gamma_\mu l)$, ...)



Outline

Observables

Our goal is to study how the dimension-6 Wilson coefficients affect the following observables.:

- Unpolarized cross sections
- Single Spin measurement
- Spin correlation

Assuming that the top and anti-top have spin directions $\hat{s}_t$ and $\hat{s}_{\bar{t}}$ respectively, The matrix-element squared for $e^+e^- \to t\bar{t}$ is:

$$|\mathcal{M}(\hat{s}_t, \hat{s}_{\bar{t}})|^2 = A + \hat{s}_t B^{(t)} + \hat{s}_{\bar{t}} B^{(\bar{t})} + \hat{s}_t \hat{s}_{\bar{t}} C^{(t\bar{t})}$$

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Spin Basis Choice

Define:

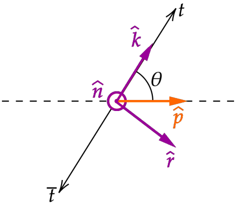
$$\hat{k} = \text{top momentum direction},$$

$$\hat{p} = \text{positron beam direction},$$

$$\hat{k} \cdot \hat{p} = \cos\theta.$$

Construct an orthonormal basis:

$$\hat{r} = \frac{\hat{p} - \hat{k}\cos\theta}{\sin\theta}, \qquad \hat{n} = \frac{\hat{p} \times \hat{k}}{\sin\theta}, \qquad \beta = \sqrt{1 - \frac{4m_t^2}{s}}.$$



[Maltoni, Severi, Tentori, Vryonidoud](2024)

Formalism

Considering 4-fermion operators and top-Z vertex corrections, $c_t \equiv \cos\theta_t$, and $s_t \equiv \sin\theta_t$, θ_t is the angle between t and $\bar{t}$

$$
\begin{aligned}
A &= F^0(2-\beta^2+\beta^2 c_t^2) + F^1 c_t + F^{At}(1+c_t^2) \\
C_{kk} &= F^0[\beta^2+(2-\beta^2)c_t^2] + F^1 c_t + F^{At}(1+c_t^2) \\
C_{rr} &= F^0(2-\beta^2)s_t^2 - F^{At} s_t^2 \\
C_{nn} &= -F^0\beta^2 s_t^2 + F^{At} s_t^2 \\
C_{kr} &= 2F^0\sqrt{1-\beta^2}\,c_t s_t + F^1 \frac{\sqrt{1-\beta^2}}{2} s_t
\end{aligned}
$$

with

$$F^i = F^i_{[SM]} + \frac{1}{\Lambda^2} F^i_{[d6]} + \frac{1}{\Lambda^4} F^i_{[d8]}$$

When $\beta \to 0$

$$F^0 \sim 1, \quad F^1 \sim \beta, \quad F^{At} \sim \beta^2.$$

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Formalism

$$
\begin{aligned}
B_k^{(t)} &= (1+c_t^2)G^0 + c_t\left[G^1 + G^{At}\right], \\
B_r^{(t)} &= \sqrt{1-\beta^2}c_t s_t G^0 + \sqrt{1-\beta^2}s_t G^1, \\
B_n^{(t)} &= 0\,.
\end{aligned}
$$

Gs are different linear combination of Wilson coefficient from Fs. This means single spin observables probe directions in Wilson-coefficient space that are invisible to traditional measurements When $\beta \to 0$

$$G^0 \sim \beta, \quad G^1 \sim 1, \quad G^{At} \sim \beta^2.$$

Formalism

$F^0_{[d6]}$ and $G^1_{[d6]}$ are proportional to different linear combinations of Wilson coefficients.

$$F^0_{[d6]}(\beta = 0) \sim e^2 Q_e Q_t C_{VV} + g_{vt} \frac{1}{(1 - M_Z^2/4m_t^2)} \{g_{ve} C_{VV} + g_{ae} C_{VA}\}$$

$$G^1_{[d6]}(\beta = 0) \sim e^2 Q_e Q_t C_{VA} + g_{vt} \frac{1}{(1 - M_Z^2/4m_t^2)} \{g_{ve} C_{VA} + g_{ae} C_{VV}\}$$

Both the unpolarized cross section and the spin-correlated terms are proportional to one linear combination of C_{VV} and C_{VA}. The single-spin terms depend on a different combination and provide different information on possible new physics. We can see this explicitly later in our numerical results.

Formalism

Considering electroweak dipole operators
The electroweak dipole operators introduce a new Dirac structure.

$$
\begin{aligned}
A_{[d6,D]} &= F^0_{[d6,D]} + F^1_{[d6,D]} c_t \,, \\
C^{(t\bar{t})}_{kk,[d6,D]} &= F^0_{[d6,D]} c_t^2 + F^1_{[d6,D]} c_t \,, \\
C^{(t\bar{t})}_{rr,[d6,D]} &= F^0_{[d6,D]} s_t^2 \,, \\
C^{(t\bar{t})}_{nn,[d6,D]} &= 0 \,, \\
C^{(t\bar{t})}_{kr,[d6,D]} &= F^0_{[d6,D]} \frac{2-\beta^2}{2\sqrt{1-\beta^2}} c_t s_t + F^1_{[d6,D]} \frac{s_t}{2\sqrt{1-\beta^2}} c_t
\end{aligned}
$$

When $\beta \to 0$

$$F^0_{[d6,D]} \sim 1, \quad F^1_{[d6,D]} \sim \beta,$$

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Formalism

Considering electroweak dipole operators.
The electroweak dipole operators introduce a new Dirac structure.

$$\begin{aligned} B_{k,[d6,D]} &= G^{0}_{[d6,D]} c_t + G^{1}_{[d6,D]} (1 + c_t^2)\,, \\ B_{r,[d6,D]} &= -G^{0}_{[d6,D]} \frac{s_t(2-\beta^2)}{2\sqrt{1-\beta^2}} + G^{1}_{[d6,D]} \frac{c_t s_t}{\sqrt{1-\beta^2}} \end{aligned} \quad (1)$$

When $\beta \to 0$

$$G^{0}_{[d6,D]} \sim 1, \quad G^{1}_{[d6,D]} \sim \beta,$$

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Angular structure of $t\bar{t}$ production

Angular decomposition

$$\frac{1}{\sigma}\frac{d\sigma}{dc_t} = \frac{1}{2}\left[1 + A_{FB}\, P_1(c_t) + A_2\, P_2(c_t)\right]$$

$P_i(c_t)$: Legendre polynomials

Angular structure of $t\bar{t}$ production

Angular decomposition

$$\frac{1}{\sigma}\frac{d\sigma}{dc_t} = \frac{1}{2}\left[1 + A_{FB}\,P_1(c_t) + A_2\,P_2(c_t)\right]$$

Dependence on F

$$\sigma \propto 2\left(1 - \frac{\beta^2}{3}\right) F^0 + \frac{4}{3} F^{At}$$

$$A_{FB} \propto F^1$$

$$A_2 \propto \frac{2}{3}\left(\beta^2 F^0 + F^{At}\right)$$

$P_i(c_t)$: Legendre polynomials

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Angular structure of $t\bar{t}$ production

Dependence on F near threshold ($\beta \to 0$)

$$\sigma \propto 2\left(1 - \frac{\beta^2}{3}\right) F^0 + \frac{4}{3} F^{At} \sim 2F^0$$

$$A_{FB} \propto F^1$$

$$A_2 \propto \frac{2}{3}\left(\beta^2 F^0 + F^{At}\right)$$

A_{FB} provides a direct probe of F^1

Near threshold, σ is dominated by F^0

A_2 offers enhanced sensitivity to F^{At}

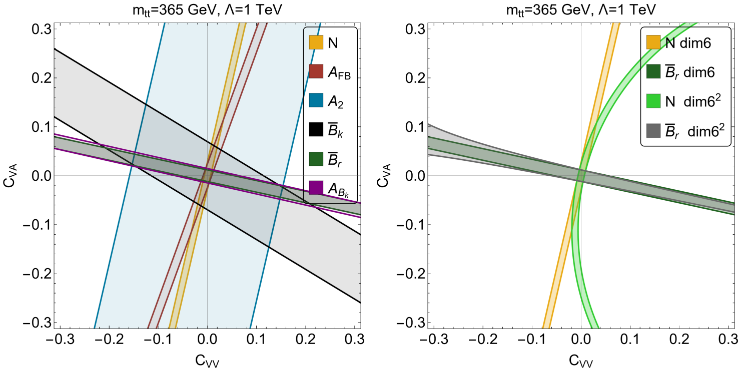
Outline

One-coefficient bounds

Expected 95% CL bounds on Λ for different $C_i = 1$ using $\sqrt{s} = 365$ GeV.
A 1% systematic uncertainty is included for all observables.
The spin correlation will never provide the strongest bound.

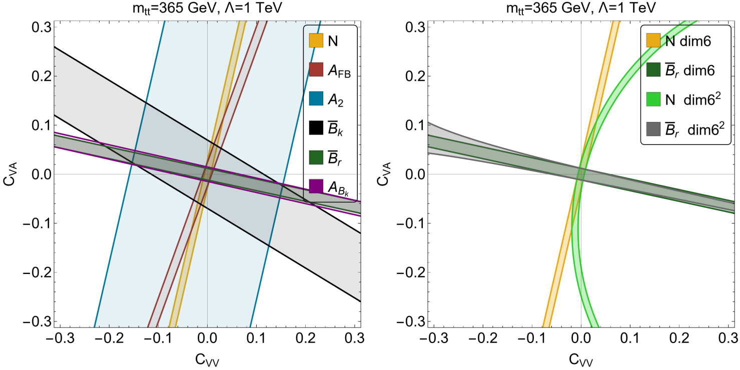
	N	A_{FB}	A_2	$\bar{B}_k$	A_{B_k}	$\bar{B}_r$	A_{B_r}	$\bar{C}_{kk}$
$\Lambda_{C_{VV}=1}[TeV]$	**14**	12	2.8	3.3	4.7	4.9	1.7	1.2
$\Lambda_{C_{VA}=1}[TeV]$	6.7	7.2	1.3	4.2	9.9	**10**	2.2	0.55
$\Lambda_{C_{AV}=1}[TeV]$	0.99	**7.9**	1.3	6.1	2.6	0.50	3.2	0.52
$\Lambda_{C_{AA}=1}[TeV]$	3.0	**16**	3.8	2.8	1.2	1.5	1.5	1.6
$\Lambda_{C_{tZ}=1}[TeV]$	3.5	3.6	1.5	1.7	4.1	**4.4**	0.97	0.62
$\Lambda_{C_{t\gamma}=1}[TeV]$	**7.4**	6.5	3.2	1.8	2.6	2.5	0.9	1.3

Two-dimensional constraints



Different observables probe different directions in parameter space.
Single spin observable is helping us to remove flat direction.

Validity of the SMEFT expansion



dim 6^2 are numerically small

Differences appear only in regions already excluded by combined fits Linear dimension-6 analysis is well justified

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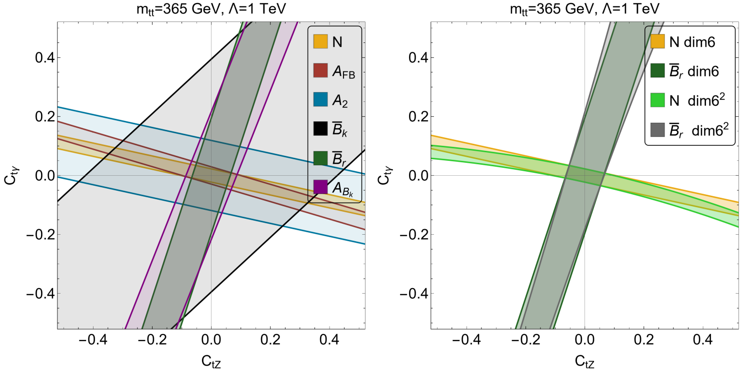
Two-dimensional constraints



The result holds for dipole operators.

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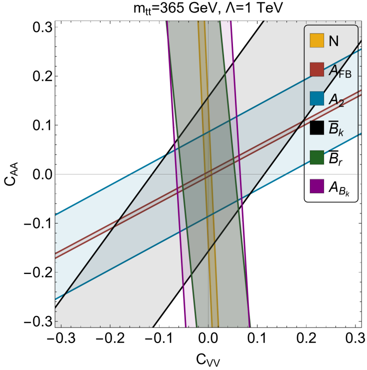
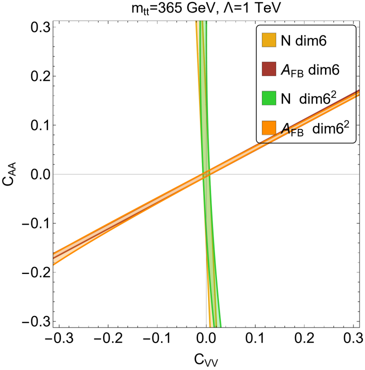
Two-dimensional constraints





Different observables probe different directions in parameter space. The potential flat direction can be resolved without spin observables through the measurement of N and A_{FB}.

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Outline

Conclusions

(1) Single-spin measurements probe different combinations of Wilson coefficients in the SMEFT parameter space than other observables, which leads to important complementarity that helps remove flat directions that can appear.

(2) Single-spin observables provide stronger sensitivity to heavy new physics compared to observables based on correlated $t\bar{t}$ spins.

(3) For the SMEFT parameter space studied here, a combination of single-spin measurements, the total event rate and the forward-backward asymmetry were sufficient to remove all degeneracies between Wilson coefficients.

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Outlook: Future Directions

Beyond tree-level

Our study is currently at tree level. Including higher-order QCD and electroweak corrections would capture additional effects.

Polarized linear colliders

Using polarized beams can significantly enhance signal-to-background ratios for many observables.

High-energy muon colliders

Operating at $\sqrt{s} \sim 3 - 10$ TeV, $t\bar{t}$ production would mainly proceed via $\gamma\gamma$ and WW fusion. This opens new possibilities to probe a wider range of top-quark couplings and explore novel phenomena.

Thank You!

Backup:4 fermion

$$
\begin{aligned}
\mathcal{O}_{Ql}^{(1)} &= (\bar{Q}\gamma^{\mu}Q)(\bar{l}\gamma_{\mu}l)\,, \\
\mathcal{O}_{Ql}^{(3)} &= (\bar{Q}\gamma^{\mu}\tau^{I}Q)(\bar{l}\gamma_{\mu}\tau^{I}l)\,, \\
\mathcal{O}_{Qe} &= (\bar{Q}\gamma^{\mu}Q)(\bar{e}\gamma_{\mu}e)\,, \\
\mathcal{O}_{tl} &= (\bar{t}\gamma^{\mu}t)(\bar{l}\gamma_{\mu}l)\,, \\
\mathcal{O}_{te} &= (\bar{t}\gamma^{\mu}t)(\bar{e}\gamma_{\mu}e).
\end{aligned}
$$

Backup: Top-Z vertex corrections

$$
\begin{aligned}
\mathcal{O}_{HQ}^{(1)} &= i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)\,, \\
\mathcal{O}_{HQ}^{(3)} &= i(H^\dagger \overleftrightarrow{D}_{\mu I} H)(\bar{Q}\gamma^\mu \tau^I Q)\,, \\
\mathcal{O}_{Ht} &= i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)\,.
\end{aligned}
$$

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Backup: Electroweak dipole operators

$$\begin{aligned}\mathcal{O}_{tW} &= (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{H}W^I_{\mu\nu}\,,\\ \mathcal{O}_{tB} &= (\bar{Q}\sigma^{\mu\nu}t)\tilde{H}B_{\mu\nu}\,.\end{aligned}$$

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Backup: F_{d6}

$$
\begin{aligned}
F^0_{[d6]} &= 8N_C e^2 Q_e Q_t C_{VV}\frac{m_t^2}{1-\beta^2} + 32N_C\frac{m_t^4}{(1-\beta^2)D_Z} g_{vt}\left\{g_{ve}C_{VV} + g_{ae}C_{VA}\right\} \\
&- \frac{4N_C e^3 Q_t Q_e C_{HV} g_{ve} v^2 m_t^2}{c_w s_w D_Z} - \frac{16N_C e C_{HV} g_{vt} v^2 m_t^4\left({g_{ae}}^2 + {g_{ve}}^2\right)}{c_w s_w {D_Z}^2}, \\
F^1_{[d6]} &= 16N_C e^2 Q_e Q_t C_{AA}\beta\frac{m_t^2}{1-\beta^2} + 64N_C\beta\frac{m_t^4}{(1-\beta^2)D_Z} g_{vt}\left\{g_{ve}C_{AA} + g_{ae}C_{AV}\right\} \\
&+ 64N_C\beta\frac{m_t^4}{(1-\beta^2)D_Z} g_{at}\left\{g_{ve}C_{VA} + g_{ae}C_{VV}\right\} - \frac{8N_C Q_t Q_e \beta e^3 C_{HA} g_{ae} v^2 m_t^2}{c_w s_w D_Z} \\
&- \frac{64N_C\beta e^2 g_{ae} g_{ve} v^2 m_t^4 (C_{HA} g_{vt} + C_{HV} g_{at})}{c_w s_w D_Z^2}, \\
F^{At}_{[d6]} &= 32N_C\frac{\beta^2 m_t^4}{(1-\beta^2)D_Z} g_{at}\left\{g_{ve}C_{AV} + g_{ae}C_{AA}\right\} - \frac{16N_C\beta^2 e C_{HA} g_{at} v^2 m_t^4\left({g_{ae}}^2 + {g_{ve}}^2\right)}{c_w s_w {D_Z}^2}.
\end{aligned}
$$

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Backup: G_{d6}

$$
\begin{aligned}
G^{0}_{[d6]} &= 8N_C e^2 Q_e Q_t \beta C_{AV} \frac{m_t^4}{1-\beta^2} + 32 N_C \beta \frac{m_t^4}{(1-\beta^2)D_Z} g_{vt} \left\{ g_{ve} C_{AV} + g_{ae} C_{AA} \right\} \\
&+ 32 N_C \beta \frac{m_t^4}{(1-\beta^2)D_Z} g_{at} \left\{ g_{ve} C_{VV} + g_{ae} C_{VA} \right\} - \frac{4 N_C Q_t Q_e \beta e^3 C_{HA} g_{ve} v^2 m_t^2}{c_w s_w D_Z} \\
&- \frac{16 N_C \beta e v^2 m_t^4 \left({g_{ae}}^2 + {g_{ve}}^2 \right) \left(C_{HA} g_{vt} + C_{HV} g_{at} \right)}{c_w s_w D_Z^2}, \\
G^{1}_{[d6]} &= 16 N_C e^2 Q_e Q_t C_{VA} \frac{m_t^2}{1-\beta^2} + 64 N_C \frac{m_t^4}{(1-\beta^2)D_Z} g_{vt} \left\{ g_{ve} C_{VA} + g_{ae} C_{VV} \right\} \\
&- \frac{64 N_C e g_{ae} g_{ve} v^2 m_t^4 C_{HV} g_{vt}}{c_w s_w {D_Z}^2} - \frac{8 N_C Q_t Q_e e^3 C_{HV} g_{ae} v^2 m_t^2}{c_w s_w D_Z}, \\
G^{At}_{[d6]} &= 64 N_C \frac{\beta^2 m_t^4}{(1-\beta^2)D_Z} g_{at} \left\{ g_{ve} C_{AA} + g_{ae} C_{AV} \right\} - \frac{64 N_C e g_{ae} g_{ve} v^2 m_t^4 \beta^2 C_{HA} g_{at}}{c_w s_w {D_Z}^2}
\end{aligned}
$$

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